Lepton flavor (universality) violation studies with heavy flavor at CMS

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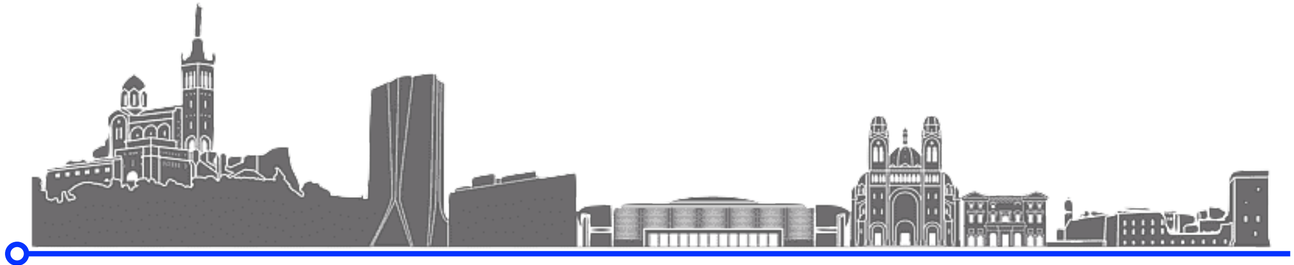
on behalf of the CMS Collaboration



Talk outline

This talk documents the CMS huge effort in lepton flavor (universality) conservation tests in heavy flavor sector

LFU

- ROPP 87 (2024) 077802 measurement of R_K ratio
- PRD 111 (2025) L051102 measurement of $R_{J/\psi}$ ratio in the τ leptonic channel
- CMS-PAS-BPH-23-001 measurement of $R_{J/\psi}$ ratio in the τ hadronic channel

LFV

- PLB 853 (2024) 138633 search for $\tau \to 3\mu$

CMS flavor program extends to Higgs, Top and Exotics sector

Lepton Flavor accidental symmetries

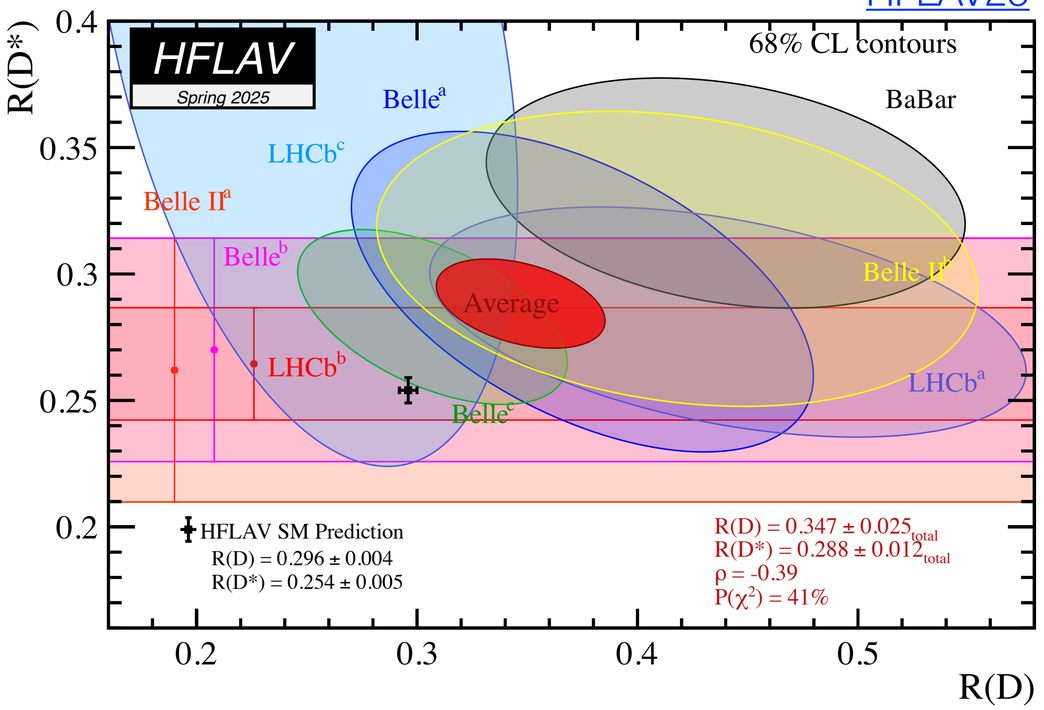
Lepton Flavor Universality Violation - LFU

- Standard Model → 3 lepton flavors with same couplings to gauge bosons
  - ♢ same rate regardless the lepton-flavor up to phase space differences

- Anomalies in $b \to s\ell\ell$ and $b \to c\ell\nu$ transitions suggest deviation from the SM predictions
  - ♢ no tension in the R_K measurement
  - ♢ deviation from SM in $B^0 \to K^{*0}\mu^+\mu^-$ angular distribution impacting P_5'
  - ♢ $R(D) - R(D^*)$ tension from the SM

- SM extension predicting different couplings → leptoquark (LQ) JHEP06(2022)169

HFLAV25



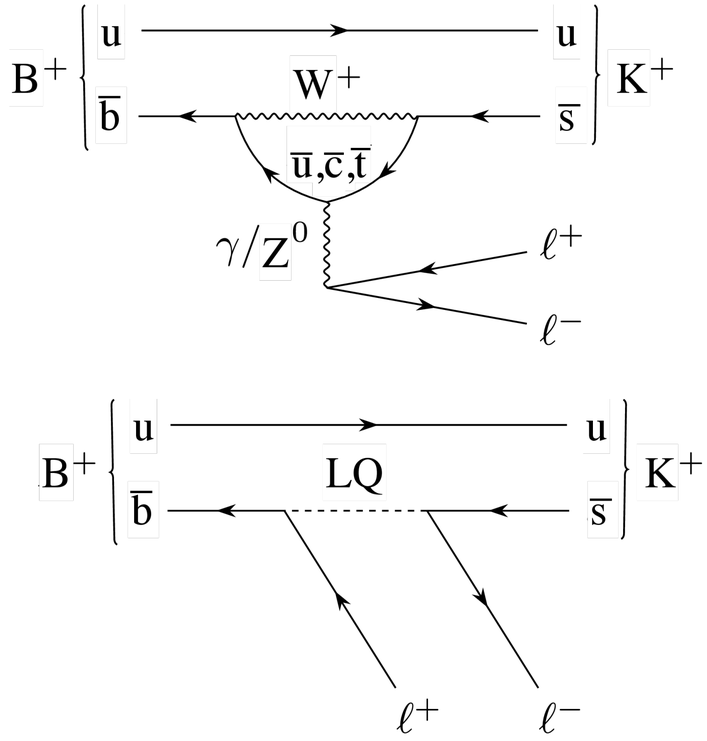
R_K measurement

R_K golden LFU test

Measurement concept

ROPP 87 (2024) 077802

- $B^{\pm} \to K^{\pm}\ell\ell$ allowed in SM via loop diagrams with branching ratios of ~ 10^{-7}
  - ♢ LFU same branching ratio for $B \to K\mu\mu$ and $B \to Kee$ within 1%
- Precision measurement to unveil **LFU violating** processes
  - ♢ minimal theoretical uncertainty using R_K observable



$$R(K) = \frac{Br(B^{\pm} \to \mu\mu K^{\pm})}{Br(B^{\pm} \to eeK^{\pm})}$$

R_K golden LFU test

Measurement concept

ROPP 87 (2024) 077802

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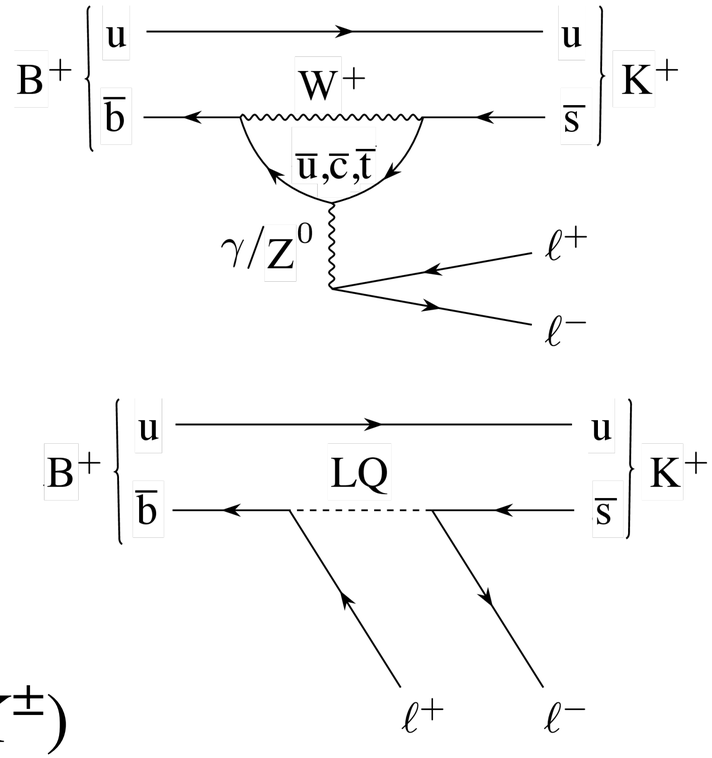
- Precision measurement to unveil **LFU violating** processes
  - ♢ minimal theoretical uncertainty using R_K observable
  - ♢ reduce experimental uncertainties normalizing $B \to K\ell\ell$ to $B \to J/\psi(\ell\ell)K$ resonant decay



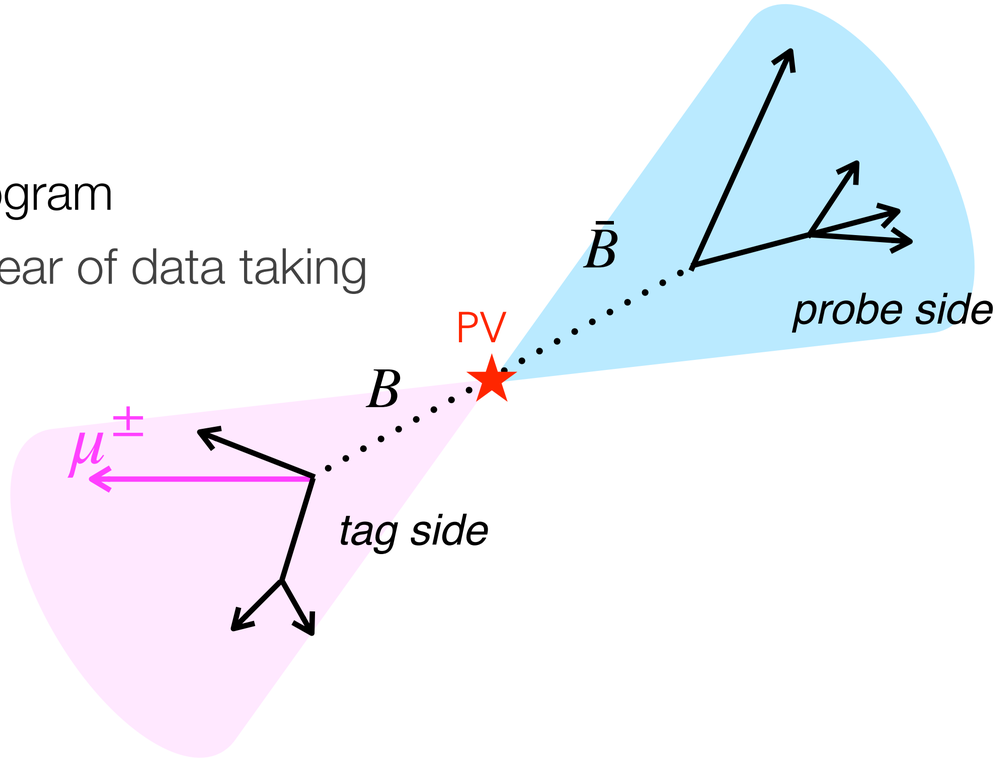
$$R(K) = \frac{Br(B^{\pm} \to \mu\mu K^{\pm})}{Br(B^{\pm} \to J/\psi(\to \mu\mu)K^{\pm})} \cdot \frac{Br(B^{\pm} \to J/\psi(\to ee)K^{\pm})}{Br(B^{\pm} \to eeK^{\pm})}$$

Rethinking data processing in CMS

Phys. Rept. 1115 (2025) 678

CMS B-parking dataset

- First challenge collect **large $B \to Kee$ sample**
  - ♢ low pT electrons, forward and hard to trigger on
- B-parking dataset a **game changing** ingredient for the CMS HF program
  - ♢ new trigger and data processing strategy deployed since 2018 year of data taking
- Trigger on displaced **muon** in the barrel region (tag side)
  - ♢ pure set of $b\bar{b}$ pairs O(10^{10})
  - ♢ semi-leptonic b-hadron decay on the *tag side*
  - ♢ unbiased set of b hadrons on the *probe side*



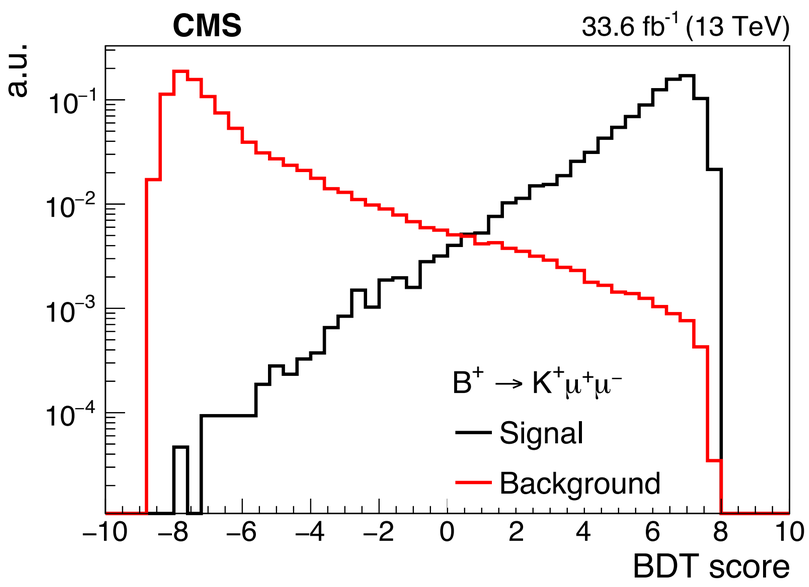
*PF = Particle Flow
**LP = Low P_T

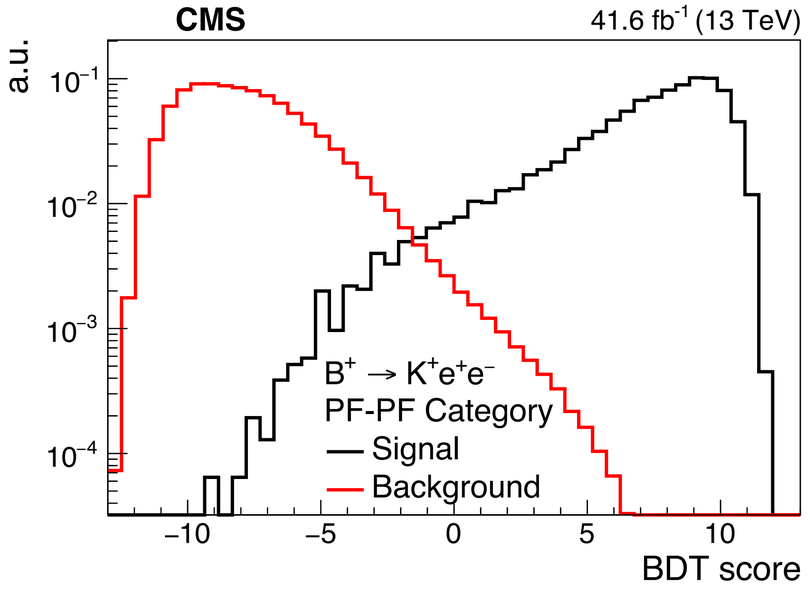
B meson reconstruction

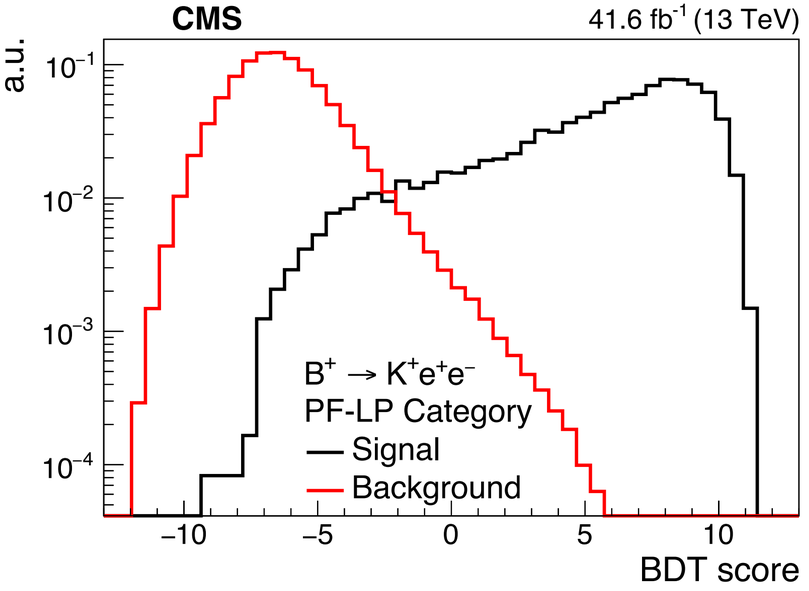
- Opposite sign leptons + one track
- $K\mu\mu$ candidates in the tag side → one is the trigger μ
- Kee candidates in the probe side split in
  - ♢ PF*-PF → 2 *standard* electrons
  - ♢ PF-LP** → *standard* + low-pT electrons

3 categories

dedicated BDT for event selection







Signal and background modeling

SR in low-q^2

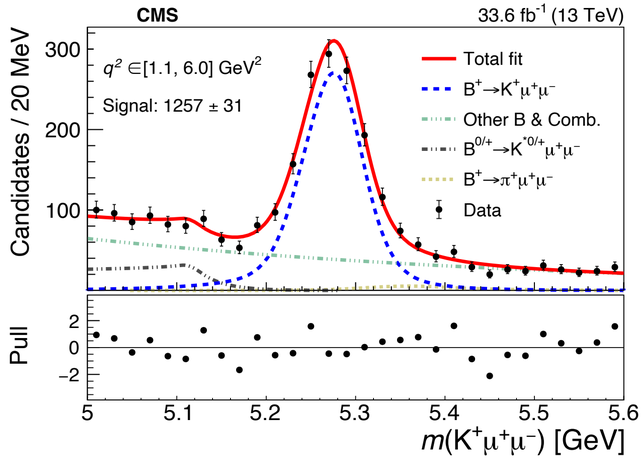
$B \to J/\psi \ell\ell$ normalization channel

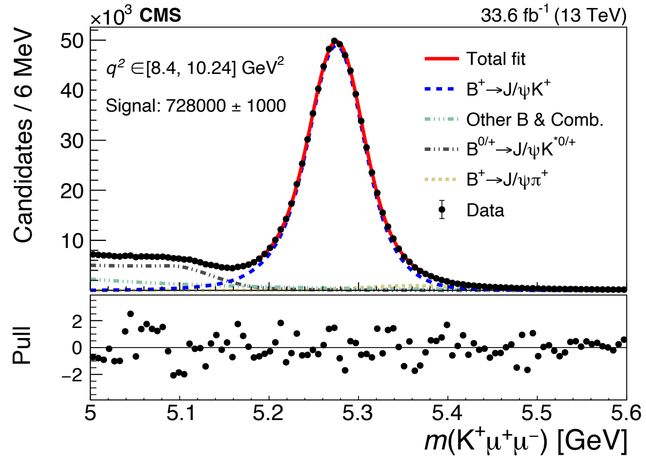
Shape analysis in q^2=$M^2_{\ell\ell}$ regions

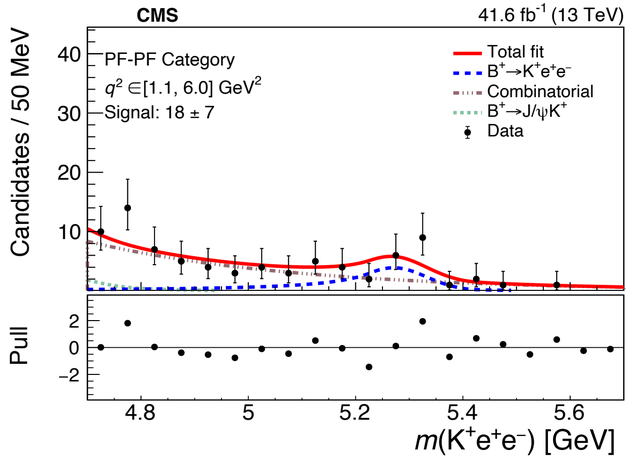
Signal Double sided Crystal Ball + Gaussian

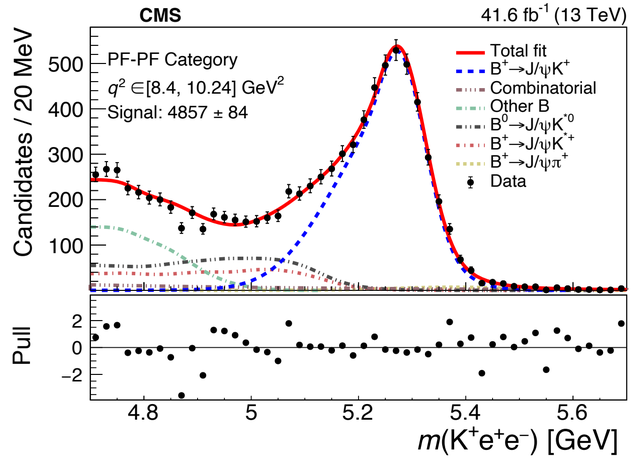
Background in SR

- Combinatorial + other b
  - ♢ muons from B + random track
  - ♢ any other B partially reco
- $B \to K^*\ell\ell$ 4-body decay partial reconstruction (μ-channel)
- Cabibbo-suppressed $B \to \pi\ell\ell$ (μ-channel)
- KJ/ψ leakage in (e-channel)









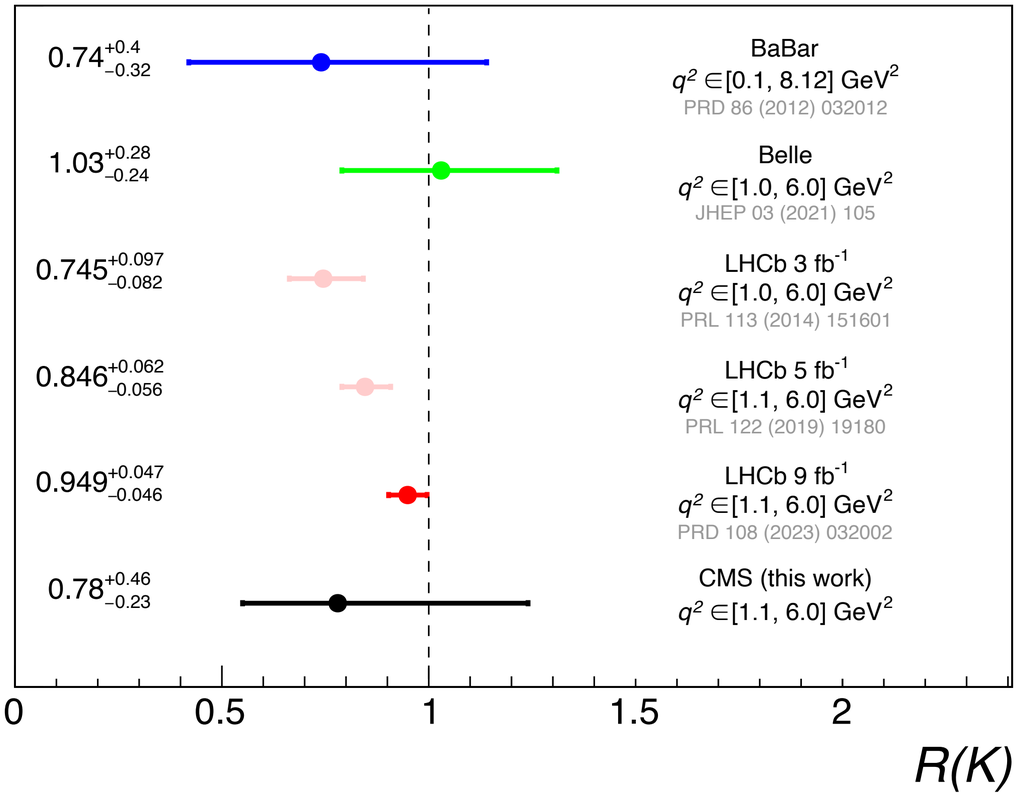
R_K measurement results

- Number of events observed in $B \to K\ell\ell$ and $B \to J/\psi\ell\ell$
  - ♢ PF-PF and PF-LP statistically combined

$$R(K) = \frac{Br(B^{\pm} \to \mu\mu K^{\pm})}{Br(B^{\pm} \to J/\psi(\to \mu\mu)K^{\pm})} \cdot \frac{Br(B^{\pm} \to J/\psi(\to ee)K^{\pm})}{Br(B^{\pm} \to eeK^{\pm})}$$

- Luminosity and $b\bar{b}$ cross-section cancel in the ratio
- Main **systematics** from background and trigger turn-on modeling
- Precision limited by **low statistics** in electron channel

$$R_K = 0.78^{+0.46}_{-0.23}(\text{stat})^{+0.09}_{-0.05}(\text{syst}) = 0.78^{+0.47}_{-0.23}$$



$R_{J/\psi}$ measurement

$R_{J/\psi}$ with leptonic τ

PRD 111 (2025) L051102

Introduction

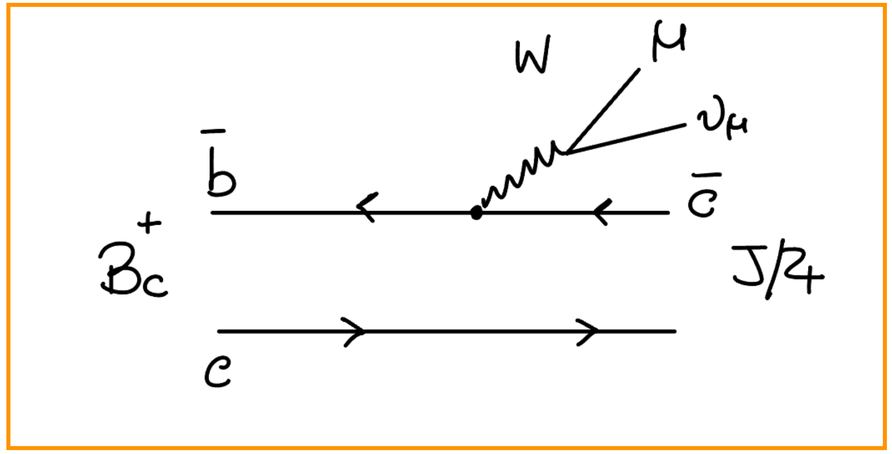
- First LFUV result in $b \to c\ell\nu_\ell$ in CMS
  - ♢ B_c produced only at hadron colliders
- **Leptonic decay $\tau \to \mu\nu_\mu\nu_\tau$**
- **Identical visible final state 3μ** different ν multiplicity
  - ♢ same reconstruction and fit simultaneously

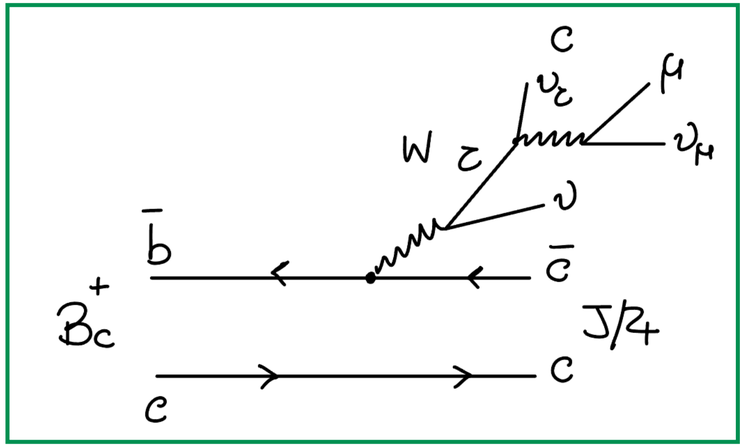
$$R_{J/\psi} = \frac{B(B_c^+ \to J/\psi\tau^+\nu)}{B(B_c^+ \to J/\psi\mu^+\nu)}$$

0.71 ± 0.17 (stat) ± 0.18 (sys)
LHCb measurement
PhysRevLett.120.121801

2σ from

0.2582 ± 0.0038
SM prediction
PhysRevLett.125.222003





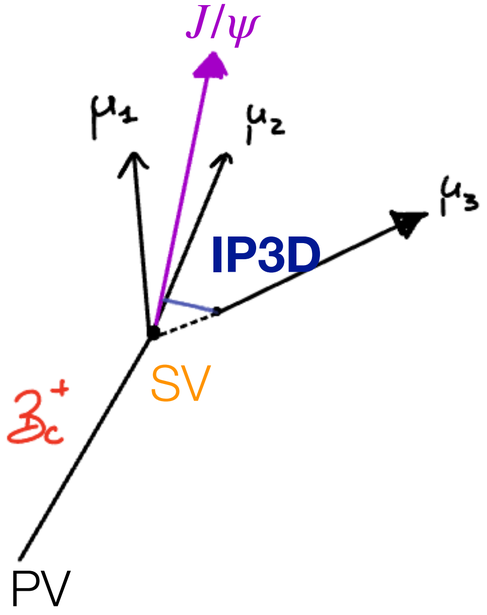
Kinematics and topology

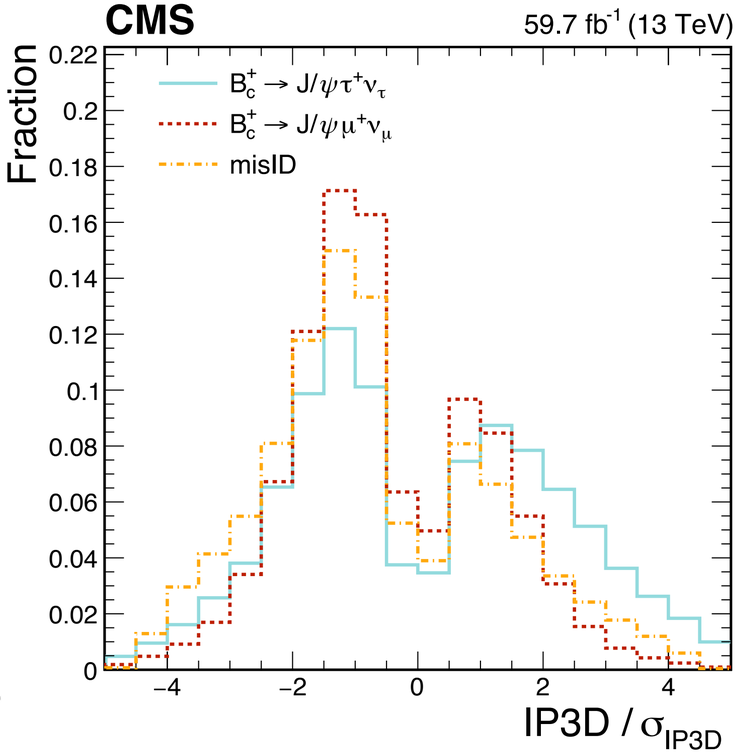
- Collinear approximation assuming p_{B_c} aligned with $p_{3\mu}$

$$p_{B_c} = \frac{m_{B_c}}{m_{3\mu}} \cdot p_{3\mu}$$

- **Goal** : separate 3ν (numerator) vs 1ν (denominator) decay leveraging on
  - ♢ $q^2 = (p_{B_c} - p_{J/\psi})^2$
  - ♢ L_{xy}/σ secondary vertex displacement
  - ♢ IP3D 3rd muon impact parameter w.r.t. J/ψ momentum

- Largest background contribution from
  - ♢ **MisID** - J/ψ + misidentified hadron
  - ♢ **b-hadrons (H_b)** $J/\psi + \mu$ from different decay chain
  - ♢ other B_c **decays**





Binned maximum likelihood fit

- Signal B_c and H_b background normalization free parameters
  - ♢ POI → $R_{J/\psi}$ value

Total of 14 categories

- **7 iso-μ_3 categories** with fit observable
  - ♢ L_{xy}/σ → constrain b-hadron background
    - * high mass enriched w/ H_b background
  - ♢ q^2 → isolate signal
    - * IP3D/σ bins better isolates τ component

- **~~7 iso-~~μ_3 categories** → constrain **misID** background from inside the fit

Category pair definitions			Fit observable
$m(3\mu)$	q^2	IP3D/σ_{IP3D}	
$<m_{B_c^+}$	$>5.5\,\text{GeV}^2$	<-2 $-2-0$ $0-2$ >2	q^2
$<m_{B_c^+}$	$<4.5\,\text{GeV}^2$	<0 >0	$L_{xy}/\sigma_{L_{xy}}$
$>m_{B_c^+}$	—	—	$L_{xy}/\sigma_{L_{xy}}$

Binned maximum likelihood fit

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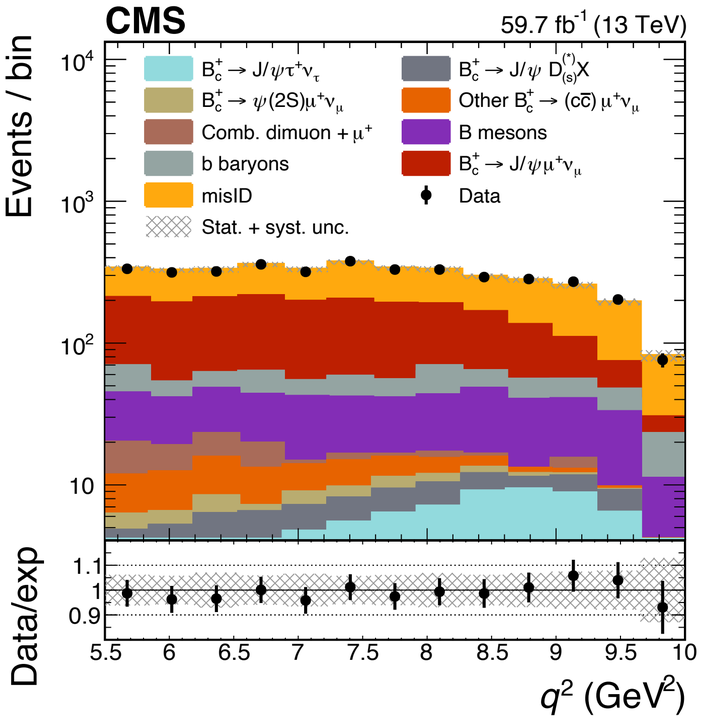
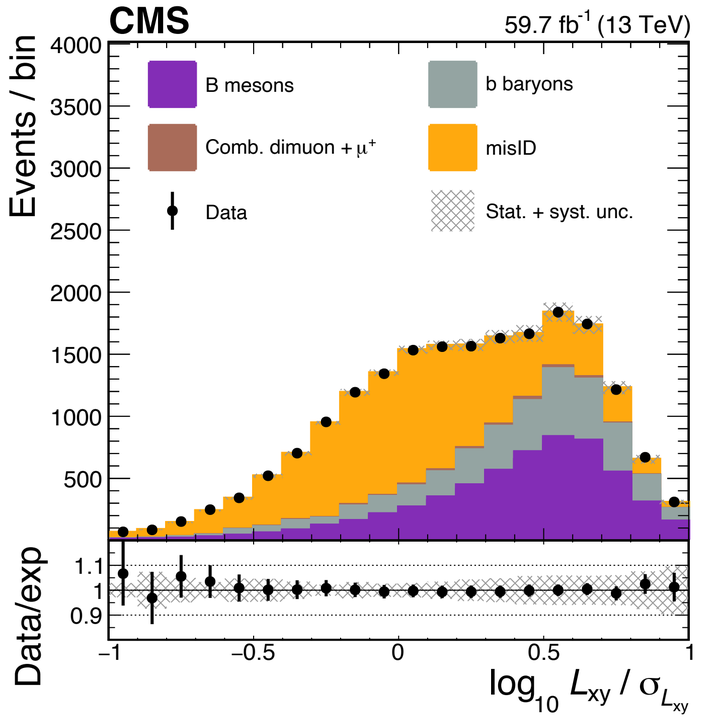




- **7 ~~iso-μ_3~~ categories** → constrain **misID** background from inside the fit

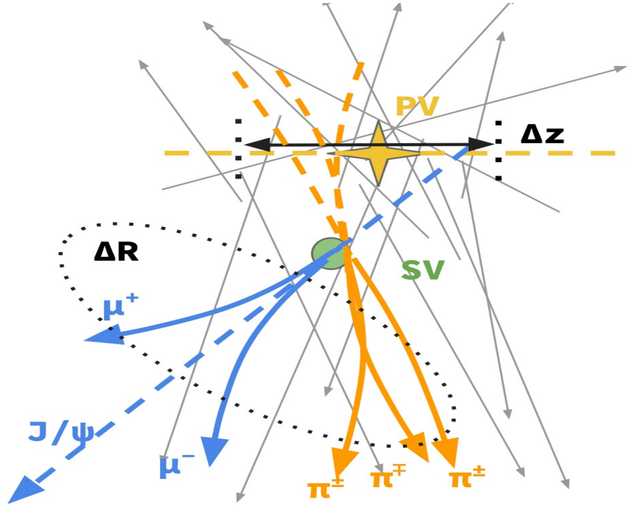
$$R(J/\psi) = 0.17^{+0.21}_{-0.22}(\text{syst})^{+0.19}_{-0.18}(\text{theo})^{+0.18}_{-0.17}(\text{stat})$$

compatible with SM prediction (0.3σ) and
LHCb measurement (1.3σ)

$R_{J/\psi}$ - hadronic τ

Introduction

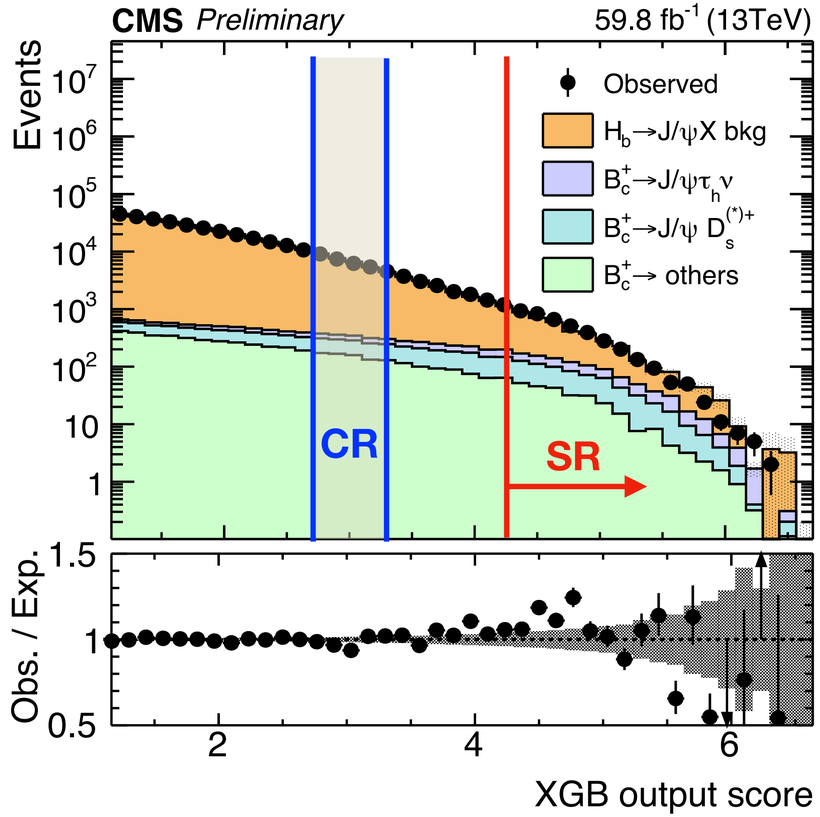
- **Hadronic decay** $\tau^+ \to \pi^+\pi^-\pi^+\nu$
  - ♢ denominator from leptonic τ analysis
- Dedicated low-pT τ reconstruction [CMS-DP-2020-039]



CMS-PAS-BPH-23-001

Background composition

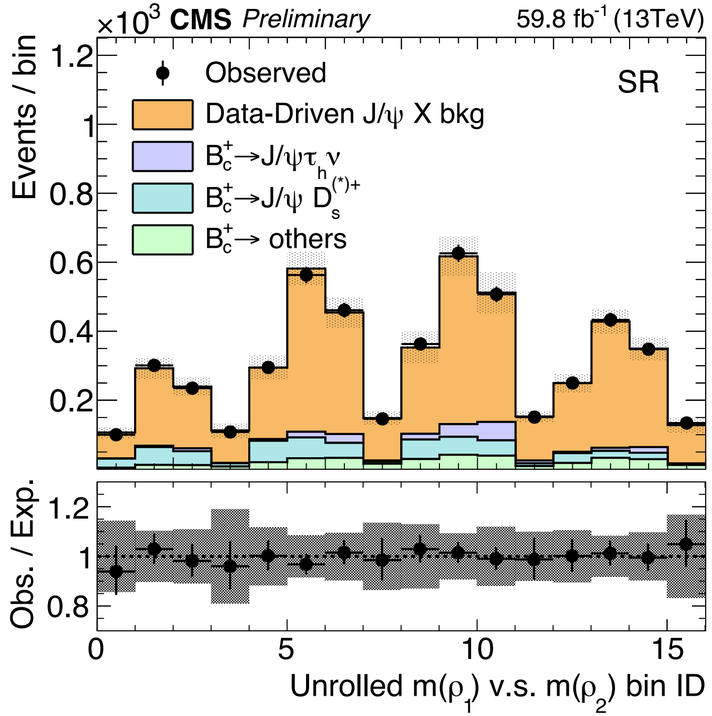
- **b-hadron** $H_b \to J/\psi + X$
- $B_c^+ \to D_s^* J/\psi$
- B_c background with feed-downs $c\bar{c} \to J/\psi$
- Suppressed via BDT selection
  - ♢ input = τ flight length significance, particles multiplicity, vertices quality, isolation, ID…
  - ♢ maximize **signal vs H_b** background discrimination

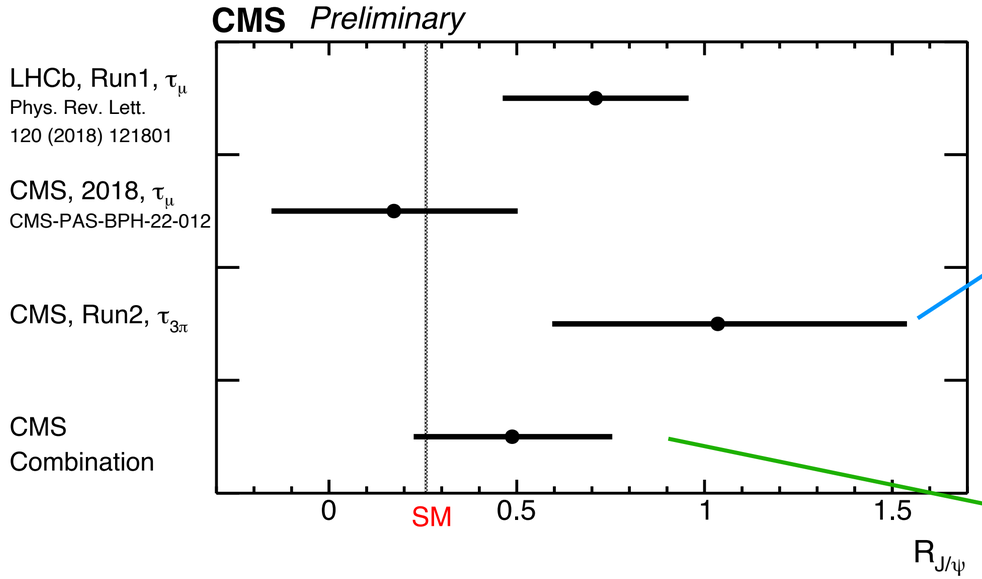


$R_{J/\psi}$ - hadronic τ

- 3 prong τ decay produce intermediate $\rho(770)$ resonance
  - ♢ ρ_1 & ρ_2 candidates from OS 2π combinations out of 3π
- Discriminating observable → unrolled $m(\rho_1)$ **vs** $m(\rho_2)$ distribution
  - ♢ simultaneous fit in **Hb bkg. CR** and **SR**

$$R_{J/\psi} = \frac{B(B_c^+ \to J/\psi\tau^+\nu)}{B(B_c^+ \to J/\psi\mu^+\nu)}$$





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

full Run2 stat. systematic uncertainty dominated

leptonic + hadronic with same denominator

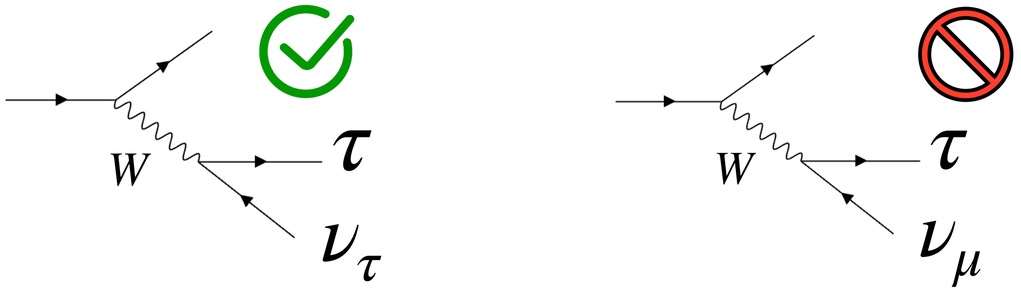
$R(J/\psi)_{\text{had+lep}} = 0.49 \pm 0.25(\text{syst}) \pm 0.09(\text{stat})$

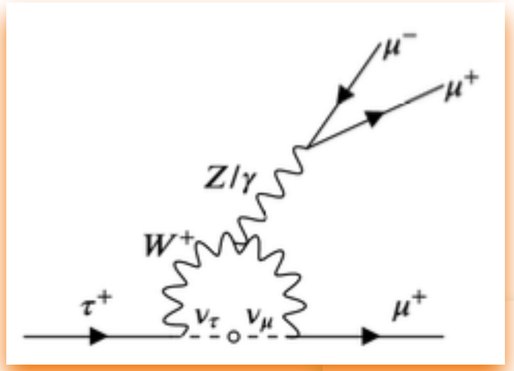
$\tau \rightarrow 3\mu$ search

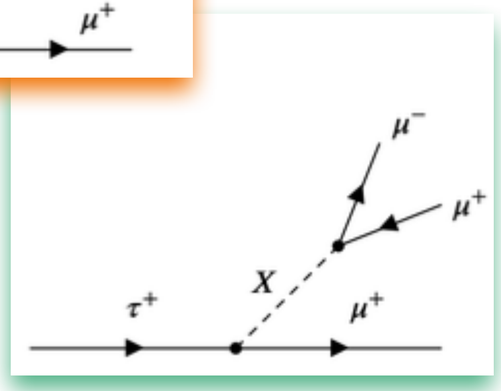
Lepton Flavor accidental symmetries

Lepton Flavor number Violation - LFV

- SM + massless left-handed neutrinos → LF number is conserved
  - ♢ forbidden vertex interaction with different flavors → not protected by any conservation law







- Observed neutrino oscillation proves LF is not a fundamental symmetry
- LFV in charged lepton interactions not yet observed
  - ♢ strongly suppressed in **SM by power of** $(M_\nu/M_W)^2$ → $Br(\tau \to 3\mu)$ ~ 10^{-55}
- SM extension predict $Br(\tau \to 3\mu)$ ~ O(10^{-9} -10^{-8}) within the CMS sensitivity reach
  - ♢ perfect playground to search for **New Physics signature**

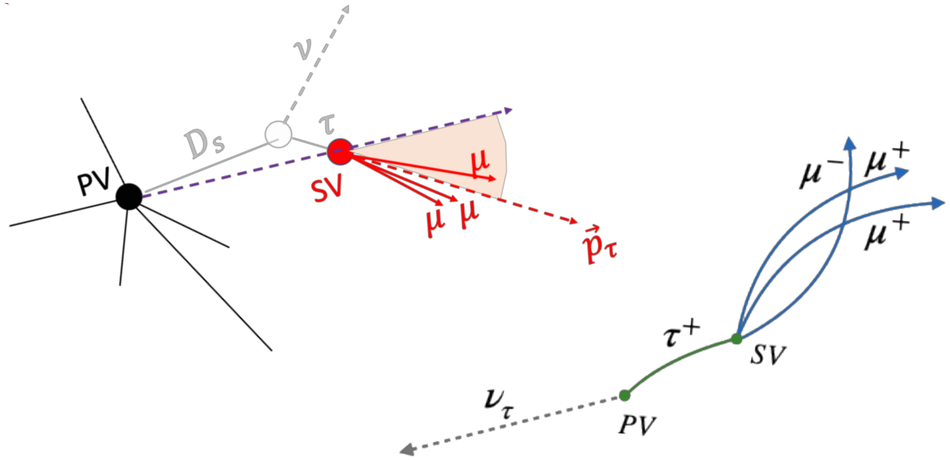
PLB 853 (2024) 138633

LFV in $\tau \to 3\mu$ decay

Introduction

- τ **production channels** investigated at CMS in **orthogonal** analyses
  - ♢ D **and** B **decays** (~10^{11} τ per fb^{-1})
    - * sensitive to fake signal muons from π and K
  - ♢ **W decays** (~10^{7} τ per fb^{-1})
    - * harder spectra and isolated topology

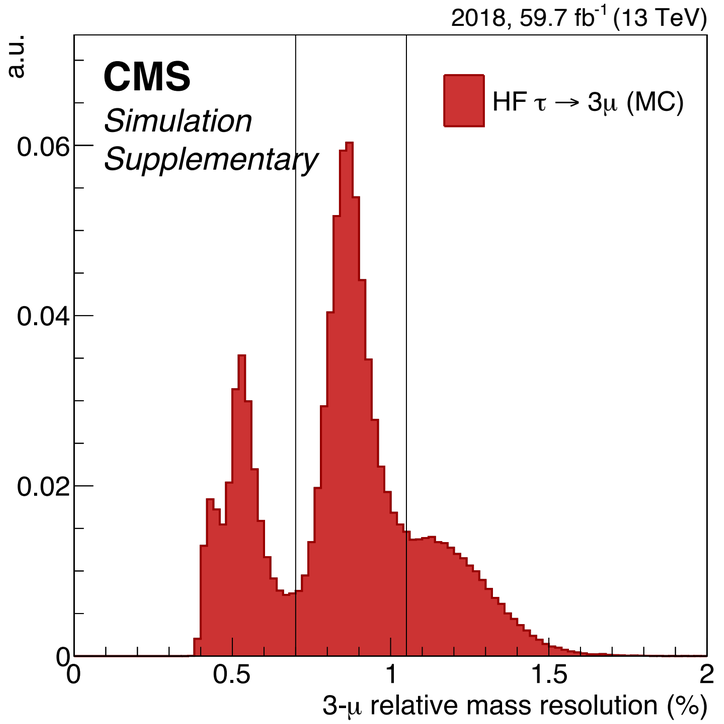
efficiency ↓ — statistic ↑



- Bump hunt in 3μ invariant mass around nominal τ mass

- $\tau \to 3\mu$ candidates from muon tracks matching trigger object
  - ♢ common vertex fit → displaced SV
  - ♢ W channel - combine with MET of the event

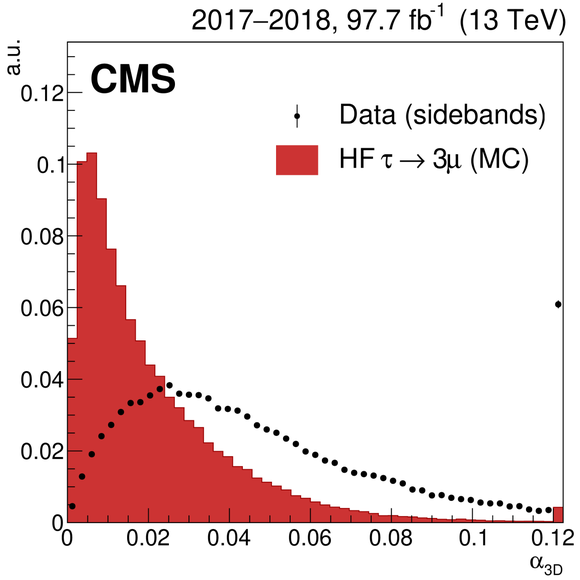
- Event categorization upon per-event 3μ mass resolution

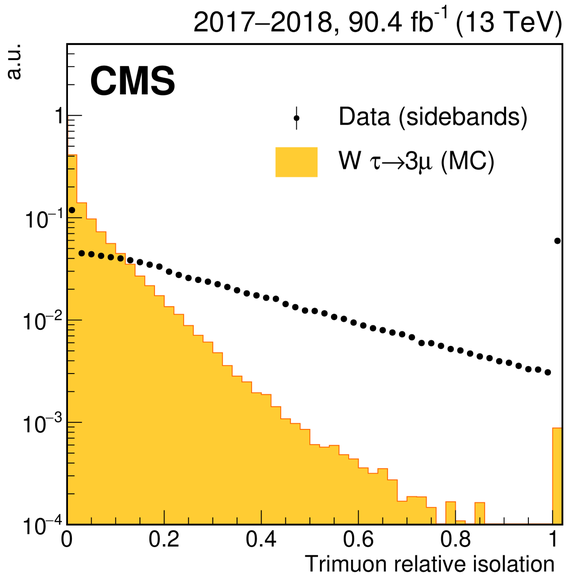


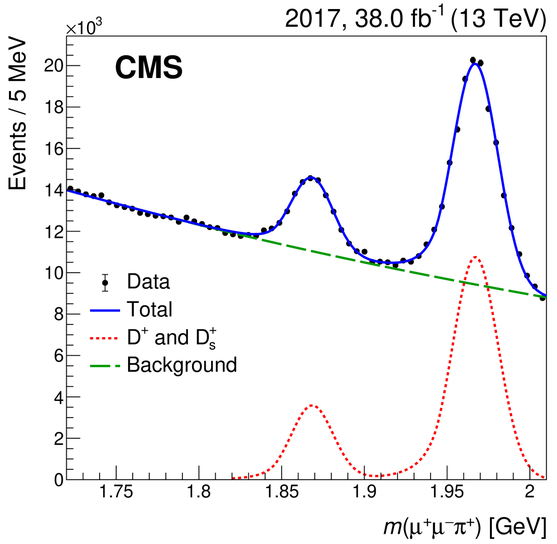
Backgrounds and validation

LFV in $\tau \to 3\mu$ decay

- **Data-driven background** modeling → mass sidebands
  - ♢ HF ch. dominated by fakes
  - ♢ W ch. SM $W \to 3\mu\nu$ + combinatorial
- Signal candidate selection with **BDT**
- Control channel $D_s \to \phi(\mu\mu)\pi$ with misID π
  - ♢ validate BD inputs/score and signal modeling
  - ♢ normalization channel for HF
- Signal like sample for HF and pure background for W channel



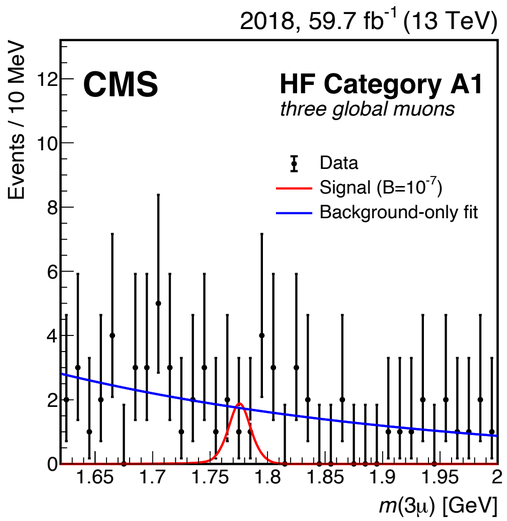


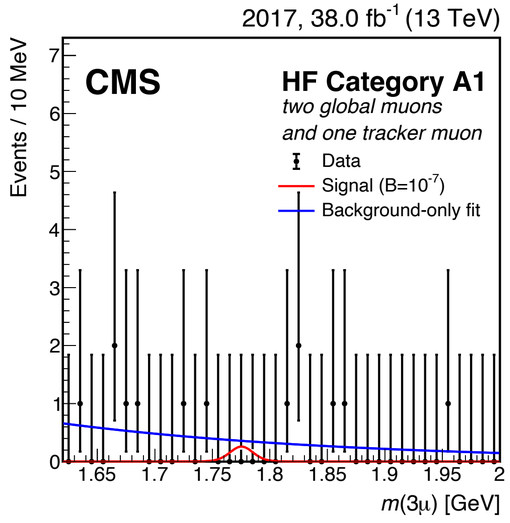


Results

LFV in $\tau \to 3\mu$ decay

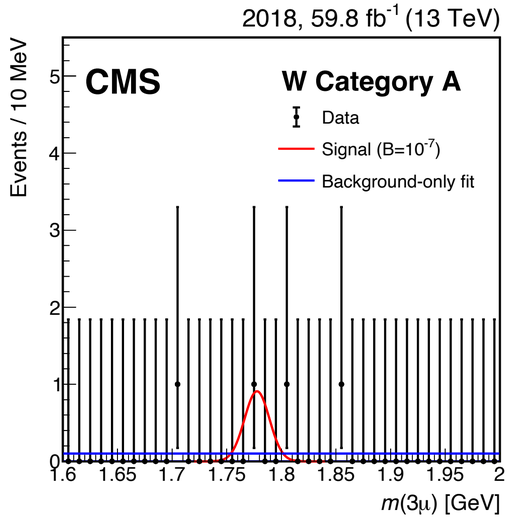
- POI signal strength scaling $B(\tau \to 3\mu)$
- Simultaneous unbinned maximum likelihood fit to $m_{3\mu}$
  - ♢ statistically dominated sensitivity
- Current best limit by Belle II $Br(\tau \to 3\mu) < 2.1 \times 10^{-8}$ @ 90% CL





HF ch obs. (exp.) UL at 90% CL

$Br(\tau \to 3\mu) < 3.4\ (3.6) \times 10^{-8}$

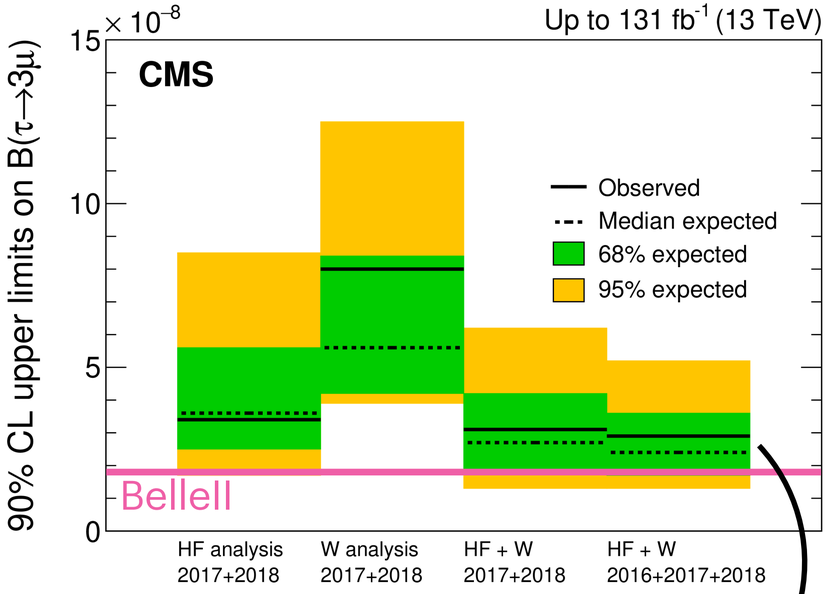


W ch obs. (exp.) UL at 90% CL

$Br(\tau \to 3\mu) < 8.0\ (5.6) \times 10^{-8}$

JHEP09(2024)062

CMS sensitivity competitive to results obtained at B-factories !!!



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Full Run2 combination

obs. (exp.) UL at 90% CL

$Br(\tau \to 3\mu) < 2.9\ (2.4) \times 10^{-8}$

Conclusions

- CMS experiment actively contributing to global effort in testing **LFU**
  - ♢ $R(K)$ measurements confirmed updated LHCb results
  - ♢ $B_c^+ \to J/\psi \ell^+ \nu_\tau$ obtain result compatible with both SM and LHCb observations
- CMS reaches a combined observed limit on **LFV** $\tau \to 3\mu$ with **competitive sensitivity** compared to B-factories
- Dedicated datasets like **B-parking** and the development of tailored reconstruction and trigger strategies are key to making CMS competitive in flavor physics
  - ♢ expanded parking program for Run3!
- **Future is bright** → include further analyses with the full Run 2 + Run 3 data and improved techniques bringing exciting opportunities to probe new physics in flavor

Backup

Muon fake rate background

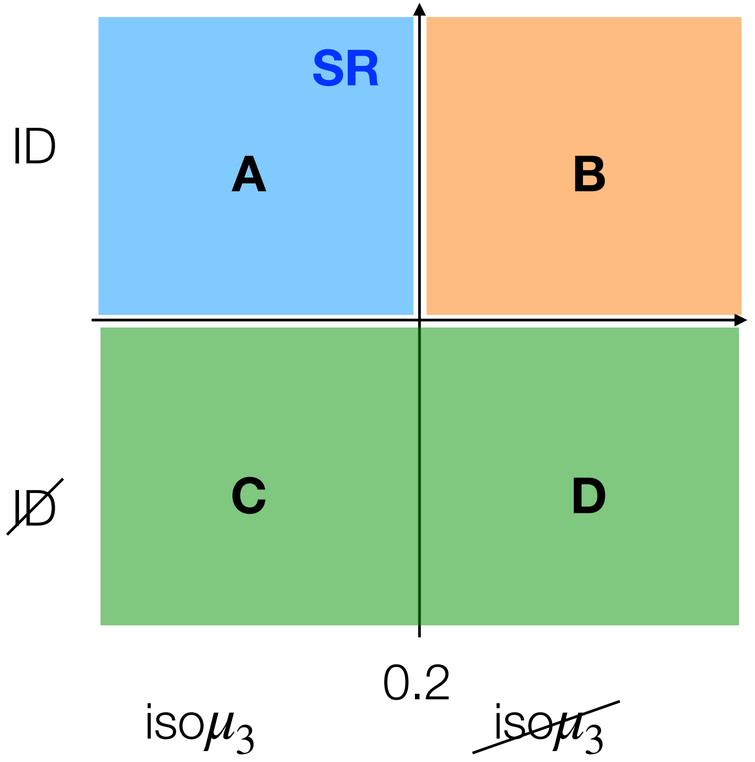
$R_{J/\psi}$ leptonic

- Largest background from fakes → 3rd muon from misidentified π or K

- Shape and yield in **SR** from 3 background enriched CRs in data
  - ♢ signal is isolated and pass muonID
- Rate of isolated fakes (fr_{iso}) modeled in the inverted ID region
  - ♢ NN classifiers output → probability of isolated misID hadron
- NN gives an event-per-event weight applied in **B** to derive fake-rate in SR

$$\text{Fakes(SR)} = fr_{\text{iso}} * \text{Data(B)} - fr_{\text{iso}} * \text{MC(B)}$$

- The misID background shape and yield is constrained in B CRs and used in the SR fit → in-situ estimation embedded in the fit model



- Validation on fakes enriched data CRs (isoμ_3 > 1.5)

Contribution

$R_{J/\psi}$ leptonic

- **Signal** τ (numerator) $B_c^+ \to J/\psi\tau^+\nu_\tau$
- **Signal** μ (denominator) $B_c^+ \to J/\psi\mu^+\nu_\mu$

- **MisID** : fakes from J/ψ + misidentified hadron
- **B-barions** and **b-mesons** $J/\psi + \mu$ from different decay chain
- B_c background
  - ♢ feed-downs $c\bar{c} \to J/\psi$
  - ♢ J/ψ + charm-hadrons $B_c^+ \to D_s^* J/\psi$
- **Combinatorial dimuon +** μ from unrelated matching and $m(\mu\mu)$ close to J/ψ