Rare Decay Measurements and Searches at CMS

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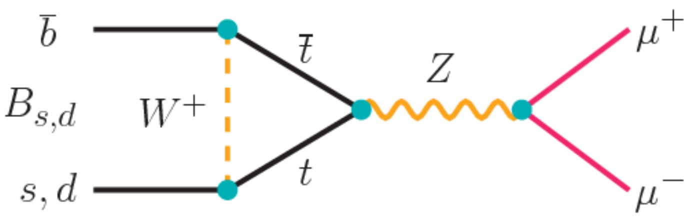
DOE Visit

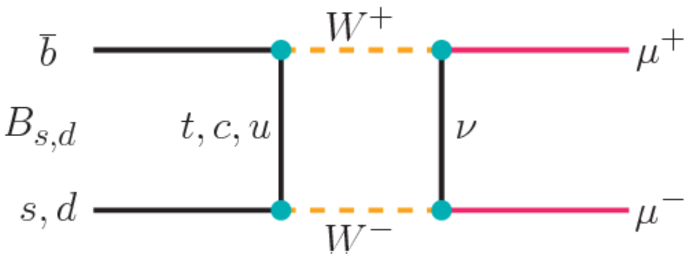
Outline

- Introduction
- Rare Decay Analyses
  - Higgs Rare Decay
  - $B_{(s)} \rightarrow \mu\mu$ Measurements
  - $D \rightarrow \mu\mu$ Search
- Extended Projects
- Conclusion

Introduction

- Rare decay measurement is one of the most promising ways to probe the new physics
  - Rare in the SM prediction, sensitive to New Physics effects
  - Covers higher energy scale compared to the direct search
- The rare decay measurements include Higgs physics and flavor physics at MIT group
  - Higgs rare decay
    - Coupling to light quarks
  - Flavor physics rare decay
    - Flavor-changing neutral current
- Research in rare decay also extends into other projects





Rare Decay Projects

- Leadership in various rare decay measurements

Higgs Physics

Higgs rare decay H → Mγ
- Higgs interactions with light quarks (u, d, s)
- Run 2 CMS Data

Flavor Physics

B rare decays $B_{(s)} \to \mu\mu$
- Run 2 CMS Data
- Constrain B anomaly

D rare decays $D \to \mu\mu$
- Run 3 CMS Data
- new inclusive dimuon trigger
- c->u transition

Run 3 soft Muon ID Development

Run 3 dimuon resonance search (dark photon, 2HDM)

Run 3 $B_{(s)} \to \mu\mu$ measurement

- MIT plays a key role in CMS flavor physics (BPH) and Higgs physics (HIG) group
  - BPH L2 convener: Dmytro Kovalskyi; rare decay L3 convener: Zhangqier Wang
  - HIG to leptons and rare decay L3 convener: Mariarosaria D'Alfonso

Higgs Rare Decay

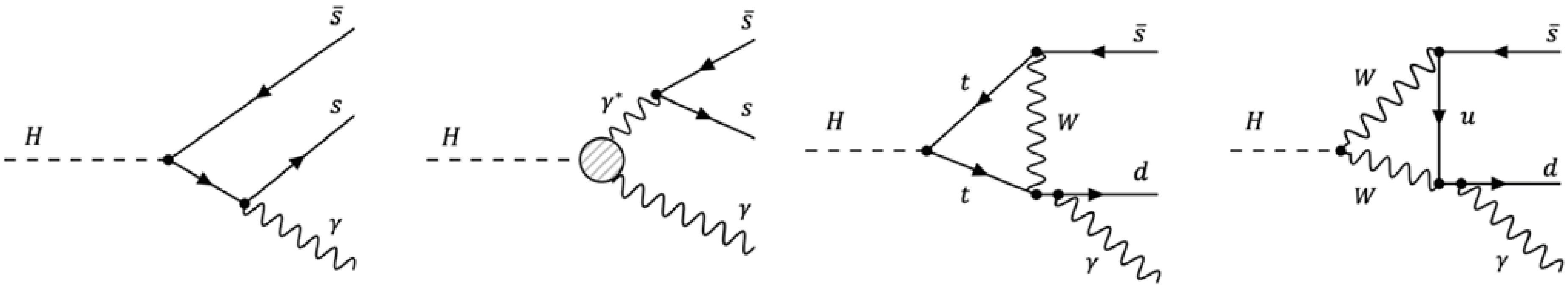
Main force:

Mariarosaria D’Alfonso

Kyungseop (Kevin) Yoon

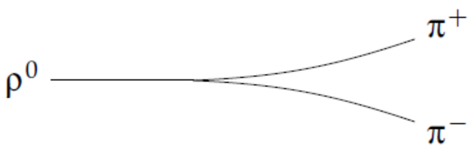
Higgs Rare Decays

- Higgs coupling to light quarks (u, d, s)
  - Suppressed coupling and large QCD background hamper direct searches
  - Class of decays suggested H->Mγ, where M is the light meson
    - Flavor-conserving probes
      - $H \to \rho^0\gamma$: Higgs coupling to u,d-quark
      - $H \to \phi\gamma$: Higgs coupling to s-quark
    - Flavor-changing probe
      - $H \to K^{*0}\gamma$: flavor-changing s and d quarks via weak interaction

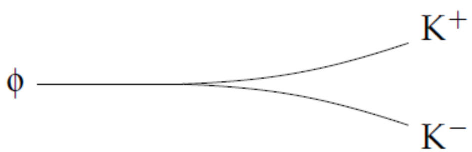


Production and Final States

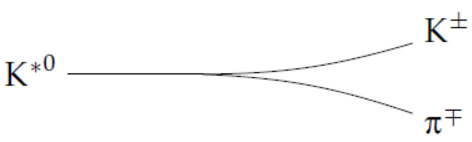
- Final states
  - High energy photon
  - Light meson decays to two hadrons
    - ditrack invariant mass is constrained to be close to meson mass



$\mathcal{BR}(\rho^0 \to \pi^+\pi^-) \sim 100\%$

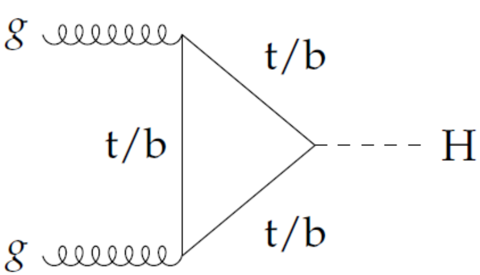


$\mathcal{BR}(\phi \to K^+K^-) \sim 49\%$

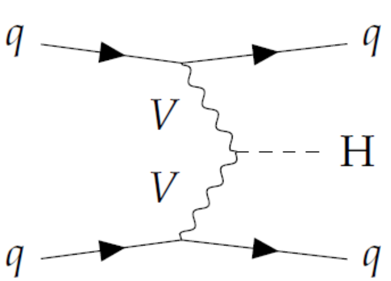


$\mathcal{BR}(K^{*0} \to K^\pm\pi^\mp) \sim 100\%$

- Higgs production categories: different selections for each categories

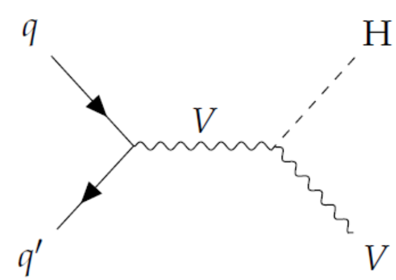


ggH



High-p_T^γ VBF

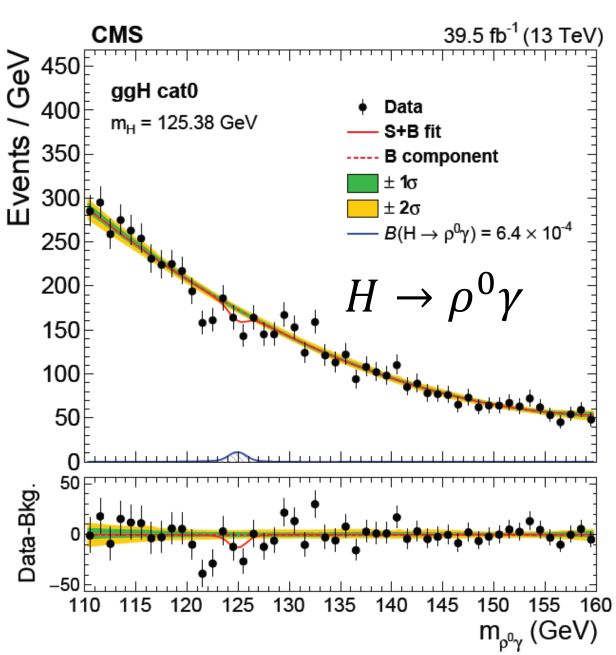
Low-p_T^γ VBF

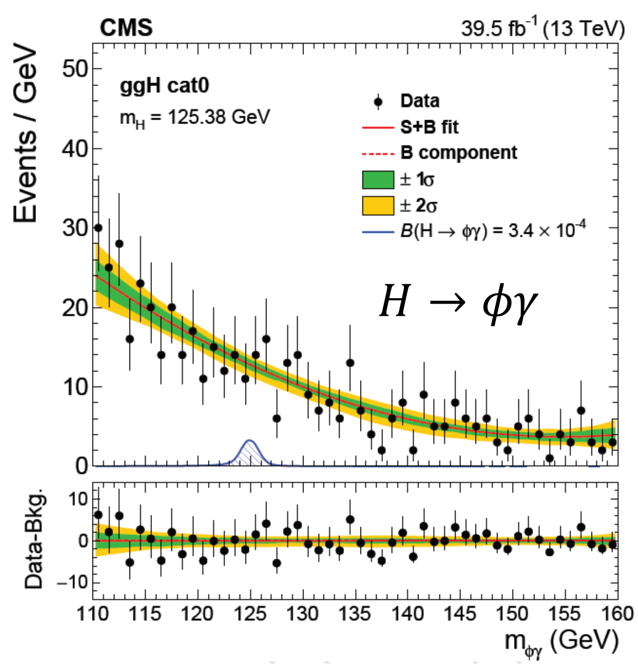


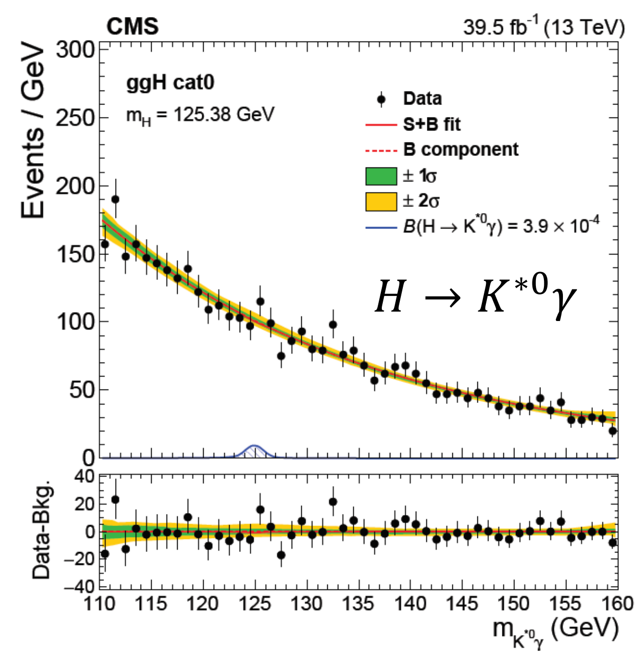
VH ($Z_{ll}H$, $W_{l\nu}H$)

Higgs Mass Projections

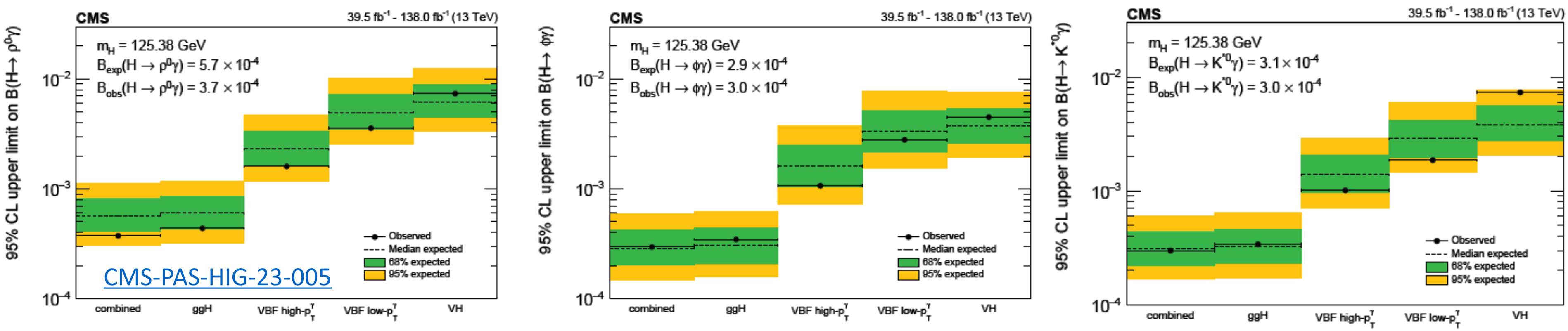
- Dedicated photon + jet with tau-ID trigger deployed in 2018 for the ggH production.
  - Tau-like jet contains ditrack system, similar to light meson
  - Photon pT> 35 GeV, tau-like jet pT > 35 GeV
  - Largely boosted the sensitivity
- Higgs mass reconstructed from photon + ditrack system







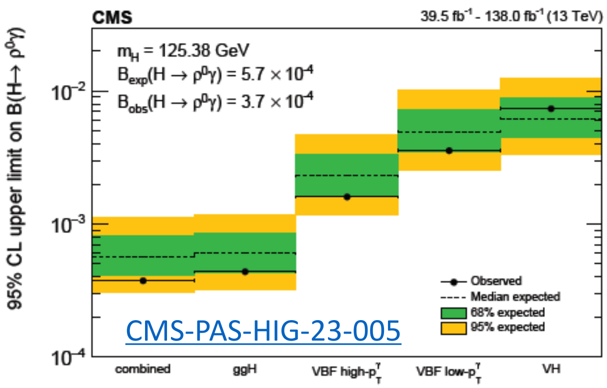
Higgs Rare Decays Result



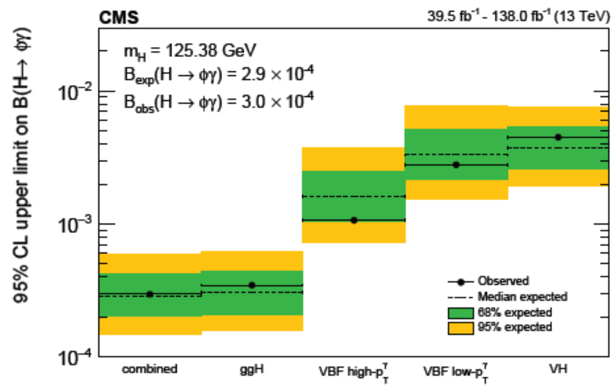
Channel	Coupling	SM prediction	Previous best measurement	This analysis
$H \to \rho^0\gamma$	u, d	$(2.31 \pm 0.11) \times 10^{-6}$	10.4×10^{-4}	$\mathbf{3.74 \times 10^{-4}}$
$H \to \phi\gamma$	s	$(1.68 \pm 0.11) \times 10^{-6}$	5.0×10^{-4}	$\mathbf{2.97 \times 10^{-4}}$
$H \to K^{*0}\gamma$	d,s (flavor-changing)	1.0×10^{-19}	2.2×10^{-4}	$\mathbf{2.99 \times 10^{-4}}$

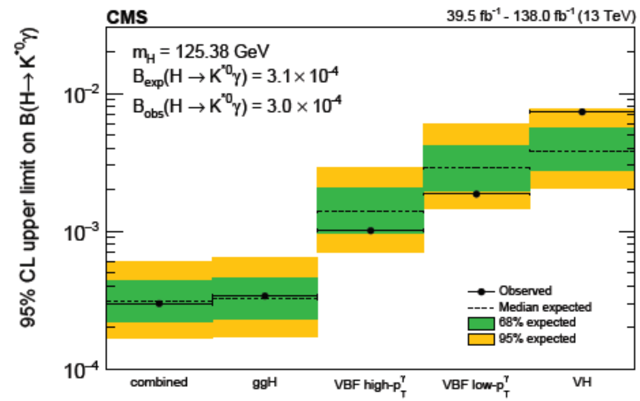
- No significant excess above the background expectations is observed
- Limits for $\rho^0\gamma$ and $\phi\gamma$ channels are the most stringent experimental limits to date
- New projects in Higgs rare decay: H->D*+γ, H → cc̄+ J/ψ

Higgs Rare Decays Result



[CMS-PAS-HIG-23-005]





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$H \to \phi\gamma$	s	$(1.68 \pm 0.11) \times 10^{-6}$	$5.0 \times$	
$H \to K^{*0}\gamma$	d,s (flavor-changing)	1.0×10^{-19}	$2.2 \times$	

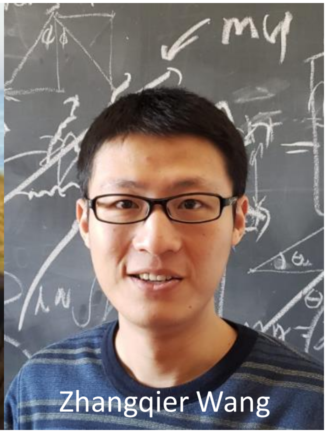
Visiting student (ETH)

Martí Pedemonte i Bernat

- No significant excess above the background expectatio
- Limits for $\rho^0\gamma$ and $\phi\gamma$ channels are the most stringent e o date
- New projects in Higgs rare decay: H->D*+γ, H → cc̄+ J/ψ

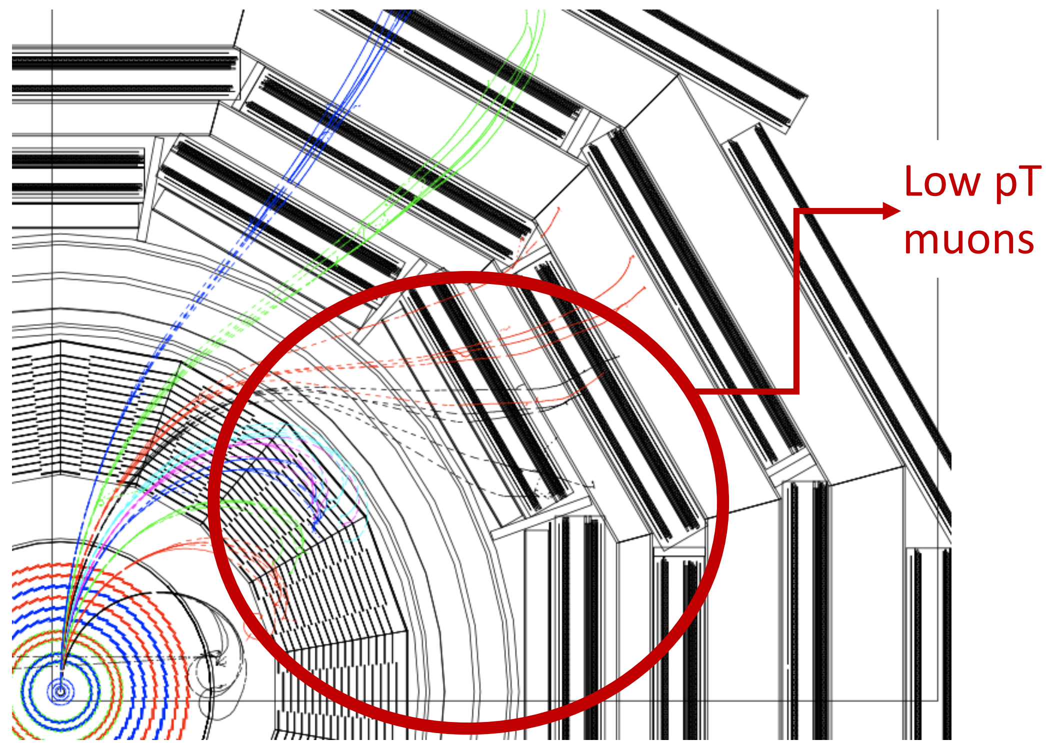
Flavor Physics Rare Decays

Main force:



Rare Decays in Flavor Physics

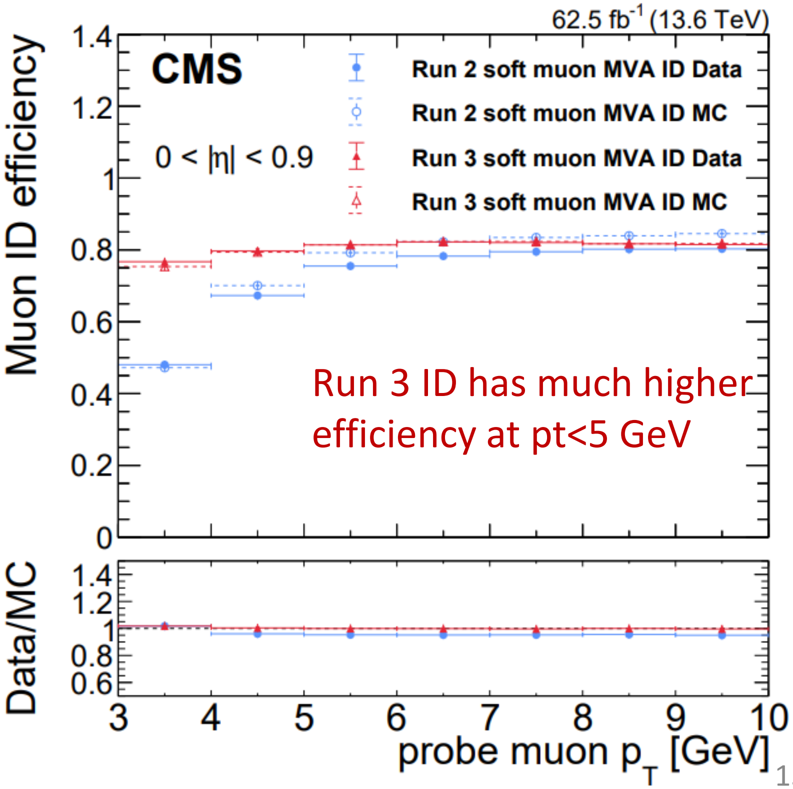
- Rare decay in the flavor physics involves muons with much lower pT compared to general analysis.
- MIT has a long history in the muon activities
  - Dmytro was the convener of the CMS Muon POG 2017-2019
  - Re-write the muon reconstruction algorithm for improvements
- Stay at the frontier of the muon related development
  - New muon identification
  - New muon triggers



Run 3 soft Muon ID

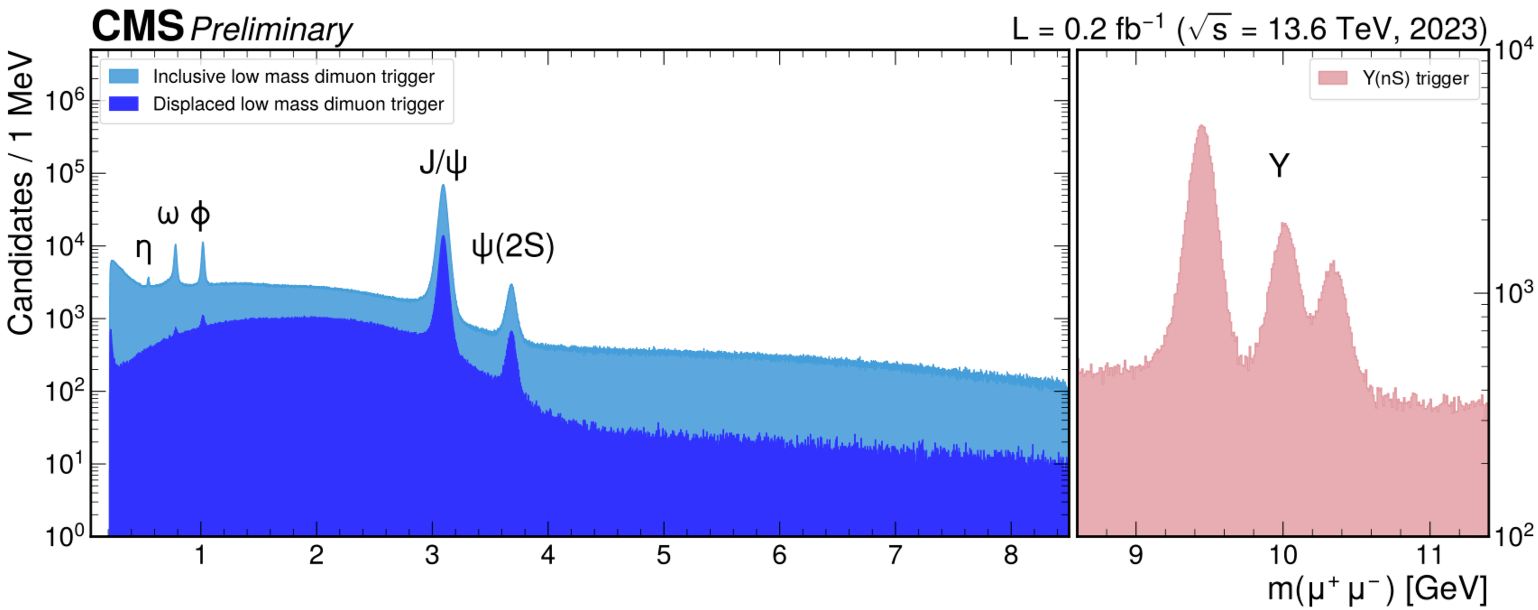
- We encountered important backgrounds from **fake muons** in rare decay searches in flavor physics
- Identifying soft muons is crucial for many physics programs at CMS
  - Fake muon backgrounds may bias the signal extraction

- Developed a MVA identification for the Run 3 soft muons
- Much better performance compared to Run 2 ID for 2022-2023 data
- The analysis is approved, entering CWR now



Inclusive Dimuon Trigger

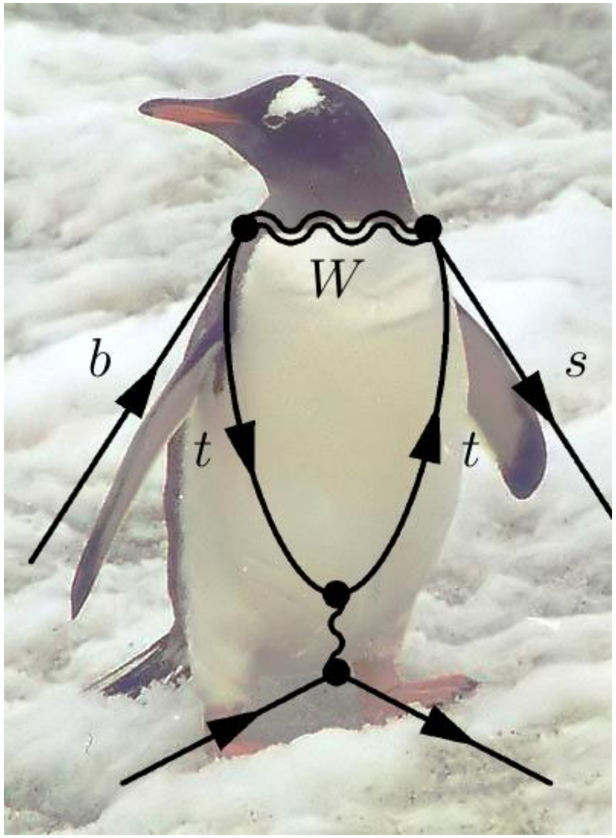
- Inclusive dimuon trigger developed using **parking** technique.
  - Expands the CMS flavor program beyond its original design.
  - Development driven by MIT group
- It covers mass range below 8.5 GeV, which will lead to many new publications.
  - Including the $D \to \mu\mu$ search



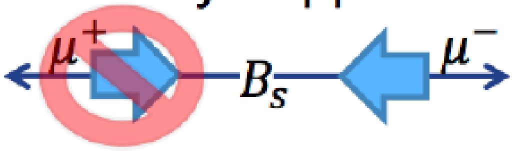
$B_{(s)} \to \mu\mu$ Measurements

Why $B_{(s)} \to \mu\mu$?

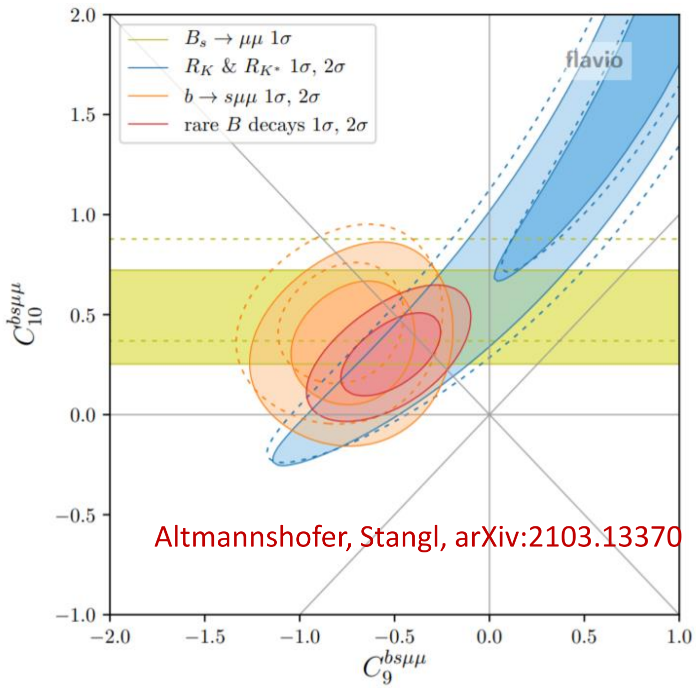
- B(s)->$\mu\mu$: meson composed of b-quark + d(s)-quark
- Rare decay in Standard Model
  - Strongly helicity suppressed
  - CKM suppression
- Standard Model prediction
  - $B_s \to \mu\mu$: $(3.66 \pm 0.14) \times 10^{-9}$
  - $B^0 \to \mu\mu$: $(1.03 \pm 0.05) \times 10^{-10}$
- Unique rare b→sℓℓ process
  - Sensitive to New Physics effects
  - Only $B_{s,H}$ meson decays into dimuon
  - Shares dominant contributions with B→K(*)ℓℓ
    - Where discrepancies from the SM are observed

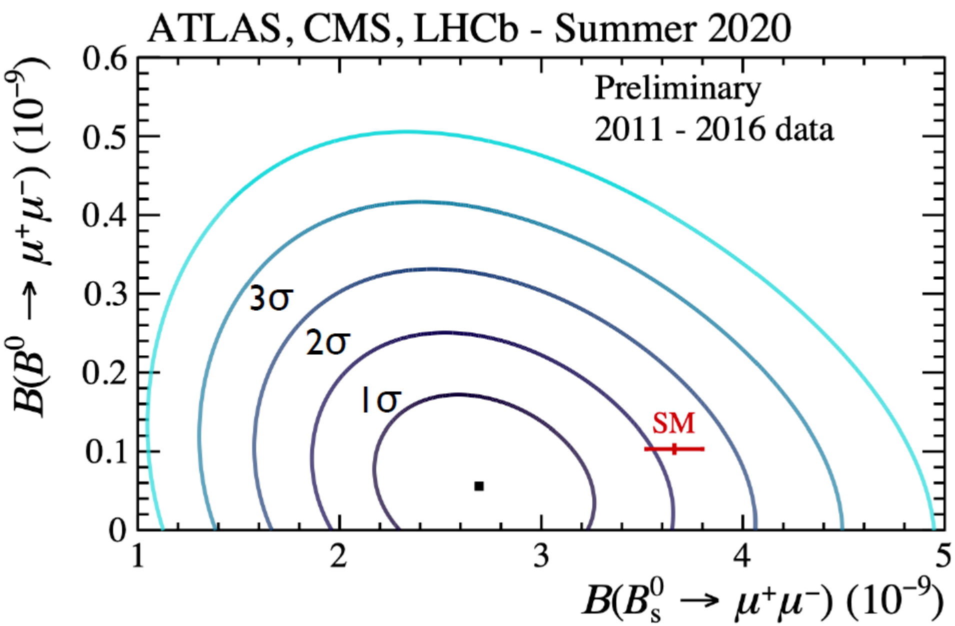


Helicity Suppressed



Rare B Decay Anomalies

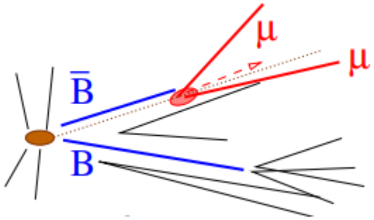




- Multiple discrepancies are observed in rare B decays
  - 2-3σ anomalies in branching ratios and angular observables
- Description with the Wilson coefficients C9 and C10 of the vector and pseudo-vector operators O9 and O10 in the effective 4-fermion interaction
  - Only O10 operator contributes to B(s)→μμ
  - B(s)->μμ had about 2.6σ tension from SM prediction.

$B_{(s)} \to \mu\mu$ Analysis Strategy

- Using full CMS Run 2 data, we aim to measure
  - $B_s \to \mu\mu$ branching fraction and lifetime
  - Search for $B^0 \to \mu\mu$



- The signal branching fractions are normalized using $B \to J/\psi K$ and $B_s \to J/\psi\varphi$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \times \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \times \frac{\epsilon_{B^+ \to J/\psi K^+}}{\epsilon_{B_s^0 \to \mu^+\mu^-}} \times \frac{f_u}{f_s}$$

External B production fraction ratio

$$or \left\{ = \mathcal{B}(B_s^0 \to J/\psi\phi) \times \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B_s^0 \to J/\psi\phi}} \times \frac{\epsilon_{B_s^0 \to J/\psi\phi}}{\epsilon_{B_s^0 \to \mu^+\mu^-}} \right\}$$

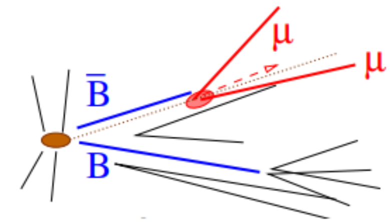
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \times \frac{N_{B^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \times \frac{\epsilon_{B^+ \to J/\psi K^+}}{\epsilon_{B^0 \to \mu^+\mu^-}} \times \frac{f_u}{f_d}$$

=1

- Allow the first order cancellation of most systematics
- $B \to J/\psi K$ normalization is the primary result, $B_s \to J/\psi\varphi$ is the alternative normalization

$B_{(s)} \to \mu\mu$ Analysis Strategy

- Using full CMS Run 2 data, we aim to measure
  - $B_s \to \mu\mu$ branching fraction and lifetime
  - Search for $B^0 \to \mu\mu$



- The signal branching fractions are normalized using $B \to J/\psi K$ and $B_s \to J/\psi\varphi$

$\mathcal{B}(B^0_s \to \mu^+$ ... $\times \frac{f_u}{f_s}$

External B production fraction ratio

$\mathcal{B}(B^0 \to \mu^+$ ... $\times \frac{f_u}{f_d}$ =1

Starting the **fs/fu** measurement using Run 3 data with the new muon trigger

- Aim to extend lower Pt and better precision

Visiting student from CIEMAT working on it

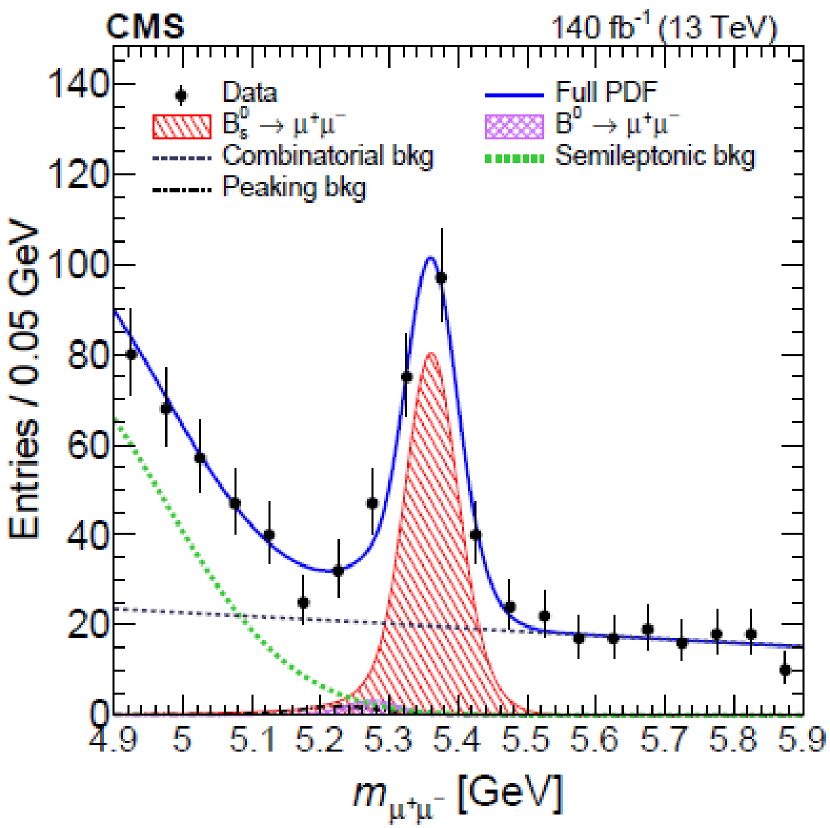
Cecilia Maria Morcillo Perez

- Allow the first order cancellation of most systematics
- $B \to J/\psi K$ normalization is the primary result, $B_s \to J/\psi\varphi$ is the alternative normalization

Unbinned ML Fit

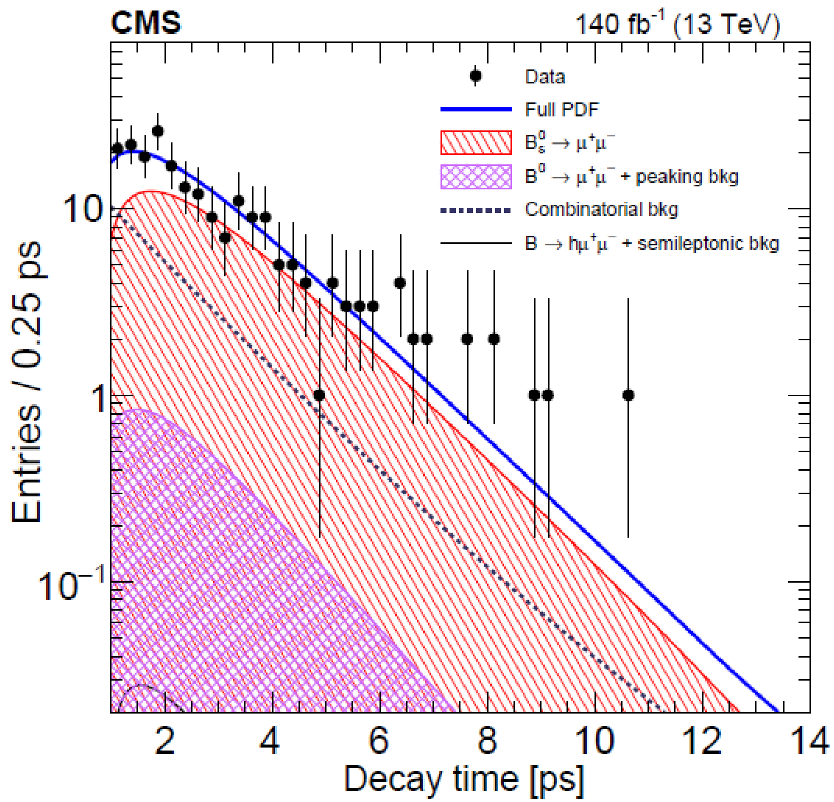
- 2D fit for branching fraction
  - Mass, mass uncertainty

$$P(m_{\mu\mu}, \sigma_{m_{\mu\mu}}) = P(m_{\mu\mu}; \sigma_{m_{\mu\mu}})P(\sigma_{m_{\mu\mu}}/m_{\mu\mu})$$



- 3D fit for lifetime
  - Mass, decay time, decay time uncertainty

$$P(m_{\mu\mu}, t, \sigma_t) = P(m_{\mu\mu})P(t|\sigma_t)P(\sigma_t)$$

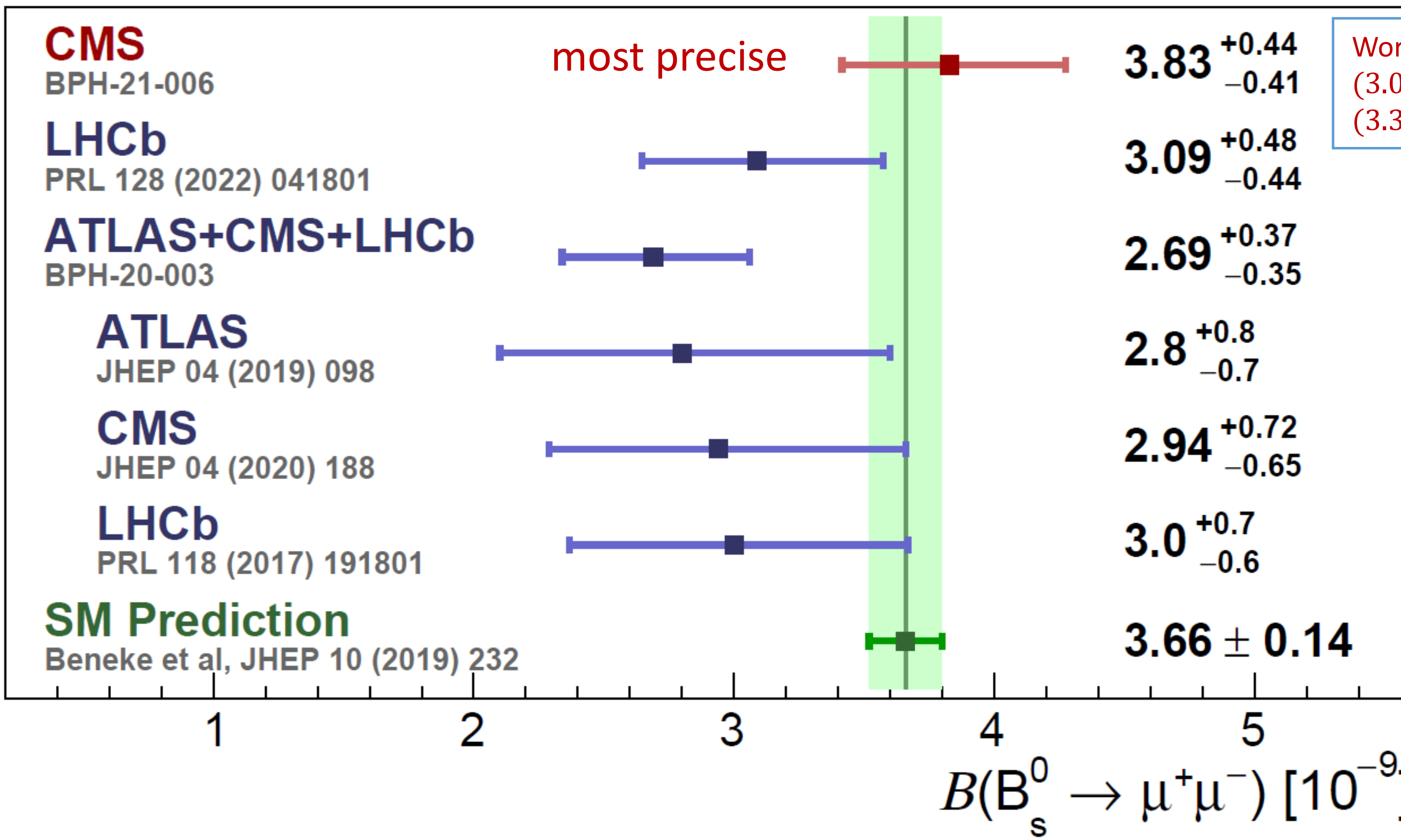


Signal region [5.28, 5.48] GeV

$B_s \to \mu\mu$ BF Results

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\text{stat})\ ^{+0.19}_{-0.16}\ (\text{syst})\ ^{+0.14}_{-0.13}\ (f_s/f_u)\right] \times 10^{-9}$$

Alternative normalization ($B_s^0 \to J/\psi\varphi$) $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.95^{+0.39}_{-0.37}\ (\text{stat})\ ^{+0.27}_{-0.22}\ (\text{syst})\ ^{+0.21}_{-0.19}\ (\text{BF})\right] \times 10^{-9}$

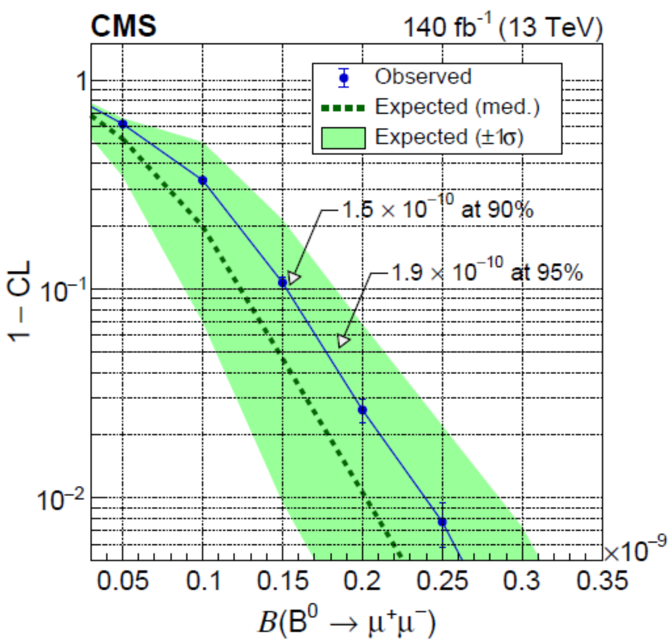


World average (PDG)
$(3.01 \pm 0.35) \times 10^{-9}$ (2023)
$(3.34 \pm 0.27) \times 10^{-9}$ (2024)

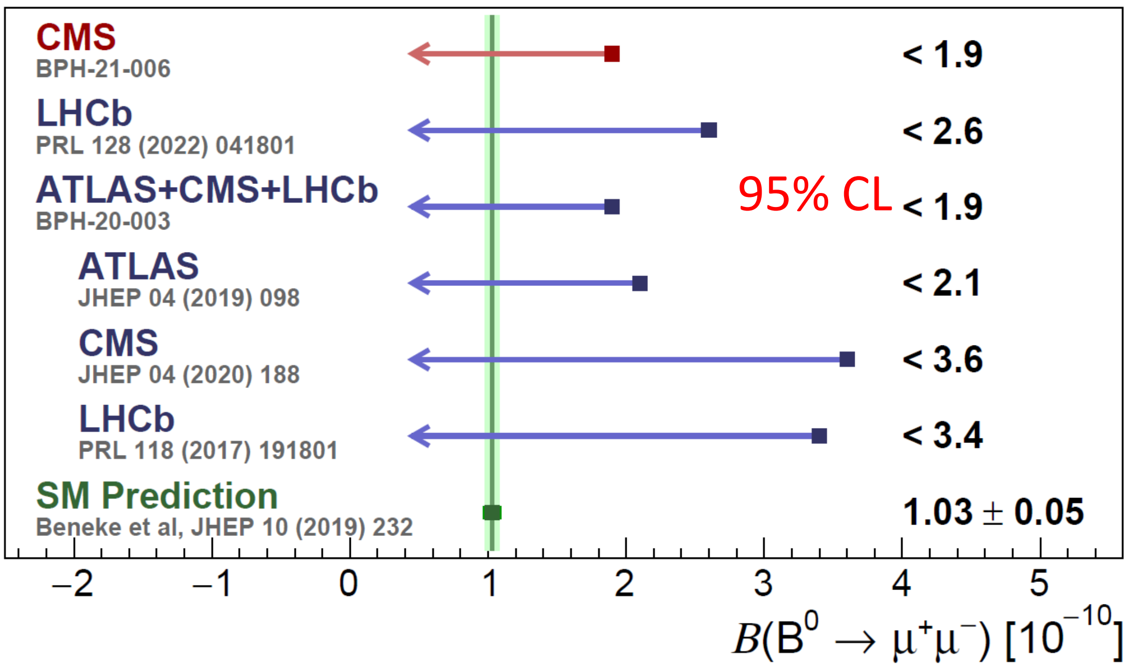
$B^0 \to \mu\mu$ BF Comparison

$$\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\ (\mathrm{stat})\ ^{+0.08}_{-0.09}\ (\mathrm{syst})\right] \times 10^{-10}$$

- The main challenge with $B^0 \to \mu\mu$ is the combinatorial background.
- It will require more data and analysis improvements to reach discovery level.
- CLs result: $\mathfrak{B}(B^0 \to \mu\mu) < 1.9 \times 10^{-10}$ (95% CL)



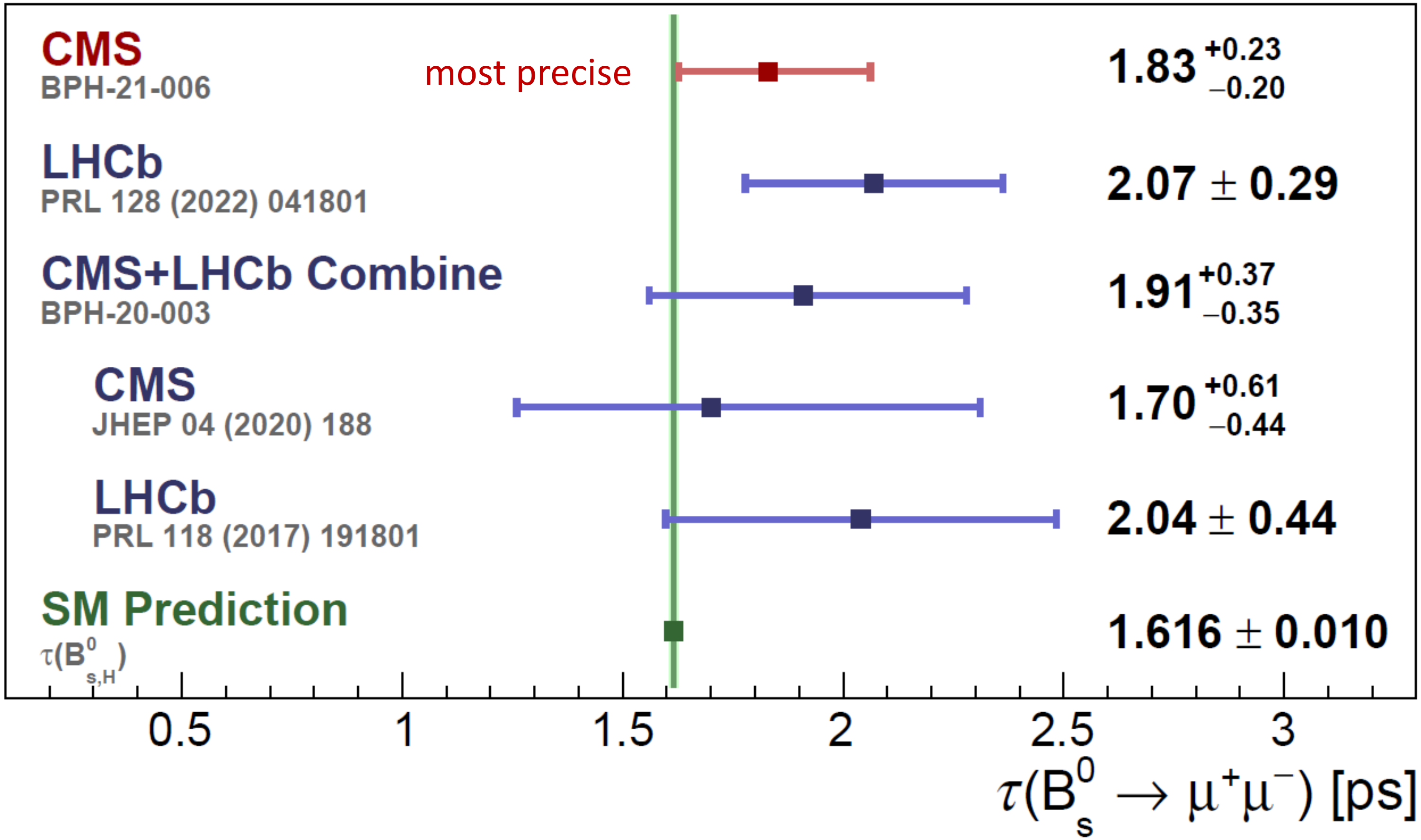
most stringent



Effective Lifetime Result

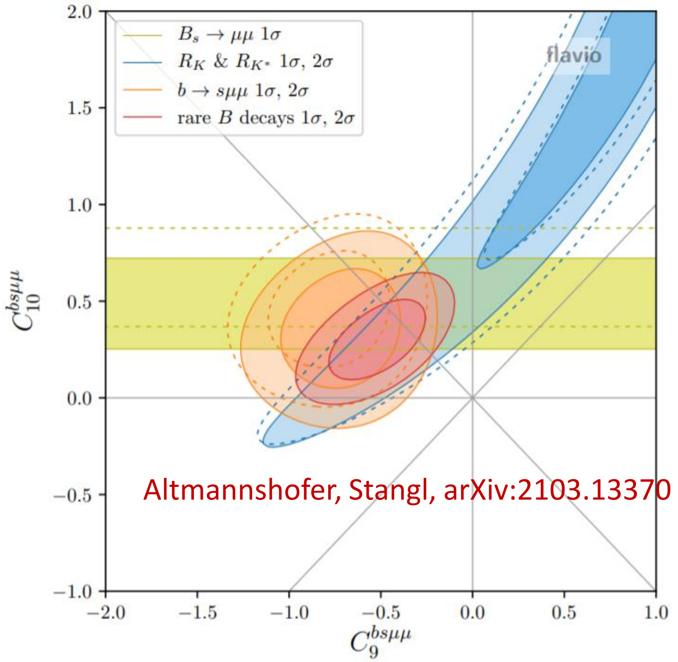
$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\text{ ps}$$

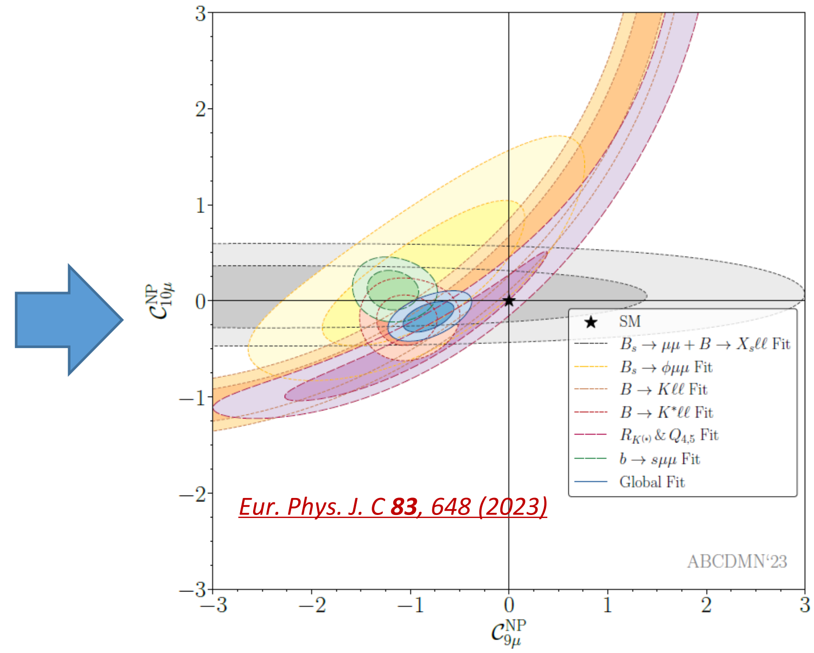
$\tau(B_{s,L}) = 1.429\ ps$
$\tau(B_{s,H}) = 1.622\ ps$
PDG2024



Impacts of $B \to \mu\mu$ Results

- Result Published in July 2023: Phys. Lett. B **842** (2023) 137955
- Relative uncertainty on BF(Bs→μμ) has been reduced from 23% to 11%.
  - The best single measurement to date, highly compatible with SM prediction
- The B(s)→μμ measurements indicate that the abnormally comes from vector leptonic coupling.





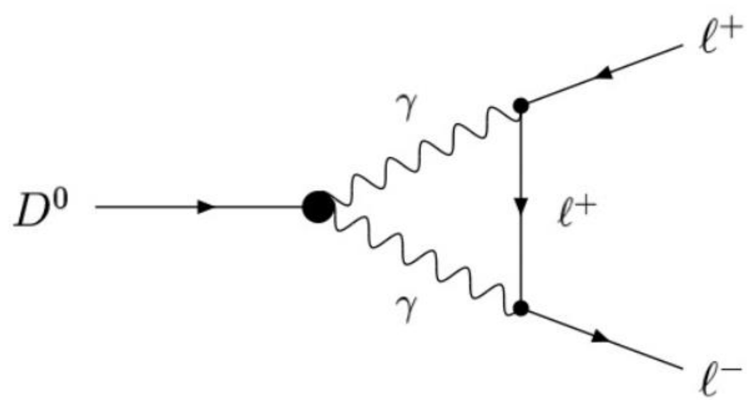
Staring Run 3 analysis: expect significant improvements, maybe first discovery of $B^0 \to \mu\mu$

$D \rightarrow \mu\mu$ Search

Rare Charm Decay

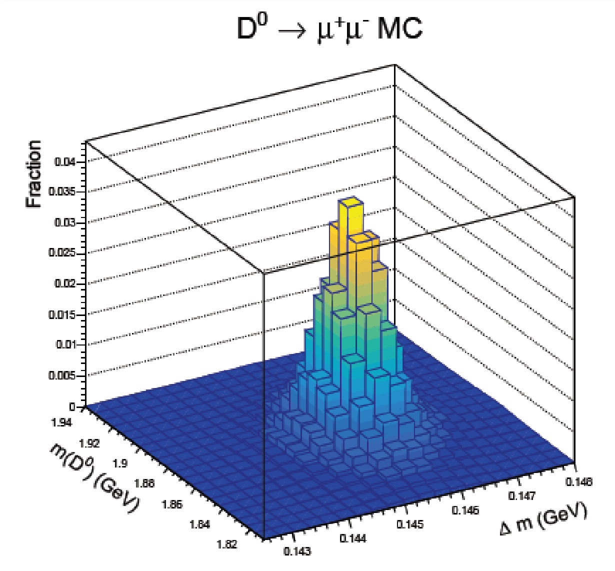
- Seach for $D^0 \rightarrow \mu\mu$ and measure its branching fraction
- The decay proceeds under charm sector FCNC, highly suppressed in SM
  - SM Prediction: BF($D^0 \rightarrow \mu\mu$) > $\sim 3 \times 10^{-13}$ (Long distance)
- Rare charm decays mediated by "c → u" transition, which is less studied, comparing to "b → s".

- It is an **unexplored area**.
  - Not discovered yet
  - Most stringent experimental search BF < 3.5×10^{-9} @95 CL (from LHCb), 4 orders of magnitude to SM
- A better result is made possible by the new Run 3 inclusive dimuon trigger.



$D \to \mu\mu$ Analysis Strategy

- **Data Used:** 2022—2023 CMS Data
- Search for cascade decay: $D^{*+} \to D^0\pi^+, D^0 \to \mu\mu$.
  - **Two independent observables – 2D Fit**
    - **m(D^0):** reconstructed D0 mass from dimuon
    - $\Delta m = m(D^*) - m(D^0)$



- Normalization method used

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) = \mathcal{B}(\mathrm{D}^0 \to \pi^+\pi^-)\frac{N_{\mathrm{D}^0\to\mu^+\mu^-}}{N_{\mathrm{D}^0\to\pi^+\pi^-}}\frac{\varepsilon_{\mathrm{D}^0\to\pi^+\pi^-}}{\varepsilon_{\mathrm{D}^0\to\mu^+\mu^-}}$$

Signal channel
$D^{*+} \to D^0\pi^+, D^0 \to \mu\mu$
Final states: 2μ + soft pion
Trigger: inclusive dimuon trigger

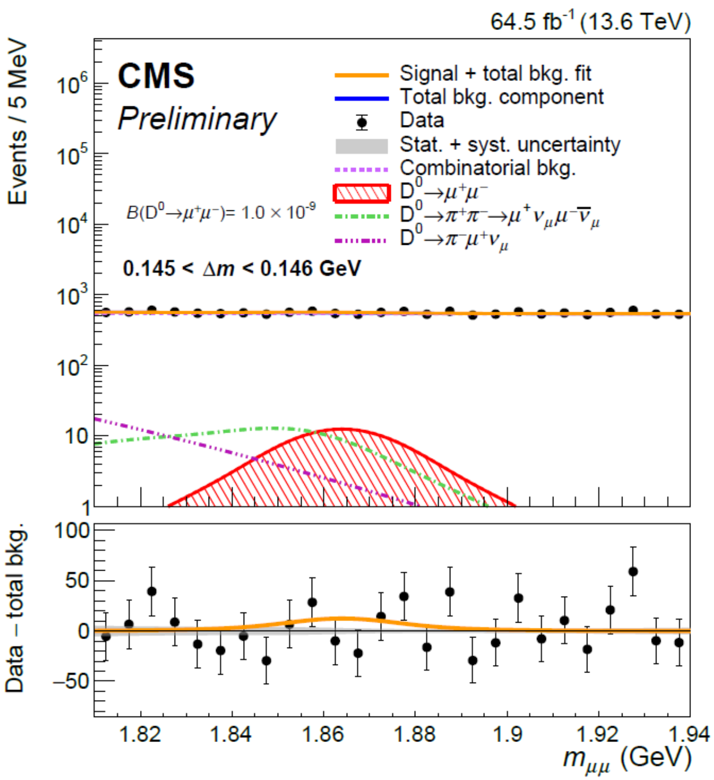
Nominal normalization channel
$D^{*+} \to D^0\pi^+, D^0 \to \pi^+\pi^-$
Final states: $2h$+ soft pion
Close kinematics with $D^0 \to \mu\mu$

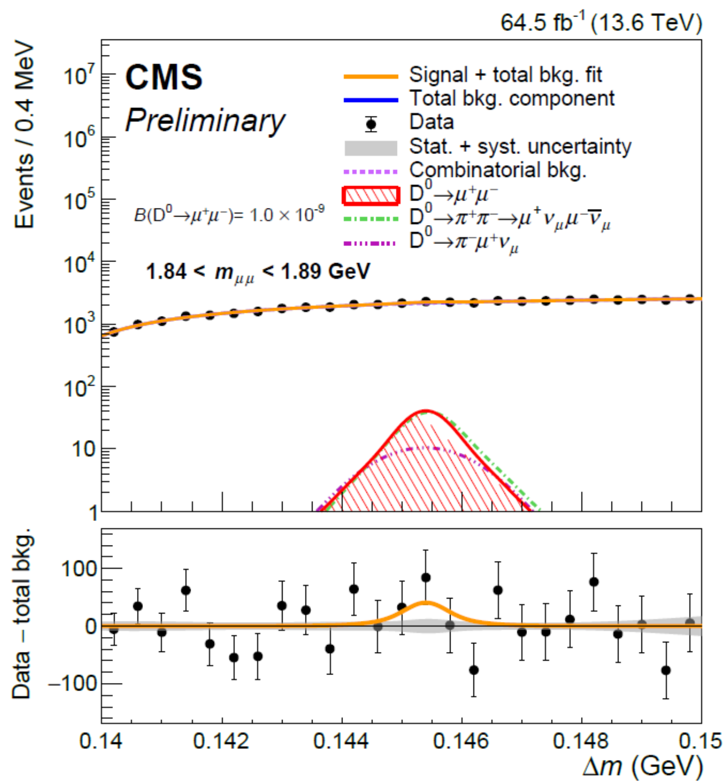
- 2D UML fit to extract the yield from $D^0 \to \mu\mu$ and $D^0 \to \pi^+\pi^-$

$D^0 \to \mu\mu$ Branching Fraction

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) < 2.6 \times 10^{-9} \text{ at 95\% confidence level}$$

- The likelihood distribution of $D^0 \to \mu\mu$
  - Central value $\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) = (1.0 \pm 0.9) \times 10^{-9}$





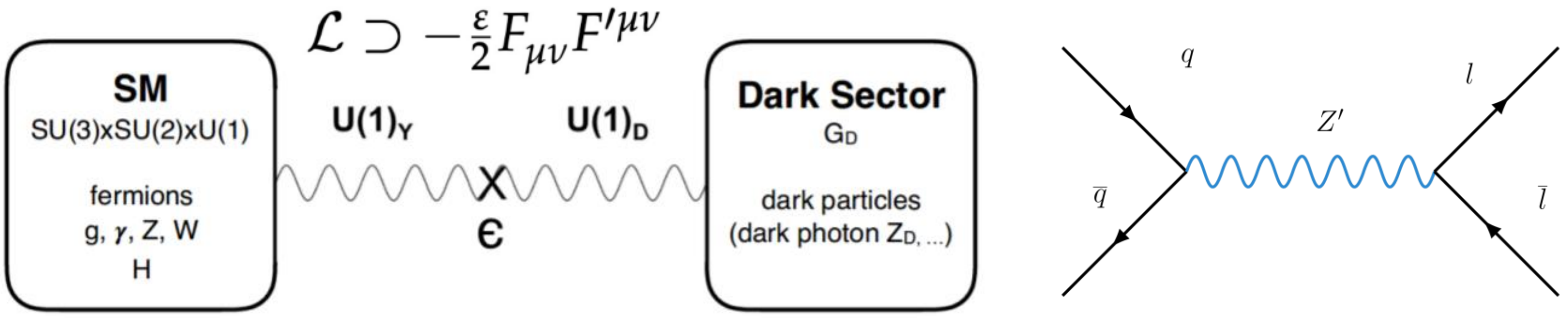
$D^0 \rightarrow \mu\mu$ Summary

- The **first publication** of the BF($D^0 \rightarrow \mu\mu$) by the CMS experiment
  - No significant excess was observed.
  - $BF < 2.6 \times 10^{-9}$ @ 95% CL, improved by 35% over the previous world's best measurement
  - Most stringent limit on charm sector FCNC
- **First Run 3 result** using the inclusive dimuon triggers (parking trigger)
  - Demonstrates the benefits of this trigger for flavor physics measurements
  - Show its potential to open up opportunities for a wide range of studies involving low-mass dimuons
- The analysis was a highlight in 2024 ICHEP
- It will soon be in CWR, expected to be published in a few months.

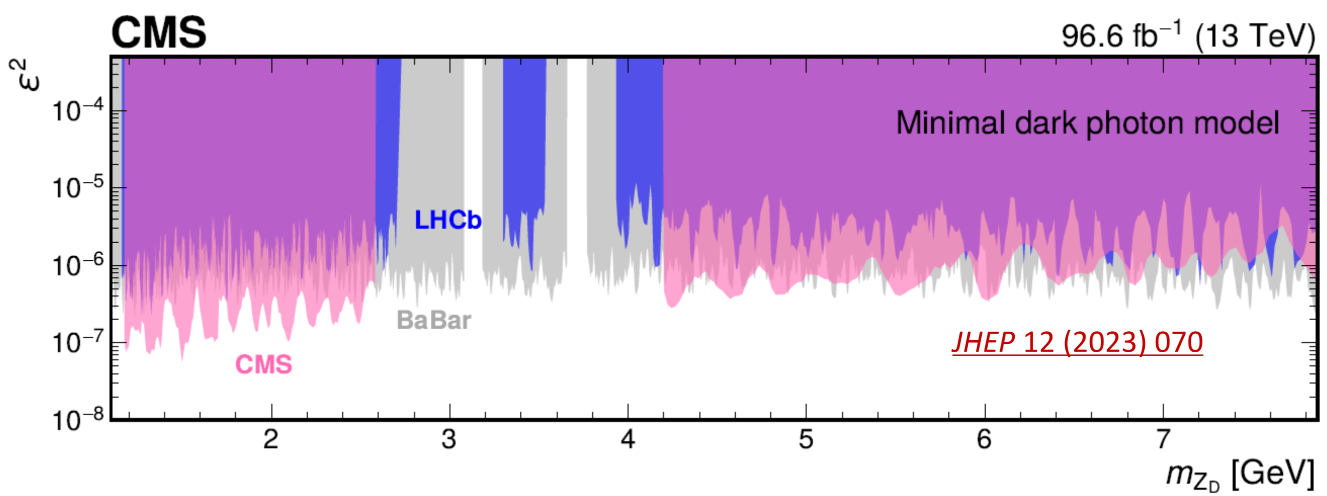
Extended Projects

GeV-Scale Dimuon Resonance

- New states at the GeV scale are motivated from several perspectives.
  - Vector portal interaction in thermal dark matter models



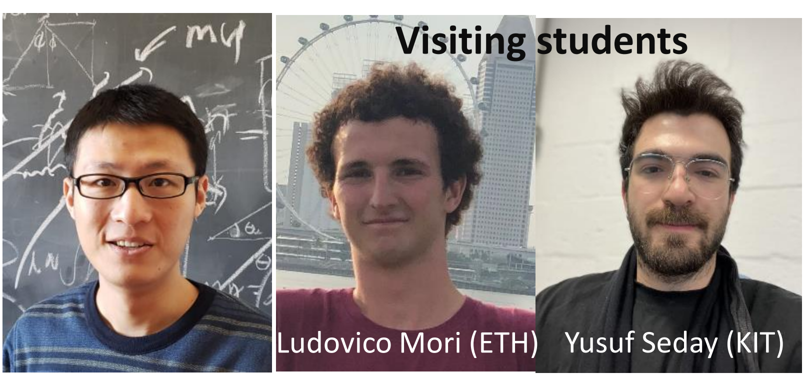
- MIT group has conducted Run 2 search using scouting trigger, leading to the most sensitive probe in such region.

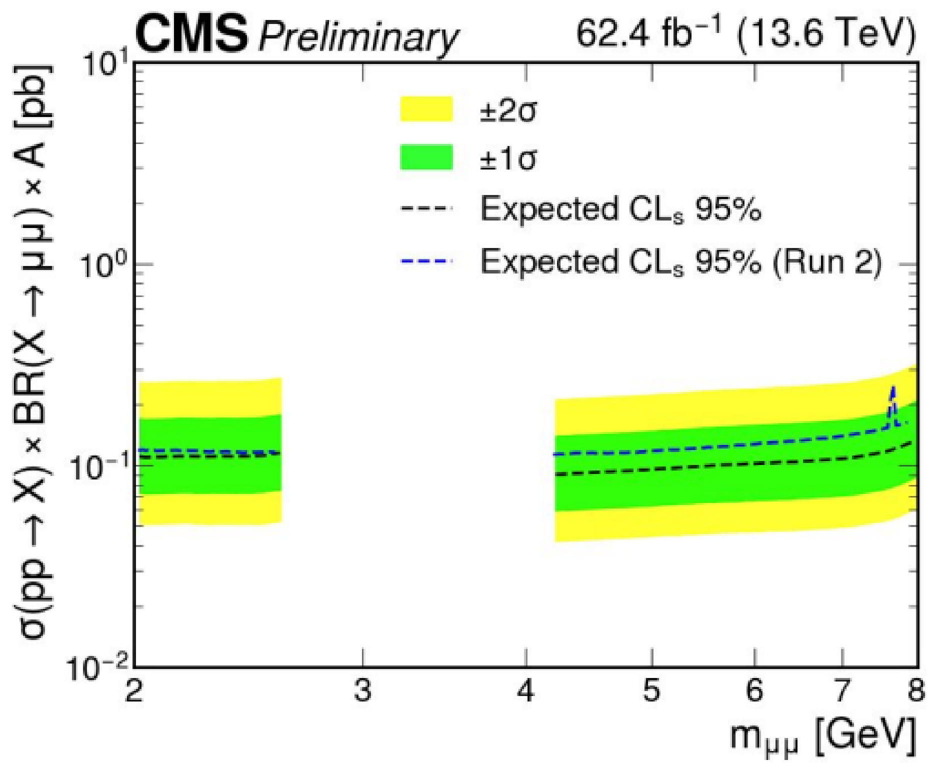


Run 3 Dark Photon Search

- With the new **inclusive dimuon trigger** in Run 3, we expect to achieve a much better performance in the dark photon search.
- Preliminary study has done on 2022-2023 data, which already gives 20% improvements

- Starting the Run 3 analysis using 2022-2024 data.
- **Expected to double the sensitivity**.





Conclusion

- MIT group has led and provided major contributions to various rare decay projects.
  - Run 2 Higgs rare decays sets most stringent limits in H->Mγ decays
  - Run 2 $B \to \mu\mu$ analysis achieves the most precise single measurements in BF and lifetime
  - Run 3 $D \to \mu\mu$ search yields the most sensitivity constrains on the charm sector FCNC.
- Key contribution to the Run 3 inclusive dimuon trigger that expends CMS physics programs involved with low pT muons.
- Developed Run 3 soft muon ID to benefit flavor physics programs.
- Several new analyses on going
  - Dark photon search using new inclusive dimuon trigger
  - Run 2 + Run 3 Higgs rare decay in more decay channels
  - $B \to \mu\mu$ analysis using Run 3 data

The End

Back up

Triggers for Higgs Rare Decay

- High-level trigger
  - Three types of triggers used for different production mode.

Tau-like trigger

Photon + jets with τ-ID
$\rightarrow$ **ggH, low-p_T^γ VBF**

- Photon $p_T^\gamma > 35$ GeV + tau-like jet $p_T^j > 35$ GeV.
- Tau-leg similar to isolated di-track system.
- Luminosity: $39.50\ \mathrm{fb}^{-1}$ (2018).

VBF-dedicated trigger

High-p_T^γ photon + VBF-like jets
$\rightarrow$ **high-p_T^γ VBF**

- Photon $p_T^\gamma > 75$ GeV + di-jet with large M_{jj} and $\Delta\eta_{jj}$.
- Active partly during 2016-17 and fully during 2018.
- Luminosities: $28.2\ \mathrm{fb}^{-1}$ (2016), $7.7\ \mathrm{fb}^{-1}$ (2017), $60\ \mathrm{fb}^{-1}$ (2018).

Leptonic trigger

Double or single lepton
$\rightarrow$ **VH**

- Single or double-muon (electron) lowest p_T thresholds vary depending on year.
- To complement selection, triggers requiring a lepton and a photon is also used.
- Luminosity: $138\ \mathrm{fb}^{-1}$ (2018).

Events Selection

- Photon

	ggH	High-p_T^γ VBF	Low-p_T^γ VBF	VH
p_T^γ [GeV]	> 38	> 75	$38 < p_T^\gamma < 75$	> 40
$\lvert\eta^\gamma\rvert$	< 2.1	< 1.4	< 2.1	< 2.5
γ-ID signal eff.	80%	90%	80%	90%

- Ditrack system

Track selection

- Originate from PV.
- Pass "high purity" criteria.

Meson definition

- Pair of oppositely charged tracks.
- $p_T > 5$ GeV, $|\eta| < 2.5$.
- At least one track $p_T > 20$ GeV.

Invariant mass

- Di-track system invariant **mass windows and sidebands** (next slide).
- $K^\pm \pi^\mp$ system: if both combinations exist, then the one closest to $m_{K^{*0}}$ is selected.
- Reject events where m_{KK} consistent with $m_{\pi\pi} / m_{K\pi}$ and have higher p_T, vice versa.

Additional isolation requirements are applied afterwards

Higgs Rare Decay Selection

	Common selections			
M selection	2 "high-purity" tracks, opposite charge $\lvert\eta^{\mathrm{trk}}\rvert < 2.5$, $p_{\mathrm{T}}^{\mathrm{trk1}} > 20$ GeV, $p_{\mathrm{T}}^{\mathrm{trk2}} > 5$ GeV, $\lvert\eta^{\mathrm{M}}\rvert < 2.1$ $0.62 < m_{\pi\pi} < 0.92$ GeV (ρ^0) / $1.008 < m_{\mathrm{KK}} < 1.032$ GeV (ϕ) / $0.84 < m_{\mathrm{K}\pi} < 0.94$ GeV (K^{*0})			
Category	ggH	VBF high-p_{T}^{γ}	VBF low-p_{T}^{γ}	VH
Integrated luminosity	39.5 fb^{-1}	86.9 fb^{-1}	39.5 fb^{-1}	138 fb^{-1}
Trigger	Photon + jet with τ-ID	High-p_{T} photon + VBF-like jets	Photon + jet with τ-ID	Double or single lepton
p_{T}^{γ} [GeV]	> 38	> 75	> 38 and < 75	> 40
$\lvert\eta^{\gamma}\rvert$	< 2.5	< 1.4	< 2.1	< 2.5
γ-ID (signal eff.)	80%	90%	80%	90%
$p_{\mathrm{T}}^{\mathrm{M}}$ [GeV]	> 38	> 30	> 38	> 40
$I^{\mathrm{ch}}(\mathrm{M})$	> 0.9	> 0.9	> 0.9	> 0.8
$I^{\mathrm{neu}}(\mathrm{M})$	> 0.8	—	—	—
Event tagging	Meson candidate within a jet with $p_{\mathrm{T}}^{\mathrm{j}} > 40$ GeV, tracks with $\Delta R < 0.07$	2 jets with $p_{\mathrm{T}}^{\mathrm{j}} > 40$ GeV, $m_{\mathrm{jj}} > 400$ GeV, $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 3$	2 jets with $p_{\mathrm{T}}^{\mathrm{j}} > 30/20$ GeV, $m_{\mathrm{jj}} > 300$ GeV, $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 3$	1 selected and isolated e/μ or 2 selected e/μ compatible with Z mass
Veto	Lepton veto, VBF-like jets veto	Lepton veto	Lepton veto	—
	BDT categories			
cat0	BDT> 0.55	BDT> 0.7	BDT> 0.7	—
cat1	$-0.4 <$BDT< 0.55	$-0.6 <$BDT< 0.7	$-0.6 <$BDT< 0.7	—

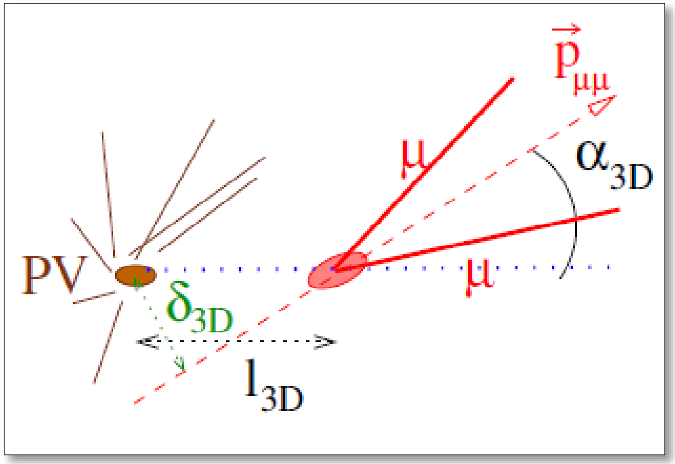
Bmm Preselections

Selection	$B_s^0 \to \mu^+\mu^-$	$B^+ \to J/\psi K^+$	$B_s^0 \to J/\psi\phi$
B candidate mass [GeV]	[4.90,5.90]	[4.90,5.90]	[4.90,5.90]
Blinding window [GeV]	[5.15,5.50]		
$p_{T\mu}$ [GeV]	> 4	> 4	> 4
$\lvert\eta_\mu\rvert$	< 1.4	< 1.4	< 1.4
3D SV displacement significance	> 6	> 4	> 4
$p_{T\mu\mu}$ [GeV]	> 5	> 7	> 7
$\mu\mu$ SV probability	> 0.025	> 0.1	> 0.1
J/ψ candidate mass [GeV]		[2.9,3.3]	[2.9,3.3]
Kaon p_T [GeV]		> 1	> 1
Mass-constrained fit probability		> 0.025	> 0.025
2D $\mu\mu$ pointing angle [rad]		< 0.4	< 0.4
ϕ candidate mass [GeV]			[1.01, 1.03]

- Selection requirements are as loose as possible
  - Provide more data to MultiVariate Analysis (MVA)
  - Limited by trigger requirements
- Normalization channel selection is optimized to match kinematics of signal
- Employ “data blinding” technique to avoid unconscious bias

Multivariate Analysis (MVA)

- Backgrounds have larger pointing angle, low-quality secondary vertex (SV) fit, worse isolation.

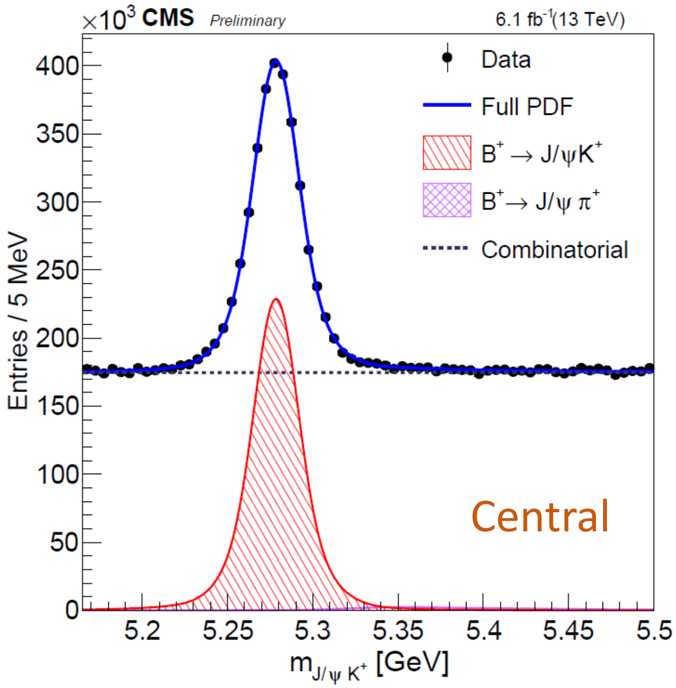


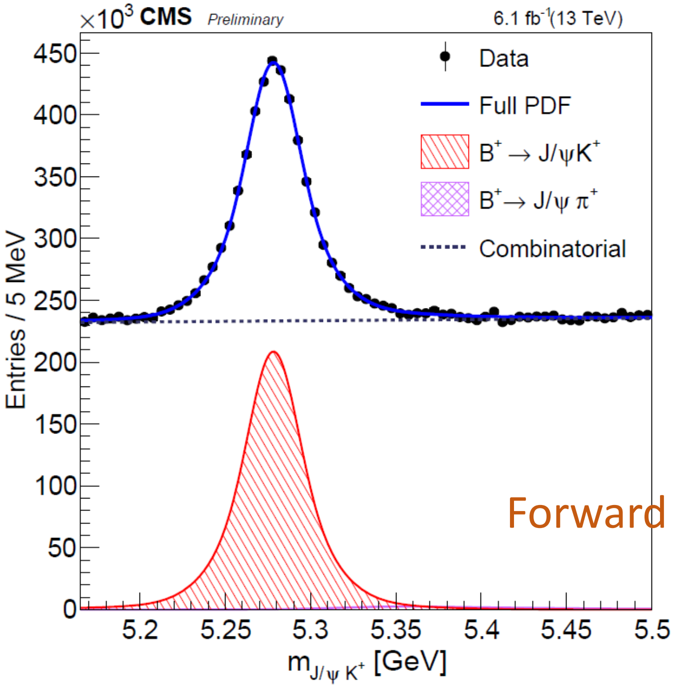
- Main observables to distinguish the signal
  - Pointing angles: α_{3D}, α_{2D}
  - Impact parameter and its significance
    - $\delta_{3D}, \delta_{3D}/\sigma(\delta_{3D})$
  - Flight length significance: $l_{3D}/\sigma(l_{3D})$
  - Isolation of B candidate and muons
  - Dimuon vertex quality

- New MVA used to select the B meson and suppress the backgrounds, labelled as $\mathrm{MVA_b}$.
  - XGBoost package (advanced gradient boosting algorithm).
  - Training sample:
    - Signal: $B_{(s)} \rightarrow \mu\mu$ MC
    - Background: data sidebands [4.9, 5.1], [5.5, 5.9] GeV

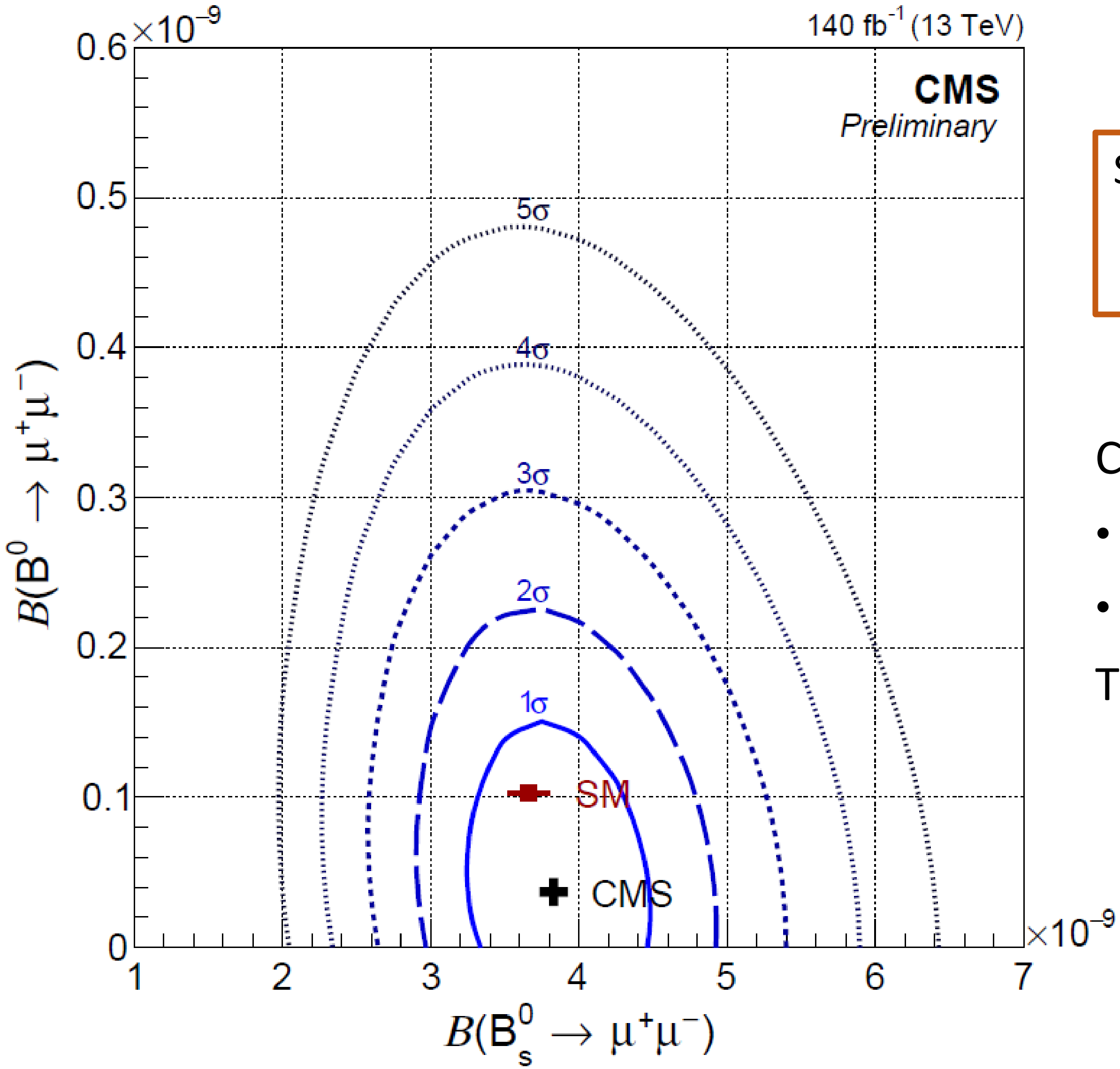
$B^+ \to J/\psi K^+$ Yield Fits

- $B^+ \to J/\psi K^+$ normalization yield are directly used for signal normalization.
  - Nominal model is built using analytical functions
    - $B^+ \to J/\psi K^+$: CB+2 Gaussian with same mean
  - Alternative is using non-parametric signal model convolved with a resolution model
- The difference between the two estimates is taken as systematics (1%)





2D Contour Plot



SM Value:
$\mathfrak{B}(B_s \to \mu\mu) = 3.66 \times 10^{-9}$
$\mathfrak{B}(B^0 \to \mu\mu) = 1.03 \times 10^{-10}$

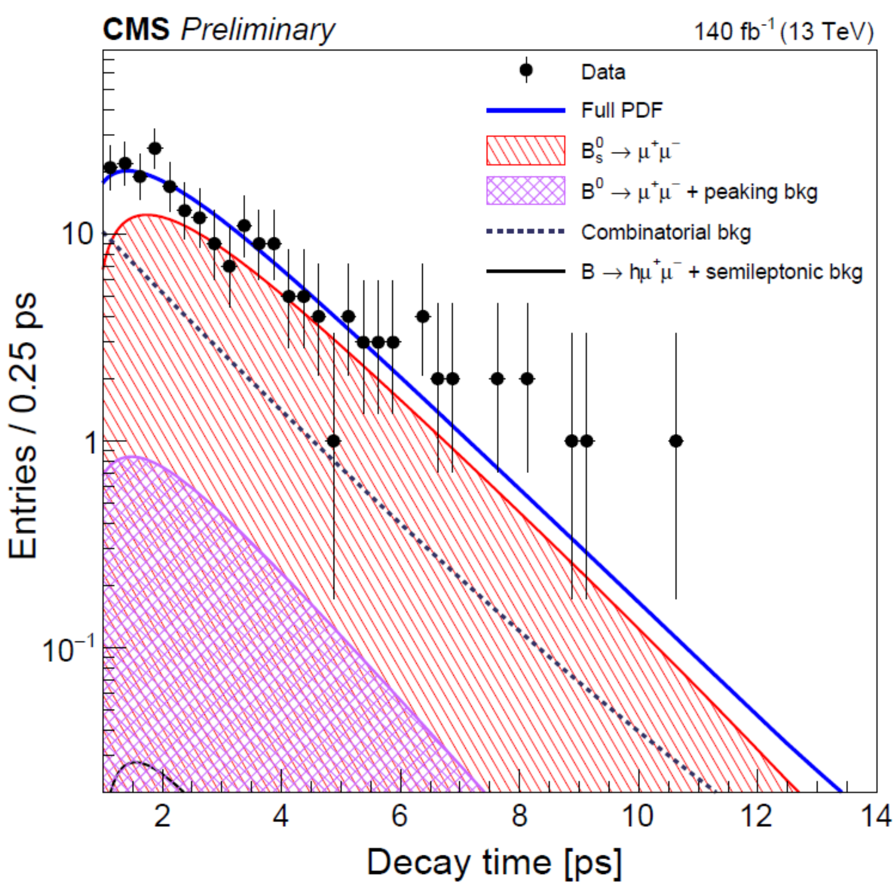
CMS measurement

- $\mathfrak{B}(B_s \to \mu\mu) = 3.83 \times 10^{-9}$
- $\mathfrak{B}(B^0 \to \mu\mu) = 0.37 \times 10^{-10}$

The SM value within one sigma

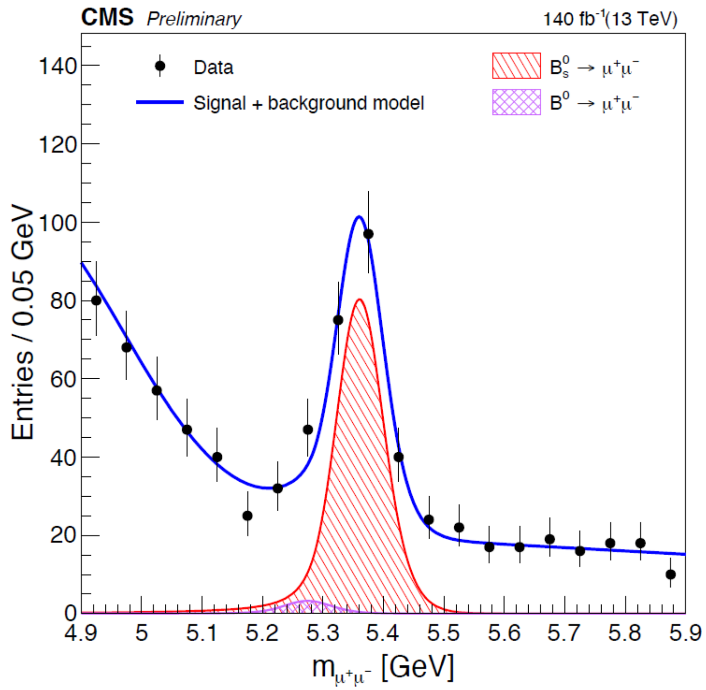
Lifetime Measurement

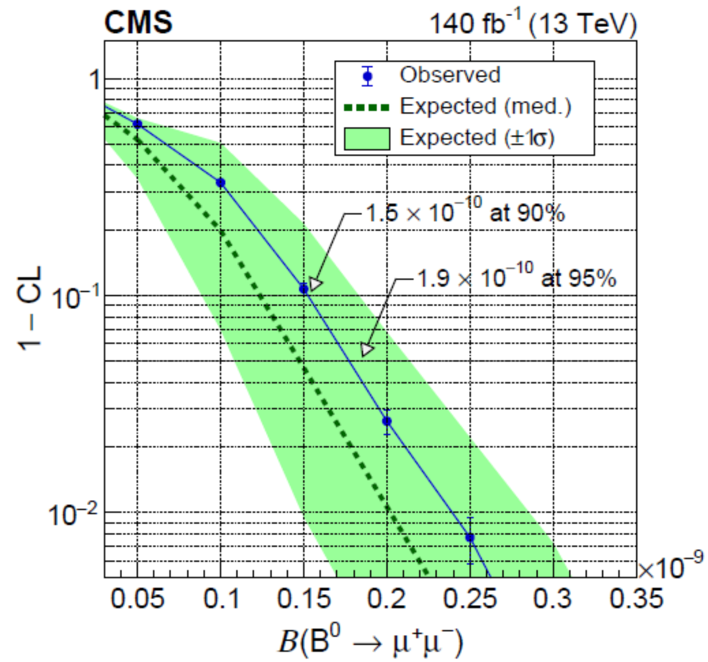
Signal region [5.28, 5.48] GeV



- In the absence of CP violation only the heavy B_s state decays into dimuon
  - Different composition of states may be allowed by New Physics.
- Use UML fit of the $m_{\mu\mu}$, decay time t, decay time uncertainty to measure $B_s \to \mu\mu$ lifetime.
  - $P = P(m)P(t|\sigma_t)P(\sigma_t)$
- Perform the same UML fit on the $B^+ \to J/\psi K^+$
  - With constructed signal-like $\mathrm{MVA_b}$
  - To derive the correction and validate the procedure

$B^0 \to \mu\mu$ BF Results





$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\ (\text{stat})\ ^{+0.08}_{-0.09}\ (\text{syst})\right] \times 10^{-10}$$

- The main challenge with $B^0 \to \mu\mu$ is the combinatorial background
- Observed (expected) significance is 0.5 (1.71) σ
  - It will require more data and analysis improvements to reach discovery level.
- CLs result:
  - $\mathfrak{B}(B^0 \to \mu\mu) < 1.9 \times 10^{-10}$ (95% CL)

Signal Normalization

- **Normalization Channel:** $D^0 \rightarrow \pi^+\pi^-$ decay, which has close kinematics with $D^0 \rightarrow \mu\mu$.
- Find the normalization yields, N(normalization).
  - 2-D fit in ZeroBias Dataset, find the fitting yields.
  - N(normalization) = N(ZeroBias Fitting) x ZeroBias Prescaling
- **Main Equation:**

$$\mathcal{B}(\mathrm{D}^0 \rightarrow \mu^+\mu^-) = \mathcal{B}(\mathrm{D}^0 \rightarrow \pi^+\pi^-)\frac{N_{\mathrm{D}^0\rightarrow\mu^+\mu^-}}{N_{\mathrm{D}^0\rightarrow\pi^+\pi^-}}\frac{\varepsilon_{\mathrm{D}^0\rightarrow\pi^+\pi^-}}{\varepsilon_{\mathrm{D}^0\rightarrow\mu^+\mu^-}}$$

  - $\varepsilon = \varepsilon_{Acc.} \times \varepsilon_{Reco.}$ is total efficiency from the MC.
  - N_{mode} is the normalization of the corresponding decay mode of data fit.
- It allows the first order cancellation of most systematics
- Also used to normalize peaking and semileptonic background.
- Alternative normalization channel $D^0 \rightarrow K^+\pi^-$ is used for cross-check
  - No obvious improvements from the statistical advantage from this channel

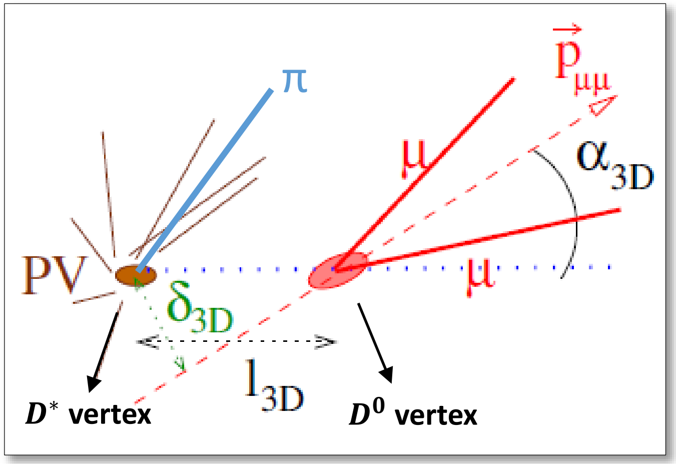
Dmm Candidate Selections

Preselection: reconstruction of $D^*(D^0 \to \mu\mu)$ and $D^*(D^0 \to \pi^+\pi^-)$ candidates

- Muon Selection
  - pT > 4, |η|<2.4
  - highPurity inner track
  - isLooseMuon
  - isTracker && isGlobal
- Pion/Kaon Selection
  - charged PFCandidate
  - pT > 4, |η|<2.4
  - highPurity inner track

Vertexing

- Soft pion compatible with PV
- PV is refitted with soft pion

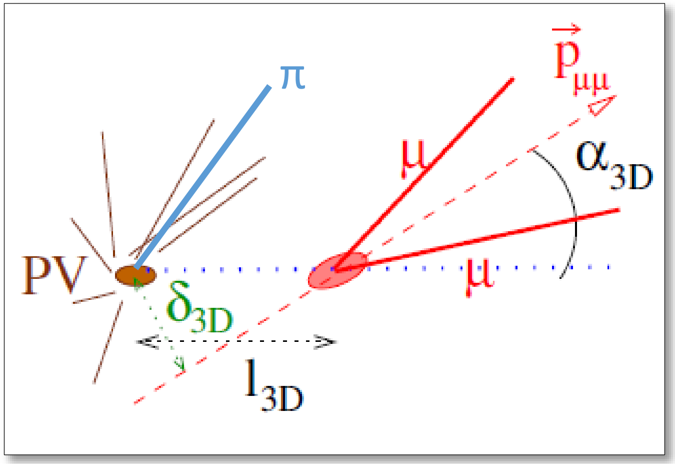


Baseline selection

- Trigger:
  - HLT_DoubleMu4_3_LowMass for signal
  - HLT_ZeroBias for normalization
- $m(D^0) \in [1.81, 1.94]$ GeV
- $\Delta m \in [0.14, 0.15]$ GeV
- Pointing angle $\alpha_{3D} < 0.1$
- D^0 vertex probability > 0.01
- D^* vertex probability > 0.1
- Flight length significance $l_{3D} / \sigma(l_{3D}) > 3$

Multivariate Analysis (MVA)

- Backgrounds have larger pointing angle, low-quality vertex fit. The pion is not as soft as the signal.

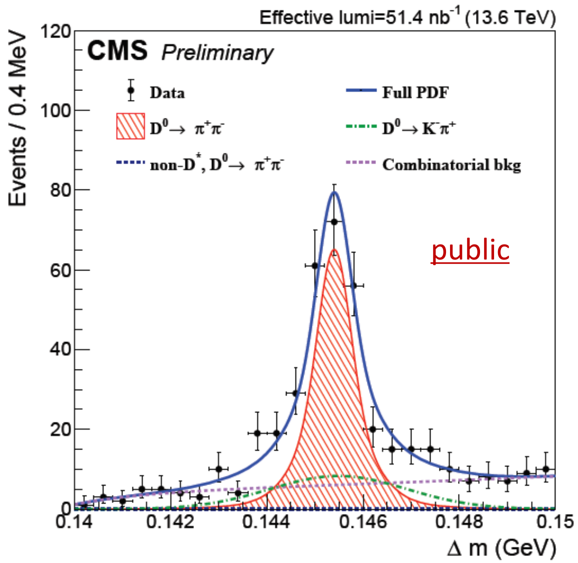


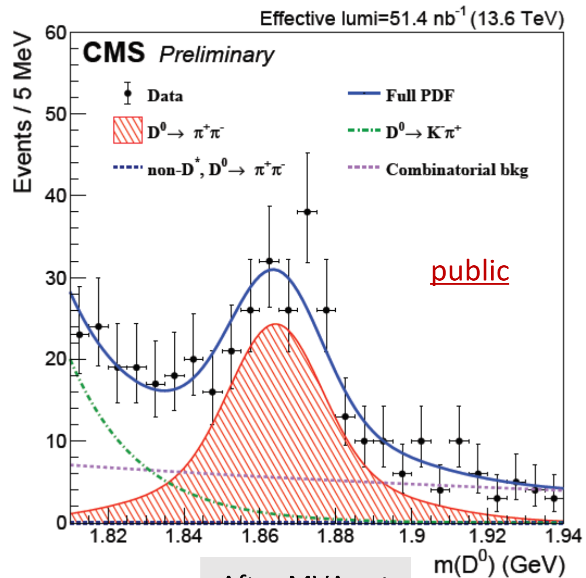
- Main observables to distinguish the signal
  - Pointing angles: α_{3D}
  - Flight length significance: $l_{3D}/\sigma(l_{3D})$
  - D^0 vertex probability
  - Impact parameter of D^0 candidate
  - pT of soft pion, muons
  - D^*vertex probability

- New MVA used to select the D^* meson and suppress the backgrounds, labelled as $\mathrm{MVA_D}$.
  - XGBoost package (advanced gradient boosting algorithm).
  - Training sample:
    - Signal: $D^{*+} \to D^0\pi^+, D^0 \to \mu\mu$ MC
    - Background: data sidebands $\Delta m \in [0.150, 0.155]$ GeV
- Optimized selection: $\mathrm{MVA_D}$>0.74

Normalization UML Fit

- 2D Fit: $P(M_{\pi\pi}, \Delta M) = P(M_{\pi\pi}) \times P(\Delta M).$
- Procedure
  - Use MC to extract fitting models
  - Shape correction extracted from Dimuon,Zerobias
  - Fit on ZeroBias to get the normalization
- Three major components
  - $D^* \to D^0\pi, D^0 \to \pi\pi$
    - Peak structure in both dM and m(μμ)
  - Combinatorial background
  - $D^* \to D^0\pi, D^0 \to K\pi$
    - Larger peak in dM, left shifted peak in m(μμ)
  - The contribution from $D^0 \to K\pi/\pi\pi$ without D* is negligible
- Normalization result after MVA cut
  - N(D->ππ)=195 $\pm$ 17
  - prescaling = 1.255×10^6





After MVA cut