A measurement of R_K at high q^2

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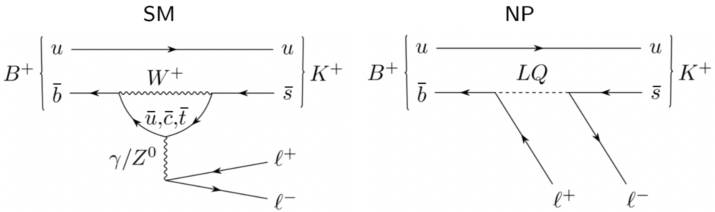
Introduction

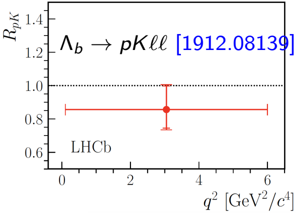


- High-q^2 R_K is a Lepton flavour universality test in the $b \to s\ell\ell$ decay $B^+ \to K^+\ell^+\ell^-$ with $\ell = \mu, e$
- In the Standard Model, couplings of gauge bosons to leptons are independent of lepton flavour
- Any deviation from unity is clean sign of new physics

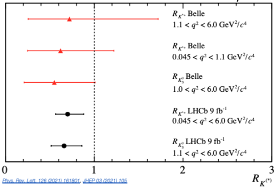
$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B^+ \to K^+e^+e^-)}{dq^2} dq^2} = 1 \ \text{(in SM)}$$

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

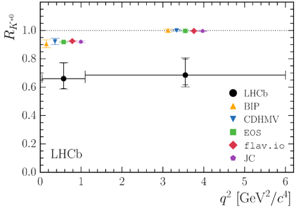
Existing evidence of LFU violation



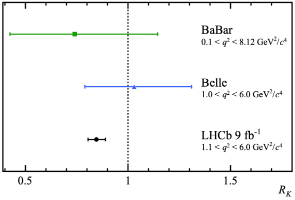
$B^+ \to K^{*+}\ell\ell, B^+ \to K^0_S\ell\ell$ [2110.09501]



$B^0 \to K^{*0}\ell\ell$ [1705.05802]



$B^+ \to K^+\ell\ell$ [2103.11769]



Analysis of R_K at central-q^2 with full run 1 and run 2 at LHCb, single measurement $> 3\sigma$:

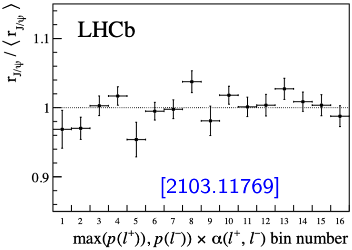
$$R_K(1.1 < q^2 < 6.0 \text{ GeV}^2/c^4) = 0.846^{+0.042+0.013}_{-0.039-0.012} \quad 3.1\sigma \text{ tension with SM.}$$

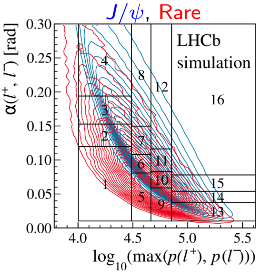
R_K measurement strategy

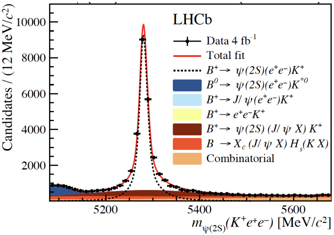
- R_K is measured in a double-ratio with control mode (J/ψ) information (identical selections).
- Determine yields from fits to invariant mass of final state particles
- Efficiencies determined from calibrated simualtion samples

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

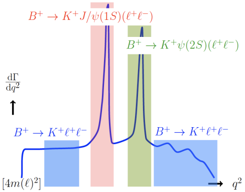
- Double ratio approach is verified by measuring $R_{\Psi(2S)}$ and demonstrating result compatible with 1.
- A more stringent check of understanding is made, by showing the single ratio $r_{J/\psi}$ is compatible with 1.
  - Additionally, that this is true for different kinematic regions

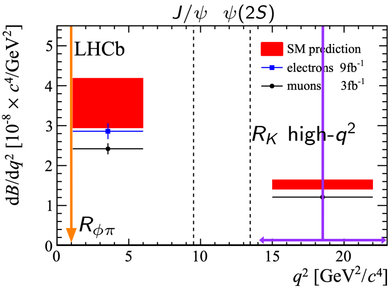


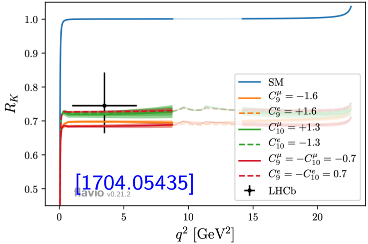




Motivation for high-q^2 R_K





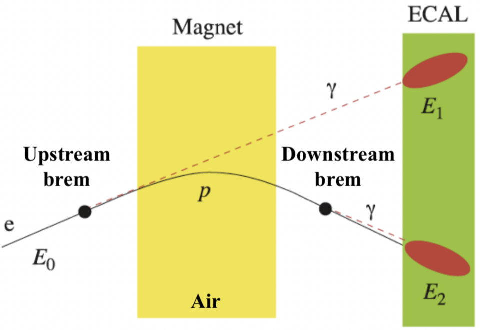


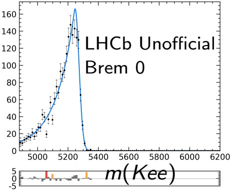
- Additional checks are essential.
- $R_{\phi\pi}$ from $D^+_{(s)} \to \phi(\ell^+\ell^-)\pi^+$ measurements - intended to demonstrate understanding of detection efficiencies at low q^2, validate double-ratio.
- An anomalous measurement of high-q^2 R_K would be tantalising confirmation of new physics
  - Especially given a different kinematic region to the central measurement and the proximity to the $\psi(2S)$ kinematics.
  - Region has different background considerations

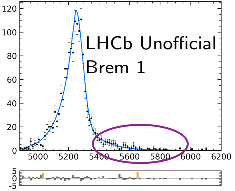
Bremsstrahlung radiation

Similarly to R_K at central-q^2 the major complication with this analysis is Bremsstrahlung radiation degrading the resolution of electron channel

- Electrons, being light charged particles, emit a large fraction of their energy as Bremsstrahlung radiation as they pass through the detector material.
- If brem is emitted before the magnet, this will affect momentum measurement.
- Have a brem recovery method, but this is far from perfect:
  - Can easily miss brem
  - Can incorrectly assign brem energy to electrons





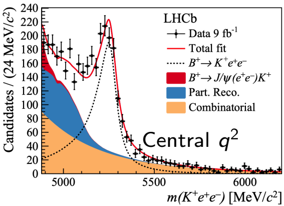


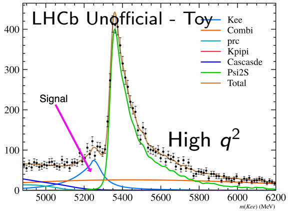
Backgrounds

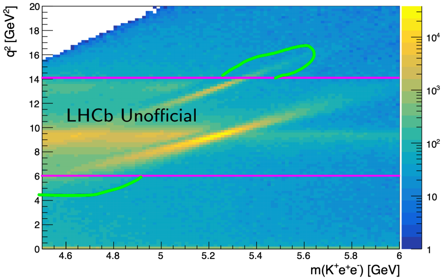
Challenge of this measurement is controlling backgrounds in $B^+ \to K^+ e^+ e^-$.

Backgrounds in electron rare mode:

- Random combinatorial
- Partially reconstructed $B^0 \to K^{*0} e^+ e^-$ or $B^0 \to K^{*+} e^+ e^-$
- Double-missID $B^+ \to K^+ \pi^+ \pi^-$
- Charm cascades (semi-leptonics), for example: $B^+ \to \bar{D}^0(\to K^+ e^- \bar{\nu}_e) e^+ \nu_e$
- $B^+ \to K^+ \psi(2S)(\to e^+ e^-)$ leakage (see next slide)

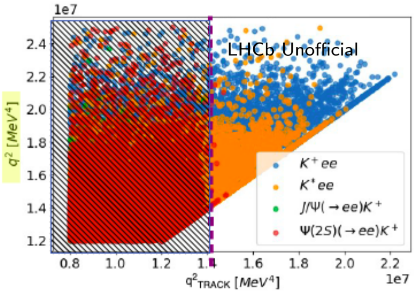






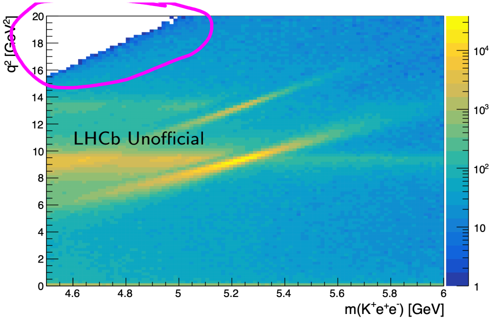
$B^+ \to K^+\psi(2S)(\to e^+e^-)$ leakage

- $\psi(2S)$ resonance is very close to high-q^2 region
- Wrongly assigned brem energy leads to leakage up in q^2
- To completely remove the background we need to cut at $q^2_{TRACK} \gtrsim 14.3$
- As migration due to brem emission is always to lower-q^2, a cut on q^2_{TRACK} is extremely efficient against $\psi(2S)$ leakage.
- Recover some signal with a dedicated q^2-BDT
  - Bring signal events back (along with a few $\psi(2S)$ events)
  - Trained to distinguish between signal and $B^+ \to K^+\psi(2S)(\to e^+e^-)$
  - Cut to be optimised with $\psi(2S)$ component in rare-mode fit
  - Effect of this BDT needs to be accounted for in definition of q^2 window



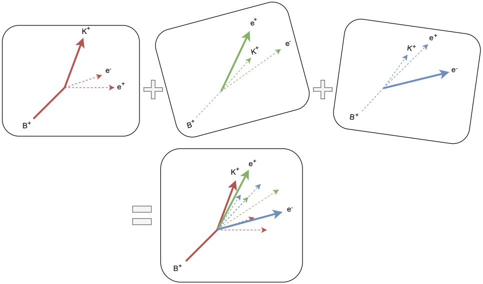
Combinatorial phase space shoulder

- At high-q^2 get cut off/shoulder in the otherwise exponential combinatorial background shape at the lower side of B mass window.
- Cannot have low m_B if you require q^2 to be this high.
- Cannot fit combinatorial background with a simple exponential function
- Effect is much more pronounced in the electron mode as with the improved resolution in the muons we can start fit window at higher $m(Kee)$ value.
- Need to settle on a parameterisation that can capture this with as few parameters as possible



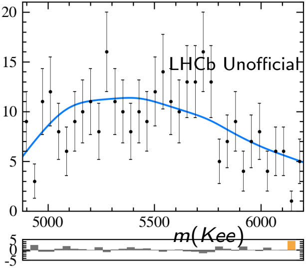
Combinatorial phase space shoulder

- Want to develop a single parameter model
  - Observe a large gain in sensitivity compared with floating 2 parameters in initial toy studies
- Initial studies look as if this might be possible
- Will need to a verify flexibility by demonstrating fits to control samples



Have multiple control samples to look at:

- $K^+e^+\mu^-$ data
- $K^+e^-e^-$ data (same-sign)
- Inverse combinatorial BDT $K^+e^+e^-$ data
- Event mixing of $K^+e^+e^-$ data

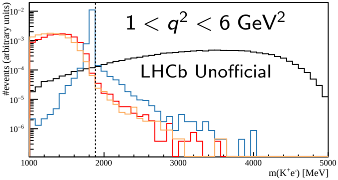


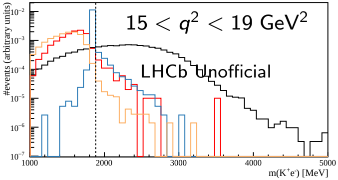
Work on this parameterisation is ongoing

Other backgrounds

Charm cascades/semi-leptonic backgrounds

- e.g. $B^+ \to \bar{D}^0(\to K^+\ell^-\bar{\nu}_\ell)\ell^+\nu_\ell$
- Removed at central-q^2 with $m(K\ell) > 1885$ MeV (lose 5% signal)
- At high-q^2 $m(K\ell)$ cut vetos 30% of signal, however toys studies suggest keeping this veto over a dedicated BDT





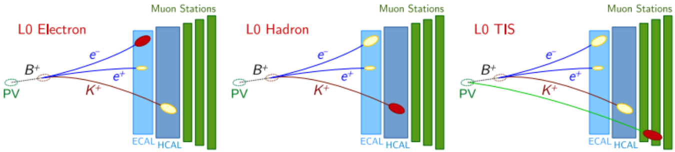
Double miss ID $B^+ \to K^+\pi^+\pi^-$

- Tighten PID cut $\to$ move from PIDe > 3 as at central-q^2 to PIDe > 4.

Partially reconstructed $B^0 \to K^{*0}e^+e^-$ **or** $B^0 \to K^{*+}e^+e^-$

- Contamination already lower at high-q^2 due to phasespace
- Additionally, use a BDT including isolation info to further reduce contamination

Trigger and fit strategy



R_K central used all of `eTOS`, `hTOS` and `TIS`, however at high-q^2:

- `eTOS`: $\sim$ 92.4% of signal (fraction of signal events in any of `eTOS`, `hTOS` and `TIS`)
- `TIS`: $\sim$ 7.5% of signal - trigger category is background dominated at high-q^2
- `hTOS`: $\sim$ 0.1% of signal

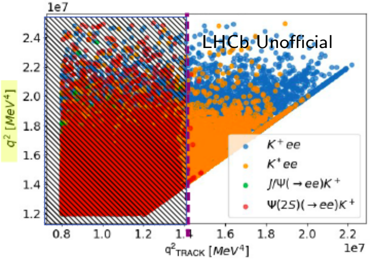
Ideally would like to fit all run periods in a single fit. This is nominal strategy, but this will change if we find major differences in expected signal/background ratios.

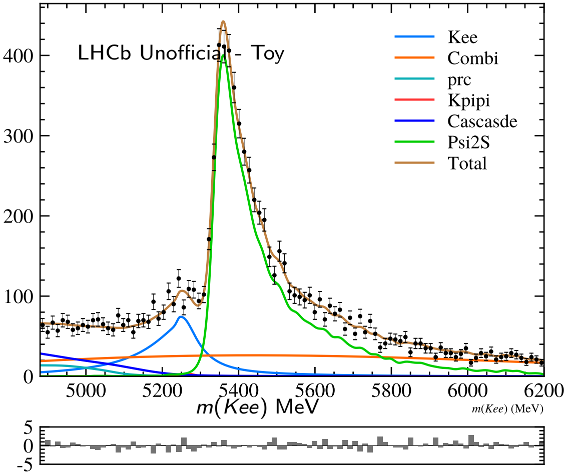
Fit optimisation:

- Many individual elements interacting in the fit
- BDT cuts, q^2_{TRACK} cut,
- Fit optimisation with a large set of R_K sensitivity toys.

Bringing everything together

- Example toy before background selections discussed.
- This example has a cut of $q^2 > 14.0\ \mathrm{GeV}^2$ (after brem energy added back).
- Large $B^+ \to K^+\psi(2S)(\to e^+e^-)$ leakage
- (Note, combinatorial BDT is applied in this plot)

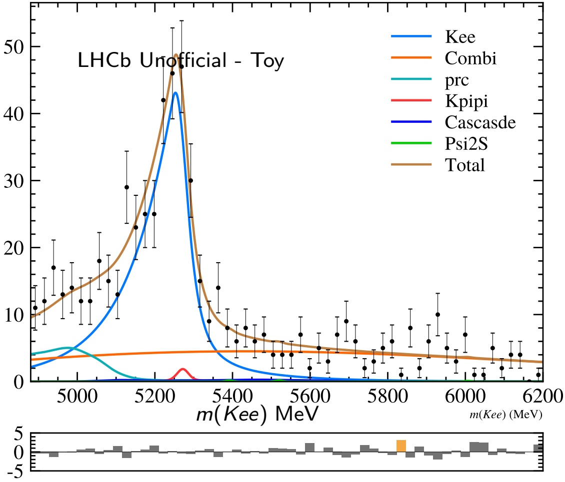




Applying background selection

Example toy with nominal fit configuration:

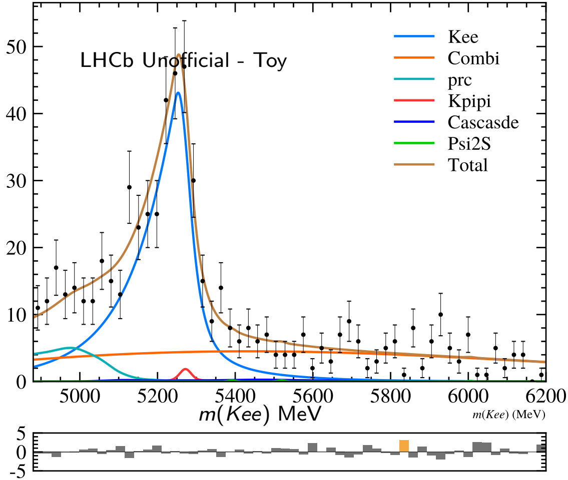
- $q^2_{TRACK} > 14.0$ GeV^2 cut to remove $\psi(2S)$ leakage
- $m(Ke) > 1885$ MeV cut to remove charm cascade/semi-leptonics
- Combinatorial BDT
- Part-reco BDT



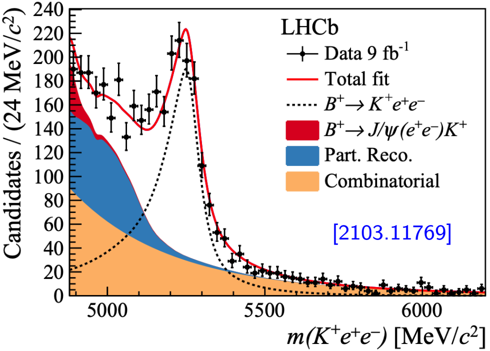
Toys and initial sensitivity estimates

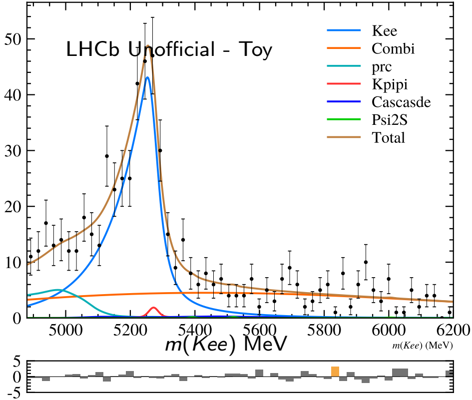
- Toys assume $R_K = 1$
- R_K sensitivity completely dominated by electron yield
- Toys show R_K is unbiased and fit errors have good statistical coverage
- **Sensitivity will be competitive with other LFU measurements**

- Note, q^2 BDT is yet to be added to these toys
  - Will only improve sensitivity
  - May require addition of a $\psi(2S)$ component in fit
  - To be optimised



Comparison to R_K at central q^2





- So far, with smaller backgrounds at high-q^2 toys show sensitivity scaling closer to $\sqrt{N}$ than at central-q^2 where larger combinatorial and part reco components under the signal peak are harder to separate.

Conclusion

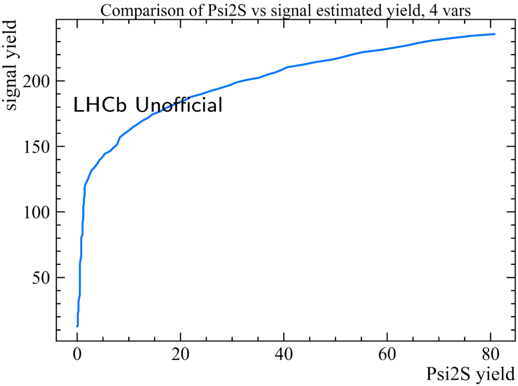
- A high-q^2 R_K measurement is a key piece of the LFU puzzle.
- An anomalous result of high-q^2 R_K would be a tantalising confirmation of new physics
  - Especially given a different kinematic region to the central-q^2 measurement, the proximity to the $\psi(2S)$ kinematics, and different background considerations.
- We have built up a strategy to address perceived difficulties with doing this measurement.
- Initial sensitivity estimates show result will be competitive
- Pieces are coming together, and a full picture is close

Thank you very much for listening, any questions?

BACKUP SLIDES

q^2 BDT

- Input variables
  - q^2
  - q^2_{TRACK}
  - Lepton kinematic information
- Optimise cut in parallel with optimisation of q^2_{TRACK} cut, all in R_K sensitivity toys including a $\psi(2S)$ component.



Partially reconstructed BDT variables

- Contamination will be lower than at central-q^2
- No phasespace for the K^* at very high q^2.
- To further reduce contamination, train BDT including charged isolation information

Similar variables to combinatorial BDT

- B^+: p_T, $\log\chi^2_{IP}$, χ^2_{DV}, DIRA, $\chi^2_{DV\leftrightarrow PV}$
- $\ell\ell$: p_T, $\log\chi^2_{IP}$
- K^+: p_T, $\log\chi^2_{IP}$
- ℓ: min,max(p_T), min,max($\log\chi^2_{IP}$)
- Charged isolation information

Cut to be optimised with toys