Heavy-flavour physics @LHC and flavour anomalies

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Course on Physics at the LHC (LIP) 29th April 2024

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

- 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



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

 $\mathcal{L}_{D=6}^{sb\ell\ell} =$



 $\left(\sum_{i=1}^{2} C_{i}\mathcal{O}_{i}^{c} + \sum_{i=3}^{10} C_{i}\mathcal{O}_{i}\right) + \lambda_{u}\left(\sum_{i=1}^{2} C_{i}\left(\mathcal{O}_{i}^{c} - \mathcal{O}_{i}^{u}\right)\right)$

Factorisation of:

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

Α

$$\operatorname{mplitude of } \mathbf{B} \to \mathsf{MII decays is:}$$

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

local hadronic

matrix

+ h.c.

$b \rightarrow sll \ observables$

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 (~1%)

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



Branching fraction measurements

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



$Bs \to \mu \mu$ and $B \to \mu \mu$

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

- described with the same effective Lagrangian as $b \rightarrow sll$
- doubly suppressed in the SM:
 - no tree-level diagram
 - helicity suppression
 - BF prediction: ~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



 $\xrightarrow{\mu^+} B_s \xrightarrow{\mu^-}$

$B^{0}_{s} \rightarrow \mu\mu$ and $B^{0} \rightarrow \mu\mu$ (CMS analysis)

3-body and partial decays Signal Bs $\rightarrow \mu\mu$ Combinatorial Background Rejection and control of the backgrounds μ^{+} is the crucial point of the analysis: Event selection based on B_s^0 B^+ multi-variate analysis (MVA) Isolation selection to reject partially-reconstructed bkg $\bar{\nu_{\mu}}$ Vertex-quality selection to reject combinatorial bkg π Dedicated muon identification via MVA B^0 K^+ Most precise single-experiment results to-date!

No tensions with SM predictions

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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 $b \rightarrow sll$ 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)

Updated analysis presented in Dec 2022

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





Results now agree with predictions!

R(K) (CMS analysis)

[2401.07090]



R(D) and $R(D^*)$

-0.5

LFU ratios can be built also using $b \rightarrow clv$ 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 $B^+ \rightarrow D^0 I^+ \nu$ (ratio: R(D)) $B0 \rightarrow D^{*-} I^+ \nu$ (ratio: R(D*))



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, m²_{miss}
 - Muon energy in B rest frame, E^*_{μ}
 - Mass squared of leptonic system, q²
- 3D template fit in 2 signal and 6 bkg-enriched categories:





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

- R(D*) measurement using hadronic tau decays
- B0 \rightarrow D*+ $\pi\pi\pi$ used as normalization w/ same final state
- Discriminating variables:
 - Mass squared of leptonic system, q²
 - Output of BDT to reject D_s
 - τ lifetime, t_{τ}
- 3D template fit





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_{I}
 - kaon decay angle, θ_{κ}
 - angle between decay planes, $\boldsymbol{\varphi}$
- in $B \rightarrow K\mu\mu$ decays 1 angle
 - dimuon system decay angle, θ_{I}

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



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

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

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



Unbinned angular analysis (LHCb)

Recently LHCb released two angular analyses of the B0 \rightarrow K*0µµ 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 \rightarrow 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)



Global fits

JOP 10

Results from $b \to sll$ decays and Bs $\to \mu \mu$ 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, C₉ and C₁₀ 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

eq)

õ

(bn)

 $\tau q)$

vq)

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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]



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