Rare decays and tests of lepton flavour universality in (b-)quark flavour physics at LHCb

Monica Pepe Altarelli (CERN)

On behalf of LHCb

Corfu Summer Institute 2021, August 30-September 7

Why flavour?

- The SM, at the current level of experimental precision and at the energies reached so far, is the most successful and best tested theory of nature at a fundamental level.

What determines the observed pattern of masses of quarks and leptons? Why are they arranged in generations? Why three?

- In the SM, the only interaction distinguishing the three flavours is the interaction of the matter fields with the Higgs boson (Yukawa interaction). The complex phases present in the Yukawa couplings are also the only source of Charge-Parity (CP) violation.

C = charge conjugation (swapping particles & antiparticles)
P = parity (spatial inversion, like reflection in a mirror)

- CP (Charge-Parity) violation is required to explain the matter-antimatter asymmetry of the Universe

Are there other sources of flavour (and CP) symmetry breaking, beside the SM Yukawa couplings?

Why flavour II?

- To be able to answer these questions is likely to shed light on physics beyond the SM…
- Flavour physics might provide the first indications of new physics at energy scales that are beyond the reach of direct searches
- CP (Charge-Parity) violation is connected to the matter-antimatter asymmetry of the Universe

Where did the anti-matter go?

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- What led to the disappearance of antimatter assuming an initial symmetric state (or that inflation washed out any possible prior asymmetry)?
  - There are anti-protons in cosmic rays, consistent with secondaries due to the interactions of cosmic-ray protons in the Interstellar Medium
  - We can produce and study anti-matter in accelerators
  - But apparently no anti-matter around us
  - This looks really strange, given that the properties of matter and antimatter are very similar.
  - Where did it go? Why is the universe 100% matter-antimatter asymmetric ?

Can the SM explain the Baryon Asymmetry of the Universe?

- CP violation in the SM too small to explain it (by many orders of magnitude)
- CP violation beyond the SM must exist!
- Where might we find it?

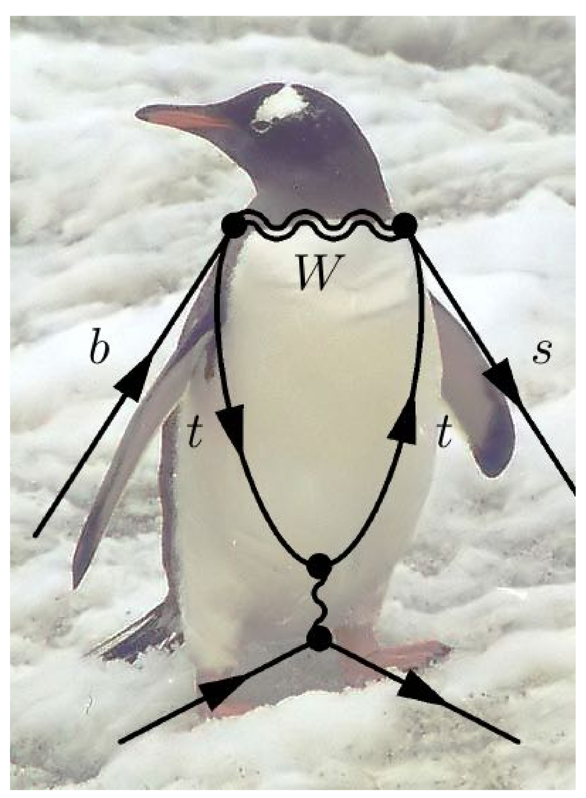
Next lecture by
Neville Harnew

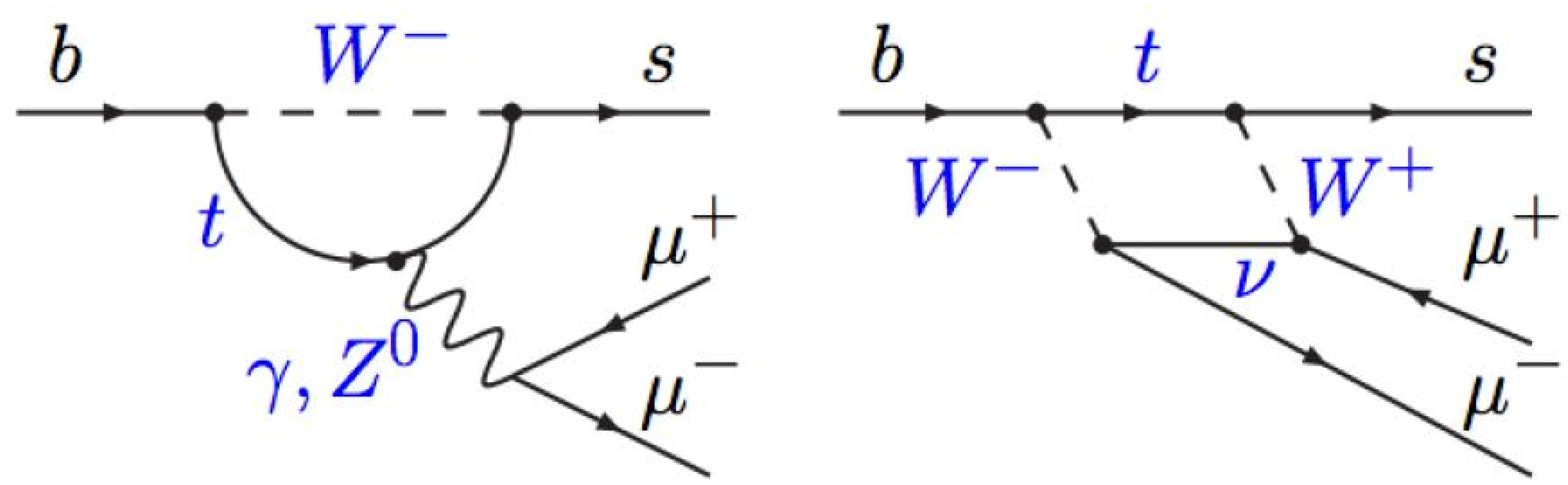
  - quark sector, as deviations from CKM predictions
  - lepton sector, e.g. as CP violation in neutrino oscillations
  - other new physics: almost all TEV-scale NP contains new sources of CP violation and precision measurements of flavour observables are generically sensitive to additions to the Standard Model

Rare b decays

Rare b decays, in a nutshell

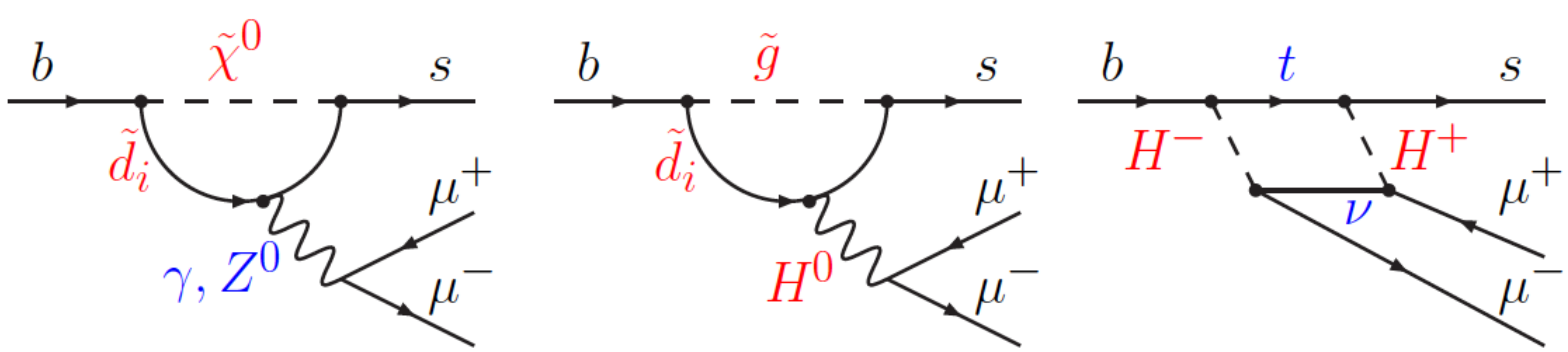
- In the SM, processes involving flavour changes between two up-type quarks (u,c,t) or between two down-type quarks (d,s,b) are forbidden at tree level and can only occur at loop level (penguin and box) → Rare FCNCs





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

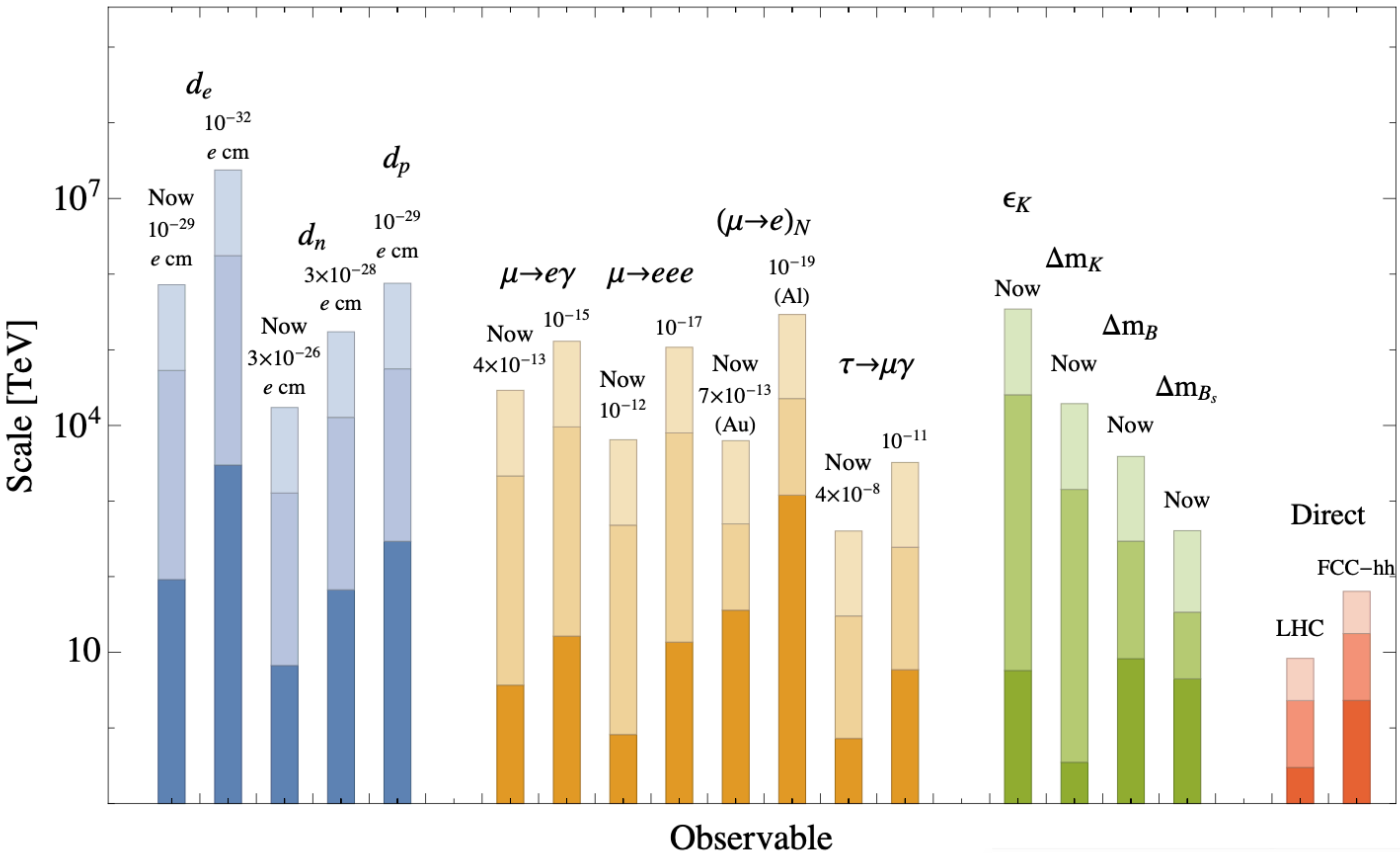
- A new particle, too heavy to be produced at the LHC, can give sizeable effects when exchanged in a loop



- Strategy: use well-predicted observables to look for deviations
- Indirect approach to New Physics searches, complementary to that of ATLAS/CMS


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


LHCb
The LHC

The LHCb collaboration

- ~1000 authors from 109 institutes in 19 countries
- ~580 publications, some with very high impact
- Main focus on heavy quark flavour…but plenty of other physics in the forward direction

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CKM & CPV

EW and QCD

Rare decays

Spectroscopy

Semileptonic decays

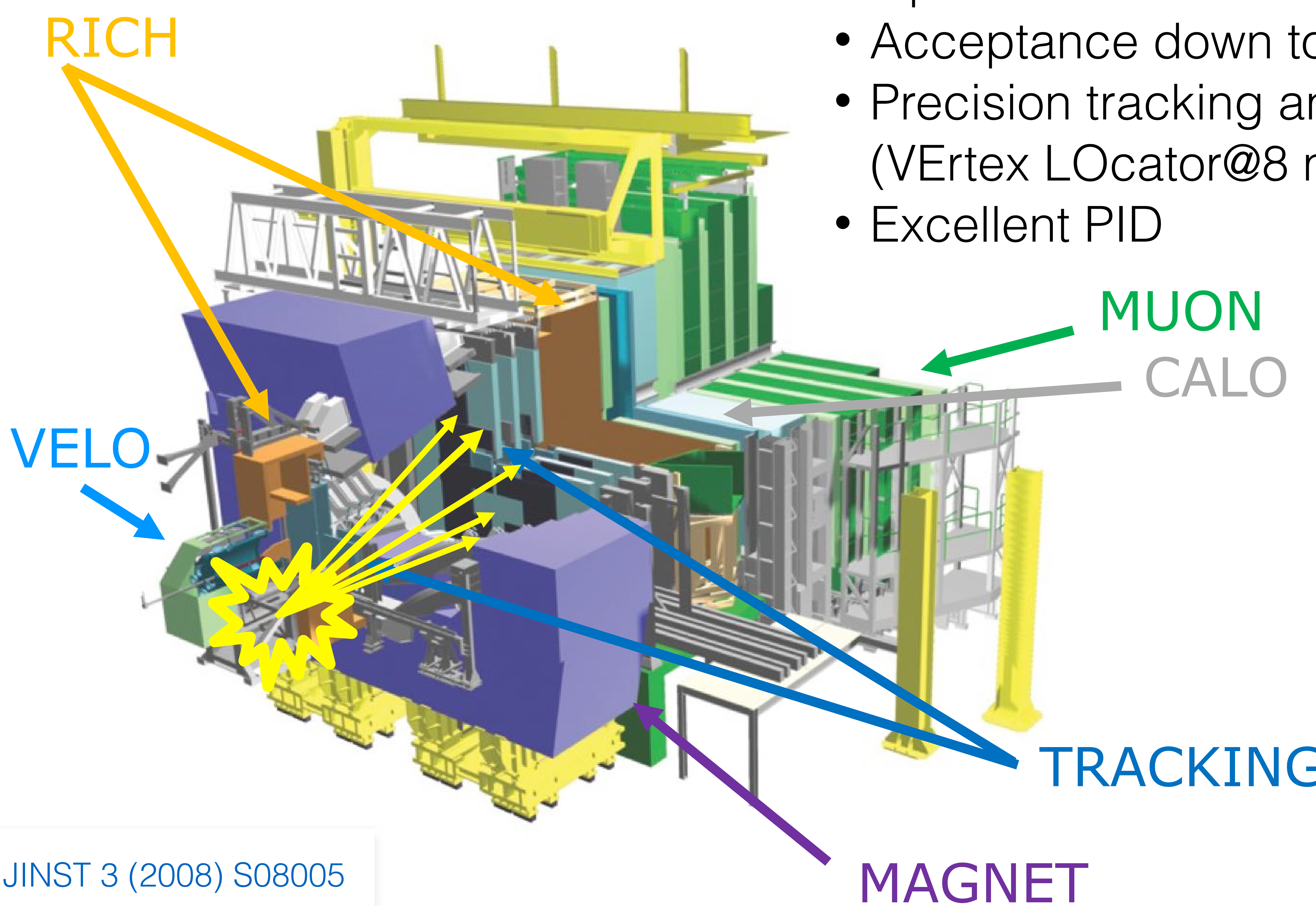
Ions and fixed target

Exotica searches

The detector with components superimposed

LHCb detector: the essentials

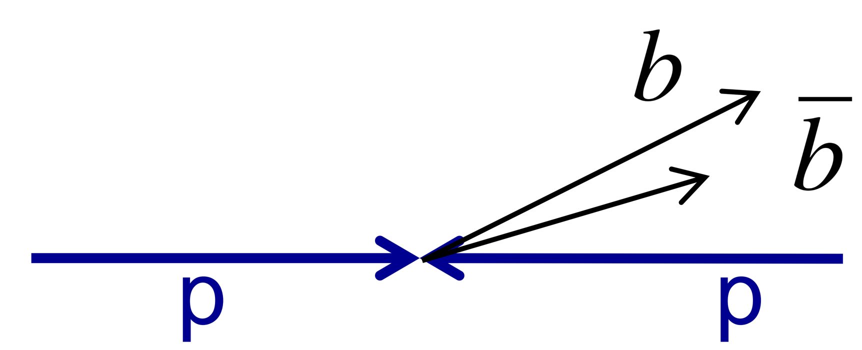
- Forward acceptance
- Efficient trigger for hadronic and leptonic modes
- Acceptance down to low p_T
- Precision tracking and vertexing (VErtex LOcator@8 mm from beam)
- Excellent PID

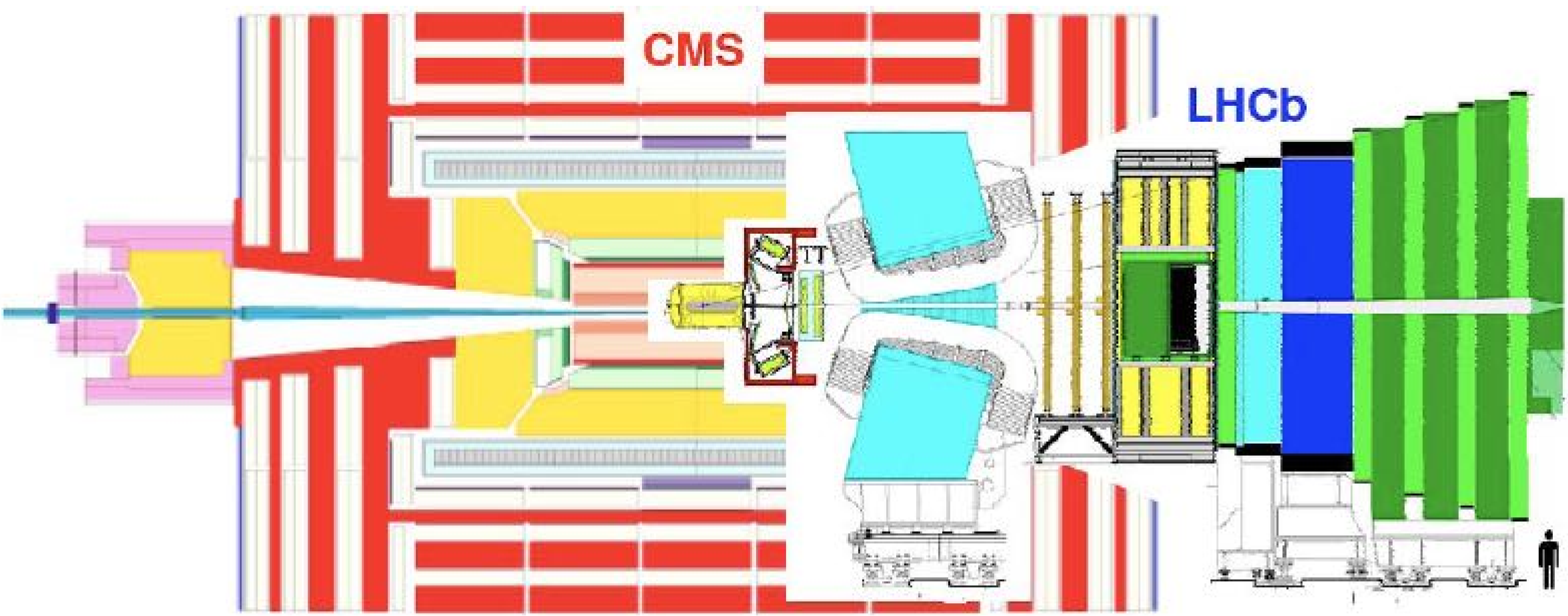


JINST 3 (2008) S08005

Why does LHCb look so different?

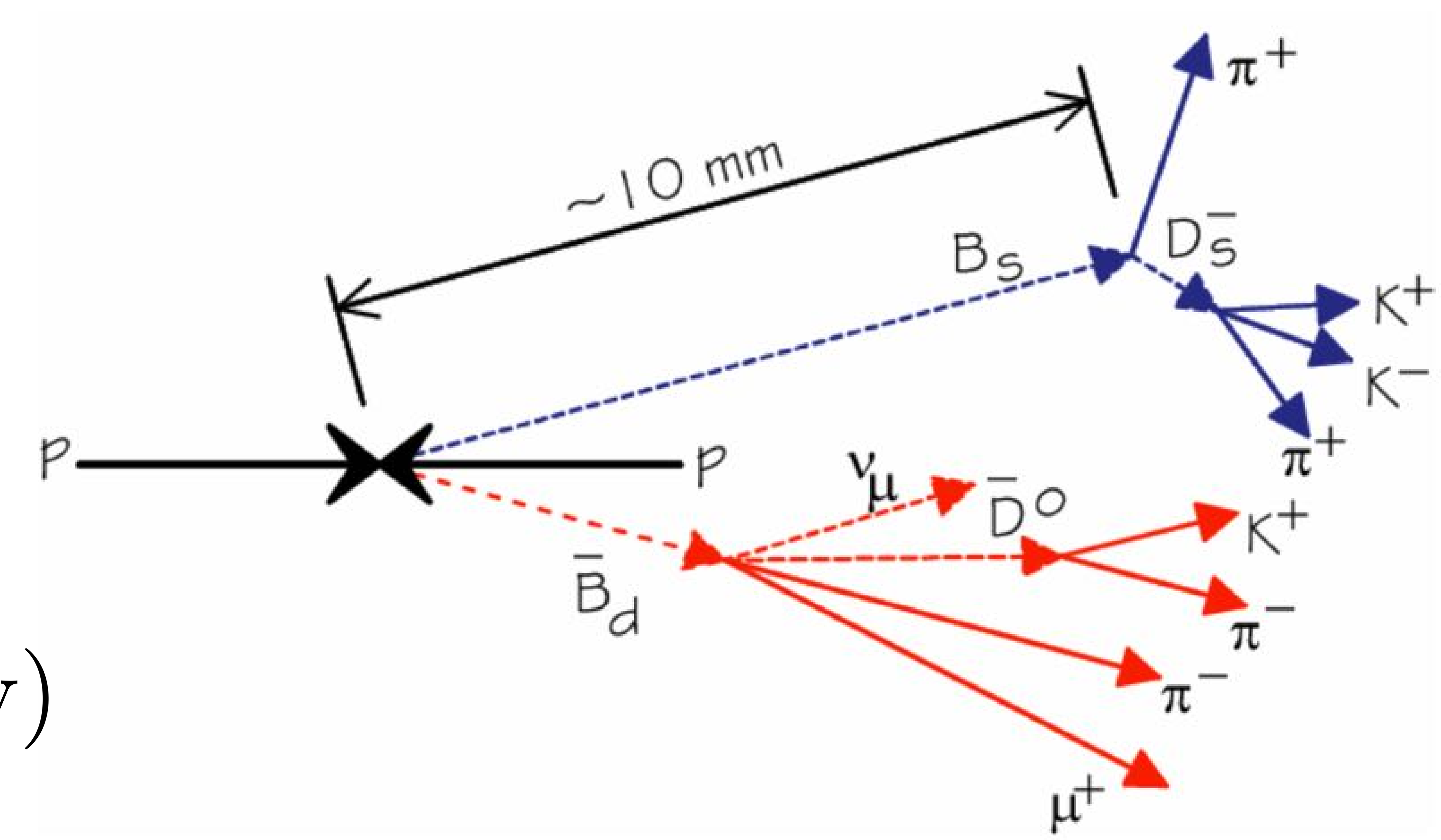
- The B mesons formed by the colliding proton beams (and the particles they decay into) stay close to the line of the beam pipe, and this is reflected in the design of the detector





b lifetime long enough for experimental detection

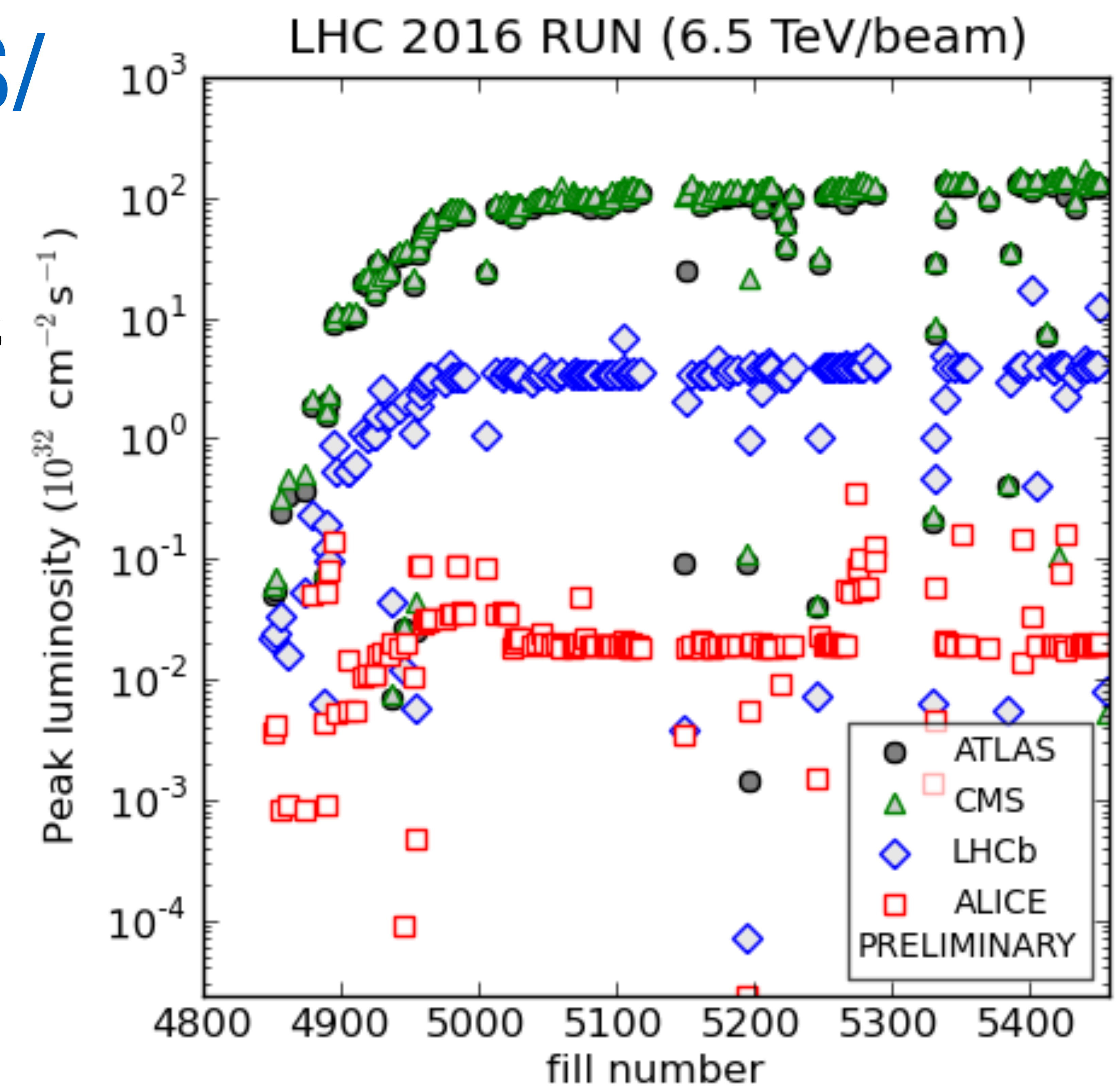
- $\tau_{\rm beauty} \sim 1.5 \cdot 10^{-12}\,{\rm s}$ $\qquad \tau \sim 1/(m^5|V_{\rm cb}|^2)$
- $D = \beta\gamma c\tau$
- @ LHC :
  - $\star\ \beta = v/c \sim 1$
  - $\star\ \gamma = E/mc^2 \sim 20 \quad (E : b \text{ energy})$
- $\text{D} = 20 \cdot 3 \cdot 10^{10} \cdot 1.5 \cdot 10^{-12} \sim 1\,\text{cm}$



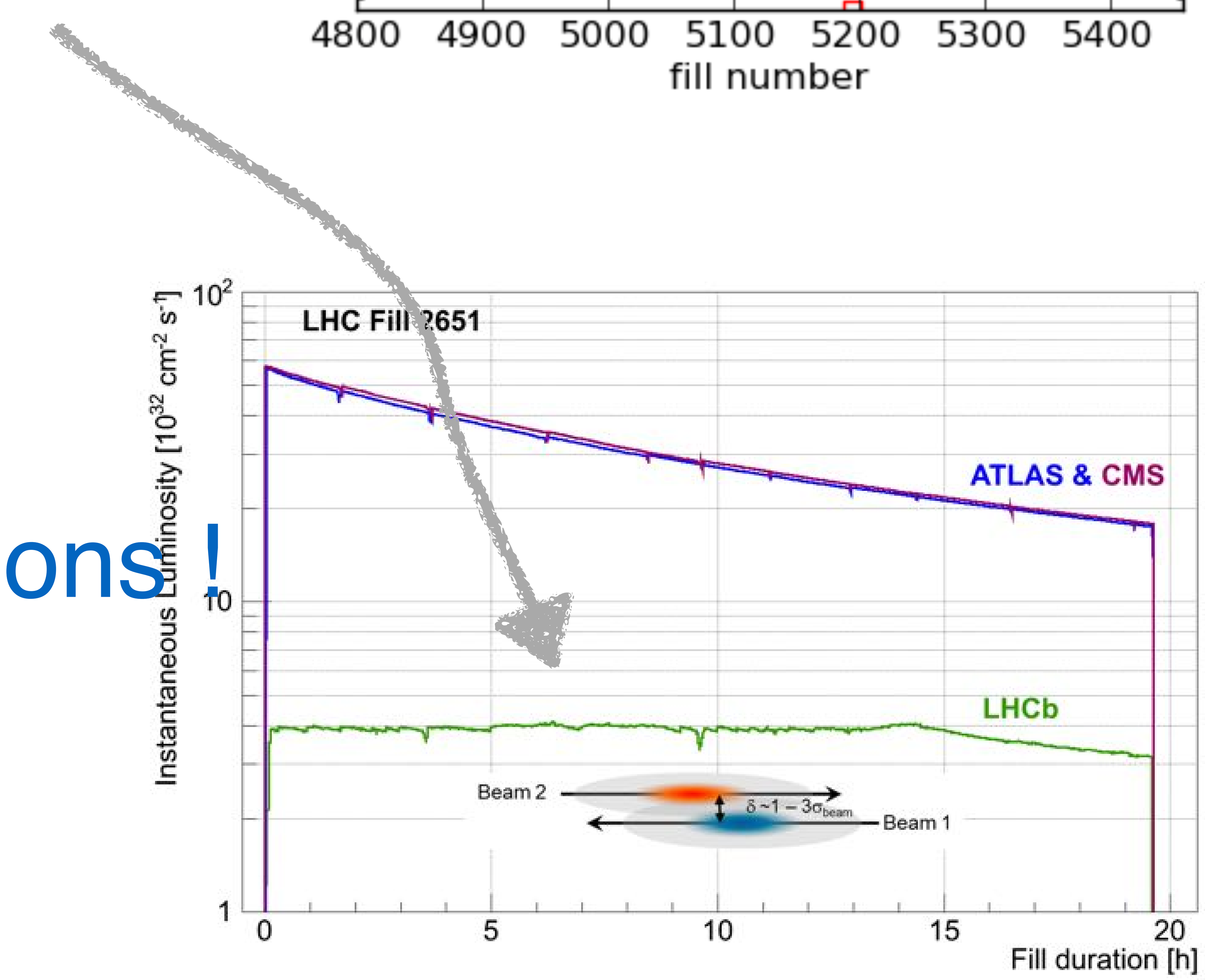
Look for displaced vertices and/or tracks with large impact parameters

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
  - $\mathscr{L}_{\text{int}} = 9\,\text{fb}^{-1}$ (LHCb), $\mathscr{L}_{\text{int}} = \sim 140\,\text{fb}^{-1}$ (ATLAS/CMS)



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



- Huge heavy quark production cross-sections !
  - $\sigma_b \sim 150\mu\text{b}$ @ $\sqrt{s}$=13 TeV (~1nb in e^+e^- @Y(4s))
    - ~10^{11} b decays/fb in acceptance
  - σ_c is ~ 20 times larger!
    - ~10^{12} c decays/fb in acceptance

Running conditions II

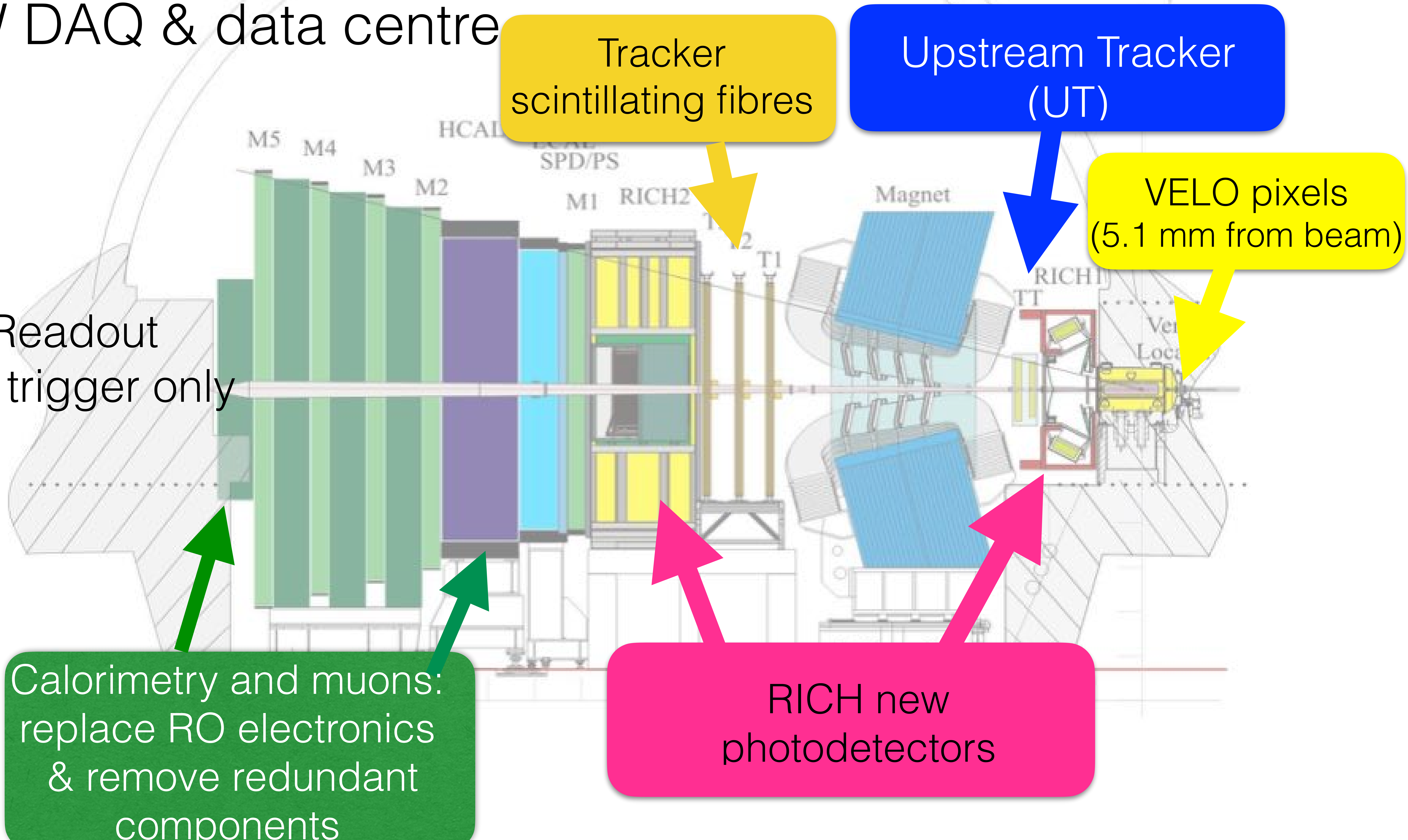
- For LHCb, more data is more important than higher energy
  - Direct searches @ATLAS/CMS: more energy → new particles could appear above threshold
  - Indirect searches: precision measurements → gain from increased production rates
- However, digesting more data is a true challenge!
  - At 13 TeV and $\mathscr{L}$=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 → requires powerful trigger

The LHCb schedule

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



The **NEW** detector

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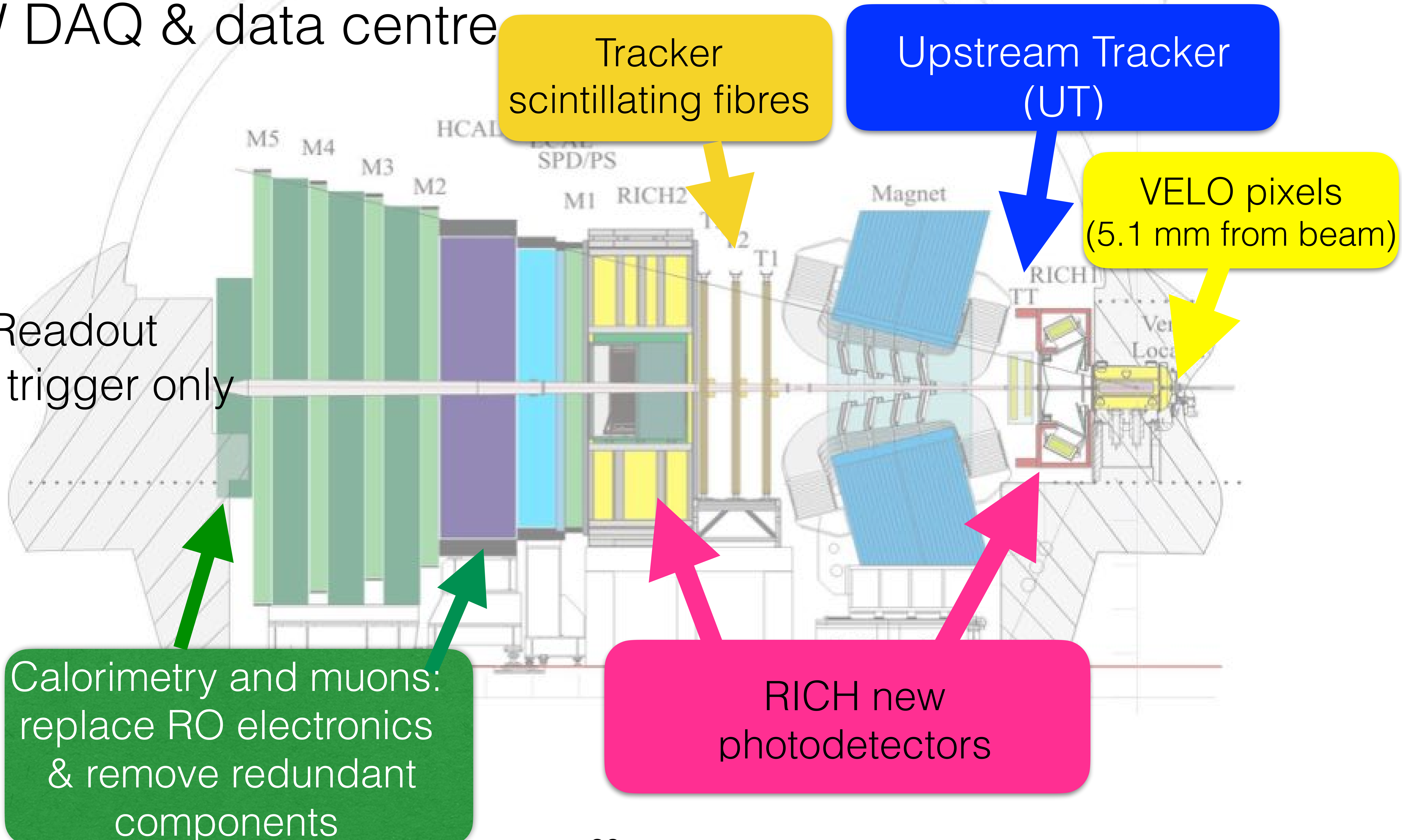
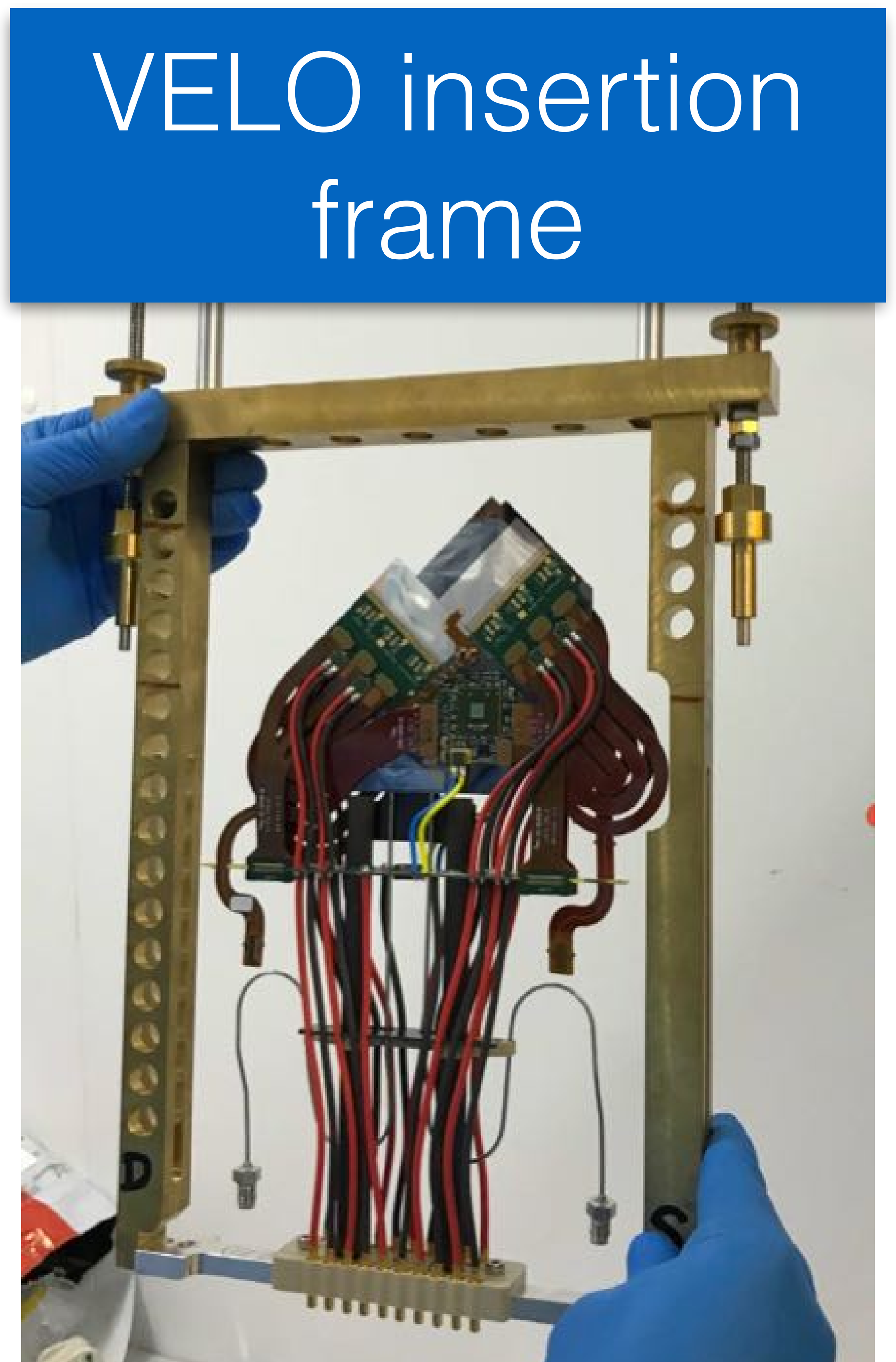
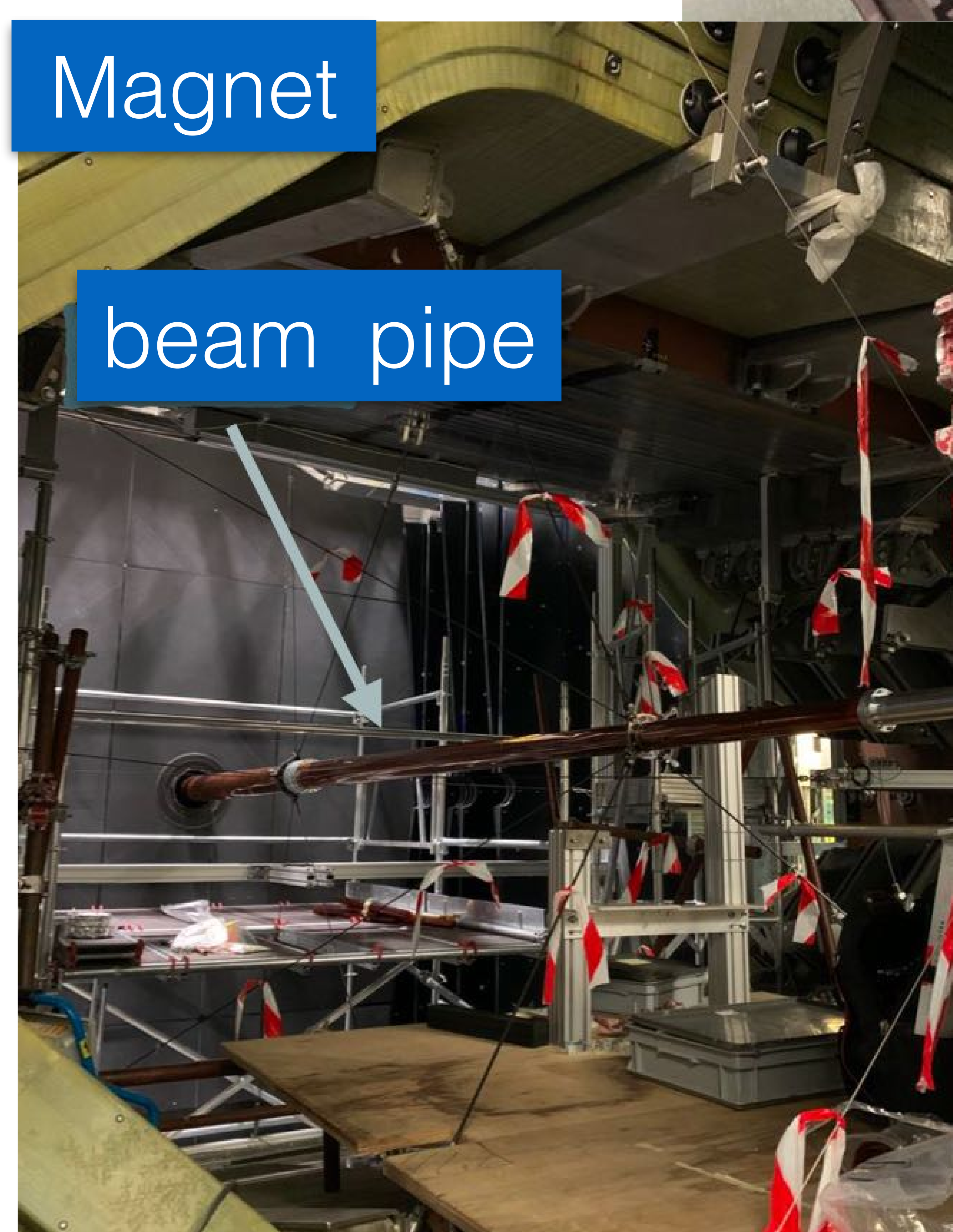


Installation being completed under very tight timescale and hard pandemic restrictions



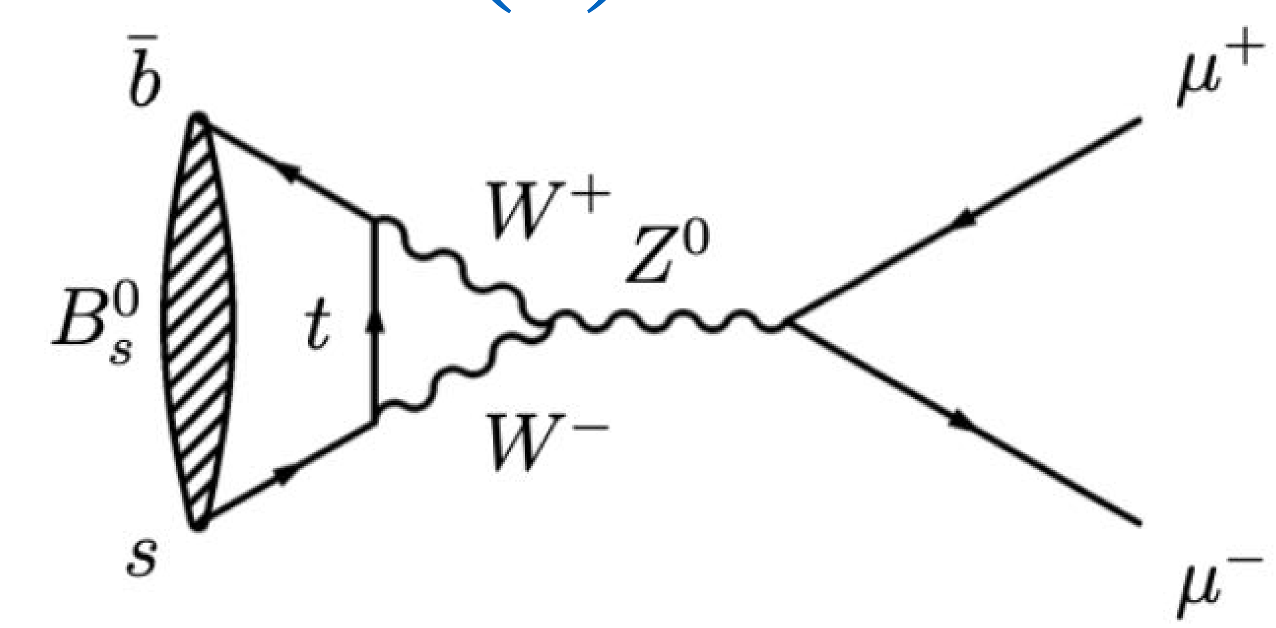


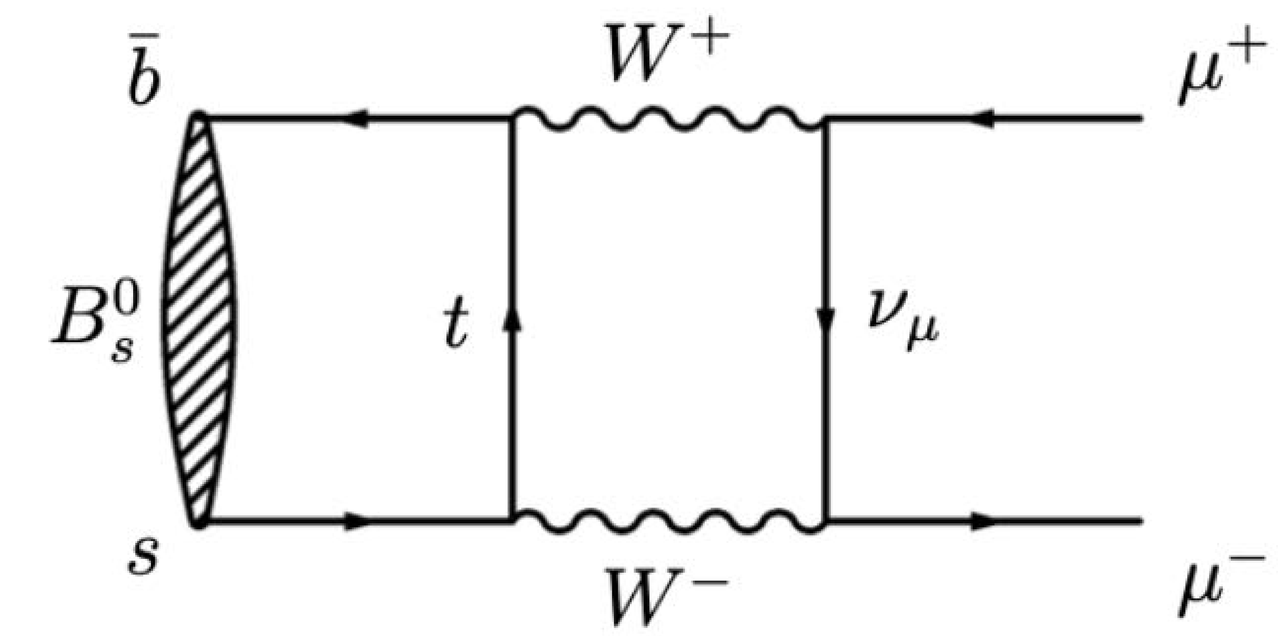
Run 2 to Upgrade

- Run 2 served as a demonstrator for the upgrade
- Two key components of upgrade selection deployed in Run 2:
  - Alignment & calibration in real time
  - Analysis with “Turbo stream” (reduced data format)
- The performance of a final analysis quality event reconstruction in real time crucial for processing large quantities of data
- In addition, the L0 hardware trigger will be removed : read the full event at 40 MHz and implement trigger in software
- Trigger-less readout allows ~2 x higher efficiency for hadronic decays at 5 x higher luminosity

B leptonic decays

One of the milestones of flavour programme $B_{(s)} \to \mu^+\mu^-$





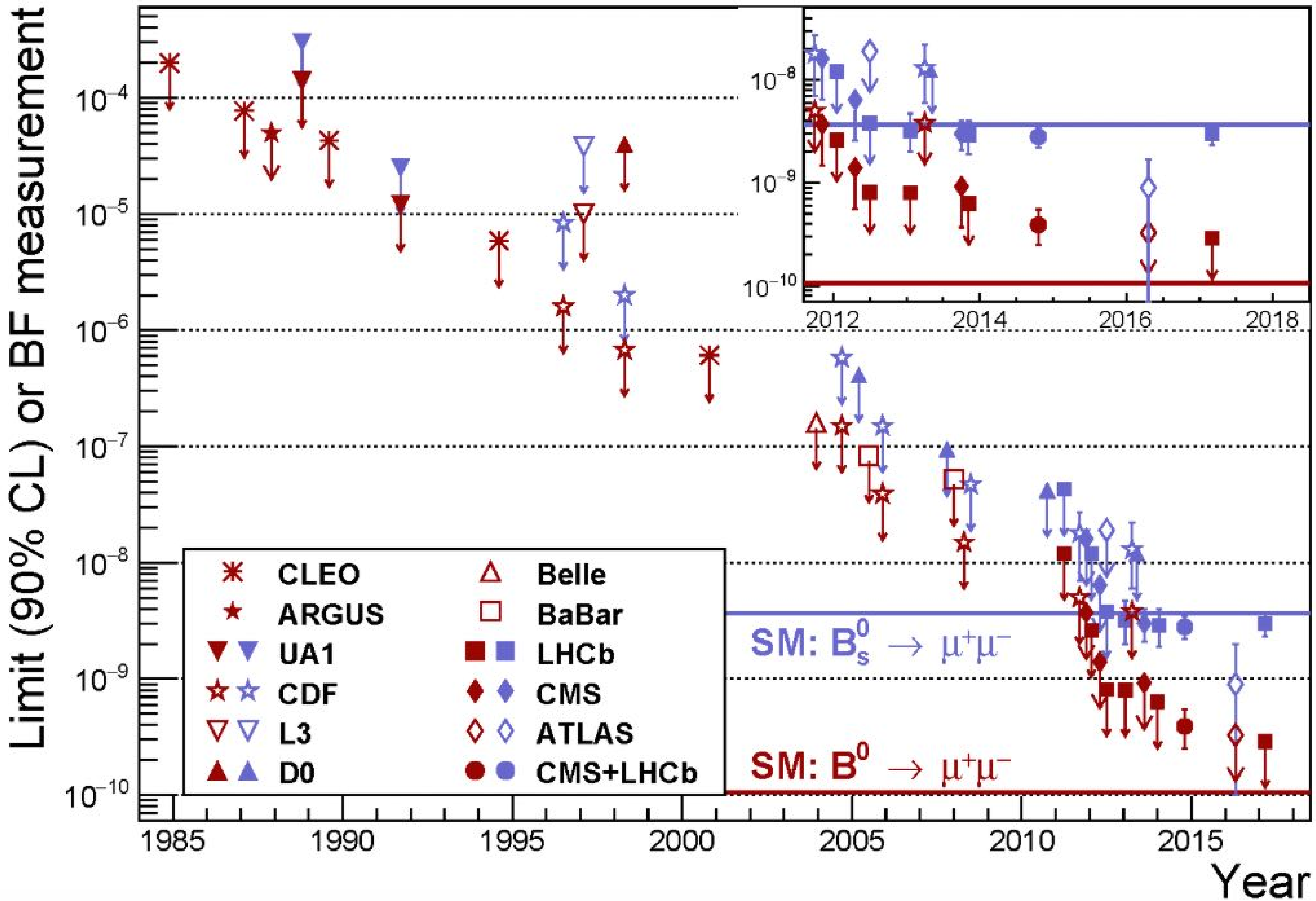
- Very suppressed in the SM
  - Loop, CKM ($|V_{ts}|^2$ for B_s) and helicity ~ $\left(\frac{m_\mu}{M_B}\right)^2$
  - Theoretically "clean" → precisely predicted:

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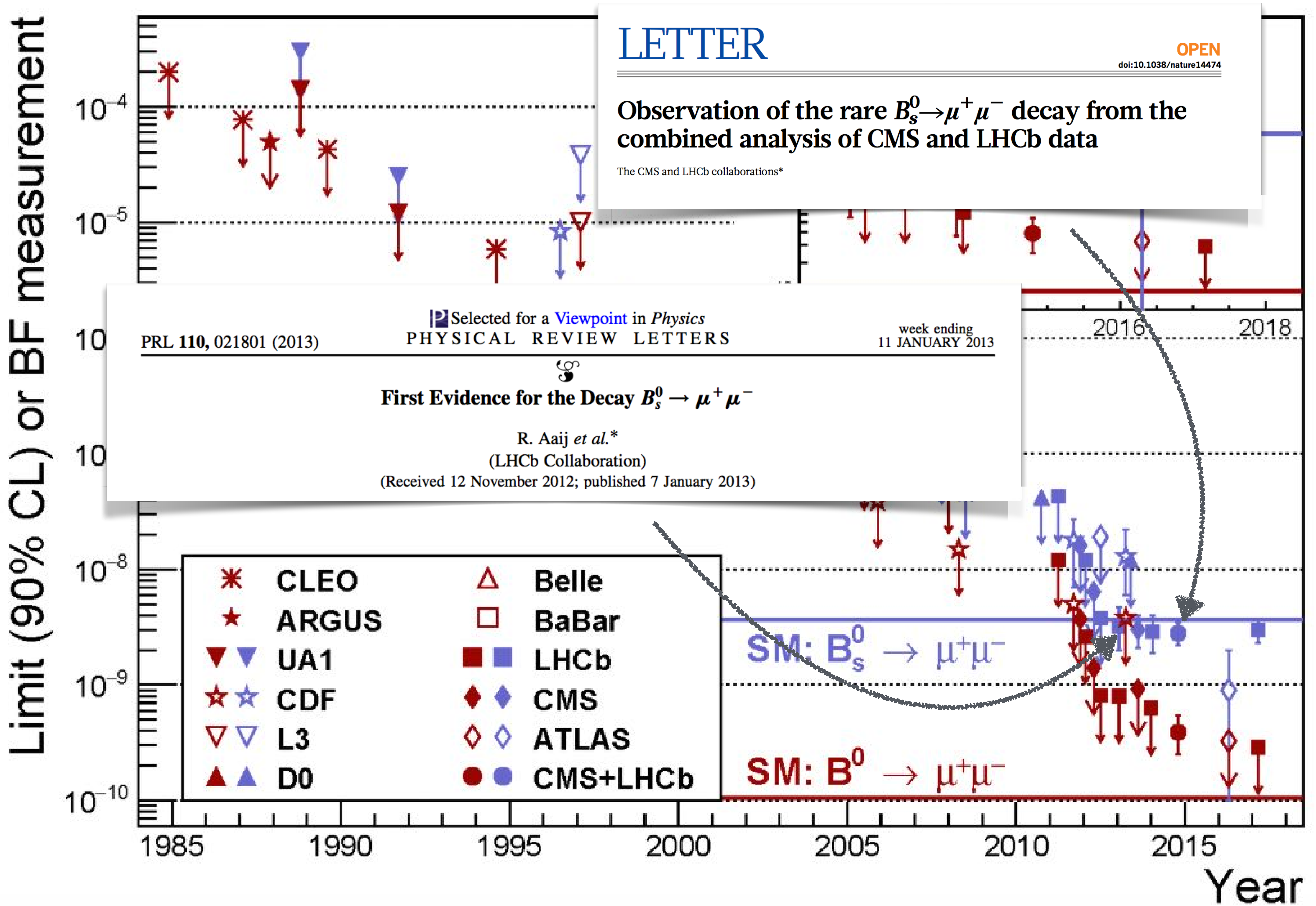


Latest LHC combination

- **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

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

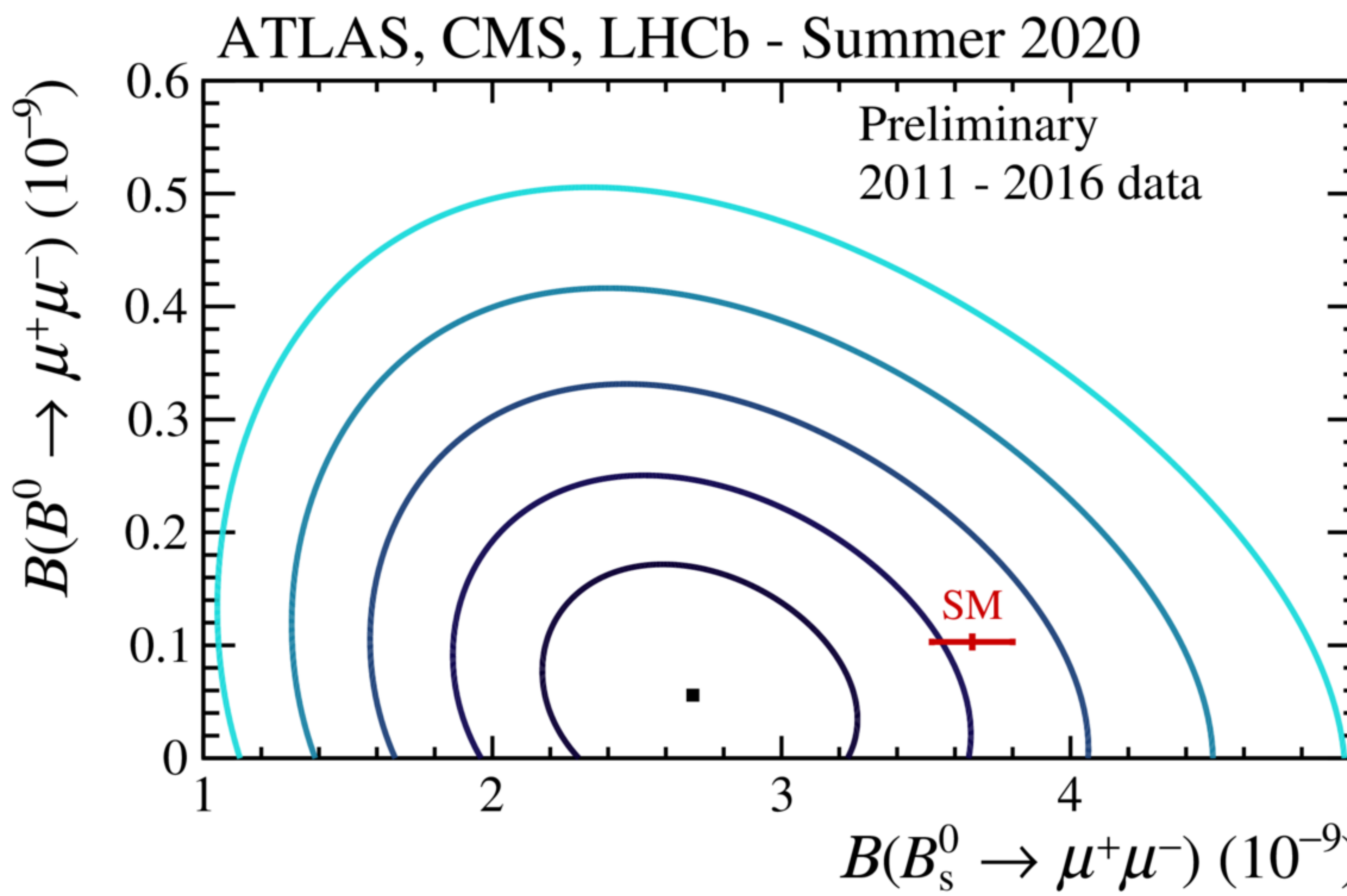
$B(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ @ 95 % CL

- **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

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



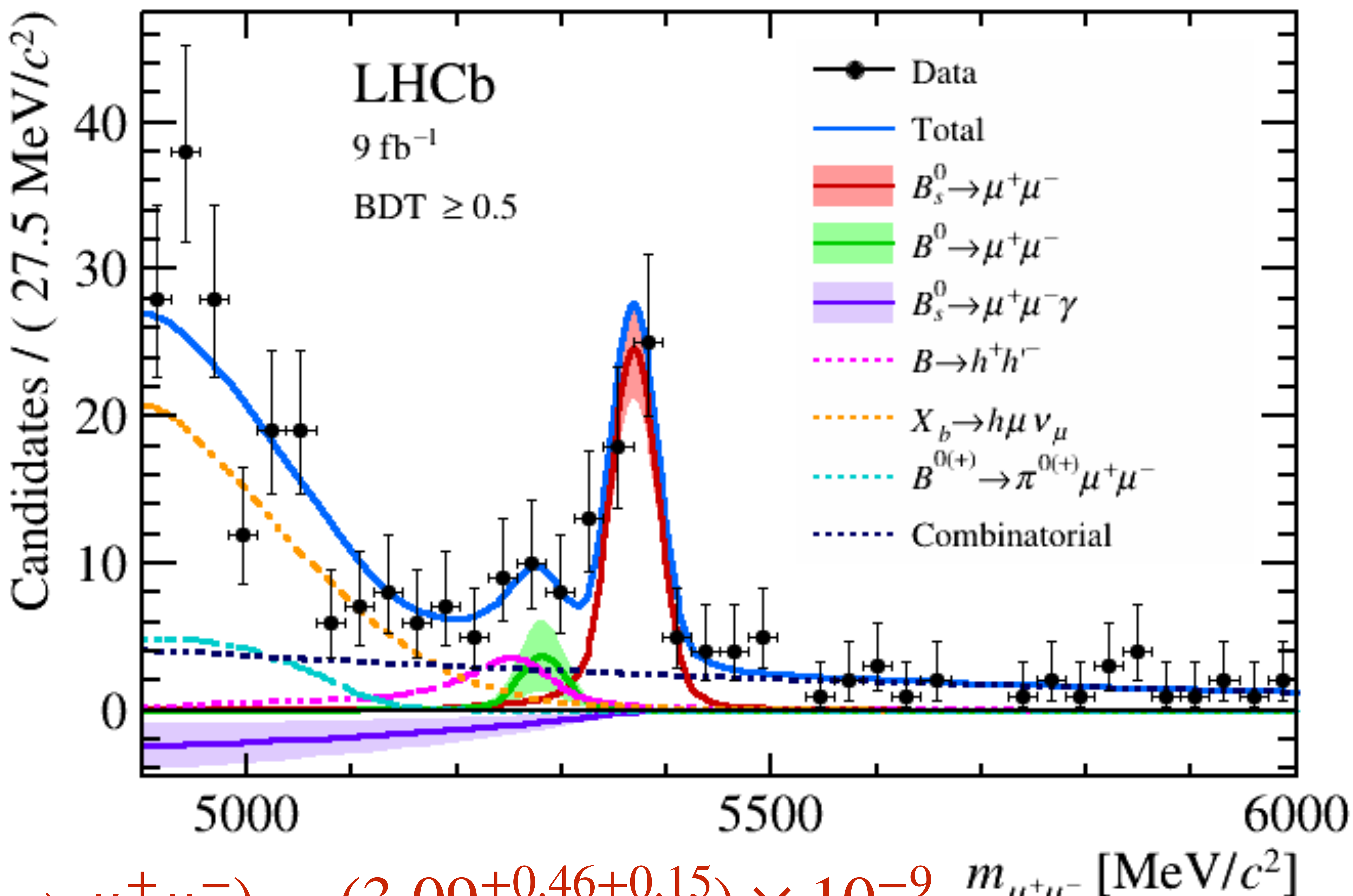
Era of precision measurements of $B_{(s)} \to \mu^+\mu^-$ has started

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

2.1σ below SM prediction

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

$B_{(s)} \to \mu^+\mu^-$: New LHCb result



Full statistics

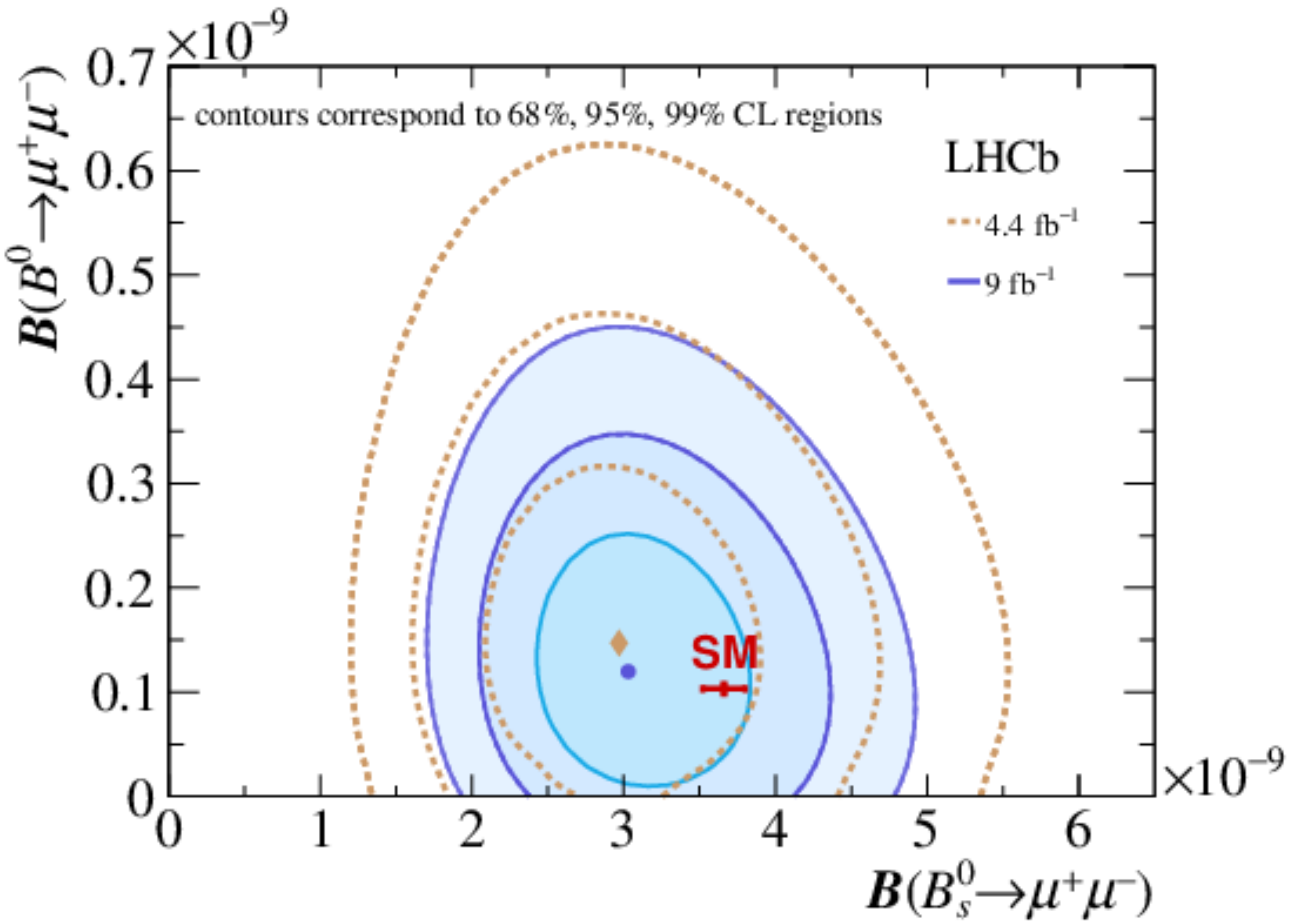
arXiv:2108.09283
arXiv:2108.09284

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

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

- $B_s \to \mu^+\mu^-$ found with significance >10 σ, but no evidence yet for $B^0 \to \mu^+\mu^-$ (1.7σ)
- Result dominated by statistical uncertainty

$B_{(s)} \to \mu^+\mu^-$: New LHCb result



Full statistics

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

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

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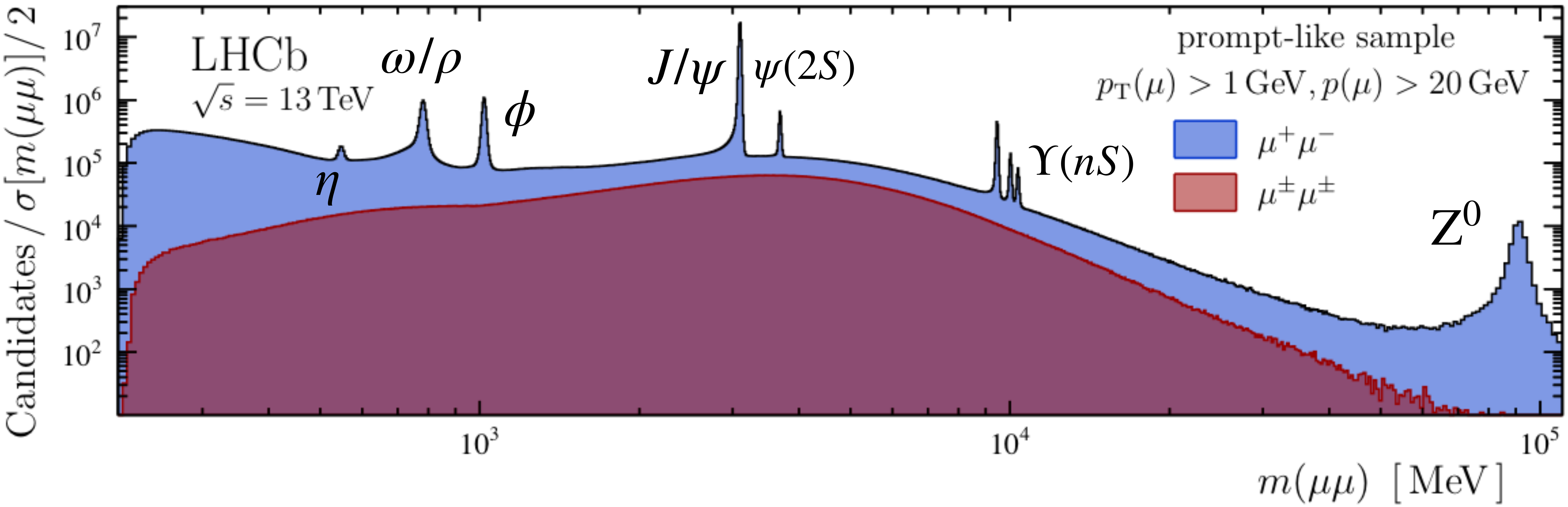
Finding a needle in a haystack!

PRL 120 (2018) 061801



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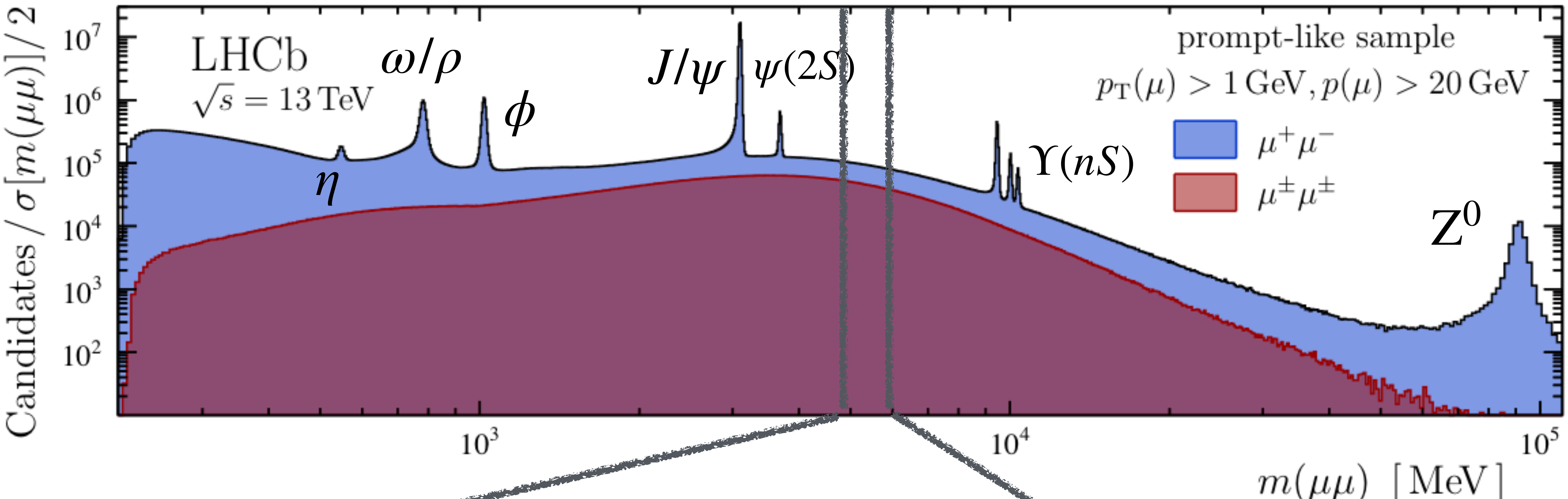
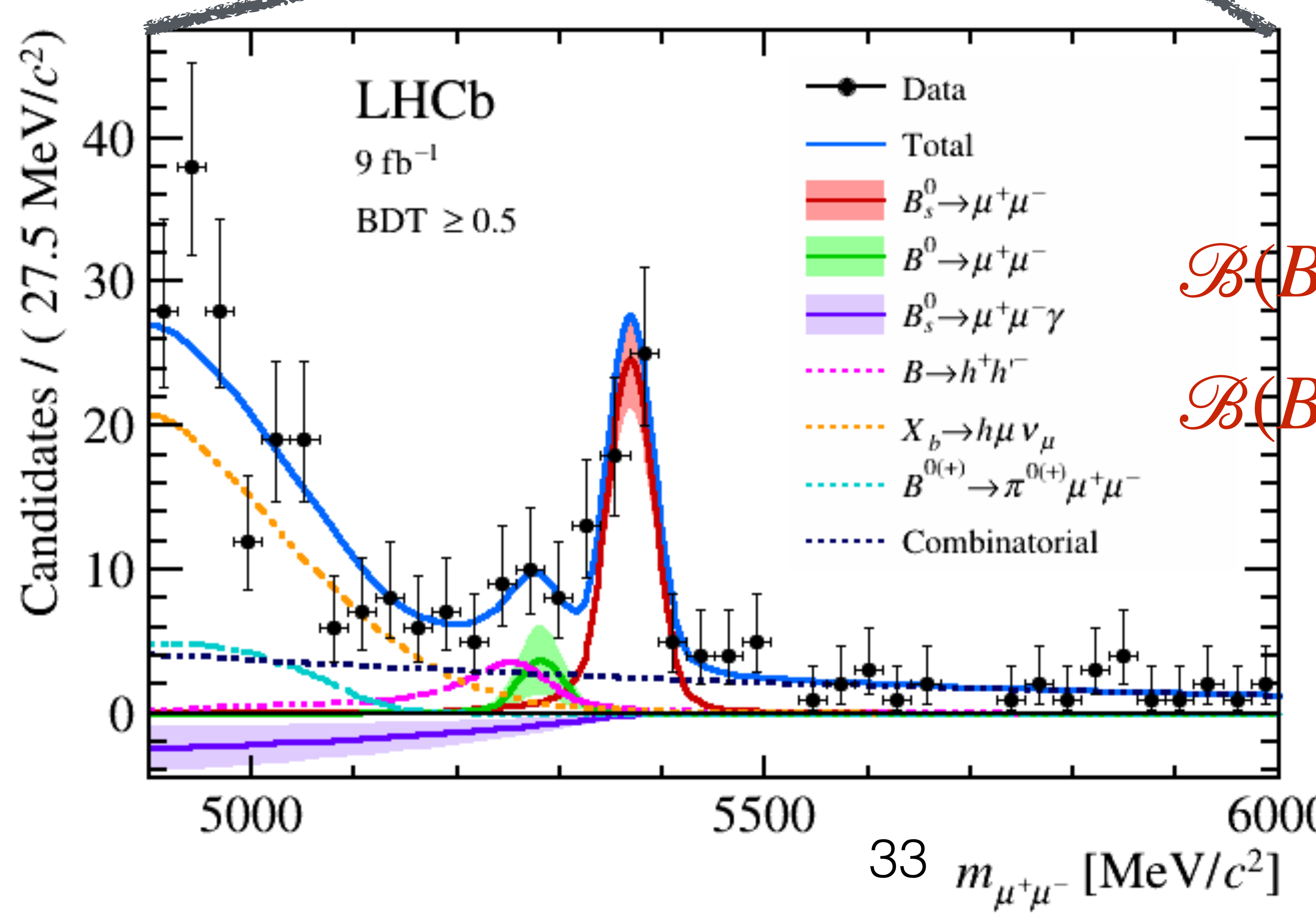
PRL 120 (2018) 061801





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

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

Finding a needle in a haystack!

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

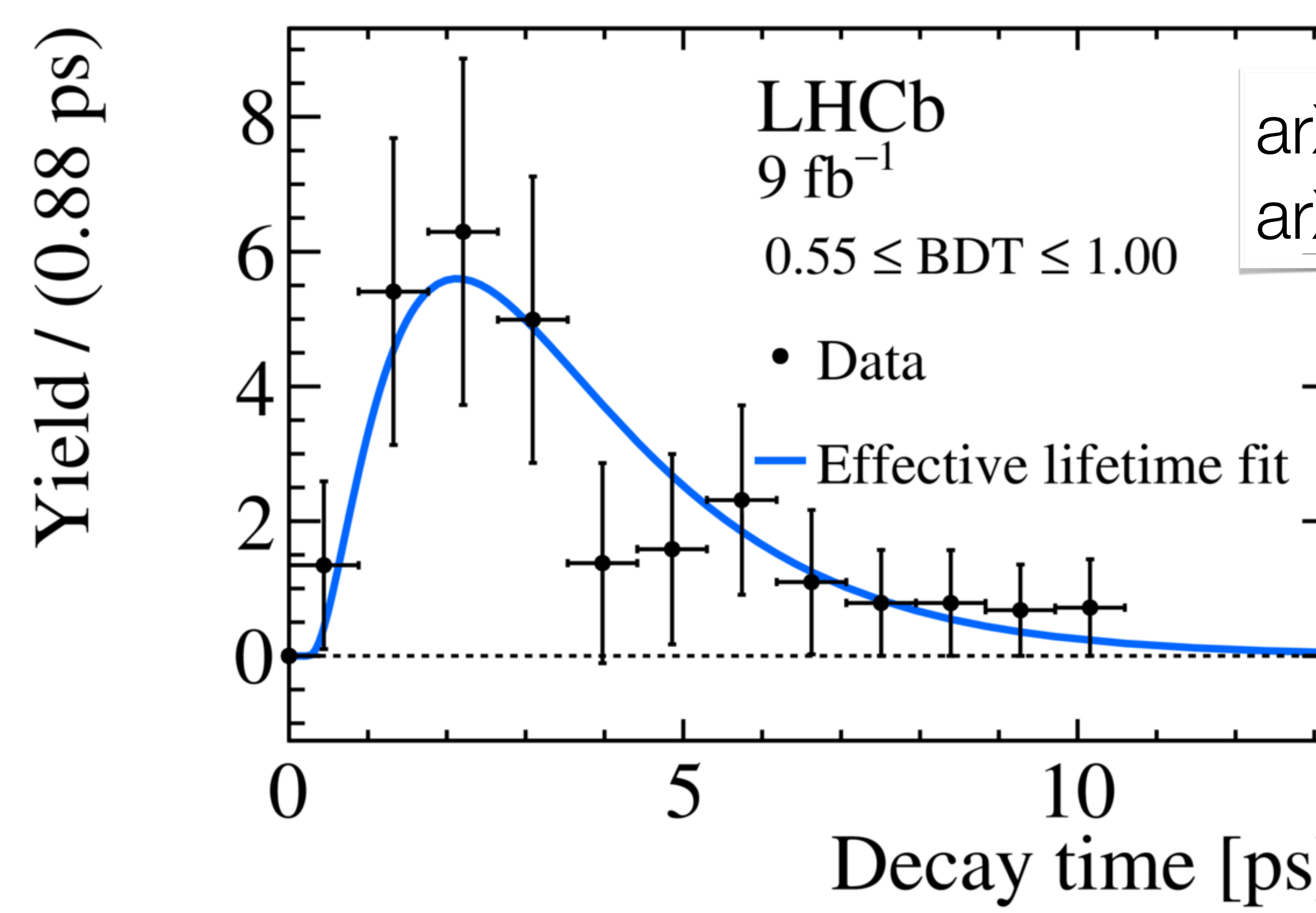
$$\Gamma(B_s(t) \to \mu^+\mu^-) \equiv \Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\overline{B}_s^0(t) \to \mu^+\mu^-)$$

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

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

$B_{s,d} \to e^+e^-$

- In SM, smaller BF wrt $B(B_s \to \mu^+\mu^-)$ due to tiny $(m_e)^2$ factor

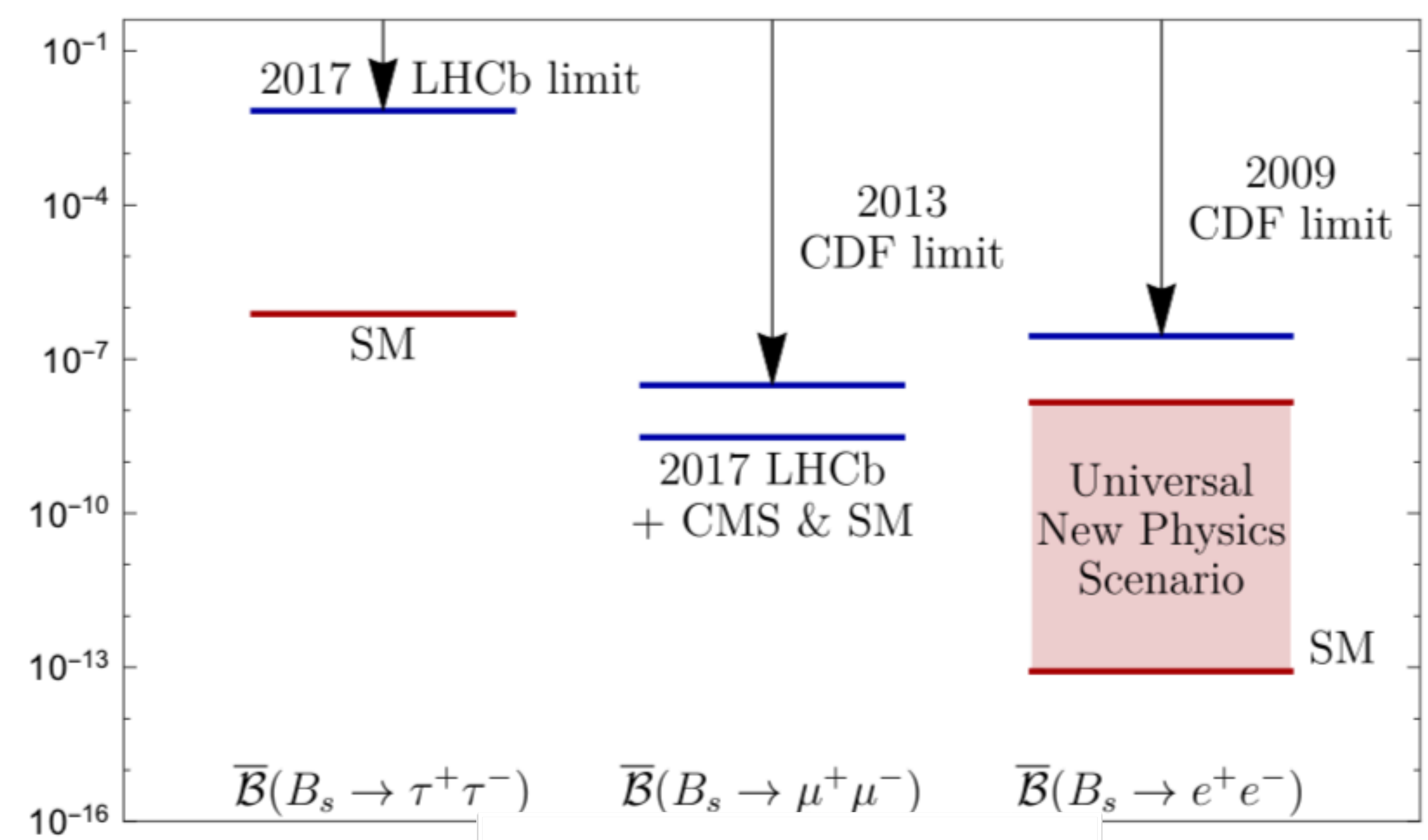
$$\mathcal{B}(B_s \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$$
$$\mathcal{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$$

Beneke et al.
JHEP 10 (2019) 232

- out of reach from the experimental point of view → very little attention
- limit by CDF (from 2009) $B_s \to e^+e^- = < 2.8 \times 10^{-7}$ @ 90 % CL

CDF: PRD102 (2009)201801

- LHCb measurement based on Run1 and partial Run 2 $(4\,\text{fb}^{-1})$ relative to $B^+ \to K^+J/\psi(\to e^+e^-)$

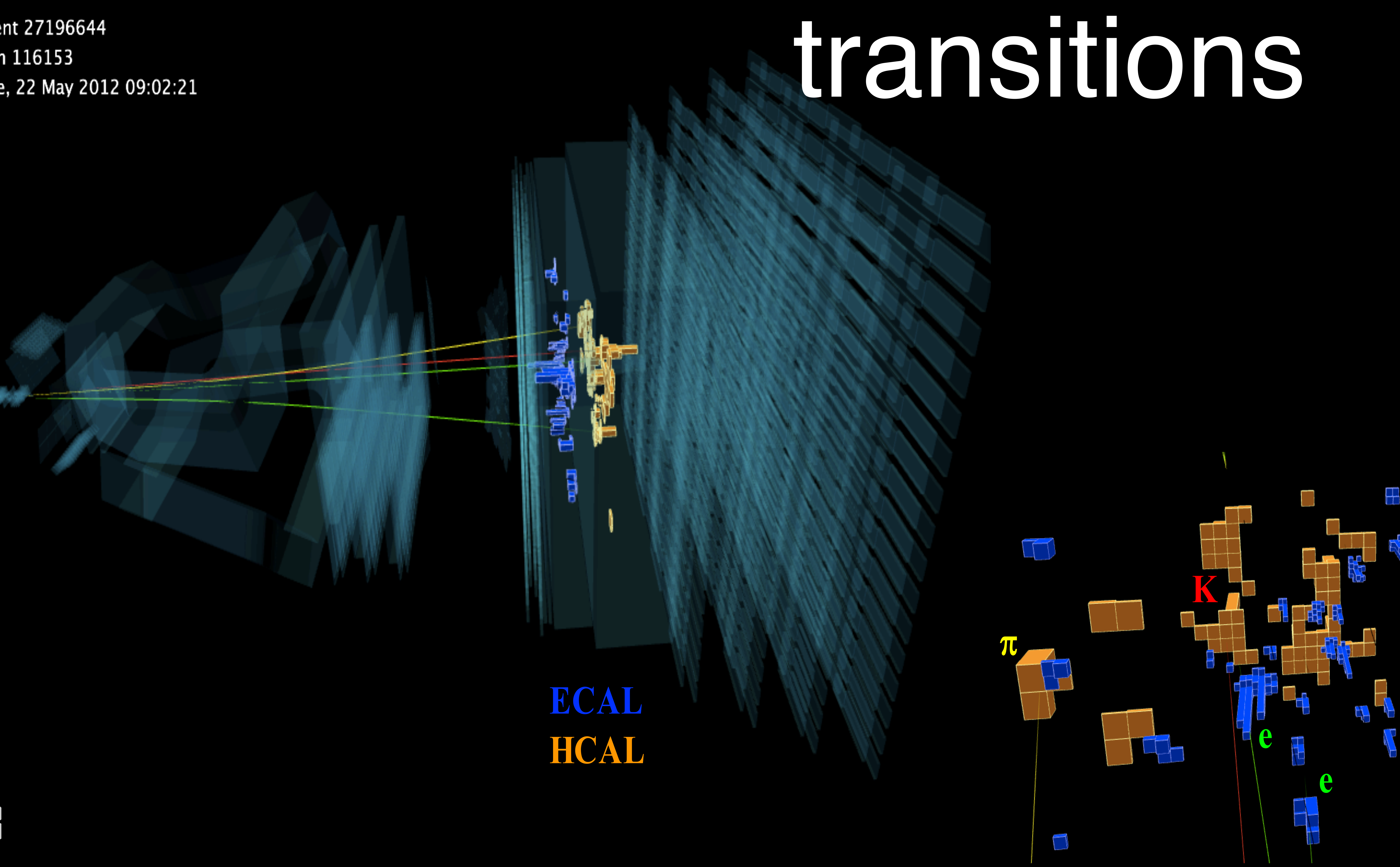


Fleischer et al.
JHEP05 (2017)156

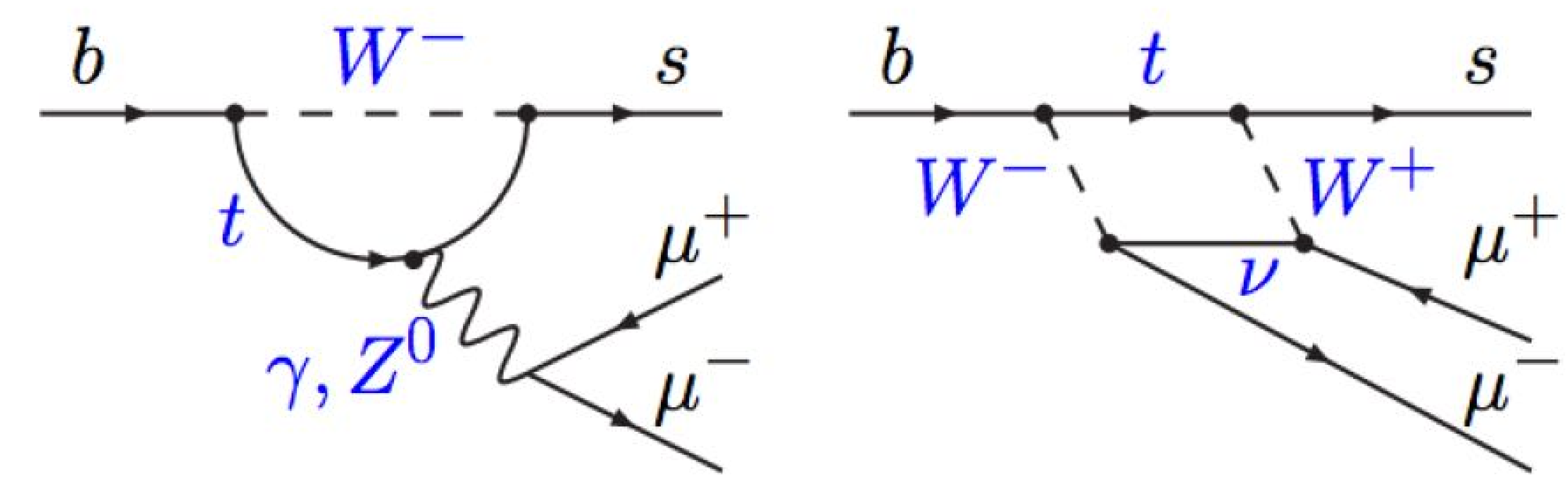
- $\mathcal{B}(B_s \to e^+e^-) < 9.4 \times 10^{-9}$ @ 90 % CL
  $\mathcal{B}(B^0 \to e^+e^-) < 2.5 \times 10^{-9}$ @ 90 % CL

PRL 124 (2020) 211802

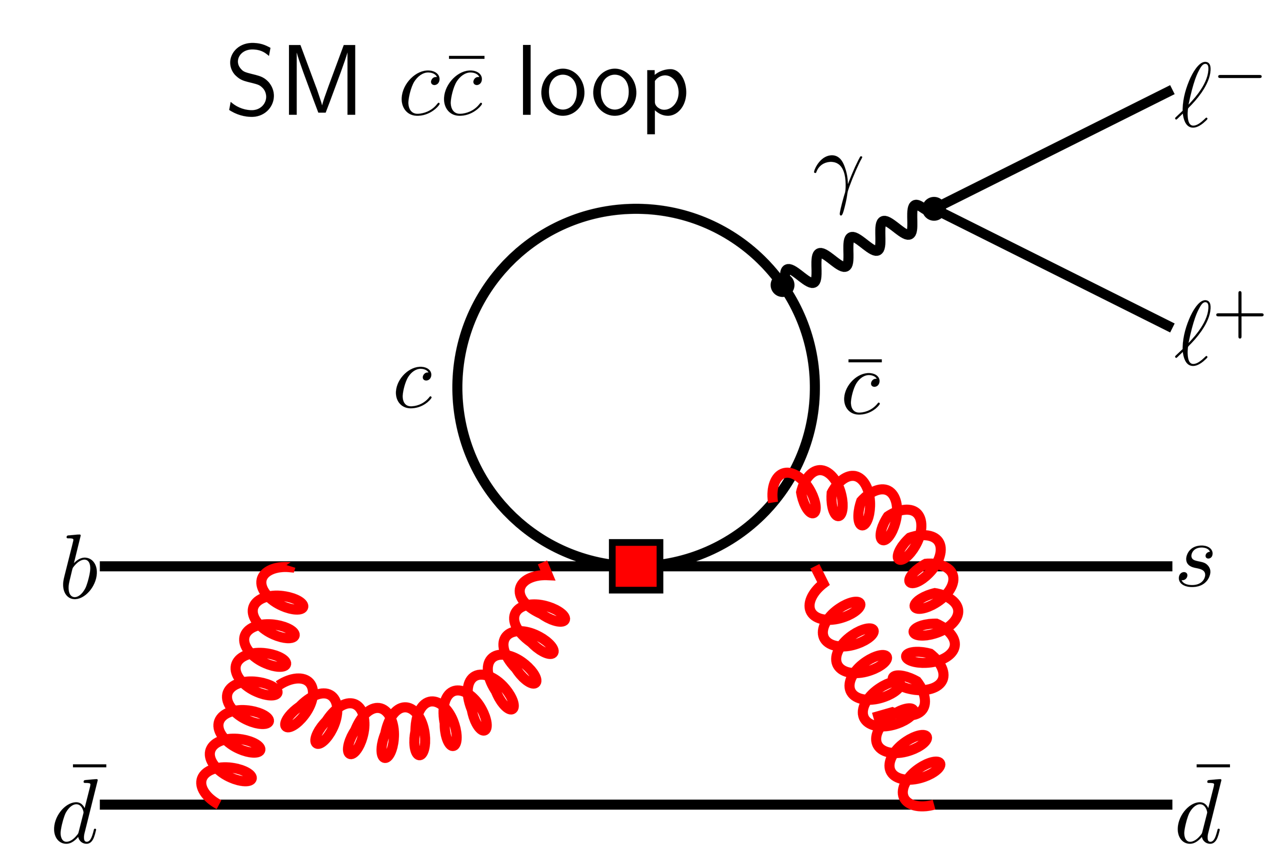
Other $b \to s\ell^+\ell^-$ transitions



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



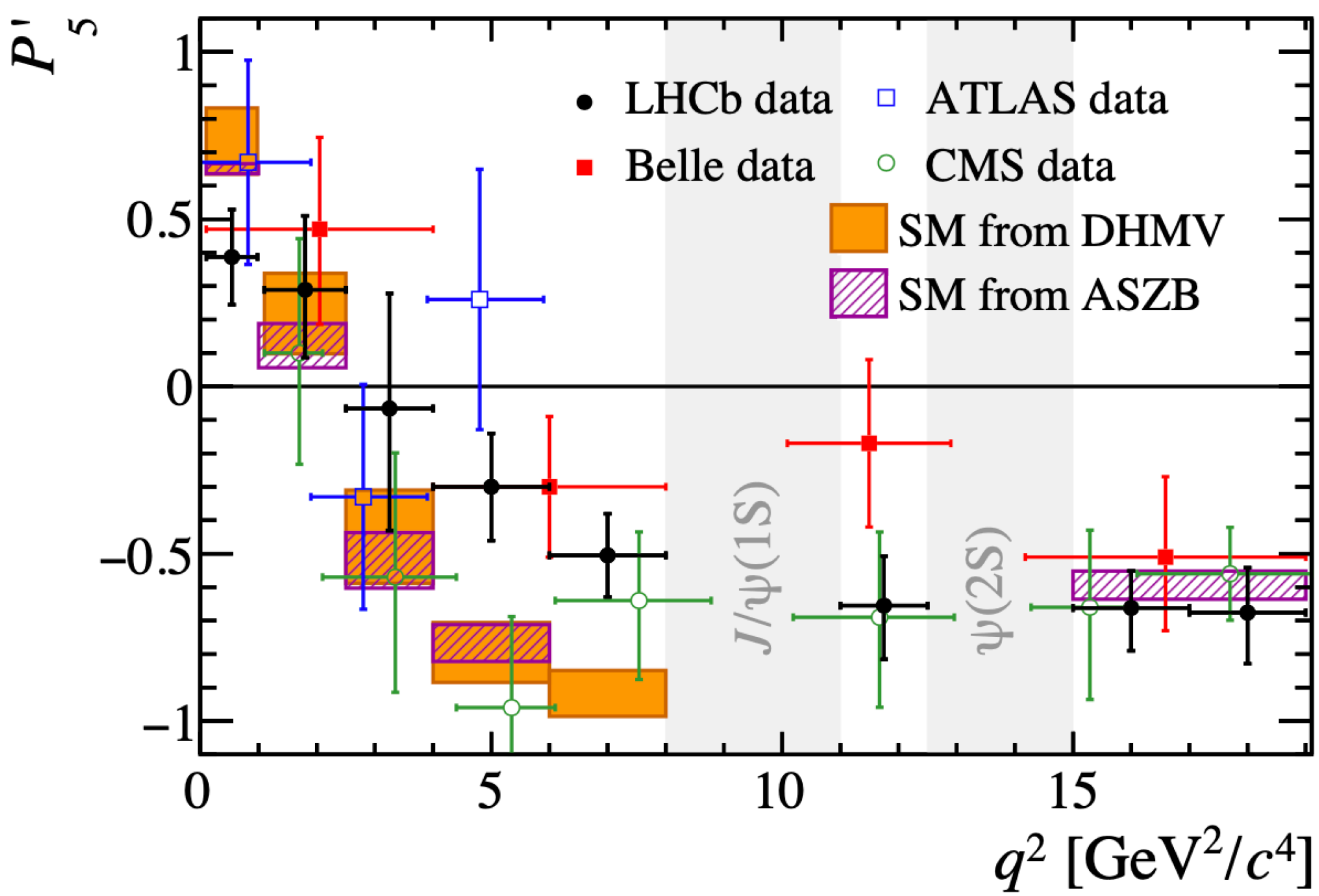
- Same loop diagrams, different spectator quarks
- Rates, angular distributions and asymmetries sensitive to NP
- A lot of phenomenological work invested in defining observables with "clean" theoretical predictions.
  - Observables form-factor free at leading order
  - Still susceptible to non-factorisable corrections
  - E.g: are we estimating correctly contributions from charm loops that produce a $\ell^+\ell^-$ pair via a virtual photon?



- Question: how clean?

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

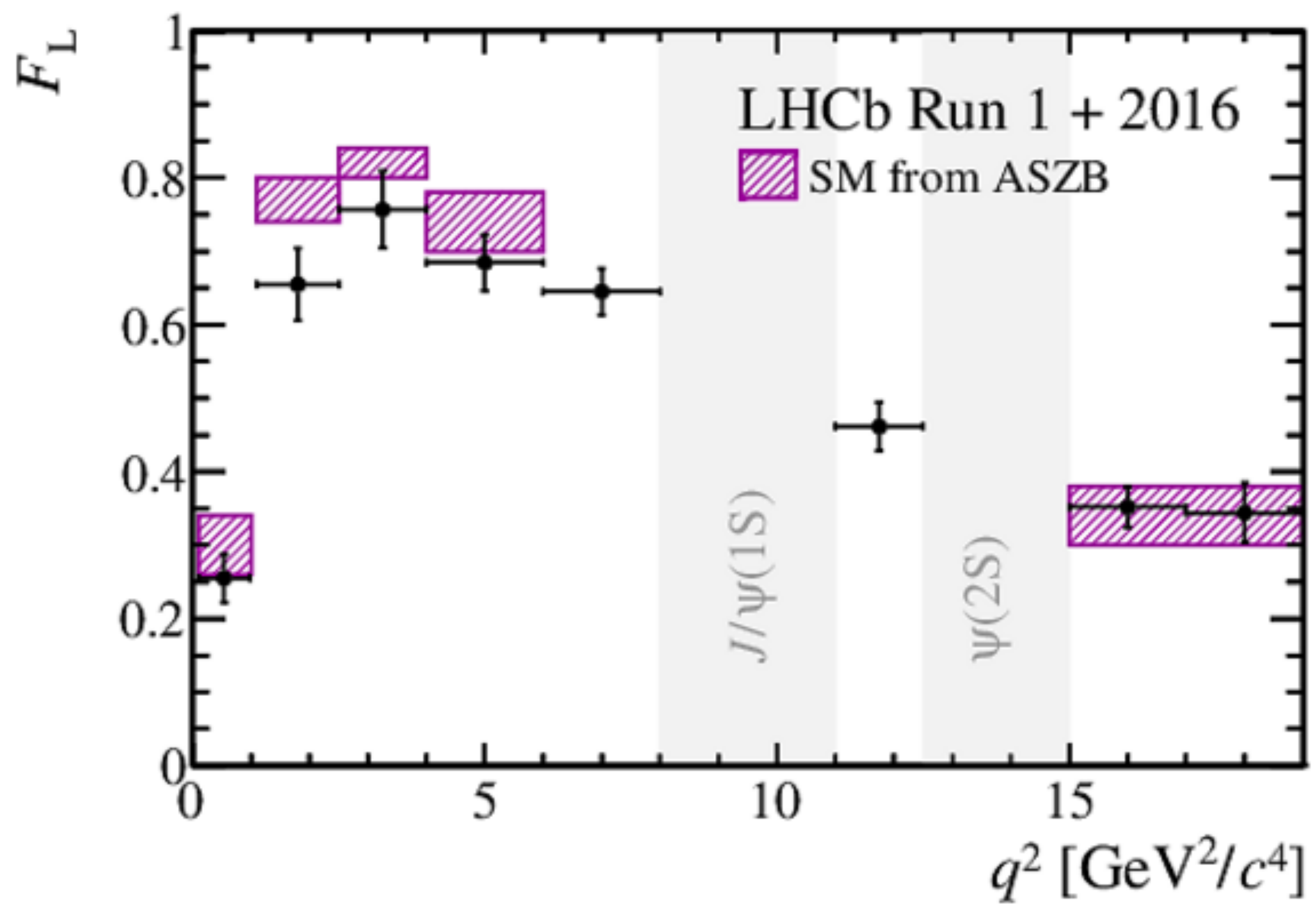
- General good agreement with SM found in most observables
- LHCb observed a tension in the "optimised variable" P_5' , not exactly intuitive, but constructed from ratios of angular observables to be robust from 'form-factor uncertainties'
- However inconclusive when adding ATLAS, CMS and Belle

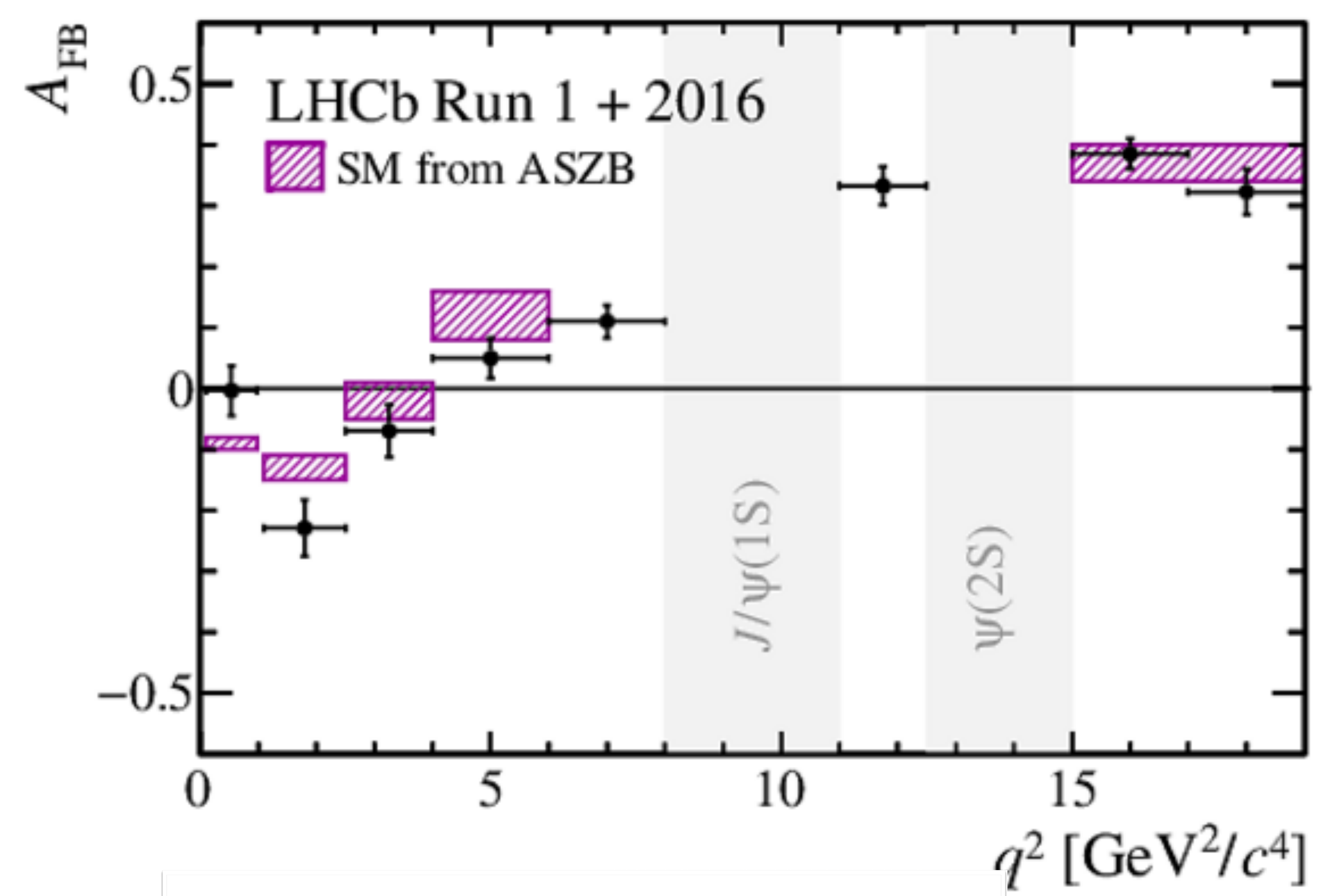


LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS: JHEP 10 (2018) 047
CMS: PLB 781 (2018) 517541

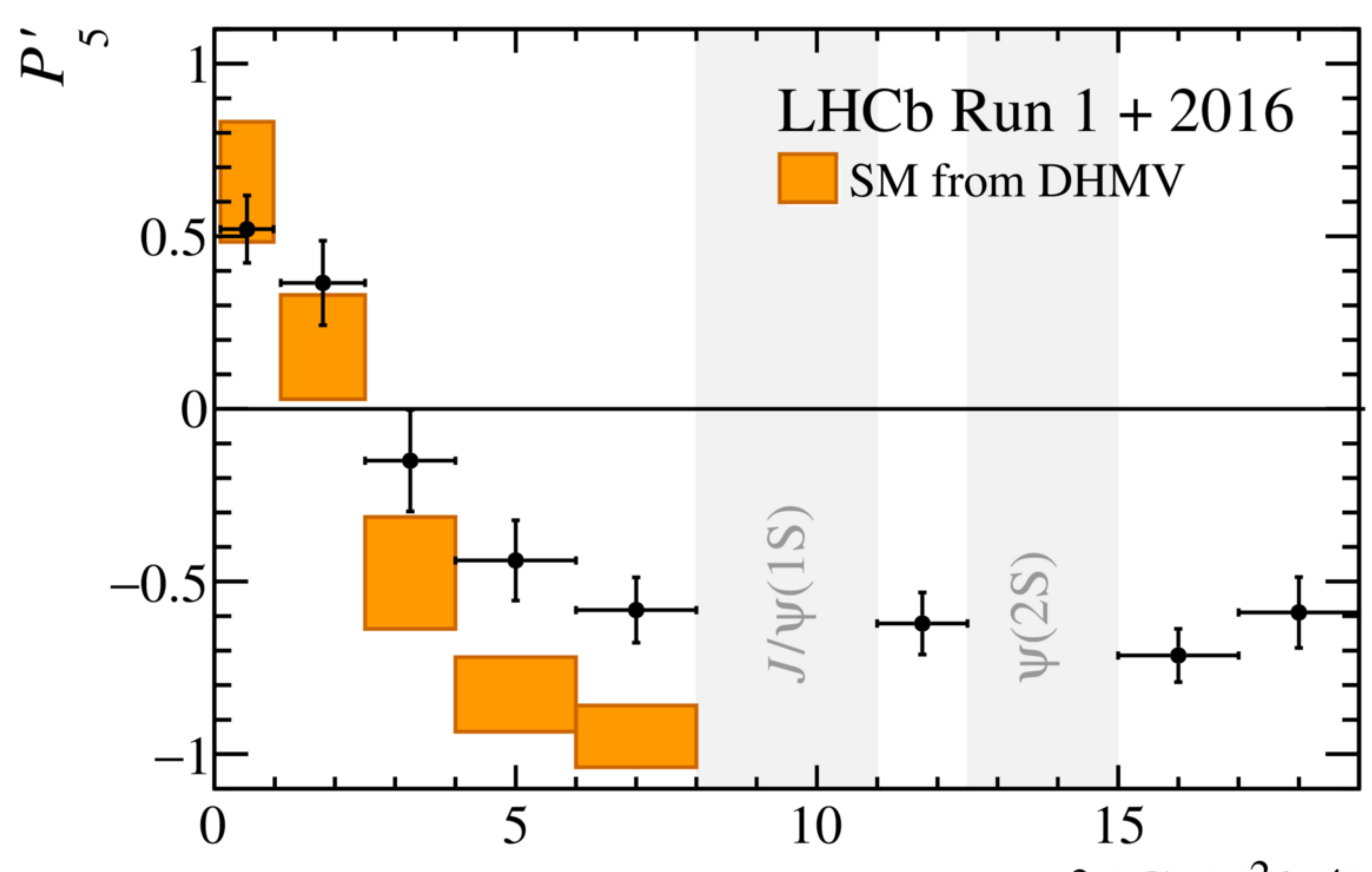
$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ angular analysis

- LHCb update based on 4.7/fb (~doubling the number of B^0 to ~5000 events)





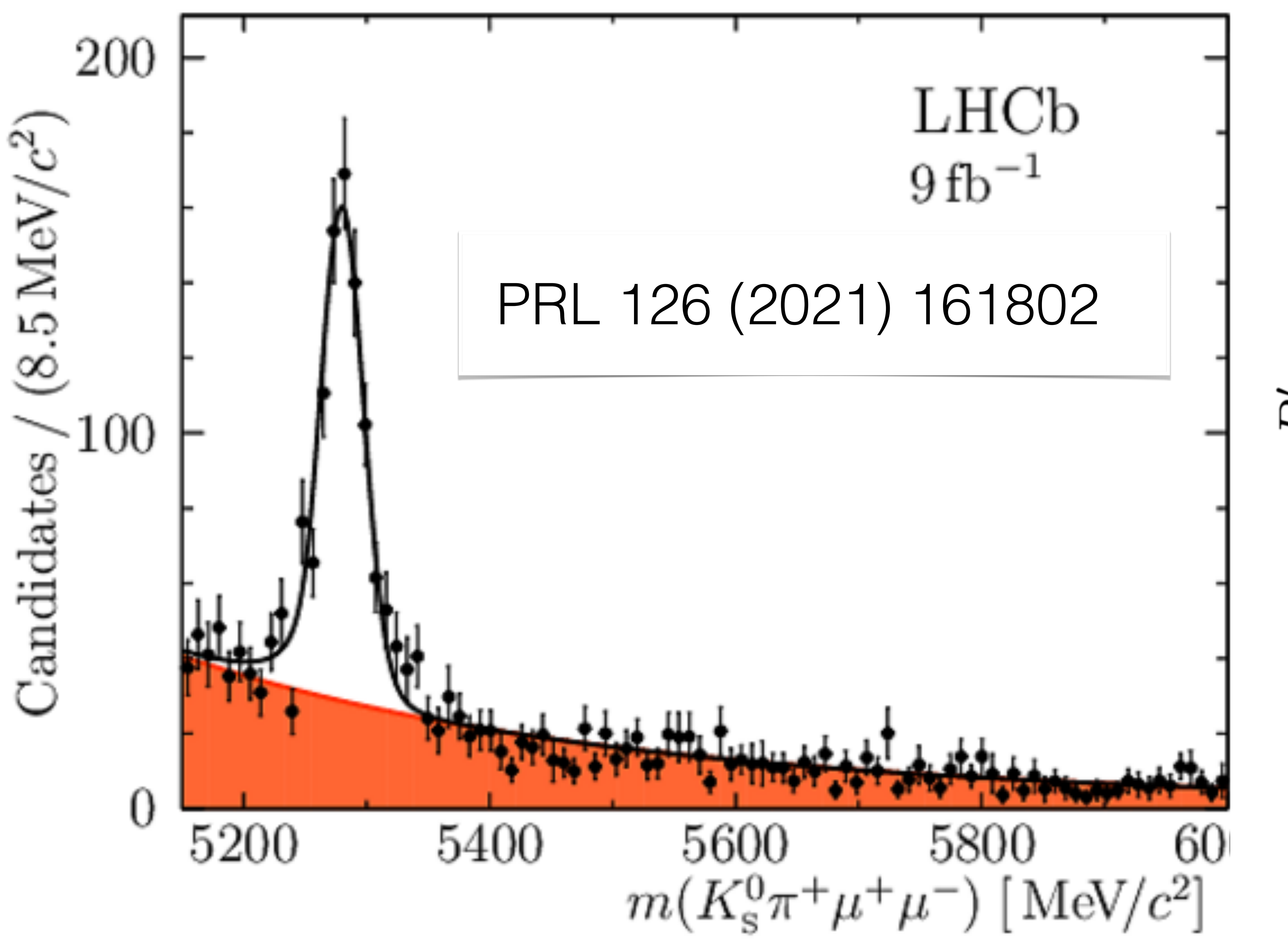
PRL 125 (2020) 011802

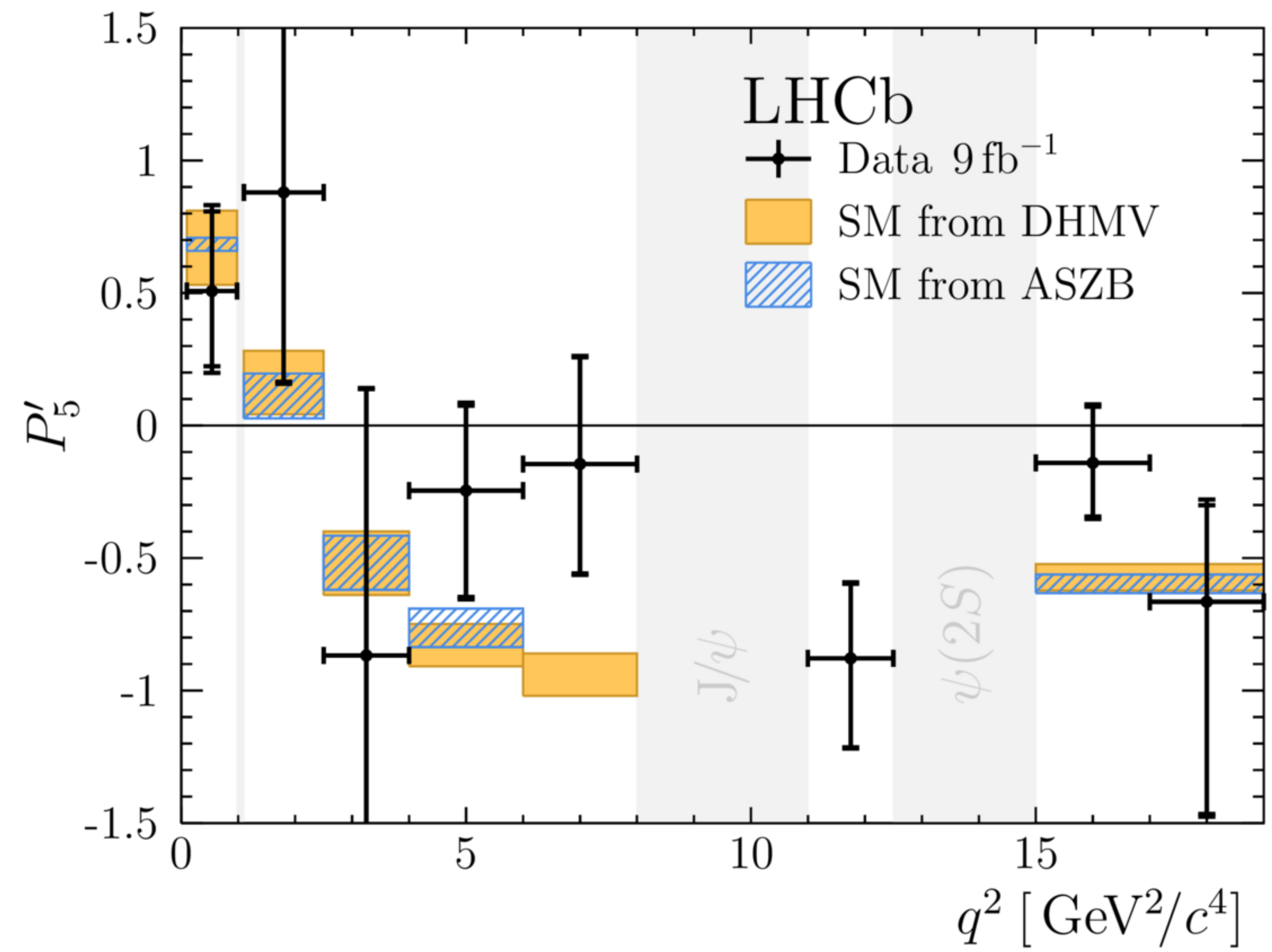


- P'_5: local tension of 2.5σ and 2.9σ in q^2 bins of [4.0,6.0] and [6.0,8.0] GeV^2
- Global analysis finds a deviation of $3.3\,\sigma$
- Consistent with previous result

New: $B^+ \to K^{*+}(\to K^0_s\pi^+)\mu^+\mu^-$ 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"





- Global 3σ tension with SM

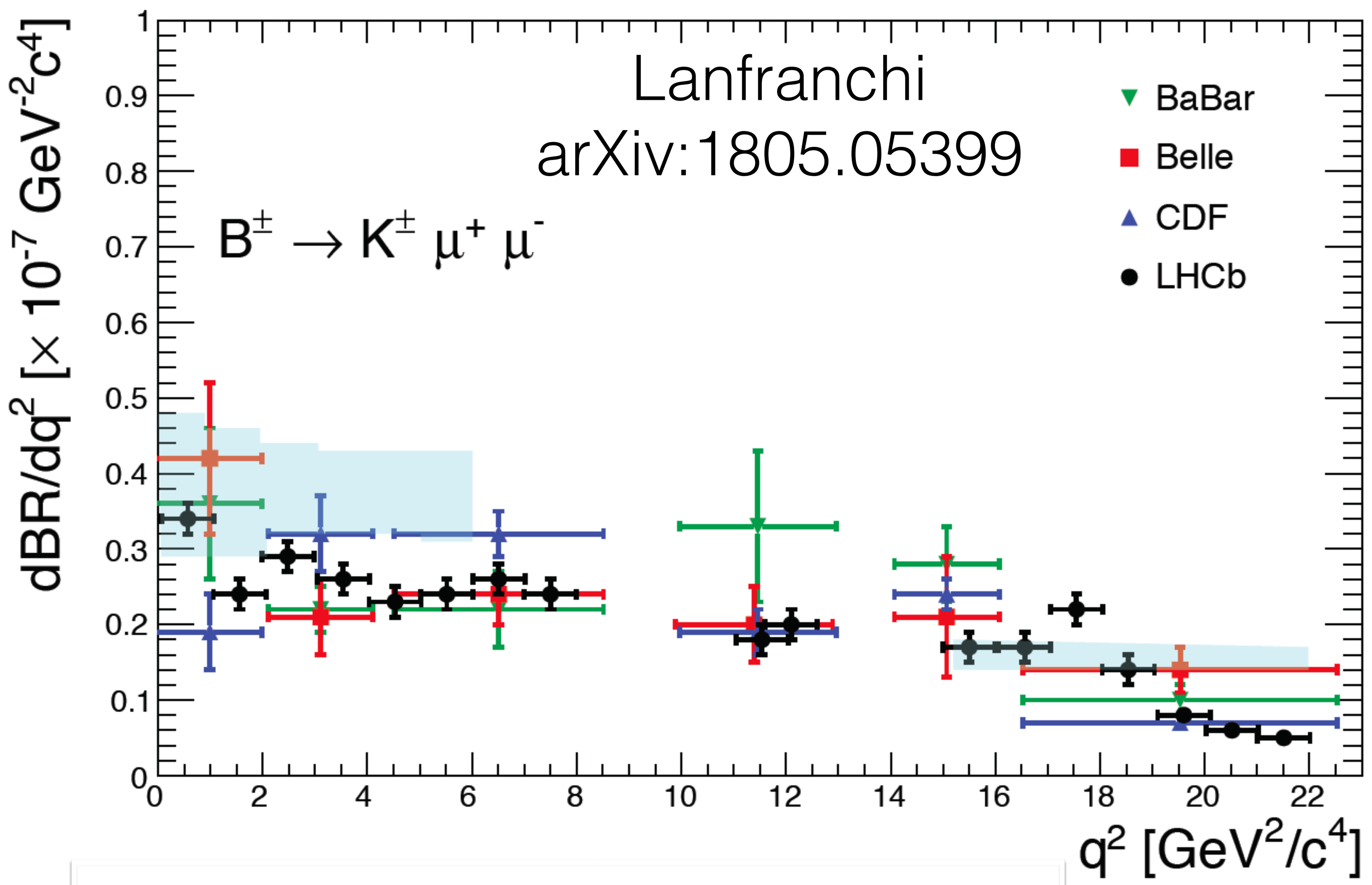
New: $B_s^0 \to \phi\mu^+\mu^-$ angular analysis

- Update with ~4 time more B_s^0 candidates (8.4/fb)

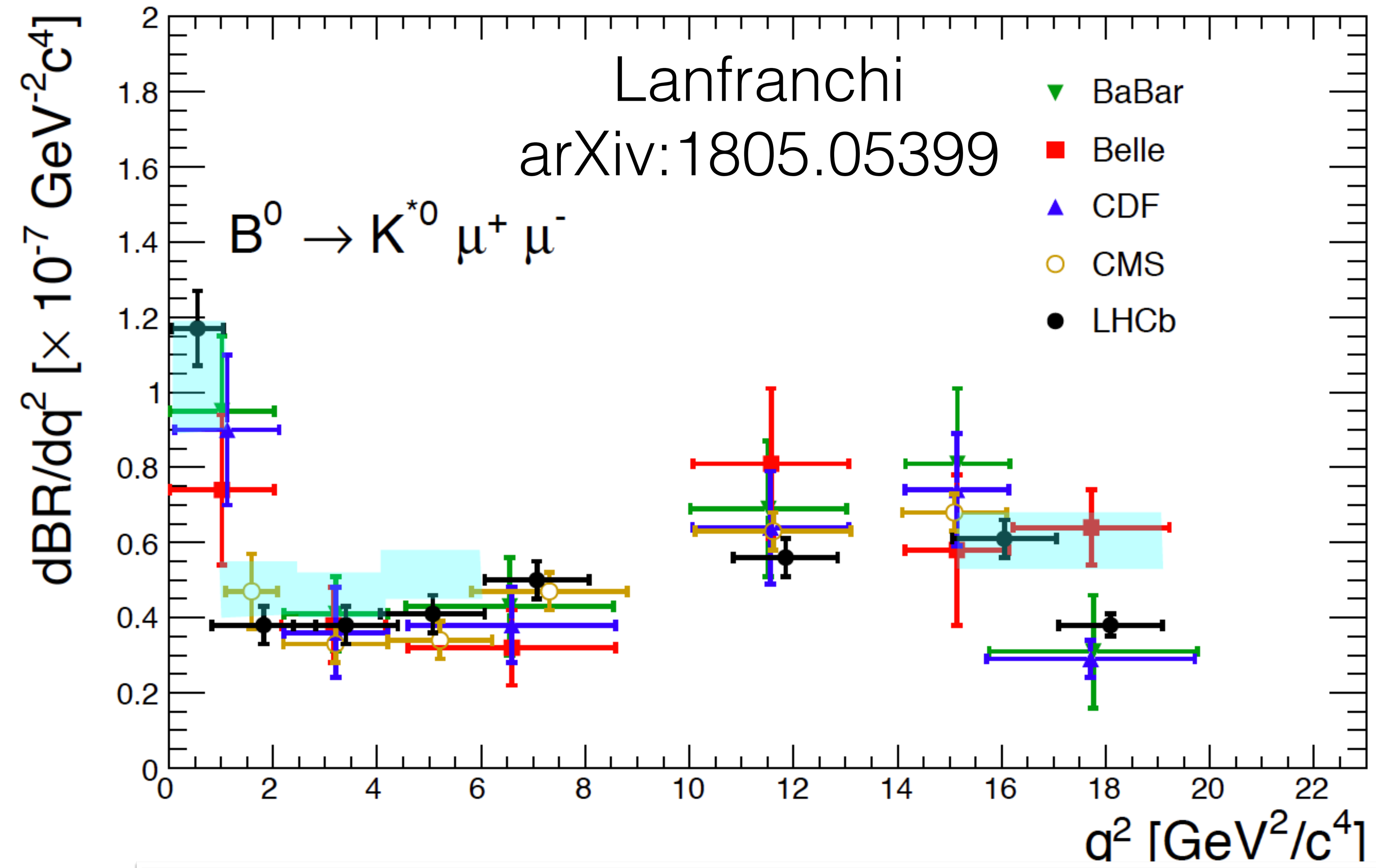
arXiv:2107.13428

- 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

Intriguing set of results in differential branching fractions for b→sμμ transitions



LHCb: JHEP 06 (2014) 133
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801
CDF: PRL 107 (2011) 201802



CMS: PLB 753 (2016) 424
LHCb: JHEP 11 (2016) 047, JHEP 04 (2017) 142
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801
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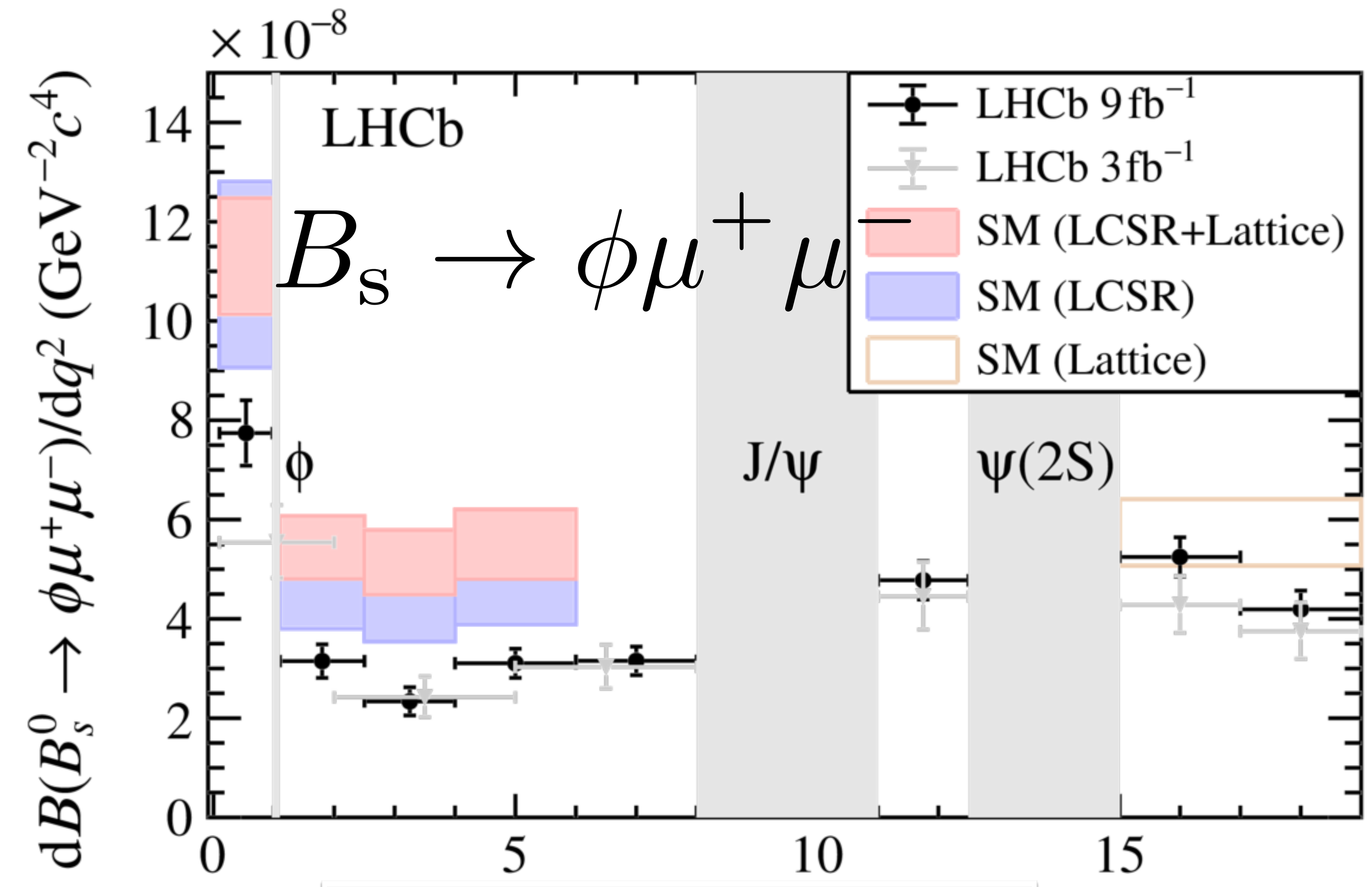
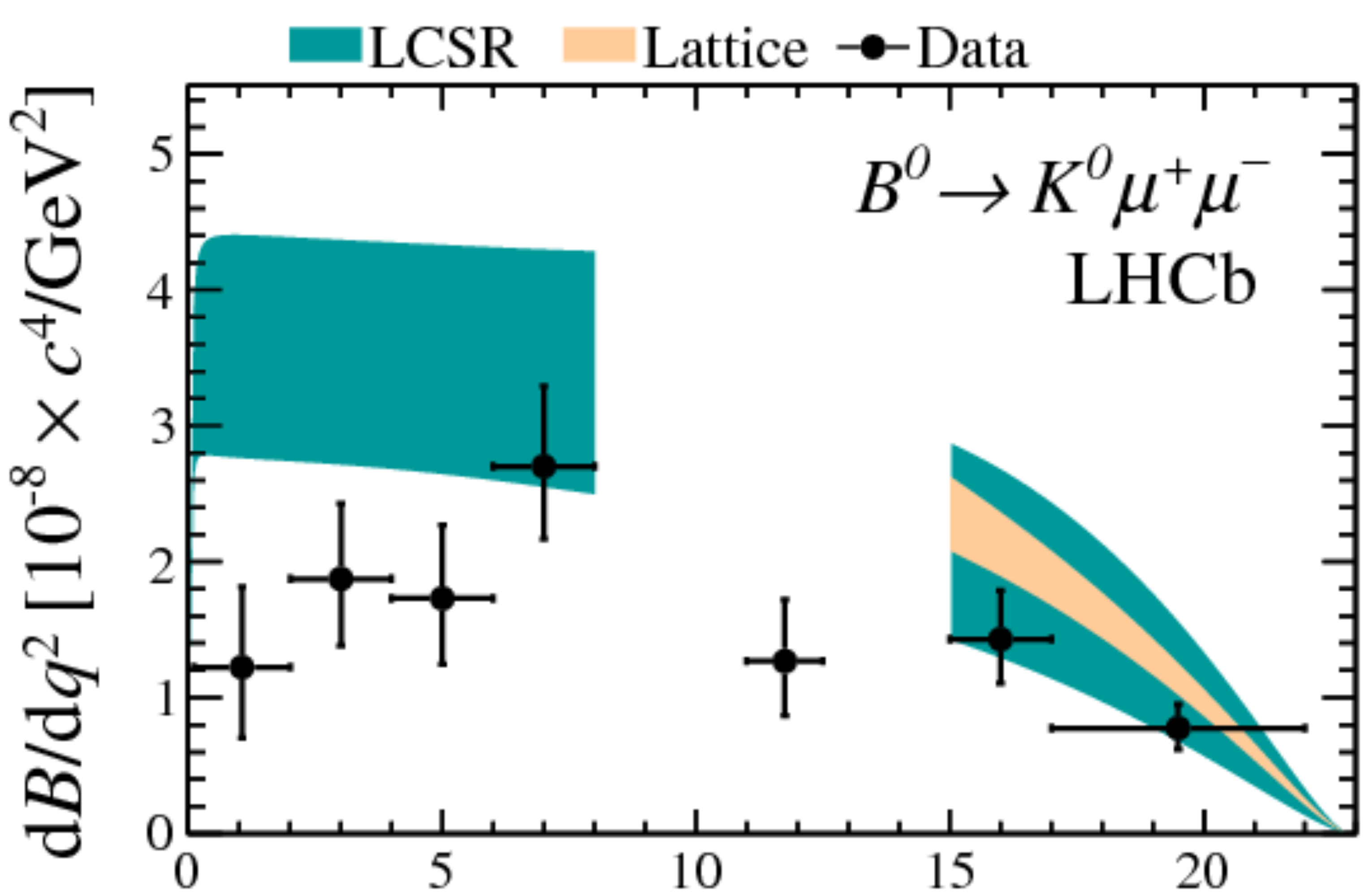


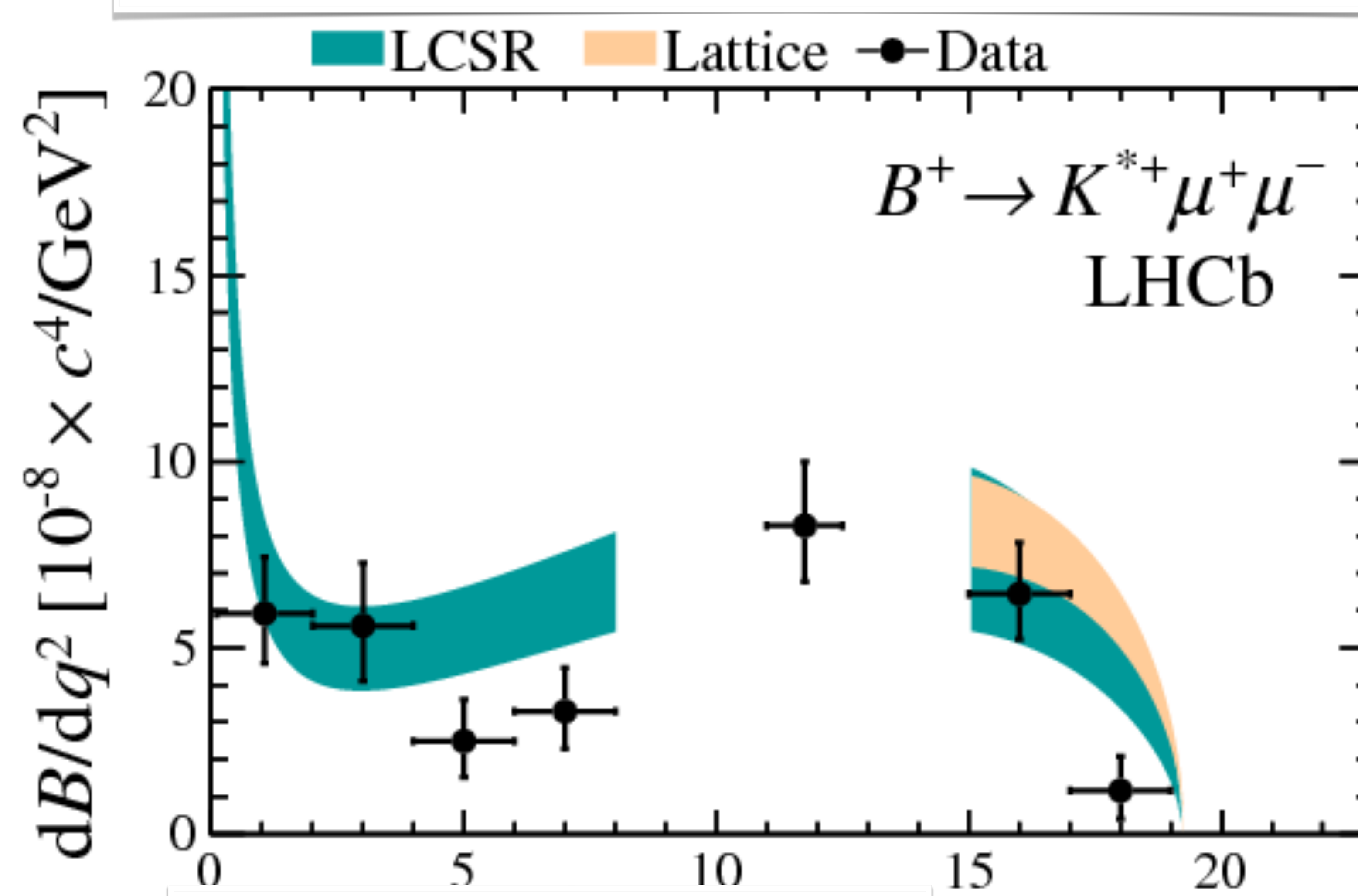
arXiv:2105.14007

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

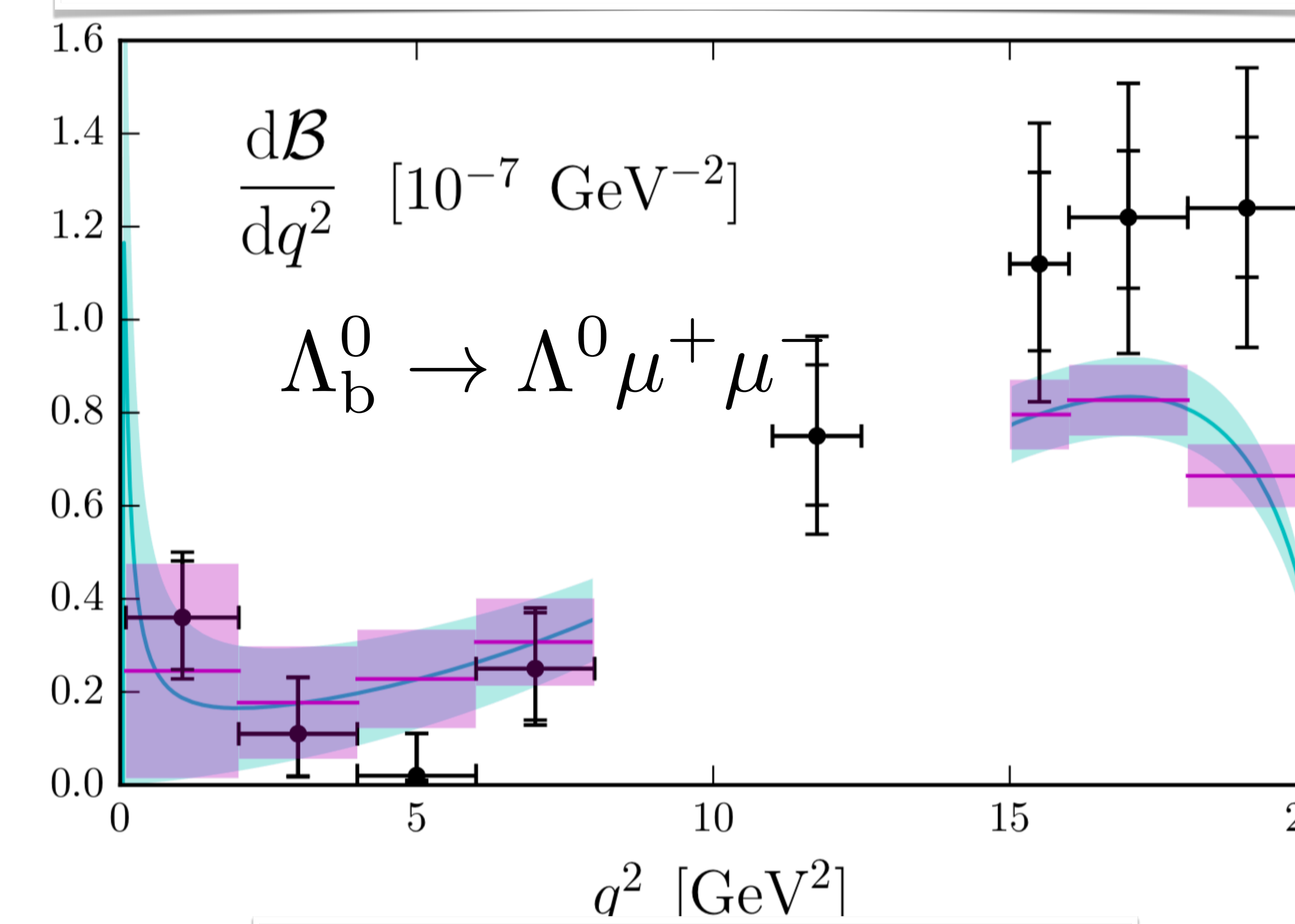
Detmold and Meinel, PRD93 074501 (2016)



JHEP 06 (2014) 133



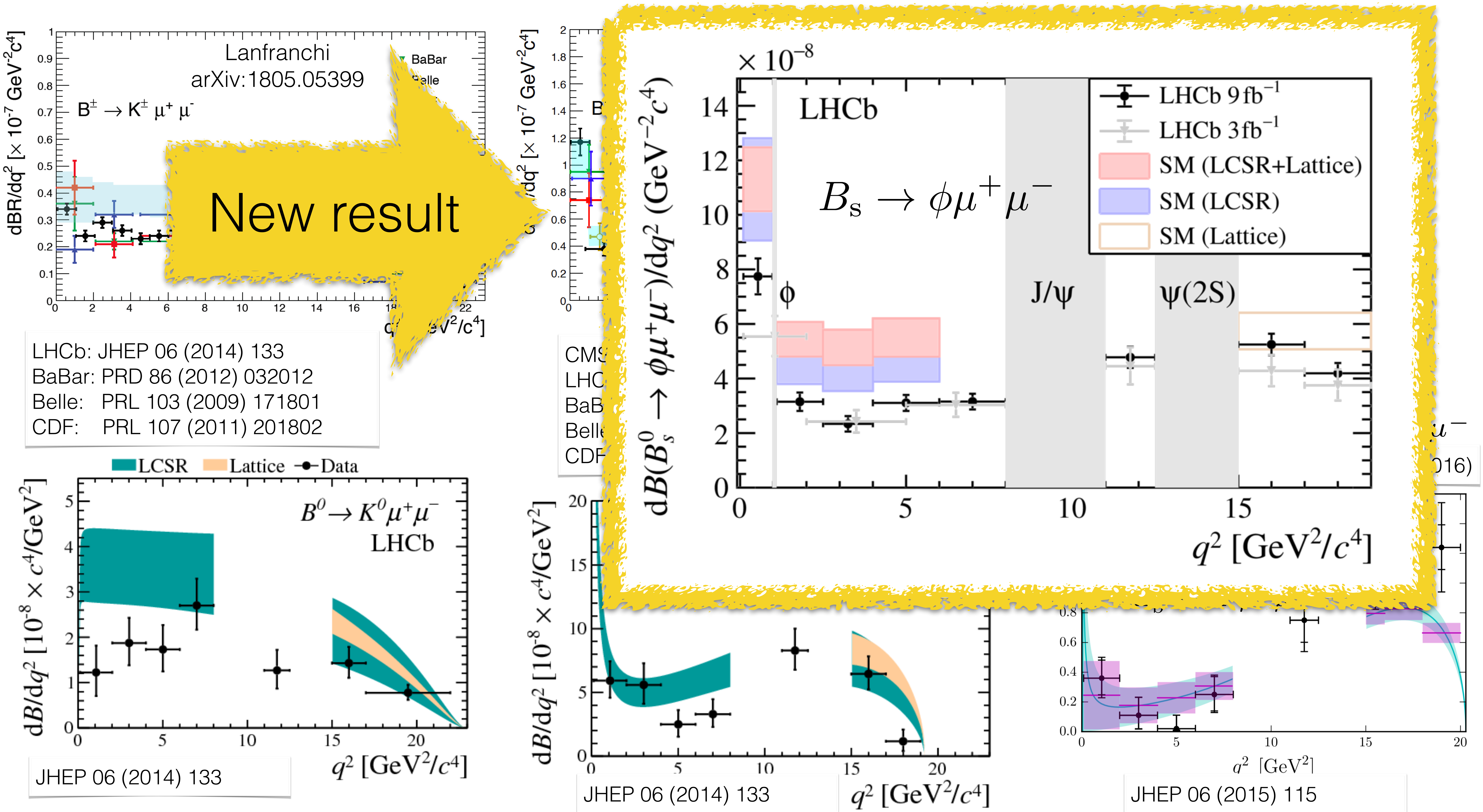
JHEP 06 (2014) 133



JHEP 06 (2015) 115

- In general, data tend to be lower than theory predictions at low q²
- Comparison limited by theoretical knowledge of form factors

Intriguing set of results in differential branching fractions for b→sμμ transitions



- Consistent with earlier measurements
- 3.6σ below SM in q^2 region between 1.1 and 6.0 GeV^2

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

- 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)

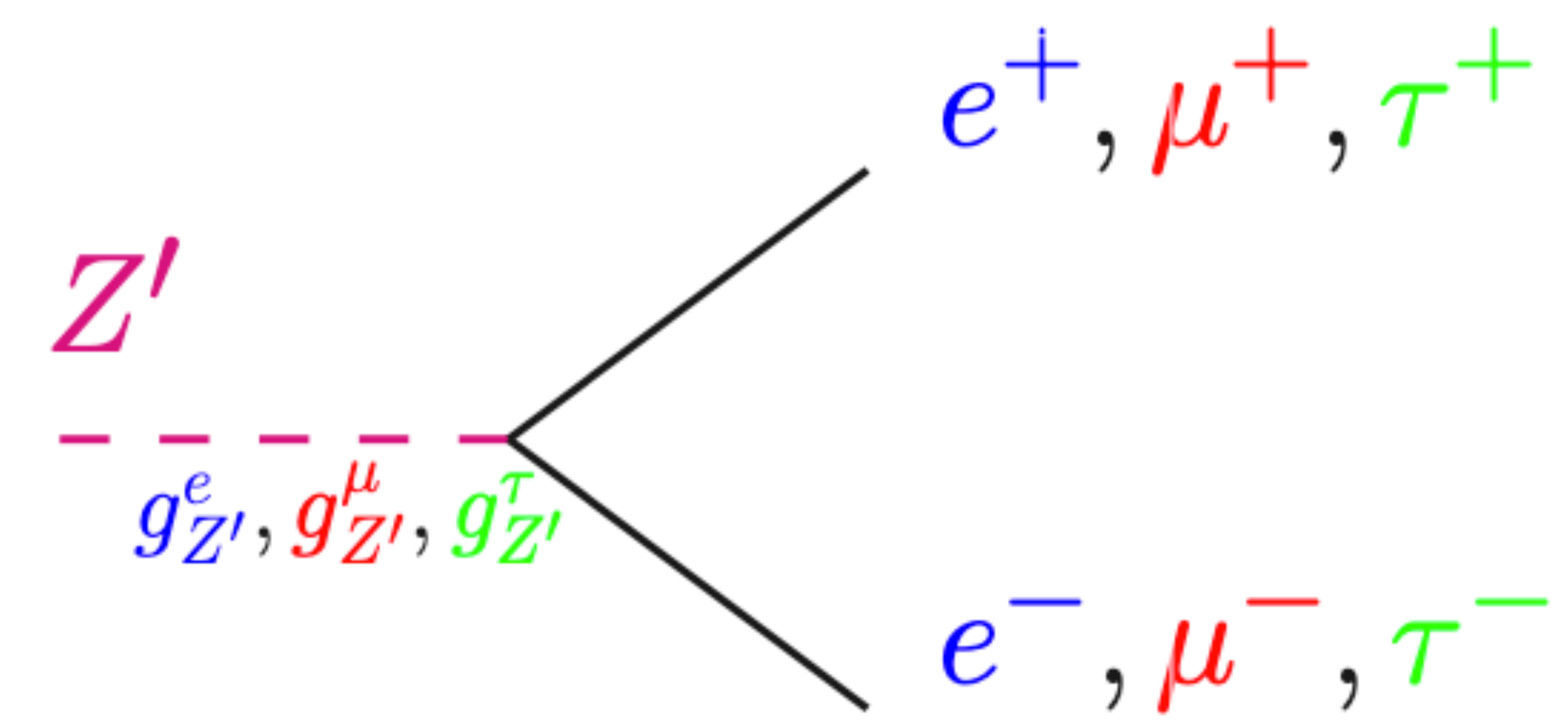
- Test LFU in $b \to s\ell^+\ell^-$ transitions, i.e. flavour-changing neutral currents with amplitudes involving loop diagrams

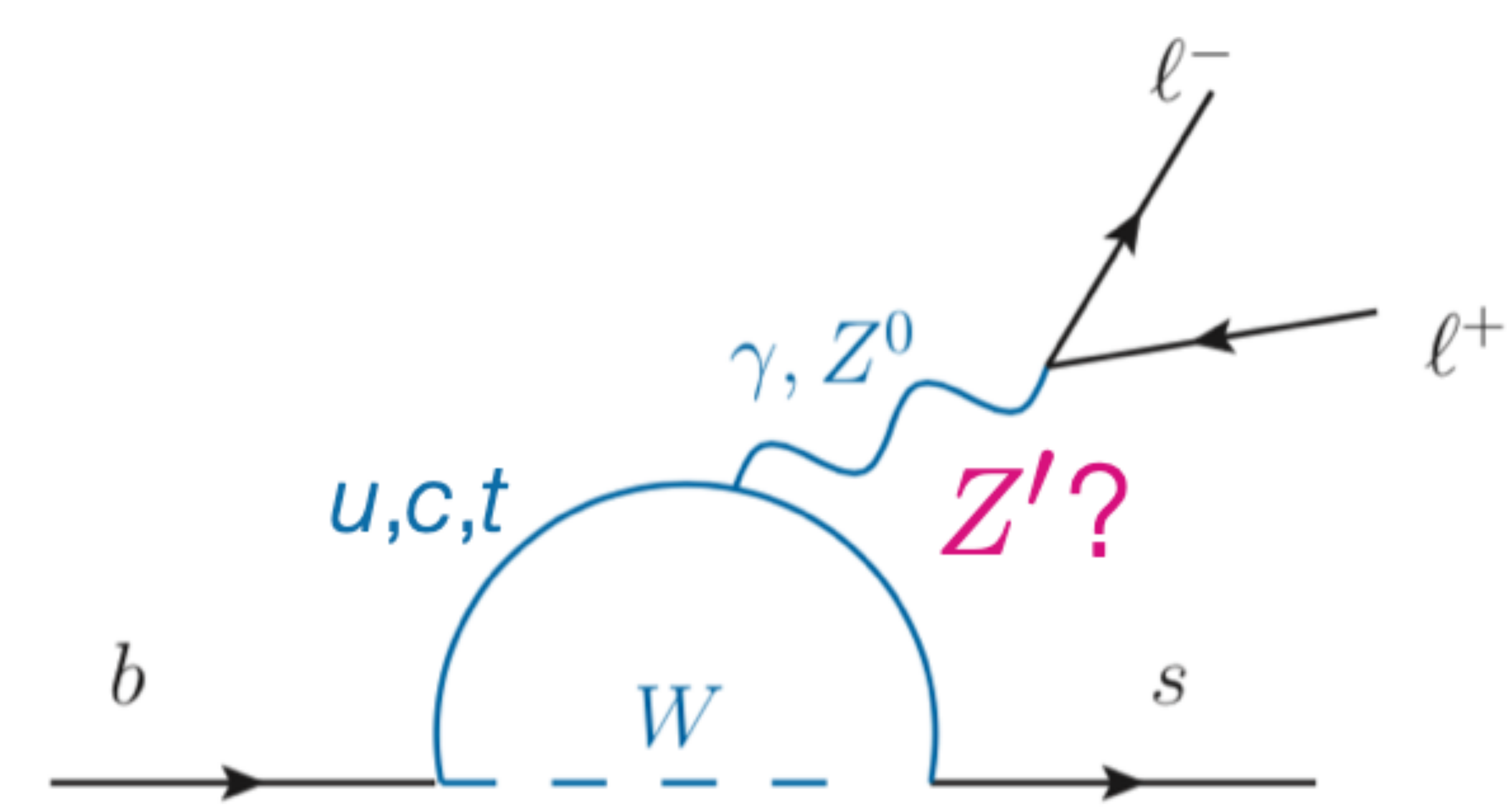
Lepton Flavour Universality II

- 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. **e**/μ 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

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

B: $B^+, B^0, B^0_{\mathrm{s}}, \Lambda^0_{\mathrm{b}}$

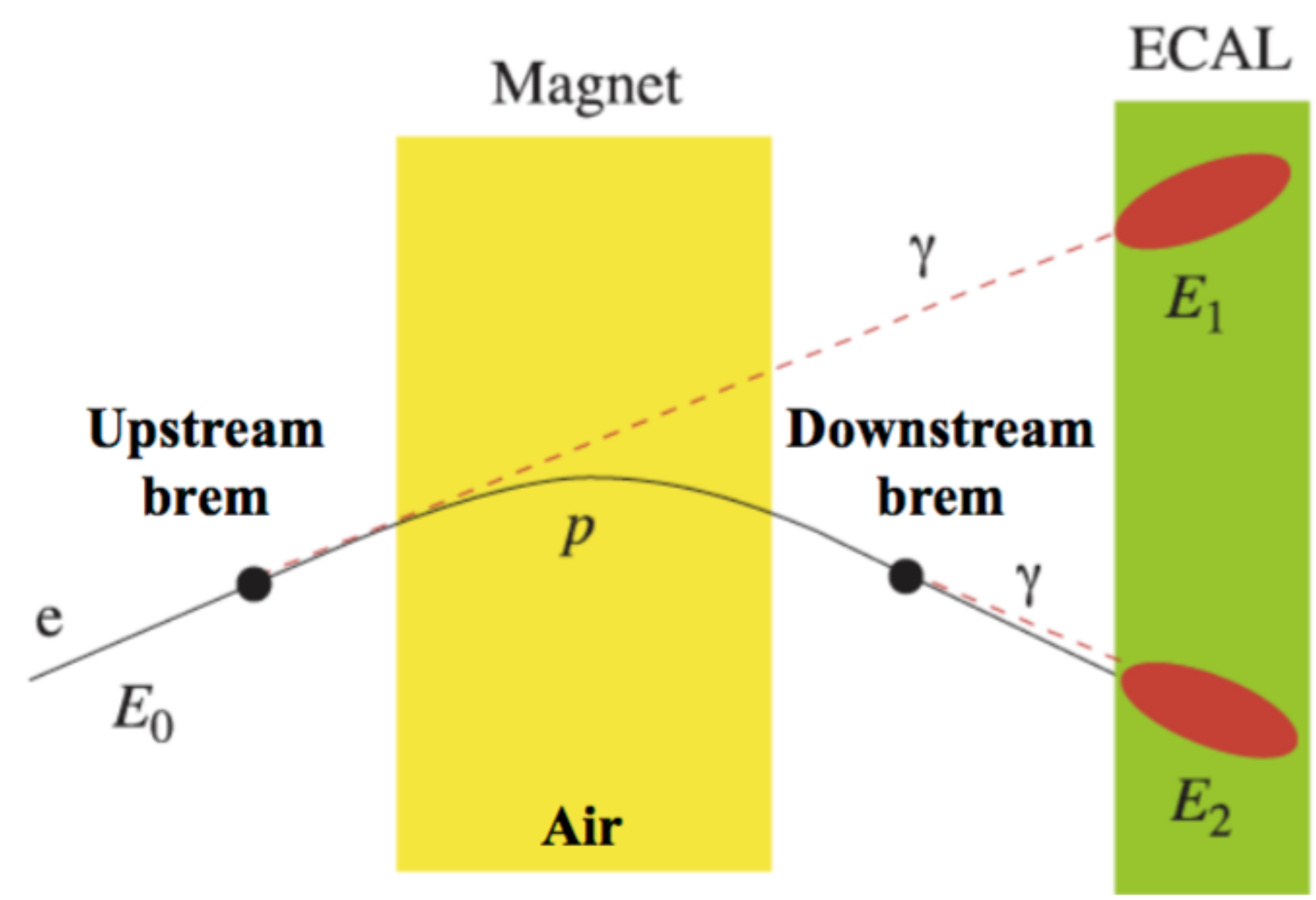
H: $K^+, K^{*0}, pK, \phi \ldots$

- 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 : $R_{\mathrm{H}} = 1$ in SM, neglecting lepton masses, with QED corrections at ~% level

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
- Lower efficiency of electron trigger

JHEP 08 (2017) 055

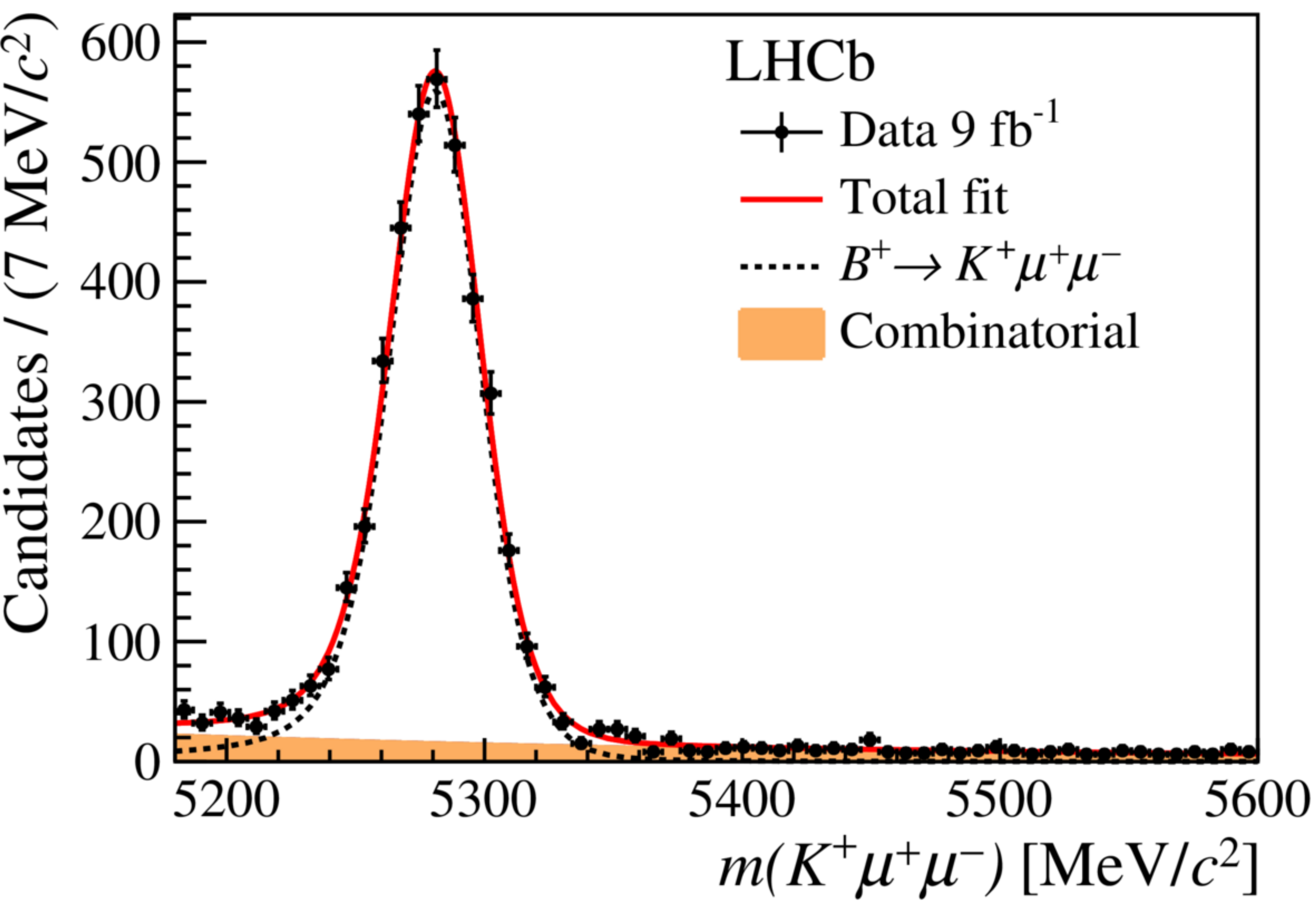


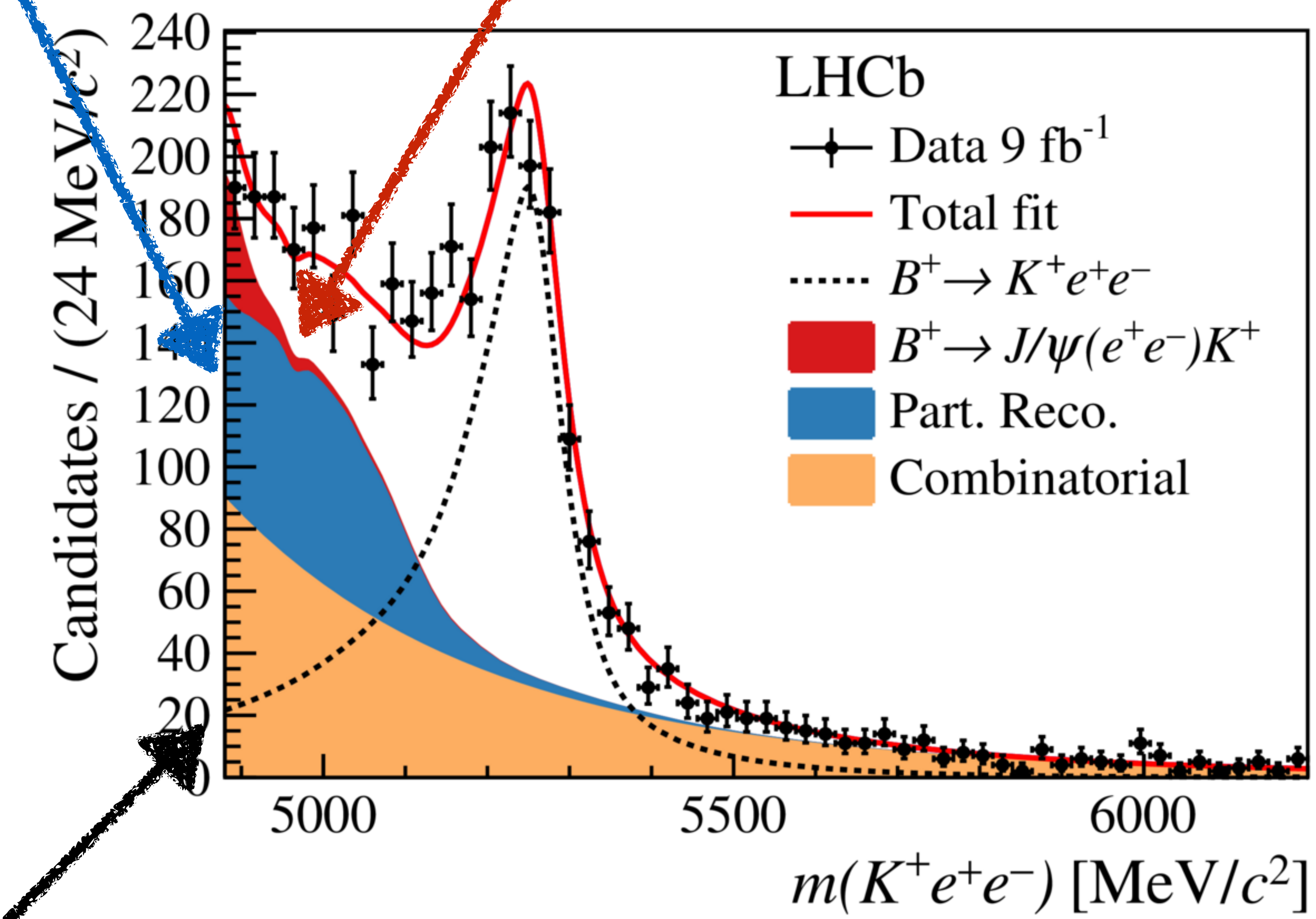
muons vs electrons

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 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

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

arXiv:2103.11769

- Based on the full LHCb statistics, ~twice as many B as in previous analysis

- Important crosschecks

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

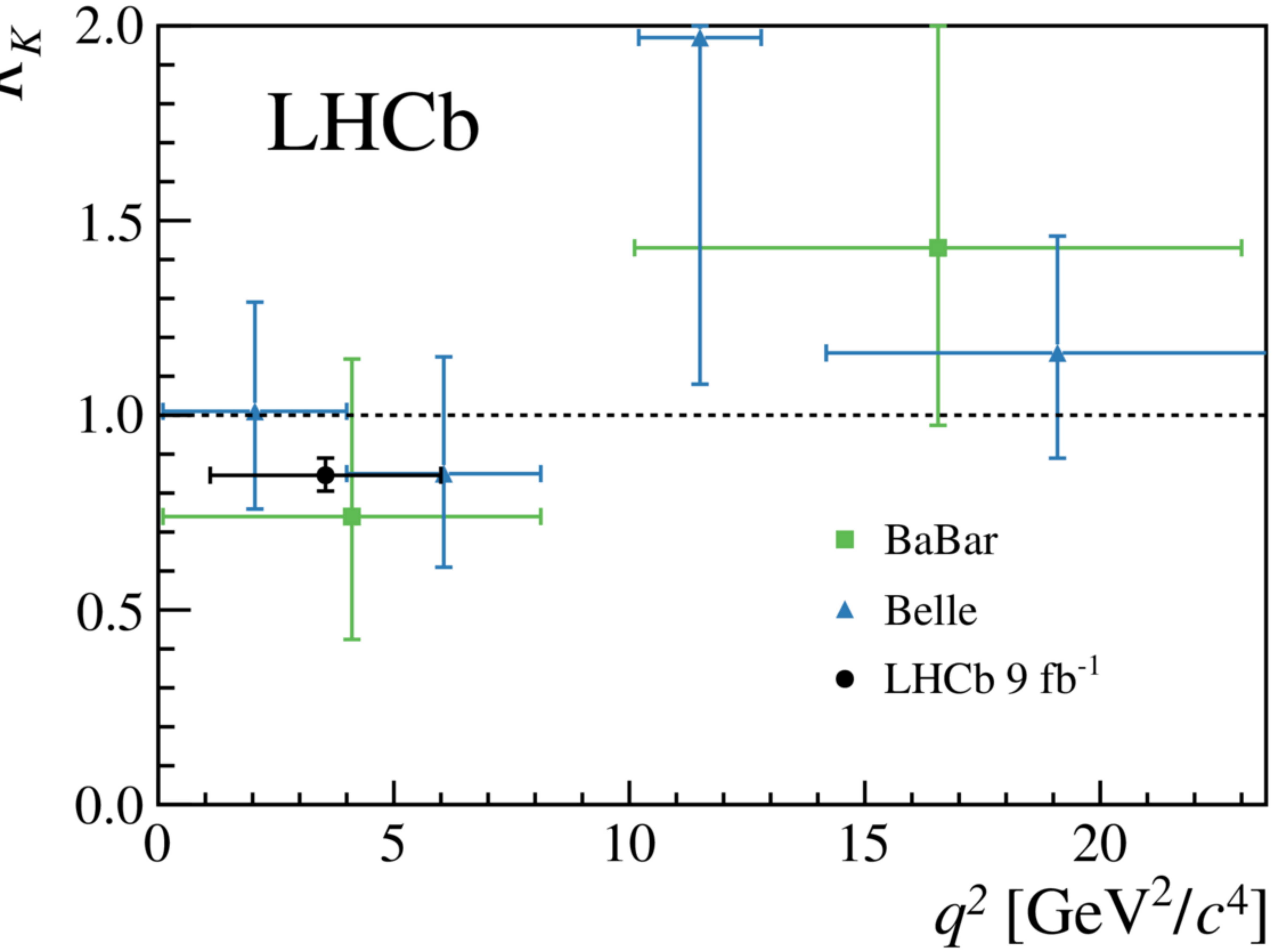
- very stringent cross-check, which requires control of the relative selection efficiencies for the resonant electron and muon modes

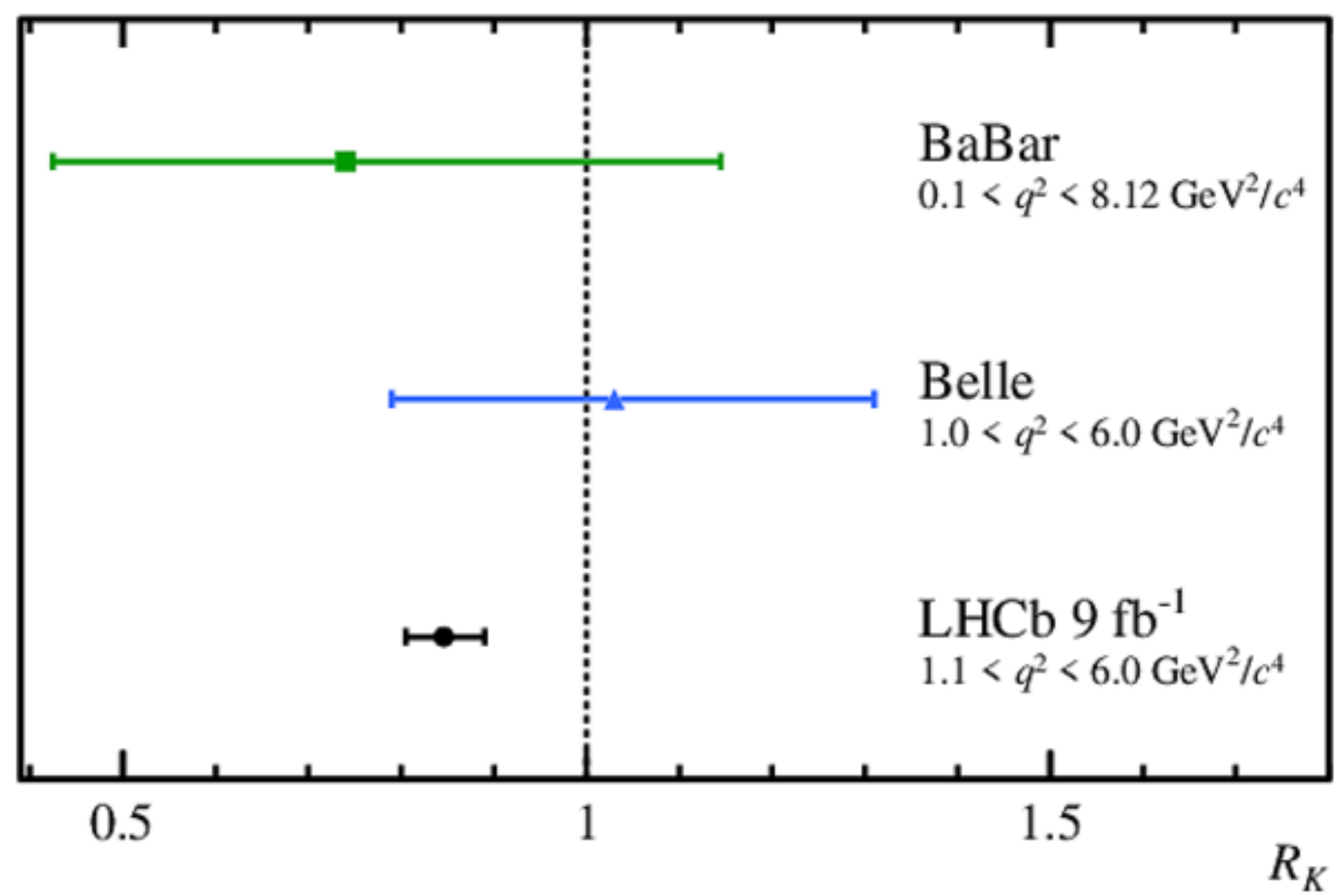
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.997 \pm 0.011$$

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

arXiv:2103.11769

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



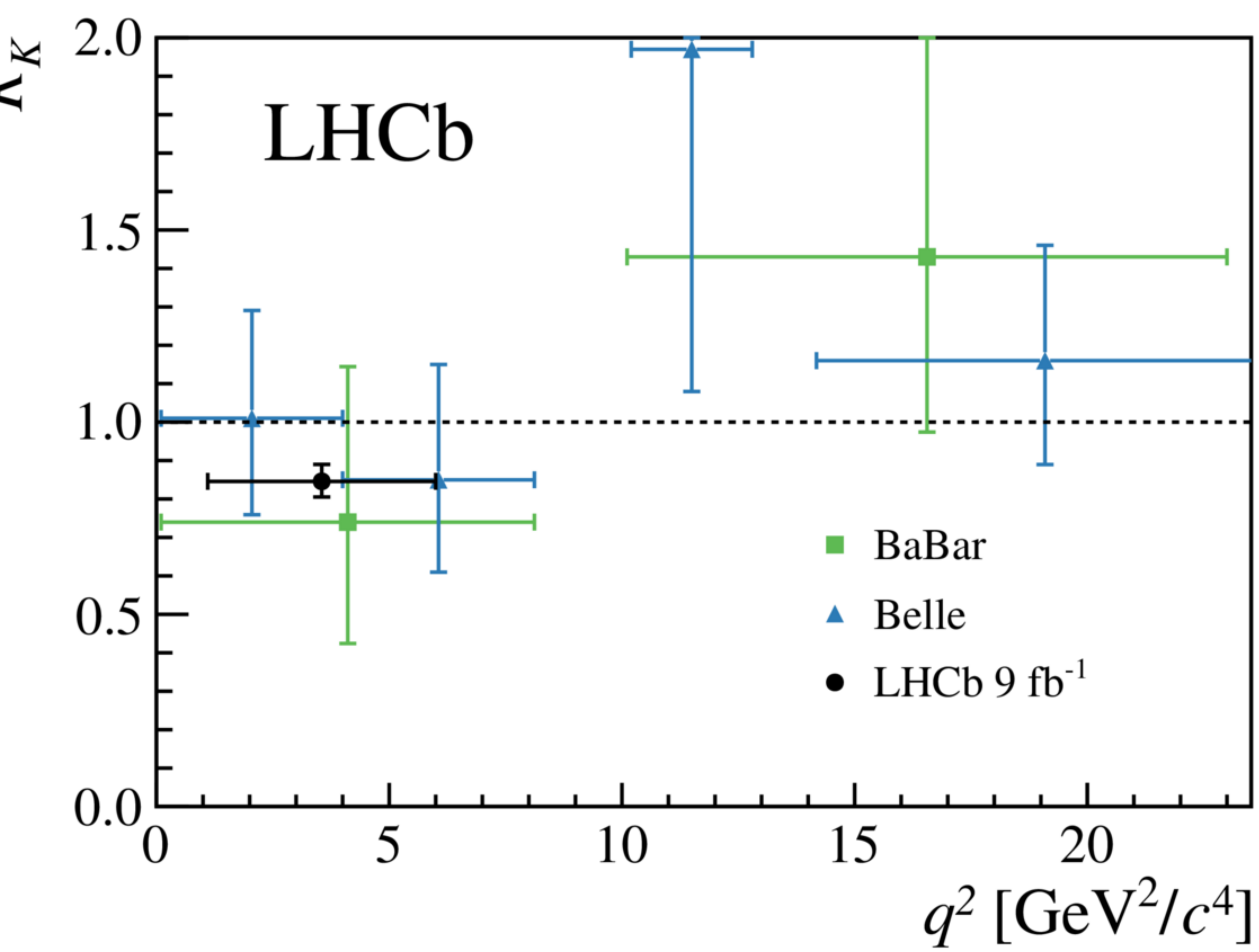


3.1 σ evidence

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

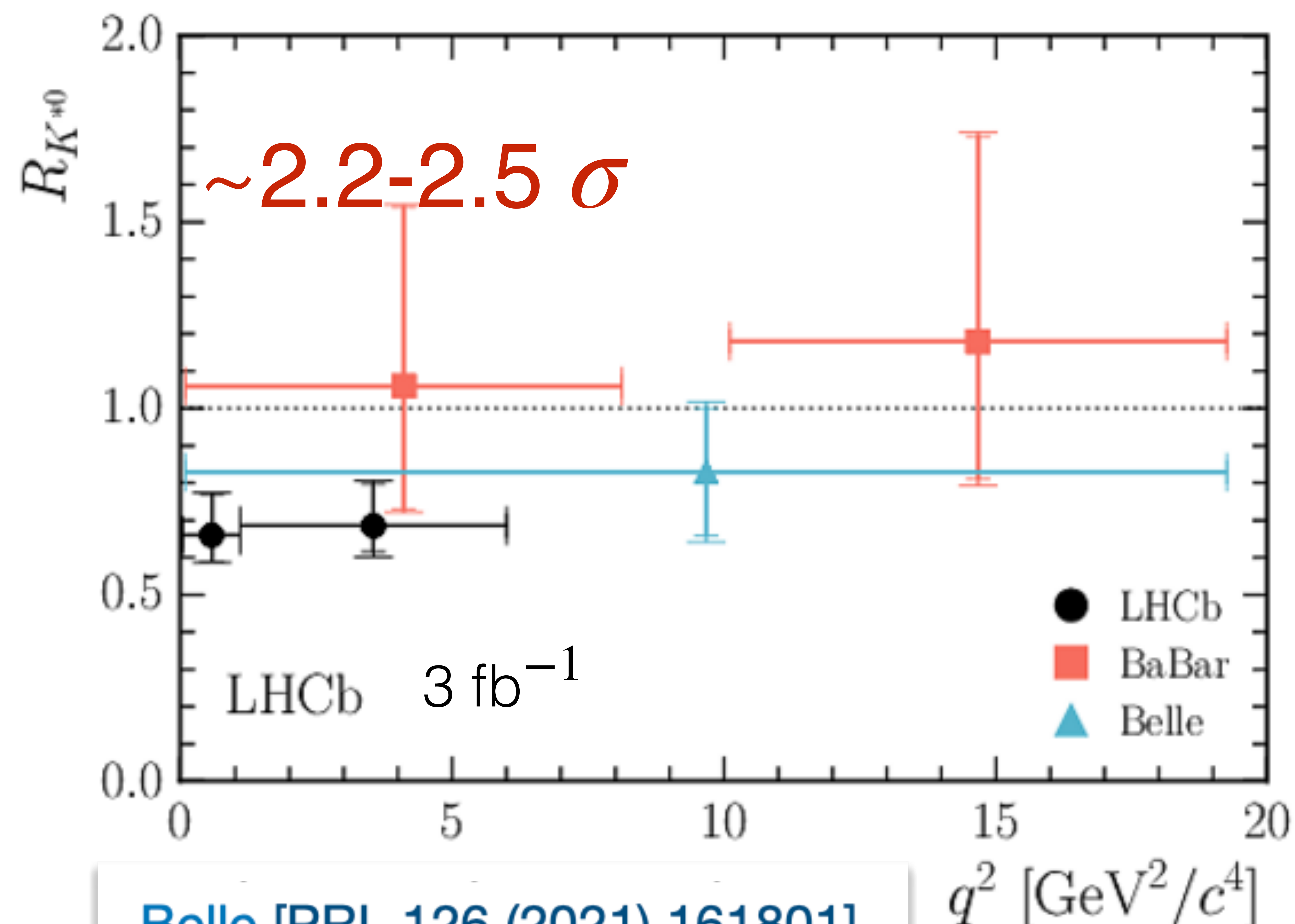
arXiv:2103.11769

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



3.1 σ evidence

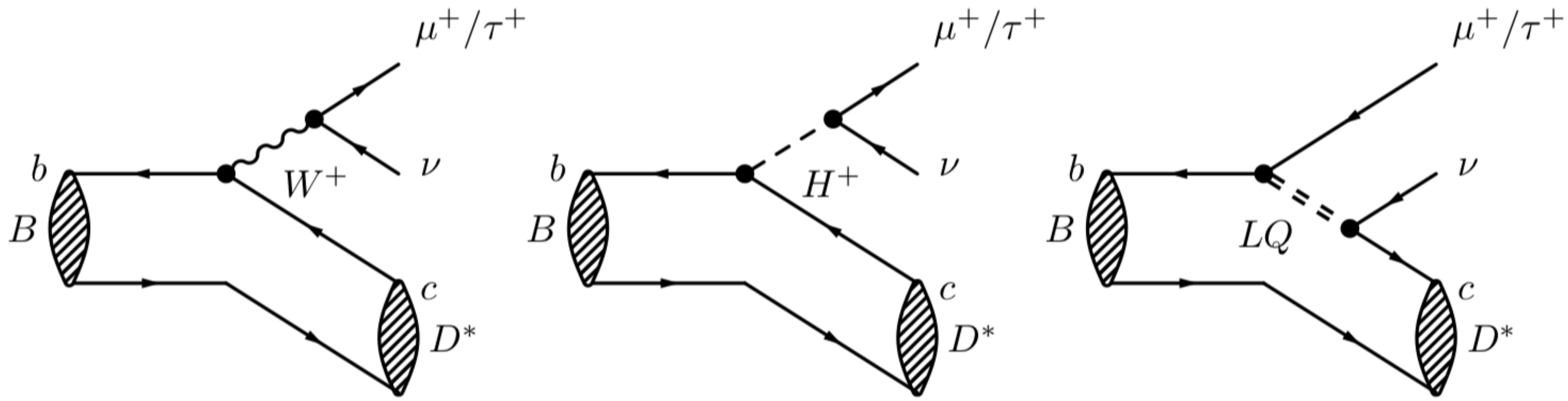
$B^0 \to K^{*0}\mu^+\mu^-$



Belle [PRL 126 (2021) 161801]
BaBar [PRD 86 (2012) 032012]
LHCb [JHEP 08 (2017) 055]

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

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

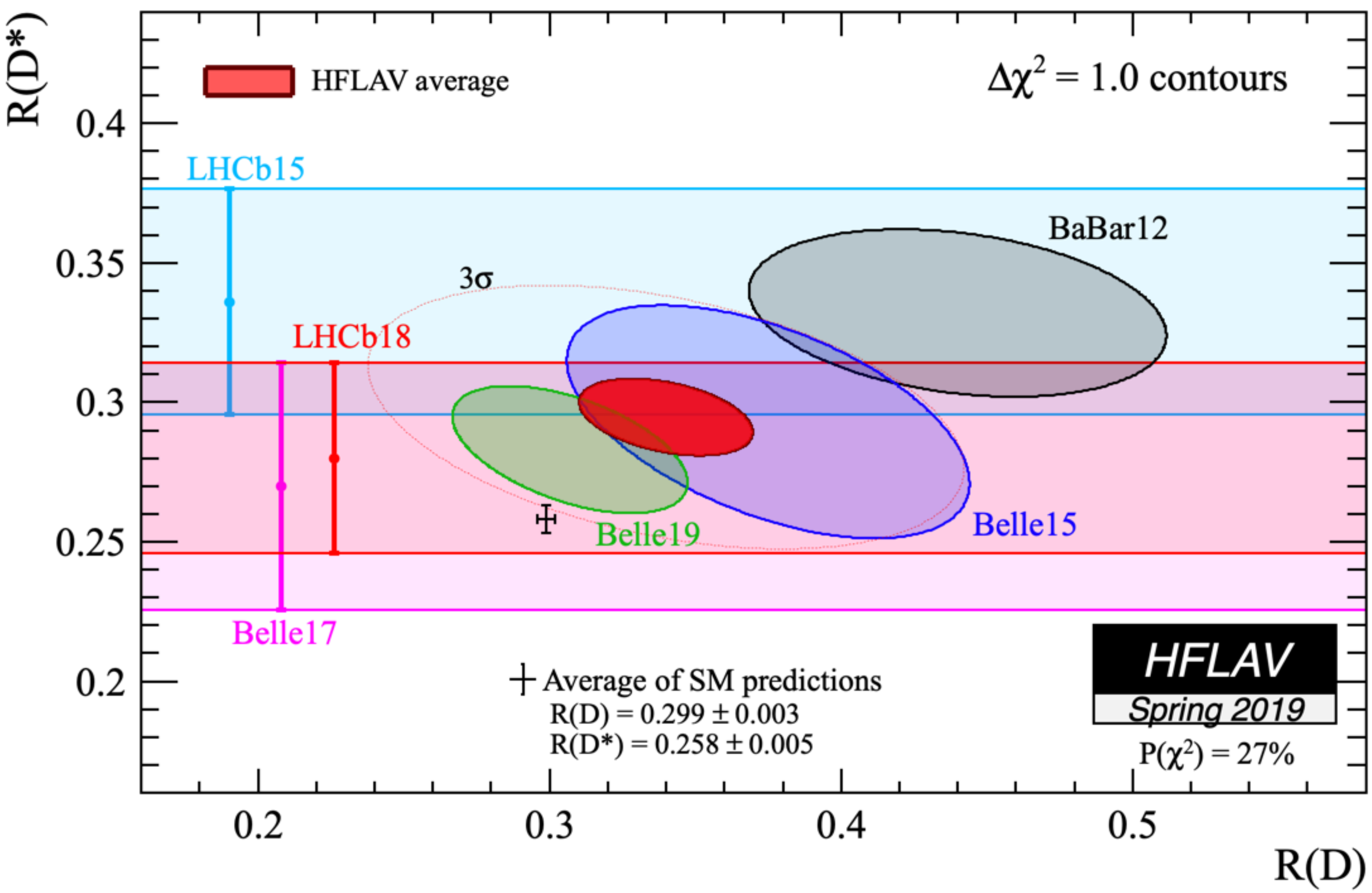


- Different class of decays (tree-level charged current with V_{cb} suppression)
- Not at all rare: $B(B^0 \to D^{*-}\tau^+\nu_\tau) \sim 1\ \%$, problem is the background
- Lepton-universality ratio R(D*) : $R(D^*) = \dfrac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$
  - sensitive to any NP model coupling preferentially to third generation leptons
- Predicted theoretically at ~1%: $R(D)_{\rm SM} = 0.299 \pm 0.003$ $R(D^*)_{\rm SM} = 0.258 \pm 0.005$

HFLAV average, 2019

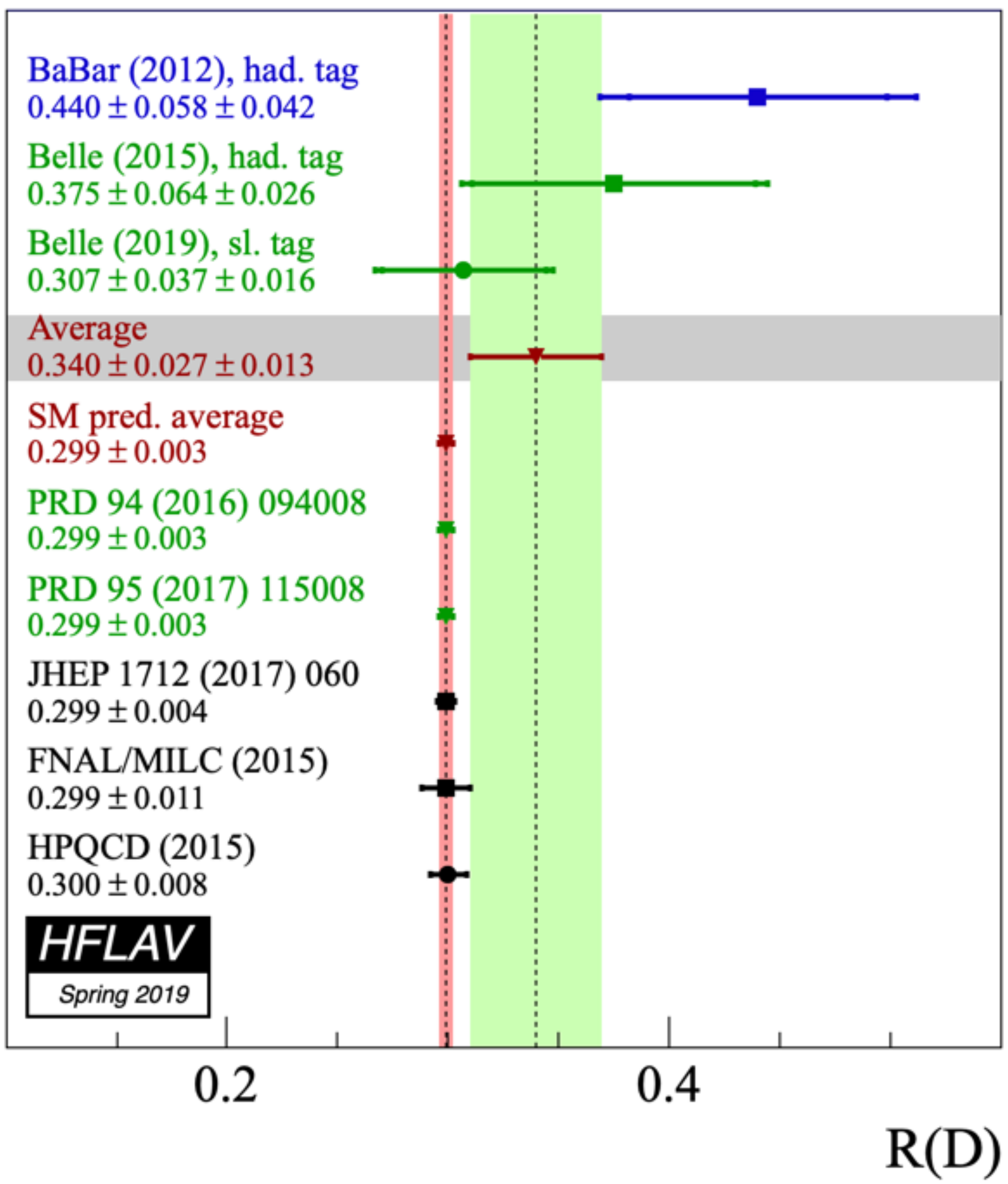
- Studied by Belle, BaBar and LHCb

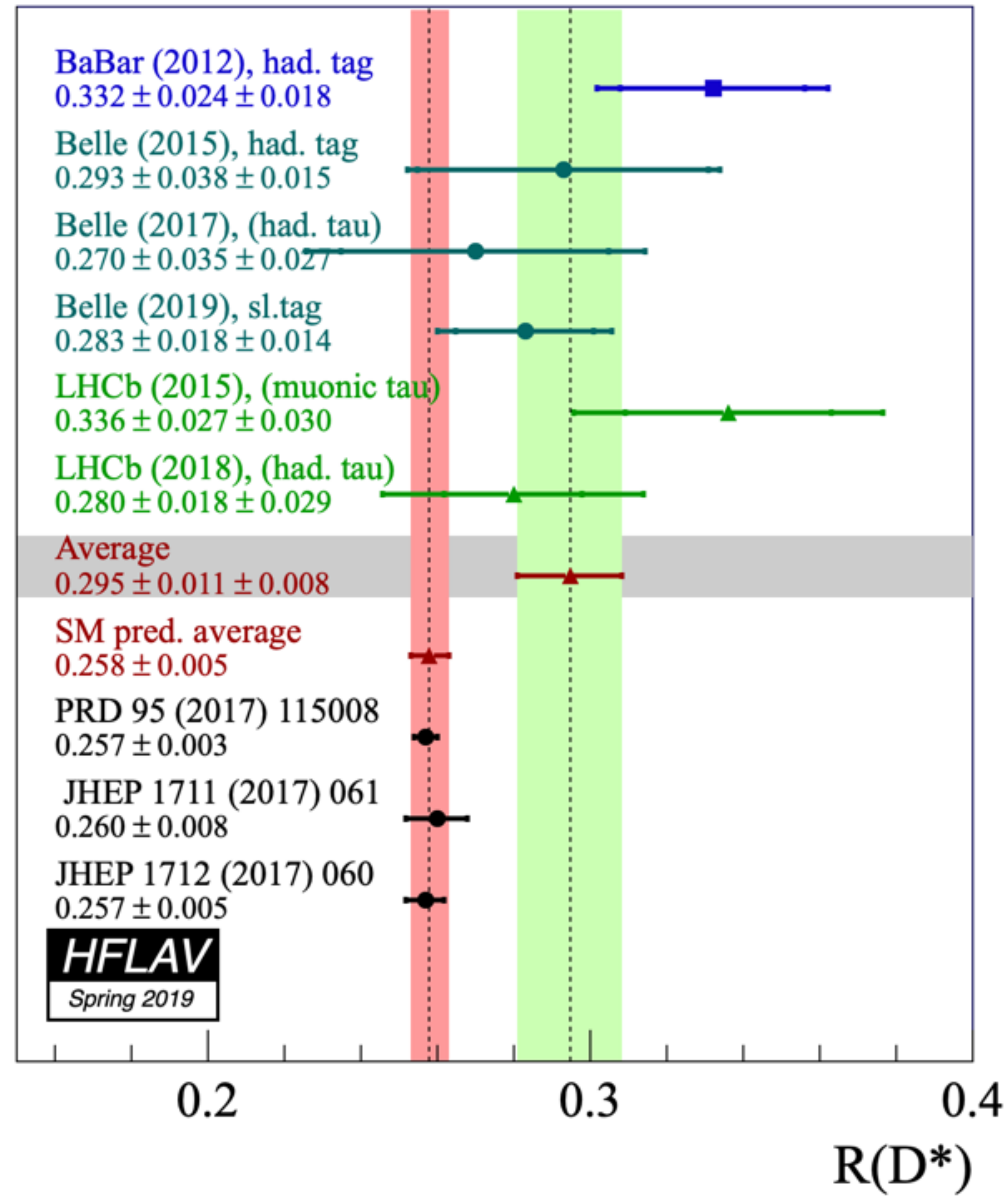
$R(D)$ vs $R(D^*)$



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

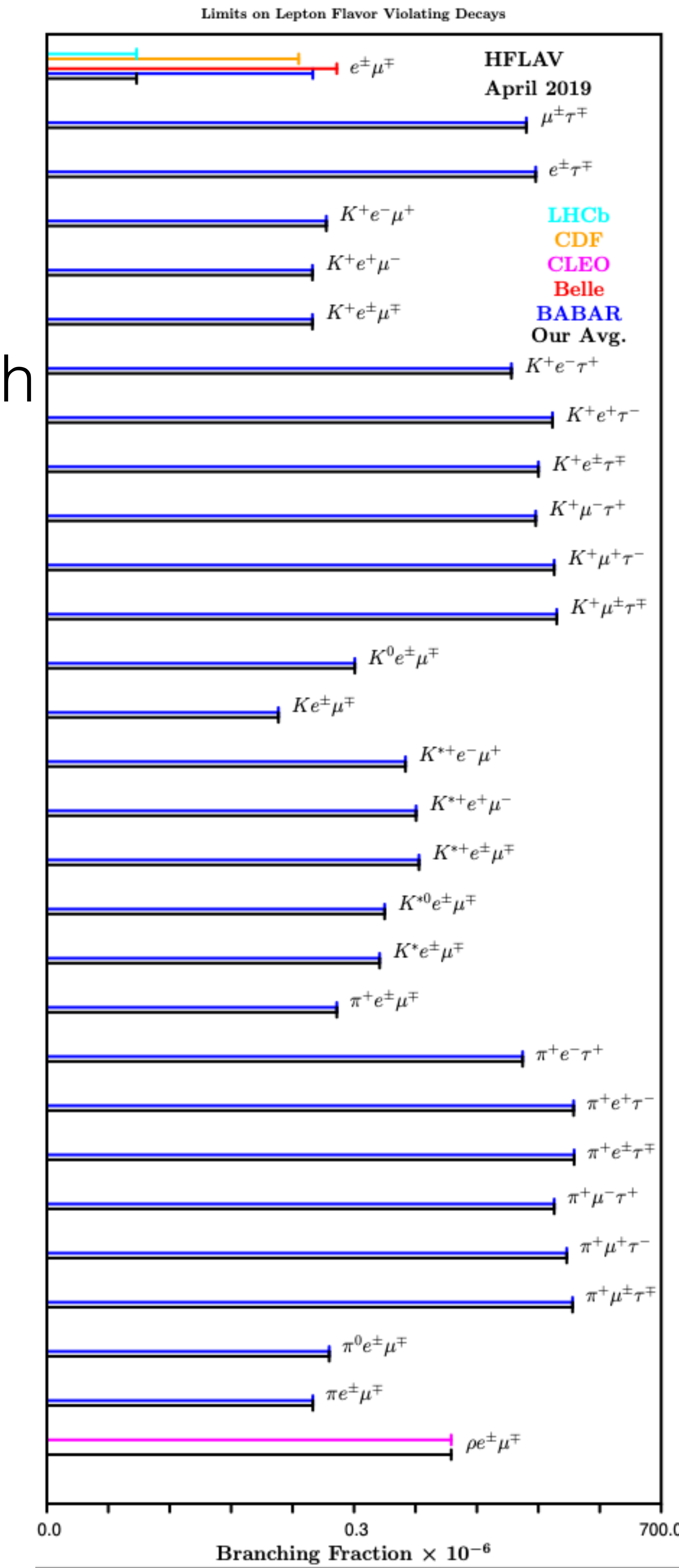
$$\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 6.3 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3 \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$$

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, but also results from ATLAS and CMS (ATLAS, CMS, LHCb flavour anomaly workshop on 20 October) while waiting for the high-precision results from the LHCb upgrade and Belle II

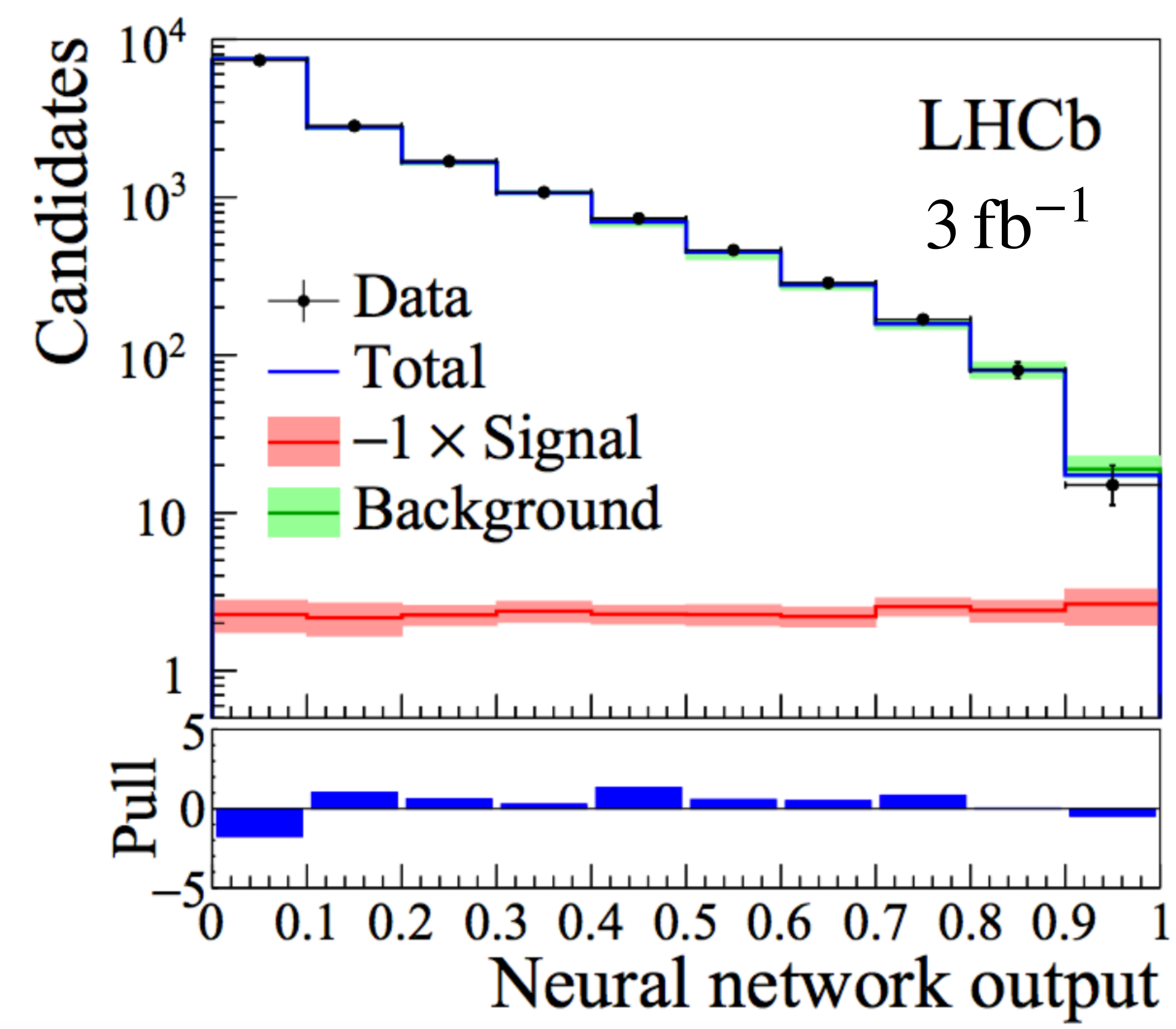
$B_{s,d} \to \tau^+\tau^-$

- In the SM, larger BF due to larger τ mass (m_τ^2/M_B^2)

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

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
- Exploit intermediate $\rho(770)^0$ resonance to define signal/control regions of $m_{\pi^-\pi^+}$, then fit MVA



- 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