Outline of the four lectures

1
- Introduction to flavour; concept of lepton flavour universality (LFU) and theory description of rare transitions of the type $b \to s\ell^+\ell^-$ (Gino Isidori)

2
- Why b physics and why it is interesting
- The CKM Matrix
- Neutral meson oscillations
- The main experiments in the field (discussing their benefits and possible shortcomings)
- Selected results on rare decays: "Anomalies"
  - Leptonic ($B_{(s)} \to \mu^+\mu^-$)
  - Semileptonic ($b \to s\ell^+\ell^-$) (branching fractions and angular distributions)

3
- Tests of LFU
  - in neutral-current mediated $b \to s\ell^+\ell^-$ transitions
  - in charged current mediated $b \to c\tau\nu$ transitions
- Search for LFV processes

4
- Theoretical interpretation of the recent anomalies in semileptonic B decays in terms of physics beyond the Standard Model (Gino Isidori)

Latest $B_{(s)} \to \mu^+\mu^-$ combination

LHCb-CONF-2020-002
CMS PAS BPH-20-003
ATLAS-CONF-2020-049

- **LHCb**, PRL 118 (2017) 191801

$B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ 7.8σ

$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 95 % CL

- **CMS**, JHEP 04 (2020) 188

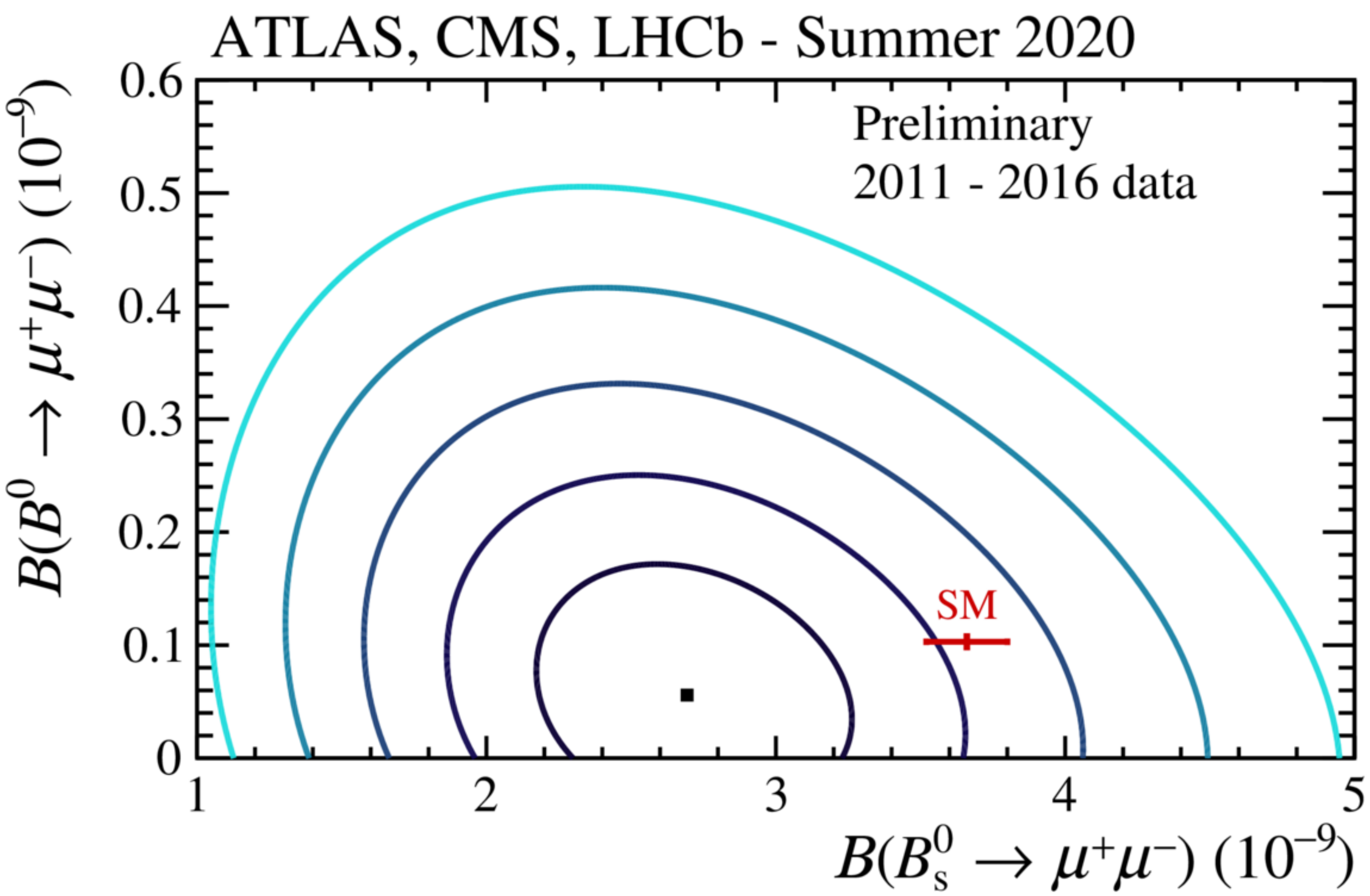
$B(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7\,(\mathrm{exp}) \pm 0.2\,(\mathrm{frag})) \times 10^{-9}$ 5.6σ

$B(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ @ 95 % CL

- **ATLAS**, JHEP 04 (2019) 098

$B(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$ 4.6σ

$B(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ @ 95 % CL



Era of precision measurements of $B_{(s)} \to \mu^+\mu^-$ has started

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

$$\mathscr{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}\ @\,95\,\%\,\mathrm{CL}$$

2.1 σ below SM prediction (2D compatibility)

Question on $B^0_{(s)} \to \tau^+\tau^-$

- Interesting for NP coupled dominantly to third generation
- In the SM, larger BF due to larger τ mass (less helicity suppressed : m_τ^2/m_B^2)

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

Bobeth et al.
PRL 112 (2014) 101801

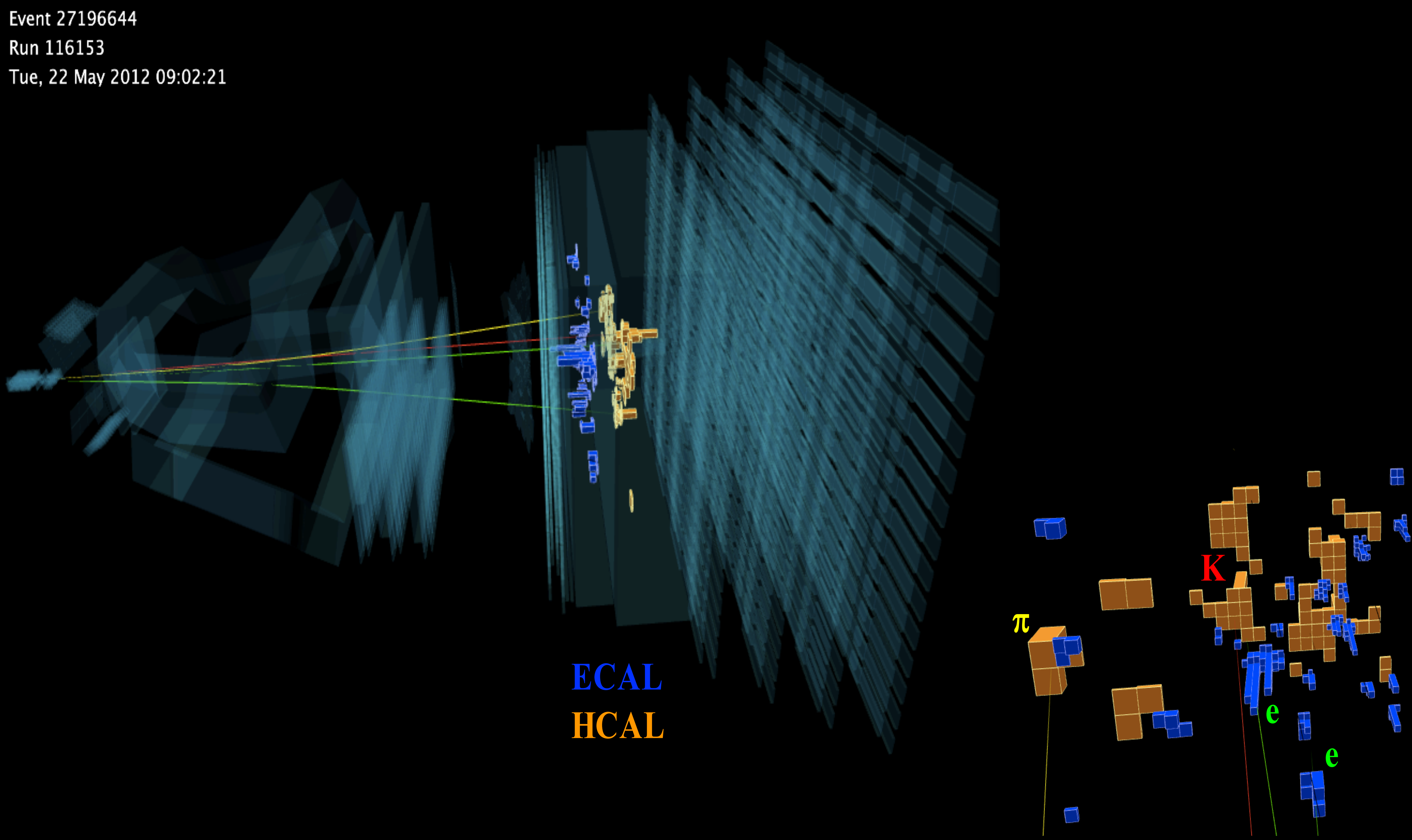
- Experimentally challenging due to undetected neutrinos in final state
- Searched by LHCb through the decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
- $B_{s,d}$ unresolvable in mass → analysis optimised for B_s
- Limits set (Run1 data):

PRL 118 (2017) 251802

$$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$ → first direct limit

$$\mathcal{B}(B_d \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$ → best limit

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



Other interesting rare decays: $B \to H_s \mu^+ \mu^-$ with $H_s = K, K^*, \phi \ldots$

- Same loop diagrams, different spectator quarks

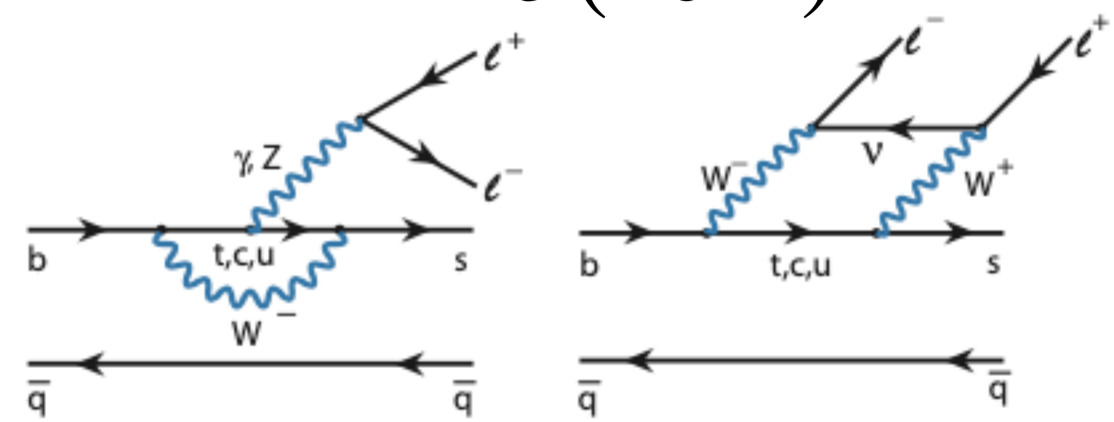
- Branching fractions (BFs) and angular distributions sensitive to NP

- A lot of phenomenological work invested in defining "clean" observables with reduced theoretical uncertainties
  - Form-factors cancel at leading order
  - E.g: are we estimating correctly contributions from charm loops that produce a $\ell^+\ell^-$ pair via a virtual photon?

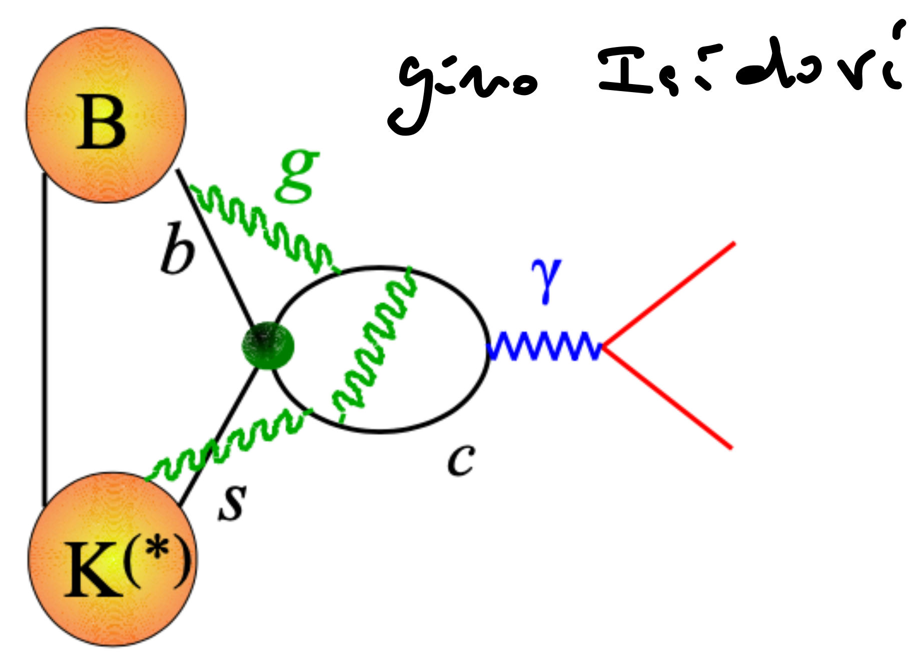
- Question: how clean?

- These theory uncertainties affect BFs and angular distributions in $B \to H_s \ell^+ \ell^-$, but *NOT* LFU ratios (clean} or $B_{(s)} \to \mu^+ \mu^-$ (clean)

BF~$\mathcal{O}(10^{-7})$



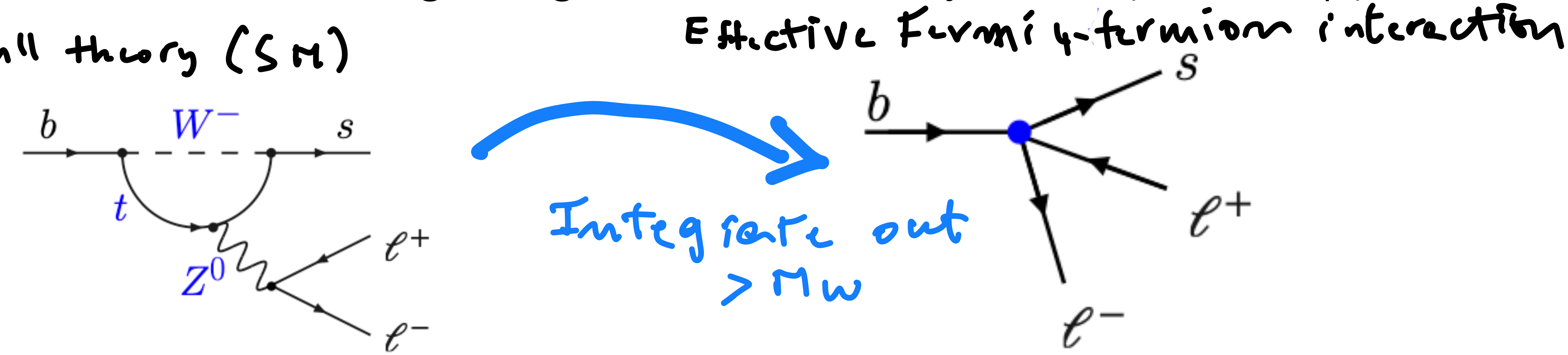
Irreducible theory error due to long distance effects, particularly large close to $c\bar{c}$ resonances



Effective Lagrangian for $b \to s\ell^+\ell^-$ transitions

Gino Isidori

- To describe these processes within the SM and beyond, construct an effective Lagrangian at the EW scale integrating out all the heavy fields (W, Z, top)



- $\mathscr{L}_{\text{eff}} \sim \Sigma_i C_i(M_W) O_i$

  ← Wilson coefficients

- Four-fermion interaction described by effective couplings $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$

- The interesting short-distance information (sensitive to NP) is encoded in the Wilson coefficients C_i (especially C_9 and C_{10})

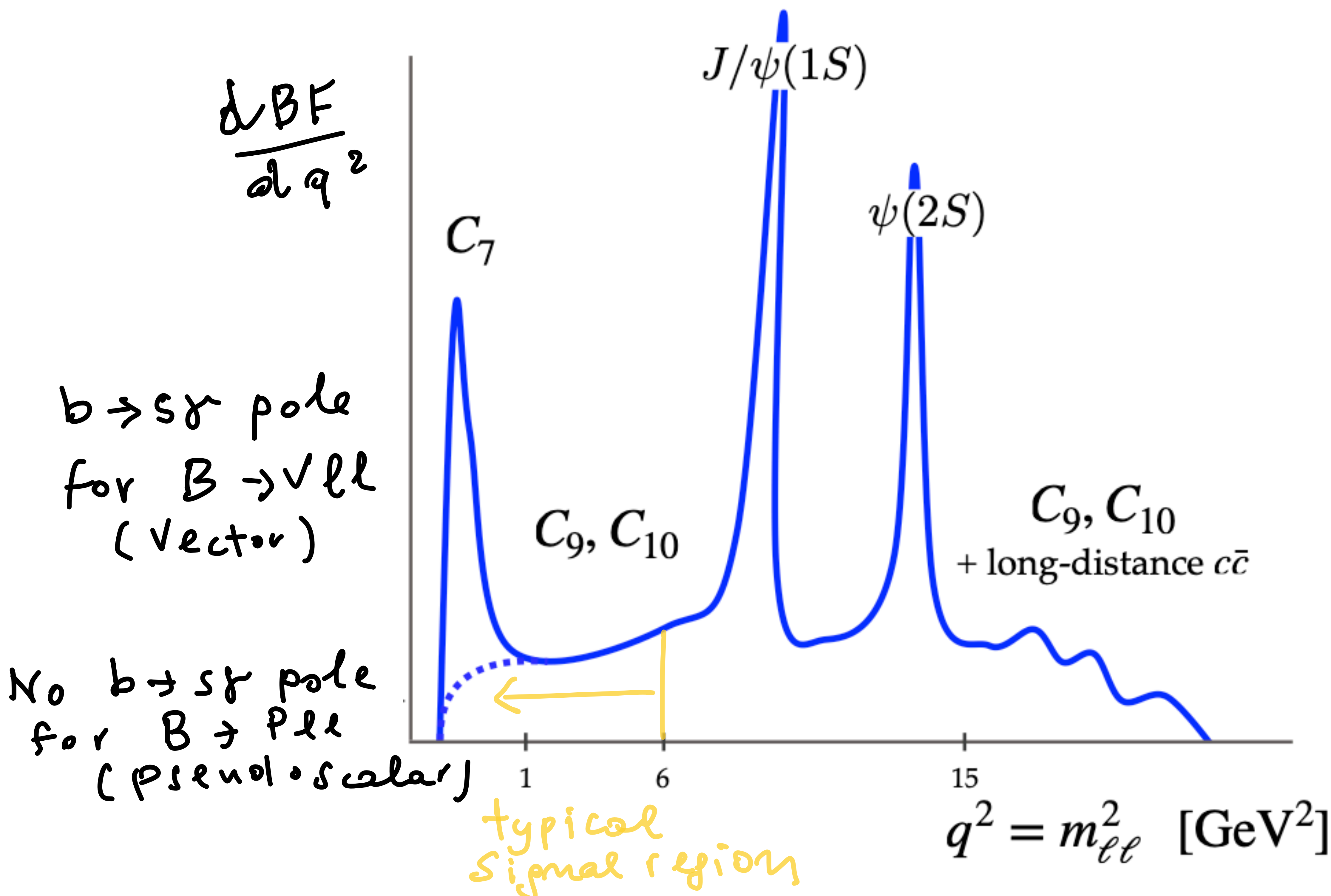
FCNC OPERATORS

$$\mathcal{O}_{10}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$ Z penguin & box

$$\mathcal{O}_9^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$ γ and Z penguin

$$Q_7 = m_b(\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$ γ penguin

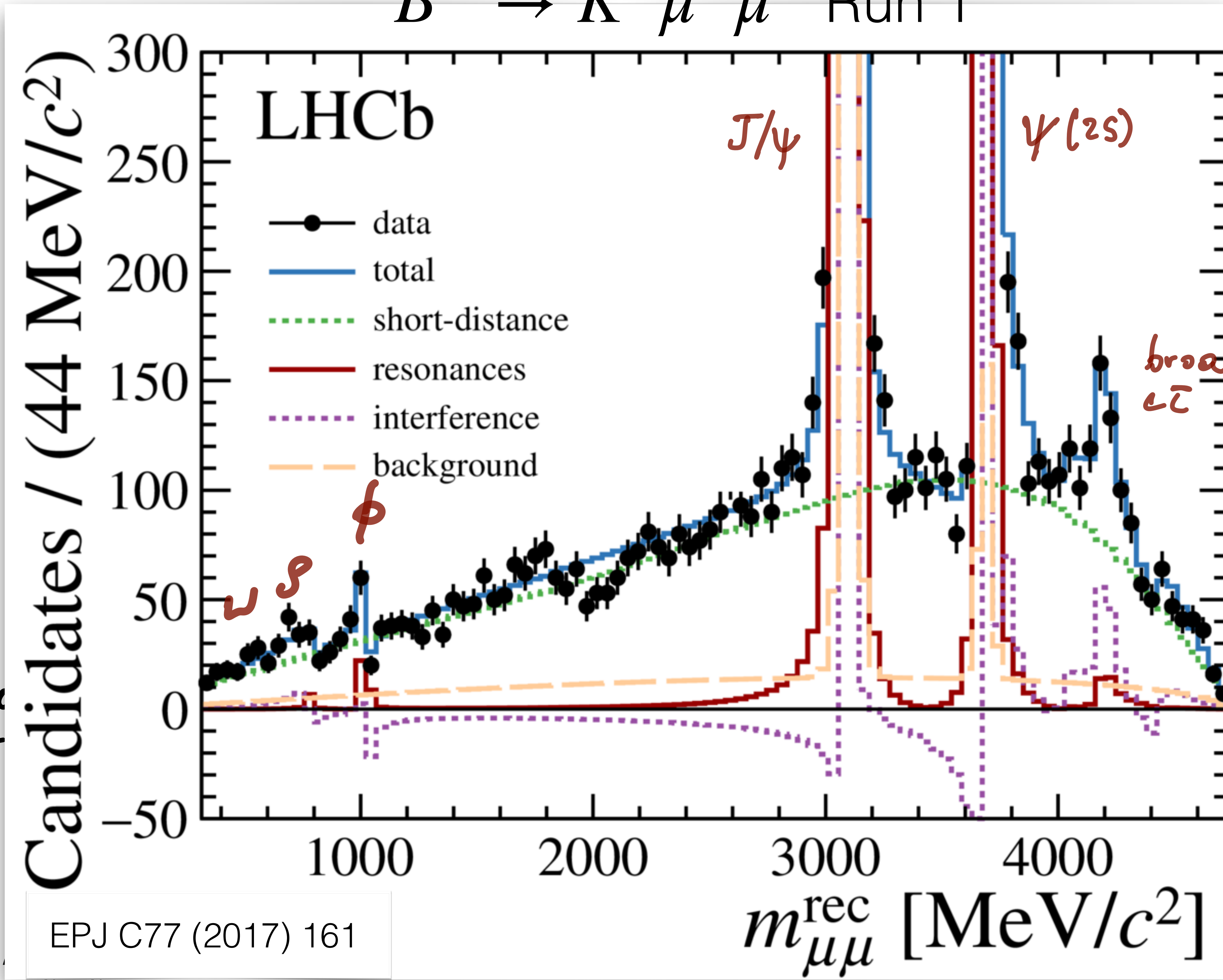
q^2 spectrum of $b \to s\ell^+\ell^-$ decays



$q^2 = m^2_{\ell^+\ell^-}$ four-momentum transfer squared between B and H_s

q^2 spectrum of $b \to s\ell^+\ell^-$ decays

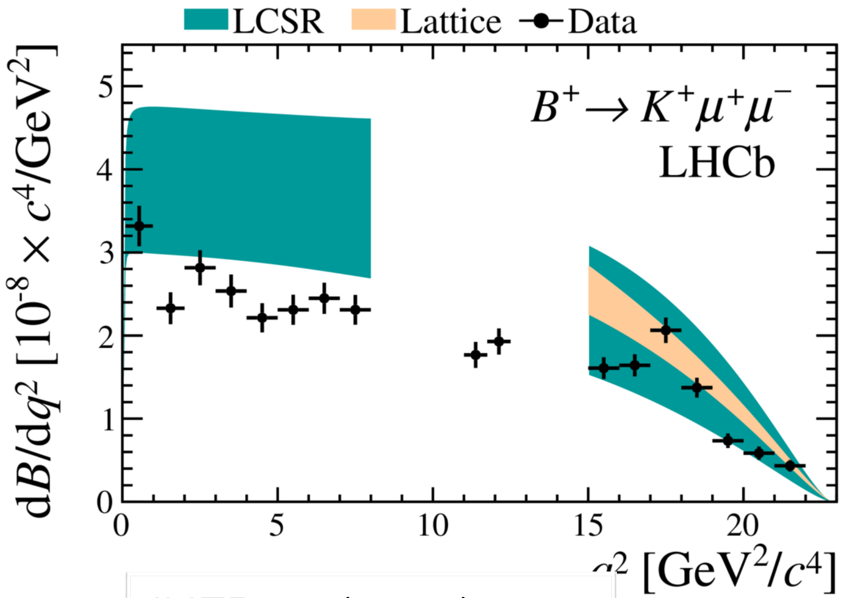
$B^+ \to K^+\mu^+\mu^-$ Run 1



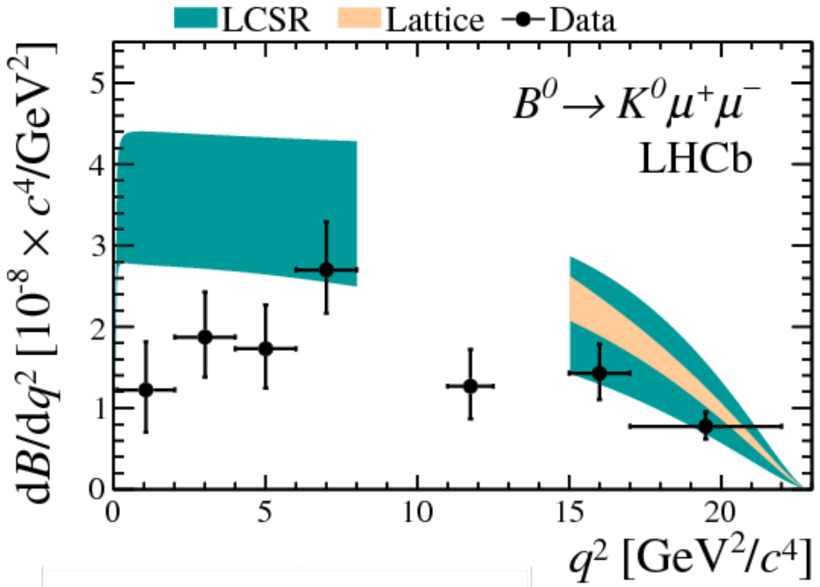
EPJ C77 (2017) 161

$q^2 =$

BF of semileptonic $b \to s\mu^+\mu^-$



JHEP 06 (2014) 133



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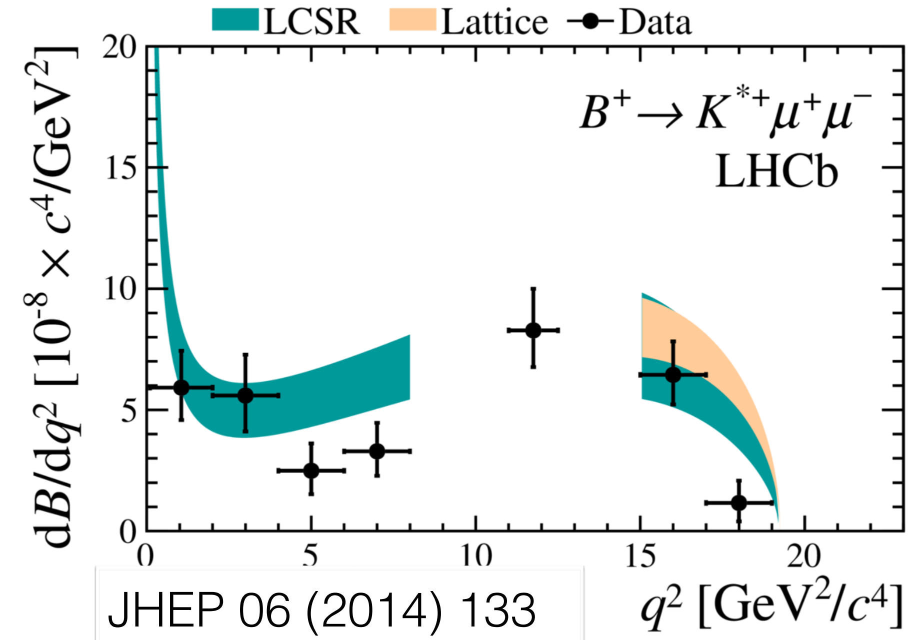
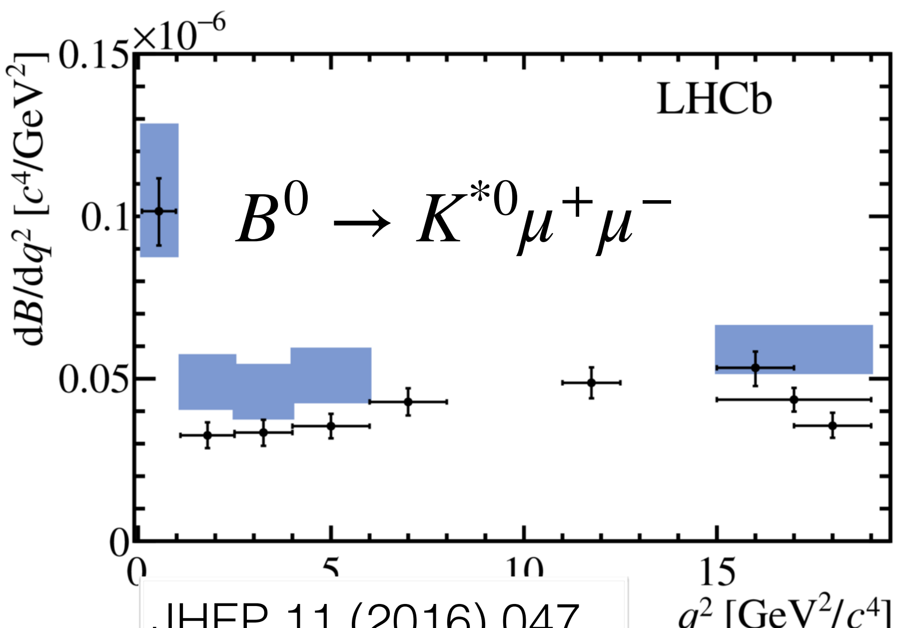
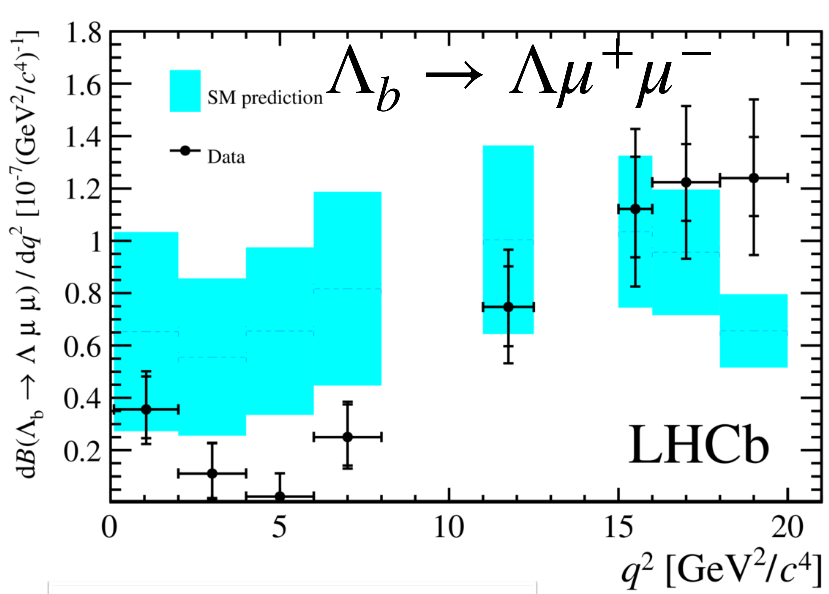


JHEP 06 (2014) 133



JHEP 11 (2016) 047,
JHEP 04 (2017) 142



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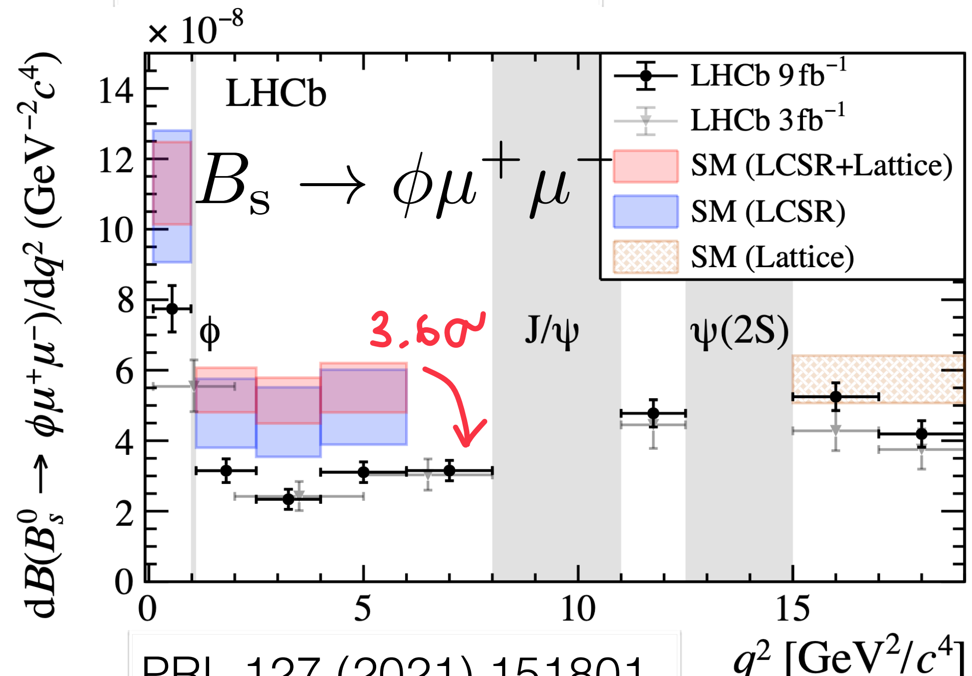
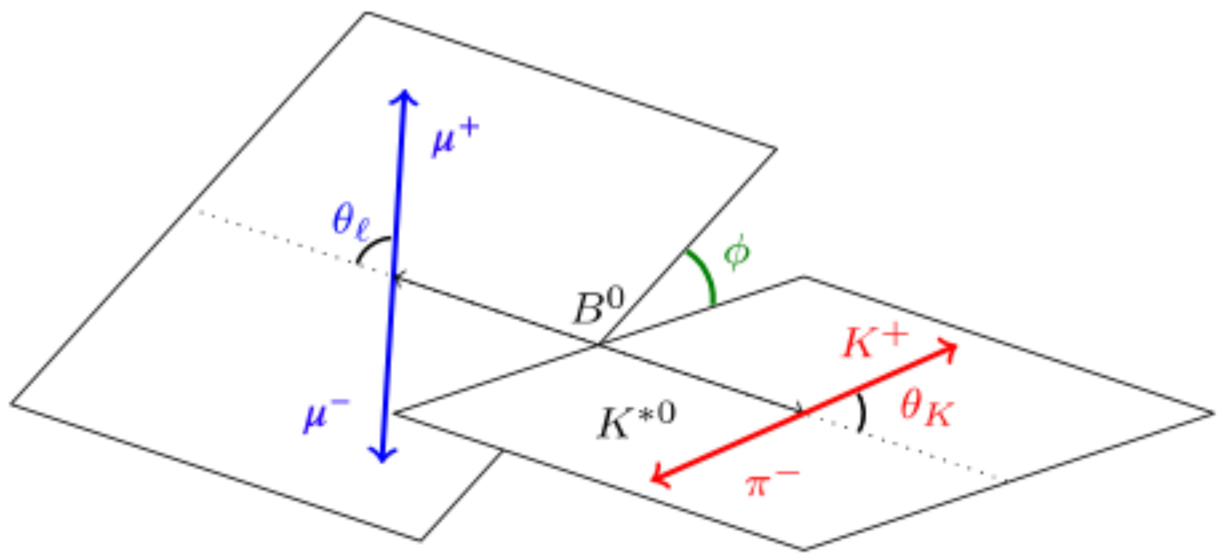


PRL 127 (2021) 151801

- In general, data tend to be lower than theory predictions at low q^2 (but uncertainties on the theory could be correlated among different modes)

Angular distributions in $B \to K^{*}\mu^{+}\mu^{-}$

- $B^0 \to K^{*0}\mu^+\mu^-$ with $K^{*0} \to K^+\pi^-$
- Decay rate fully described in terms of $\boldsymbol{\Omega} = (\cos\theta_\ell, \cos\theta_k, \phi)$, $q^2 = m^2_{\mu^+\mu^-}$



$$\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

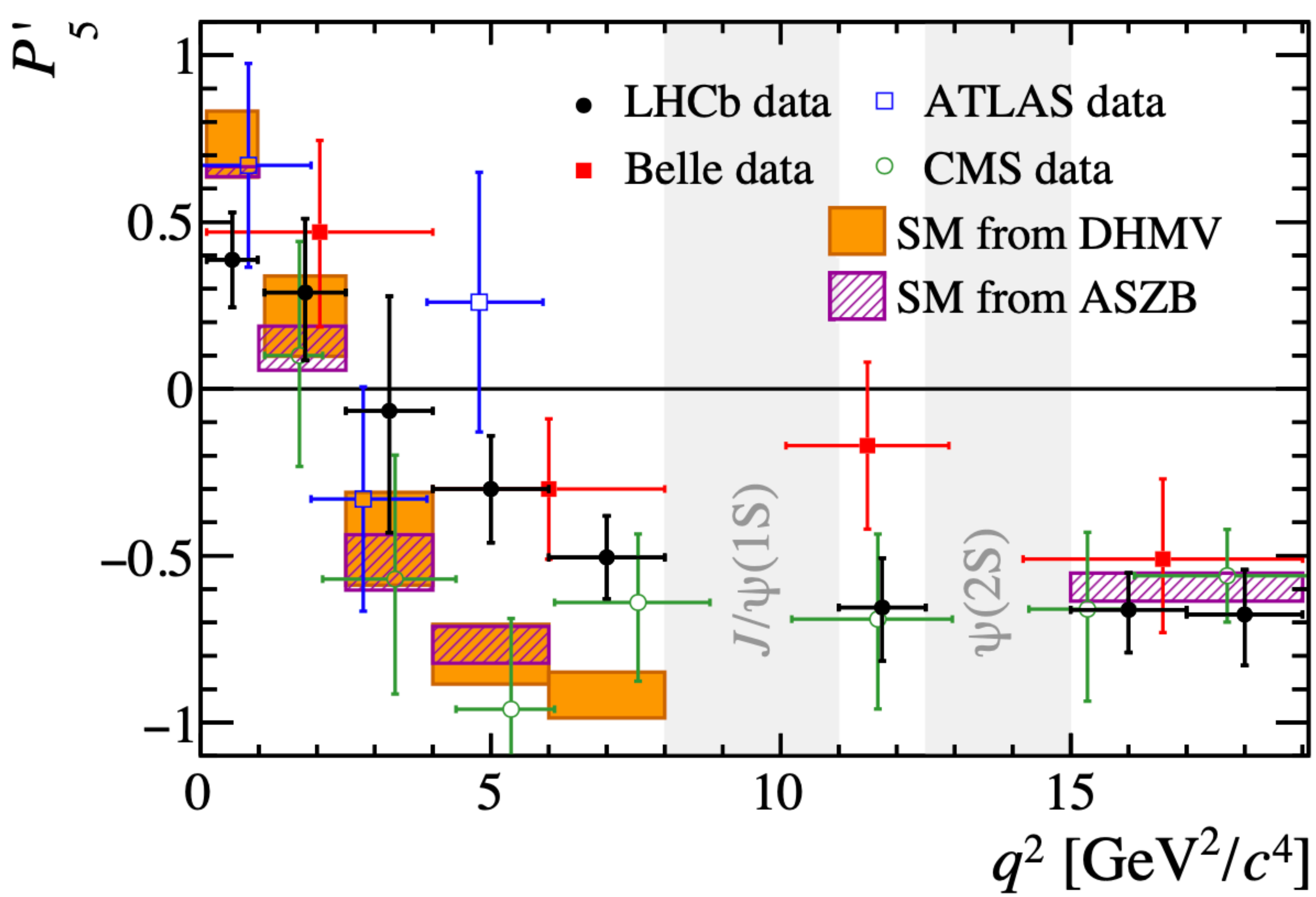
angular coefficients

angular functions

combination of different K^{*0} amplitudes that depend on Wilson coefficients and form-factors

$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ angular analysis (old LHCb result with 3/fb)

- LHCb observed a tension in the "optimised variable" P'_5 , not exactly intuitive, but constructed from ratios of angular observables to be robust from 'form-factor uncertainties'
- However, inconclusive when adding ATLAS, CMS and Belle

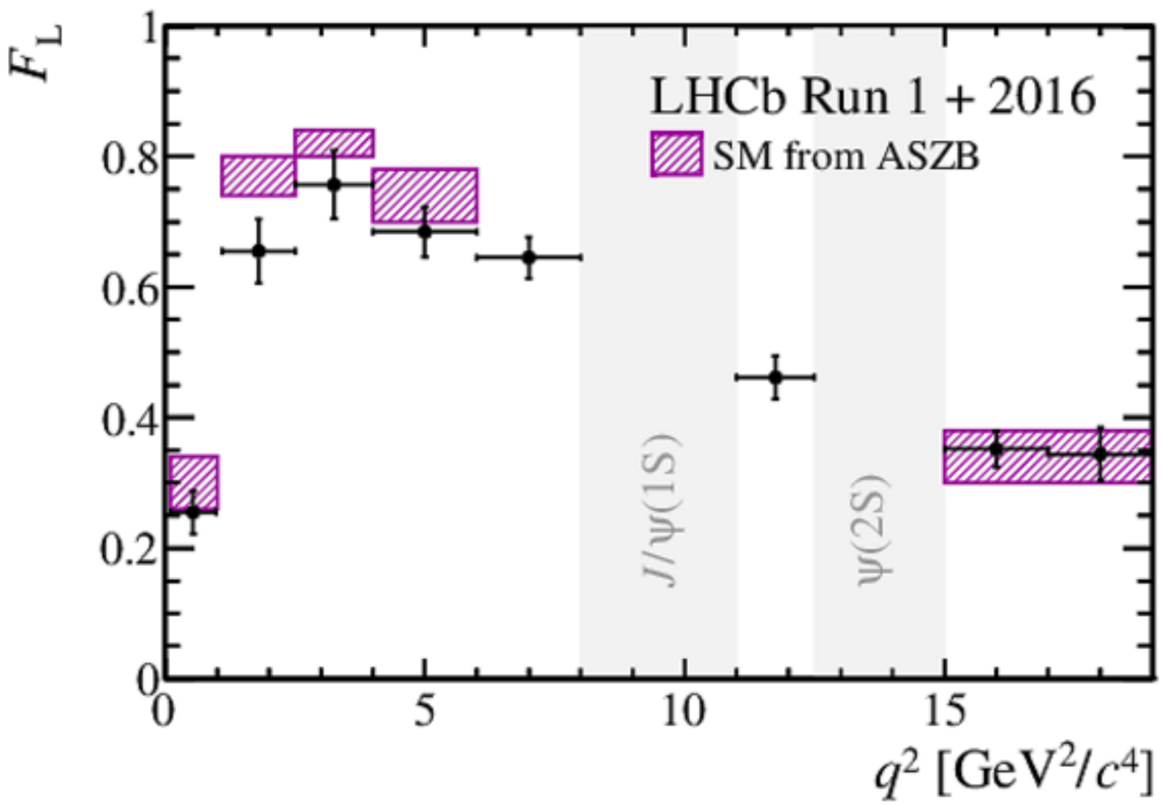


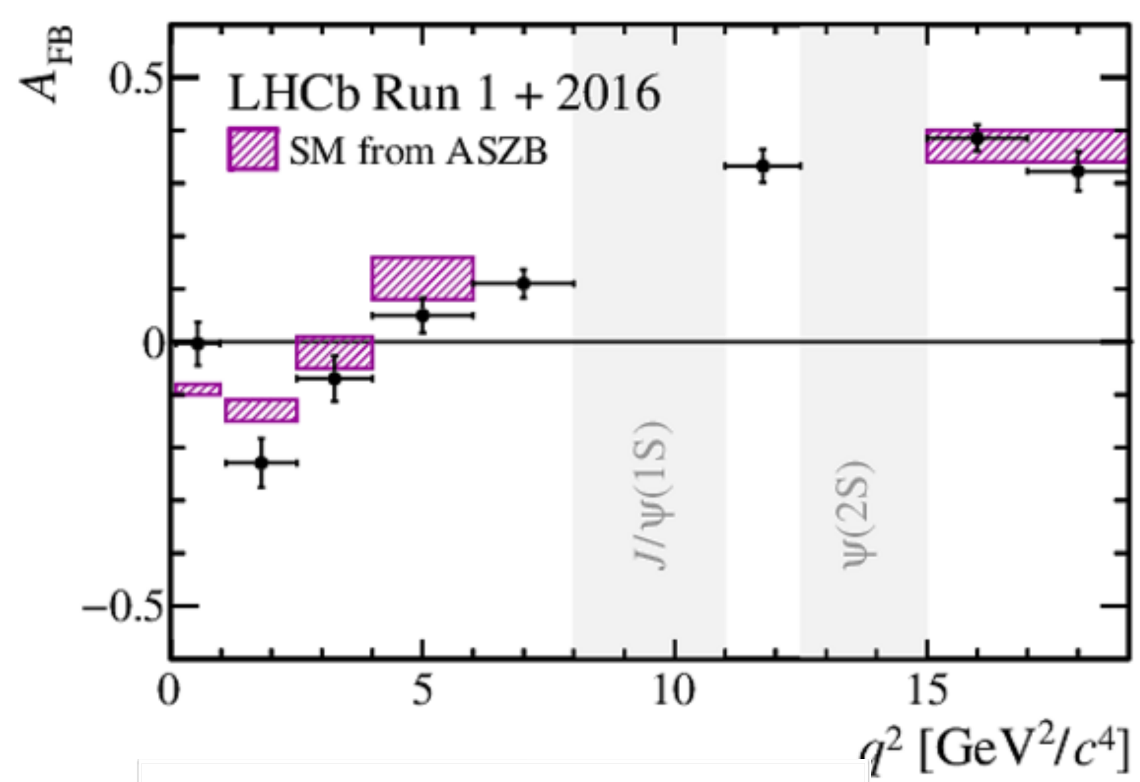
LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS: JHEP 10 (2018) 047
CMS: PLB 781 (2018) 517541

$P'_5 = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$, with F_L and S_5 combinations of K^{*0} spin amplitudes dependent on Wilson coefficients and form factors

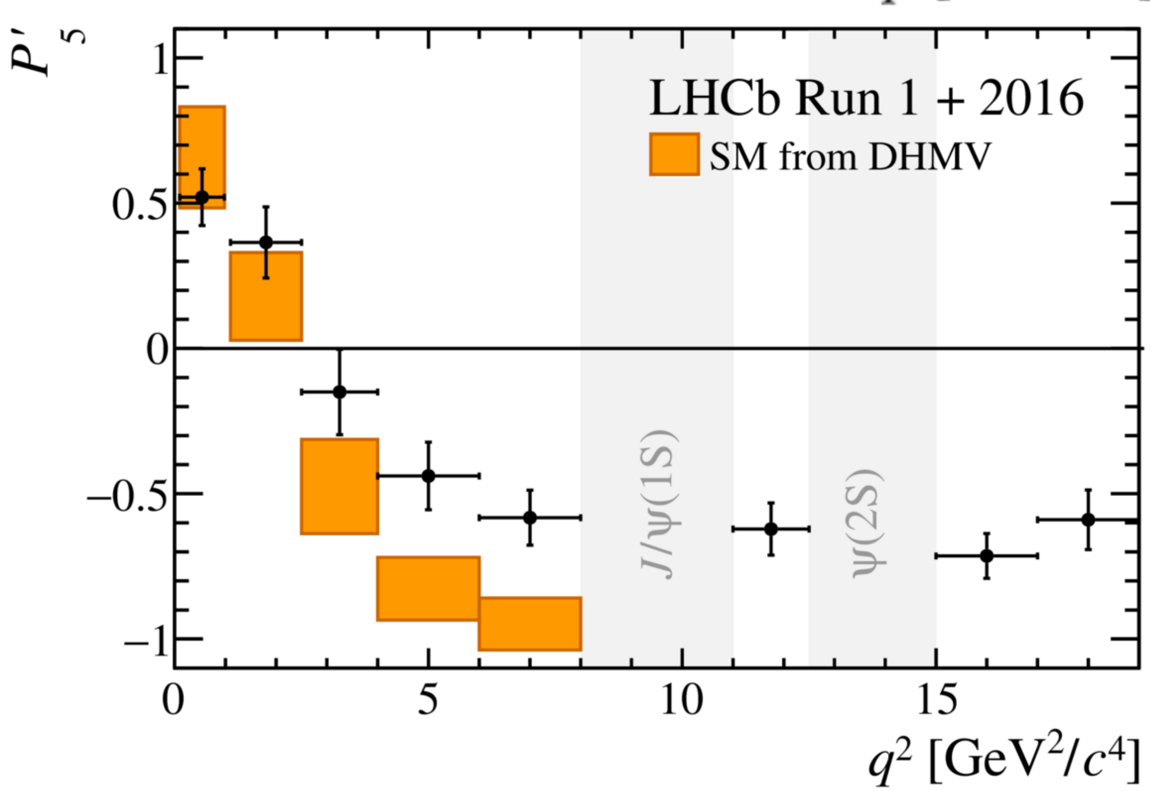
$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ angular analysis

- LHCb update based on 4.7/fb (~doubling the number of B^0 to ~4600 events)





PRL 125 (2020) 011802



- P'_5: local tension of 2.5σ and 2.9σ in q^2 bins of [4.0,6.0] and [6.0,8.0] GeV^2
- Global fit to angular observables finds a deviation of $3.3\,\sigma$ (shift wrt SM value of C_9)
- Consistent with previous result

TESTS OF LEPTON FLAVOUR UNIVERSALITY

Lepton Flavour Universality

- The property that the three charged leptons (e, μ , τ) couple in a universal way to the SM gauge bosons

- In the SM the only flavour non-universal terms are the three lepton masses: $m_\tau, m_\mu, m_e \leftrightarrow$ 3477 / 207/ 1 (boring!)

- Turn this "boring" property into a powerful tool to discover physics beyond the SM

- The SM quantum numbers of the three families could be an "accidental" low-energy property: the different families may well have a very different behaviour at high energies, as signalled by their different masses

- If NP couples in a non-universal way to the three lepton families, then we can discover it by comparing classes of rare decays involving different lepton pairs (e.g. e/μ or μ/τ)

- Test LFU in $b \rightarrow s\ell^+\ell^-$ transitions, i.e. flavour-changing neutral currents with amplitudes involving loop diagrams

Precise tests of LFU in π decays

- Ratio of BFs $R_{e/\mu} = \dfrac{\Gamma\left(\pi^+ \to e^+\nu(\gamma)\right)}{\Gamma\left(\pi^+ \to \mu^+\nu(\gamma)\right)}$ provides the best test of electron–muon universality in charged-current weak interactions

  $\pi^+ \to e^+\nu$ is helicity suppressed

- $R_{e/\mu}(\mathrm{SM}) = 1.23524(15) \times 10^{-4}$, one of the most precisely calculated weak interaction observable involving quarks

- $R_{e/\mu}(\exp) = 1.2327(23) \times 10^{-4}$ Very accurate test!
  (New experiment PIONEER at PSI approved to improve the experimental accuracy by factor 15)

The family of R ratios

- Comparing the rates of $B \to He^+e^-$ and $B \to H\mu^+\mu^-$ allows precise testing of lepton flavour universality

$$R_{\rm H}\left[q^2_{\rm min}, q^2_{\rm max}\right] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B\to H\mu^+\mu^-)}{{\rm d}q^2}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B\to He^+e^-)}{{\rm d}q^2}} \;, \quad q^2 = m^2(\ell\ell)$$

B: $B^+, B^0, B^0_s, \Lambda^0_b$

H: $K^+, K^{*0}, pK, \phi \ldots$.

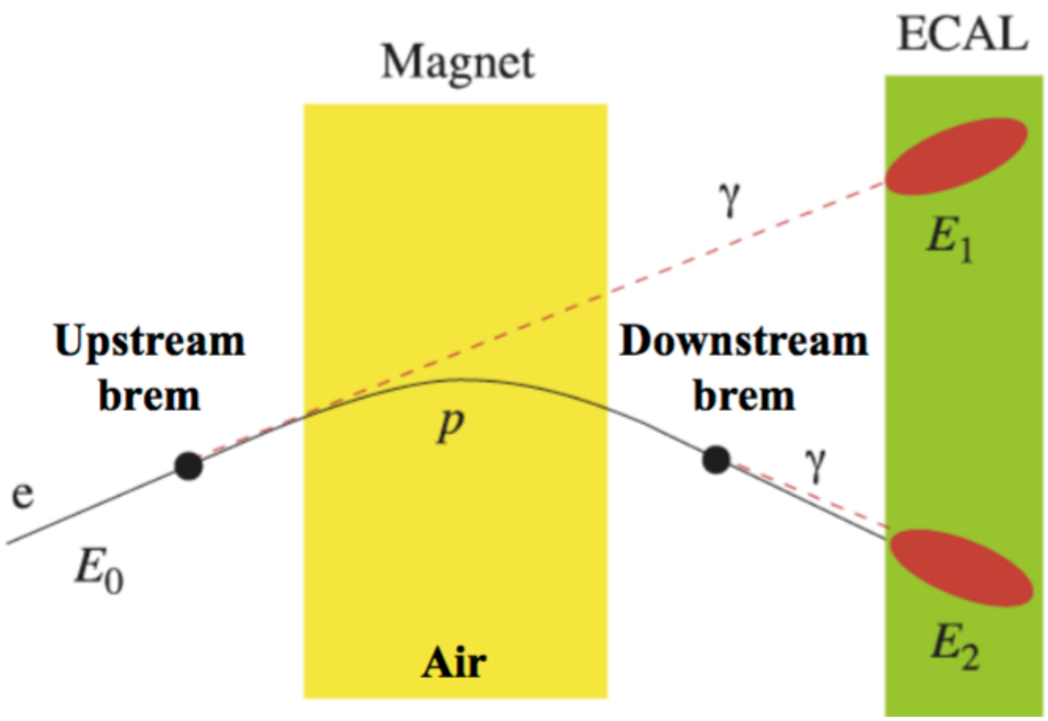
- These ratios are clean probes of NP :
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons
  - Small theoretical uncertainties because hadronic uncertainties cancel : $R_{\rm H} = 1$ in SM, neglecting lepton masses, with QED corrections at ~% level (when physical observables defined with LHCb choice of cuts on q^2 and on the reconstructed B mass, see Bordone, Isidori, Pattori)

Lepton identification is anything but universal!

- High occupancy in calorimeters→ trigger thresholds are higher for electrons (~2.5 to 3.0 GeV) than for muons (~1.5 to 1.8 GeV)
- Electrons emit a large amount of bremsstrahlung, degrading momentum and mass resolution. Two situations :

  - Downstream brem (wrt dipole bending magnet) Photon energy in the same calorimeter cell as the electron and momentum correctly measured
  - Upstream of the magnet Photon energy in different calorimeter cells than electron and momentum evaluated after bremsstrahlung

JHEP 08 (2017) 055



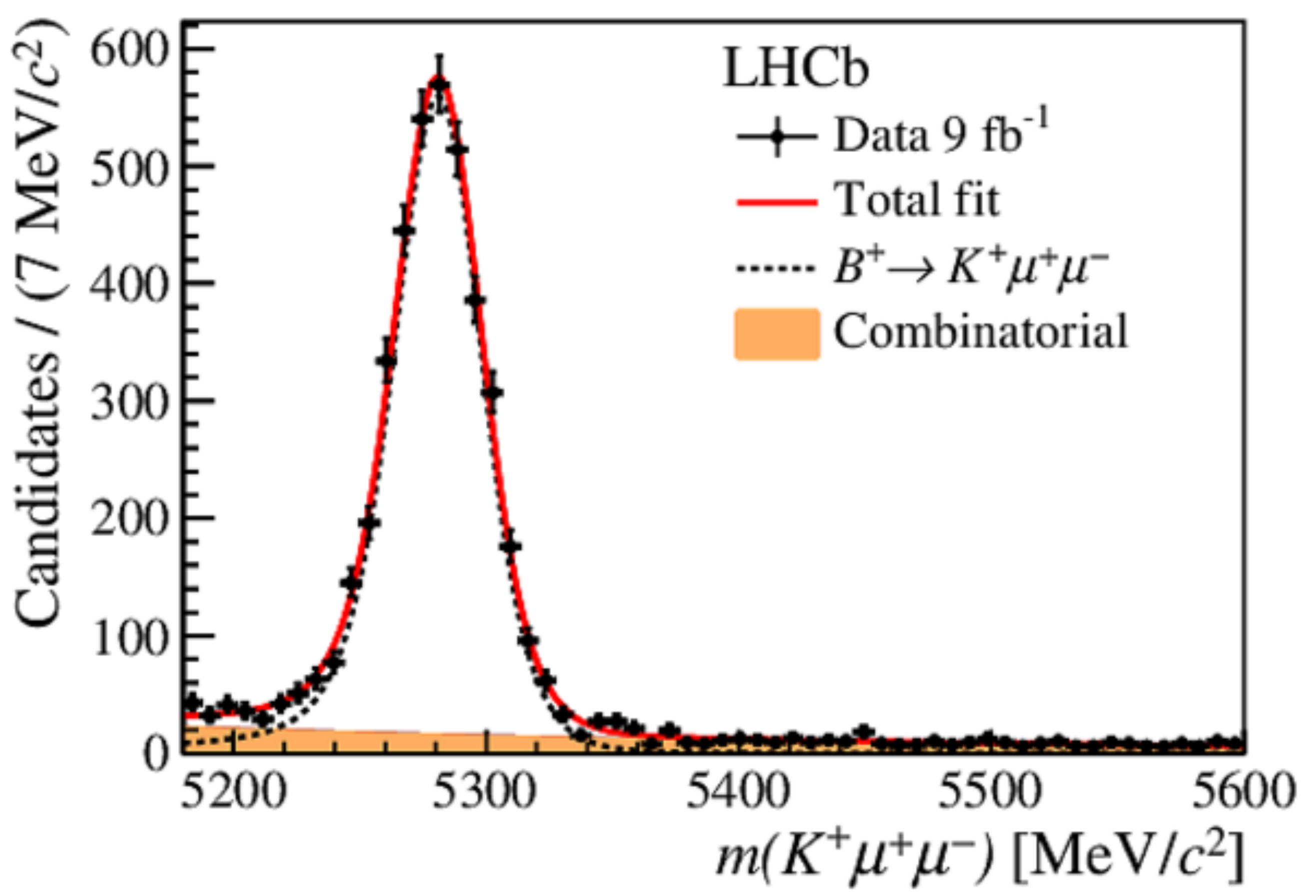
→ Look for photon clusters compatible with electron direction before magnet and "add" the cluster energy back to the electron momentum (if $E_T > 75\text{MeV}$)

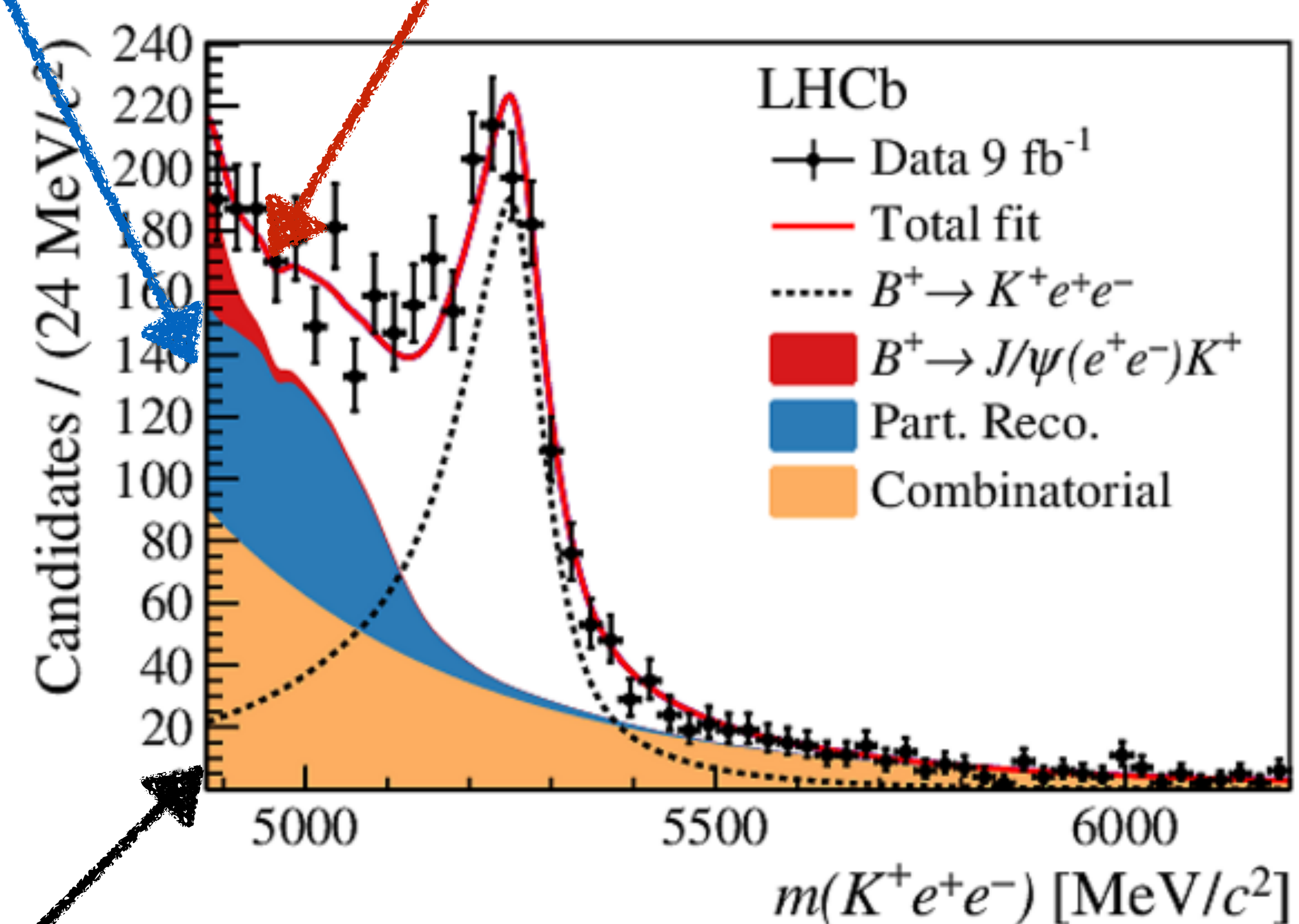
muons vs electrons

- Even after Bremsstrahlung recovery di-electron pair and B meson still have degraded mass resolution

Partially reconstructed background, mainly from $B^{0,+} \to K^{*0,+} e^+ e^-$ where a pion is lost

$B^+ \to K^+ J/\psi(e^+e^-)$ events where a photon is not reconstructed





Longer radiative tail due to bremsstrahlung

arXiv:2103.11769
Nature Physics

Measure as a double ratio

- To mitigate muon and electron differences, measurement performed as a double ratio with "resonant" control modes $B^0 \to J/\psi H$, which are not expected to be affected by NP:

$$R_{\mathrm{H}} = \frac{\mathcal{B}(B^0 \to H\mu^+\mu^-)}{\mathcal{B}(B^0 \to HJ/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to He^+e^-)}{\mathcal{B}(B^0 \to HJ/\psi(\to e^+e^-))}$$

$$R_H = \frac{N(B \longrightarrow H\mu^+\mu^-)}{\varepsilon(B \longrightarrow H\mu^+\mu^-)} \times \frac{\varepsilon(B \longrightarrow He^+e^-)}{N(B \longrightarrow He^+e^-)} \times \frac{N(B \longrightarrow HJ/\psi(e^+e^-))}{\epsilon(B \longrightarrow HJ/\psi(e^+e^-))} \times \frac{\varepsilon(B \longrightarrow HJ/\psi(\mu^+\mu^-))}{N(B \longrightarrow HJ/\psi(\mu^+\mu^-))}$$

→ Relevant experimental quantities: yields & (trigger, reconstruction and selection) and efficiencies for the four decay modes

- Similarities between the experimental efficiencies of the non resonant and resonant modes ensure a substantial reduction of systematic uncertainties in the double ratio. Note, however, that the cancellation does not apply to background.

- $r_{J/\psi} = \dfrac{B(B \to HJ/\psi(\mu^+\mu^-))}{B(B \to HJ/\psi(e^+e^-))}$ known to be compatible with unity within 0.4%

- Analyses performed blind

R_K measurement ($9\,\mathrm{fb}^{-1}$)

- Performed in q^2 interval $1.1 < q^2 < 6.0\,\mathrm{GeV}^2$

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

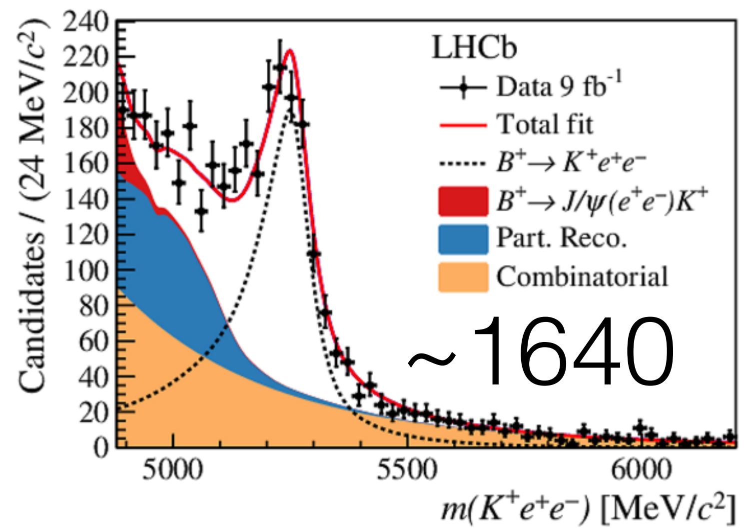
- Rare and J/ψ mode share identical selection apart from cut in q^2

$$R_K = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\;\varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\;\varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\;\varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\;\varepsilon^{J/\psi}_{e^+e^-}}$$

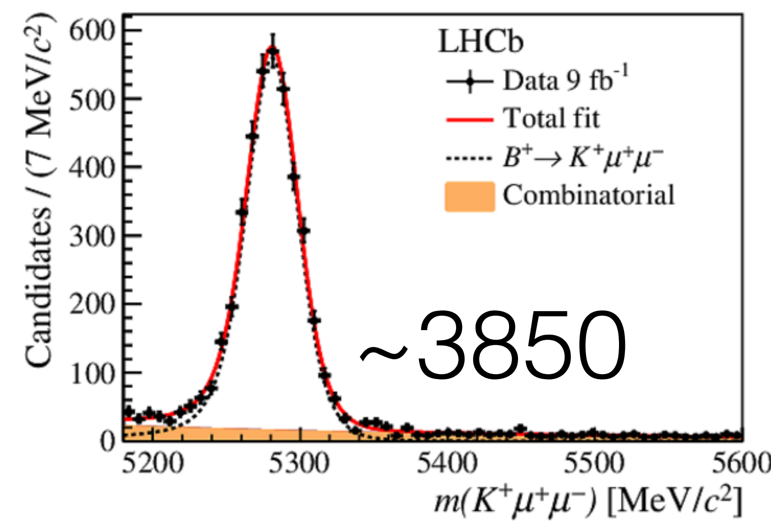
- Yields determined from fits to the invariant mass distributions
- Efficiencies computed using simulation calibrated with control channels in data

arXiv:2103.11769
Nature Physics

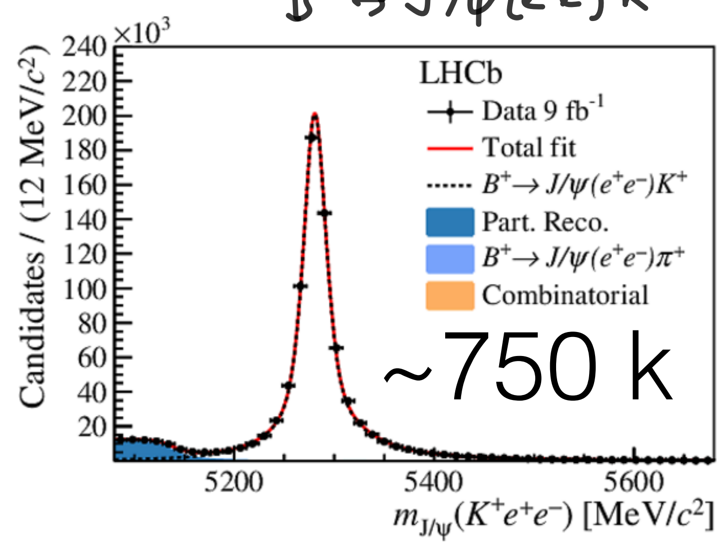
$B^+ \to K^+e^+e^-$



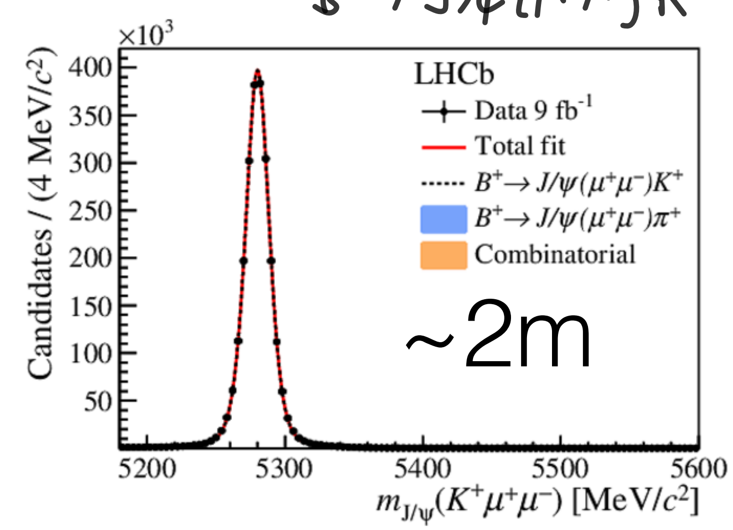
$B^+ \to K^+\mu^+\mu^-$



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



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



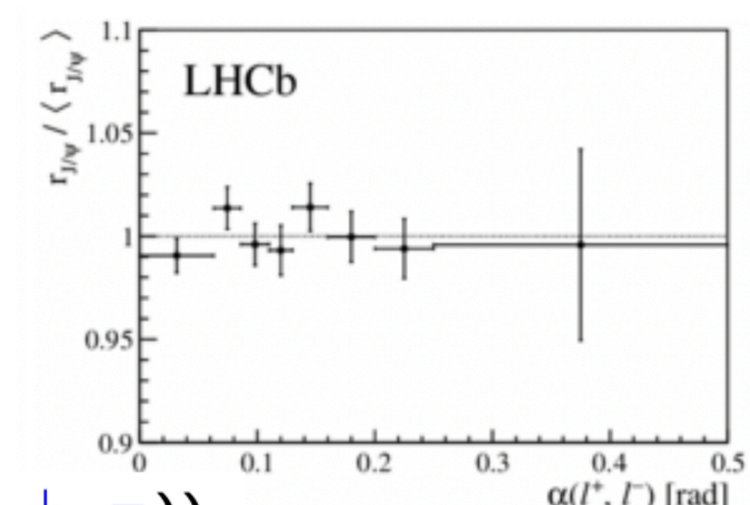
R_K cross-checks

- Large number of crosschecks performed before unblinding the results
- To ensure that the efficiencies are under control, measure

arXiv:2103.11769
Nature Physics

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

- Very stringent test, which does not benefit from the cancellation of the experimental systematics provided by the double ratio



- $r_{J/\psi} = 0.981 \pm 0.020$ - checked across datasets, samples and as a function of kinematics

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = 0.997 \pm 0.011$$

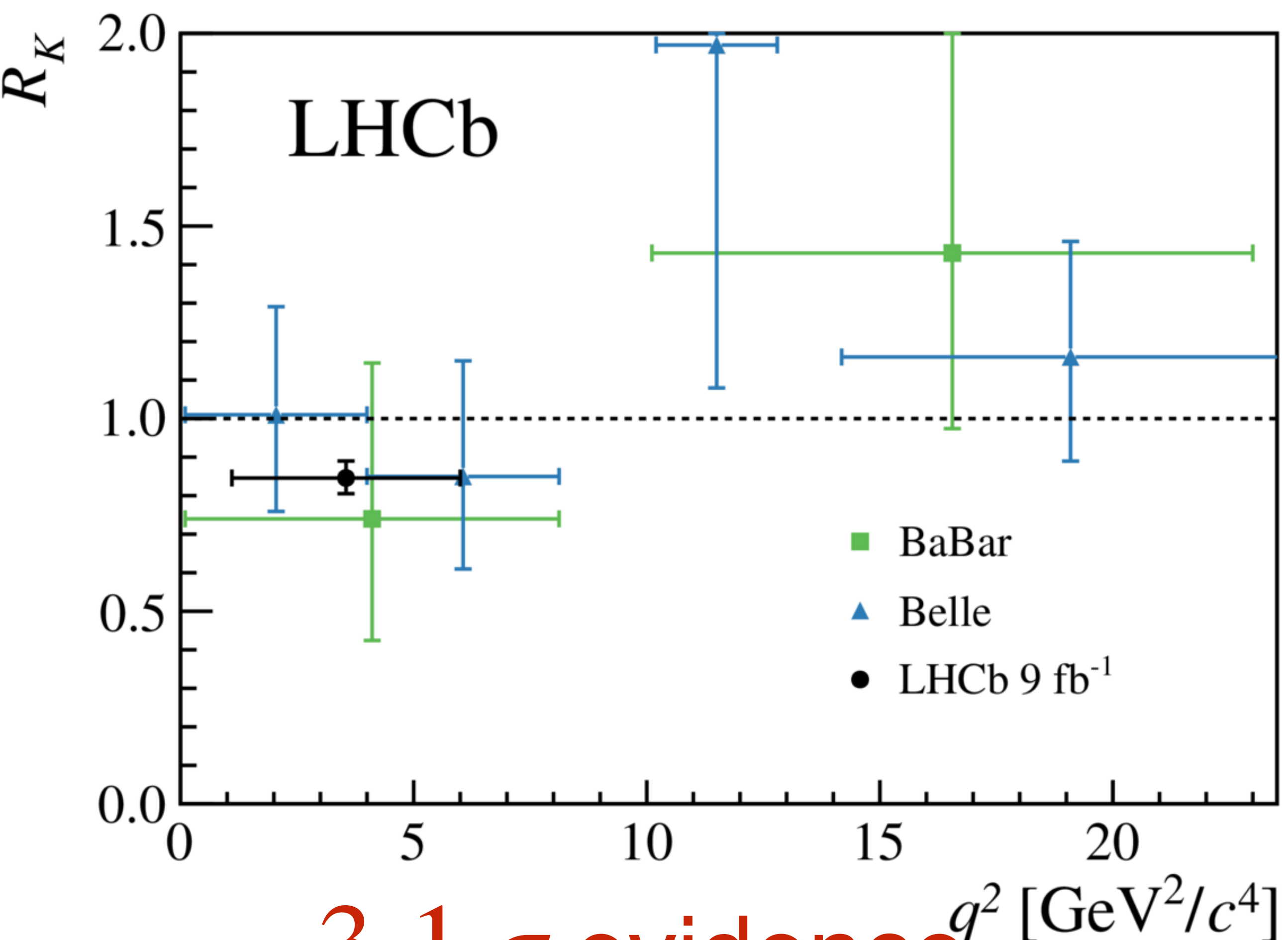
validation of the double-ratio procedure at q^2 away from J/ψ

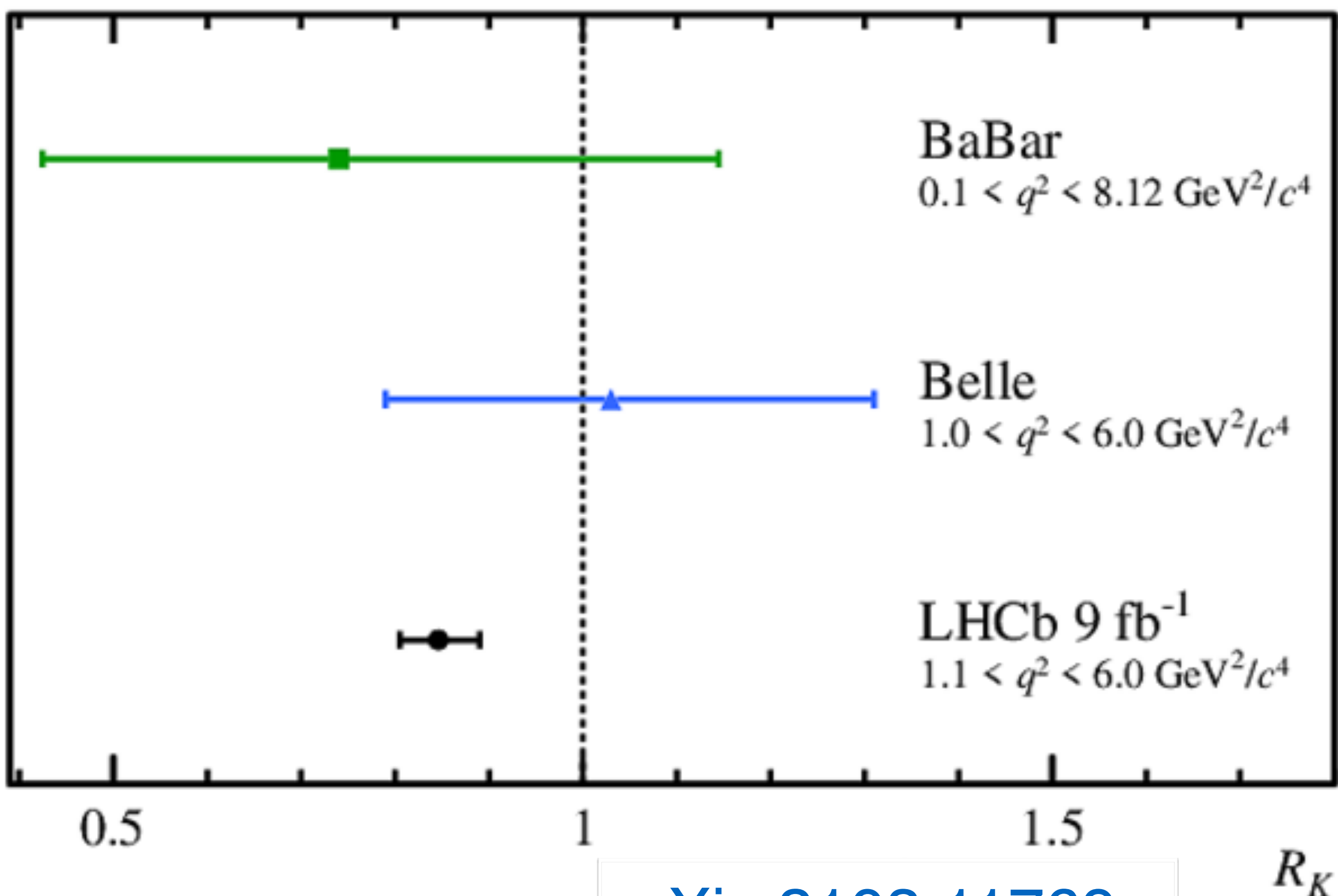
- If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus R_K) changes by ~3%

$R_K \; (B^+ \to K^+\ell^+\ell^-)$

- $R_K(1.1 < q^2 < 6.0\,\text{GeV}^2) = 0.846^{+0.042}_{-0.039}\,(\text{stat})\,^{+0.013}_{-0.012}\,(\text{syst})$

Dominant systematics (~1%) is due to modelling of signal and background components used in the fit





3.1 σ evidence

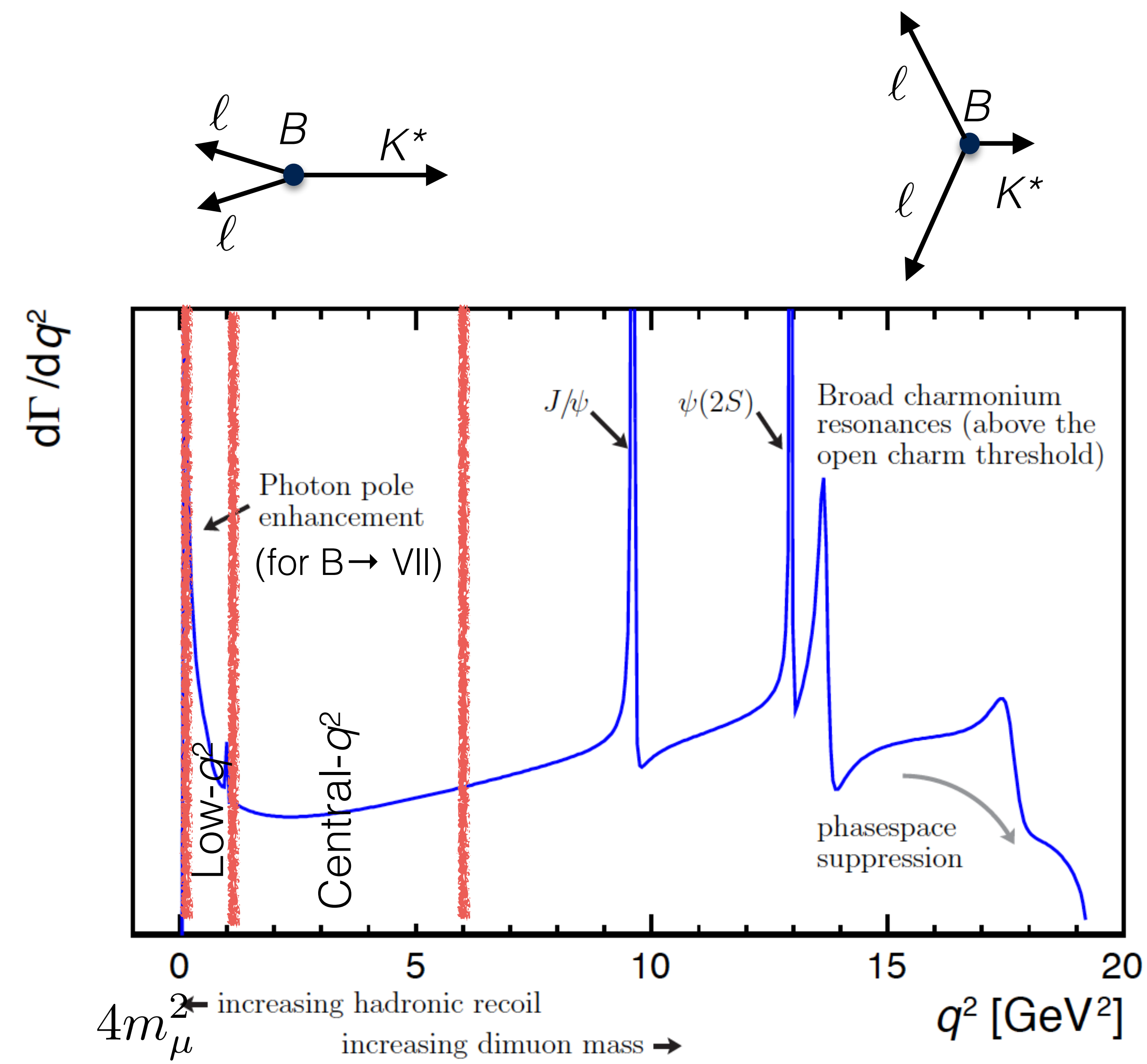
arXiv:2103.11769
Nature Physics

Another ratio: R_{K*}

$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

$$K^{*0}(892) \to K^+\pi^-$$

- LHCb performed measurement in two q^2 bins that are sensitive to different NP contributions (Run 1 data, 3 fb^{-1}):
  - Low-q^2 bin: [0.045,1.1] GeV^2
  - Central-q^2 bin: [1.1,6.0] GeV^2

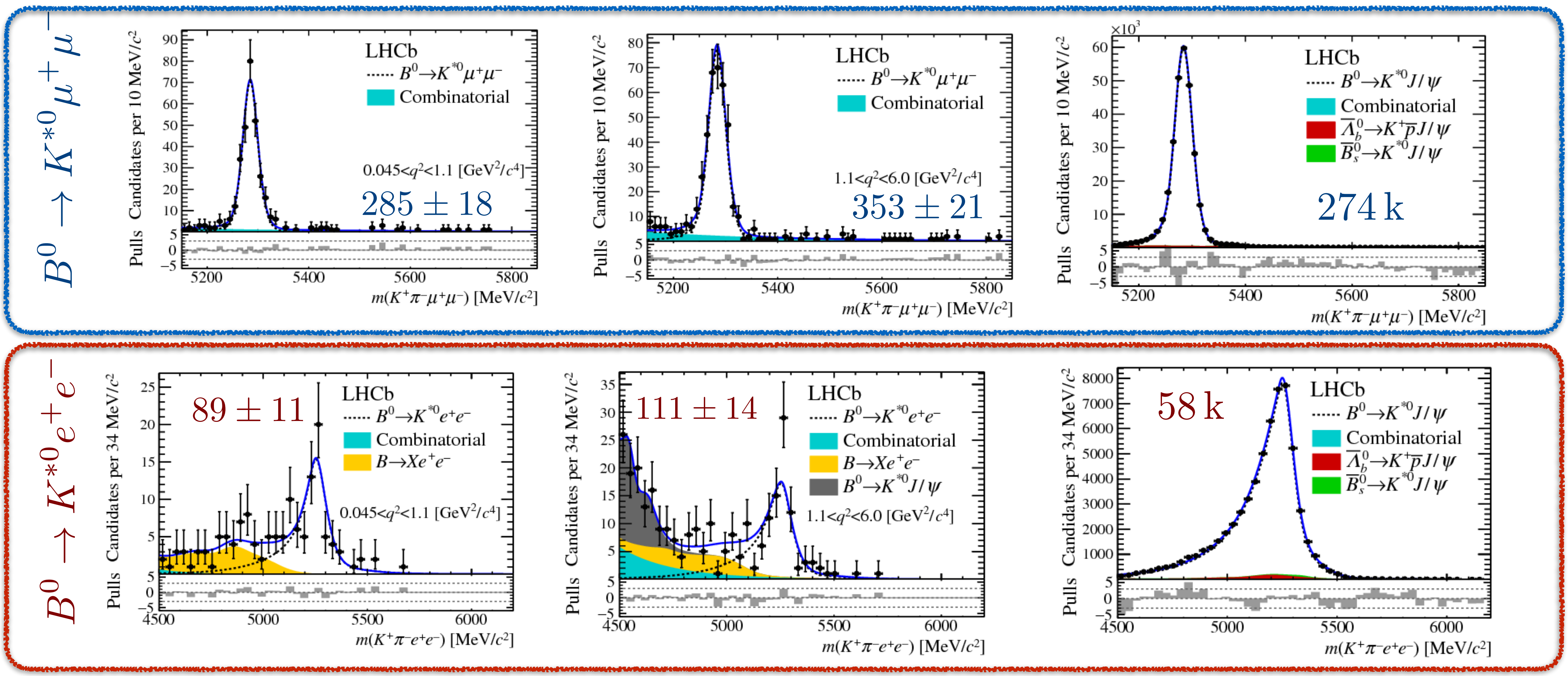


JHEP 08 (2017) 055

Fit to the invariant masses

JHEP 08 (2017) 055

Low-q^2 | Central-q^2 | $B^0 \to K^* J/\psi(\to \ell^+\ell^-)$



- Precision of measurement driven by statistics of electron sample : ~90 and 110 signal candidates in low-q^2 and central-q^2 , muon sample 3-5 times larger

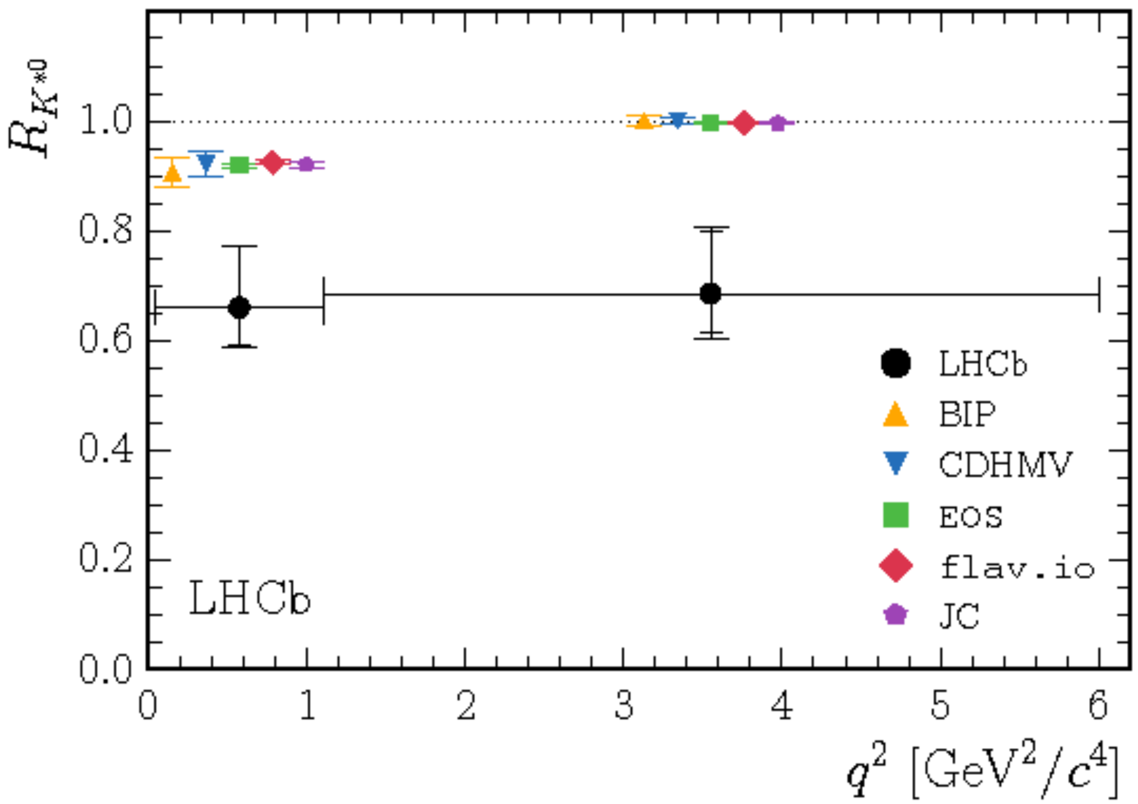
Crosschecks

- Large number of crosschecks performed before unblinding the results
- $r_{J/\psi} = \dfrac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$
  - test of absolute scale of the efficiencies
- $R_{\psi(2S)} = \dfrac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Bigg/ \dfrac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$ → 2% measurement, within 1σ from unity
- $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ in agreement with JHEP 04 (2017) 142
- If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus R_{K*}) changes by less than 5%

JHEP 08 (2017) 055

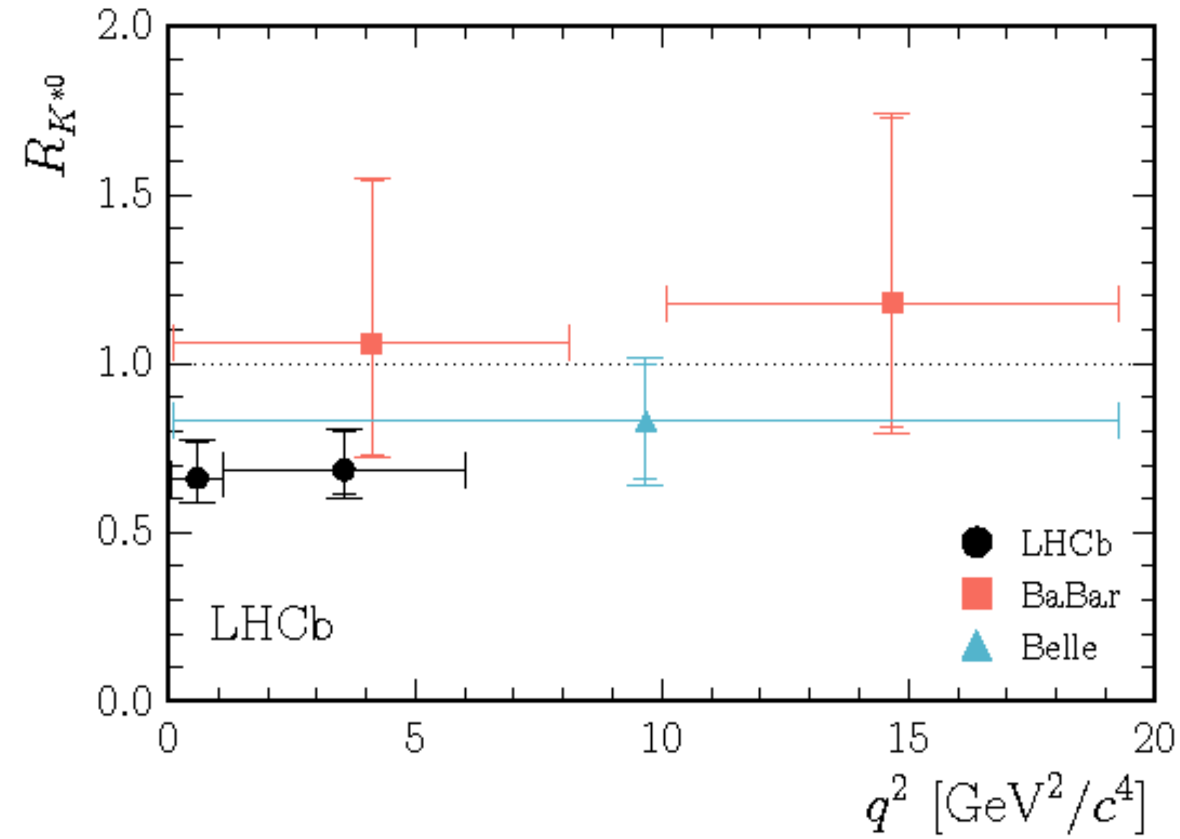
R_{K^*} results

Comparison with SM predictions



BIP: arXiv:1605.07633
CDHMV: arXiv:1510.04239, 1605.03156, 1701.08672
EOS: arXiv:1610.08761, https://eos.github.io
flav.io: arXiv:1503.05534, 1703.09189, flav-io/flavio
JC: arXiv:1412.3183

Comparison with BaBar & Belle



BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

LHCb: JHEP 08 (2017) 055

$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\,\text{GeV}^2 \end{cases}$$

2.1 - 2.3 σ
2.4 - 2.5 σ
below SM expectations

Tests of LFU with $B^0 \to K_s^0 \ell^+ \ell^-$ and $B^+ \to K^{*+} \ell^+ \ell^-$

arXiv:2110.09501

- Isospin partners of $B^+ \to K^+ \ell^+ \ell^-, B^0 \to K^{*0} \ell^+ \ell^-$, so potentially affected by the same NP
- Both channels involve long-lived $K_s^0 \to \pi^+ \pi^-$ ($K^{*+} \to K_s^0 \pi^+$) → similar BF than their isospin partners, but lower efficiency because of the K_s^0 reconstruction
- $R_{K_s^0}$ and $B(B^0 \to K_s^0 \ell^+ \ell^-)$ measured in the region $1.1 < q^2 < 6\,\mathrm{GeV}^2$
- For $R_{K^{*+}}$ and $B(B^+ \to K^{*+} \ell^+ \ell^-)$ q^2 range extended down to $0.045\ \mathrm{GeV}^2$ to increase statistics
- Ratios and differential BFs normalised to control modes $B^0 \to J/\Psi(\ell^+ \ell^-)\, K_S^0$, $B^+ \to J/\Psi(\ell^+ \ell^-)\, K^{*+}$

Tests of LFU with $B^0 \to K^0_{\rm S}\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$

- $$R^{-1}_{K^{(*)}} = \frac{\mathcal{B}(B\to K^{(*)}e^+e^-)}{\mathcal{B}(B\to J/\psi\,(e^+e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to J/\psi\,(\mu^+\mu^-)\,K^{(*)})}$$
$$= \left(\frac{N^{ee}_{\rm sig}}{\epsilon^{ee}_{\rm sig}}\cdot\frac{\epsilon^{ee}_{\rm con}}{N^{ee}_{\rm con}}\right) \Big/ \left(\frac{N^{\mu\mu}_{\rm sig}}{\epsilon^{\mu\mu}_{\rm sig}}\cdot\frac{\epsilon^{\mu\mu}_{\rm con}}{N^{\mu\mu}_{\rm con}}\right)$$ with $K^{(*)} = K^0_{\rm S}, K^{*+}$

- $$r^{-1}_{J/\psi K^{(*)}} \equiv \frac{\mathcal{B}\left(B\to J/\psi\,(e^+e^-)\,K^{(*)}\right)}{\mathcal{B}\left(B\to J/\psi\,(\mu^+\mu^-)\,K^{(*)}\right)} = \frac{N^{ee}_{\rm con}}{N^{\mu\mu}_{\rm con}}\frac{\epsilon^{\mu\mu}_{\rm con}}{\epsilon^{ee}_{\rm con}}$$

$$r^{-1}_{J/\psi K^0_{\rm S}} = 0.977 \pm 0.008 \pm 0.027$$
$$r^{-1}_{J/\psi K^{*+}} = 0.965 \pm 0.011 \pm 0.034$$

arXiv:2110.09501

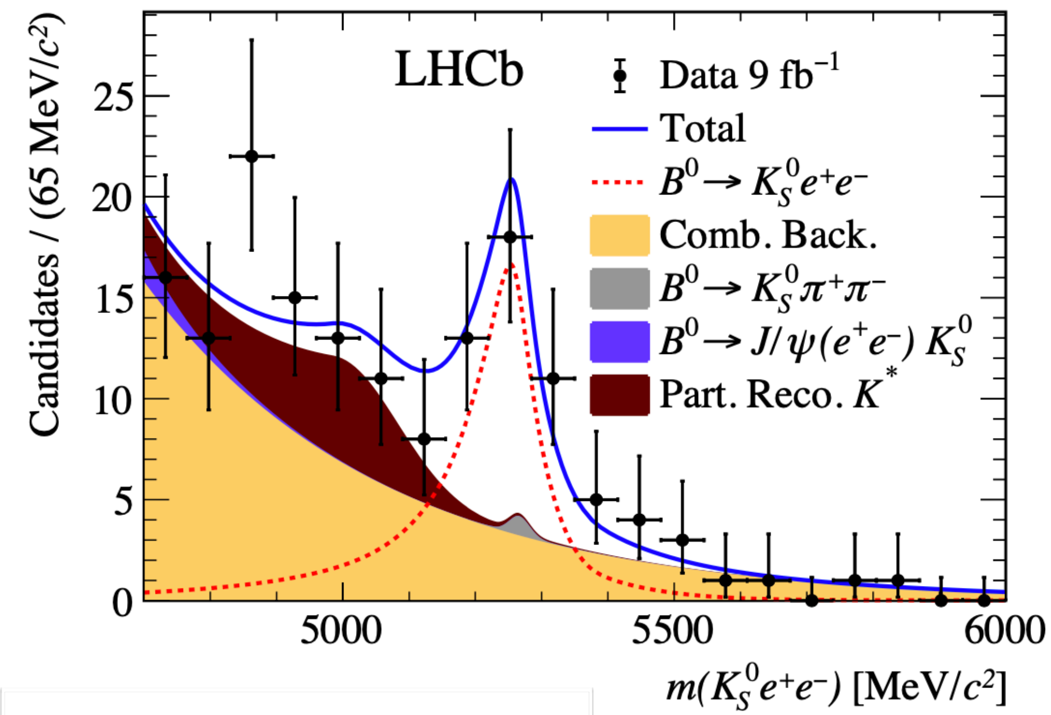
- $$R^{-1}_{\psi(2S)K^0_{\rm S}} = 1.014 \pm 0.030\,(\text{stat.}) \pm 0.020\,(\text{syst.})$$
$$R^{-1}_{\psi(2S)K^{*+}} = 1.017 \pm 0.045\,(\text{stat.}) \pm 0.023\,(\text{syst.})$$

Tests of LFU with $B^0 \to K^0_s \ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$

- e^+e^- modes observed for first time:

$$\frac{d\mathcal{B}(B^0 \to K^0 e^+e^-)}{dq^2} = (2.6 \pm 0.6 \pm 0.1) \times 10^{-8}\,\mathrm{GeV}^{-2}$$

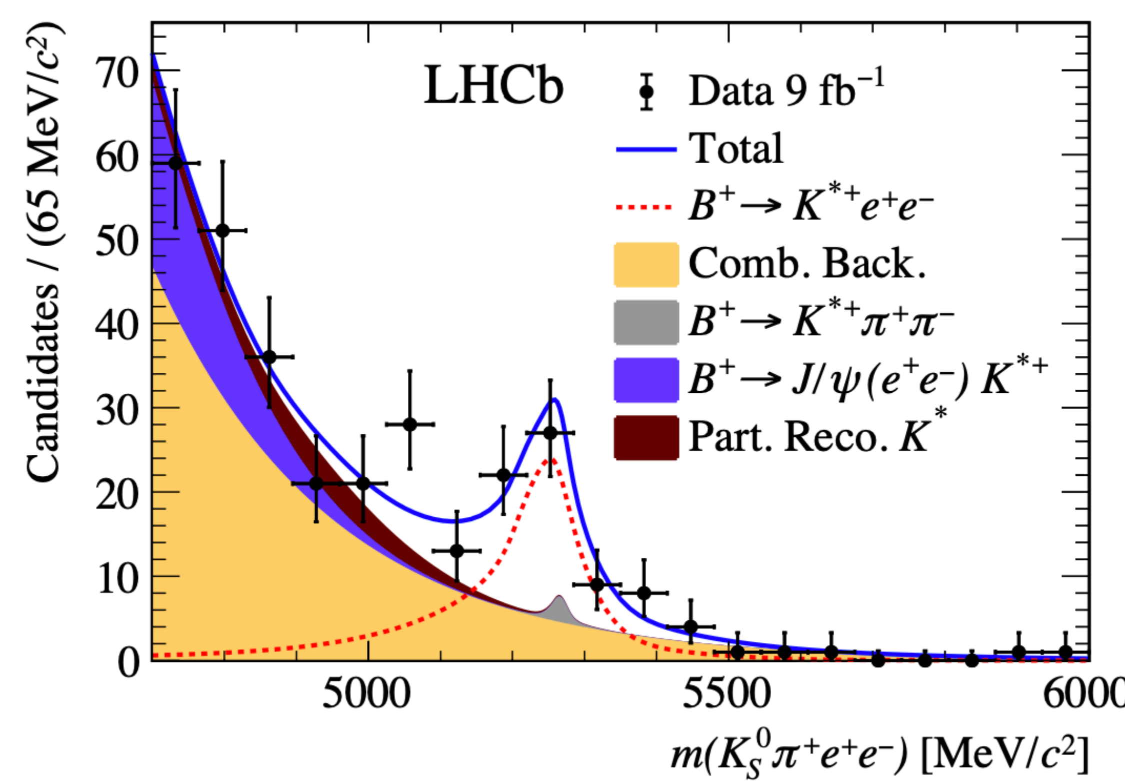
$q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2$ $\quad 5.3\sigma$



arXiv:2110.09501

$$\frac{d\mathcal{B}(B^+ \to K^{*+} e^+e^-)}{dq^2} = (9.2^{+1.9+0.8}_{-1.8-0.6}) \times 10^{-8}\,\mathrm{GeV}^{-2}$$

$q^2 \in [0.045, 6.0]\ \mathrm{GeV}^2$ $\quad 6.0\sigma$



$R_{K^0_S}$ & $R_{K^{*+}}$

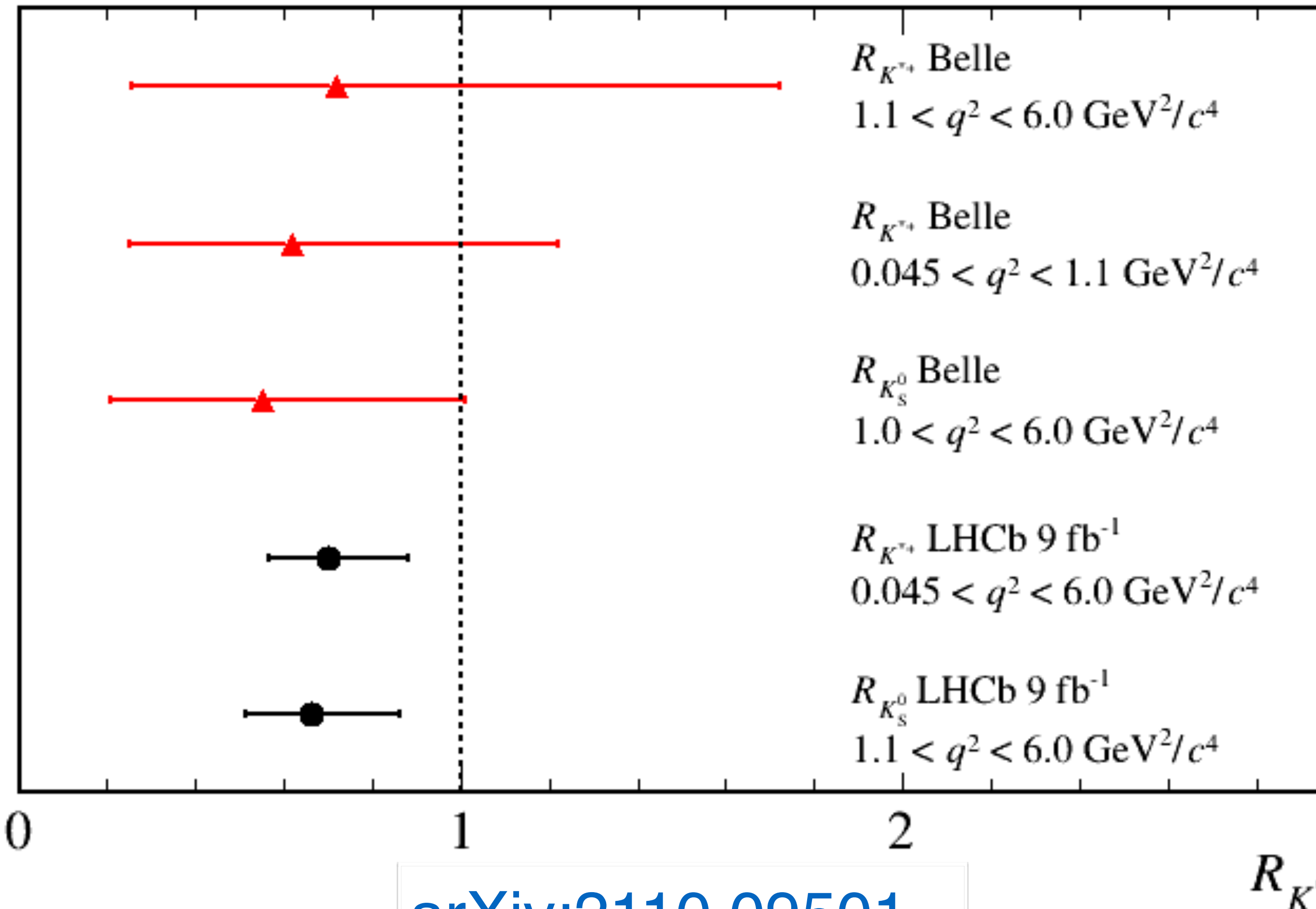
- Results are in agreement with SM and with previous results from Belle

$$R_{K^0_S} = 0.66^{+0.20}_{-0.14}(\text{stat.})^{+0.02}_{-0.04}(\text{syst})$$

$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\text{stat.})^{+0.03}_{-0.04}(\text{syst})$$

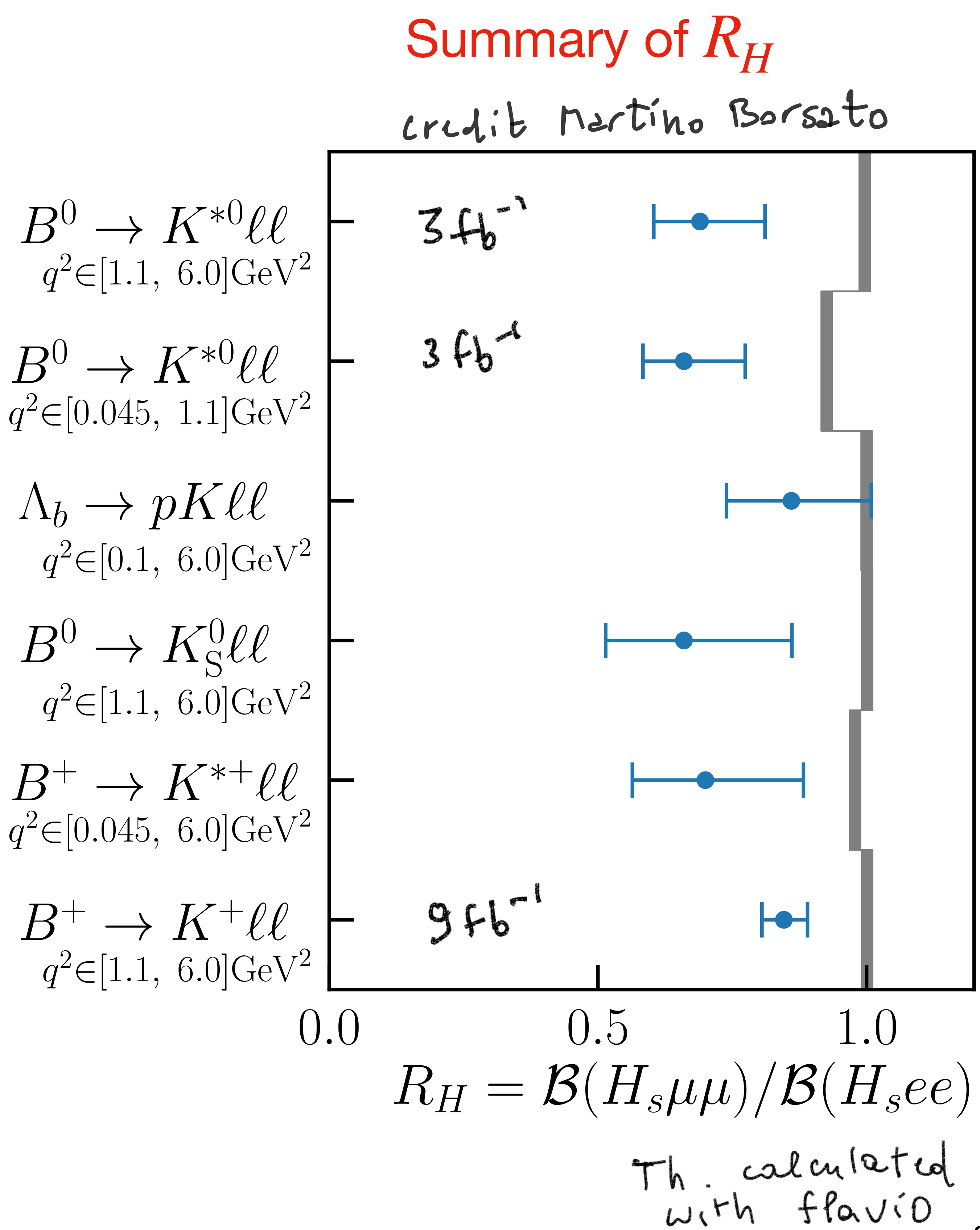
- Central values exhibit same pattern of deviation of isospin partners R_{K^+} and $R_{K^{*0}}$

- Paper dedicated to the memory of Sheldon Stone [1946-2021]

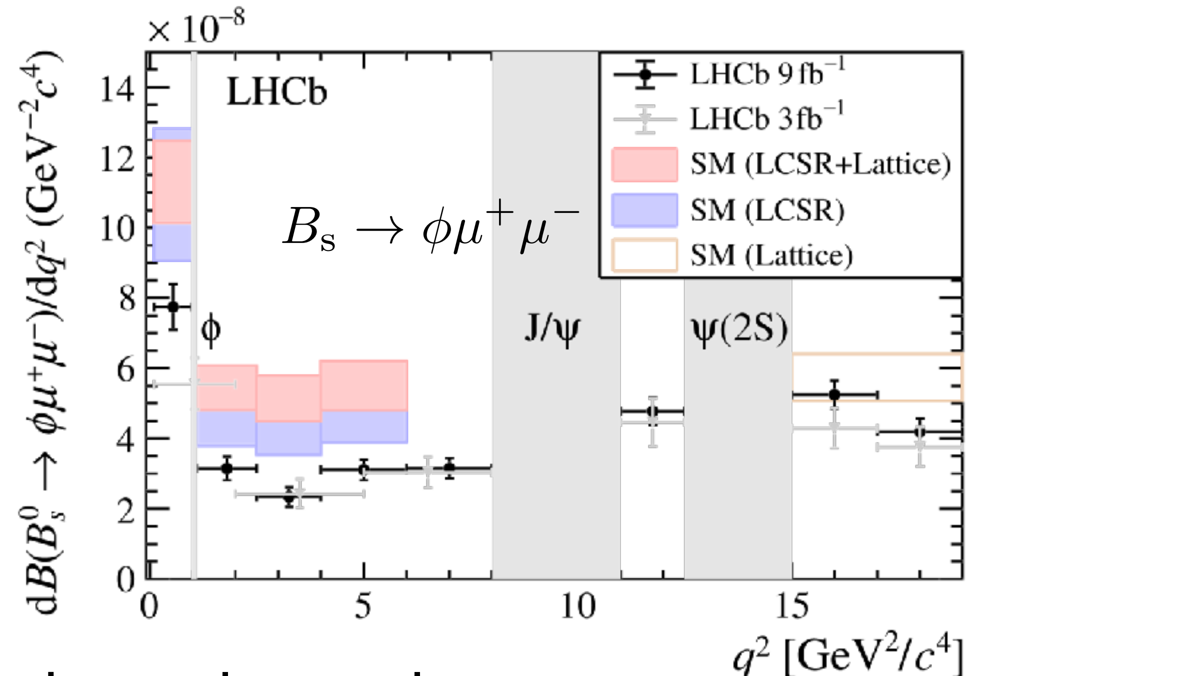


arXiv:2110.09501

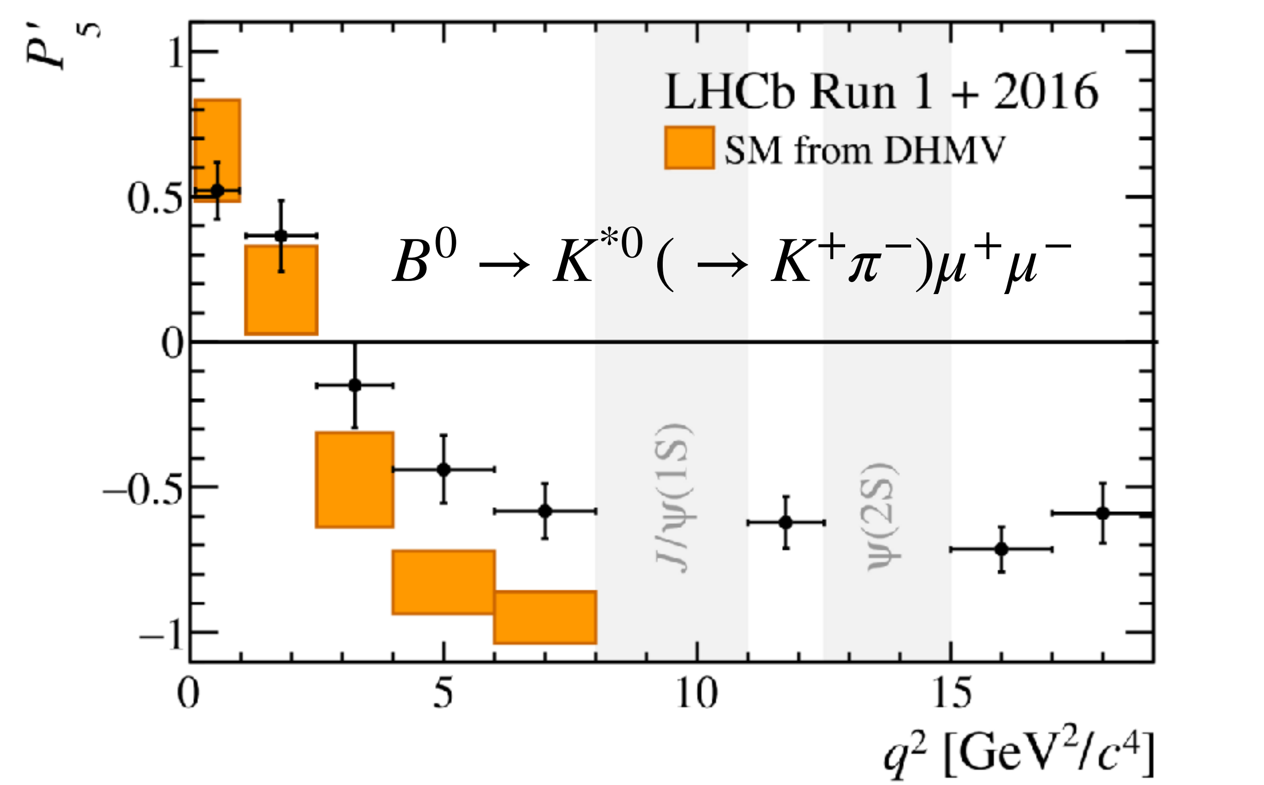
A very intriguing pattern



- Coherent set of $b \to s\ell\ell$ tensions in BFs
  $B^+ \to K^+\mu^+\mu^-, B^0 \to K^{(*)0}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-$.

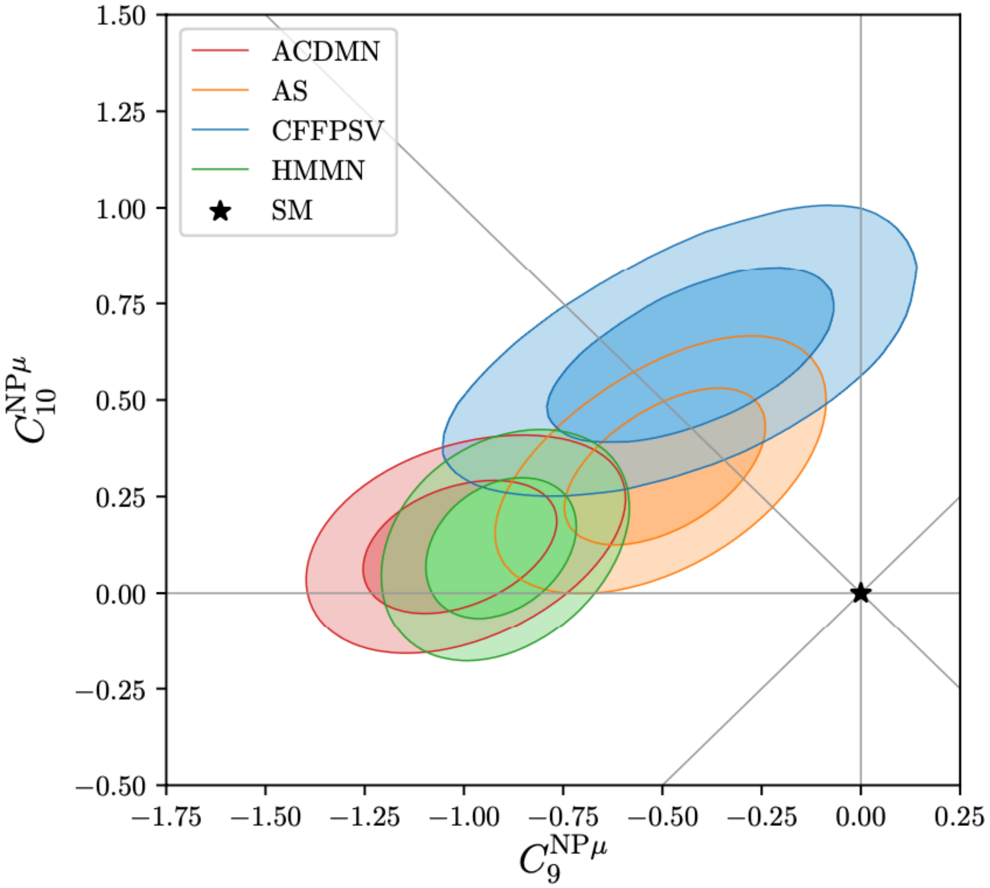


- and angular analyses

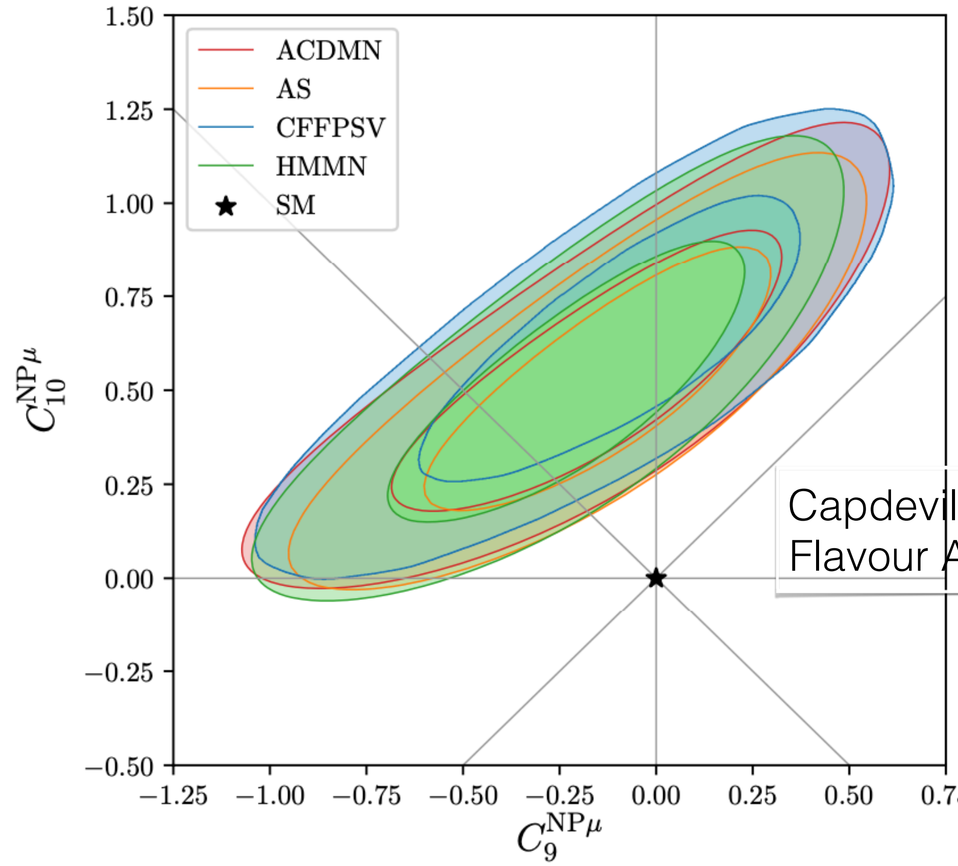


Global fit to $b \to s\ell^+\ell^-$ data

Global fit of $b \to s\ell^+\ell^-$



Fit of LFU observables & $B \to \mu^+\mu^-$



C_9 (Vector) and
C_{10} (Axial-vector) couplings

Capdevila, Fedele, Neshatpour, Stangl
Flavour Anomaly Workshop, 20 October 2021

- Discrepancy in numerous $b \to s\ell^+\ell^-$ observables can be explained consistently

- P'_5 anomaly [$B \to K^*\mu\mu$ angular distribution]
- Smallness of all $B \to H_s\,\mu\mu$ rates
- LFU ratios (μ vs. e) in $H_b \to H_s\, ll$ decays
- Smallness of BR($B_s \to \mu\mu$)

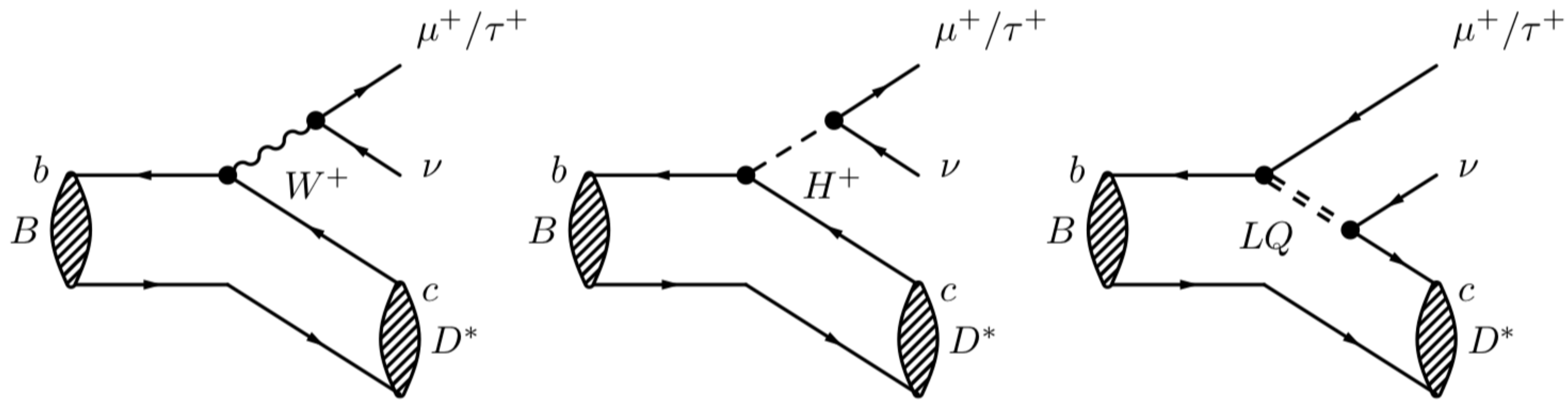
Gino's categorization

= th. error $\lesssim 1\%$

= th. error few %

Another puzzling result in tree-level $b \to c$ transitions

LFU studies in $B \to D^{(*)}\tau\nu$ decays



- Different class of decays (tree-level charged current with V_{cb} suppression)

- Not at all rare: $B(B^0 \to D^{*-}\tau^+\nu_\tau) \sim 1\,\%$, problem is the background

- Lepton-universality ratio R(D*) : $R(D^*) = \dfrac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$
  - sensitive to any NP model coupling preferentially to third generation leptons

- Predicted theoretically at ~1%: $R(D)_{SM} = 0.299 \pm 0.003$
  $R(D^*)_{SM} = 0.258 \pm 0.005$

HFLAV average, 2019

- Studied by Belle, BaBar and LHCb

Experimental challenges

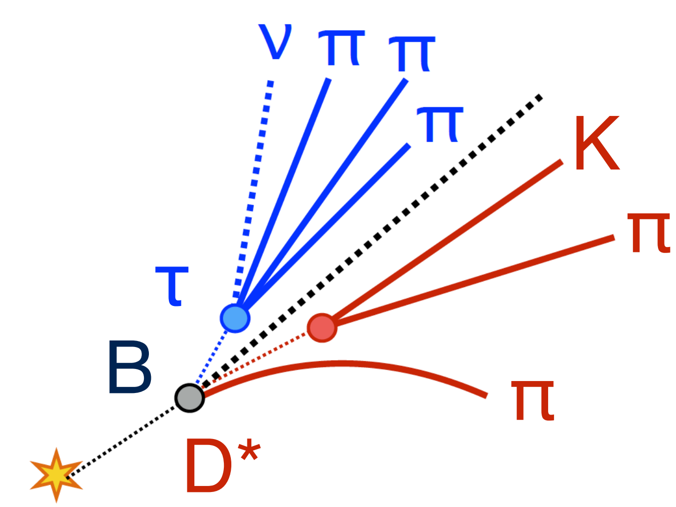
- $B^0 \to D^{*-}\tau^+\nu_\tau$: at least two neutrinos in the final state (three if using $\tau \to \mu\nu\nu$)

- At the LHC, as opposed to B factories, the rest of the event does not provide any useful kinematic constraint. However, profit from large boost and excellent vertexing capabily

- LHCb used both $\tau^+ \to \mu^+\nu\bar{\nu}$ and $\tau^+ \to \pi^+\pi^-\pi^+$

$$\begin{cases} \tau^+ & \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau \\ D^{*-} & \to \overline{D}^0(\to K^+\pi^-)\pi^- \end{cases}$$

Three-prong mode used for the first time!

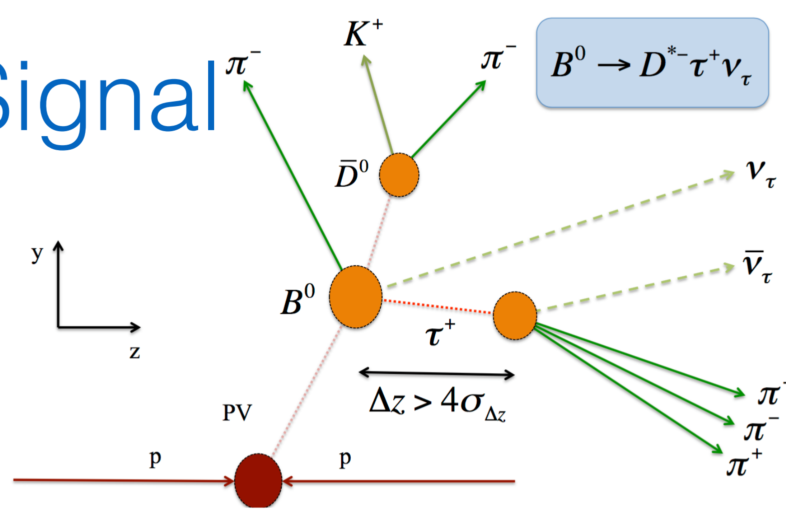


  - A semileptonic decay with no (charged) lepton in final state (one K, five π) ➞ Zero background from $B^0 \to D^{*-}\mu^+\nu_\mu X$
  - However, signal to noise ratio less than 1% ➞ need at least 10^3 rejection!
  - Large background, notably from $B \to D^{*-}3\pi X$ (BF~100 x signal) and $B \to D^{*-}D_S^+(X)$ (BF~10 x signal, same vertex topology)

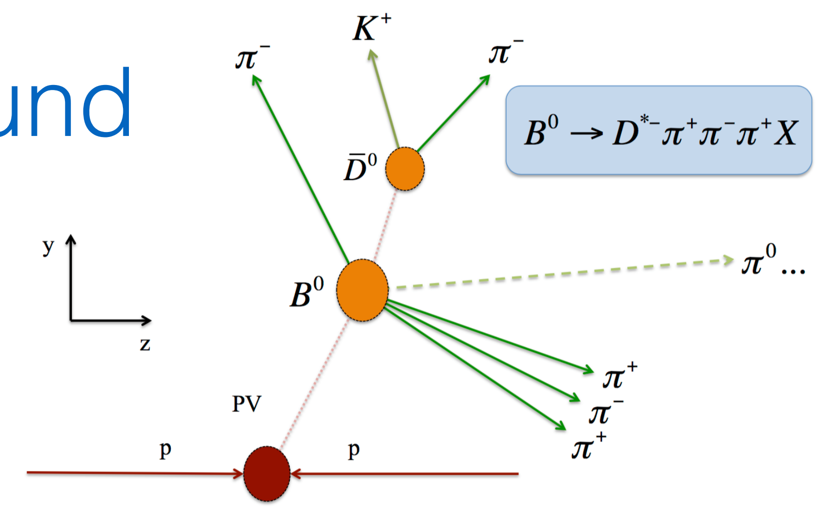
Background reduction

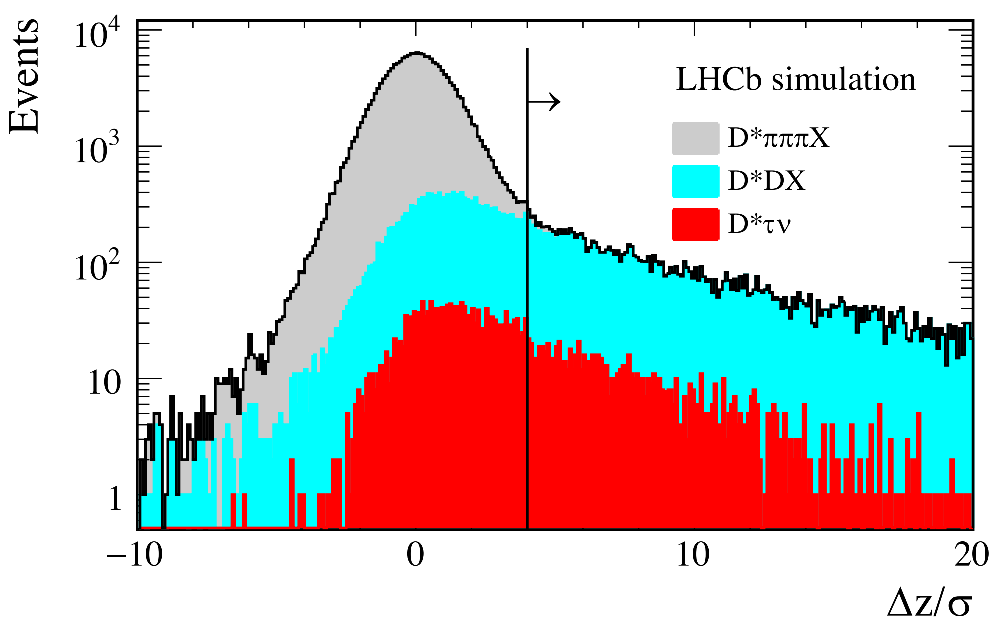
- Separation between B and 3π vertices (Δz>4σ$_{\Delta z}$) crucial to obtain the required rejection of $B \to D^{*-}3\pi X$

Signal



Background



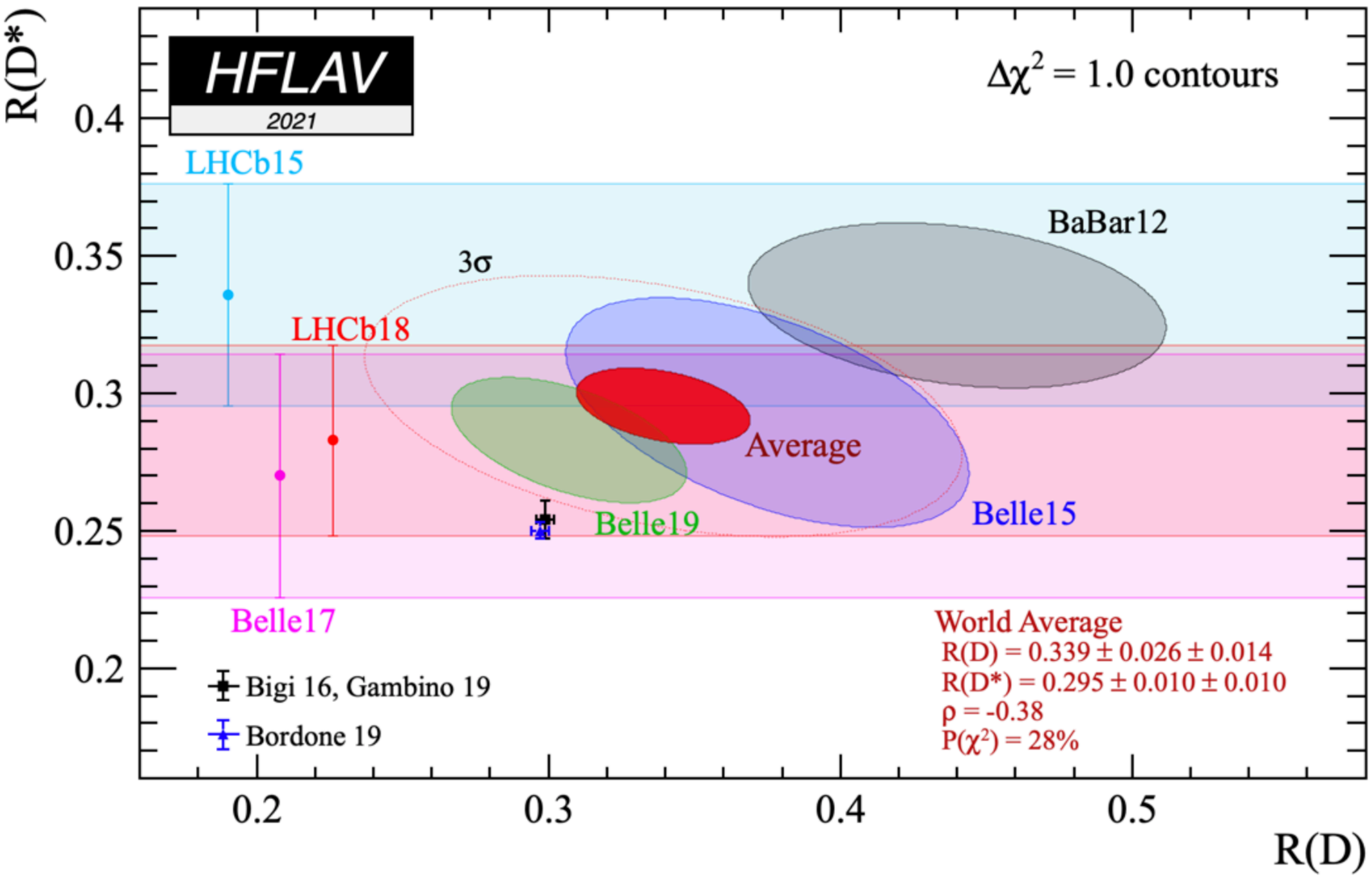


- Remaining double-charm background ($B \to D^{*-}D_S^+(X)$) suppressed by employing a multivariate classifier

PRL120 (2018) 171802
PRD 97 (2018) 072013

$$R(D^{*-}) = 0.291 \pm 0.019\,(\mathrm{stat}) \pm 0.026\,(\mathrm{syst}) \pm 0.013\,(\mathrm{ext})$$ ~1.1σ > SM

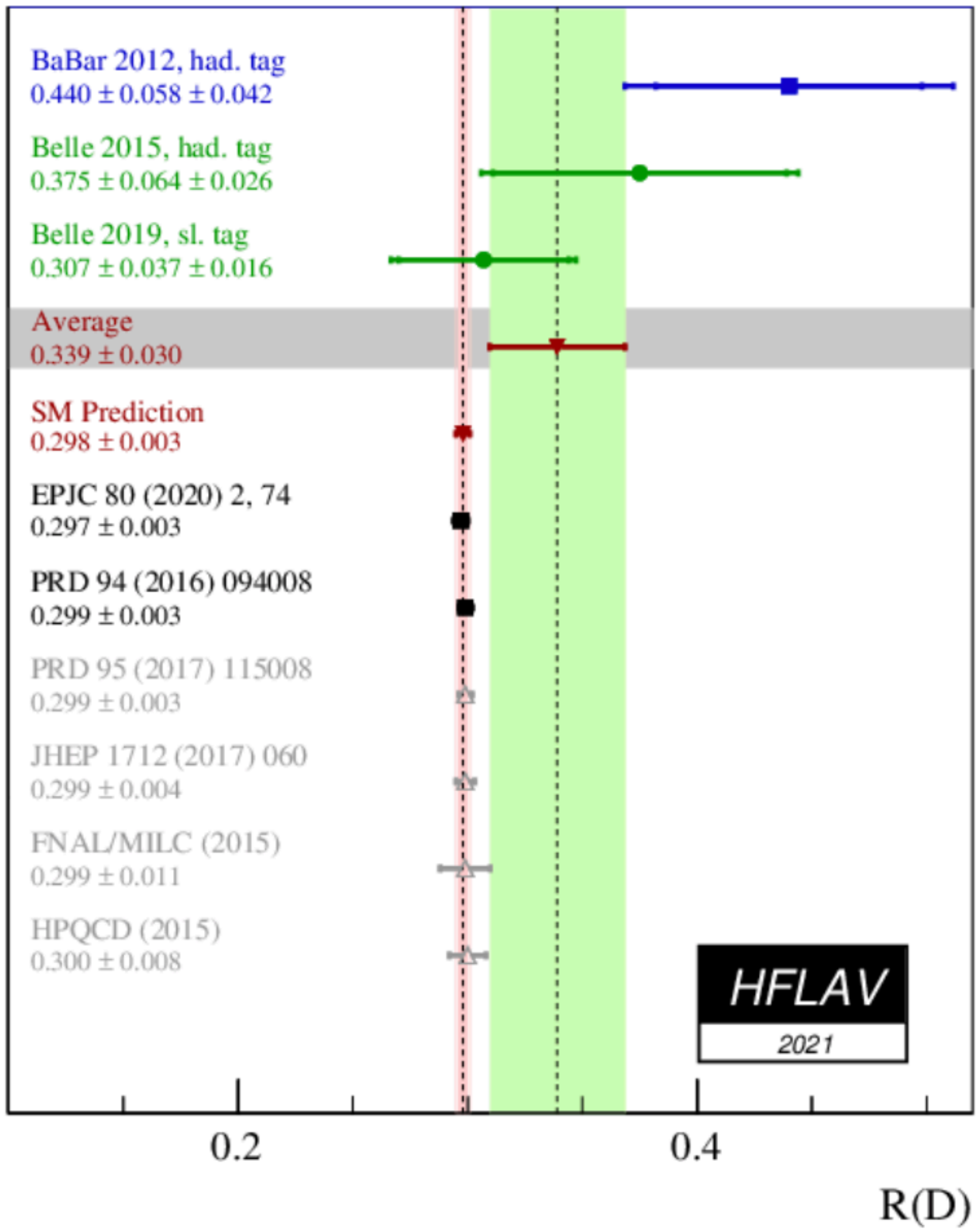
$R(D)$ vs $R(D^*)$

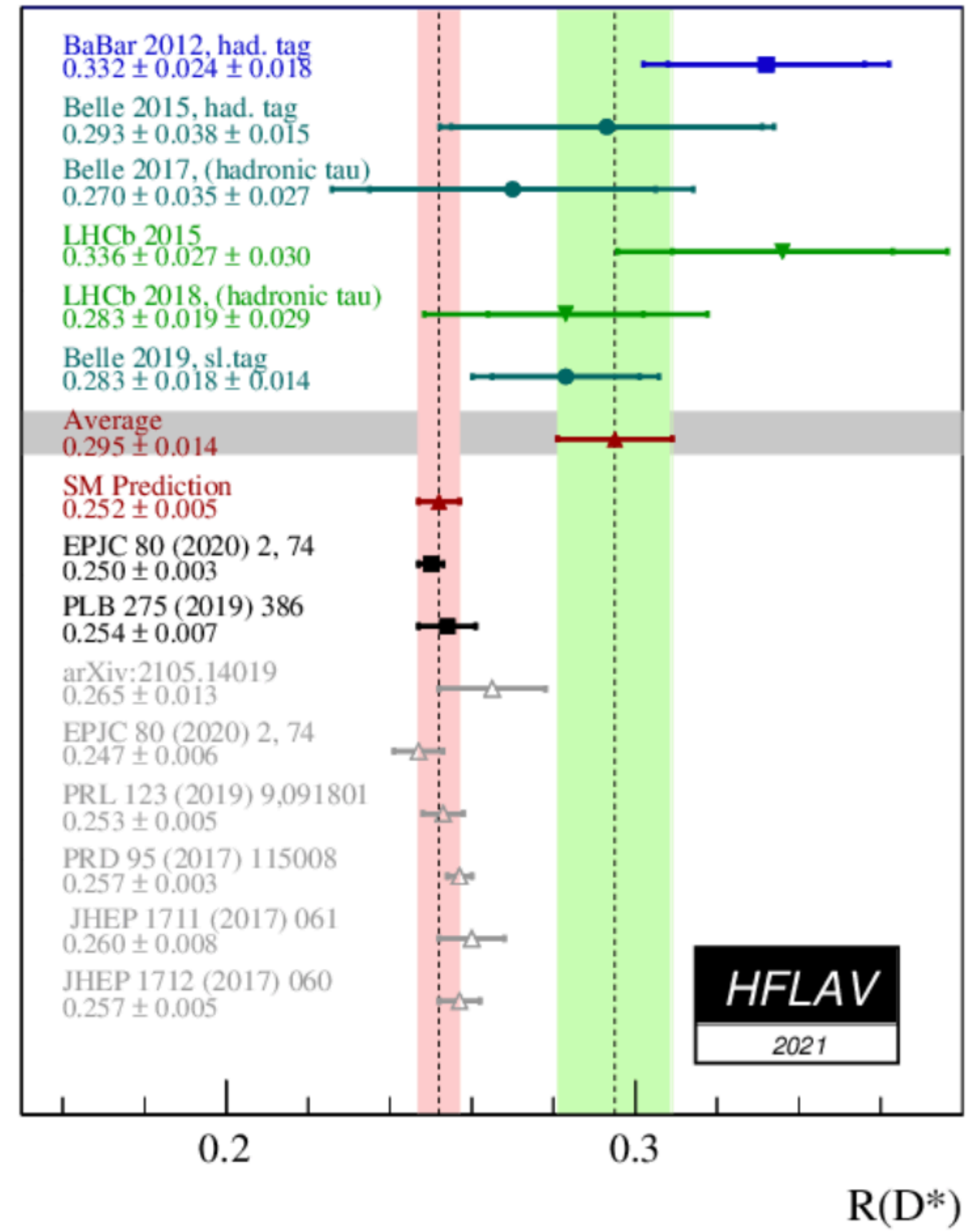


BaBar to deliver another precise measurement of $R(D^{(*)})$ after a decade, more data-driven

- All experiments see an excess wrt SM predictions: $\sim 3.4\sigma$ tension
- intriguing as it occurs in a tree-level SM process ($\Lambda_{NP} \lessapprox 3\,\mathrm{TeV}$)
- 2.9σ effect on $R(D^*)$

$R(D)$ vs $R(D^*)$





- All experiments see an excess wrt SM predictions: $\sim 3.4\sigma$ tension
- intriguing as it occurs in a tree-level SM process ($\Lambda_{NP} \lesssim 3\,\mathrm{TeV}$)
- 2.9σ effect on $R(D^*)$

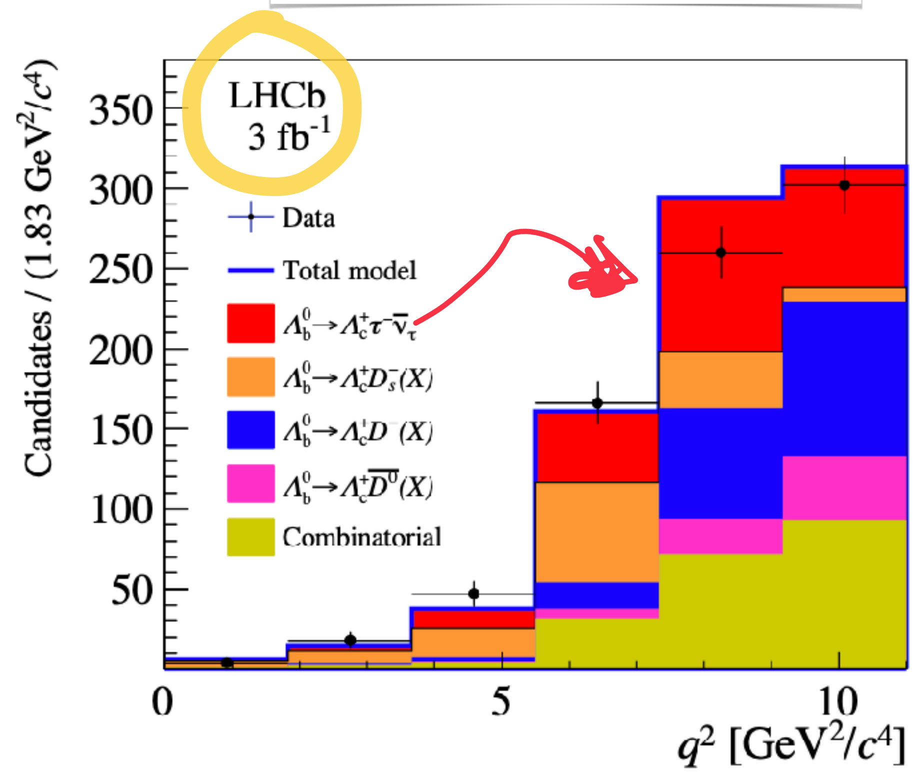
Measurement of $B(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)$ and $R(\Lambda_c)$ with $\tau \to 3\pi$

- Decay observed for the first time with 6.1σ significance

arXiv:2201.03497

- Measure

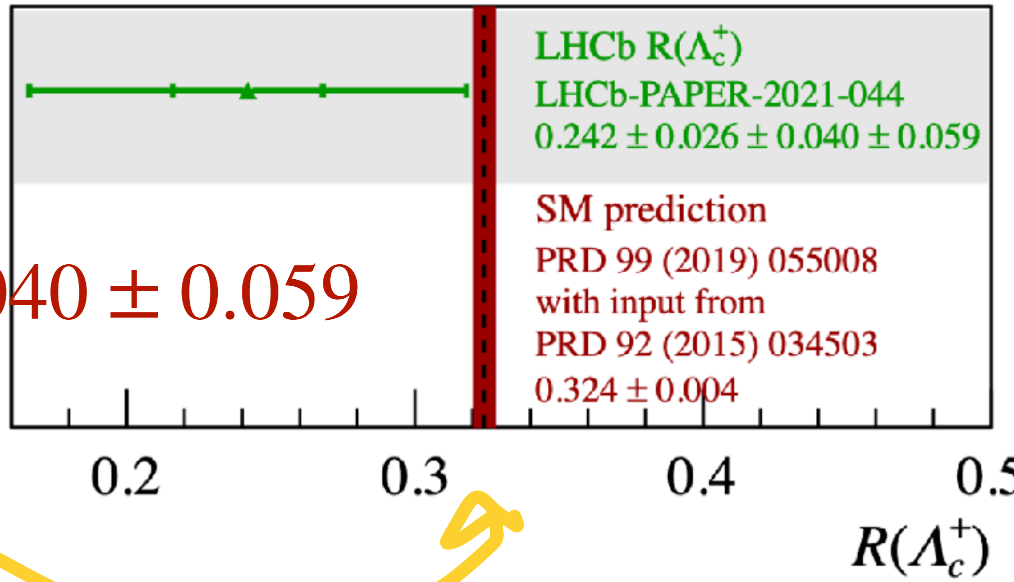
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \frac{1}{\mathcal{B}(\tau^- \to 3\pi(\pi^0)\nu_\tau)}$$



- Input from CDF+LHCb on $B(\Lambda_b^0 \to \Lambda_c^+ 3\pi)$ gives
  $B(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\,\%$

- Input from DELPHI on $B(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)$ gives

$$R(\Lambda_c^+) \equiv \frac{B(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{B(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)} = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$



in agreement with SM

A word on LFV

- Many models proposed to explain these tensions naturally allow for LFV processes with rates that are experimentally accessible

- Searches for $b \to s\mu^{\pm}e^{\mp}$ are particularly important in view of the anomalies. Published limits from LHCb:

$$B(B^0_{(s)} \to \mu^{\pm}e^{\mp}) < 5.4 \times 10^{-9} \text{ @ } 90\,\%\,\text{CL}$$

$$B(B^+ \to K^+\mu^+e^-) < 6.4 \times 10^{-9} \text{ @ } 90\,\%\,\text{CL}$$

$$B(B^+ \to K^+\mu^-e^+) < 7.0 \times 10^{-9} \text{ @ } 90\,\%\,\text{CL}$$

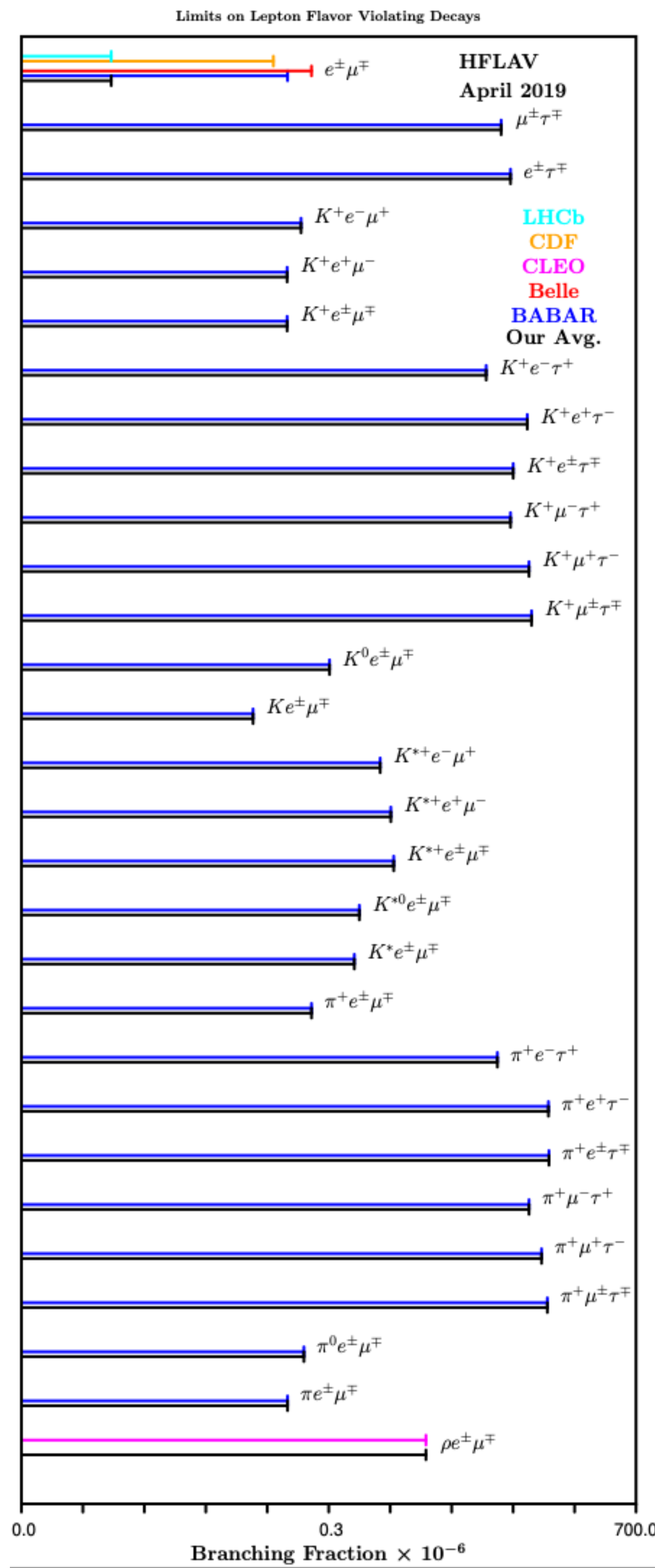
$3\ \text{fb}^{-1}$

- Most stringent new limits on semileptonic LFV $b \to s\mu^{\pm}e^{\mp}$ decays to date:

Limits at 90 % CL: (LHCb preliminary)

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.69 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.73 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 9.94 \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to \phi\mu^{\pm}e^{\mp}) < 15.9 \times 10^{-9}$$

B decays



Take home message

- Precise measurements of flavour observables provide a powerful way to probe for NP effects beyond the SM, complementing direct searches for NP. This is particularly relevant in the absence of direct collider production of new particles.

- Many world record results. For some topics we have moved from exploration to precision measurements.

- Most of these results show good compatibility with the SM, but hints of LFU violation are still persisting! This has generated a lot of interesting theoretical ideas.

- Need more data to test these hints: full analysis of Run 2 but also results from ATLAS and CMS (ATLAS, CMS), while waiting for the high-precision results from the LHCb upgrade and Belle II


SM

In case you would like to know more

- V. Vagnoni: MISP 2019 lectures
- T. Gershon: CERN Summer Student Programme 2016 lecture 1, lecture 2, lecture 3, lecture 4
- G. Isidori: CERN, Summer Student Programme 2017, Lectures on Flavour Physics and CP Violation
- The recent "Flavour Anomalies in Heavy Quark Decays", Albrecht, van Dyk, Langenbruch, arXiv:2107.04822

……..

- Excellent book about to be published "New Physics in b decays", by Artuso, Isidori and Stone, which I should acknowledge. This was something that kept Sheldon busy until the very last moments of his life.