Heavy-flavour physics @LHC and flavour anomalies

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Course on Physics at the LHC (LIP)
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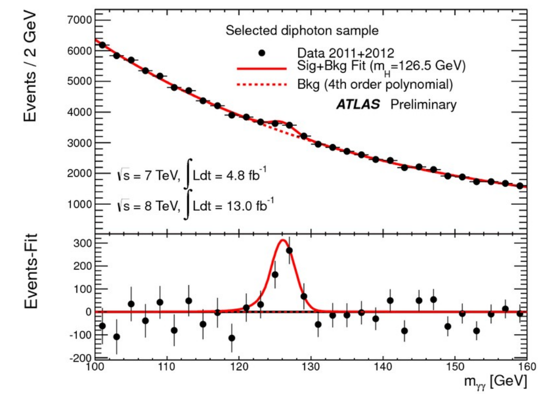
List of touched topics

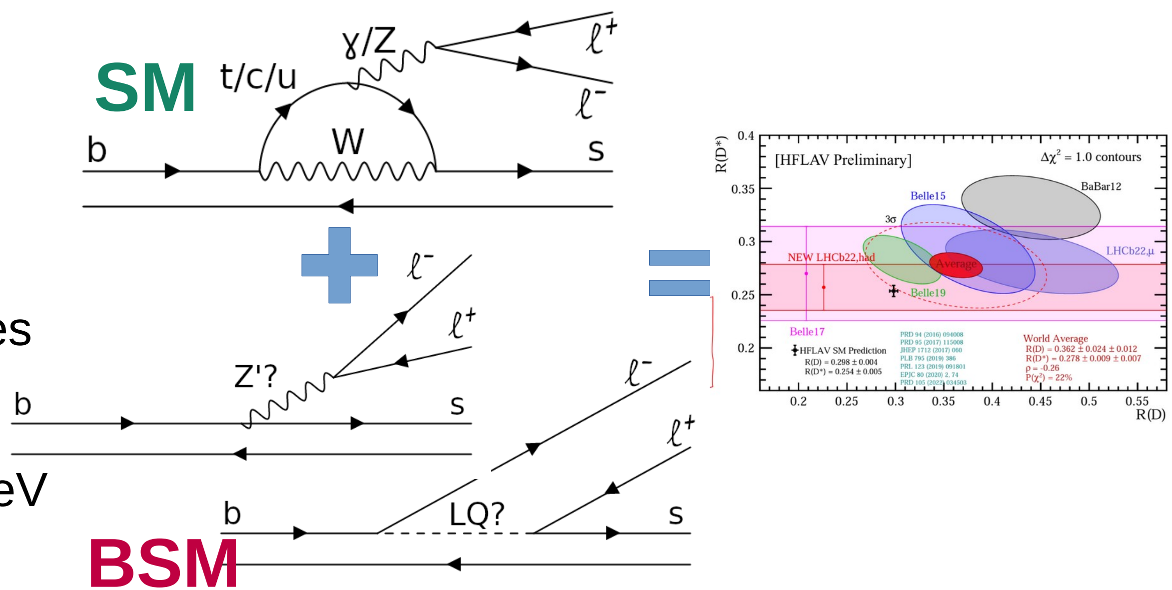
- Introduction
- Theory framework
- Branching fraction measurements
- Lepton Flavour Universality tests
- Angular analyses
- Global fit to the flavour anomalies

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



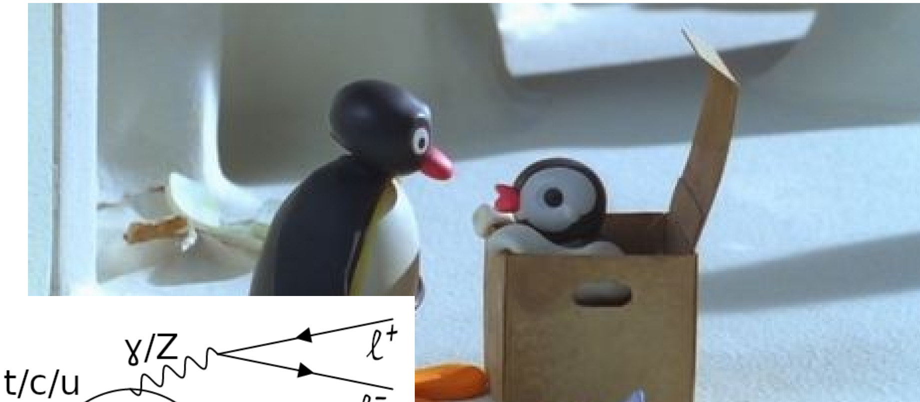
Rare decays

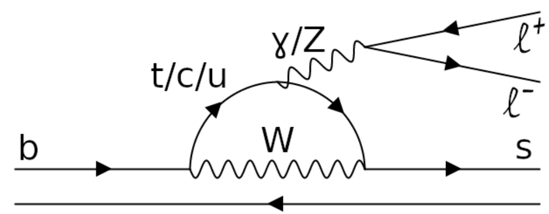
Best environment to indirectly search for new physics is in **rare decays** of SM particles

- sensitive to new particles with lower couplings or higher mass

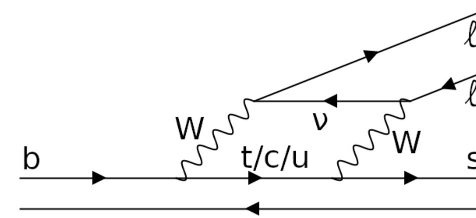
One of the most promising category is **flavour-changing neutral currents** decays $b \to s\, l^+ l^-$

- 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



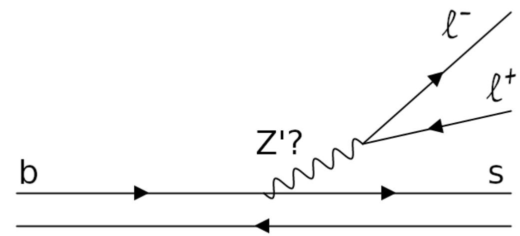


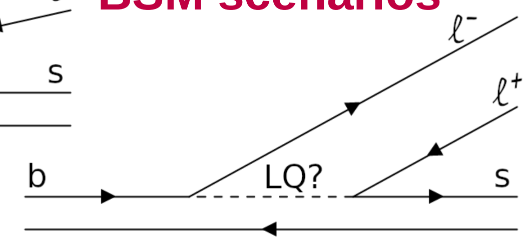
Penguin diagram



Box diagram

Tree-level BSM scenarios

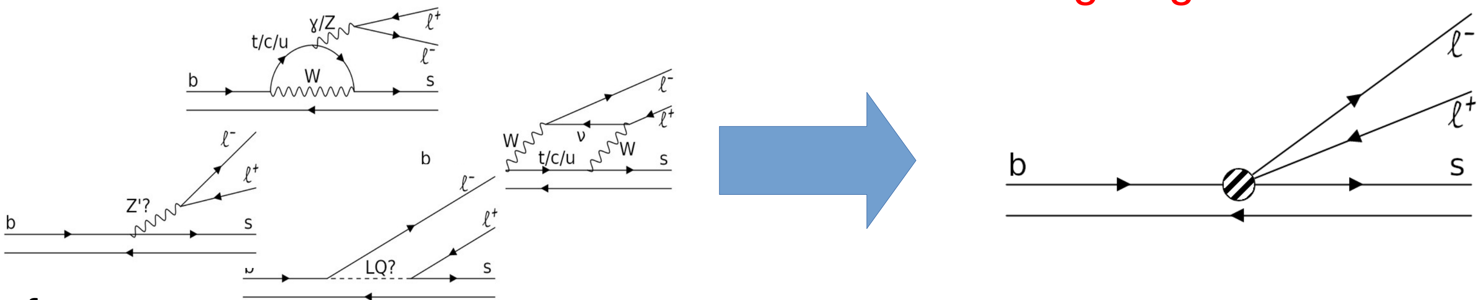




Effective field theory

Decays described in the framework of Effectove Field Theory

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

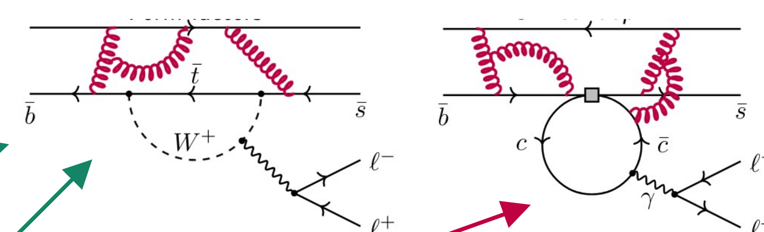


Factorisation of:

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

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

local hadronic matrix elements



Amplitude of B→Mll decays is:

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

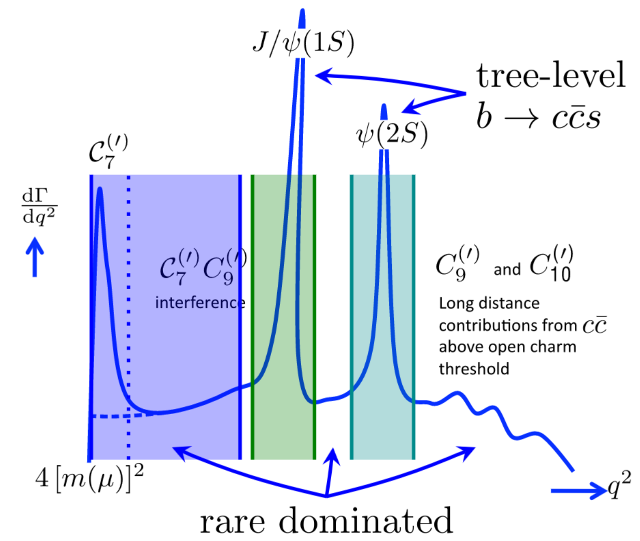
non-local hadronic matrix elements

$b \to sll$ 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%)

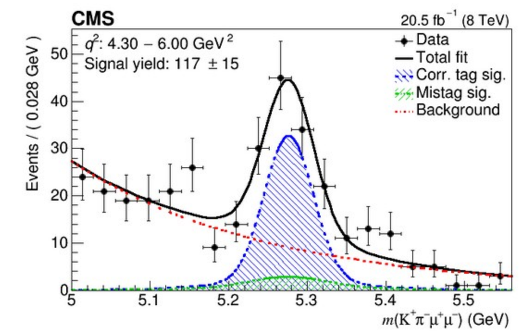
all these measurements are performed in bins of the two-lepton invariant mass squared, q^2

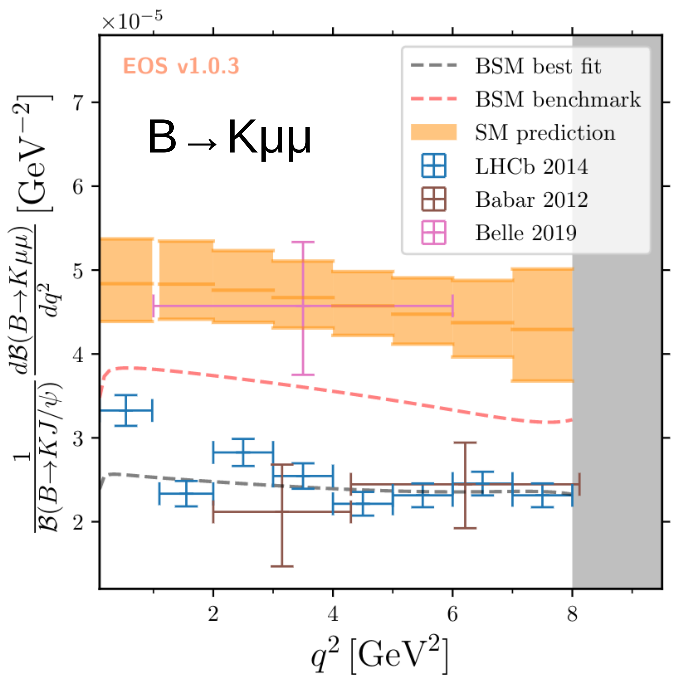


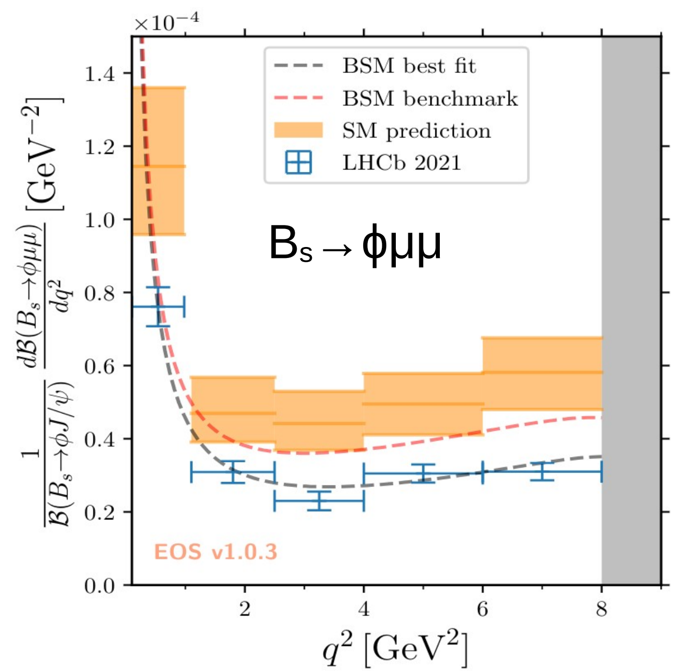
Branching fraction measurements

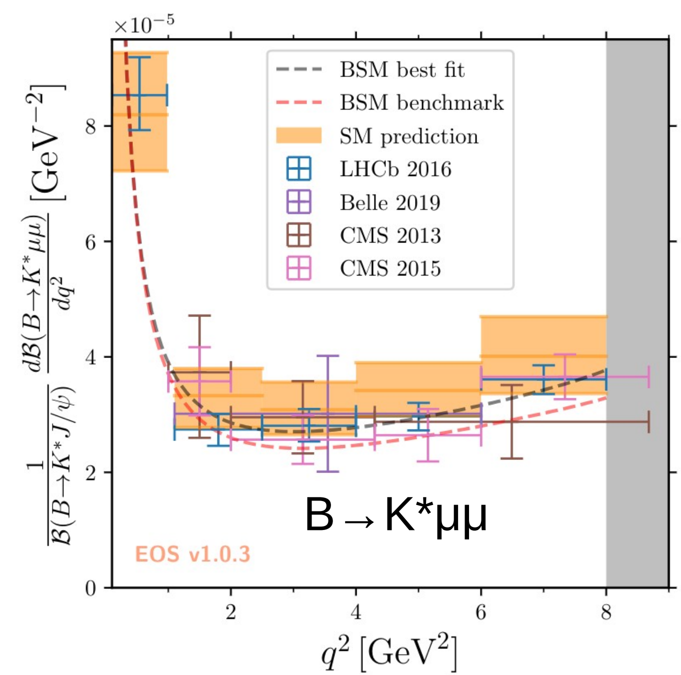
Branching fraction of b→sμμ decays measured both at B-factories and LHC

- 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





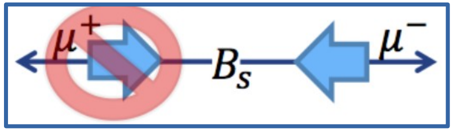


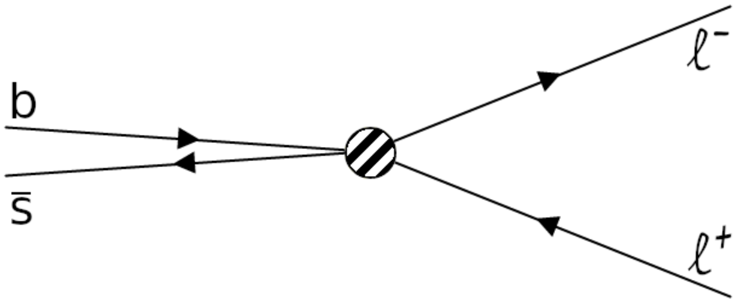


Bs → μμ and B → μμ

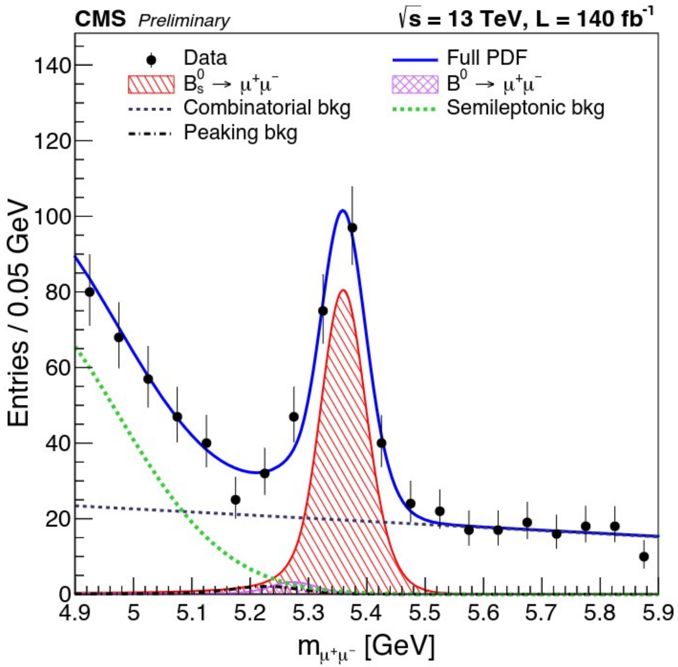
$B^0_s \to \mu\mu$ decay

- 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



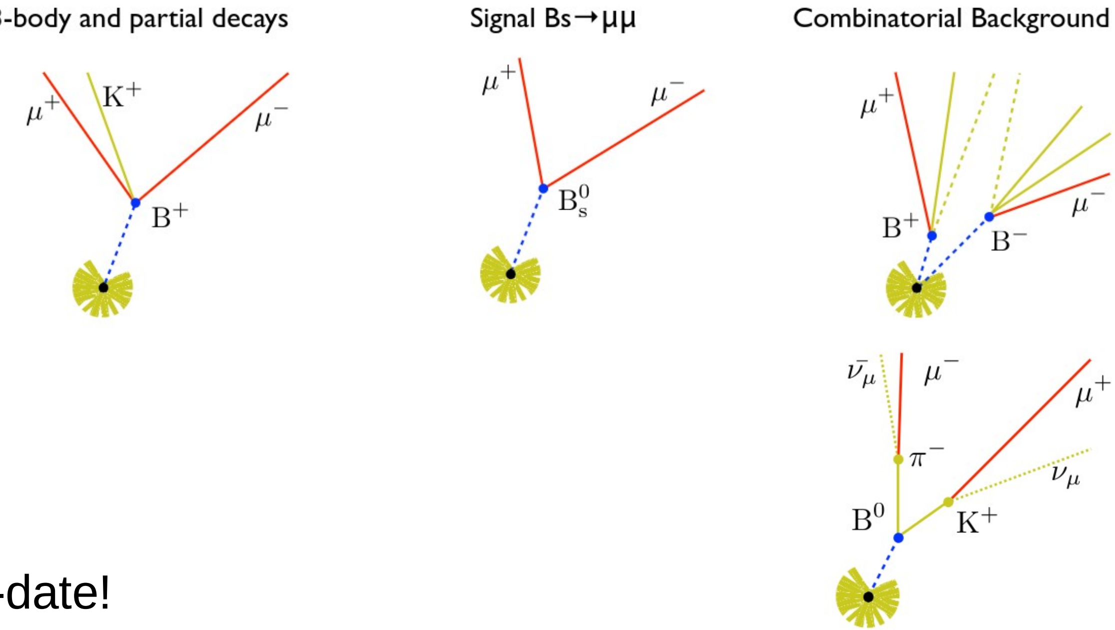
$B^0 \to \mu\mu$ decay

- 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)

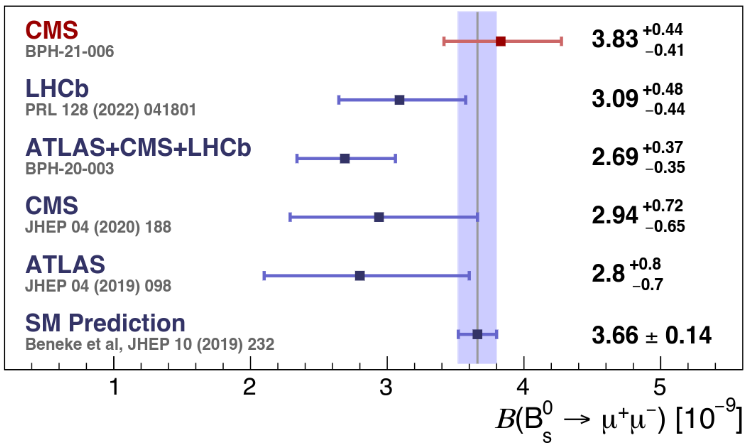
Rejection and control of the backgrounds is the crucial point of the analysis:

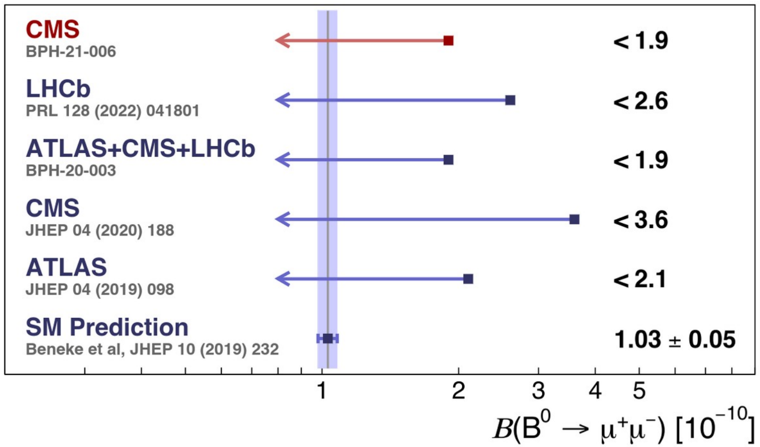
- Event selection based on multi-variate analysis (MVA)
- Isolation selection to reject partially-reconstructed bkg
- Vertex-quality selection to reject combinatorial bkg
- Dedicated muon identification via MVA



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

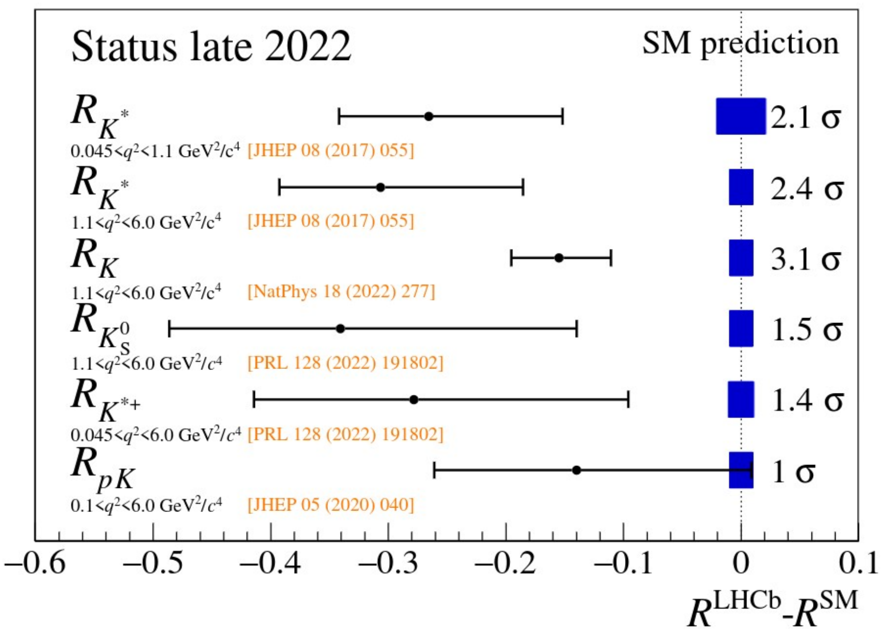
$$R_{K,K^*} = \frac{\mathcal{B}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathcal{B}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}$$

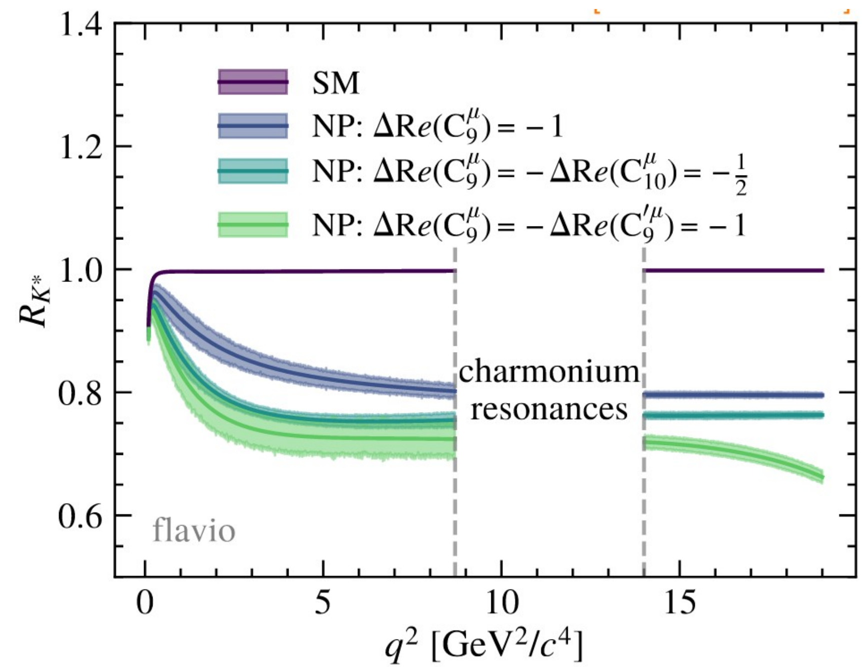
- In this ratio, hadronic uncertainties of SM BFs cancel exactly
  - only QED uncertainties
  - if ratio different than 1, clear indication of BSM effects
- Experimentally challenging
  - Very different reconstruction techniques for muons and electrons
  - Calorimeter noise don’t allow low thresholds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

R(K) and R(K*)

Several b → 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





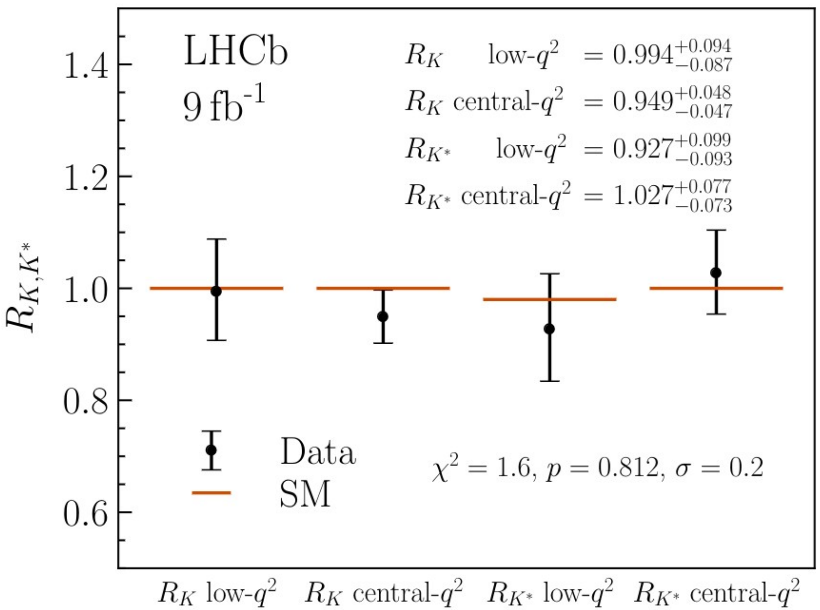
R(K) and R(K*) (LHCb analysis)

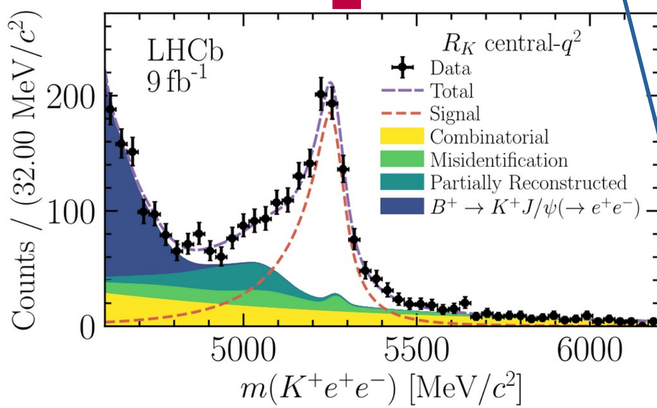
[2212.09152] [2212.09153]

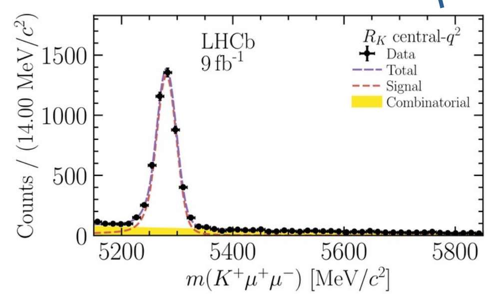
New analysis presented in Dec 2022

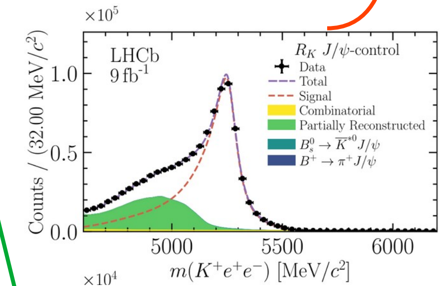
- use of double-ratio with resonant J/ψ channel, to mitigate uncertainties on electron reco
- simultaneous fit to $B^0 \to K^{*0} l^+ l^-$ and $B^+ \to K^+ l^+ l^-$ candidates
- improved control of bkg by use of more control regions

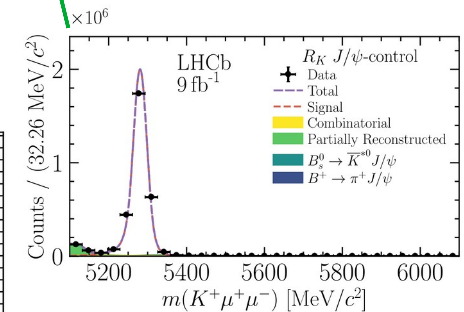
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ e^+e^-)} \times \overbrace{\frac{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))}}^{r^{-1}_{J/\psi}=1 \text{ [PRD 88 (2013) 3]}}$$











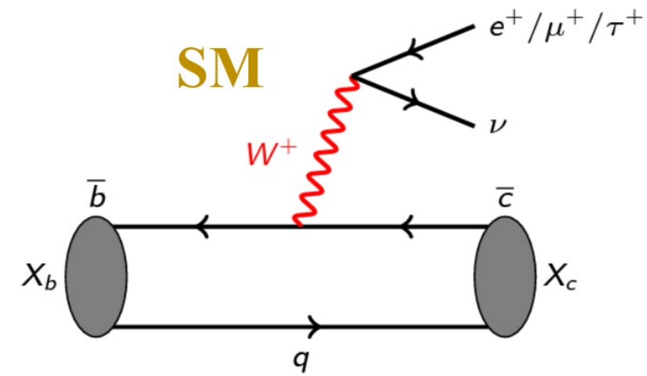
Results now agree with predictions!

R(D) and R(D*)

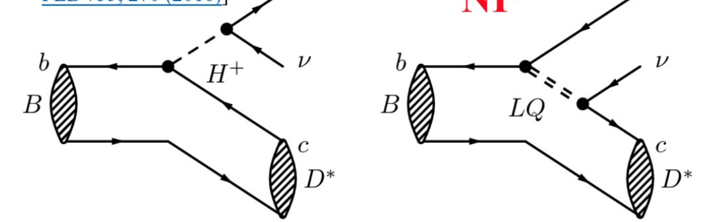
LFU ratios can be built also using b→clν decays

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

- 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*))

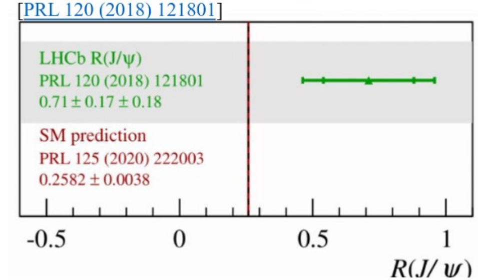


[PRD 85, 094025 (2012), PLB 755, 270 (2016)]



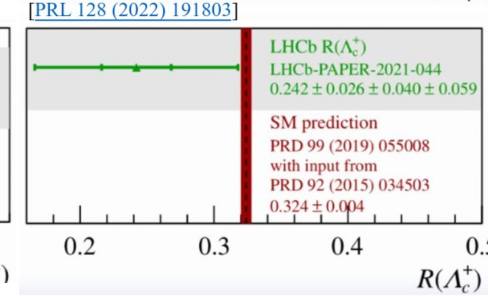
$B^+_c \to J/\psi\ l^+\ \nu$

[PRL 120 (2018) 121801]



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

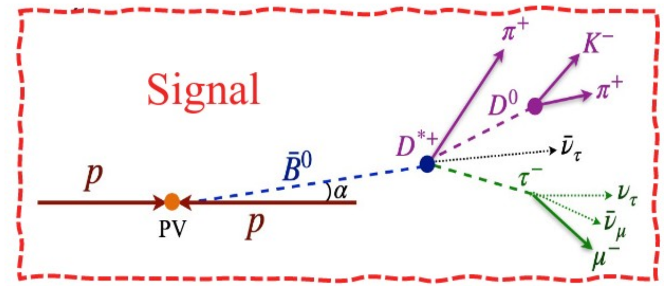
[PRL 128 (2022) 191803]

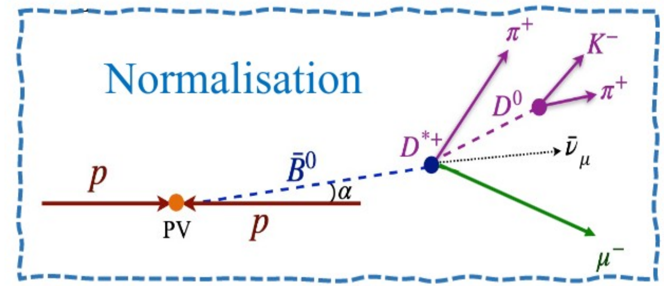


R(D) and R(D*) (LHCb analyses)

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

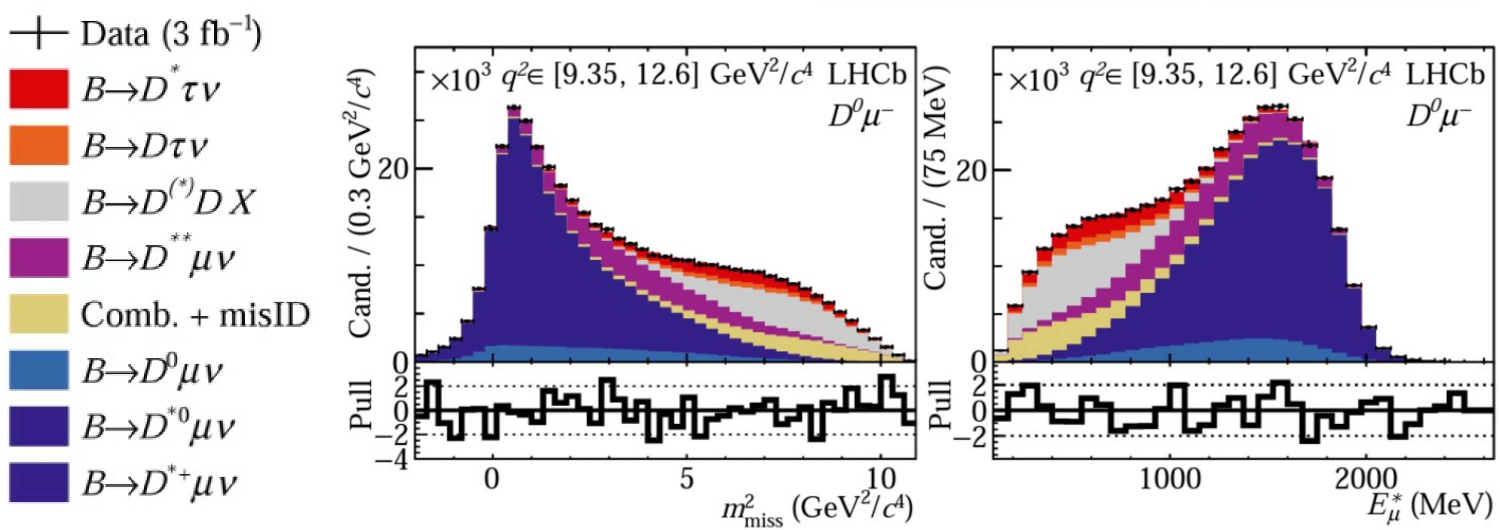
- identical visible final state
- signal decay had three neutrinos produced
- discriminating variables:
  - missing B-mass squared, m^2_{miss}
  - Muon energy in B rest frame, E^*_μ
  - Mass squared of leptonic system, q^2





- 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

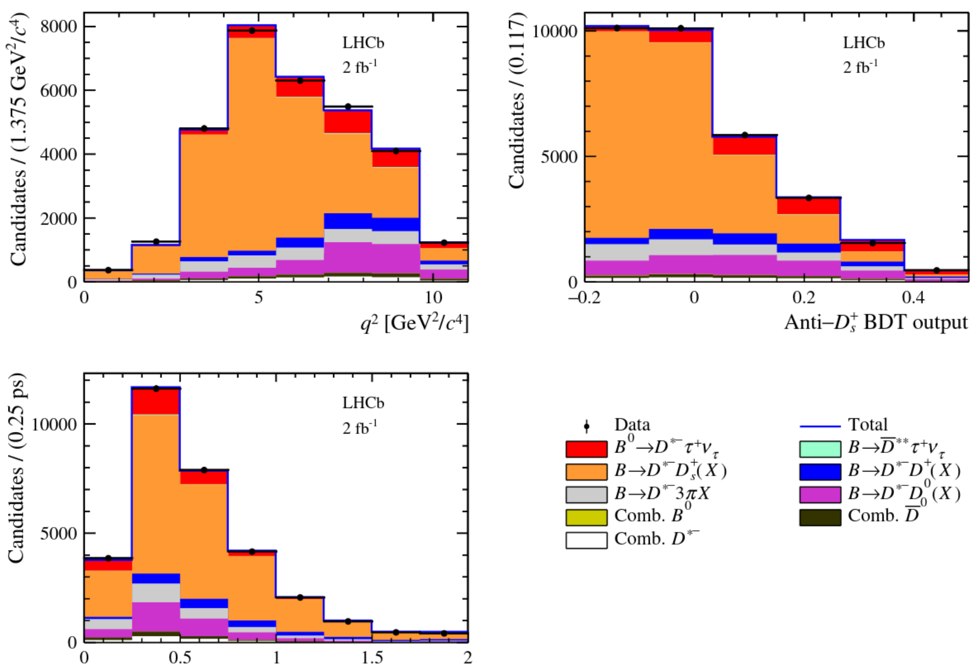
- B0 → D*+πππ used as normalization w/ same final state
- Discriminating variables:
  - Mass squared of leptonic system, q^2
  - Output of BDT to reject D_s
  - τ lifetime, t_τ
- 3D template fit

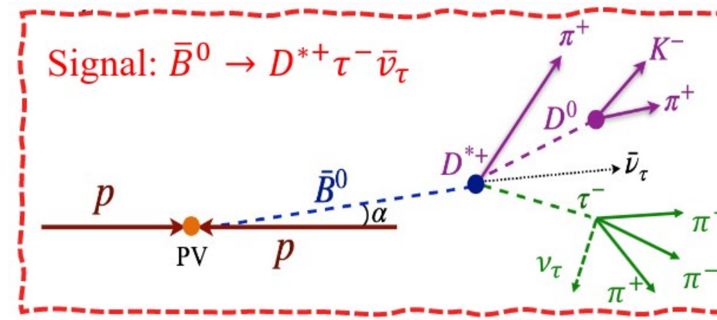
Measure

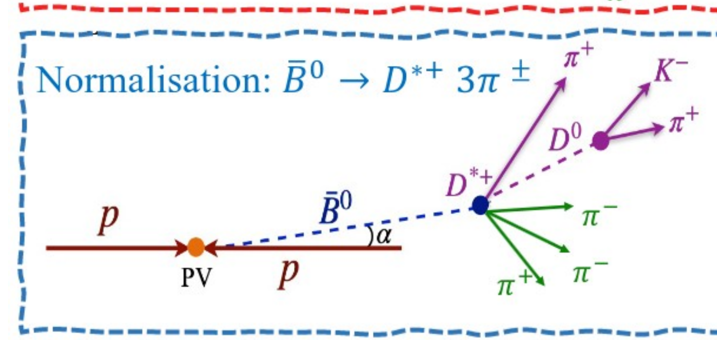
$$K(D^*) = \frac{BF(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{BF(\bar{B}^0 \to D^{*+}\,3\pi^\pm)}$$

External input

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





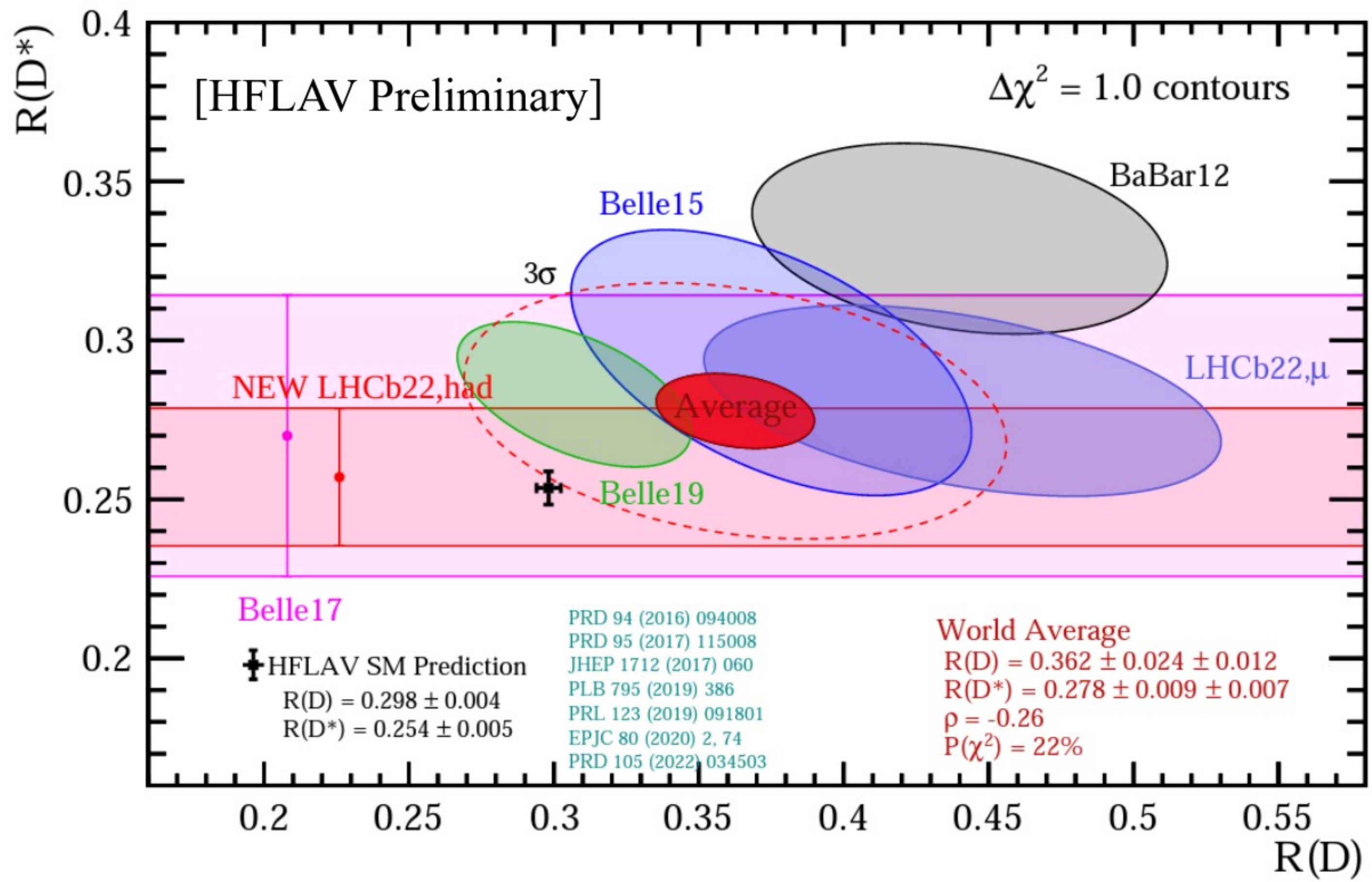


R(D) and R(D*)

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

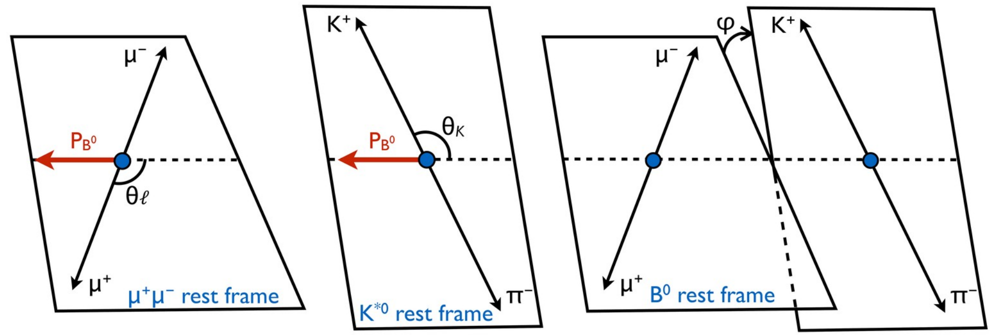
In b → sll decays, also the angular distribution of final-state particles can be studied

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

Distribution of helicity angles analysed

- in B → K*μμ decays 3 angles are defined
  - dimuon system decay angle, θ_l
  - kaon decay angle, θ_K
  - angle between decay planes, ϕ
- in B → Kμμ decays 1 angle
  - dimuon system decay angle, θ_l

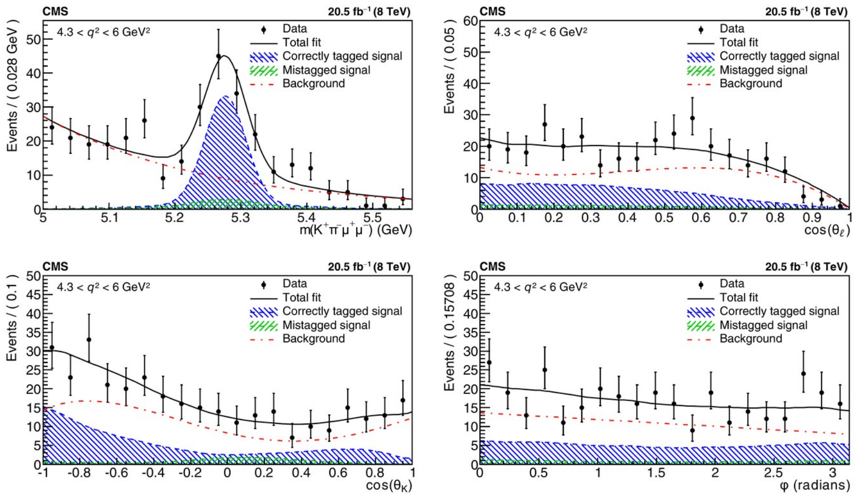
Dependence on helicity angle parametrized as sum of 3D spherical harmonic, with up to 8 angular parameters



Angular decay rate for B → K*μμ decay

$$
\begin{aligned}
\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{32\pi}\Big[&\frac{3}{4}F_T\sin^2\theta_K + F_L\cos^2\theta_K \\
&+ (\frac{1}{4}F_T\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l \\
&+ \frac{1}{2}P_1F_T\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\
&+ \sqrt{F_TF_L}(\frac{1}{2}P_4'\sin 2\theta_K\sin 2\theta_l\cos\phi + P_5'\sin 2\theta_K\sin\theta_l\cos\phi) \\
&- \sqrt{F_TF_L}(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P_8'\sin 2\theta_K\sin 2\theta_l\sin\phi) \\
&+ 2P_2F_T\sin^2\theta_K\cos\theta_l - P_3F_T\sin^2\theta_K\sin^2\theta_l\sin 2\phi)\Big]
\end{aligned}
$$

Angular analyses



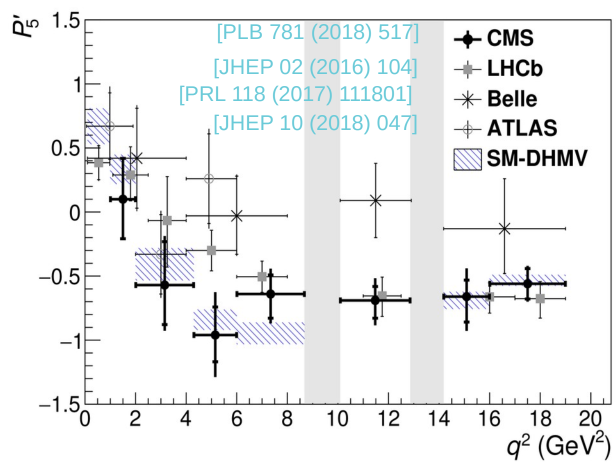
4D fit performed on the B-mass candidate and angular distributions

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

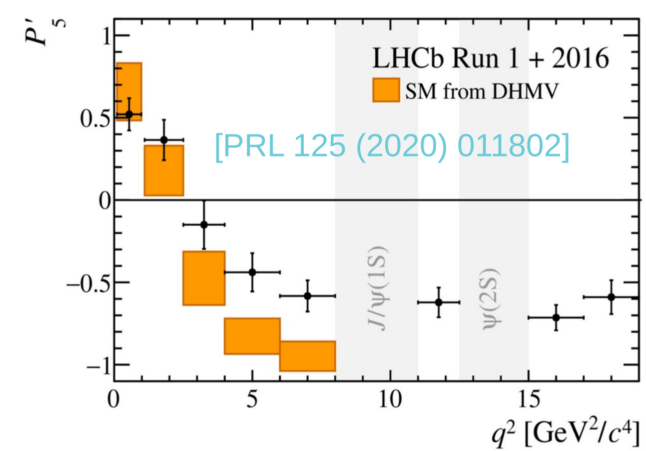
Results for one of the angular parameters, P'5, show a tension with SM predictions in the q2 region below the charmonium resonances

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

Run 1 results



+ partial run 2 LHCb



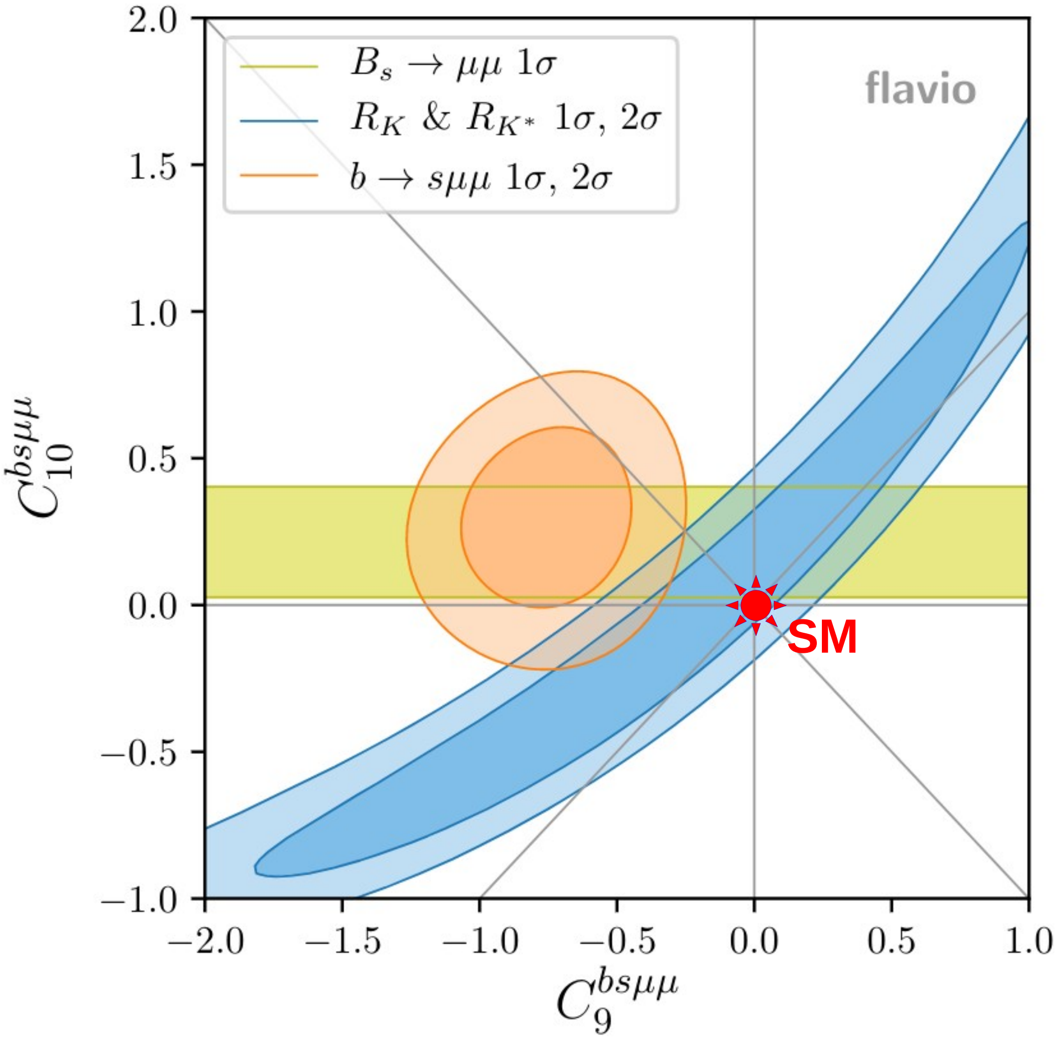
Global fits

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

Plot here shows current status of the art
- 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

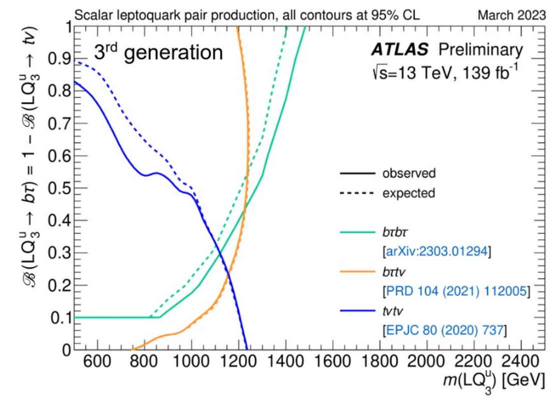
Currently, most of the tension comes from b→sμμ measurements (BF and angular)

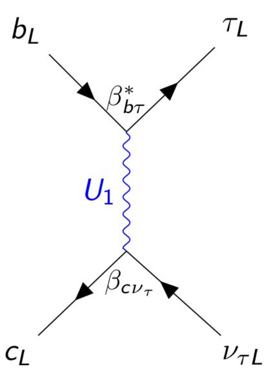


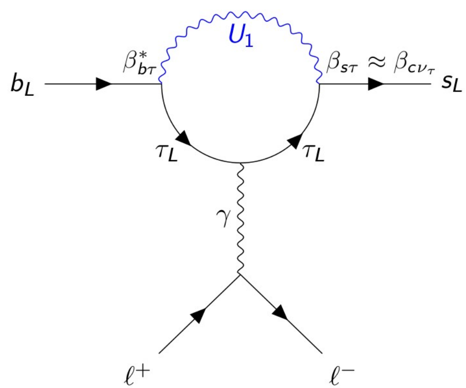
Popular BSM explanations

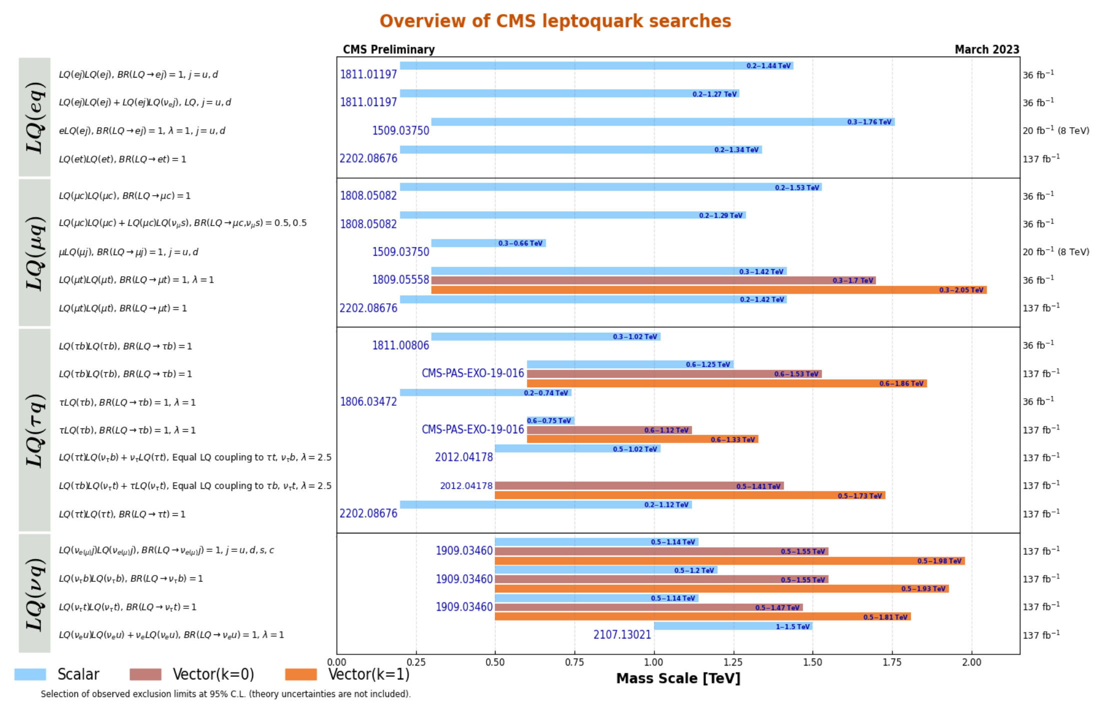
Leptoquark is a good candidate to explain both $R(D^{(*)})$ and $b \rightarrow sll$ tensions

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 the upcoming LHC data is a very interesting opportunity to shed light on these tension