Latest results on EW penguin modes from LHCb and future prospects

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Probing New Physics with EW penguins

Look at observables that:

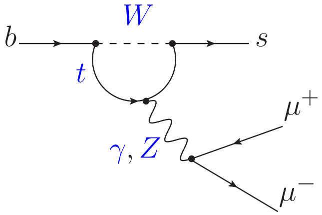
1. Have a small SM contribution
2. Can be measured to high precision
3. Can be predicted to high precision

→ Flavour Changing Neutral Currents in SM

- Loop level
- GIM suppressed
- Left-handed chirality

→ NP could violate any of these

$\Delta F = 1$ Rare B decays



An intriguing set of results

1. Tests of Lepton Flavour Universality in decay rates of $B \to K^{(*)}\ell^+\ell^-$
   $\to$ Cancellations of hadronic uncertainties in predictions

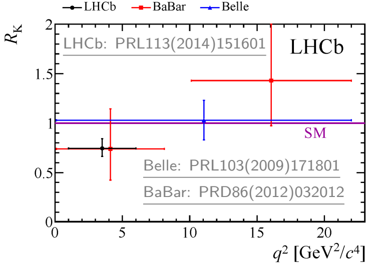
2. Measurements of decay rates of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$
   $\to$ Large theory uncertainties.

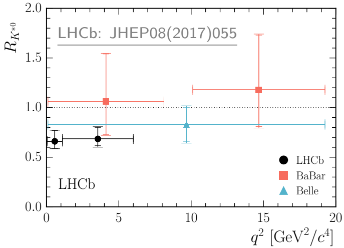
3. Angular analyses of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$
   $\to$ Can access observables with reduced dependence on theory uncertainties

1. Lepton Flavour Universality tests

- Ratios of form: $\frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to K^{(*)}e^+e^-)} = 1.0$ in SM with $\mathcal{O}(10^{-4})$ error [JHEP07(2007)040]
- Up to $\mathcal{O}(1\%)$ corrections due to QED corrections [EPJC76(2016)8,440]
  $\to$ Any statistically significant deviation is smoking gun for New Physics

$$\to \text{Measure: } R_{K^{(*)}} = \frac{\int \frac{d\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{dq^2} dq^2}{\int \frac{d\mathcal{B}(B\to K^{(*)}e^+e^-)}{dq^2} dq^2}$$





Run1: R_K: Central-q^2: 2.6σ from SM
Run1: R_{K^*}: Low-q^2: 2.1-2.3σ from SM, Central-q^2: 2.4-2.5σ from SM

NEW: Update of R_K in $1.1 < q^2 < 6.0\ \text{GeV}/c^2$

[LHCb arXiv:1903.09252]

- Completely re-optimised 2011 and 2012 data and re-designed analysis strategy
- Added 2015 and 2016 collected during LHCb's Run2

  $\rightarrow$ Double the sample size compared to previous analysis

Details of measurement

- Performance of electron and muon final states differs in LHCb
  - Electrons emit more bremsstrahlung through interactions with LHCb detector

    $\rightarrow$ Worse mass and q^2 resolution

    $\rightarrow$ Lower reconstruction efficiency
- Measure R_K in using a double-ratio involving rare- and resonant- modes

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

$\rightarrow$ Cancel out most systematic uncertainties

NEW: R_K key ingredients

$$R_K = \frac{N(K^+\mu^+\mu^-)}{N(K^+J/\psi(\mu^+\mu^-))} \times \frac{N(K^+J/\psi(e^+e^-))}{N(K^+e^+e^-)} \times \frac{\varepsilon(K^+J/\psi(\mu^+\mu^-))}{\varepsilon(K^+\mu^+\mu^-)} \times \frac{\varepsilon(K^+e^+e^-)}{\varepsilon(K^+J/\psi(e^+e^-))}$$

$\rightarrow$ Key to control ratios of efficiencies and of yields

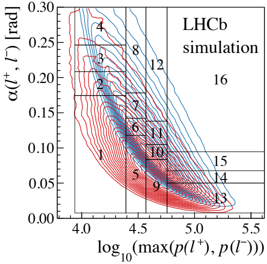
Efficiency ratios from simulation calibrated using data control channels

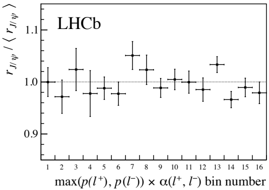
- Calibrate: B^+ kinematics, Tracking, Particle ID, Trigger, Resolution
- Associated systematic uncertainty $< 1\%$
- Check efficiencies are correct using:

  $$r_{J/\psi} = \frac{\mathcal{B}(B^+J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+J/\psi(e^+e^-))} = 1.0$$

  Measure: $r_{J/\psi} = 1.014 \pm 0.035$(stat.+syst)
- Differential $r_{J/\psi}$ demonstrates efficiencies are understood in all points of phase-space

rare, J/ψ



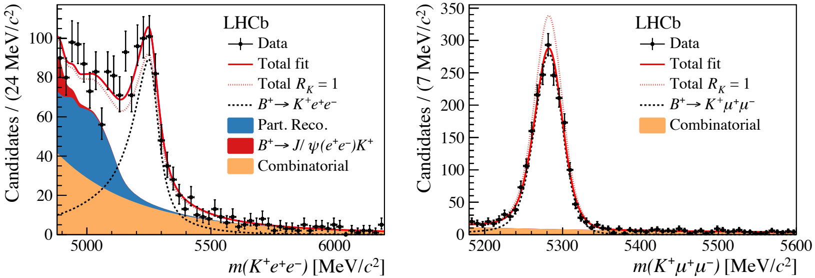


[LHCb arXiv:1903.09252]

NEW: R_K mass fits

- A single fit to the $m(K^+\ell^+\ell^-)$ distributions of rare and J/ψ mode is performed to obtain R_K

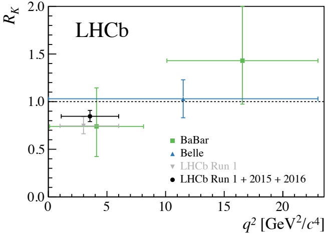
[LHCb arXiv:1903.09252]
$N_{Kee} = 760$, $N_{K\mu\mu} = 1940$ in $1.1 < q^2 < 6.0\text{GeV}^2/c^4$



- Partially reconstructed backround shape in $B^+ \to K^+e^+e^-$ taken from simulated $B^0 \to K^{*0}e^+e^-$, assosciated systematic 1%

Run1 and 2015, 2016 data: $\mathbf{R_K} = \mathbf{0.846}^{+\mathbf{0.060}}_{-\mathbf{0.054}}(\text{stat.})^{+\mathbf{0.016}}_{-\mathbf{0.014}}(\text{syst.})$
[LHCb arXiv:1903.09252]
Previous Run1 measurement: $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$
[LHCb PRL113(2014)151601]

[LHCb arXiv:1903.09252]



- New measurement $\sim 2.5\sigma$ from SM

  Dominant systematic uncertainties:
  Fit shape, calibration of trigger and B^+ kinematics

  $\rightarrow$ Full Run2 analysis ongoing (doubles number of B's) will help clarify things

  $\rightarrow$ Angular $b \rightarrow s\ell^+\ell^-$ analyses with Run2 data underway

If fit Run1 and 2015,2016 data were fit separately (accounting for correlations):

- Previous Run1 results vs. this Run1 result: $< 1\sigma$
- Run1 results vs. Run2 result: 1.9σ

$\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$:

- Compatible with previous result [LHCb JHEP06(2014)133] at $< 1\sigma$
- Run1 and Run2 results compatible at $< 1\sigma$

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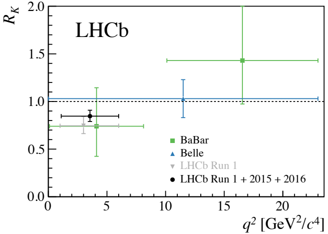


Run1 and 2015, 2016 data: [LHCb arXiv:1903.09252]

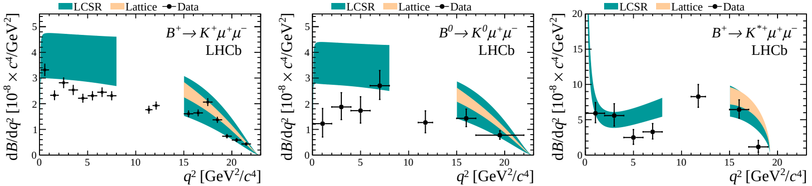
$$\left.\frac{d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{dq^2}\right|_{1.1<q^2<6.0} = (28.6^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9}\mathrm{GeV}^2/c^{-4}$$

using $\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$ from [LHCb JHEP06(2014)133]

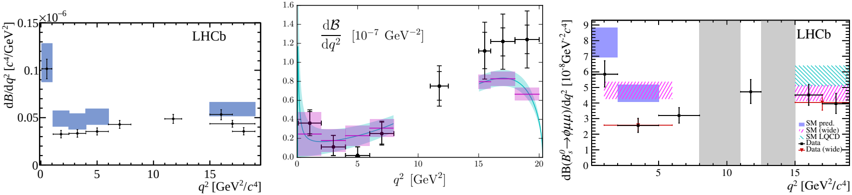
2. Differential branching fractions

- 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)

2. Differential branching fractions

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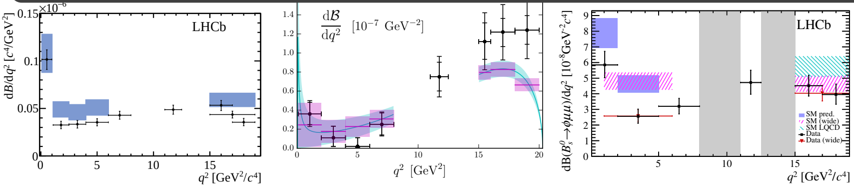
Uncertainty of Run1 $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ and $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ measurements dominated by knowledge of $\mathcal{B}(B \to J/\psi K^{(*)})$ from B-factories.

- Updated measurements from Belle2 crucial
- Can still measure q^2 spectrum with high precision
- Asymmetries and ratios between $b \to s$ and $b \to d$ processes test MFV and will be dominated by stat. uncertainties for a while still



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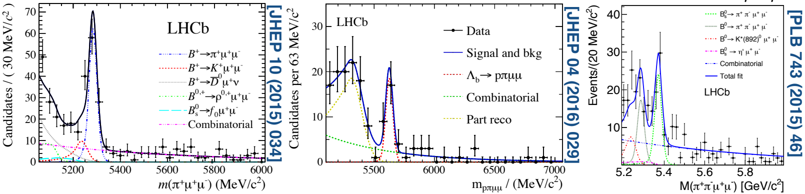
- Measurements below SM prediction ($2-3\sigma$ depending on final state)

Measurements of $b \to d\mu^+\mu^-$ decays

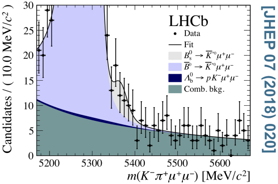
$B^+ \to \pi^+\mu^+\mu^-$ $\Lambda_b \to N^*\mu^+\mu^-$ $B^0 \to \pi^+\pi^-\mu^+\mu^-$



credit: Tom Blake

- Run1 and 2015,2016 data have provided observations of numerous $b \to d\mu^+\mu^-$ processes

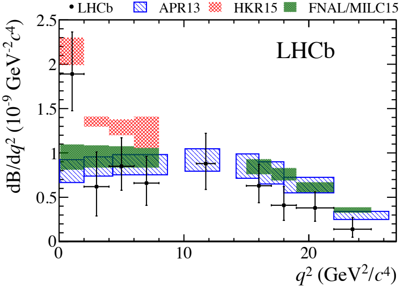
- Evidence of $B^0_s \to \bar{K}^{*0}\mu^+\mu^-$ opens up tests of MFV comparing angular observables with $B \to K^{*0}\mu^+\mu^-$ with LHCb upgradeII
  - Precision commensurate to Run1 $B^0 \to K^{*0}\mu^+\mu^-$)



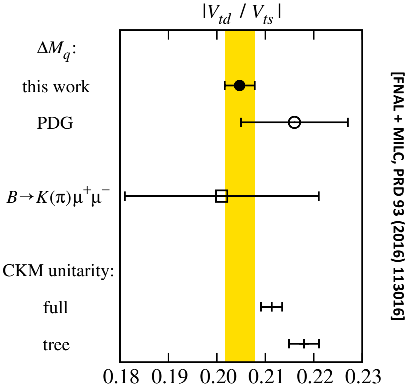
$B^+ \to \pi^+\mu^+\mu^-$

- In SM $\frac{\mathcal{B}(B^+\to\pi^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+\mu^+\mu^-)} \sim \left|\frac{V_{td}}{V_{ts}}\frac{f_{B\to\pi}}{f_{B\to K}}\right|^2$

$B^+ \to \pi^+\mu^+\mu^-$ LHCb [JHEP10(2015)034]



LHCb [JHEP10(2015)034]

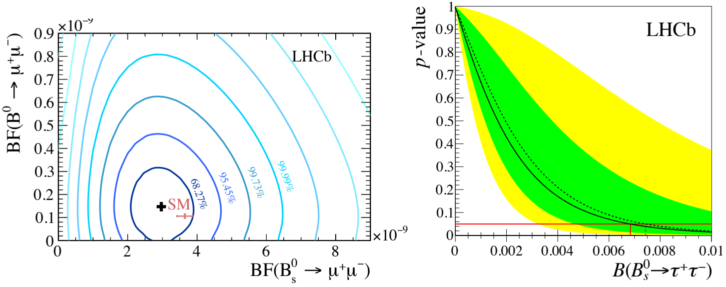


- $b \to d\ell^+\ell^-$ statistically limited even with LHCb Upgrade II data
- Expect 10-fold improvement in experimental error
- Modest improvements in Lattice predictions also required to maximise gain

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

- Branching fraction measurement provides stringent constraints on axial-vector and (pseudo-)scalar couplings

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

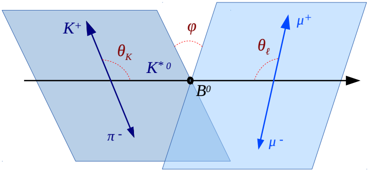


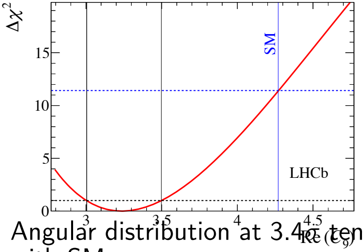
$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95%CL World first
$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$ at 95%CL World best
Full Run2 updates ongoing. LHCb Upgrade II needed to fully exploit (see Christoph's talk)

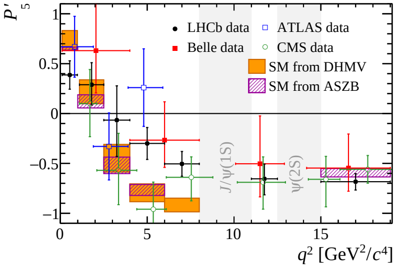
- Measure $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ to $\sim 5\%$ (on par with current theory error)
- Given current anomalies, $B \to e^+e^-$ and $B \to \tau^+\tau^-$ can be used to exclude models with 300fb^{-1}

3. $B^0 \to K^{*0}\mu^+\mu^-$ 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
- Update of observables binned in q^2 with Run1+Run2 data underway
- Plans to directly fit for WCs from angular and q^2 distribution
  [Hurth et al [JHEP11(2017)176], [Chrzaszcz et al 1805.06378], [Blake et al EPJC(2018)78:453]

$B^0 \to K^{*0} e^+ e^-$ 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 by fitting a folded angular distribution

$\Lambda_b \to \Lambda\mu^+\mu^-$ angular analysis

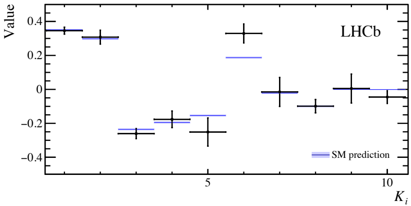
- Method of moments to deterimine full basis of angular observables in $\Lambda_b \to \Lambda\mu^+\mu^-$ decays
[LHCb JHEP09(2018)146]

- Measure in $15 < q^2 < 20$ GeV$^2/c^4$ using Run1+2015,2016 data

- K_{11}-K_{34} proportional to Λ_b production polarisation

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi}\sum_i^{34} K_i f_i(\vec{\Omega})$$

[LHCb JHEP09(2018)146]



Combine subset of K_i to form:

$A_{\rm FB}^{\ell}$ = -0.39 $\pm$ 0.04(stat) $\pm$ 0.01(syst)

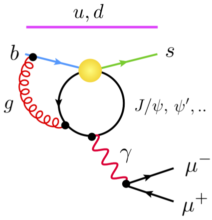
$A_{\rm FB}^{h}$ = -0.30 $\pm$ 0.05(stat) $\pm$ 0.02(syst)

$A_{\rm FB}^{\ell h}$ = 0.25 $\pm$ 0.04(stat) $\pm$ 0.01(syst)

- K_{11}-K_{34} compatible with zero
- $K_6 \sim 2.6\sigma$ from SM

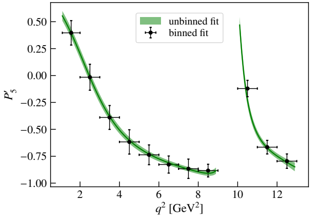
Charming interlude I

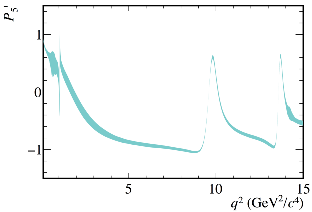
- Anomalies in $b \to s\mu^+\mu^-$ have shed doubt on control of theory uncertainties related to the "charm-loop"



- Extract both short- and long-distance contribution from data through angular and q^2 spectrum
[Lyon et al 1406.0566], [Bobeth et al EPJC(2018)786:451], [Blake et al EPJC(2018)78:453]

Left: LCSR+analyticity [Chrzaszcz et al 1805.06378], Right: Breit-Wigners [Blake et al EPJC(2018)78:453]



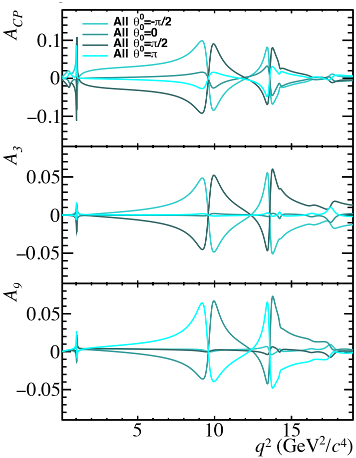


Expected post-fit precision on P_5' with full Run2 data

Charming interlude II

- Look at effect of interference between short- and long-distance $B \to K^* \mu^+ \mu^-$ amplitudes on CP-odd observables A_i
- Knowledge of strong-phase variation offers sensitivity to NP weak phases in the vector amplitude of $b \to s\ell\ell$ decays

$C_9^{NP} = -1.0 - 1.0i$

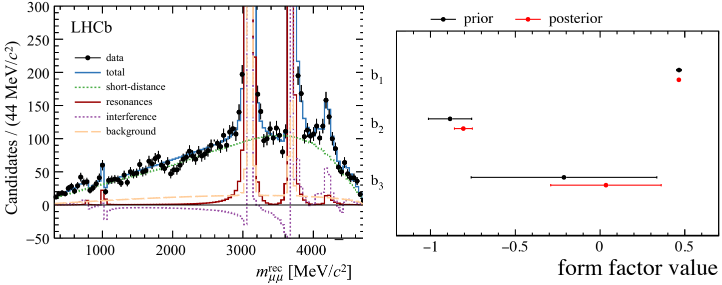


[Blake et al EPJC(2018)78:453]

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

[LHCb Run1 Eur. Phys.J. C(2017)77:161]



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

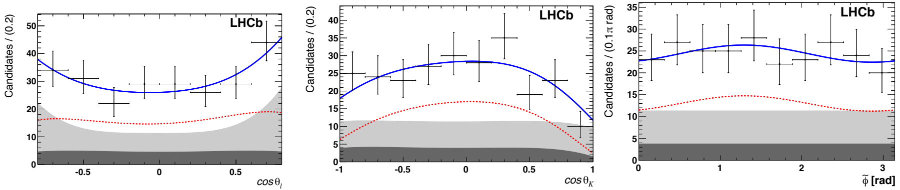
Summary

- Run1 and Run2 of LHCb have ushered precision era in $b \to s\ell\ell$ transitions revealing intriguing tensions
- Update to R_K using data between 2011-2016 results in $\sim 2.5\sigma$ tension to SM
  - More measurements needed to clarify situation
- Working on adding 2017,2018 data doubling the number of B's
- R_K^* and angular analyses of $B \to K^*\ell^+\ell^-$ within Run2 on their way
  $\to$ Clarify situation
- Full exploitation of these decays can only be achieved through LHCb Upgrade II (see Christoph's talk)

Backup

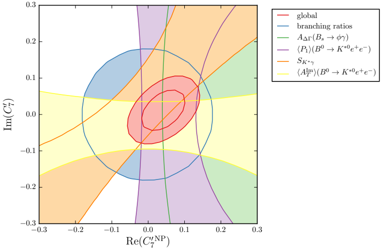
$B^0 \to K^{*0}e^+e^-$ angular analysis LHCb [JHEP04(2015)064]

- Measure angular observables in $0.0004 < q^2 < 1\text{GeV}^2$
  $\to$ dominated by C_7' contributions
- ~ 150 signal candidates $\to$ Fit in $cos\theta_\ell$, $cos\theta_K$ and "folded" ϕ to measure A_{T2}, A_T^{Im}, A_T^{Re}, F_L



- Measurements complementary to BFs and $A_{CP}(t)$ of $B \to K^*\gamma$ and $B_s \to \phi\gamma$
- Provide one of strongest constraints to C_7'

Paul, Straub [1608.02556]



If instead the Run 1 and Run 2 were fitted separately:

$$R_{K\ \mathrm{Run\ 1}}^{\mathrm{new}} = 0.717^{+0.083}_{-0.071}{}^{+0.017}_{-0.016}, \quad R_{K\ \mathrm{Run\ 2}} = 0.928^{+0.089}_{-0.076}{}^{+0.020}_{-0.017},$$

$$R_{K\ \mathrm{Run\ 1}}^{\mathrm{old}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$ (PRL113(2014)151601) ,

Compatibility taking correlations into account:

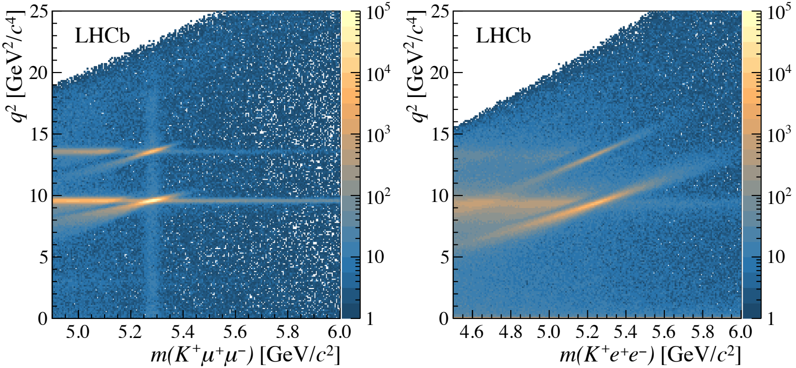
- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1\ \sigma$;
- Run 1 result vs. Run 2 result: $1.9\ \sigma$.

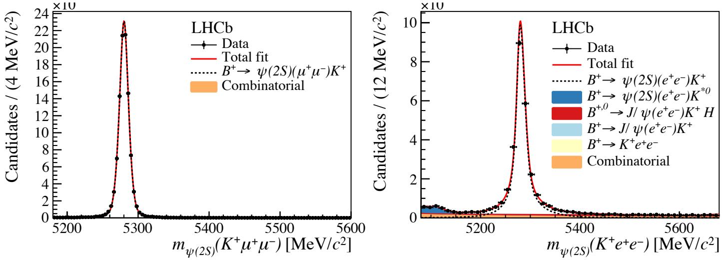
$B^+ \to K^+\mu^+\mu^-$ branching fraction:

- Compatible with previous result (JHEP06(2014)133) at $< 1\ \sigma$;
- Run 1 and Run 2 results compatible at $< 1\ \sigma$.

$B^+ \to K^+e^+e^-$ branching fraction:

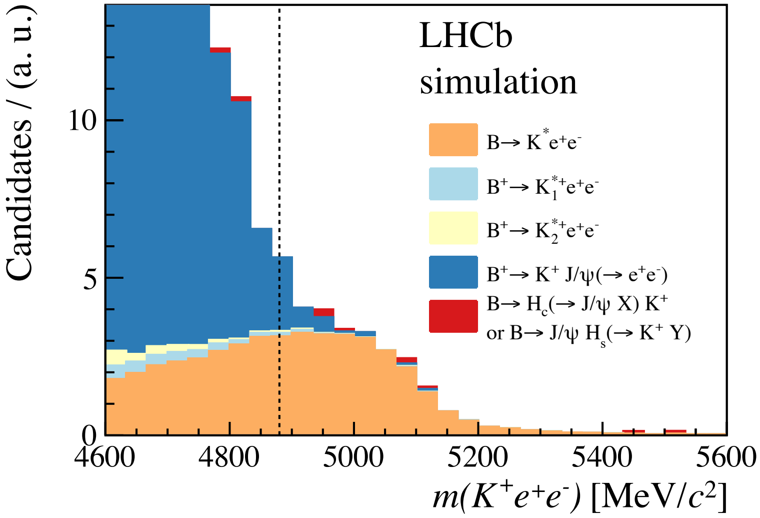
$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2) = (28.6^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

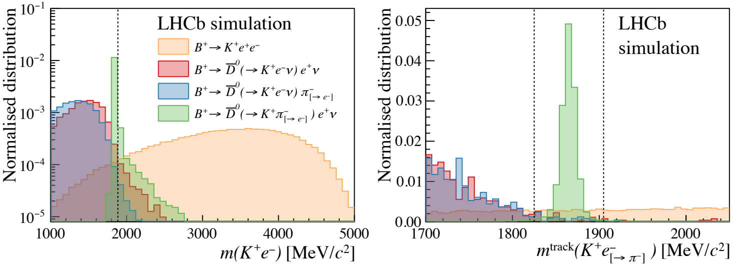

LHCb
q^2 [GeV$^2/c^4$]
$m(K^+\mu^+\mu^-)$ [GeV/c^2]
LHCb
q^2 [GeV$^2/c^4$]
$m(K^+e^+e^-)$ [GeV/c^2]



$$R_K^{\psi(2S)} = 0.986 \pm 0.013$$

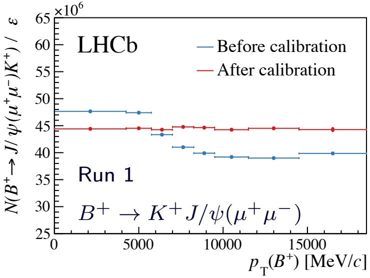
Thibaud Humair


LHCb
simulation
B→ K* e+e-
B+→ K1*+ e+e-
B+→ K2*+ e+e-
B+→ K+ J/ψ(→ e+e-)
B→ Hc(→ J/ψ X) K+
or B→ J/ψ Hs(→ K+ Y)
Candidates / (a. u.)
0
5
10
4600
4800
5000
5200
5400
5600
m(K+e+e-) [MeV/c2]



Thibaud Humair

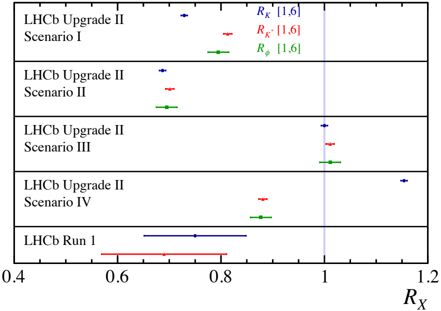
- After calibration, very good data/MC agreement in all key observables



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