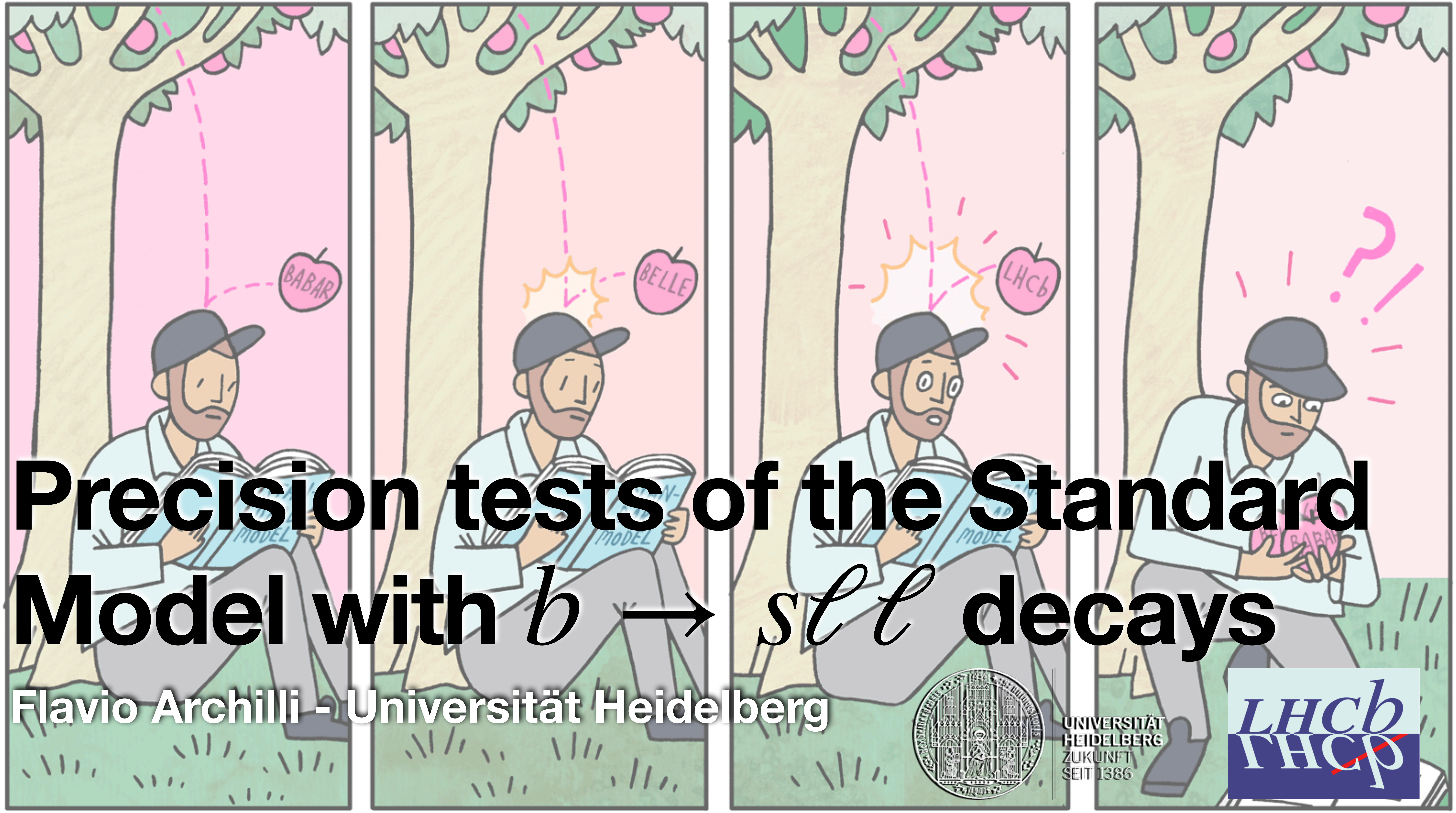

Precision tests of the Standard Model with $b \to s\ell\ell$ decays

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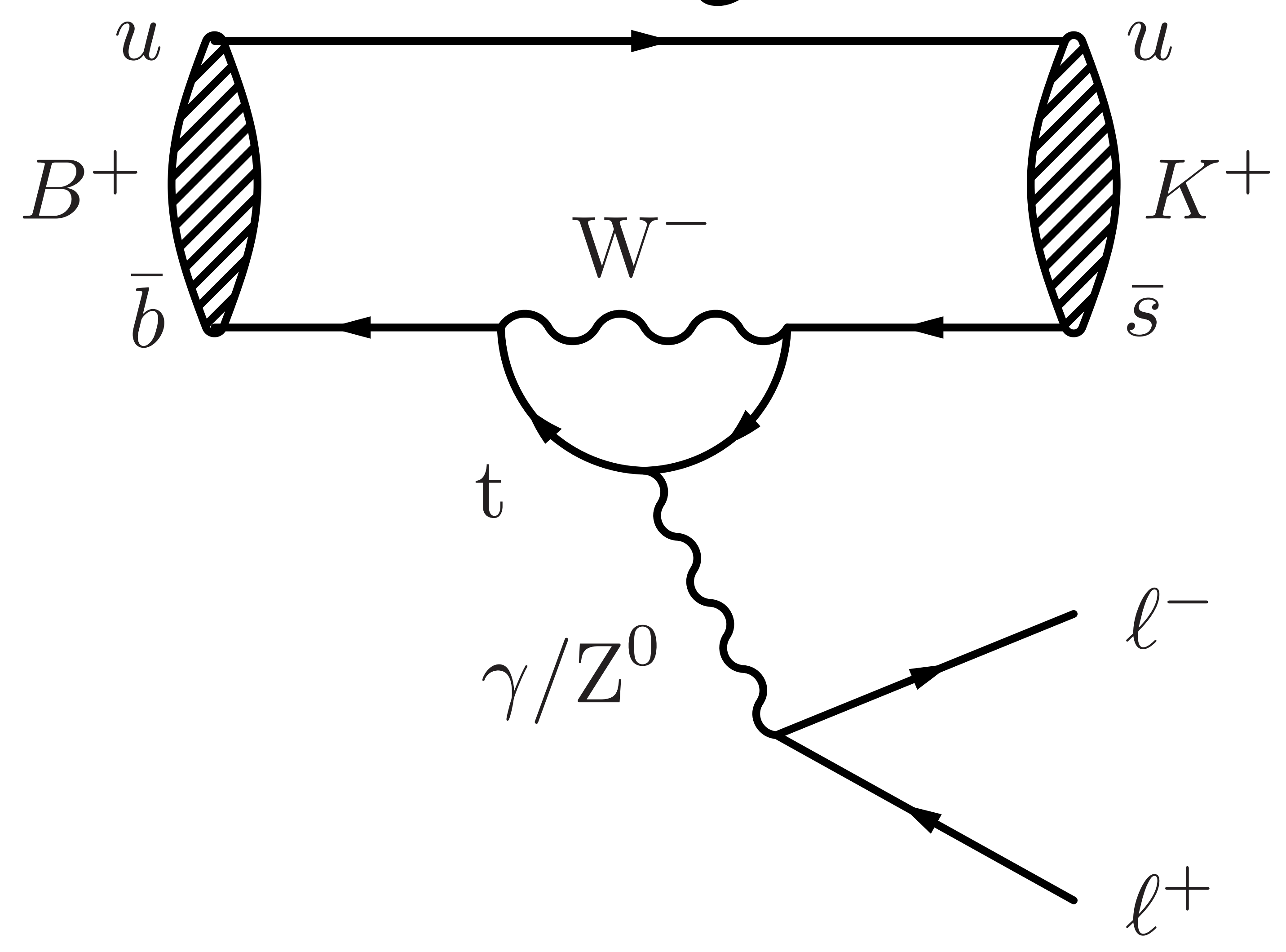
LHCb

Mini-workshop Congiunto INFN LNF - INFN Roma: New results on theoretically clean observables in rare B-meson decays from LHCb

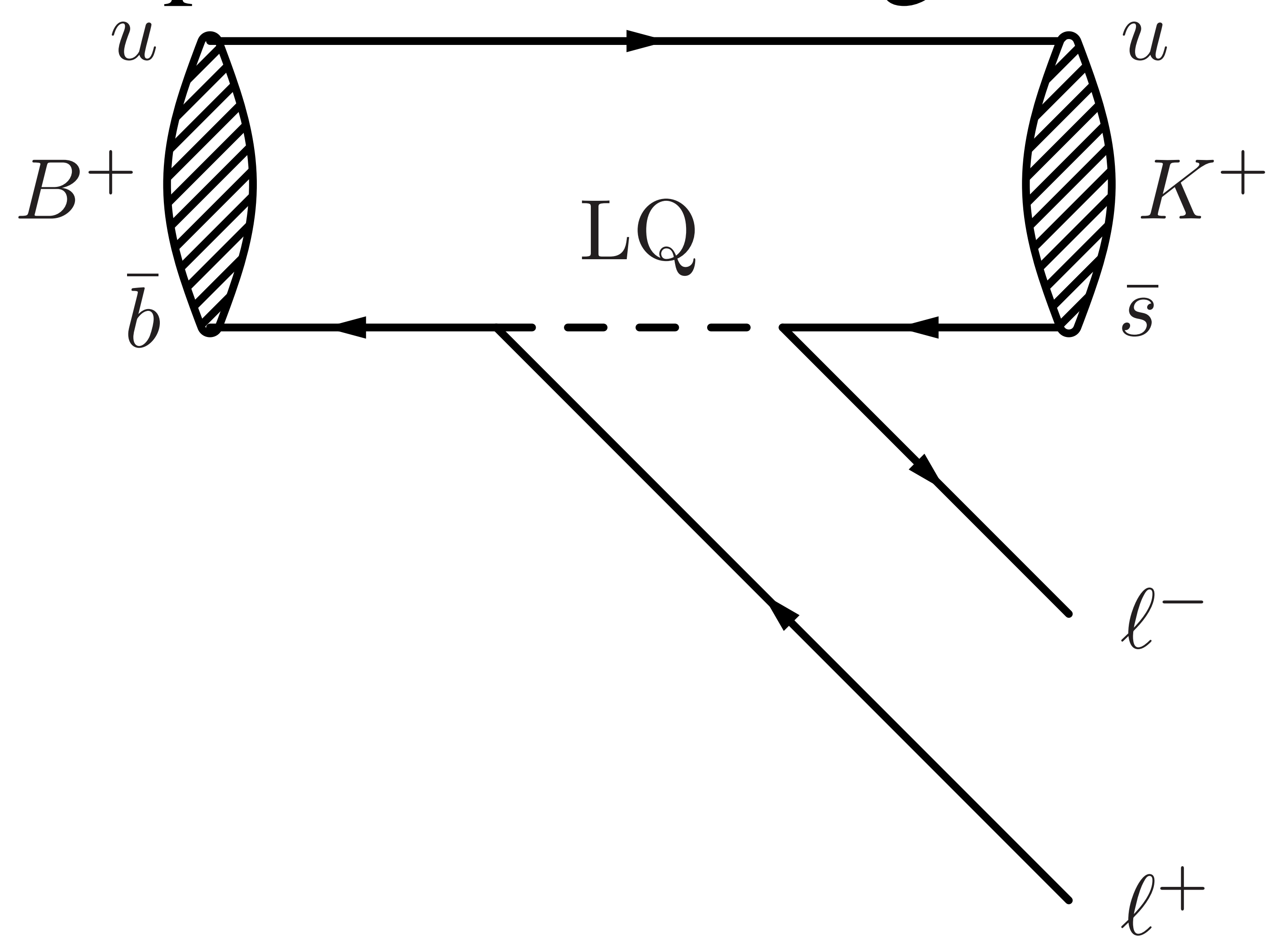
$B \to K\ell^+\ell^-$ family

- Similarly to $B_s^0 \to \mu^+\mu^-$ decays, they are FCNC $b \to s\ell\ell$ transitions with an hadron in the final state: $B^+ \to K^+\ell^+\ell^-, B \to K^*\ell^+\ell^-, B_s \to \phi\ell^+\ell^-, \Lambda_b \to \Lambda^*\ell^+\ell^-$ ...

SM diagram



possible NP diagram

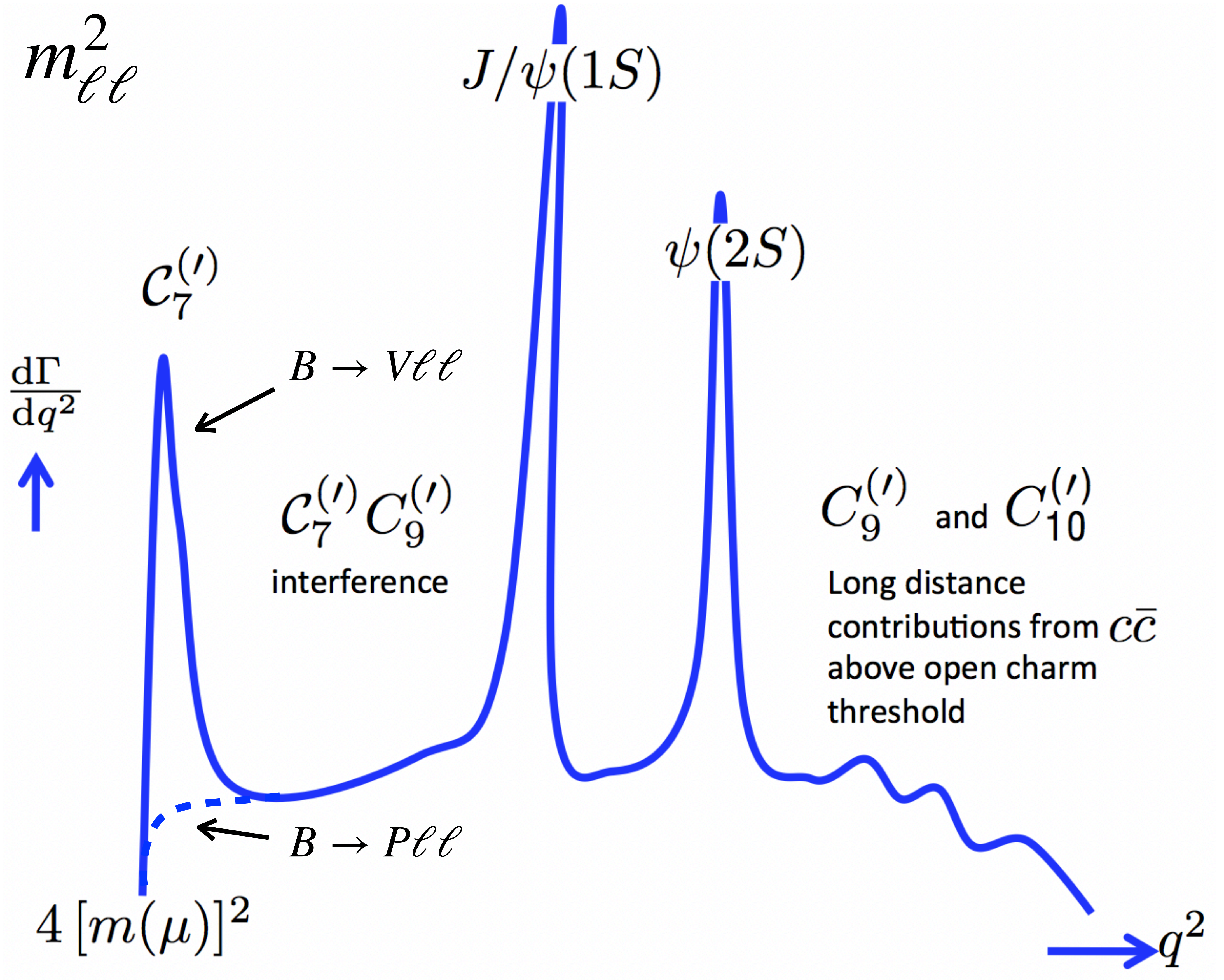


- Multitude of observables complementary to $B_s^0 \to \ell^+\ell^-$

- No helicity suppression, higher branching fractions ~ 10^{-6}

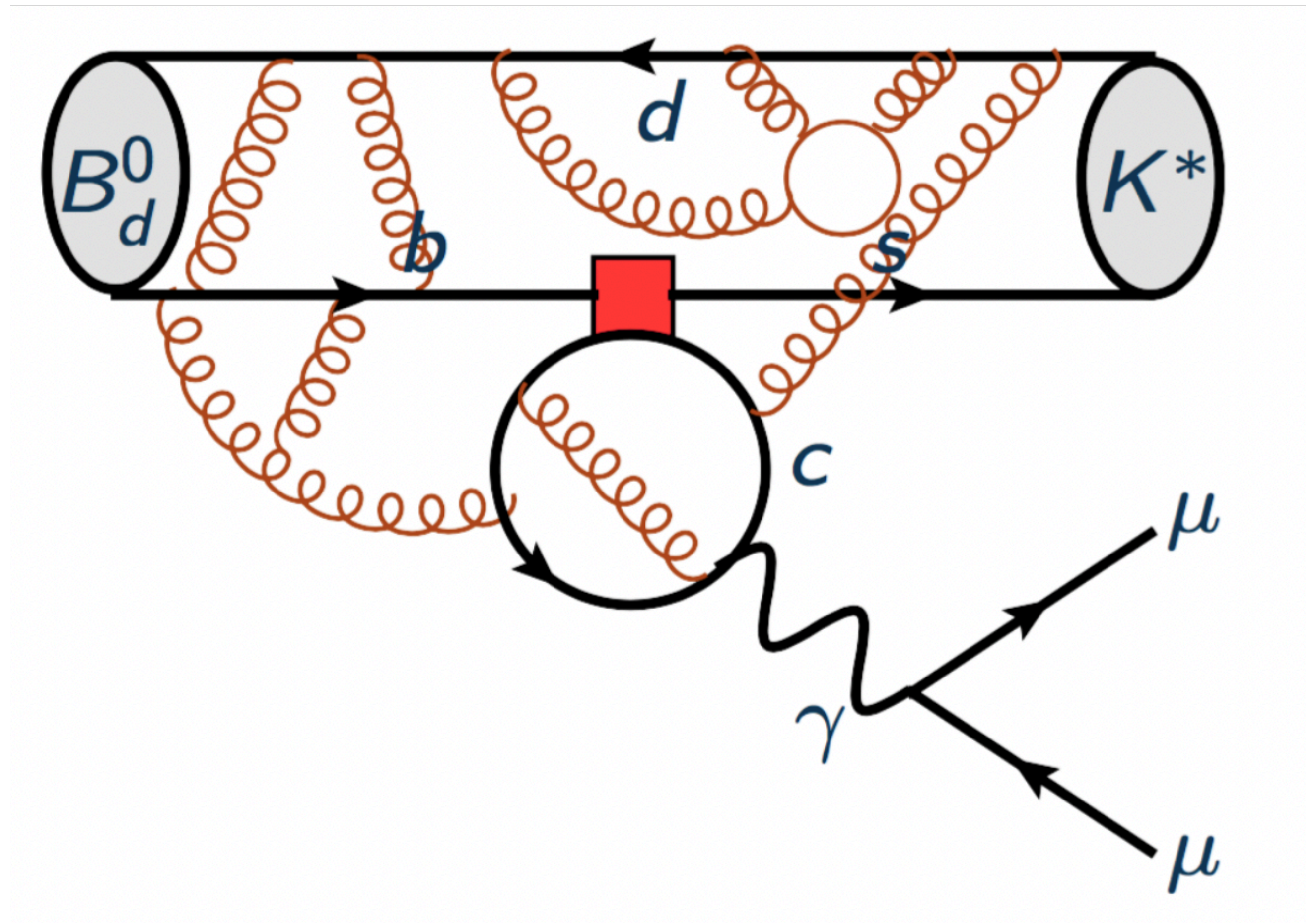
$b \to s\ell\ell$ observables

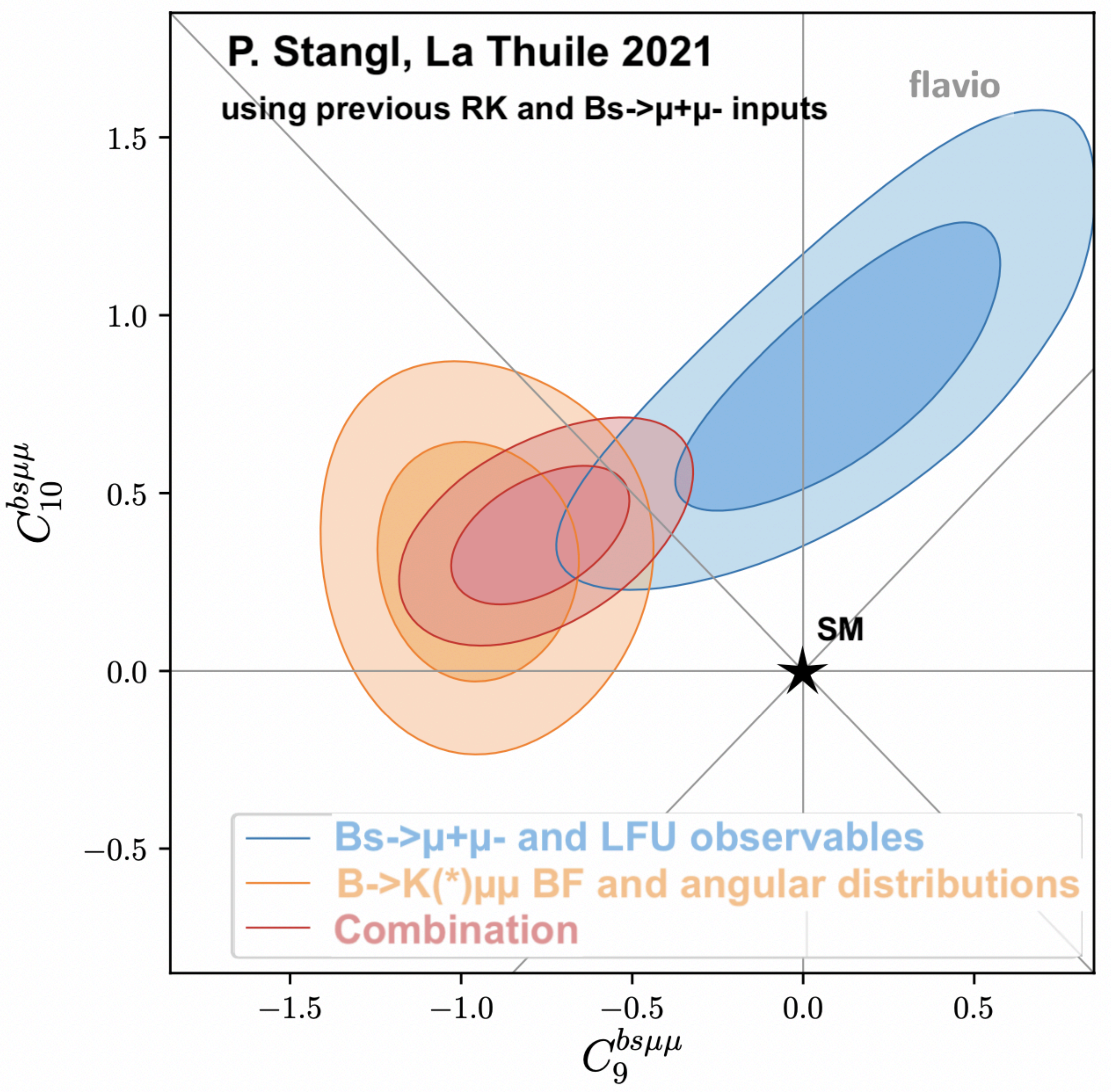
- Physics depends on dilepton invariant mass $q^2 = m^2_{\ell\ell}$
- Observables available:
  - Branching fractions (difficult to predict)
  - Angular observables (cleaner, but still tricky)
  - Lepton universality (theoretically clean)
- Over the past decade observed a coherent set of tensions with the SM predictions



Global fits

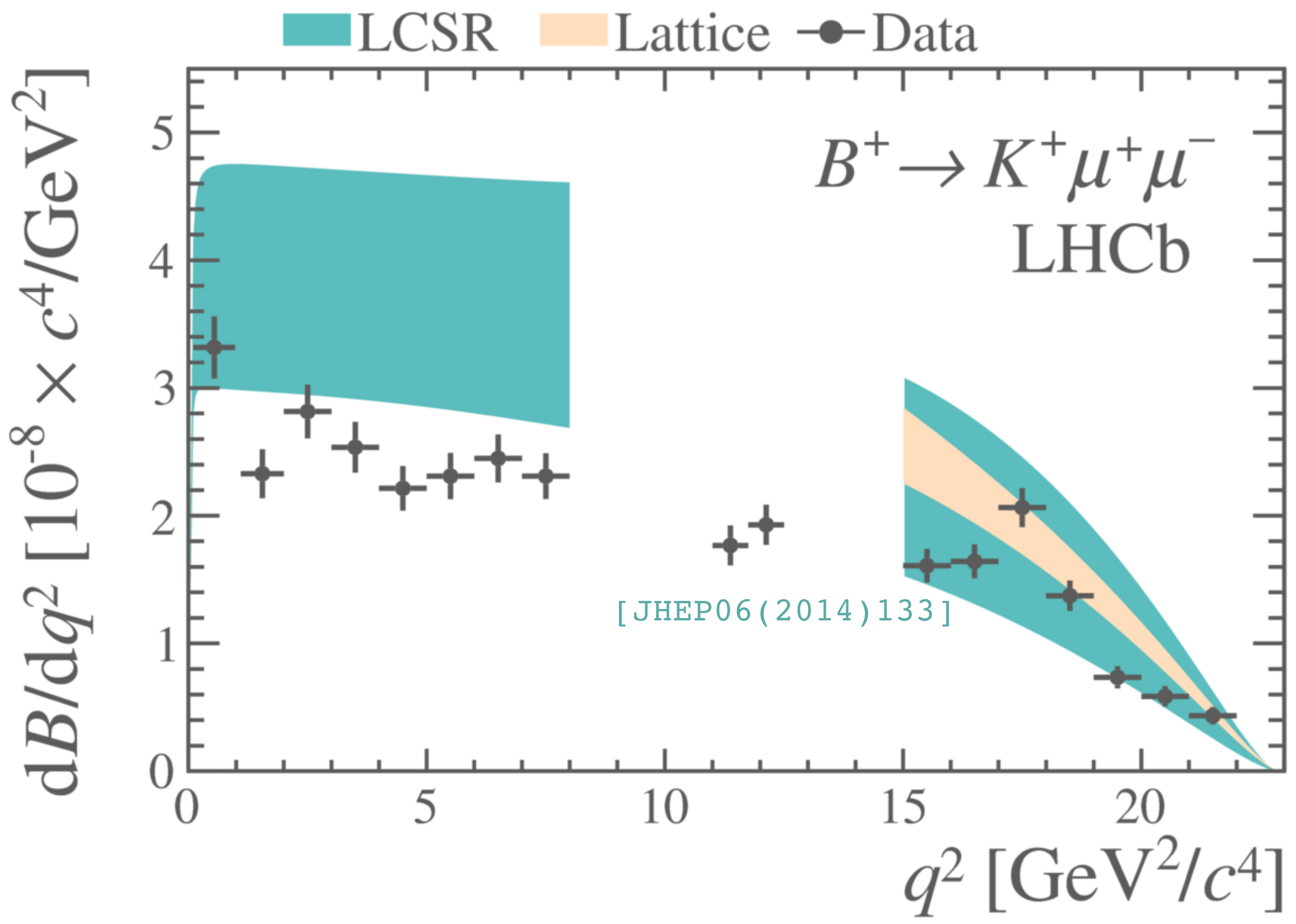
- Combination of all $b \to s\ell^+\ell^-$ measurements
- Measurement point to new vector coupling C_9^μ
- $B \to K^{(*)}\ell\ell$ BF and angular observables potentially suffer from hadronic uncertainties

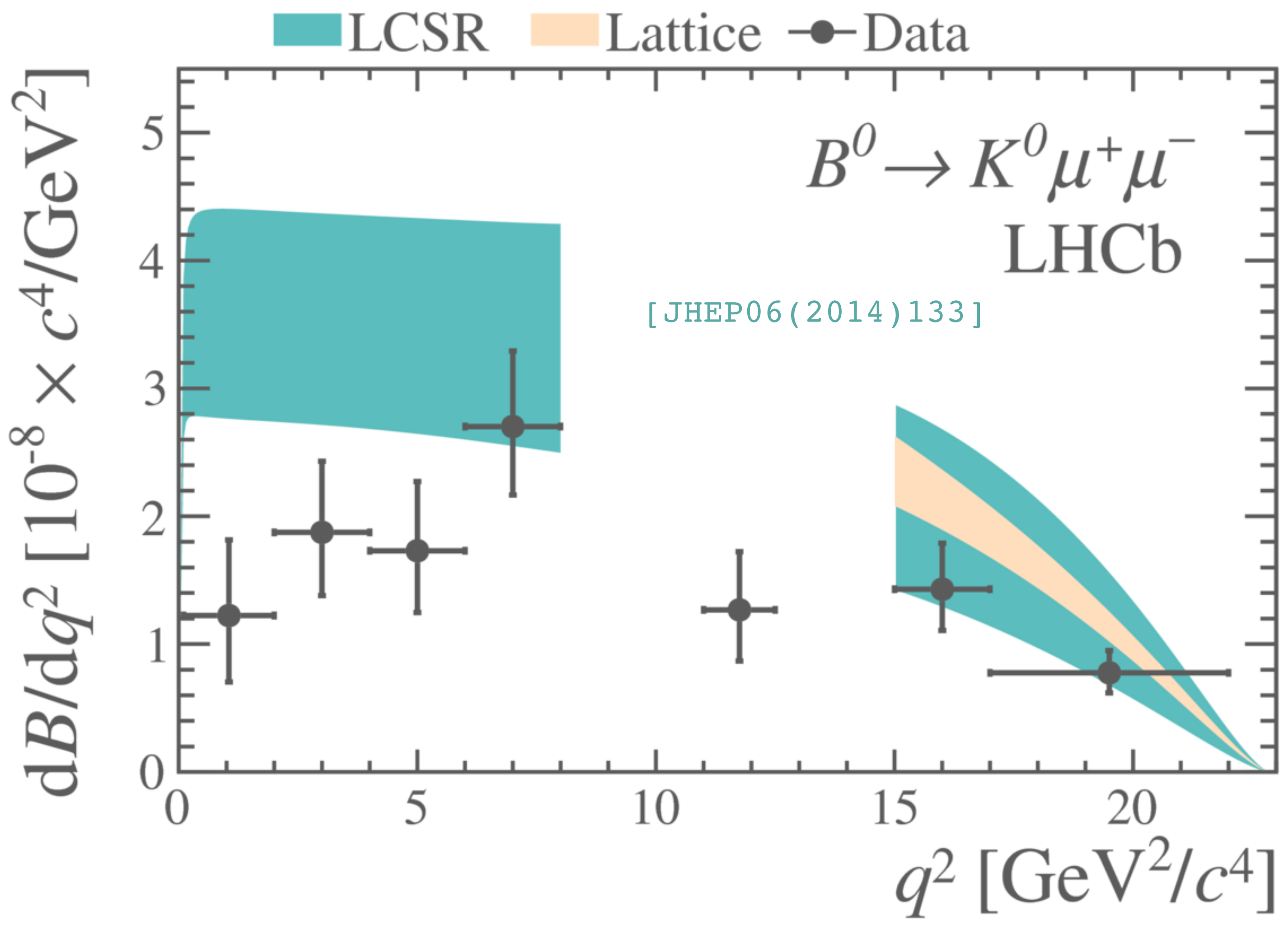


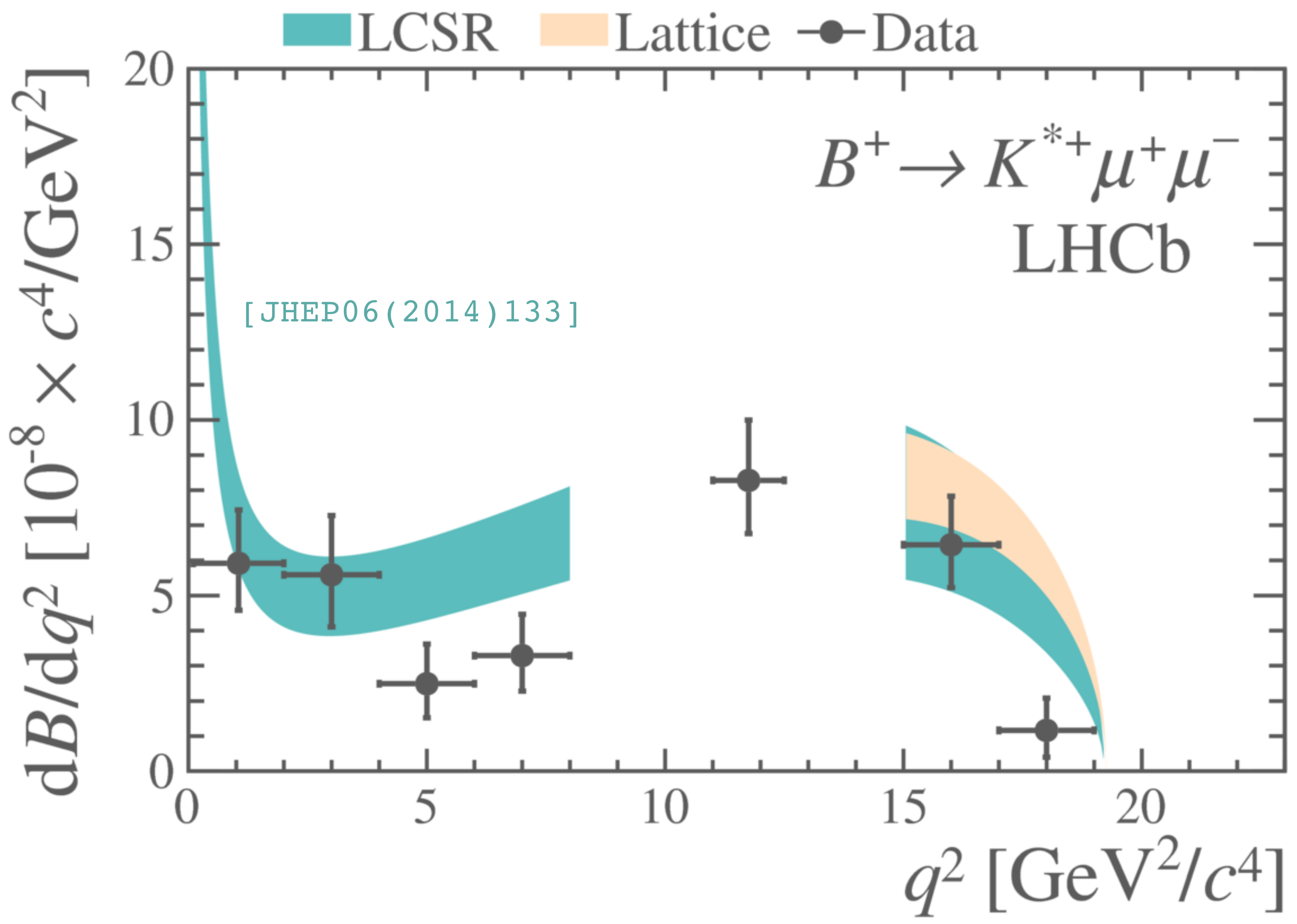


- $B_s^0 \to \mu^+\mu^-$ and LFU observables have a very clean theory predictions: **improving experimental precision is critical**

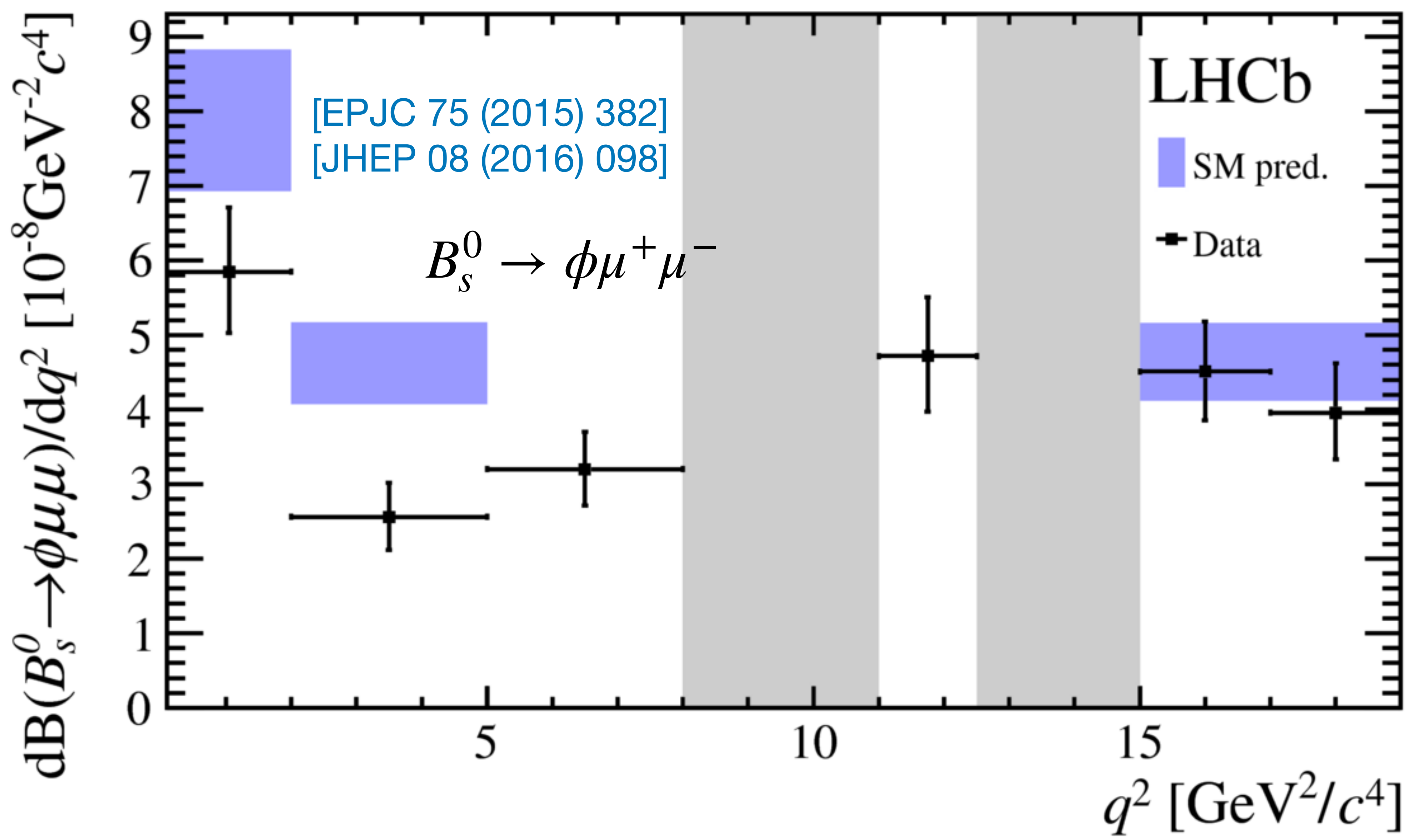
Branching fractions of semileptonic $b \to s\mu\mu$





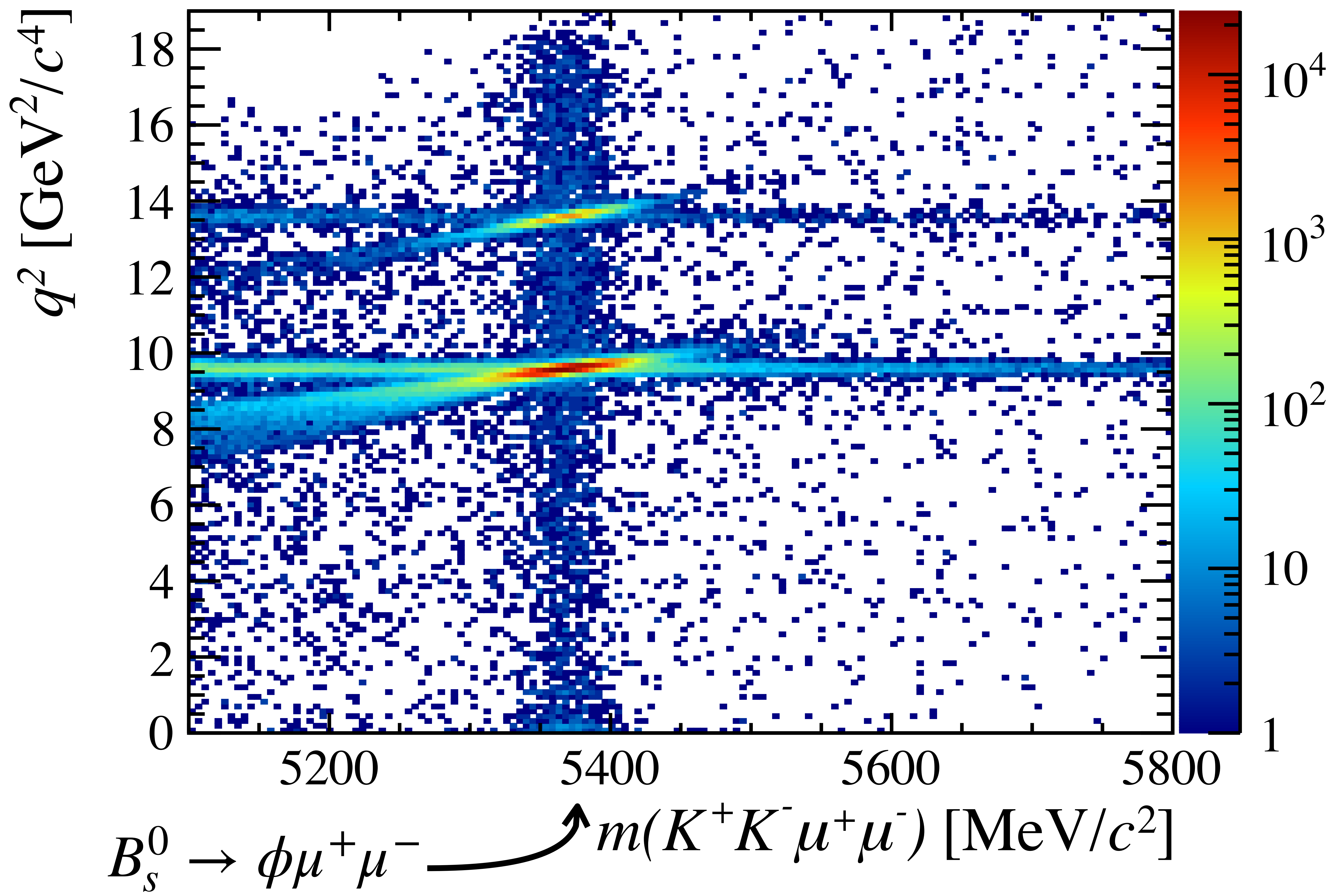


- $d\mathscr{B}/dq^2$ in exclusive $b \to s\mu\mu$ seems to undershoot SM predictions
- Theory uncertainties ~20-30% (hadronic form factors)
- Run 1 result: $\mathscr{B}(B_s^0 \to \phi\mu^+\mu^-)$ around 3σ lower wrt SM expectation at low q^2
- Today: Update with Run 1 + Run 2 data set



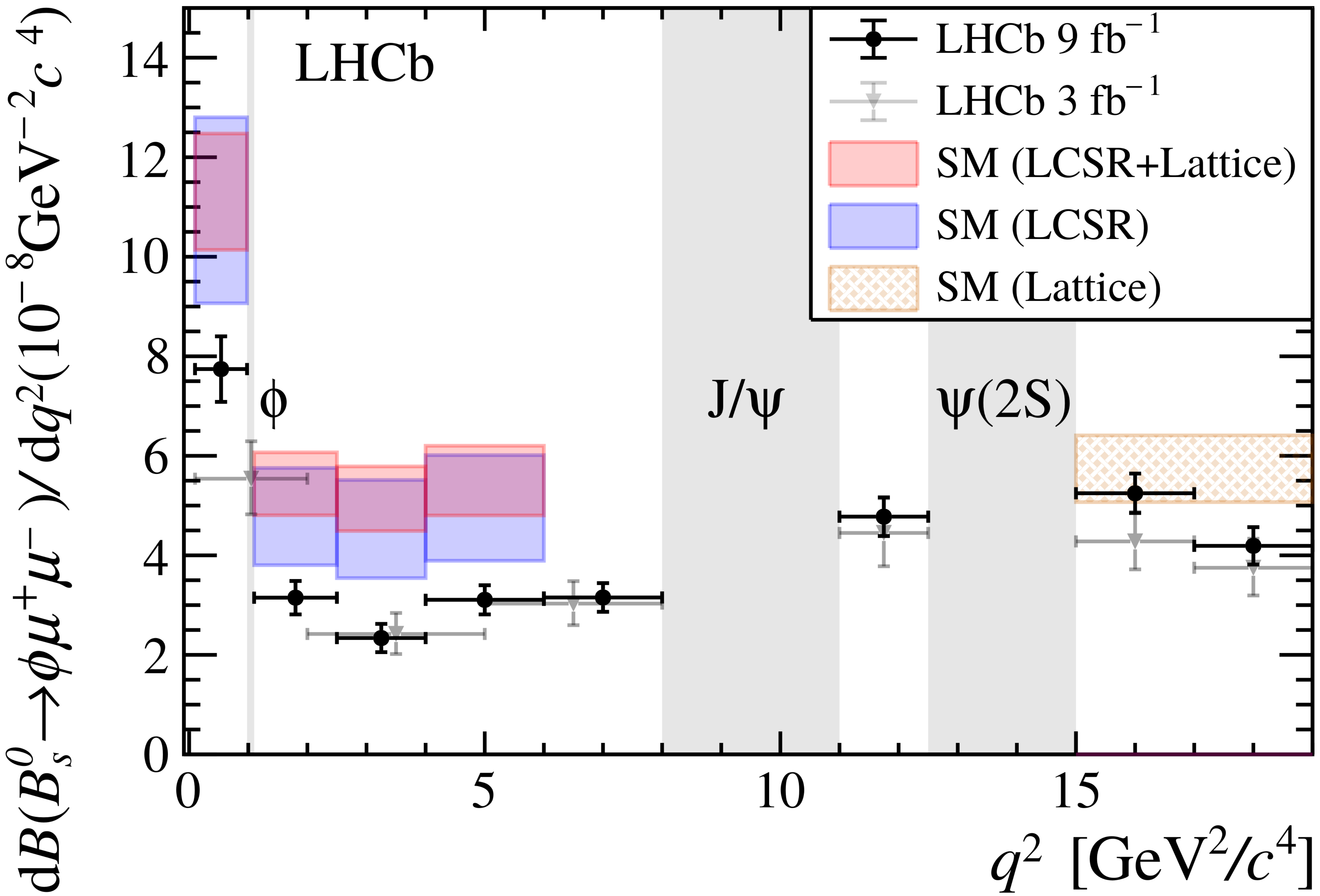
Selection and strategy

- Offline selection based on:
  - Flight distance of B_s^0
  - PID information to separate kaons from muons
  - $|m_{K^+K^-} - m_\phi| < 12\,\mathrm{MeV}/c^2$
- Further background rejection obtained by the use of a multivariate classifier:
  - $B_s^0 \to J/\psi\phi$ for signal and upper sideband for background



$\mathscr{B}(B_s^0 \to \phi\mu^+\mu^-)$ result

- Run 1 result:
  - [JHEP 09 (2015) 179], [LHCb-PAPER-2020-046]
- SM LCSR:
  - [JHEP 08 (2016) 098], [EPJ C 75 (2015 382)], [arxiv:1810.08132]
- SM LCSR+Lattice:
  - +[PRL 112 (2014) 212003], +[PoS LATTICE2014 (2015) 372]



Low-q^2 ([1.1,6.0] GeV$^2/c^4$): $d\mathscr{B}/dq^2 = (2.88 \pm 0.21)\times 10^{-8}\,\text{GeV}^2/c^4$

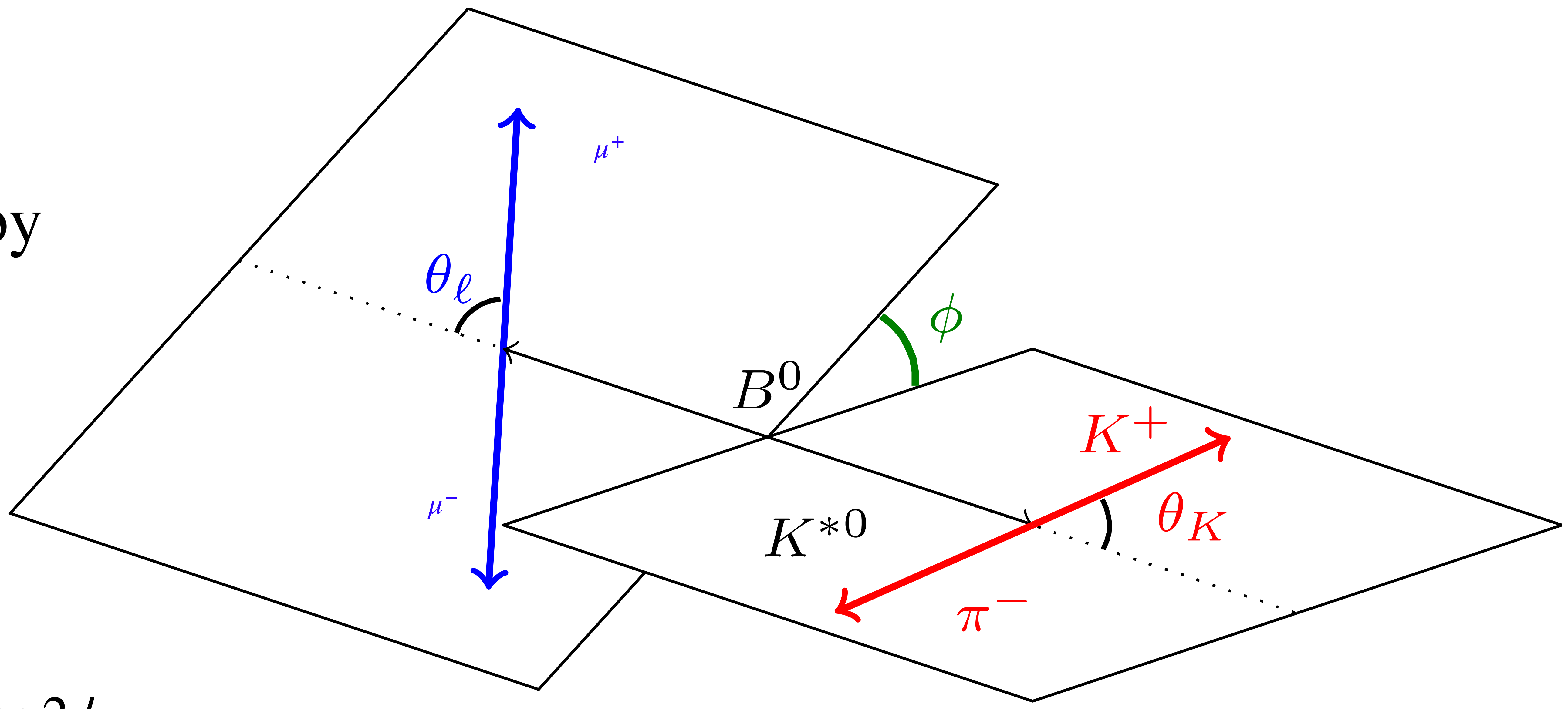
1.8σ (SM LCSR) $d\mathscr{B}/dq^2 = (4.77 \pm 1.01)\times 10^{-8}\,\text{GeV}^2/c^4$

3.6σ (SM LCSR+Lattice) $d\mathscr{B}/dq^2 = (5.37 \pm 0.66)\times 10^{-8}\,\text{GeV}^2/c^4$

Integrated over q^2: $\mathscr{B}(B_s^0 \to \phi\mu^+\mu^-) = (\,8.14 \pm \underbrace{0.21}_{\text{stat.}} \pm \underbrace{0.16}_{\text{syst.}} \pm \underbrace{0.21}_{\text{norm.}} \pm \underbrace{0.03}_{q^2\text{ extrap.}})\times 10^{-7}$

Angular analysis

- $B \to K^*(\to K\pi)\mu^+\mu^-$ can be fully-described by 4-dimensional decay rate:



$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma+\bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi}[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+\tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi]$$

- 8 observables F_L, A_{FB}, S_i depend on C_7 C_9 and C_{10} and FF → large uncertainty at leading order

- Re-parametrisation of the angular coefficients with reduced dependency on FF: $P_5' = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$

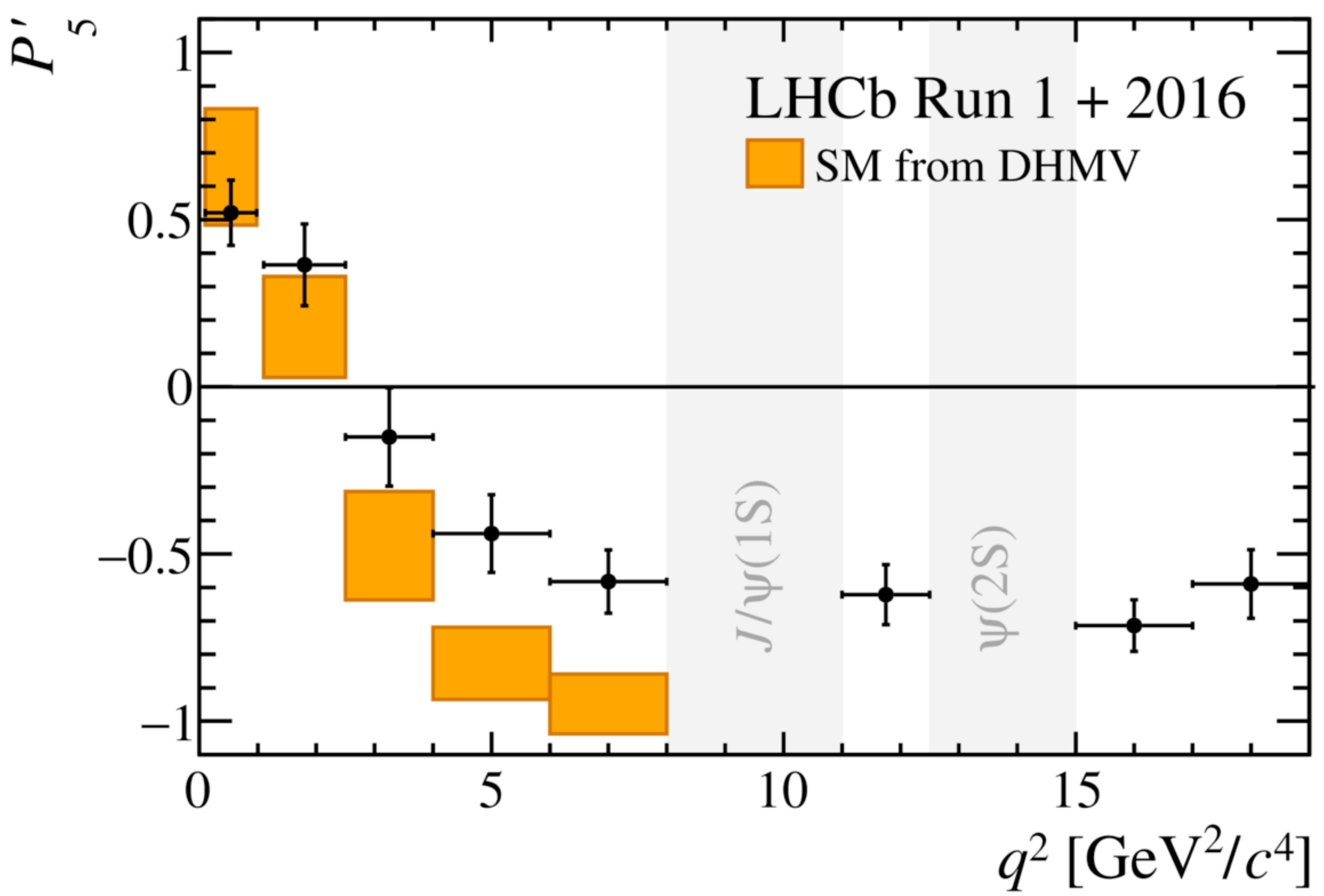
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$

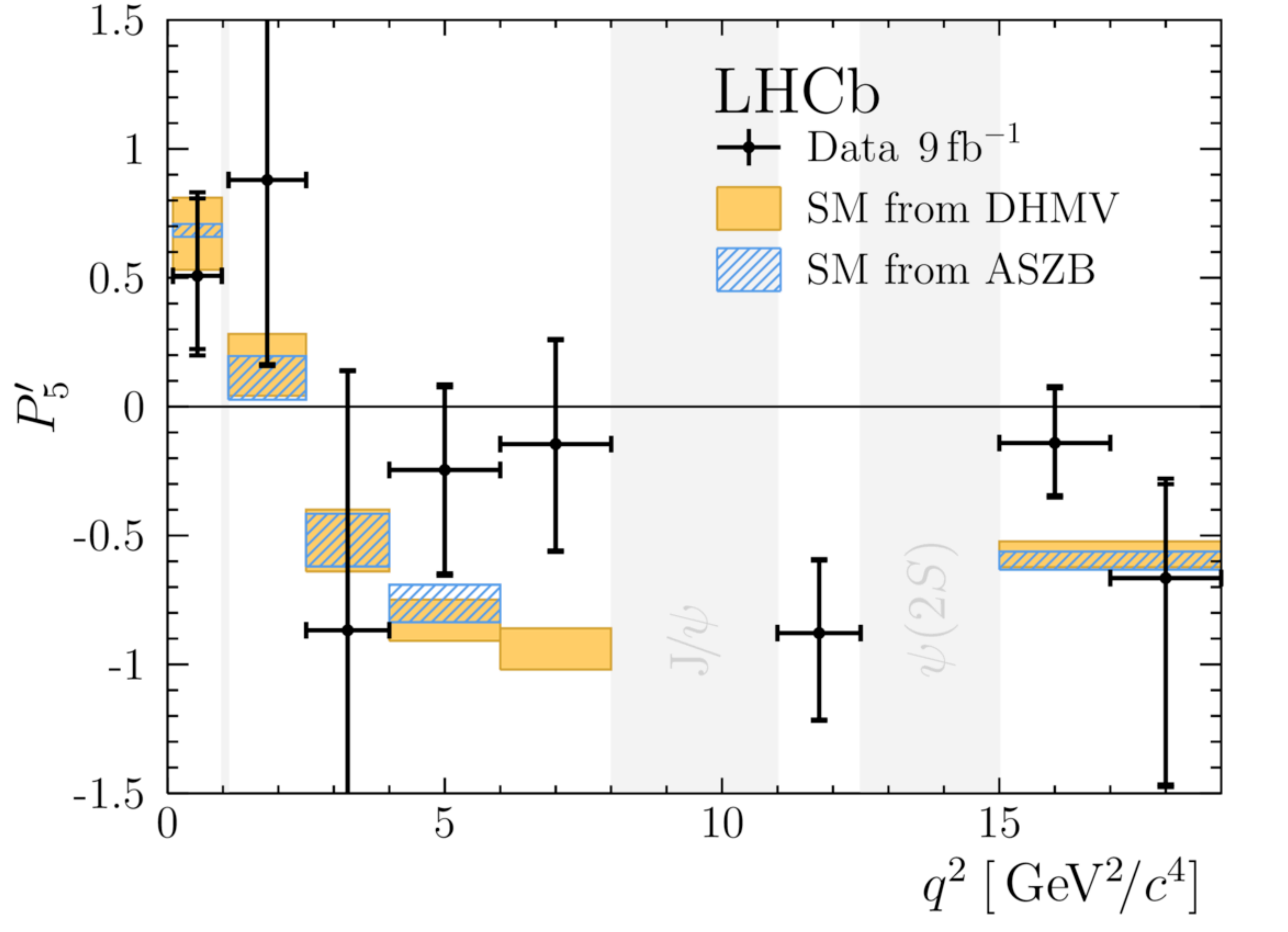
$B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 0118002]

- Update using Run1+2016 data
- Tension with SM: 3.3σ

$B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802]

- Update using Run1+Run2 data
- Tension with SM: 3.1σ





Lepton Flavour Universality

- In the SM, leptons couples with the gauge bosons in the same way, only difference between the three families is the mass
    - BF differs only by the phase space and helicity suppression
- Strong test of lepton universality using ratio:

$$R_{K^{(*)}} = \frac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\simeq} 1$$

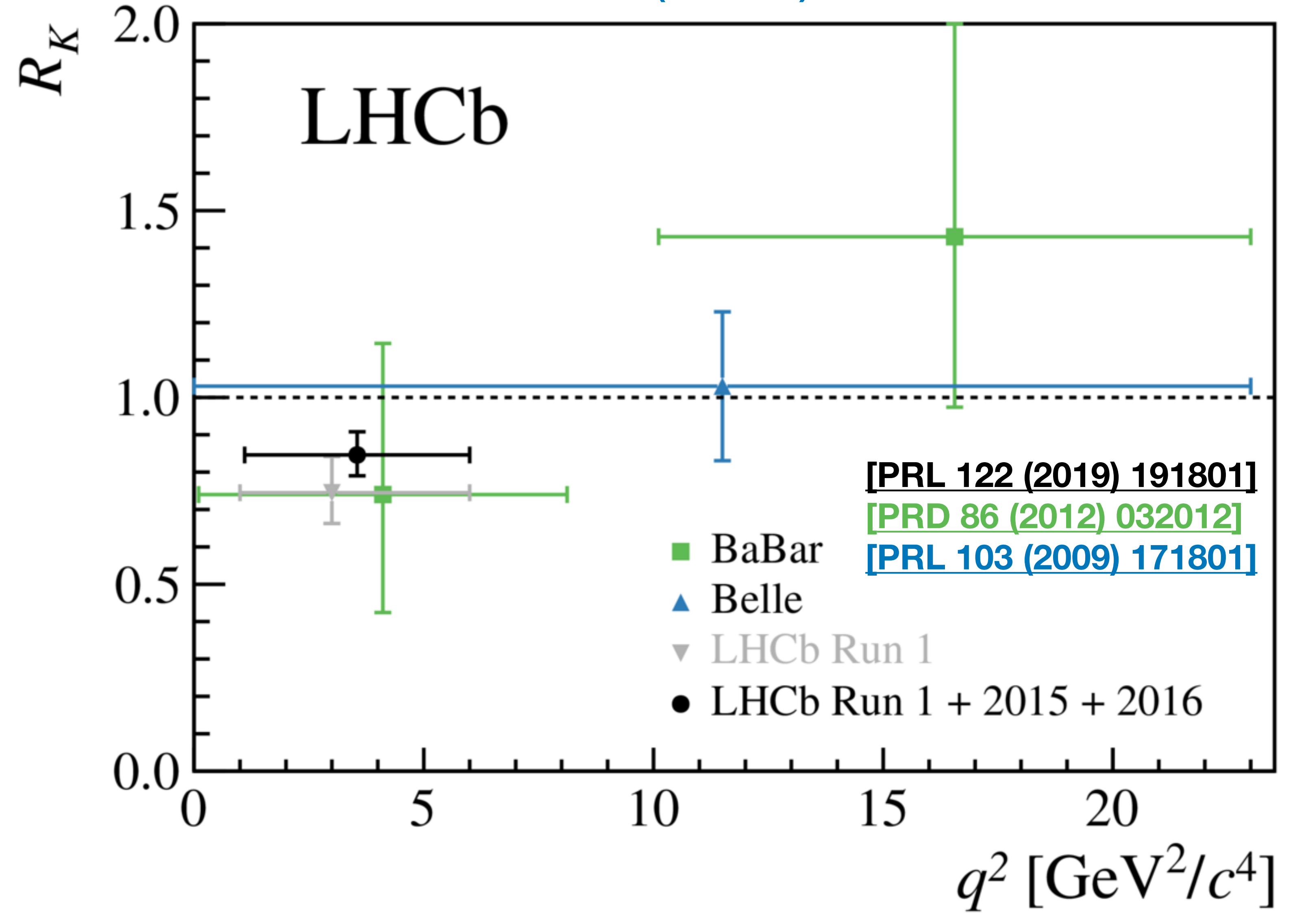
- Extremely clean test:
    - cancellation of hadronic form-factors uncertainties in predictions. $\sim\mathcal{O}(10^{-4})$ uncertainty
    - possible deviation from QED corrections $\sim\mathcal{O}(1\%)$ below resonance

[Bordone, Isidori, Pattori EPJC(2016)76:440]

➡Any significant deviation in $R_{K^{(*)}}$ is a clear sign of New Physics

Lepton Flavour Universality tests

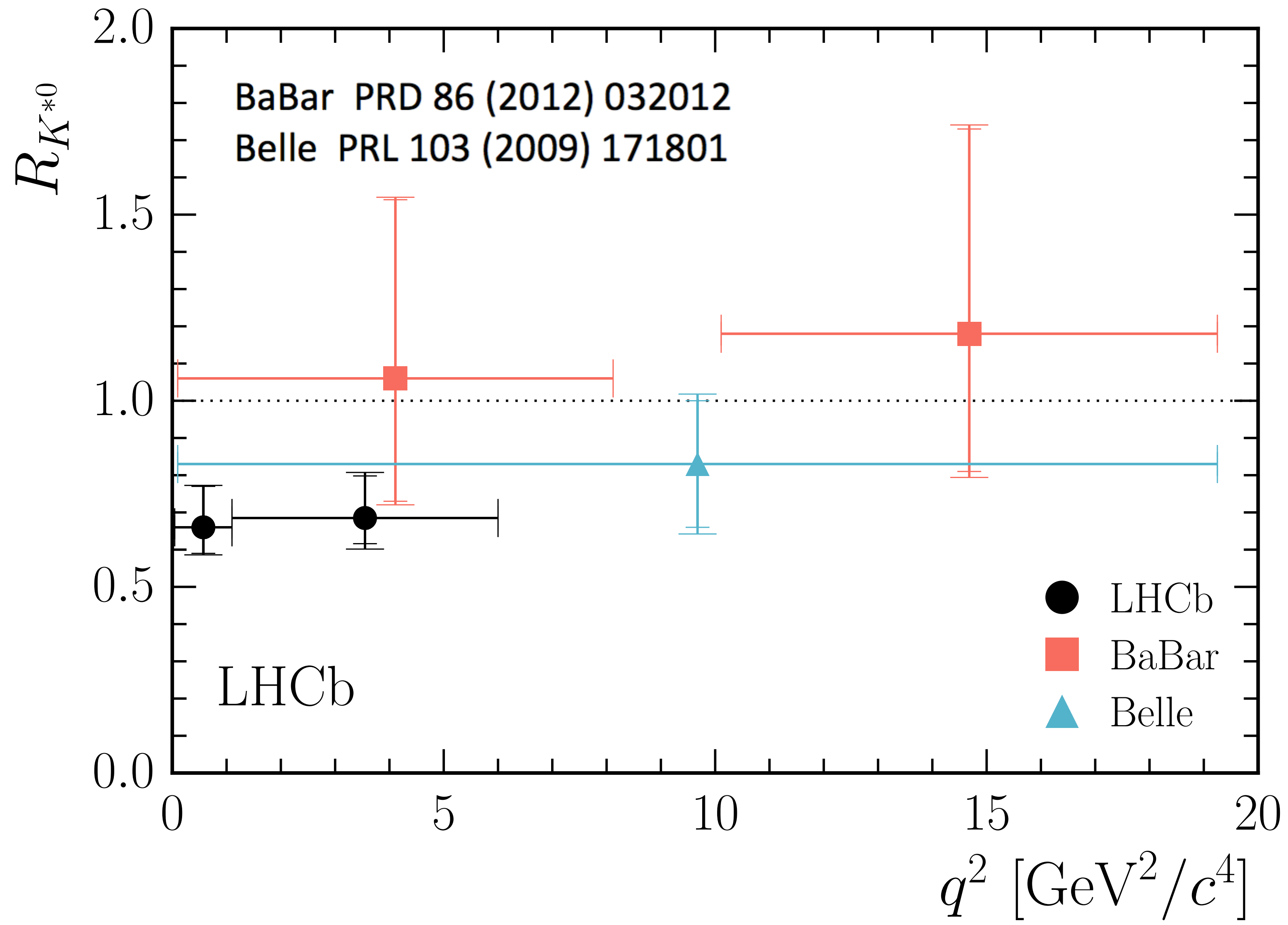
PRL 122 (2019) 191801



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

R_K with 5fb^{-1}

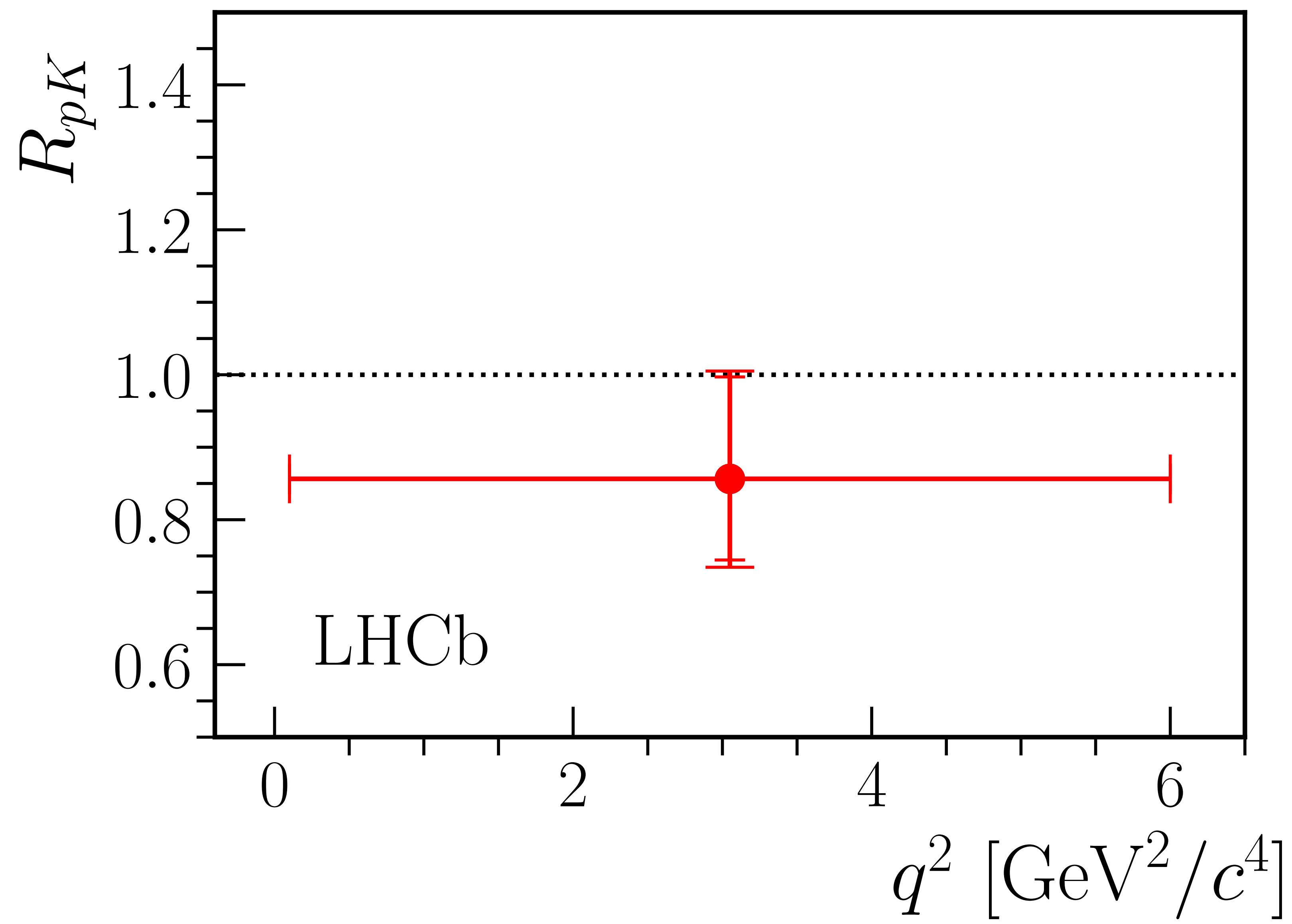
JHEP 08 (2017) 055



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

R_{K*} with 3fb^{-1}

JHEP 05 (2020) 040



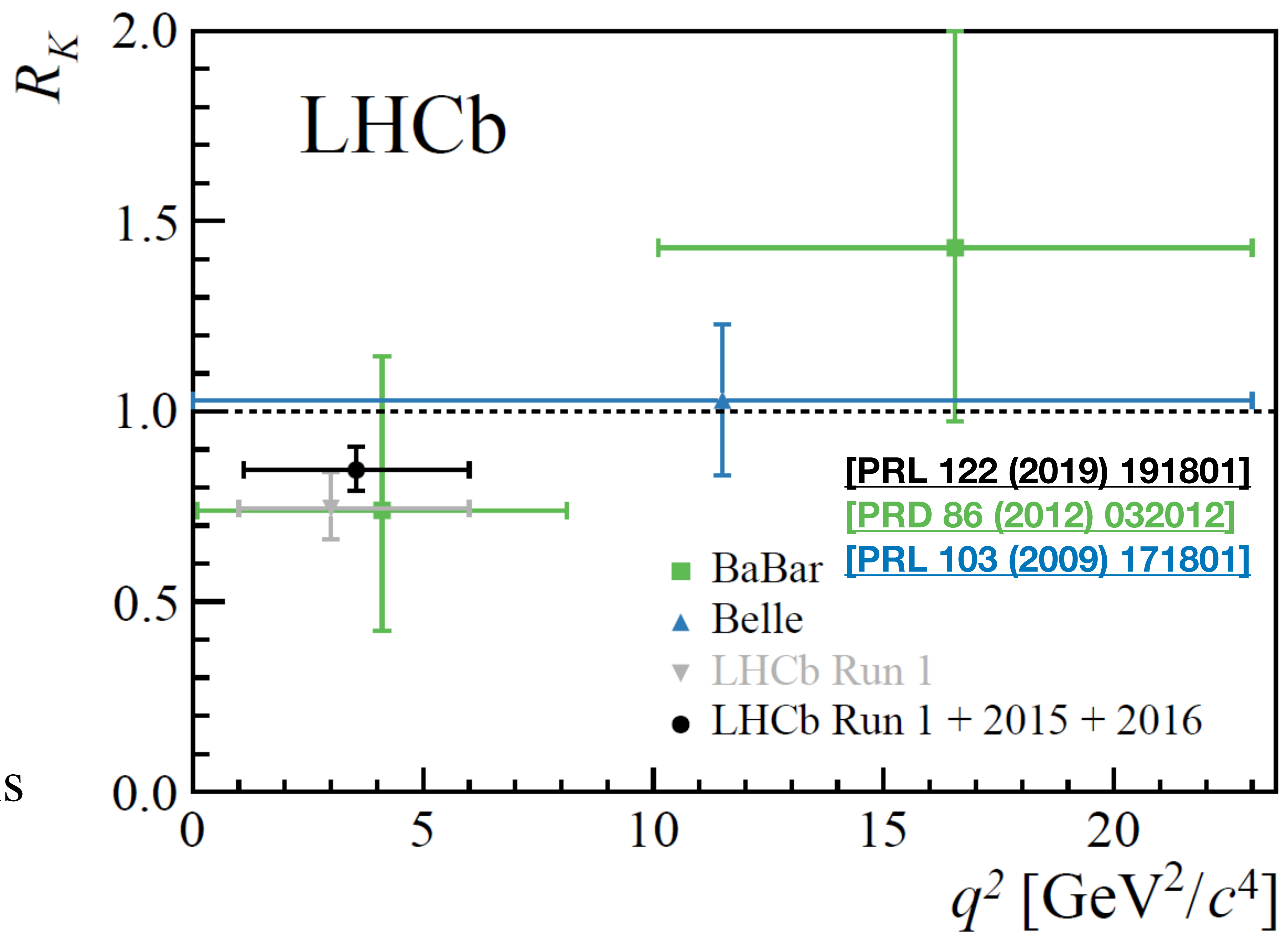
$\Lambda_b \to pK\ell^+\ell^-$

R_{pK} with 4.7fb^{-1}

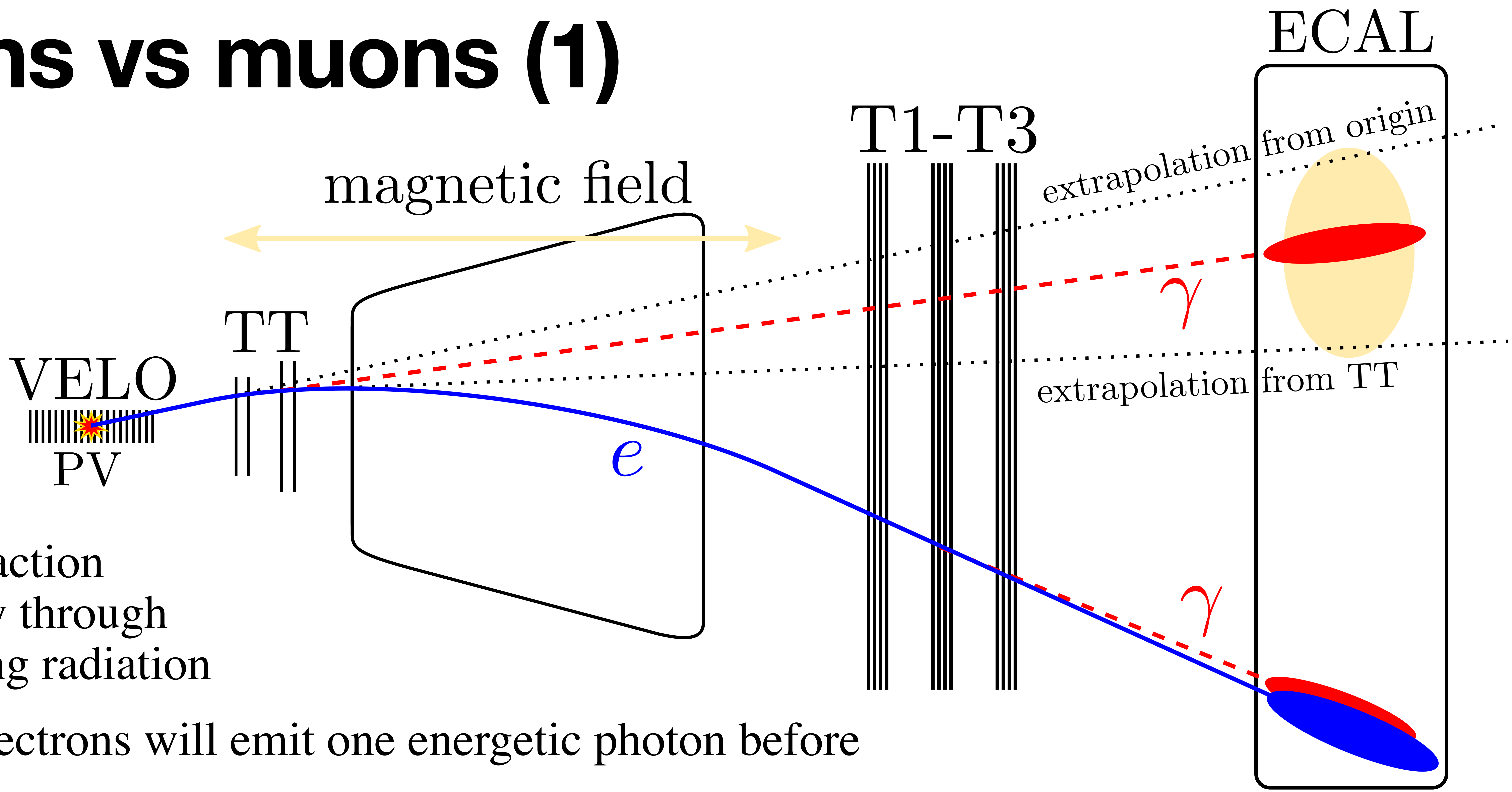
R_K with the full LHCb data set

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

- Previous measurement in tension with the SM at 2.5σ
- This update:
  - Add remaining $4\mathrm{fb}^{-1}$ of Run 2 collected in 2017 and 2018
  - Doubling the number of B's as previous analysis
- Follow the same analysis strategy as our previous measurement



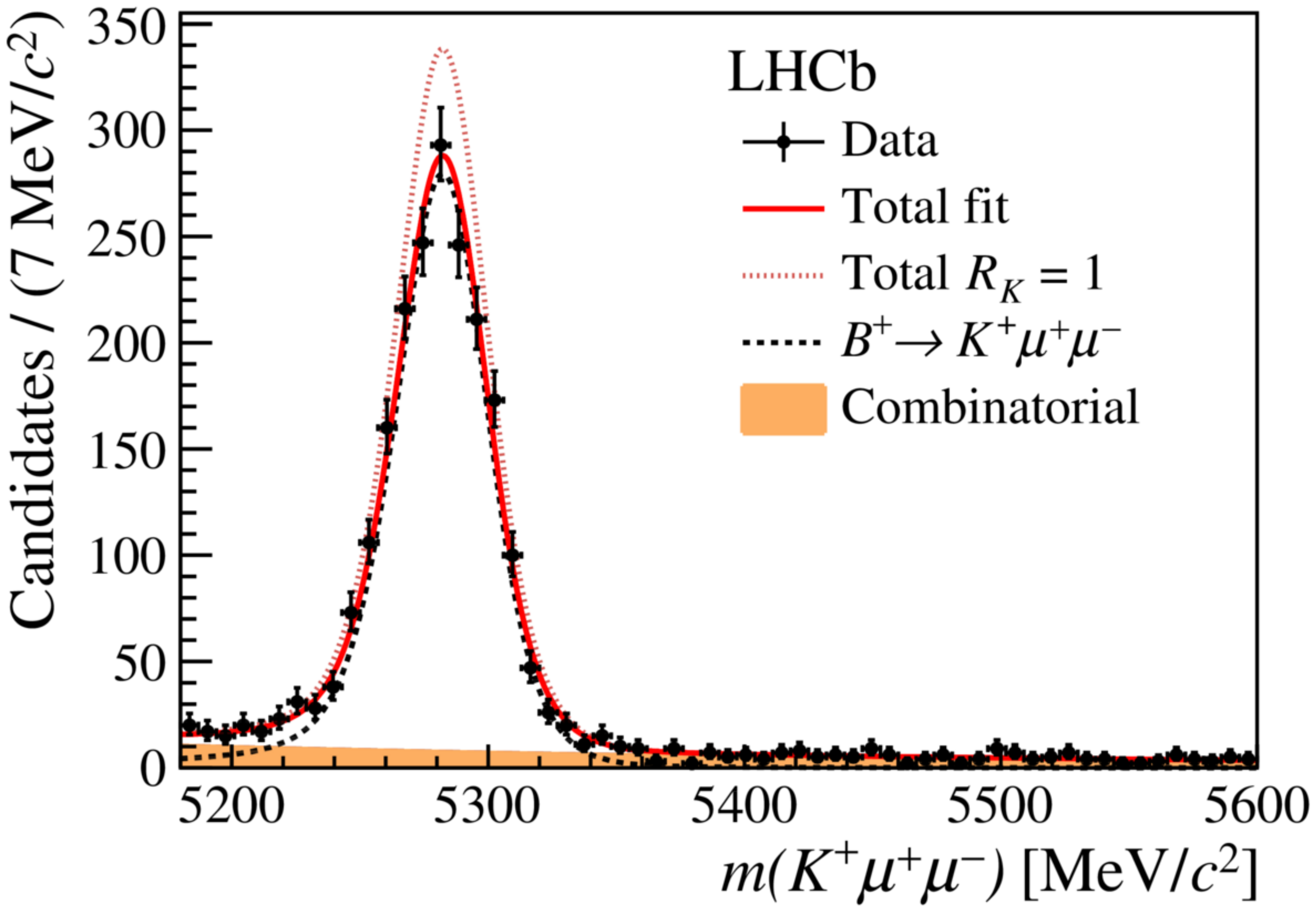
Electrons vs muons (1)

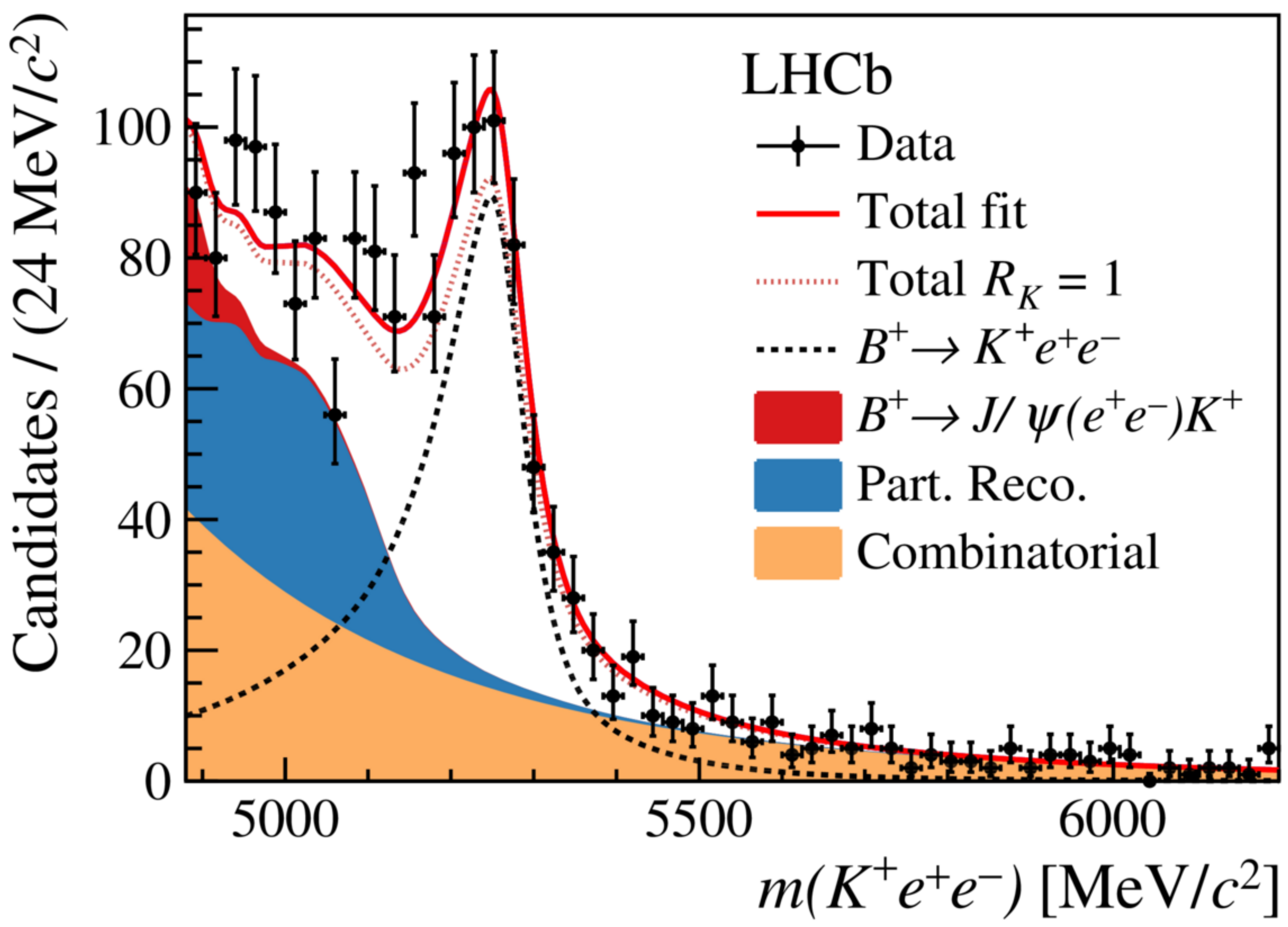


- Electrons lose a large fraction of their energy through Bremsstrahlung radiation
- Most of the electrons will emit one energetic photon before magnet
  - Look for photon clusters compatible with the direction of the electron before the magnet
  - Recover the energy loss by adding the cluster energy back to the electron momentum

Electrons vs muons (2)

From previous result, LHCb [PRL122(2019)191801]

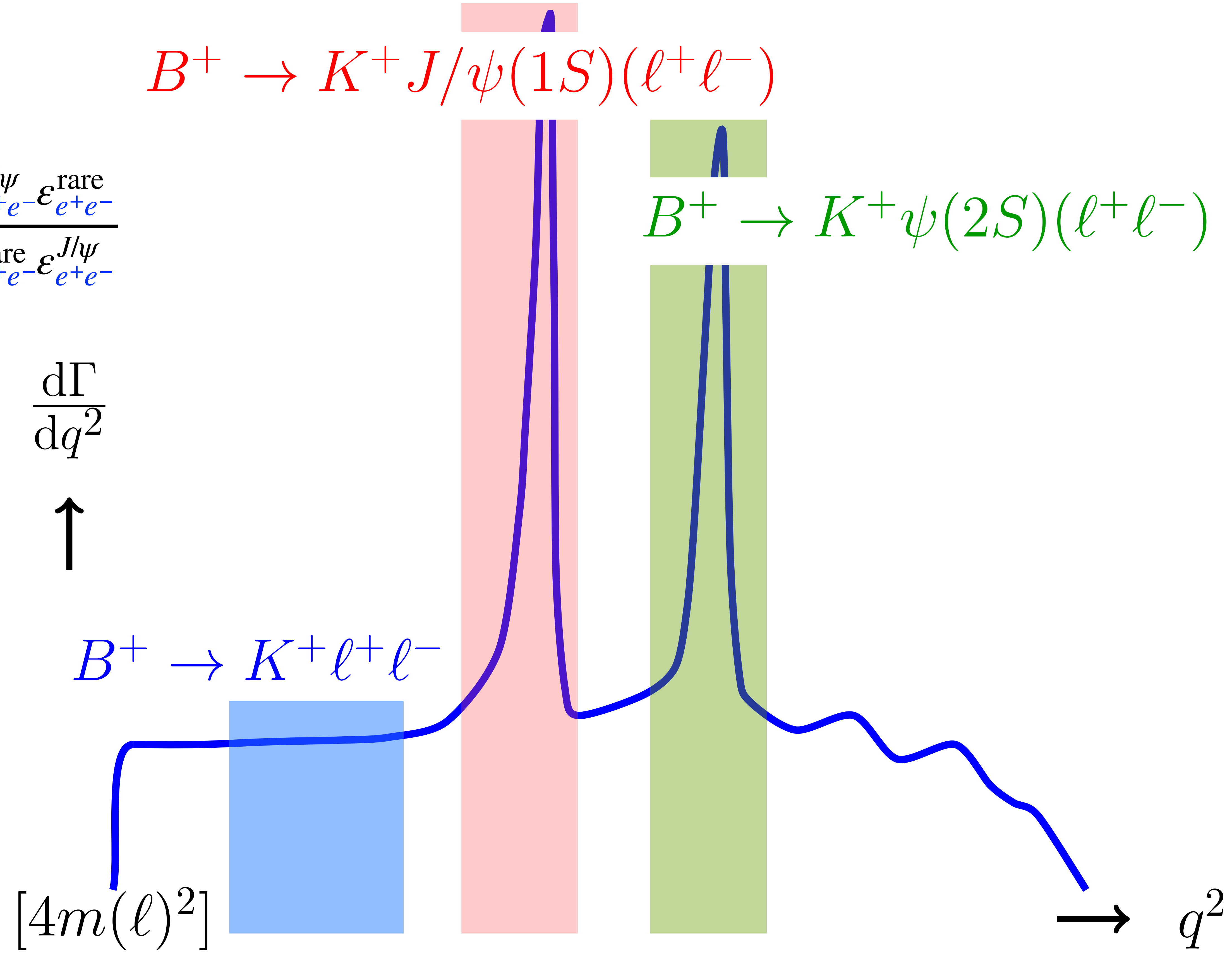




- Bremsstrahlung recovery not sufficient, worse mass resolution!
- Lower trigger rate in case of electrons due to ECAL occupancy (higher thresholds)
  - Use of 3 exclusive trigger categories for e^+e^- final states
- Tracking and Particle ID efficiencies larger for muons

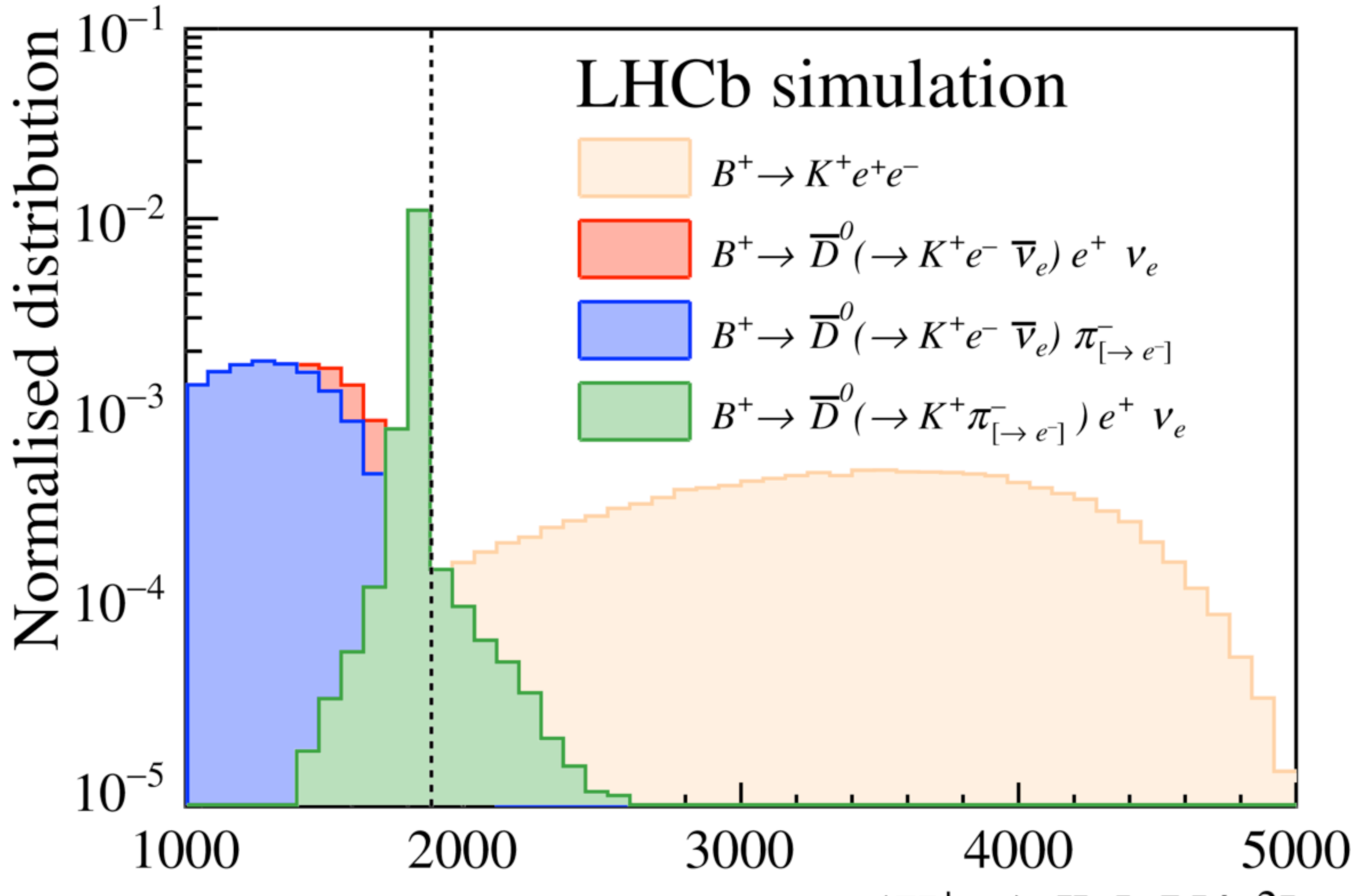
Measurement strategy

- Measure R_K as a double ratio to cancel out most systematics:
  - $R_K = \dfrac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \dfrac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \dfrac{N^{\mathrm{rare}}_{\mu^+\mu^-}\varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{\mathrm{J}/\psi}_{\mu^+\mu^-}\varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \dfrac{N^{\mathrm{J}/\psi}_{e^+e^-}\varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\varepsilon^{J/\psi}_{e^+e^-}}$
- Rare and J/ψ modes share identical selections except 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

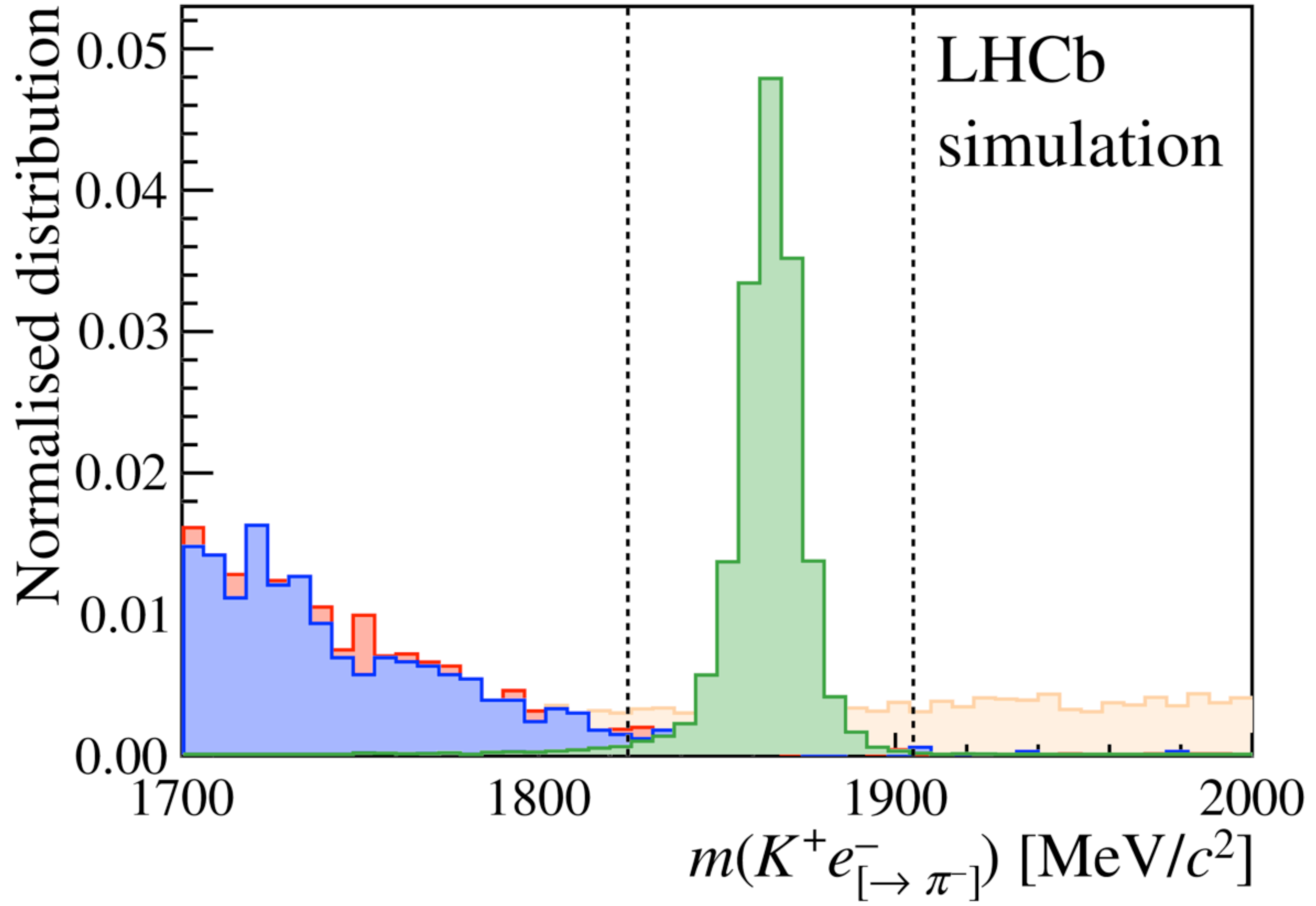


Selection and background

- Peaking backgrounds from exclusive B-decays suppressed to negligible level using particle ID and mass vetos
  - cascade backgrounds: e.g. $B^+ \to \overline{D}^0(\to K^+e^-\nu)e^+\overline{\nu}$: cut on $m(K^+\ell^-) > m_{D^0}$
  - misID 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)



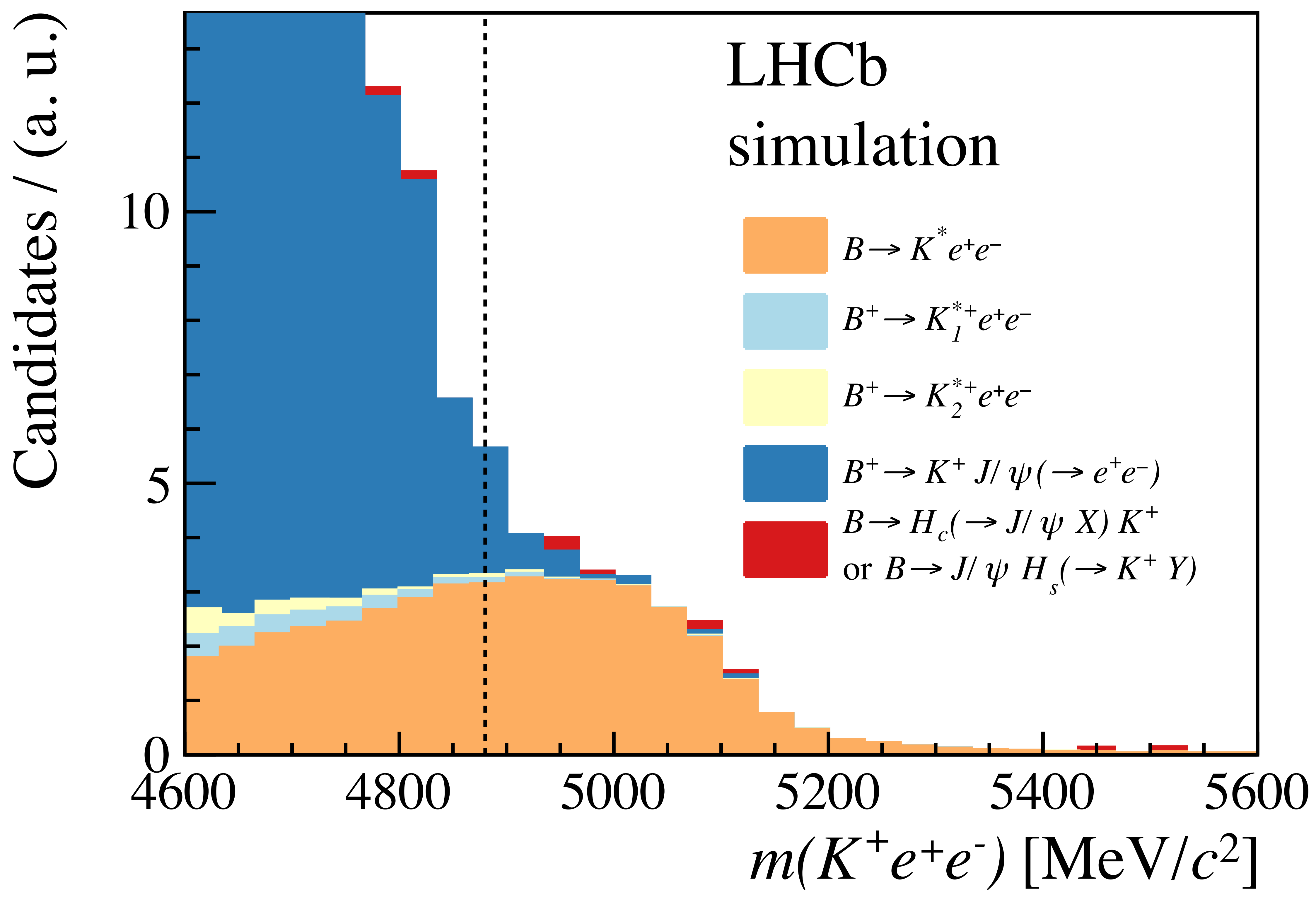
[arxiv:2103.11769]



Background

PRL 122 (2019) 191801

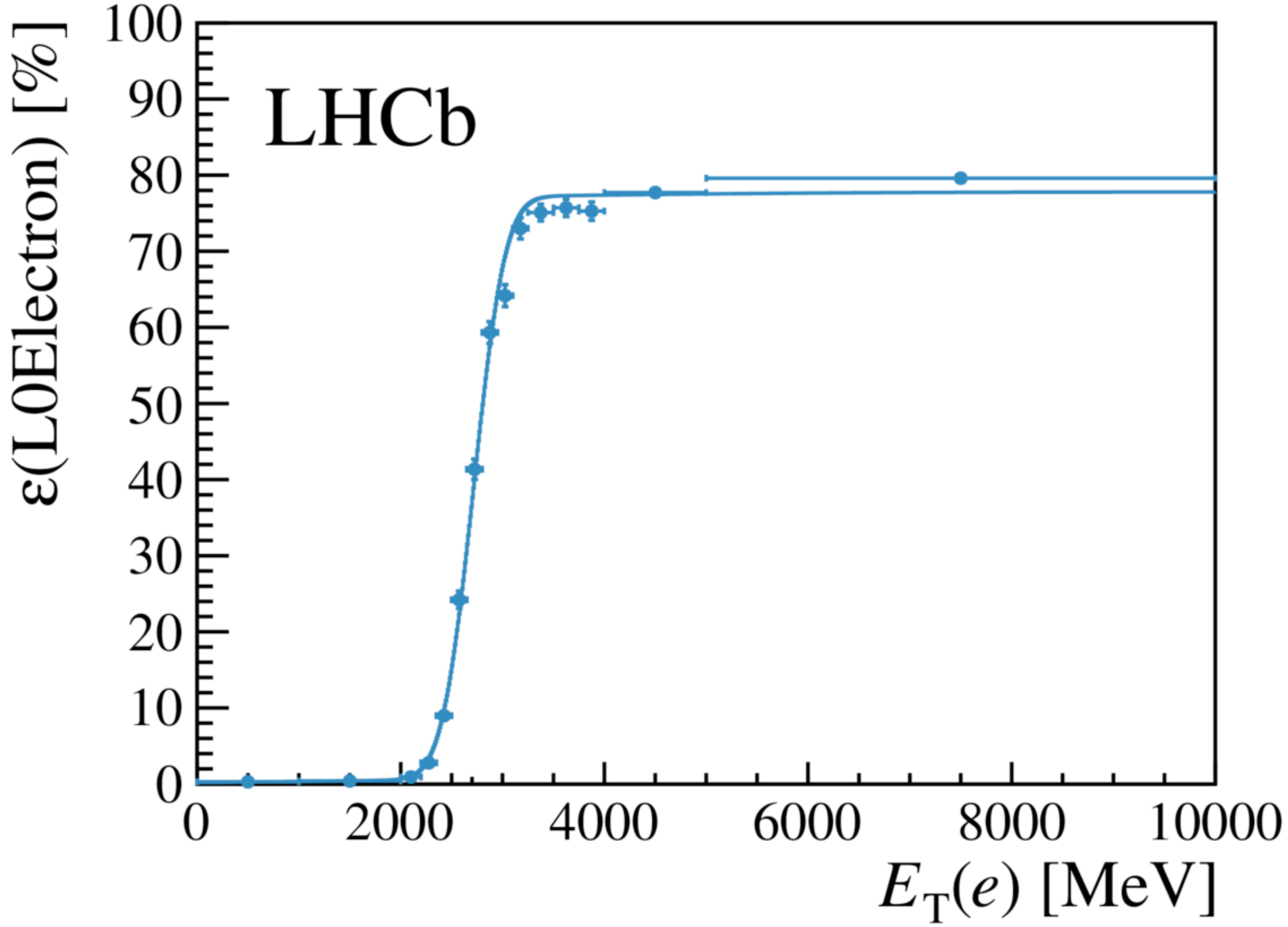
- Residual background suppressed by choice of $m(K^+\ell^+\ell^-)$ window
  - $B^+ \to K^+ J/\psi(e^+e^-)$
  - Partially reconstructed dominated by $B \to K^+\pi^- e^+e^-$ decays
  - Model in fit calibrating simulated templates from data and by constraining their fractions between trigger categories
  - Cross-check using control regions and changing $m(K^+\ell^+\ell^-)$ window



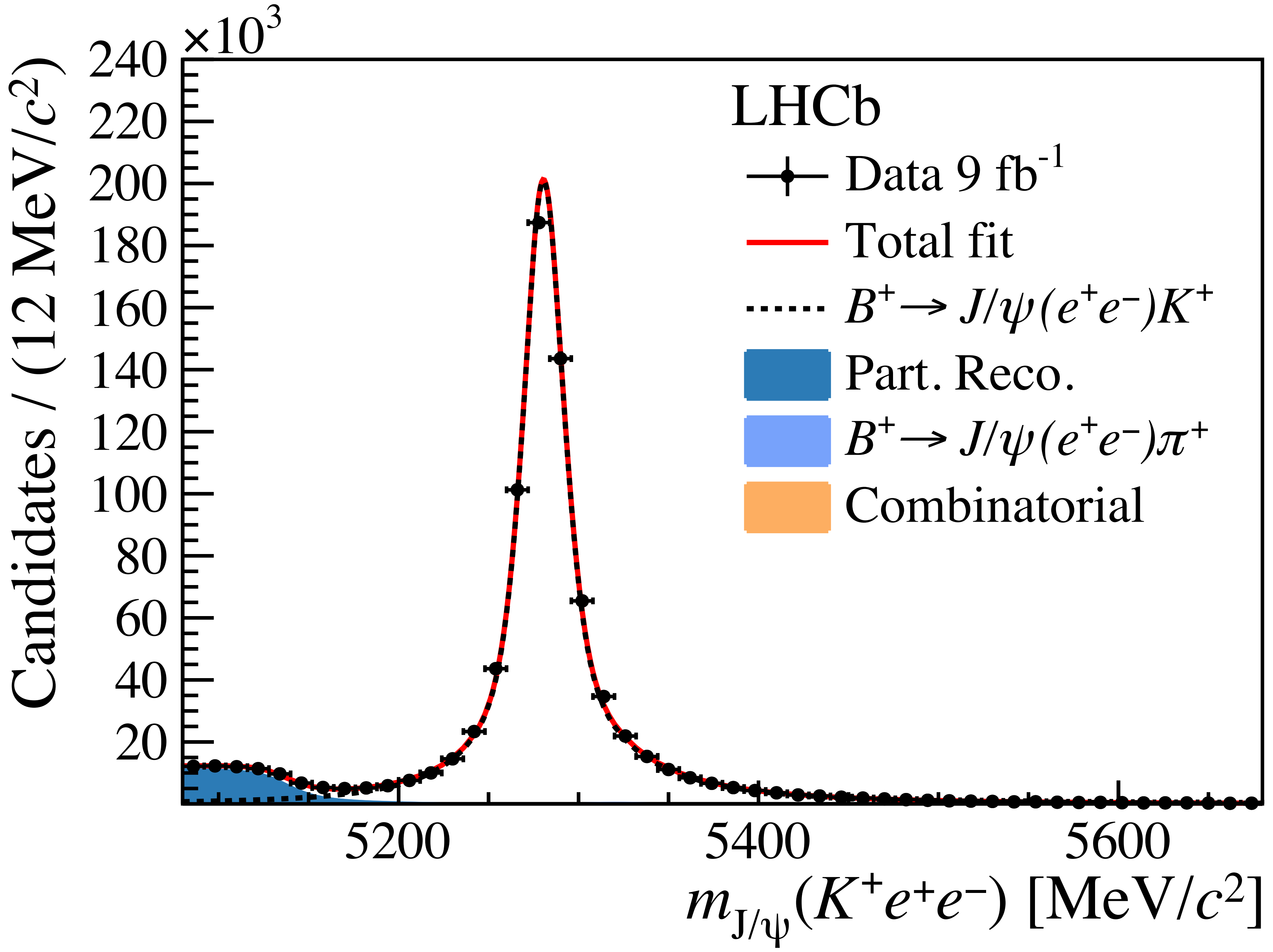
Efficiency calibration

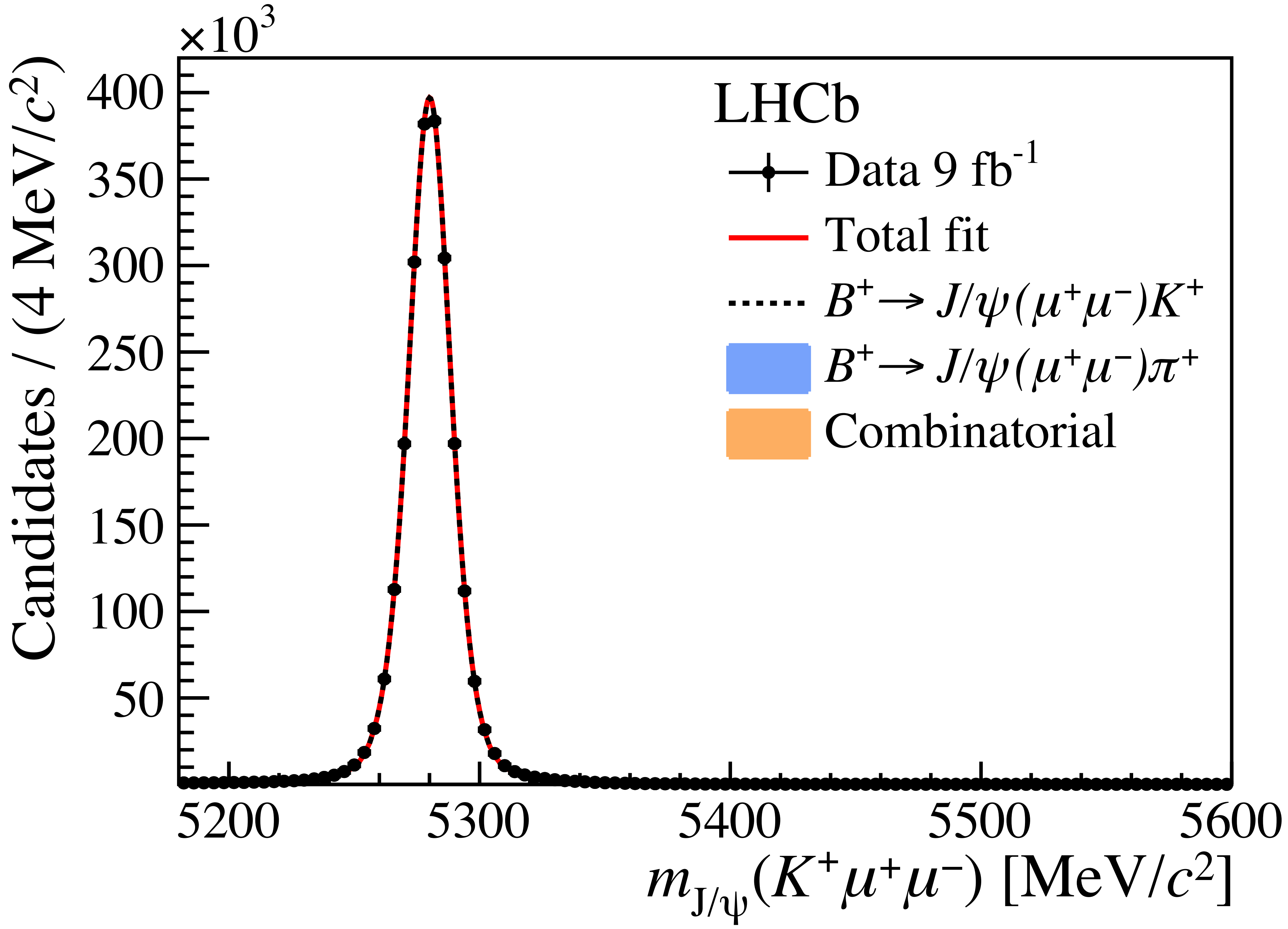
- Efficiencies estimated from simulated samples, calibrated on control data. Identical procedure to our previous measurement [PRL 122 (2019) 191801], and it covers:
  - Trigger efficiency
  - Particle identification efficiency
  - B^+ kinematics
  - Resolution of q^2 and $m(K^+e^+e^-)$
- This leads to %-level control of efficiency ratios. Verify procedure through host of cross-checks

Example measurement of electron trigger performace



Charmonium control mode





- $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ decays:
  - Excellent control channel: samples of 750k electrons and 2.3M muons
  - Can be isolated from background using J/ψ mass constrain

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

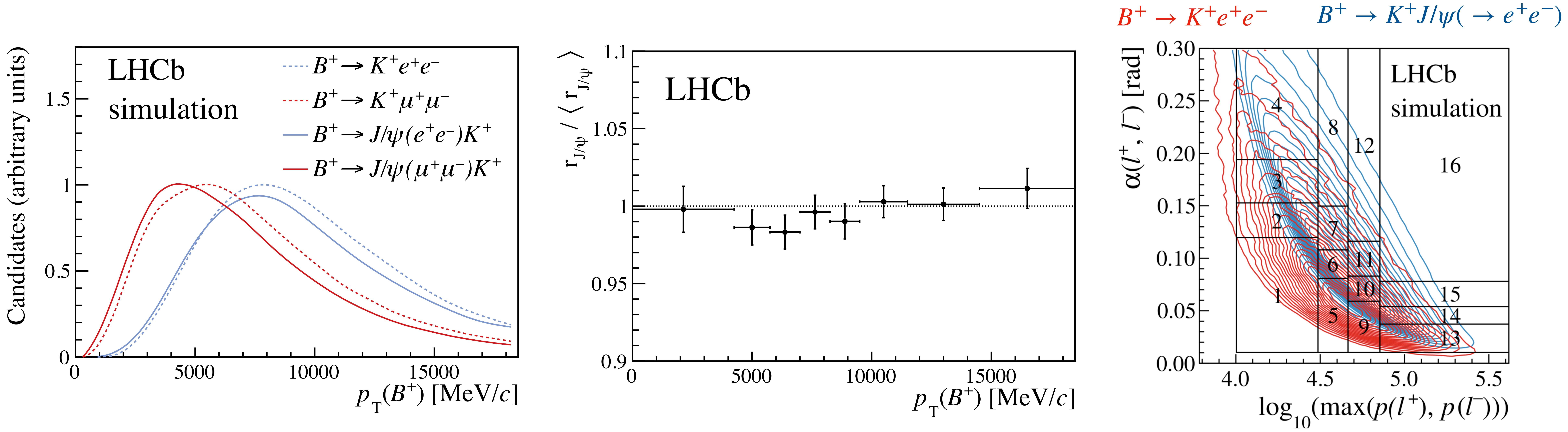
- To ensure that the efficiencies are under control, check

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = \frac{N^{\mu\mu}_{J/psi}}{\varepsilon^{\mu\mu}_{J/psi}} \Bigg/ \frac{N^{ee}_{J/psi}}{\varepsilon^{ee}_{J/psi}} = 1$$

- known to be true within 0.4% (very stringent check!)
- Result:
  - $r_{J/\psi} = 0.981 \pm 0.020 \text{ (stat + syst)}$
- 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

- Test efficiencies are understood in all kinematic regions by checking $r_{J/\psi}$ is flat in all variables examined.

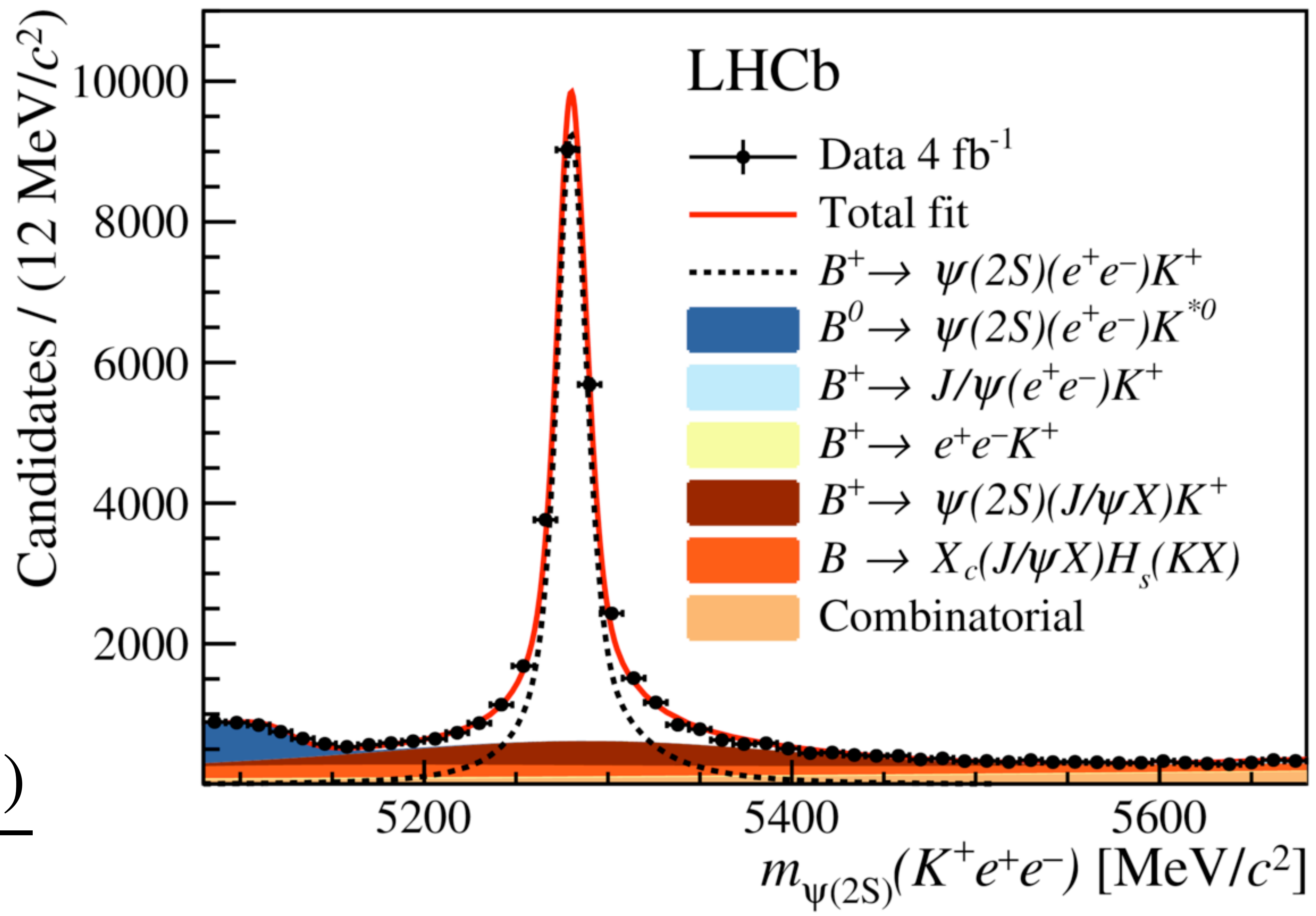


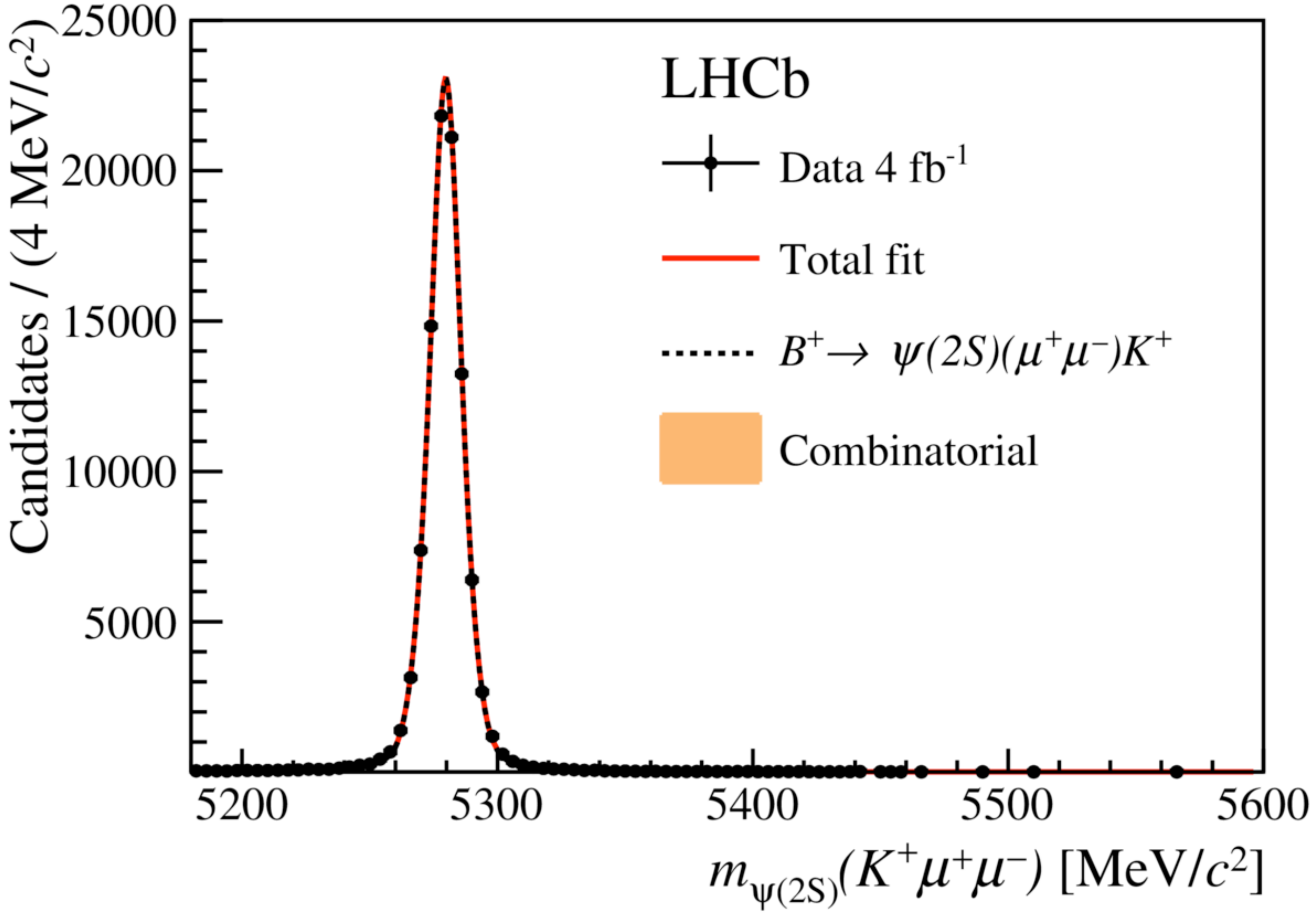
- Flatness of $r_{J/\psi}$ 2D plots gives confidence that efficiencies are understood across entire decay phase-space.
  - If take departure from flatness as genuine rather than fluctuations (accounting for rare-mode kinematics) bias expected on R_K is 0.1%

[arxiv:2103.11769]

Cross-check: $R_{\psi(2S)}$

- Can also test that R_K measured at the $\psi(2S)$ is 1:
  - $R_{\psi(2S)} = \dfrac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \dfrac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$
- Validation of q^2 dependence of efficiency correction
- Compatible with unity to 1% precision: $R_{\psi(2S)} = 0.997 \pm 0.011$ (stat + syst)





Systematic uncertainties

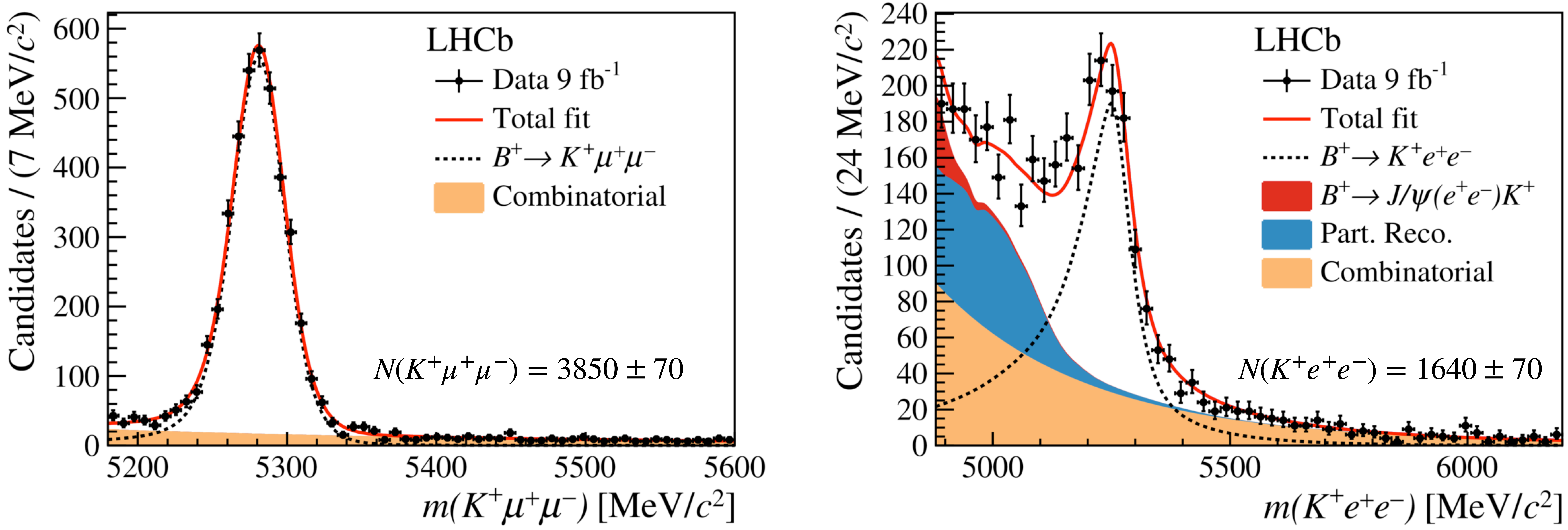
- **Dominant source: ~1%**
  - Choice of fit model
    - Associated signal and partially reconstructed background shape
  - Statistics of calibration samples
    - Bootstrapping method that takes into account correlations between calibration samples and final measurement
- **Sub-dominant sources: ~0.1%**
  - 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

[arxiv:2103.11769]

- 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 $B^+ \to K^+J/\psi(\ell^+\ell^-)$ decays



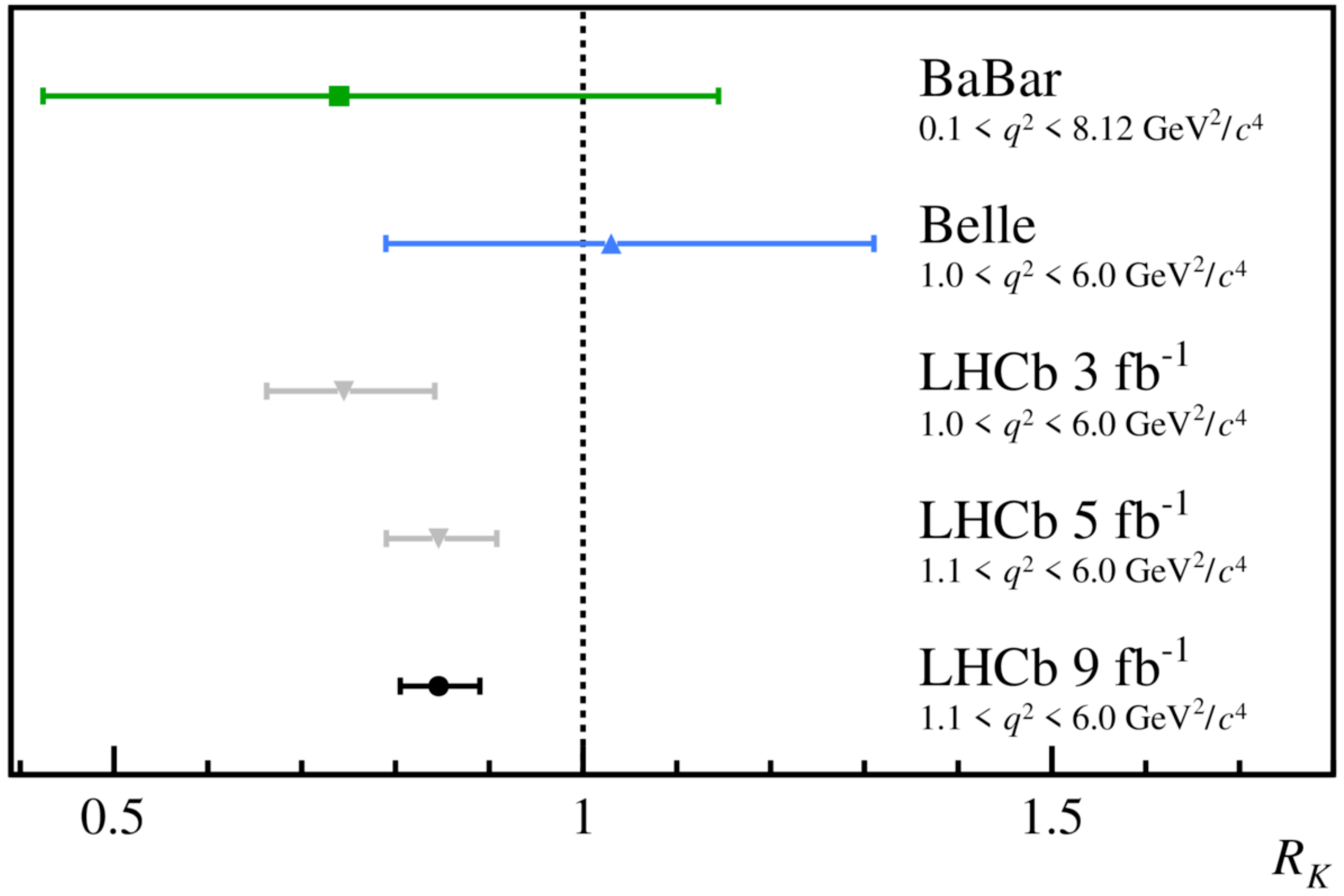
- Correlated uncertainties on efficiency ratios included as multivariate constraint in likelihood [arxiv:2103.11769] Submitted to Nature Physics

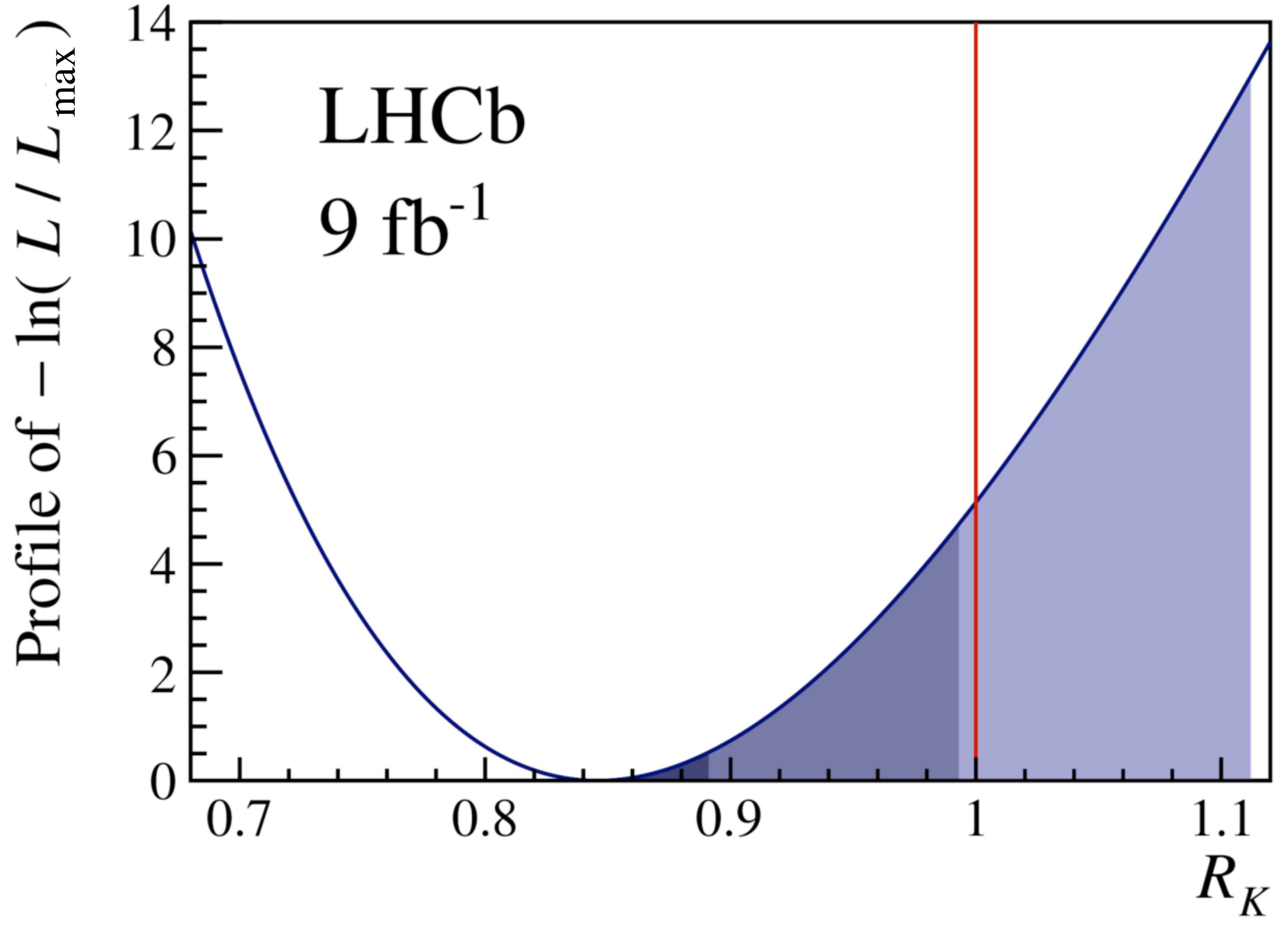
R_K with full Run 1 and Run 2 data sets

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

- p-value under SM hypothesis: 0.001
    - 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 1% theory uncertainty on R_K [EPJC76(2016)8,440]





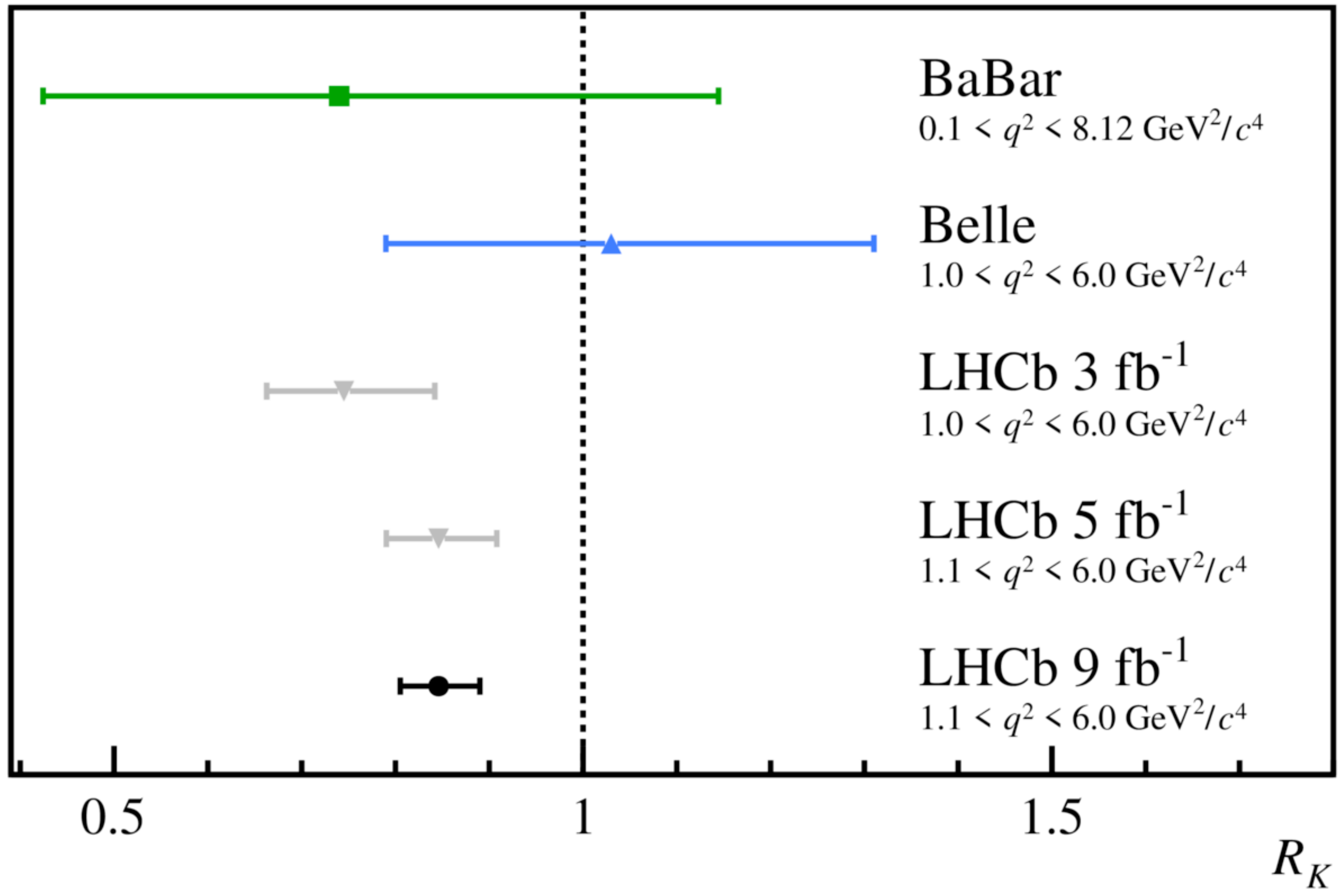
[arxiv:2103.11769] Submitted to Nature Physics

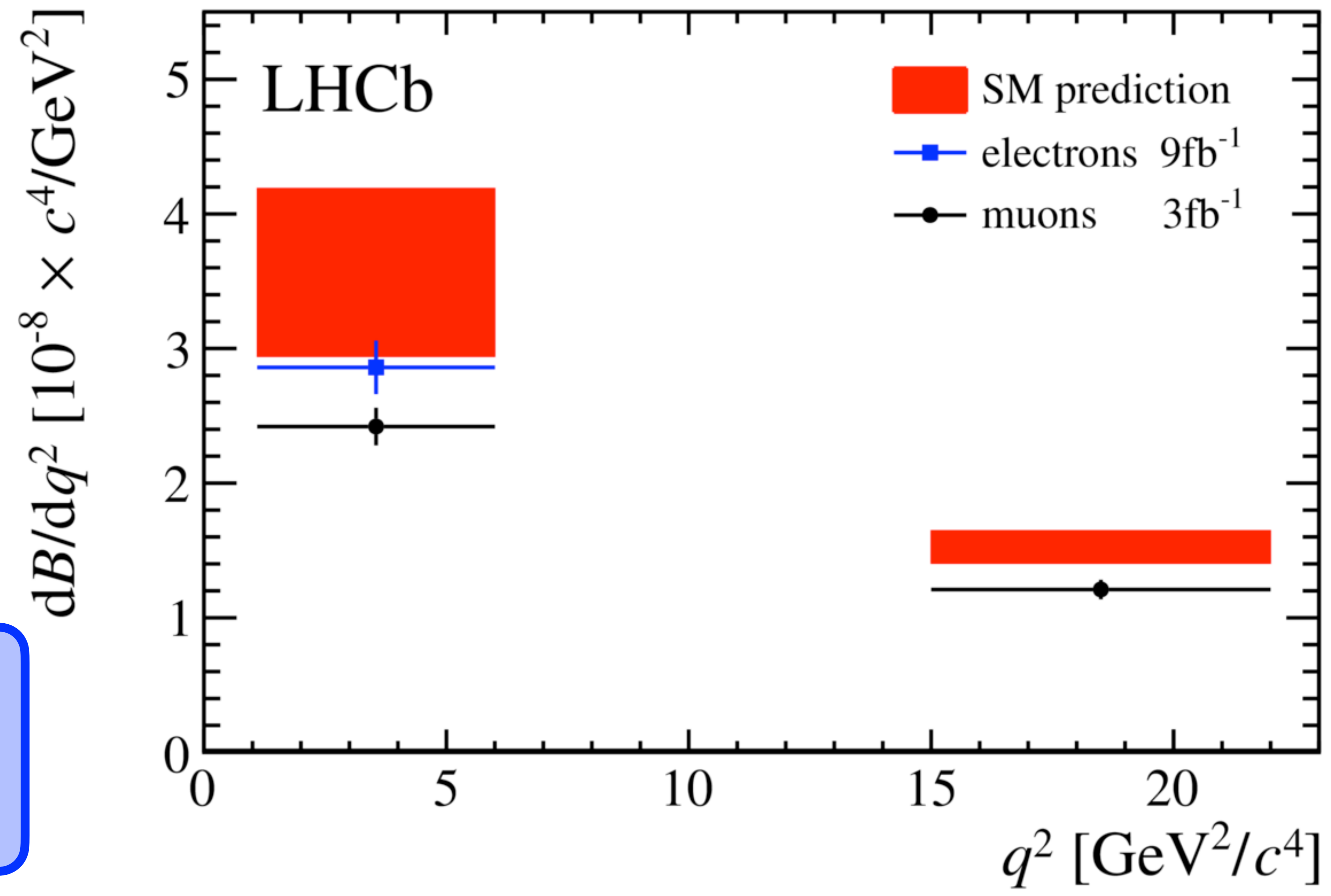
R_K with full Run 1 and Run 2 data sets

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

- p-value under SM hypothesis: 0.001
  - Evidence of LFU violation at 3.1σ
- Using R_K and previous measurement of $\mathscr{B}(B^+ \to K^+\mu^+\mu^-)$ determine [JHEP06(2014)133] $\mathscr{B}(B^+ \to K^+e^+e^-)$
  - Suggests electrons are more SM-like than muons.

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

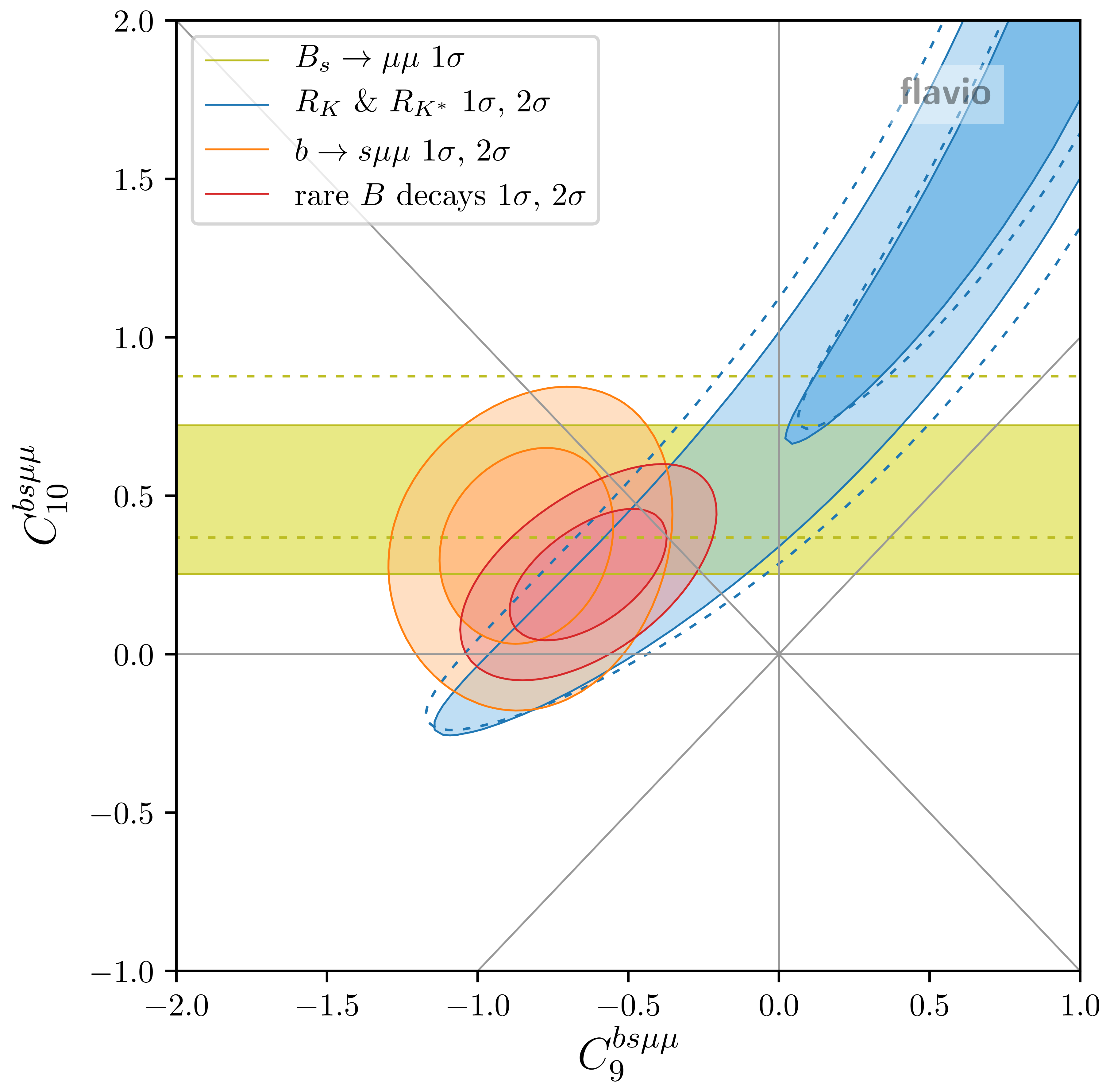


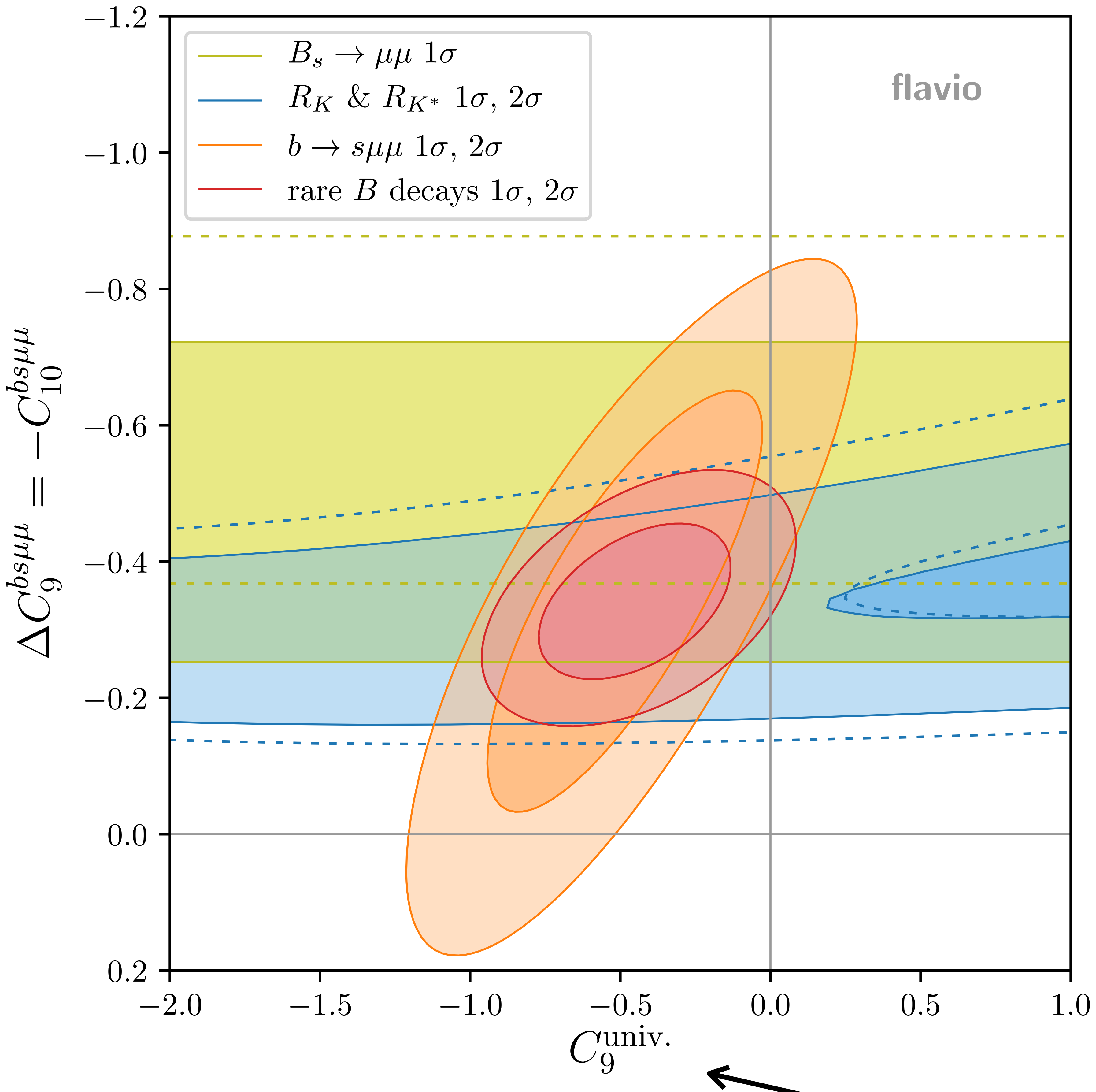


Current EFT fit

Similar fits from other groups:
Algueró et al., arXiv:1903.09578
Kowalska et al., arXiv:1903.10932
Ciuchini et al., arXiv:2011.01212
Datta et al., arXiv:1903.10086
Arbey et al., arXiv:1904.08399
Geng et al., arXiv:2103.12738

Fit from W. Altmannshofer and P. Stangl arXiv:2103.13370





Lepton universal contribution to C_9 could be mimicked by $c\bar{c}$ effects

Projections

LHCb

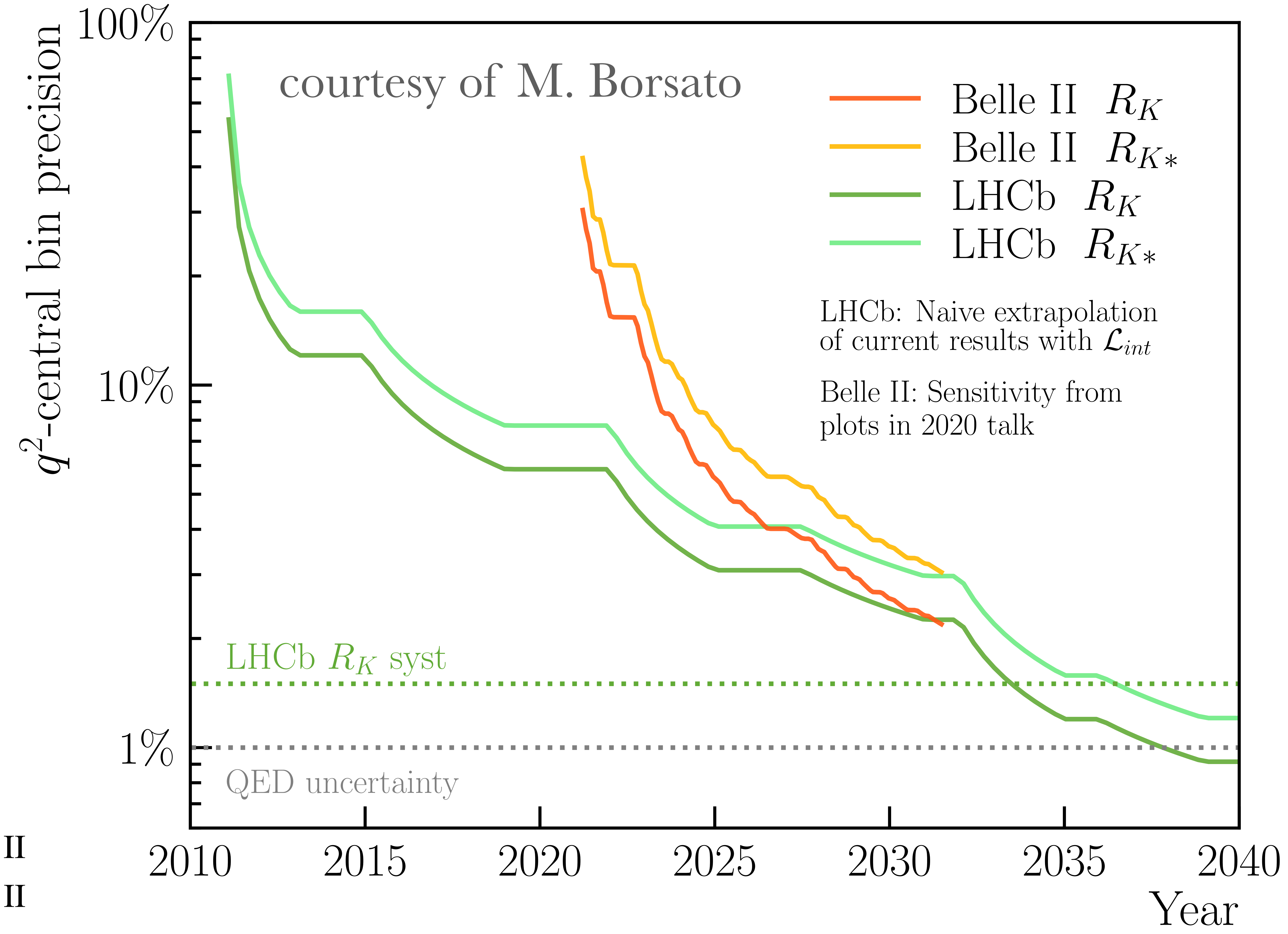
- Higher luminosity 50 fb^{-1} by the end of Run 4

Belle II

- Much cleaner than LHC environment
- Aim at collecting 50 ab^{-1} around 2031
- Not as much stat as LHCb in charged modes:

$K^+\mu\mu$: 1 fb^{-1} LHCb $\simeq$ 2.5 ab^{-1} Belle II

$K^+e^+e^-$: 1 fb^{-1} LHCb $\simeq$ 1 ab^{-1} Belle II



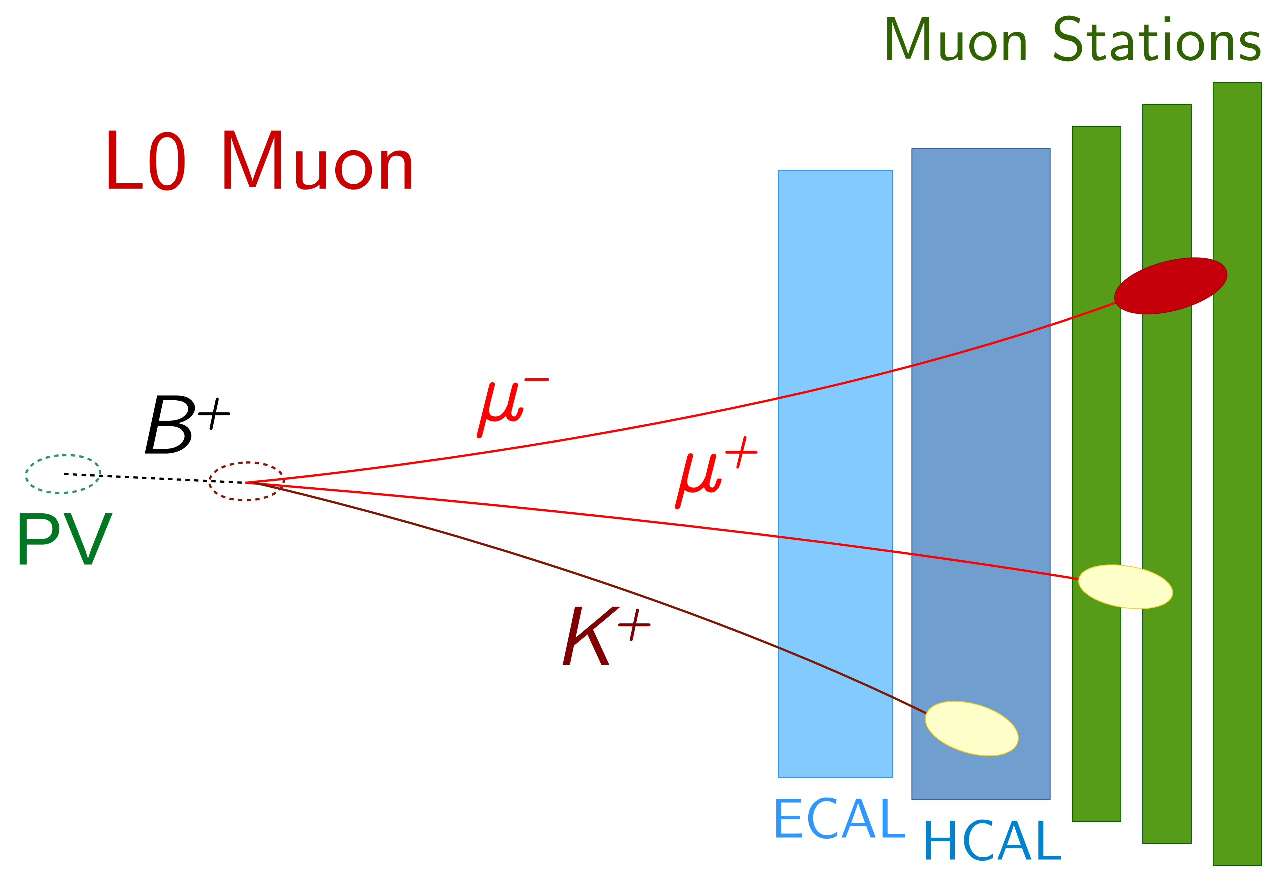
Conclusions

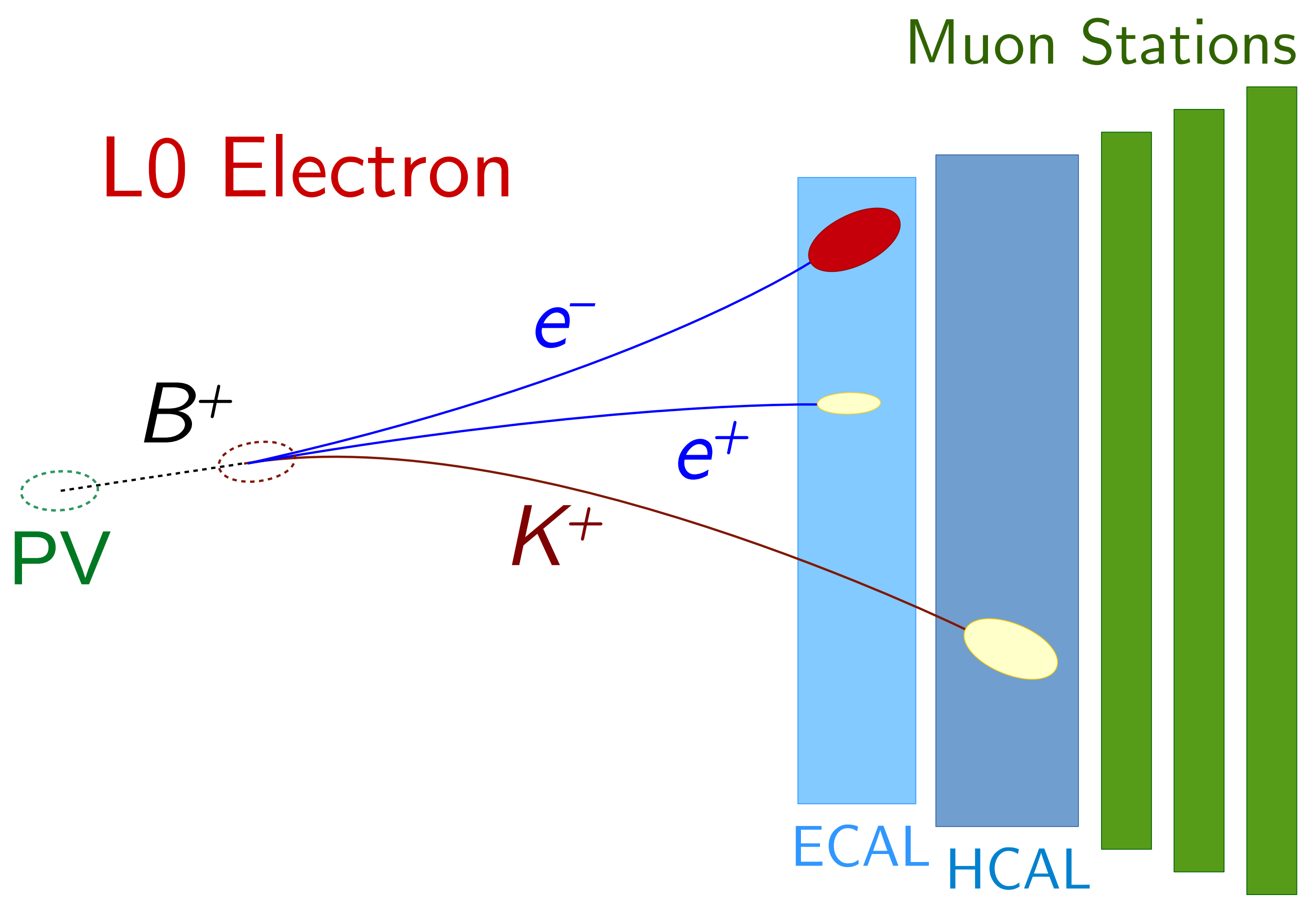
- Flavour anomalies in the $b \to s\ell\ell$ sector were reinforced by recent measurements
  - Several 3σ deviations, all in $b \to s\ell\ell$
  - EFT Global fits point to a coherent pattern
- More measurements needed to solve the puzzle
  - Upcoming analyses of Run 2 data: R_{K*} update and other R_X tests, Angular analysis, LFV measurements. ...
  - Upcoming LHCb upgrade
  - Other experiments: Belle II, CMS, ATLAS

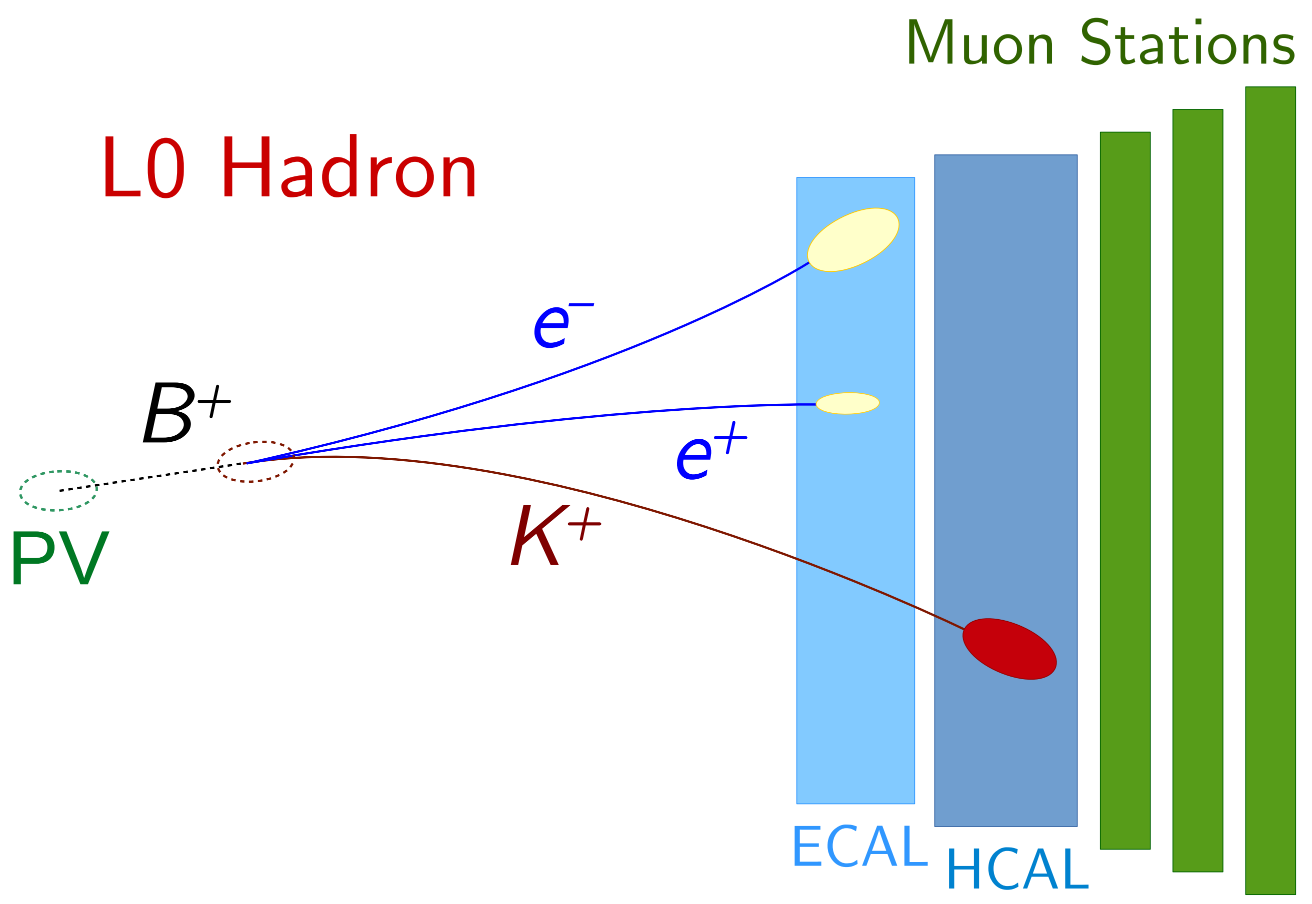
Backup

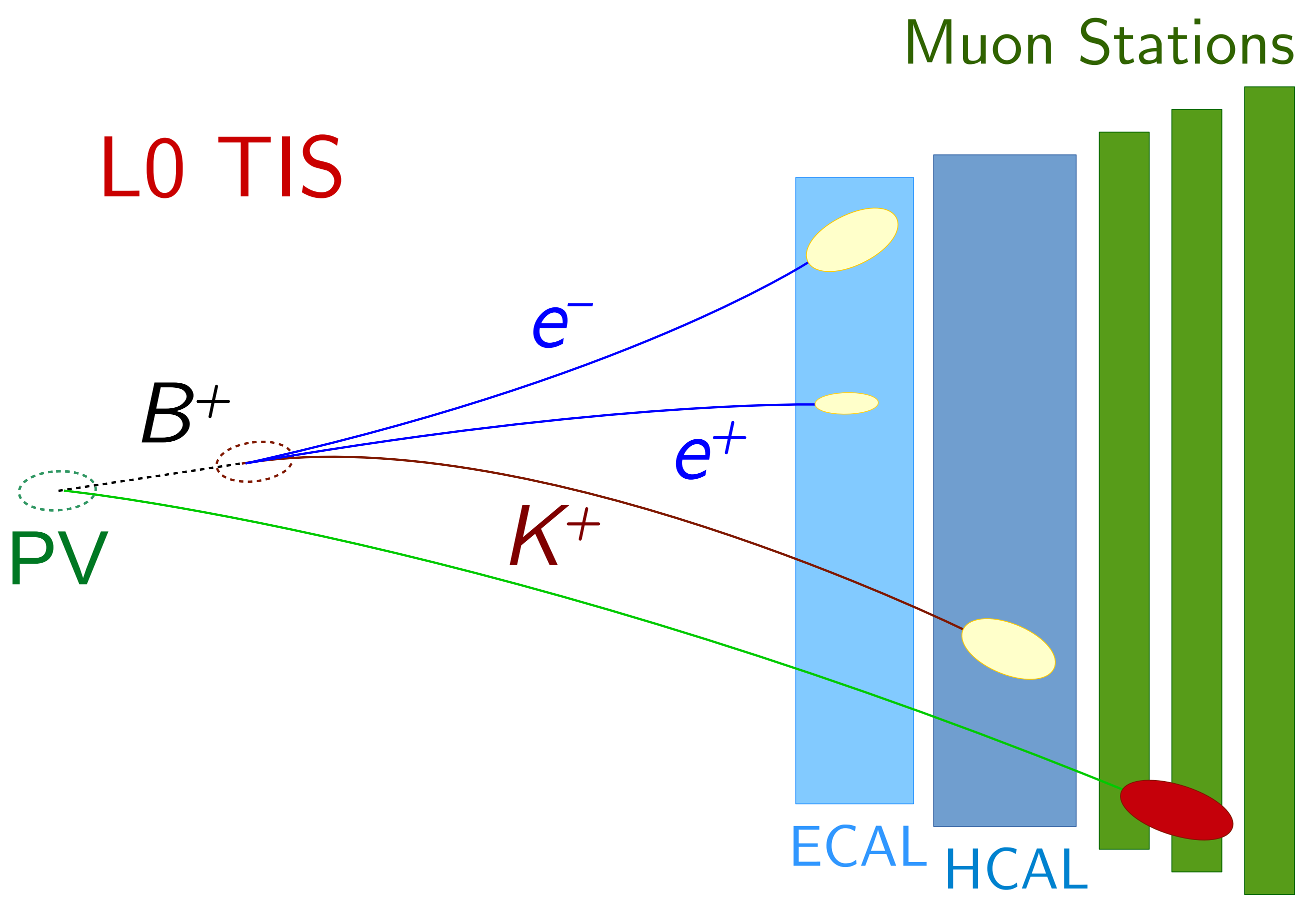
Trigger strategy

- 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

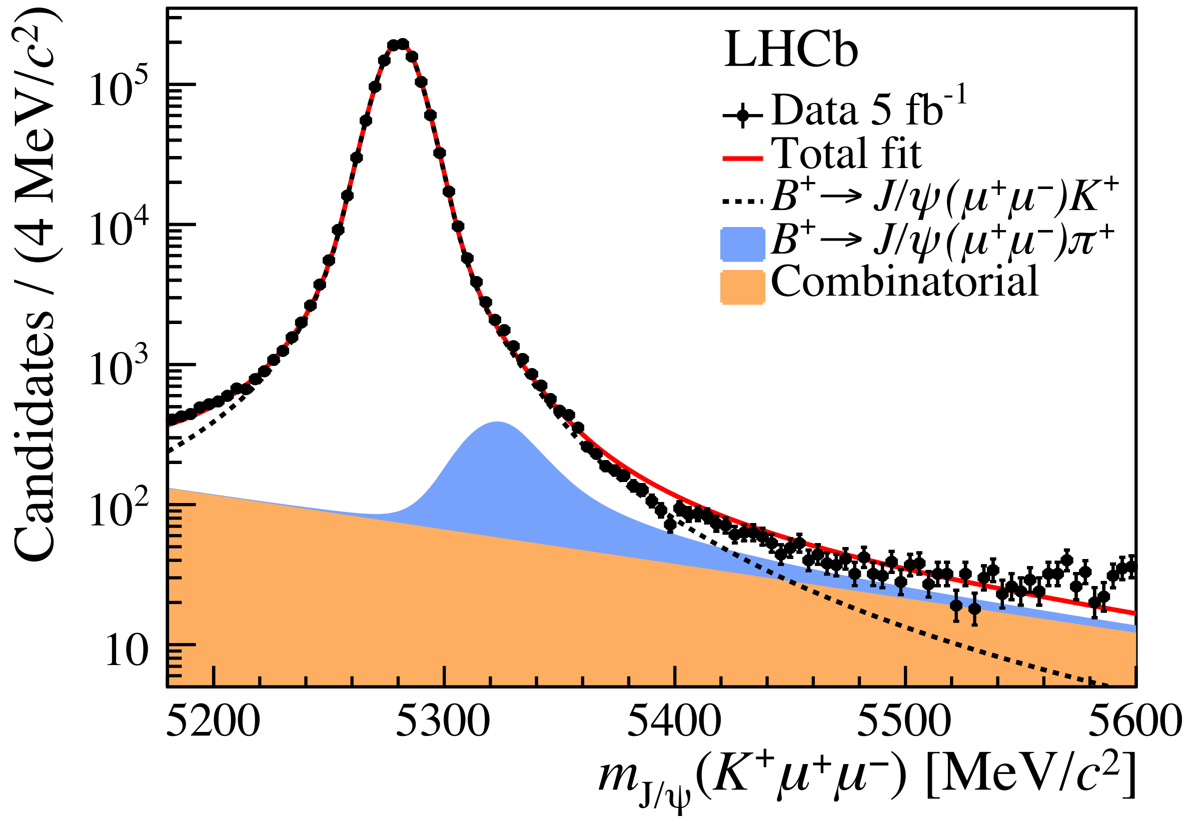




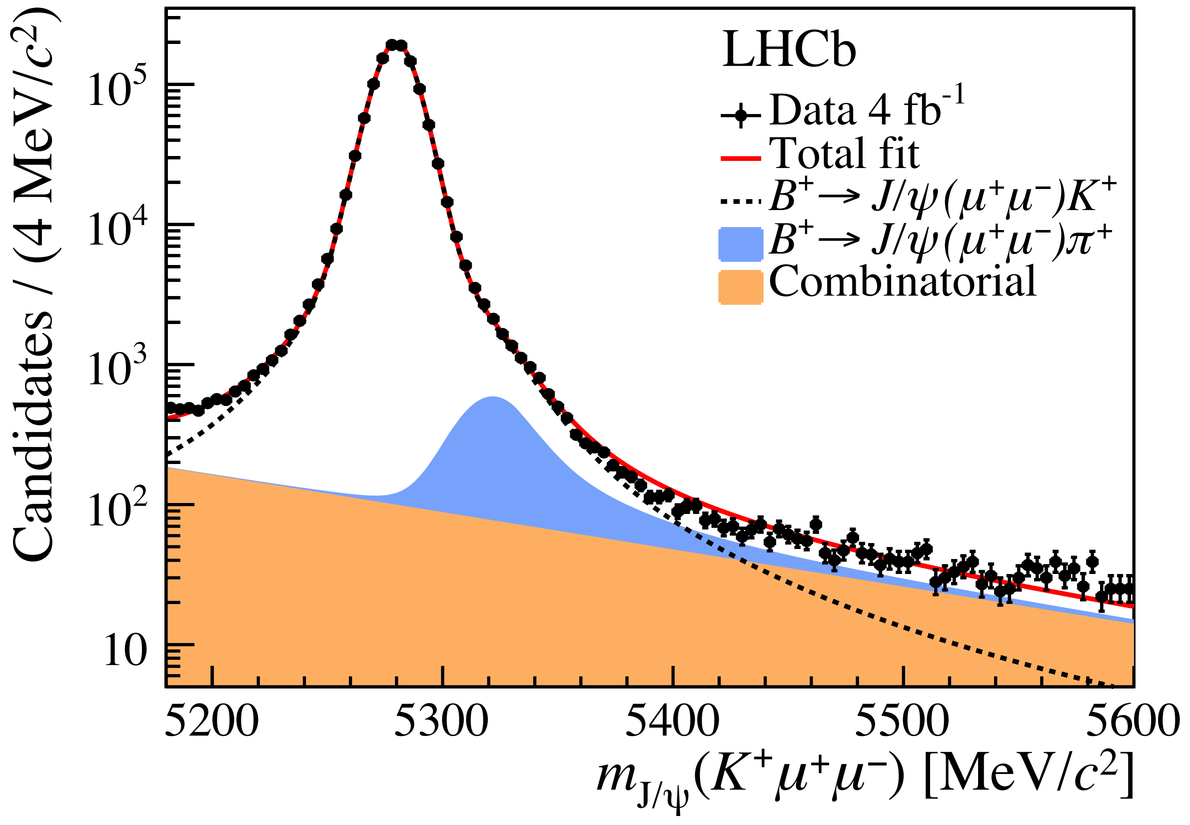




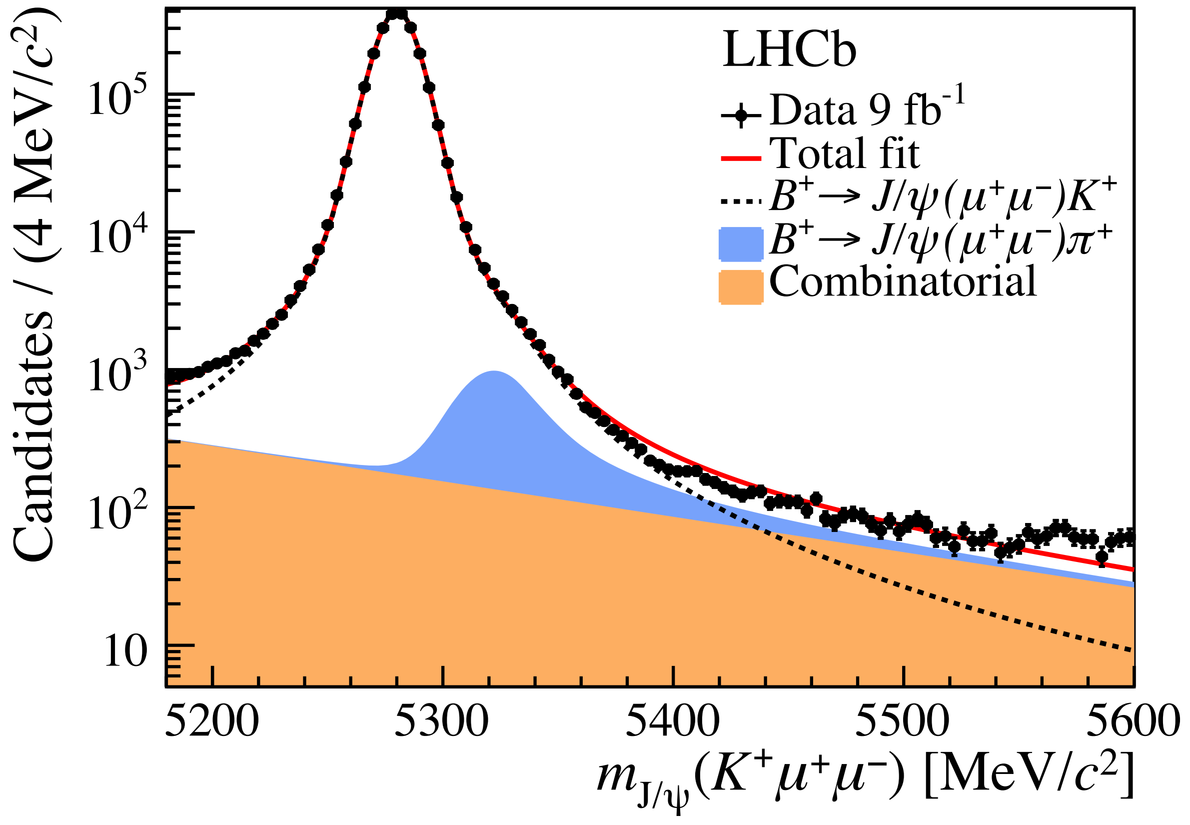
Control mode fits



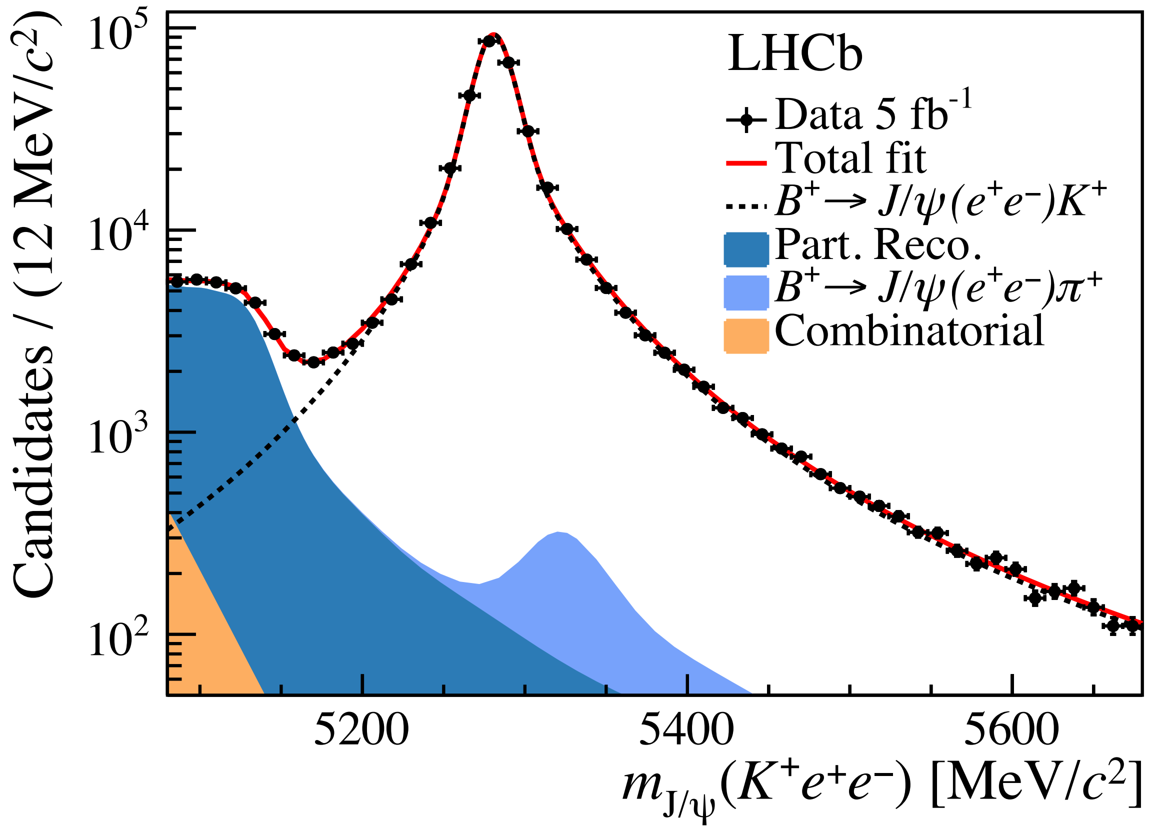
Previous data



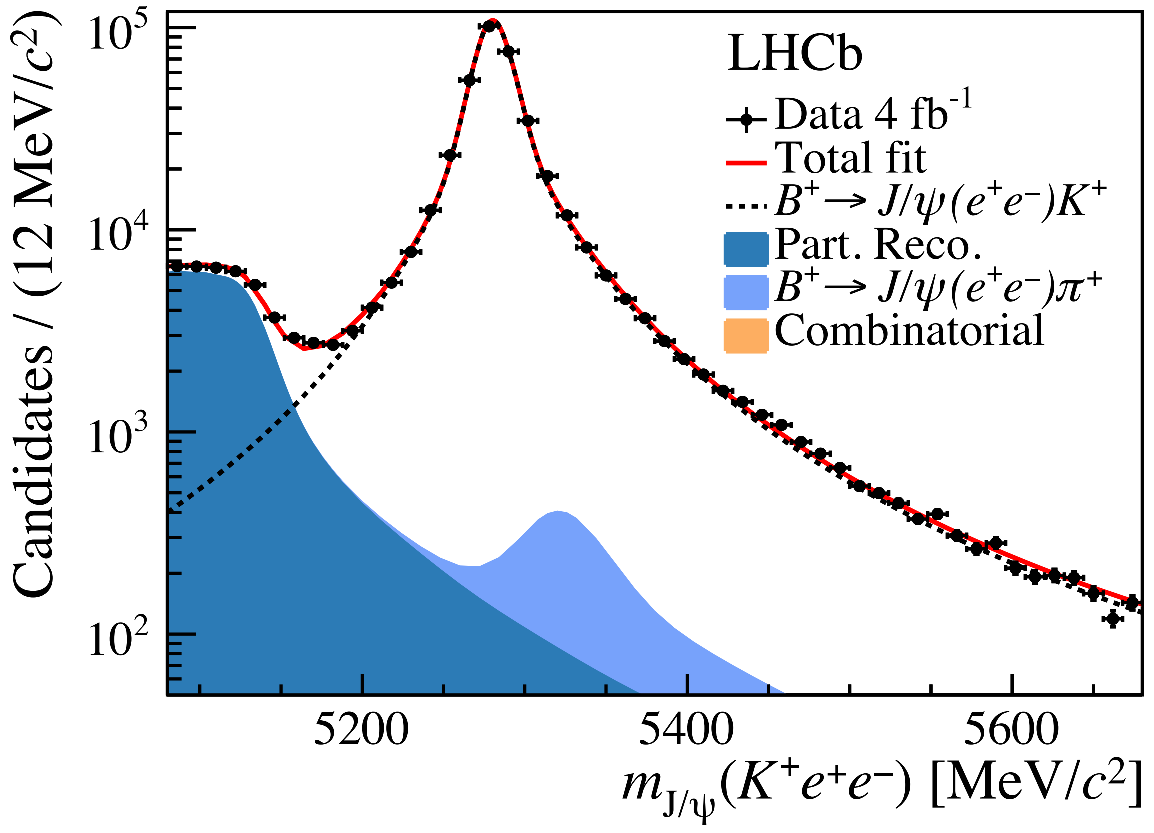
New data



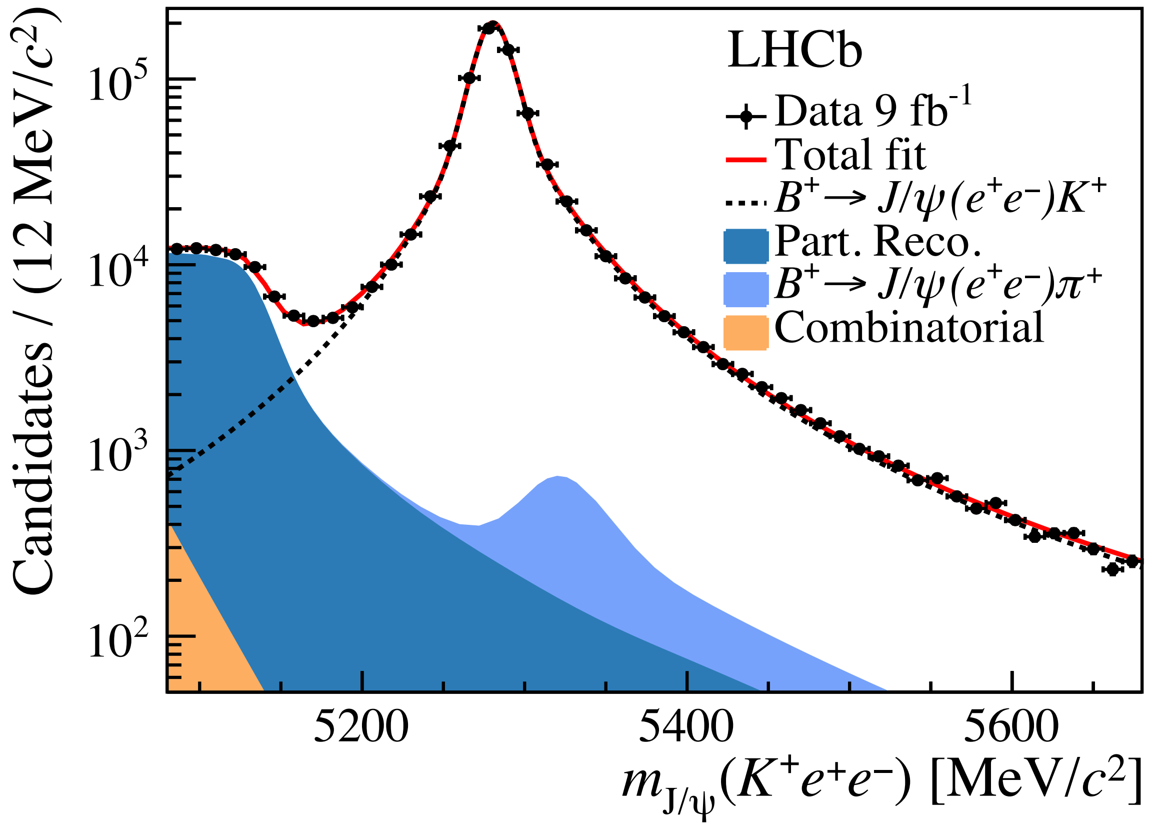
Total data



Previous data



New data



Total data

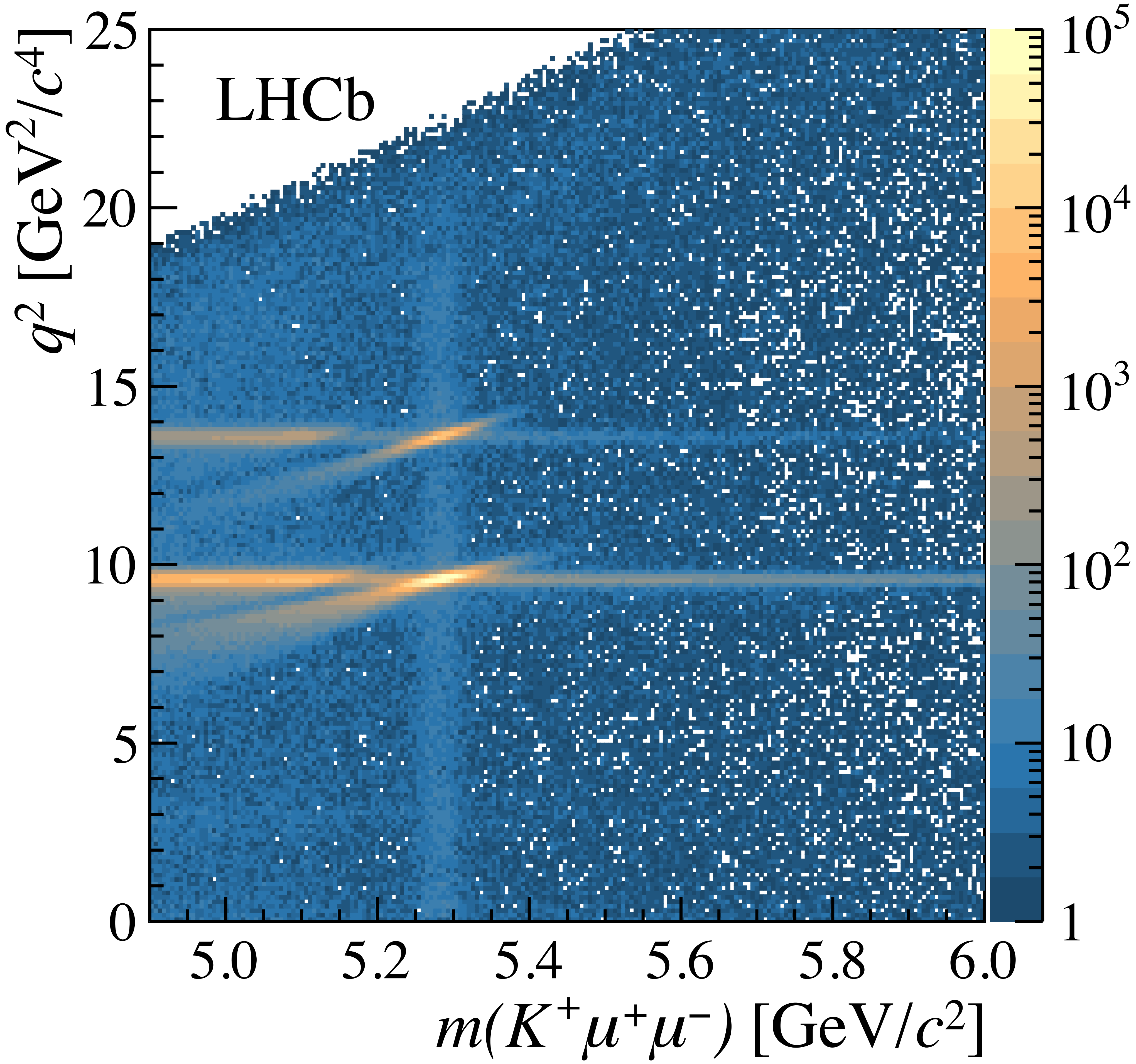
Signal shape

- The $m(K^+\ell^+\ell^-)$ distributions of the rare mode are obtained from simulated decays, calibrating the peak and width of the distribution using $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ data.

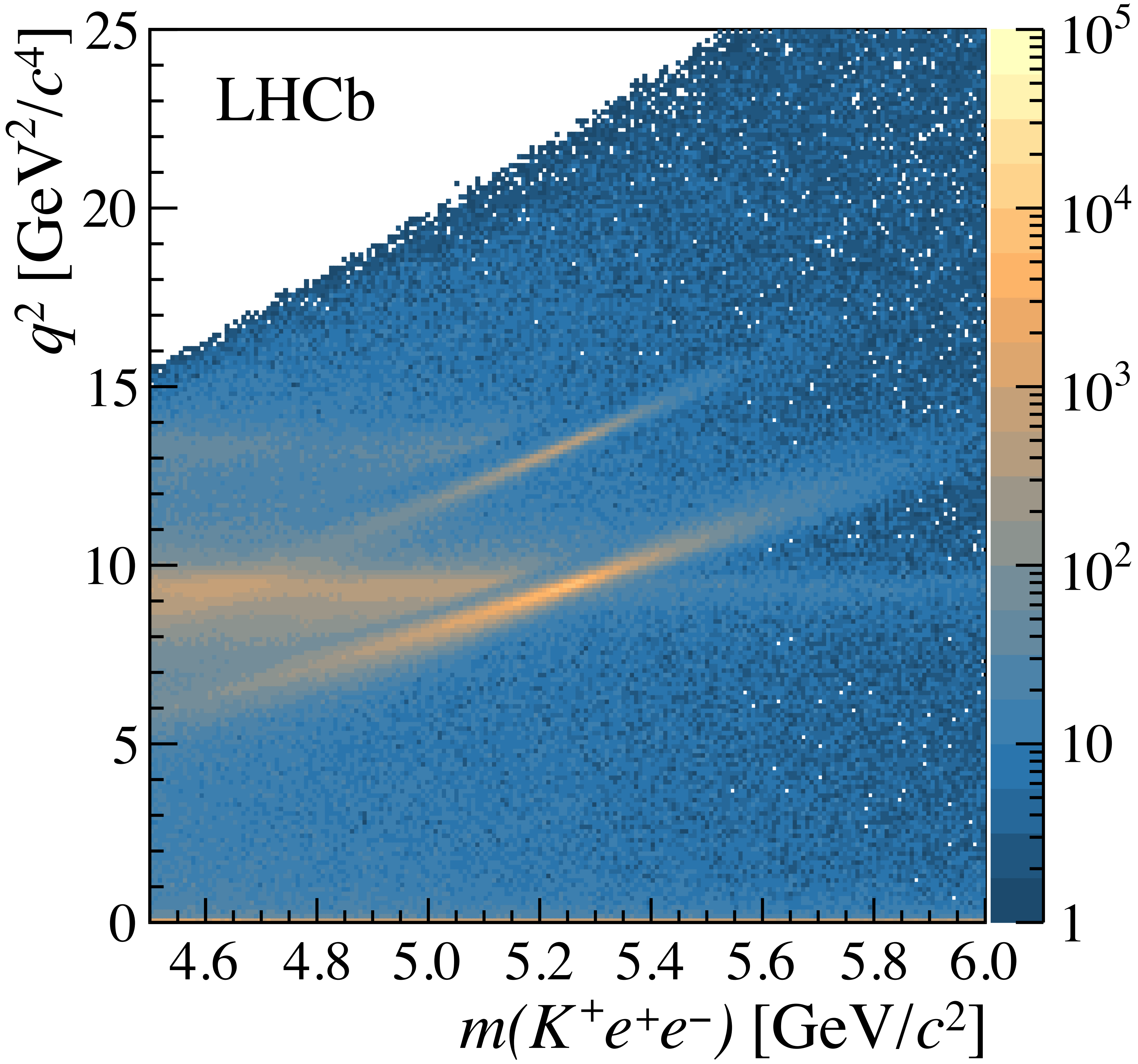
- In the subsequent fit to the rare mode the $m(K^+\ell^+\ell^-)$ lineshape is fixed.

- 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

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

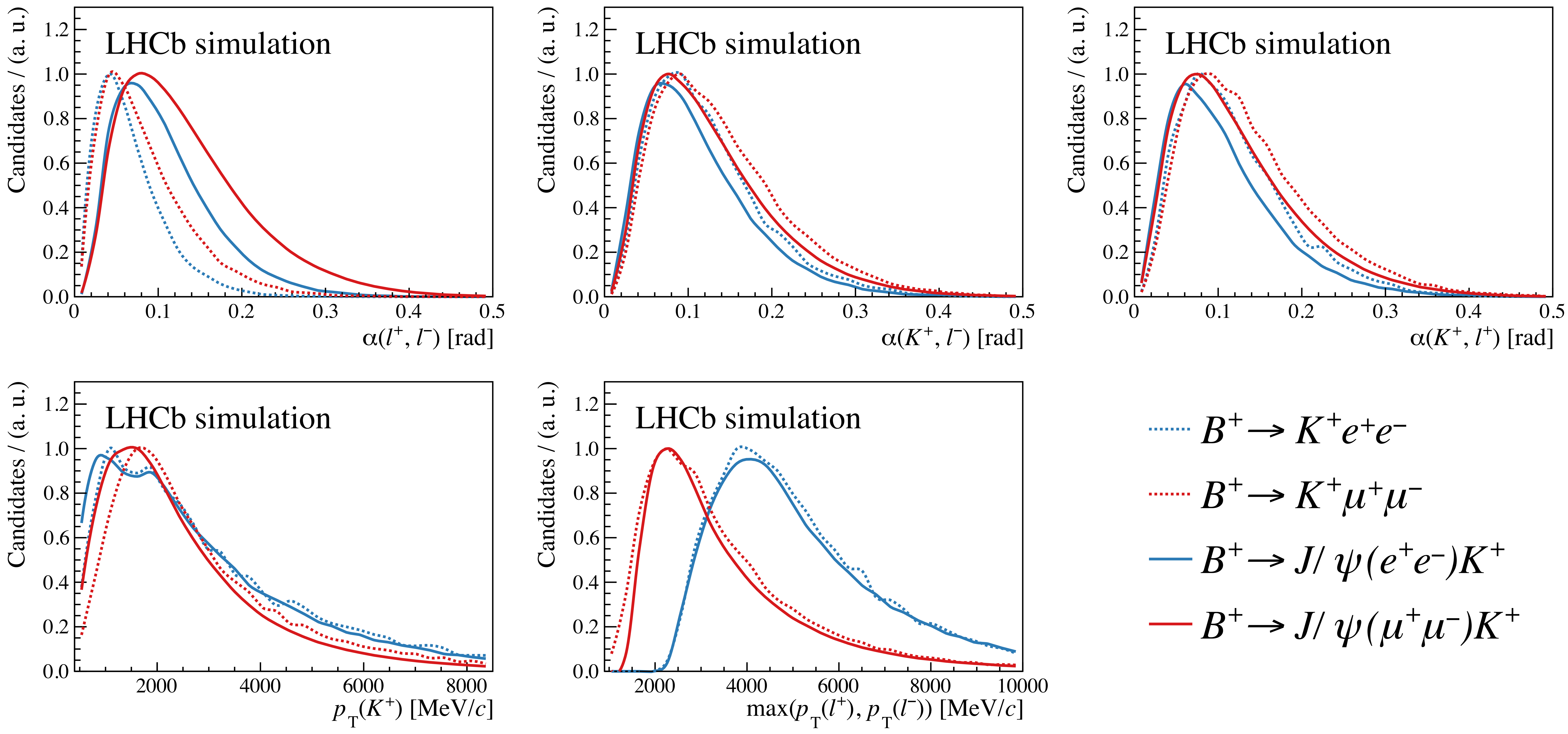


LHCb
q^2 [GeV^2/c^4]
25
20
15
10
5
0
5.0
5.2
5.4
5.6
5.8
6.0
$m(K^+\mu^+\mu^-)$ [GeV/c^2]
10^5
10^4
10^3
10^2
10
1

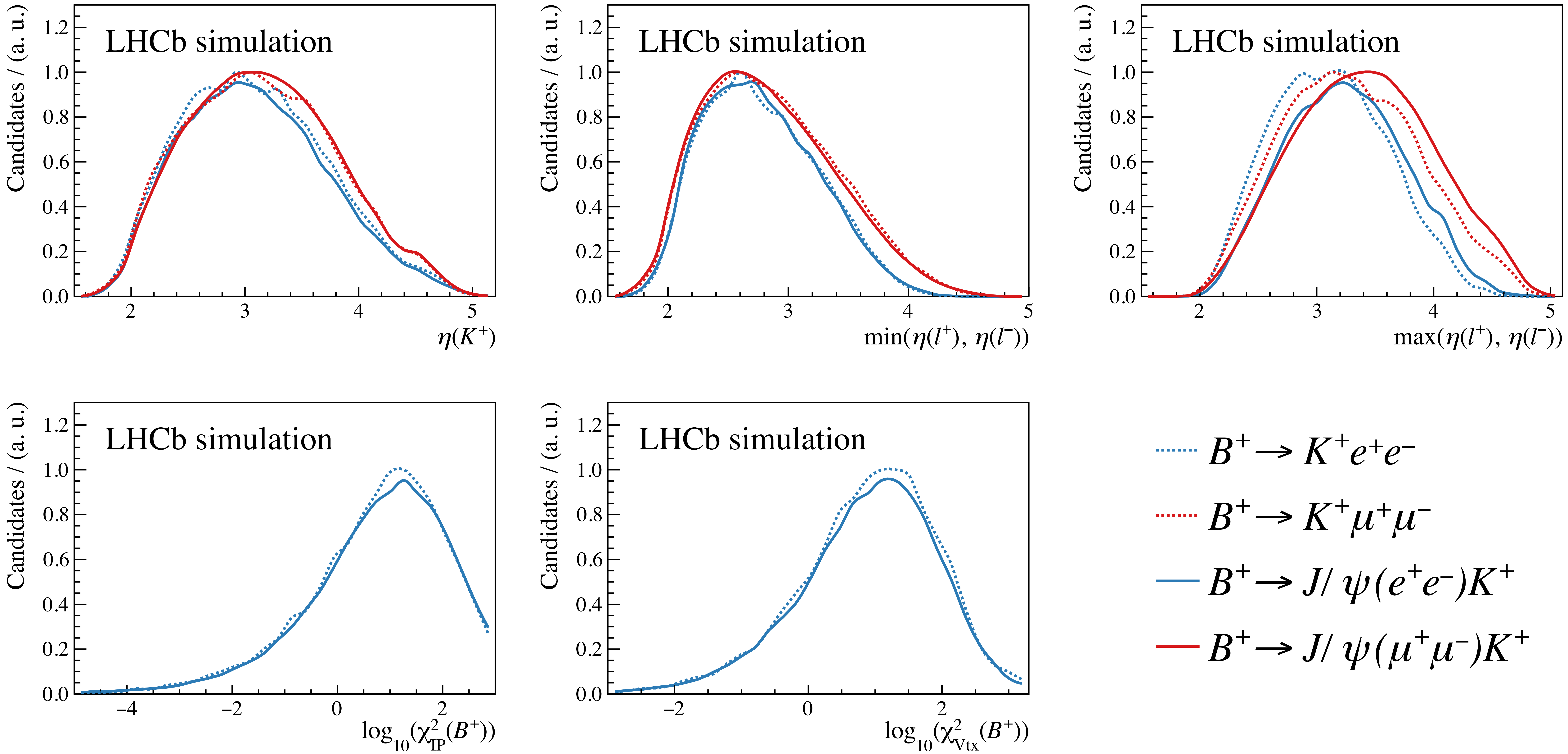


LHCb
q^2 [GeV^2/c^4]
25
20
15
10
5
0
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
$m(K^+e^+e^-)$ [GeV/c^2]
10^5
10^4
10^3
10^2
10
1

Parameter overlap



Parameter overlap



Efficiency calibration

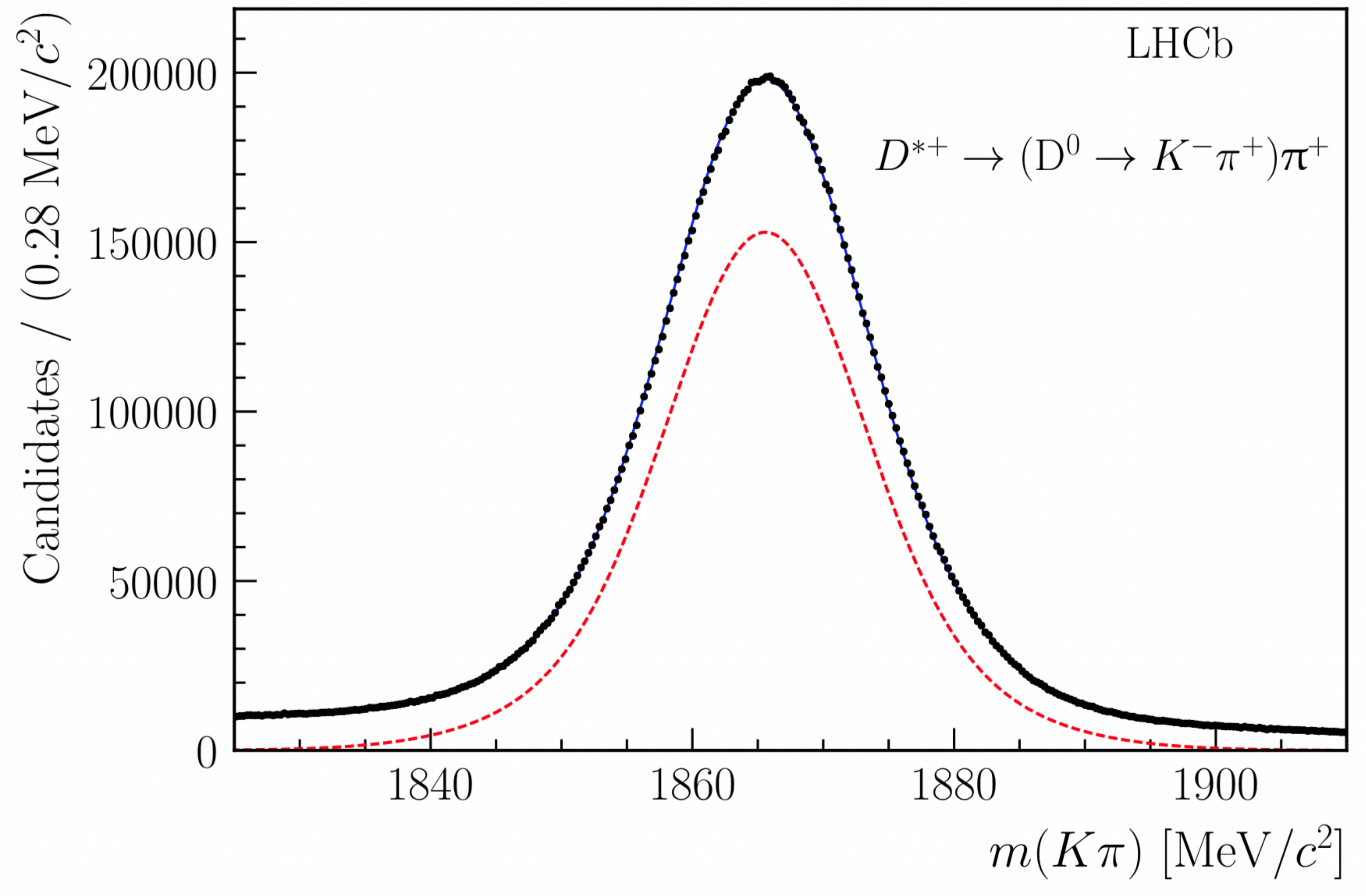
- Ratio of efficiencies determined with simulation carefully calibrated using control channels selected from data:

- Particle ID calibration: tune particle ID variables for diff. particle species using kinematically selected calibration samples ($D^{*+} \to D^0(K^-\pi^+)\pi^+ \dots$) [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

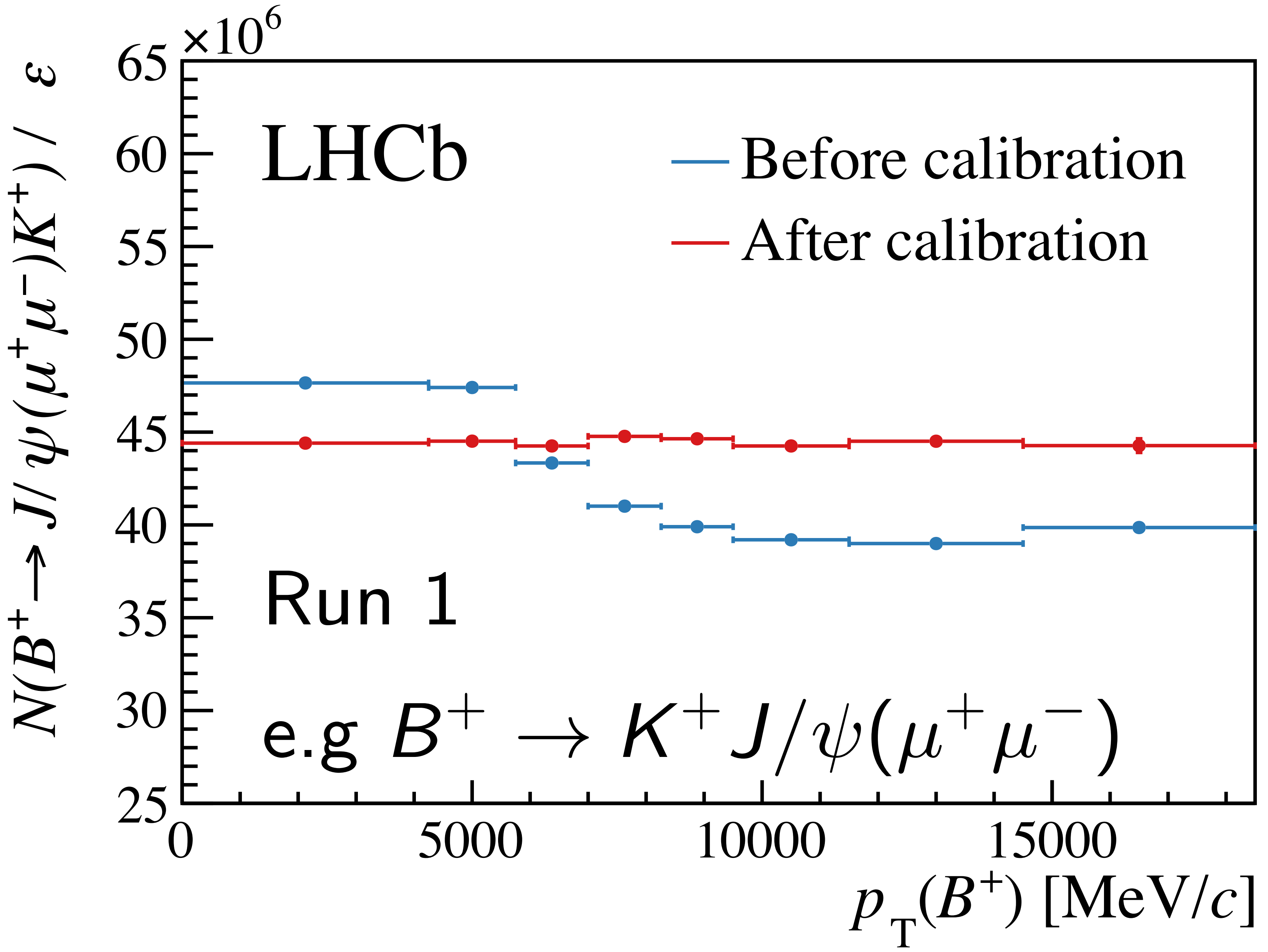
- Calibration of B^+ kinematics

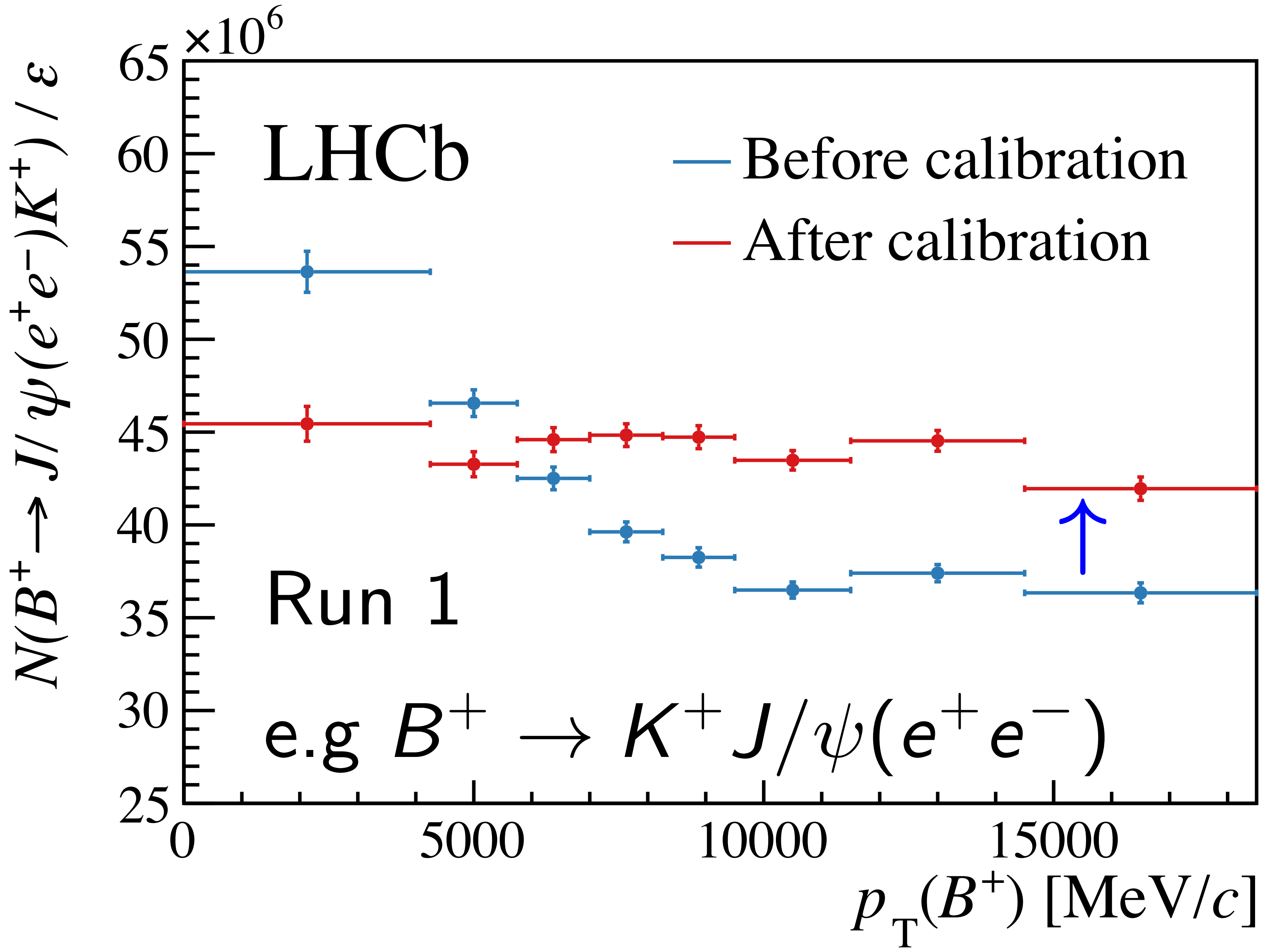
- Trigger efficiency calibration



Efficiency calibration

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

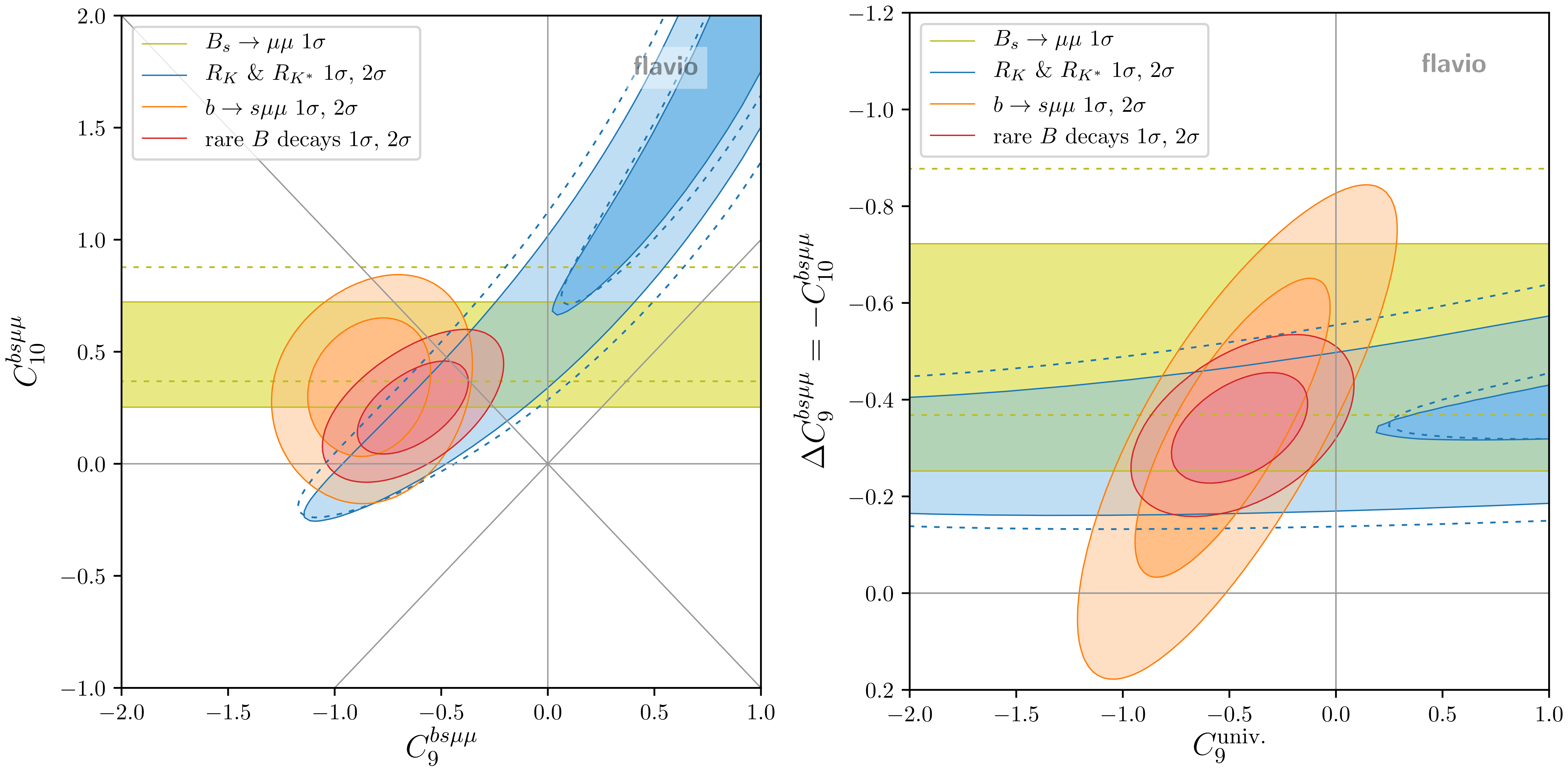




- Maximal effect of turning off corrections results in relative shift R_K $(+3 \pm 1)\ \%$ compared to 20% in $r_{J/\psi}$.
  Demonstrates the robustness of the double-ratio method in suppressing systematic biases that affect the resonant and nonresonant decay modes similarly.

Current EFT fit

- Consider new physics in $b \to s\mu\mu$ only results:
  - Clean observables ($R_{K^{(*)}}$, $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$): pull of 4.7σ in C_{10} or $C_9 - C_{10}$
  - Other $b \to s\mu\mu$ observables: pull of 4.9σ in C_9 or $C_9 - C_{10}$
  - All rare B decays: pull of 6.2σ in C_9 or $C_9 - C_{10}$
- Otherwise, slightly favoured:
  - universal contribution to C_9 from $b \to s\ell\ell$
  - $b \to s\mu\mu$ contributes to $C_9 - C_{10}$



[arXiv:2103.13370]

Angular analysis

$$\frac{1}{\mathrm{d}(\Gamma+\overline{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\overline{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$

$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$

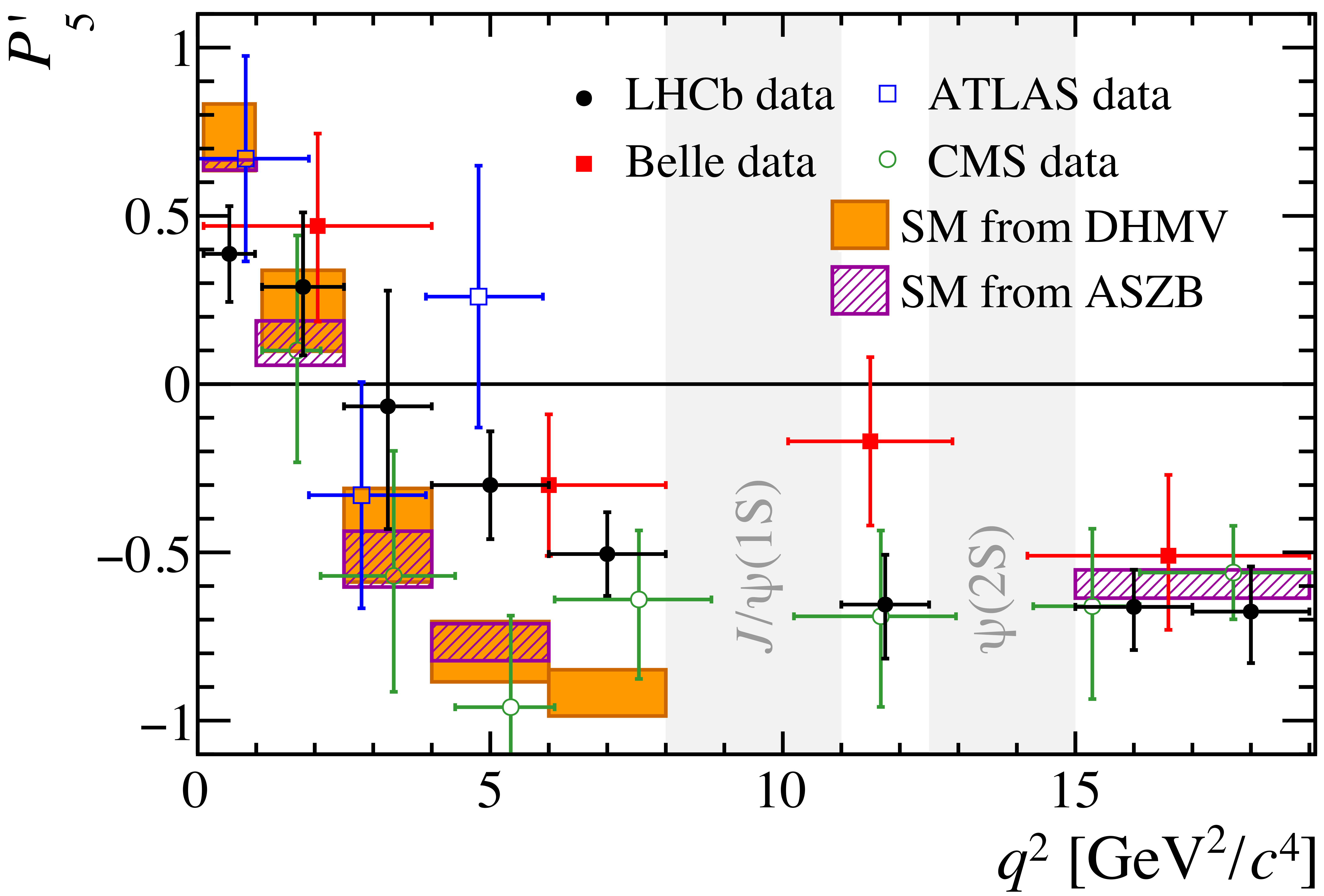
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$

$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$

$$+\frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$

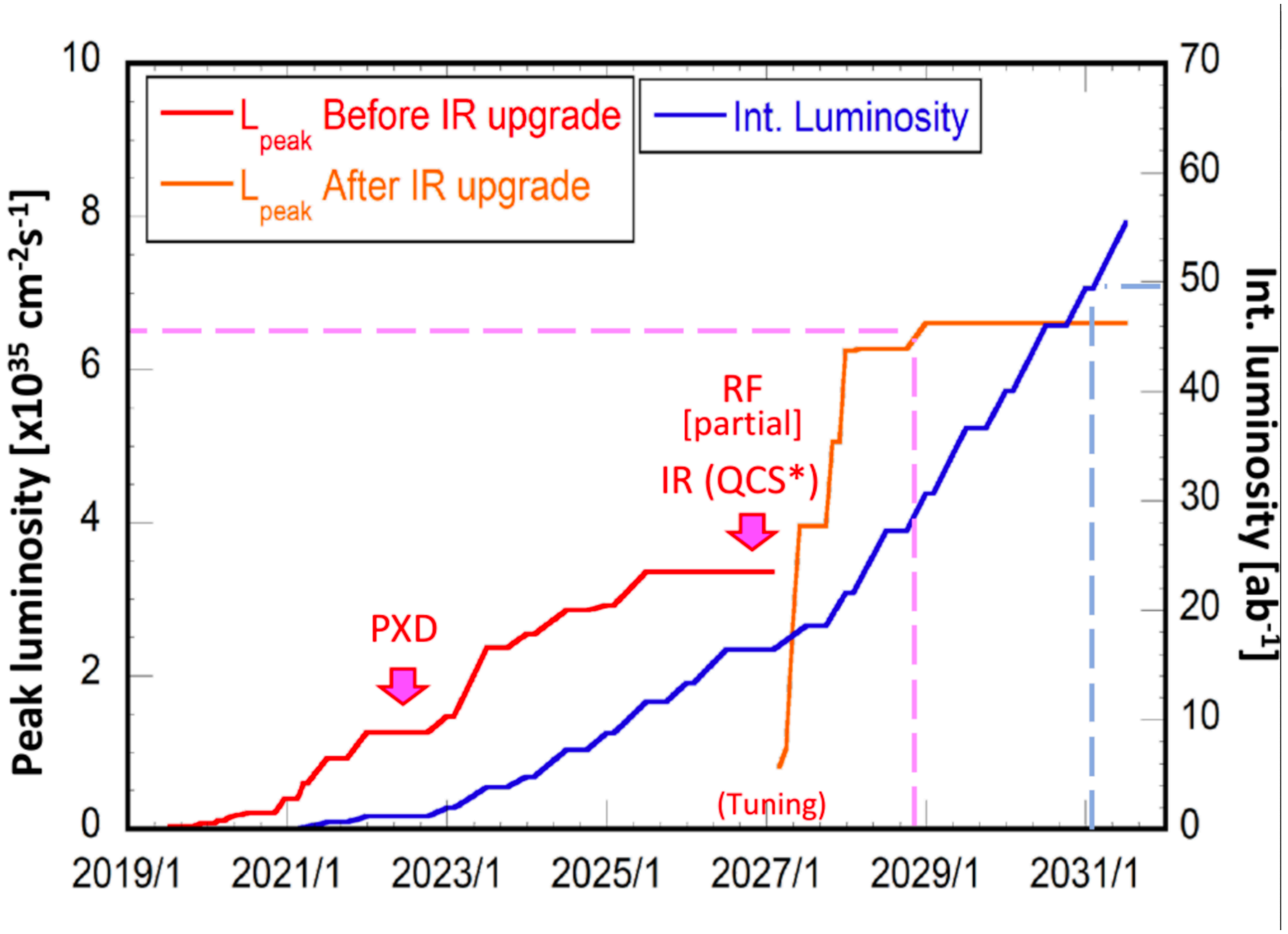
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi]$$

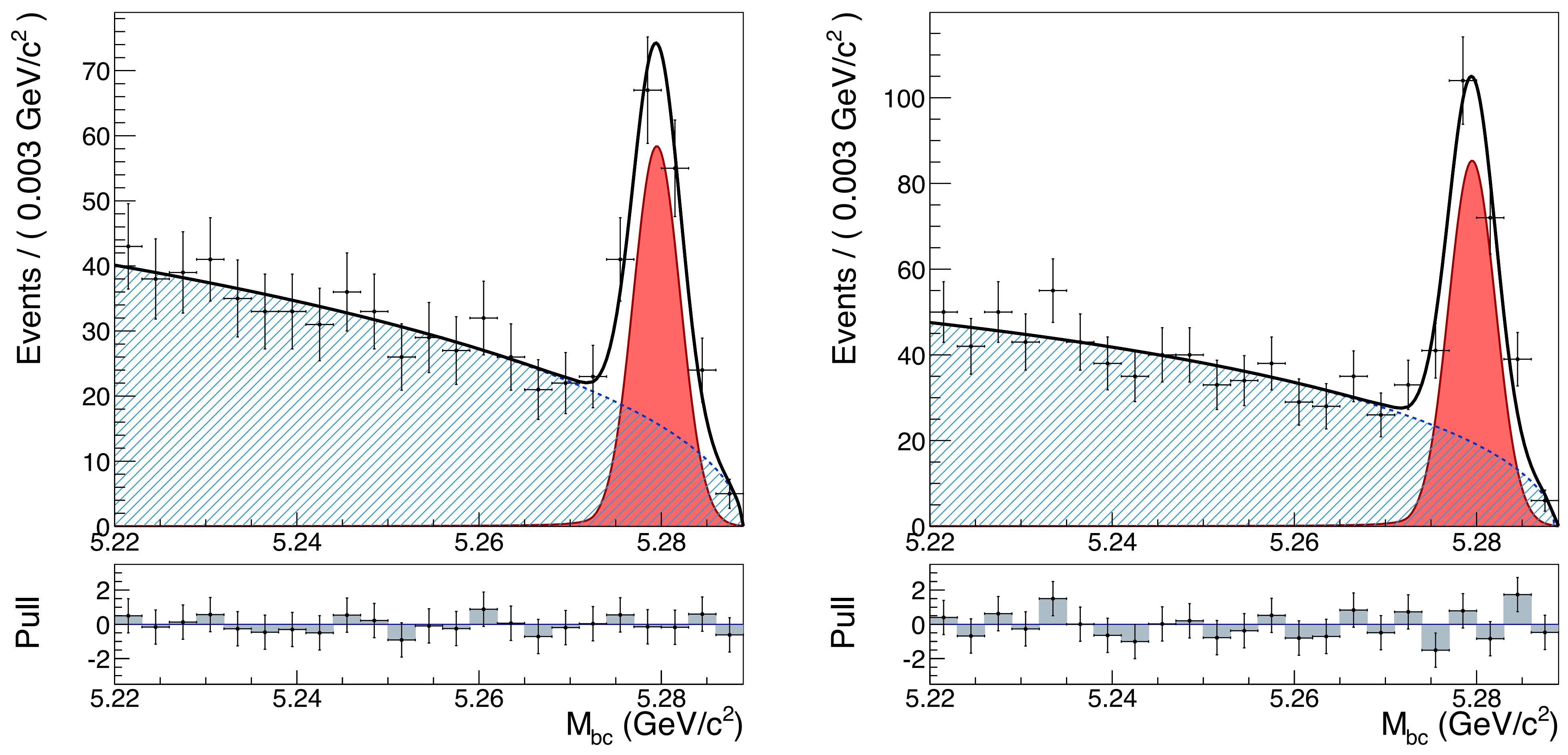
[LHCb, JHEP 02 (2016) 104, Belle, PRL 118 (2017) 111801, CMS-PAS-BPH-15-008, ATLAS-CONF-2017-023]



Belle II

- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - Much cleaner than LHC environment
  - Cross-section $\mathcal{O}$(nb): need huge luminosity
- Belle II is ramping up
  - Aim at collecting 50 ab^{-1} around 2031
  - Not as much stat as LHCb in charged modes:
    $K^+\mu\mu$: 1 fb^{-1} LHCb $\simeq$ 2.5 ab^{-1} Belle II
    $K^+e^+e^-$: 1 fb^{-1} LHCb $\simeq$ 1 ab^{-1} Belle II
  - Belle II can do things that are impossible at LHCb
  - Essential validation of the anomalies





Response to muons and electrons is very similar!