Lepton Flavor and Lepton Flavor Universality Violation in heavy flavor decays at CMS

Blois 2024
35th Rencontres de Blois on "Particle Physics and Cosmology"

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on behalf of the CMS Collaboration

Lepton Flavour Violation (LFV)

- **Standard Model (SM) → no principle that ensures lepton flavor conservation**
  - Violation: Observation of neutrino oscillation
  - Charged LFV processes still strongly suppressed $\mathcal{O}(10^{-55})$

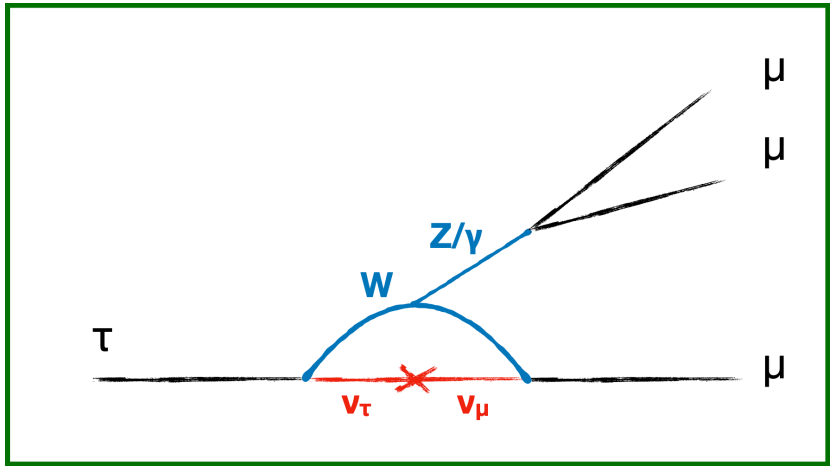
    [Eur. Phys. J. C (2020) 80:438]

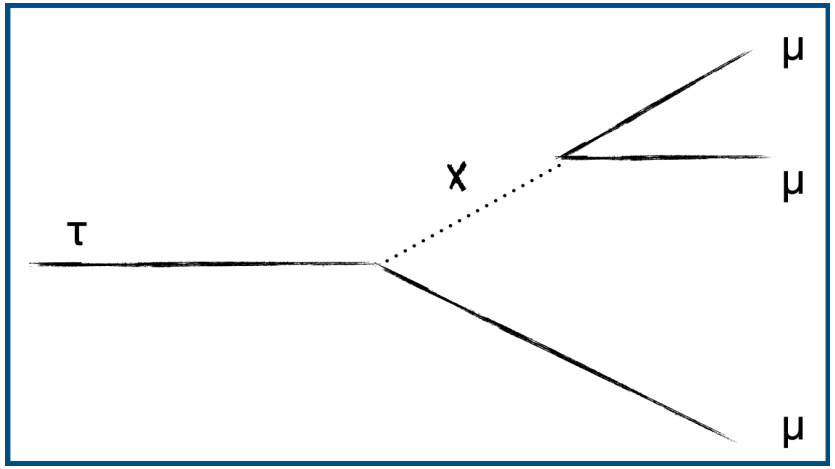
- **$\tau \to 3\mu$ decay: excellent probe for LFV test at colliders**
  - Extensions to the SM → predict a much higher BRs, which can be tested in current experiments
  - Expected values: $\mathcal{O}(10^{-10}) - \mathcal{O}(10^{-8})$ [JHEP10(2018)148]
  - Very clean final state, easy to trigger and reconstruct
  - Best result achieved so far:

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

In this talk: CMS results on Full Run2 data

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





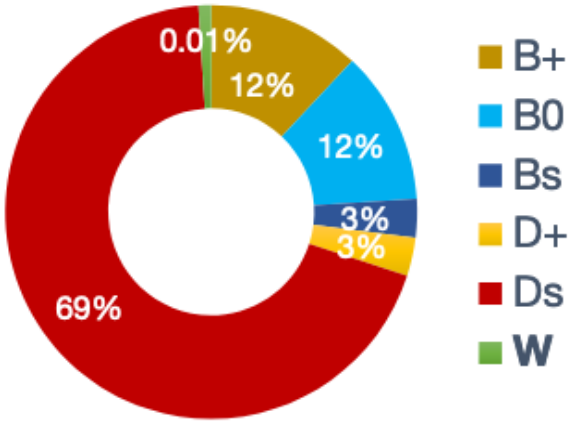
$\tau \rightarrow 3\mu$ decay: analysis strategy

PLB 853 (2024) 138633

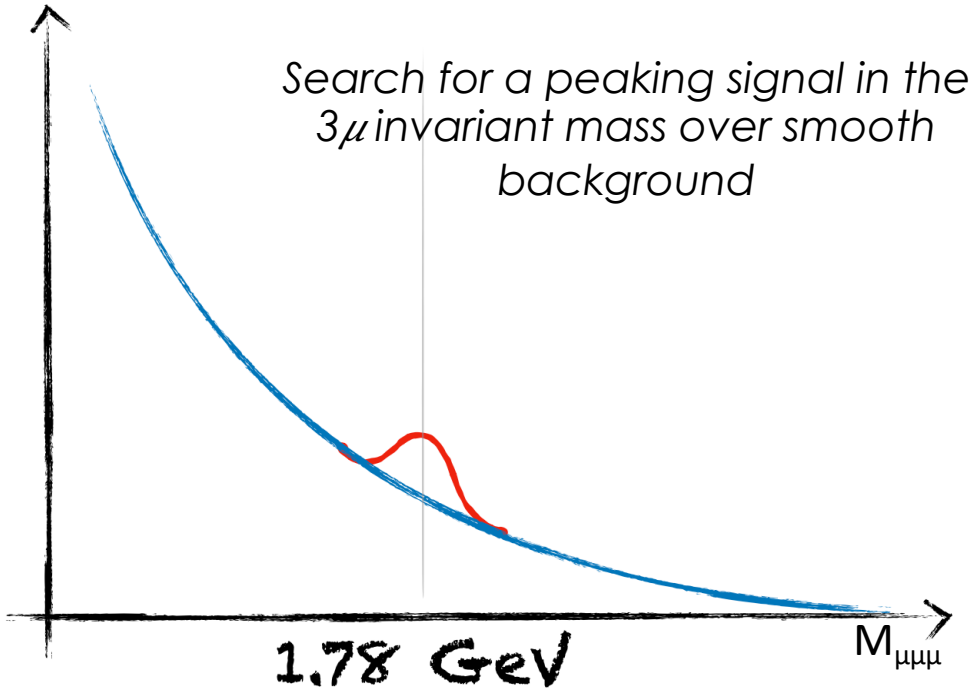
- 2017-2018 pp collisions at $\sqrt{s}$=13 TeV (L=97.7/fb)
- Previously: 33/fb on 2016

- Dedicated trigger for each channel of the analysis:
  - **Heavy flavour (HF):** tau from decays of B and D mesons
    - High stat, low-pT leptons and higher background
  - **W**: tau from decay of the W boson
    - low stat, high-pT leptons in the final state + MET

- **Signal Candidates**: 3 muons at charge ±1 selected by the trigger + offline selections
  - Common displaced vertex, reconstruction quality, invariant mass



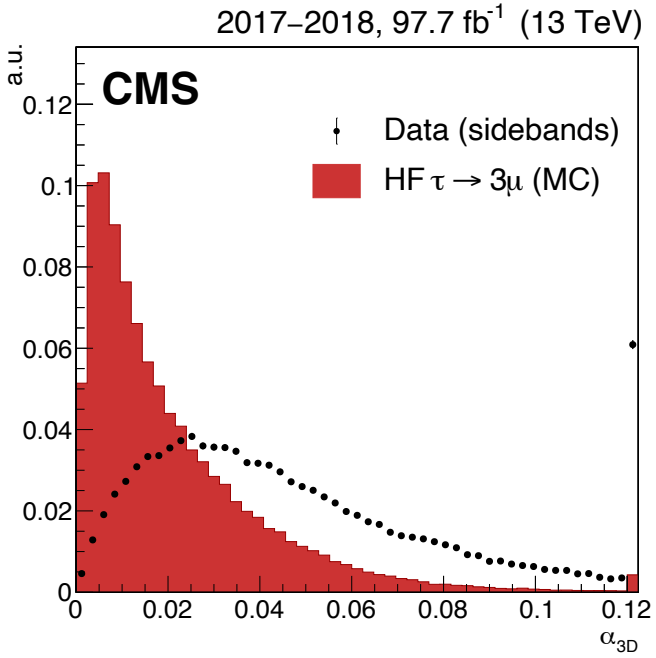
Search for a peaking signal in the 3μ invariant mass over smooth background

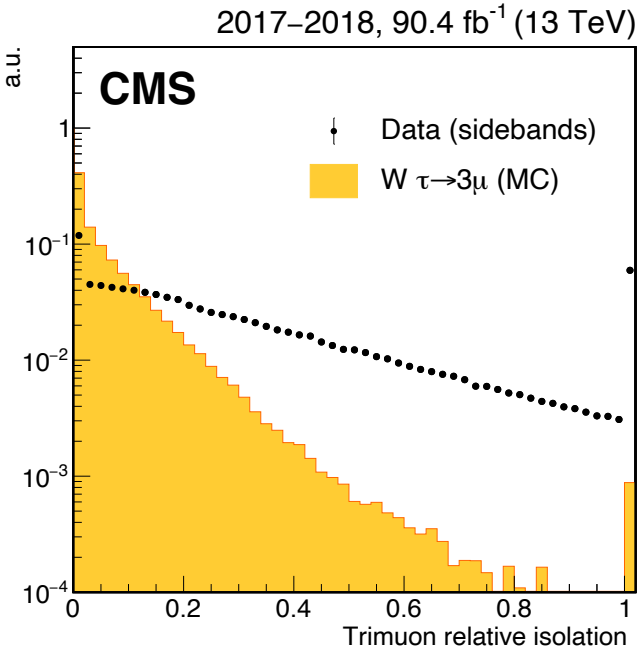


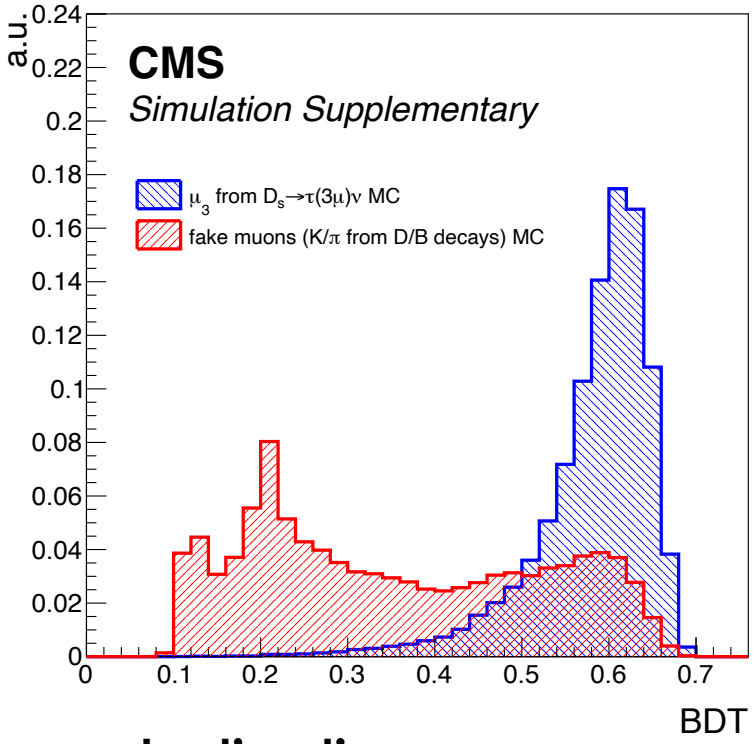
$\tau \rightarrow 3\mu$ decay: Background

Background Composition :

- two real muons plus one fake
- 3 genuine muons two of which come from resonances (φ(1020) ω(783), Ds → η (μμγ) μν)
- Other combinatorial
- W channel: SM W→3μ







Background estimation:
Fit data sidebands, used as proxy for background

Background suppression

- BDT based MVA muon ID
- Per-event BDT classifier with per-muon and per-triplet variables as an input
- W channel: cut on the three-muon displacement

$\tau \rightarrow 3\mu$ decay: Signal extraction

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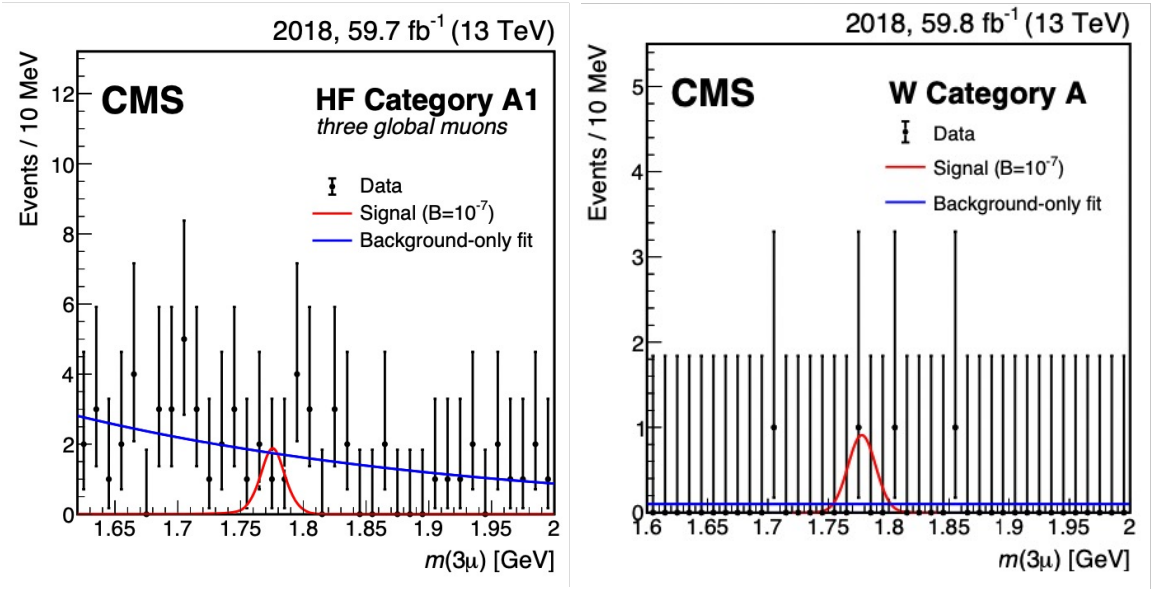
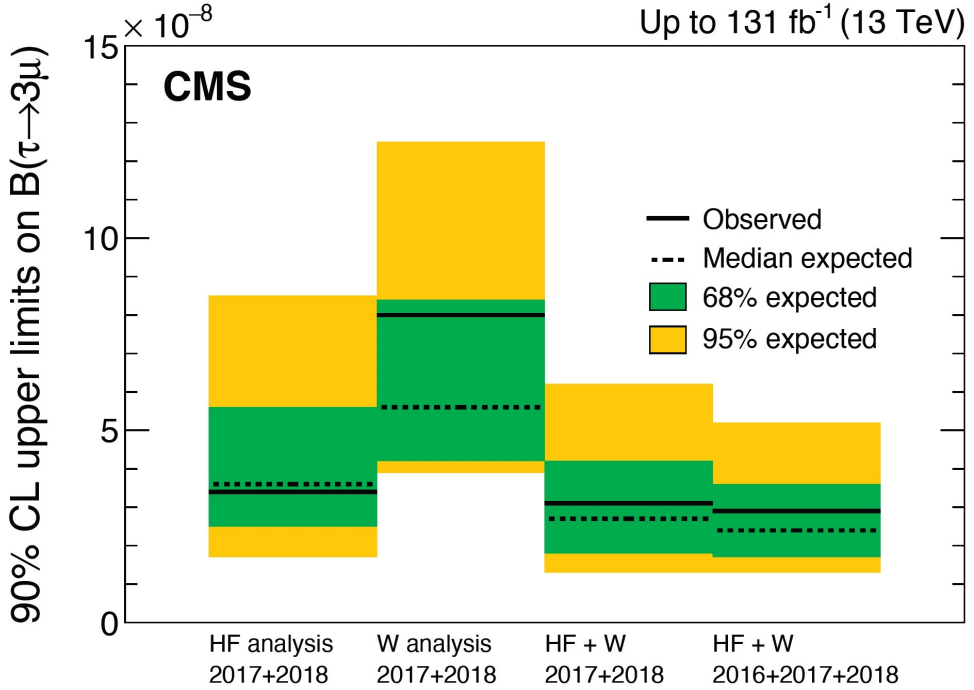
- Event **categorization** based on production mode, data taking period, three-muon mass resolution
- Signal extraction on the **three-muon mass shape**
- Results dominated by **statistical** uncertainty

2017+2018 analysis results:
- **HF:** observed (exp) upper limit: 3.4×10^{-8} (3.6×10^{-8}) 90% CL
- **W:** observed (exp) upper limit: 8.0×10^{-8} (5.6×10^{-8}) 90% CL

2016 analysis results: doi:10.1007/JHEP01(2021)163
- $8.8\times(10^{-8})$ 90% CL

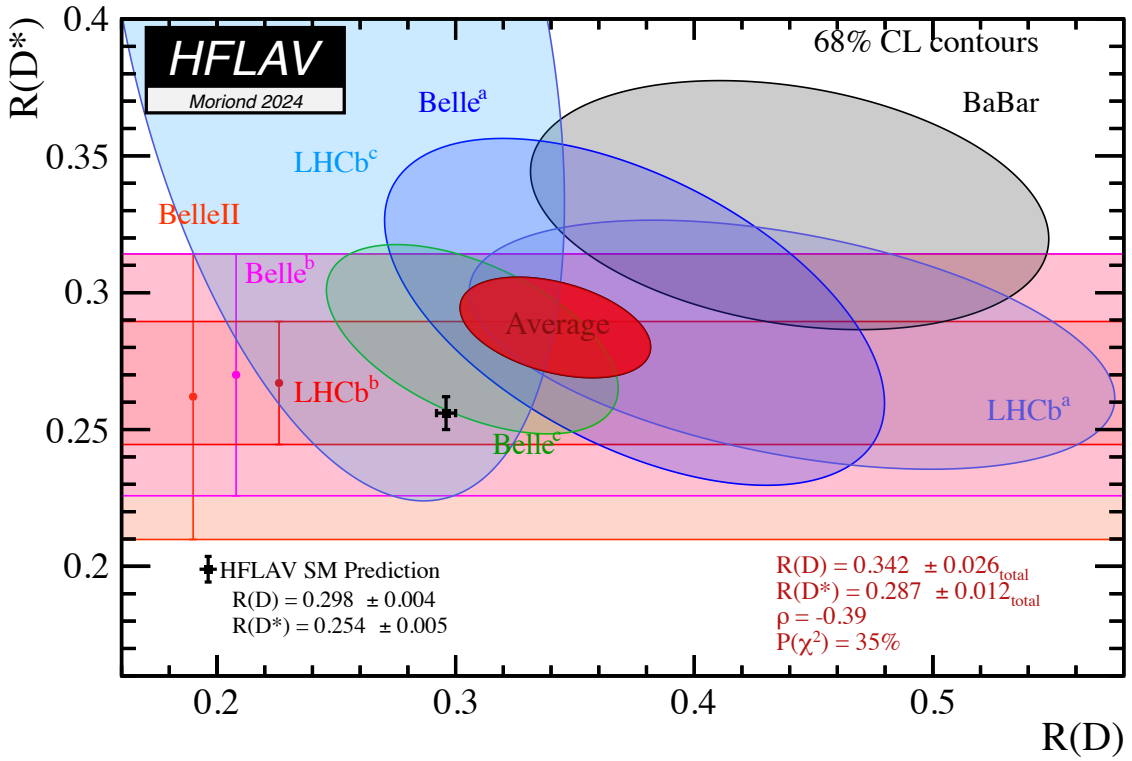
Full Run 2 result: $2.9\times10^{-8}(2.4\times10^{-8})$ 90% CL





Lepton Flavour Universality (LFU)

- Standard Model: **different generations** of leptons have the **same couplings** to gauge bosons;
- The Yukawa coupling exhibits a flavour structure, giving different mass to each charged lepton family



- Beyond Standard Model: could alter the branching fractions differently for each lepton species.
- **R(D)-R(D*): 3σ tension with SM**

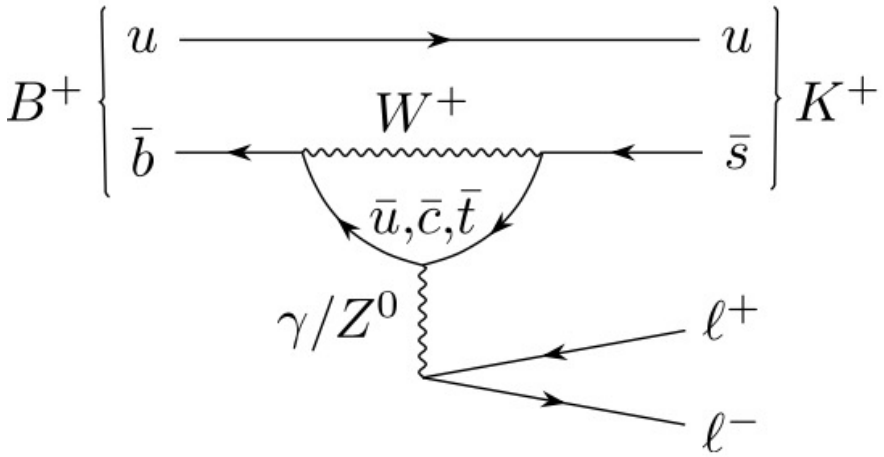
Lepton Flavour Universality (LFU)

$b \to sll$

$$R(K) = \frac{\mathcal{B}(B \to \mu\mu K)}{\mathcal{B}(B \to eeK)}$$

SM: 1.00 ± 0.01

- Small BR (loop level)
- Neutrino-less

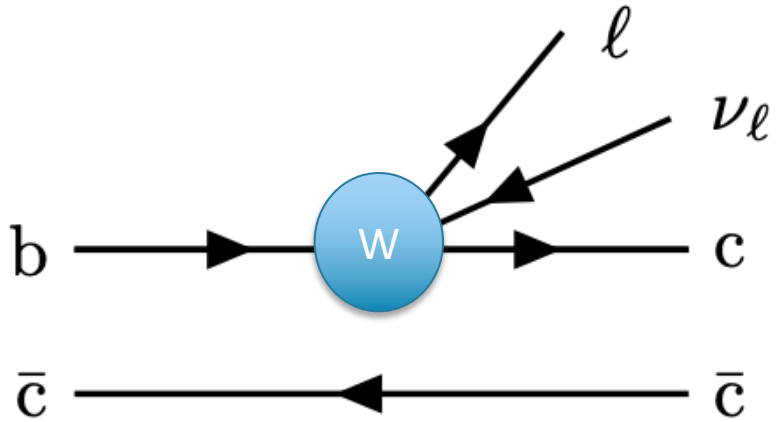


$b \to c l \nu_l$

$$R(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi\tau\nu_\tau)}{\mathcal{B}(B_c \to J/\Psi\mu\nu_\mu)}$$

SM: 0.2582 ± 0.0038 Phys. Rev. Lett. 125, 222003

- Large BR (tree level)
- Neutrinos in the final state



Lepton Flavour Universality (LFU)

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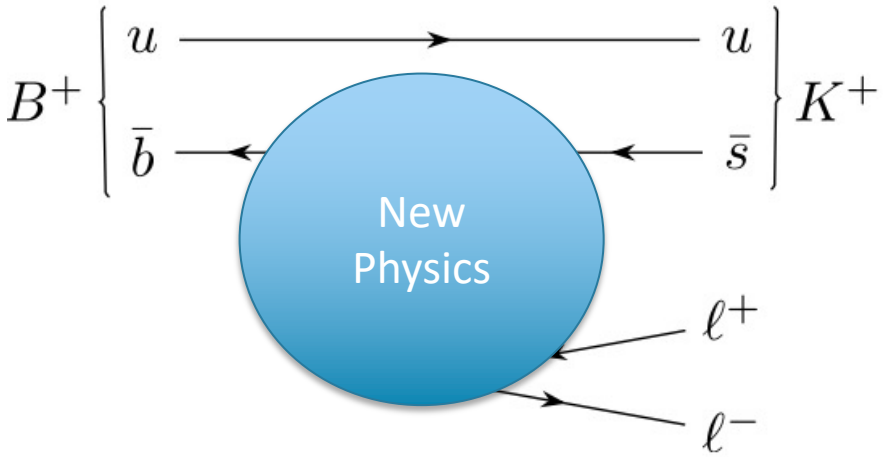
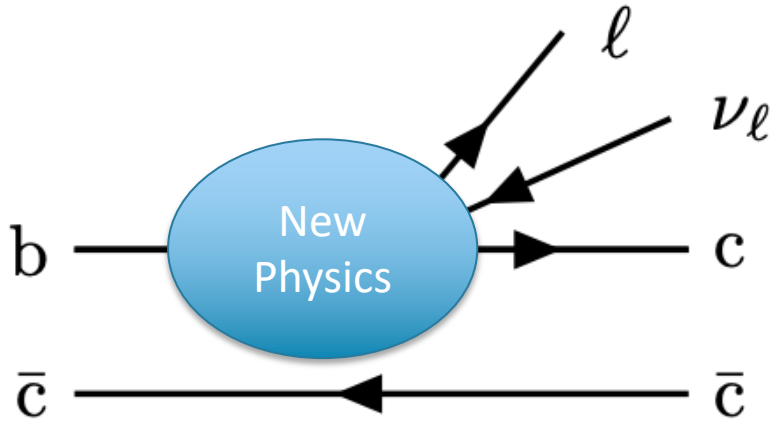


$b \to cl\nu_l$

$$R(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi\tau\nu_\tau)}{\mathcal{B}(B_c \to J/\Psi\mu\nu_\mu)}$$

SM: 0.2582 ± 0.0038 Phys. Rev. Lett. 125, 222003

- Large BR (tree level)
- Neutrinos in the final state



$B^{\pm} \to K^{\pm}\ell\ell$ search strategy

- B-parking dataset: 10^{10} unbiased B-hadron events collected with single muon triggers
- $\mathcal{L}$ = 41.6 /fb https://arxiv.org/abs/2403.16134

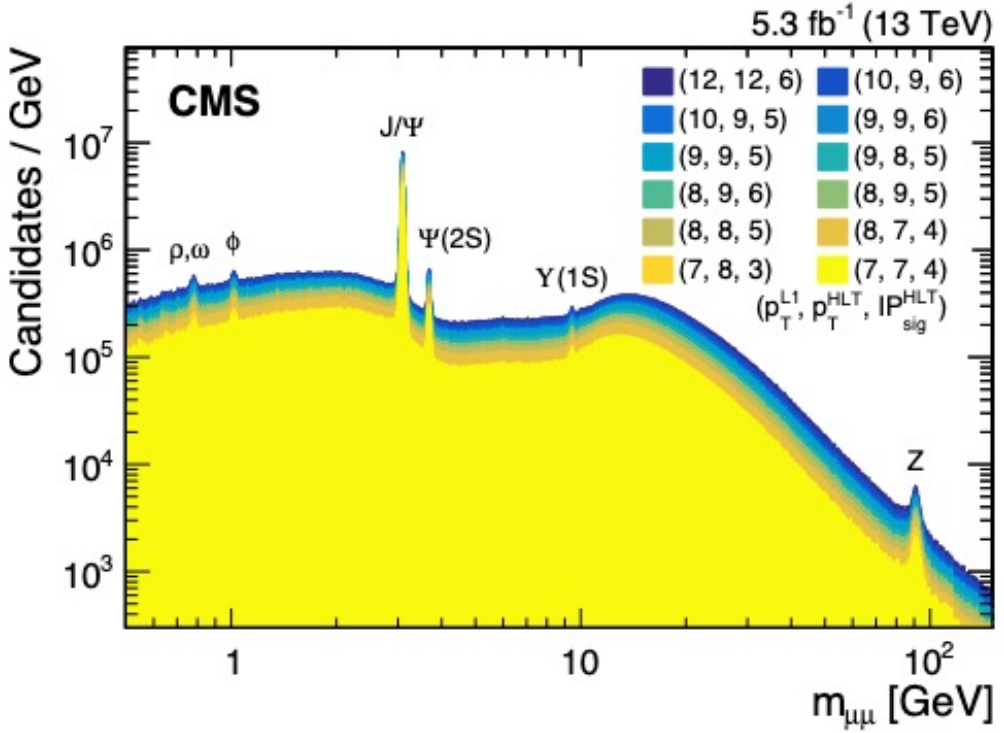
$B^{\pm} \to K^{\pm}\mu\mu$:

- 1 μ selected from the HLT (tag side)
- 1 OS μ in the muon system acceptance

$B^{\pm} \to K^{\pm}ee$: probe side of the HLT, 2 categories:

- 2 Particle Flow (PF) electrons
- 1 PF+1 LP (**Dedicated low-pT electron ID**, LP)

Loose selections on common vertex, lepton reconstruction quality, invariant mass



$$R(K) = \frac{\mathcal{B}(B \to \mu\mu K)}{\mathcal{B}(B \to eeK)}$$

$B^{\pm} \to K^{\pm}\ell\ell$ search strategy

2024 Rep. Prog. Phys. 87 077802

$$R(K) = \frac{\mathcal{B}(B \to \mu\mu K)}{\mathcal{B}(B \to eeK)}$$

Background

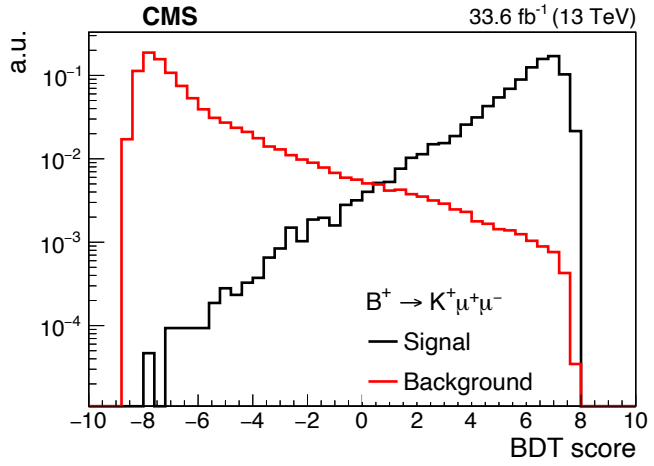
- Sources: Combinatorial, Partially reconstructed B decays;
- Rejection: suppressed via BTD.

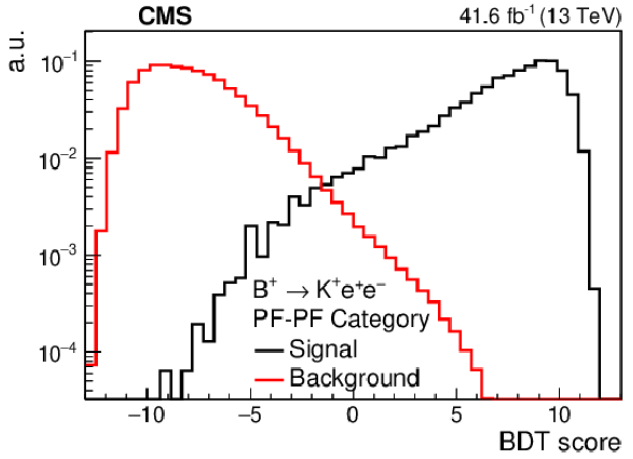
Normalization

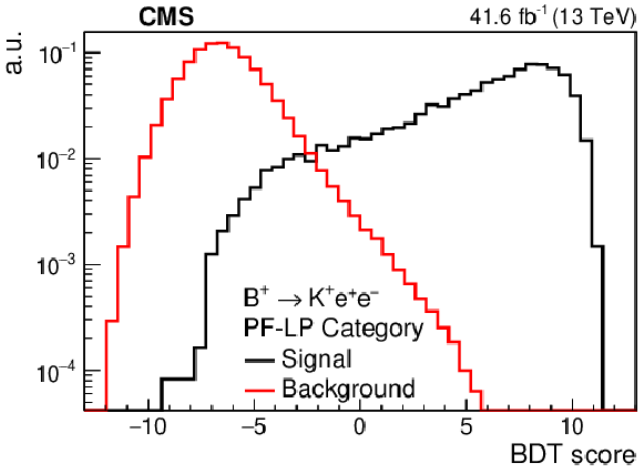
R(K) measured via a double ratio

- Normalization with $B^{\pm} \to K^{\pm} J/\psi(\ell\ell)$ control region to cancel out systematics

$$R(\mathrm{K})\left(q^2\right)\left[q^2_{\min}, q^2_{\max}\right] = \frac{\left[\frac{\mathcal{B}\left(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-\right)\left[q^2_{\min}, q^2_{\max}\right]}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mu^+\mu^-)\mathrm{K}^+)}\right]}{\left[\frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mathrm{e}^+\mathrm{e}^-)\left[q^2_{\min}, q^2_{\max}\right]}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mathrm{e}^+\mathrm{e}^-)\mathrm{K}^+)}\right]}$$







LFU violation in $B^{\pm} \to K^{\pm}\ell\ell$: results

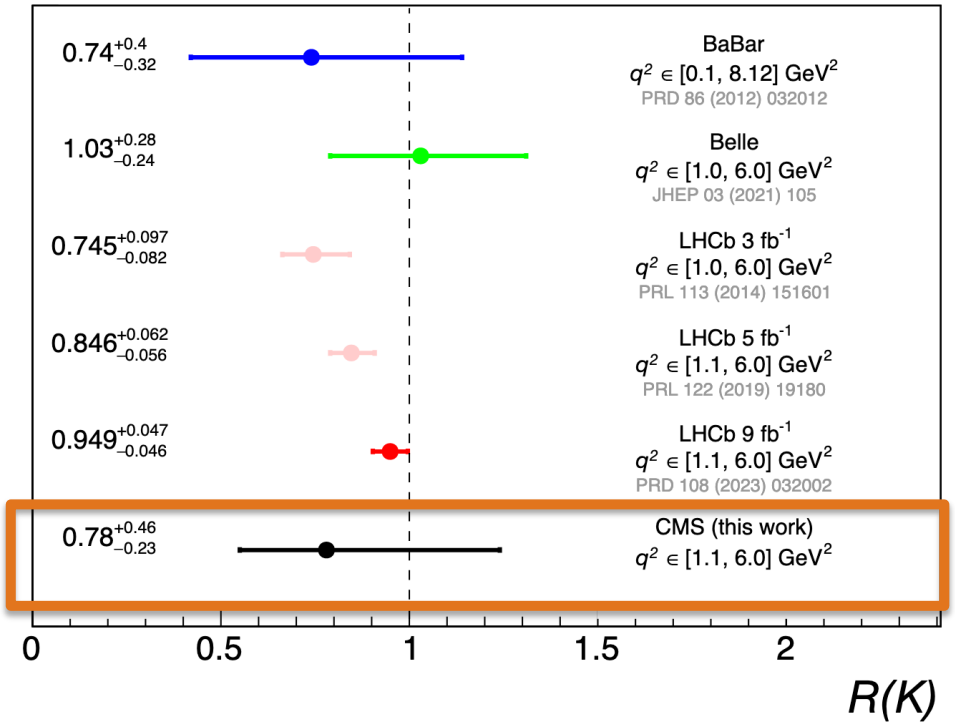
2024 Rep. Prog. Phys. 87 077802

R(K) compatible with the SM

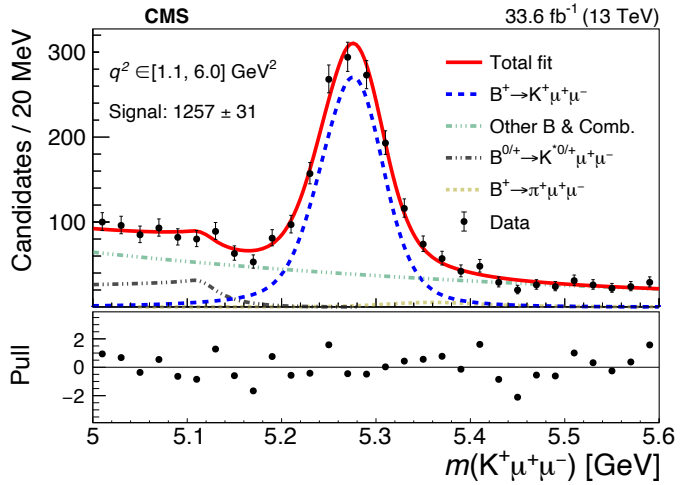
- R(K) in $q^2 \in [1.1; 6.0]$ GeV^2 in agreement with the world-average

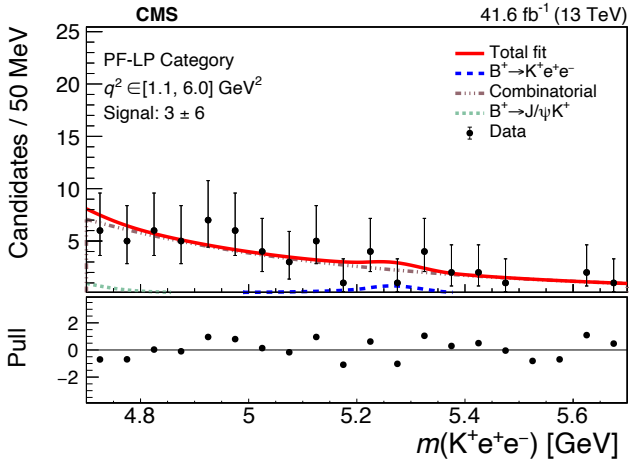
$$R(K) = 0.78^{+0.46}_{-0.23}\ (stat)\ ^{+0.09}_{-0.05}(sys)$$

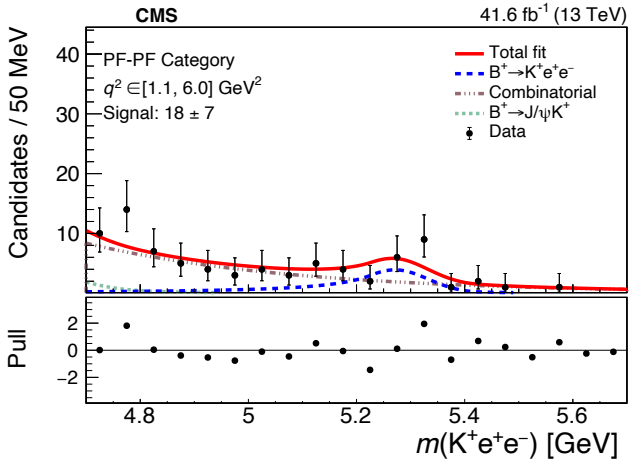
- Limited by small stat. in the electron channel.
- Main syst: background description, trigger turn-on



Signal extraction via maximum likelihood fit of the $K^{\pm}\ell\ell$ invariant mass.







LFU in $B_c^+ \to J/\Psi \ell \nu_\ell$

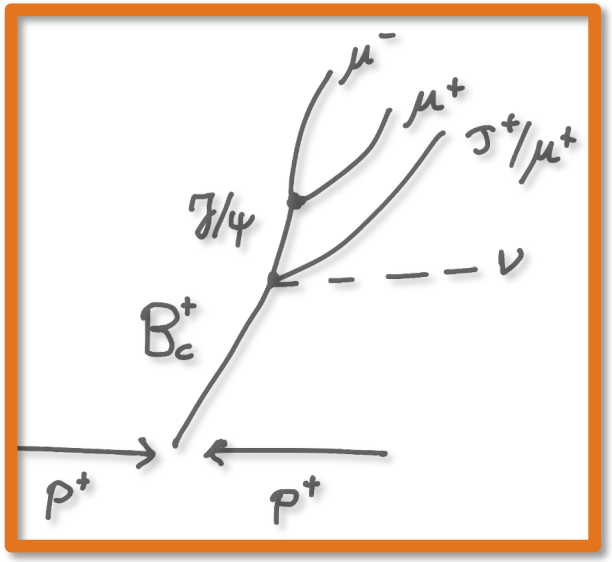
$$R(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi \tau \nu_\tau)}{\mathcal{B}(B_c \to J/\Psi \mu \nu_\mu)}$$

- Events with J/ψ $\to \mu\mu$ decays considered
- Two possible channels depending on τ decay

Leptonic channel

$$R(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi \tau \nu_\tau)}{\mathcal{B}(B_c \to J/\Psi \mu \nu_\mu)}$$

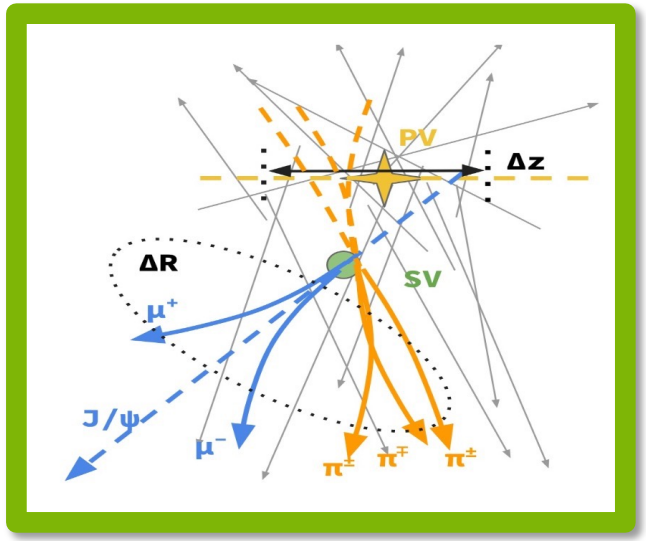
$\tau \to \mu \nu_\mu \nu_\tau$



Hadronic channel

$\tau \to \pi\pi\pi\nu_\tau$

$$R(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi \tau \nu_\tau)}{\mathcal{B}(B_c \to J/\Psi \mu \nu_\mu)}$$



LFU in $B_c^+ \to J/\Psi \ell \nu_\ell$: leptonic channel $\tau \to \mu \nu_\mu \nu_\tau$

arxiv.2408.00678

- **2018 pp collisions at 13 TeV ($\mathcal{L}$ =59.7 /fb)** collected with a dedicated trigger

$$R(J/\Psi) = \frac{\mathcal{B}(B_c \to J/\Psi \tau \nu_\tau)}{\mathcal{B}(B_c \to J/\Psi \mu \nu_\mu)}$$

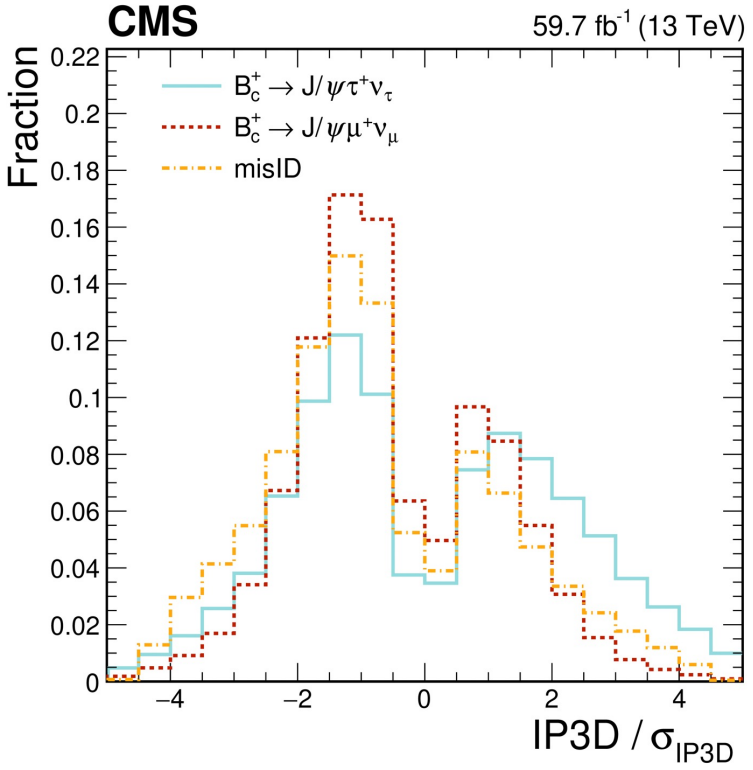
- Signal: 3μ events + neutrino(s) for numerator and denominator
- Online selections: 2 OS μ compatibile with J/ψ + 1 μ (p_T: 5,3,0 GeV and $\eta < 2.5$)
- Offline selections: impact parameter, reconstruction quality, invariant mass (of J/ψ and B), vertex probability

Discriminating variables:

- $q^2 = (p_{Bc} - p_{J/\Psi})^2$ for $1\boldsymbol{\nu}/3\,\boldsymbol{\nu}$
- 3D IP significance of μ_3
- significance of J/ψ displacement (L_{xy}/σ_{Lxy})

Background sources:

- Fake muons: J/ψ $\to \mu\mu$ + misidentified hadron (K or π)
- $H_B \to J/\psi + \mu$ (or combinatorial muon)
- Combinatorial μμ (in J/ψ mass range)
- $B_c \to J/\psi$ + charmed hadrons



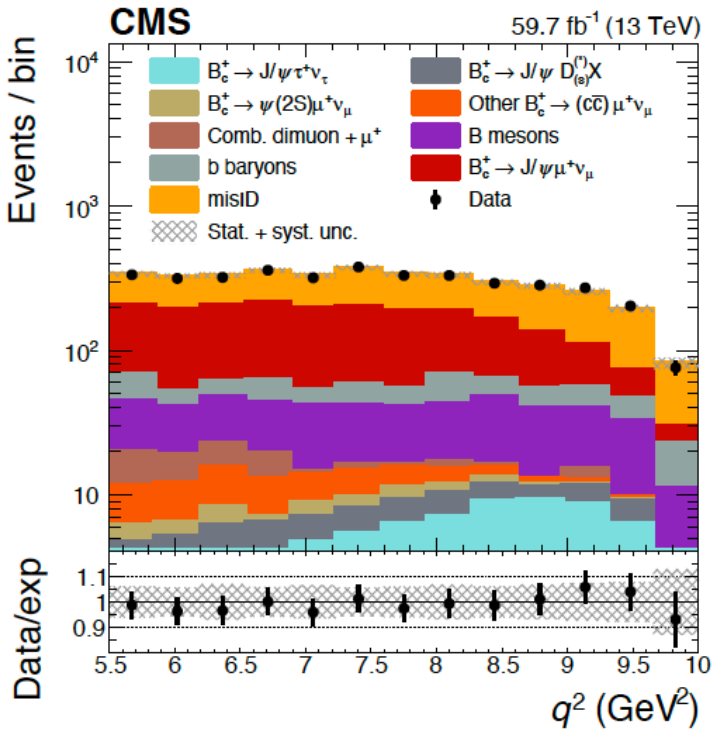
$B_c^+ \to J/\Psi \ell \nu_\ell$ leptonic channel $\tau \to \mu \nu_\mu \nu_\tau$: results

arxiv.2408.00678

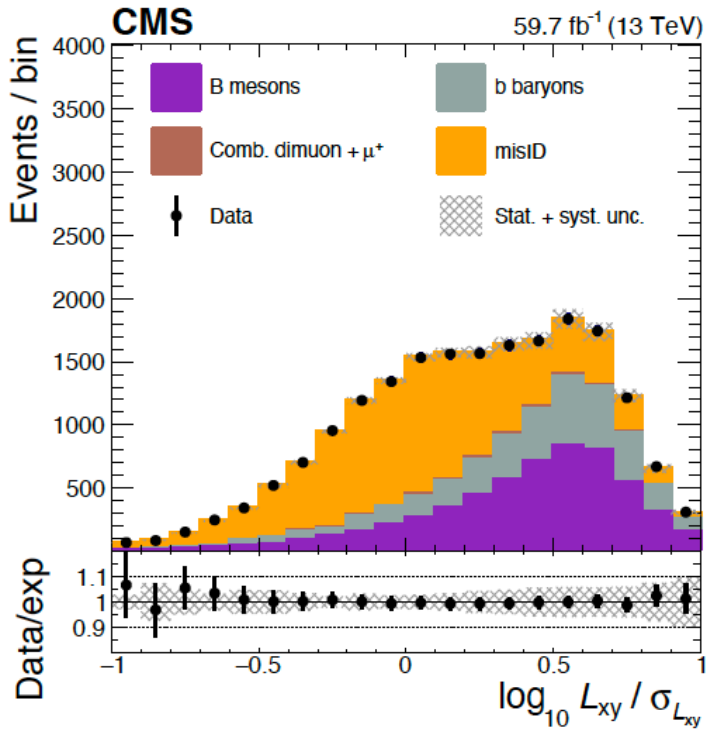
Categorization: 14 categories based on
- q^2
- 3D IP significance
- 3μ mass
- Relative isolation of the third muon

Signal extraction
- Simultaneous maximum likelihood 14 categories
  - q^2 and significance of J/ψ displacement used for signal extraction
- Statistical close to systematics
- Main systematics:
  - B_c form factors
  - Mis-ID background estimation,
  - MC statistics

q^2 distribution for the signal-enriched category



L_{xy}/σ_{Lxy} distribution for a background like category



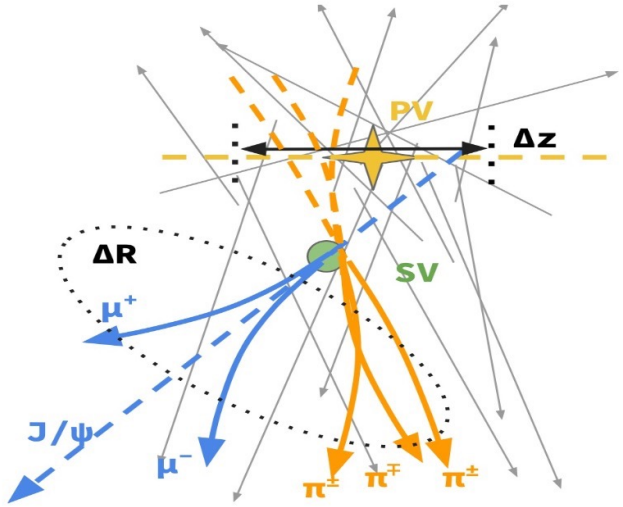
$$R(J/\psi) = 0.17^{+0.18}_{-0.17}\ (stat)\ ^{+0.21}_{-0.22}(sys)\ ^{+0.19}_{-0.18}(theo)$$

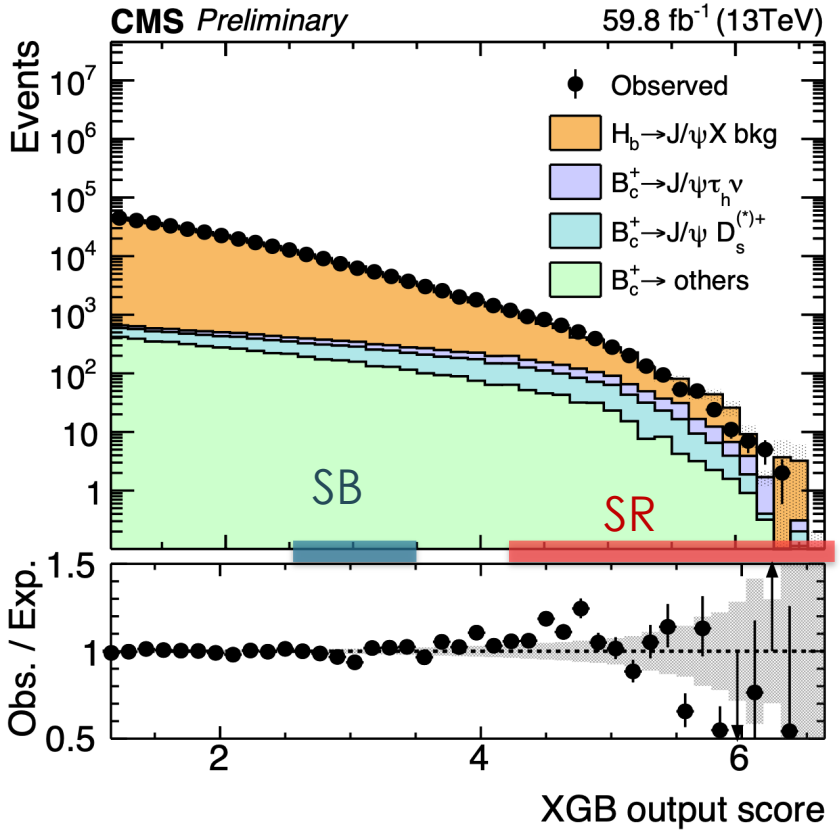
$B_c^+ \to J/\Psi \ell \nu_\ell$ hadronic channel $\tau \to \pi\pi\pi\nu_\tau$

CMS-PAS-BPH-23-001

- 2016-2018 p-p collisions at 13 TeV (138 /fb):
  - Online selections: 2 OS μ compatibile with J/ψ + 1 track
  - Offline selections: online+ 3 tracks with common vtx displaced wrt PV
  - Dedicate low pT hadronic tau reconstruction

Measurement of the numerator





Background sources

- $H_b \to J/\psi + X$ (main bkg)
- $B_c^+ \to J/\psi$ + charmed hadrons

- **Background rejection** via BDT: 18 input variables related to:
  - kinematics of the B-meson
  - τ candidate
  - global event-level observables.

BDT used to define Signal region and Sideband region

$B_c^+ \to J/\Psi \ell \nu_\ell$ hadronic channel $\tau \to \pi\pi\pi\nu_\tau$

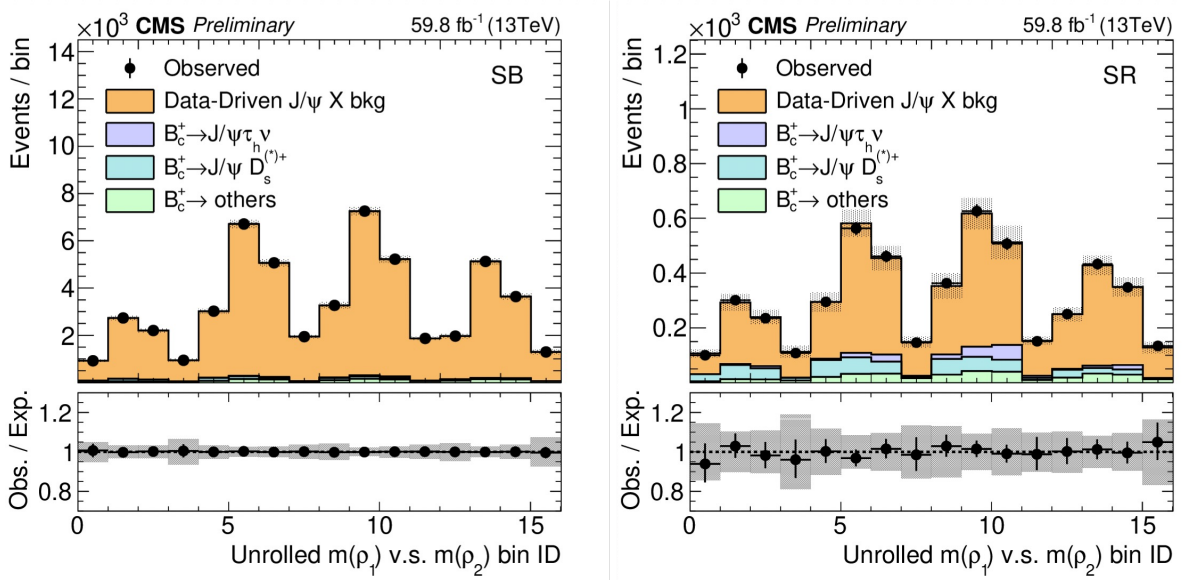
- Estimate $H_b \to J/\psi + X$ bkg with a data driven method.
  - Assume signal is mediated by ρ(770) → π+π-
  - Define ρ_1 and ρ_2 as the 2 possible OS π combinations
  - Estimation via simultaneous fit of SB, SR and leptonic data channel

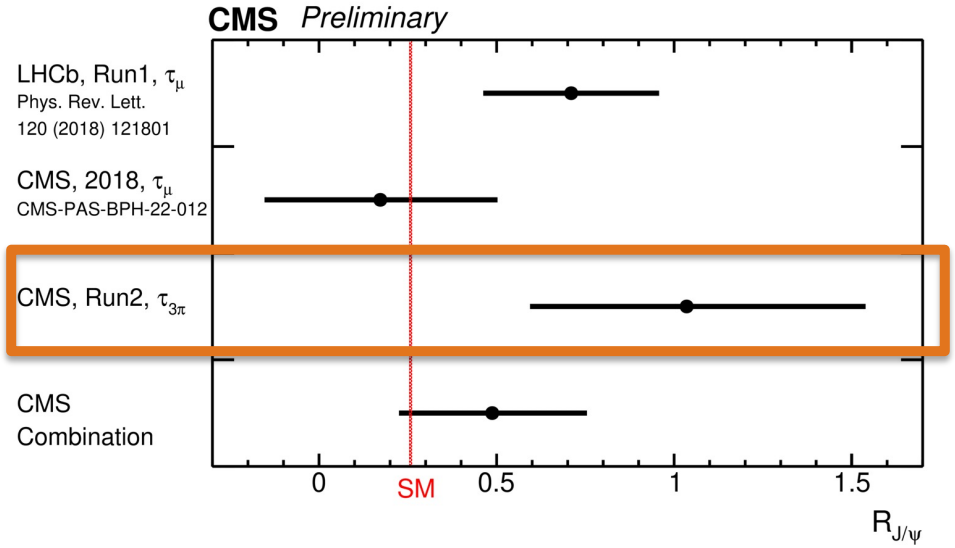
Results:

- $R(J/\psi)$ obtained via simultaneous fit with the leptonic τ analysis →close to 1
- Combining with the leptonic channel:

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

- Consistent with the SM prediction within 1σ
  - Hadronic and leptonic channels share same denominator: combined result obtained performing an overall simultaneous fit





Conclusions

LFV and LFUV powerful tools to look for new physics

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