Heavy-flavour physics @LHC and flavour anomalies

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Course on Physics at the LHC

28th April 2025

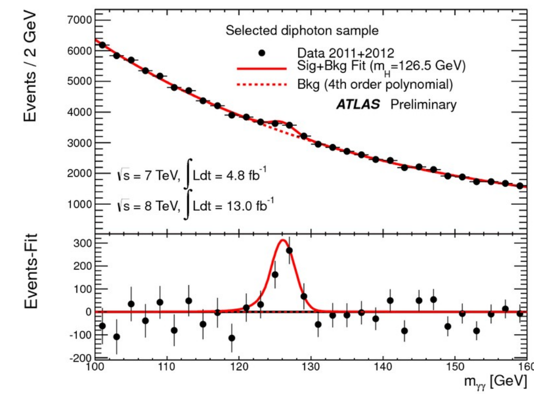
List of touched topics

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

Indirect searches for new physics

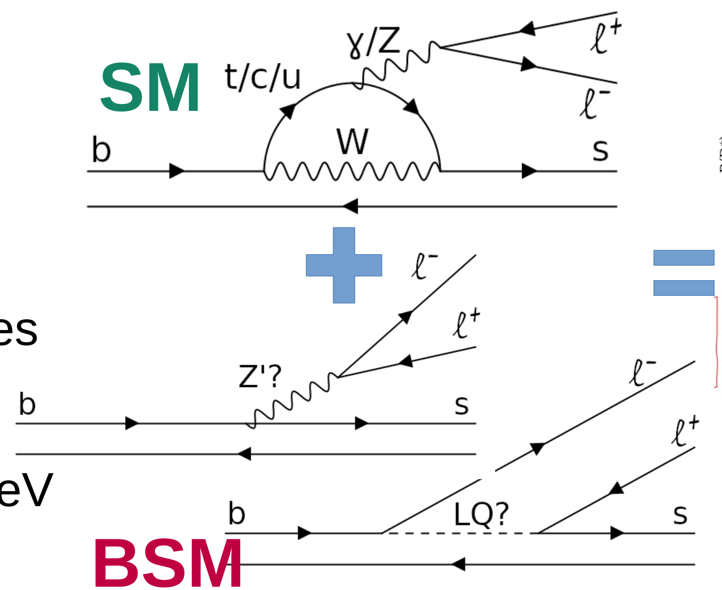
Direct searches for physics Beyond the Standard Model (BSM)

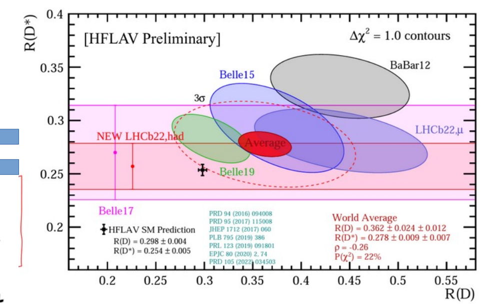
- Aim at the production of new particles in the collisions, and the observation of their decay products
- Give clear evidence of BSM
- Are limited by energy scale of collisions and production cross-section



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





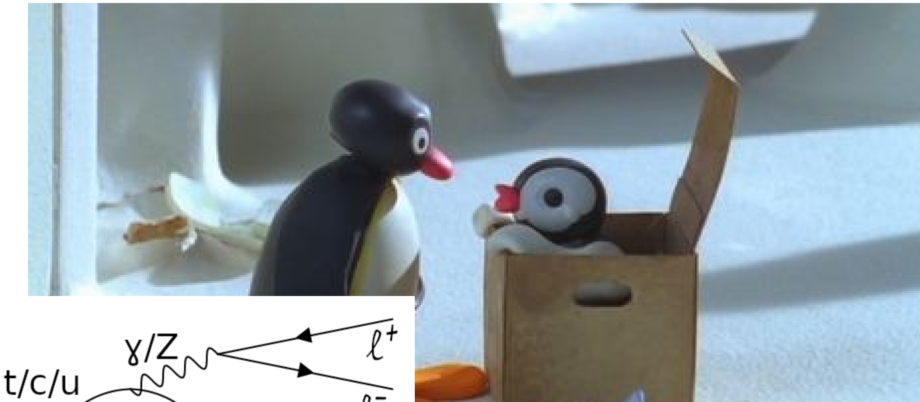
Rare decays

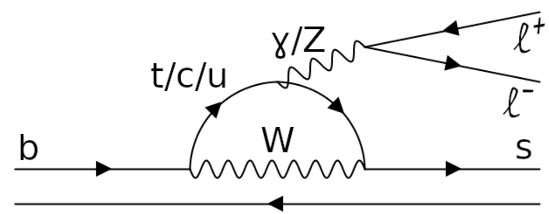
Best environment to indirectly search for new physics is in **rare decays** of SM particles

- sensitive to new particles with lower couplings or higher mass

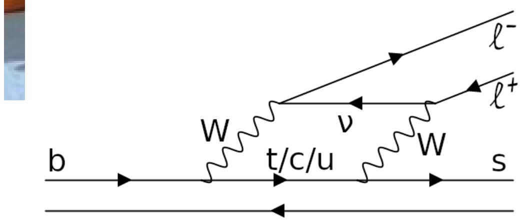
One of the most promising category is **flavour-changing neutral currents** decays $b \to s\, l^+ l^-$

- 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

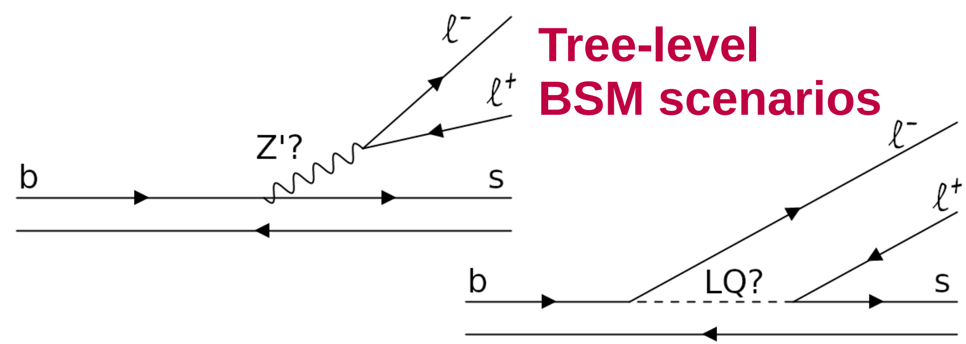




Penguin diagram



Box diagram

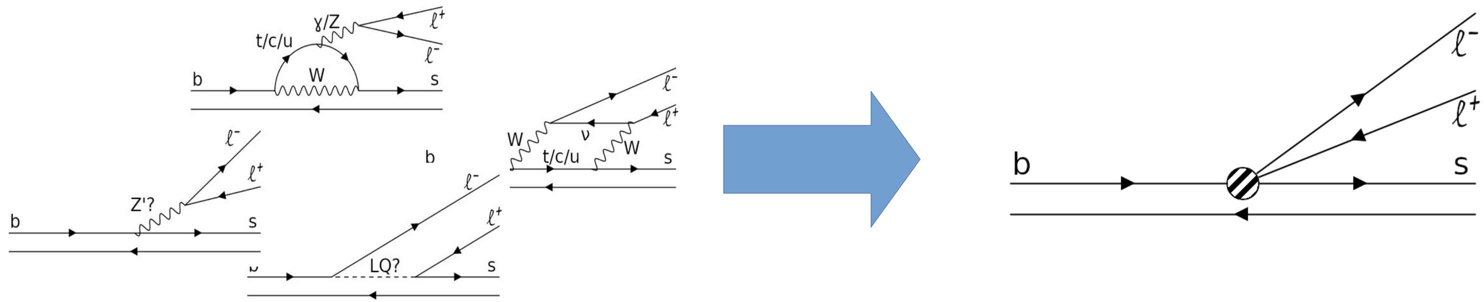


Tree-level BSM scenarios

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

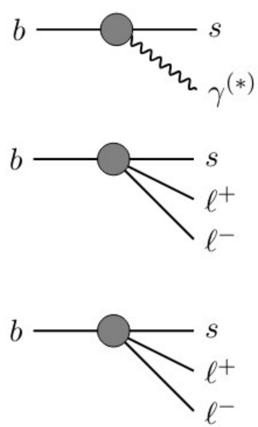


$$\mathcal{L}^{sb\ell\ell}_{D=6} = \frac{4G_F}{\sqrt{2}}\left[\lambda_t\left(\sum_{i=1}^{2} C_i\mathcal{O}_i^c + \sum_{i=3}^{10} C_i\mathcal{O}_i\right) + \lambda_u\left(\sum_{i=1}^{2} C_i\left(\mathcal{O}_i^c - \mathcal{O}_i^u\right)\right)\right] + \text{h.c.}$$

Factorisation of:

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

Effective Field Theory

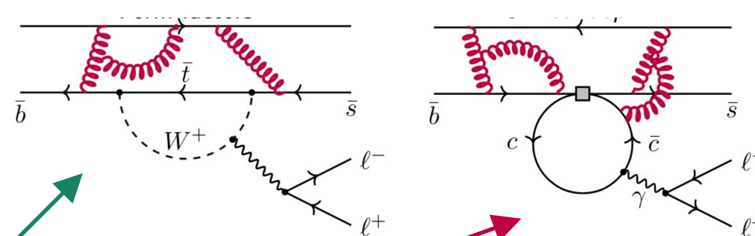


	Coupling	Operator
Photon penguin	$\mathcal{C}_7^{(\prime)}$	$\frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$
Electroweak penguin	$\mathcal{C}_9^{(\prime)}$	$(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$
Scalar penguin	$\mathcal{C}_S^{(\prime)}$	$\frac{m_b}{m_B}(\bar{s}P_{R(L)}b)(\bar{\mu}\mu)$
	$\mathcal{C}_P^{(\prime)}$	$\frac{m_b}{m_B}(\bar{s}P_{R(L)}b)(\bar{\mu}\gamma_5\mu)$

$b\to s\gamma$ ($\mathcal{C}_7$); $b\to s\ell\ell$ ($\mathcal{C}_7$, $\mathcal{C}_9$, $\mathcal{C}_{10}$); $B_s^0\to\mu^+\mu^-$ ($\mathcal{C}_{10}$, $\mathcal{C}_S$, $\mathcal{C}_P$)

Transversity amplitudes for B→Mll decays:

local hadronic matrix elements



$$\mathcal{A}^{M\ell\ell} \equiv \frac{G_F\,\alpha_e V_{tb}V_{ts}^*}{\sqrt{2}\pi}\left\{(C_9\,L_V^\mu + C_{10}\,L_A^\mu)\,\mathcal{F}_\mu^{B\to M} - \frac{L_V^\mu}{q^2}\left[2im_bC_7\,\mathcal{F}_{T,\mu}^{B\to M} + 16\pi^2\mathcal{H}_\mu^{B\to M}\right]\right\}$$

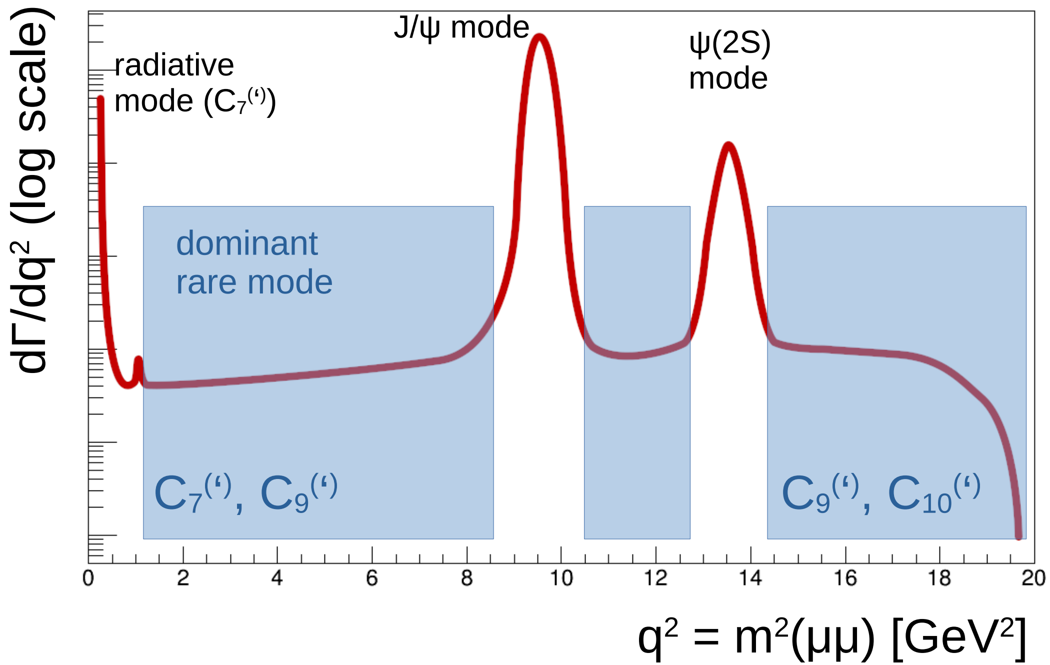
non-local hadronic matrix elements

$b \to sll$ observables

What can we experimentally measure in $b \to sll$ 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 (~1%)

The dilepton mass spectrum



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

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

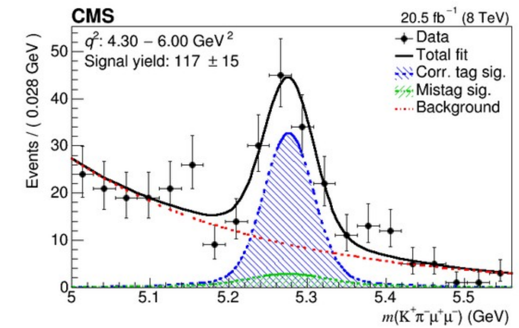
Analyses performed splitting the q2 range in bins

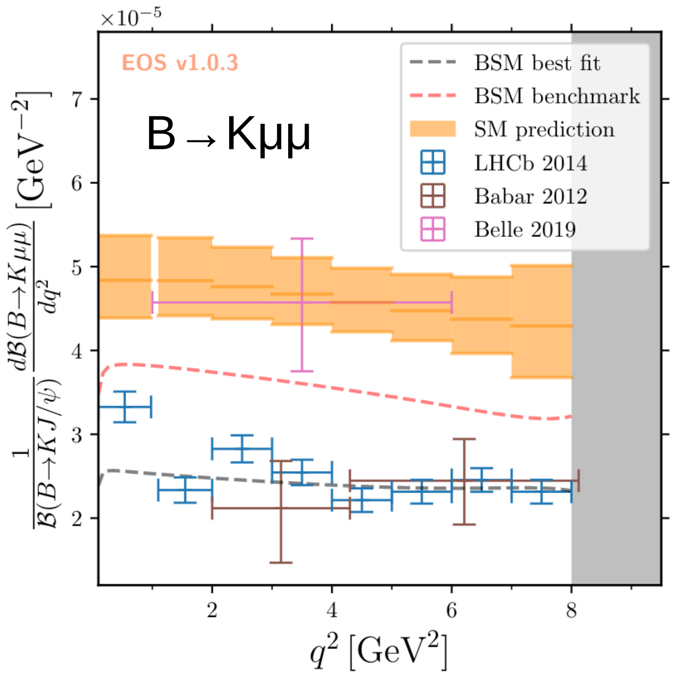
- independent analysis in each signal bin
- two bins dedicated to the J/ψ and ψ(2S) resonant modes

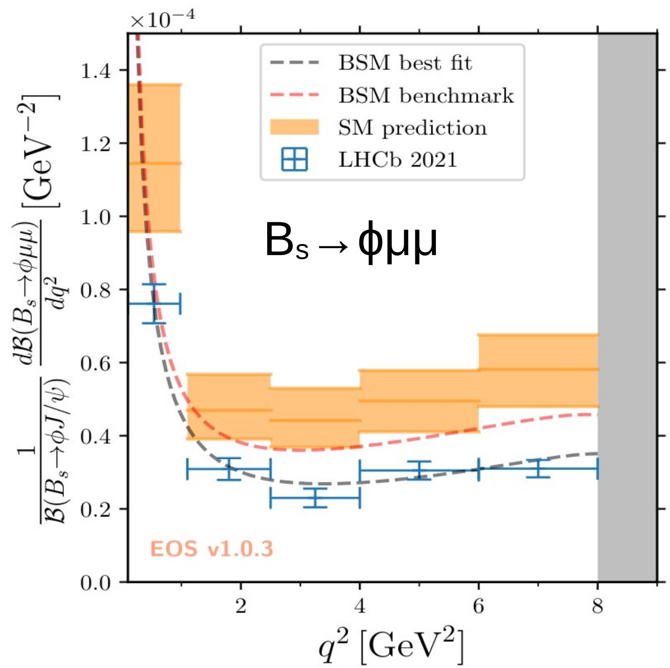
Branching fraction measurements

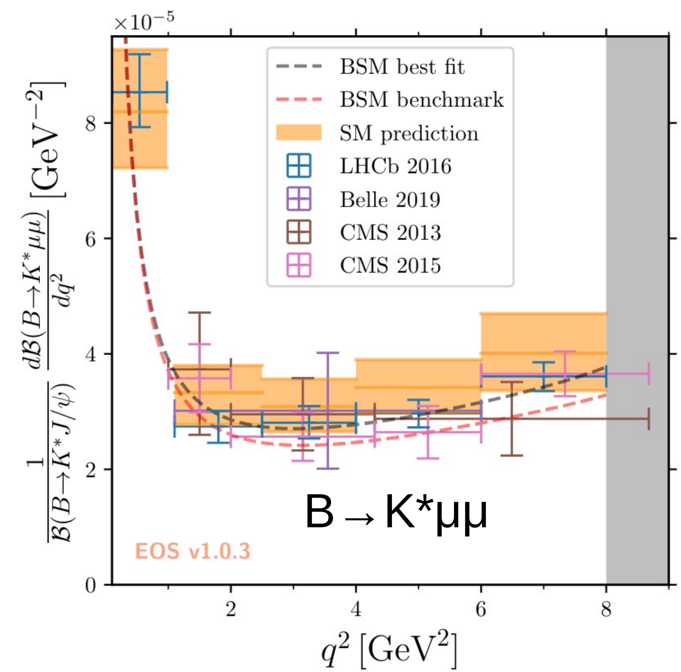
Branching fraction of b→sμμ decays measured both at B-factories and LHC

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





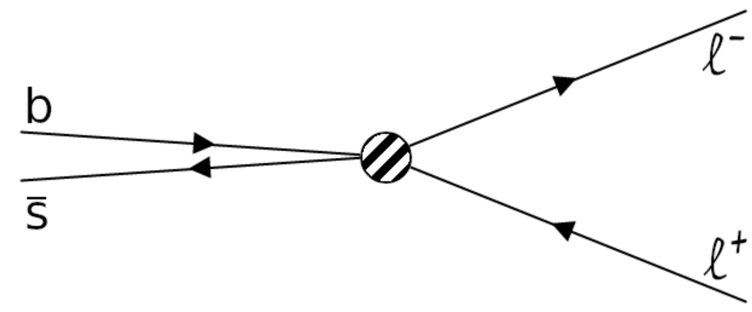




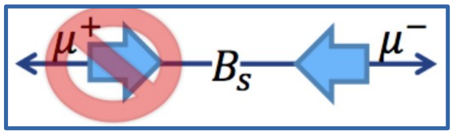
Bs → μμ and B → μμ

$B^0_s \to \mu\mu$ decay

- described with the same effective Lagrangian as b → sll

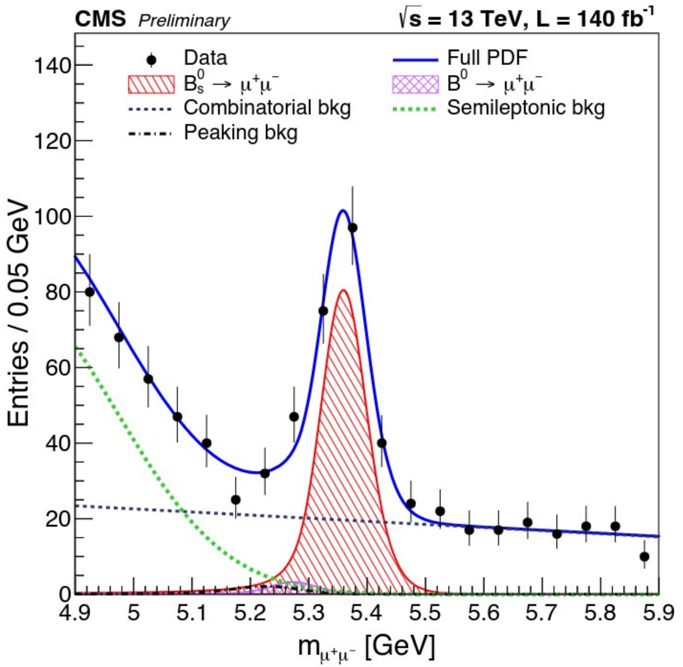


- doubly suppressed in the SM:
  - no tree-level diagram
  - helicity suppression
  - BF prediction: ~3.6 10^{-9}



- fully leptonic final state
  - very accurate prediction

- very clean experimental signature



$B^0 \to \mu\mu$ decay

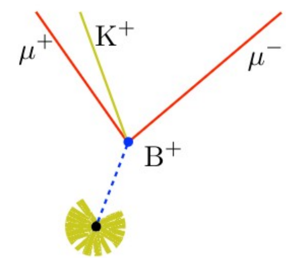
- same as above, but with additional suppression from elements of CKM matrix
- BF prediction: ~10^{-10}

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

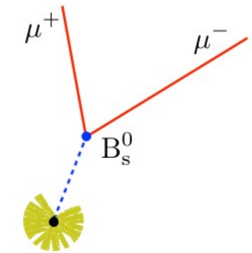
Rejection and control of the backgrounds is the crucial point of the analysis:

- 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

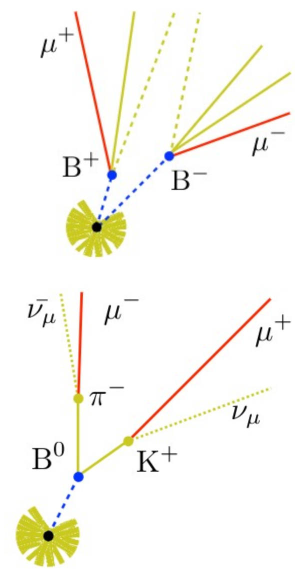
3-body and partial decays



Signal Bs→μμ

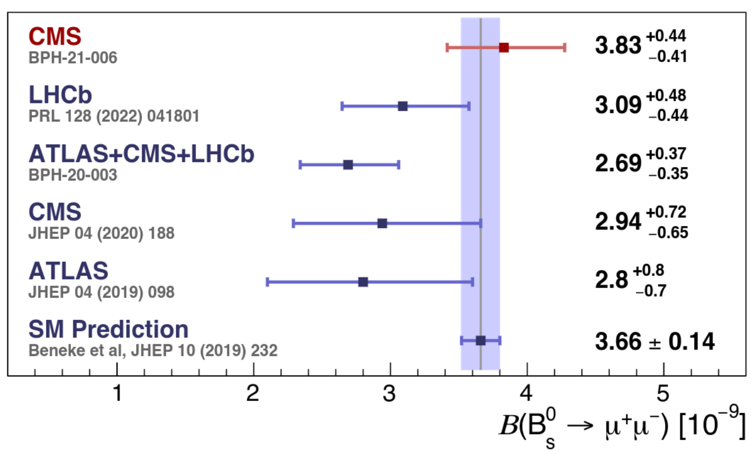


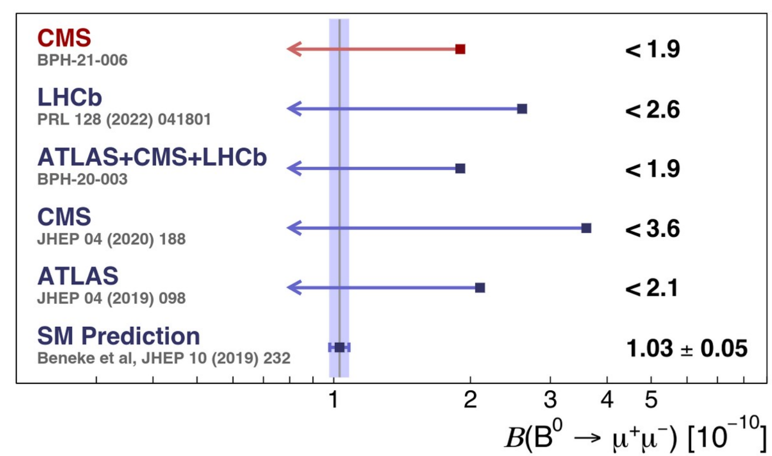
Combinatorial Background



Most precise single-experiment results to-date!

No tensions with SM predictions





Lepton Flavour Universality tests

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

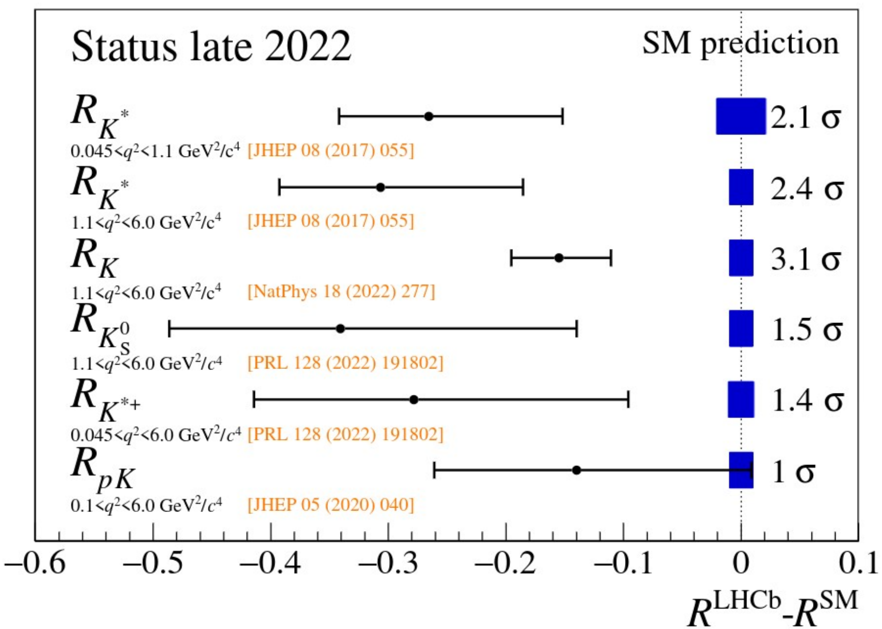
- In b→sll decays the ratio is defined between muonic and electronic decays (tauonic decay not observed yet)

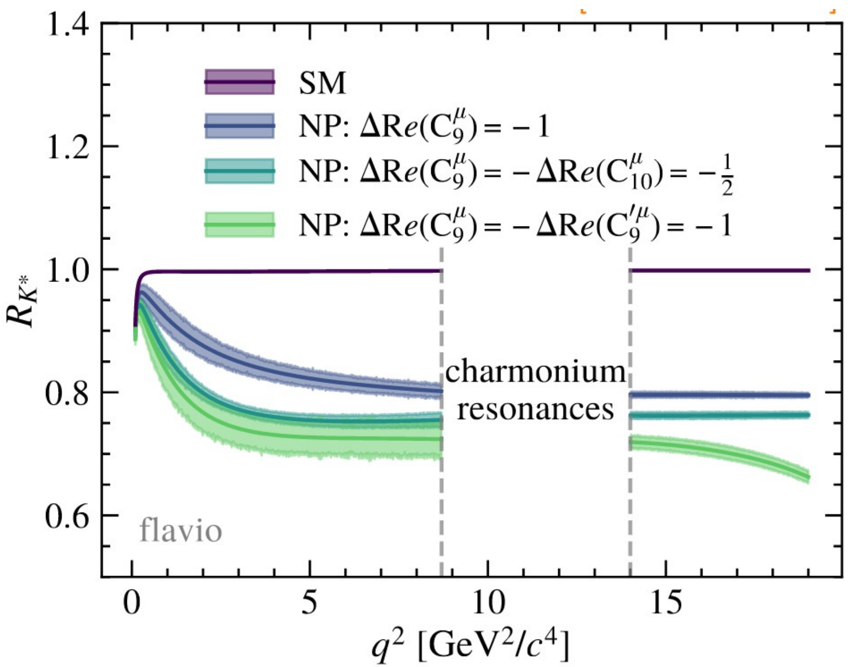
$$R_{K,K^*} = \frac{\mathcal{B}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathcal{B}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}$$

- In this ratio, had[…]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→sll decay channel investigated by LHCb
- measurements in the q2 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)

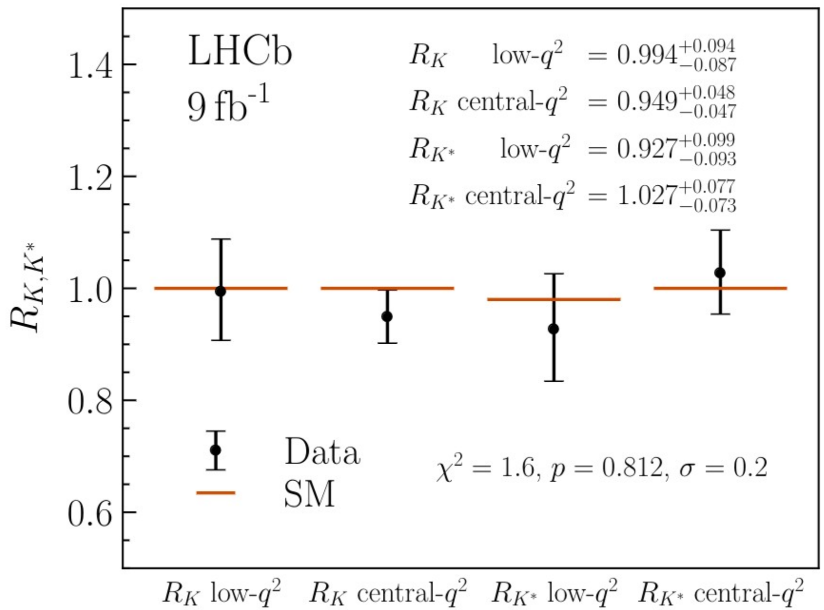
[2212.09152] [2212.09153]

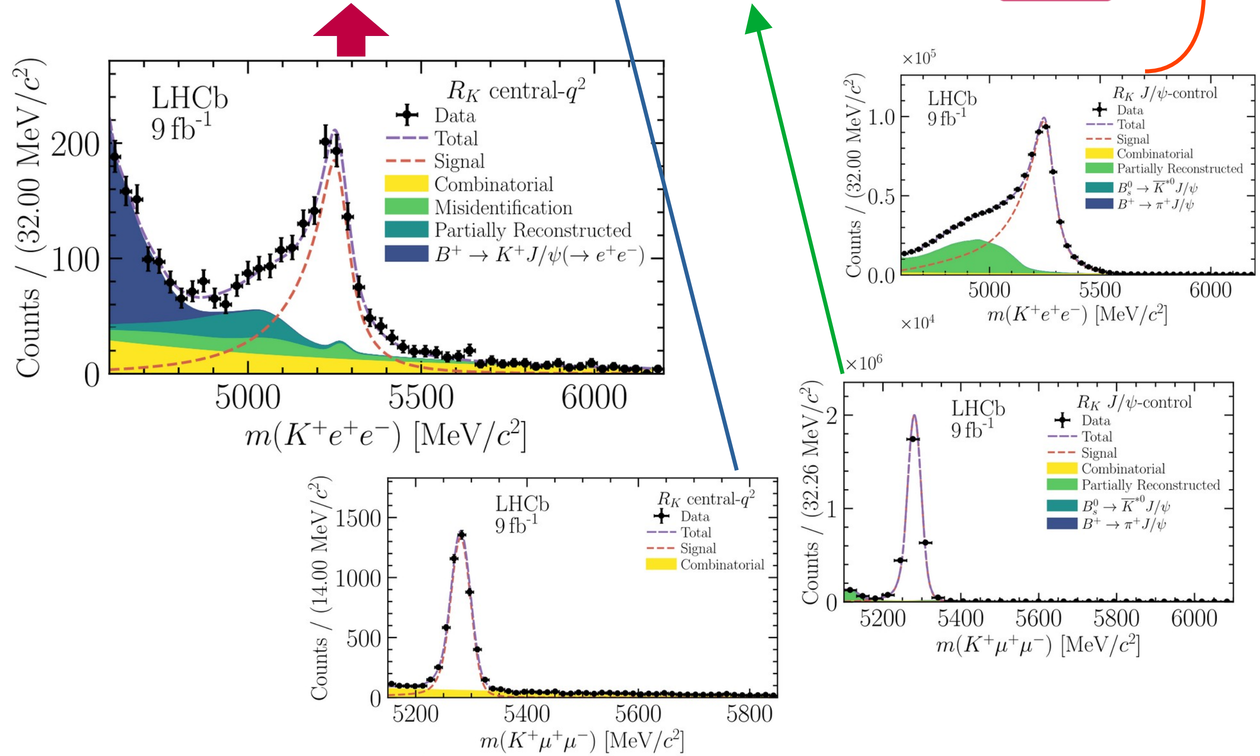
Updated analysis presented in Dec 2022

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

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

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





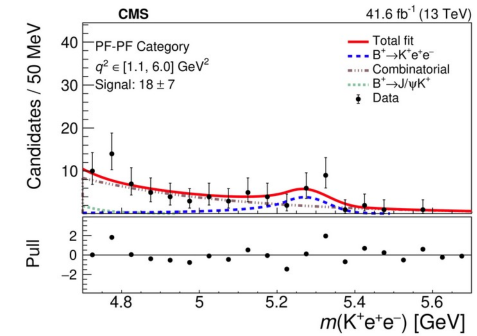
Results now agree with predictions!

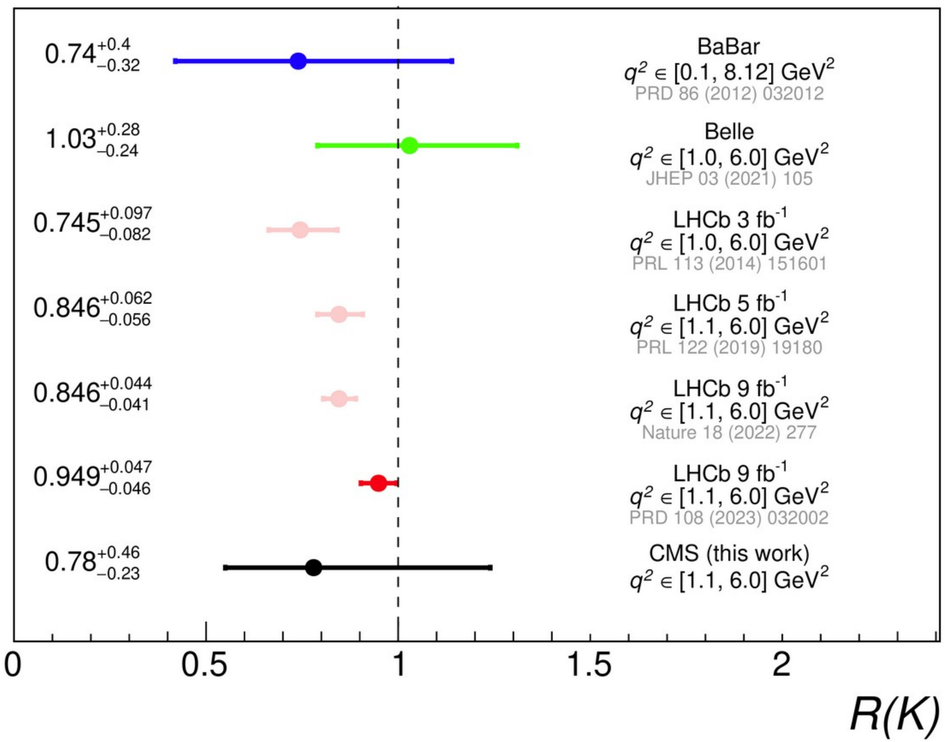
R(K) (CMS analysis)

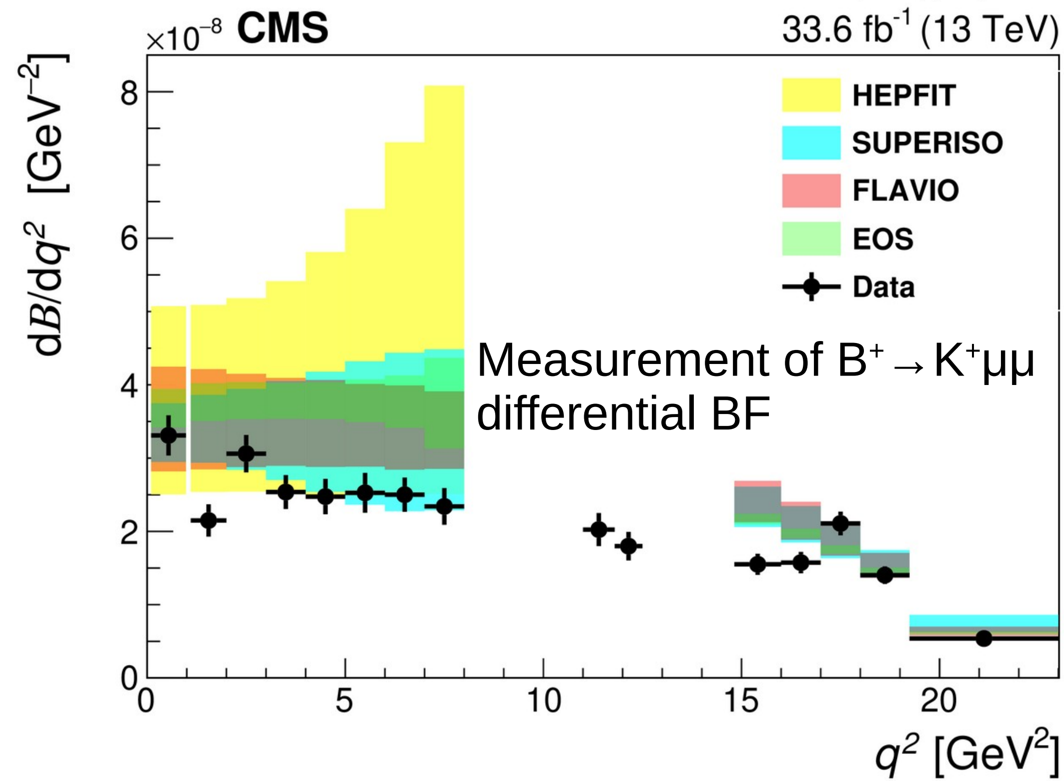
[2401.07090]

CMS, during the 2018 data taking, developed an innovative trigger technique, to collect sample of ~10^10 unbiassed 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







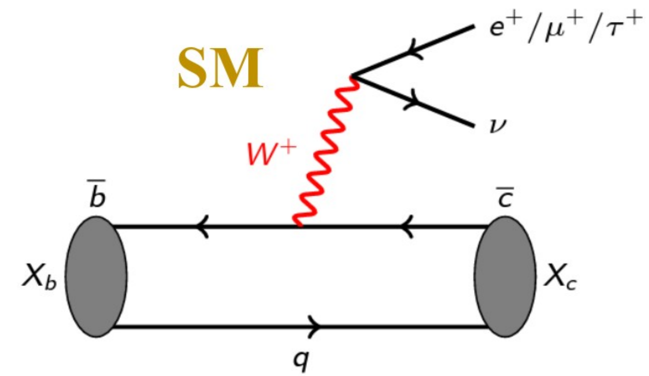
Measurement of $B^+ \to K^+\mu\mu$ differential BF

R(D) and R(D*)

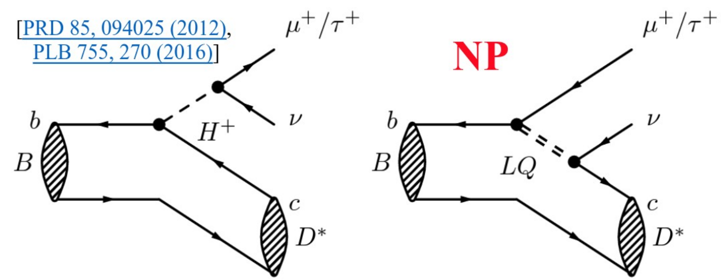
LFU ratios can be built also using b→clν decays

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

- not a rare decay
  - BSM need to have larger coupling to produce visible effects
- ratio built between tauonic decay and muonic
  - predicted to be ~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 $B^+ \to D^0 l^+ \nu$ (ratio: R(D)) $B0 \to D^{*-} l^+ \nu$ (ratio: R(D*))

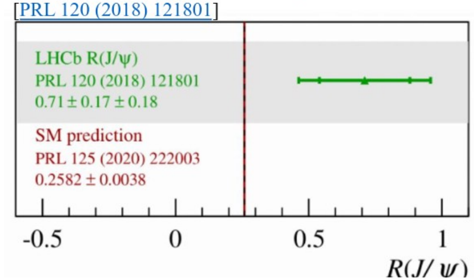


[PRD 85, 094025 (2012), PLB 755, 270 (2016)]



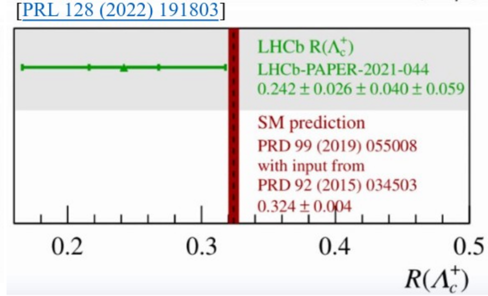
$B^+_c \to J/\psi\ l^+ \nu$

[PRL 120 (2018) 121801]



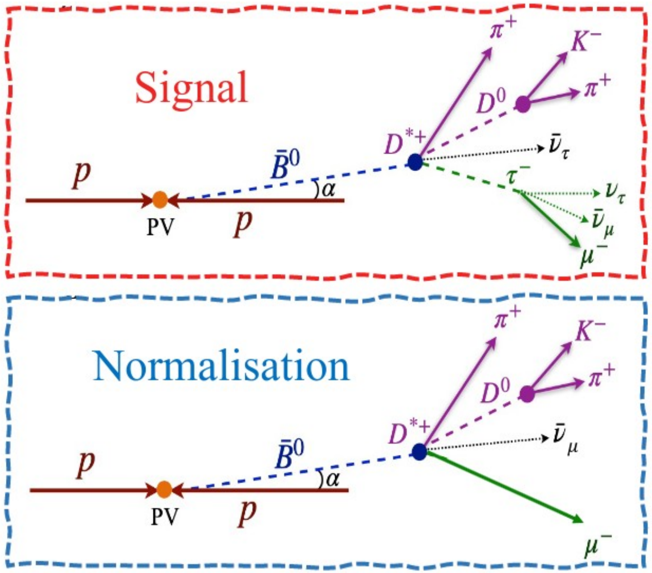
$\Lambda_b \to \Lambda_c^-\ l^+ \nu$

[PRL 128 (2022) 191803]



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^2_{miss}
  - Muon energy in B rest frame, E^*_μ
  - Mass squared of leptonic system, q^2

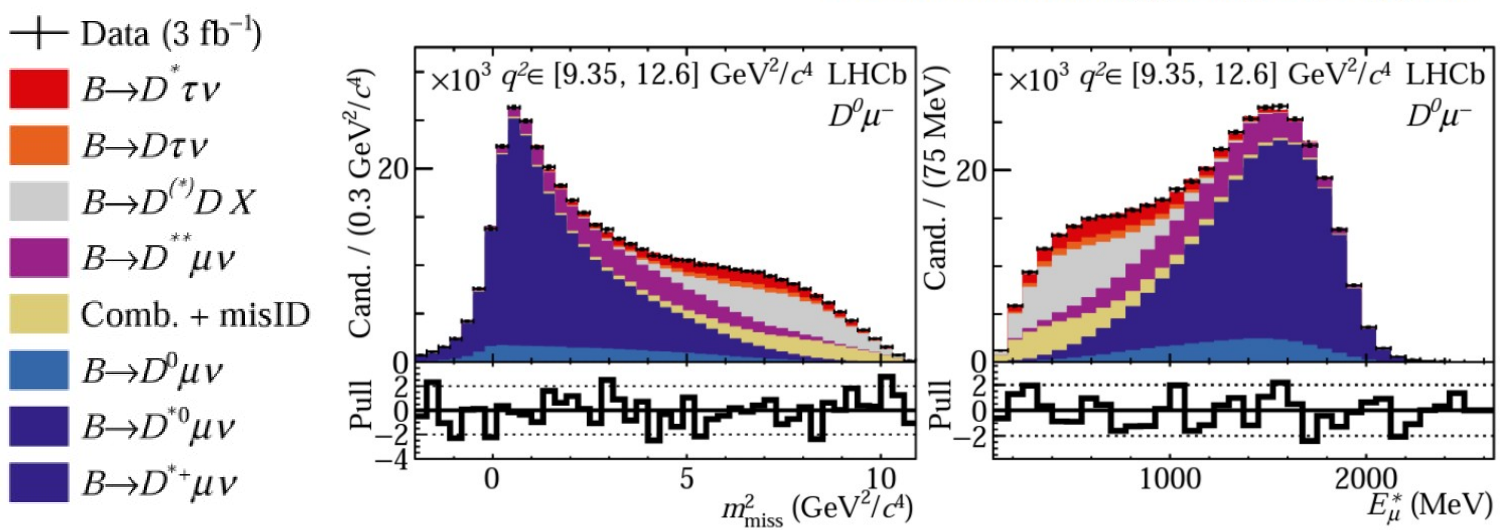


- 3D template fit in 2 signal and 6 bkg-enriched categories:

signal R(D*)
signal R(D)

norm R(D)

norm R(D*)



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

R(D*) measurement using hadronic tau decays

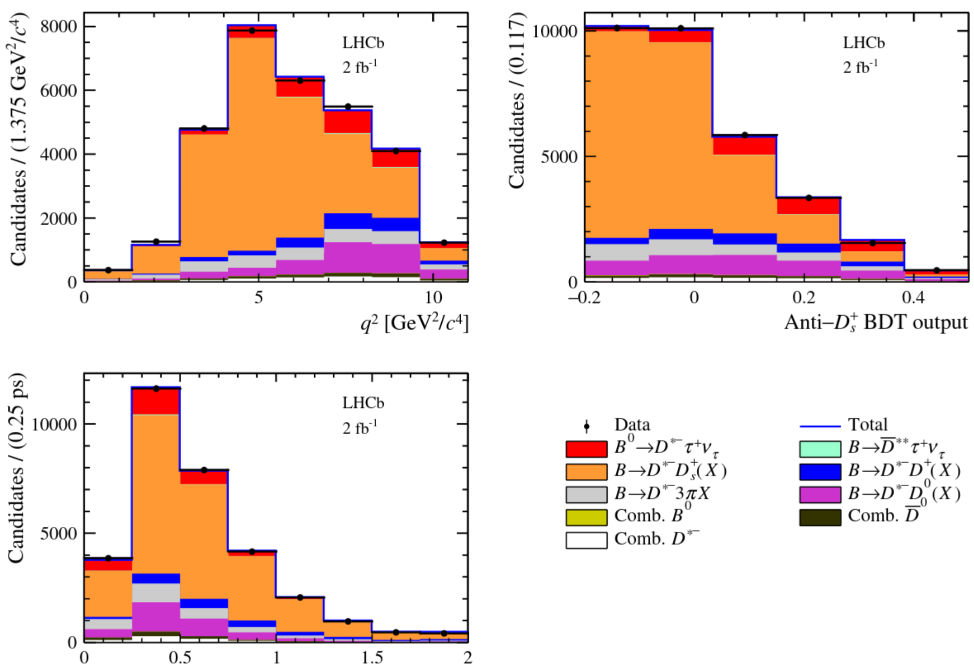
- B0→D*+πππ used as normalization w/ same final state
- Discriminating variables:
  - Mass squared of leptonic system, q^2
  - Output of BDT to reject D_s
  - τ lifetime, t_τ
- 3D template fit

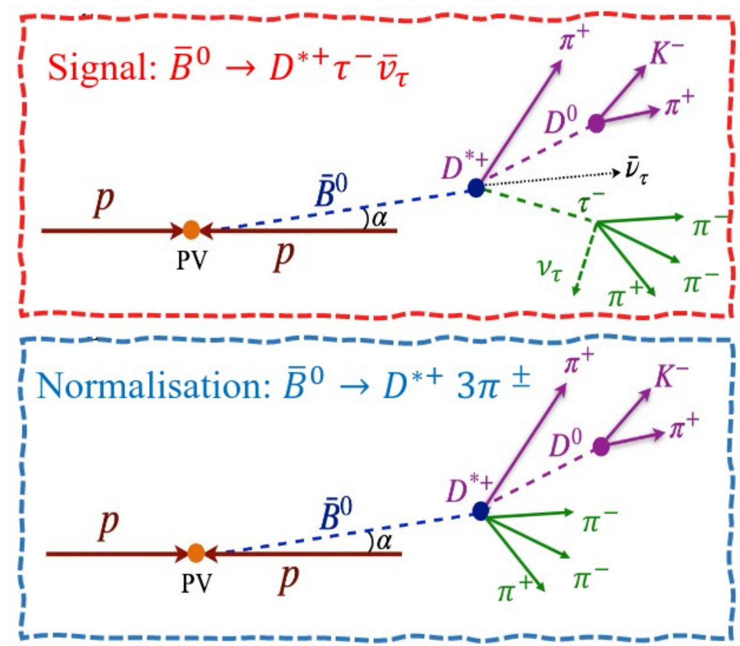
Measure

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

External input

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



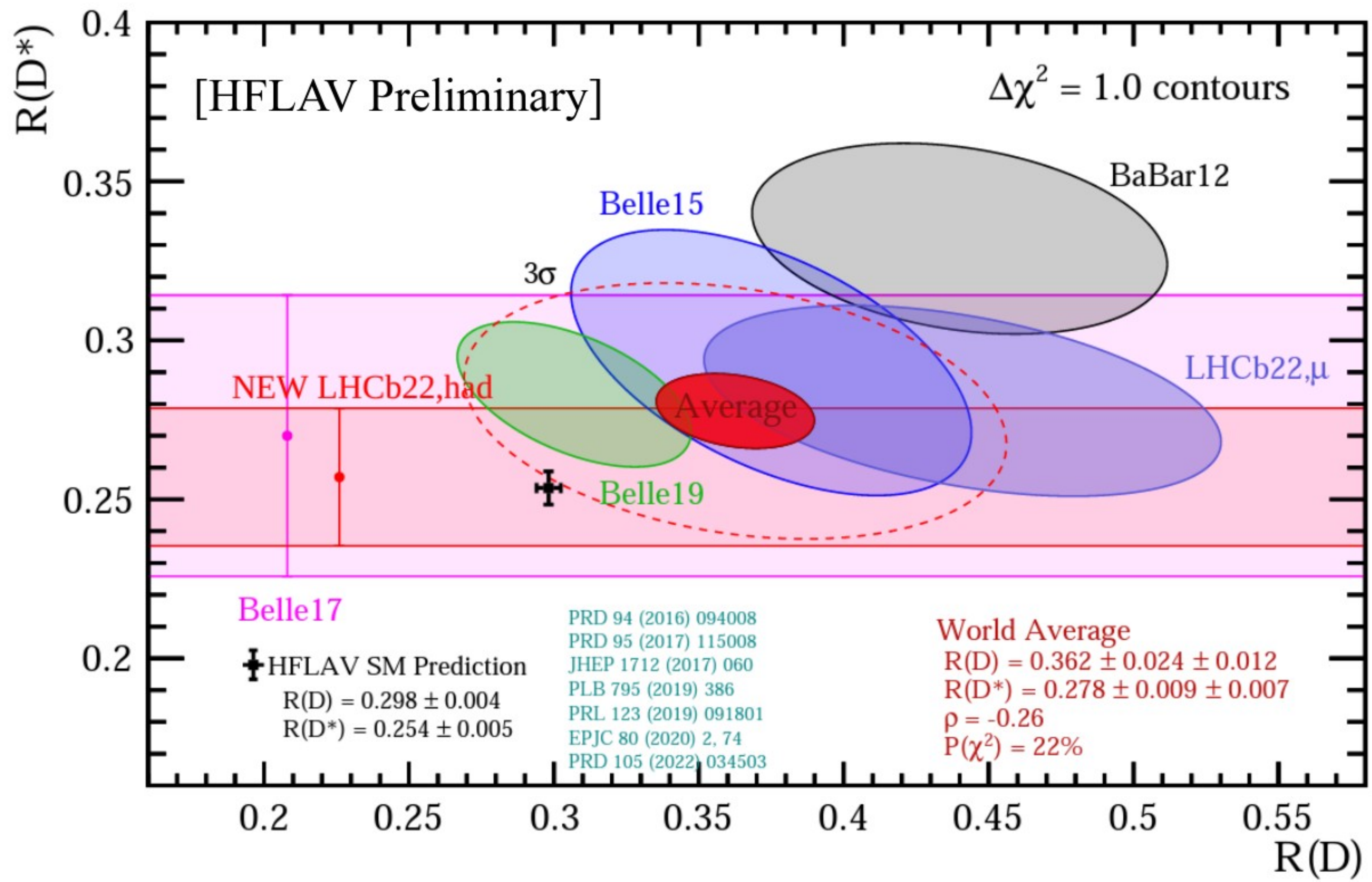


R(D) and R(D*)

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 σ from SM prediction



Angular analyses

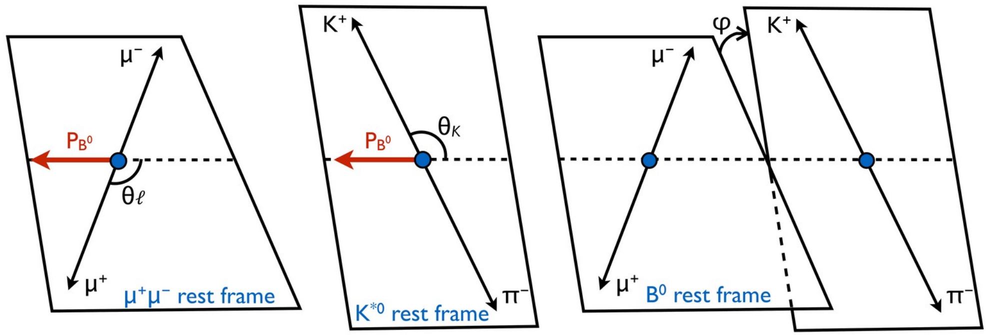
In $b \rightarrow sll$ decays, also the angular distribution of final-state particles can be studied

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, θ_l
  - kaon decay angle, θ_K
  - angle between decay planes, ϕ
- in $B \rightarrow K \mu\mu$ decays 1 angle
  - dimuon system decay angle, θ_l

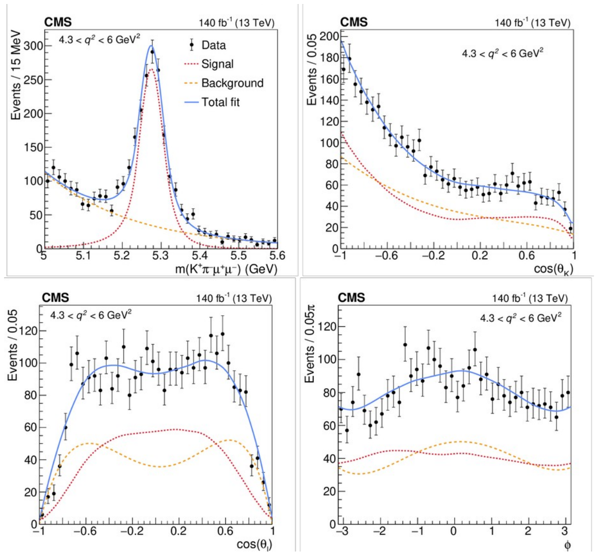
Dependence on helicity angle parametrized as sum of 3D spherical harmonic, with up to 8 angular parameters



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

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

Angular analyses



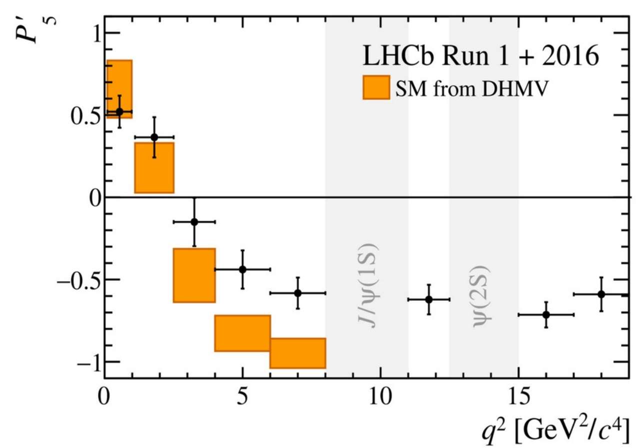
4D fit performed on the B-mass candidate and angular distributions

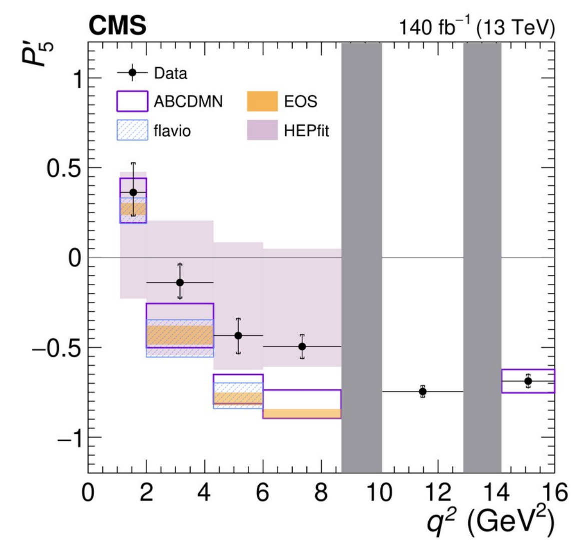
- impact of candidate reconstruction and selection included in the fit function
- resonant charmonium decays used as control regions to validate the fit

Results for one of the angular parameters, P’5, show a tension with SM predictions in the q2 region below the charmonium resonances

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

Run 2 results





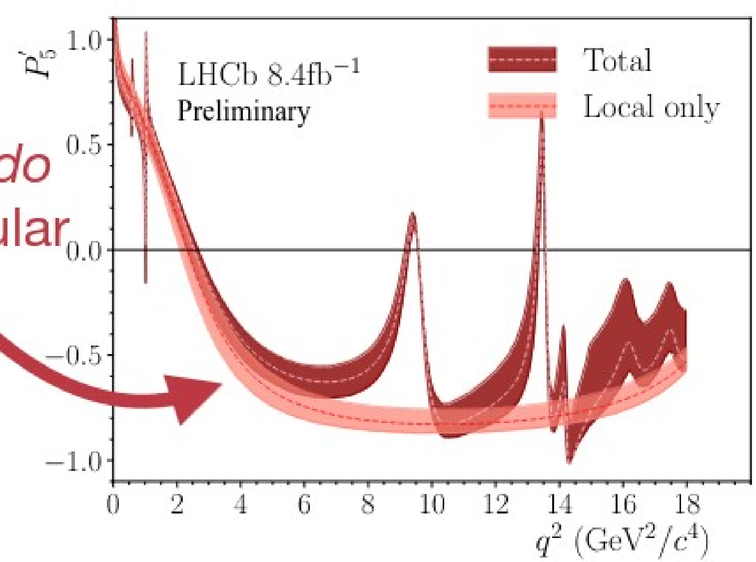
Unbinned angular analysis (LHCb)

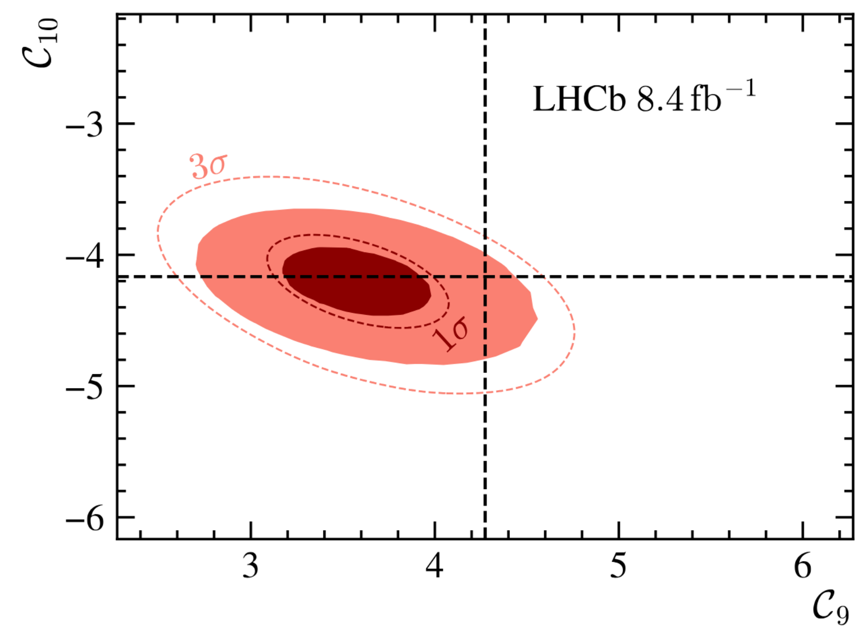
[PRD 109 (2024) 052009]

Recently LHCb released two angular analyses of the $B0 \rightarrow K^{*}0\mu\mu$ decay in which q2 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 → Wilson coefficients directly extracted from the fit

Results still show some tensions wrt the SM, but more modest (2.1 σ for C9, 1.5 σ globally)

Nonlocal contributions *do* influence angular observables

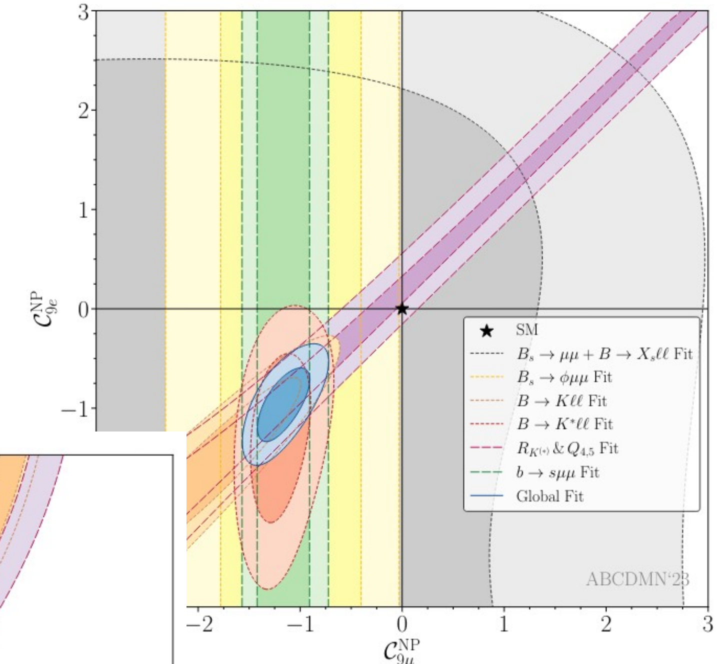


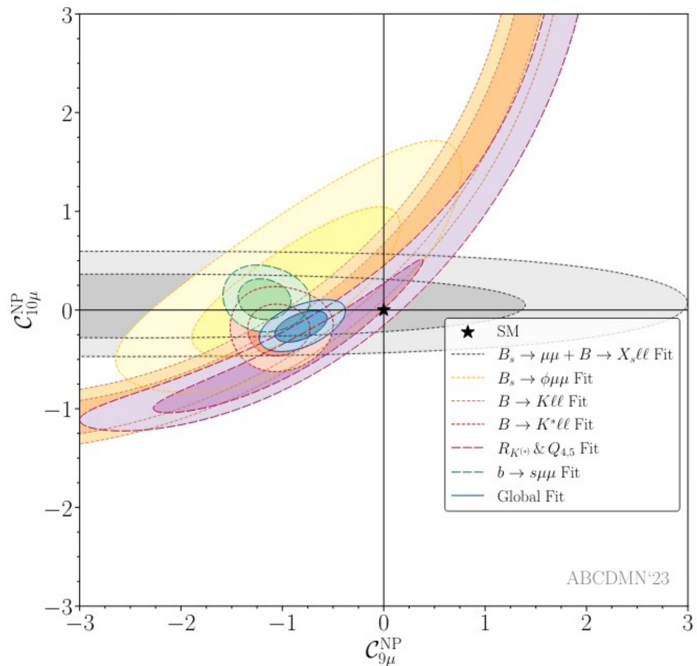


Global fits

Results from b→sll decays and Bs→μμ 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



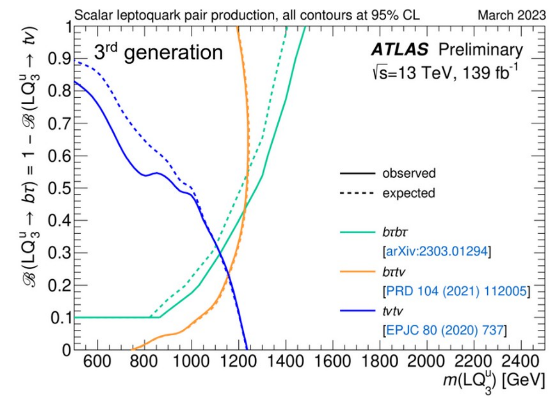


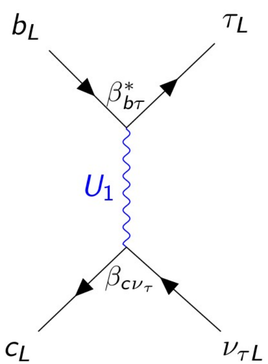
Currently, most of the tension comes from b→sμμ measurements (BF and angular)

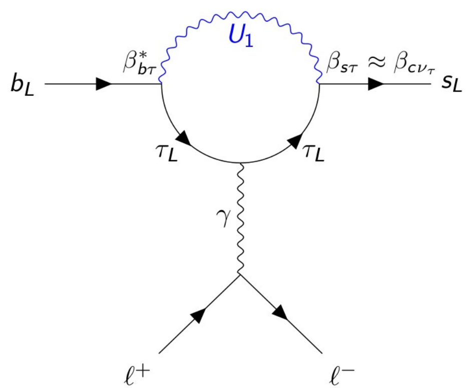
Popular BSM explanations

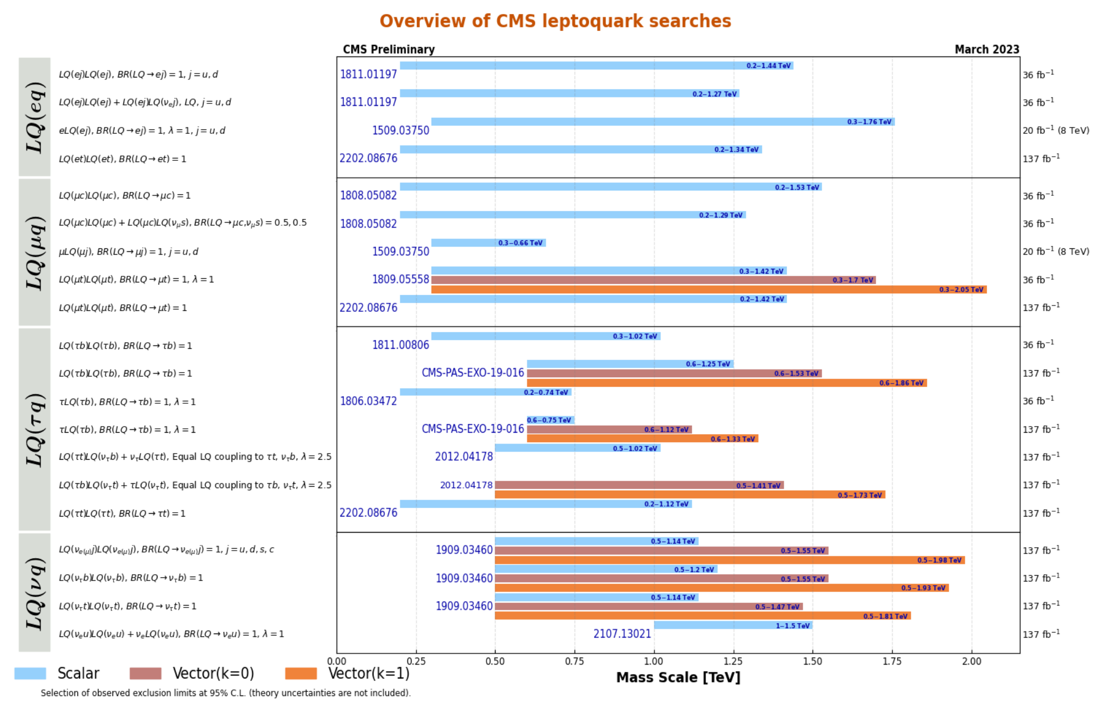
Leptoquark is a good candidate to explain both $R(D^{(*)})$ and $b \to sll$ tensions

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









Crivellin et al. [1807.02068]

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 $b \to sll$ 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)