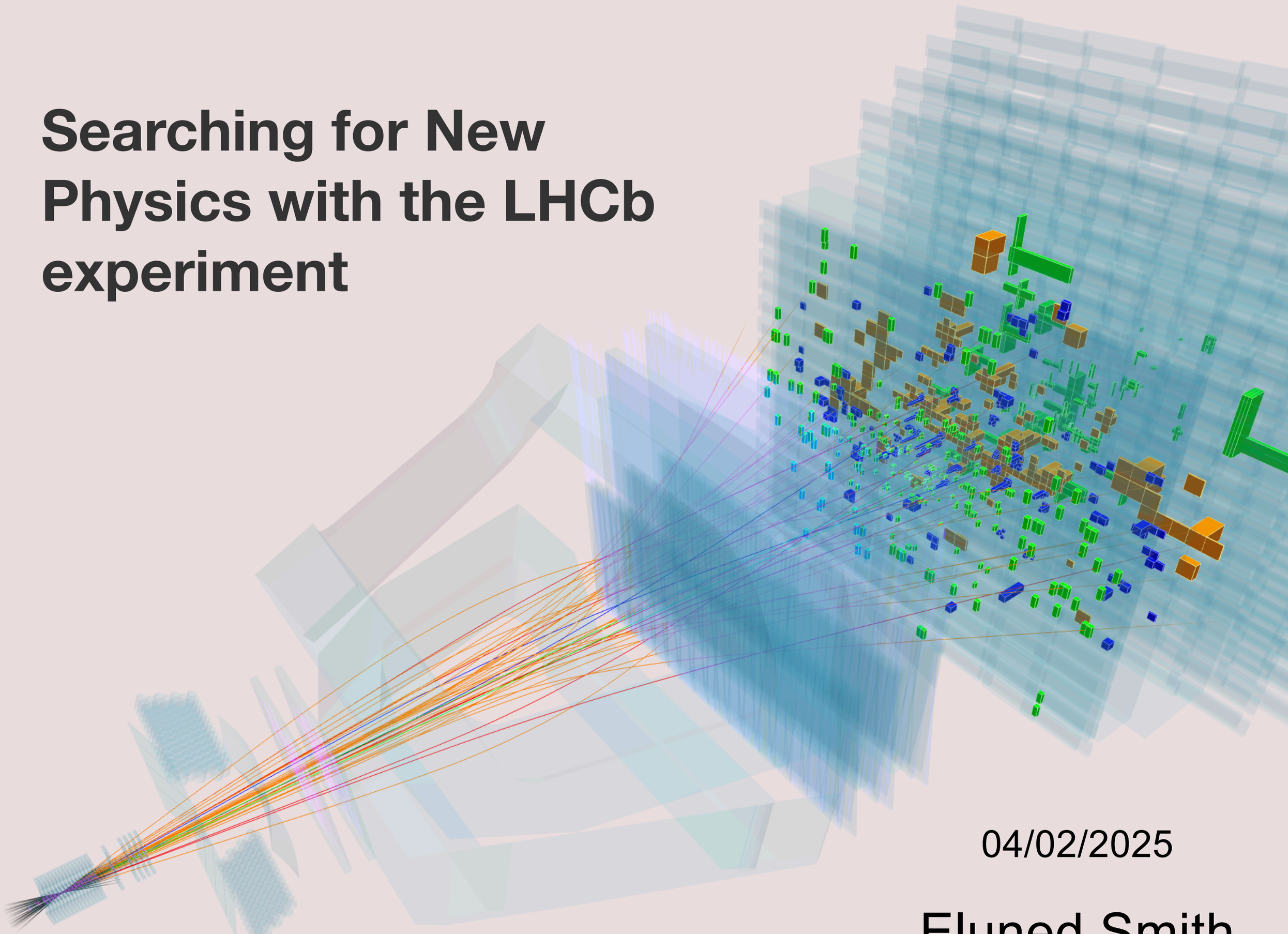
Searching for New Physics with the LHCb experiment



04/02/2025

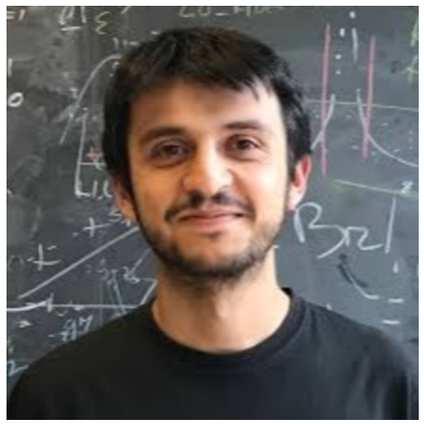
Eluned Smith

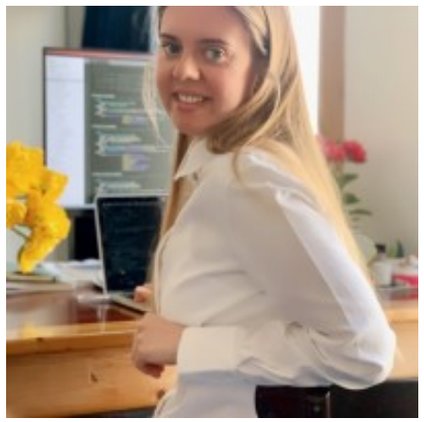
Who we are

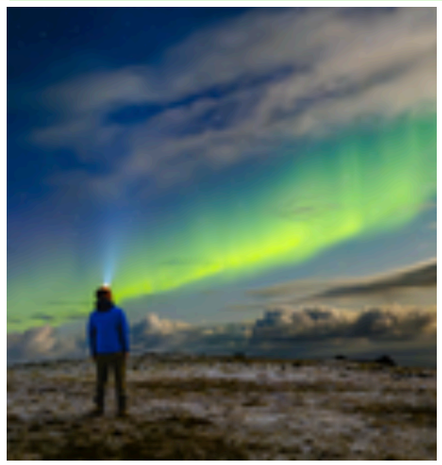
The team :)

ML/Computing

LHCb analysis | FCC-ee/LHCb | ML/Computing | ML/Computing | LHCb analysis







Michele | Anja | Katya | Julian | Sebastian

Martin (just graduated)

+ Con who is starting with us as a PhD in September

+ 1 or 2 other students

What we do

LHCb analysis

Analyse data from the LHCb experimental at CERN to search for new physics

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Development of fast-ML on FPGAs

Develop ultra-low latency, radiation hard neural networks to run on the detector electronics of our read-out systems

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FCC-ee

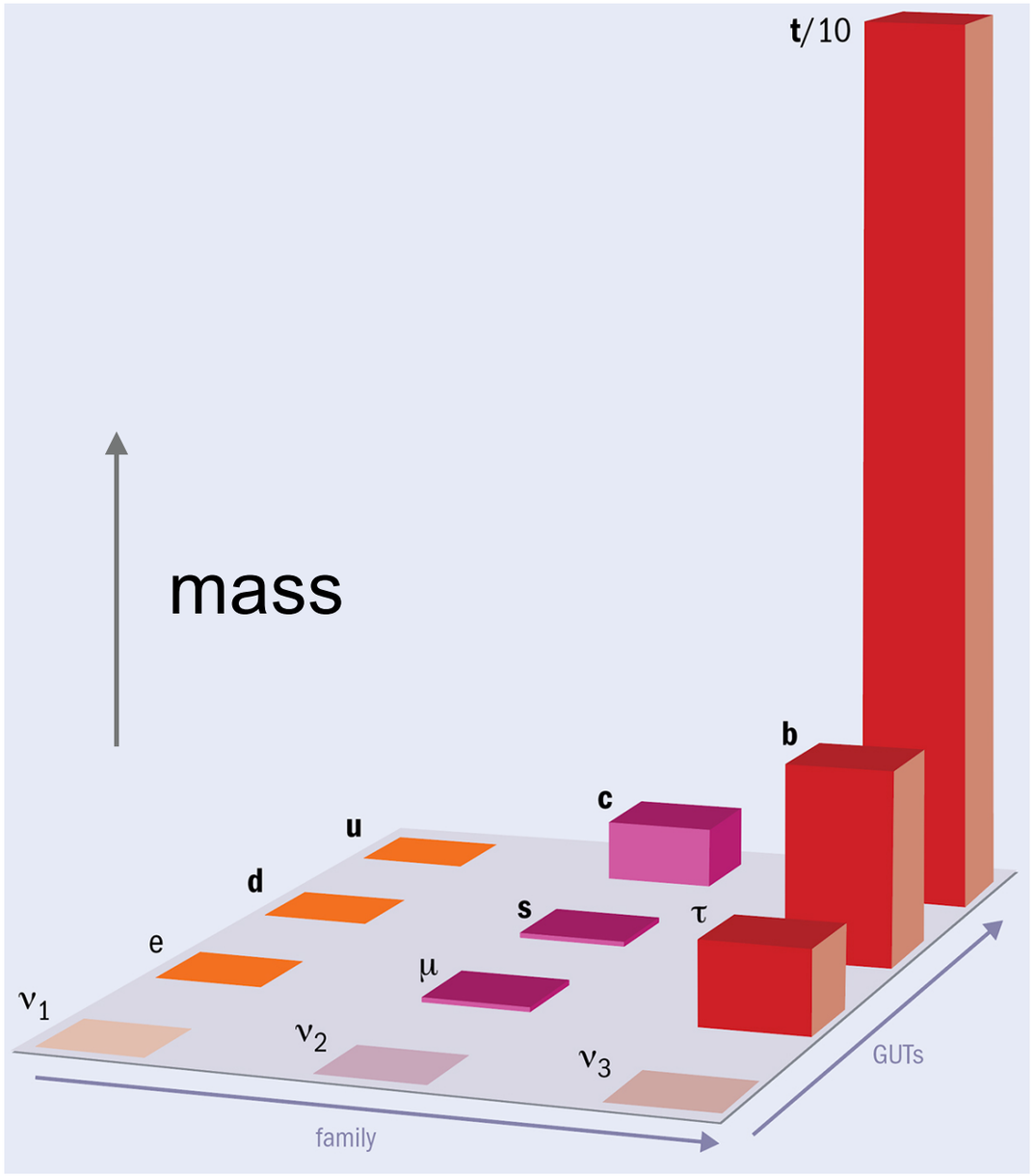
Investigate potential detector designs for the Future Circular Collider

LHCb analysis

Beauty quarks and new particles

Looking for new fundamental particles

The Standard Model



+ force carriers and Higgs boson

Looking for new fundamental particles

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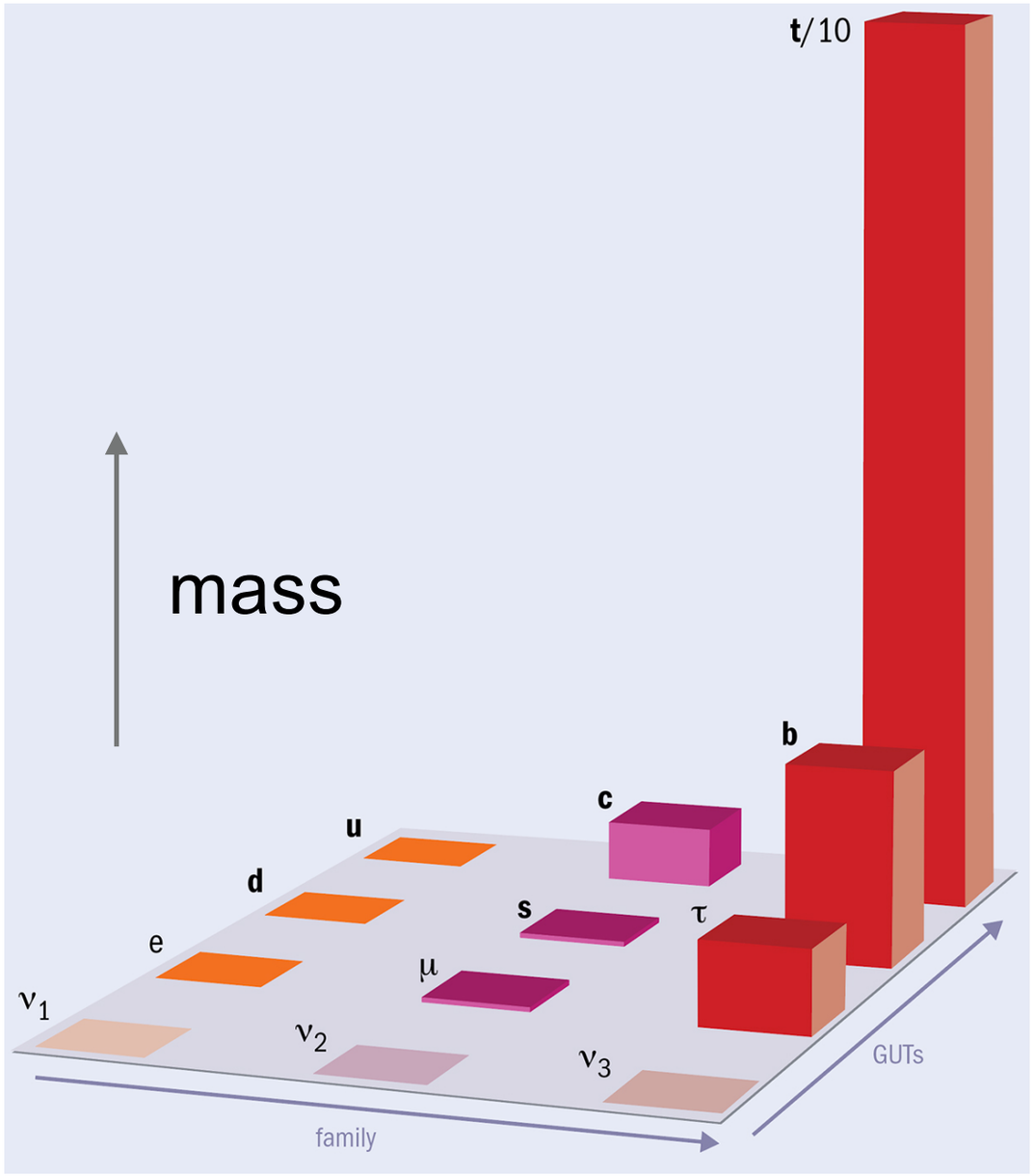

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The Standard Model leaves many open questions:

- Why does matter dominate anti-matter?
- What is Dark Matter?
- Why is the third generation so much heavier?

Looking for new fundamental particles

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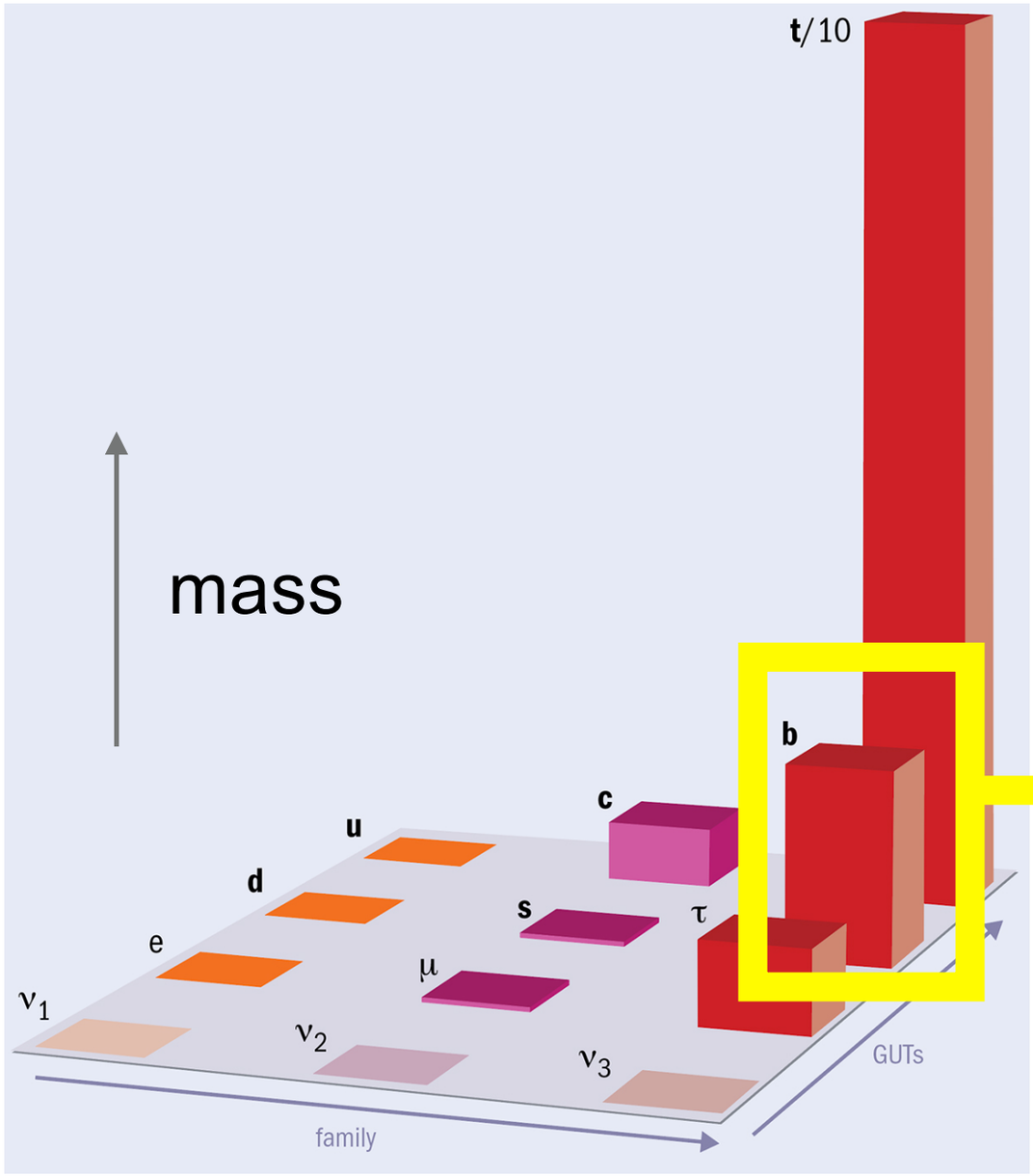

+ force carriers and Higgs boson

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- Why does matter dominate anti-matter?
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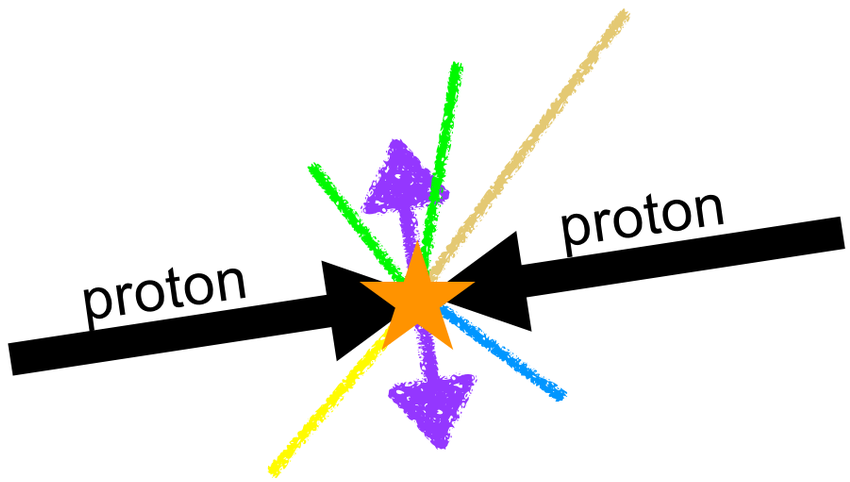
- Why is the third generation so much heavier?

Heaviest stable quark (beauty quark) can help answer these questions

How to look for New Physics

Direct searches

$E=mc^2$



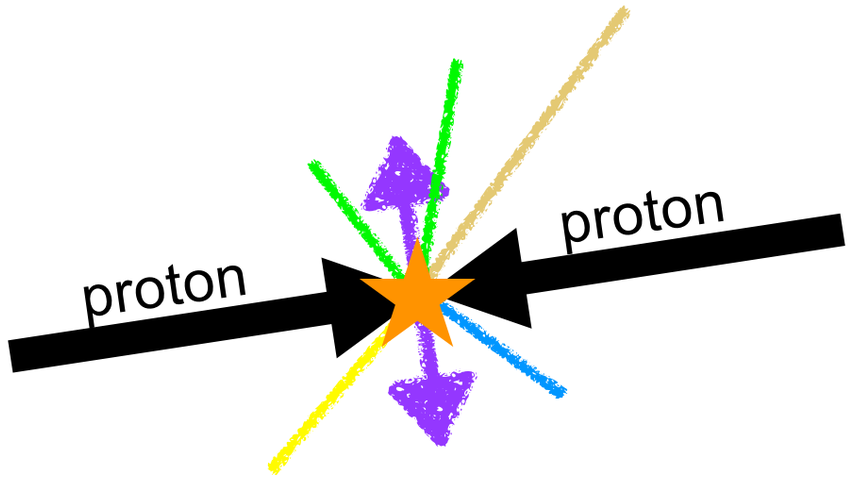
NP particle

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

How to look for New Physics

Direct searches

E=mc²



NP particle

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

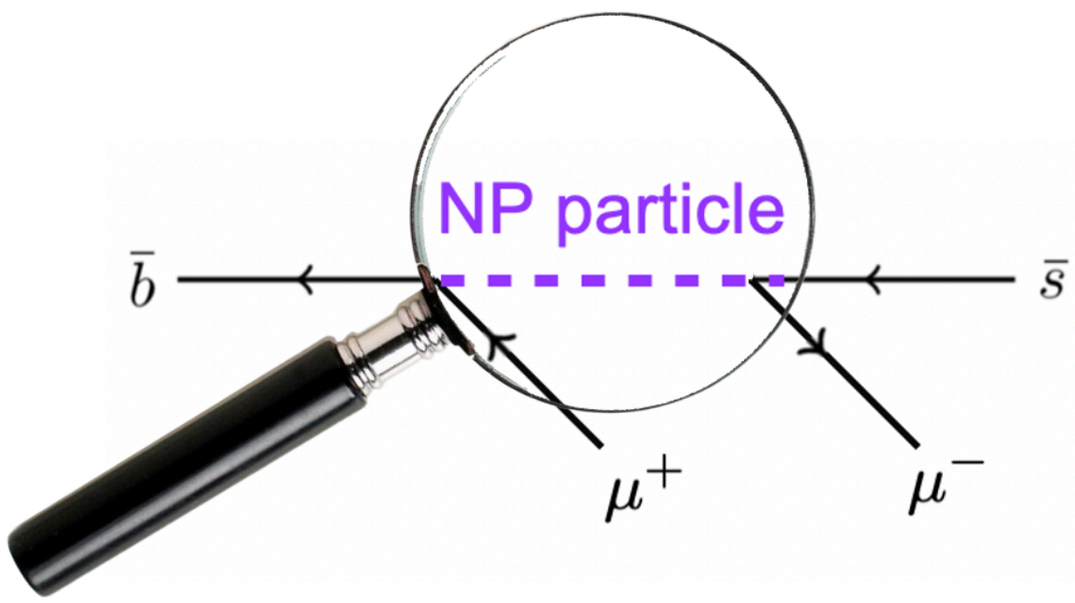
Indirect searches

Heisenberg's uncertainty principle

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

mc²>> **E** if Δt small

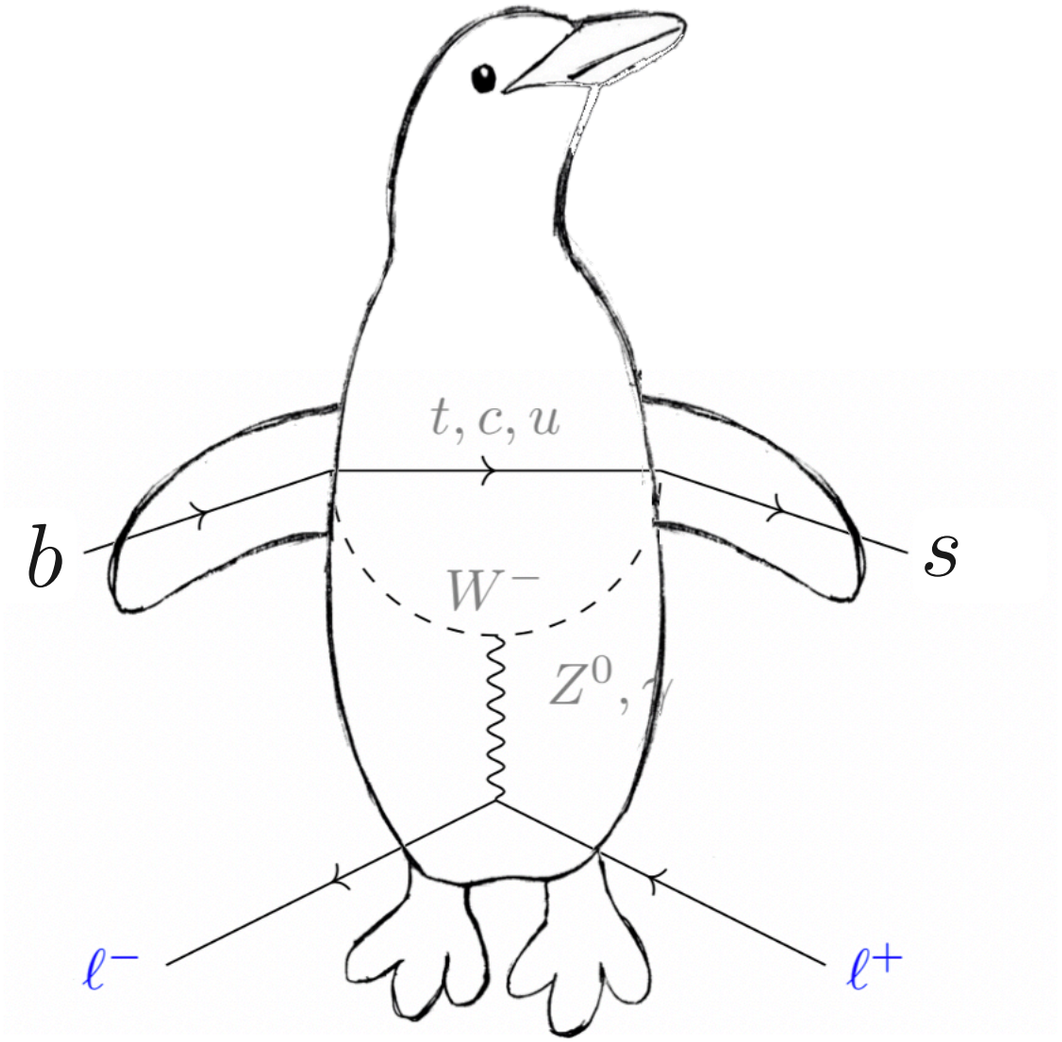
m ~ $\mathcal{O}(100\,\mathrm{TeV})$ JHEP 1411 (2014) 121



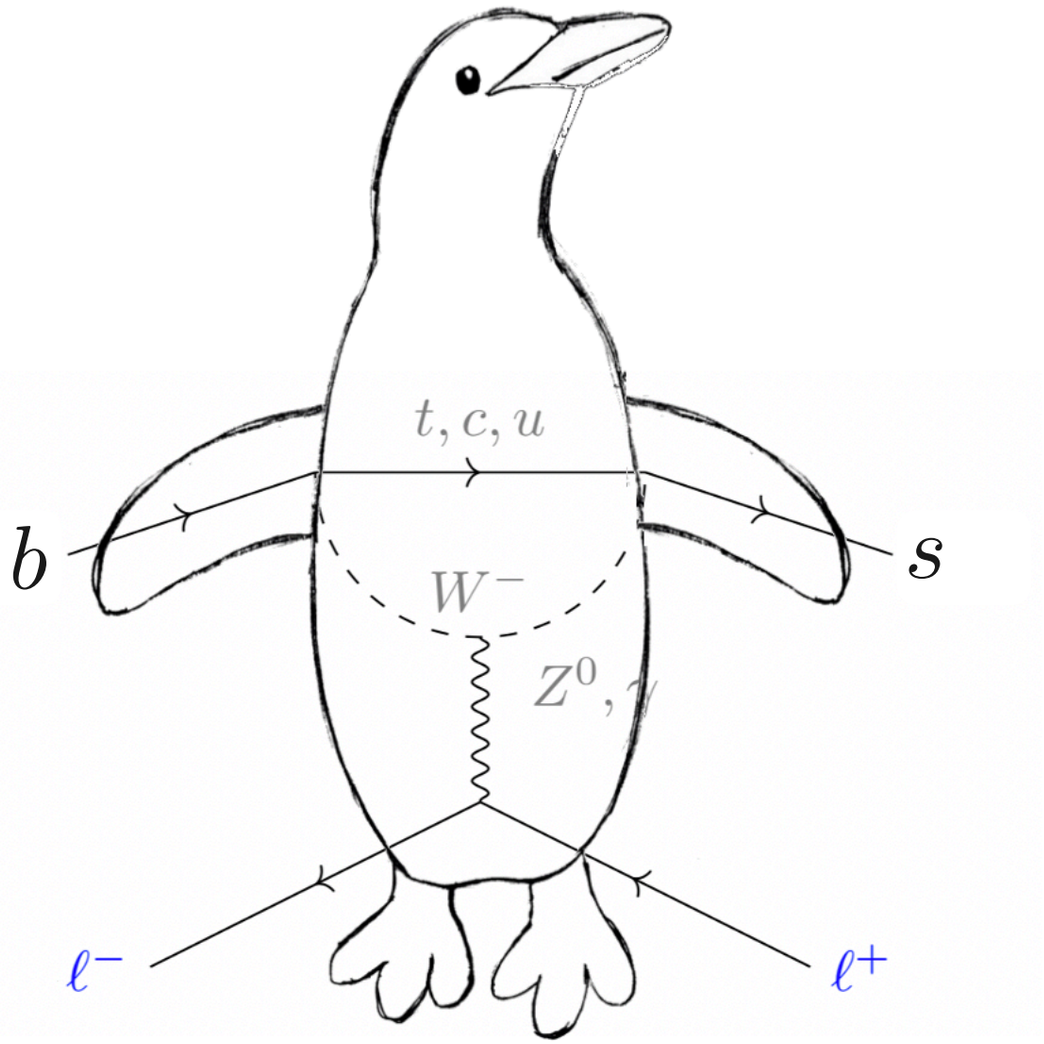
This is a penguin

This is a penguin

This is a rare penguin

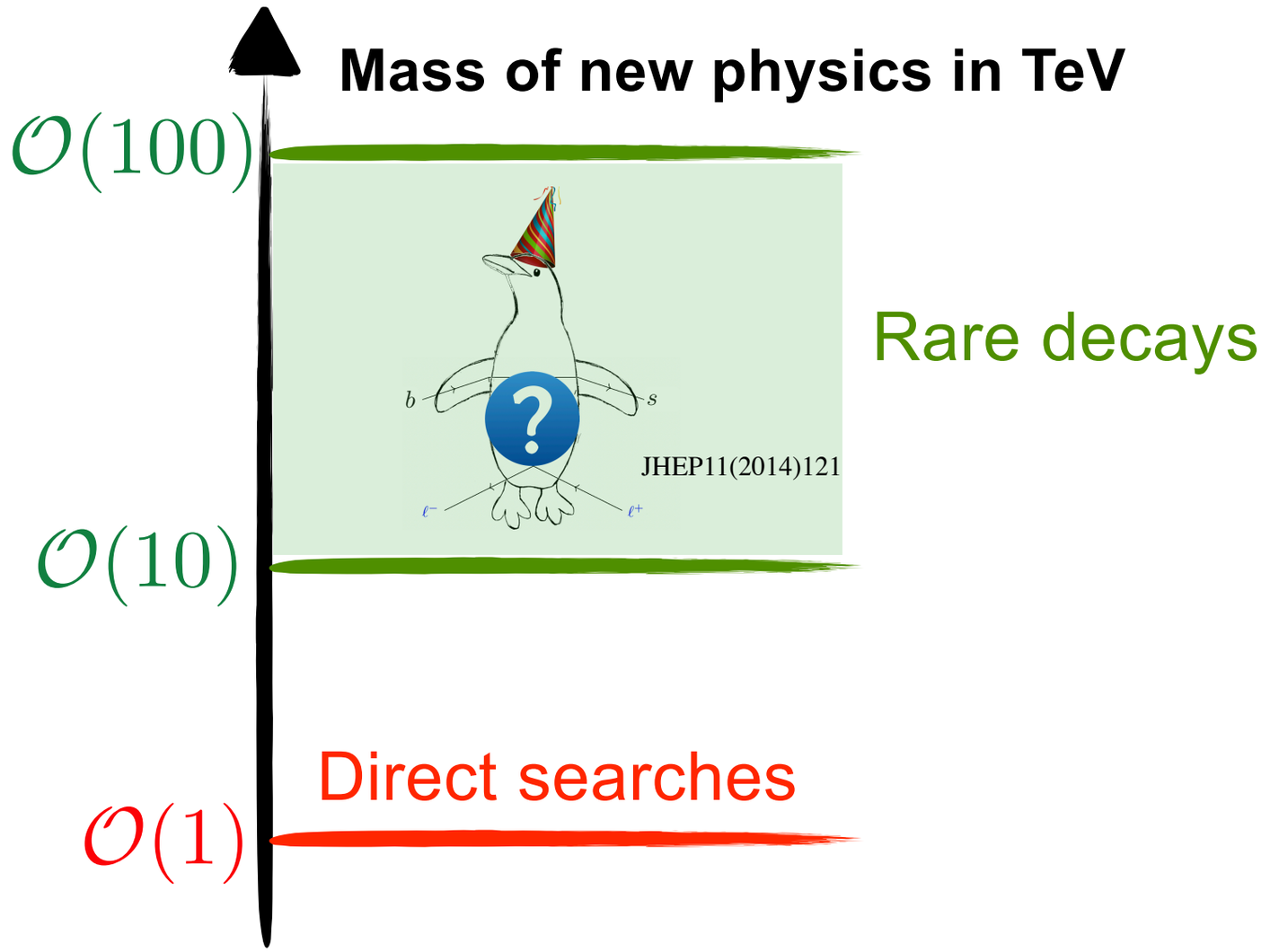


Electroweak Penguins



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

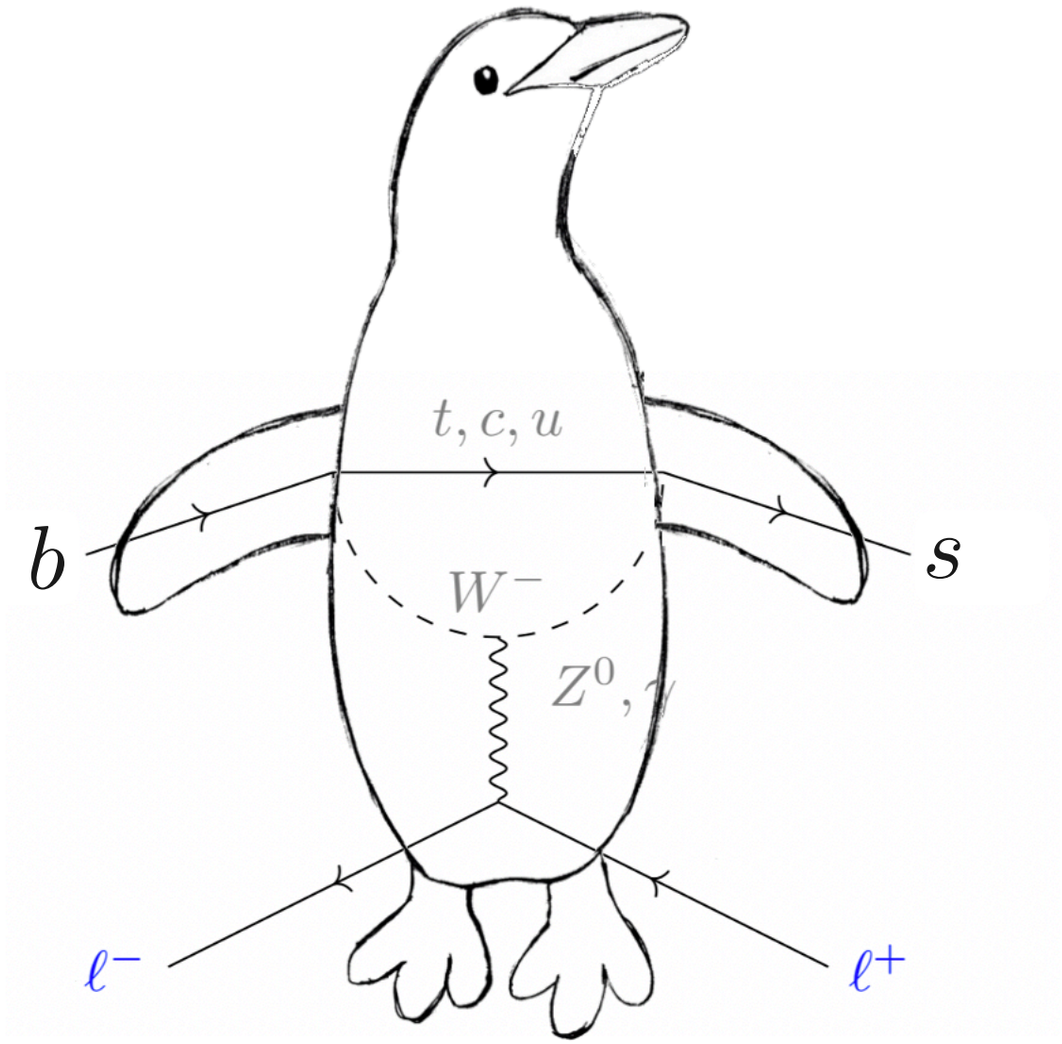
Standard Model



New Physics beyond the TeV

Suppression = very sensitive to New Physics diagrams

Electroweak Penguins



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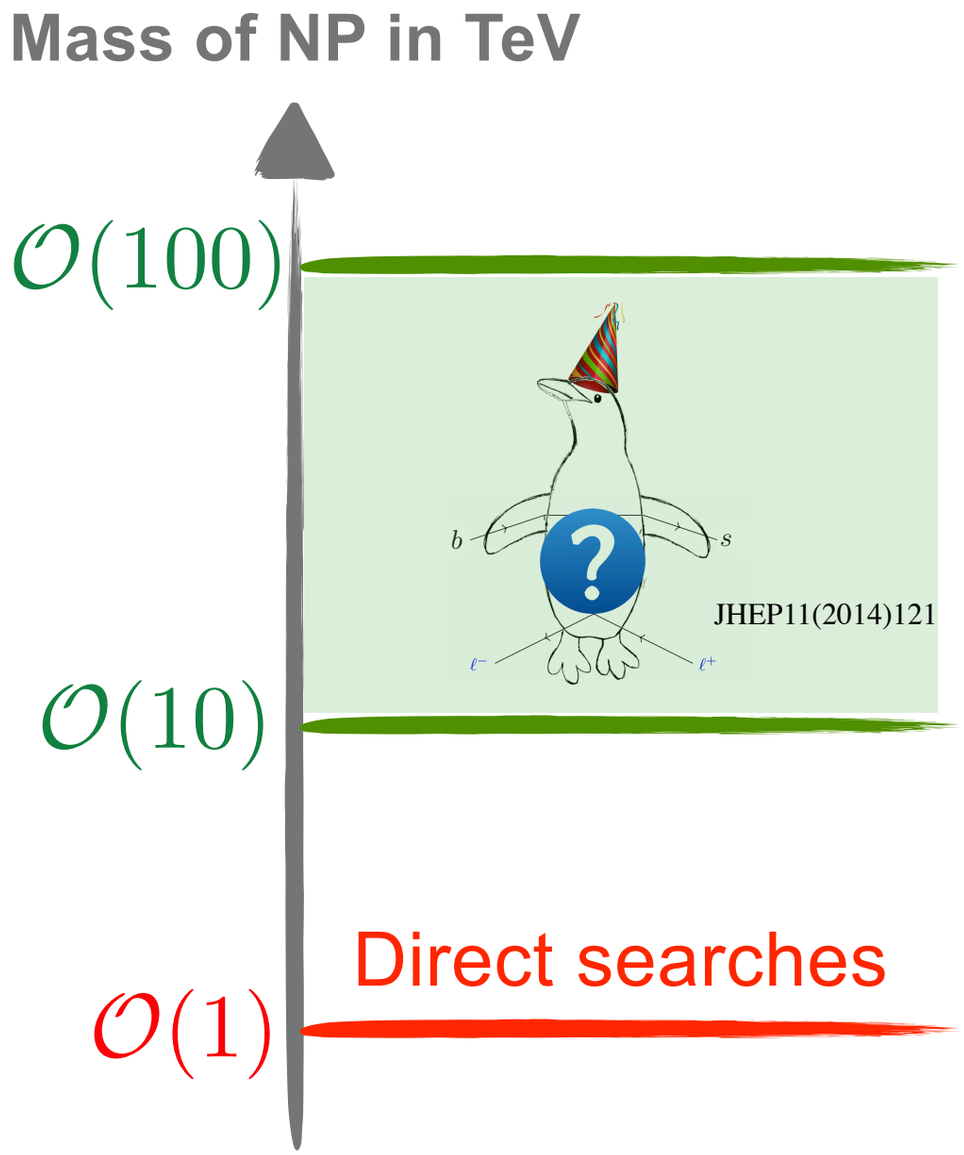

Collide at bigger energies (e.g. FCC-hh ~2070)

New Physics beyond the TeV

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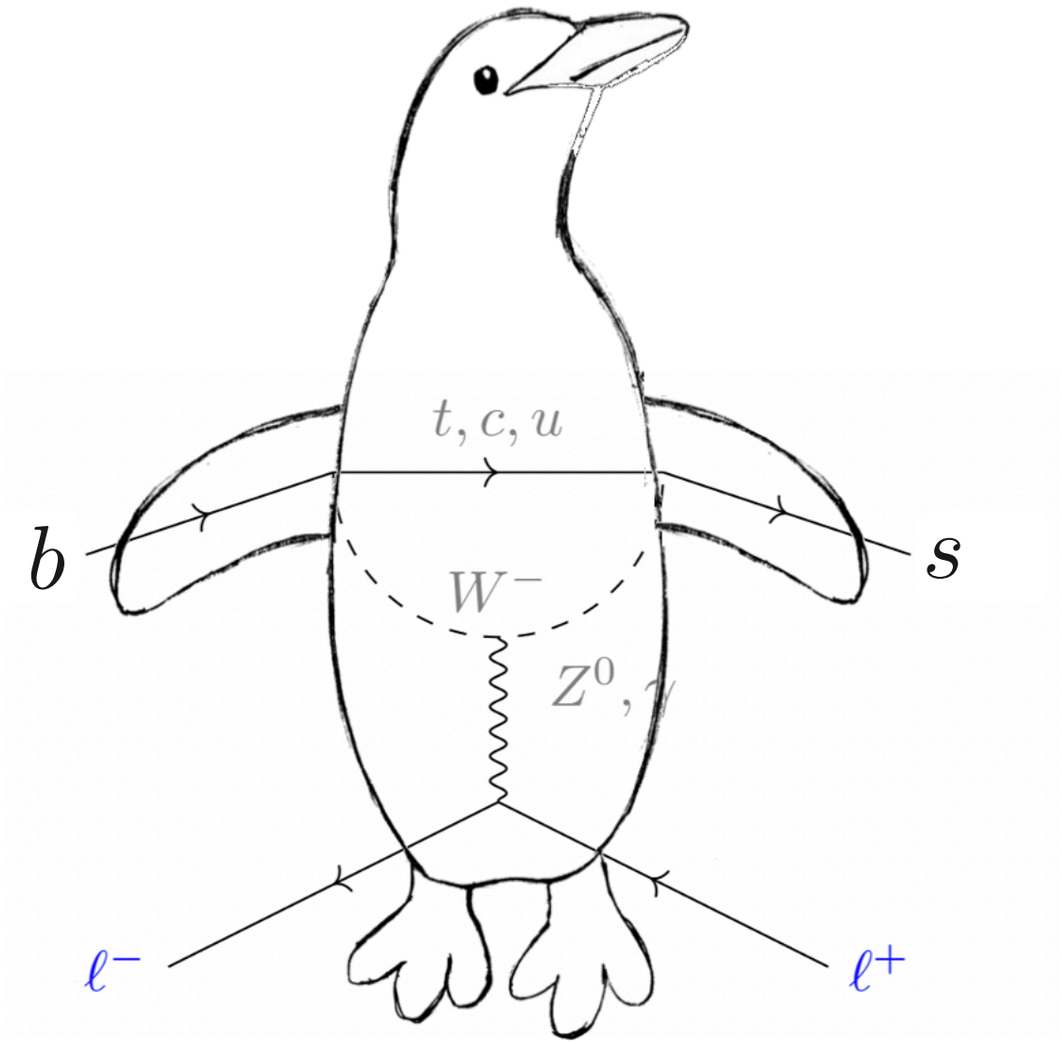
Electroweak Penguins



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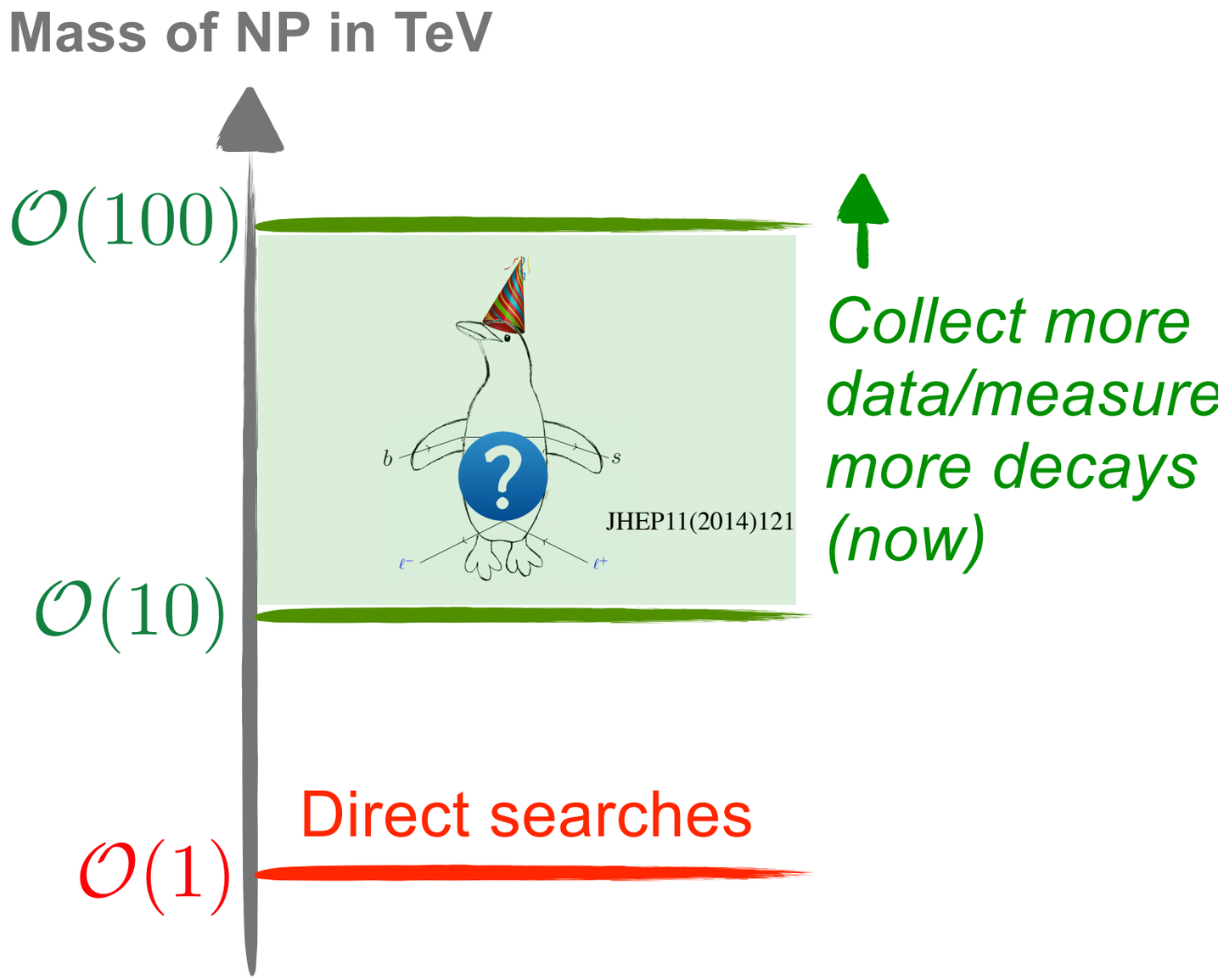
Standard Model



New Physics beyond the TeV

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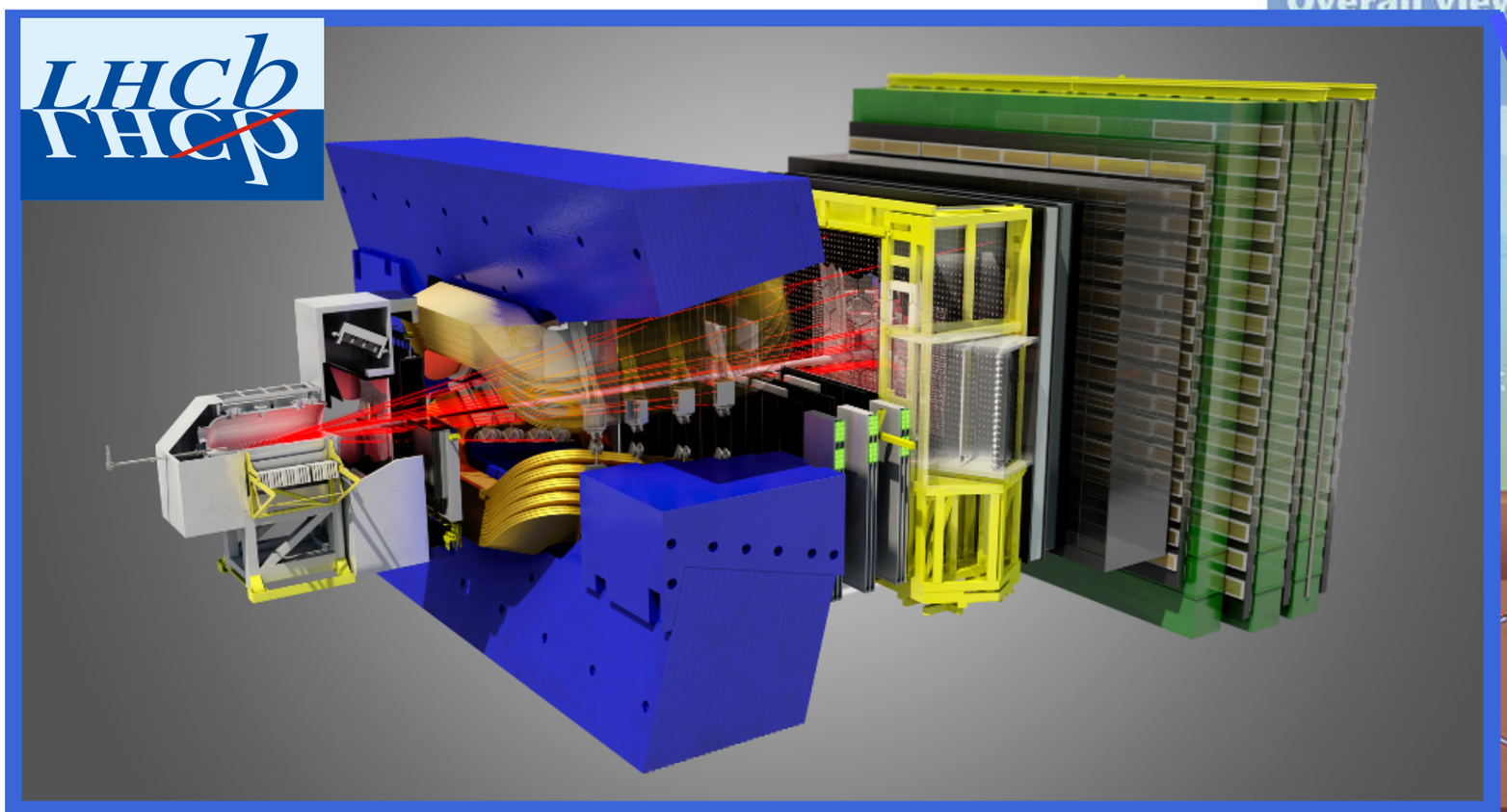
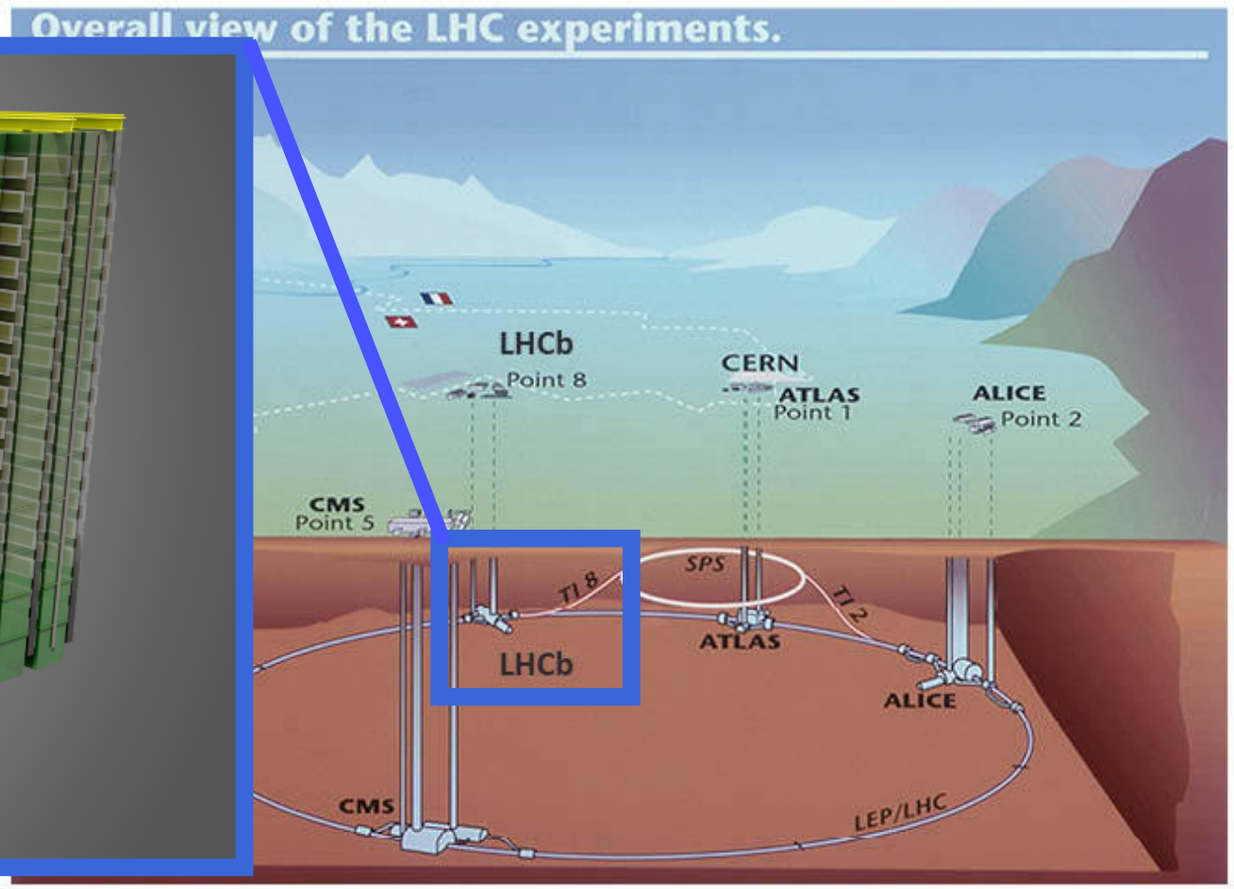
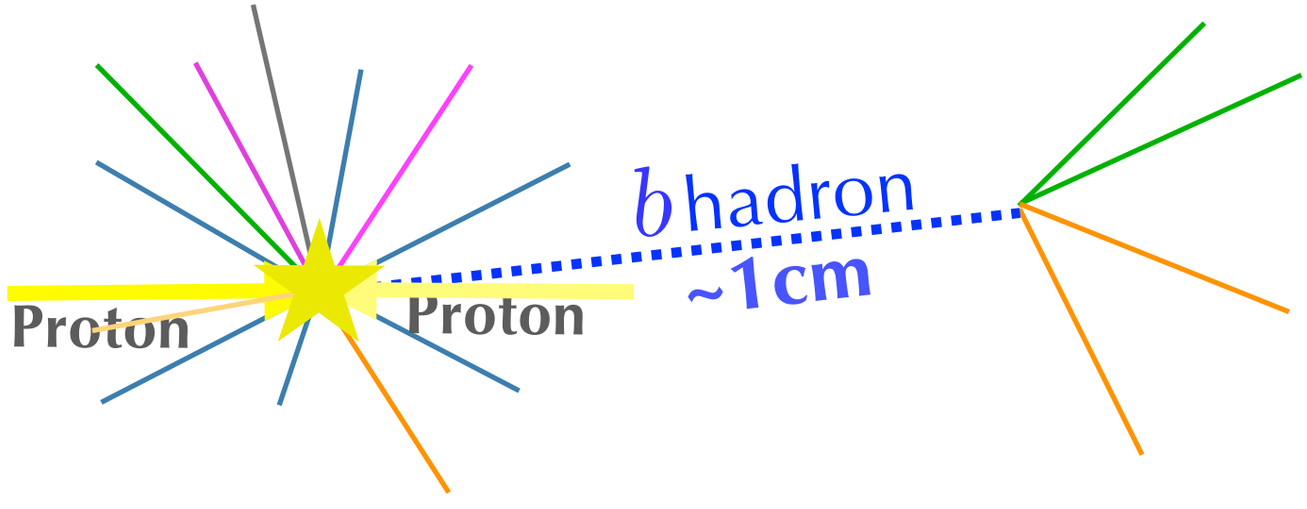
Measuring b hadrons: LHCb experiment





The original precision-measurement experiment: specialises in heavy quark decays:



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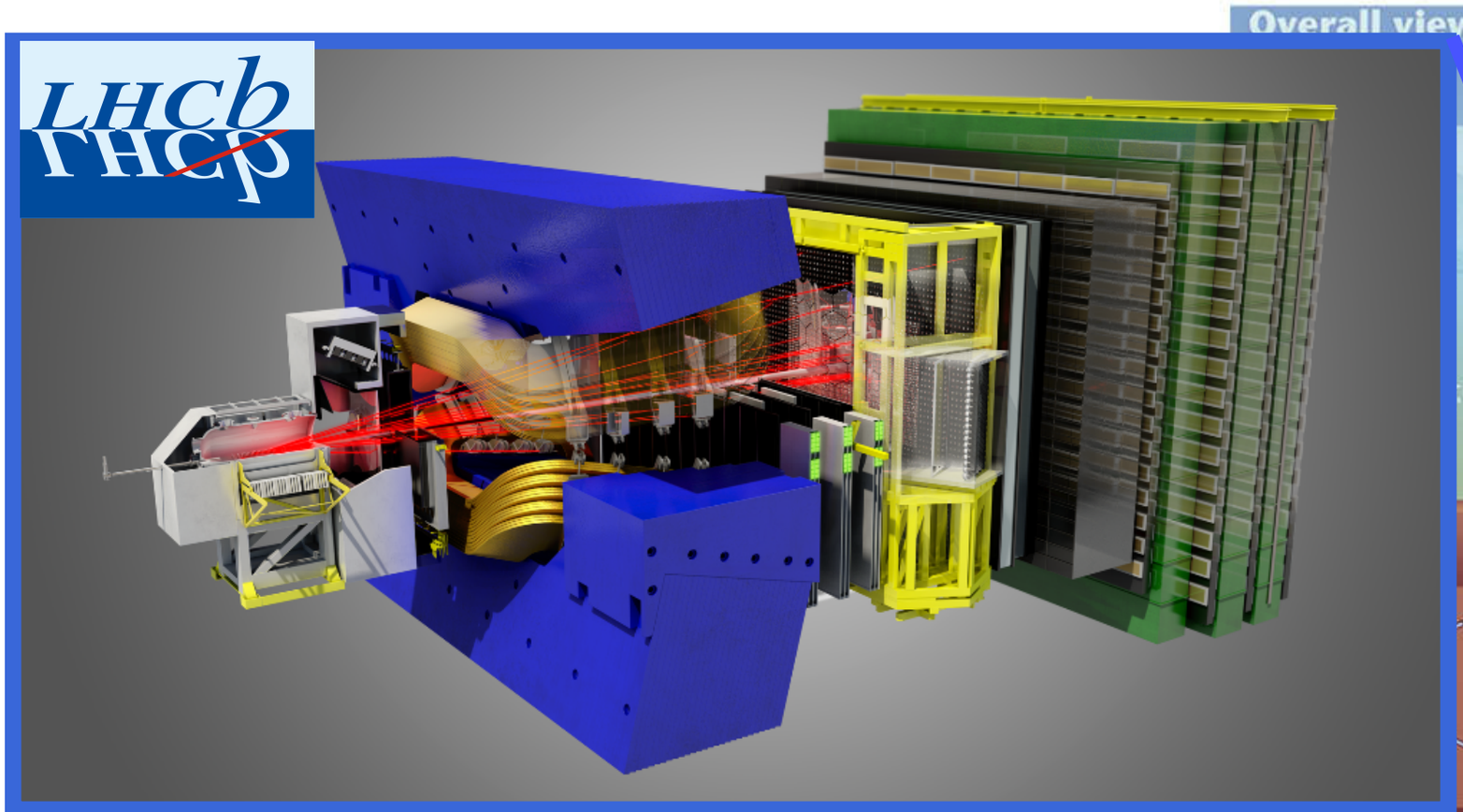
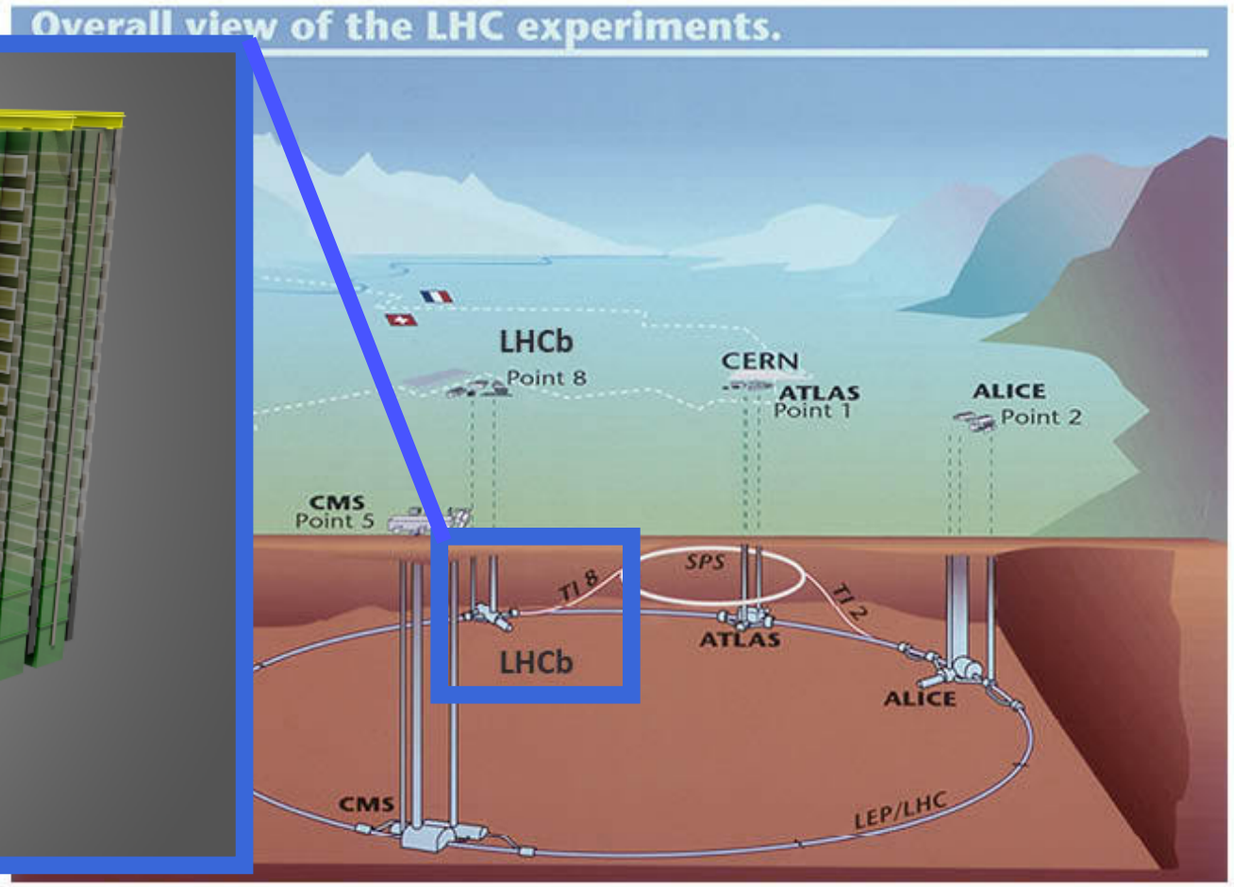


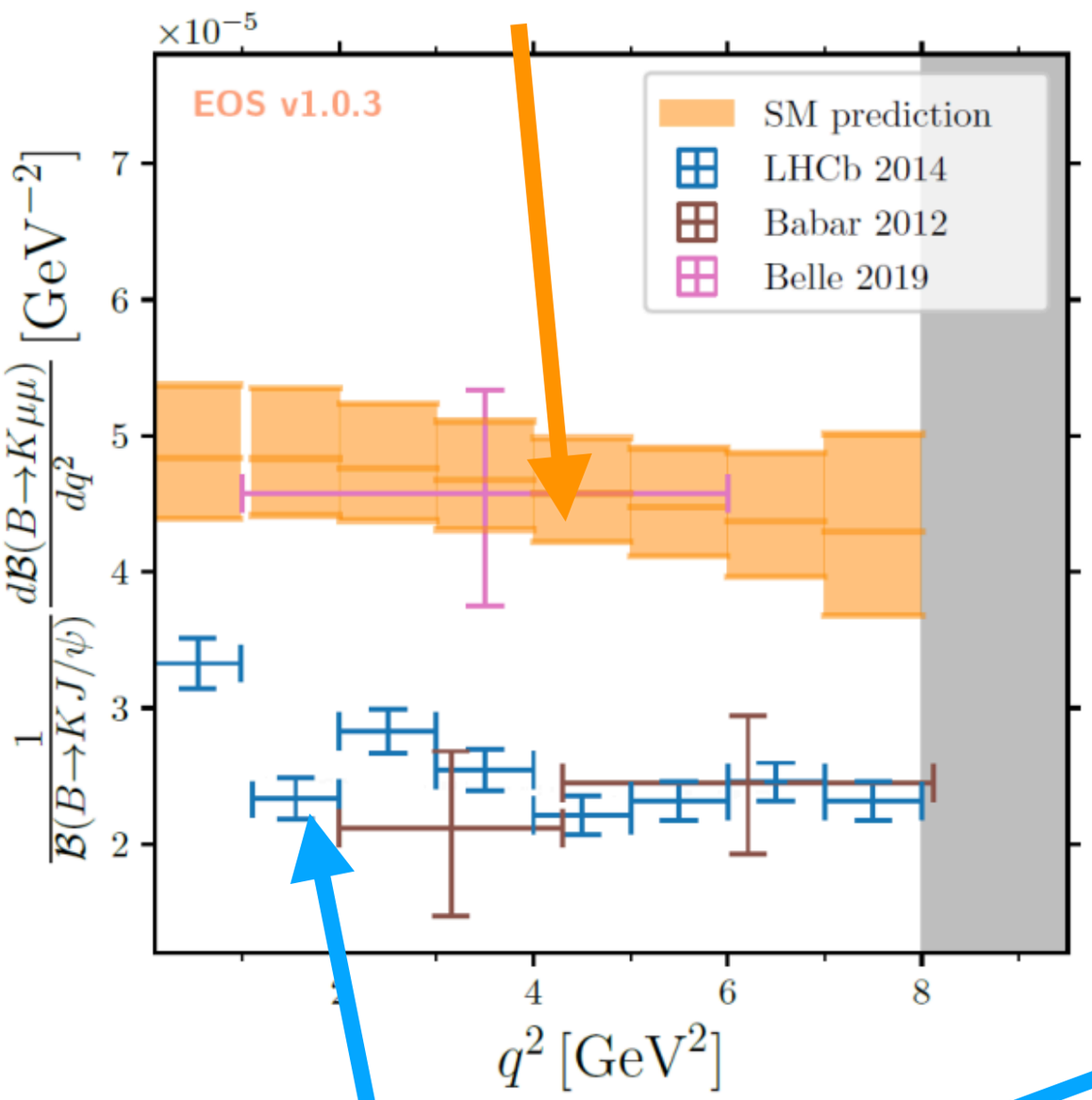


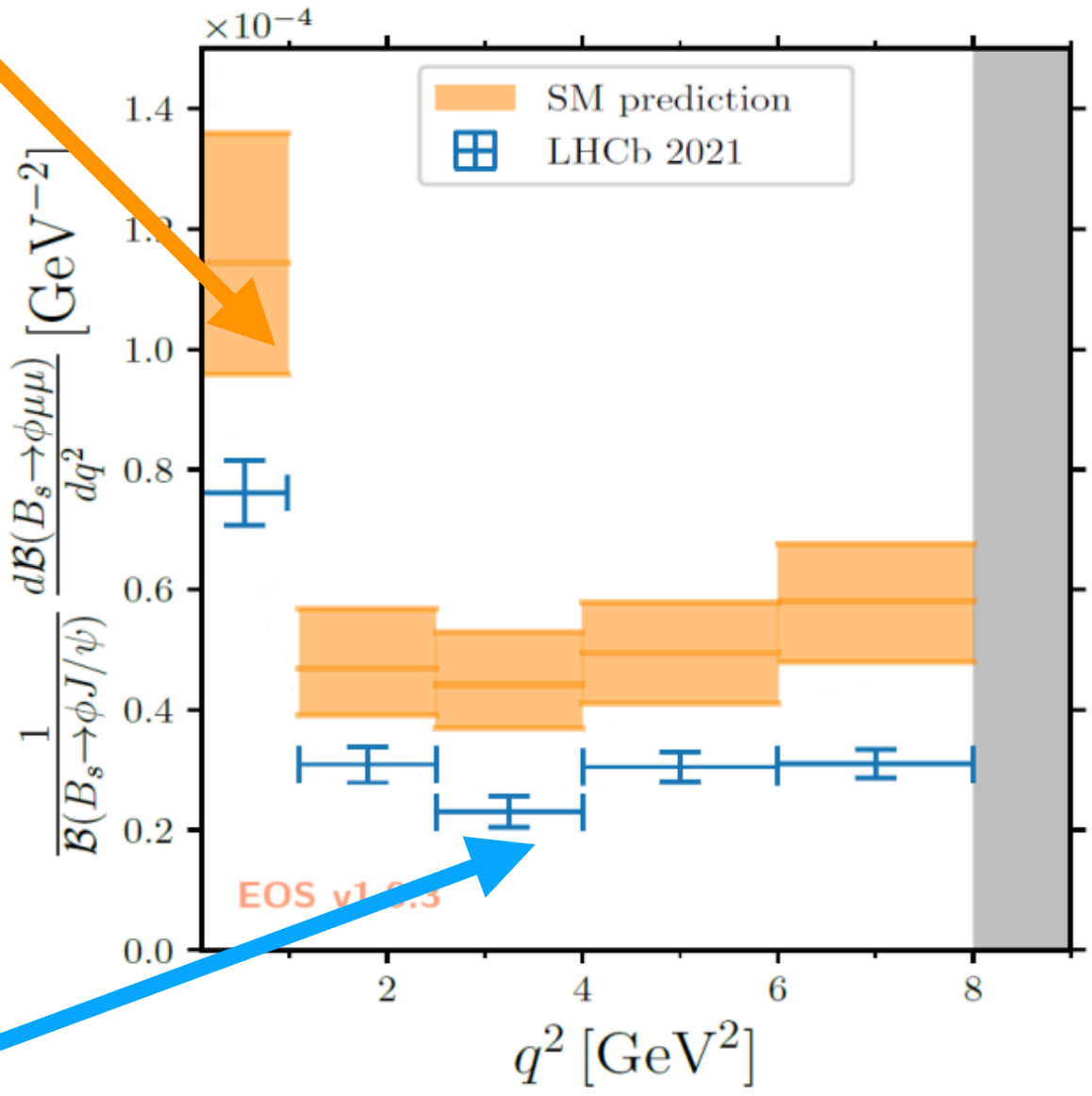
- World leading measurements of CP-violation
- Discovered over 70 new hadrons including new states of matter
- Observed significant deviations from SM in rare penguin decays

Deviations in rare penguins: we don’t see enough

Deviations in rare penguins: we don't see enough

Latest SM predictions (Lattice QCD)





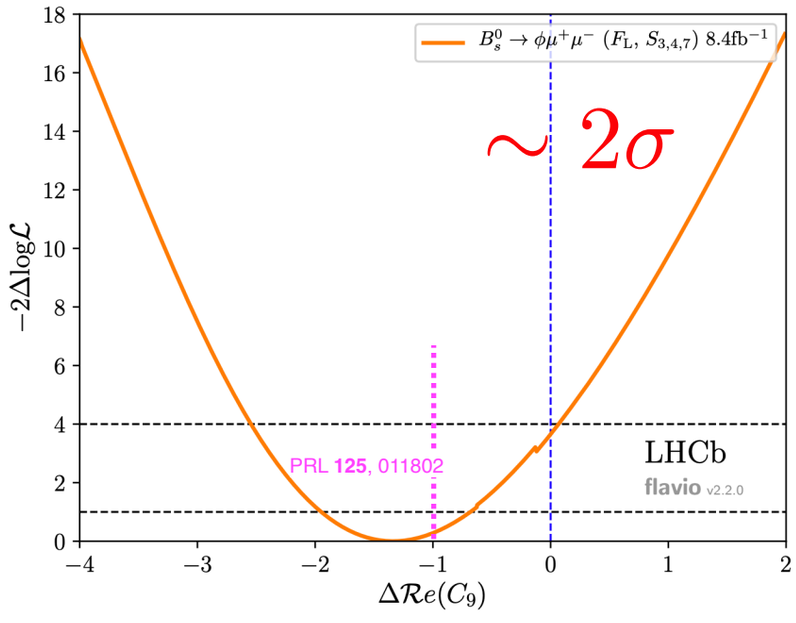
What we measure

And their angular distributions aren't as we except

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

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

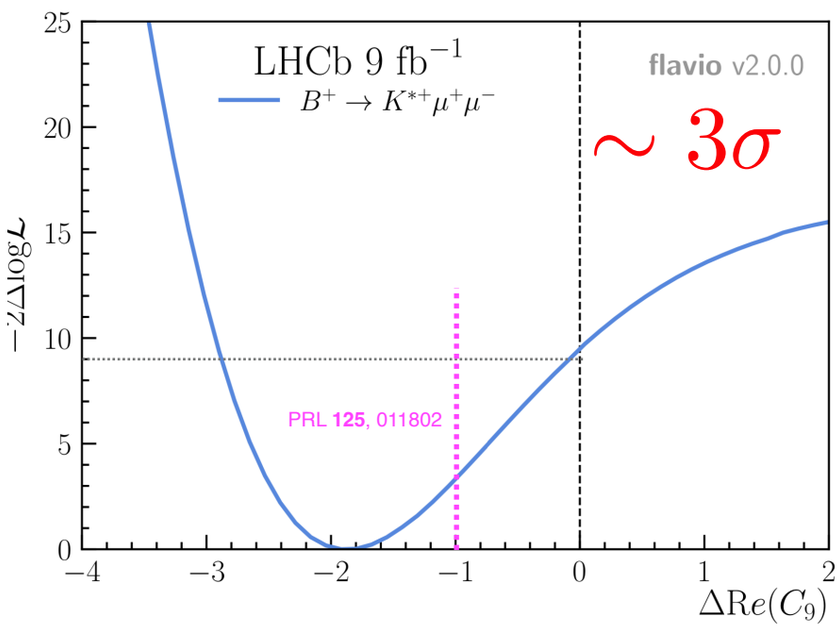
JHEP 11 (2021) 043



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

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

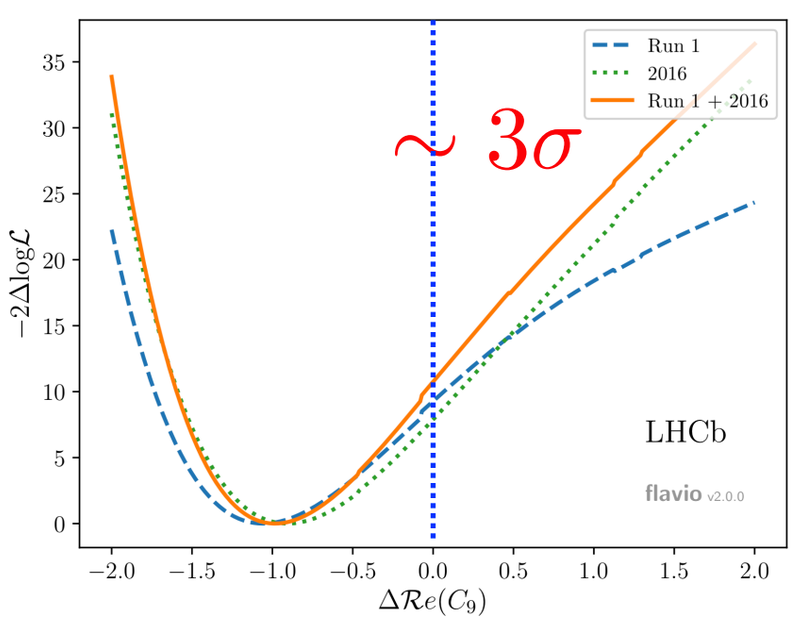
Phys. Rev. Lett. **126**, 161802



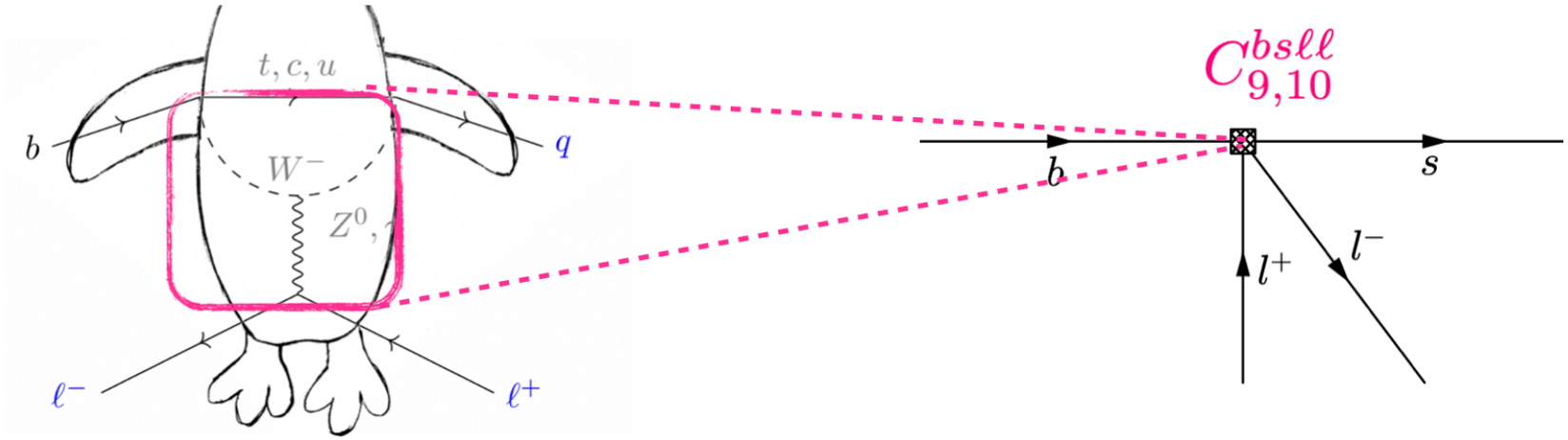
$$B^0 \to K^{*0}\mu^+\mu^-$$

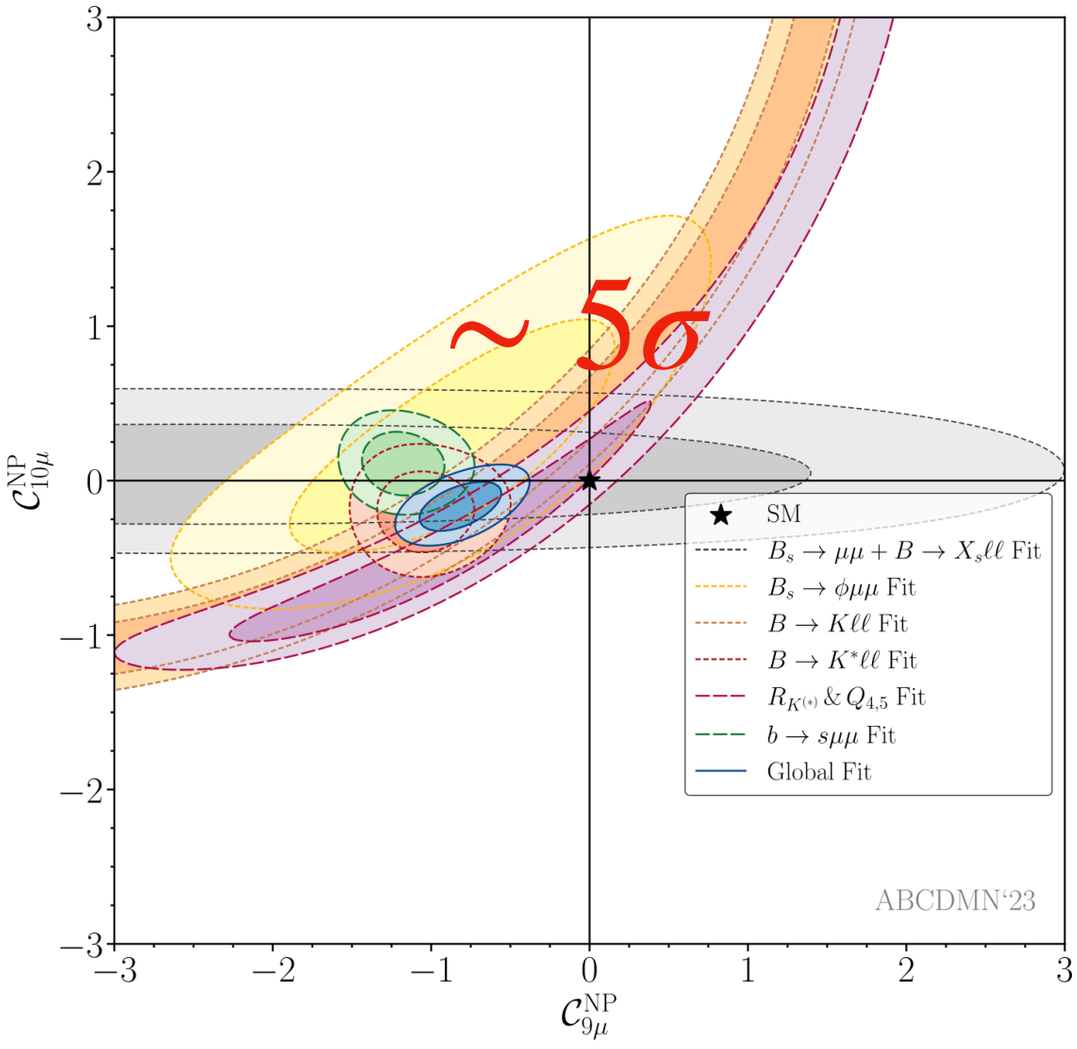
$$\Delta\mathcal{R}e(\mathcal{C}_9) = -0.99^{+0.25}_{-0.21}$$

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



Global fit to underlying effective couplings





- Results across all observables consistent

- Overall deviation from SM at the 3-5 σ level - but sig. depends on theory assumptions

> 5σ combined, first beyond-SM discovery at LHC?

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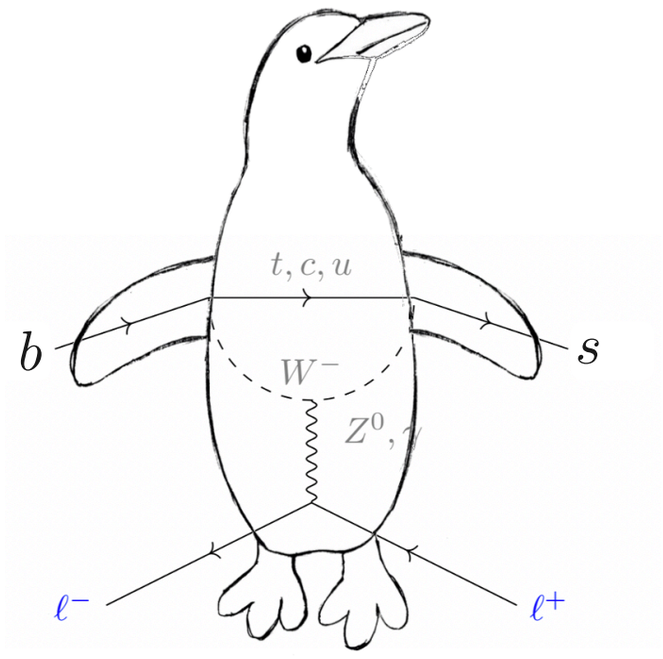
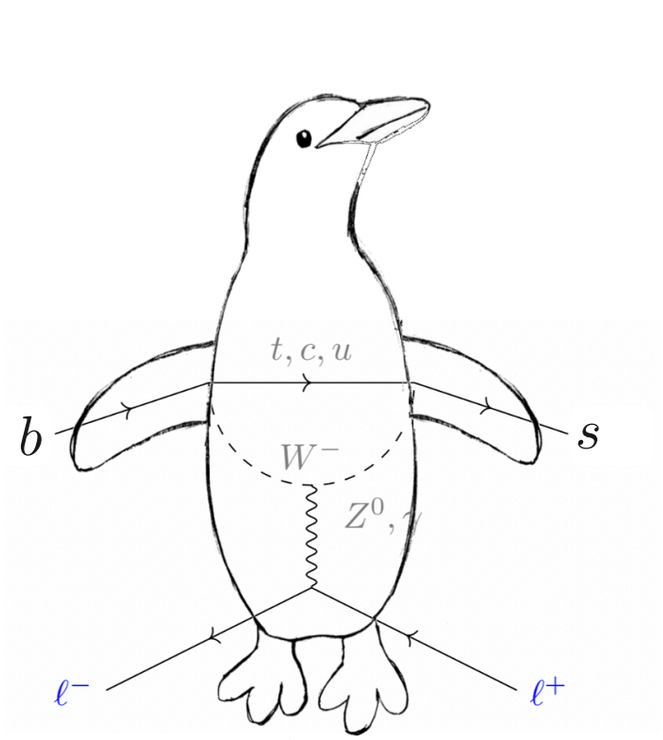


$+$ **?** $=$ deviations

> 5σ combined, first beyond-SM discovery at LHC?

Option 1 - New Physics



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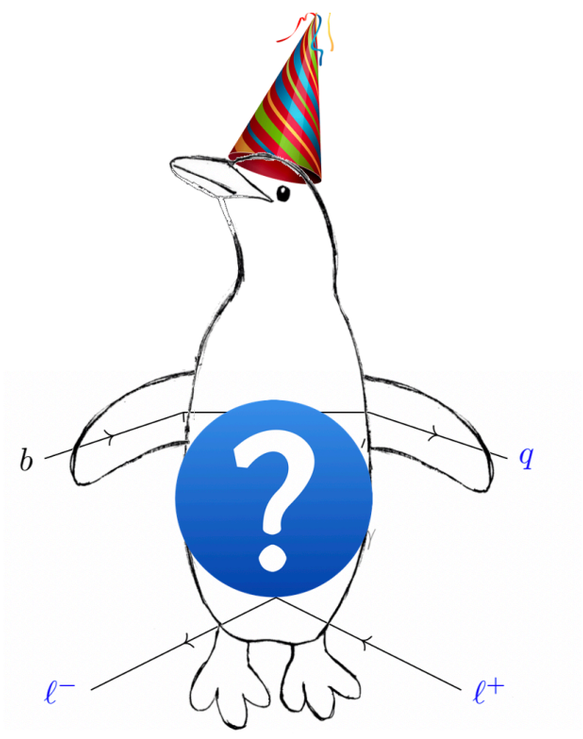

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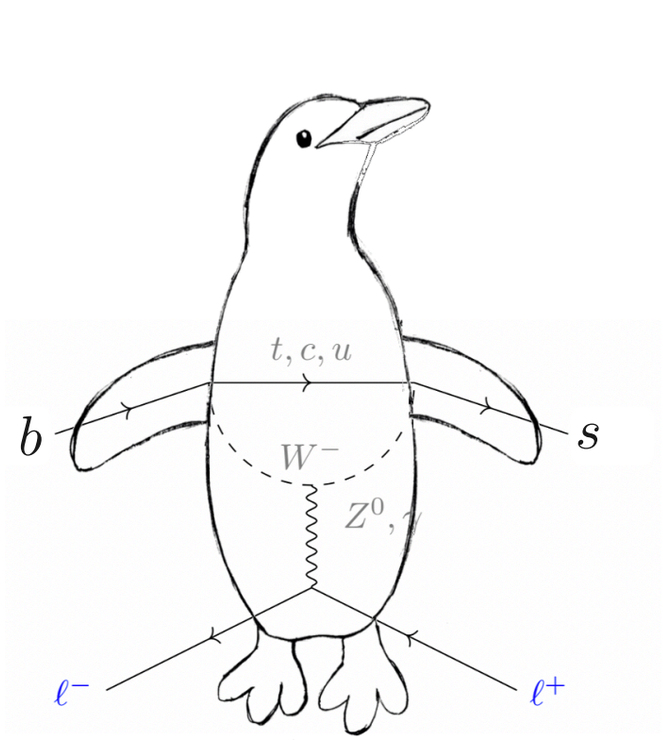

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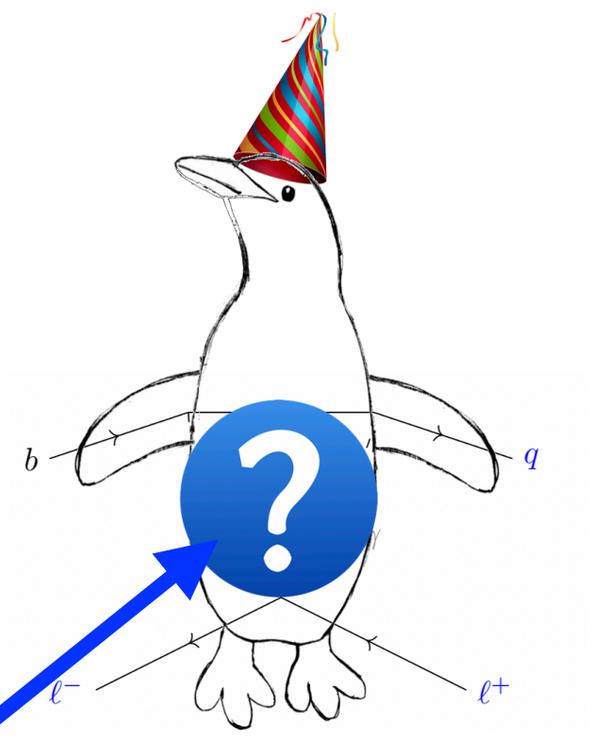
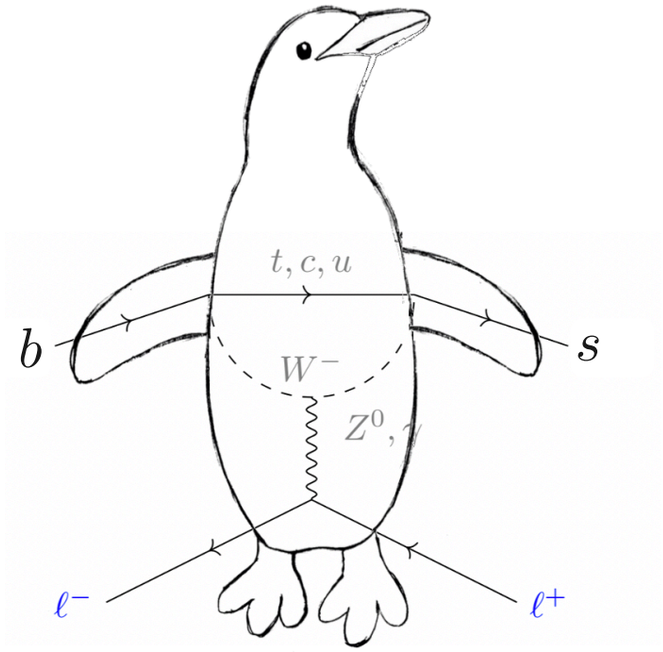


= deviations

CP violating? Leptoquark? = PhD projects

> 5σ combined, first beyond-SM discovery at LHC?

Option 2 - misunderstood QCD processes



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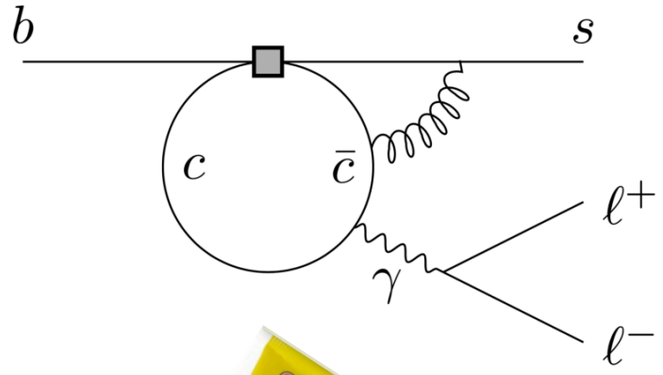
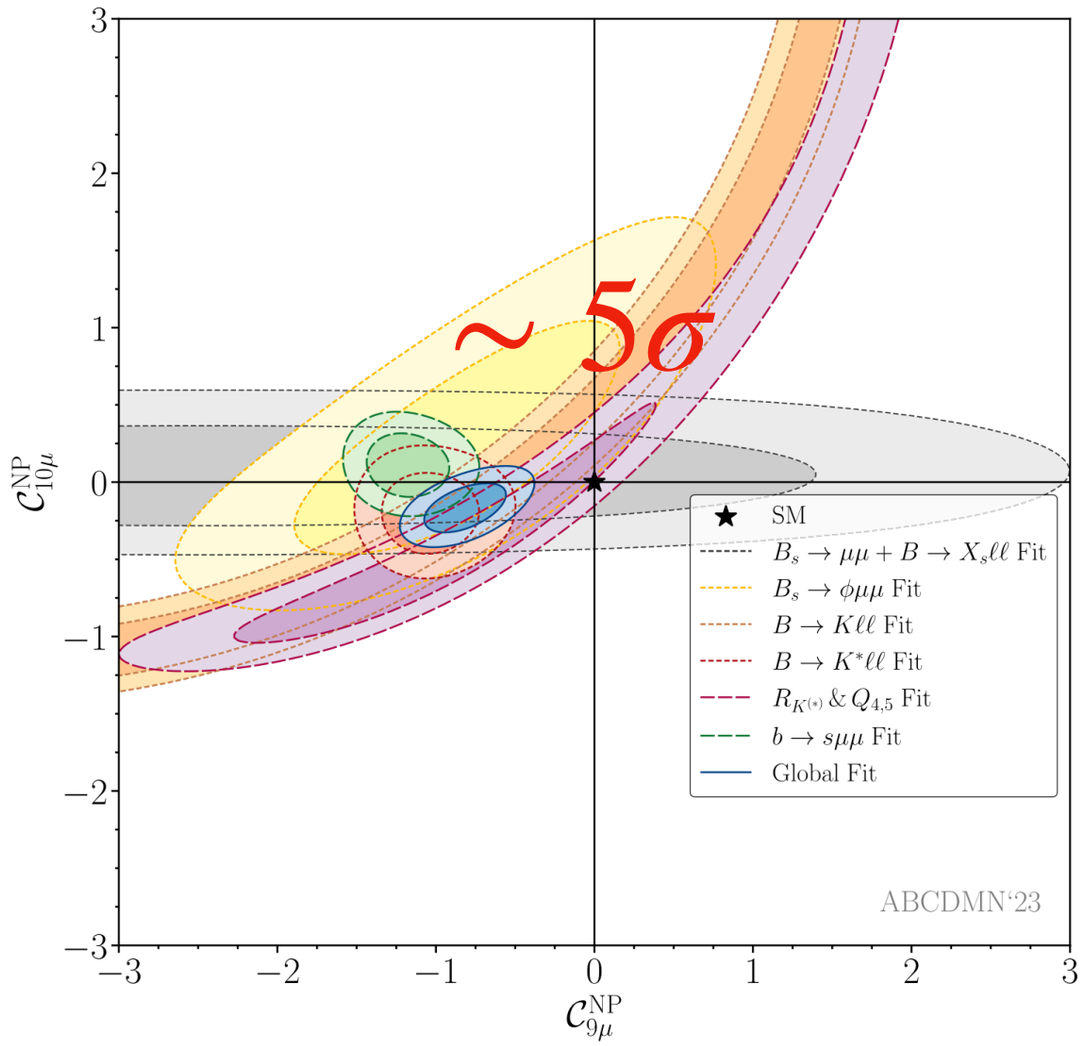


+

= deviations

PhD Projects



Perform 5 (for 6!) dimensional fits in order to **fully analyse** the final states of electroweak penguin decays

Use the results to understand whether these deviations are due to heavy new physics !!

Machine-learning on FPGAs

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->

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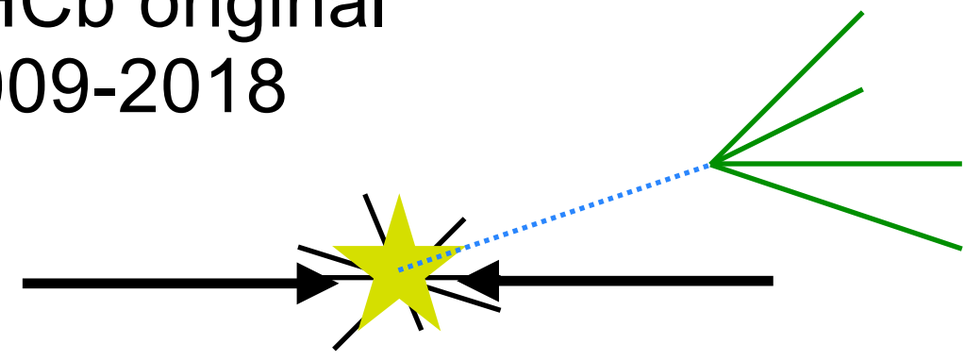
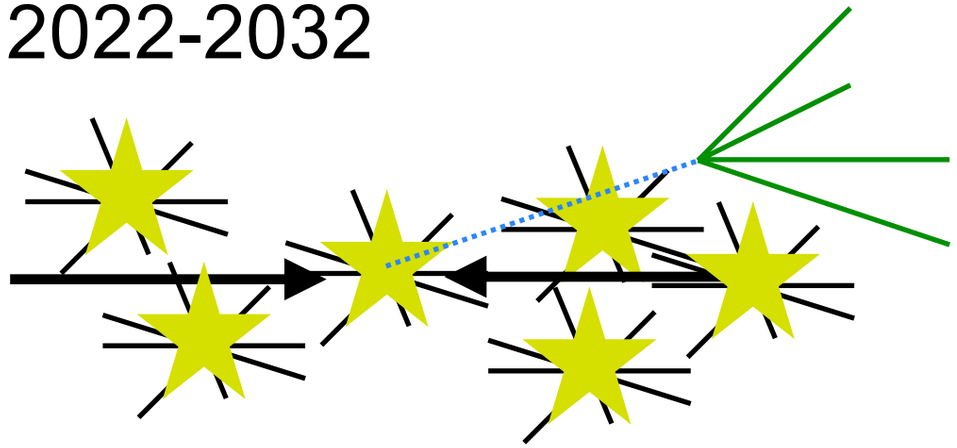
2011-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2038	2038->

LHCb original
2009-2018



~1 pp collision per bunch-crossing

LHCb Upgrade I
2022-2032



~6 pp collisions per bunch-crossing

Machine-learning on FPGAs

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LHCb original
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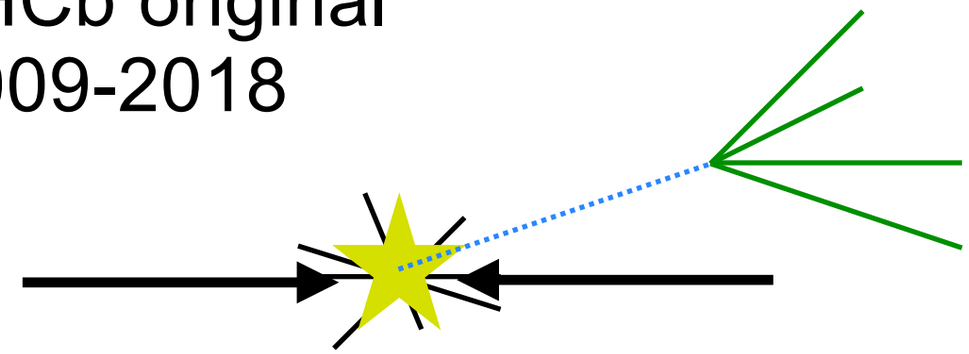

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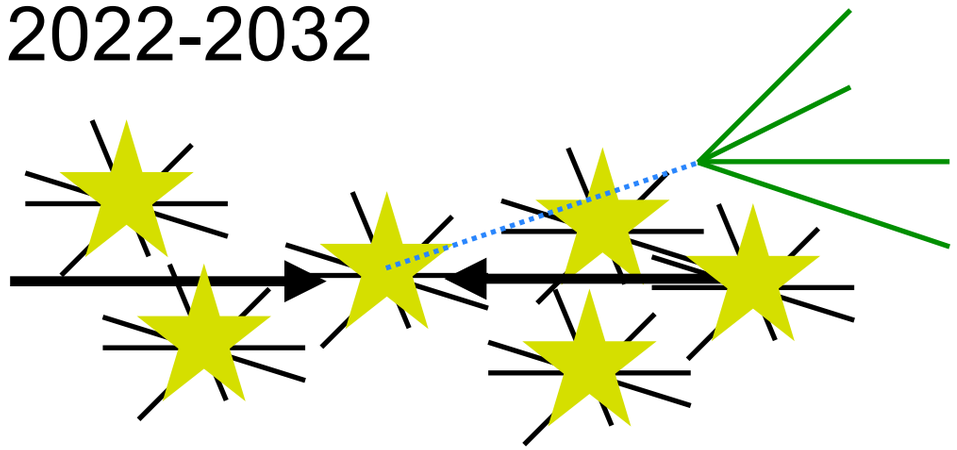
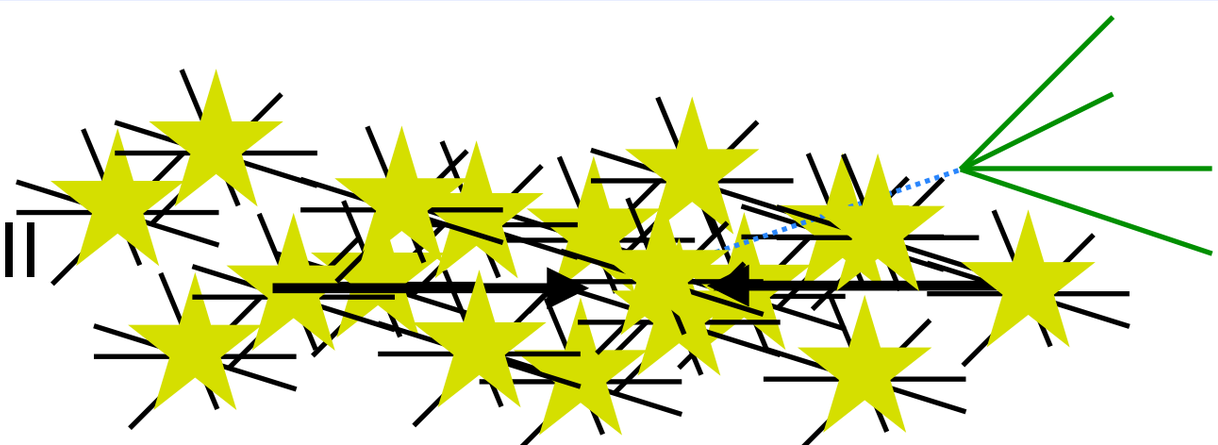


~6 pp collisions per bunch-crossing

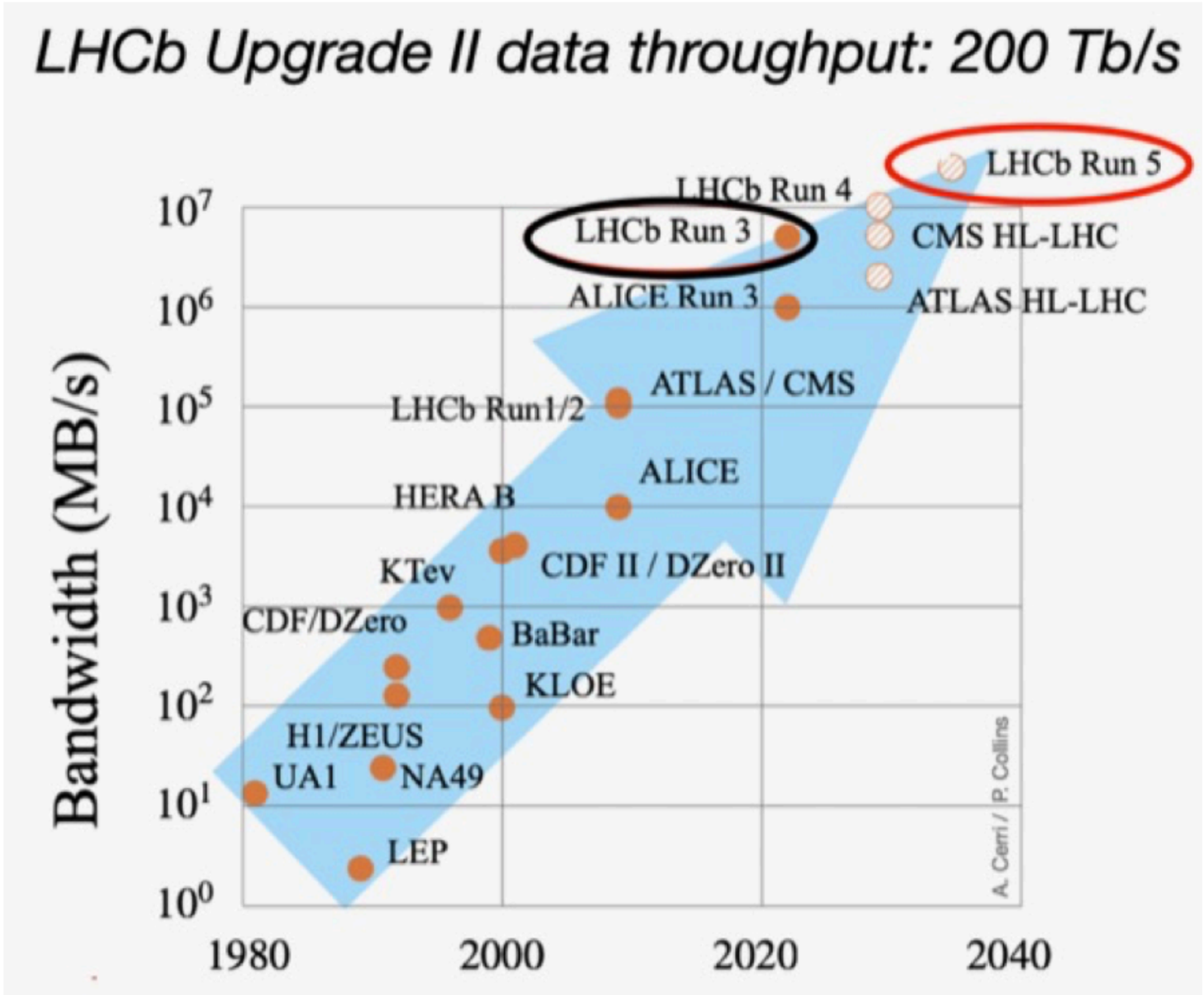
LHCb Upgrade II
2033 onwards



~40 pp collisions per bunch-crossing

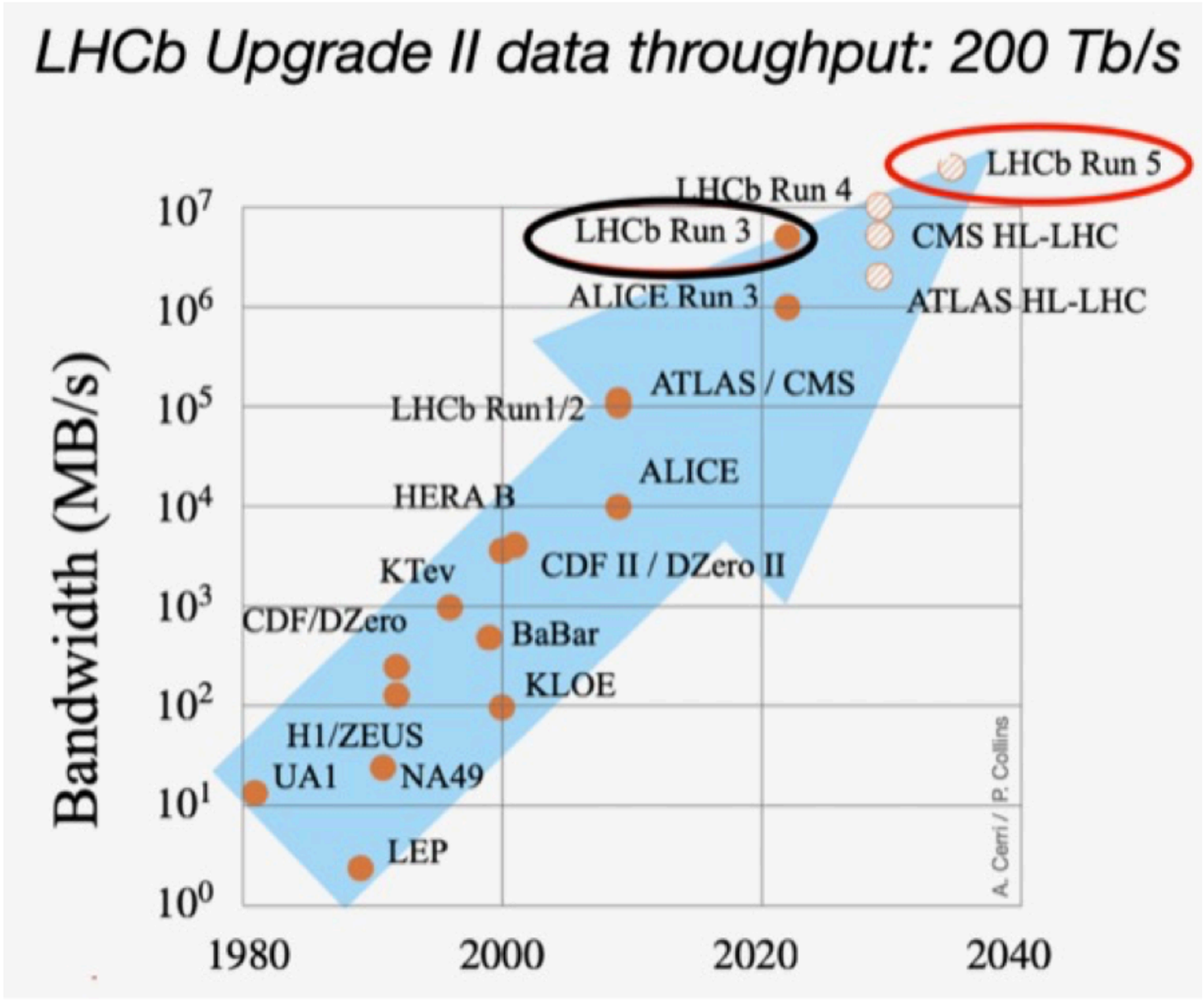
+ ~30 million bunch crossings a second!

Machine-learning on FPGAs



LHCb Upgrade II will produce highest bandwidth of any LHC experiment

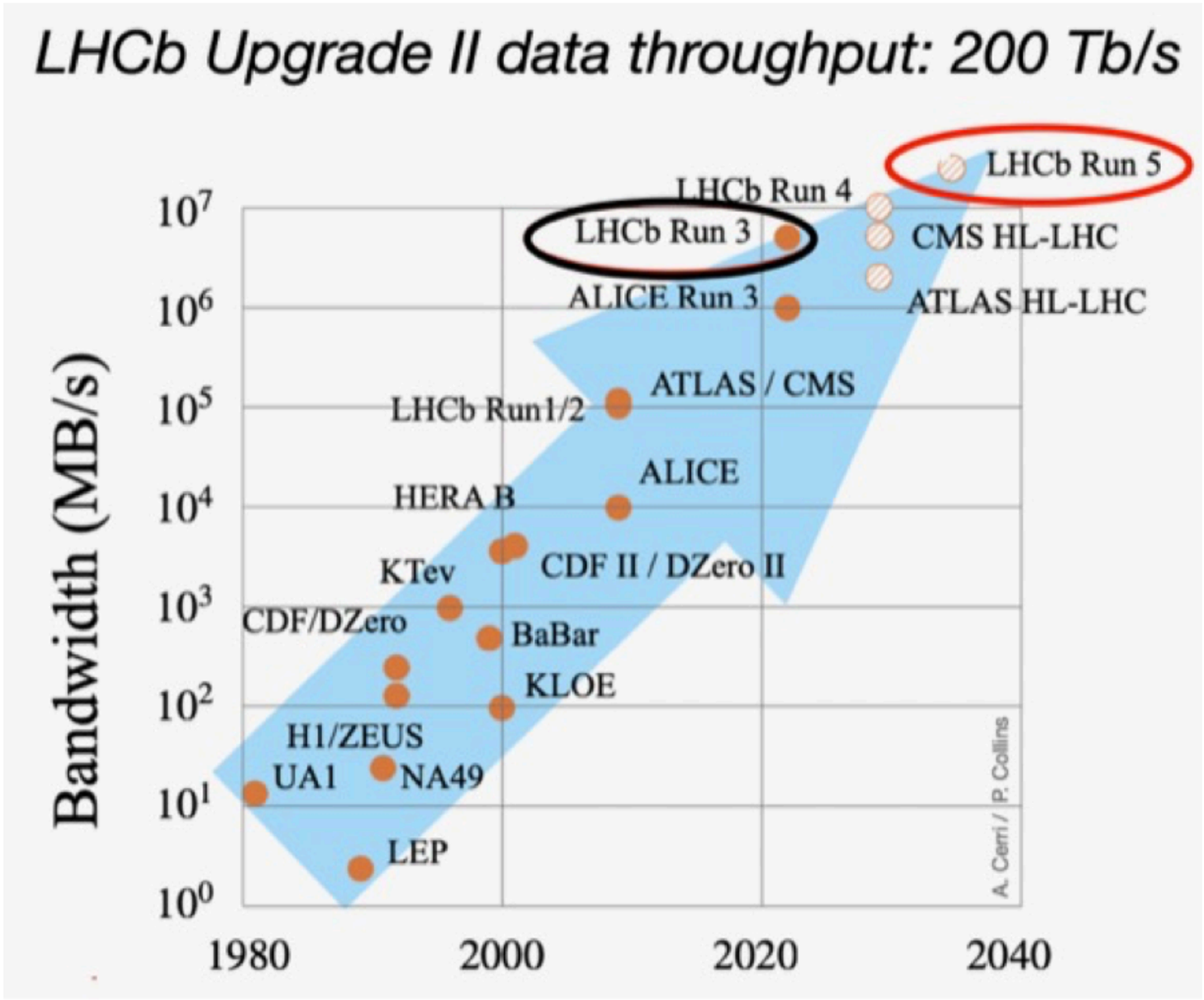
Machine-learning on FPGAs



LHCb Upgrade II will produce highest bandwidth of any LHC experiment

First LHC experiment to run without a hardware trigger (40 Tb/s)

Machine-learning on FPGAs

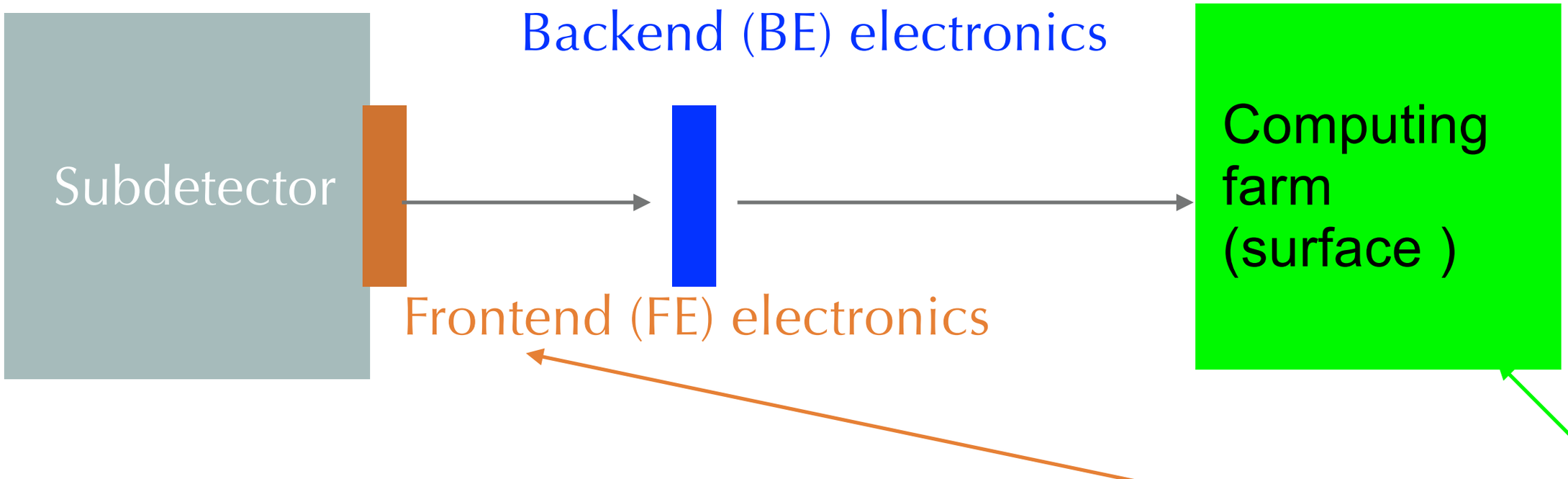


LHCb Upgrade II will produce highest bandwidth of any LHC experiment

First LHC experiment to run without a hardware trigger (40 Tb/s)

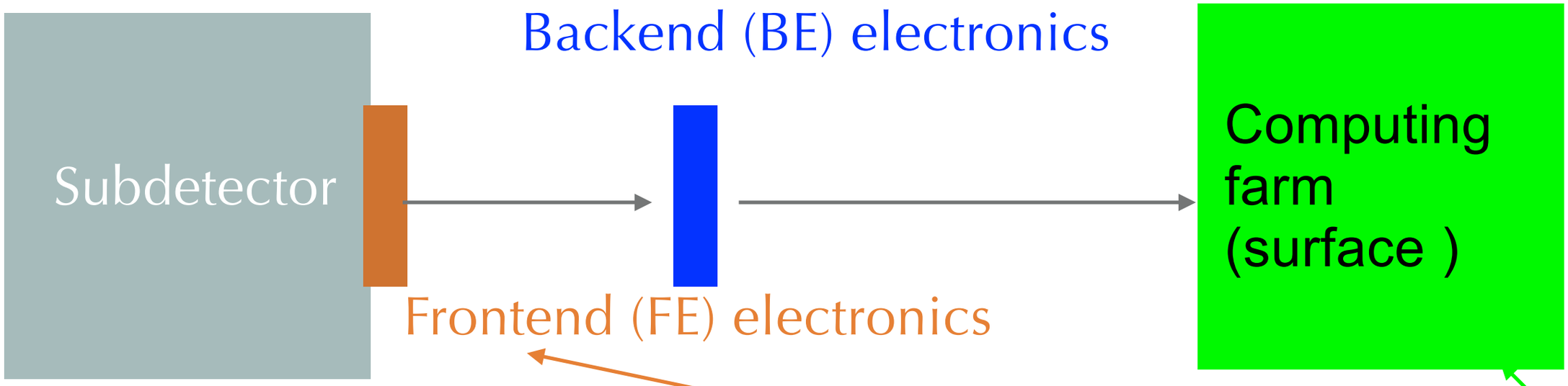
By 2030 we need to handle 200 Tb/s….

Machine-learning on FPGAs



Can we implement machine learning algorithms here instead of here?

Machine-learning on FPGAs



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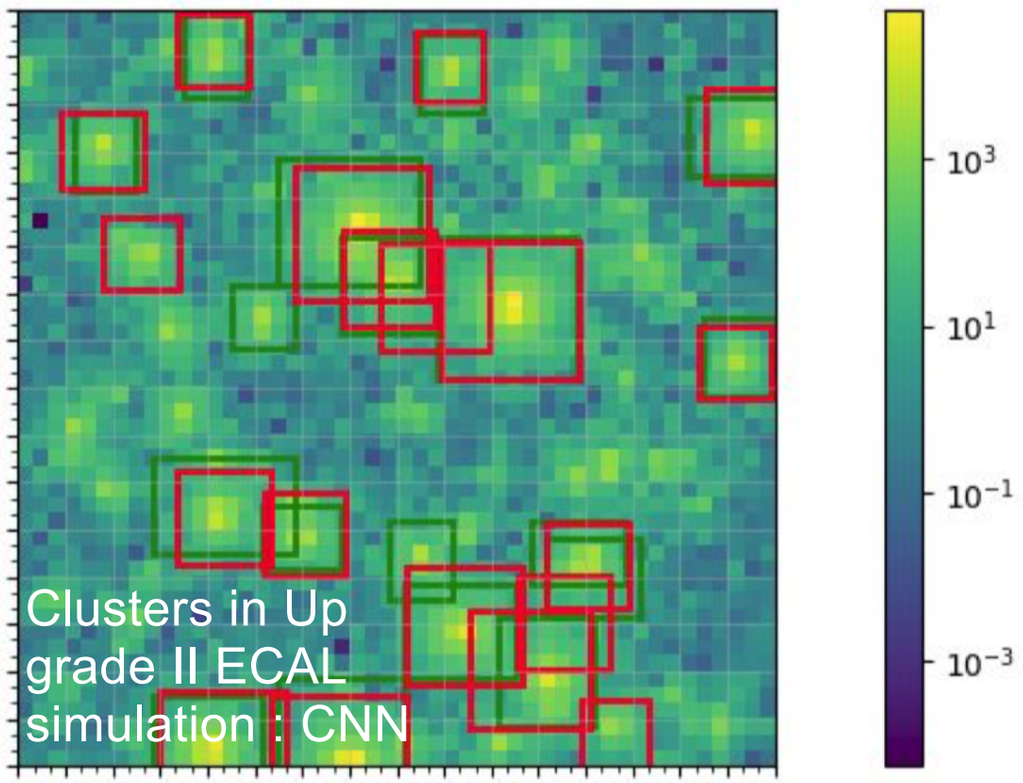
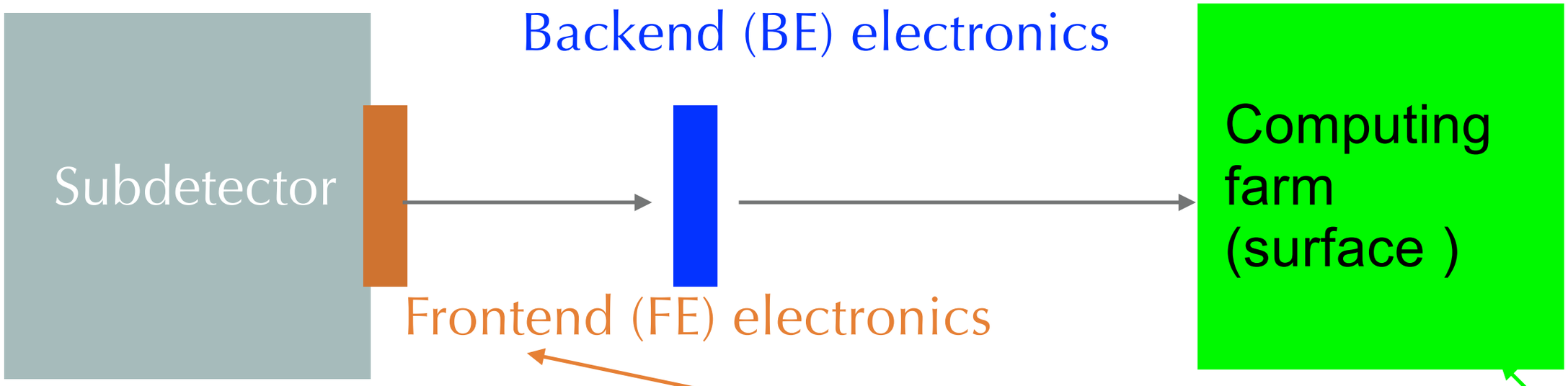


New developing field in low-latency AI, little adaption so far in LHCb

Machine-learning on FPGAs



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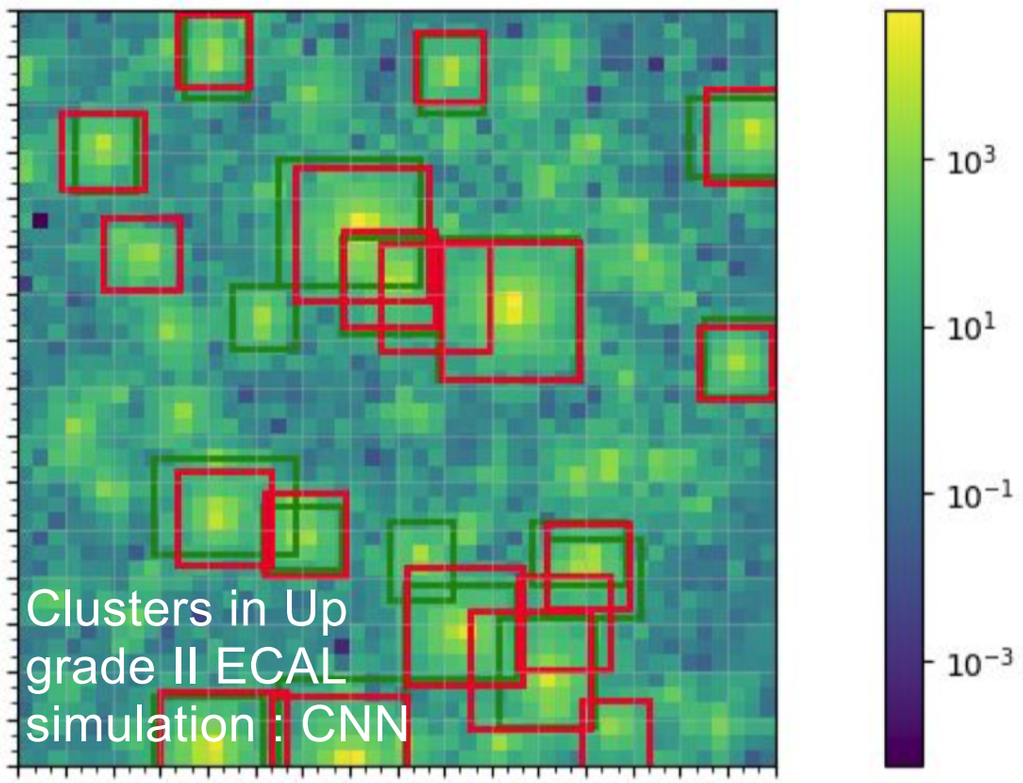
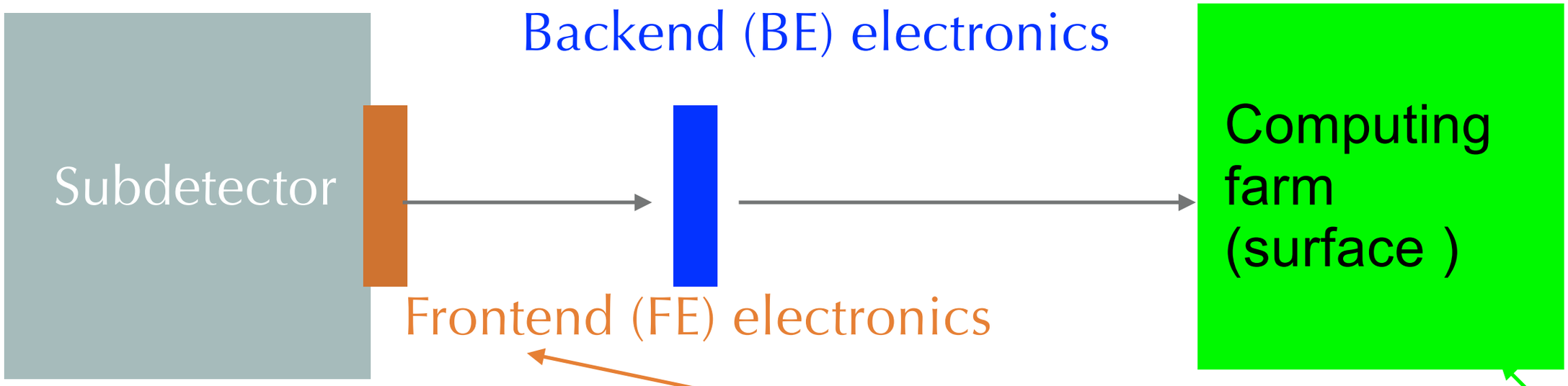


New developing field in low-latency AI

Developing auto encoders with inference of ~ 20 nanosecond

Working look at making neural net itself radiation hard.

Machine-learning on FPGAs



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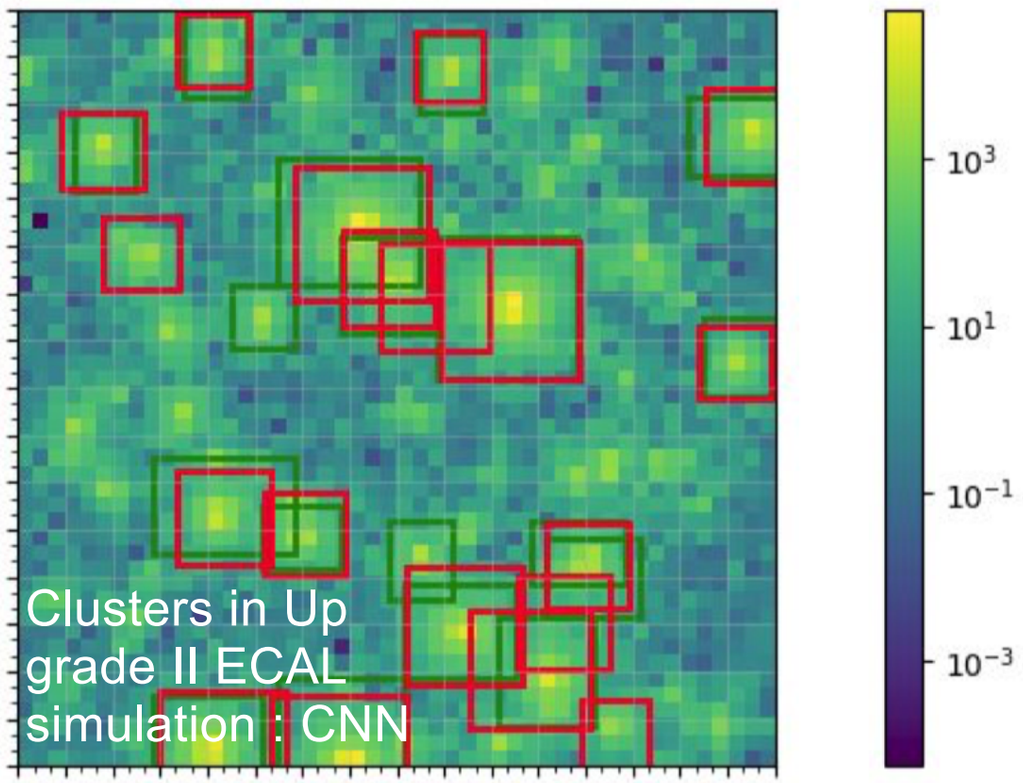

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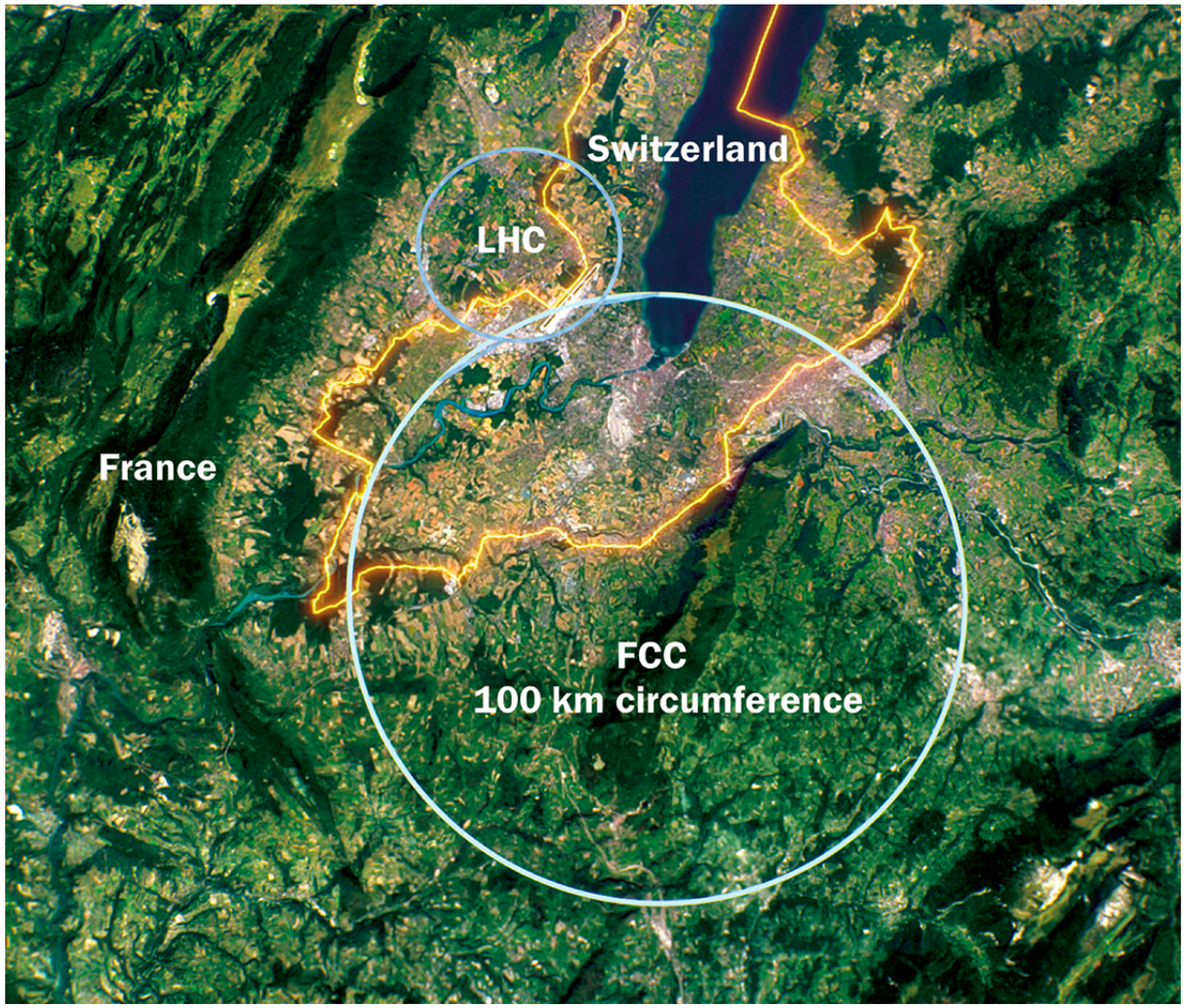
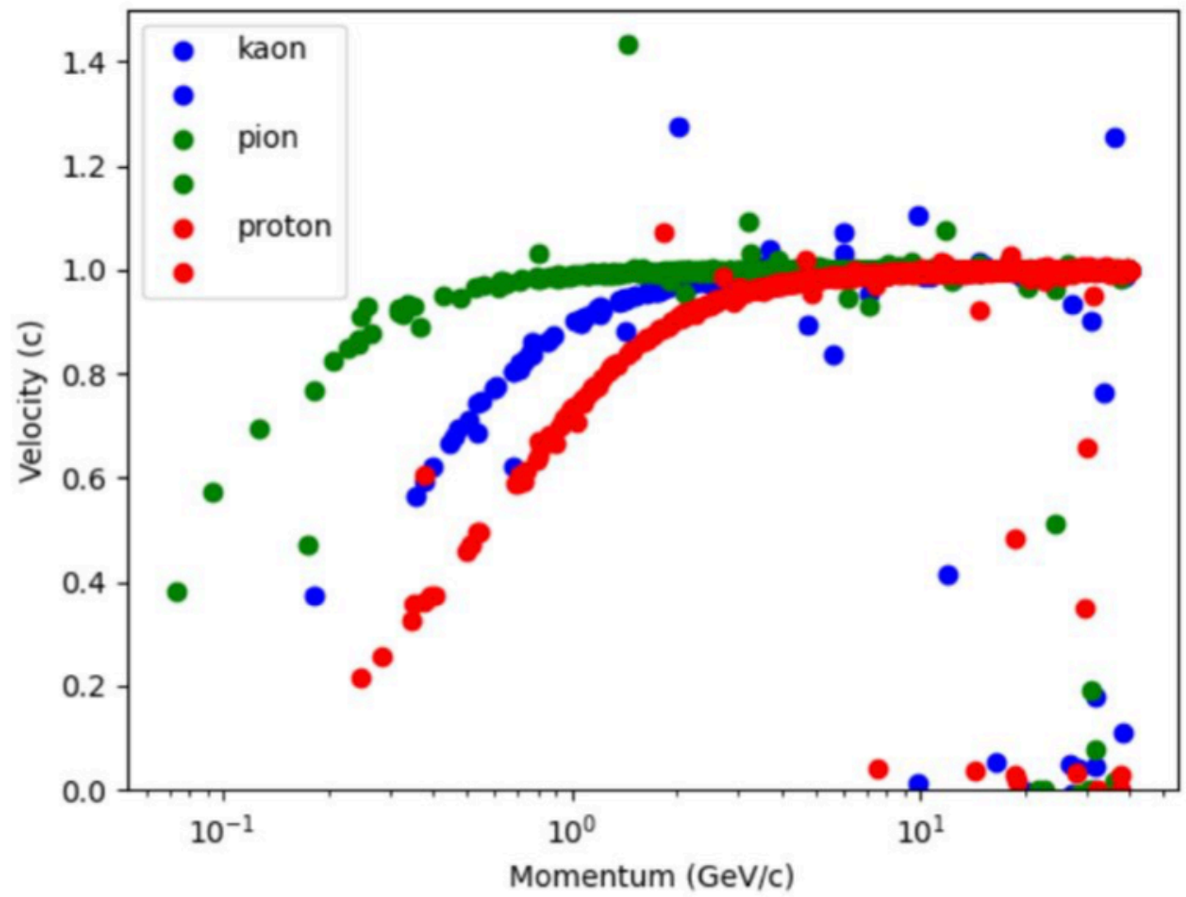
PhD involvement welcome!!

Feasibility studies at the FCC-ee

Future circular collider potentially a replacement of LHC

Looking at developing particle identification requirements for detectors





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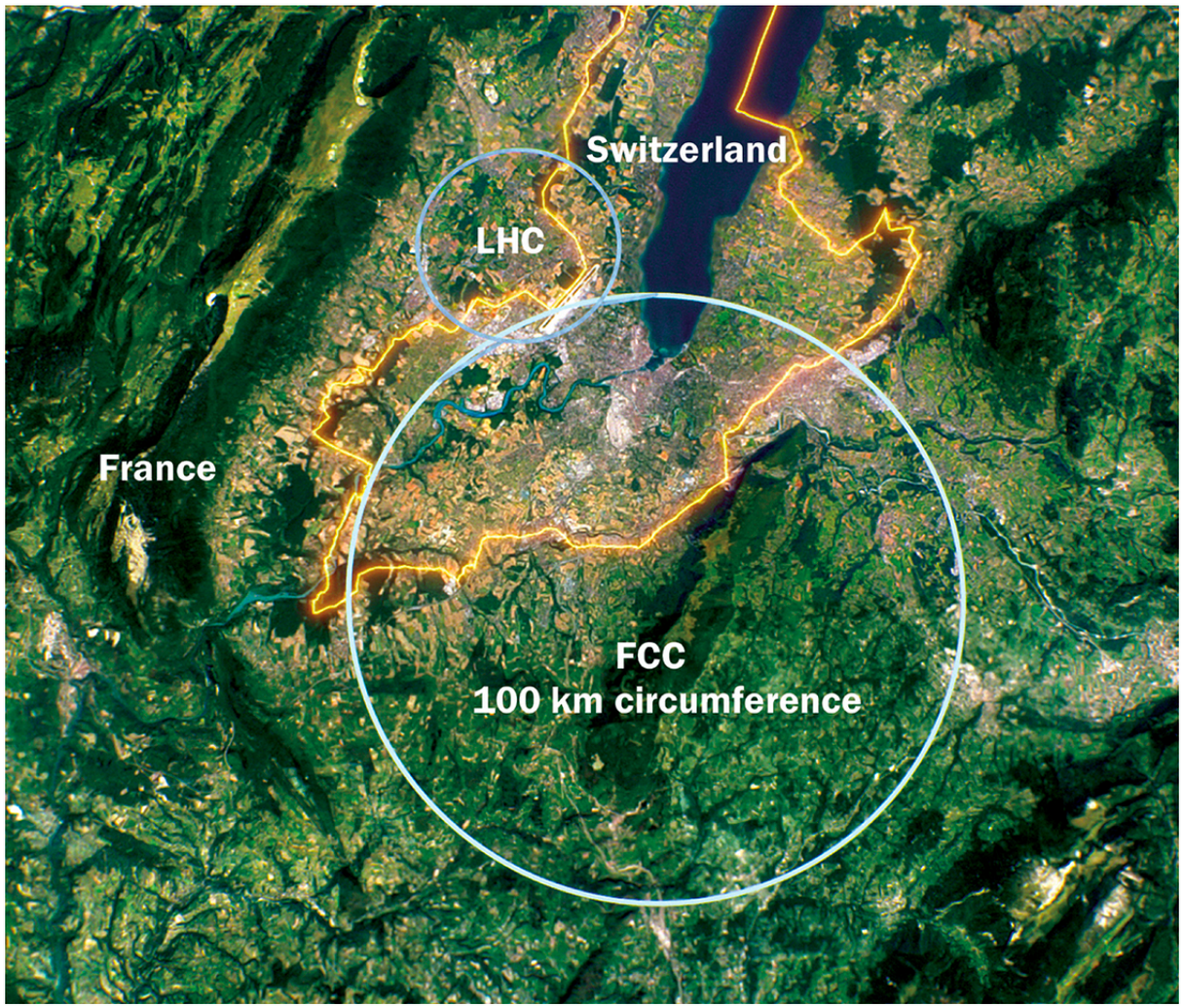
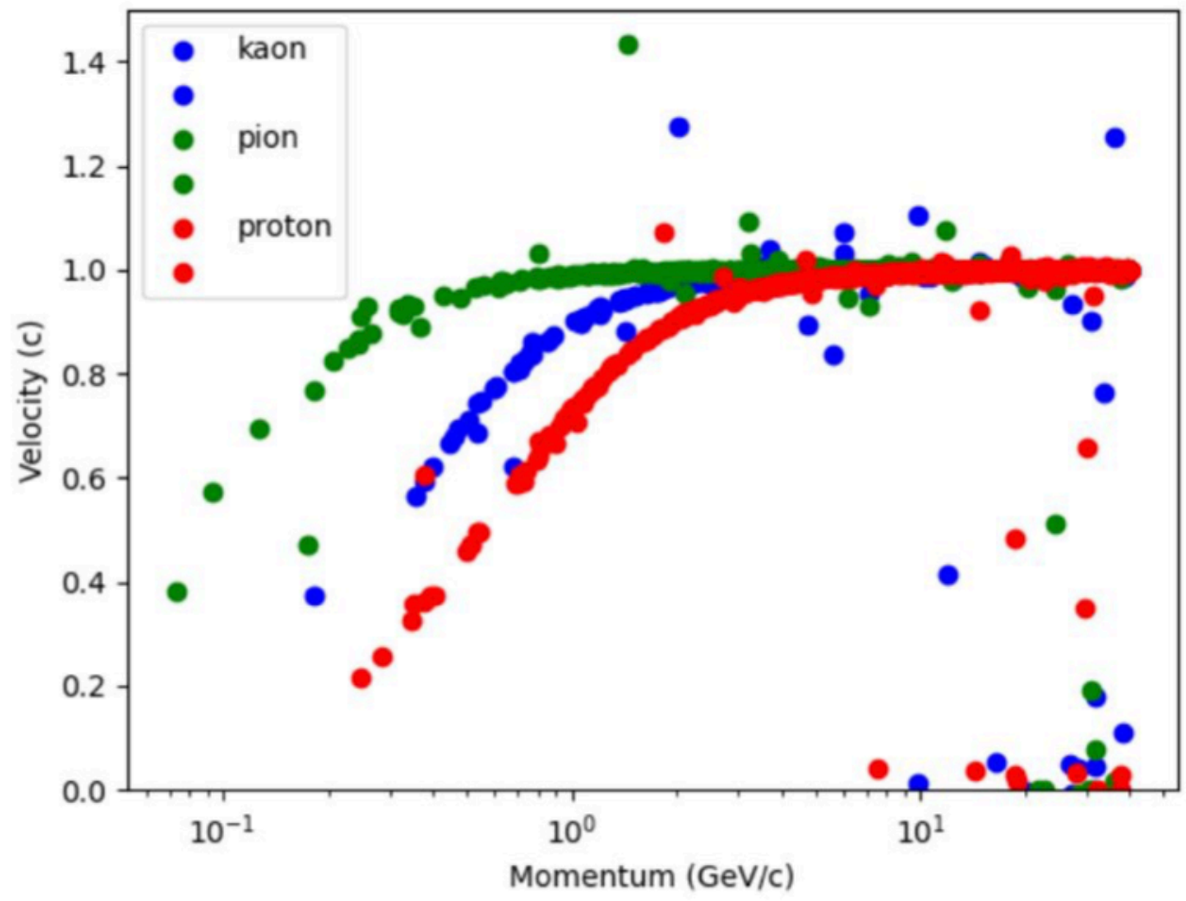




PhD involvement welcome!!

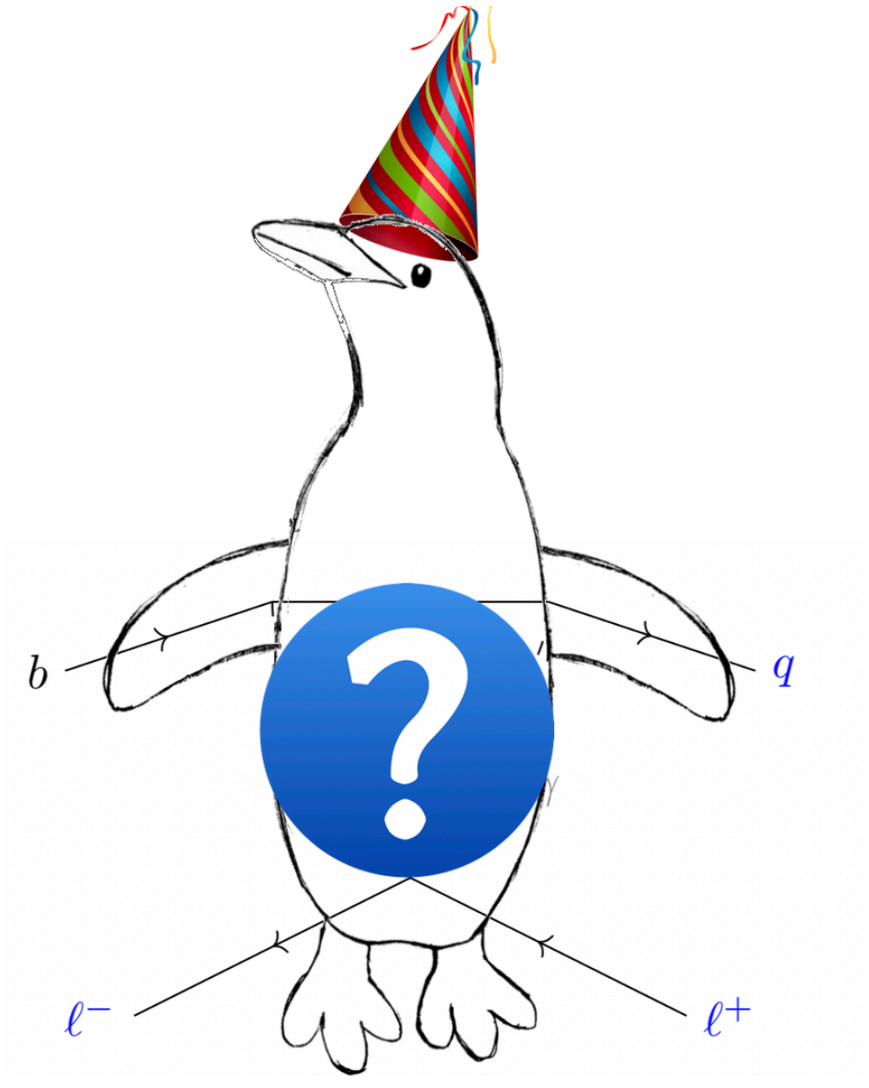
Want to know more?

Drop me an email at
eluned@mit.edu

Drop Anja an email at
anbeck@mit.edu

My office: 24-417

Anja's office: 24-416

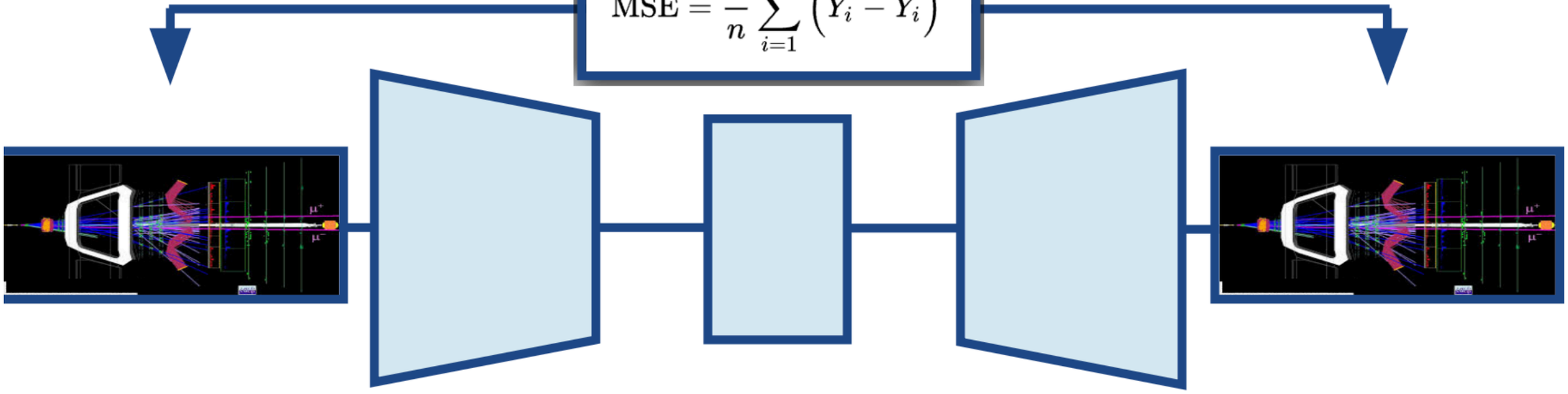


Machine-learning on FPGAs

- *Encode* input in smaller dimensional space 1024 → 4 → 1024
- *Minimize* mean squared error during the autoencoder training to find an optimal configuration of the network weights
- In the past I developed an AE with ***80ns*** latency *Nature Machine Intelligence*

more details

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2$$



Machine-learning on FPGAs

The performance is checked with reco vs original pulse shape on a 100 GeV sample (that was not used for training) → perfect reconstruction of the full pulse shape from 4 floats

Note this using test beam simulation, so no pile up; studies with smaller number of samples ongoing