

# Heavy-flavour physics @LHC and flavour anomalies

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Course on Physics at the LHC  
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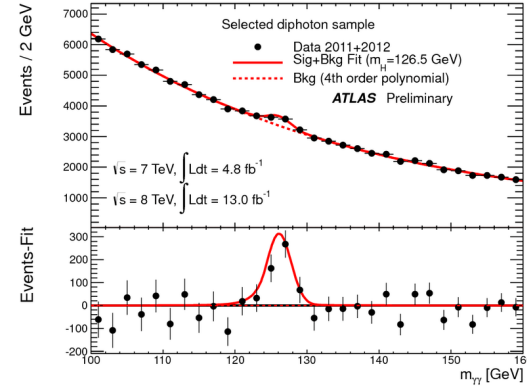
# List of touched topics

- Introduction
- Theory framework
- Branching fraction measurements
- Lepton Flavour Universality tests
- Angular analyses
- Global fit to the flavour anomalies

# Indirect searches for new physics

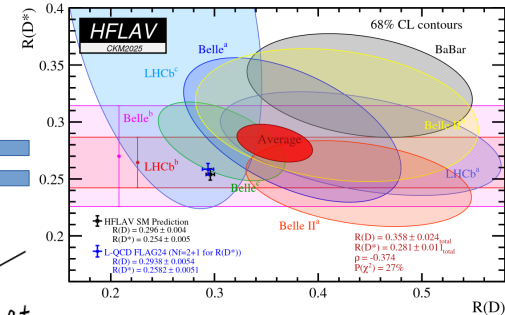
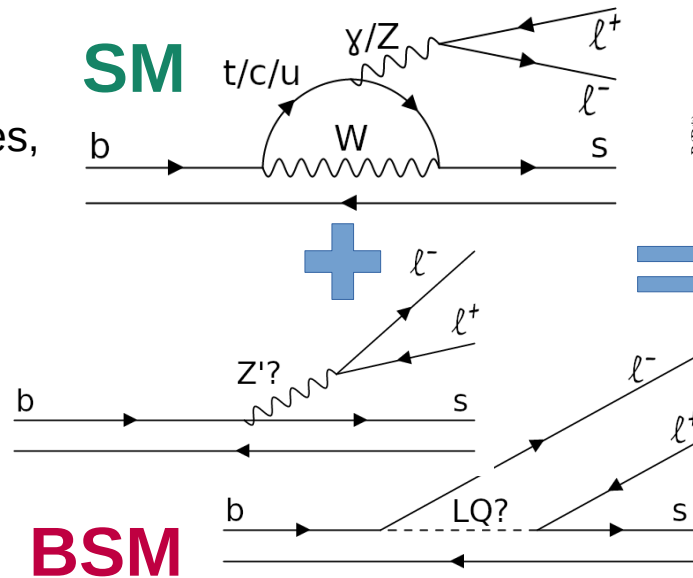
## Direct searches for physics Beyond the Standard Model (BSM)

- Aim at the production of new particles in the collisions, and the observation of their decay products
- Give clear evidence of BSM
- Are limited by energy scale of collisions and production cross-section



## Indirect BSM searches

- Aim at precise measurements of SM processes, to compare them with theory predictions
- BSM effects can interfere with the SM processes and produce visible differences
- No limits on energy scale, since the contribution can be virtual
- We can probe scales higher than 10 TeV



# Rare decays

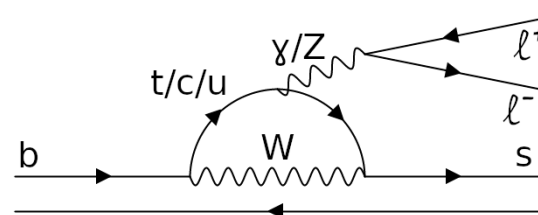
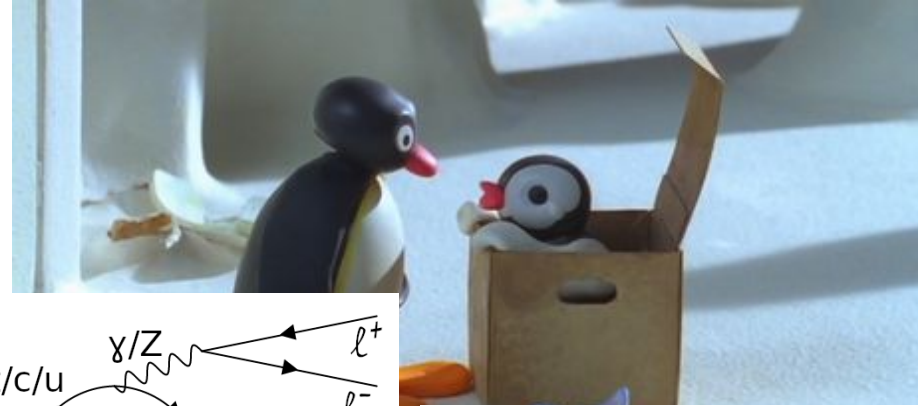
Best environment to indirectly search for new physics is in **rare decays** of SM particles

- sensitive to new particles with lower couplings or higher mass

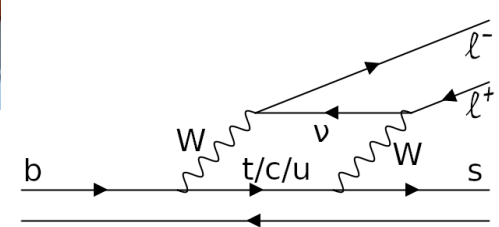
One of the most promising category is **flavour-changing neutral currents** decays

$b \rightarrow s l^+ l^-$

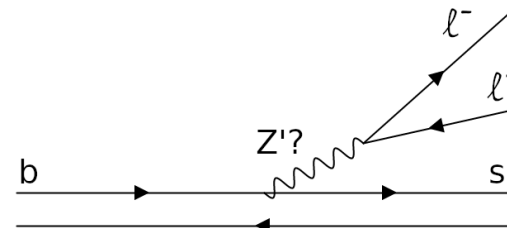
- in SM there is no diagram at tree level
  - leading order: EW penguin and box diagrams
- BSM can contribute
  - in the loop of these diagrams
  - at three level, with mediators that couples to different generations



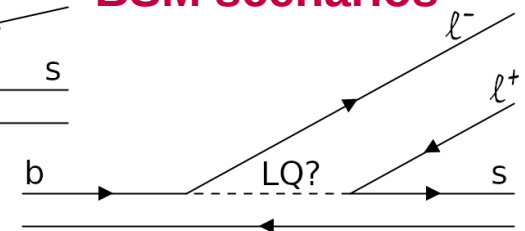
**Penguin diagram**



**Box diagram**



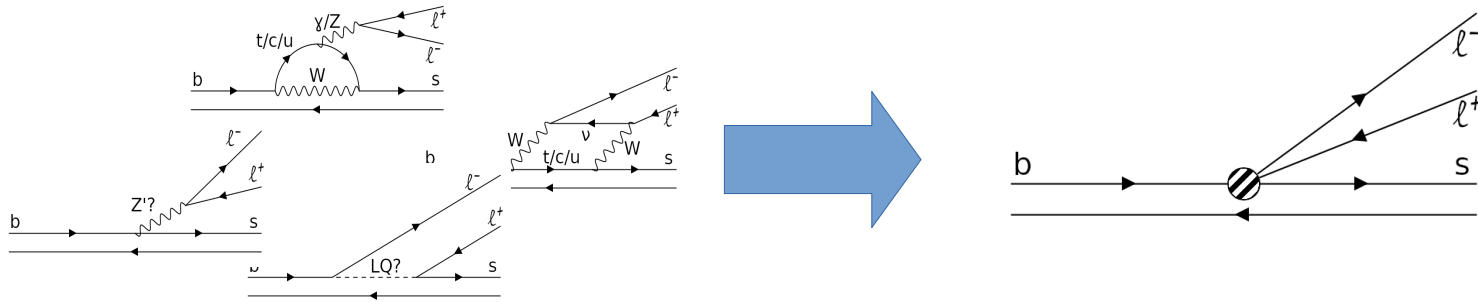
**Tree-level BSM scenarios**



# Effective Field Theory

Decays described in the framework of Effective Field Theory

- degrees of freedom at weak energy scale or higher are integrated out
- additional 6th-dimensional terms added to the **effective Lagrangian**

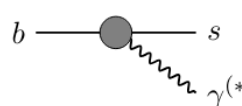
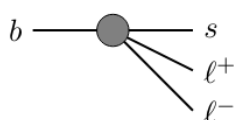
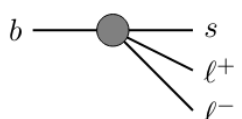


Factorisation of:

- Wilson coefficients  $C_i$ 
  - short-distance contributions
  - known with high accuracy
- Operators  $O_i$ 
  - long-distance contributions
  - affected by hadronic uncertainties

$$\mathcal{L}_{D=6}^{sbl\ell} = \frac{4G_F}{\sqrt{2}} \left[ \lambda_t \left( \sum_{i=1}^2 C_i \mathcal{O}_i^c + \sum_{i=3}^{10} C_i \mathcal{O}_i \right) + \lambda_u \left( \sum_{i=1}^2 C_i (\mathcal{O}_i^c - \mathcal{O}_i^u) \right) \right] + \text{h.c.}$$

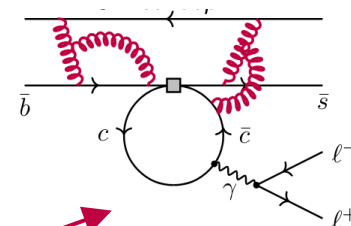
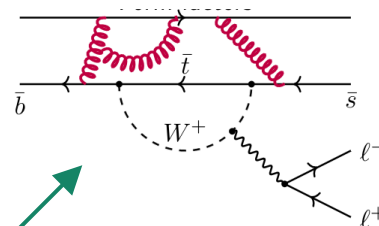
# Effective Field Theory

	Coupling	Operator	
	$C_7^{(\prime)}$	$\frac{m_b}{e} (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$	$\left[ \begin{array}{l} b \rightarrow s \gamma \\ b \rightarrow s \ell \ell \end{array} \right]$
	$C_9^{(\prime)}$ $C_{10}^{(\prime)}$	$(\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \mu)$ $(\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \gamma_5 \mu)$	
	$C_S^{(\prime)}$ $C_P^{(\prime)}$	$\frac{m_b}{m_B} (\bar{s} P_{R(L)} b) (\bar{\mu} \mu)$ $\frac{m_b}{m_B} (\bar{s} P_{R(L)} b) (\bar{\mu} \gamma_5 \mu)$	$\left[ \begin{array}{l} B_s^0 \rightarrow \mu^+ \mu^- \\ \mu^+ \mu^- \end{array} \right]$

**Transversity amplitudes for  $B \rightarrow M \ell \ell$  decays:**

$$\mathcal{A}^{M\ell\ell} \equiv \frac{G_F \alpha_e V_{tb} V_{ts}^*}{\sqrt{2}\pi} \left\{ (C_9 L_V^\mu + C_{10} L_A^\mu) \mathcal{F}_\mu^{B \rightarrow M} - \frac{L_V^\mu}{q^2} \left[ 2im_b C_7 \mathcal{F}_{T,\mu}^{B \rightarrow M} + 16\pi^2 \mathcal{H}_\mu^{B \rightarrow M} \right] \right\}$$

local hadronic matrix elements



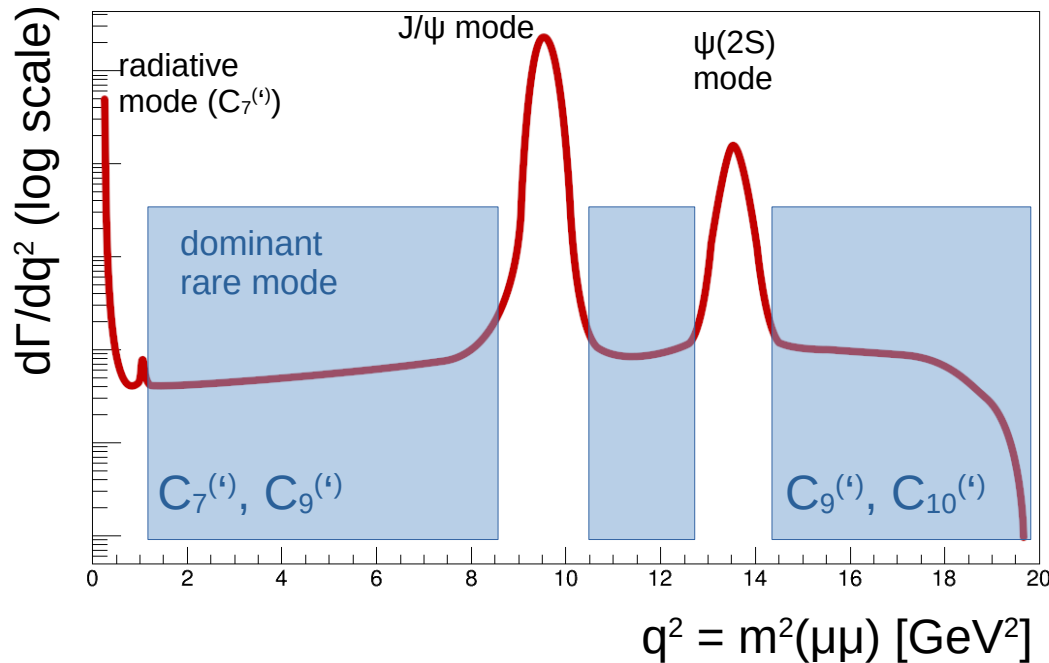
non-local hadronic matrix elements

# $b \rightarrow sll$ observables

What can we experimentally measure in  $b \rightarrow sll$  decays?

- Branching fractions
  - Simple experimental analysis
  - Theory predictions fully sensitive to hadronic uncertainties
- Angular distributions
  - Experimental analysis makes use of complex fits to measure angular parameters
  - Set of parameters defined to simplify hadronic uncertainties at leading order
- Lepton Flavour Universality ratios
  - Experimentally challenging, due to different detector interactions of electrons, muons and taus
  - Hadronic uncertainties simplify in the ratio, and predictions have small uncertainties ( $\sim 1\%$ )

# The dilepton mass spectrum



The spectrum of the two-lepton invariant mass ( $q$ ) is critical:

- allow to isolate tree-level  $b \rightarrow c\bar{c}s$  transitions, in which leptons are produced via charmonium resonance ( $J/\psi$  or  $\psi(2S)$ )
- different regions have different sensitivity to Wilson coefficients

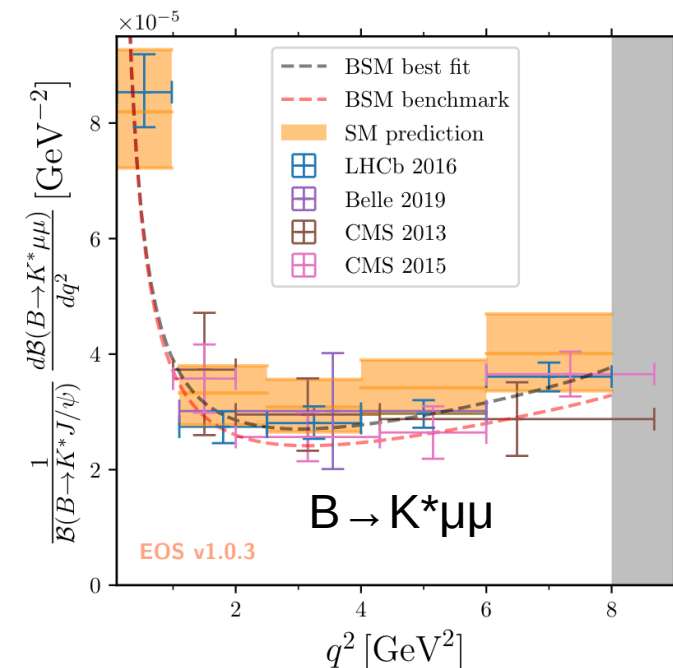
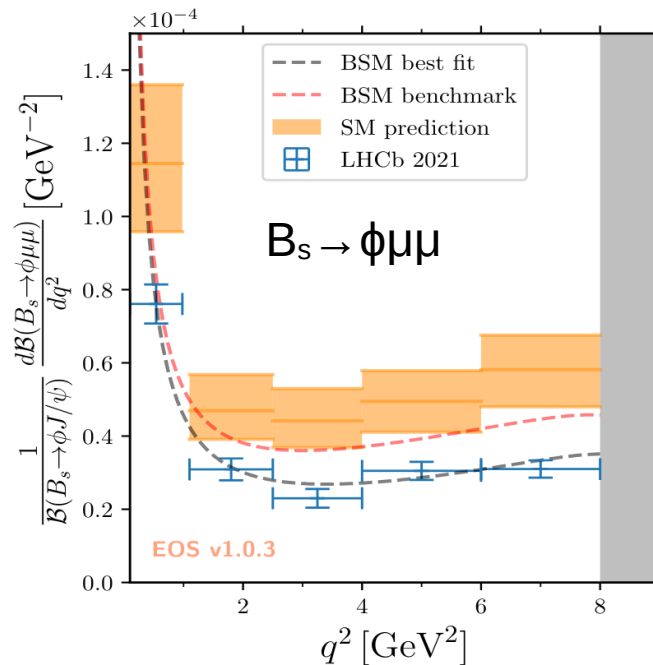
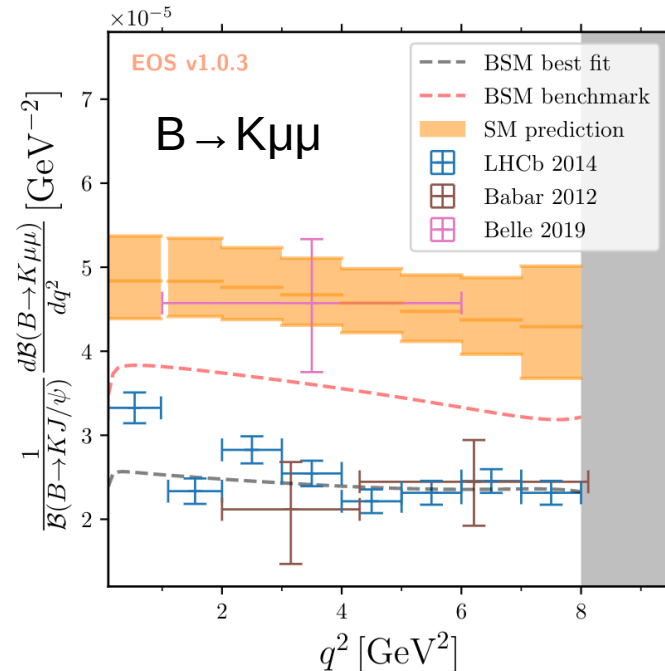
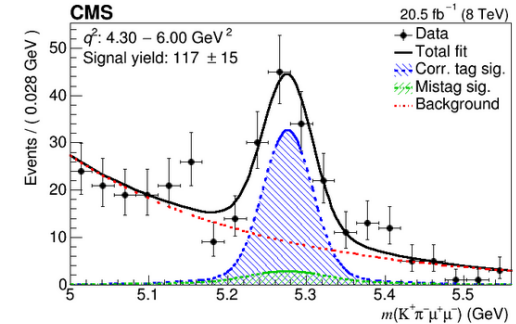
Analyses performed splitting the  $q^2$  range in bins

- independent analysis in each signal bin
- two bins dedicated to the  $J/\psi$  and  $\psi(2S)$  resonant modes

# Branching fraction measurements

Branching fraction of  $b \rightarrow s \mu\mu$  decays measured both at B-factories and LHC

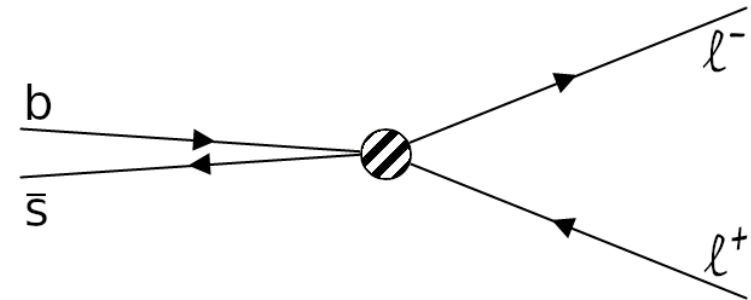
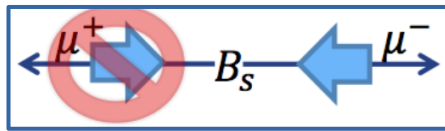
- Signal yield measured from fit to B-candidate mass
- Resonant  $b \rightarrow s J/\psi$  ( $J/\psi \rightarrow \mu\mu$ ) used as normalization (BF already known with high precision)
- Results are systematically lower than SM prediction
- Modification of C9 and C10 Wilson coefficients can cover the gap



# $B_s \rightarrow \mu\mu$ and $B \rightarrow \mu\mu$

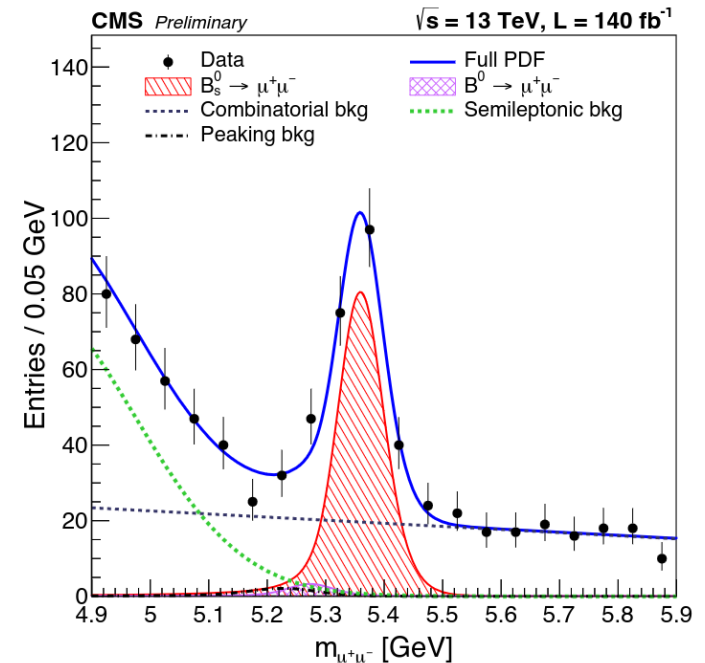
## $B_s^0 \rightarrow \mu\mu$ decay

- described with the same effective Lagrangian as  $b \rightarrow sll$
- doubly suppressed in the SM:
  - no tree-level diagram
  - helicity suppression
  - BF prediction:  $\sim 3.6 \cdot 10^{-9}$
- fully leptonic final state
  - very accurate prediction
- very clean experimental signature



## $B^0 \rightarrow \mu\mu$ decay

- same as above, but with additional suppression from elements of CKM matrix
- BF prediction:  $\sim 10^{-10}$



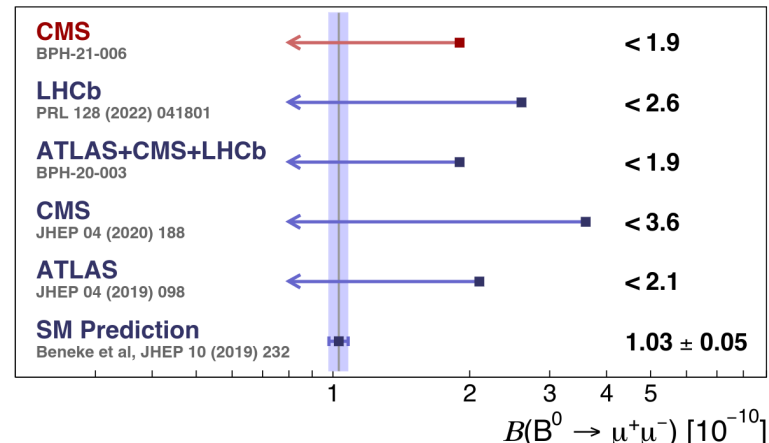
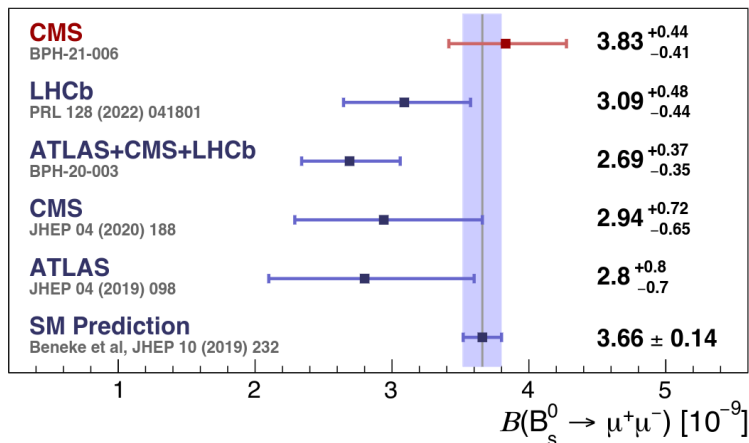
# $B_s^0 \rightarrow \mu\mu$ and $B^0 \rightarrow \mu\mu$ (CMS analysis)

Rejection and control of the backgrounds is the crucial point of the analysis:

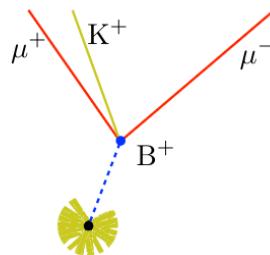
- Event selection based on multi-variate analysis (MVA)
- Isolation selection to reject partially-reconstructed bkg
- Vertex-quality selection to reject combinatorial bkg
- Dedicated muon identification via MVA

Most precise single-experiment results to-date!

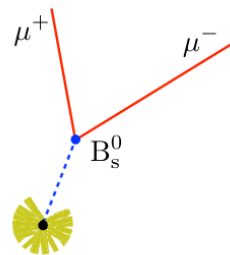
No tensions with SM predictions



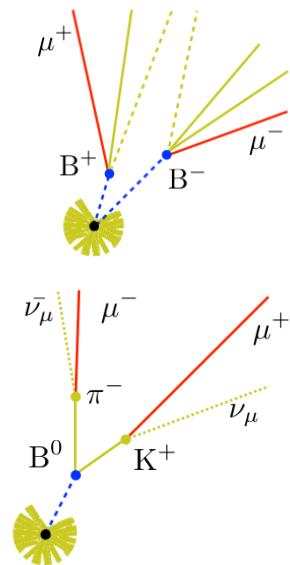
3-body and partial decays



Signal  $B_s \rightarrow \mu\mu$



Combinatorial Background



# Lepton Flavour Universality tests

LFU can be tested by measuring the ratios of the branching fraction of decays in different lepton generations

- In  $b \rightarrow sll$  decays the ratio is defined between muonic and electronic decays (tauonic decay not observed yet)

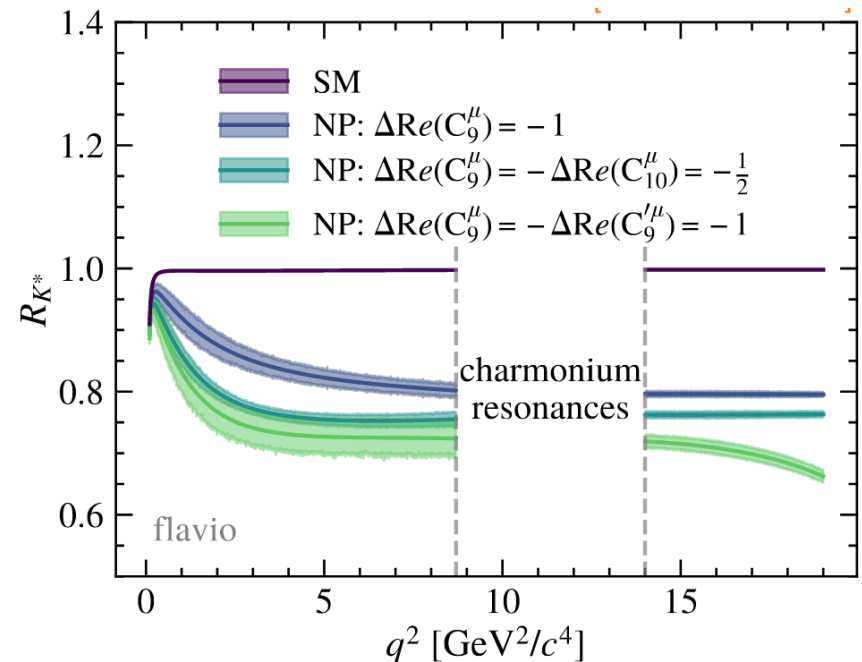
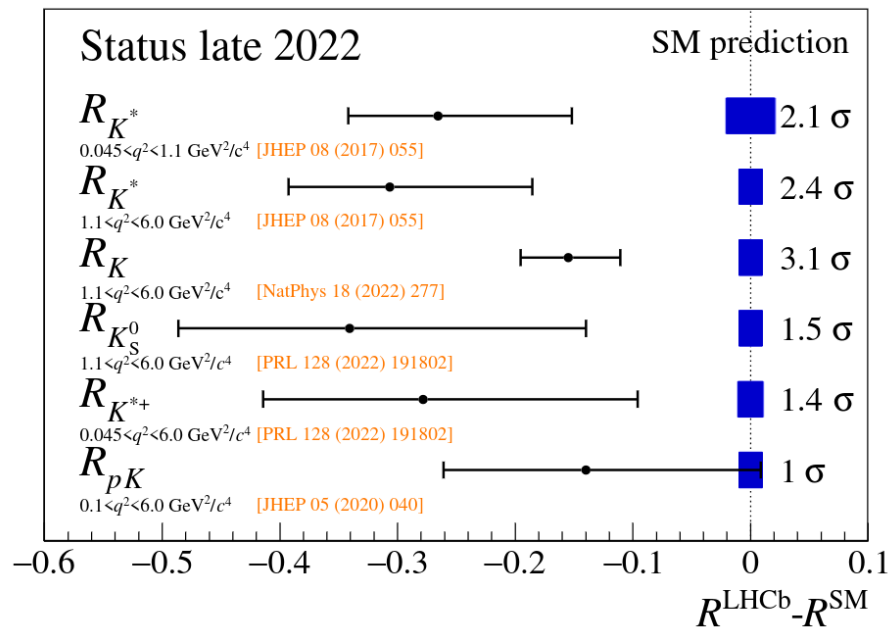
$$R_{K,K^*} = \frac{\mathcal{B}(B^{(+,0)} \rightarrow K^{(+,*0)} \mu^+ \mu^-)}{\mathcal{B}(B^{(+,0)} \rightarrow K^{(+,*0)} e^+ e^-)}$$

- In this ratio, hadronic uncertainties of SM BFs cancel exactly
  - only QED uncertainties
  - if ratio different than 1, clear indication of BSM effects
- Experimentally challenging
  - Very different reconstruction techniques for muons and electrons
  - Calorimeter noise don't allow low thresholds for electron selections
  - Bremsstrahlung produces losses in electron energy and reduces trajectory resolution

# R(K) and R(K\*)

Several  $b \rightarrow sll$  decay channel investigated by LHCb

- measurements in the  $q^2$  region below the charmonium resonances
- results until late 2022 seemed to consistently point toward a ratio lower than 1
- this discrepancy can be explained by deviation in Wilson coefficients



# R(K) and R(K\*) (LHCb analysis)

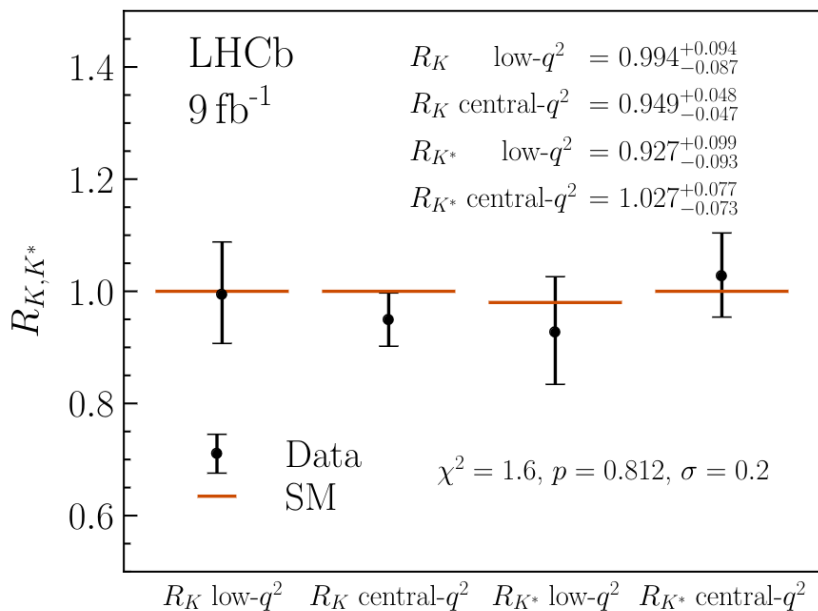
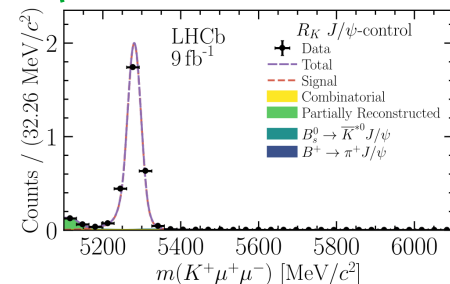
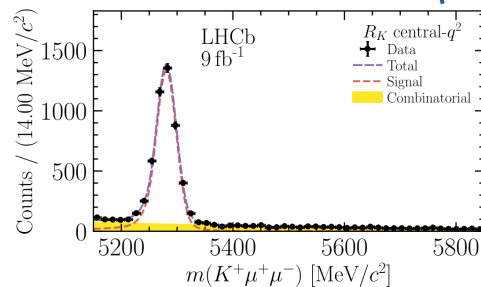
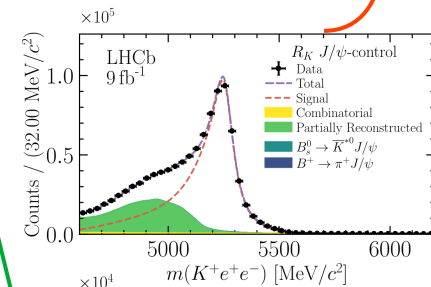
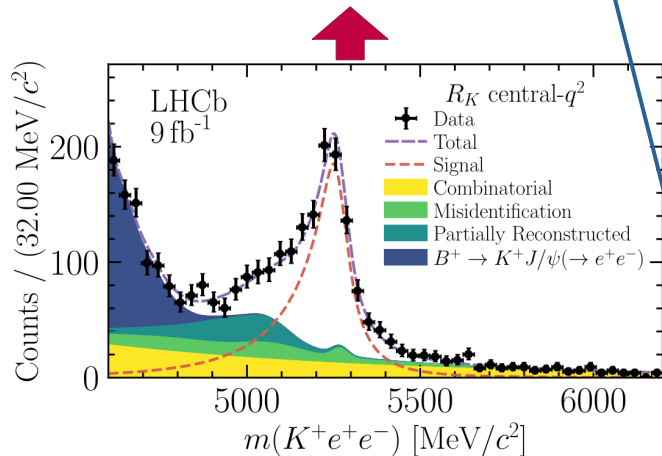
[2212.09152] [2212.09153]

Updated analysis presented in Dec 2022

- use of double-ratio with resonant J/ψ channel, to mitigate uncertainties on electron reco
- simultaneous fit to B<sup>0</sup> → K<sup>\*0</sup>l<sup>+</sup>l<sup>-</sup> and B<sup>+</sup> → K<sup>+</sup>l<sup>+</sup>l<sup>-</sup> candidates
- improved control of bkg by use of more control regions

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \times \frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-))}$$

$r_{J/\psi}^{-1} = 1$  [PRD 88 (2013) 3]



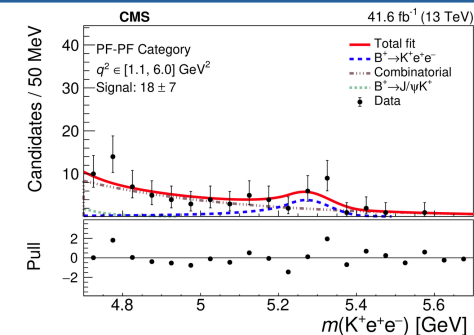
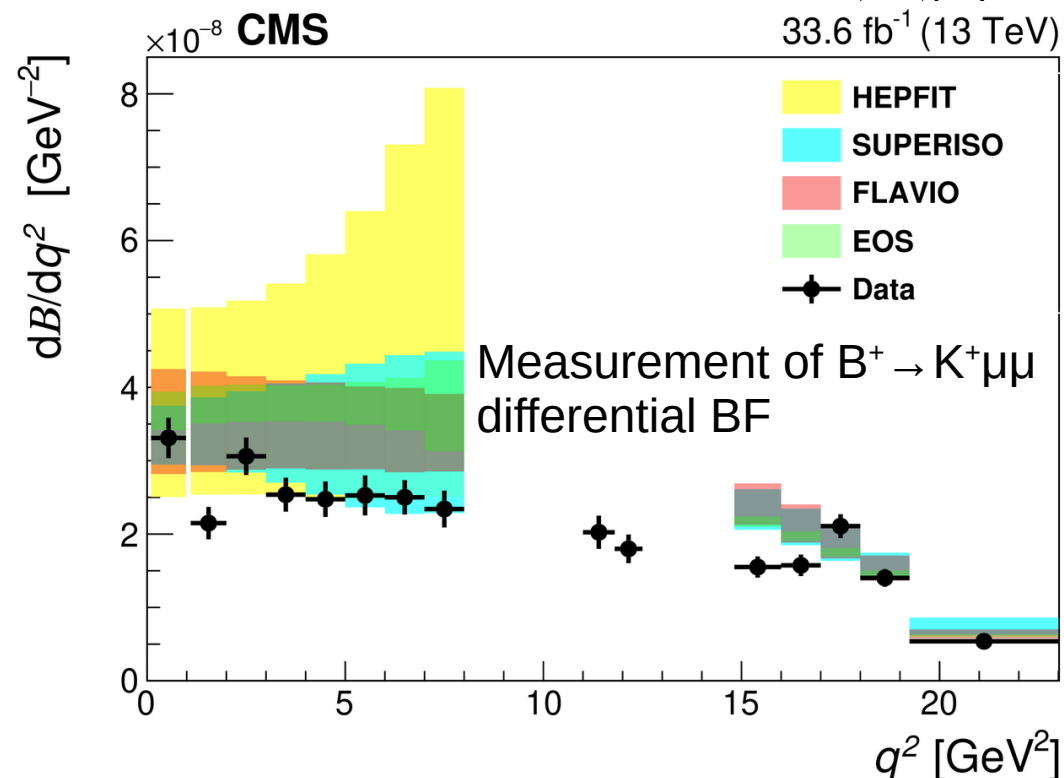
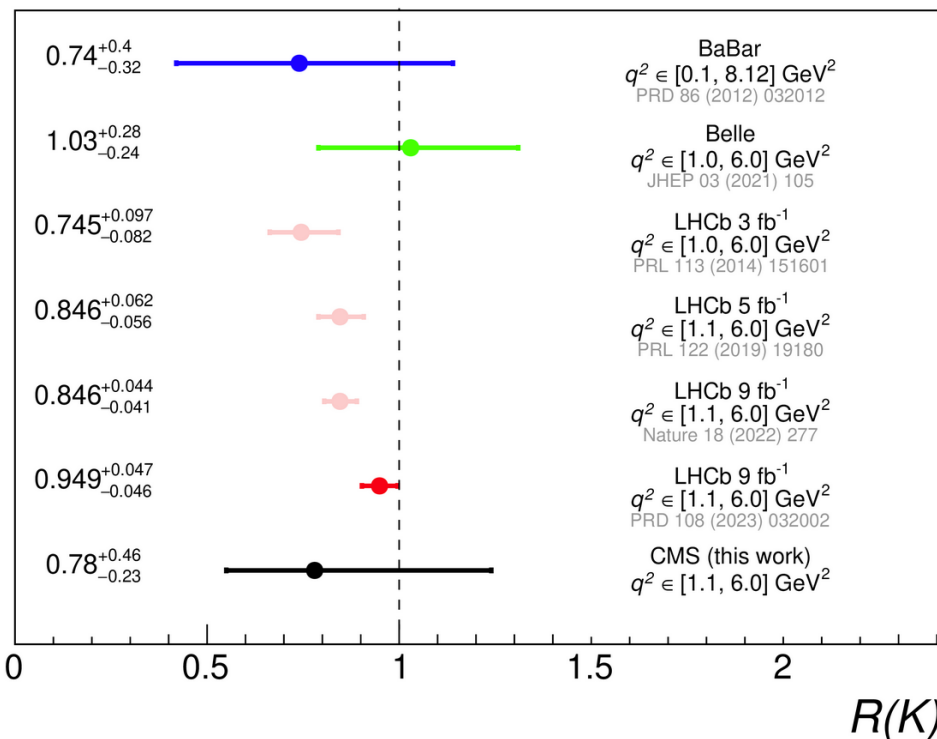
Results now agree with predictions!

# R(K) (CMS analysis)

[2401.07090]

CMS, during the 2018 data taking, developed an innovative trigger technique, to collect sample of  $\sim 10^{10}$  unbiased B hadrons

This allowed performing LFU tests even if no low-pT-electron trigger was available. Precision of the R(K) result limited by low efficiency of electron reconstruction at low pT

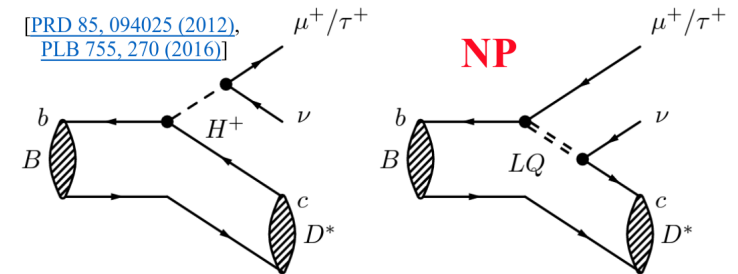
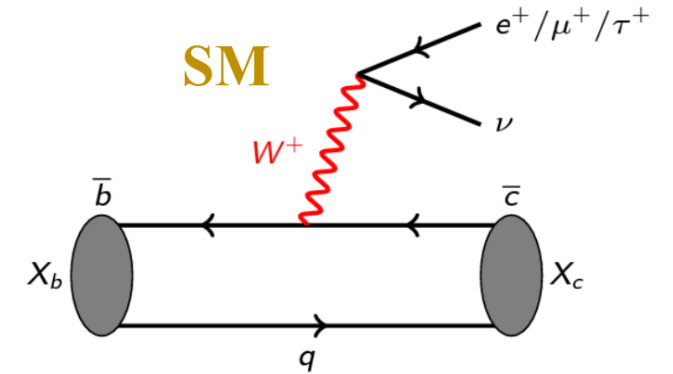
33.6 fb<sup>-1</sup> (13 TeV)

# R(D) and R(D\*)

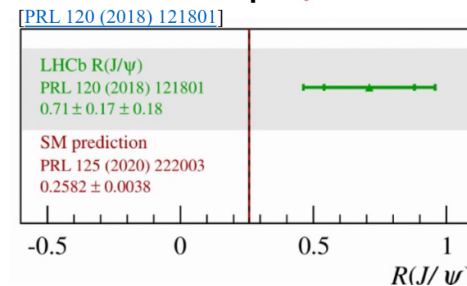
LFU ratios can be built also using  $b \rightarrow cl\nu$  decays

$$R(X_c) = \frac{BF(X_b \rightarrow X_c l \nu)}{BF(X_b \rightarrow X_c l' \nu)}$$

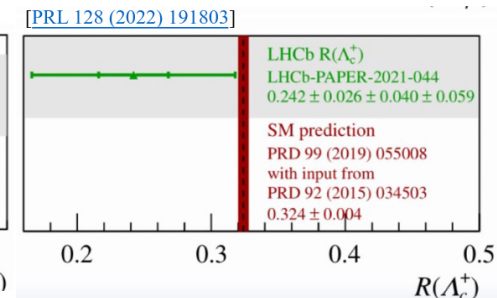
- not a rare decay
  - BSM need to have larger coupling to produce visible effects
- ratio built between tauonic decay and muonic
  - predicted to be  $\sim 0.3$  in SM, because of higher tau mass and narrower phase-space
- also here, many decay channels can be measured
  - most precise measurements from  $B^+ \rightarrow D^0 l^+ \nu$  (ratio: R(D))
  - $B^0 \rightarrow D^{*+} l^+ \nu$  (ratio: R(D\*))



$B_c^+ \rightarrow J/\psi l^+ \nu$



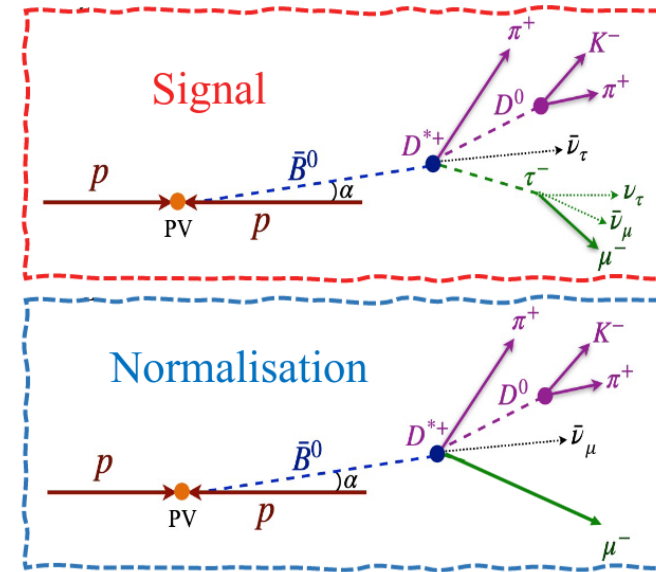
$\Lambda_b \rightarrow \Lambda_c^- l^+ \nu$



# R(D) and R(D\*) (LHCb analyses)

Combined R(D) and R(D\*) measurement using muonic tau decays

- identical visible final state
- signal decay had three neutrinos produced
- discriminating variables:
  - missing B-mass squared,  $m_{\text{miss}}^2$
  - Muon energy in B rest frame,  $E_{\mu}^*$
  - Mass squared of leptonic system,  $q^2$
- 3D template fit in 2 signal and 6 bkg-enriched categories:

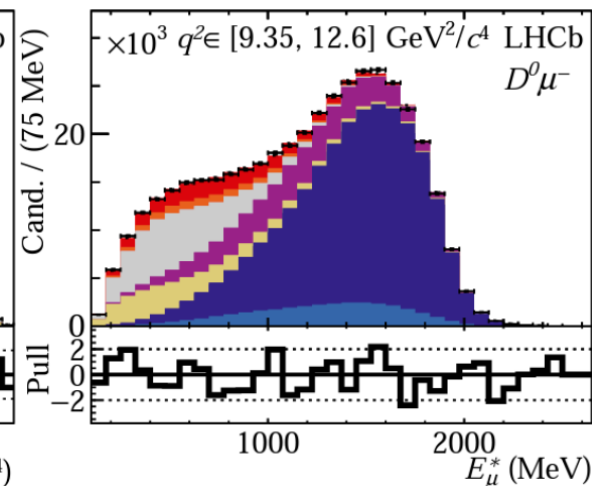
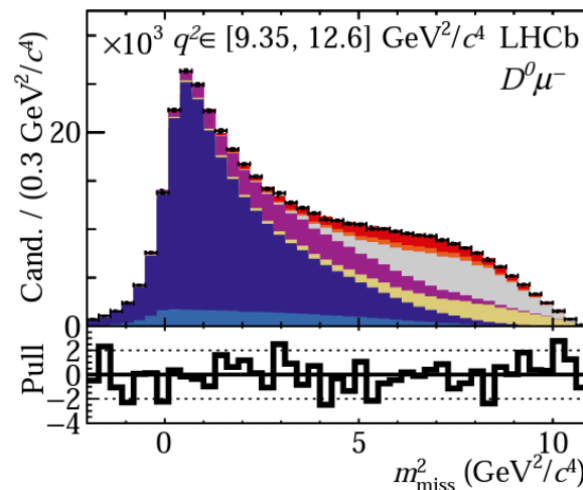


signal R(D\*)  
signal R(D)

norm R(D)

norm R(D\*)

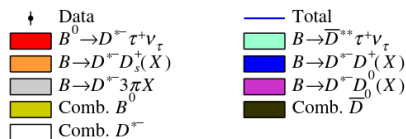
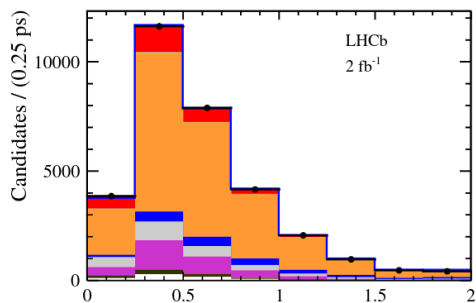
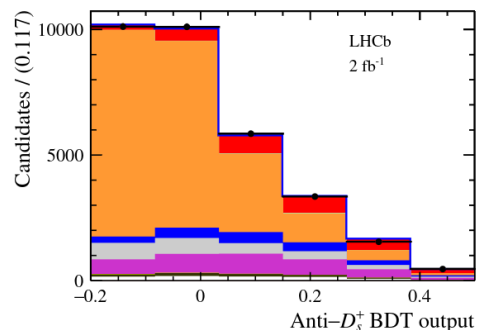
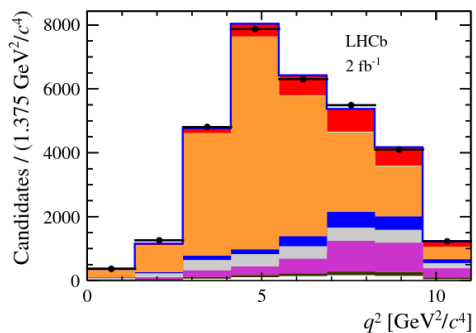
- + Data (3 fb<sup>-1</sup>)
- $B \rightarrow D^* \tau \nu$
- $B \rightarrow D \tau \nu$
- $B \rightarrow D^{(*)} D X$
- $B \rightarrow D^{**} \mu \nu$
- Comb. + misID
- $B \rightarrow D^0 \mu \nu$
- $B \rightarrow D^{*0} \mu \nu$
- $B \rightarrow D^{*+} \mu \nu$



# R(D) and R(D\*) (LHCb analyses)

R(D\*) measurement using hadronic tau decays

- $B^0 \rightarrow D^{*+} \pi \pi \pi$  used as normalization w/ same final state
- Discriminating variables:
  - Mass squared of leptonic system,  $q^2$
  - Output of BDT to reject  $D_s$
  - $\tau$  lifetime,  $t_\tau$
- 3D template fit

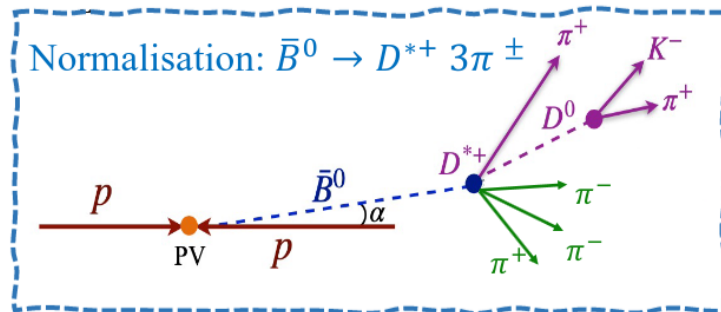
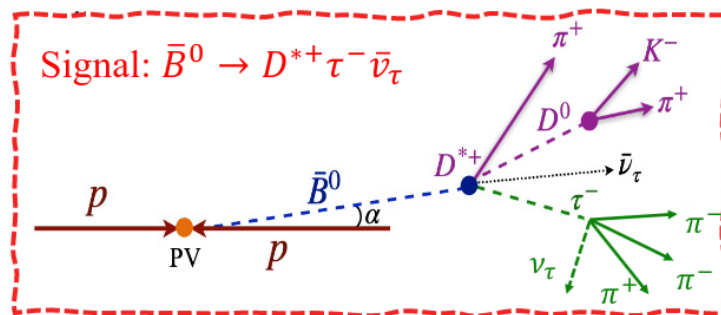


$$K(D^*) = \frac{BF(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{BF(\bar{B}^0 \rightarrow D^{*+} 3\pi^\pm)}$$

Measure

$$R(D^*) = K(D^*) \times \frac{BF(\bar{B}^0 \rightarrow D^{*+} 3\pi^\pm)}{BF(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)}$$

External input

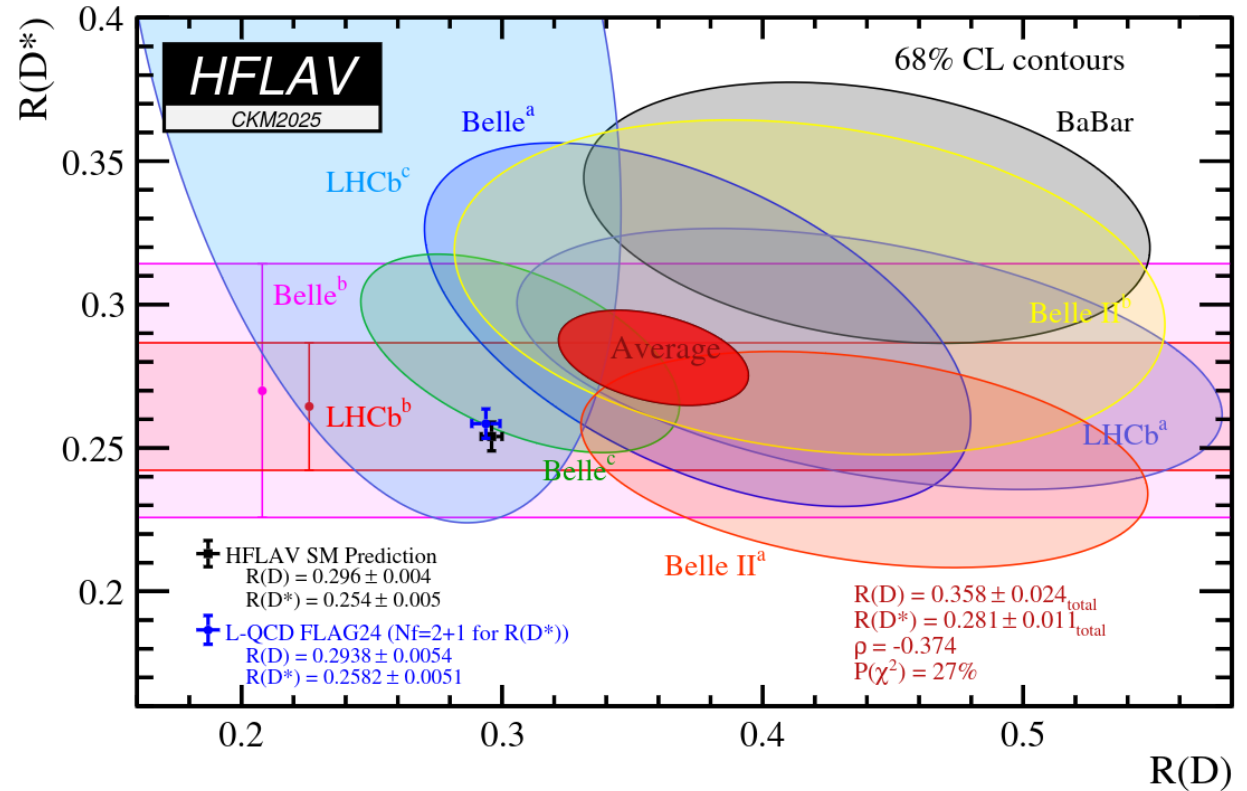


# R(D) and R(D\*)

Recent results from LHCb add to a quite populated set of measurements from B-factories

The effect is to mitigate the tension on R(D\*), and increment the one for R(D)

Average currently at  $3.1 \sigma$  from SM prediction



# Angular analyses

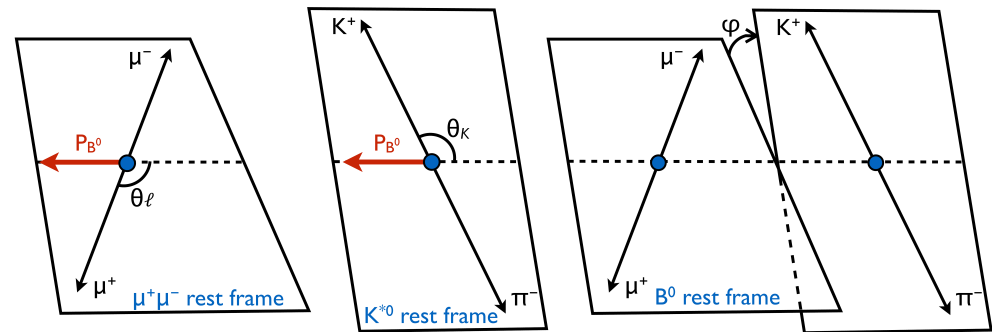
In  $b \rightarrow sll$  decays, also the angular distribution of final-state particles can be studied

This will allow a more in-depth analysis of the decay amplitude from the EFT

Distribution of helicity angles analysed

- in  $B \rightarrow K^* \mu \mu$  decays 3 angles are defined
  - dimuon system decay angle,  $\theta_l$
  - kaon decay angle,  $\theta_K$
  - angle between decay planes,  $\phi$
- in  $B \rightarrow K \mu \mu$  decays 1 angle
  - dimuon system decay angle,  $\theta_l$

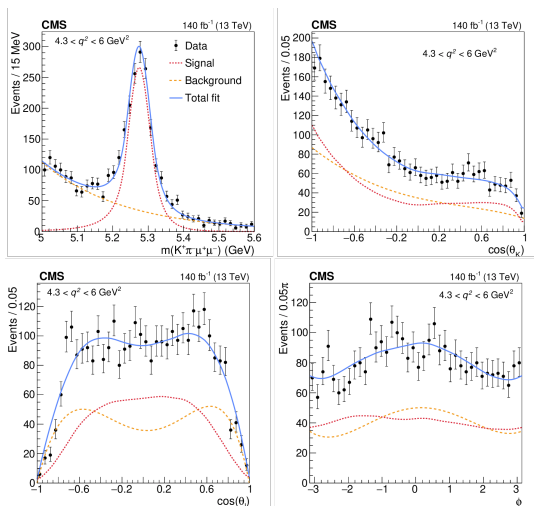
Dependence on helicity angle parametrized as sum of 3D spherical harmonic, with up to 8 angular parameters



Angular decay rate for  $B \rightarrow K^* \mu \mu$  decay

$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{32\pi} \left[ \frac{3}{4} F_T \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\
+ \left( \frac{1}{4} F_T \sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2\theta_l \\
+ \frac{1}{2} P_1 F_T \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ \sqrt{F_T F_L} \left( \frac{1}{2} P_4' \sin 2\theta_K \sin 2\theta_l \cos \phi + P_5' \sin 2\theta_K \sin \theta_l \cos \phi \right) \\
- \sqrt{F_T F_L} \left( P_6' \sin 2\theta_K \sin \theta_l \sin \phi - \frac{1}{2} P_8' \sin 2\theta_K \sin 2\theta_l \sin \phi \right) \\
\left. + 2P_2 F_T \sin^2 \theta_K \cos \theta_l - P_3 F_T \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$

# Angular analyses

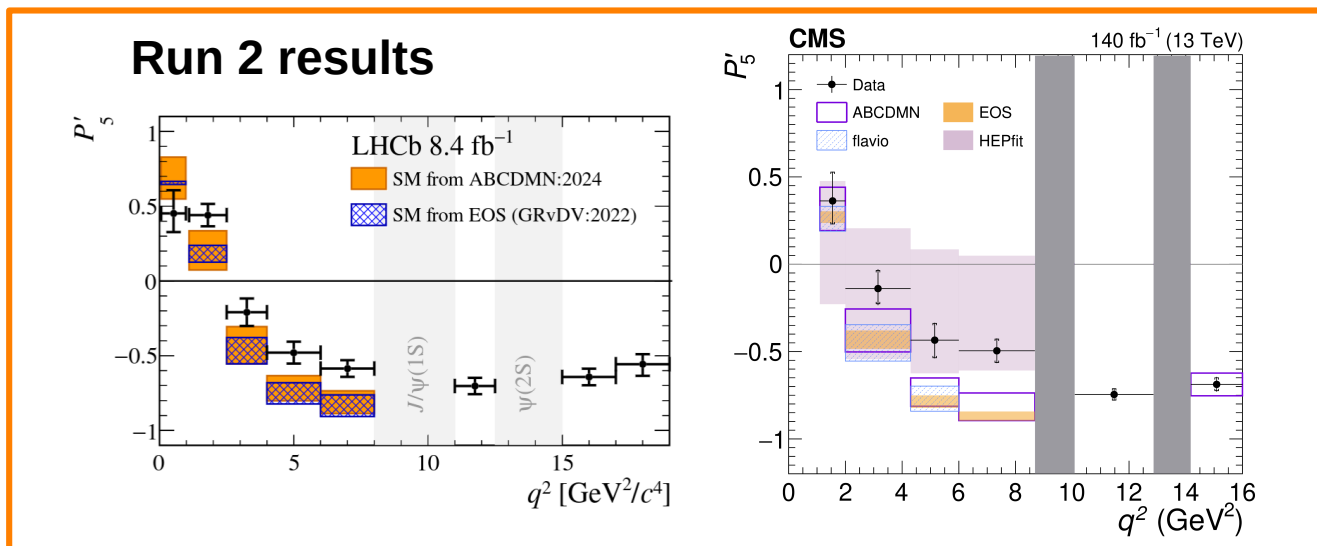


4D fit performed on the B-mass candidate and angular distributions

- impact of candidate reconstruction and selection included in the fit function
- resonant charmonium decays used as control regions to validate the fit

Results for one of the angular parameters,  $P'_5$ , show a tension with SM predictions in the  $q^2$  region below the charmonium resonances

Impact of hadronic uncertainties on non-local form factors is under study in the theory community



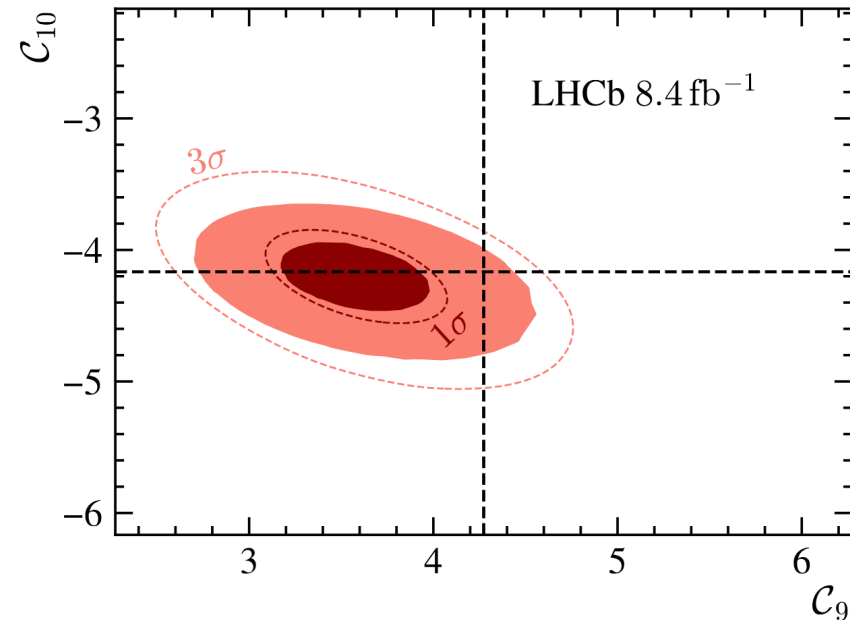
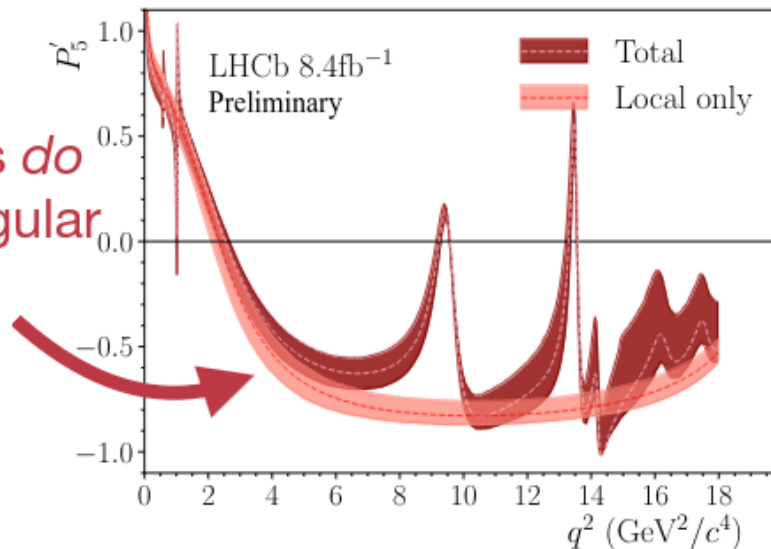
# Unbinned angular analysis (LHCb)

[PRD 109 (2024) 052009]

Recently LHCb released two angular analyses of the  $B^0 \rightarrow K^{*0} \mu \mu$  decay in which  $q^2$  is parametrized with an analytical function and the form factors (both local and non-local) are evaluated from the fit, using only some constraints from LCSR and Lattice QCD calculations  $\rightarrow$  Wilson coefficients directly extracted from the fit

Results still show some tensions wrt the SM, but more modest (2.1  $\sigma$  for  $C_9$ , 1.5  $\sigma$  globally)

Nonlocal contributions *do* influence angular observables



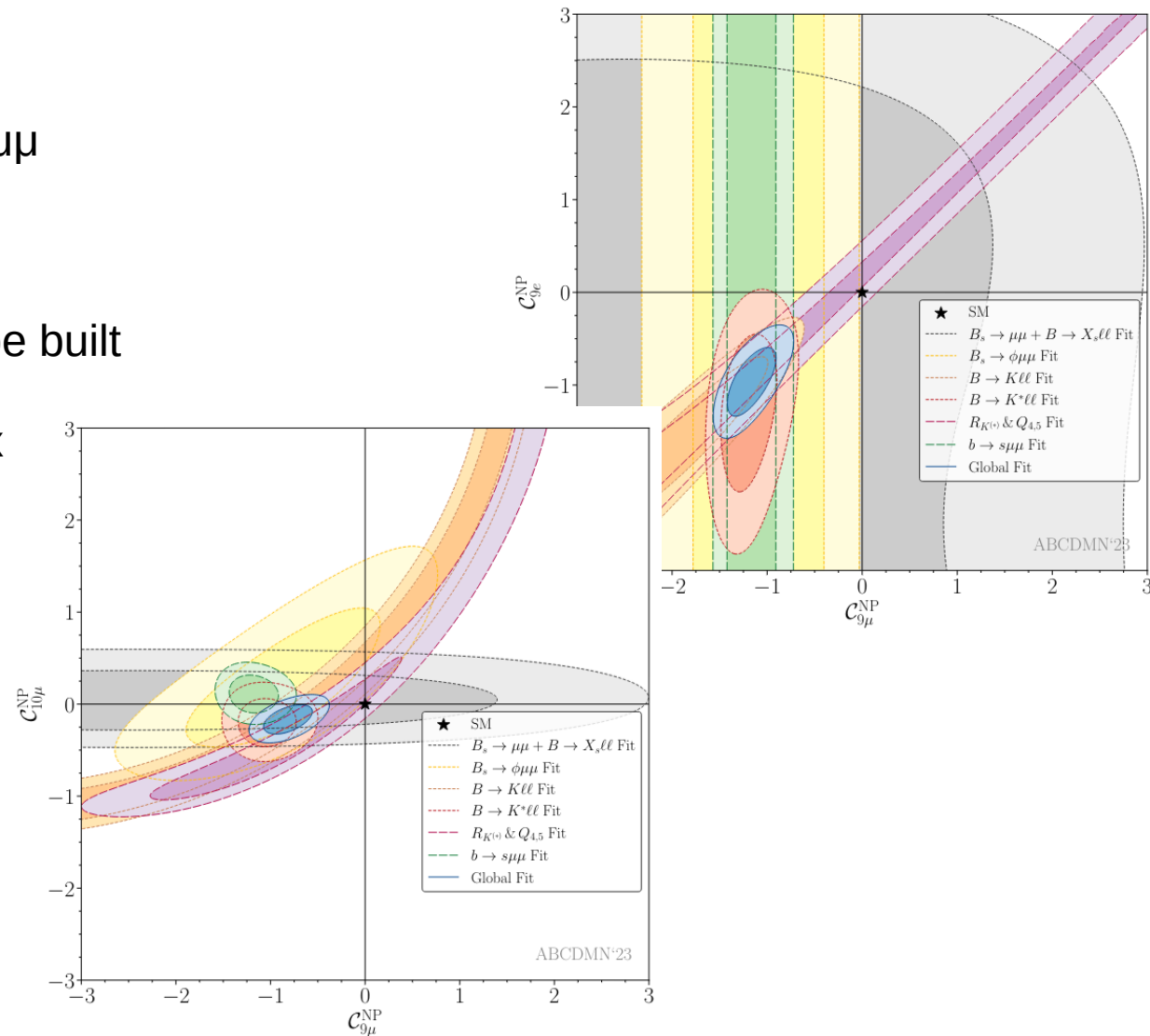
# Global fits

Results from  $b \rightarrow sll$  decays and  $B_s \rightarrow \mu\mu$  can be used to extract information on Wilson coefficients

In this way, a consistent picture can be built

- only two Wilson coefficients are left floating,  $C_9$  and  $C_{10}$  for muon vertex
- others are kept fixed to SM values
- SM prediction is the origin
  - axes show BSM contribution

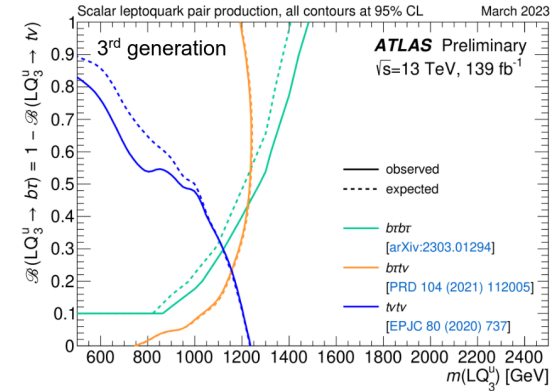
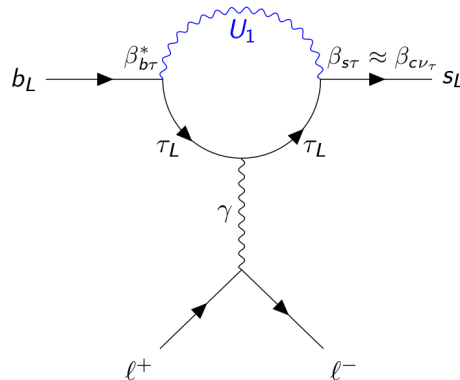
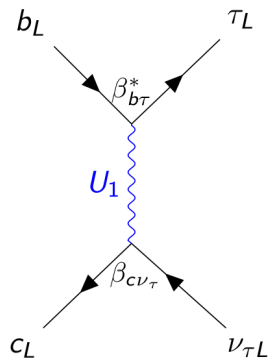
Currently, most of the tension comes from  $b \rightarrow s\mu\mu$  measurements (BF and angular)



# Popular BSM explanations

Leptoquark is a good candidate to explain both  $R(D^{(*)})$  and  $b \rightarrow sll$  tensions

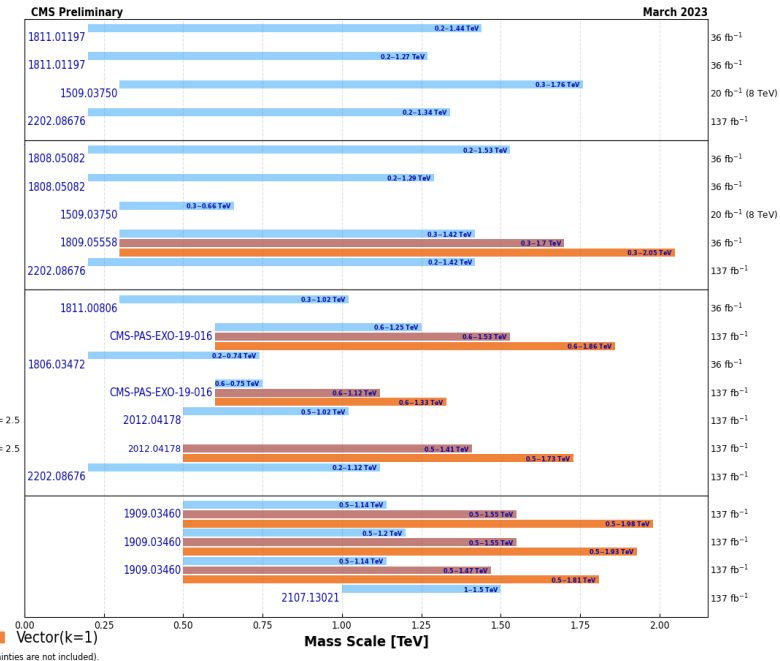
Direct searches so far excluded leptoquark models up to masses of 1-2 TeV



Crivellin et al. [1807.02068]

- $LQ(eq)$** 
  - $LQ(ej)LO(ej), BR(LQ \rightarrow ej) = 1, j = u, d$
  - $LQ(ej)LO(ej) + LO(ej)LO(\nu_j), LQ, j = u, d$
  - $eLQ(ej), BR(LQ \rightarrow ej) = 1, \lambda = 1, j = u, d$
  - $LQ(e\ell)LO(e\ell), BR(LQ \rightarrow e\ell) = 1$
- $LQ(\mu q)$** 
  - $LQ(\mu c)LO(\mu c), BR(LQ \rightarrow \mu c) = 1$
  - $LQ(\mu c)LO(\mu c) + LO(\mu c)LO(\nu_s), BR(LQ \rightarrow \mu c, \nu_s) = 0.5, 0.5$
  - $\mu LQ(\mu j), BR(LQ \rightarrow \mu j) = 1, j = u, d$
  - $LQ(\mu\ell)LO(\mu\ell), BR(LQ \rightarrow \mu\ell) = 1, \lambda = 1$
  - $LQ(\mu\ell)LO(\mu\ell), BR(LQ \rightarrow \mu\ell) = 1$
- $LQ(\tau q)$** 
  - $LQ(\tau b)LO(\tau b), BR(LQ \rightarrow \tau b) = 1$
  - $LQ(\tau b)LO(\tau b), BR(LQ \rightarrow \tau b) = 1$
  - $\tau LQ(\tau b), BR(LQ \rightarrow \tau b) = 1, \lambda = 1$
  - $\tau LQ(\tau b), BR(LQ \rightarrow \tau b) = 1, \lambda = 1$
  - $LQ(\tau\tau)LO(\nu_\tau b) + \nu_\tau LO(\tau\tau),$  Equal LQ coupling to  $\tau b, \nu_\tau, \lambda = 2.5$
  - $LQ(\tau b)LO(\nu_\tau d) + \nu_\tau LO(\nu_\tau d),$  Equal LQ coupling to  $\tau b, \nu_\tau, \lambda = 2.5$
  - $LQ(\tau\tau)LO(\tau\tau), BR(LQ \rightarrow \tau\tau) = 1$
- $LQ(\nu q)$** 
  - $LQ(\nu_{ij})LO(\nu_{ij}), BR(LQ \rightarrow \nu_{ij}) = 1, j = u, d, s, c$
  - $LQ(\nu_i b)LO(\nu_i b), BR(LQ \rightarrow \nu_i b) = 1$
  - $LQ(\nu_i \ell)LO(\nu_i \ell), BR(LQ \rightarrow \nu_i \ell) = 1$
  - $LQ(\nu_{ij})LO(\nu_{ij}) + \nu_{ij} LO(\nu_{ij}), BR(LQ \rightarrow \nu_{ij}) = 1, \lambda = 1$

## Overview of CMS leptoquark searches



# Summary

- Rare decays of heavy-flavour hadrons are being thoroughly studied at LHC
- They proved to be a great laboratory to perform indirect searches for BSM physics
- A set of tensions with respect to the prediction emerged in the  $b \rightarrow sll$  measurements
- These tensions span between branching fraction measurements LFU tests and angular analyses
- The continuation of this type of measurements with the Run 2 and Run 3 LHC data is a very interesting opportunity to shed light on these tension
  - More precise measurements can help figuring out their nature (BSM or non-local effects)

