NuFact 2024 - The 25th International Workshop on Neutrinos from Accelerators

Recent LFV results from CMS

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Outline

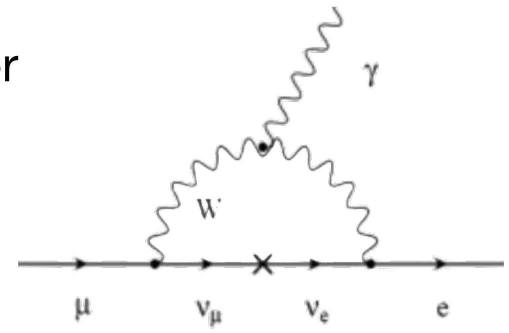
Run 2 data

- ***Top quark sector:***
  - Search for LFV in top quark production and decay to 3l
  - Search for LFV in top quark interactions with an up-type quark, a muon and a tau lepton
- ***Exotic signatures:***
  - Search for LFUV via Z'→μμ + one or two b-jets
- ***B-Physics:***
  - Search for the LFV decays $\tau \to 3\mu$
  - R(K): Test of LFU in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ decays
  - R(J/ψ): Test of LFU in $B_c^{+} \to J/\psi\, \tau^{+}\nu_{\tau}$ / $B_c^{+} \to J/\psi\mu^{+}\nu_{\mu}$ decays

LF(U)V and possible New Physics scenarios

Lepton Flavor Violation: no fundamental symmetry enforcing lepton flavor conservation in **the SM extended to include neutrino oscillations**

- LFV in the charged sector through ν oscillation predicted with $\mathcal{B}\sim10^{-55}$, any observation would indicate NP!

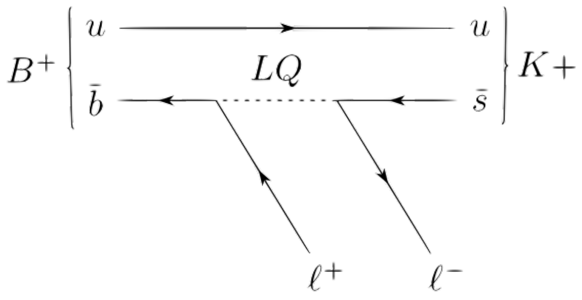


Lepton Flavor Universality: In the SM, the couplings of the leptons to the gauge bosons (W, Z) are of equal strength

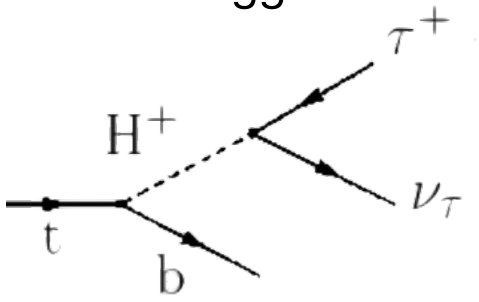
- the Yukawa coupling exhibits a flavour structure, giving each charged lepton family different mass
- additional forces could exhibit similar favour structures, and have enhanced couplings to 3rd generation leptons

Many **BSM theories** predict LFV with $\mathcal{B}\sim10^{-8}$, **accessible by present-day experiments!**

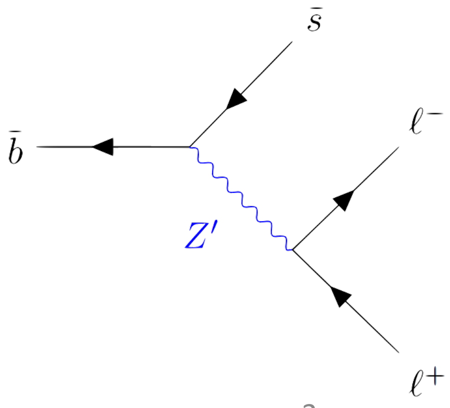
- Leptoquarks



- Extended Higgs sector / Technicolor



- Heavy Gauge bosons (W'/Z')



cLFV in the top quark sector: an EFT interpretation

Effective Lagrangian used to parametrise the cLFV top interactions throught relevant dimention-6 operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_a C_a^{(6)} O_a^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Scale of new physics ~ 1 TeV

Structure	Operator	Definition	Wilson coefficient
Scalar	$O^{1(ijkl)}_{\ell equ}$	$(\bar{\ell}_i e_j)\varepsilon(\bar{q}_k u_l)$	$C_{\ell equ1}$
Vector	$O^{1(ijkl)}_{\ell q} = O_{\ell q}$	$(\bar{\ell}_i \gamma^\mu \ell_j)(\bar{q}_k \gamma^\mu q_l)$	$C_{\ell q}$
	$O^{(ijkl)}_{\ell u}$	$(\bar{\ell}_i \gamma^\mu \ell_j)(\bar{u}_k \gamma^\mu u_l)$	$C_{\ell u}$
	$O^{(ijkl)}_{eq}$	$(\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l)$	C_{eq}
	$O^{(ijkl)}_{eu}$	$(\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_l)$	C_{eu}
Tensor	$O^{3(ijkl)}_{\ell equ}$	$(\bar{\ell}_i \sigma^{\mu\nu} \ell_j)\varepsilon(\bar{q}_k \sigma_{\mu\nu} u_l)$	$C_{\ell equ3}$

6 Wilson Coefficients: 3 Lorentz structures × 2 choices of light quark flavor

Search for cLFV in the top quark sector: $\mu e t q$

Probe $\mu e t q$ coupling in EFT in t production and decay, where q=u/c

Signal signature:

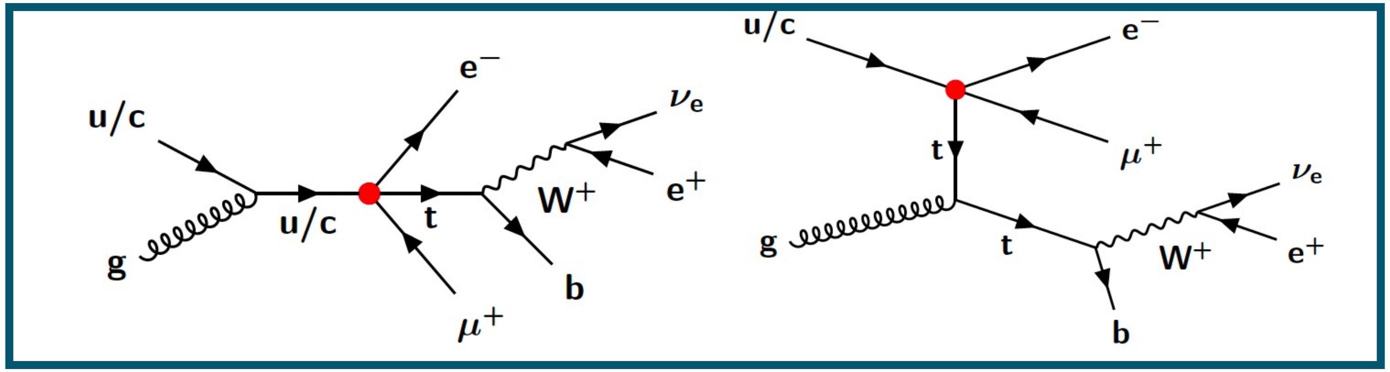
- OS eμ pair
- Leptonic top quark decay → additional lepton + one b-jet
- one/zero light jet (u/c)

Background:

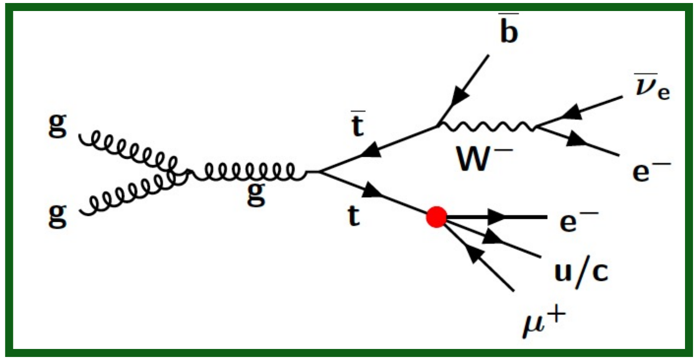
- Prompt (WZ, multiboson, $t(\bar{t})$ +X(X)) from simulation
- Non-prompt data-driven estimation

Statistically dominated, main systematics: lepton reco. and iso, jet modelling, non-prompt leptons

Two Signal regions defined:



CFLV in single top production

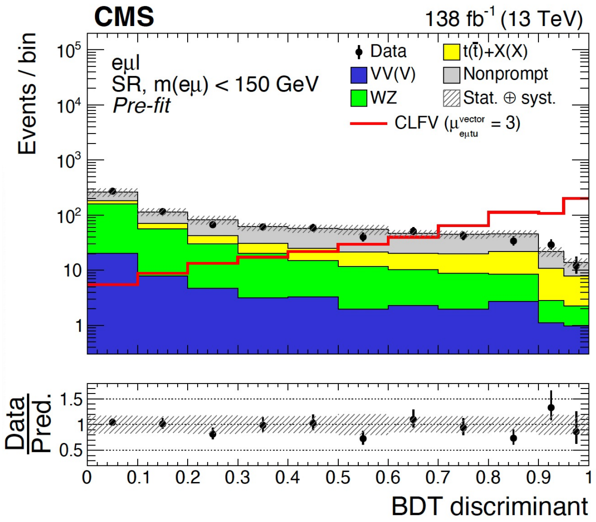


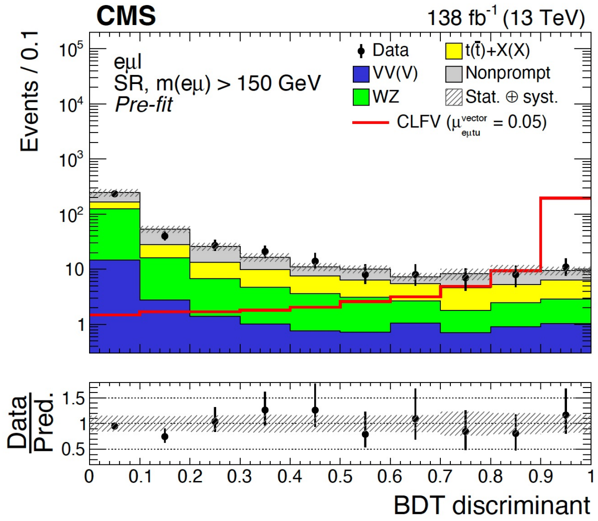
$t\bar{t}$ production + CLFV in top decay

SR + $m(e\mu) < 150\,\mathrm{GeV}$: top quark decay enriched,
SR + $m(e\mu) > 150\,\mathrm{GeV}$: top quark production enriched.

Search for cLFV in the top quark sector: $\mu e t q$

Binary discriminator (BDT) trained for each SR

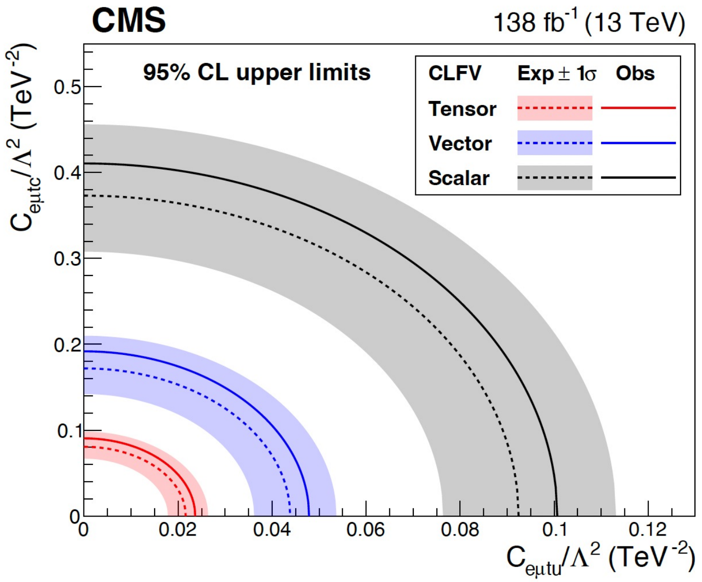


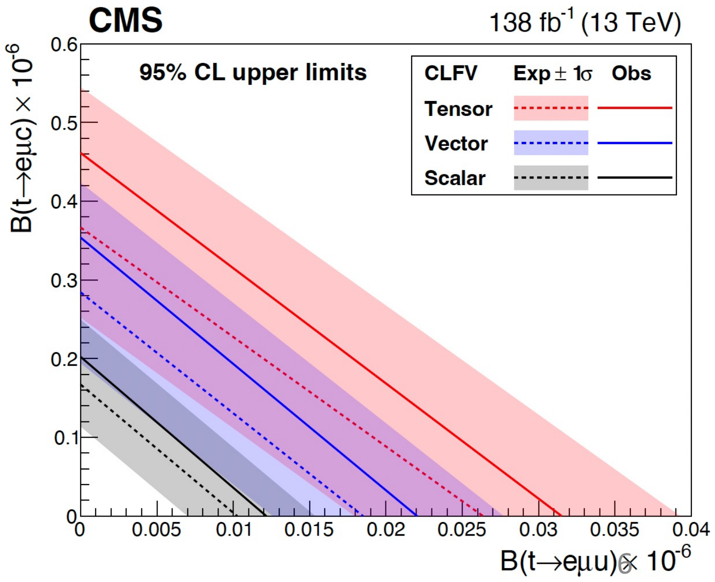


No excess observed. Limits on WCs converted to limits on branching fractions of LFV top decay

Most stringent limits on $\mathcal{B}(t \to e\mu q)$ to date

CLFV coupling	Lorentz structure	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	**Obs.**
$e\mu tu$	Tensor	0.027 (0.018–0.040)	**0.032**
	Vector	0.019 (0.013–0.028)	**0.022**
	Scalar	0.010 (0.007–0.016)	**0.012**
$e\mu tc$	Tensor	0.396 (0.272–0.585)	**0.498**
	Vector	0.296 (0.203–0.440)	**0.369**
	Scalar	0.178 (0.122–0.266)	**0.216**





CMS-TOP-22-011

Search for cLFV in the top quark sector: $\mu\tau tq$

Probe $\mu\tau tq$ coupling in EFT in t production and decay, where q=u/c

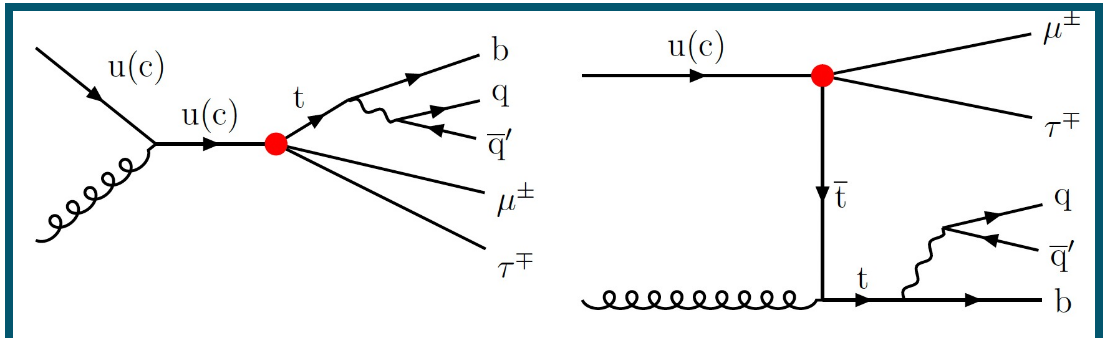
Signal signature:

- OS μ and τ_h pair
- ≥ 3 jets, including one b-jet

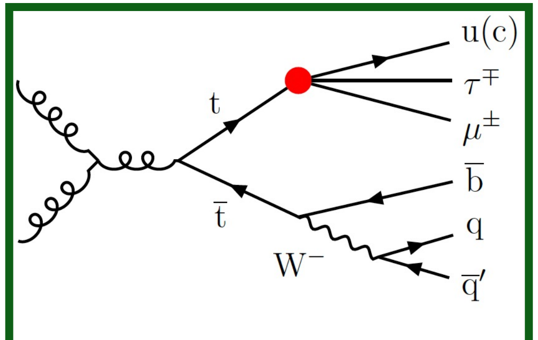
Background:

- Prompt backgrounds based on the simulation
- Jets mis-identified as hadronic taus estimated data-driven

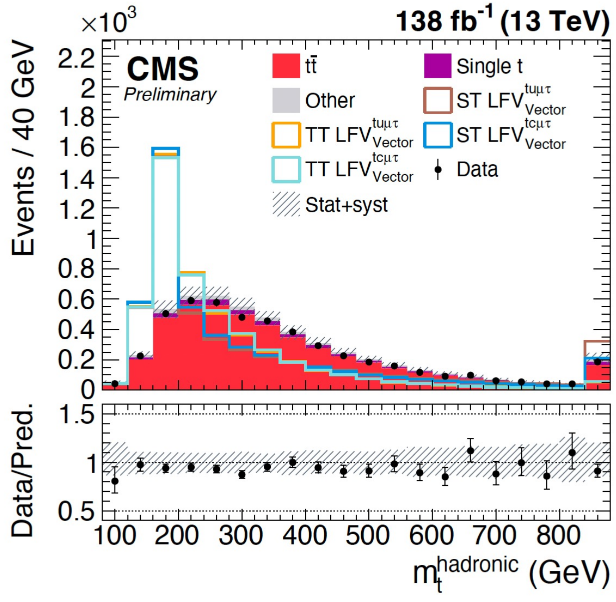
Hadronically decaying top quark reconstructed by minimizing $\chi 2$ of top quark and W boson mass

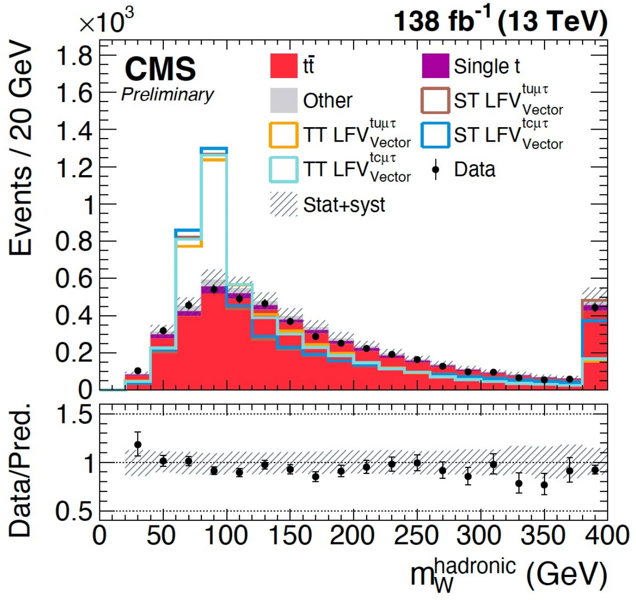


CFLV in single top production



$t\bar{t}$ pair production + CLFV in top decay



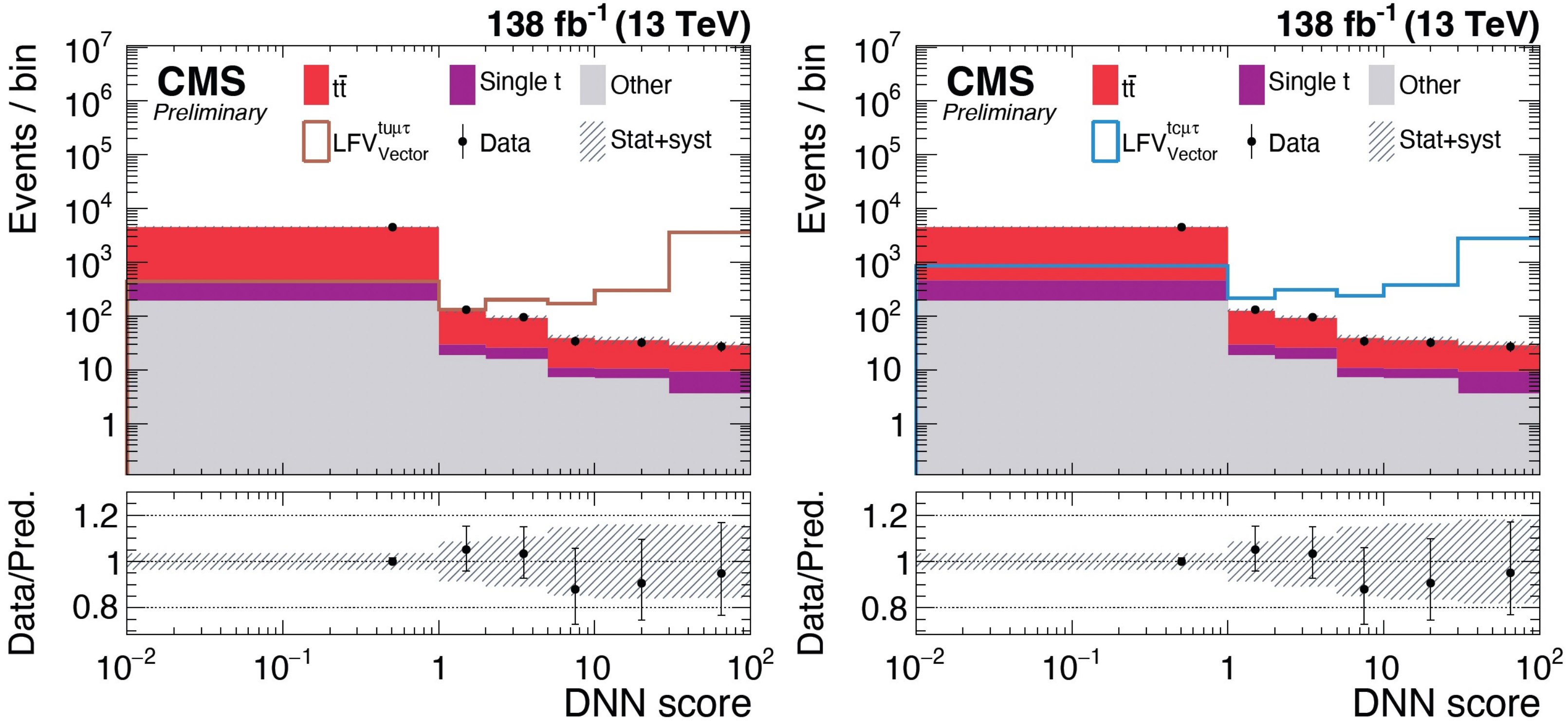


CMS-TOP-22-011

Search for cLFV in the top quark sector: $\mu\tau tq$

DNN for multiclass discrimination: background, ST CLFV, TT CLFV

- Important features: m_{top}, $m_{\mu\tau}$, m_W, p_T of μ and τ
- Probabilities combined into a single score



Uncertainties:
Limited sample size (5-30%), closure between data and MC-driven SF (10-35%)

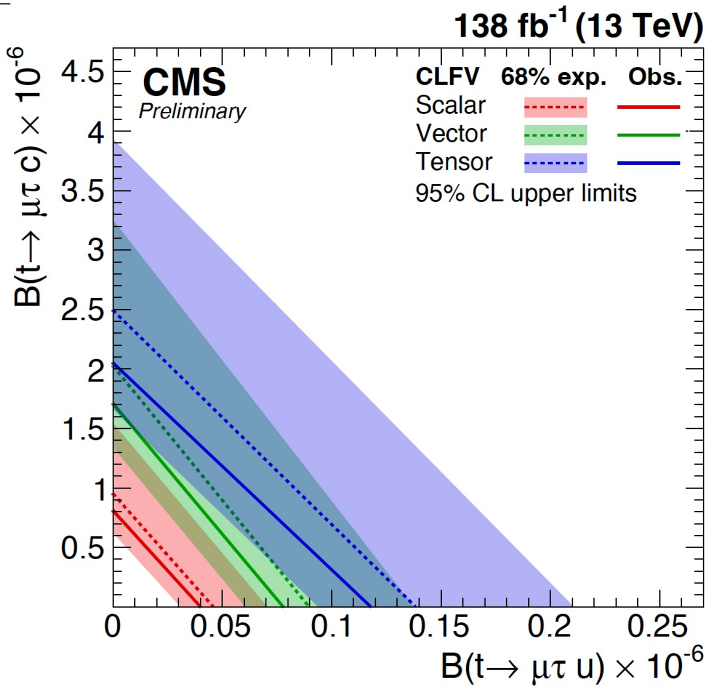
$$\text{DNN score} = \frac{0.1p(\text{TT CLFV}) + 0.9p(\text{ST CLFV})}{p(\text{background})}$$

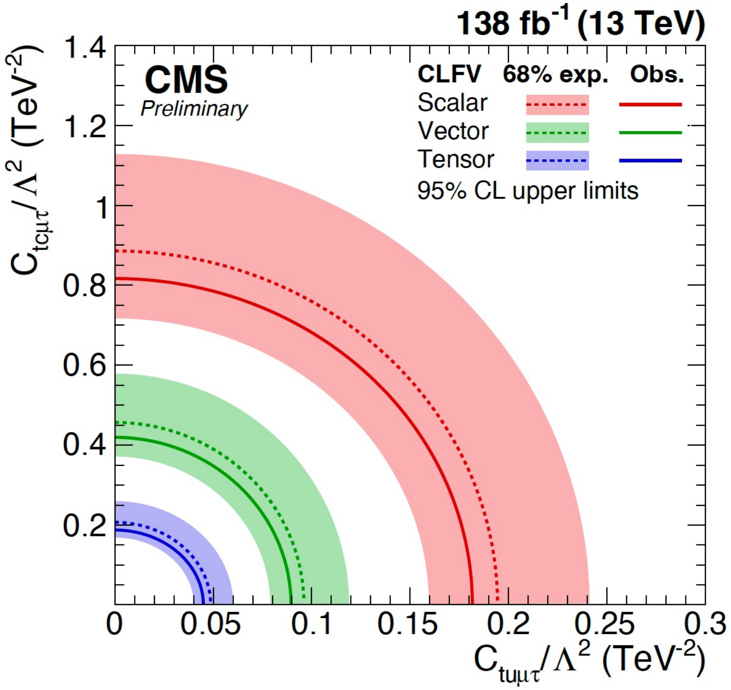
Search for cLFV in the top quark sector: $\mu\tau tq$

Interaction	Type	σ [fb]	$C_{tq\mu\tau}/\Lambda^2$ [TeV^{-2}]	$\mathcal{B}(t \to \mu\tau q)[10^{-6}]$
$tu\mu\tau$	Scalar	2.039 (2.337) [1.574, 3.594]	0.182 (0.194) [0.16, 0.241]	0.040 (0.046) [0.031, 0.071]
	Vector	2.384 (2.746) [1.857, 4.213]	0.09 (0.096) [0.079, 0.119]	0.078 (0.09) [0.061, 0.138]
	Tensor	2.834 (3.326) [2.257, 5.063]	0.045 (0.049) [0.04, 0.06]	0.118 (0.138) [0.094, 0.211]
$tc\mu\tau$	Scalar	4.269 (5.02) [3.291, 8.142]	0.817 (0.886) [0.717, 1.128]	0.81 (0.953) [0.625, 1.545]
	Vector	7.213 (8.552) [5.663, 13.734]	0.419 (0.457) [0.372, 0.579]	1.71 (2.027) [1.342, 3.255]
	Tensor	7.927 (9.633) [6.427, 15.2]	0.188 (0.207) [0.169, 0.26]	2.052 (2.494) [1.664, 3.936]

No excess observed. Limits on WCs converted to limits on branching fractions of LFV top decay

Comparable limits to the $e\mu$ channel analyses





Search for a low-mass Z' associated with b-jets

- Probing Z' production via enhanced couplings to third quark generation.
- Here extending previous studies (doi:10.1007/JHEP10(2023)) to low-mass region (126-352 GeV)

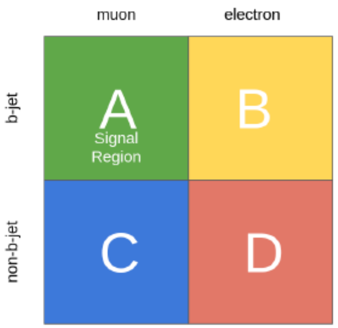
Signal signature:

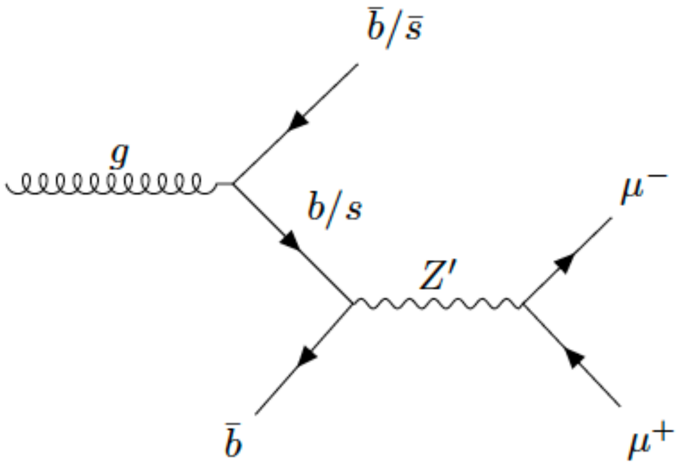
- $Z' \rightarrow \mu^+\mu^-$
- One or two jets, min. one b-jet
- Two SRs defined: $SR_b^{\mu\mu}$ (1jet) and $SR_{b+j/b}^{\mu\mu}$ (2jets)

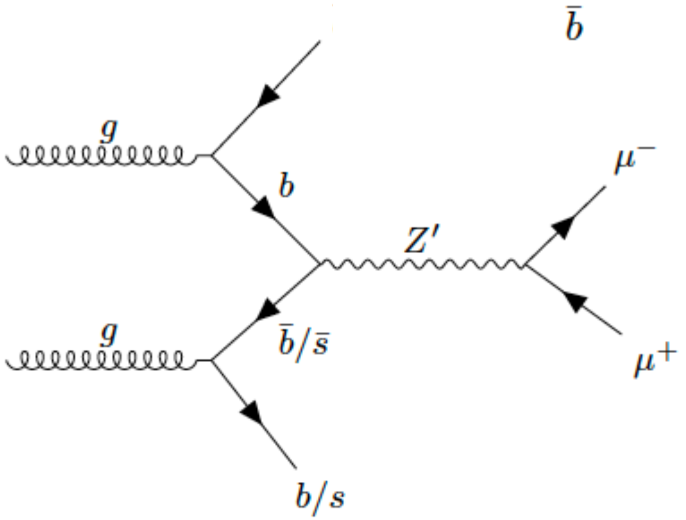
Background:

- DY at lower dilepton masses, $t\bar{t}$ at higher
- Fully data-driven background prediction (ABCD method)
  - CRs with di-electron and non b-jet states

N_b	N_{jets}^{all}	$\mu\mu$	ee
≥ 1	2	$SR^{\mu\mu}_{b+j/b}$	$CR^{ee}_{b+j/b}$
0	2	$CR^{\mu\mu}_{j+j}$	CR^{ee}_{j+j}
1	1	$SR^{\mu\mu}_{b}$	CR^{ee}_{b}
0	1	$CR^{\mu\mu}_{j}$	CR^{ee}_{j}







Non-universal flavour production via bottom quark or bottom-strange quark coupling.

Search for a low-mass Z’ associated with b-jets

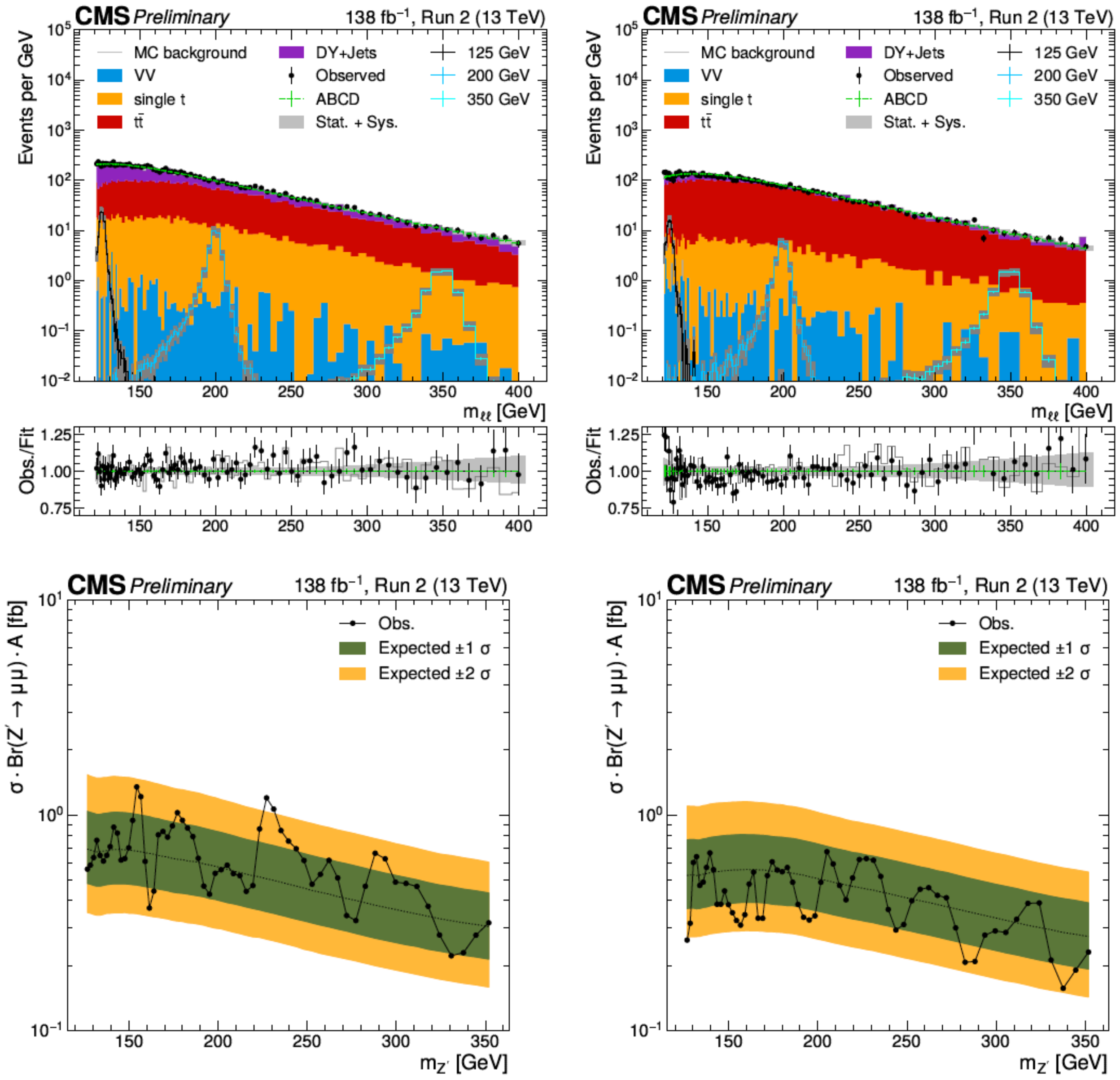
Relevant systematics: background fit, Jet energy scale and resolution

Simultaneous ML fit across data-taking years in both jet multiplicity categories to extract any potential signal contributions.

No deviation from background expectation

Results are provided in model-independent way, i.e. the two SR are not combined to **avoid assumptions on the mix of processes**

- acceptances for each production category is provided in the paper for further interpretation of the results



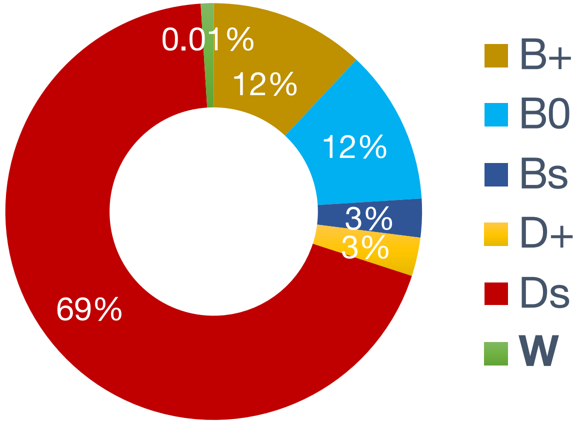
PLB 853 (2024) 138633

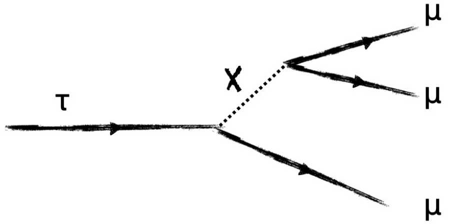
Search for LFV decay $\tau \to 3\mu$

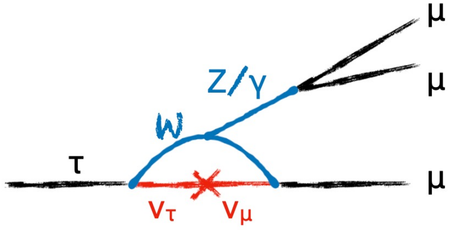
$\tau \to 3\mu$ transitions: golden channel for CLFV
- Fully reconstructed final state
- Clean experimental signature
- Abundant τ production at the LHC

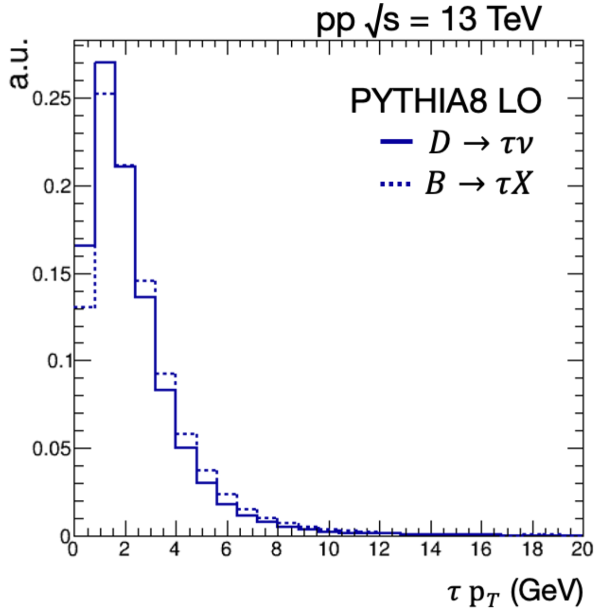
W channel: low stat, high-pT leptons in the final state + MET

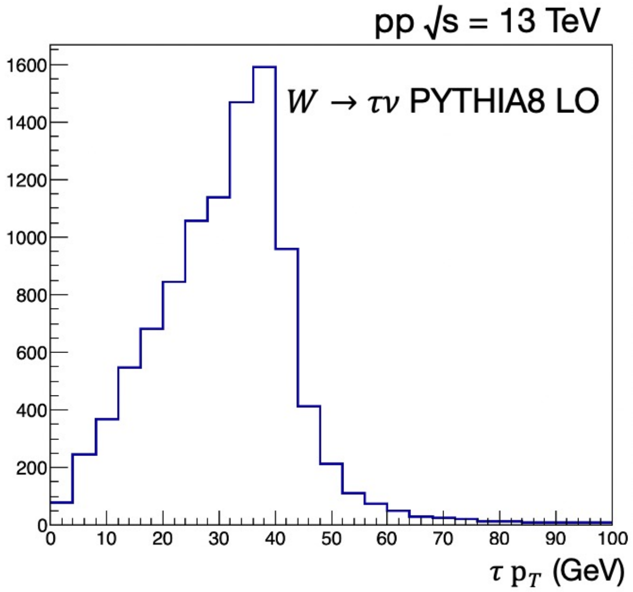
HF channel: high stat, low-pT leptons and higher background











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

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

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Search for LFV decay $\tau \rightarrow 3\mu$

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

- 3μ with common displaced vertex

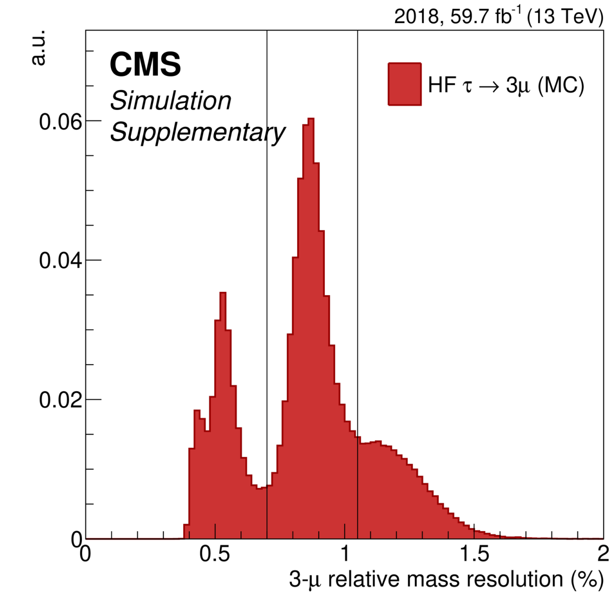
Events **categorised** to enhance sensitivity based on m(3μ) resolution, production mode, year

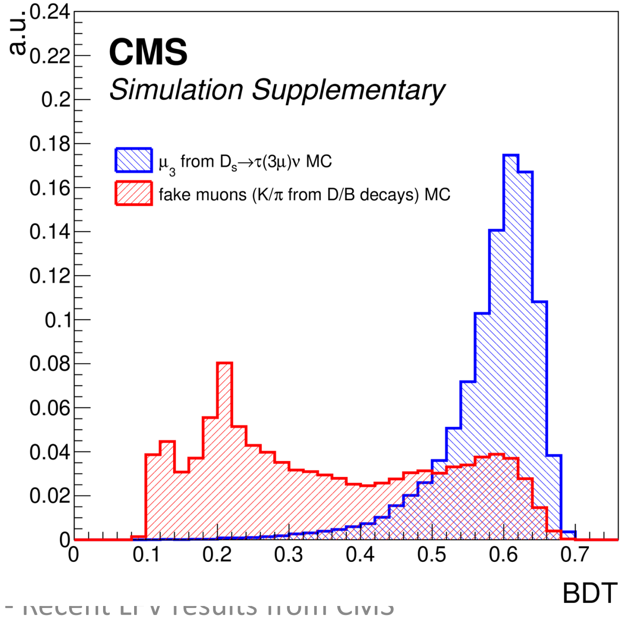
Background:

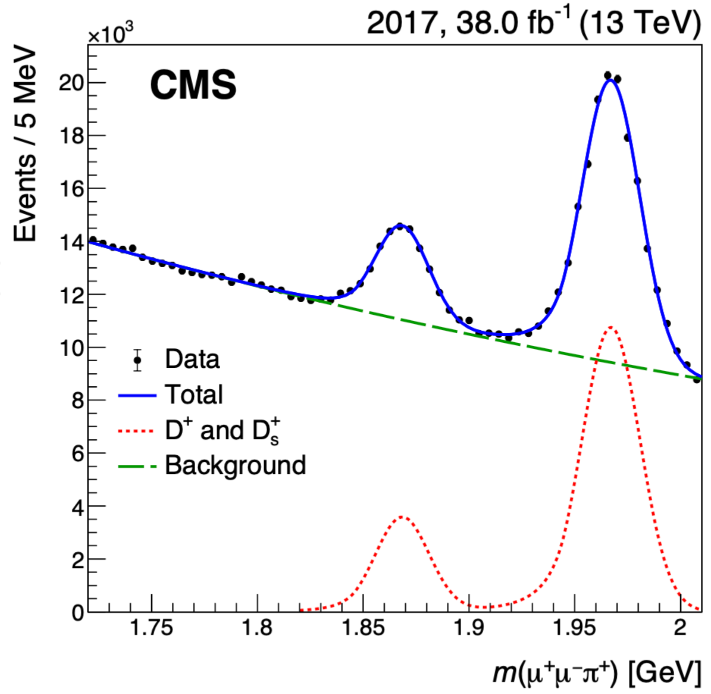
- two real muons plus one fake (typically decay-in-flight)
- 3 genuine muons two of which come from resonances (ϕ(1020) ω(783), Ds → η (μμγ) μν)
- Other combinatorial

Data sidebands as proxy for background

MVA muon ID and BDT classifier for **background suppression**







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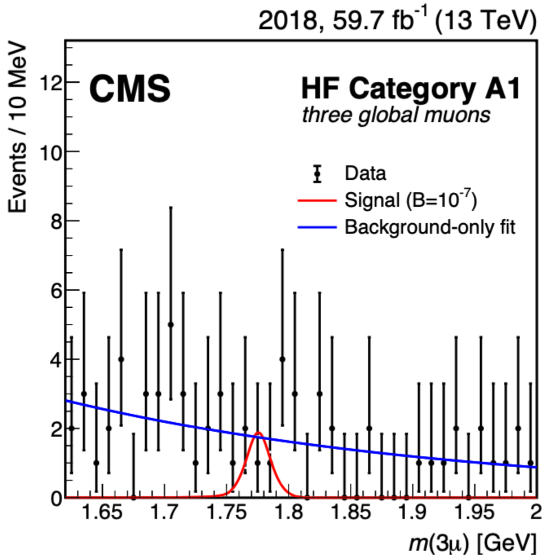
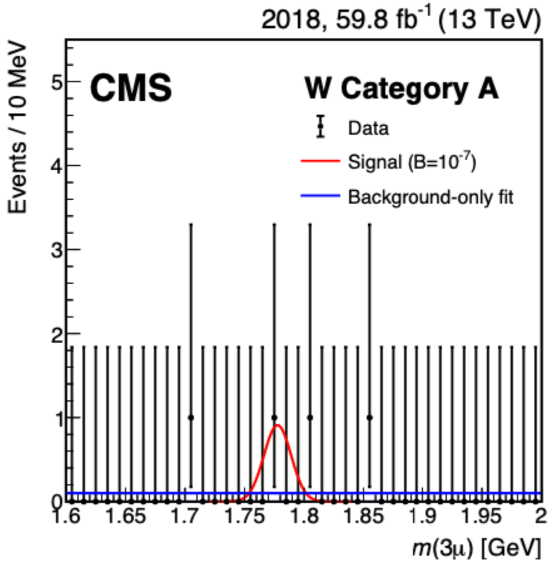
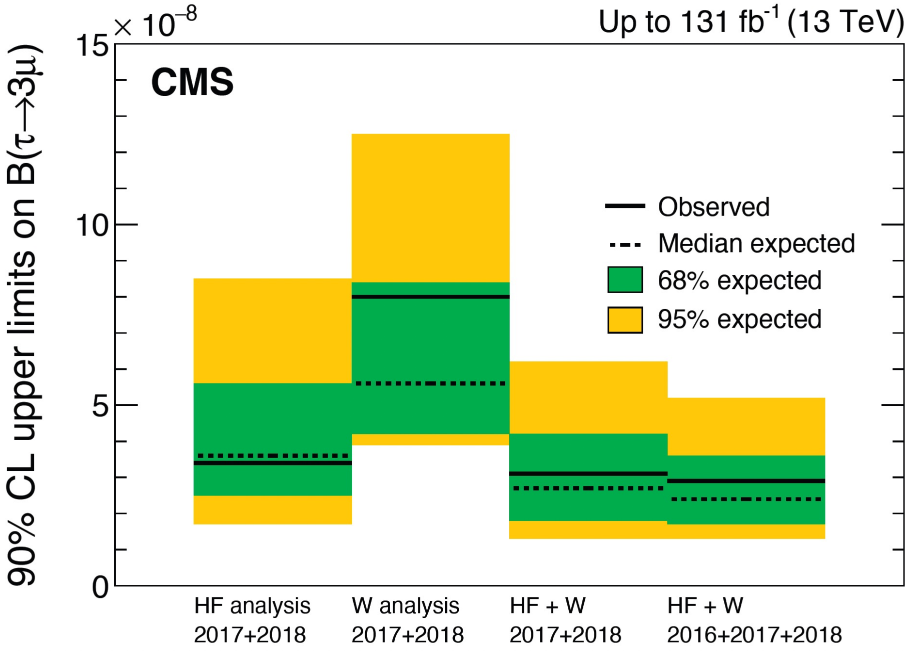
Search for LFV decay $\tau \to 3\mu$







Dominant systematics related to signal normalisation, muon reconstruction and identification efficiencies etc

Results dominated by statistical uncertainty

2017+2018 analysis results:

HF channel: observed (exp) upper limit:
3.4×10^{-8} (3.6×10^{-8}) 90% CL

W channel: observed (exp) upper limit:
8.0×10^{-8} (5.6×10^{-8}) 90% CL

Analysis of 2016 data from previous paper:
doi:10.1007/JHEP01(2021)163

Full Run 2 result: 2.9×10^{-8} (2.4×10^{-8}) 90% CL

Tests of LFU in the Heavy Flavor sector

$b \to s\ell\ell$

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

- Small BR (loop level)
- Precise theoretical predictions
- Neutrino-less

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

SM: 1.00 ± 0.01

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

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

- Large BR (tree level)
- Theory and syst. uncertainties
- Neutrinos in the final state

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

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

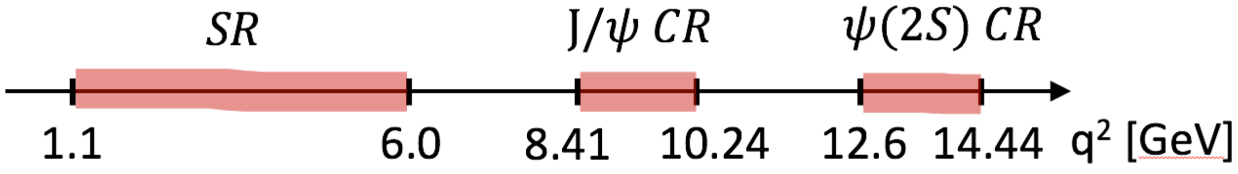
Rep. Prog. Phys. 87 077802

R(K): test of LFU in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ decays

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

Dataset: B-parking 2018 sample
(*https://arxiv.org/abs/2403.16134*)

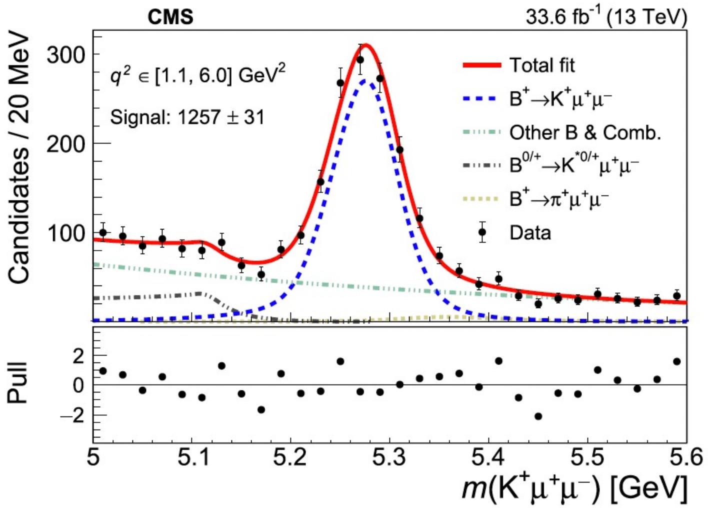
Strategy: fit the $K\ell\ell$ invariant mass in three q^2 regions

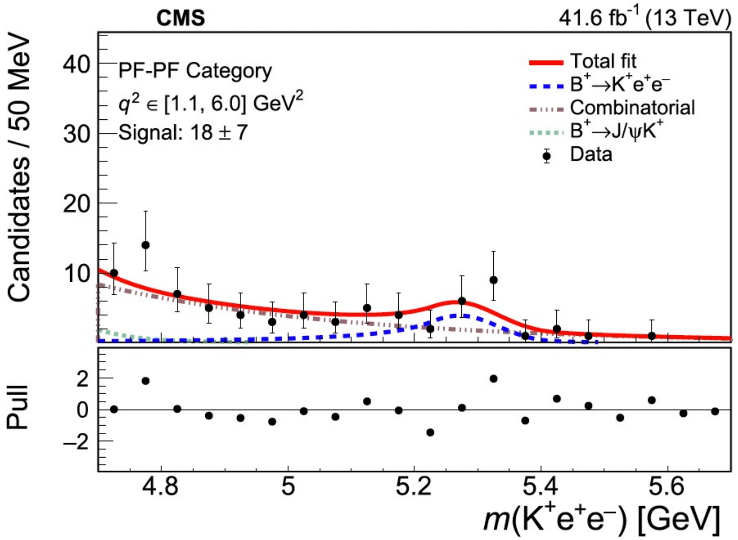


Dedicated **low-pT electron** reconstruction and ID down to 1 GeV

Background: combinatorial, partially reconstructed $B^0 \to K^*(892)^0\ell\ell$, leakage from resonant J/ψ and $\psi(2S)$

Background suppression via BDT





Rep. Prog. Phys. 87 077802

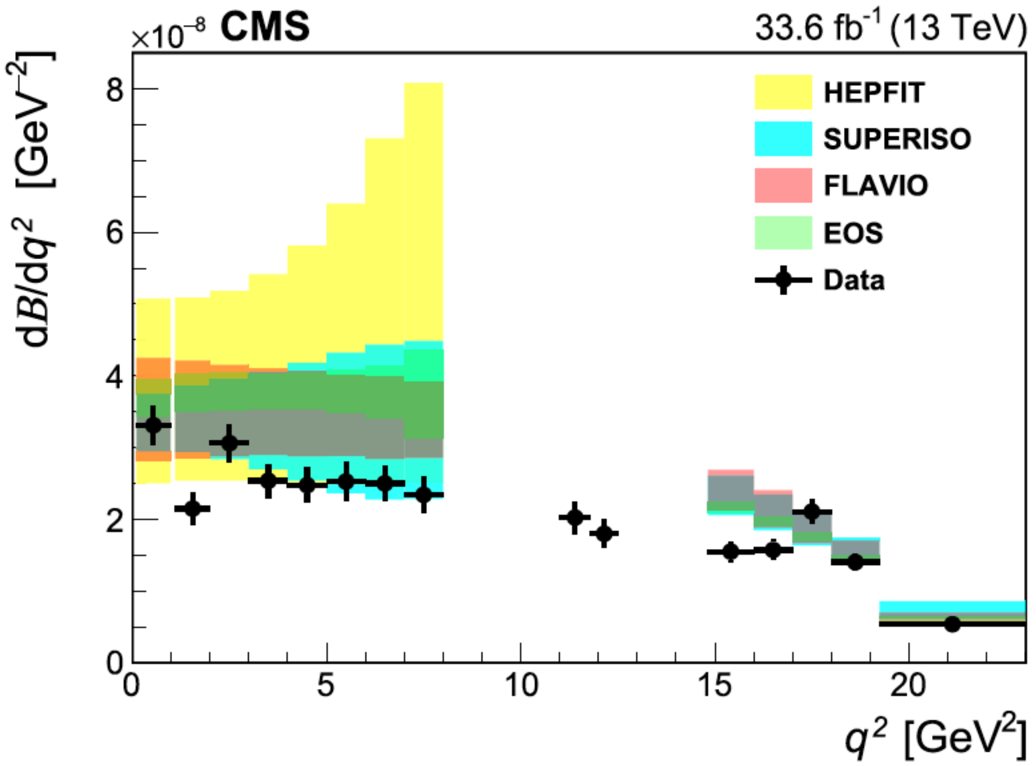
R(K): test of LFU in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ decays

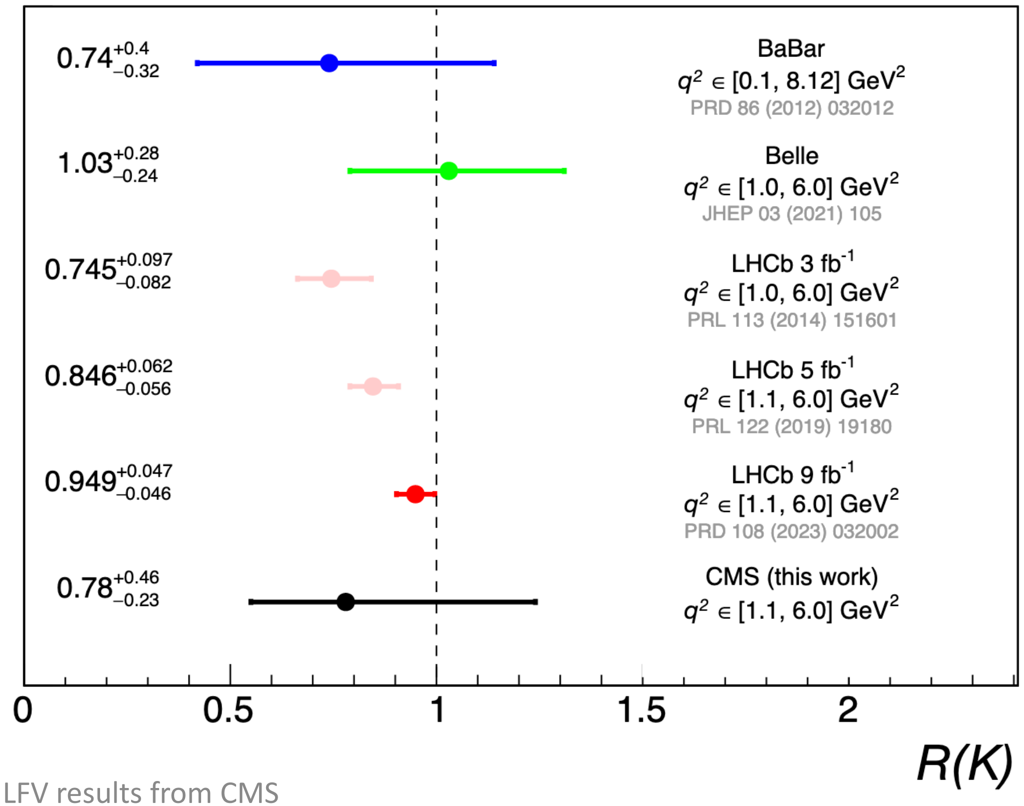
Results: compatible with the SM

R(K) in $q^2 \in [1.1; 6.0]$ GeV² in agreement with the world-average, with **unc. reduced by 40%**

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

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





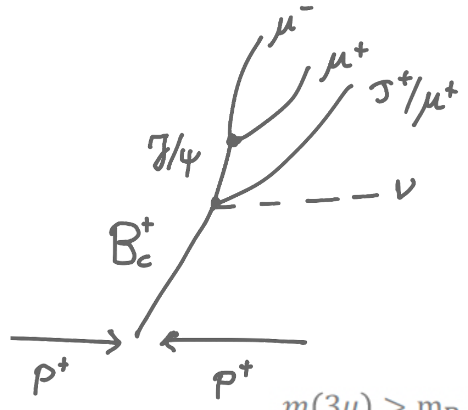
arXiv:2408.00678 submitted to PRL

R(J/ψ): Test of LFU in $B_c^+ \to J/\psi\, \ell^+ \nu_\ell$ decays (leptonic τ)

Dataset: 3μ events collected in 2018

Signal: 3μ+neutrinos → both numerator and denominator have same reco. and fit

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



Discriminating variables:

- $q^2 = (p_B - p_{J/\psi})$ for 1ν/ 3ν separation
- 3D IP significance between J/ψ and μ
- significance of J/ψ displacement

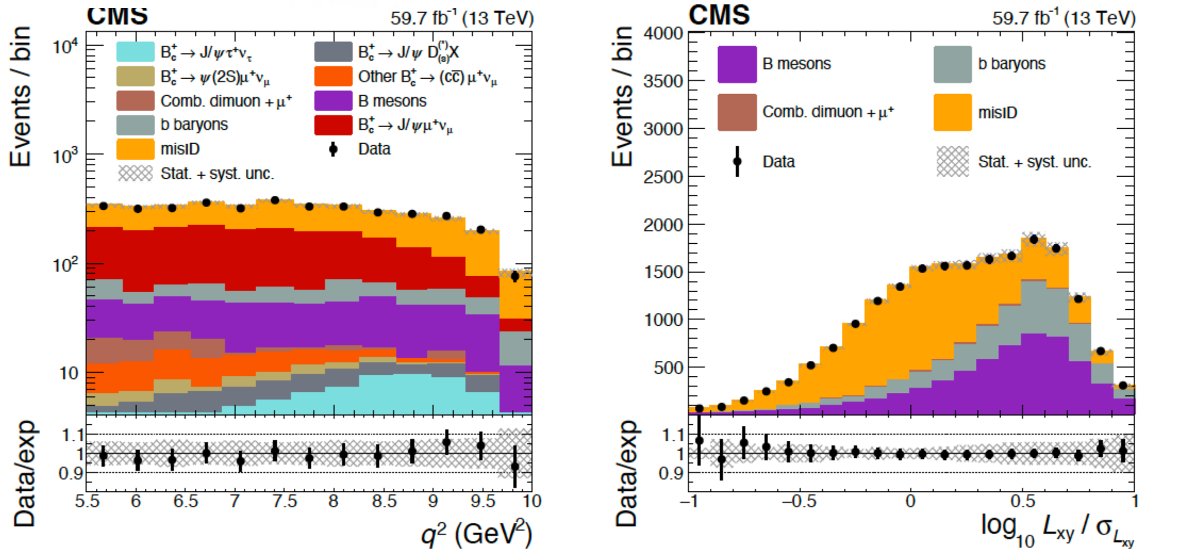
Simultaneous binned maximum likelihood template fit of 14 regions:

- bkg. w. J/ψ and μ from hadron decays simulated, and constrained in high mass control region (CR)
- misID: in-flight decay of $K^\pm$ and $\pi^\pm$ NN weighting extrapolated from CRs
- Combinatorial modelled from low dimuon mass

Statistical close to syst., main syst.: Bc form factors, misID, MC stats, kinematic modelling

$m(3\mu) < m_{B_c}$ & $q^2 > 5.5$ GeV^2 & IP3D/σ_{IP3D}> 2

$m(3\mu) > m_{B_c}$



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

CMS-PAS-BPH-23-001

R(J/ψ): Test of LFU in $B_c^+ \to J/\psi\, \ell^+ \nu_\ell$ decays (hadronic τ)

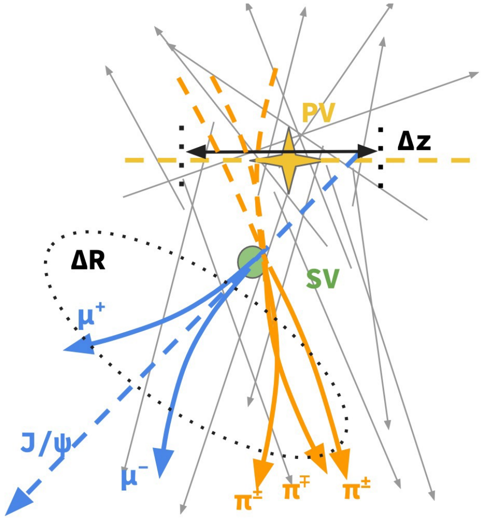
Dataset: full Run 2, J/ψ + track trigger

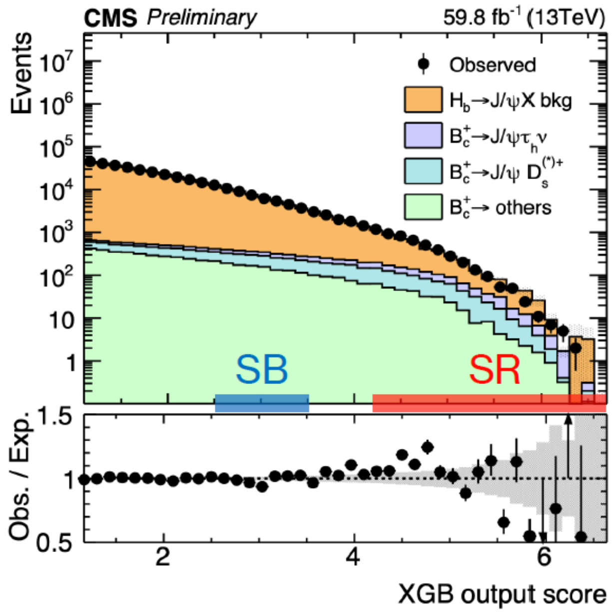
Signal: $J/\psi \to \mu\mu$ and $\tau \to \pi\pi\pi(+\pi^0)$ neutrinos (dedicated low p_T τ_h reconstruction ref)

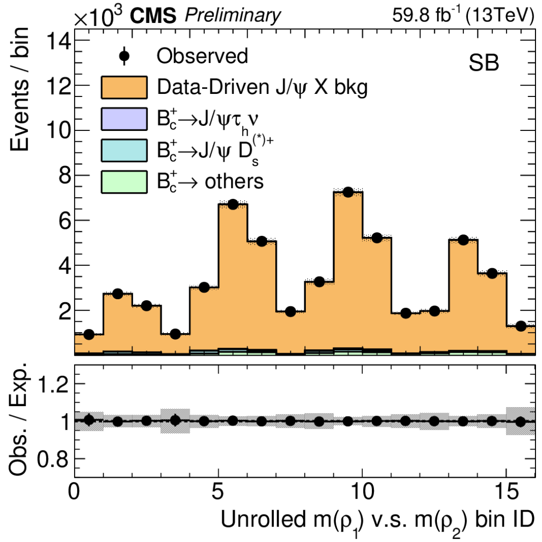
Background: non-Bc hadrons $H_b \to J/\psi X$, $B_c \to J/\psi D_s^{(*)}$ and other B_c decays

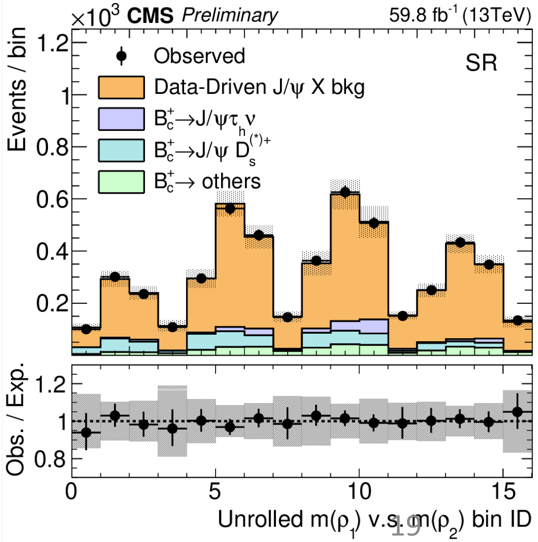
Background suppression via BDT
τ flight length significance, particle multiplicity, isolation, vertex fit

Final state pions sorted in p_T and combined in OS pairs (ρ_1 and ρ_2)
→ Unrolled ρ_1 vs ρ_2 used for sim. maximum likelihood fit to the signal region and









CMS-PAS-BPH-23-001

R(J/ψ): Test of LFU in $B_c^+ \to J/\psi\, \ell^+ \nu_\ell$ decays (hadronic τ)

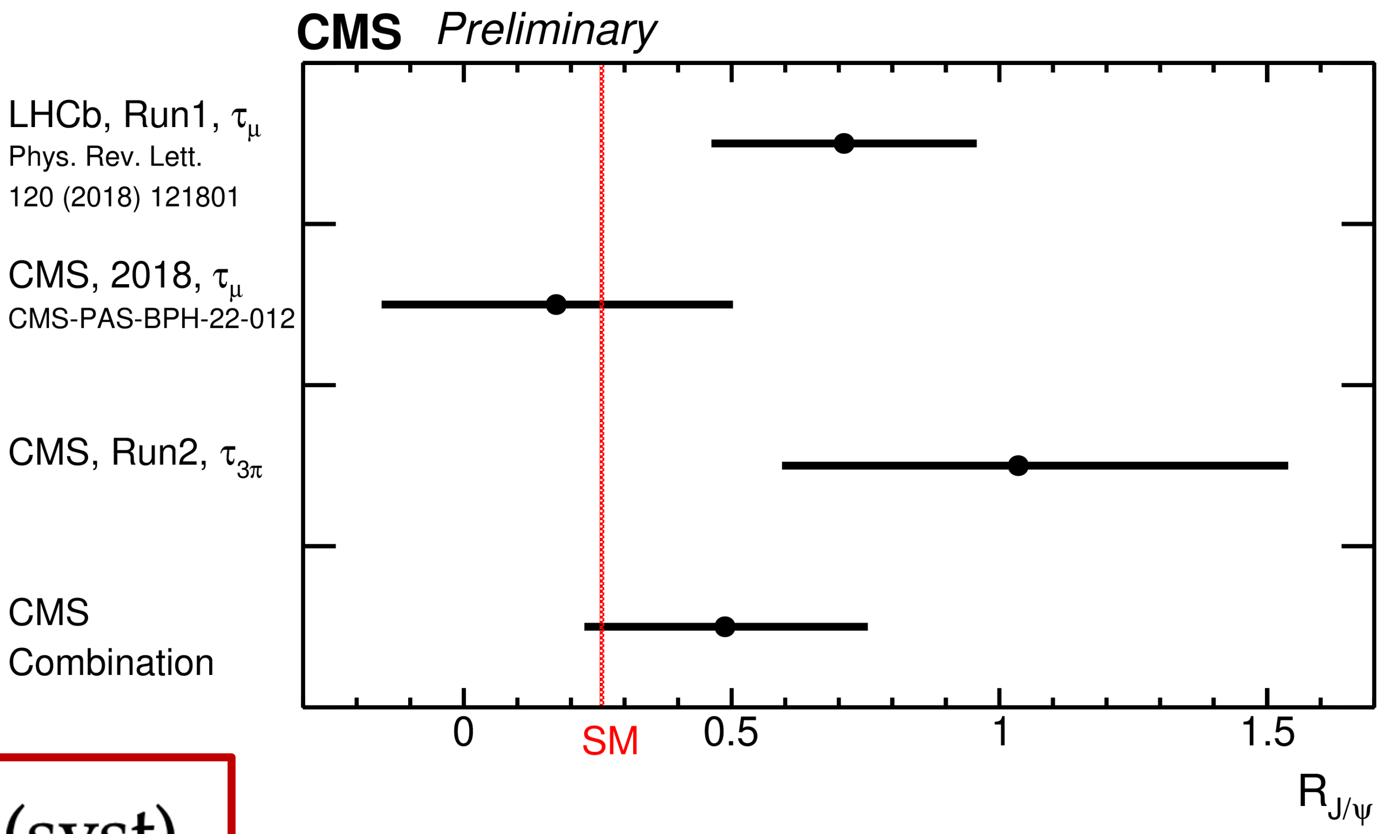
Results:

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

- Sensitivity driven by 2018
- Dominated by syst. unc.

Hadronic and leptonic channels share same denominator: combined result obtained performing an overall simultaneous fit

$$\mathcal{R}_{J/\psi} = 0.49 \pm 0.25\,(\text{stat}) \pm 0.09\,(\text{syst})$$



Conclusions

LFV and LFUV potentially sensitive instrument to look for new physics

CMS physics programme embraces LF(U)V searches in different sectors:

- In the top quark sector, an EFT approach provides model-indepentent limits on $\mu e t q$ and $\mu \tau t q$ (new!) interactions
- Connections between LFU and third quark generation is probed by searches for new neutral boson Z' coupling to third family quarks, providing complementary approaches to existing searches
- Extensive flavor physics program explores LFV and LFUV with competitive results
    - Run 2 exclusion limits on $\tau \to 3\mu$
    - First R(K) measurement at CMS
    - New R(J/ψ) result with hadronic τ

→ More to come with Run 3 data!