# Heavy flavor rare decays at CMS

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on behalf of the CMS collaboration

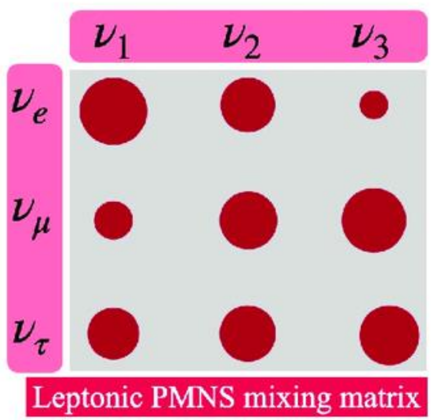
# Outline

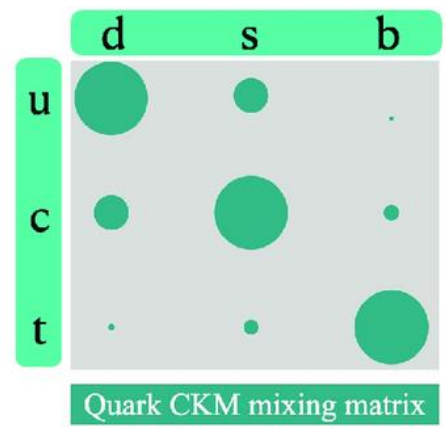
- **Introduction**
- **Search for lepton flavor violation (LFV) and lepton flavor universality violation (LFUV) at CMS**
  - Search for $\tau \to 3\mu$ at CMS
  - Prospect of LFUV in B physics at CMS
- **Measurements of $b \to sll$ rare decays at CMS**
  - $B_s^0 \to \mu^+\mu^-$ decay properties and search for $B^0 \to \mu^+\mu^-$ decay
  - $b \to sll$ angular analyses
- **Summary**

# Introduction: flavor

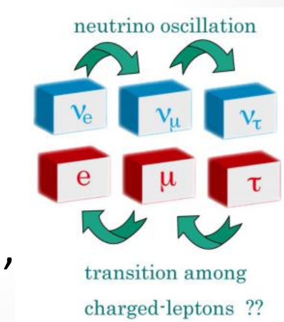
- In particle physics, flavor refers to the species of an elementary particle. The Standard Model (SM) counts six flavors of quarks and six flavors of leptons. They are conventionally parameterized with flavor quantum numbers.

- The SM has its mechanism (weak interaction) to encode the flavor-changing.

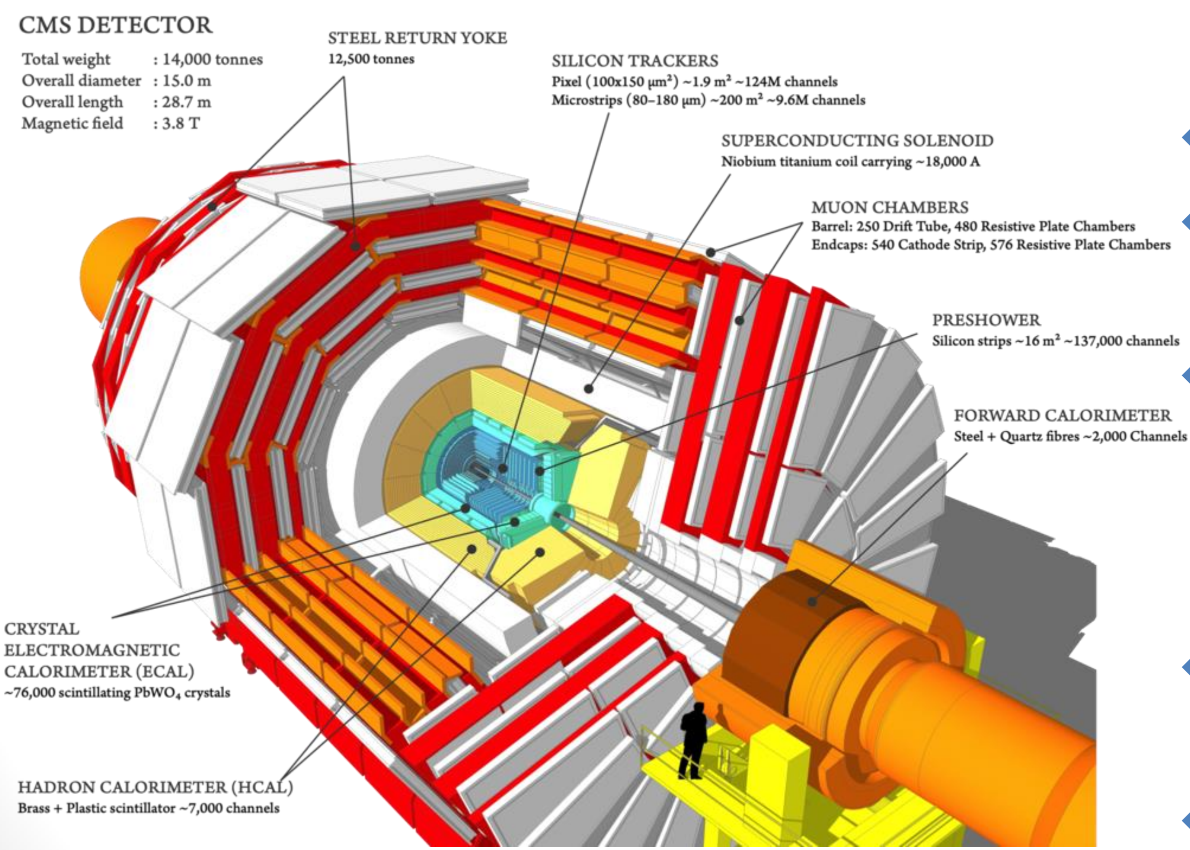



- Heavy flavor rare/forbidden decays: Searches for New Physics (NP)
  - Search for the decays violating the SM prediction, e.g. LFV…
  - Search for the decays' properties different to the SM prediction, e.g. branching fraction...



# Introduction: CMS




- COM energy 13 TeV
- Lumi ~ $10^{34}$ $cm^{-2}s^{-1}$
- $\Delta p_T/p_T$ ~ 1% when $p_T < 100$ GeV
- transverse impact parameter resolution O(10 — 100μm)
- Vertex resolution O(20 — 100μm)
- Covering most of the 4π solid angle

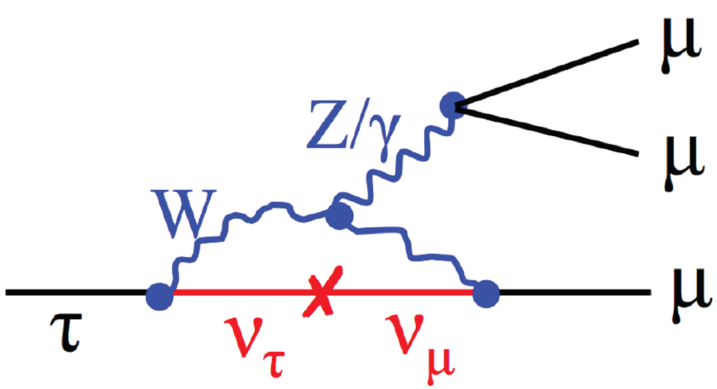
# Test of lepton flavor (universality) violation at CMS

# lepton flavor violation



- LFV in the SM: neutrino oscillations
- Experiments of charged LFV: search for phenomena beyond the SM (BSM)

- In SM, charged LFV happens in loop diagrams with neutrino mixing, the branching fraction is strongly suppressed (e.g. $B(\tau \to 3\mu) \sim 10^{-55}$).

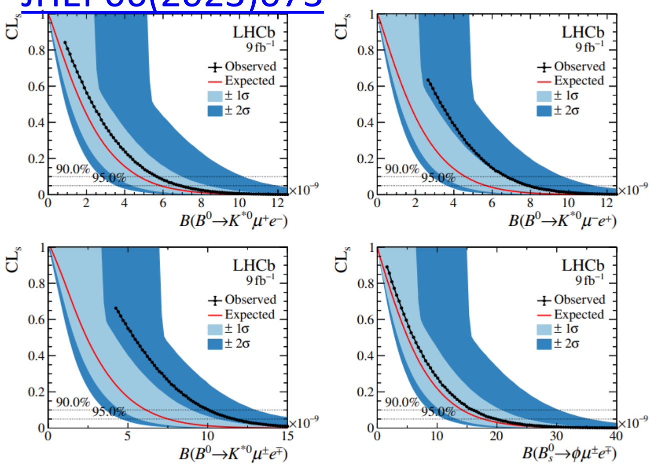



- A number of SM extensions predict a much larger LFV τ decay branching fraction (e.g. $B(\tau \to 3\mu) \sim 10^{-10}$–$10^{-8}$).

# Tests of LFV

- Many experiments have presented various results of LFV tests

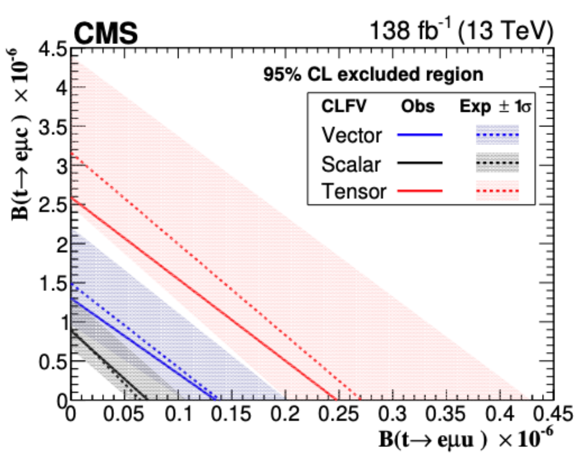
**LHCb: $B^0 \rightarrow K^{*0}\mu^{\pm}e^{\mp}$ and $B^0_s \rightarrow \phi\mu^{\pm}e^{\mp}$**
JHEP06(2023)073



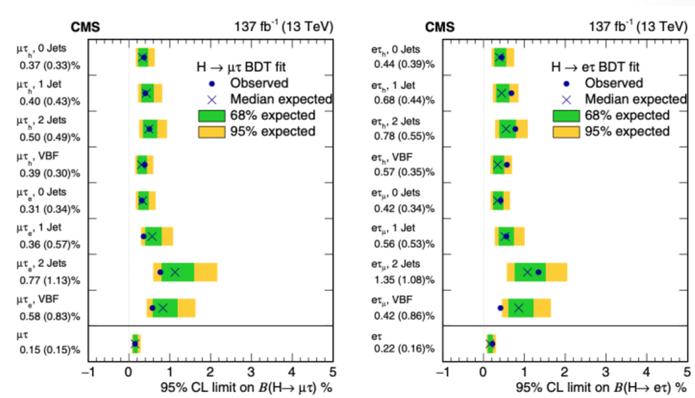

**Belle: τ decays into three leptons**
Phys.Lett.B 687 (2010) 139-143

| Mode | $\varepsilon$ (%) | $N_{BG}$ | $\sigma_{syst}$ (%) | $N_{obs}$ | $\mathcal{B}$ ($\times 10^{-8}$) |
|---|---|---|---|---|---|
| $\tau^- \to e^-e^+e^-$ | 6.0 | $0.21 \pm 0.15$ | 9.8 | 0 | $< 2.7$ |
| $\tau^- \to \mu^-\mu^+\mu^-$ | 7.6 | $0.13 \pm 0.06$ | 7.4 | 0 | $< 2.1$ |
| $\tau^- \to e^-\mu^+\mu^-$ | 6.1 | $0.10 \pm 0.04$ | 9.5 | 0 | $< 2.7$ |
| $\tau^- \to \mu^-e^+e^-$ | 9.3 | $0.04 \pm 0.04$ | 7.8 | 0 | $< 1.8$ |
| $\tau^- \to e^+\mu^-\mu^-$ | 10.1 | $0.02 \pm 0.02$ | 7.6 | 0 | $< 1.7$ |
| $\tau^- \to \mu^+e^-e^-$ | 11.5 | $0.01 \pm 0.01$ | 7.7 | 0 | $< 1.5$ |

**CMS: $t \rightarrow e\mu q$**
HEP06(2022)082




**CMS: $H \rightarrow \mu\tau$ and $H \rightarrow e\tau$**
PhysRevD.104.032013



# Search for τ → 3μ at CMS



## JHEP01(2021)163

- Based on data collected with the CMS detector in 2016, corresponding to an integrated luminosity of 33.2$fb^{-1}$.
- Targeted τ production from two sources:
  - Hadron decays
  - W boson decays
- No signal observed, a combined limit of the two τ production channels is $\mathbf{B(\tau \rightarrow 3\mu) < 8.0 \times 10^{-8}}$ **at 90% CL.**

## CMS BPH-21-005 (latest one!)

- Based on data collected with the CMS detector in 2016-2018, corresponding to 138 $fb^{-1}$
- Targeted τ production from two sources:
  - Hadron decays (prompt D meson decays, b hadron decays, and non-prompt D meson decays)
    - Signal: $D_s \rightarrow \tau + v$ (including prompt $D_s$ and $B \rightarrow D_s$); $B^+$ or $B^0 \rightarrow \tau + X$
  - W bosons
    - Signal: $W \rightarrow \tau + v$

# Search for τ → 3μ at CMS: HF analysis

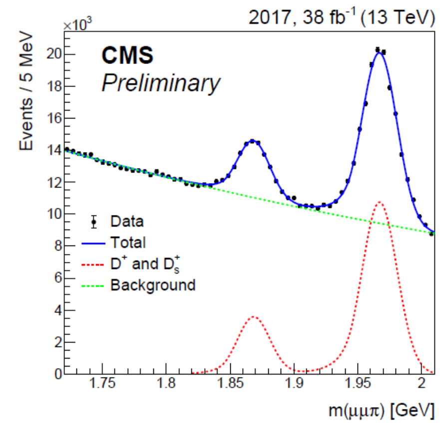
CMS BPH-21-005

- τ produced in heavy-flavor (charm and bottom) hadron decays
  - The main source of τ lepton production at the LHC
  - Features low transverse momentum ($p_T$) muons in the final state
  - Suffering from higher background
- Event selection:
  - Loose pre-selection
  - A BDT is used to suppress fake muons
  - Events categorization
    - Events are categorized according to the mass resolution, which is strongly correlated with the pseudo-rapidity
    - Mass scale and resolution agreements in data and MC are studied using the $D_s \to \phi\pi$ events
    - Three parts, labeled A, B, C
  - The analysis BDT is trained in each mass-resolution to suppress dominant backgrounds:
    - Each category is then further divided into several sub-categories based on the BDT score

# Search for τ → 3μ at CMS: HF analysis

CMS BPH-21-005

- $D_s$→τ normalization channel: $D_s \to \phi(2\mu)\,\pi \to \mu\mu\pi$




- Relation between the signal channels and the normalization channel:

$$N_{3\mu(\mathrm{D})} = N_{\mu\mu\pi} \frac{\mathcal{B}(\mathrm{D_s^+} \to \tau^+ \nu)}{\mathcal{B}(\mathrm{D_s^+} \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(\mathrm{D})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{D})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\mathrm{trig}}_{3\mu(\mathrm{D})}}{\epsilon^{2\mu\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu)$$

$$N_{3\mu(\mathrm{B})} = N_{\mu\mu\pi}\, f \frac{\mathcal{B}(\mathrm{B} \to \tau + \mathrm{X})}{\mathcal{B}(\mathrm{D_s^+} \to \phi\pi^+ \to \mu^+\mu^-\pi^+)\mathcal{B}(\mathrm{B} \to \mathrm{D_s^+} + \mathrm{X})} \frac{\mathcal{A}_{3\mu(\mathrm{B})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{B})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\mathrm{trig}}_{3\mu(\mathrm{B})}}{\epsilon^{2\mu\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu)$$

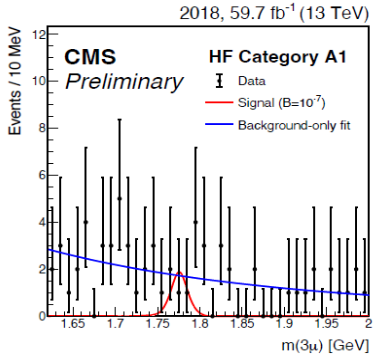
- Non-$D_s$ contributions:
  - B → τ (~25% of the total), based on MC, but verified by comparing decay length of B → $D_s$ in data and MC
  - Very small contributions from $B_s$ and $D^+$ based on MC

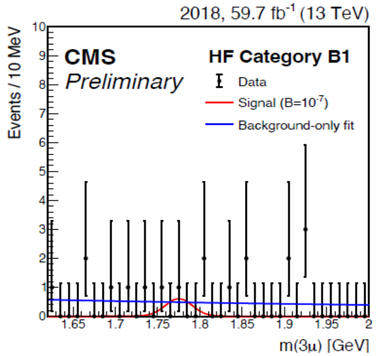
# Search for τ → 3μ at CMS: HF analysis

CMS BPH-21-005

- Systematics:
  - Main uncertainties in signal yields:
    - Statistical uncertainty of the $D_s \to \phi\pi$ channel
    - HF hadron decay branching fractions used in the signal normalization
    - BDT requirement efficiency, studied using the $D_s \to \phi\pi$ channel
  - Uncertainties in shapes :
    - Muon momentum scale and resolution impact on signal shapes
    - Background function form choice (exponential, power low, polynomial)

- Results obtained by a simultaneous un-binned maximum likelihood fit to the trimuon mass distributions in all categories



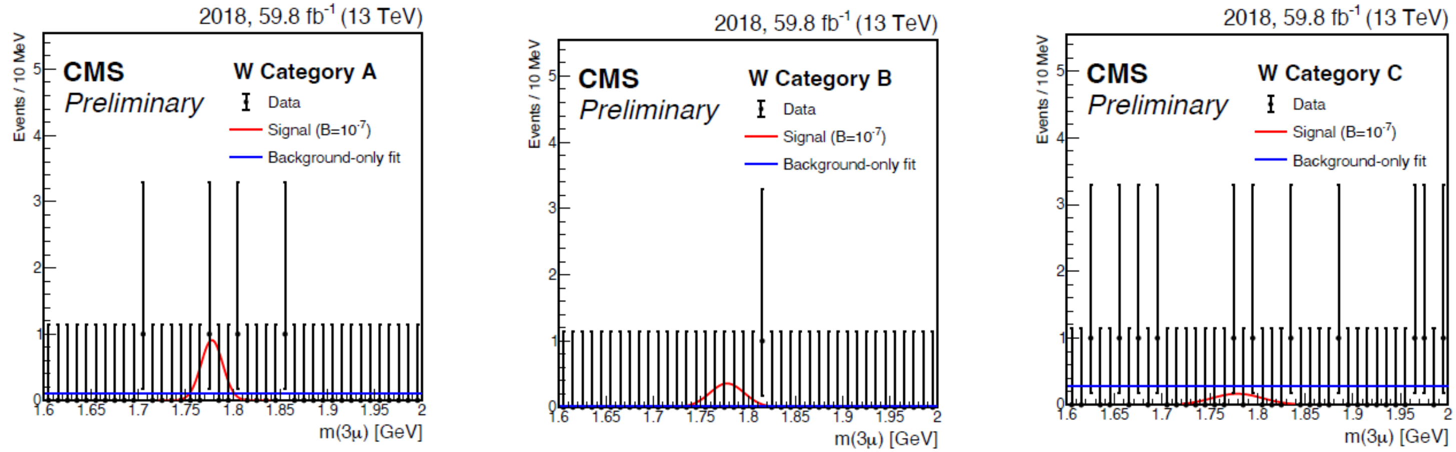




**The observed (expected) upper limit on Br(τ→3μ) is found to be of $3.4 \times 10^{-8}$ ($3.6 \times 10^{-8}$) at 90% CL**

# Search for τ → 3μ at CMS: W analysis

CMS BPH-21-005

- τ produced in W boson decays
  - Feature higher-$p_T$ muons
  - Typically isolated from hadronic activities
  - With significantly large missing transverse momentum
- Same analysis strategy as for the HF analysis:
  - Loose pre-selection
  - Event categorization and m(3μ) fit
  - Multivariate analysis used to suppress backgrounds

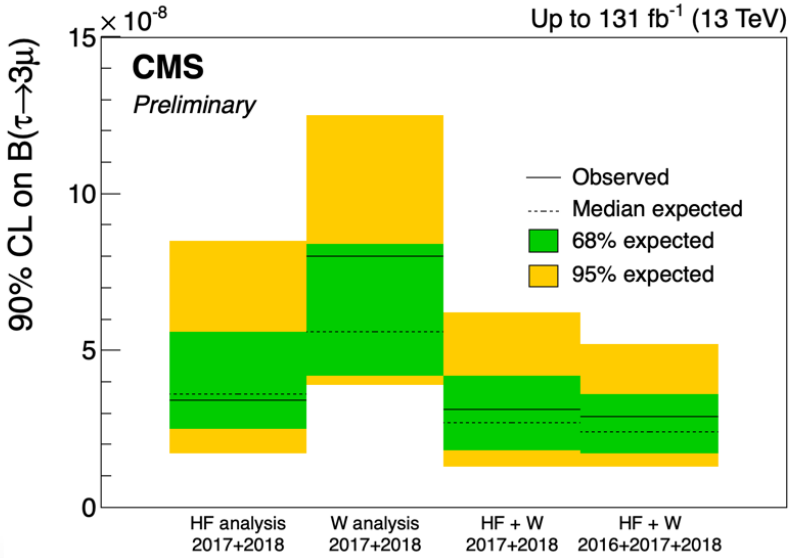



**Observed (expected) upper limit on Br(τ→3μ) $8.0\times10^{-8}$ ($5.6\times10^{-8}$) at 90% CL**

# Search for τ → 3μ at CMS: results

CMS BPH-21-005

- The HF and W analyses, together with the previously published 2016 data result, are combined
- Events that pass the final selections of both analyses are removed from the HF analysis
- Systematics are assumed to be uncorrelated between the HF analysis and the W analysis
- Results dominated by statistical uncertainty

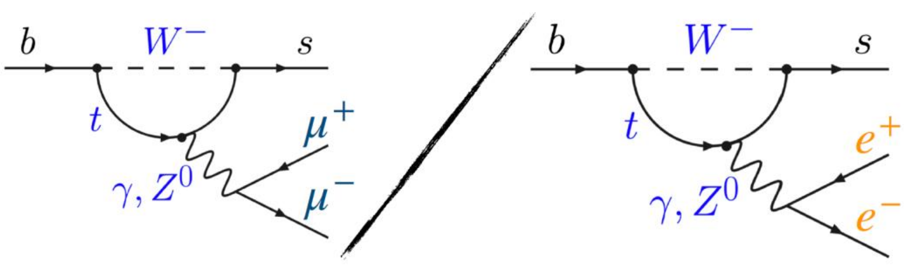



**The observed (expected) upper limit is 2.9x10-8 (2.4x10-8) at 90% CL**

# Prospect of LFUV in B physics at CMS

- The lepton flavor universality (LFU): a phenomenon that electroweak gauge bosons couple equally to all three families of leptons
- LFU is an accidental symmetry: may be violated in models beyond the SM
- ***LFUV will clearly state that NP participates in the flavor-changing processes.***

- b→sll processes are ideal for experiments to look for NP
  - The amplitudes are highly suppressed in SM (~ $10^{-6}$), sensitive to NP
  - SM predicts the dynamics with high precision
  - Can be fully reconstructed in experiment



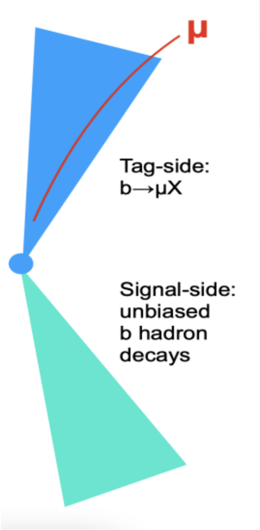

$$R_h = \frac{\Gamma(B \to h\mu^+\mu^-)}{\Gamma(B \to he^+e^-)}$$

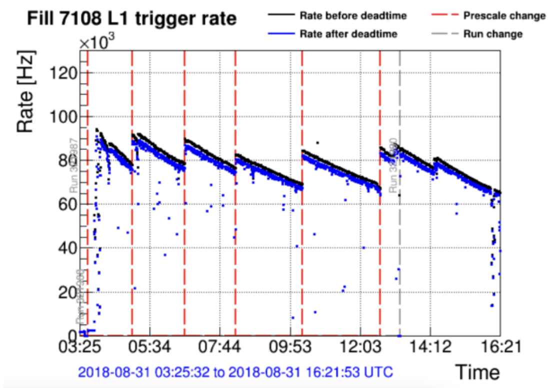
→**A requirement on large samples of B mesons**

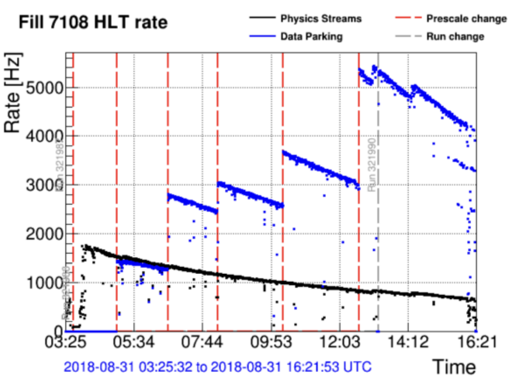
# Prospect of LFUV in B physics at CMS

**CMS B-Parking:** [CMS DP -2019/043]

- A sample of 10 billion events contains the unbiased decays of b hadrons.
- Data are recorded in 2018, with a trigger logic that requires the presence of a single, displaced muon:
  - “Tag-side“: b hadron that undergoes a $b \to \mu X$ decay.
  - “Signal-side“: b hadron decays naturally as it is not biased.
- The trigger thresholds evolve during a fill, as the instantaneous luminosity ($\mathcal{L}_{inst}$) falls.




- Trigger purity is in the range 60–90% depending on the thresholds.

# Prospect of LFUV in B physics at CMS

**CMS B-Parking:** CMS DP -2019/043

- Large amount of unbiased B hadrons recorded by CMS B-parking campaign:

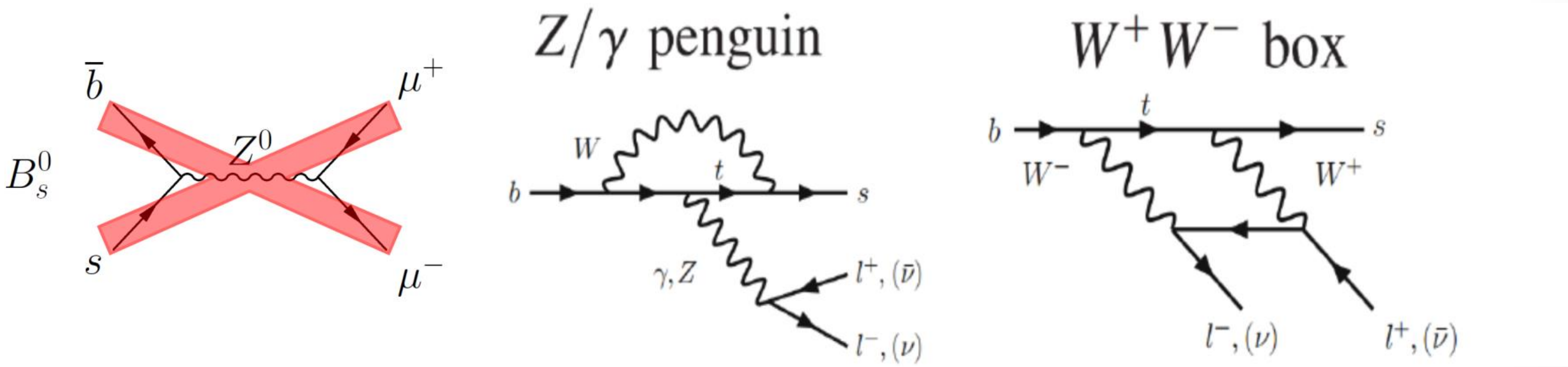
| Mode | $N_{2018}$ | $f_B$ | $\mathcal{B}$ |
|---|---|---|---|
| Generic b hadrons | | | |
| $B^0_d$ | $4.0 \times 10^9$ | 0.4 | 1.0 |
| $B^{\pm}$ | $4.0 \times 10^9$ | 0.4 | 1.0 |
| $B_s$ | $1.2 \times 10^9$ | 0.1 | 1.0 |
| b baryons | $1.2 \times 10^9$ | 0.1 | 1.0 |
| $B_c$ | $1.0 \times 10^7$ | 0.001 | 1.0 |
| Total | $1.0 \times 10^{10}$ | 1.0 | 1.0 |
| Events for $R_K$ and $R_{K^*}$ analyses | | | |
| $B^0 \to K^* \ell^+ \ell^-$ | 2600 | 0.4 | $6.6 \times 10^{-7}$ |
| $B^{\pm} \to K^{\pm} \ell^+ \ell^-$ | 1800 | 0.4 | $4.5 \times 10^{-7}$ |

- The samples can benefit for several measurements on the B rare decays, such as the R(K) measurement for LFU test …
- CMS Run3 has its B-parking with updated triggers

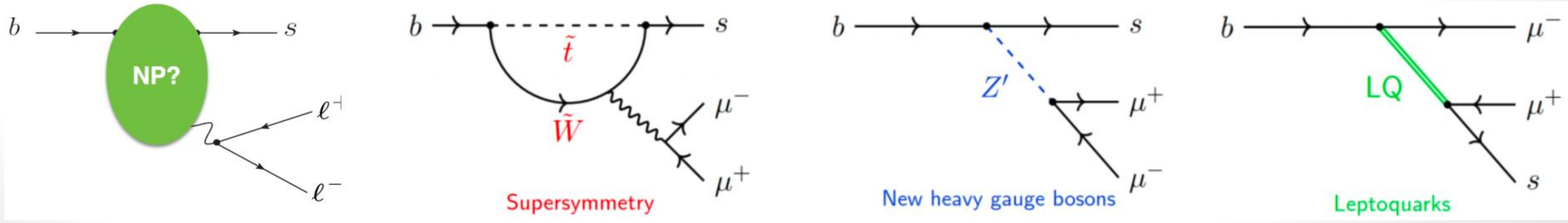
# Measurements of b →sll rare decays at CMS

# b→sll process

- NP can be discovered by two ways:
  1. by producing new particles or new decays
  2. by searching for discrepancies between measured observables and SM predictions.
- In SM, b→sll is a flavor-changing neutral current (FCNC) process forbidden at tree level.

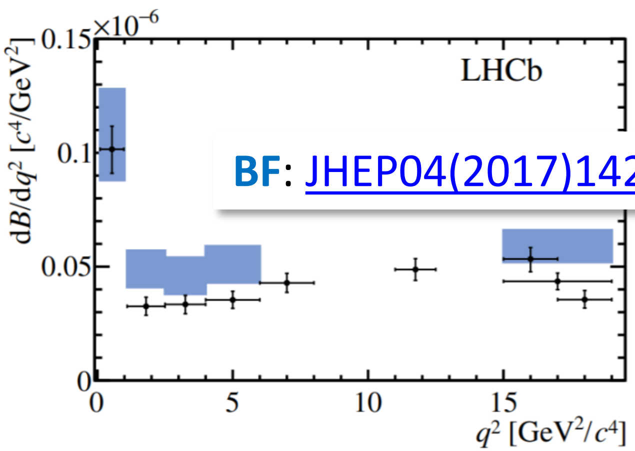



- NP can contribute to the diagrams and make pronounced modifications.

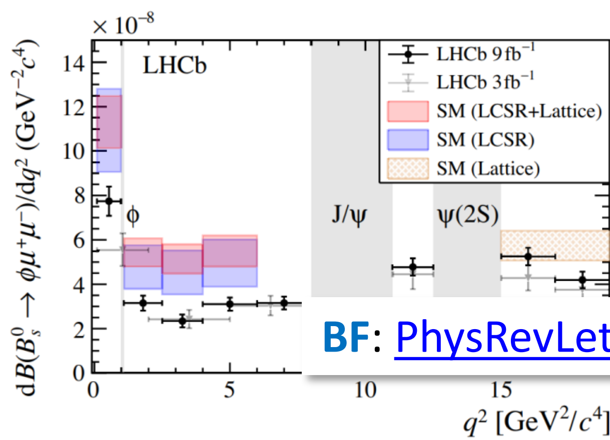


# b→sll anomaly

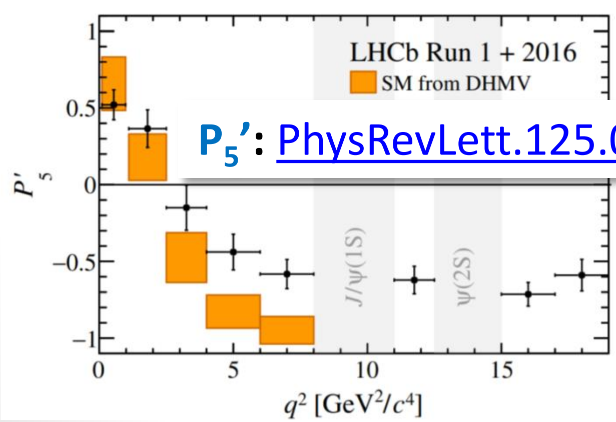
- Some observables of **b→sll** process are found deviating from SM predictions by 2-3σ, e.g. branching fraction, $P_5'$…



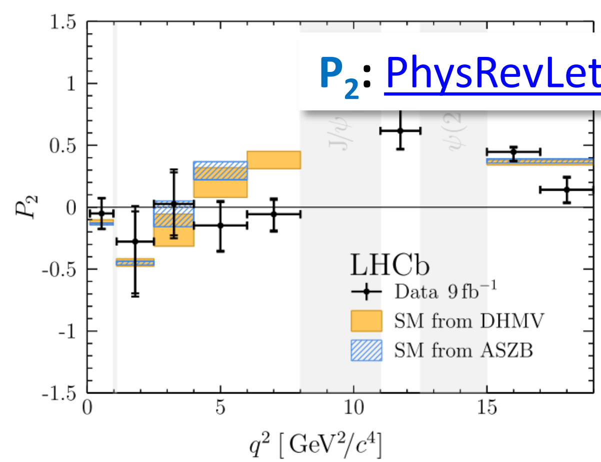

**BF**: JHEP04(2017)142




**BF**: PhysRevLett.127.151801




**$P_5'$**: PhysRevLett.125.011802

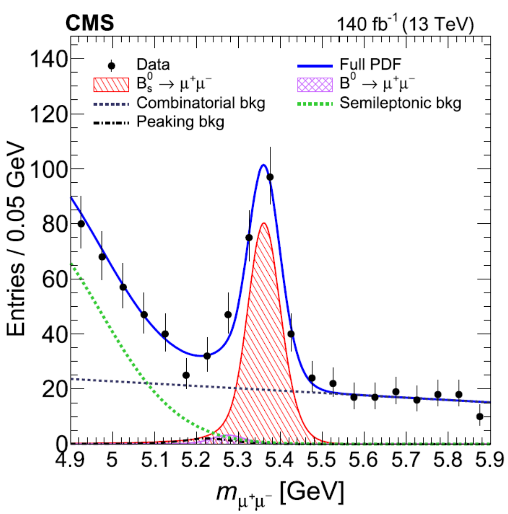



**$P_2$**: PhysRevLett.126.161802

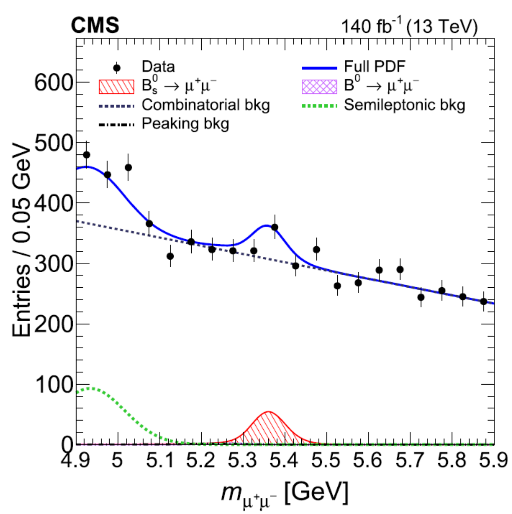
# $B_s^0 \to \mu^+\mu^-$ decay properties

- Latest result of iterative measurements.
- Based on data collected with the CMS detector in 2016–2018 corresponding to an integrated luminosity of 140$fb^{-1}$.

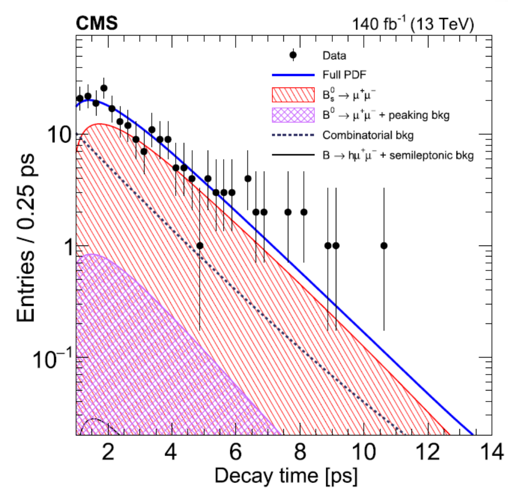
[Phys.Lett.B 842 (2023) 137955](Phys.Lett.B 842 (2023) 137955)




*dMVA>0.99(upper)*




*0.99 >dMVA>0.90(lower)*

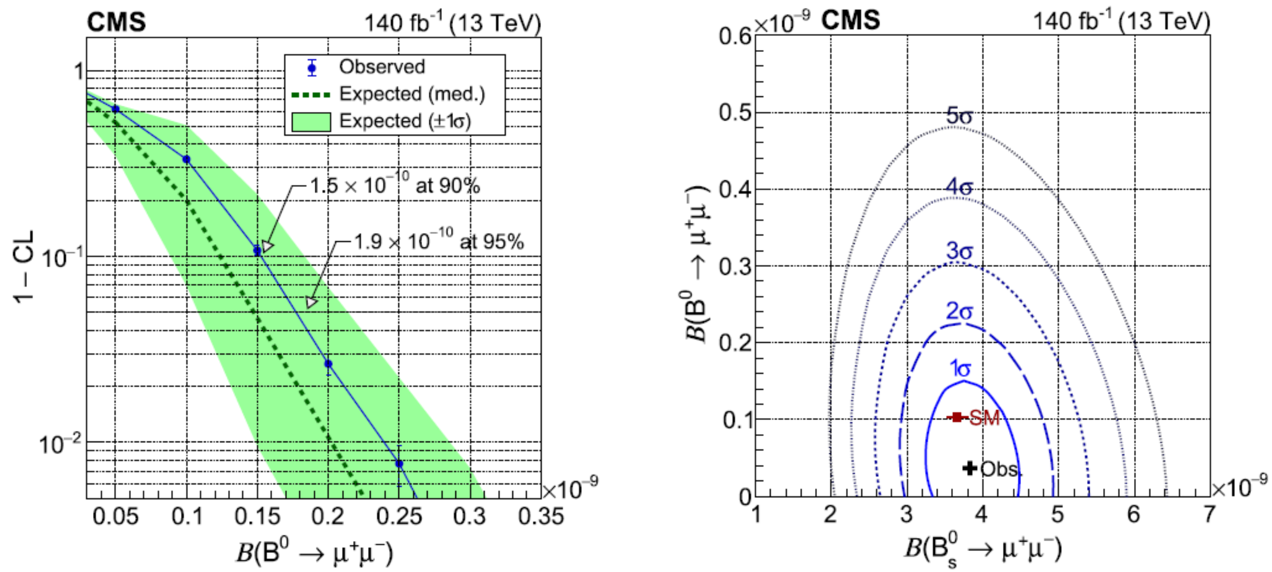



$$B(B_s^0 \to \mu^+\mu^-) = [3.83^{+0.38}_{-0.36}(stat)^{+0.19}_{-0.16}(syst)^{+0.14}_{-0.13}(f_s/f_u)] \times 10^{-9}$$

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

# Search for $B^0 \to \mu^+\mu^-$ decay

- Latest result of iterative measurements. Phys.Lett.B 842 (2023) 137955
- Based on data collected with the CMS detector in 2016–2018 corresponding to an integrated luminosity of $140 fb^{-1}$.
- No evidence of $B^0 \to \mu^+\mu^-$ has been found.



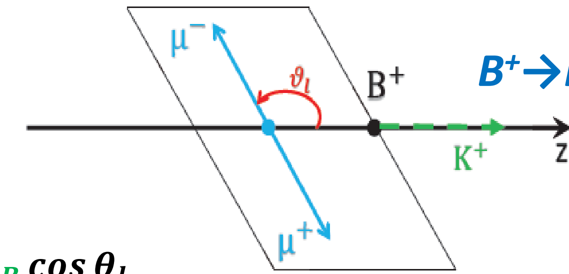

$$\mathrm{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at 95\% CL.}$$

# Angular analysis

- The b→sll decays can be fully described by: the angles of the final state particles, and a series of angular parameters, e.g:

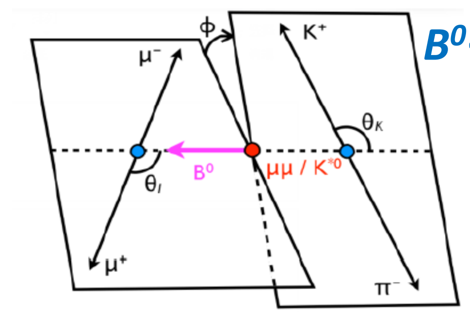
$$\frac{1}{\Gamma}\frac{d\Gamma[B^+\to K^+\mu^+\mu^-]}{d\cos\theta_l} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_l) + \frac{1}{2}F_H + A_{FB}\cos\theta_l$$

$B^+\to K^+\mu^+\mu^-$



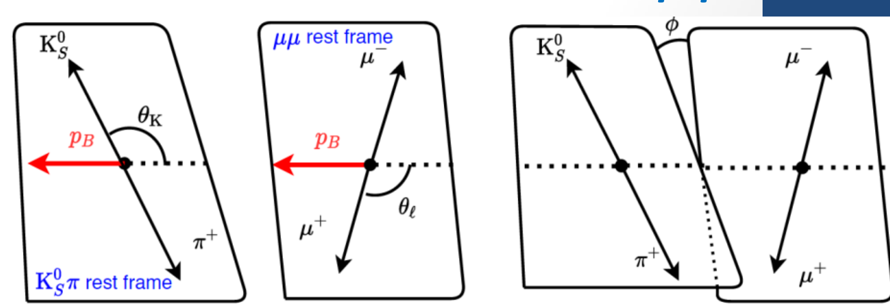

- The angular parameters are functions of q² (square of the di-muon mass)
- The SM has robust predictions of the angular parameters.
- Several angular parameters are:
  - With low theoretical uncertainities,
  - Predicted to be a very small value at SM,
  - Sensitive to specific BSM contribution.

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




- CMS collaboration has presented several results consistent with the SM predictions

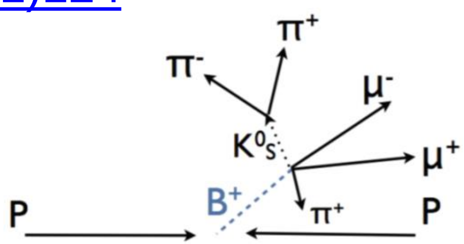
$B^+\to K^{*+}\mu^+\mu^-$



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

**$B^+ \to K^{*+}\mu^+\mu^-$: JHEP04(2021)124**

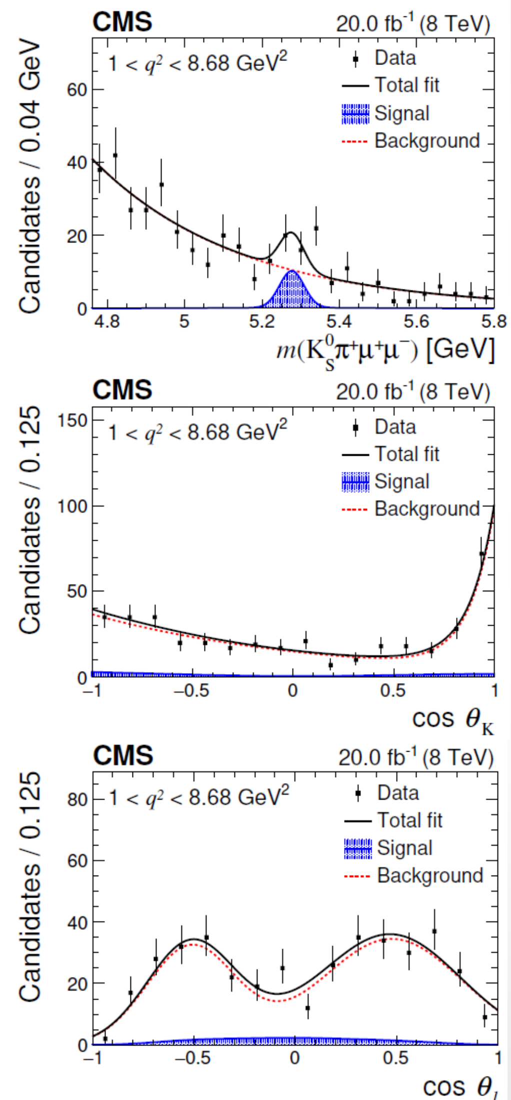
- Final state: $\pi^+\pi^+\pi^-\mu^+\mu^-$
- The decay can be fully described by the three angles ($\theta_\ell$, $\theta_K$, $\phi$) and $q^2$




- Differential decay rate (integrate out $\phi$):

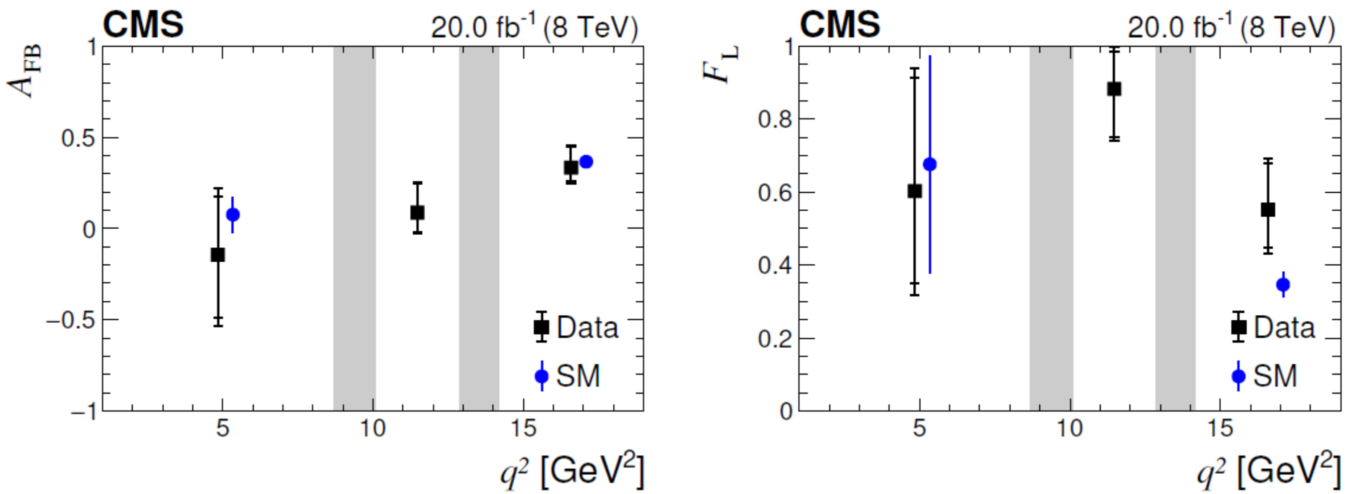
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_\mathrm{K}} = \frac{9}{16}\left[\frac{1}{2}(1-F_\mathrm{L})\left(1-\cos^2\theta_\mathrm{K}\right)\left(1+\cos^2\theta_l\right) + 2F_\mathrm{L}\cos^2\theta_\mathrm{K}\left(1-\cos^2\theta_l\right) + \frac{4}{3}A_{FB}(1-\cos^2\theta_\mathrm{K})\cos\theta_l\right]$$

- Two observables, the forward-backward asymmetry of the muon ($A_{FB}$) and the longitudinal polarization fraction of the $K^{*+}$ ($F_L$), are measured as a function of $q^2$



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

**$B^+ \to K^{*+}\mu^+\mu^-$: JHEP04(2021)124**

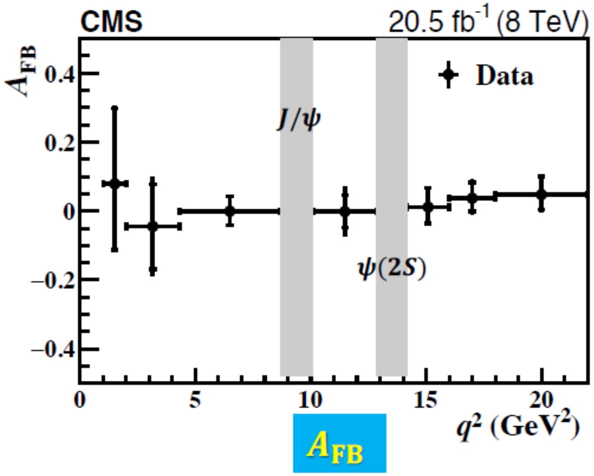


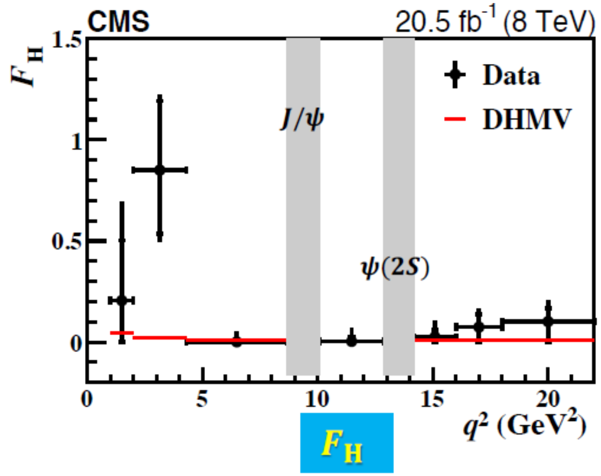

| $q^2$ (GeV$^2$) | $Y_S$ | $A_{FB}$ | $F_L$ |
|---|---|---|---|
| 1–8.68 | $22.1 \pm 8.1$ | $-0.14^{+0.32}_{-0.35} \pm 0.17$ | $0.60^{+0.31}_{-0.25} \pm 0.13$ |
| 10.09–12.86 | $25.9 \pm 6.3$ | $0.09^{+0.16}_{-0.11} \pm 0.04$ | $0.88^{+0.10}_{-0.13} \pm 0.05$ |
| 14.18–19 | $45.1 \pm 8.0$ | $0.33^{+0.11}_{-0.07} \pm 0.05$ | $0.55^{+0.13}_{-0.10} \pm 0.06$ |

- The events are fit in three $q^2$ bins ranging from 1 to 19 GeV$^2$
- $A_{FB}$ and $F_L$ in bins of $q^2$ are found to be consistent with the SM prediction.

# Angular analysis: $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$

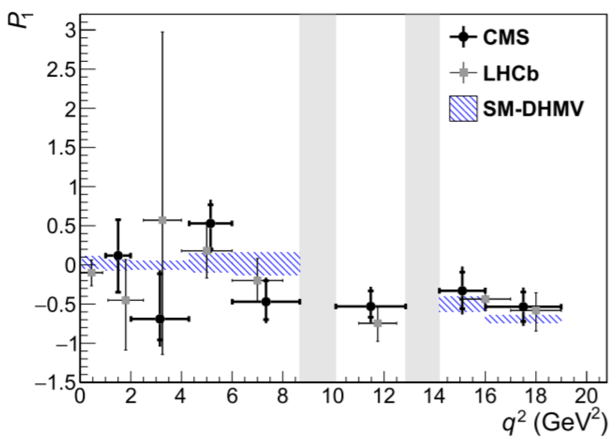
**$B^+ \to K^+\mu^+\mu^-$:** PhysRevD.98.112011

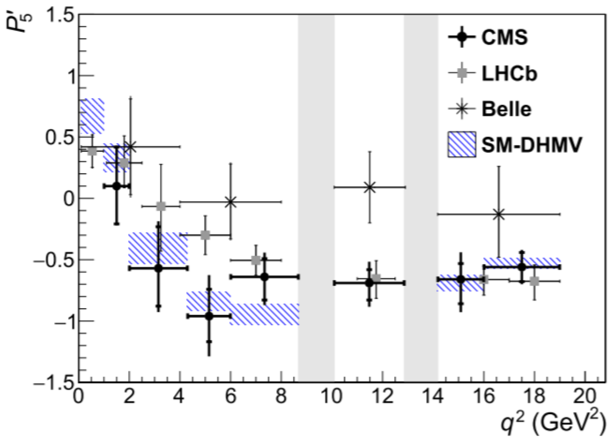



- The events are measured in seven $q^2$ bins ranging from 1 to 22 $GeV^2$
- The measured $A_{FB}$ and $F_H$ are in agreement with the SM predictions.

**$B^0 \to K^{*0}\mu^+\mu^-$:** Phys.Lett.B 781 (2018) 517-541




- The events are fit in seven $q^2$ bins ranging from 1 to 19 $GeV^2$
- The measured ($P_1$, $P_5'$ are in agreement with the SM predictions

# Summary

- The heavy flavor rare decays continue to be a intriguing field to search for the BSM phenomena.
- The measurements at CMS currently presented results consistent with the SM predictions.
- New analyses (R(K), angular analyses…) are ongoing at CMS, with larger amount of datasets and updated technics.

# END

# Thank you!