Flavour anomalies in $b \to s\ell^+\ell^-$ transitions at LHCb

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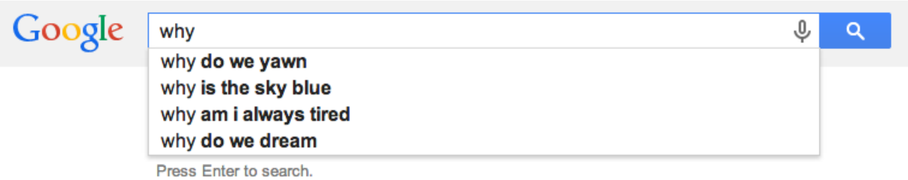
Overview

- Introduction to Rare B decays
- Flavour Anomalies
- Interpretations
- Final Thoughts

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?

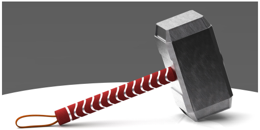
$\rightarrow$ SM is low-energy effective theory

What is the energy scale where new physics shows up?

Experimental approaches

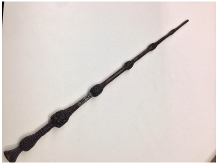
SM could be a low-energy effective theory of a more fundamental theory at higher energy scale with new particles, dynamics/symmetries.

Direct approach



- Rely on high energy collisions to produce new particle(s) on-mass-shell, observed through their decay products

Indirect approach (typical of flavour)



- New particles appear off-mass-shell in heavy flavour processes, leading to deviations from SM expectations

Indirect probe of high NP scales

Look at observables that:

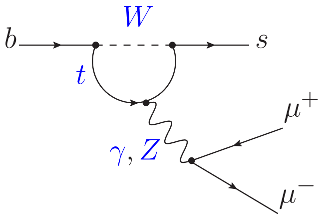
1. The SM contribution is small
2. Can be measured to high precision
3. Can be predicted to high precision

$\rightarrow$ Flavour Changing Neutral Currents in SM

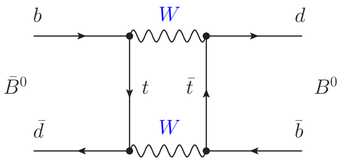
- Loop level
- GIM suppressed
- Left-handed chirality

$\rightarrow$ NP could violate any of these

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

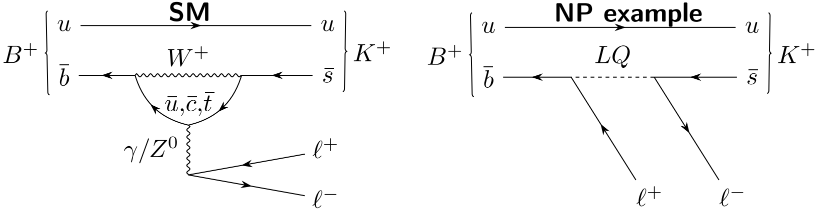


$\Delta F = 2$ **B Mixing**



Types of $b \to s\ell^+\ell^-$ decays

- Occur through $b \to s\ell^+\ell^-$ transition and contain a hadron in the final state. e.g $B^+ \to K^+\ell^+\ell^-$, $B^0 \to K^{*0}\ell^+\ell^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda^*\ell^+\ell^-$...



- Offer multitude of observables.

Theory formalism

- The Operator Product Expansion lies at the heart of the description of rare B decay measurements

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

- "Integrate" out heavy ($\mu \geq m_W$) field(s) and introduce set of:
  - Wilson coefficients C_i describing the (perturbative) short distance part
  - Operators $\mathcal{O}_i$ describing the (non-perturbative) long distance part
    - Account for strong interaction effects difficult to calculate

Sensitivity to New Physics

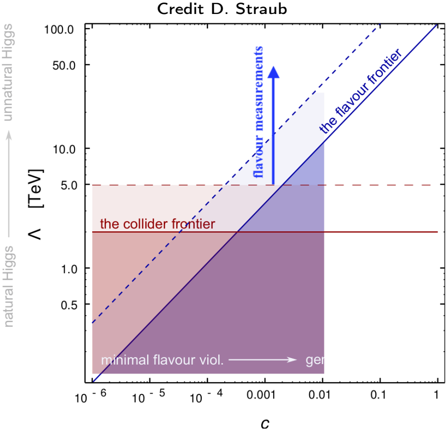
- Different decays sensitive to different operators:

Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to X_{s(d)}\gamma$
$\mathcal{O}_7 \sim (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$ EM	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L \gamma^{\mu} b_L)(\bar{\ell}\gamma_\mu \ell)$ Vector $\ell\bar{\ell}$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L \gamma^{\mu} b_L)(\bar{\ell}\gamma_5\gamma_\mu \ell)$ Axial vector $\ell\bar{\ell}$	✓	✓	
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$ (Pseudo-)Scalar $\ell\bar{\ell}$	(✓)	✓	

Can also get quark chirality flipped counterparts

$\rightarrow$ Probe the complete basis of new physics operators

Collider vs Flavour searches



New Physics scale given current experiment and theory status in rare B decays:

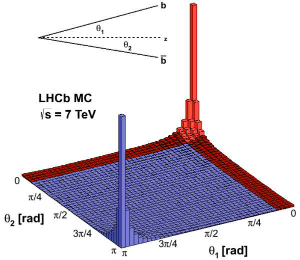
$$\Lambda_9 \gtrsim (0.6 - 35)\ \text{TeV}$$
$$\Lambda_7 \gtrsim (1.5 - 90)\ \text{TeV}$$

depending on couplings and tree/loop level

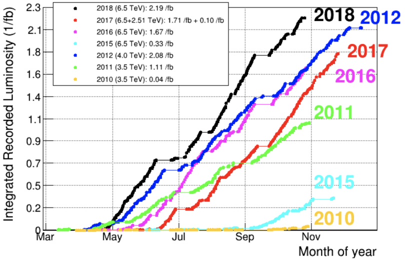
- $b \to s\ell\ell$ transitions probe very high energy scales particularly for generic flavour couplings

Setting the scene

- LHC $\sigma_{b\bar{b}} = 460\,\mu$b @ $\sqrt{s} = 13$ TeV (scale $\sim$ linear with $\sqrt{s}$)
- $\sigma_{b\bar{b}}$ in LHCb acceptance $\sim 100\,\mu$b
  - c.f $\sigma_{b\bar{b}} = 0.001\,\mu$b @ B-factories

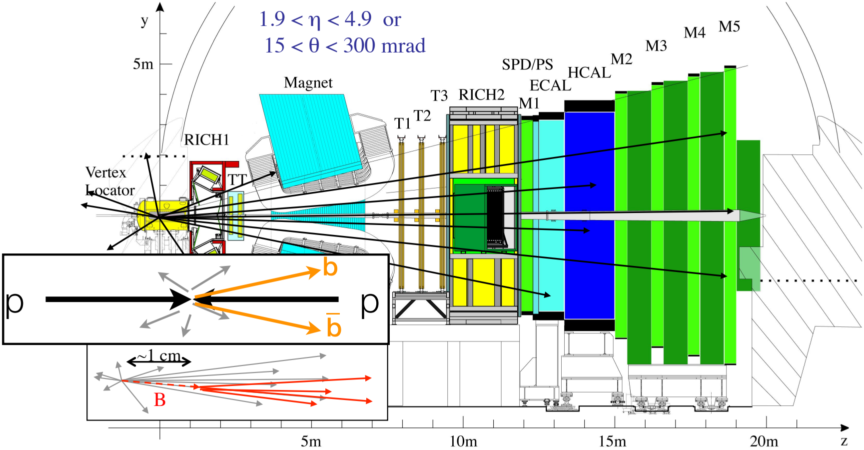


Run 2: 6fb^{-1} @ $\sqrt{s} = 13$TeV
Run 1: 3fb^{-1} @ $\sqrt{s} = 7, 8$TeV,



$L_{inst}^{Max} = 4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ (double the design value)

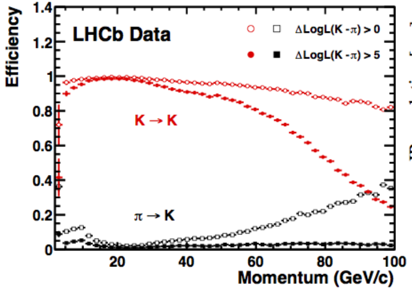
The LHCb detector

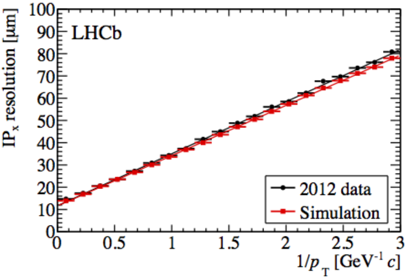


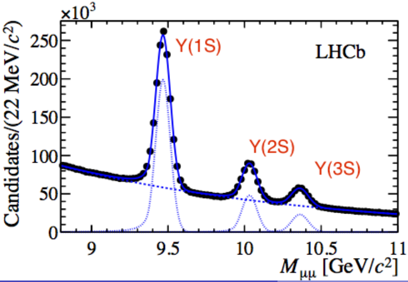
- UK responsible for VeLo and RICH systems
- *B*-lifetime means displaced secondary vertex

Detector performance

[Int.J.Mod.Phys.A30(2015)1530022]







- **Tracking** $\delta p/p = 0.4 - 0.6\%$
- **Muon** $\epsilon_{\mu}^{id} = 98\%$ for 1% mis-id
- Mass resolution $J/\psi \to \mu\mu$
  - LHCb: 13 MeV
  - CMS: 28 MeV [arXiv:1011.4193]
  - ATLAS: 46 MeV [arXiv:1104.3038]

Flavour Anomalies

Over the past decade we have observed a coherent set of tensions with SM predictions

In $b \to s\ell^+\ell^-$ transitions (FCNC)

1. **Branching Fractions**
   $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$

2. **Angular analyses**
   $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$

3. **Lepton Flavour Universality involving μ/e ratios**
   $B^0 \to K^{*0}\ell^+\ell^-$, $B^+ \to K^+\ell^+\ell^-$

In $b \to c\ell\nu$ transitions (tree-level)

4. **Lepton Flavour Universality involving μ/τ ratios**
   $B \to D^{(*)}\ell\nu$

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Lepton Flavour Universality tests

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour
  $\rightarrow$ Branching fractions differ only by phase space and helicity-suppressed contributions

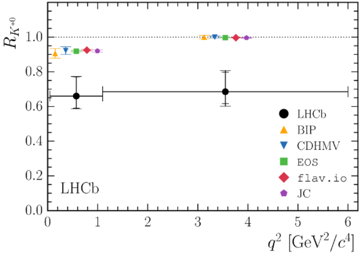
- Ratios of the form:

$$R_{K^{(*)}} := \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \rightarrow K^{(*)}e^+e^-)} \overset{\mathrm{SM}}{\cong} 1$$

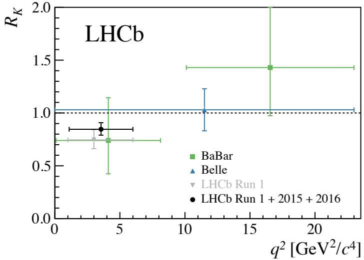
- In SM free from QCD uncertainties affecting other observables
  $\rightarrow \mathcal{O}(10^{-4})$ uncertainty [JHEP07(2007)040]
- Up to $\mathcal{O}(1\%)$ QED corrections [EPJC76(2016)8,440]

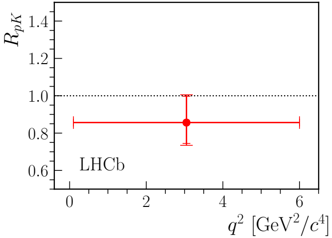
$\rightarrow$ **Any significant deviation is a smoking gun for New Physics.**

Lepton Flavour Universality tests (pre-March 2021)



BaBar:[PRD86(2012)032012],Belle:[PRL103(2009)171801]





Left: $B^0 \to K^{*0}\ell^+\ell^-$ R_{K^*} 3fb^{-1}
[JHEP08(2017)055]

Right: $B^+ \to K^+\ell^+\ell^-$ R_K 5fb^{-1}
[PRL122(2019)191801]

Bottom: $\Lambda_b \to pK\ell^+\ell^-$ R_{pK} 4.7fb^{-1}
[JHEP05(2020)040]

($q^2 \equiv$ dilepton invariant mass squared)

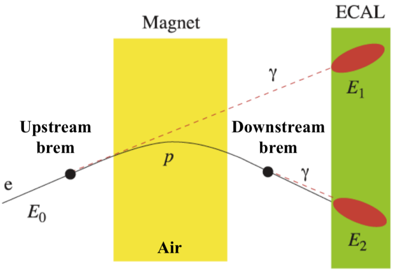
Latest $b \to s\ell\ell$ LFU tests

$$R_{K^{(*)}} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B\to K^{(*)}e^+e^-)}{dq^2} dq^2}$$

- Update R_K in $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ with the full Run2 dataset (doubling the number of B's as previous analysis)
- New LFU tests with:
  - $B^+ \to K^{*+}(\to K_S\pi^+)\ell^+\ell^-$ ($R_{K^{*+}}$)
  - $B^0 \to K_S\ell^+\ell^-$ (R_{K_S})

Electrons vs muons (I)

- Electrons lose a large fraction of their energy through Bremsstrahlung in detector material



- Most electrons will emit one energetic photon the before magnet.

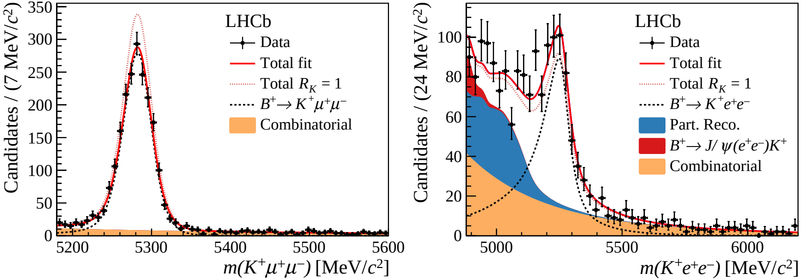
  $\rightarrow$ Look for photon clusters in the calorimeter ($E_T > 75\,\mathrm{MeV}$) compatible with electron direction before magnet.

  $\rightarrow$ Recover brem energy loss by "adding" the cluster energy back to the electron momentum.

Electrons vs muons (II)

- Even after the Bremsstrahlung recovery electrons still have degraded mass and q^2 resolution

From previous result, LHCb [PRL122(2019)191801]



- L0 calorimeter trigger requires higher thresholds, than L0 muon trigger, due to high occupancy.

  $\rightarrow$ Use 3 exclusive trigger categories for e^+e^- final states

  1. $e^\pm$ from signal-B; 2. $K^\pm$ from signal-B; 3. rest of event

- Particle ID and tracking efficiency larger for muons than electrons

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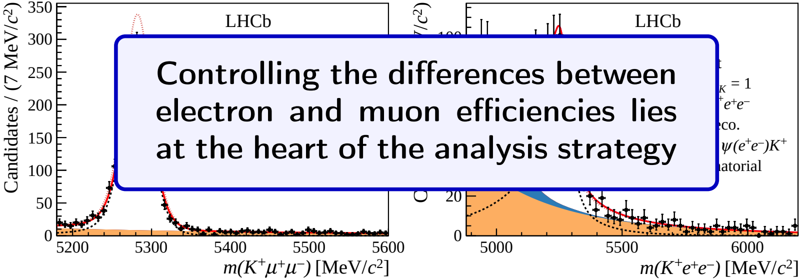

Controlling the differences between electron and muon efficiencies lies at the heart of the analysis strategy

- L0 calorimeter trigger requires higher thresholds, than L0 muon trigger, due to high occupancy.

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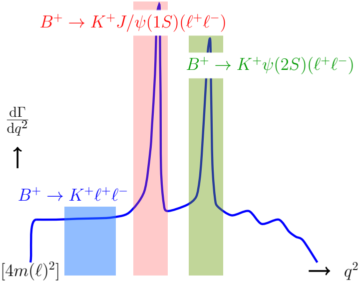
Measurement Strategy

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \frac{N^{\rm rare}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\rm rare}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\rm rare}_{e^+e^-}}{N^{\rm rare}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$

$\rightarrow$ R_K is measured as a **double ratio** to cancel out most systematics

- Rare and J/ψ modes share identical selections apart from cut on q^2
- Yields determined from a fit to the invariant mass of the final state particles
- Efficiencies computed using simulation that is calibrated with control channels in data (trigger, kinematics, PID, resolution)



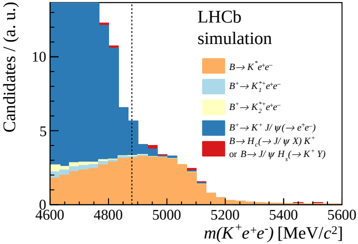
($q^2 \equiv$ dilepton invariant mass squared)

Selection and backgrounds

- Use particle ID requirements and mass vetoes to suppress peaking backgrounds from exclusive B-decays to negligible levels
  - Backgrounds of e.g $B^+ \to \bar{D}^0(\to K^+e^-\nu)e^+\bar{\nu}$: cut on $m_{K^+e^-} > m_{D^0}$
  - Mis-ID backgrounds, e.g. $B \to K\pi^+_{(\to e^+)}\pi^-_{(\to e^-)}$: cut on electron PID
- Multivariate selection to reduce combinatorial background and improve signal significance (BDT)

Residual backgrounds suppressed by choice of $m(K^+\ell^+\ell^-)$ window

- $B^+ \to K^+J/\psi(e^+e^-)$
- Partially reconstructed dominated by $B \to K^+\pi^-e^+e^-$ decays
- Model in fit by constraining their fractions between trigger categories and calibrating simulated templates from data.



Cross-check our estimates using control regions in data and changing $m(K^+\ell^+\ell^-)$ window in fit

Cross-check: Measurement of $r_{J/\psi}$

LHCb [arXiv:2103.11769]Accepted by Nature Physics

- To ensure that the efficiencies are under control, check

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 1,$$

known to be true within 0.4% [Particle Data Group].
$\rightarrow$ Very stringent check, as it requires direct control of muons vs electrons.

- Result:

$$r_{J/\psi} = 0.981 \pm 0.020\ (\mathrm{stat} + \mathrm{syst})$$

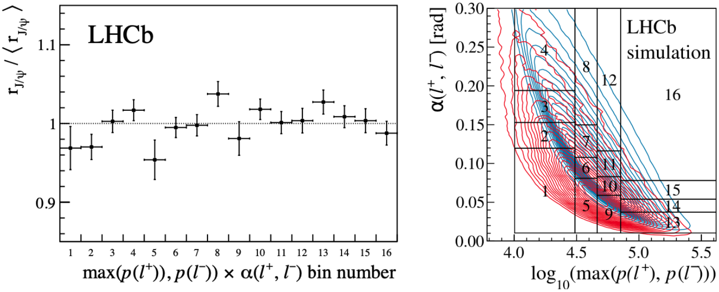
- Checked that the value of $r_{J/\psi}$ is compatible with unity for new and previous datasets and in all trigger samples.

Cross-check: $r_{J/\psi}$ as a function of kinematics

LHCb [arXiv:2103.11769]Accepted by Nature Physics

- Test efficiencies are understood in all kinematic regions by checking $r_{J/\psi}$ is flat in all variables examined.

$B^+ \to K^+e^+e^-$ $B^+ \to J/\psi(e^+e^-)K^+$



- Flatness of $r_{J/\psi}$ 2D plots gives confidence that efficiencies are understood across entire decay phase-space.
  $\rightarrow$ If take departure from flatness as genuine rather than fluctuations (accounting for rare-mode kinematics) bias expected on R_K is 0.1%

Cross-check: Measurement of $R_{\psi(2S)}$

LHCb [arXiv:2103.11769]Accepted by Nature Physics

Measurement of the double ratio

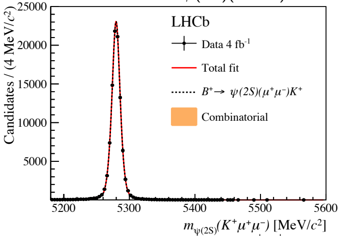
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

- Independent validation of double-ratio procedure at q^2 away from J/ψ
- Result well compatible with unity:

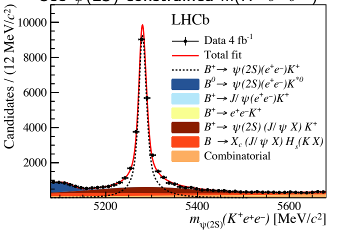
$$R_{\psi(2S)} = 0.997 \pm 0.011\ (\mathrm{stat+syst})$$

$\rightarrow$ can be interpreted as world's best LFU test in $\psi(2S) \rightarrow \ell^+\ell^-$

Fit to new $B^+ \to \psi(2S)(\ell^+\ell^-)K^+$ data



Use $\psi(2S)$ constrained $m(K^+\ell^+\ell^-)$



Systematic uncertainties

LHCb [arXiv:2103.11769]

Dominant sources: $\sim 1\%$

- Choice of fit model
  - Associated signal and partially reconstructed background shape
- Statistics of calibration samples
  - Bootstrapping method that takes into account correlations between calibration samples and final measurement

Sub-dominant sources: $\sim 1‰$

- Efficiency calibration

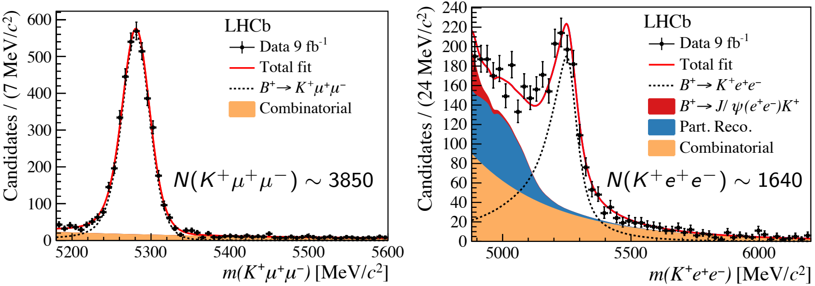
  $\rightarrow$ Dependence on tag definition and trigger biases
  $\rightarrow$ Precision of the q^2 and $m(K^+e^+e^-)$ smearing factors
  $\rightarrow$ Inaccuracies in material description in simulation
  ...

Total relative systematic of 1.5% in the final R_K measurement
$\rightarrow$ Expected to be statistically dominated

Measuring R_K

LHCb [arXiv:2103.11769]

- R_K is extracted as a parameter from an unbinned maximum likelihood fit to $m(K^+\mu^+\mu^-)$ and $m(K^+e^+e^-)$ distributions in $B^+ \to K^+\ell^+\ell^-$ and $B^+ \to J/\psi(\ell^+\ell^-)K^+$ decays



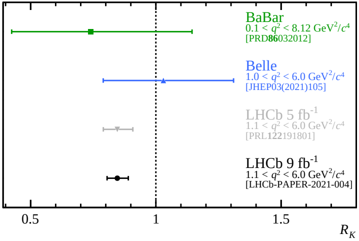
- Correlated uncertainties on efficiency ratios included as multivariate constraint in likelihood

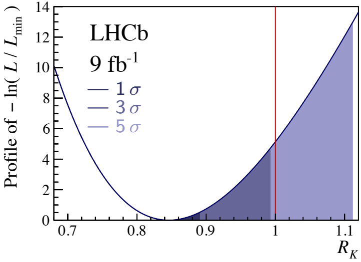
R_K with full Run1 and Run2 dataset

LHCb [arXiv:2103.11769]Accepted by Nature Physics

$$R_K = 0.846 \,^{+0.042}_{-0.039}\,(\text{stat})\,^{+0.013}_{-0.012}\,(\text{syst})$$

- p-value under SM hypothesis: 0.0010
  $\rightarrow$ Evidence of LFU violation at 3.1σ
- Compatibility with the SM obtained by integrating the profiled likelihood as a function of R_K above 1
  - Taking into account the 1% theory uncertainty on R_K [EPJC76(2016)8,440]





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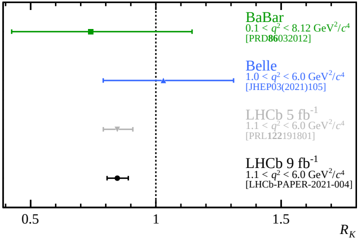
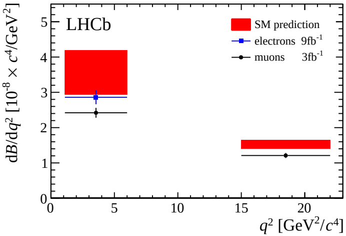
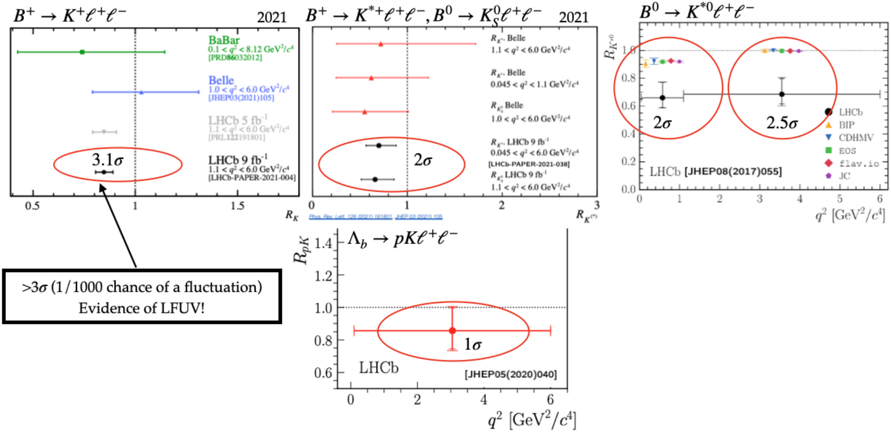
- p-value under SM hypothesis: 0.0010 $\rightarrow$ Evidence of LFU violation at 3.1σ
- Using R_K and previous measurement of $\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$ [JHEP06(2014)133] determine $\mathcal{B}(B^+ \rightarrow K^+e^+e^-)$.
- Suggests electrons are more SM-like than muons.





$$\frac{\mathrm{d}\mathcal{B}(B^+\rightarrow K^+e^+e^-)}{\mathrm{d}q^2} = (28.6\ ^{+1.5}_{-1.4}(\text{stat})\ \pm 1.4(\text{syst})) \times 10^{-9}\ c^4/\,\text{GeV}^2.$$

All $b \to s\ell\ell$ LFU measurements as of 2022



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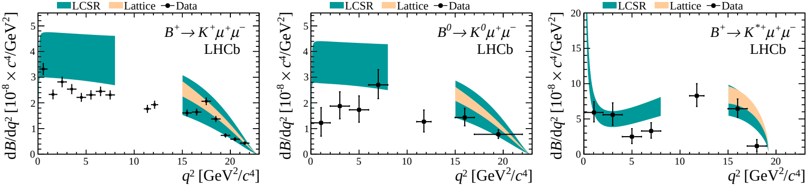
In $b \to c\ell\nu$ transitions (tree-level)

4. Lepton Flavour Universality involving μ/τ ratios
   $B \to D^{(*)}\ell\nu$

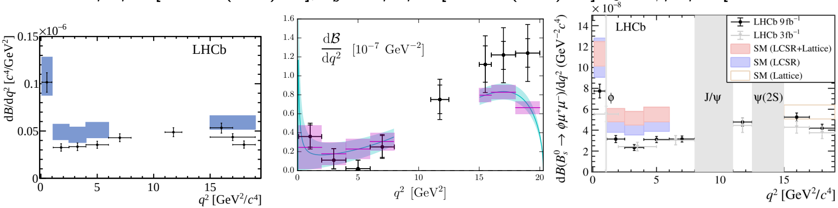
1. Decay Rates

- Measurements consistently below theory predictions at low $q^2 \equiv m^2_{\ell\ell}$ for many $b \to s\mu^+\mu^-$ decays

[JHEP06(2014)133]



$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [PRL127.151801]

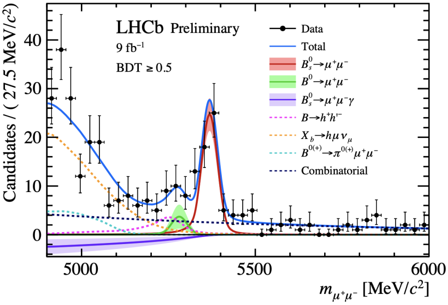


- SM predictions suffer from large hadronic uncertainties

1. Decay Rates – The golden one

New $B^0_{(s)} \to \mu^+\mu^-$ measurement by LHCb last March [2108.09283]

- Precise SM prediction (4% uncertainty)
  [Bobeth et al PRL112.101801], [Beneke et al JHEP10(2019)232]
- Combination with CMS and ATLAS $\to$ measurement compatible with SM at 2σ

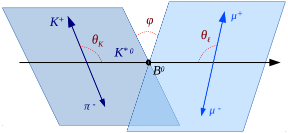


- $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$

- $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$ compatible with background only at 1.7σ and 1.5σ

- Best limits on: $\mathcal{B}(B^0_{(s)} \to e^+e^-) < 2.5(9.4) \times 10^{-9}$ at 95% CL
  $\mathcal{B}(B^0_{(s)} \to \tau^+\tau^-) < 2.1(6.8) \times 10^{-3}$ at 90% CL
  [LHCb PRL124.211802], [LHCb PRL118.251802]
  $\to$ SM contribution scales as $m^2_{e,\tau}/m^2_\mu$ compared to $B^0_{(s)} \to \mu^+\mu^-$

2. Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



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

$$\frac{1}{\Gamma'_{full}}\frac{d^4\Gamma}{dq^2\,d\cos\theta_K\,d\cos\theta_l\,d\phi} =$$

Matias et al
JHEP05(2013)137

$$\frac{9}{32\pi}\Big[\frac{3}{4}F_T\sin^2\theta_K + F_L\cos^2\theta_K + (\frac{1}{4}F_T\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l$$

$$+\frac{1}{2}P_1F_T\sin^2\theta_K\sin^2\theta_l\cos 2\phi + \sqrt{F_TF_L}\left(\frac{1}{2}P'_4\sin 2\theta_K\sin 2\theta_l\cos\phi + P'_5\sin 2\theta_K\sin\theta_l\cos\phi\right)$$

$$+2P_2F_T\sin^2\theta_K\cos\theta_l - \sqrt{F_TF_L}\left(P'_6\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}Q'\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$

$$-P_3F_T\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big](1-F_S) + \frac{1}{\Gamma'_{full}}W_S$$

The coefficients of the polluting term can be parametrized as

$$\frac{W_S}{\Gamma'_{full}} = \frac{3}{16\pi}\left[F_S\sin^2\theta_\ell + A_S\sin^2\theta_\ell\cos\theta_K + A_S^4\sin\theta_K\sin 2\theta_\ell\cos\phi\right.$$

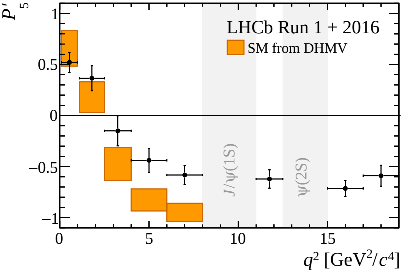
$$\left.+A_S^5\sin\theta_K\sin\theta_\ell\cos\phi + A_S^7\sin\theta_K\sin\theta_\ell\sin\phi + A_S^8\sin\theta_K\sin 2\theta_\ell\sin\phi\right]$$

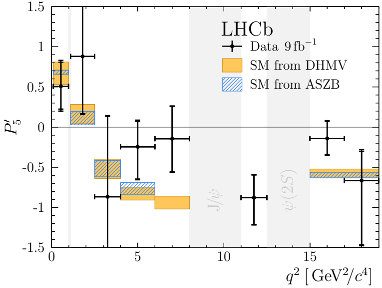
- Measure 16 observables (CP symmetric and asymmetric) through a quasi 4D angular and $m_{K\pi}$ fit in bins of q^2
- Each observable sensitive to different types of new physics couplings

2. Angular analyses of $B \to K^{*}\mu^{+}\mu^{-}$

- The large number of observables cover full spectrum of new physics models
  - Orthogonal expt. systematics and more precise theory predictions

Left: $B^{0} \to K^{*0}\mu^{+}\mu^{-}$ [PRL125011802(2020)], Right: $B^{+} \to K^{*+}\mu^{+}\mu^{-}$ [arXiv:2012.13241]





- Combination of all angular observables suggests $\sim 3\sigma$ tension with SM predictions in each channel
- New $B_s \to \phi\mu\mu$ angular analysis from LHCb [JHEP 11 (2021) 043] consistent with SM at 1.9σ

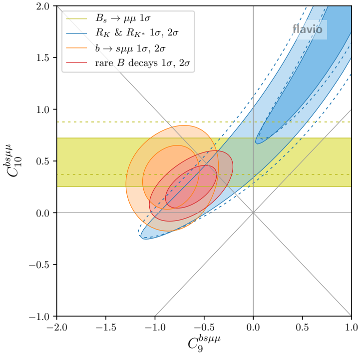
Putting it all together

- Combination all $b \to s\ell^+\ell^-$ measurements
  - $> 6\sigma$ from SM

- $B_s \to \mu^+\mu^-$ and LFU observables have very clean theory predictions.
  - $\sim 4.5\sigma$ from SM
  - Global significance 4.3σ from SM

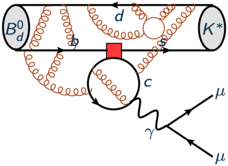
    Isidori et al [PLB822(2021)136644]

- Measurements point to new vector coupling (C_9^μ)



- $B \to K^{(*)}\mu^+\mu^-$ BF and angular observables potentially suffer from underestimated hadronic uncertainties.

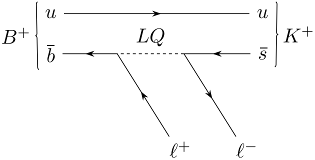
  $\to$ Can extract hadronic contributions directly from data
  [Bobeth et al EPJC(2018)78:451], [Pomery, KP et al EPJC(2018)78:453]



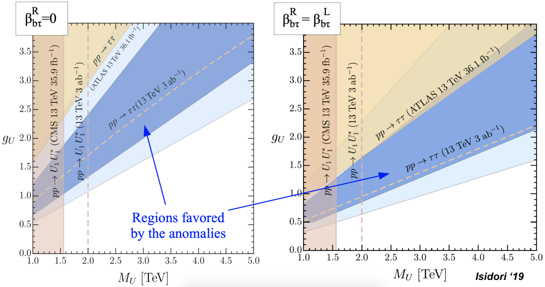
Interpretations

Models that address anomalies can also explain hierarchical structure of quark and lepton mass matrices Isidori et al [PLB(2018)317]

- Leptoquarks Isidori et al, Greljo et al, Buttazzo et al...



Highly predictive models: **High energy signatures**

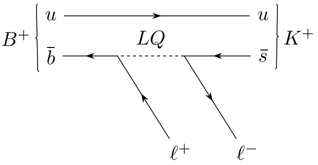


- Third generation dominance and $SU(2)_L$ invariance (link to $b \to c\ell\nu$ LFUV) means leptoquark mass < 5TeV!
- With 3ab^{-1} $pp \to \tau\tau$ ATLAS/CMS probe significant fraction of parameter space

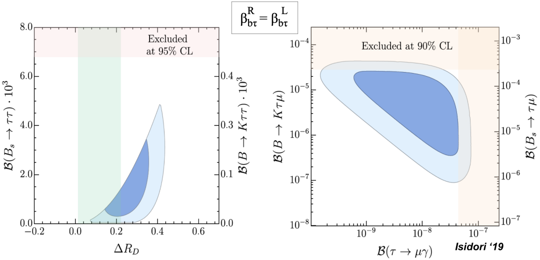
Interpretations

Models that address anomalies can also explain hierarchical structure of quark and lepton mass matrices Isidori et al [PLB(2018)317]

- Leptoquarks Isidori et al, Greljo et al, Buttazzo et al...



Highly predictive models: **Low energy signatures**



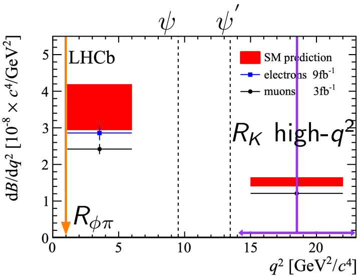
- 10^3 enhancement of $b \to s\tau\tau$ and $b \to s\tau\mu$ that LHCb and Belle2 will be sensitive to

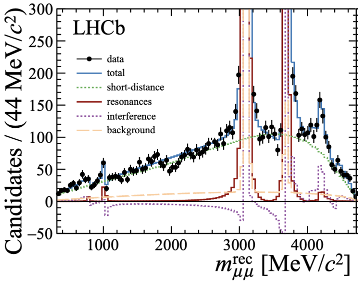
Crucial followup measurements

- Measure R_K at $q^2 > 4m_D^2$ and test experimental methodology with control mode at $q^2 = 1\,\mathrm{GeV}^2/c^4$
- Update $R_{...}$ and angular measurements with full Run2 data from LHCb (and CMS?)
- LFU tests of angular observables eg $Q_5 = P_5'(\mu\mu)$-$P_5'(ee)$
- Measure charm loops in $B \to K^{(*)}\mu^+\mu^-$ from the data

  $\to$ Can extract hadronic contributions directly from data

  [Bobeth et al EPJC(2018)78:451], [Blake, KP et al EPJC(2018)78:453]
- Measurements with τs e.g $B \to K\tau\tau$, $B \to K\tau\mu$





Final thought

- Lack of New Physics in direct searches at the LHC lifts requirement of Minimal Flavour Violation.

  $\rightarrow$ Flavour measurements sensitive to large new physics scales beyond reach of current or future colliders.

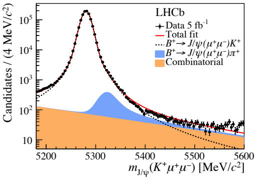
- Without guidance on scale of New Physics, Flavour measurements are key!

- Whether these anomalies are eventually established or evaporate, they have reminded us that multiple flavour measurements have the ability to triangulate the energy scale of new physics.

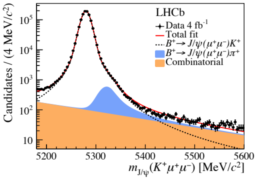
Backup

Control mode fits

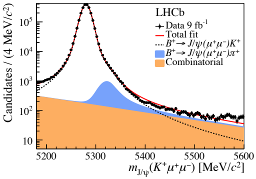
LHCb [arXiv:2103.11769]



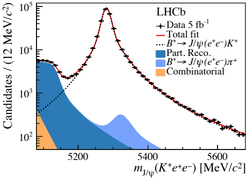
Previous data



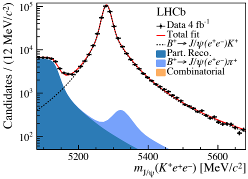
New data



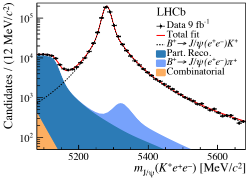
Total data



Previous data



New data



Total data

Signal Lineshape

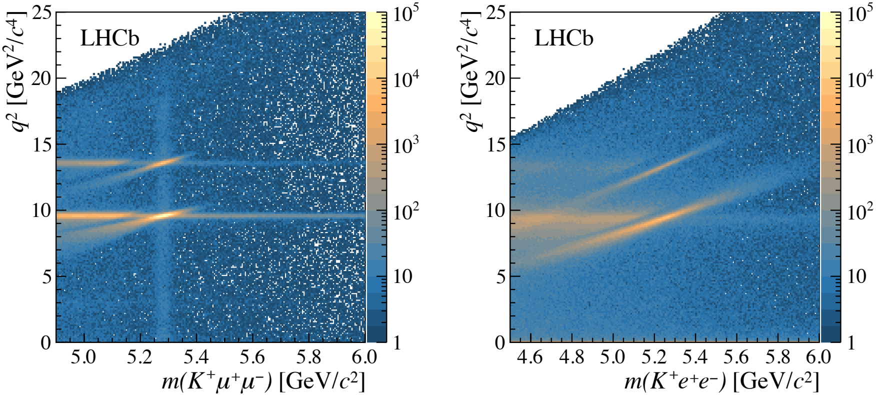
- The $m(K^+\ell^+\ell^-)$ distributions of the rare mode are obtained from simulated decays, calibrating the peak and width of the distribution using $B^+ \to J/\psi(\ell^+\ell^-)K^+$ data.

- In the subsequent fit to the rare mode the $m(K^+\ell^+\ell^-)$ lineshape is fixed.

- The q^2 scale/resolution in the simulation is corrected using the same procedure
  $\to$ the efficiency of the q^2 cut is calibrated from the data

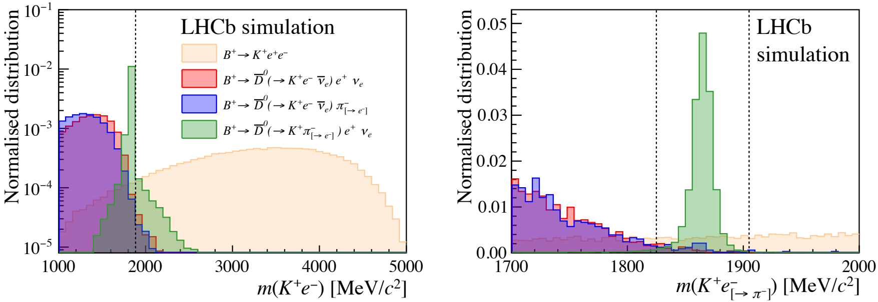
$B^+ \to K^+\ell^+\ell^-$

[PRL122(2019)191801]

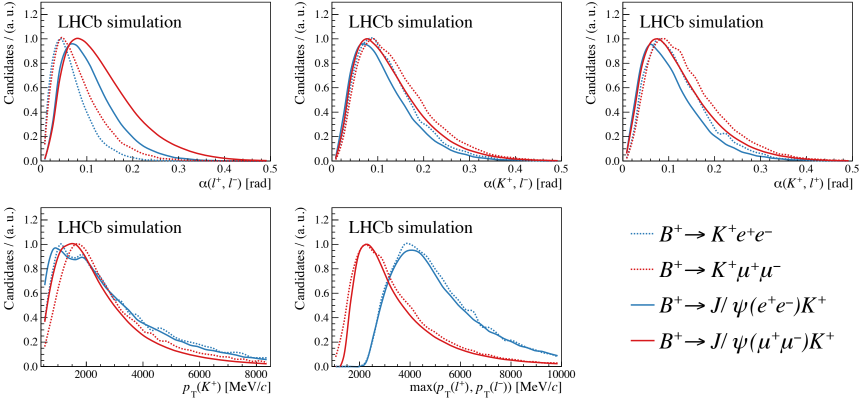


Semileptonic vetos

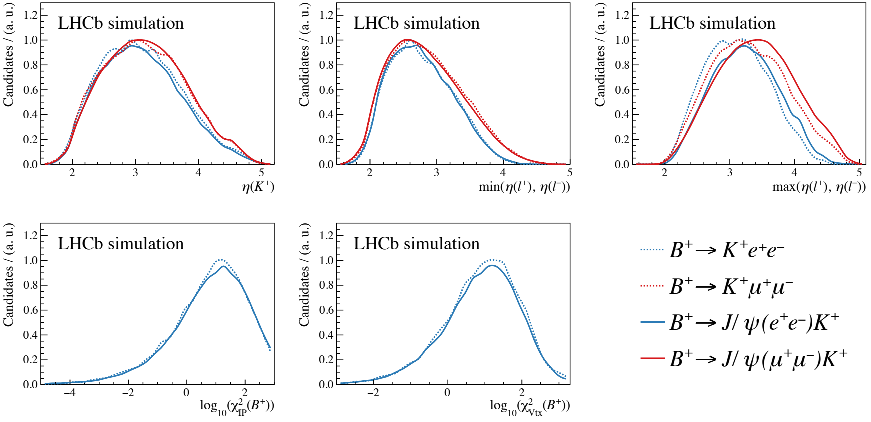
LHCb [arXiv:2103.11769]



Parameter overlap (I)



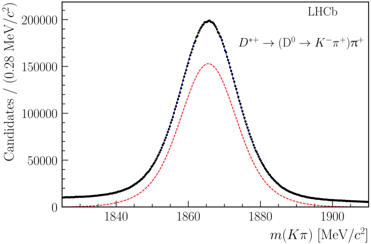
Parameter overlap (II)



Efficiency calibration

Ratio of efficiencies determined with simulation carefully calibrated using control channels selected from data:

- Particle ID calibration
  - Tune particle ID variables for diff. particle species using kinematically selected calibration samples ($D^{*+} \to D^0(K^-\pi^+)\pi^+$...) [EPJ T&I(2019)6:1]
- Calibration of q^2 and $m(K^+e^+e^-)$ resolutions
  - Use fit to $m(J/\psi)$ to smear q^2 in simulation to match that in data
- Calibration of B^+ kinematics
- Trigger efficiency calibration



Calibration of B^+ kinematics

- Calibrate the simulation so that it describes correctly the kinematics of the B^+'s produced at LHCb.
- Compare distributions in data and simulation using $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ candidates.
- Iterative reweighing of $p_T(B^+) \times \eta(B^+)$, but also the vertex quality and the significance of the B^+ displacement.

[PRL 122 (2019) 191801]

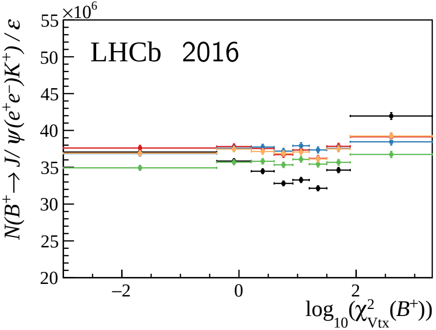
none

$\mu\mu$ L0Muon, nominal

$\mu\mu$ L0TIS

ee L0Electron

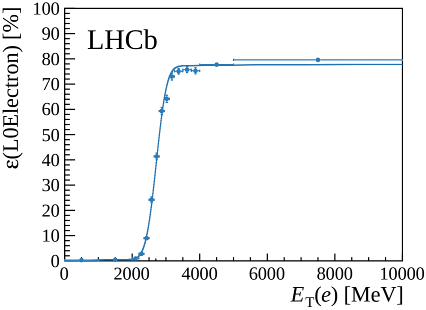
$VTX\chi^2$: ee L0Electron, $p_T(B)\times\eta(B)$, $IP\chi^2$: $\mu\mu$ L0Muon



$\to$ Systematic uncertainty from RMS between all these weights

Trigger efficiency

The trigger efficiency is computed in data using $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ decays through a tag-and-probe method



Especially for the electron samples, need to take into consideration some subtleties:

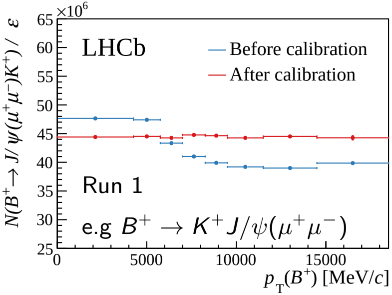
- dependence on how the calibration sample is selected,
- correlation between the two leptons in the signal.

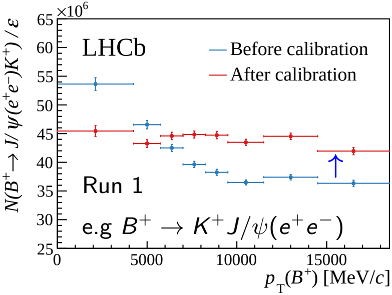
Repeat calibration with different samples/different requirements on the accompanying lepton

→ Associated systematic in the ratio of efficiencies is small

Efficiency calibration summary

- After calibration, very good data/MC agreement in all key observables





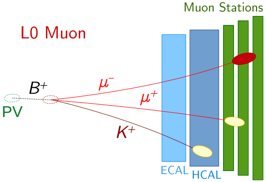
Maximal effect of turning off corrections results in relative shift R_K $(+3 \pm 1)\%$ compared to 20% in $r_{J/\psi}$.
Demonstrates the robustness of the double-ratio method in suppressing systematic biases that affect the resonant and nonresonant decay modes similarly.

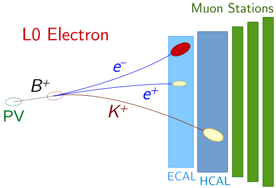
Trigger strategy

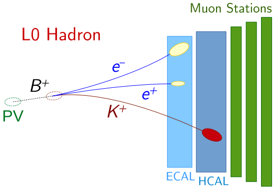
[Credit: Dan Moise]

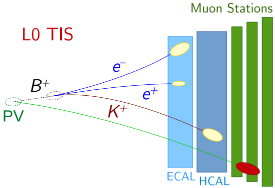
Same approach as in the previous analysis:

- for $\mu\mu$ channels, trigger on muons: `L0Muon`
- for *ee* channels, use three exclusive trigger categories: `L0Electron`, `L0Hadron`, `L0TIS`
- systematics calculated and cross-checks performed for each trigger individually





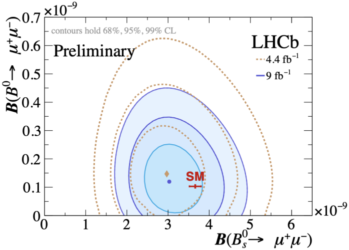


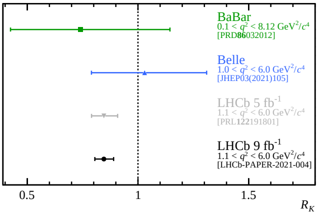


Conclusions

Using the full LHCb dataset to date, presented:

1. Single most precise measurement of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$, improved precision on $\tau_{\mu^+\mu^-}$ and first every limit on $B_s^0 \to \mu^+\mu^-\gamma$
2. Updated R_K measurement $\to$ 3.1σ departure from LFU!
   $\to$ Reframing discussion on flavour anomalies

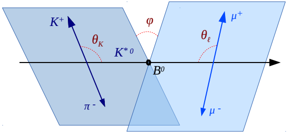




Complementarity between R_K and $\mathcal{B}(B_s^0 \to \mu^+\mu^+)$ measurements crucial moving forward.

"...perhaps the end of the beginning."

2. Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



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

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega}) \quad \text{and}$$
$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega}) \ ,$$

- I_i: bilinear combinations of 6 P-wave and 2 S-wave helicity amplitudes (since K^{*0} can be found in $J = 1$ and $J = 0$)
- Reparametrise distribution in terms of:

$$S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right) \quad \text{and}$$
$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right) .$$

- Determine 8 S_i and 8 A_i for P-wave K^{*0} through a quasi 4D angular and $m_{K\pi}$ fit in bins of q^2

What are these I_is I hear you ask?

i	I_i	f_i
$1s$	$\frac{3}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K$
$1c$	$\lvert\mathcal{A}_0^{\rm L}\rvert^2 + \lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K$
$2s$	$\frac{1}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K \cos 2\theta_l$
$2c$	$-\lvert\mathcal{A}_0^{\rm L}\rvert^2 - \lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K \cos 2\theta_l$
3	$\frac{1}{2}\left[\lvert\mathcal{A}_\perp^{\rm L}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2\right]$	$\sin^2\theta_K \sin^2\theta_l \cos 2\phi$
4	$\sqrt{\frac{1}{2}}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_l \cos\phi$
5	$\sqrt{2}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K \sin\theta_l \cos\phi$
$6s$	$2{\rm Re}(\mathcal{A}_\parallel^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_\parallel^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin^2\theta_K \cos\theta_l$
7	$\sqrt{2}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K \sin\theta_l \sin\phi$
8	$\sqrt{\frac{1}{2}}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_l \sin\phi$
9	${\rm Im}(\mathcal{A}_\parallel^{\rm L*}\mathcal{A}_\perp^{\rm L} + \mathcal{A}_\parallel^{\rm R*}\mathcal{A}_\perp^{\rm R})$	$\sin^2\theta_K \sin^2\theta_l \sin 2\phi$

10	$\frac{1}{3}\left[\lvert\mathcal{A}_{\rm S}^{\rm L}\rvert^2 + \lvert\mathcal{A}_{\rm S}^{\rm R}\rvert^2\right]$	1
11	$\sqrt{\frac{4}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K$
12	$-\frac{1}{3}\left[\lvert\mathcal{A}_{\rm S}^{\rm L}\rvert^2 + \lvert\mathcal{A}_{\rm S}^{\rm R}\rvert^2\right]$	$\cos 2\theta_l$
13	$-\sqrt{\frac{4}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K \cos 2\theta_l$
14	$\sqrt{\frac{2}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\parallel^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin\theta_K \sin 2\theta_l \cos\phi$
15	$\sqrt{\frac{8}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin\theta_l \cos\phi$
16	$\sqrt{\frac{8}{3}}{\rm Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\parallel^{\rm L*} - \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin\theta_l \sin\phi$
17	$\sqrt{\frac{2}{3}}{\rm Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\perp^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin 2\theta_l \sin\phi$

And what do the amplitudes look like?

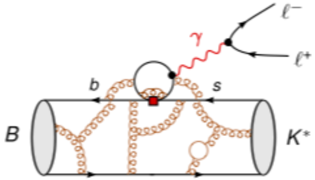
[JHEP 0901(2009)019] Altmannshofer et al.

$$\mathcal{A}_0^{L,R}(q^2) = -8N\frac{m_B m_{K^*}}{\sqrt{q^2}}\left\{(C_9 \mp C_{10})A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}}C_7 T_{23}(q^2) + \mathcal{G}_0(q^2)\right\},$$

$$\mathcal{A}_\parallel^{L,R}(q^2) = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{(C_9 \mp C_{10})\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}C_7 T_2(q^2) + \mathcal{G}_\parallel(q^2)\right\},$$

$$\mathcal{A}_\perp^{L,R}(q^2) = N\sqrt{2\lambda}\left\{(C_9 \mp C_{10})\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}C_7 T_1(q^2) + \mathcal{G}_\perp(q^2)\right\},$$

- $\mathbf{C}_{7,9,10}$: Wilson coefficients
- $\mathbf{A}_i$, $\mathbf{T}_i$, $\mathbf{V}_i$: $B \to K^*$ form factors
- $\mathbf{G}_{\parallel,\perp,0}$: Charm-loop contribution



P_5' what?

- Can also reparametrise angular distribution in terms of less form-factor dependent observables (so-called P_i basis) e.g:

$$P_5' \sim \frac{Re(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{(|A_0^L|^2 + |A_0^R|^2)(|A_\perp^L|^2 + |A_\perp^R|^2 + |A_\parallel^L|^2 + |A_\parallel^R|^2)}}$$

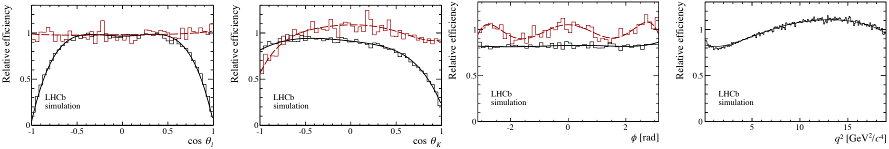
- Recent advancements in form-factor calculations coupled with availability of experimental correlations between all observables makes this reparametrisation less important

Acceptance correction

- Trigger, reconstruction and selection efficiency distorts the angular and q^2 distribution of $B^0 \to K^{*0}\mu^+\mu^-$
- Acceptance correction parametrised using 4D Legendre polynomials
- Use moment analysis in $B^0 \to K^{*0}\mu^+\mu^-$ MC to obtain coefficients c_{klmn}
- Measurements in $B^0 \to J/\psi K^{*0}$ control mode in excellent agreemnt with expectation

$$\varepsilon(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \sum_{klmn} c_{klmn} P_k(\cos\theta_\ell) P_l(\cos\theta_K) P_m(\phi) P_n(q^2)$$

1D projections



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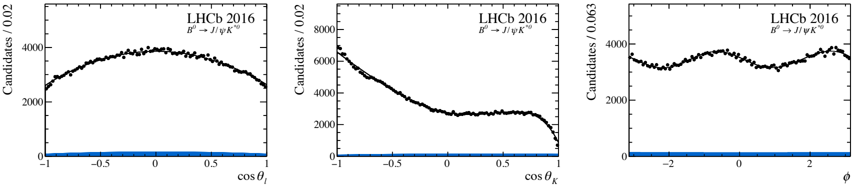
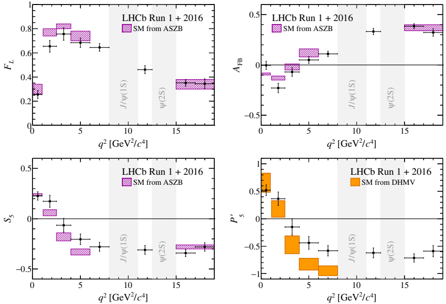
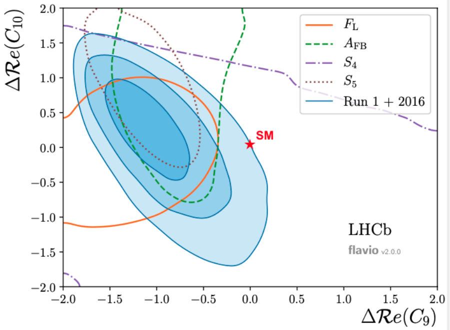


Angular analysis results

Latest update of the 8 CP-averaged observabes using data up to 2016
[Phys. Rev. Lett. 125 (2020) 011802]

Just show a subset here

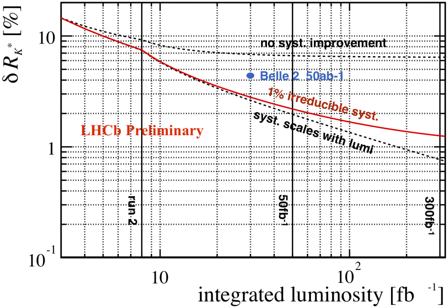




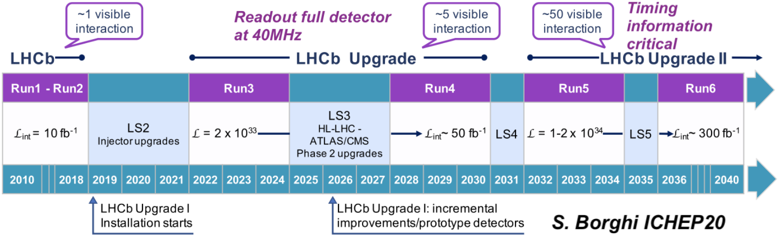
- Suggesting anomalous vector-dilepton coupling (C_9)
- Working on update with twice the data!

Rare decays in Run3 and beyond

- Still have x2 the data to study for most of these analyses just from Run2 alone
  - Much clearer picture in less than 1 year's time
- Angular and LFU measurements statistically limited even after Run3 of the LHC
- Increased dataset → determine theory nuisances directly from the data improving theory accuracy and precision
  - Working with existing data on this

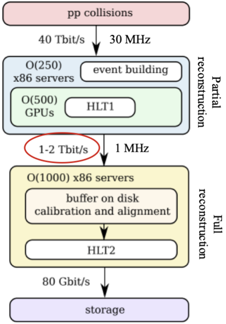


- Larger datasets also bring LHCb's sensitivitiy to τ final states comparable to theory predictions that explain anomalies
  → Smoking gun signatures of anomalies



S. Borghi ICHEP20

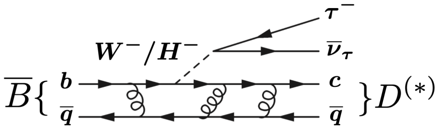
- Upgrade for Run3 driven by having to read out full detector at 30MHz and higher instantaneous lumi ($4 \times 10^{32} \to 2 \times 10^{33} \mathrm{cm}^{-2} s^{-1}$)
- Fully-software trigger using GPUs for HLT1 and CPUs for HLT2 (RTA before HLT2)
- Upgrade readout electronics of every detector subsystem
- VELO pixels, Sci-Fi tracker, UT silicon strip, new RICH with MaPMT



Comput. Softw. Big Sci. (2020) 4, 7
CERN-LHCC-2020-006

LFU tests with $b \to c\ell\nu$

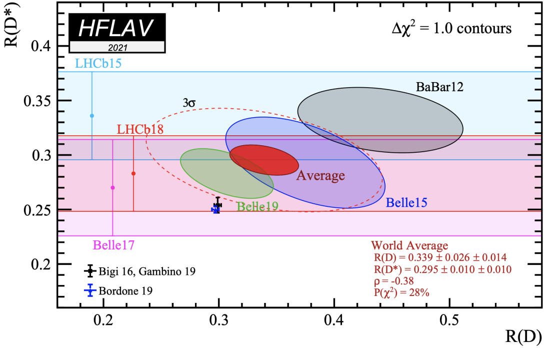
$$R_{D^{(*)}} := \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

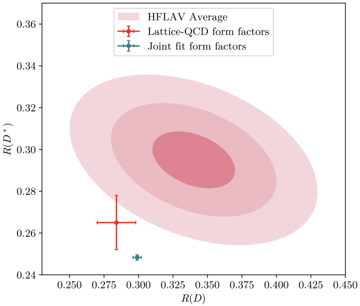


- Good theoretical control due to factorisation of leptonic and hadronic components in decay.
- Tree level process in SM $\to$ requires huge new physics contribution in contrast to $b \to s\ell\ell$ where the SM is suppressed.

$b \to c\ell\nu$ LFU status

- Combination of LHCb results and BaBar/Belle
  - Precision dominated by B-factories
  - Measurements with LHCb's Run2 underway
- Tension with SM $\sim 3.1\sigma$
- New FNAL/MILC lattice results on $B \to D^*$: $< 3\sigma$ FNAL/MILC [2105.14019]





- Further results from lattice and experiment are needed

R_{Λ_c} for $b \to c\ell\nu$ LFU

Hot of the press!

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2021-265
LHCb-PAPER-2021-044
January 10, 2022

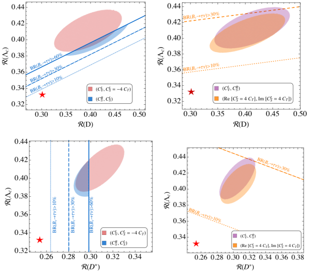
Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$

LHCb collaboration†

Abstract

The first observation of the semileptonic b-baryon decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$, with a significance of $6.1\,\sigma$, is reported using a data sample corresponding to $3\,\text{fb}^{-1}$ of integrated luminosity, collected by the LHCb experiment at centre-of-mass energies of 7 and 8 TeV at the LHC. The τ^- lepton is reconstructed in the hadronic decay to three charged pions. The branching fraction $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\%$ is obtained, where uncertainties are statistical, systematic and from the external branching fraction of the normalisation channel $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$. The ratio of semileptonic branching fractions $\mathcal{R}(\Lambda_c^+) \equiv \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)$ is derived to be $0.242 \pm 0.026 \pm 0.040 \pm 0.059$, where the external branching fraction uncertainty from the channel $\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu$ contributes to the last term. This result is in agreement with the Standard Model prediction.

Submitted to Phys. Rev. Lett.



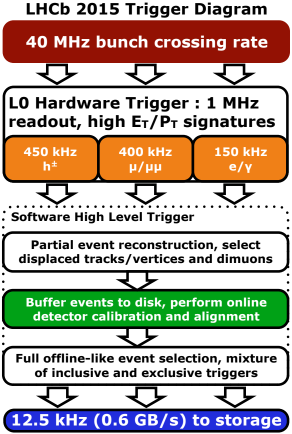
Blanke et al arXiv:1211:0960

FIG. 3. Preferred $1\,\sigma$ regions in the four two-dimensional scenarios in the $\mathcal{R}(D^{(*)})$–$\mathcal{R}(\Lambda_c)$ plane for $\text{BR}(B_c \to \tau\nu) < 60\%$. The regions of the plot in the left panel correspond to the scenarios $(C_V^L, C_S^L = -4C_T)$ (red) and (C_S^R, C_S^L) (blue), while the plots on the right side correspond to (C_V^L, C_S^R) (purple) and $(C_S^L = 4\,C_T)$ (orange). The solid, dashed and dotted lines refer to a limit on $\text{BR}(B_c \to \tau\nu)$ of 60%, 30% and 10%, respectively. The stars represent the SM predictions.

The LHCb trigger in Run 2

The challenge

- Only 1 in 200 pp inelastic events contain a *b*-quark
- Looking for *B*-hadron decays with $BF \sim 10^{-6} - 10^{-9}$



Major development for Run 2:

- Buffer all events after HLT1 to perform calibrations and alignment
  - Determine calibration and alignment constants per fill (minutes)
  - Global offline-like reconstruction using these constants
  - Major step towards realising upgrade trigger strategy (see later)

$\rightarrow$ More selective triggers e.g offline like particle ID in the trigger!