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Searches for lepton flavor universality violation at CMS

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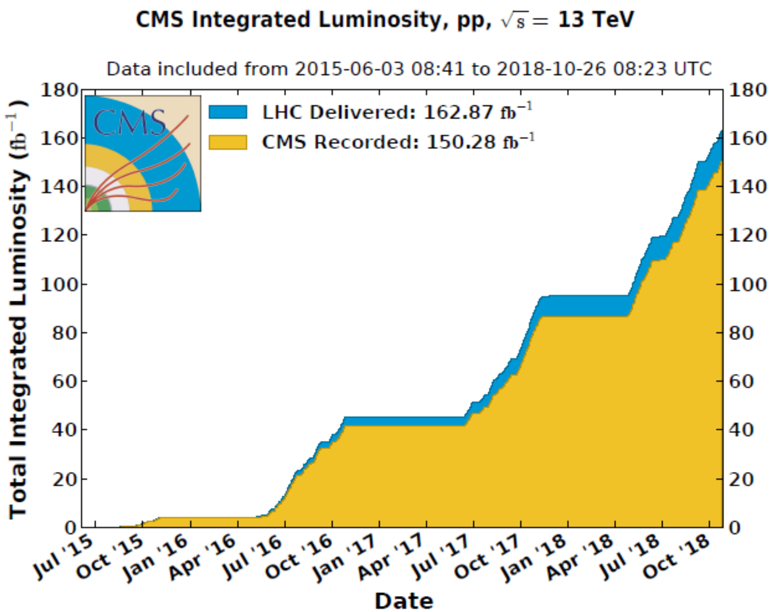
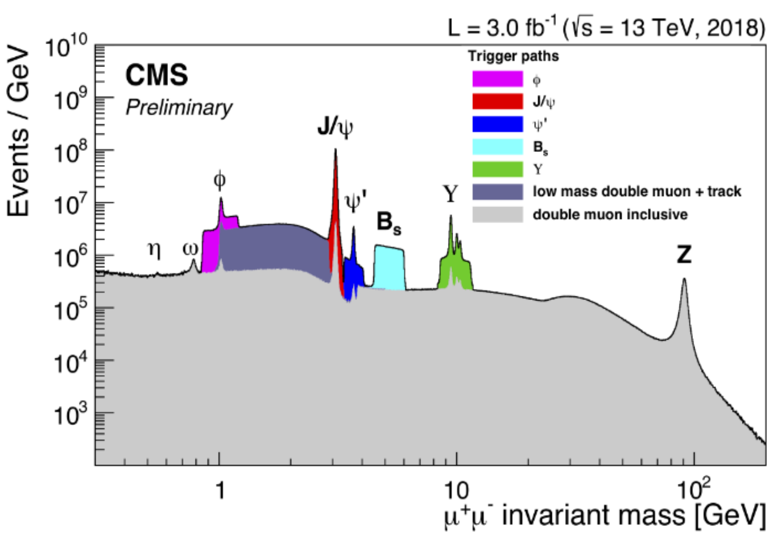
Outline:

1. Introduction
2. R(K) measurement now (and henceforth) with CMS.
3. R(J/ψ) – only at LHC and now CMS in the game.
4. Search for charge-lepton flavor violating $\tau+ \rightarrow \mu+ \mu+ \mu-$
   --- towards the depth gained by Belle.
5. Summary

Introduction: the discussed results were obtained with the RUN II data





- 160 fb^{-1} has been delivered by the LHC in Run 2 (2015-2018) at $\sqrt{s}$=13 TeV.

- Very efficient data collection by CMS with improved track momentum resolution→ recorded over 140 fb^{-1} of physics-quality data.

- Ingenious trigger algorithms were developed for efficient online event selection.

CMS is contributing intensively into the heavy flavor and particularly in the searches of the BSM Physics in ***b-hadron decays***

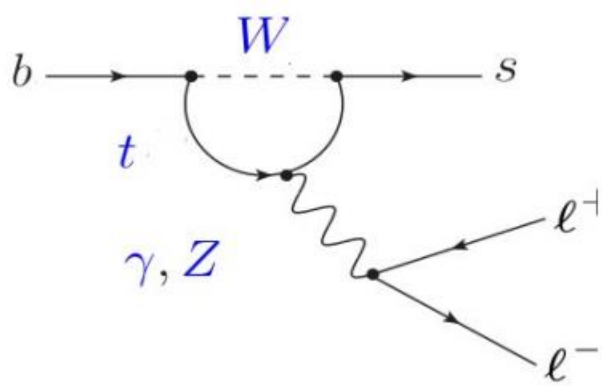
In this talk selected ***new results*** from 13 TeV data sample will be discussed

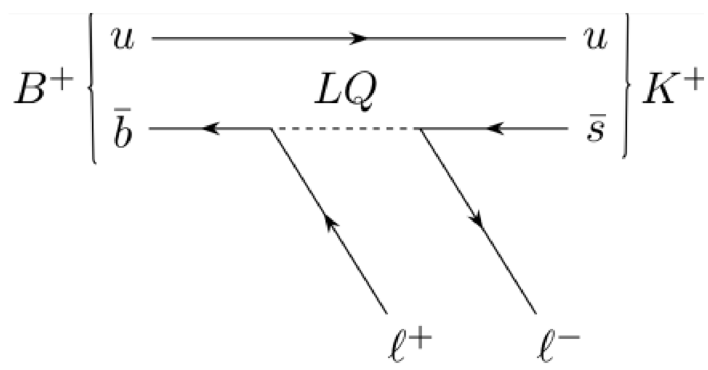
$R(K) = Br(B^+ \rightarrow K^+ \mu^+ \mu^-) / Br(B^+ \rightarrow K^+ e^+ e^-)$

In the SM the electrons and muons have identical couplings to gauge bosons.
This is known as Lepton Flavor Universality (LFU).

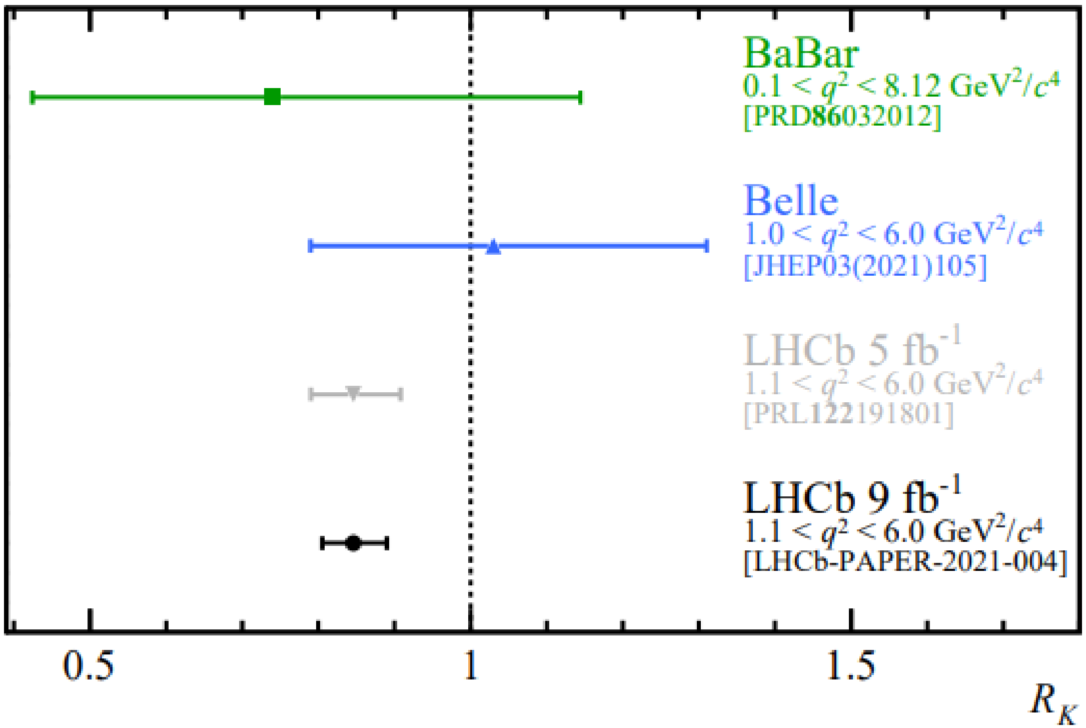
Rare B decays provide excellent place to test LFU.

Loop diagrams → Beyond SM physics might affect observables such as Br.fr. and R(K)





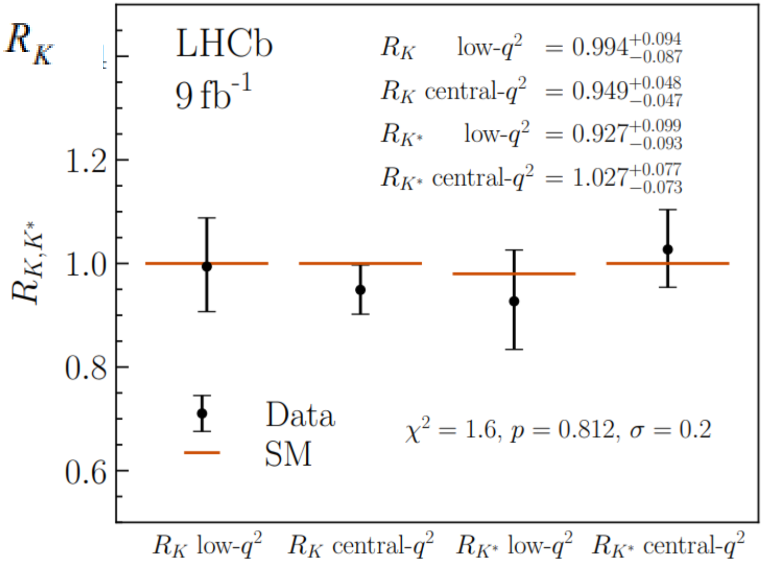
Experimental situation with R(K)



was

In SM this is 1 with 1% accuracy

now



Method and data sample

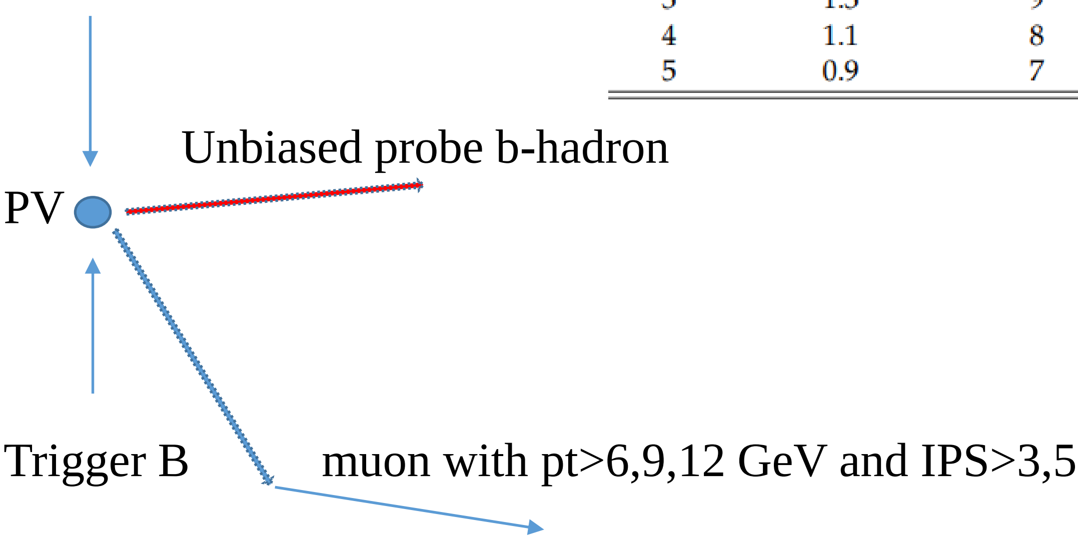
$$R(\mathrm{K})(q^2) = \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-)(q^2)}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mu^+\mu^-)\mathrm{K}^+)} \bigg/ \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mathrm{e}^+\mathrm{e}^-)(q^2)}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi(\mathrm{e}^+\mathrm{e}^-)\mathrm{K}^+)} .$$

The $R(\mathrm{K})$ ratio is measured in the q^2 region from 1.1 to 6.0 GeV^2, referred to as the "low-q^2"

This measurement became possible in CMS thanks to innovative trigger in 2018 data taking. This is the BParking trigger which collected and storage 10 billion unbiased b-hadron decays.

To collect B+ --> e+e-K+ events
in 2018 a dedicated trigger was proposed, developed and successfully implemented: BParking

Setting	Peak $\mathcal{L}$ $[10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	L1 p_T^μ thr. [GeV]	HLT p_T^μ thr. [GeV]	HLT μ IP_{sig} thr.	Purity [%]	Peak HLT rate [kHz]
1	1.7	12	12	6	92	1.5
2	1.5	10	9	6	87	2.8
3	1.3	9	9	5	86	3.0
4	1.1	8	8	5	83	3.7
5	0.9	7	7	4	59	5.4

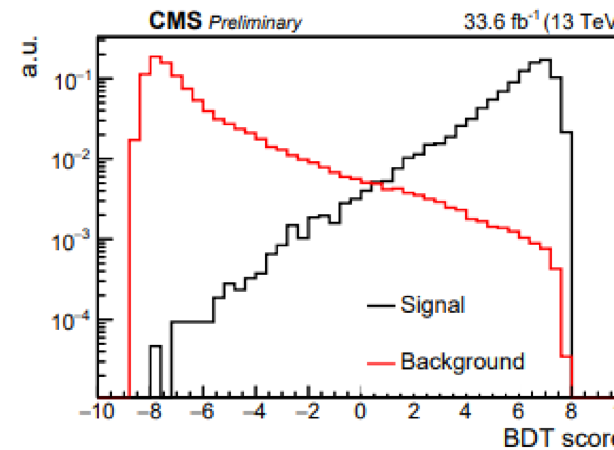


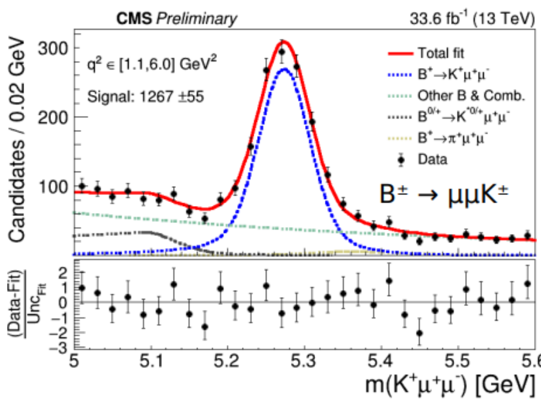
Stored on tape;
Long delay in reconstruction

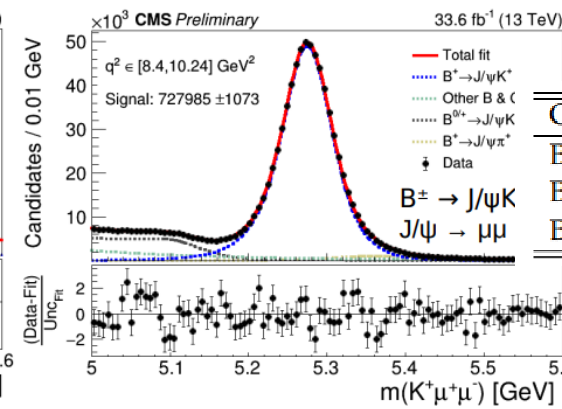
Reconstruction of events for R(K) measurement: main features

Standard full reconstruction of b-hadron in CMS:

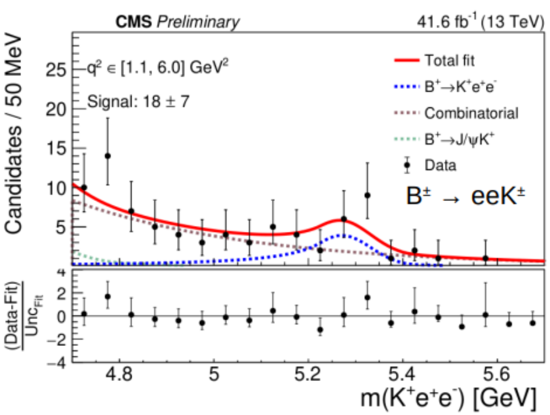
- Combine leptons with tracks
- Special procedure for reconstruction of low pt electrons
- 3 BDT for final selection

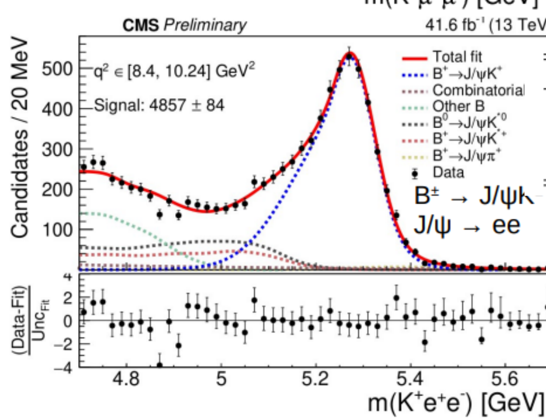






Channel	q^2 range	Yield
$B^+ \to K^+\mu^+\mu^-$	1.1–6.0 GeV^2	1267 ± 55
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	8.41–10.24 GeV^2	727 985 ± 1073
$B^+ \to \psi(2S)(\mu^+\mu^-)K^+$	12.60–14.44 GeV^2	68 292 ± 495





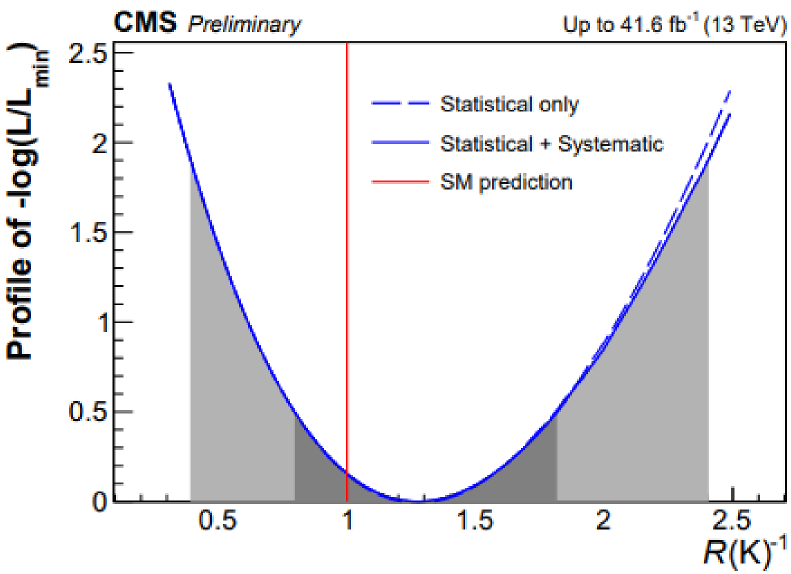
Channel	q^2 range	PF-PF yield	PF-LP yield
$B^+ \to K^+e^+e^-$ (low-q^2)	1.1–6.0 GeV^2	17.9 ± 7.2	3.0 ± 5.9
$B^+ \to J/\psi(e^+e^-)K^+$	8.41–10.24 GeV^2	4856.9 ± 83.7	2097.8 ± 58.1
$B^+ \to \psi(2S)(e^+e^-)K^+$	12.60–14.44 GeV^2	320.2 ± 20.4	93.9 ± 10.9

The Br.fr. Measurement and R(K) final results

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-, 1.1 < q^2 < 6.0\,\text{GeV}^2)$$
$$= (12.42 \pm 0.54\,(\text{stat}) \pm 0.11\,(\text{MC stat}) \pm 0.40\,(\text{syst})) \times 10^{-8}$$
$$= (12.42 \pm 0.68) \times 10^{-8}.$$

Package	$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ $[10^{-8}]$
Measurement	12.4 ± 0.7
EOS	18.9 ± 1.3
FLAVIO	17.1 ± 2.7
SUPERISO	16.5 ± 3.4
HEPFIT	19.8 ± 7.3

From simultaneous fit (minimizing likelihood function of 1/R(K):



$$R(K) = 0.78^{+0.46}_{-0.23}\,(\text{stat})^{+0.09}_{-0.05}\,(\text{syst}) = 0.78^{+0.47}_{-0.23}, \quad (7)$$

LFU in semileptonic b-hadron decays

In the SM b→c (e, μ, τ) ν_l transition is mediated with the same lepton-boson coupling.

Differences in Br.fr's is due to different lepton masses.

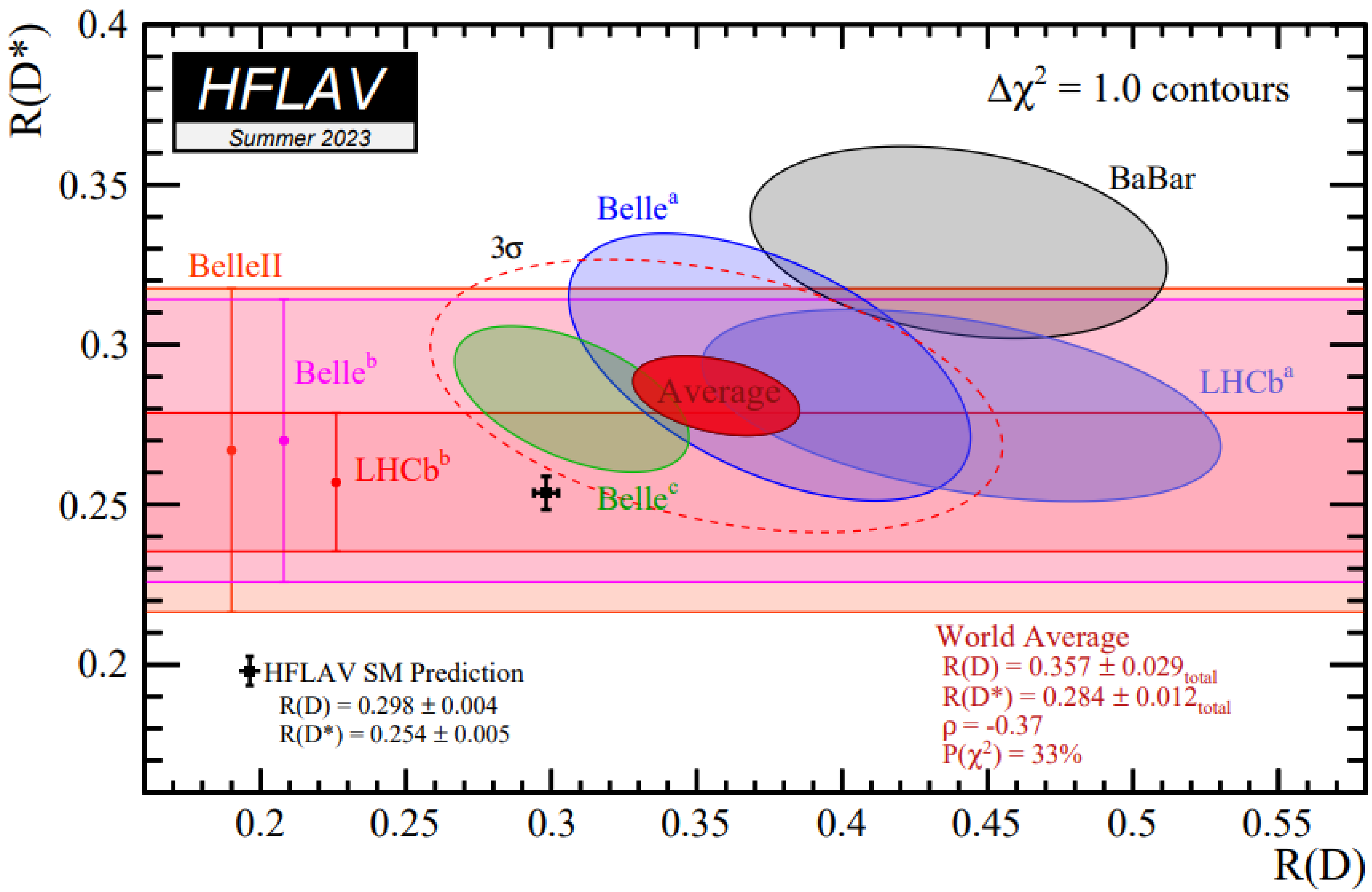
→ SL decays are sensitive probes of LFU which can be violated by several BSM theories (extended Higgs sector, extended gauge sector, leptoquarks, …).

There is no direct evidence for BSM particles
but they could contribute to SM through virtual processes.

Anomalies in R(Hc)

In recent years b→c τν has been studied by Belle, BaBar, Belle2, LHCb

3σ tension
with SM



$\mathbf{R(J/\psi)}$ =
$Br(Bc+ \rightarrow J/\psi\ \tau+\ \nu \mid \tau+ \rightarrow \mu+\nu\nu)$ / $Br(Bc+ \rightarrow J/\psi\ \mu+\nu)$

Can be measured **only at LHC**.
At CMS it is easy to collect such events thanks to **3-muon trigger**
but very **hard experimental analysis** due to missing neutrinos.

SM prediction=0.2582(38)

LHCb measured R(J/psi) = 0.71 +- 0.17 +- 0.18

Both channels have similar visible final state (3 muons) and therefore can be reconstructed in the same way and simultaneously fitted.

The analysis feature: one should separate between 3 neutrinos channel (numerator) and 1 neutrino channel (denominator)

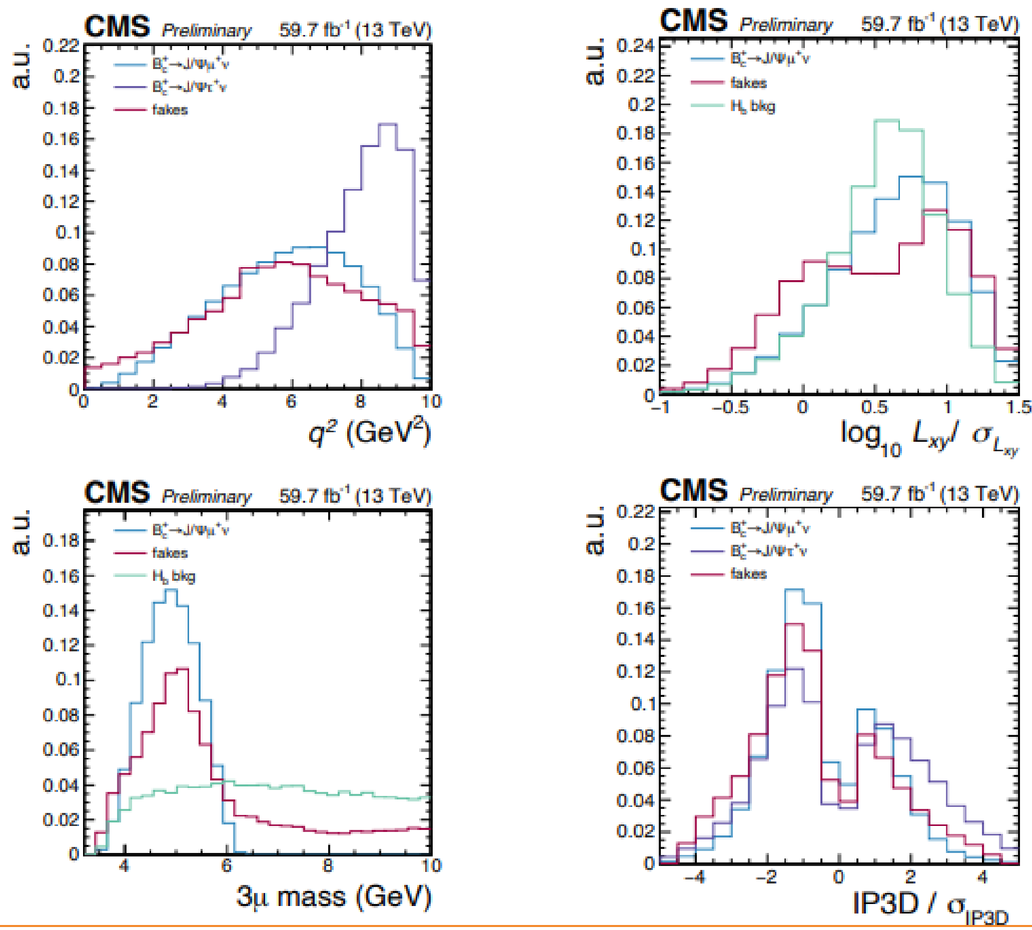
→ use kinematic observable $\mathbf{q^2=(p_{Bc}-p_{J/\psi})^2}$

Where we approximate Bc+ 4-momentum by $p_{Bc} = (M_{Bc}/M_{reco}) * p_{reco}$

R(J/ψ) =

Br(Bc+ → J/ψ τ+ ν | τ+→μ+νν) / Br(Bc+ → J/ψ μ+ν)

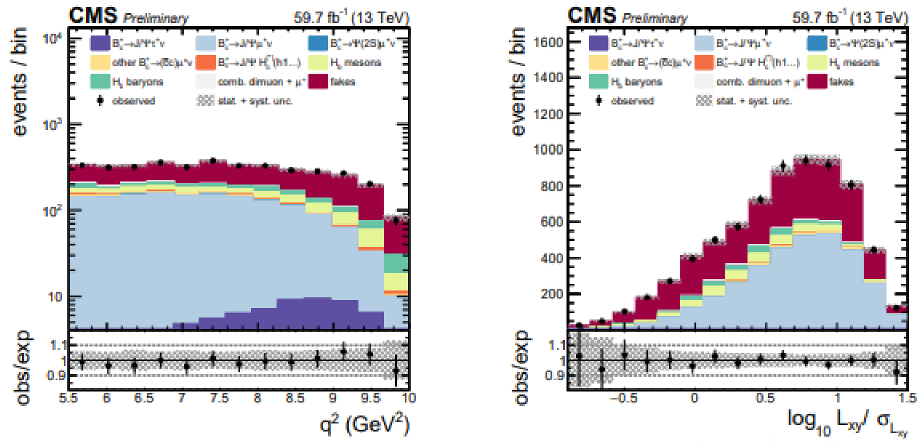
Variables to separate signals and backgrounds:



The first CMS result on R(Hc)

R(J/ψ) = Br(Bc+ → J/ψ τ+ ν | τ+→μ+νν) / Br(Bc+ → J/ψ μ+ν)

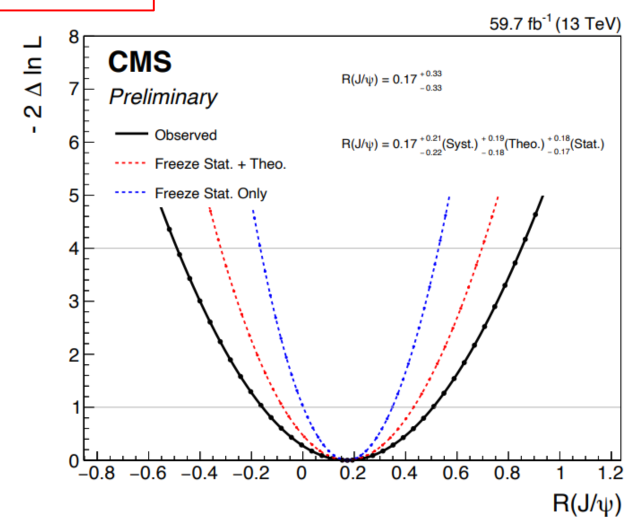
Results of the fit (selected plots):



R(J/ψ) = 0.17 ± 0.33 = $0.17^{+0.18}_{-0.17}\,(\text{stat.})^{+0.21}_{-0.22}\,(\text{syst.})^{+0.19}_{-0.18}\,(\text{theo.})$

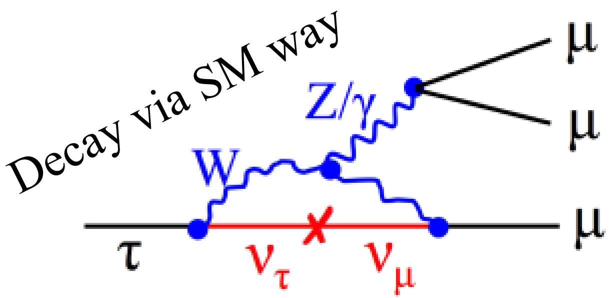
Systematics is dominated by Bc+ semileptonic decay form factors

Compatible with SM within 0.3 σ , with LHCb - within 1.3 σ



CMS: Search for charge-lepton flavor violating $\tau \to 3\mu$

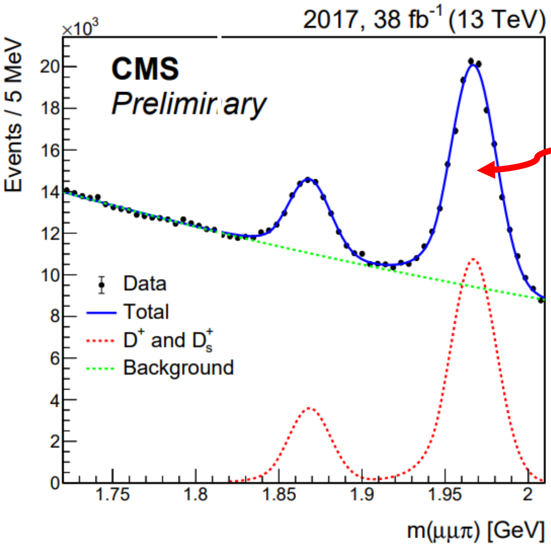
- Many New-Physics models predict Br.fr. enhancement
- Previous searches were performed by
  Belle[1], BaBar[2], LHCb[3], ATLAS[4]



[1]Phys. Lett. B687 (2010) 139143
[2]Phys. Rev. D81 (2010) 111101
[3]JHEP 02 (2015) 121
[4]Eur. Phys. J. C (2016) 76:232

- Most stringent limit by Belle[1]: Br.fr < 2.1 10^{-8} @90%CL

- **New** CMS analysis: search for $\tau \to 3\mu$ in a sample of τ's produced in D and B decays as well as in $W \to \tau\nu$ using data collected in 2017-18 (138 fb^{-1})



Normalization channel
$Ds+ \to \phi\pi+ \to (\mu+\mu-)\pi+$

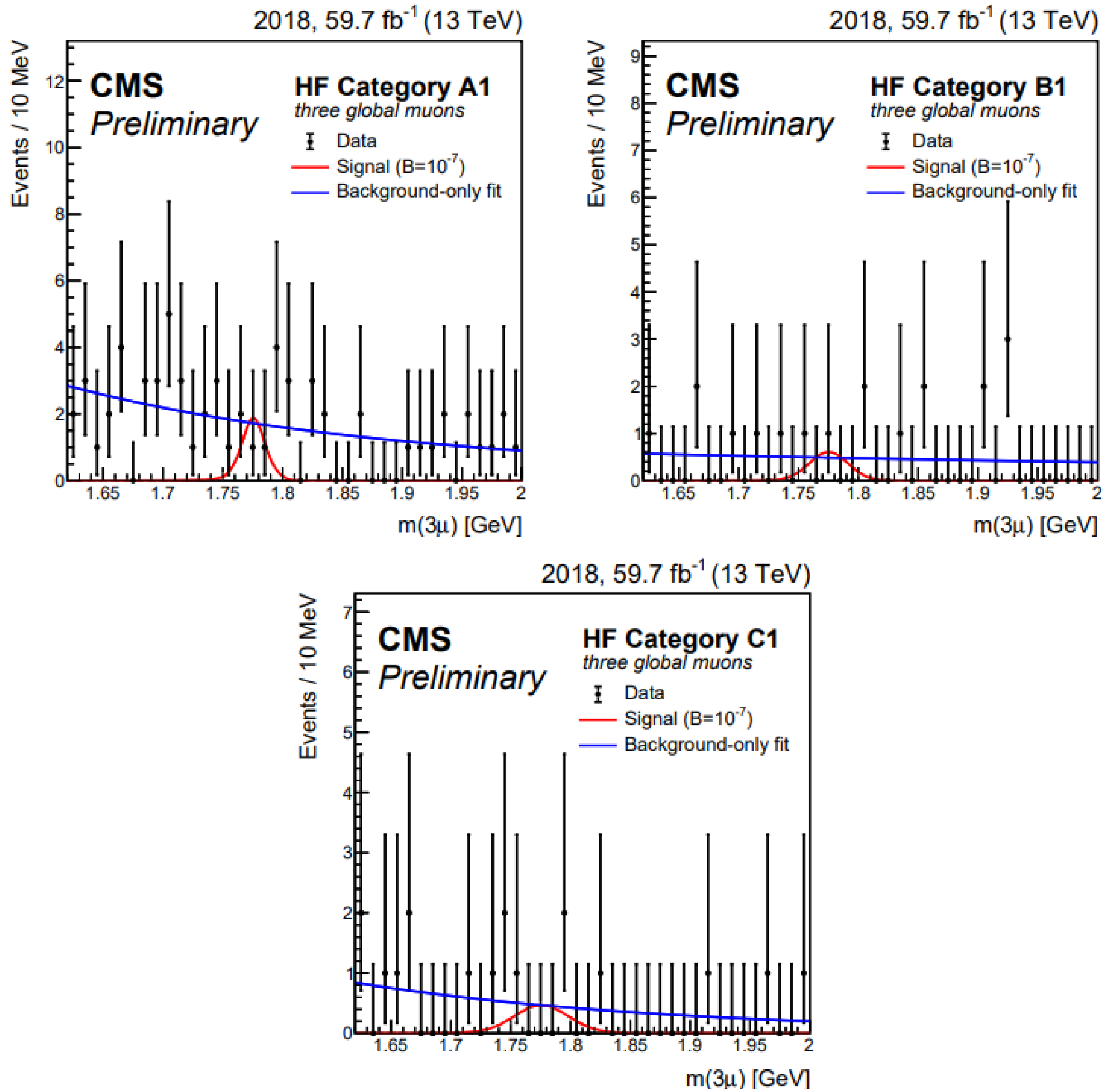
9 categories:

- 3 categories by mass resolution due to different muon rapidity;
- then train BDT discriminator using vertex and muon qualities; output for each resolution category divided into 3 subcategories
- ML fit performed simultaneously on the 6 categories

CMS: Search for $\tau \to 3\mu$

CMS-PAS-BPH-21-005

τ from heavy flavor

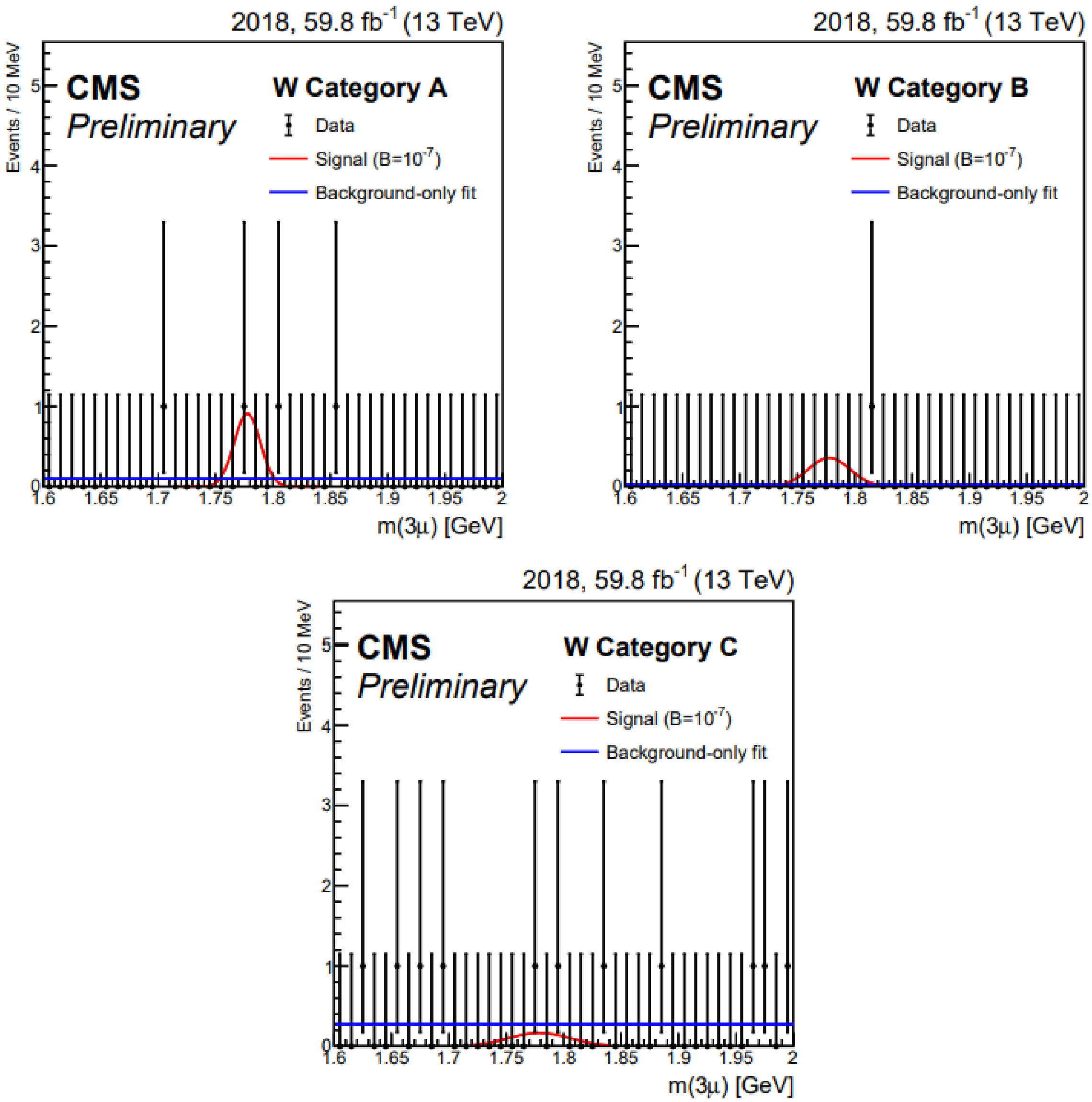


No excess is observed in the signal region

CMS: Search for $\tau \rightarrow 3\mu$

CMS-PAS-BPH-21-005

τ from W

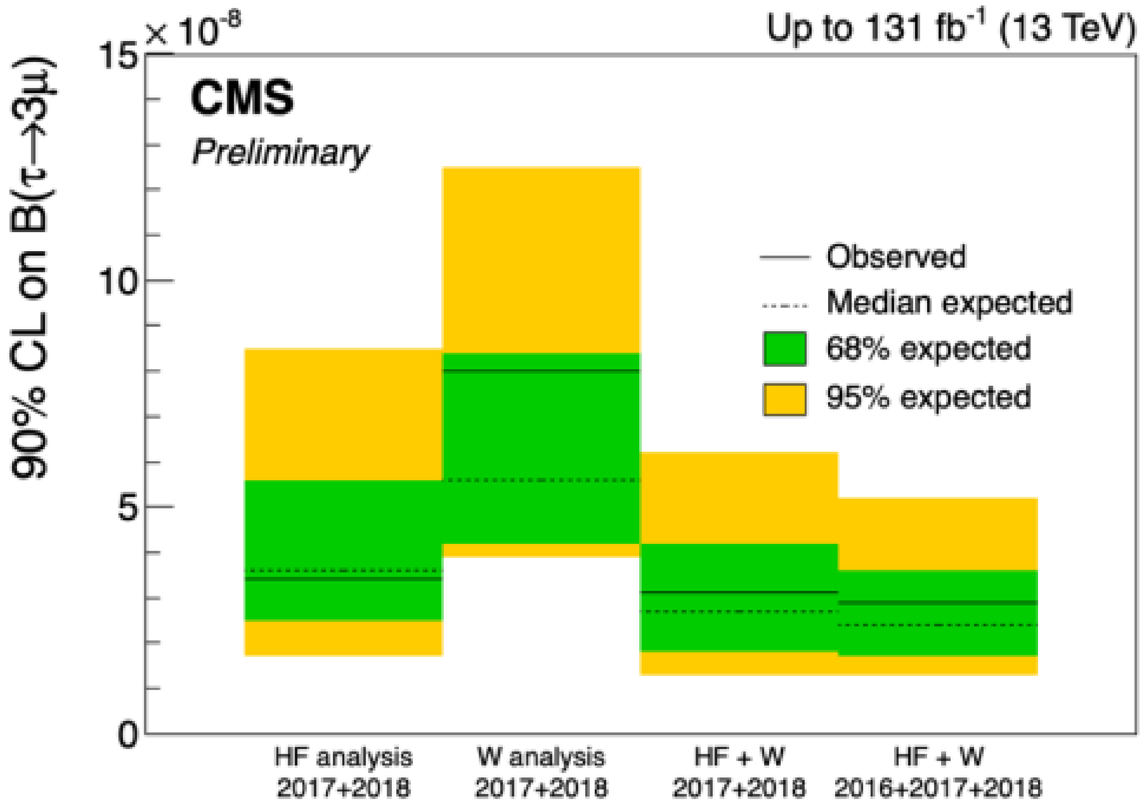


No excess is observed in the signal region

CMS: Search for $\tau \to 3\mu$

CMS-PAS-BPH-21-005

Results:



Combination with 2016 result gives:

Extracted (expected) UL @ 90% CL:
$Br(\tau \to 3\mu) < 2.9\ (2.4) \times 10^{-8}$

Although designed for high-pt physics,
CMS is good experiment for heavy flavor physics
where one can also search for BSM physics (LFV)

Summary

- New results from CMS on Lepton Flavor (Unification) Violation :
  - 1) - the first measurement from Bparking data set →

$$R(\mathrm{K}) = 0.78^{+0.46}_{-0.23}\,(\mathrm{stat})^{+0.09}_{-0.05}\,(\mathrm{syst}) = 0.78^{+0.47}_{-0.23},$$

    - statistics is limited by electron channel,
    - will be improved with RUN 3 data

  - 2) - the first test of LFV using b→c τ ν transition
    - $R(J/\psi) = 0.17 \pm 0.33$
    - compatible with SM within 0.3 σ and with LHCb - within 1.3 σ

- Search for charged lepton flavor violating decay $\tau \to 3\mu$

  no excess observed, UL set: Br.fr. < 2.9×10^{-8} @90% CL.

CMS will continue to test the SM prediction in **LFV** sector.

Backup slides

Table 4: Input variables used in the electron channel BDTs, for both PF-PF and PF-LP categories.

Variable	Description
$p_T(e_1/e_2/K^+/B^+)/m(K^+e^+e^-)$	Transverse momenta of e_1, e_2, K^+, and B^+ candidates, respectively, divided by the invariant mass of the B^+ candidate
$\Delta z(e_{1,2}, K^+)$	Longitudinal distance between the points of origin of each electron and the kaon
$\|d_{3D}(K^+, e^+e^-)\|/\sigma_{\|d_{3D}(K^+, e^+e^-)\|}$	Kaon 3D impact parameter significance with respect to the dielectron secondary vertex
$p(B^+\text{ vtx})$	B^+ candidate SV fit χ^2 probability
$L_{xy}/\sigma_{L_{xy}}$	B^+ candidate secondary vertex transverse displacement significance
$\cos\alpha_{2D}(B^+)$	Cosine of the angle in the transverse plane between the B^+ candidate momentum and the vector connecting the beam-spot and the B^+ candidate SV
$\Delta R(e^+, e^-)$	ΔR between the two electrons
$\Delta R(e_{1,2}, K^+)$	ΔR between each electron and the kaon
$\frac{\|\mathbf{p}(e^+e^-)\times\mathbf{r}\|-\|\mathbf{p}(K^+)\times\mathbf{r}\|}{\|\mathbf{p}(e^+e^-)\times\mathbf{r}\|+\|\mathbf{p}(K^+)\times\mathbf{r}\|}$	Asymmetry of the momentum of the dielectron system and that of the K^+ momentum with respect to the B^+ candidate trajectory, where $\mathbf{r}$ is a unit vector connecting the PV and the B^+ candidate SV
$\text{ID}(e_{1,2})$	Electron identification BDT score for each of the two electrons
$I^{\text{rel}}_{\Delta R=0.4}(e_1/e_2/K^+)$	Relative track isolation in a $\Delta R < 0.4$ cone for e_1, e_2, and K^+, respectively

Table 2: Input variables used in the muon channel BDT.

Variable	Description
$\cos\alpha_{3D}$	Cosine of the angle between the momentum vector of the B^{+} candidate and the vector connecting the primary and secondary vertices
$p(B^{+}\ \mathrm{vtx})$	Probability of the B^{+} candidate vertex derived from the kinematic fit, derived from the normalized χ^2 of the vertex
L_{xy}/σ_{xy}	Significance of the B^{+} candidate vertex displacement with respect to the beam-spot
$p_{T}(B^{+})$	Transverse momentum of B^{+} candidate after the kinematic fit
$p_{T}(K^{+})$	Transverse momentum of the K^{+} candidate after the kinematic fit
$\min\Delta R(\mu, K^{+})$	ΔR distance between the K^{+} candidate and the closest muon
$\min\Delta z(\mu, K^{+})$	Δz distance between the points of origin of the K^{+} candidate and the closest muon along the beam axis direction
$\mathrm{Iso}(\mu_{\mathrm{lead}})$	PF isolation for the p_{T}-leading muon, computed using all PF candidates (neutral and charged, excluding the muon itself) within $\Delta R < 0.4$ of the muon