Tests of LFU and searches for LFV in heavy flavor decays at CMS

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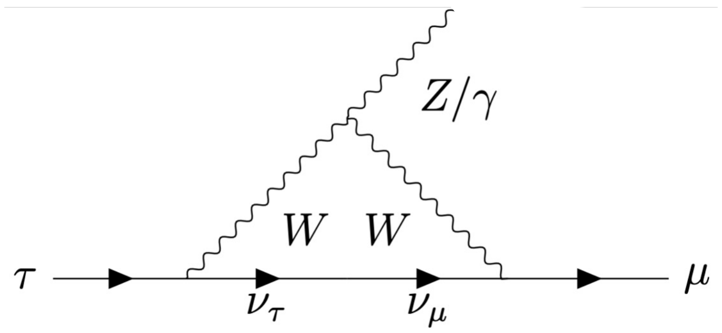
Overview

Lepton Flavour Violation (LFV):

- Standard Model (SM) → no principle that ensures lepton flavor conservation
  - Observation of neutrino oscillation
  - Charged LFV processes still strongly suppressed $\mathcal{O}(10^{-55})$
- Extensions to the SM → predict a much higher BRs, which can be tested in current experiments
  - Expected values: $\mathcal{O}(10^{-10}) - \mathcal{O}(10^{-8})$



Charged LFV only via loop diagrams with neutrino oscillation

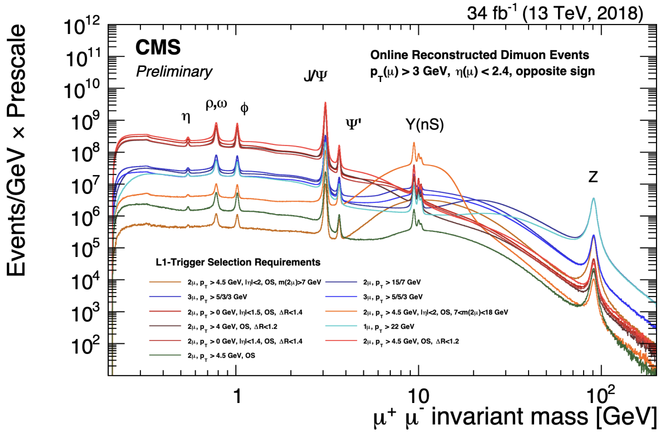
Lepton Flavour Universality Violation (LFUV):

- Standard Model (SM) → different generations of leptons (e, μ, τ) have the same couplings to gauge bosons;
- Beyond Standard Model (BSM) → Alter the branching fractions differently for each lepton species.

Overview

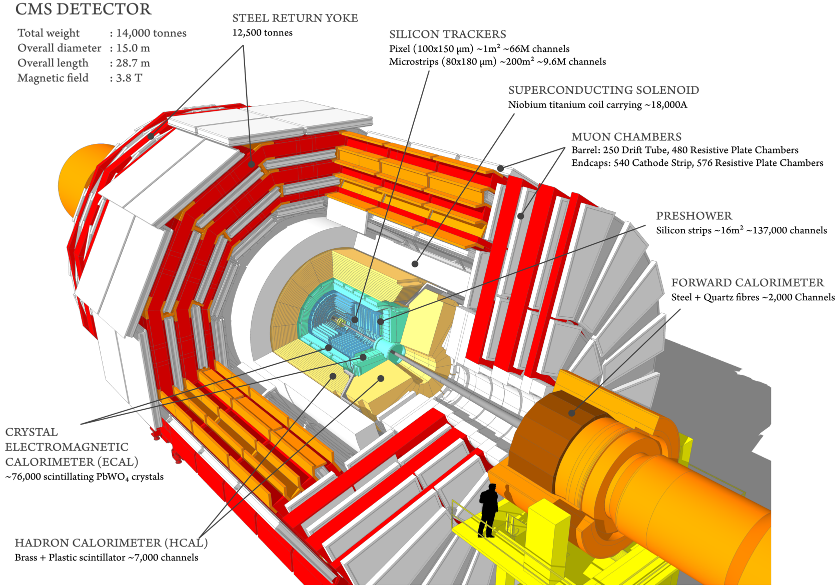
Run2 results obtained by CMS:

- Possible thanks to the powerful CMS trigger system
  - (ex. B-Parking)



In this presentation:

- Search for $\tau \to 3\mu$ decay [Phys. Lett. B 853 (2024) 138633] **LFV**
- Measure of R(K) ratio [Rep. Prog. Phys. 87 (2024) 077802] **LFUV**
- Measure of R(J/ψ) ratio: **LFUV**
  - Leptonic channel [arXiv.2408.00678]
  - Hadronic channel [CMS-PAS-BPH-23-001]

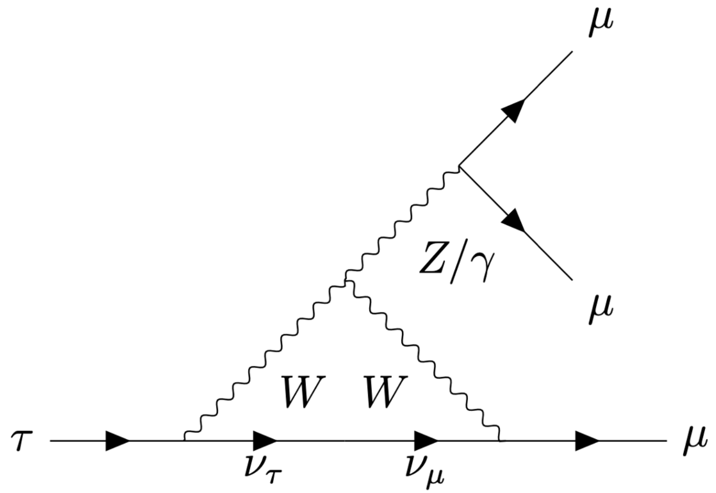


Search for $\tau \rightarrow 3\mu$ decay

LFV

Motivations:

- The SM allows charged LFVs through neutrino oscillation, but with small BRs
  - $\mathcal{B}(\tau \rightarrow 3\mu) \sim \mathcal{O}(10^{-54})$ [Eur. Phys. J. C (2020) 80:438]
- Extensions to the SM predict a much higher BRs
  - Expected values: $\mathcal{B}(\tau \rightarrow 3\mu) \sim \mathcal{O}(10^{-8})$ [JHEP10(2018)148]
- Best result achieved so far:
  - $\mathcal{B}(\tau \rightarrow 3\mu) < 1.9 \cdot 10^{-8}$ @ 90% C.L. by Belle II [arXiv.2405.07386] (2024)



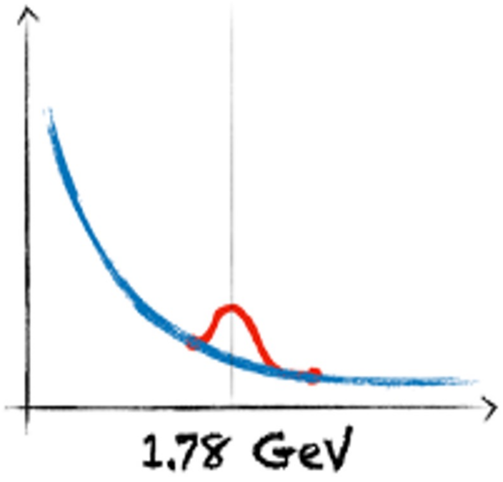
$\boldsymbol{\tau \rightarrow 3\mu}$
Decay in the Standard Model

Search for $\tau \to 3\mu$ decay

LFV

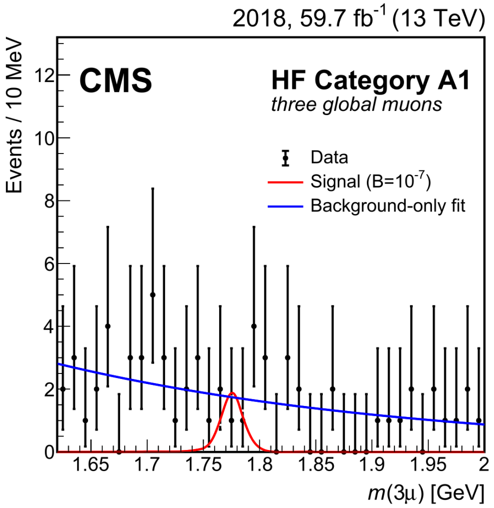
Analysis strategy:

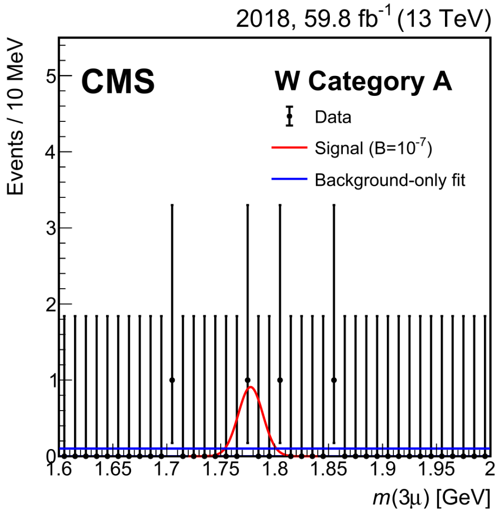
- 2017-2018 p-p collisions at 13 TeV (97.7 /fb) with a dedicated trigger for each channel of the analysis:
  - **Heavy flavour (HF):** tau from decays of B and D mesons
  - **W**: tau from decay of the W boson
- **Signal Candidates**: 3 muons at charge ±1 selected by the trigger + offline selections (common vertex, reconstruction quality, invariant mass)
- **Background rejection**:
  - Vetoes on resonances $\phi \to \mu\mu$ and $\omega \to \mu\mu$
  - MVA to suppress fakes developed specifically for the HF channel
  - BDT for suppression of combinatorial background
- **Event categorization** based on the invariant mass resolution
  - 3 categories per year and per channel

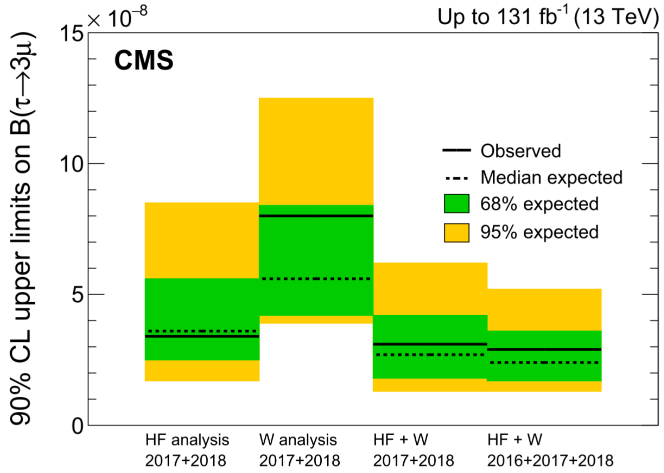


Search for $\tau \rightarrow 3\mu$ decay

LFV







[Phys. Lett. B 853 (2024) 138633]

Results:

- Signal extracted from maximum likelihood fit of the invariant mass of the 3 muons for each category
  - HF: (gaussian + crystalball) + exponential
  - W: gaussian + polynomial
- Observed (expected) upper limit @ 90% C.L.
  - $\mathcal{B}(\tau \rightarrow 3\mu) < 3.1(2.7) \cdot 10^{-8}$ with 2017/2018 data
- Combination with the 2016 result [JHEP01(2021)163]
  - $\mathcal{B}(\tau \rightarrow 3\mu) < 2.9(2.4) \cdot 10^{-8}$ @ 90% C.L.

The **best result** obtained with a hadronic collider!

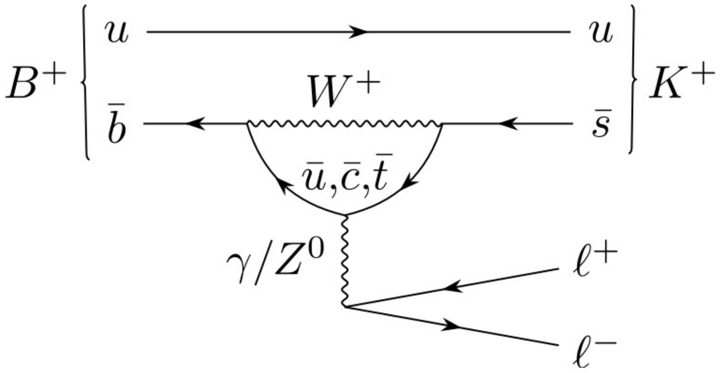
Current world best limit:
$\mathcal{B}(\tau \rightarrow 3\mu) < 1.9 \cdot 10^{-8}$ @ 90% C.L.
by Belle II [arXiv.2405.07386]

Test of LFU in $B^{\pm} \to K^{\pm} l^{+} l^{-}$ decays

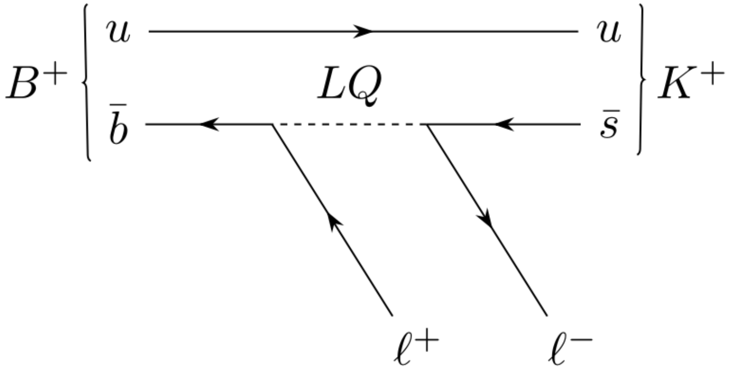
LFUV

Motivations:

- The SM allows for $\bar{b} \to \bar{s}\, l^{+} l^{-}$ only via loop diagrams
  - FCNC transition → very small BR: $\mathcal{O}(10^{-7})$
  - Fully reconstructed final state
  - SM prediction: $R(K) = \frac{BR(B^{\pm} \to K^{\pm} \mu^{+} \mu^{-})}{BR(B^{\pm} \to K^{\pm} e^{+} e^{-})} = 1.00 \pm 0.01$ [Eur. Phys. J. C 76, 440 (2016)]
- BSM physics could modify the BRs differently for different lepton species
  - Example: via a leptoquark with flavor-dependent couplings
- Best results achieved so far:
  - $R(K) = 0.949^{+0.047}_{-0.046}$ by LHCb [Phys. Rev. D 108 (2023) 032002]
  - $R(K) = 1.03^{+0.28}_{-0.24}$ by Belle [JHEP 03 (2021) 105]



$B^{\pm} \to K^{\pm} l^{+} l^{-}$ in the SM



$B^{\pm} \to K^{\pm} l^{+} l^{-}$ in BSM theory that introduces a leptoquark (LQ) with flavor-dependent couplings

Test of LFU in $\mathrm{B}^{\pm} \to \mathrm{K}^{\pm} l^{+} l^{-}$ decays

LFUV

Analysis strategy:

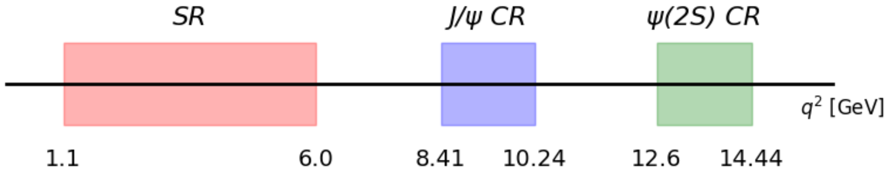
- 2018 p-p collisions at 13 TeV (41.6 /fb) collected with the B-parking technique. Two channels:
  - $\mathbf{B}^{\pm} \to \mathbf{K}^{\pm}\boldsymbol{\mu}^{+}\boldsymbol{\mu}^{-}$ → 1 μ selected from the HLT (tag side) + 1 OS μ in the muon system acceptance
  - $\mathbf{B}^{\pm} \to \mathbf{K}^{\pm}\boldsymbol{e}^{+}\boldsymbol{e}^{-}$ → probe side of the HLT, 2 Particle Flow (PF) electrons <u>or</u> 1 PF + e identified by a **dedicated low-p_T electron ID** (LP)
  - Both channels: Loose selections on common vertex, reconstruction quality, invariant mass

Goal: $$R(K) = \frac{BR(\mathrm{B}^{\pm}\to\mathrm{K}^{\pm}\mu^{+}\mu^{-})}{\boldsymbol{BR(B^{\pm}\to K^{\pm} J/\psi(\to\mu^{+}\mu^{-}))}} \Big/ \frac{BR(\mathrm{B}^{\pm}\to\mathrm{K}^{\pm}e^{+}e^{-})}{\boldsymbol{BR(B^{\pm}\to K^{\pm} J/\psi(\to e^{+}e^{-}))}}$$

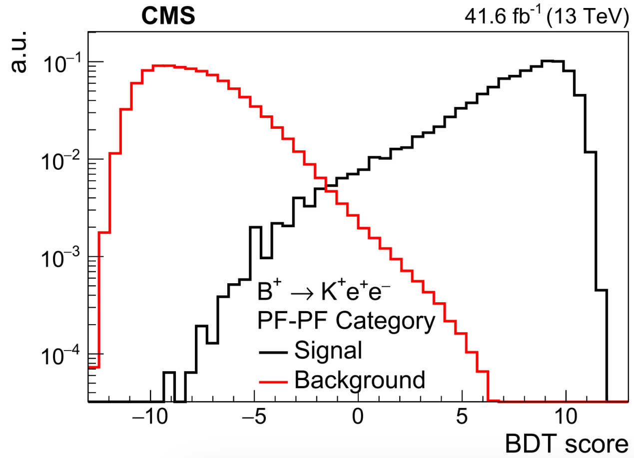
Cancel out sys. unc. !

$\boldsymbol{BR(J/\psi \to \mu^{+}\mu^{-}) - BR(J/\psi \to e^{+}e^{-})} = 0.0 \pm 0.007$

- 3 q^2 regions per channel:



- Background rejection:
  - Sources: Combinatorial, Partially reconstructed B decays;
  - Suppressed via BTD.



Test of LFU in $B^{\pm} \to K^{\pm} l^{+} l^{-}$ decays

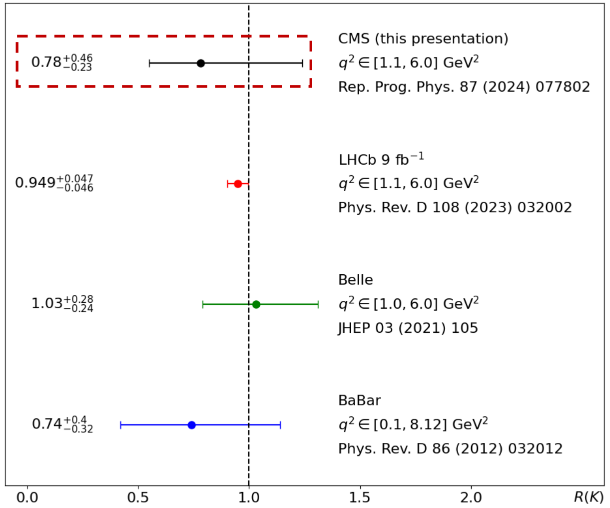
LFUV

Results:

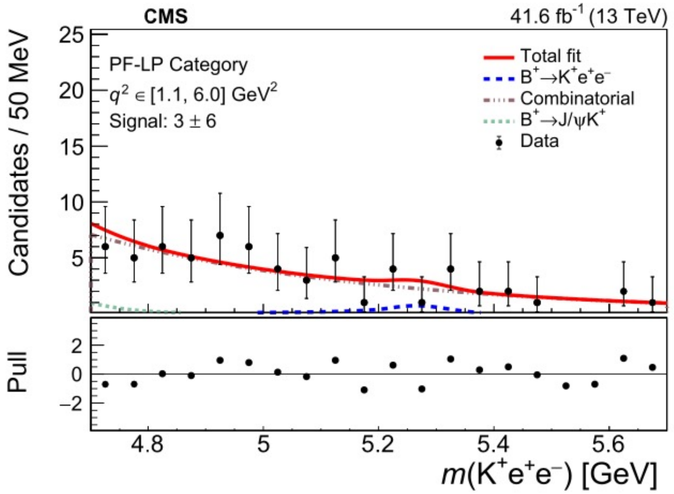
Signal is obtained via maximum likelihood fit of the $m(Kl^{+}l^{-})$ invariant mass. R(K) is measured to be:

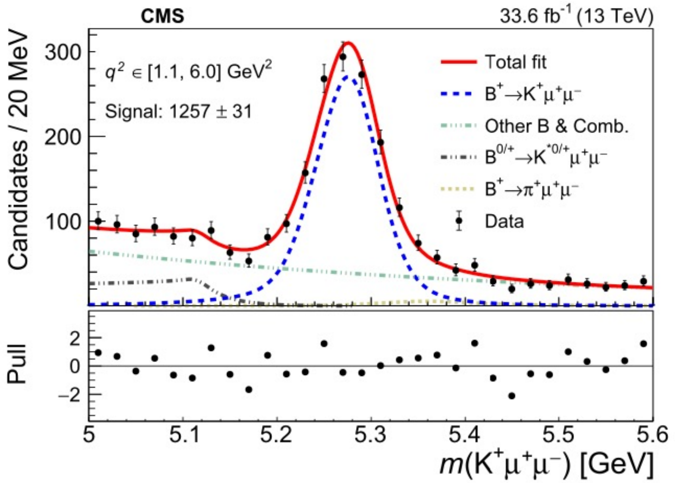
$$R(K) = 0.78^{+0.46}_{-0.23}(stat)^{+0.09}_{-0.05}(sys)$$

Compatible within 1σ with the SM prediction:

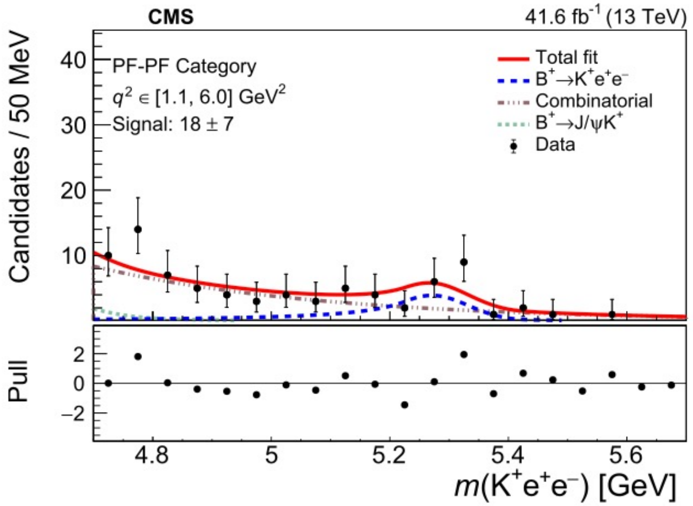


[Rep. Prog. Phys. 87 (2024) 077802]





Analysis bottleneck: low statistic in the electron channel

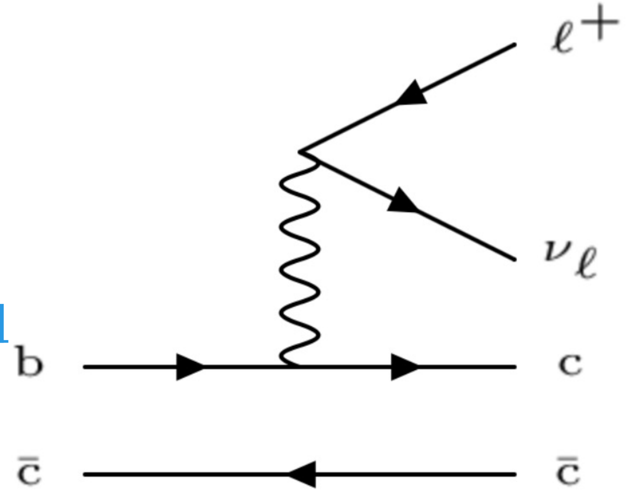


Test of LFU in $B_c^+ \to J/\psi l^+ \nu_l$ decays

LFUV

Motivations:

- The SM allows for $b \to c\, l^- \nu_l$ at tree level
  - Very large BR
  - Missing energy (neutrino in final state)
  - Precise prediction: $R(J/\psi) = \frac{BR(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{BR(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)} = 0.2582 \pm 0.0038$ [PhysRevLett.125.222003]
- BSM physics could modify this ratio [Phys. Rev. D 92, (2015) 054018]
- Best result achieved so far:
  - $R(J/\psi) = 0.71 \pm 0.17(stat) \pm 0.18(sys)$ by LHCb [Phys. Rev. Lett 120 (2018) 121801]
- At CMS, two possible channels (depending on τ decay)
  - **Leptonic channel**: $\tau \to \mu \nu_\mu \nu_\tau$
  - **Hadronic channel**: $\tau \to \pi\pi\pi$



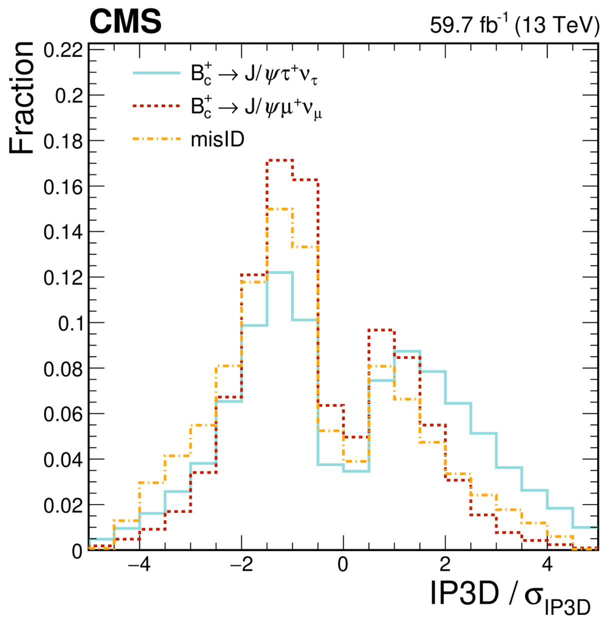
Test of LFU in $B_c^+ \to J/\psi l^+ \nu_l$

Leptonic Channel

LFUV

Analysis strategy:

- 2018 p-p collisions at 13 TeV (59.7 /fb) collected with a dedicated trigger
  - $B_c^+ \to J/\psi(\to \mu\mu)\,\tau^+(\to \mu^+ \nu_\mu \nu_\tau)\nu_\tau$ (NUM) and $B_c^+ \to J/\psi(\to \mu\mu)\,\mu^+\nu_\mu$ (DEN) with **3 μ + 1 or 3 ν** in the **final state**
  - Online selections: 2 OS μ compatibile with J/ψ + 1 μ ($p_T > 5, 3, 0$ GeV and $|\eta| < 2.5$)
  - Offline selections: impact parameter, reconstruction quality, invariant mass (of J/ψ and B_c^+), vertex probability
- Background sources:
  - $H_b \to J/\psi + \mu$ (or combinatorial muon)
  - $B_c^+ \to J/\psi$ + charmed hadrons
  - Fake muons: $J/\psi(\to \mu\mu)$ + misidentified hadron (K or π)
  - Combinatorial μμ (in J/ψ mass range)
- Categorization (7 categories x 2 (muon isolation cut)) based on:
  - $q^2 = (p_{B_c^+} - p_{J/\psi})^2$
  - Significance of $dis(J/\psi\ vtx, BS)$ in the transverse plane
  - 3D IP significance
  - 3μ mass



Test of LFU in $B_c^+ \to J/\psi l^+ \nu_l$

Leptonic Channel

LFUV

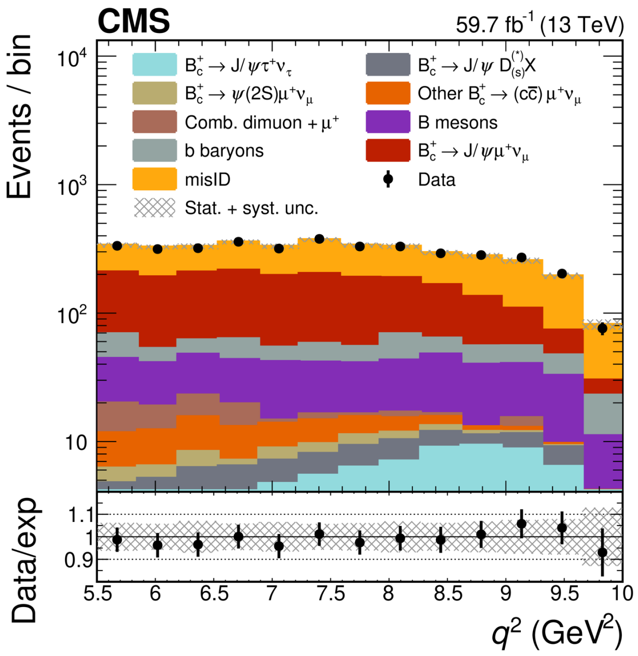
Results:

From the maximum likelihood of each category the following ratio is obtained:

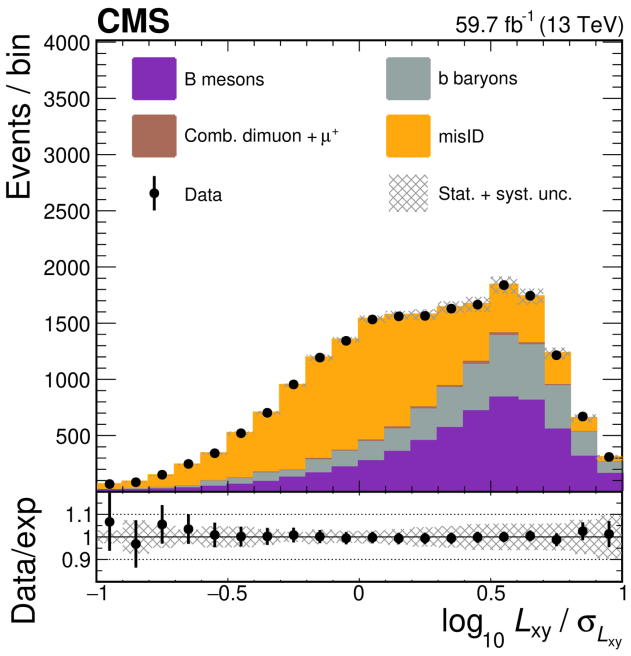
$$R(J/\psi) = 0.17^{+0.18}_{-0.17}(stat)^{+0.21}_{-0.22}(sys)^{+0.19}_{-0.18}(theo)$$

[arXiv.2408.00678]

Compatible within 0.3 σ with the SM prediction and within 1.3 σ with the LHCb results*



q^2 distribution for the signal-enriched category: $m(3\mu) < m_{B_c}$ & $q^2 > 5.5$ GeV^2 & IP3D/σ_{IP3D}> 2



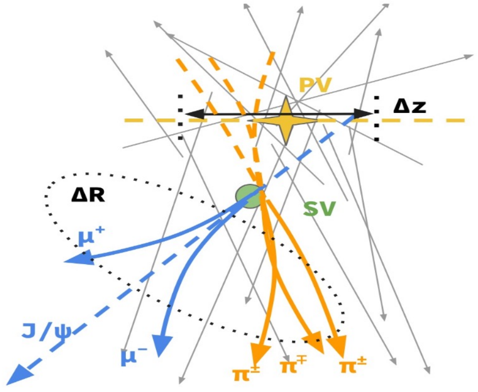
$L_{xy}/\sigma_{L_{xy}}$ distribution for a background like category: $m(3\mu) > m_{B_c}$

* $R(J/\psi) = 0.71 \pm 0.17(stat) \pm 0.18(sys)$
[Phys. Rev. Lett 120 (2018) 121801]

Test of LFU in $B_c^+ \to J/\psi l^+ \nu_l$

Hadronic Channel

LFUV



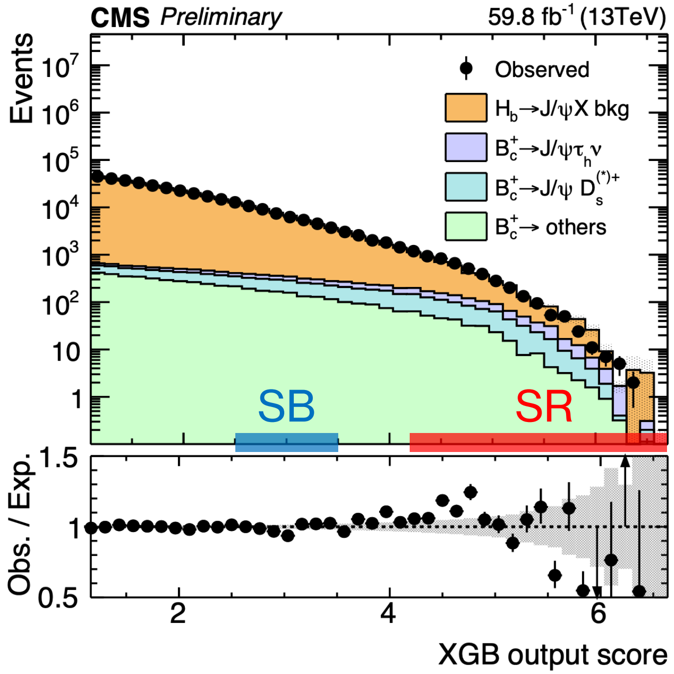
Goal: $R(J/\psi) = \frac{BR(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{BR(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)}$

Where $\tau \to \pi\pi\pi\bar{\nu}_\tau$

From the previous analysis

Analysis strategy:

- 2016-2018 p-p collisions at 13 TeV (138 /fb):
  - Online selections: 2 OS μ compatibile with J/ψ + 1 track
  - Offline selections: 3 tracks with common vtx displaced wrt PV and 3(trk mass)<1.7GeV
- Background sources:
  - $H_b \to J/\psi + X$ (main bkg)
  - $B_c^+ \to J/\psi$ + charmed hadrons
    - Mainly $B_c^+ \to J/\psi\, D_s^{(*)+}$
- Background rejection via BDT:
  - 18 input variables related to the kinematics of the B-meson, τ candidate and global event-level observables.

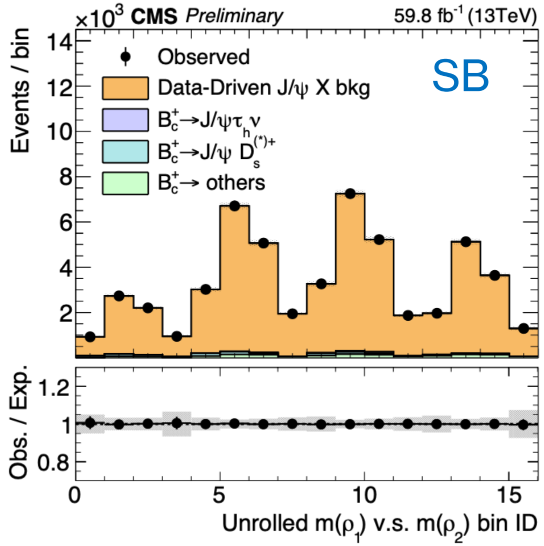


Test of LFU in $B_c^+ \to J/\psi l^+ \nu_l$

Hadronic Channel

LFUV

- Estimate $H_b \to J/\psi + X$ bkg with a data driven method.
  - In signal channel: $\tau \to \pi\pi\pi$ mainly due to intermediate $\rho(770) \to \pi\pi$
  - Define ρ_1 and ρ_2 as the 2 possible OS π combinations
  - Estimation via simultaneous fit of SB, SR and leptonic data channel



Results:

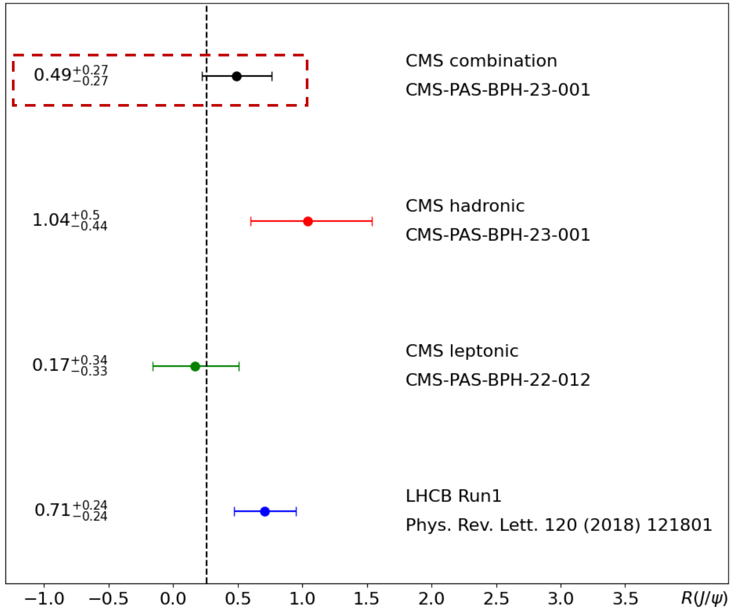
- $R(J/\psi)$ obtained via simultaneous fit with the leptonic τ analysis

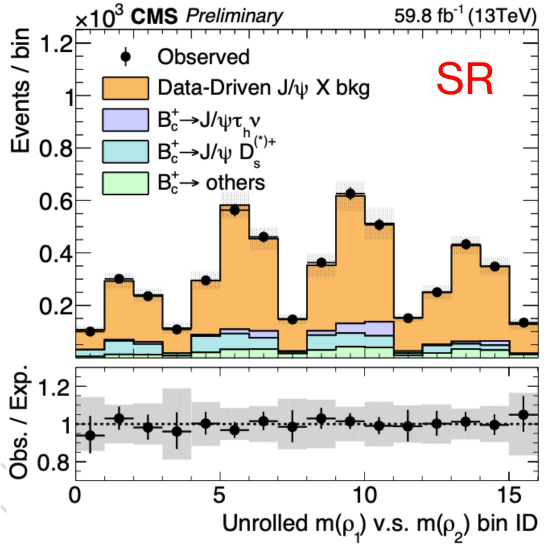
$$R(J/\psi)_{had} = 1.04^{+0.50}_{-0.44}$$

- Combining with the leptonic channel:

$$R(J/\psi) = 0.49 \pm 0.25(sys) \pm 0.09(stat)$$

  - Consistent with the SM prediction within 1σ. [CMS-PAS-BPH-23-001]





Conclusions

Recent CMS results on searches for LFV and LFUV

LFV Search for $\tau \rightarrow 3\mu$

- Best result obtained at a hadron collider
- Still limited by statistics

LFUV mesure of R(K) and R(J/ψ)

- Both compatible with SM within 1 σ
- CMS results compatible with those from machines designed for B-physics

Thanks for your attention!

Backup

Search for $\tau \rightarrow 3\mu$ decay

The LHC is a τ factory:

Two main sources of τ leptons at the LHC:

- Heavy Flavour (HF) channel (~ 99.9 %)
  - Low p_T and high |η|
  - Sensitive to the presence of K and π mis-identified as muons
- W channel (~ 0.01 %)
  - High p_T and low |η|

Process 1	Process 2	No. of τ fo
$pp \rightarrow c\bar{c} + \ldots$	$D \rightarrow \tau\nu_\tau$ (95% D_s, 5% $D^\pm$)	$11.8 \cdot 10^{12}$ *
$pp \rightarrow b\bar{b} + \ldots$	$B \rightarrow \tau\nu_\tau + \ldots$ (44% $B^\pm$, 45% B^0, 11% B_s^0)	$5.45 \cdot 10^{12}$
	$B \rightarrow D(\tau\nu_\tau) + \ldots$ (98% D_s, 2% $D^\pm$)	$1.86 \cdot 10^{12}$
$pp \rightarrow W + \ldots$	$W \rightarrow \tau\nu_\tau$	$1.99 \cdot 10^9$
$pp \rightarrow Z + \ldots$	$Z \rightarrow \tau\tau$	$3.86 \cdot 10^8$

* Refers to the number of τ expected for an integrated luminosity of 97.7 fb^{-1}

Search for τ → 3μ decay

Event categorization:

Data and MC are divided into three categories based on the resolution of the invariant mass:

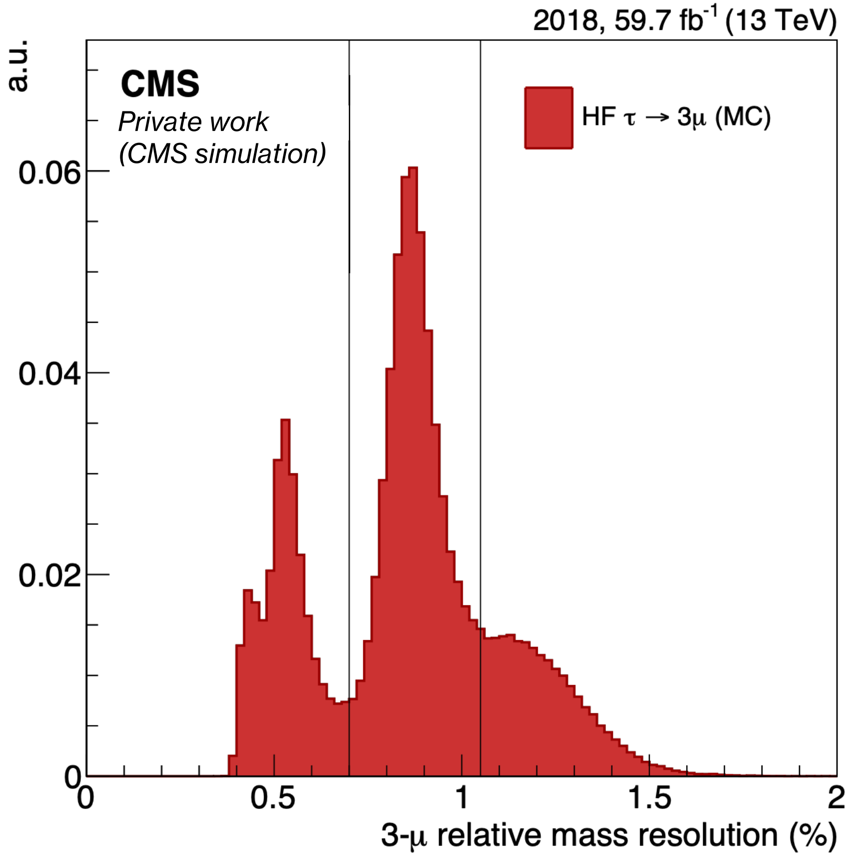
$$\sigma_m/m = \frac{\sqrt{\sum_{i=1}^{3}(m(\delta\tau_i)-m(\tau))^2}}{m(\tau)}$$

where $\delta\tau_i = (p_{Ti} + \delta p_{Ti}, \eta_i, \phi_i, m_i) + \sum_{j=1, j\neq i}^{3}(p_{Tj}, \eta_j, \phi_j, m_j)$

A. $\frac{\sigma_m}{m} < 0.7\%$

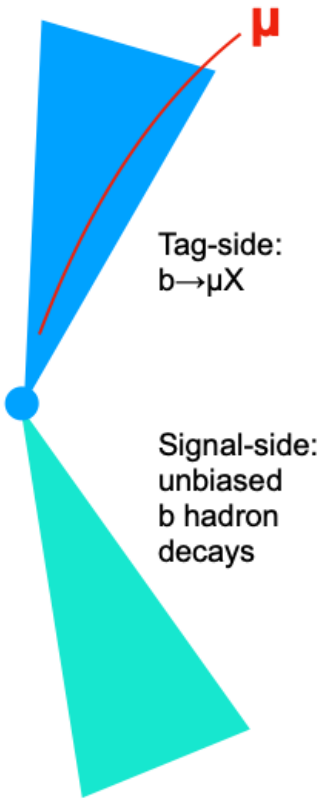
B. $0.7\% \frac{<\sigma_m}{m} < 1.1\%$

C. $\sigma_m/m > 1.1\%$



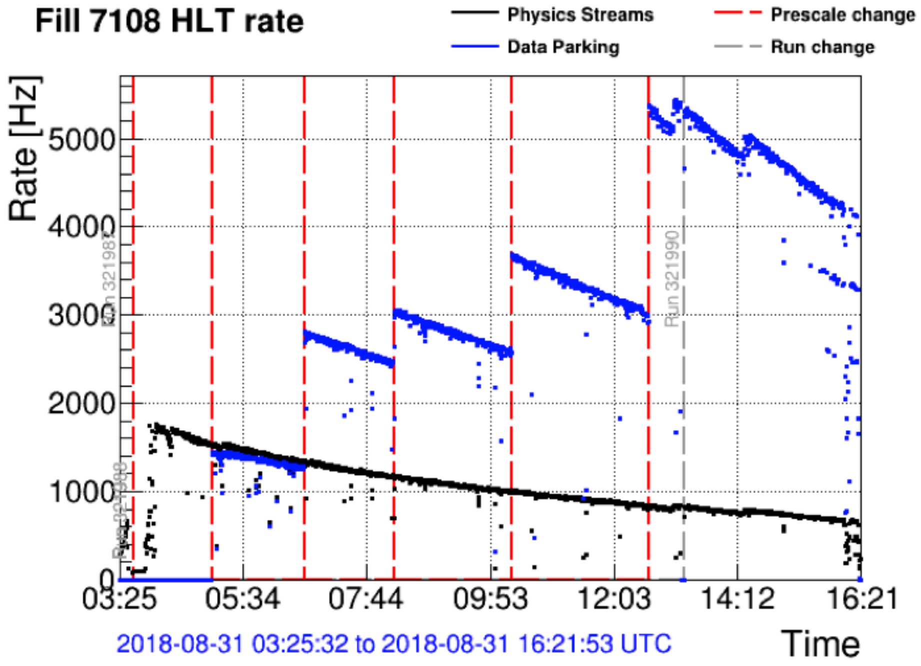
These regions are related to the pseudorapidity of muons in the final state and reflect the geometry of the internal tracker that dominates the resolution on the p_T for low- p_T muons

Test of LFU in $B^{\pm} \rightarrow K^{\pm} l^{+} l^{-}$ decays



B-Parking dataset :

- Collected from single muon triggers
- Rate that increases in steps as the rate of the Physics Stream decreases
- The B-parking dataset contains ~10 billion unbiased decays of hadrons containing b quarks
- Integrated luminosity equal to 41.5±1.0 fb^{-1}



[CMS DP -2019/043]