Recent results on flavour anomalies and lepton flavour (universality) violation at CMS

CKM 2023 Santiago de Compostela
18-22 September 2023

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Outline

Search for Lepton Flavour Violating $\tau \to 3\mu$ decays

CMS-PAS-BPH-21-005

Test of Lepton Flavor Universality in semileptonic B_c decays - $R(J/\psi)$

CMS-PAS-BPH-22-012

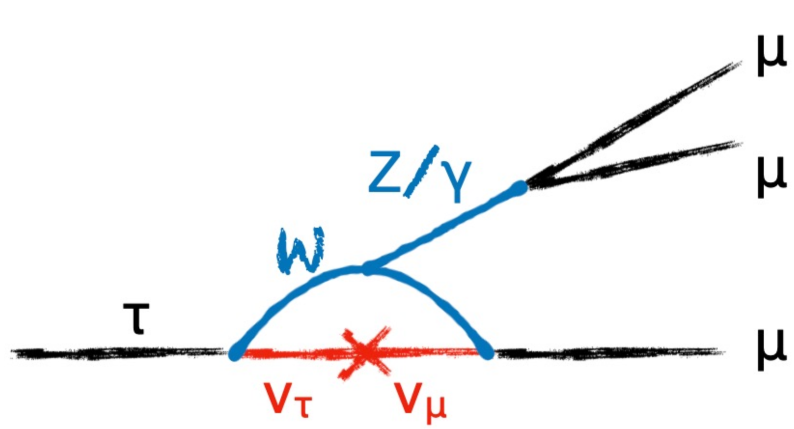
Test of Lepton Flavor Universality $B^+ \to K^+\ell\ell$ decays ($R(K)$) and measurement of $d(\mathscr{B}(B^+ \to K^+\mu\mu))/dq^2$

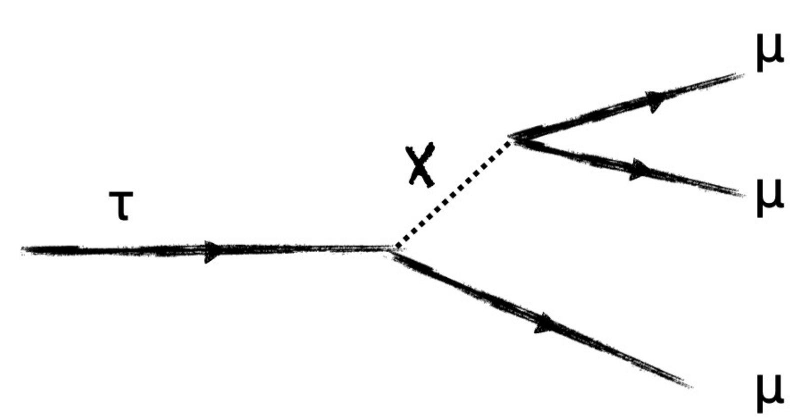
CMS-PAS-BPH-22-005

Lepton Flavour Violation $\tau \to 3\mu$ decays

- **charged LFV decays extremely suppressed in the SM**
  possible only through neutrino oscillations with minuscule BR ~10^{-55}
  10.1140/epjc/s10052-020-8059-7

- **if observed, manifest indication of NP**
  some models predict enhancements up to BR~10^{-9}
  10.1393/ncr/i2018-10144-0
  10.1007/JHEP10(2018)148





Search for LFV $\tau \to 3\mu$ decays

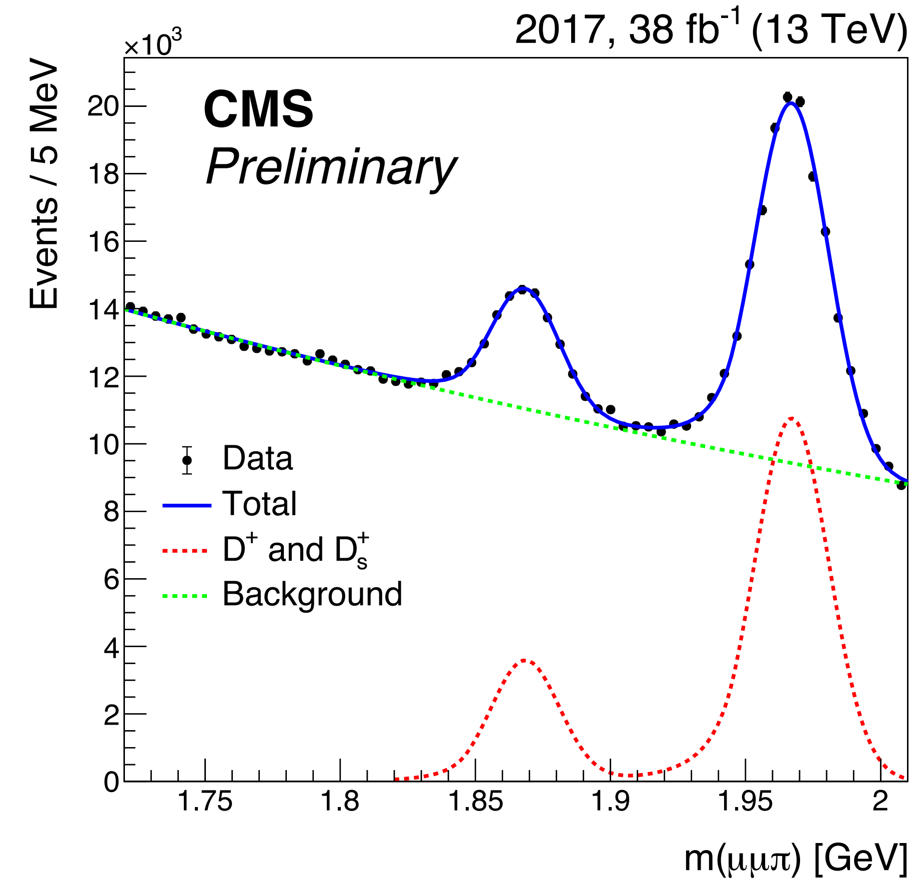
CMS-PAS-BPH-21-005

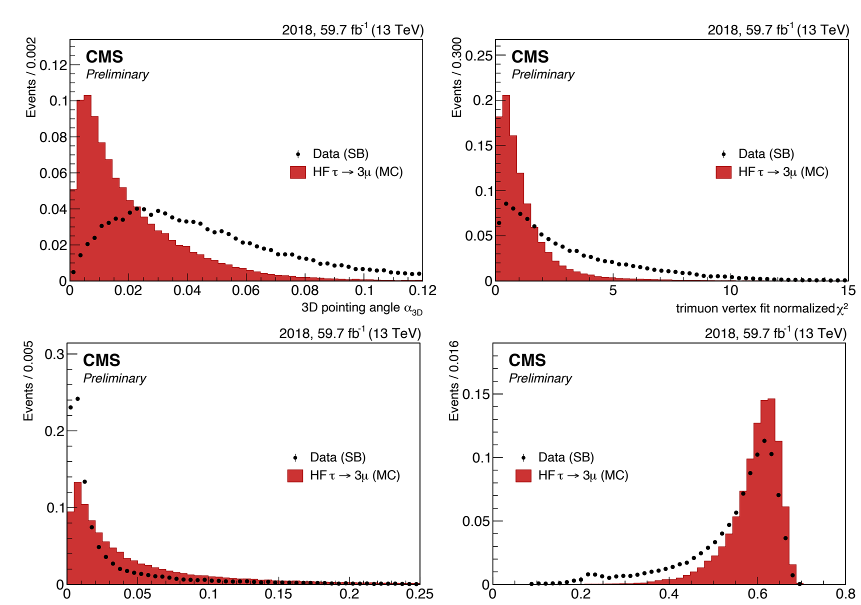
- **search for a narrow peak at** $m_{3\mu} = m_\tau = 1.78\ \mathrm{GeV}$
  collimated 3μ "*jet*", secondary vertex detached from IP
- **two sources of** τ **lepton considered**
  Heavy Flavours, D and B decays
  W boson decays
- **main backgrounds: cascade decays with** ≥ 1 **fake muon**
  veto di-μ $\phi(1020)$ and $\omega(782)$ resonances
- **analysis of 2017, 2018 data combined with analysis of 2016 dataset** (JHEP 01 (2021) 163) **for total** $\mathscr{L} = 131\ \mathrm{fb}^{-1}$
  2017+2018
  improved triggers, better selection BDT, additional categories

Search for LFV $\tau \to 3\mu$ decays

Heavy Flavours

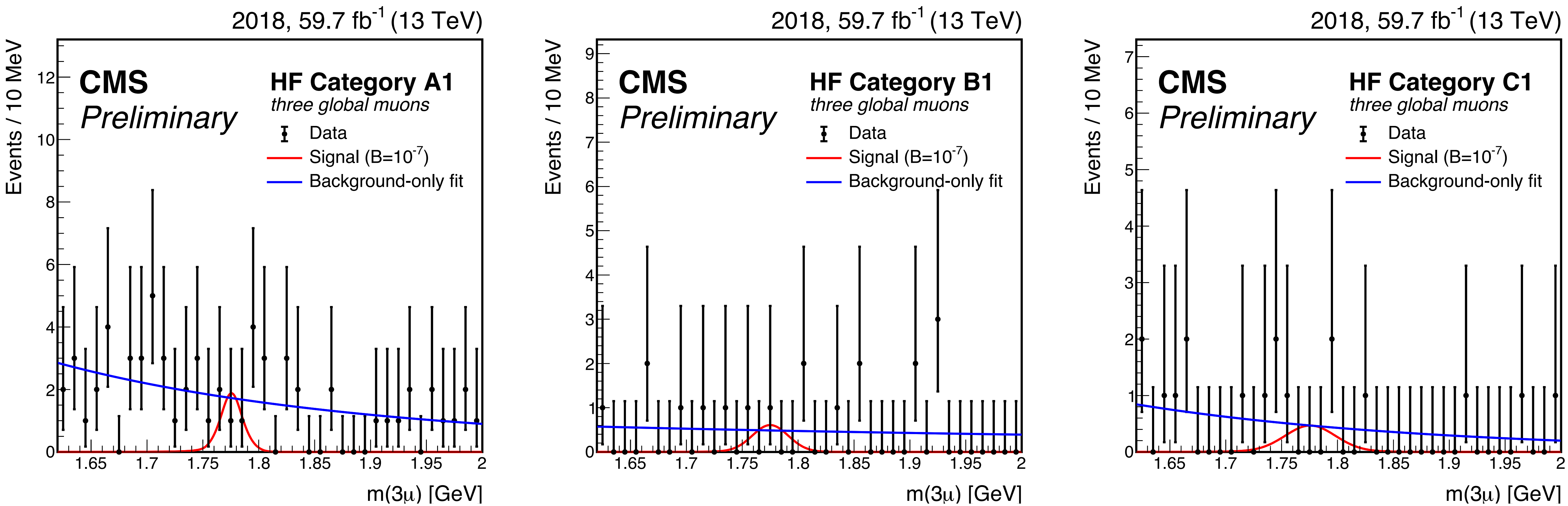
- **primary production mode $D_s \to \tau(3\mu)\nu$**
  - secondary from B and $D^{\pm}$ and cascade decays
- **abundant production but acceptance-limited**
  - muons are soft and forward
  - CMS reco $p_T^{min} \gtrsim 3(1.5)$ GeV for central (forward) muons
- **norm./control channel $D_s \to \phi(\mu\mu)\pi$**
  - contribution of B → D decays derived from fit to decay length
- **categorisation**
  - year (2x), mass resolution (3x), BDT score (3x), 3rd muon global/trk (2x)





Search for LFV $\tau \to 3\mu$ decays

Heavy Flavours



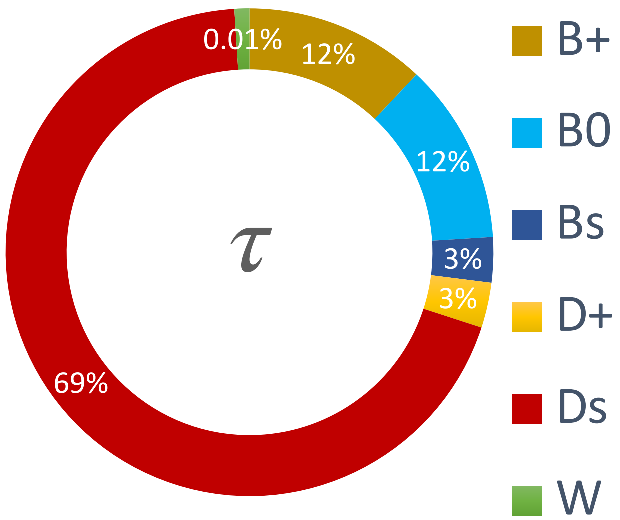
- **excerpt of final $m_{3\mu}$ plots**

  sorted from higher (left) to lower (right) mass resolution

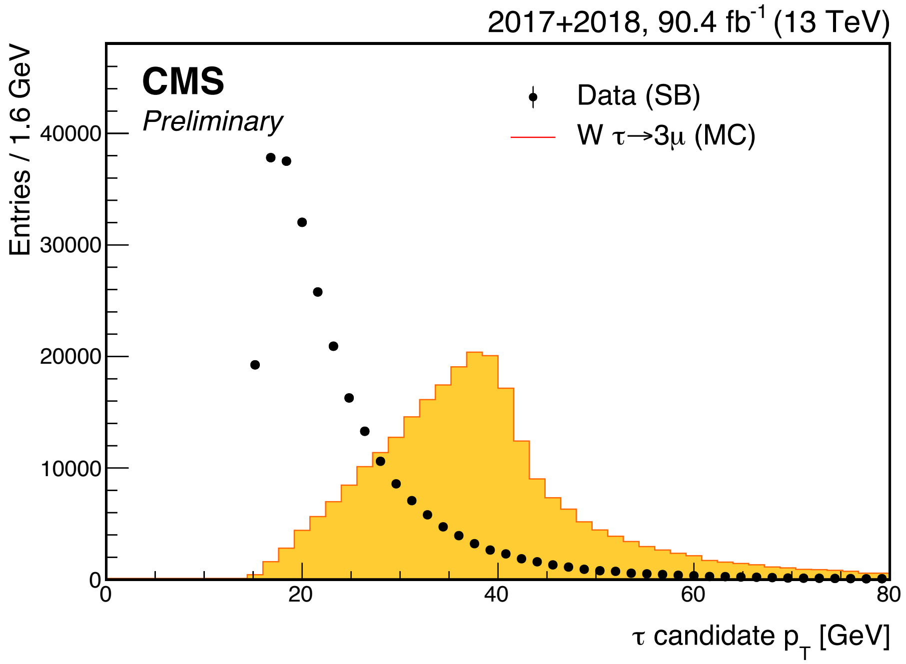
- **background PDF constrained from sidebands**

Search for LFV $\tau \to 3\mu$ decays

$W \to \tau(3\mu)\nu$

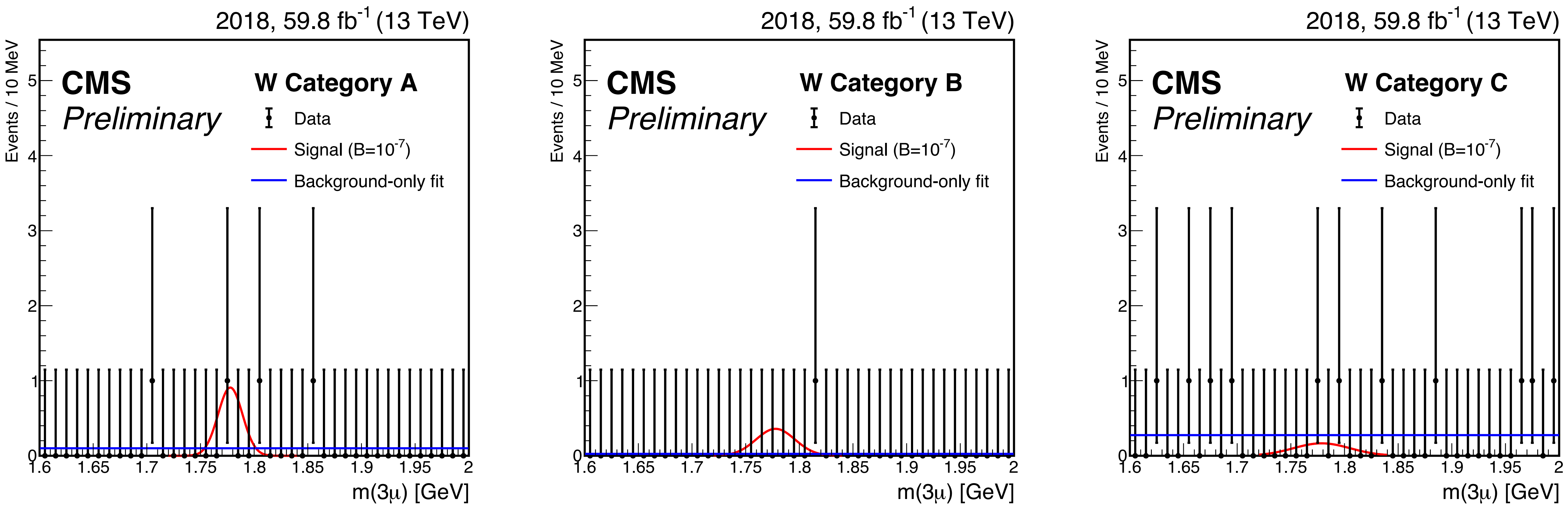


- **comparatively smaller σ, cross section limited**
- **clean experimental signature signature**
  - isolated, high p_{T}, 3μ candidate recoiling against large $E_{\mathrm{T}}^{\mathrm{miss}}$
  - leverage m_W hypothesis to find p_z^{miss}
- **normalisation by σ and $\mathscr{L}$**
- **categorisation** by year (2x) mass resolution (3x)



Search for LFV $\tau \to 3\mu$ decays

$W \to \tau(3\mu)\nu$



- **excerpt of final $m_{3\mu}$ plots**

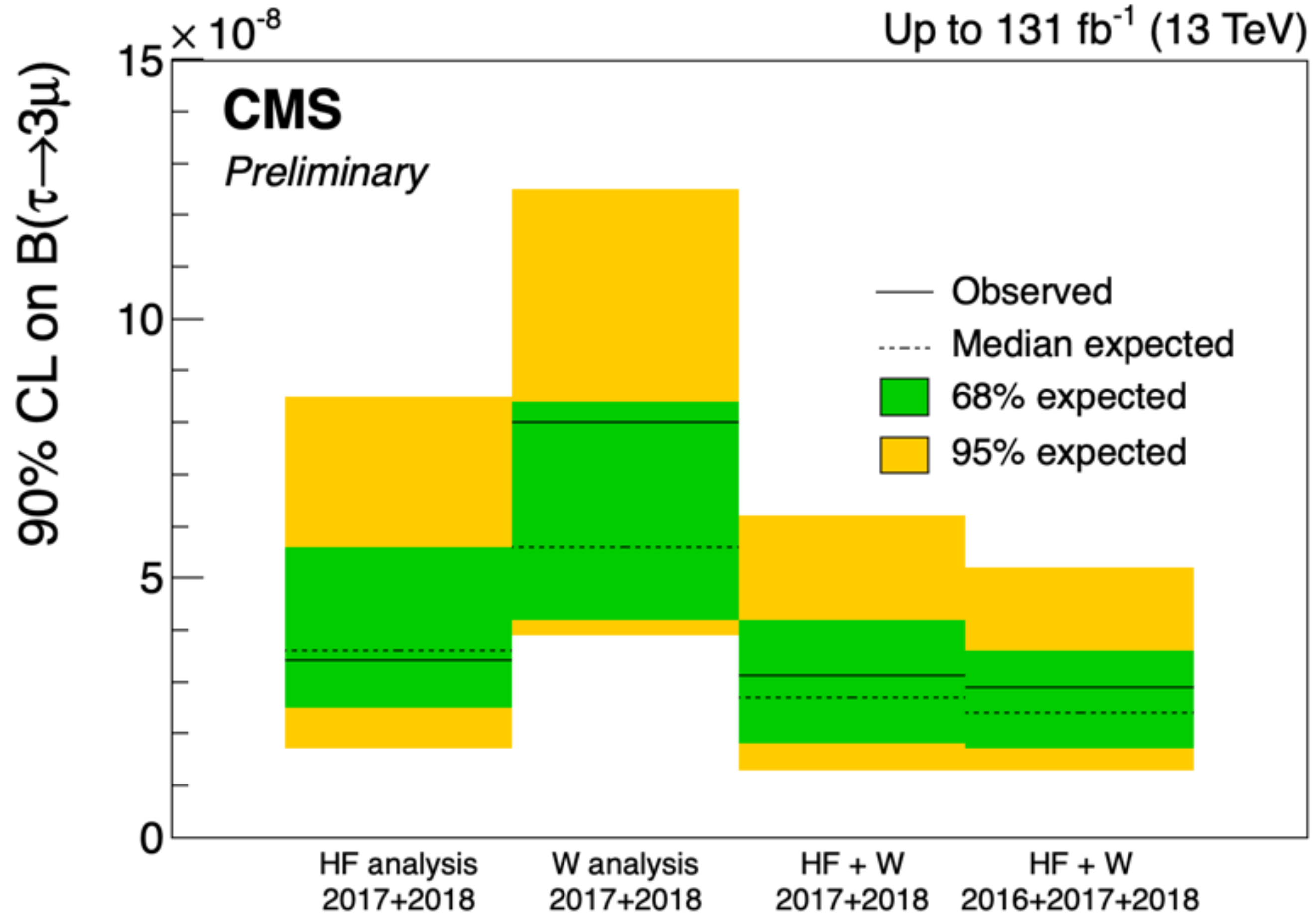
  sorted from higher (left) to lower (right) mass resolution

- **background PDF constrained from sidebands**

- **almost zero background**

Search for LFV $\tau \to 3\mu$ decays

Results and prospects



- **observed (expected)** $\mathscr{B}(\tau \to 3\mu) < 2.9\,(2.4) \cdot 10^{-8}$ **at 90% CL**
- **competitive with world's best from Belle** $\mathscr{B}(\tau \to 3\mu) < 2.1 \cdot 10^{-8}$
  Phys.Lett.B 687 (2010) 139-143
- **Run3 analysis underway, additional** $38(28)\,\mathrm{fb}^{-1}$ **in 2022 (2023)**
  better triggers, low backgrounds, *expected to improve faster than* $\sqrt{\mathscr{L}}$

Flavour Universality tests

$b \to s\ell\ell$ transitions

- at loop level → smaller BR
- fully reconstructed final states
- precise theoretical predictions

$$R(H_s) = \frac{\mathcal{B}(H_b \to H_s\,\mu\mu)}{\mathcal{B}(H_b \to H_s\,ee)}$$

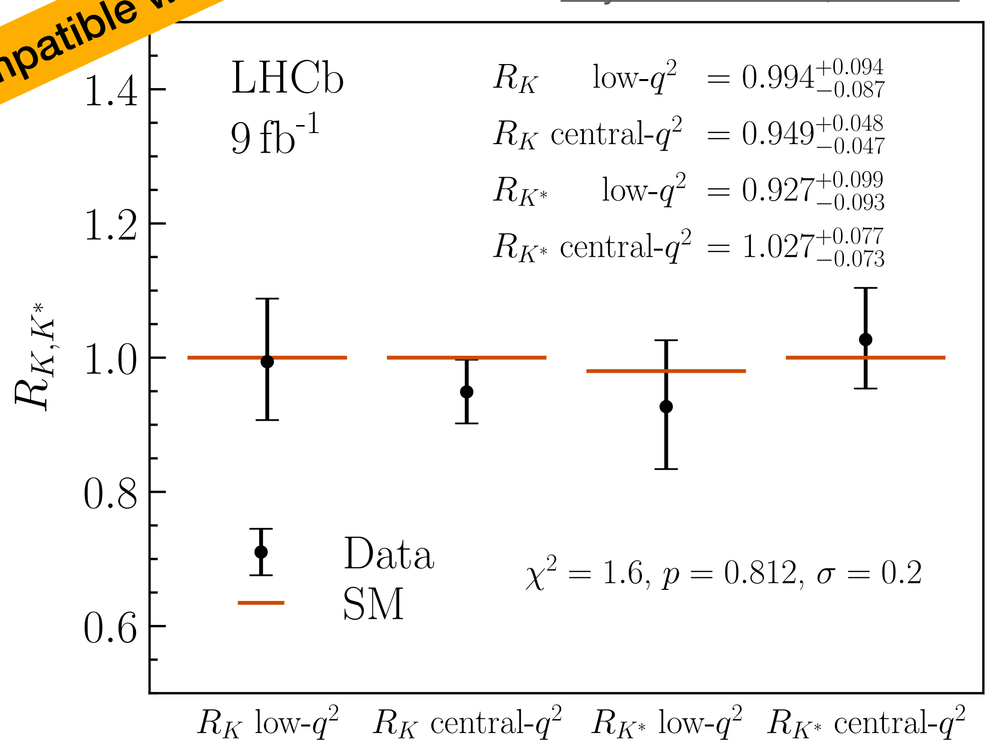
$b \to c\ell\nu_\ell$ transitions

- at tree level → larger BR
- neutrinos on the final state
- subject to larger theory uncert.

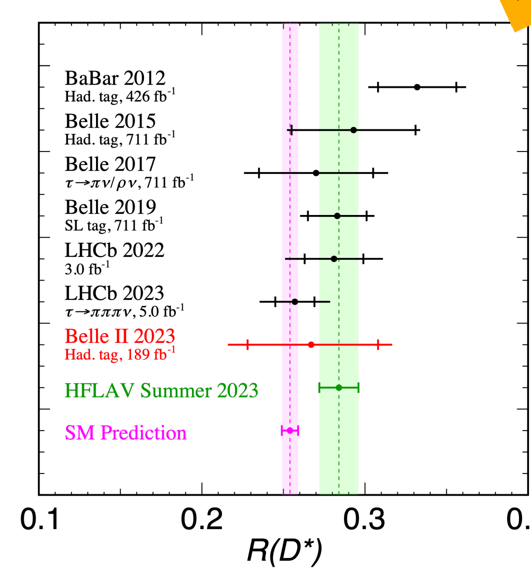
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c\,\tau\nu_\tau)}{\mathcal{B}(H_b \to H_c\,\mu\nu_\mu)}$$

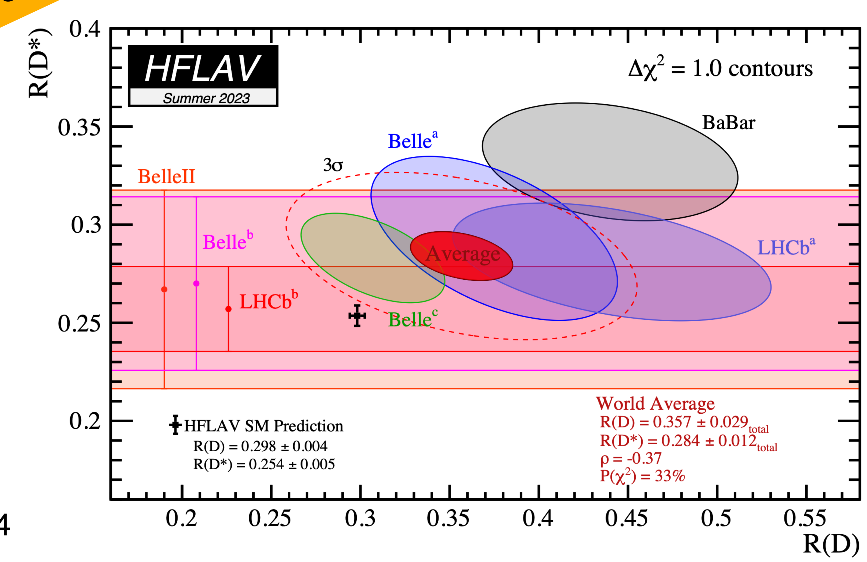
compatible with SM

Phys. Rev. D 108, 032002



~3σ tension

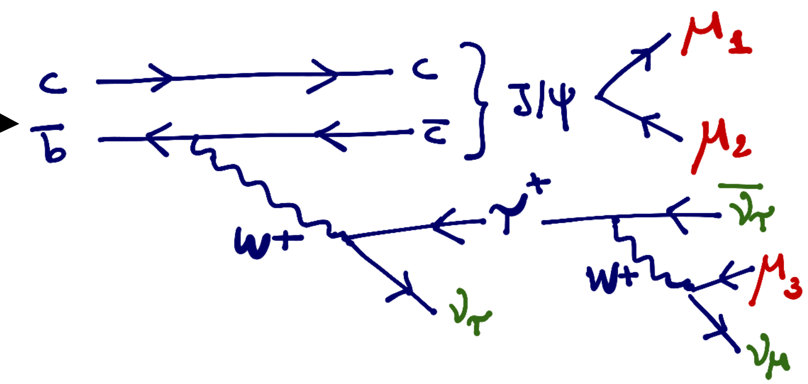


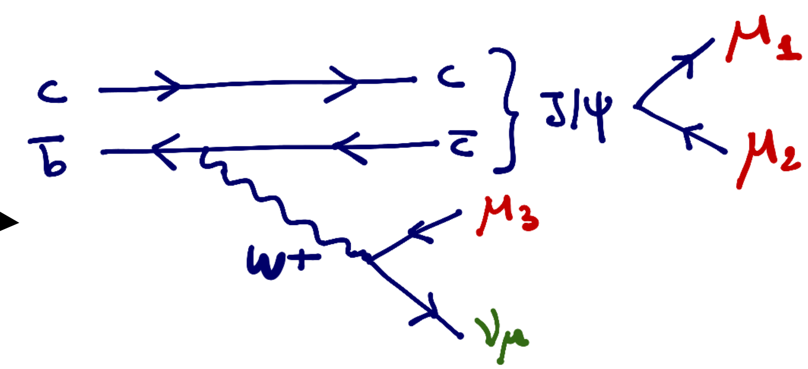


LFUV test: measurement of $R(J/\psi)$

CMS-PAS-BPH-22-012

$$R(J/\psi) = \frac{\mathscr{B}(B_c \to J/\psi\, \tau\, \nu_\tau)}{\mathscr{B}(B_c \to J/\psi\, \mu\, \nu_\mu)}$$





- **SM prediction** $R(J/\psi) = 0.26$ Phys. Rev. Lett. 125, 222003
- **LHCb** $R(J/\psi) = 0.71 \pm 0.17\,(\text{stat.}) \pm 0.18\,(\text{syst.})$ Phys. Rev. Lett. 120, 121801

  2σ deviation

- **three muon final state,** $J/\psi \to \mu\mu$ **and** $\tau \to \mu\nu_\mu\nu_\tau$

LFUV test: measurement of $R(J/\psi)$

Analysis design at a glance

- **2018 dataset** $\mathscr{L} = 59.7\,\mathrm{fb}^{-1}$
- **same** 3μ **+** $1(3)\nu$ **final state for numerator** τ **(denominator** μ**)**
  undetected neutrino(s) → missing momentum
- **simultaneous ML binned template fit**
  parameter of interest $R(J/\psi)$
- ***collinear approximation*** **to infer full** B_c **momentum**
  $p_{B_\mathrm{c}} = m_{B_\mathrm{c}}^{\mathrm{PDG}} / m_{3\mu}^{\mathrm{vis}} \cdot p_{3\mu}^{\mathrm{vis}}$
- **distinguish** $1\,\nu$ **vs.** $3\,\nu$ **via kinematic variables e.g.**
  $q^2 = (p_{B_\mathrm{c}} - p_{J/\psi})^2$ mass of the leptonic system
- **J/Ψ + μ trigger, basic kinematic/ID selections on three-muon candidate**
  μ_3 also required to be isolated

LFUV test: measurement of $R(J/\psi)$

Signal and background processes

- **signals**

  $B_c \to J/\psi\tau\nu$ (num)

  $B_c \to J/\psi\mu\nu$ (den)

- ***fake* muon background** — data driven

  J/ψ + misID had

  (mostly $K \to \mu\nu$)

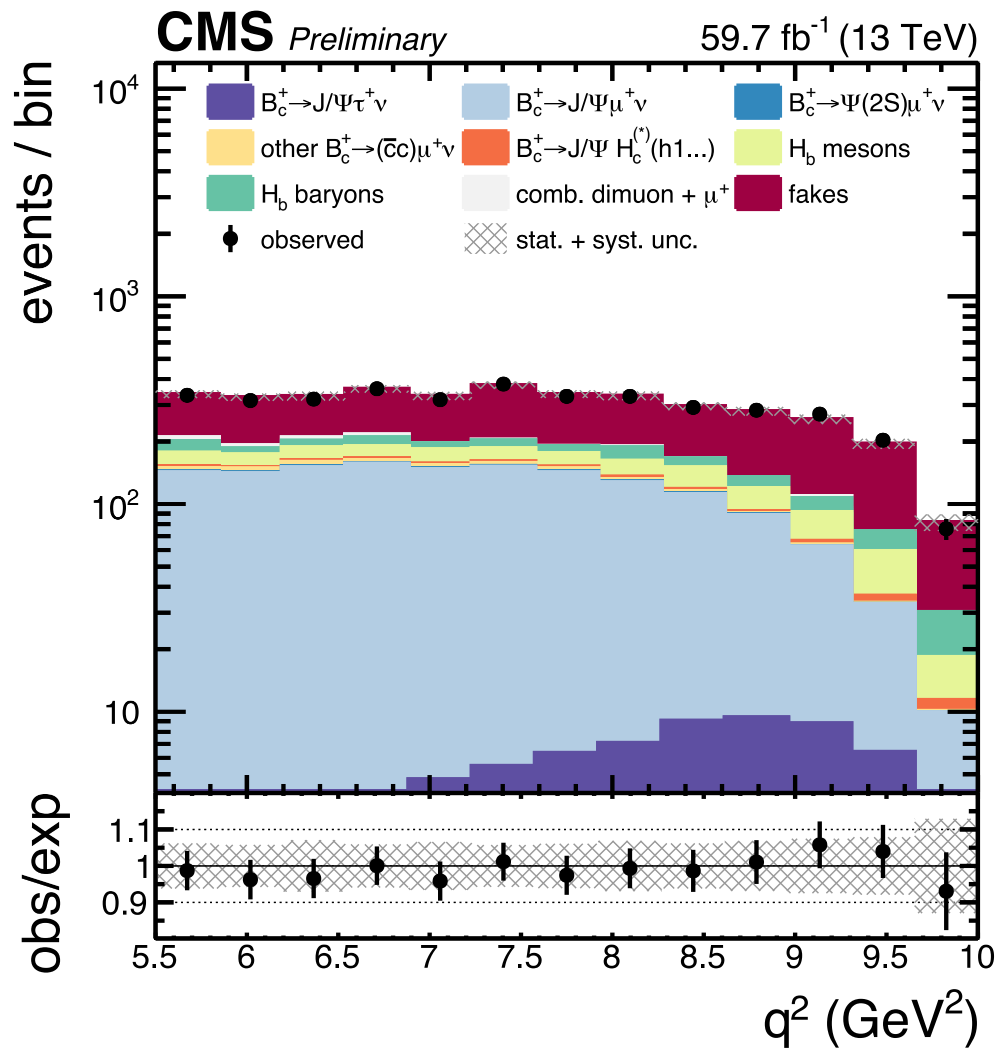
- **H_b background** — simulation + control region

  J/ψ b-hadron + μ

  (98% combinatorial)

- $B_c \to J/\psi + D^{(*)}_{(s)}$, $B_c \to (c\bar{c})\mu\nu$, $B_c \to \psi(2S)\mu\nu$ — simulation

- **combinatorial dimuon + X** — data driven



LFUV test: measurement of $R(J/\psi)$

Signal and background processes

- signals
  $B_c \to J/\psi\tau\nu$ (num)
  $B_c \to J/\psi\mu\nu$ (den)
- ***fake* muon background**
  J/ψ + misID had
  (mostly $K \to \mu\nu$)

dominant background

- **H_b background**
  J/ψ b-hadron + μ
  (98% combinatorial)

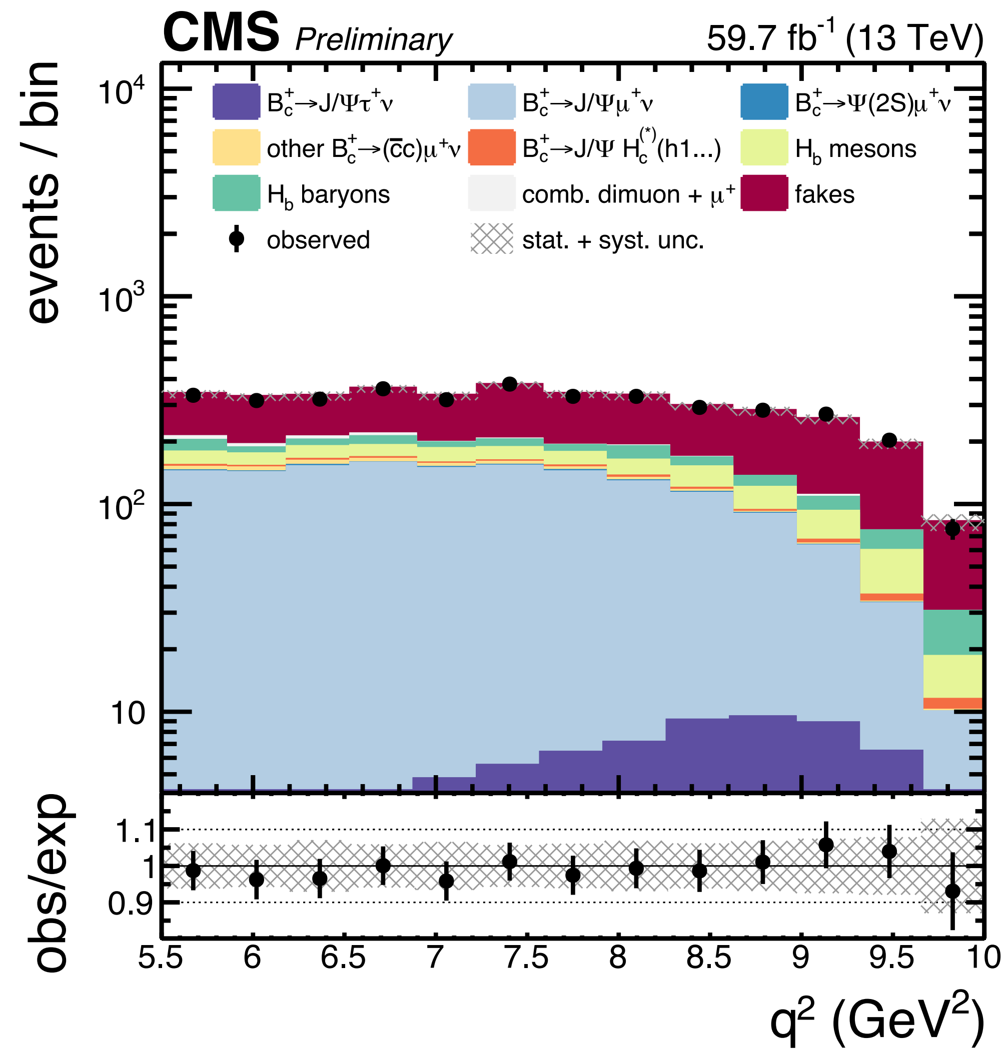
simulation + control region

- $B_c \to J/\psi + D_{(s)}^{(*)}$, $B_c \to (c\bar{c})\mu\nu$, $B_c \to \psi(2S)\mu\nu$

simulation

- **combinatorial dimuon + X**

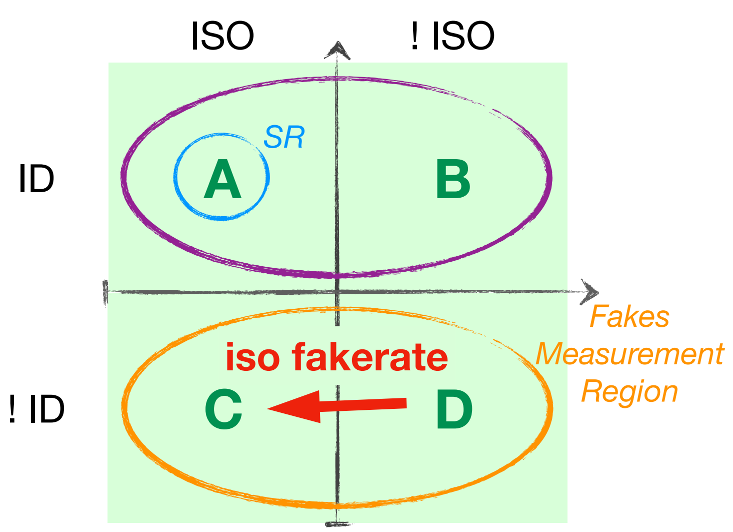
data driven

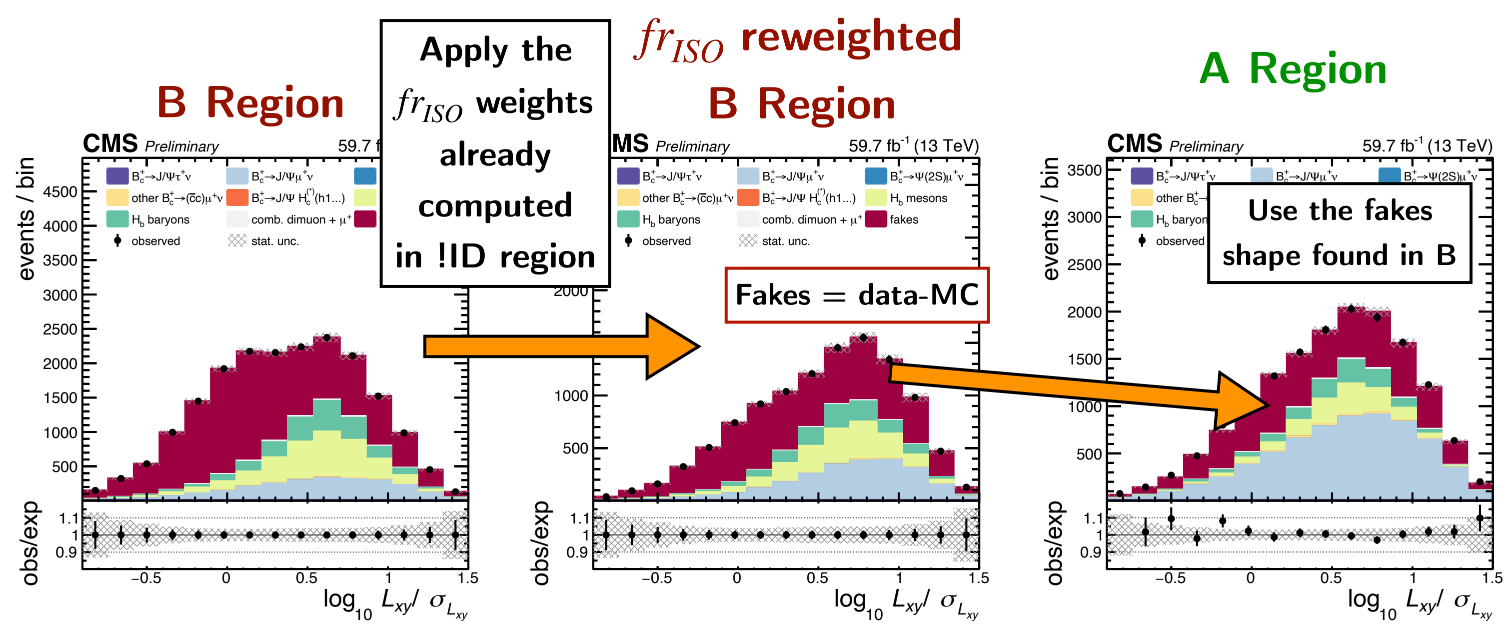


LFUV test: measurement of $R(J/\psi)$

Fakes background

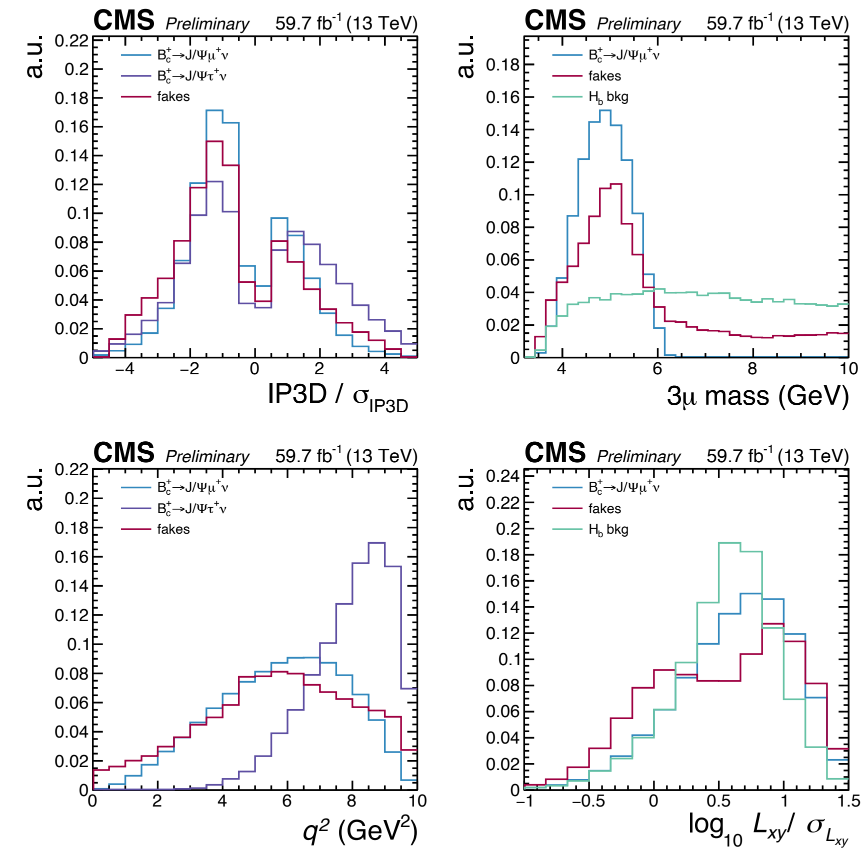
- **fake-rate probability fr_{ISO} measured in region adjacent to signal region** (inverted μ_3 ID)
- fr_{ISO} **fitted using NN classifiers to model multidimensional dependencies** (kinematics, topology…)
- ***in situ*** estimate, incorporated in the final ML fit



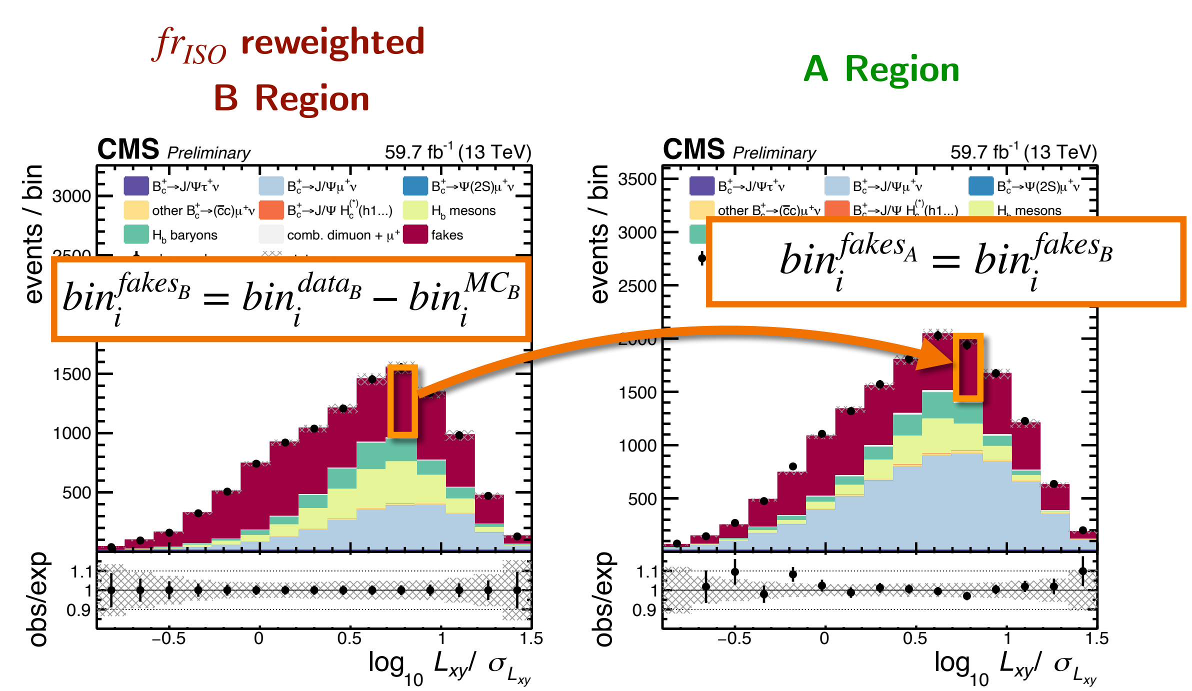


LFUV test: measurement of $R(J/\psi)$

Fit model

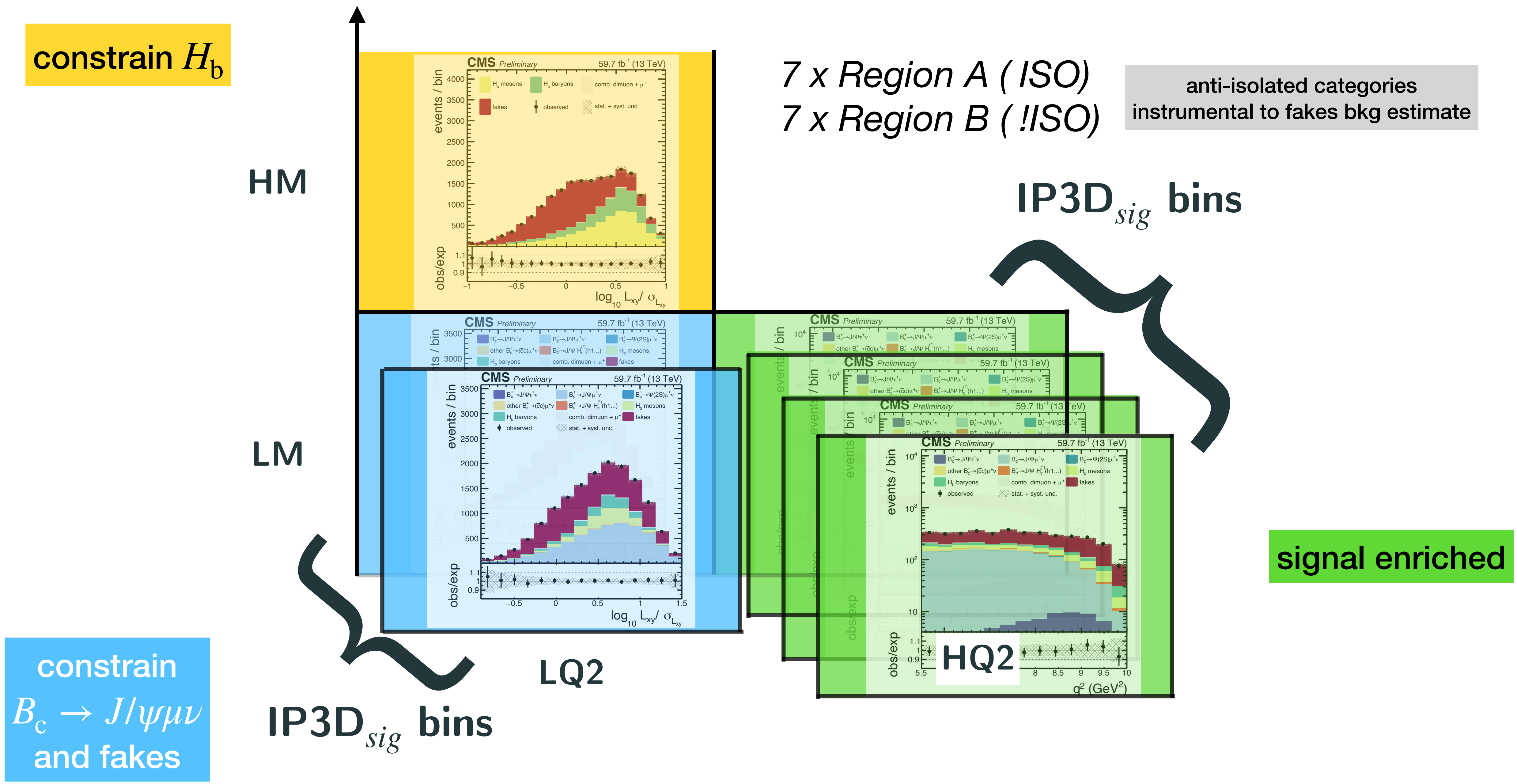


- **binned maximum likelihood template fit**
  7(x2) categories
- $R(J/\psi)$ **parameter of interest**
- **fit to four observables, distinguish $B_c \to J/\psi\tau\nu$, $B_c \to J/\psi\mu\nu$, H_b and fakes**
- ***in situ* estimate of fake muon background**



LFUV test: measurement of $R(J/\psi)$

Fit model



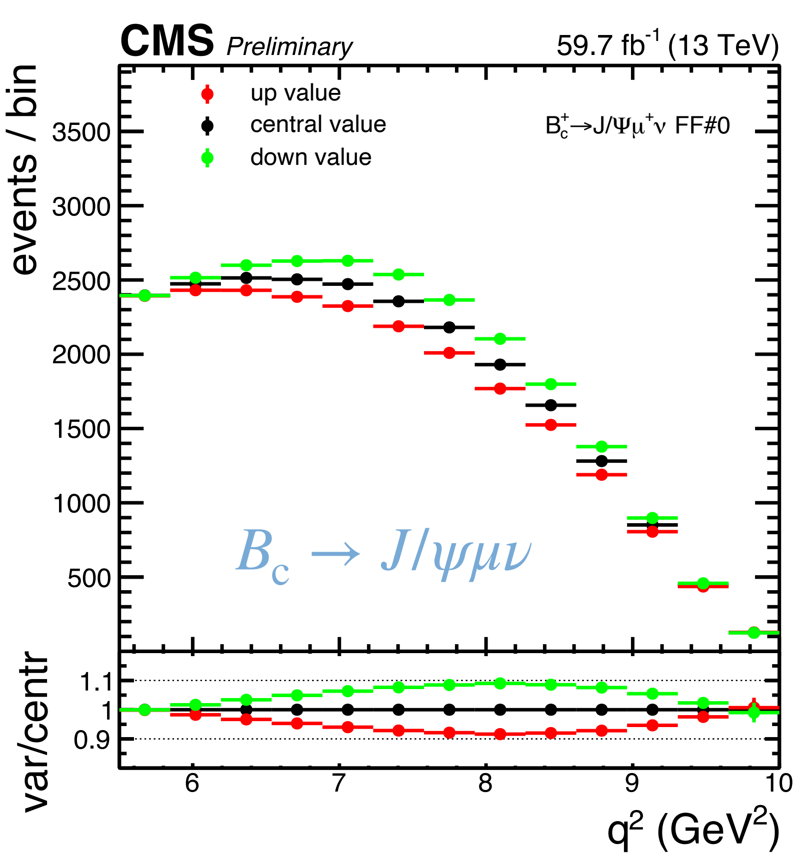
LFUV test: measurement of $R(J/\psi)$

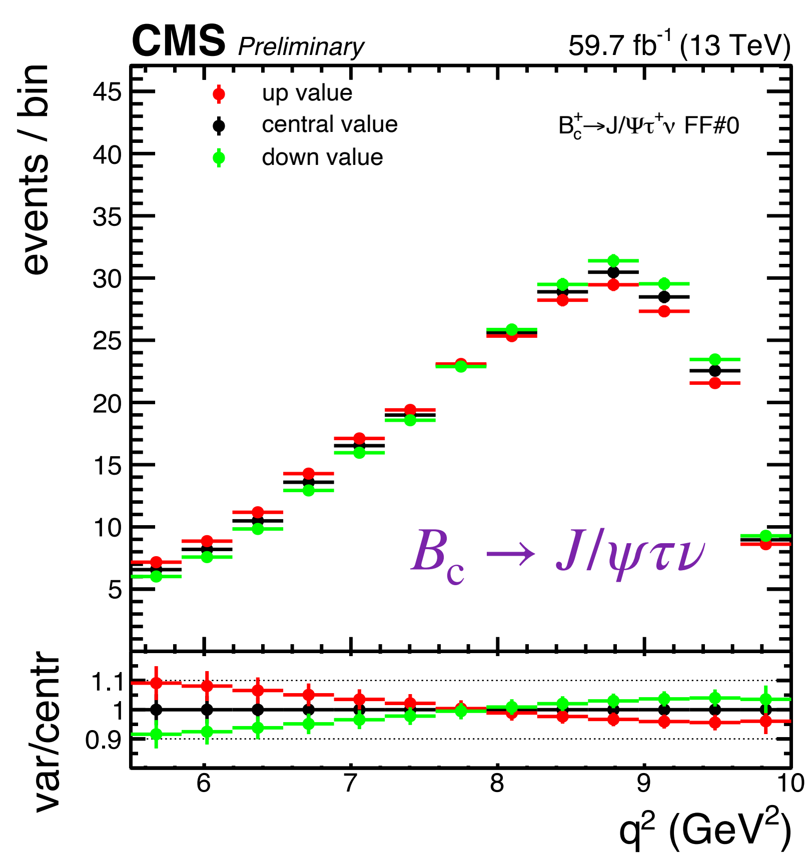
Uncertainties

uncertainties incorporated in ML fit as nuisance parameters, profiled

H_b and B_c norm. free floating, constrained in control regions

Contribution	Uncertainty type	Rel. uncertainty	$\Delta R(J/\psi) \cdot 10^{-2}$
B_c^+ form factors	10 shapes	–	18.2
fakes stat. non closure	bin-by-bin shapes	–	11.3
fakes background	2 shapes	–	4.2
fakes background	norm.	13.0%(+5% HM cat.)	2.5
finite MC size	bin-by-bin shapes	–	5.3
$IP3D/\sigma_{IP3D}$, $L_{xy}/\sigma_{L_{xy}}$ corr.	2 shapes	–	4.4
muon ID, iso, trigger	norm.	6.6%	2.5
J/ψ comb. norm.	norm.	20.0%	1.3
B_c^+ bkg. BRs	norm.	10.0 – 38.0%	0.7
H_b sample composition	norm.	10.0% for each H_b^i	0.5
Other	norm.	–	< 0.1



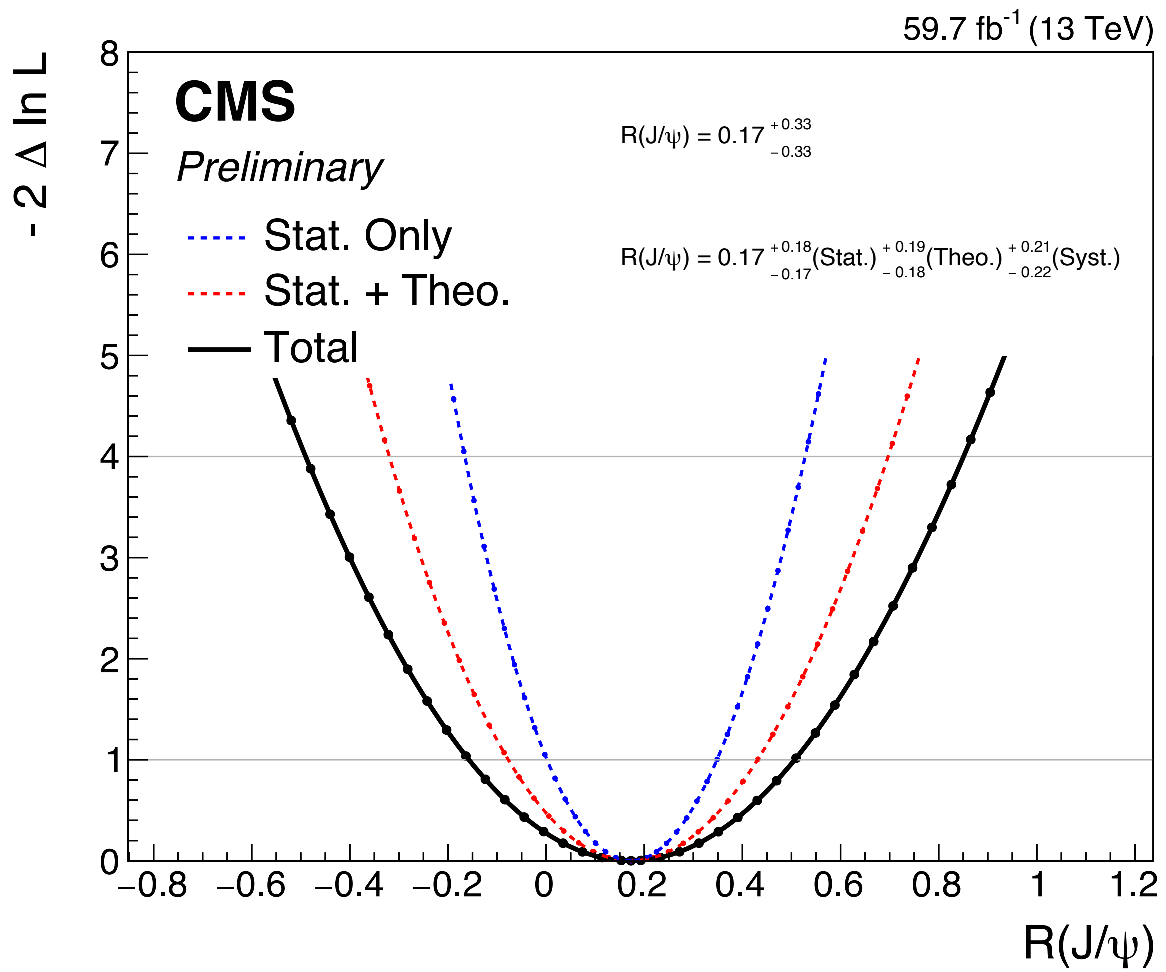


form factors [1] [2]
dominant uncertainty

large impact on key kinematic observable q^2

LFUV test: measurement of $R(J/\psi)$

Results



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

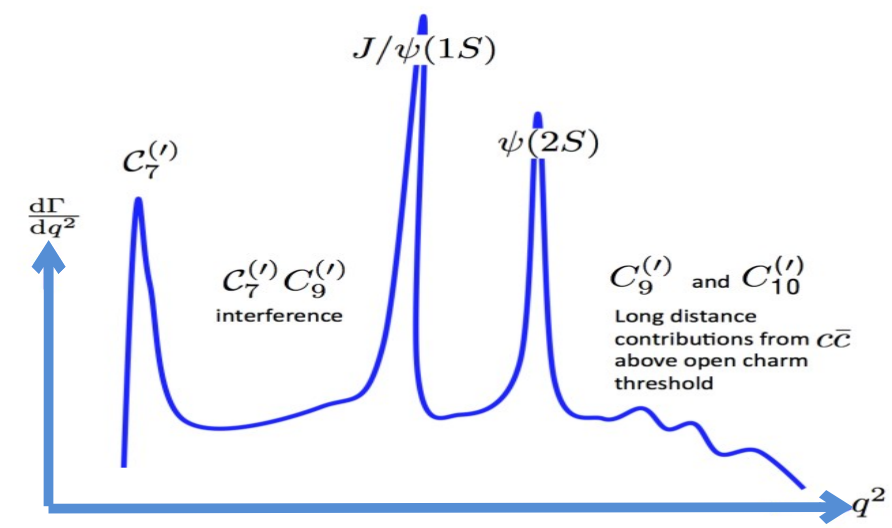
$$R(J/\psi) = 0.17 \pm 0.33$$

- **first LFUV result in $b \to c\ell\nu$ transitions at CMS**
  on partial Run2 dataset
- in agreement with both SM 0.26 and LHCb 0.17 ± 0.25 within less than 1σ
- **sensitivity expected to significantly improve in coming iterations**

LFUV test: $R(K)$ and $d(\mathcal{B}(B^+ \to K\mu\mu))/dq^2$

CMS-PAS-BPH-22-005

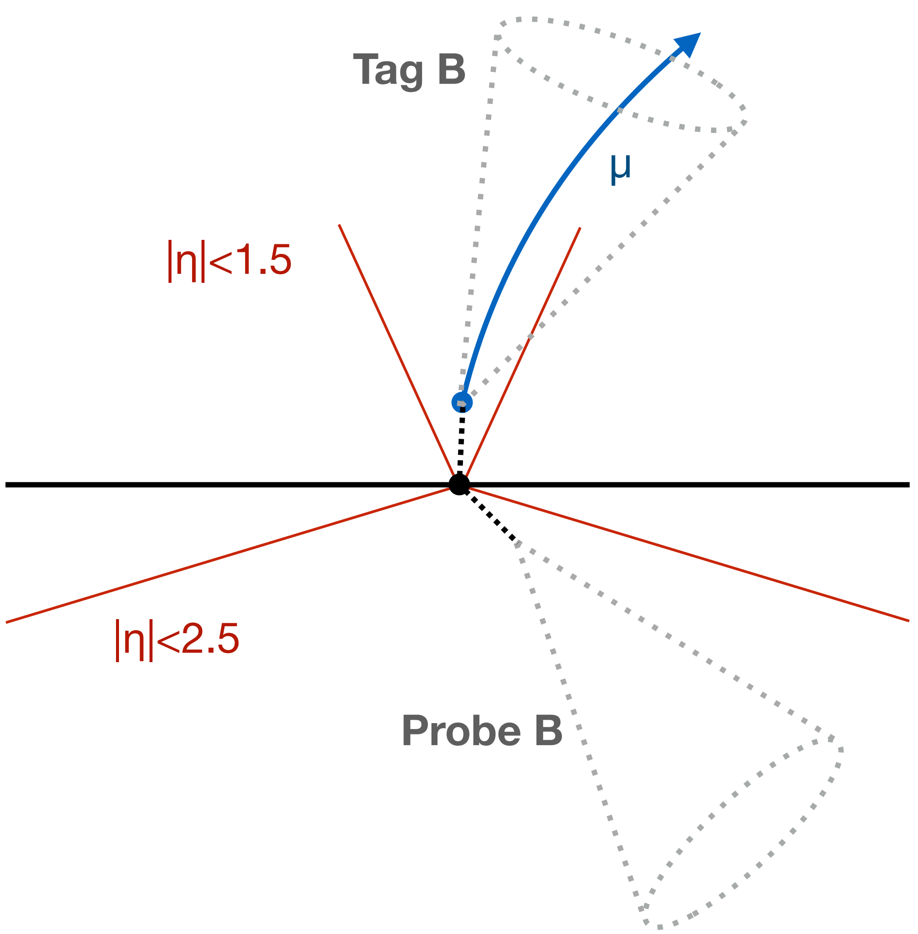
$$R(K) = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))} \cdot \frac{\mathcal{B}(B^+ \to K^+J/\psi(ee))}{\mathcal{B}(B^+ \to K^+ee)}$$



- **R(K) defined as a double ratio to minimise impact of unc.** measured in $1.1 < q^2 < 6.0$ GeV^2 bin, away from resonances
- **soft electrons challenging at CMS** at trigger reco and ID level
- provide measurement of muon part of the ratio in finer q^2 bins as standalone result

LFUV test: $R(K)$ and $d(\mathcal{B}(B^+ \to K\mu\mu))/dq^2$

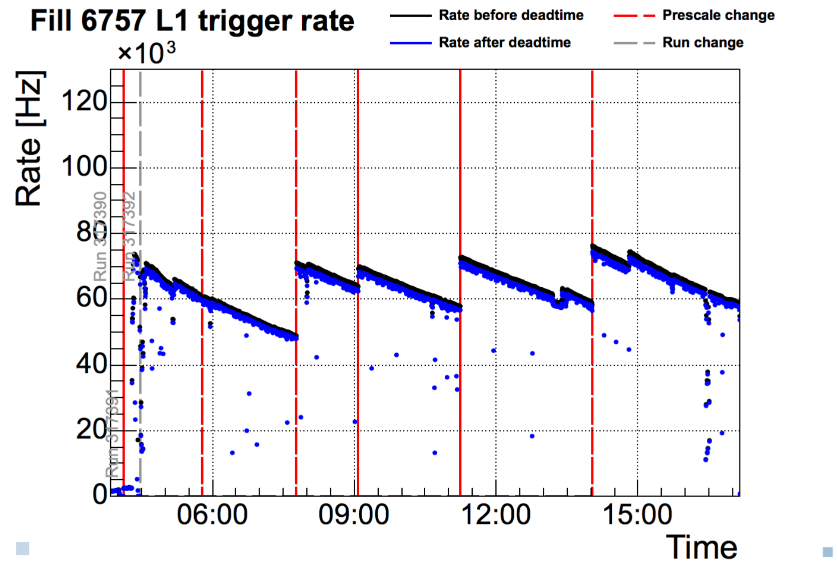
BParking trigger strategy



- b-quarks are produced in pairs
- **displaced single-μ triggers to select semileptonic b-hadron decays on the *"tag"* side …**
- **… and collect a large O(10^10) unbiassed sample of b-hadrons on the *"probe"* side**

  access to all possible decays,
  including electron, fully hadronic

- **deployed in 2018 $\mathscr{L} = 41.6\,\mathrm{fb}^{-1}$ ~70% of total $\mathscr{L}$**
  - progressively relax L1/HLT thresholds during LHC fill as instantaneous lumi goes down
  - fully exploit CMS data acquisition potential
  - reconstruction postponed to LS2 hence nickname *"parking"*
  - purity above 70%

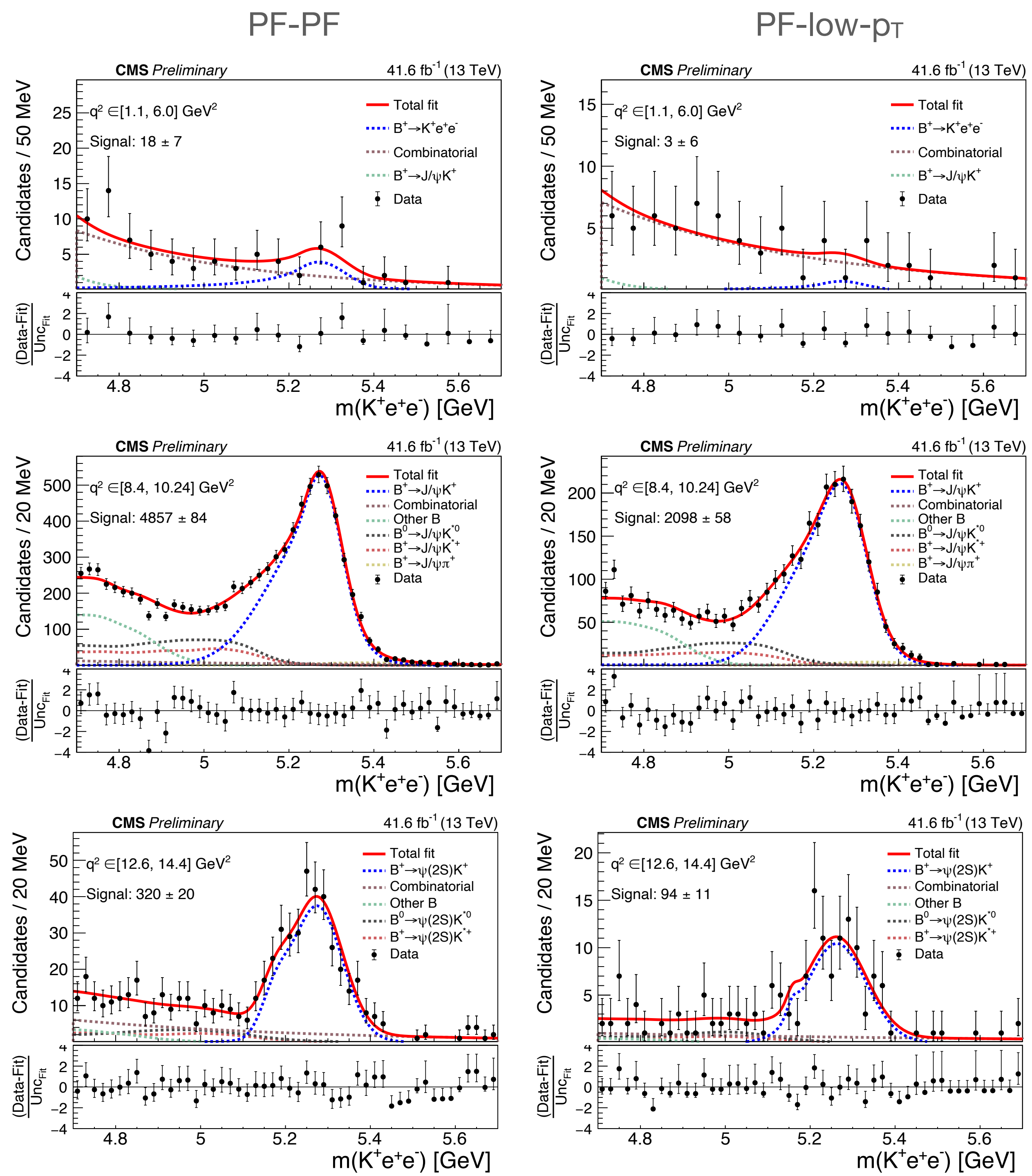


LFUV test: measurement of $R(K)$

$B^+ \to K^+ee$

$$R(K) = \frac{\mathscr{B}(B^+ \to K^+\mu\mu)}{\mathscr{B}(B^+ \to K^+J/\psi(\mu\mu))} \cdot \frac{\mathscr{B}(B^+ \to K^+J/\psi(ee))}{\mathscr{B}(B^+ \to K^+ee)}$$

- **electron reconstruction improved for better acceptance at low p_T**
  two categories PF-PF, PF-low-pT
- **event BDT to suppress backgrounds**
  fake-ele bkg negligible
- **fits in three q^2 bins**
  - $1.1 < q^2 < 6.0\ \mathrm{GeV}^2$ non-resonant
    denominator
  - $8.4 < q^2 < 10.24\ \mathrm{GeV}^2$ J/ψ resonant
    normalisation in double ratio
  - $12.6 < q^2 < 14.4\ \mathrm{GeV}^2$ $\psi(2S)$ resonant
    for validation e.g. J/Ψ / Ψ(2S)

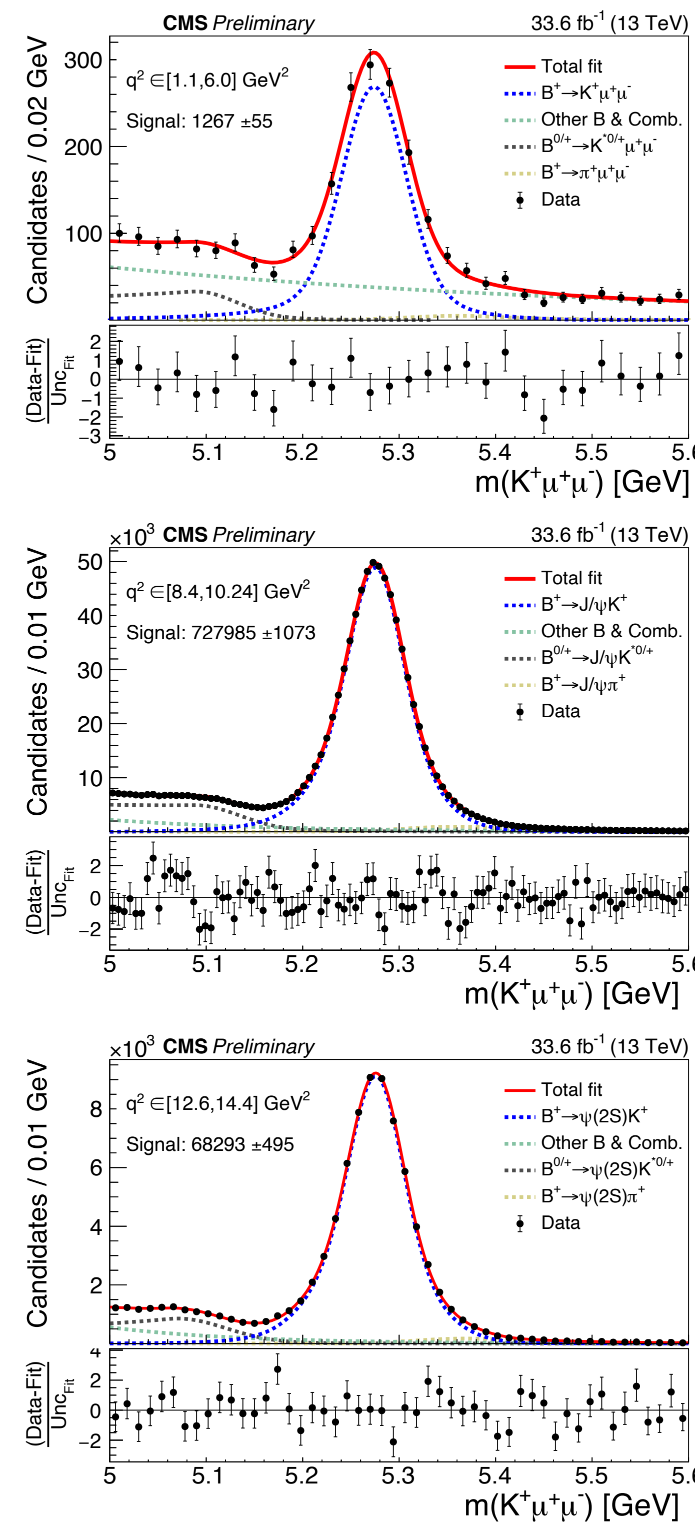


LFUV test: measurement of $R(K)$

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

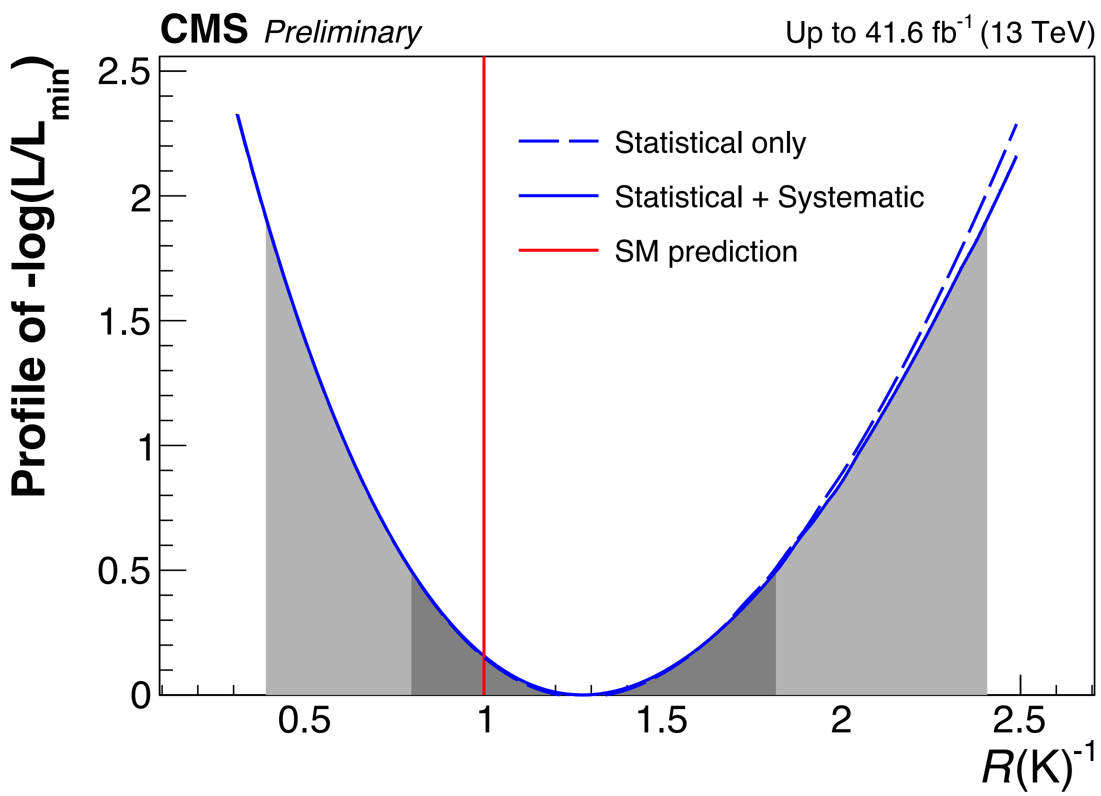
$$R(K) = \frac{\mathscr{B}(B^+ \to K^+ \mu\mu)}{\mathscr{B}(B^+ \to K^+ J/\psi(\mu\mu))} \cdot \frac{\mathscr{B}(B^+ \to K^+ J/\psi(ee))}{\mathscr{B}(B^+ \to K^+ ee)}$$

- **on the “tag” side for better stats**
- **event BDT to suppress backgrounds**
- **fits in the same three q^2 bins**
  - $1.1 < q^2 < 6.0$ GeV^2 non-resonant
    numerator
  - $8.4 < q^2 < 10.24$ GeV^2 J/ψ resonant
    normalisation in double ratio
  - $12.6 < q^2 < 14.4$ GeV^2 $\psi(2S)$ resonant
    for validation



LFUV test: measurement of $R(K)$

Results

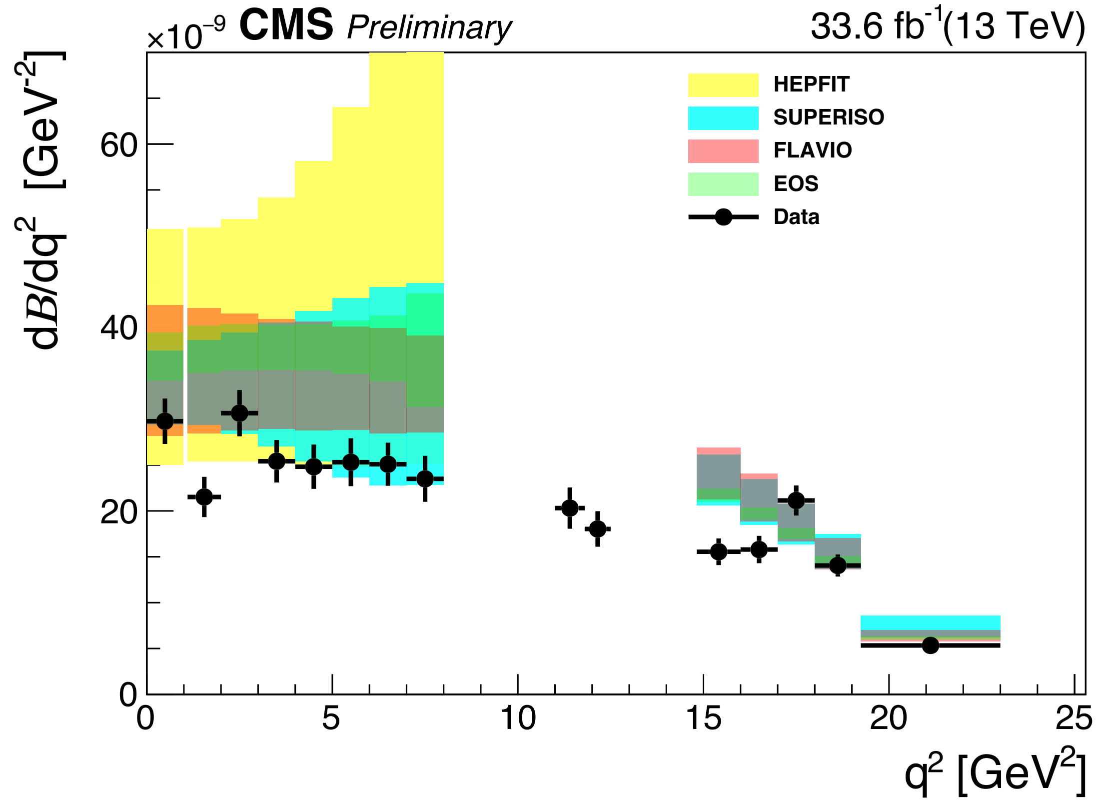


$$R(K) = 0.78^{+0.46}_{-0.23}\,(\text{stat.})\,^{+0.09}_{-0.05}\,(\text{syst.})$$

- **first measurement of LFU in $b \to s\ell\ell$ transitions at CMS**
- **R(K) compatible with SM at less than 1 σ**
- uncertainty dominated by limited statistics in the electron channel
- expect significant increase in stats thanks to revised trigger strategy in Run3

Measurement of $d(\mathscr{B}(B^+ \to K^+\mu\mu))/dq^2$

- **differential $\mathscr{B}$ normalised to resonant channel $\mathscr{B}(B^+ \to J/\psi K^+)$**
- $d\mathscr{B}/dq^2$ **systematically lower than theoretical predictions**
  models are affected by sizable uncert.
- consequently, $\mathscr{B}$ in $1.1 < q^2 < 6.0\ \mathrm{GeV}^2$ low too
- **similar effect observed by LHCb**
  JHEP 06 (2014) 133
- competitive precision



$$\mathscr{B}(B^+ \to K^+\mu\mu),\ 1.1 < q^2 < 6.0\ \mathrm{GeV}^2 =$$
$$(1.242 \pm 0.054\,(\mathrm{stat.}) \pm 0.011\,(\mathrm{MC\ stat.}) \pm 0.040\,(\mathrm{syst.})) \times 10^{-7}$$

Conclusions

CMS is complementing its rich BPH program with the dedicated LF(U)V measurements

competitive with specialist experiments, in particular in muonic final states

first iteration of LFUV analyses needed to build the necessary expertise

significant improvements expected from larger datasets collected with better triggers and more advanced techniques