General Lepton Universality Tests

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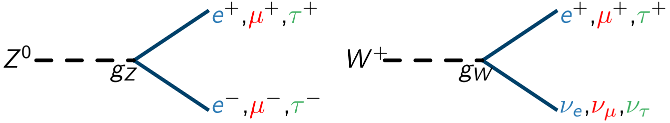
Lepton Flavour Universality in the Standard Model

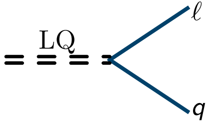
- **LFU**: Coupling of $W^{\pm}$ and Z^0 to charged **L**eptons is **F**lavour **U**niversal ($g_e = g_\mu = g_\tau$);
- Well documented from $Z^0 \to \ell^+\ell^-$ and $W^+ \to \ell\nu$ LEP measurements;



- LFU well established for μ and e flavours in J/ψ, π^+ and K^+ (semi-)leptonic decays, e.g.:

$$J/\psi \to \ell^+\ell^- \quad \pi^+ \to \ell^+\nu \quad K^+ \to \pi^+\ell^+\ell^-$$

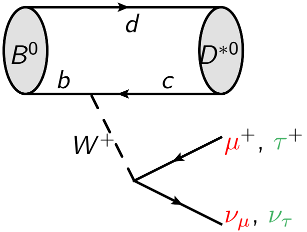
Some extensions to the SM predict new particles that can break LFU (e.g. Z', leptoquark).
⇒ Significant breaking of LFU is a clear sign of New Physics.
⇒ **Today:** focus on LFU in B decays at LHCb



LFU in charged currents: $B \to D^{(*)}\tau^+\nu_\tau$ / $B \to D^{(*)}\mu^+\nu_\mu$

$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)}$$

- Tree level: large branching fractions $\mathcal{O}(1-5\%)$;
- Clean theory prediction for $R_{D^{(*)}}$ as hadronic uncertainties mainly cancel out.



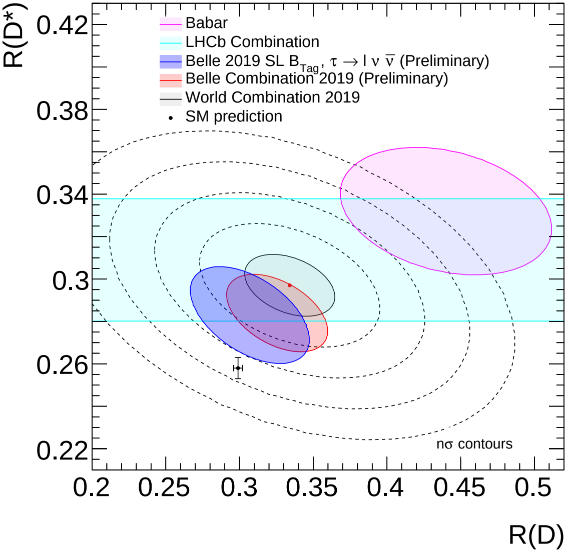
Two LHCb measurements of R_{D^*} using 2011+2012 data:

- Muonic: $\tau^+ \to \mu^+\nu_\mu\overline{\nu_\tau}$ PRL 115(2015)111803
- Hadronic: $\tau^+ \to \pi^+\pi^+\pi^-\overline{\nu_\tau}(\pi^0)$ PRD 97(2018)072013

Many other results R_{D^*} and R_D from B factories:

- Using various τ decays;
- Reconstructing the opposite B in a hadronic or a semileptonic channel.

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



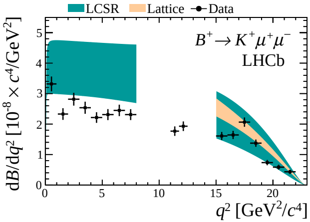
Including Belle's new R_{D^*} result using semileptonic tag[(1)], $R(D^*)$ and $R(D)$ combination is $\sim 3.1\ \sigma$ from SM (previous combination was $3.8\,\sigma$).

(1) Giacomo Caria, Moriond 2019, (arXiv:1904.08794).

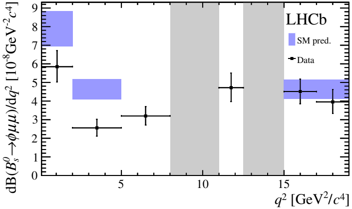
Experimental results for $b \to s\mu^+\mu^-$ (Run 1 LHCb data)

- $b \to s\ell^+\ell^-$ decays are loop-suppressed and rare ($\mathcal{B} \sim 10^{-6}$);
- $b \to s\mu^+\mu^-$ decays have been studied in details at LHCb:

Branching Fractions:

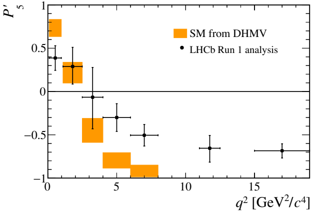


JHEP06(2014)133



JHEP09(179)2015

Angular observables:



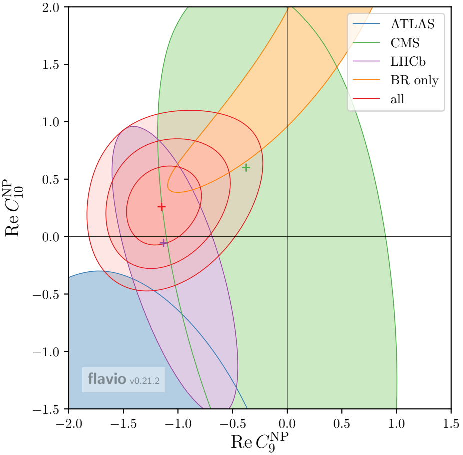
JHEP02(2016)104

- In range $1 < q^2 < 6\,\mathrm{GeV}^2$, $b \to s\mu\mu$ $\mathcal{B}$ and angular variables show discrepancies wrt SM;
- Taken individually, discrepancies are at the $\sim 2.5 - 3.5\sigma$ level.

Global analysis of $b \to s\mu^+\mu^-$

- $b \to s\ell^+\ell^-$ can be described in a low-energy effective theory involving effective coupling constants (or Wilson coefficients) C_i;
- The presence of NP would shift the value of these coefficients;
- Can fit angular observables and $\mathcal{B}$ results for the Wilson coefficients;

$\Rightarrow$ Angular and BR measurements consistently point to same effect: shift of C_9^μ or $C_9^\mu - C_{10}^\mu$ from their SM values at a level of $\sim 4\,\sigma$.



Eur. Phys. J. C (2017) 77:377

LFU and $b \to s\ell^+\ell^-$ decays

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- Tensions in $b \to s\mu^+\mu^-$ are very striking...
- ... but $b \to s\mu^+\mu^-$ observables have hadronic uncertainties, making interpretation difficult i.e. charm-loop contributions interfere with rare decay and could mimic NP effects.

Measure (JHEP0712(2007)040):

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{=} 1.0$$

- All hadronic effects cancel in these ratios: immaculate theoretical predictions of $R_{K^{(*)}}$
  - Small deviation from 1, $\mathcal{O}(1\%)$, due to radiative corrections (EPJC76(2016)440).

$\Rightarrow$ any statistically significant deviation of these ratios from 1 is a sign of New Physics.

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- Tensions in $b \to s\mu^+\mu^-$ are very striking...

Today: discuss LHCb's new R_K measurement

Compared to the previous LHCb measurement using 2011 and 2012 data:

- The analysis of 2011 and 2012 data is completely re-optimised, the analysis strategy re-designed;
- 2015 and 2016 LHCb data are added;
- In total, updated analysis uses twice as many B's as the previous analysis.

arXiv:1903.09252 (submitted to PRL)

Selection (arXiv:1903.09252)

Main steps of the selection are:

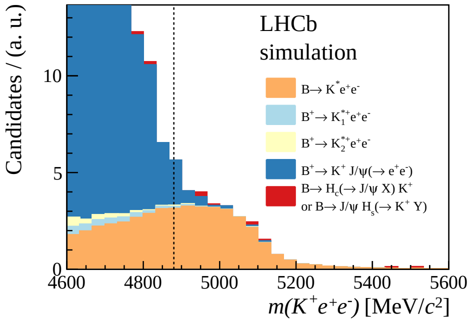
- q^2 range $1.1 < q^2 < 6.0\ \mathrm{GeV}^2$,

$\Rightarrow$ Compared to previous analysis, shifted 1.0 to $1.1\ \mathrm{GeV}^2$ to veto out $B^+ \to K^+\phi(\to \ell^+\ell^-)$;

- Requirement $m(K^+\ell^-) > m(D^0)$ to eliminate $B \to D(\to K^+\ell^-\overline{\nu}_\ell X)\ell^+\nu_\ell Y$;

- Multivariate selection to eliminate background from random combinations of tracks,

$\Rightarrow$ Based on finding three tracks forming a good vertex, significantly displaced from the proton-proton collision.



Remaining background expected after full selection:

- For $B^+ \to K^+\mu^+\mu^-$: only random combinations of tracks;
- For $B^+ \to K^+e^+e^-$: partially reconstructed B decays and leakage from J/ψ mode.

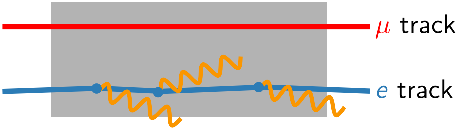
R_K measurement at LHCb

Need two inputs to measure R_K: yields and efficiencies.

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} = \frac{N(K^+\mu\mu)}{N(K^+ee)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+\mu\mu)}$$

Electron and muon tracks very different in LHCb:

- Electrons interact with material and emit bremsstrahlung;
  - worse mass and q^2 resolution;
  - lower reconstruction efficiency.
- Better PID and trigger performances for muons.



Critical aspect in the analysis: get the electron efficiencies fully under control.

R_K measurement at LHCb

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$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$

$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

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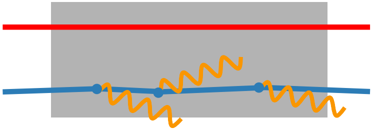

Critical aspect in the analysis: get the electron efficiencies fully under control.
$\Rightarrow$ use **double ratio** to cancel out most systematic uncertainties.

Efficiency computation

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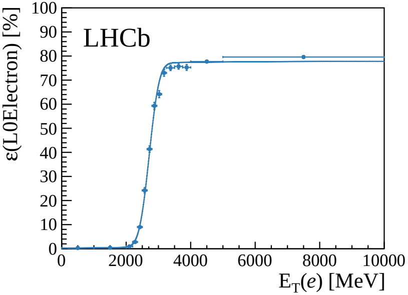
Ratio of efficiencies determined with simulation carefully calibrated using control channels selected from the data:

- Calibration of B^+ kinematics;
- Tracking efficiency calibration;
- Particle ID calibration (method described in EPJ T&I(2019)6:1);
- Trigger calibration (right plot);
- Calibration of q^2 and $m(Kee)$ resolution.

Ratio of efficiencies controlled to an excellent level and checked with alternative samples wherever possible.

Detailed evaluation of systematic uncertainties shows uncertainties at each step are $< 1\%$.



Measurement of the electron trigger efficiency using $B^+ \to J/\psi(e^+e^-)K^+$ data.

Cross-check 1: $r_{J/\psi}$ in 1D

To check efficiencies are correct, check:

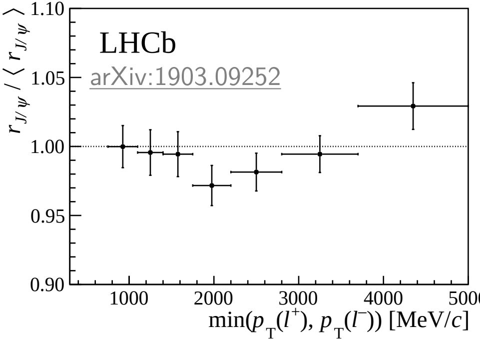
$$r_{J/\psi} = \frac{\mathcal{B}(B \to K^+ J/\psi(\mu\mu))}{\mathcal{B}(B \to K^+ J/\psi(ee))} = 1.0,$$

Result:

$$r_{J/\psi} = 1.014 \pm 0.035 \text{ (stat. + syst.)}$$

- Check that efficiencies are understood as a function of any variable:

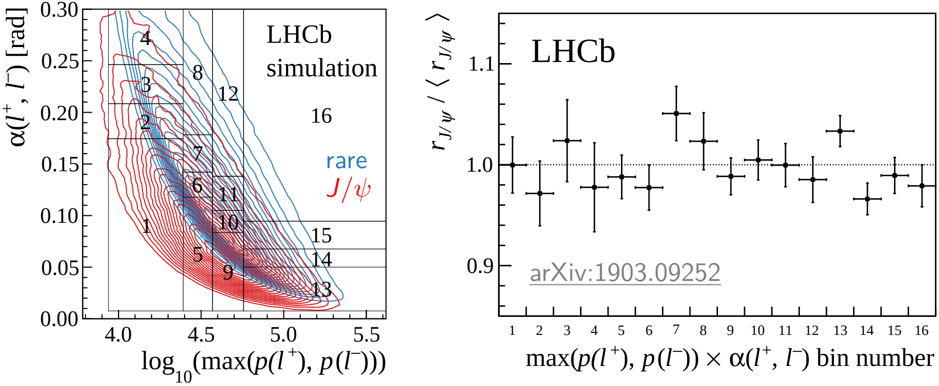
⇒ differential $r_{J/\psi}$ demonstrates it is the case: $r_{J/\psi}$ is flat for all variables examined.



Given expected $\min(p_T(\ell^+), p_T(\ell^-))$ spectra, bias expected on RK if deviations are genuine rather than fluctuations is 0.1%.

Cross-check 2: $r_{J/\psi}$ in 2D

- Pick two variables from those that can be used to parametrise the decay in LHCb frame;
- Select $B^+ \to J/\psi K^+$ events in 2D bins, and compute $r_{J/\psi}$ in each bin:



Flatness of $R^{2D}_{J/\psi}$ plots gives confidence that efficiencies are understood over all phase-space.

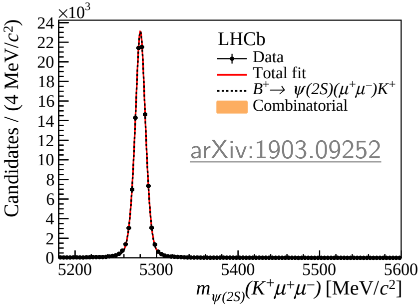
Cross-check 3: $R_K^{\psi(2S)}$

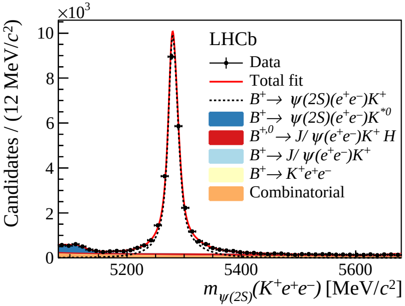
Other cross-check: measure the double ratio

$$R_K^{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu\mu))}{\mathcal{B}(B^+ \to K^+\psi(2S)(ee))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))} ,$$

and check compatibility with unity.

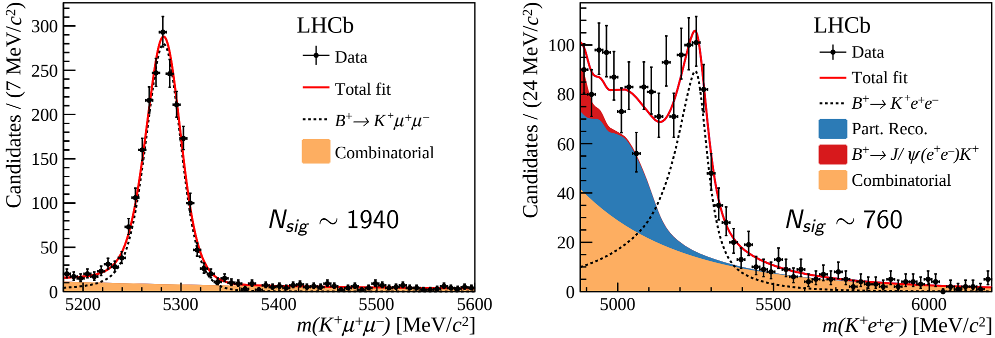
Find: $R_K^{\psi(2S)} = 0.986 \pm 0.013$ (stat. + syst.).





Fit to $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

A single fit to the $m(K^+\ell^+\ell^-)$ distributions is performed to determine R_K simultaneously using the whole LHCb 2011 to 2016 data taking into account all correlations (arXiv:1903.09252):



Partially reconstructed background shape in $B^+ \to K^+e^+e^-$ taken from simulated $B^0 \to K^{*0}(K^+\pi^-)e^+e^-$, associated systematic is 1%.

R_K result with 2011 to 2016 data arXiv:1903.09252

Using 2011 and 2012 LHCb data, R_K was:

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.}),$$

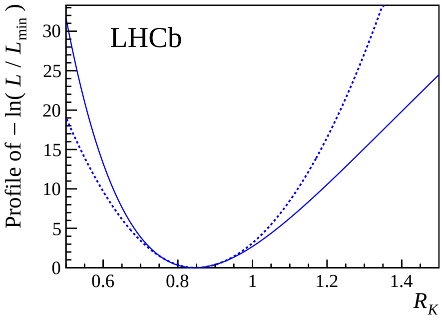
$\sim 2.6\,\sigma$ from SM (PRL113(2014)151601).

Adding 2015 and 2016 data, R_K becomes:

$$\boldsymbol{R_K = 0.846\ ^{+0.060}_{-0.054}(\text{stat.})\ ^{+0.016}_{-0.014}(\text{syst.})}$$

$\sim$ **$2.5\,\sigma$** from SM.

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



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Branching fractions and other results arXiv:1903.09252

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

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

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

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 $< 1\,\sigma$.

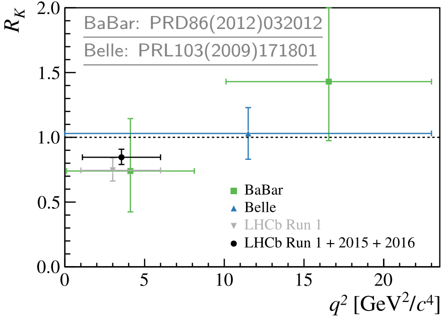
$B^+ \to K^+e^+e^-$ **branching fraction**:

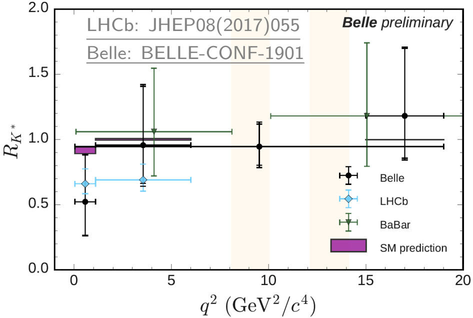
$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2) = (28.6^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

Current status of R_{K^*} and R_K

Results summarised here include:

- New LHCb R_K result discussed before;
- New Belle R_{K^*} result presented at Moriond 2019.





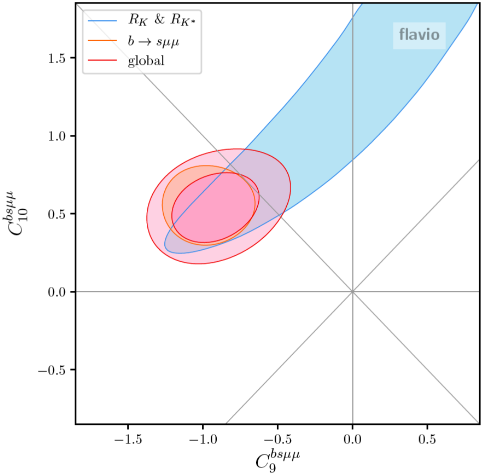
- LHCb results are all below 1.0 at a level of $2.0 - 2.5\,\sigma$;
- Belle and Babar results are compatible with 1.0, but lower precision.

Global fit LFU and $b \to s\mu^+\mu^-$

Fit $b \to s\mu^+\mu^-$ branching fractions and angular observables together with R_K and R_{K^*}:

- $b \to s\mu^+\mu^-$ couplings are free in the fit;
- $b \to se^+e^-$ are fixed to SM expectation.

Before new LHCb and Belle results:
LFU, branching fractions and angular results all compatible with shift of coefficients $C_{9,10}$ in muon mode, but electron mode SM-like.



Plots from David Straub's talk at Moriond EW 2019 (arXiv:1903.10434).

Global fit LFU and $b \to s\mu^+\mu^-$

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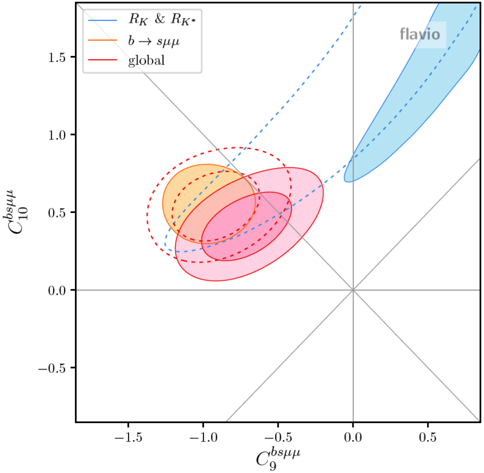
- $b \to s\mu^+\mu^-$ couplings are free in the fit;
- $b \to se^+e^-$ are fixed to SM expectation.

After new LHCb and Belle results:
Hypotheses requiring a shift in the muon mode, and no shift in the electron mode, are not quite as well motivated.



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Conclusion and outlook

Intriguing anomalies in LFU tests with B decays!

Recent Belle's R_{K^*}, R_{D^*} and LHCb's R_K results significantly improve the precision, but don't really yield a clearer picture...

Much remains to be done with the LHCb data in hand:

- Update $R_{K^{(*)}}$, R_{D^*} with full Run 2 data
  $\Rightarrow 2\times$ as many B's as in present R_K update.
- Many other observables:
  - R_K and R_{K^*} in the high q^2 bin;
  - LFU in other $b \to s\ell^+\ell^-$ decays, e.g. $B_s \to \phi\ell^+\ell^-$, $\Lambda_b \to p^+K^-\ell^+\ell^-$;
  - LFV (next talk by Giampiero).

With full LHCb Run 2 data available (up to 2018), the beginning of Belle 2 data taking, and LHCb upgraded detector starting data taking in 2021, we can expect the flavour anomalies to soon be understood.

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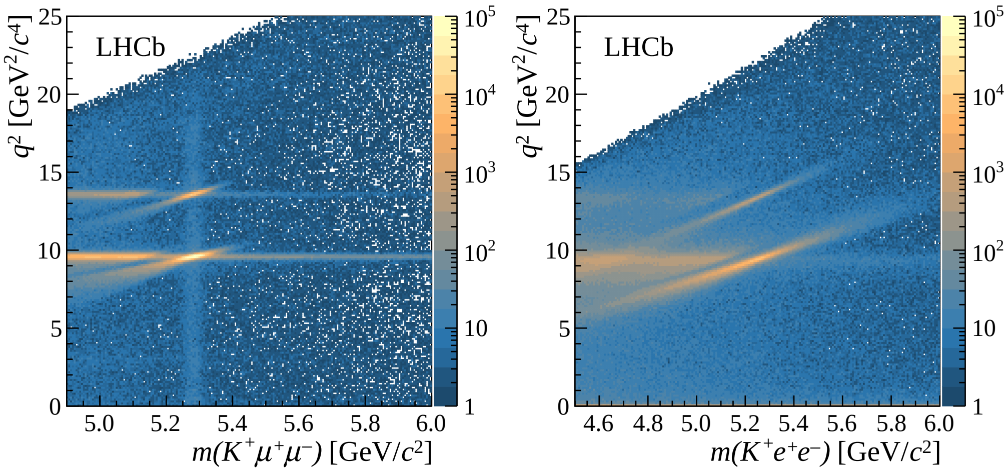
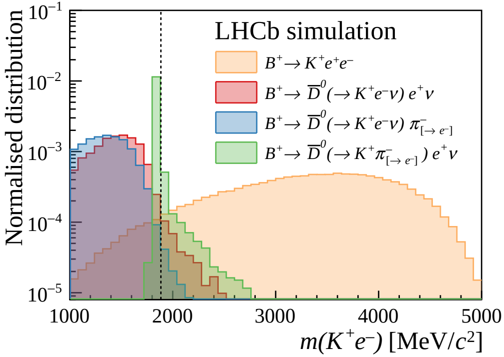
Thank you

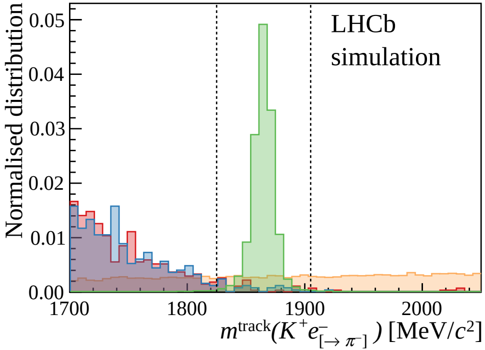
Back-up

2D q^2, m plot

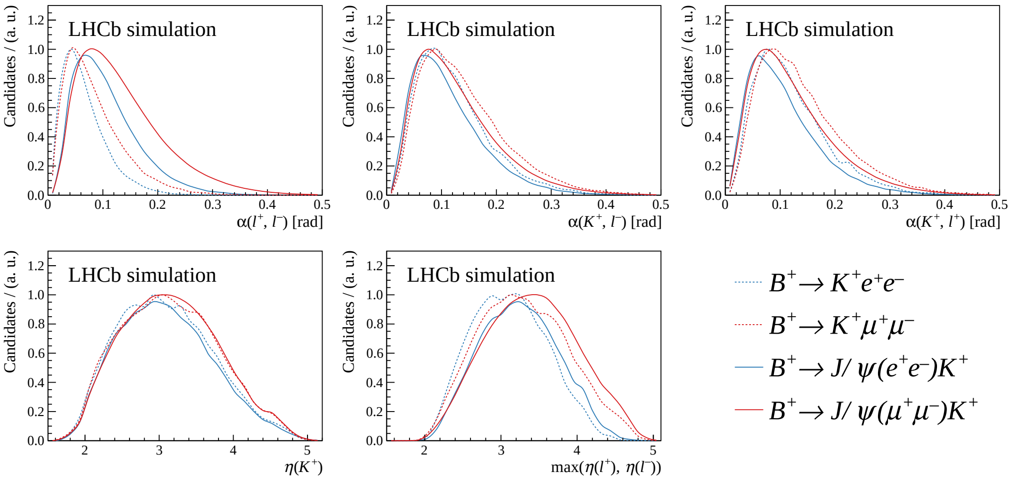

LHCb
25
20
15
10
5
0
q^2 [GeV^2/c^4]
5.0
5.2
5.4
5.6
5.8
6.0
$m(K^+\mu^+\mu^-)$ [GeV/c^2]
10^5
10^4
10^3
10^2
10
1
LHCb
25
20
15
10
5
0
q^2 [GeV^2/c^4]
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
$m(K^+e^+e^-)$ [GeV/c^2]
10^5
10^4
10^3
10^2
10
1

Cascade vetoes

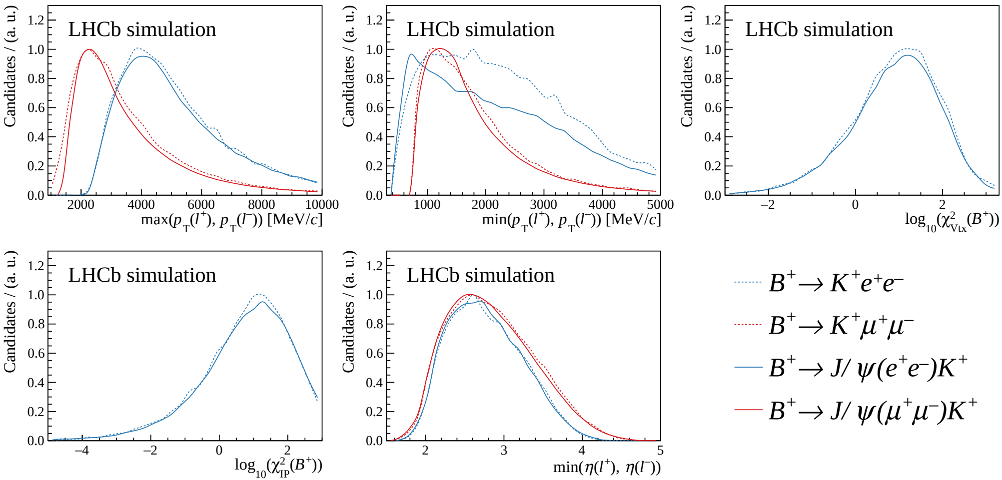




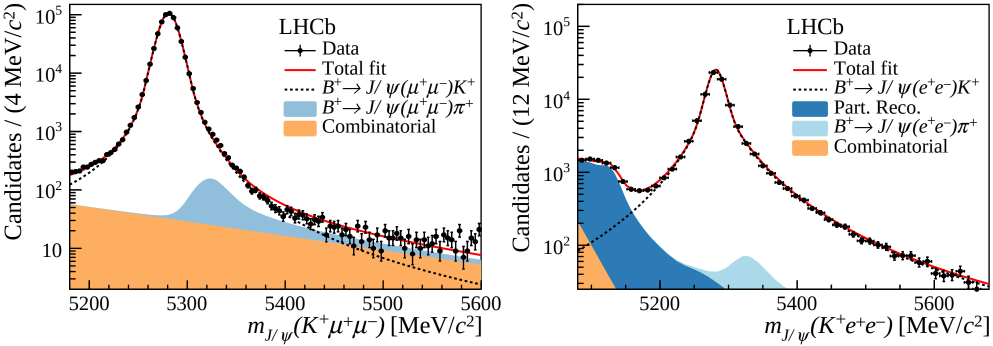
Distributions (1)



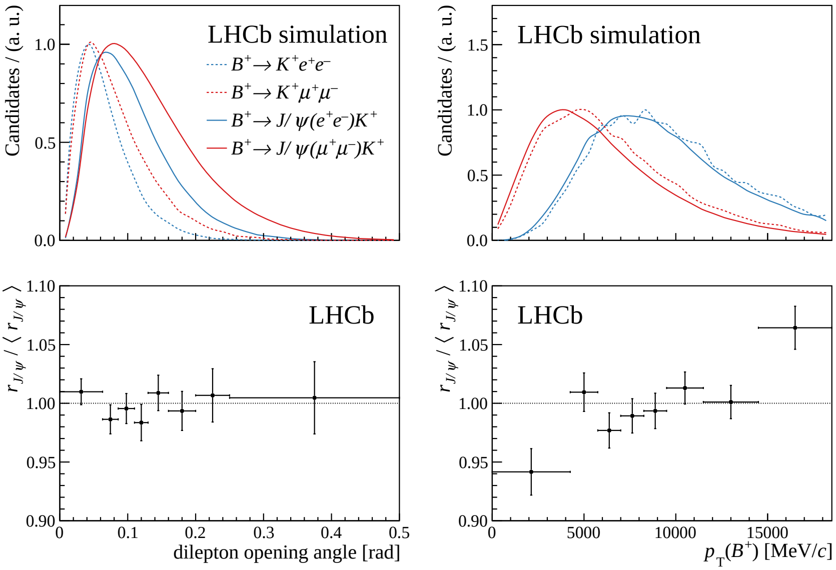
Distributions (2)



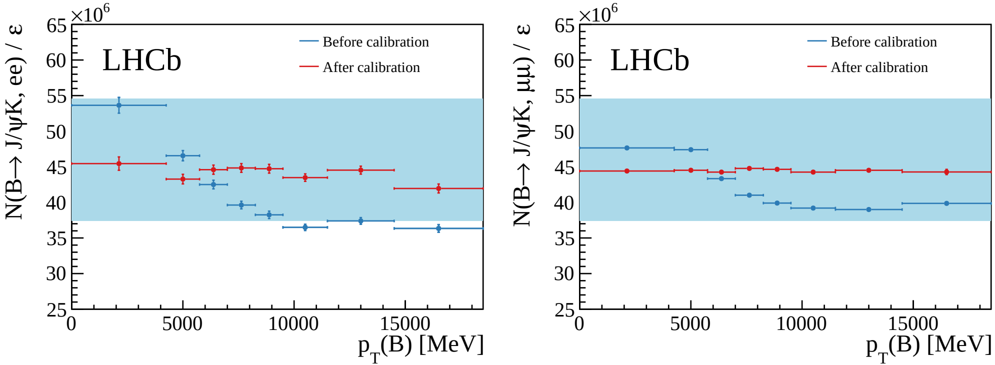
Fits to resonant mode



Supplementary $r_{J/\psi}$ 1D



Efficiency calibration



Selection 2: trigger

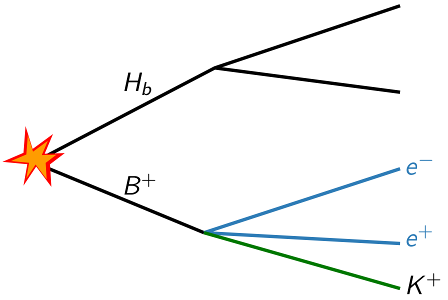
The LHCb trigger only records events with high-p_T tracks.

For the $B^+ \to K^+ \mu^+ \mu^-$ mode, dedicated muon detector is very efficient at finding high-p_T muon tracks.

For the $B^+ \to K^+ e^+ e^-$, cannot use the muon detector.

Use three different triggers based on

- One of the electrons;
- The kaon;
- The opposite b hadron.



Total trigger efficiency of electron modes $\sim 2\times$ smaller than muon mode.

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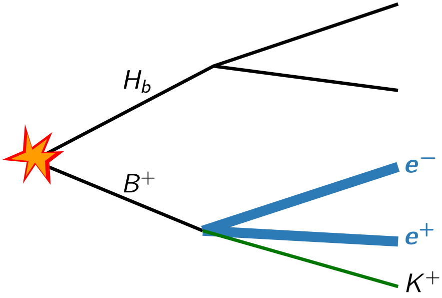

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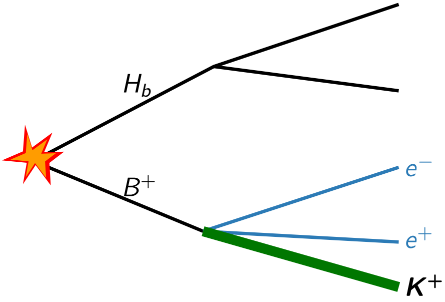

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Selection 2: trigger

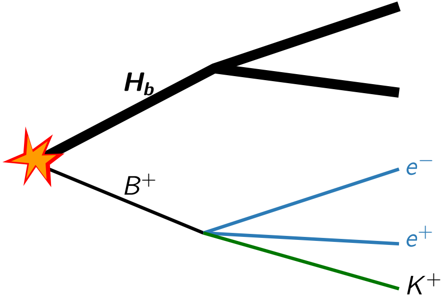
The LHCb trigger only records events with high-p_T tracks.

For the $B^+ \to K^+\mu^+\mu^-$ mode, dedicated muon detector is very efficient at finding high-p_T muon tracks.

For the $B^+ \to K^+e^+e^-$, cannot use the muon detector.

Use three different triggers based on

- One of the electrons;
- The kaon;
- **The opposite *b* hadron.**



Total trigger efficiency of electron modes $\sim 2\times$ smaller than muon mode.