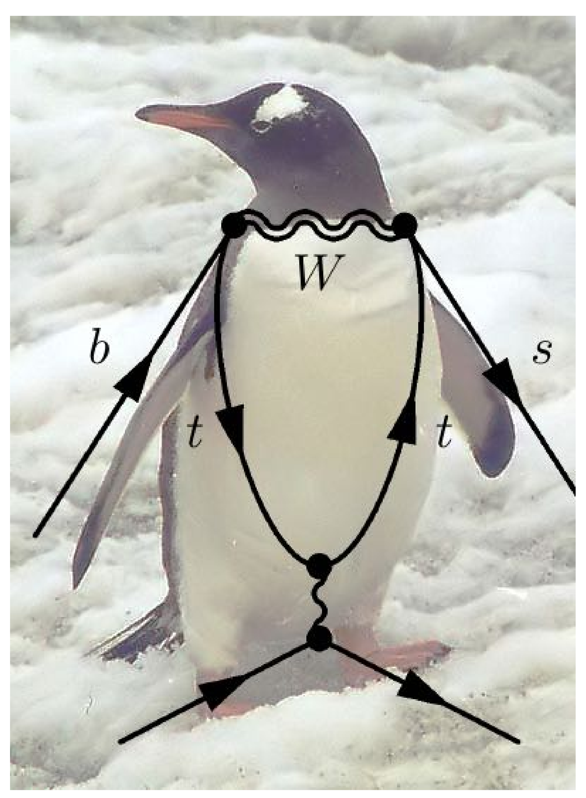
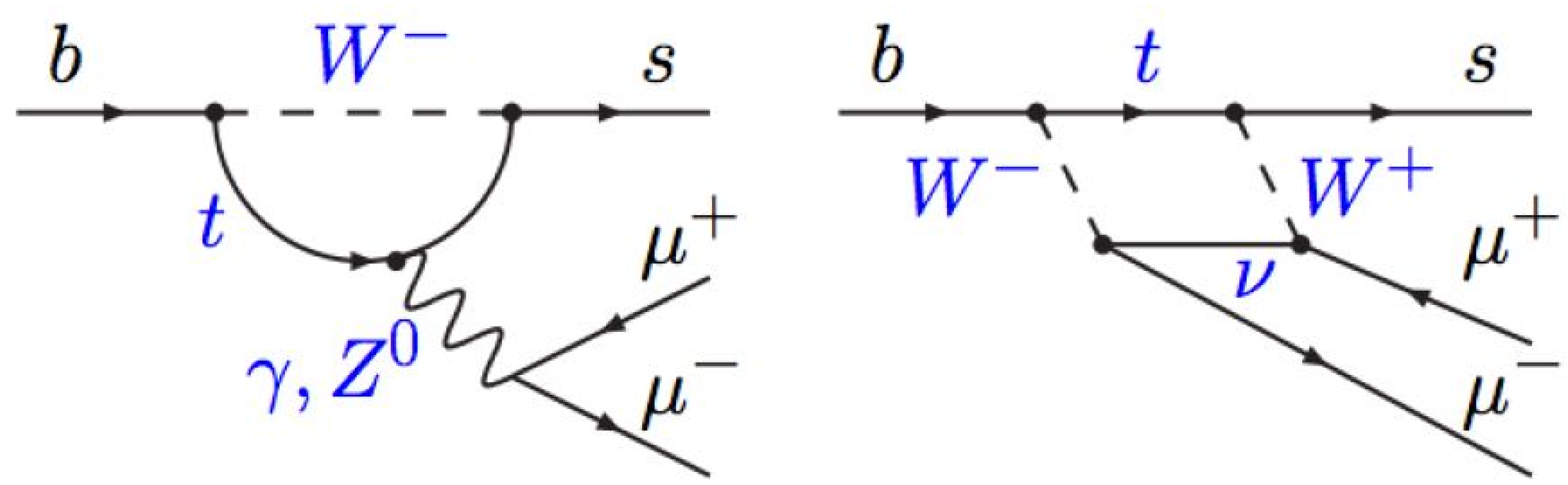
Rare b decays and tests of lepton flavour universality at LHCb

Monica Pepe Altarelli (CERN)
on behalf of LHCb

Rare b decays

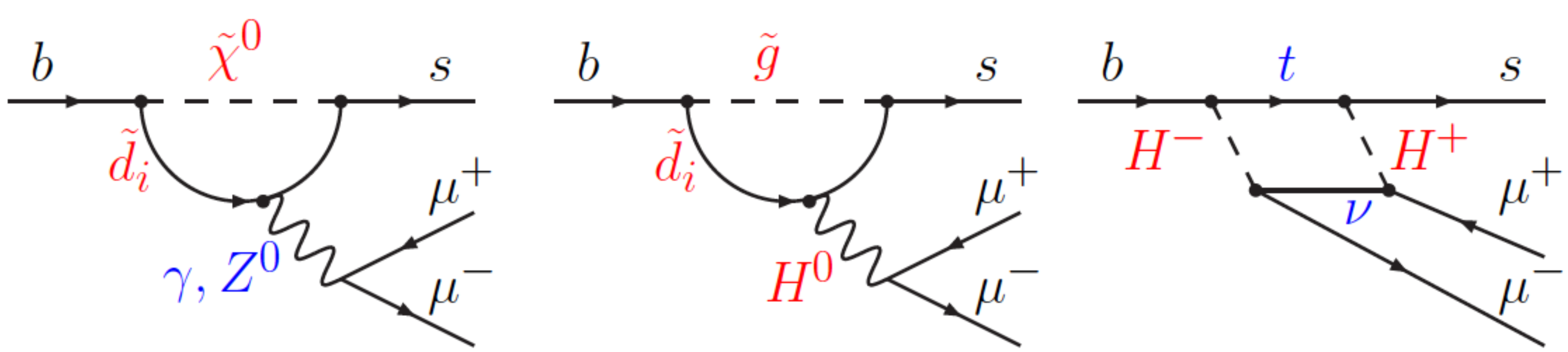
- In the SM, processes involving flavour changes between two up-type quarks (u,c,t) or between two down-type quarks (d,s,b) are forbidden at tree level and can only occur at loop level (penguin and box) → Rare FCNCs





$b \to s\ell^+\ell^-$ transitions
(BF 10^{-6} to 10^{-10})

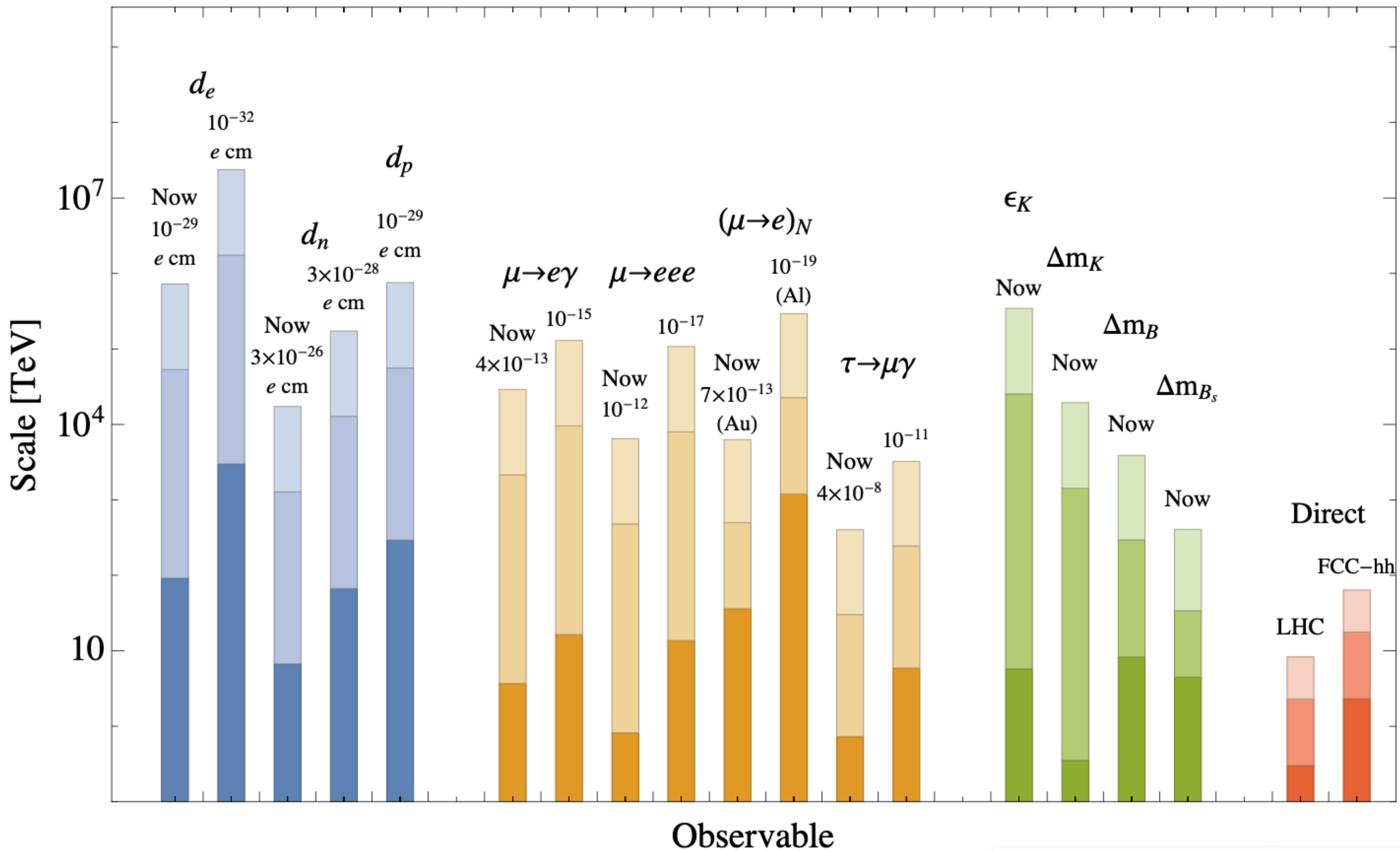
- A new particle, too heavy to be produced at the LHC, can give sizeable effects when exchanged in a loop



- Strategy: use well-predicted observables to look for deviations
- Indirect approach to NP searches, complementary to that of ATLAS/CMS
- Experimentally friendly (no neutrinos and two leptons in the final state)

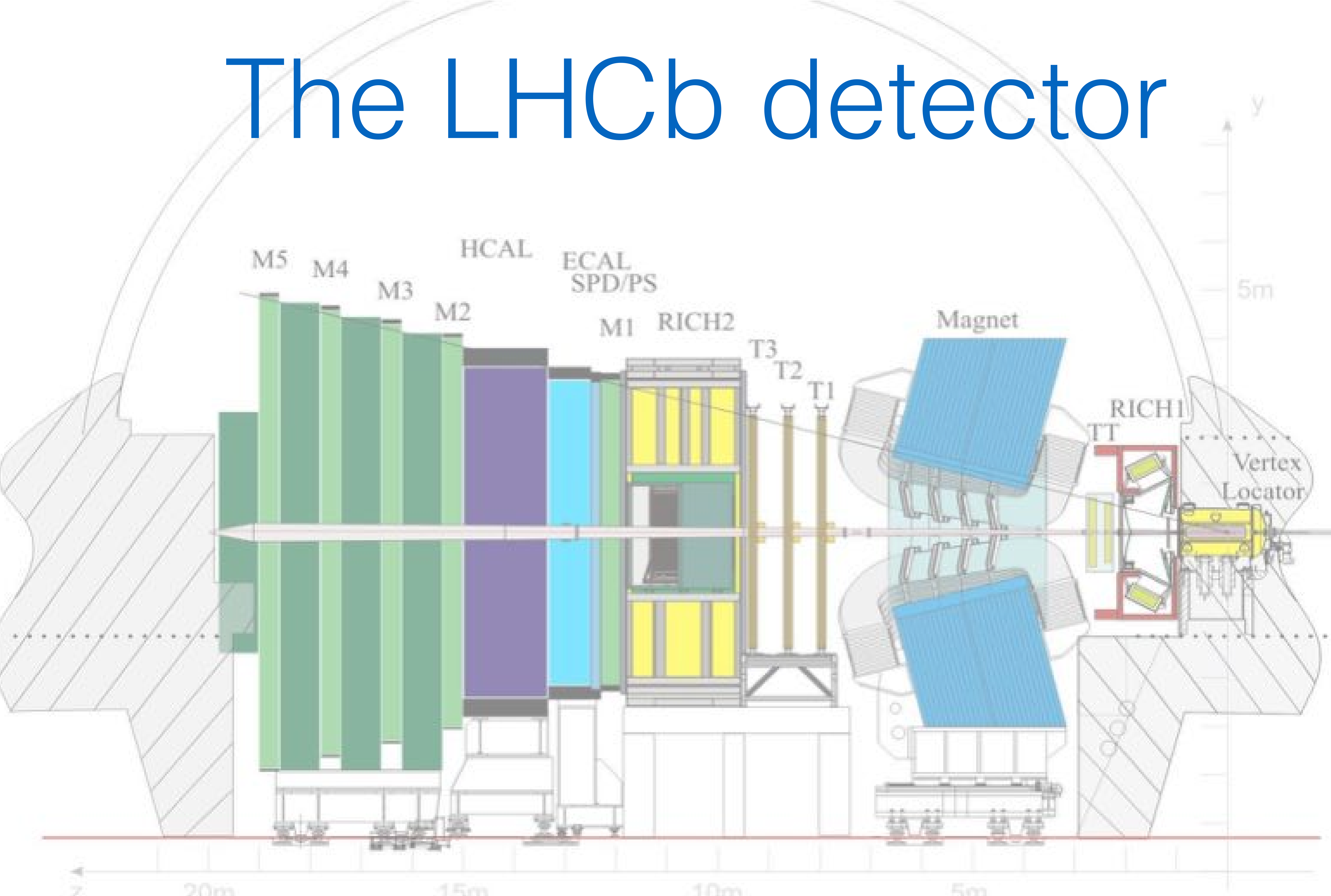

A window on
NP at high
scales

Energy reach of various indirect precision tests of physics beyond the SM compared to direct searches



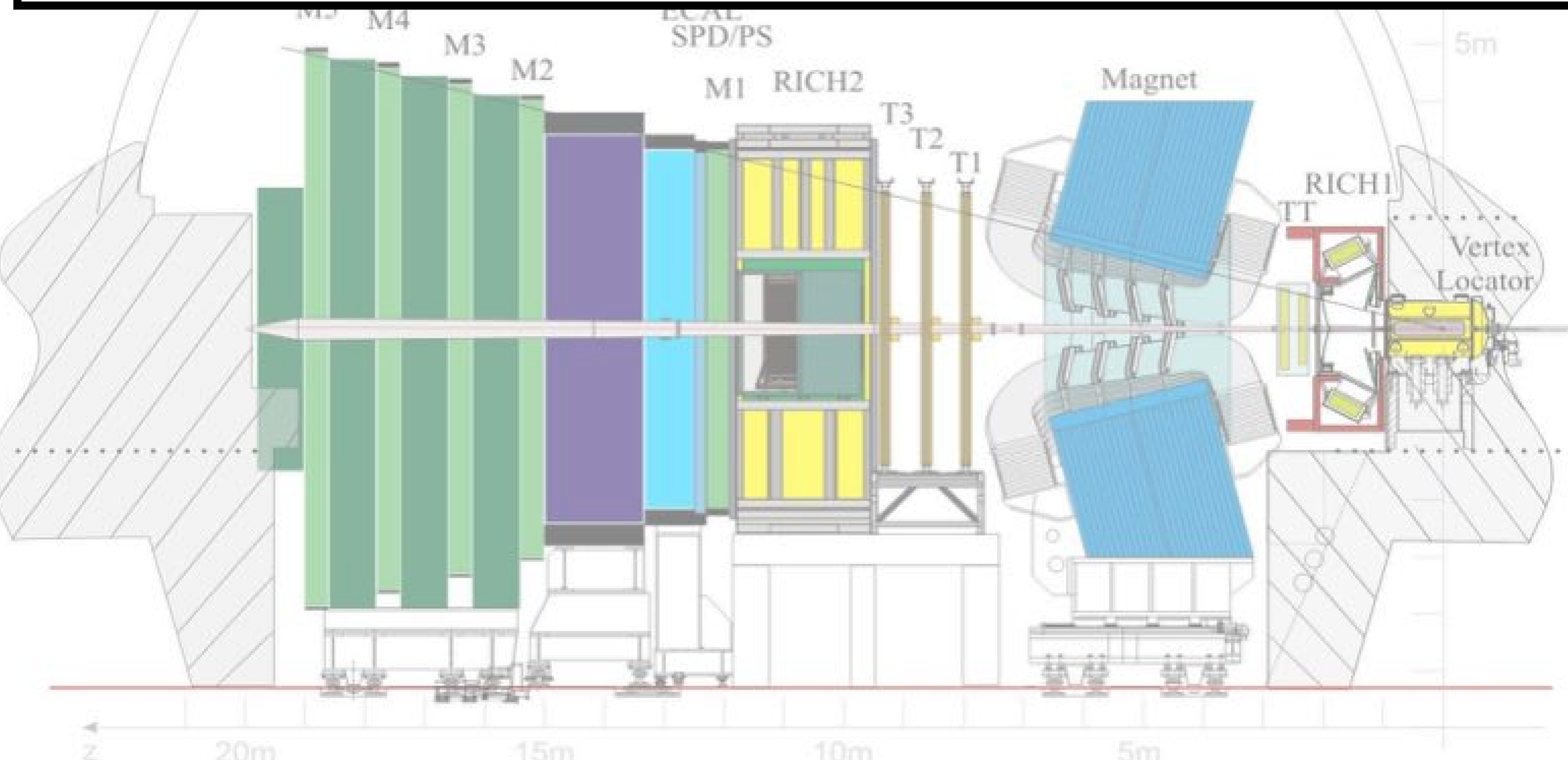
Matt Reece, DOE Basic Research Needs Study on HEP Detector R&D

The LHCb detector



JINST 3 (2008) S08005

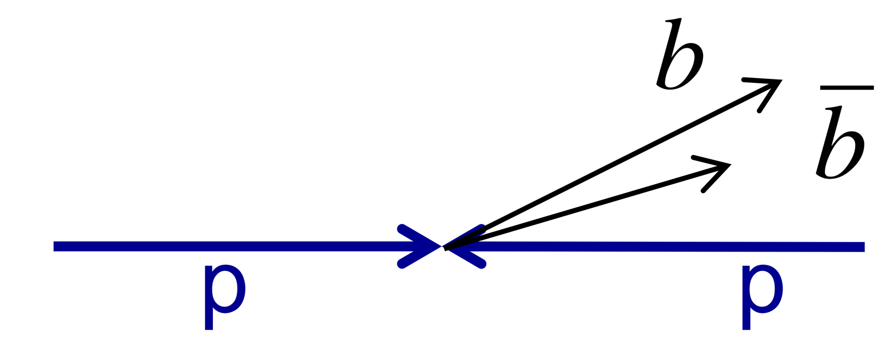
- Forward acceptance
- Efficient trigger for hadronic and leptonic modes
- Acceptance down to low p_T
- Precision tracking and vertexing (VErtex LOcator@8 mm from beam)
- Excellent PID

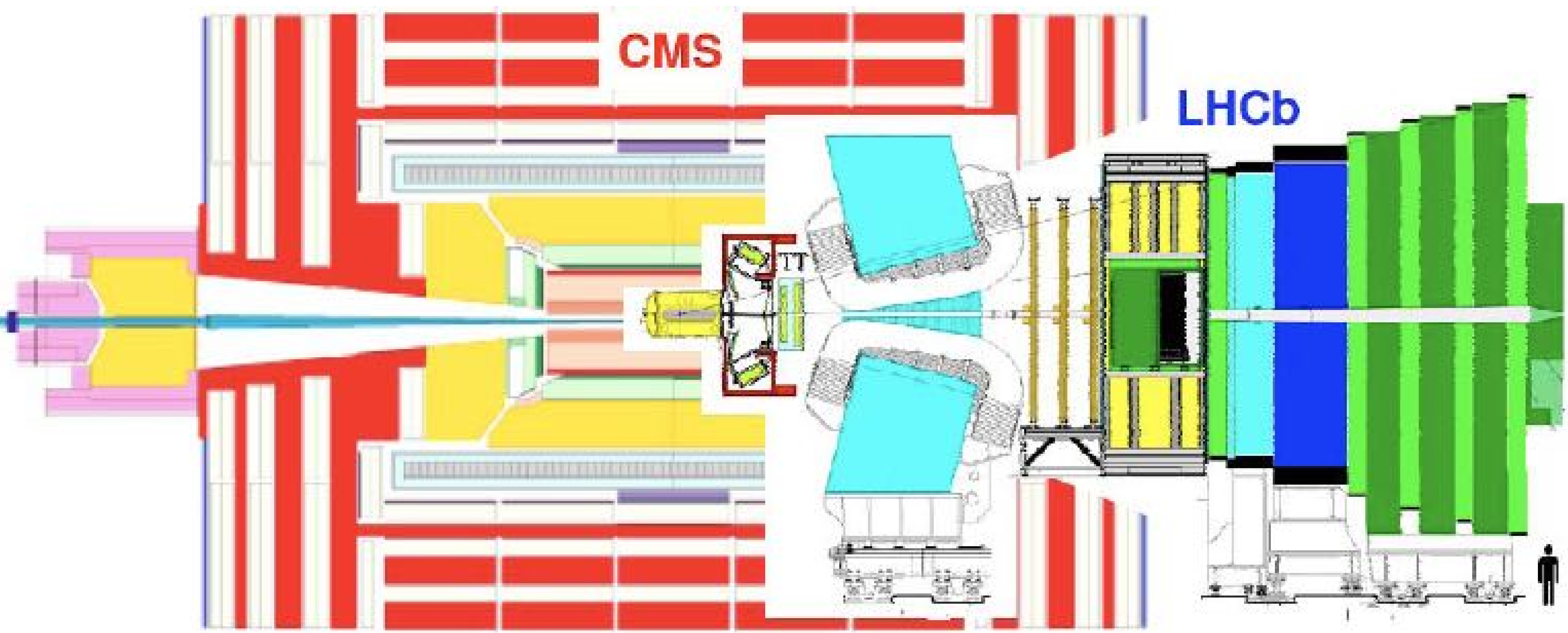


JINST 3 (2008) S08005

Why does LHCb look so different?

- The B mesons formed by the colliding proton beams (and the particles they decay into) stay close to the line of the beam pipe, and this is reflected in the design of the detector





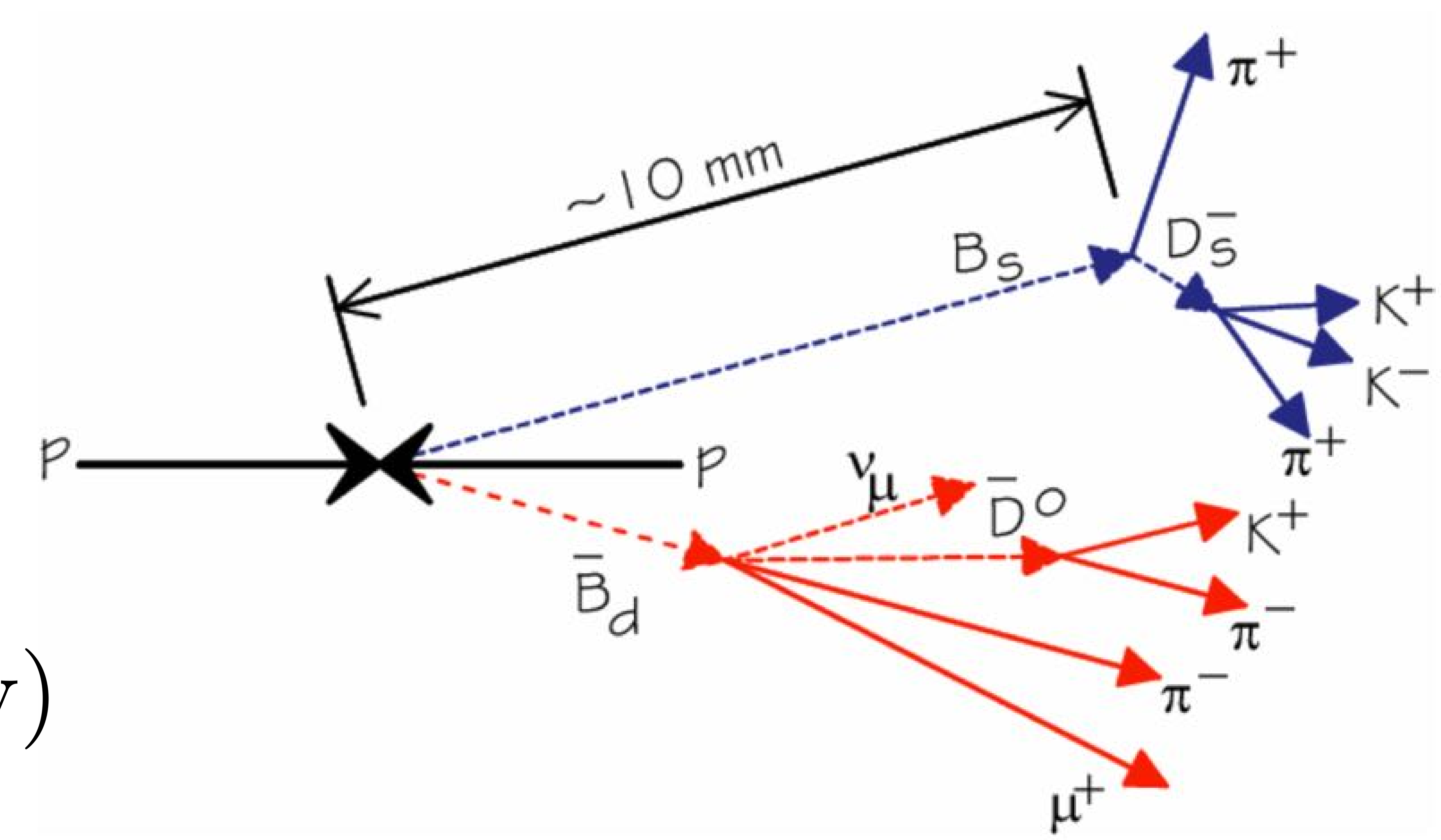
b lifetime long enough for experimental detection

- $\tau_{\mathrm{beauty}} \sim 1.5 \cdot 10^{-12}\,\mathrm{s}$ $\qquad \tau \sim 1/(m^5 |V_{\mathrm{cb}}|^2)$
- $D = \beta\gamma c\tau$
- @ LHC :

  ⋆ $\beta = v/c \sim 1$

  ⋆ $\gamma = E/mc^2 \sim 20 \quad (E : b \text{ energy})$

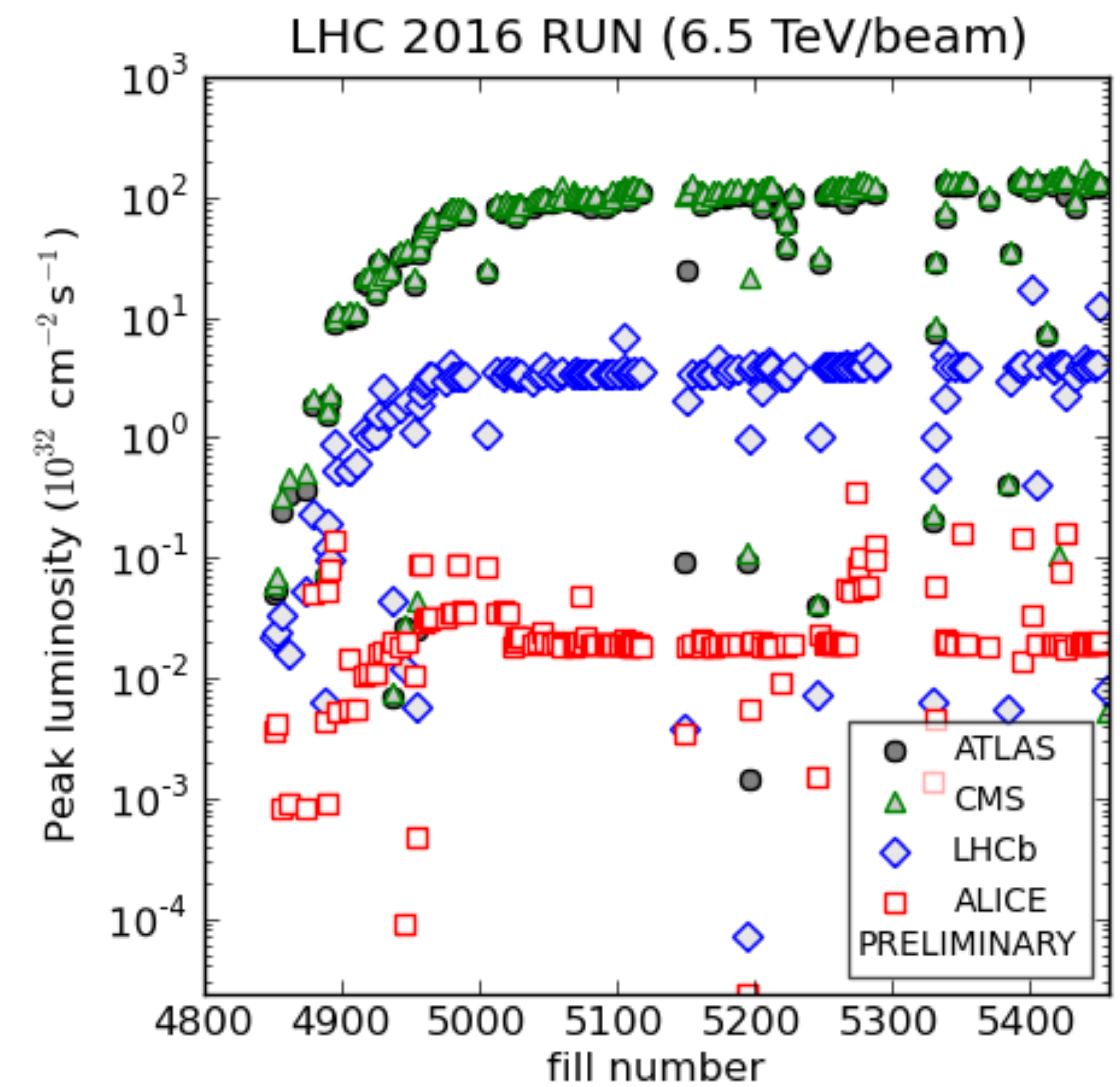
- $\mathrm{D} = 20 \cdot 3 \cdot 10^{10} \cdot 1.5 \cdot 10^{-12} \sim 1\,\mathrm{cm}$



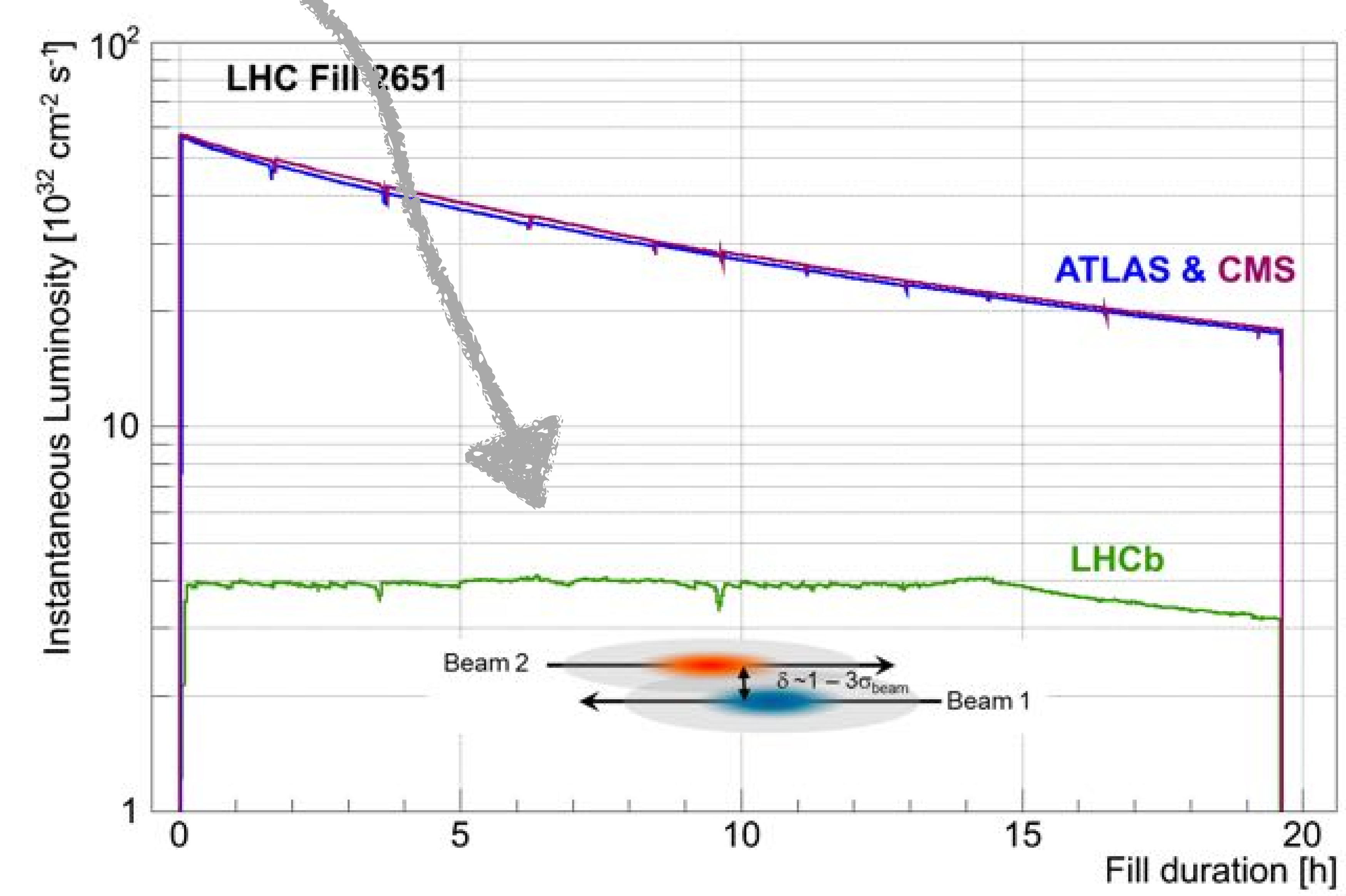
Look for displaced vertices and/or tracks with large impact parameters

Running conditions

- LHCb designed to run at lower $\mathscr{L}$ than ATLAS/CMS
  - Mean number of interactions/bunch crossing ~1 (Runs 1&2)
  - Tracking, Particle Identification sensitive to pileup
  - $\mathscr{L}_{\rm int} = 9\,{\rm fb}^{-1}$ (LHCb), $\mathscr{L}_{\rm int} = \sim 170\,{\rm fb}^{-1}$ (ATLAS/CMS)



- pp beams displaced to reduce $\mathscr{L}$
  - $\mathscr{L}$ ~ 4.0 x10^{32} cm^{-2}s^{-1} (LHCb) to be increased to 2.0 x 10^{33} cm^{-2}s^{-1} in Run 3
  - $\mathscr{L}$ ~ 10^{34} cm^{-2}s^{-1} (ATLAS/CMS)



- Huge heavy quark production cross-sections !
  - $\sigma_{b\bar{b}} \sim 550\,\mu{\rm b}$ @ √s=13 TeV (~1nb in e^+e^- @ $\Upsilon(4S)$)
    - ~10^{11} b decays/fb in acceptance
  - $\sigma_{c\bar{c}}$ is ~ 20 times larger!
    - ~10^{12} c decays/fb in acceptance

Running conditions - II

- For LHCb, more data is more important than higher energy
  - Direct searches @ATLAS/CMS: more energy → new particles could appear above threshold
  - Indirect searches: precision measurements → gain from increased production rates
- However, digesting more data is a true challenge!
  - At 13 TeV and $\mathscr{L}$=2x10^{33}/cm^2/sec, ~100 kHz $b\bar{b}$ and ~1MHz $c\bar{c}$ pairs in detector acceptance
  - Most interesting b-hadron decays occur at 10^{-5} probability or lower
  - Big challenge !

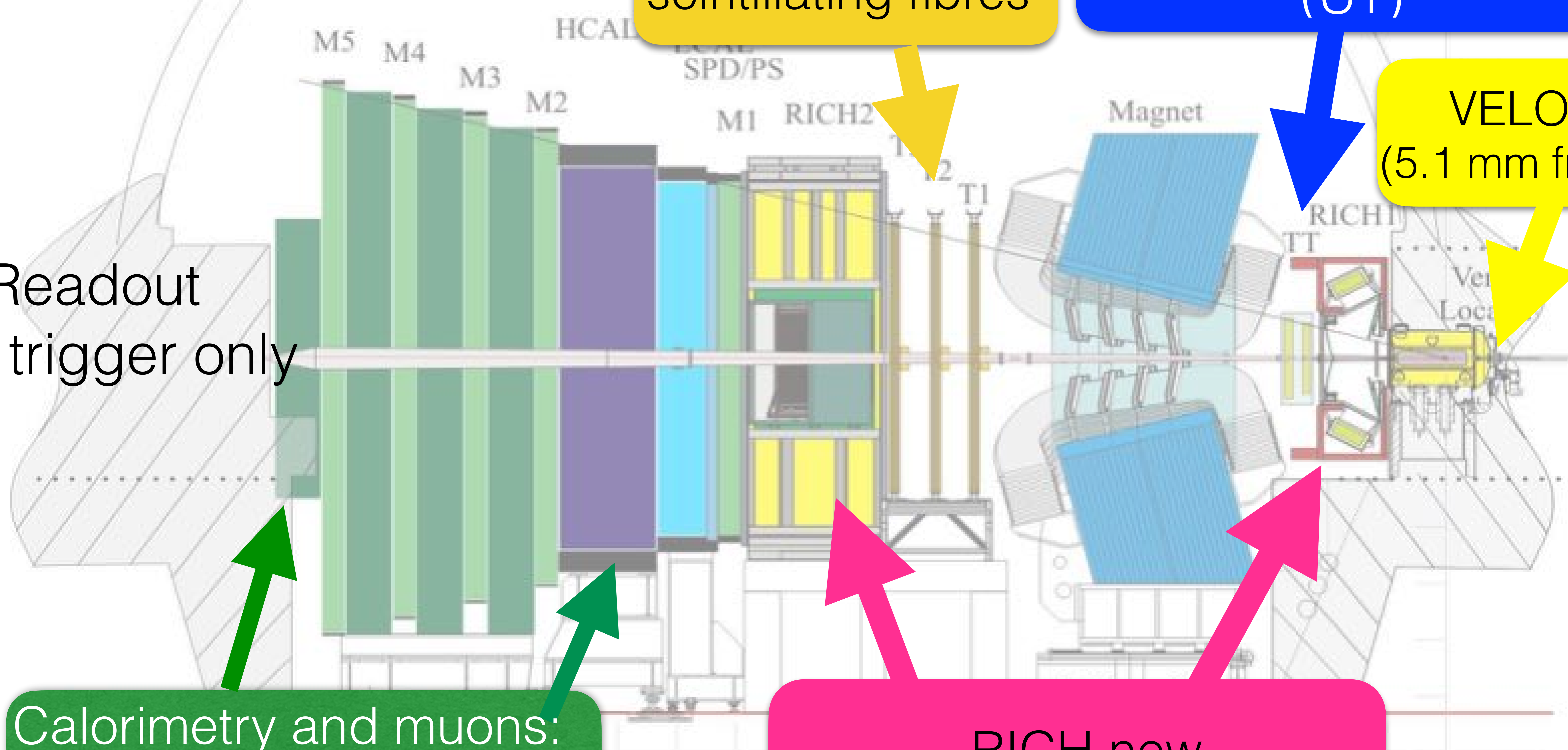
The LHCb schedule

Cavern closure 31 March 2022

The upgraded detector

- Less than 10% of all channels will be kept!
- NEW RO electronics
- NEW DAQ & data centre

40 MHz Readout
Software trigger only



Tracker scintillating fibres

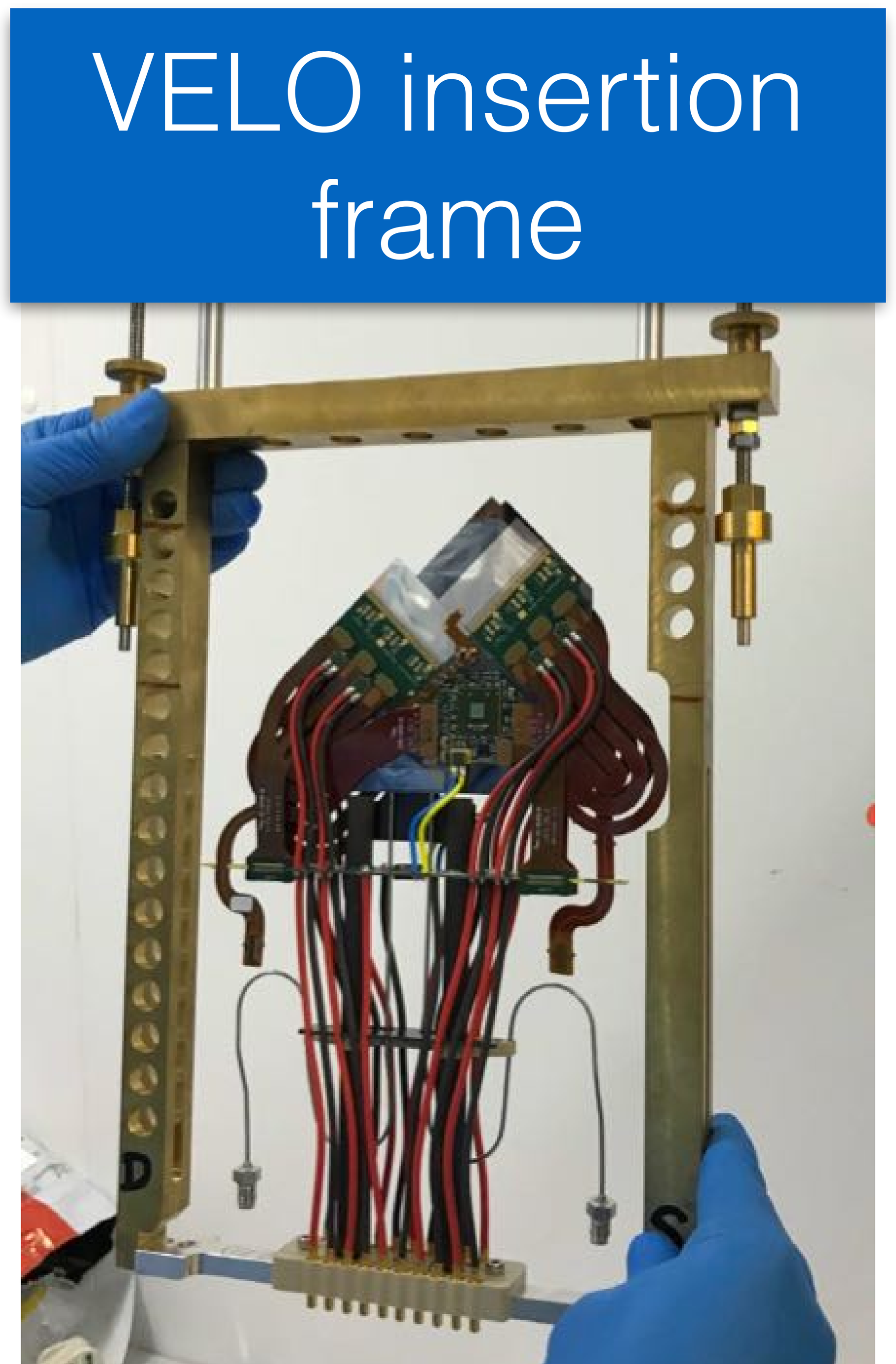
Upstream Tracker (UT)

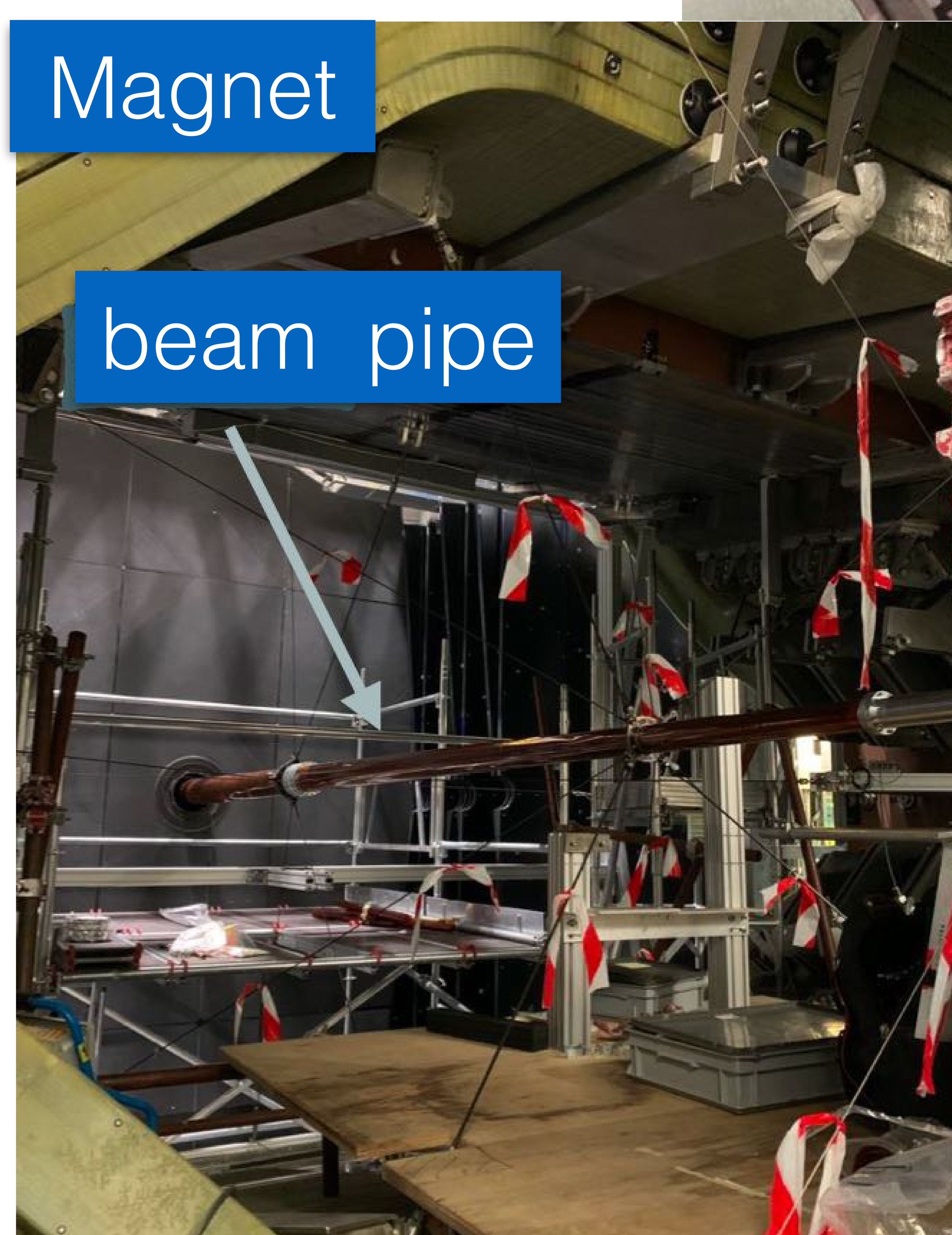
VELO pixels (5.1 mm from beam)

Calorimetry and muons: replace RO electronics & remove redundant components

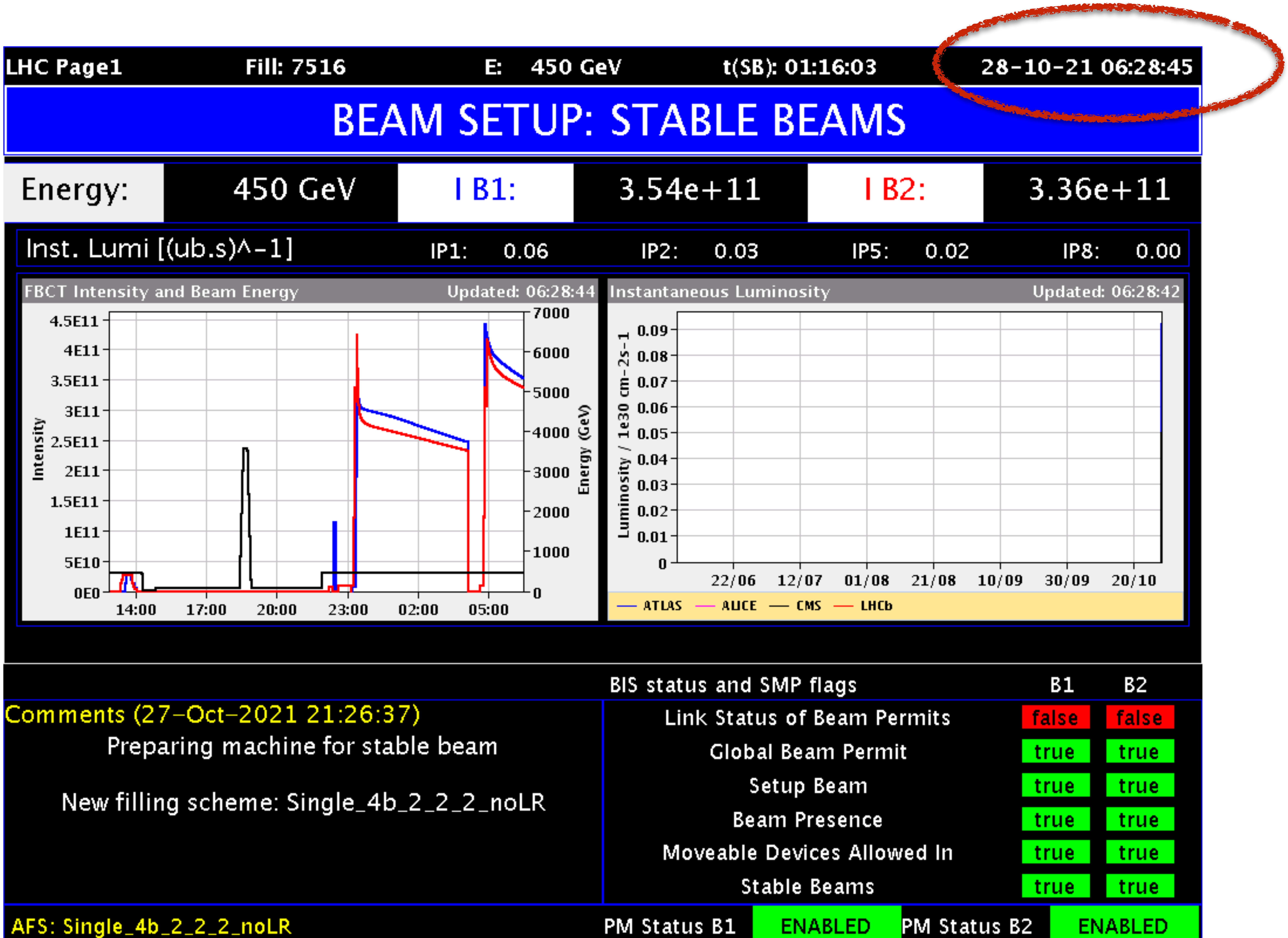
RICH new photodetectors

Installation being completed under very tight timescale and hard pandemic restrictions



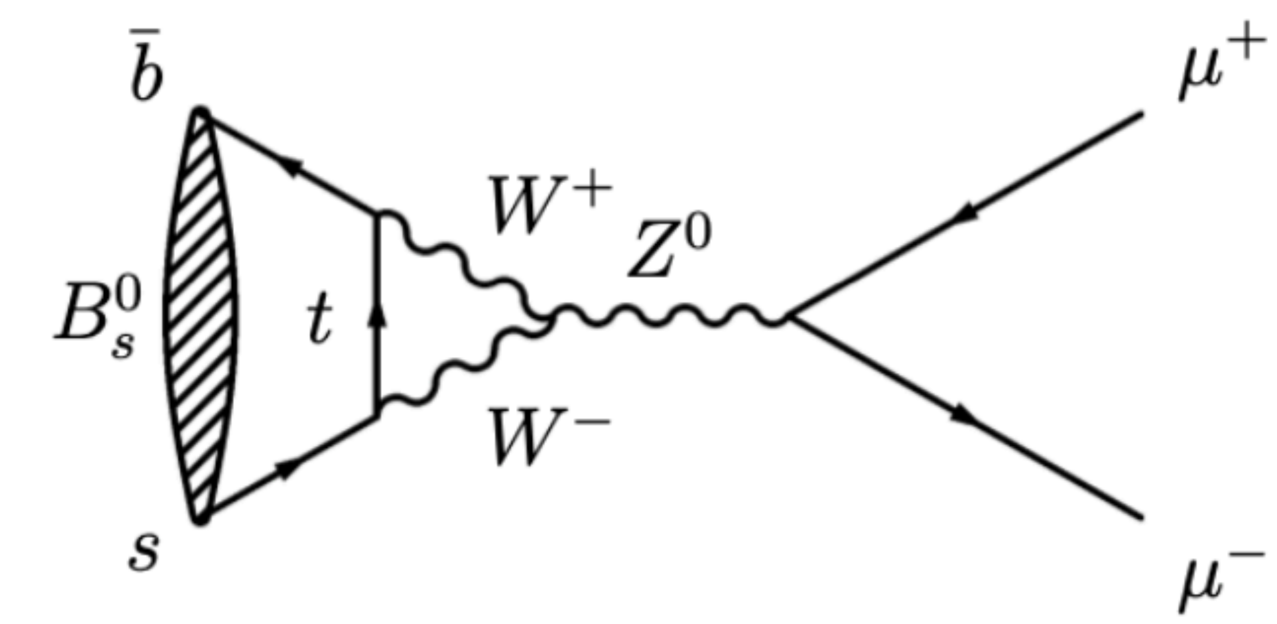


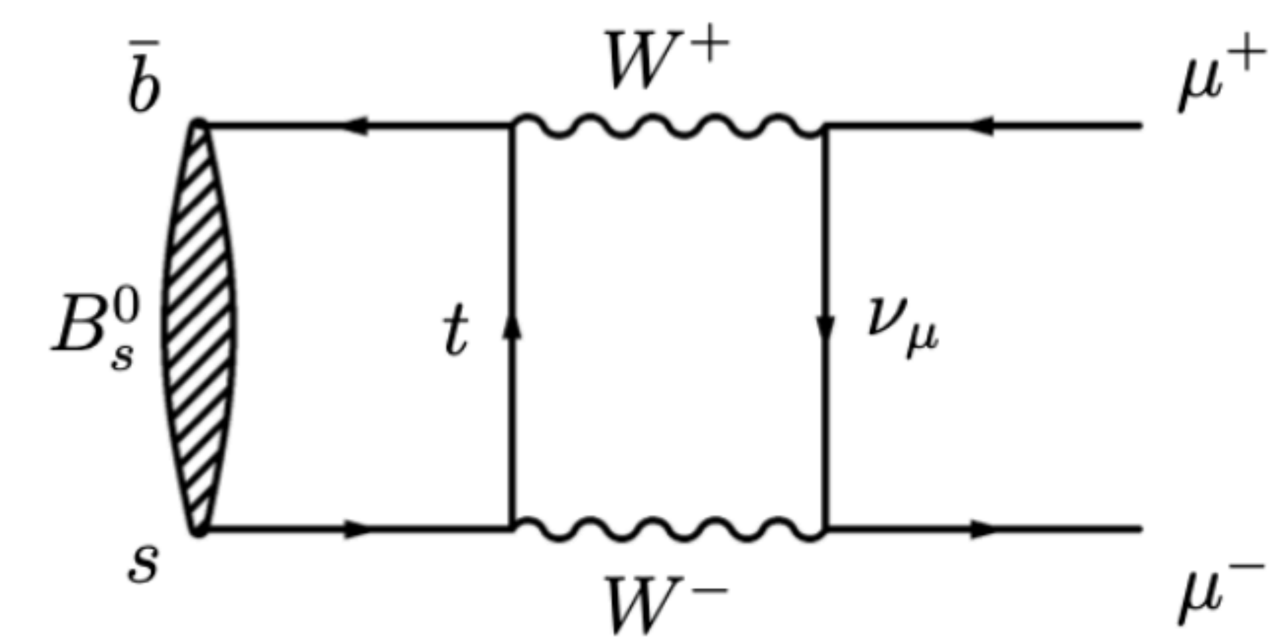
First collisions in LHCb with upgraded RICH2, Calo and Muon detectors!



B leptonic decays

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





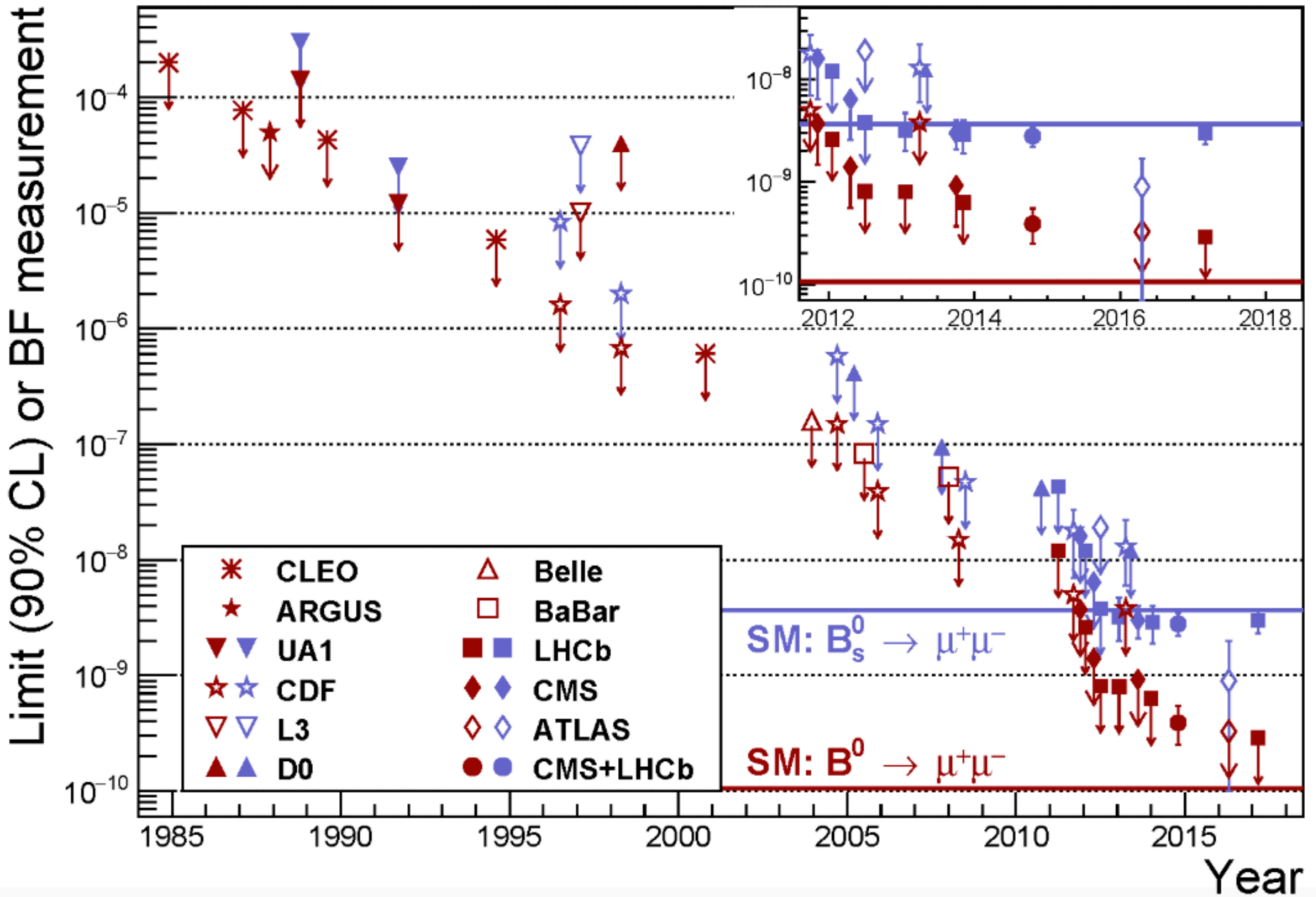
- Very suppressed in the SM
  - Loop, CKM ($|V_{ts}|^2$ for B_s) and helicity $\sim \left(\frac{m_\mu}{M_B}\right)^2$
  - Theoretically "clean" → precisely predicted

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.14) \times 10^{-9} \quad (\sim 4\%)$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.03 \pm 0.05) \times 10^{-10}$$

Bobeth et al.
PRL 112 (2014) 101801
Beneke et al.
JHEP 10 (2019) 232

- Sensitive to NP
  - A large class of NP theories, such as SUSY, predict significantly higher values for the $B_{(s)}$ decay probability
- Very clean experimental signature
  - Studied by all high-energy hadron collider experiments

30 years of effort!



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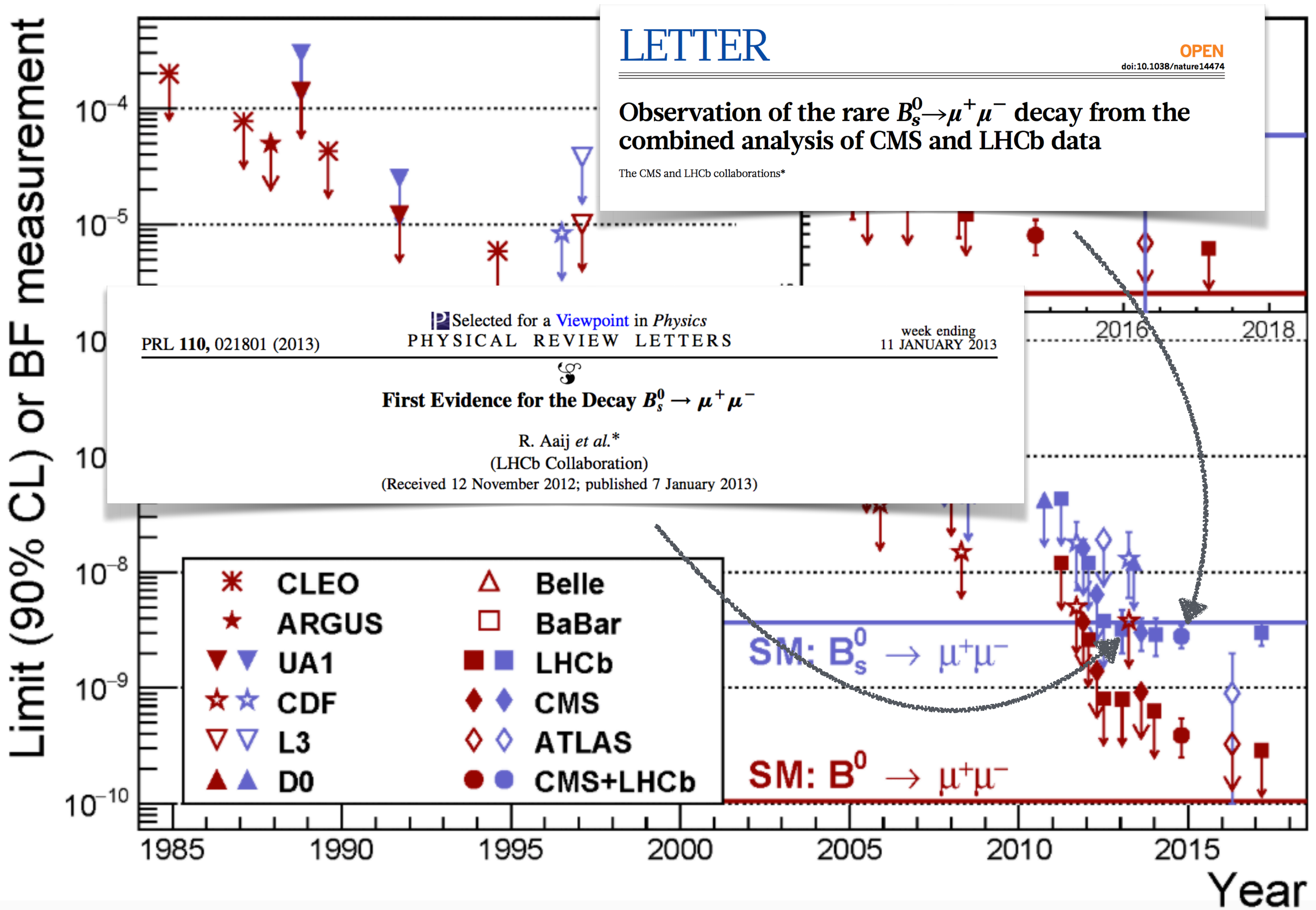


Finding a needle in a haystack!

Latest LHC 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

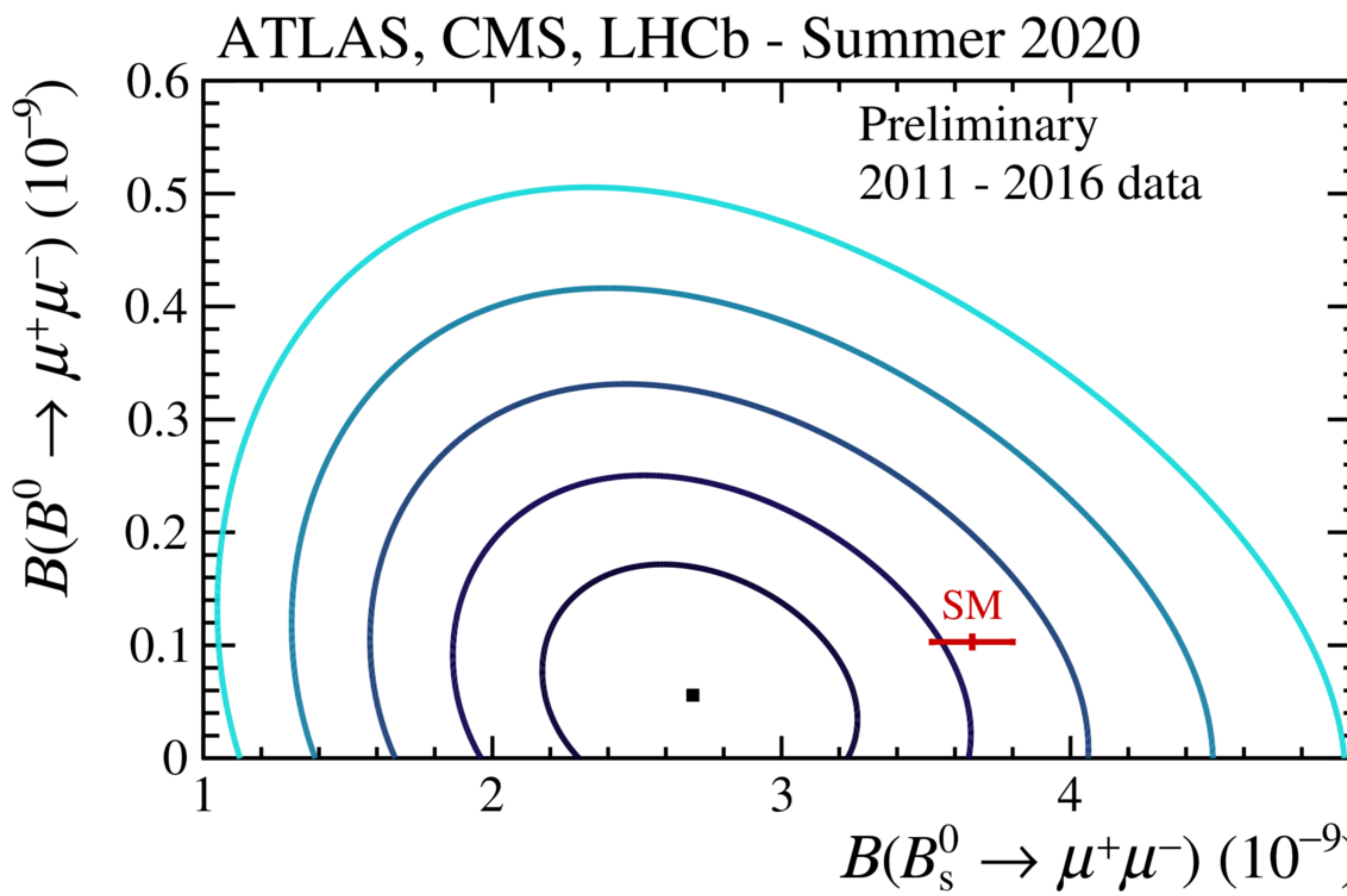
$B(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7\,(\mathrm{exp}) \pm 0.2\,(\mathrm{frag})) \times 10^{-9}$ 5.6σ

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



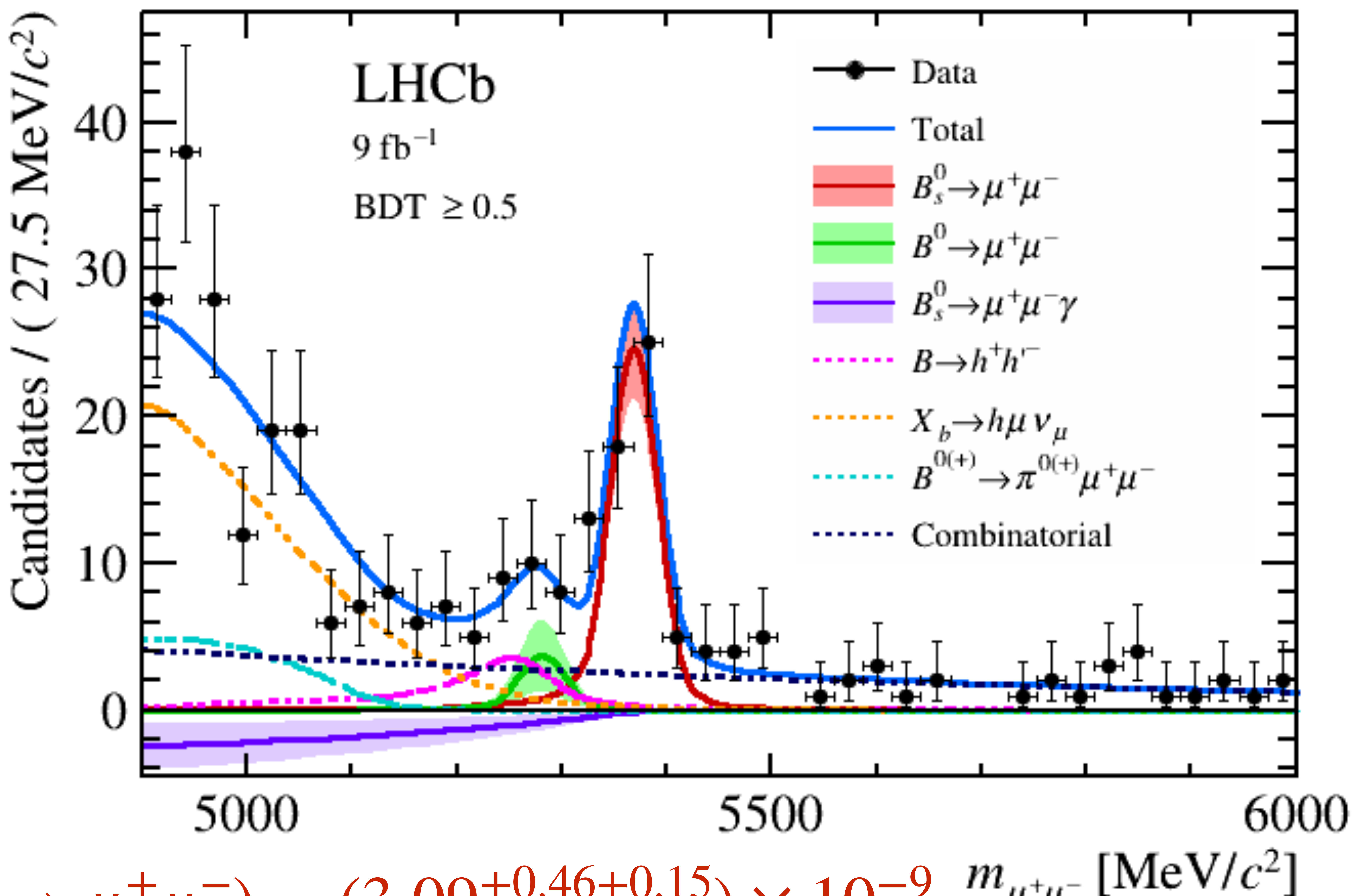
Era of precision measurements of $B_{(s)} \to \mu^+\mu^-$ has started

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

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

2.1 σ below SM prediction (2D compatibility)

$B_{(s)} \to \mu^+\mu^-$: LHCb runs 1&2



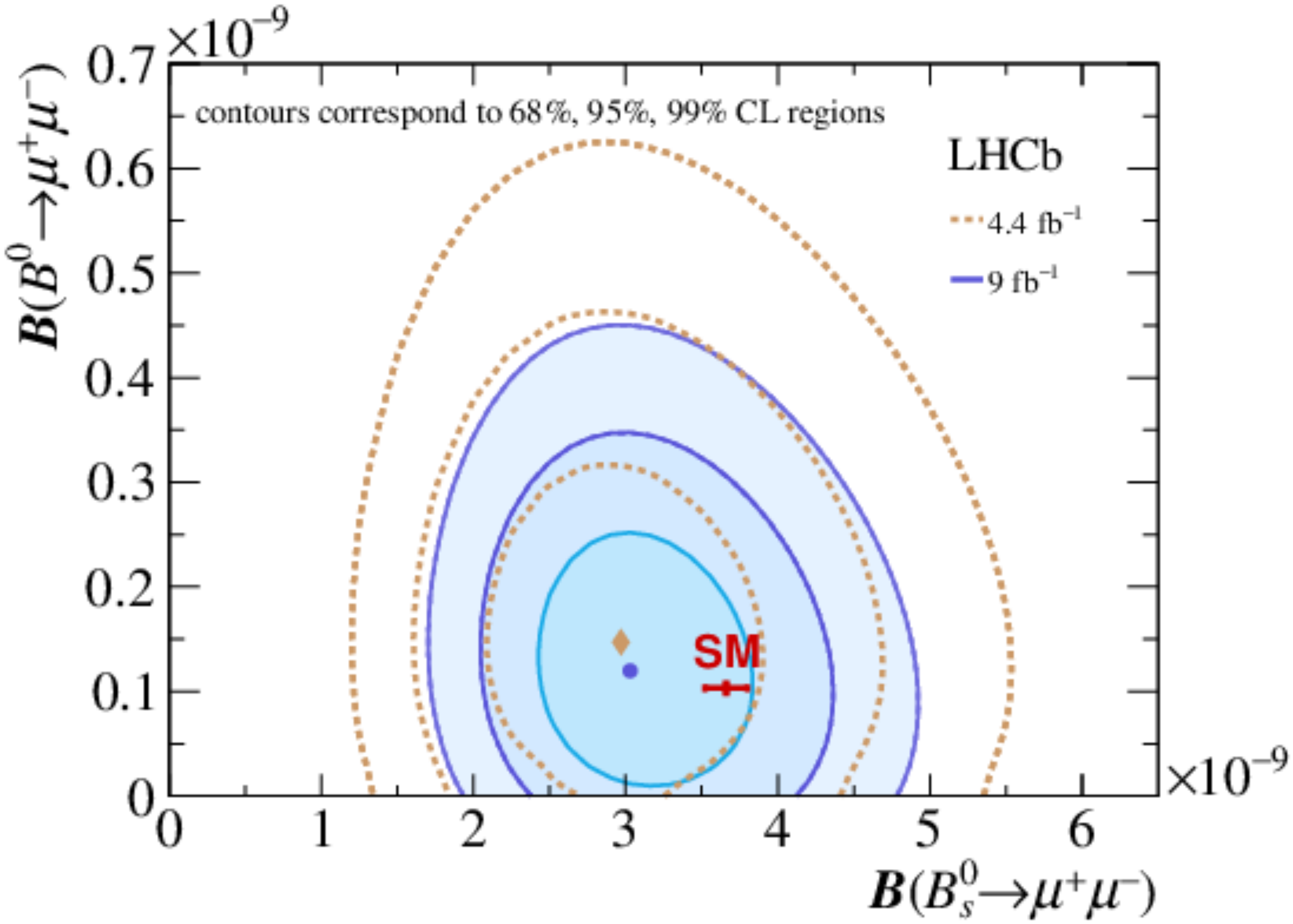
arXiv:2108.09283
arXiv:2108.09284

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

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \,@\, 95\,\%\,\mathrm{CL}$$

- $B_s \to \mu^+\mu^-$ found with significance >10 σ, but no evidence yet for $B^0 \to \mu^+\mu^-$ (1.7σ)
- Result dominated by statistical uncertainty
- Expect 10% precision with ATLAS/CMS Run 2

$B_{(s)} \to \mu^+\mu^-$: LHCb runs 1&2



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

$B \to H\mu^+\mu^-$ with $H = K, K^*, \phi \ldots$

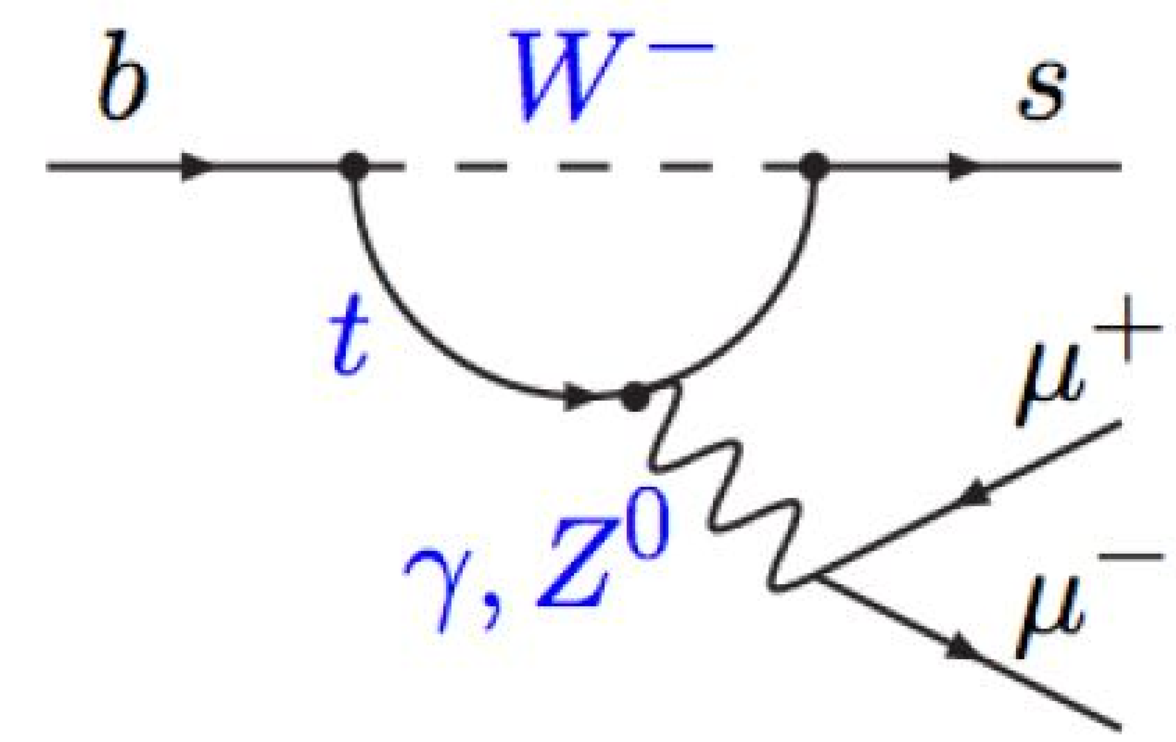
- Unlike the purely leptonic, not helicity suppression → larger BFs of $\mathcal{O}(10^{-7})$

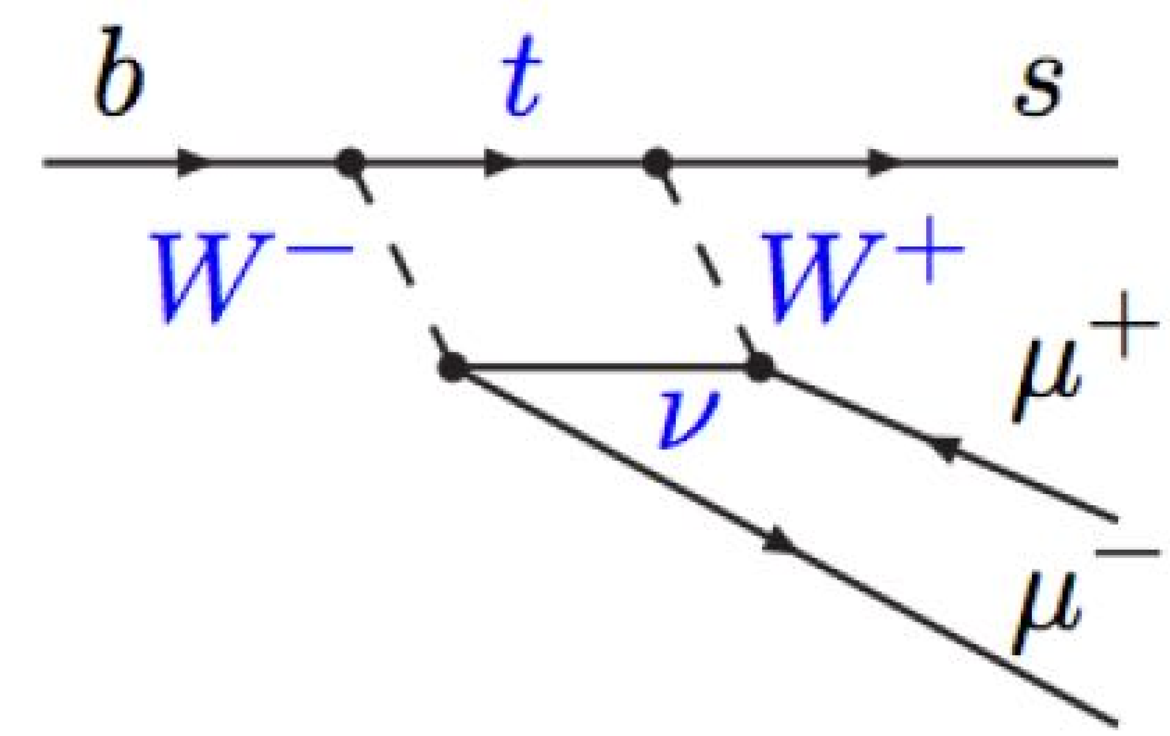
- Branching fractions and angular distributions sensitive to NP

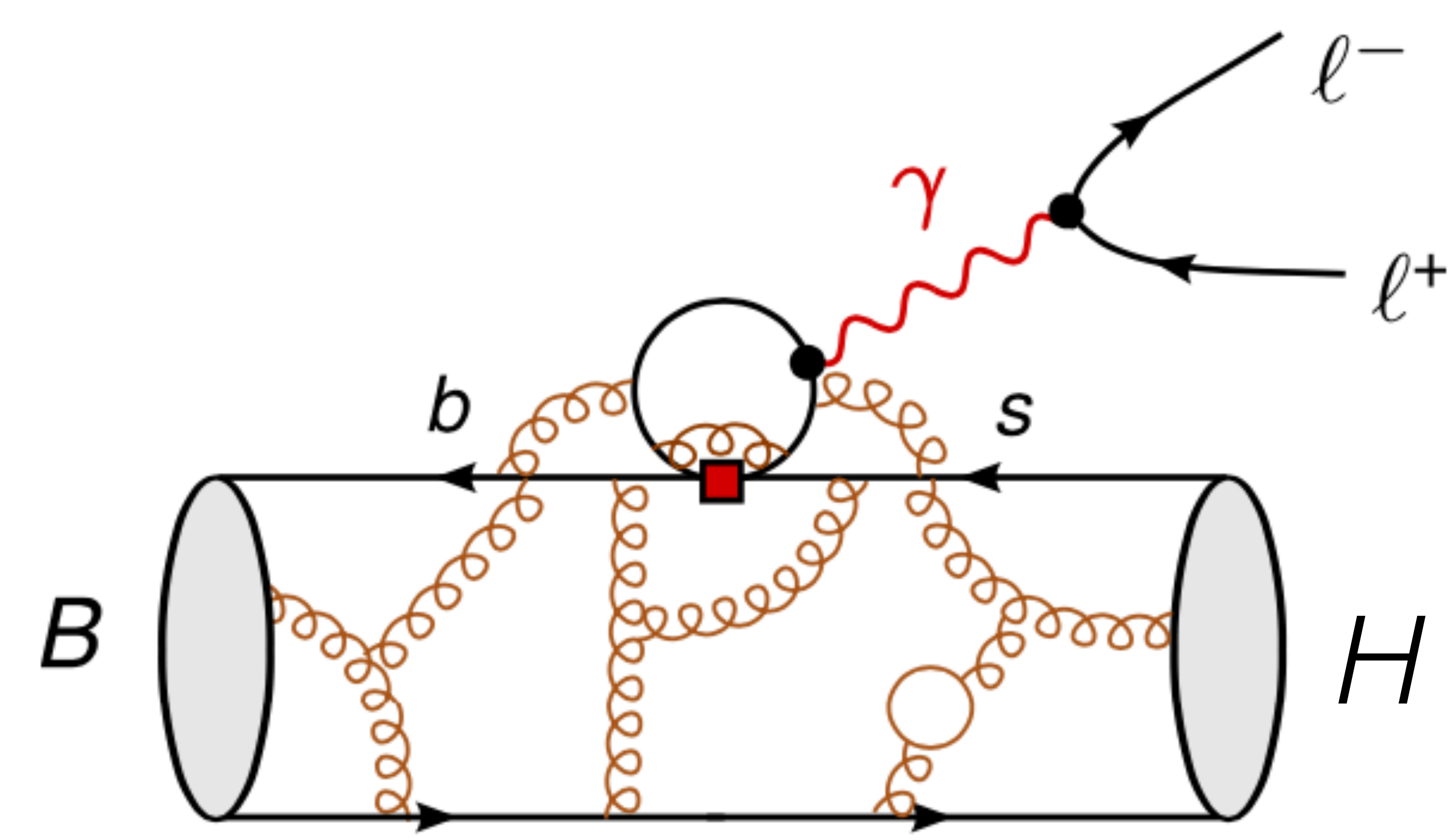
- A lot of phenomenological work invested in defining observables with reduced theoretical uncertainties
  - Form-factors cancel at leading order
  - Still susceptible to non-factorisable corrections

- Question: how clean? [Talk by Altmannshofer]

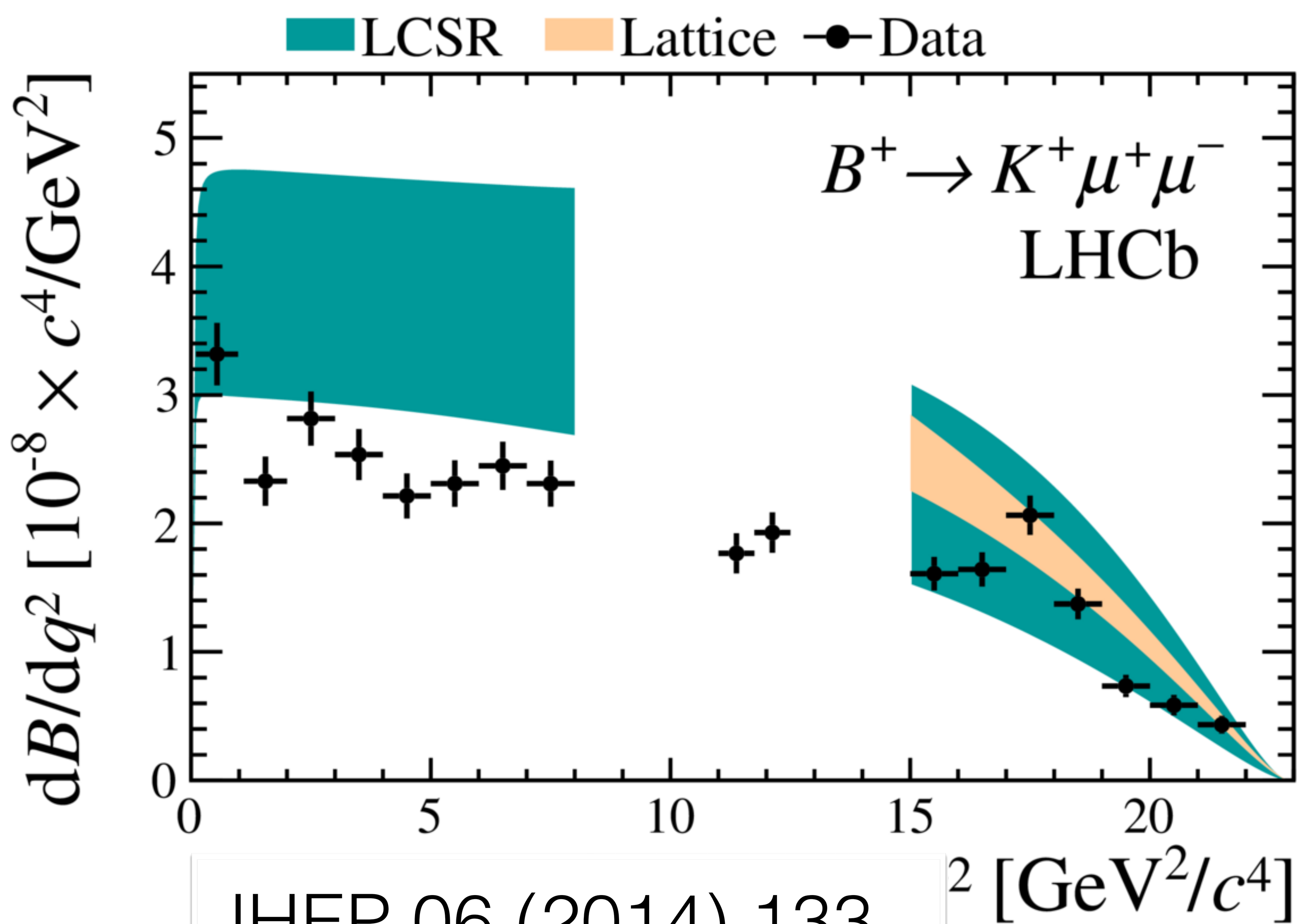
- “Non-local” matrix elements are the main source of theory uncertainty affecting BFs and angular distributions in $B \to H\ell^+\ell^-$, but *NOT* LFU observables
  - E.g: are we estimating correctly contributions from charm loops that produce a $\ell^+\ell^-$ pair via a virtual photon?



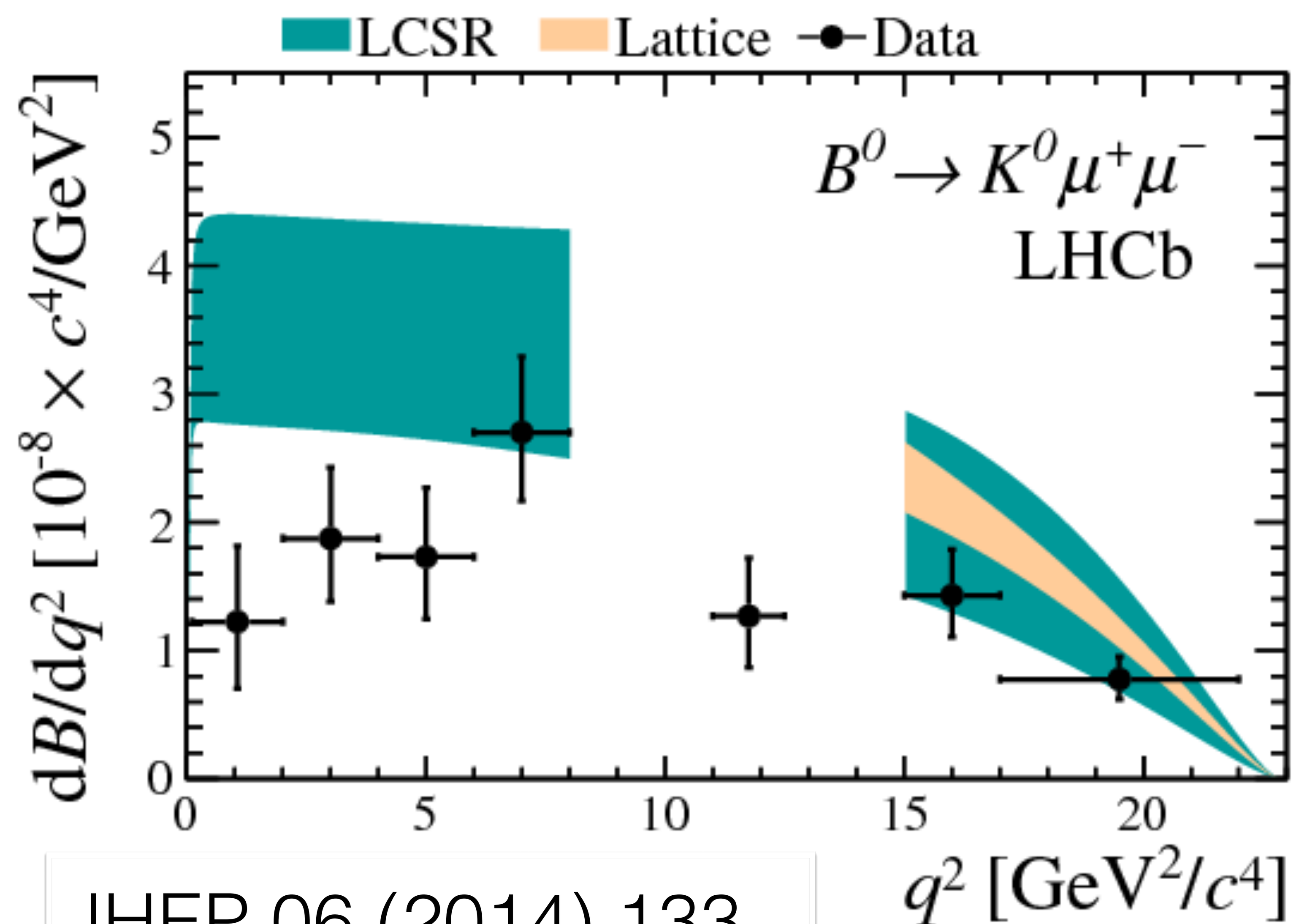




$b \to s\mu^+\mu^-$ differential BF



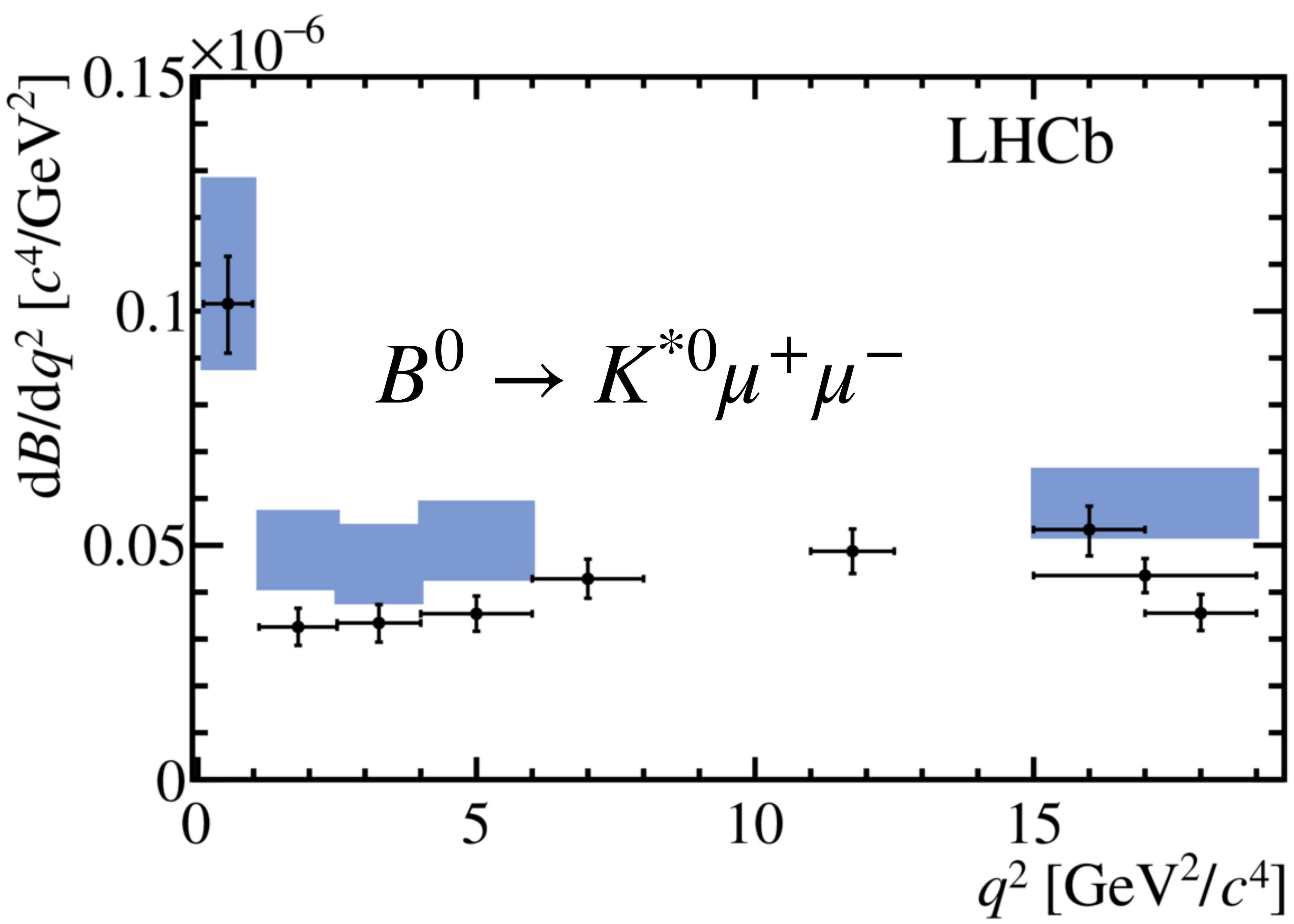
JHEP 06 (2014) 133



JHEP 06 (2014) 133

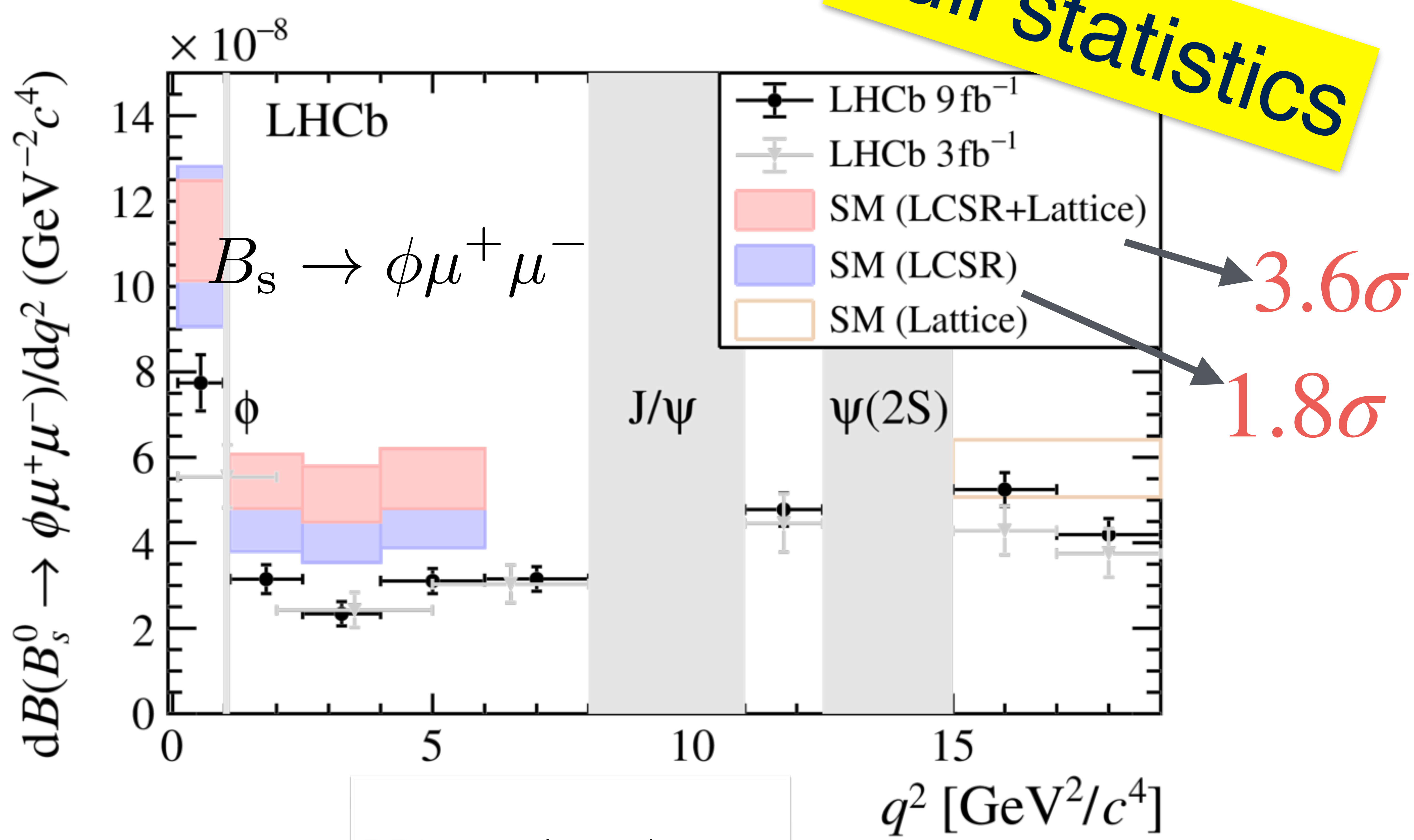
- In general, data tend to be lower than theory predictions at low q^2 (but prediction uncertainties are correlated)
- Comparison limited by large theoretical uncertainty of form factors

Full statistics



JHEP 04 (2017) 142

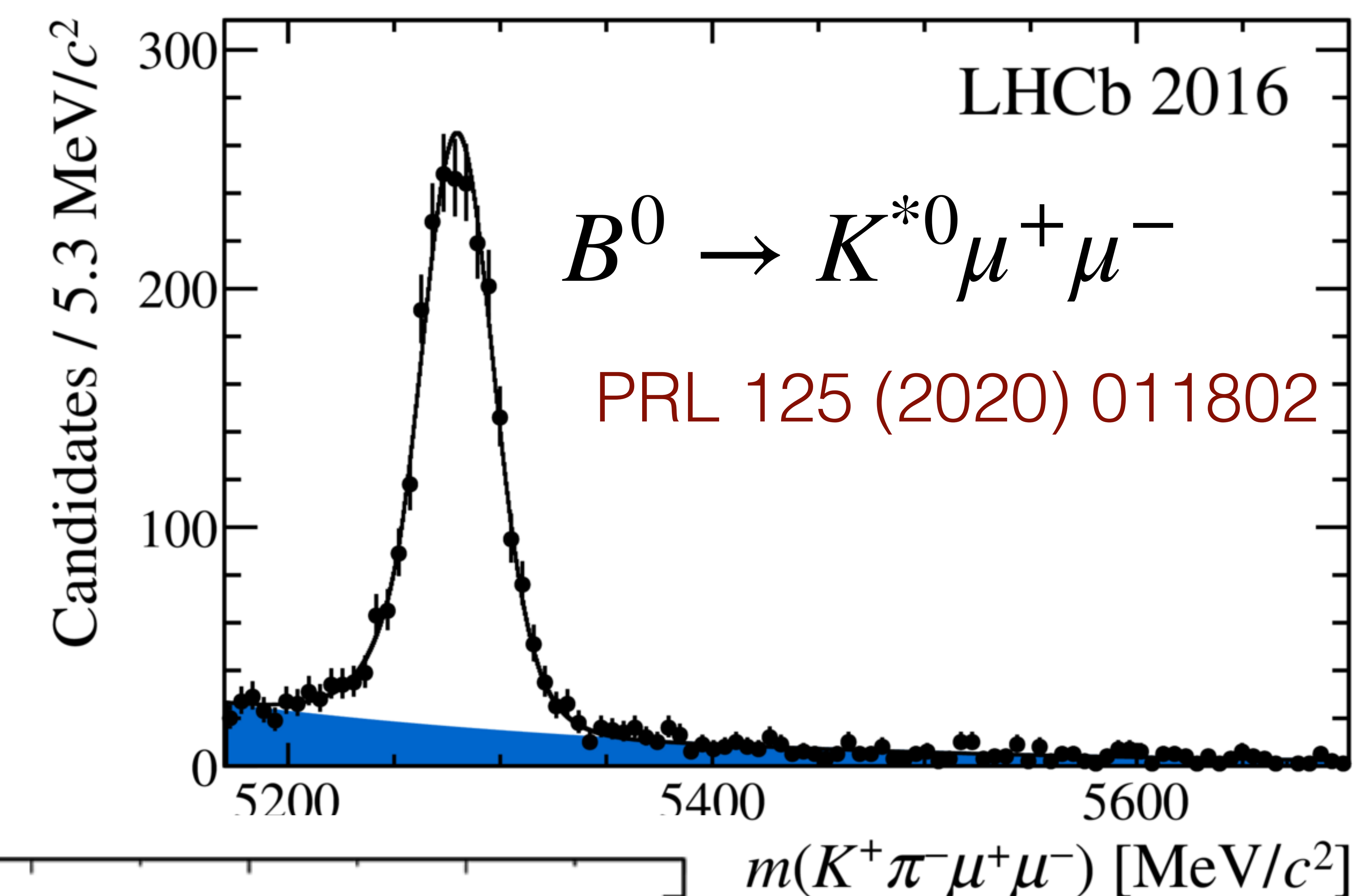
$$q^2 = m^2_{\mu^+\mu^-}$$

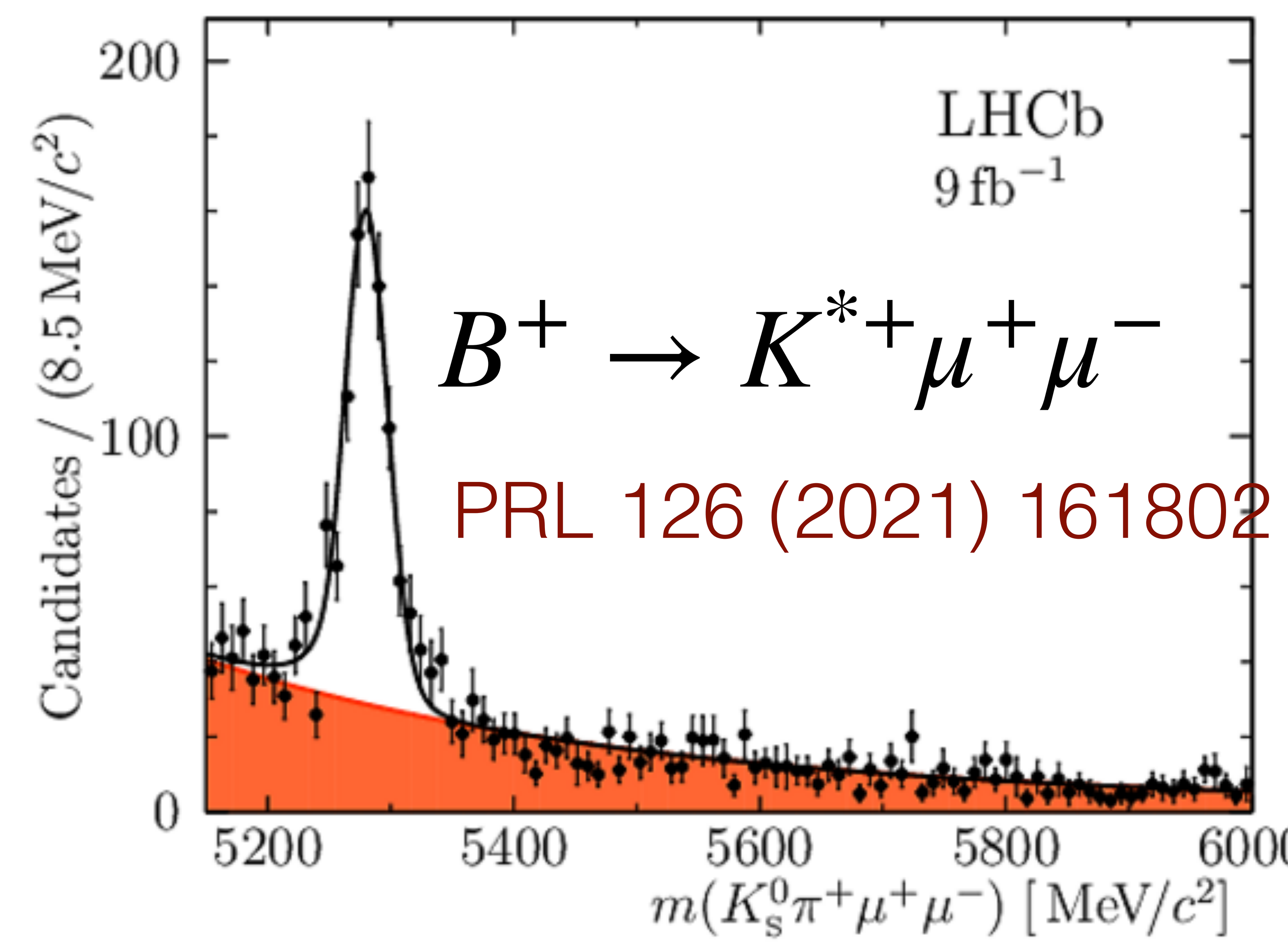


PRL 127 (2021) 15

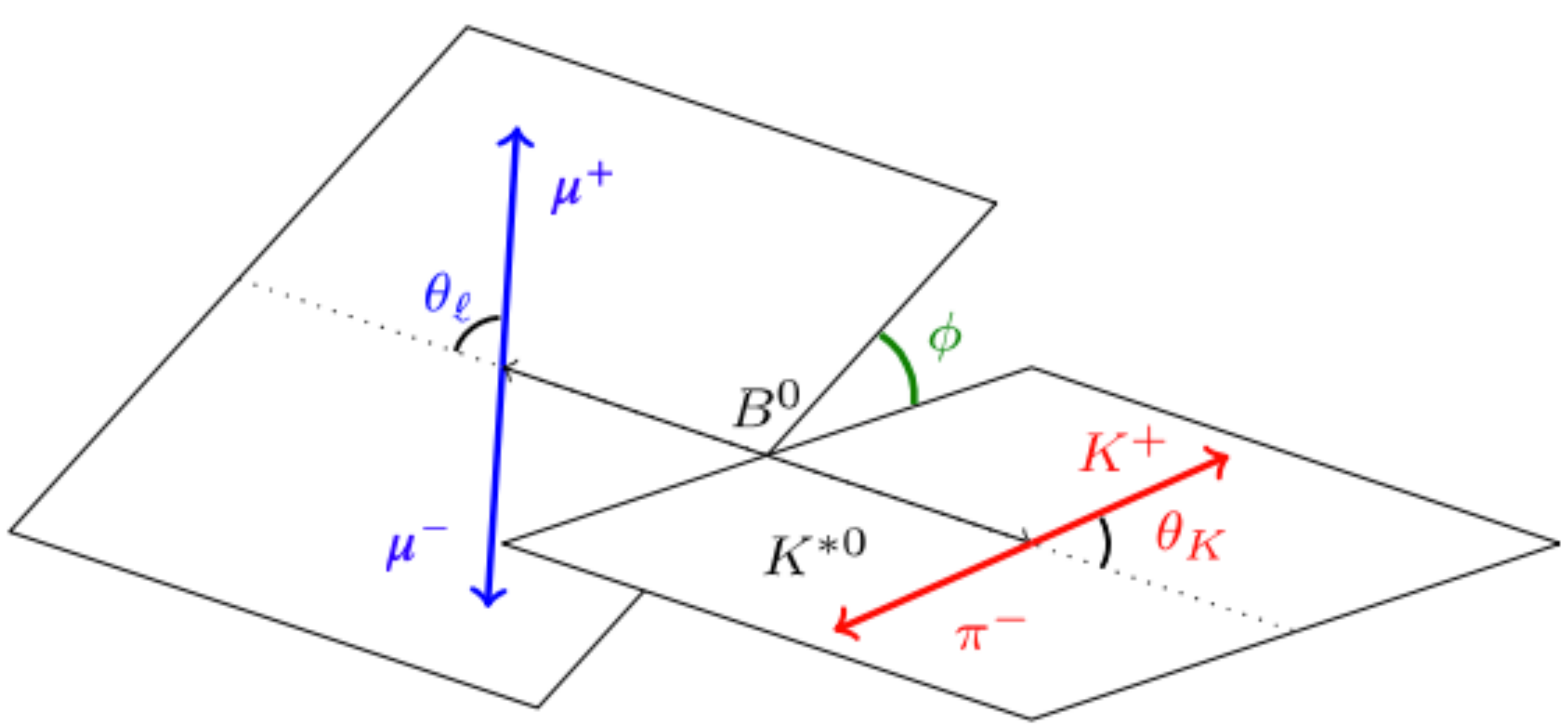
$b \to s\mu^+\mu^-$ angular analyses

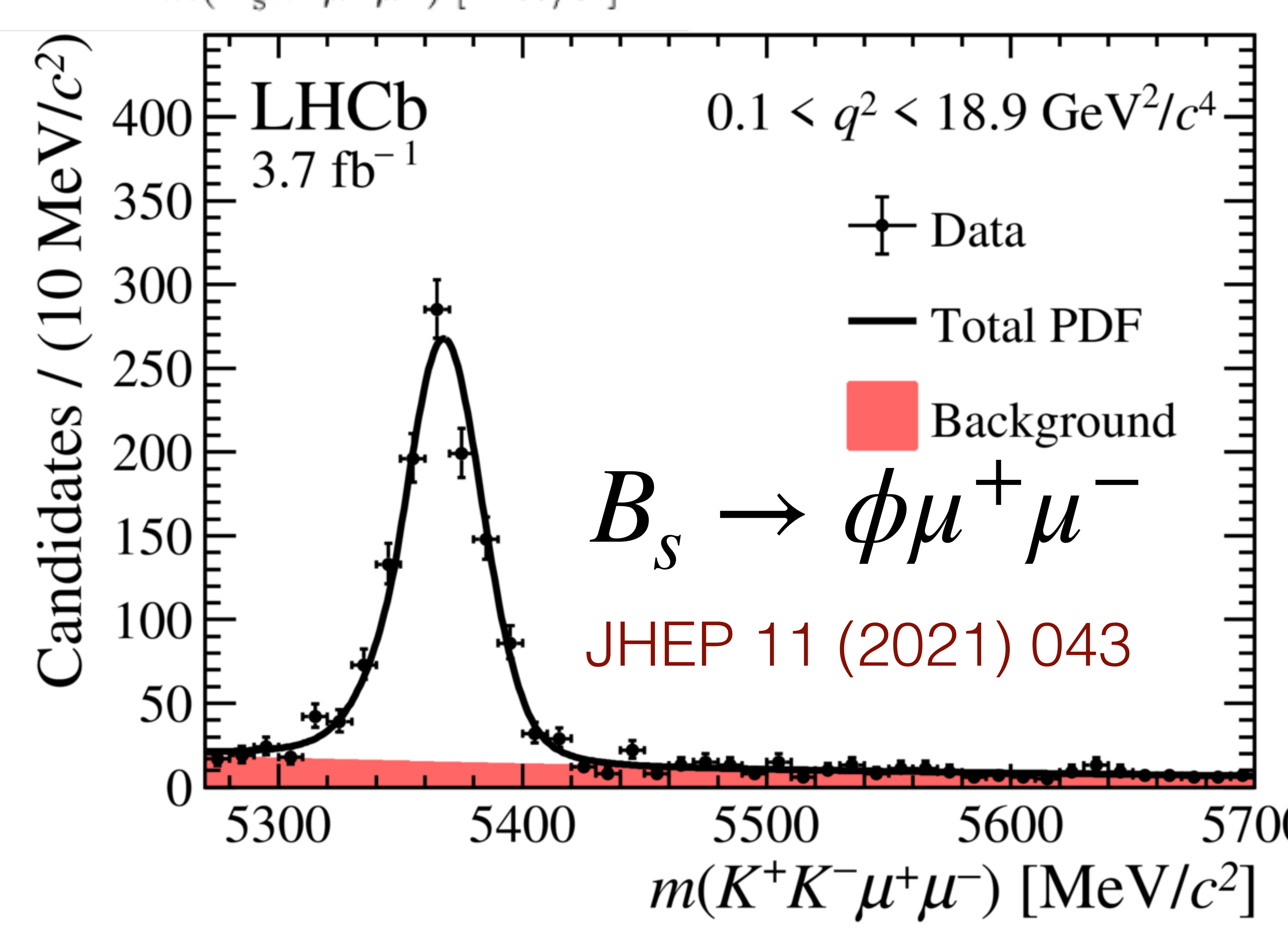
- Recent LHCb results :
  - $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ with 4.7/fb (~4600 events)
  - $B^+ \to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-$ with 9/fb (~700 events)
  - $B_s \to \phi(\to K^+K^-)\mu^+\mu^-$ with 8.4/fb (~1900 events)





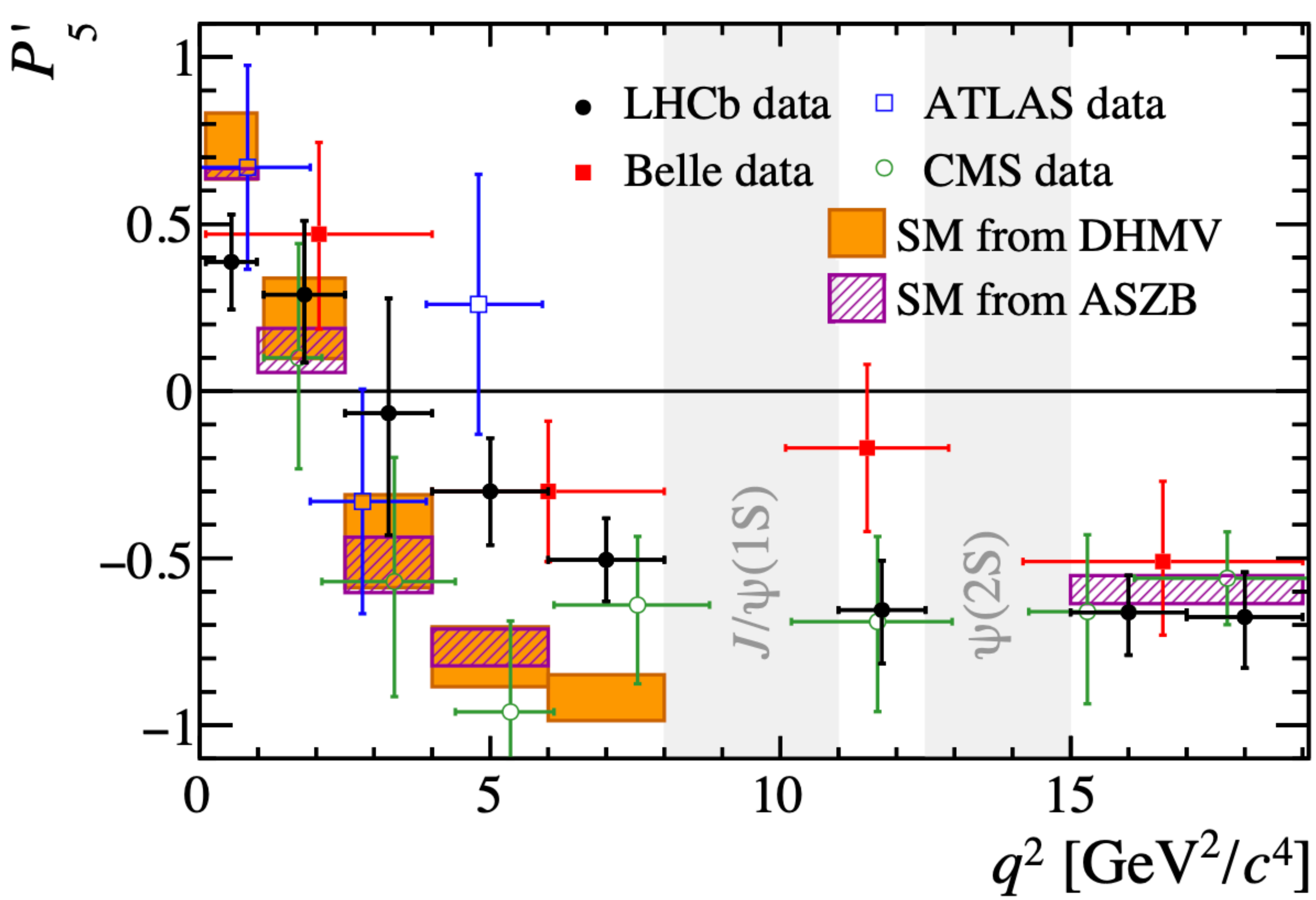
- $B \to V\mu^+\mu^-$ 4-body decay can be fully described by 3 decay angles and q^2





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

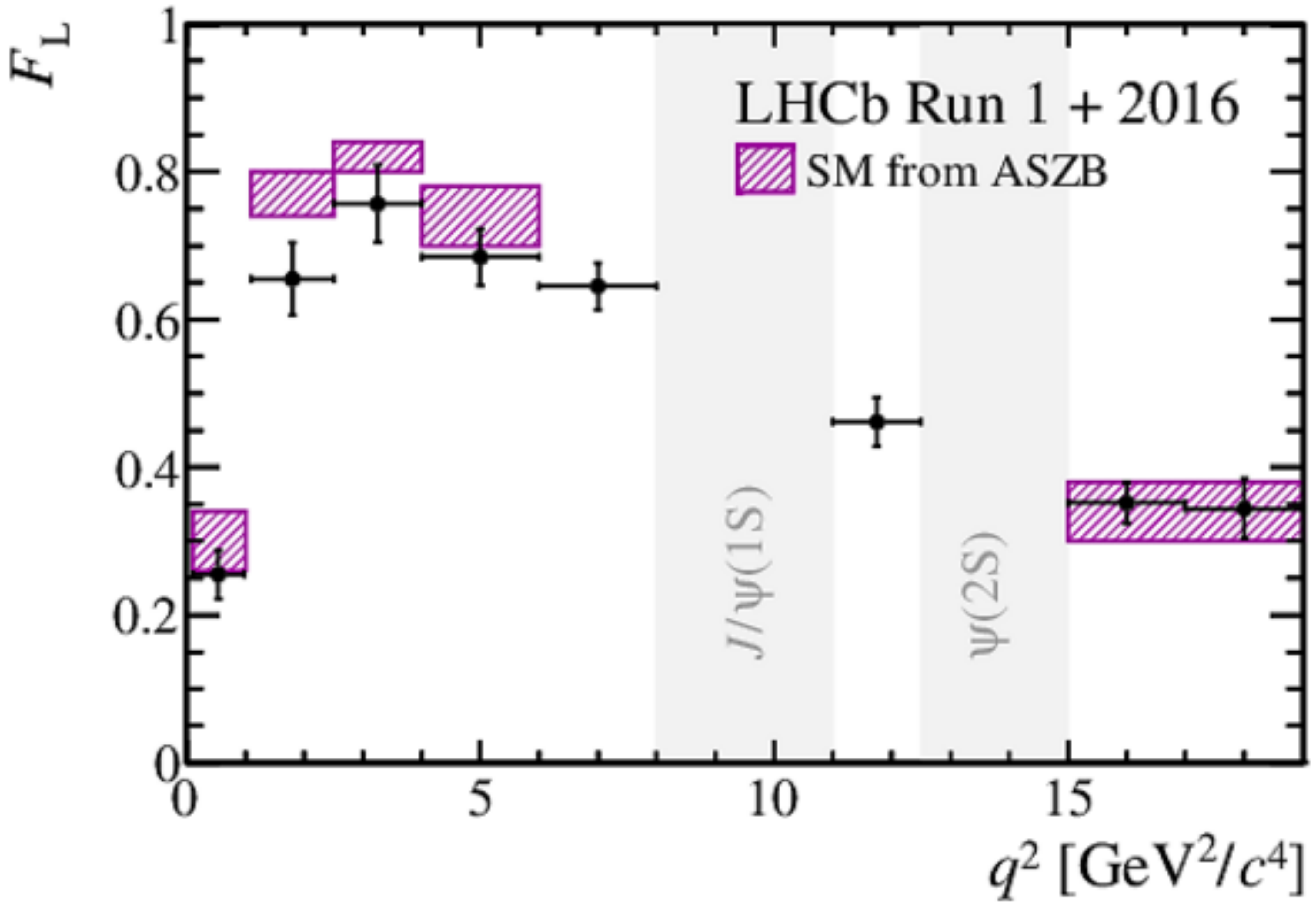


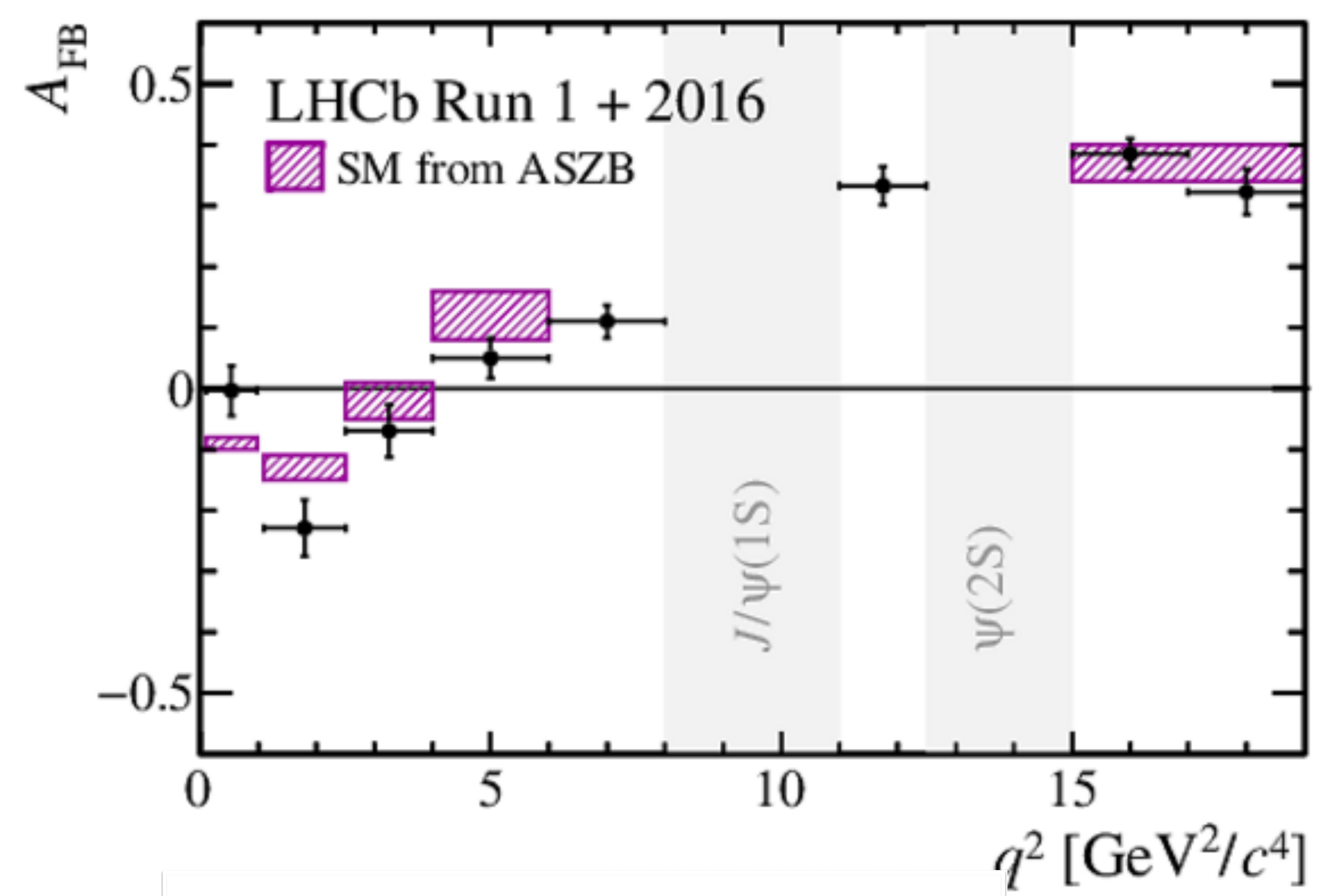
LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS: JHEP 10 (2018) 047
CMS: PLB 781 (2018) 517541

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

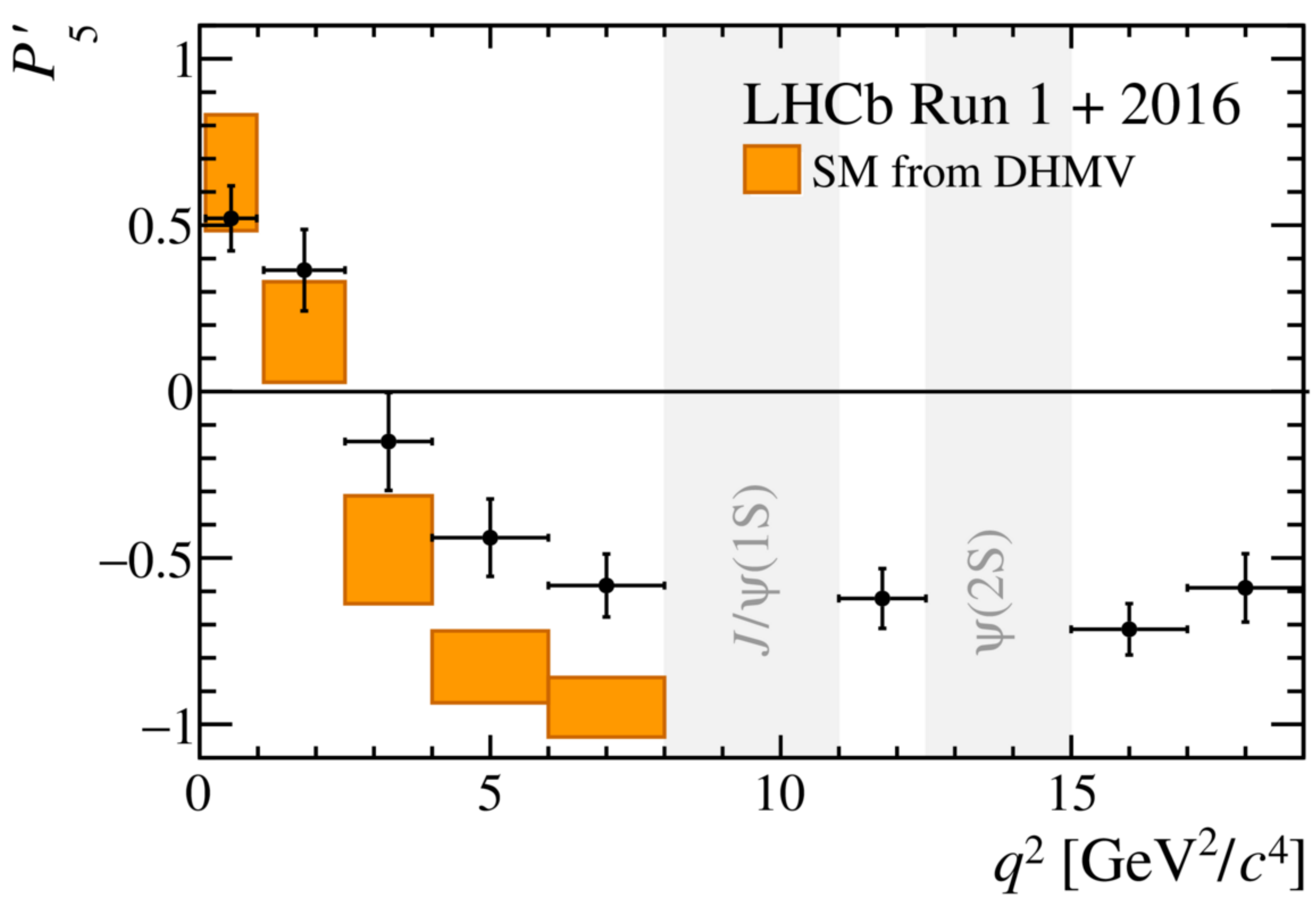
$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ angular analysis

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





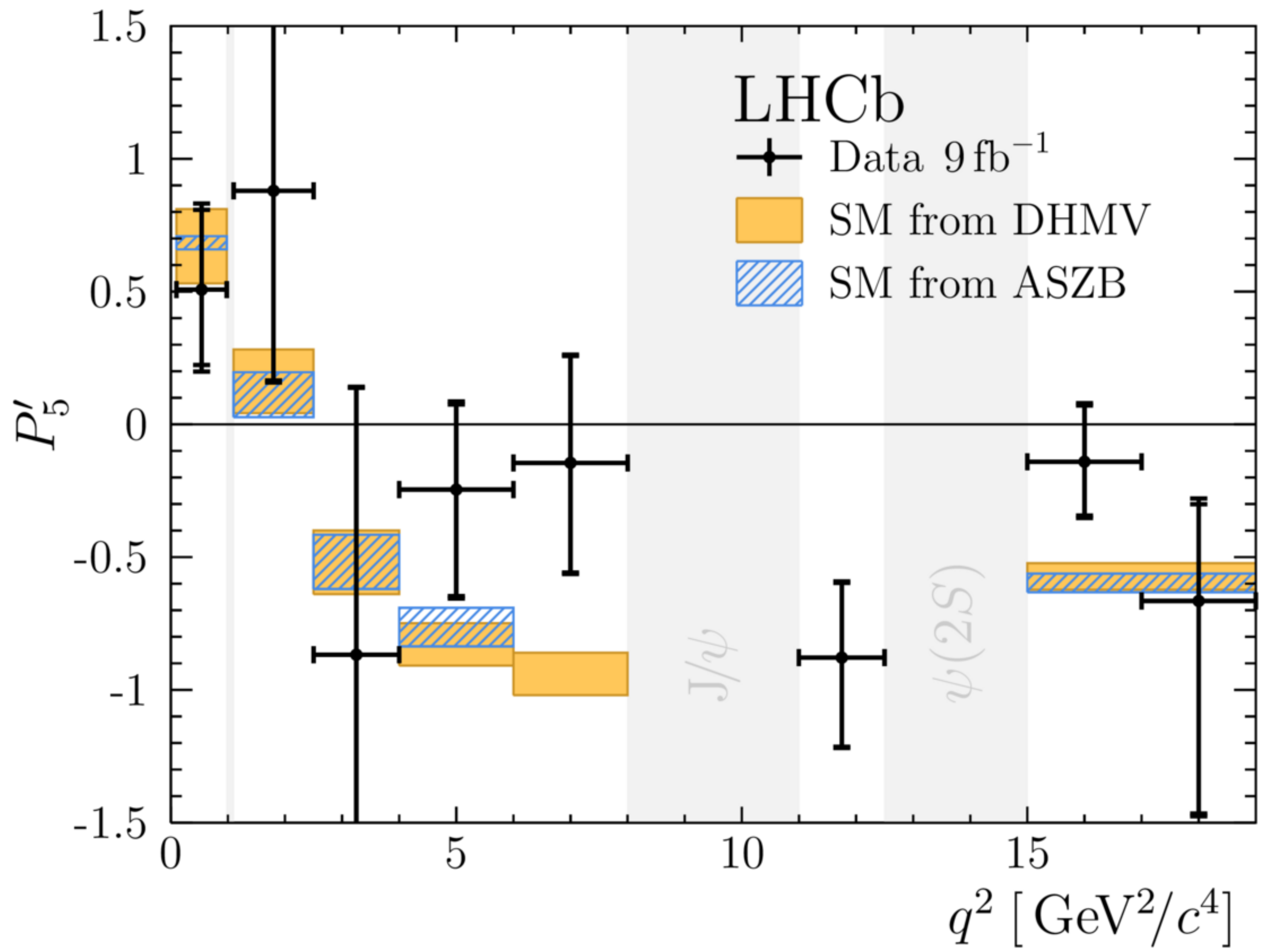
PRL 125 (2020) 011802



- 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 analysis finds a deviation of $3.3\,\sigma$
- Consistent with previous result

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

- First measurement of full set of angular observables for this decay, based on full statistics
- More difficult experimentally, smaller signal yield: observables determined using a “folding technique”



PRL 126 (2021) 161802

- Global 3σ tension with SM

$B_s^0 \to \phi\mu^+\mu^-$ angular analysis

JHEP 11 (2021) 043

- Update with ~4 time more B_s^0 candidates (8.4/fb)
- Final state $K^+K^-\mu^+\mu^-$ not flavour specific → untagged decay rate (no distinction between B_s^0 , $\overline{B_s^0}$)
- Results compatible with SM predictions

See also talk by A.Gioventu'

Tests of LFU in $b \to s\ell^+\ell^-$ transitions

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
- 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 mass
- 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. μ/e or μ/τ)
- Test LFU in $b \to s\ell^+\ell^-$ transitions, i.e. flavour-changing neutral currents with amplitudes involving loop diagrams

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

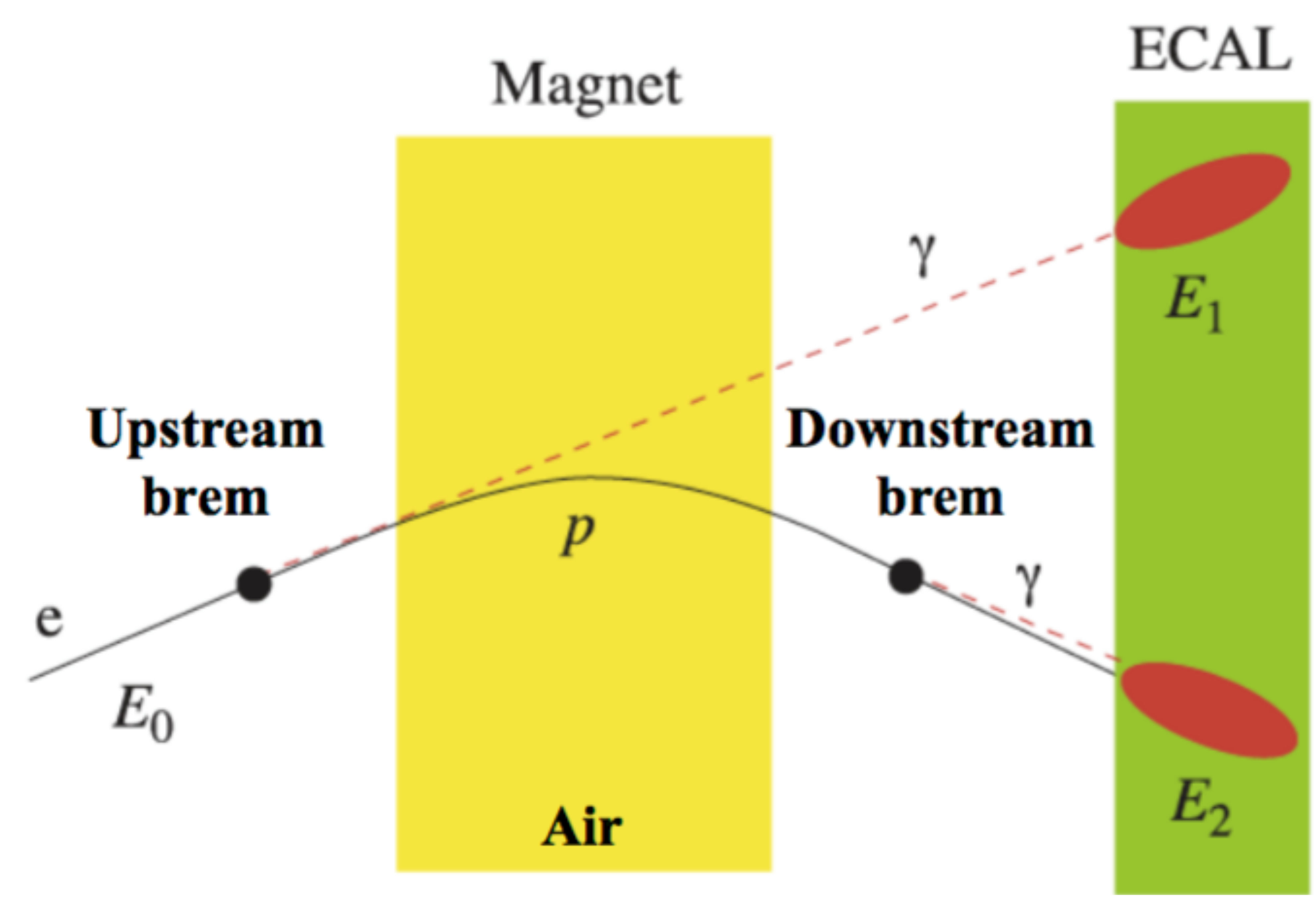
H: $K^+, K^{*0}, pK, \phi \ldots.$

- 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)

Very challenging measurements

- Lepton identification is anything but universal!
- Electrons emit a large amount of bremsstrahlung, degrading momentum and mass resolution
- Attempt to recover the emitted photons
  - Doesn't capture all
  - Some misattributed

JHEP 08 (2017) 055



- Lower efficiency of electron trigger

  $p_T(\mu^{+-}) > 1.5 - 1.8$ GeV

  - $E_T(e^{+-}) > 2.5 - 3.0$ GeV

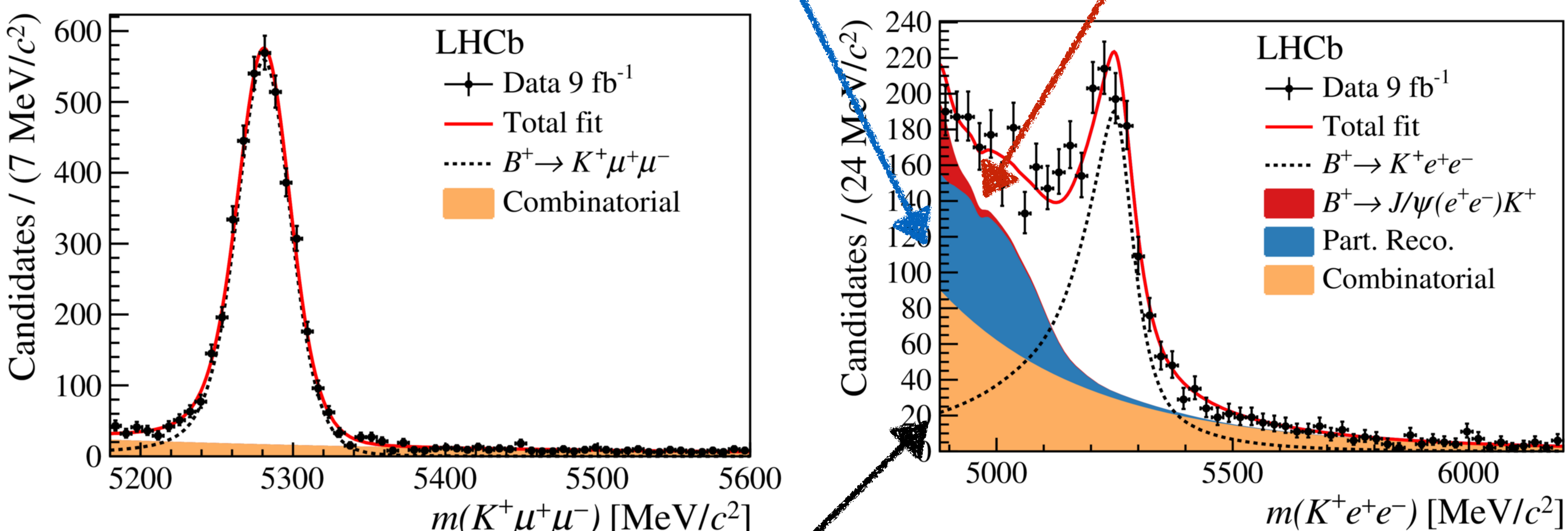
- R_H measurements at LHCb limited by electron mode

muons vs electrons

arXiv:2103.11769

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

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



Longer radiative tail due to bremsstrahlung

Measure as a double ratio

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

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

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

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

- Similarities between the experimental efficiencies of the non resonant and resonant modes ensure a substantial reduction of systematic uncertainties in the double ratio

- Analyses performed blind

LFU tests @LHCb

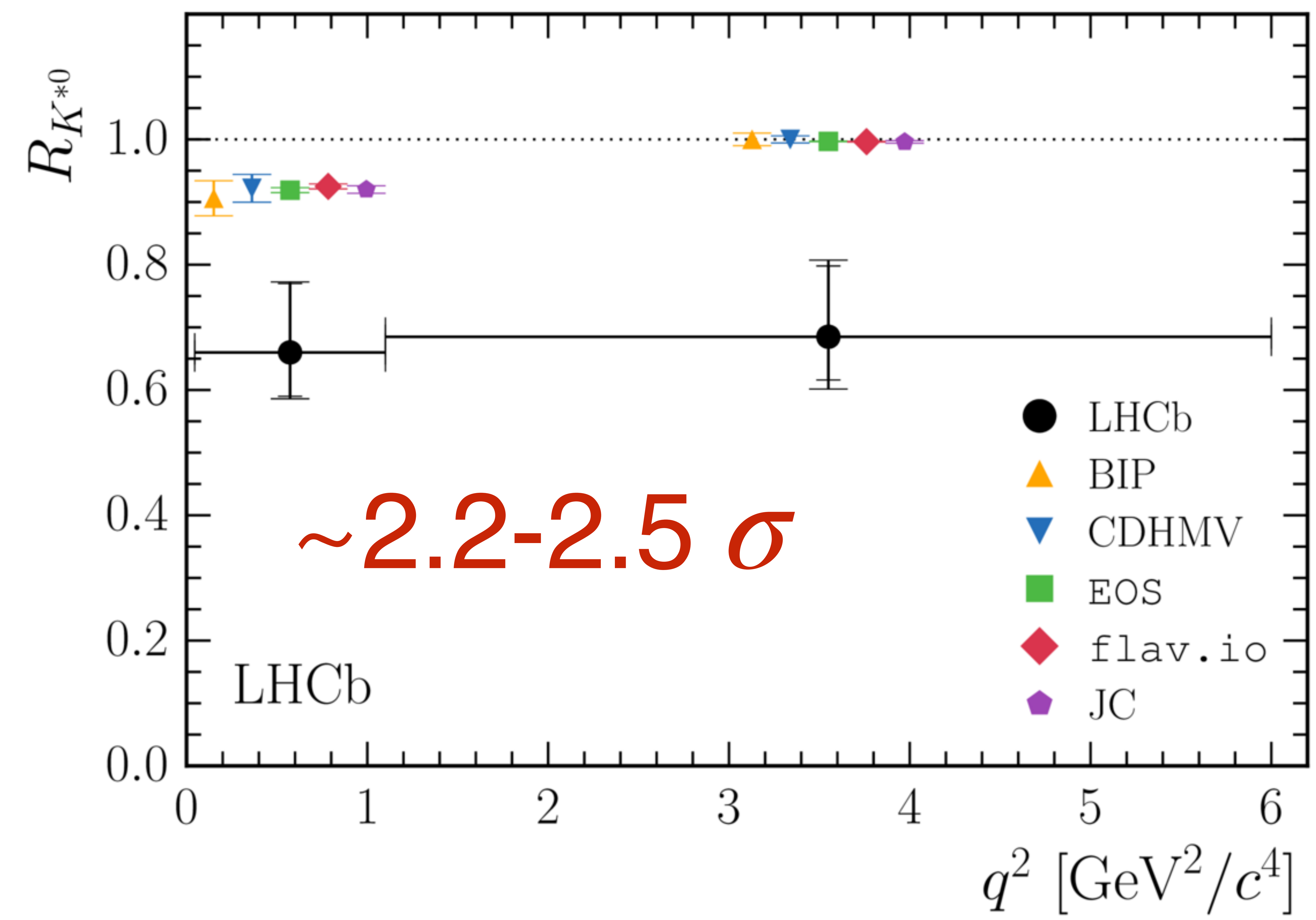
- $B^0 \to K^{*0}\ell^+\ell^-$ with 3/fb

$$R_{K^{*0}} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}) \text{ in } [0.045,1.1] \text{ GeV}^2$$

$$R_{K^{*0}} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}) \text{ in } [1.1,6.0] \text{ GeV}^2$$

→ $2.2 - 2.5\,\sigma$ deviations from SM

$B^0 \to K^{*0}\mu^+\mu^-$ JHEP 08 (2017) 055



- $\Lambda_b^0 \to pK^-\ell^+\ell^-$ with 4.7/fb

$$R_{pK}(0.1 < q^2 < 6\,\text{GeV}^2) = 0.86^{+0.14}_{-0.11} \pm 0.05$$

→compatible with SM; showcases the unique capabilities to access high-statistics heavy flavour baryon decays @LHC; first observation with significance $> 7\sigma$ of $\Lambda_b^0 \to pK^-e^+e^-$

JHEP 05 (2020) 040

- $B^+ \to K^+\ell^+\ell^-$ with 9/fb (full Run1 & 2 statistics)

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

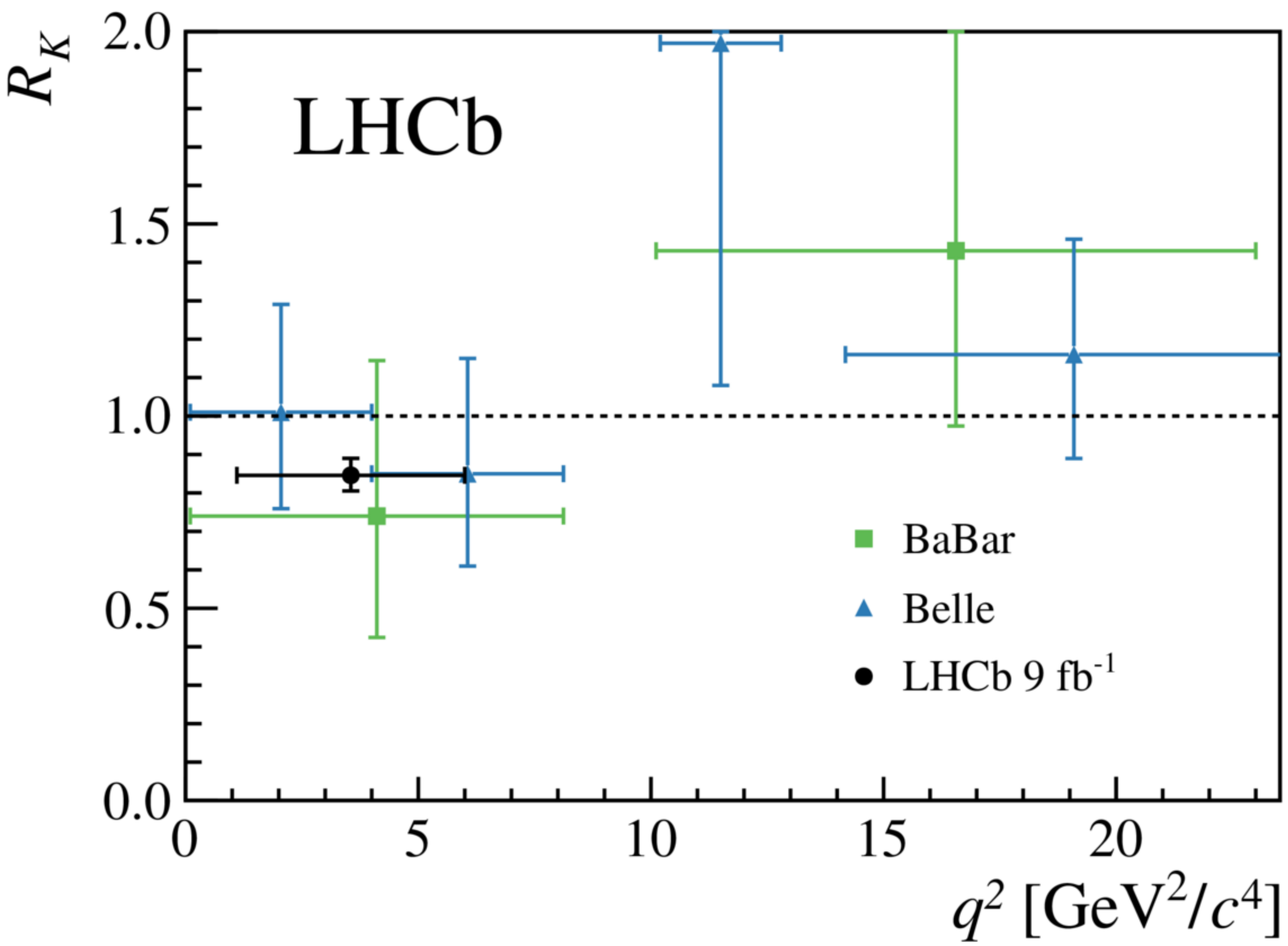
arXiv:2103.11769

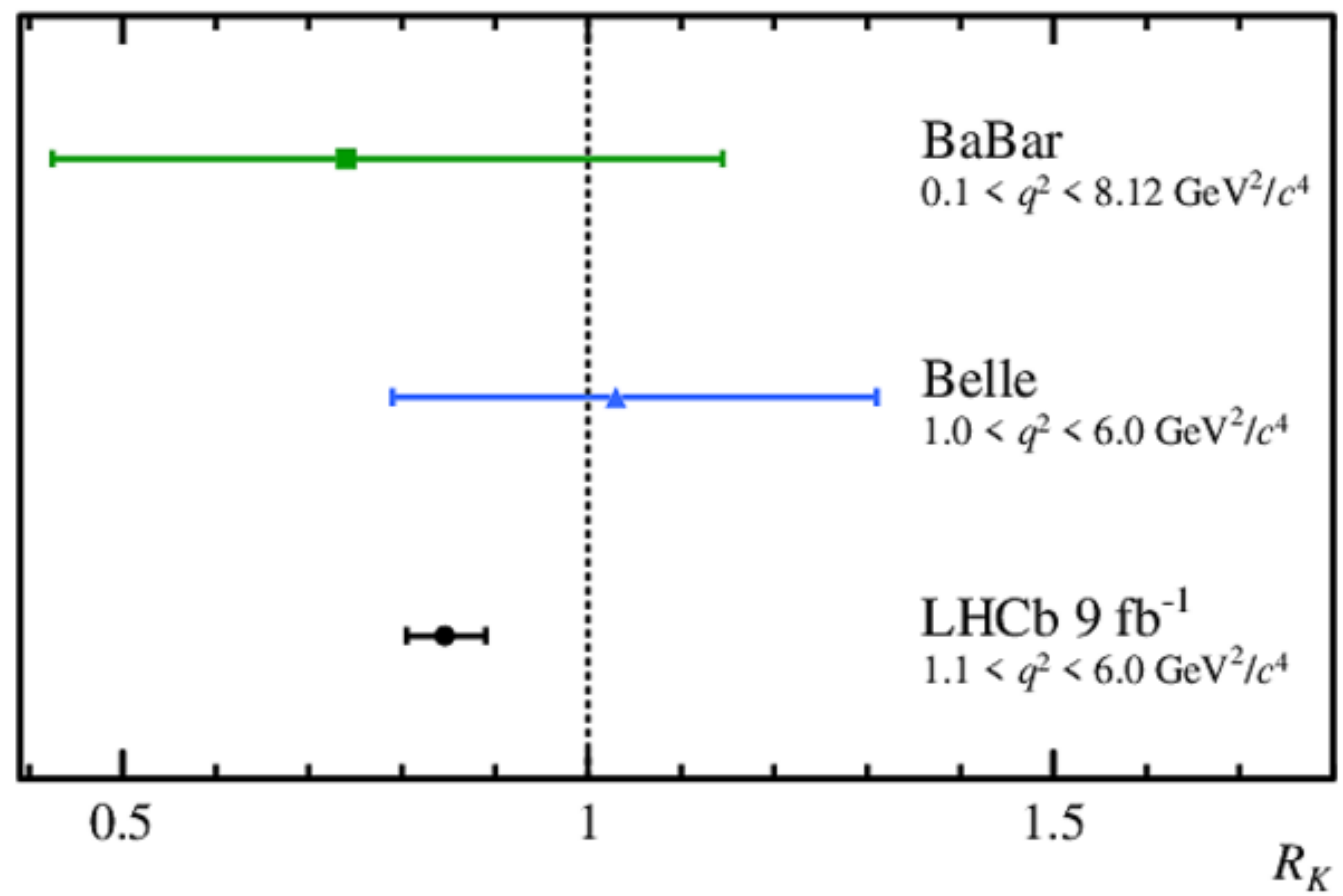
→$3.1\,\sigma$ deviations from SM

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

arXiv:2103.11769

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





3.1 σ evidence

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

arXiv:2103.11769

- Result validated by important crosschecks

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = \frac{\mathcal{N}(\mu^+\mu^-)}{\varepsilon(\mu^+\mu^-)} \Bigg/ \frac{\mathcal{N}(e^+e^-)}{\varepsilon(e^+e^-)} = 0.981 \pm 0.020$$

- $r_{J/\psi}$ very stringent cross-check, which requires control of the relative selection efficiencies for the resonant electron and muon modes

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

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

NEW

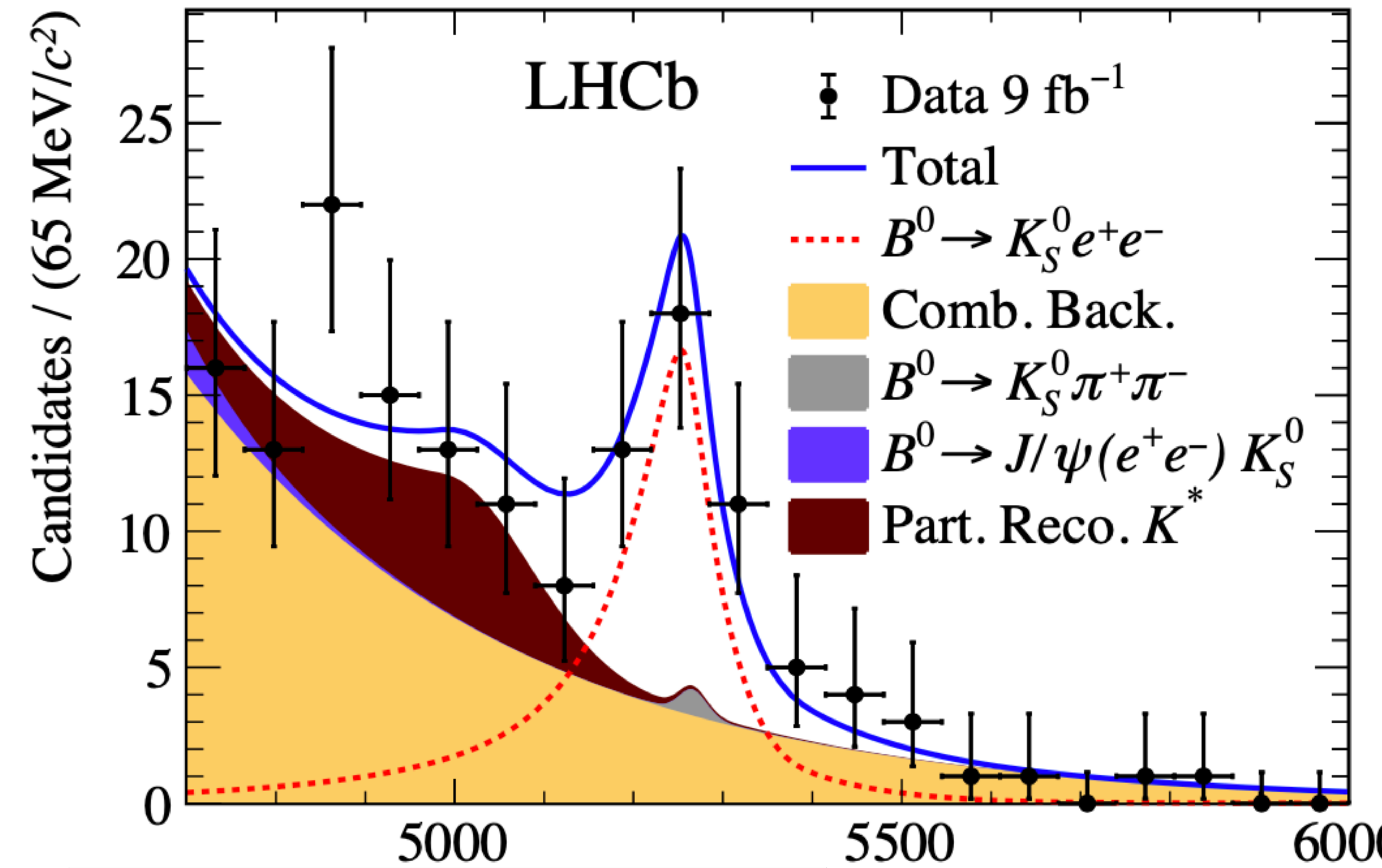
- Both channels involve long-lived $K^0_S \to \pi^+\pi^-$ ($K^{*+} \to K^0_S\pi^+$) → lower efficiency than corresponding isospin partner decays
- For B^+, q^2 range extended down to $0.045\ \mathrm{GeV}^2$ to increase statistics
- e^+e^- modes observed for first time:

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

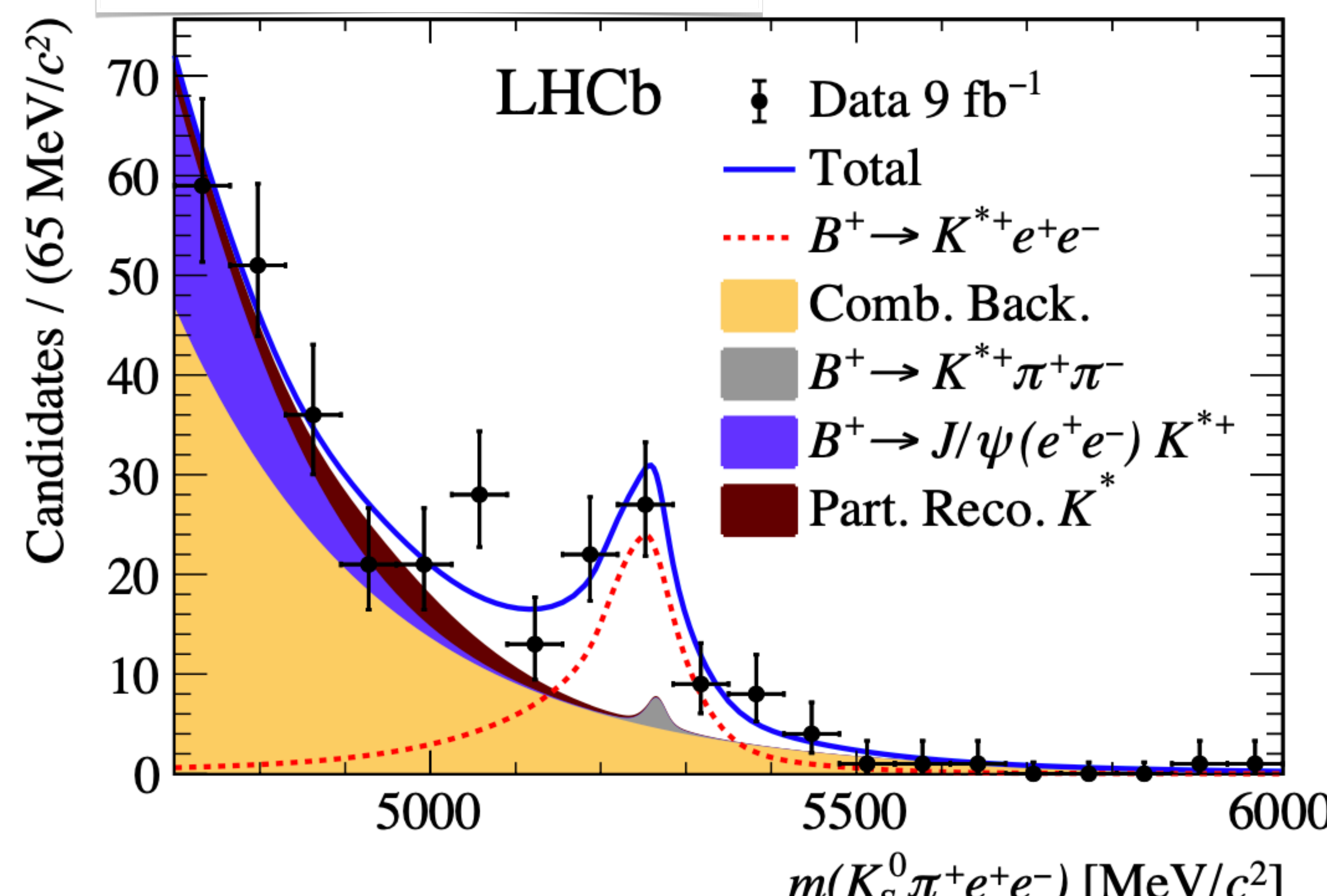
$q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2$ 5.3σ

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

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



arXiv:2110.09501



$J/\Psi \to \ell^+\ell^-$ control mode

NEW

- Ratios and differential BFs normalised to control modes $B^0 \to J/\Psi(\ell^+\ell^-)\,K_S^0$, $B^+ \to J/\Psi(\ell^+\ell^-)\,K^{*+}$

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

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

$$r^{-1}_{J/\psi K_S^0} = 0.977 \pm 0.008 \pm 0.027$$

$$r^{-1}_{J/\psi K^{*+}} = 0.965 \pm 0.011 \pm 0.034$$

arXiv:2110.09501

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

NEW

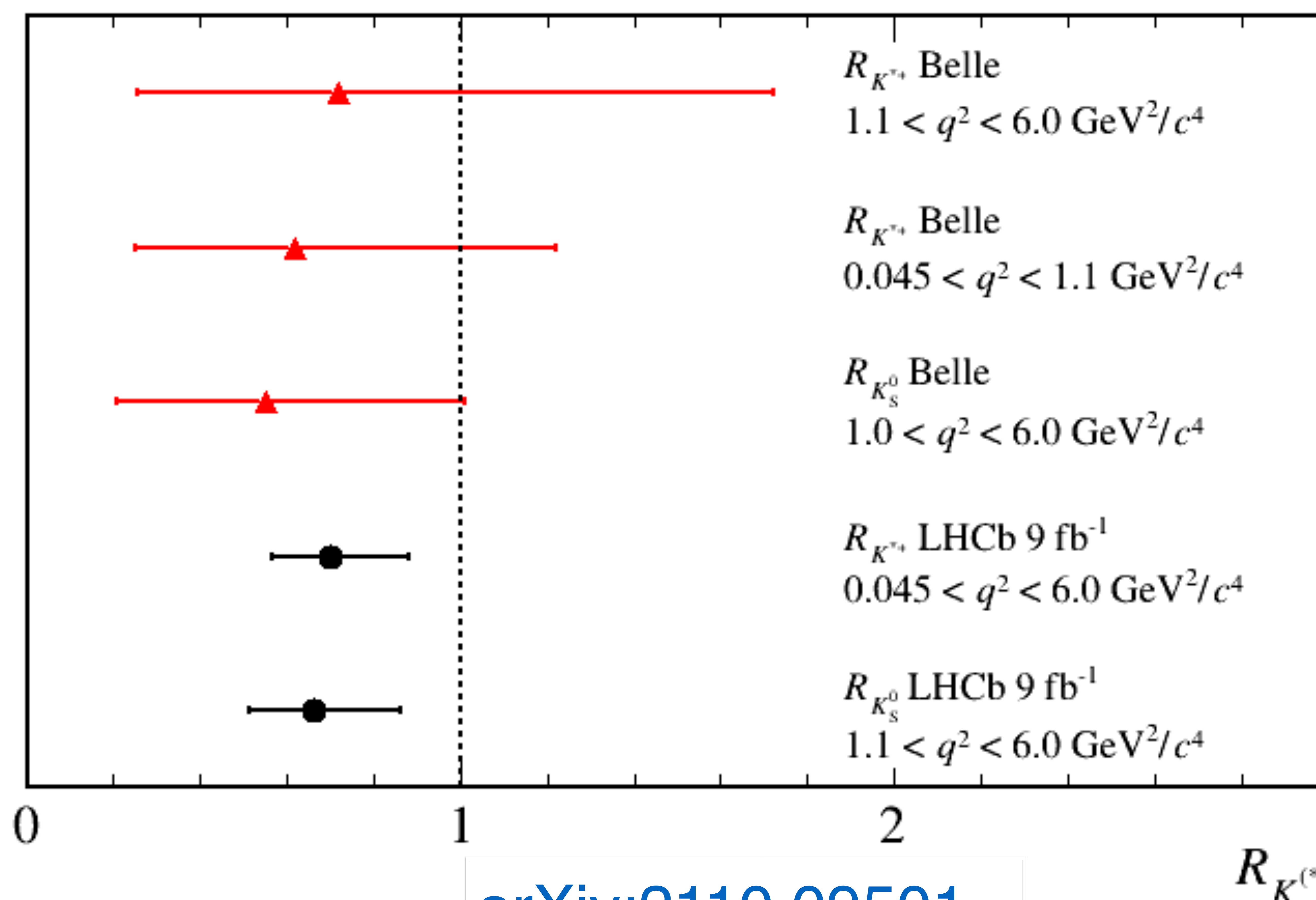
- Results are in agreement with SM (at $\sim 1.5\,\sigma$) and with previous results from Belle

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

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

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

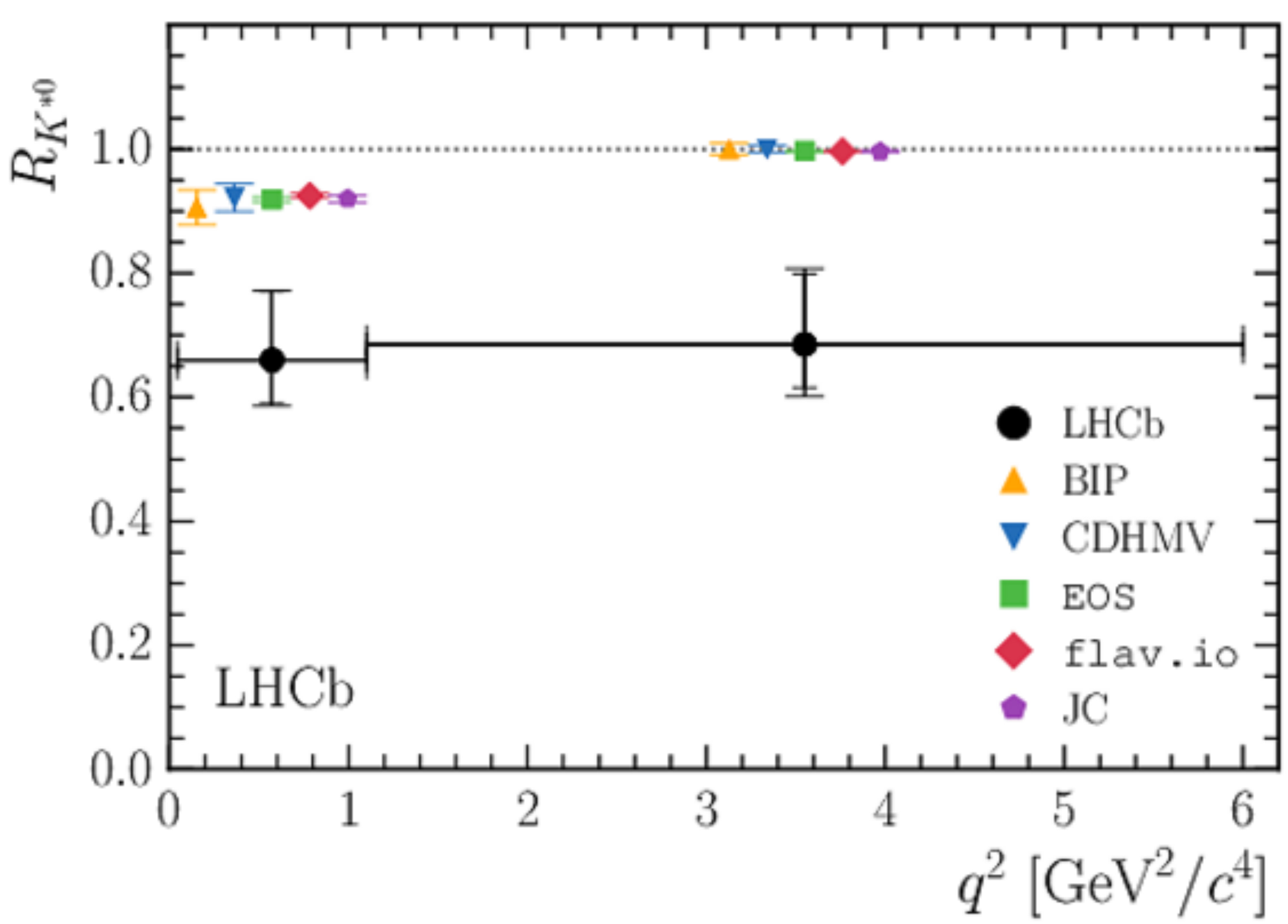
- Paper dedicated to the memory of our great colleague Sheldon Stone [1946-2021]

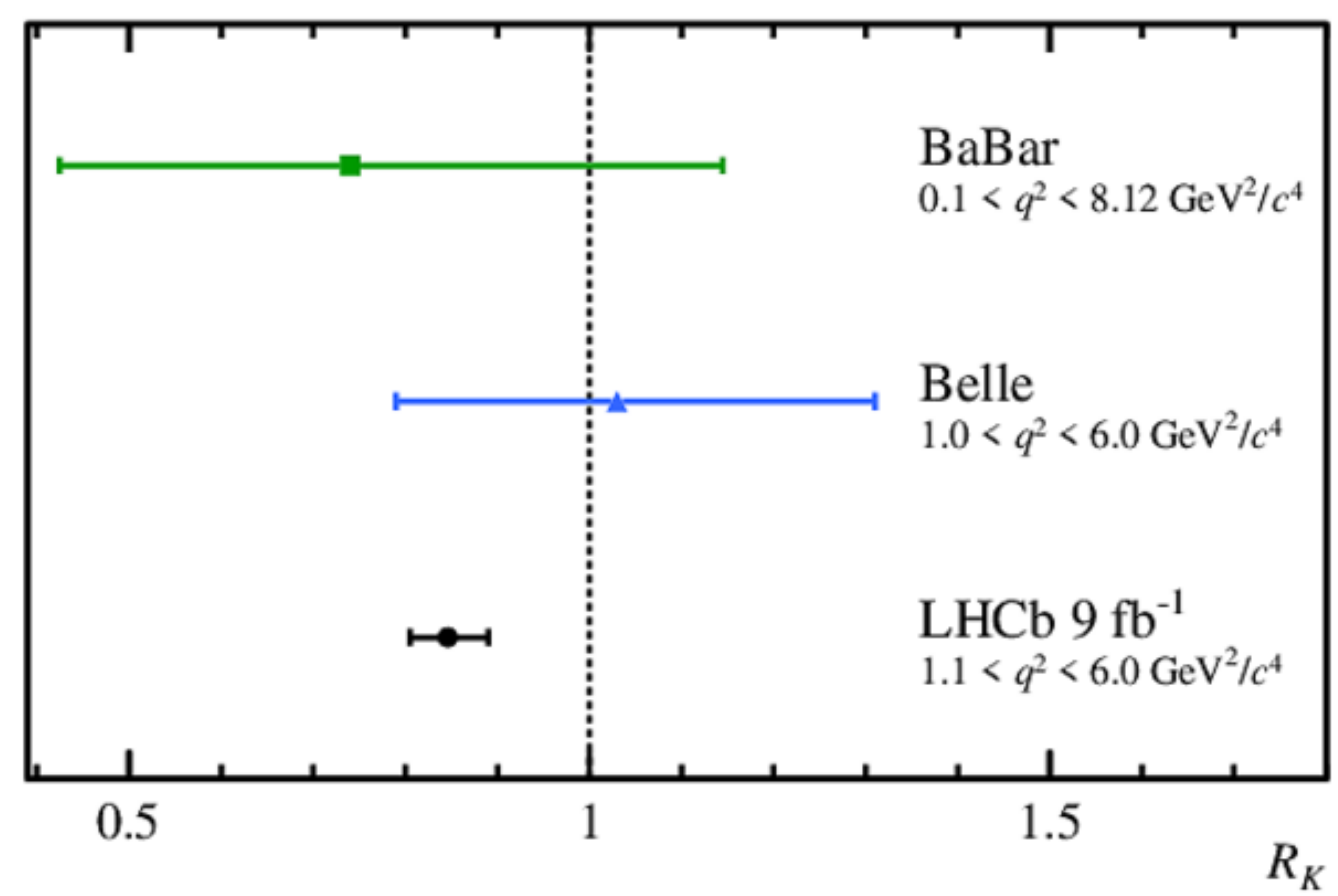


arXiv:2110.09501

Summary of LFU results in $b \to s\ell\ell$

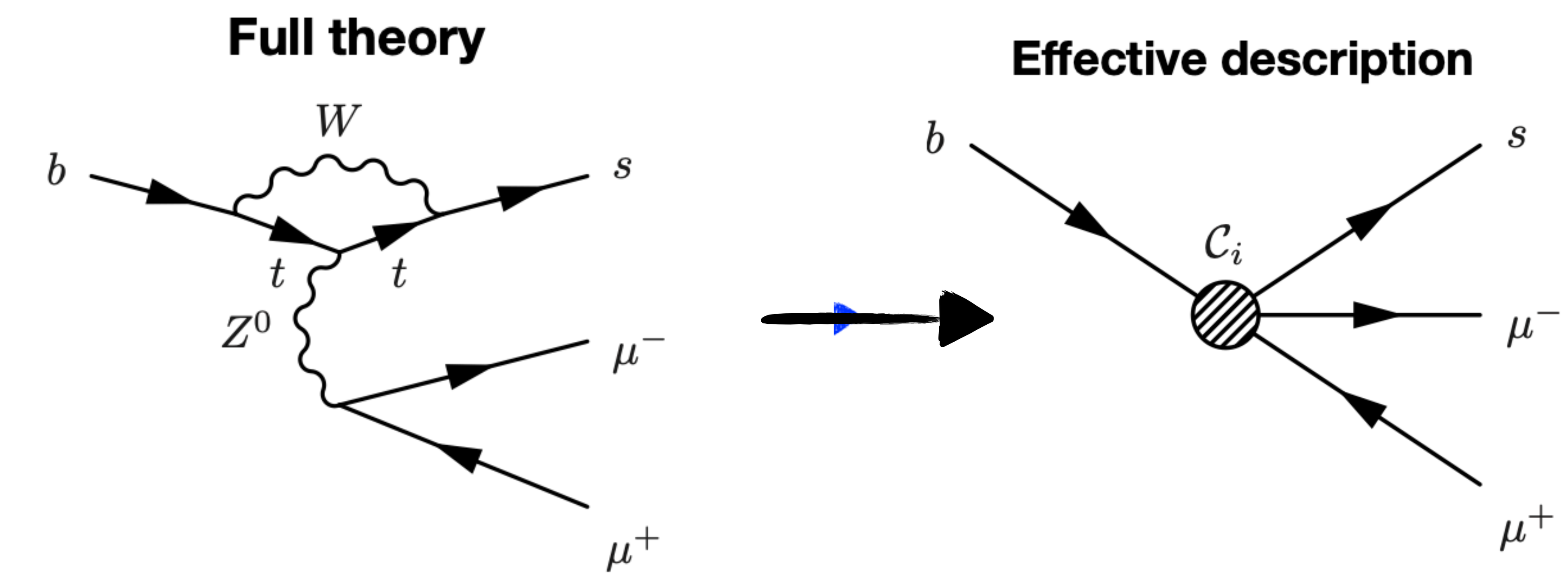
$R_{K^{*0}}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst})$	3/fb	$\sim 2.2\,\sigma$	JHEP 08 (2017) 055
$R_{K^{*0}}^{[1.1,6.0]} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst})$	3/fb	$\sim 2.5\,\sigma$	JHEP 08 (2017) 055
$R_{K^{+}}^{[1.1,6.0]} = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{syst})$	9/fb	$\sim 3.1\,\sigma$	arXiv:2103.11769
$R_{pK}^{[1.1,6.0]} = 0.86^{+0.14}_{-0.11}(\text{stat}) \pm 0.05(\text{syst})$	4.7/fb	$\sim 1\,\sigma$	JHEP 05 (2020) 040
$R_{K_s^0}^{[1.1,6.0]} = 0.66^{+0.20}_{-0.14}(\text{stat})^{+0.02}_{-0.04}(\text{syst})$	9/fb	$\sim 1.5\,\sigma$	arXiv:2110.09501
$R_{K^{*+}}^{[1.1,6.0]} = 0.70^{+0.18}_{-0.13}(\text{stat})^{+0.03}_{-0.04}(\text{syst})$	9/fb	$\sim 1.4\,\sigma$	arXiv:2110.09501



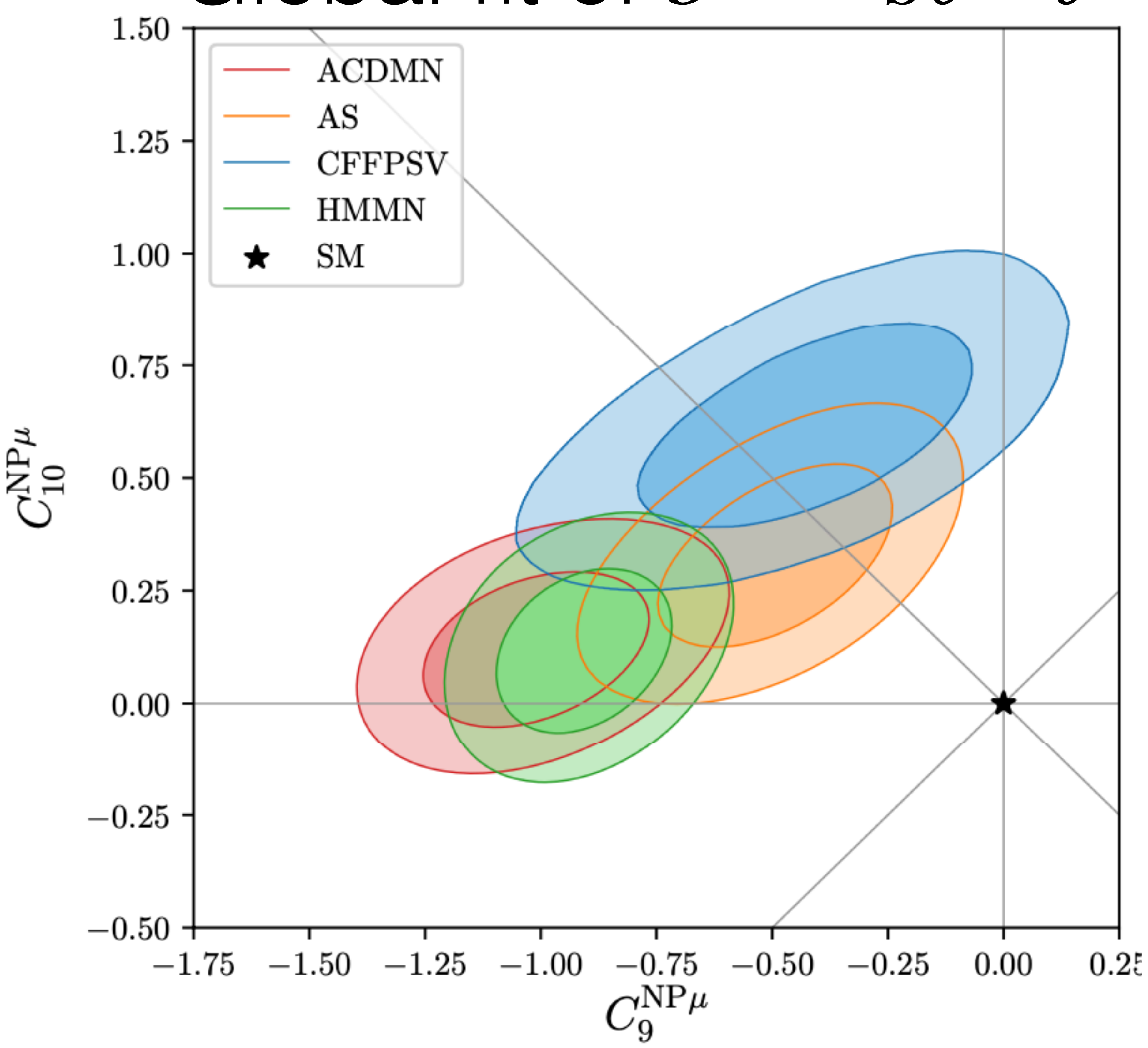


Global fit to $b \to s\ell^+\ell^-$ data

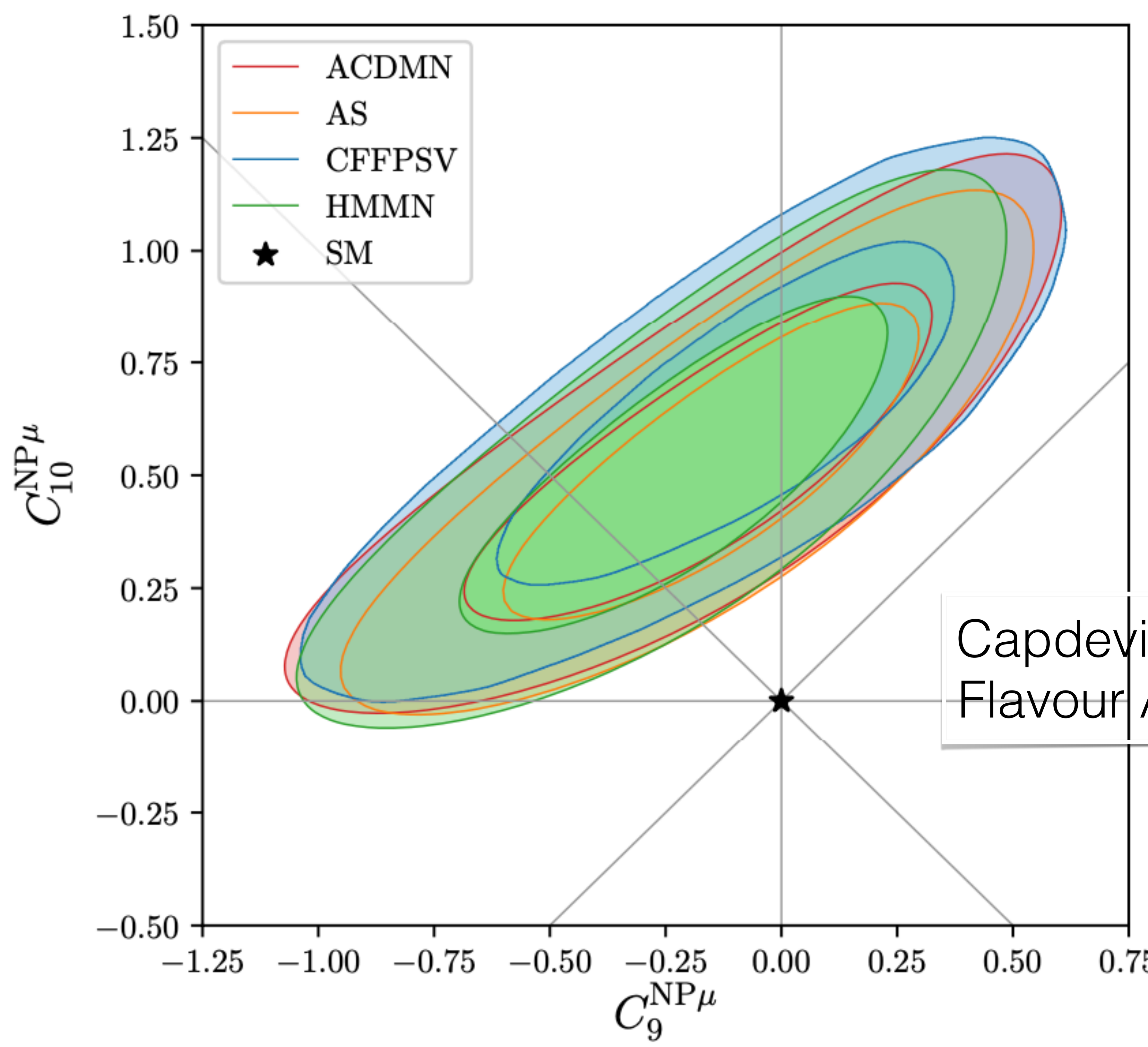
- Weak effective theory in which “heavy fields” (Higgs, top, W, Z) are encoded in “Wilson coefficients” $C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}}$



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

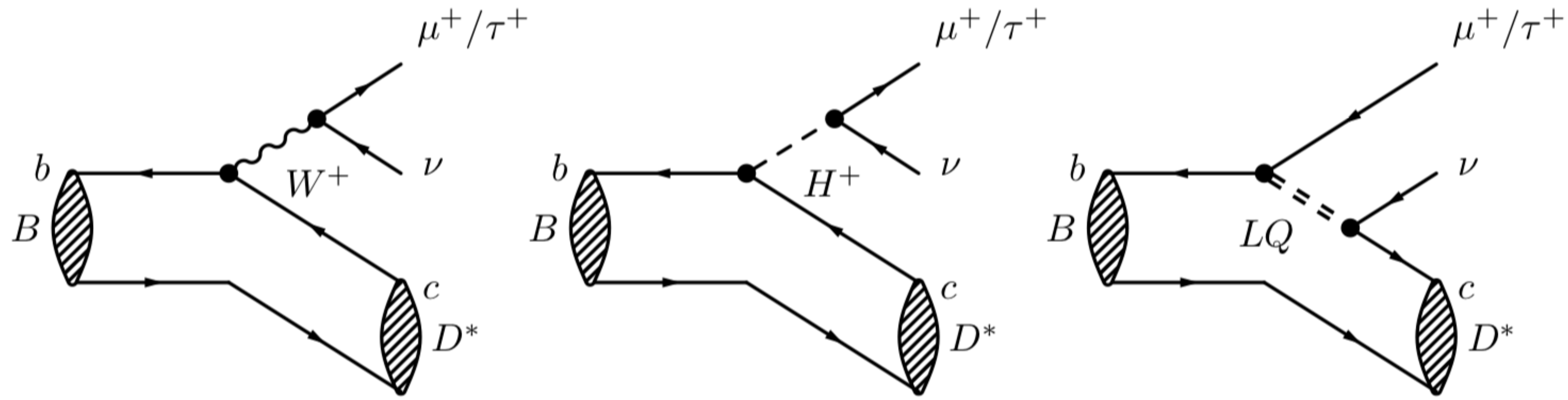
Capdevila, Fedele, Neshatpour, Stangl
Flavour Anomaly Workshop, 20 October 2021

- Discrepancy in numerous $b \to s\ell^+\ell^-$ observables can be explained consistently through a modification of the effective couplings induced by, eg, a heavy neutral boson or a leptoquark

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

See talk by A.Gioventu'

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*) : $R(D^*) = \dfrac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$

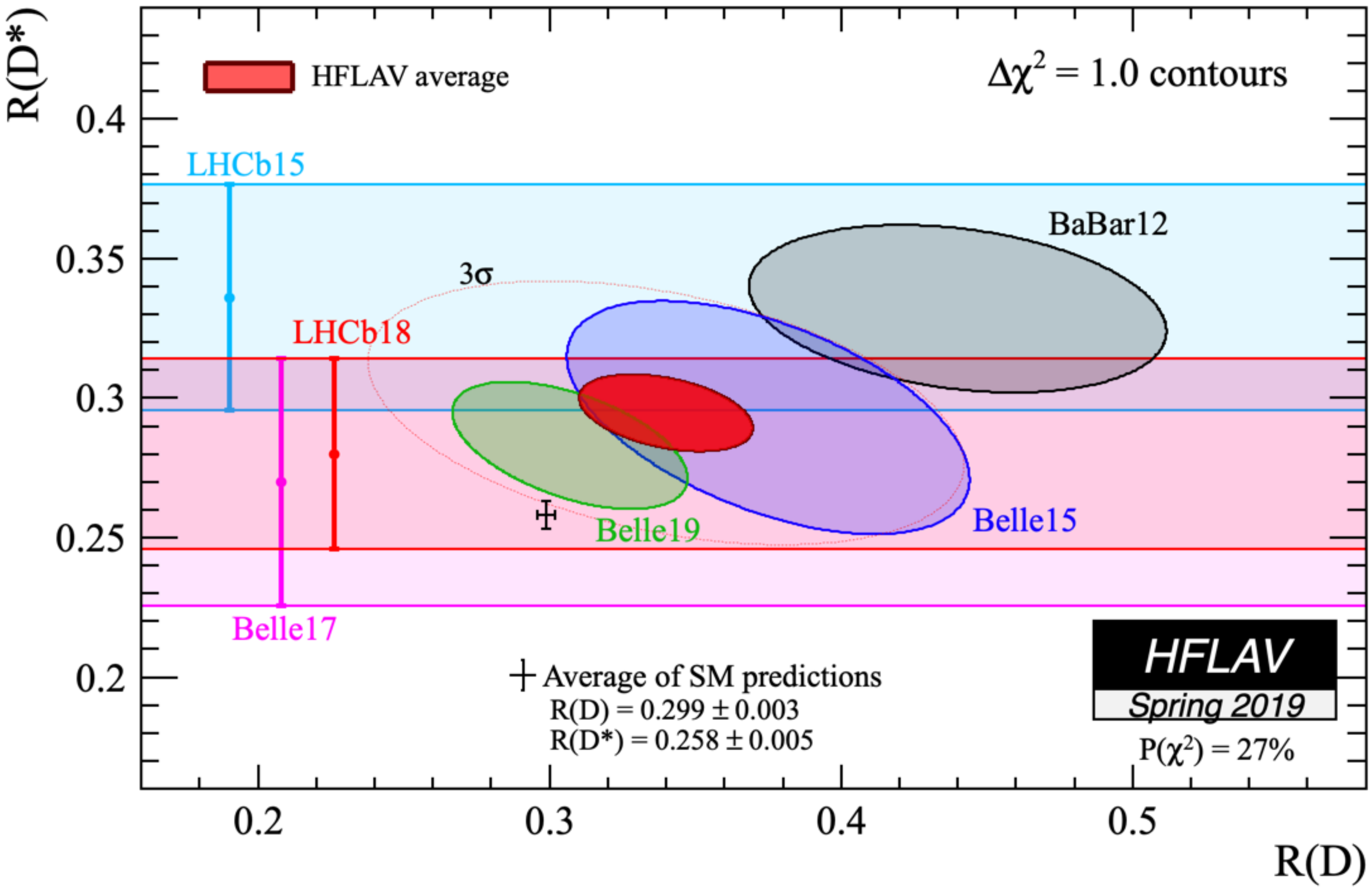
  - sensitive to any NP model coupling preferentially to third generation leptons

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

HFLAV average, 2019

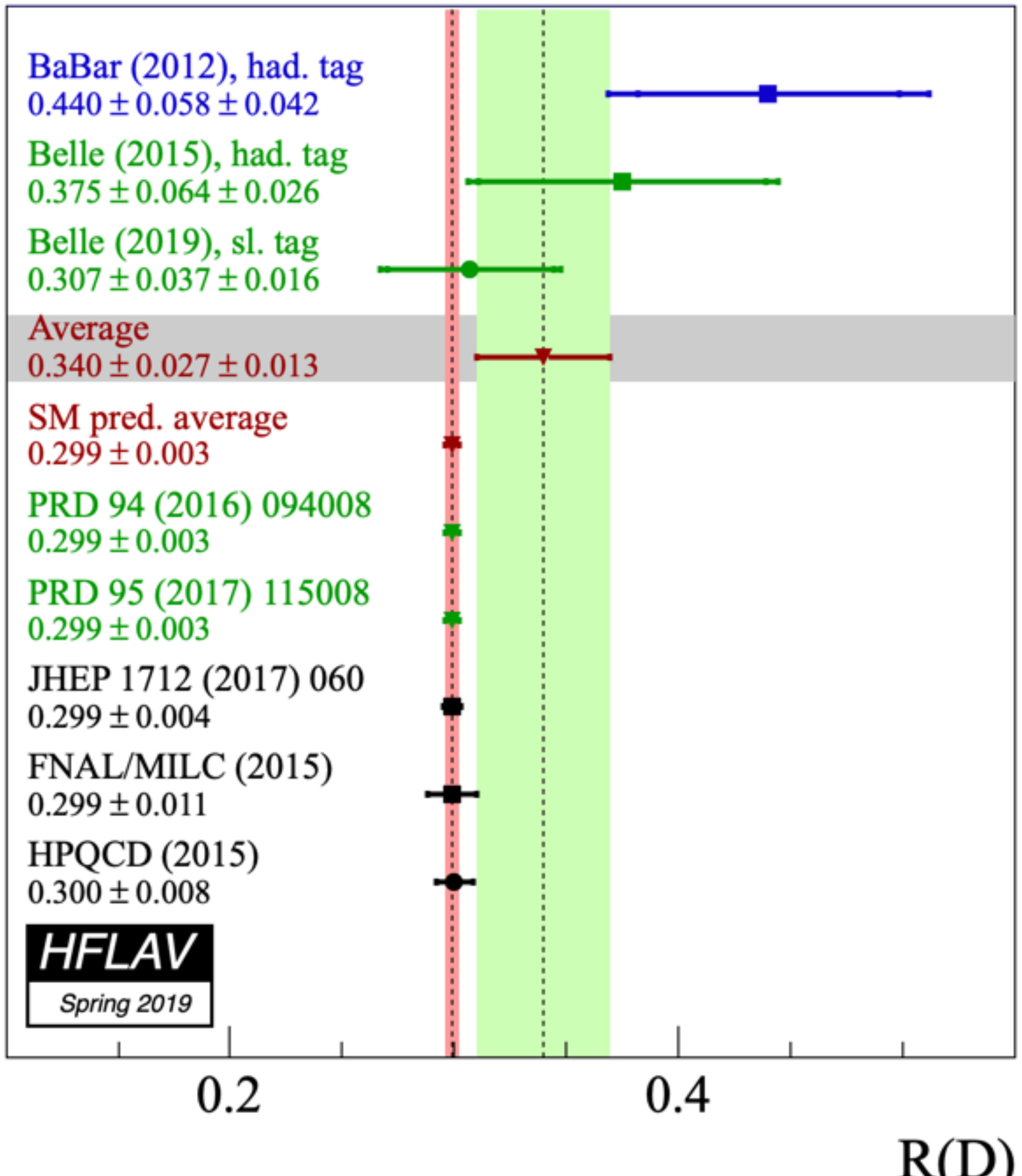
- Studied by Belle, BaBar and LHCb

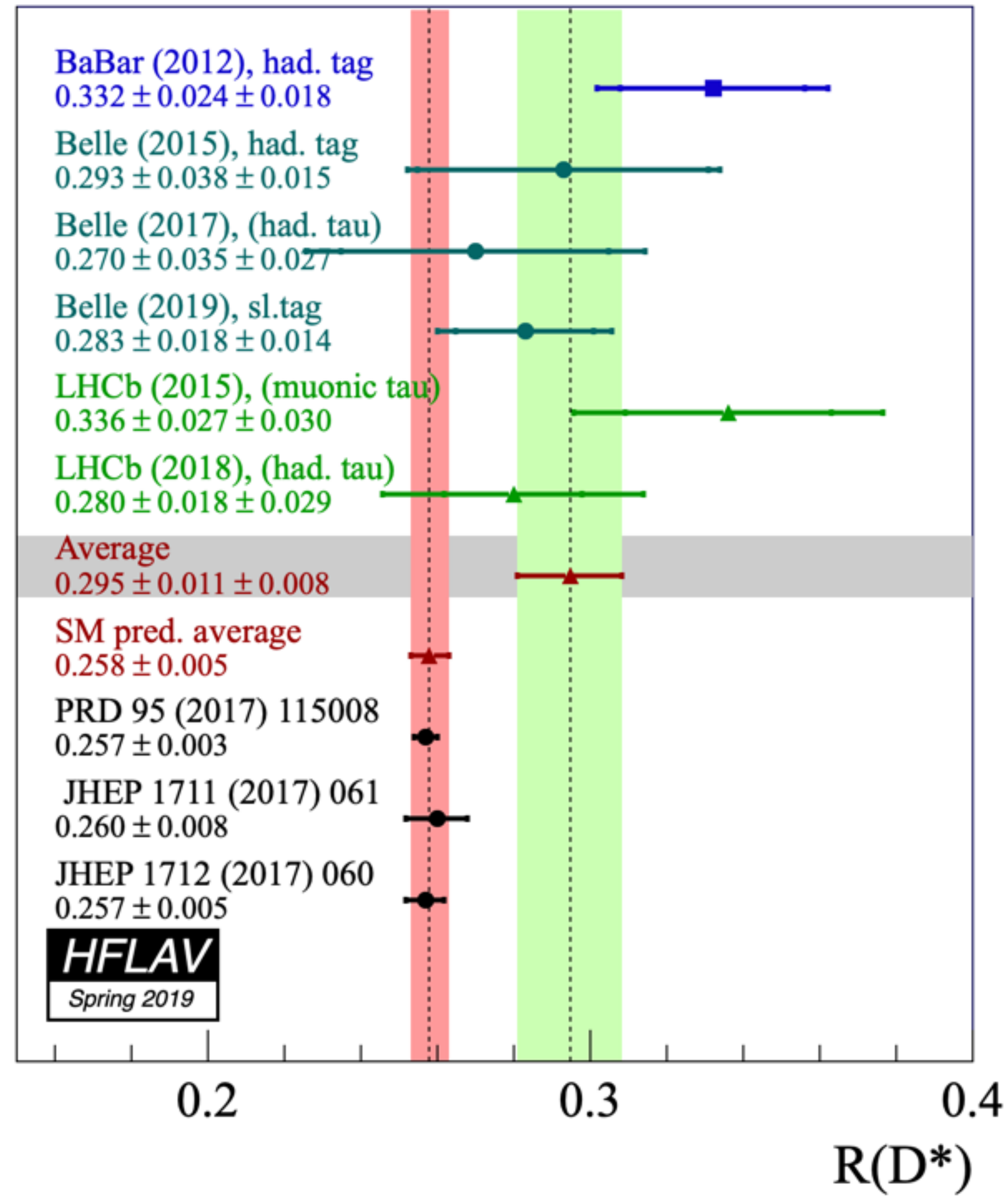
$R(D)$ vs $R(D^*)$



- All experiments see an excess wrt SM predictions
- $\sim 3.1\sigma$ tension (2.5 σ on $R(D^*)$)
- Intriguing as it occurs in a tree-level SM process

$R(D)$ and $R(D^*)$





- All experiments see an excess wrt SM predictions
- 3σ tension (2.5 σ on $R(D^*)$)
- Intriguing as it occurs in a tree-level SM process

A word on LFV

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

- Neutral decays ($@95\,\%\,CL$)

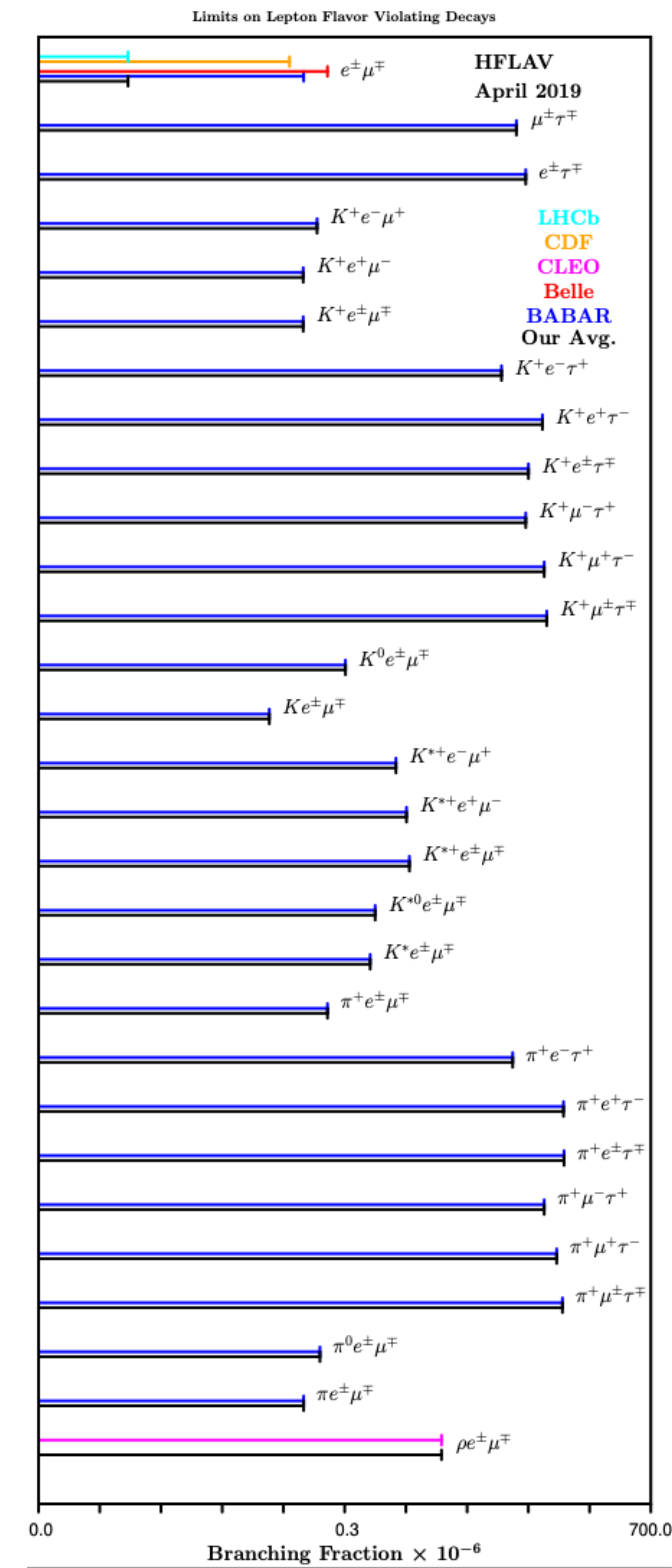
$$\mathcal{B}(B_s^0 \to e^{\pm}\mu^{\mp}) < 6.3 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-9}$$
$$\mathcal{B}(B_s^0 \to \tau^{\pm}\mu^{\mp}) < 4.2 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to \tau^{\pm}\mu^{\mp}) < 1.4 \times 10^{-5}$$

JHEP 1803(2018) 078
PRL 123(2019) 211801

- Charged decays

PRL123 (2019) 241802
JHEP 06 (2020) 129

$$\mathscr{B}(B^+ \to K^+\mu^-e^+) < 9.5 \times 10^{-9} \,@95\,\%\,\mathrm{CL}$$
$$\mathscr{B}(B^+ \to K^+\mu^+e^-) < 8.8 \times 10^{-9} \,@95\,\%\,\mathrm{CL}$$
$$\mathscr{B}(B^+ \to K^+\mu^-\tau^+) < 4.5 \times 10^{-5} \,@95\,\%\,\mathrm{CL}$$



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 (e.g. measurement of R_X, i.e. R_K&R_{K*} simultaneously, $R(D)$&$R(D*)$ but also results from ATLAS and CMS while waiting for the high-precision results from the LHCb upgrade and Belle II

Extra slides

Effective B_s lifetime

- An observable sensitive to NP and complementary to branching fraction
- For B_s mesons, the sizeable difference between the decay widths of the light and heavy mass eigenstates $\Delta\Gamma_s$ allows us to define:

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\Gamma(B_s(t) \to \mu^+\mu^-)dt}{\int_0^\infty \Gamma(B_s(t) \to \mu^+\mu^-)dt}$$

Expectation value of untagged time-dependent rate

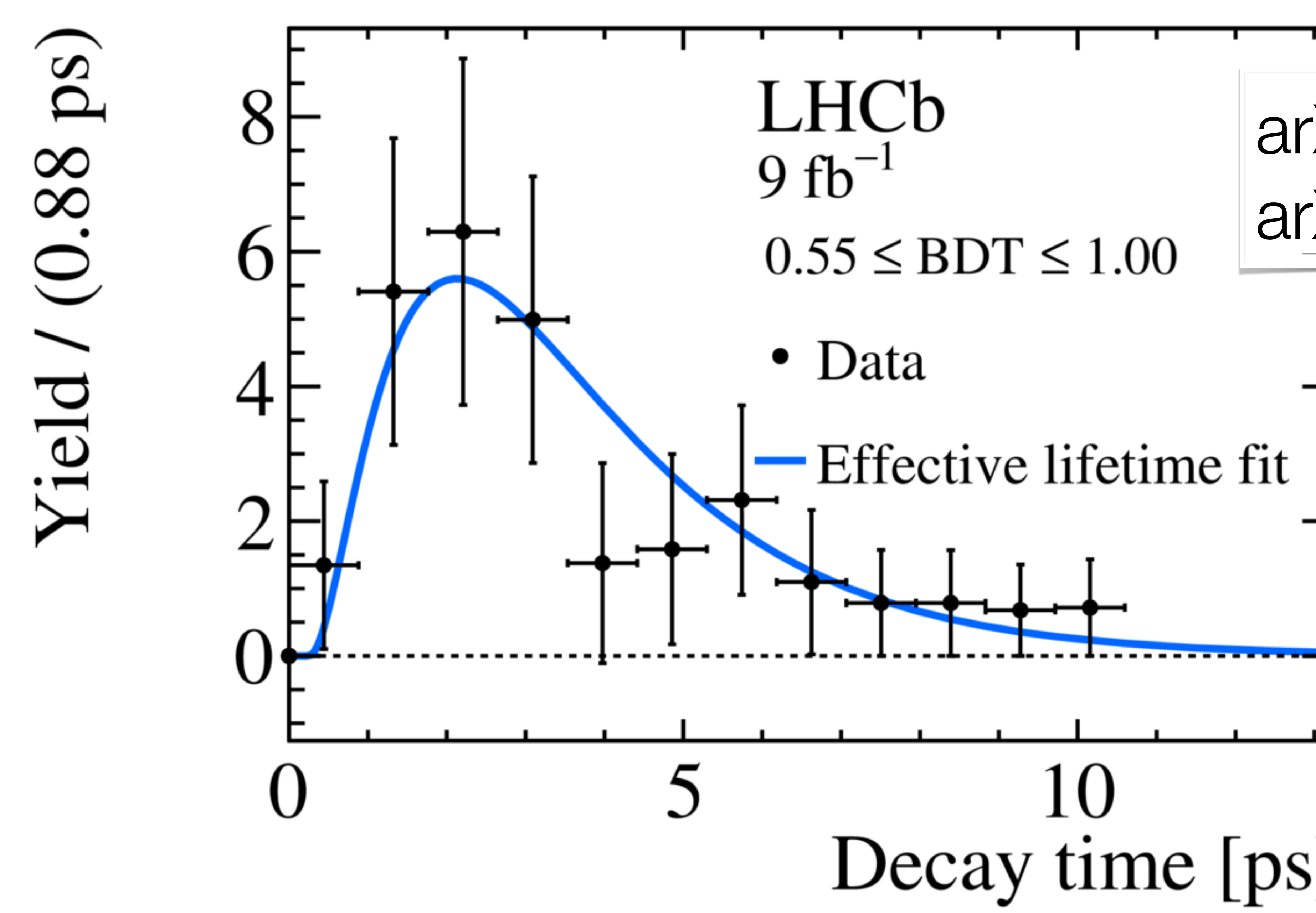
$$\Gamma(B_s(t) \to \mu^+\mu^-) \equiv \Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\overline{B}{}_s^0(t) \to \mu^+\mu^-)$$

$$\propto (1 - A_{\Delta\Gamma_s})e^{-\Gamma_L t} + (1 + A_{\Delta\Gamma_s})e^{-\Gamma_H t}$$

De Bruyn et al, PRL 109 (2012) 041801

$$A_{\Delta\Gamma} \equiv \frac{\Gamma(B_s^H \to \mu^+\mu^-) - \Gamma(B_s^L \to \mu^+\mu^-)}{\Gamma(B_s^H \to \mu^+\mu^-) + \Gamma(B_s^L \to \mu^+\mu^-)}$$

- In SM $A_{\Delta\Gamma} = 1$, i.e. B_s system evolves with the lifetime of the heavy B_s mass eigenstate, but in NP scenarios $A_{\Delta\Gamma}$ could be anywhere in range [-1,1]



arXiv:2108.09283
arXiv:2108.09284

$$\tau_{\text{eff}}(B_s(t) \to \mu^+\mu^-) = (2.07 \pm 0.29 \pm 0.03)\ \text{ps}$$

Consistent with SM at ~2σ