Lepton flavour (universality) violation studies at CMS

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On behalf of the CMS Collaboration

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ICHEP 2024 - Prague

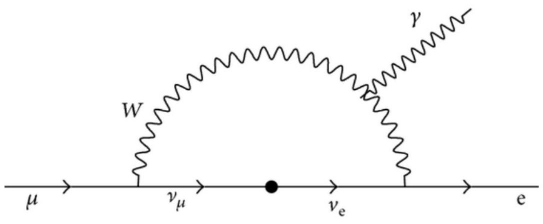
Lepton flavour (universality) violation

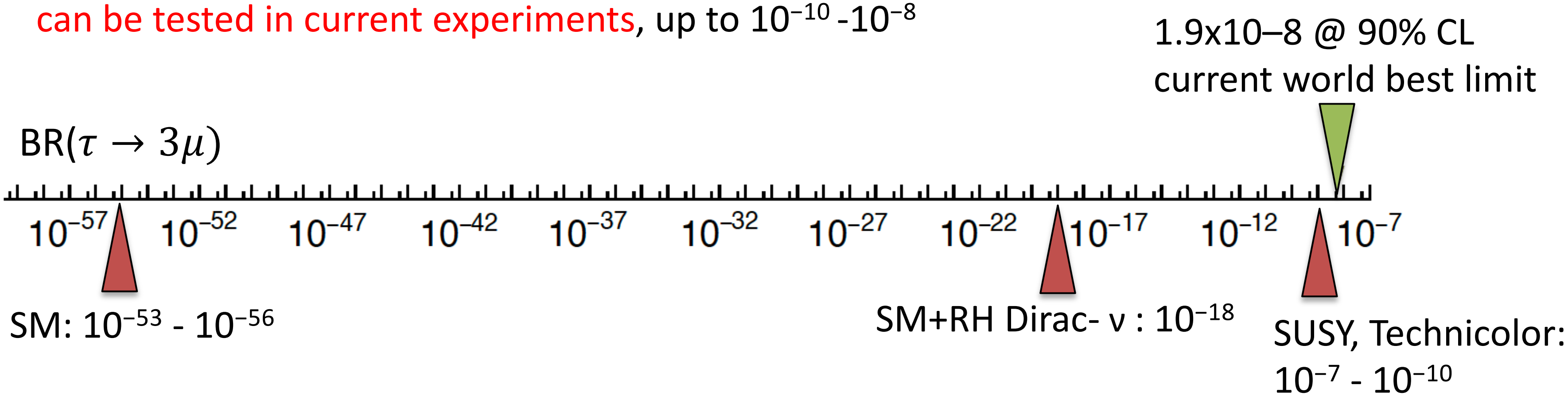
Lepton Flavour Violation (LFV)

No symmetry enforcing lepton flavour conservation in SM

- Neutrino oscillations exist: evidence of LFV in neutral leptons
- Charged LFV happens in loop diagrams with ν mixing, but it is strongly suppressed in the SM (rate $\sim 10^{-55}$)

  https://link.springer.com/article/10.1140/epjc/s10052-020-8059-7
- SM extensions predict a much larger BR which can be tested in current experiments, up to 10^{-10} -10^{-8}





Lepton Flavour Universality Violation (LFUV)

- SM: 3 generations of leptons with the same gauge couplings (W, Z)
- NP could enhance couplings to 3rd generation leptons

LFV and LFUV decays represent a diversified ground for BSM searches

LFV/LFUV as probe for New Physics

The CMS experiment can access a large set of BSM scenarios

- Many results available and many analyses ongoing

Huge effort in the past years to make LF(U)V measurements possible also in the B-physics sector in CMS

- Developments at trigger and reconstruction level

In this talk I concentrate on heavy mesons and leptons

BPH-21-005: search for $\tau \rightarrow 3\mu$ 10.1016/j.physletb.2024.138633

BPH-22-005: measurement of the RK ratio 10.1088/1361-6633/ad4e65

BPH-22-012: measurement of the R(J/ψ) ratio in the τ leptonic channel

BPH-23-001: measurement of the R(J/ψ) ratio in the τ hadronic channel **NEW**

Many other results available as well in the Higgs, Top and Exotic sector and presented in this conference

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

PLB 853 (2024) 138633

Experimentally clean channel

Two sources of tau leptons exploited:

- Heavy flavour decays: ~10^{11} τ_s /fb^{-1} ; ~70% D, 30% B
- W bosons decays: ~10^{7} τ_s /fb^{-1}

Signature: charge-one three muons events from a displaced vertex

Analysis strategy: bump search in the 3 muons invariant mass

Events categorization to boost sensitivity:
based on invariant mass resolution, production mode, year

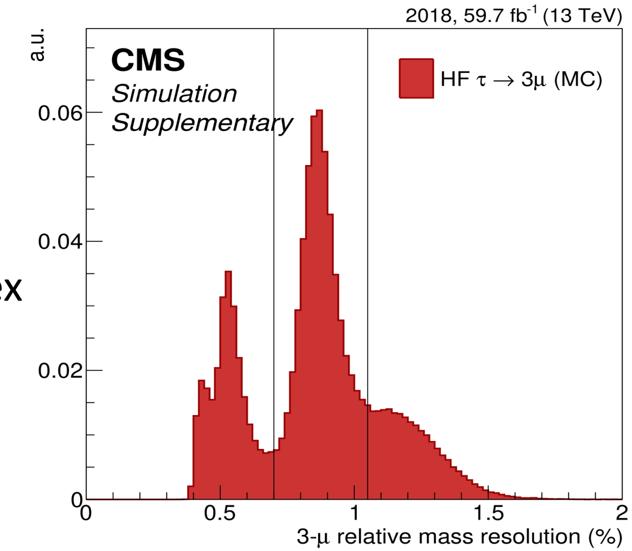
Main backgrounds:

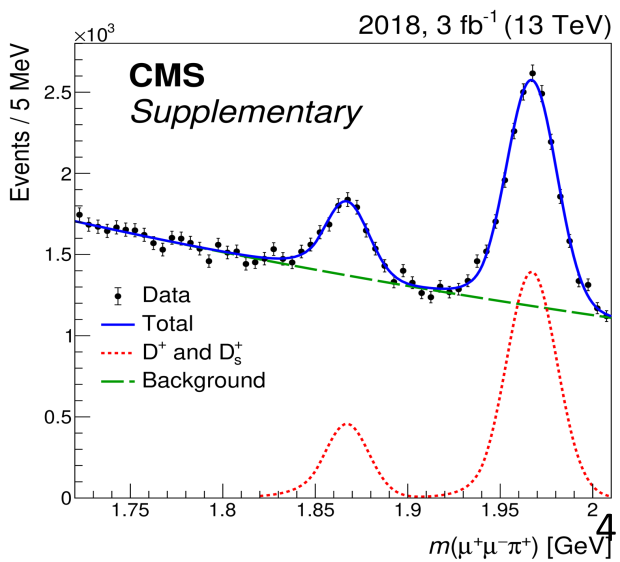
- 2 real muons + 1 fake
  - e.g. B → D + μ + X; D → μ + ν + Kaon; Kaon fakes muon
- 3 real muons, two from a resonance (ω, ϕ …)
- Combinatorial background

Background suppression mostly using BDT discriminators
+ dedicated cut-based selections

Control channel: $Ds \rightarrow \phi\pi \rightarrow \mu\mu\pi$

- Also used as a normalization channel for the HF analysis





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

PLB 853 (2024) 138633

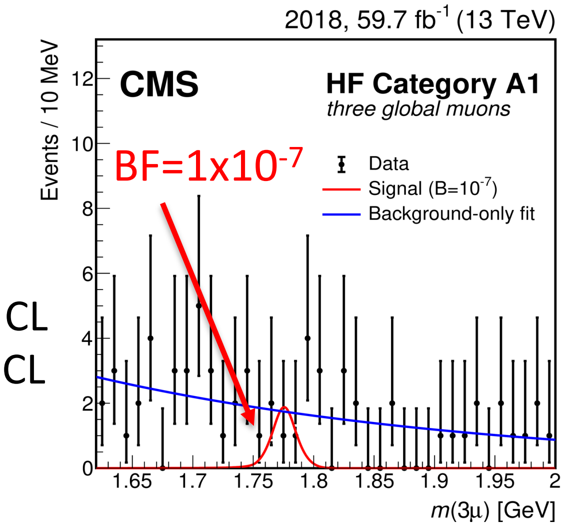
Analysis based on 2017+2018 data

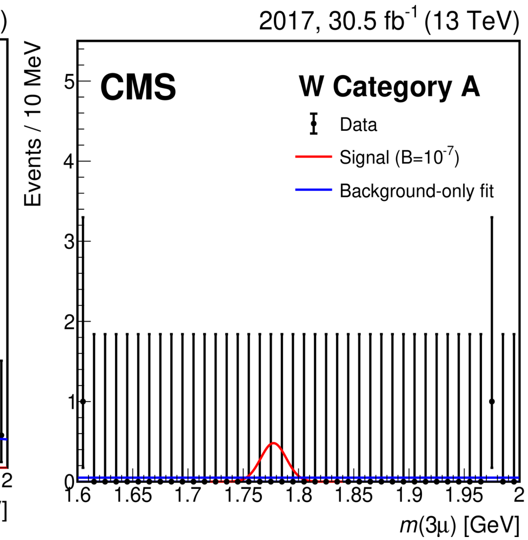
No hint of signal found, upper limits set on the τ→3μ branching ratio

Observed (expected) upper limit:

$BR(\tau \rightarrow 3\mu, HF) < 3.4\ (3.6)$ x10^{-8} @90% CL

$BR(\tau \rightarrow 3\mu,\ W) < 8.0\ (5.6)$ x10^{-8} @90% CL





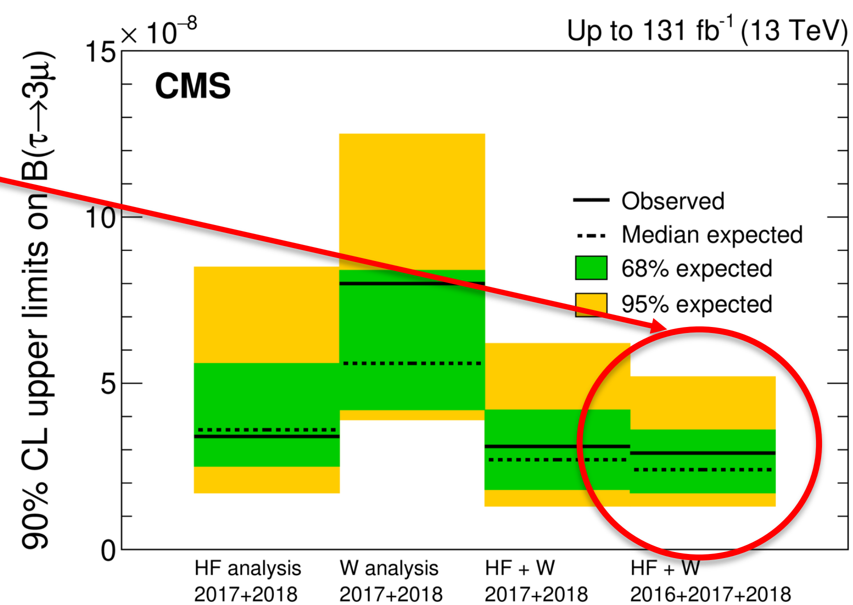
Results are statistically combined with a previous CMS analysis based on 2016 data CMS JHEP 01 (2021) 163

$BR(\tau \rightarrow 3\mu) < 2.9\ (2.4)$ x10^{-8} @90% CL

- Best LHC limit
  (ATLAS and LHCb: results on Run1 data)

Current best world limit by BelleII (2024):

$BR(\tau \rightarrow 3\mu) < 1.9$ x10^{-8} @90% CL



LFUV

Two main transitions investigated in the Heavy Flavour sector

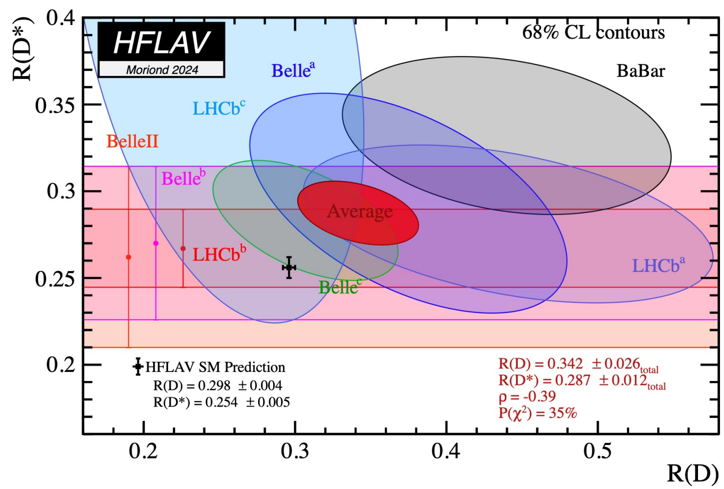
$b \rightarrow sll$

- $R(Hs) = \frac{\mathfrak{B}(Hb \rightarrow Hs\mu\mu)}{\mathfrak{B}(Hb \rightarrow Hsee)}$
- Small BR (loop level)
- Precise predictions
- Neutrino-less

$b \rightarrow cl\nu_l$

- $R(H_c) = \frac{\mathfrak{B}(Hb \rightarrow Hc\tau\nu\tau)}{\mathfrak{B}(Hb \rightarrow Hc\mu\nu\mu)}$
- Large BR (tree level)
- Sensitive to theory and syst. uncertainties
- Neutrinos in the final state

Most recent results on RK and RK* in good agreement with SM



$\sim 3\sigma$ tension with SM

LFUV

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- $R(Hs) = \frac{\mathfrak{B}(Hb \rightarrow Hs\mu\mu)}{\mathfrak{B}(Hb \rightarrow Hsee)}$
- Small BR (loop level)
- Precise predictions
- Neutrino-less

$$R_K = \frac{BF(B \rightarrow \mu\mu K)}{BF(B \rightarrow eeK)}$$

Theoretically clean; SM prediction = 1.00 ± 0.01

Most recent results on RK and RK* in good agreement with SM

RK: overview

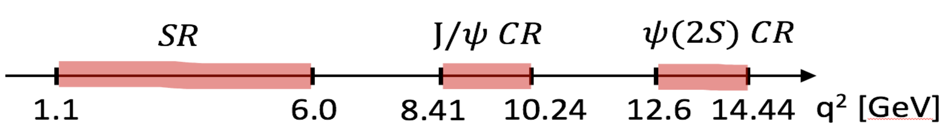
[2024 *Rep. Prog. Phys.* **87** 077802](#)
Just published!

$$R_K = \frac{BF(B \to \mu\mu K)}{BF(B \to J/\psi K, J/\psi \to \mu\mu)} \Big/ \frac{BF(B \to eeK)}{BF(B \to J/\psi K, J/\psi \to ee)}$$

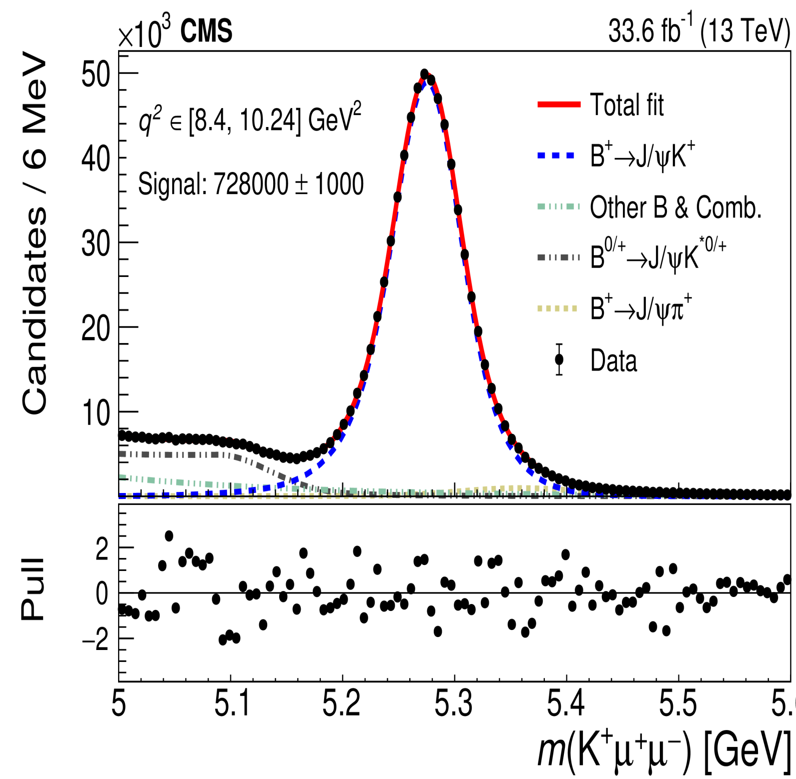
Experimentally cleaner; systematics cancellation

Measurement overview:

- Innovative technique to collect data:
  2018 B-parking https://arxiv.org/abs/2403.16134
- Fit to Kll invariant mass in 3 q^2 regions

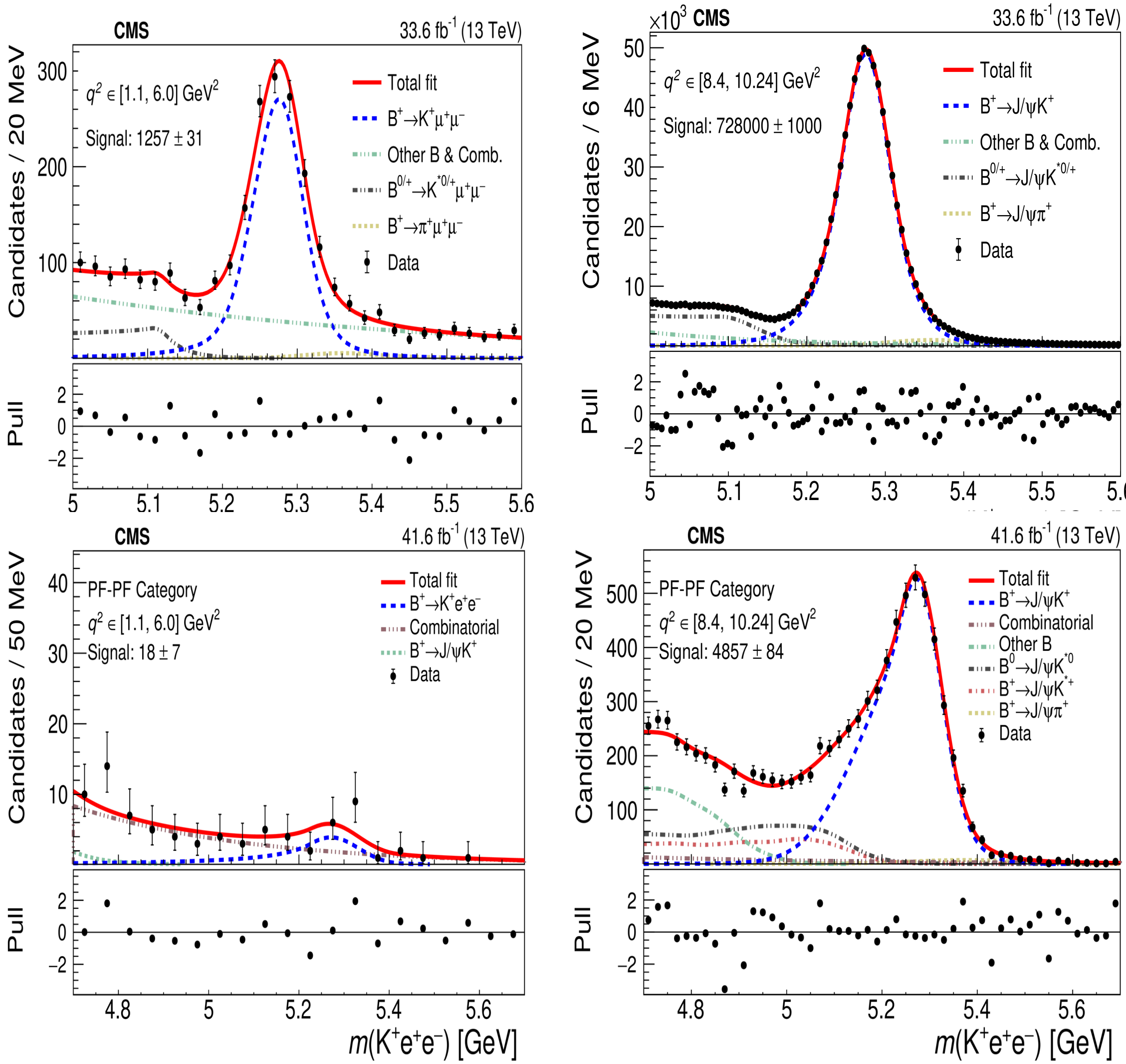


- Dedicated *low p_T electron* reconstruction / ID
- Main backgrounds: combinatorial,
  partially reconstructed $B^{0/+} \to K^*(892)^0 ll$,
  any other B decay (J/ψX or sequential), J/ψ leakage
  Background suppression mostly using
  BDT discriminators



RK, results

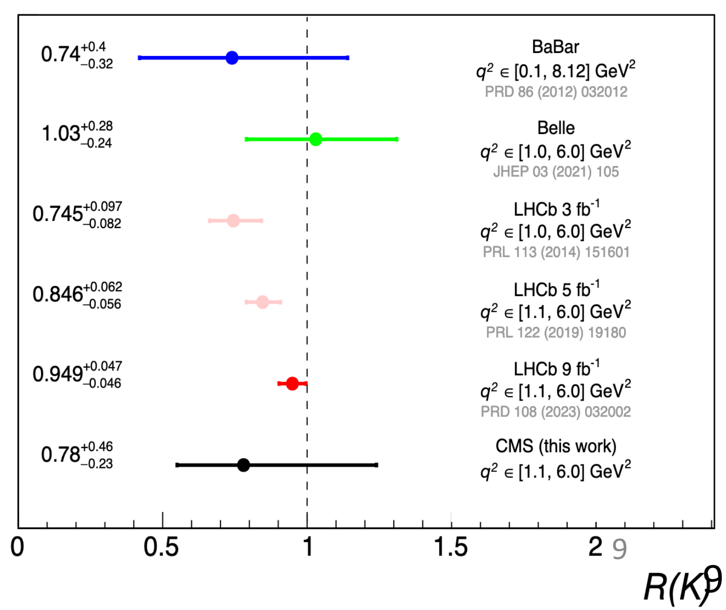
2024 *Rep. Prog. Phys.* **87** 077802



RK value extracted with a profile likelihood using RK^{-1}

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

- Precision dominated by small statistics in the electron channel
- Main systematics: background description and trigger turnon
- Compatible within 1σ with SM



In the same paper (see backup)
$B \to K\mu\mu$ inclusive and differential BR in q^2

LFUV

Two main transitions investigated in the Heavy Flavour sector

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

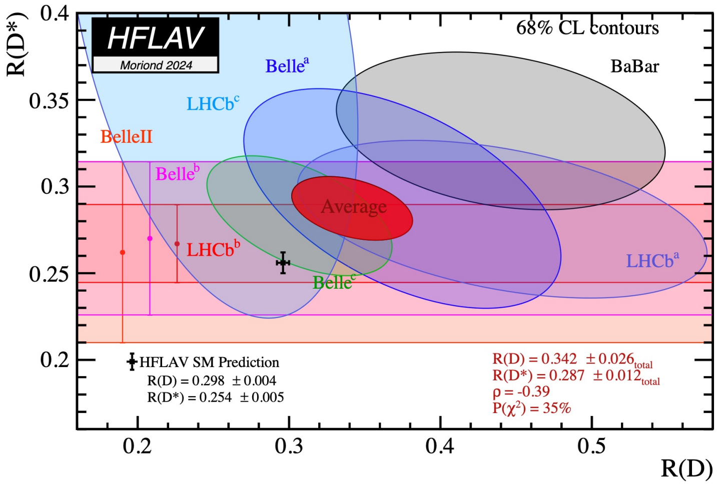
SM: 0.2582 ± 0.0038 PRL 125, 222003 (2018)

Not much studied because Bc can not be produced at B-factories

Both leptonic and hadronic decays of the τ lepton could be exploited

$b \to c l \nu_l$

- $R(H_c) = \frac{\mathfrak{B}(Hb \to Hc\tau\nu\tau)}{\mathfrak{B}(Hb \to Hc\mu\nu\mu)}$
- Large BR (tree level)
- Sensitive to theory and syst. uncertainties
- Neutrinos in the final state



$\sim 3\sigma$ tension with SM

R(J/ψ), leptonic τ

τ decay : $\tau \rightarrow \mu\nu\tau\nu\mu$

Final state signature: 3μ + neutrinos (3 or 1) for numerator and denominator

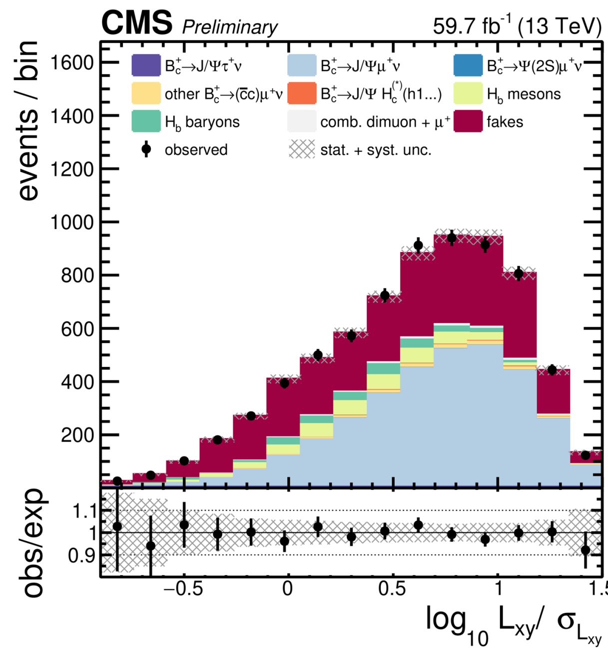
- Same reconstruction and simultaneous fit

Separate 1ν/3ν using $q^2=(p^{Bc}- p^{J/\psi})^2$

- Collinear approximation to estimate the Bc 4-momentum: $p^{Bc} = \frac{m^{PDG}(Bc)}{m(3\mu)}\ p^{3\mu}$

Main backgrounds:

- Muon fakes: J/ψ + misidentified hadron (mostly $K \rightarrow \mu\nu$)
- Hb bkg: combinatorial J/ψ + μ
- Bc bkg:
  - Feeddowns ($c\bar{c}$ to J/ψ)
  - Other J/ψ + charmed hadrons (mostly $B^+_c \rightarrow D^{(*)}s$ J/ψ)
- Combinatorial $\mu\mu$

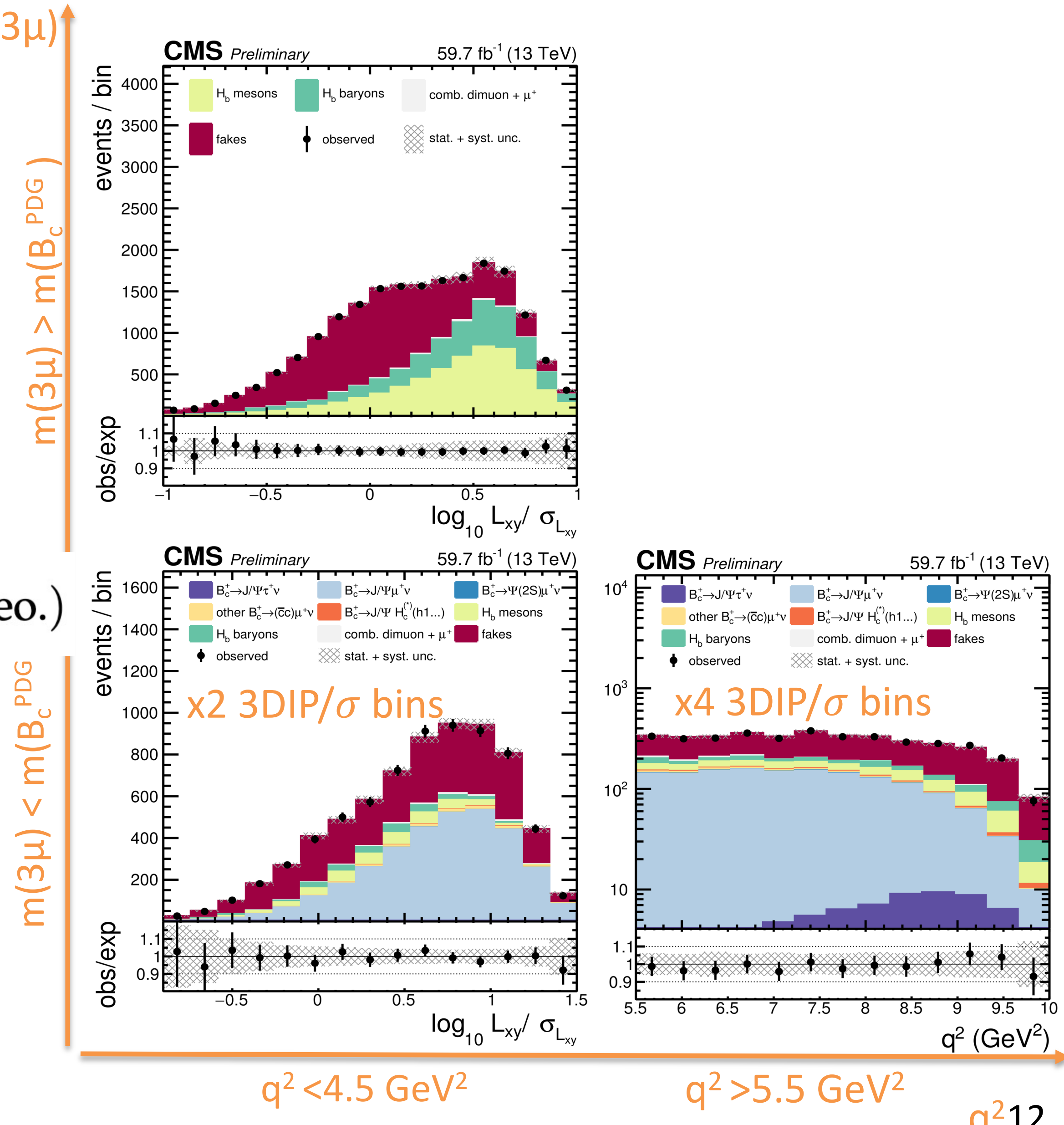


Discriminating variables:

- q^2
- Lxy /σ(Lxy) of J/ψ vtx → to discriminate Hb from fakes
- m(3μ) → to isolate Hb bkg
- 3D IP significance b/w 3rd muon and J/ψ vertex → to discriminate τ signal from fakes

R(J/ψ), leptonic τ

Complex fit,
performed in 7 different categories,
for 2 bins of 3[rd] μ isolation / each cat



Results:

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

Compatible
- within 0.3σ with SM prediction
- within 1.3σ with LHCb result
  0.71 $\pm$ 0.17 (stat) $\pm$ 0.18 (syst)

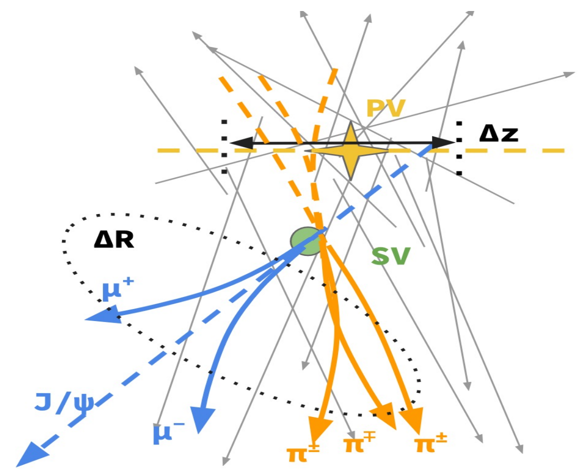
- Theory syst: Bc form factors
- Main experimental systematic uncertainty related to fakes

NEW!

R(J/ψ), hadronic τ

[CMS-PAS-BPH-23-001](#)

Run2 data, 138/fb



Denominator from BPH-22-012

Numerator: τ decay is $\tau \to \pi\pi\pi$

- Dedicated low p_T τ reconstruction and identification

Main backgrounds:

Hb → J/ψ + X

- Hb = non Bc hadrons
- Dominant background by far

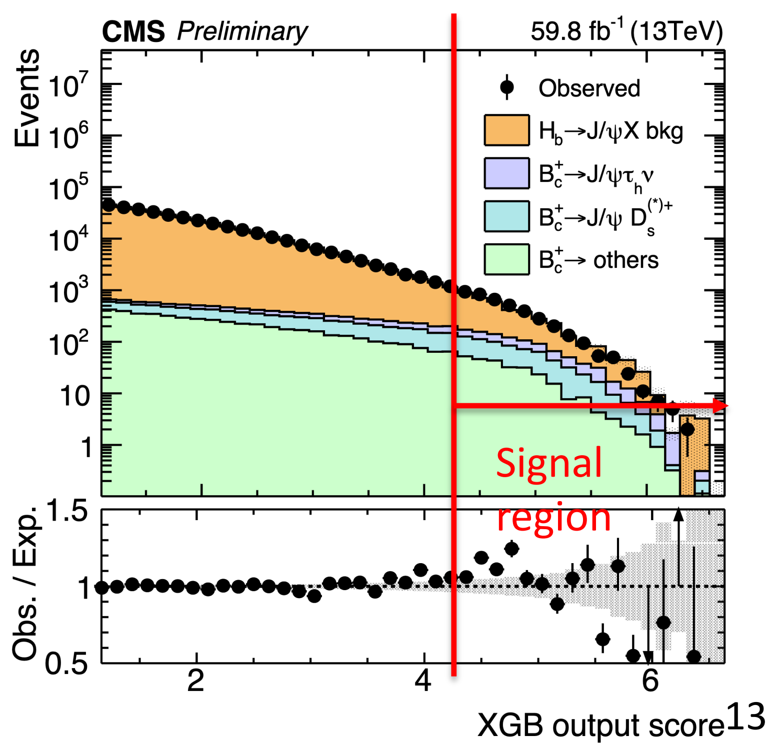
Bc → $J/\psi D^{(*)}s$

Other Bc decays,

- E.g. Bc→ $J/\psi D^{+(*)}$, Bc→ $J/\psi D^{+} K0^{(*)}$, Bc→ $J/\psi D^{0(*)} K^{+}$

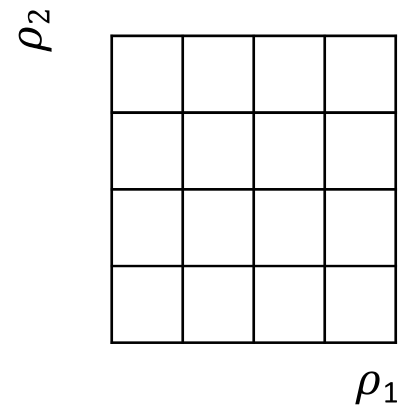
Background suppression using a BDT discriminator:

- Variables: τ flight length sign., particles multiplicity, vertices quality, isolation, ID…
- Main goal: maximize signal vs Hb separation



CMS-PAS-BPH-23-001

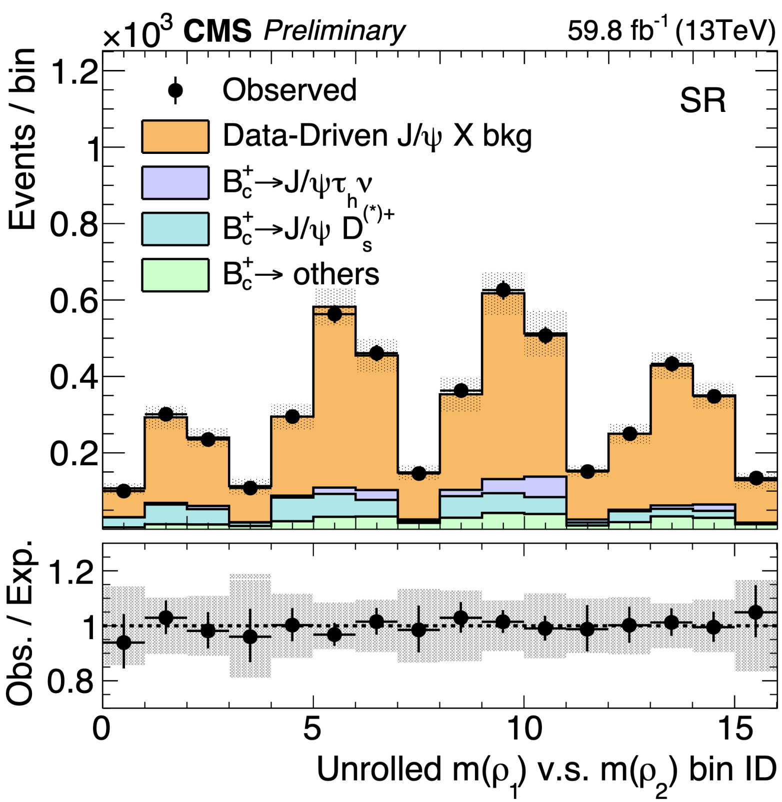
R(J/ψ) hadronic: results



3 prong τ decays likely produce an intermediate ρ(770) resonance , then $\rho \rightarrow \pi\pi$

- Pions ordered in p_T
- 2 opposite charge combinations used to construct ρ_1 and ρ_2
- Unrolled ρ_1 vs ρ_2 distribution used as discriminating variable

Simultaneous fit to signal region and Hb background control region



Results:

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

Combining the three years, sensitivity driven by 2018

Systematic uncertainties dominate

Full combination performed with BPH-22-012

R(J/ψ) $_{lept+had}$ = 0.49 ± 0.25 (syst) $\pm$ 0.09 (stat)

R(J/ψ) hadronic: results

3 prong τ decays likely produce an intermediate ρ(770) resonance , then $\rho \to \pi\pi$

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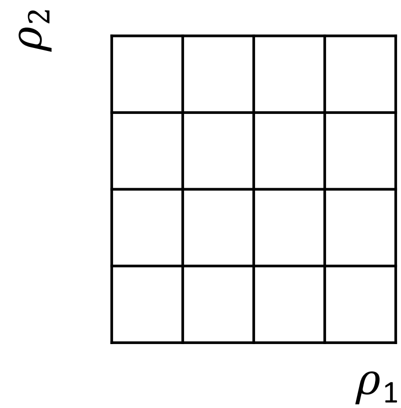

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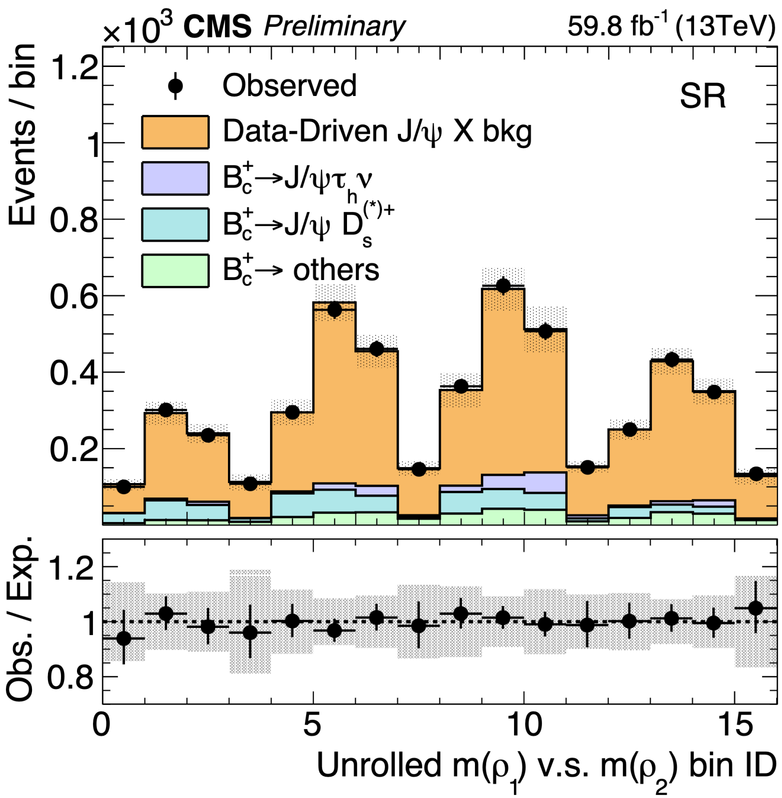
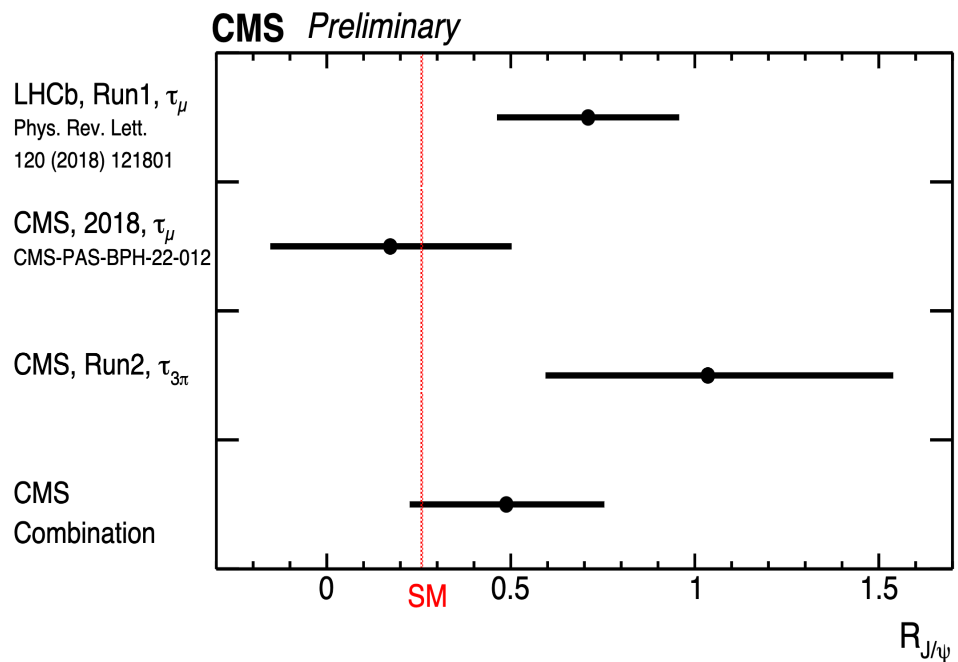




Conclusions

LF(U)V is a very exciting field to look for new physics

Run2 results on $\tau \rightarrow 3\mu$ did not show an enhancement of the BR beyond 10^{-8}

- Competitive limits set
- Analysis statistical limited, close to be sensitive to the most optimistic BSM models

A new result on R(J/ψ) with hadronic τ decays has been presented for the first time

Run2 RK and R(J/ψ) results prove
the robustness and adaptability of the CMS detector trigger, software and analysis
and the ability of a general-purpose experiment to contribute to these measurements

Stay tuned for new results from Run-2 and Run-3!

(https://arxiv.org/abs/2403.16134)

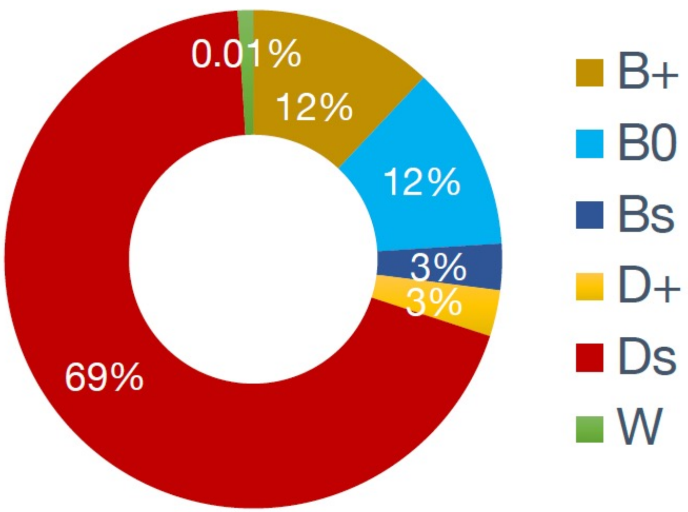
Backup

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

Experimentally clean channel

- fully reconstructed final state
- no irreducible SM backgrounds
- precise muon reconstruction @CMS

Two main sources of tau leptons in CMS: heavy flavour decays and W bosons



HF decays: ~10^{11} τ_s /fb^{-1} ; ~70% D, 30% B

- Abundant
- Low p_T and high $|\eta|$ leptons
- Less efficient trigger and selection
- More sensitive to fake πs, Ks

W decays: ~10^{7} τ_s /fb^{-1}

- Less abundant
- Higher p_T and more central leptons
- W kinematics provides additional handles

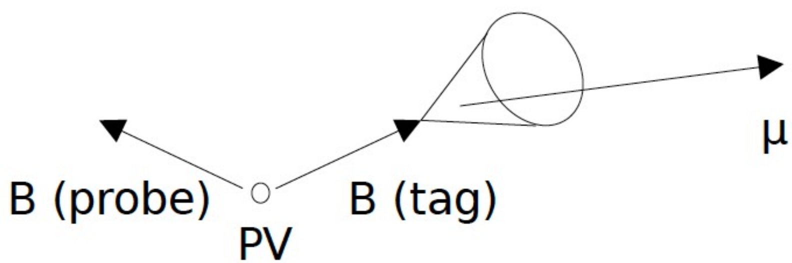
Search for $\tau \rightarrow 3\mu$ decay: world status

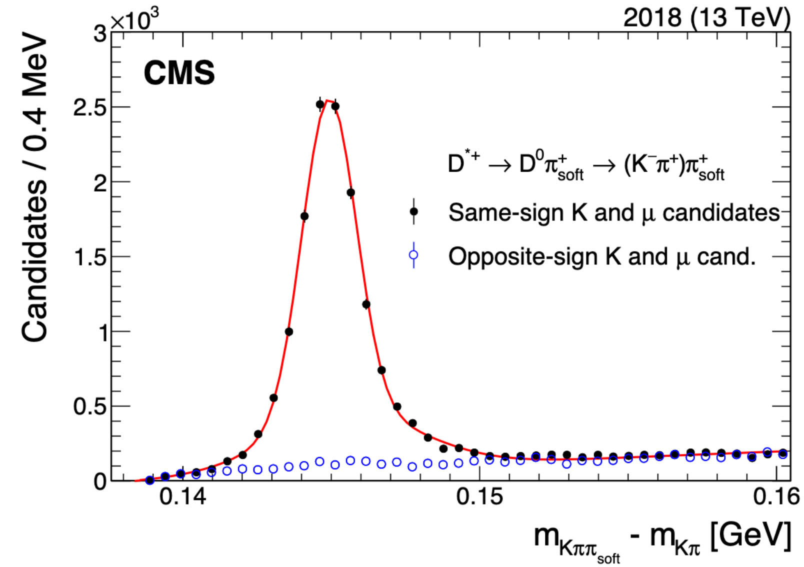
Year	Collab.	Process	Data	Expected [*]	Observed [*]
2010	Belle	$ee \rightarrow \tau\tau$	782 fb^{-1}	-	2.1
2010	BaBar	$ee \rightarrow \tau\tau$	468 fb^{-1}	4.0	3.3
2014	LHCb	$D/B \rightarrow \tau X$	3.0 fb^{-1} (pp 7-8 TeV)	5.0	4.6
2016	ATLAS	$W \rightarrow \tau\nu$	20.3 fb^{-1} (pp 8 TeV)	39	38
2023	CMS	$D/B \rightarrow \tau X$ and $W \rightarrow \tau\nu$	131 fb^{-1} (pp 13 TeV)	2.4	2.9
2024	Belle II	$ee \rightarrow \tau\tau$	424 fb-1	-	1.9

[*] $\times 10^{-8}$@ 90% C.L.

2018 B-parking

- Trigger on displaced μ, BF($b\bar{b} \rightarrow \mu X$)~40%
- Exploit spare trigger rate during LHC fill
    - Up to 30KHz at L1, up to 5.5 kHz at HLT
- Unbiased probe side
- ~10 billion unbiased B decays collected

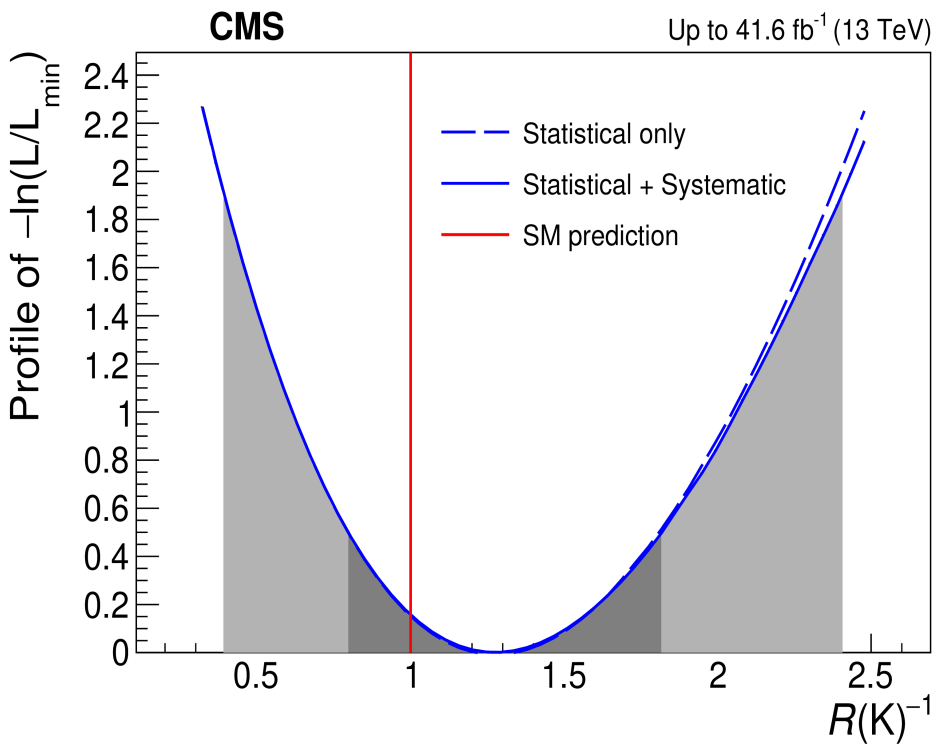




Average purity: 80%, measured with $B^0 \rightarrow D^* \mu\nu_\mu \rightarrow D^0\pi_{soft}\mu\nu_\mu \rightarrow K\pi\pi_{soft}\mu\nu_\mu$

$\mathcal{L}$ $[10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	L1 p_T^μ thr. [GeV]	HLT p_T^μ thr. [GeV]	HLT μ IP_{sig} thr.	Purity [%]	Peak HLT rate [kHz]	$\int \mathcal{L} dt$ $[\mathrm{fb}^{-1}]$
1.7	12	12	6	92	1.5	34.7
1.5	10	9	6	87	2.8	6.9 + 26.7
1.3	9	9	5	86	3.0	20.9
1.1	8	8	5	83	3.7	8.3
0.9	7	7	4	59	5.4	6.9

RK: yields & likelihood scan



Channel	q^2 range [GeV^2]	Yield
$B^+ \to K^+\mu^+\mu^-$	1.1–6.0	1267 ± 55
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	8.41–10.24	728 000 ± 1000
$B^+ \to \psi(2S)(\mu^+\mu^-)K^+$	12.60–14.44	68 300 ± 500

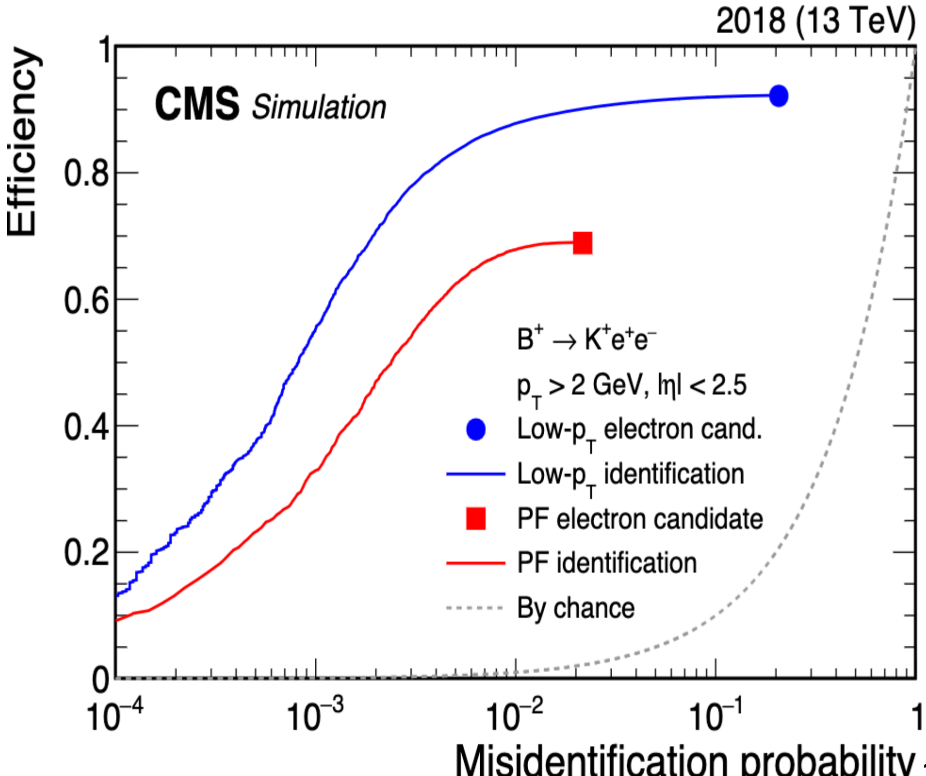
Channel	q^2 range [GeV^2]	PF-PF yield	PF-LP yield
$B^+ \to K^+e^+e^-$	1.1–6.0	17.9 ± 7.2	3.0 ± 5.9
$B^+ \to J/\psi(e^+e^-)K^+$	8.41–10.24	4857 ± 84	2098 ± 58
$B^+ \to \psi(2S)(e^+e^-)K^+$	12.60–14.44	320 ± 20	94 ± 11

RK: electrons

Misidentification rate after eleID : 10^{-3} -10^{-4} per electron

Possible peaking background : $B^+ \to K^+ h_1 h_2$,
dominated by $B^+ \to K^+ \pi\pi$ (BR~10^{-5}; $D^0\pi^+$ contribution subtracted)

Checked on $B^+ \to D^0(\to K^+\pi^-)\pi^+$ and $B^+ \to K^+\pi^-\pi^+$ MC:
<0.3 events in both electron analysis categories (i.e. <0.2% and 6% wrt signal yield)



$\mathrm{B} \rightarrow K\mu\mu$ BR

Differential measurement:

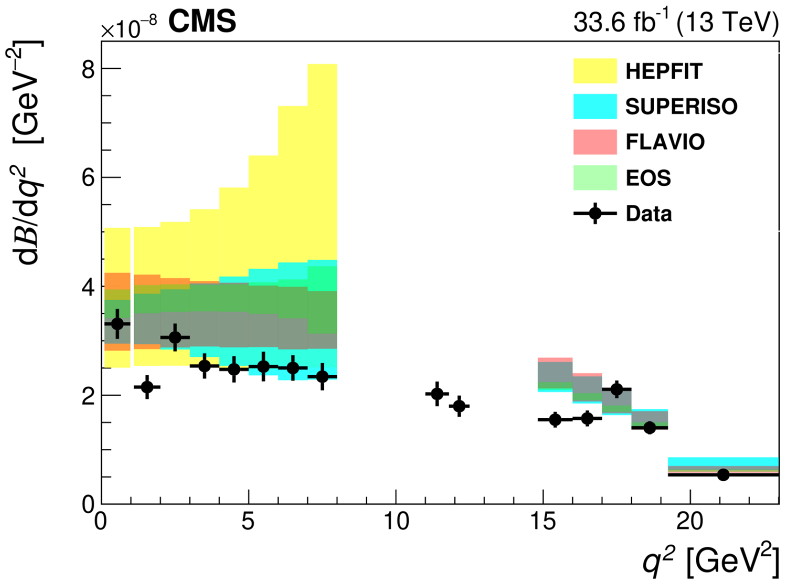
- Measurement done normalizing to the J/ψ control region
- Simultaneous fit to all q^2 bins, linear parameterization of the mass dependence on q^2
- Data generally lower than predictions up to high q^2

Inclusive BR in $1.1 < q^2 < 6.0$ GeV^2:

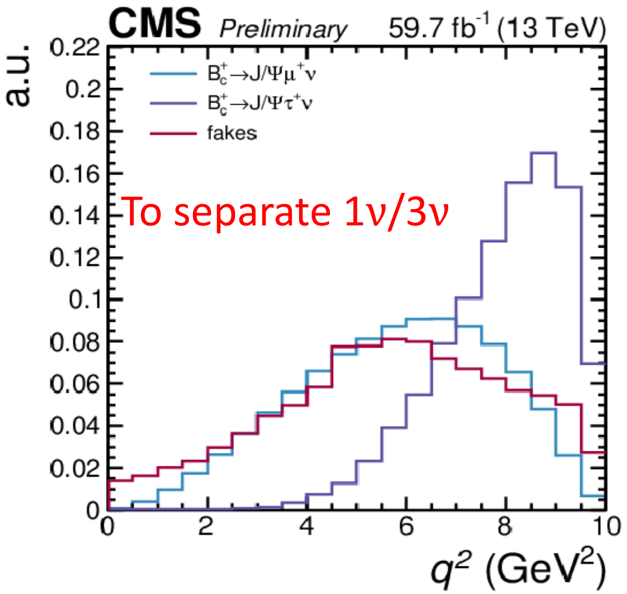
- Eff x acc ~costant in this bin
- Result consistent with world average, precision comparable to LHCb
- Theory prediction higher than experimental results

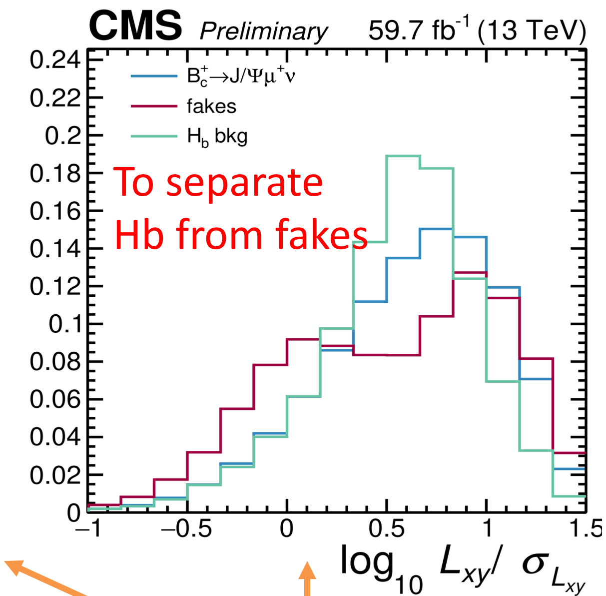
Source	$\mathcal{B}(\mathrm{B}^+ \rightarrow \mathrm{K}^+\mu^+\mu^-)[1.1, 6.0]$ GeV^2 $[10^{-8}]$
Measurement	12.42 ± 0.68
EOS	18.9 ± 1.3
FLAVIO	17.1 ± 2.7
SUPERISO	16.5 ± 3.4
HEPFIT	19.8 ± 7.3

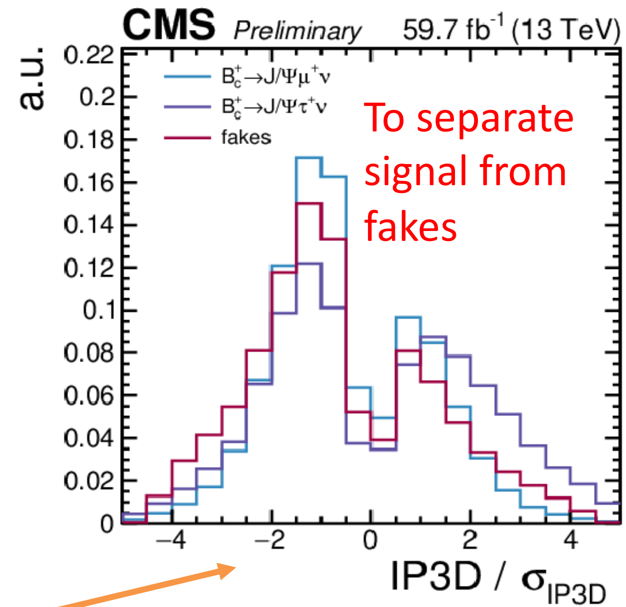
q^2 range [GeV^2]	Signal yield	Branching fraction $[10^{-8}]$
0.1–0.98	260 ± 20	2.91 ± 0.24
1.1–2.0	197 ± 19	1.93 ± 0.20
2.0–3.0	306 ± 23	3.06 ± 0.25
3.0–4.0	260 ± 21	2.54 ± 0.23
4.0–5.0	251 ± 23	2.47 ± 0.24
5.0–6.0	264 ± 27	2.53 ± 0.27
6.0–7.0	267 ± 21	2.50 ± 0.23
7.0–8.0	256 ± 23	2.34 ± 0.25
11.0–11.8	207 ± 19	1.62 ± 0.18
11.8–12.5	172 ± 16	1.26 ± 0.14
14.82–16.0	272 ± 20	1.83 ± 0.17
16.0–17.0	246 ± 17	1.57 ± 0.15
17.0–18.0	317 ± 19	2.11 ± 0.16
18.0–19.24	242 ± 19	1.74 ± 0.15
19.24–22.9	158 ± 19	2.02 ± 0.30

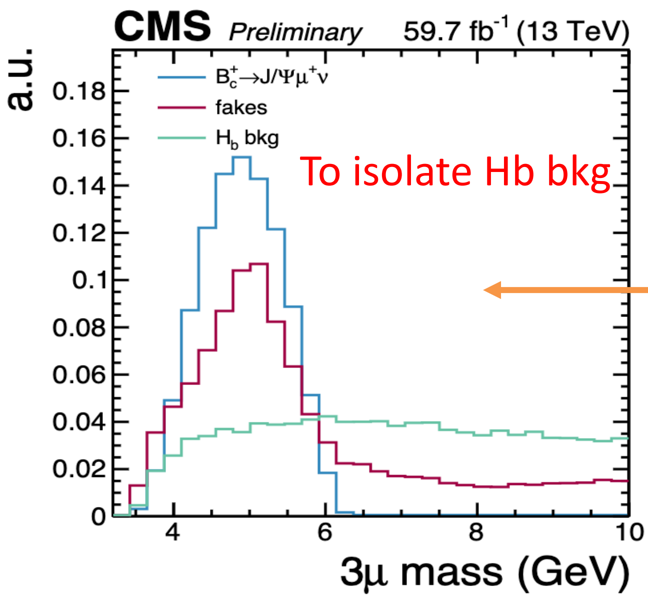


R(J/ψ), leptonic τ: variables





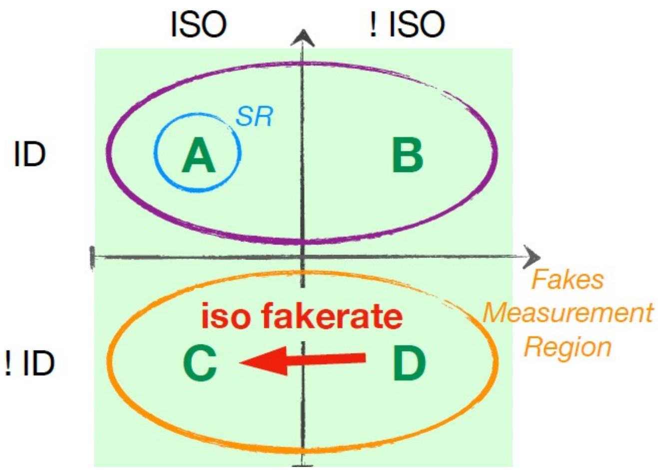




$m(3\mu) < m(B_c^{PDG})$

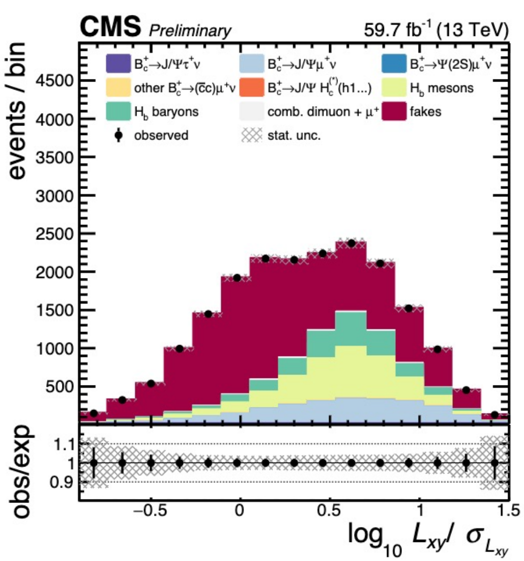
Preselection level

R(J/ψ), leptonic τ: fakes

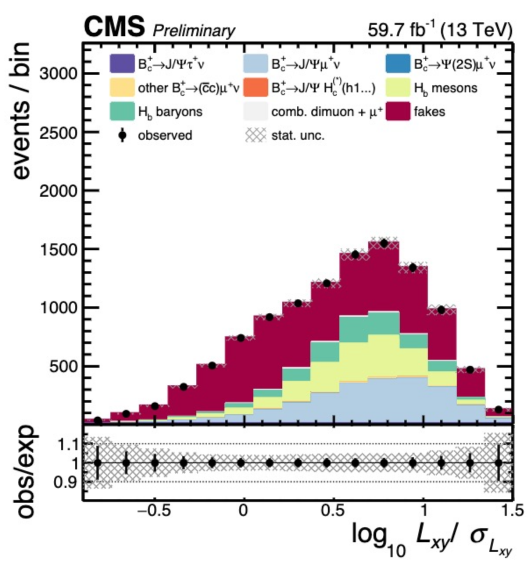


- Four regions defined based on 3rd μ isolation (ISO) and ID
- Measurement of iso fakerate (fr_{ISO}) in !ID:
  - Fit in multiple dimensions using NN classifiers
  - Outputs interpreted as event-by-event weights
- Application of fr_{ISO} weights to events in B to get fakes in A

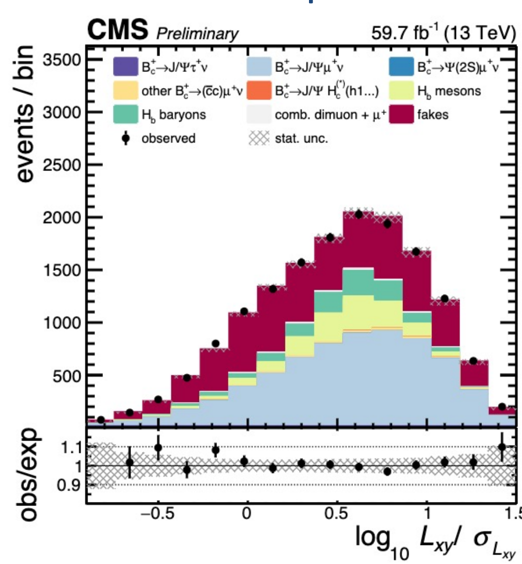
B region



fr_{ISO} weighted B region:
Fakes = data-MC



A region:
use fakes shape found in B

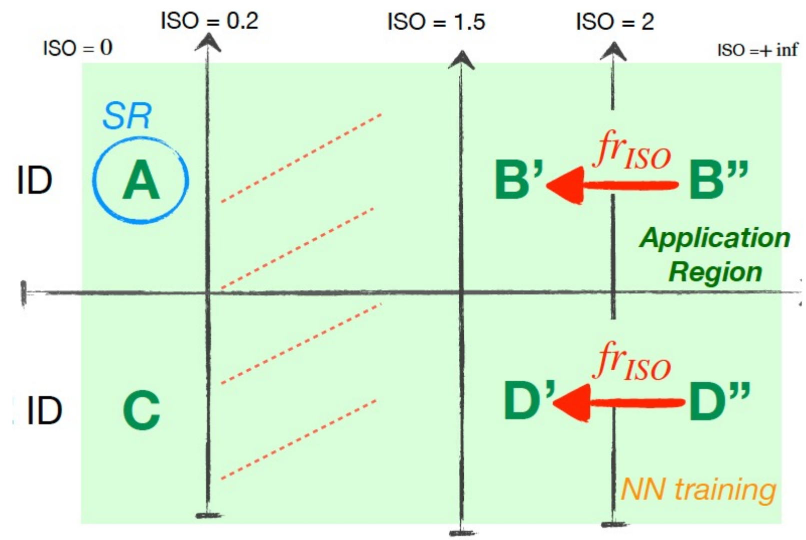


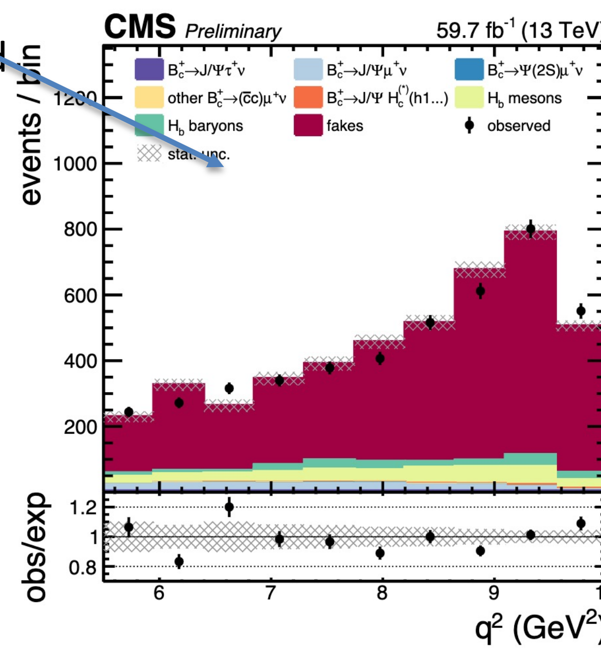
R(J/ψ), leptonic τ: fakes validation

- Several validation performed
- Most representative:
  validation using data control-regions B' – B''
- Good closure in B'

- Conservative bin-by-bin uncertainties added to account for limited statistics of the test

- Additional systematics on normalization and shape based on closure tests on MC and on "rotated" method





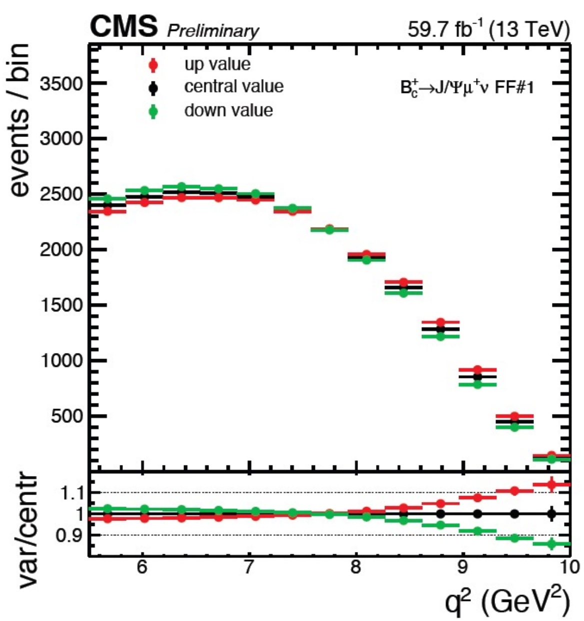
R(J/ψ), leptonic τ: Bc form factors

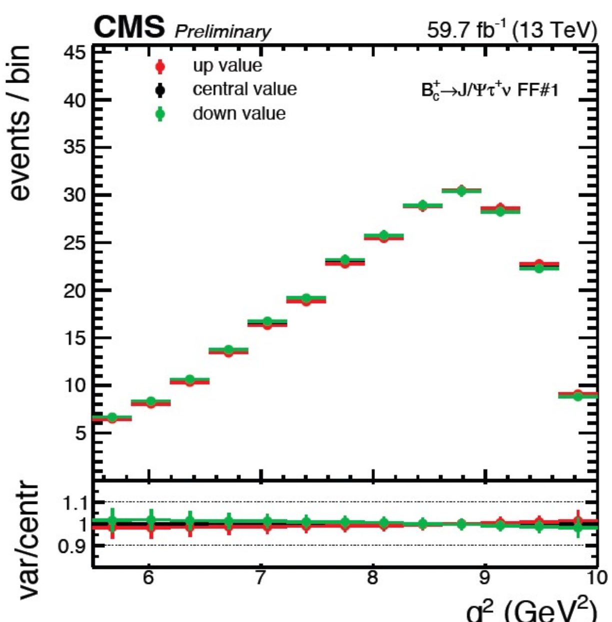
Contribution	Uncertainty type	Rel. uncertainty	$\Delta R(J/\psi) \cdot 10^{-2}$
B_c^+ form factors	10 shapes	–	18.2
fakes stat. non closure	bin-by-bin shapes	–	11.3
fakes background	2 shapes	–	4.2
fakes background	norm.	13.0%(+5% HM cat.)	2.5
finite MC size	bin-by-bin shapes	–	5.3
$IP3D/\sigma_{IP3D}$, $L_{xy}/\sigma_{L_{xy}}$ 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

MC generated with Kiselev FF and reweighted to use the BGL parameterization with Hammer

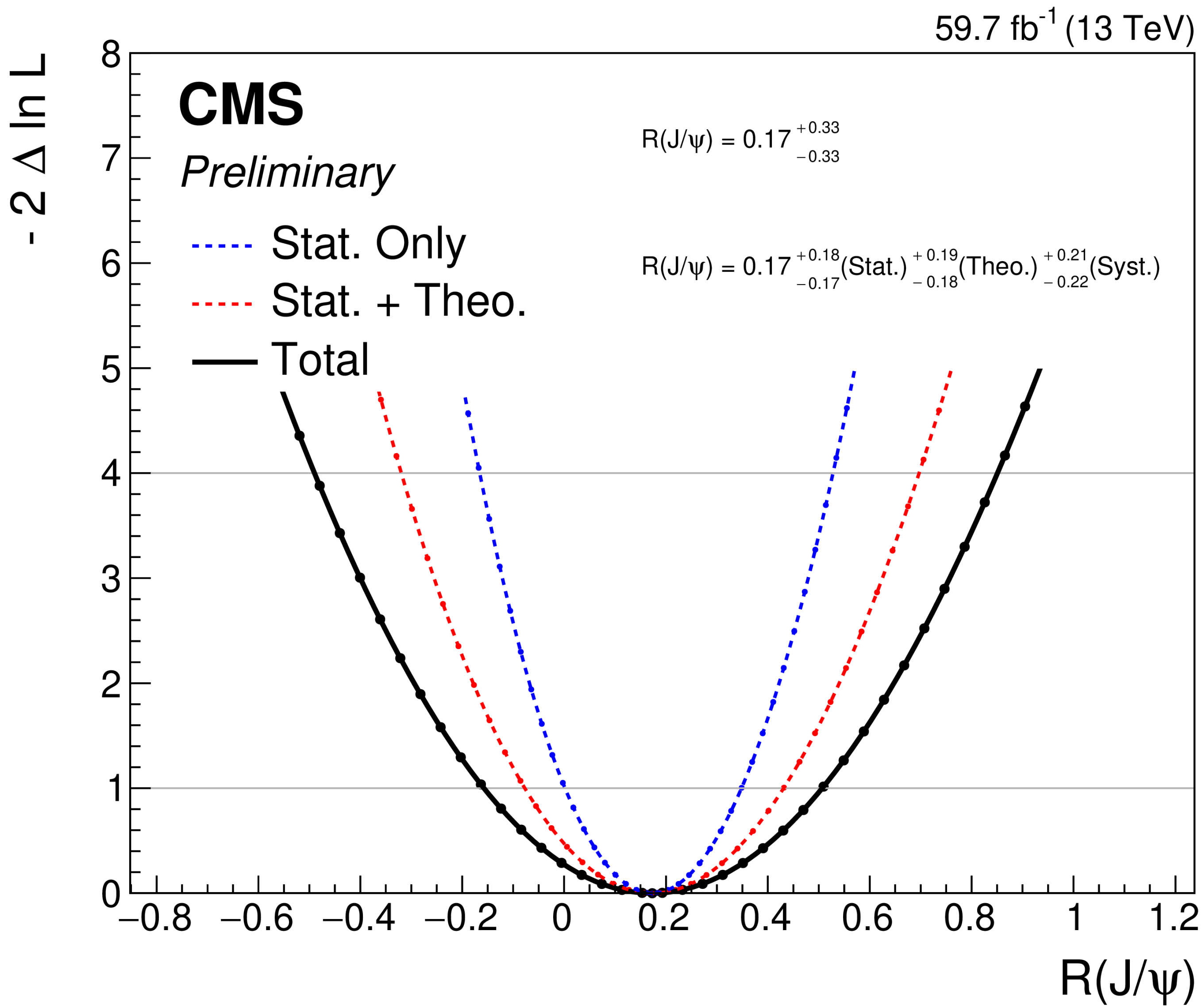
Both for μ and τ signal

All 11 parameters variations considered as shape systematics





R(J/ψ), leptonic τ: likelihood scan



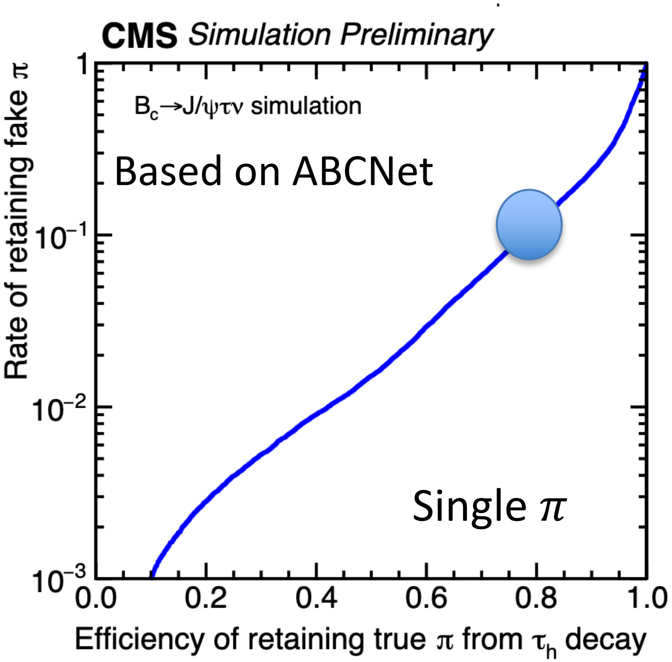
Low pT τ

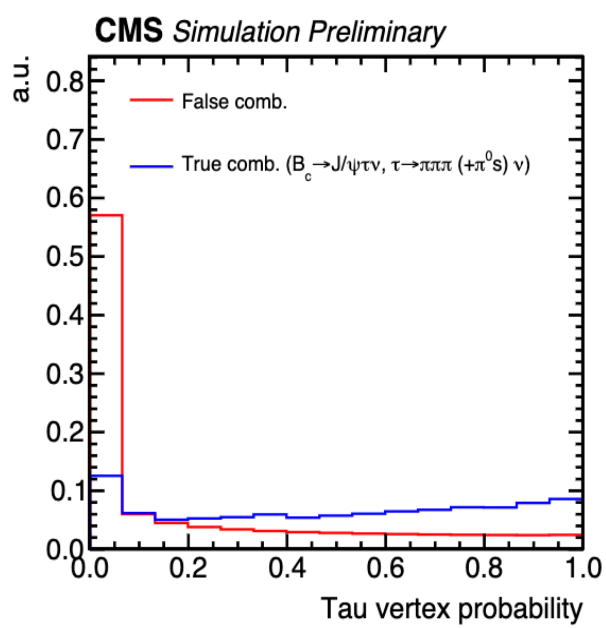
CMS-DP-2020-039

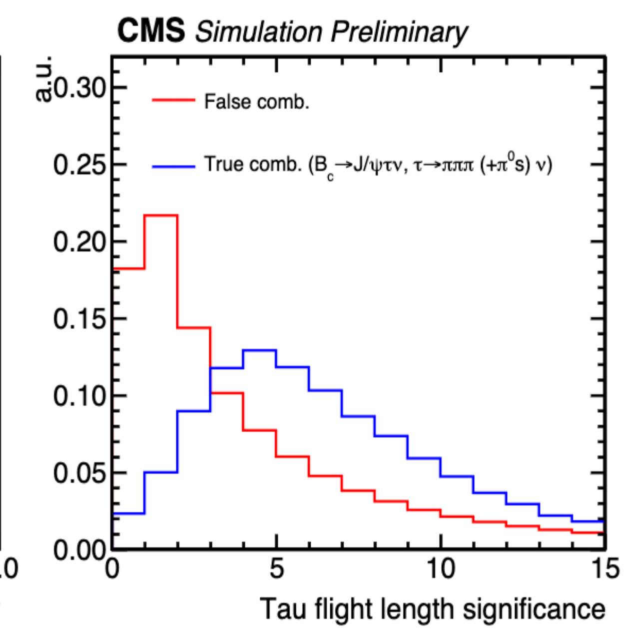
In CMS there is a dedicated algorithm for identifying hadronic τs (Hadron-Plus-Strip) seeded by a jet with con ΔR=0.4. In the low p_T regime, πs from the τ decay are spread over a large $\eta - \phi$ region and are not confined in a single jet

Dedicated algorithm in 3 steps:

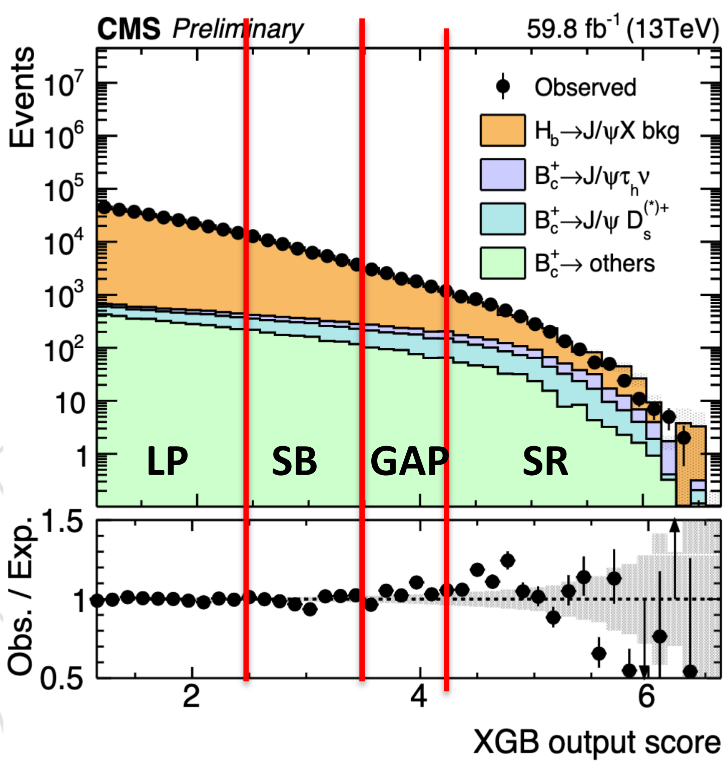
- PV choice
- Pre-filtering: suppress charged πs not originating from the τ
  - Compatibility with PV, J/ψ and J/ψ vertex
- Triplet filtering: τ vtx probability, mass, pT, flight length significance
- Final selection







R(J/ψ) hadronic: Hb background



- 4 regions defined: low-purity (LP), sidebands (SB), gap and signal region (SR)
- The Hb → J/ψ + X background in the SB is constructed as difference between data and MC
- Extrapolation factors based on the simulation are used to move from SB to SR.
- Several validations performed given the relevance of this estimate for the measurement
  - Extrapolation from SB to GAP
  - Extrapolation from SB to SR with inverted τ selection
- Good agreement overall, differences → systematics

- Normalization uncertainty: 30% (from validations)
- Shape uncertainties:
  - Variations of extrapolation factors (bin by bin)
  - Stat uncertainty from SB data
- All uncorrelated between years