Rare B decays

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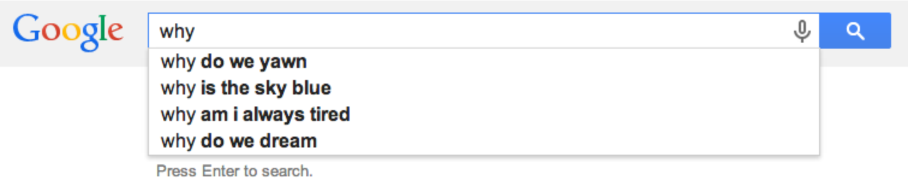
Introduction



- Why is there a hierarchy of fermion masses?
- Why do elements of the CKM matrix have a large spread?
- What is the origin of CP violation in the universe?
- What is the origin of dark matter?

$\rightarrow$ SM is low-energy effective theory

What is the scale Λ where new physics shows up?

How to probe high NP scales

Look at observables that:

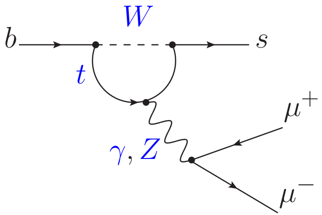
1. The SM contribution is small
2. Can be measured to high precision
3. Can be predicted to high precision

$\rightarrow$ Flavour Changing Neutral Currents in SM

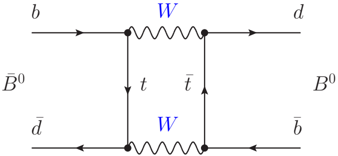
- Loop level
- GIM suppressed
- Left-handed chirality

$\rightarrow$ NP could violate any of these

$\Delta F = 1$ **Rare B decays**



$\Delta F = 2$ **See Mika's talk**



SM as effective theory

- "Integrate" out heavy ($m \geq m_W$) field(s) and introduce set of Wilson coefficients C_i, and operators $\mathcal{O}_i$ encoding short and long distance effects

- New physics enters at larger scale Λ_{NP}

$$\mathcal{H}_{eff} \approx -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts(d)} \sum_i C_i^{SM} \mathcal{O}_i^{SM} + \sum_{NP} \frac{c_{NP}}{\Lambda^2_{NP}} \mathcal{O}_{NP}$$

for 6 dim operators $\mathcal{O}_{NP}$

Sensitivity to New Physics

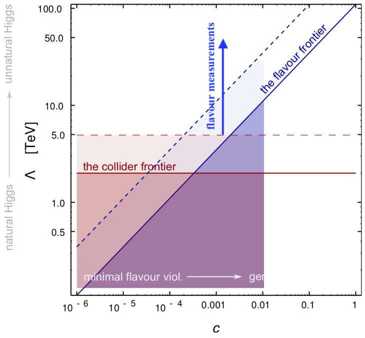
- Different decays probe different operators:

Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to X_{s(d)}\gamma$
$\mathcal{O}_7$ EM	✓		✓
$\mathcal{O}_9$ Vector dilepton	✓		
$\mathcal{O}_{10}$ Axial-vector dilepton	✓	✓	
$\mathcal{O}_{S,P}$ (Pseudo-)Scalar dilepton	(✓)	✓	

- Also include chirality flipped counterparts

Collider vs Flavour searches

Credit D. Straub



NP scale given current experiment and theory status

$$\Lambda_9 \gtrsim (0.6 - 35)\ \text{TeV}$$

$$\Lambda_7 \gtrsim (1.5 - 90)\ \text{TeV}$$

depending on flavour couplings and tree/loop level

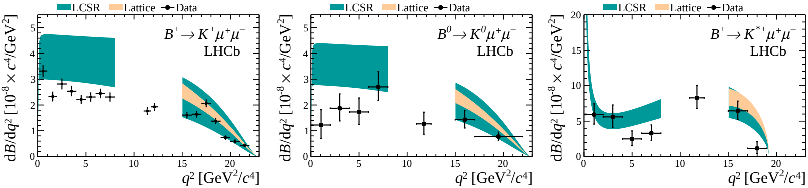
- Flavour physics probes very high energy scales particularly for generic flavour couplings

An intriguing set of results

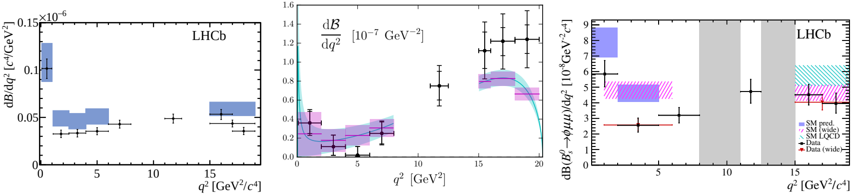
1. Differential branching fractions

- Measurements of $d\mathcal{B}/dq^2$ of $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$

Experiment: [JHEP06(2014)133], [JHEP09(2015)179], [JHEP06(2015)115], [JHEP06(2015)115]



$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]



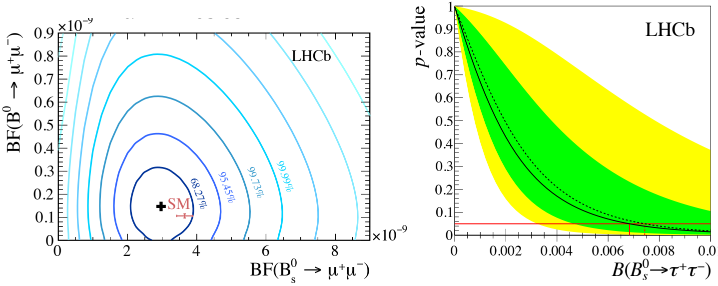
Theory: Bobeth et al [JHEP07(2011)067], Bharucha et al [JHEP08(2016)098], Detmold et al [PRD93,074501(2016)], Horgan et al [PRD89(2014)]

- Measurements below SM prediction ($2 - 3\sigma$ depending on final state)
- Measurements motivated higher precise in predictions

Branching fractions of $B \to \ell^+\ell^-$

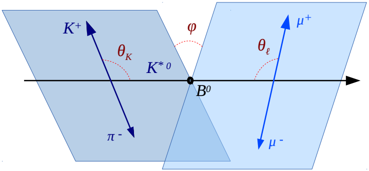
- Branching fraction measurement provides stringent constraints on axial-vector and (pseudo-)scalar couplings
- Precise $\mathcal{B}(B \to \mu^+\mu^-)$ prediction ($\sim 5\%$)

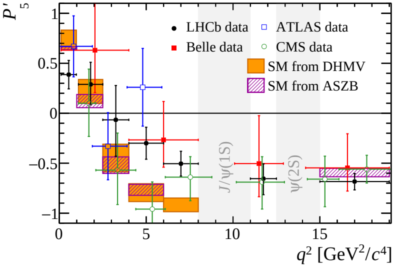
Left: $B \to \mu^+\mu^-$ [PRL118(2017)191801], Right: $B_s \to \tau^+\tau^-$ [PRL118(2017)251802]

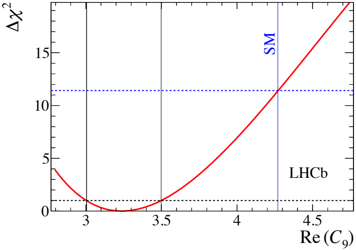


2. $B^0 \to K^{*0}\mu^+\mu^-$ angular measurements

- Rich amplitude structure $\to$ 8 CP-even and 8 CP-odd observables



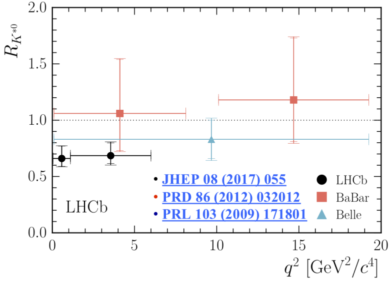


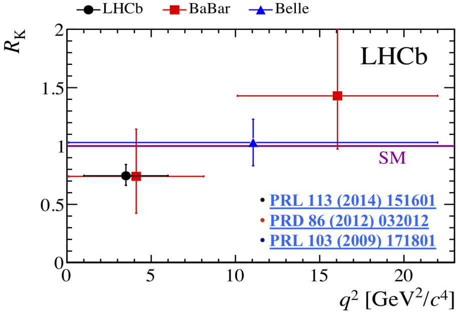


- Angular distribution at 3.4σ tension with SM
  $\to$ Anomalous vector-dilepton coupling

3. Lepton Flavour Universality tests

Measurement of: $R_{K^{(*)}} = \dfrac{d\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/dq^2}{d\mathcal{B}(B \to K^{(*)}e^+e^-)/dq^2}$



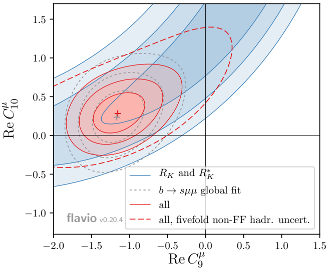


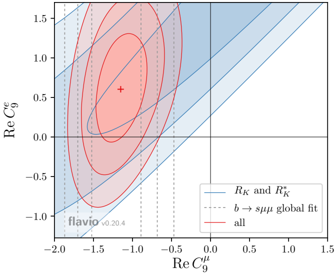
R_K: Central-q^2: 2.6σ from SM

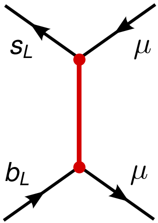
R_{K^*}: Low-q^2: 2.1-2.3σ from SM

R_{K^*}: Central-q^2: 2.4-2.5σ from SM

Putting it all together







Matias et al [1704.05340], Altmannshofer et al [1703.09189]...

- Global fits show $> 5\sigma$ tension with SM
- **Consistent picture emerging between LFUV observables and angular, branching fraction measurements**
- New vector non-universal coupling! $\rightarrow$ Leptoquark?
  Hiller et al [1801.09399] Bordone et al [1712.01368]
  Greljo et al [JHEP07(2015)142] Buttazzo et al [JHEP08(2016)035]
  Di Luzio et al [1712.06572] B_s mixing!!!
  ...apologies...
- Some models also explain 4σ LFUV anomaly in $B \rightarrow D^{(*)}\ell\nu$ transitions
- Precision of LHCb PhaseII and more measurements critical to pin down model of NP

Shopping list

1 Confirm/Refute anomaly through further measurements of LFUV observables
  - LFUV angular observables e.g $P_5'(\mu\mu) - P_5'(ee)$
  - Observation of NP using theoretically cleanest observables alone

2 Measurements of $b \to s\mu^+\mu^-$ observables to improve understanding of hadronic uncertainties
  - $B \to K^{(*)}$ form-factors
  - Charm loop contributions

3 Imprint of NP in related modes and tests of MFV
  - B_s mixing, $b \to d\ell\ell$, modes with τ's in final state
  - $B \to K^{(*)}\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$ (Belle2 and NA62)

4 Look for Lepton Flavour Violation using $B \to (X)\ell\ell^{'}$, $D \to (X)\ell\ell^{'}$
  - LFUV generally implies Lepton Flavour Violation

    e.g Glashow et al [PRL114,091801(2015)]
  - Models predict significant enhancements in within reach of future flavour experiments including Belle2

Bottom line

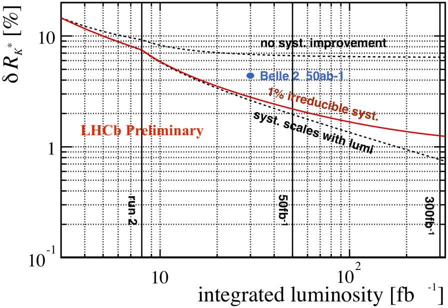
- Anomalies persist:
  - Analyses of a whole host of rare B-decays, D-decays and K-decays to pin down exact details of model
    $\rightarrow$ Flavour measurements imperative:
    LHCb+PhaseII, Belle2, NA62++

- Anomalies go away:
  - Analyses of a whole host of rare B-decays, D-decays and K-decays to explore energy scales far beyond the reach of colliders
    $\rightarrow$ Flavour measurements imperative:
    LHCb+PhaseII, Belle2, NA62++

Rare decays at LHCb PhaseII

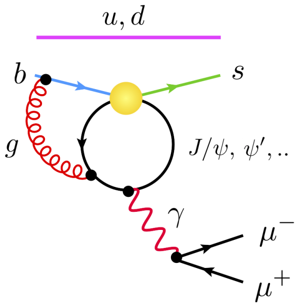
2018-2021	Run 3 (2021-2023)	2023-2025	Run 4 (2025-2028)	2028-2030	Run 5 (2030-2035+)
Shutdown	~23fb^{-1}	Shutdown	~50fb^{-1}	Shutdown	~300fb^{-1}
LHCb upgrade PhaseI				LHCb upgrade PhaseII	

- Angular and LFU measurements statistically limited even after PhaseI
  - Dominant systematic uncertainties statistical in nature



- Maintain/improve performance through: material reduction, higher segmentation ECAL, timing information
- Measure $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ to $\sim 5\%$ (on par with current theory error)
  - NP effects in $B \to e^+e^-$ and $B \to \tau^+\tau^-$ means with 300fb^{-1} can exclude models

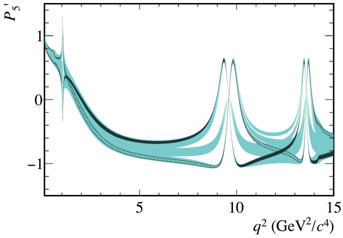
Charming interlude



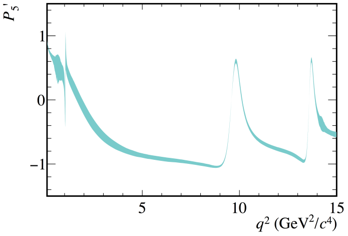
- Anomalies in $b \to s\mu^+\mu^-$ have shed doubt on control of theory uncertainties related to the "charm-loop"

- Can extract the charm contribution directly from data
  Lyon et al [1406.0566], Bobeth et al [1707.07305], Blake et al [1709.03921]

Left: Current theory uncertainty,



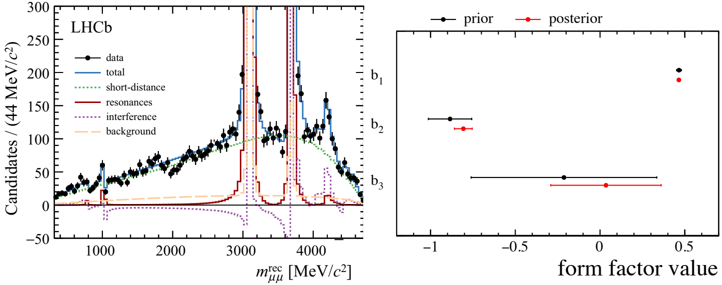
Right: Expected theory uncertainty using data



$B \to K^{(*)}$ form factors

- Global fits of Wilson coefficients to Rare-B decay data rely on precise predictions $B \to K^{(*)}$ form factors
- Great advancements by theory and Lattice QCD community
  Khodjamirian et al [1703.04765], Bharucha et al [1503.05534], Horgan et al [1310.3722], Meinel et al [1608.08110], Buchard et al [1509.06235,1507.01618]...
- Expect further improvements in theory predictions coming through further developments in lattice QCD or otherwise

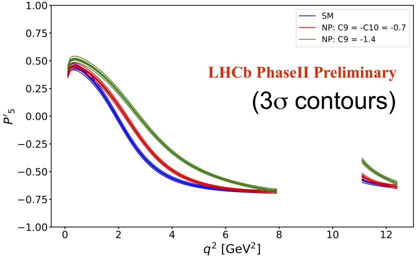
[Eur. Phys.J. C(2017)77:161]

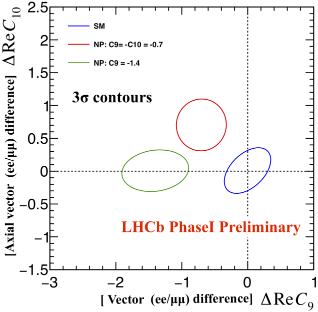


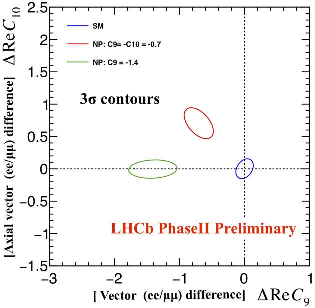
- Can also use our data to further improve on precision [Eur. Phys.J. C(2017)77:161]

Rare decays at LHCb PhaseII cont'd

- Assuming control of systematics, $B \to K^* \ell^+ \ell^-$ angular analyses will be able to distinguish between a large variety of NP models
- Difference between μ and e couplings: Smoking gun of NP!

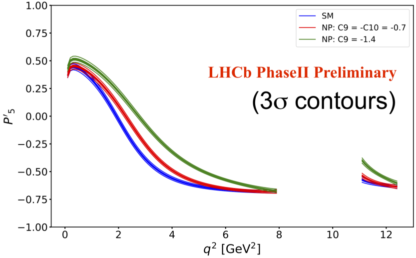


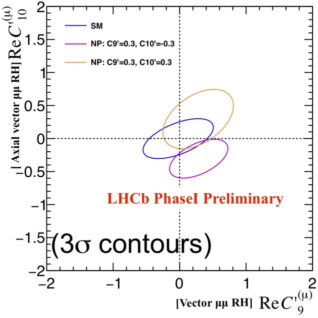


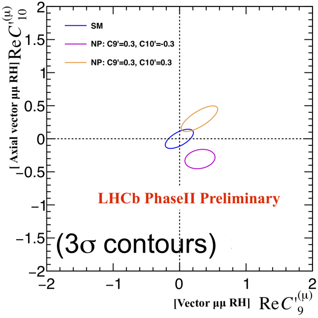


Rare decays at LHCb PhaseII cont'd

- Assuming control of systematics, $B \to K^* \ell^+ \ell^-$ angular analyses will be able to distinguish between a large variety of NP models
- Precision measurements of Left-,Right-handed couplings and new sources of CPV





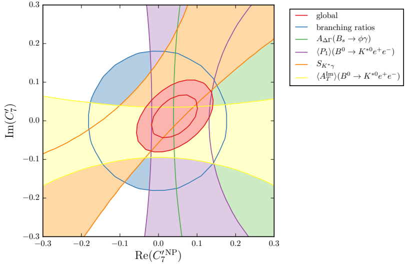


Rare decays at LHCb PhaseII cont'd

EM operators ($C_7^{(\prime)}$) can be constrained to high precision through:

- $B^0 \to K^{*0} e^+ e^-$ angular analysis provides one of strongest constraints
- CP asymmetry of $B_s \to \phi\gamma$
- Belle2 also important:
  - CP asymmetries in $B^0 \to K_s \pi^0 \gamma$
  - In(Ex)clusive branching fraction of $b \to s\gamma$
  - ...

Current status Paul, Straub [1608.02556]



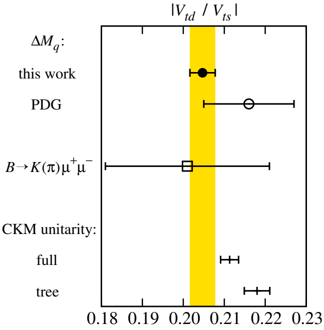
Tests of Minimal Flavour Violation

- Compare $b \to d\ell^+\ell^-$ and $b \to s\ell^+\ell^-$ transitions
- In SM $\frac{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)} \sim \left|\frac{V_{td}}{V_{ts}} \frac{f_{B\to\pi}}{f_{B\to K}}\right|^2$

  $\to$ Test of Minimal Flavour Violation

- $b \to d\ell^+\ell^-$ statistically limited even with LHCb phaseII data
- Expect 10-fold improvement in experimental error
- Modest improvements in Lattice predictions also required to maximise gain

LHCb [JHEP10(2015)034]



[FNAL + MILC, PRD 93 (2016) 113016]

Tests of Minimal Flavour Violation

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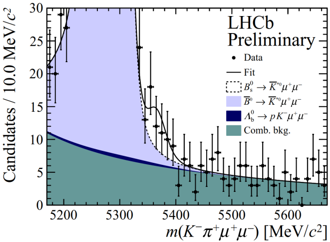
  $\to$ Test of Minimal Flavour Violation

First evidence of $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$
Moriond 2018



- $b \to d\ell^+\ell^-$ statistically limited even with LHCb phaseII data
- Expect 10-fold improvement in experimental error
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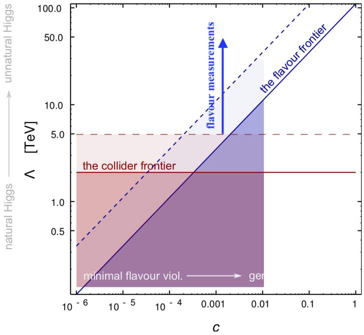
- MFV test in angular observables also possible with LHCb phaseII
  - Comparison between $B^0 \to K^{*0}\mu^+\mu^-$ and $b \to d$ equivalent $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ (precision commensurate to Run1 $B^0 \to K^{*0}\mu^+\mu^-$)

Naturalness' loss → Flavour's gain

- Lack of NP in direct searches lifts requirement of MFV
  - Large Λ_{NP} reach from flavour

Credit D. Straub



	CKM+Loop	CKM+Tree	$\mathcal{O}(1)$+Loop	$\mathcal{O}(1)$+Tree
$\Lambda_{NP}^{9(10)(')}$(TeV)	~ 2	~ 10	~ 20	~ 100
$\Lambda_{NP}^{7(')}$(TeV)	~ 5	~ 20	~ 60	~ 300

my own guesstimates by LHCb PhaseII with grain of salt...

Summary

- Clear case to continue exploration of Rare B Decays with vastest dataset available
- Precision required can only be achieved through LHCb PhaseII

Backup

LHCb signal yields

channel	Run 1	Run 2	Run 3,4 (50fb^{-1})
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	2,400	9,000	80,000
$B^0 \to K^{*+}(K^0_S\pi^+)\mu^+\mu^-$	160	600	5,500
$B^0 \to K^0_S\mu^+\mu^-$	180	650	5,500
$B^+ \to K^+\mu^+\mu^-$	4,700	17,500	150,000
$\Lambda_b \to \Lambda\mu^+\mu^-$	370	1500	10,000
$B^+ \to \pi^+\mu^+\mu^-$	93	350	3,000
$B^0_s \to \mu^+\mu^-$	15	60	500
$B^0 \to K^{*0}e^+e^-$ (low q^2)	150	550	5,000
$B_s \to \phi\gamma$	4,000	15,000	150,000

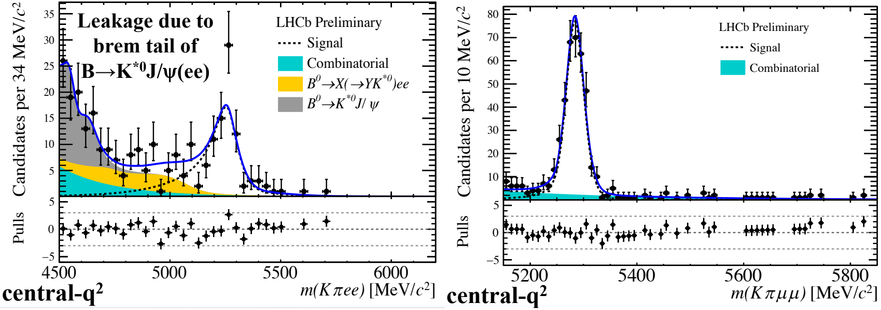
Naively scaling with luminosity and linear scaling of $\sigma_{b\bar{b}}$ with $\sqrt{s}$

- More $b \to s\ell\ell$ decays in Run 1 than $B \to J/\psi K^*$ of B-factories!

Lepton Universality tests

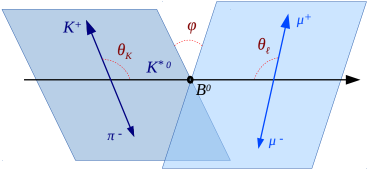
- Challenging measurement due to differences in detector performance between electrons and muons

Left: $B \to K^{*0} e^+ e^-$, Right: $B \to K^{*0} \mu^+ \mu^-$



- Measure in regions of reco'd q^2 regions and correct to true q^2 accounting for bin-migrations using simulated events calibrated to data
- $R_{K^{(*)}}$ measured pre-FSR, using PHOTOS for correction
- Validate measurement with $B \to K^* \gamma$, $B \to J/\psi K^*$ and $B \to \psi(2S) K^*$

Angular analyses



- Differential decay rate of $B^0 \to K^{*0}\mu^+\mu^-$:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

- Measurements of the full basis observables and their correlations minimise the impact of hadronic uncertainties

$B^0 \to K^{*0}e^+e^-$ angular analysis prospects

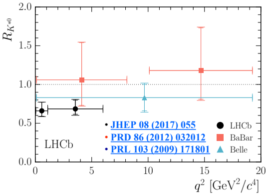
- With Run2, by 2018 data expect $B^0 \to K^{*0}e^+e^-$ yield:
  - ~ 400 in $0.045 < q^2 < 1.1$ GeV^2
  - ~ 500 in $1.1 < q^2 < 6$ GeV^2
  - Similar to $B^0 \to K^{*0}\mu^+\mu^-$ with Run1 data in same bin

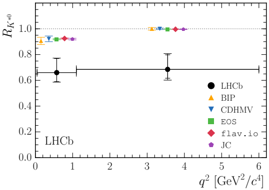
  $\to$ Measurements of multiple angular observables possible through multi-dimensional ML fits

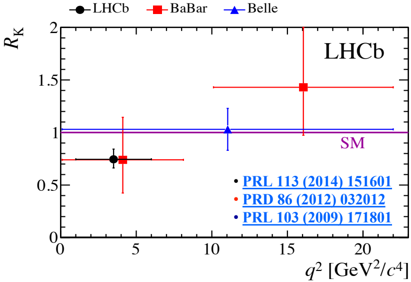
  $\to$ Different experimental effects compared to $R_K^{(*)}$
  - Larger backgrounds than muon case will require good understanding of their angular distribution
  - More robust methods also being investigated

Lepton Flavour Universality tests

Measurement of: $R_{K^{(*)}} = \dfrac{d\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/dq^2}{d\mathcal{B}(B \to K^{(*)}e^+e^-)/dq^2}$







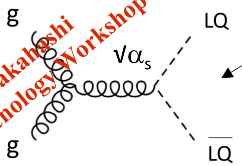
R_K: Central-q^2: 2.6σ from SM

R_{K^*}: Low-q^2: 2.1-2.3σ from SM

R_{K^*}: Central-q^2: 2.4-2.5σ from SM

Leptoquark: search strategy

Prod.



Focus on pair production

- Dominant production mode
- Model-independent cross-section

Focus on scalar LQ

(vector LQ depends on models)

decay

In case of LQ → 3rd gen.

Q = 2/3 or 4/3

$$\text{LQ} \rightarrow \begin{cases} \tau + b \ (\text{Br} = \beta) \\ \nu_\tau + t \ (\text{Br} = 1 - \beta) \end{cases}$$

Q = 1/3 or 5/3

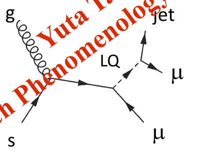
$$\begin{cases} \tau + t \ (\text{Br} = \beta) \\ \nu_\tau + b \ (\text{Br} = 1 - \beta) \end{cases}$$

Final state LQLQ → $\boxed{2\tau + 2b}$ / $2\nu_\tau + 2t$; $\boxed{2\tau + 2t}$ / $2\nu_\tau + 2b$

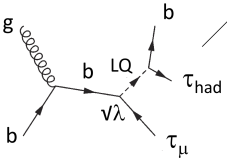
Same final states as stop / sbottom pair prod.
→ recasting is possible (no need to do new analysis)

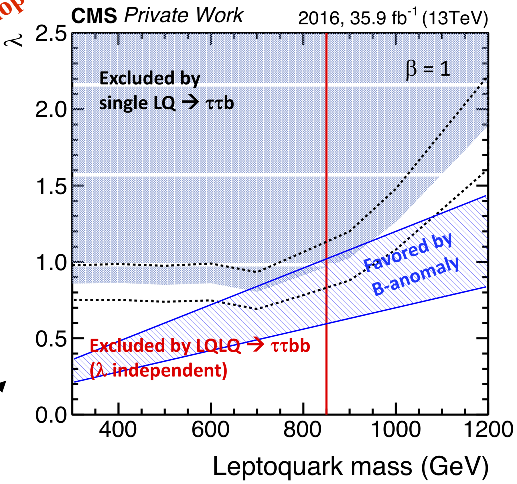
Single LQ prod. decaying to ττb: How far we can go?

CMS-EXO-12-043:
8TeV, 19.6/fb



13TeV, 36/fb





Complementary !