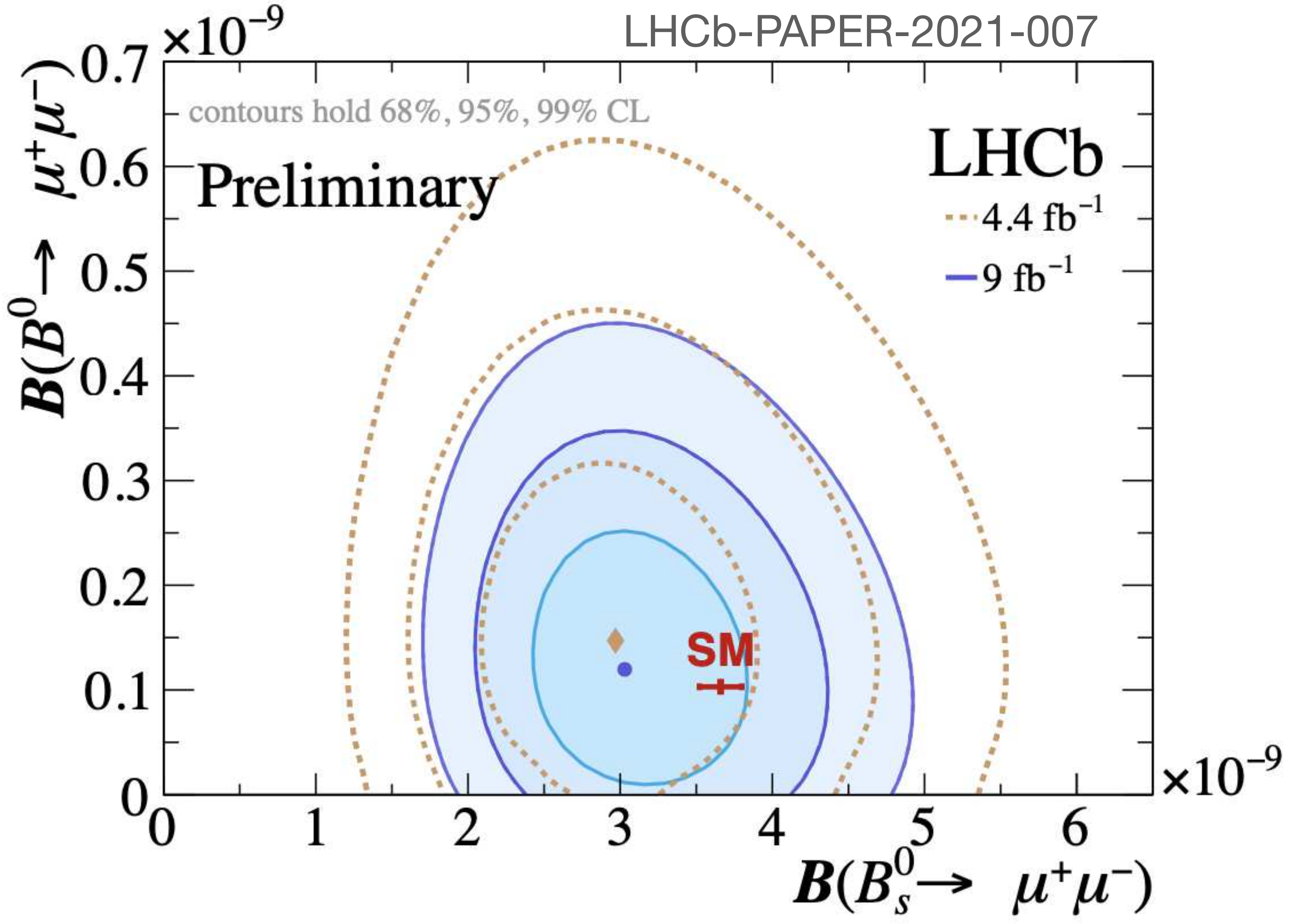
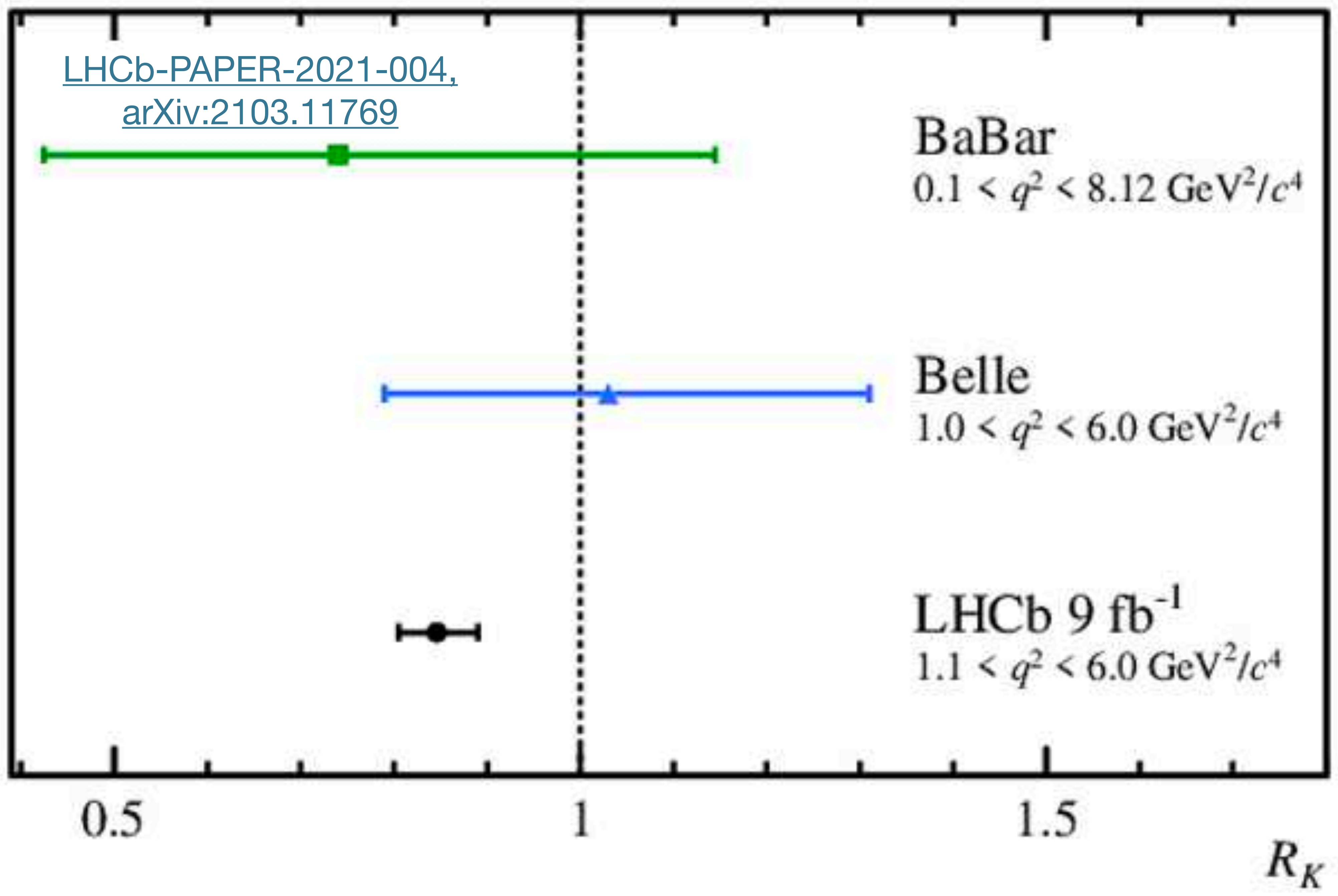
New results on rare B decays at LHCb

KITP Precision21





Patrick Owen - many thanks to Kostas Petridis

University of Zurich[UZH]

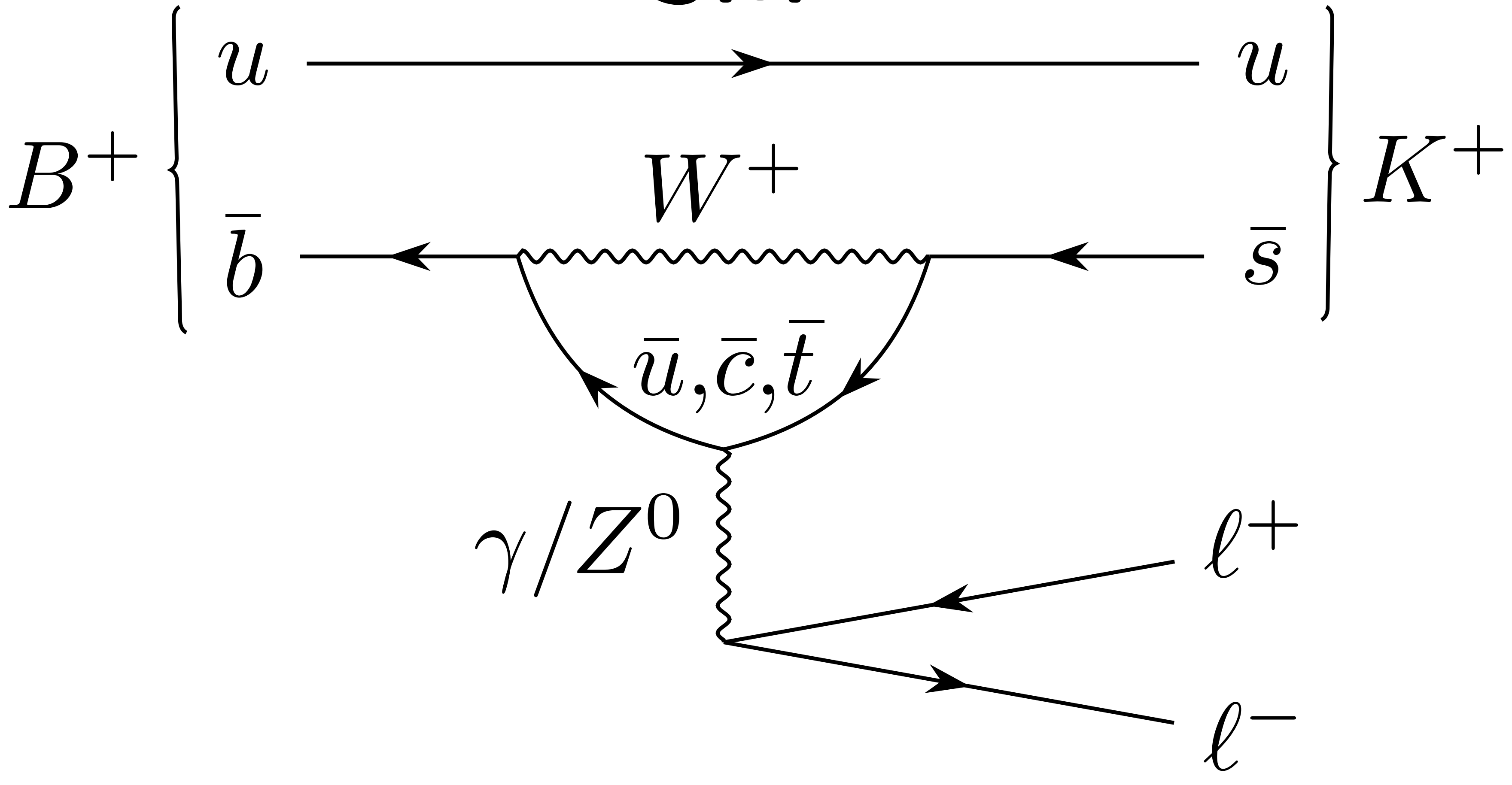
29/03/21

Disclaimer

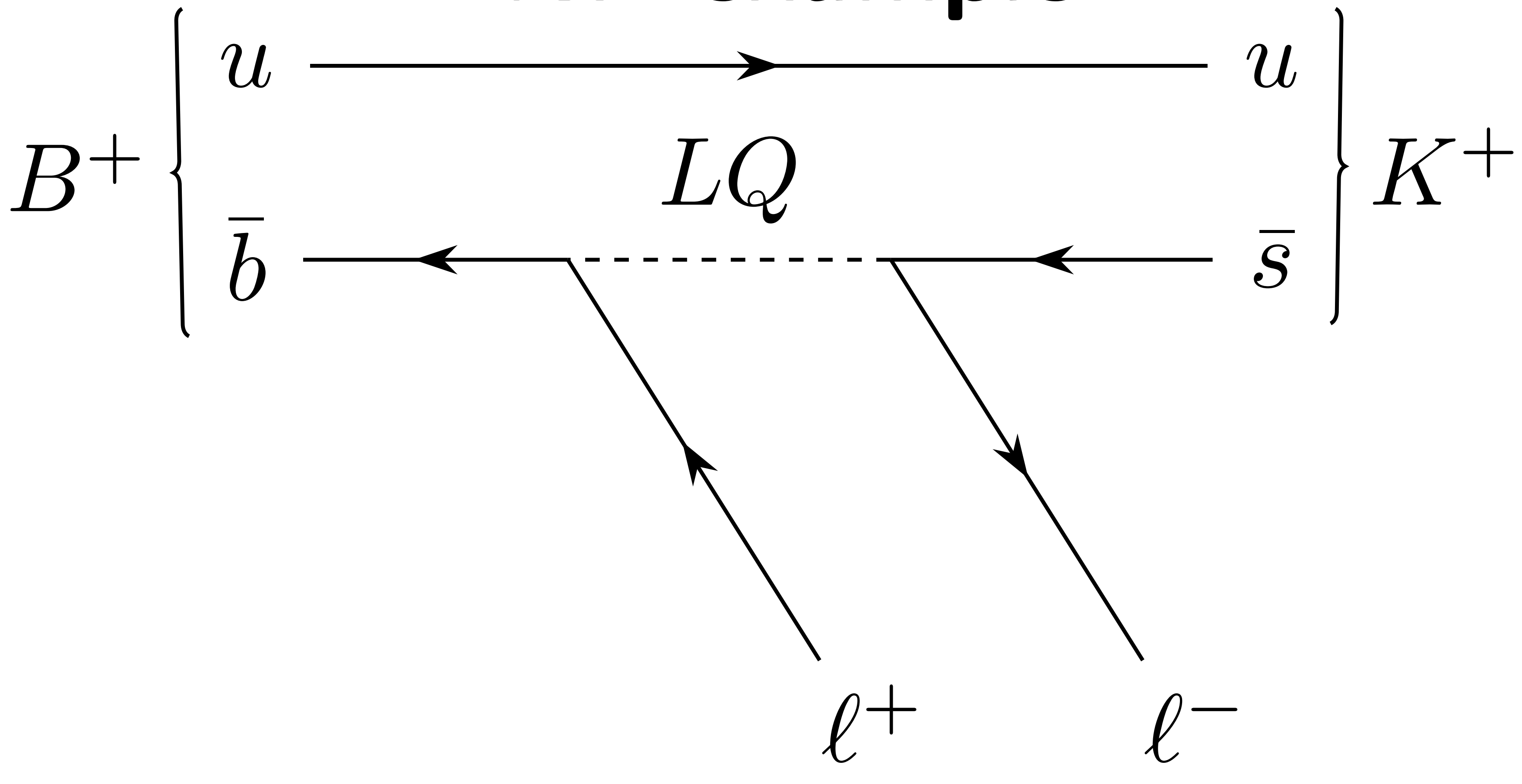
- Not a formal presentation, just a few plots to get discussion going.
    - More coherent story can be found at the recent LHC seminar
- Interrupt at any time.
- Kostas’ slides attached to the end of this as backup (ask away).

$b \to s\ell\ell$ decays

SM



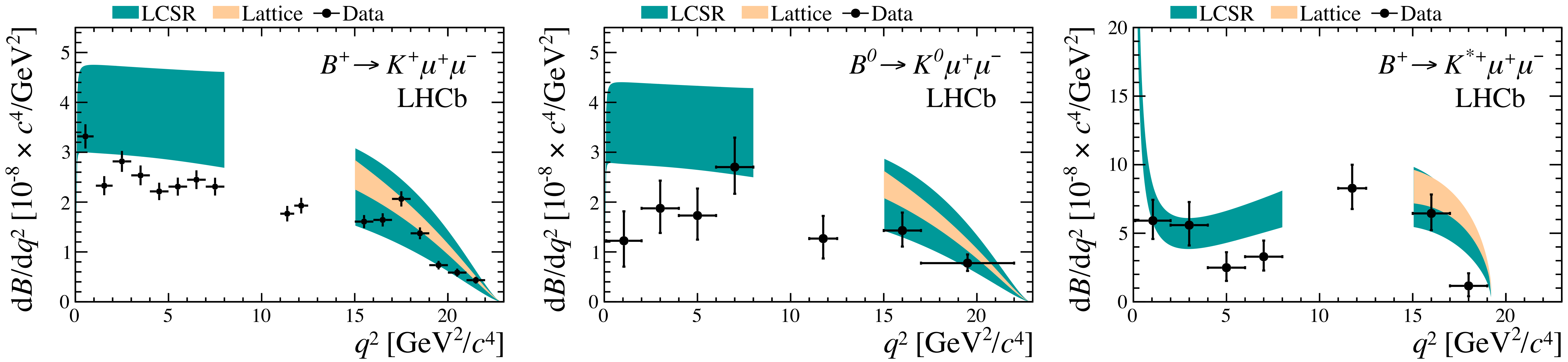
NP example



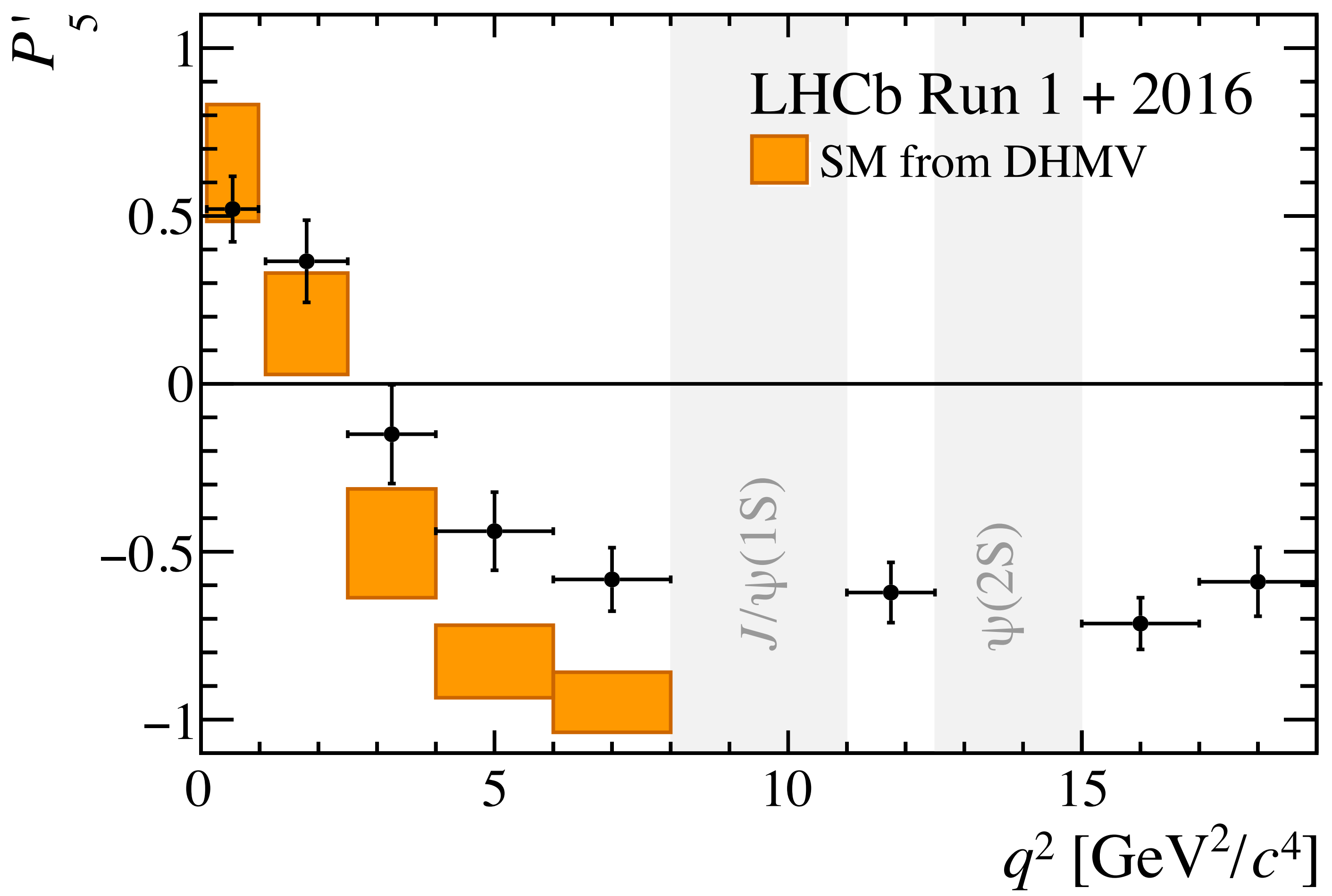
- Semileptonic: Theory can be controlled.
- Suppressed: NP can have large relative contribution.

Muonic results

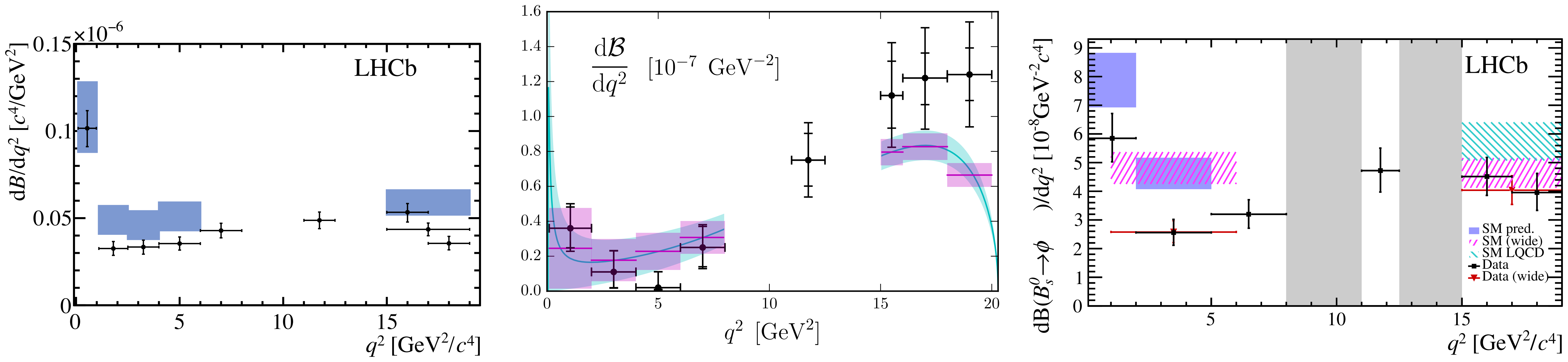
[JHEP06(2014)133]



[PRL125011802(2020)]

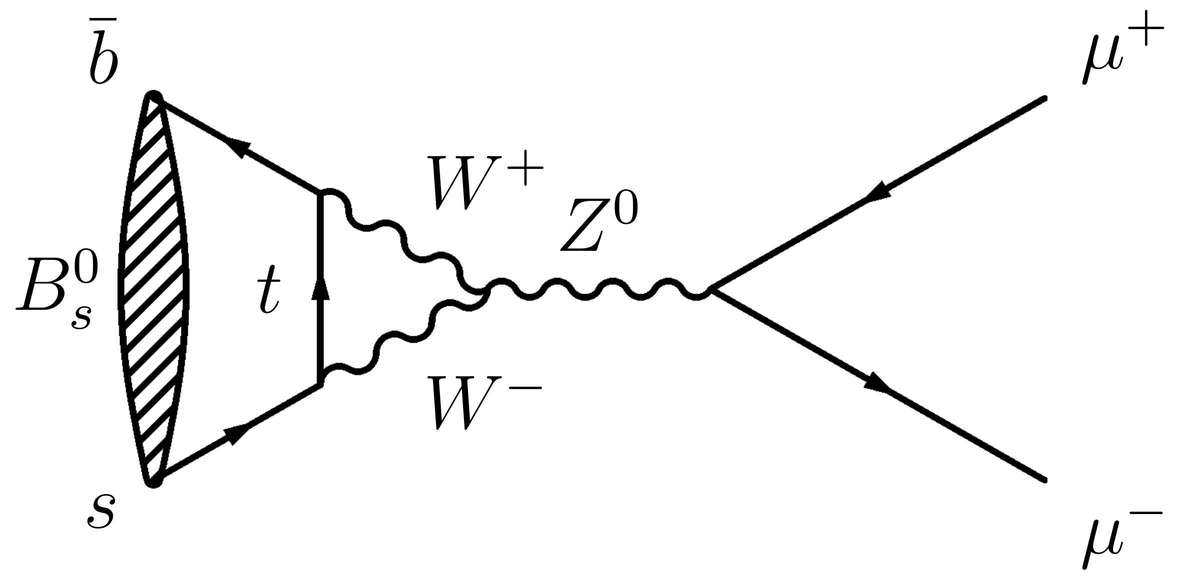


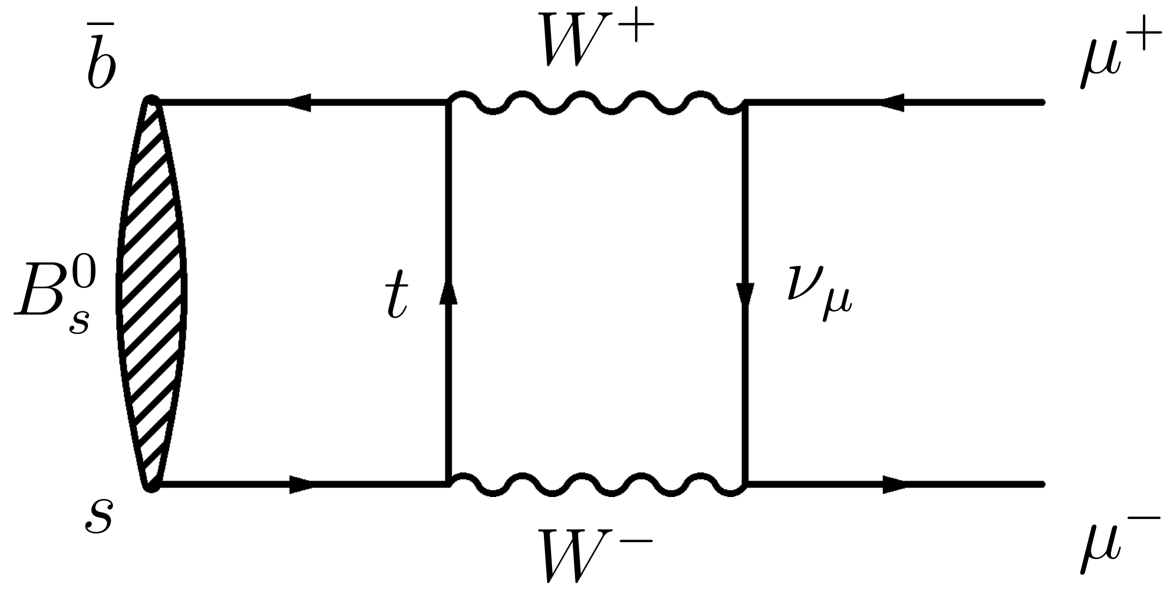
$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]



- Different theory uncertainties between decay modes/observables.

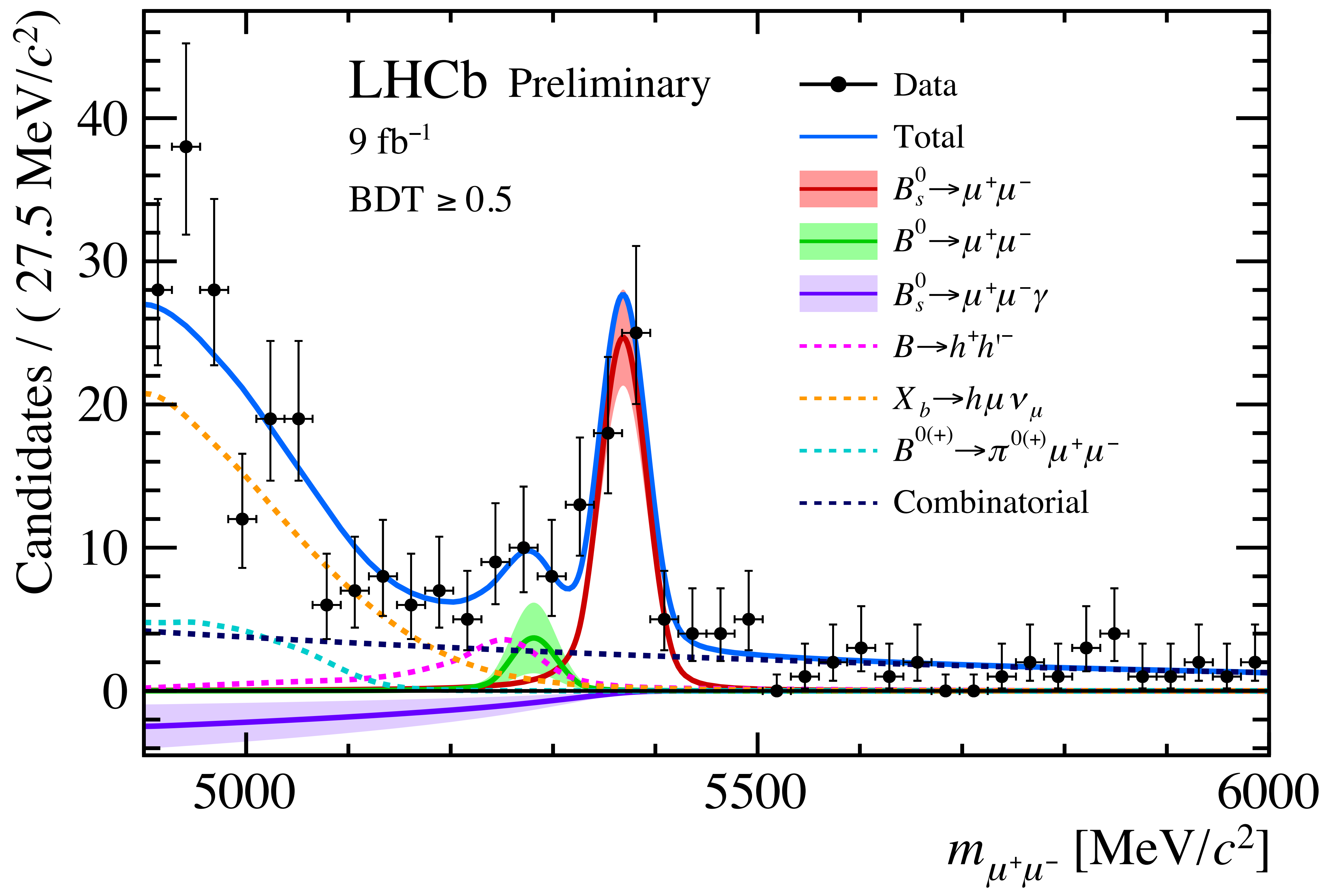
$B_s \to \mu\mu$





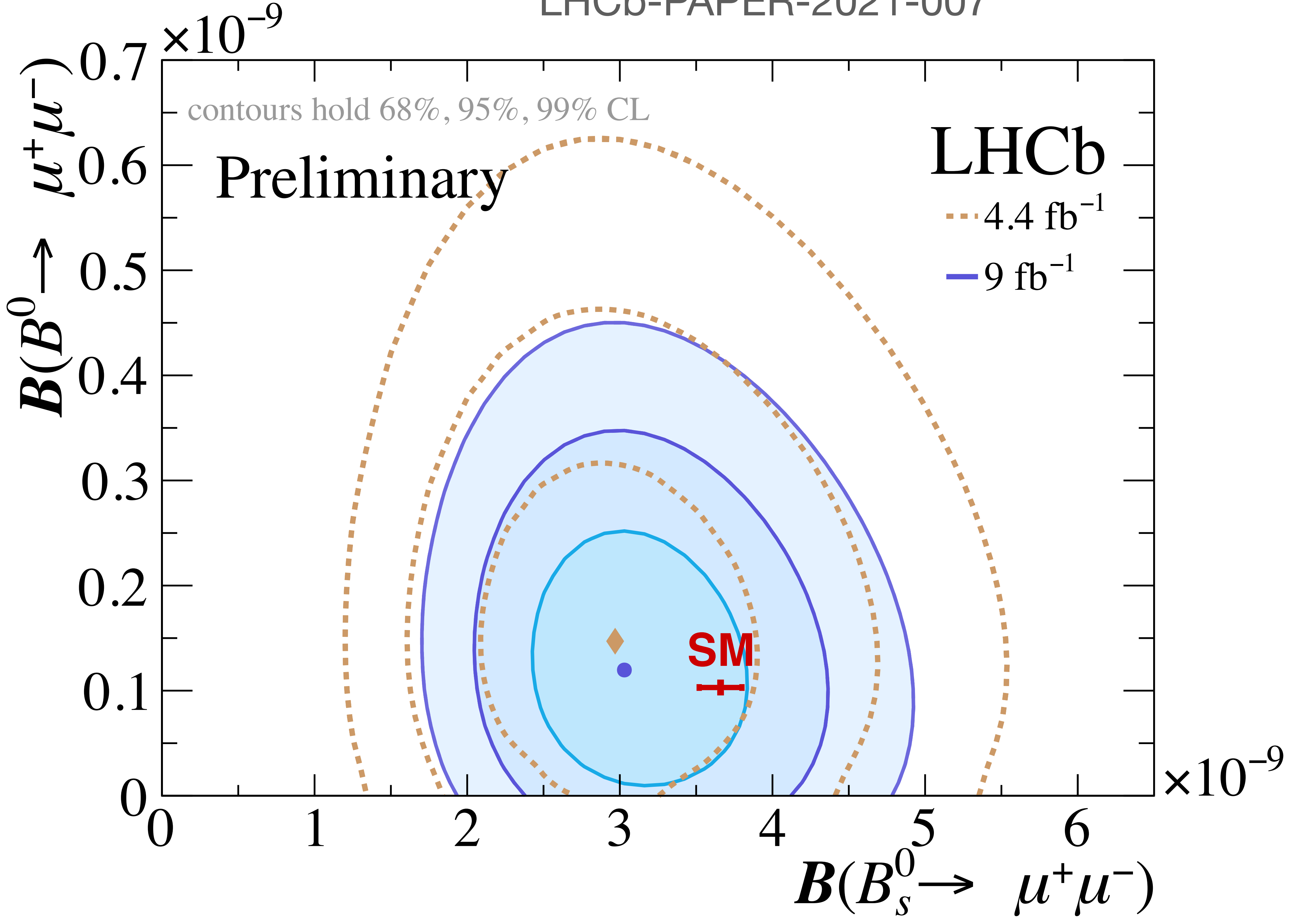
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.03 \pm 0.05) \times 10^{-10}$$

[JHEP 10 (2019) 232]



● $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (10.8σ)

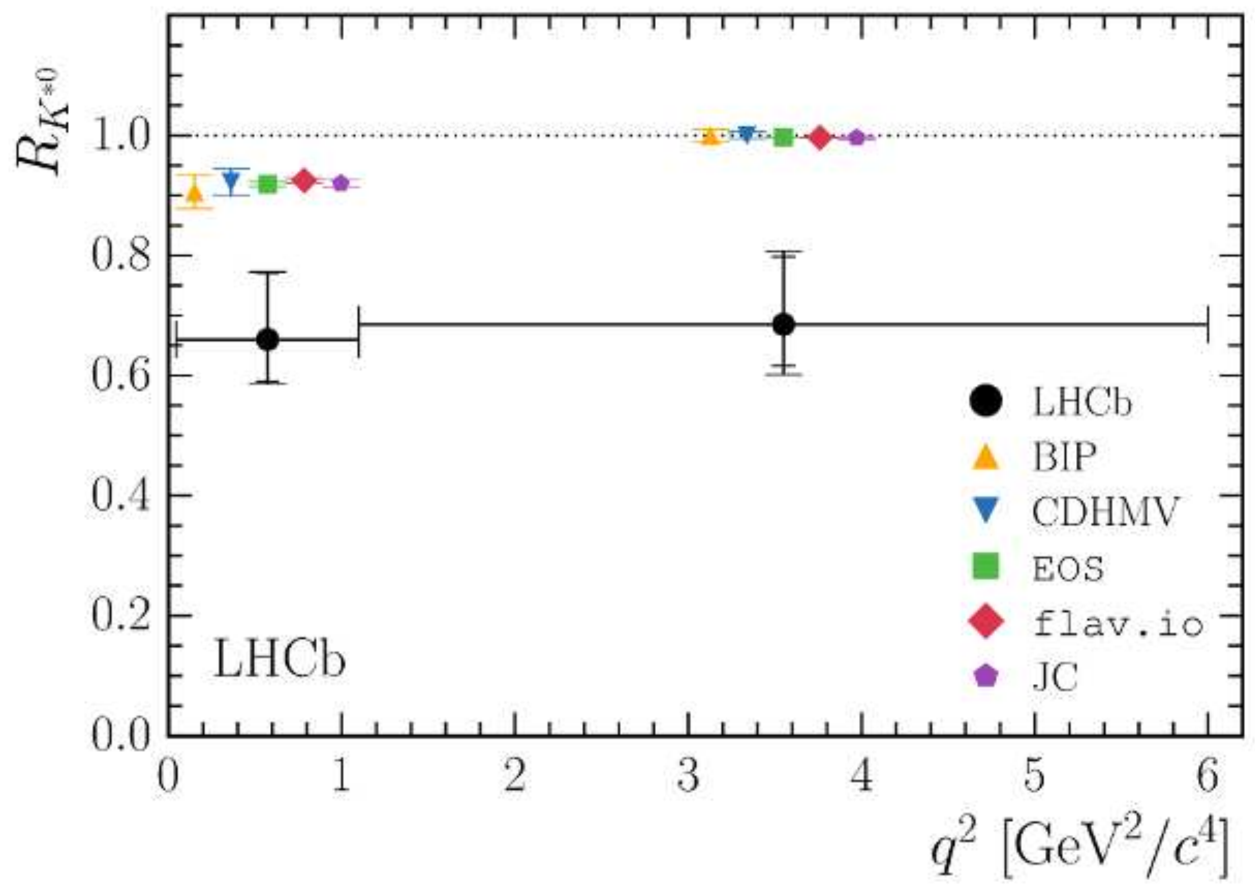
LHCb-PAPER-2021-007



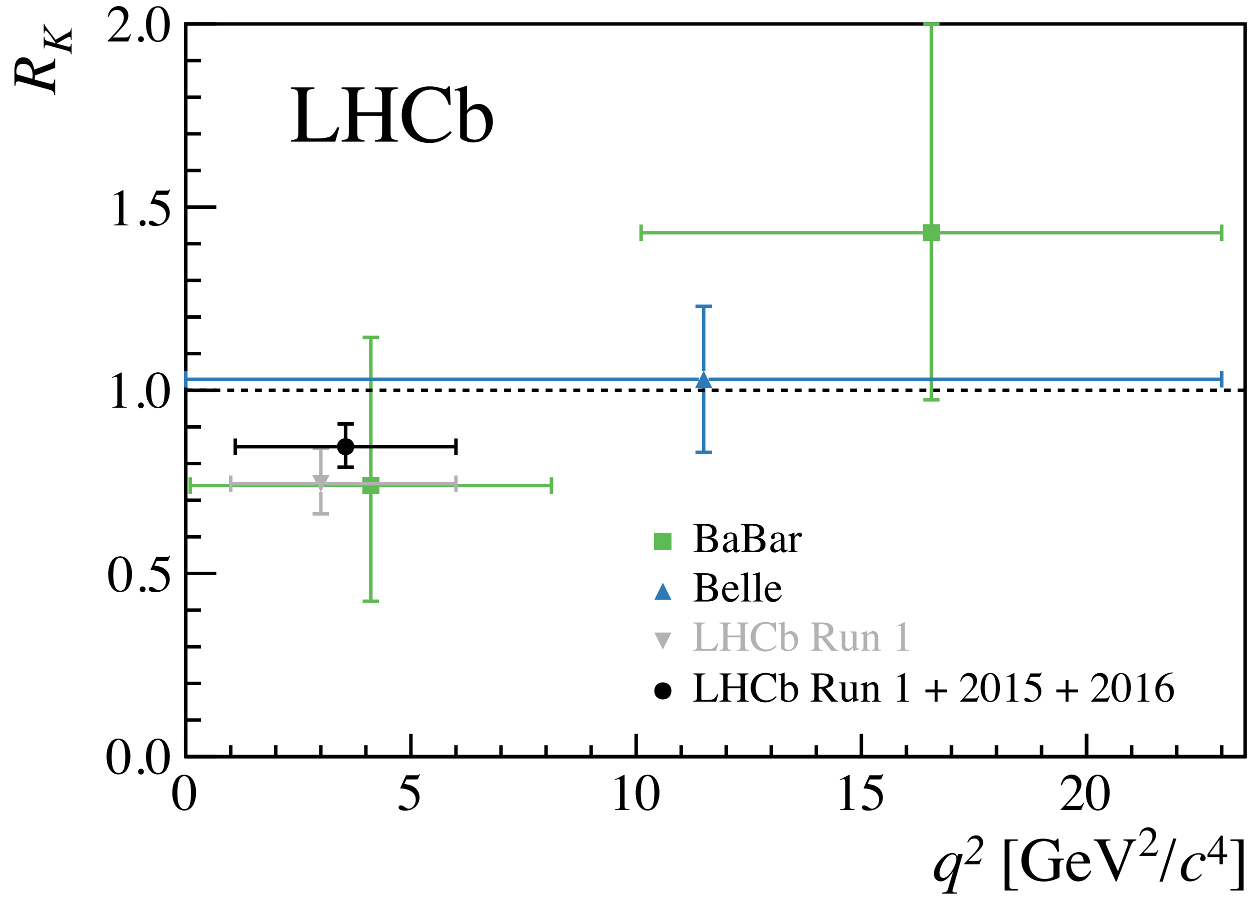
Result uses new fs/fd measurement: LHCb-PAPER-2020-046

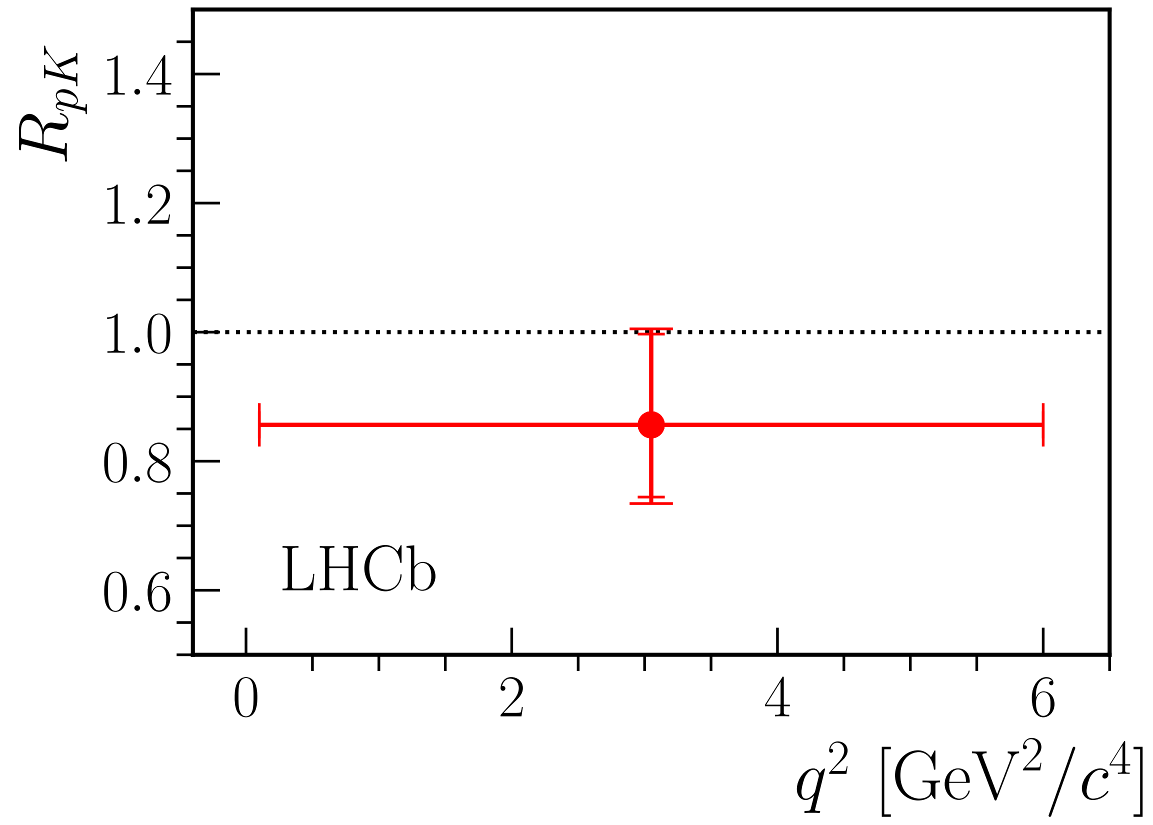
LFU measurements

$$R_H \equiv \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2}\, dq^2}$$



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





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

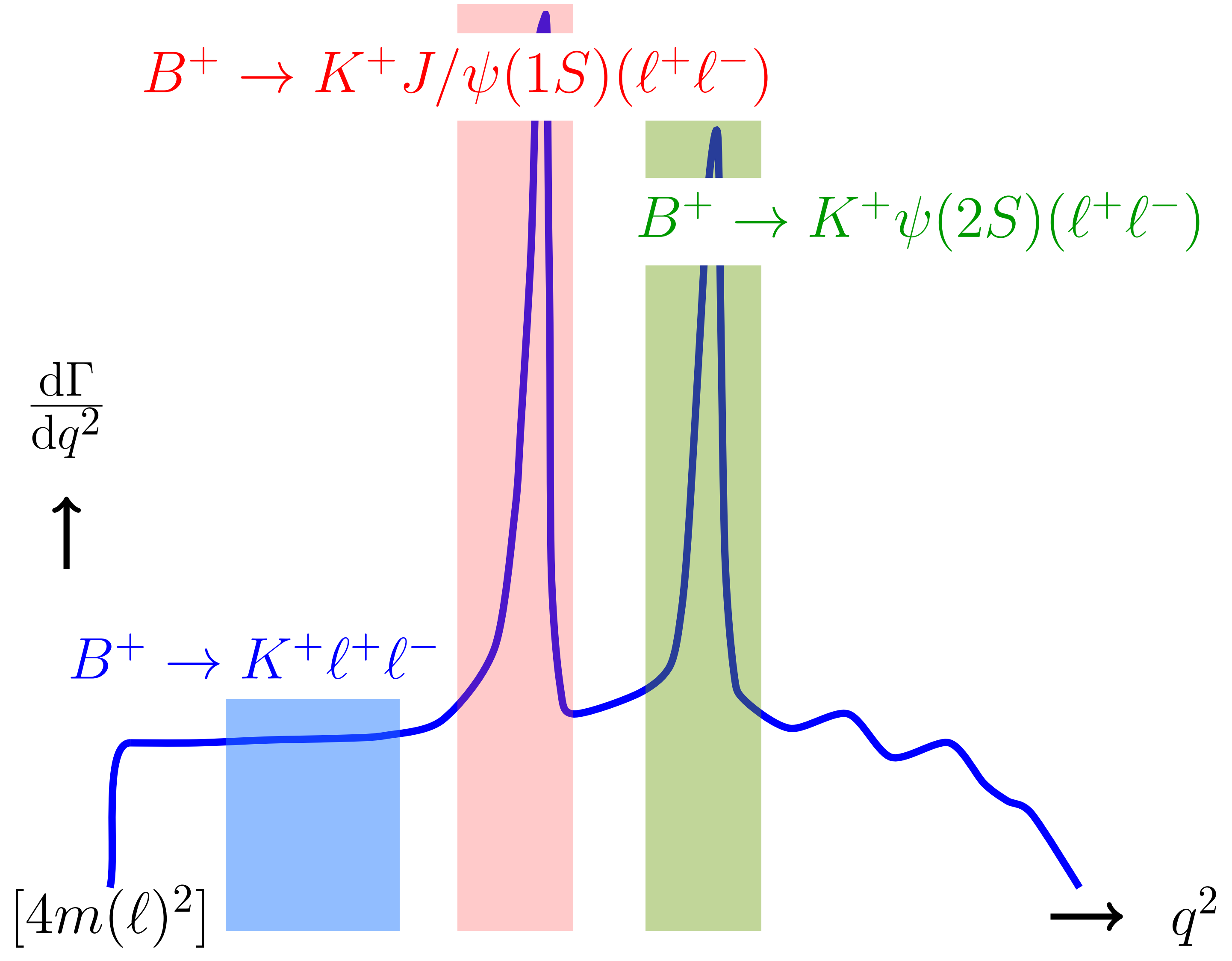
Right: $B^+ \to K^+\ell^+\ell^-$ R_K 5fb^{-1}
[PRL122(2019)191801]

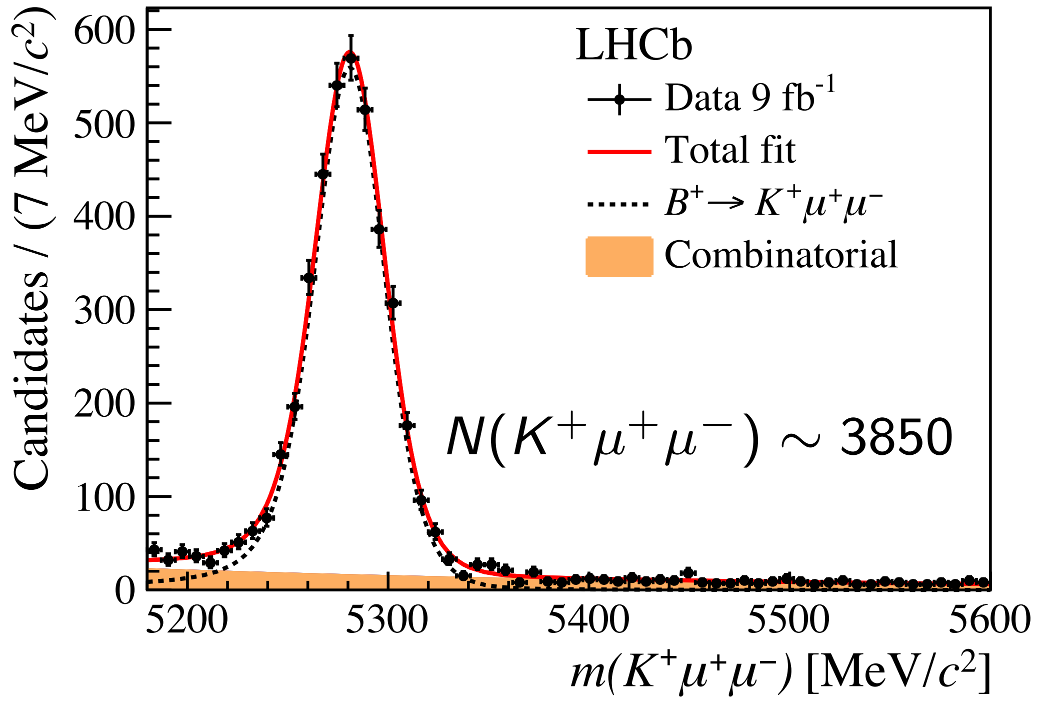
Bottom: $\Lambda_b \to pK\ell^+\ell^-$ R_{pK} 4.7fb^{-1}
[JHEP05(2020)040]

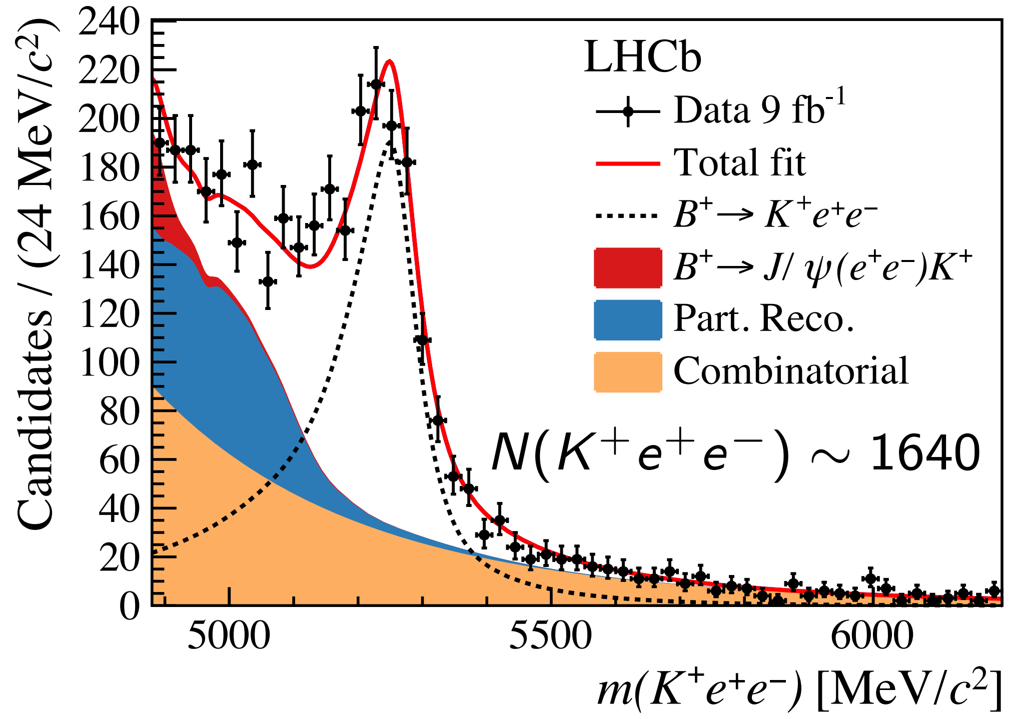
New R_K measurement

LHCb-PAPER-2021-004, arXiv:2103.11769

$$R_K = \frac{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{d\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{d\mathcal{B}(B^+\to K^+e^+e^-)}{dq^2} dq^2} = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+\to K^+e^+e^-)}{\mathcal{B}(B^+\to K^+J/\psi(e^+e^-))} = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$







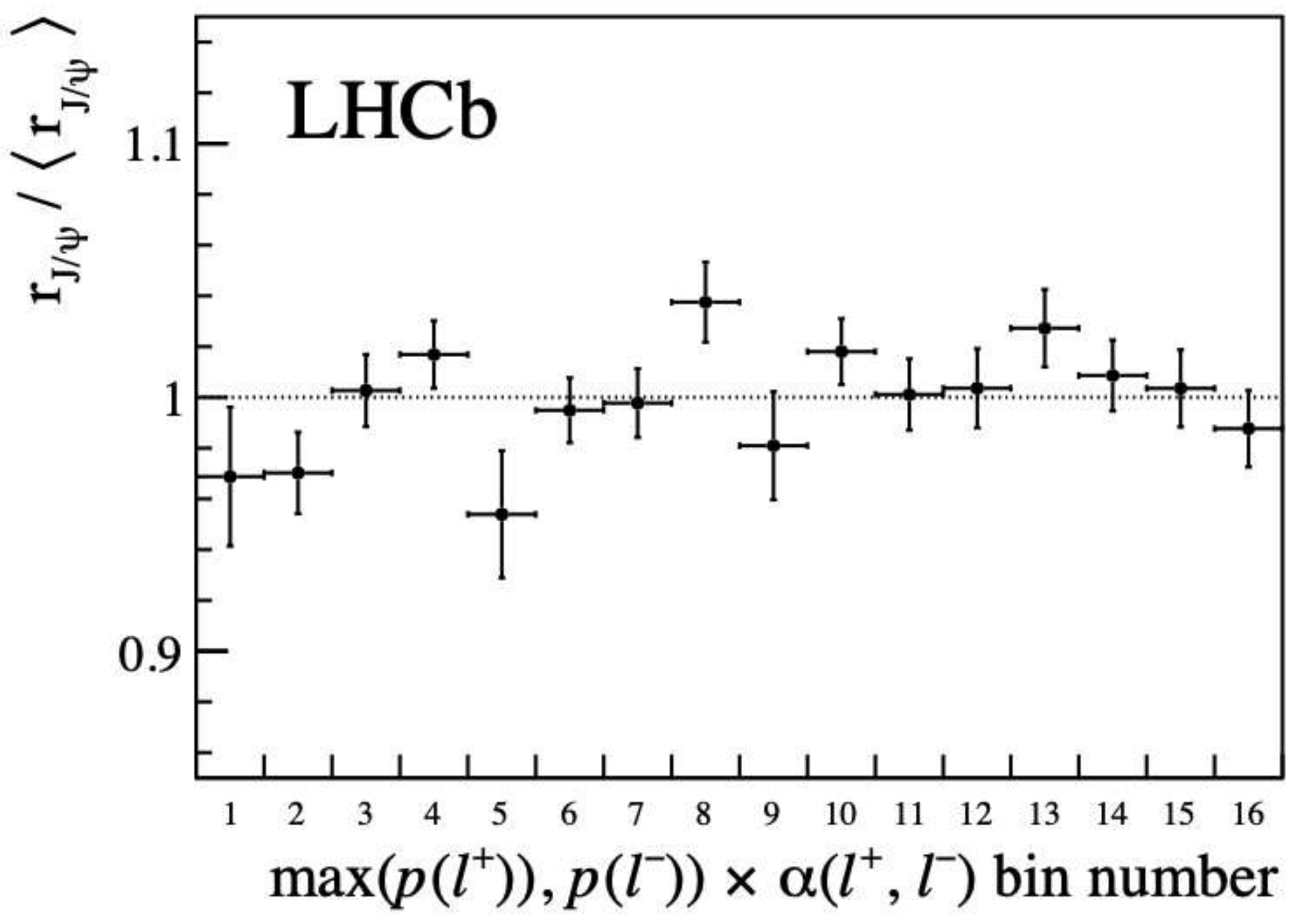
- Control signal yield determination and efficiency calculation.

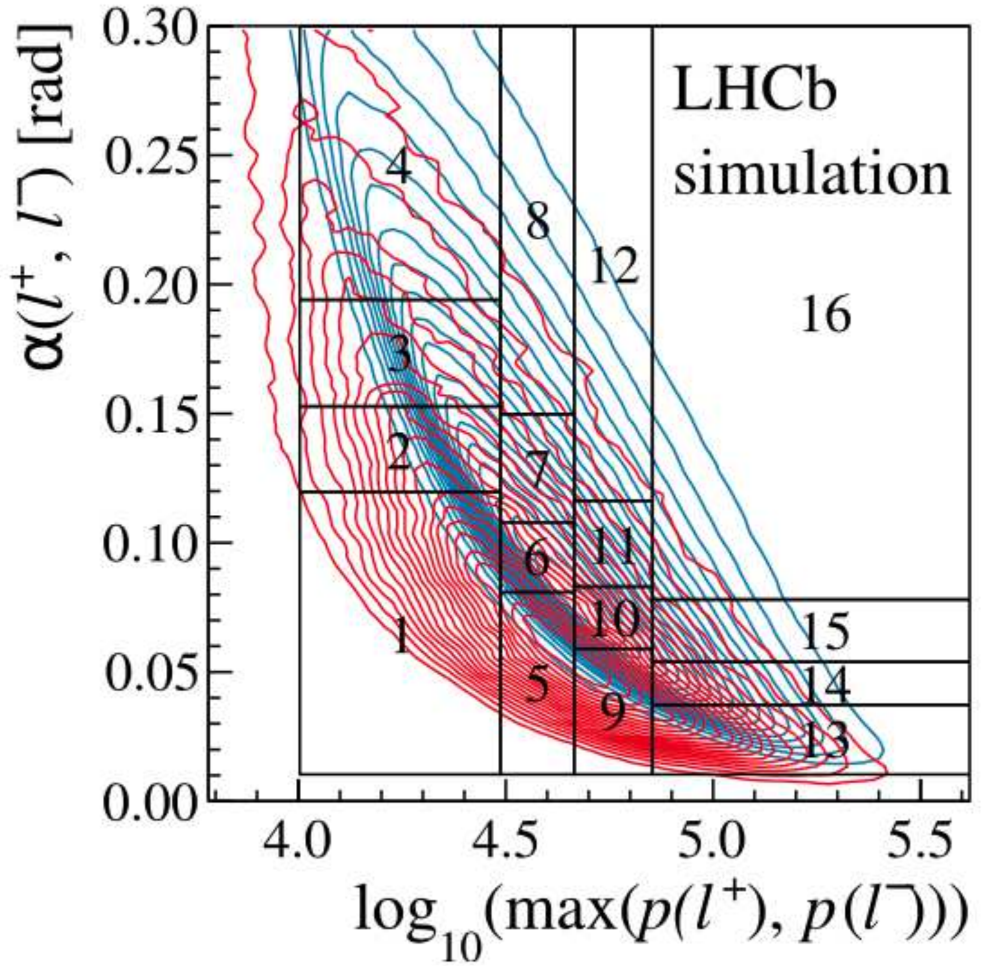
Cross-checks

LHCb-PAPER-2021-004, arXiv:2103.11769

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 1 \qquad r_{J/\psi} = 0.981 \pm 0.020\ (\mathrm{stat + syst})$$

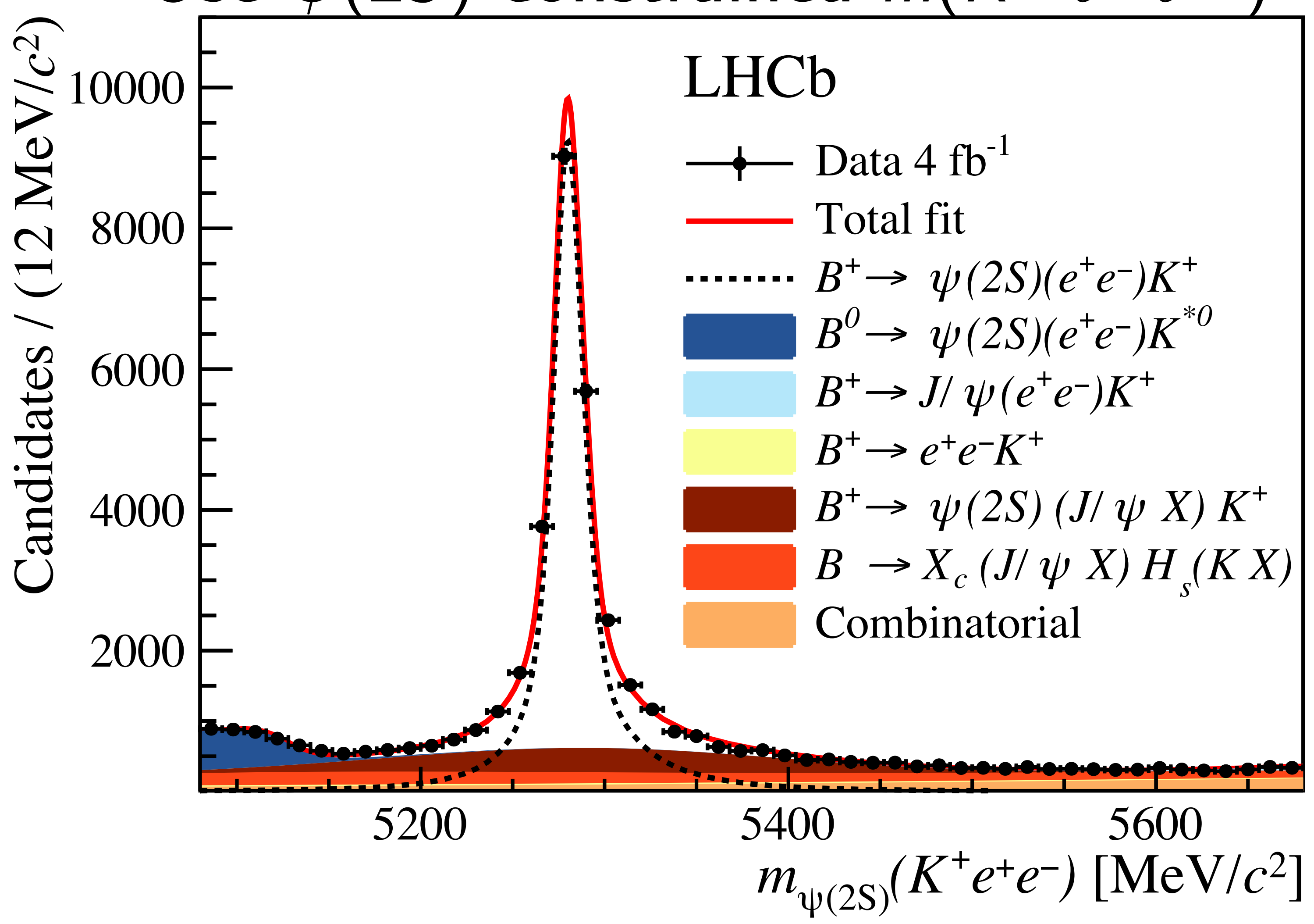
- Absolute control of lepton efficiencies required - significantly beyond the requirements of the measurement.





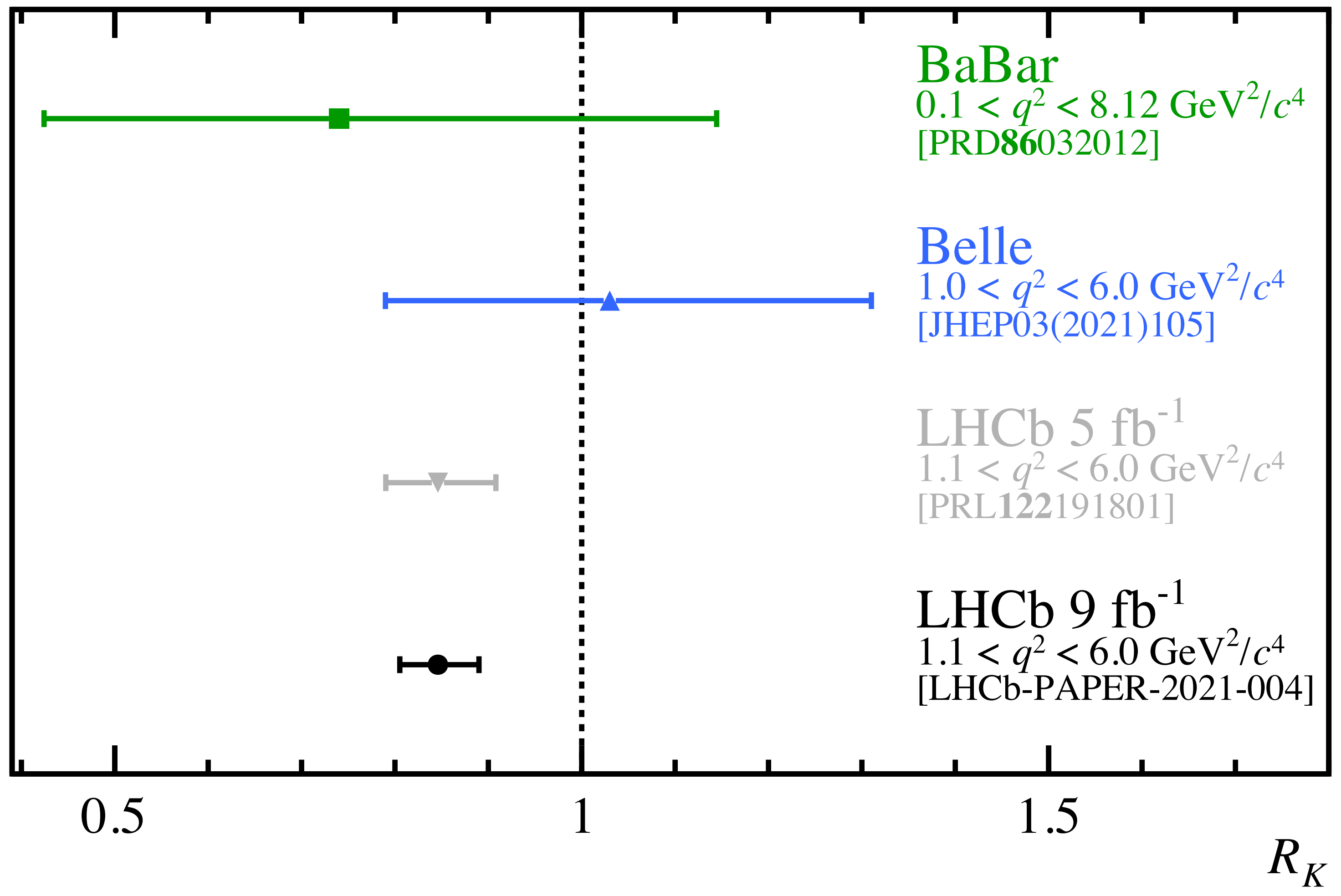
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+ \psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ \psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))}$$

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

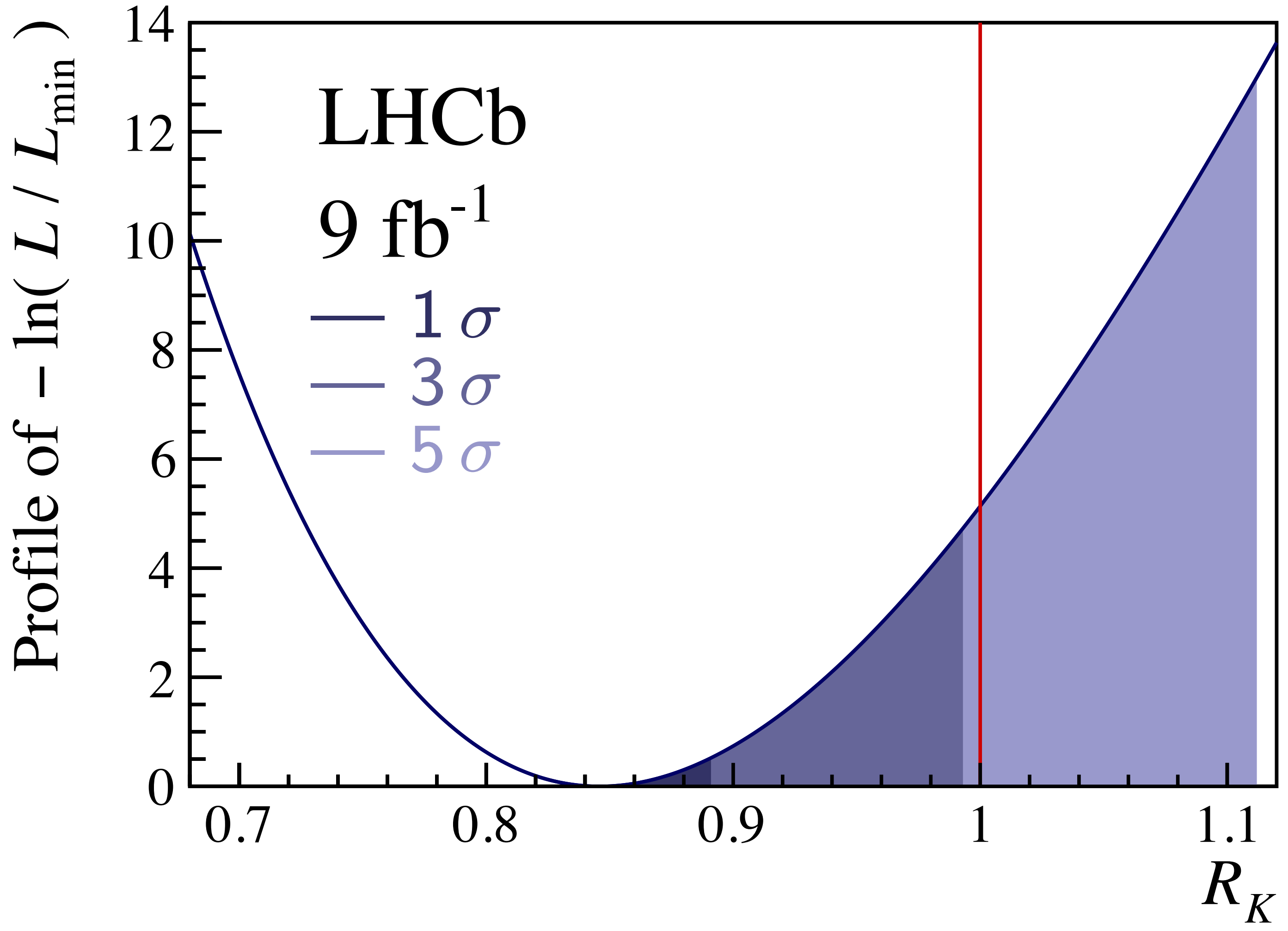


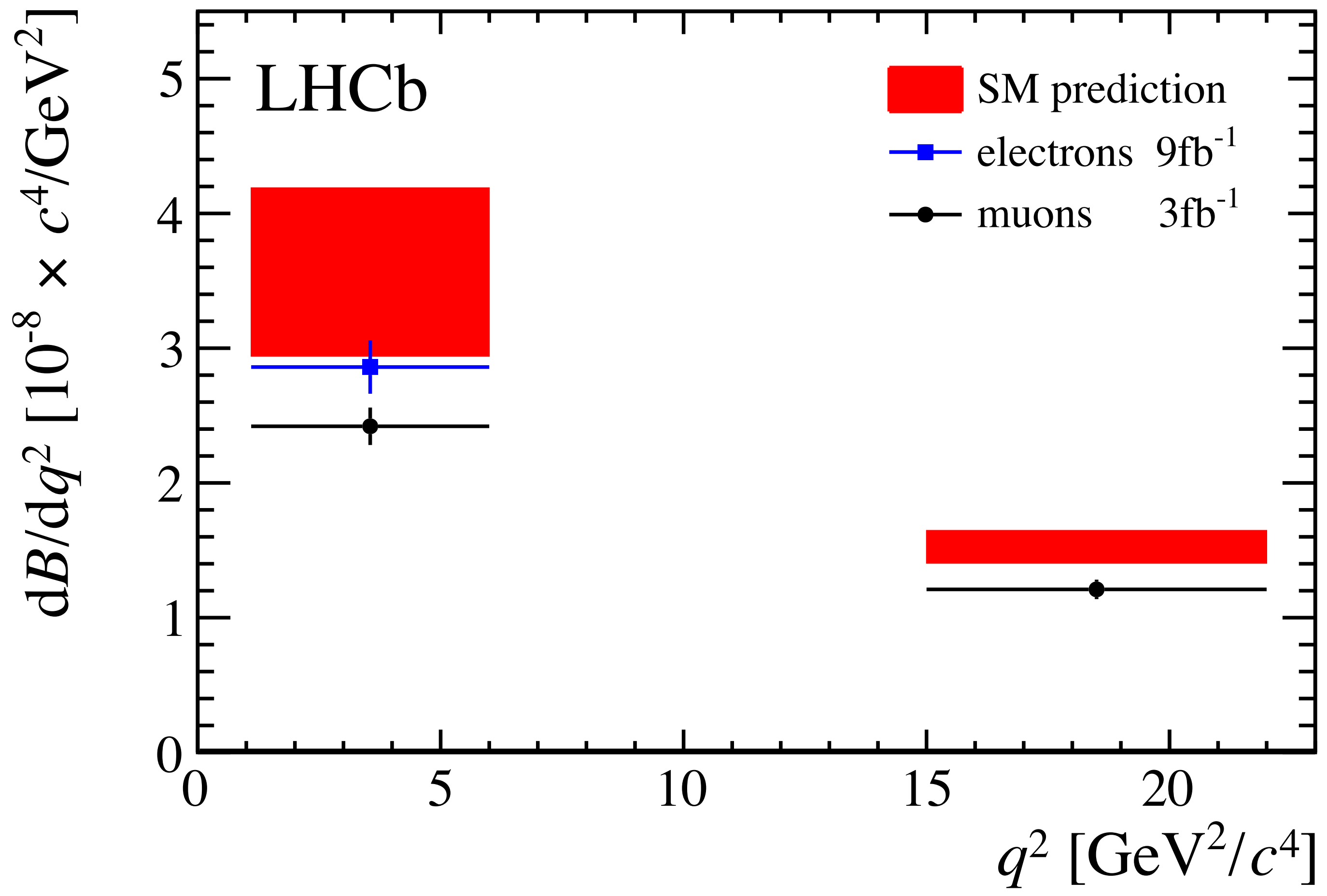
- Efficiencies can be ported across q^2.

Results



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



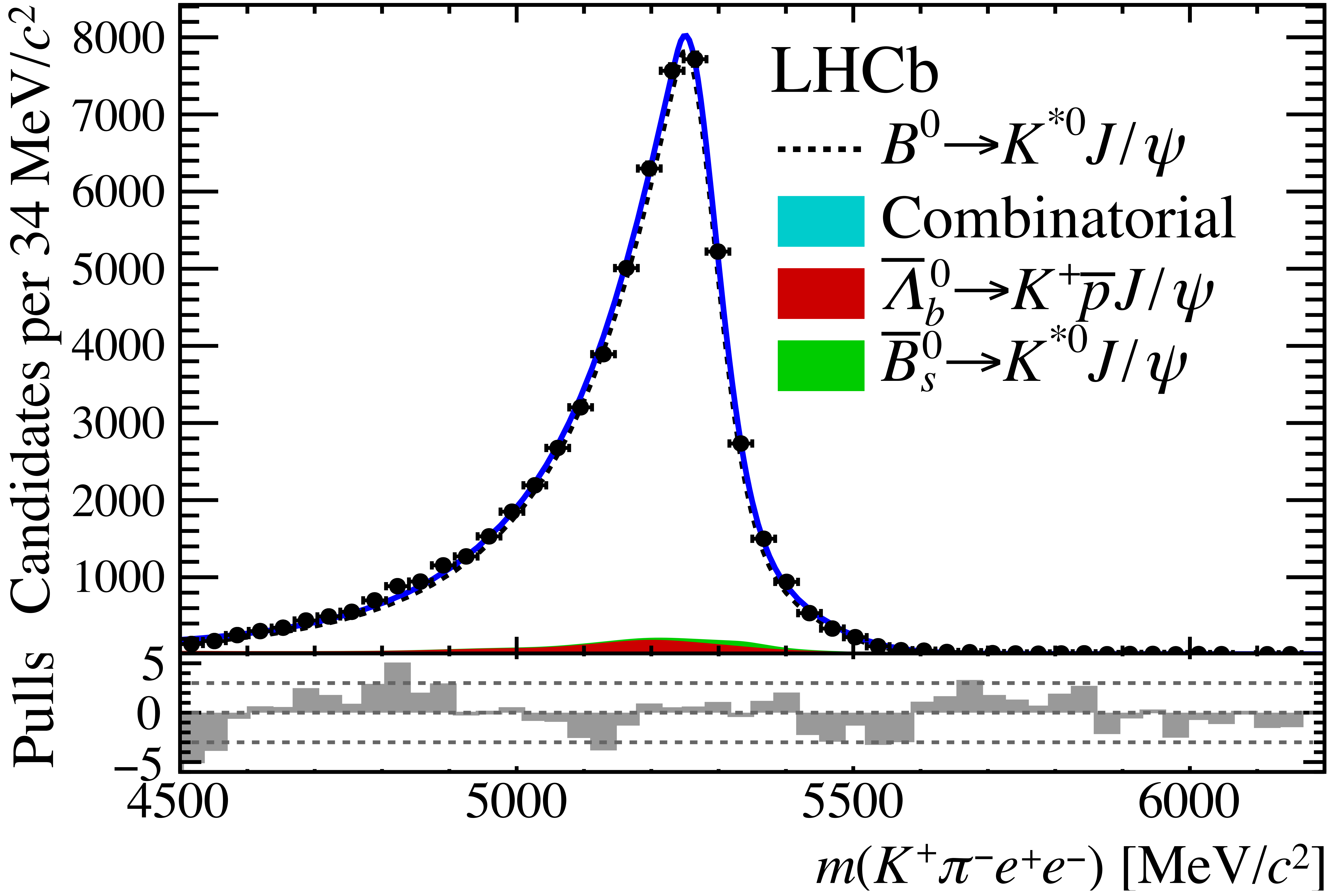


- Electrons more SM like.

Next

- R_{K^*}, R_{pK} update, R_ϕ, $R_{K^{*+}}$...
- R_K and R_{K^*} at high q^2.
- Angular analyses of $B \to K^{(*)} e^+ e^-$ and $B \to K^{(*)} \mu^+ \mu^-$ decays.
- Further validation of our understanding of reconstruction effects at low q^2.
- $b \to s\tau\tau$ and LFV measurements with τ's
- ...

Unconstrained mass



Left: $B^0 \to K^{*0}\ell^+\ell^-$ R_{K^*} 3fb^{-1}

[JHEP08(2017)055]

New results on theoretically clean observables in rare B-meson decays from LHCb

2. Test of Lepton Flavour Universality in $B^+ \to K^+\ell^+\ell^-$ decays

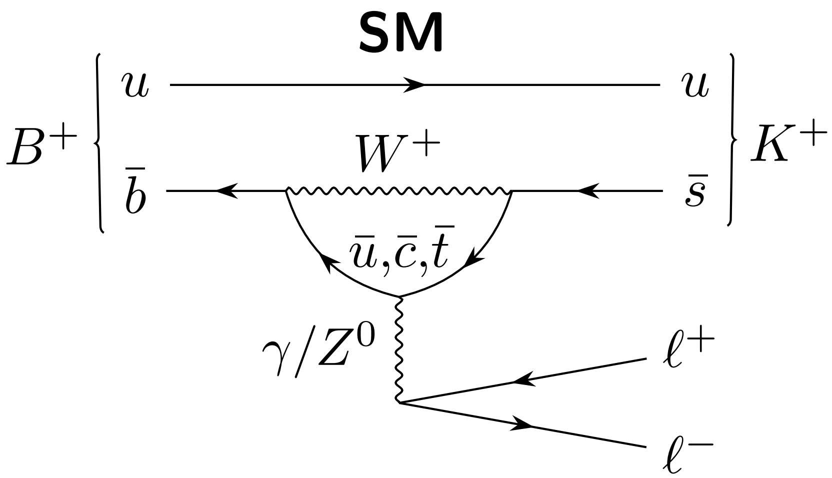
Konstantinos A. Petridis on behalf of the LHCb collaboration

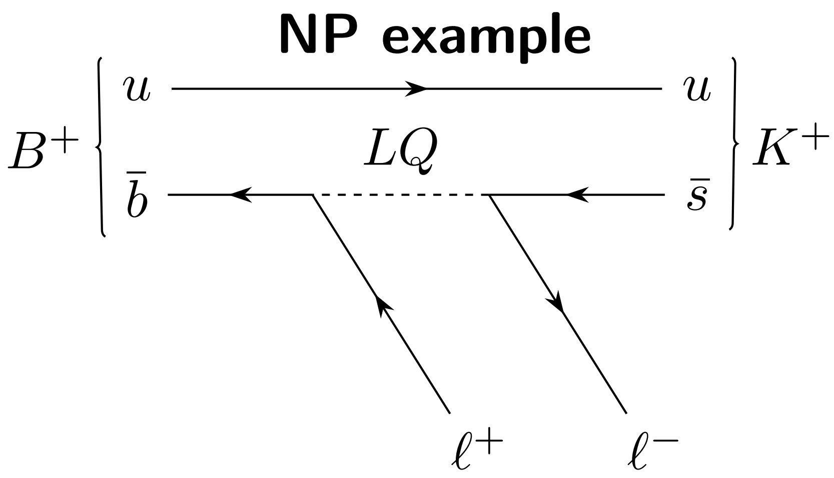
University of Bristol

March 23, 2021

$B^+ \to K^+\ell^+\ell^-$ and related decays

- Occur through $b \to s\ell^+\ell^-$ transition but in contrast to $B_s^0 \to \ell^+\ell^-$, 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 complementary to $B_s^0 \to \ell^+\ell^-$ measurements.

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**
   $B^0 \to K^{*0}\ell^+\ell^-$, $B^+ \to K^+\ell^+\ell^-$

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

Lepton Flavour Universality tests (I)

- 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

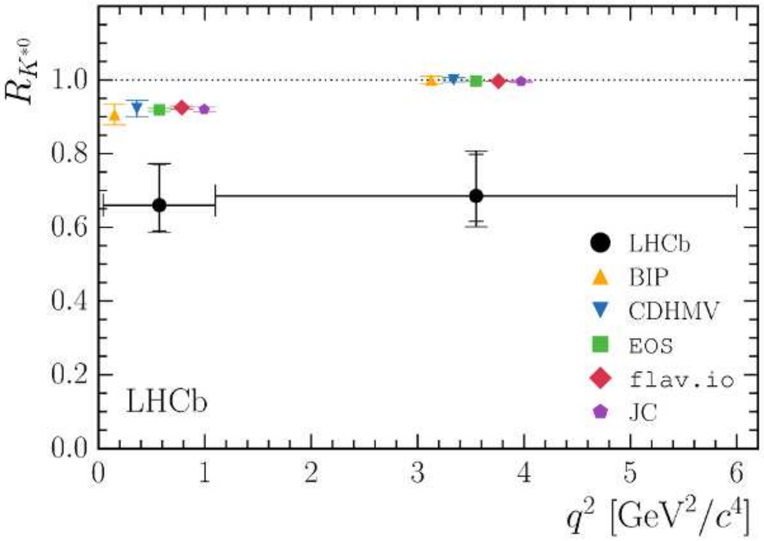
- Ratios of the form:

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

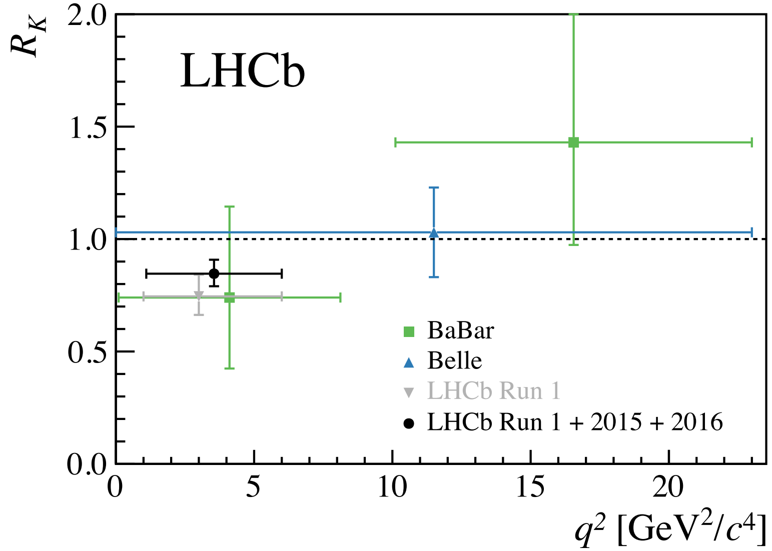
- In SM free from QCD uncertainties affecting other observables
  $\rightarrow \mathcal{O}(10^{-4})$ uncertainty [JHEP07(2007)040]
- Up to $\mathcal{O}(1\%)$ QED corrections [EPJC76(2016)8,440]

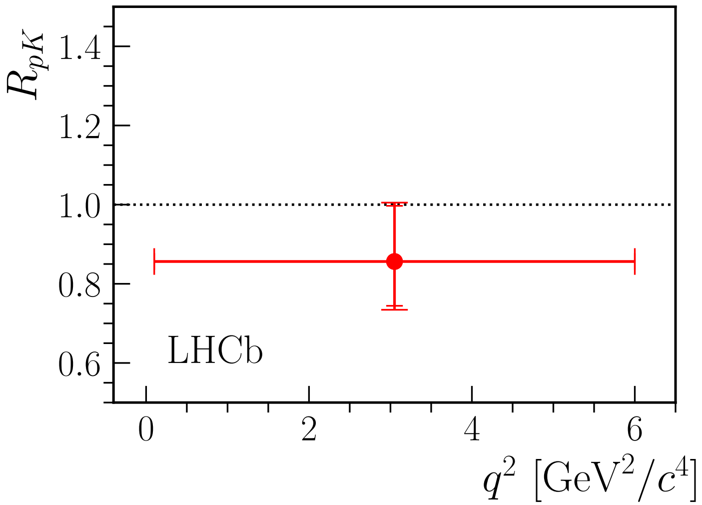
$\rightarrow$ **Any significant deviation is a smoking gun for New Physics.**

Lepton Flavour Universality tests (II)



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





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

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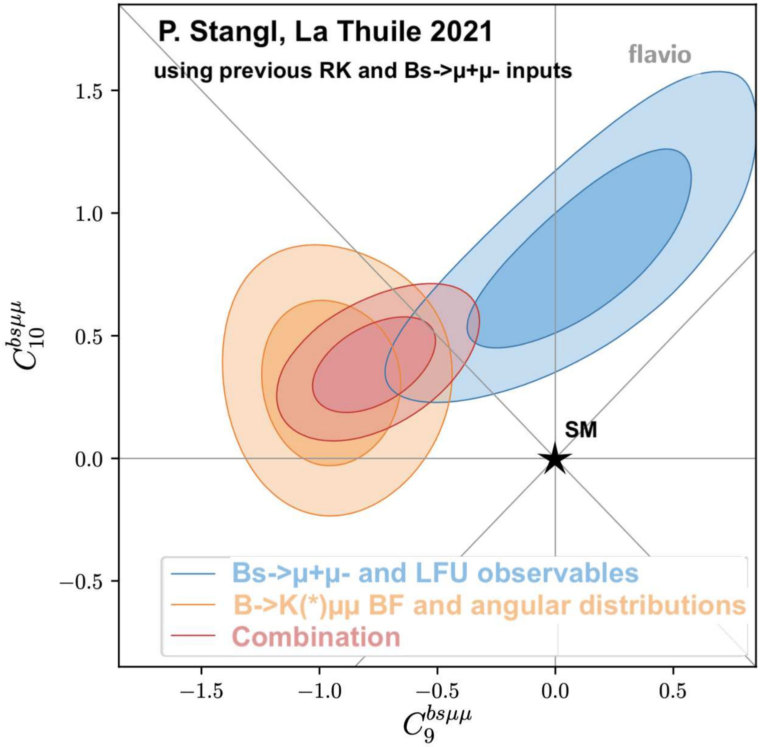
[JHEP05(2020)040]

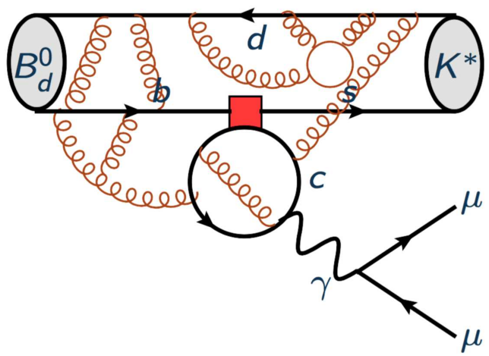
($q^2 \equiv$ dilepton invariant mass squared)

Global fits

- Combination all $b \to s\ell^+\ell^-$ measurements
- Measurements point to new vector coupling (C_9^{μ})
- $B_s \to \mu^+\mu^-$ and LFU observables have very clean theory predictions.



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



Improving experimental precision of LFU observables is critical.

Today: R_K with the full LHCb dataset

$$R_K = \frac{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

Measurement performed in $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$

- Previous measurement [PRL122(2019)191801] used $5\,\mathrm{fb}^{-1}$ of data.
  $3\,\mathrm{fb}^{-1}$ of Run1
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  $\rightarrow$ $9\,\mathrm{fb}^{-1}$ in total.
  $\rightarrow$ Doubling the number of B's as previous analysis.

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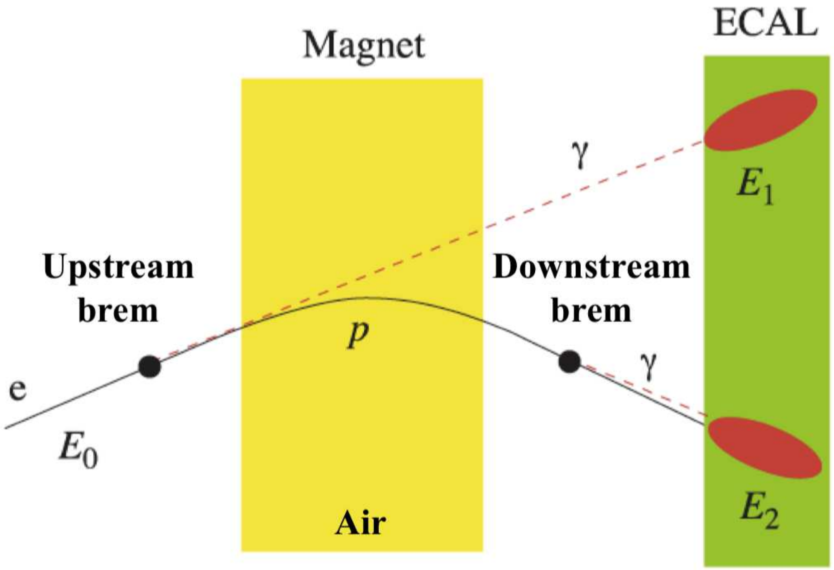
- Follow the same analysis strategy as our previous measurement.

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.

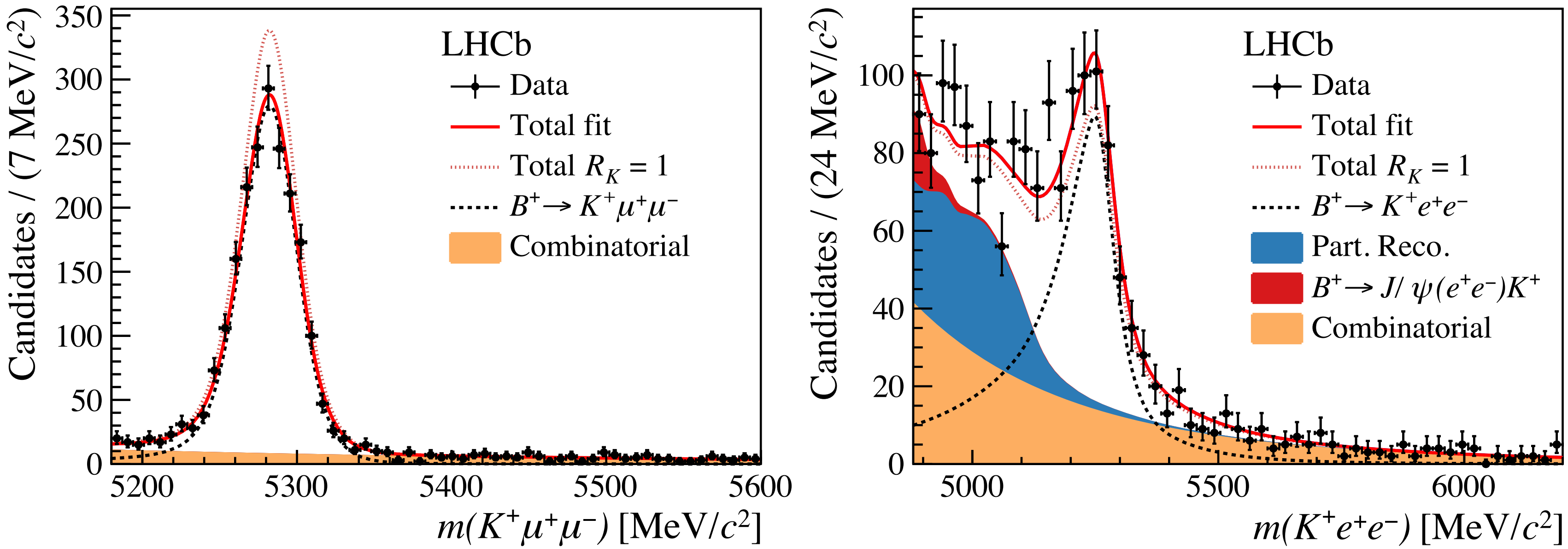
  → Look for photon clusters in the calorimeter ($E_T > 75\,\mathrm{MeV}$) compatible with electron direction before magnet.

  → 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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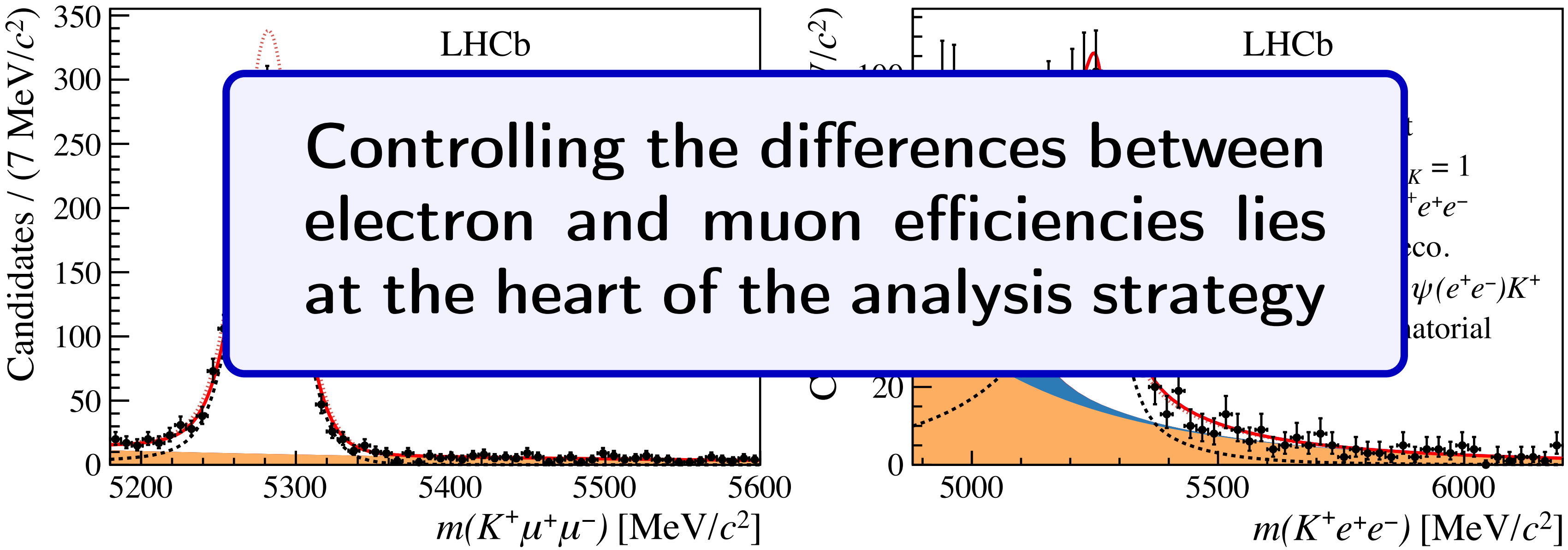

Controlling the differences between electron and muon efficiencies lies at the heart of the analysis strategy

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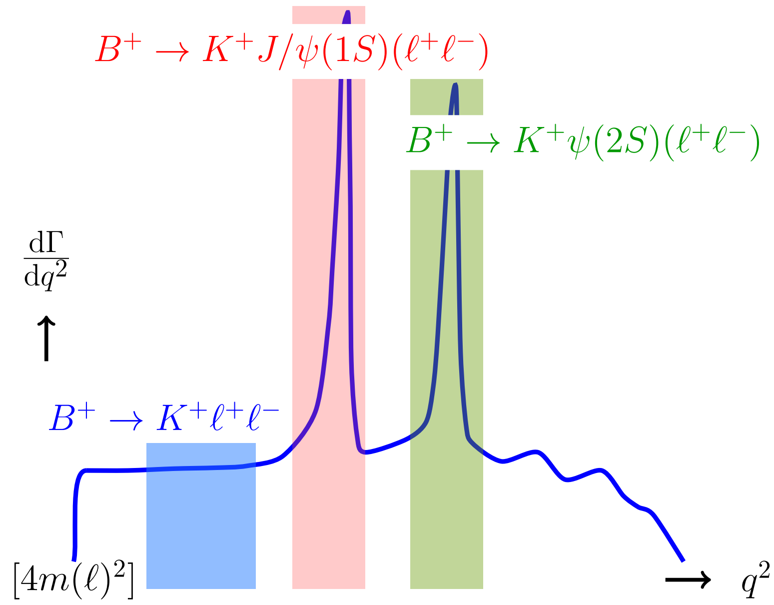
- Particle ID and tracking efficiency larger for muons than electrons

Measurement Strategy

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

$\rightarrow$ 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



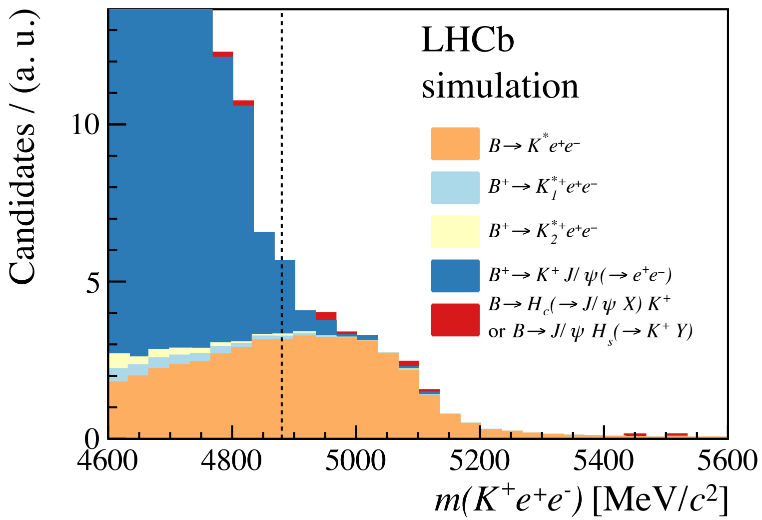
($q^2 \equiv$ dilepton invariant mass squared)

Selection and backgrounds

- As in our previous measurement, 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

Efficiency calibration

Following identical procedure to our previous measurement, the simulation is calibrated based on control data for the following quantities:

- Trigger efficiency.
- Particle identification efficiency.
- B^+ kinematics.
- Resolutions of q^2 and $m(K^+e^+e^-)$.

Verify procedure through host of cross-checks.

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

[LHCb-PAPER-2021-004]

- 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:

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

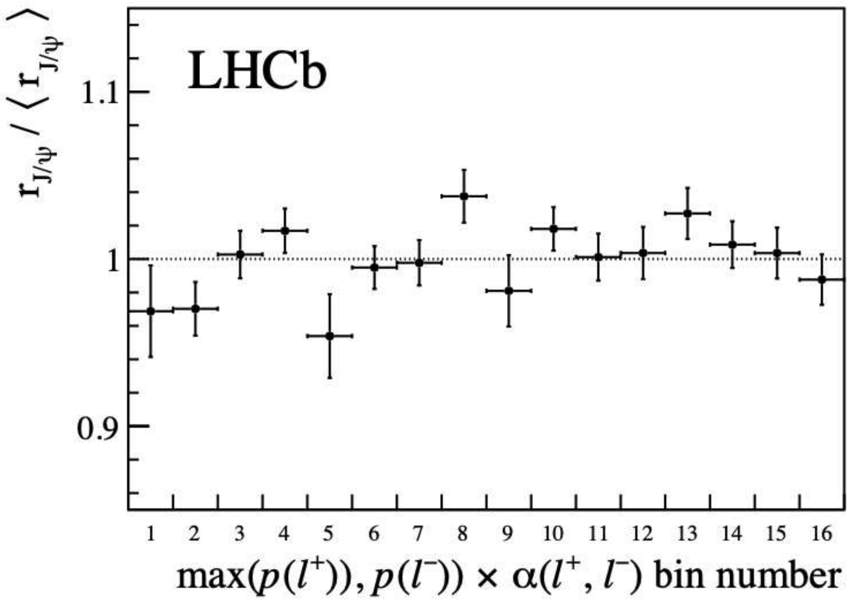
- Checked that the value of $r_{J/\psi}$ is compatible with unity for new and previous datasets and in all trigger samples.

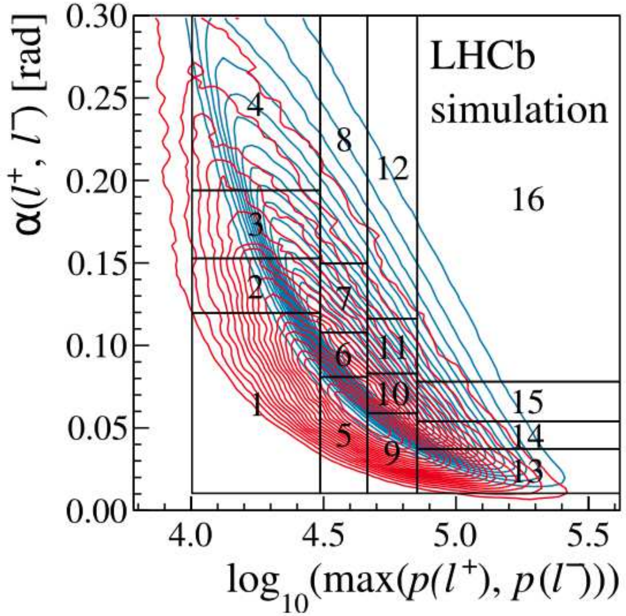
Cross-check: $r_{J/\psi}$ as a function of kinematics

[LHCb-PAPER-2021-004]

- 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-PAPER-2021-004]

Measurement of the double ratio

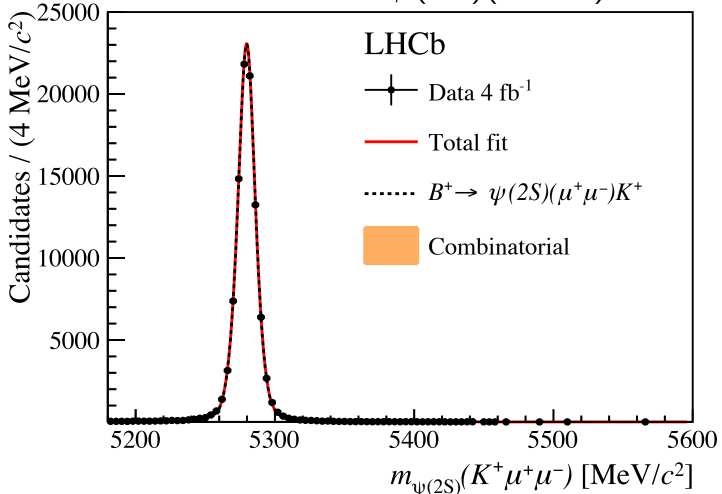
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

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

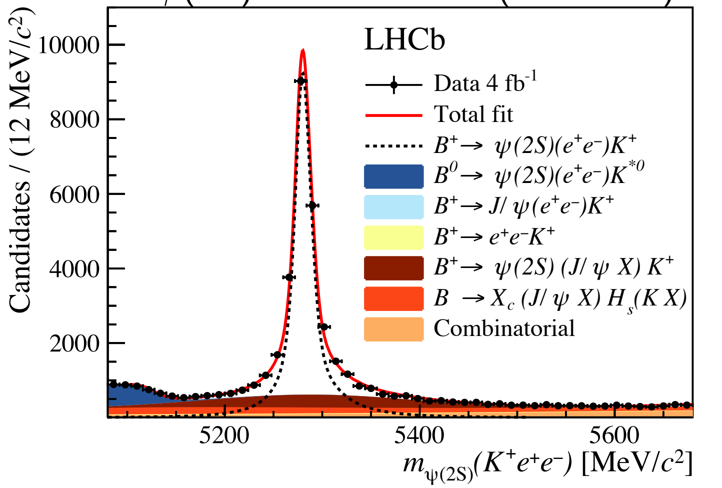
$$R_{\psi(2S)} = 0.997 \pm 0.011\,(\text{stat} + \text{syst})$$

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

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



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



Systematic uncertainties

[LHCb-PAPER-2021-004]

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

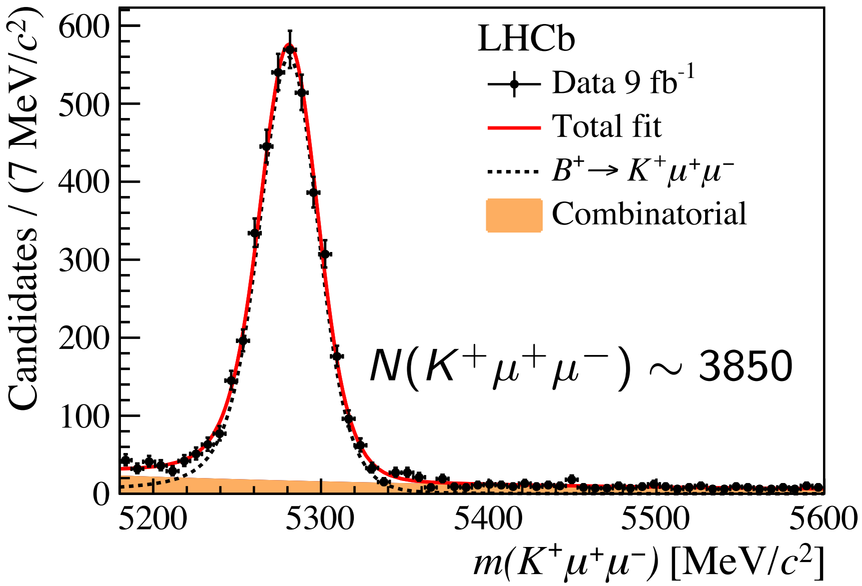
  → Dependence on tag definition and trigger biases
  → Precision of the q^2 and $m(K^+e^+e^-)$ smearing factors
  → Inaccuracies in material description in simulation
  ...

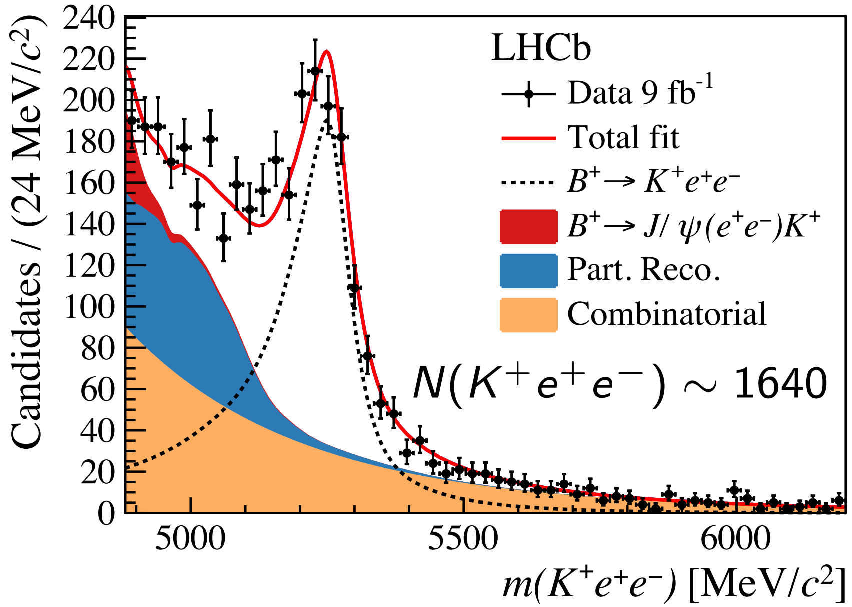
Total relative systematic of 1.5% in the final R_K measurement
→ Expected to be statistically dominated

Measuring R_K

[LHCb-PAPER-2021-004]

- 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





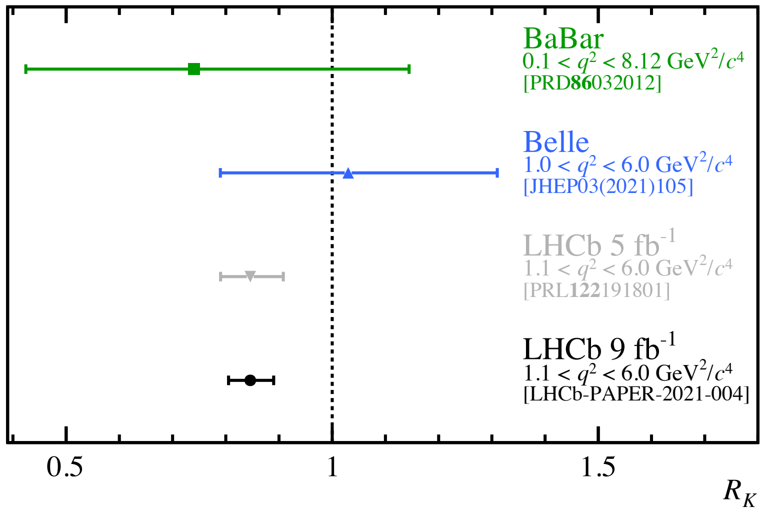
- Correlated uncertainties on efficiency ratios included as multivariate constraint in likelihood

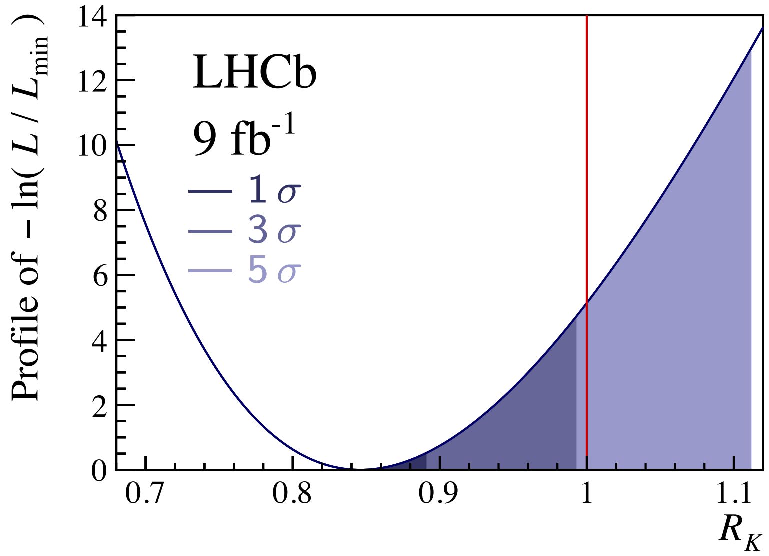
R_K with full Run1 and Run2 dataset

[LHCb-PAPER-2021-004]Submitted to 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]





R_K with full Run1 and Run2 dataset

[LHCb-PAPER-2021-004] Submitted to Nature Physics

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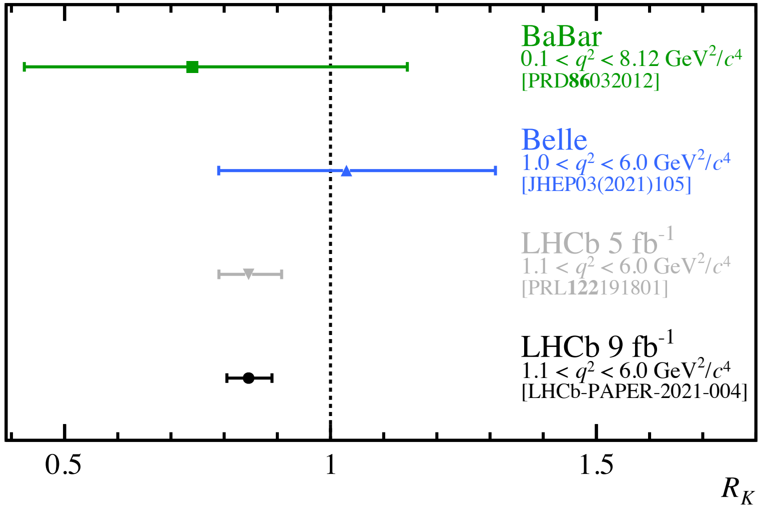
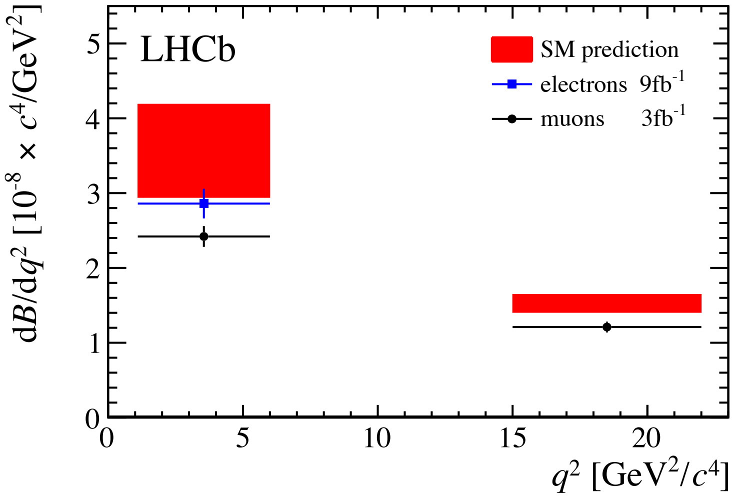
- p-value under SM hypothesis: 0.0010
  $\rightarrow$ Evidence of LFU violation at 3.1σ
- Using R_K and previous measurement of $\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$ [JHEP06(2014)133] determine $\mathcal{B}(B^+ \rightarrow K^+e^+e^-)$.
- Suggests electrons are more SM-like than muons.



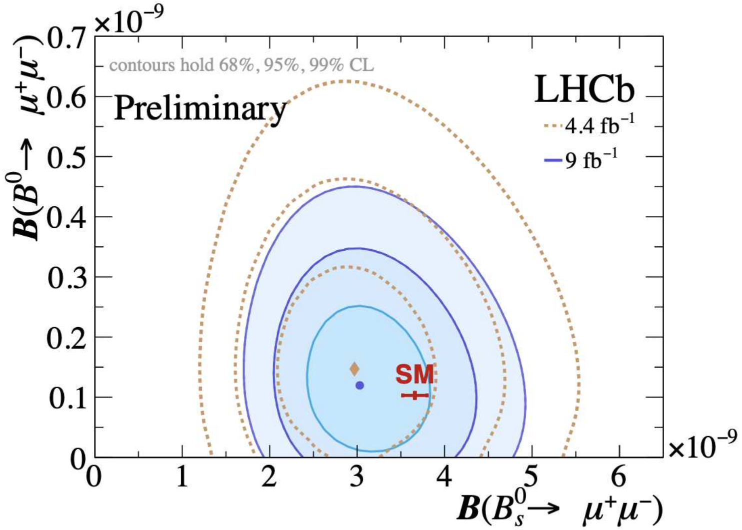


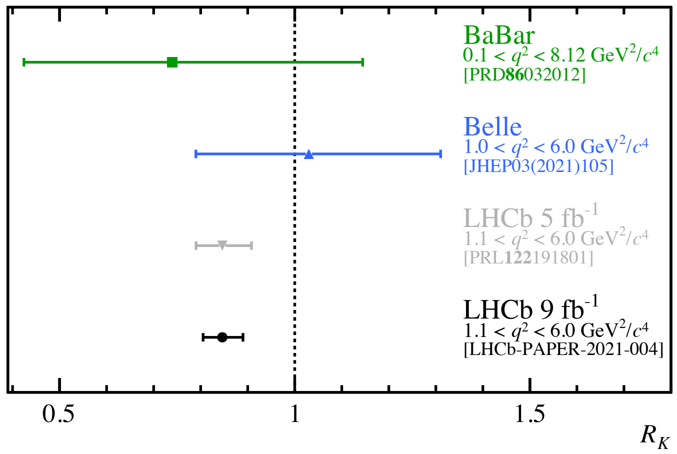
$$\frac{d\mathcal{B}(B^+ \rightarrow K^+e^+e^-)}{dq^2} = (28.6\ ^{+1.5}_{-1.4}(\text{stat})\ \pm 1.4(\text{syst})) \times 10^{-9}\ c^4/\,\text{GeV}^2.$$

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."

Outlook

Many more measurements underway with full LHCb dataset

- R_{K^*}, R_{pK} update, R_ϕ, $R_{K^{*+}}$...
- R_K and R_{K^*} at high q^2.
- Angular analyses of $B \to K^{(*)} e^+ e^-$ and $B \to K^{(*)} \mu^+ \mu^-$ decays.
- Further validation of our understanding of reconstruction effects at low q^2.
- $b \to s\tau\tau$ and LFV measurements with τ's
- ...

$\rightarrow$ Current dataset will offer clearer picture

For a definitive understanding, Run3 is imperative.

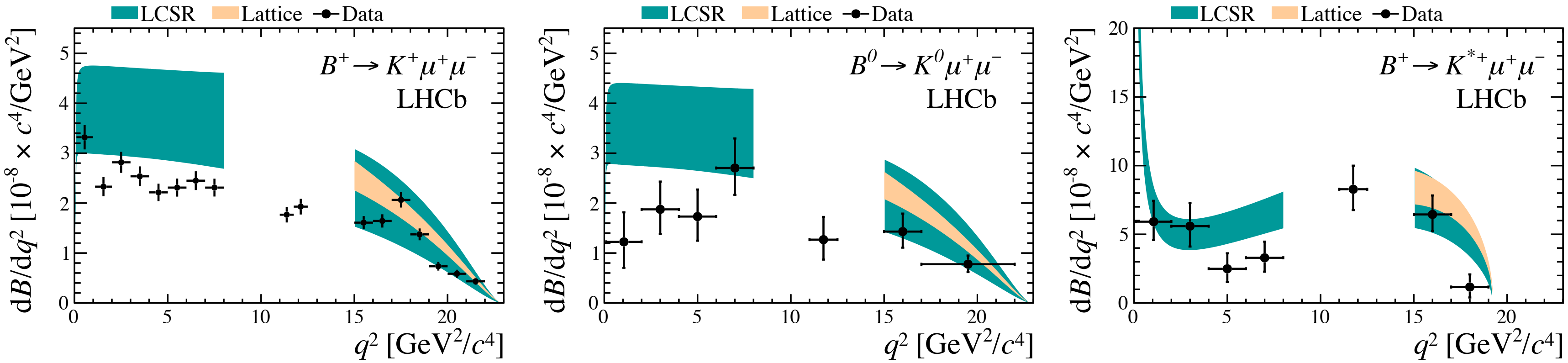
Input from our LHC and Belle2 colleagues is important.

Backup

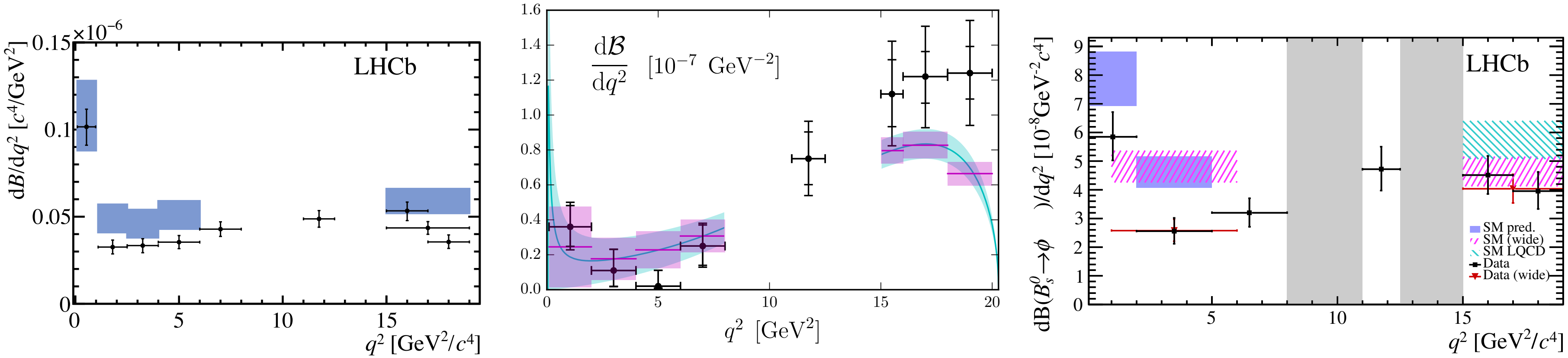
1. Decay Rates

- 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] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]

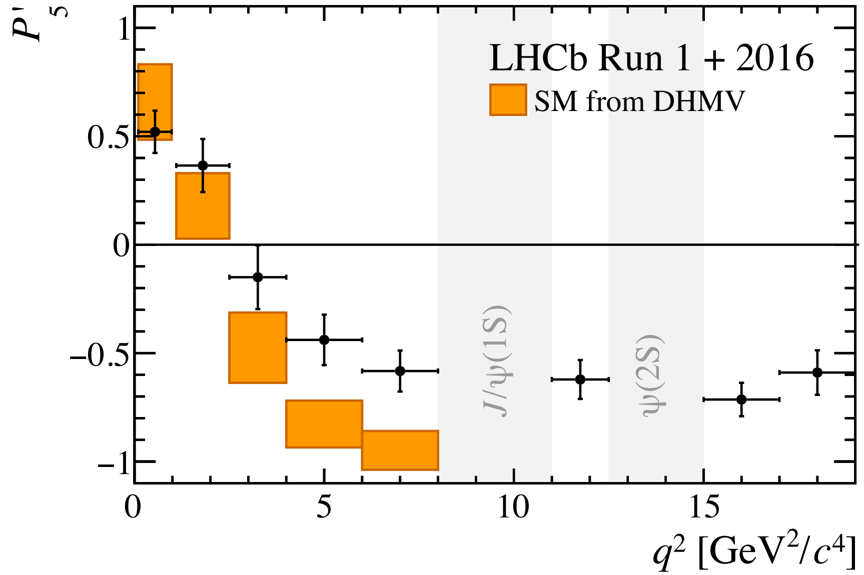


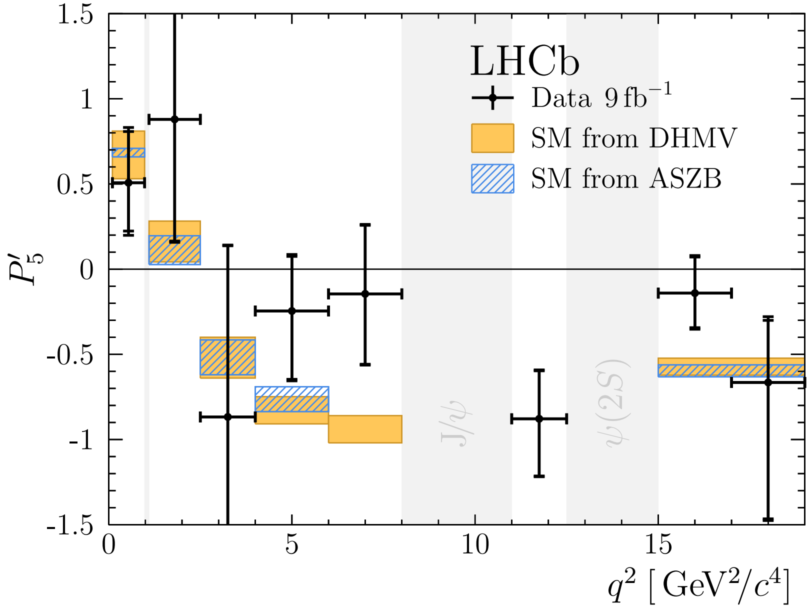
- SM predictions suffer from large hadronic uncertainties

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

- Large number of observables offering complementary constraints on NP compared to BF's
- Orthogonal experimental 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]

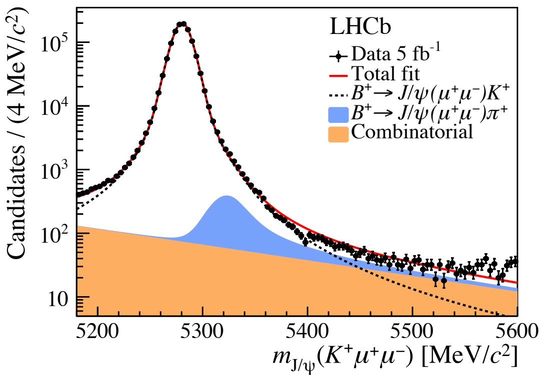




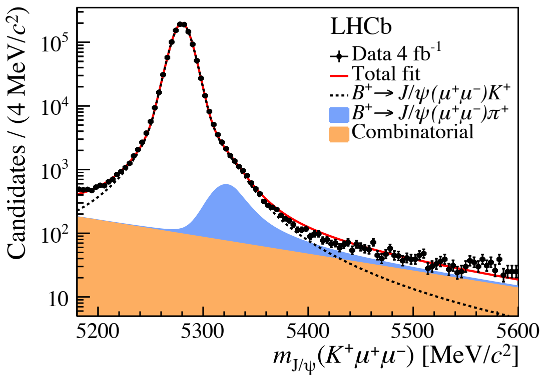
- Combination of all angular observables suggests $\sim 3\sigma$ tension with SM predictions in each channel

Control mode fits

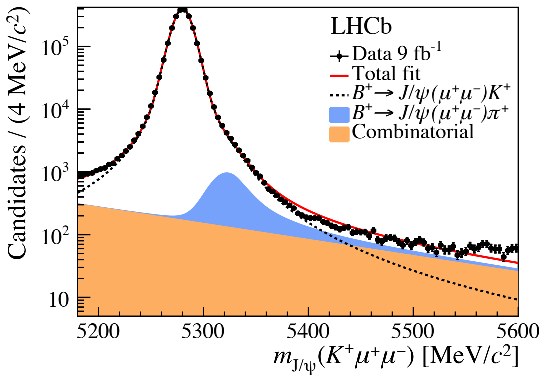
[LHCb-PAPER-2021-004]



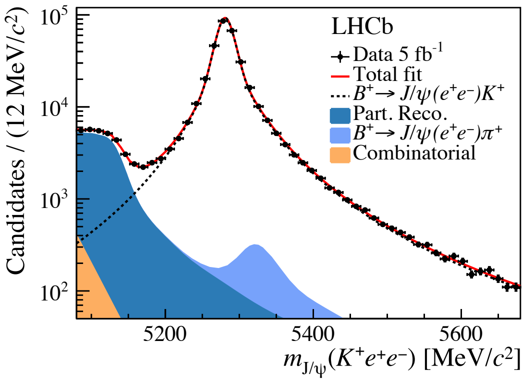
Previous data



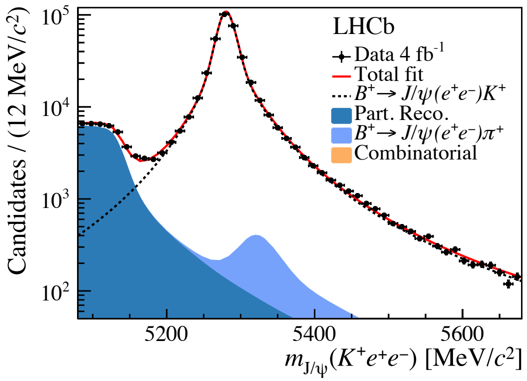
New data



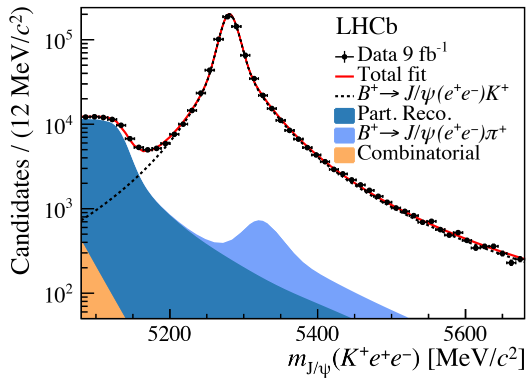
Total data



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.

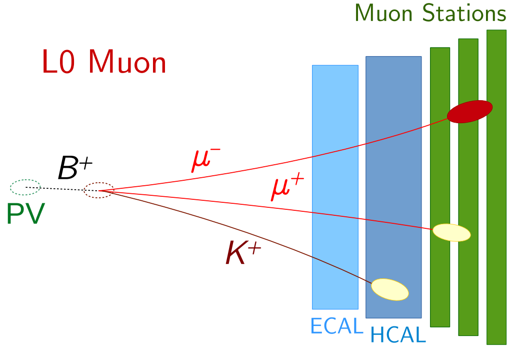
- The q^2 scale/resolution in the simulation is corrected using the same procedure
$\to$ the efficiency of the q^2 cut is calibrated from the data

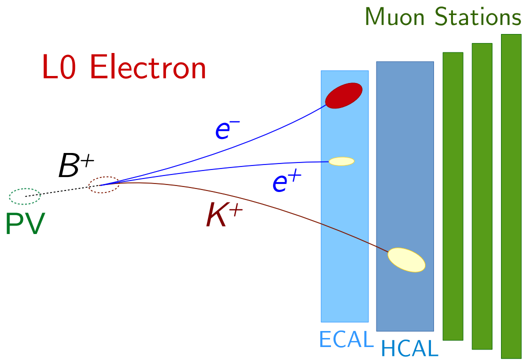
Trigger strategy

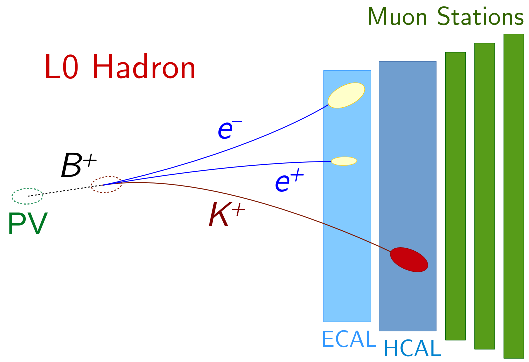
[Credit: Dan Moise]

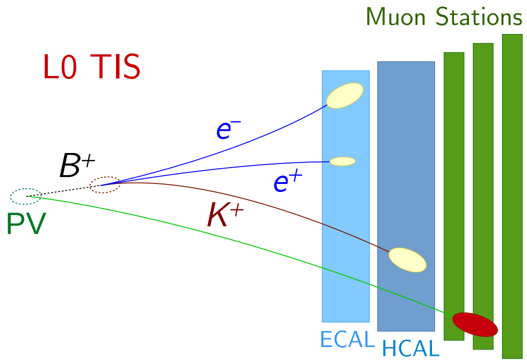
Same approach as in the previous analysis:

- 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



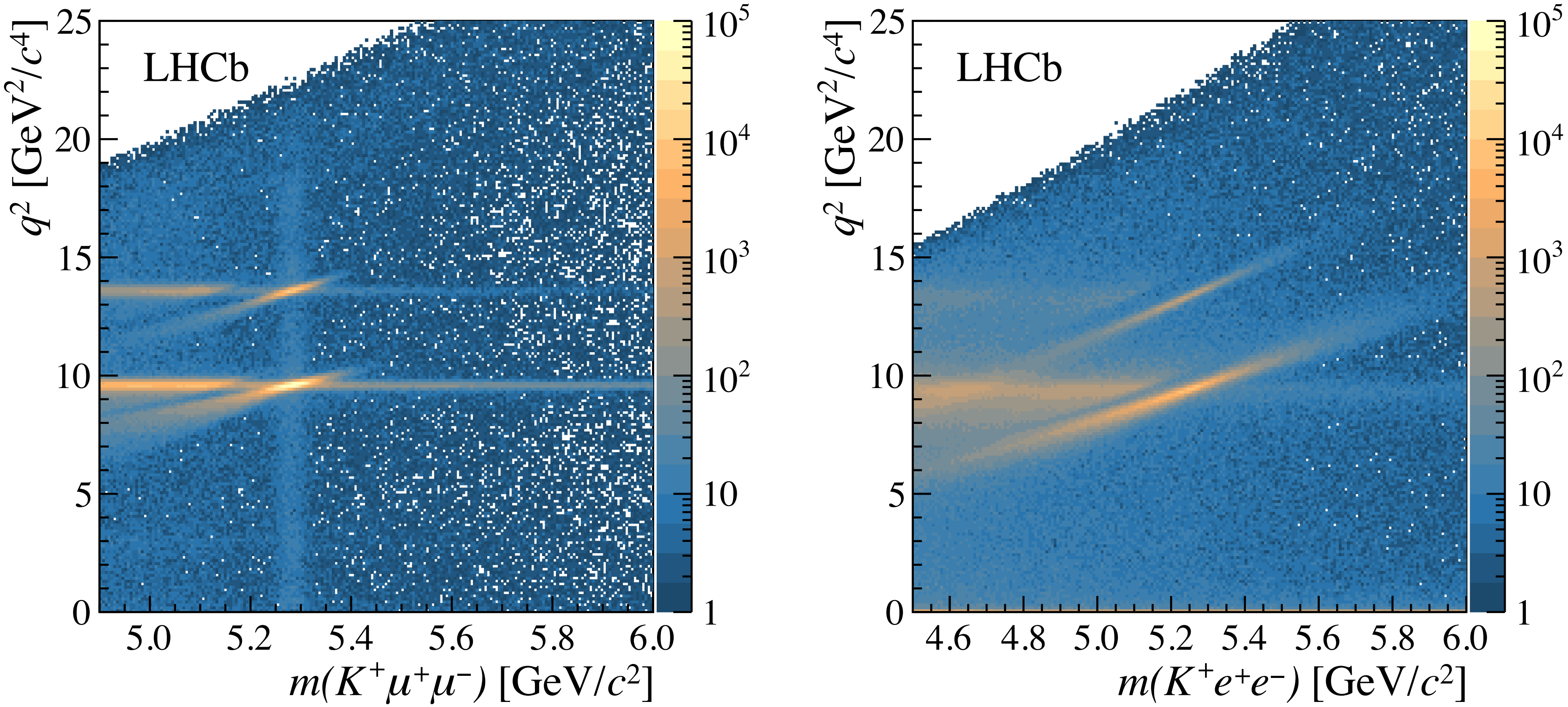






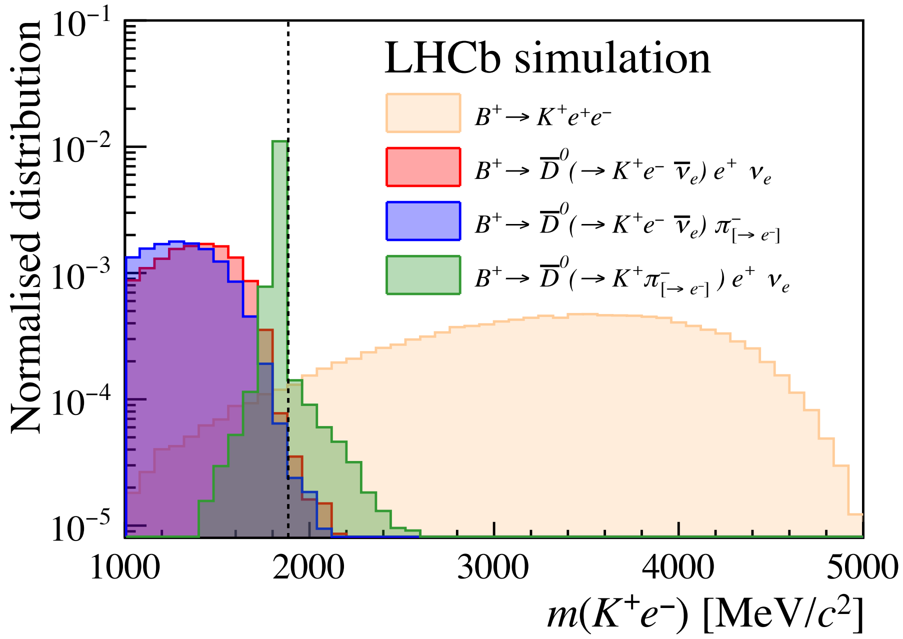
$B^+ \to K^+\ell^+\ell^-$

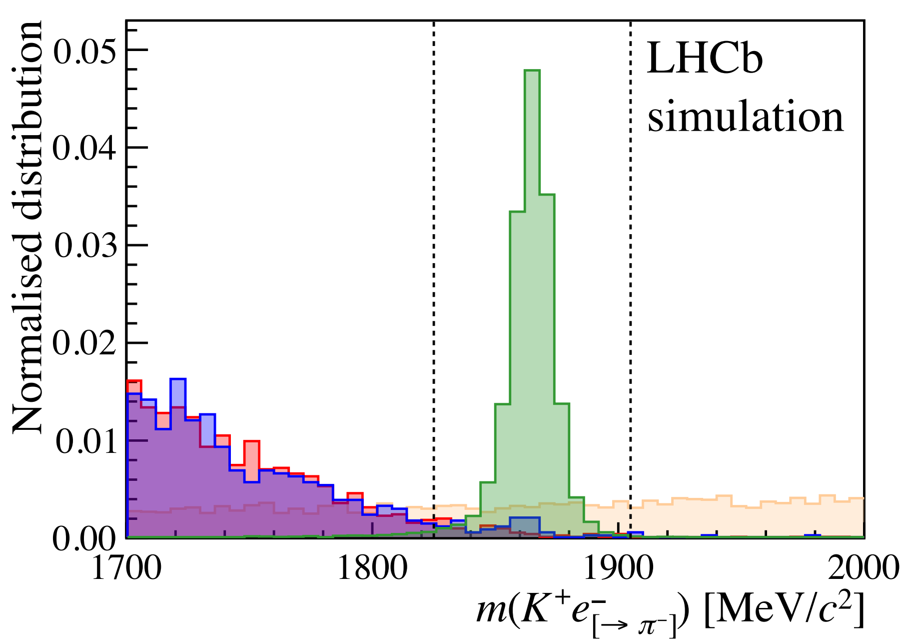
[PRL122(2019)191801]



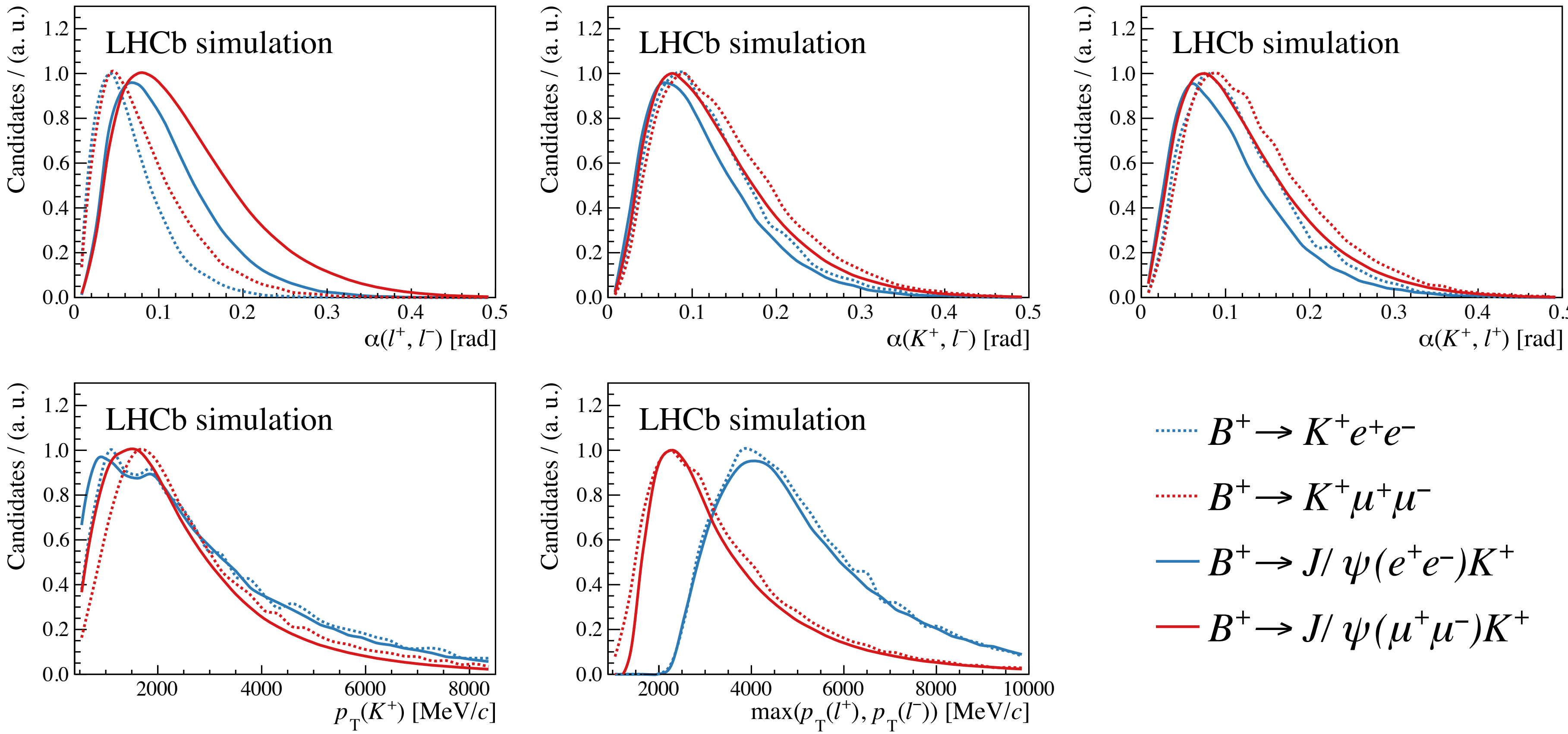
Semileptonic vetos

[LHCb-PAPER-2021-004]

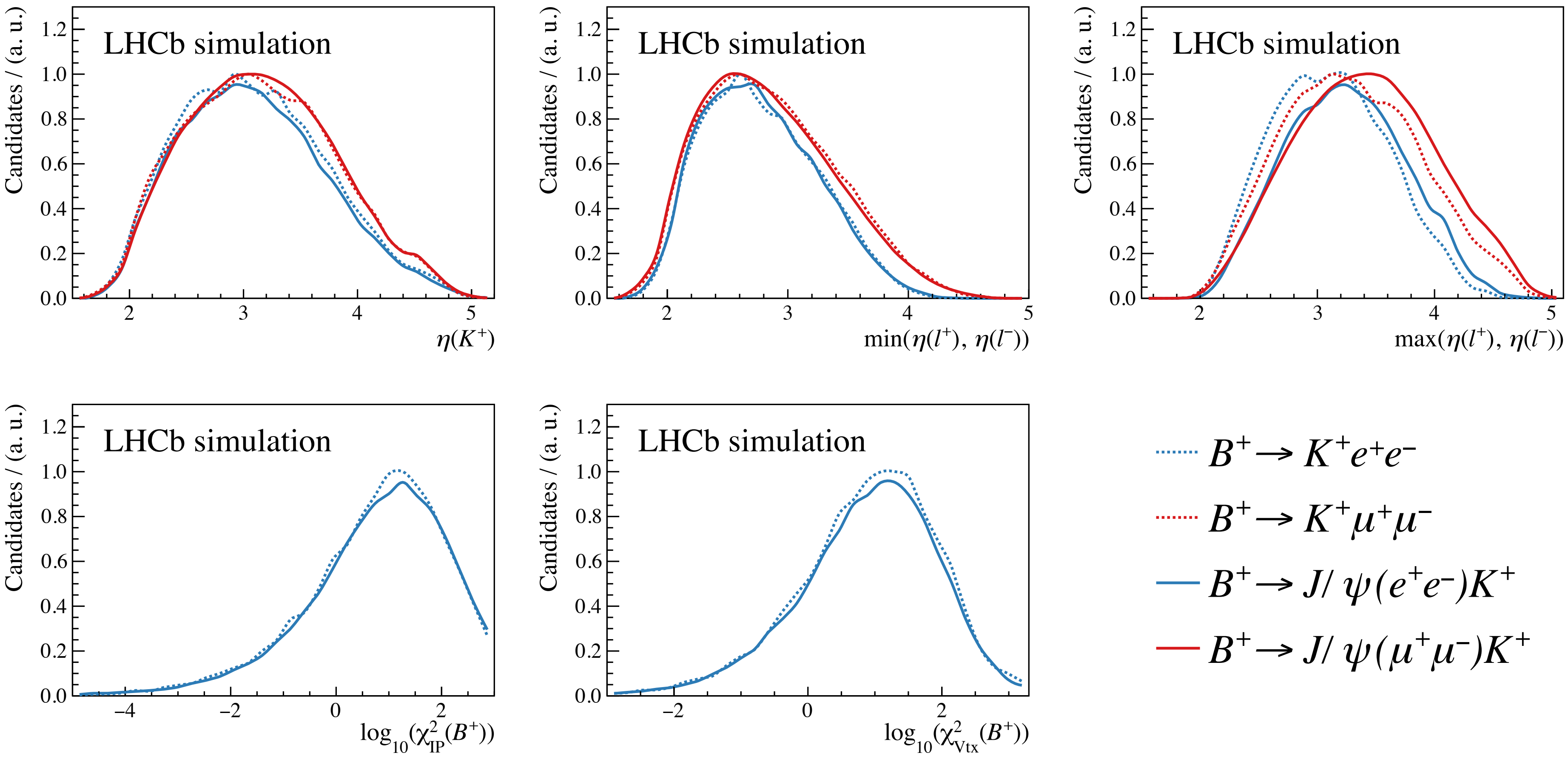




Parameter overlap (I)



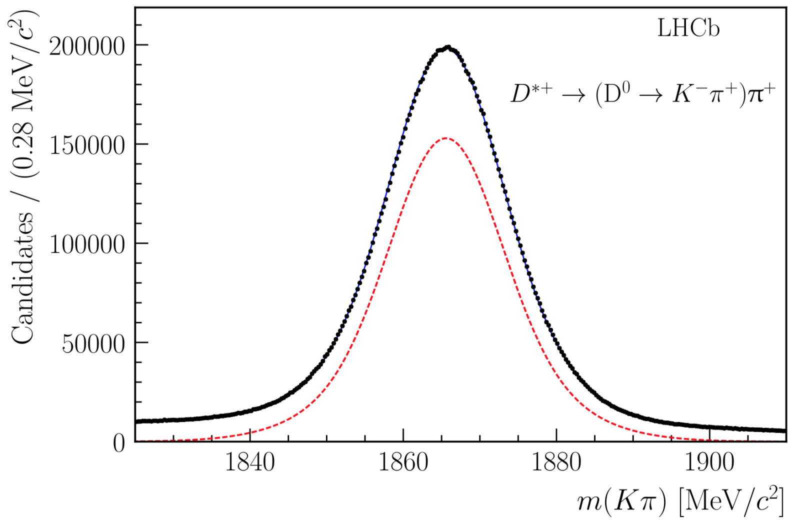
Parameter overlap (II)



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]

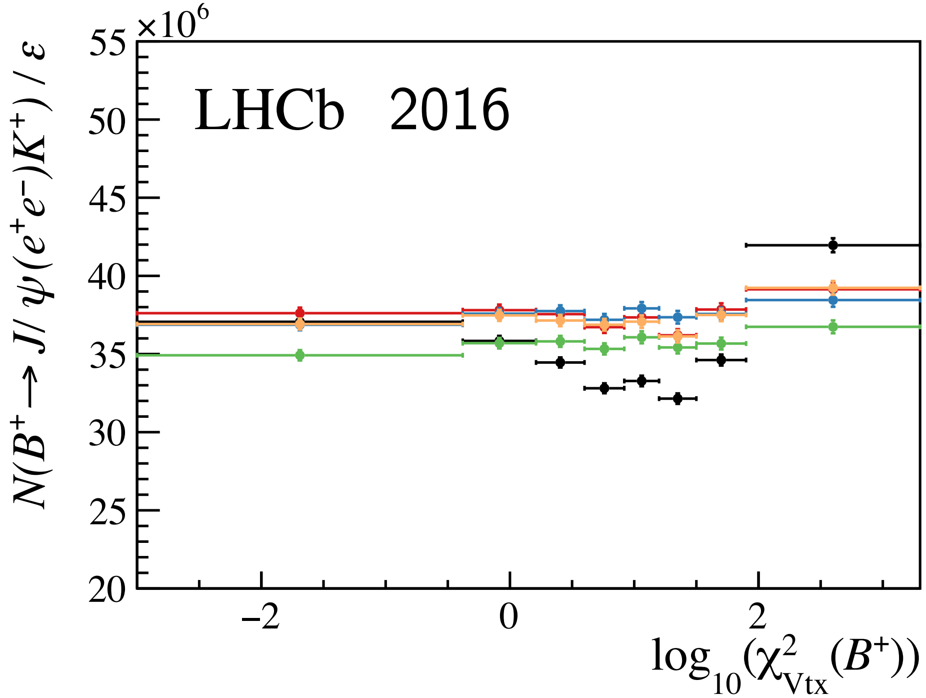
none

$\mu\mu$ `L0Muon`, nominal

$\mu\mu$ `L0TIS`

ee `L0Electron`

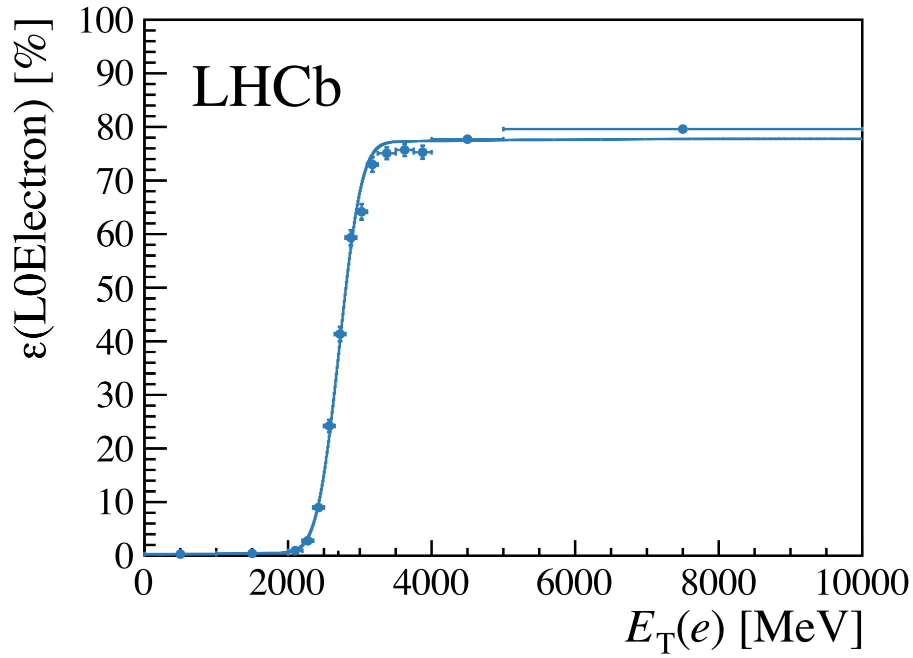
$VTX\chi^2$: ee `L0Electron`, $p_T(B)\times\eta(B)$, $IP\chi^2$: $\mu\mu$ `L0Muon`



$\to$ 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:

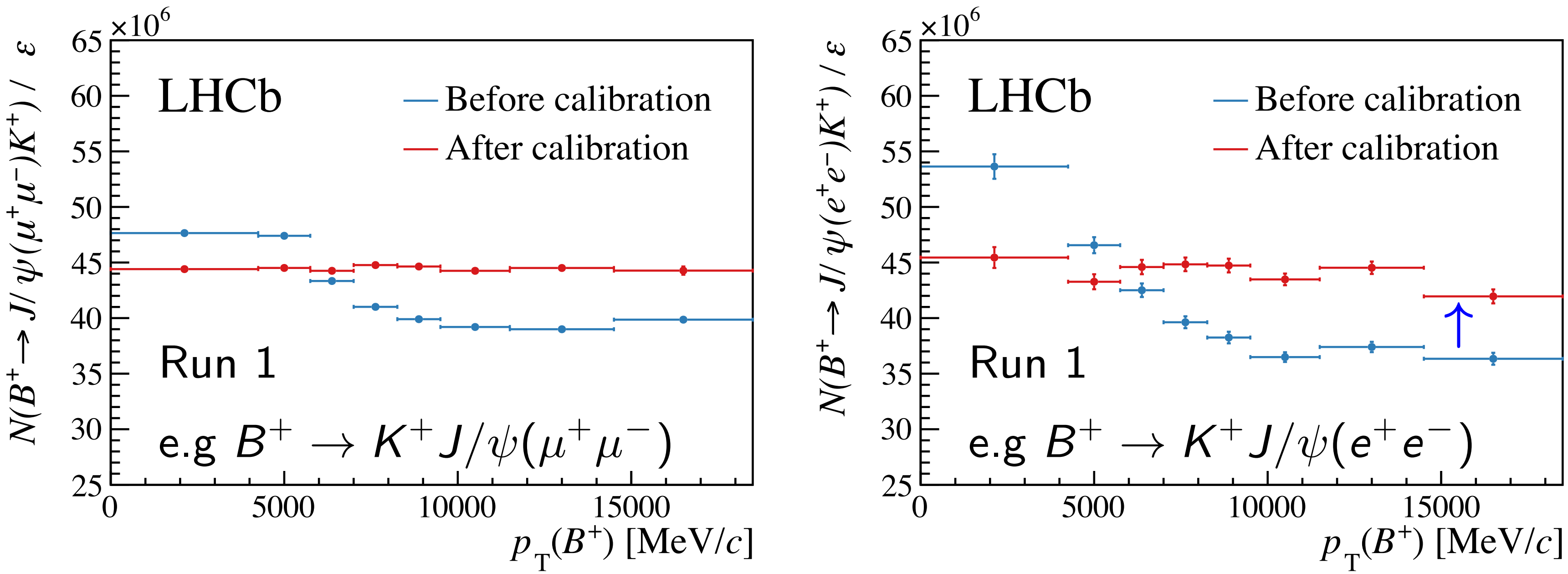
- dependence on how the calibration sample is selected,
- correlation between the two leptons in the signal.

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

$\to$ 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.

New results on rare B decays and their implications

Wolfgang Altmannshofer
waltmann@ucsc.edu

UC SANTA CRUZ

KITP Program
"New Physics from Precision at High Energies"
March 29, 2021

SM Predictions for R_K (and R_{K^*})

$$R_{K^{(*)}} = 1$$

SM Predictions for R_K (and R_{K^*})

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right)$$

phase space
(tiny effect)

SM Predictions for R_K (and R_{K^*})

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right) \times \left(1 + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right) + \mathcal{O}(\alpha_s)\right)$$

phase space
(tiny effect)

hadronic corrections
(tiny effect)

SM Predictions for R_K (and R_{K^*})

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right) \times \left(1 + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right) + \mathcal{O}(\alpha_s)\right) + \mathcal{O}\left(\frac{\alpha_{\text{em}}}{\pi} \log^2\left(\frac{m_e^2}{m_\mu^2}\right)\right)$$

phase space
(tiny effect)

hadronic corrections
(tiny effect)

QED corrections
(soft and collinear photon emission)

SM Predictions for R_K (and R_{K^*})

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right) \times \left(1 + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right) + \mathcal{O}(\alpha_s)\right) + \mathcal{O}\left(\frac{\alpha_{\rm em}}{\pi}\log^2\left(\frac{m_e^2}{m_\mu^2}\right)\right)$$

phase space
(tiny effect)

hadronic corrections
(tiny effect)

QED corrections
(soft and collinear photon emission)

- QED corrections seem to be under control at the level of the total rate, given the experimental cuts on e.g. the reconstructed B meson mass

  Bordone, Isidori, Pattori 1605.07633, Isidori, Nabeebaccus, Zwicky 2009.00929

$$R_K^{[1,6]} = 1.00 \pm 0.01 \ , \quad R_{K^*}^{[1.1,6]} = 1.00 \pm 0.01 \ , \quad R_{K^*}^{[0.045,1.1]} = 0.91 \pm 0.03$$

- potentially larger QED effects at the differential level

Model Independent New Physics Analysis

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \Big(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \Big)$$

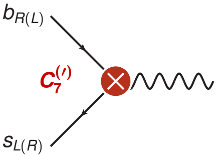
$$\simeq \mathcal{H}_{\rm eff}^{\rm SM} - \frac{1}{(35\text{TeV})^2} \sum_i \Big(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \Big)$$

Model Independent New Physics Analysis

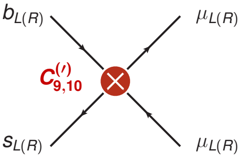
$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

$$\simeq \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{1}{(35\text{TeV})^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

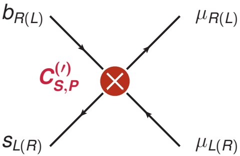
magnetic dipole operators



semileptonic operators



scalar operators



$C_7^{(\prime)} (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$, $C_9^{(\prime)} (\bar{s} \gamma_\mu P_{L(R)} b)(\bar{\ell} \gamma^\mu \ell)$, $C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\ell} P_{L(R)} \ell)$

$C_{10}^{(\prime)} (\bar{s} \gamma_\mu P_{L(R)} b)(\bar{\ell} \gamma^\mu \gamma_5 \ell)$

neglecting tensor operators and additional scalar operators

Complementary Sensitivity

	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'	C_S, C_S'
$B \to (X_s, K^*)\gamma$	★			
$B_s \to \phi\gamma$	★			
$B \to (X_s, K, K^*)\ \ell^+\ell^-$	★	★	★	⋆
$B_s \to \phi\ \ell^+\ell^-$	★	★	★	⋆
$\Lambda_b \to \Lambda\ \ell^+\ell^-$	★	★	★	⋆
$B_s \to \mu^+\mu^-$			★	★

many processes and many observables
are modified simultaneously

$\Rightarrow$ global fits are required

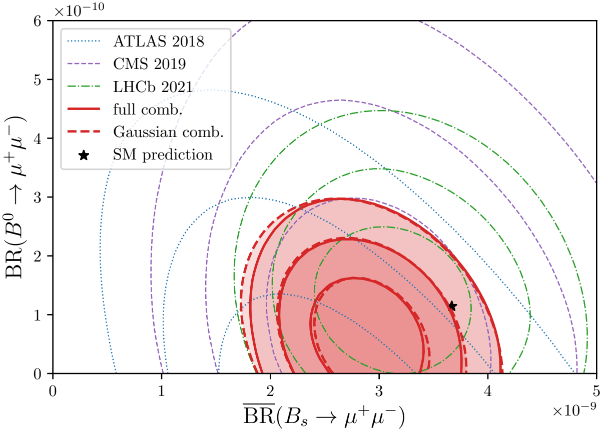
two papers from last week (+ O(10) more in the last few years)

Geng, Grinstein, Jäger, Li, Martin Camalich, Shi 2103.12738

WA, Stangl 2103.13370

Tension in $B_s \to \mu^+\mu^-$?

WA, Stangl 2103.13370 (also Geng, Grinstein, Jäger, Li, Martin Camalich, Shi 2103.12738)



$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = (2.93^{+0.33}_{-0.35}) \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$ (Bobeth et al. 1908.07011)

New Physics in Electrons

WA, Stangl 2103.13370

	LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull
C_9^{bsee}	$+0.74^{+0.20}_{-0.19}$	4.1σ		
C_{10}^{bsee}	$-0.67^{+0.17}_{-0.18}$	4.2σ		
$C_9^{\prime bse}$	$+0.35^{+0.18}_{-0.17}$	2.1σ		
$C_{10}^{\prime bsee}$	$-0.31^{+0.16}_{-0.16}$	2.0σ		
$C_9^{bsee} = C_{10}^{bsee}$	$-1.40^{+0.26}_{-0.26}$	4.0σ		
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.37^{+0.10}_{-0.10}$	4.2σ		

New Physics in Electrons

WA, Stangl 2103.13370

	LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull
C_9^{bsee}	$+0.74^{+0.20}_{-0.19}$	4.1σ	$+0.75^{+0.20}_{-0.19}$	4.1σ
C_{10}^{bsee}	$-0.67^{+0.17}_{-0.18}$	4.2σ	$-0.66^{+0.16}_{-0.17}$	4.3σ
$C_9^{\prime bse}$	$+0.35^{+0.18}_{-0.17}$	2.1σ	$+0.39^{+0.19}_{-0.18}$	2.3σ
$C_{10}^{\prime bsee}$	$-0.31^{+0.16}_{-0.16}$	2.0σ	$-0.29^{+0.15}_{-0.16}$	2.0σ
$C_9^{bsee} = C_{10}^{bsee}$	$-1.40^{+0.26}_{-0.26}$	4.0σ	$-1.28^{+0.24}_{-0.23}$	4.1σ
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.37^{+0.10}_{-0.10}$	4.2σ	$+0.37^{+0.10}_{-0.10}$	4.3σ

New Physics in Muons

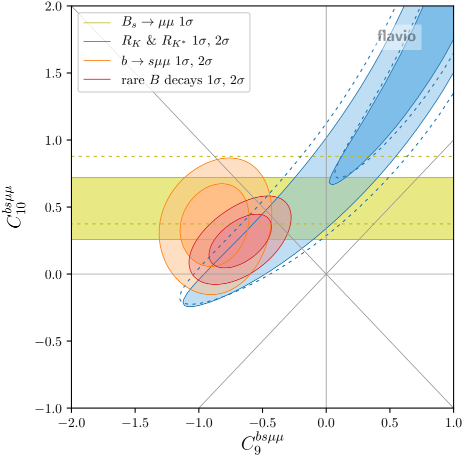
WA, Stangl 2103.13370

	LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull
$C_9^{bs\mu\mu}$	$-0.74^{+0.20}_{-0.21}$	4.1σ		
$C_{10}^{bs\mu\mu}$	$+0.60^{+0.14}_{-0.13}$	4.7σ		
$C_9^{\prime bs\mu\mu}$	$-0.31^{+0.16}_{-0.17}$	2.0σ		
$C_{10}^{\prime bs\mu\mu}$	$+0.05^{+0.12}_{-0.12}$	0.4σ		
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.43^{+0.18}_{-0.18}$	2.5σ		
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.35^{+0.08}_{-0.08}$	4.7σ		

WA, Stangl 2103.13370

	LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull
$C_9^{bs\mu\mu}$	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.82^{+0.14}_{-0.14}$	6.2σ
$C_{10}^{bs\mu\mu}$	$+0.60^{+0.14}_{-0.13}$	4.7σ	$+0.56^{+0.12}_{-0.12}$	4.9σ
$C_9^{\prime bs\mu\mu}$	$-0.31^{+0.16}_{-0.17}$	2.0σ	$-0.09^{+0.13}_{-0.13}$	0.7σ
$C_{10}^{\prime bs\mu\mu}$	$+0.05^{+0.12}_{-0.12}$	0.4σ	$+0.01^{+0.10}_{-0.09}$	0.1σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.43^{+0.18}_{-0.18}$	2.5σ	$-0.06^{+0.11}_{-0.11}$	0.5σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.35^{+0.08}_{-0.08}$	4.7σ	$-0.43^{+0.07}_{-0.07}$	6.2σ

Fits of Pairs of Wilson Coefficients (1)



WA, Stangl 2103.13370

good compatibility between lepton flavor universality ratios, $B_s \to \mu^+\mu^-$ and the other $b \to s\mu\mu$ observables (P_5' and friends)

Best fit point :

$$C_9^{bs\mu\mu} \simeq -0.67$$
$$C_{10}^{bs\mu\mu} \simeq +0.24$$

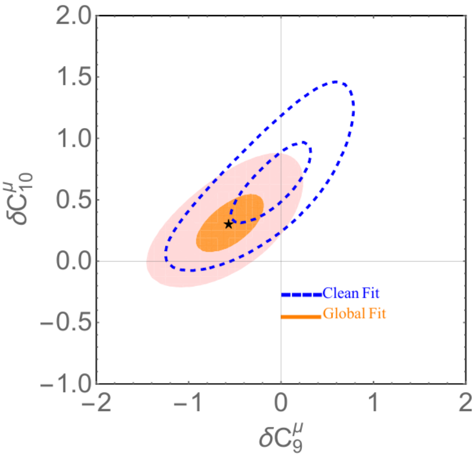
for comparison:

$$C_9^{\rm SM} \simeq -C_{10}^{\rm SM} \simeq 4$$

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

$$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

Fits of Pairs of Wilson Coefficients (2)



Geng, Grinstein, Jäger, Li, Martin Camalich, Shi 2103.12738

reasonable agreement

Best fit point:

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$C_{10}^{bs\mu\mu} \simeq +0.30$

for comparison:

$C_9^{\rm SM} \simeq -C_{10}^{\rm SM} \simeq 4$

$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$

$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$

Simplified Models

- Tree level Z' models:
  - Z' mass could be as light as $O(10)$ GeV (if couplings to quarks and electrons are sufficiently tiny to evade direct searches), could be as heavy as several TeV.
  - Strong constraints from B_s meson oscillations (Z' contributes at tree level).

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  - Leptoquarks eed to be heavier than $O(1)$ TeV to avoid direct searches at the LHC.
  - contribute to meson oscillations at the loop level $\rightarrow$ less constrained than Z' models.
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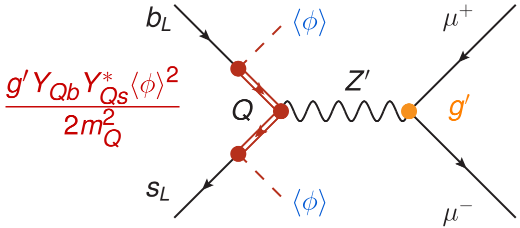
  - The U_1 vector leptoquark ($\sim$ a gauge boson of Pati-Salam) can simultaneously also explain R_D and R_{D^*}.
- Loop models:
  - many options, e.g. right-handed sbottoms with RPV couplings.
  - Models typically have several states with masses $O(1)$ TeV with largish couplings to the SM $\rightarrow$ typically strongly constrained.

Z' based on gauging $L_\mu - L_\tau$ (He, Joshi, Lew, Volkas PRD 43, 22-24)
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009



predicted Lepton Universality Violation in rare B decays!

Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

Probing the Z' Parameter Space

Neutrino Tridents

B_s mixing

$(g-2)_\mu$

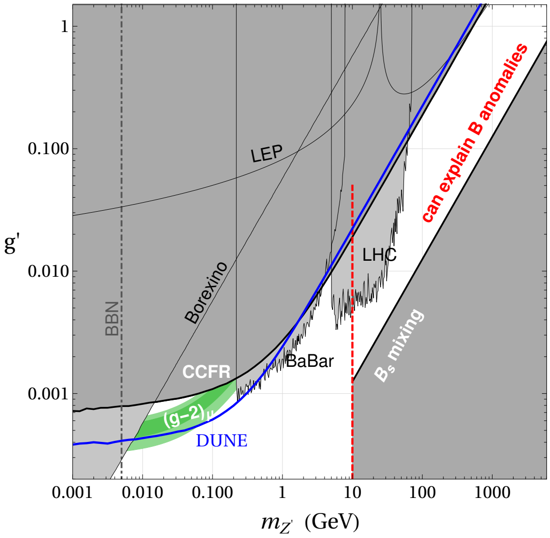
νe scattering

$Z \to \ell\ell$

$Z \to 4\mu$

$e^+e^- \to 4\mu$

WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



Summary

- Global fit results did not change qualitatively compared to previous interations.
- Very encouraging to see that the significance of the R_K anomaly increased with more statistics!
- Want to see the same for R_{K^*} and related observables.