Lepton Flavour Universality tests with heavy flavour decays at LHCb

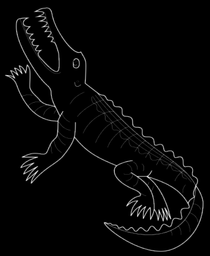
Harry Cliff

Cavendish Laboratory, University of Cambridge

On behalf of the LHCb Collaboration

Rencontres de Blois on Particle Physics and Cosmology

Tuesday 4th June 2019



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Outline

This talk will focus on a much-anticipated recent result from LHCb…

PHYSICAL REVIEW LETTERS **122,** 191801 (2019)

Editors' Suggestion

Search for Lepton-Universality Violation in $B^+ \to K^+\ell^+\ell^-$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 25 March 2019; published 13 May 2019)

A measurement of the ratio of branching fractions of the decays $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ is presented. The proton-proton collision data used correspond to an integrated luminosity of 5.0 fb^{-1} recorded with the LHCb experiment at center-of-mass energies of 7, 8, and 13 TeV. For the dilepton mass-squared range $1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$ the ratio of branching fractions is measured to be $R_K = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$, where the first uncertainty is statistical and the second systematic. This is the most precise measurement of R_K to date and is compatible with the standard model at the level of 2.5 standard deviations.

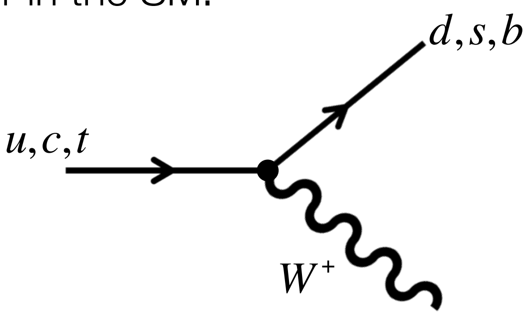
DOI: 10.1103/PhysRevLett.122.191801

… and briefly explore upcoming measurements in this area.

Phys.Rev.Lett. 122 (2019) no.19, 191801

Why $B\to K\, l^+ l^-$ decays?

Only the W bosons can change quark flavour in the SM.



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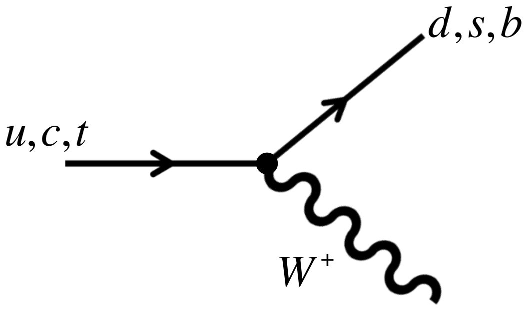

Only transitions between up-type and down-type quarks are allowed at tree-level.

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Inter-generational transitions suppressed by powers of $\lambda \sim 0.22$.

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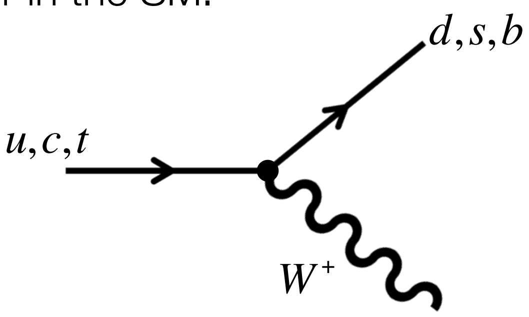

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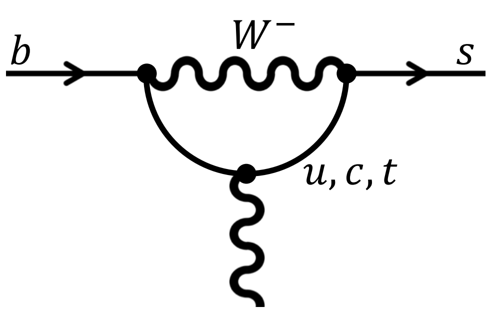

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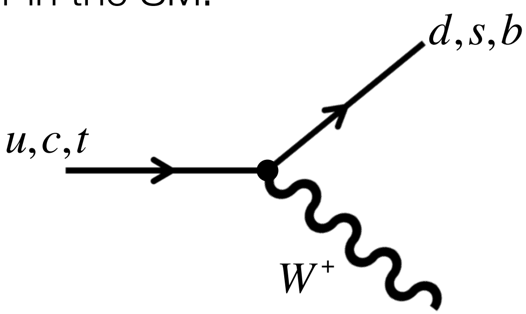

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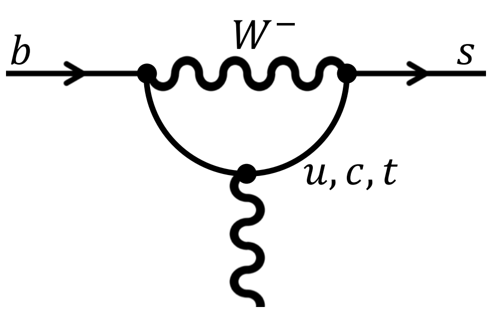
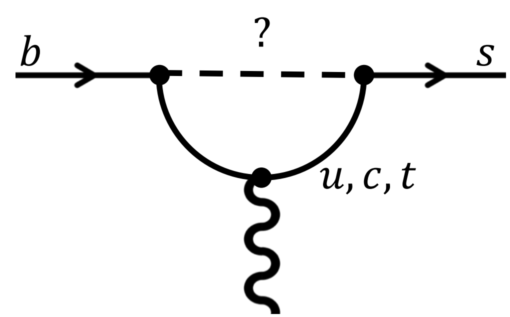


Suppressed by GIM mechanism and must include at least one off-diagonal CKM element.

New TeV-scale quantum fields can mediate decays and alter observables.



In some cases provides sensitivity to resonances up to 1000 TeV.

Why tests of lepton universality?

Semi-leptonic $b \to s l^+ l^-$ decays are theoretically challenging due to hadronic uncertainties. BUT ratio of branching fractions:

$$R_K \equiv \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^+ \to K^- e^+ e^-)}{dq^2} dq^2}$$

cancels hadronic uncertainties, allowing precise predictions. In the SM R_K =1 to within 1% for $1.1 < q^2 < 6\ \mathrm{GeV}^2$ [Eur.Phys.J. C76 (2016) no.8, 440], which excludes charmonium resonances.

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Well known tensions in rare B decays from LHCb:

$$R_{K^+}[1 < q^2/\mathrm{GeV}^2 < 6] = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.035(\mathrm{syst})$$

Phys.Rev.Lett. 113 (2014) 151601

$$R_{K^{*0}}[0.045 < q^2/\mathrm{GeV}^2 < 1.1] = 0.66^{+0.11}_{-0.07}(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$
$$R_{K^{*0}}[1.1 < q^2/\mathrm{GeV}^2 < 6.0] = 0.69^{+0.11}_{-0.07}(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

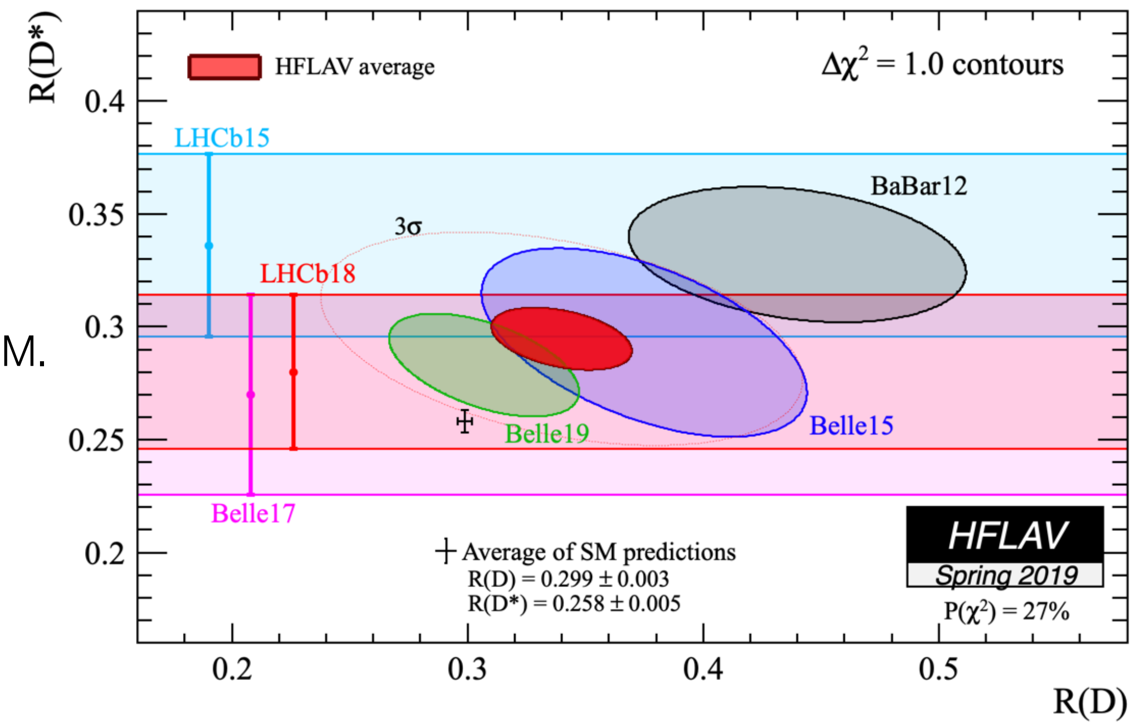
JHEP 1708 (2017) 055

Why tests of lepton universality?

Tensions in other observables:

$$R_{D^{(*)}} \equiv \frac{\mathrm{BF}\left(B \to D^{(*)}\tau\nu_\tau\right)}{\mathrm{BF}\left(B \to D^{(*)}\mu\nu_\mu\right)}$$

with world-average of D^+, D^0 and D^* results showing 3.08σ tension with SM.



HFLAV (2019)

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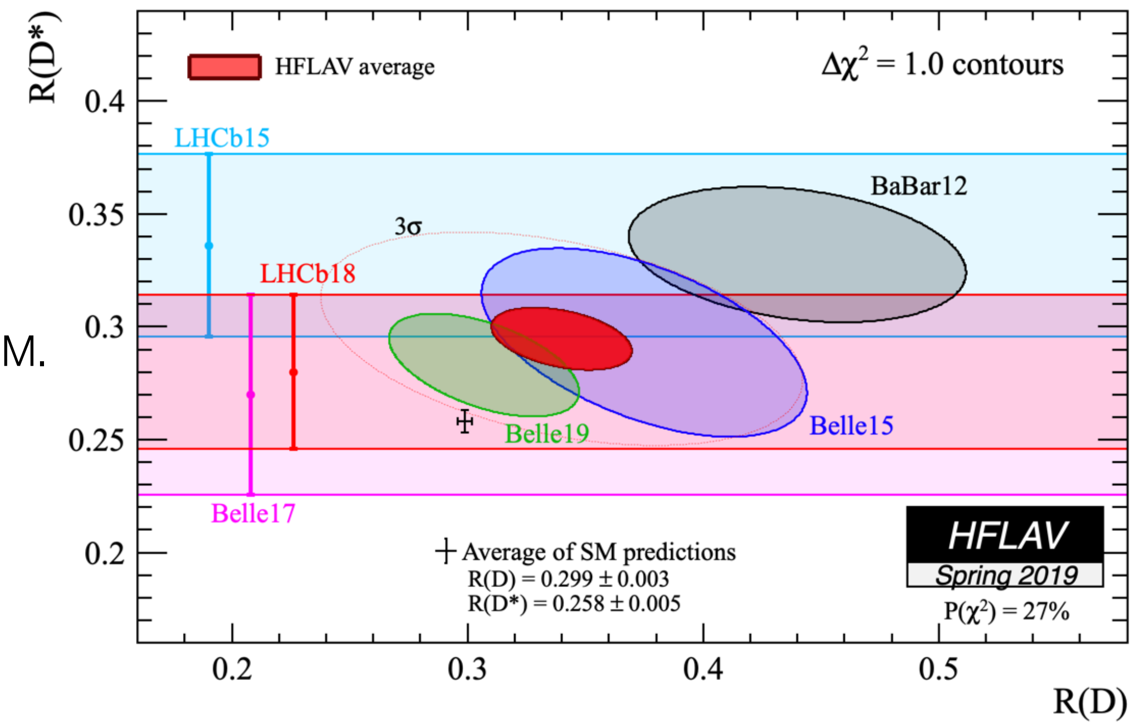


HFLAV (2019)

Also:

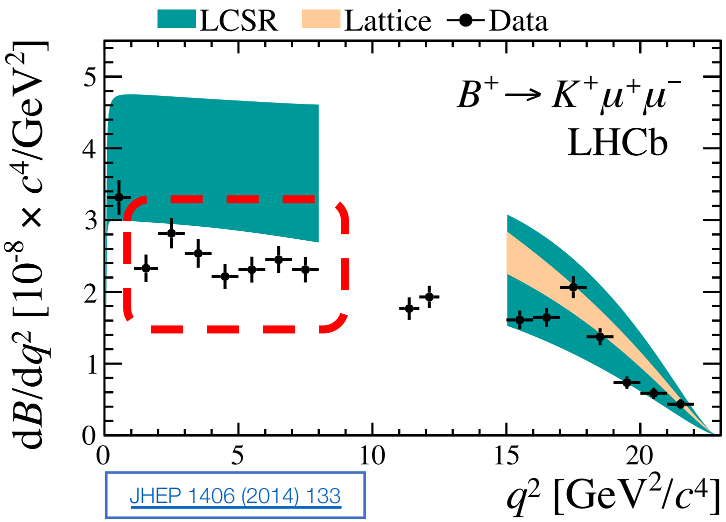
$$\frac{2\mathrm{BF}(W \to \tau\nu_\tau)}{\mathrm{BF}(W \to e\nu_e) + \mathrm{BF}\left(W \to \mu\nu_\mu\right)} = 1.066 \pm 0.025$$

~2.6σ tension with SM.

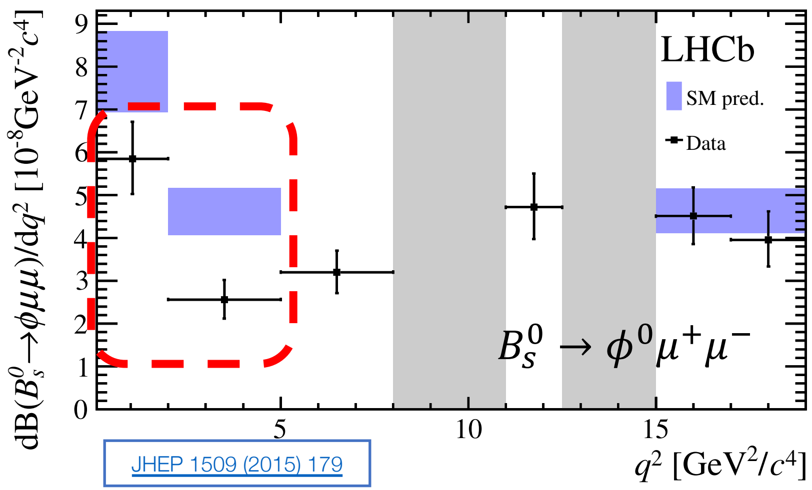
Phys.Rept. 532 (2013) 119-244

Anomalies in $b \to s\mu^+\mu^-$

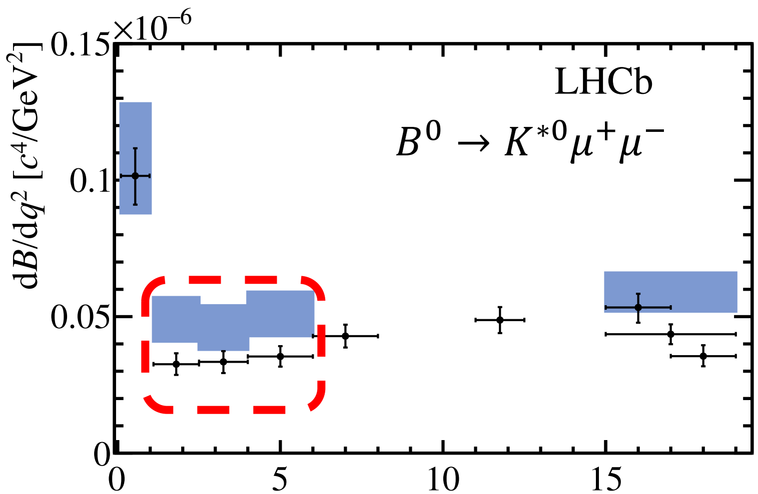
Also…



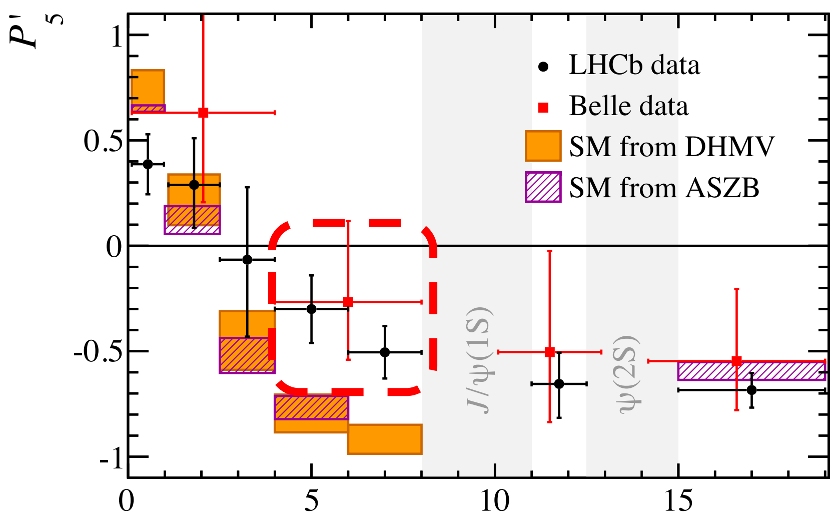
JHEP 1406 (2014) 133



JHEP 1509 (2015) 179



JHEP 04 (2017) 142



JHEP 1602 (2016) 104

BELLE-CONF-1603

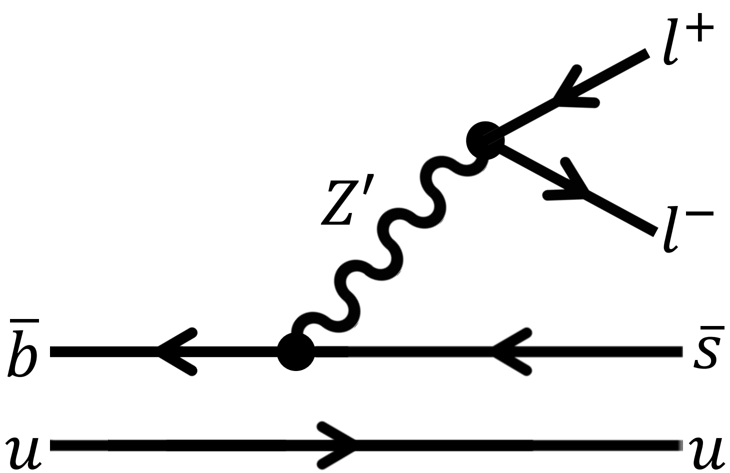
JHEP 1412 (2014) 125

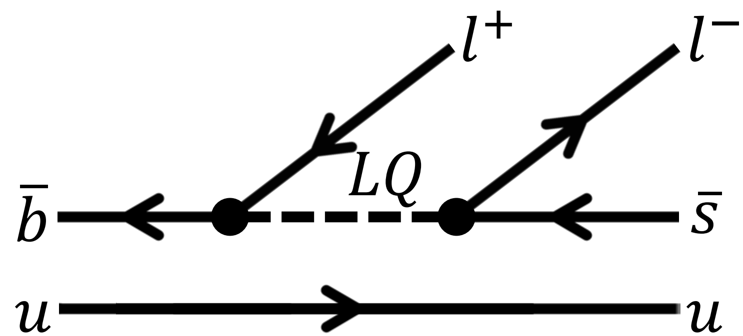
Eur.Phys.J. C75 (2015) no.8, 382

New physics?

Together, these anomalies form an intriguing pattern…

Possible coherent explanation involving tree-level new physics competing with SM loop and box diagrams.



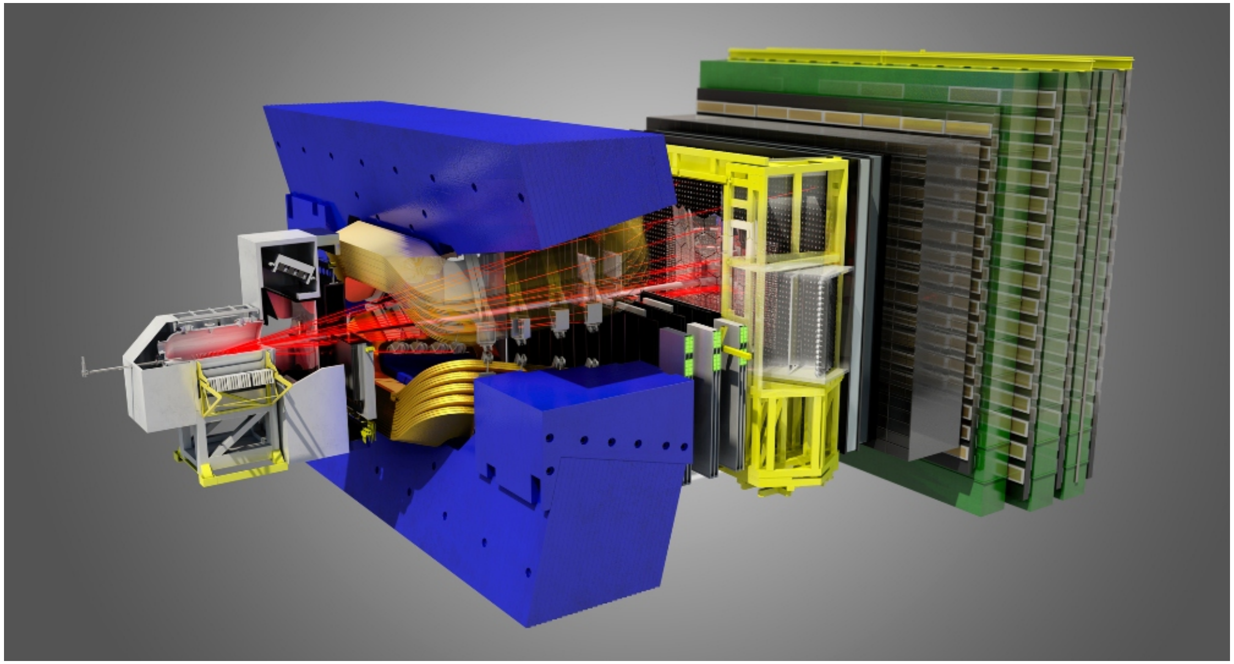


May be probing Z' or leptoquarks with masses well beyond the energy reach of the LHC!

JINST 3 (2008) S08005

LHCb

LHCb is a forward-arm spectrometer full instrumented in the forward region ($2 < \eta < 5$) including:



- Excellent vertex resolution from a silicon strip detector surrounding the interaction point (VELO).
- Particle identification from two ring-imaging Cherenkov (RICH) detectors, calorimeter and muon system.
- Electromagnetic calorimeter used to trigger and identify electrons and perform recovery of bremsstrahlung photons.

LHCb's core physics programme is to test the Standard Model at high precision and perform indirect searches for new physics in the decays of beauty and charm hadrons.

Experimental strategy

Data sample: 5fb^{-1} total:

- 3fb^{-1} Run 1 (2011, 2012) 7,8 TeV
- 2fb^{-1} Run 2 (2015, 2016) 13 TeV

Key experimental challenge: different trigger and reconstruction efficiencies for muons and electrons.

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Systematic uncertainties substantially reduced by measuring double ratio:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}\big(B^+ \to K^+J/\psi(\mu^+\mu^-)\big)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}\big(B^+ \to K^+J/\psi(e^+e^-)\big)}$$

using J/ψ control modes. $J/\psi \to e^+e^- = J/\psi \to \mu^+\mu^-$ to within 0.4%.

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Double ratio measured as: From mass fit From simulation

$$R_K = \frac{N(B^+ \to K^+\mu^+\mu^-) \cdot N\big(B^+ \to K^+J/\psi(e^+e^-)\big)}{N\big(B^+ \to K^+J/\psi(\mu^+\mu^-)\big) \cdot N(B^+ \to K^+e^+e^-)} \times \frac{\epsilon(B^+ \to K^+e^+e^-) \cdot \epsilon\big(B^+ \to K^+J/\psi(\mu^+\mu^-)\big)}{\epsilon\big(B^+ \to K^+J/\psi(e^+e^-)\big) \cdot \epsilon(B^+ \to K^+\mu^+\mu^-)}$$

Signal and control samples

Measurement performed in range $1.1 < q^2 < 6\ \mathrm{GeV}^2$, where charmonium resonances are excluded and theoretical predictions are precise.

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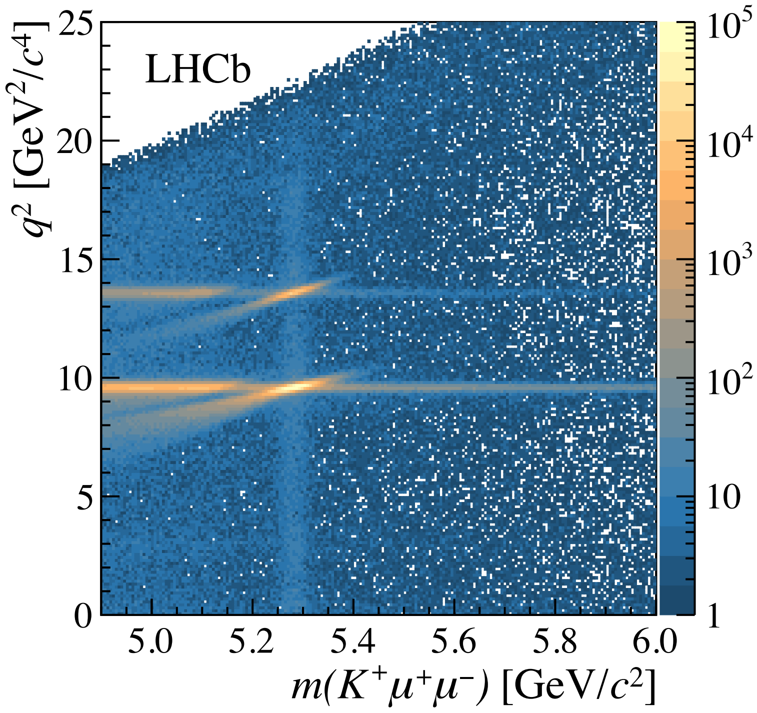

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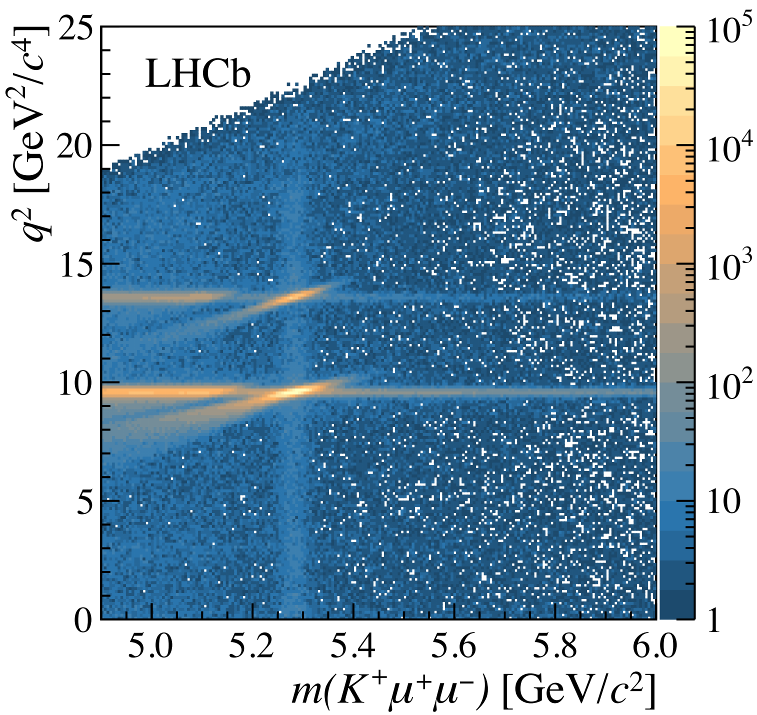

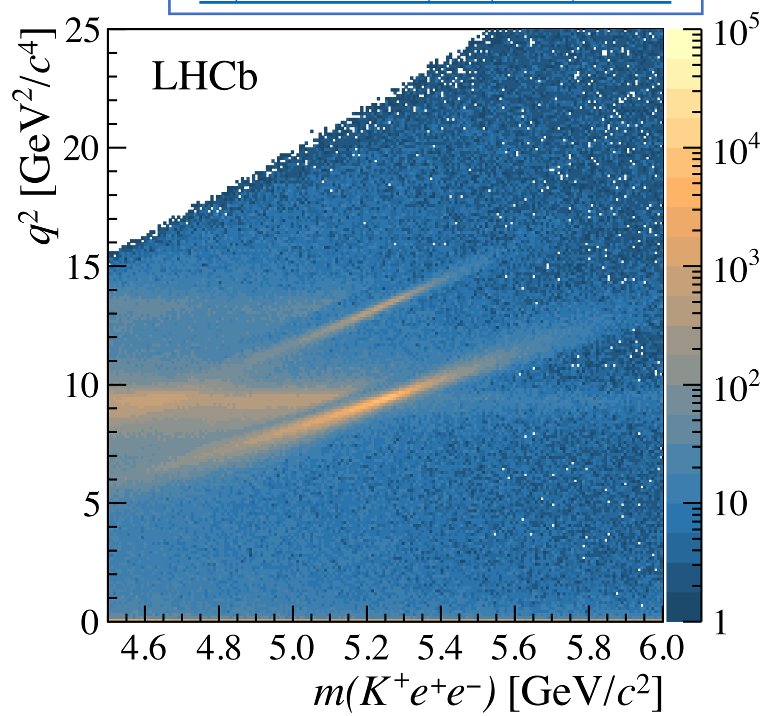

Wider q^2 region in electron control mode due to long bremsstrahlung tail.

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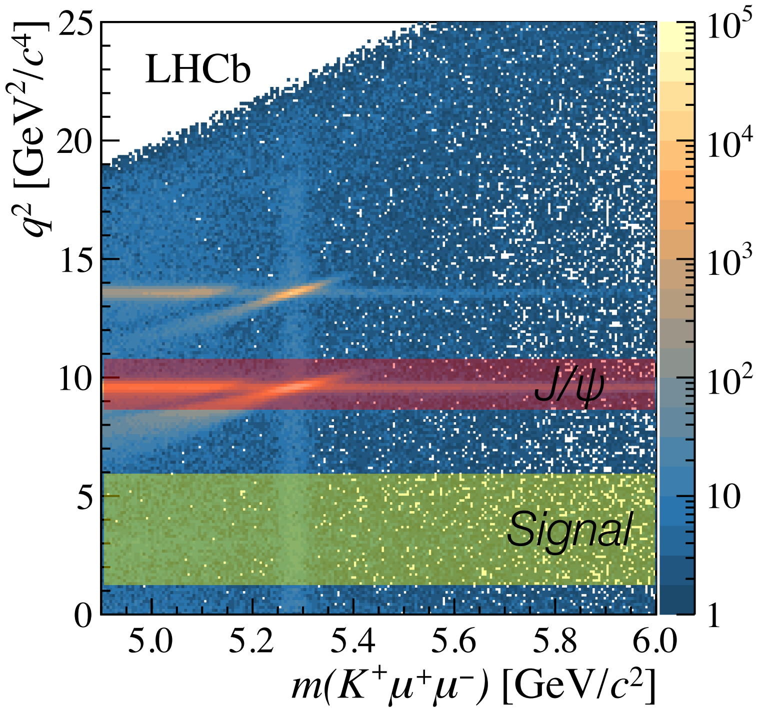

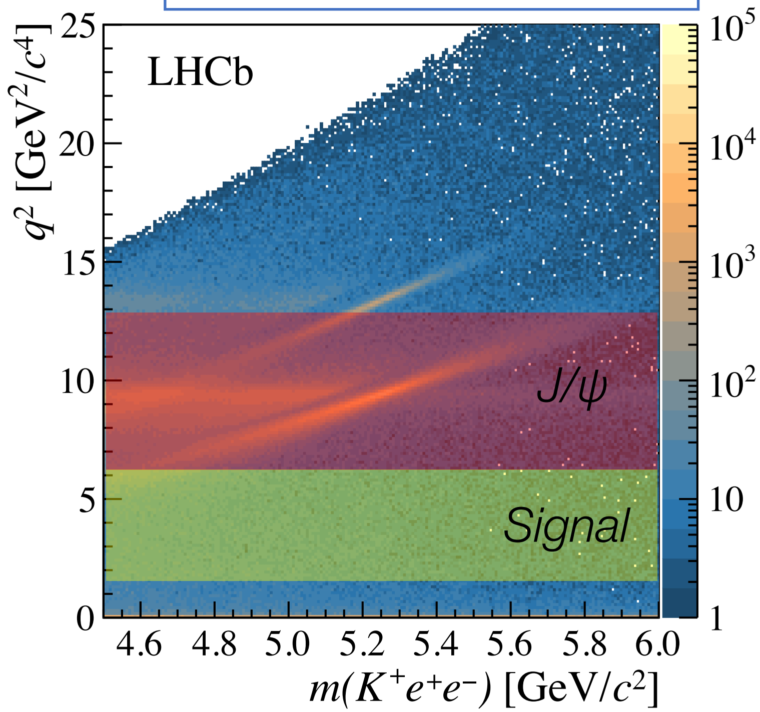

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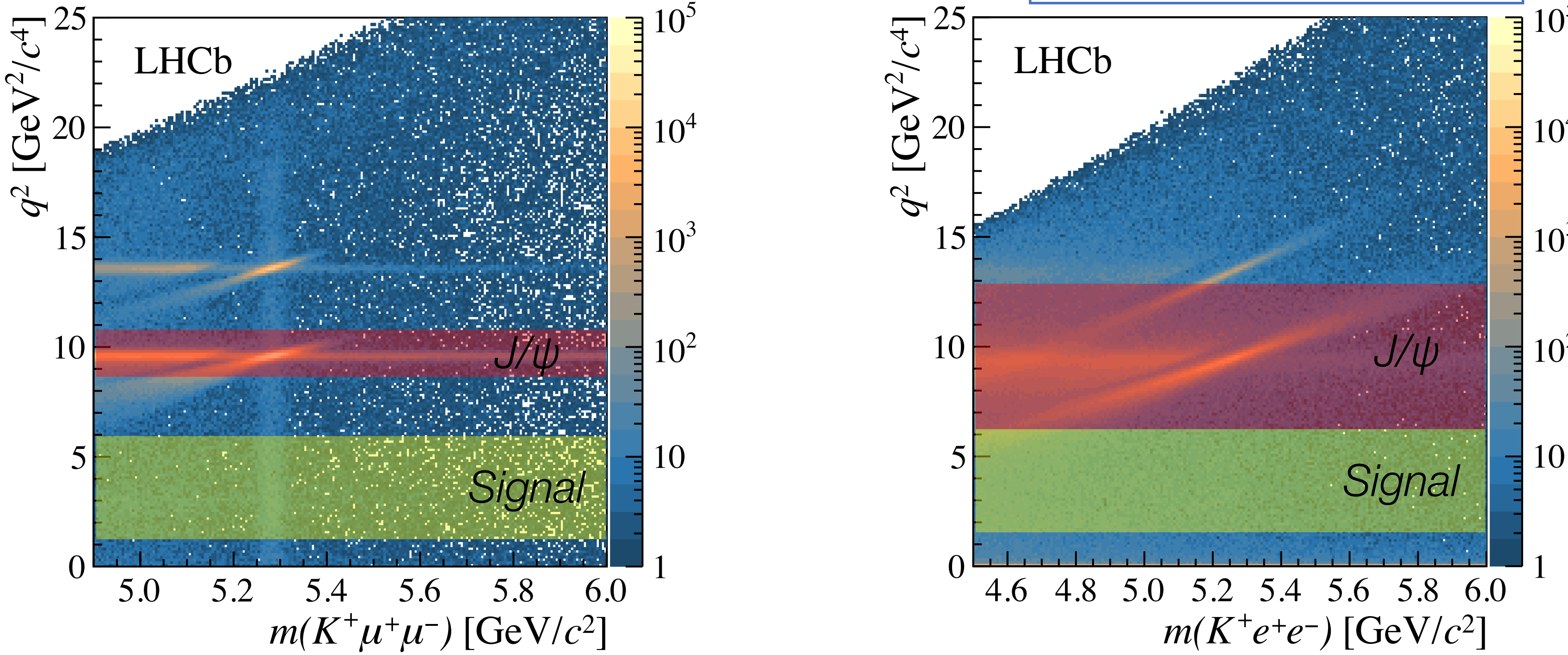

Wider q^2 region in electron control mode due to long bremsstrahlung tail.

B^+ mass includes J/ψ mass constraint in control mode to improve resolution.

Decay mode	q^2 [GeV$^2/c^4$]	$m_{(J/\psi)}(K^+\ell^+\ell^-)$ [GeV/c^2]
nonresonant e^+e^-	1.1 – 6.0	4.88 – 6.20
resonant e^+e^-	6.00 – 12.96	5.08 – 5.70
nonresonant $\mu^+\mu^-$	1.1 – 6.0	5.18 – 5.60
resonant $\mu^+\mu^-$	8.68 – 10.09	5.18 – 5.60

Event selection

Trigger

- Muon decay triggered by high p_T muons
- Three electron decay trigger categories:
  - Triggered by electron in ECAL
  - Triggered by hadron in HCAL
  - Triggered by the rest of the event

Candidates then selected by specific software triggers.

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Selection

Form candidates from kaon and two oppositely charged leptons:

- Identify kaon / leptons using PID info from RICH, ECAL and Muon System
- Bremsstrahlung photons recovered for electrons (see later)
- Candidates must have high pT, good vertex displaced from PV and have a momentum that points back to the PV

Multivariate classifier (BDT) trained on simulation (signal) and high mass data (background) suppresses 99% of combinatorial background while retaining 85% of signal.

Backgrounds

Cascade $b \to c$ decays potentially dangerous backgrounds due to large branching fractions.

Most problematic for rare electron decay where they could contaminate low $m(K^+e^+e^-)$ region and overlap with signal brem tail.

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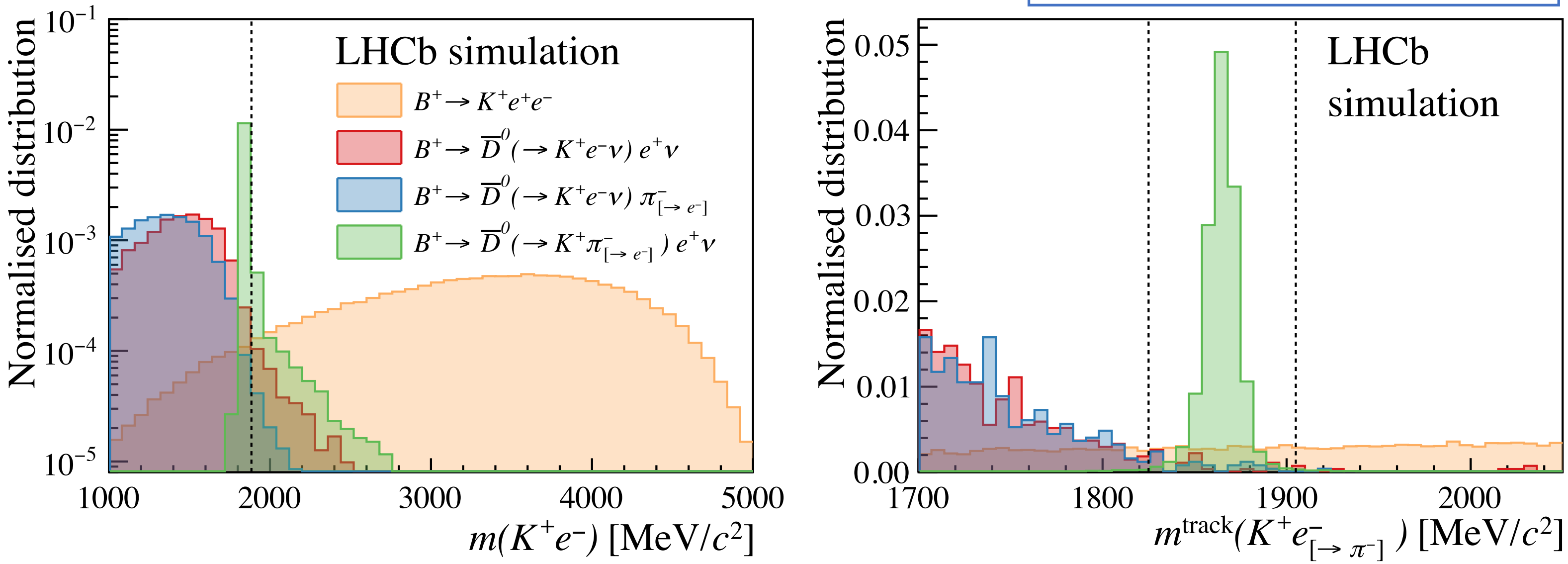

Reduced to negligible levels while retaining 97% (95%) of muon (electron) signal by:

- $m(K^+e^-) > m(D^0)$
- $m(K^+\pi^-)$ not consistent with $m(D^0)$

Efficiency calculation

Efficiencies calculated using simulation. Simulation corrected to account for data-MC differences:

1. PID efficiency weights taken from data calibration samples
2. Hardware and software trigger corrected with tag and probe $B^+ \to K^+ J/\psi(l^+ l)$ data
3. B^+ kinematics corrected with $B^+ \to K^+ J/\psi(\mu^+ \mu^-)$ data
4. q^2 resolution corrected using $m(l^+ l)$ of J/ψ peak

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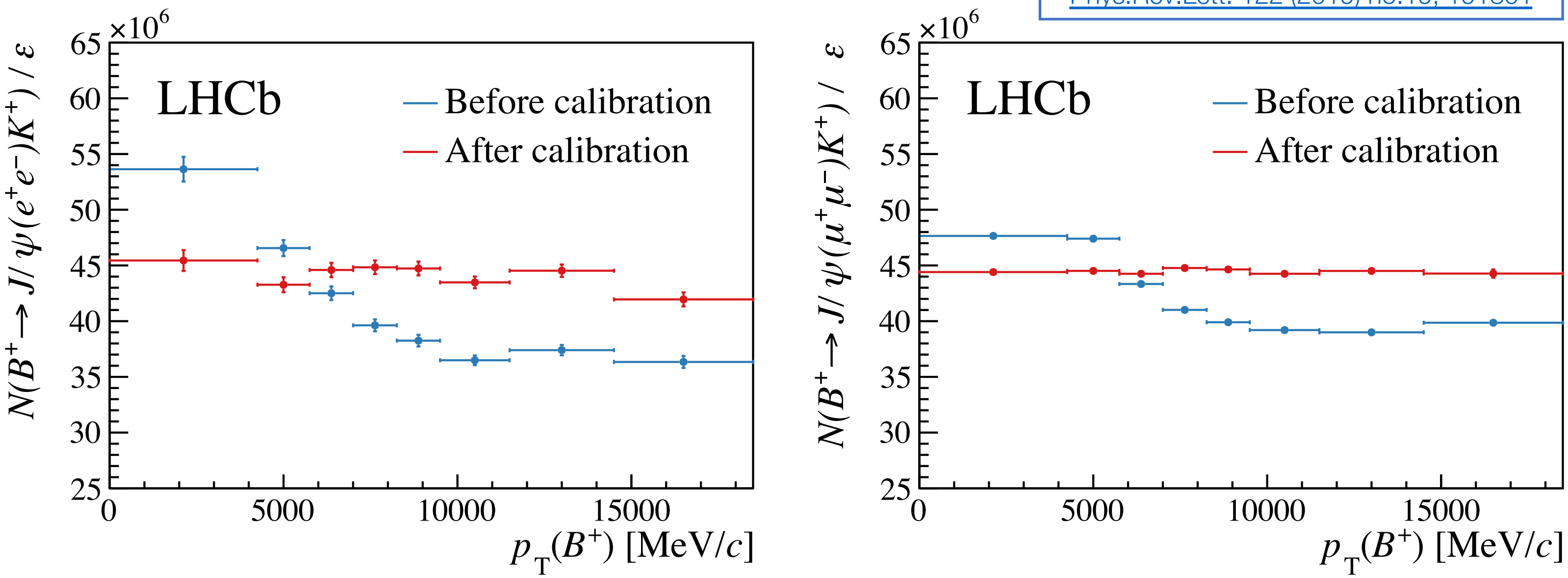


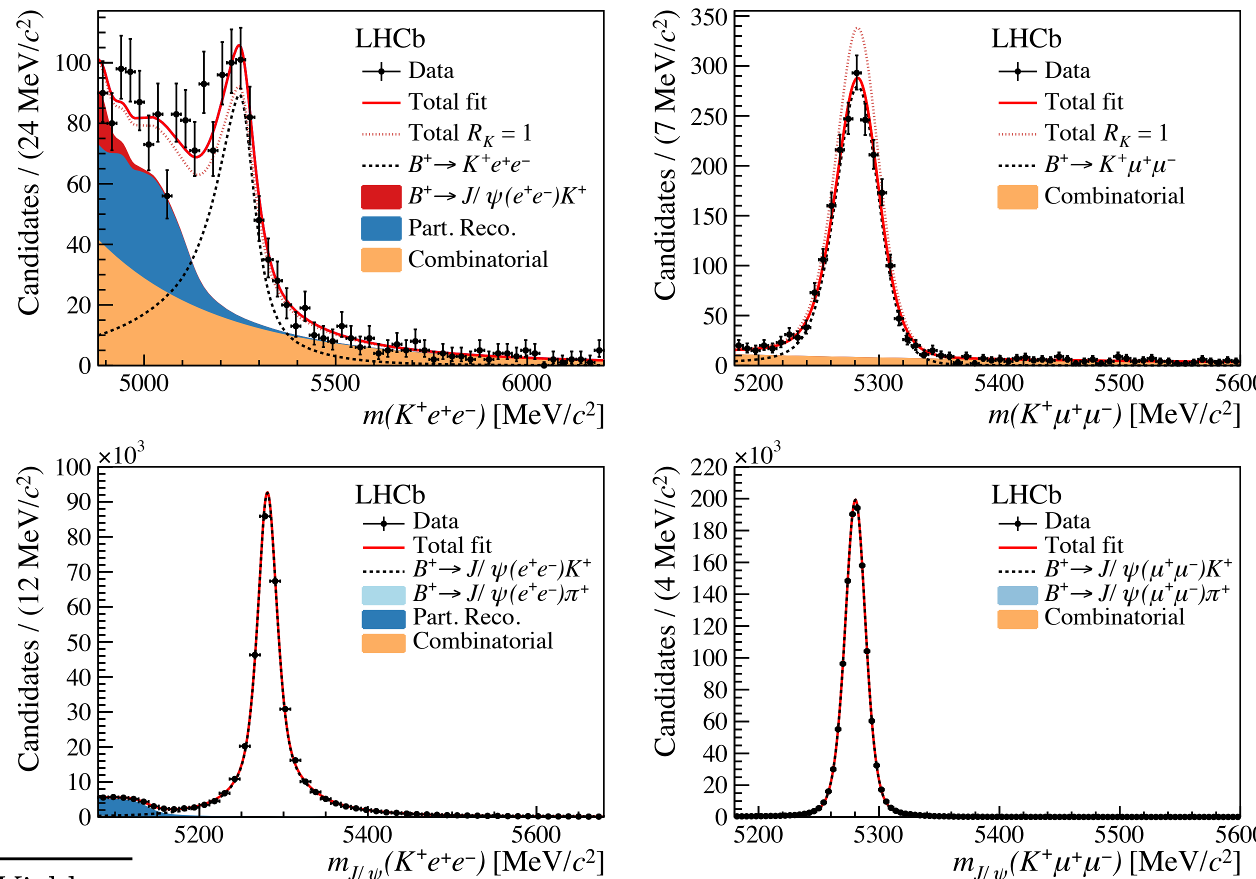
Overall effect of these corrections is at the 0.02 level on R_K – highly robust!

Mass fit

Simultaneous fit used to extract R_K and $B^+ \to K^+\mu^+\mu^-$ yield. Resonant yields constrained to results from separate fits.

Shapes determined from fits to simulation:

- Multi-core gaussians with power law tails
- Signal electron mode modelled with three functions corresponding to number of brem photons recovered
- Partially reconstructed background yields allowed to float freely



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Decay Mode	Event Yield
$B^+ \to K^+e^+e^-$	766 ± 48
$B^+ \to K^+\mu^+\mu^-$	$1\,943 \pm 49$
$B^+ \to J/\psi(\to e^+e^-)K^+$	$344\,100 \pm 610$
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$	$1\,161\,800 \pm 1\,100$

Systematic uncertainties

Most systematic uncertainties eliminated by double ratio.

Two categories of systematic uncertainties remain:

1. Those affecting the non-resonant (signal) decay yields
    - Choice of mass shapes (checked using pseudo-experiments): 1.1%
2. Those affecting the efficiency double-ratio calculation:
    - Efficiency calibrations: all < 1%
    - Statistics of simulation and calibration samples: 1.0%

Total systematic uncertainty = 1.7%

Cross-checks

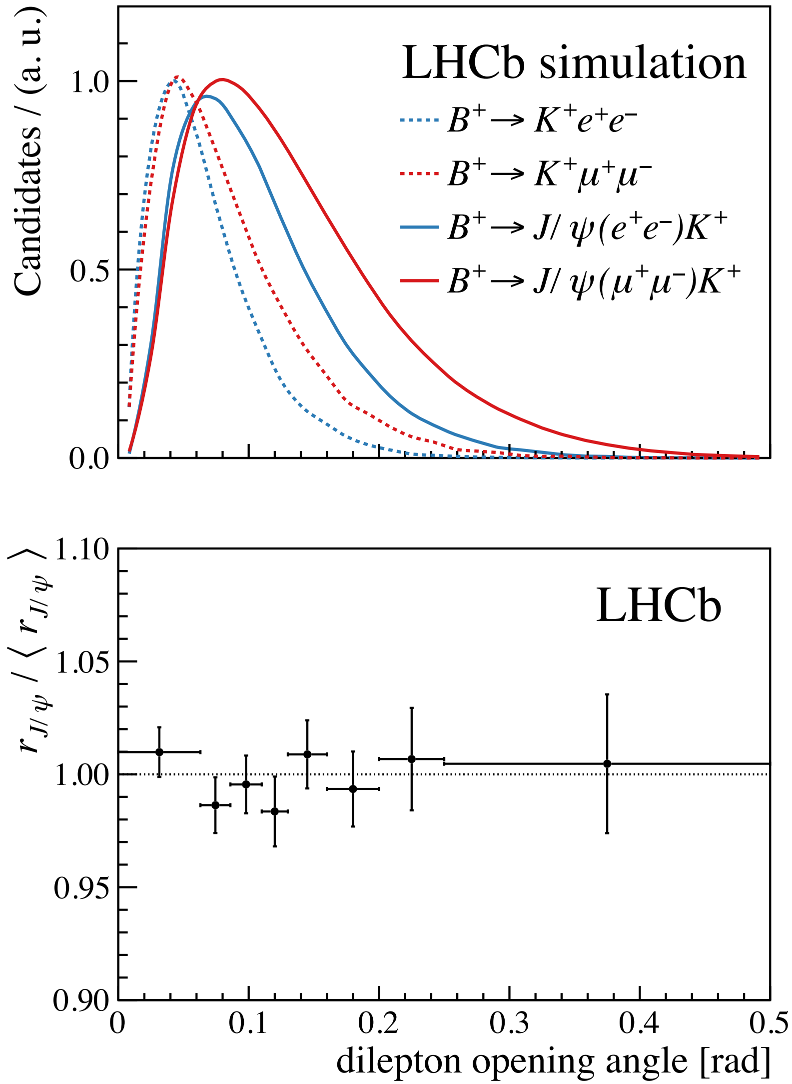
Several cross-checks performed to detect biases due to differences between signal and control modes.

Measure the (much more challenging) quantity:

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

Measured as $r_{J/\psi} = 1.014 \pm 0.035$.

Stable as a function of dilepton opening angle.



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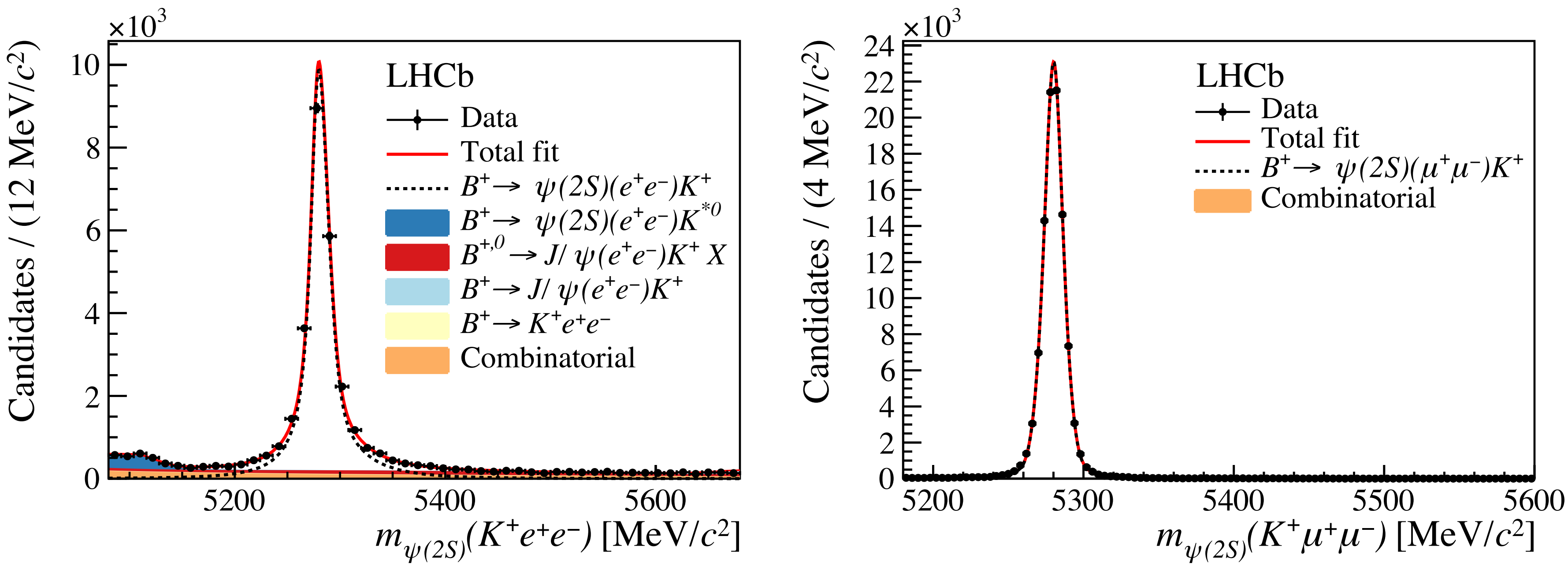
More cross-checks

Also measure

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



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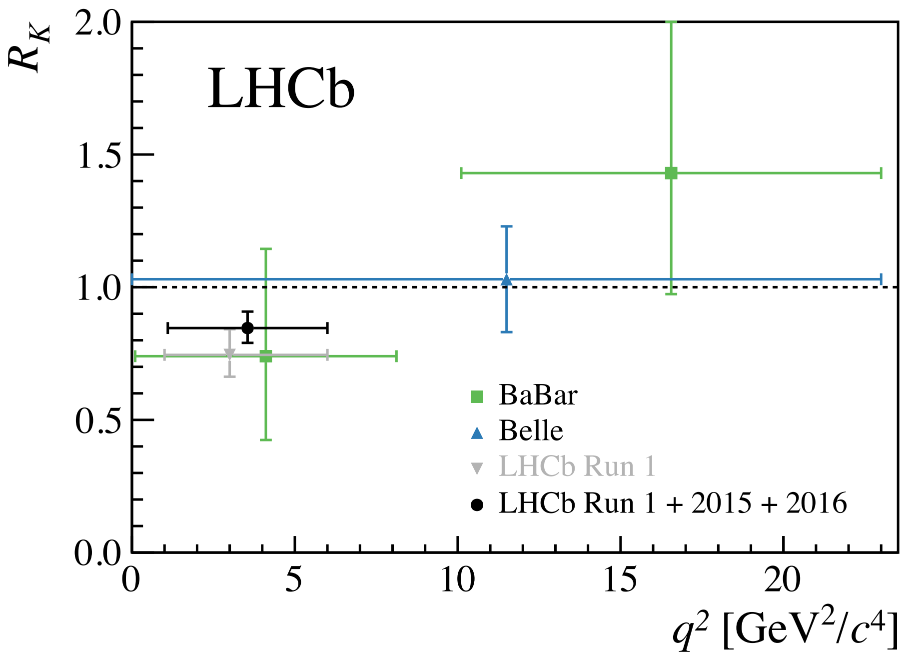
Result: $R_{\psi_{2S}} = 0.986 \pm 0.013$

Results

Final result:

$$R_K = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$$



Consistent with SM at 2.5σ.

Similar tension as before – R_K moves towards SM but error reduces.

Broken down by data-taking period results consistent at 1.9σ:

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$$R_K(\text{Run 1}) = 0.717^{+0.083}_{-0.071}{}^{+0.017}_{-0.016}$$

$$R_K(\text{Run 2}) = 0.928^{+0.089}_{-0.076}{}^{+0.020}_{-0.017}$$

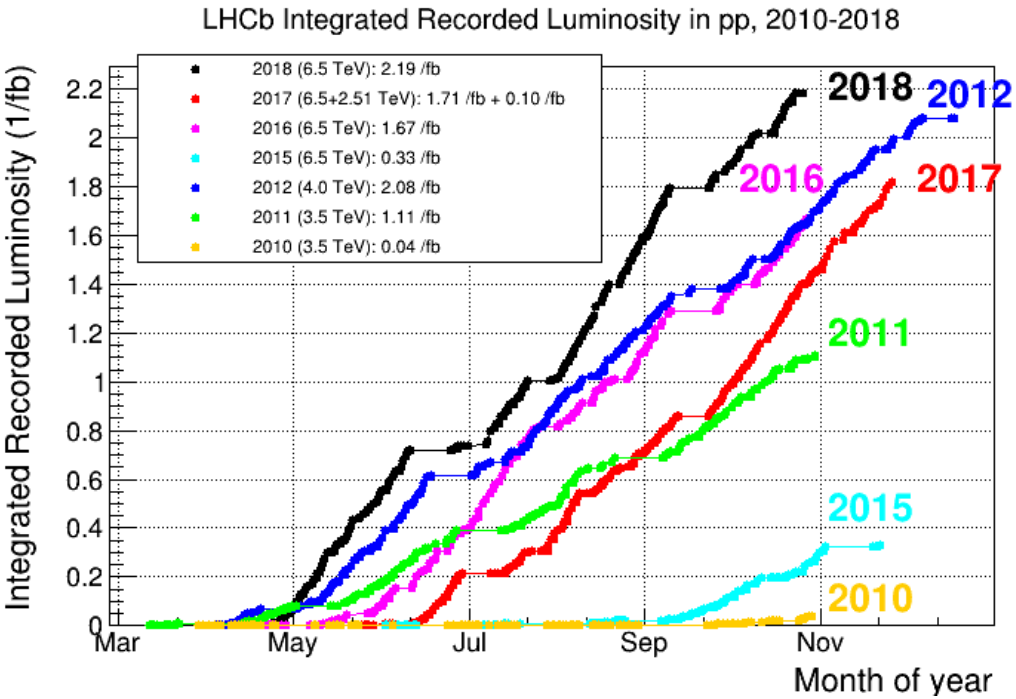
New Run 1 result consistent with old result $R_K(\text{Run 1, old}) = 0.745^{+0.090}_{-0.074} \pm 0.036$ within 1σ, taking overlap of data samples into account.

Future work

Current analysis uses 3fb^{-1} from Run 1 and 2fb^{-1} from Run 2 but much more data on disk:

2017 : 1.7 fb^{-1}
2018 : 2.1 fb^{-1}

Represents approx. double existing sample due to c.o.m. energy and improved electron trigger and reconstruction efficiency.



Many other LFU measurements in the works:

- $B^0 \to K^{*0} l^+ l^-$
- $B^0 \to K_S^0 l^+ l^-$
- $B^+ \to K^{*+} l^+ l^-$
- $B_s^0 \to \phi l^+ l^-$
- $\Lambda_b^0 \to p K^- l^+ l^-$
- $B^+ \to K^+ \pi^+ \pi^- l^+ l^-$
- $B^0 \to K^+ \pi^+ l^+ l^-$

Conclusions

Highly intriguing set of anomalies in B decays to leptons, with possibly consistent pattern in $b \to s\mu\mu$ decays and *R* measurements.

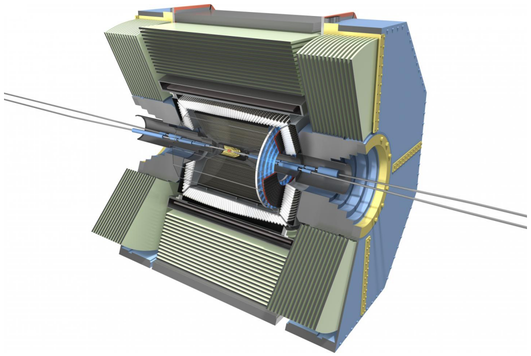
Presented updated search for lepton universality violation in $B^+ \to K^+\mu^+\mu^-$ decays using part of Run 2 data taken at LHCb:

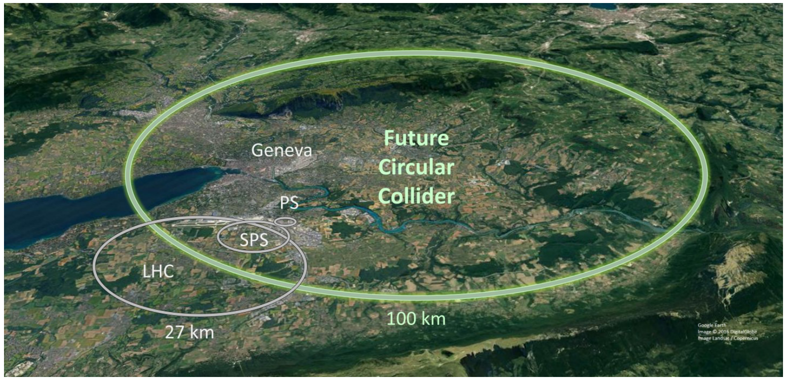
- Result moves towards SM but still in tension at 2.5σ
- Run 1 and Run 2 results consistent within 1.9σ

Full Run 2 analysis and measurements of similar ratios will clarify situation.

LHCb Upgrade (5 x higher lumi, starting data-taking in 2021) and Belle II will confirm NP or not.

If NP, direct observation of Z' or leptoquarks may require a future hadron collider (e.g. FCC).



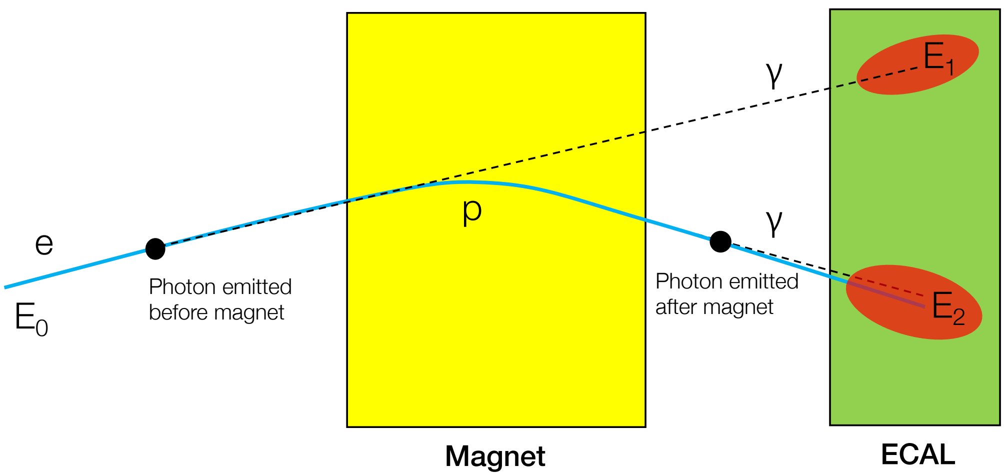


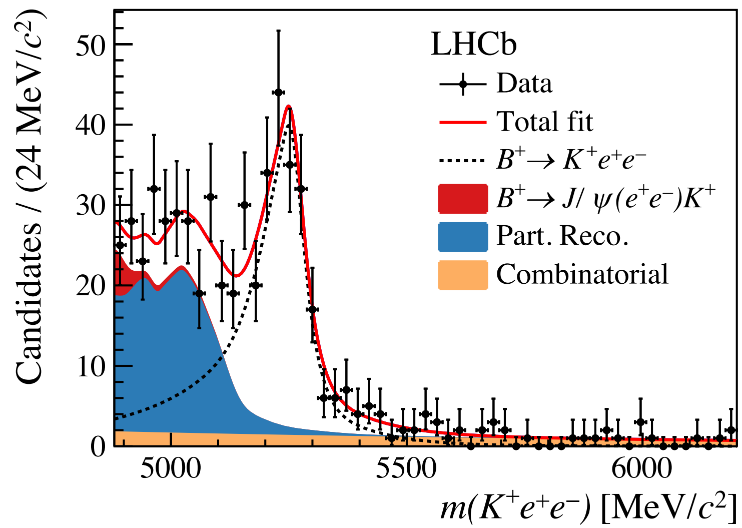
Backup

Bremsstrahlung recovery

Electrons typically radiate ~20% of their energy as bremsstrahlung photons due to interaction with detector material.

Photons radiated before the magnet are particularly problematic – underestimate of momentum.





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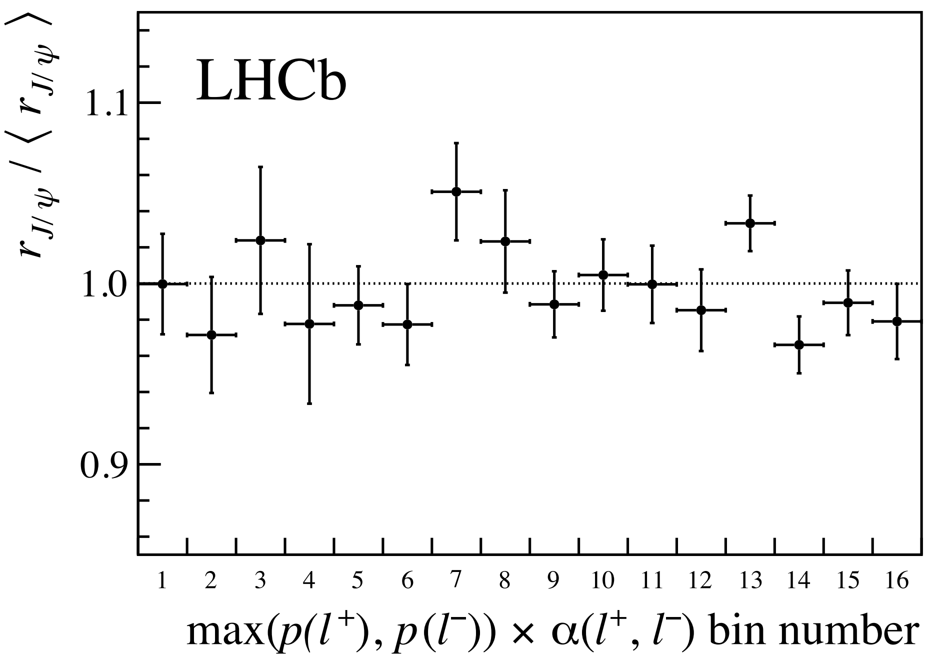
Bremsstrahlung recovery process searches for clusters in the calorimeter:

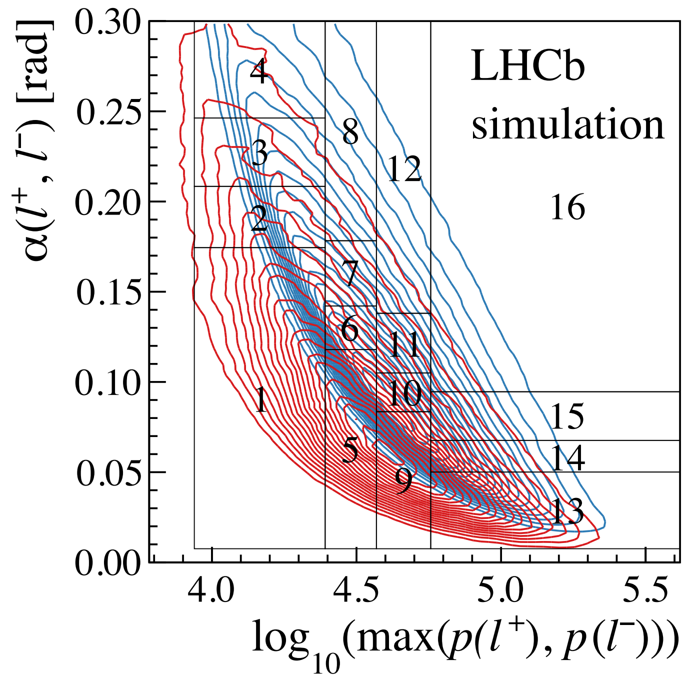
1. Consistent with electron flight direction before magnet
2. Not associated with any other track.

If found, energy added to electron momentum calculation.

Even more cross-checks

Also measure $r_{J/\psi}$ in 2D bins of lepton opening angle and lepton momentum.





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Consistent with unity.