Physics at the Z pole

Reminder - what is the Z pole.

What the Z can tell us directly

Flavour at the Z pole

Physics at the Z pole

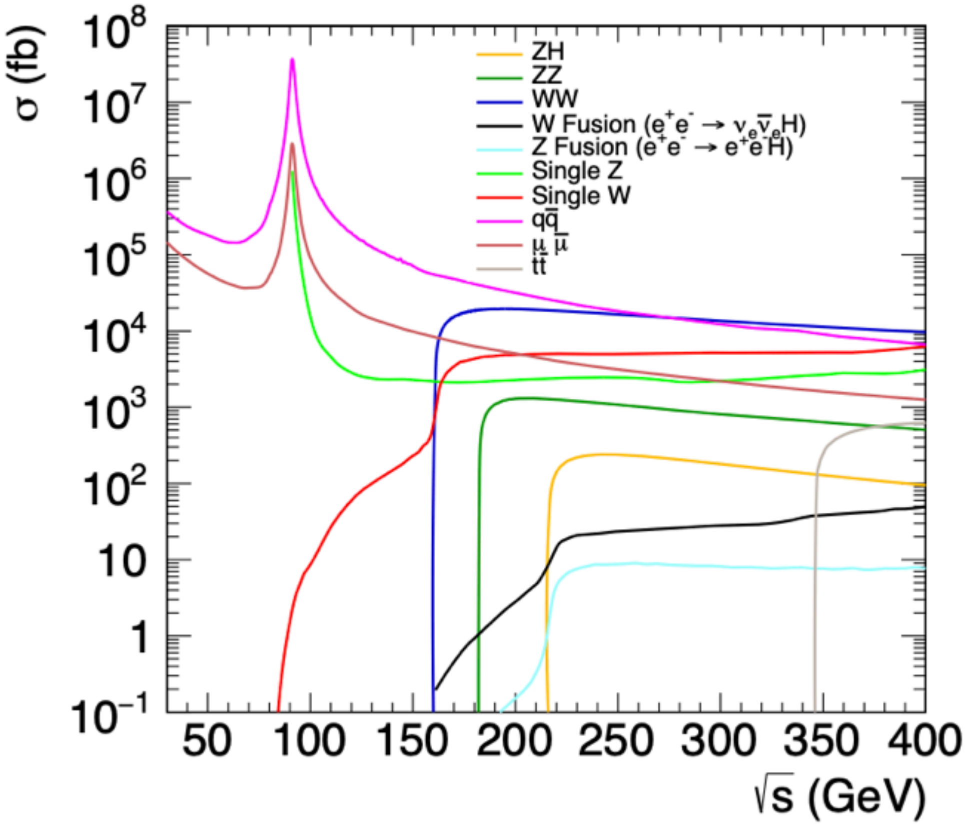
Reminder - what is the Z pole.

What the Z can tell us directly

Flavour at the Z pole

Heavy flavour bias as I am a heavy flavour person…

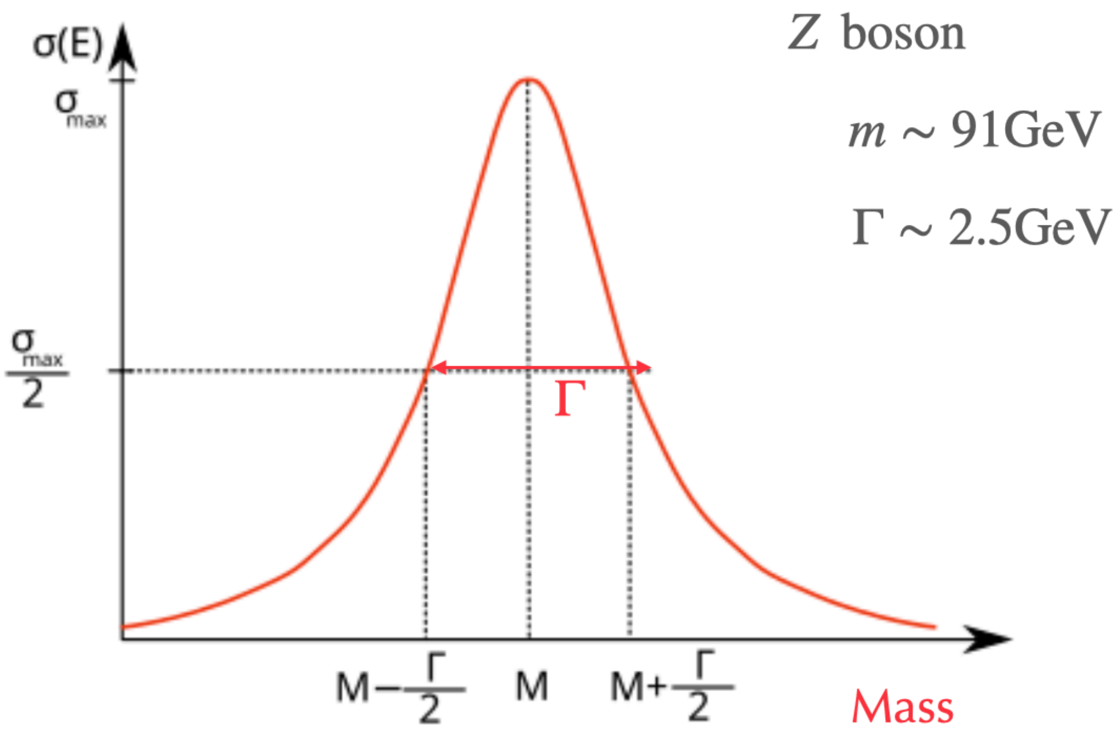
Physics at the Z pole summary



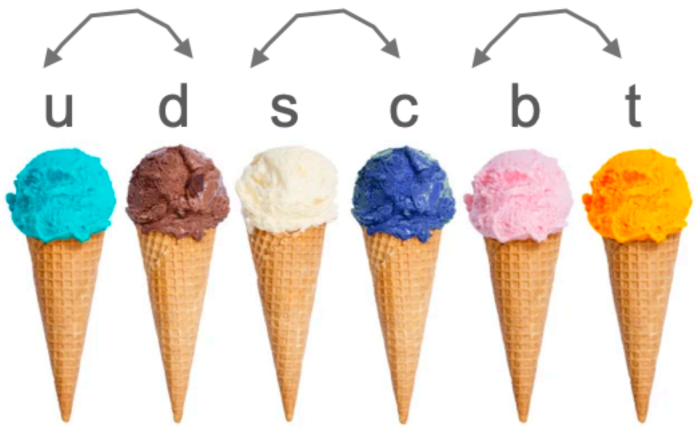
We will have most statistics at the Z-pole (5 x 10^{12} Z bosons)!!!

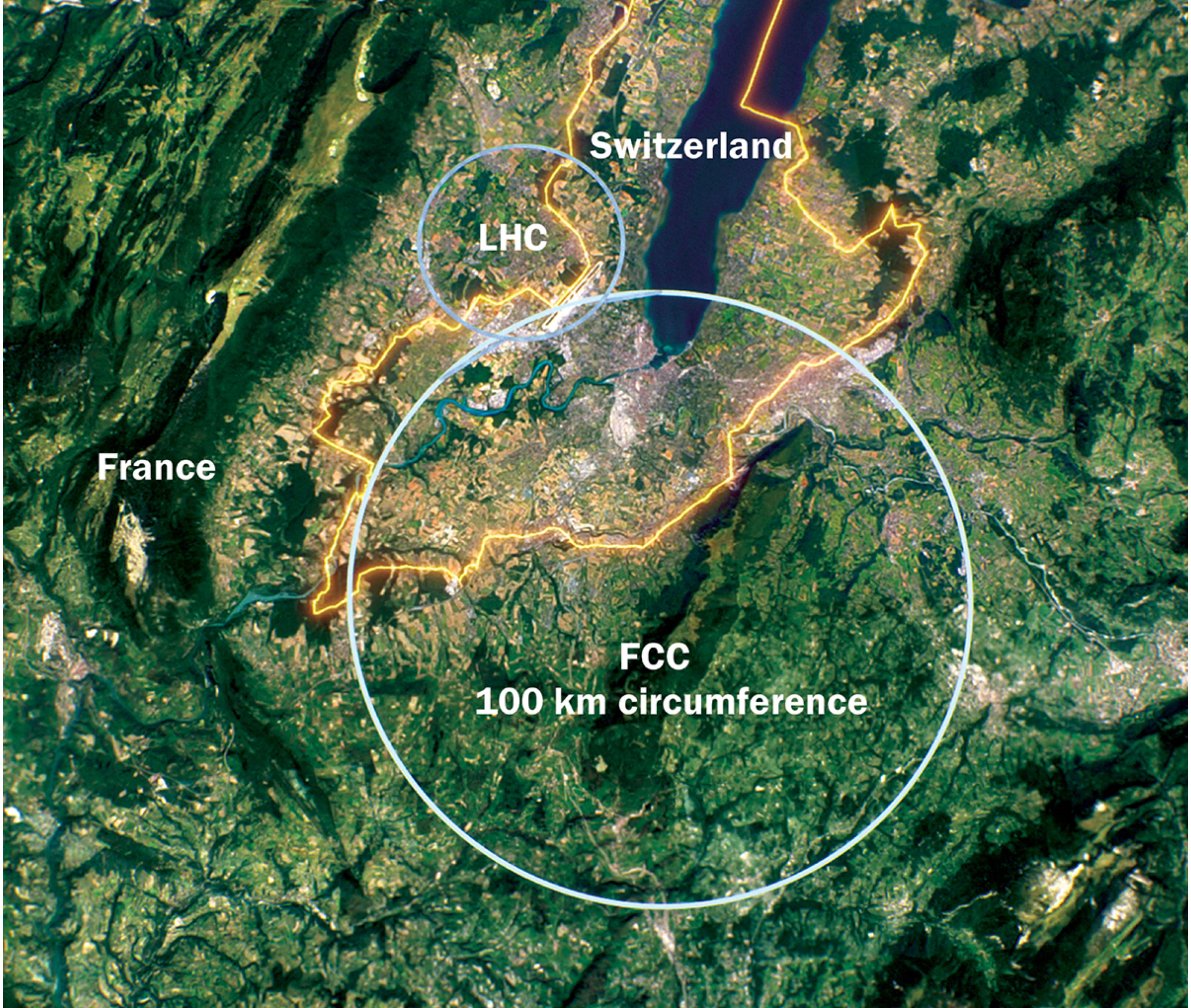
Both electroweak + flavour measurements

Electroweak measurements



Flavour

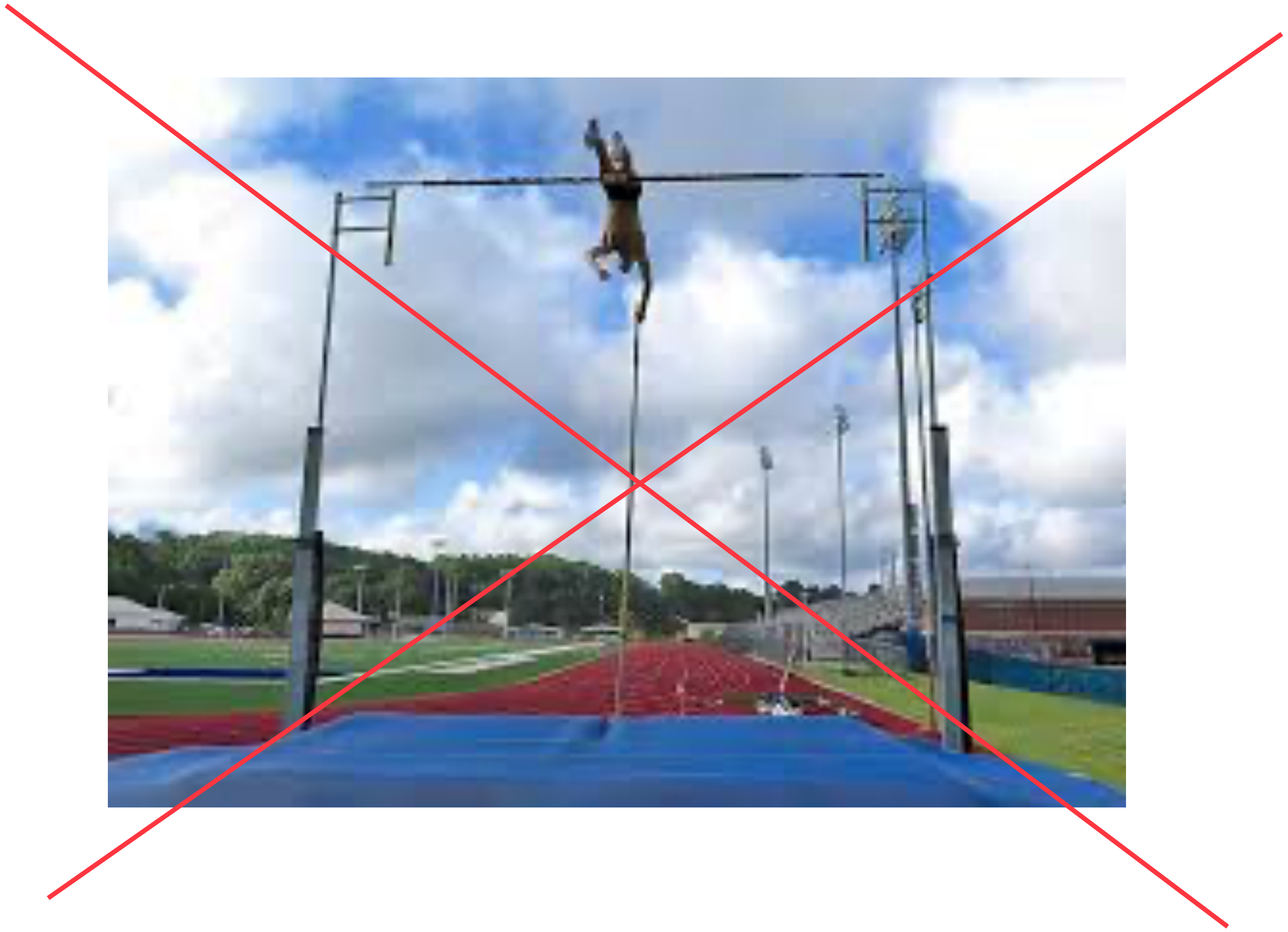



Switzerland
LHC
France
FCC
100 km circumference

What is a pole?

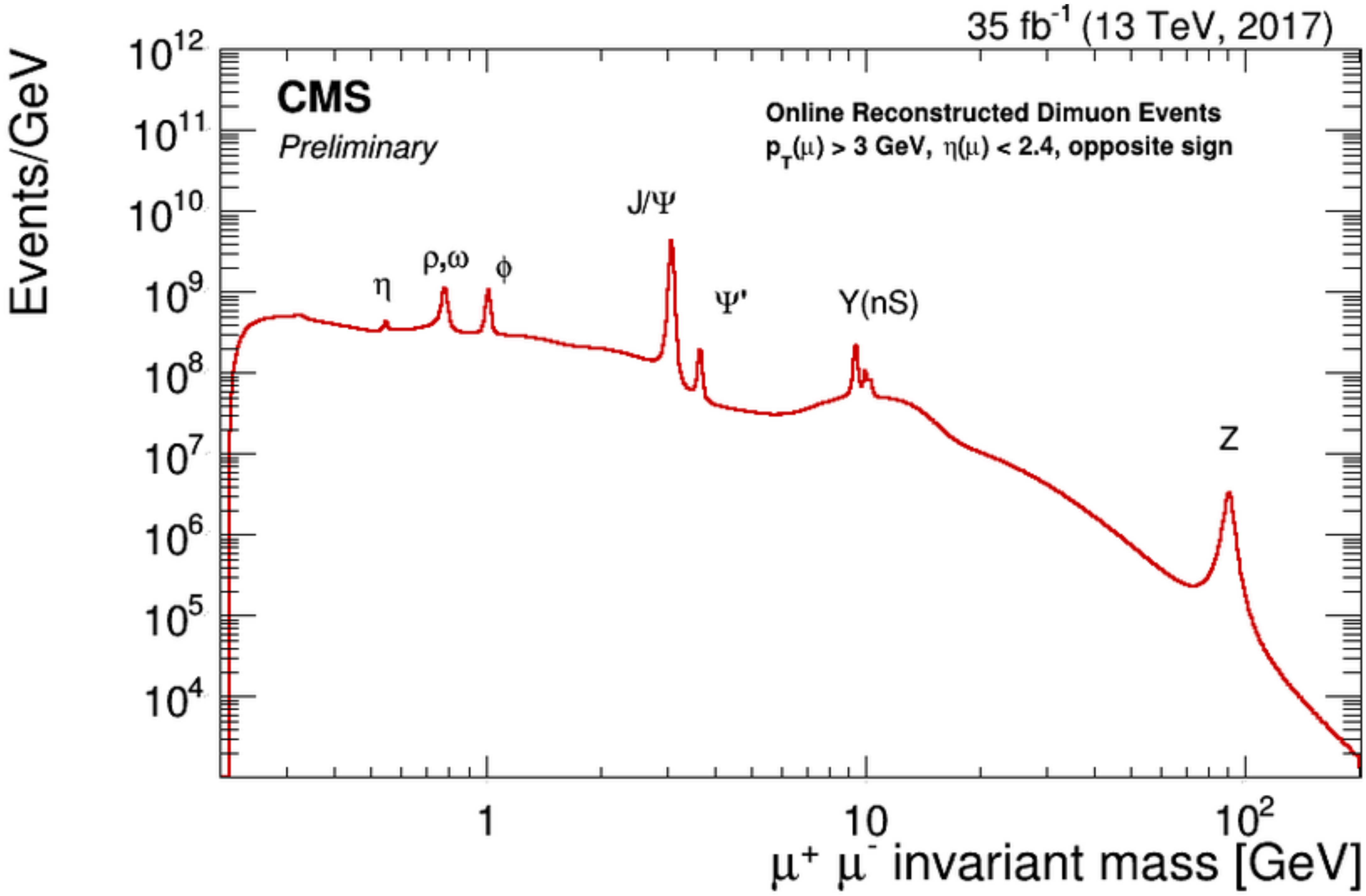
What is a pole?

What is a pole?



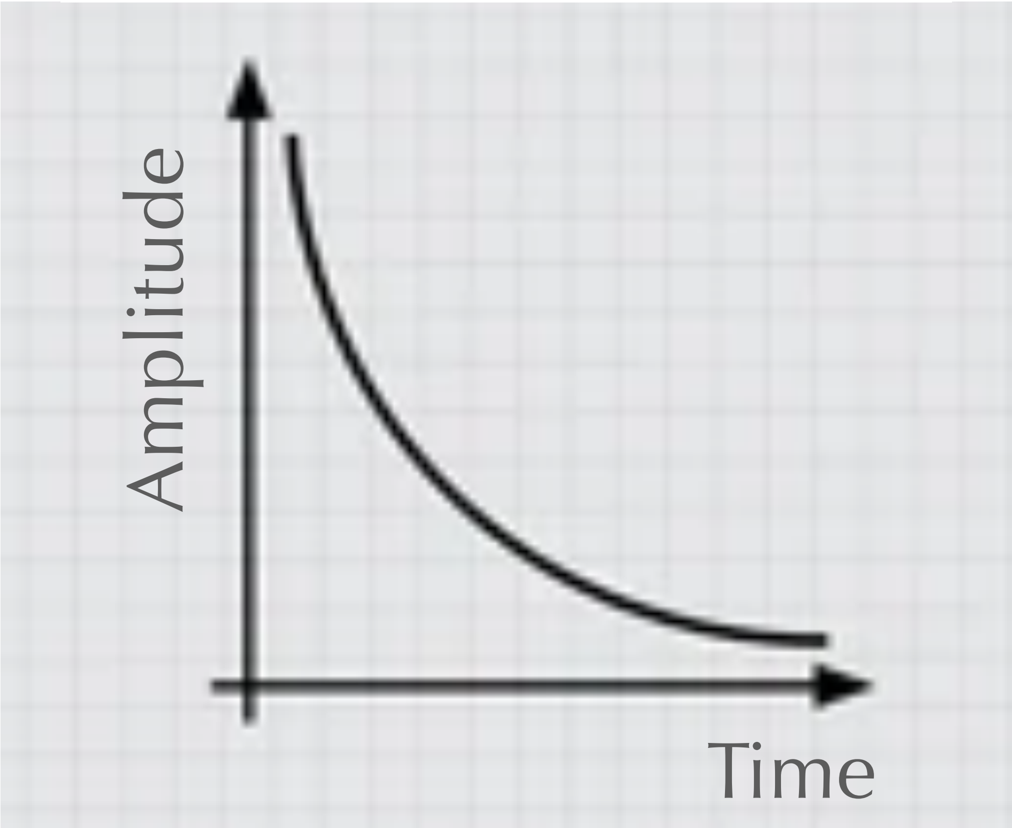
What is a pole?

Jargon term -> when ever your invariant mass hits a real (on-shell) particle



Poles can be described by Breit-Wigners functions

$$\psi(t) = \psi_0 \, e^{-\Gamma t/2} \, e^{-iE_0 t}$$



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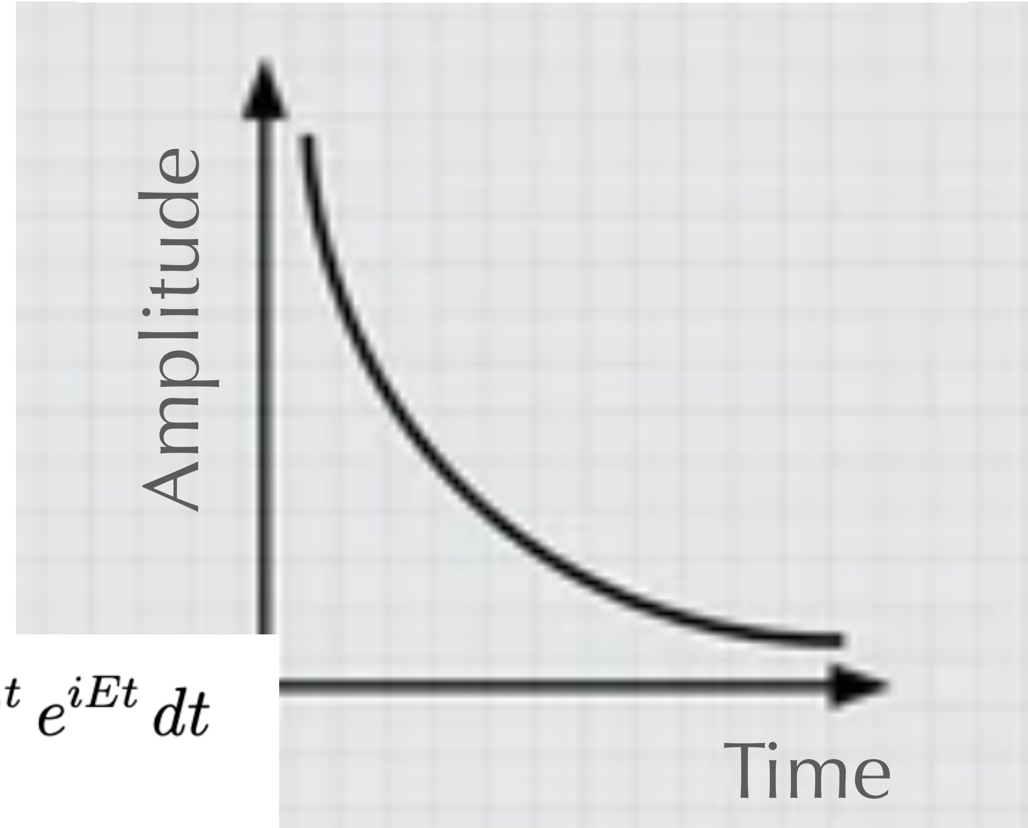


Fourier-transform exponential decay (+ phase oscillation)

$$\psi(E) = \int \psi(t)\, e^{iEt}\, dt = \int \psi_0\, e^{-\Gamma t/2}\, e^{-iE_0 t}\, e^{iEt}\, dt$$

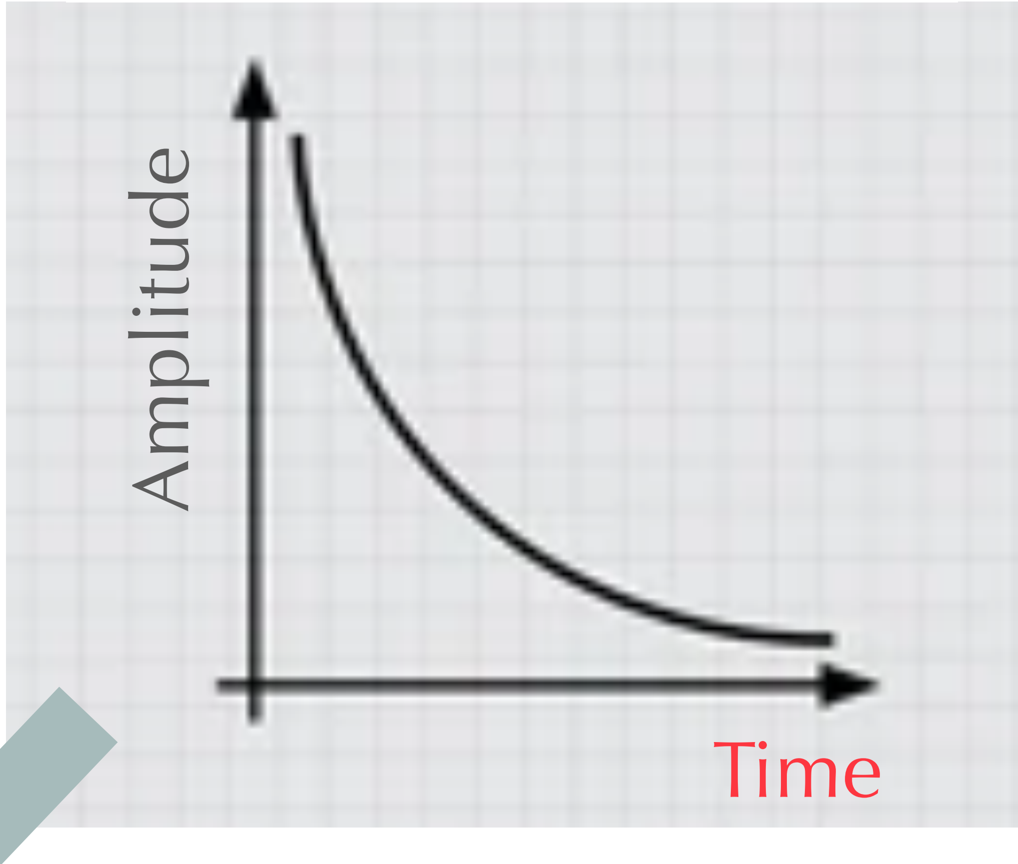
$$= \int \psi_0\, e^{i[(E-E_0)+i\Gamma/2]t}\, dt$$

Breit-Wigner (BW)

$$\psi(E) \sim \frac{1}{E-E_0+i\Gamma/2}$$

Poles can be described by Breit-Wigners functions

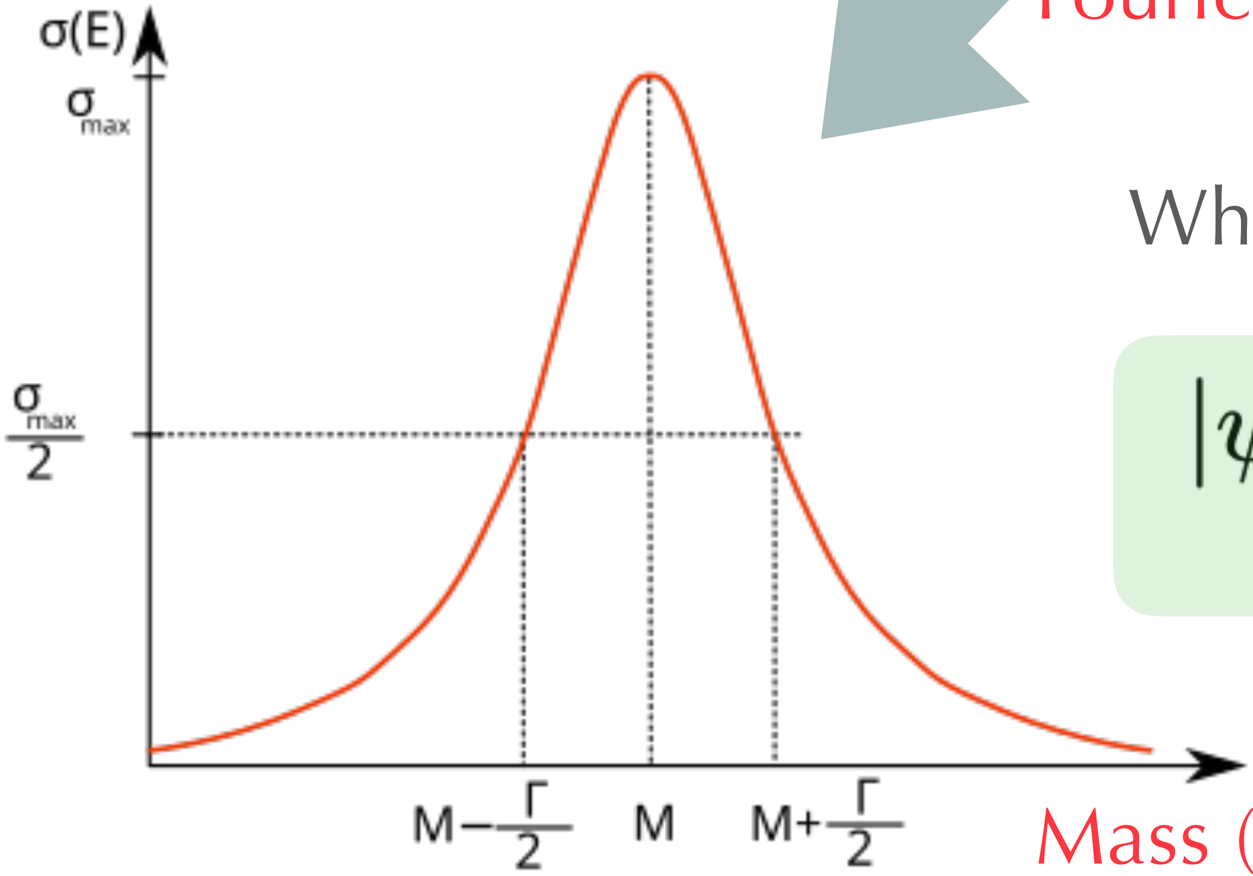
$$\psi(t) = \psi_0 \, e^{-\Gamma t/2} \, e^{-iE_0 t}$$



Breit-Wigner (BW)

$$\psi(E) \sim \frac{1}{E - E_0 + i\Gamma/2}$$

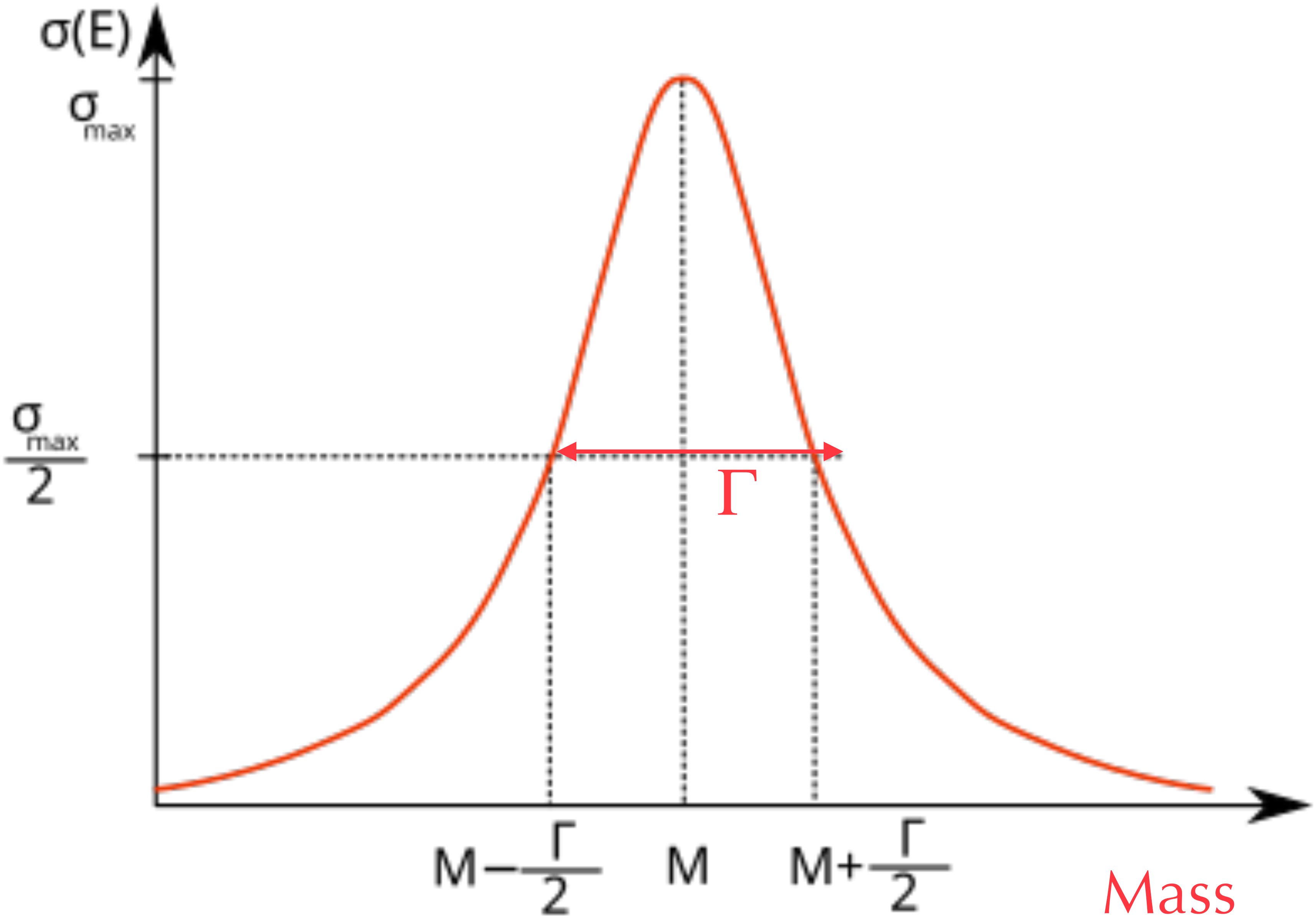
Fourier-Transform



Mass (energy)

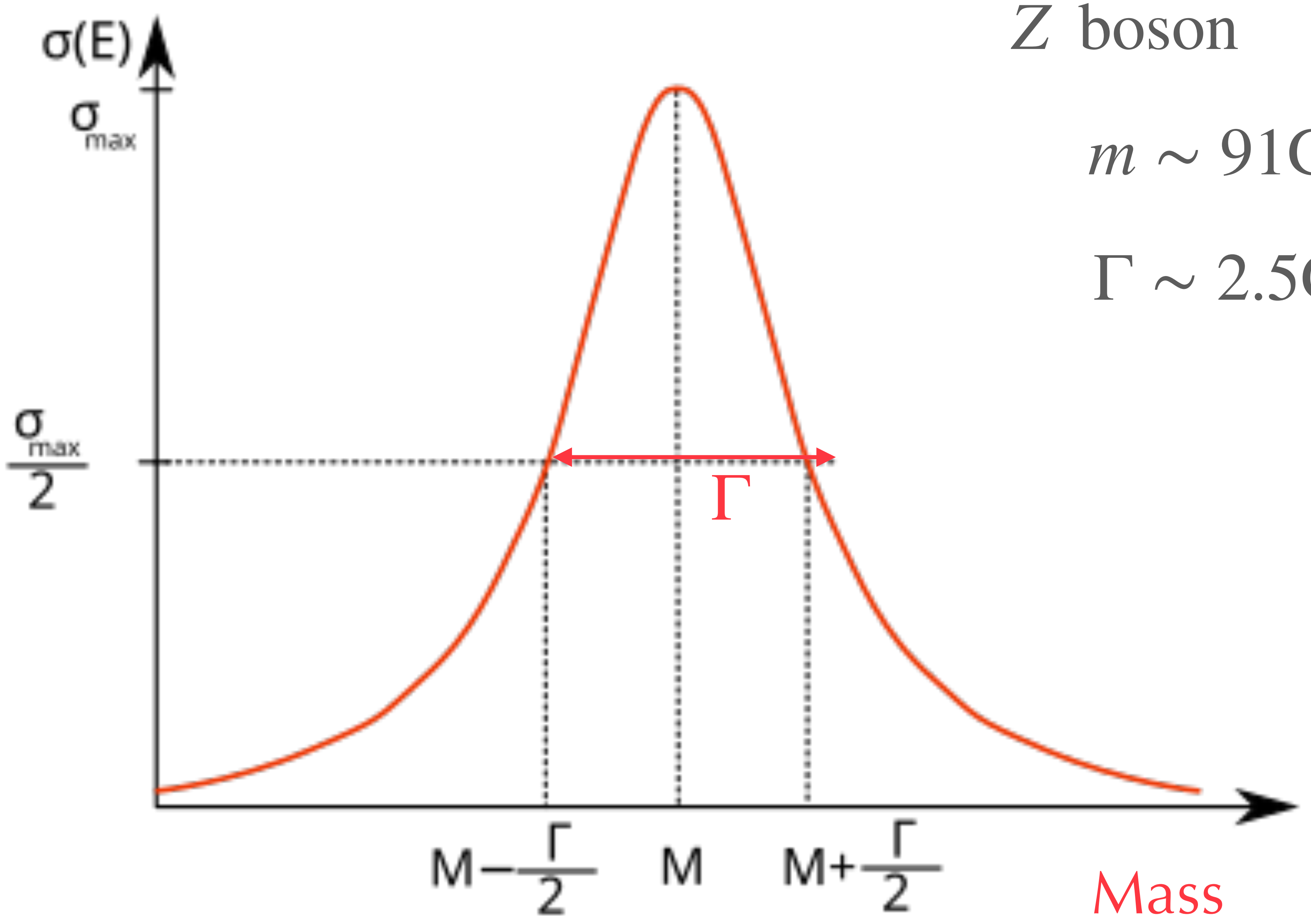
What we observed = BW squared

$$|\psi(E)|^2 \sim \frac{1}{(E - E_0)^2 + \Gamma^2/4}$$



In natural units $\Gamma = 1/\tau$

Total decay width = one over particle lifetime



Z boson

$m \sim 91\text{GeV}$

$\Gamma \sim 2.5\text{GeV}$

In natural units $\Gamma = 1/\tau$

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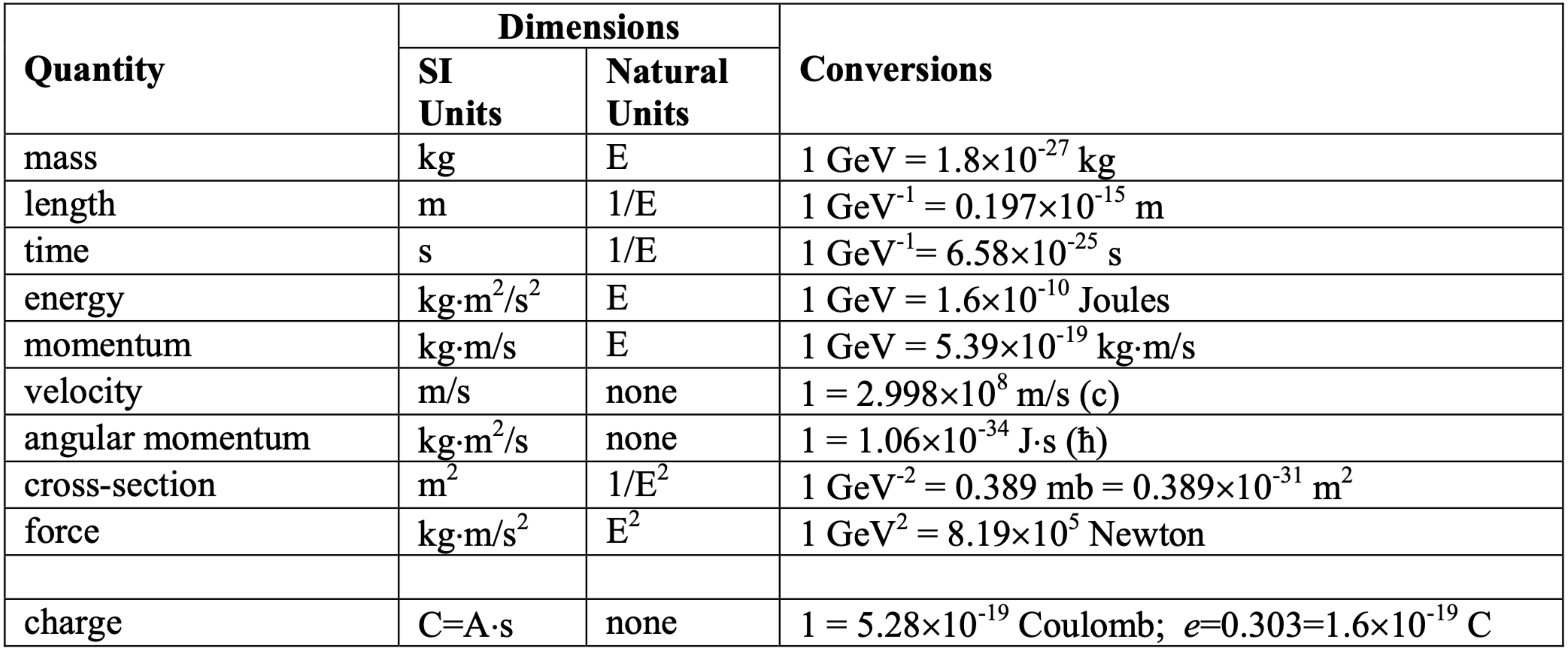


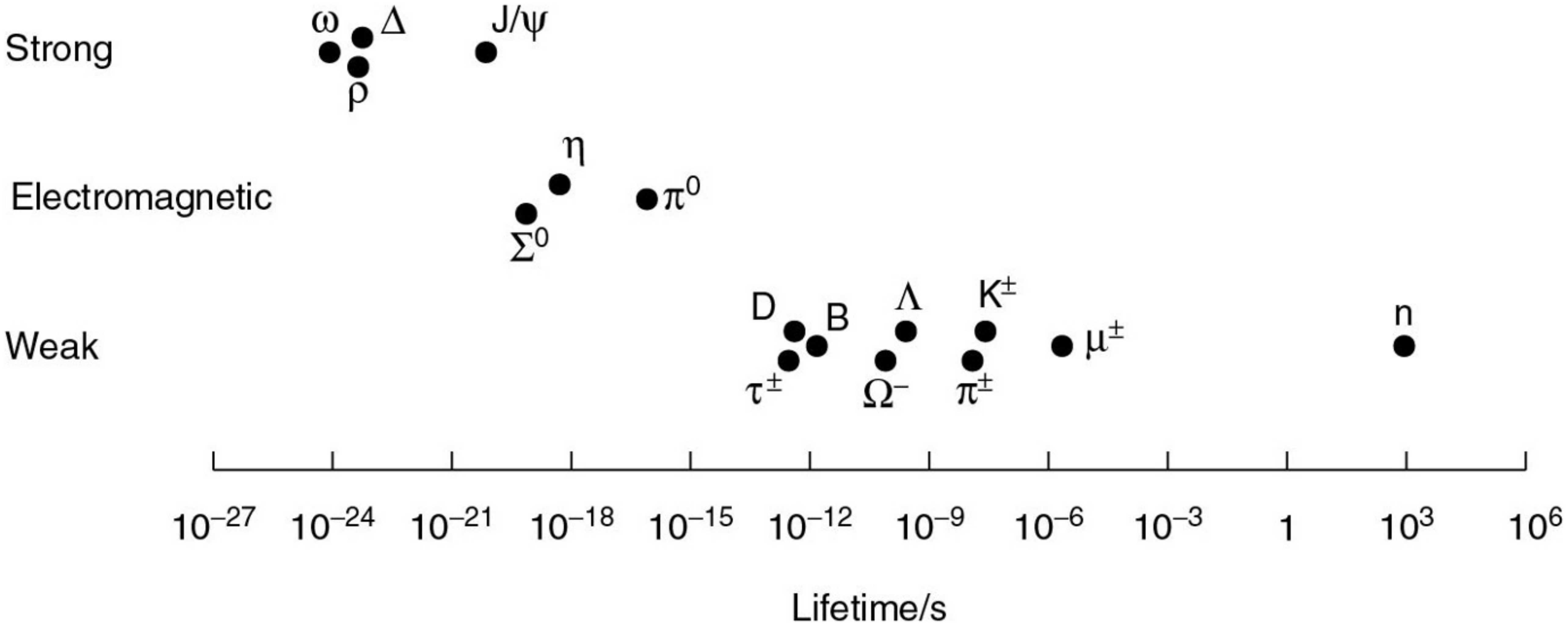
Quantity	Dimensions		Conversions
	SI Units	Natural Units	
mass	kg	E	1 GeV = 1.8×10^{-27} kg
length	m	1/E	1 GeV^{-1} = 0.197×10^{-15} m
time	s	1/E	1 GeV^{-1}= 6.58×10^{-25} s
energy	$\mathrm{kg{\cdot}m^2/s^2}$	E	1 GeV = 1.6×10^{-10} Joules
momentum	kg·m/s	E	1 GeV = 5.39×10^{-19} kg·m/s
velocity	m/s	none	1 = 2.998×10^{8} m/s (c)
angular momentum	$\mathrm{kg{\cdot}m^2/s}$	none	1 = 1.06×10^{-34} J·s (ħ)
cross-section	$\mathrm{m^2}$	$1/\mathrm{E}^2$	1 GeV^{-2} = 0.389 mb = 0.389×10^{-31} $\mathrm{m^2}$
force	$\mathrm{kg{\cdot}m/s^2}$	E^2	1 GeV^{2} = 8.19×10^{5} Newton
charge	C=A·s	none	1 = 5.28×10^{-19} Coulomb; e=0.303=1.6×10^{-19} C

Z boson

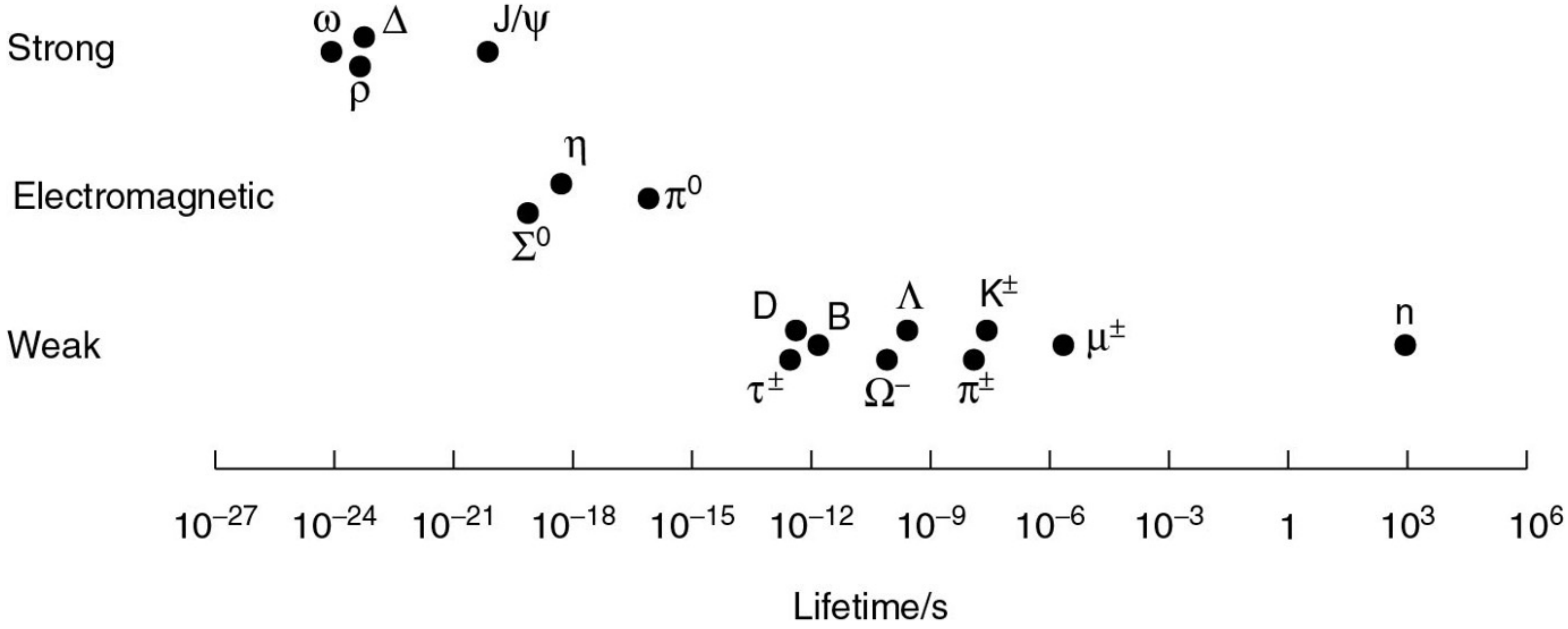
$m \sim 91\mathrm{GeV}$

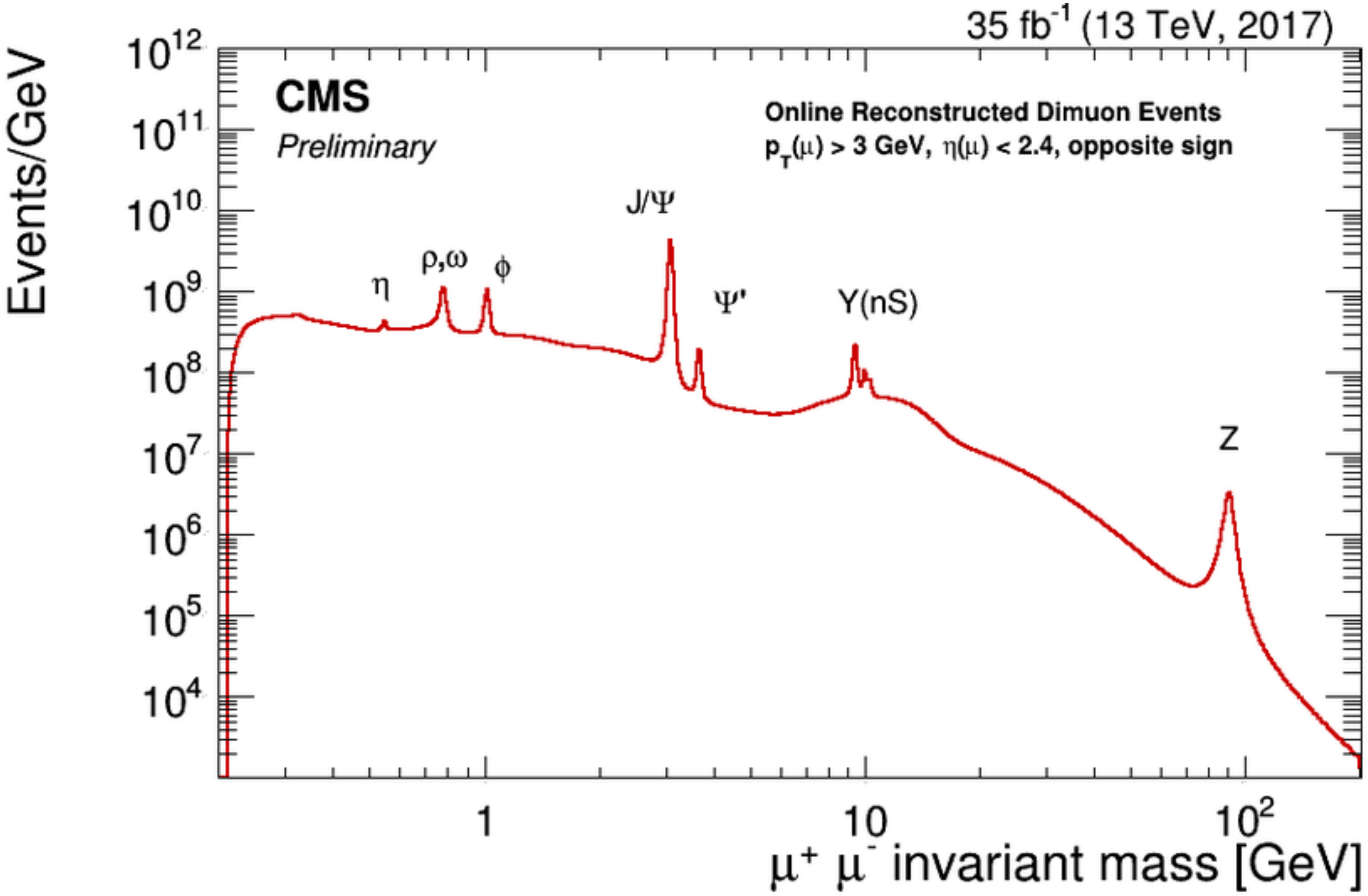
Lifetime is of order 10^{-25} seconds

$\Gamma \sim 2.5\mathrm{GeV}$



10^{-25} seconds is very short - narrow width - very “pole” like

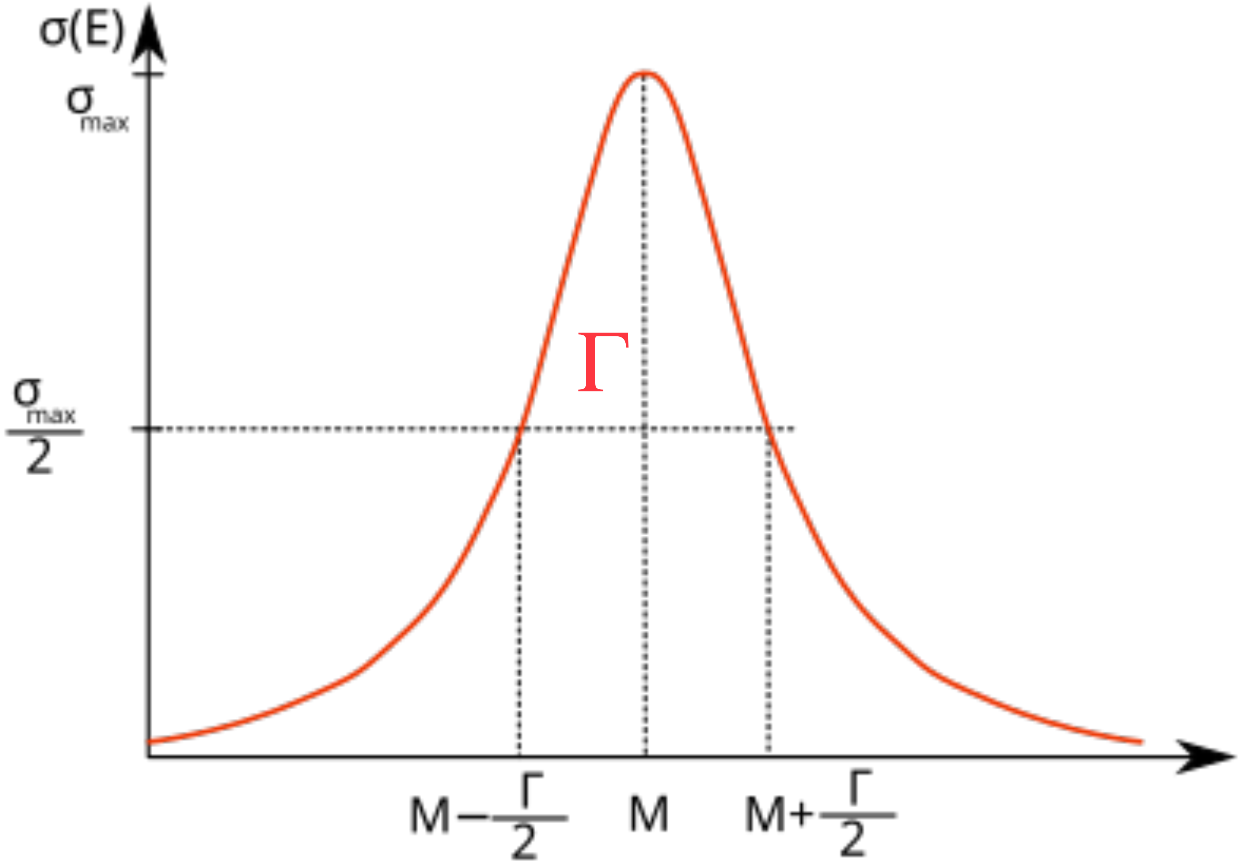




Why is the width of the Z here larger than other particles with same lifetime?

So what can measuring the Z pole tell us?

We know the total decay width Γ from the mass peak width



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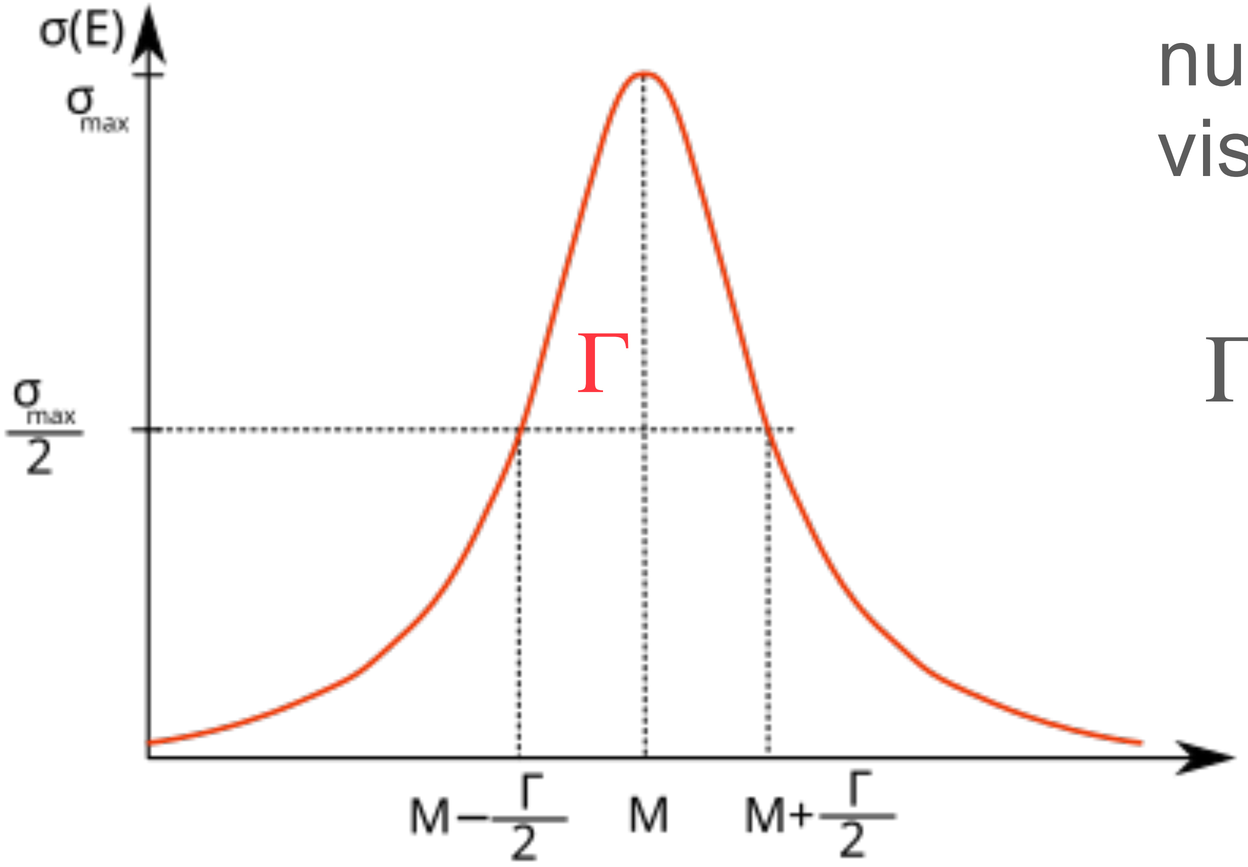

We can count the relative number of processes that are visible in our detector to get

$$\Gamma^x_{partial}/\Gamma = N(Z \to x\bar{x})/N_Z$$

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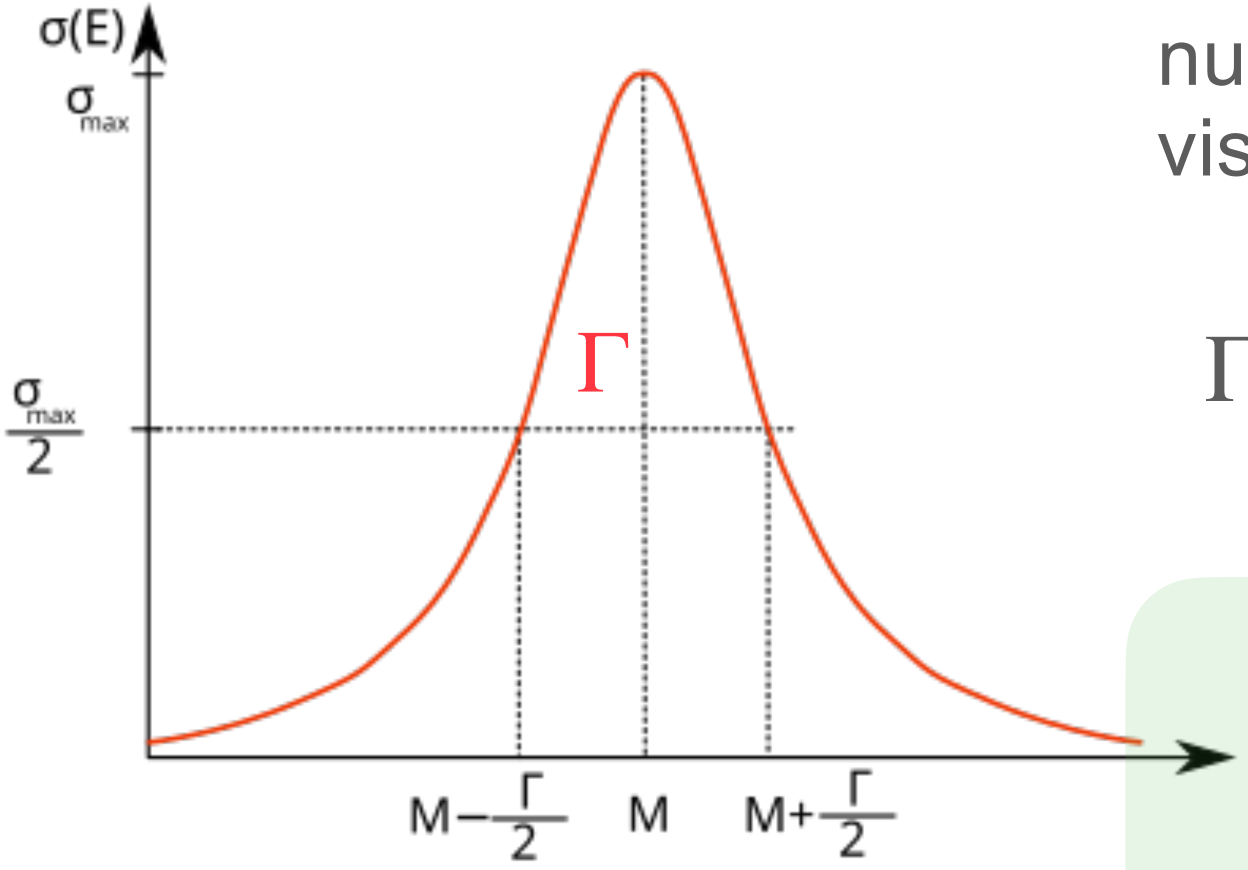


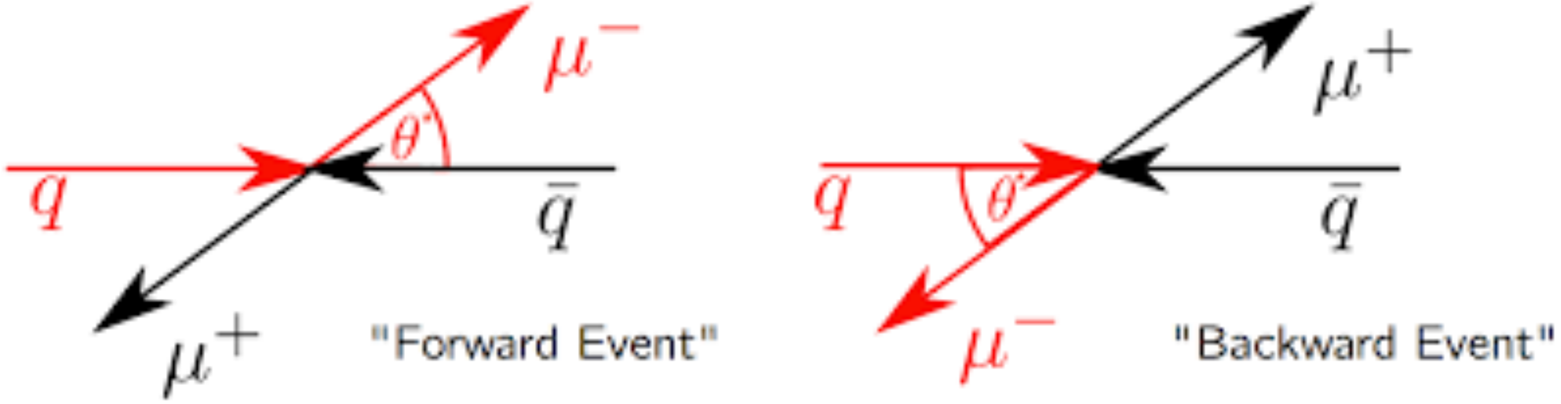
We can count the relative number of processes that are visible in our detector to get

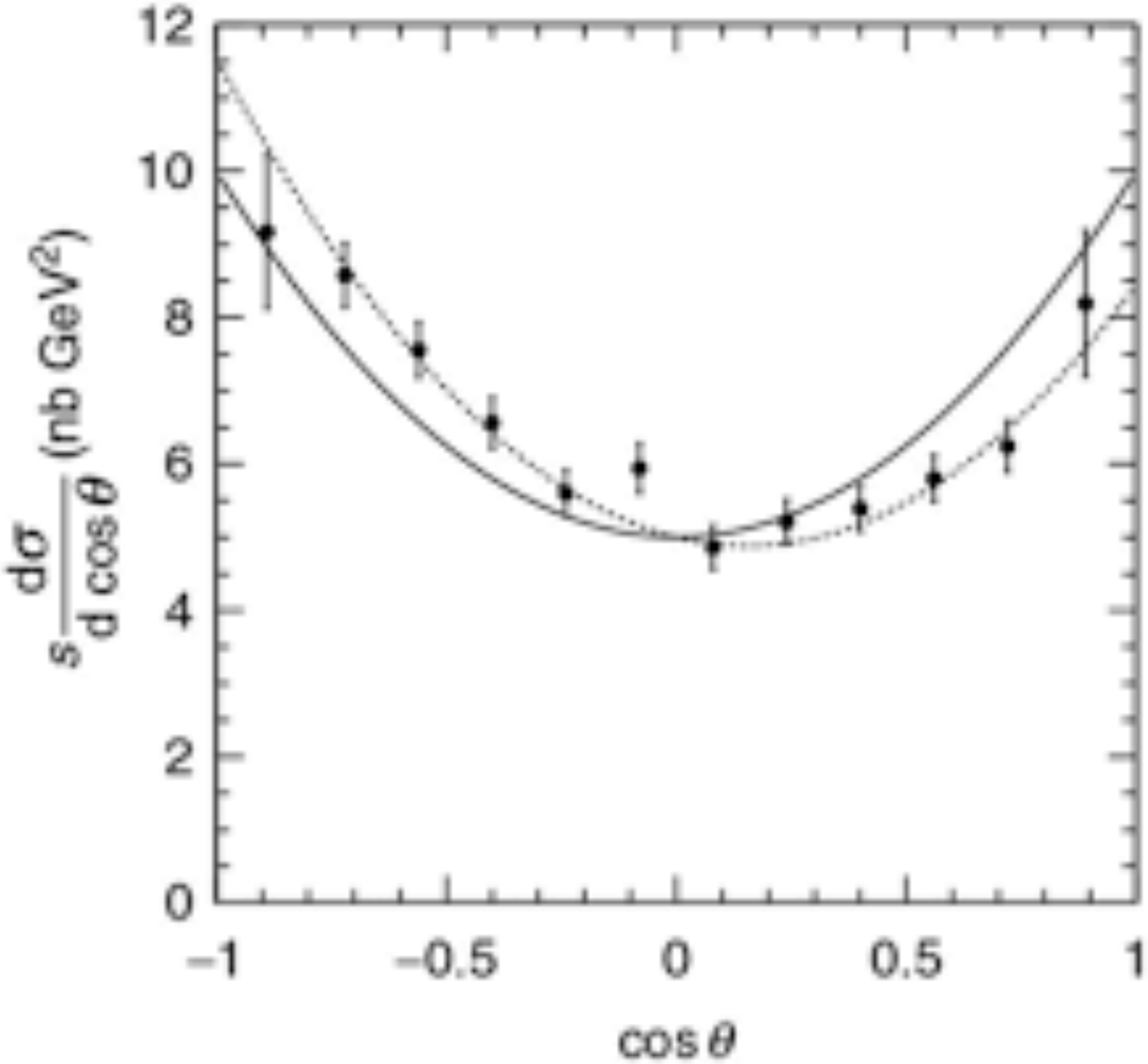
$$\Gamma^x_{partial}/\Gamma = N(Z \to x\bar{x})/N_Z$$

$$1 - \sum_x \Gamma^x_{partial}/\Gamma =$$

proportion of Z decays which go to invisible states

Another key Electro-weak observable: A_{FB}

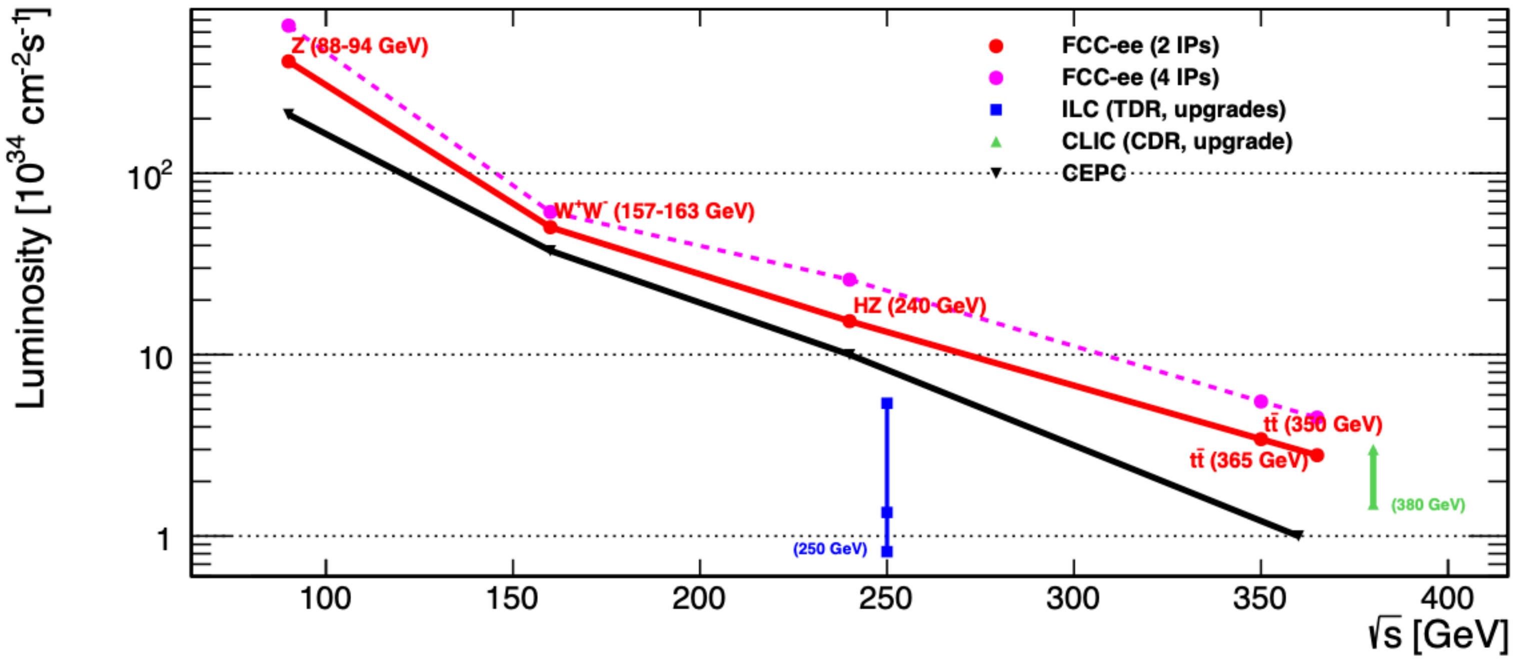


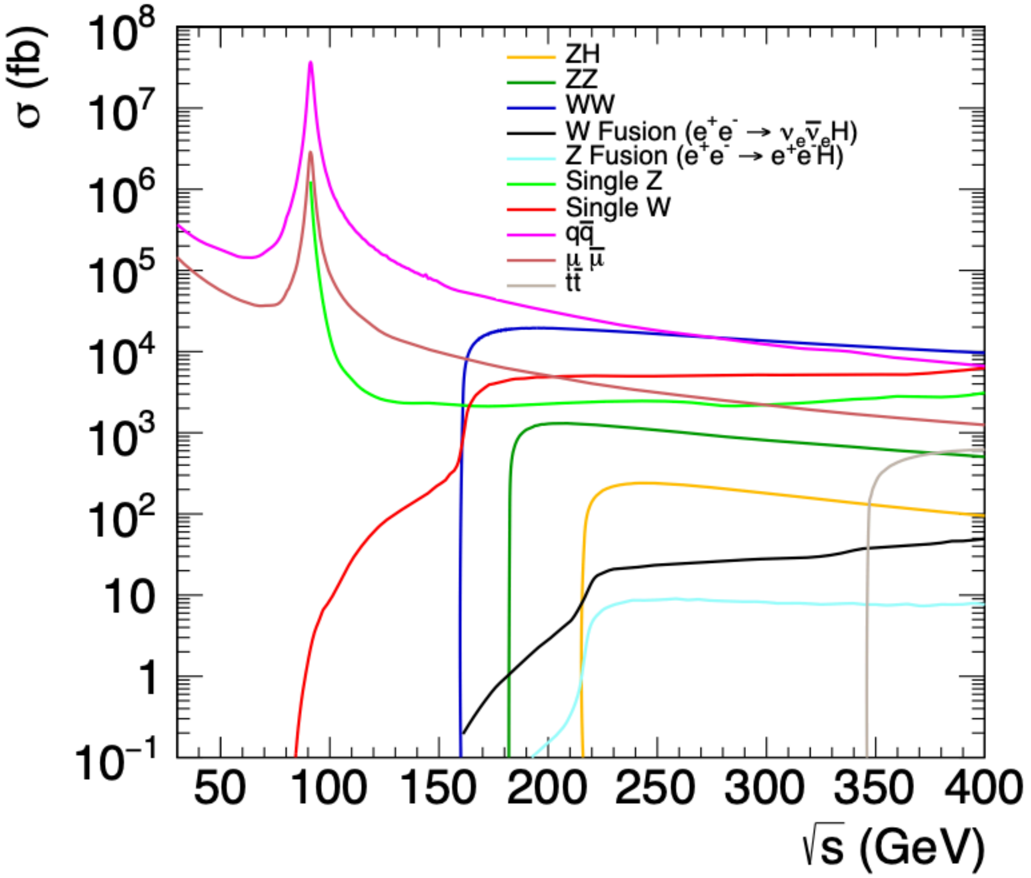


Forward - backward asymmetry (A_{FB}) in $Z \rightarrow f\bar{f}$ decays in non-zero because Z only couples to left-handed fermions /right-handed anti-fermions

Amount of asymmetry tells us about weak mixing angle θ_w

Run plan for FCC-ee





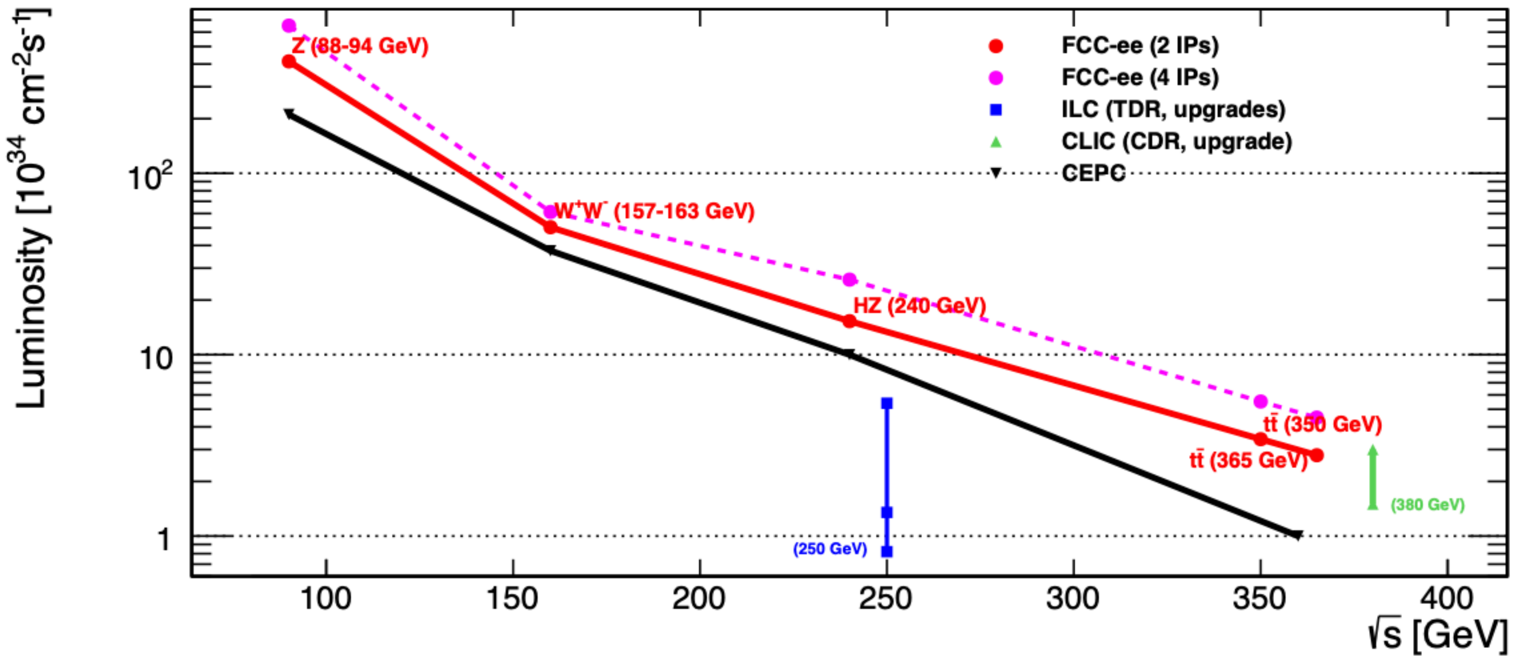
Energy

Working point	Z years 1-2	Z, later	WW	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	115	230	28	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34
Physics goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\rightarrow$ H	10^6 $t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H	

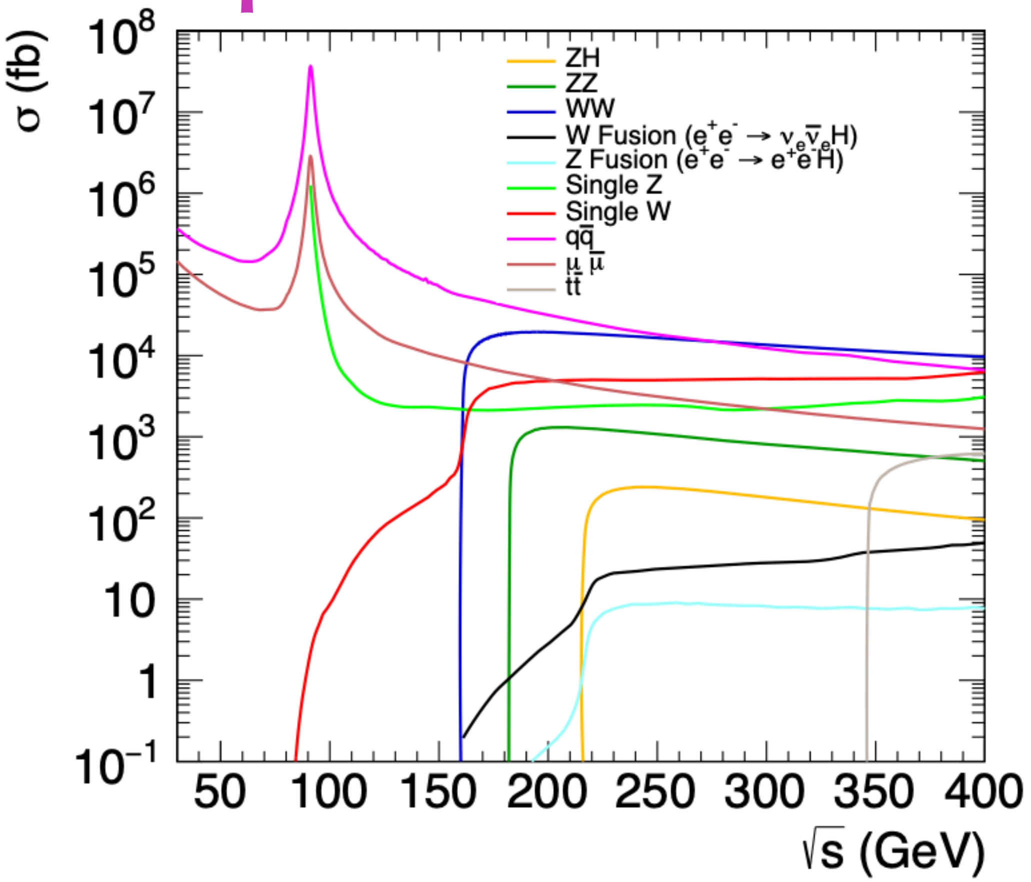
Accuracy

[FCC Snowmass 2021, 2203.06520]

Run plan for FCC-ee



Z-pole!!!



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Accuracy

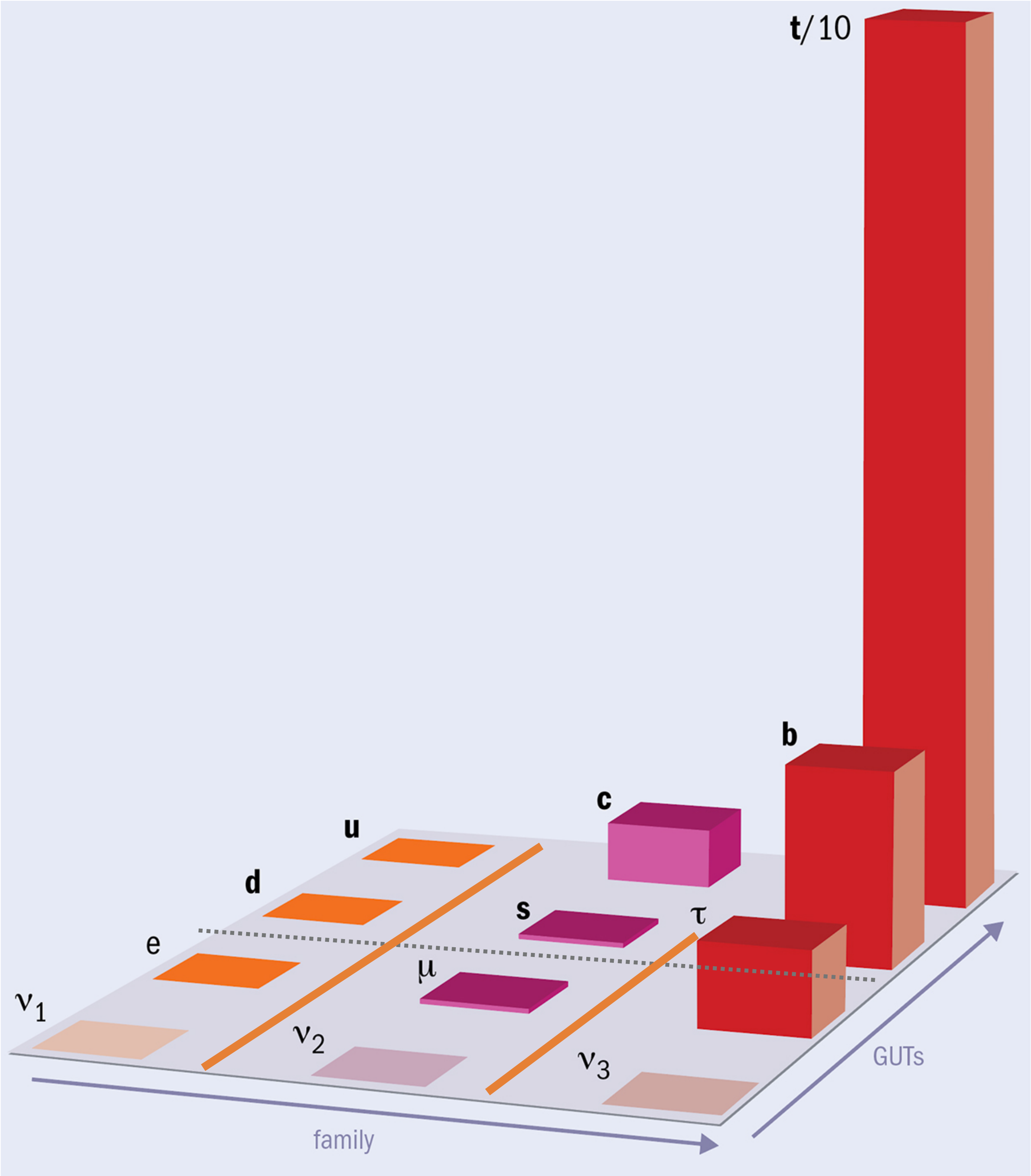
[FCC Snowmass 2021, 2203.06520]

Studying flavour at the Z pole

Of the $O(10^{12})$ Z-bosons produced at tera-Z:

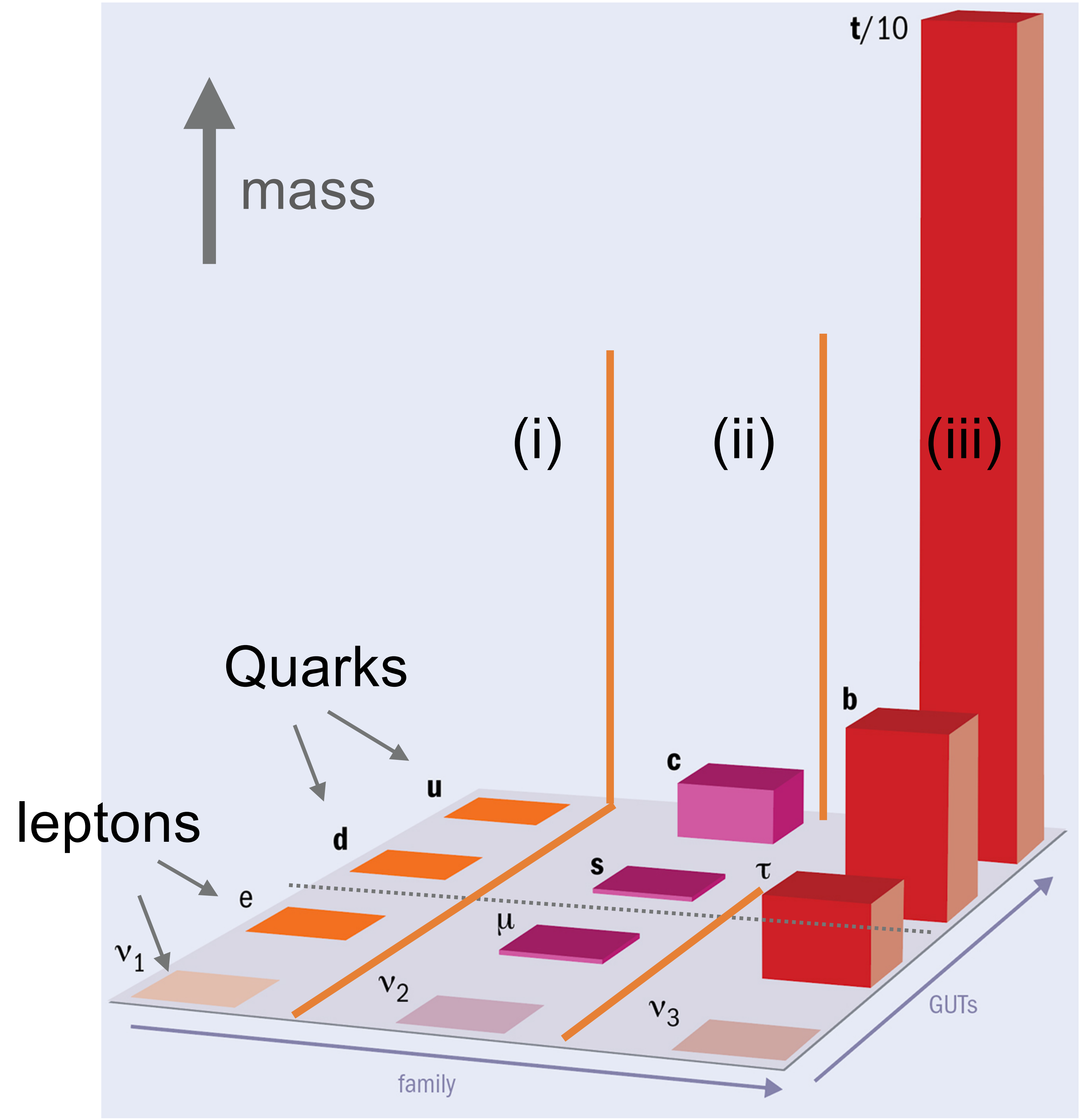
- 15% decay to $b\bar{b}$
- 12% decay to $c\bar{c}$
- 3% decay to $\tau^+\tau^-$

What is flavour?



+ force carriers and Higgs boson

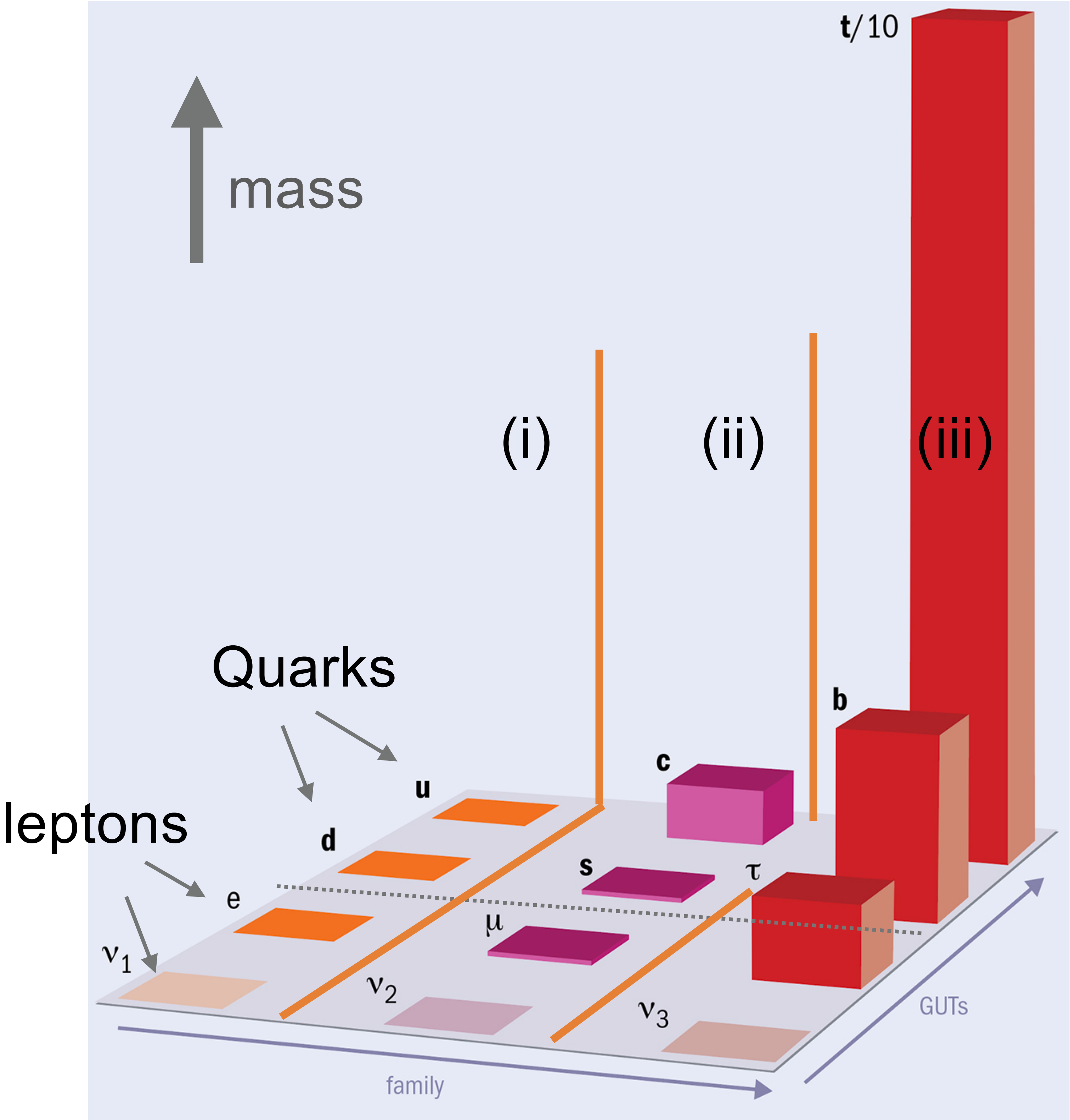
What is flavour?



3 generations of particles, with increasing mass

+ force carriers and Higgs boson

What is flavour?



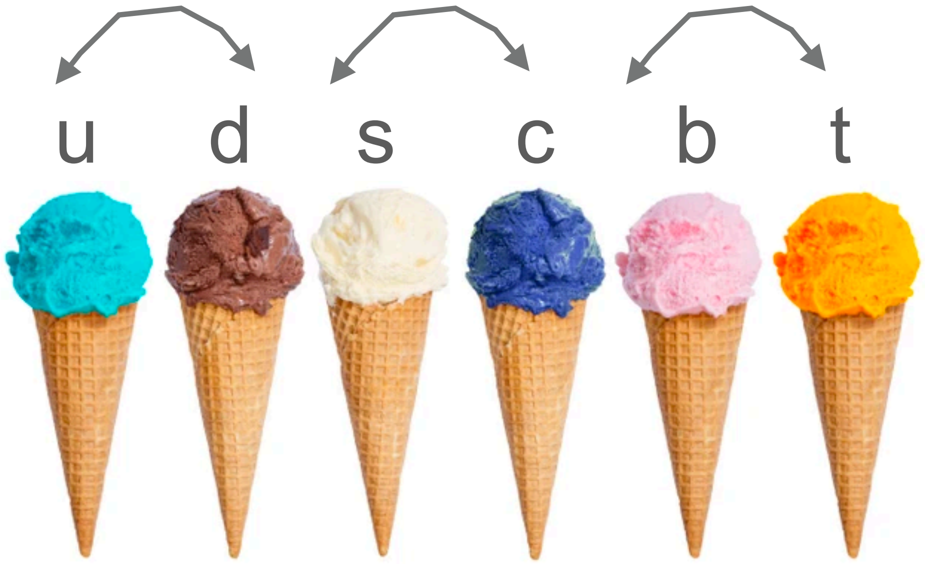
3 generations of particles, with increasing mass

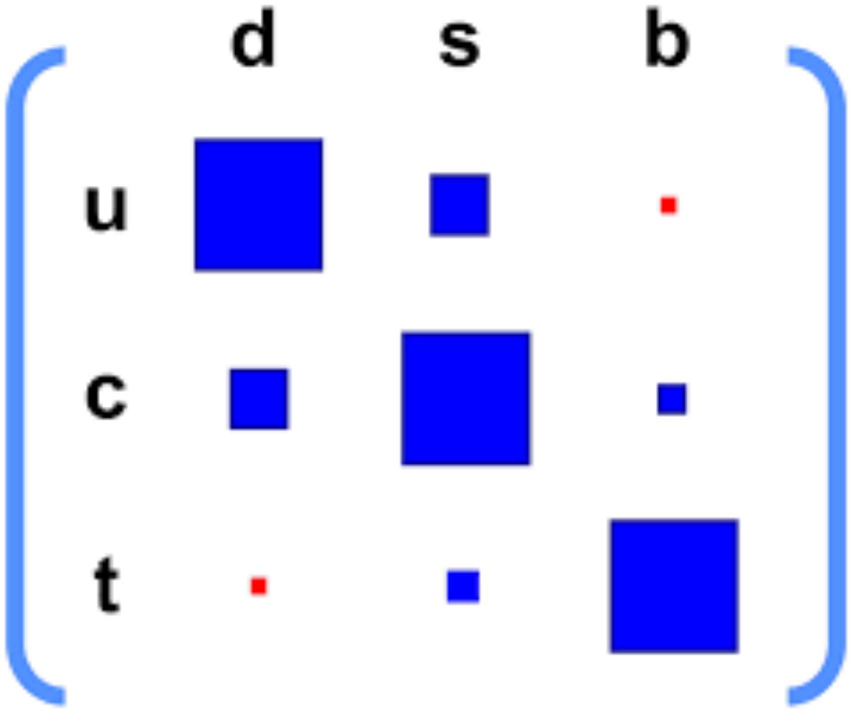
Different "flavours" of quarks /leptons

+ force carriers and Higgs boson

Flavour physics

Flavour physics: study of particle decays that change flavour



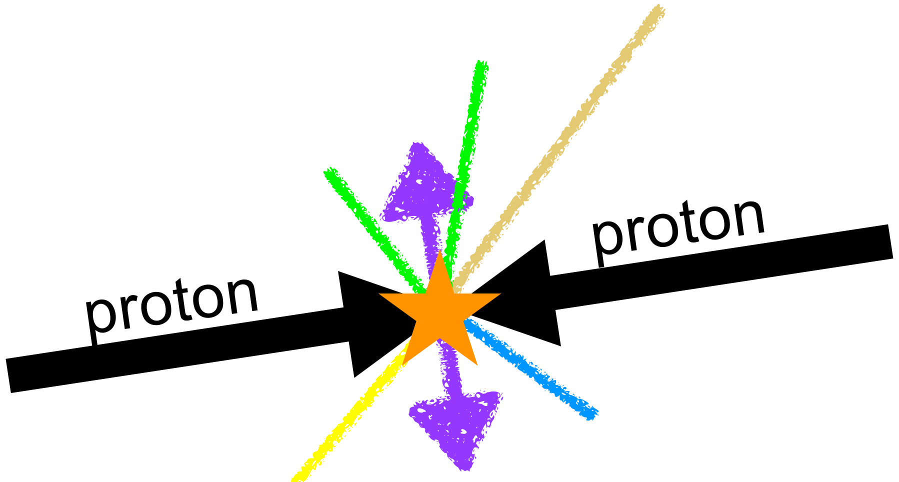


The probability with which one quark flavour decays to another encapsulated by the “CKM” matrix

How to look for New Physics

Direct searches

E=mc^2



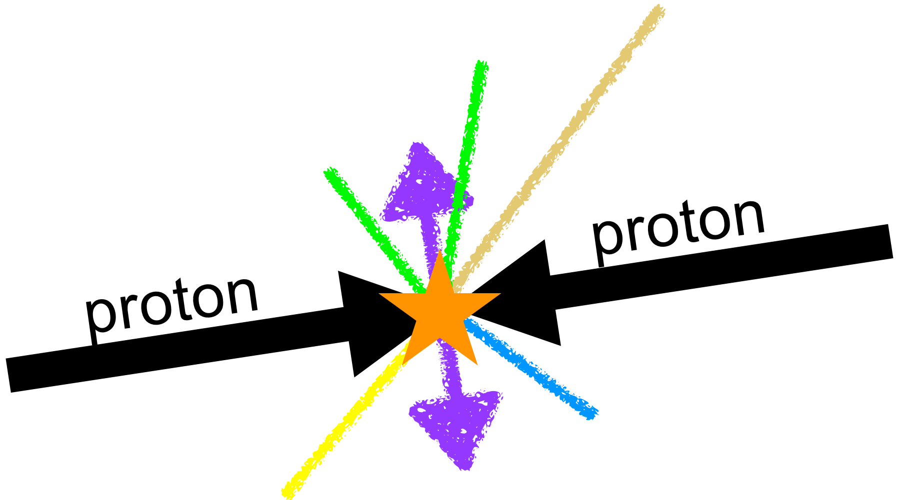
NP particle

Mass of new particle limited by collision energy $(\sim 14\,\mathrm{TeV})$

How to look for New Physics

Direct searches

$E=mc^2$



NP particle

Mass of new particle limited by collision energy $(\sim 14\,\text{TeV})$

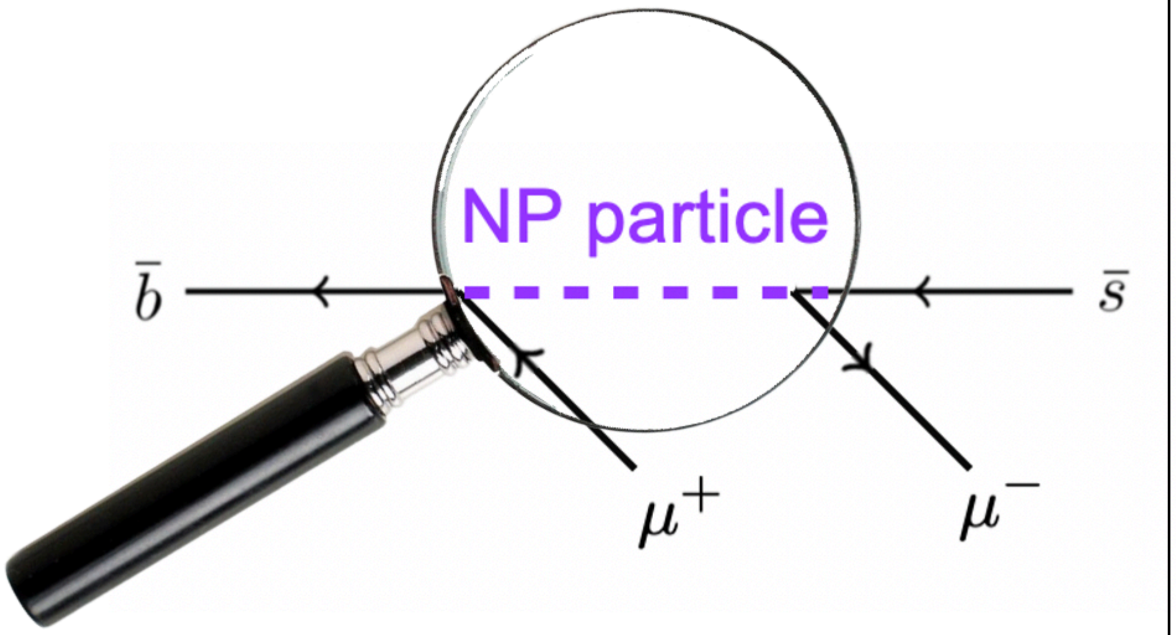
Indirect searches

Heisenberg’s uncertainty principle

$$\Delta E \Delta t > \frac{\hbar}{2}$$

$mc^2 >> E$ if Δt small

$m \sim \mathcal{O}(100\,\text{TeV})$ JHEP 1411 (2014) 121



How to look for New Physics

Direct searches

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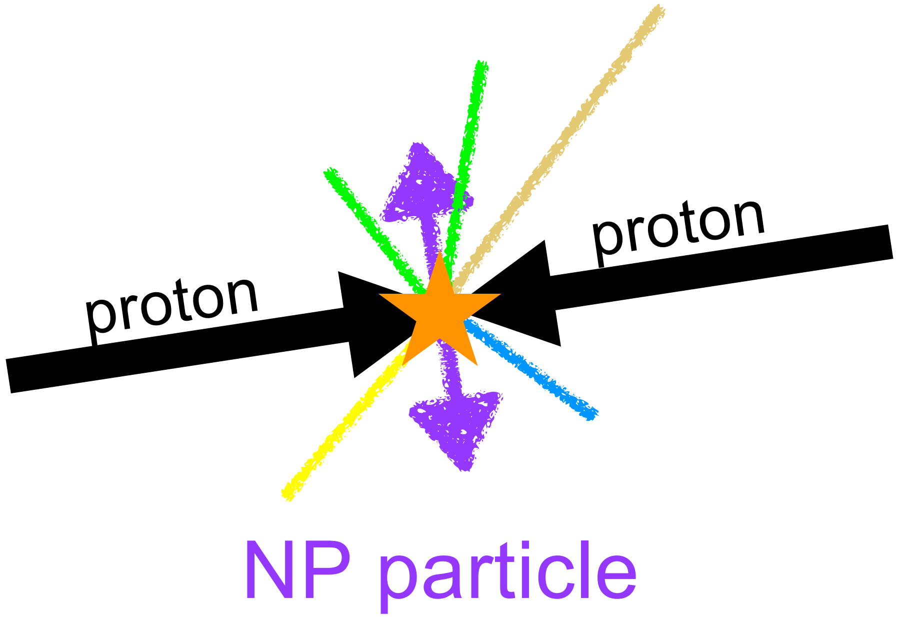
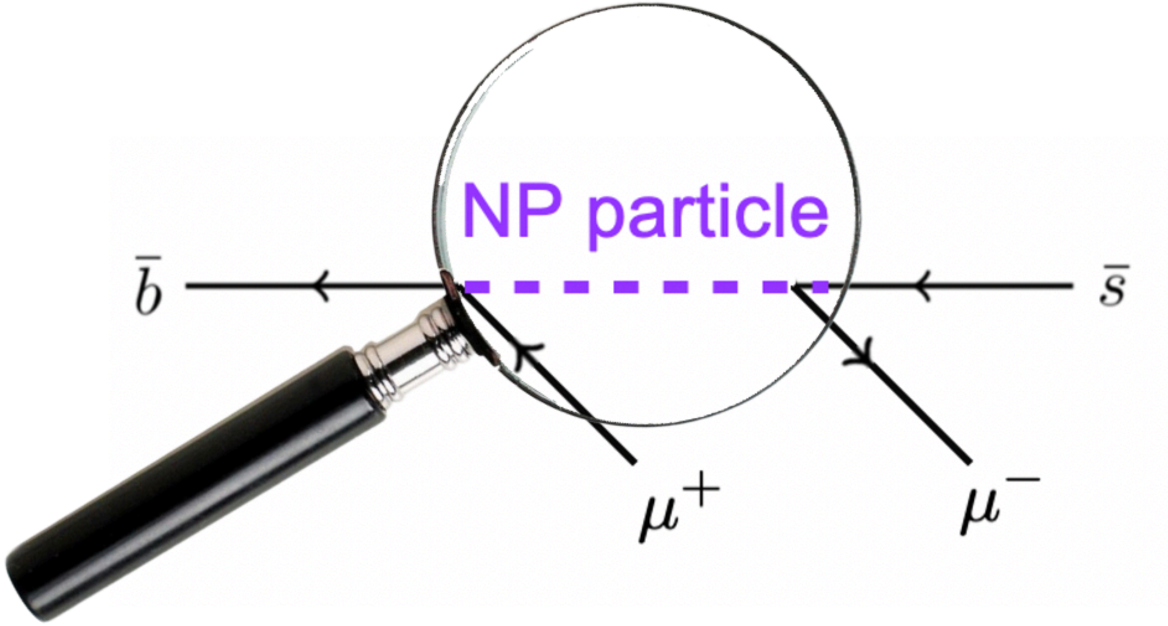


Mass of new particle limited by collision energy $(\sim 14\,\mathrm{TeV})$

Indirect searches

Studying flavour allows us to search for heavier new particles



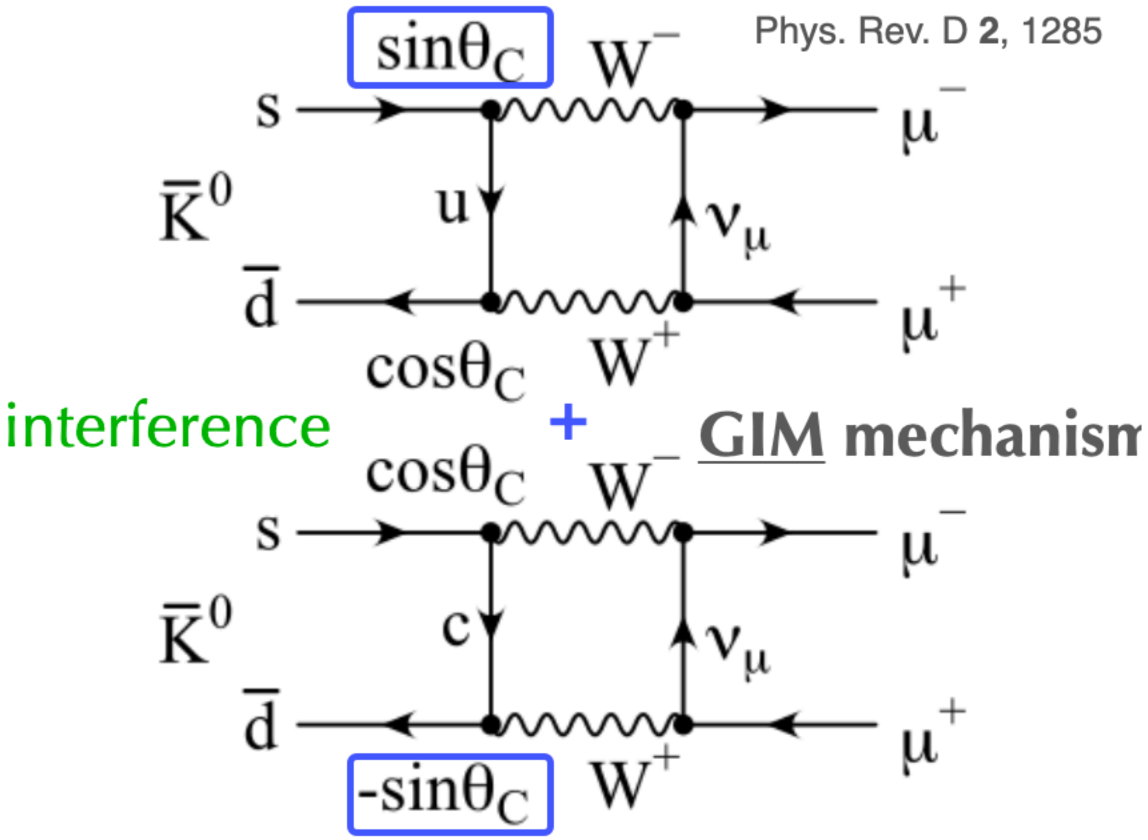
The power of flavour - a history lesson

- Lesson from history: new physics tends to show up at precision frontier before energy frontier

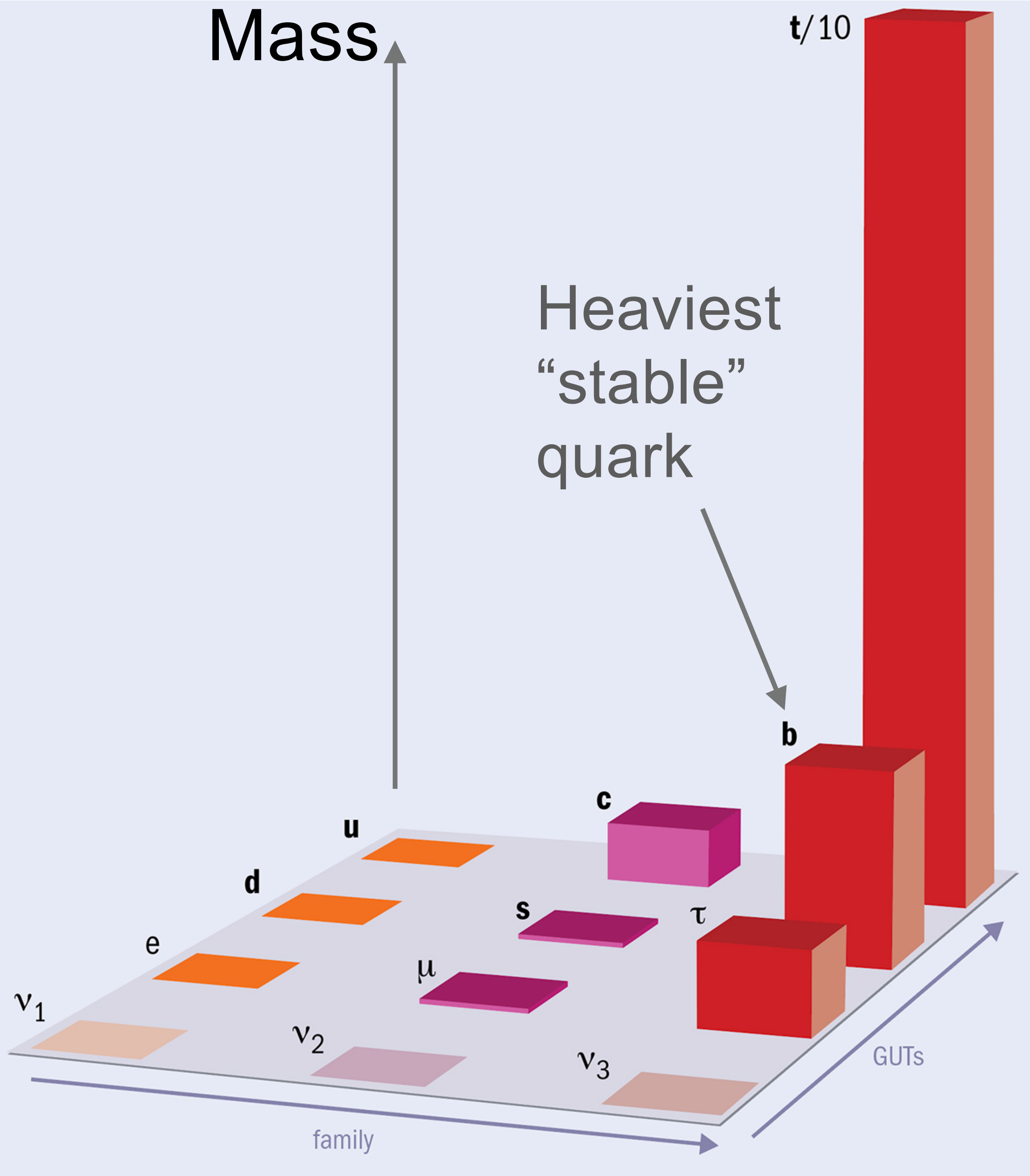
For example to few $K_L \to \mu^+\mu^-$ were seen in the late 1960s compared to SM predictions

Led to the prediction of a fourth quark (the charm quark), found in the mid 1970s here at MIT

prediction of charm



Why study decays of beauty (b) quarks?

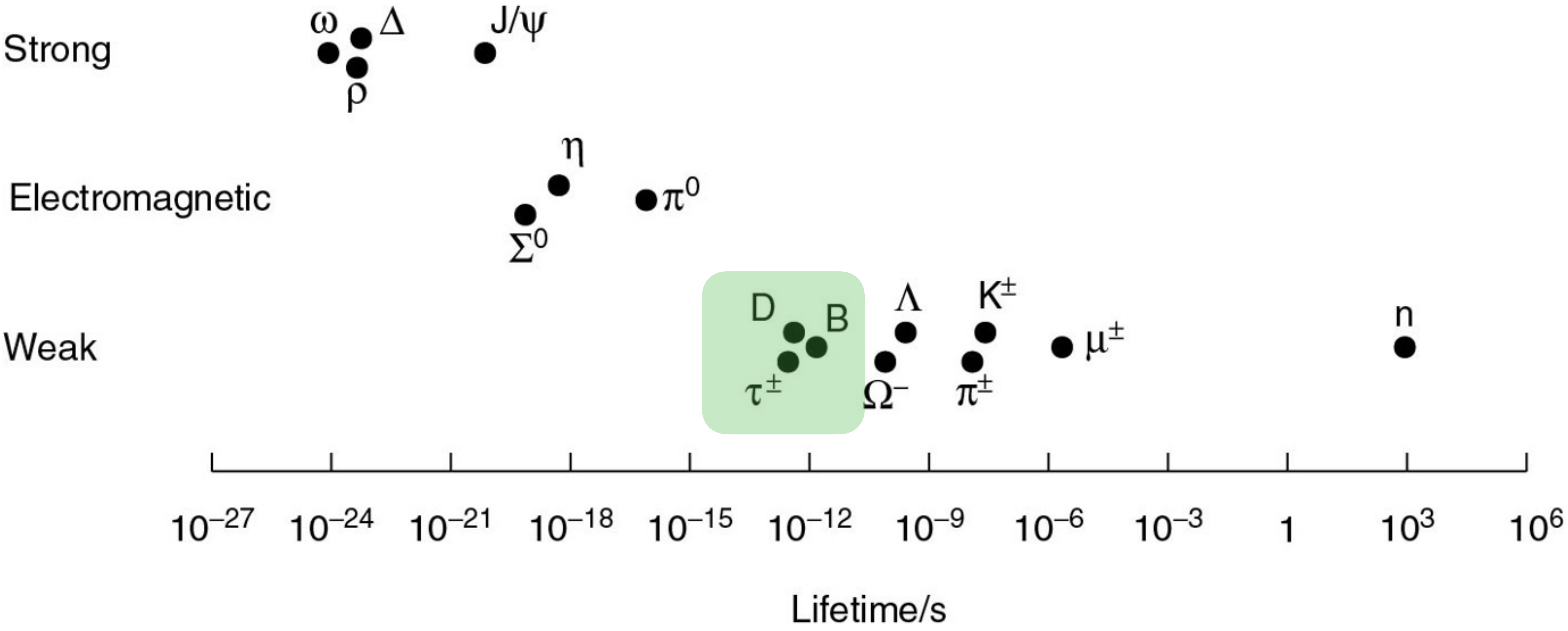


New Physics is assumed to be heavy!

Many favoured NP models predicted enhanced coupling to 3rd generation quarks (b, t)

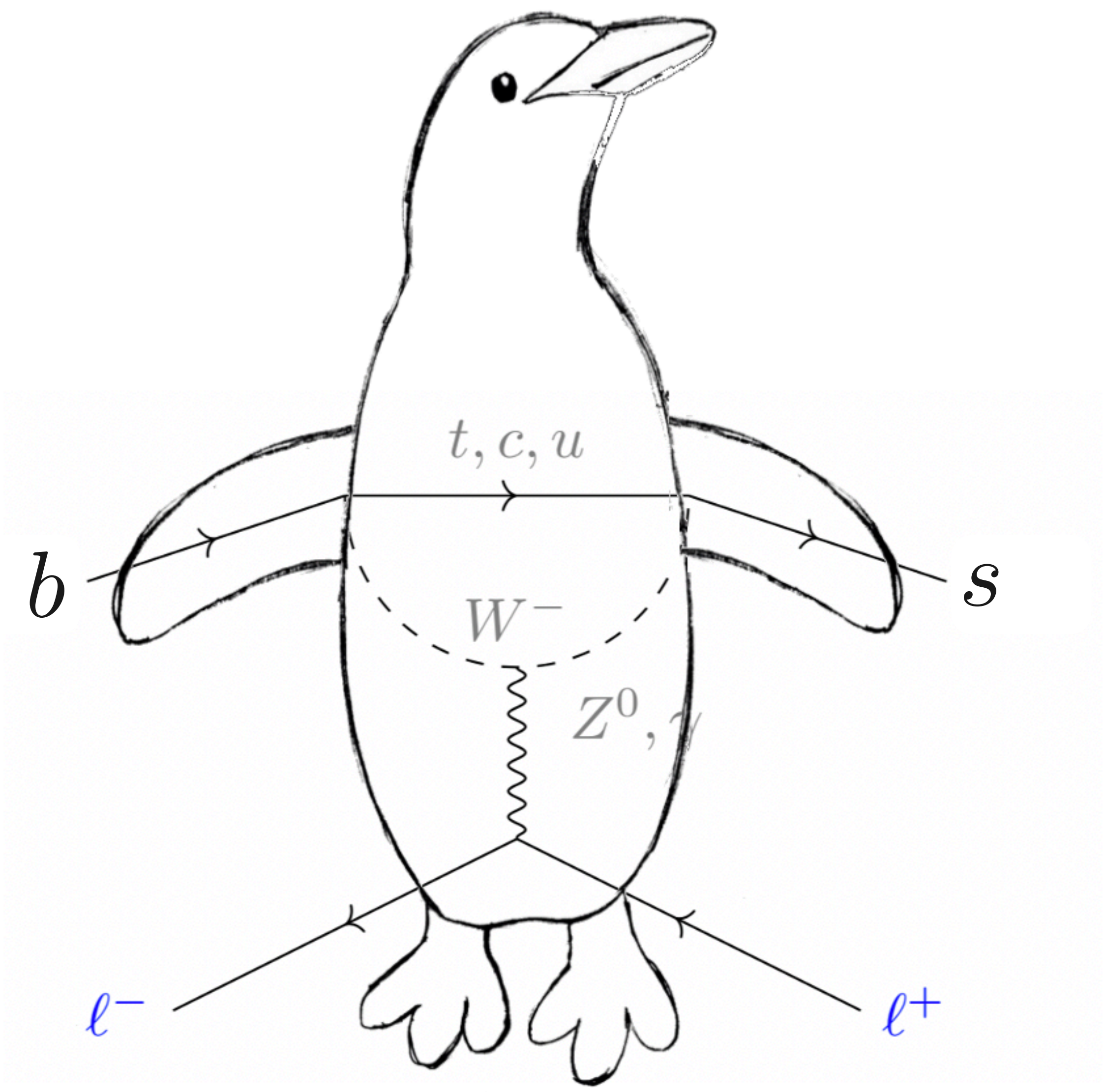
Experimental properties of b quarks also allows them to be *precisely measured*

Why study decays of beauty (b) quarks?



Only decay weakly -> long-lived in our detector

Example: electroweak Penguins

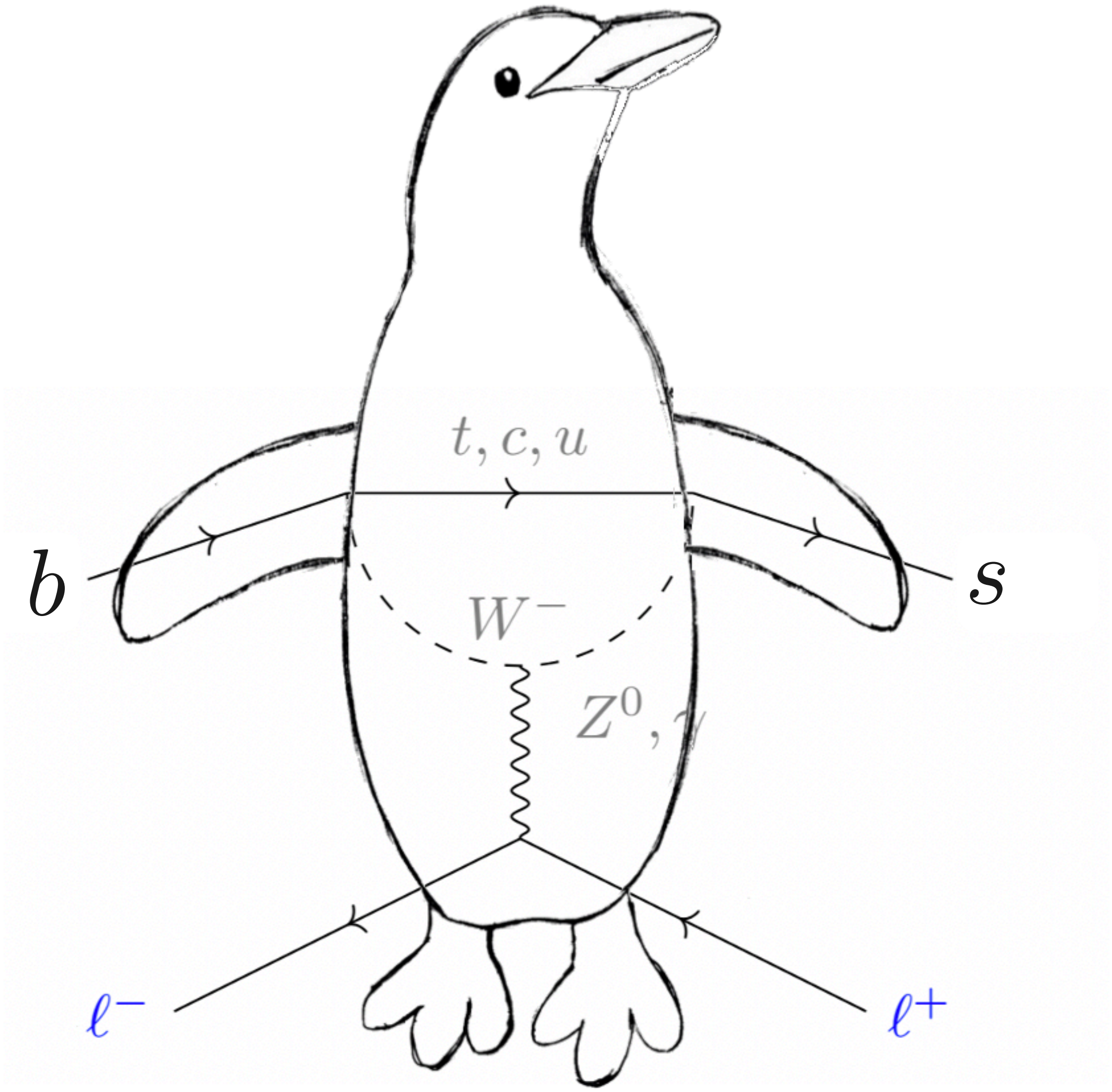


$$b \to s\ell^+\ell^-$$

Standard Model

Suppressed in the SM as mediated via loop diagrams

Example: electroweak Penguins



$$b \to s\ell^+\ell^-$$

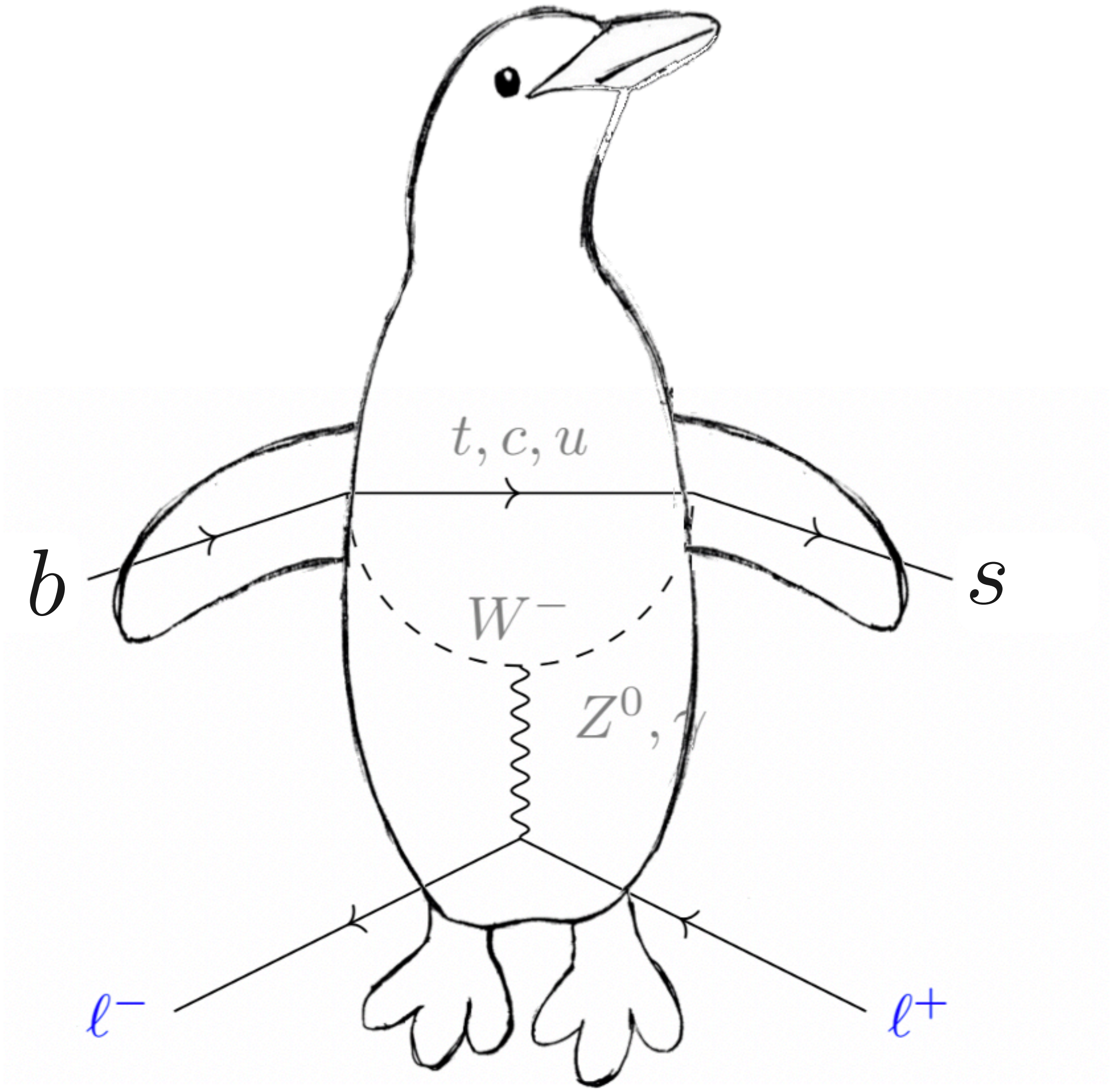
Standard Model

New Physics

Suppressed in the SM as mediated via loop diagrams

Suppression = very sensitive to New Physics diagrams

Electroweak Penguins



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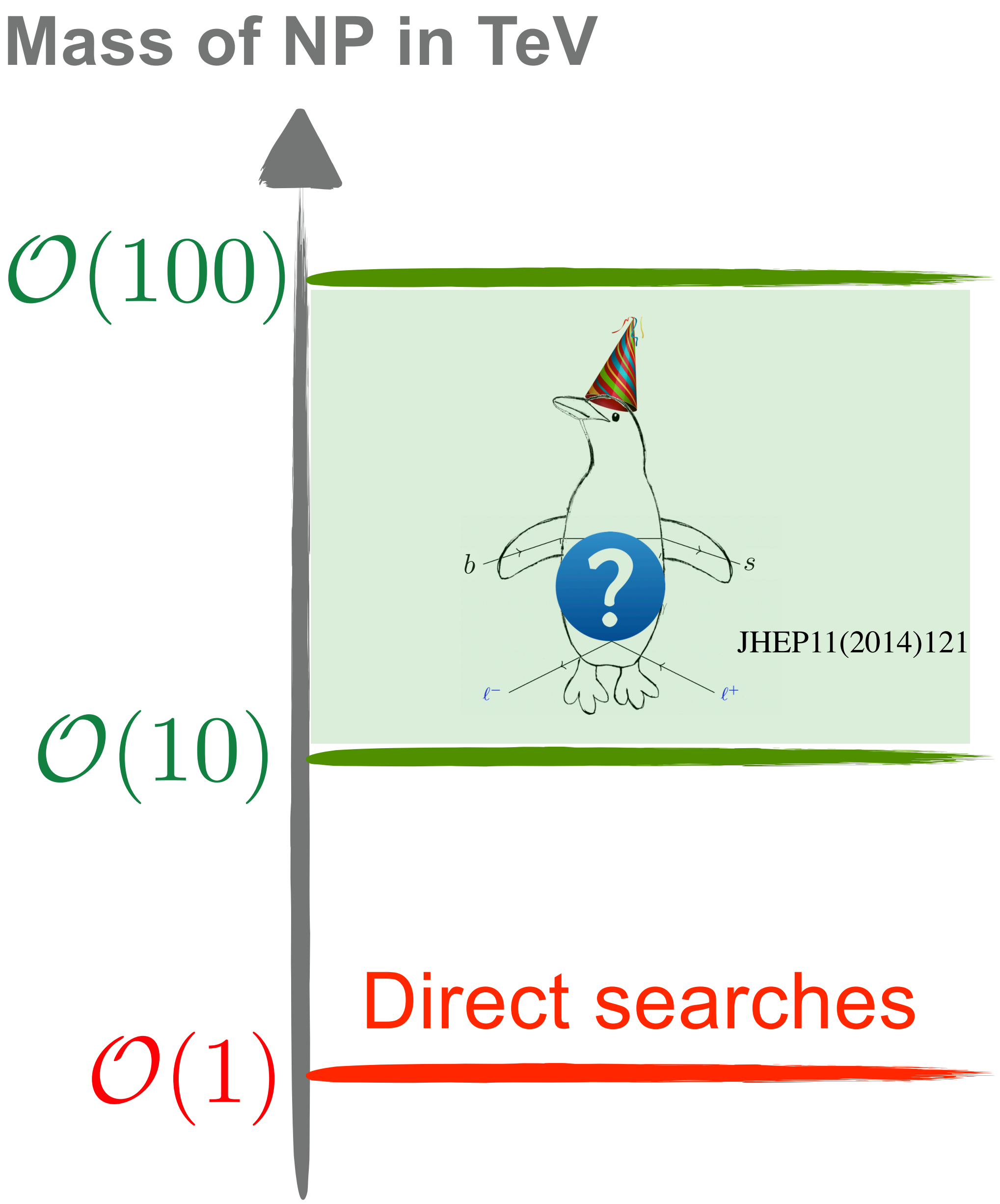
Standard Model



Mass of NP in TeV

$\mathcal{O}(100)$

$\mathcal{O}(10)$

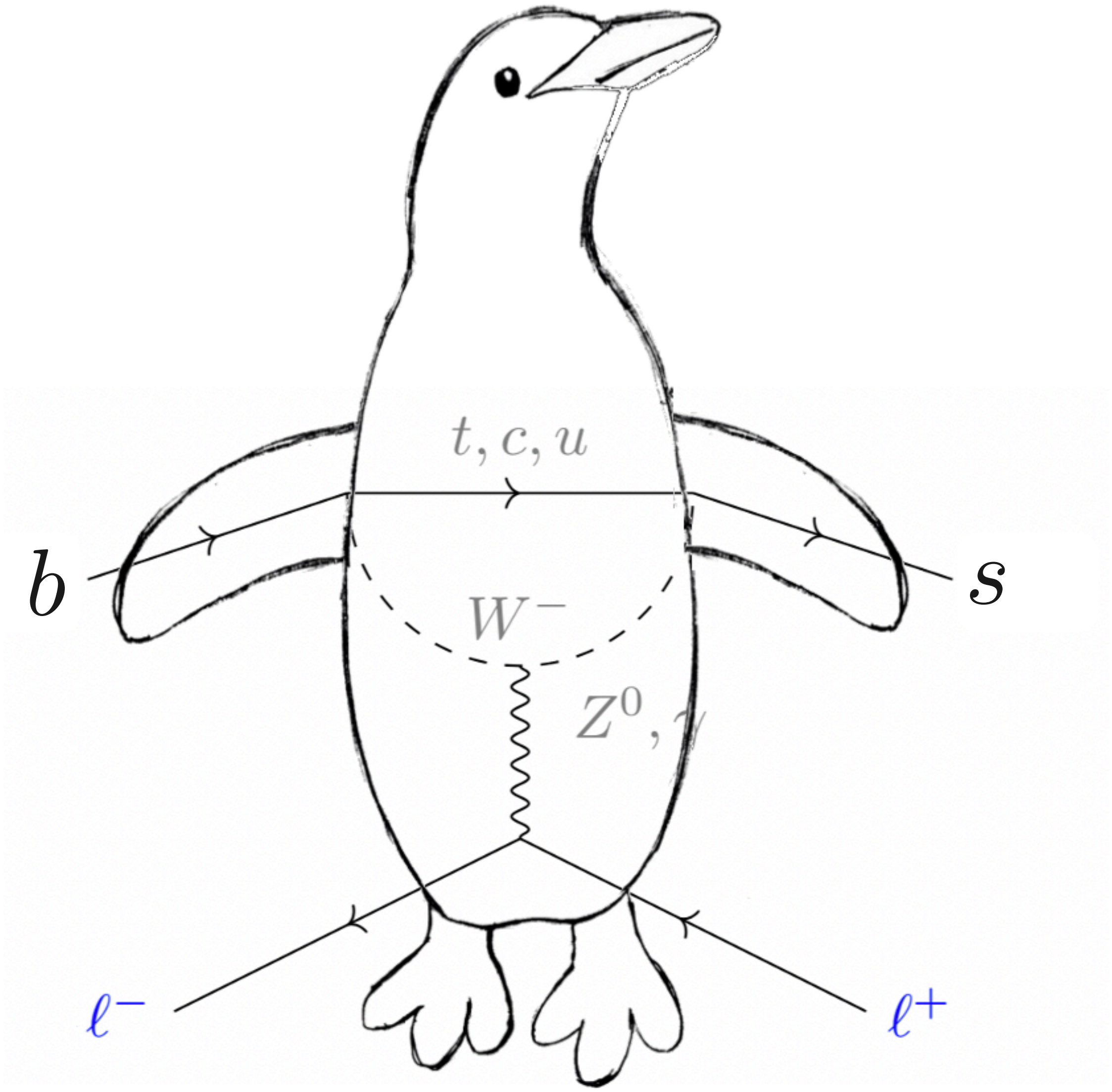
Direct searches

$\mathcal{O}(1)$

New Physics beyond the TeV

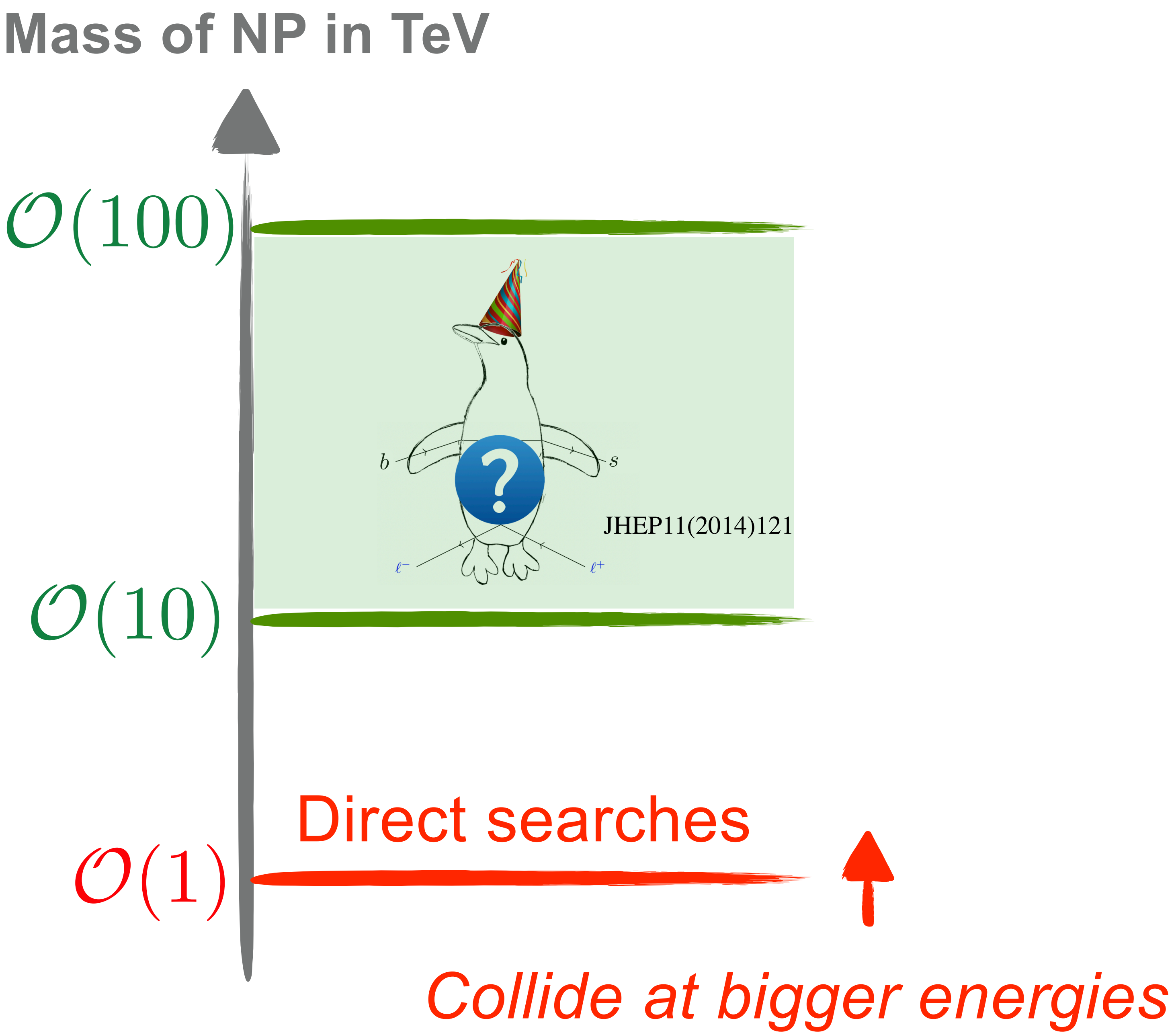
Suppression = very sensitive to New Physics diagrams

Electroweak Penguins



$$b \to s\ell^+\ell^-$$

Standard Model



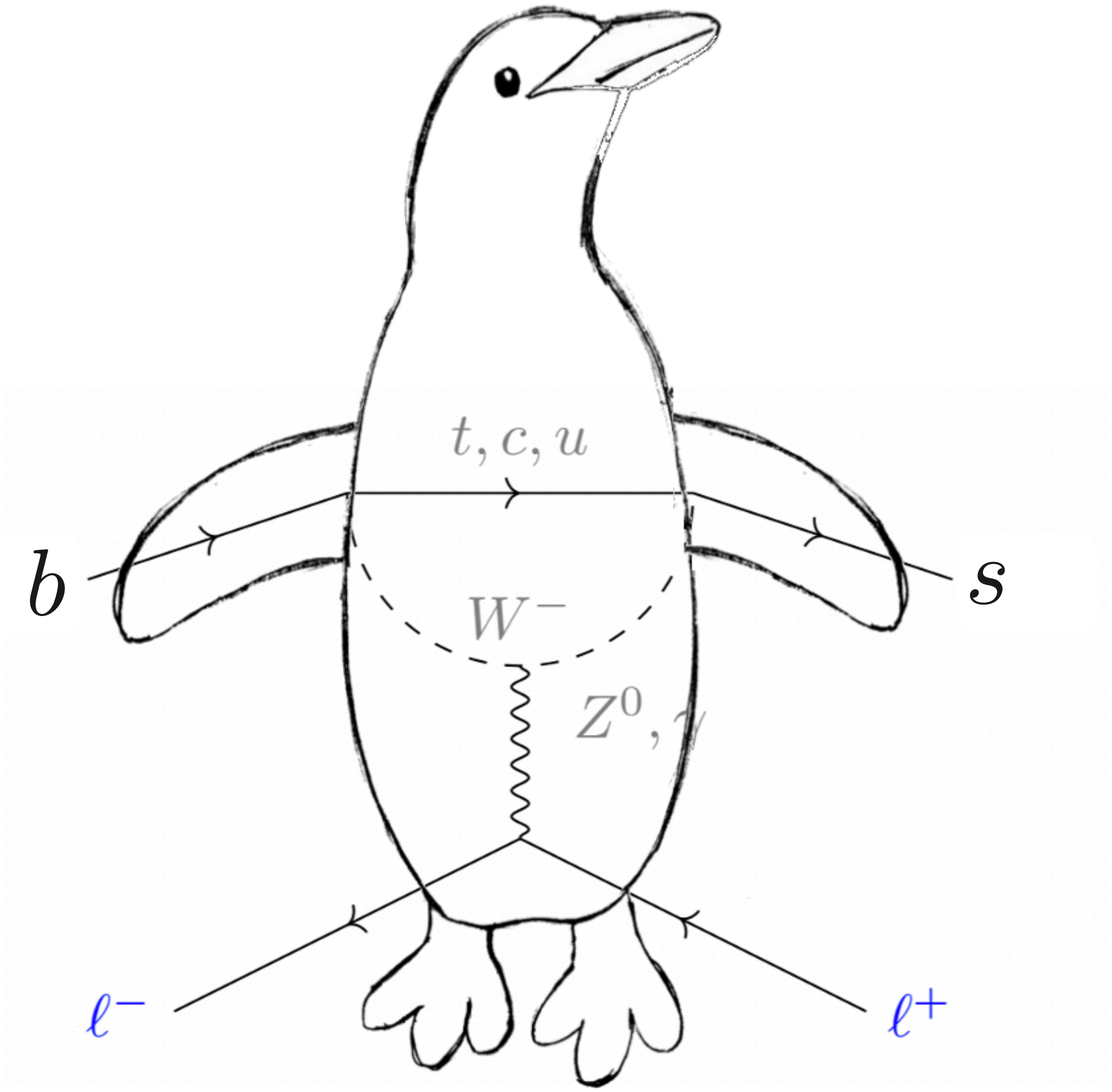
Direct searches

Collide at bigger energies

New Physics beyond the TeV

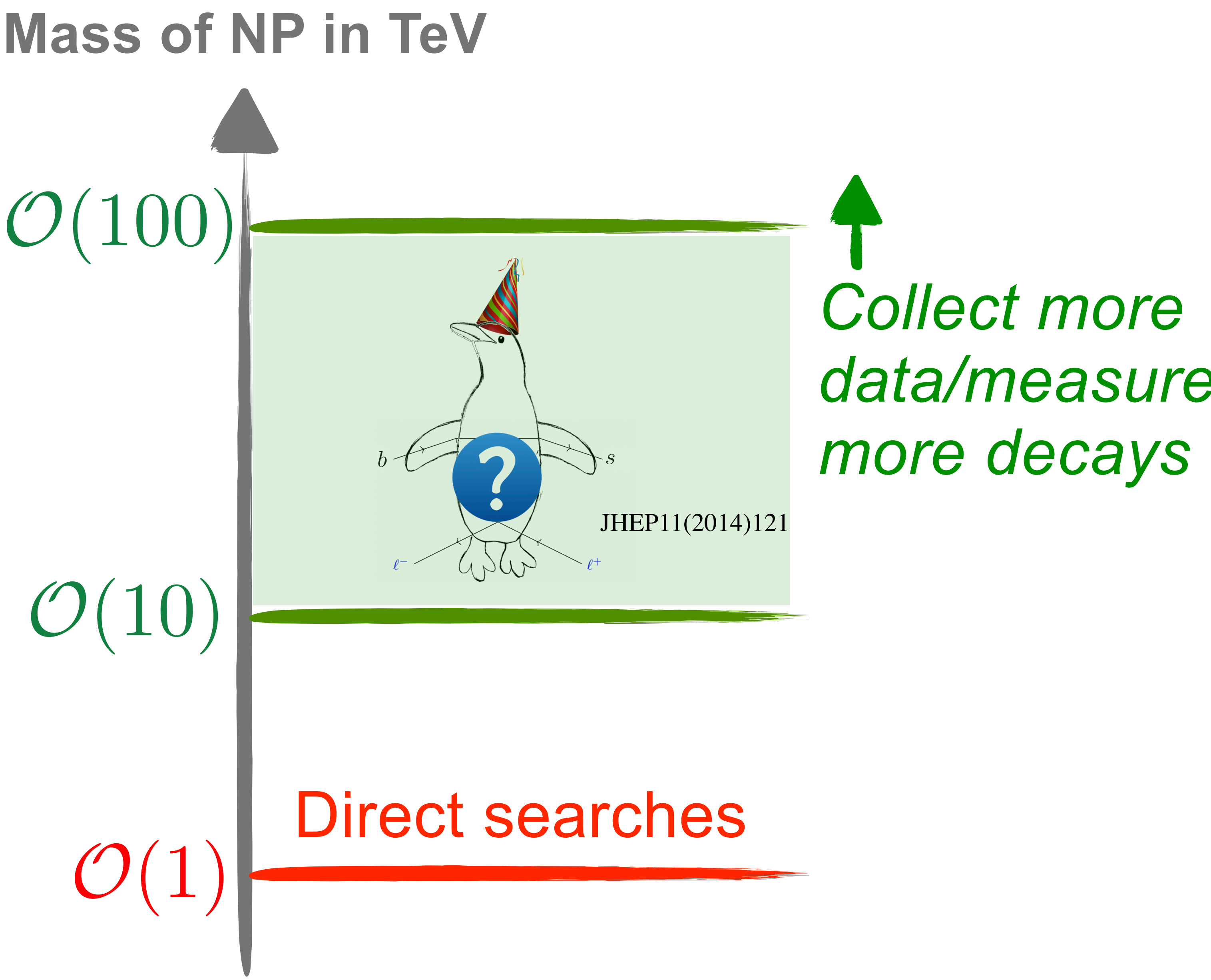
Suppression = very sensitive to New Physics diagrams

Electroweak Penguins



$$b \to s\ell^+\ell^-$$

Standard Model


Mass of NP in TeV

$\mathcal{O}(100)$

$\mathcal{O}(10)$

$\mathcal{O}(1)$

Collect more data/measure more decays

Direct searches

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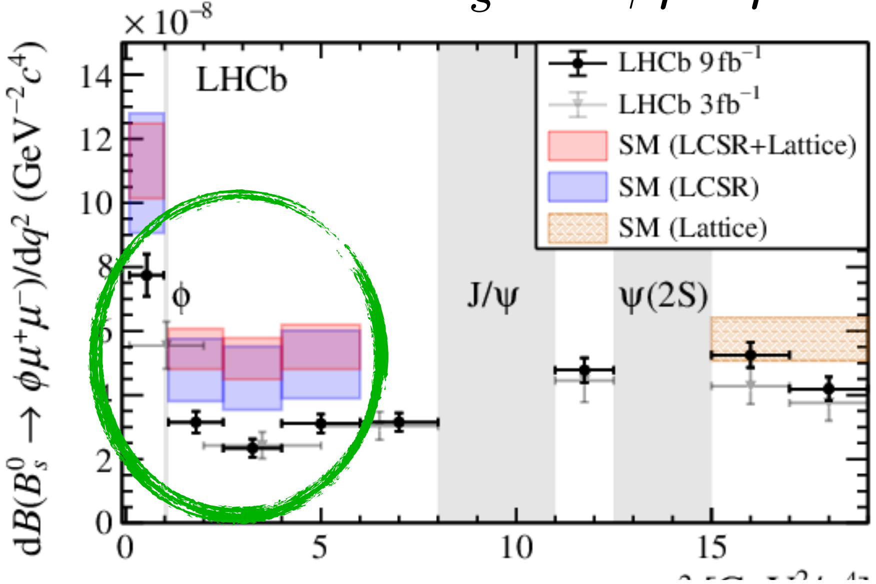
New Physics beyond the TeV

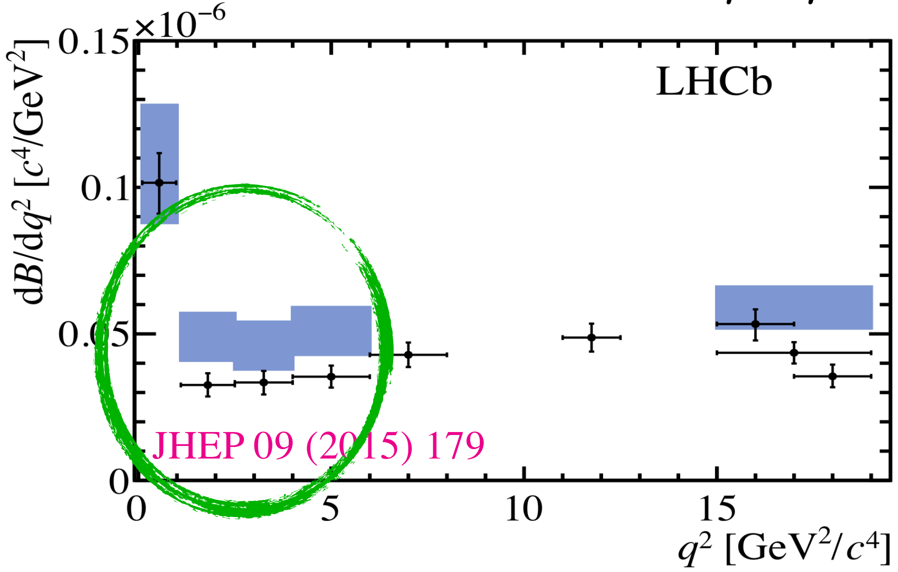
Suppression = very sensitive to New Physics diagrams

Summary of branching fractions

$B_s^0 \to \phi\mu^+\mu^-$



$B^0 \to K^{*0}\mu^+\mu^-$



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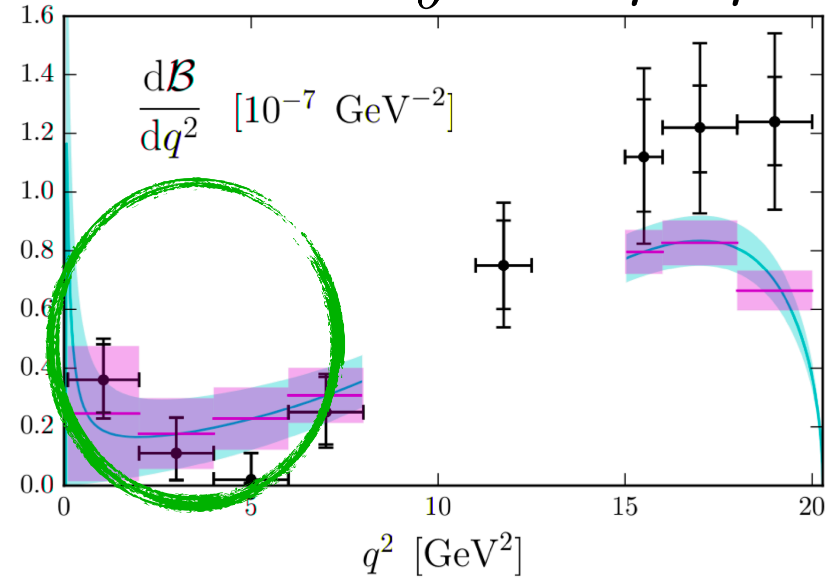
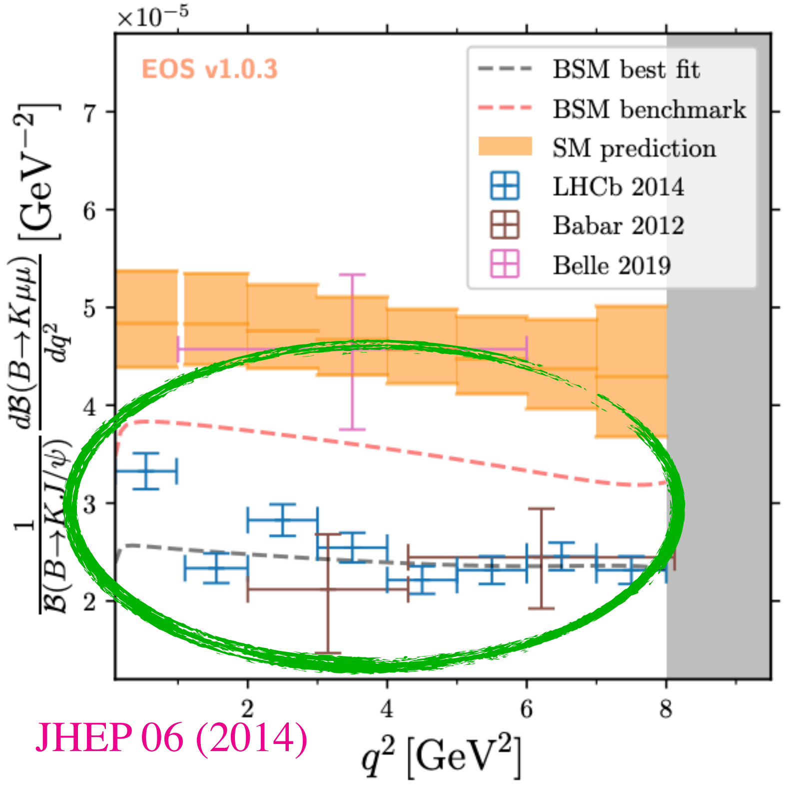
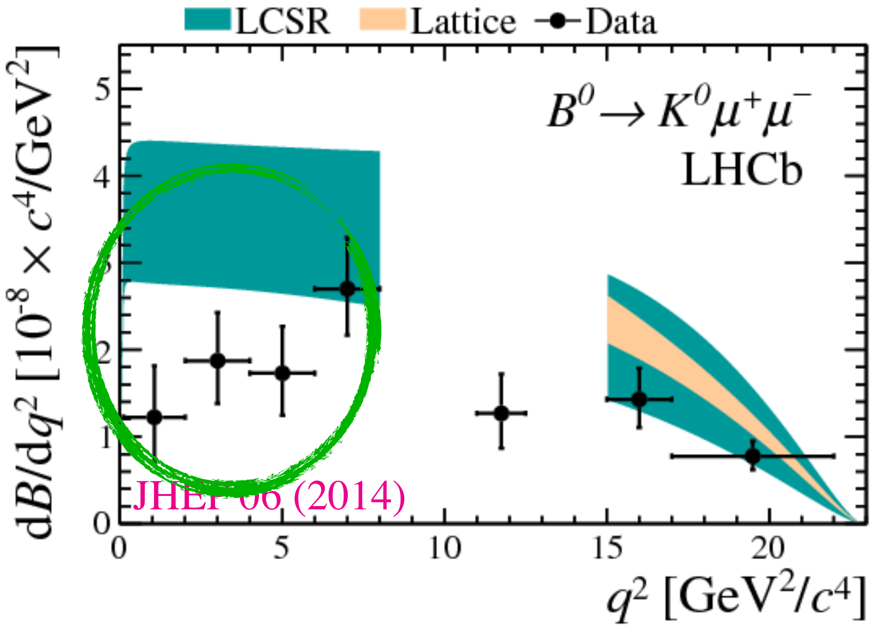
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

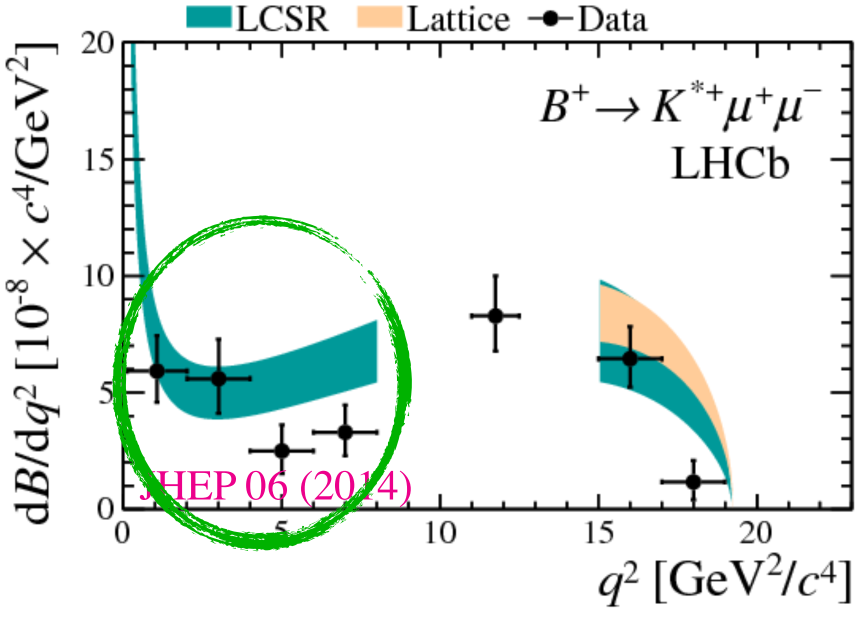




JHEP 06 (2014)



JHEP 06 (2014)

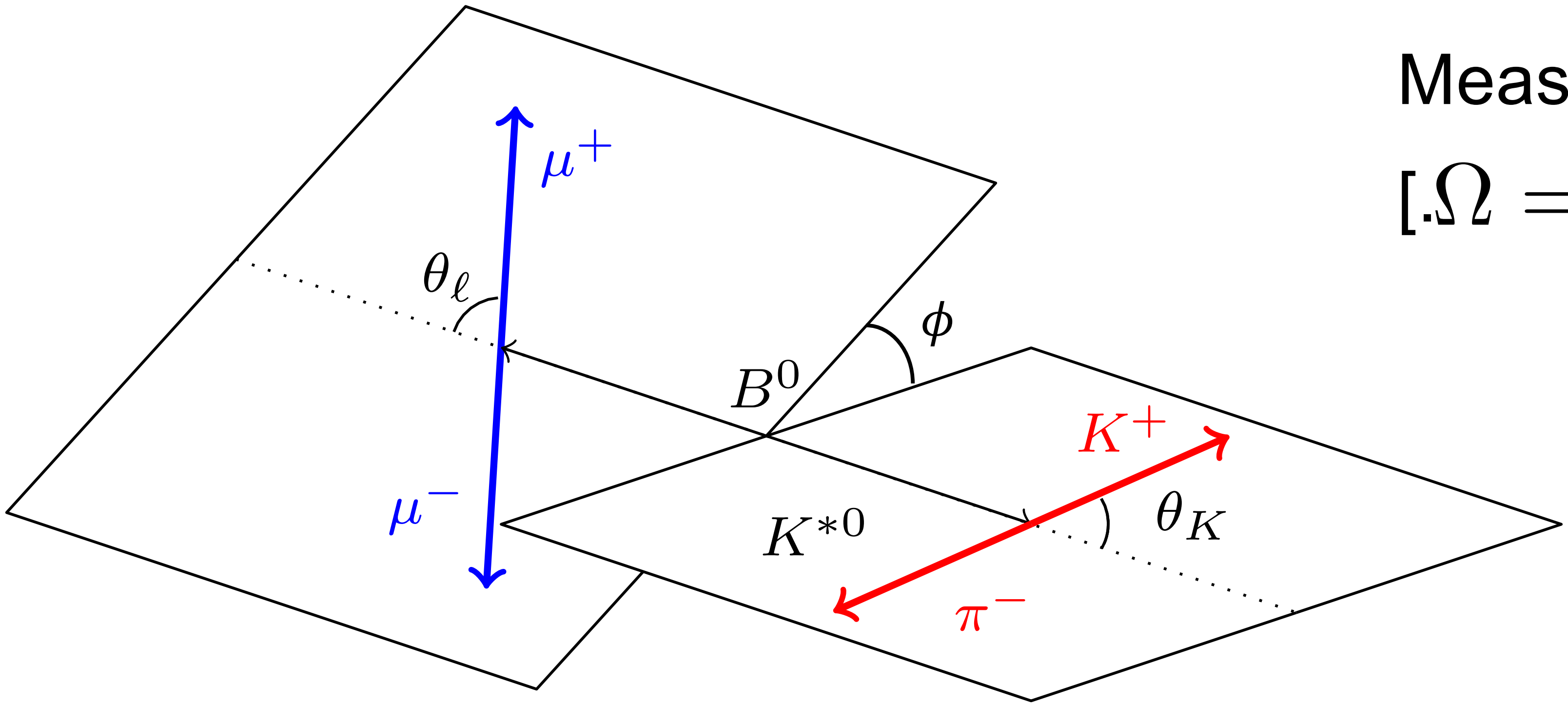


JHEP 06 (2014)

Same pattern, decay rate too low!!

Angular analysis

Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$



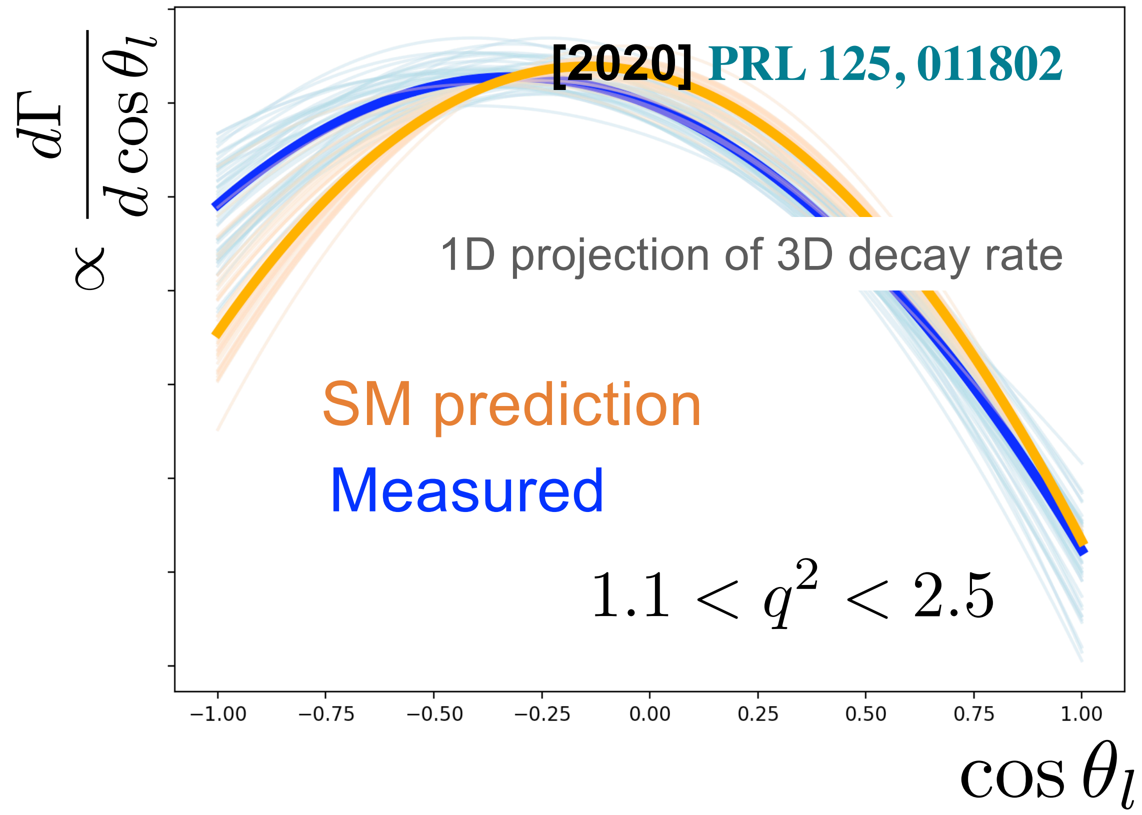
Measure decay rate across

[$\Omega = \cos\theta_l, \cos\theta_k, \phi$] and q²

angular coefficients - **8 in total**

$$\frac{\mathrm{d}^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{d}\hat{\Omega}\mathrm{d}q^2} = \sum_i I_i(q^2) f_i(\Omega)$$

angular functions



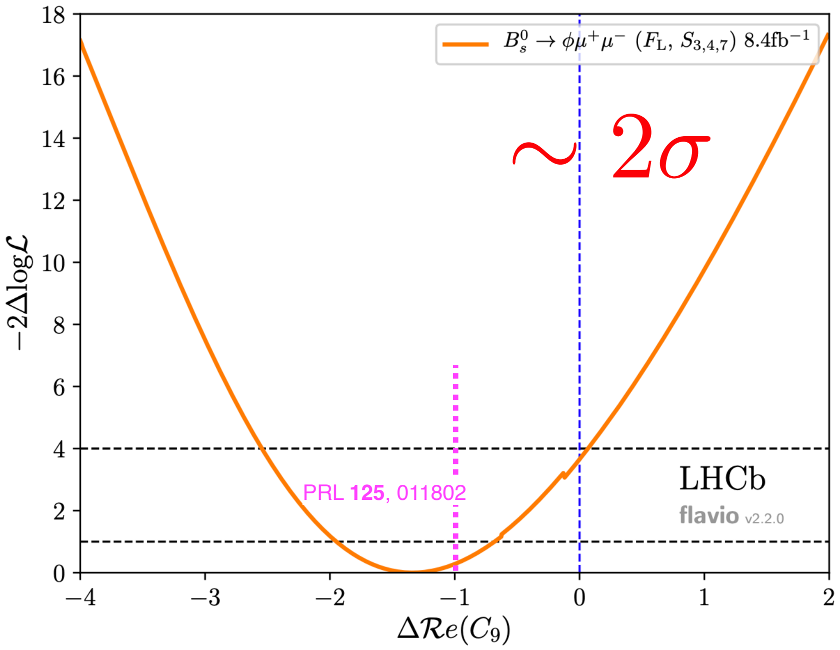
Perform in bins of q²

Summary of angular analysis

$B_s^0 \to \phi\mu^+\mu^-$

$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.3\,^{+0.7}_{-0.6}$

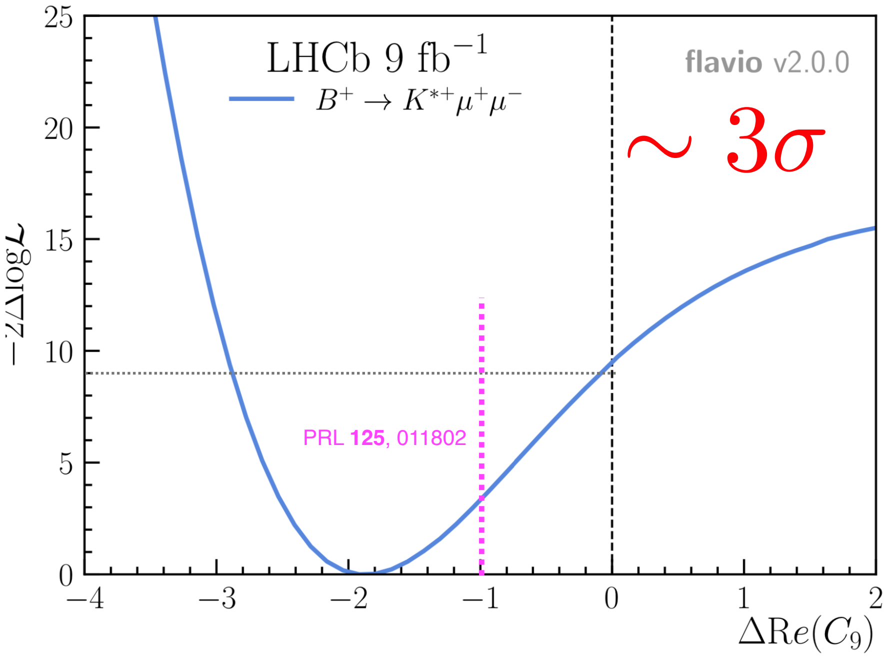
JHEP 11 (2021) 043



$B^+ \to K^{*+}\mu^+\mu^-$

$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.9$

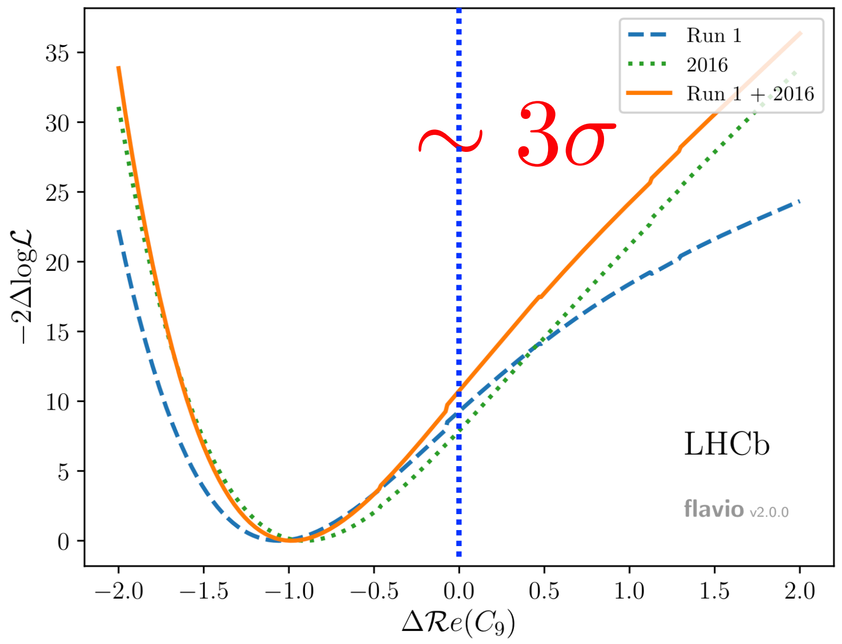
Phys. Rev. Lett. **126**, 161802



$B^0 \to K^{*0}\mu^+\mu^-$

$\Delta\mathcal{R}e(\mathcal{C}_9) = -0.99^{+0.25}_{-0.21}$

Phys. Rev. Lett. **125**, 011802



Same pattern, negative definitions in effective coupling

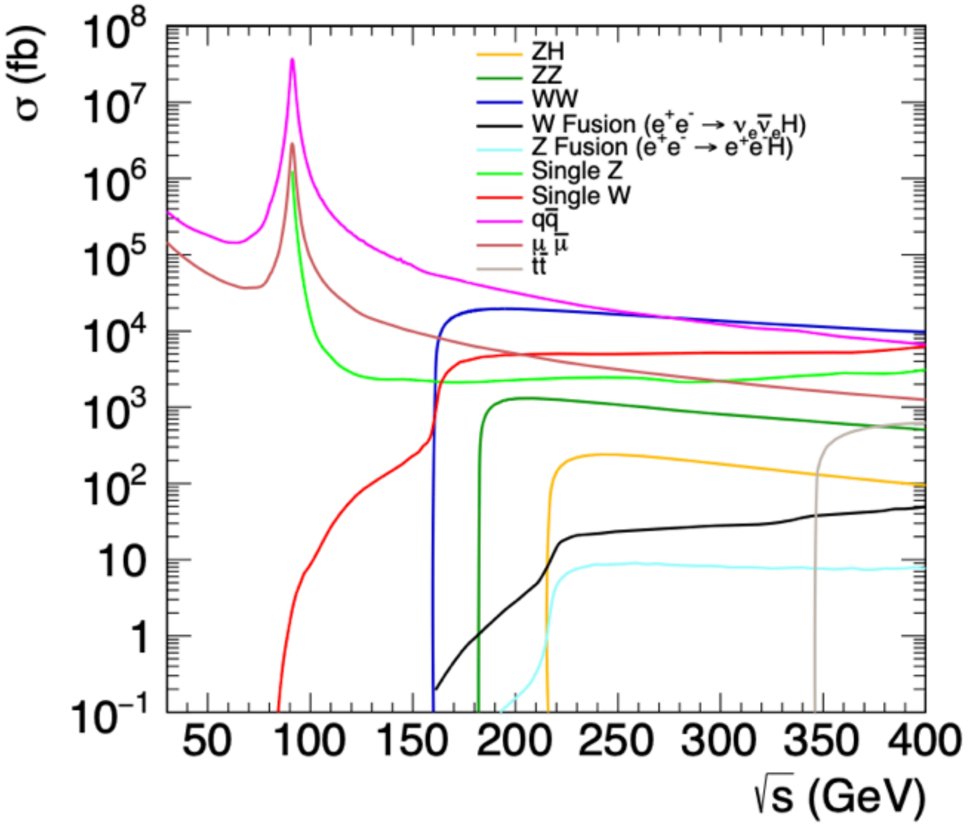
Studying flavour at the FCC

We will have unique sensitivity to certain decays

In particular $b \to s\tau\tau$ decays, and $b \to s\nu\bar{\nu}$

Polarisation of Z boson also gives new information in Λ_b^0 baryon decays (Mero/Asher project)

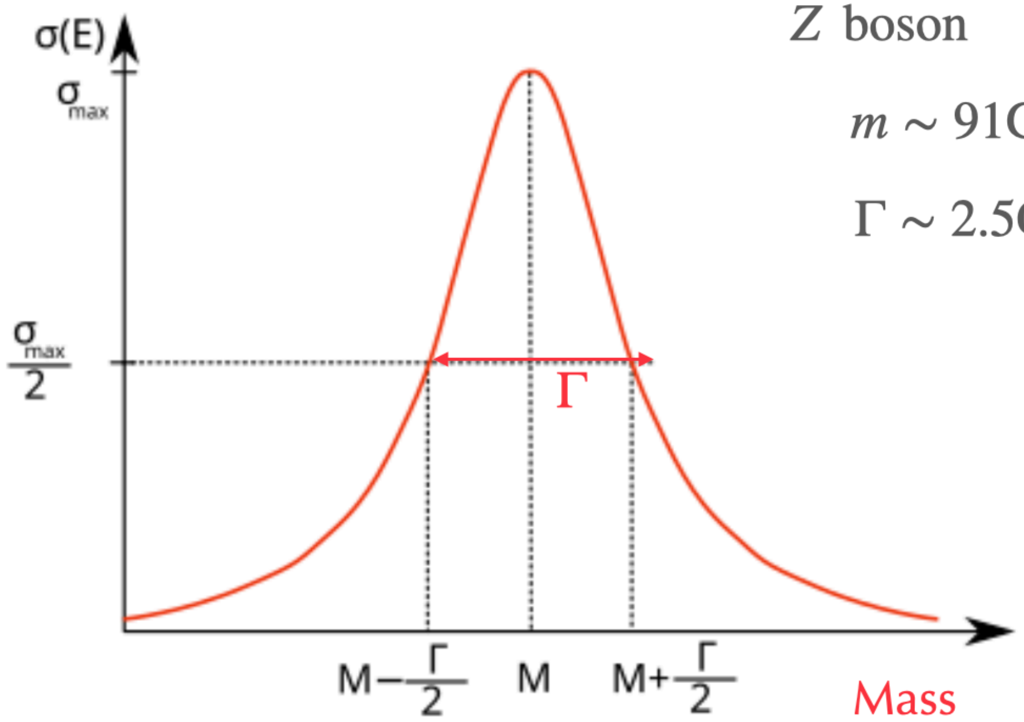
Physics at the Z pole summary



We will have most statistics at the Z-pole!

Many things to be done with 5×10^{12} Z bosons

Electroweak measurements

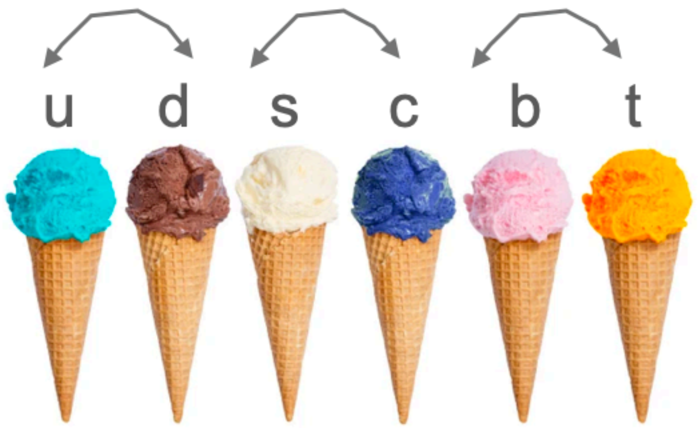


Z boson

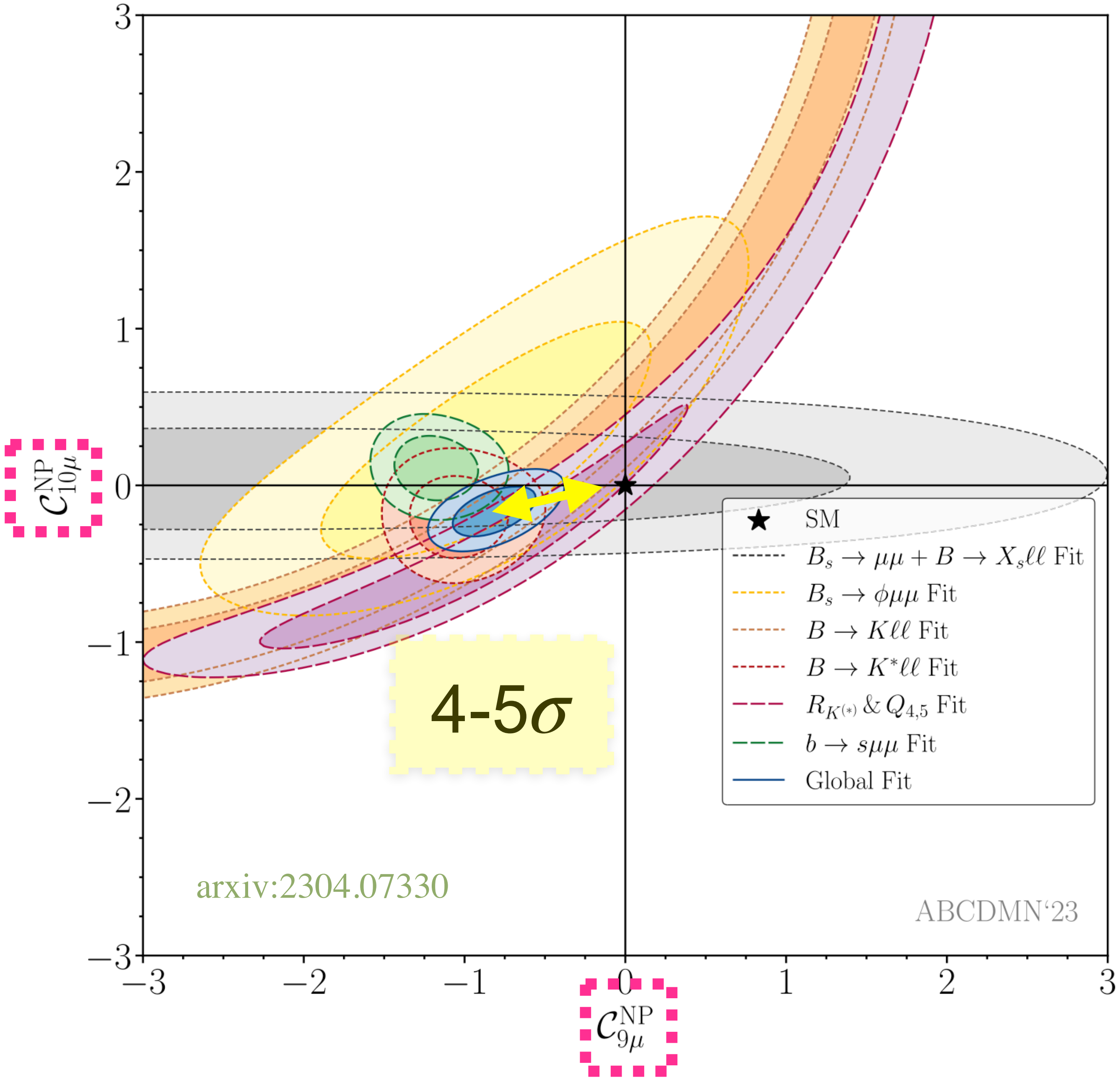
$m \sim 91\text{GeV}$

$\Gamma \sim 2.5\text{GeV}$

Flavour



Global deviation from SM over all $b \to s\ell\ell$?



Highest experimental precision in $b \to s\mu^+\mu^-$ decays

Combine branching fraction and angular information for all experiments and measured $b \to s\mu^+\mu^-$ modes

Disagreement with SM at level of 4-5σ

Long-standing discrepancy- why aren't we claiming new physics?

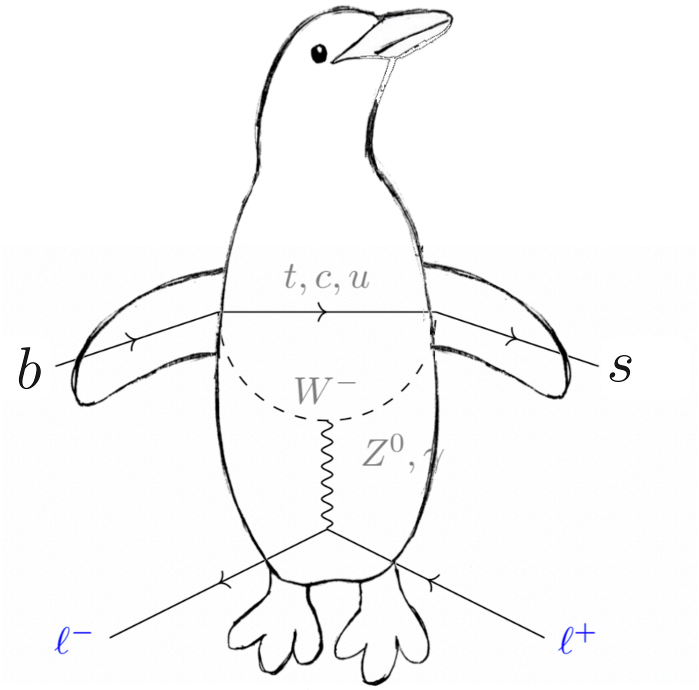
Hadronic cleanliness

Lepton Flavour Universality and $B_s \to \mu^+\mu^-$

Angular analyses

Branching fractions

Cause of anomalies?

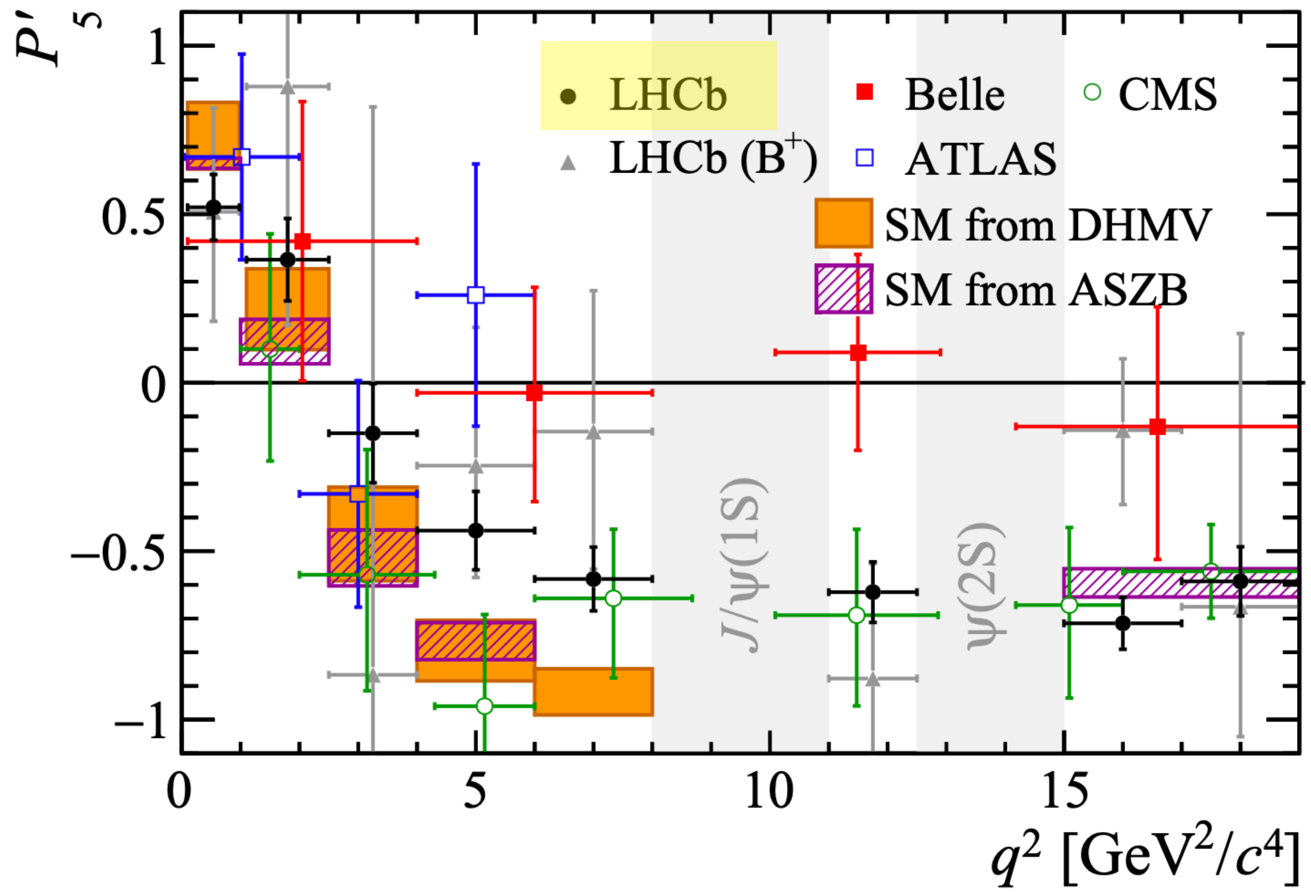


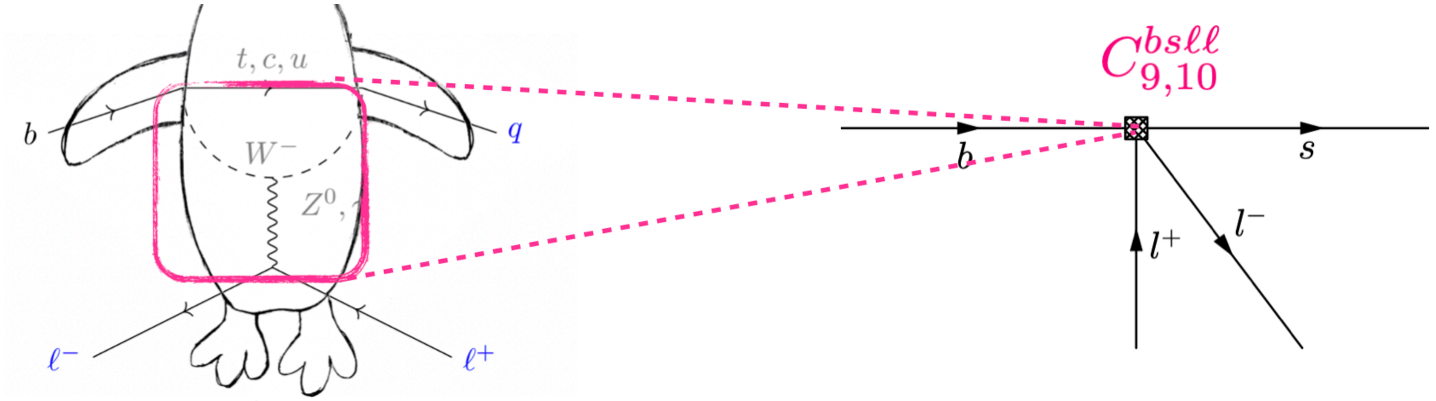
+ ? = deviations

Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

LHCb B0 PRL 125, 011802 (2020) . LHCb B+ PRL 161802 (2021) ATLAS: JHEP 10 (2018) 047

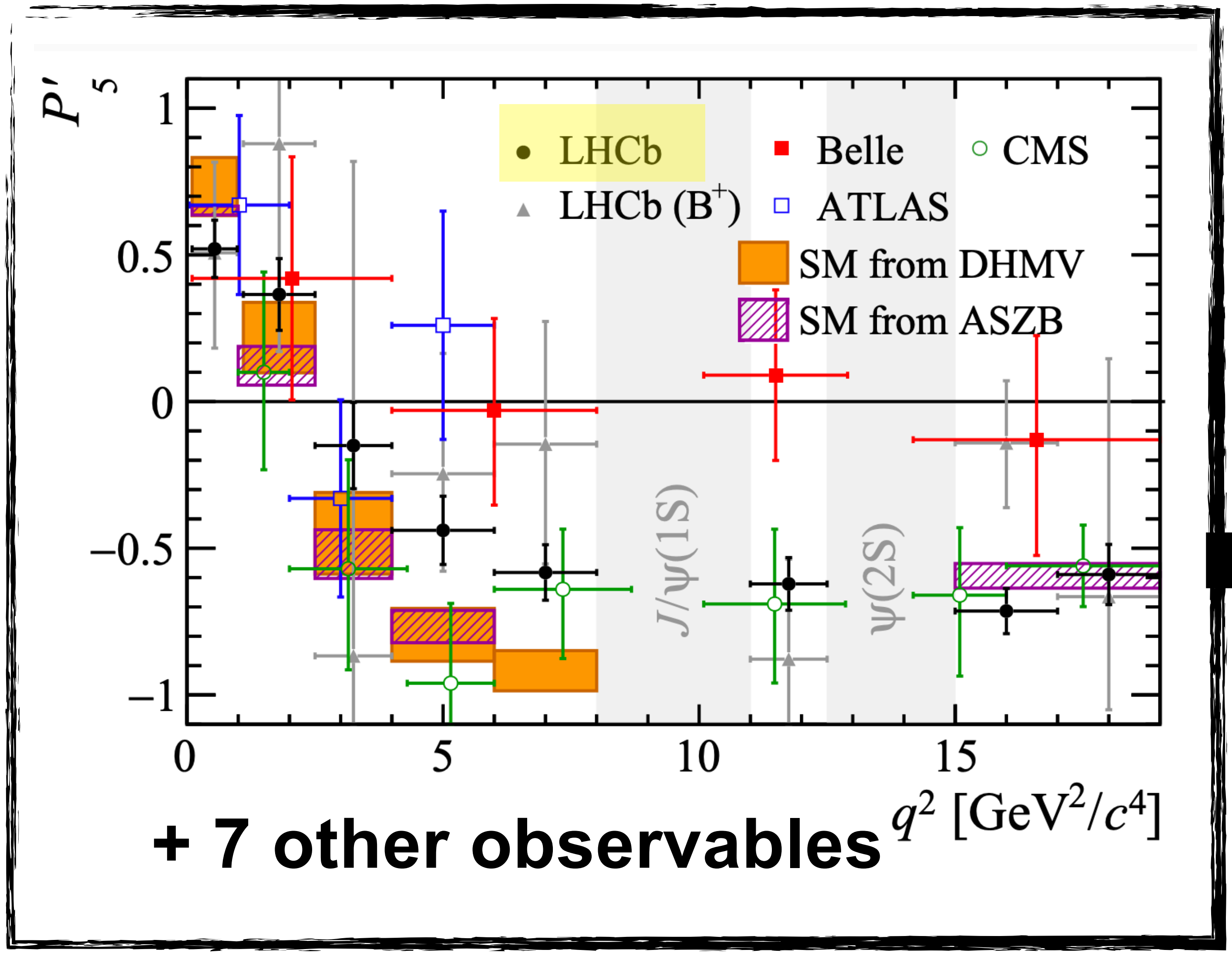
Belle: PRL 118 (2017), CMS:PLB 781 (2018) 517541



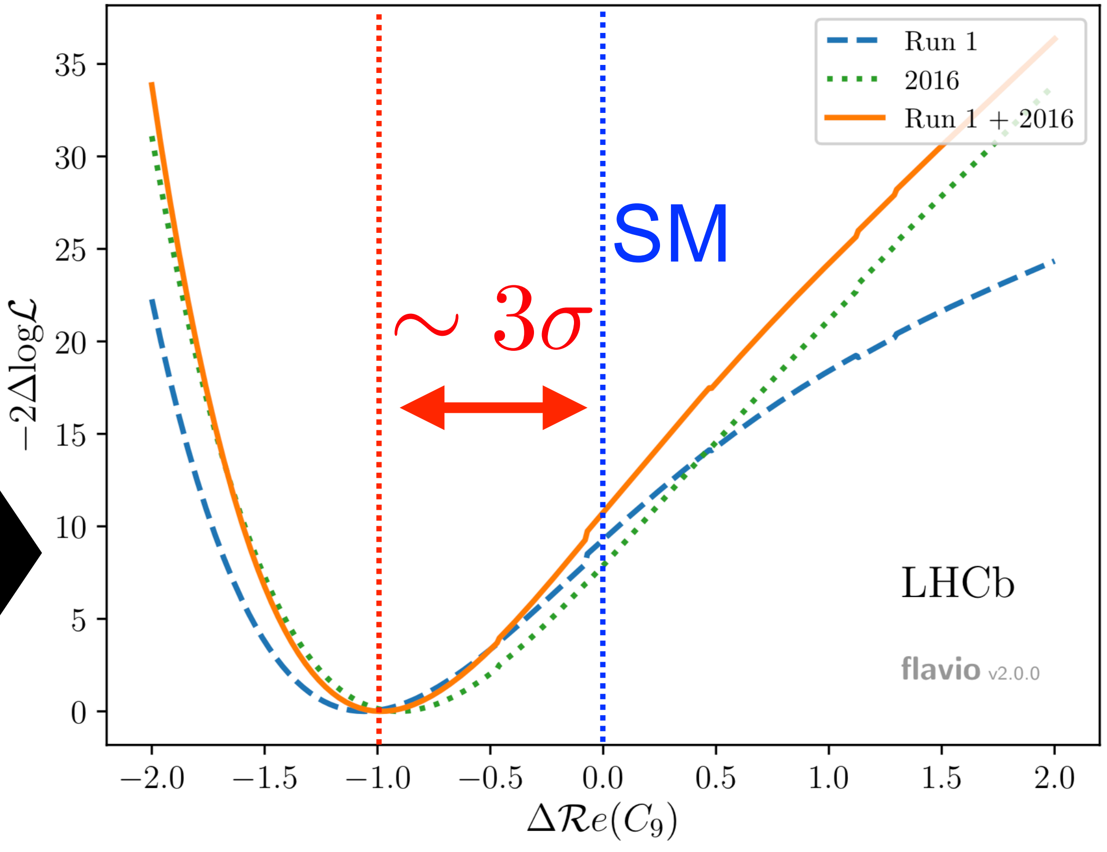


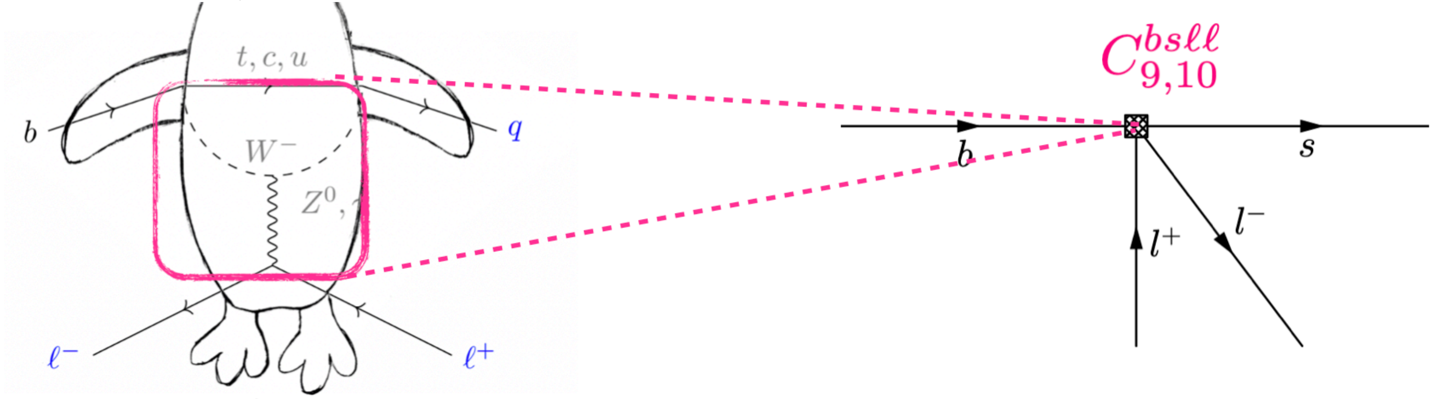
[2020] PRL 125, 011802

Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$



+ 7 other observables



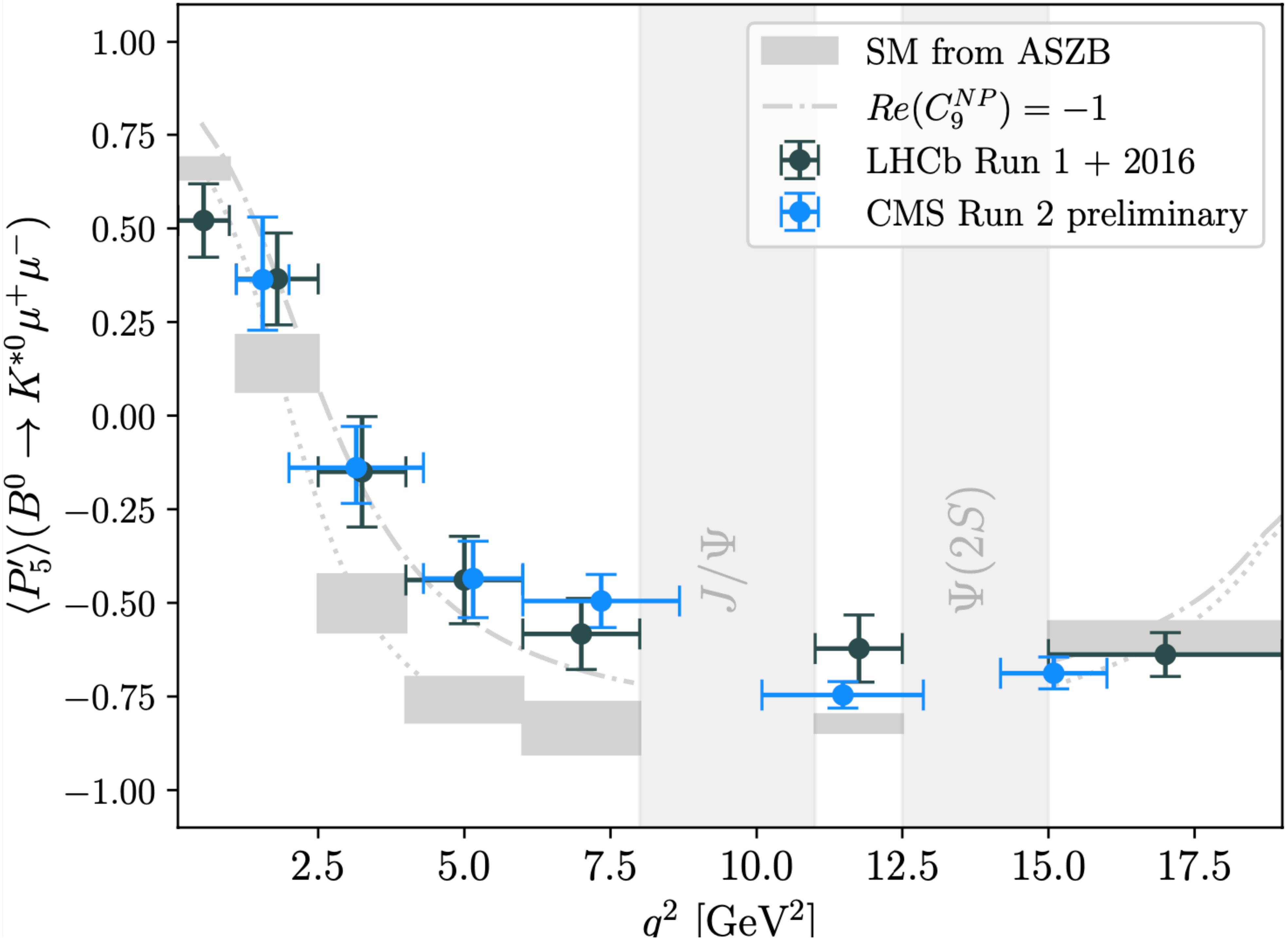


Express “global” agreement of all 8 observables with SM in terms of underlying effective couplings

[2020] PRL 125, 011802

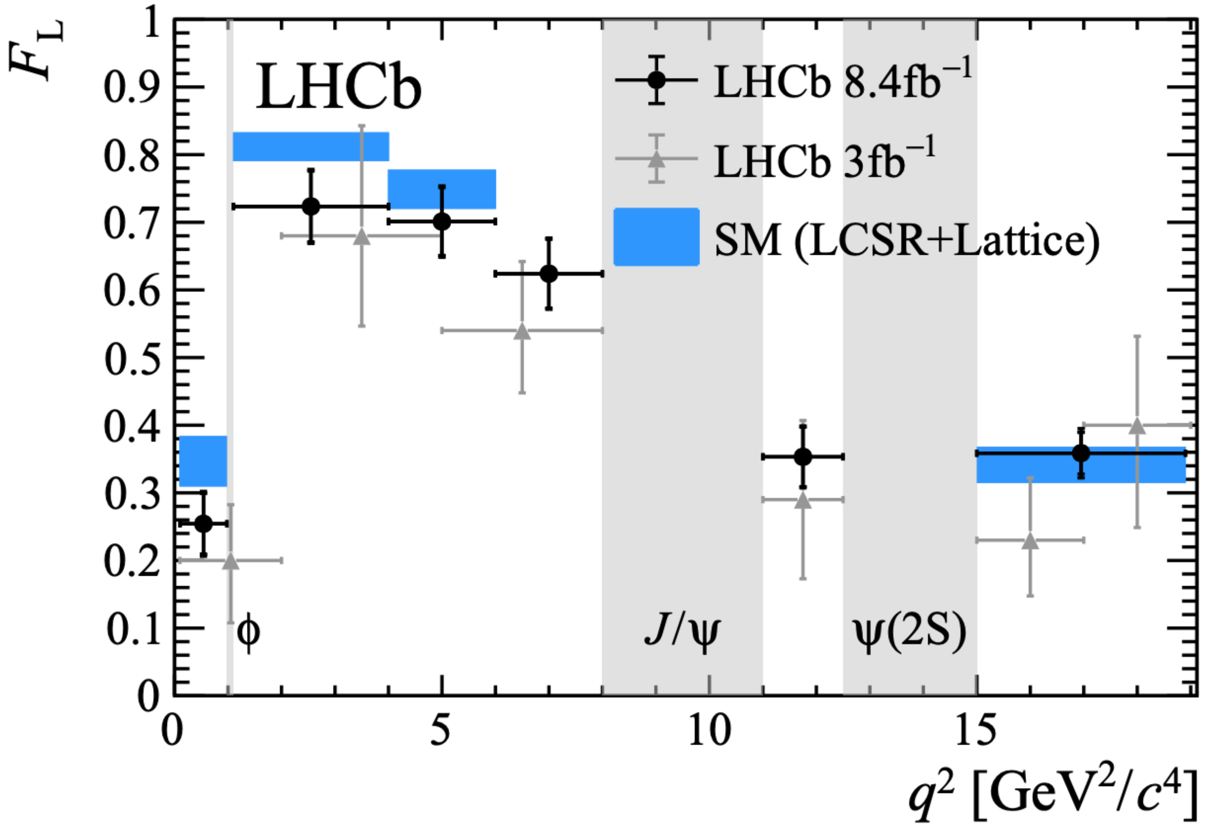
p-value ~0.001

Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$



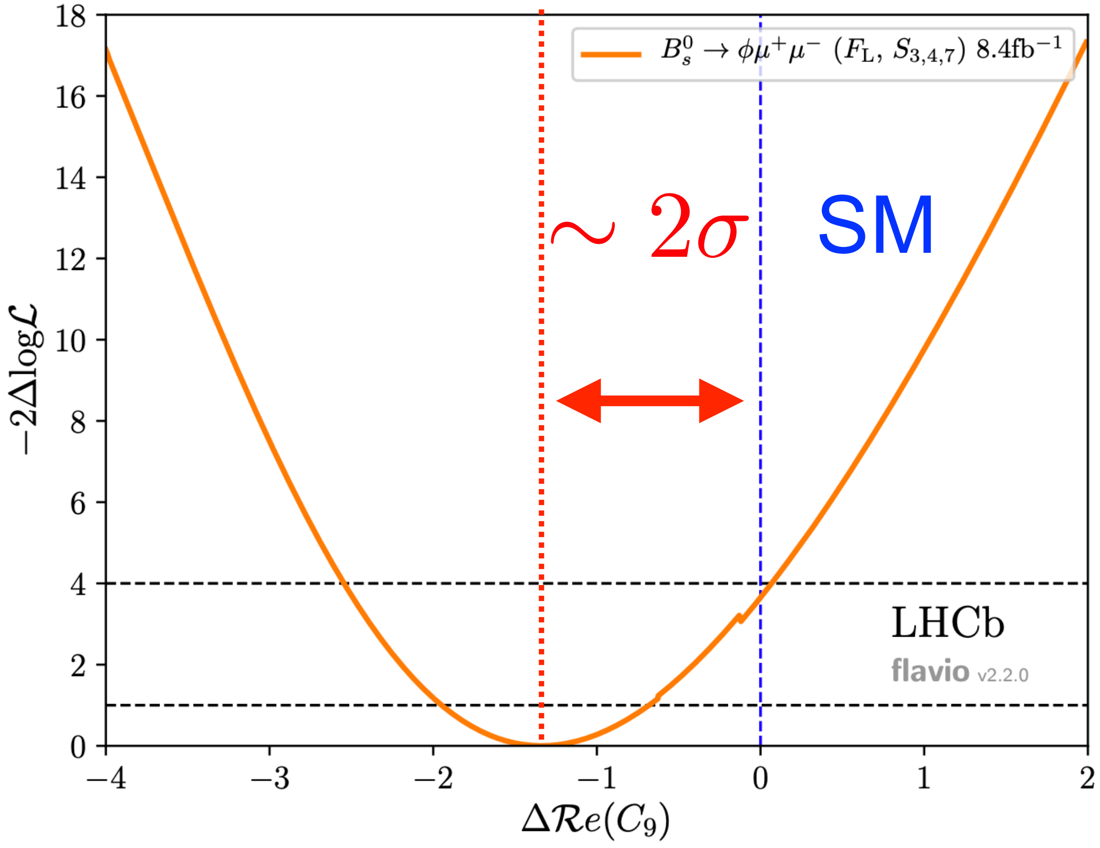
New CMS Run 2 bang on with LHCb Run 1 + 2016

Angular analysis of $B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$



+ 3 other observables

[2021] JHEP 11 (2021) 043

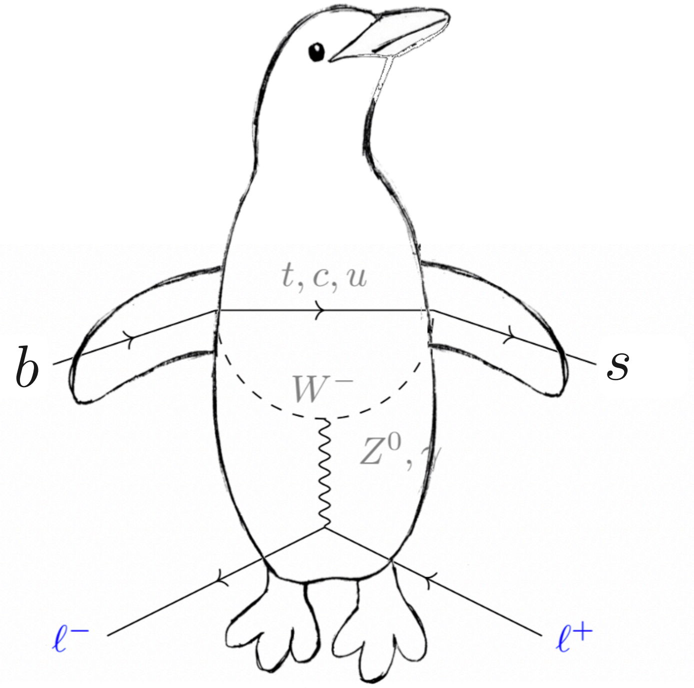


Express “global” agreement of all 4 observables with SM in terms of underlying effective couplings

p-value ~0.05

Cause of anomalies?

Option 1 - New Physics



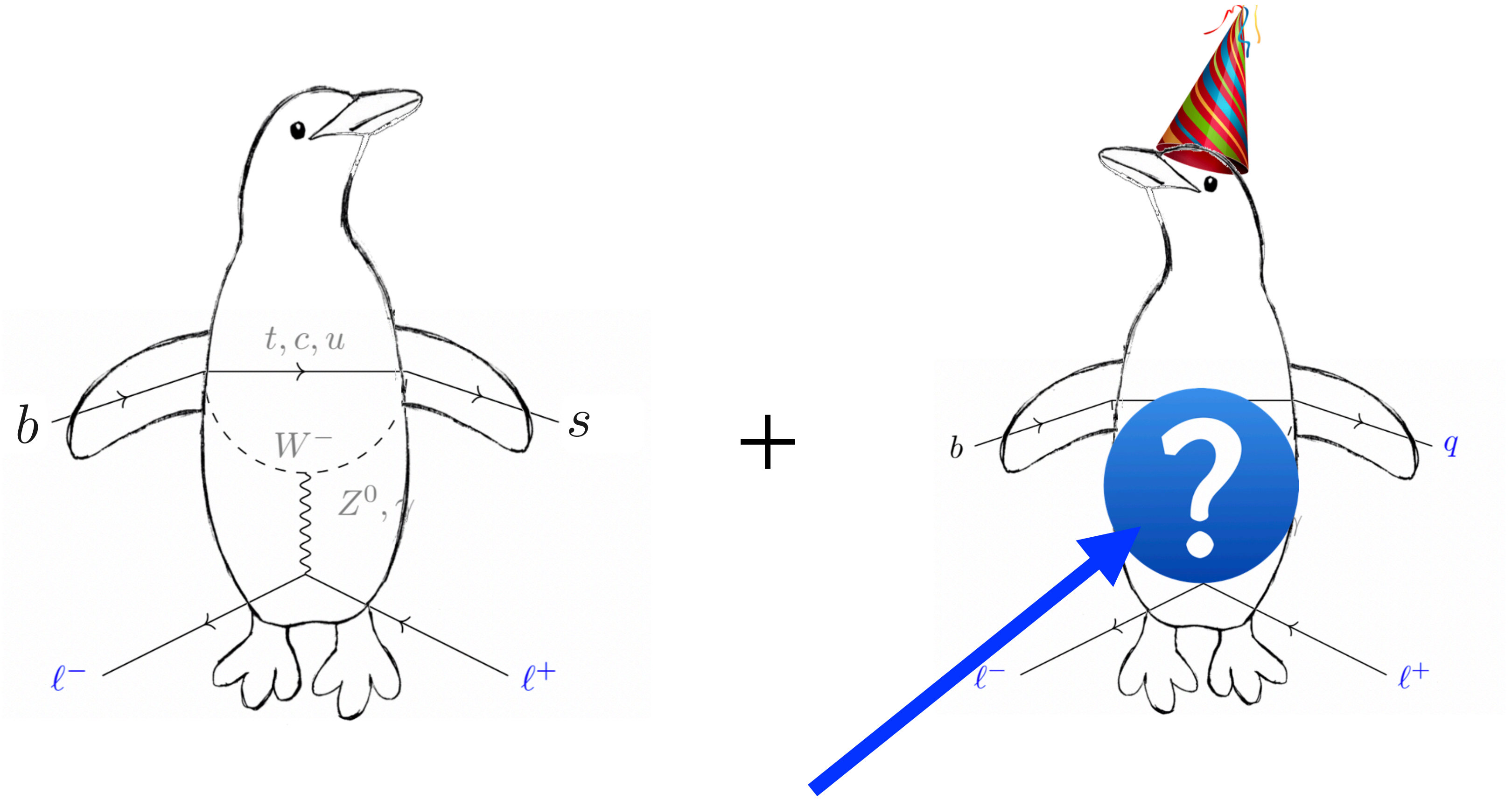
+

= deviations

Cause of anomalies?

Option 1 - New Physics

- e.g. enhancements in $b \to s\tau^+\tau^-$ gives combined explanation for B-anomalies

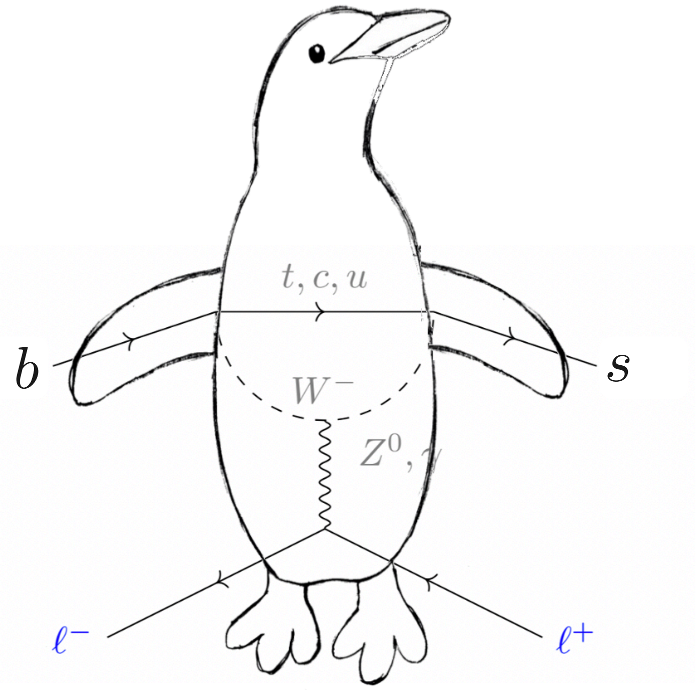


= deviations

CP violating? Leptoquark? $b \to s\tau^+\tau^-$?

Cause of anomalies?

Option 2 - misunderstood QCD processes



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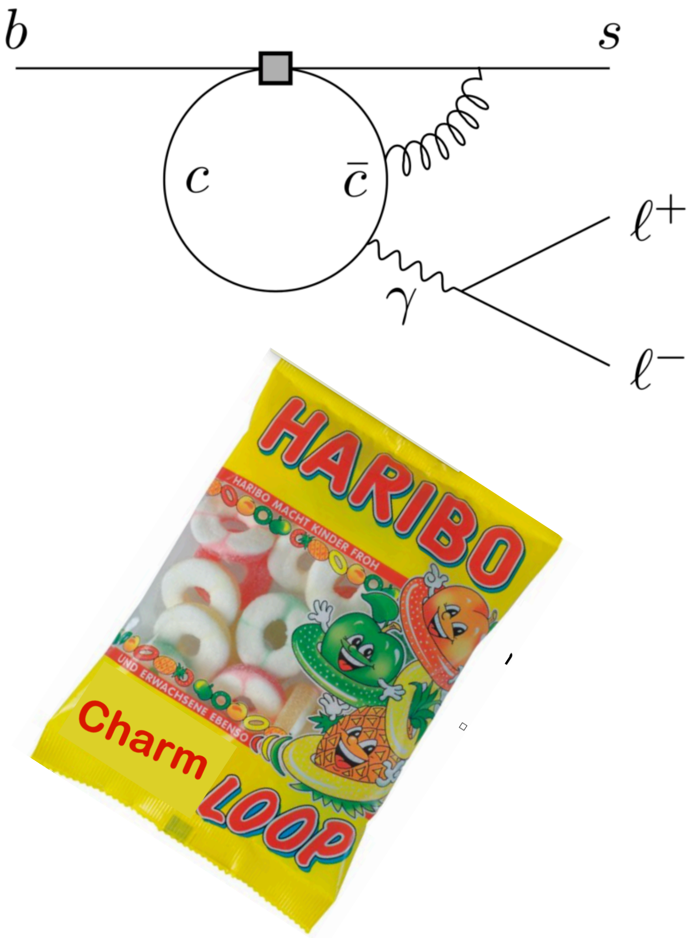
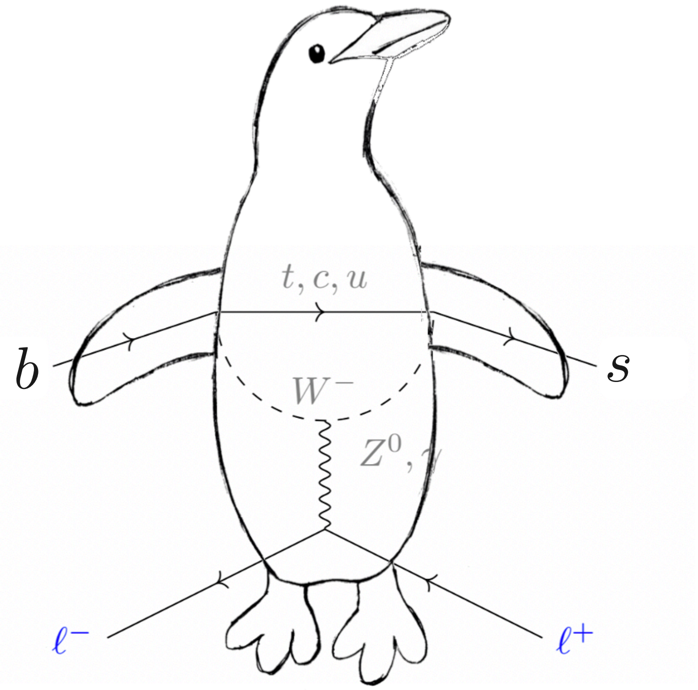


= deviations

Cause of anomalies?

Option 2 - misunderstood QCD processes

- $b \to s c\bar{c}[c\bar{c} \to \gamma^* \to \mu^+\mu^-]$ (charm-loops) difficult to calculate and can mimic deviations in C_9



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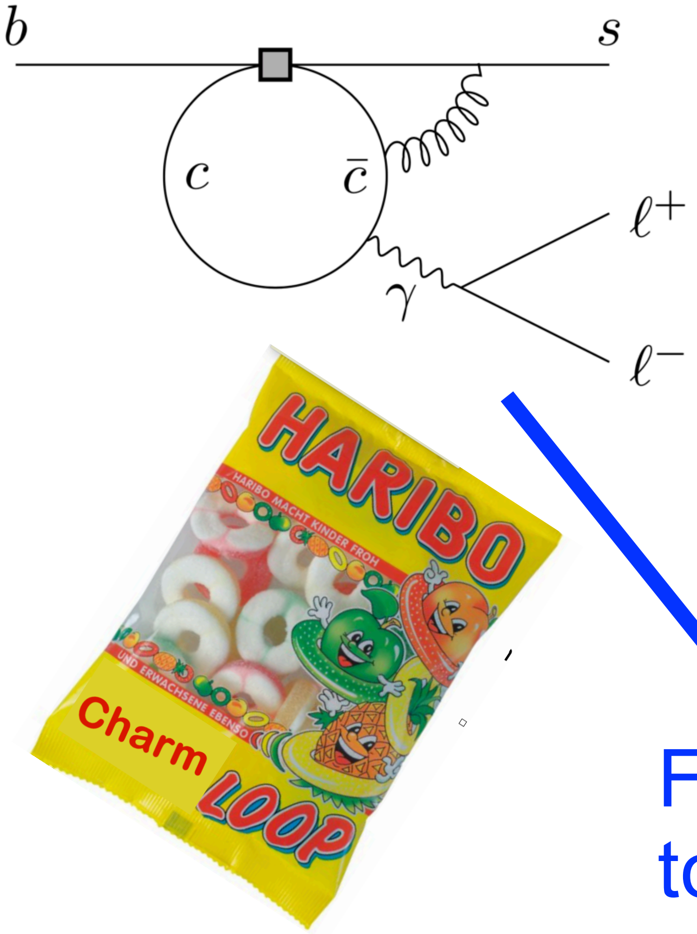
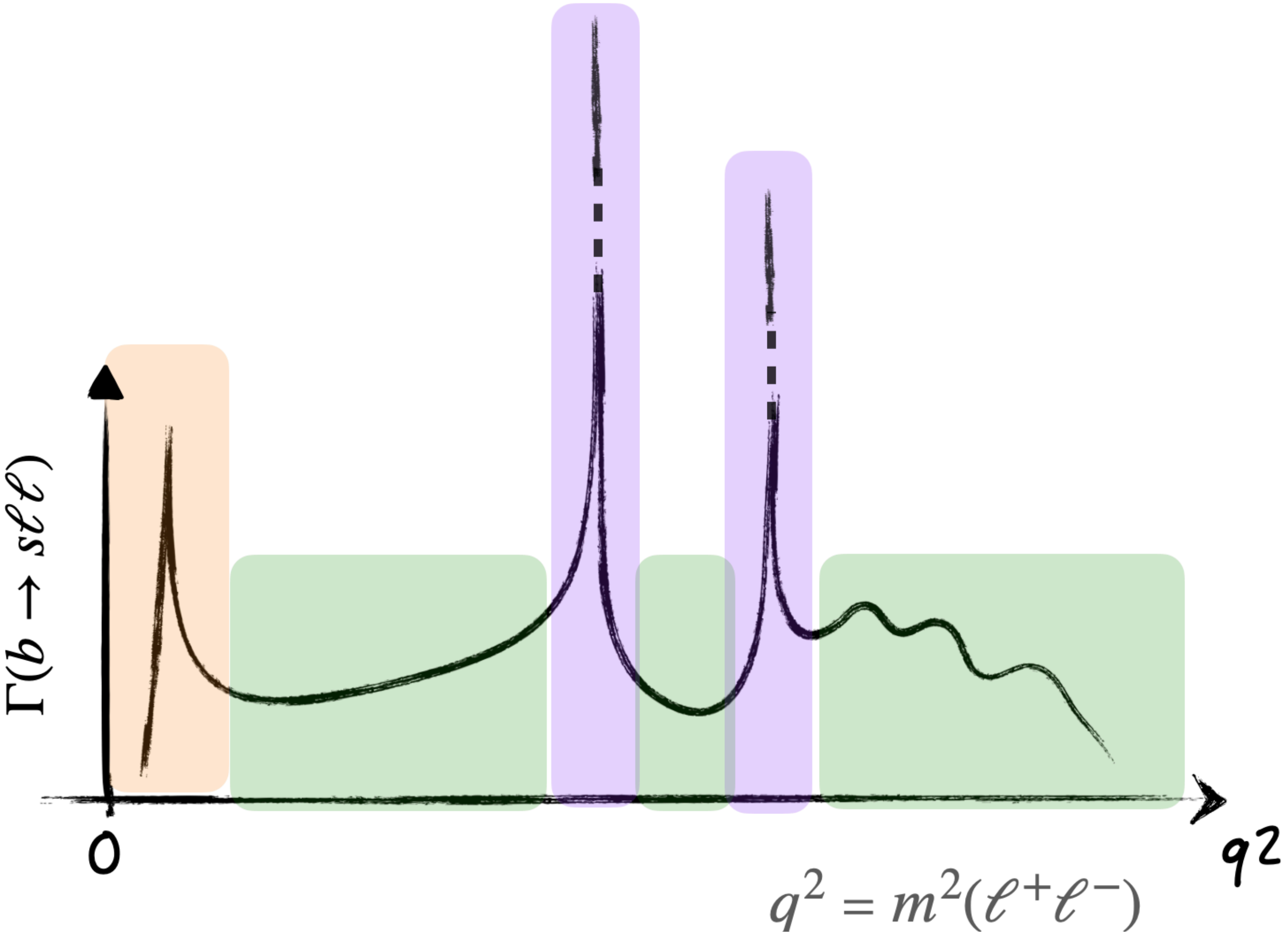


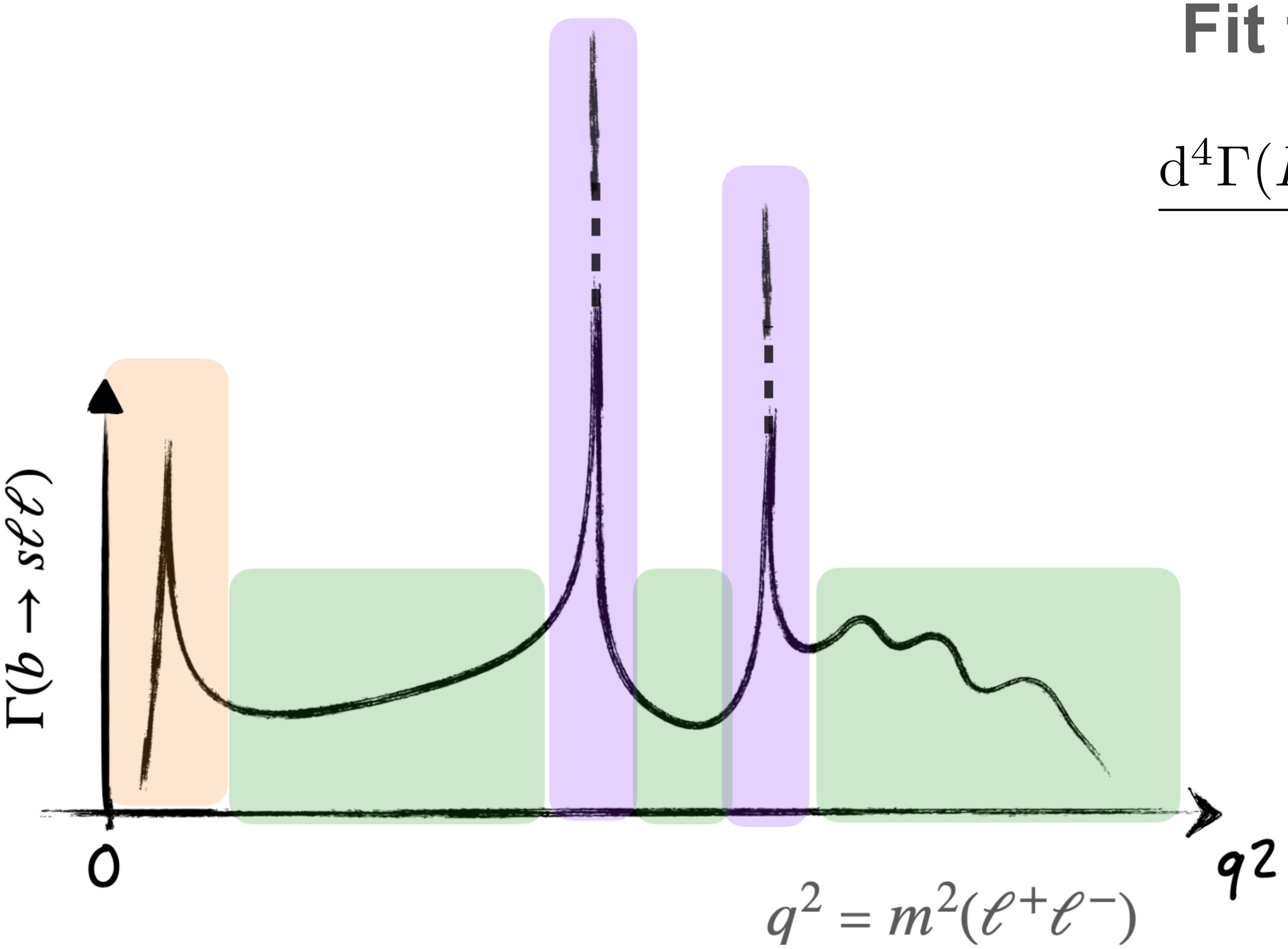
$=$ deviations

Fit theory models to data to constrain amplitudes

Fit q^2 spectrum continuously to disentangle long (non-local) and short distance contributions to $B^0 \to K^{*0}\mu^+\mu^-$



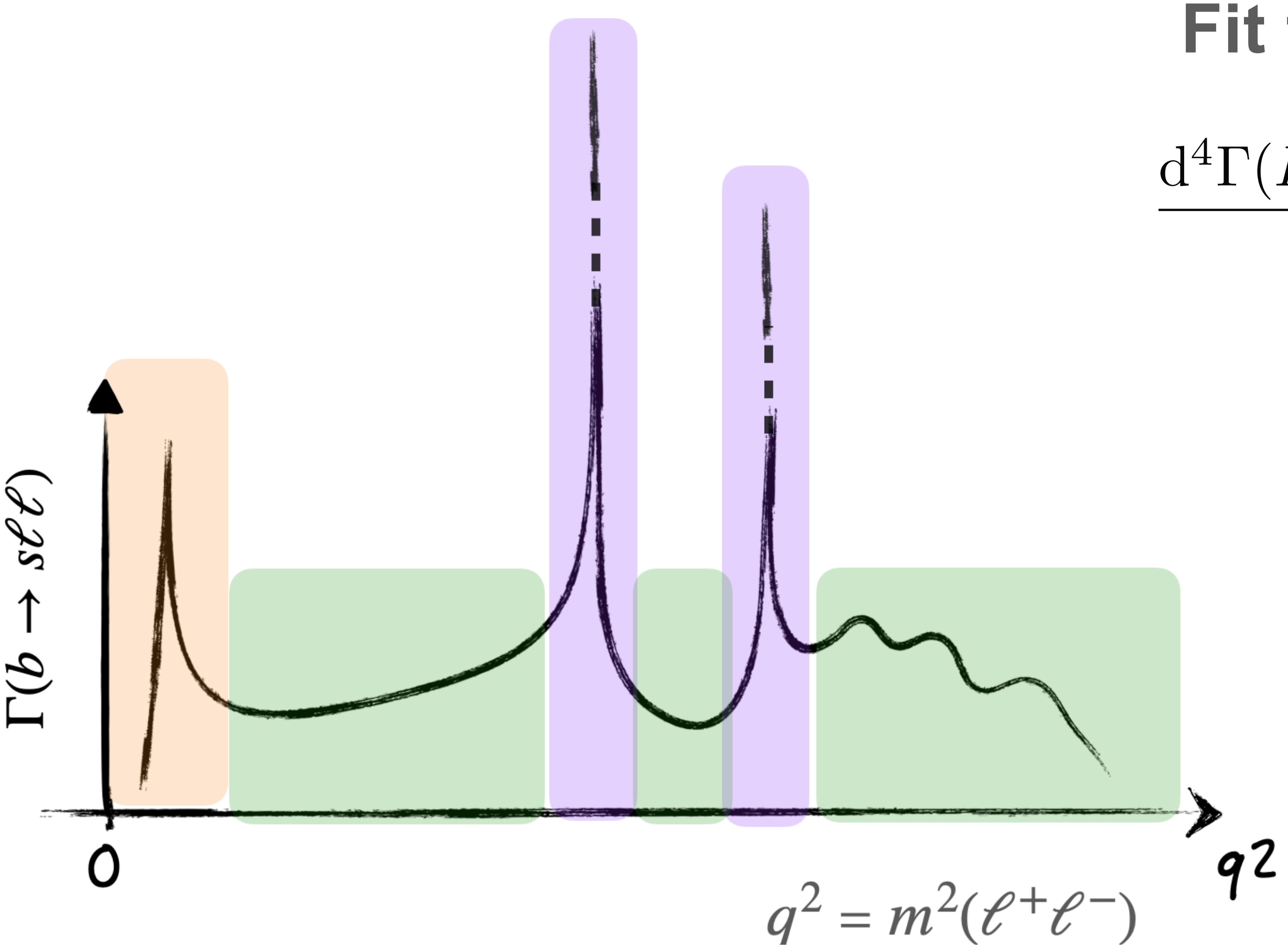
Fit q^2 spectrum continuously to disentangle long (non-local) and short distance contributions to $B^0 \to K^{*0}\mu^+\mu^-$



Fit the angular *and* q^2 spectrum

$$\frac{\mathrm{d}^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{d}\hat{\Omega}\mathrm{d}q^2} = \sum_i \underline{I_i(q^2)}\,\underline{f_i(\Omega)}$$

Fit q^2 spectrum continuously to disentangle long (non-local) and short distance contributions to $B^0 \to K^{*0}\mu^+\mu^-$



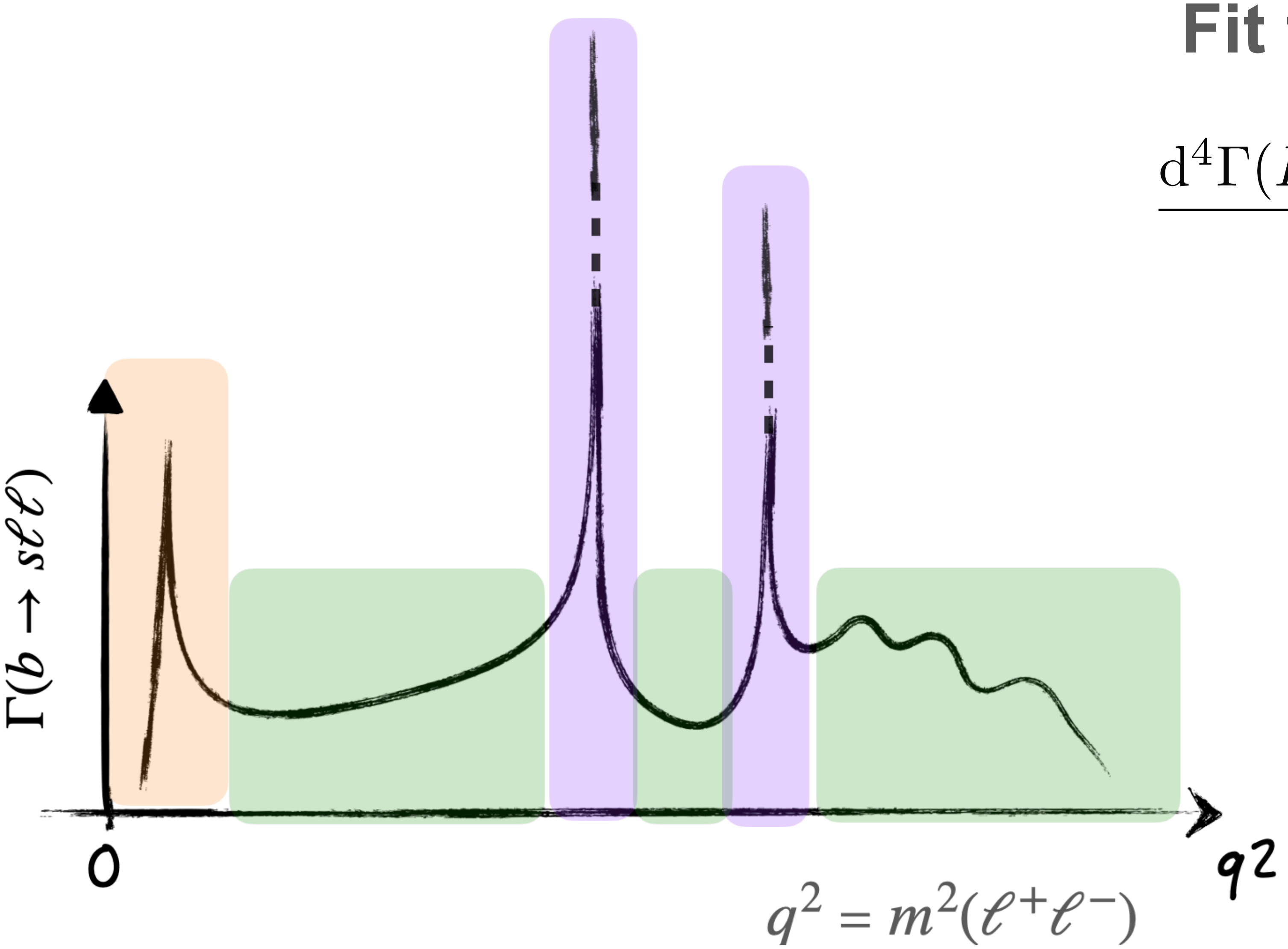
Fit the angular *and* q^2 spectrum

$$\frac{d^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{d\hat{\Omega}dq^2} = \sum_i \underline{I_i(q^2)}\,\underline{f_i(\Omega)}$$

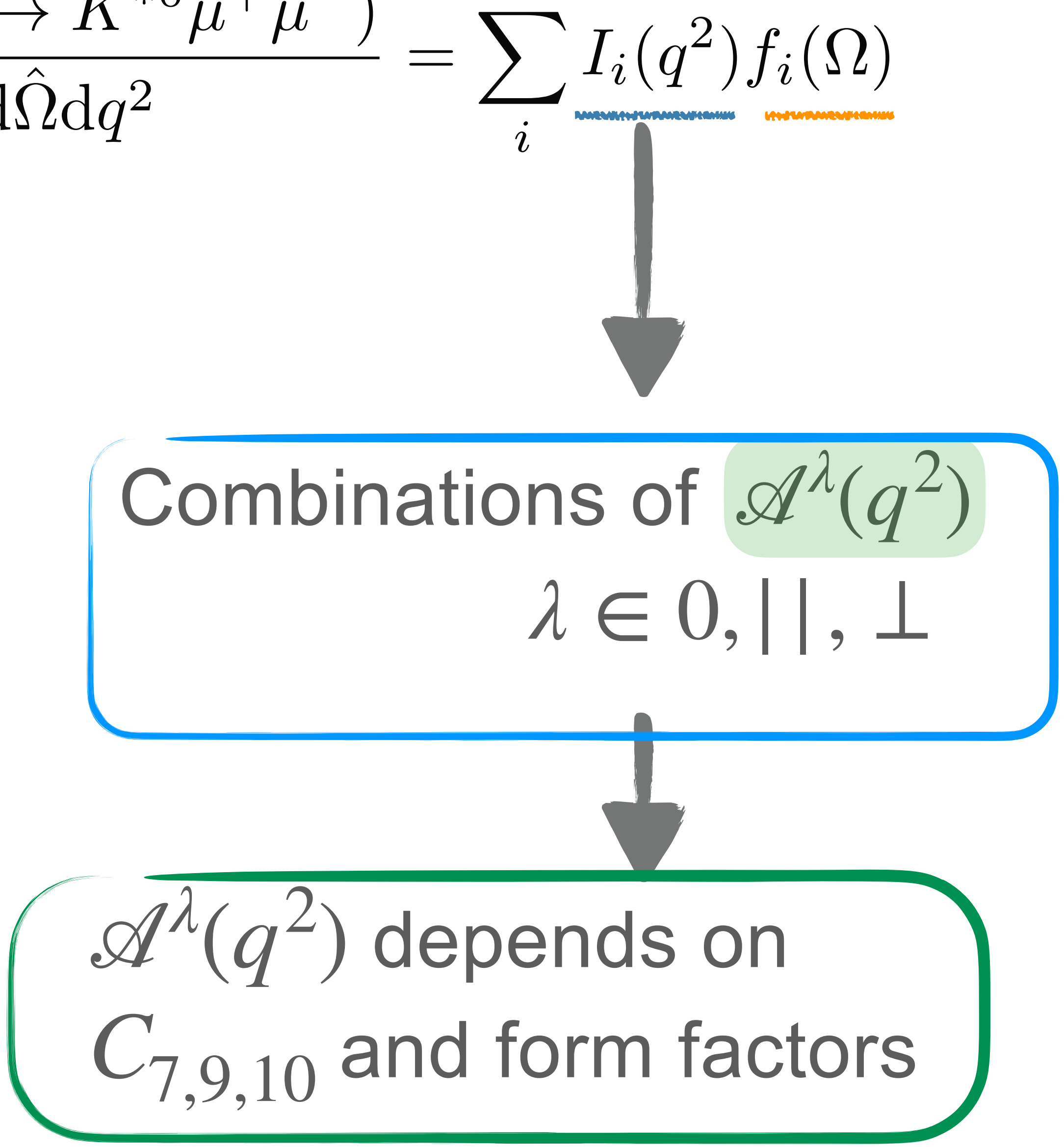
Combinations of $\mathscr{A}^\lambda(q^2)$

$\lambda \in 0, ||, \perp$

Fit q^2 spectrum continuously to disentangle long (non-local) and short distance contributions to $B^0 \to K^{*0}\mu^+\mu^-$



Fit the angular *and* q^2 spectrum

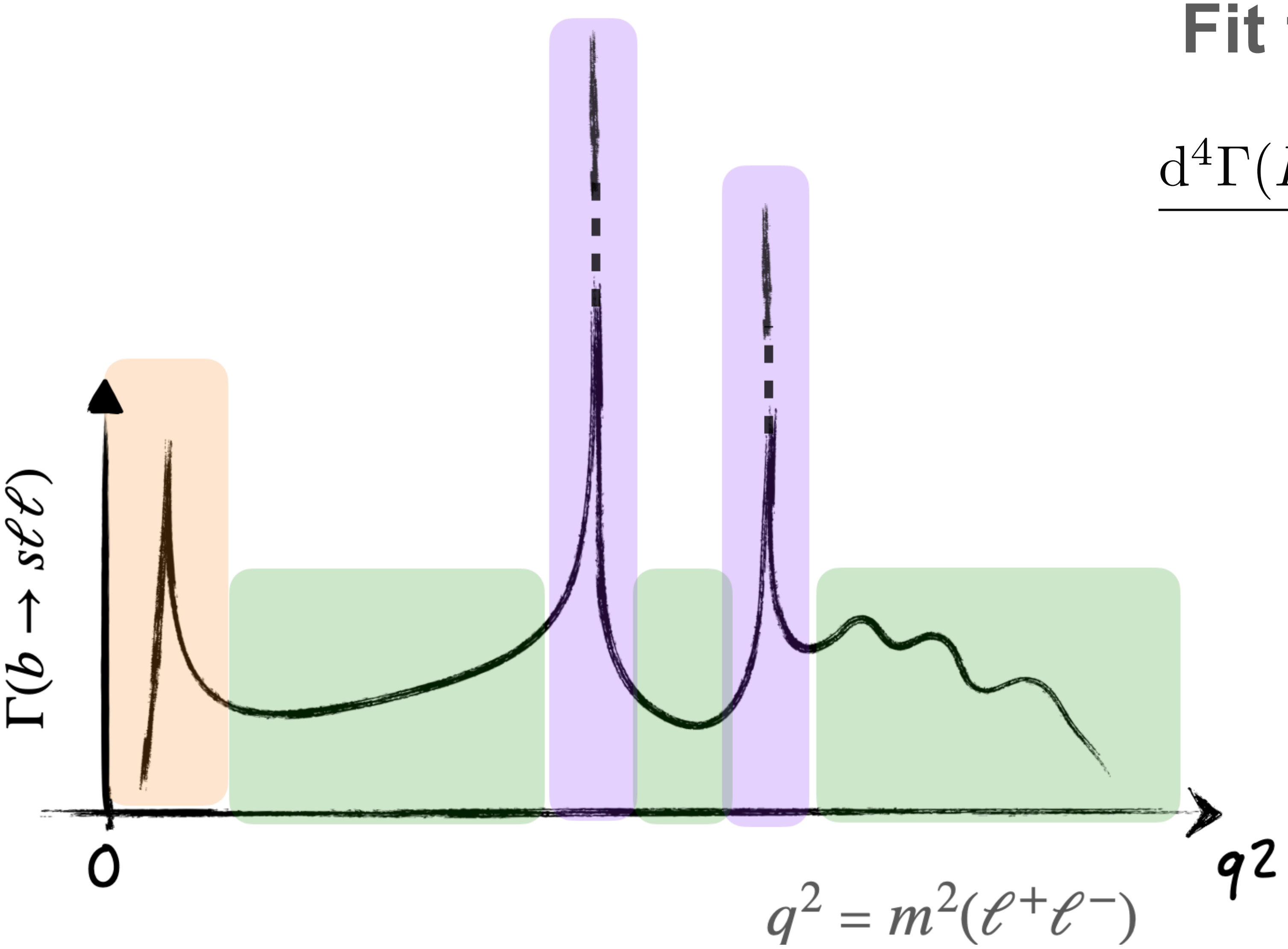


$$\frac{d^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{d\hat{\Omega}dq^2} = \sum_i \underline{I_i(q^2)}\,\underline{f_i(\Omega)}$$

Combinations of $\mathscr{A}^\lambda(q^2)$
$\lambda \in 0, ||, \perp$

$\mathscr{A}^\lambda(q^2)$ depends on $C_{7,9,10}$ and form factors

Fit q^2 spectrum continuously to disentangle long (non-local) and short distance contributions to $B^0 \to K^{*0}\mu^+\mu^-$



Fit the angular *and* q^2 spectrum

$$\frac{\mathrm{d}^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{d}\hat{\Omega}\mathrm{d}q^2} = \sum_i I_i(q^2) f_i(\Omega)$$

Combinations of $\mathscr{A}^\lambda(q^2)$

$\lambda \in 0, ||, \perp$

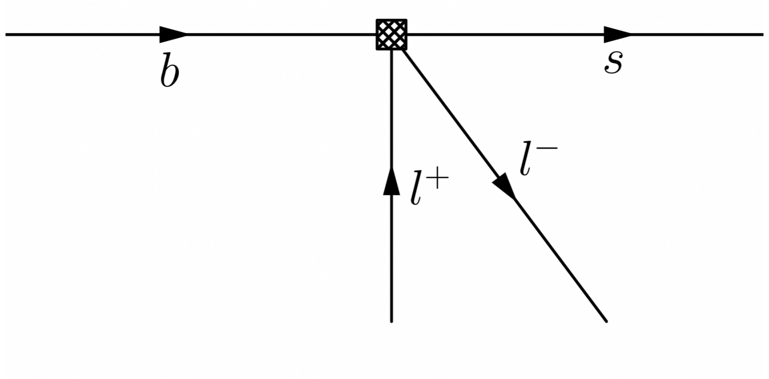
$\mathscr{A}^\lambda(q^2)$ depends on $C_{7,9,10}$ and form factors

C_9 (vector) is altered by non-local charm-loop

Parameterising non-local form-factors

$\lambda \in 0, ||, \perp$

$C_{9,\lambda}^{eff}(q^2) =$



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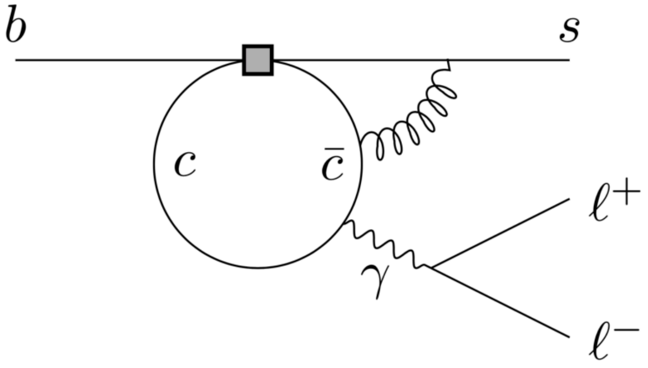
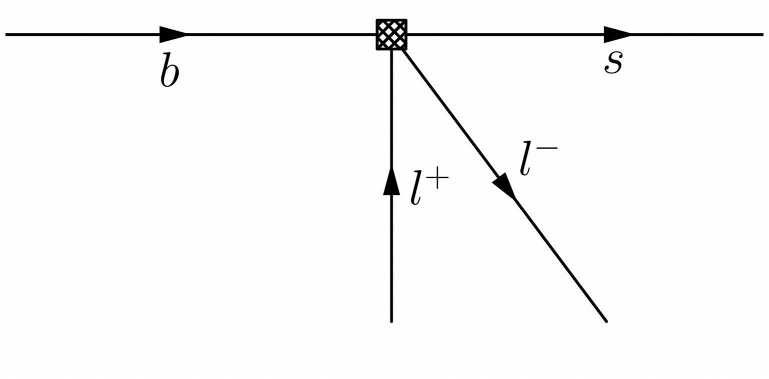
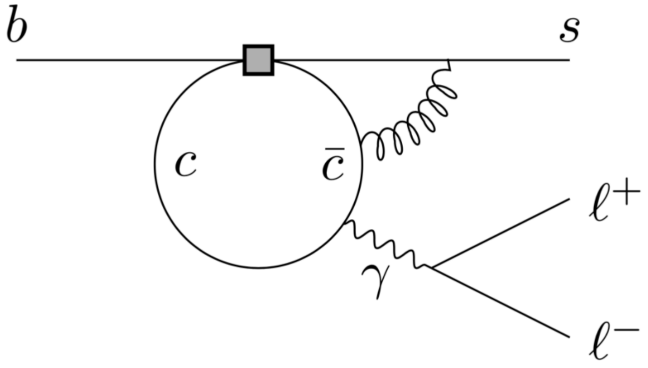


$$C_{9,\lambda}^{eff}(q^2) = C_9 + H_\lambda(q^2)$$

Parameterising non-local form-factors

$\lambda \in 0, ||, \perp$

$C^{eff}_{9,\lambda}(q^2) =$ 

$+$ 

$$C^{eff}_{9,\lambda}(q^2) = C_9 + \boxed{H_\lambda(q^2)}$$

Two different analyses done, with different models for $H_\lambda(q^2)$:

- ➤ Z-expansion (LHCb-PAPER-2023-033,032), partial q^2
- ➤ Amplitude analysis over full q^2 (LHCb-PAPER-2024-011)

Z-expansion

Polynomial-expansion

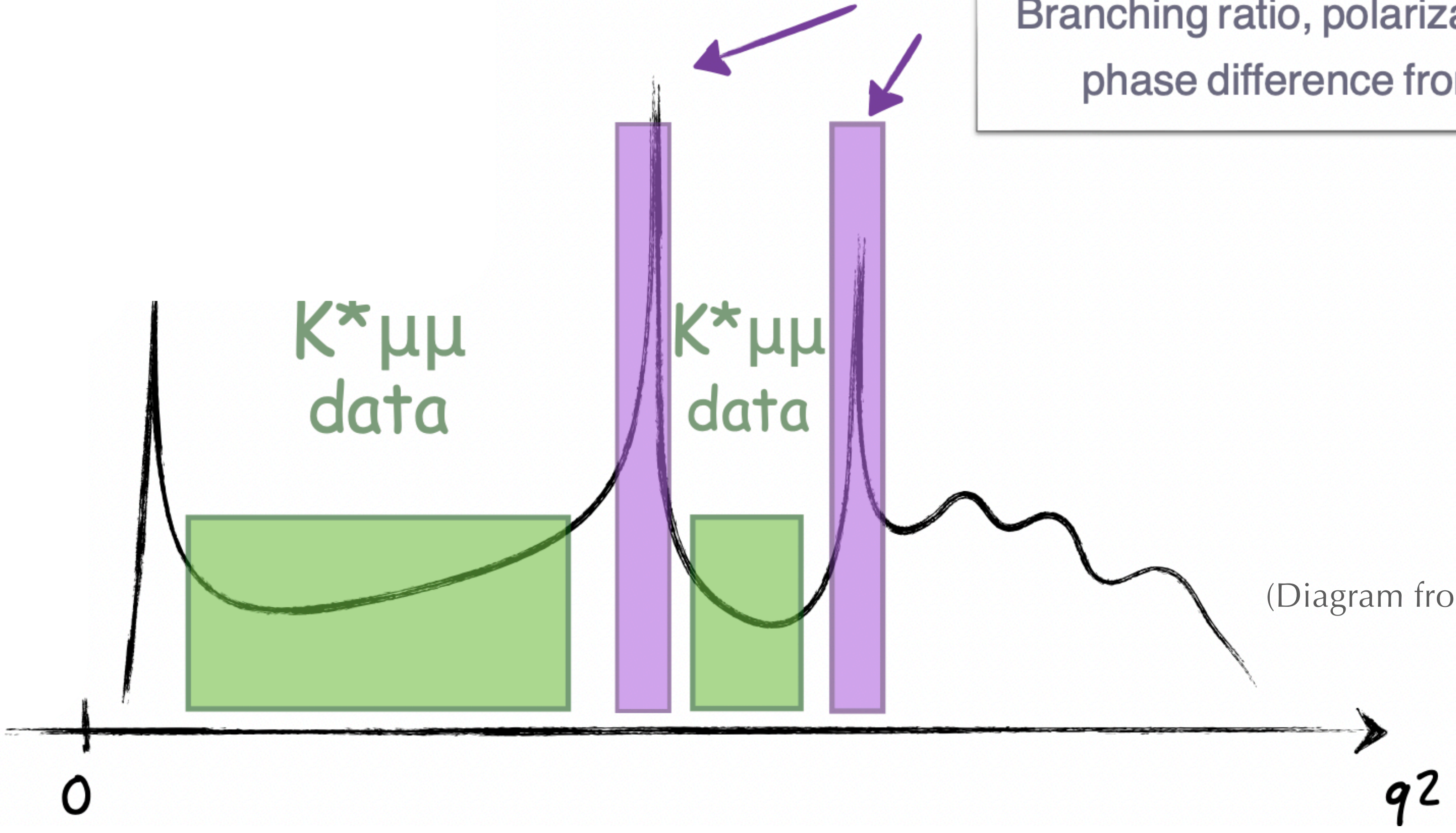
$$\mathcal{H}_\lambda(z) = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \times \ldots \times \sum_n \alpha_{\lambda.n} z^n$$

z = remapping of q^2

Experimental measurements

Branching ratio, polarization fraction and phase difference from $B^0 \rightarrow \psi_n K^{*0}$

PRD 76 031102(R) (2007)
PRD 88 052002 (2013)
PRD 88 074026 (2013)
PRD 90 112009 (2014)



(Diagram from A. Mauri)

Polynomial-expansion

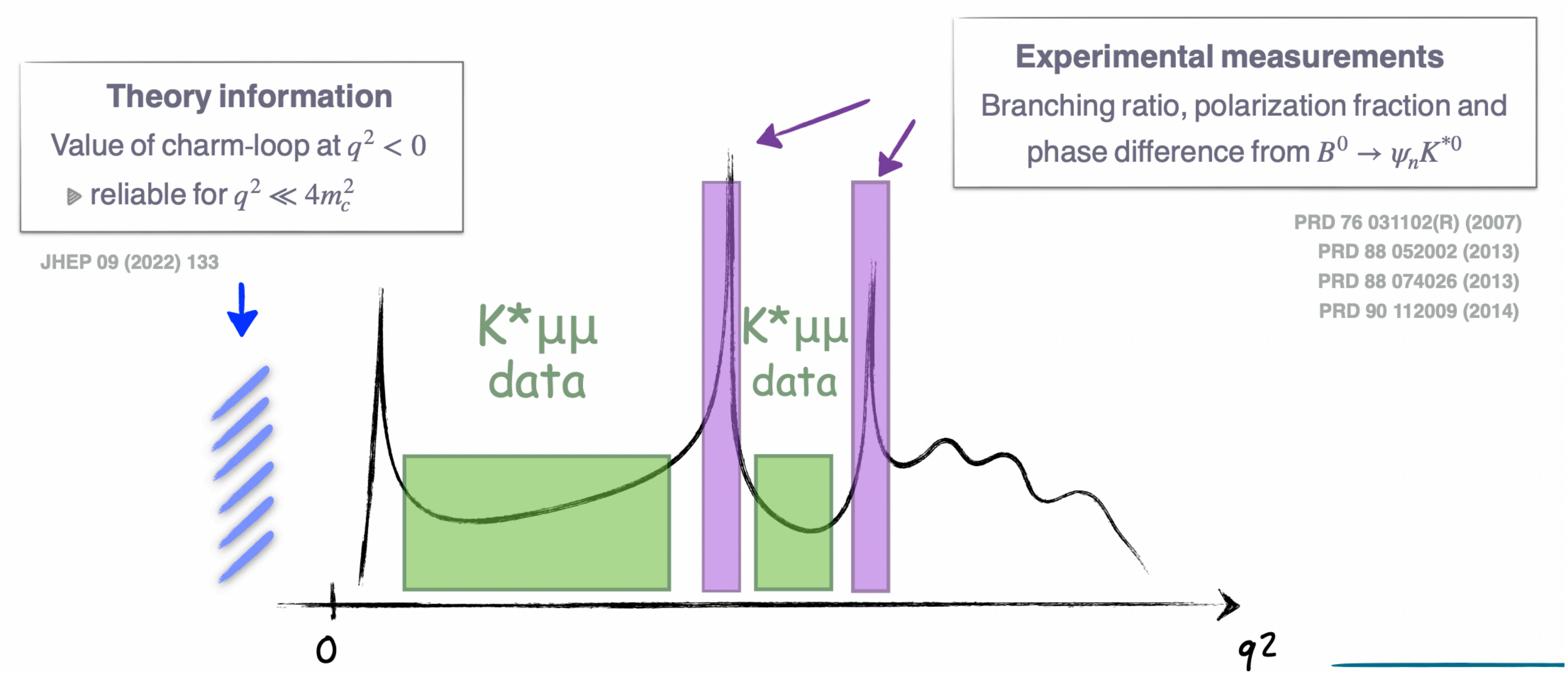
Z-expansion

$$\mathcal{H}_\lambda(z) = \frac{1 - zz^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - zz^*_{\psi(2S)}}{z - z_{\psi(2S)}} \times \ldots \times \sum_n \alpha_{\lambda.n} z^n$$

2 models used:

- With theory info from <q^2 (n = 4)
- With no theory info (n = 2)

z = remapping of q^2



Theory information

Value of charm-loop at $q^2 < 0$

▶ reliable for $q^2 \ll 4m_c^2$

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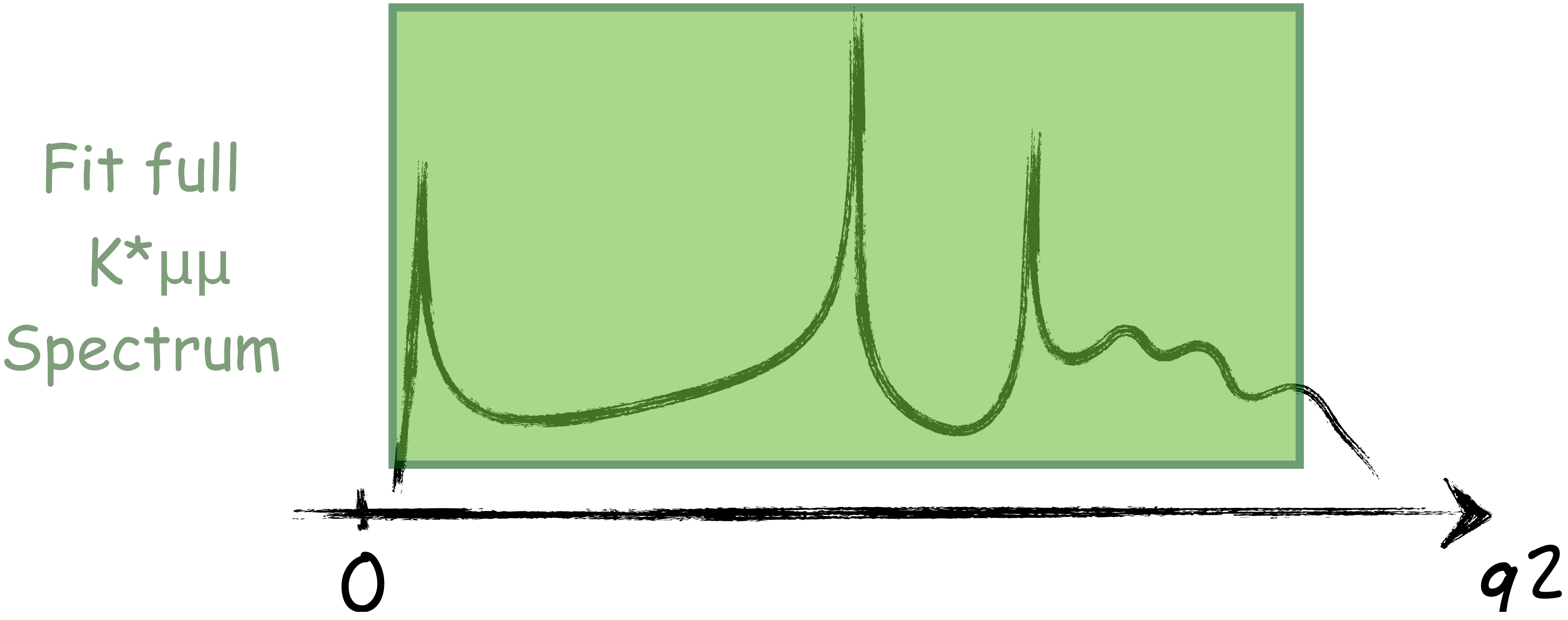
Experimental measurements

Branching ratio, polarization fraction and phase difference from $B^0 \to \psi_n K^{*0}$

PRD 76 031102(R) (2007)
PRD 88 052002 (2013)
PRD 88 074026 (2013)
PRD 90 112009 (2014)

Amplitude parameterisation

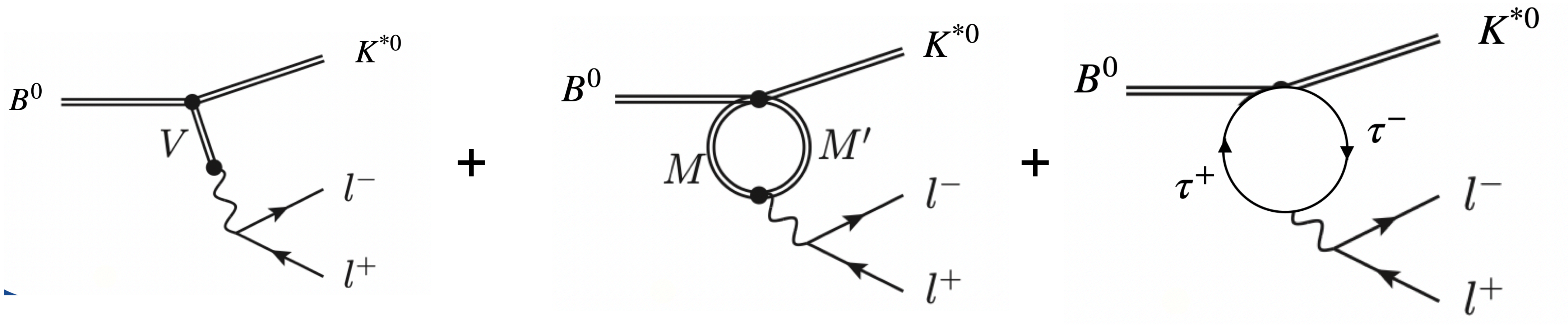
$$H_\lambda(q^2) = \sum_{j=all\, possible\, resonances} A_{\lambda,j}\mathscr{L}(q^2) = |A_{\lambda,j}|\, e^{i\delta_{j},\lambda}\mathscr{L}(q^2)$$



Amplitude analysis over all q^2 - new!

$$H_\lambda(q^2) = \sum_{j=all\ possible\ resonances} A_{\lambda,j}\mathscr{L}(q^2) = |A_{\lambda,j}|e^{i\delta_{j,\lambda}}\mathscr{L}(q^2)$$

$$H_\lambda(q^2) =$$



1-particle contributions

Includes:

$\omega(782)$,	$\psi(2S)$,
$\rho(770)$,	$\psi(3770)$,
$\phi(1020)$,	$\psi(4040)$,
J/ψ,	$\psi(4160)$

2-particle contributions

Includes:

$D\overline{D}$,

$D^*\overline{D}$,

$D^*\overline{D}^*$

Tau loop contribution

Sensitive to C_9^τ

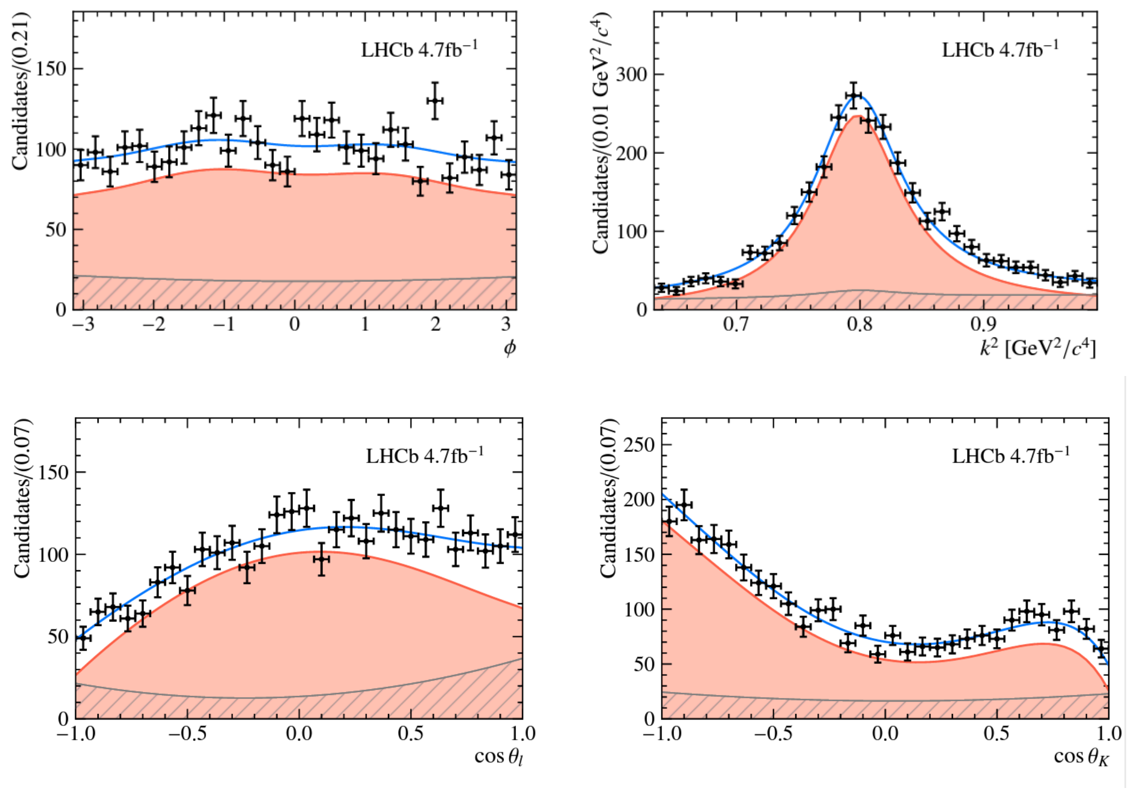
$\mathscr{L} = Breit - Wigner$

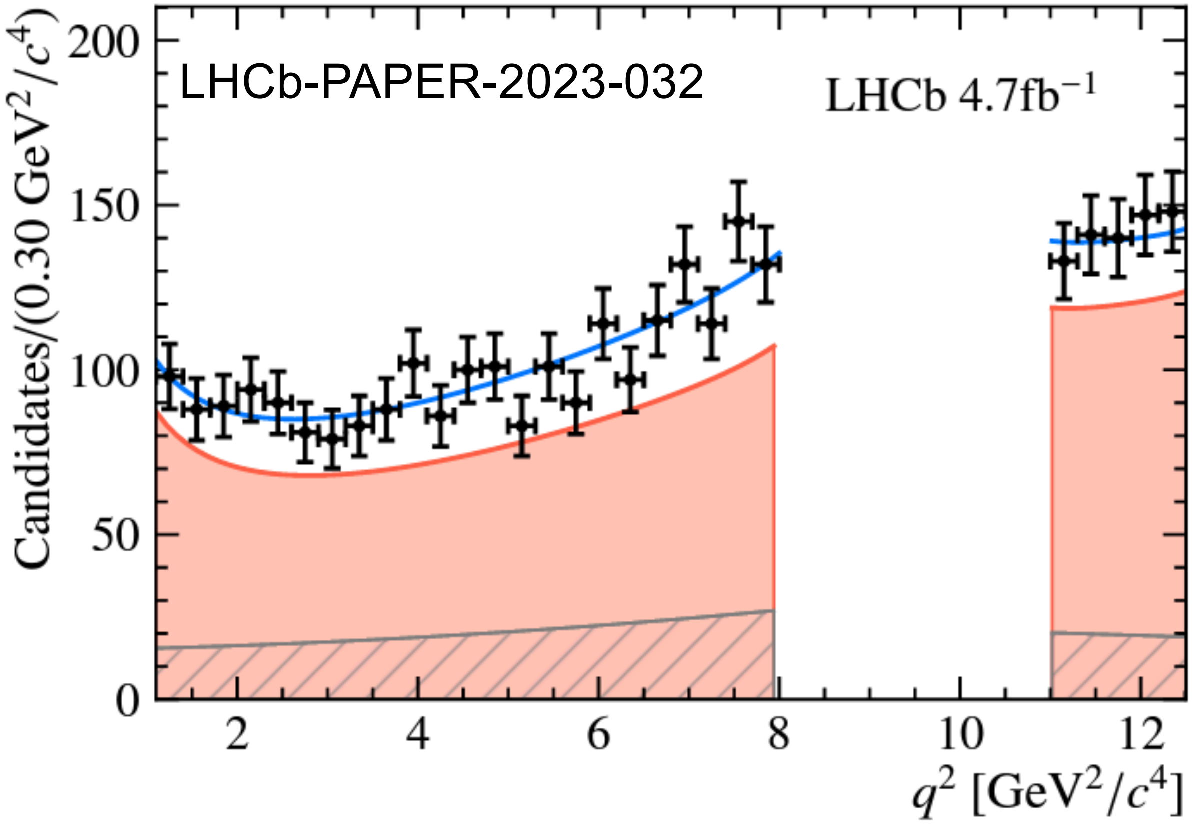
$\mathscr{L} = Dispersion - relation$

Fit projections

Z-expansion

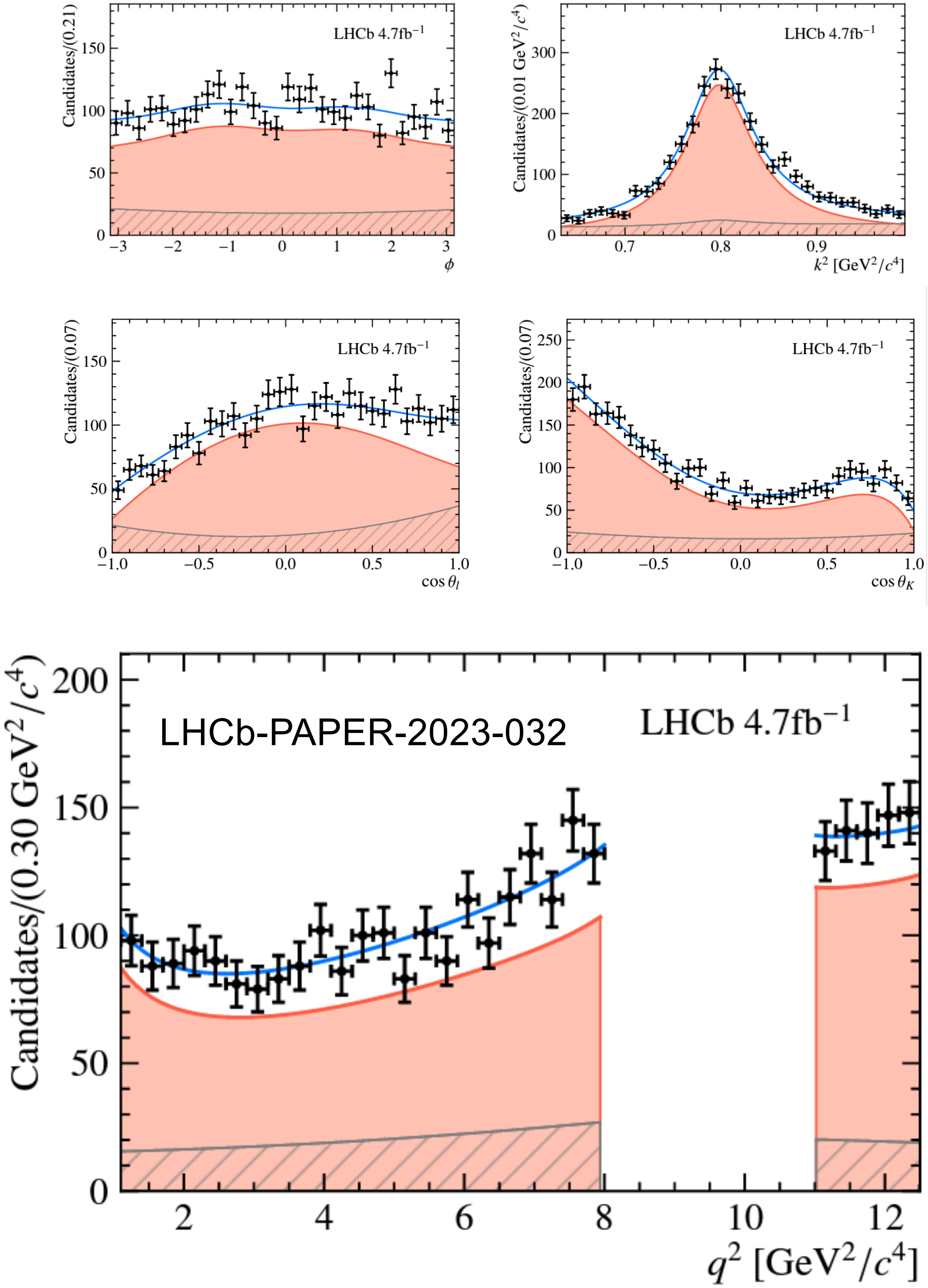
Amplitude model



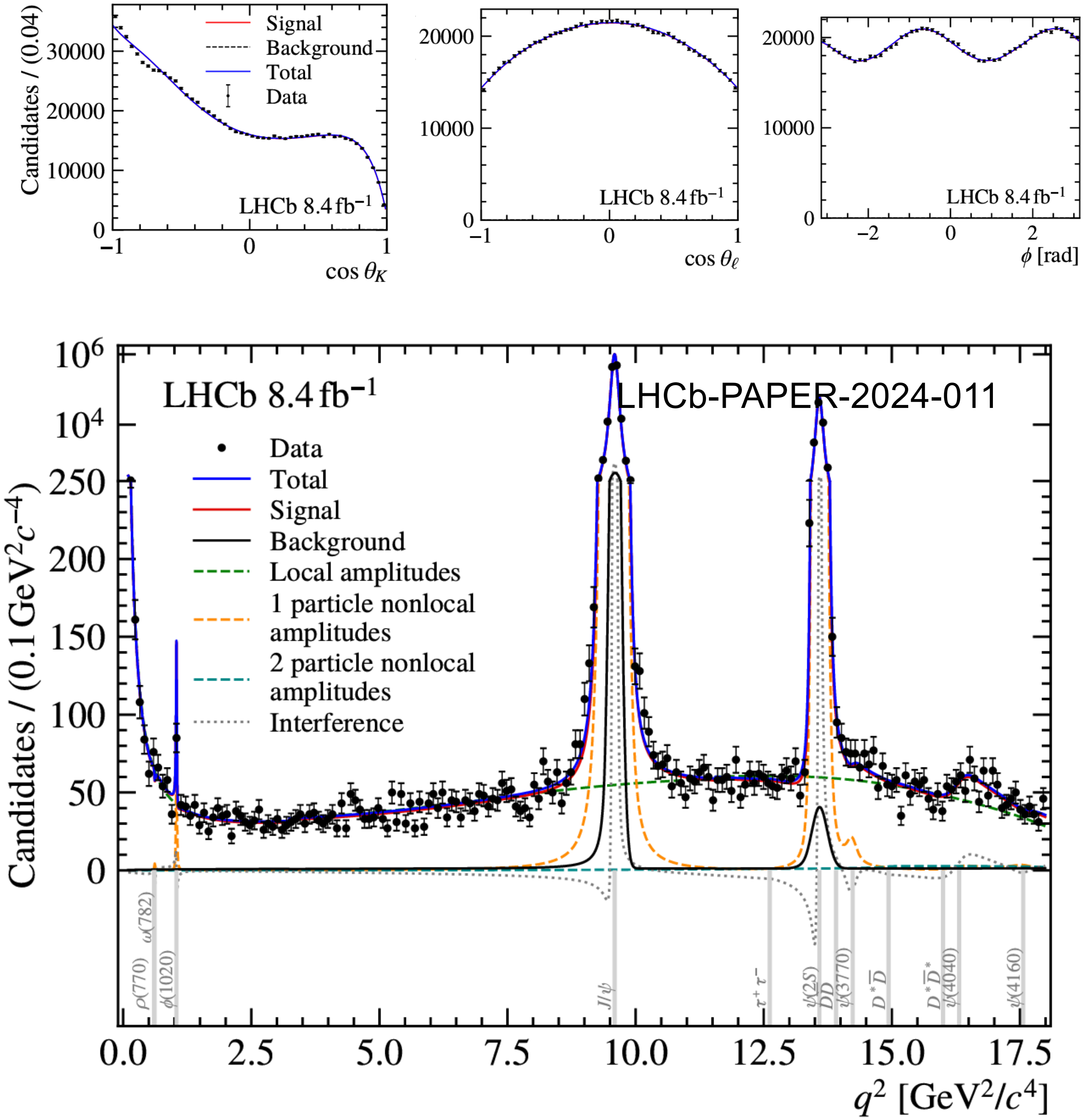


Fit projections

Z-expansion

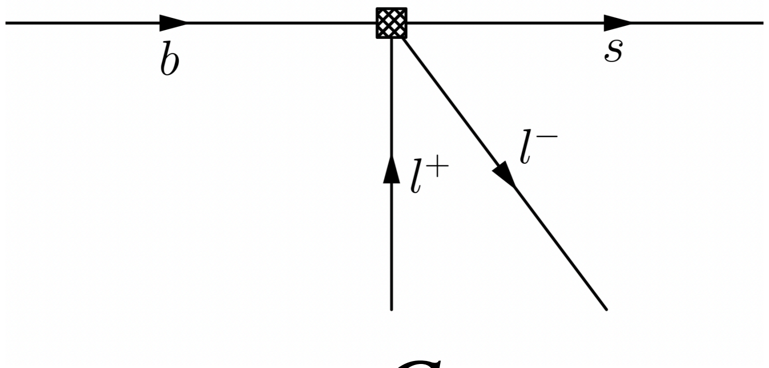


Amplitude model



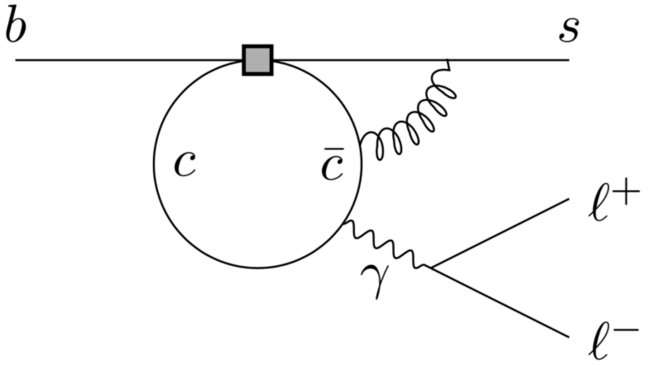
Size of $H_\lambda(q^2)$?

$$C^{eff}_{9,\lambda}(q^2) =$$

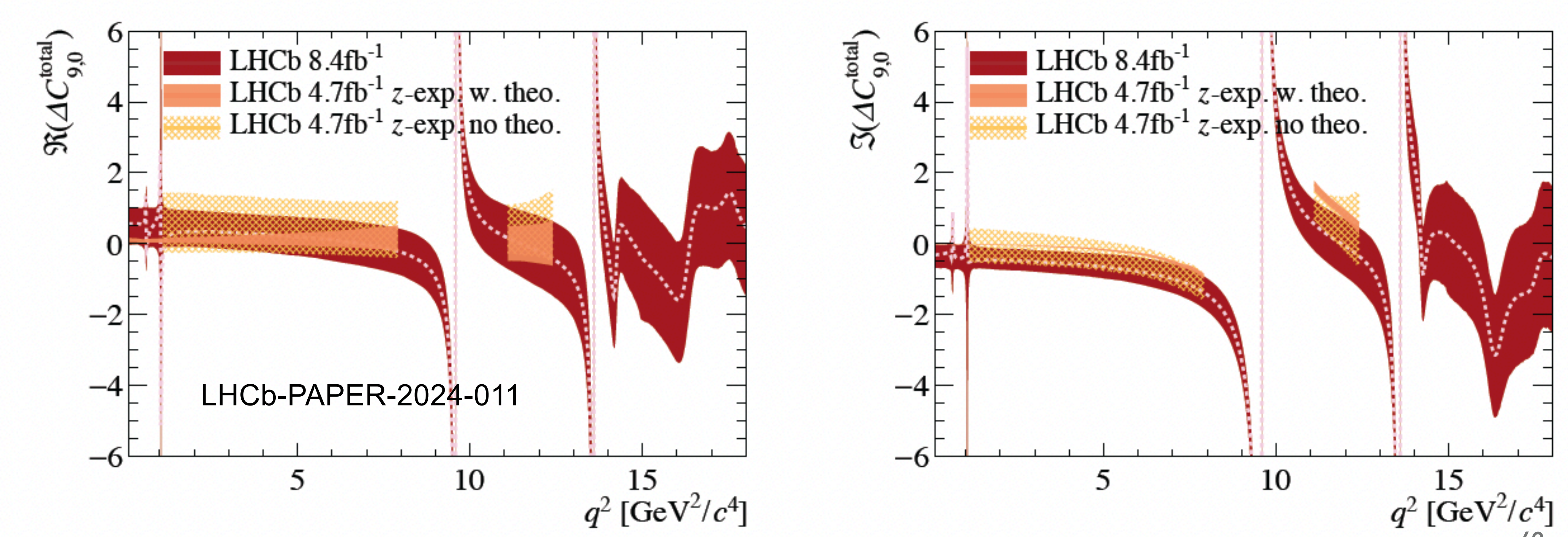


C_9

$+$



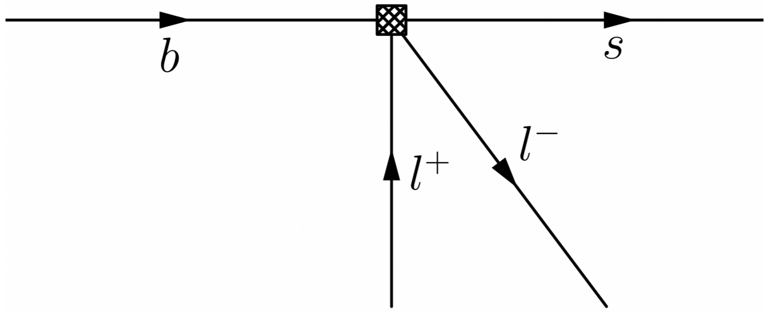
$H_\lambda(q^2)$



LHCb-PAPER-2024-011

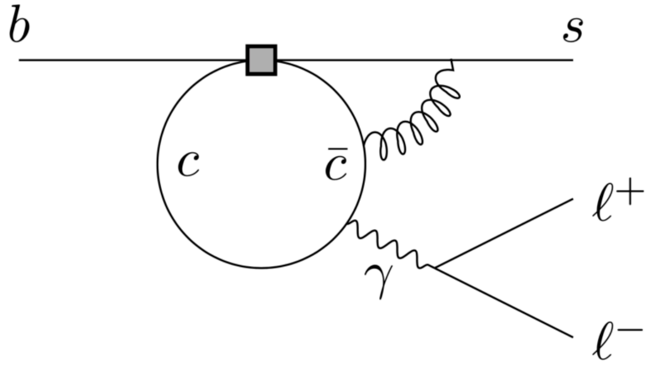
Size of $H_\lambda(q^2)$?

$C^{eff}_{9,\lambda}(q^2) =$



C_9

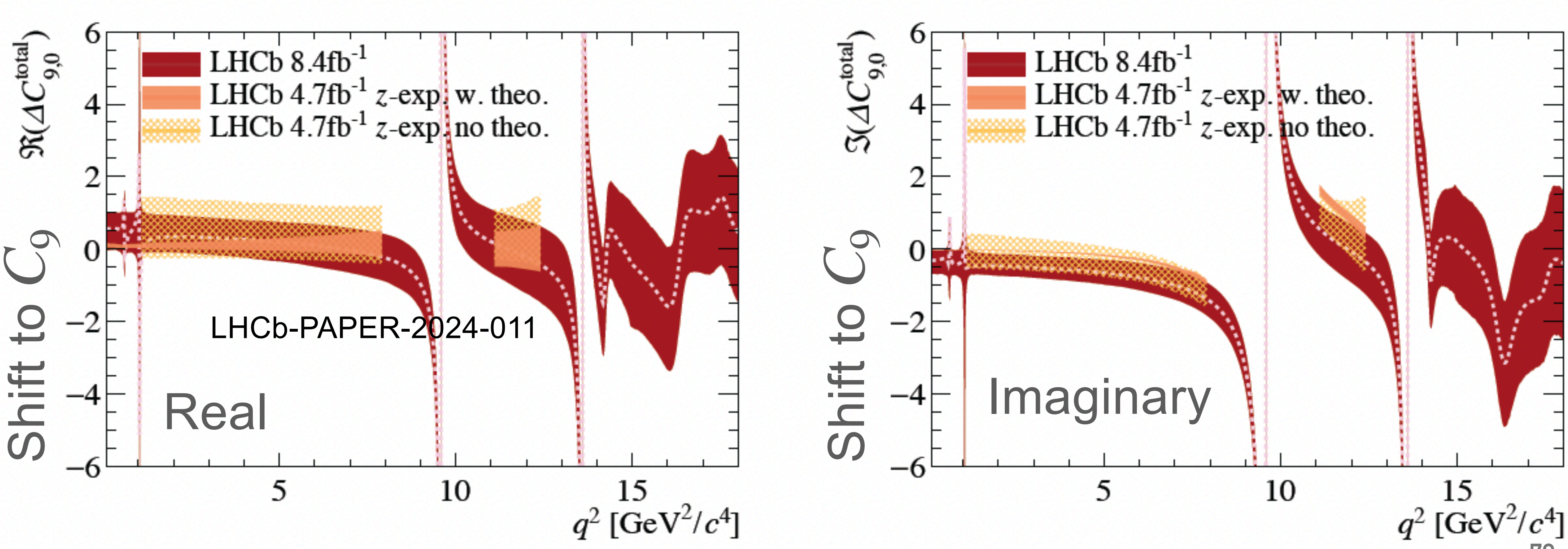
$+$



$H_\lambda(q^2)$

Z-expansion Amplitude

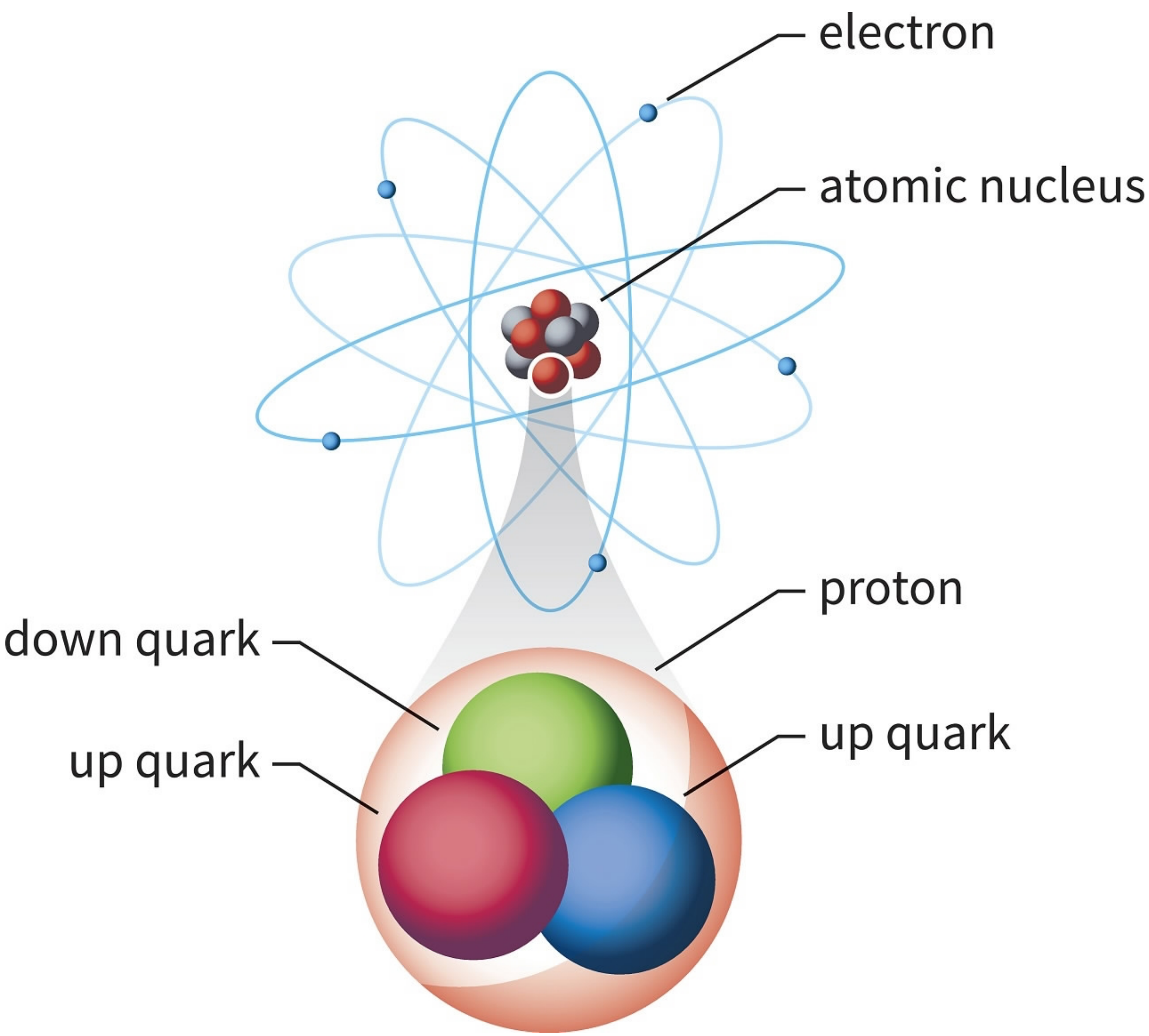
Example $\lambda = 0$



LHCb-PAPER-2024-011

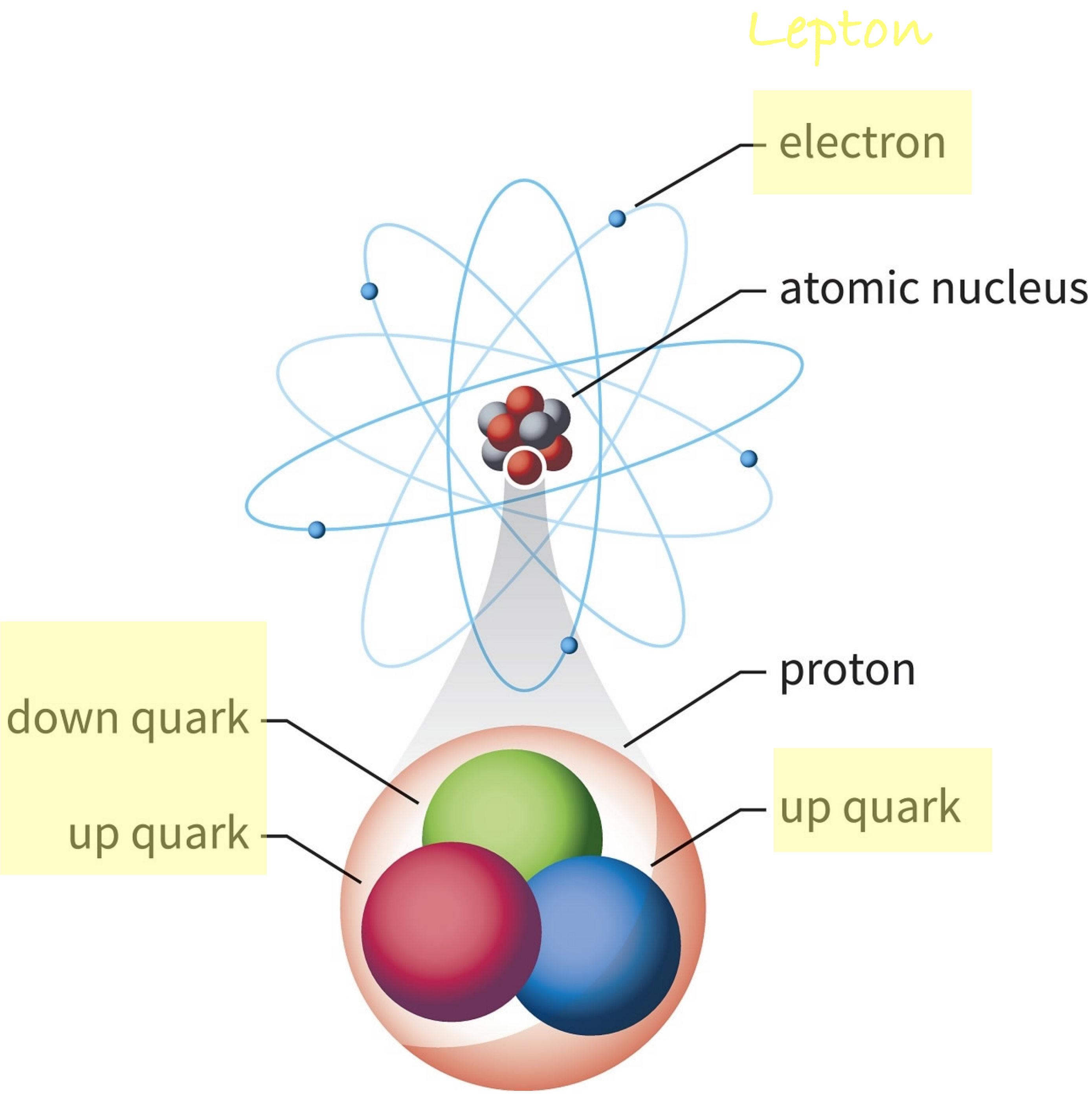
Measured values of C_9 ?

The building blocks of matter



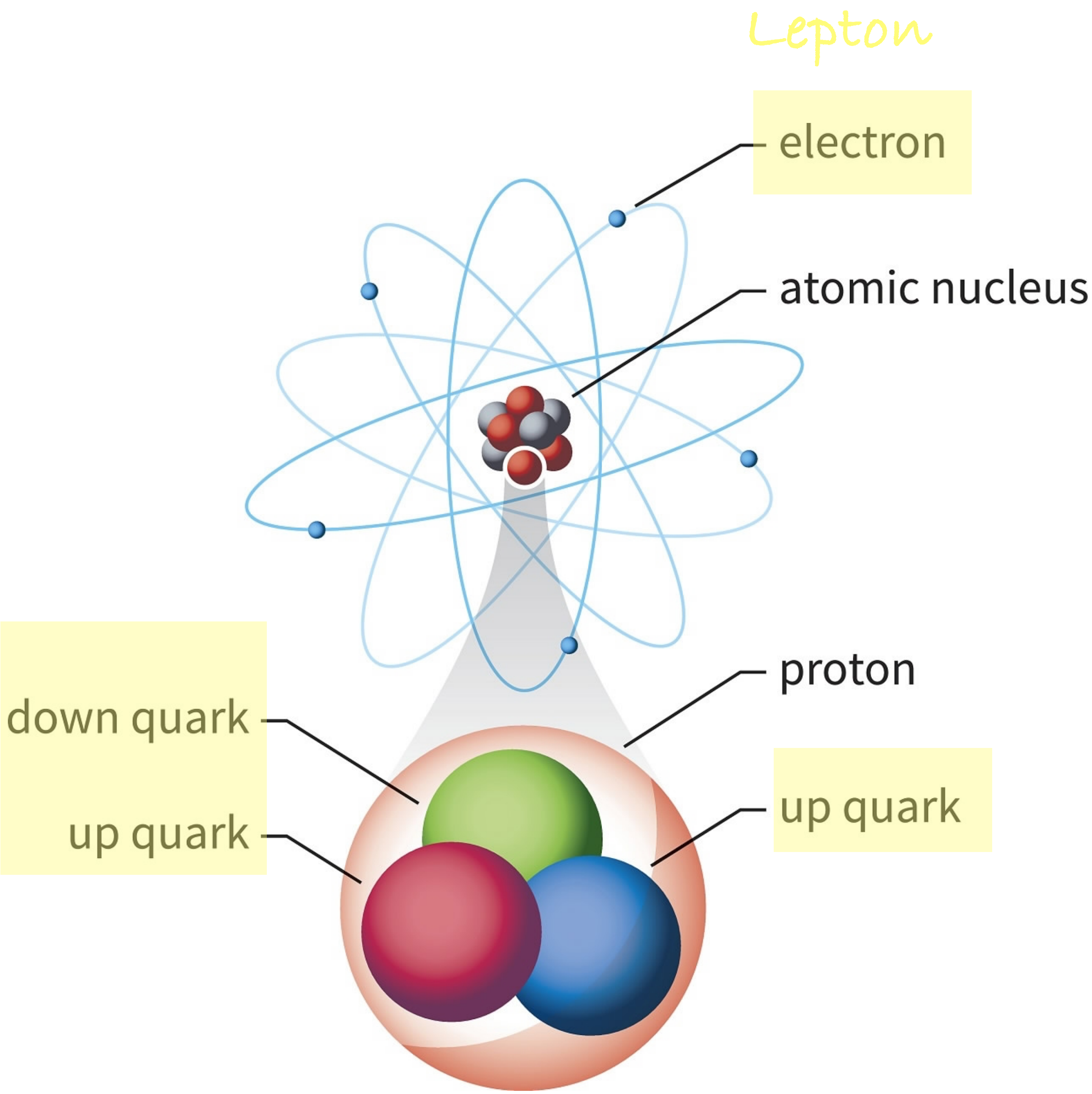
The matter around us is built from electrons and up and down quarks

The building blocks of matter



The matter around us is built from electrons and up and down quarks

The building blocks of matter



The matter around us is built from electrons and up and down quarks

Interact via three forces:

- Electromagnetism (photon)
- strong force (gluon)
- weak force ($Z^0/W^{\pm}$ boson)

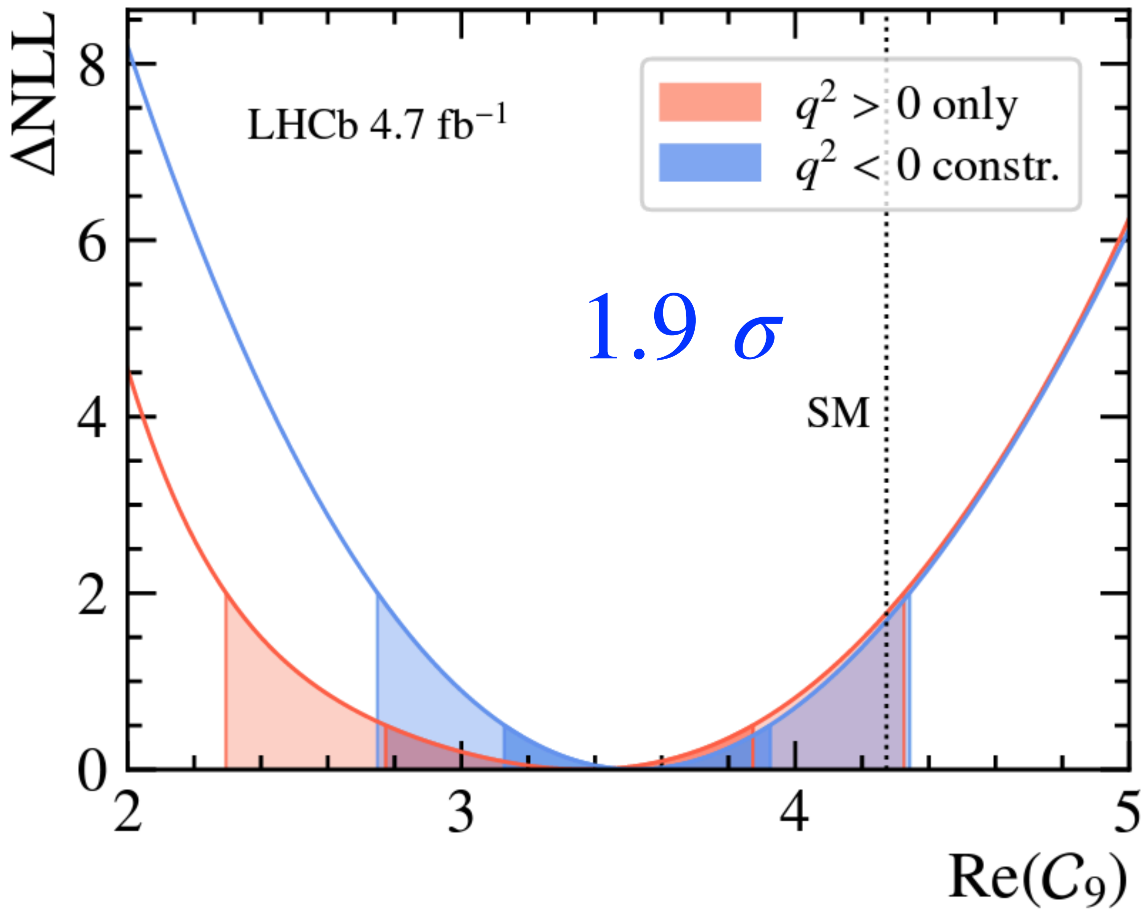
Measured values of C_9 ?

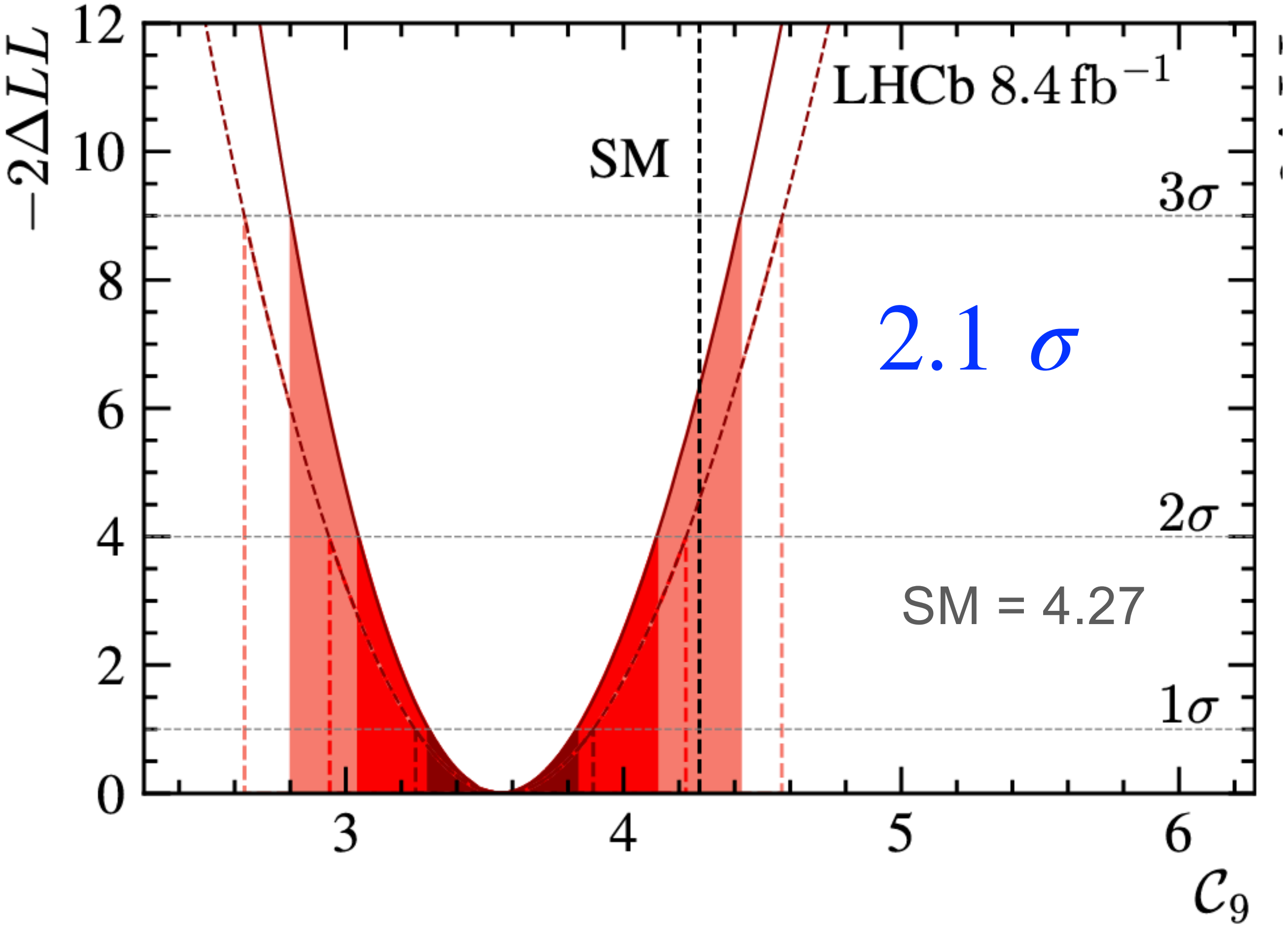
LHCb-PAPER-2023-032

LHCb-PAPER-2024-011

Z-expansion

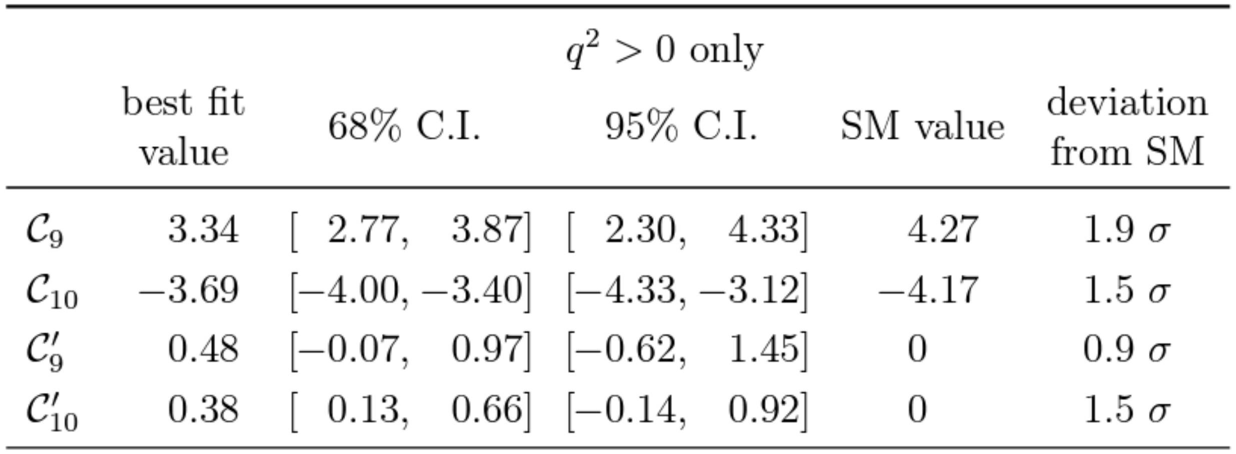
Amplitude model



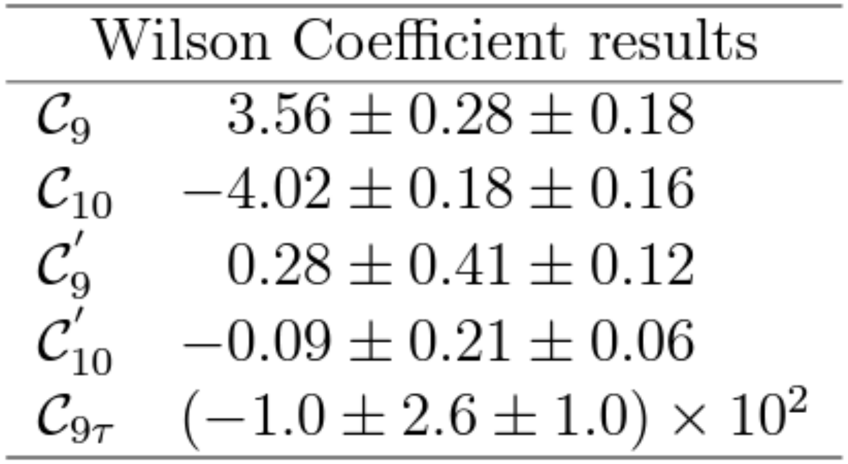


$$\Delta C_9^{NP} = -0.93^{+0.53}_{-0.57}$$

$$\Delta C_9^{NP} = -0.71 \pm 0.33$$



	$q^2 > 0$ only				
	best fit value	68% C.I.	95% C.I.	SM value	deviation from SM
$\mathcal{C}_9$	3.34	[2.77, 3.87]	[2.30, 4.33]	4.27	1.9 σ
$\mathcal{C}_{10}$	−3.69	[−4.00, −3.40]	[−4.33, −3.12]	−4.17	1.5 σ
$\mathcal{C}_9'$	0.48	[−0.07, 0.97]	[−0.62, 1.45]	0	0.9 σ
$\mathcal{C}_{10}'$	0.38	[0.13, 0.66]	[−0.14, 0.92]	0	1.5 σ

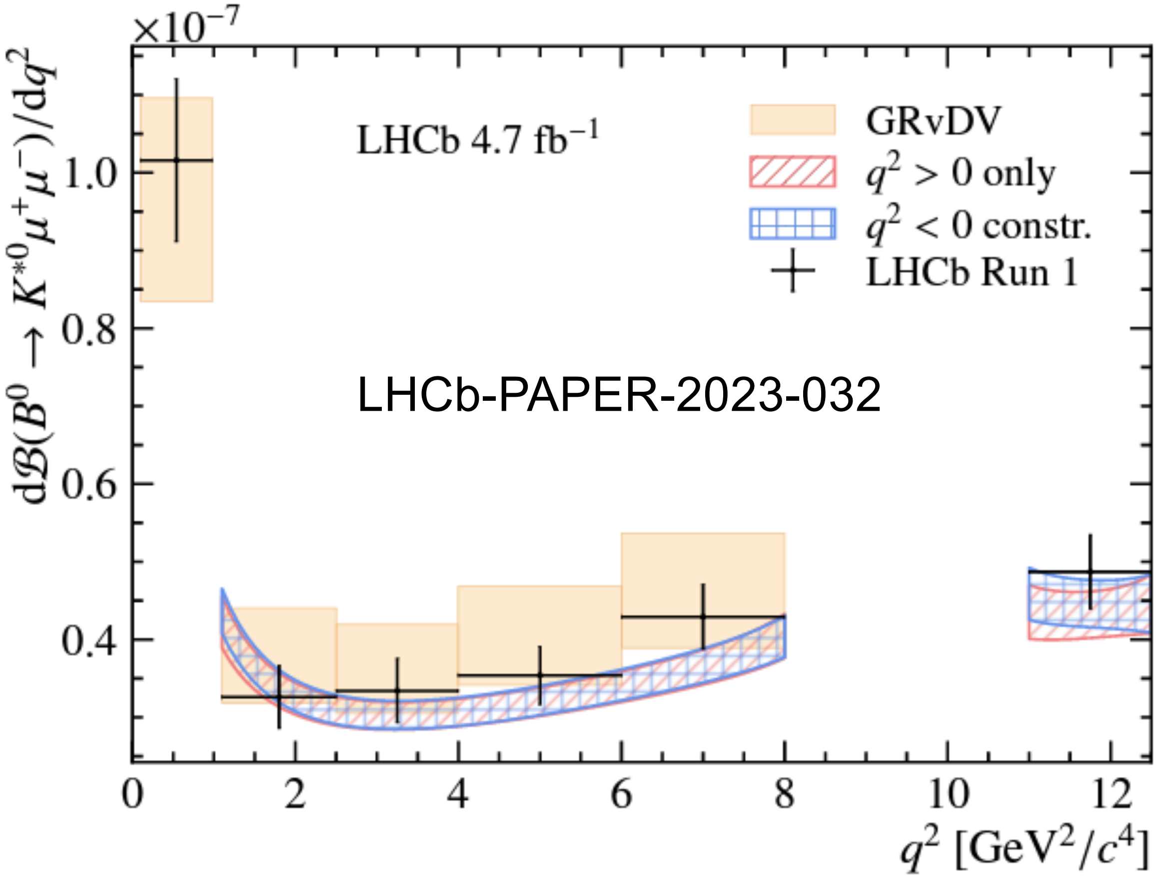


Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}_9'$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}_{10}'$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

Affect of non-local contributions on branching fractions?

Z-expansion

-comparison with previous measurements

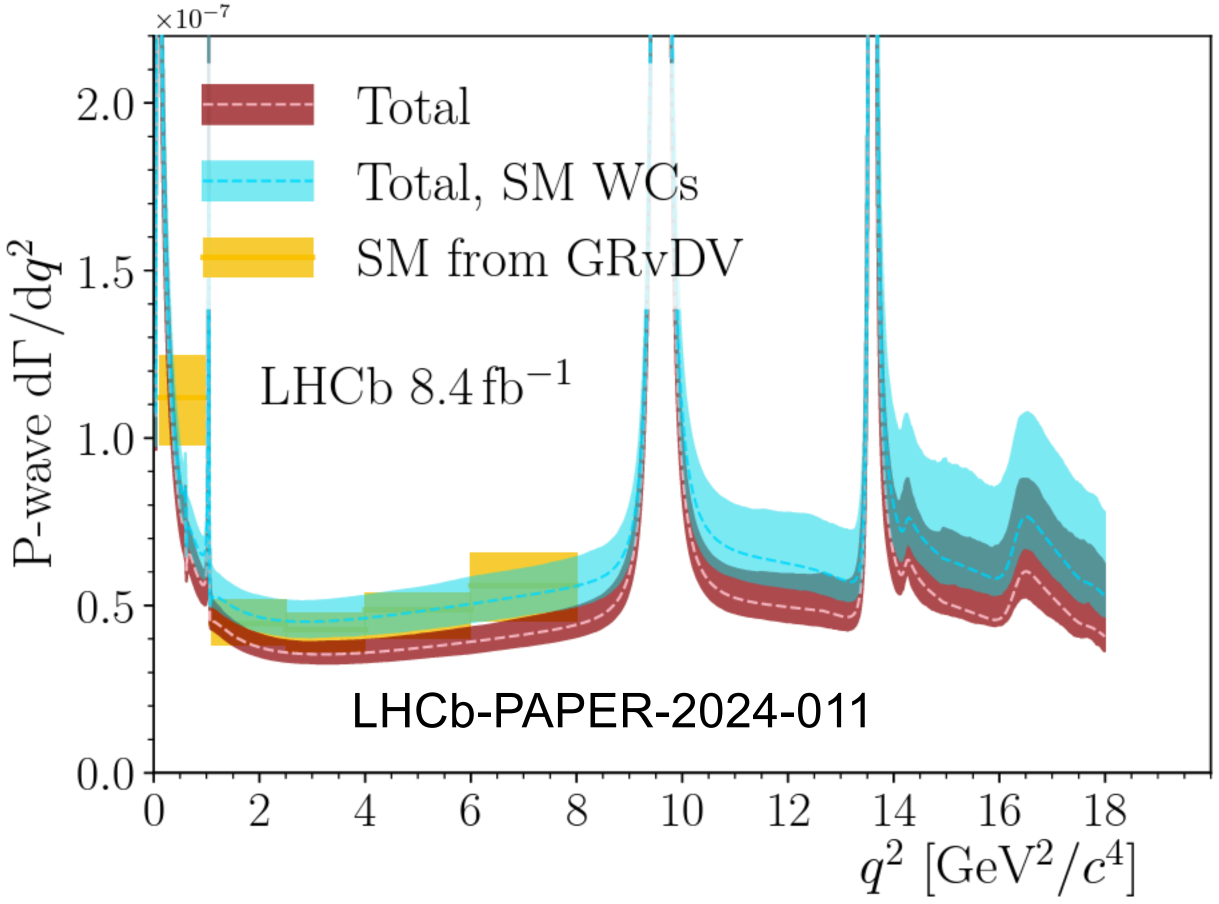


LHCb-PAPER-2023-032

Increased tension with respect to previous measurements

Amplitude model

- affect on SM predictions



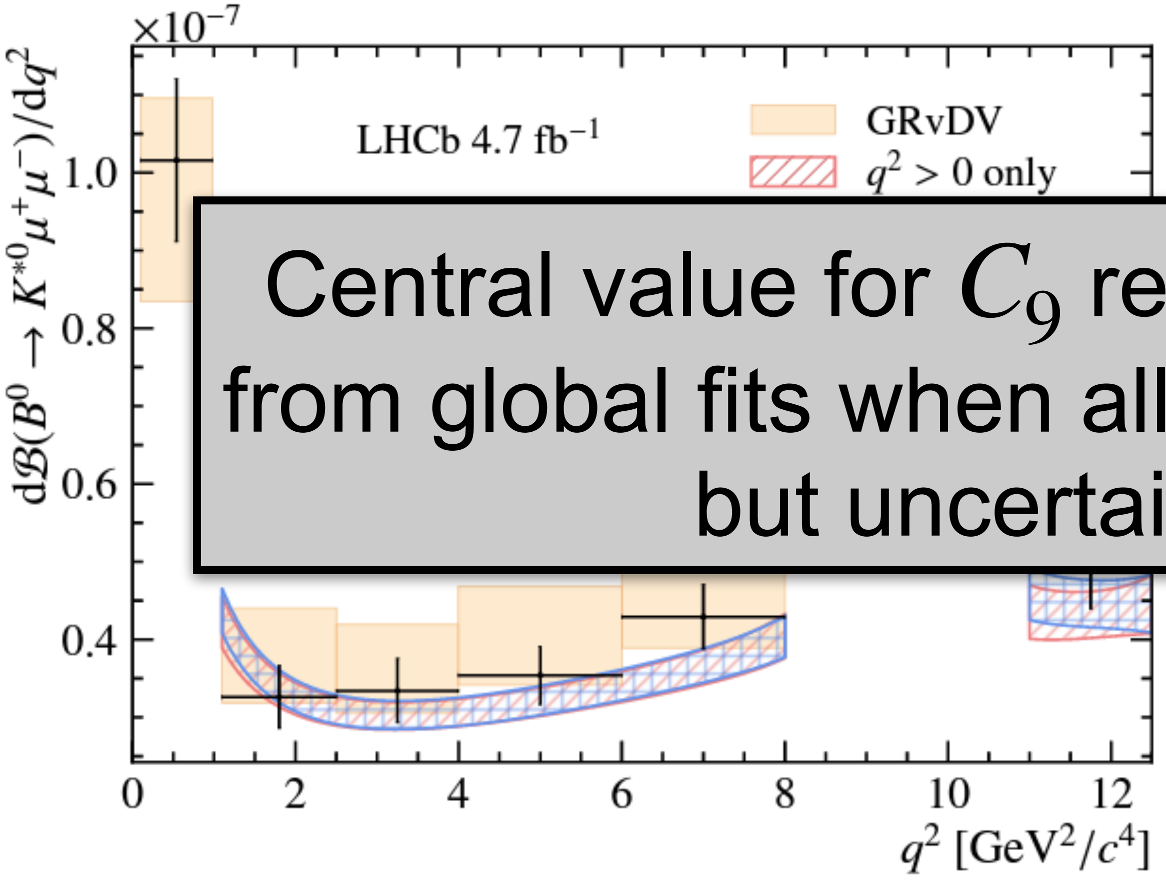
LHCb-PAPER-2024-011

Minimal modification to SM predictions, tension remains

Affect of non-local contributions on branching fractions?

Z-expansion

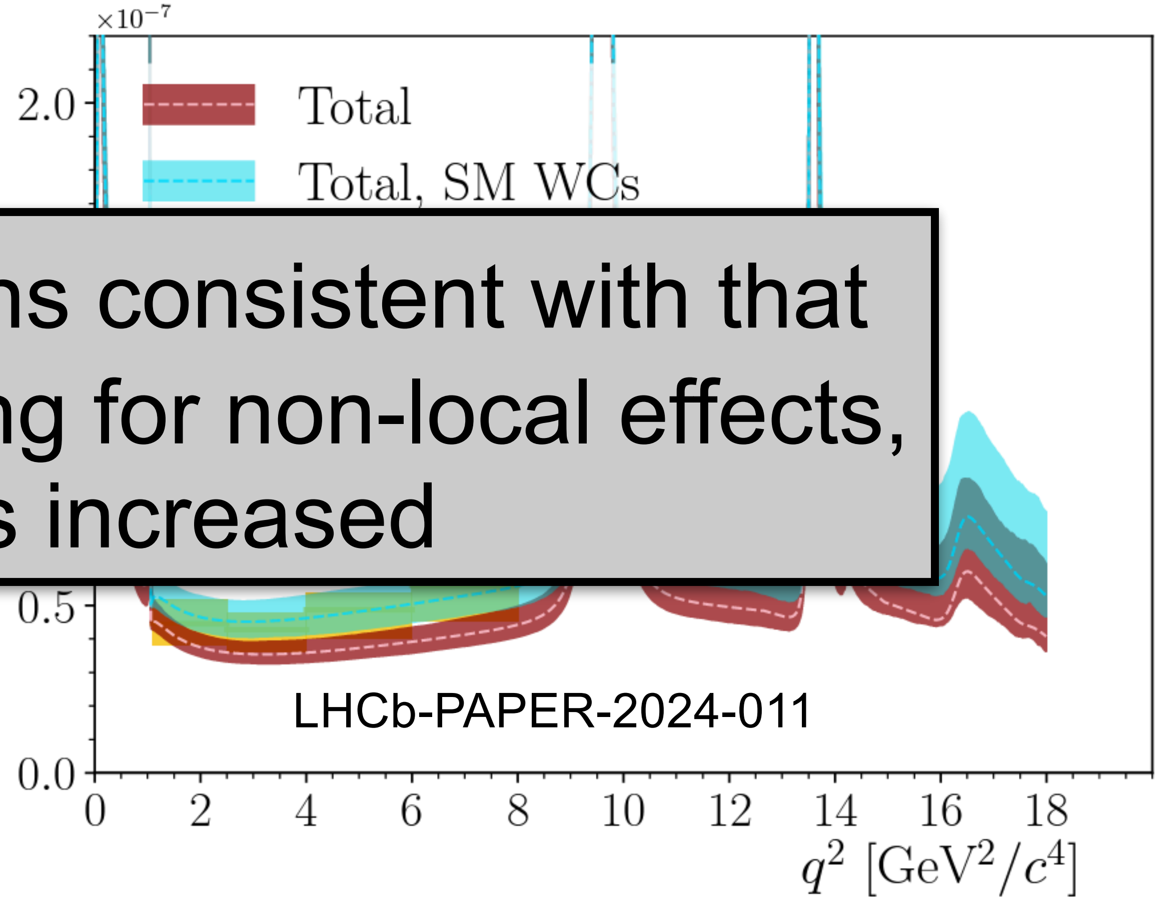
-comparison with previous measurements



Increased tension with respect to previous measurements

Amplitude model

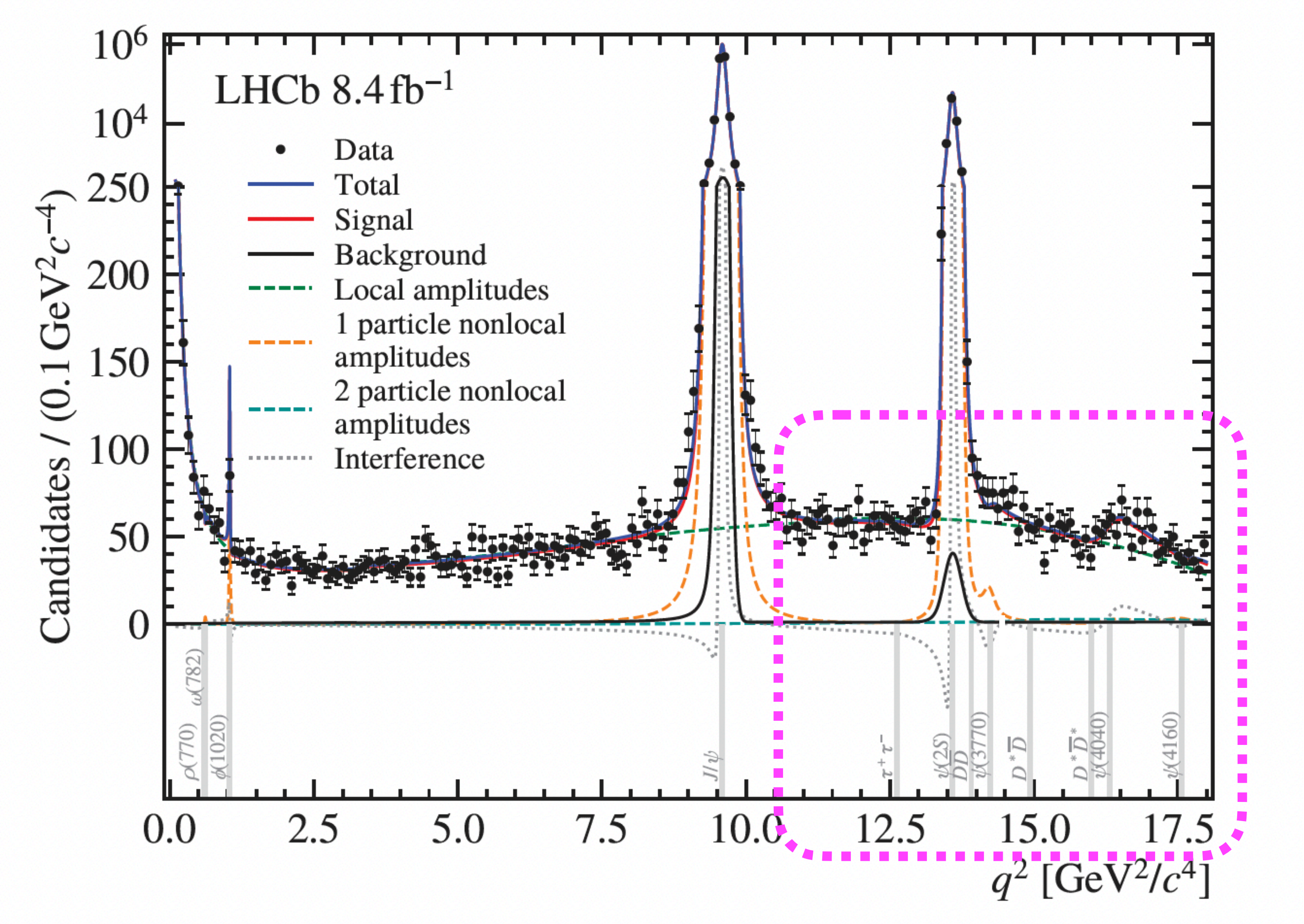
- affect on SM predictions



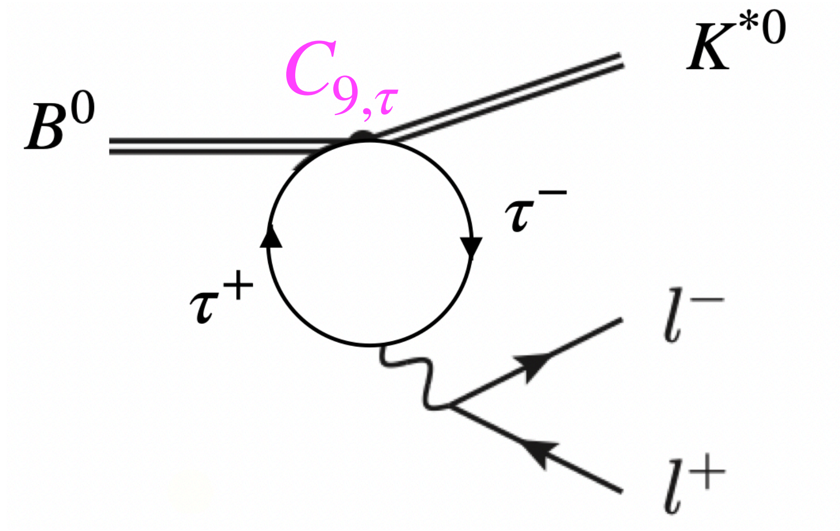
Minimal modification to SM predictions, tension remains

Central value for C_9 remains consistent with that from global fits when allowing for non-local effects, but uncertainties increased

Bonus: worlds first direct measurement of $C_{9\tau}$



LHCb-PAPER-2024-011



Muon analysis is sensitive to $C_{9,\tau}$ via

$$B^0 \to K^{*0}[\tau^+\tau^- \to \gamma^* \to \mu^+\mu^-]$$

$\propto C_{9,\tau}$

Convert to 90% CL on
$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) \sim [1.7 - 2.2] \times 10^{-3}$

Best direct measurement of $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-)$ = 3.1×10^{-3} 90% CL Belle, Phys. Rev. D108 (2023) L011102

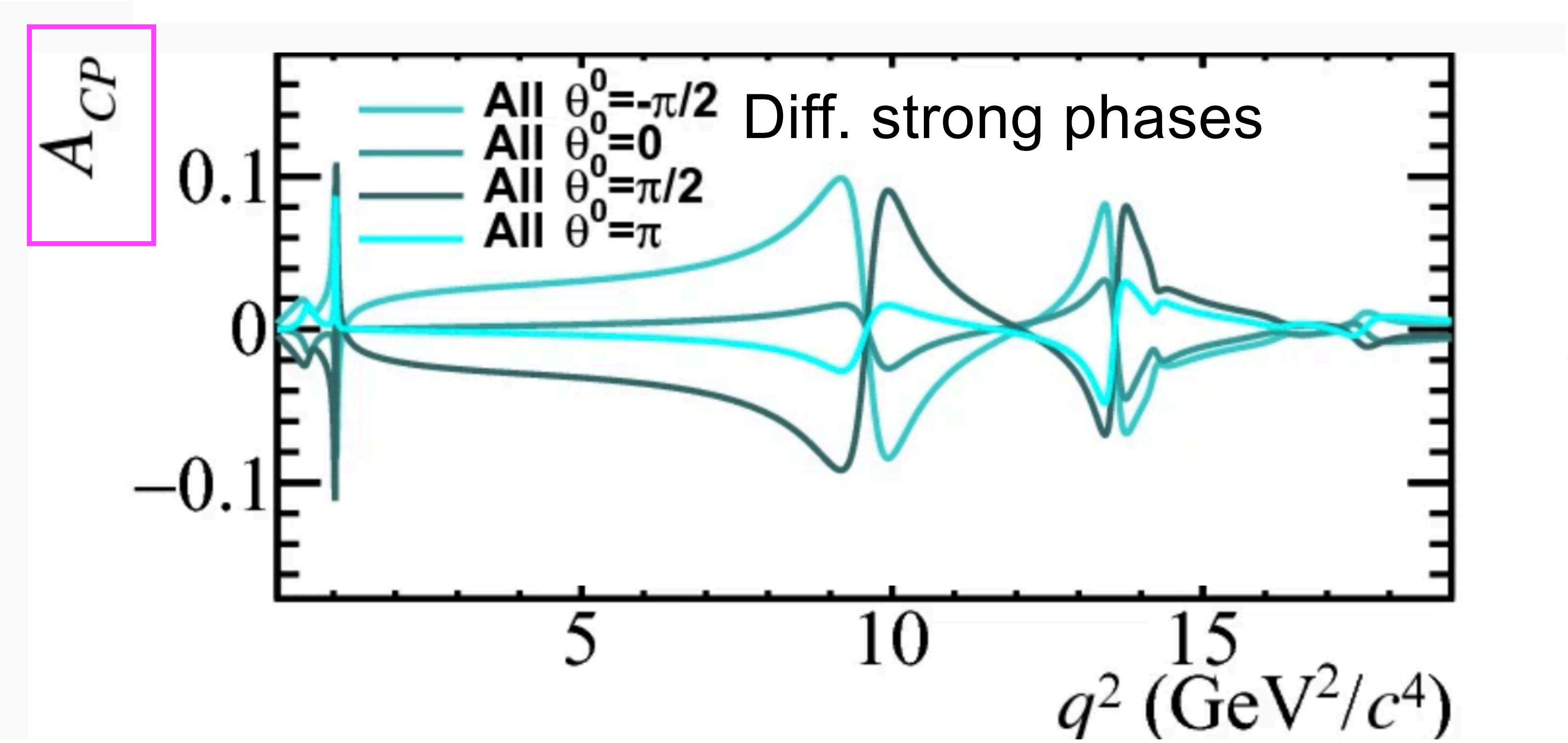
Worlds first direct measurement of $C_{9,\tau}$

$$C_{9,\tau} = (-1.0 \pm 2.6 \pm 1.0) \times 10^2$$

SM prediction $\mathscr{O}(10^{-7})$, NP models $\mathscr{O}(10^{-4})$

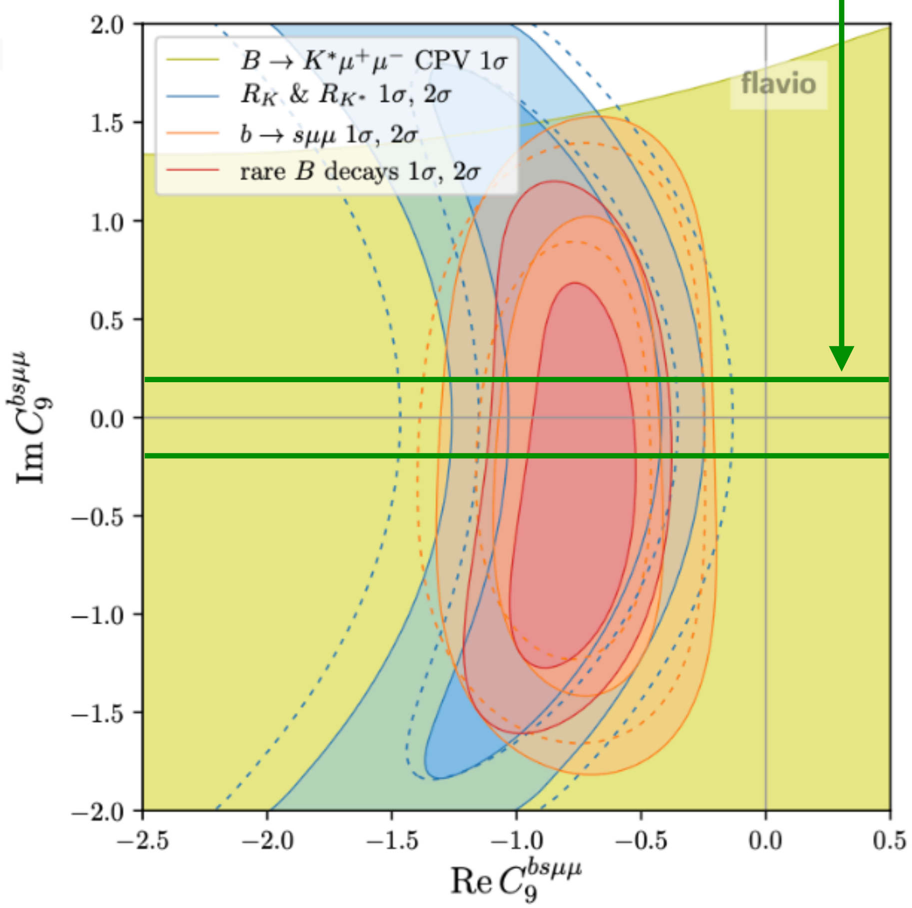
Extension of model (WIP): Constraining CP violation in $B^0 \to K^{*0}\mu^+\mu^-$

Decay rate asymmetry between $B^0/\overline{B}^0$



Diff. strong phases

Expected limits from this work



Can use method to measure the weak (CP-violating) phase over the whole q^2 spectrum for the first time, by measuring $Im(C_i)$

Large strong phase from charmonium gives increased sensitivity: expected order of magnitude improvement on current limits

Hadronic cleanliness

Lepton Flavour Universality
and $B_s \to \mu^+\mu^-$

Angular analyses

Branching fractions

Hadronic cleanliness

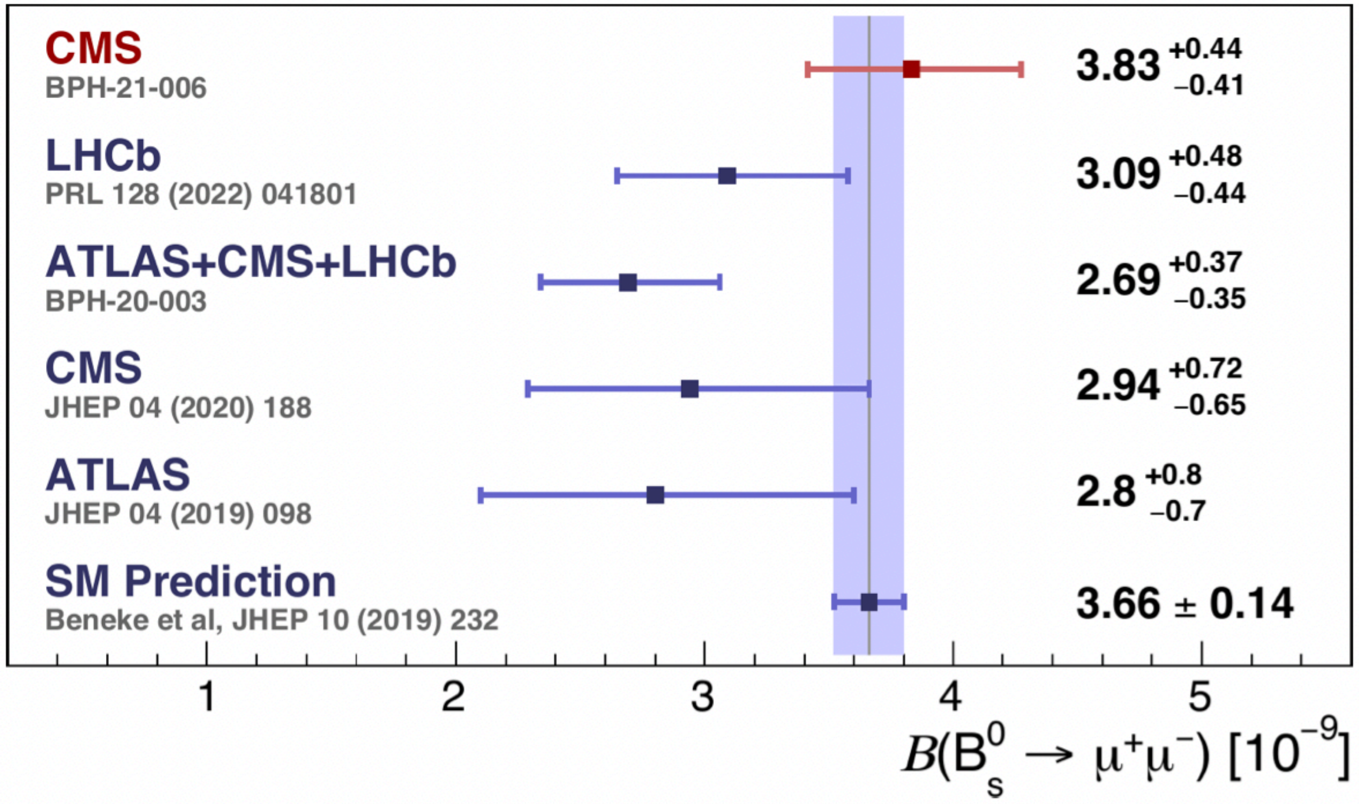
Lepton Flavour Universality and $B_s \to \mu^+\mu^-$

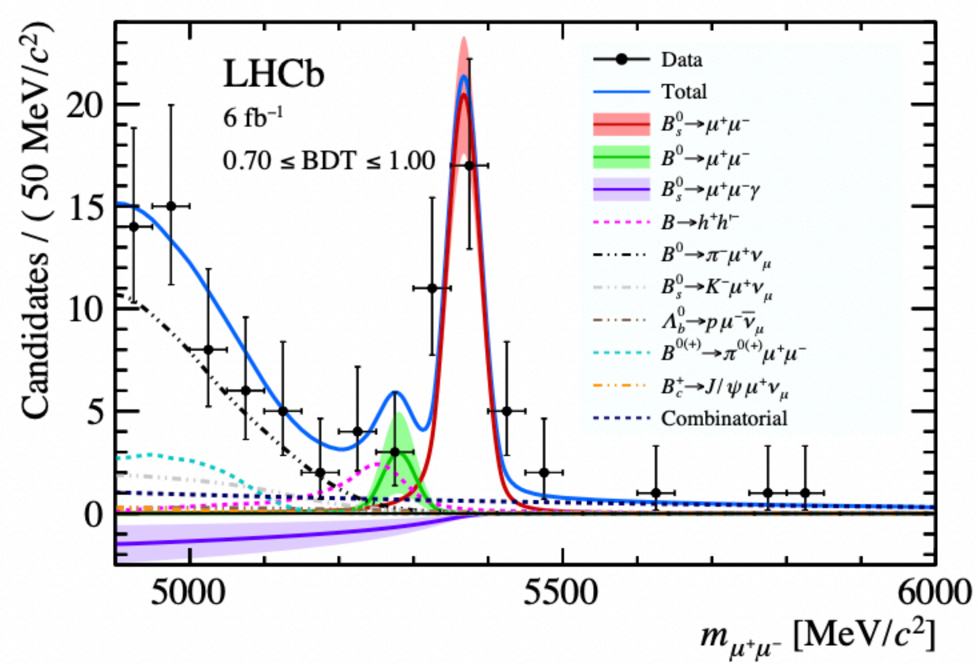
Angular analyses

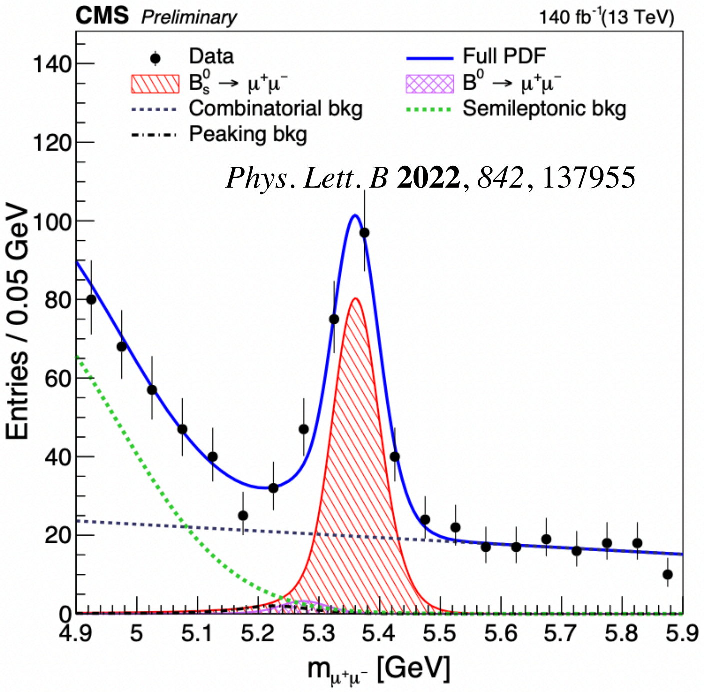
Branching fractions

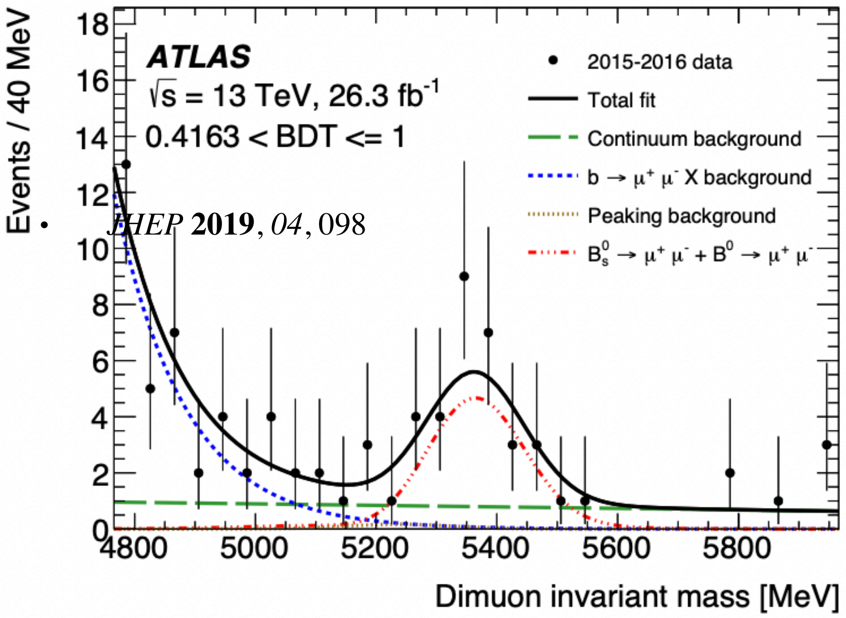
$B_s \to \mu^+\mu^-$: branching fraction

Clean observable, sensitive to C_{10} but not C_9



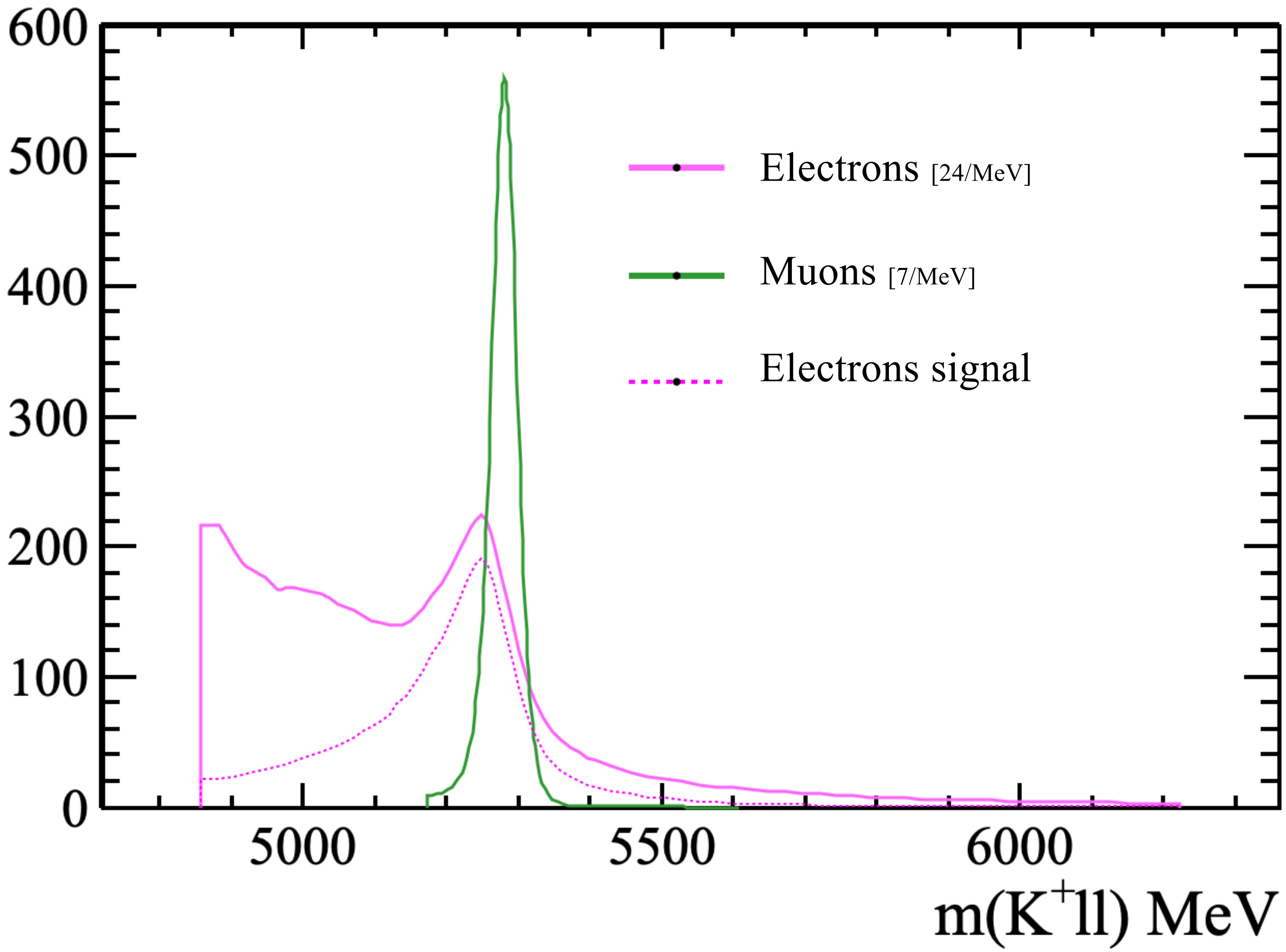

Phys. Lett. **2022**, *128*, 041801


Phys. Lett. B **2022**, *842*, 137955


JHEP **2019**, *04*, 098

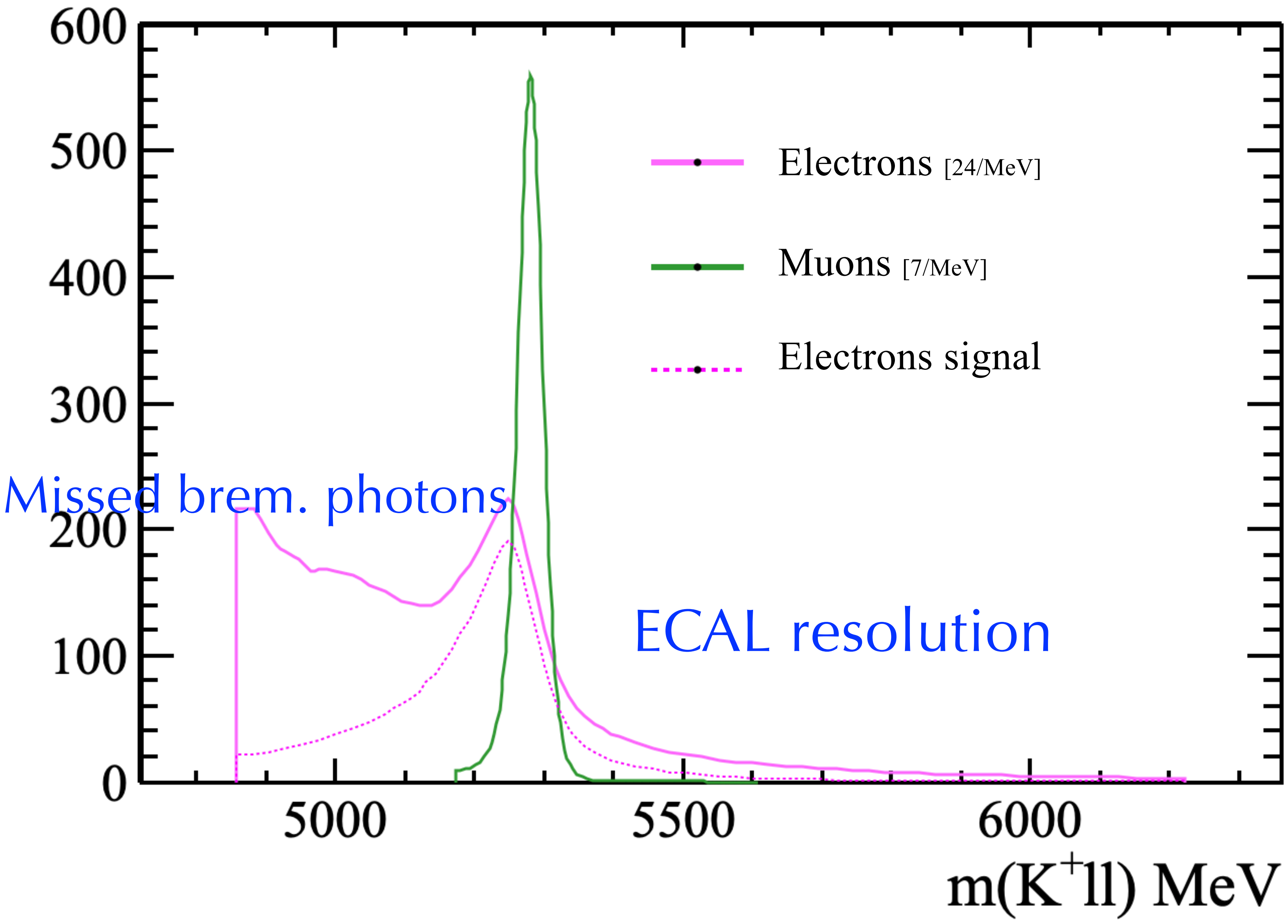
Lepton Flavour Universality

$$R(X) = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)}$$

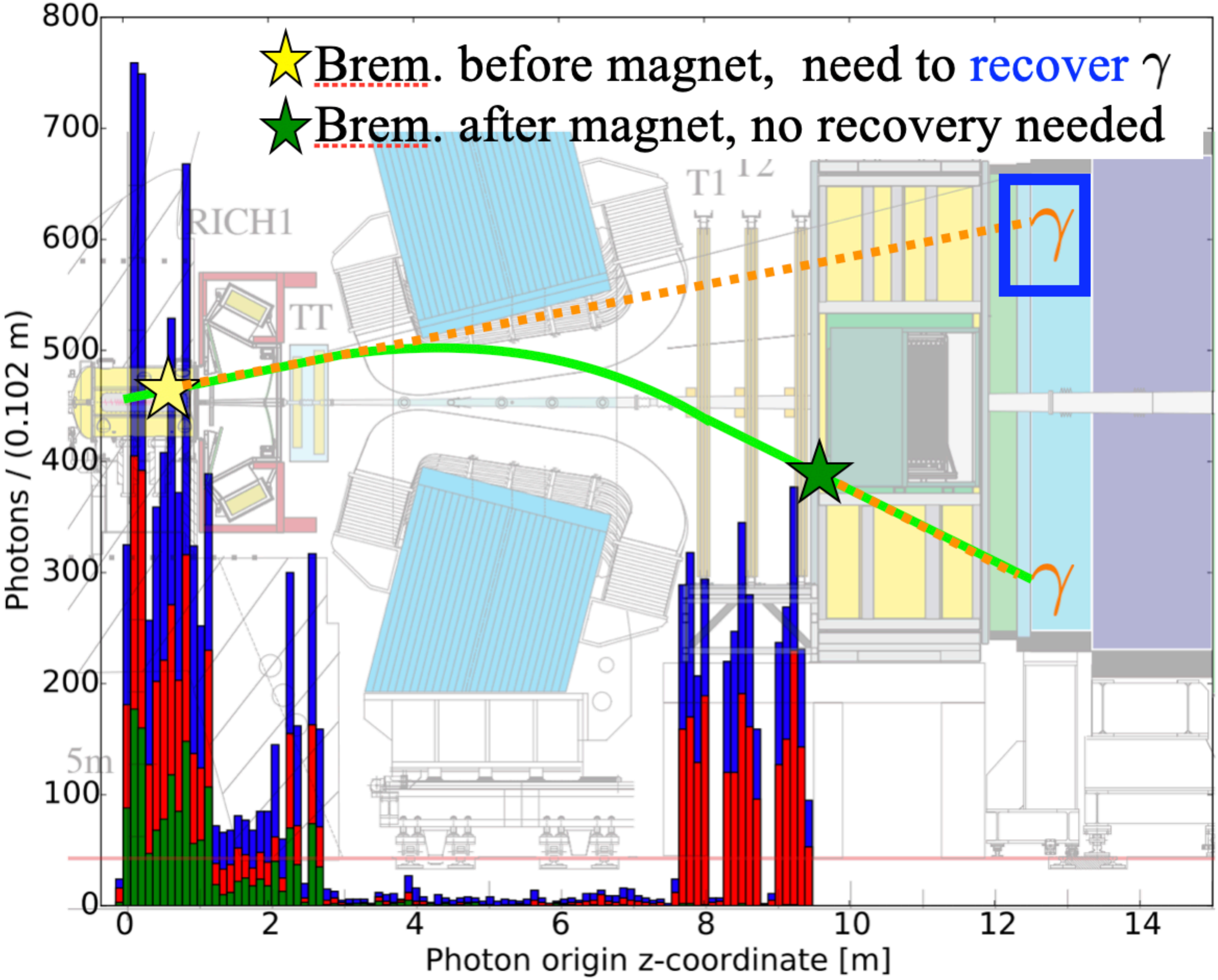


Lepton Flavour Universality

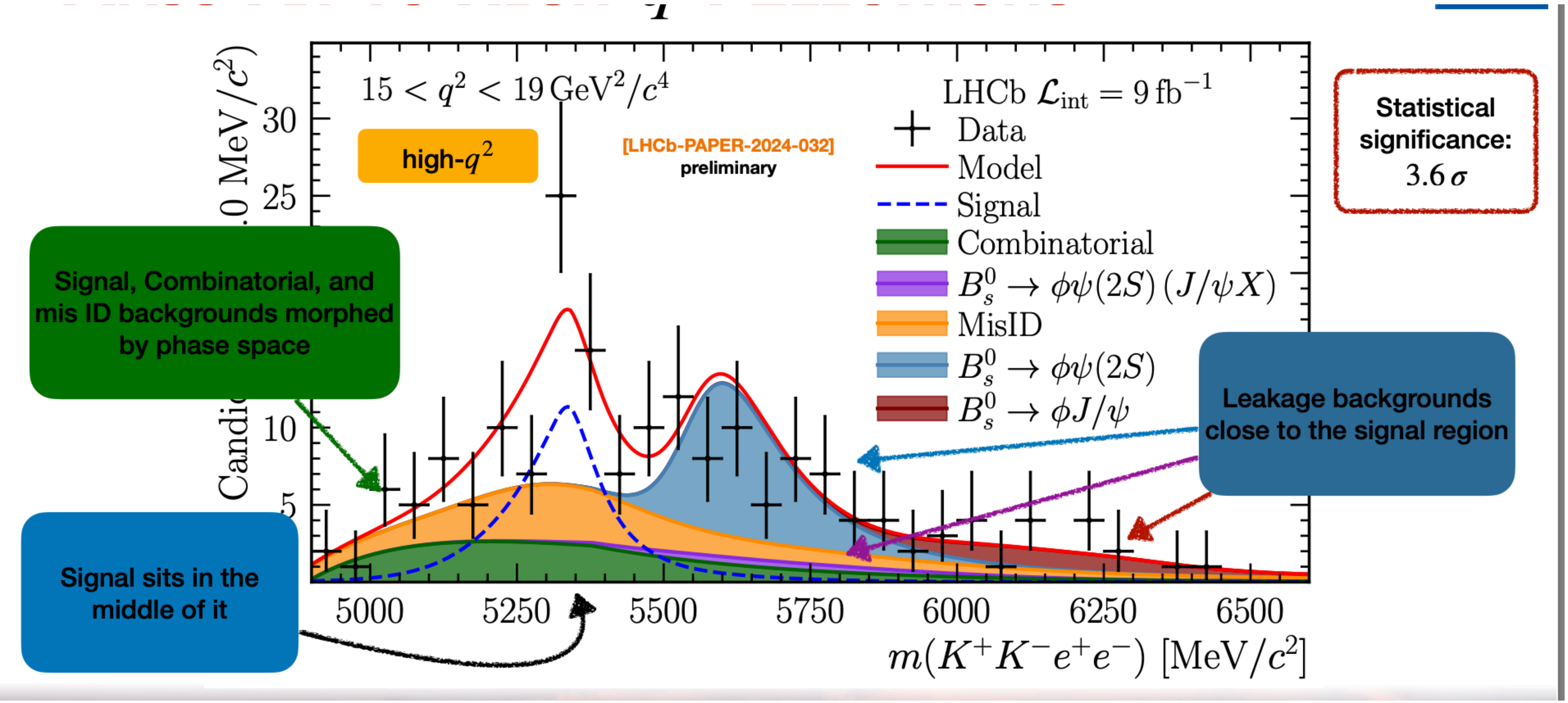
$$R(X) = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)}$$



Lepton Flavour Universality



First test of lepton universality in $B_s^0 \to \phi \ell^+ \ell^-$ *decays*



Statistical significance:
$3.6\,\sigma$

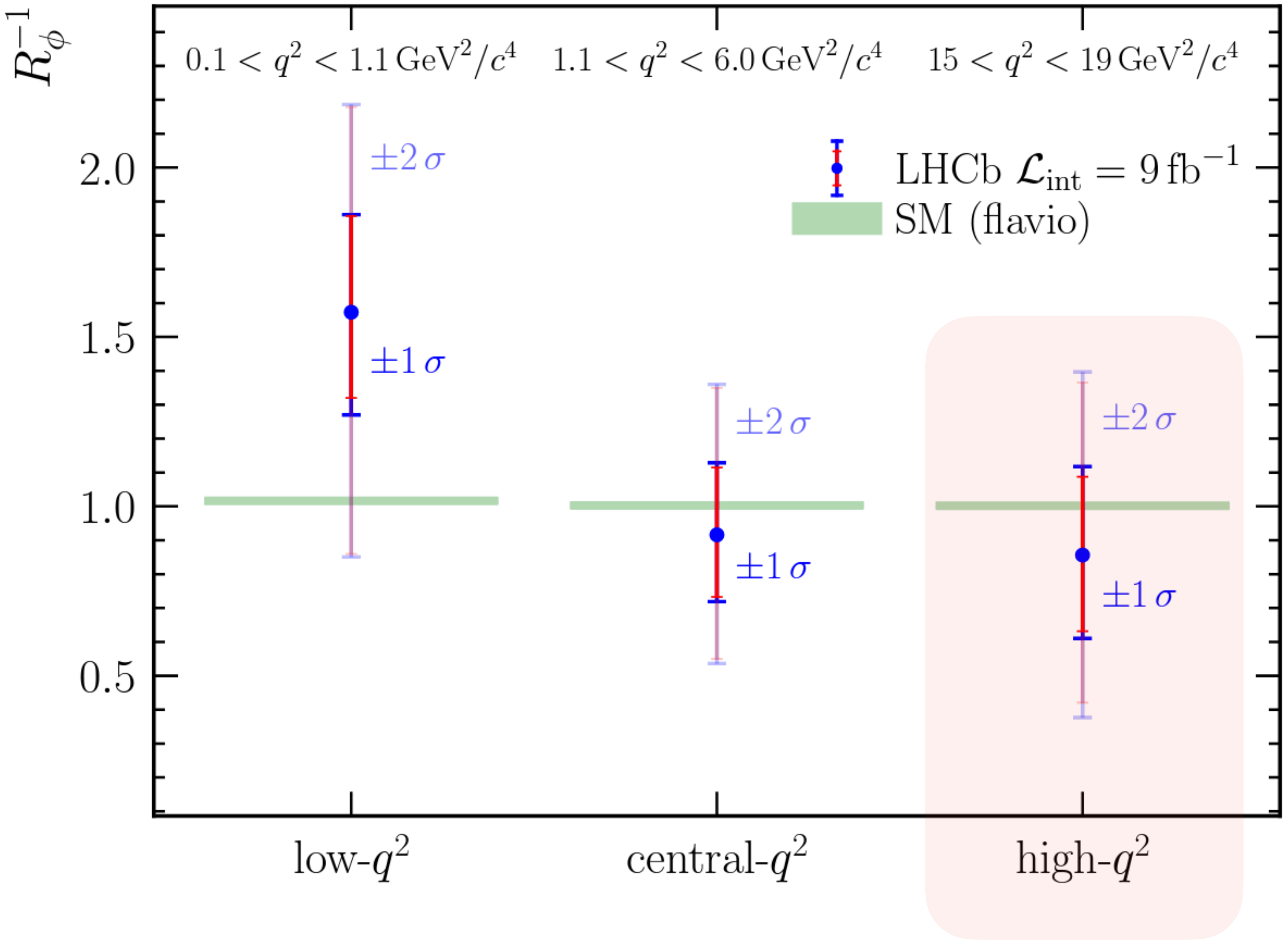
Signal, Combinatorial, and mis ID backgrounds morphed by phase space

Signal sits in the middle of it

Leakage backgrounds close to the signal region

First test of lepton universality in $B_s^0 \to \phi \ell^+ \ell^-$ *decays*

arXiv:2410.13748 (Oct. 2024, submitted to PRL)



World's first measurement of lepton-flavour universality the B_s^0 system

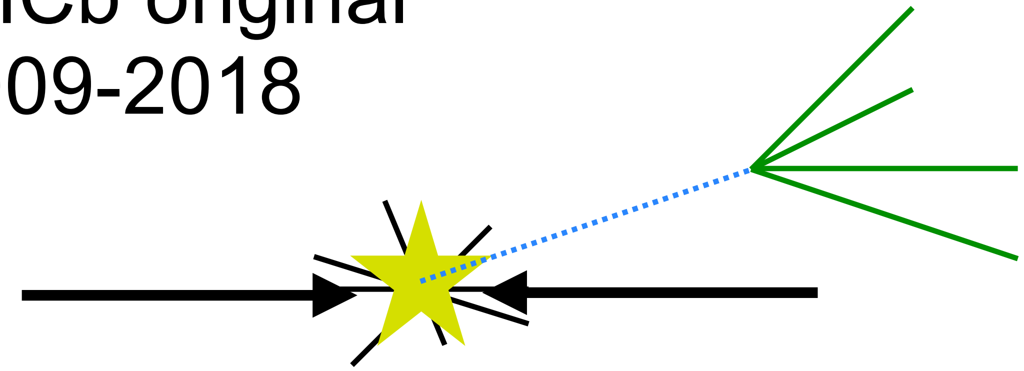
World's first measurement of lepton-flavour universality *in any rare penguin decay* in this experimentally-difficult kinematic region

Looking forward

The LHCb detectors

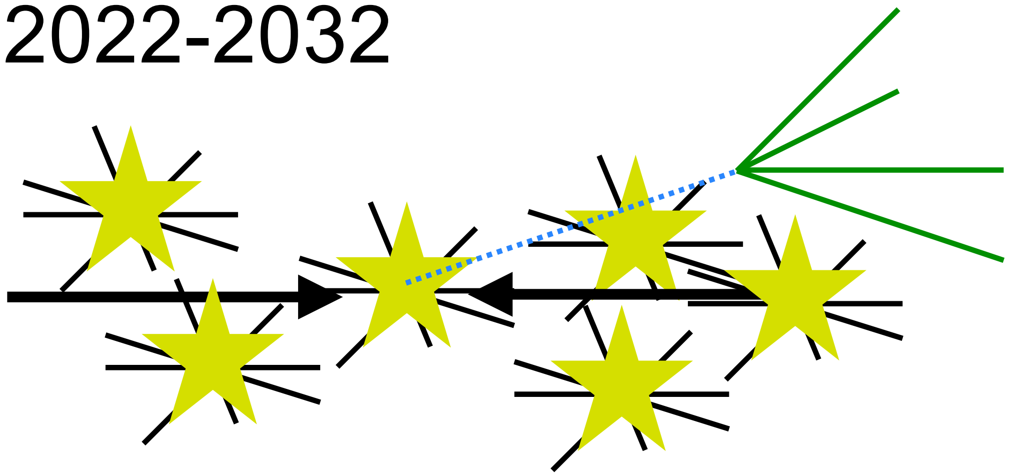
Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
$\mathcal{L} = 4 \times 10^{32}/cm^2s$ $\int \mathcal{L}\,dt = 9$ fb^{-1}	LHCb Upgrade I	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\,dt \approx 23$ fb^{-1}	LHCb Upgrade Ib	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\,dt \approx 50$ fb^{-1}	LHCb Upgrade II	$\mathcal{L} = 2 \times 10^{34}/cm^2s$	$\int \mathcal{L}\,dt \approx 300$ fb^{-1}
2011-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2038	2038->

LHCb original
2009-2018



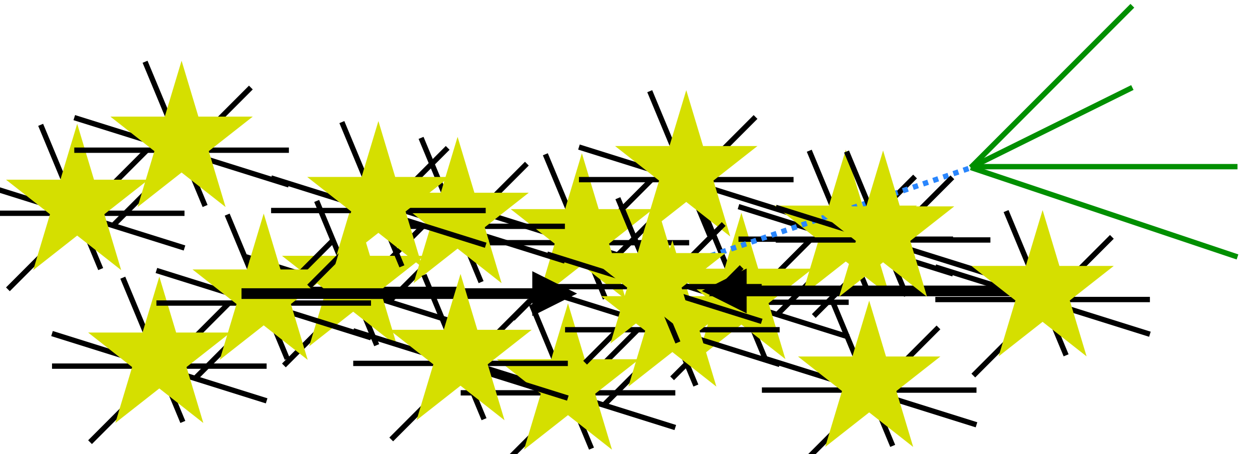
~1 pp collision per bunch-crossing

LHCb Upgrade I
2022-2032



~6 pp collisions per bunch-crossing

LHCb Upgrade II
2033 onwards



~40 pp collisions per bunch-crossing

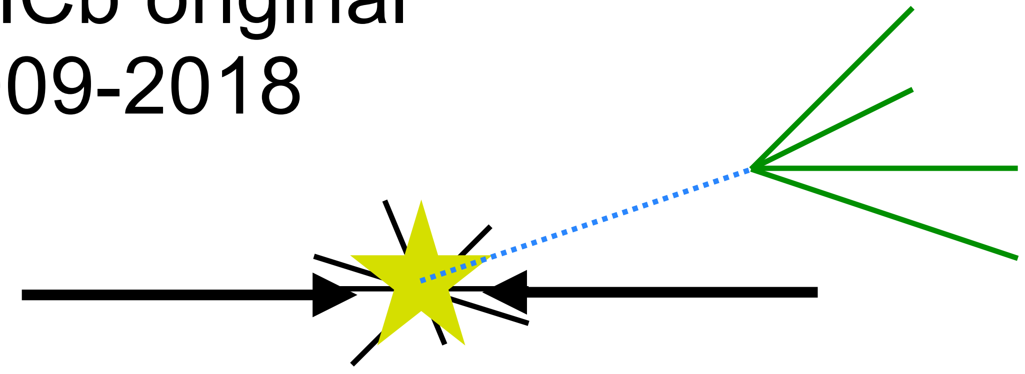
+ ~30 million bunch crossings a second!

The LHCb detectors

2025: upto ~3 times as much data as currently

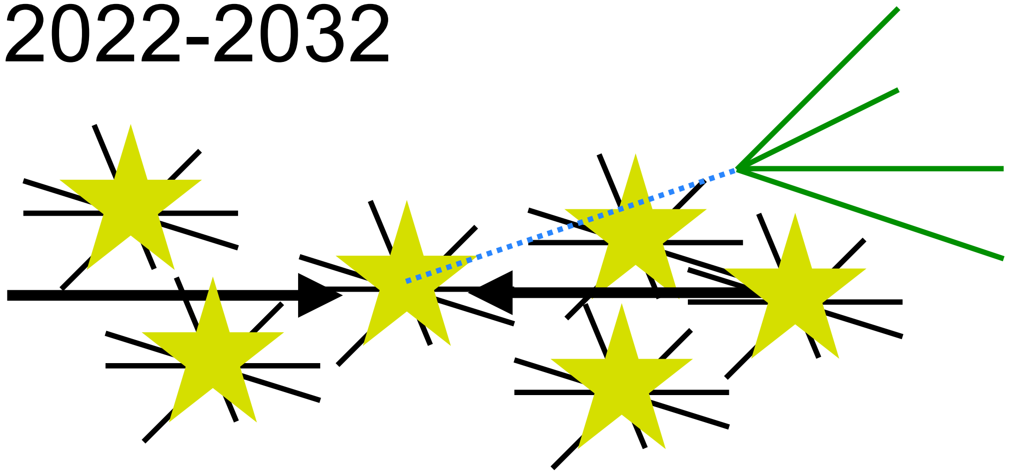
Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
$\mathcal{L} = 4 \times 10^{32}/cm^2 s$ $\int \mathcal{L}\, dt = 9$ fb^{-1}	LHCb Upgrade I	$\mathcal{L} = 2 \times 10^{33}/cm^2 s$ $\int \mathcal{L}\, dt \approx 23$ fb^{-1}	LHCb Upgrade Ib	$\mathcal{L} = 2 \times 10^{33}/cm^2 s$ $\int \mathcal{L}\, dt \approx 50$ fb^{-1}	LHCb Upgrade II	$\mathcal{L} = 2 \times 10^{34}/cm^2 s$	$\int \mathcal{L}\, dt \approx 300$ fb^{-1}
2011-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2038	2038->

LHCb original
2009-2018



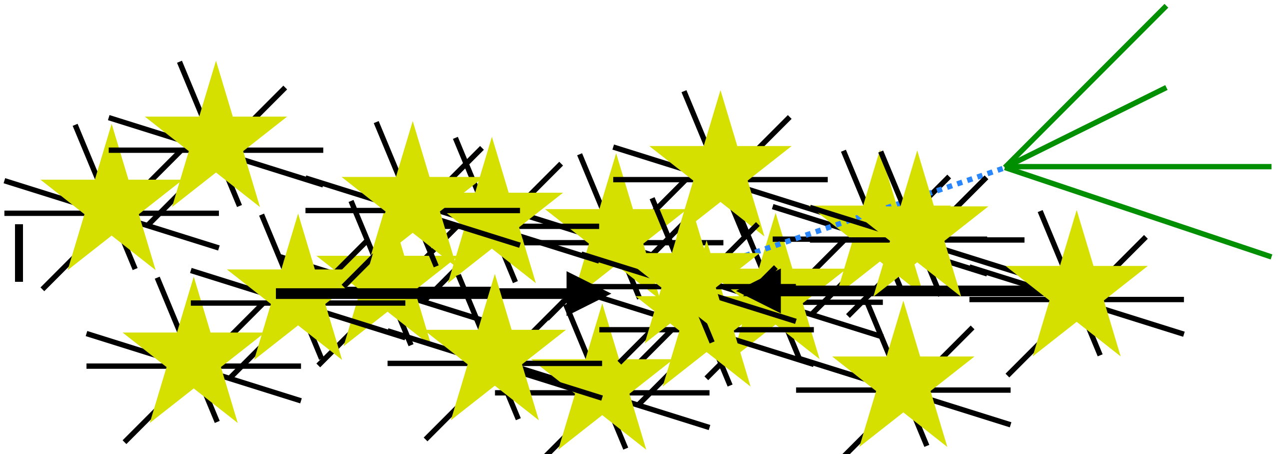
~1 pp collision per bunch-crossing

LHCb Upgrade I
2022-2032



~6 pp collisions per bunch-crossing

LHCb Upgrade II
2033 onwards

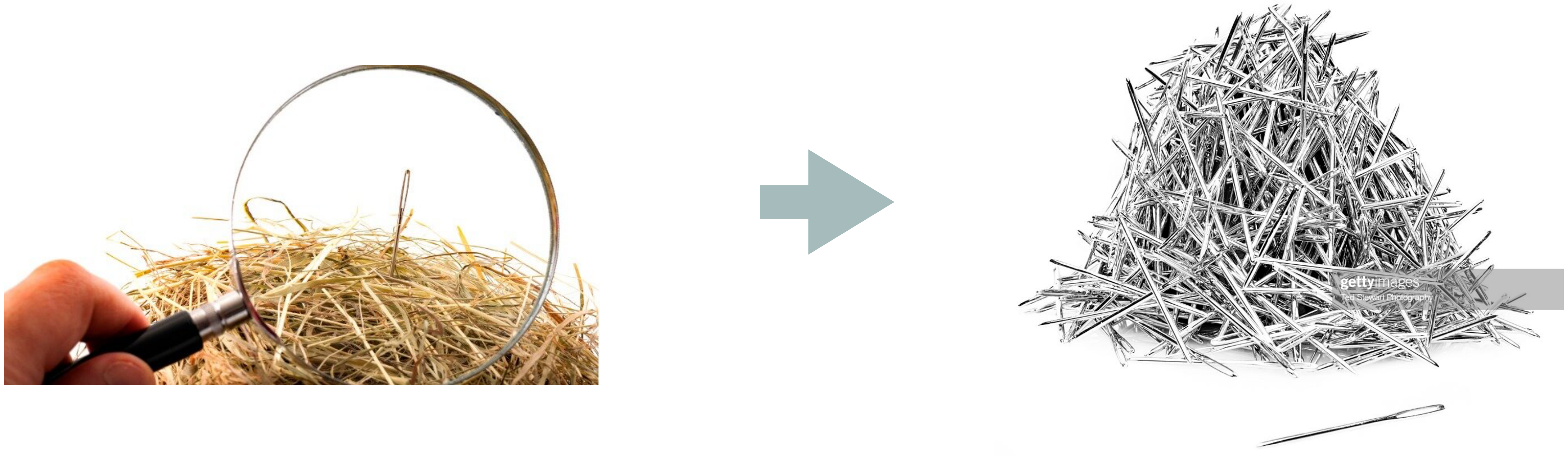


~40 pp collisions per bunch-crossing

+ ~30 million bunch crossings a second!

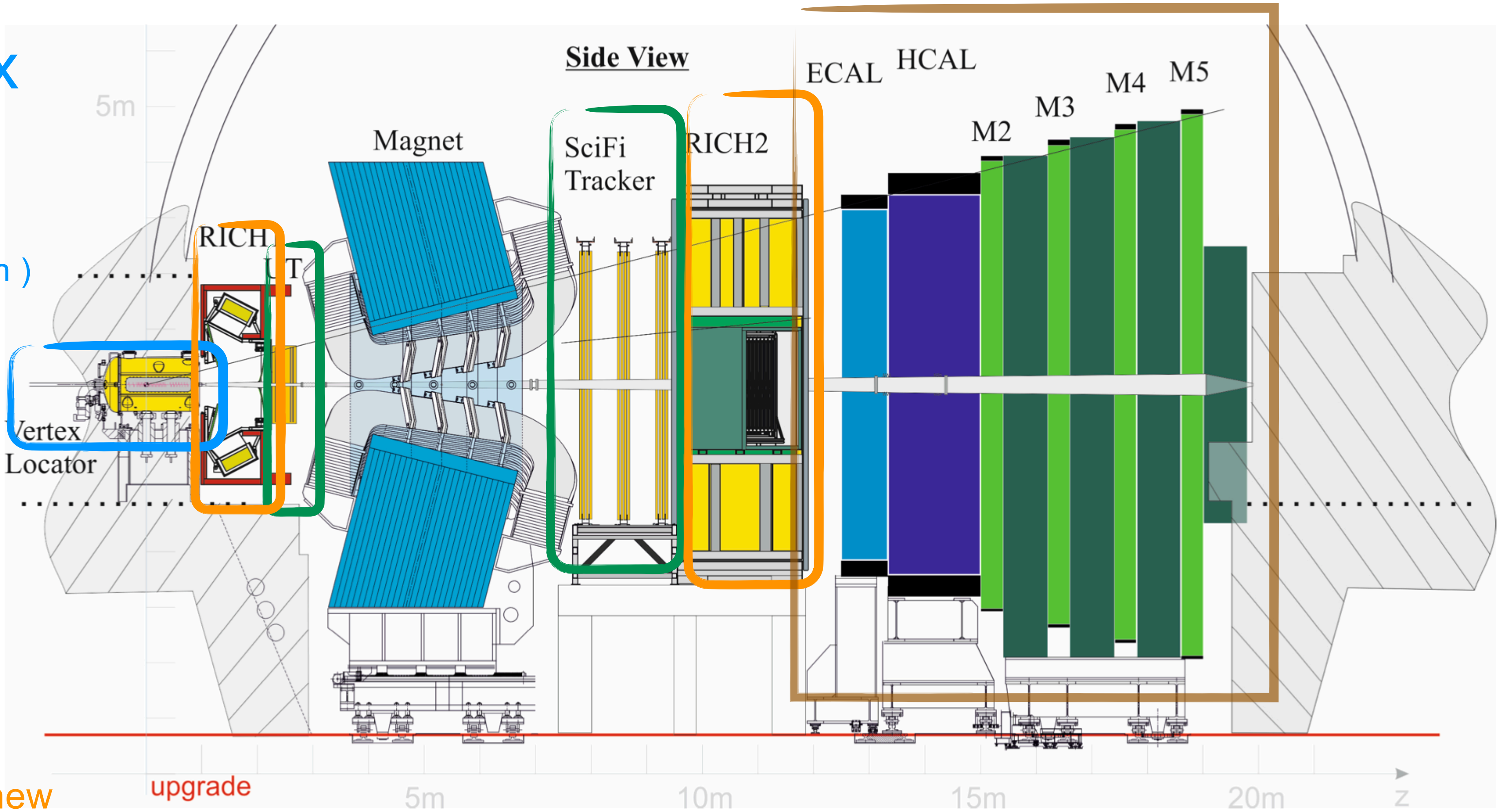
LHCb Upgrade I

- Lumi increase means that ~24% (2%) of events have a reconstructable $c\overline{c}$ ($b\overline{b}$) pair



- Remove hard-ware trigger (trigger-readout 40MhZ), software trigger operating at 30MhZ (!)
- Online alignment and calibration: real-time analysis
- Significant efficiency gains, particularly for low-p_T hadrons + electrons

Summary of Upgrade I changes



New Vertex detector (Si-microstrip-> Si-pixel, closer to beam, improved IP resolution)

New PID detector, new photon detectors, readout + modified optics/mechanics

New tracking system (Si-strip + straw-tubes ->Scintillating fibres,+ Si-strip UT > granularity)

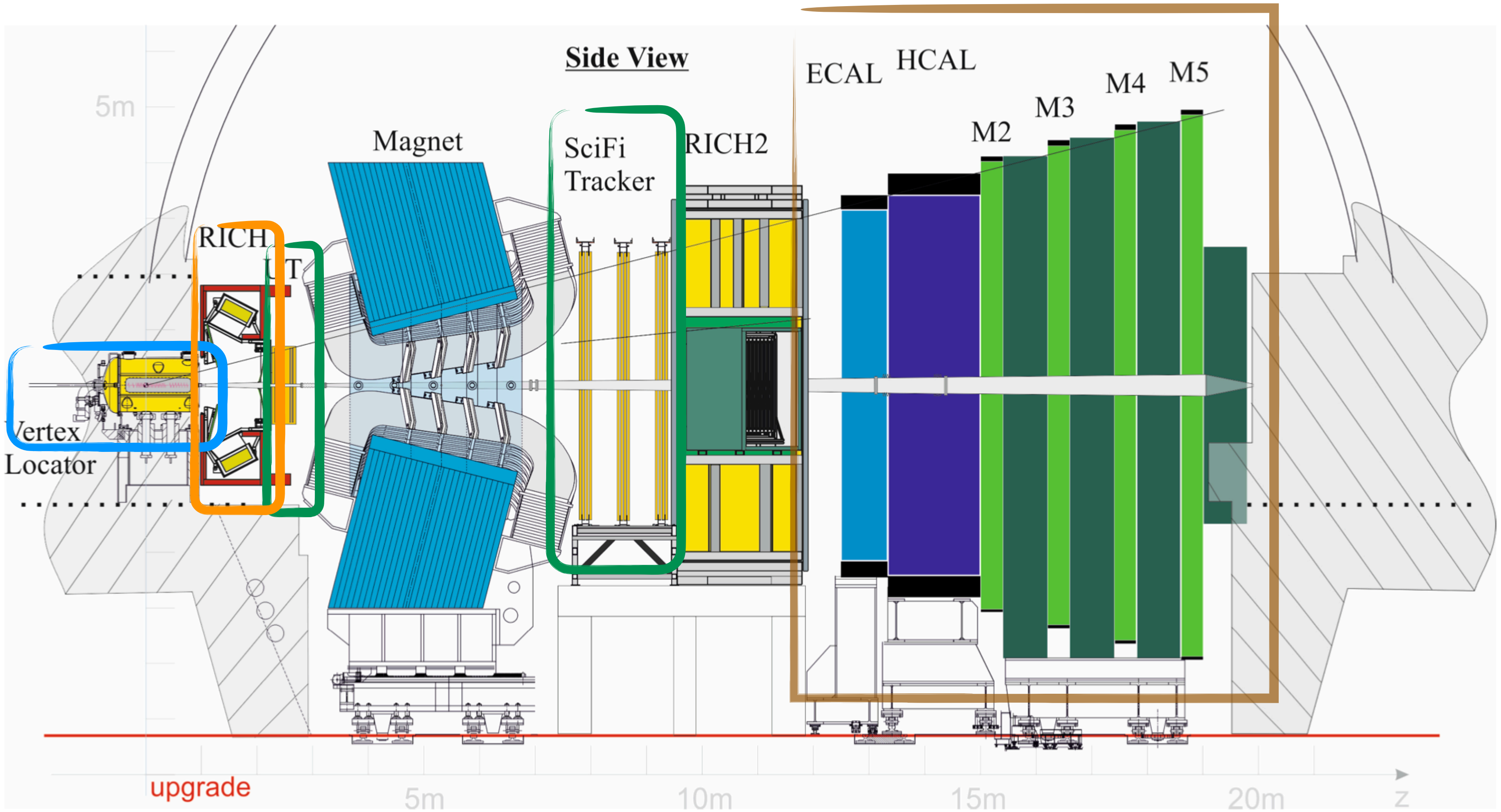
New read out

+ new DAQ/data centre

Status of LHCb commissioning

LHC accident = we can have no closed VELO in 2023…

Will need a intervention during End of Year stop

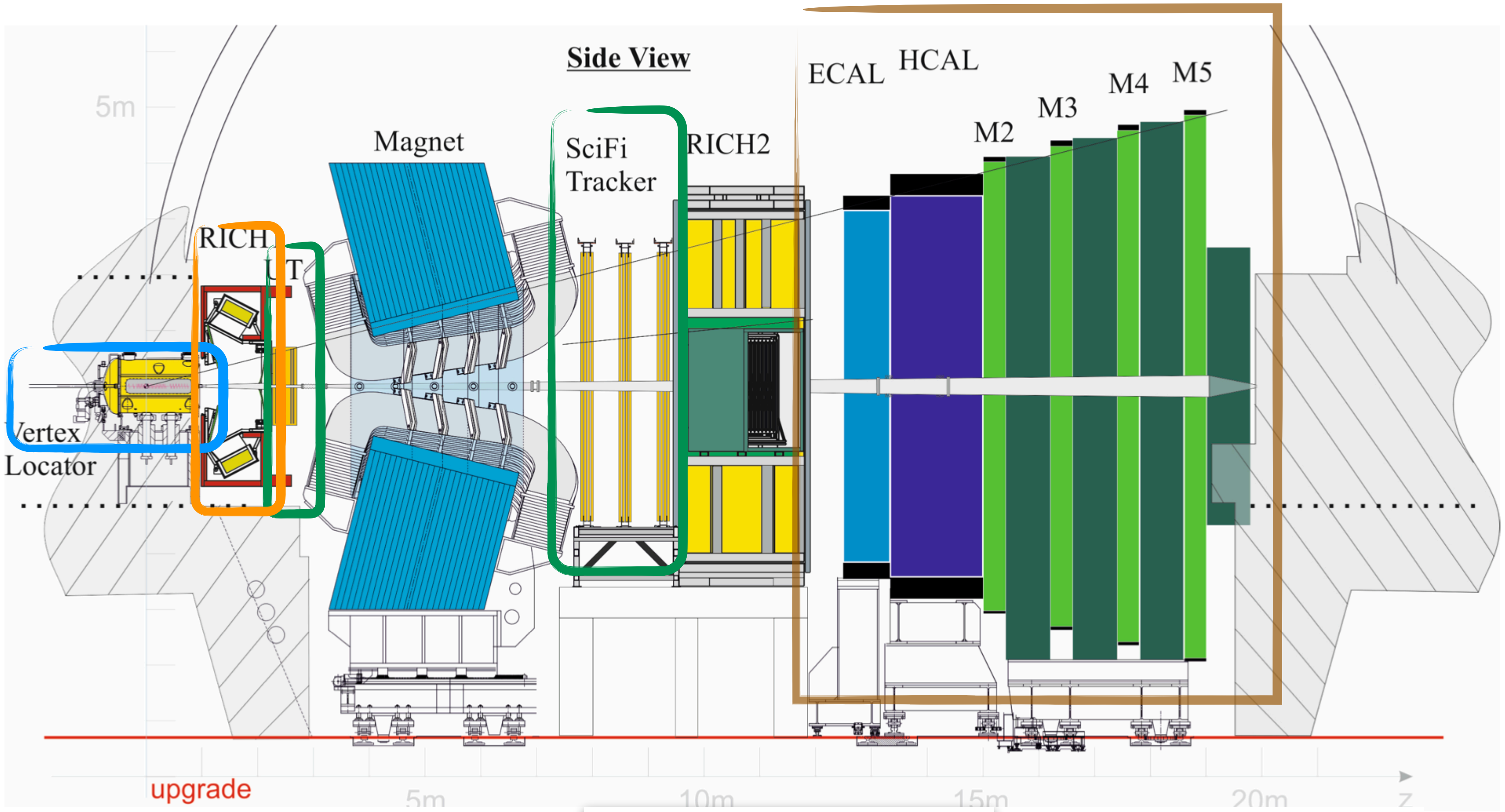


Status of LHCb commissioning

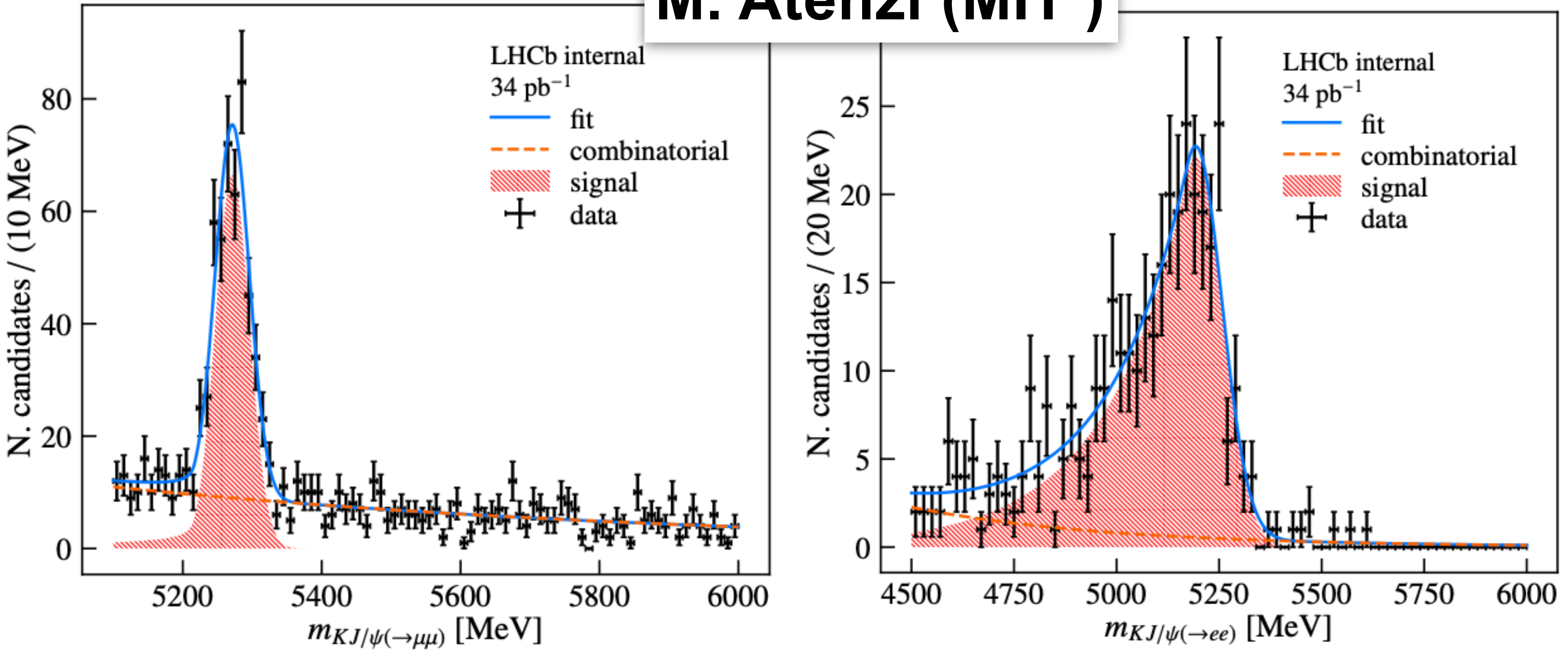
LHC accident = we can have no closed VELO in 2023…

Will need a intervention during End of Year stop

BUT the data we have looks good



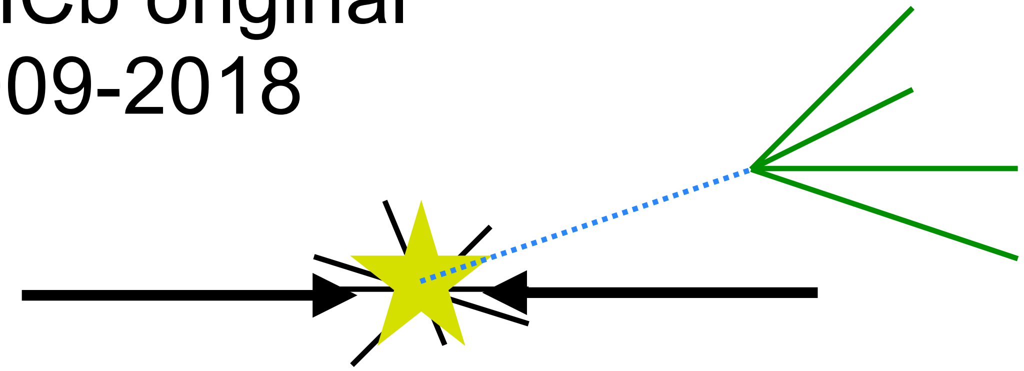
M. Atenzi (MIT)



The LHCb detectors 2035: upto ~30 times as much data as currently

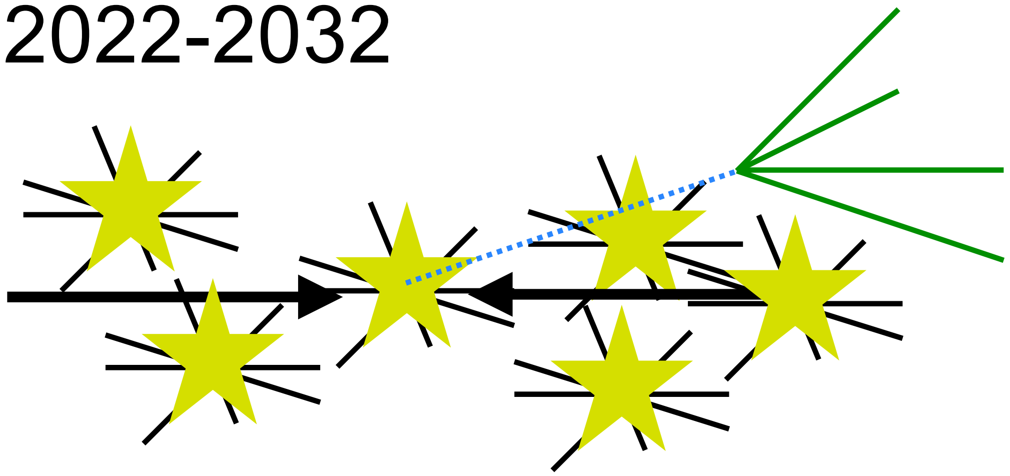
Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
$\mathcal{L} = 4 \times 10^{32}/cm^2s$ $\int \mathcal{L}\, dt = 9\ \text{fb}^{-1}$	LHCb Upgrade I	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\, dt \approx 23\ \text{fb}^{-1}$	LHCb Upgrade Ib	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\, dt \approx 50\ \text{fb}^{-1}$	LHCb Upgrade II	$\mathcal{L} = 2 \times 10^{34}/cm^2s$	$\int \mathcal{L}\, dt \approx 300\ \text{fb}^{-1}$
2011-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2038	2038->

LHCb original
2009-2018



~1 pp collision per bunch-crossing

LHCb Upgrade I
2022-2032



~6 pp collisions per bunch-crossing

LHCb Upgrade II
2033 onwards

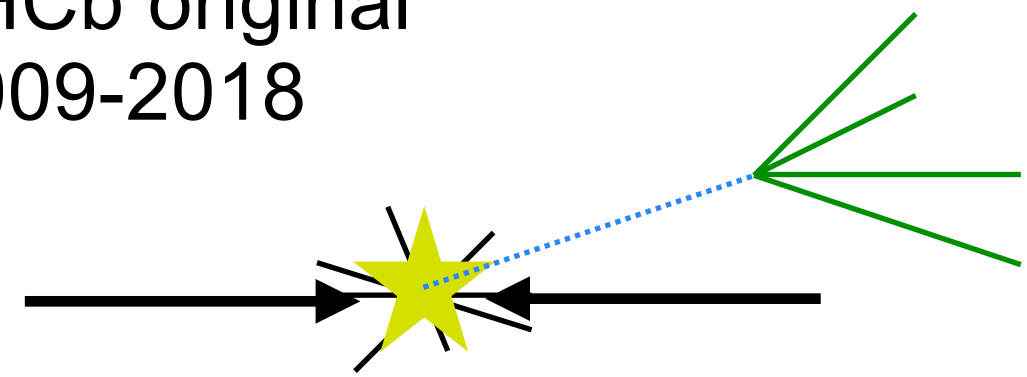
~40 pp collisions per bunch-crossing

+ ~30 million bunch crossings a second!

How to get more data..

Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
$\mathcal{L} = 4\times10^{32}/cm^2s$ $\int \mathcal{L}\,dt = 9$ fb^{-1}	LHCb Upgrade I	$\mathcal{L} = 2\times10^{33}/cm^2s$ $\int \mathcal{L}\,dt \approx 23$ fb^{-1}	LHCb Upgrade Ib	$\mathcal{L} = 2\times10^{33}/cm^2s$ $\int \mathcal{L}\,dt \approx 50$ fb^{-1}	LHCb Upgrade II	$\mathcal{L} = 2\times10^{34}/cm^2s$	$\int \mathcal{L}\,dt \approx 300$ fb^{-1}
2011-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2038	2038->

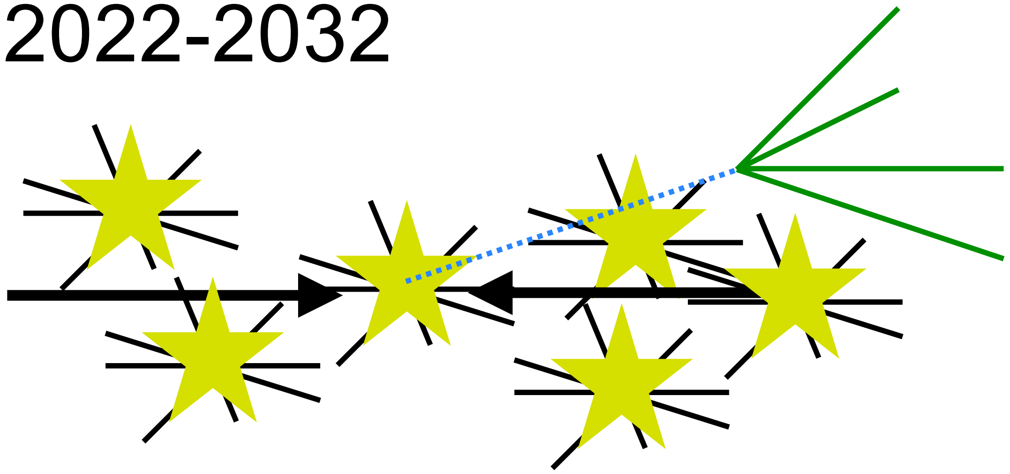
LHCb original
2009-2018



~1 pp collision per bunch-crossing

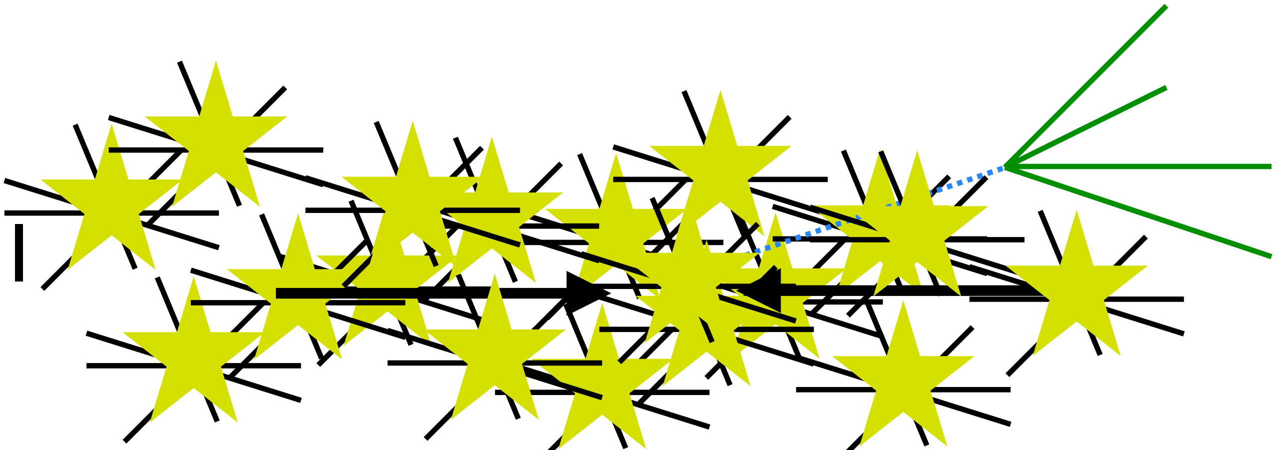
We are here….

LHCb Upgrade I
2022-2032



~6 pp collisions per bunch-crossing

LHCb Upgrade II
2033 onwards



~40 pp collisions per bunch-crossing

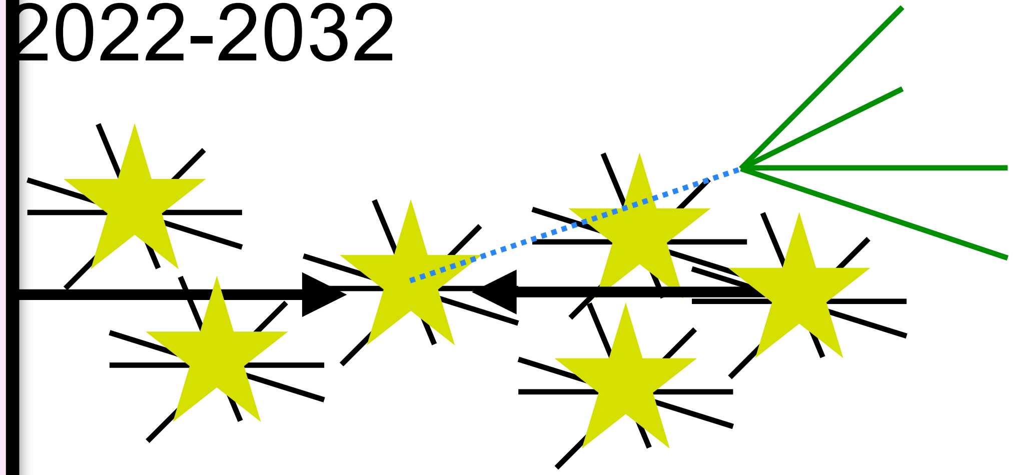
We have ~30 million bunch crossings a second!

Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
$\mathcal{L} = 4 \times 10^{32}/cm^2s$ $\int \mathcal{L}\, dt = 9$ fb^{-1}	LHCb Upgrade I	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\, dt \approx 23$ fb^{-1}	LHCb Upgrade Ib	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\, dt \approx 50$ fb^{-1}	LHCb Upgrade II	$\mathcal{L} = 2 \times 10^{34}/cm^2s$	$\int \mathcal{L}\, dt \approx 300$ fb^{-1}
2011-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2038	2038->

How do we get here?

- Detector is limit, not LHC
- Requires new timing technologies
- Higher granularity
- Low material budget
- Improvements to detector readout

LHCb Upgrade I
2022-2032



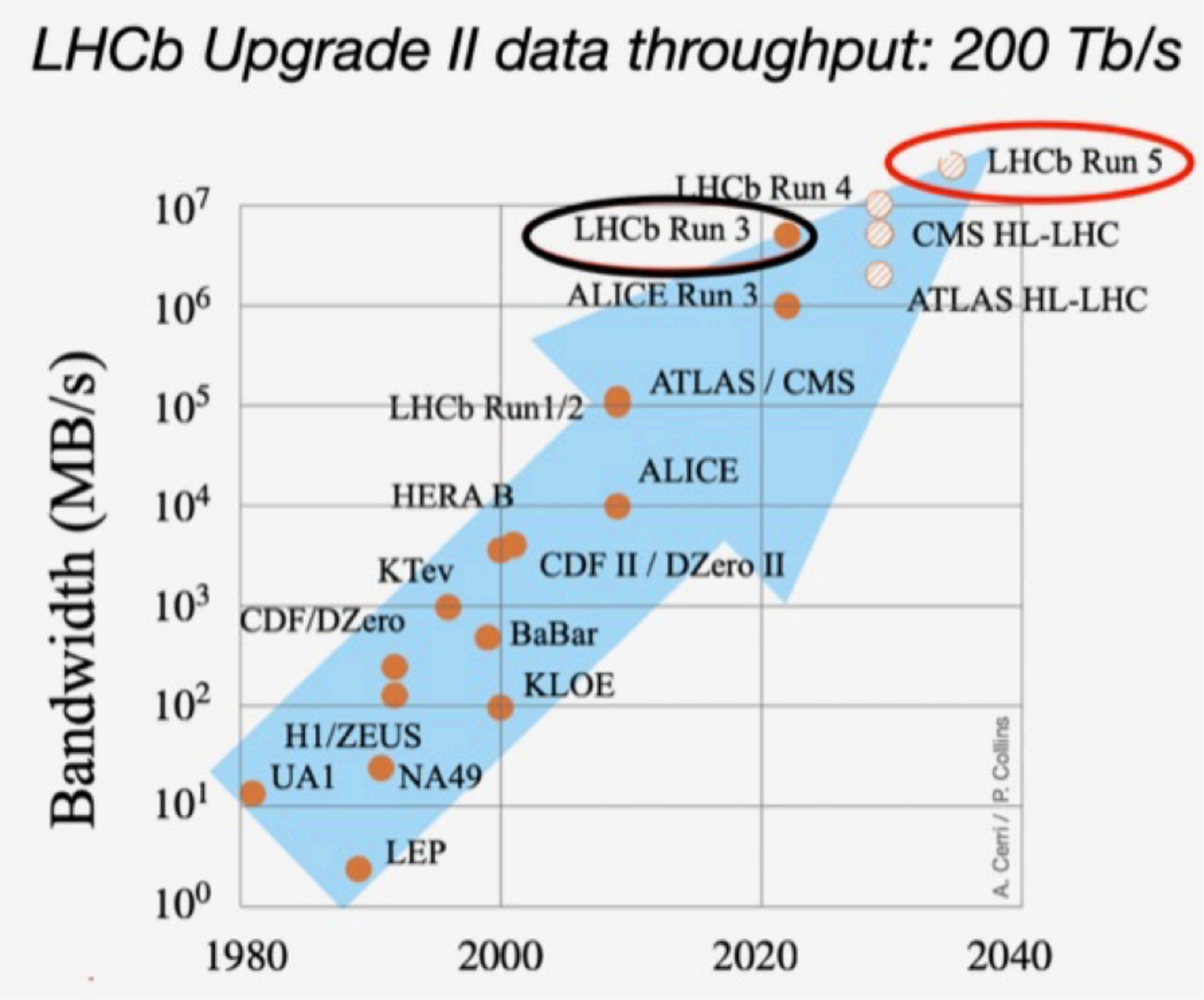
~6 pp collisions per bunch-crossing

LHCb Upgrade II
2033 onwards

~40 pp collisions per bunch-crossing

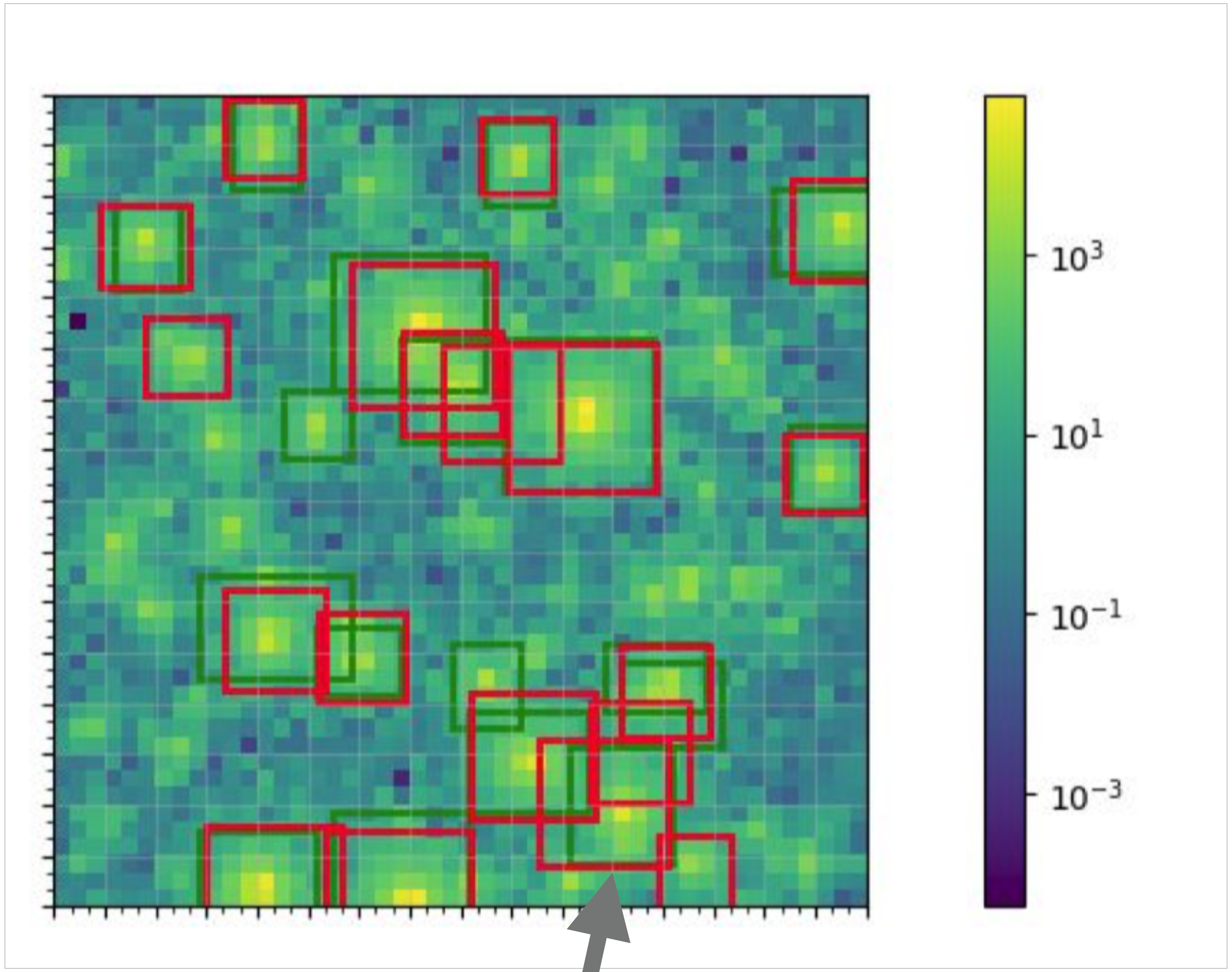
We have ~30 million bunch crossings a second!

LHCb readout Upgrade II



- 40→200 Tb/s
- Need novel data-processing techniques
- Perform algorithms at read-out stage?

LHCb readout Upgrade II



e.g. program neural nets on FPGAs (chips already present at detector readout) to already find clusters in ECAL

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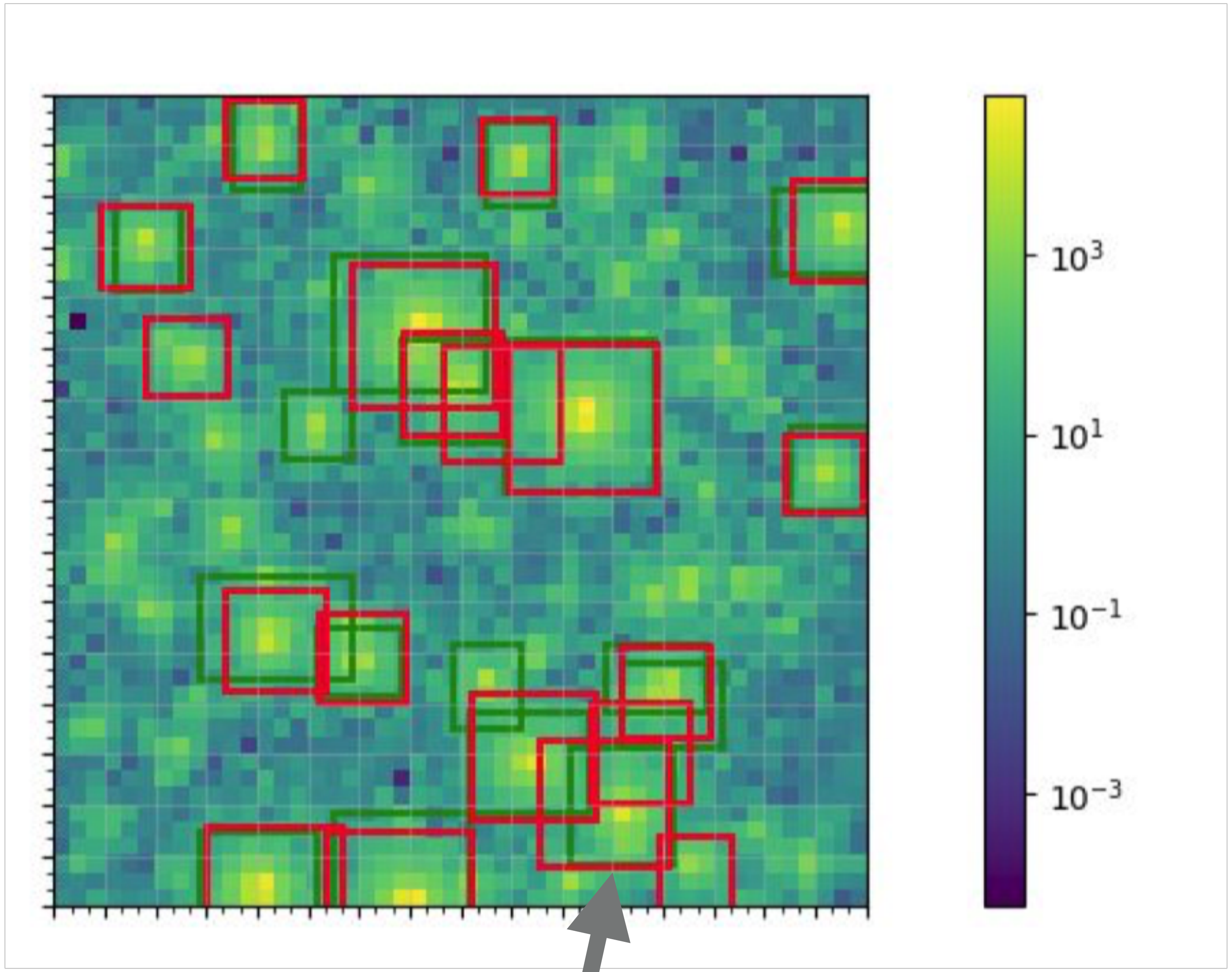
LHCb readout Upgrade II



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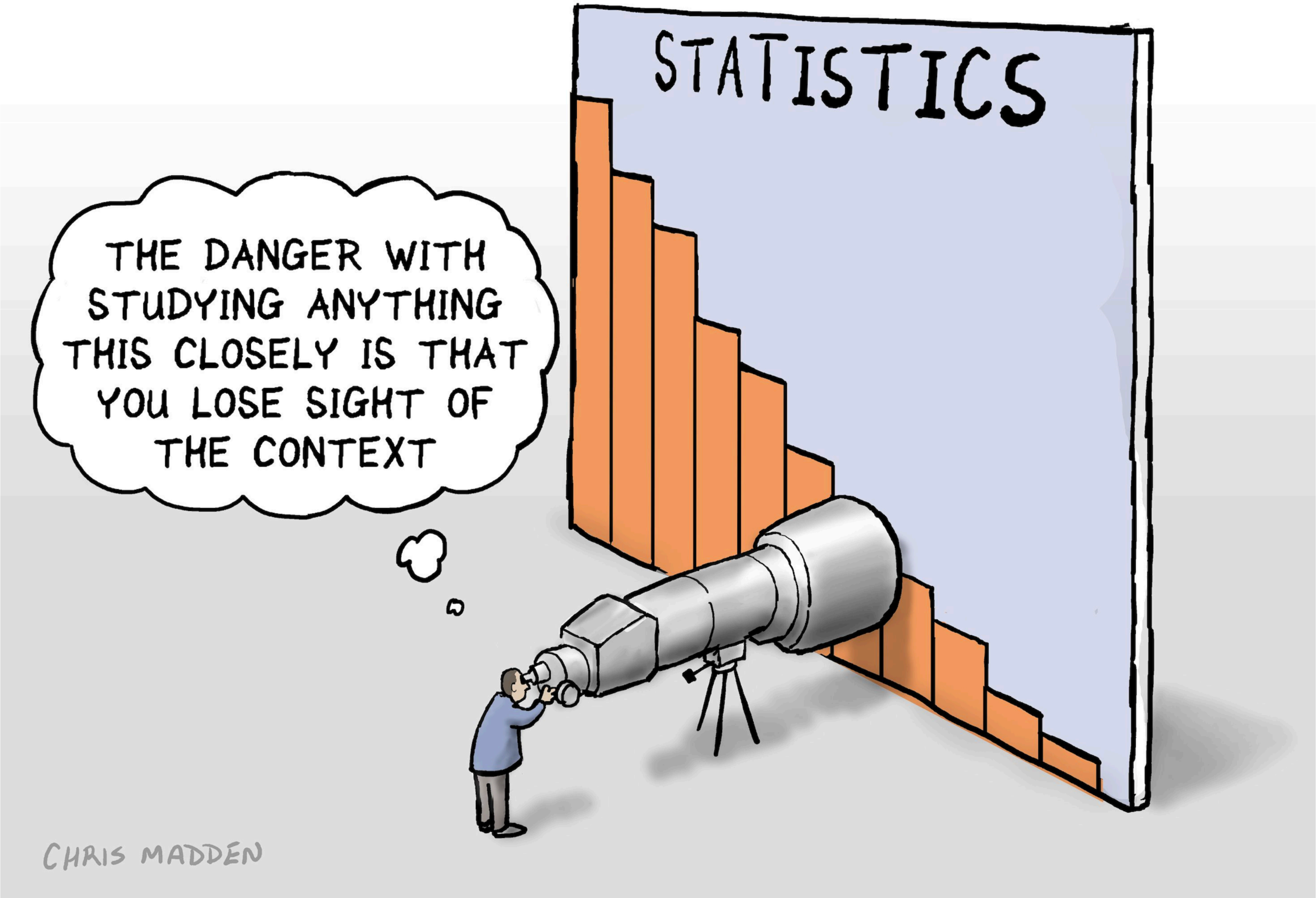
- 40→200 Tb/s
- Need novel data-processing techniques
- Perform ML-based algorithms on FPGAs used on front and back end electronics

MIT will lead FPGA readout efforts for ECAL

Context overview and summary



Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
$\mathcal{L} = 4 \times 10^{32}/cm^2s$ $\int \mathcal{L}\, dt = 9$ fb^{-1}	LHCb Upgrade I	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\, dt \approx 23$ fb^{-1}	LHCb Upgrade Ib	$\mathcal{L} = 2 \times 10^{33}/cm^2s$ $\int \mathcal{L}\, dt \approx 50$ fb^{-1}	LHCb Upgrade II	$\mathcal{L} = 2 \times 10^{34}/cm^2s$	$\int \mathcal{L}\, dt \approx 300$ fb^{-1}
2011-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2038	2038->

Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
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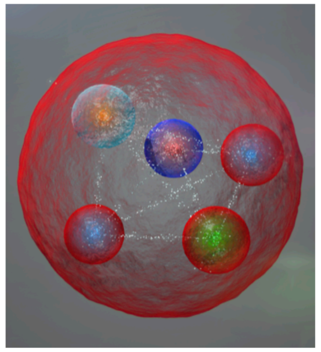
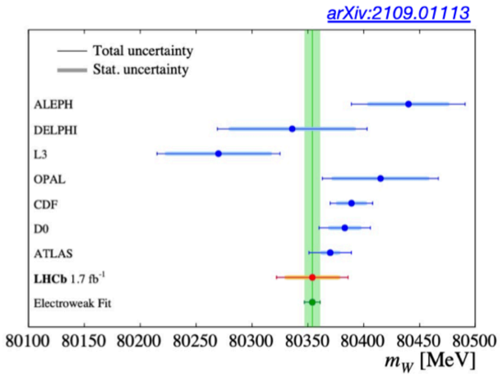
LHCb original 2009-2018: 9fb^{-1}



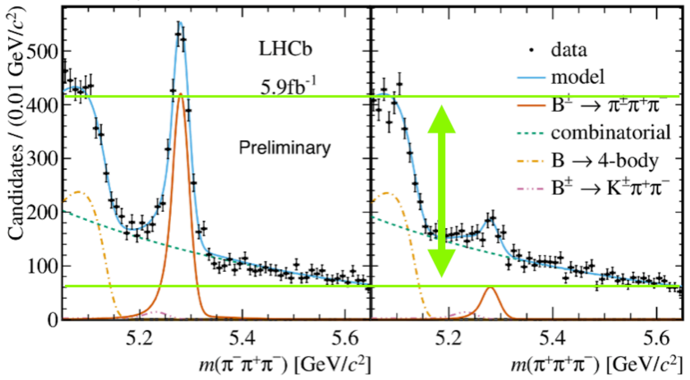
First discovery of a pentaquark

First CP-violation in charm

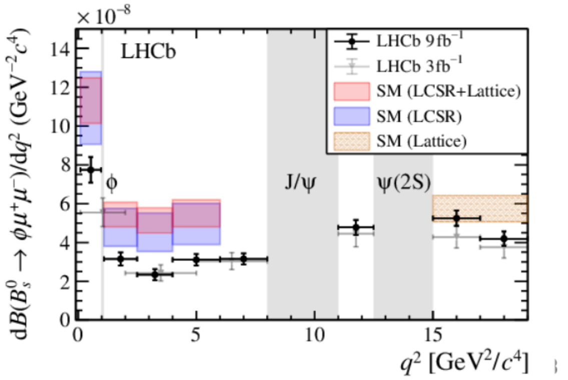


Electroweak physics in forward region

Largest CP violation ever observed, CKM angle, γ, measured to ~ 4^0



Unexpected tensions in rare penguin transitions



- Expected, and unexpected, successes
- **~5σ tension seen in across range of $b \to s\mu^+\mu^-$ decays**
- 3σ tension in $b \to c\ell\nu$ decays

B anomalies

Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
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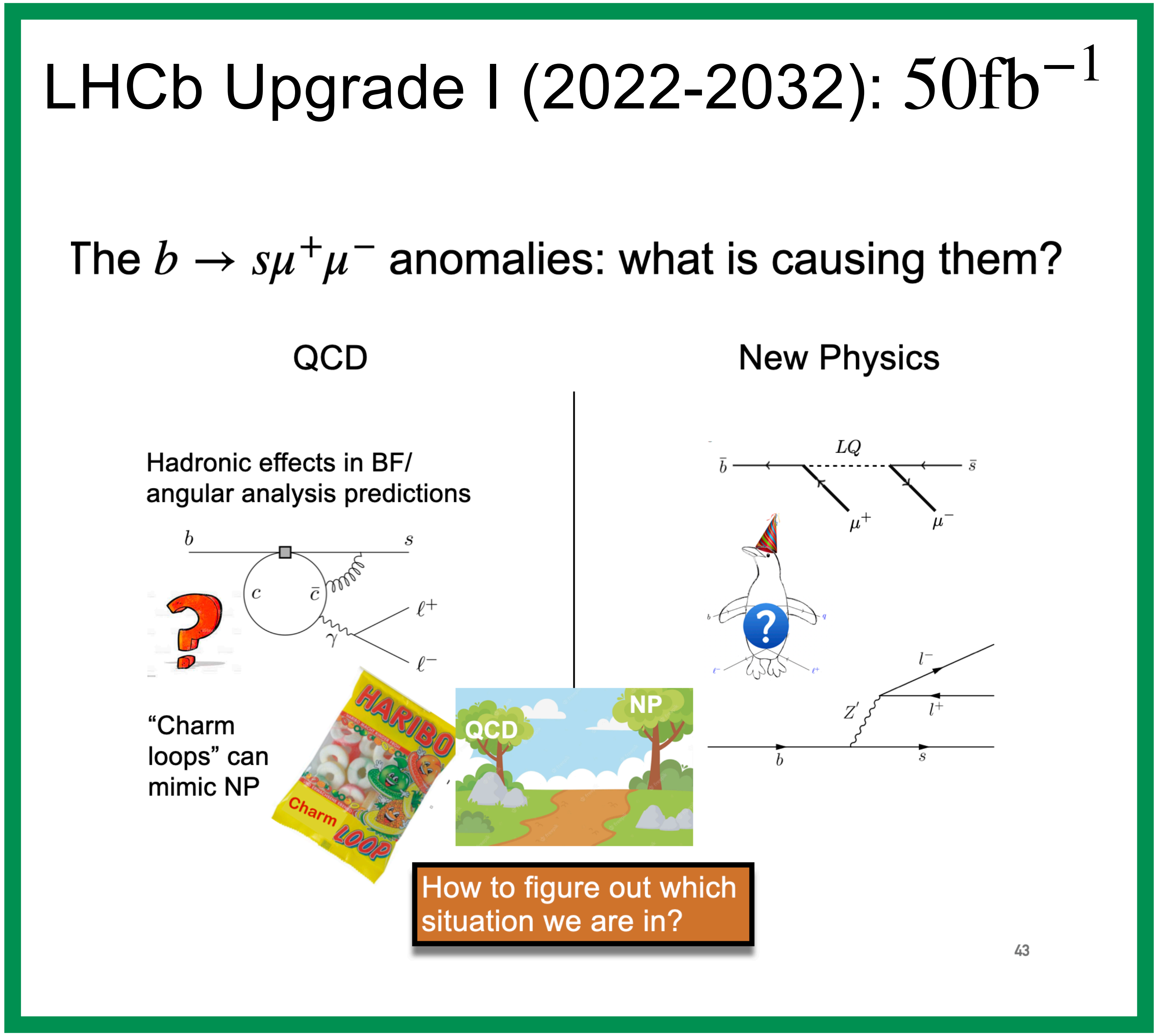

LHCb Upgrade I (2022-2032): 50fb^{-1}

The $b \to s\mu^+\mu^-$ anomalies: what is causing them?

QCD

New Physics

Hadronic effects in BF/ angular analysis predictions

“Charm loops” can mimic NP

How to figure out which situation we are in?

43

- Additional data + new observables →clarify source of B anomalies
- Other areas (particularly strange/ charm) will see key improvements

Run 1&2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5/Run 6
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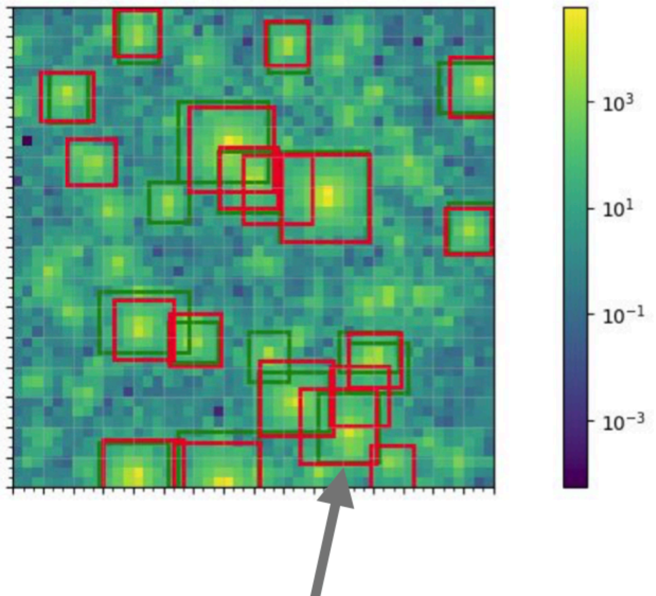
LHCb Upgrade II (2032-…): 50fb^{-1}

LHCb readout Upgrade II



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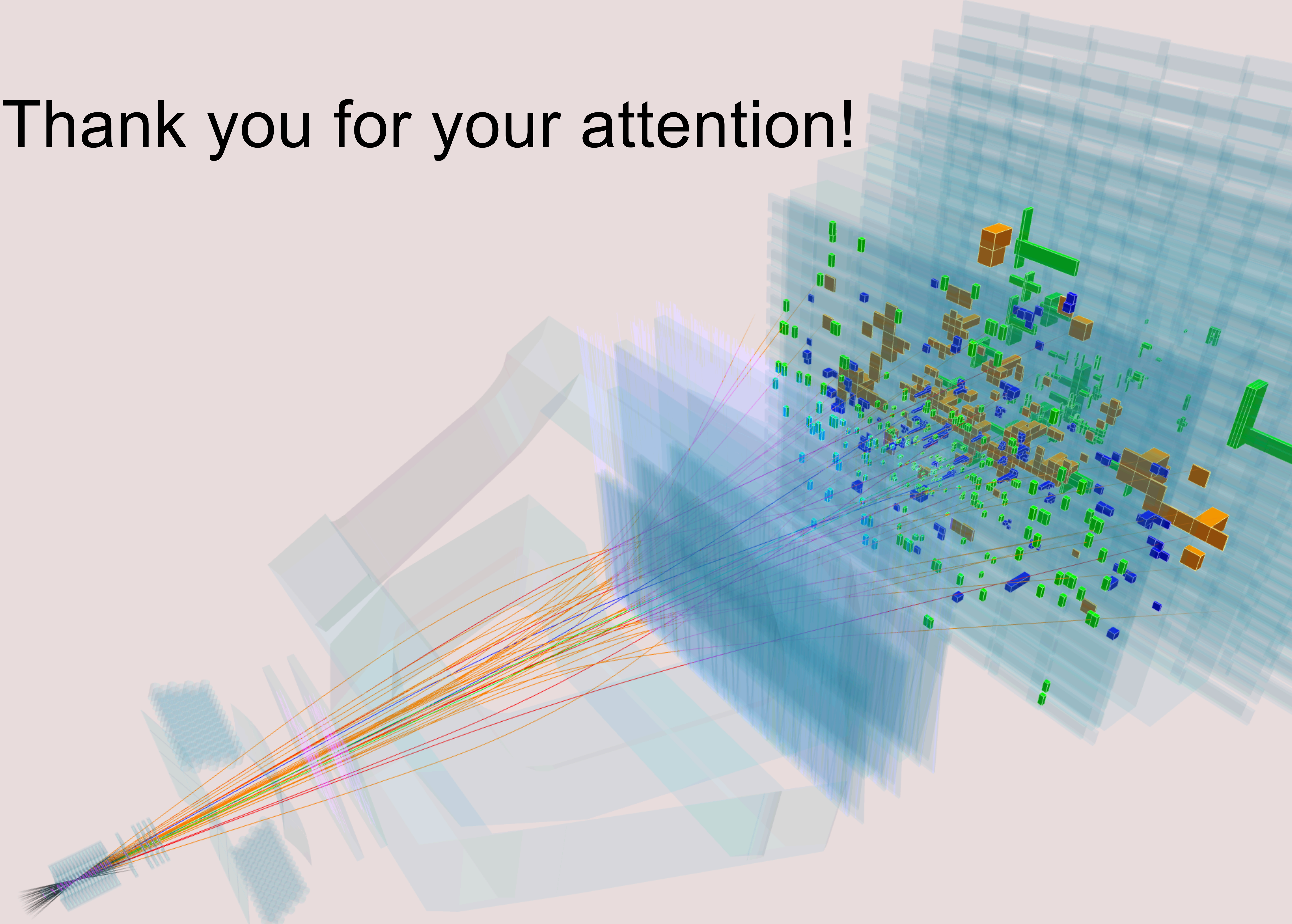
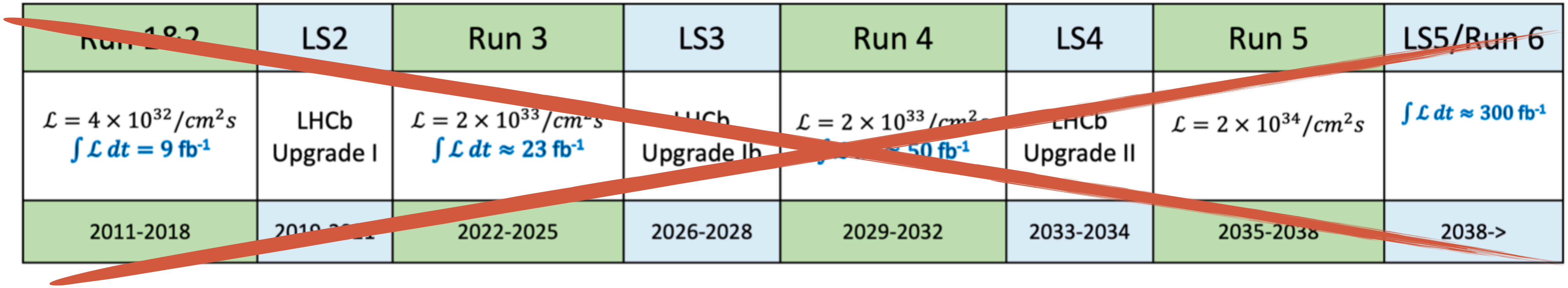
- 40→200 Tb/s
- Need novel data-processing techniques
- Perform ML-based algorithms on FPGAs used on front and back end electronics

- Upgrade II will reach unprecedented precision→ unprecedented Λ_{NP}
- Detector R&D ongoing
- Will rely on ML implemented on FPGAs to deal with data throughput

Thank you for your attention!





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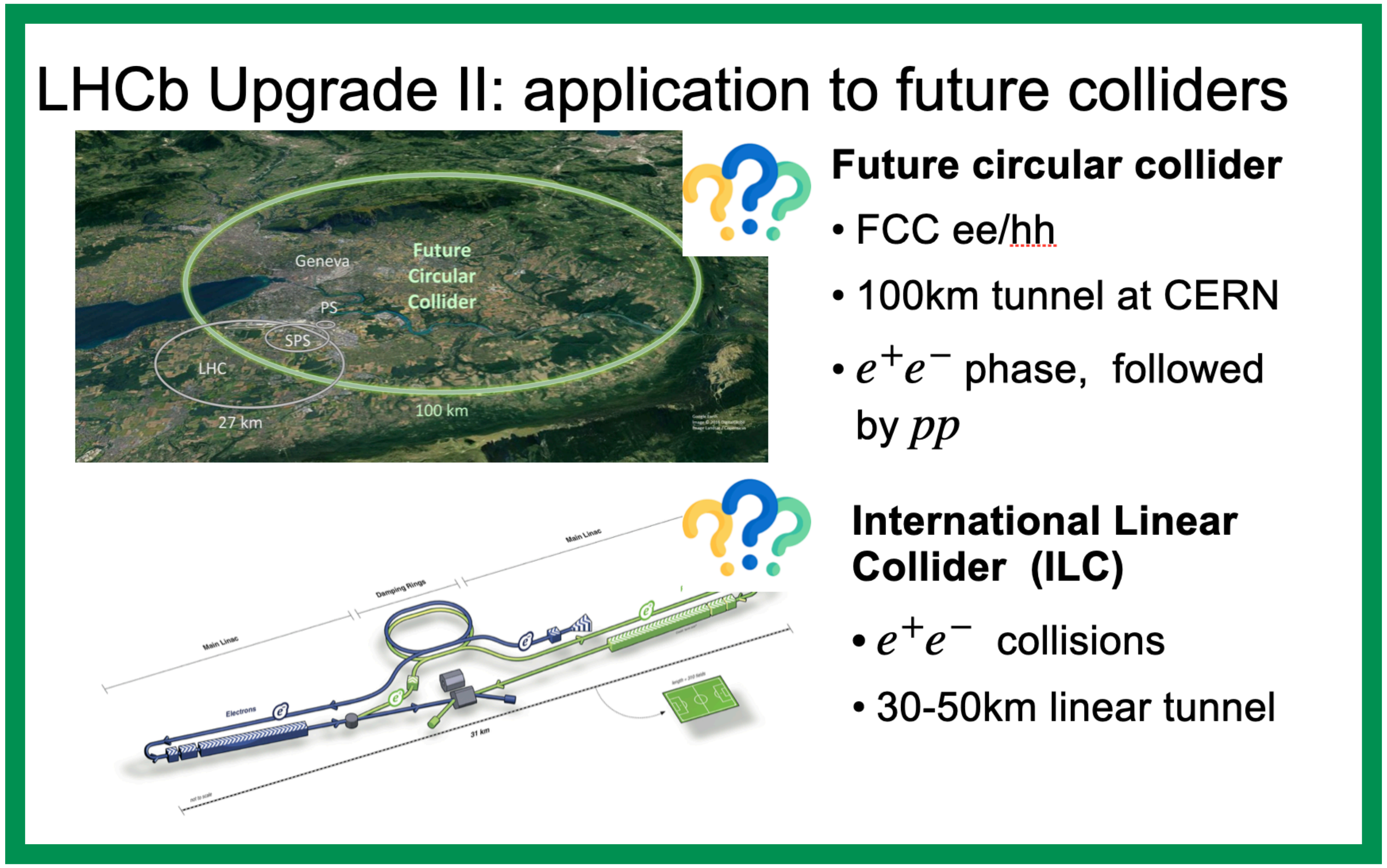
….future detectors?



LHCb Upgrade II: application to future colliders

Future circular collider

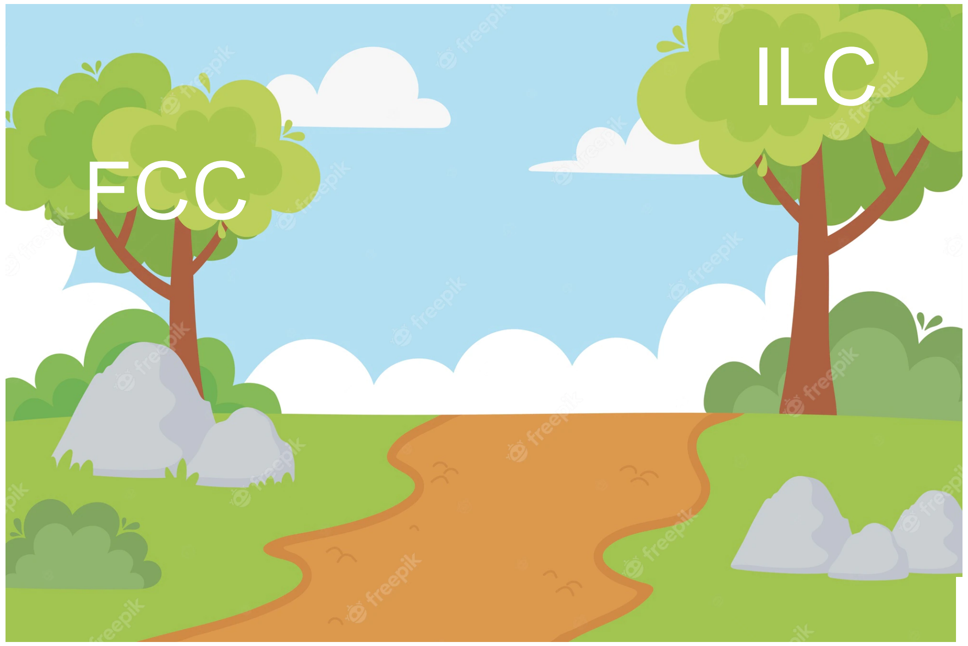
- FCC ee/hh
- 100km tunnel at CERN
- e^+e^- phase, followed by pp

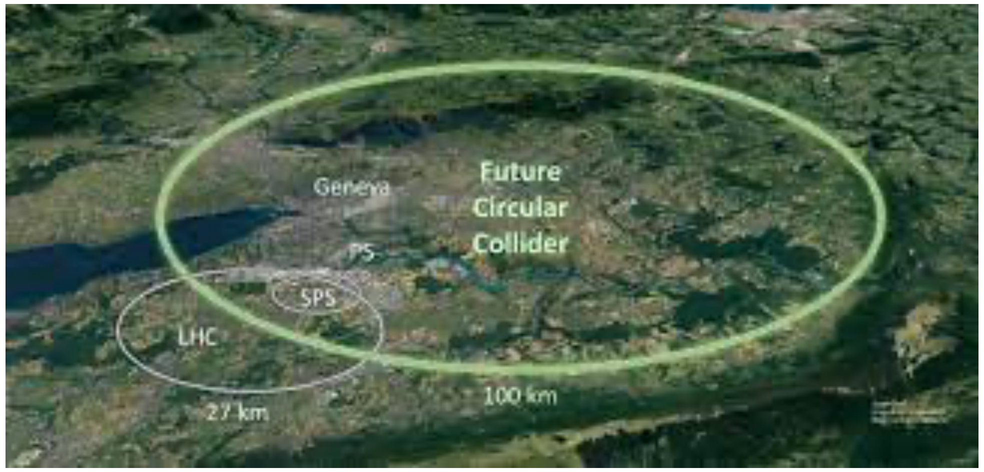
International Linear Collider (ILC)

- e^+e^- collisions
- 30-50km linear tunnel

- Initial post-LHC era for HEP most likely e^+e^-
- Confirmation of B anomalies could put New Physics energy scale within reach of e.g. FCC-hh

LHCb Upgrade II as a future pathfinder

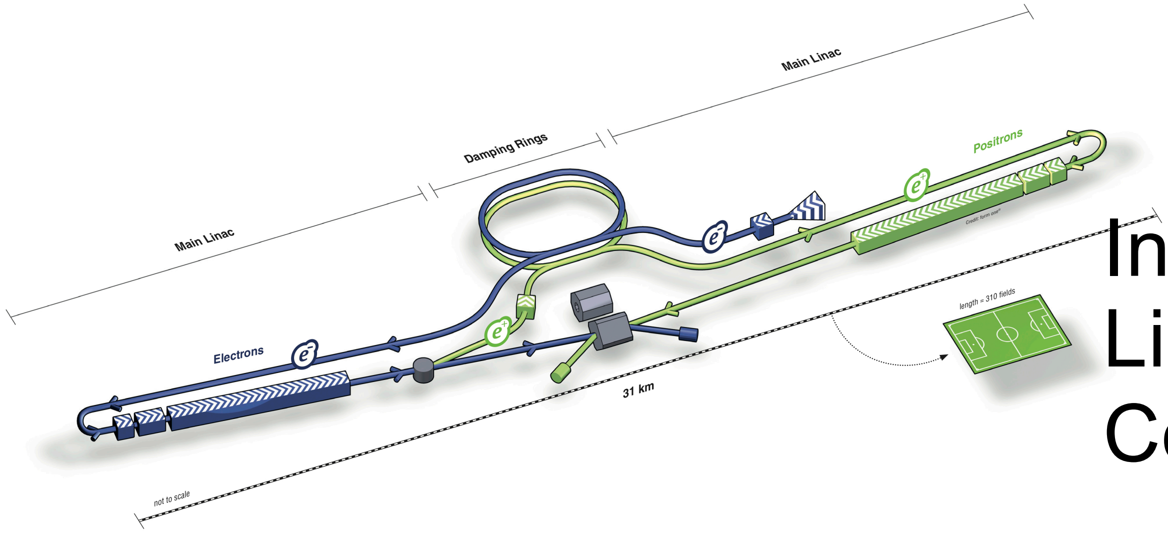




Future circular collider

First generation of post-LHC accelerators will focus on ee

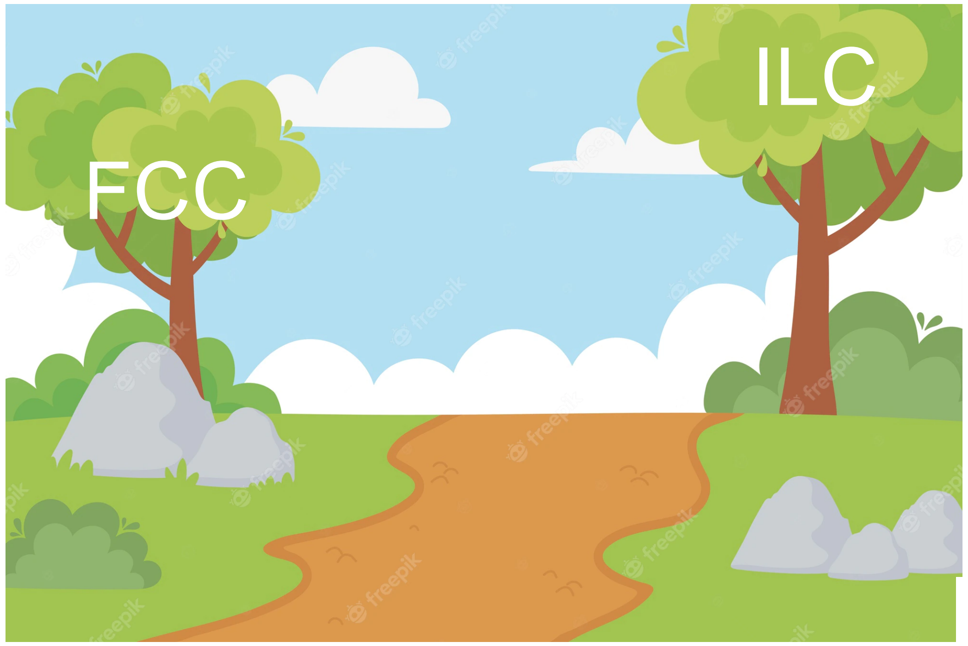
Some options accommodate dedicated flavour experiment

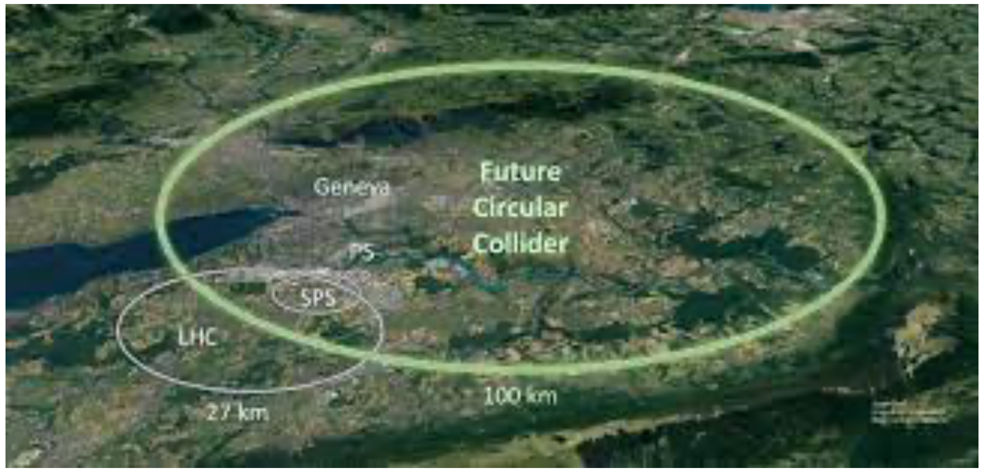


International Linear Collider

- LHCb Upgrade II will be first use of HV-CMOS technology on large scale
- Unprecedented timing resolution
- Unprecedented read-out rate - MENTION ECAL? FOCUS ON FLAV OR MORE GENERAL?

LHCb Upgrade II as a future pathfinder





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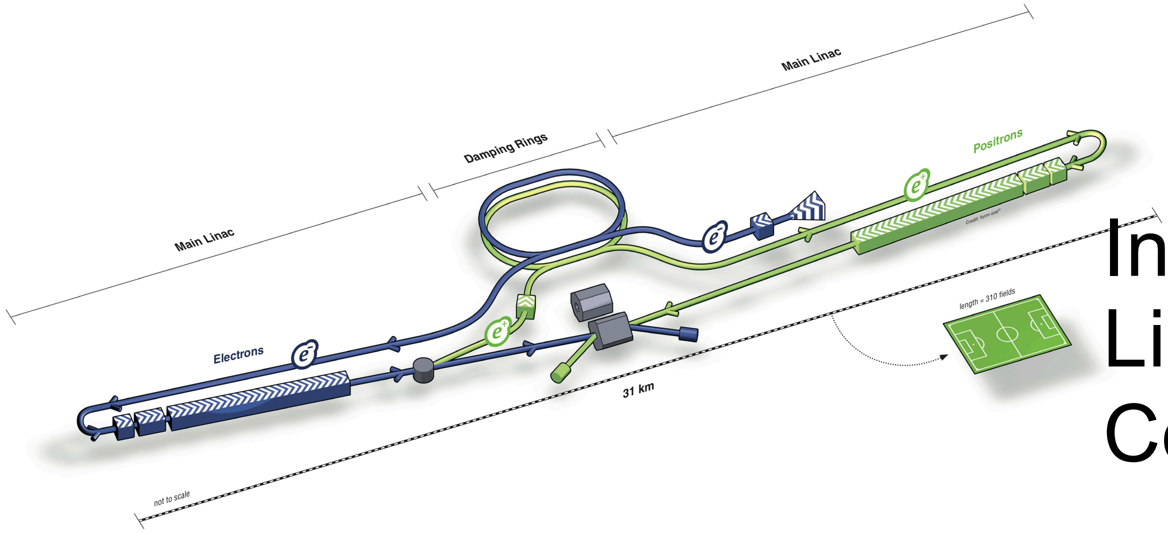

International Linear Collider

First generation of post-LHC accelerators will focus on ee

Some options accommodate dedicated flavour experiment

LHCb Upgrade II shows feasibility of heavy flavour in high-lumi envir:

- First use of HV-CMOS technology on large scale
- Unprecedented timing resolution
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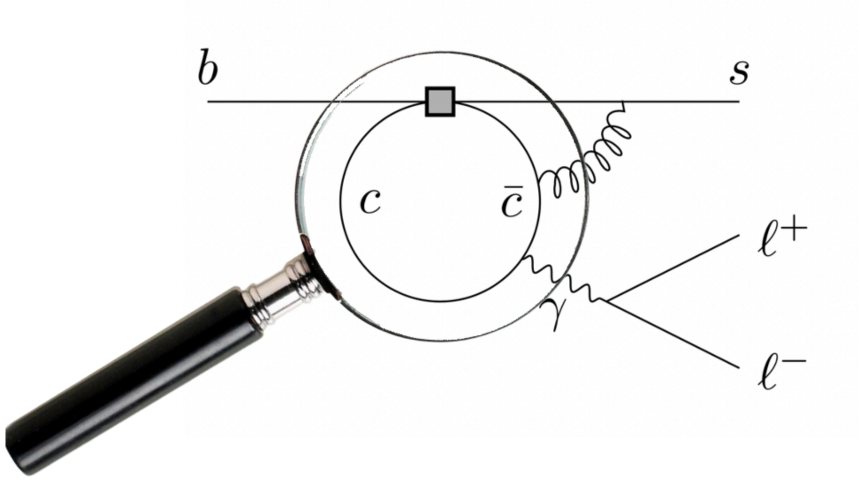
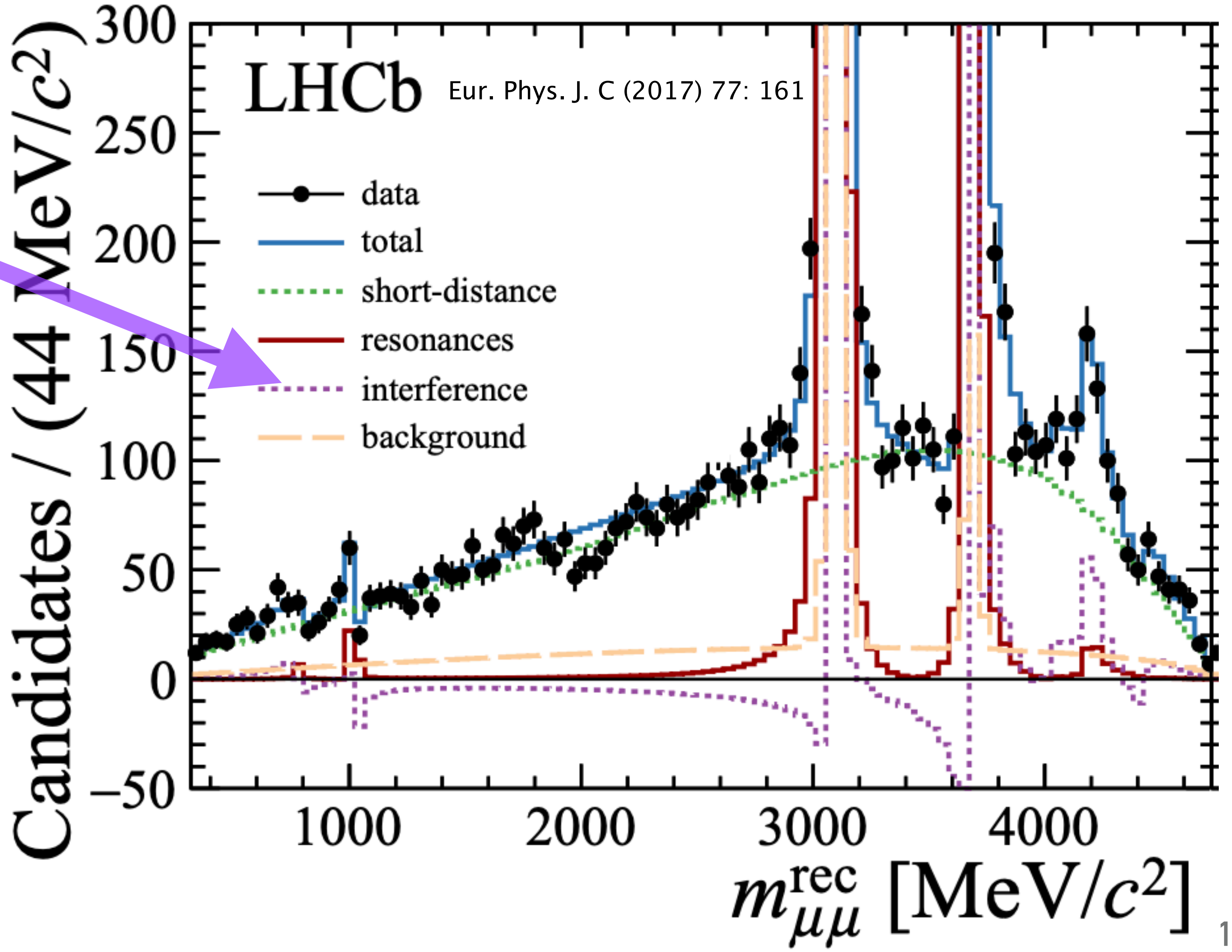


Achieved by fitting both the angular **and q²** distributions of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

Measure charm-loops in data

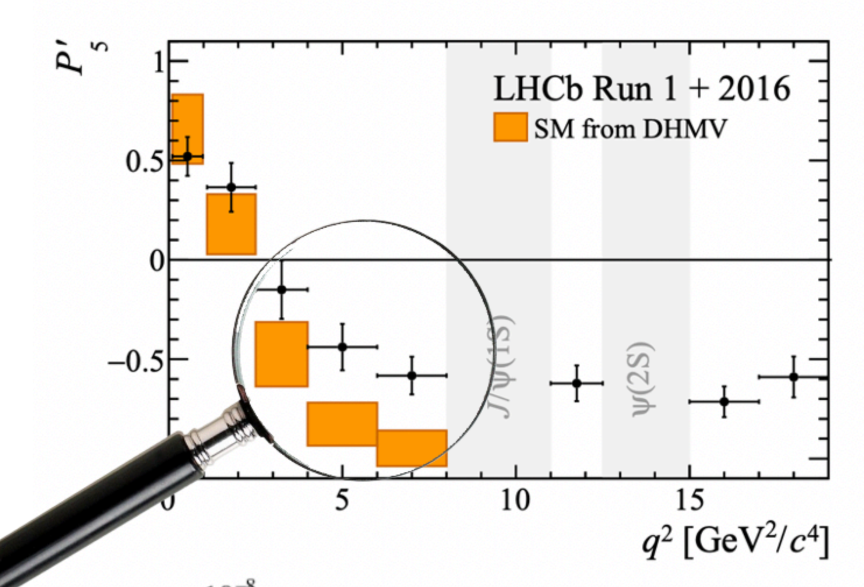
Fit for interference in data

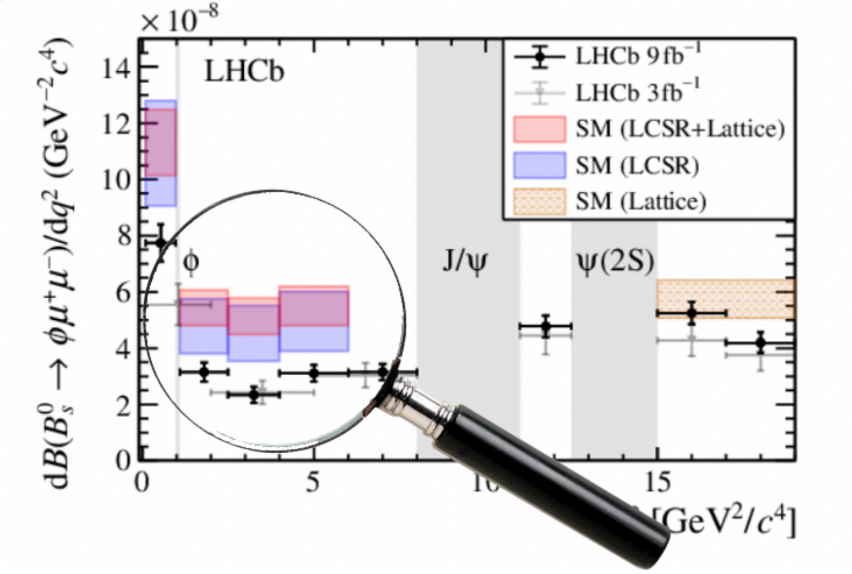
$B^0 \to K^{*0}\mu^+\mu^-$ more complex, but more information



The Flavour anomalies: what is causing them?

Fluke

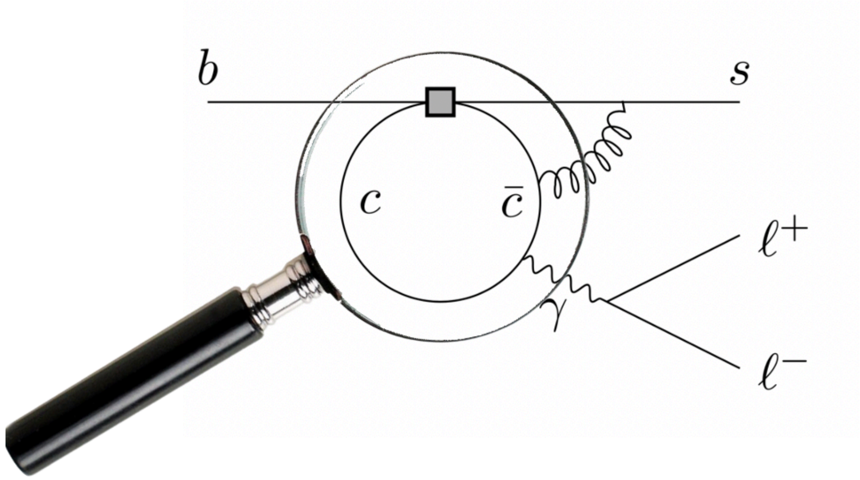




Add more data

New LHCb detector - **commissioning!**

Fallacy



Measure charm-loops in data

Experimental bias in LFU? **Angular analysis of electrons**

New Physics

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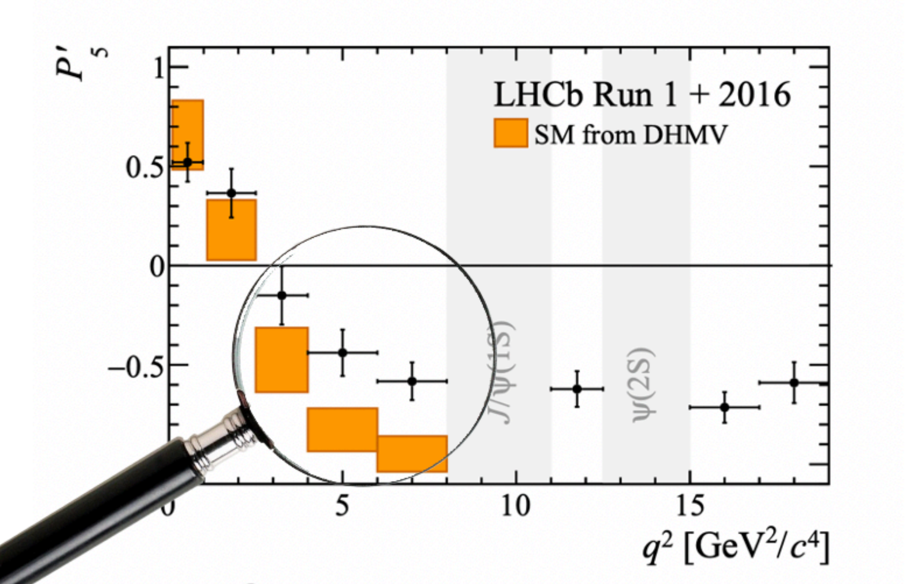

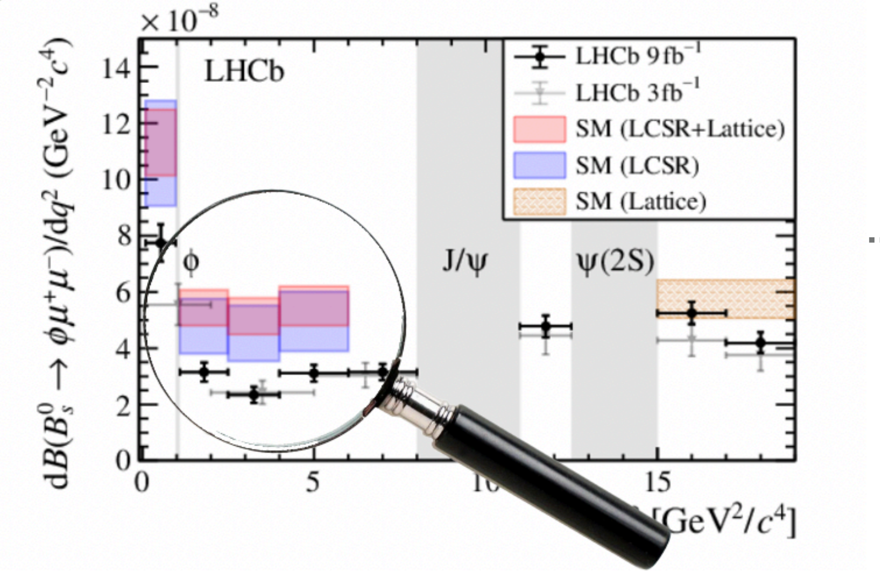

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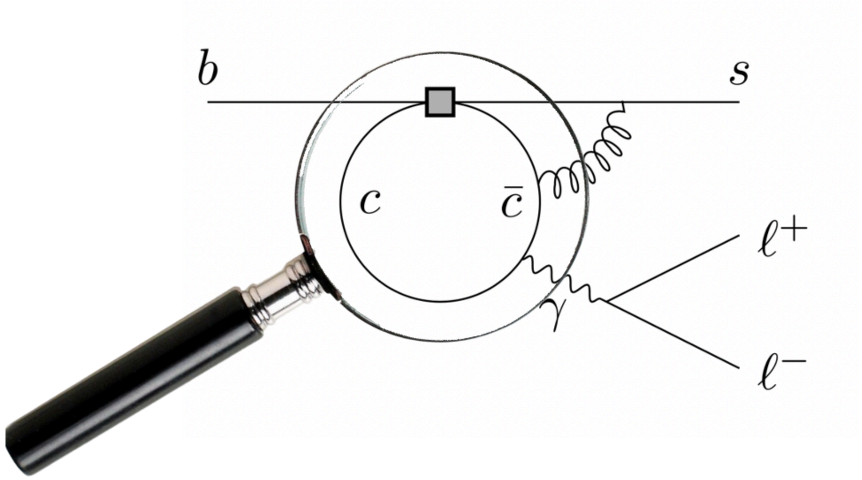


Measure charm-loops in data

Experimental bias in LFU? **Angular analysis of electrons**

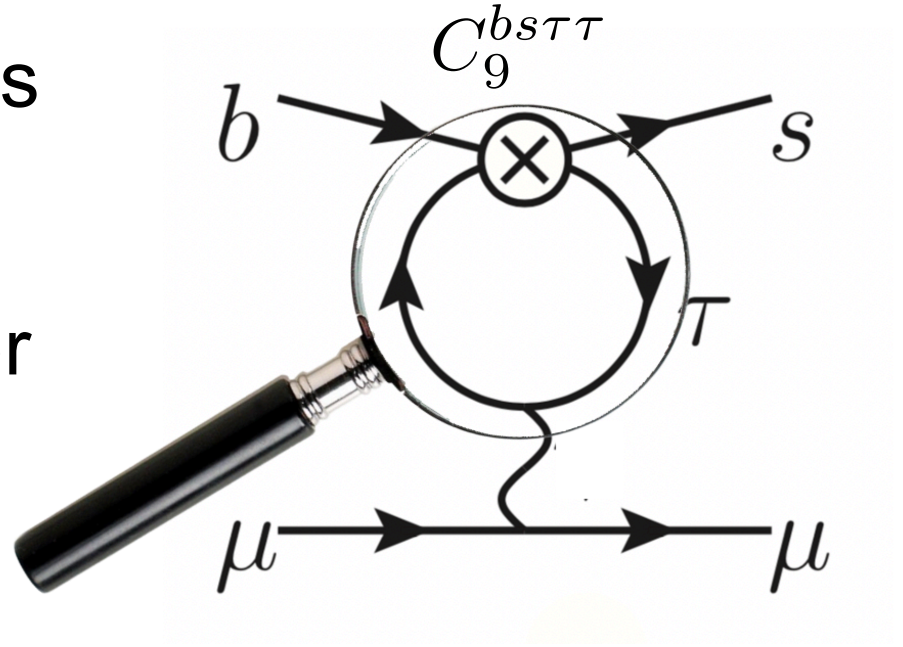
New Physics

Search for $B^0 \to K^{*0}\tau^+\tau^-$ via non-local effects on $B^0 \to K^{*0}\mu^+\mu^-$

Favoured NP explanations for Flavour Anomalies predict large enhancements in $b \to s\tau\tau$

τ's are very difficult, no $b \to s\tau\tau$ process ever observed

Use interference effects on $b \to s\mu\mu$ instead!



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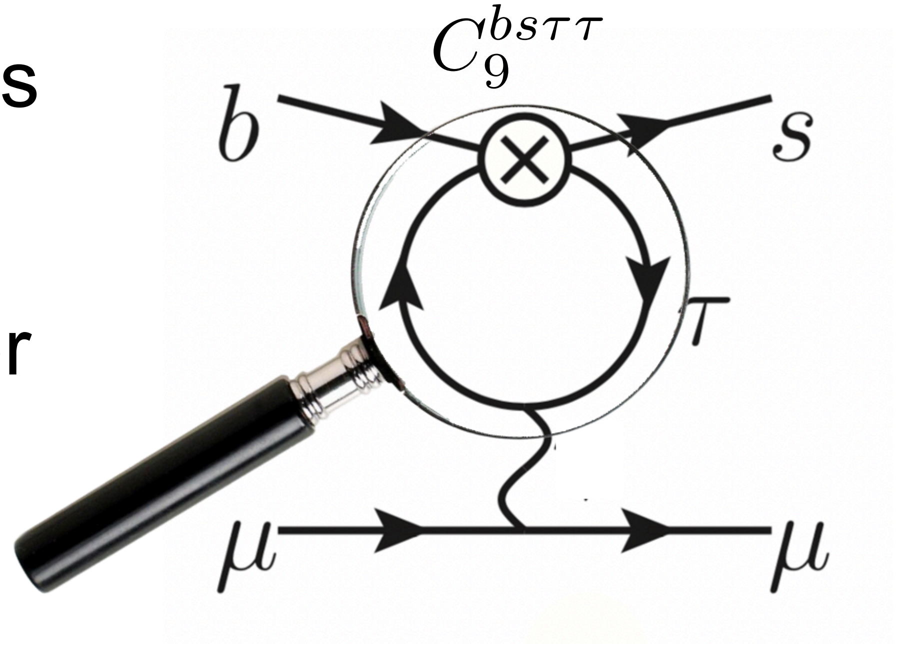
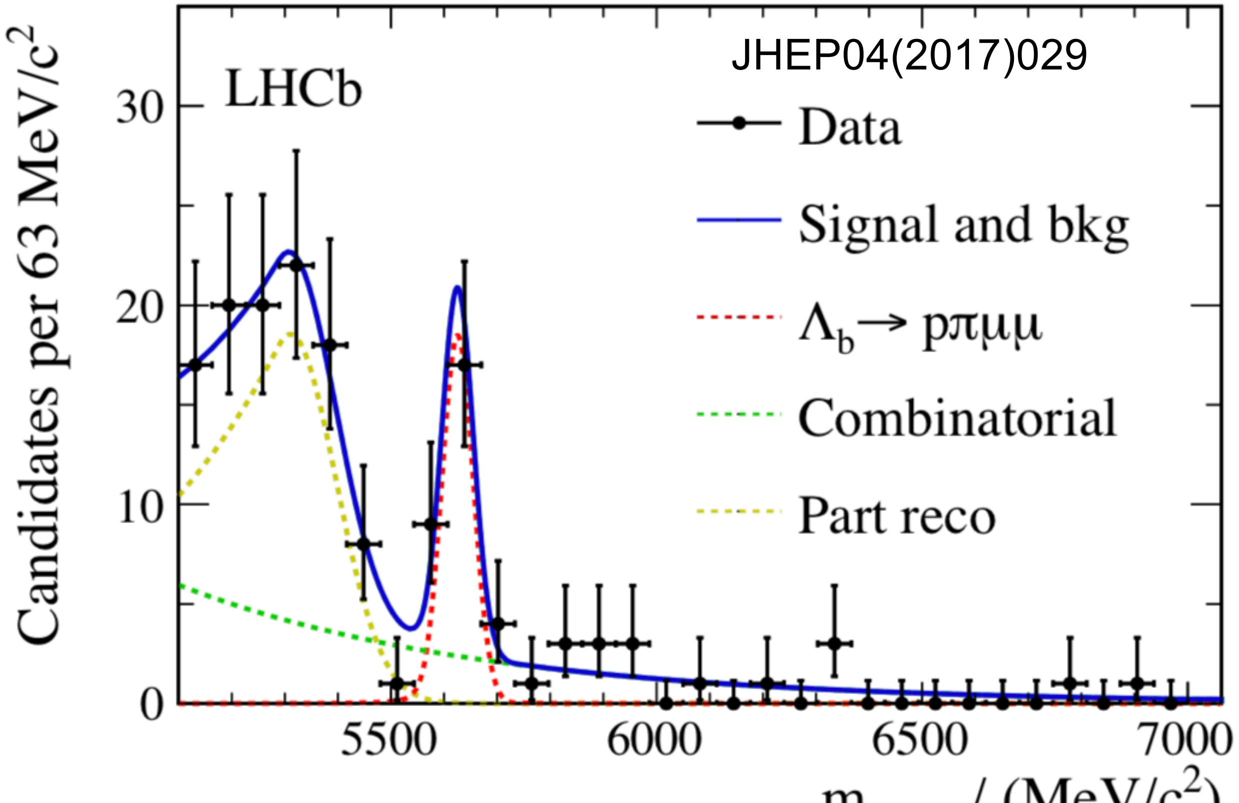


First LFU tests in $b \to d\ell\ell$

Favoured NP explanations for Flavour Anomalies predict effects in $b \to d\ell\ell$

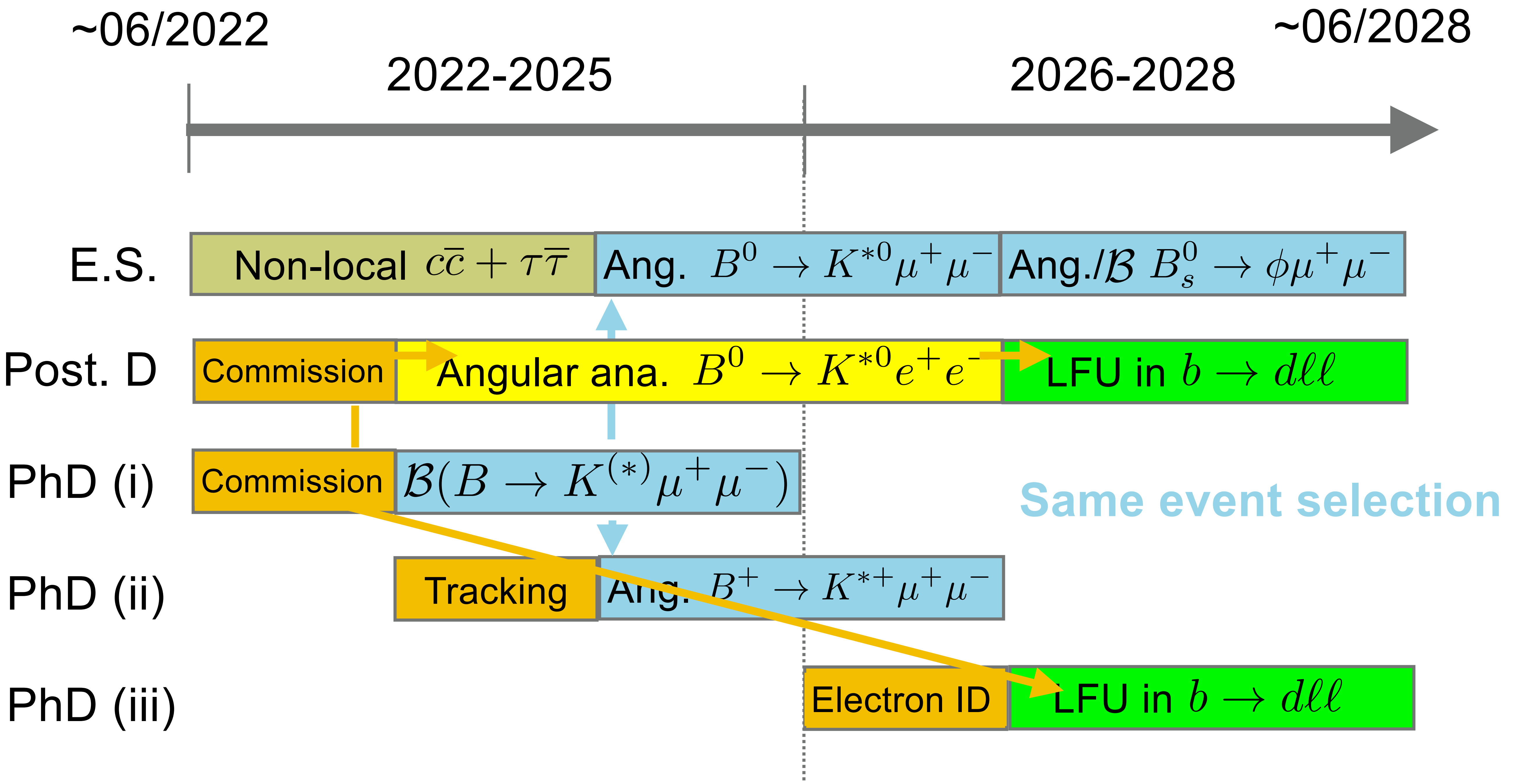
Perform first LFU tests in this sector

Example $b \to d\mu\mu$ transition



contact author: **E.Smith**

Project organisation



~06/2022

~06/2028

2022-2025

2026-2028

E.S.: Non-local $c\bar{c} + \tau\bar{\tau}$ | Ang. $B^0 \to K^{*0}\mu^+\mu^-$ | Ang./$\mathcal{B}$ $B^0_s \to \phi\mu^+\mu^-$

Post. D: Commission | Angular ana. $B^0 \to K^{*0}e^+e^-$ | LFU in $b \to d\ell\ell$

PhD (i): Commission | $\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)$

PhD (ii): Tracking | Ang. $B^+ \to K^{*+}\mu^+\mu^-$

PhD (iii): Electron ID | LFU in $b \to d\ell\ell$

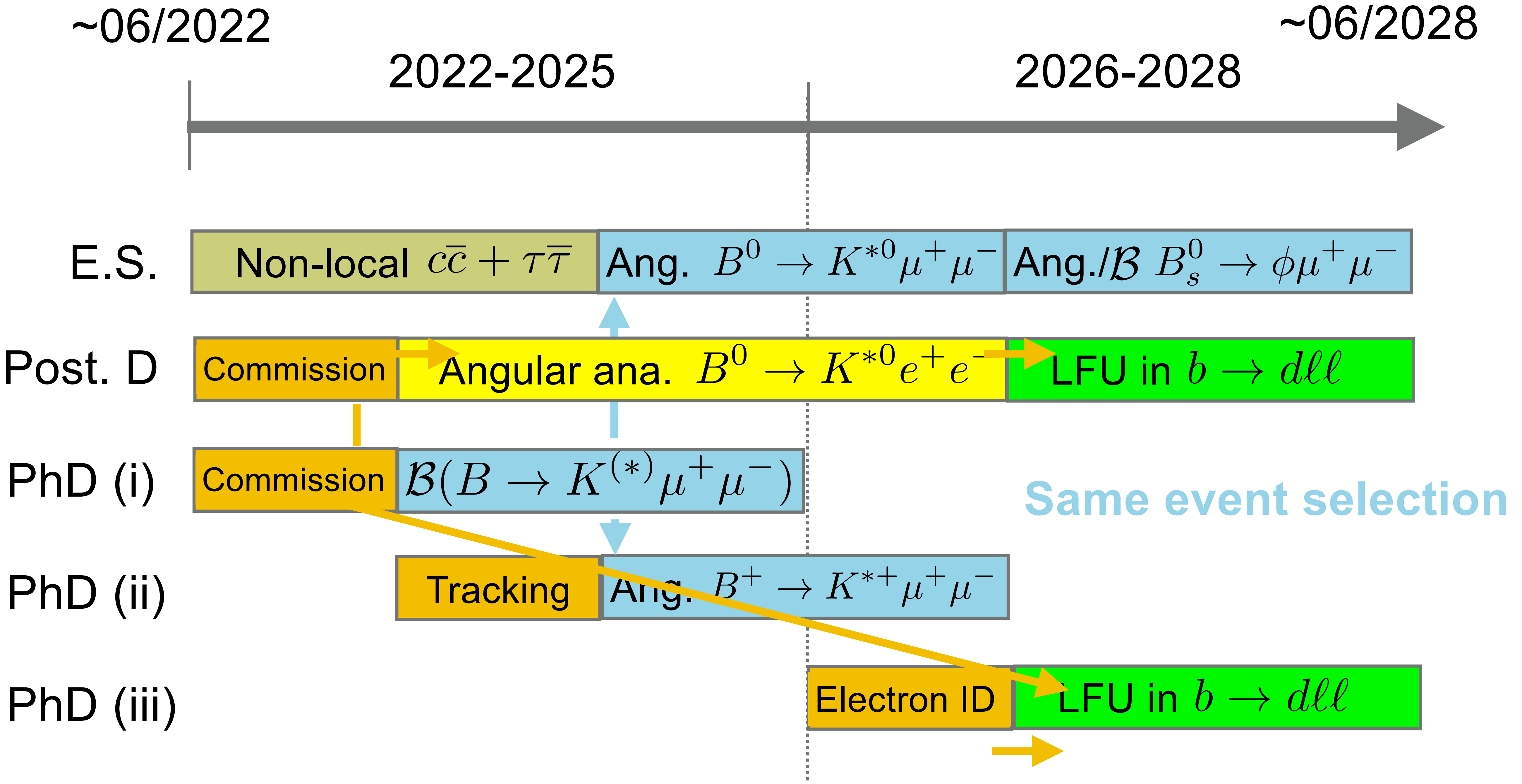
Same event selection

[A] [B]

[C] [D] [E]

Same simulation correction framework

Project organisation



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Post. D

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PhD (iii)

Electron ID

LFU in $b \to d\ell\ell$

Same event selection

Improved electron ID vital for very rare modes

[A] [B]

[C] [D] [E]

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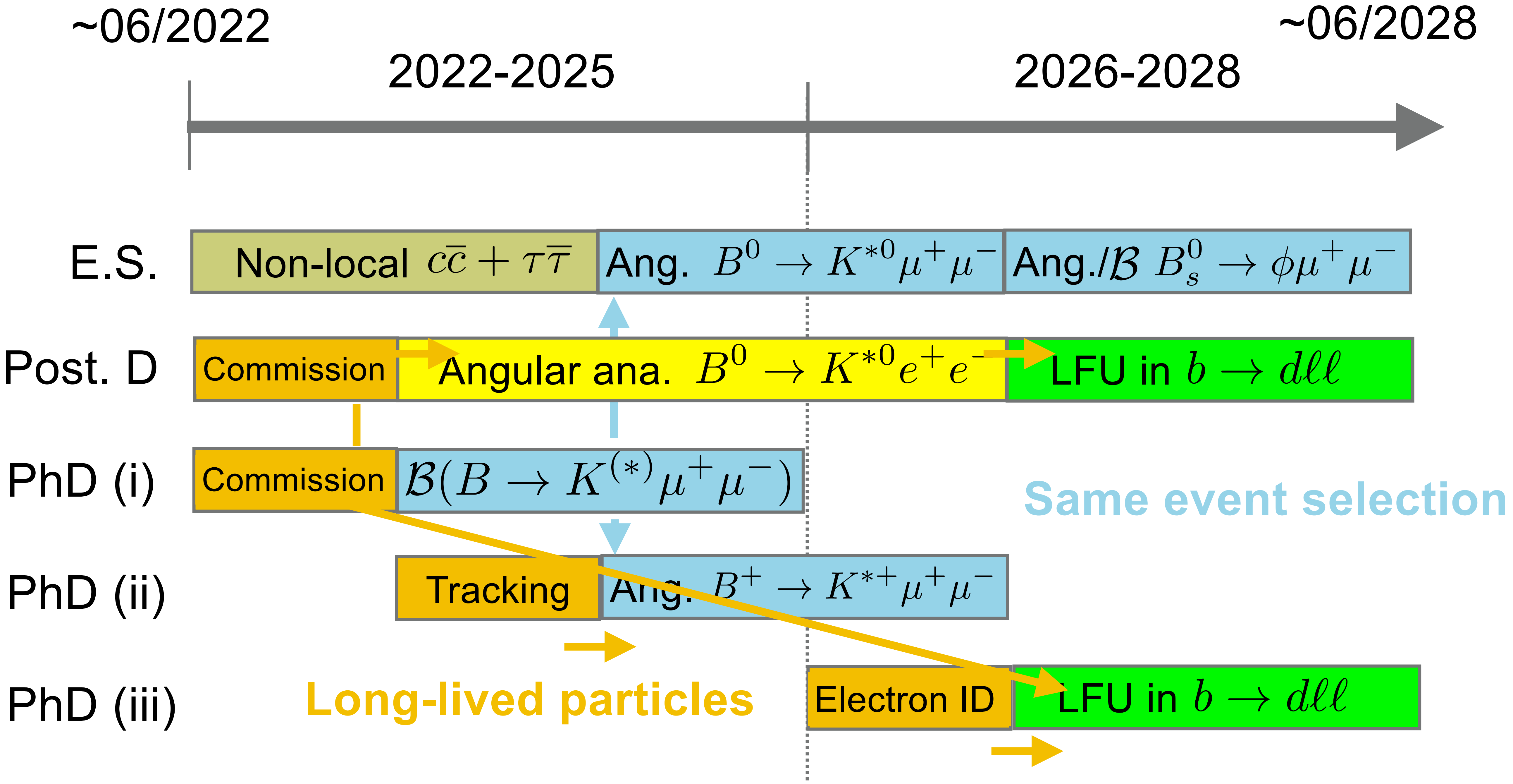
Project organisation



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Same event selection

Long-lived particles

Improved electron ID vital for very rare modes

Same simulation correction framework

[A] [B]
[C] [D] [E]

Group ethos

Group ethos

Weekly group and analysis meetings

Regular one-to-one chats

Visibility within the collaboration

Supplementary training and summer-schools

Conferences and time at CERN

Why Heidelberg?

- Heidelberg LHCb group is well established, and perform work complementary to proposed project

- Heidelberg offers an excellent environment for junior group leaders, and I will be provided with additional doctoral student support

- I will be given the opportunity to teach, which will allow me to attract the best PhD and Masters students

- The existing expertise at Heidelberg will allow me to increase my impact within LHCb outside of pure analysis work, important for next career steps

Gender and diversity

Gender and diversity

Within LHCb: The Laura Bassi initiative

Founded by myself to find bottom-up solutions to diversity issues in HEP

LHCb-PHO-GEN-2020-002

what? where?

LHCb is a particle physics experiment that studies high energy collisions produced by the Large Hadron Collider, at CERN. It is run by a large international collaboration, with participation from 19 different countries.

from 2010 to 2020

women: 101 → 252
members: 690 → 1383
countries: 15 → 19
institutes: 54 → 88

Number of women increased by a factor 2.5. Members in the collaboration doubled. Percentage of women increased from 15% to 18%! Four more countries and 29 more institutes joined the LHCb experiment.

who?

We have a total of 1383 members, of which 252 are women. From students to professors, women in LHCb participate in and lead projects in fields such as electronics, engineering, computing and data analysis.

why?

LHCb's mission is to uncover the mysteries of the universe by making precise measurements of known processes that may be sensitive to new particles. LHCb physicists are trying to answer many questions including why antimatter disappeared after the Big Bang, leaving us with a universe made almost entirely of matter.

when?

To celebrate International Women's day, we are sharing some photographs that give insight into the diverse experiences and passions of women in the LHCb experiment.

International Women's Day 08/03/2020

Regular meetings to tackle diversity and other issues

Actionable solutions

Active online forum

Gender and diversity

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LHCb experiment at CERN

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Active online forum

← Outreach initiatives

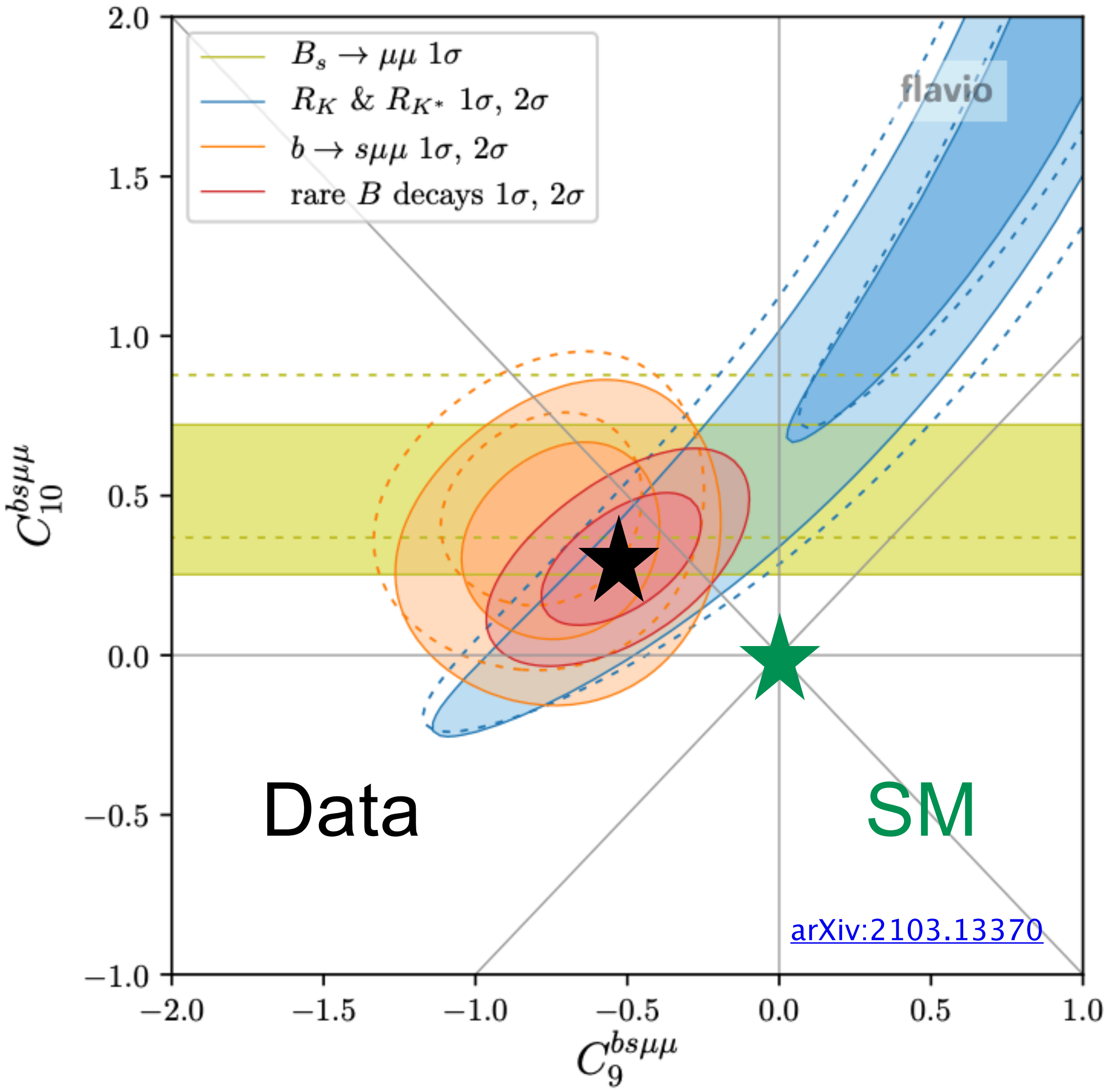
Within my group and Heidelberg

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Ensure family-friendly working environment

Continue my involvement in mentorship schemes and outreach with schools

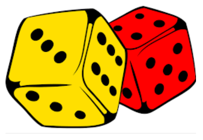
Summary



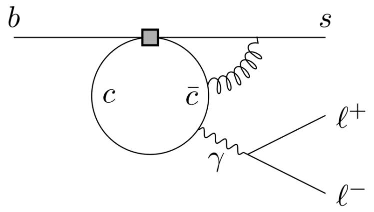
arXiv:2103.13370

The Flavour anomalies:

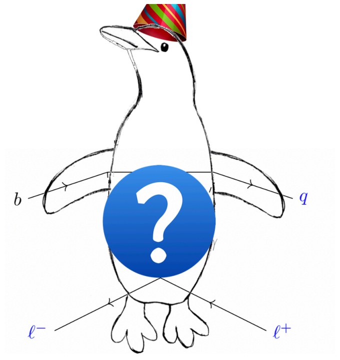
Fluke,



fallacy



or New Physics?

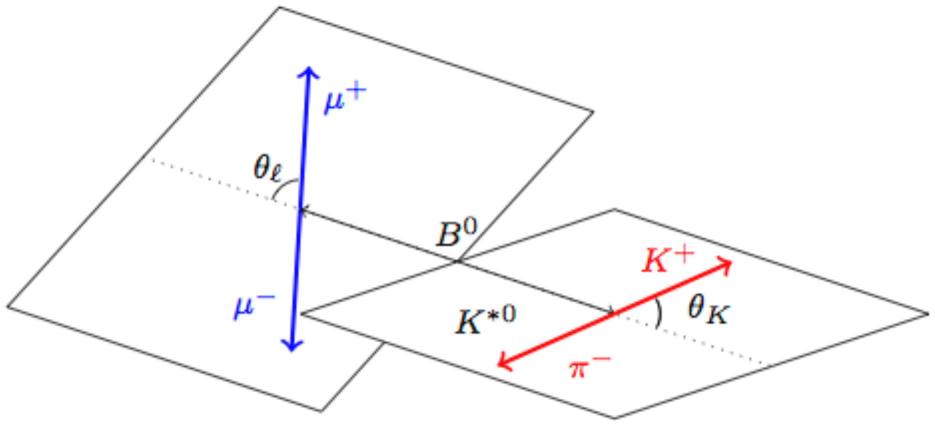


Understanding the Flavour anomalies **vital to field**

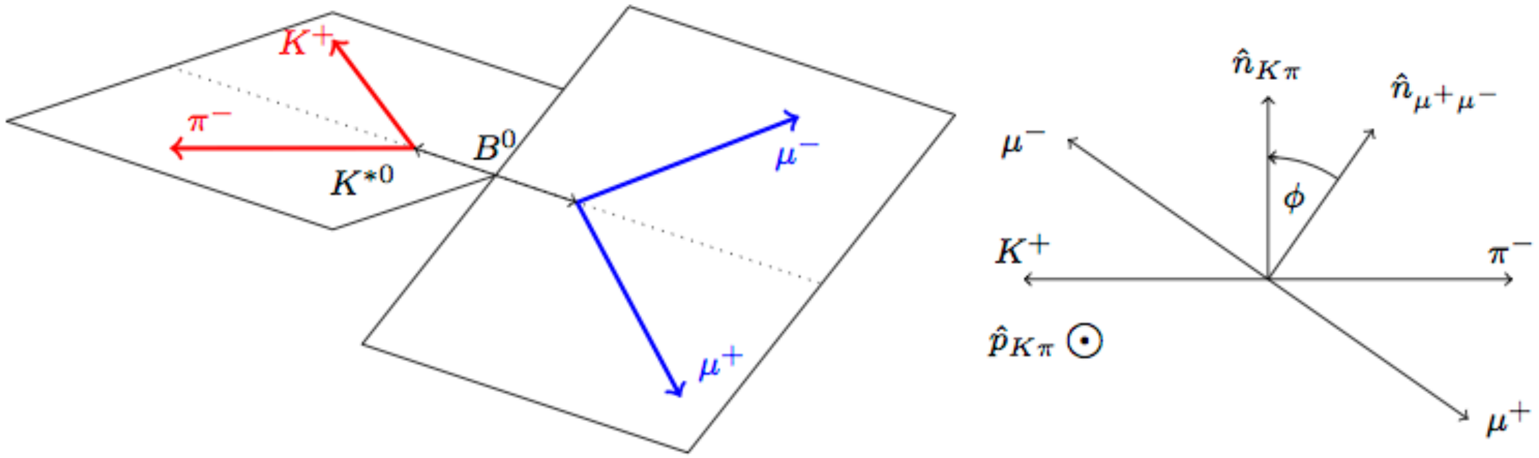
Emmy Noether-Programm DFG Deutsche Forschungsgemeinschaft

Use new measurements and new data to uniquely distinguish underlying cause

Angular analyses ($B \to V(\to hh)\ell^+\ell^-$)



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay

S_i **basis**

8 q² dependent observables describe 4D (3 angles + q²) distribution

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\,\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\bigg|_\mathrm{P} = \begin{aligned}[t] &\frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_\mathrm{L}})\sin^2\theta_K \\ &+\boxed{F_\mathrm{L}}\cos^2\theta_K+\tfrac{1}{4}(1-\boxed{F_\mathrm{L}})\sin^2\theta_K\cos 2\theta_l \\ &-\boxed{F_\mathrm{L}}\cos^2\theta_K\cos 2\theta_l+\boxed{S_3}\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\ &+\boxed{S_4}\sin 2\theta_K\sin 2\theta_l\cos\phi+\boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi \\ &+\tfrac{4}{3}\boxed{A_\mathrm{FB}}\sin^2\theta_K\cos\theta_l+\boxed{S_7}\sin 2\theta_K\sin\theta_l\sin\phi \\ &+\boxed{S_8}\sin 2\theta_K\sin 2\theta_l\sin\phi+\boxed{S_9}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]. \end{aligned} \tag{29}$$

F_L : fraction of longitudinal polarisation of di-muon system

A_{FB} : forward-backward asymmetry of di-muon system

“Clean” Lepton Flavour Universality (LFU) observables

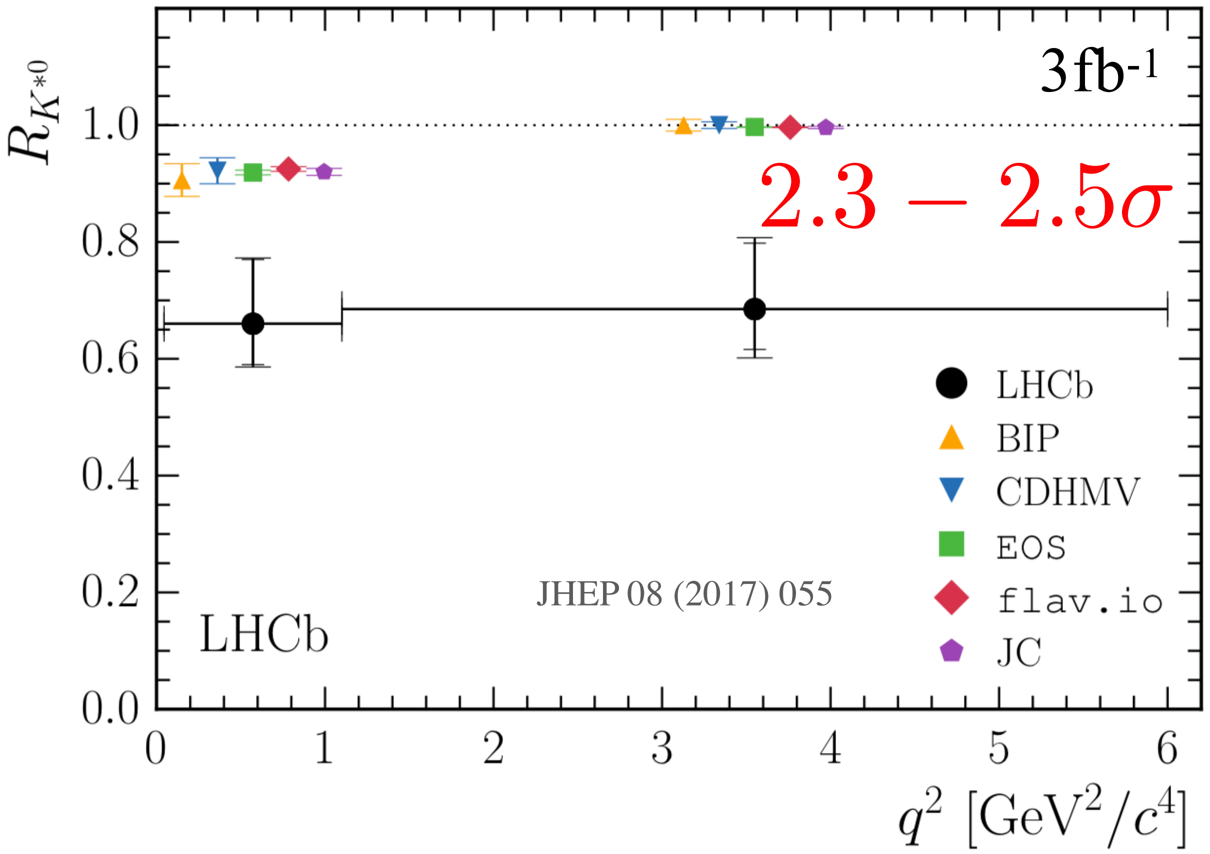
- Muons vs electron decay rates, **hadron uncertainties cancel**
- **Unambiguous sign of NP** if deviates from SM expectation

“Clean” observables:

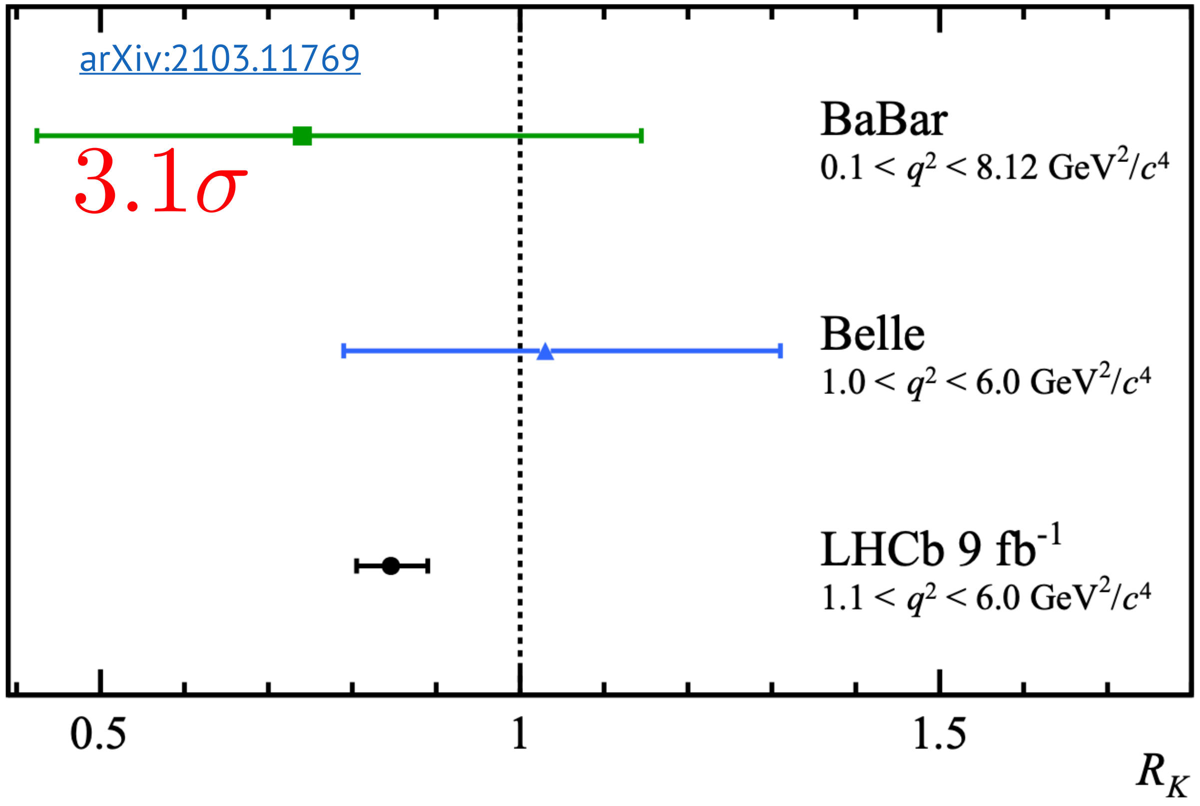
$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$$

$q^2 = m^2(\ell^+\ell^-)$

$B^0 \to K^{*0}ll$



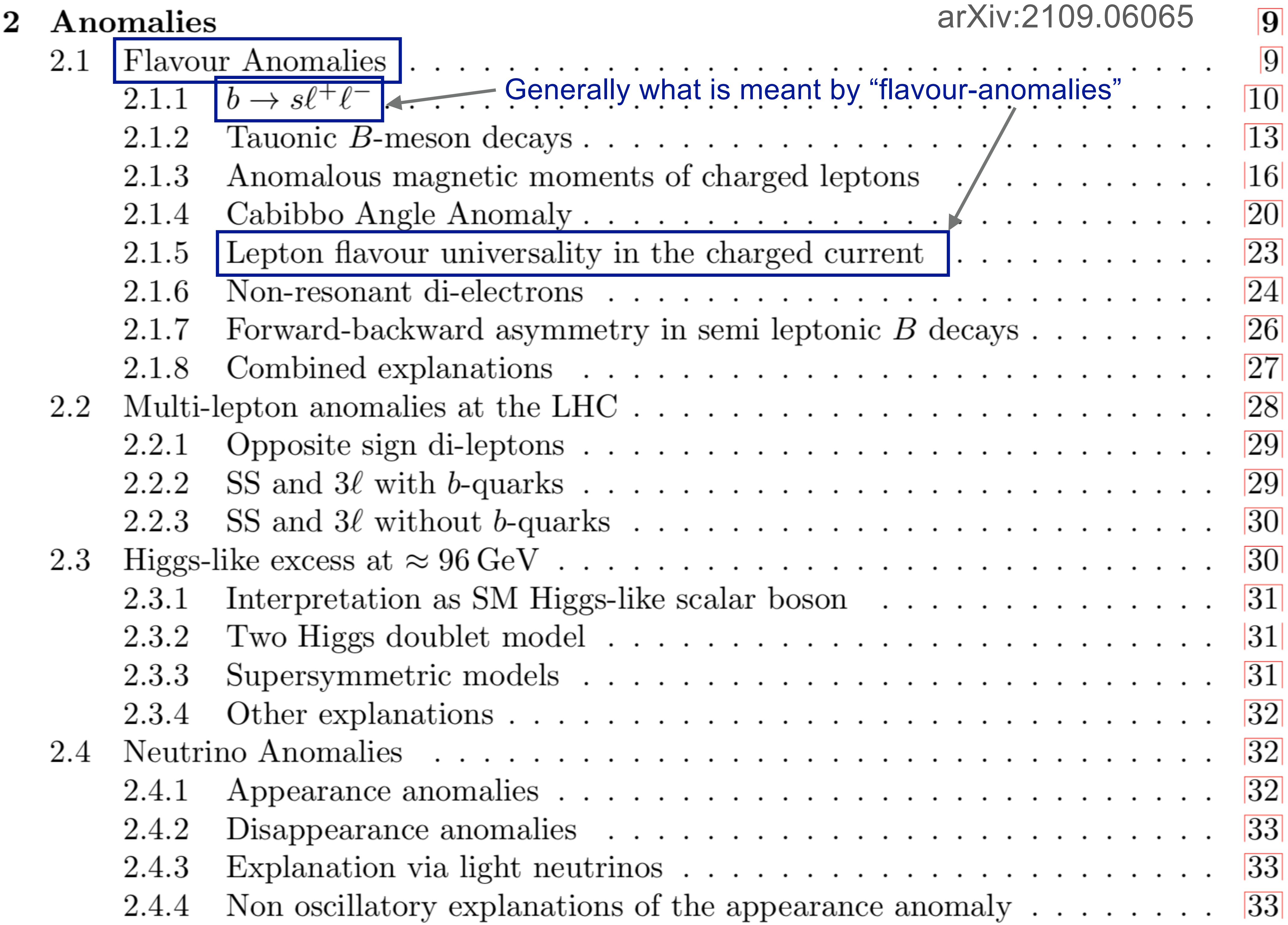
$B^+ \to K^+ll$



$+\,\Lambda_b^0 \to pK\ell^+\ell^-$: $R_{pK}^{-1} = 1.17^{+0.18}_{-0.16} \pm 0.07$

+ new results coming very soon

Why these anomalies?

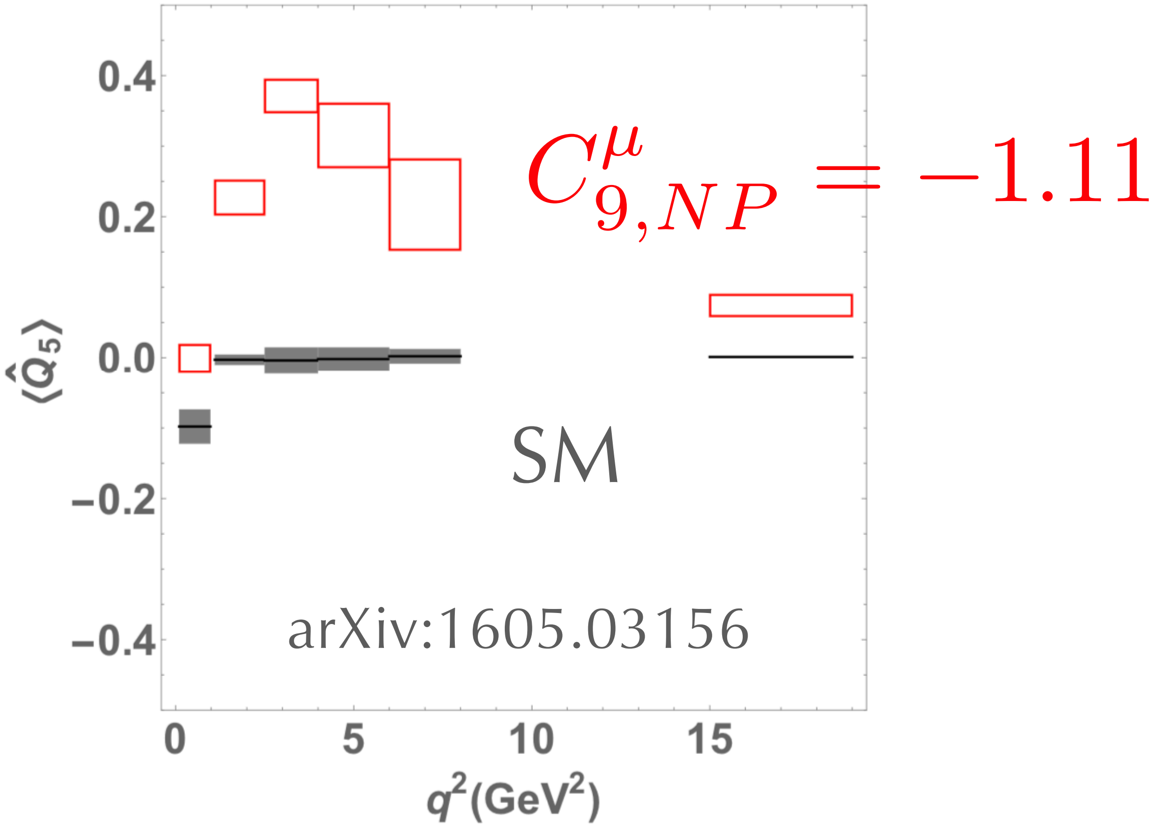


arXiv:2109.06065

Generally what is meant by “flavour-anomalies”

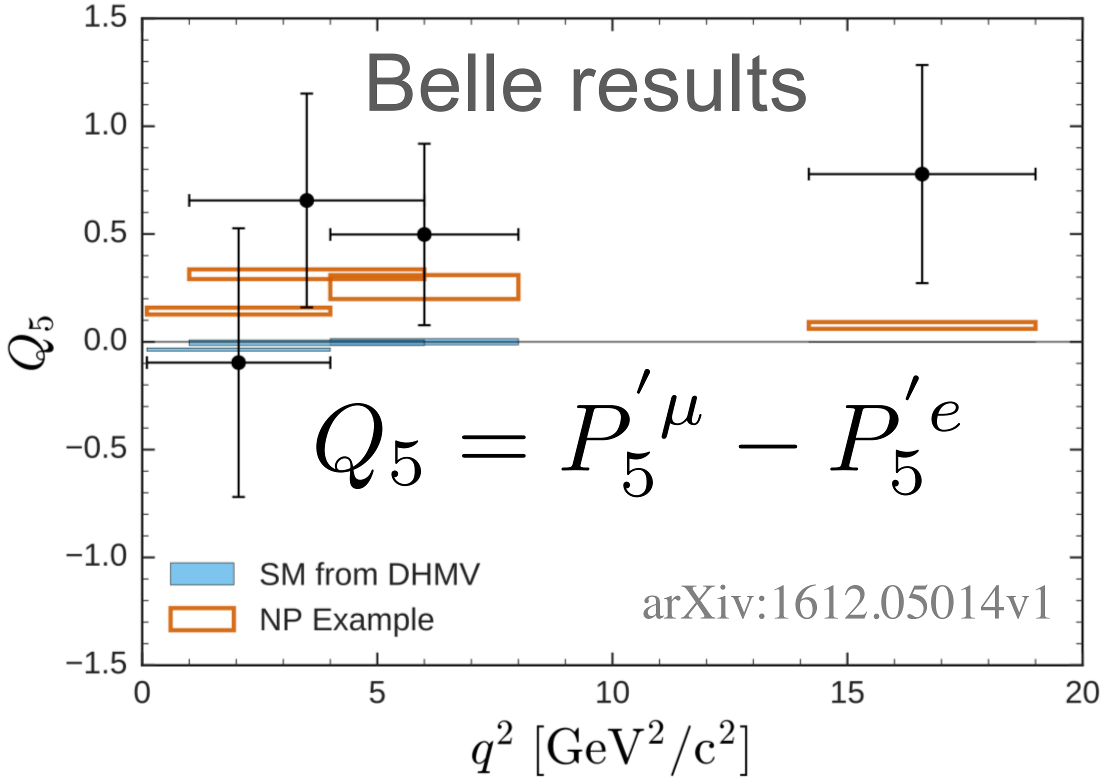
Are we ambulance chasing?

The future is angular…


$C^{\mu}_{9,NP} = -1.11$

SM

arXiv:1605.03156


Belle results

$Q_5 = P_5^{'\mu} - P_5^{'e}$

arXiv:1612.05014v1

- A full angular analysis of $B \to V(\to hh)e^+e^-$ modes:
  - Confirm LFU results in experimentally orthogonal way
  - **Gives far more in-depth info on the structure of NP**
  - Can construct observables between electrons and muons with less dependence on charm loop

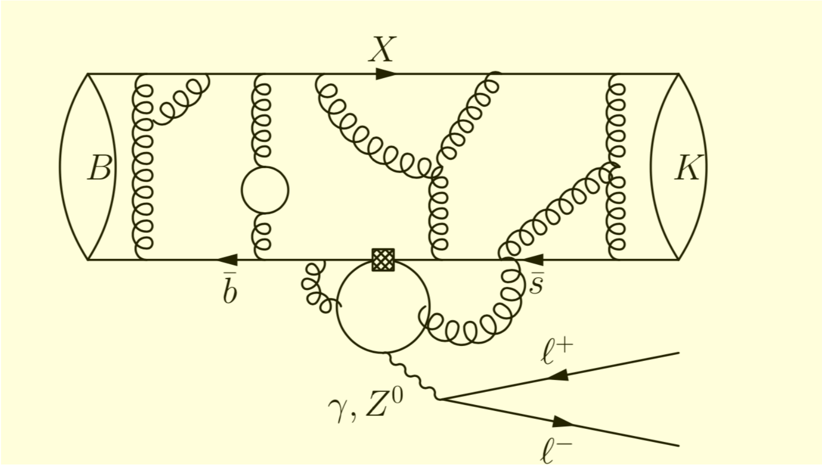
And also data-driven…

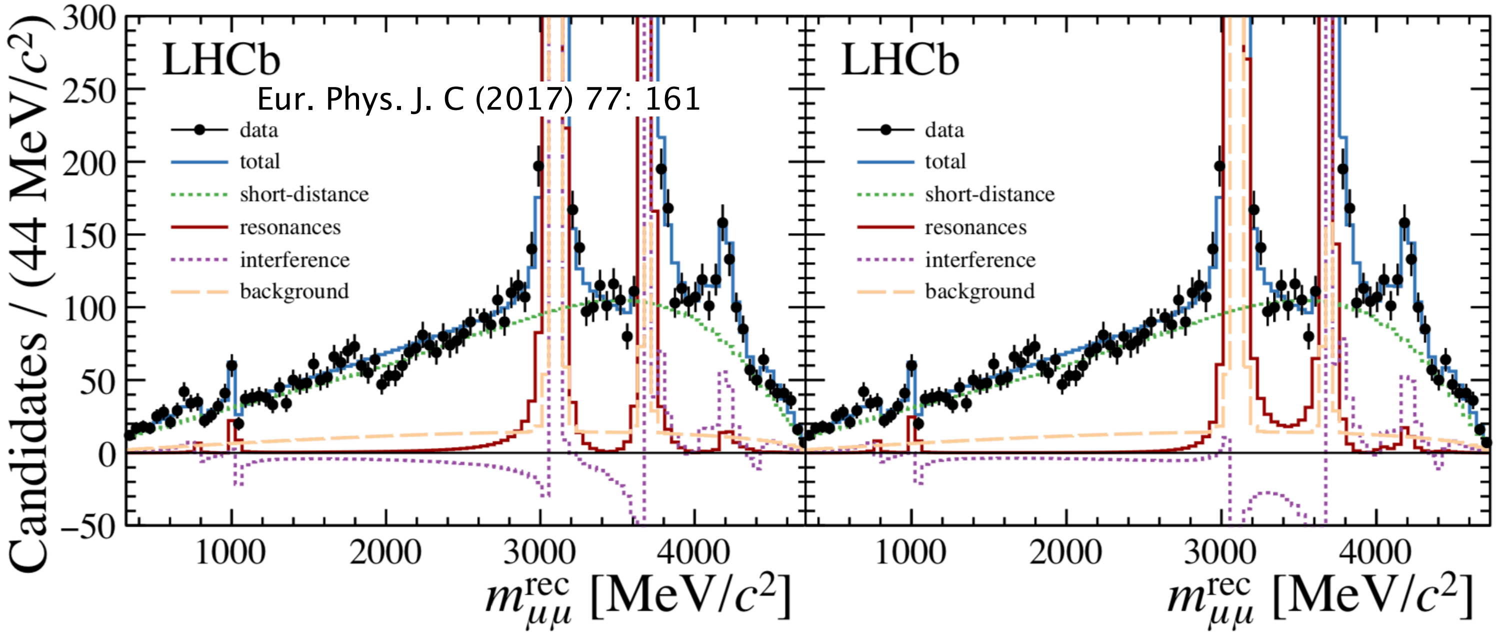
- Fit directly for Wilson Coefficients and extract charm-loop interference from data

$$\mathcal{A}_\perp^{\mathrm{L(R)}} = \mathcal{N}\sqrt{2\lambda}\left\{\left[(\mathcal{C}_9^{\mathrm{eff}} + \mathcal{C}_9'^{\mathrm{eff}}) \mp (\mathcal{C}_{10}^{\mathrm{eff}} + \mathcal{C}_{10}'^{\mathrm{eff}})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathcal{C}_7^{\mathrm{eff}} + \mathcal{C}_7'^{\mathrm{eff}})T_1(q^2)\right\}$$

$$C_9^{eff} = C_9 + \sum_j \underbrace{\eta_j}_{\text{magnitude}}\overbrace{e^{i\delta_j}}^{\text{relative phase}}\underbrace{A_j^{res}(q^2)}_{\text{lineshape}}$$

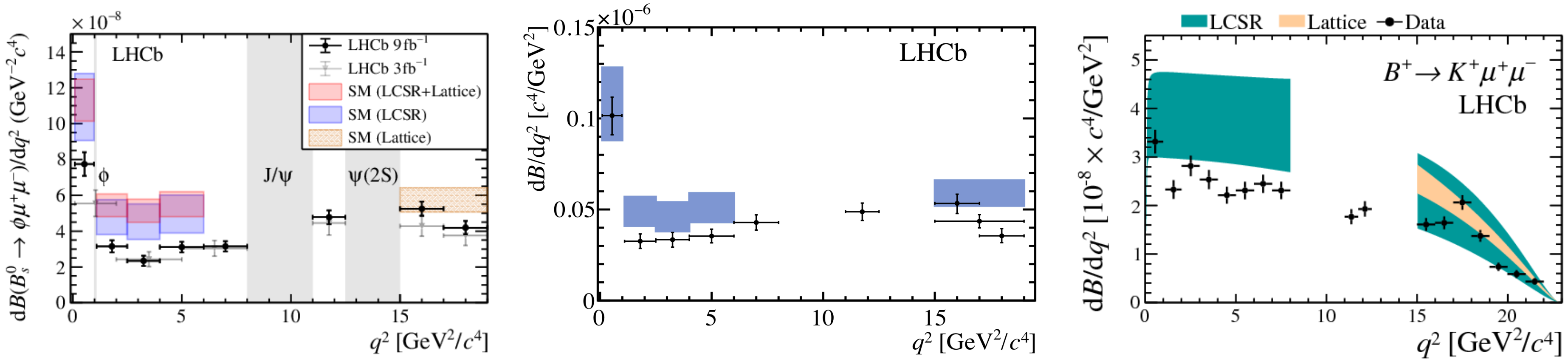
Breit-wigner or dispersion relation for line shape




Eur. Phys. J. C (2017) 77: 161

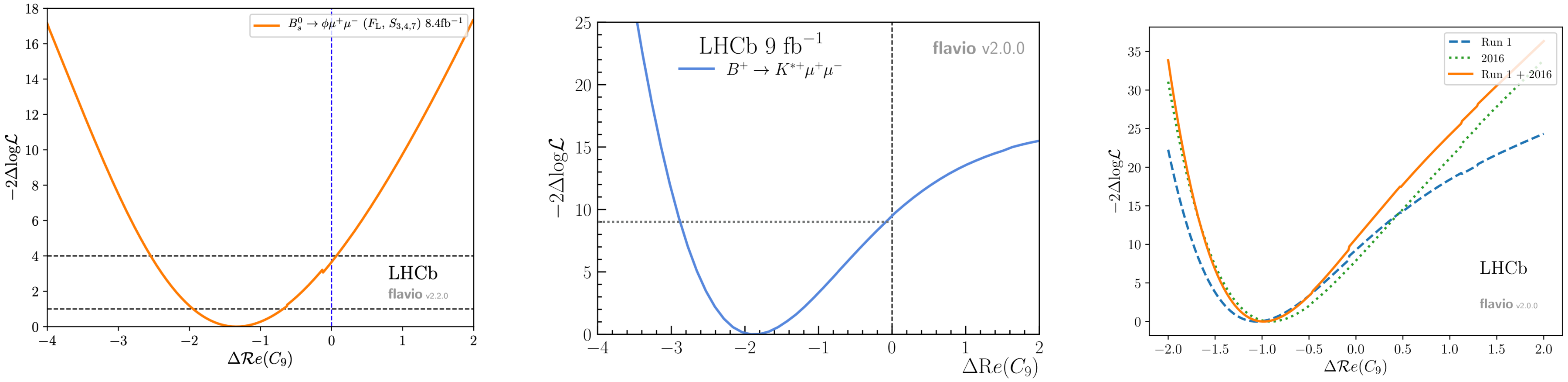
- Measured for $B^+ \to K^+\mu^+\mu^-$(minimal interference found), ongoing for $B^0 \to K^{*0}\mu^+\mu^-$

what $b \to s\ell^+\ell^-$ observables we have



Branching fractions

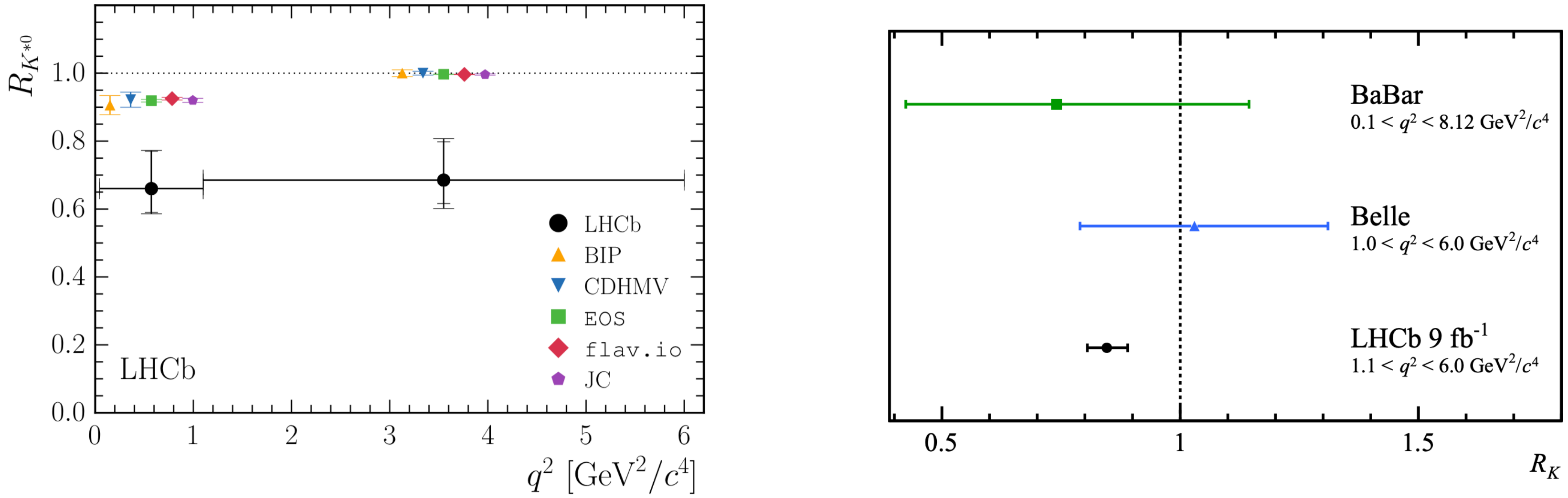
$> 3\sigma$



Angular analysis

$> 3\sigma$

Theoretical robustness



Lepton Flavour Universality (LFU)

$> 3\sigma$

Experimental summary: LFU + electrons

Lepton Flavour Universality tests defined as $R(X) = \dfrac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$

In practice measure double-ratio:

$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)} \Big/ \frac{\mathcal{B}(B \to XJ/\psi[\to \mu\mu])}{\mathcal{B}(B \to XJ/\psi[\to ee])}$$

e.g. for RK

$$= \boxed{\frac{\mathcal{N}_{B^+\to K^+\mu^+\mu^-}}{\mathcal{N}_{B^+\to K^+J/\psi(\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B^+\to K^+J/\psi(\to e^+e^-)}}{\mathcal{N}_{B^+\to K^+e^+e^-}}} \cdot \boxed{\frac{\varepsilon_{B^+\to K^+J/\psi(\to\mu^+\mu^-)}}{\varepsilon_{B^+\to K^+\mu^+\mu^-}} \cdot \frac{\varepsilon_{B^+\to K^+e^+e^-}}{\varepsilon_{B^+\to K^+J/\psi(\to e^+e^-)}}}$$

https://indico.cern.ch/event/1106753/

Yields from fits to invariant mass

Efficiencies from simulation

- Double ratio very robust against systematic effects, single ratio:

$$r(J/\psi) = 0.981 \pm 0.020$$

Although electrons more challenging, deviation from SM is largely due to the muon modes, not electrons

$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = (28.6\,^{+1.5}_{-1.4} \pm 1.3) \times 10^{-9}\,c^4/\mathrm{GeV}^2$$

(arXiv:2103.11769)

Sub-Project [E]

Isospin asymmetry and BF of $B \to K\mu^+\mu^-$

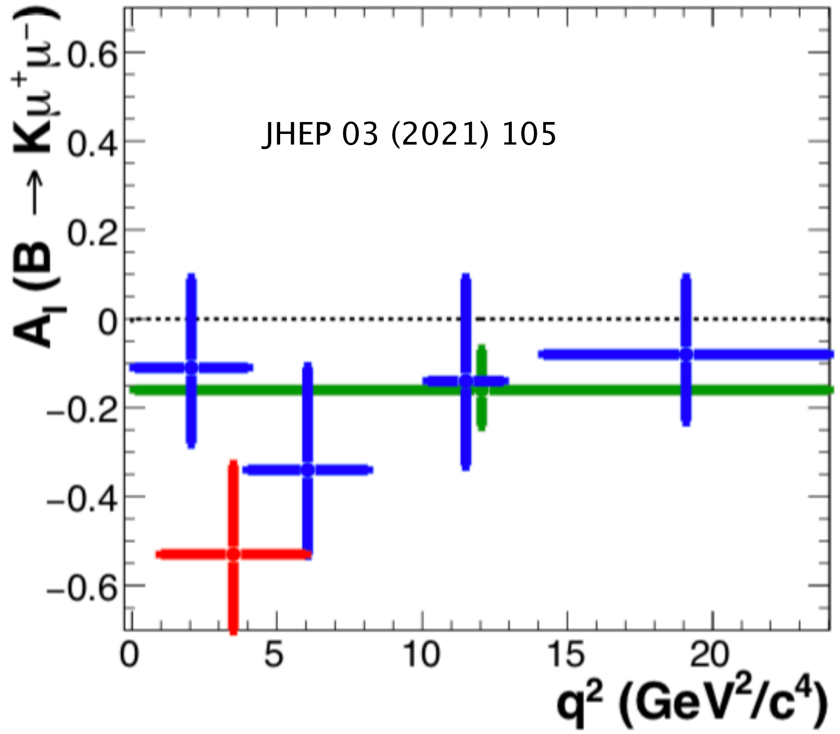
$$A_I^{K^{(*)}\mu\mu} = \frac{\mathcal{B}(B \to K^{(*)0}\mu^+\mu^-) - \frac{\tau^0}{\tau^+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)0}\mu^+\mu^-) + \frac{\tau^0}{\tau^+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}.$$

Develop selection to be used in angular analyses

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

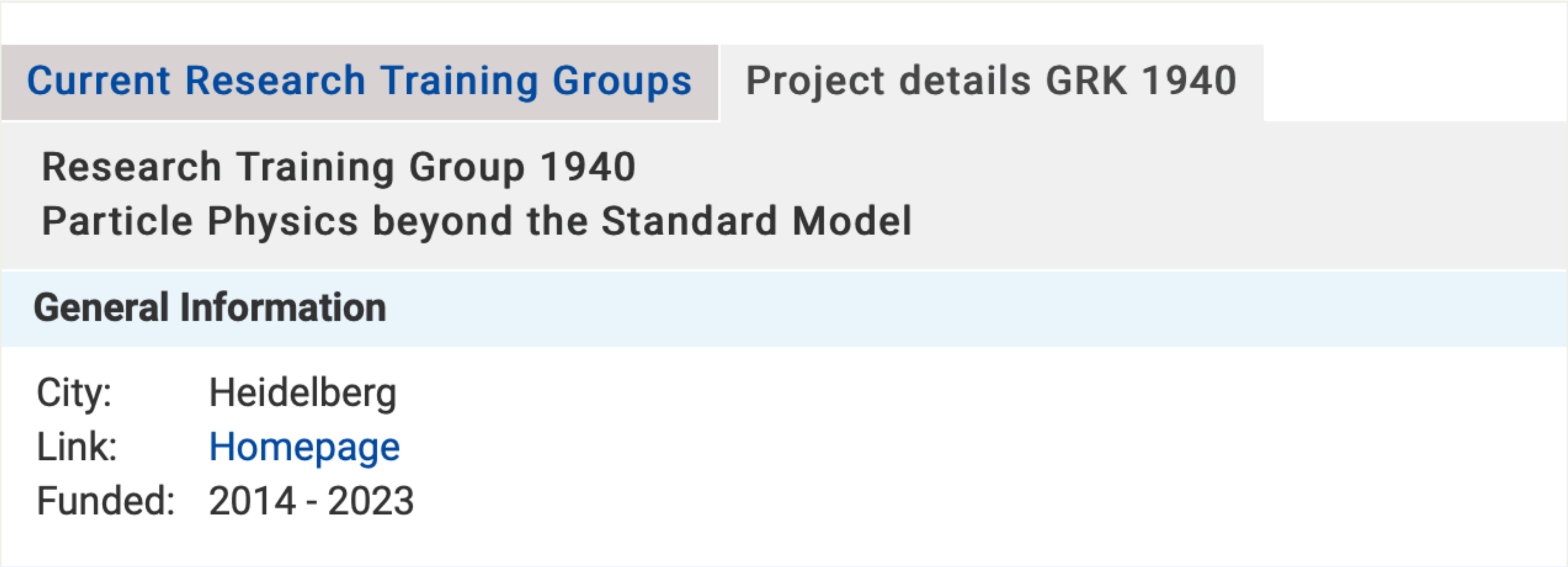
Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$

Angular analysis of $B_s^0 \to \phi\mu^+\mu^-$



Heidelberg initiatives

- Field of focus 2 (150k, 3 years PhD + travel)
- Student training: GRK-1940



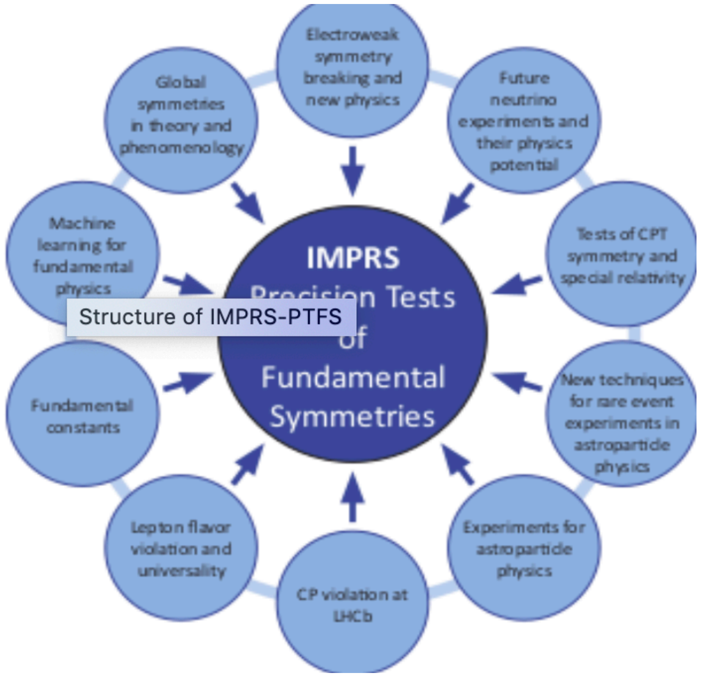
Current Research Training Groups | Project details GRK 1940

Research Training Group 1940
Particle Physics beyond the Standard Model

General Information

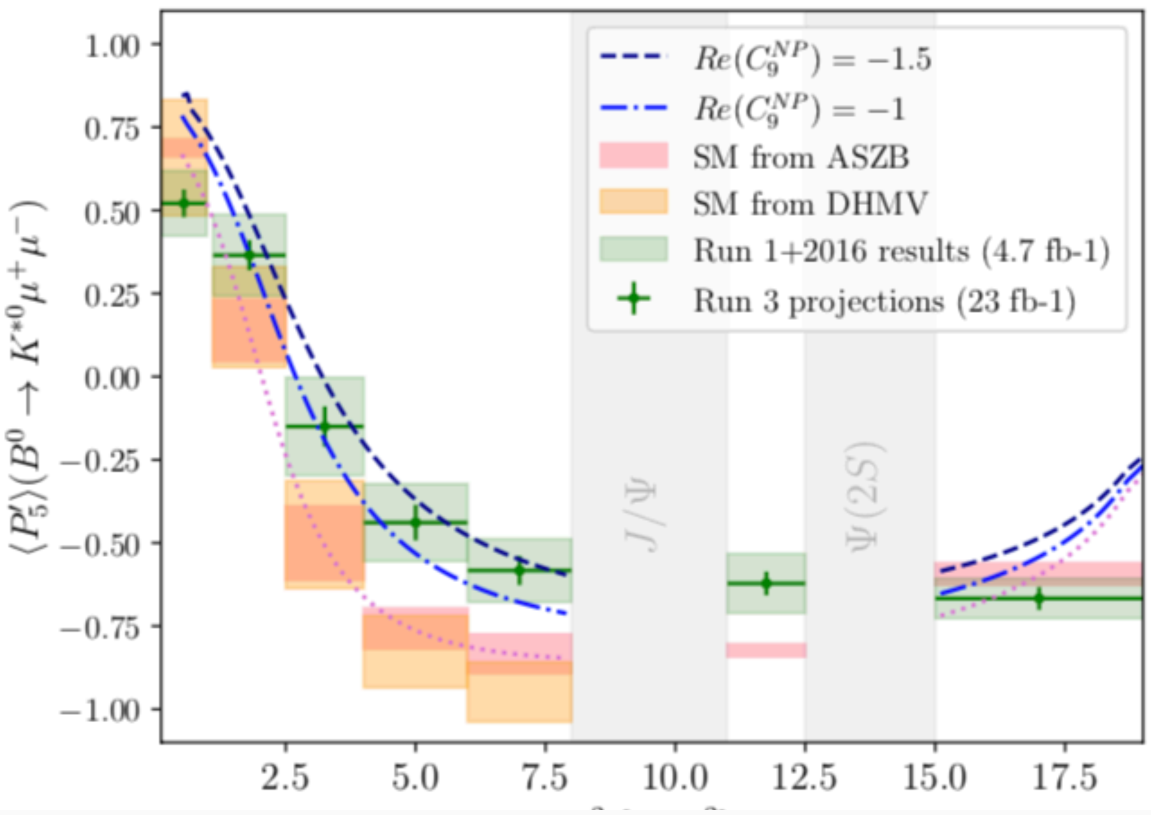
City: Heidelberg
Link: Homepage
Funded: 2014 - 2023

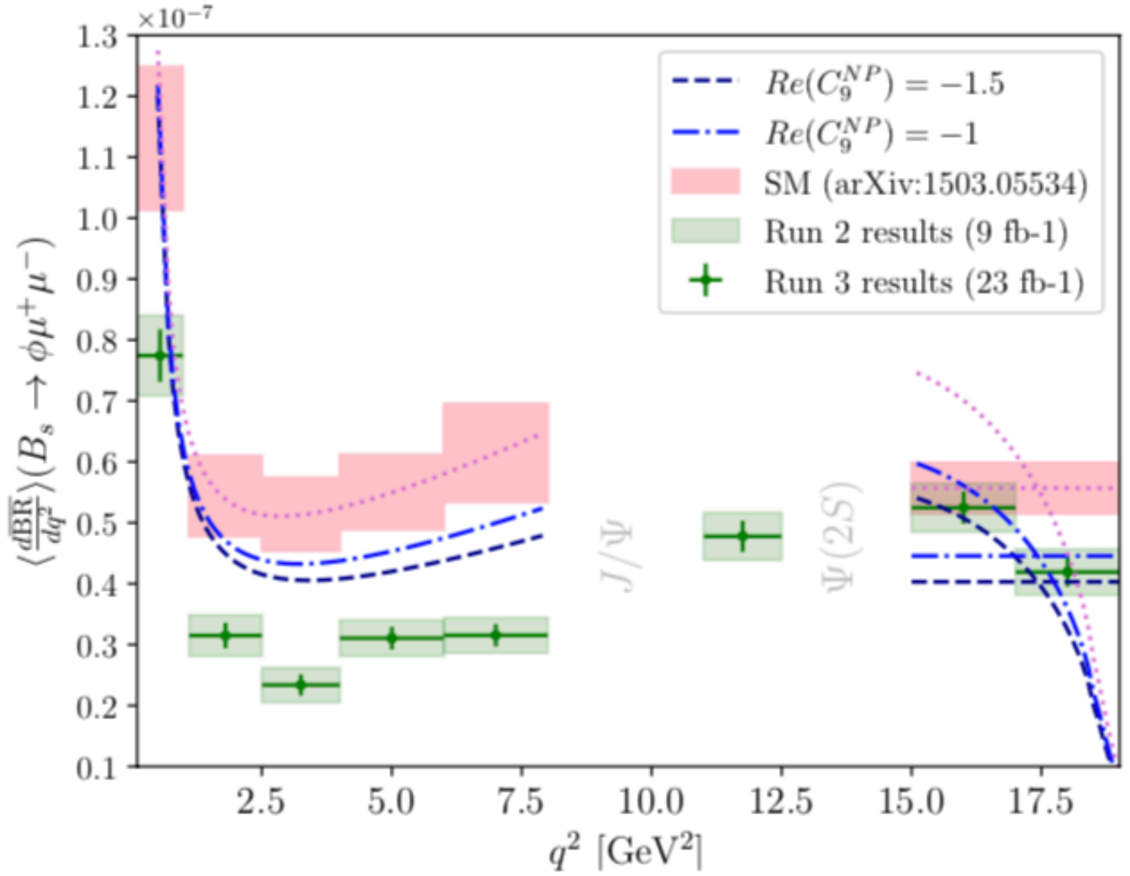
- Student training: IMPRS-PTFS (MPI/University)

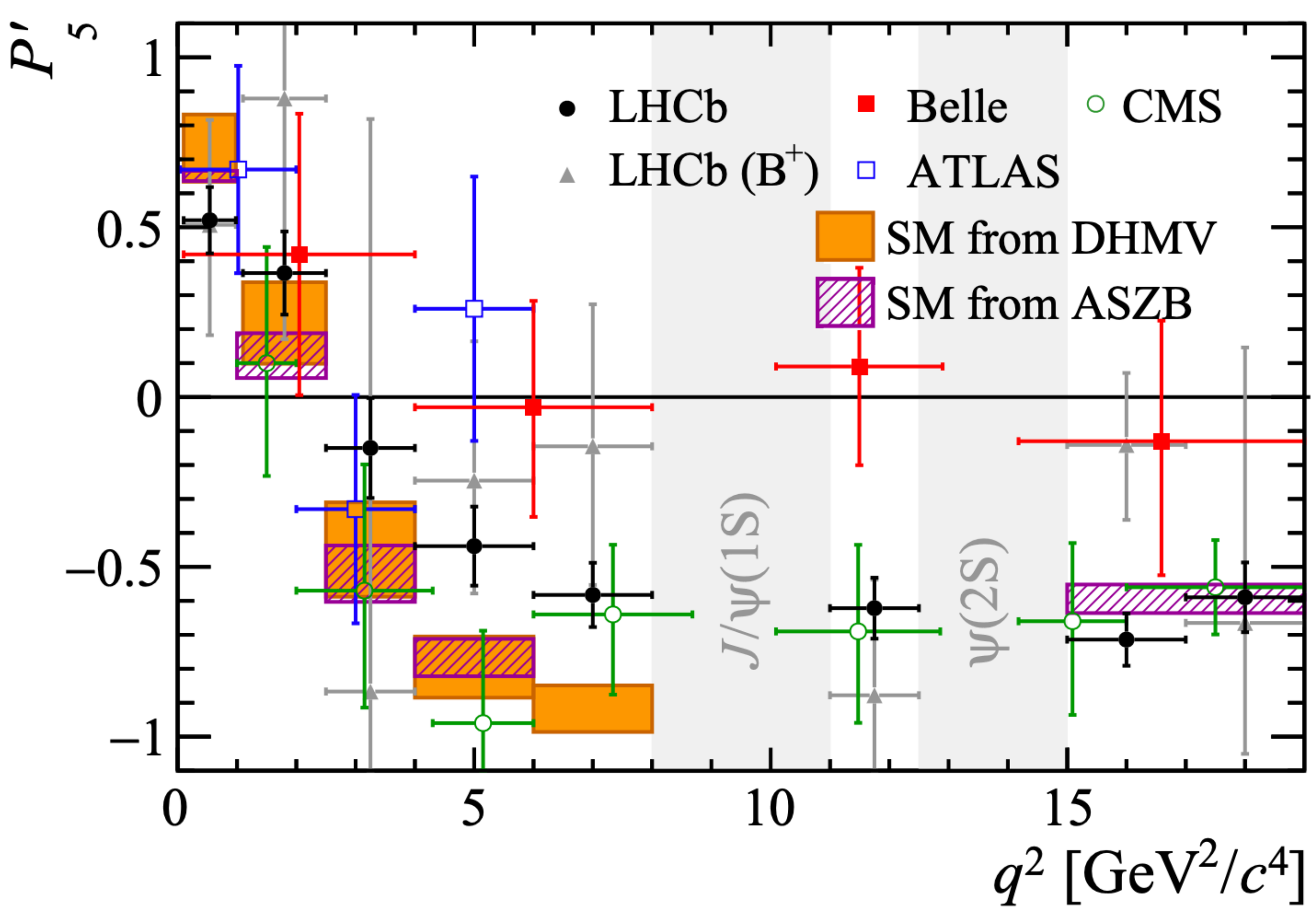


INTERNATIONAL
MAX PLANCK
RESEARCH SCHOOL
PT
FS
FOR PRECISION TESTS
OF FUNDAMENTAL
SYMMETRIES

After Run 3







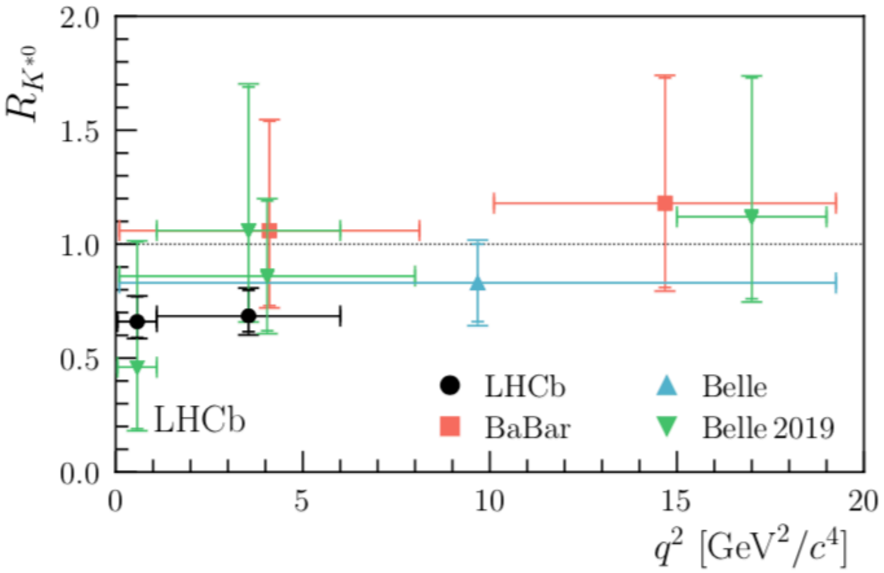
Other measurements

Belle: PRL 118 (2017), CMS:PLB 781 (2018) 517541

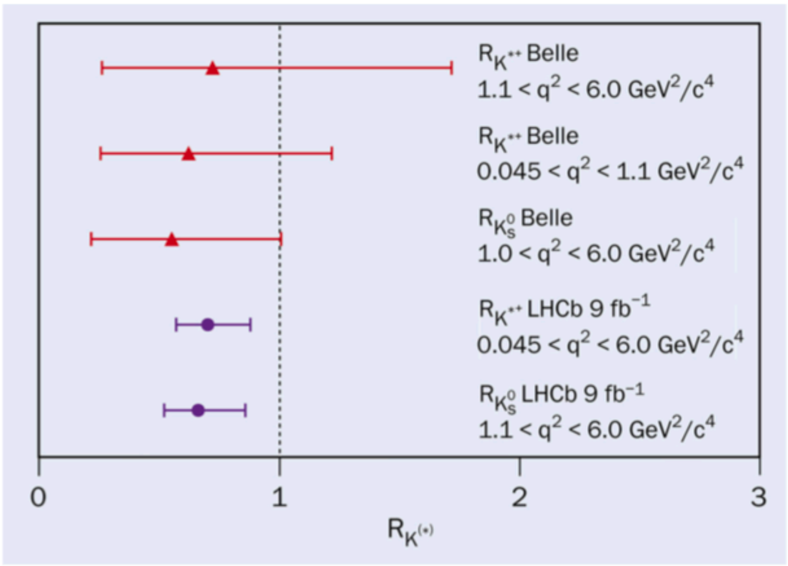
LHCb B0 PRL 125, 011802 (2020) . LHCb B+ PRL 161802 (2021) ATLAS: JHEP 10 (2018) 047

LFU

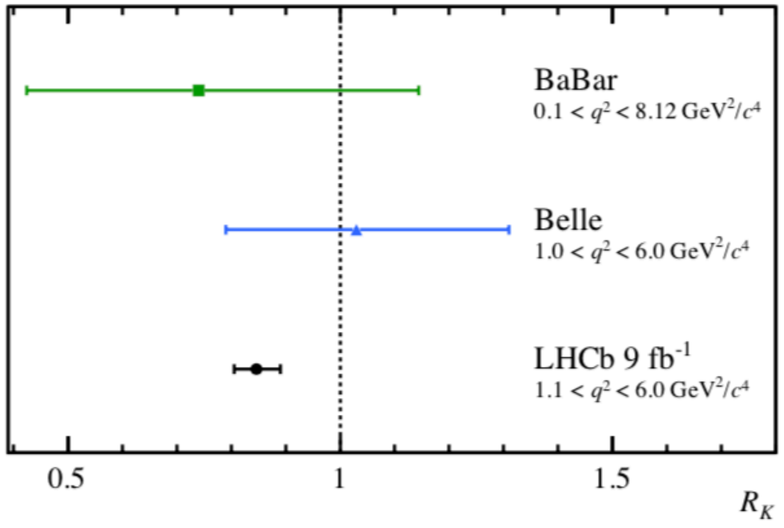
(a)



(b)



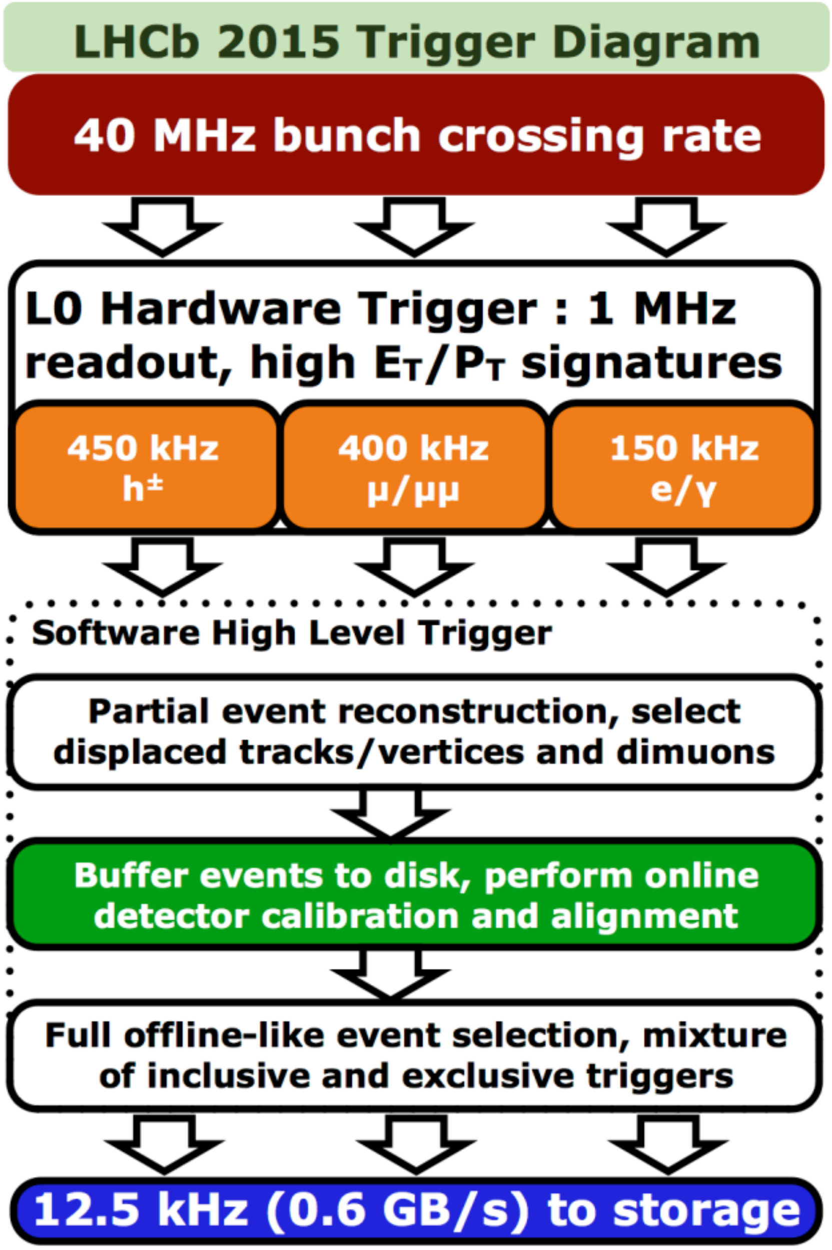
(c)



$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}\,,$$

Belle II - 11% in RK with 5ab$^{-1,}$ summer 2022 expect 1ab-1

Run 3 trigger



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$

400 kHz μ/μμ

150 kHz e/γ

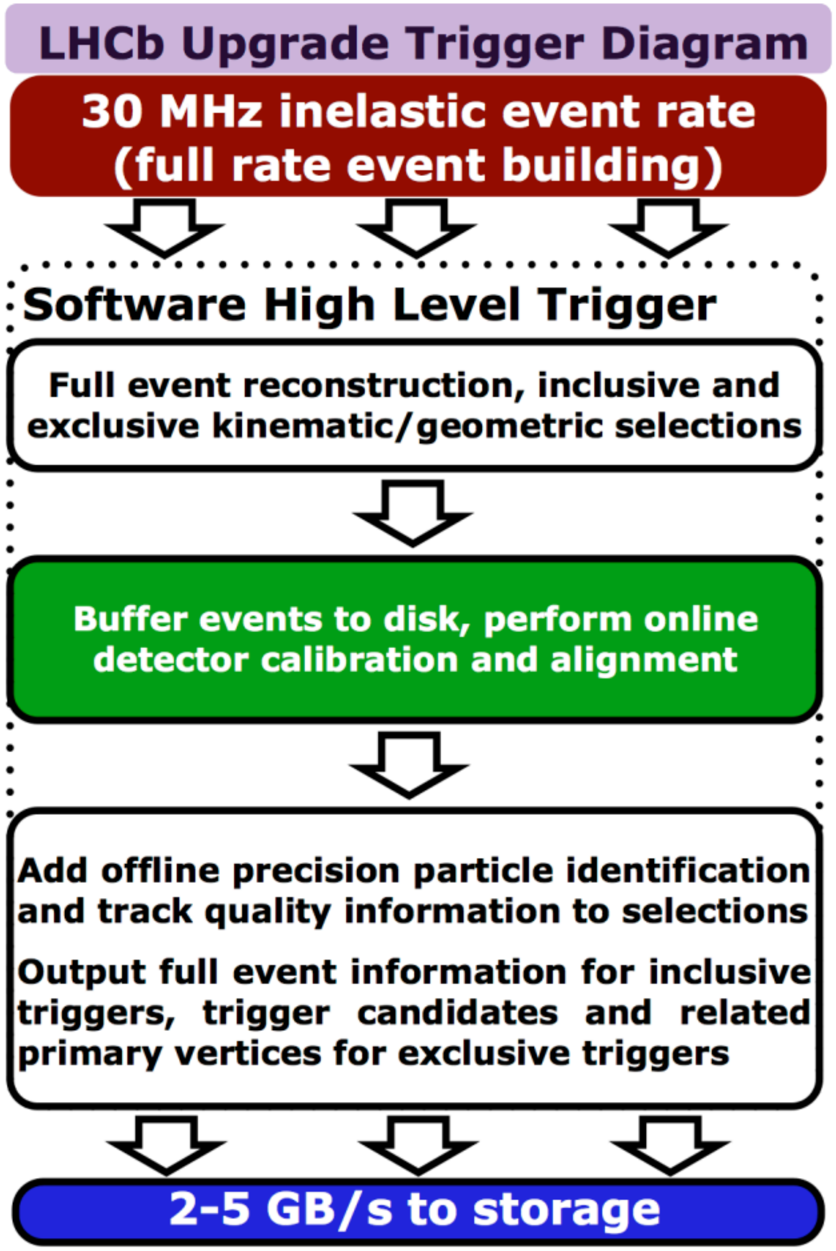
Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

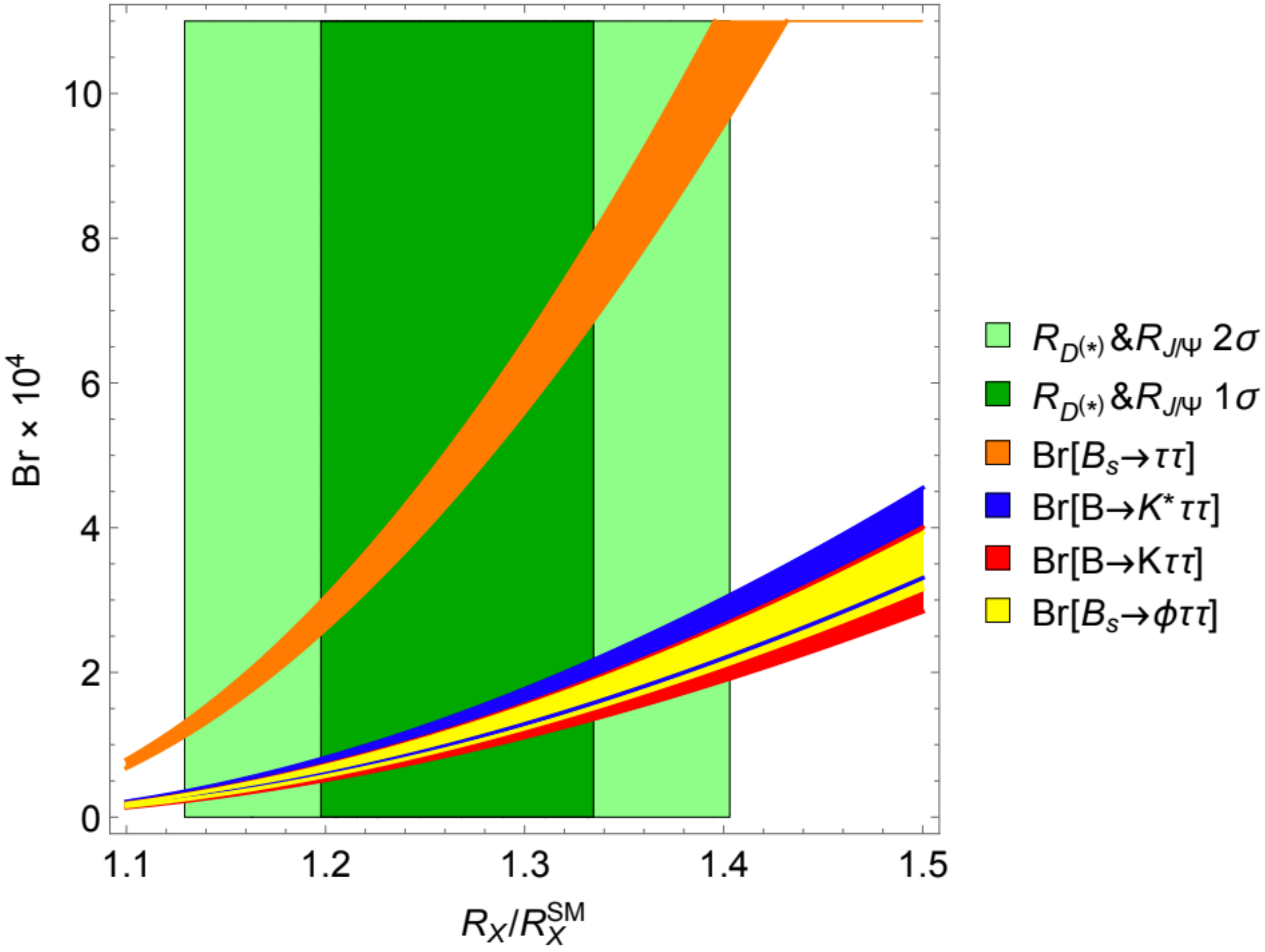
2-5 GB/s to storage

What about the tau's?

$$\mathrm{Br}\big(B \to K\tau^+\tau^-\big)_{\mathrm{EXP}} \leq 2.25 \times 10^{-3}$$

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3}$$

- $b \to s\tau^+\tau^-$ decays are "most-wanted" on wish-list: common explanations for charged-current and $b \to s\ell^+\ell^-$ anomalies predict enhanced $b \to s\tau^+\tau^-$

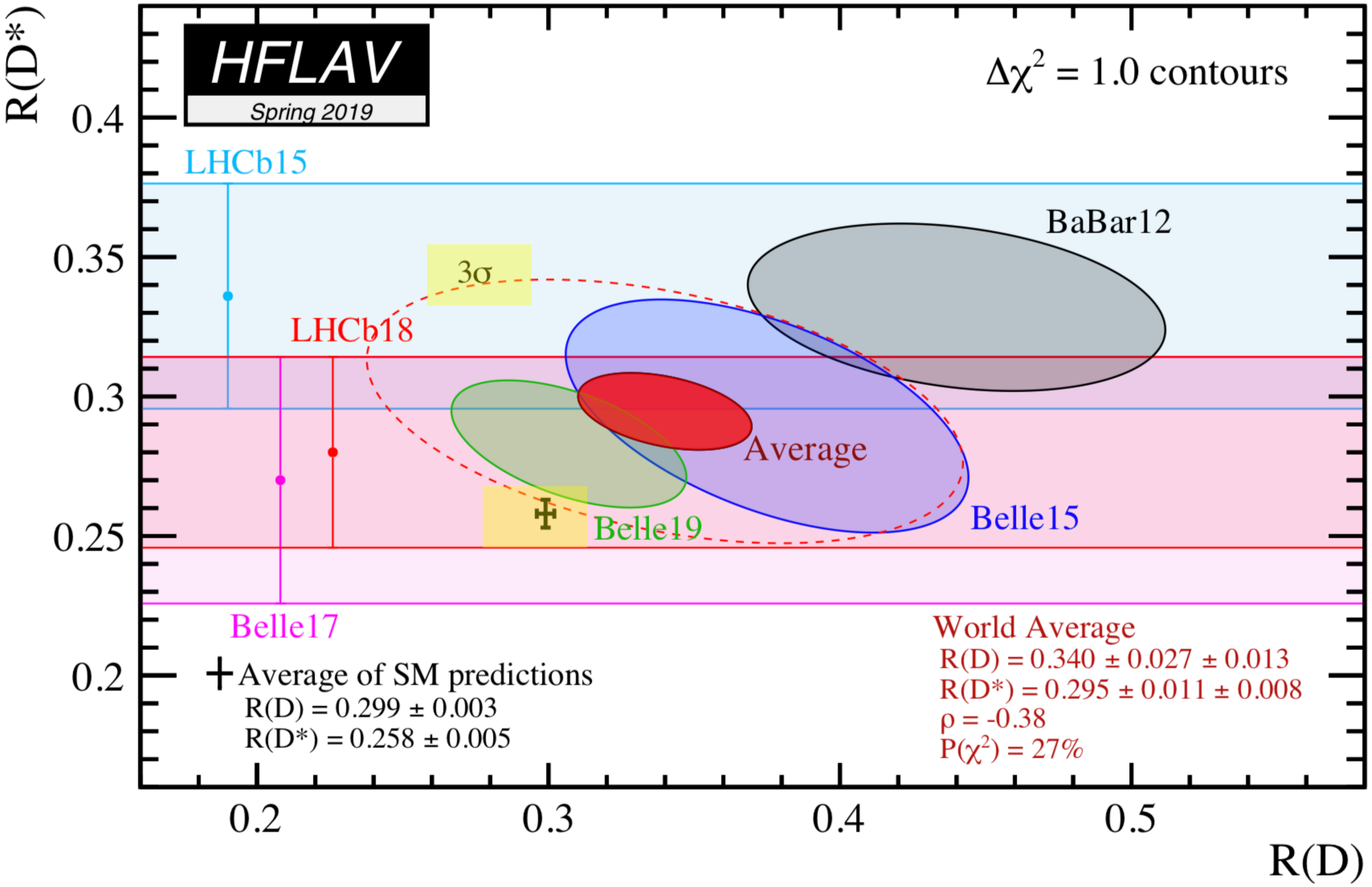


Tree-level $b \to c\ell\nu$ decays

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

$\ell = e, \mu$ [Belle]

$\ell = \mu$ [LHCb]



Babar. Phys. Rev. Lett. 109, 101802 (2012)

Belle15 Phys. Rev. **D92**, 7, 072014 (2015)

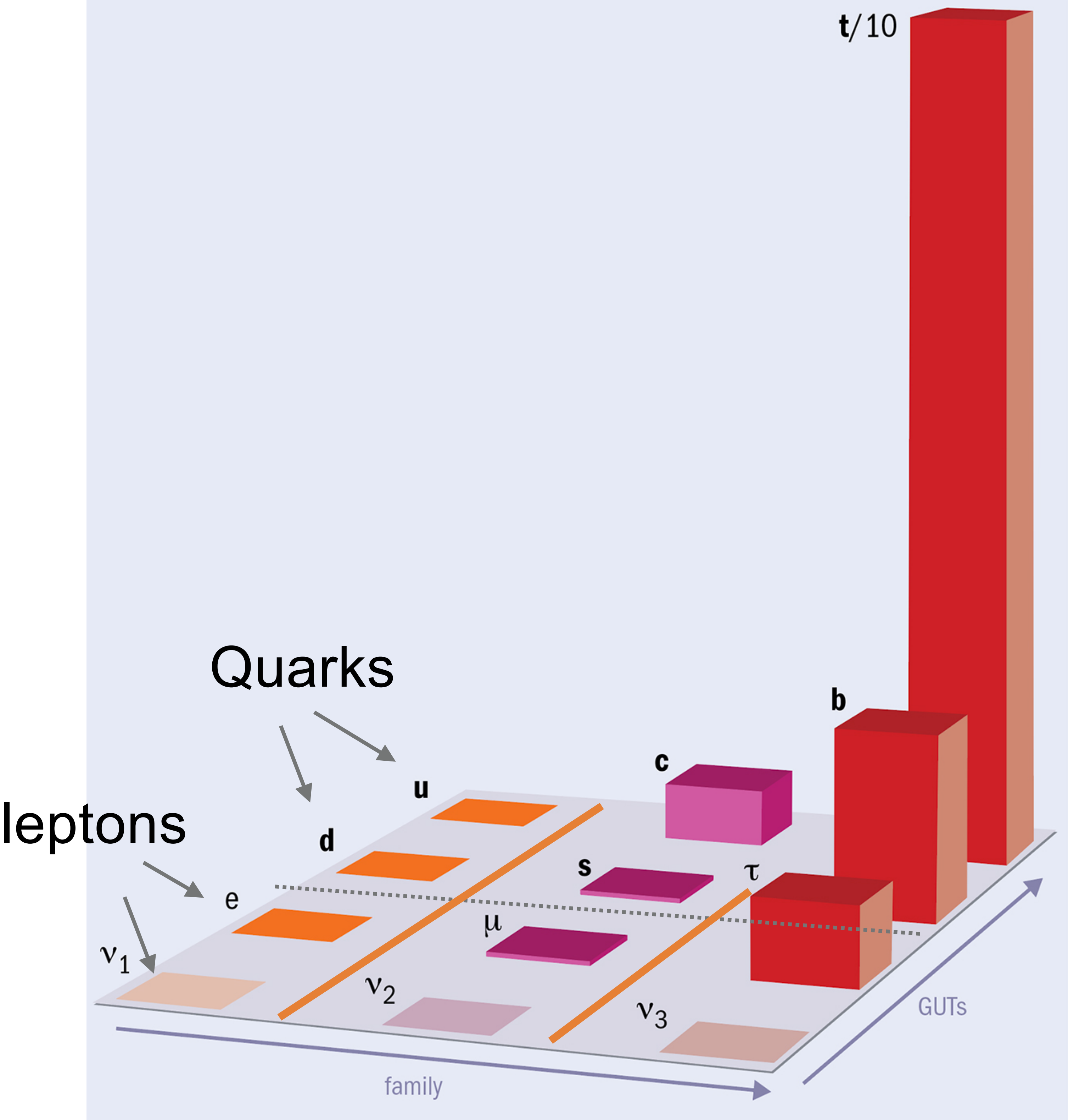
Belle17 Phys. Rev. Lett. **118**, 21, 211801 (2017)

Belle19 Phys. Rev. Lett. 124, 161803 (2020)

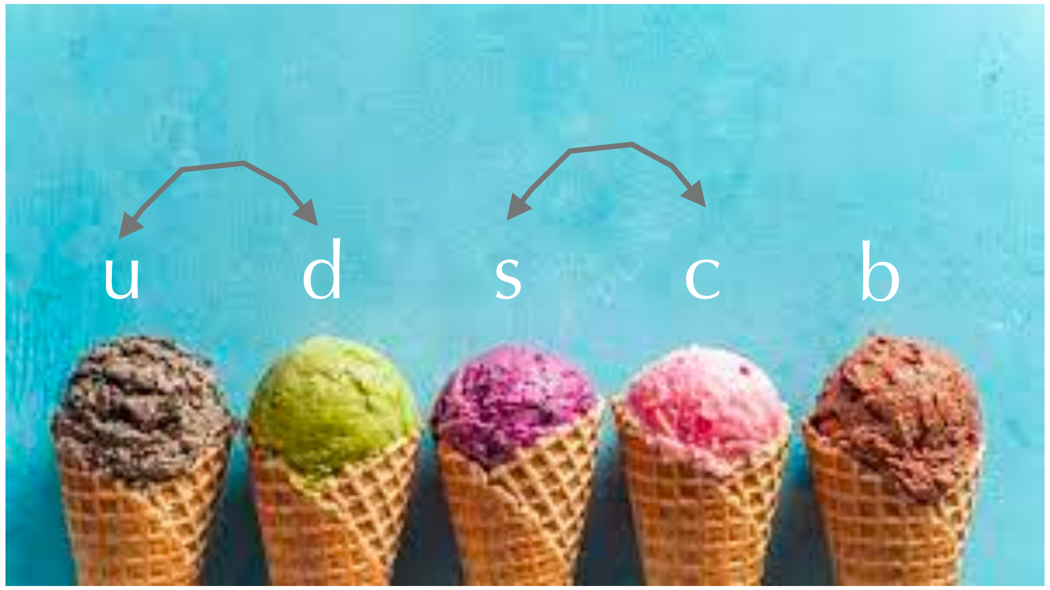
LHCb15 Phys. Rev. Lett. 115, 111803 (2015)

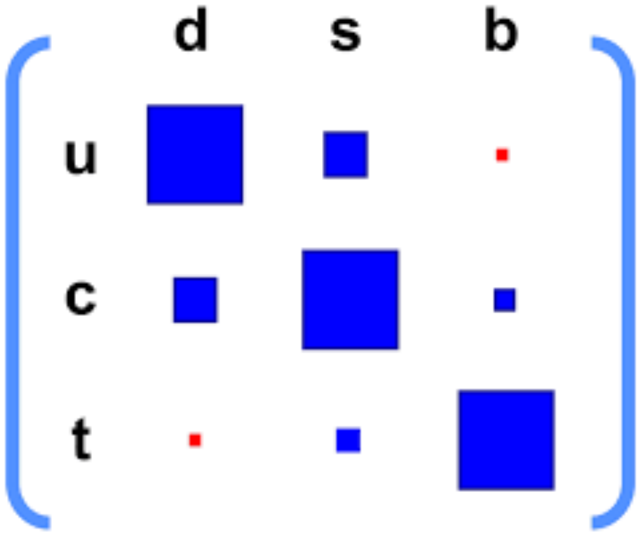
LHCb18 Phys. Rev. D 97, 072013 (2018)

Weak force allows flavours to change

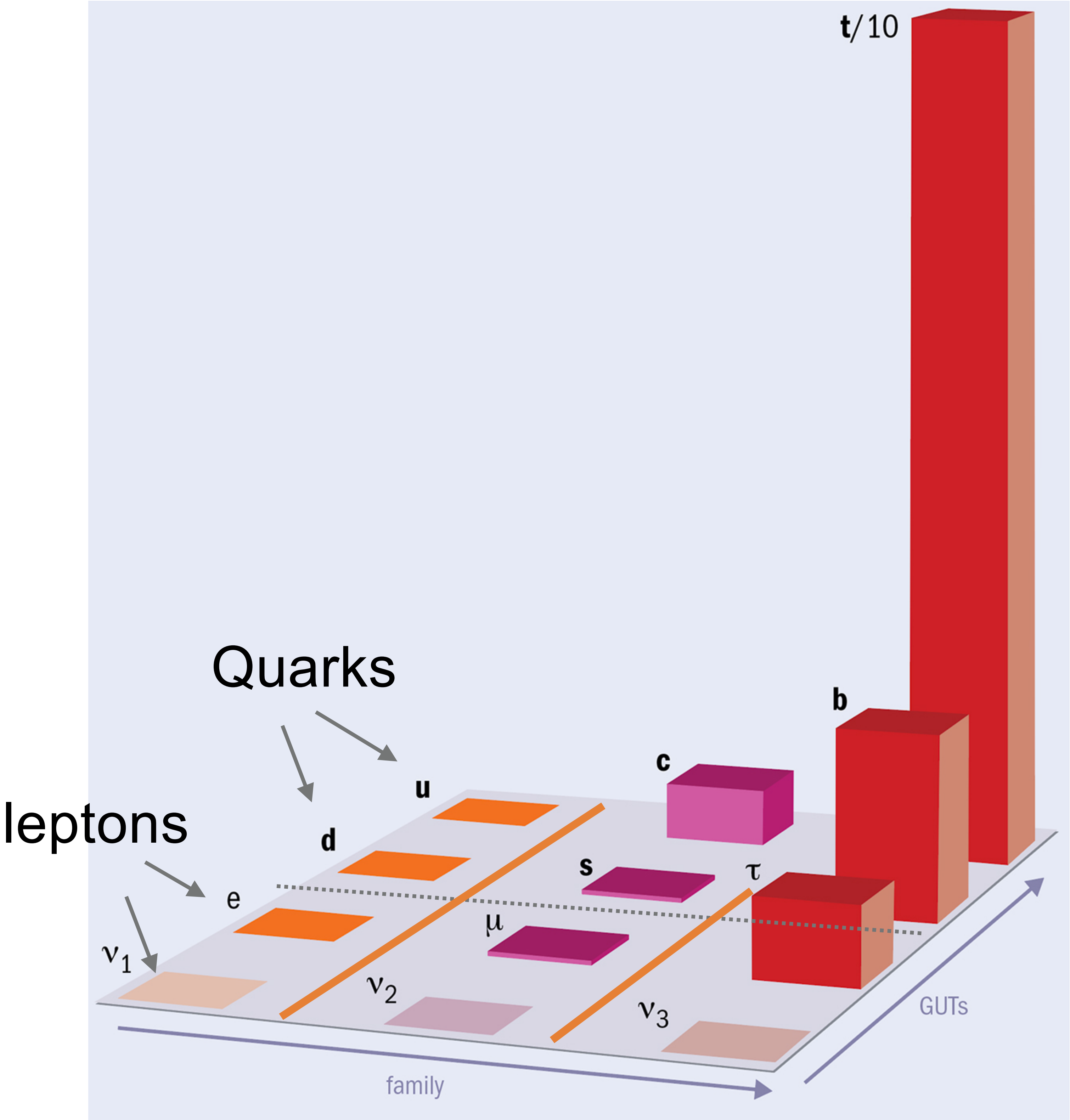

Quarks

leptons





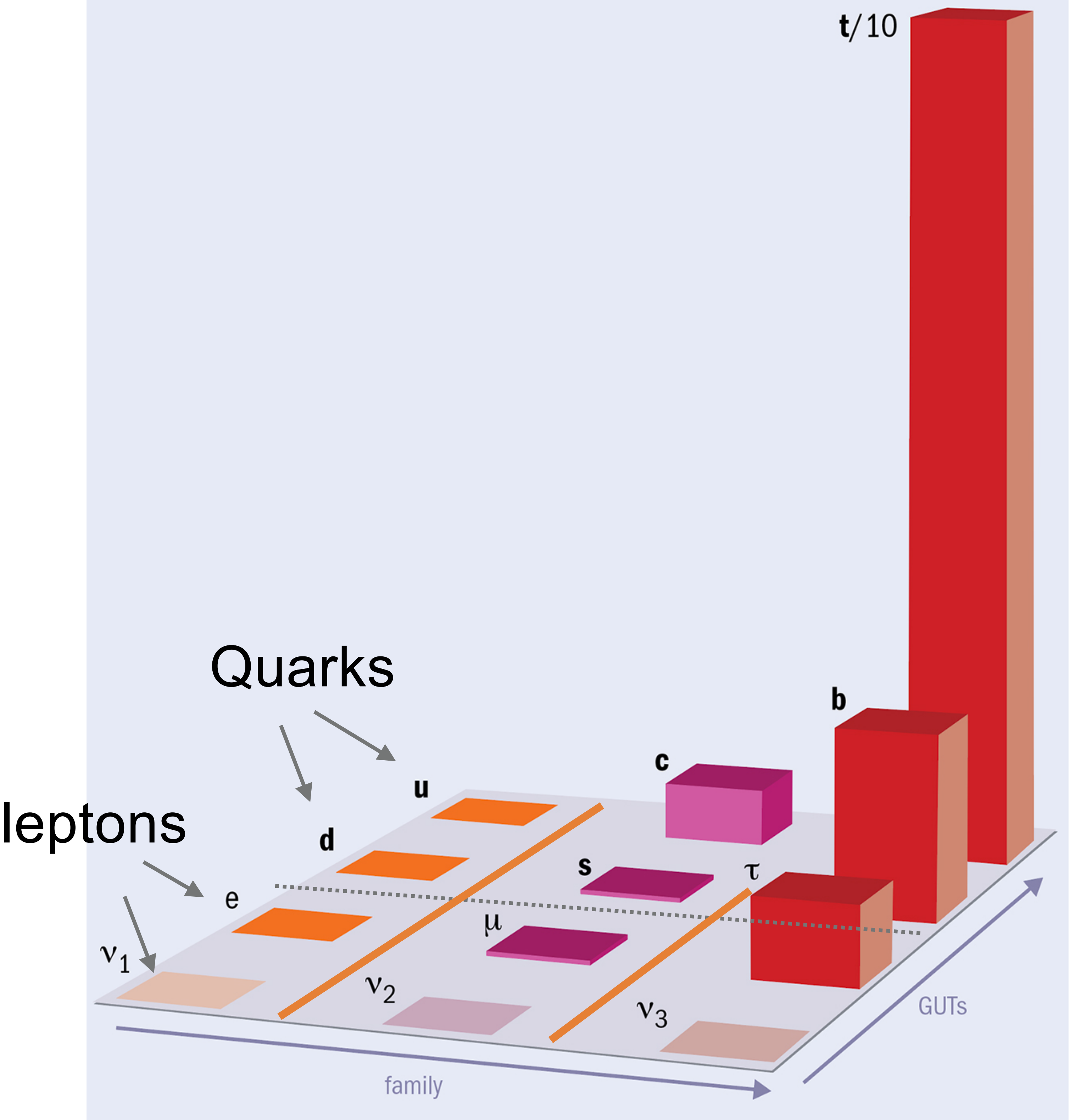
The likelihood of this happening = CKM matrix



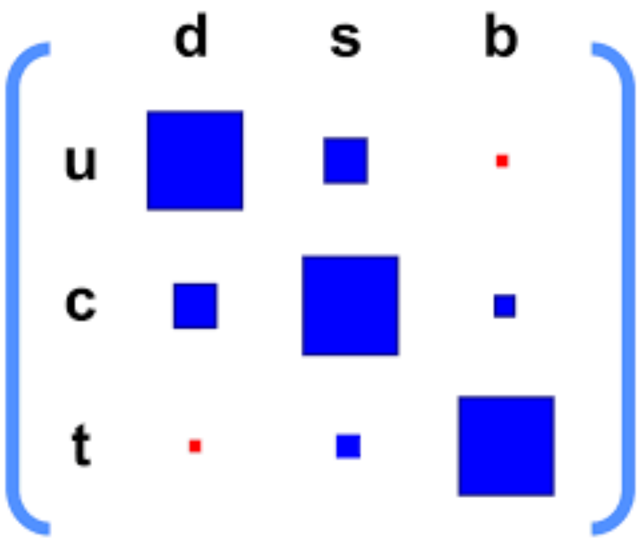
There are two other generations, which much heavier masses

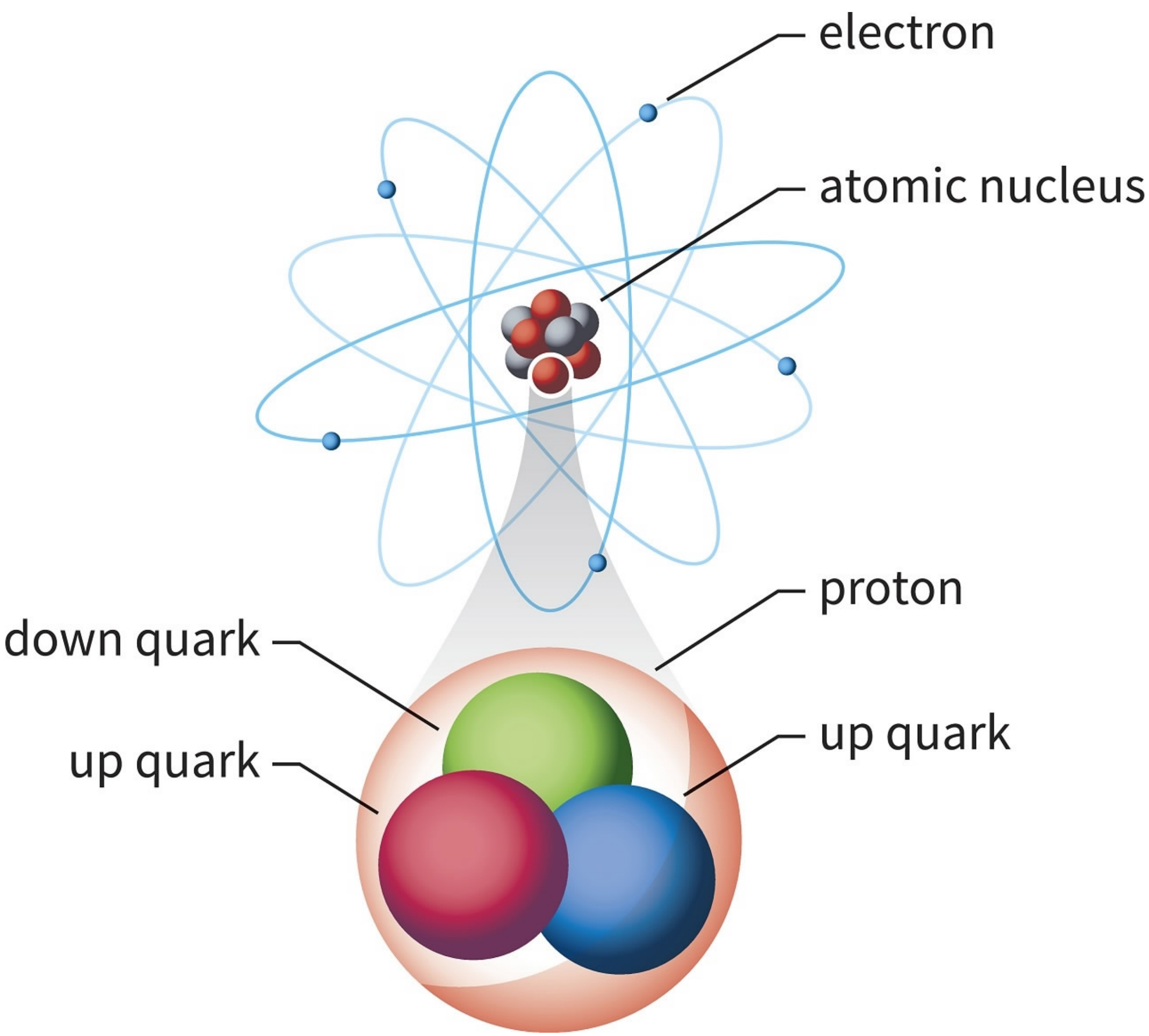
each type of quark (u, d, s,..) or lepton (e, nu,..) = different flavour

How often one quark flavour decays into another summarised by the CKM matrix


Quarks

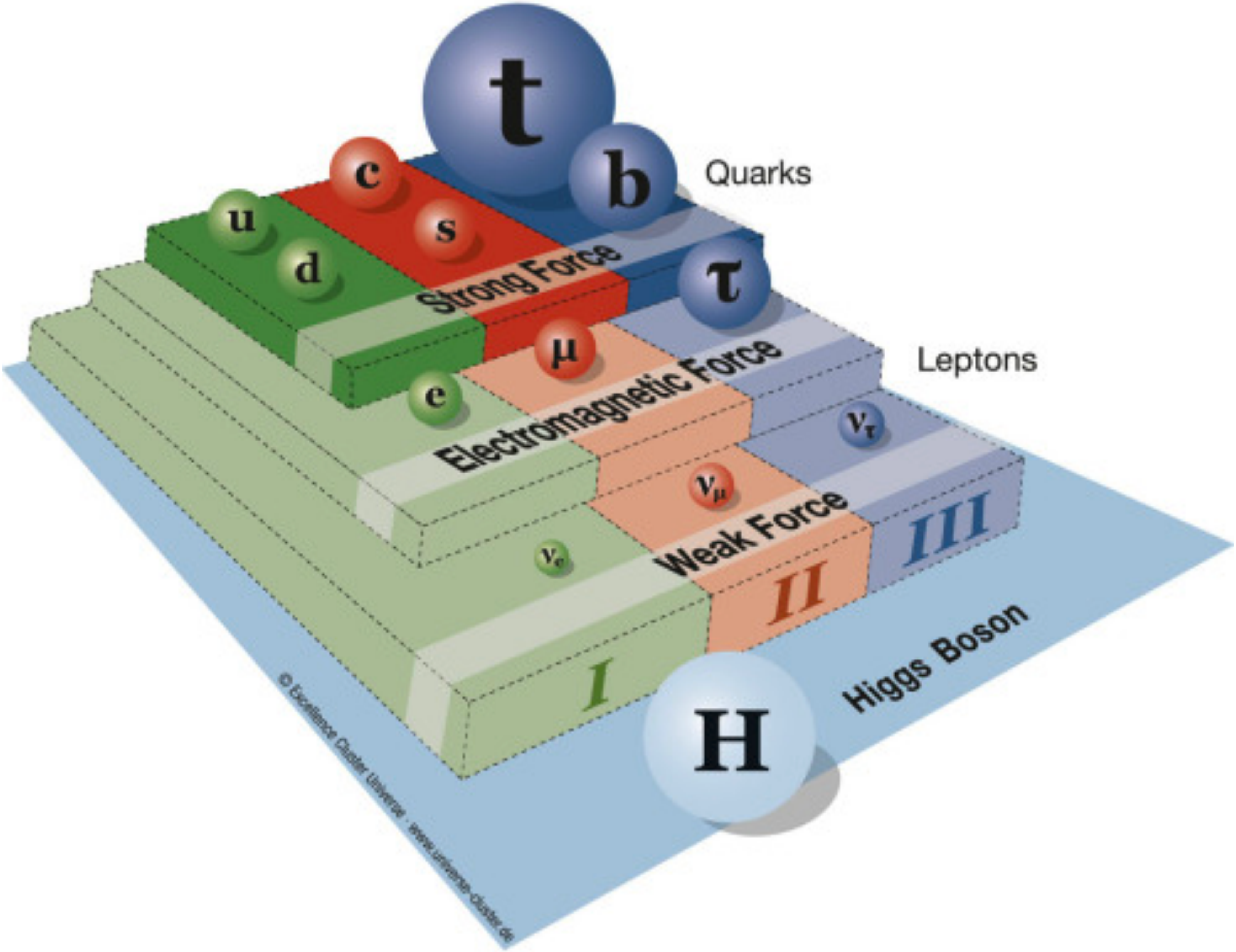
leptons





These are the first, and lightest, of 3 generation of particles

Each generation is identical, save for



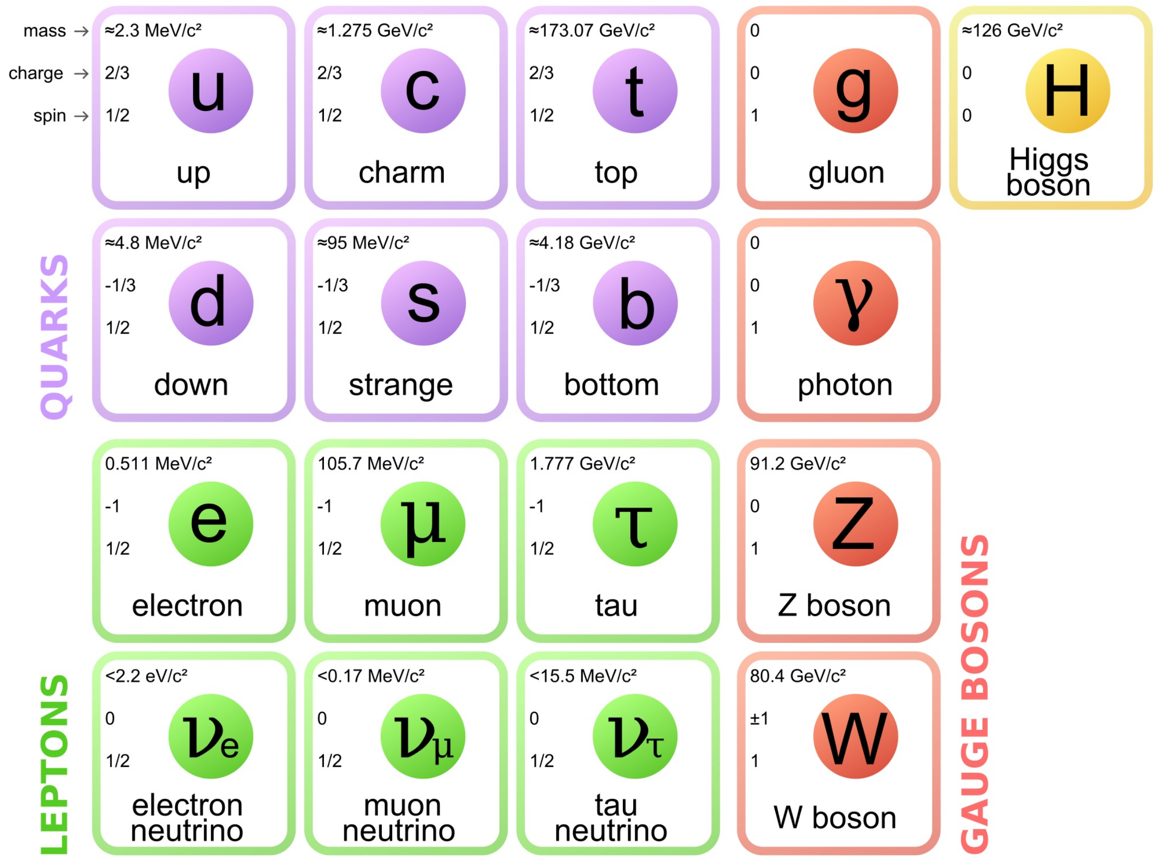
The matter around is made up of the fundamental particles: electrons, up quarks and down quarks

These are the first, and lightest, generation of particles

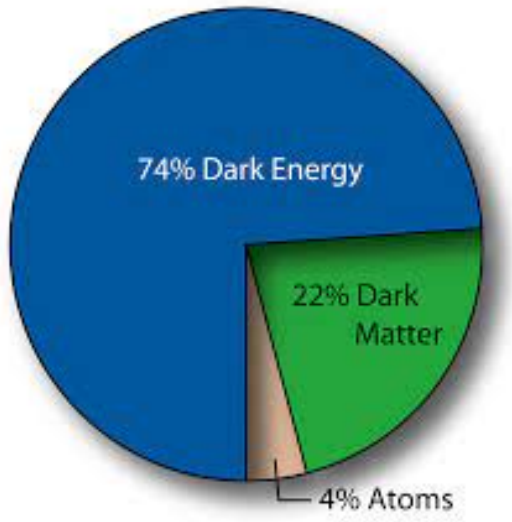
The Standard Model and New Physics

The Standard Model (SM)

Describes all known forces and particles (minus gravity)



We know SM is not complete



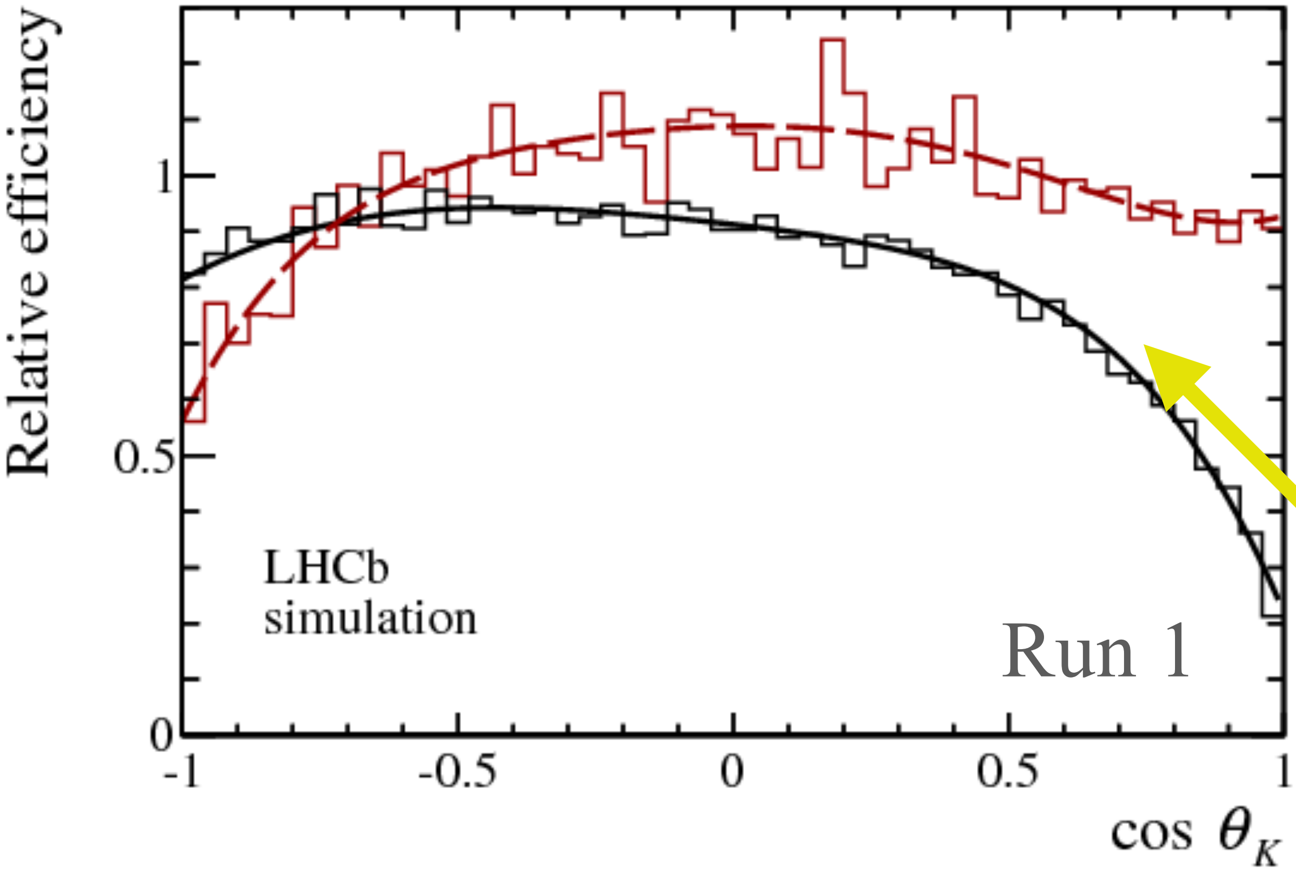
For example, no candidate in SM for Dark Matter

Deficits in the SM point to the existence of new forces: New Physics

Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

Parameterise angular efficiency in 4D using Legendre polynomials:

$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{klmn} c_{klmn} P_k(\cos\theta_l) P_l(\cos\theta_K) P_m(\phi) P_n(q^2)$$



$0.1 < q^2 < 0.98\,\mathrm{GeV}^2/c^4$

$18.0 < q^2 < 19.0\,\mathrm{GeV}^2/c^4$

The efficiency across the angles and q^2 is not flat

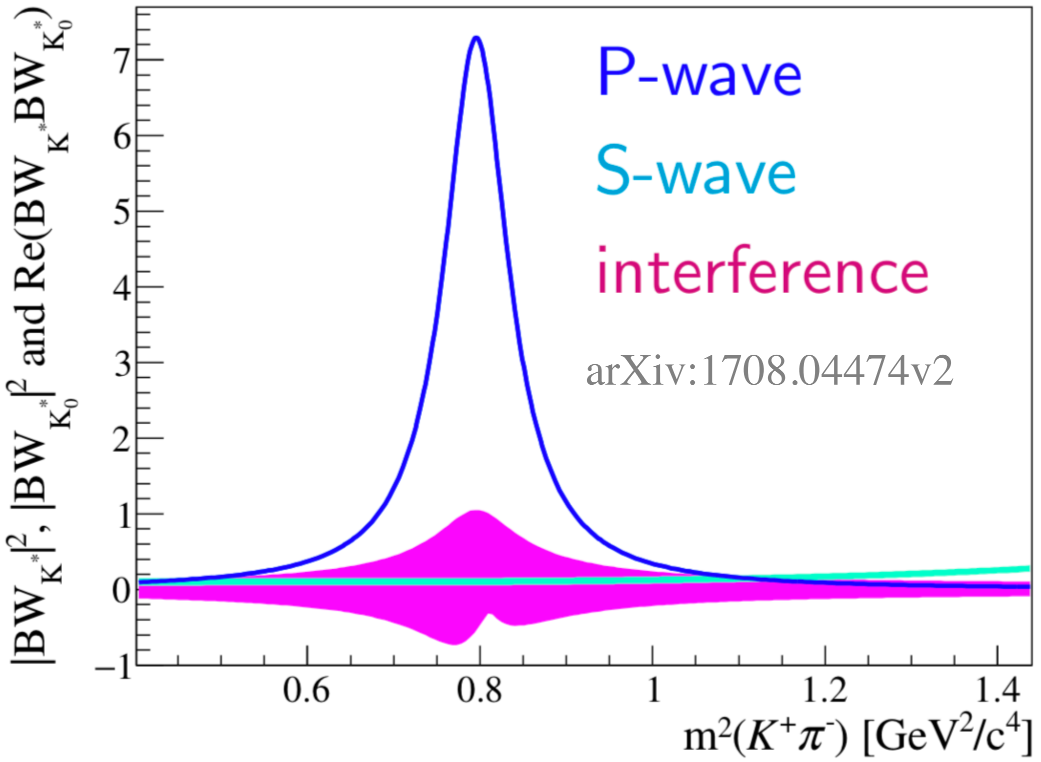
Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

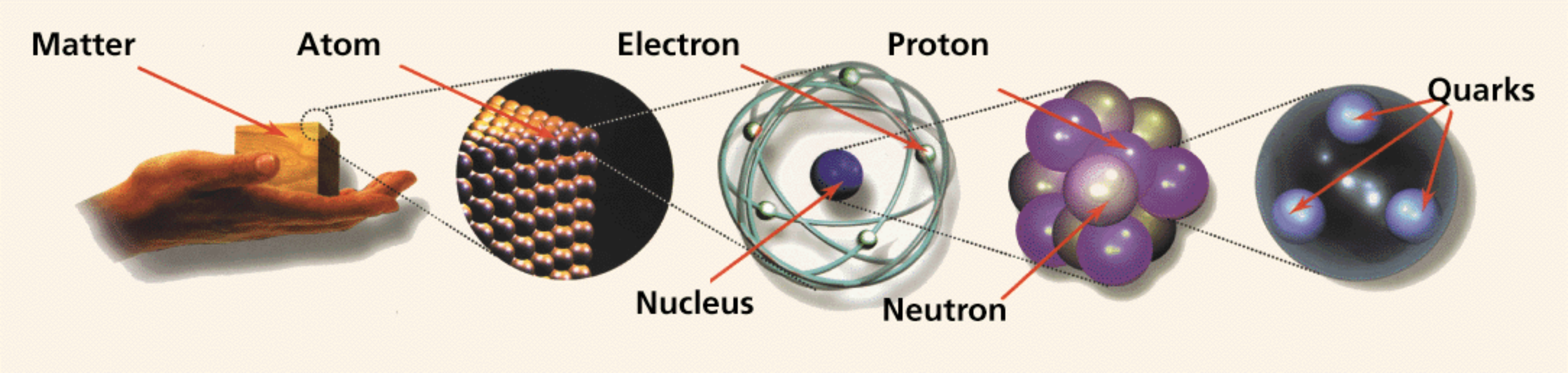
- ➤ Background contribution from spin 0 resonances (S-wave)
- ➤ Fit for these contributions + interference
- ➤ Simultaneously fit the $m_{K\pi}$ distribution to better separate P-wave and S-wave

P-wave (K^{*0} - 8 terms)

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{S+P}} = (1-F_S)\boxed{\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{P}}}$$

$$+\frac{3}{16\pi}\Big[F_S\sin^2\theta_l + S_{S1}\sin^2\theta_l\cos\theta_K$$
$$+ S_{S2}\sin 2\theta_l\sin\theta_K\cos\phi$$
$$+ S_{S3}\sin\theta_l\sin\theta_K\cos\phi$$
$$+ S_{S4}\sin\theta_l\sin\theta_K\sin\phi$$
$$+ S_{S5}\sin 2\theta_l\sin\theta_K\sin\phi\Big].$$




Matter
Atom
Electron
Proton
Quarks
Nucleus
Neutron

LFU tests + electrons

Lepton Flavour Universality tests defined as $R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$

In practice measure double-ratio:

$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)} \Big/ \frac{\mathcal{B}(B \to XJ/\psi[\to \mu\mu])}{\mathcal{B}(B \to XJ/\psi[\to ee])}$$

- Double ratio very robust against systematic effects, single ratio:

$$r(J/\psi) \quad = 0.981 \pm 0.020$$

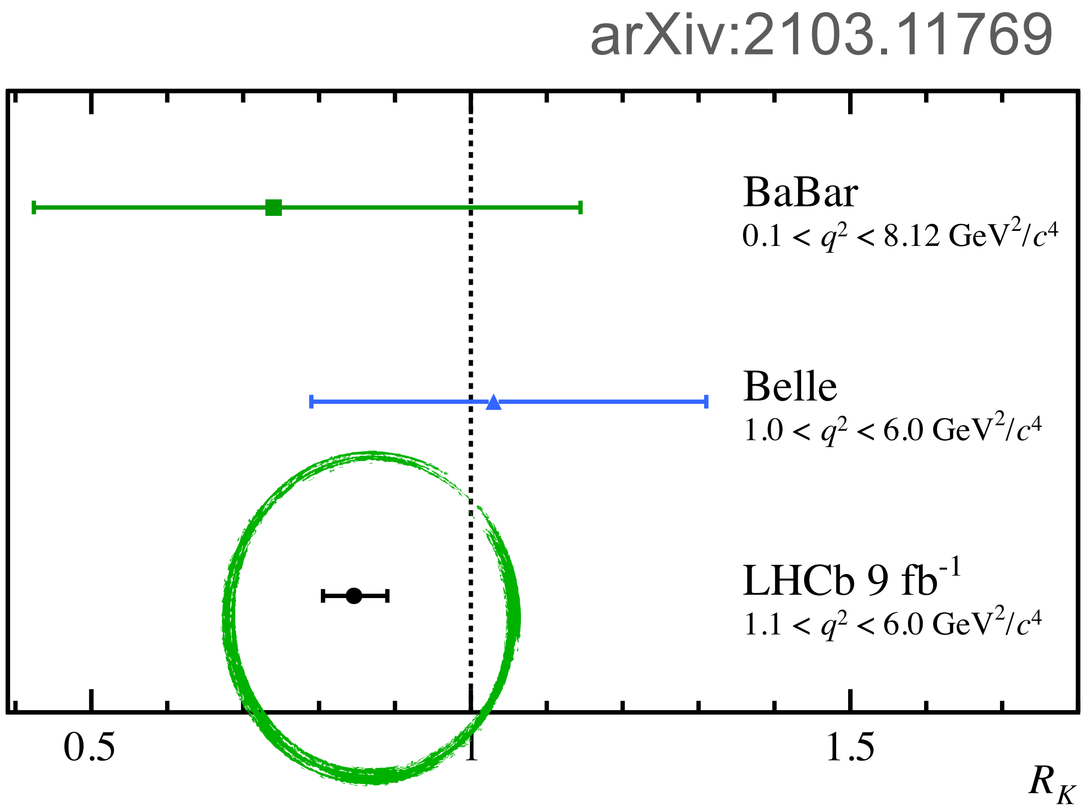
Although electrons more challenging, deviation from SM is largely due to the muon modes, not electrons

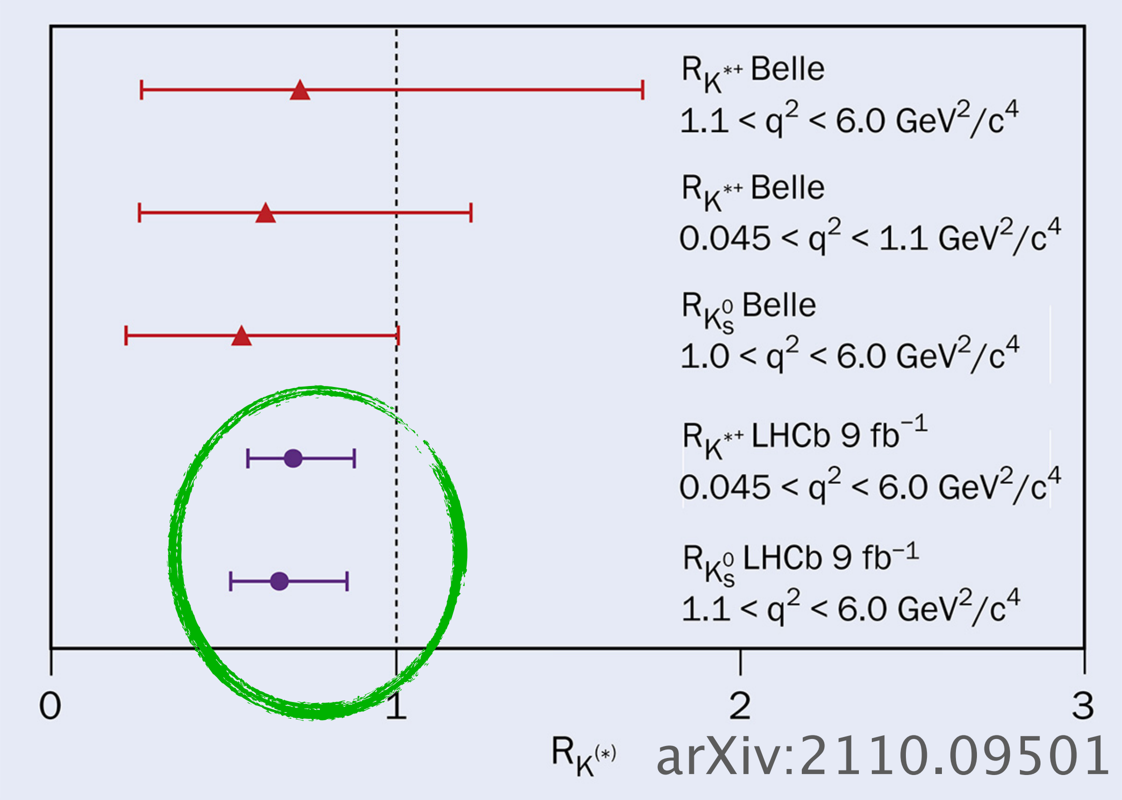
$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+\,0.042}_{-\,0.039}\,^{+\,0.013}_{-\,0.012}$$

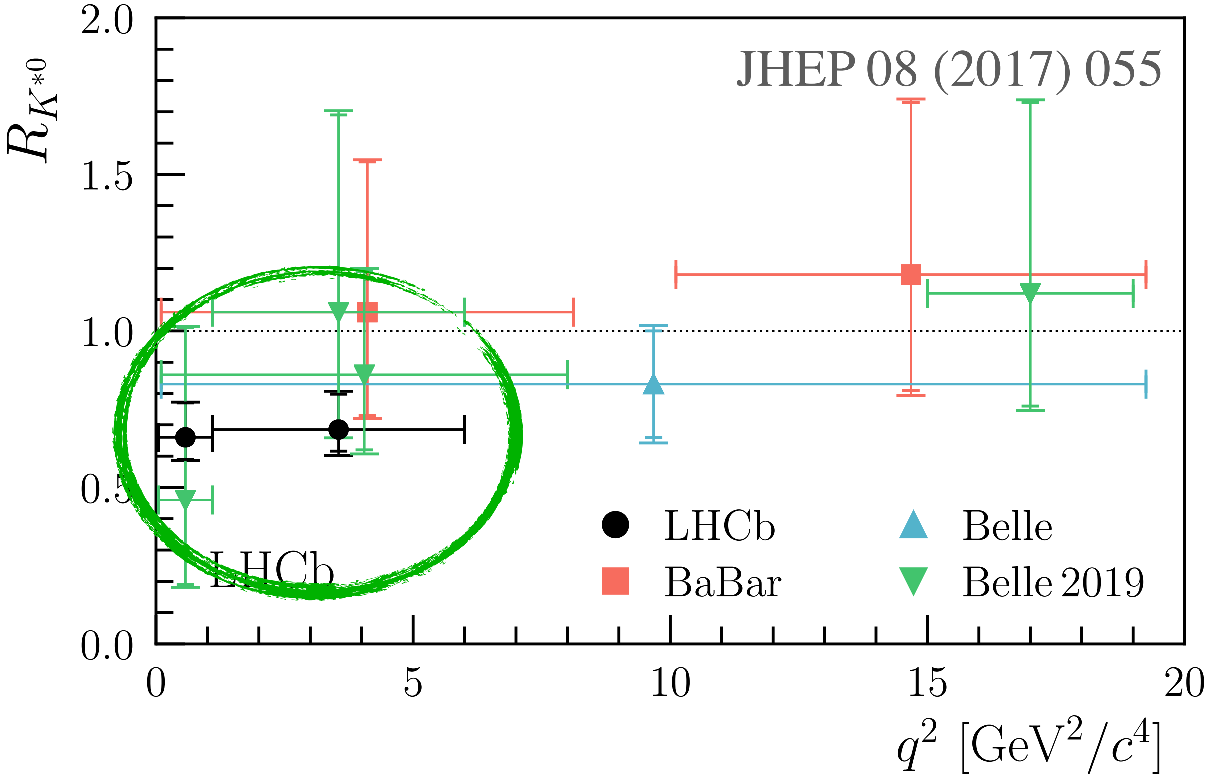
$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = (28.6\,^{+\,1.5}_{-\,1.4} \pm 1.3) \times 10^{-9}\,c^4/\mathrm{GeV}^2$$

(arXiv:2103.11769)

Summary: Lepton Flavour Universality


arXiv:2103.11769


arXiv:2110.09501

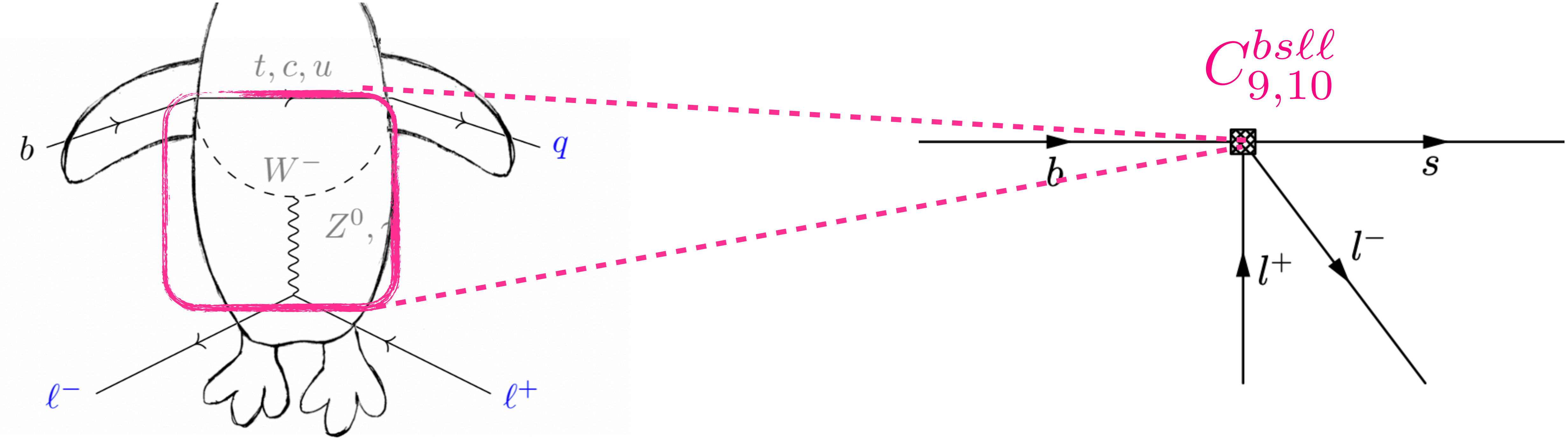

JHEP 08 (2017) 055

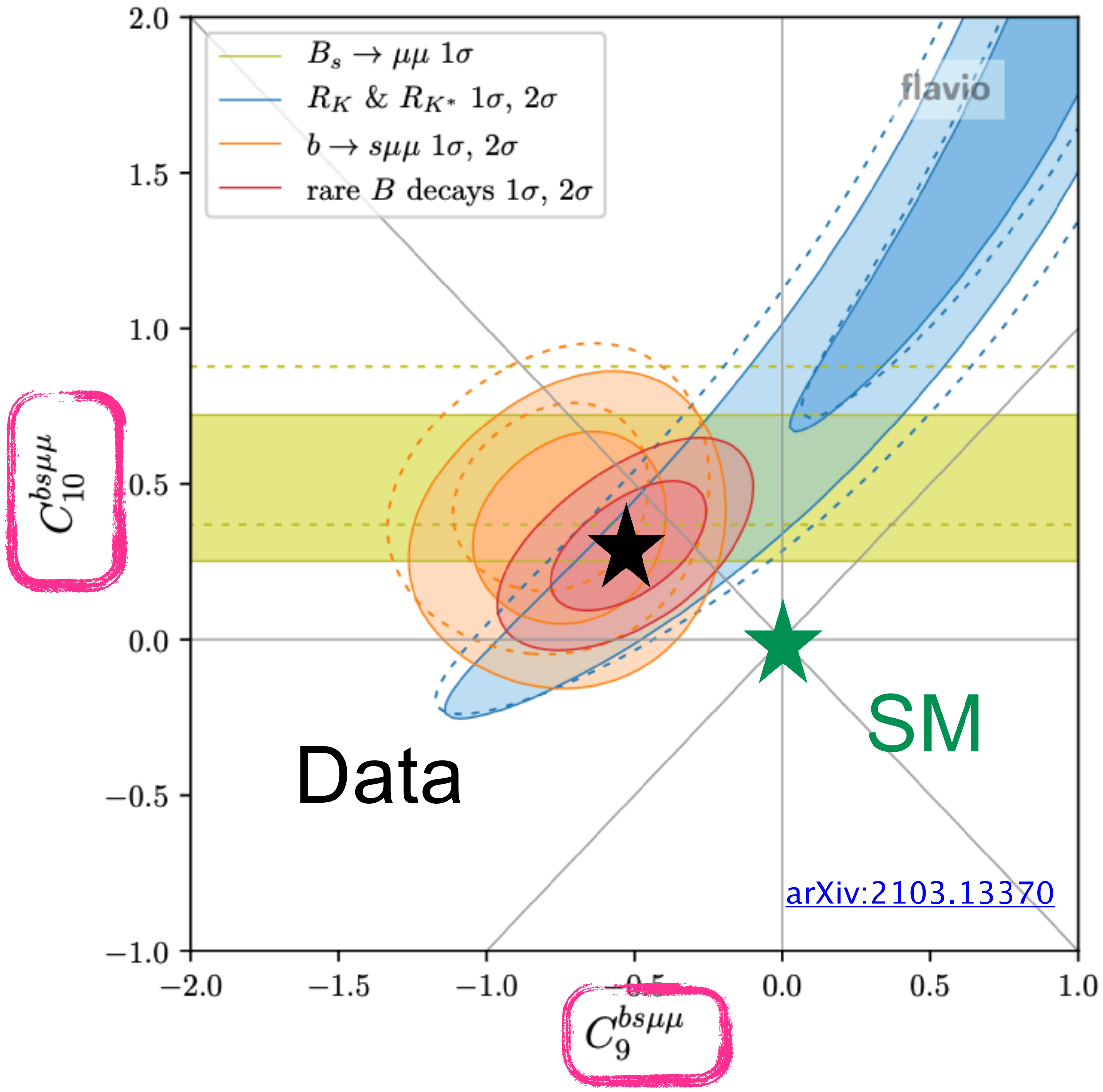
$$+ \quad \Lambda_b^0 \to pK\ell^+\ell^-: \quad \text{JHEP 2020, 40 (2020)}$$

$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

Same pattern, ratios below the SM prediction

The Flavour Anomalies





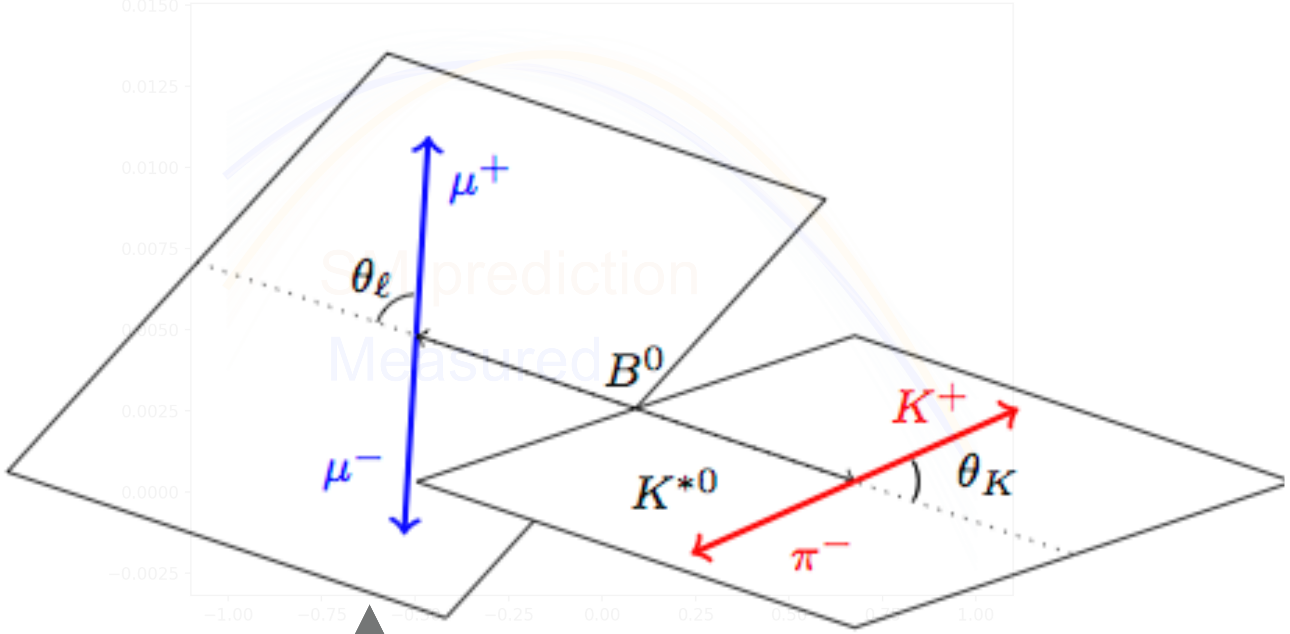
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (C_i\mathcal{O}_i + C_i'\mathcal{O}_i')$$

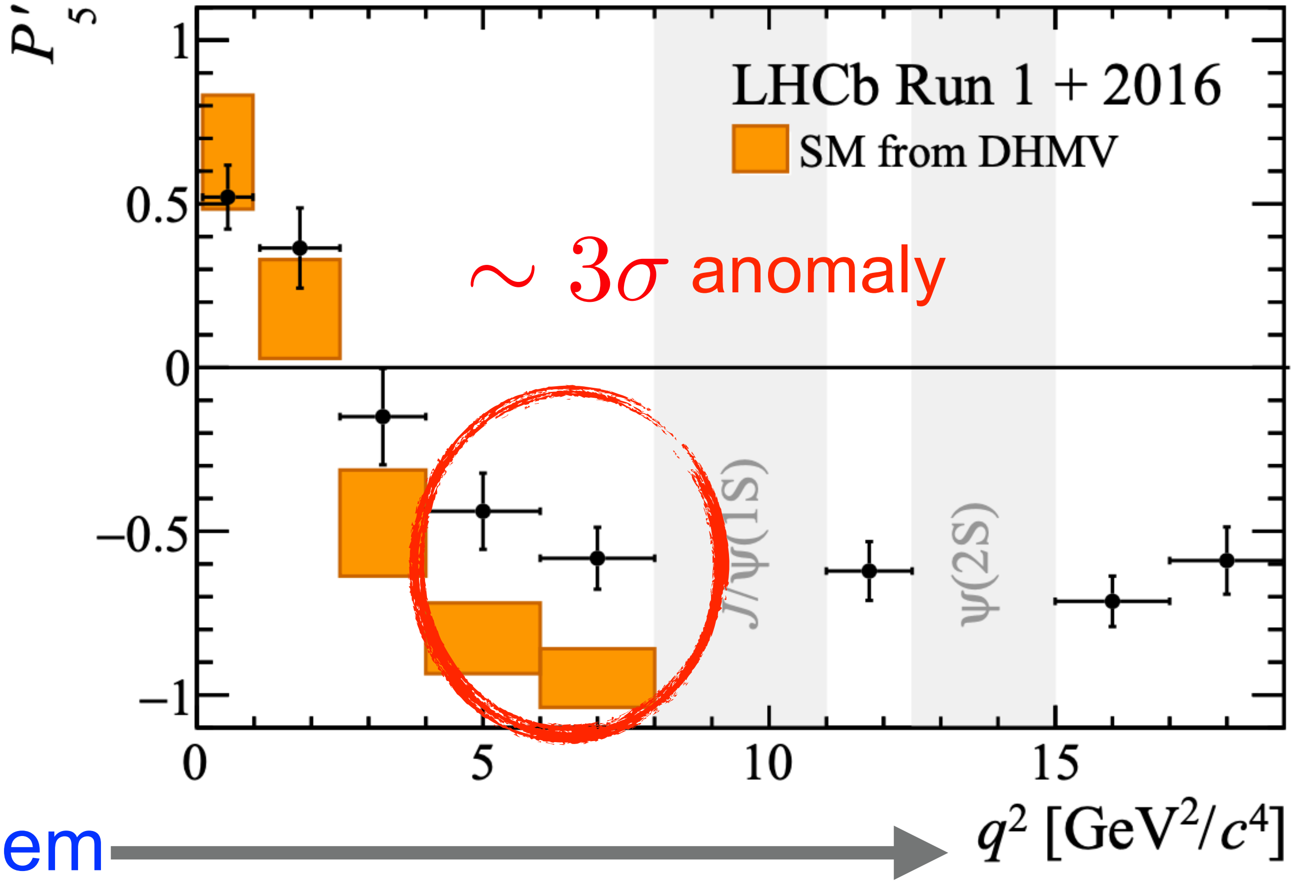
Combine all $b \to s\ell^+\ell^-$ measurements and fit for $b \to s\ell^+\ell^-$ effective couplings

~ 7σ tension with SM when combined
p-value <0.00001

Example: angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

4 particles in final-state: decay described by 3 angles and q²= $m^2(\ell^+\ell^-)$





$\sim 3\sigma$ anomaly

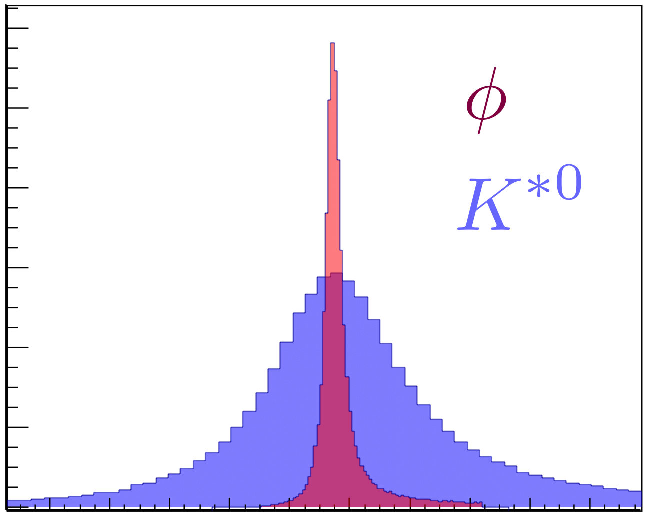
Invariant mass of the dilepton system

[2020] **PRL 125, 011802** Flagship analysis for LHCb

Internal contact author: **E. Smith**, top ten cited LHC papers of 2020, 3.3σ tension from the SM

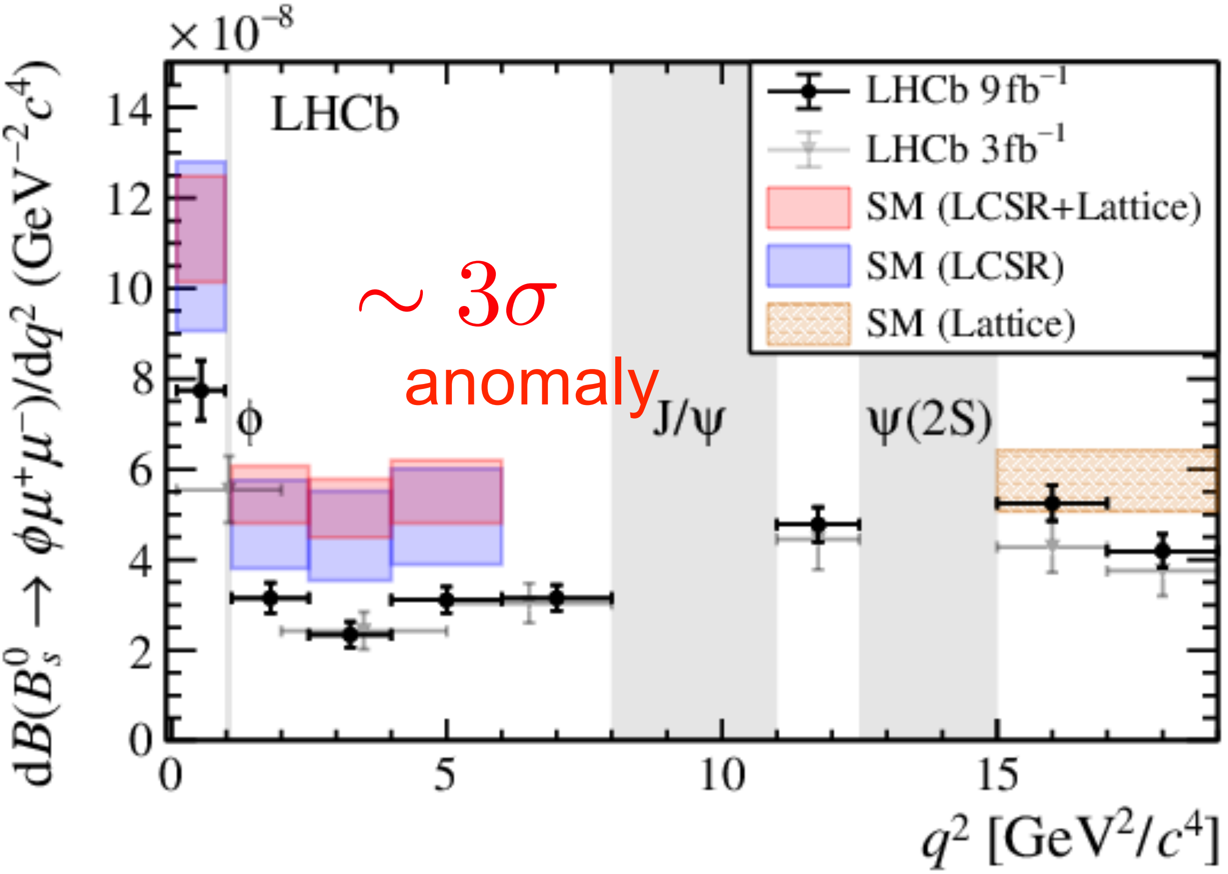
Example: $B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$

Narrow width of meson and CP symmetric state give additional information



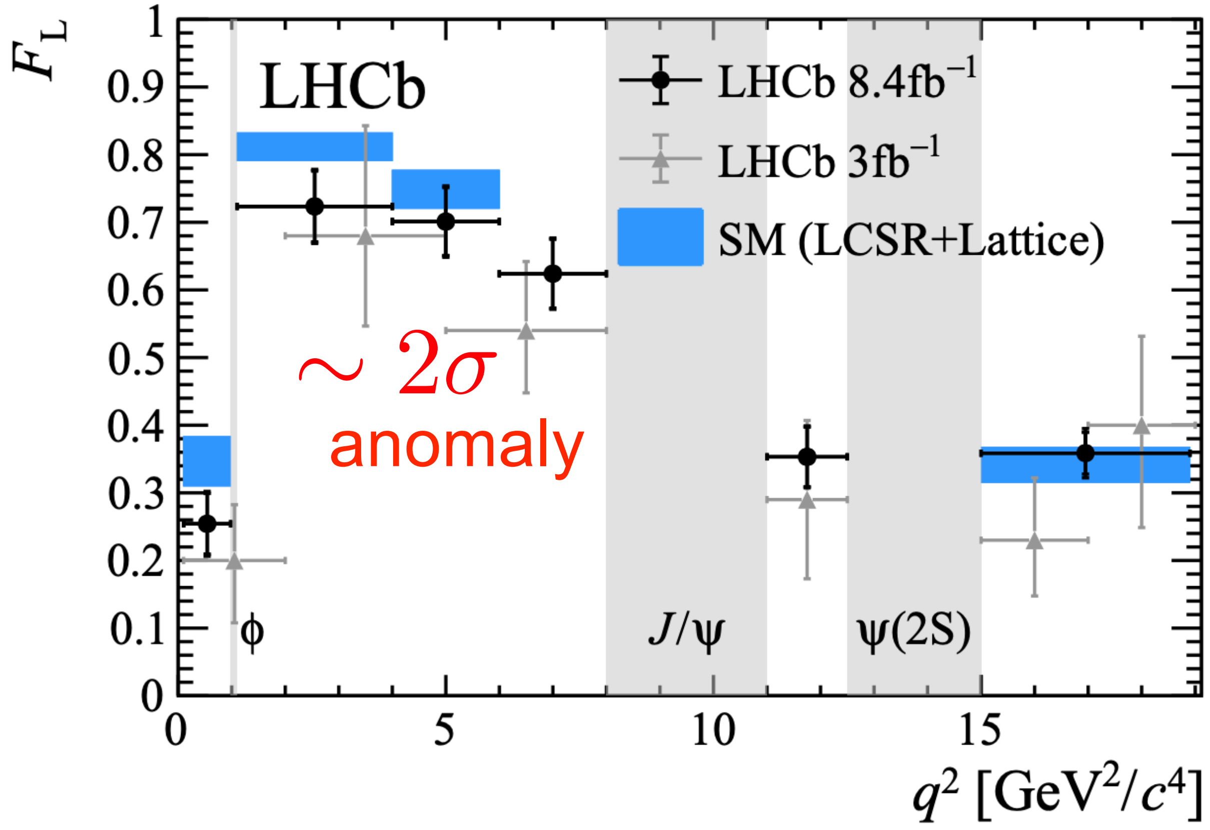
Branching fraction:

Angular analysis:



$\sim 3\sigma$ anomaly

[2021] PRL 127, 151801



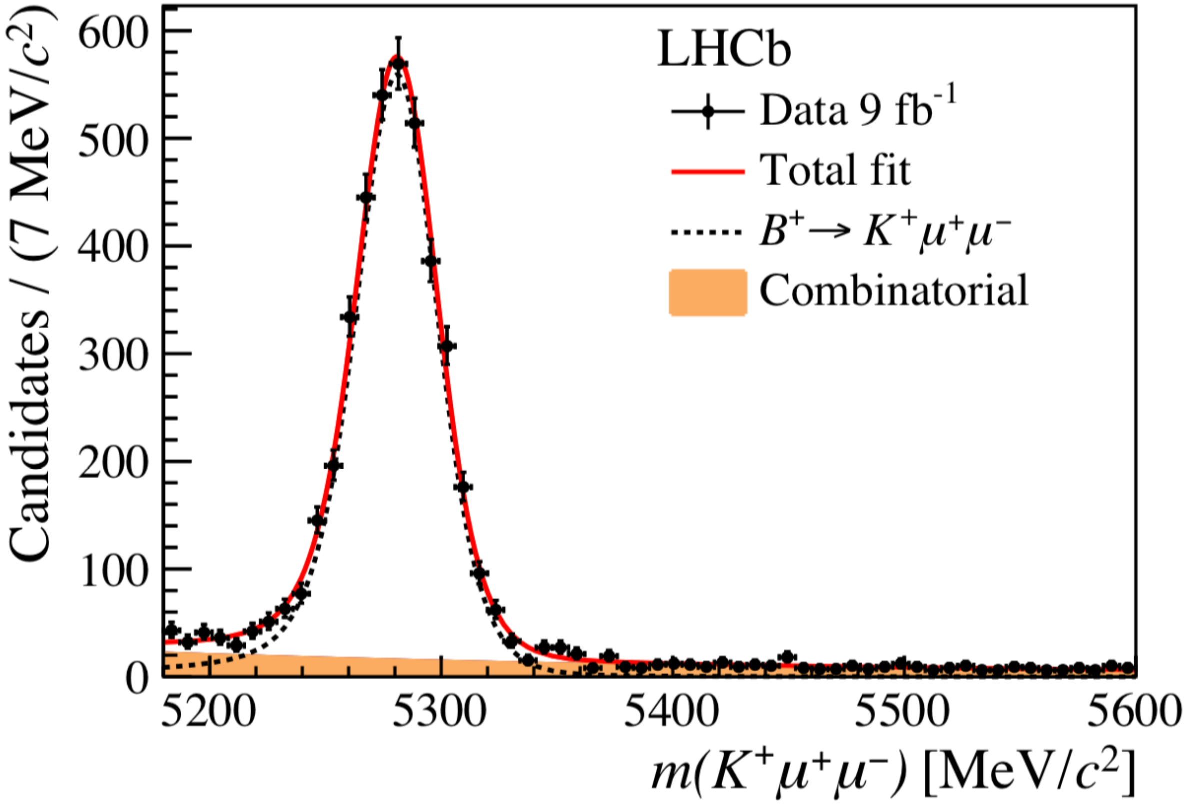
$\sim 2\sigma$ anomaly

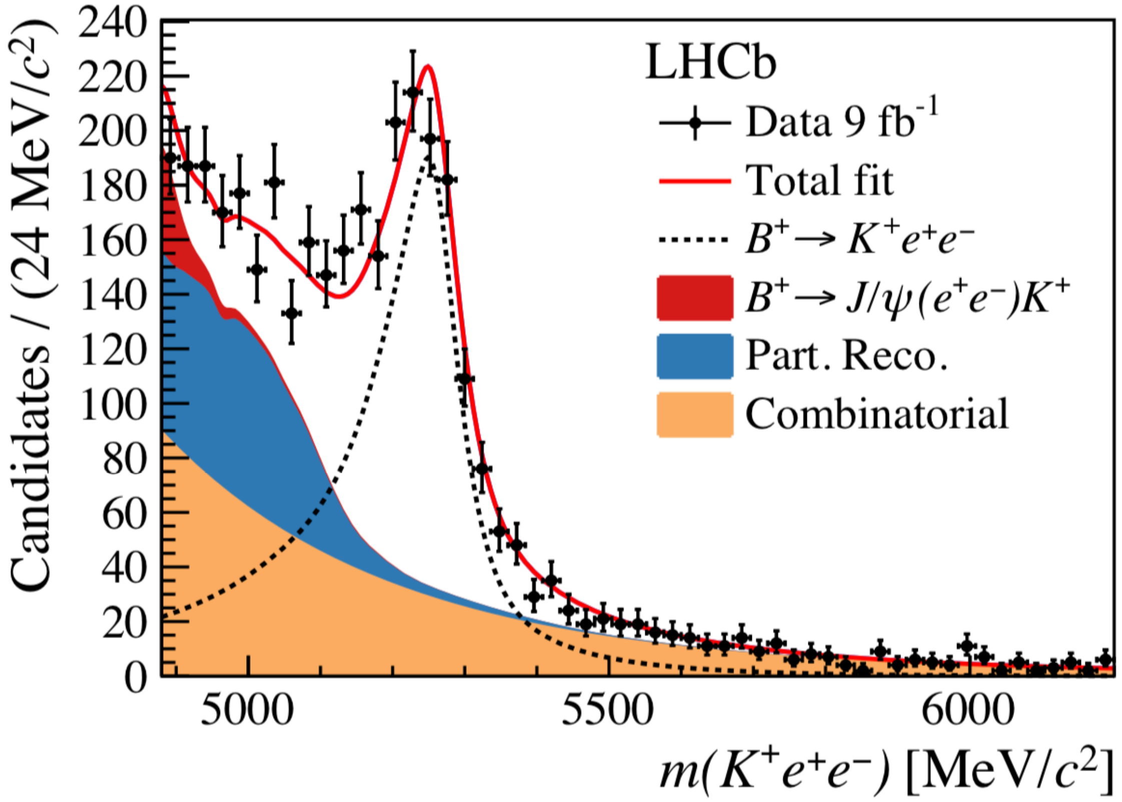
[2021] JHEP 11 (2021) 043

Internal contact author: **E. Smith + student**

Internal contact author: **E. Smith + student**

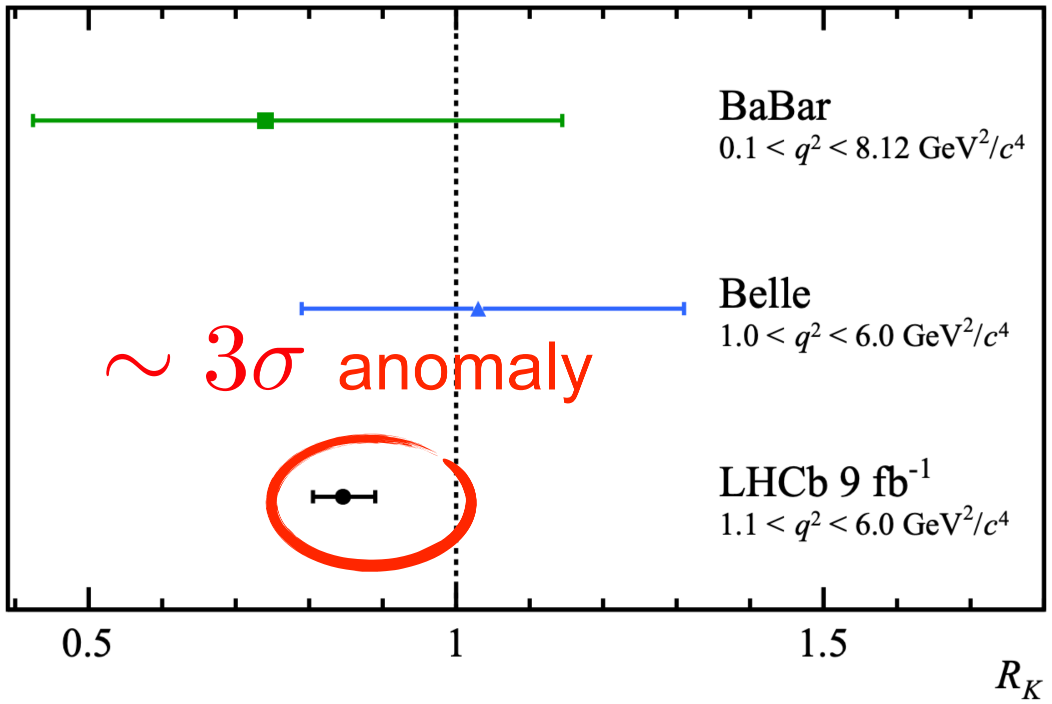
Example: Lepton Flavour Universality





$$R(K) = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

Precisely predicted to be ~1 in SM



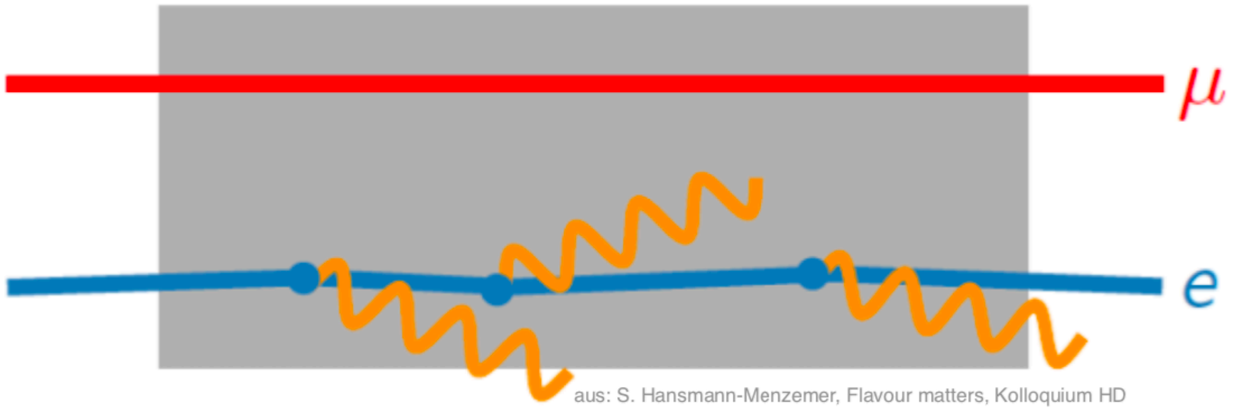
$\sim 3\sigma$ anomaly

[2021] accepted by Nature Physics

arXiv:2103.11769 I coordinated as working group convenor

I currently measure LFU in, $R(X)$, for $X = K^{*0}, \phi$

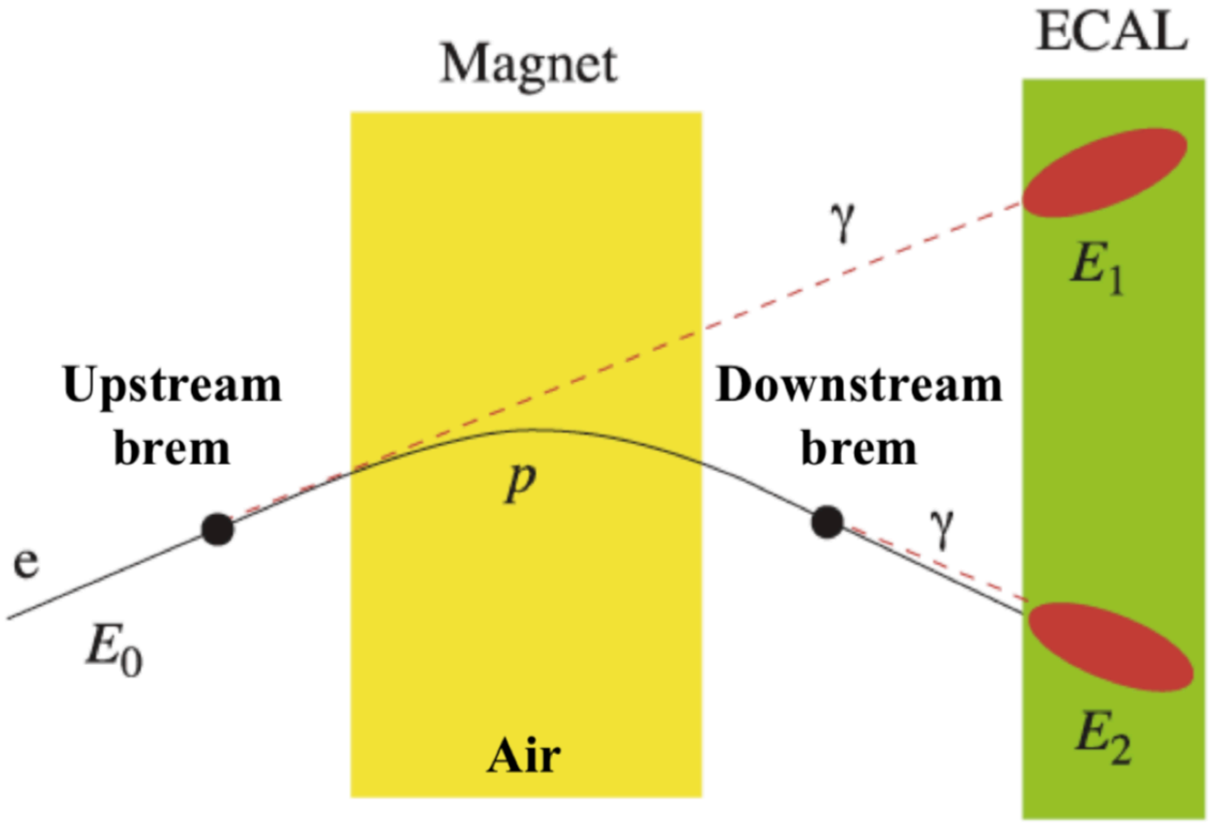
Challenges with electrons



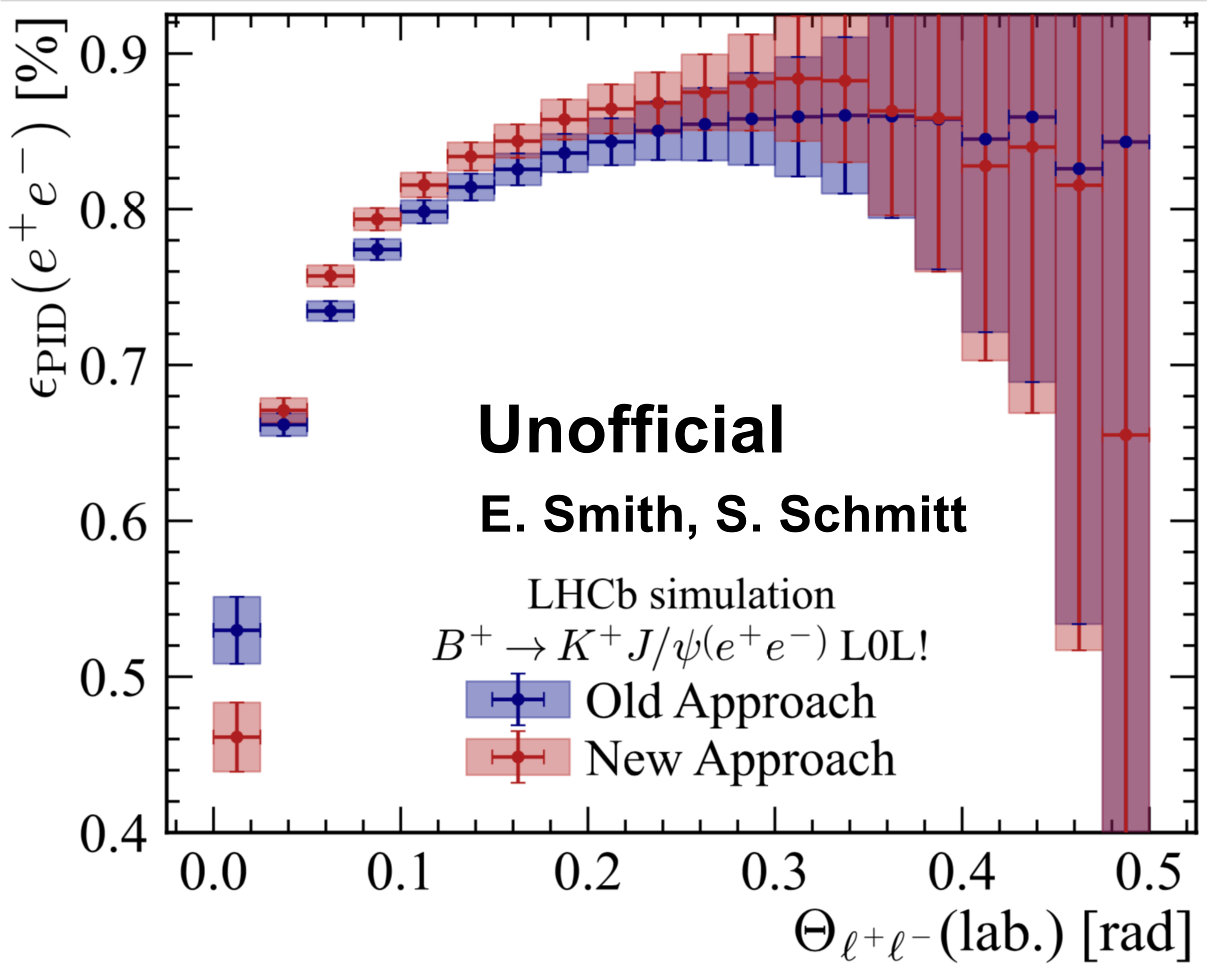
aus: S. Hansmann-Menzemer, Flavour matters, Kolloquium HD

$m_e << m_\mu$

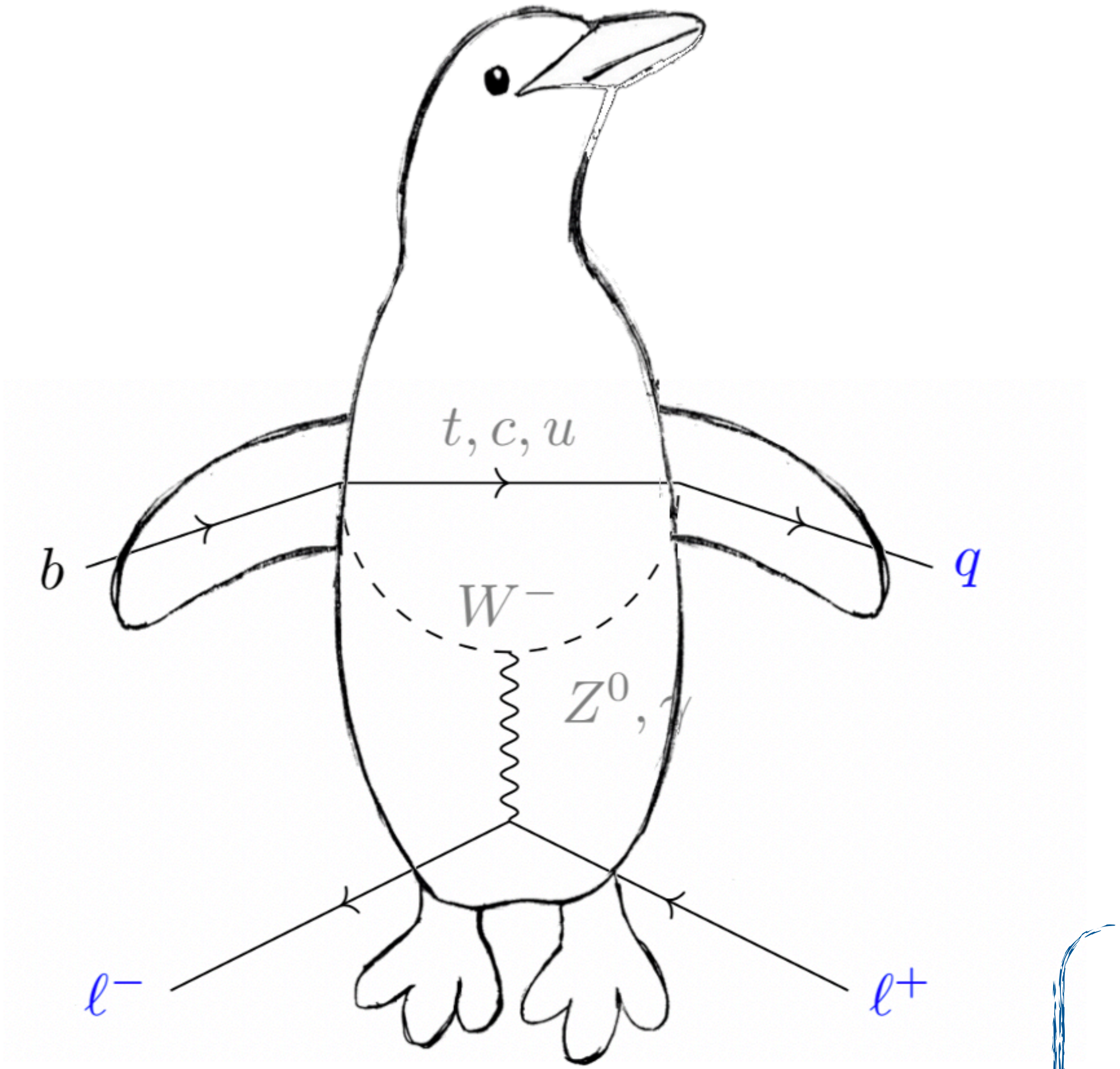
➡ Bremsstrahlung



Understanding electron detector-response description in simulation vital



Electroweak Penguins



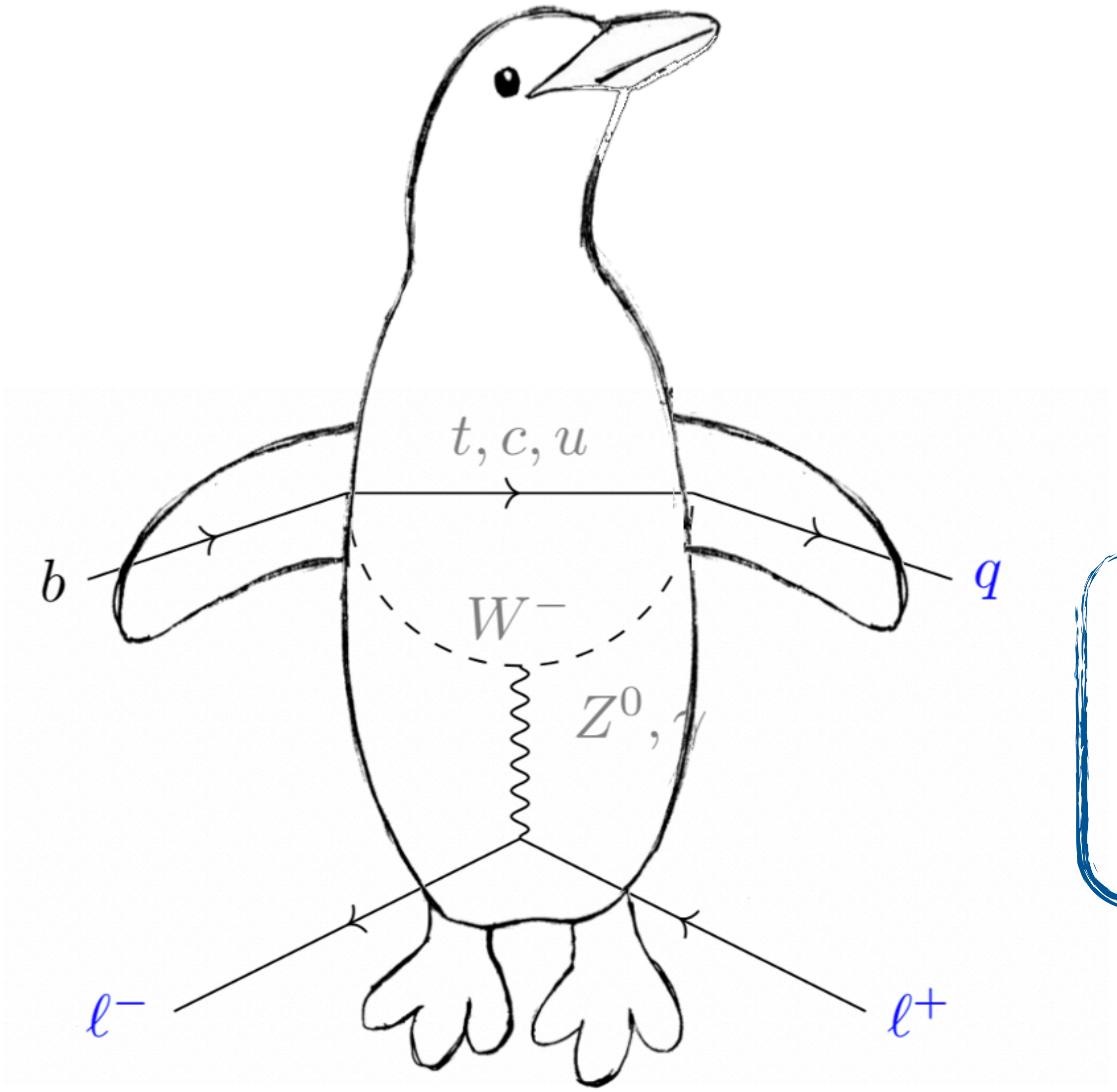
$$b \to q\ell^+\ell^-$$

ℓ = μ e τ

difficulty →

SM is agnostic to lepton type (Lepton Flavour Universality) but **experimental challenges differ**

Electroweak Penguins



$$b \to q\ell^+\ell^-$$

$$q = s \quad d$$

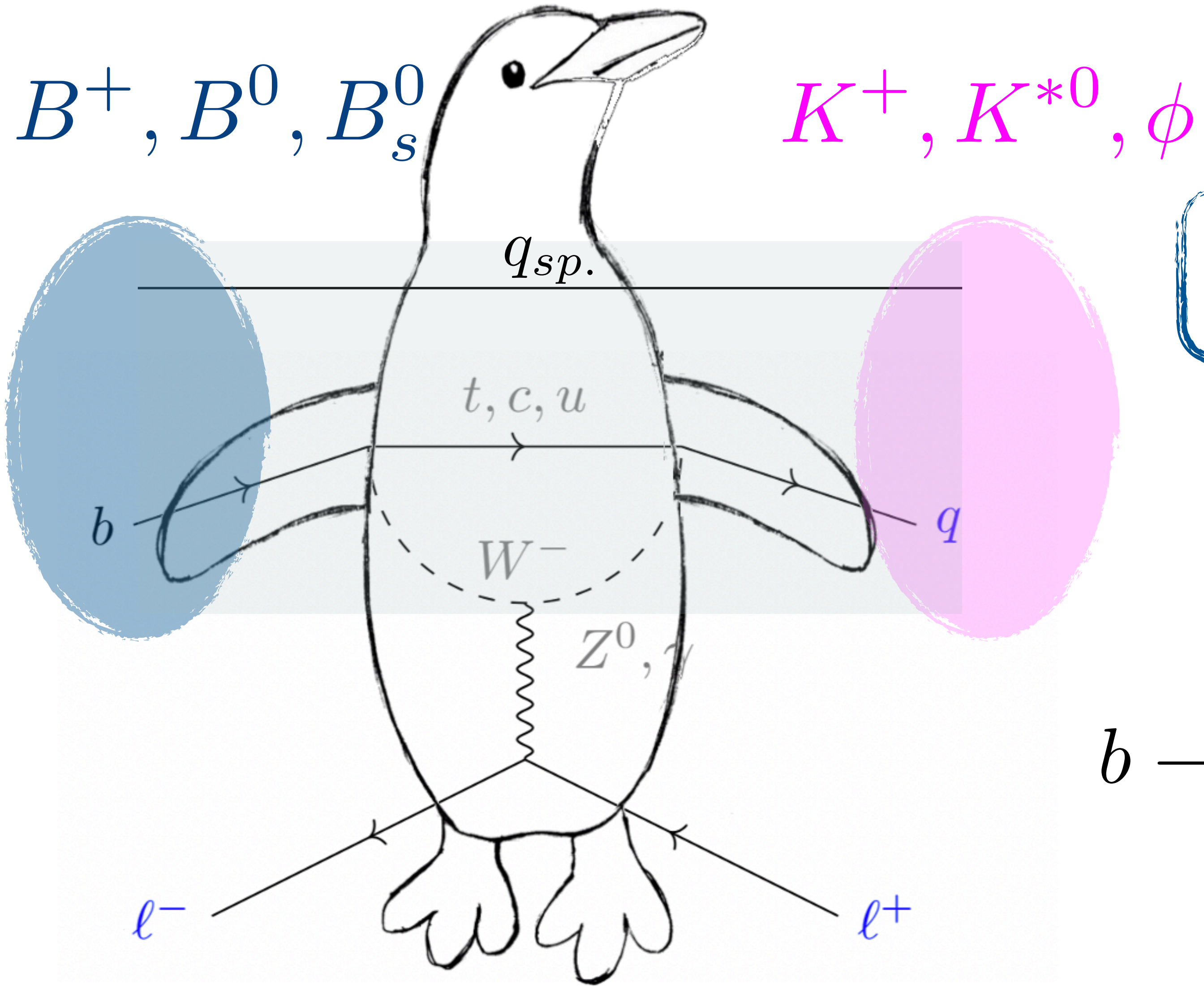
$$b \to s\ell^+\ell^- \sim 25 \times b \to d\ell^+\ell^-$$

$$\ell = \mu \quad e \quad \tau$$

difficulty →

Most analyses to date on $b \to s\ell^+\ell^-$, as $b \to d\ell^+\ell^-$ very suppressed

Electroweak Penguins



$$b \to q\ell^+\ell^-$$

$$\boxed{q_{sp.} = \quad u, d, s}$$

$$q \;=\; s \quad d$$

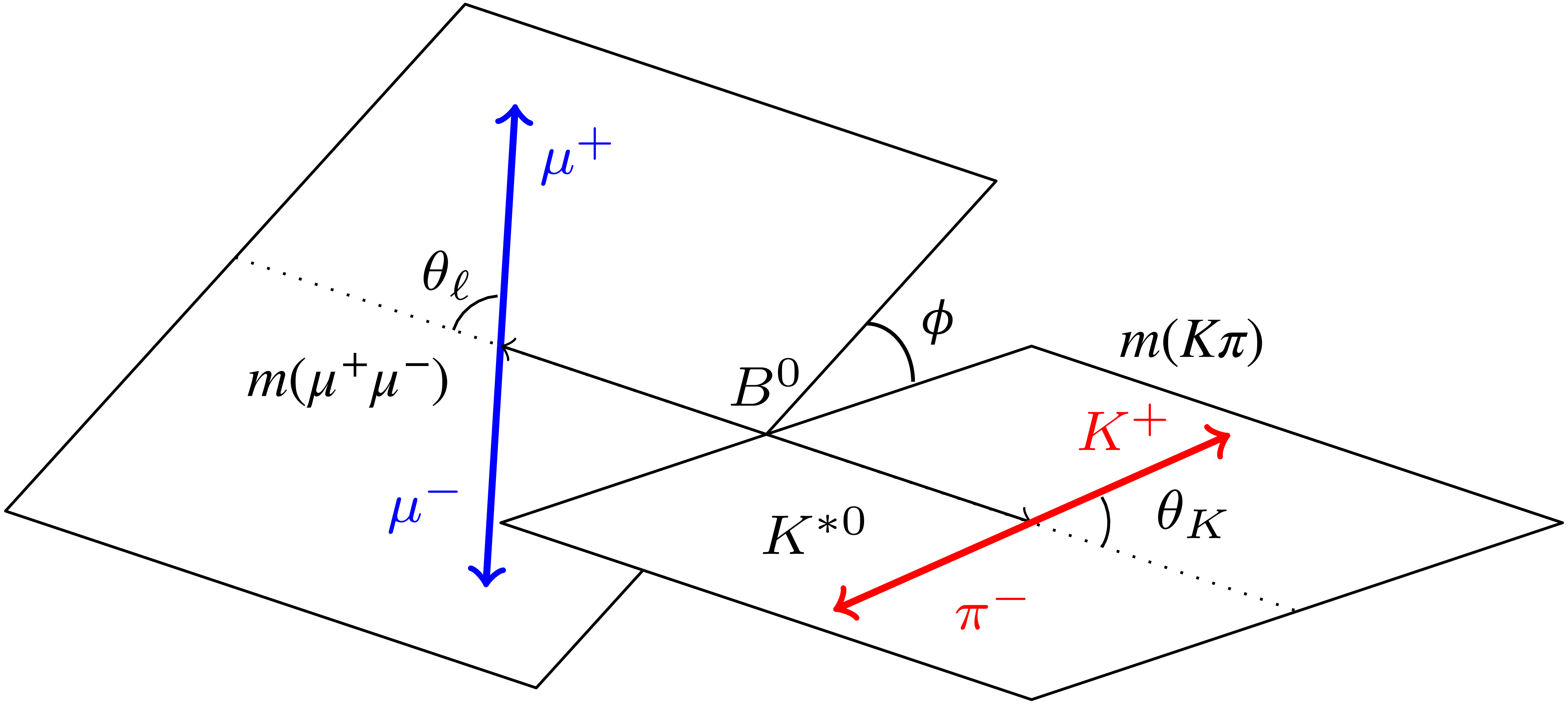
$$b \to s\ell^+\ell^- \sim 25 \times b \to d\ell^+\ell^-$$

$$\ell \;=\; \mu \quad e \quad \tau$$

difficulty →

Different spectator quarks gives different final-state particles

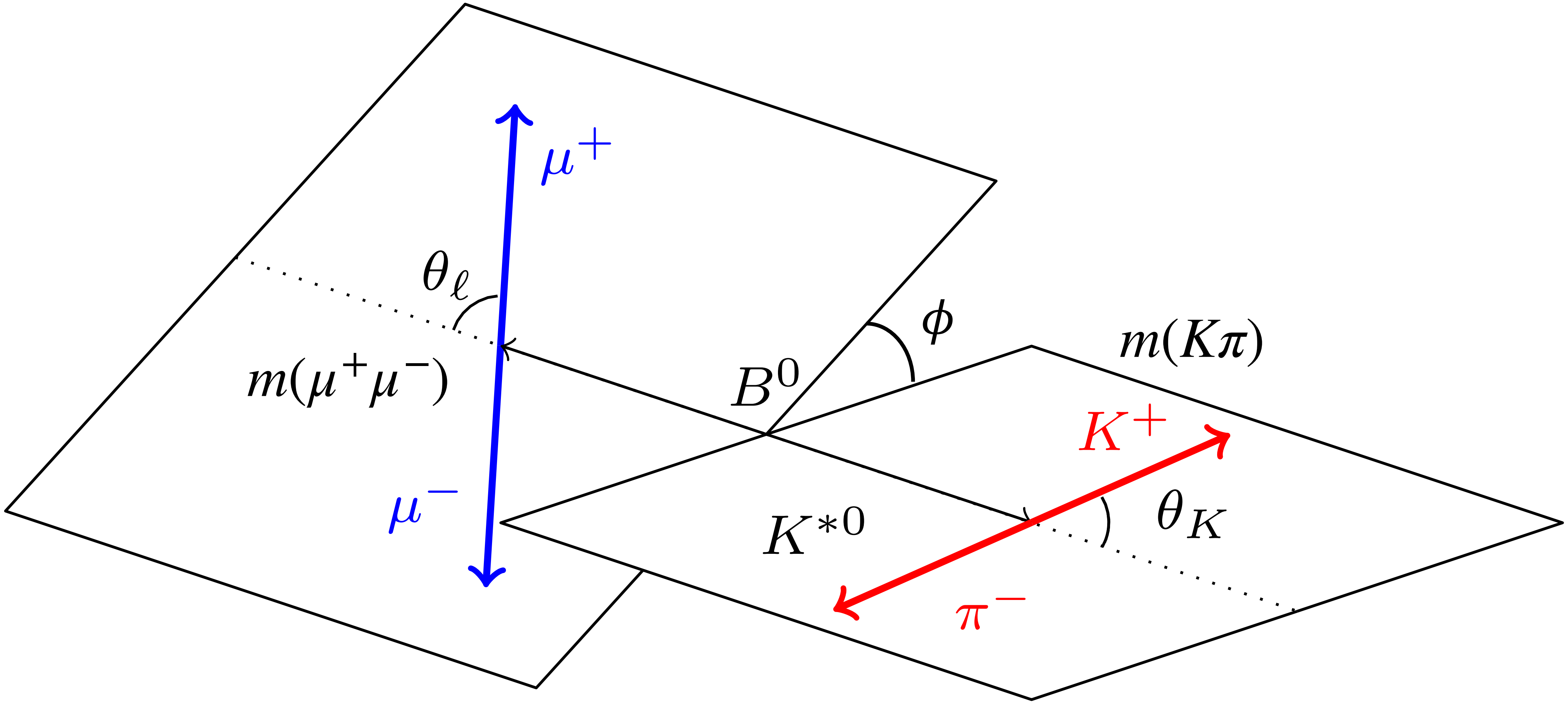
What do we want to measure?



5 degrees of freedom in a 4-body decay:

- 3 angles
- Invariant mass of hadron system
- Invariant mass of dilepton system
  $(q^2 = m^2(\ell\ell))$

What do we want to measure?



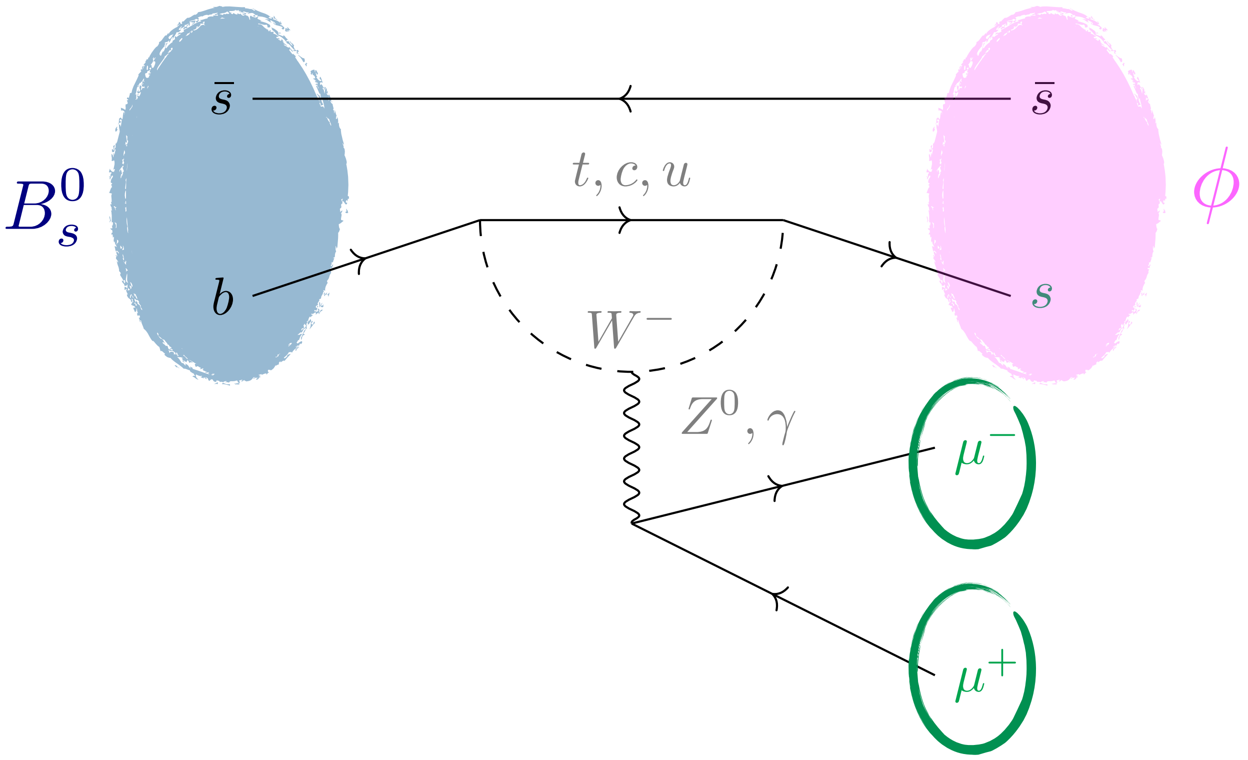
5 degrees of freedom in a 4-body decay:

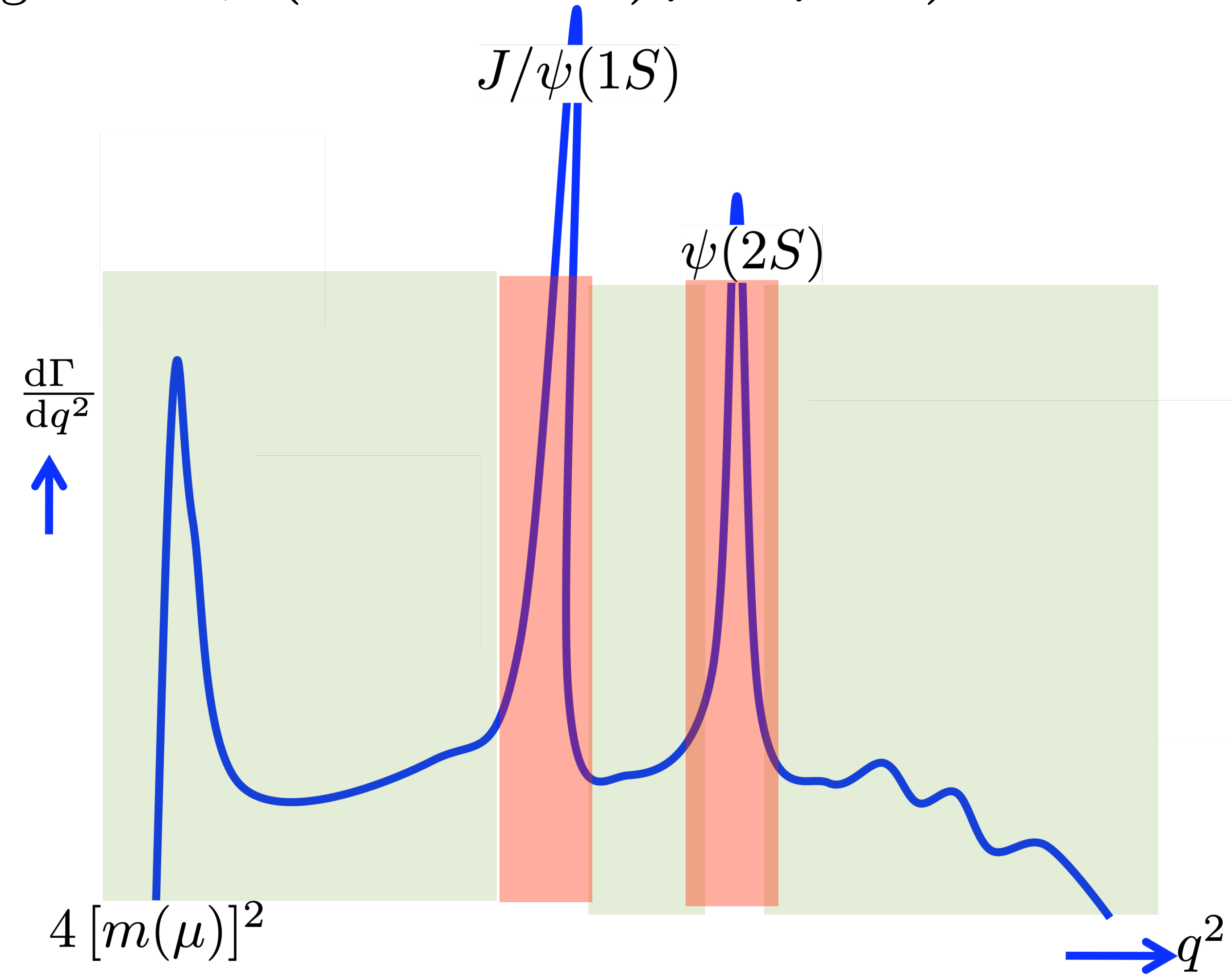
- 3 angles
- Invariant mass of hadron system
- Invariant mass of dilepton system ($q^2 = m^2(\ell\ell)$)

$\Gamma(q^2)$ = branching fraction ($\mathscr{B}$) measurement

$\Gamma(m(hh), q^2, \Omega)$ = angular analysis

Example: $\mathcal{B}(B_s^0 \to \phi(K^+K^-)\mu^+\mu^-)$





q² = [invariant mass of dilepton system]²

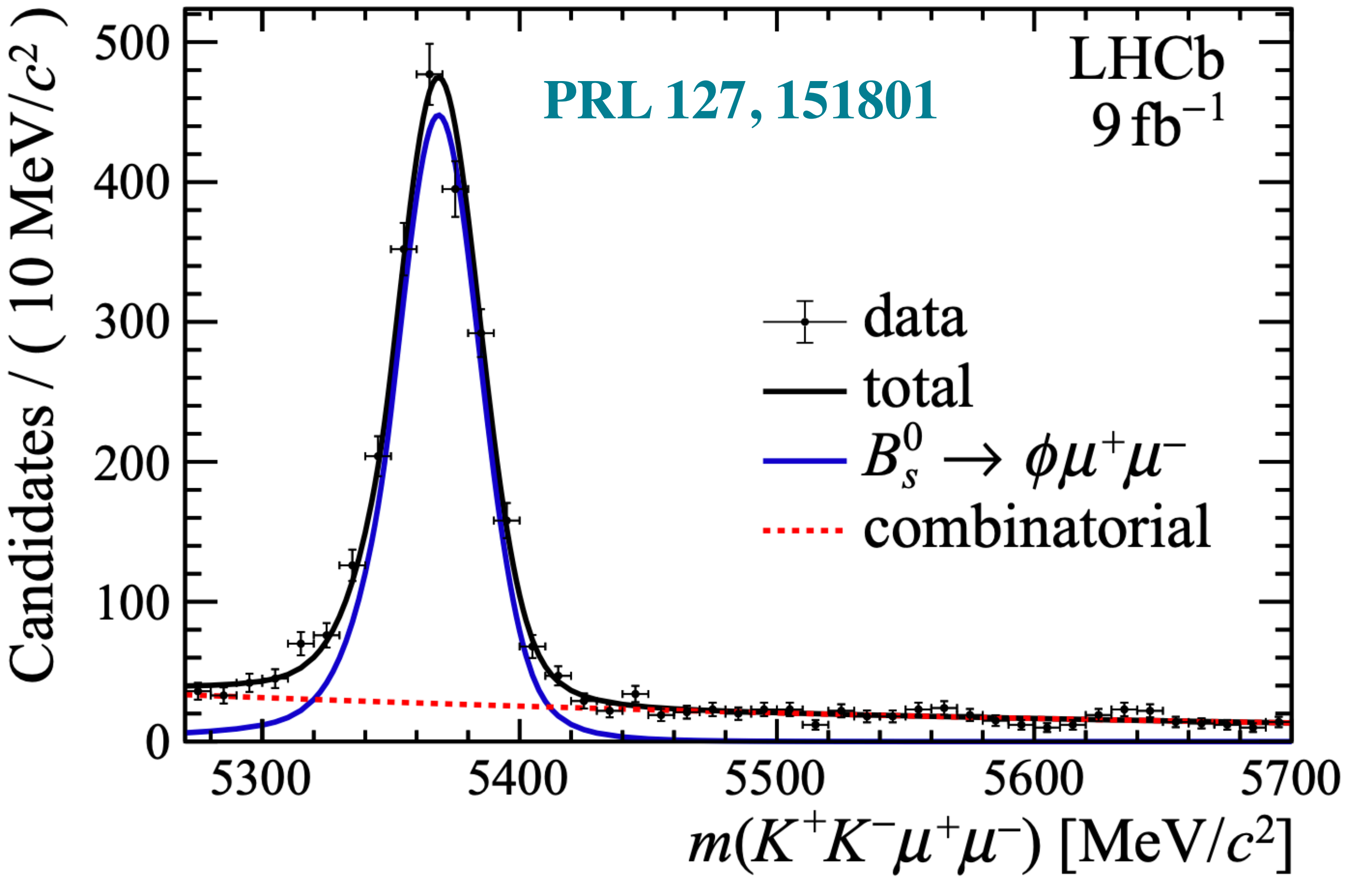
$\mathcal{B}$ proportional to decay rate, Γ

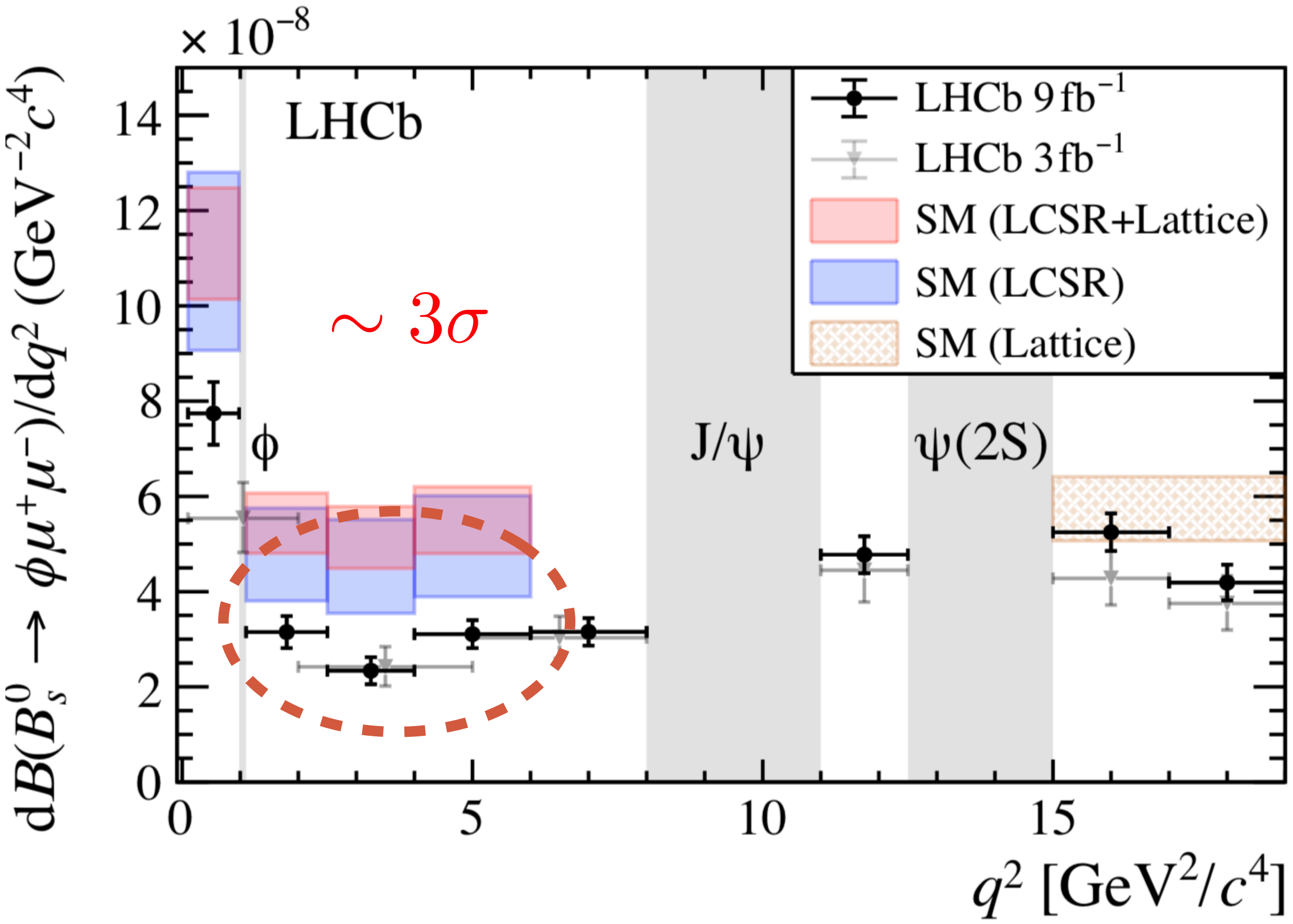
Measure $d\mathcal{B}/dq^2$ to capture underlying q² distribution

✓ $b \to s\mu\mu$ decays dominate

✗ $b \to s\bar{c}c[\to \mu^+\mu^-]$ decays dominate

Example: $\mathcal{B}(B_s^0 \to \phi(K^+K^-)\mu^+\mu^-)$





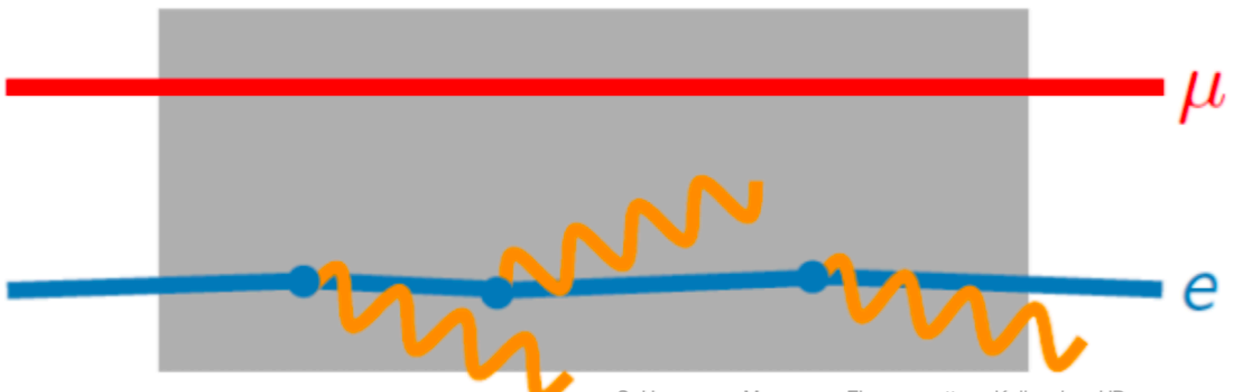
$\sim 3\sigma$

[2021] **PRL 127, 151801**

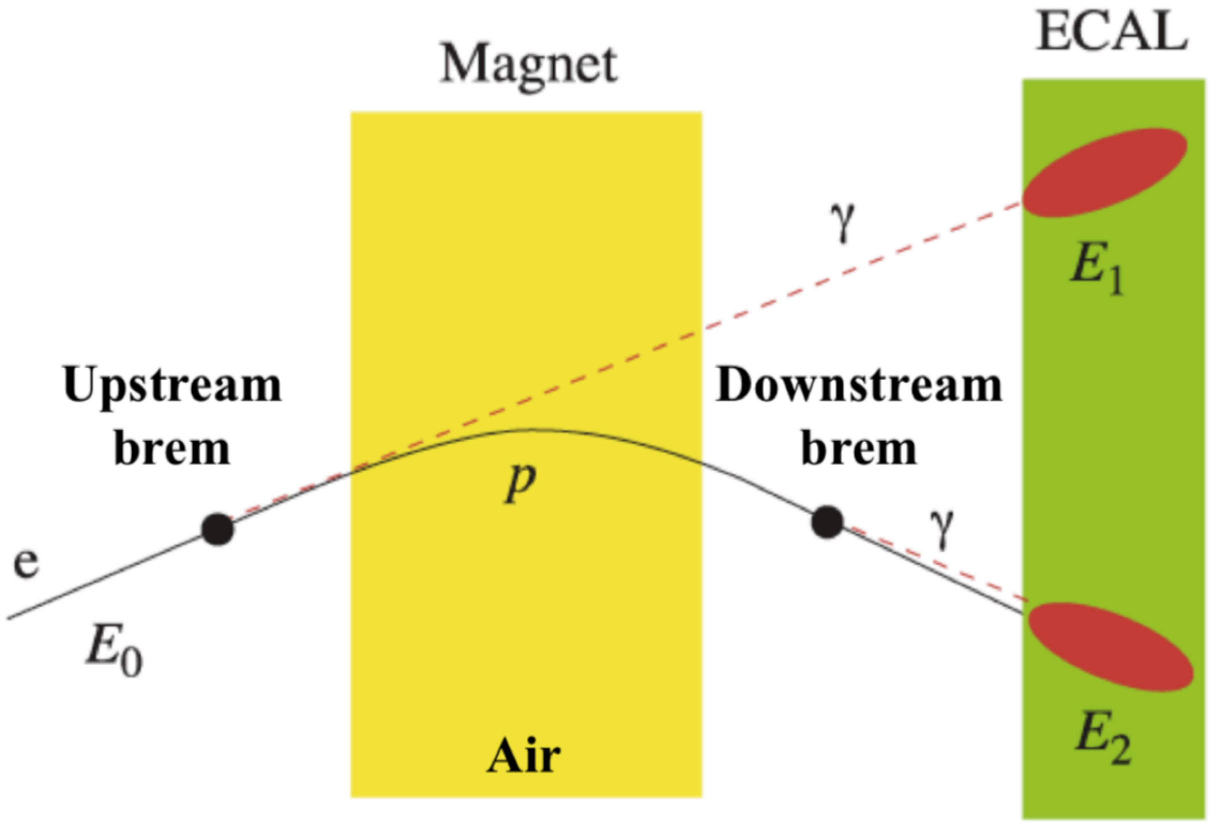
Local discrepancy with SM hypothesis at level of 3.6σ in region $1.1<q^2<6.0$ GeV (p-value ~ 0.0003)

[in same paper we also made first observation of a spin-2 $b \to s\ell^+\ell^-$ transition with the decay mode $B_s^0 \to f_2^{'}\mu^+\mu^-$]

Challenges with electrons



aus: S. Hansmann-Menzemer, Flavour matters, Kolloquium HD



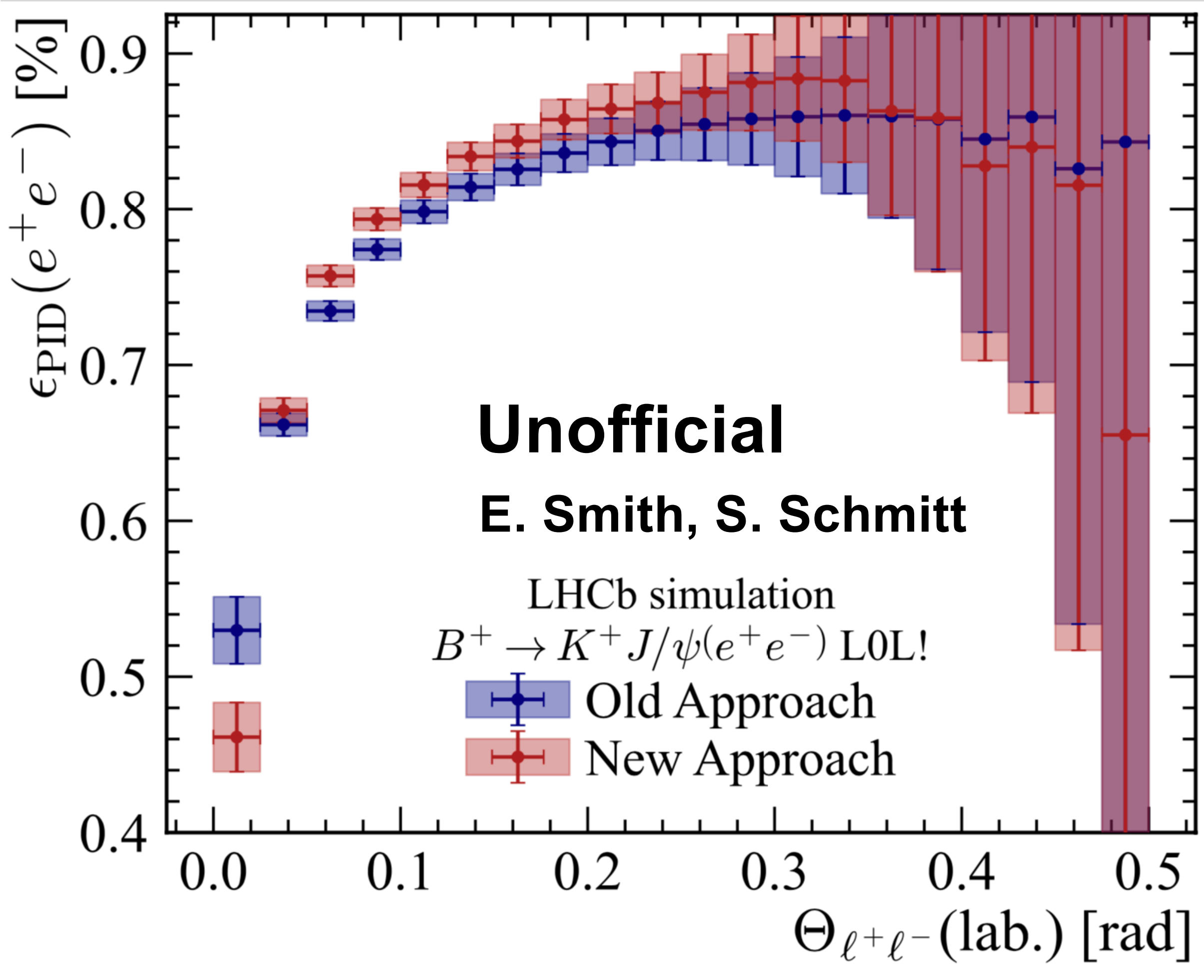
$m_e << m_\mu$

➡ Bremsstrahlung

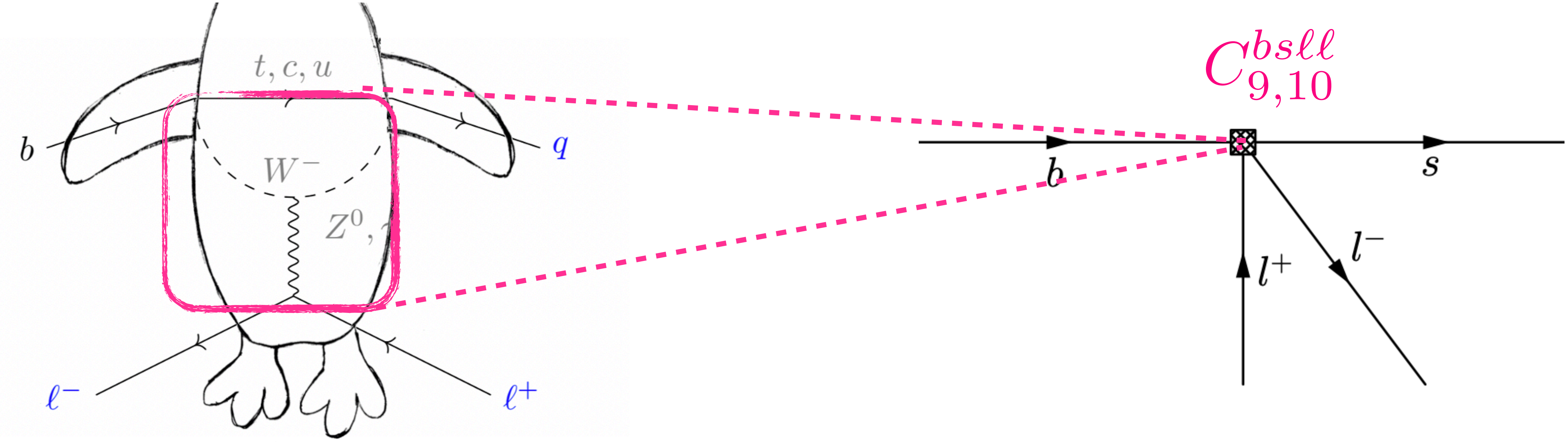
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

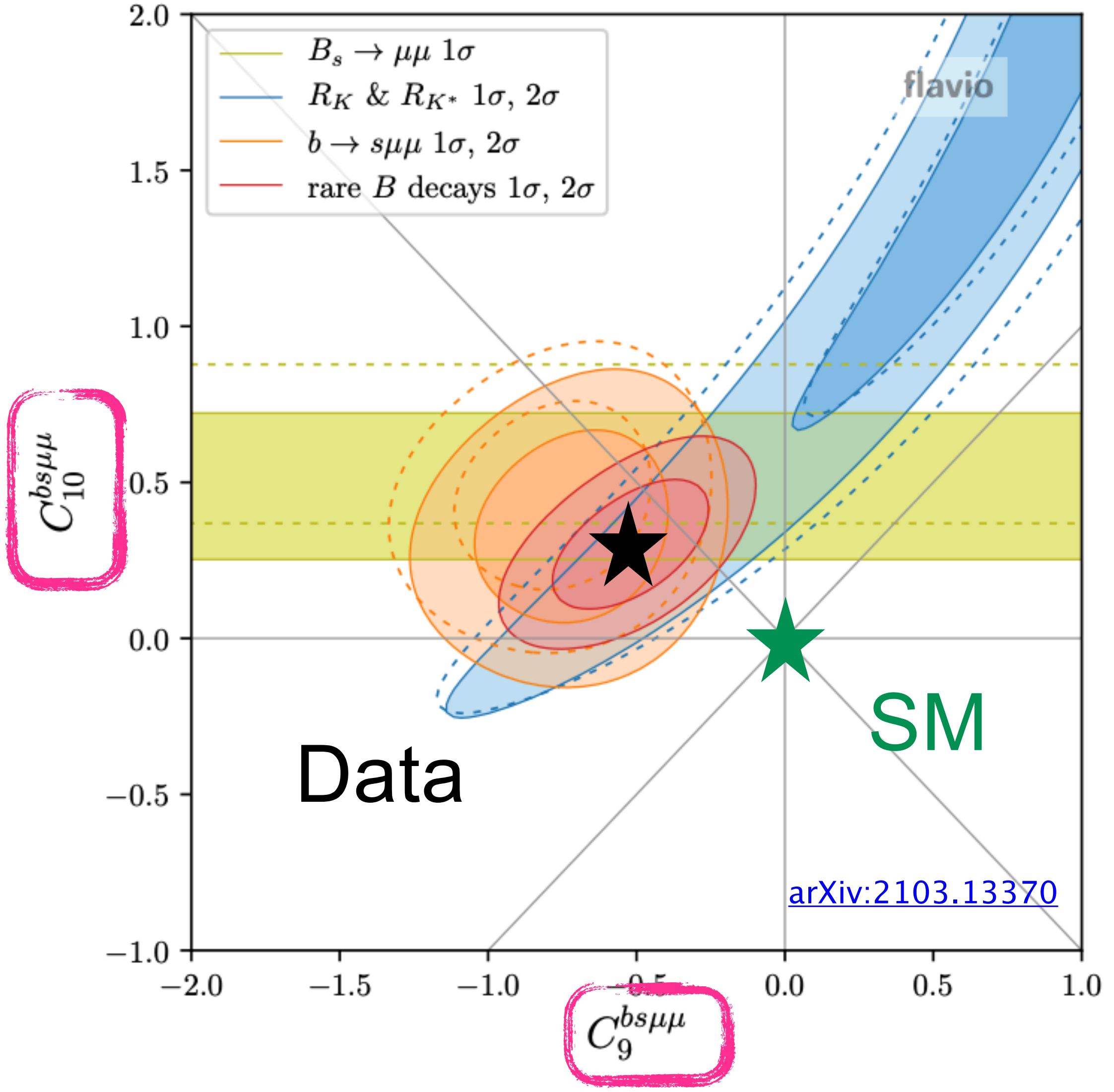
Understanding electron detector-response description in simulation vital

Build on my current research



The Flavour Anomalies

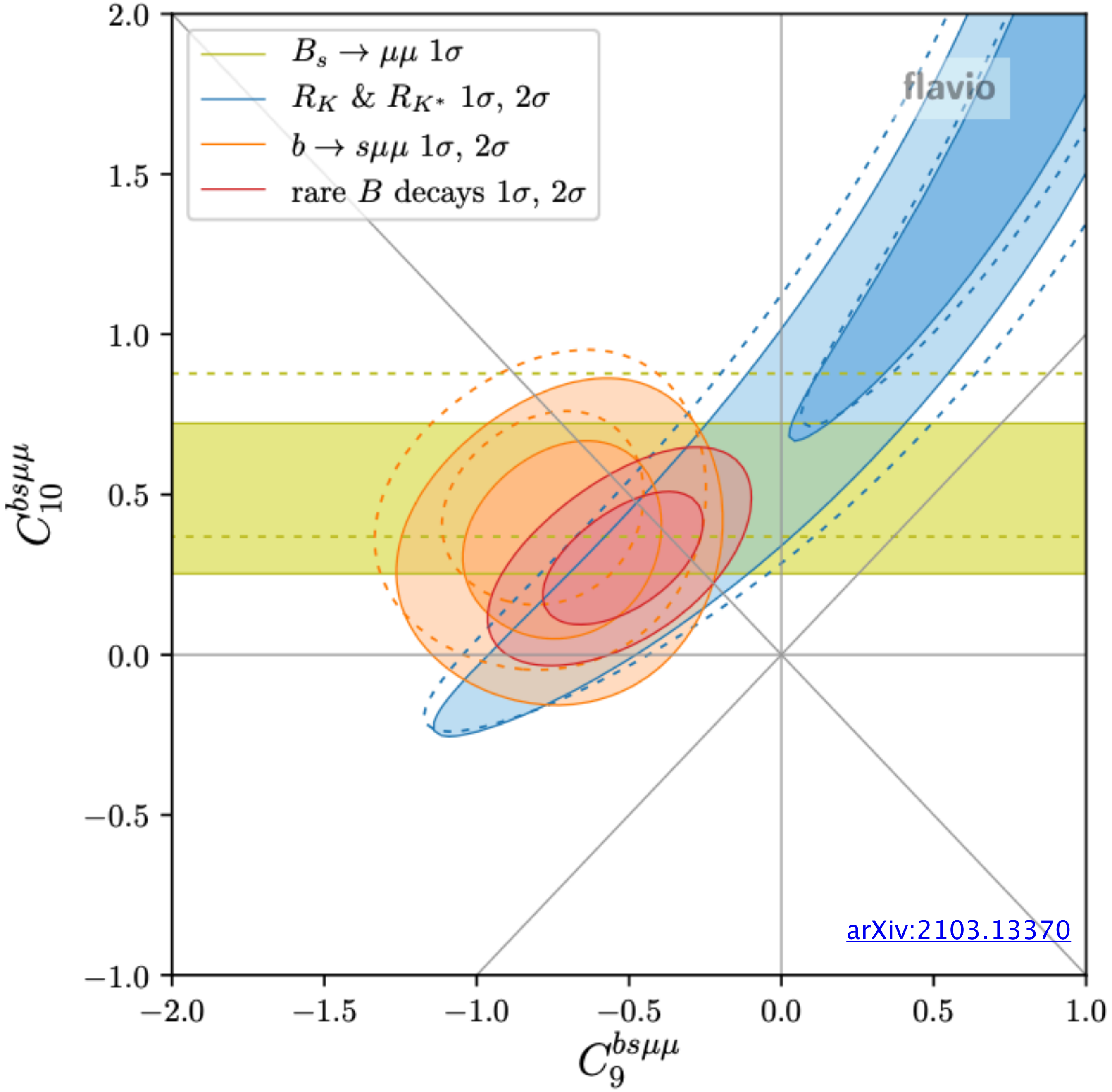




Combine all $b \to s\ell^+\ell^-$ measurements and fit for $b \to s\ell^+\ell^-$ effective couplings

~ 7σ tension with SM when combined

The Flavour Anomalies



arXiv:2103.13370

Lepton Flavour Universality

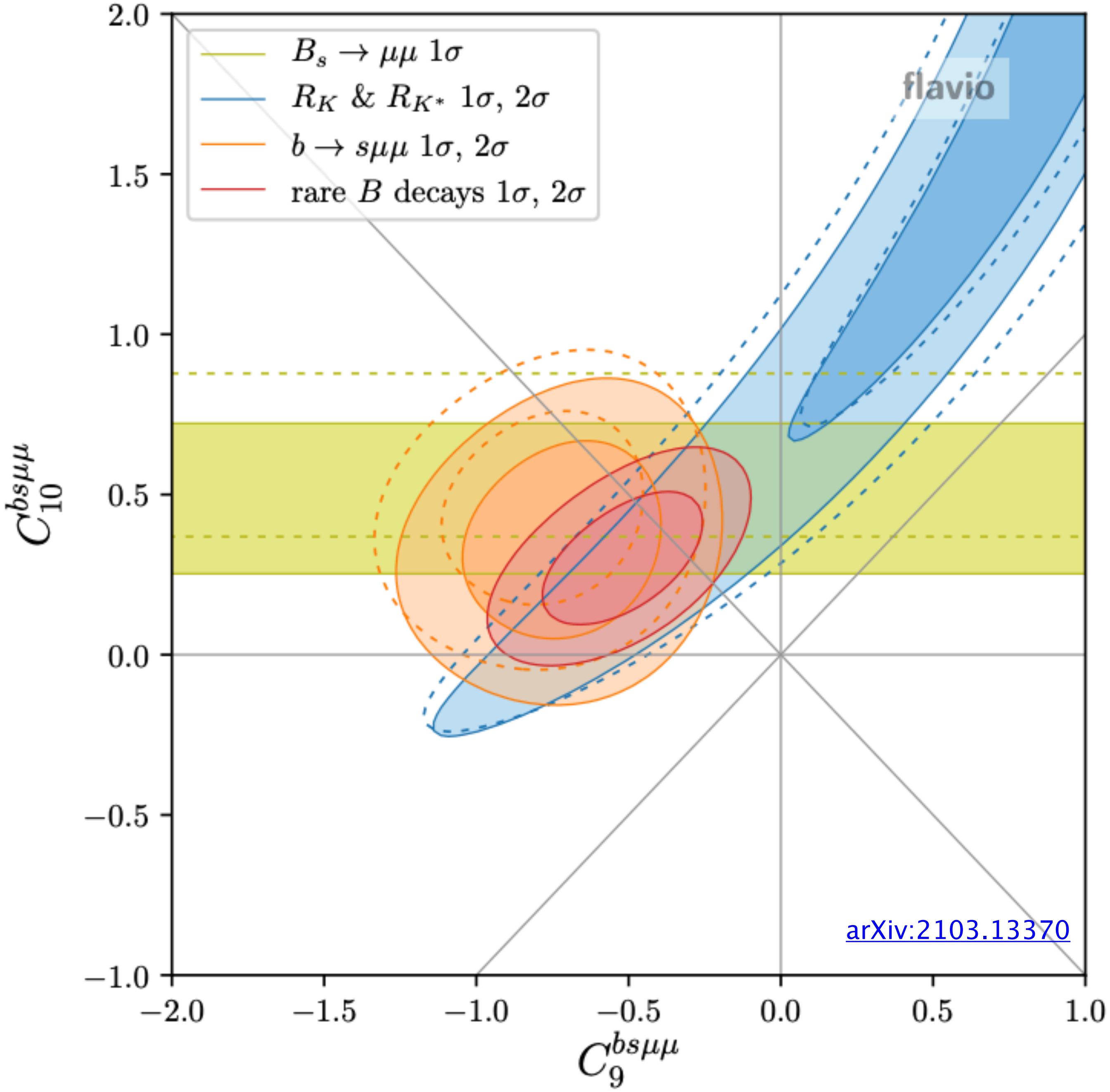
✓

$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$$

Very precisely known in SM

Gives a 4σ tension

The Flavour Anomalies



arXiv:2103.13370

Lepton Flavour Universality

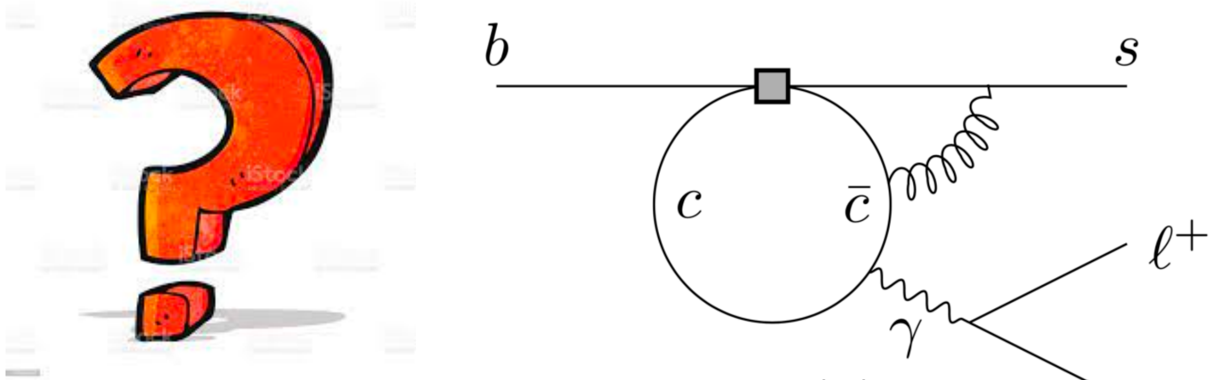
✓

$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$$

Very precisely known in SM

Gives a 4σ tension

$\mathcal{B}(b \to s\mu\mu), b \to s\mu\mu$ angular



$$b \to sc\bar{c} >> b \to s\ell\ell$$

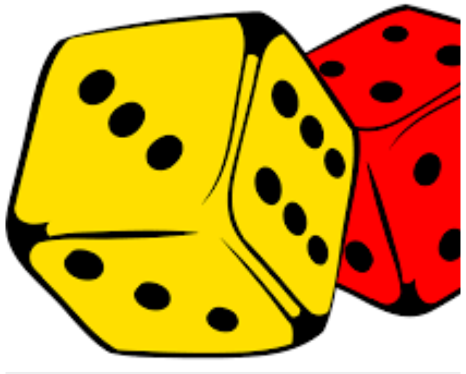
Non-local charm-loop

Cannot be derived from first principles

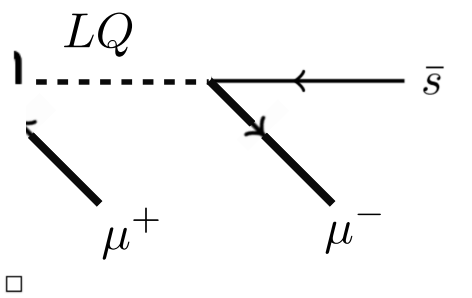
The b->smumu anomalies: what is causing them?

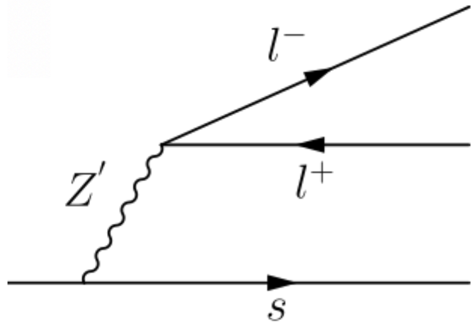
Fluke

Statistical fluk



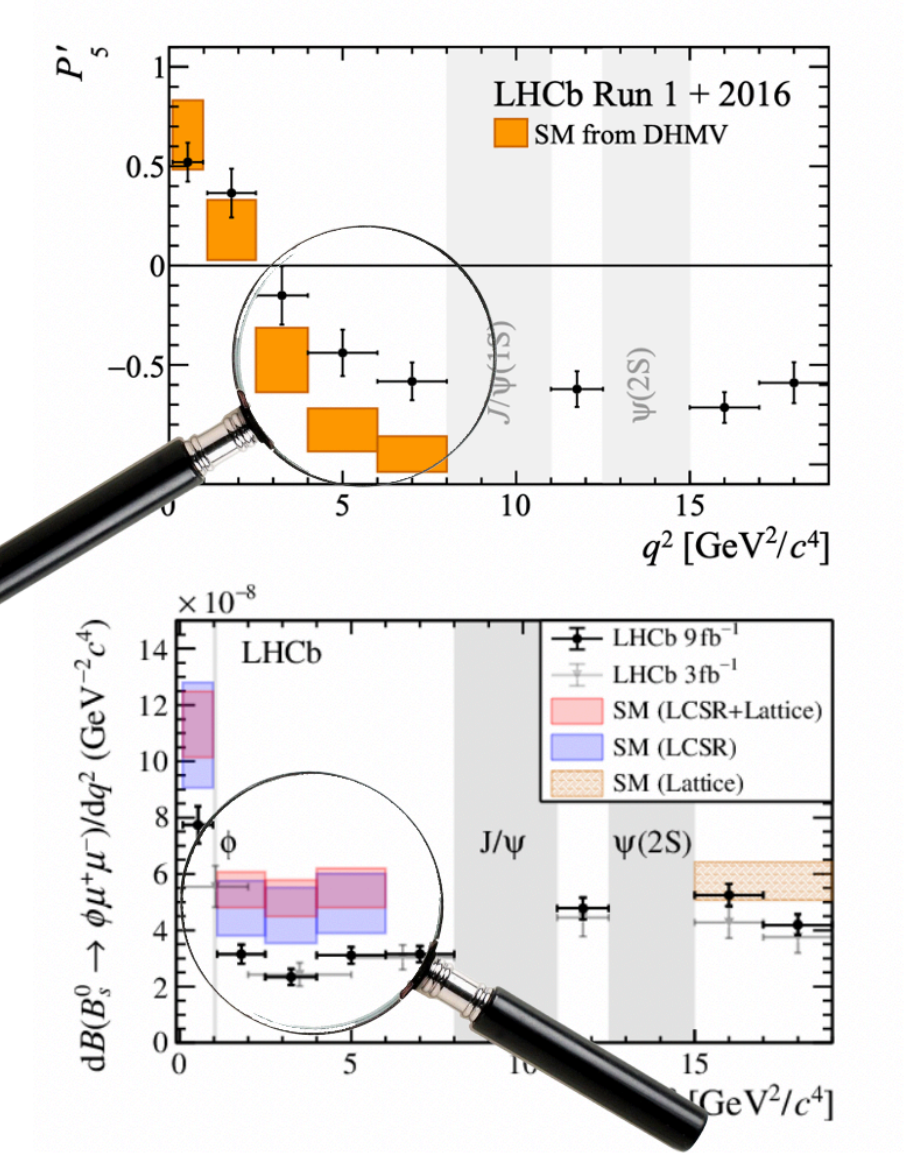
Physics





The Flavour anomalies: what is causing them?

Fluke



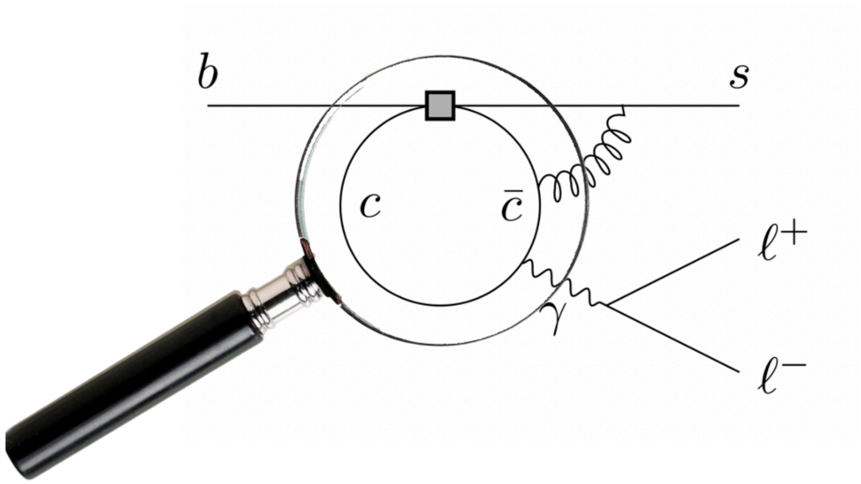
Add new data

New LHCb
detector running
from this year

Fallacy

New Physics

Measuring the charm-loop using data



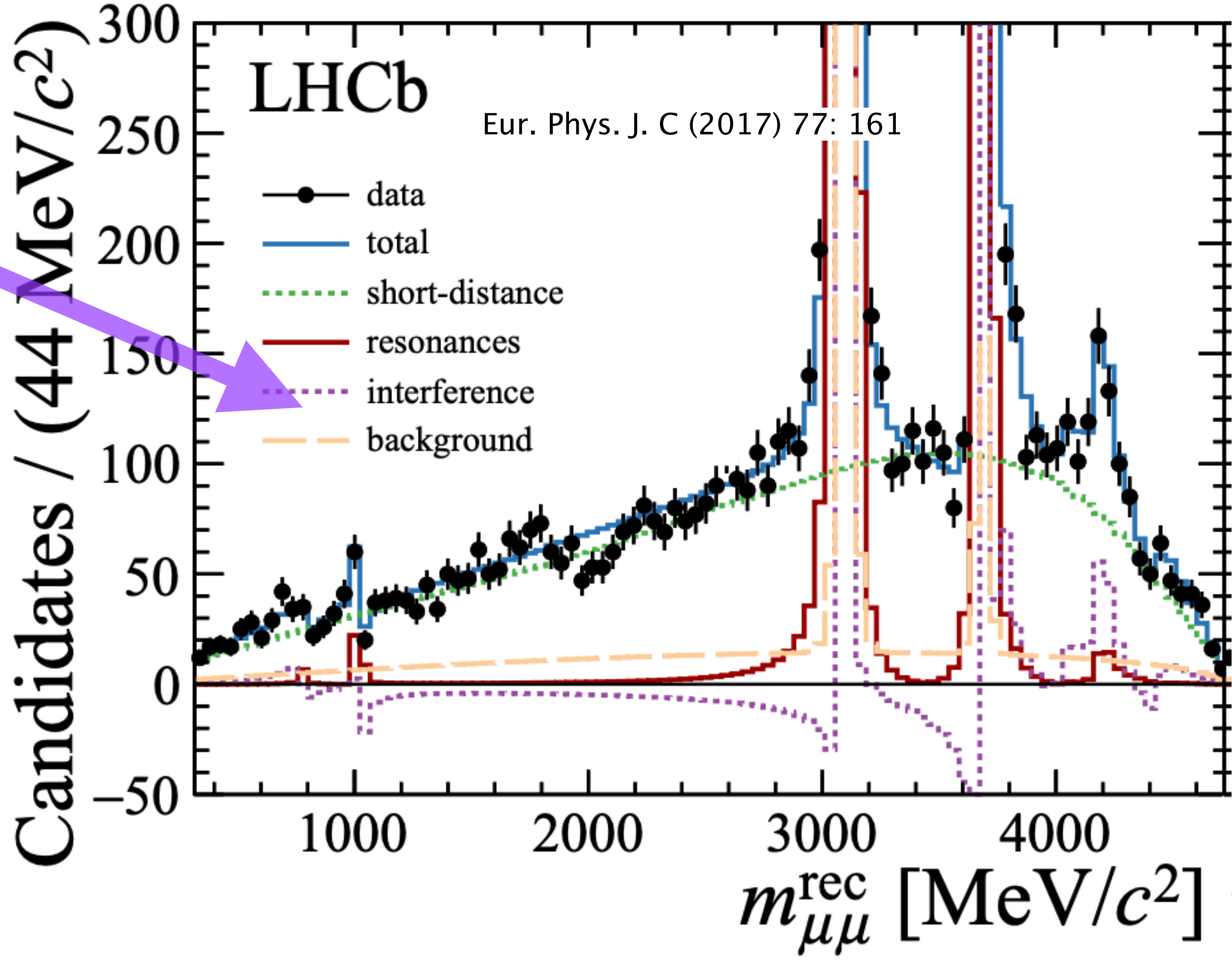
Understanding effects of charm-loops on b->sll decays central to understanding the flavour-anomalies

Fit for effective couplings directly, allowing interference effects from charm-loops to be measured

Achieved by fitting both the angular **and q²** distributions of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

Fit for interference in data

$B^0 \to K^{*0}\mu^+\mu^-$ more complex, but more information



Eur. Phys. J. C (2017) 77: 161

C

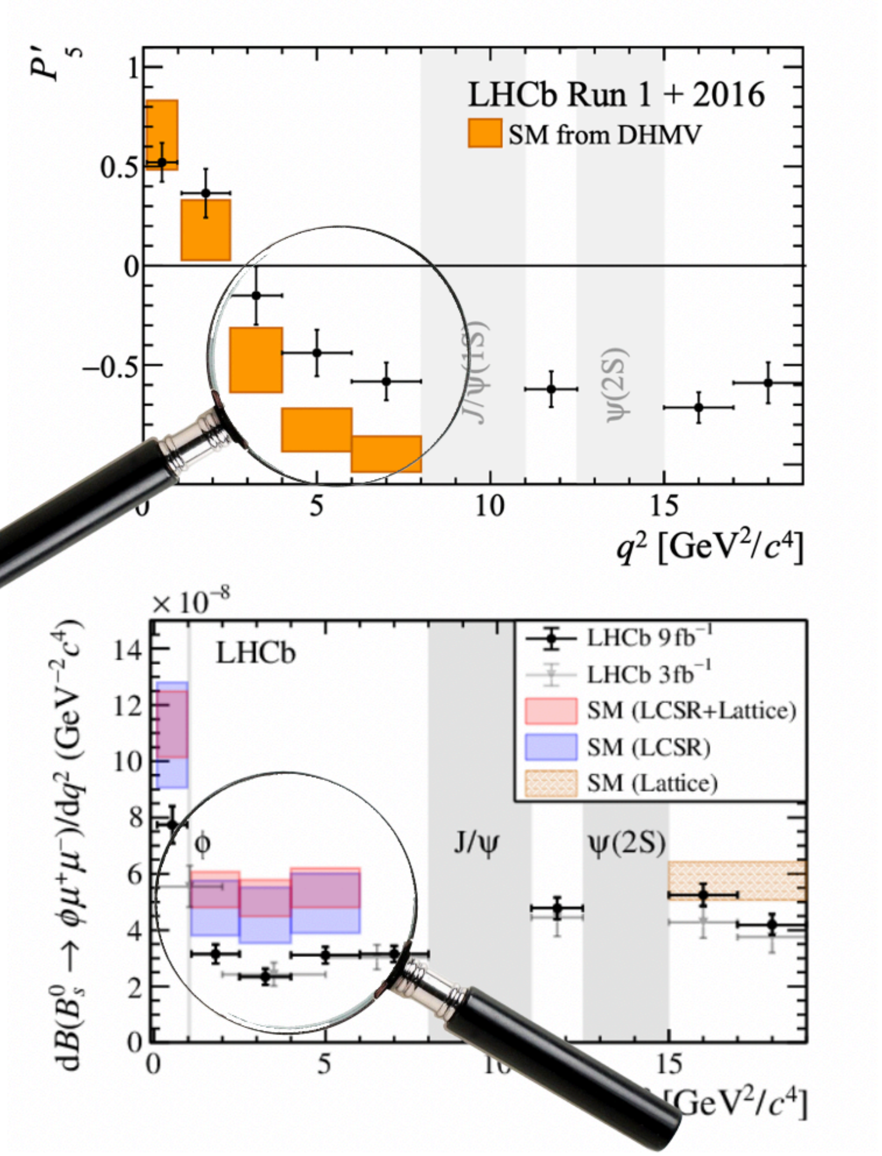
Proposal

The Flavour anomalies: what is causing them?

Fluke	Fallacy	New Physics

The Flavour anomalies: what is causing them?

Fluke



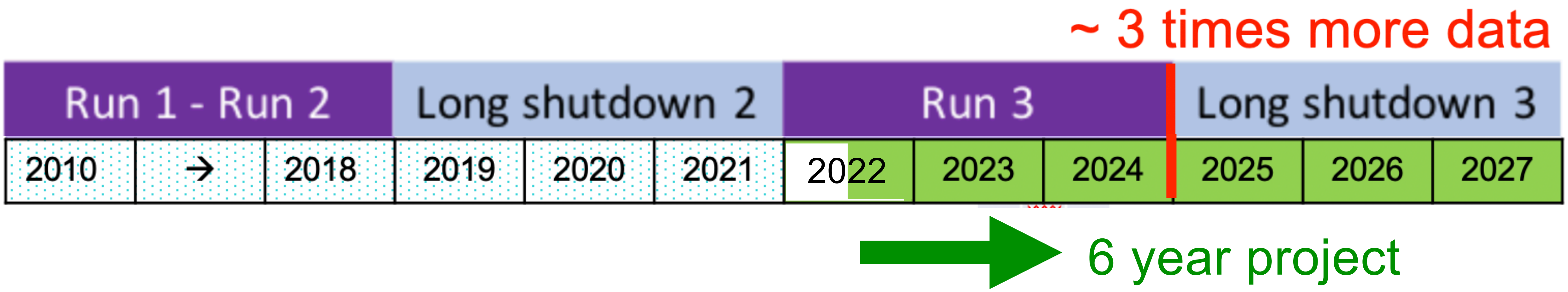
Add more data

New LHCb detector - **commissioning**

Fallacy

New Physics

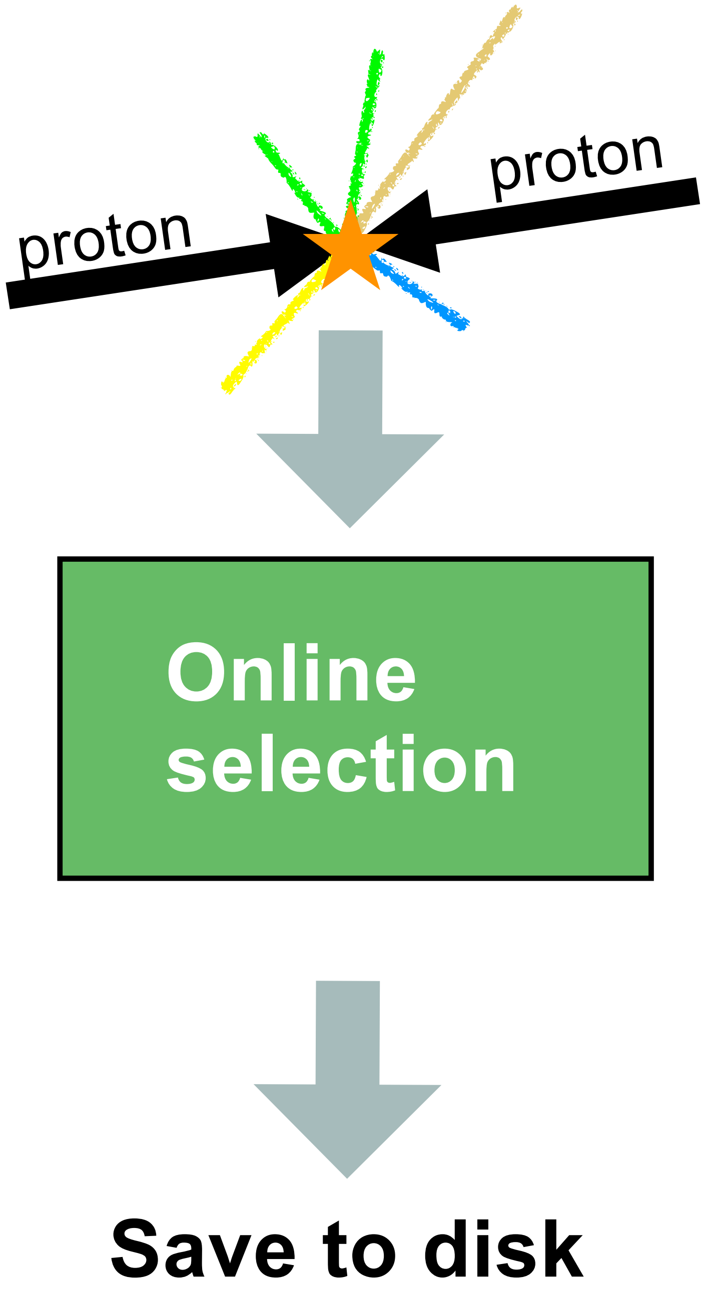
Run 3 data-taking



~ 3 times more data

Run 1 - Run 2			Long shutdown 2			Run 3			Long shutdown 3		
2010	→	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

6 year project



Online selection

Save to disk

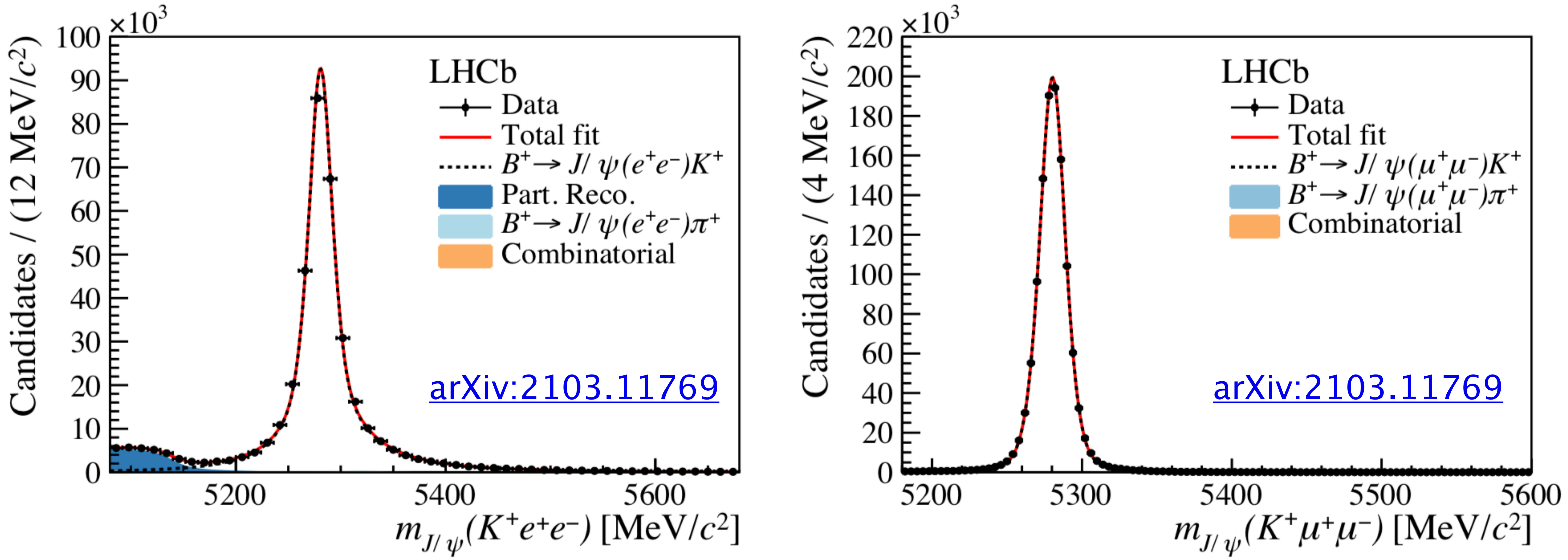
5 times higher instantaneous luminosity

Only save necessary event information

I have developed the **online selections** for Rare Decays: [LHCb-PUB-2019-013, A.Albero,.. , E.Smith,..]

Higher occupancy will also be challenging for electrons

Detector commissioning in early measurements



arXiv:2103.11769

arXiv:2103.11769

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))} = 1$$ if correctly calibrated

Requires a thorough understanding of the detector-response description in simulation for the new detector

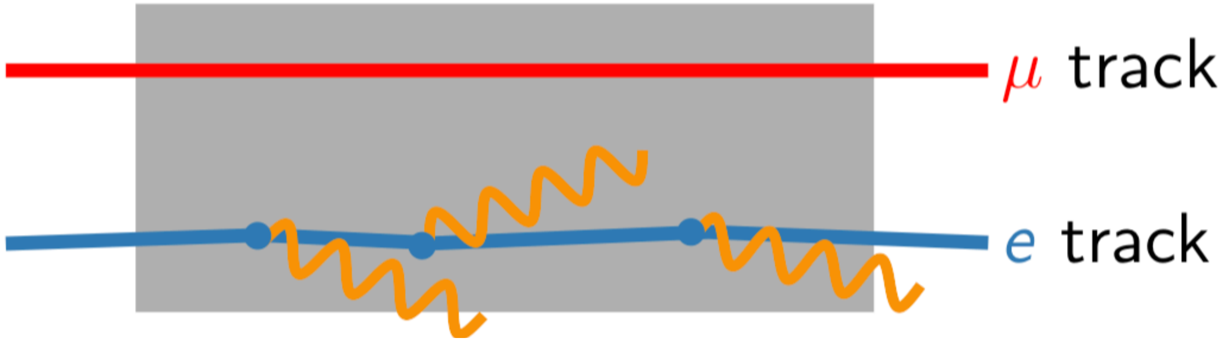
Will validate the online selections for the first time on data

Data-driven corrections to simulation developed here will be used for all electron measurements in Run 3

Electron identification and track reconstruction

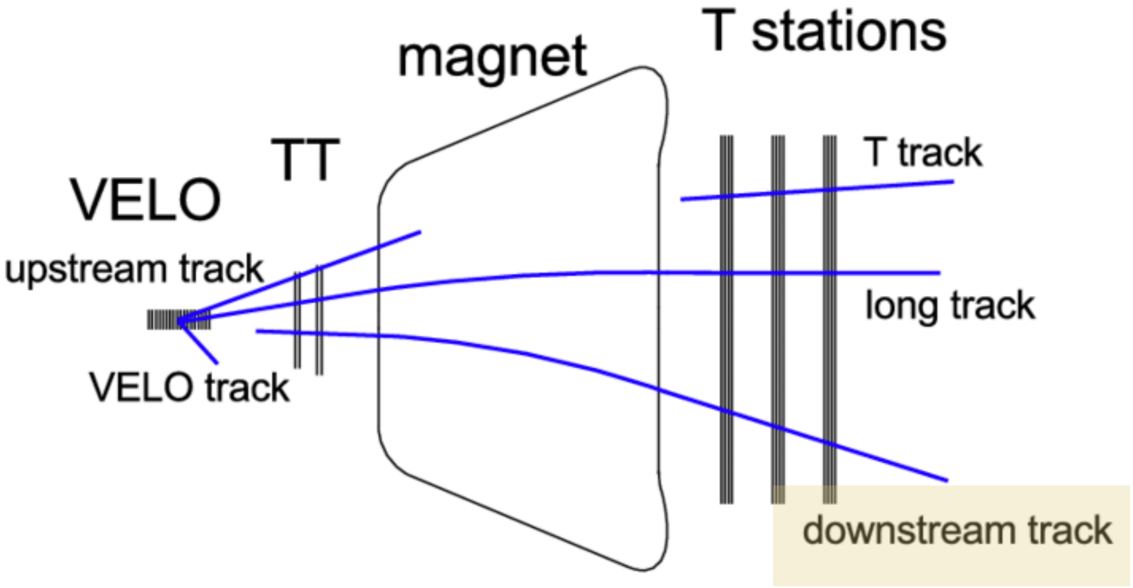
Electron identification more challenging in Run 3

Exploit additional information to improve identification



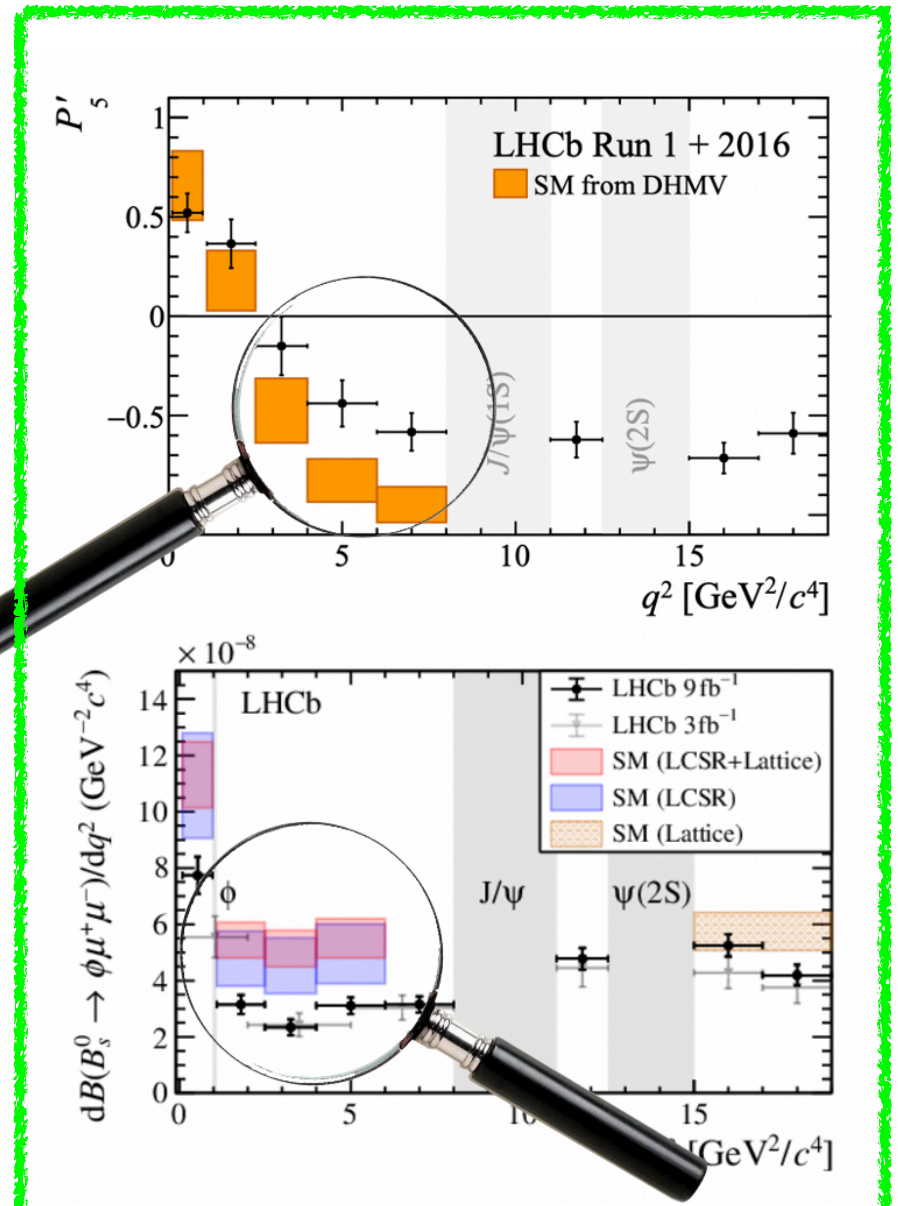
Long-lived particles like the K_s^0 are important for Rare Decay measurements

Take over effort on the maintenance and optimisation of tracking algorithm for long-lived particles (downstream tracks)



The Flavour anomalies: what is causing them?

Fluke



Add more data

New LHCb detector - **commissioning!**

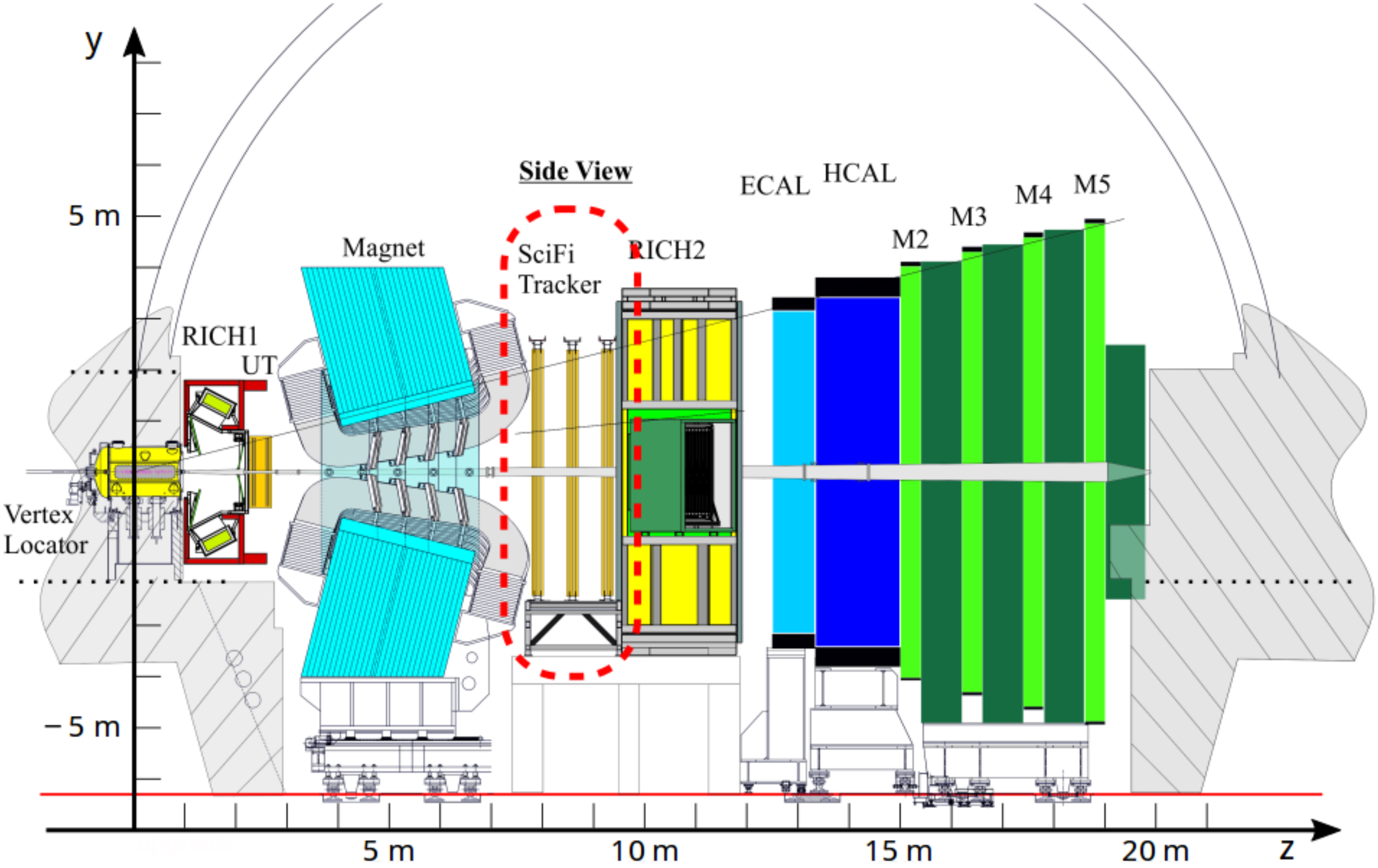
Fallacy

New Physics

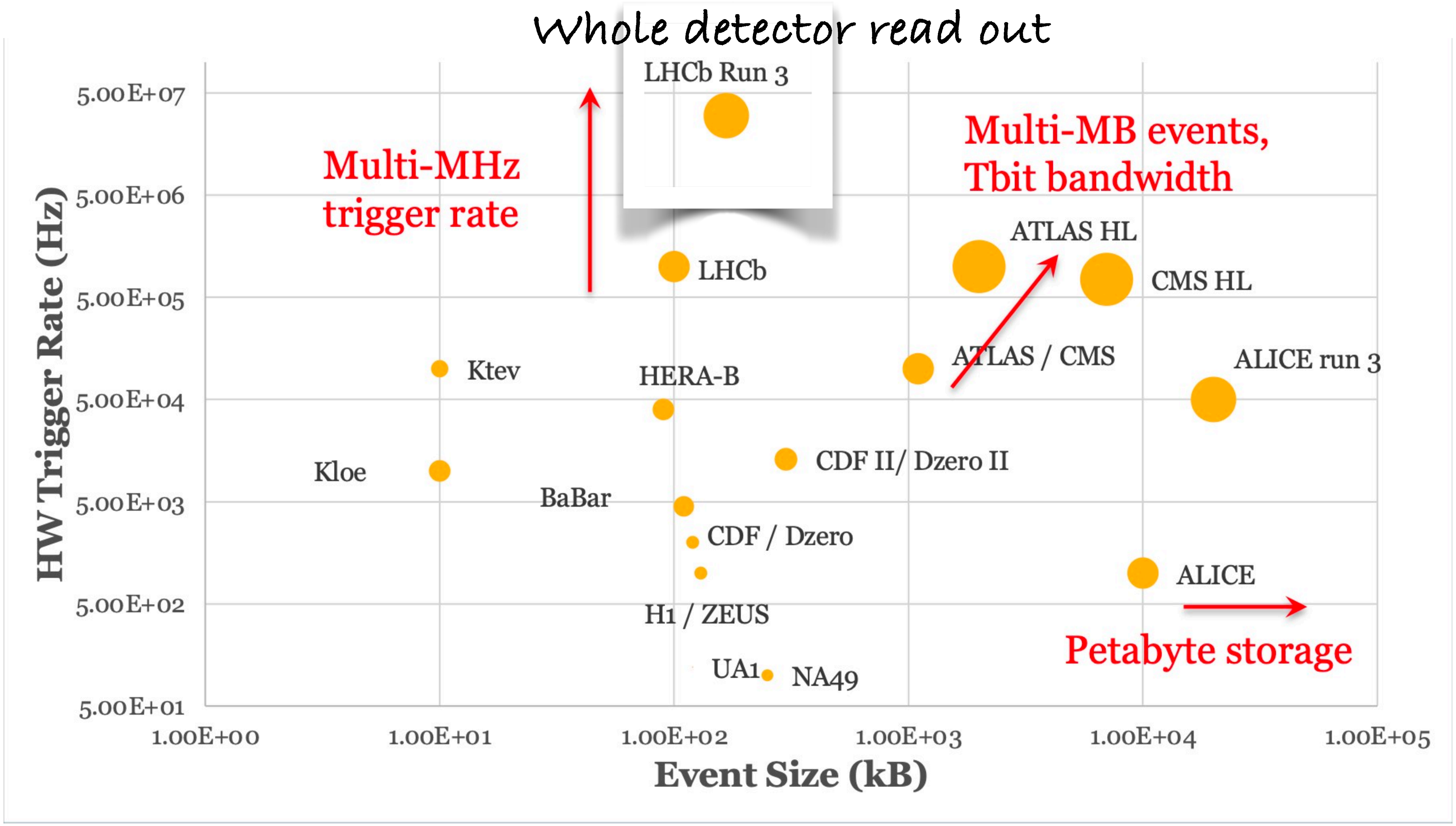
Upgrade ||: tracking

Downstream tracking station needs to instrument large area (~5m^2)

Upgrade I: use scitiallting fibres   (Sci Fi)

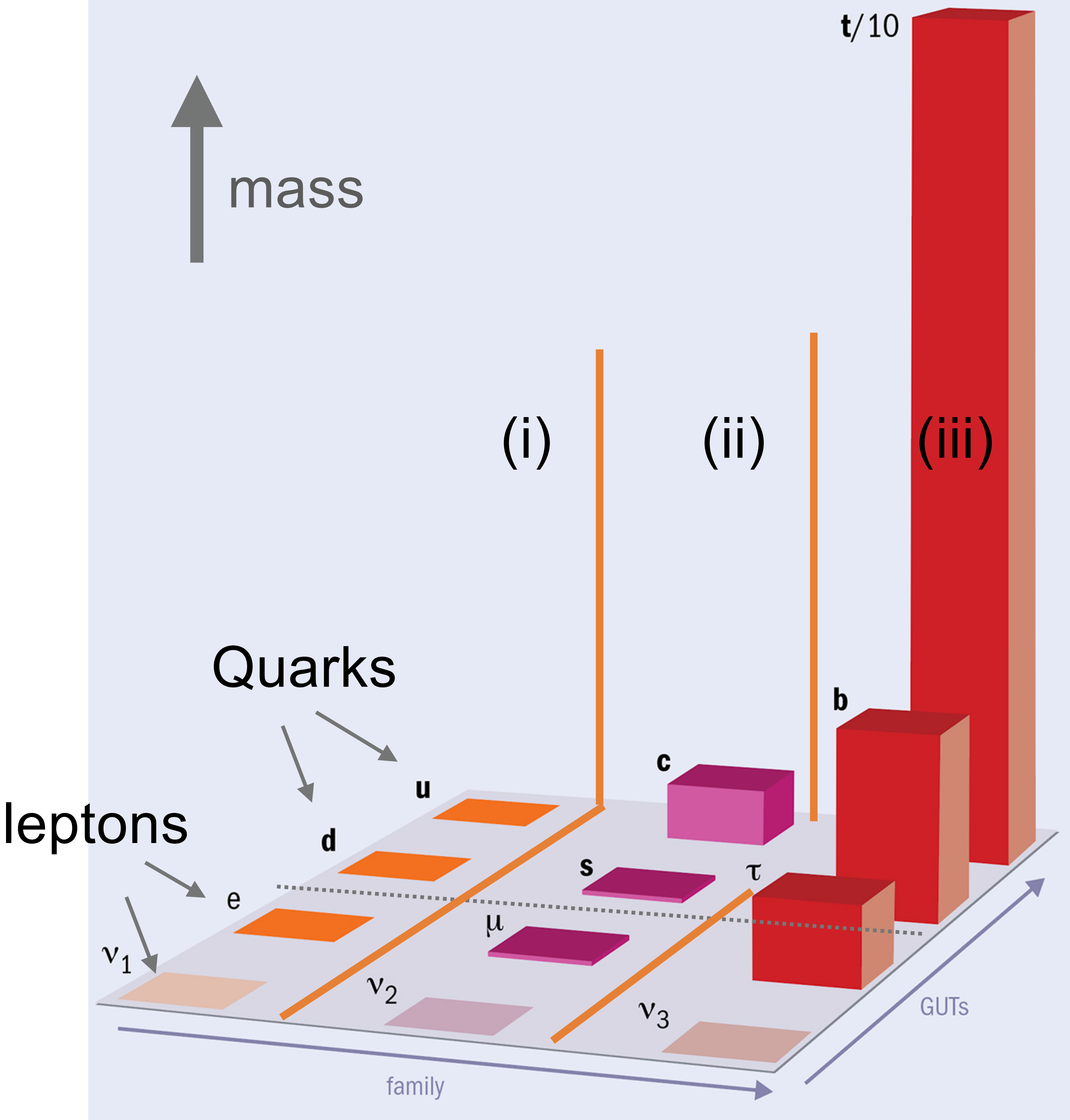


LHCb readout system: Upgrade I (Run 3)



- As of Upgrade I, LHCb reads out the *whole* detector on GPUs
- Calibrate detector in real-time: save less of each event
- Only LHC experiment to have trigger less readout
- Access more hadron/electron final states with lower p_T

All known fundamental particles (the SM)



There are two other “generations” of particles, with much heavier masses

Referred to as “flavours” of quarks /leptons

+ force carriers and Higgs boson

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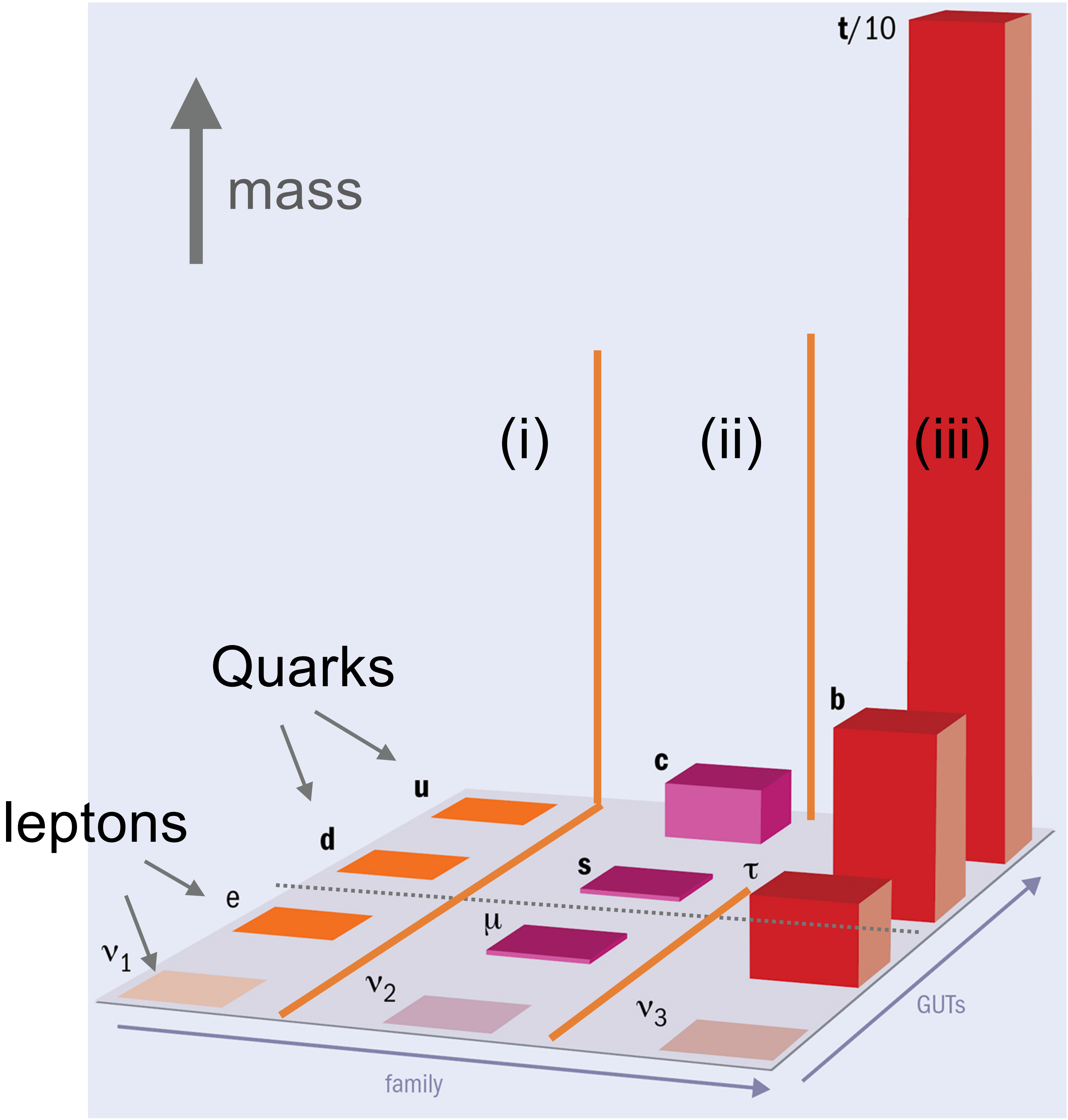

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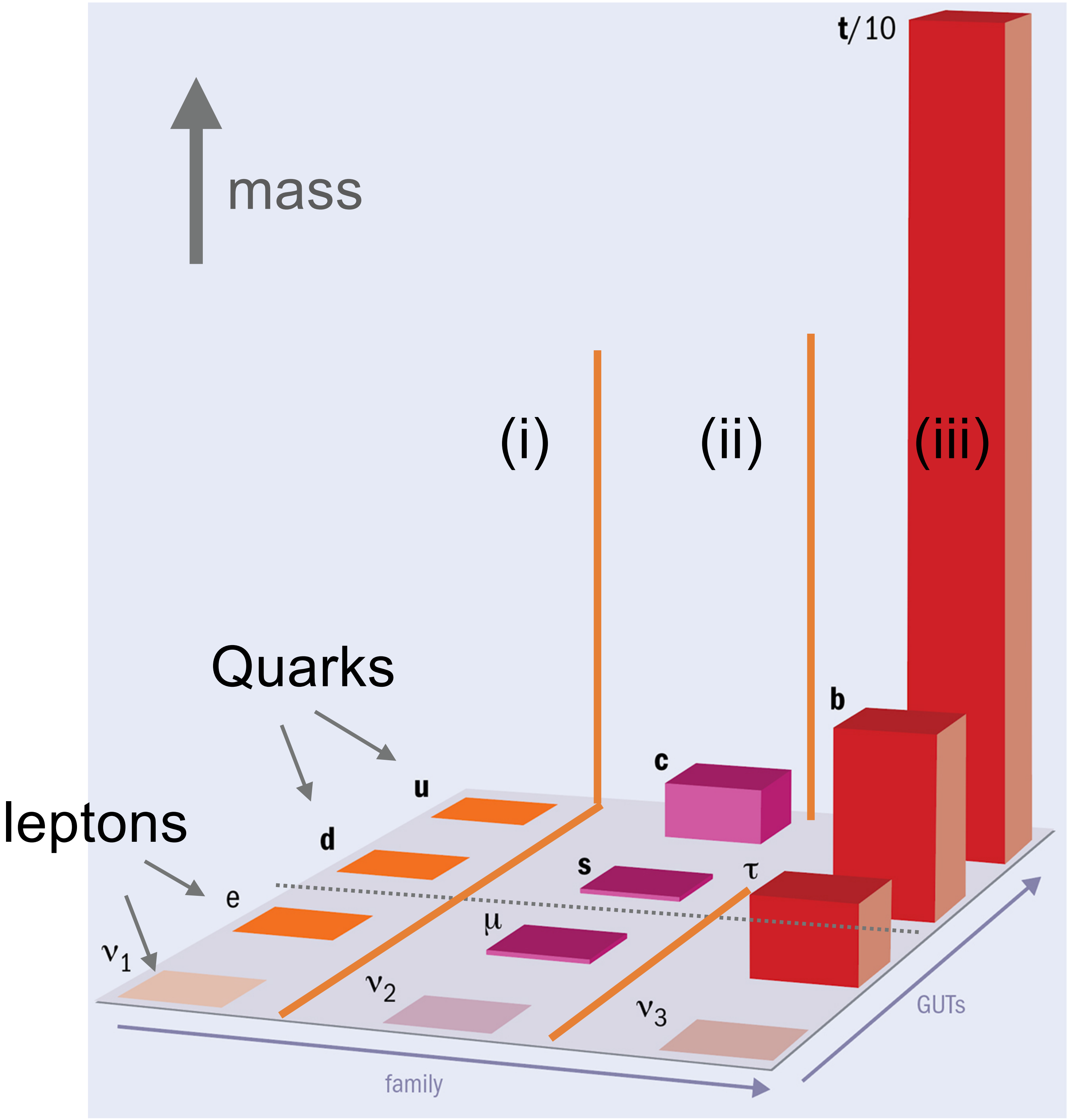

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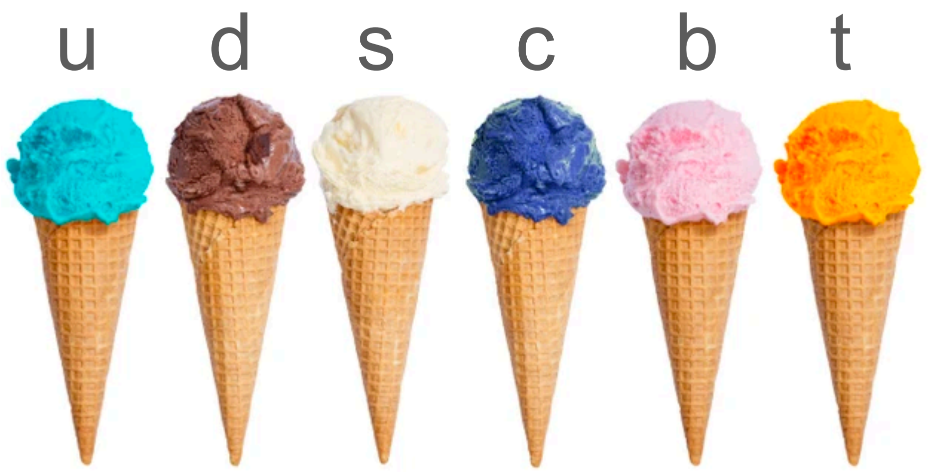

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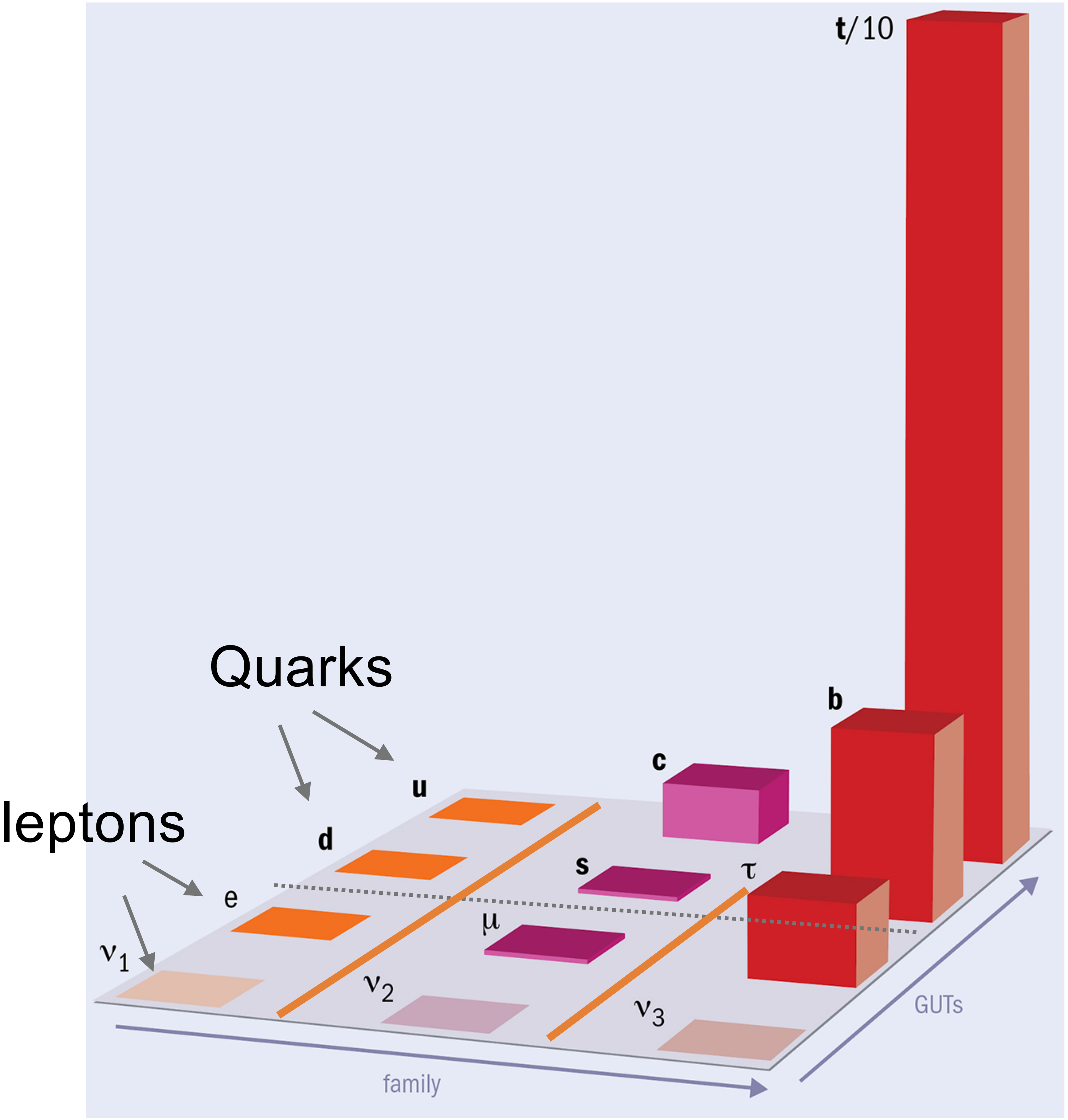
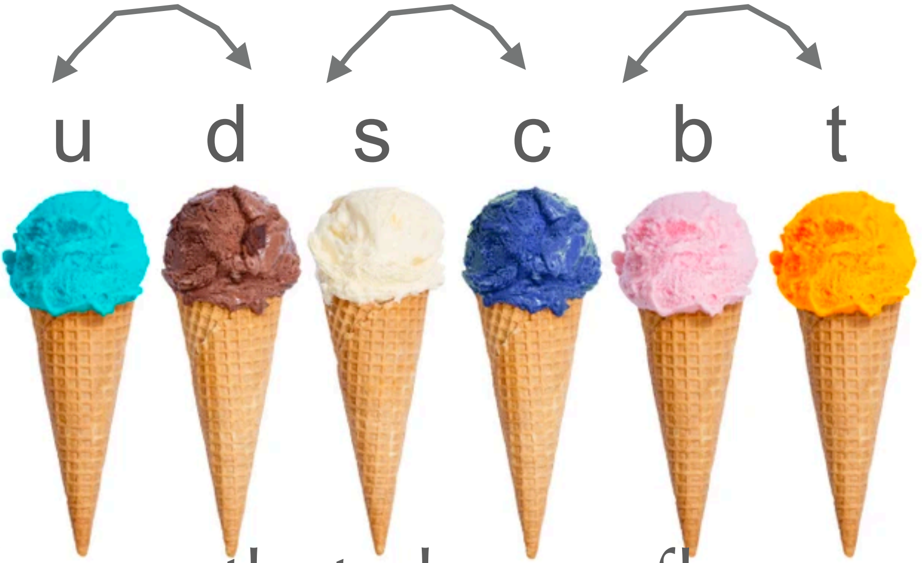


There are two other generations, with much heavier masses

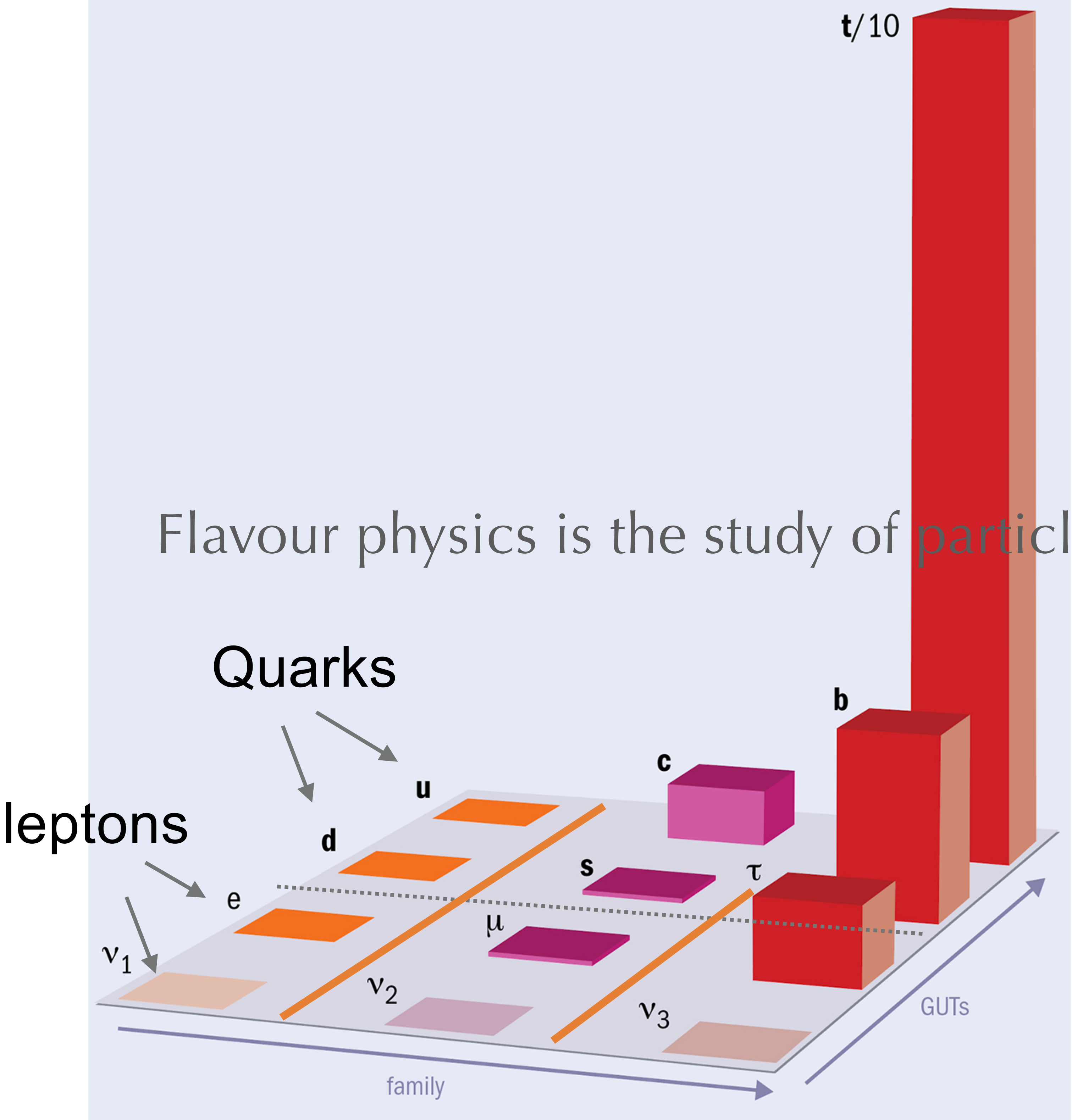
Referred to as “flavours” of quarks /leptons

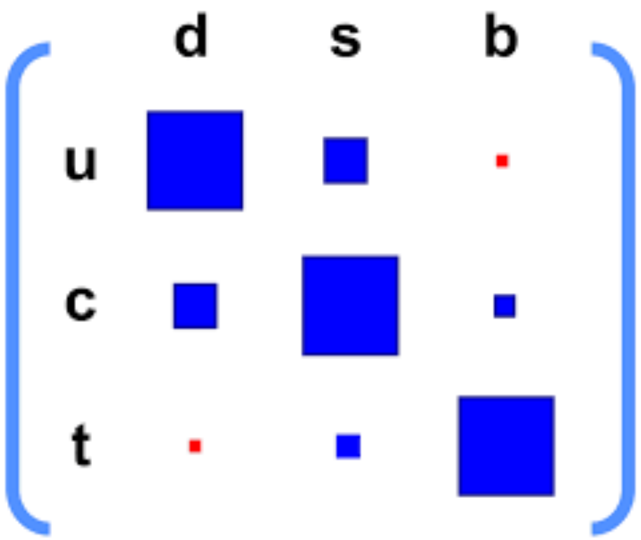
+ force carriers and Higgs boson

Weak force allows flavours to change



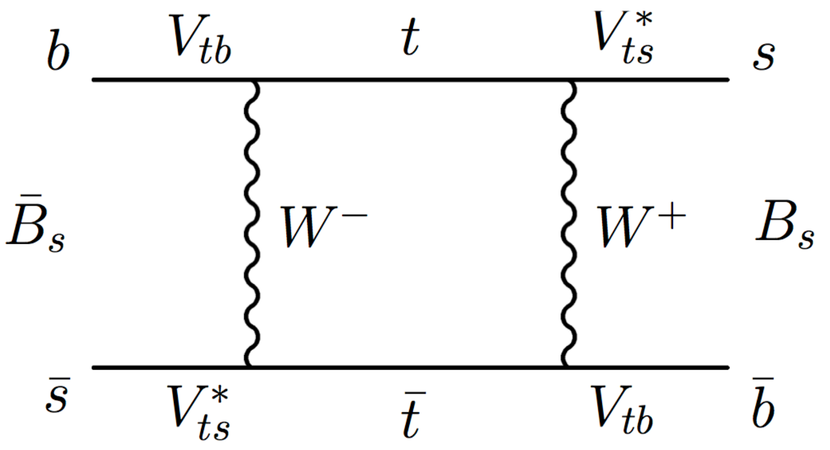
Flavour physics is the study of particle decays that change flavour



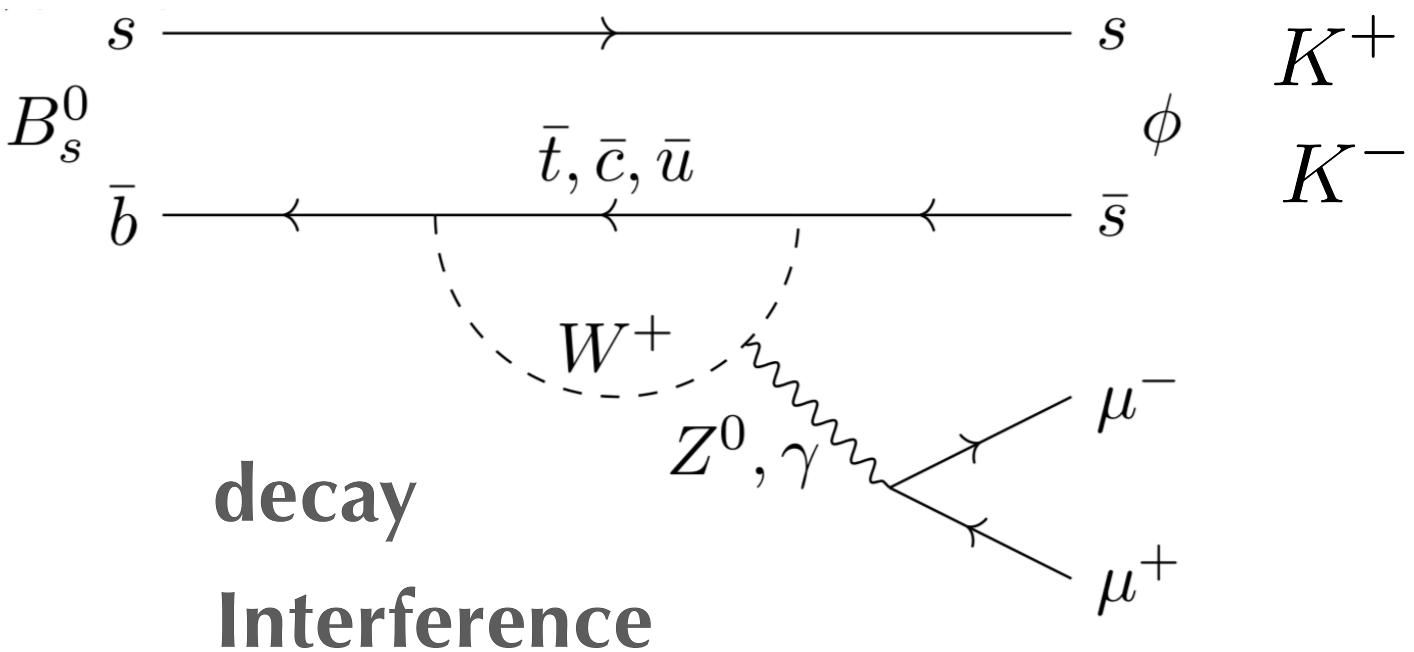


The likelihood of this happening = CKM matrix

Time-dependent angular analysis

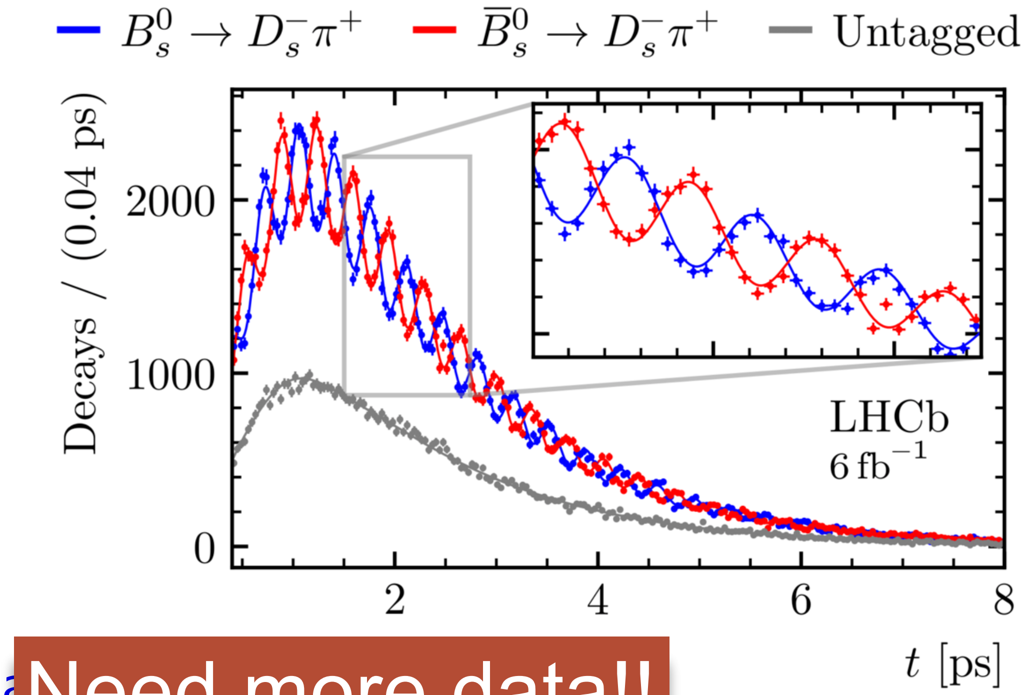


Mixing + **decay**



+ **Interference**

= new observables from $b \to s\mu^+\mu^-$ decays with flavour-symmetric final-states



$$J_i(t) + \widetilde{J}_i(t) = e^{-\Gamma t}\Big[(J_i + \widetilde{J}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\Big]$$

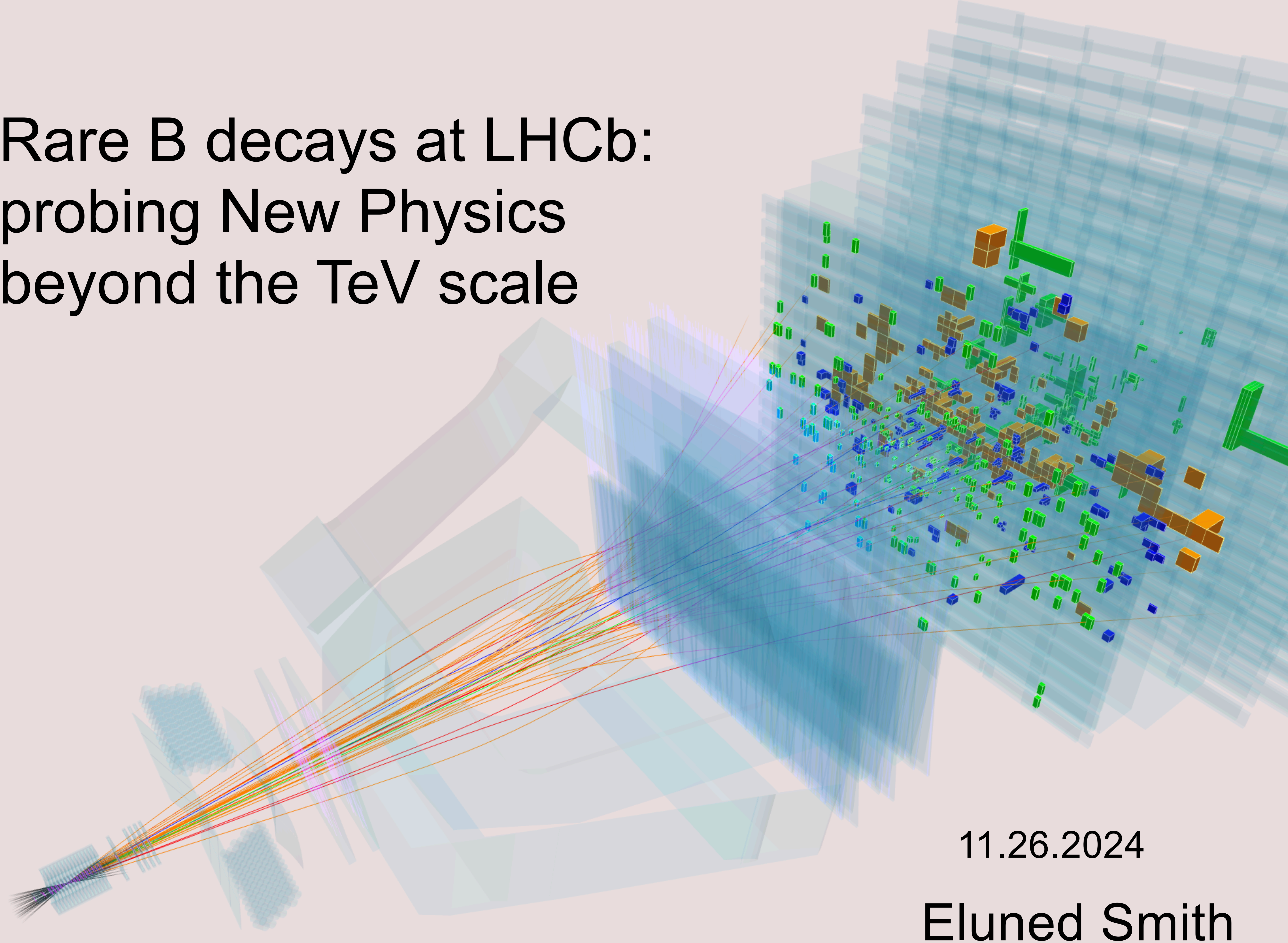
$$J_i(t) - \widetilde{J}_i(t) = e^{-\Gamma t}\Big[(J_i - \widetilde{J}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big] \,,$$

$$x \equiv \Delta m/\Gamma, \, y \equiv \Delta\Gamma/(2\Gamma)$$

First time-dependent CP violation analysis in a rare mode - variables give unique separation between NP scenarios

Need more data!!

Rare B decays at LHCb: probing New Physics beyond the TeV scale

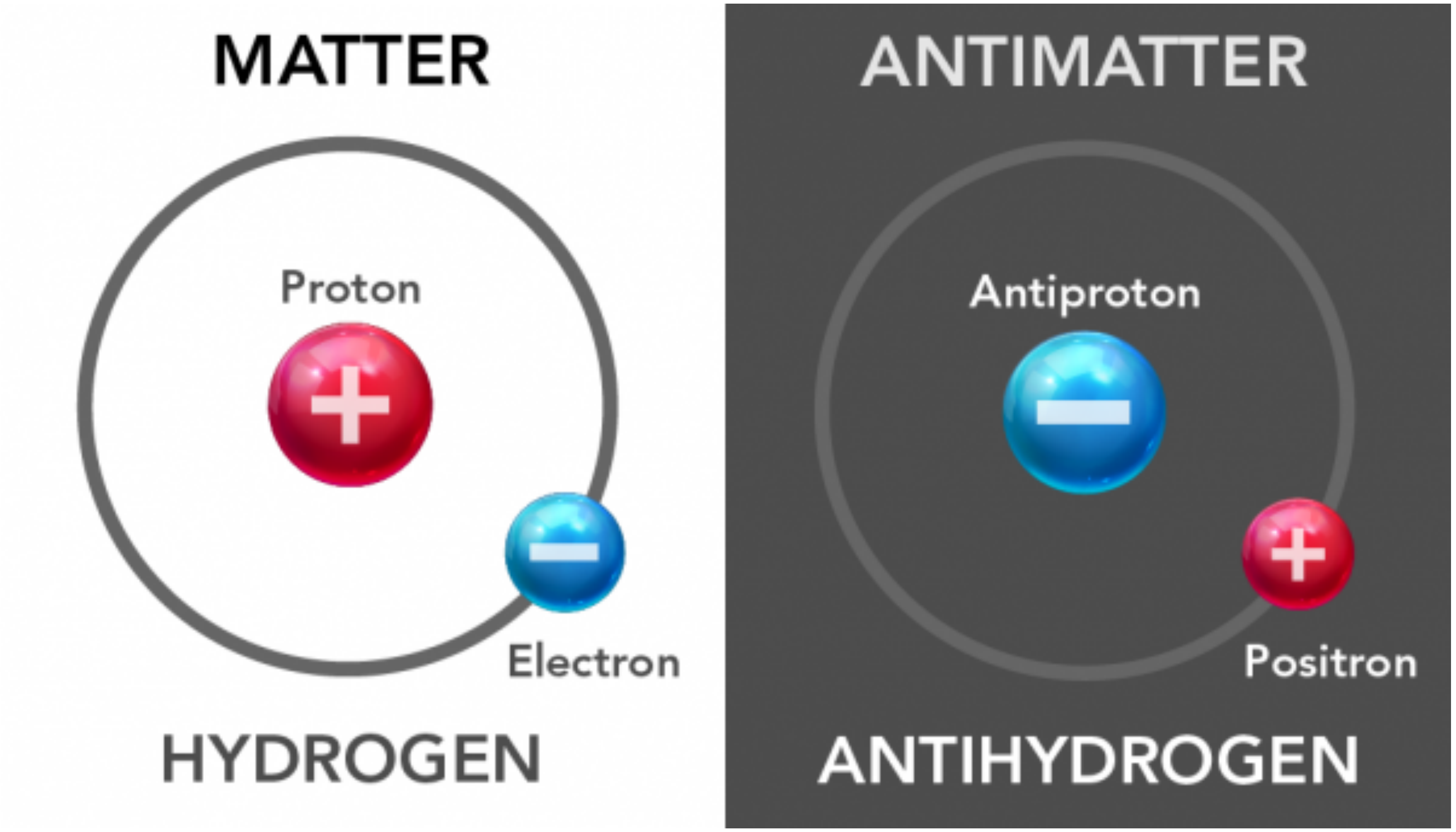


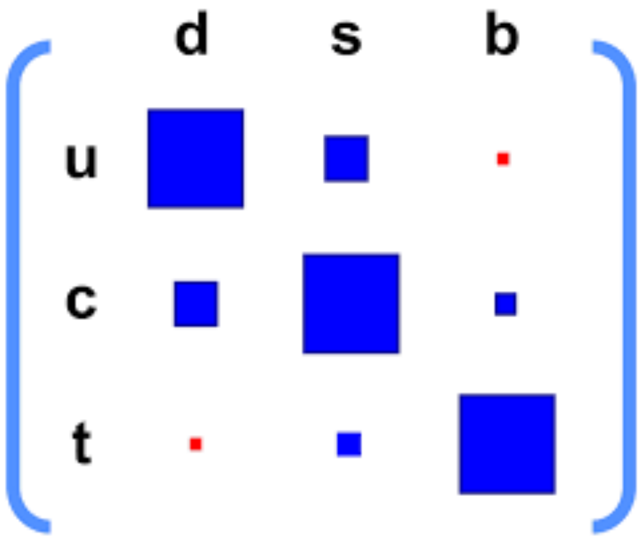
11.26.2024

Eluned Smith

Flavour and missing anti-matter

- We exist because matter dominates, but we don’t know *why*
- The couplings in the CKM matrix diff. between matter and anti-matter (CP violation), but not enough to explain our universe (!)





- There must exist unknown forces and particles beyond the Standard Model, we call these hypothetical particles New Physics

Probing the TeV scale with rare decays?

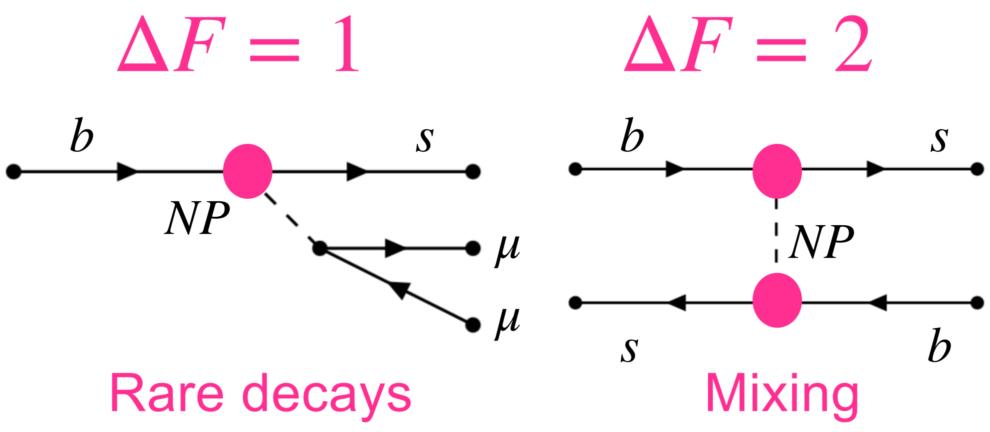
Decays described with SM Hamiltonian ($\mathcal{H}$)

Additional contribution from NP $(\Delta F = 1)$:

$$\mathcal{H}_{NP} \propto \frac{\boxed{\kappa}}{\boxed{\Lambda_{NP}^2}}$$

Coupling

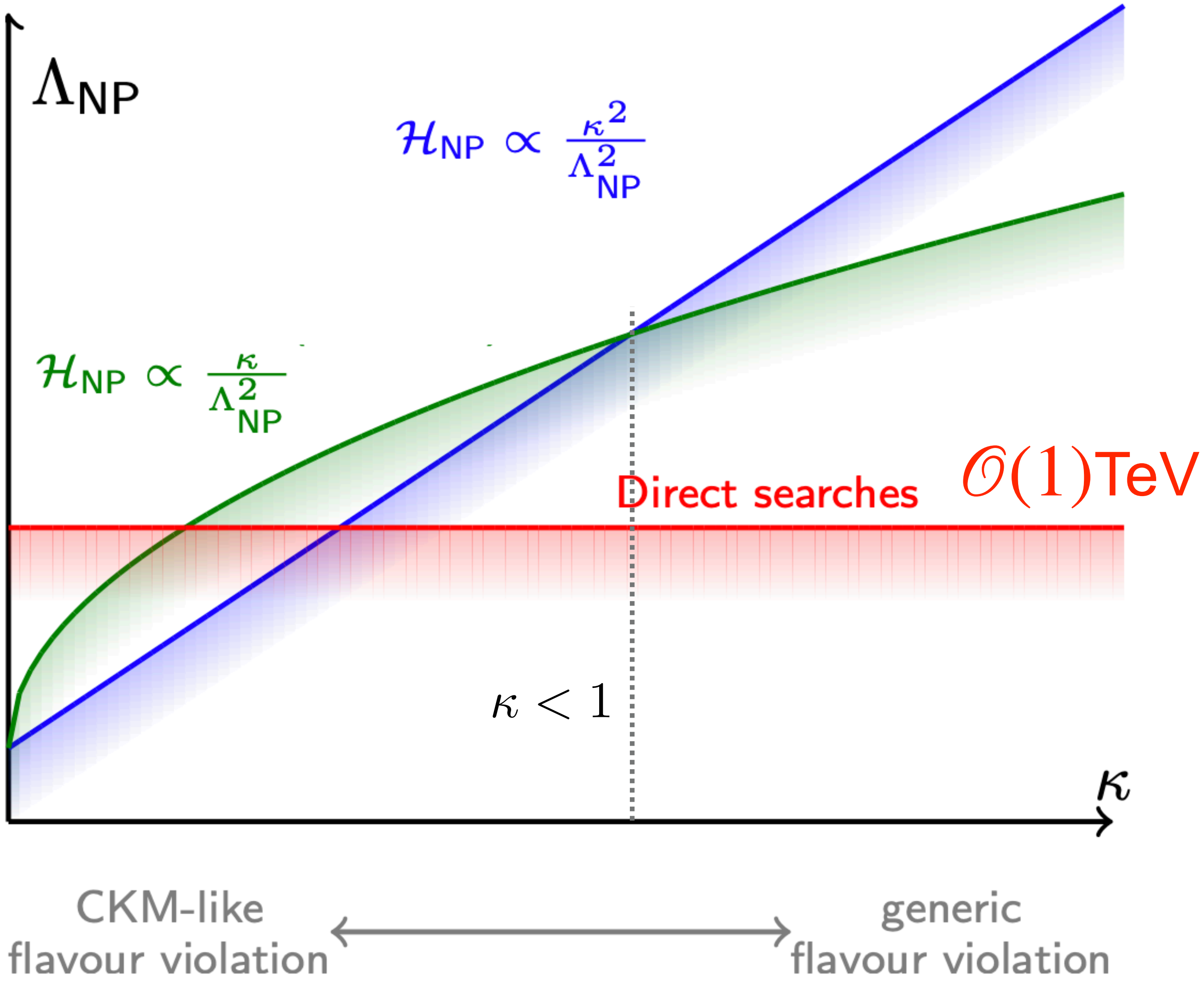
Mass of NP particle



More precise our constraints, heavier mass scale we can probe

Larger NP coupling, heavier mass scale

$$\Lambda_{NP} \propto \frac{\sqrt{k}}{\boxed{\Delta(experiment)}}$$



Mass scale probed currently with rare decays depends on NP model:

→ $\mathcal{O}(10)$-$\mathcal{O}(100)$TeV

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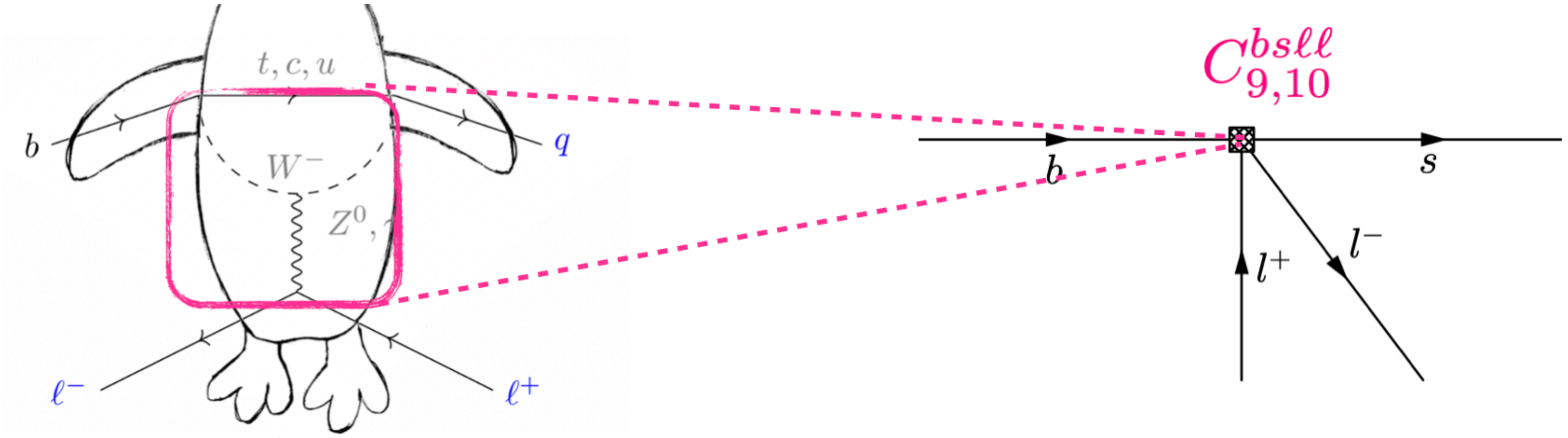
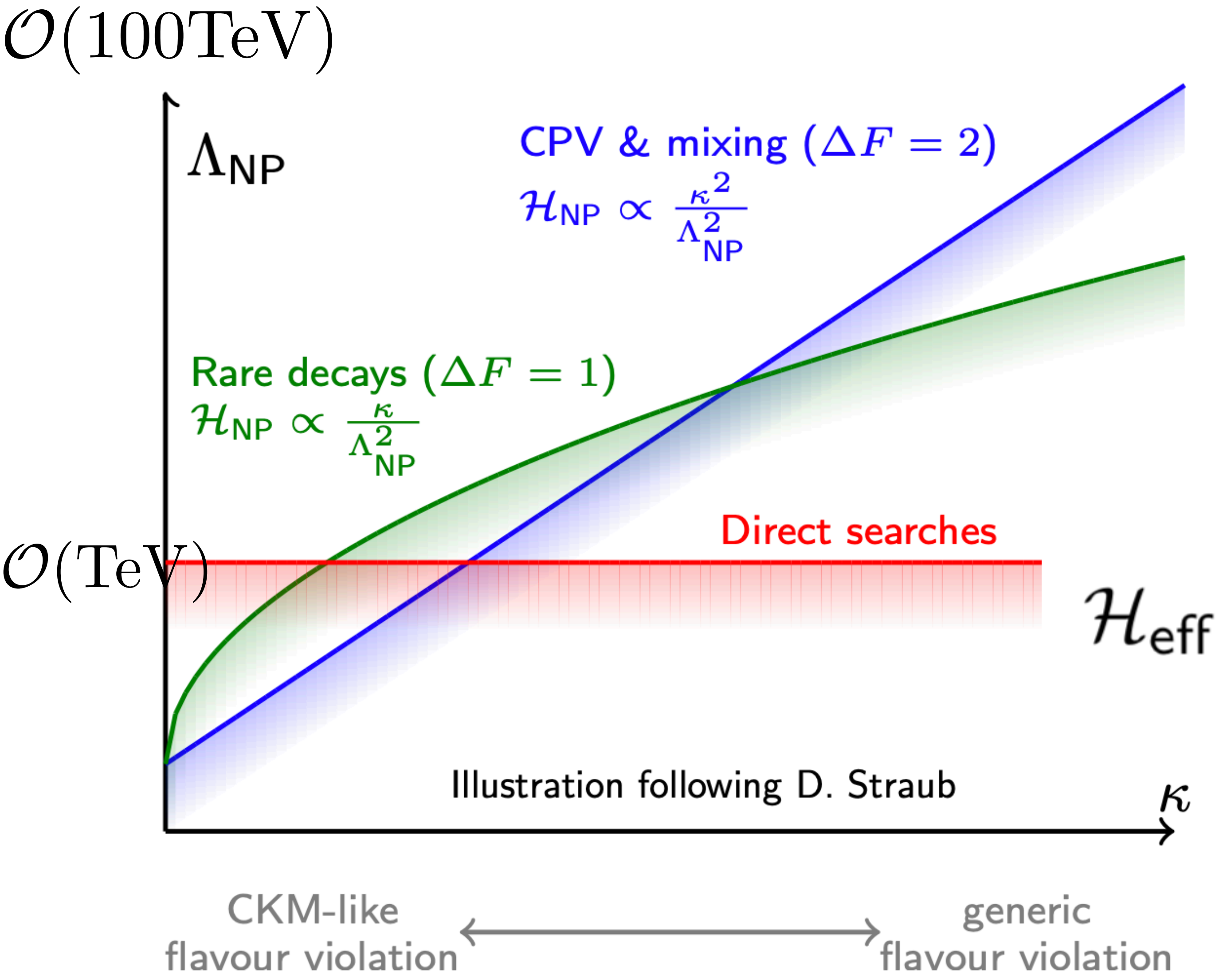
Probing the TeV scale with rare decays



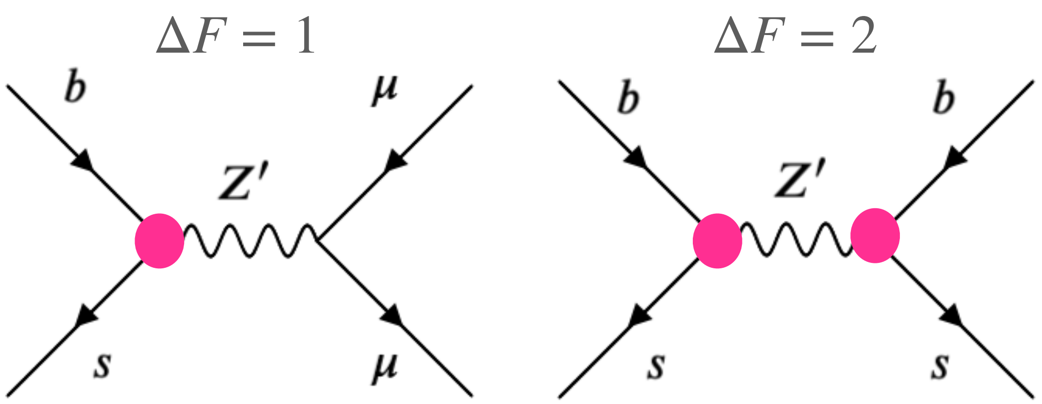


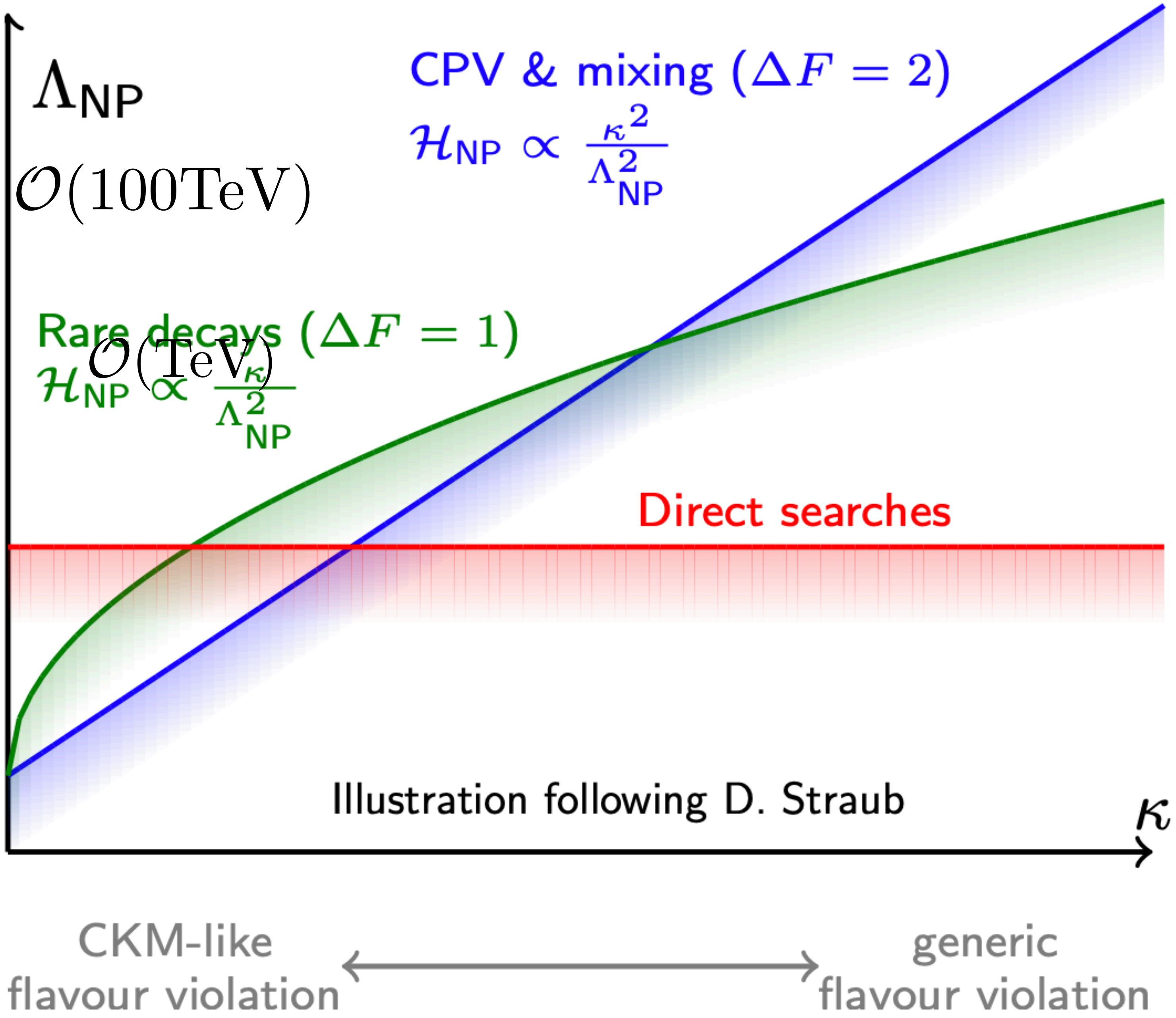
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i'$$

Probing the TeV scale with rare decays?

Decays described with SM Hamiltonian ($\mathcal{H}$)

Additional contribution from NP





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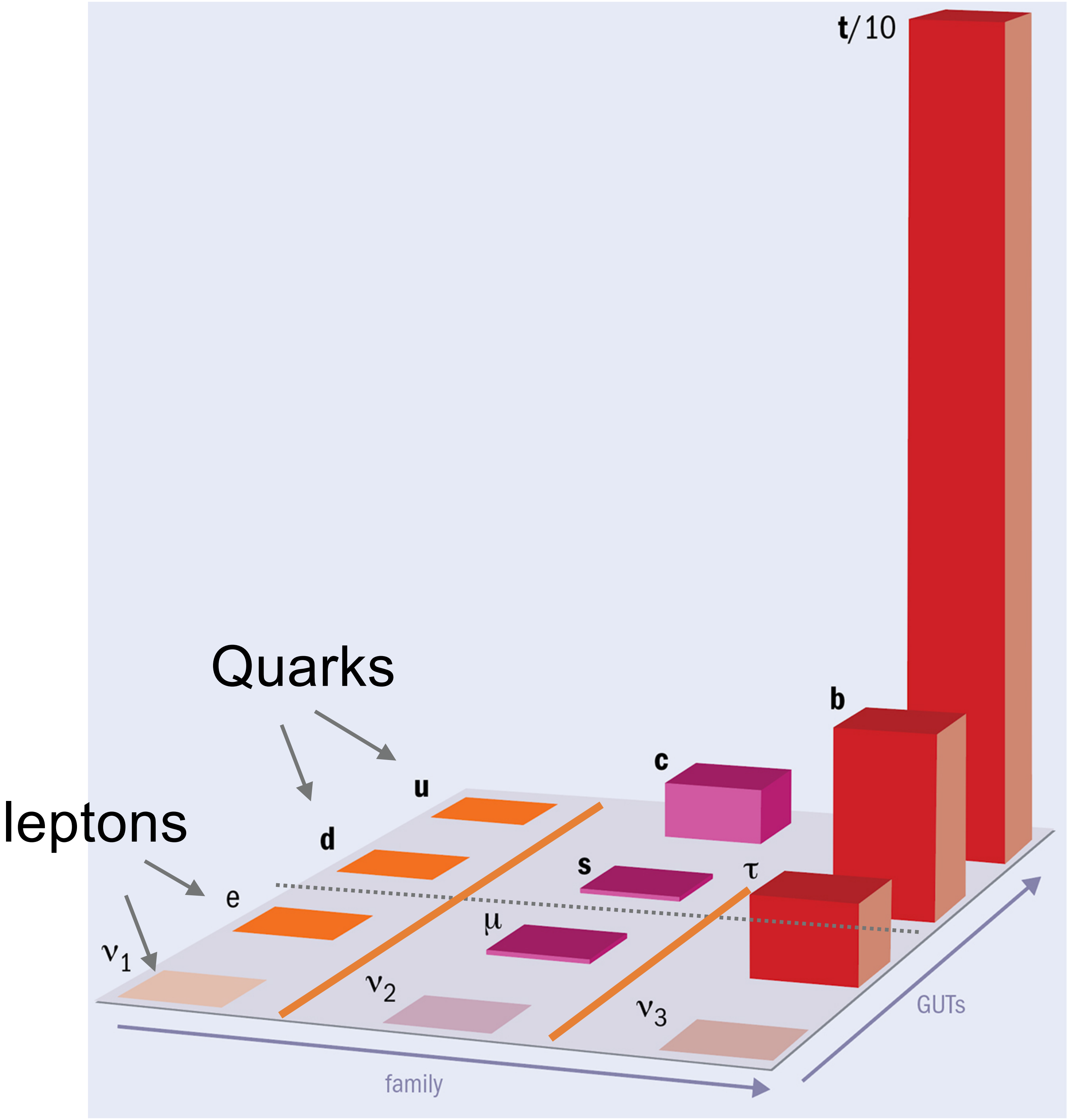

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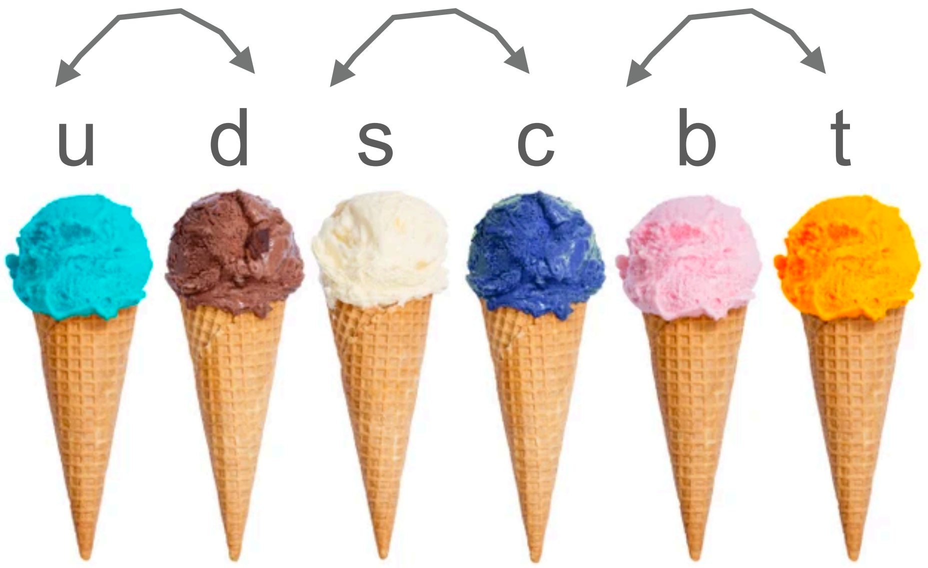
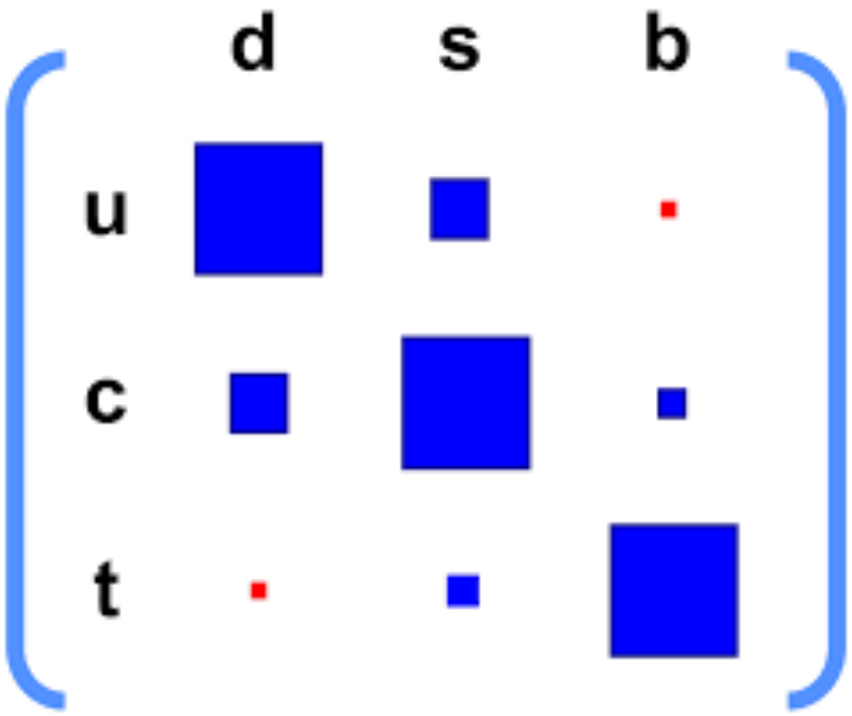
Weak force allows flavours to change



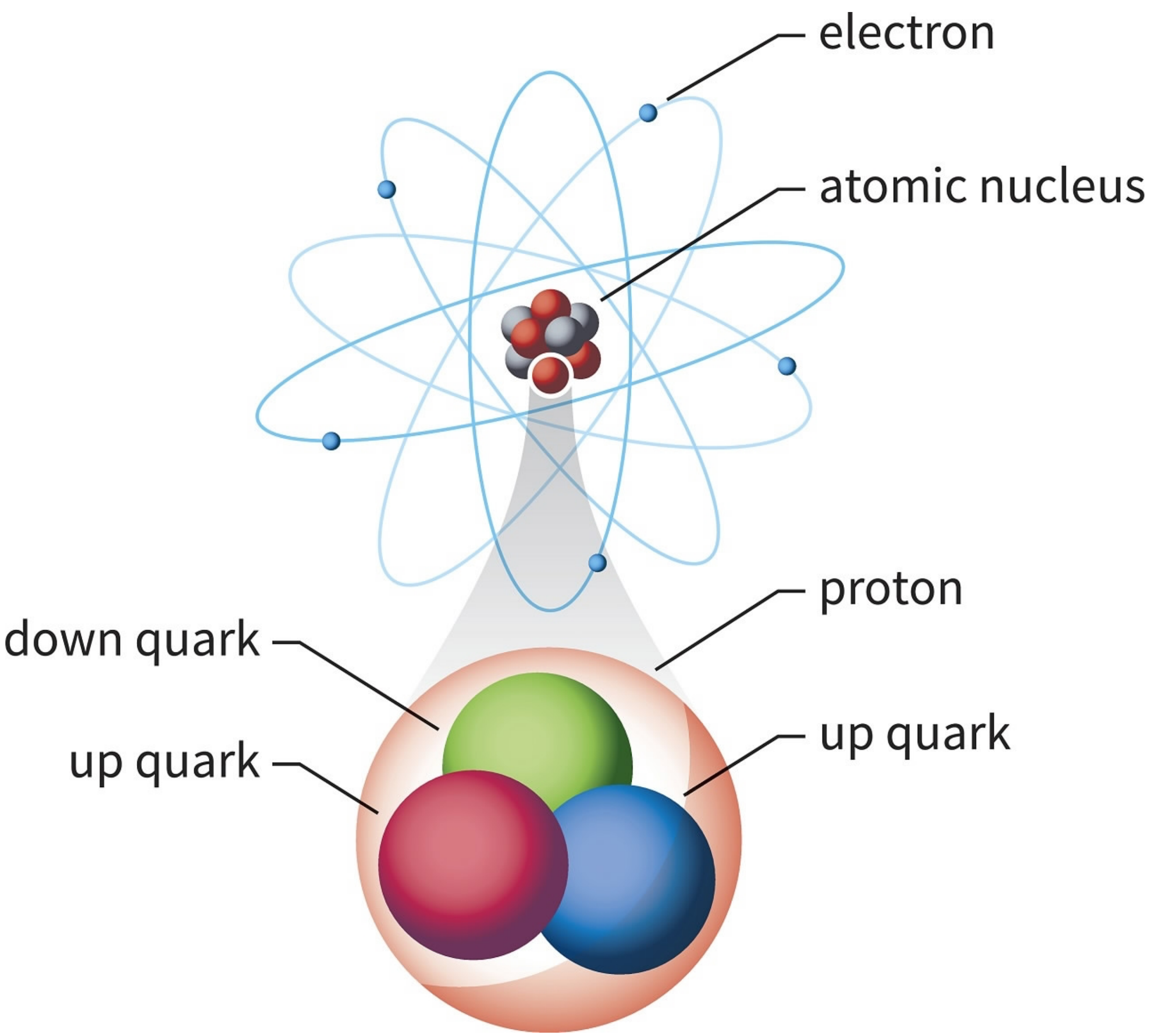


The probability with which one quark flavour decays to another encapsulated by the “CKM” matrix

Flavour physics: study of particle decays that change flavour

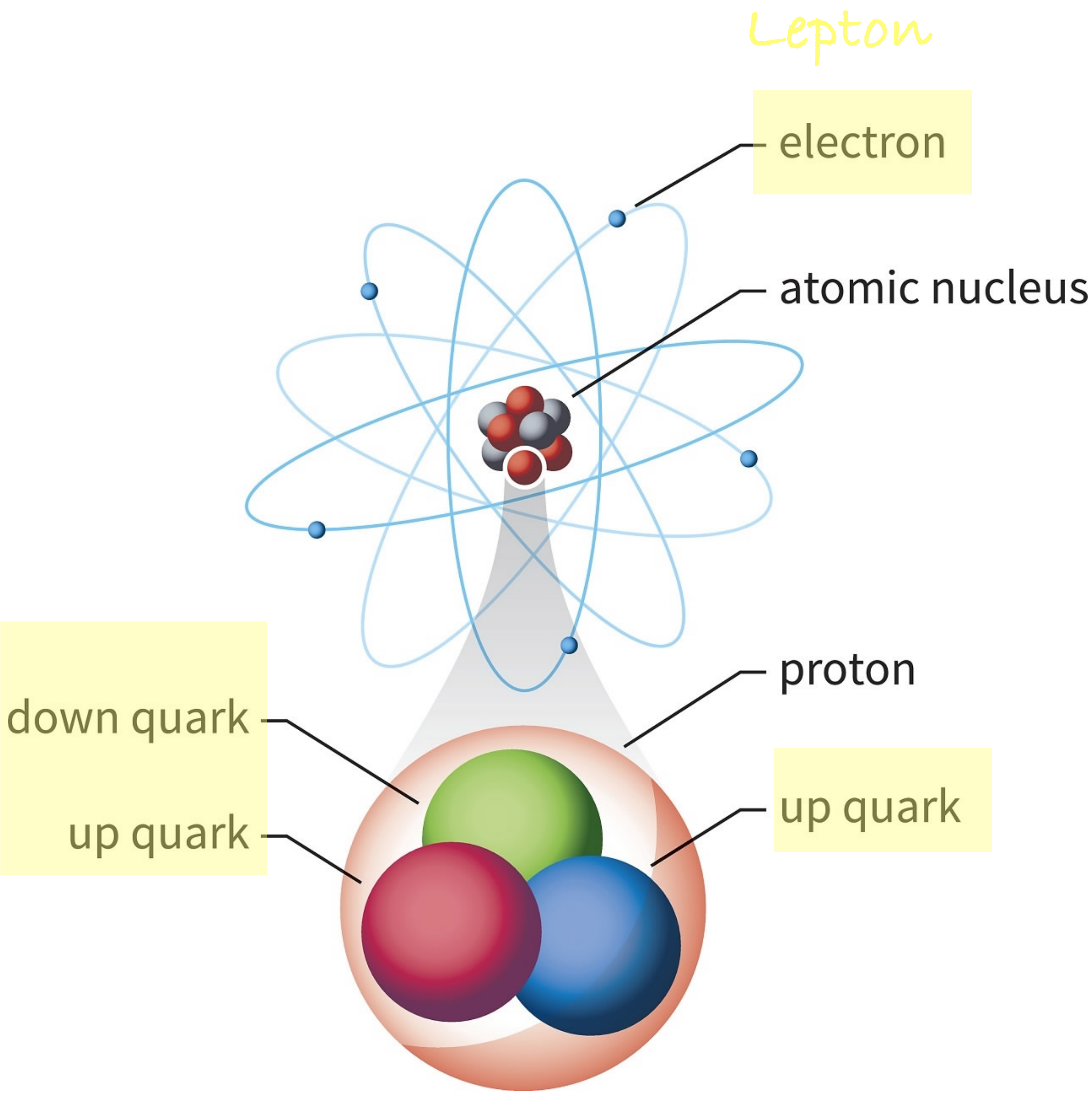
Allows us to also probe CKM matrix

The building blocks of matter



The matter around us is built from electrons and up and down quarks

The building blocks of matter



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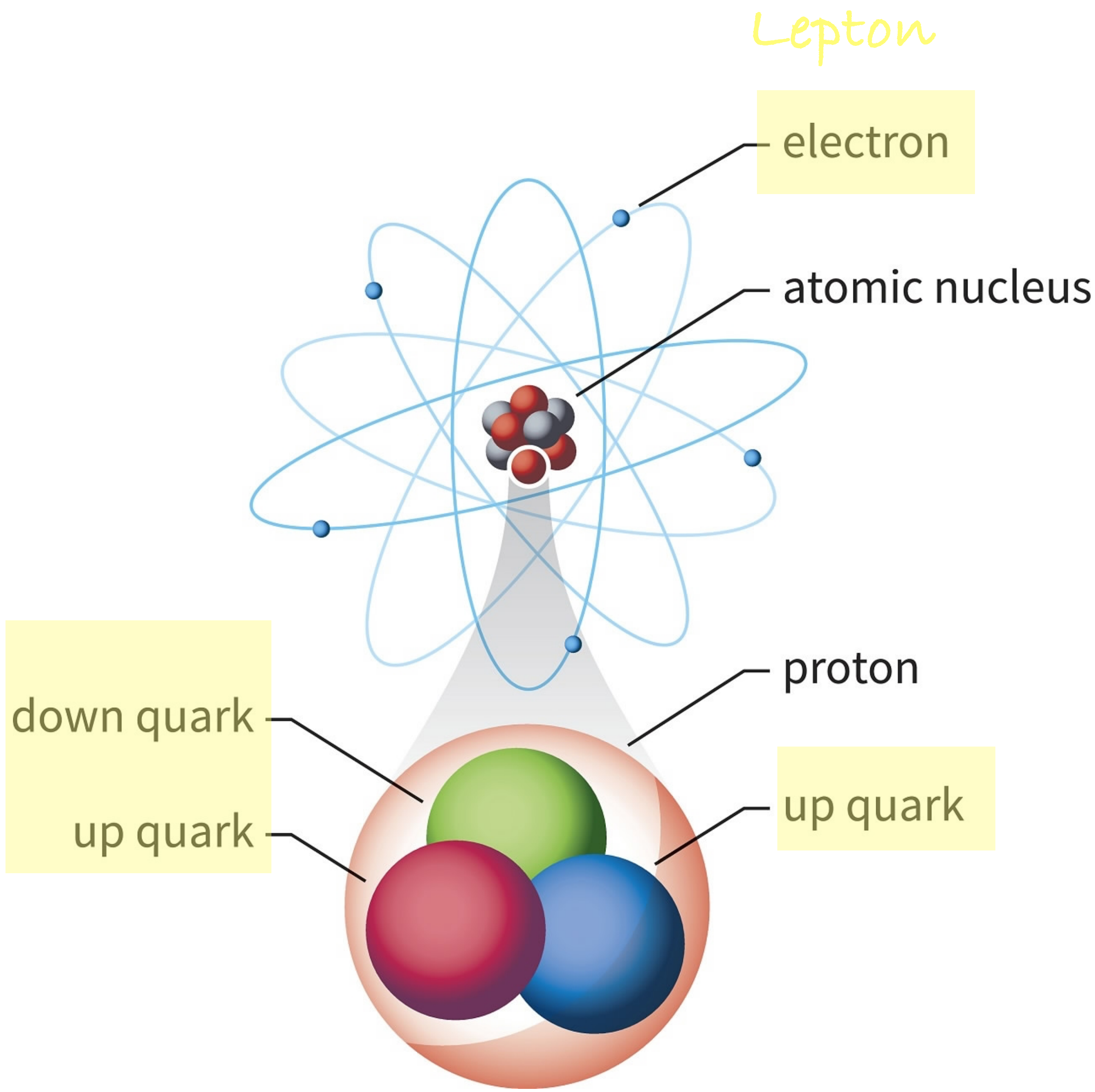
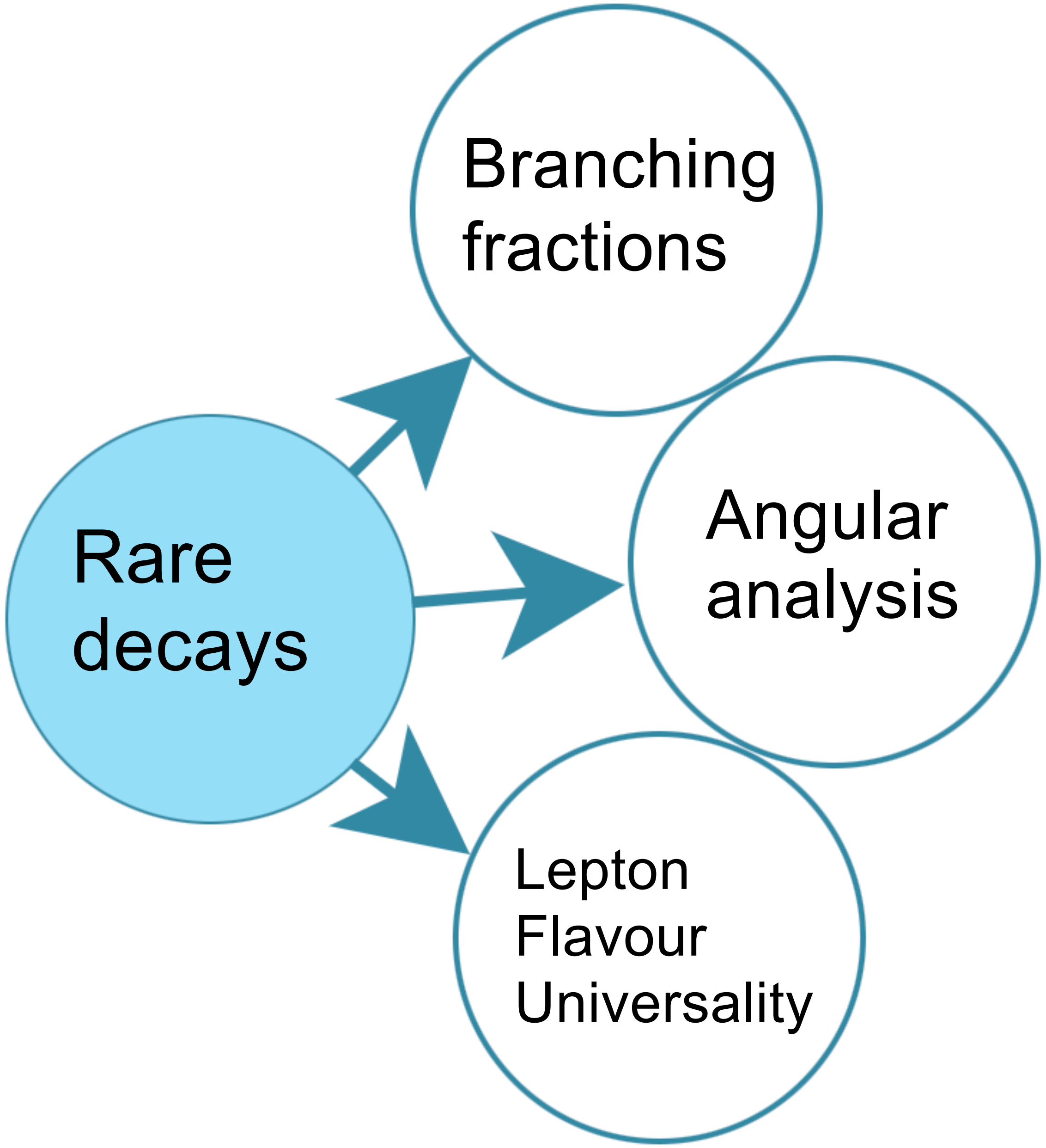


The matter around us is built from electrons and up and down quarks

Interact via three forces:

- Electromagnetism (photon)
- strong force (gluon)
- weak force ($Z^0/W^{\pm}$ boson)

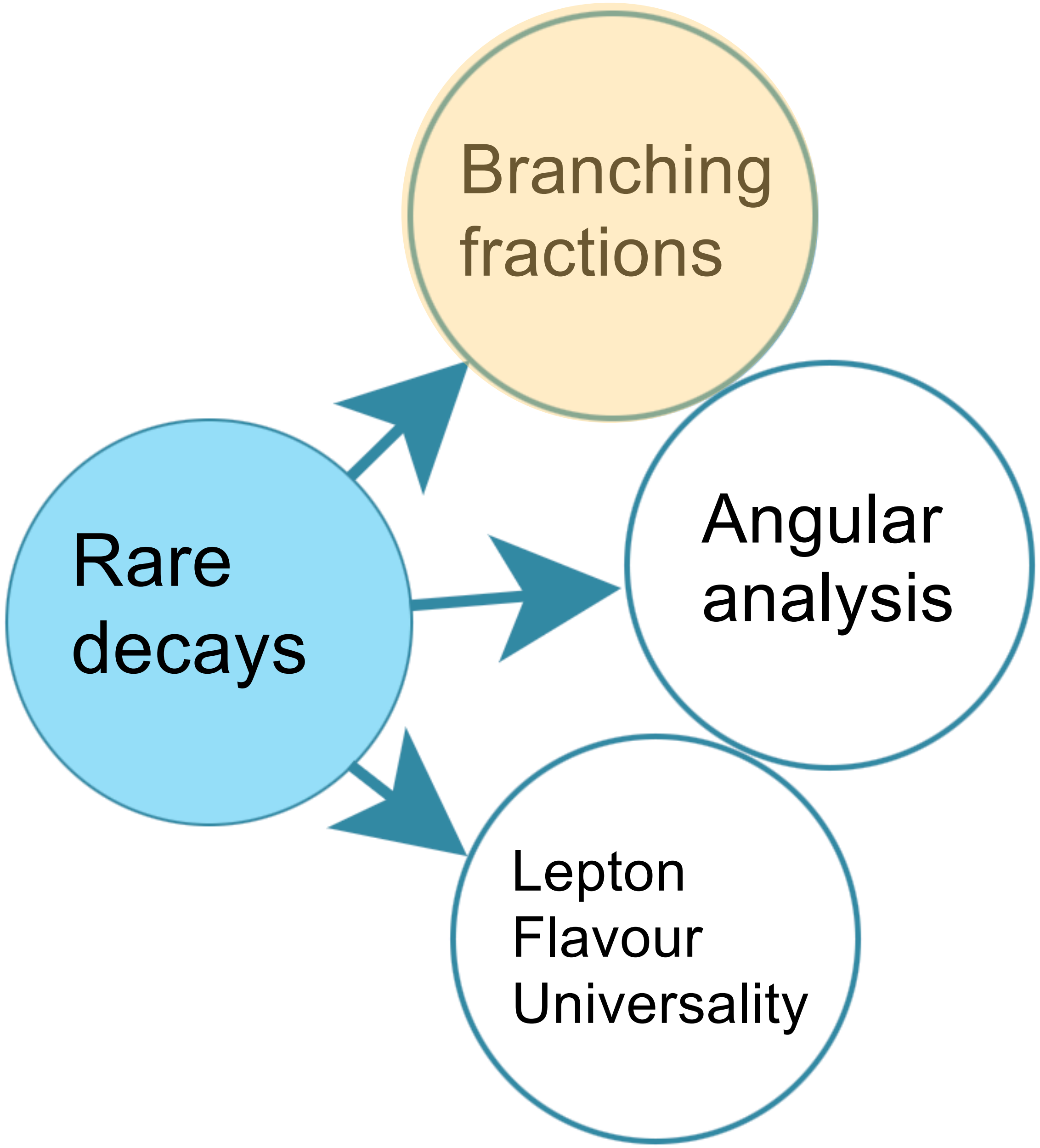


Rare decays

Branching fractions

Angular analysis

Lepton Flavour Universality



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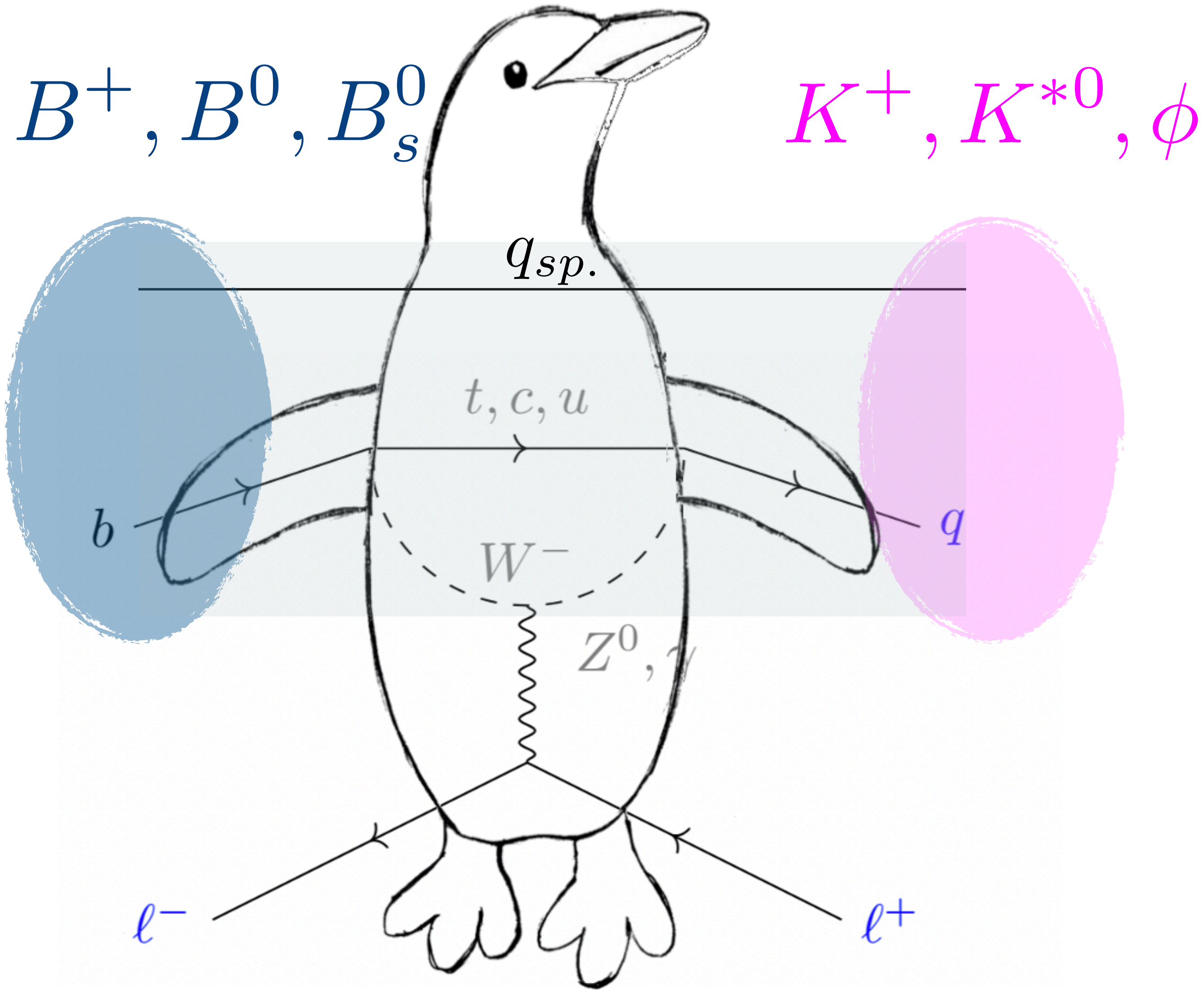
Electroweak Penguins



$$b \to q\ell^+\ell^-$$

$q_{sp.} = \quad u, d, s$

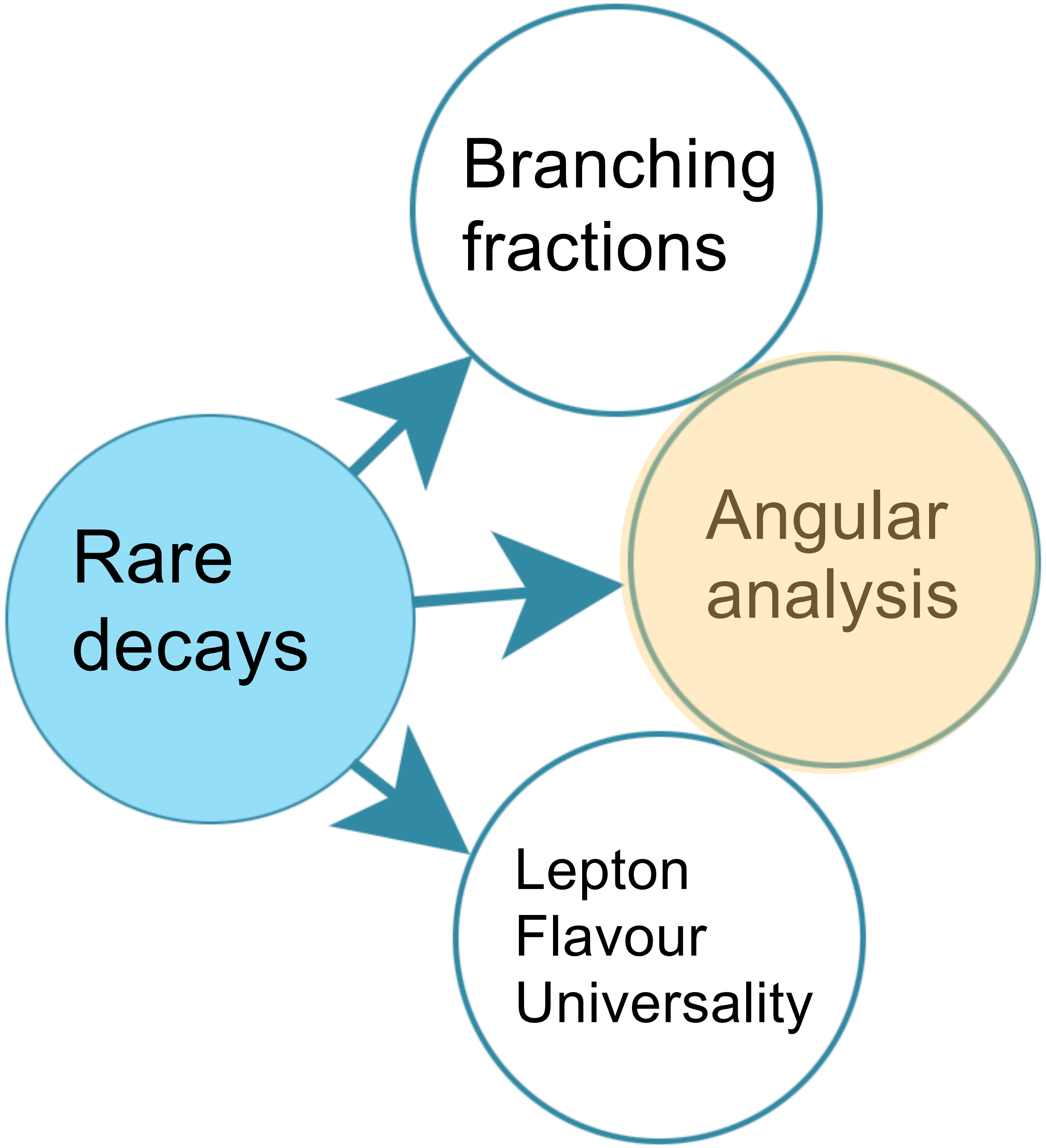
$q \quad = \quad s \quad d$

$\ell \quad = \quad \mu \quad e \quad \tau$

difficulty →

Current research focus

All decays covered by LHCb Rare Decays working group (~100 active members) which I have convened since 2021



Rare decays

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Angular analysis

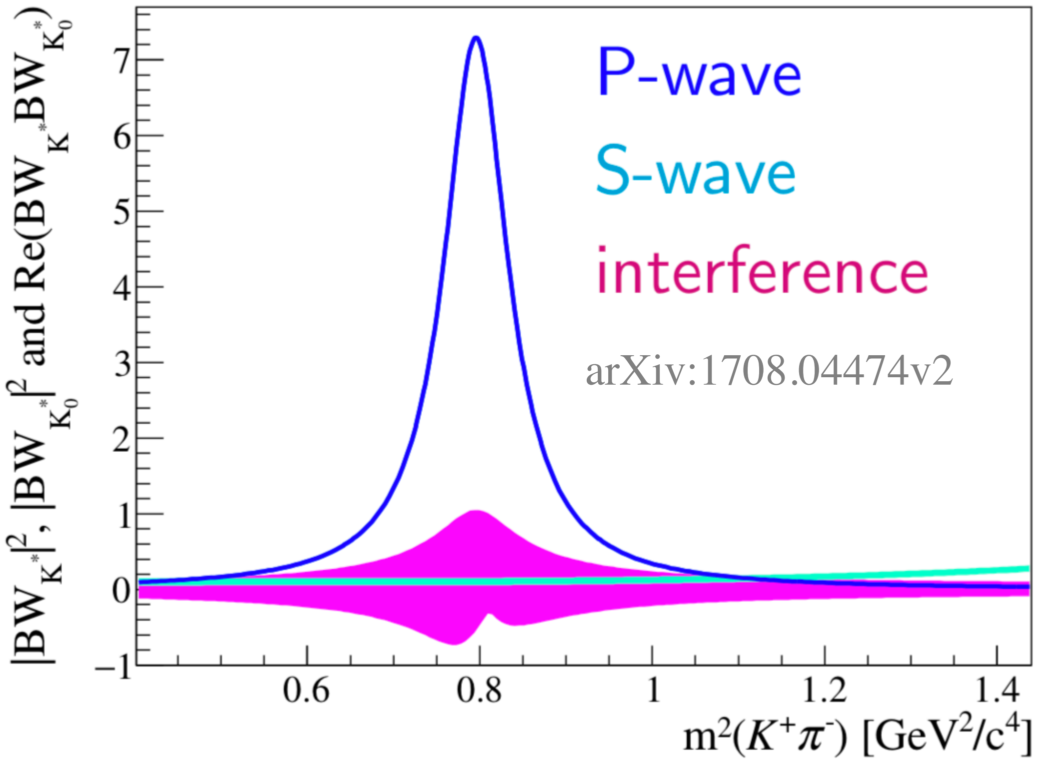
Lepton Flavour Universality

Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

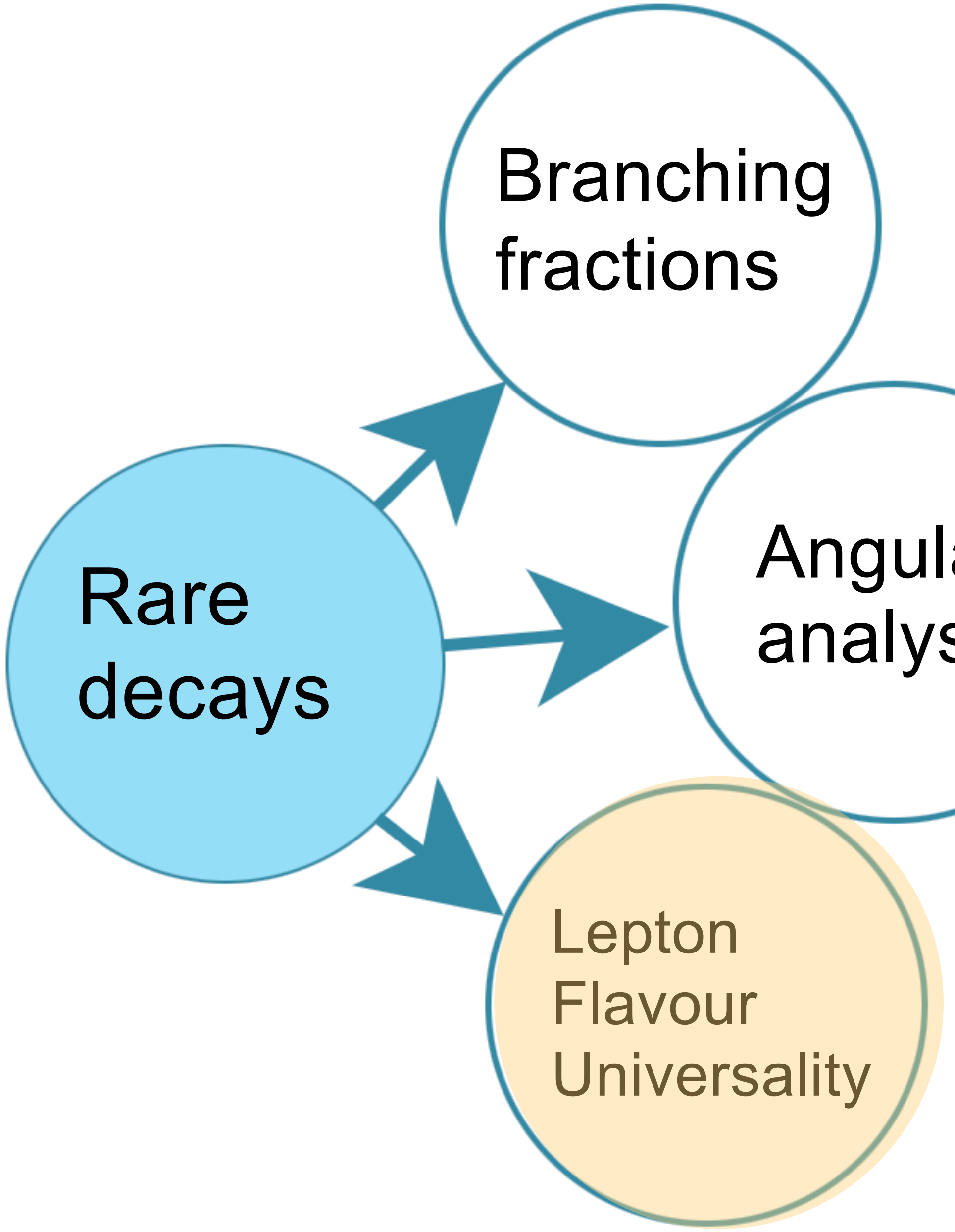
- “Background” contribution from spin 0 resonances (S-wave)
- Fit for these contributions + interference
- Simultaneously fit the $m_{K\pi}$ distribution to better separate P-wave and S-wave

P-wave (K^{*0} - 8 terms)

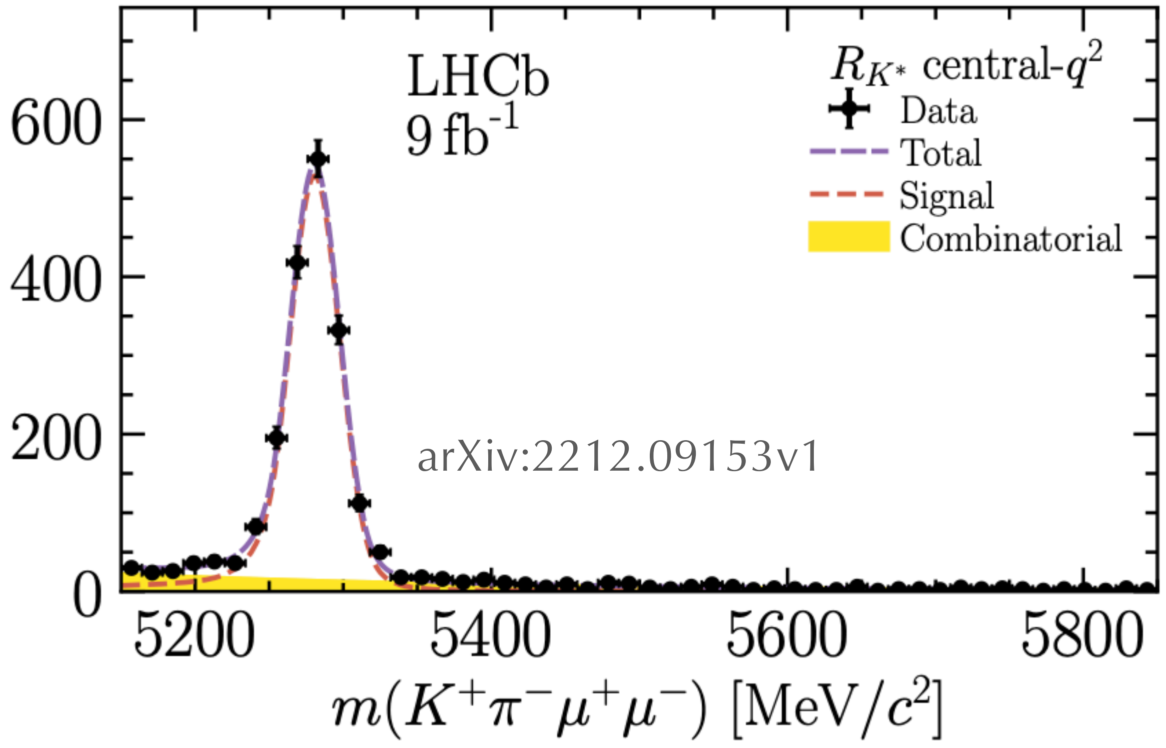
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{S+P}} = (1-F_S)\boxed{\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{P}}}$$
$$+\frac{3}{16\pi}\Big[F_S\sin^2\theta_l + S_{S1}\sin^2\theta_l\cos\theta_K$$
$$+ S_{S2}\sin 2\theta_l\sin\theta_K\cos\phi$$
$$+ S_{S3}\sin\theta_l\sin\theta_K\cos\phi$$
$$+ S_{S4}\sin\theta_l\sin\theta_K\sin\phi$$
$$+ S_{S5}\sin 2\theta_l\sin\theta_K\sin\phi\Big].$$



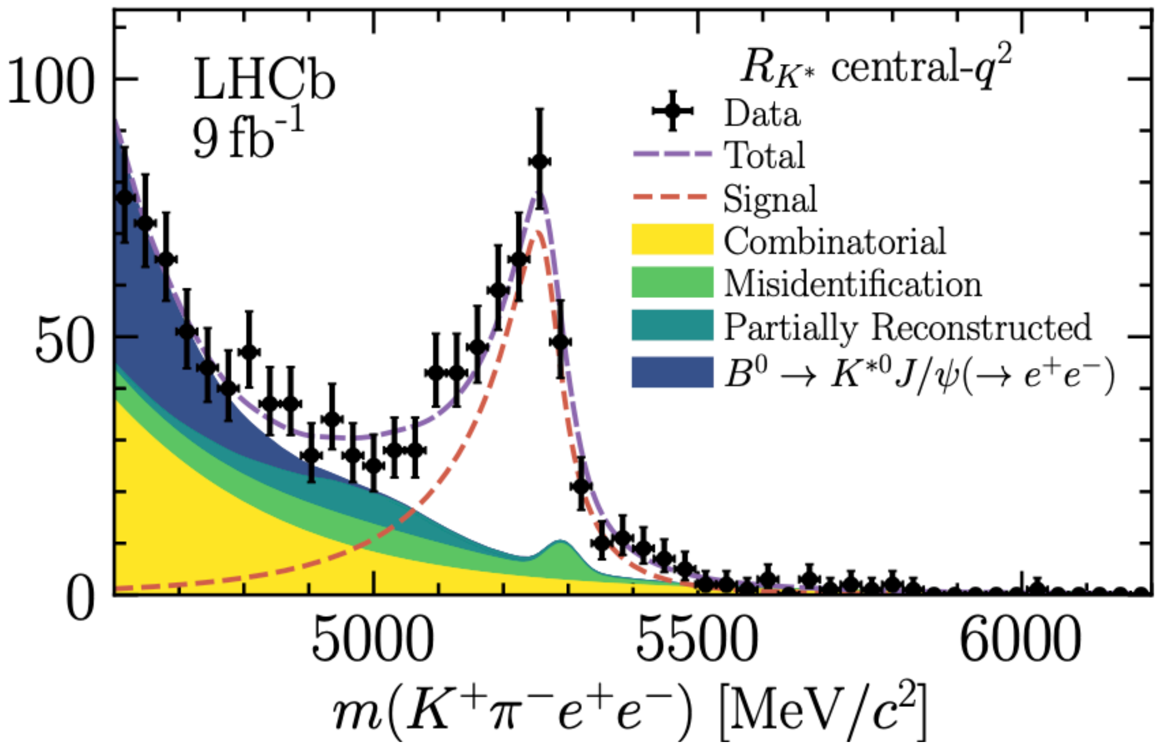
arXiv:1708.04474v2

Branching fractions
Angular analysis
Rare decays
Lepton Flavour Universality

Example: Lepton Flavour Universality

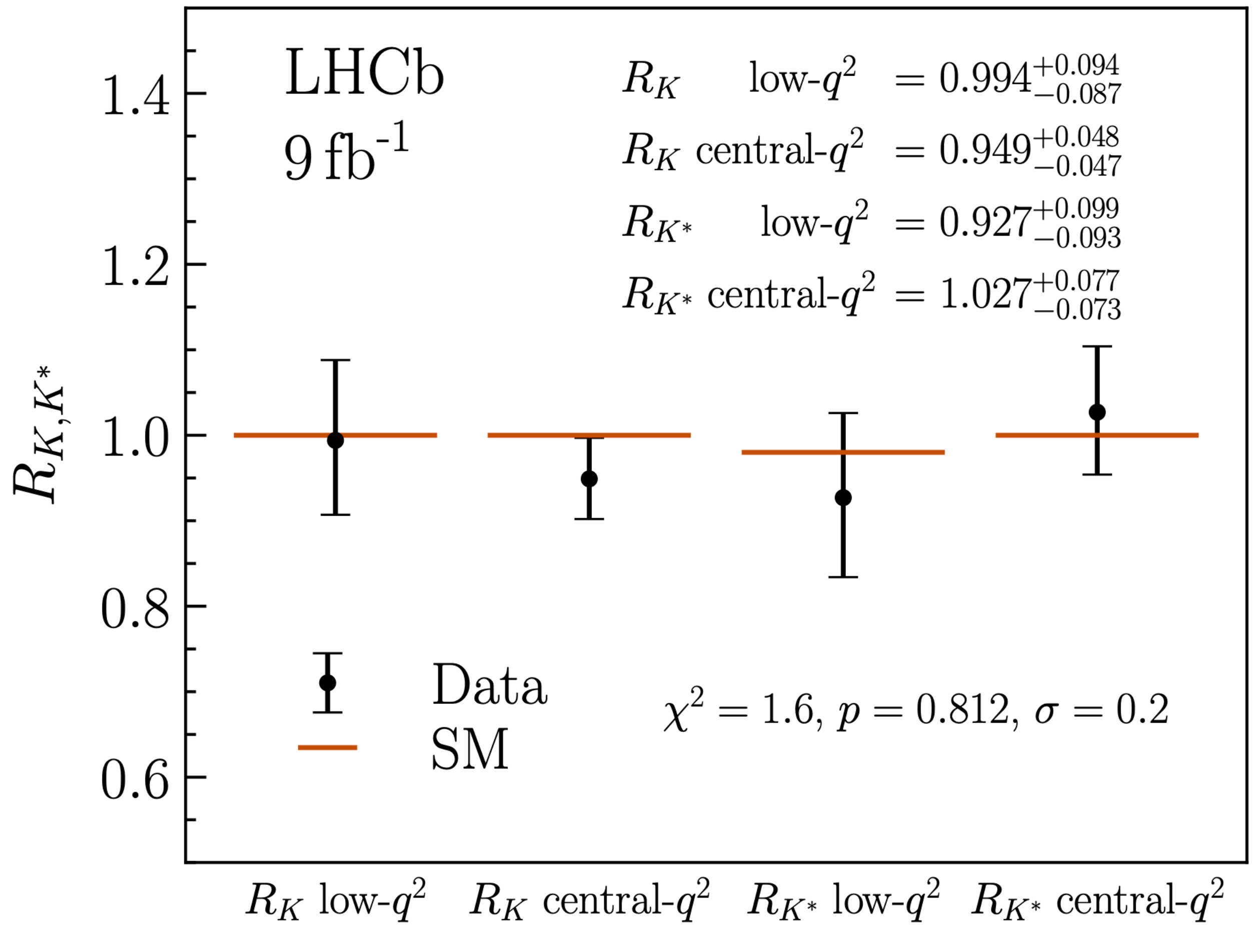


arXiv:2212.09153v1

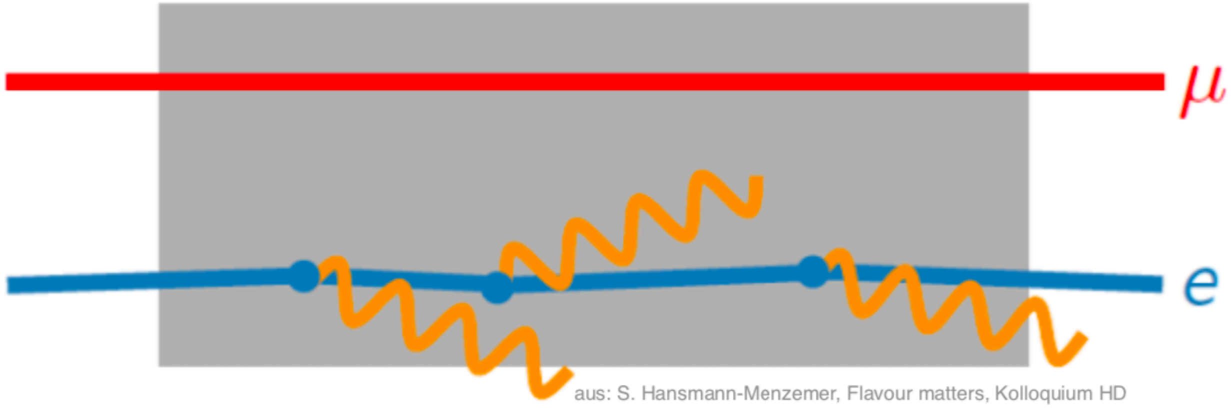


$$R(X) = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)}$$

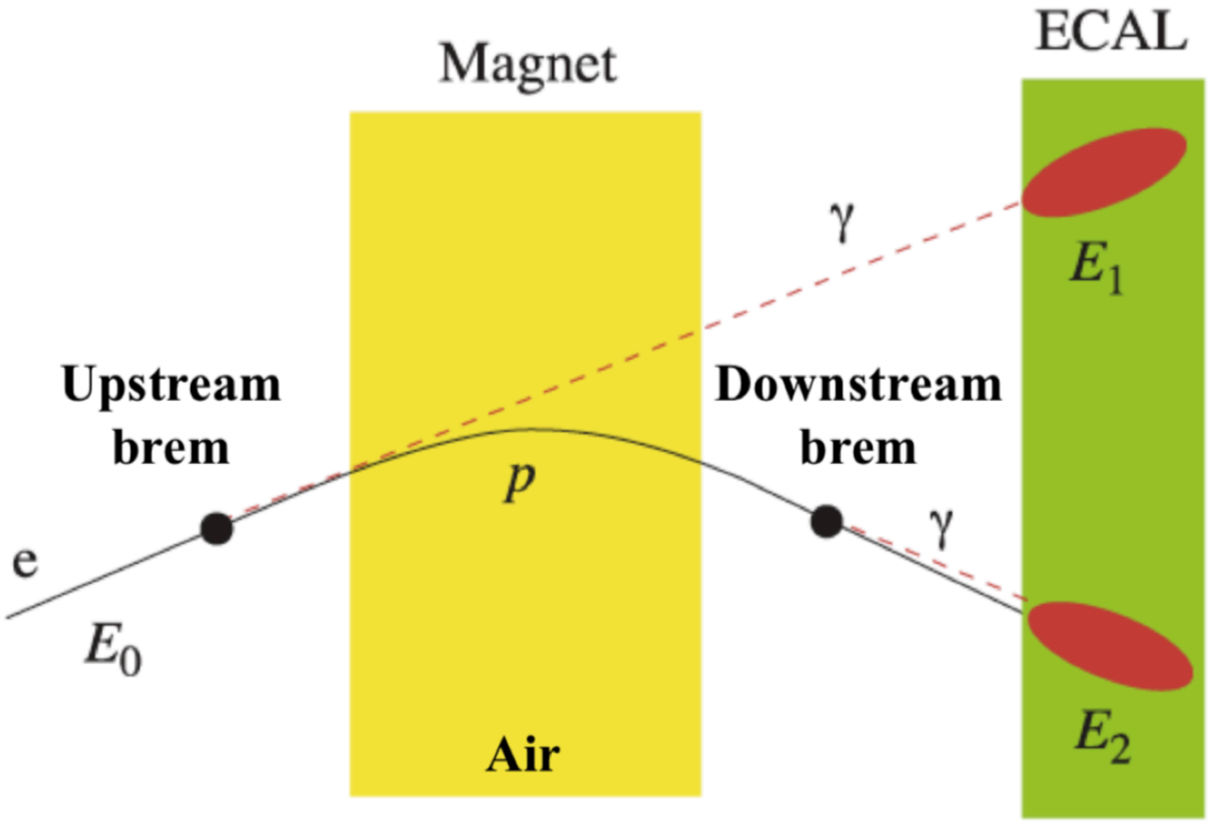
Precisely predicted to be ~1 in SM



Challenges with electrons



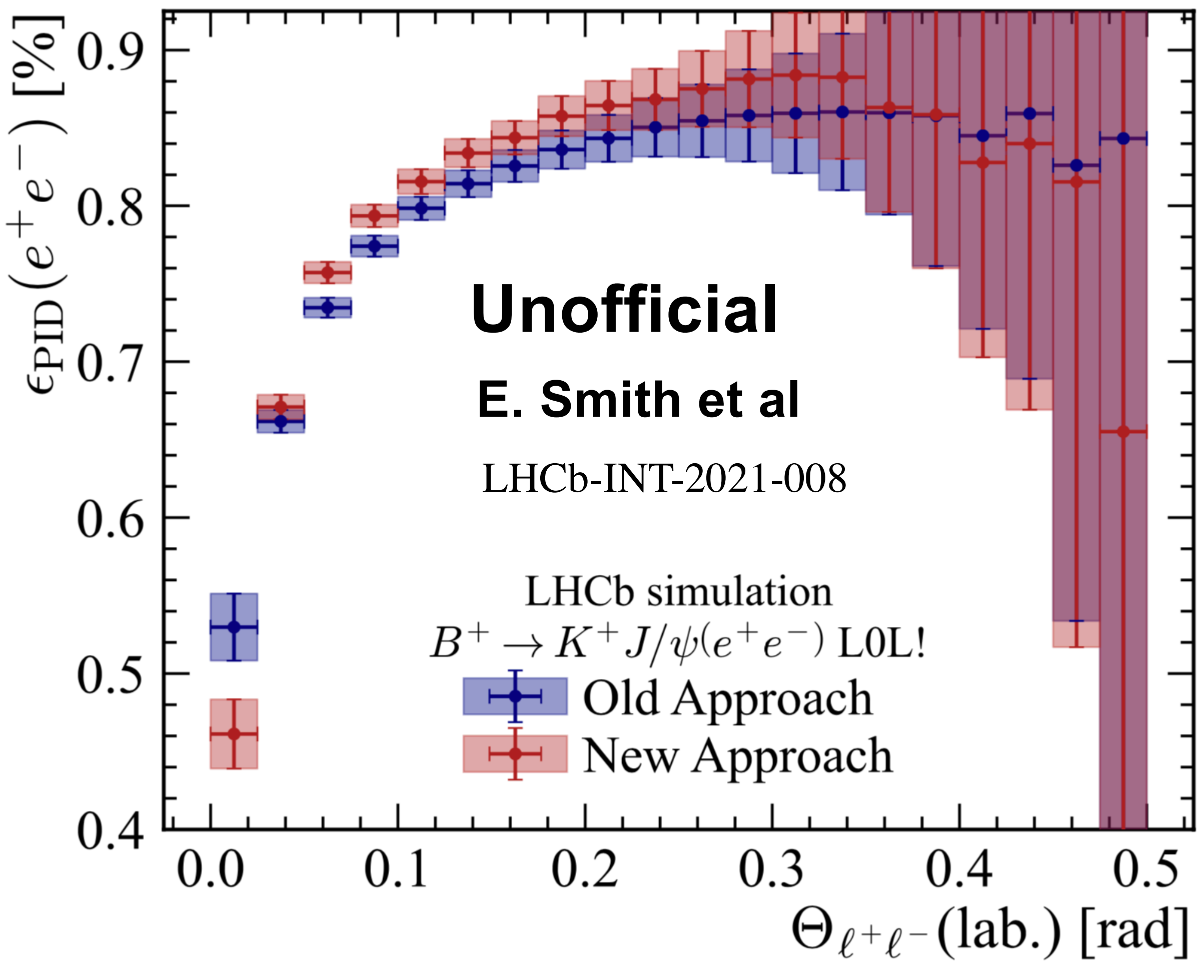
aus: S. Hansmann-Menzerer, Flavour matters, Kolloquium HD



$m_e << m_\mu$

➡ Bremsstrahlung

Understanding electron detector-response description in simulation vital

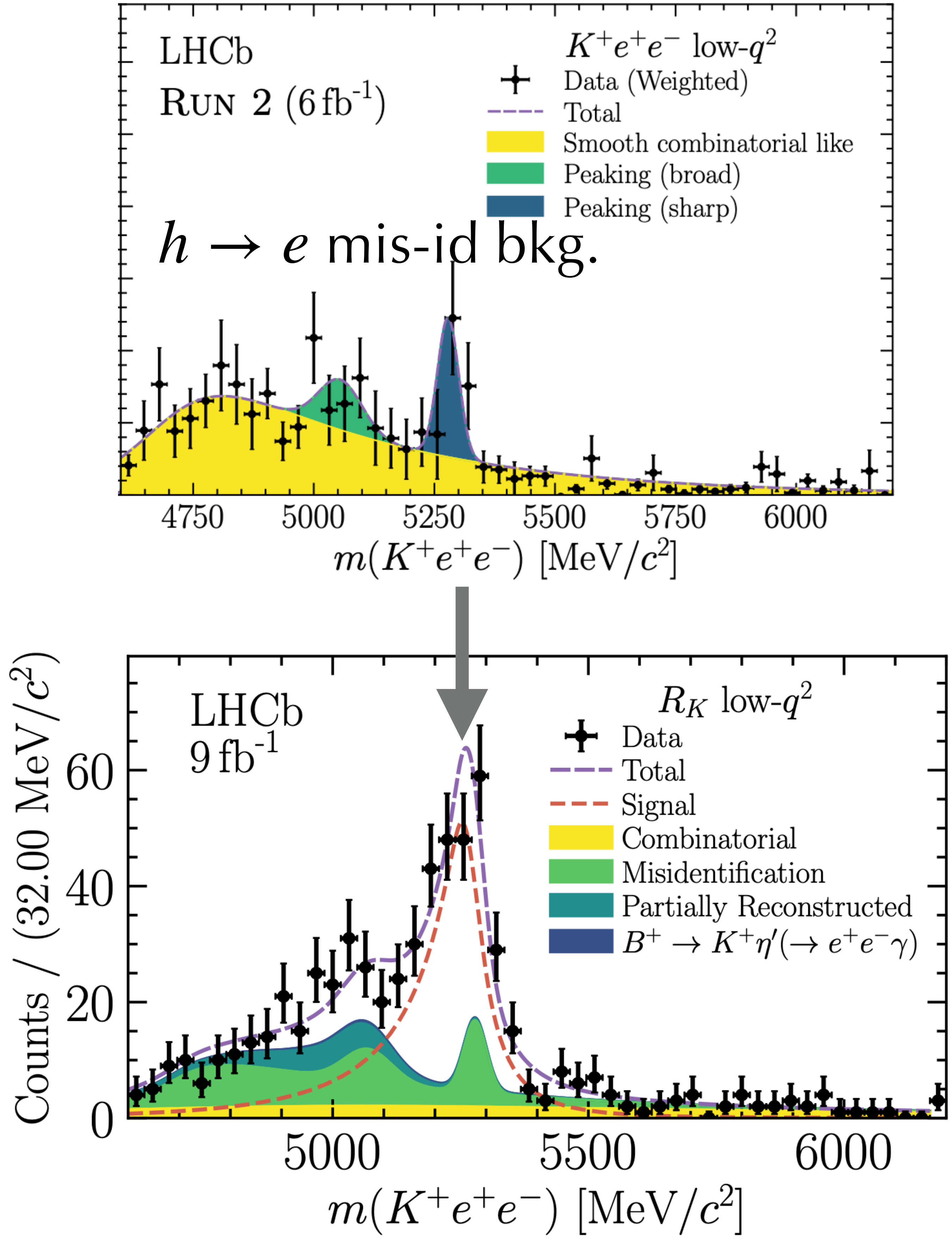


Challenges with electrons

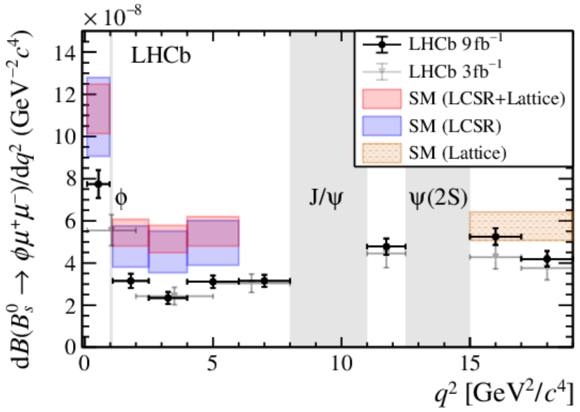
Understanding backgrounds a challenge

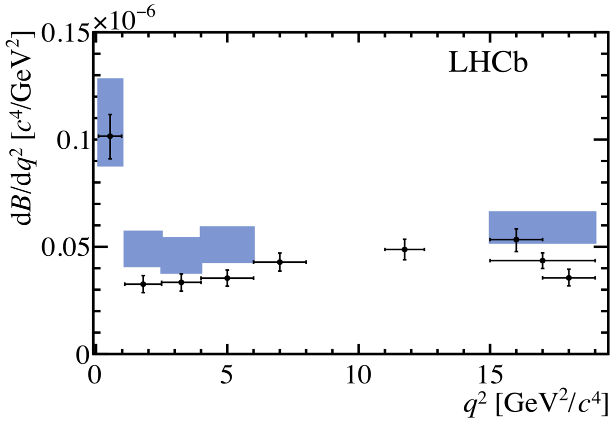
I currently lead measurements of $R(\phi)$ and $R(K\pi)$, where the $K\pi$ systems comes from above ~1 GeV

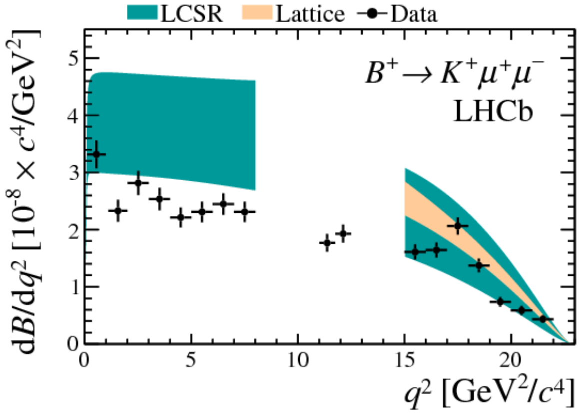
Both these modes have less background components than in existing measurements



Interim recap: summary of summaries

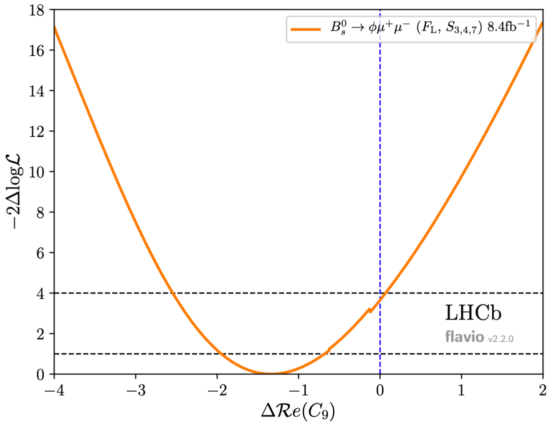


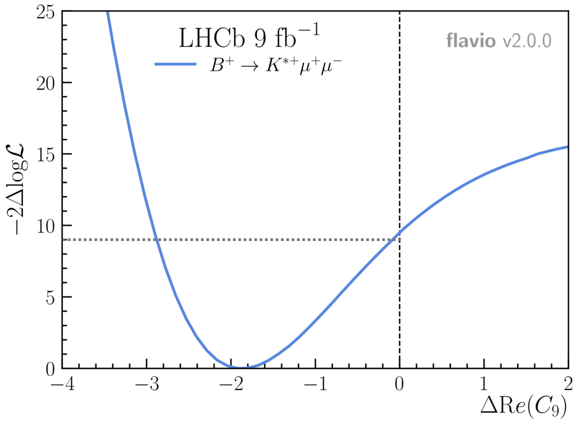


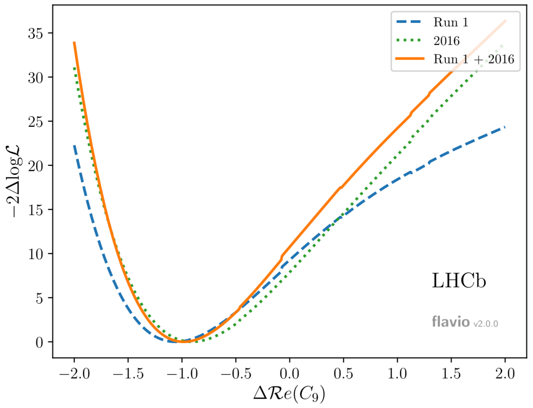


Branching fractions

$> 3\sigma$

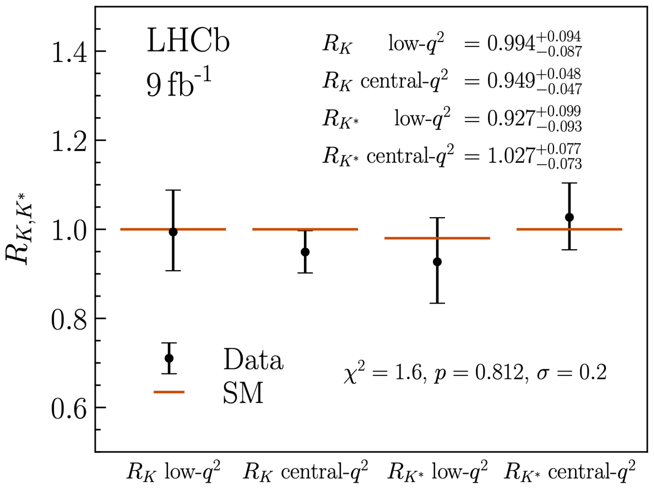


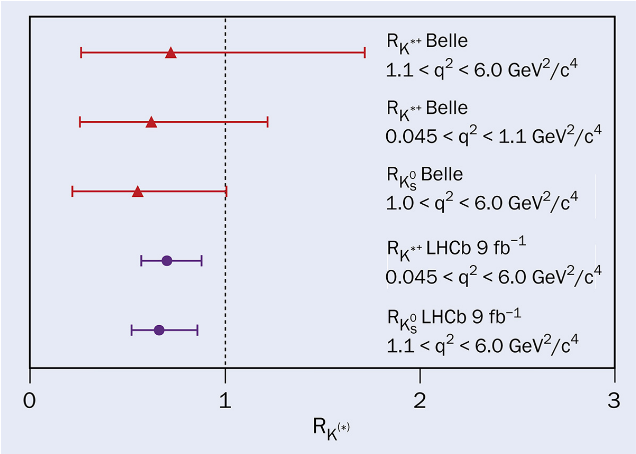




Angular analysis

$> 3\sigma$



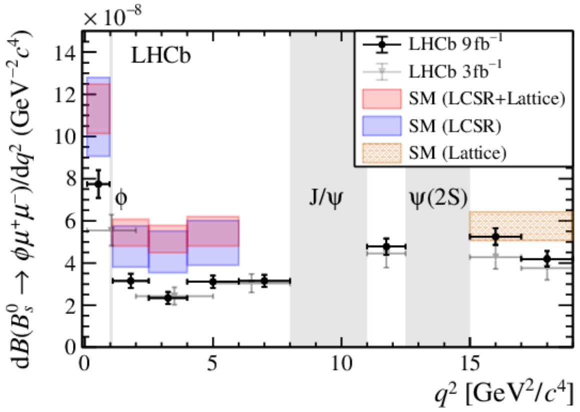


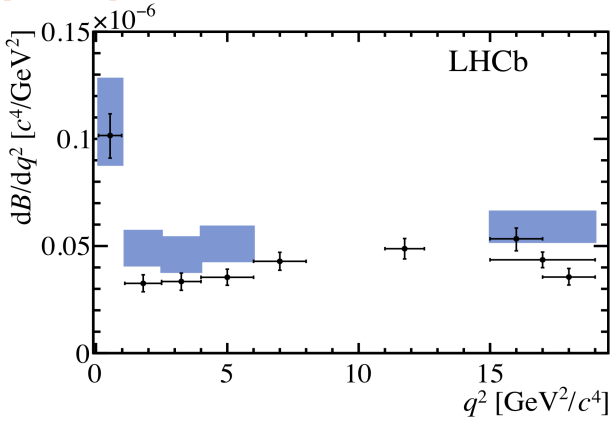
Lepton Flavour Universality (LFU)

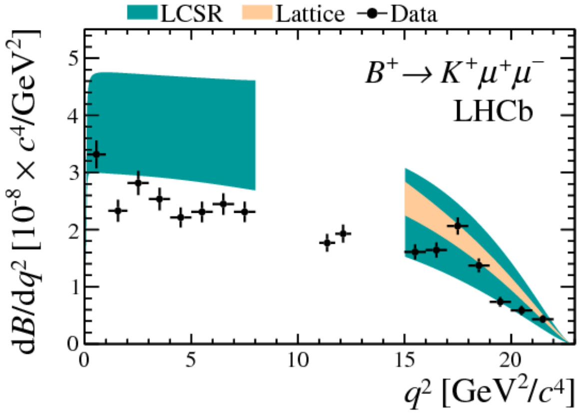
SM-like

Interim recap: summary of summaries

$b \to s\mu^+\mu^-$ anomalies

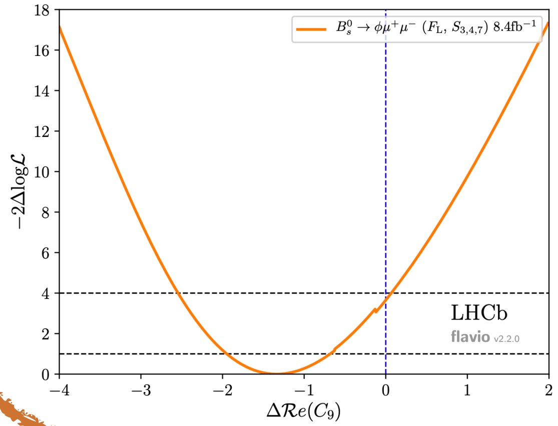


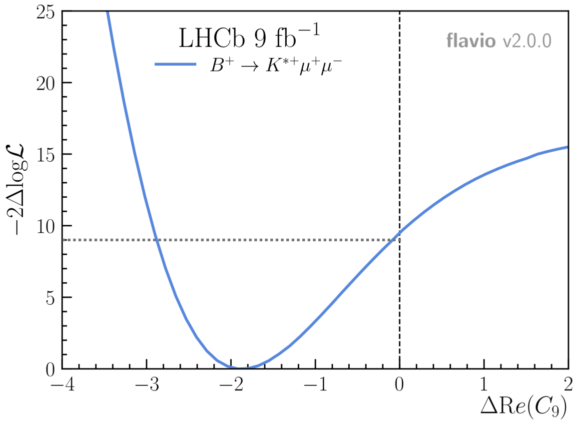


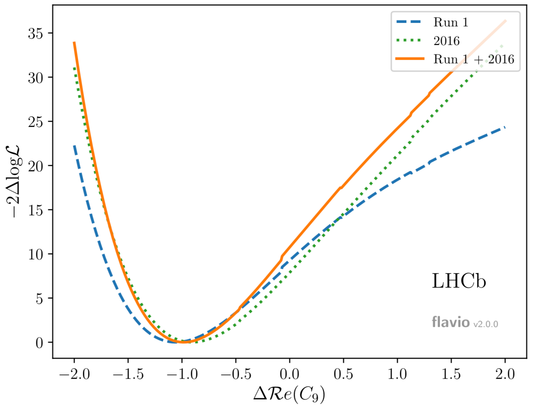


Branching fractions

$> 3\sigma$

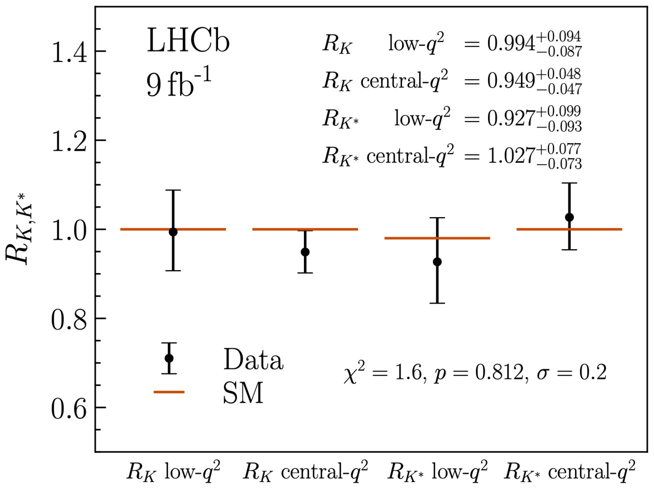


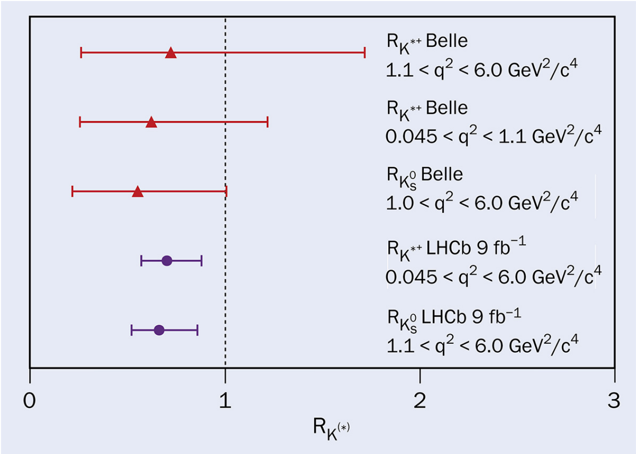




Angular analysis

$> 3\sigma$





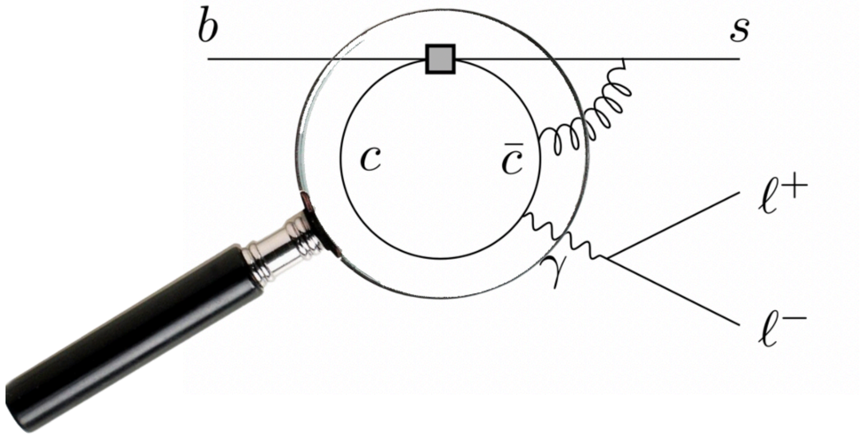
Lepton Flavour Universality (LFU)

SM-like

The $b \to s\mu^+\mu^-$ anomalies: what is causing them?

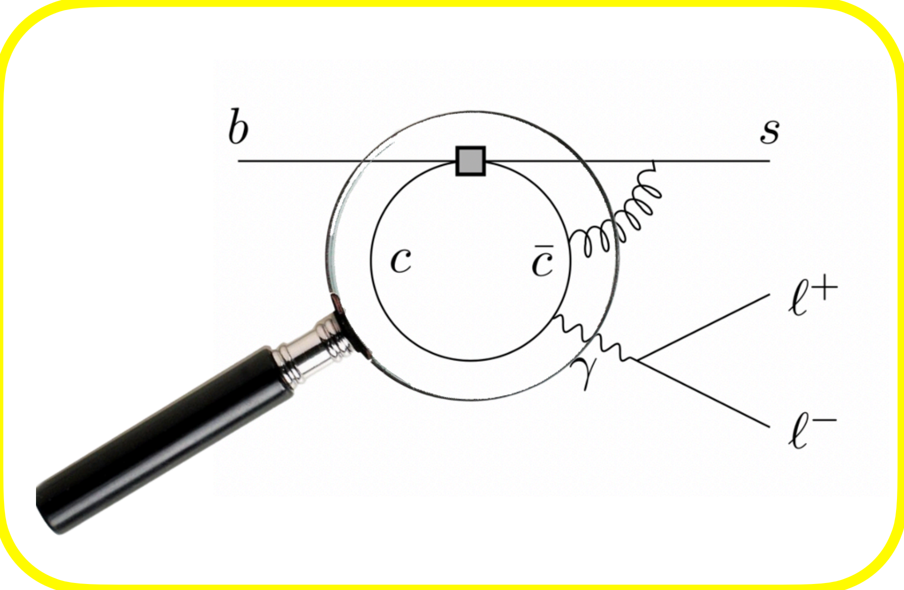
QCD

New Physics



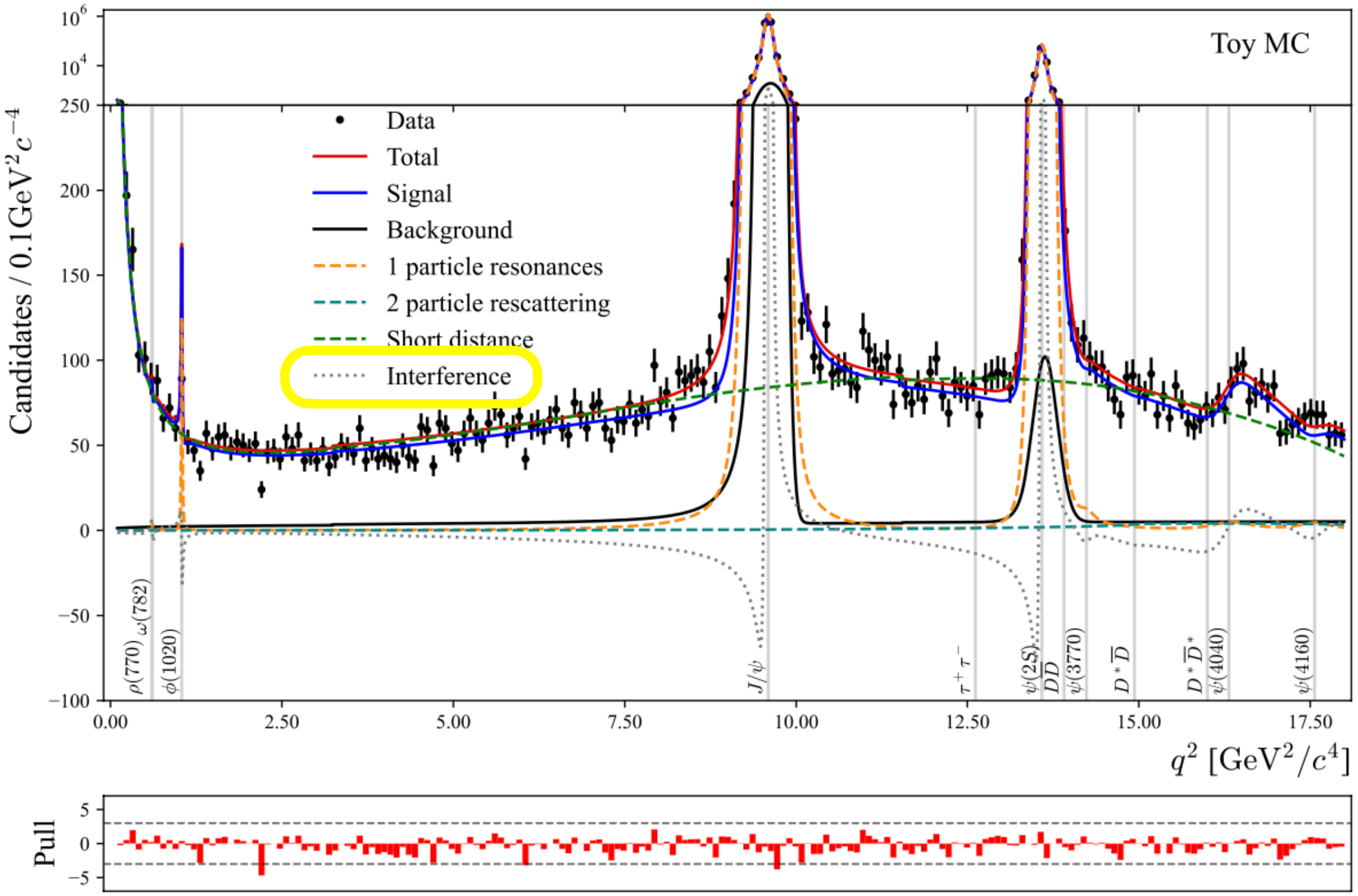
Measure charm-loops in data

Measuring the charm-loop using data



Fit for effective couplings directly, allowing interference effects between charm-loops and signal to be measured

- First work of its kind: resolution +angular fits = highly complex
- Help determine whether $B \to K^{*0}\mu^+\mu^-$ anomaly is



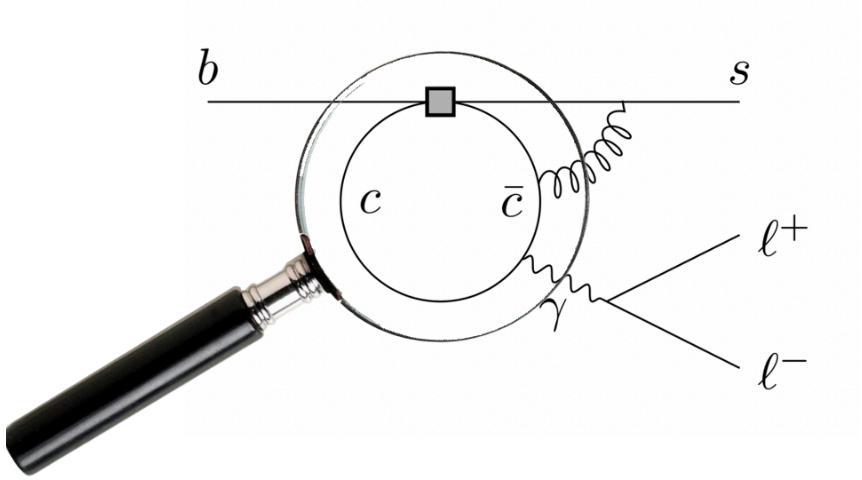
Or

Possible with existing data

The $b \to s\mu^+\mu^-$ anomalies: what is causing them?

QCD

New Physics



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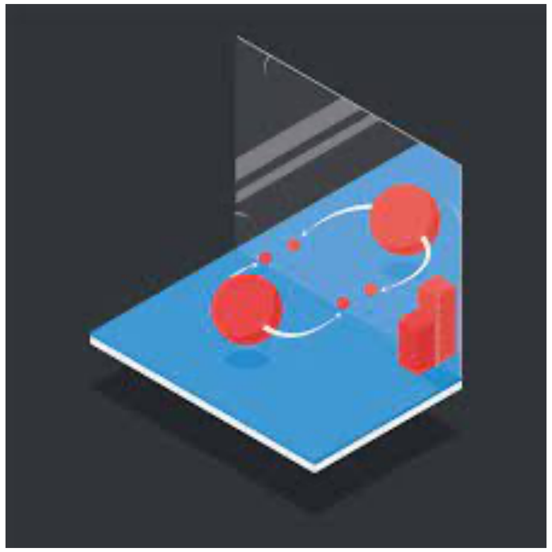

Probe CP-violation in $b \to s\mu^+\mu^-$ ("clean")

The $b \to s\mu^+\mu^-$ anomalies: what is causing them?

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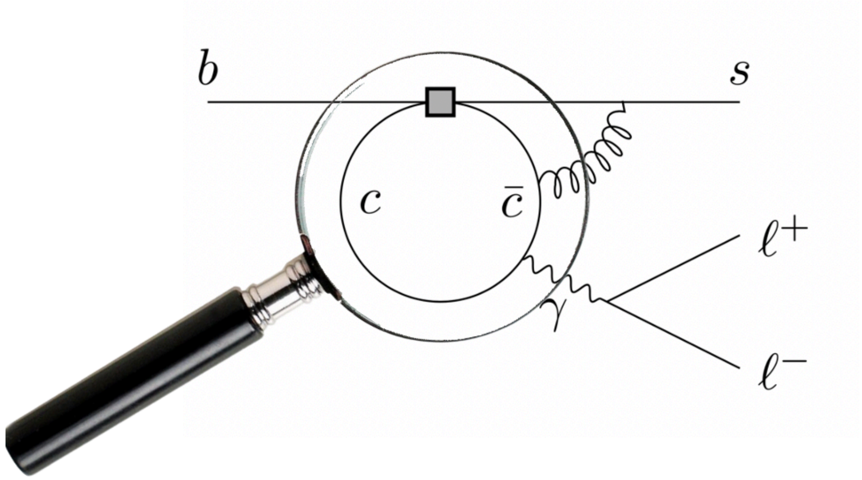

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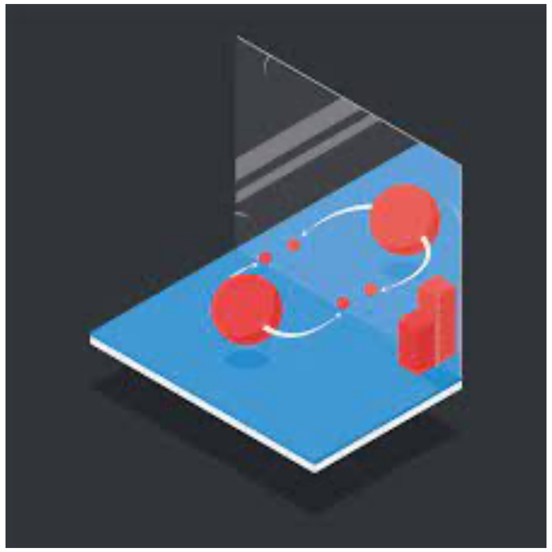
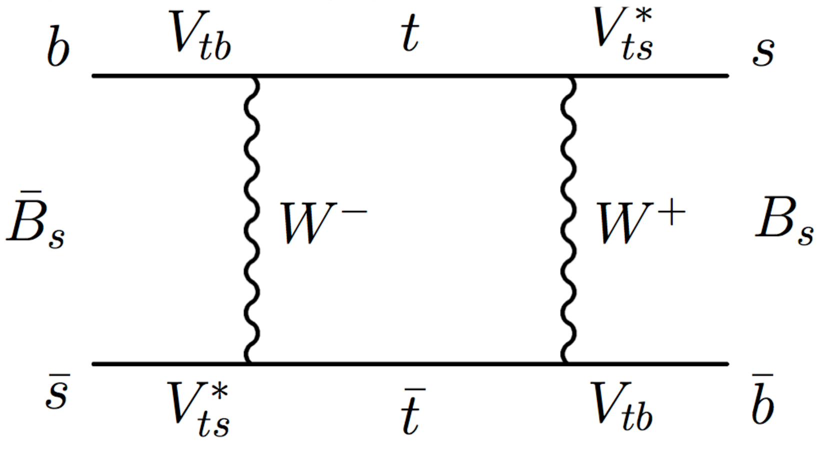


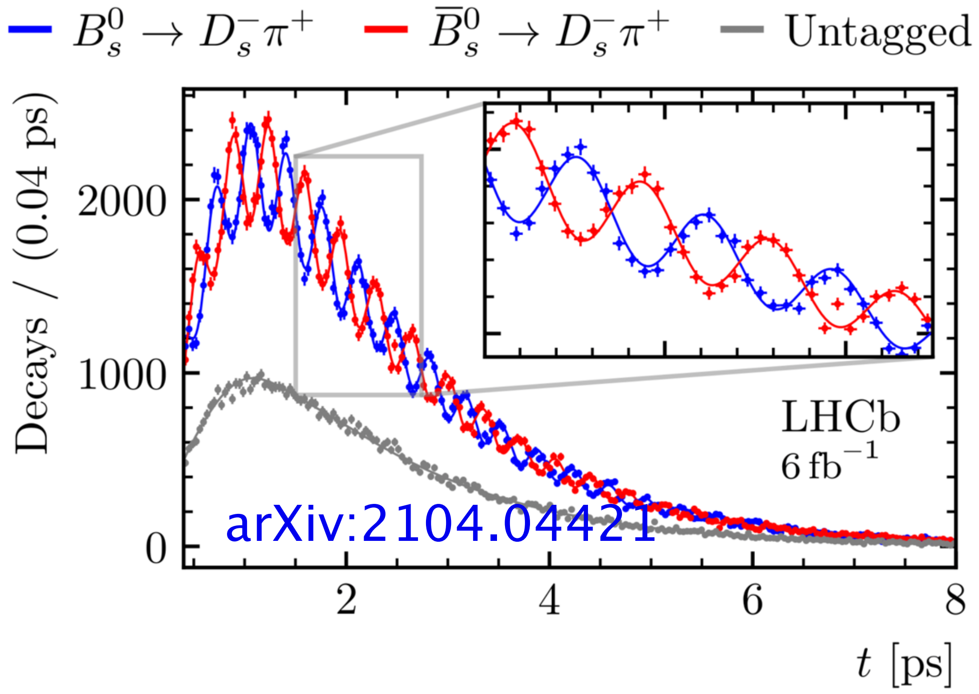
Probe CP-violation in $b \to s\mu^+\mu^-$ ("clean")

Time-dependent angular analysis

Neutral B meson



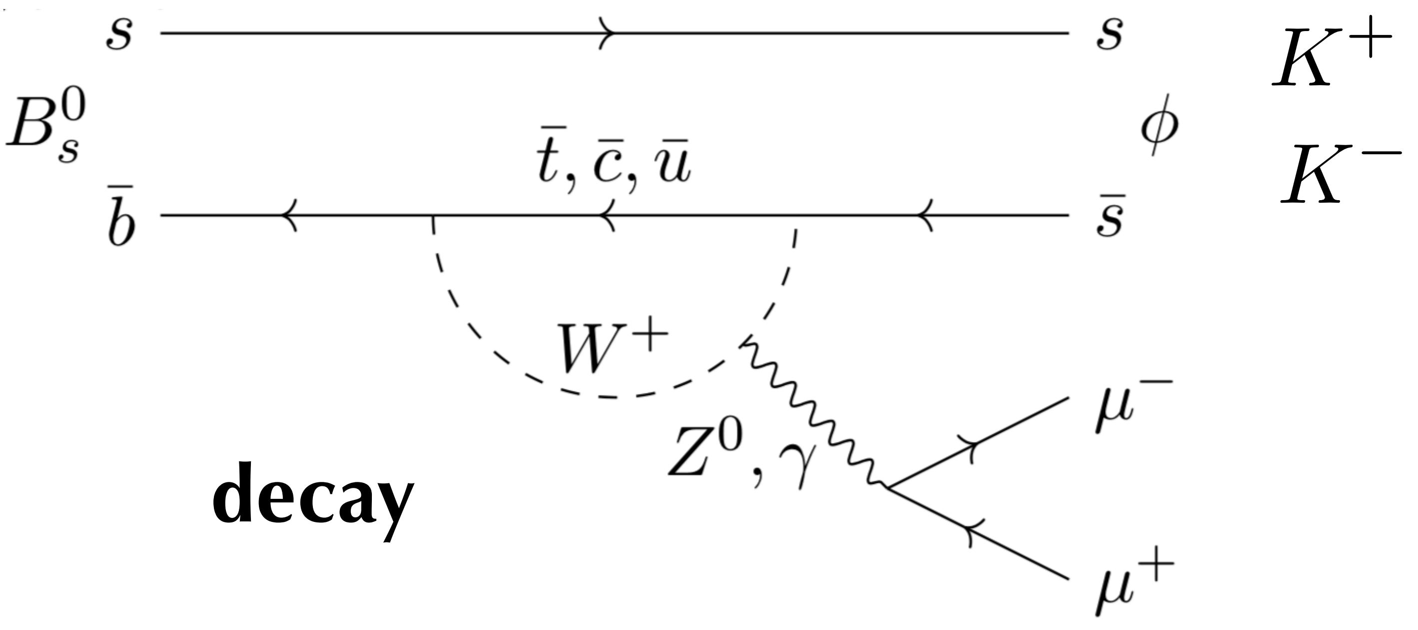
Mixing



arXiv:2104.04421

+

CP-symmetric final-state



decay

$B_s \to \phi\mu^+\mu^-$

$\bar{B}_s \to \phi\mu^+\mu^-$

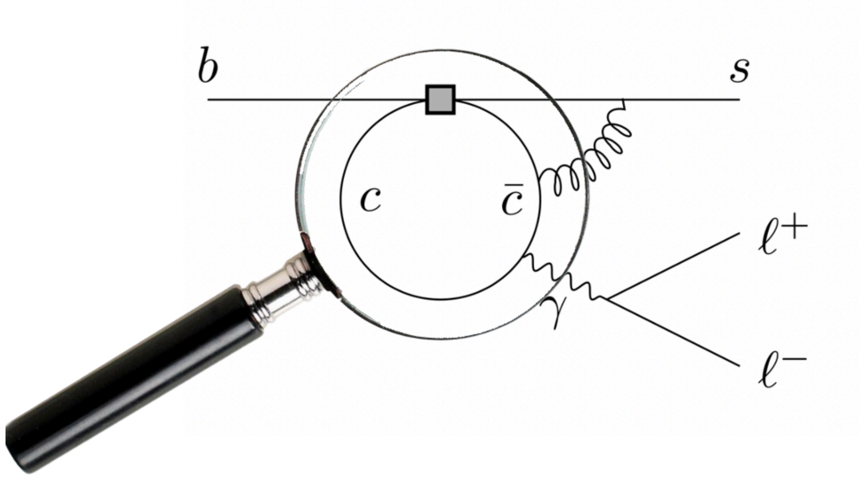
= Interference

Need more data!!

- Would be first time-dependent analysis in a $b \to s\mu^+\mu^-$mode
- Unique separation between NP scenarios
- Both CP-violating+conserving obs.

The $b \to s\mu^+\mu^-$ anomalies: what is causing them?

QCD



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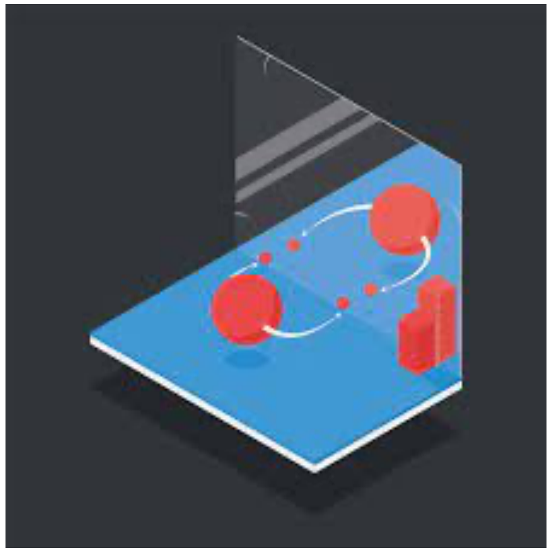
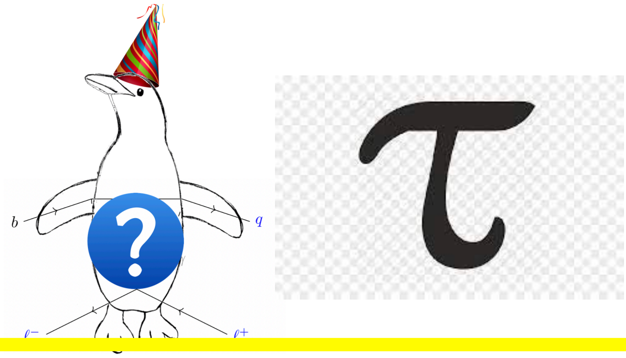


Probe CP-violation in $b \to s\mu^+\mu^-$ ("clean")

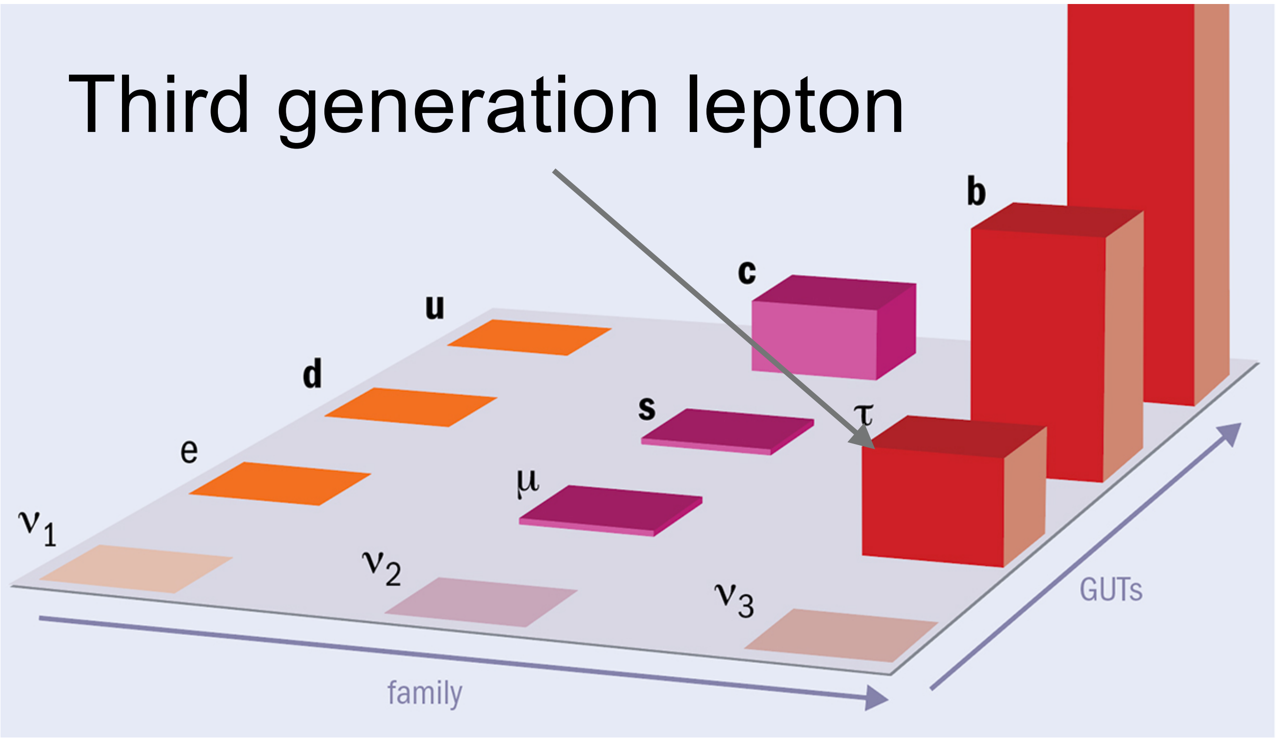
New Physics

"If it were NP, what other variables might it effect?"

Enhancements in $b \to s\tau^+\tau^-$?



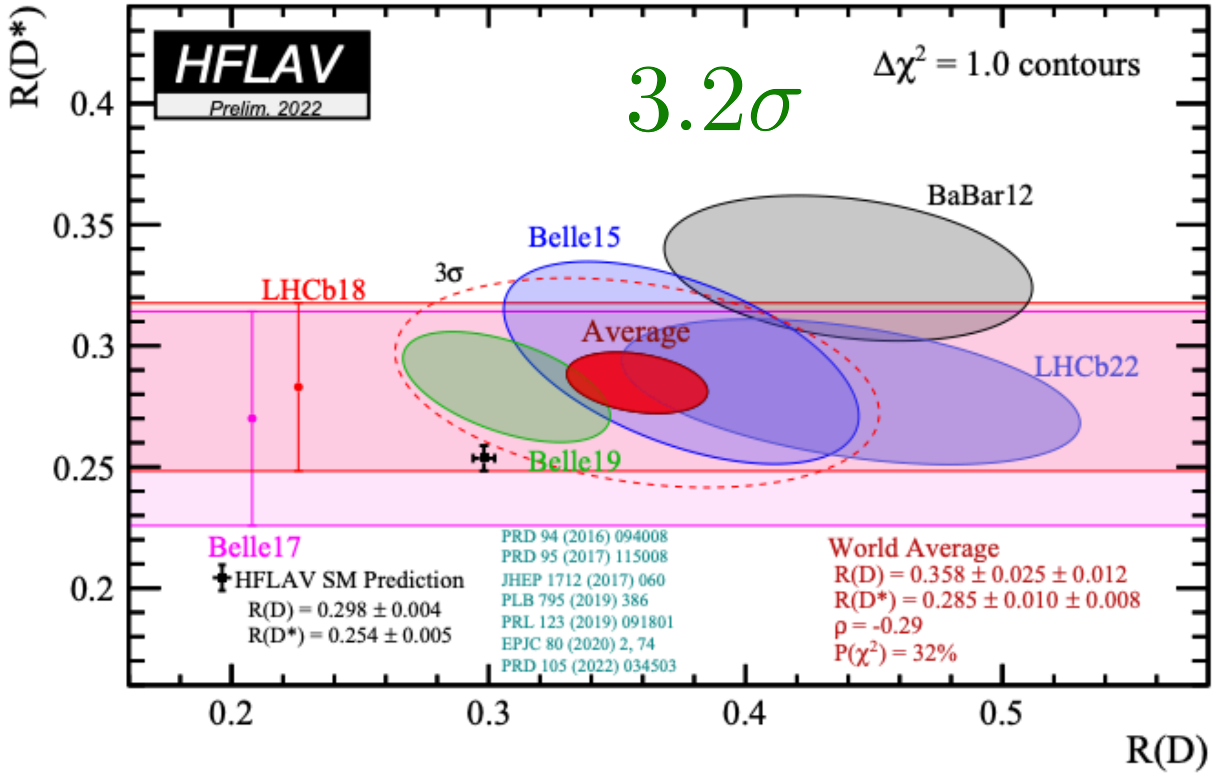
A brief hia-taus….



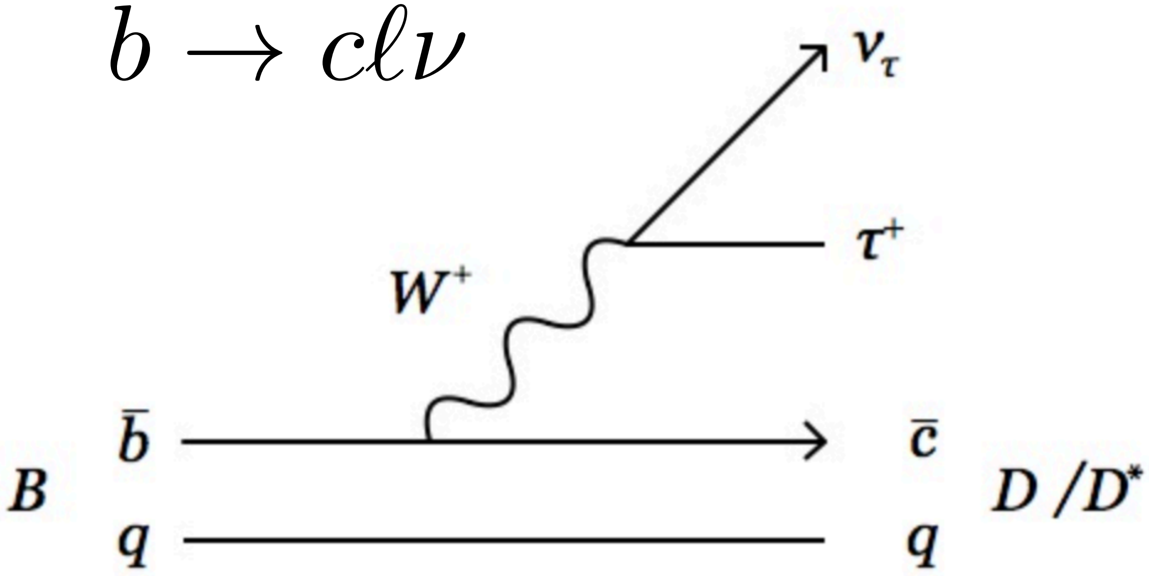
Third generation lepton

This talk and my research focuses on suppressed neutral current $b \to s\ell\ell$ transitions: only muons & electrons measurable

A brief hia-taus….



$b \to c\ell\nu$



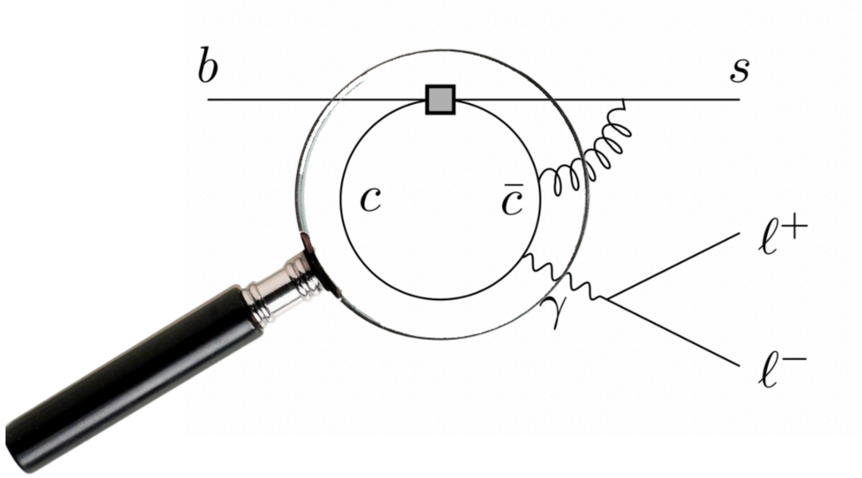
This talk and my research focuses on suppressed neutral current $b \to s\ell\ell$ transitions: only muons & electrons measurable

However, there are also anomalies in the tree-level charged current $b \to c\ell\nu$ with τ's vs light leptons (muons and electrons)

Combined explanation of neutral and charged current anomalies (collectively: “B anomalies”) predict large effects in $b \to s\tau^+\tau^-$

The $b \to s\mu^+\mu^-$ anomalies: what is causing them?

QCD



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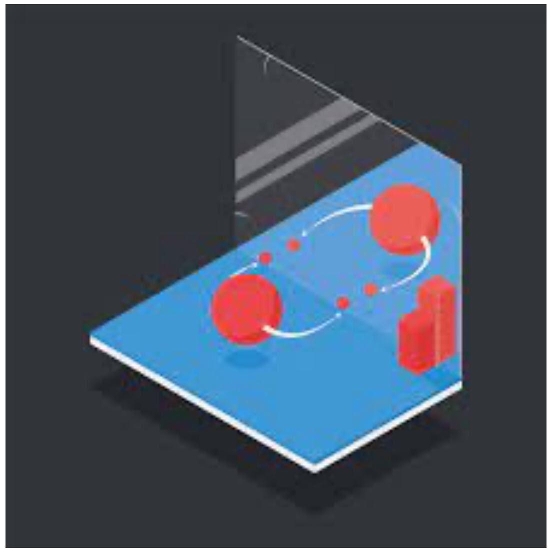

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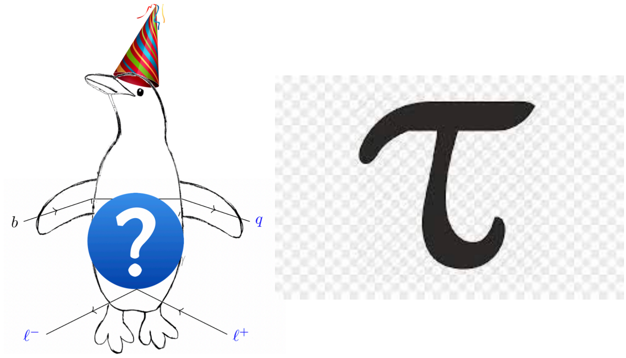
Enhancements in $b \to s\tau^+\tau^-$?



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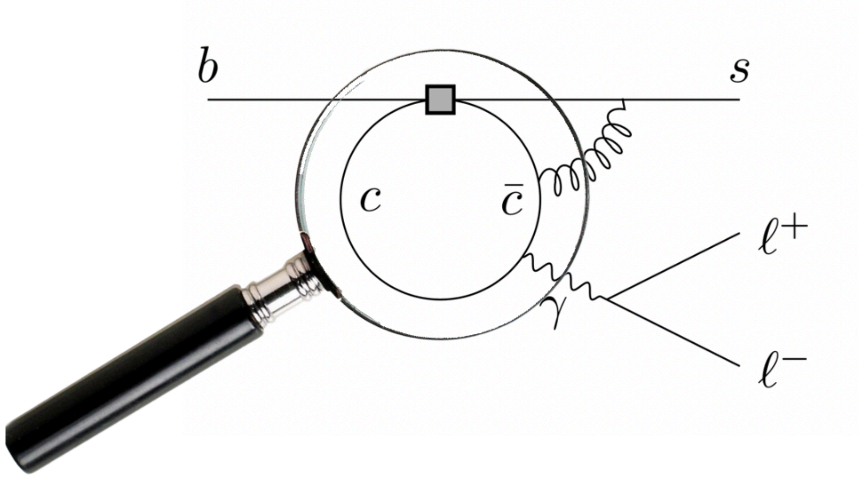

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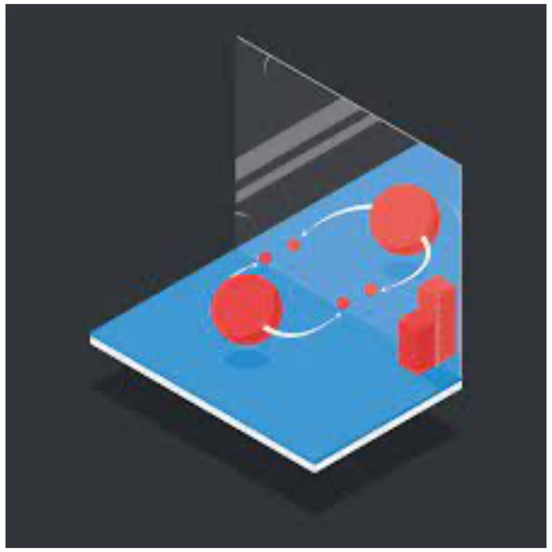
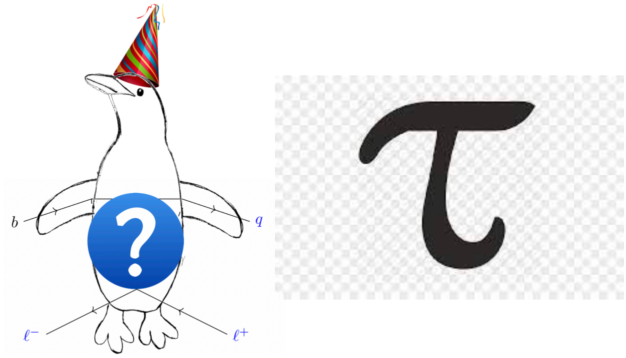


Probe CP-violation in $b \to s\mu^+\mu^-$ ("clean")

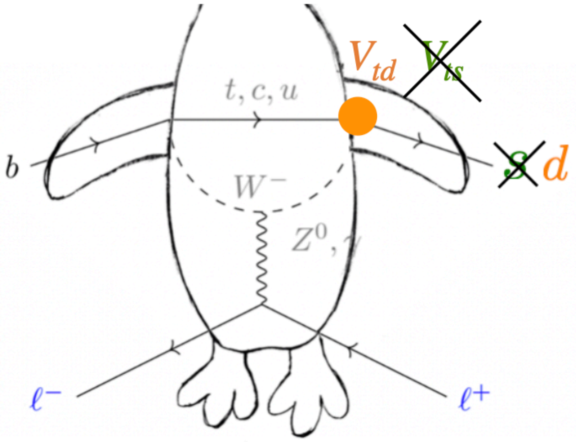
New Physics

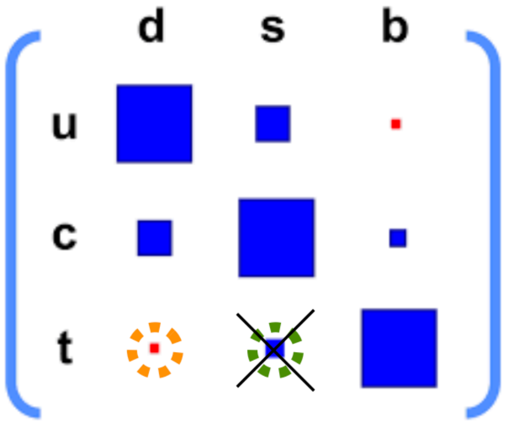
"If it were NP, what other variables might it effect?"

Enhancements in $b \to s\tau^+\tau^-$**?**



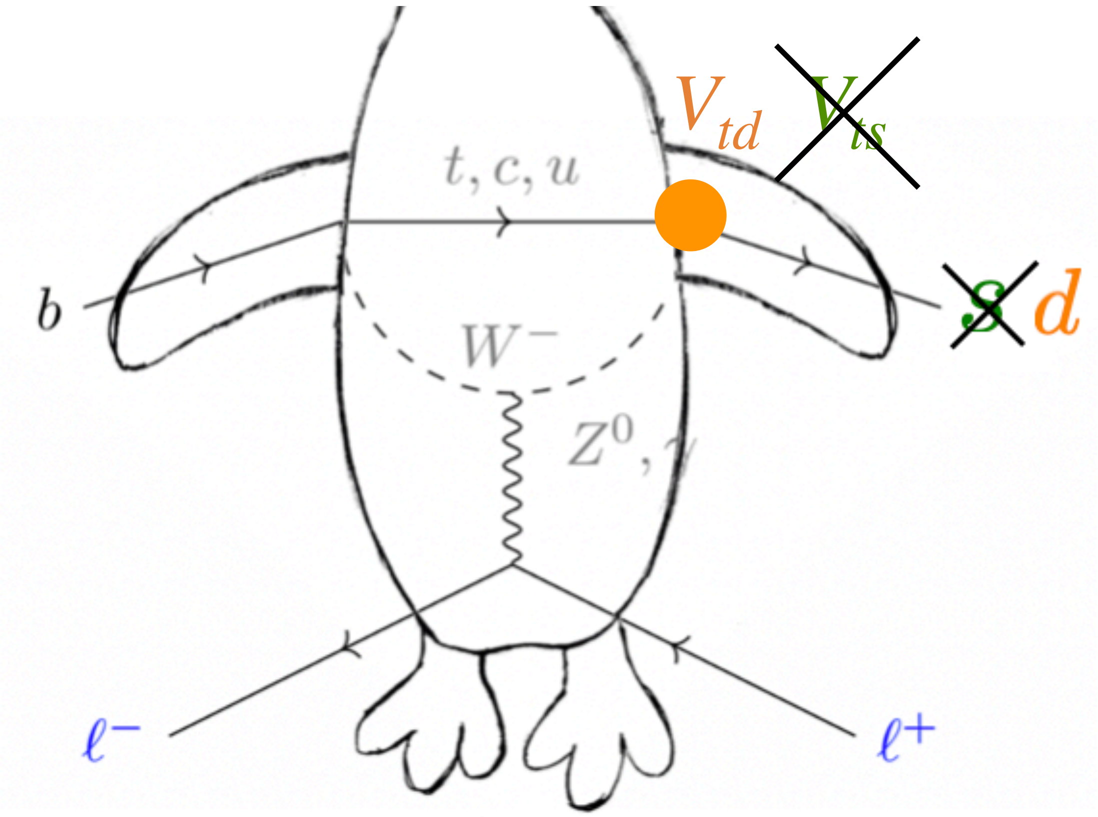
Effects in $b \to d\ell^+\ell^-$?

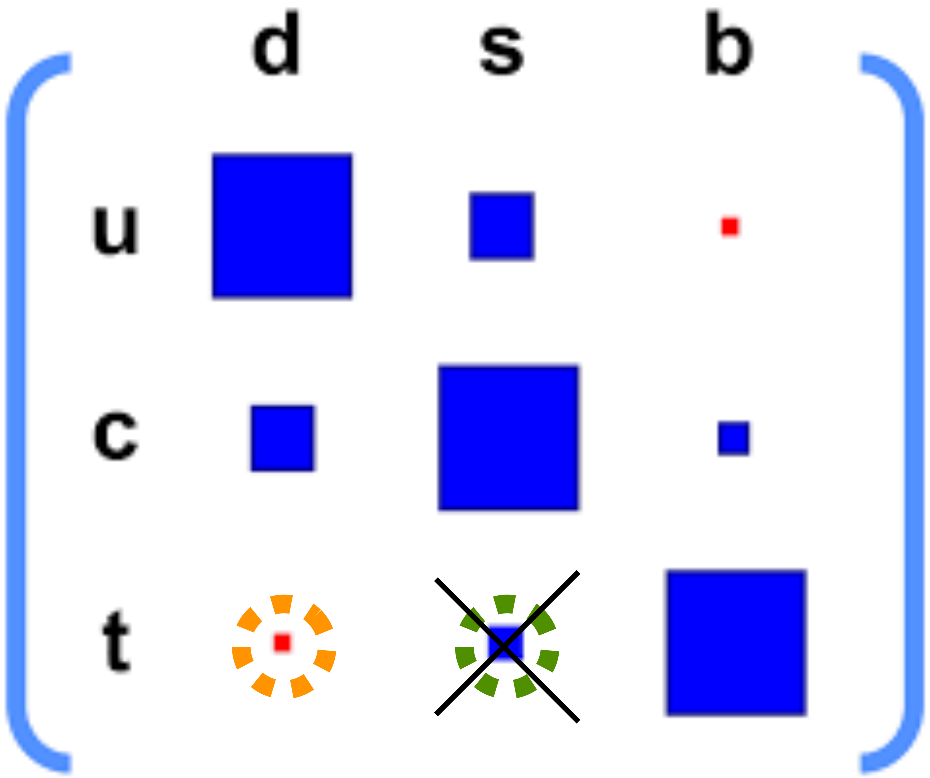




What about $b \to d\ell^+\ell^-$ decays?

- Decay rates around $|V_{ts}/V_{td}|^2 \approx 25$ smaller than $b \to s\ell^+\ell^-$
- Many explanations for $b \to s\ell^+\ell^-$ anomalies predict effects in $b \to d\ell^+\ell^-$
- If NP flavour structure is non-SM like, could see huge effects

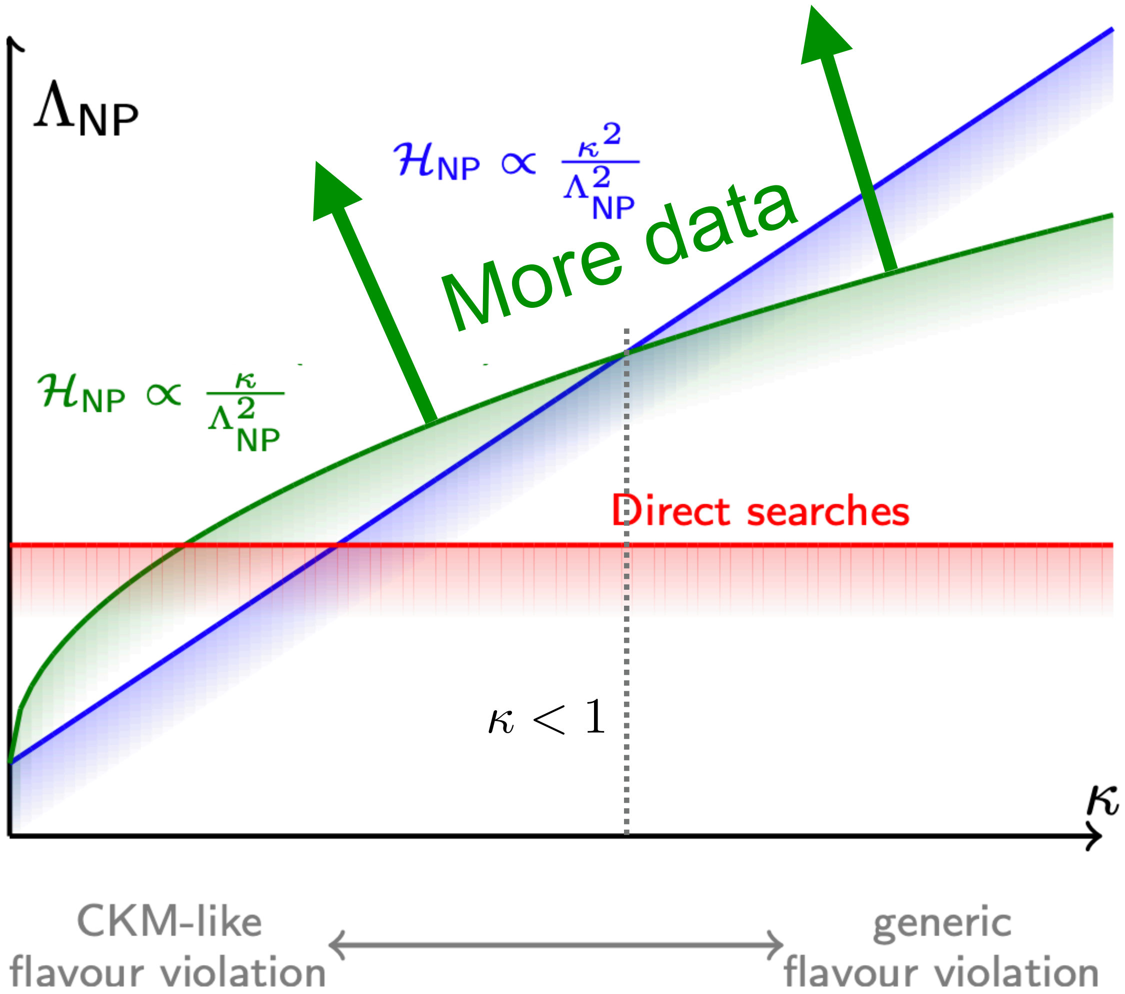




Need more data!!

What about $b \to d\ell^+\ell^-$ decays?

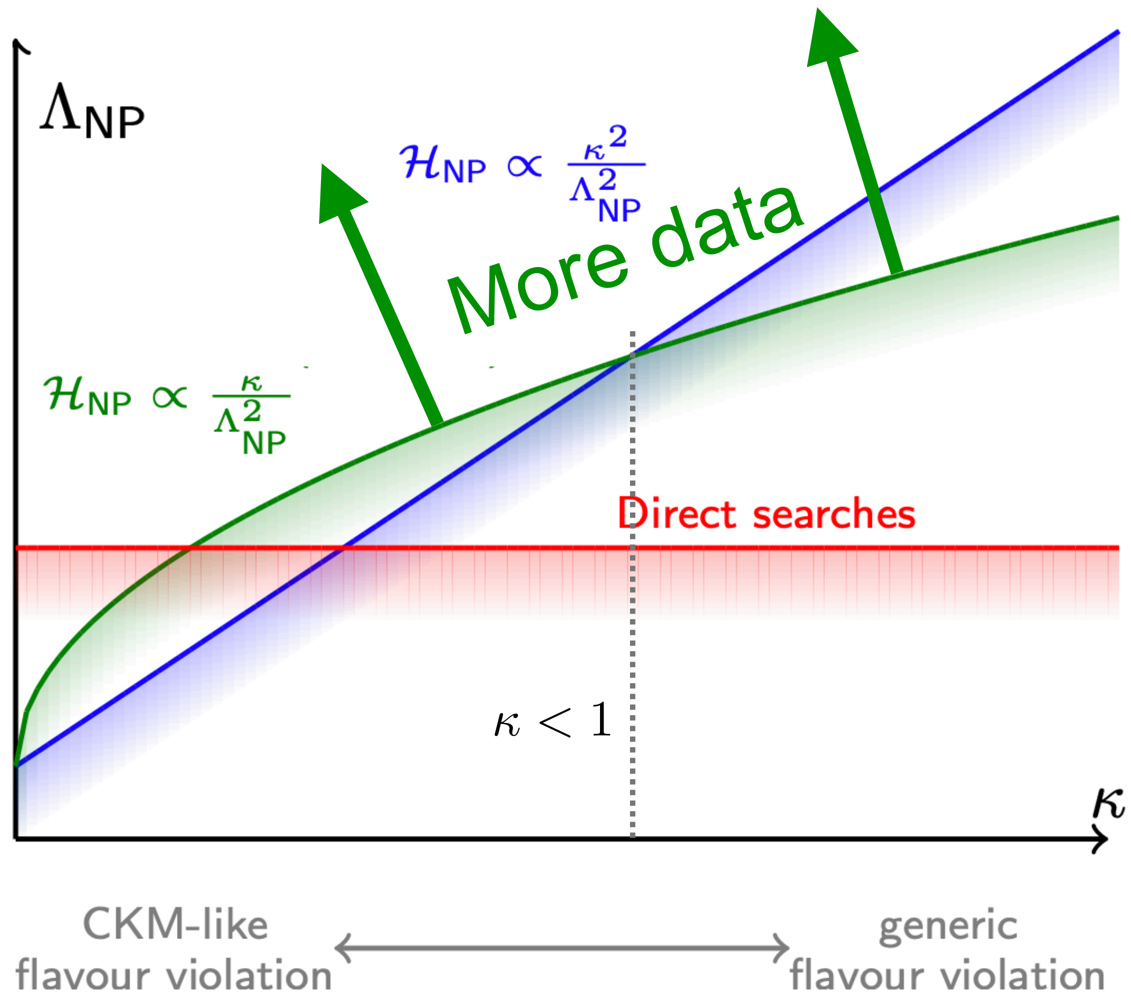
- Uncertainties will be statistically dominated, even by Upgrade II, direct link between new data + higher NP scales

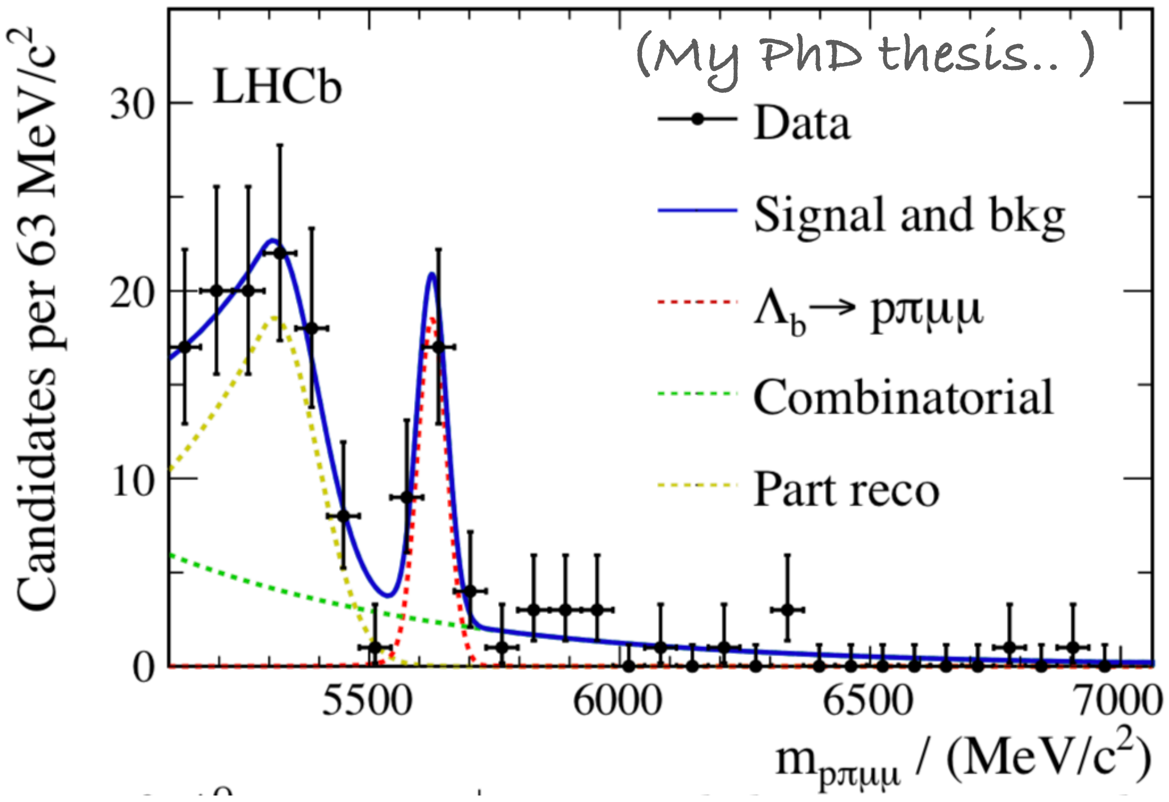


Need more data!!

What about $b \to d\ell^+\ell^-$ decays?

- Uncertainties will be statistically dominated, even by Upgrade II, direct link between new data + higher NP scales
- To date, very limited measurements, with Upgrade II, even angular analysis will be possible





Need more data!!

The $b \to s\mu^+\mu^-$ anomalies: what is causing them?

QCD

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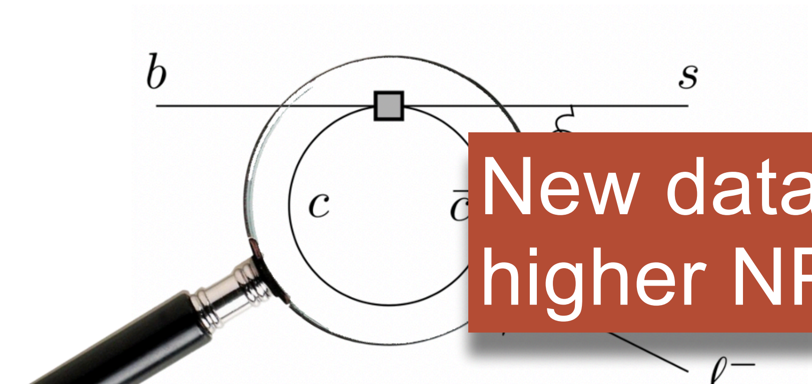

“If it were NP, what other

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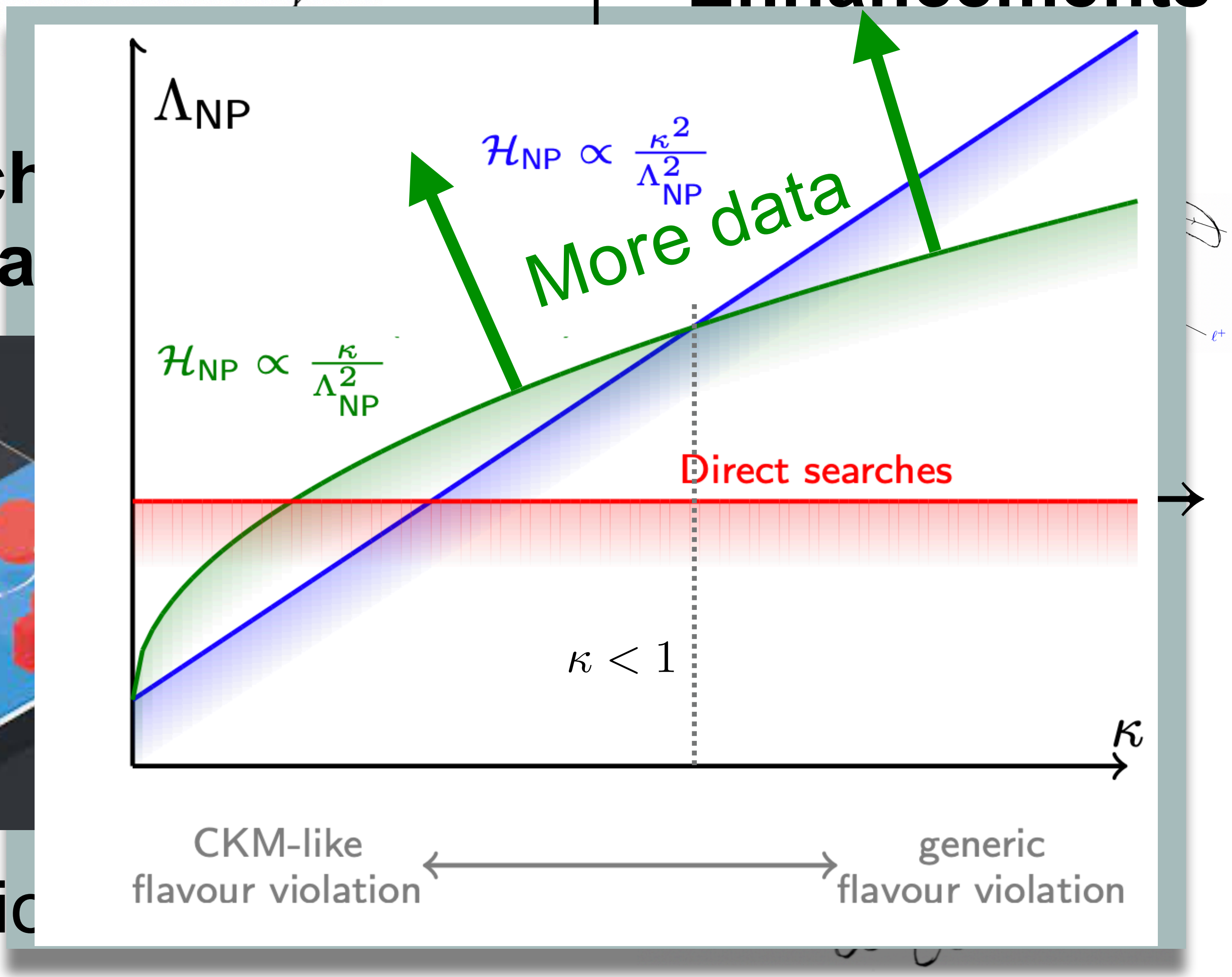
New data = more precision, higher NP scales

Enhancements in $b \to s\tau^+\tau^-$?



Measure ch
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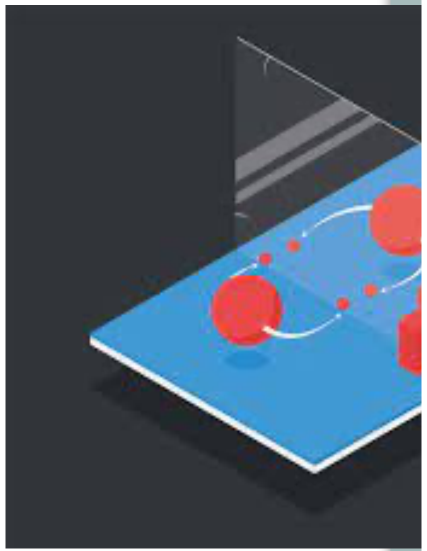
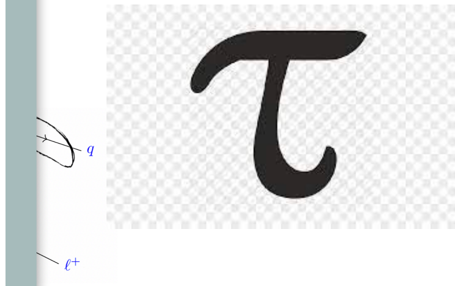
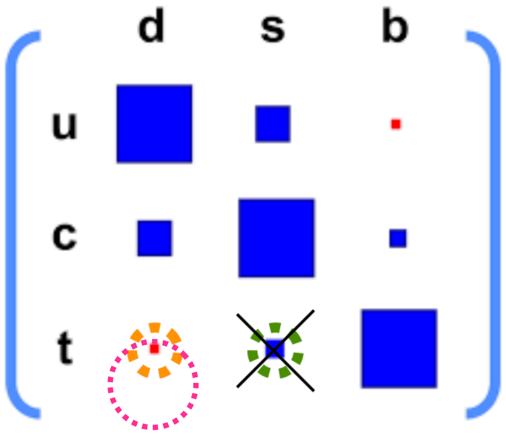


Probe CP-vi

$b \to s\mu^+\mu^-$ (“clean”)



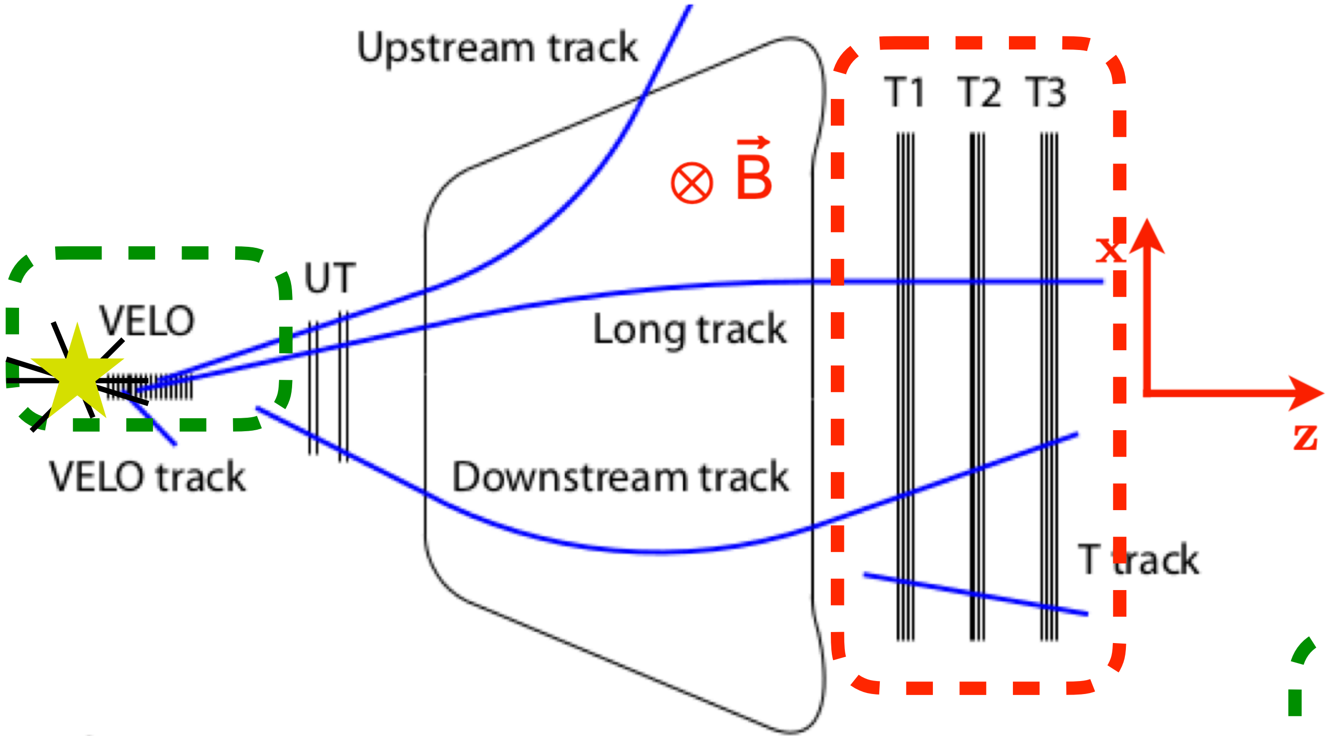
$\to d\ell^+\ell^-$?

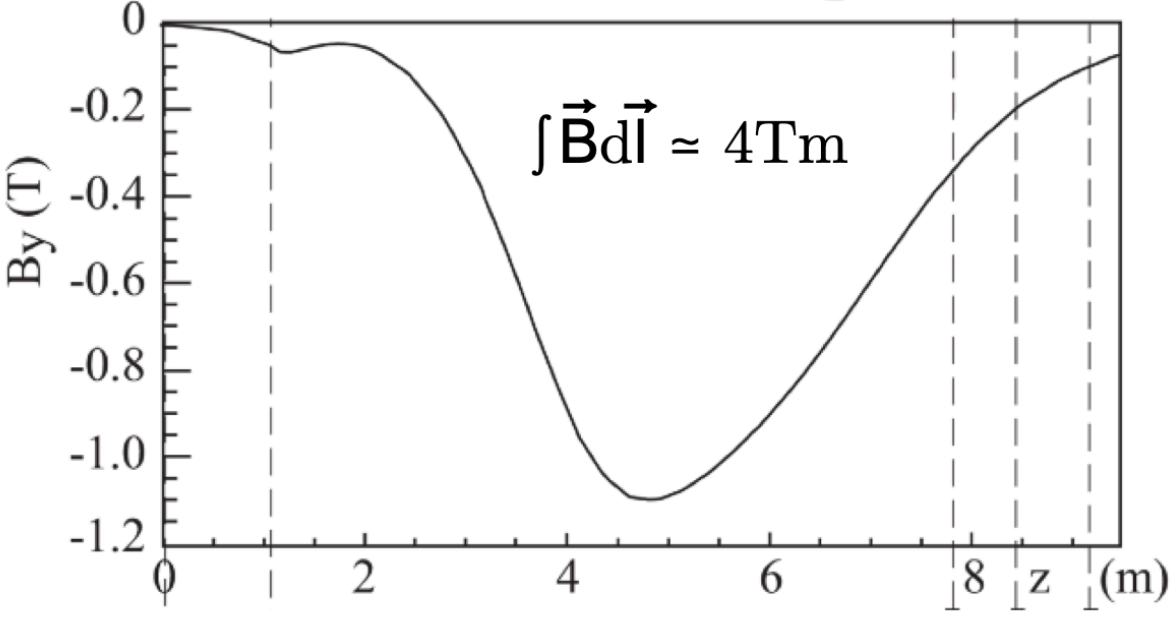


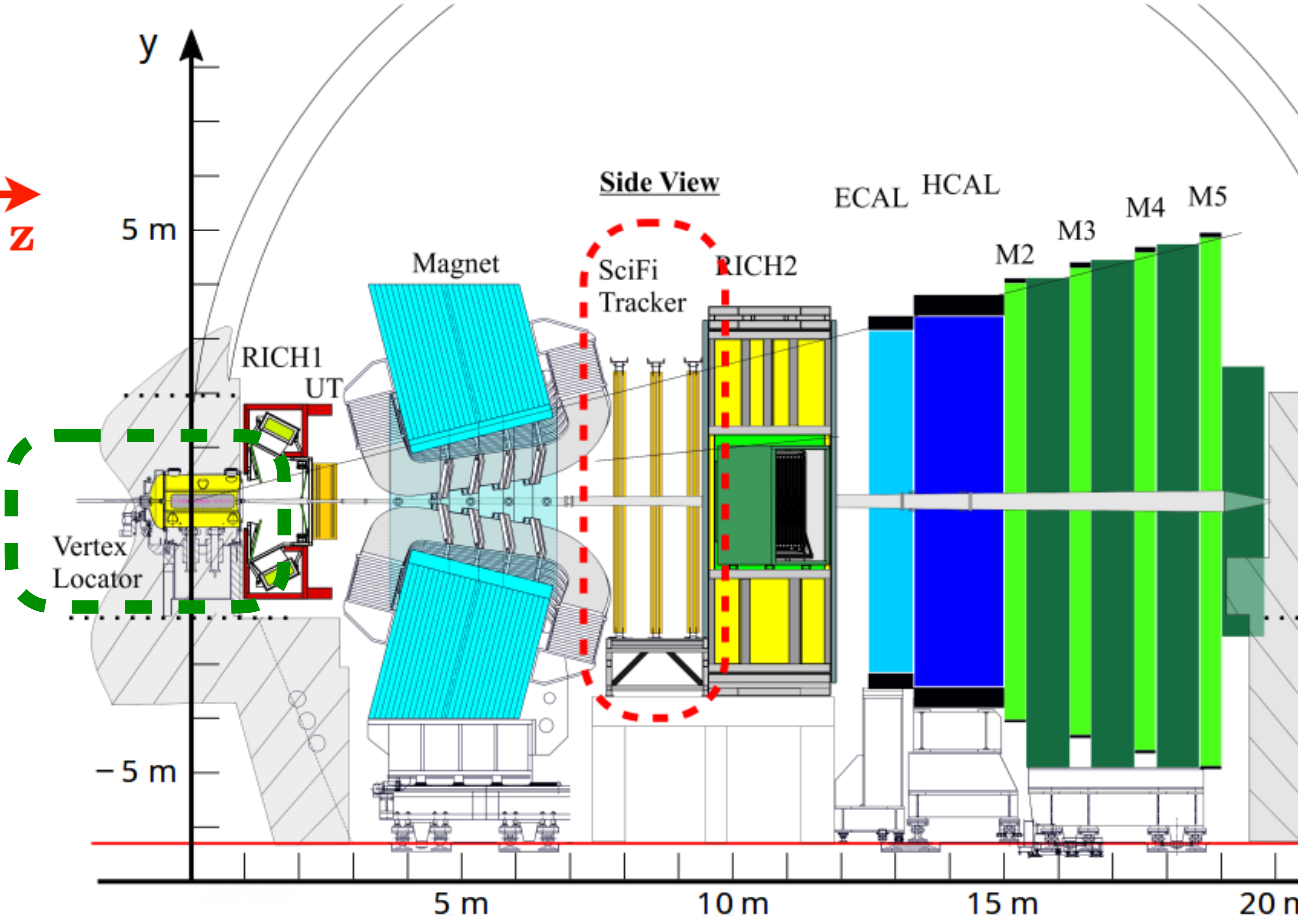
Upgrade II: tracking

Downstream tracking station: instrument large area (~12x30m^2)

Upgrade I: use scintillating fibres   (Sci Fi)







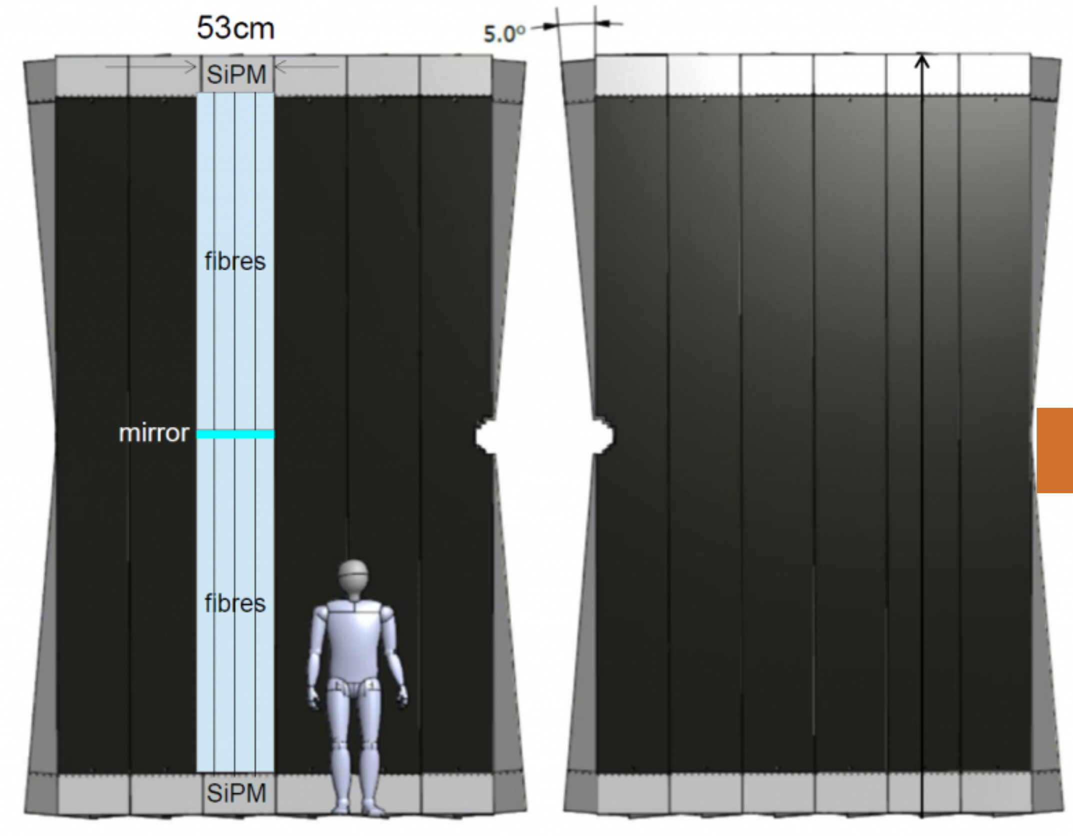
Upgrade II: tracking

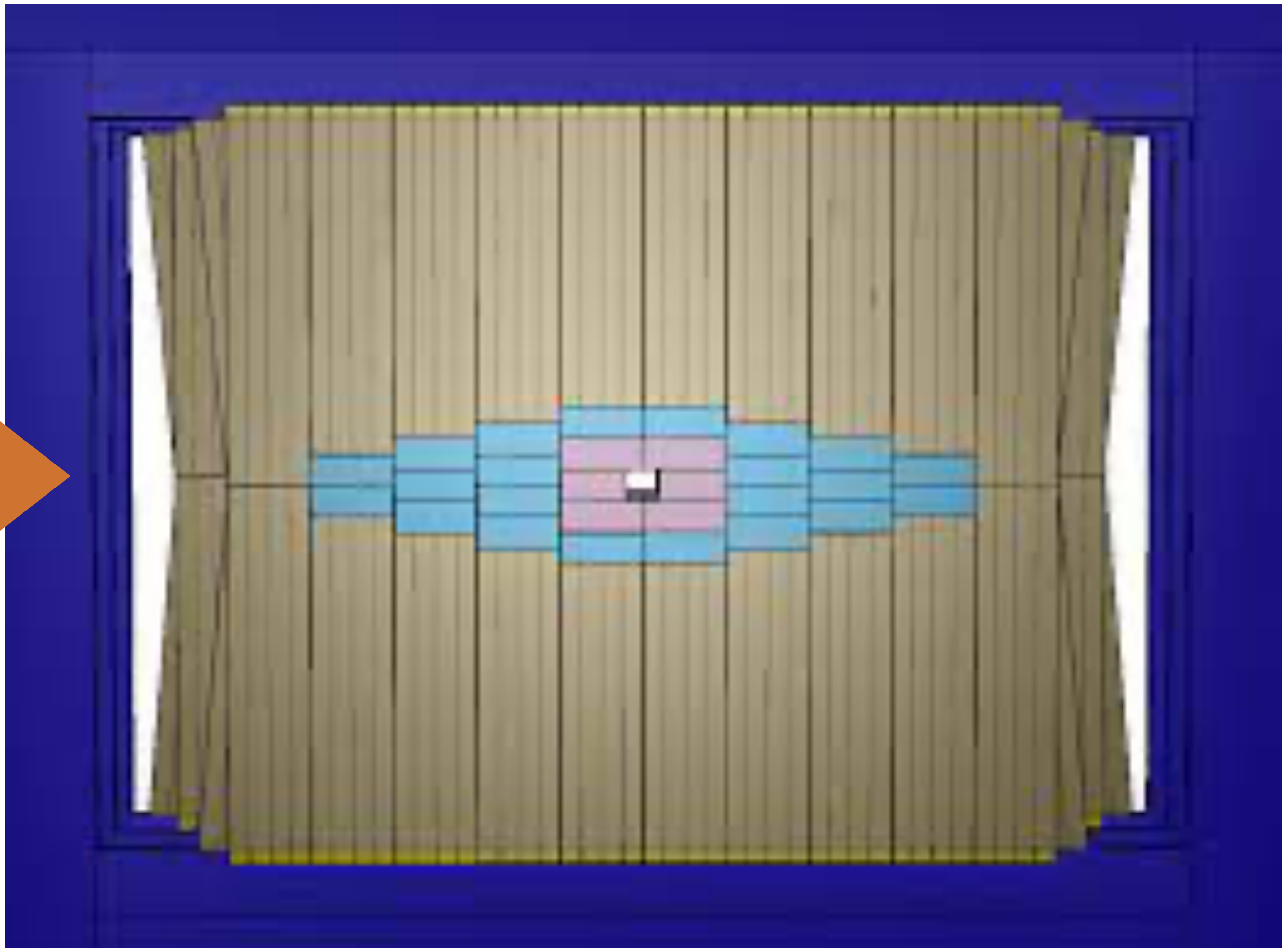
Upgrade II: SciFi alone = ghost rate too high + radiation hardness issues

Upgrade II: tracking

Upgrade II: SciFi alone = ghost rate too high + radiation hardness issues

Add in silicon detector to central region



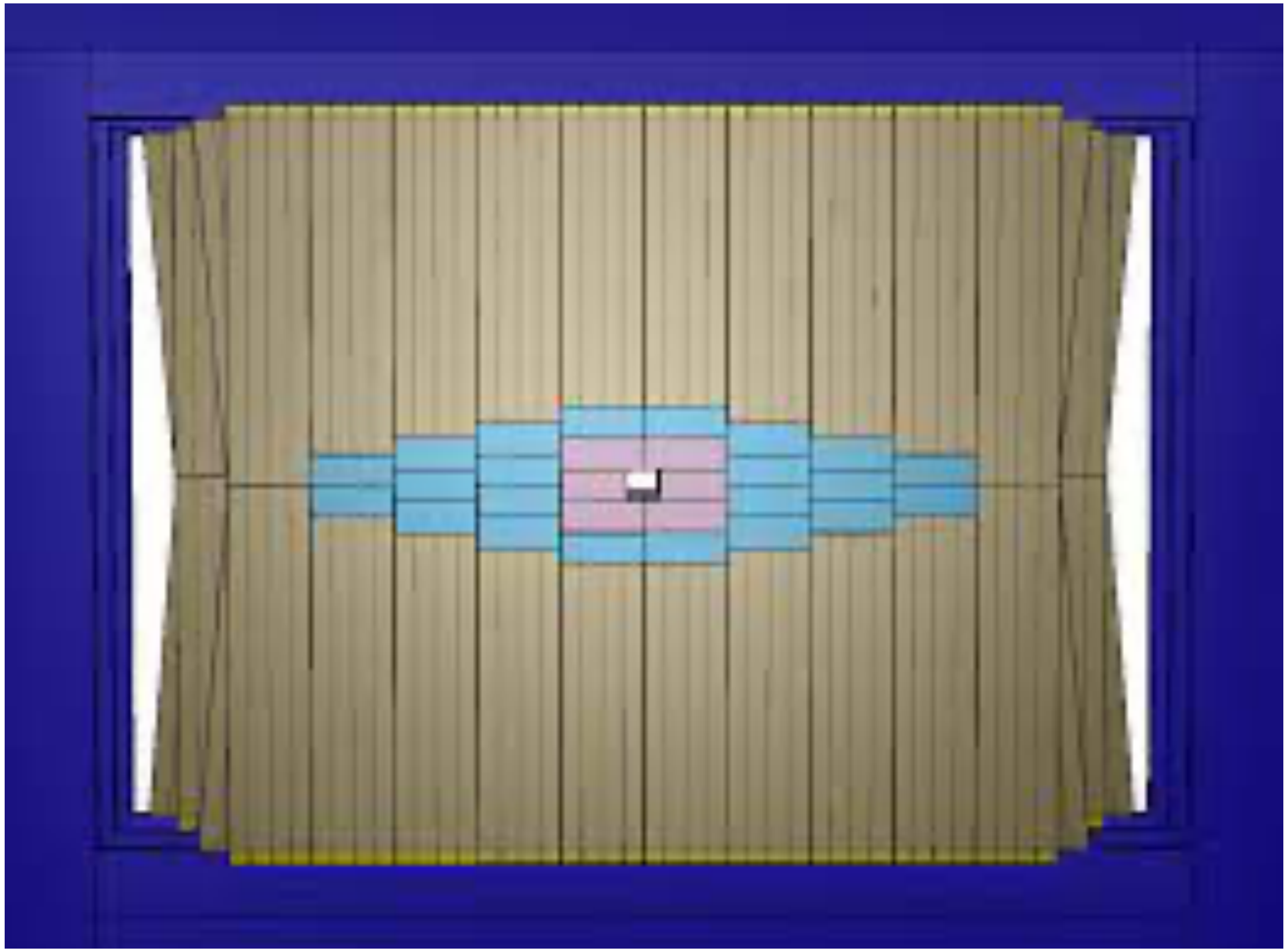


Upgrade II: tracking

Silicon pixels:

- high granularity in x-y
- radiation hard

Install in LS4 (2032), inner section potentially LS3



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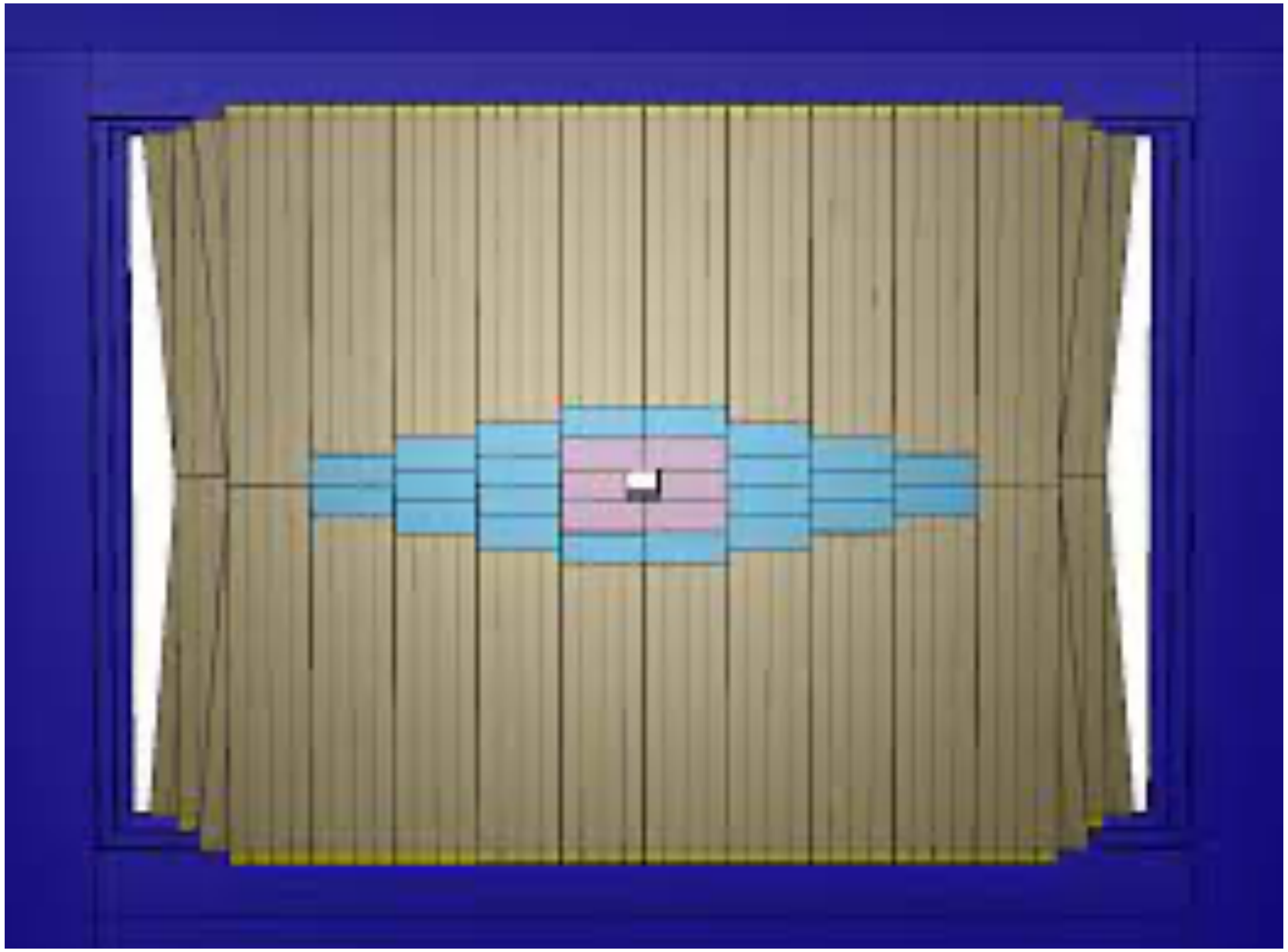

τ_{drift}^{-1}

$\sim 10{-}100\mathrm{ps}$

= resilient against radiation damage

Read-out+senso

in one = lower material budget

Likely use High Voltage Monolithic Active Pixels (HV-MAPs)

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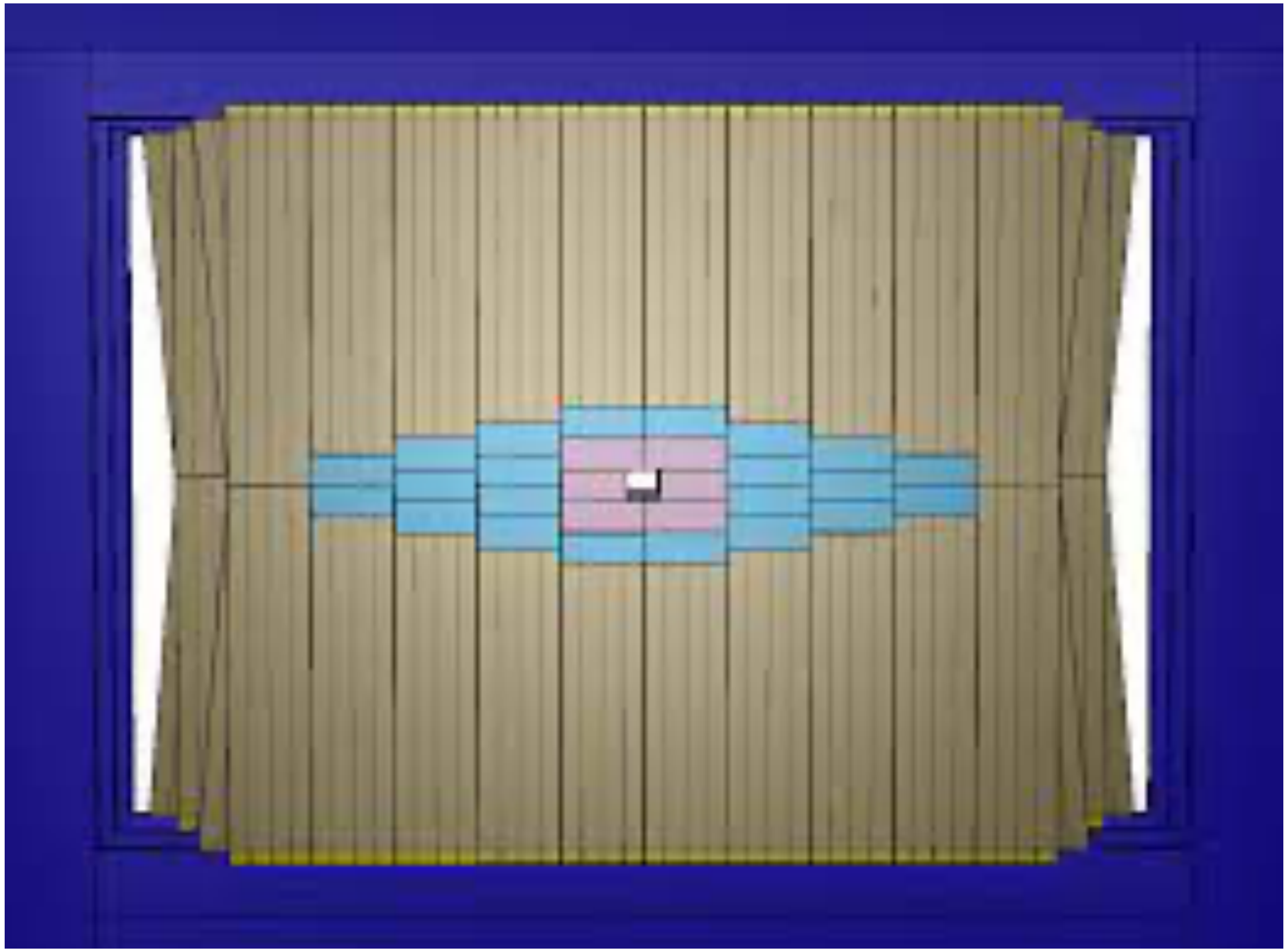

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Pixels made using industrial HV-CMOS process, relatively cheap

Based on existing MuPix and ATLASPix designs: arXiv:2002.07253

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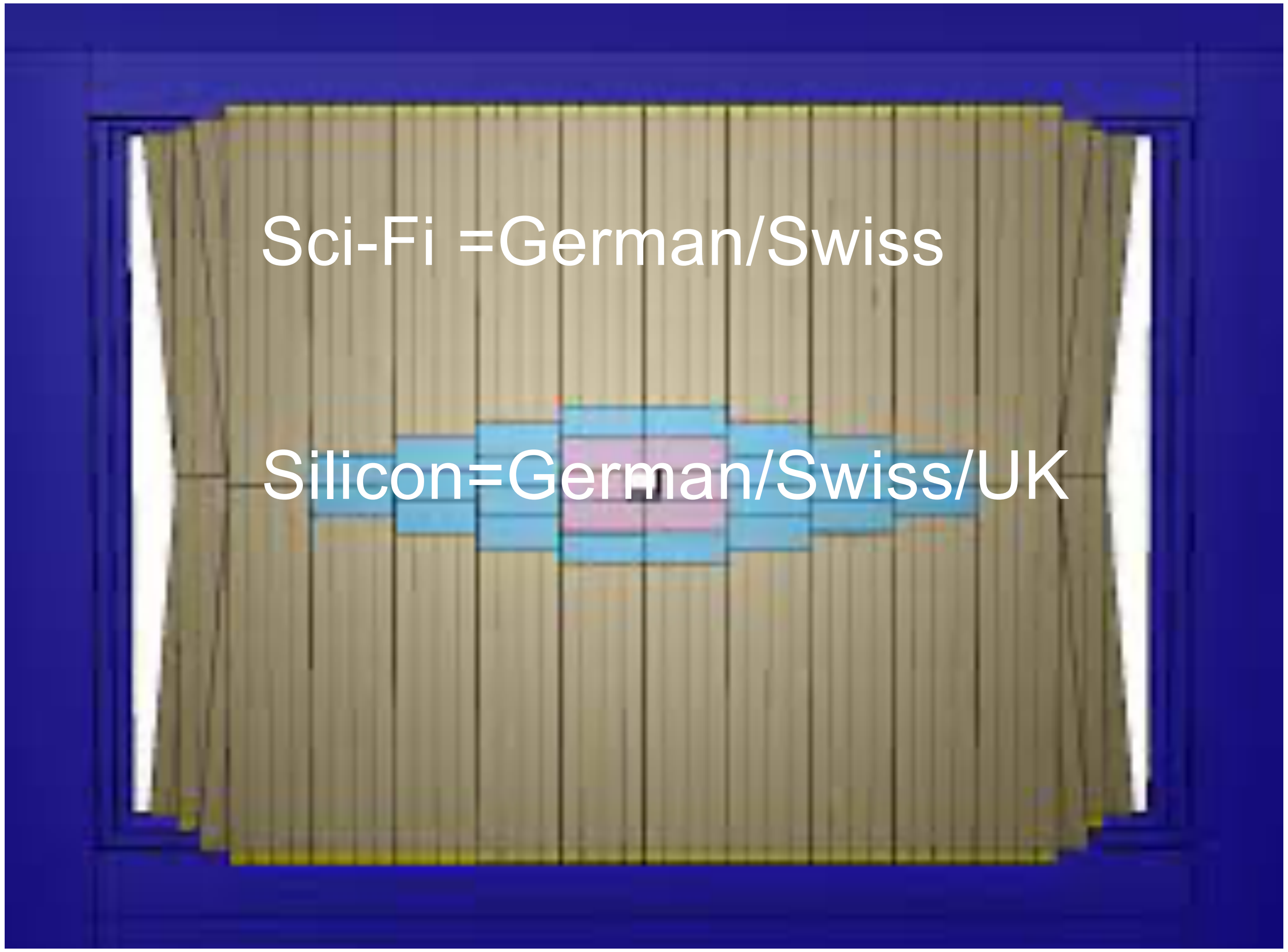

Sci-Fi =German/Swiss

Silicon=German/Swiss/UK

$\tau_{drift}^{-1} \sim 10\text{--}100\text{ps}$

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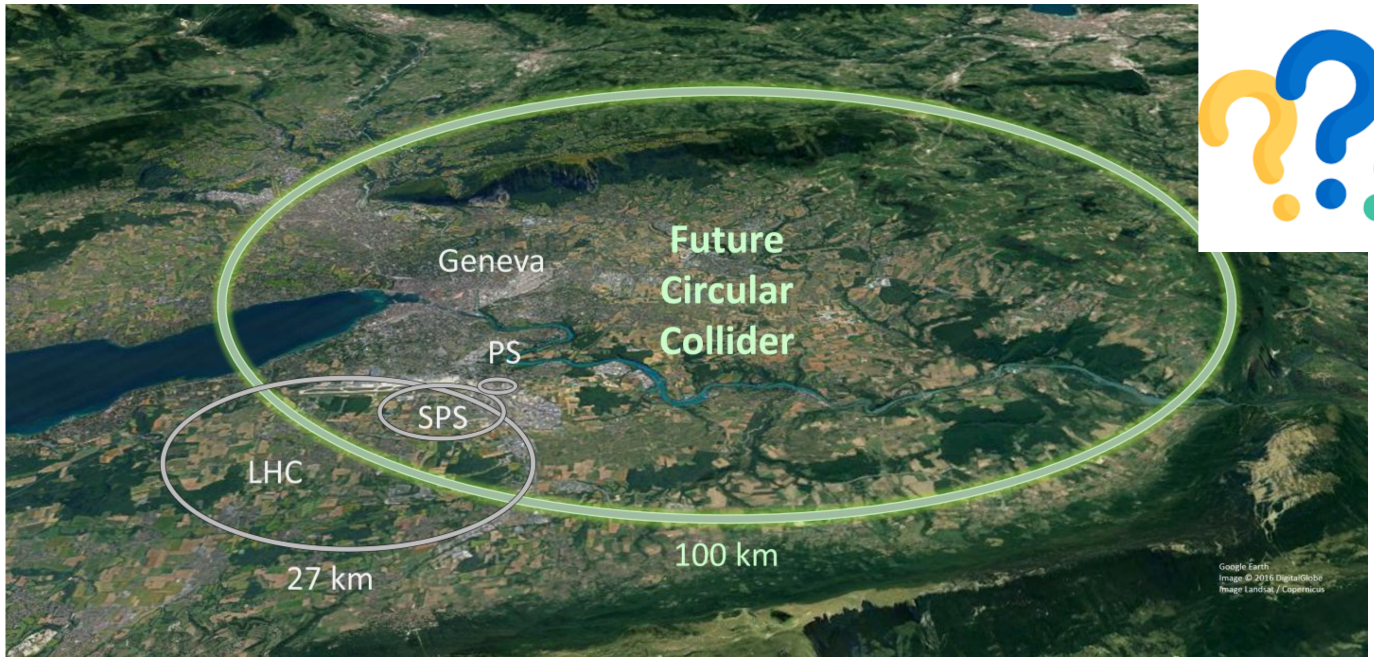
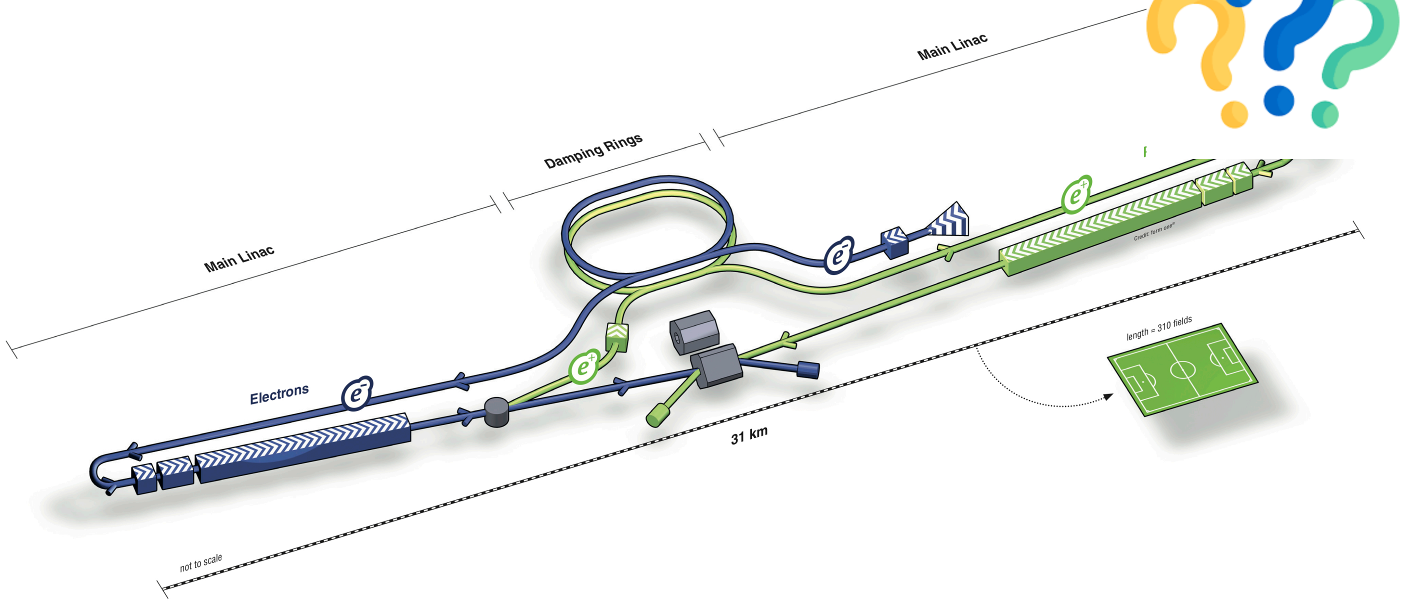
LHCb Upgrade II: application to future colliders



Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

Future circular collider

- FCC ee/hh
- 100km tunnel at CERN
- e^+e^- phase, followed by pp

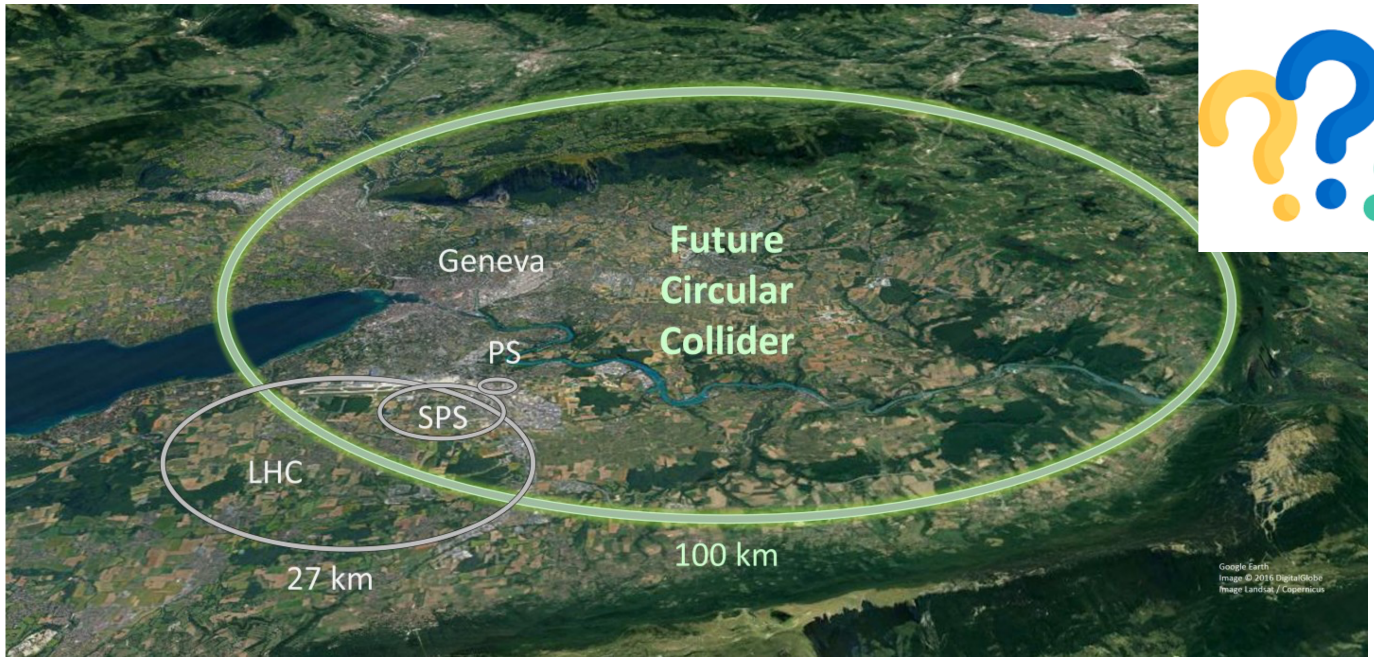


Credit: form one®

International Linear Collider (ILC)

- e^+e^- collisions
- 30-50km linear tunnel

LHCb Upgrade II: application to future colliders



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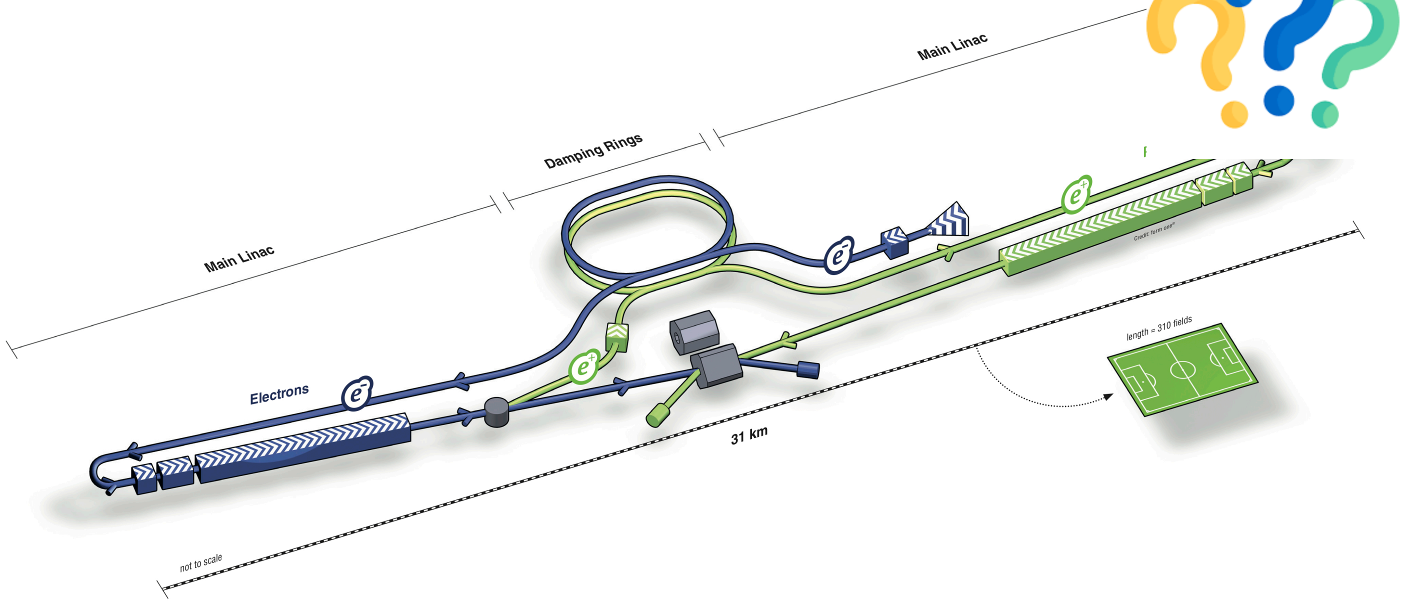


International Linear Collider (ILC)

- e^+e^- collisions
- 30-50km linear tunnel

- LHCb Upgrade II: first use of HV-CMOS technology on large scale
- This new technology will likely be prevalent in future detectors
- Expertise developed in-group here will be invaluable going forward

LHCb readout system

- If LHC experiments recorded everything:~ 40Tb/s - **10% of internet traffic !!**
- Throwaway non-“interesting” events on the fly
- LHCb is unique at the LHC in that “interesting” events occur for us at every bunch crossing

ATLAS EXPERIMENT

CMS

LHCb

Hadronic cleanliness (not to scale)

Lepton Flavour Universality

$b \to s\mu^+\mu^-$anomalies

Angular analyses

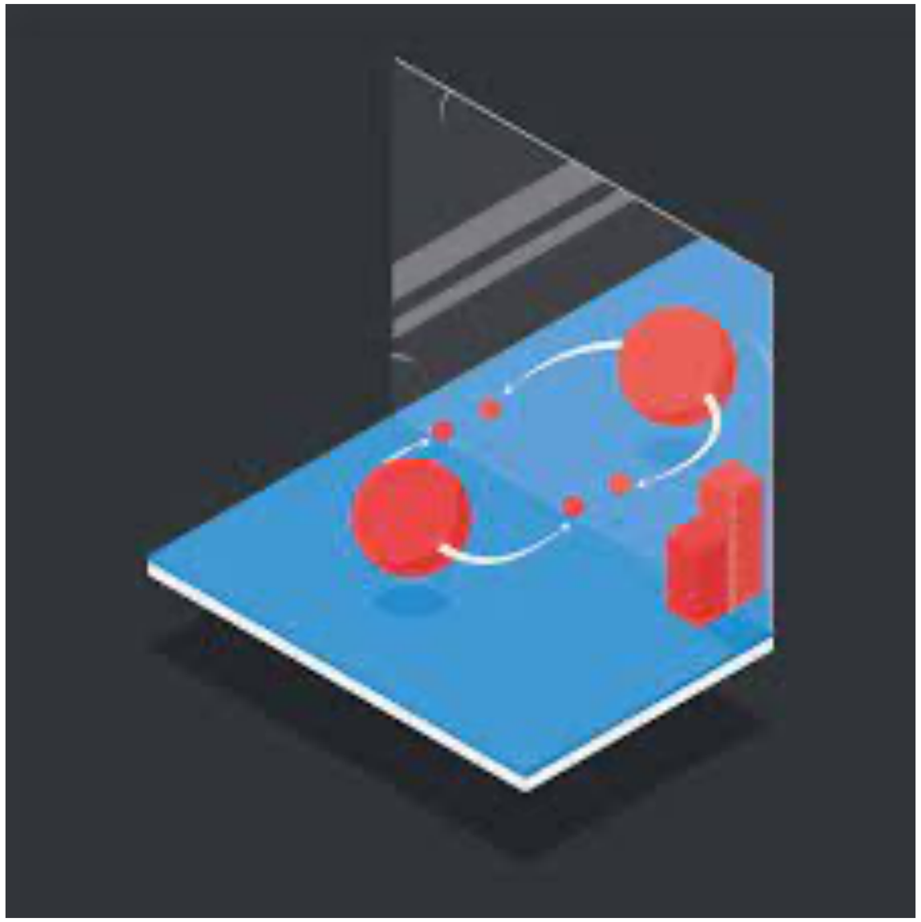
Branching fractions

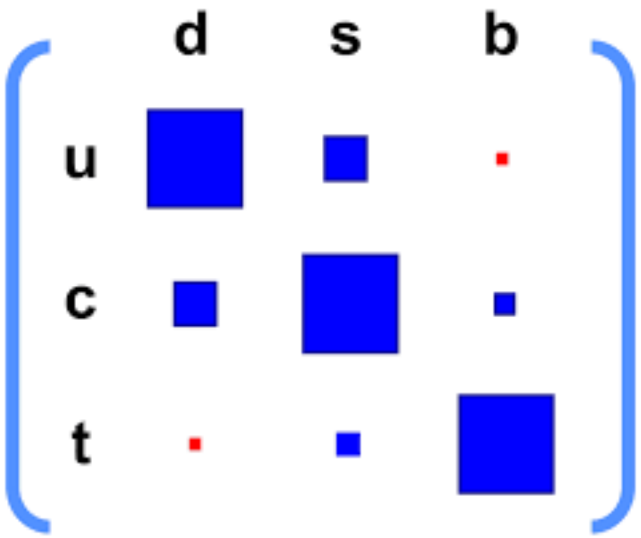
Flavour and missing anti-matter

- We exist because matter dominates, but we don't know *why*
- The couplings in the CKM matrix diff. between matter and anti-matter (CP violation), but not enough to explain our universe (!)

Anti-matter: invert charge of matter (C-conjugation)

P-conjugation: flip spatial coordinates





- There must exist unknown forces and particles beyond the Standard Model, we call these hypothetical particles New Physics

Probing beyond the TeV scale with rare decays?

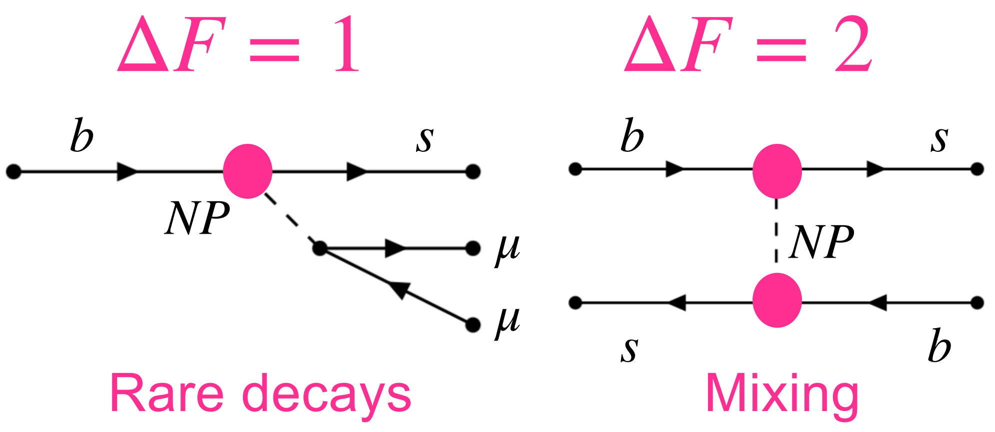
Decays described with SM Hamiltonian ($\mathcal{H}$)

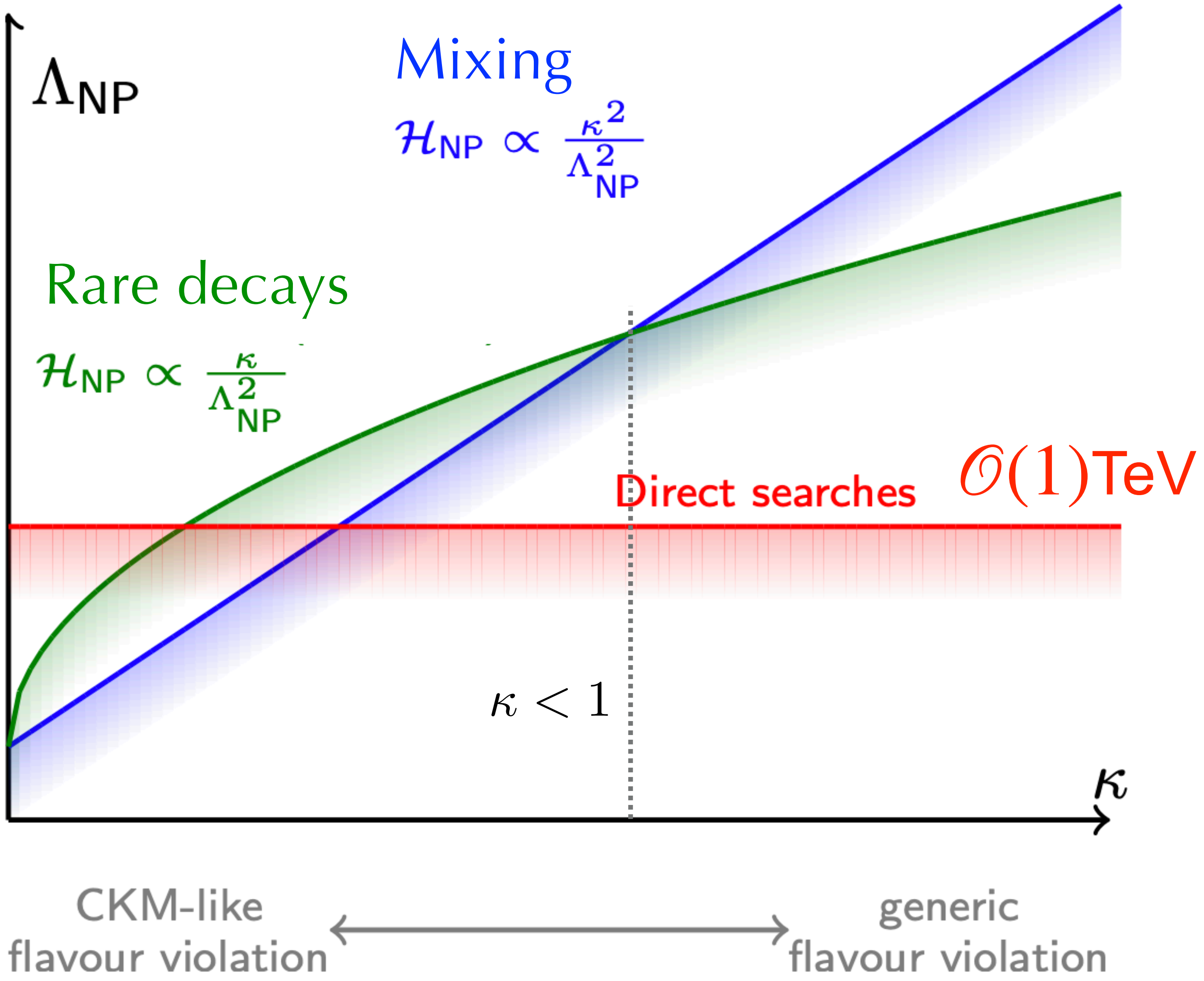
Additional contribution from NP ($\Delta F = 1$):

$$\mathcal{H}_{NP} \propto \frac{\boxed{\kappa}}{\boxed{\Lambda^2_{NP}}}$$

Coupling

Mass of NP particle





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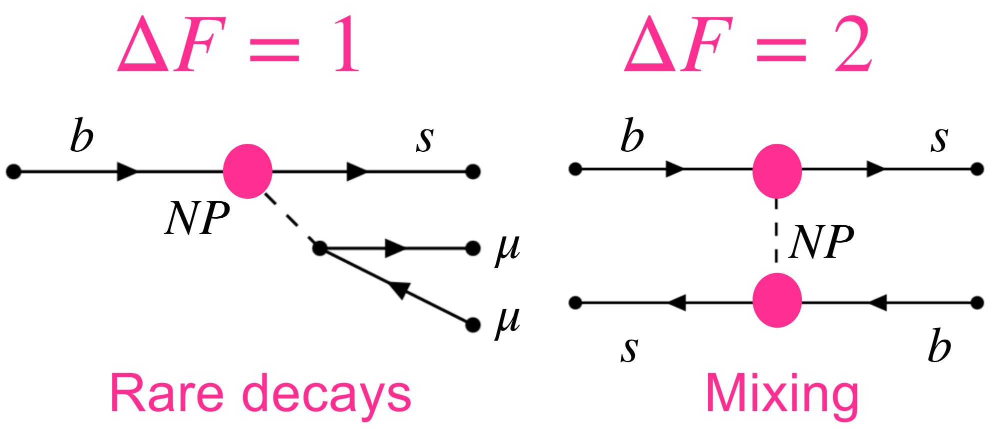

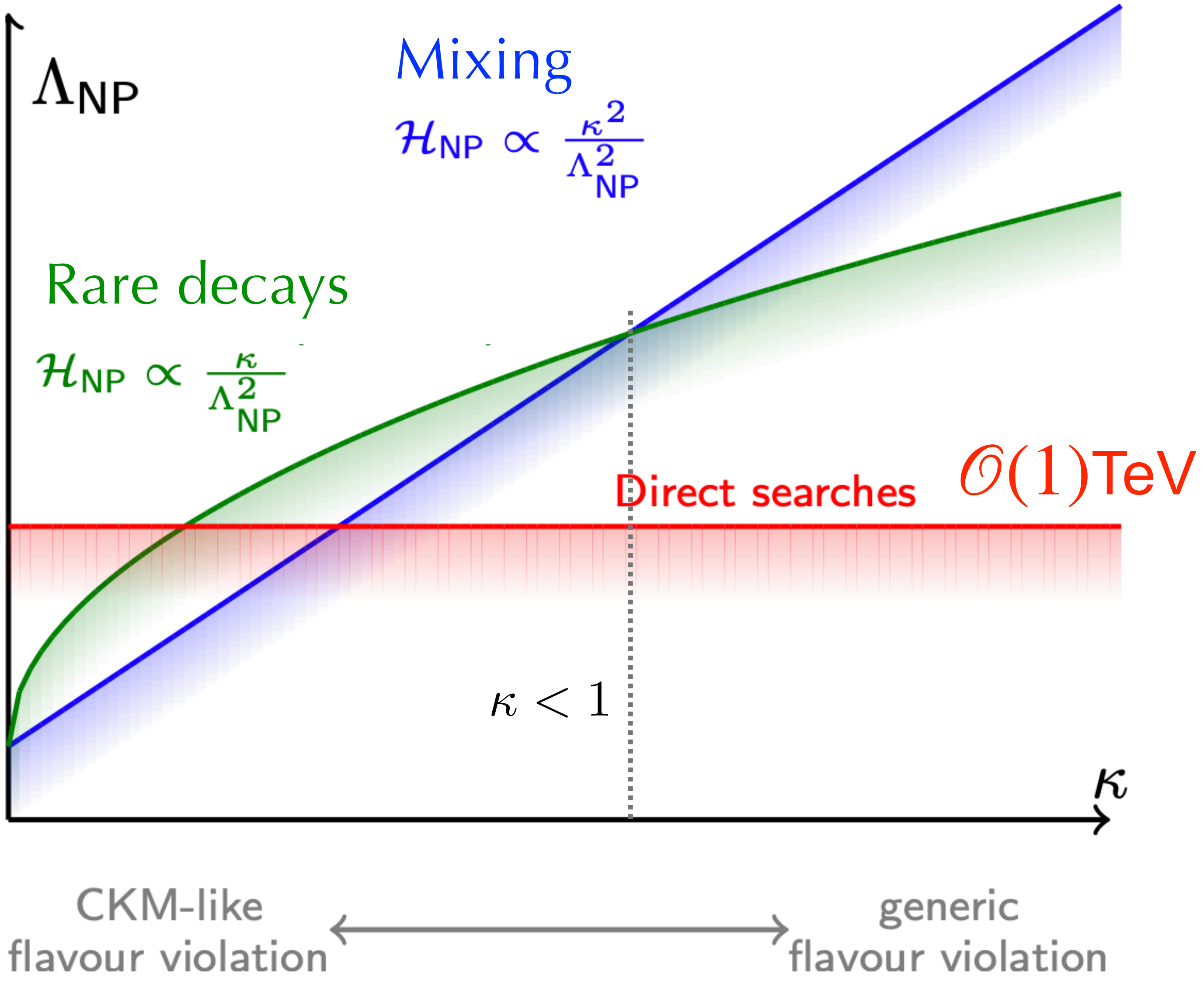

Mass scale probed currently with rare decays depends on NP model:

→ $\mathcal{O}(10)$-$\mathcal{O}(100)$TeV JHEP11(2014)121

Direct LHC searches ~ $\mathcal{O}(1)$TeV

Probing beyond the TeV scale with rare decays?

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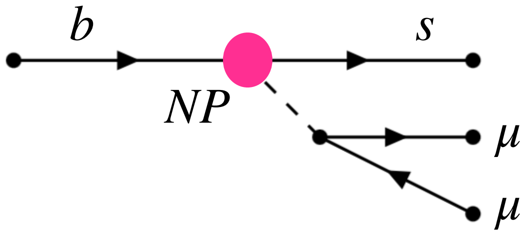
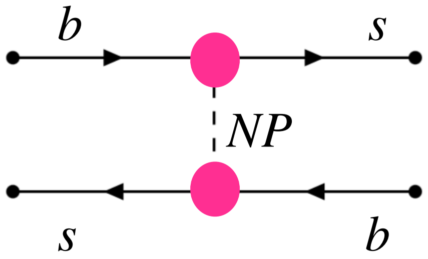
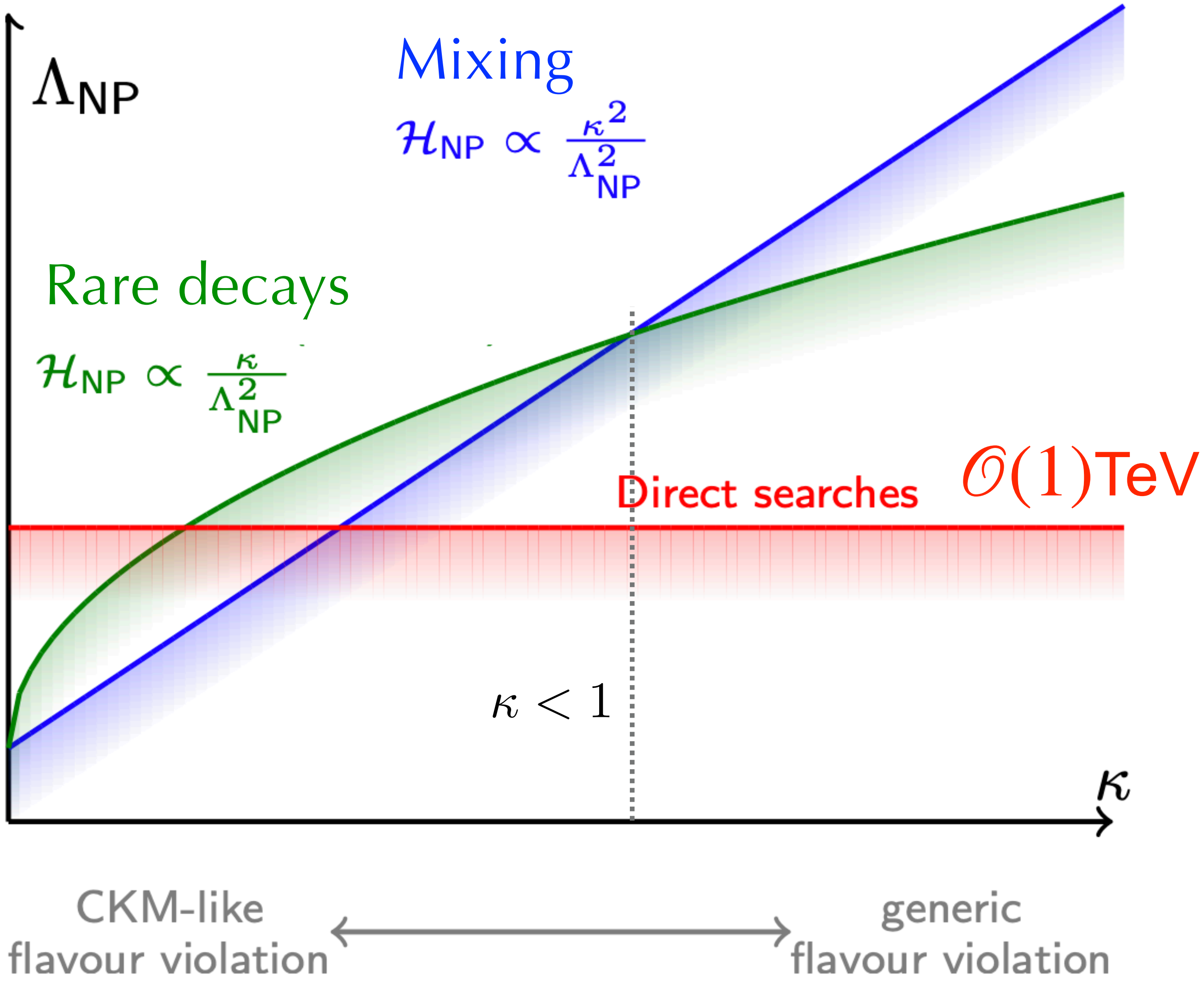


Rare decays

$\Delta F = 2$



Mixing



Mass scale probed currently with rare decays depends on NP model:

→ $\mathcal{O}(10)$-$\mathcal{O}(100)$TeV JHEP11(2014)121

Direct LHC searches ~ $\mathcal{O}(1)$TeV

More precise our constraints, heavier mass scale we can probe

$$\Lambda_{NP} \propto \frac{\sqrt{k}}{\boxed{\Delta(experiment)}}$$

Probing beyond the TeV scale with rare decays

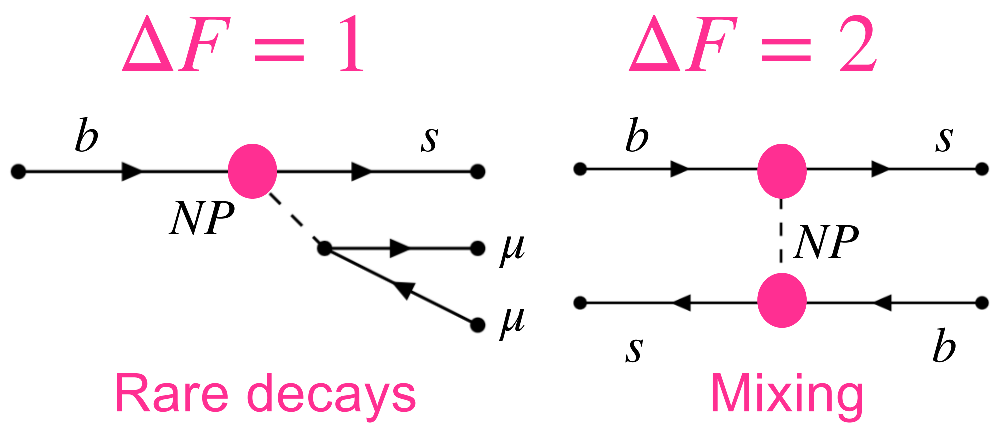
Decays described with SM Hamiltonian ($\mathcal{H}$)

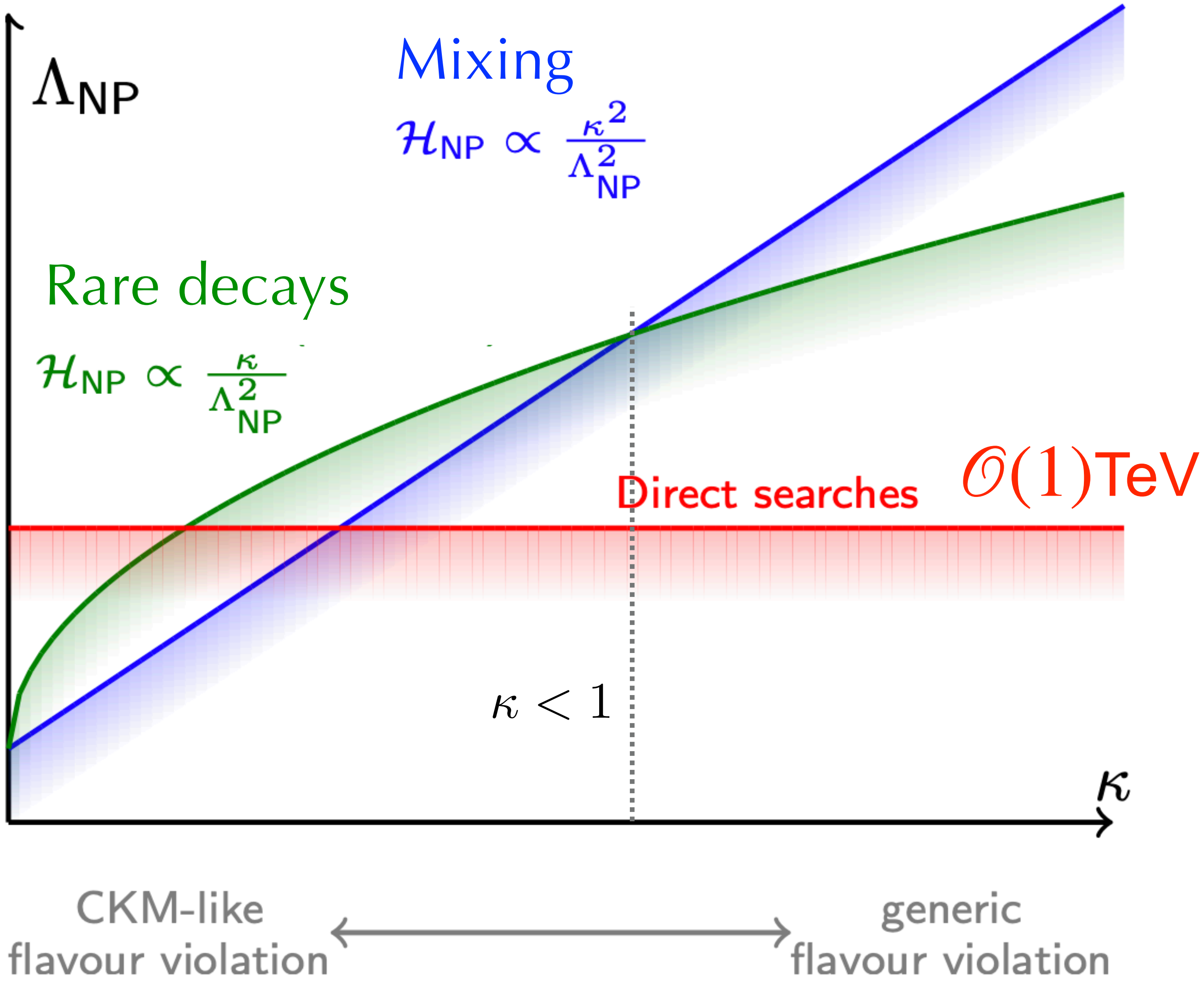
Additional contribution from NP ($\Delta F = 1$):

$$\mathcal{H}_{NP} \propto \frac{\boxed{\kappa}}{\boxed{\Lambda^2_{NP}}}$$

Coupling

Mass of NP particle





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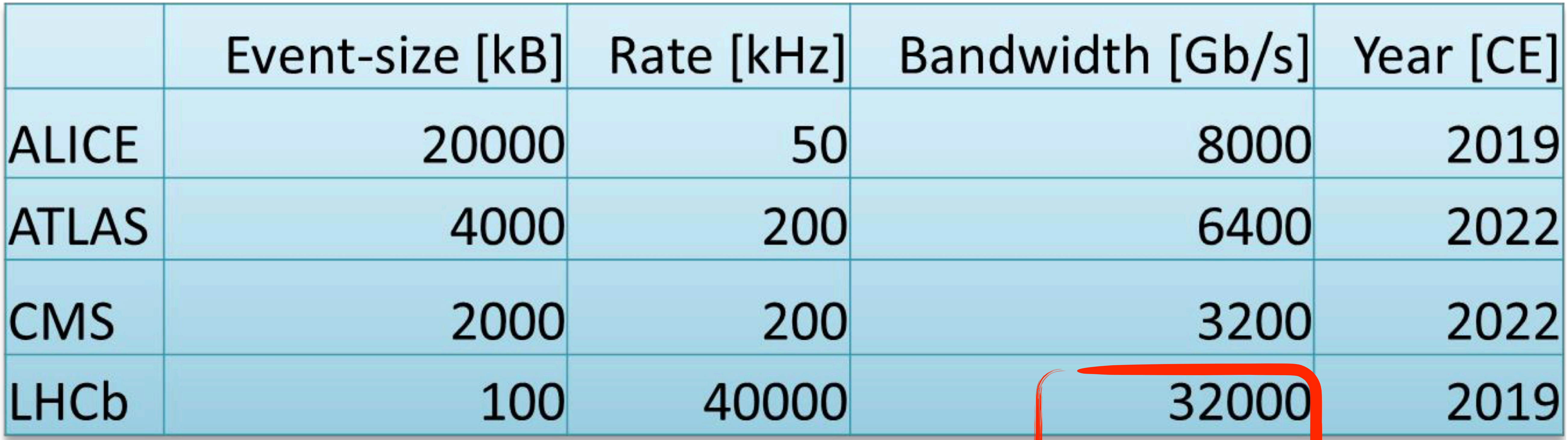
Different rare decay observables probe different models

LHCb readout system: Upgrade I (Run 3)



	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year [CE]
ALICE	20000	50	8000	2019
ATLAS	4000	200	6400	2022
CMS	2000	200	3200	2022
LHCb	100	40000	32000	2019

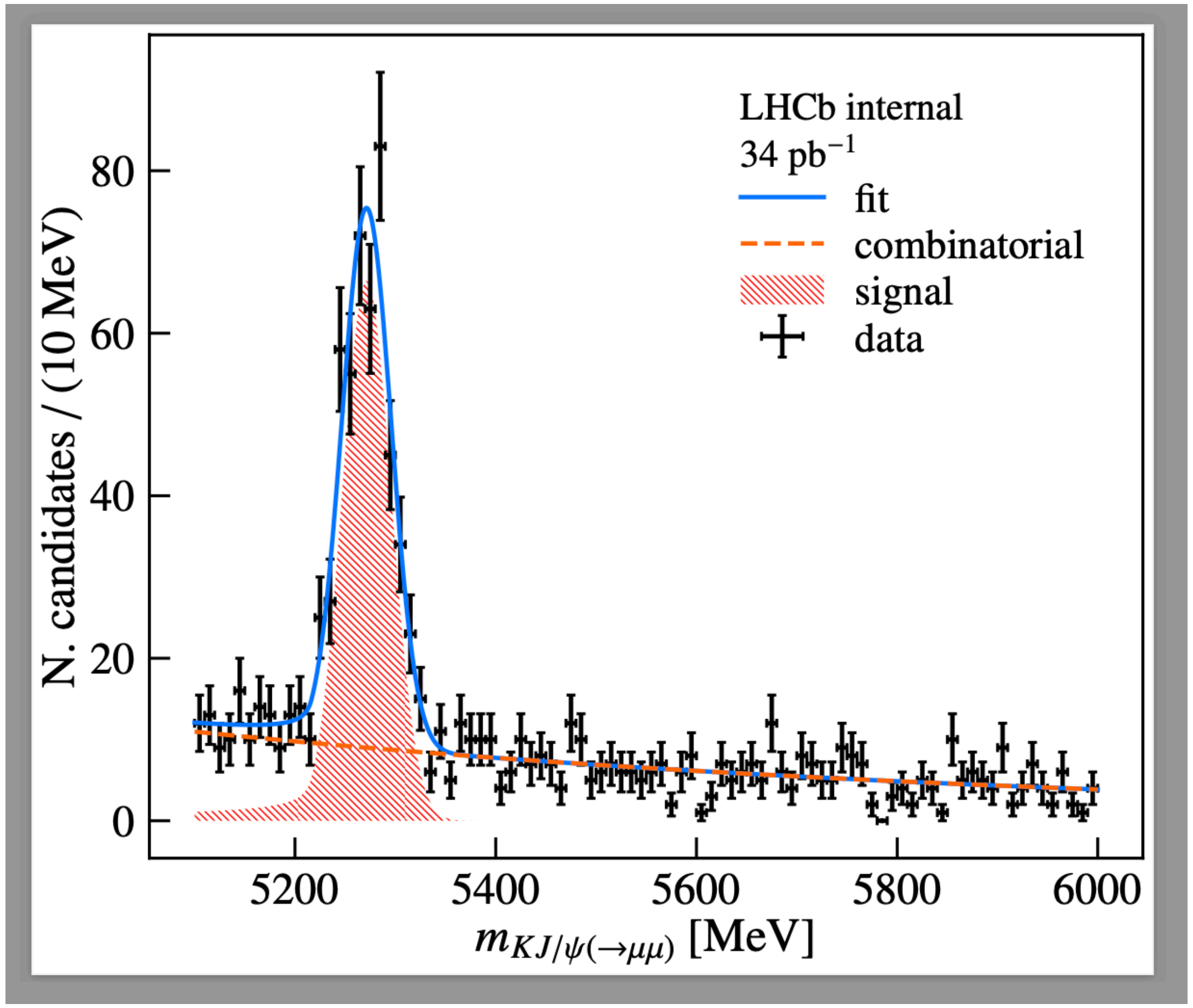
~30 Tb/s!!

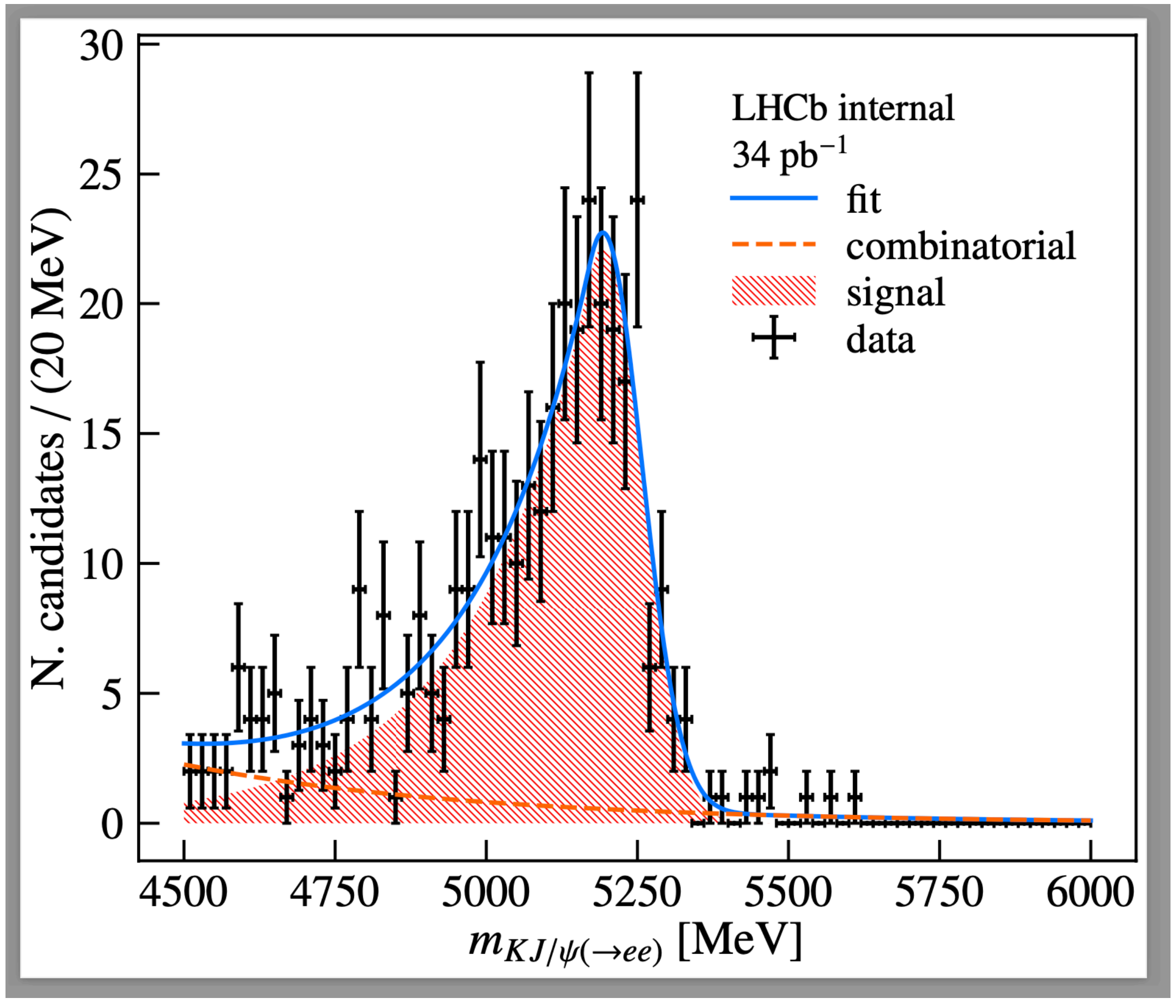
Courtesy N. Neufeld

- As of Upgrade I, LHCb reads out the *whole* detector on GPUs
- Calibrate detector in real-time: save less of each event
- Access more hadron/electron final states with lower p_T
- Development of selections for rare decays: Smith et al [LHCb-PUB-2019-013]

First analyses with Run 3 LHCb data

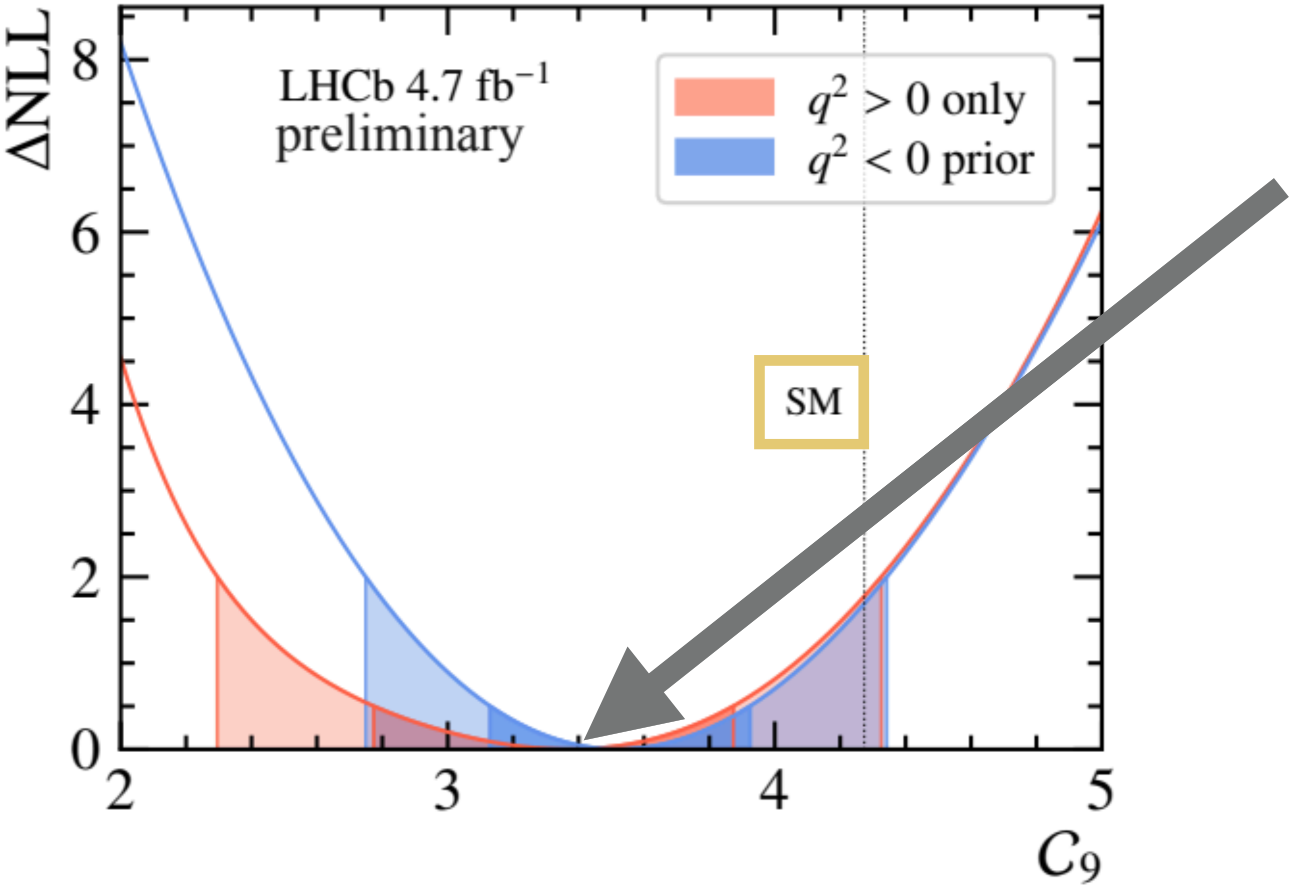
- LHCb Upgrade I “first data” plots for LHCC courtesy of Michele Atenzi (MIT, Smith)





First measurement of QCD “charm-loop” effects

- **Flavour anomalies:** $\sim 5\sigma$ global tensions between $b \to s\ell^+\ell^-$ measured effective couplings (C_9/C_{10}) and SM
- **Heavy New Physics** or misunderstood **long-distance QCD** effects (charm-loops) ?
  - First time parameterising charm loop in $B^0 \to K^{*0}\mu^+\mu^-$



Allowing for charm-loop with model, still **find same negative shift in couplings** (but larger uncertainty due to more params. In fit)

(Smith is analysis proponent, Atenzi performing LFU version of analysis)