Rare Decays at CMS

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On behalf of the CMS Collaboration

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Outline of the talk

- CLFV decay of $\tau \rightarrow \mu\mu\mu$ (DOI: 10.1007/JHEP01(2021)163)

- Rare Decay of $\mathrm{B} \rightarrow \mu\mu$ (DOI: 10.1007/JHEP04(2020)188, CMS-PAS-BPH-20-003)

- Angular Analysis $B^{+} \rightarrow K^{*+}\mu\mu$ (DOI: 10.1007/JHEP04(2021)124)

Why Rare Decays?

- Flavor change in charged leptons is not necessarily forbidden by any symmetry of the SM; yet no such decay is observed

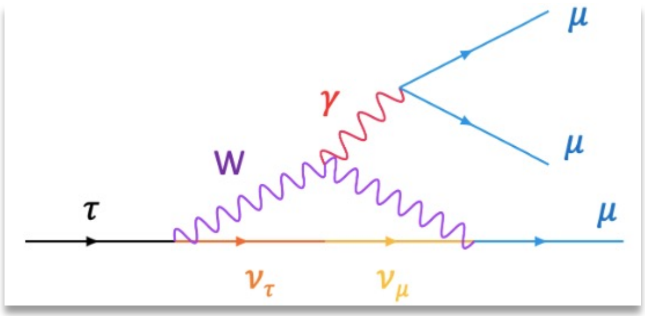
- The Flavor Changing Neutral Currents (FCNCs) are suppressed in the SM; Larger branching ratios could indicate BSM physics

- Precision measurements of observables needed to check for potential discrepancies in the SM predictions

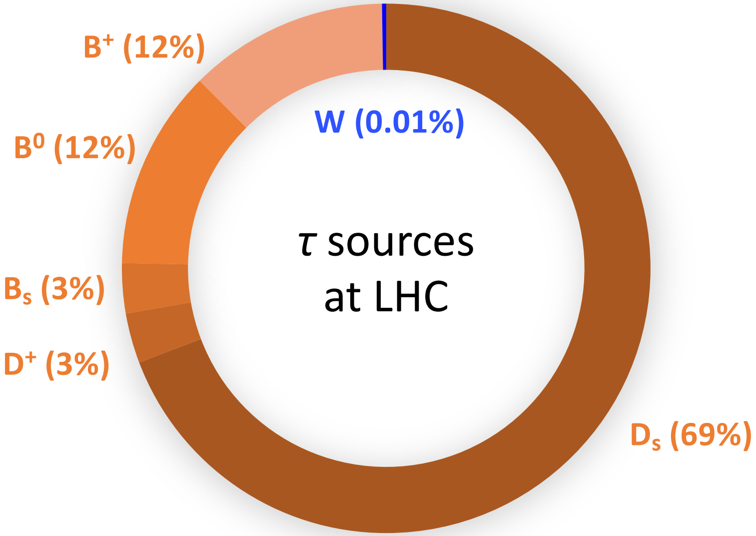
Search for CLFV Decay of $\tau \rightarrow \mu\mu\mu$

- $\tau \rightarrow \mu\mu\mu$ decay is suppressed in the SM, but several BSM theories predict higher branching ratios (~ O(10^{-54})) accessible by current detector technologies
- Searches have been performed by many experiments over last six decades, but no excess has been observed yet
- At LHC, searches for CLFV τ decays are favored by their abundant production O(10^{11})/fb^{-1}
- As opposed to e^+e^- colliders, τs produced at LHC have significantly more background and hence the analysis is more challenging

Experiment	Observed (Expected) upper limit on B($\tau \rightarrow 3\mu$) (x 10^8 at 90% C.L.)
Belle	2.1 (-)
BaBar	3.3 (4.0)
LHCb (Run I data)	4.6 (5.0)
ATLAS (Run I data)	38 (39)

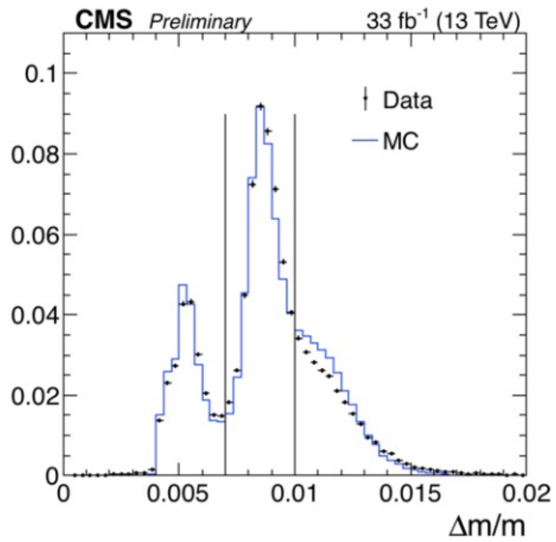


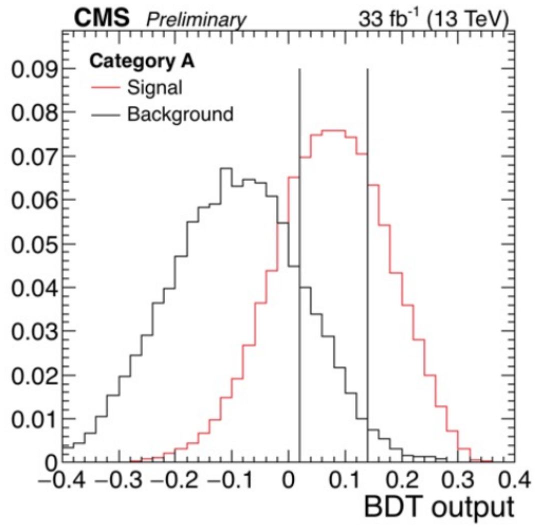
SM decay of $\tau \rightarrow \mu\mu\mu$ occurring via neutrino oscillation with a branching ratio of O(10^{-54})

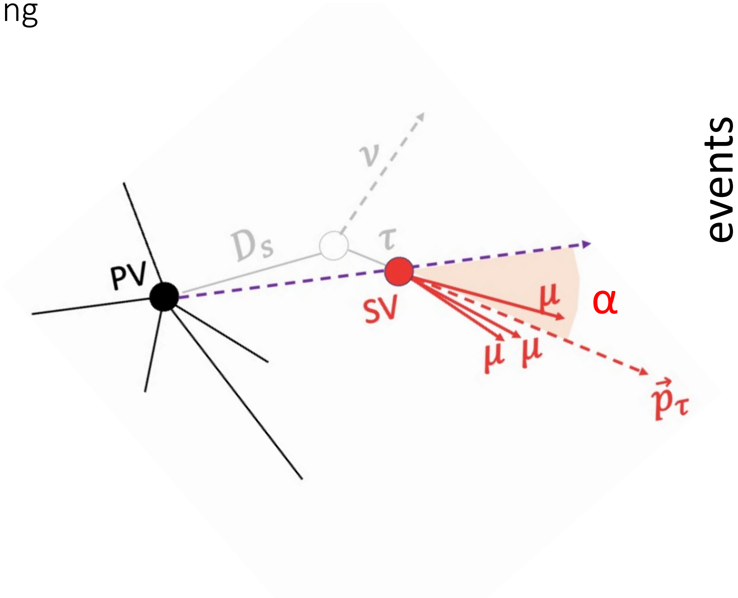


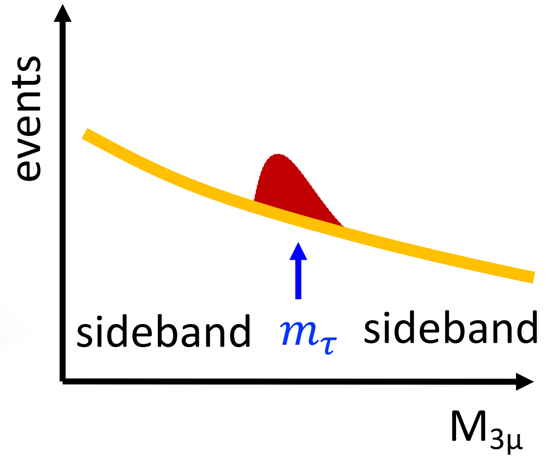
Search Strategy (Heavy Flavor Channel)

- Characterized by
  - Displaced Secondary Vertex
  - low momenta muons boosted in the forward region
  - High QCD background
- Dedicated online triggers for online event selection
  - Two muons and a track forming a displaced vertex (HF)
- Event categorization based on mass resolution
  - Mass resolution of the tau candidate can vary upto 3 times depending on the η
- Multivariate Analysis (BDT) for background rejection
  - vertex χ^2
  - vertex displacement significance
  - α angle
  - muon quality observables
- Signal extraction in multiple categories









Signal Normalization (Heavy Flavor channel)

- Number of signal events:

$$N_{\mathrm{sig(Ds)}} = \mathcal{L}\,\sigma\,(pp \to \mathrm{D_s})\,\mathcal{B}(\mathrm{D_s} \to \tau)\mathcal{B}(\tau \to 3\mu)A_{3\mu(D_s)}\epsilon^{3\mu}{}_{\mathrm{reco}}\epsilon^{3\mu}{}_{\mathrm{trig(sig)}}$$

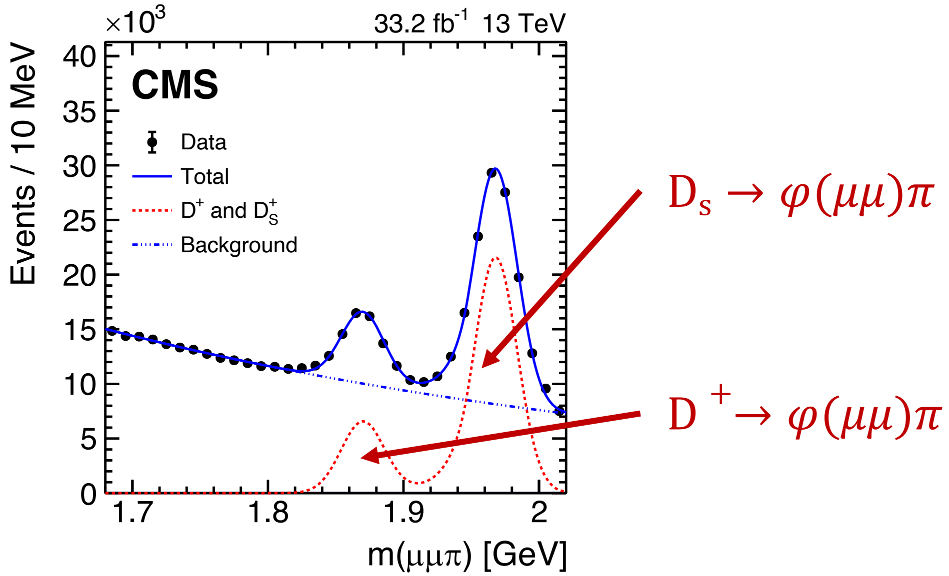
- $\mathrm{D_s}$ Yield from $\mathrm{D_s} \to \Phi\,(\mu\mu)\pi$ decay:

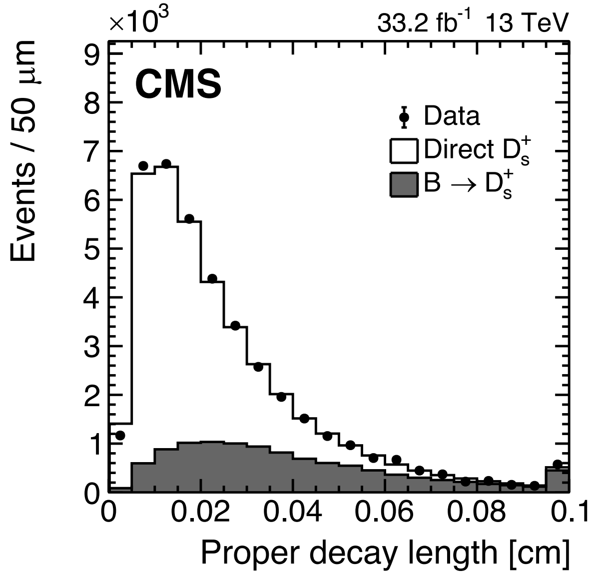
$$N = \mathcal{L}\,\sigma\,(pp \to \mathrm{D_s})\,\mathcal{B}(\mathrm{D_s} \to \varphi\pi \to \mu\mu\pi)A_{\mu\mu\pi(D_s)}\epsilon^{2\mu\pi}{}_{\mathrm{reco}}\epsilon^{2\mu}{}_{\mathrm{trig}(\mu\mu\pi)}$$

- $$N_{\mathrm{sig(Ds)}} = N\,\frac{\mathcal{B}(\mathrm{D_s}\to\tau)}{\mathcal{B}(\mathrm{D_s}\to\Phi\pi\to\mu\mu\pi)}\,\frac{A_{3\mu(D_s)}}{A_{\mu\mu\pi(D_s)}}\,\frac{\epsilon^{3\mu}{}_{\mathrm{reco}}}{\epsilon^{2\mu\pi}{}_{\mathrm{reco}}}\,\frac{\epsilon^{3\mu}{}_{\mathrm{trig(sig)}}}{\epsilon^{2\mu}{}_{\mathrm{trig}(\mu\mu\pi)}}\,\mathcal{B}(\tau \to 3\mu)$$

- The signal yield is independent of the luminosity and cross section measurements

- The B contribution to the signal is assessed through $\mathrm{D_s} \to \varphi(\mu\mu)\pi$ channel
  - Fit two templates of $\mathrm{D_s}$ decay length corresponding to prompt and non-prompt decays, derived from MC, to background subtracted data and extract the relative fraction

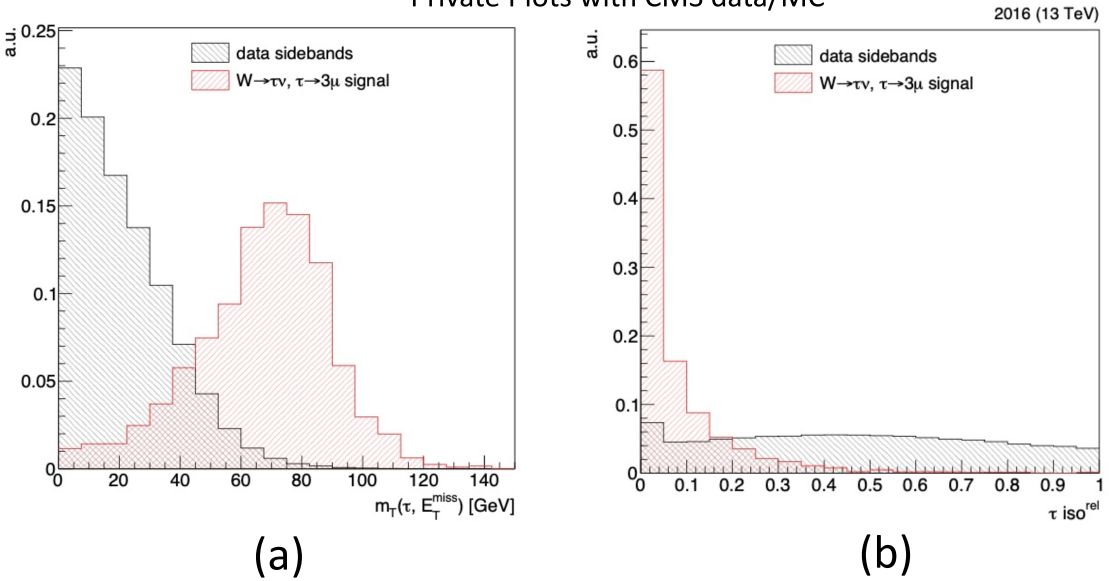




Search Strategy (W channel)

- Even after having a small contribution to the τ production at LHC (~ 0.01%), W channel has significant advantages
  - Fewer background sources
  - Isolated high momentum muons
  - Higher trigger and offline selection efficiency
  - Presence of large MET in the final state
- Online trigger selection
  - Dedicated three muon triggers
- MVA analysis using BDT for background rejection
  - Transverse mass W
  - Tau Isolation
  - Muon Id variable
- Event categorization based on the mass resolution (barrel, endcap)

Private Plots with CMS data/MC



(a) Transverse mass of W can be reconstructed from MET. (b) Background events from QCD have larger activity around the tau candidate. larger Isolation variable proves to be an excellent discriminator in BDT.

Signal Selection Efficiency

	HF channel	W channel
Muon acceptance*	1.5%	64%
Trigger efficiency	2%	23.5%

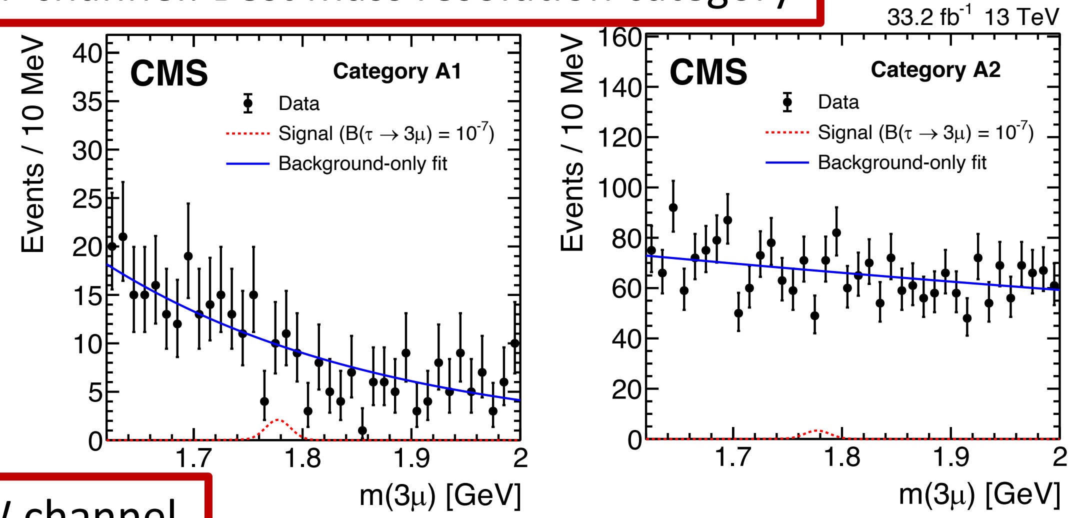
*Muon acceptance: all 3 muons have p>2.5 and eta<2.4

Combination and Future Prospects

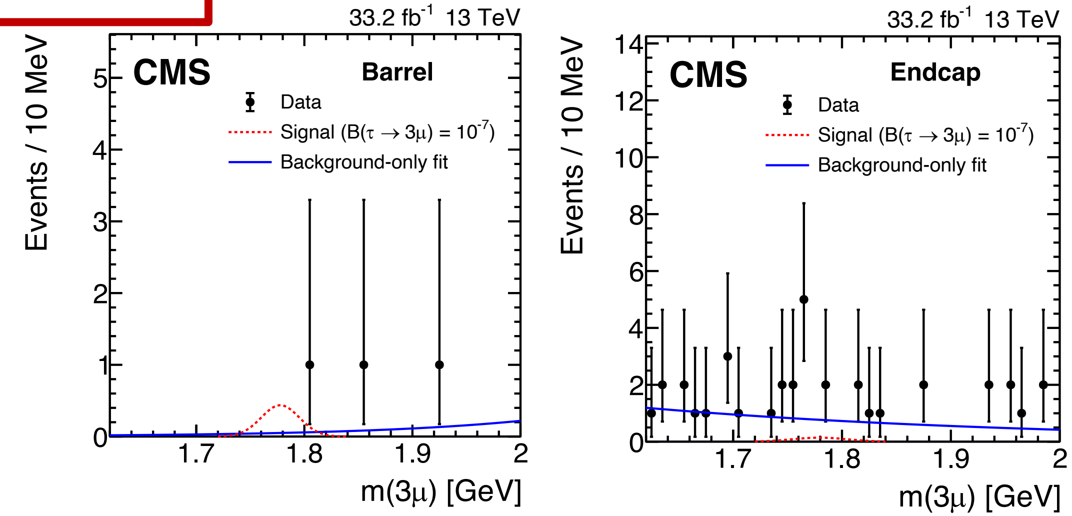
CMS-PAS-BPH-17-004

- 2 categories from W channel are combined with 6 categories rom the HF channel
- Observed (Expected) limit is 8.0 (6.9) x 10^{-8} at 90% C.L.
- Fitting W boson and HF events separately returns an observed(expected) upper limits of 20 x 10^{-8} (13 x 10^{-8}) and 9.2 x 10^{-8} (10.0 x 10^{-8}) at 90% C.L.
- Full Run 2 analysis is currently ongoing and the results are going to be released soon
  - 4 times more integrated luminosity
  - new pixel detector since 2017

HF channel: Best mass resolution category

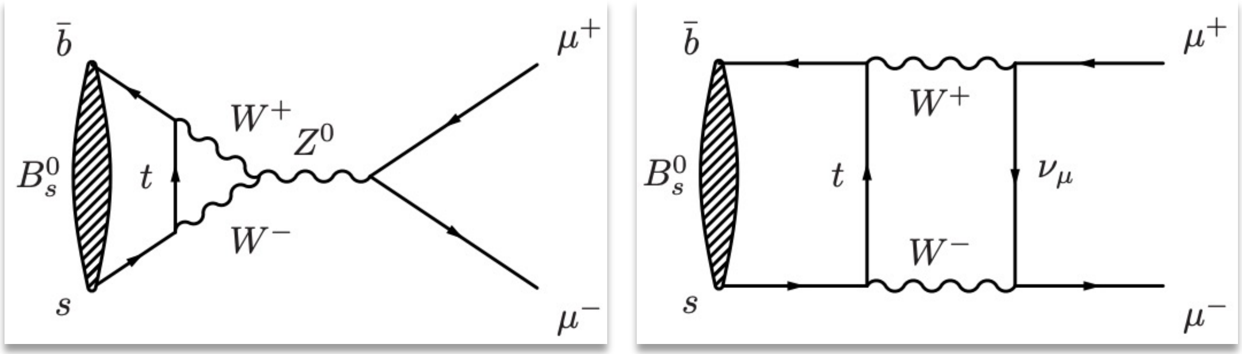


W channel



Rare Decay of B → $\mu\mu$

- SM decay suppressed by CKM and helicity
  - $B(B^0_s \to \mu\mu)$ = (3.57 ± 0.17) x 10^{-9}
  - $B(B^0 \to \mu\mu)$ = (1.06 ± 0.09) x 10^{-10}
- Theoretical uncertainties in the branching ratios have been reduced in the recent years
- Contributions from BSM processes could either enhance or further suppress the branching ratios
- B^0_s can be expressed as a linear combination of the two mass eigenstates- heavy (B^0_{sH}) and light(B^0_{sL})
- The SM predicts that the lifetime of the $B^0_s \to \mu\mu$ receives contribution from the heavy state
- Contributions from new physics could change the contributions from heavy and light mass states ($R_H^{\mu\mu}$, $R_L^{\mu\mu}$)
- Searches have been performed in ATLAS, CMS and LHCb



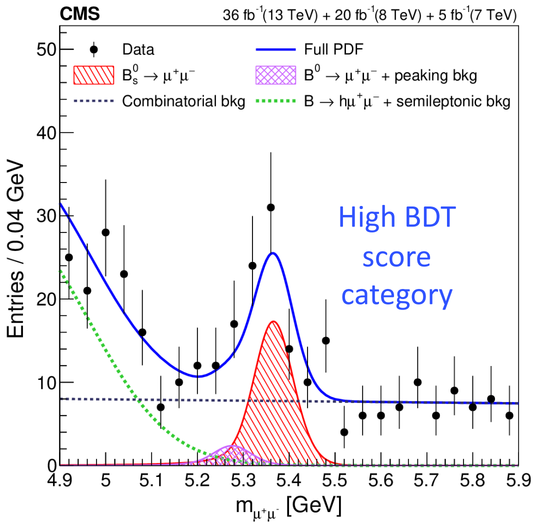
Experiment	$B(B^0_s \to \mu\mu)$ x 10^9	$B(B^0 \to \mu\mu)$x 10^{10}
CMS (Run I)	$3.0^{+1.0}_{-0.9}$	<11 @ 95% C.L.
CMS+LHCb (Run I)	$2.8^{+0.7}_{-0.6}$	$3.9^{+1.6}_{-1.4}$
ATLAS (Run I+2015+2016)	$2.8^{+0.8}_{-0.7}$	<2.1 @ 95% C.L.
LHCb (Run I+ Run II)	$3.0 \pm 0.6^{+0.3}_{-0.2}$	<3.4 @ 95% C.L.

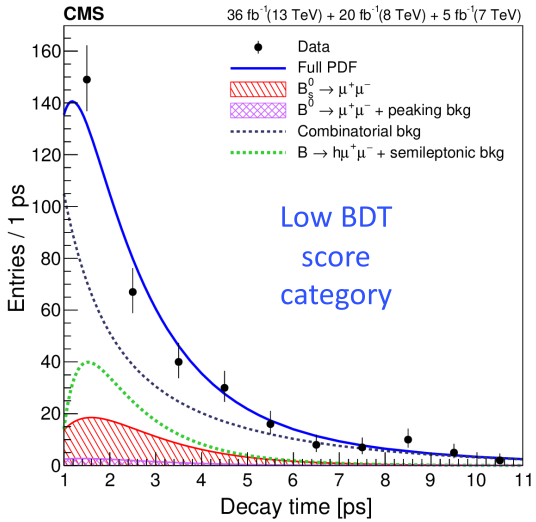
Rare Decay of B → $\mu\mu$

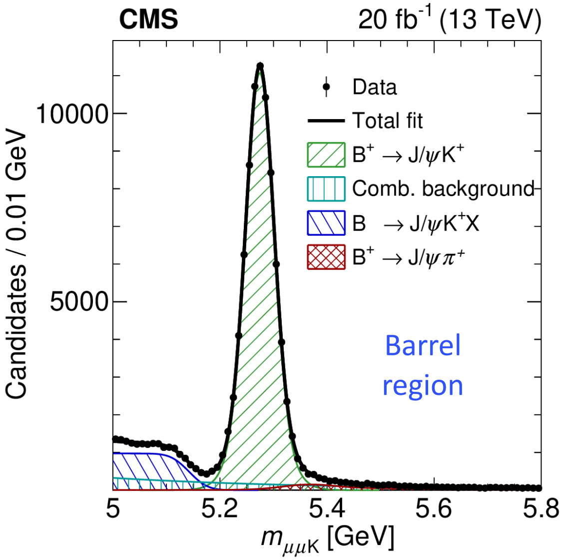
- HLT selection using opposite sign dimuons displaced from the vertex
- Background contributions from semi-leptonic and hadronic combinatorial decays, rare decays of $B_s \to K\mu\nu$, $\Lambda_b \to p\mu\nu$, $B_s \to KK$ with the hadrons misidentified as a muon
- MVA analysis used to perform signal-background discrimination
- Signal Normalization performed using the $B \to J/\psi(\mu\mu)K^+$

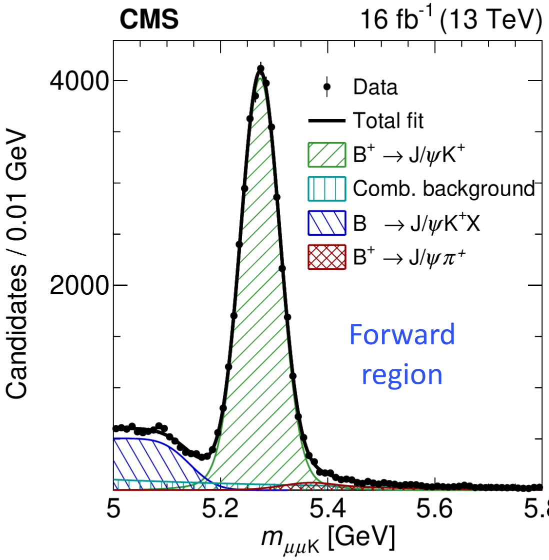
$$\mathcal{B}(B_s^0 \to \mu\mu) = \frac{n^{obs}_{B_s^0}}{N(B \to J/\psi K)} \frac{f_s}{f_d} \frac{A_{B^+}}{A_{B_s^0}} \frac{\varepsilon_{B^+}}{\varepsilon_{B_s^0}} \mathcal{B}(B \to J/\psi(\mu\mu)K)$$

- Signal yields are extracted in the bins of the output of the MVA
- The ratio of fragmentation fraction (f_s/f_d) is known with limited precision and is the dominant source of systematics









- Binned two-dimensional profile likelihoods obtained by each experiment from their fit to the dimuon invariant mass distributions
- The branching ratio of $B^0{}_s \rightarrow \mu\mu$ has been measured to be

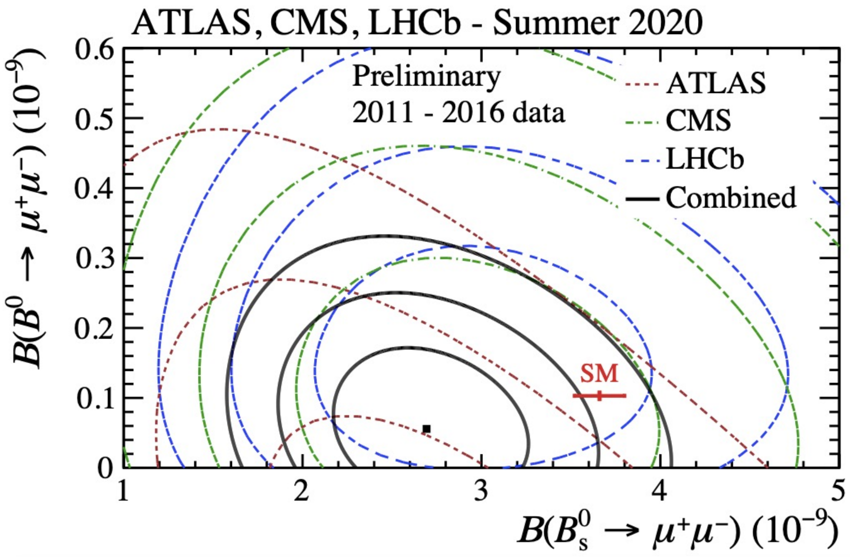
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.69\,^{+0.37}_{-0.35}) \times 10^{-9}$$

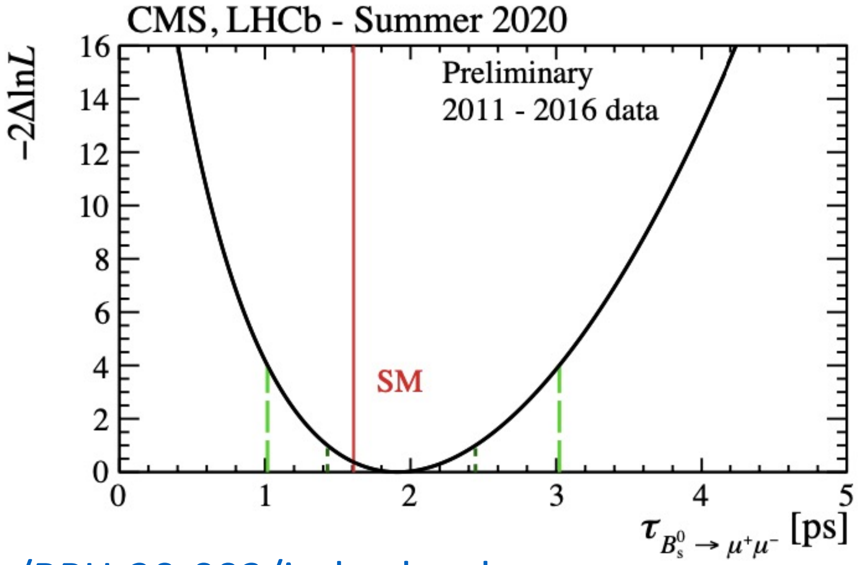
- An upper limit has ben set on the branching ratios of $B^0 \rightarrow \mu\mu$:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) \; < \; 1.6 \times 10^{-10} \text{ at } 90\% \text{ CL}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) \; < \; 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

- The results are compatible with the SM predictions within 2.1 standard deviations with the inclusion of theoretical uncertainties
- The effective lifetime of $B^0{}_s \rightarrow \mu\mu$ has been measured to be

$$\tau_{B^0_s \to \mu^+\mu^-} = 1.91^{+0.37}_{-0.35}\,\text{ps}$$





*https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-20-003/index.html

Angular Analysis $B^+ \to K^{*+}\mu\mu$

- $b \to sll$ FCNC process which if forbidden at tree level in SM, but only allowed through penguin and box diagrams
- Presence of BSM particles mediating the decay could alter the differential decay rate

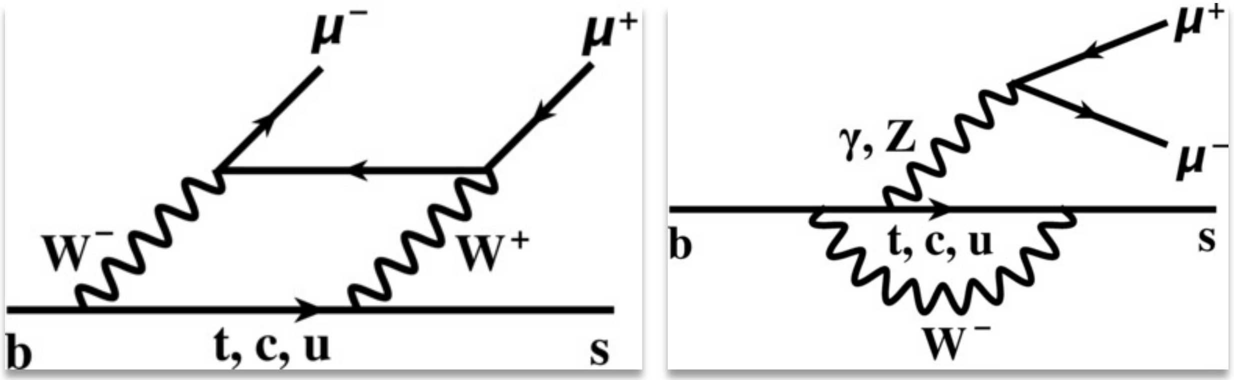
$$\frac{1}{\Gamma_l}\frac{d^3\Gamma_l}{d\cos\theta_l\, d\cos\theta_k} = \frac{9}{16}\{\frac{2}{3}[F_S + 2A_S\cos\theta_k](1+\cos^2\theta_l)$$

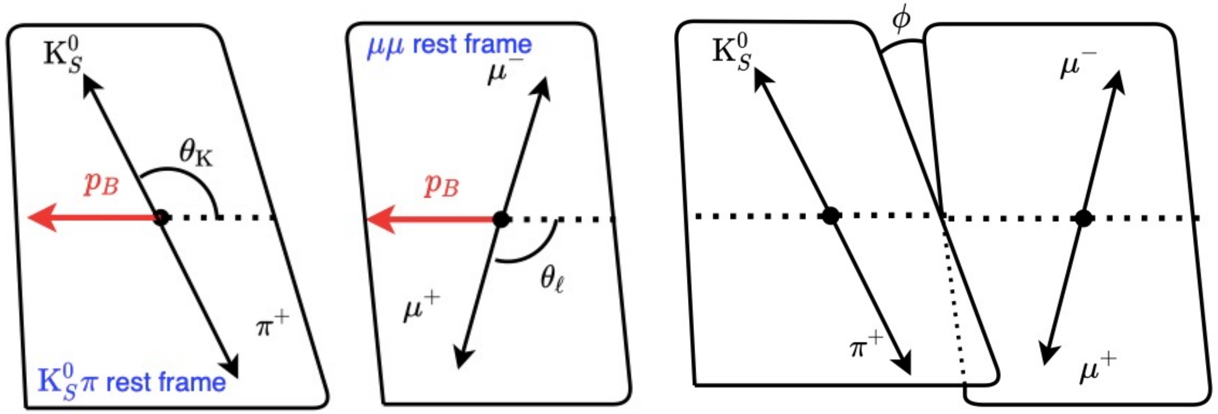
$$+(1-F_S)[2F_L(\cos^2\theta_k)(1+\cos^2\theta_l)$$

$$+\frac{1}{2}(1-F_L)(1+\cos^2\theta_k)(1+\cos^2\theta_l)$$

$$+\frac{3}{4}A_{FB}(1-\cos^2\theta_k)\cos\theta_l]\}$$

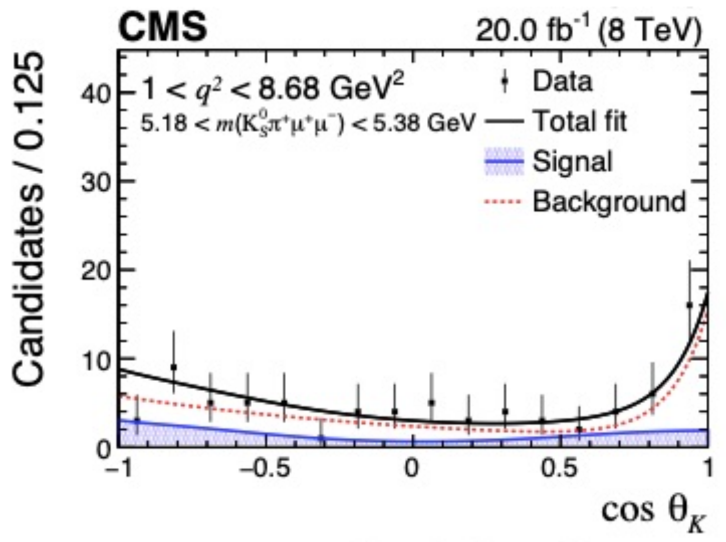
- θ_k: Angle between K_s and $-\mathbf{p}(B^+)$ in the K^* rest frame
- θ_l: Angle between μ^+ and $-\mathbf{p}(B^+)$ in the dimuon rest frame
- F_L: K^* longitudinal polarization factor
- A_{FB}: muon forward-backward symmetry
- F_s: S-wave fraction
- A_S: Interference amplitude between S and P wave



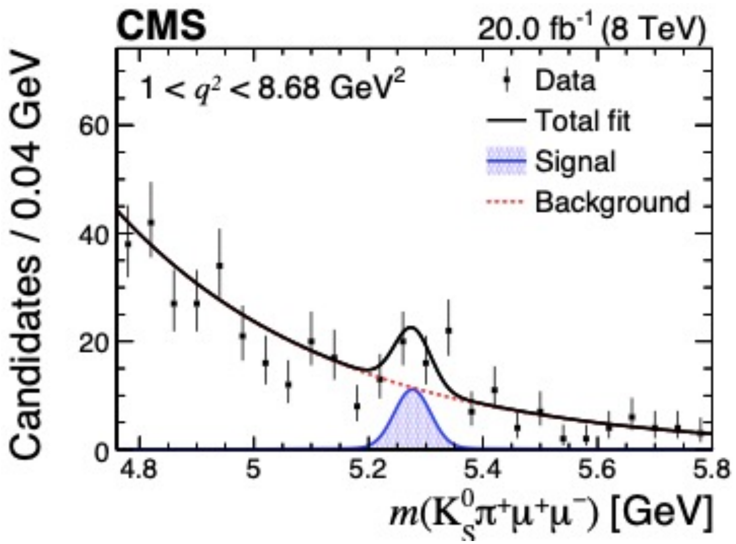


Analysis Strategy

- Analysis performed in three different q^2 (1-19 GeV) bins from 3D extended maximum-likelihood fit to angular distribution to extract the parameters A_{FB} and F_L
- Dedicated HLT to trigger on low momenta dimuon events with a displaced vertex
- Offline reconstruction of displaced secondary vertex
- Veto on J/ψ and ψ(2S) masses based on q^2
- Simulated shapes of the signal are used to generate PDFs and the efficiency as a function of θ_k, θ_l



$$\text{pdf}\,(m, \cos\theta_k, \cos\theta_l) = Y_S S^m(m) S^a(\cos\theta_k, \cos\theta_l)\varepsilon(\cos\theta_k, \cos\theta_l) + Y_B B^m(m) B^{\theta_K}(\cos\theta_k) B^{\theta_l}(\cos\theta_l)$$



YS, YB: signal and background yields (free parameters)

$S^m(m)$: signal mass shapes (derived from simulations)

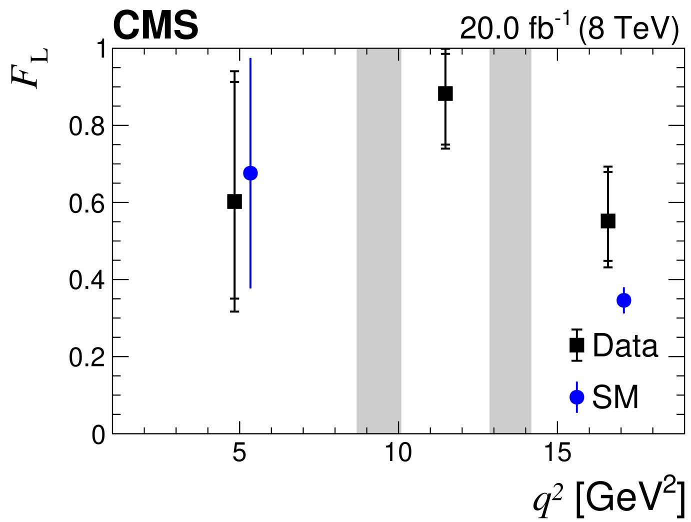
$B^m(m)$: exponential function (free parameter)

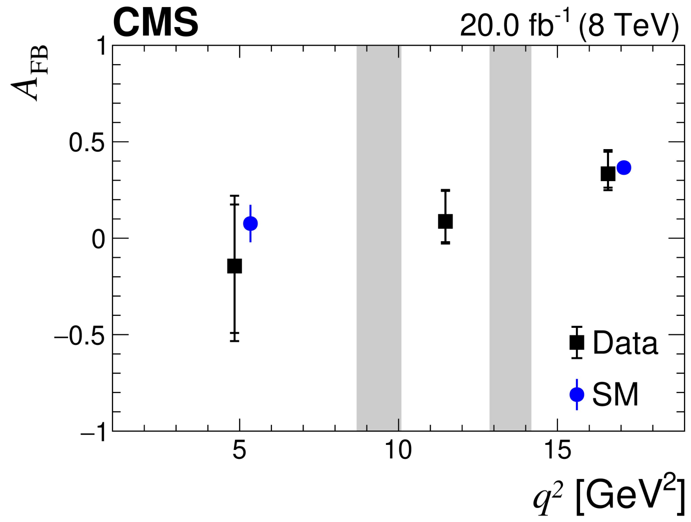
$B^{\theta_K}(\cos\theta_k)$, $B^{\theta_l}(\cos\theta_l)$: Background shapes (sidebands)

Results

CMS-PAS-BPH-15-009

- The results performed using Run I data indicate no deviations from the SM predictions
- The systematics were driven by the uncertainty in background shapes and extension of backgrounds to the sideband regions
- The parameters A_{FB} and F_L are extracted in each q^2 bin (dimuon invariant mass)
- The results are consistent with the SM predictions
- The measurements using the full Run II dataset are currently ongoing





Conclusions

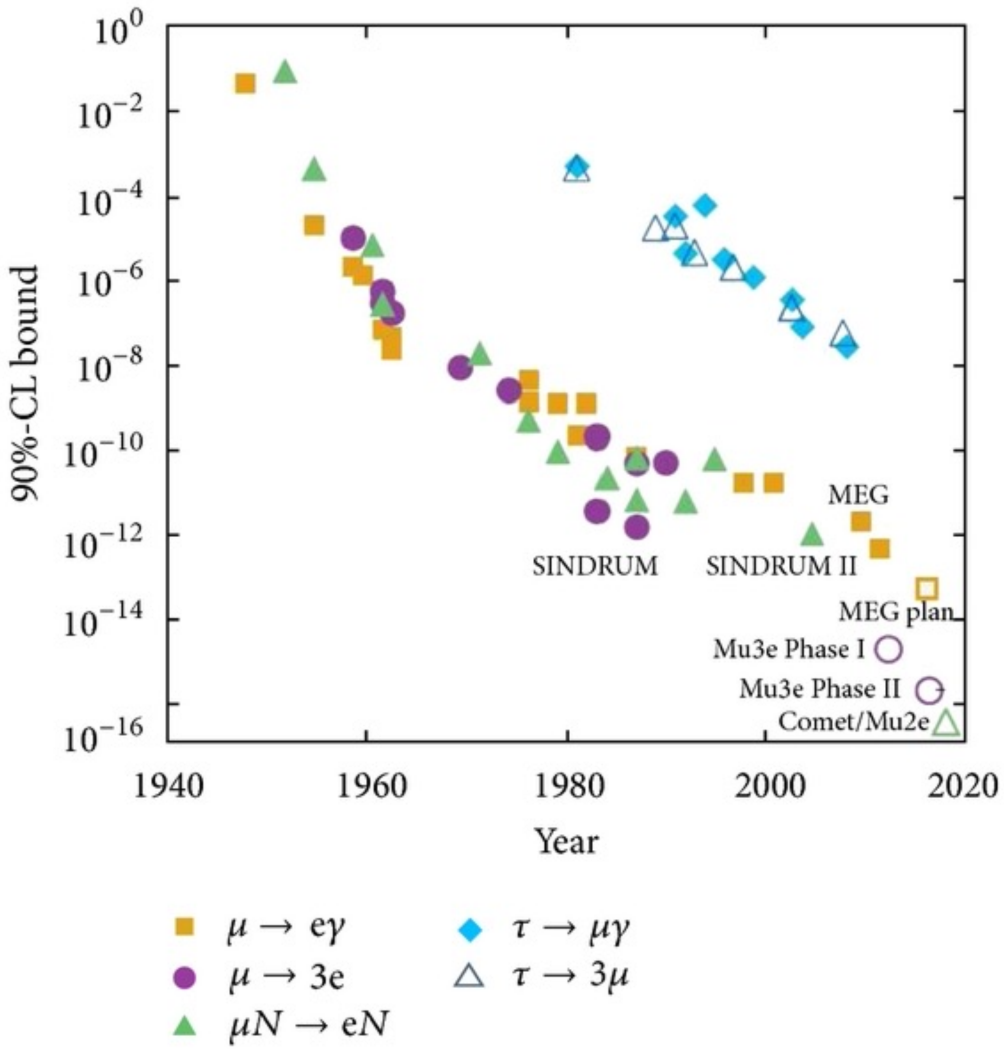
- A search for $\tau \rightarrow \mu\mu\mu$ was performed at CMS using both Heavy Flavor (HF) and W channels; the combined limit on the branching ratio is obtained to be 8.0 x 10^{-8} at 90% C.L.; no excess is seen

- The results obtained from ATLAS, CMS and LHCb experiments on $B^0_{(s)} \rightarrow \mu^+\mu^-$ decays obtained from the data collected between 2011 and 2016 have been combined; The effective lifetime of $\tau_{B^0_s \rightarrow \mu^+\mu^-}$ is the most precise measurement to date.

- The angular analysis of $\mathrm{B}^+ \rightarrow \mathrm{K}^{*+}\mu\mu$ is performed and the parameters F_L and A_{FB} are measured; no deviations from the SM are observed

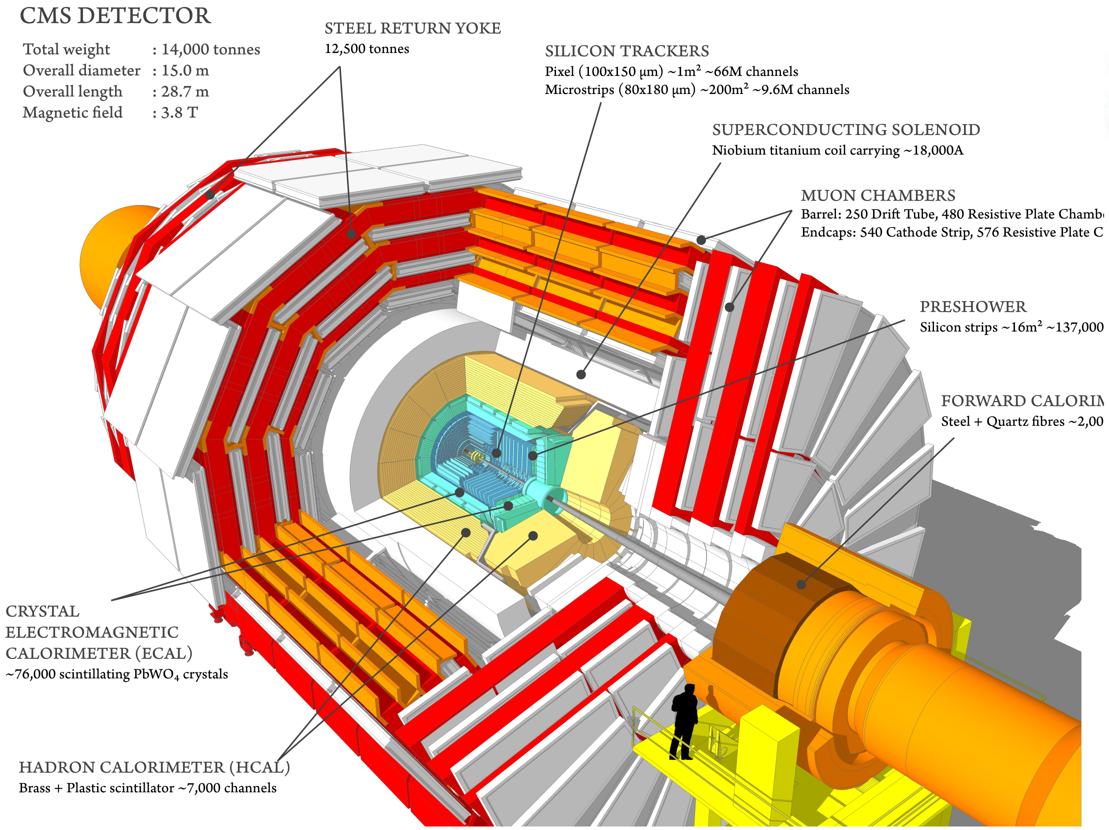
Backup

History of CLFV decays

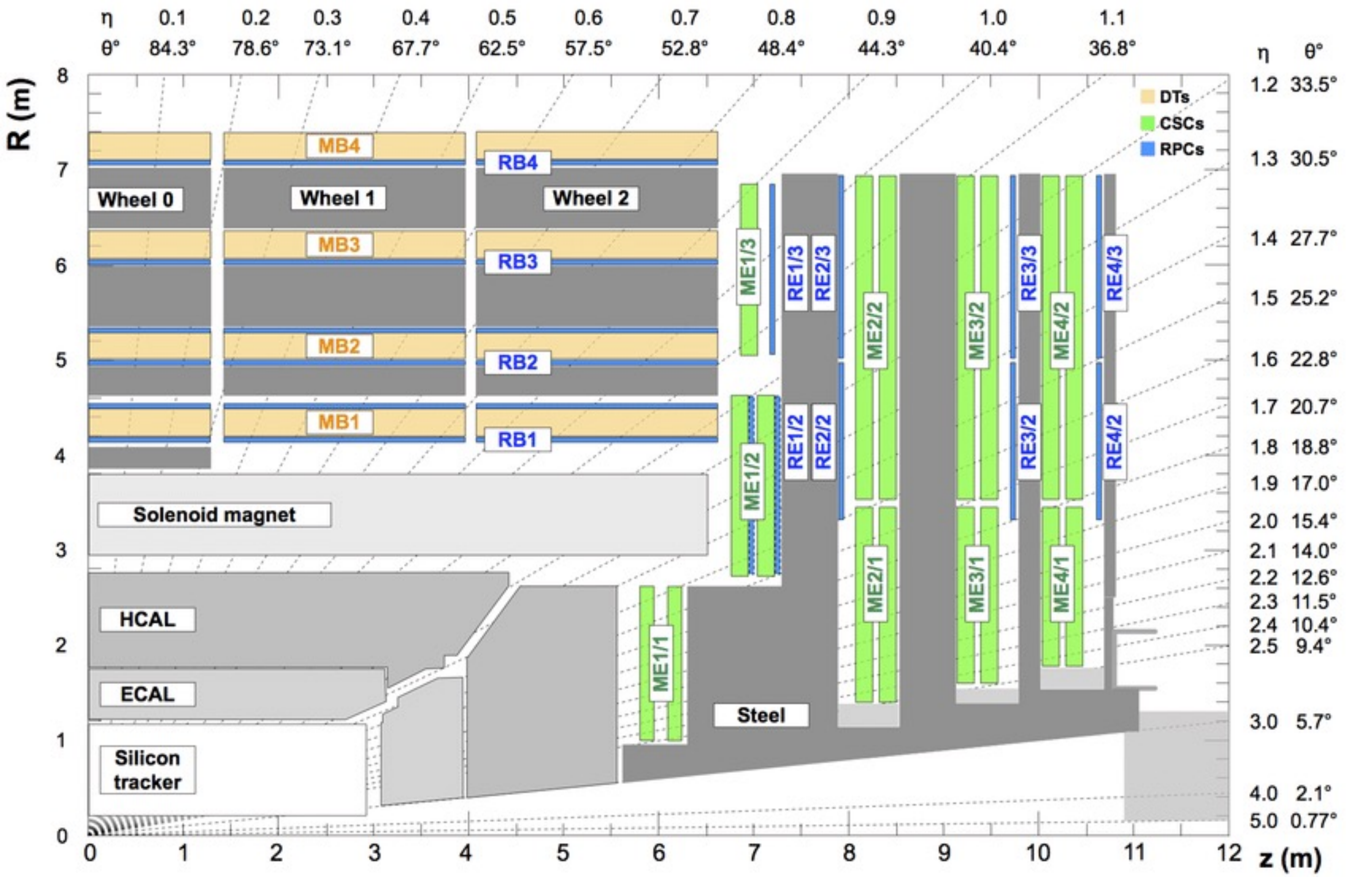


CMS Detector

3D Model of the Detector Design



Muon System

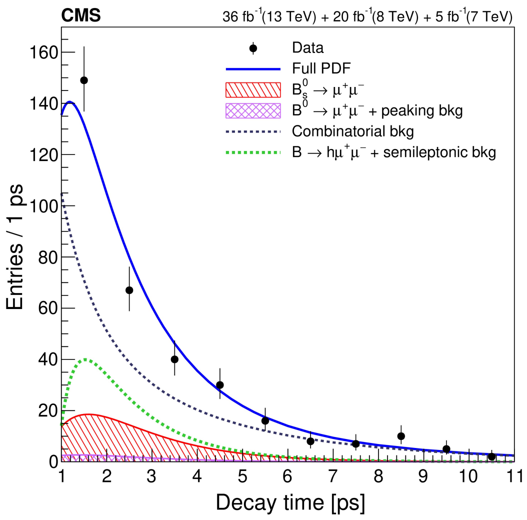


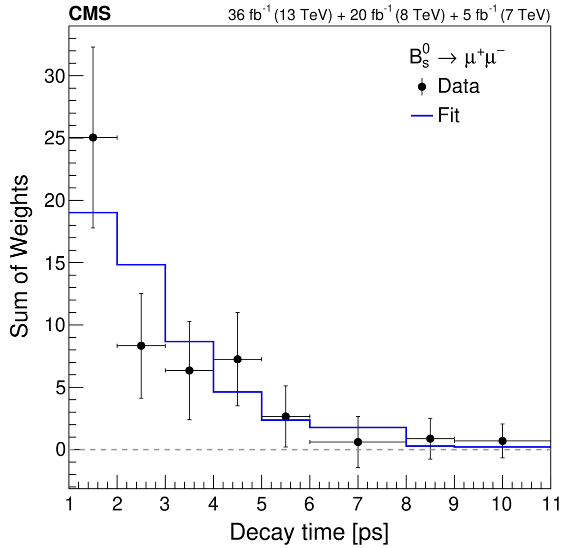
Effective Lifetime

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\,\Gamma(B_s(t)\to\mu^+\mu^-)\,dt}{\int_0^\infty \Gamma(B_s(t)\to\mu^+\mu^-)\,dt} = \frac{\tau_{B_s^0}}{1-y_s^2}\left(\frac{1+2\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right)$$

$$\tau_{B_s^0\to\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2}\left[\frac{1+2\mathcal{A}_{\Delta\Gamma}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma}y_s}\right]$$

$$y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s}, \qquad \mathcal{A}_{\Delta\Gamma} \equiv \frac{R_H^{\mu^+\mu^-}-R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-}+R_L^{\mu^+\mu^-}}$$





Reference: https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-16-004/index.html