Searches for New Physics in rare B decays

IoP - HEPP & AP 2022

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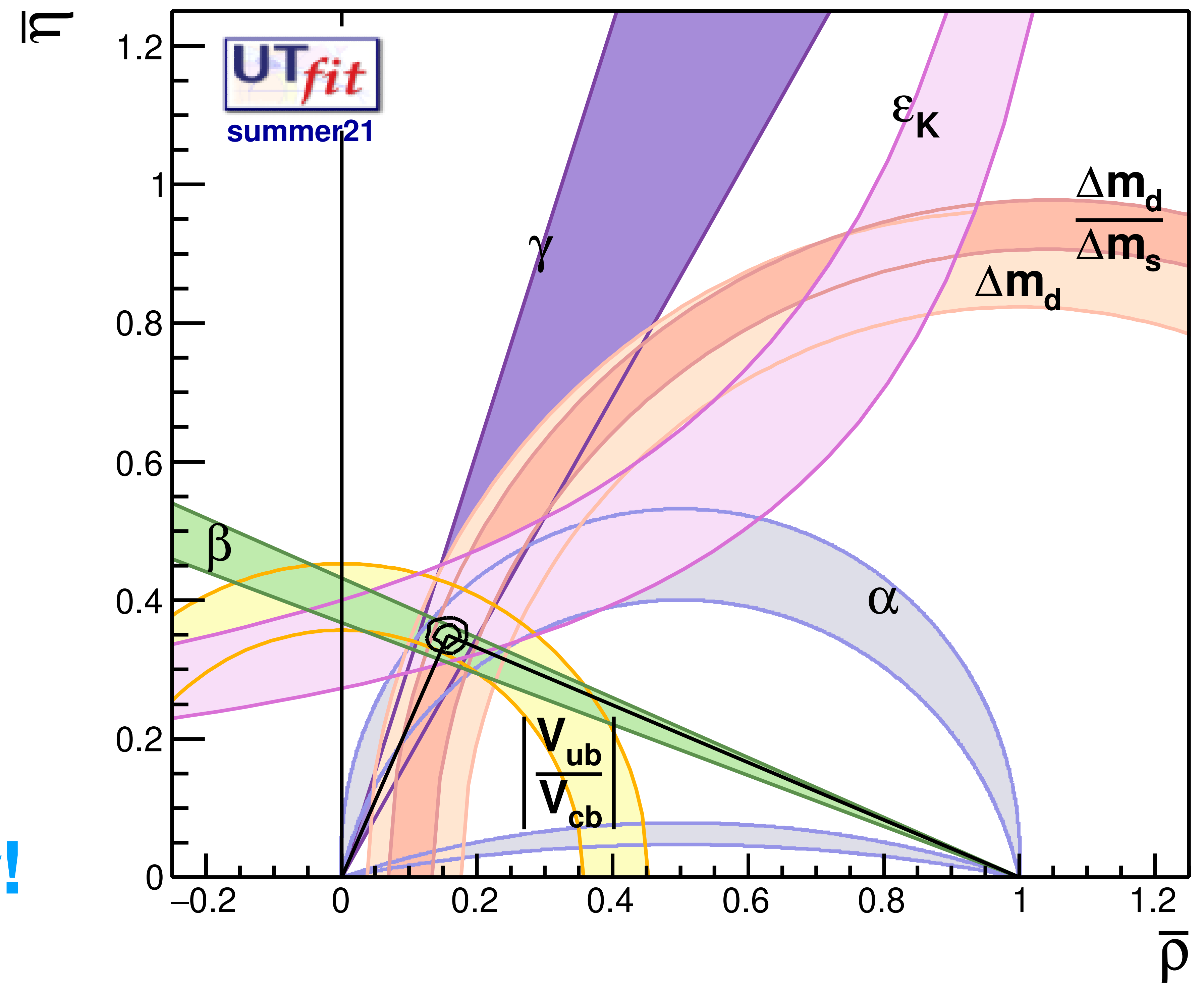
with results from LHCb, ATLAS, CMS, Belle and Belle II

New Physics searches with Flavour

- Flavour: powerful tool to search for New Physics (NP) indirectly
  - Look for inconsistencies with the Standard Model
- Sensitive to large energy scales,
  - Increase precision in flavour ⇒ stronger bound on NP scale
  - Even beyond the reach of direct searches

    Could be the first place we see hints of something new!

M. Bona (EPS-HEP 2021)



Rare B decays

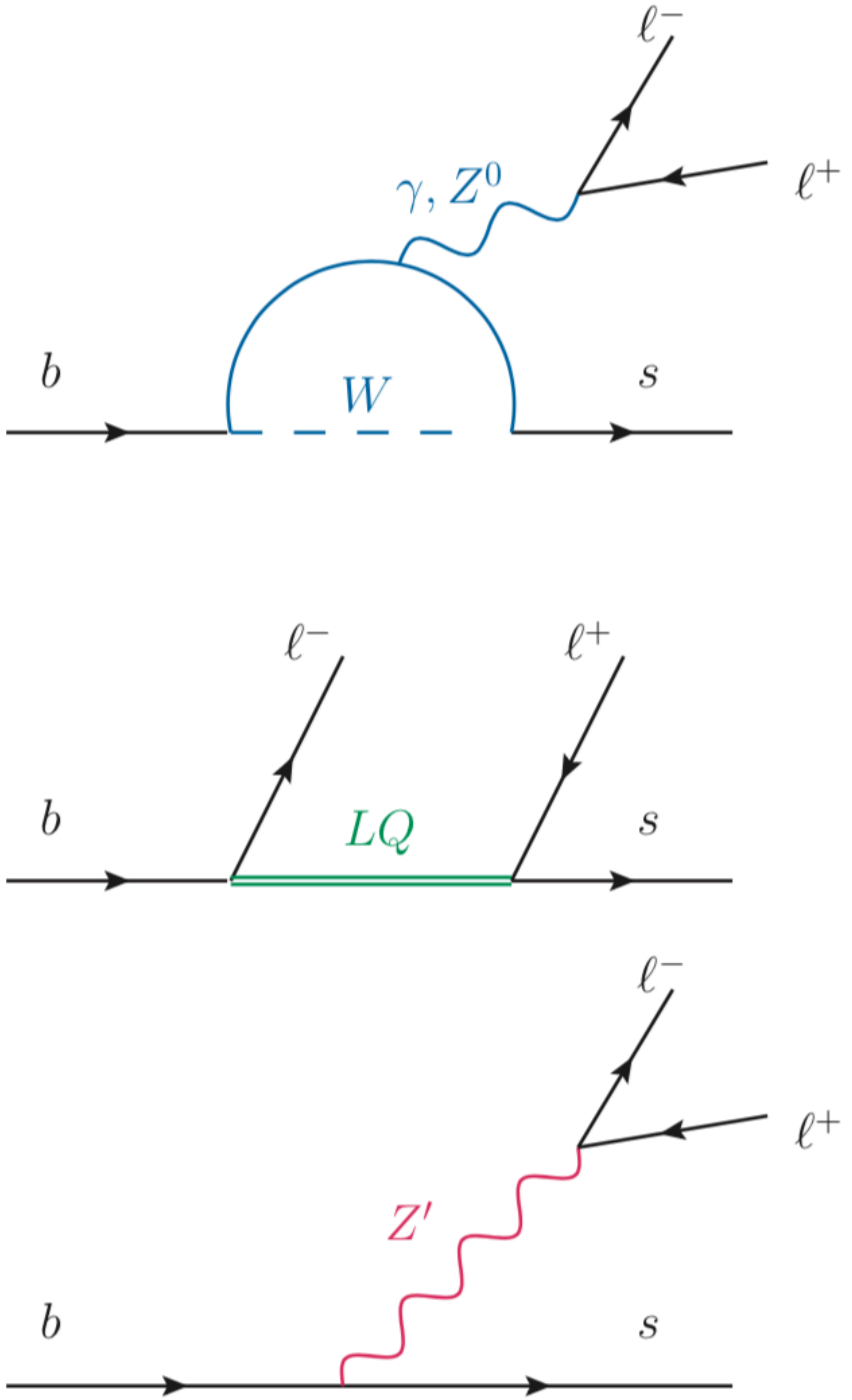
Processes that are suppressed or even forbidden in the SM

- Effects of new physics can be relatively large
- Access high mass scales, due to virtual contributions

FCNC transitions, such as $b \to s(d)\ell\ell$ decays, are excellent candidates for indirect NP searches

Rare B decays offer rich phenomenology:

- Branching ratios, angular observables, LFU ratios…

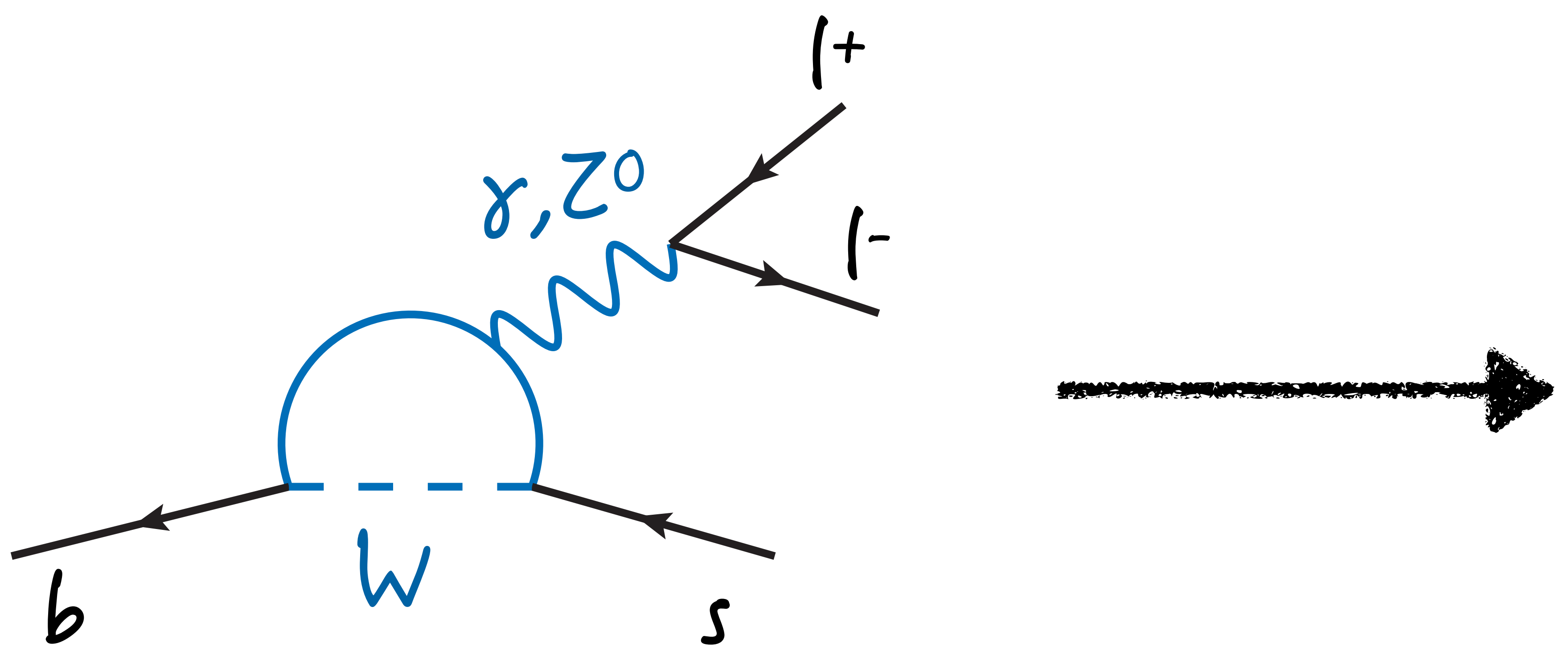


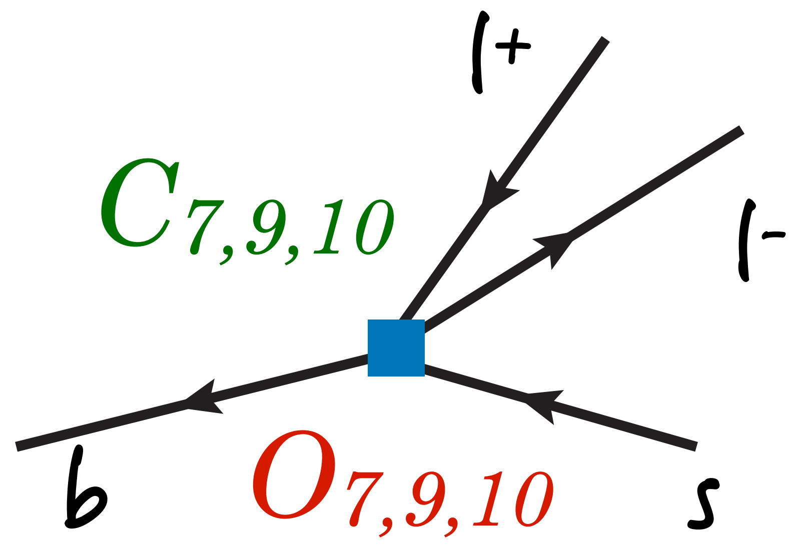
Theoretical framework - Effective theory

Can describe these interactions in terms of an effective Hamiltonian that describes the full theory at lower energies (μ) $\mathcal{H}_{\text{eff}} \sim \sum_i C_i(\mu)\mathcal{O}_i(\mu)$

$C_i(\mu)$ → Wilson Coefficients (perturbative, short-distance physics, sensitive to $E > \mu$)

O_i → Local operators (non-perturbative, long-distance physics, sensitive to $E < \mu$)

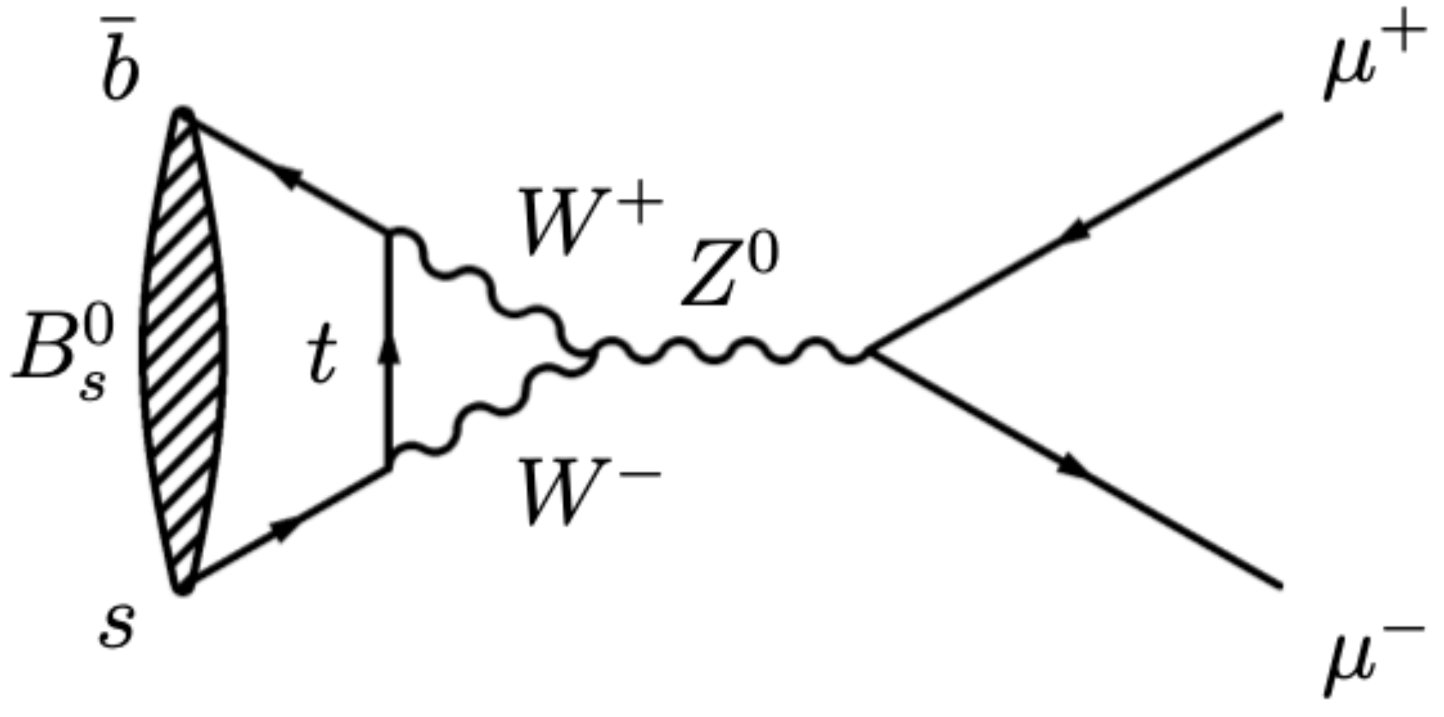


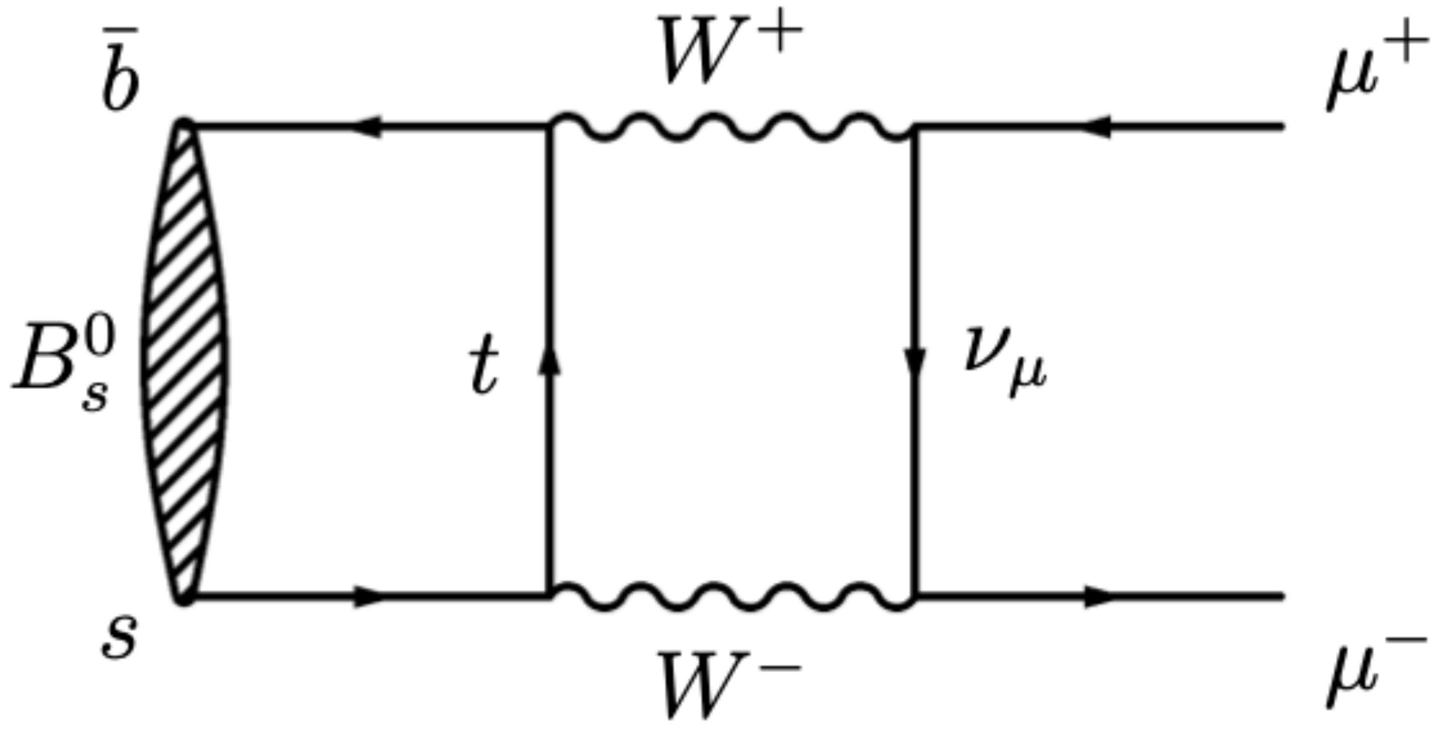


O_7 : photon
O_9 : vector
O_{10} : axial-vector

NP will modify the measured value of the Wilson coefficients present in the SM or introduce new operators

Fully leptonic decays: $B^0_{(S)} \rightarrow \mu^+\mu^-$





- Flavour Changing Neutral Current and helicity suppressed

[Beneke et al, JHEP 10 (2019) 232]

- Fully leptonic final state: Very precise SM prediction
  - Sensitive to new (pseudo-)scalar contributions

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

$B^0_{(S)} \to \mu^+\mu^-$ @ LHC

ATLAS EXPERIMENT

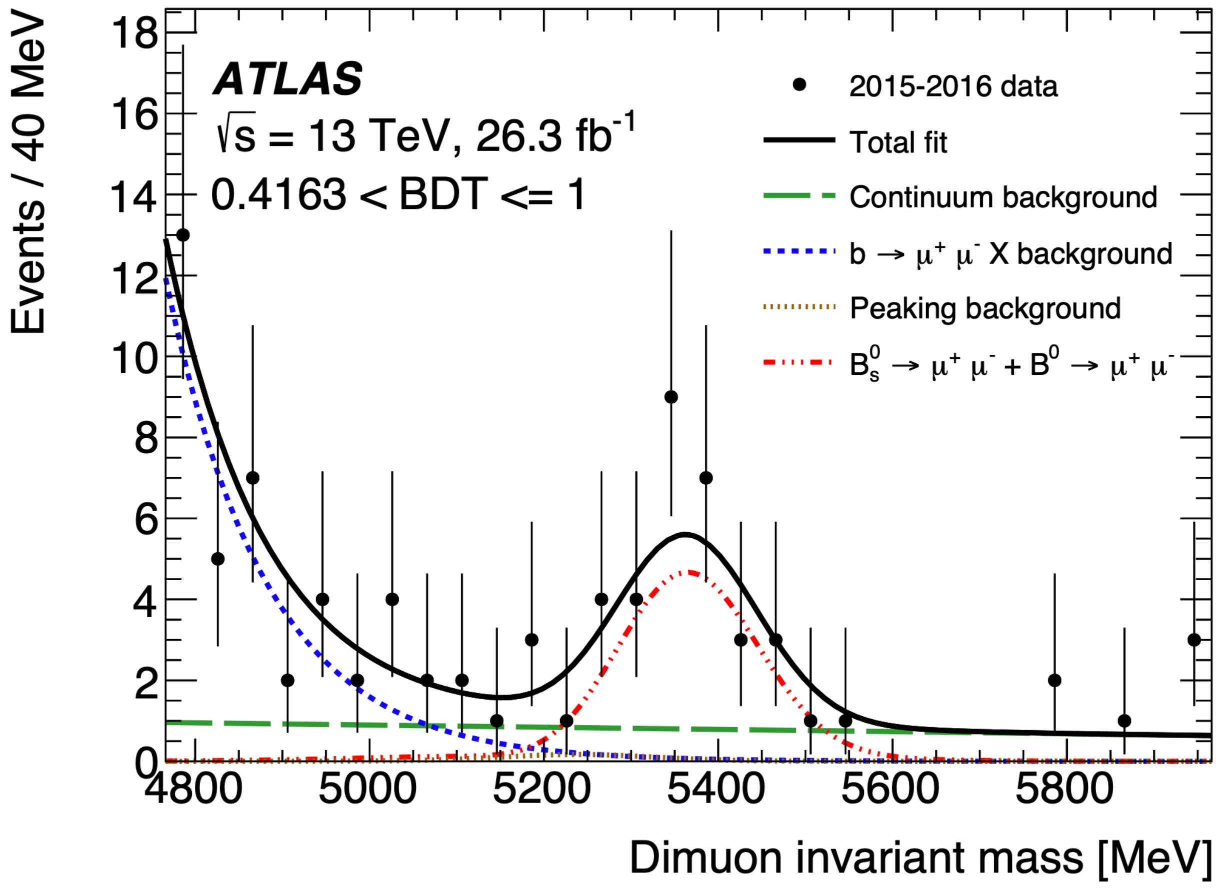
[JHEP 04 (2019) 098]

2015 & 2016 dataset (26.5/fb) +
Run1 result (25/fb)

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

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

B_s significance: 4.6σ



CMS

[JHEP 04 (2020) 188]

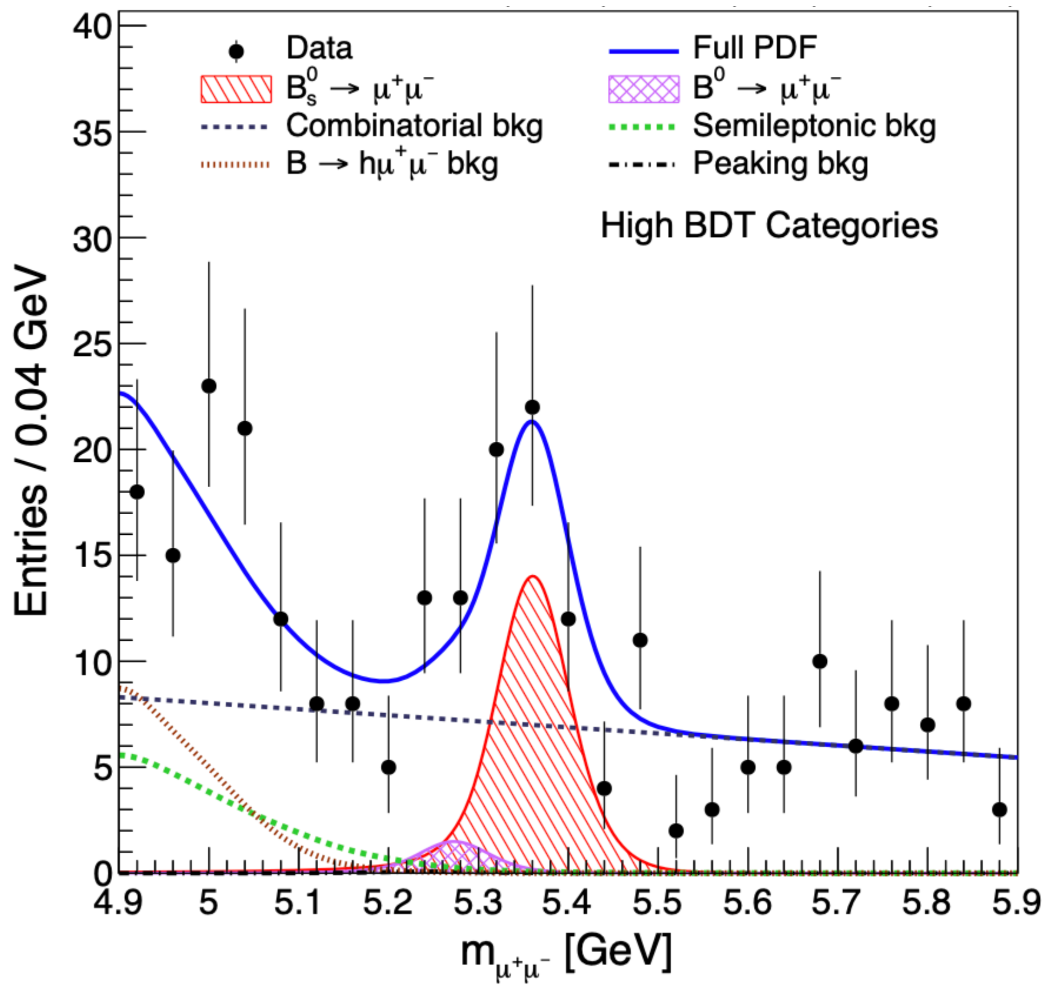
Run1 (25/fb) + 2016 (36/fb)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9\ \pm 0.7)) \times 10^{-9}$$

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

$$\tau_{\mathrm{eff}}(B_s^0 \to \mu^+\mu^-) = 1.70\ ^{+0.61}_{-0.44}\ \mathrm{ps}$$

B_s significance: 5.6σ



LHCb

[PRL 128, (2022) 041801]

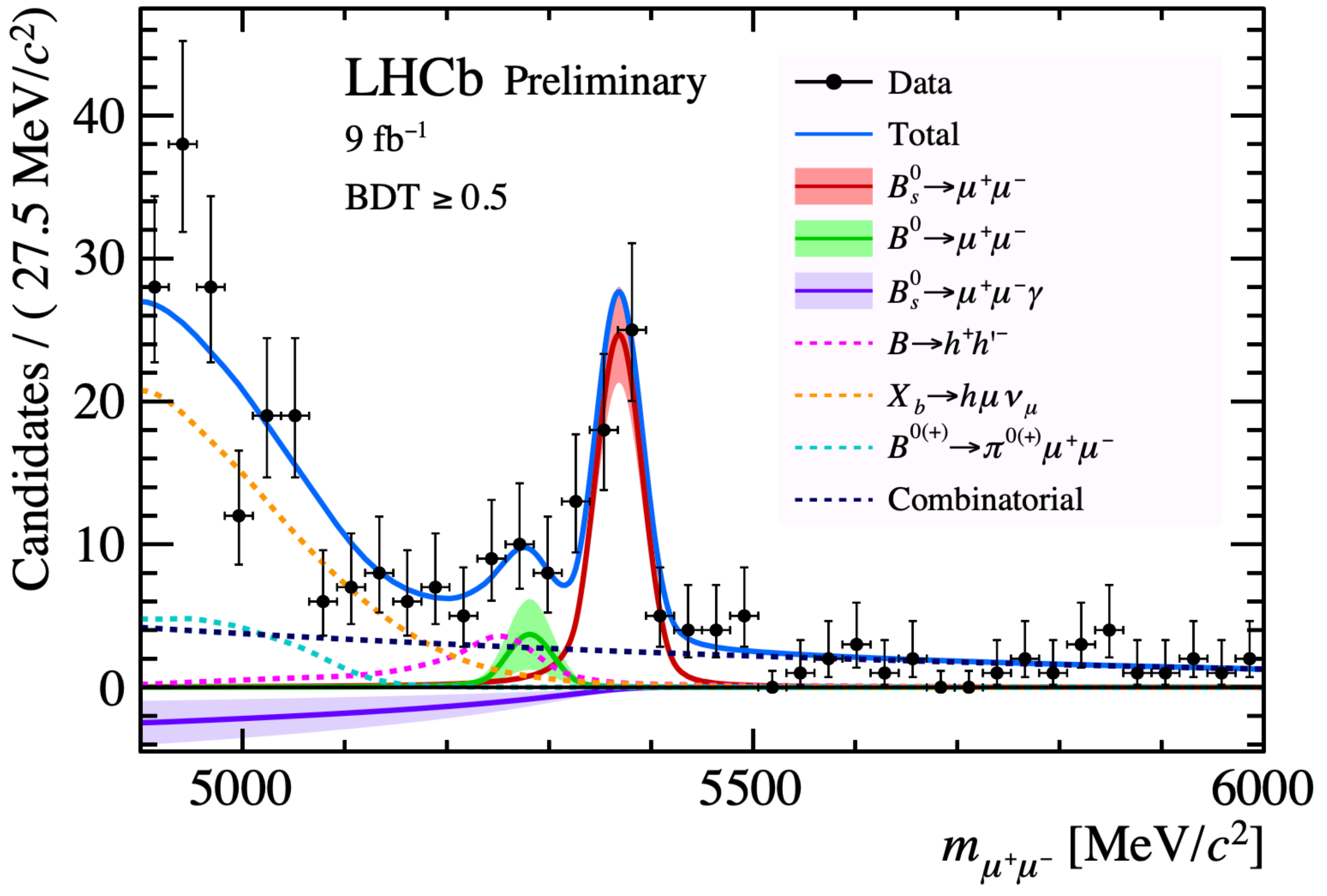
Full Run1 + Run2 (9/fb)

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

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

$$\tau_{\mathrm{eff}}(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\ \mathrm{ps}$$

B_s significance> 10σ



$B^0_{(S)} \to \mu^+\mu^-$ @ LHC

ATLAS EXPERIMENT

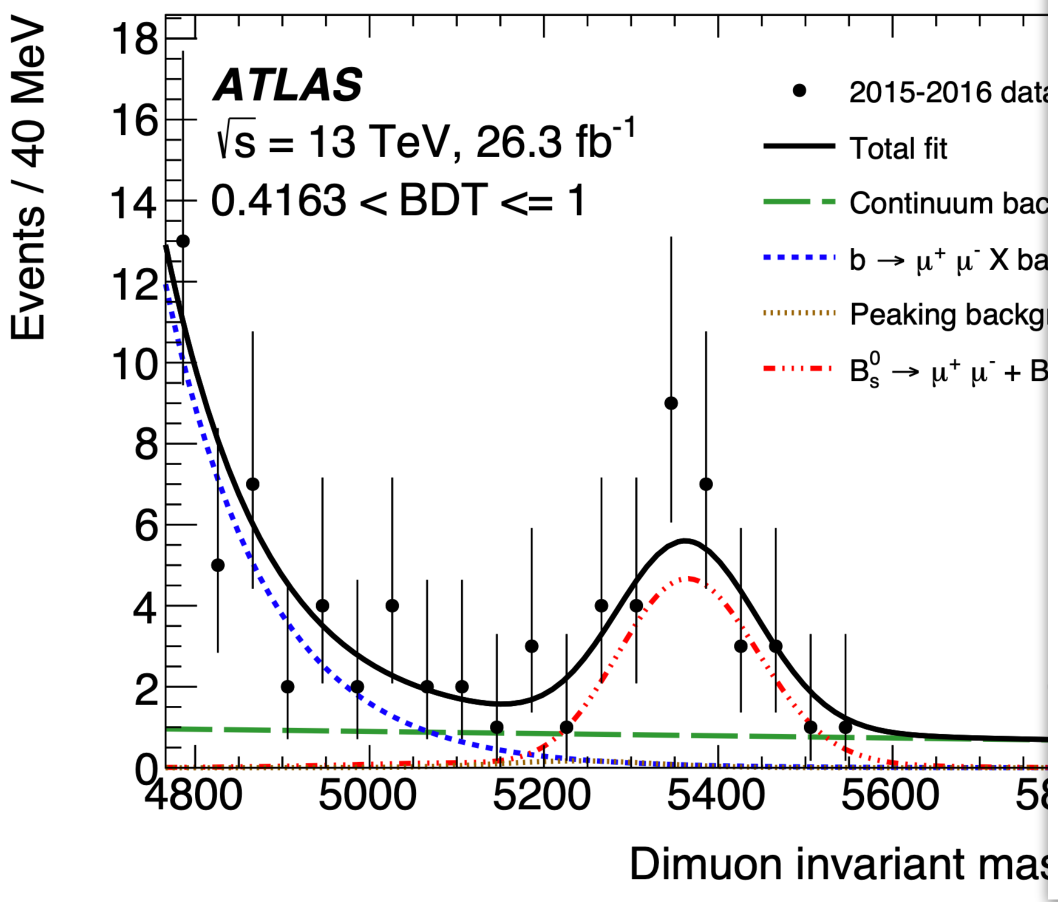
[JHEP 04 (2019) 09

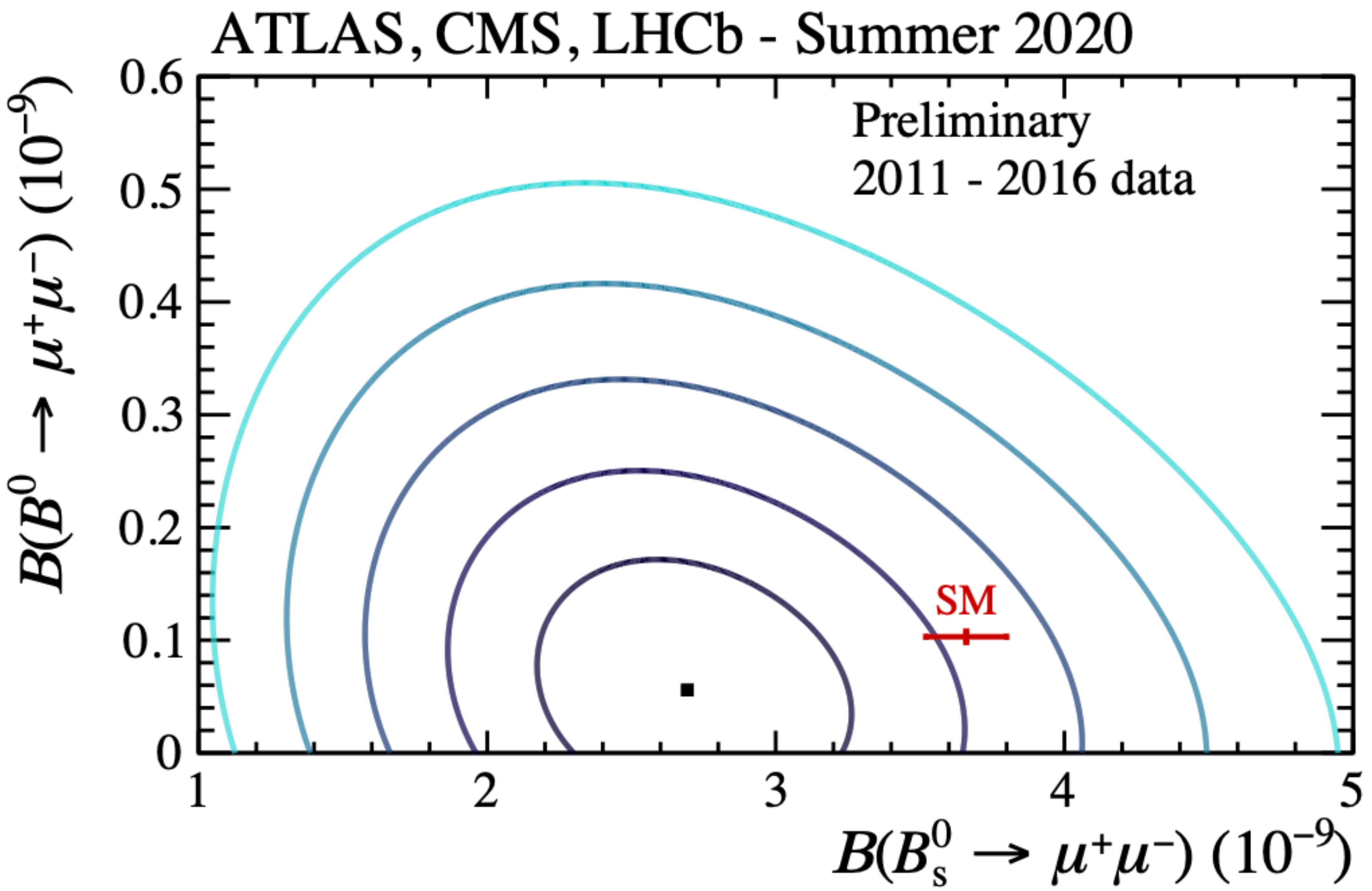
2015 & 2016 dataset (26.5
Run1 result (25/fb)

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8\ ^{+0.}_{-0.}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10$

B_s significance: 4.6





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

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

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

Compatible with the SM at 2.1σ

22) 041801]

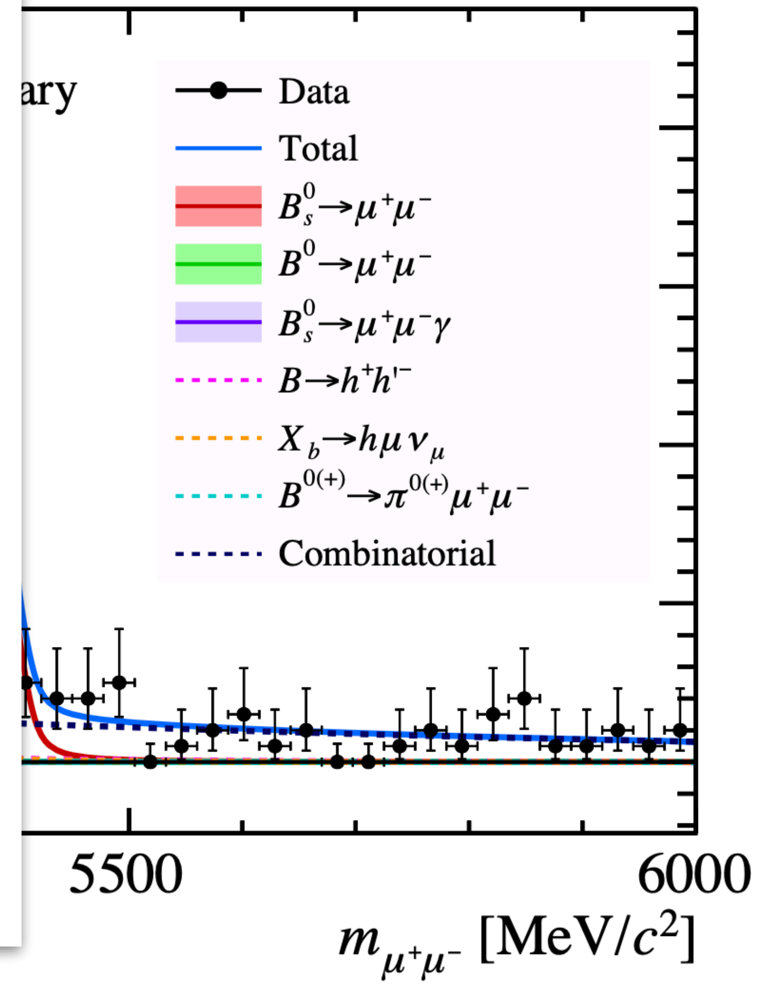
Run2 (9/fb)

$.09\ ^{+0.46}_{-0.43}\ ^{+0.15}_{-0.11}) \times 10^{-9}$

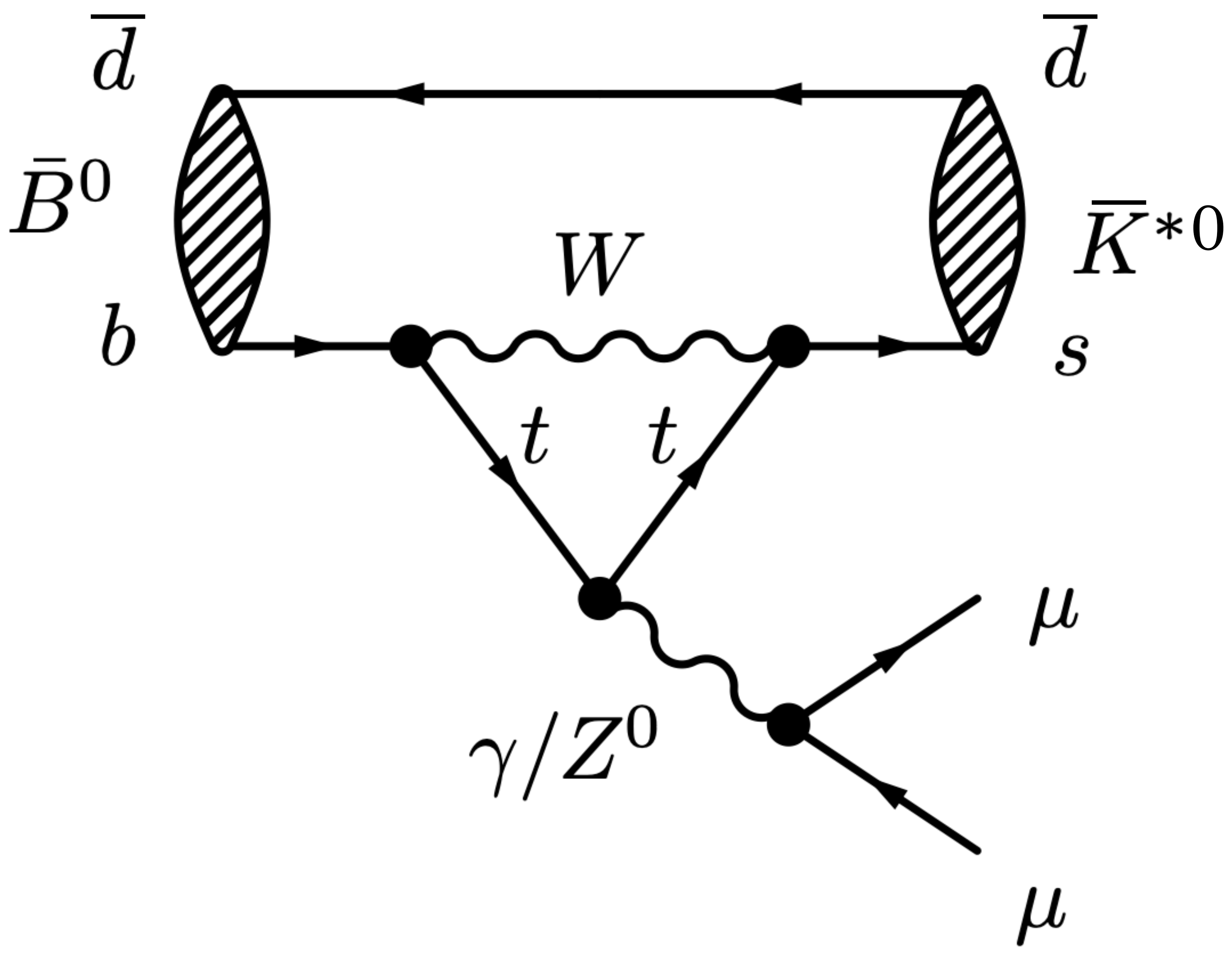
6×10^{-10} (95 % CL)

$2.07 \pm 0.29 \pm 0.03$ ps

cance> 10σ

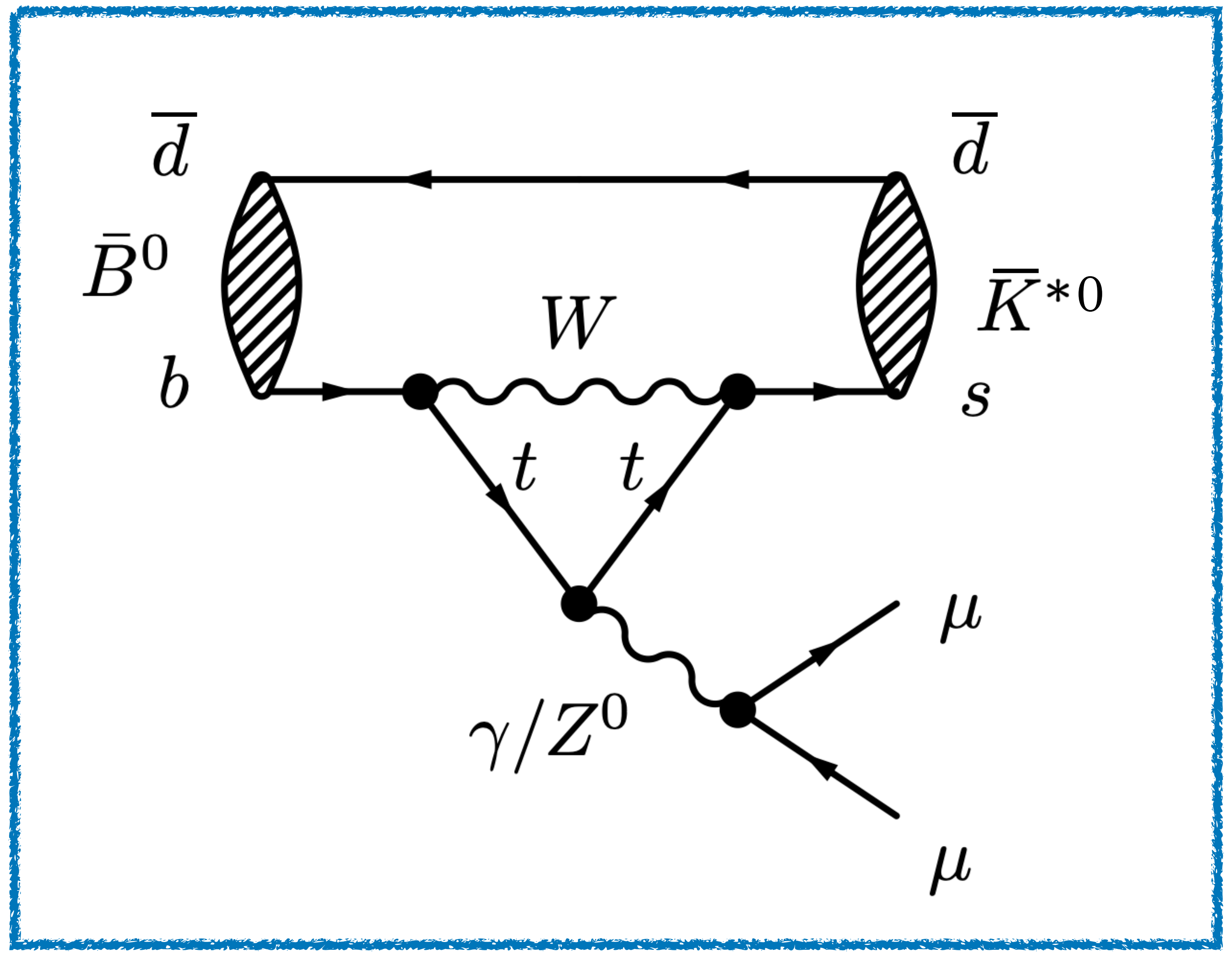


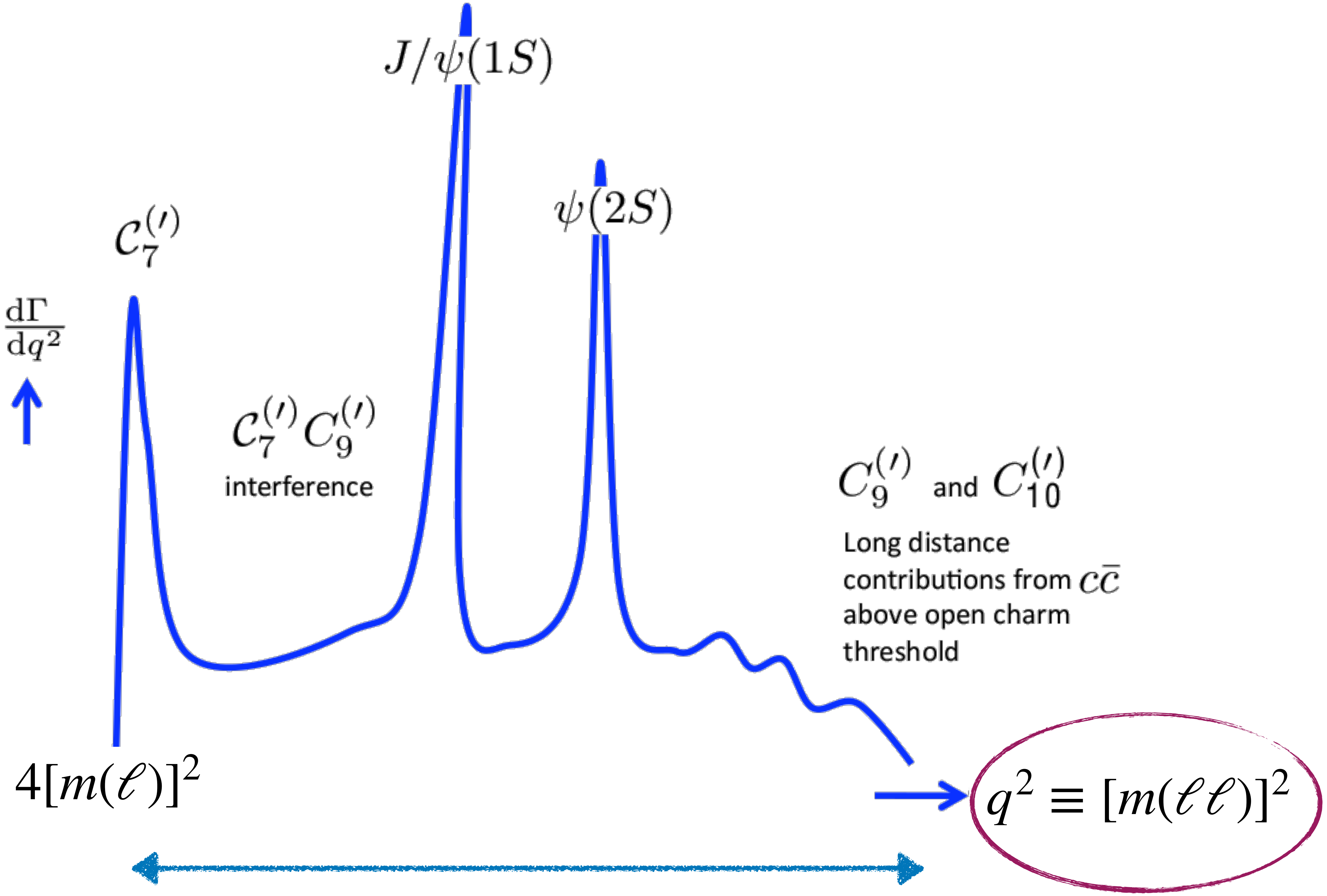
Semileptonic $b \to s\ \ell^+\ \ell^-$ decays



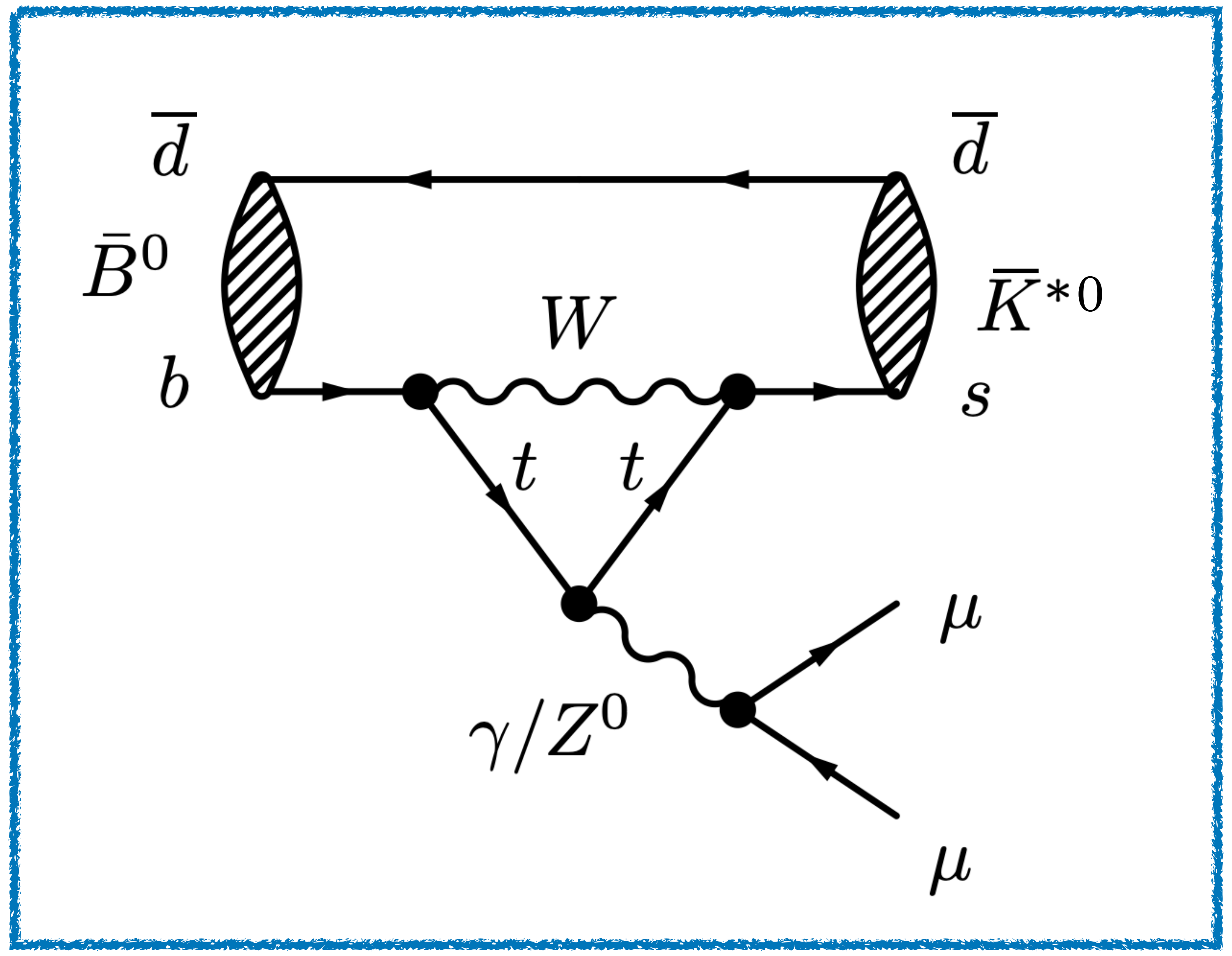
- Less suppressed (BR~10^{-6}) and rich phenomenology: BR's, angular observables, …
- Hadronic system in the final state, theoretical predictions more challenging
  - Some observables will profit from cancellation of QCD nuisances

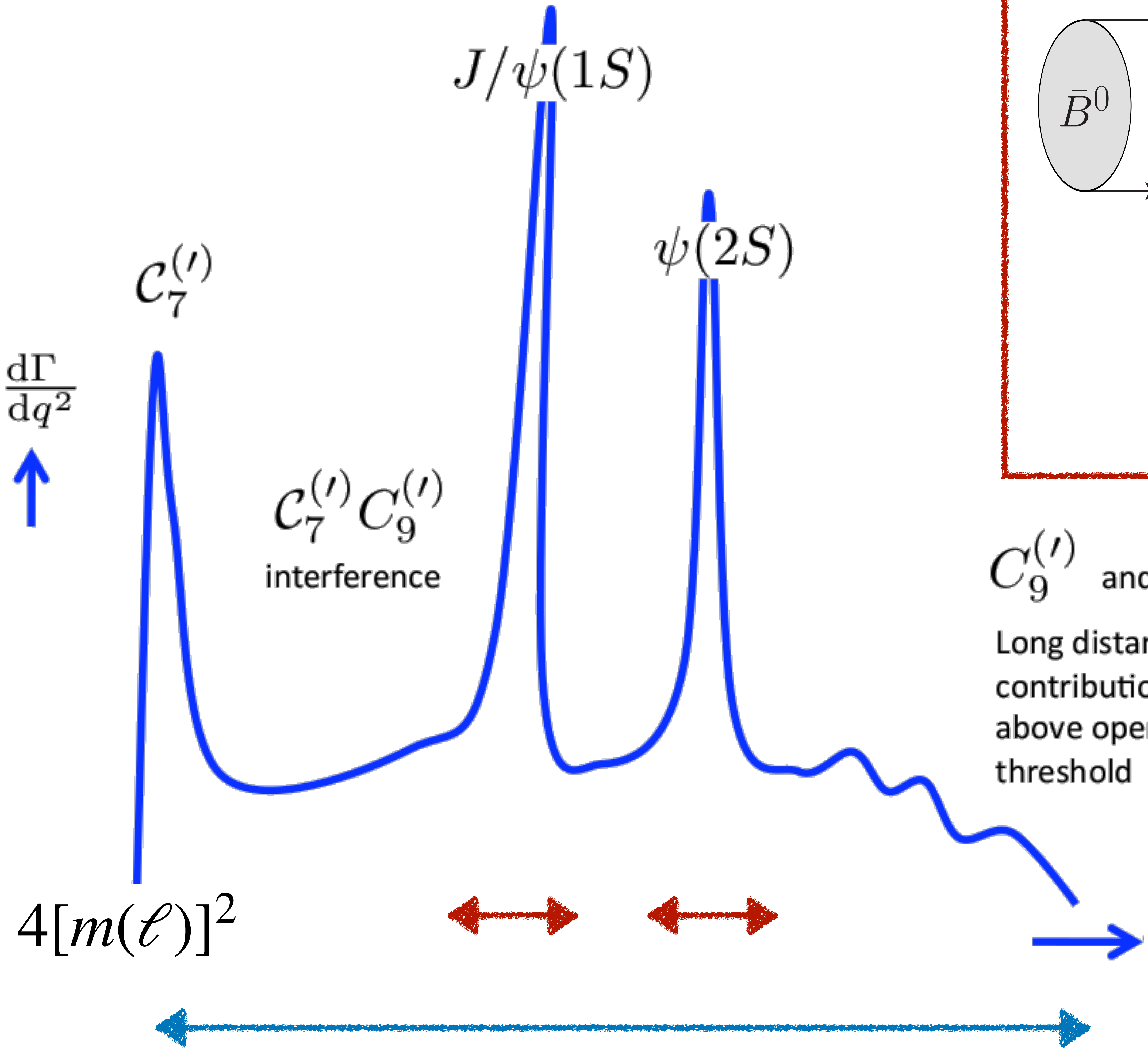
$b \to s\ \ell^+ \ell^-$ decays: The di-lepton spectrum

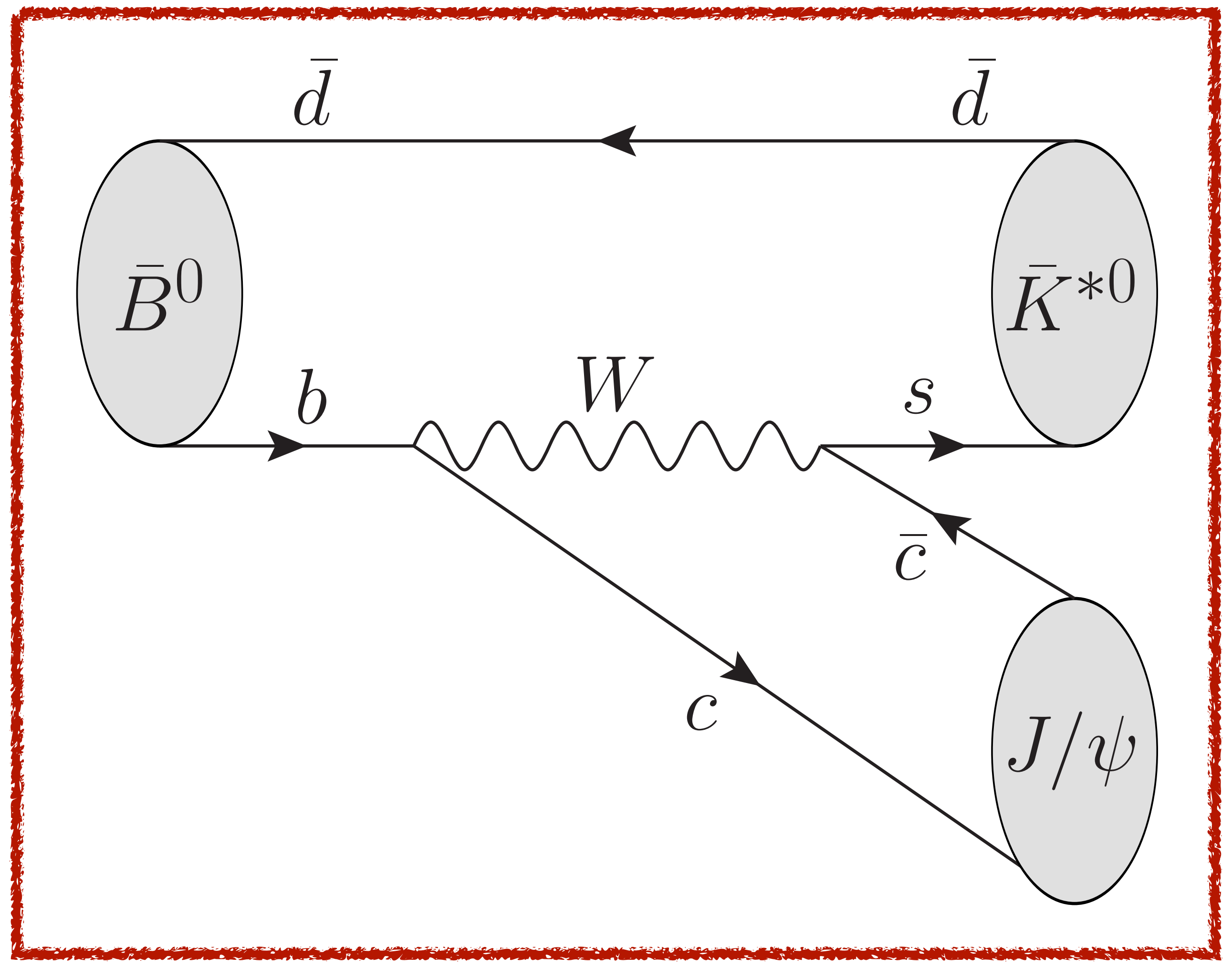




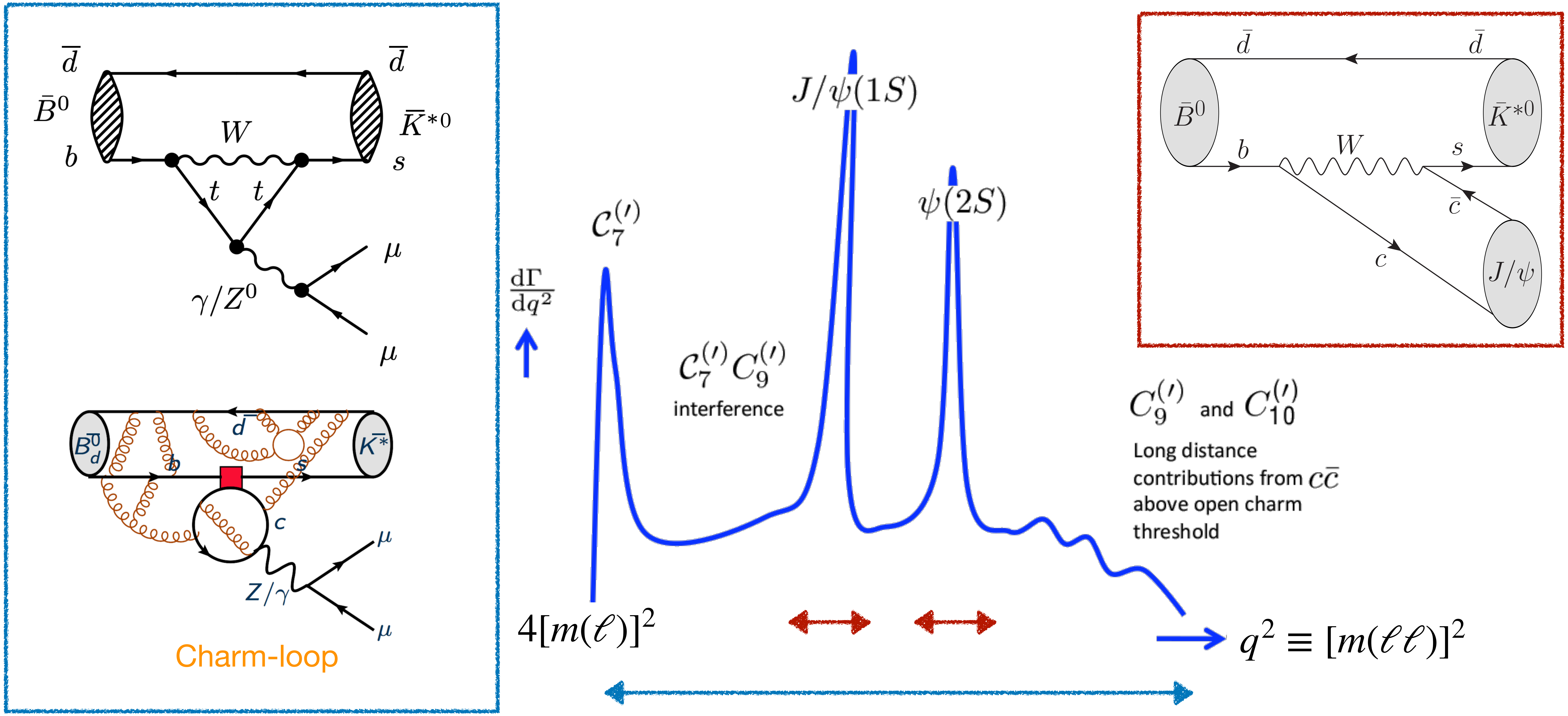
$b \to s\ \ell^+ \ell^-$ decays: The di-lepton spectrum







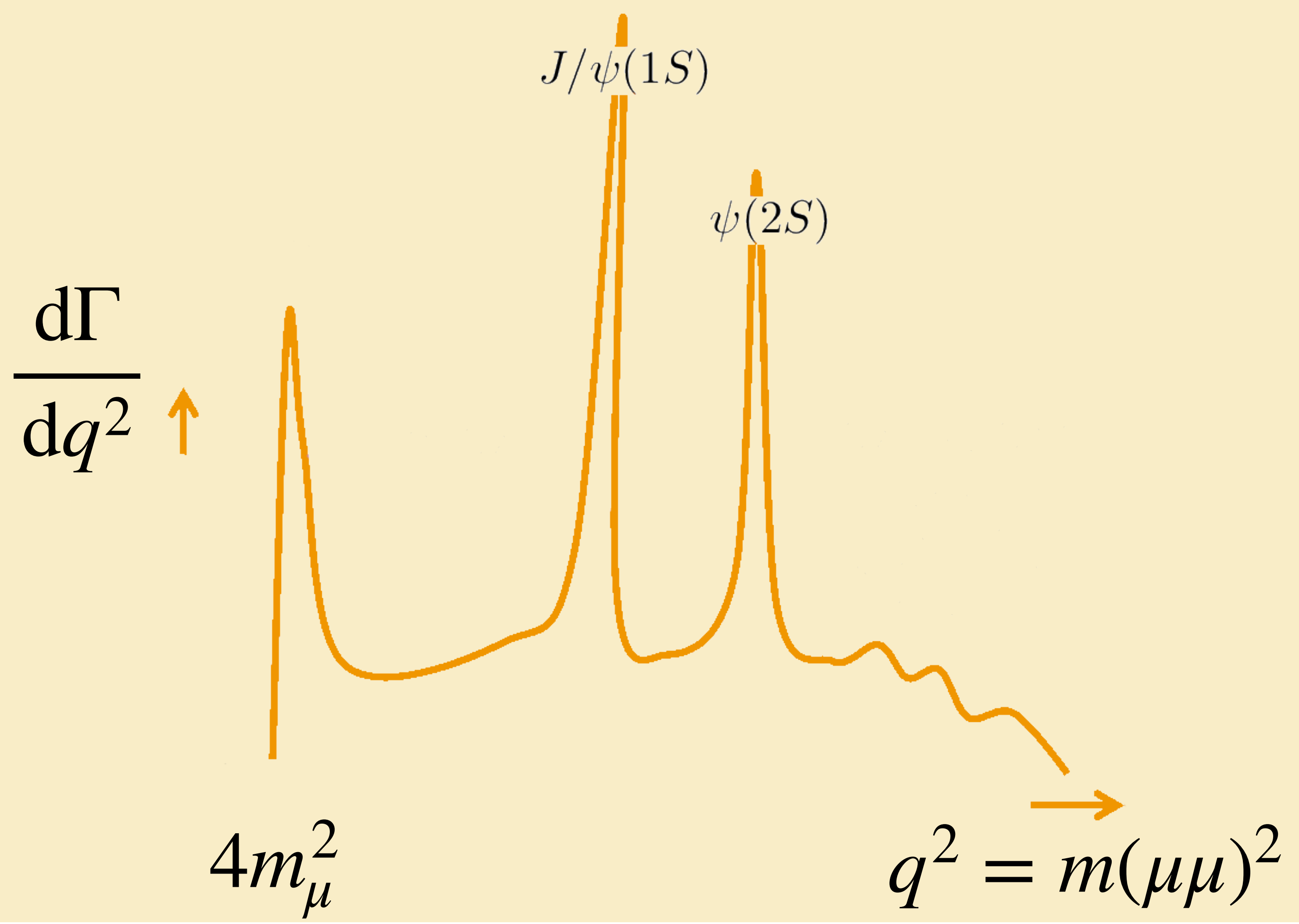
$b \to s\, \ell^+ \ell^-$ decays: The di-lepton spectrum



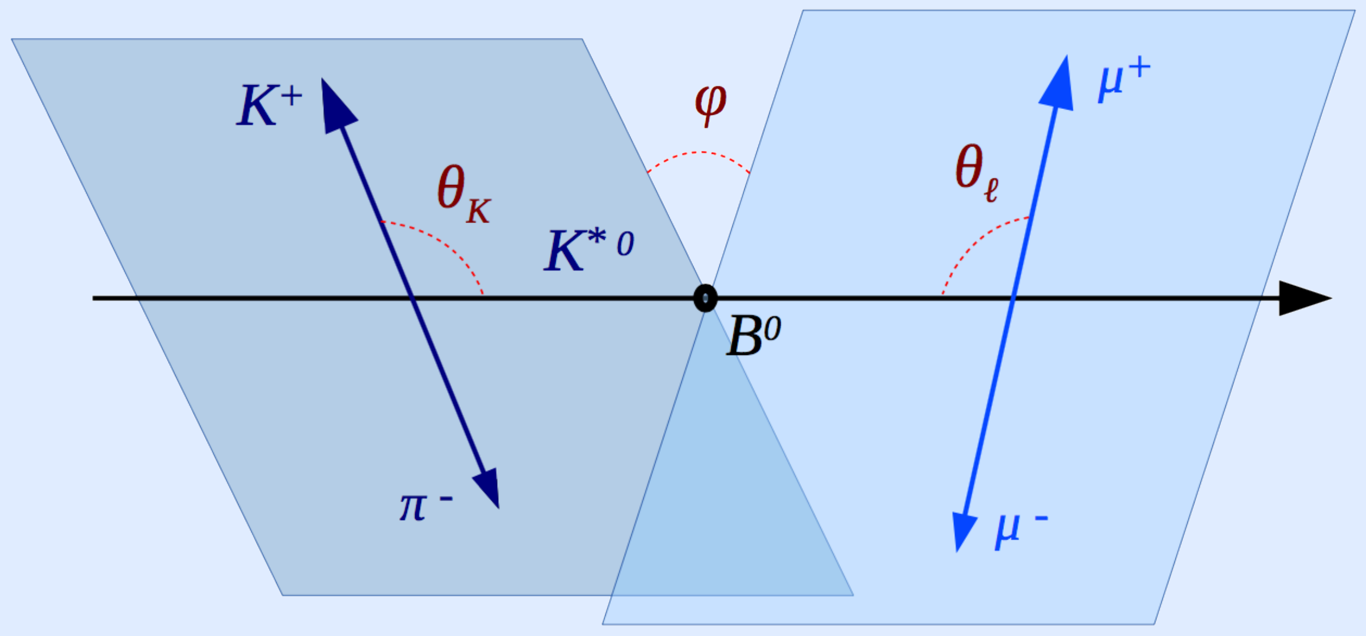
$b \rightarrow s\, \mu^+ \mu^-$ anomalies

- In recent years, tensions with the SM predictions have been observed in these processes
  - Different observables will have different sensitivity to New Physics

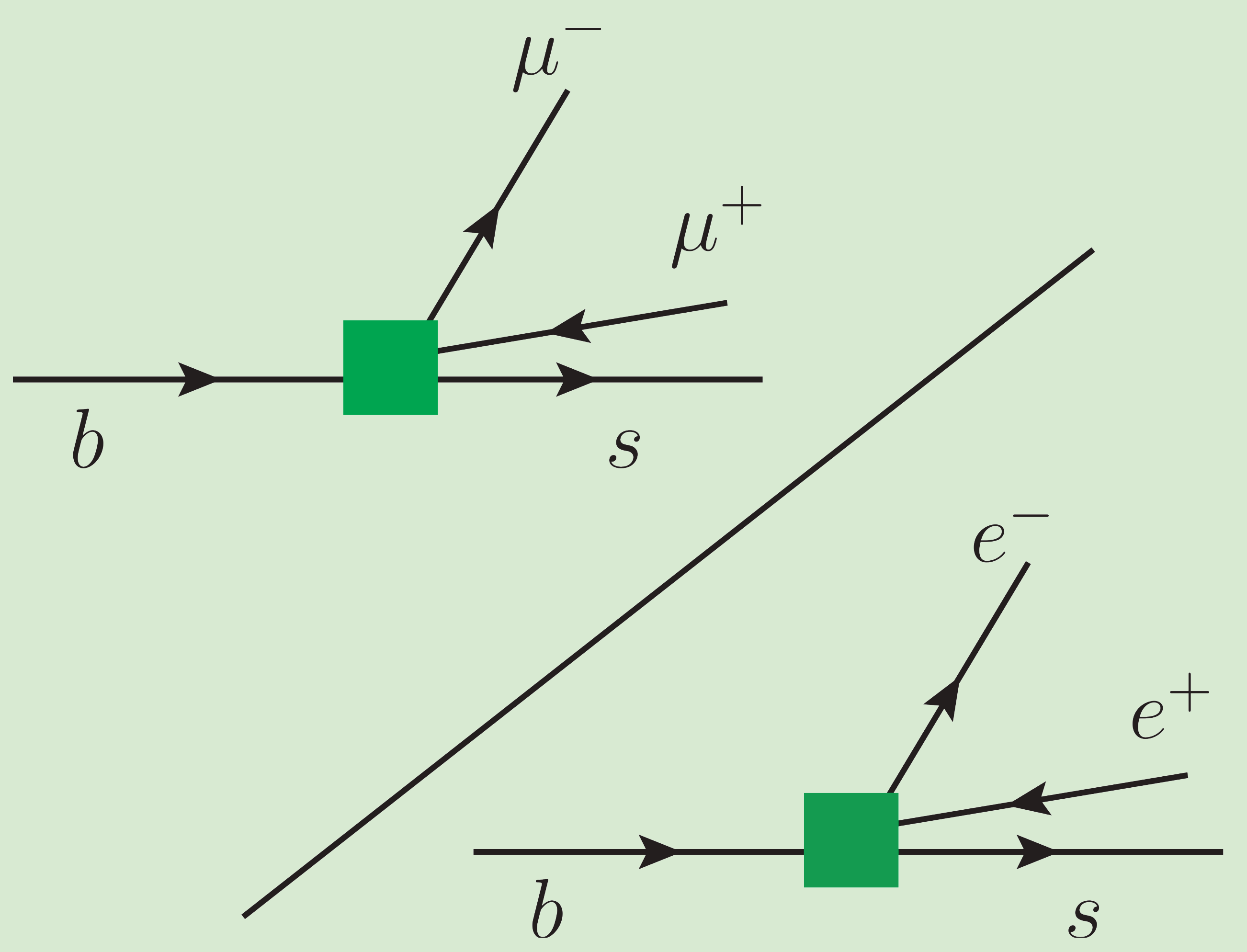
Low branching ratios



Angular observables

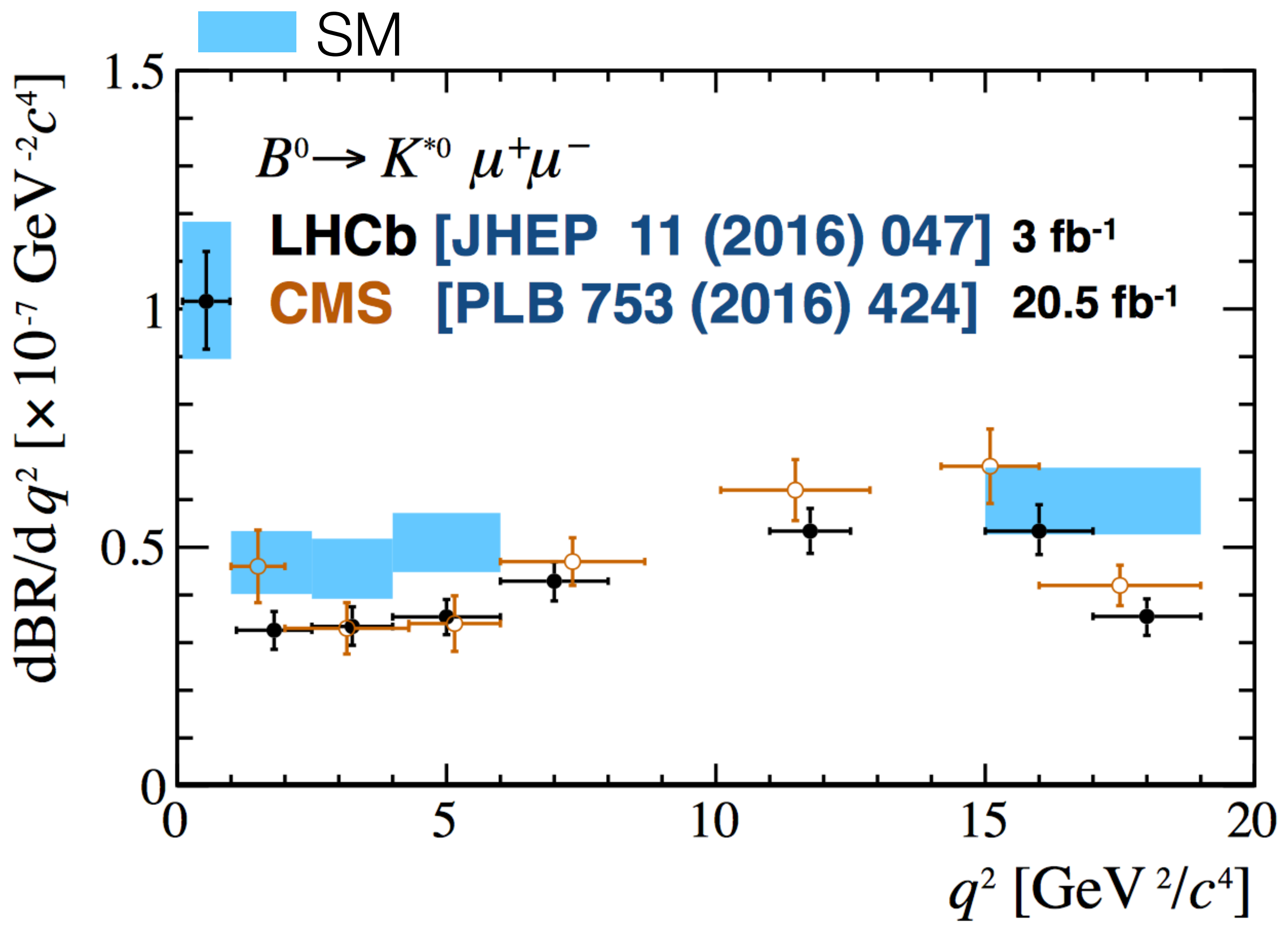


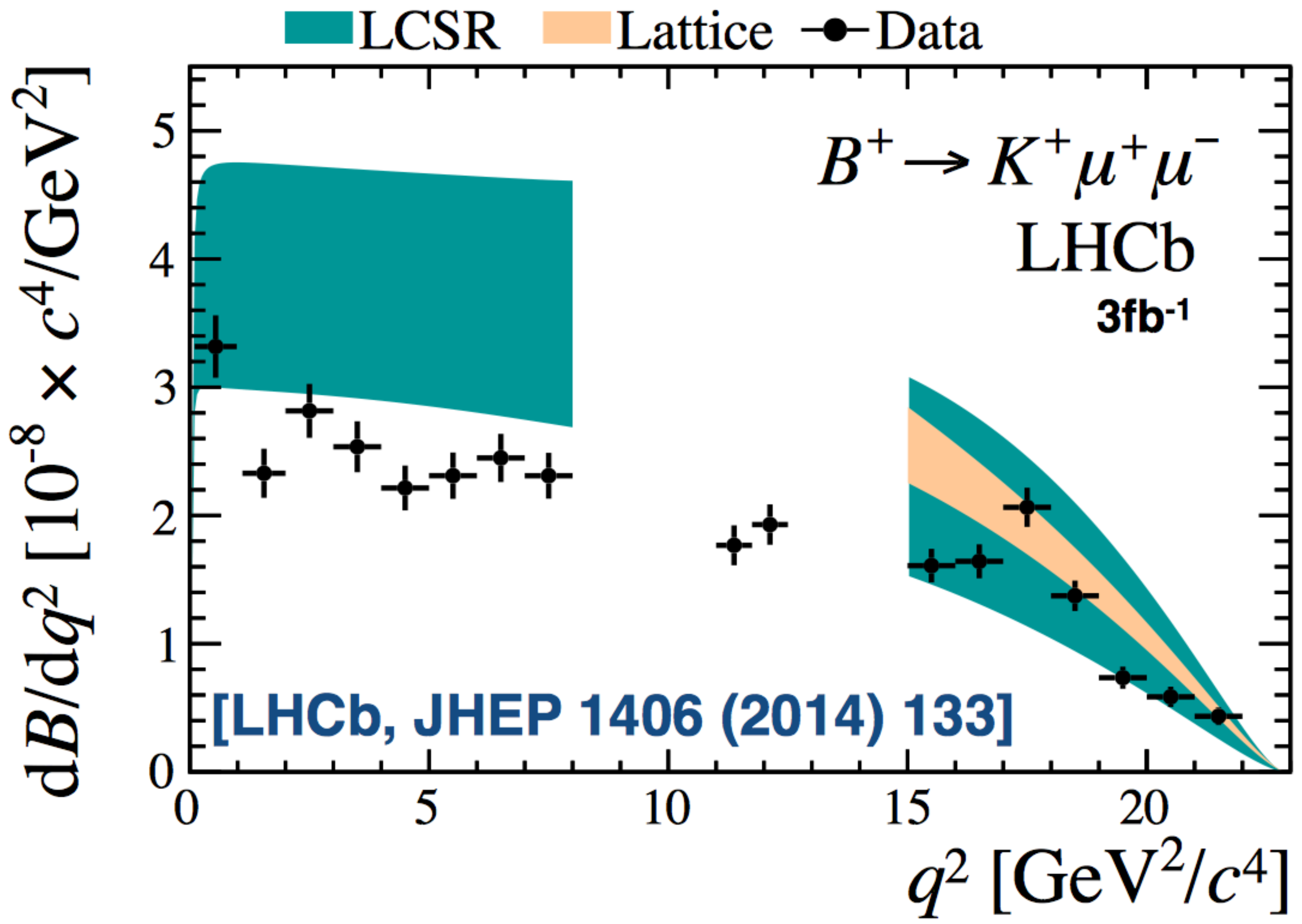
Lepton Flavour Universality



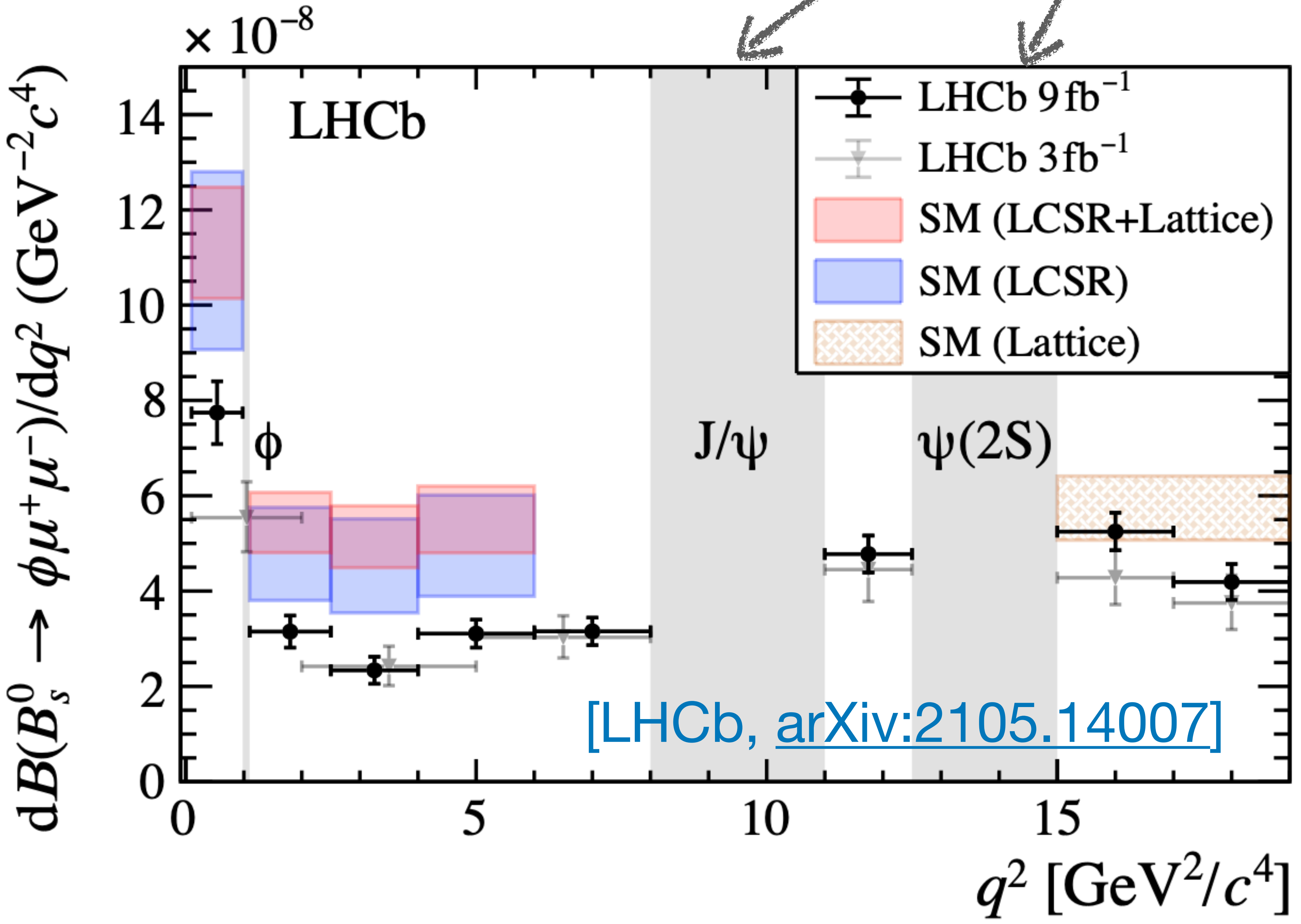
Theoretically 'cleaner'

$b \to s\, \mu^+ \mu^-$ branching ratios





Charmonium vetoes



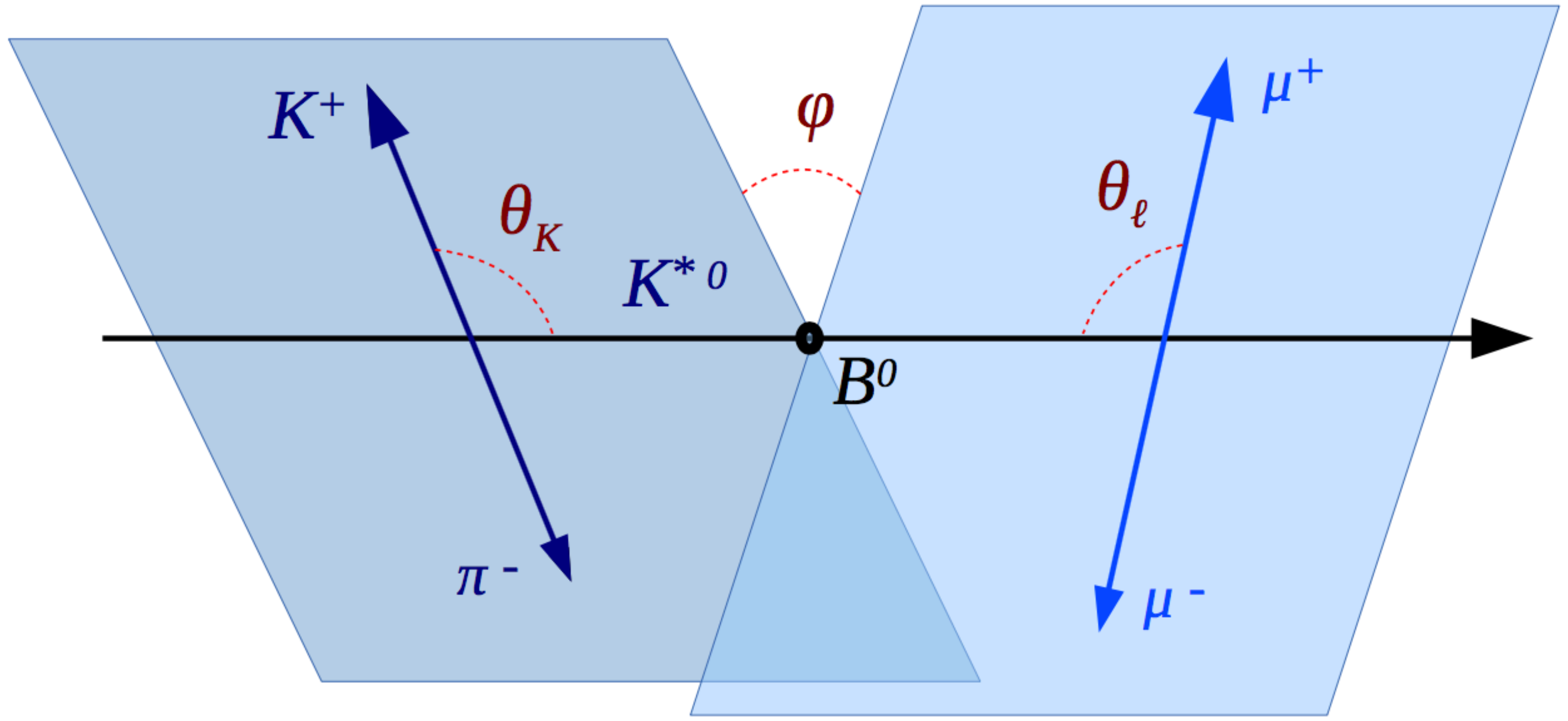
Recent update of $B_s^0 \to \phi\mu^+\mu^-$ from LHCb

- In the region $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$ compatibility with the SM at 3.6σ

$b \to s\, \mu^+\mu^-$ angular observables

Complementary constraints on NP & orthogonal experimental systematics compared to BR's

For $B \to V\mu\mu$, differential decay rate can be described by 3 angles and q^2:



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_\mathrm{P} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Give access to observables with reduced dependence on hadronic effects, e.g.:

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

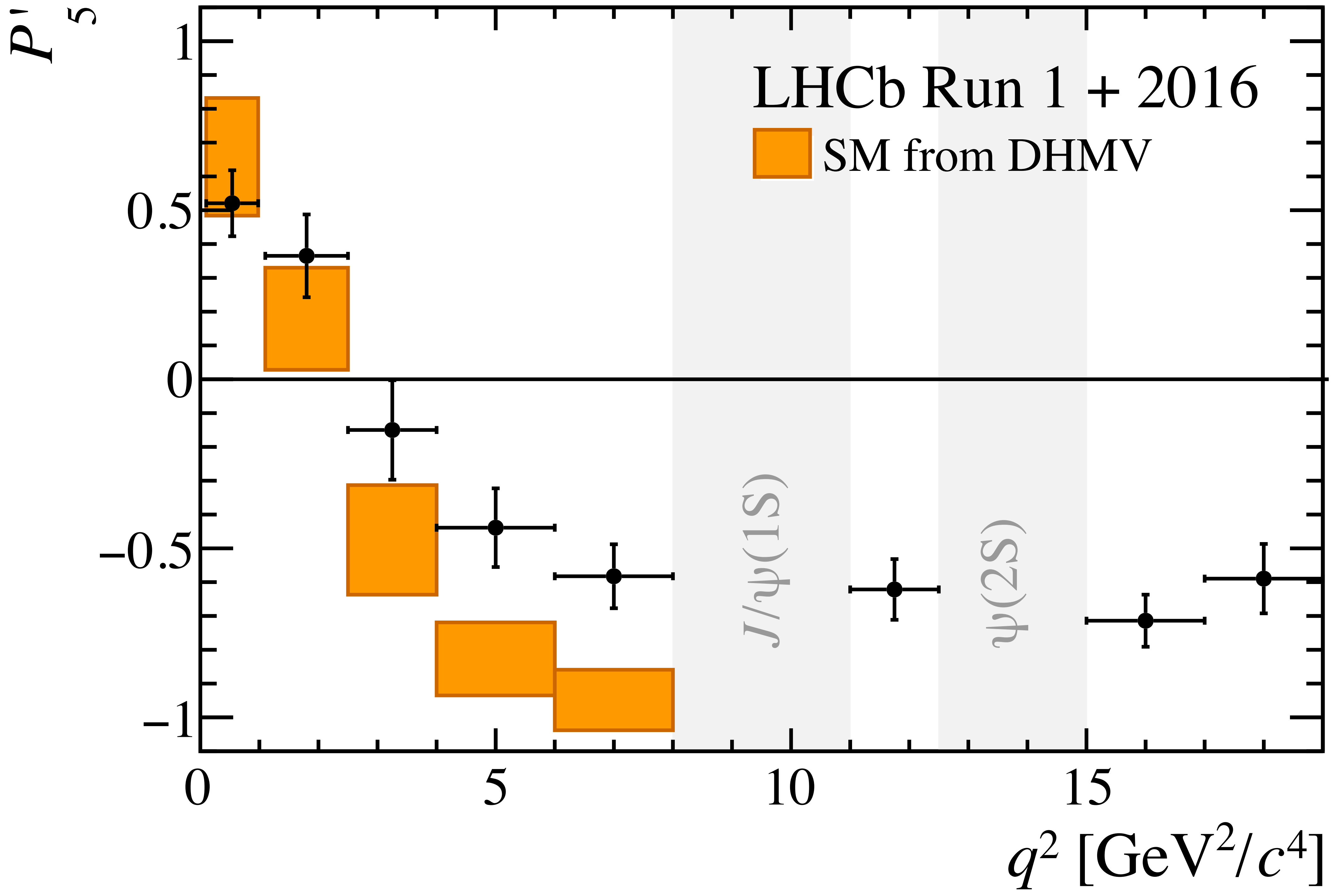
[JHEP 1204 (2012) 104]

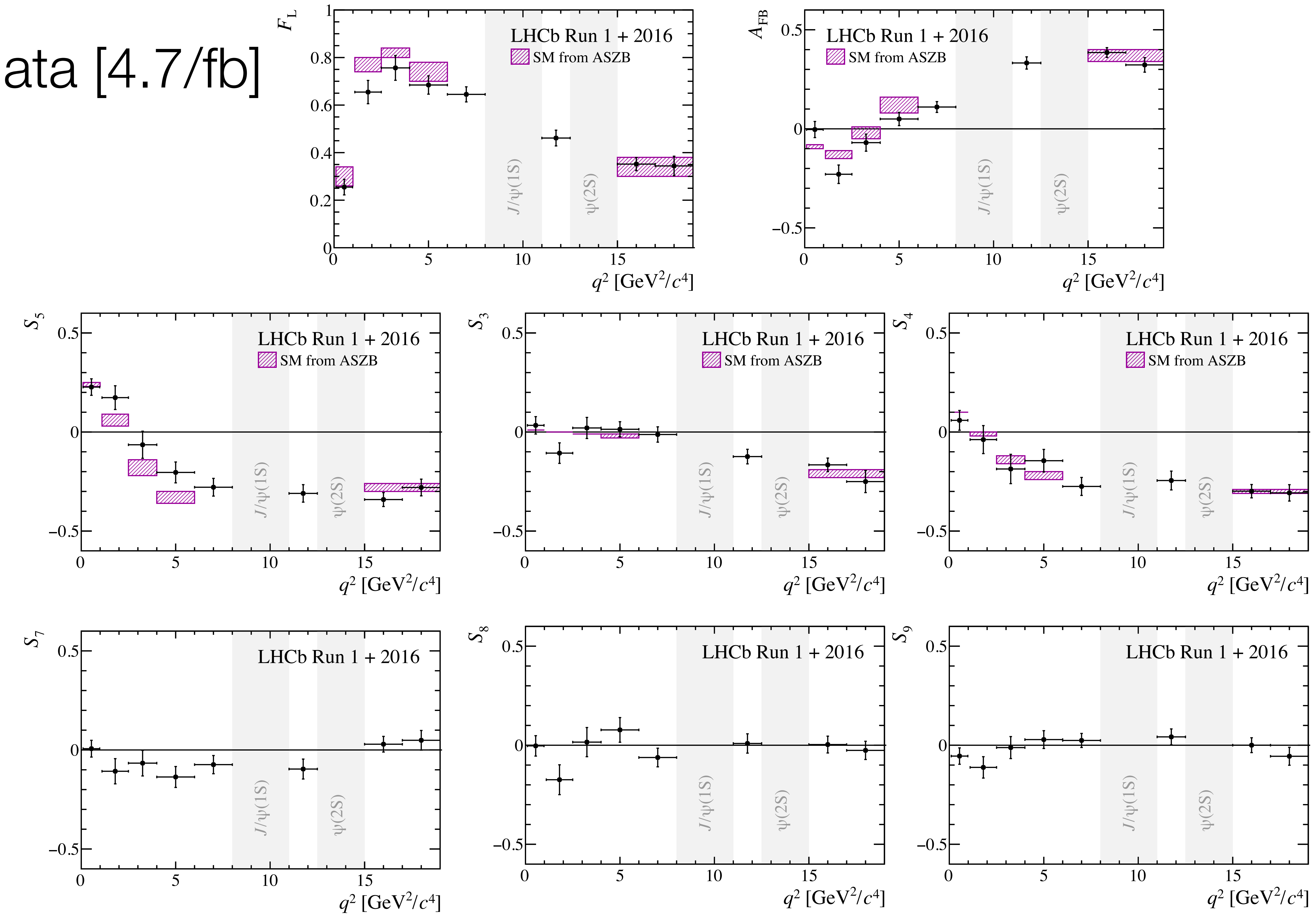
$B^0 \to K^{*0} \mu^+\mu^-$ angular analysis

[PRL 125 (2020) 011802]

Most precise result from LHCb's Run1+2016 data [4.7/fb]

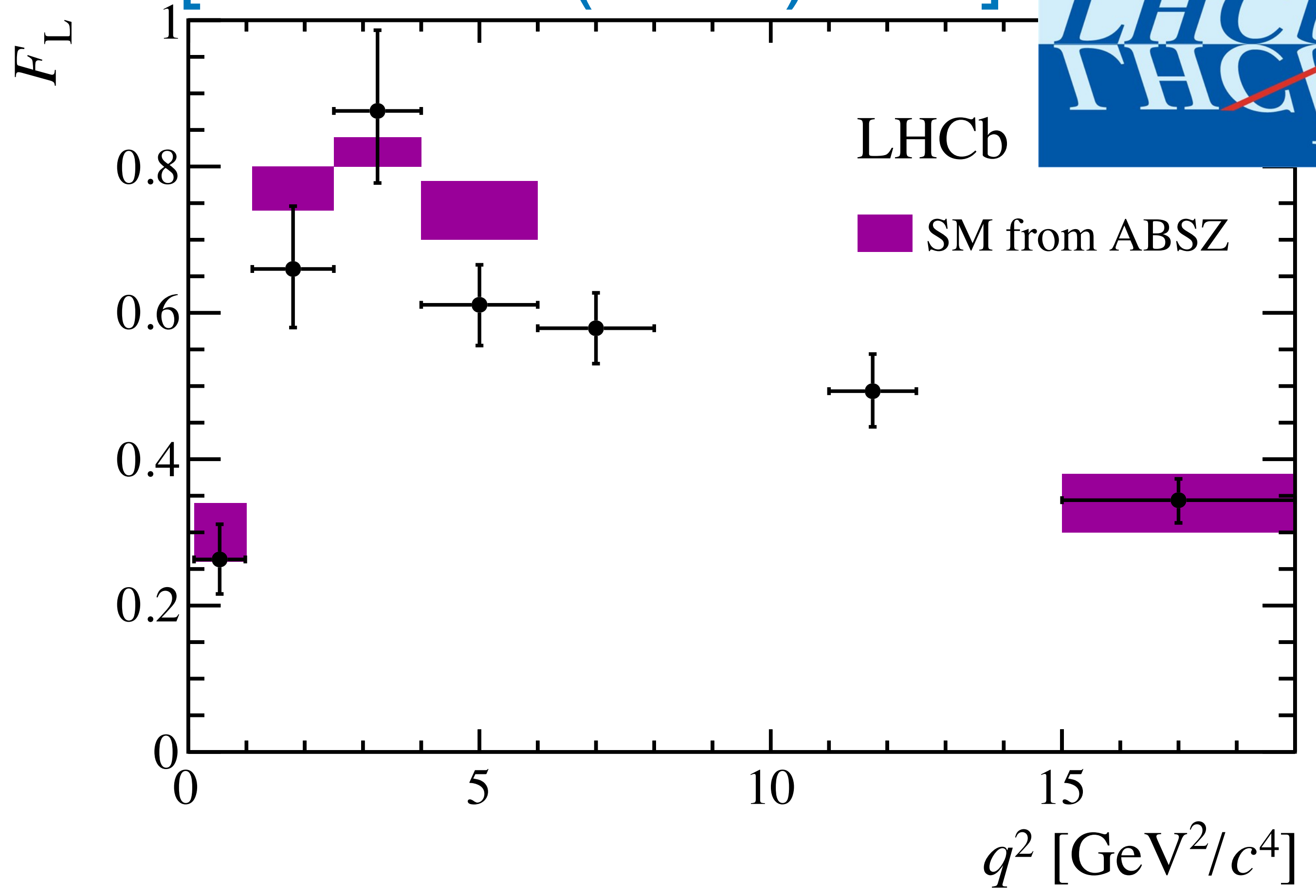
- Global tension with the SM at 3.3σ



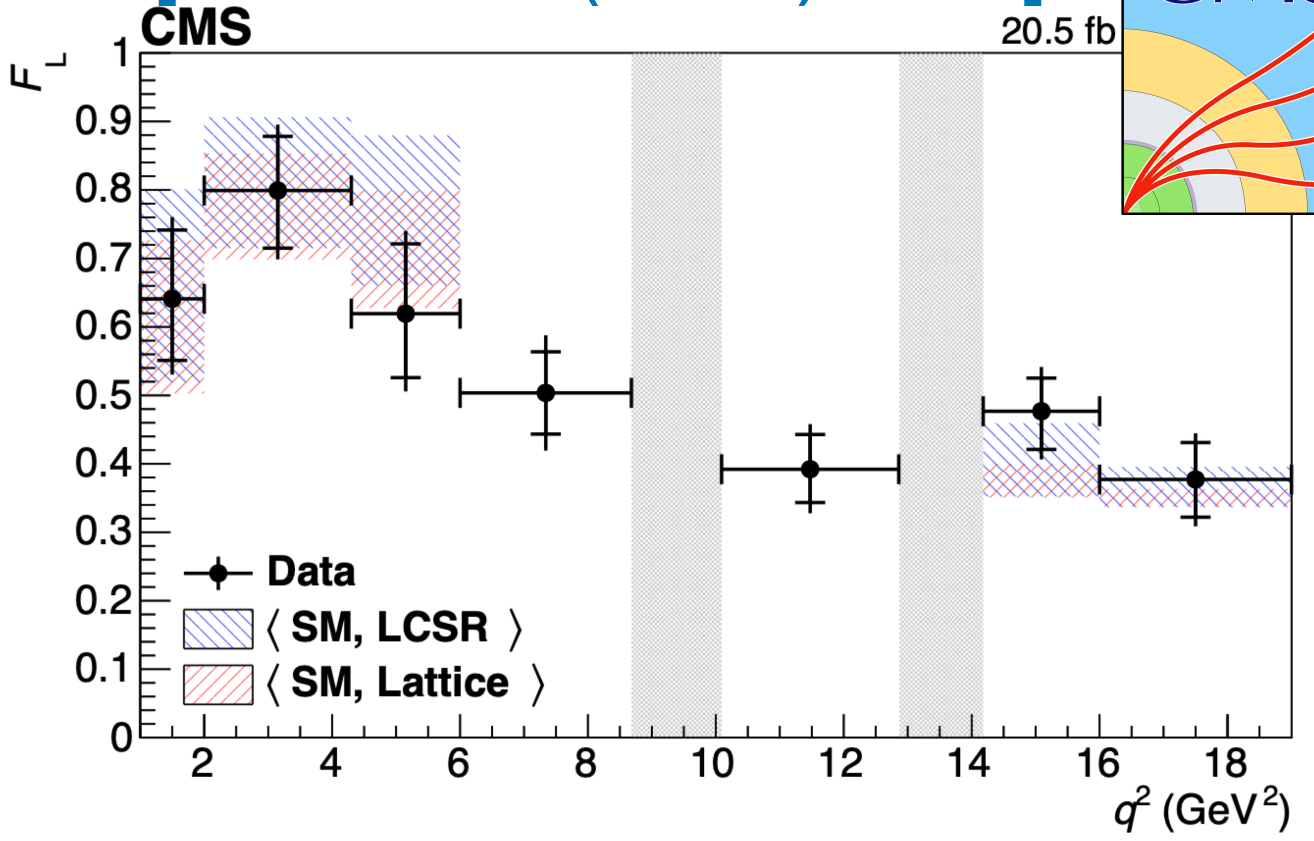


$B^0 \to K^{*0} \mu^+ \mu^-$ angular analysis

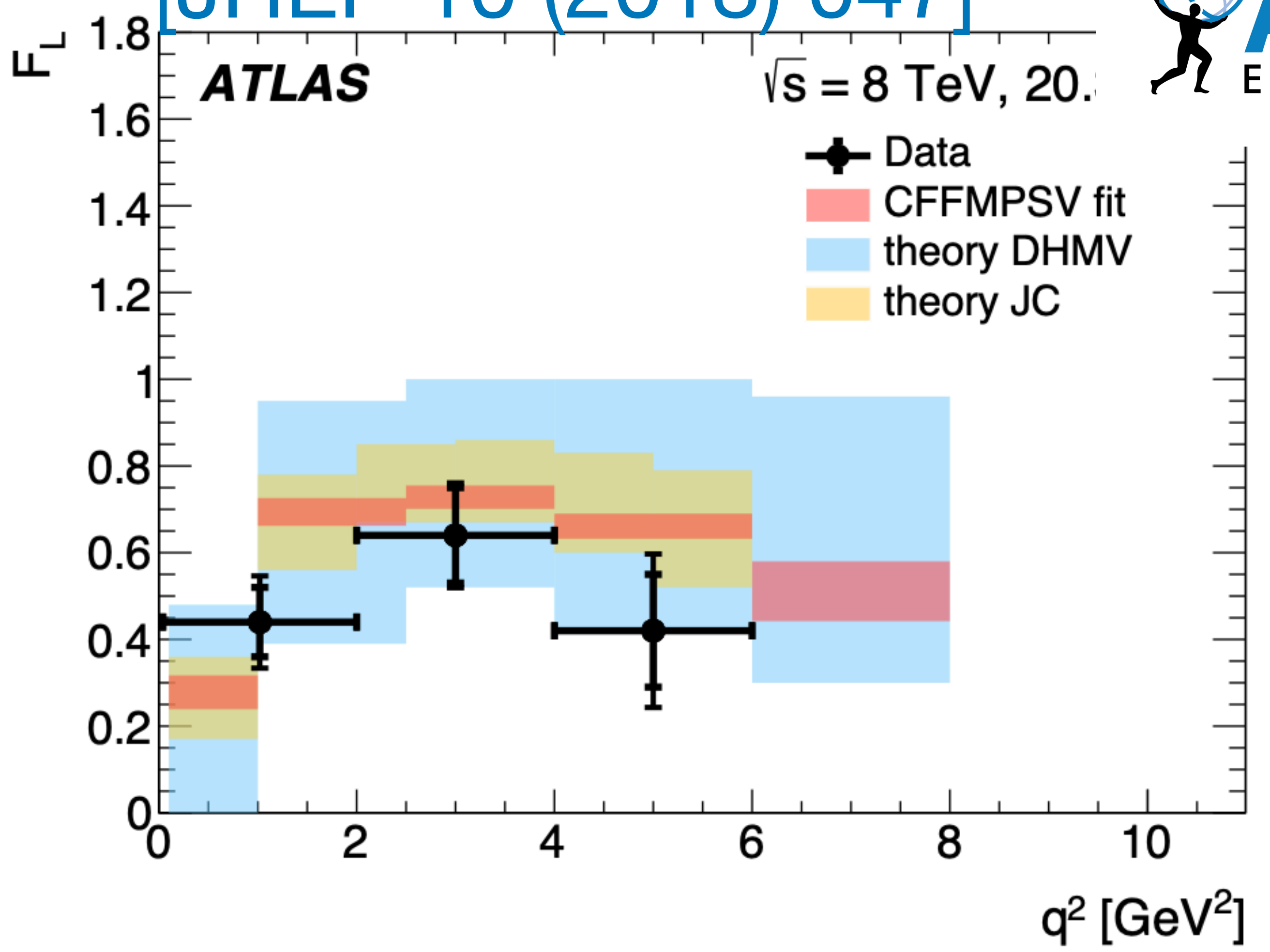
[JHEP 02 (2016) 104]

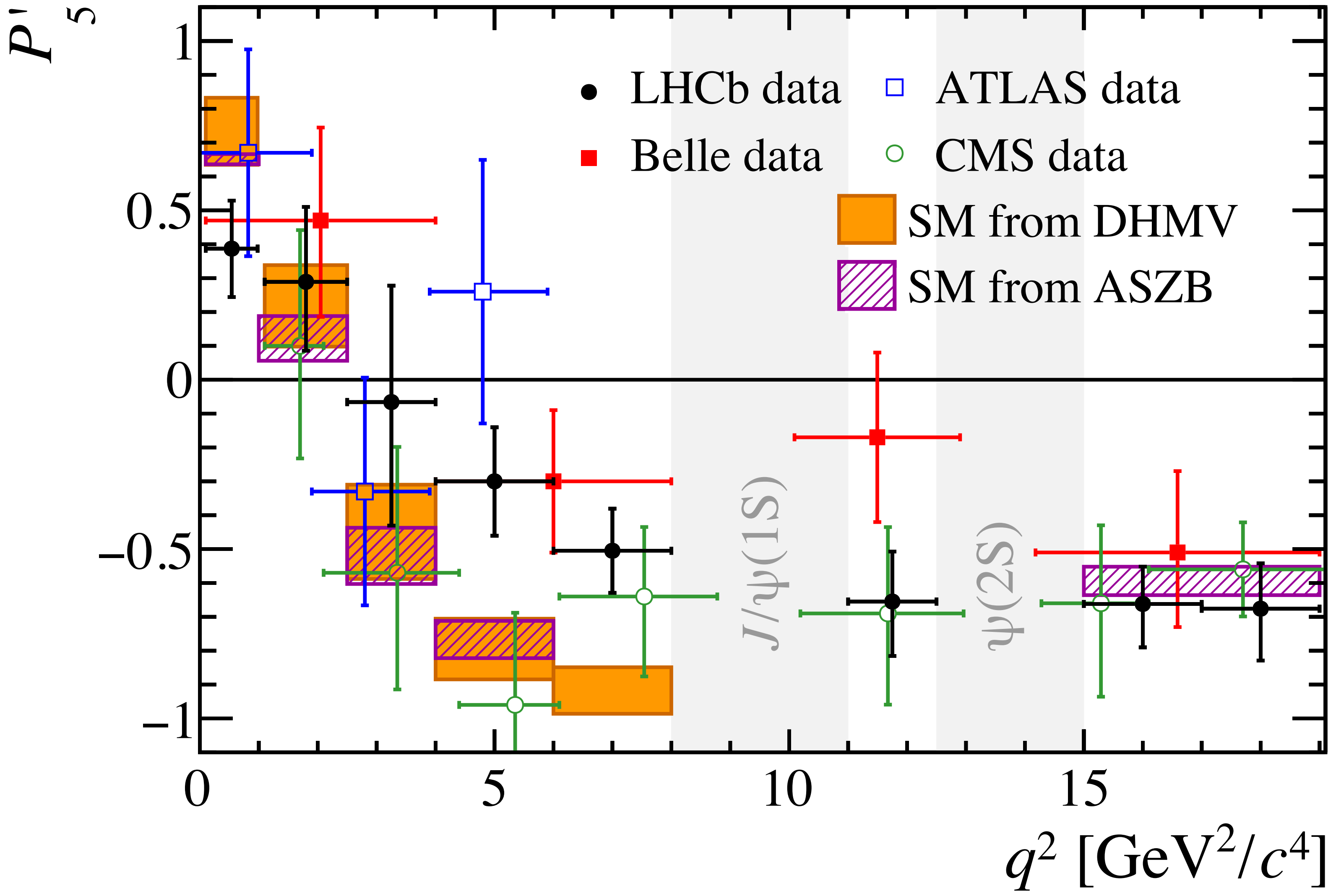


[PLB 753 (2016) 424]



[JHEP 10 (2018) 047]



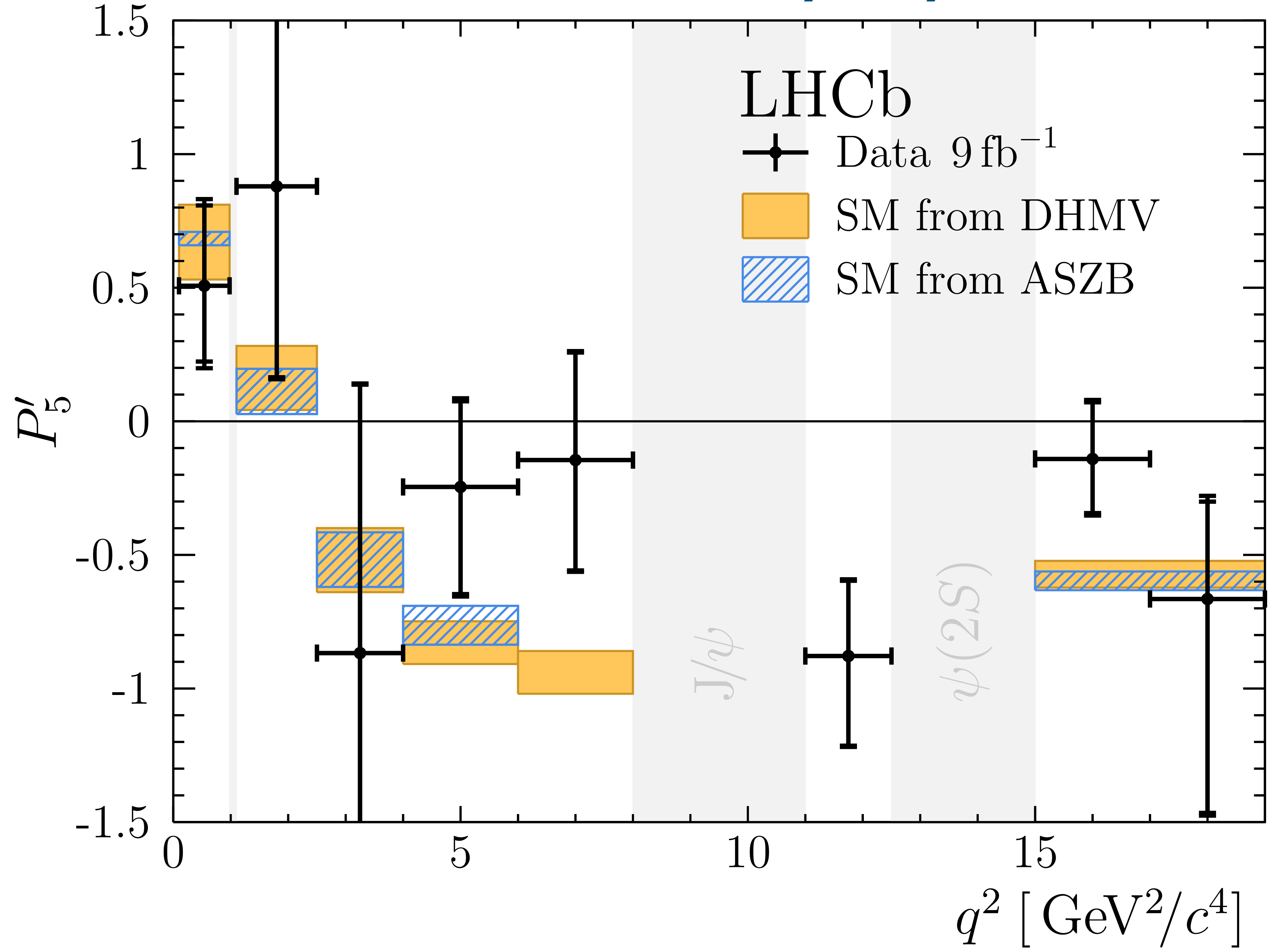


Compatible results from ATLAS, CMS and Belle, need more data to get to a conclusion

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

Angular analyses in other modes

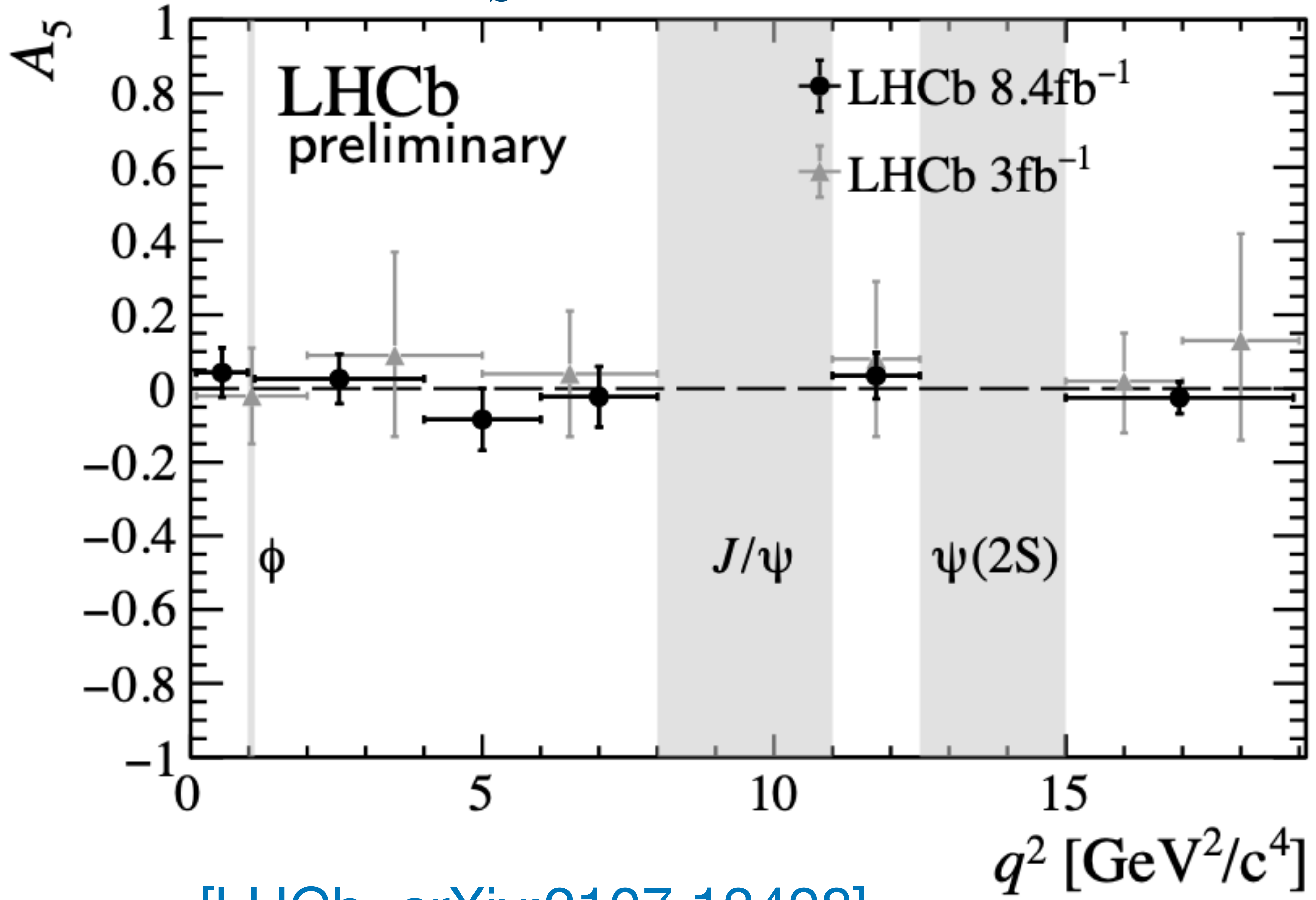
$B^+ \to K^{*+}\mu^+\mu^-$



LHCb [PRL 126 (2021) 161802]

- More challenging experimentally, due to long-lived Ks
- Global tension with the SM at 3.3σ

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



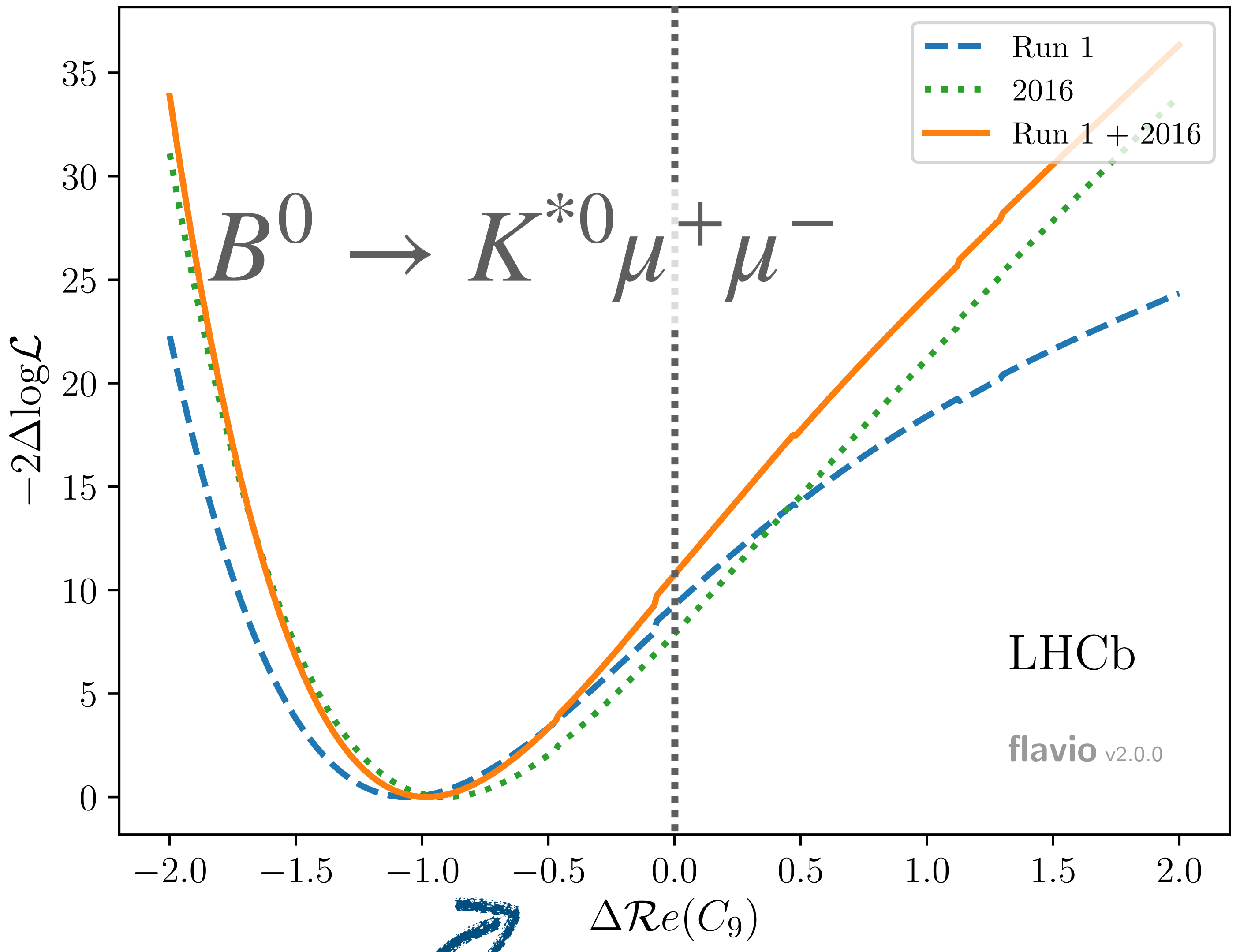
[LHCb, arXiv:2107.13428]

- No self-tagging final state, different set of observables accessible to untagged analysis
- Compatible with SM at 1.9σ

Angular analyses in other modes

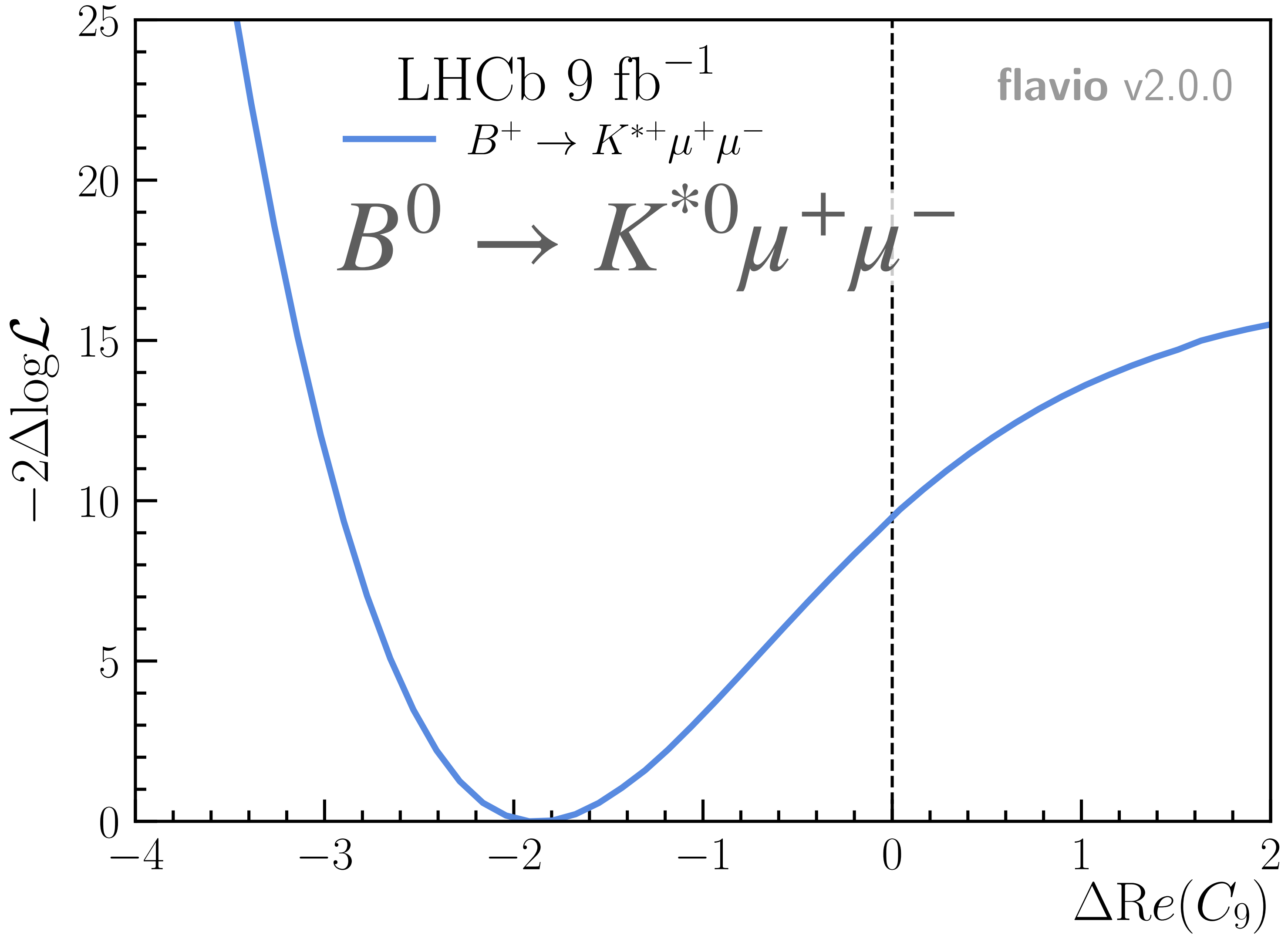
Suggestive similar trend in several $b \to s\mu\mu$ decays, but we need more data

[PRL 125 (2020) 011802]

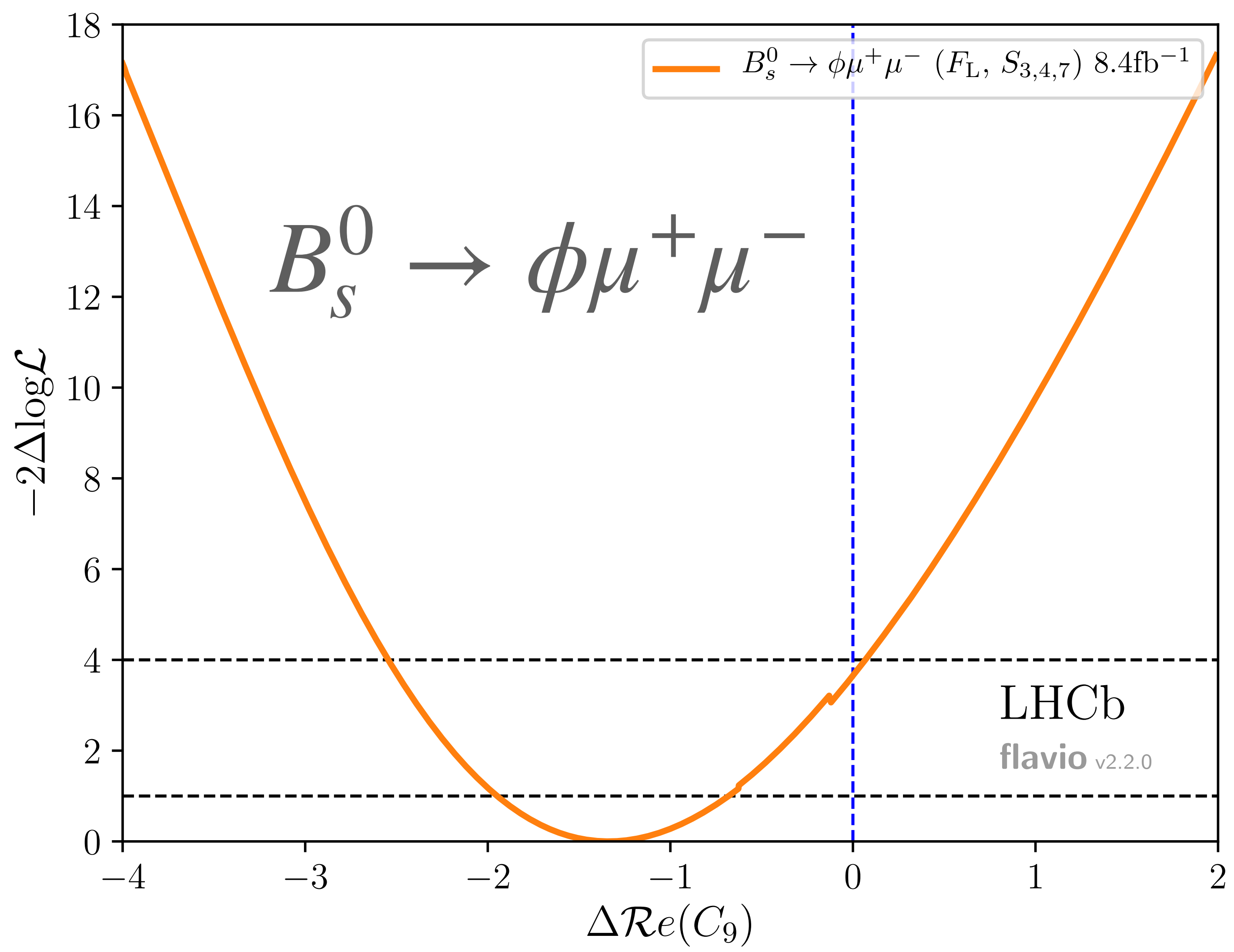


New vector coupling?

[PRL 126 (2021) 161802]



[LHCb, arXiv:2107.13428]



Lepton Flavour Universality tests

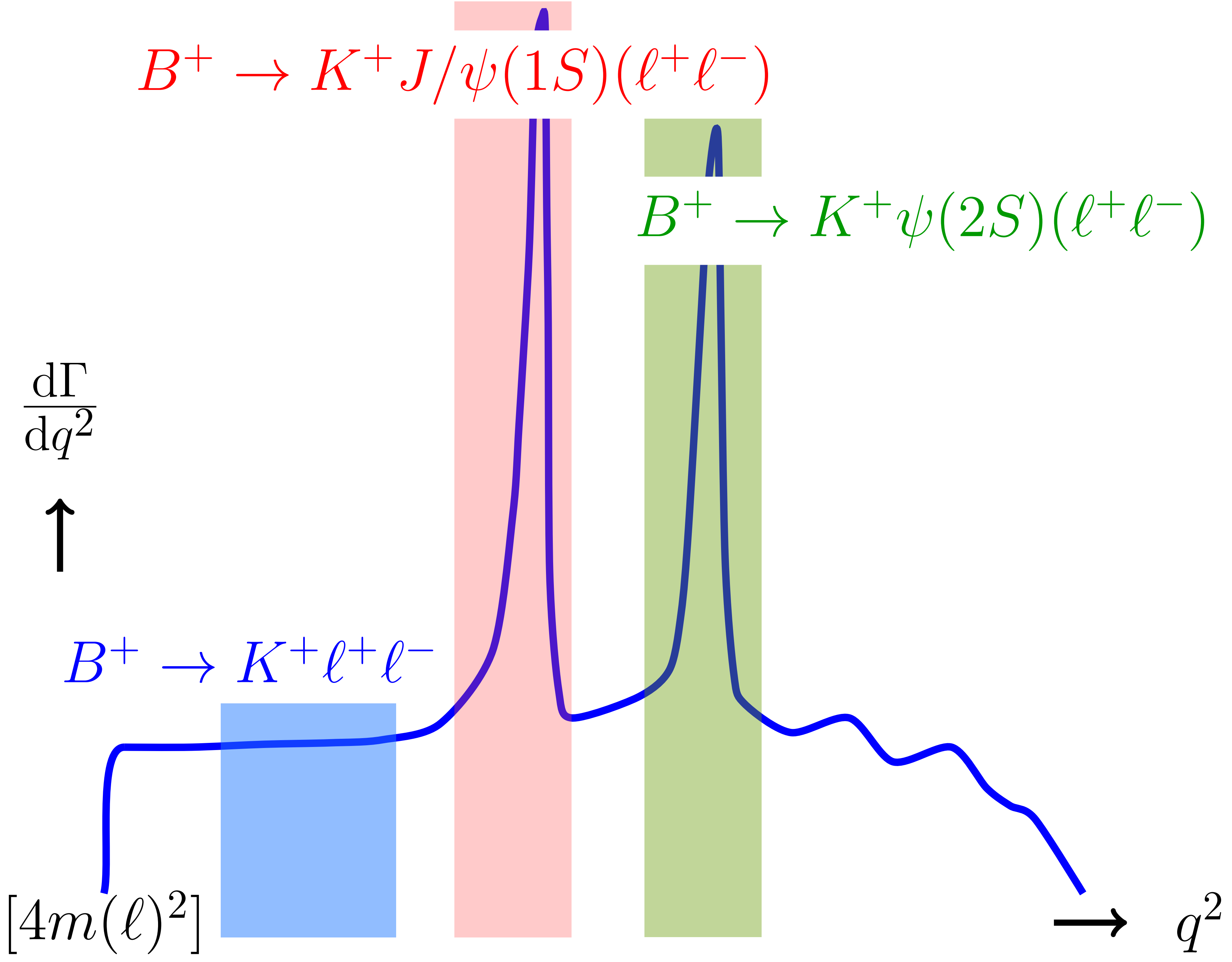
- In the SM, couplings of gauge bosons lepton flavour universal
  - Branching ratios of e, μ and τ differ only due to lepton mass

$$R_K = \frac{\int \frac{\mathrm{d}\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int \frac{\mathrm{d}\Gamma(B^+ \to K^+ e^+ e^-)}{\mathrm{d}q^2}\mathrm{d}q^2} \stackrel{\mathrm{SM}}{\cong} 1$$

- Very well predicted in the SM ⇒ **Any significant deviation is a smoking gun for NP**
  - Hadronic contributions cancel in the ratio, uncertainties $O(10^{-4})$ [JHEP 07 (2007) 040]
  - QED corrections can be up to $O(10^{-2})$ [EPJC 76 (2016) 8,440]

LFU measurements at LHCb

- Measure R_K as a double ratio, relative to equivalent ratio for $B^+ \to K^+ J/\psi(\ell\ell)$ decays
  - reduces impact of the differences in efficiency between electrons and muons



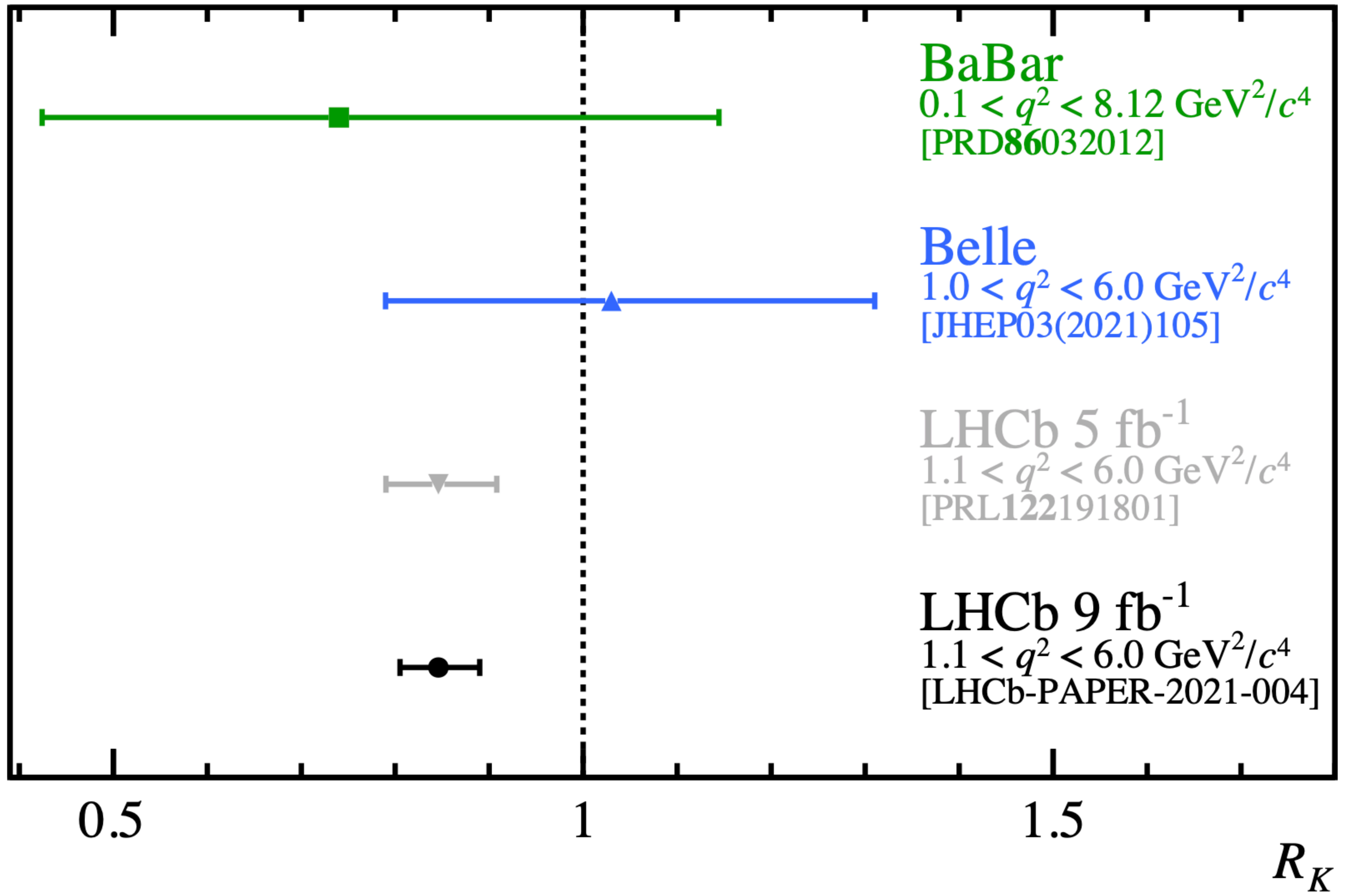
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

$$= \frac{N(K^+\mu^+\mu^-)}{N(K^+J/\psi(\mu^+\mu^-))} \cdot \frac{N(K^+J/\psi(e^+e^-))}{N(K^+e^+e^-)}$$

$$\cdot \frac{\varepsilon(K^+J/\psi(\mu^+\mu^-))}{\varepsilon(K^+\mu^+\mu^-)} \cdot \frac{\varepsilon(K^+e^+e^-)}{\varepsilon(K^+J/\psi(e^+e^-))}$$

R_K measurement

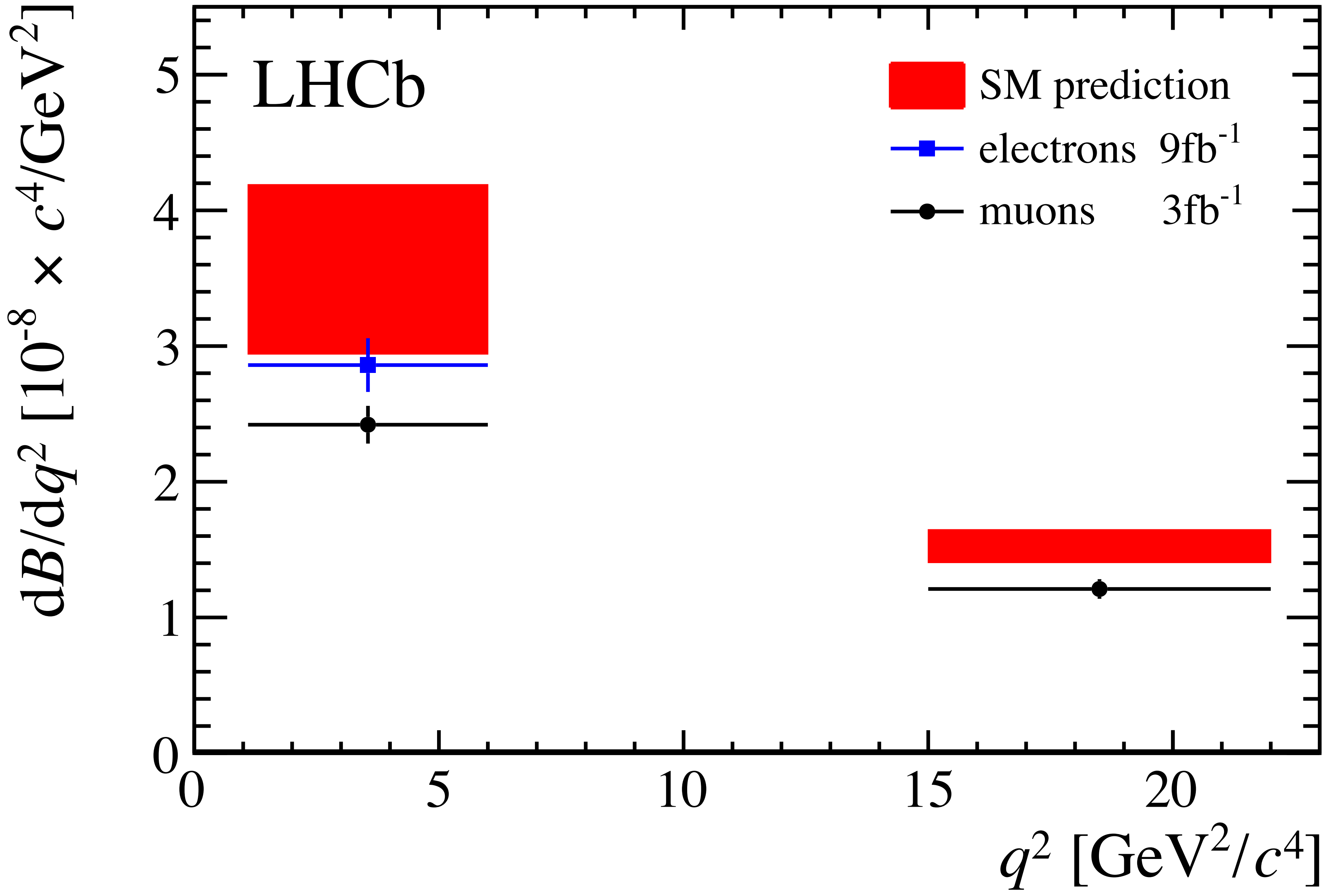
[LHCb, Nature Phys 18 (2022) 277]



Full Run1 & Run2 result

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

Consistency with the SM expectation at **3.1 σ**

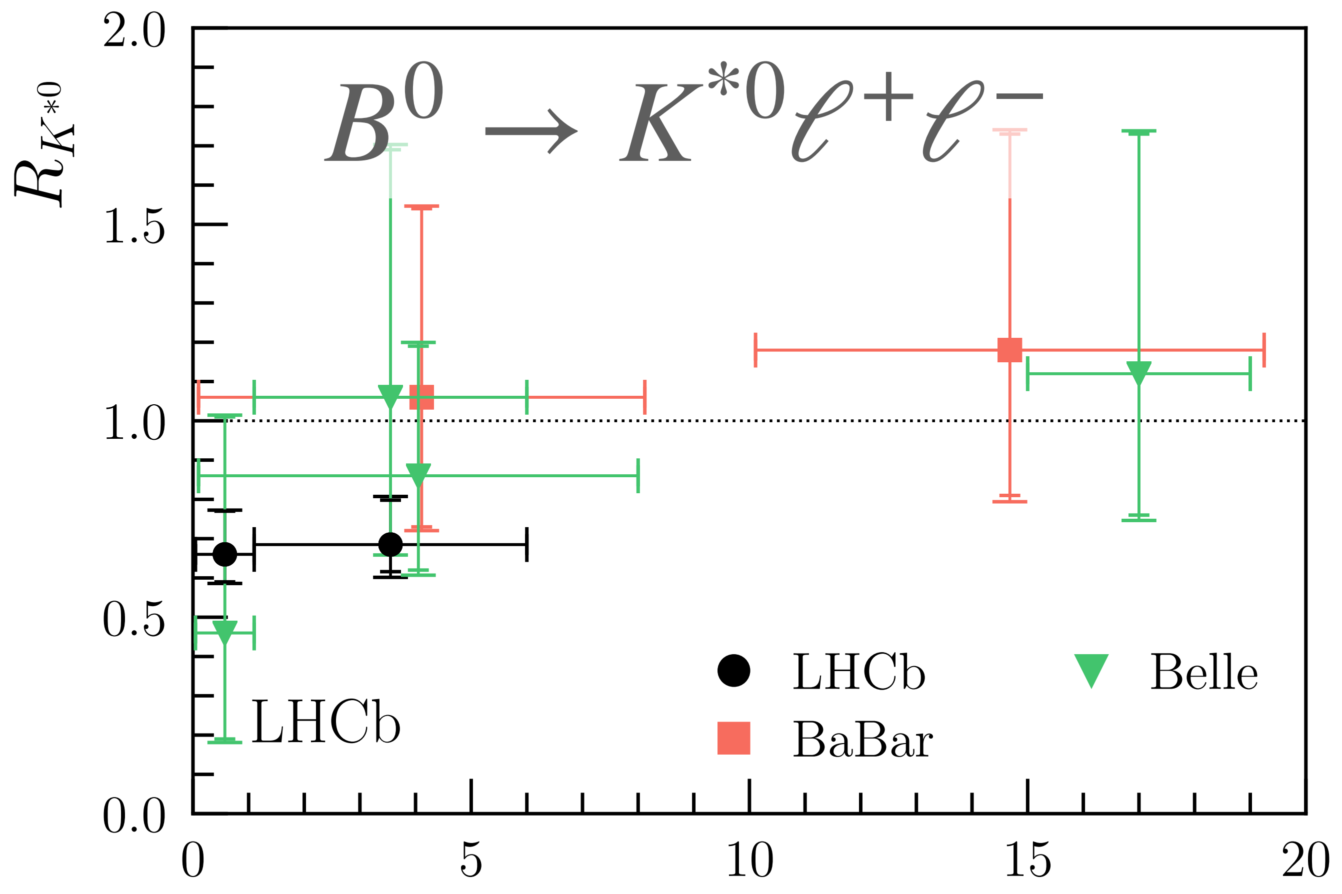


Combining this measurement of R_K with

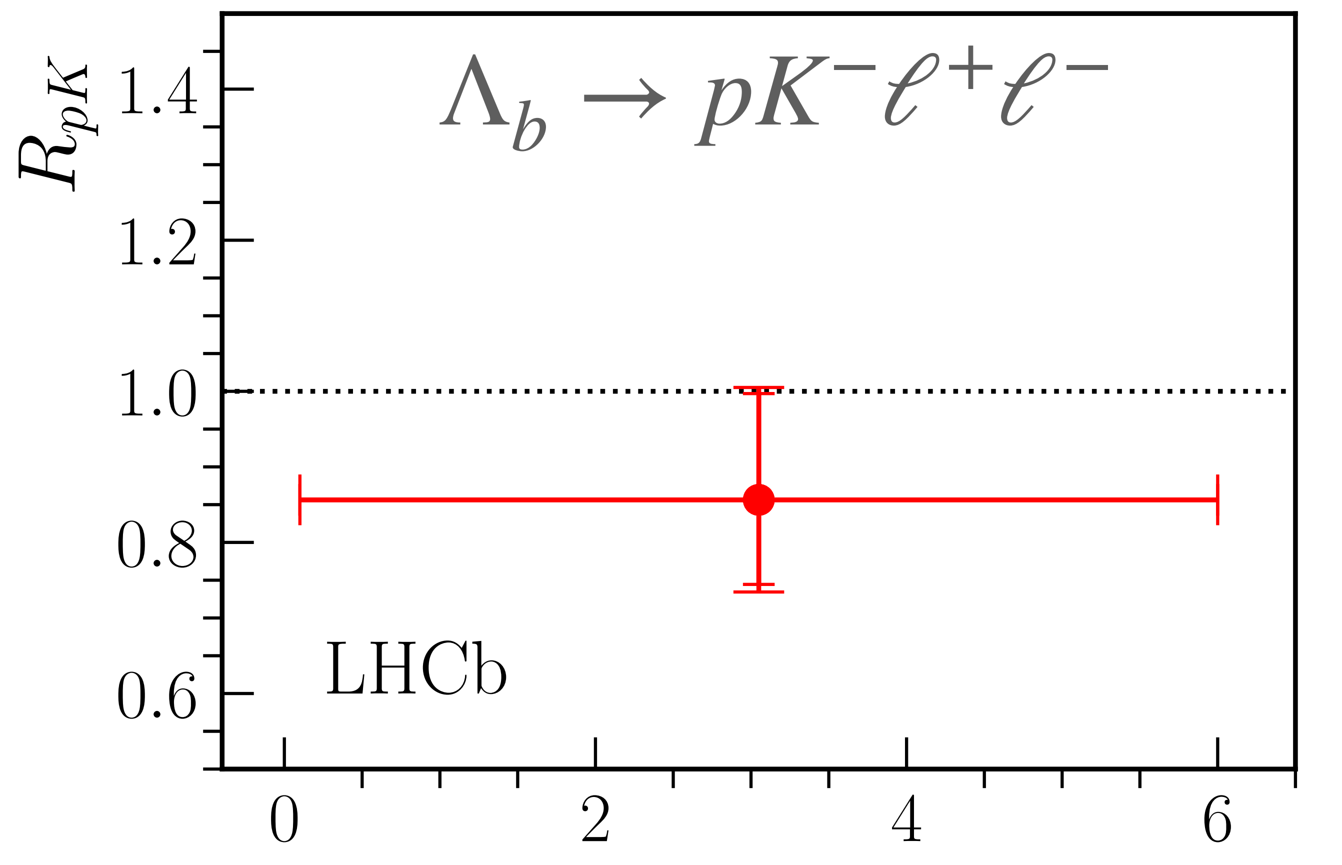
$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ from [LHCb, JHEP 06 (2014) 133]

$$\left.\frac{d\mathcal{B}(B^+ \to K^+e^+e^-)}{dq^2}\right|_{1.1<q^2<6.0} = (28.6\ ^{+1.5}_{-1.4}(\text{stat}) \pm 1.4(\text{syst})) \times 10^{-9}\ c^4/\text{GeV}^2$$

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

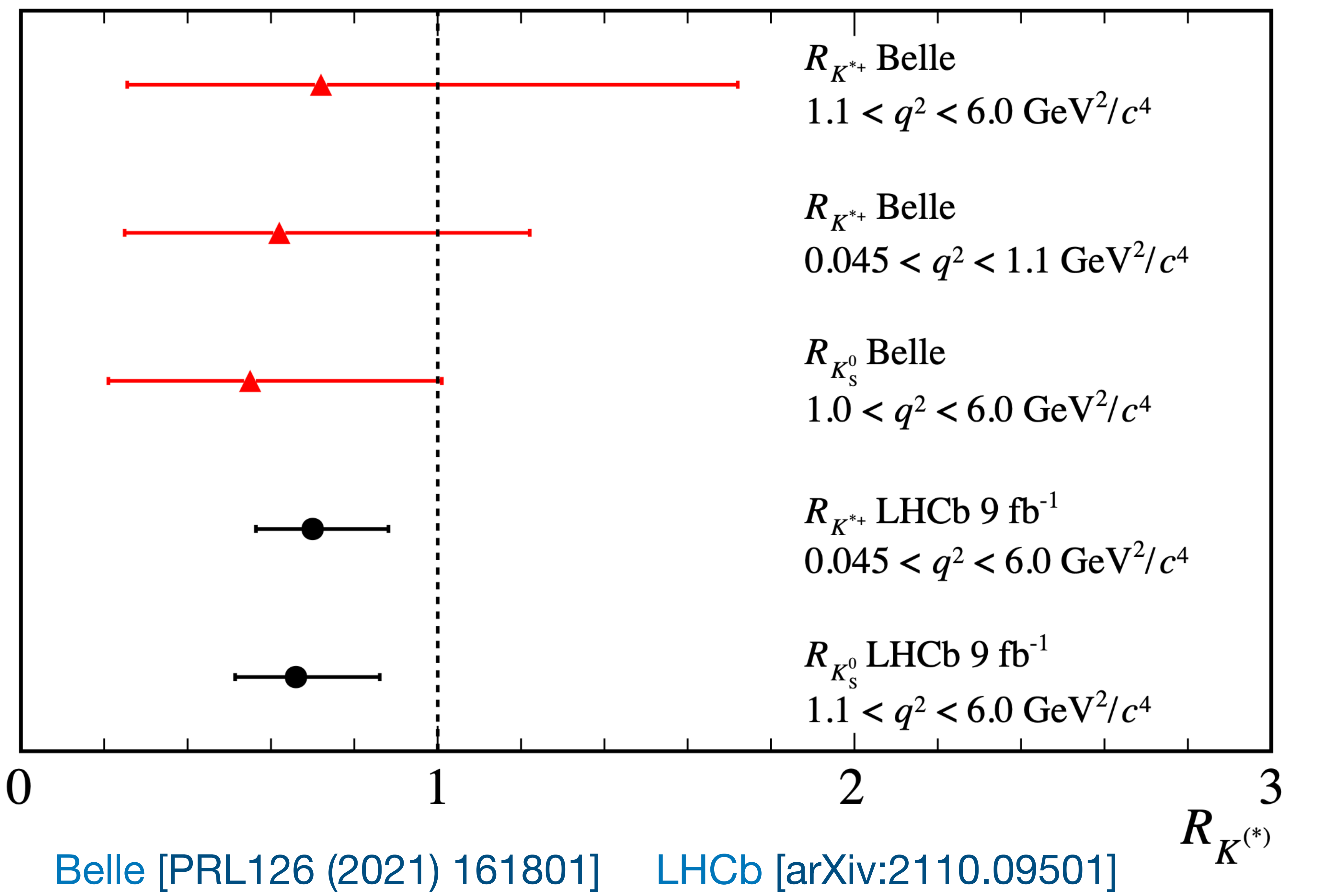


Belle [PRL 126 (2021) 161801]
BaBar [PRD 86 (2012) 032012]
LHCb [JHEP 08 (2017) 055]



LHCb [JHEP 05 (2020) 040]

New measurements of $R_{K^{*+}}$ and R_{KS}, compatible with the SM at 1.5σ and 1.6σ



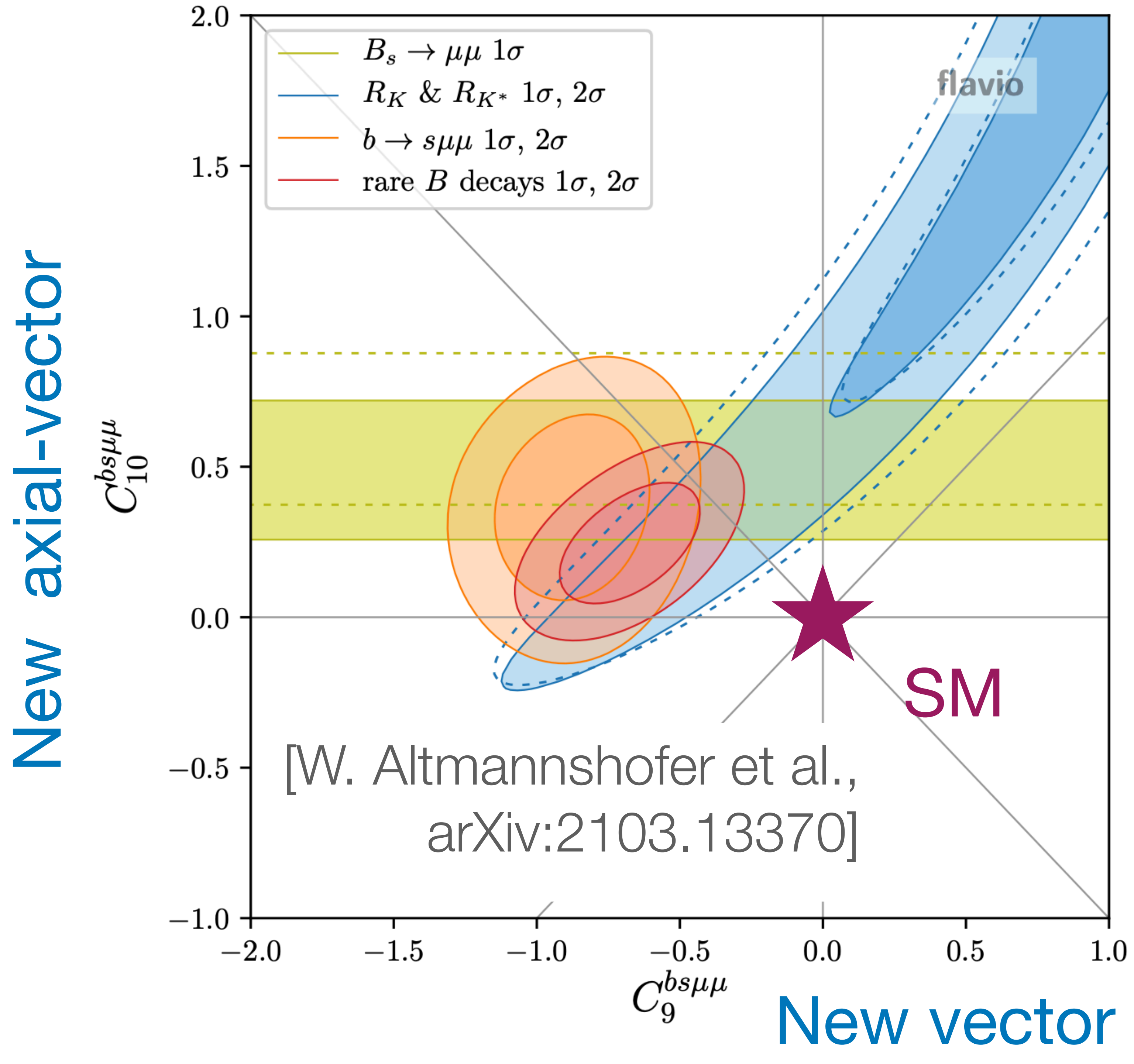
$B^+ \to K^{*+}\ell^+\ell^-$

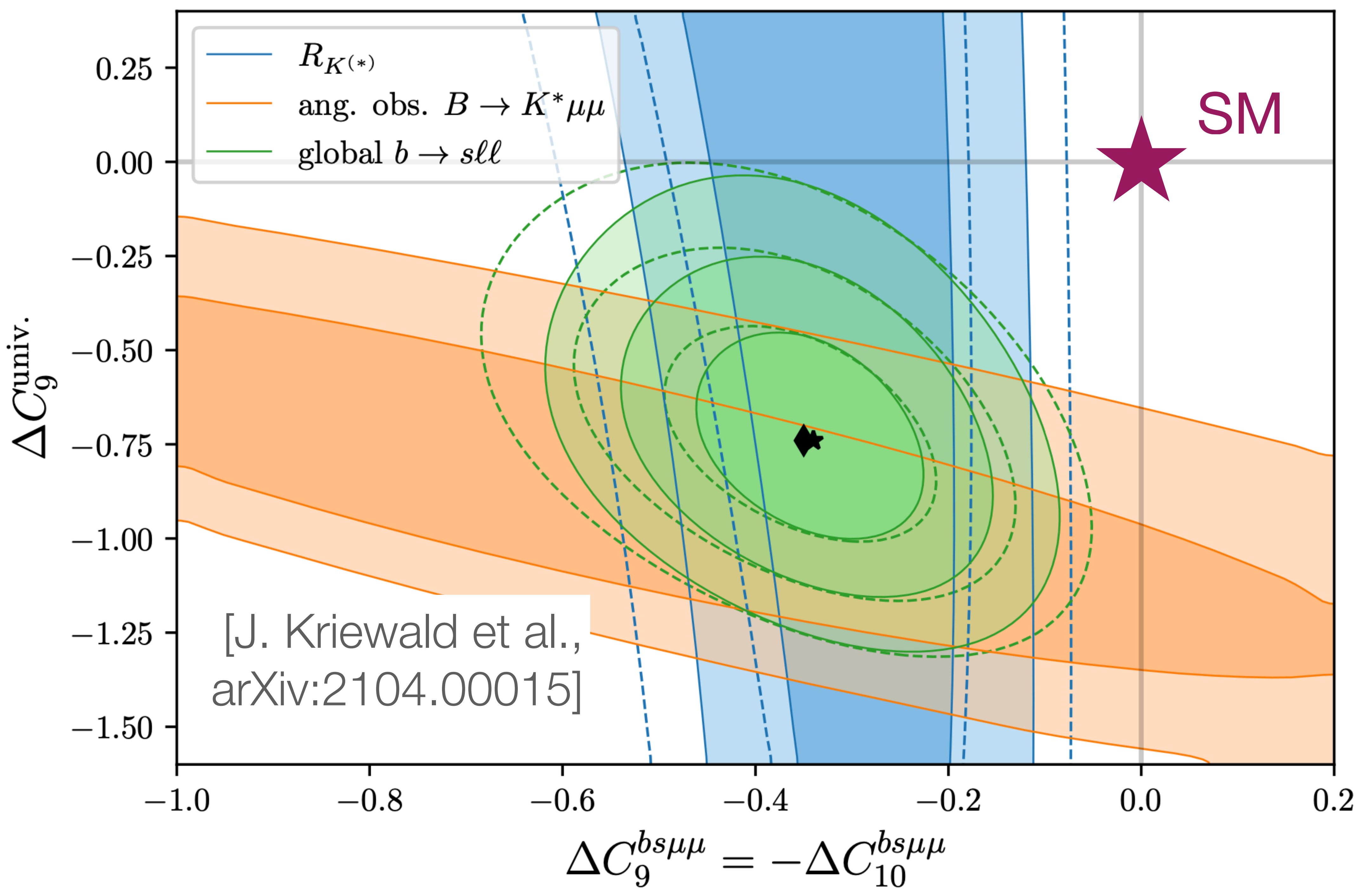
$B^0 \to K_S\, \ell^+\ell^-$

Belle [PRL126 (2021) 161801] LHCb [arXiv:2110.09501]

Global fit to b→sℓℓ measurements

[Similar fits by M. Algueró et al., C. Cornella et al., L-G. Geng et al. and many others]





Perform a fit to all measurements, to establish what WC's are preferred by the data

- Best fit point in tension with the SM: significance of 4-7σ depending on scenario/inputs
- Tension between R(*) & b → sμ+μ– observables (could be reduced by LFU contribution to C9)

Critical to improve the precision in all of these measurements to clarify this picture

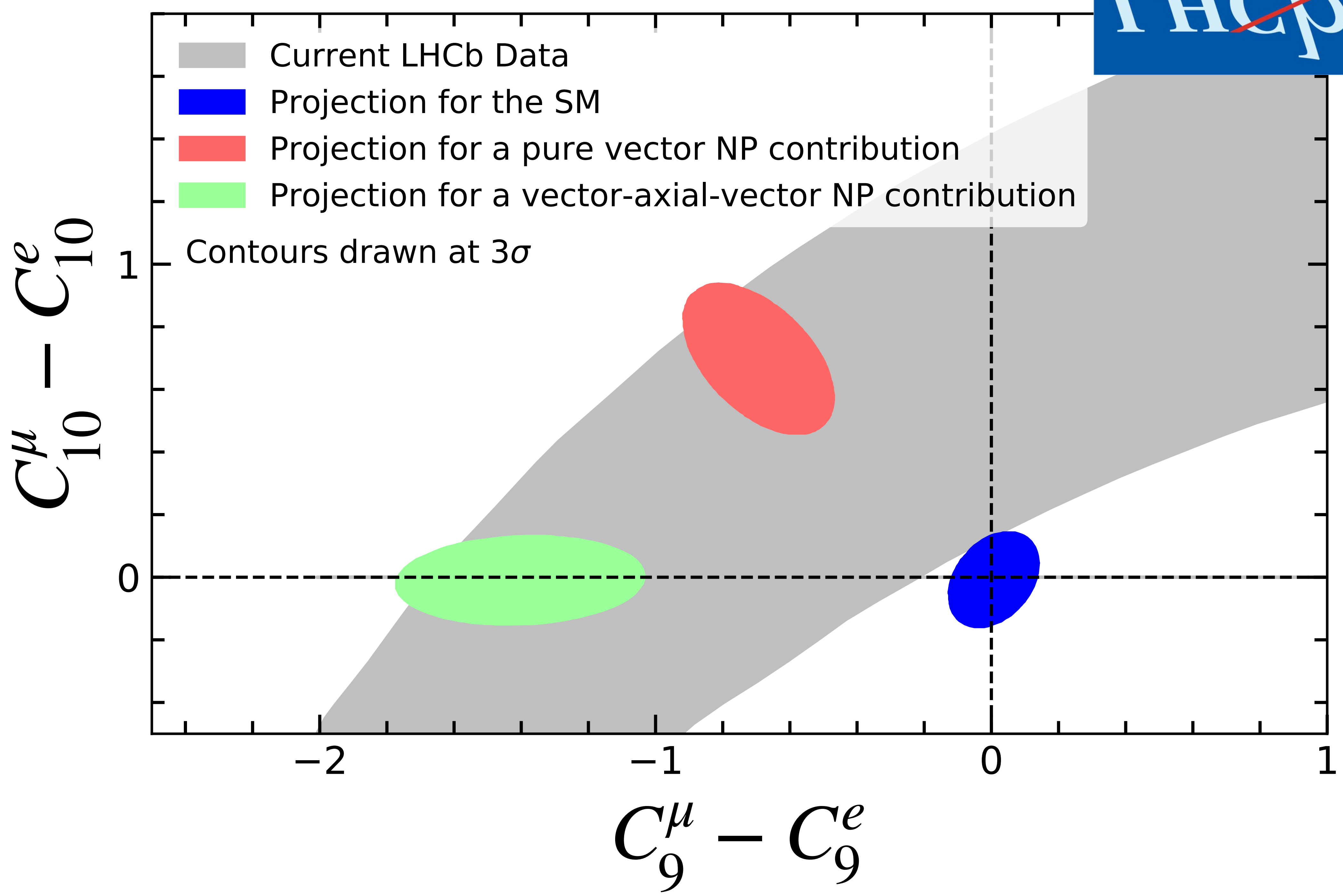
How do we find out more?

From LHCb many results still to come from Run1+2 data

- LFU test in different channels: RK*0, Rϕ, RKππ...
- Update of angular observables of b → sμ+μ– decays
- Measurements of b → sττ processes and LFV involving τ's

and start of Run3 opens the door to a very significant jump in precision and access to 'rarer' processes

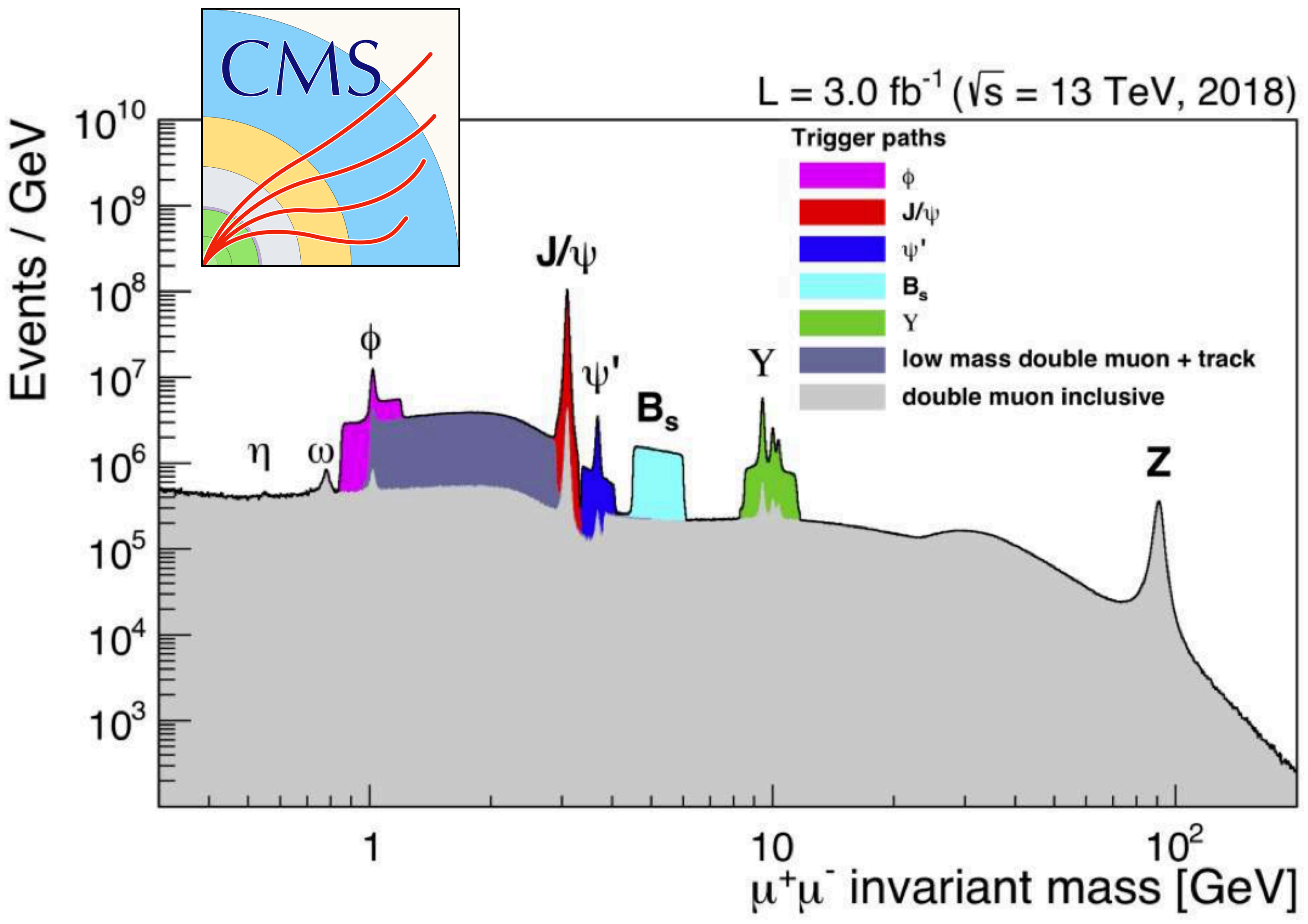
[LHCb, arXiv:1808.08865]

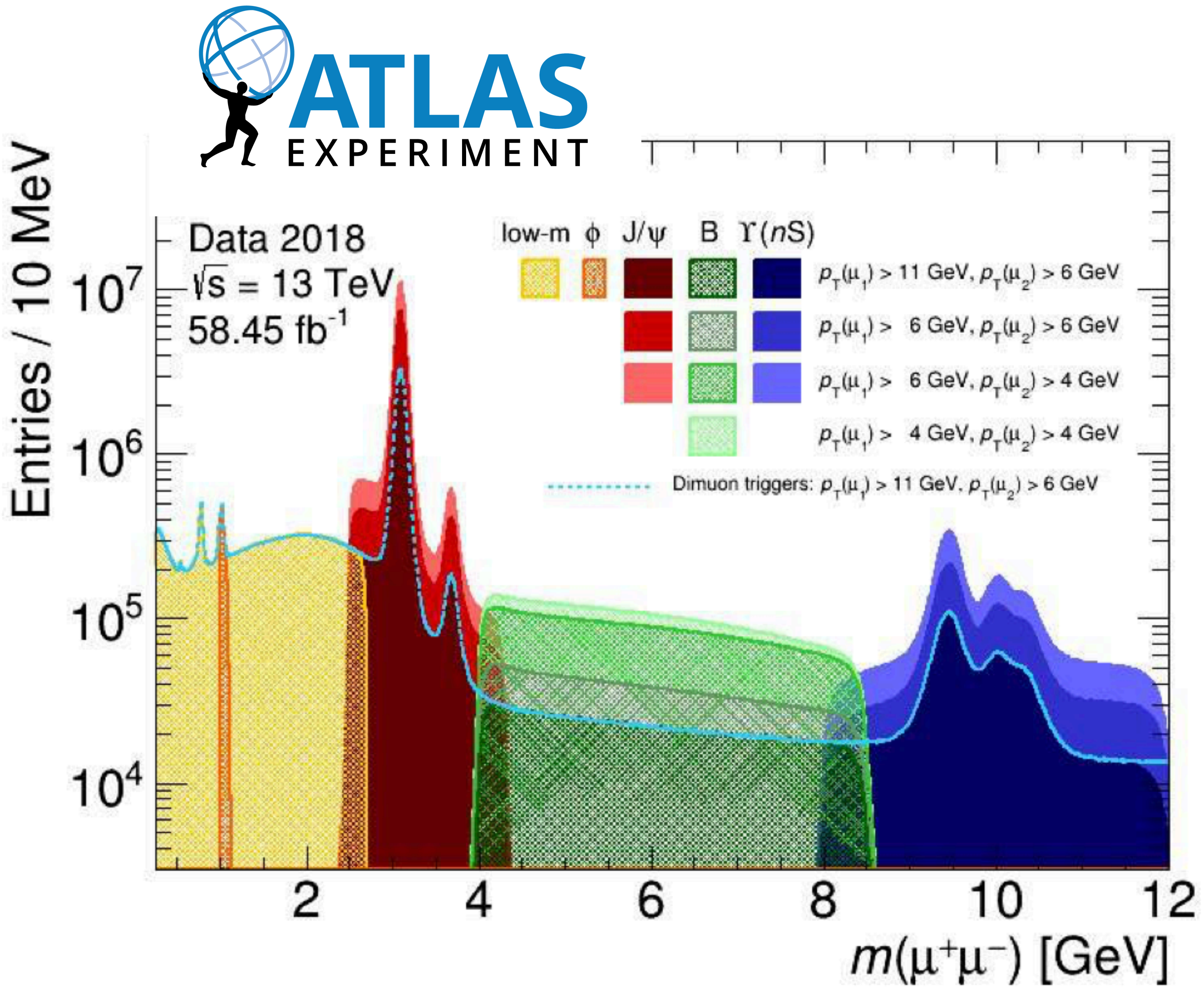


How do we find out more?

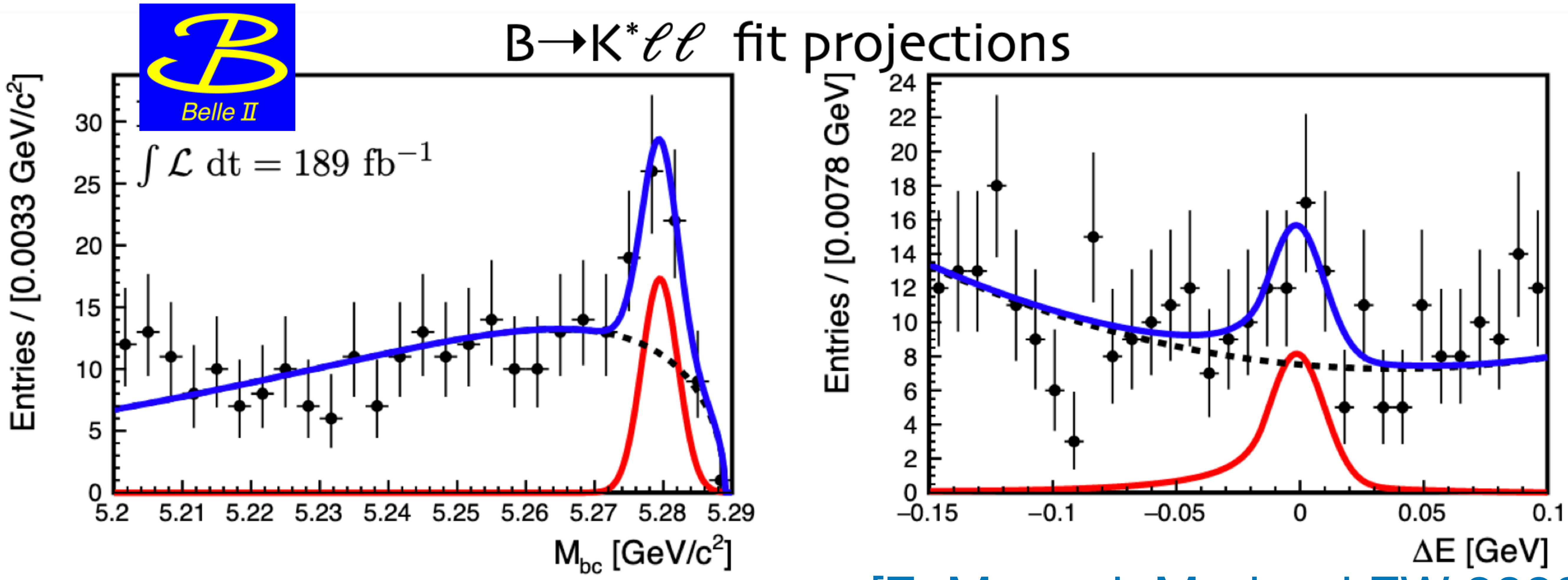
[F. Simone, Moriond EW 2022]

- ATLAS and CMS have a dedicated B-physics programme, with active effort into rare decays





- Belle II, a dedicated flavour experiment at KEK (Japan) starting to join in the exploration of the anomalies



[E. Manoni, Moriond EW 2022]

Summary

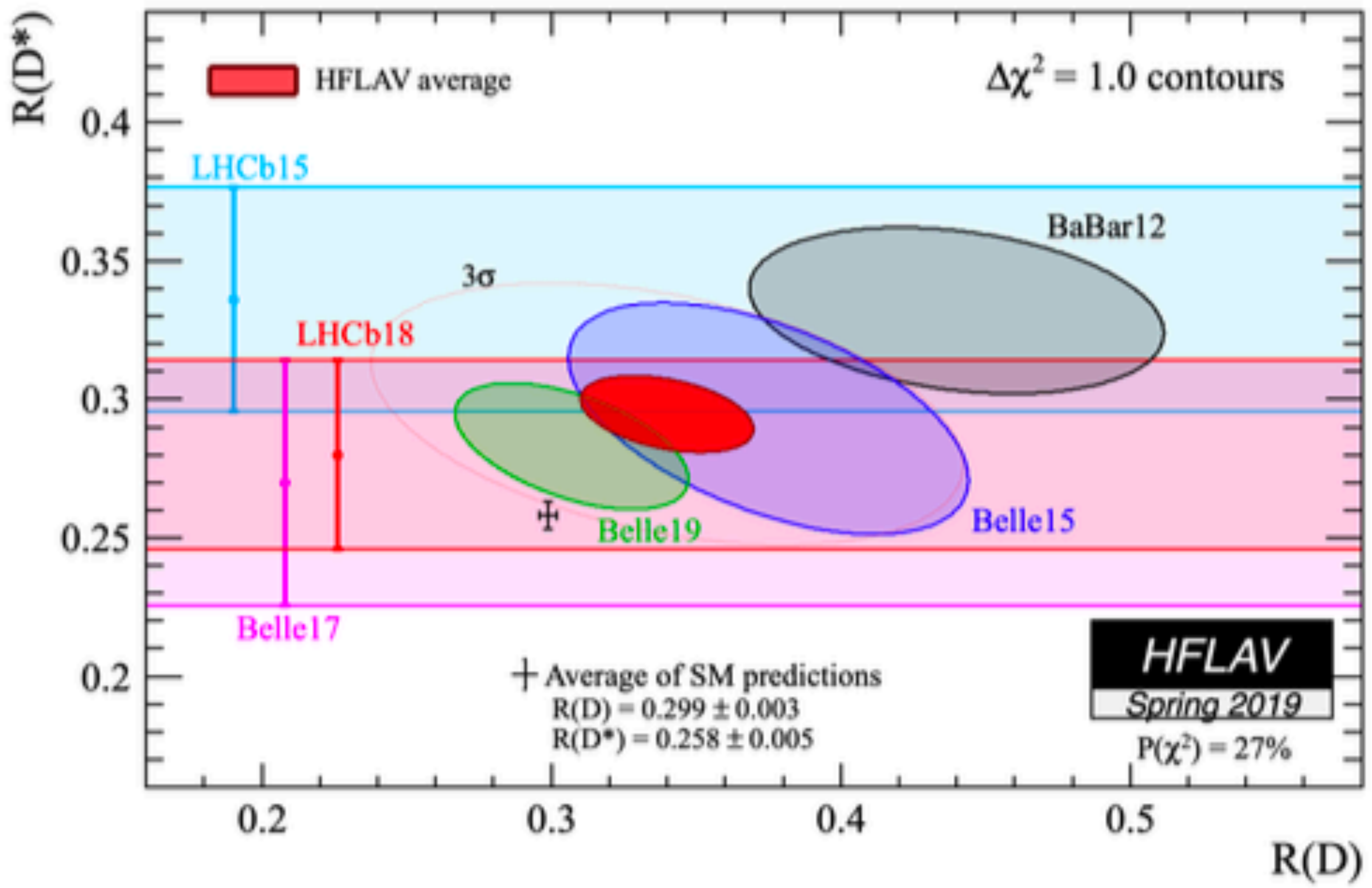
- Rare B-hadron decays offer an excellent tool to search for NP
  - Interesting anomalies arising in $b \to s\ell\ell$ transitions, need more data to understand what they mean

- Luckily, many results expected with the full exploitation of LHC's Run2 dataset, and Run3 just started!
  - Crucial interplay between LHCb, ATLAS, CMS and Belle II

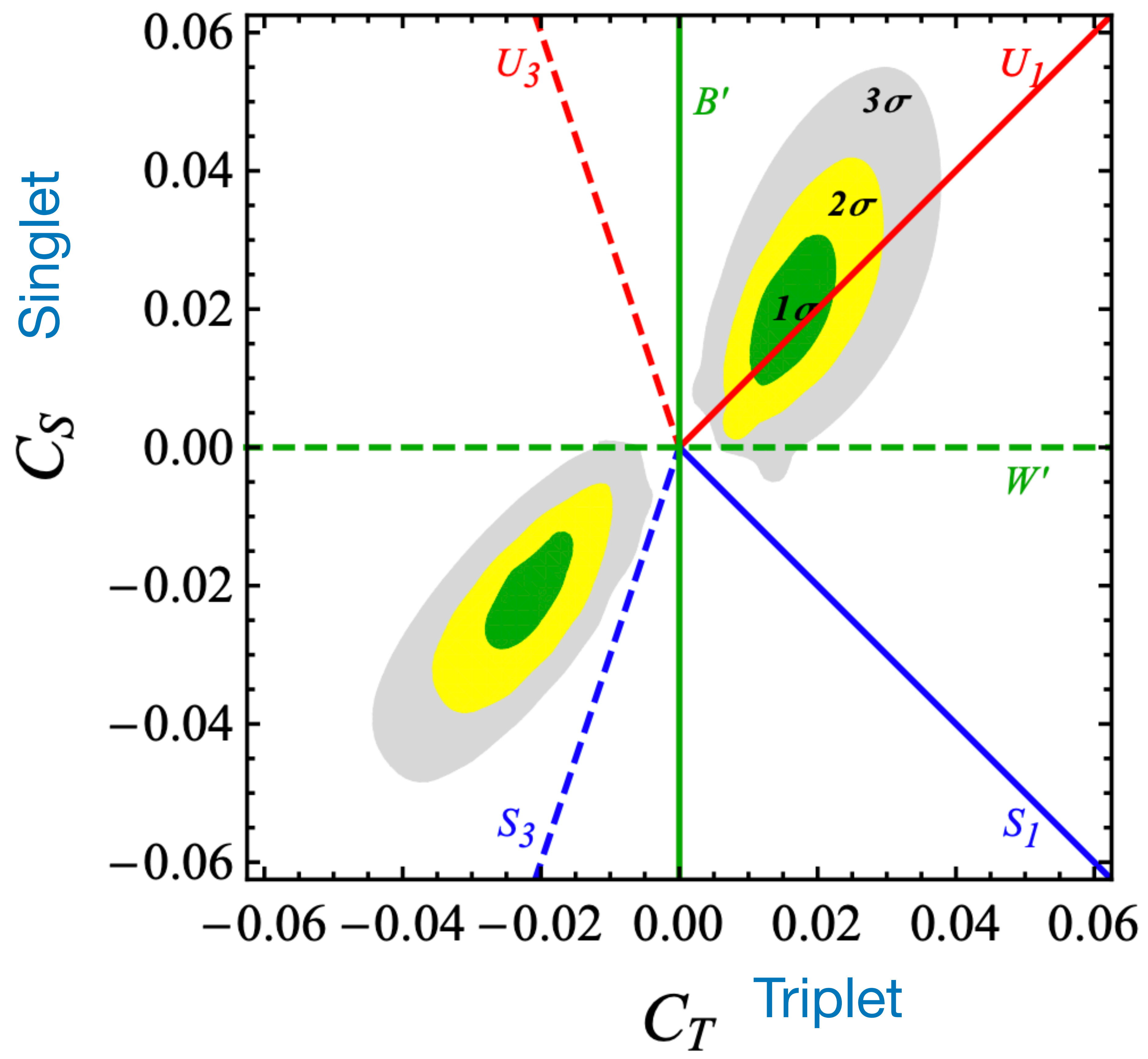
Exciting times for flavour physics

Backup

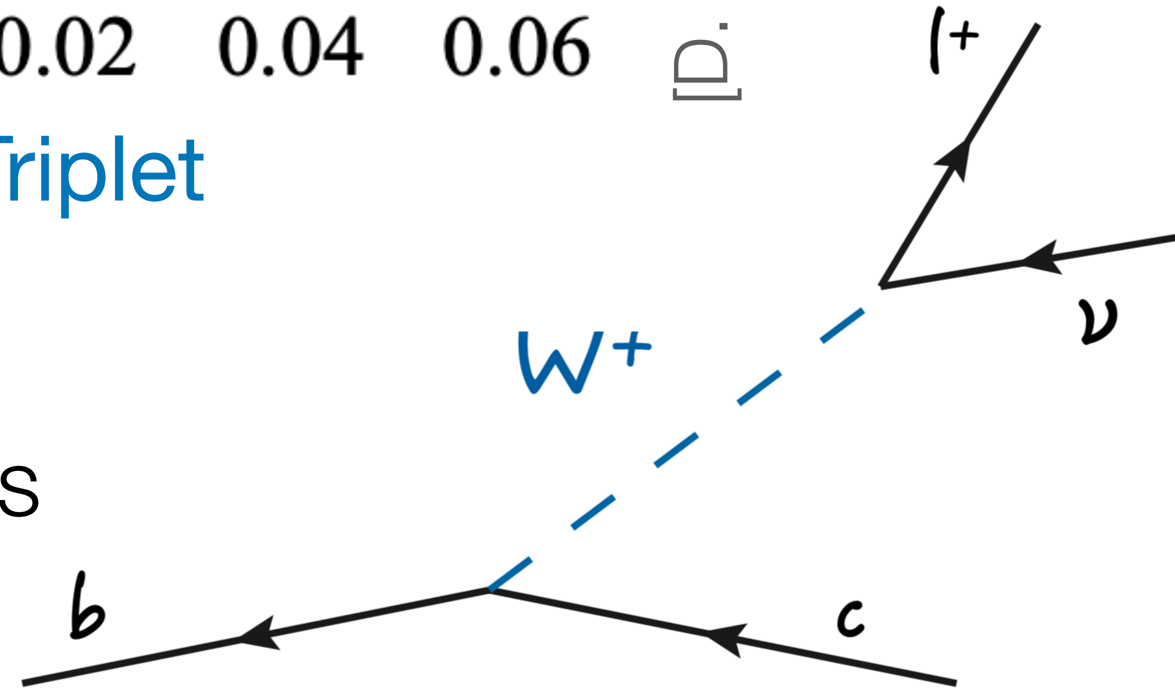
Connection with charged currents



$$R(D^{(*)}) = \frac{B \to D^{(*)}\tau\nu_\tau}{B \to D^{(*)}\mu\nu_\mu}$$



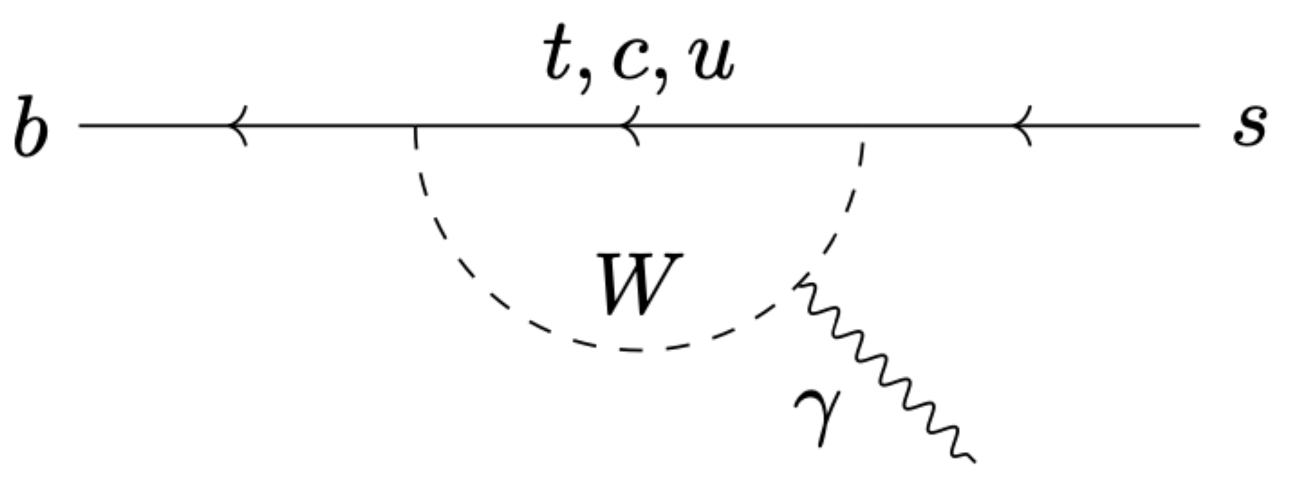
[D. Buttazzoa, A. Greljoa, G. Isidoria, D. Marzocca, arXiv:1706.07808]



Several analyses also try to connect the rare decays anomalies with LFU in charged currents

- Successful simplified models use e.g. vector leptoquarks

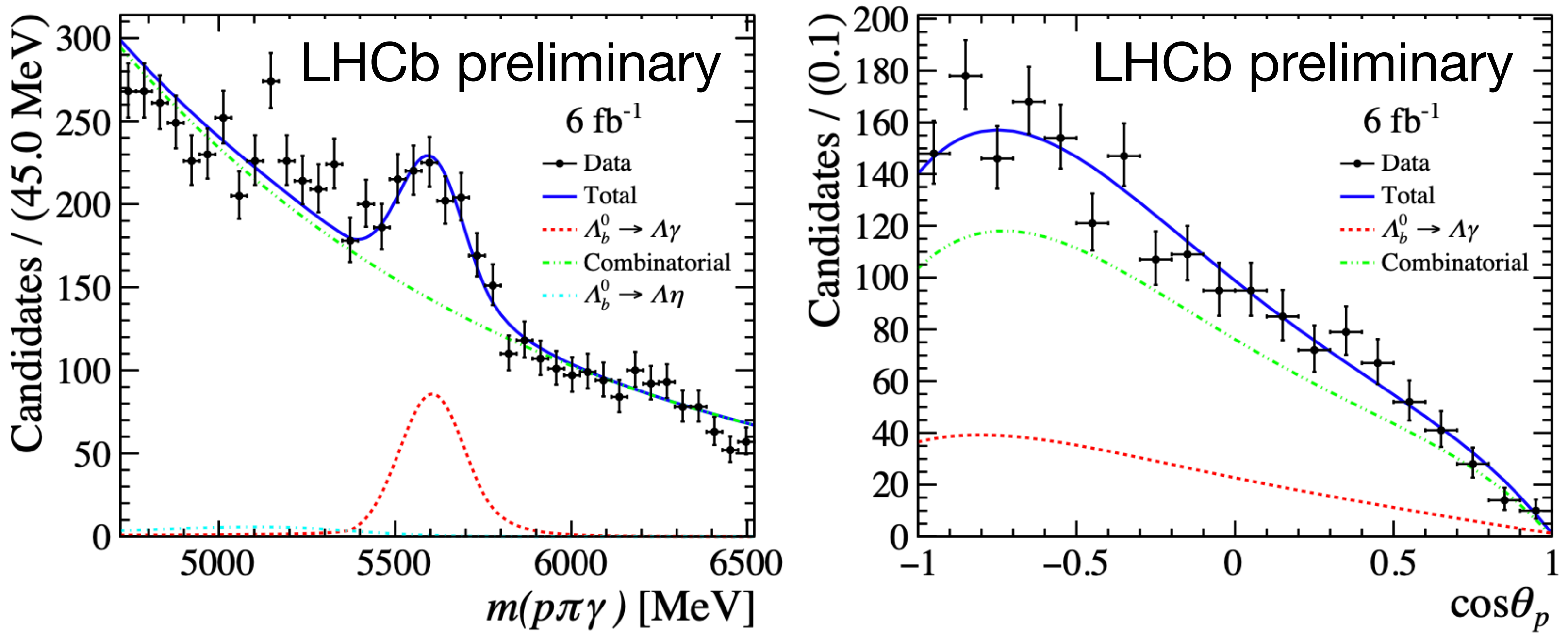
Radiative decays



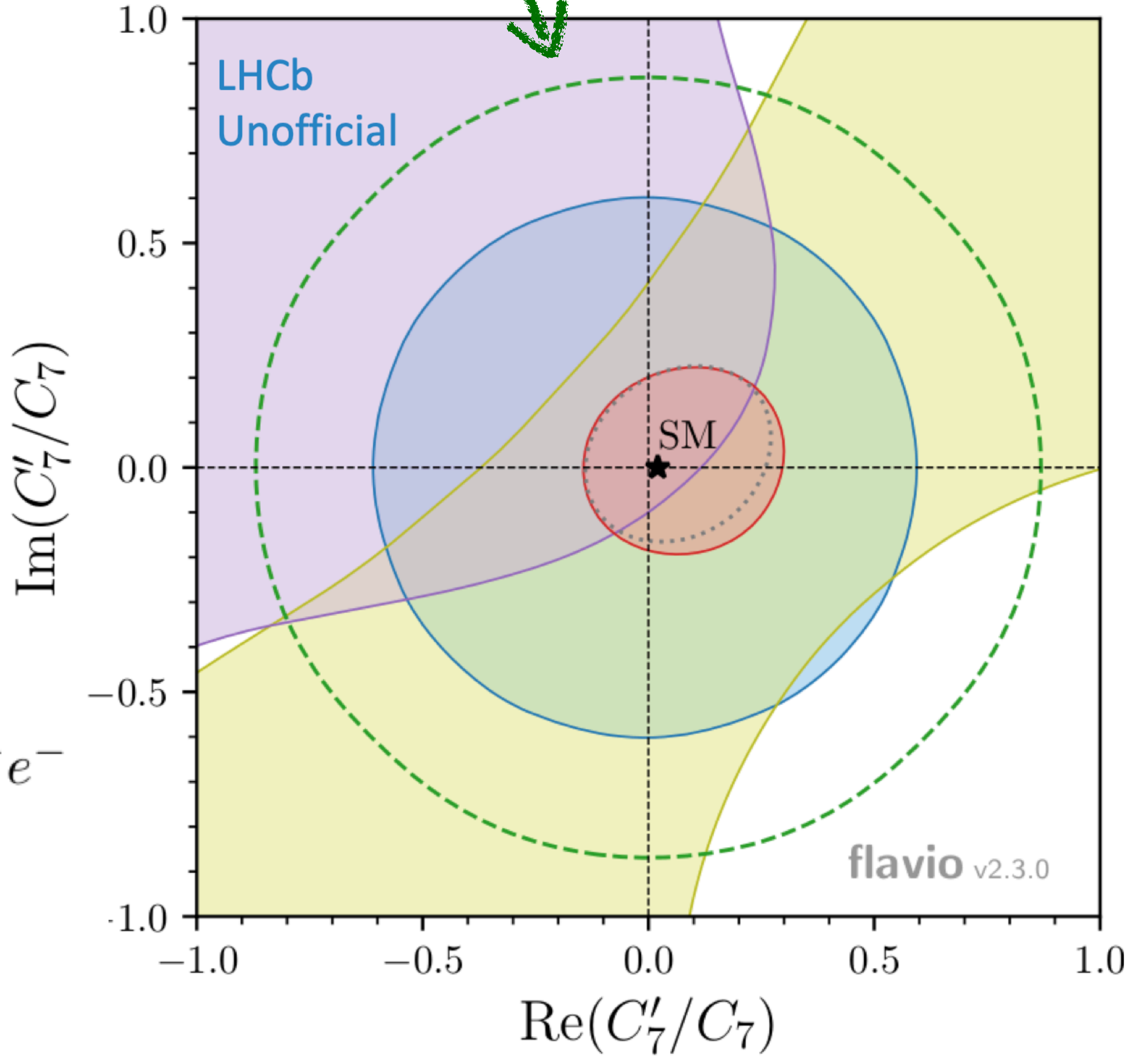
- Photons from radiative penguins predominantly left-handed in the SM
  - C_7 (C_7') is the left(right)-handed $b \to s\gamma$ effective coupling

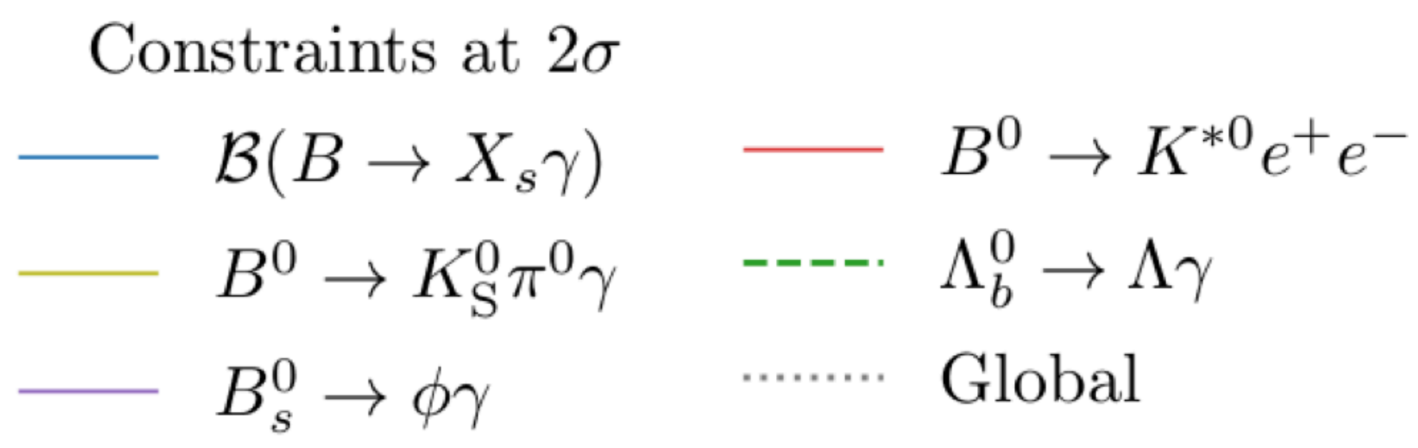
New

Angular analysis of $\Lambda_b^0 \to \Lambda^0\,\gamma$



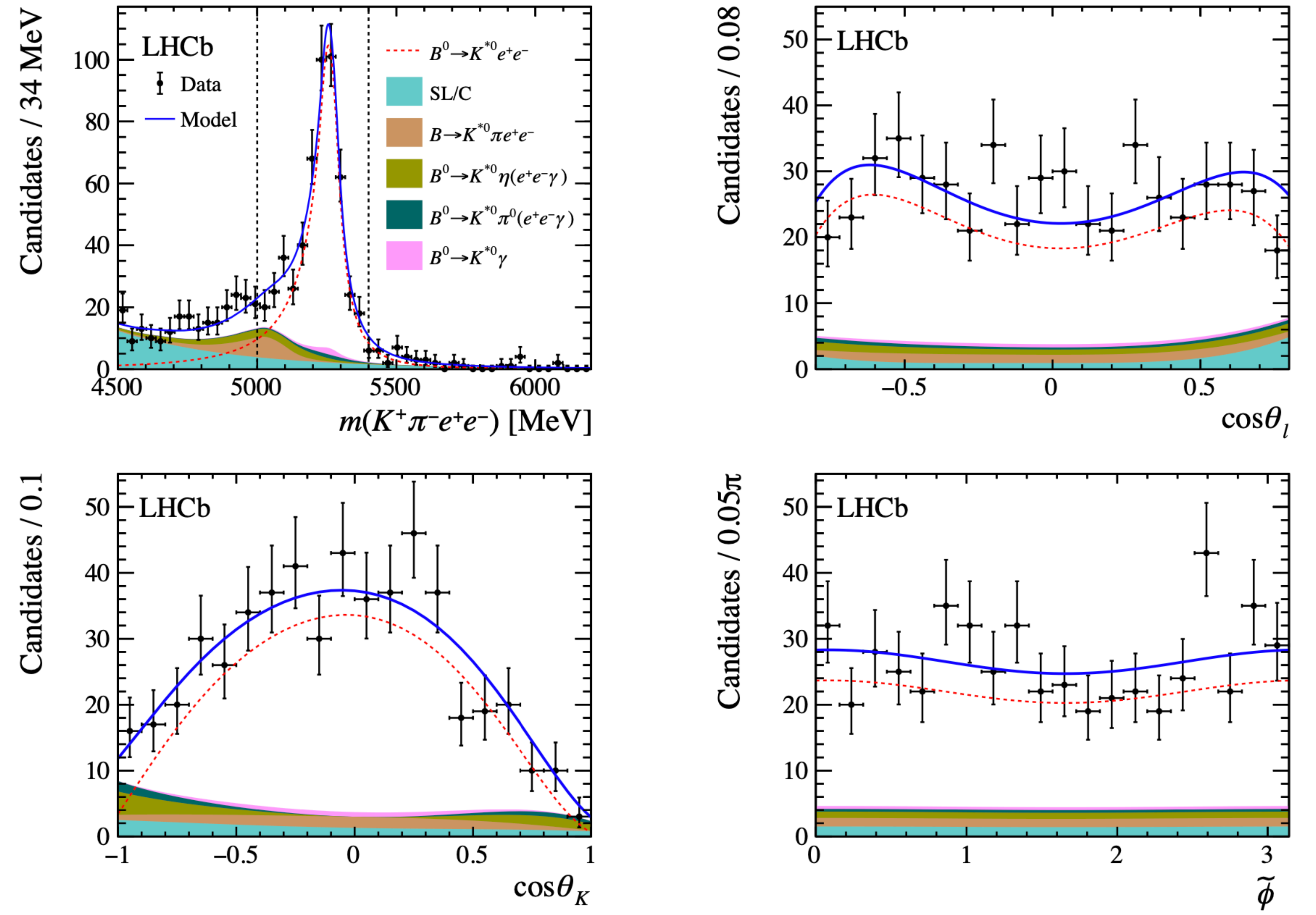
[LHCb-PAPER-2021-030
in preparation]





$B^0 \to K^{*0}ee$ with full Run1+2

$q^2 \in [0.0008, 0.257]\ \mathrm{GeV}^2/c^4$



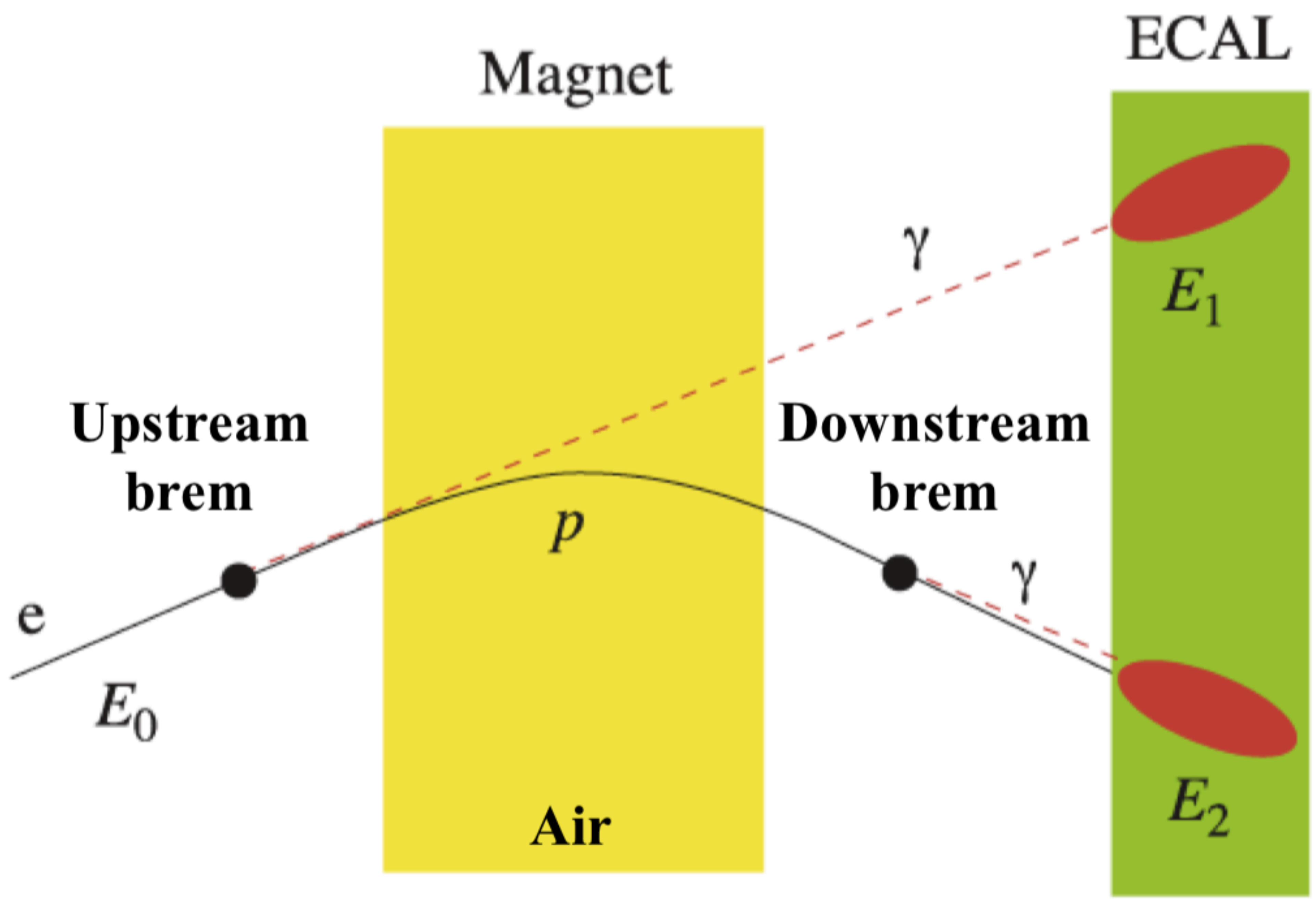
[JHEP 12 (2020) 081]

LFU measurements at LHCb

[LHCb, arXiv:2103.11769]

- Electrons lose a large fraction of their energy through Bremsstrahlung radiation
  - Bremsstrahlung recovery: Look for photon clusters in the calorimeter (ET > 75 MeV) compatible with electron direction before magnet

- After this correction electrons still have
  - Lower reconstruction/trigger/PID efficiency
  - Worse mass and q2 resolution (more background)



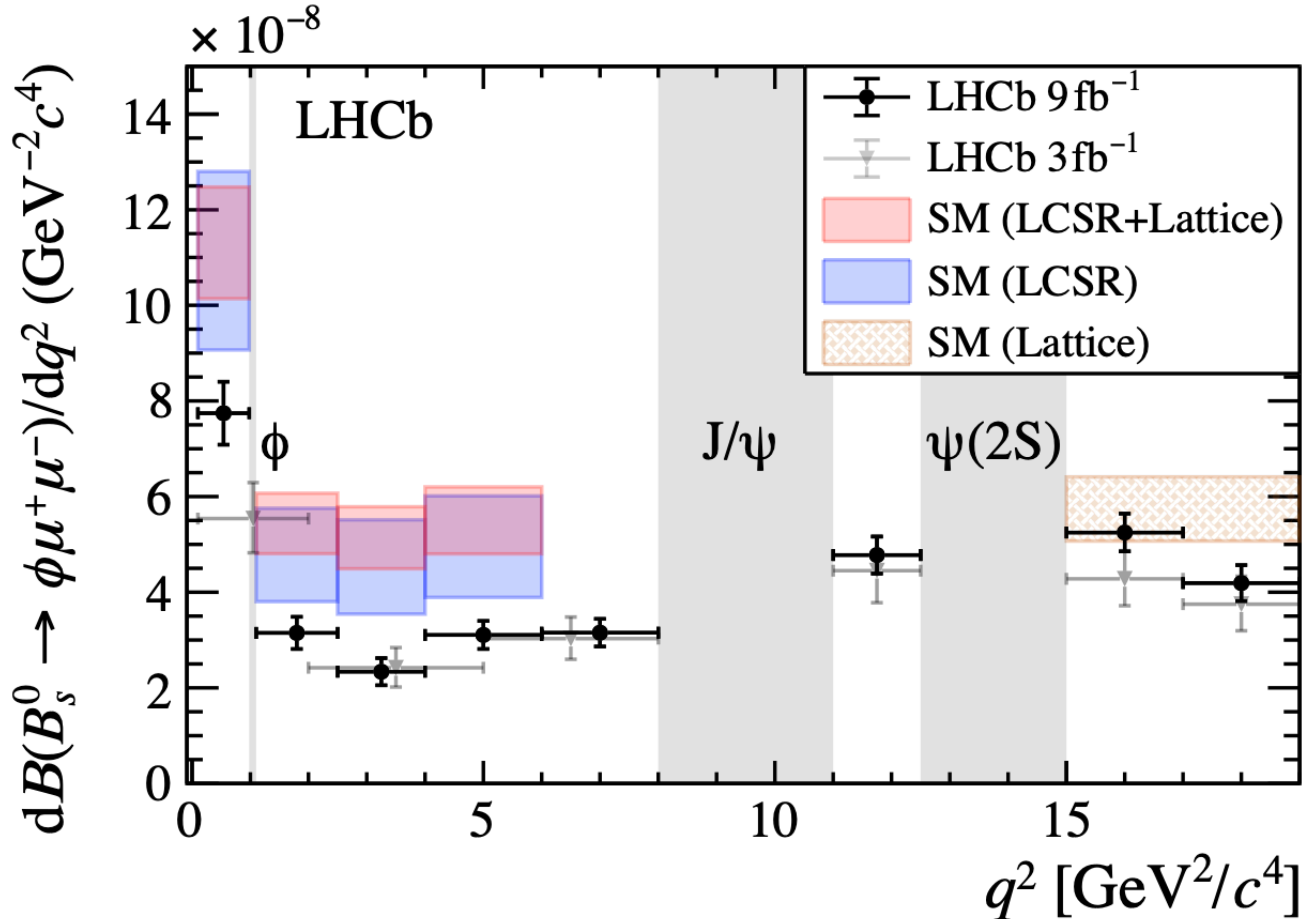
$B^0_S \to \phi\, \mu^+\mu^-$ and $B^0_S \to f_2\, \mu^+\mu^-$

[LHCb, arXiv:2105.14007]

- Update using full Run1+Run2 dataset
- In the region $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$

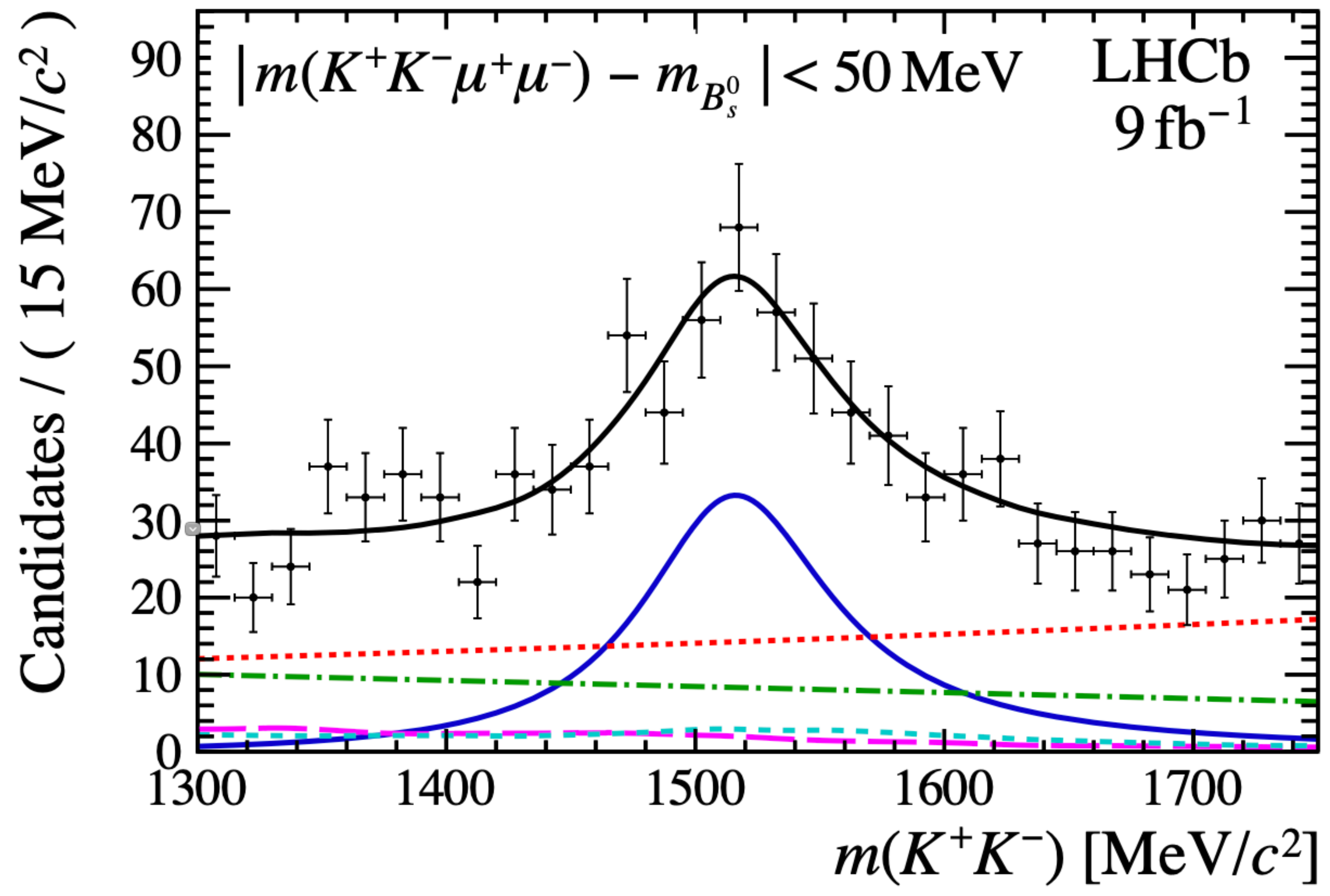
$$\mathrm{d}\mathcal{B}(B^0_s \to \phi\mu^+\mu^-)/\mathrm{d}q^2 = (2.88 \pm 0.21) \times 10^{-8}$$

  - Tension with the SM at 3.6 σ level
    (1.8 σ with LCSR alone)



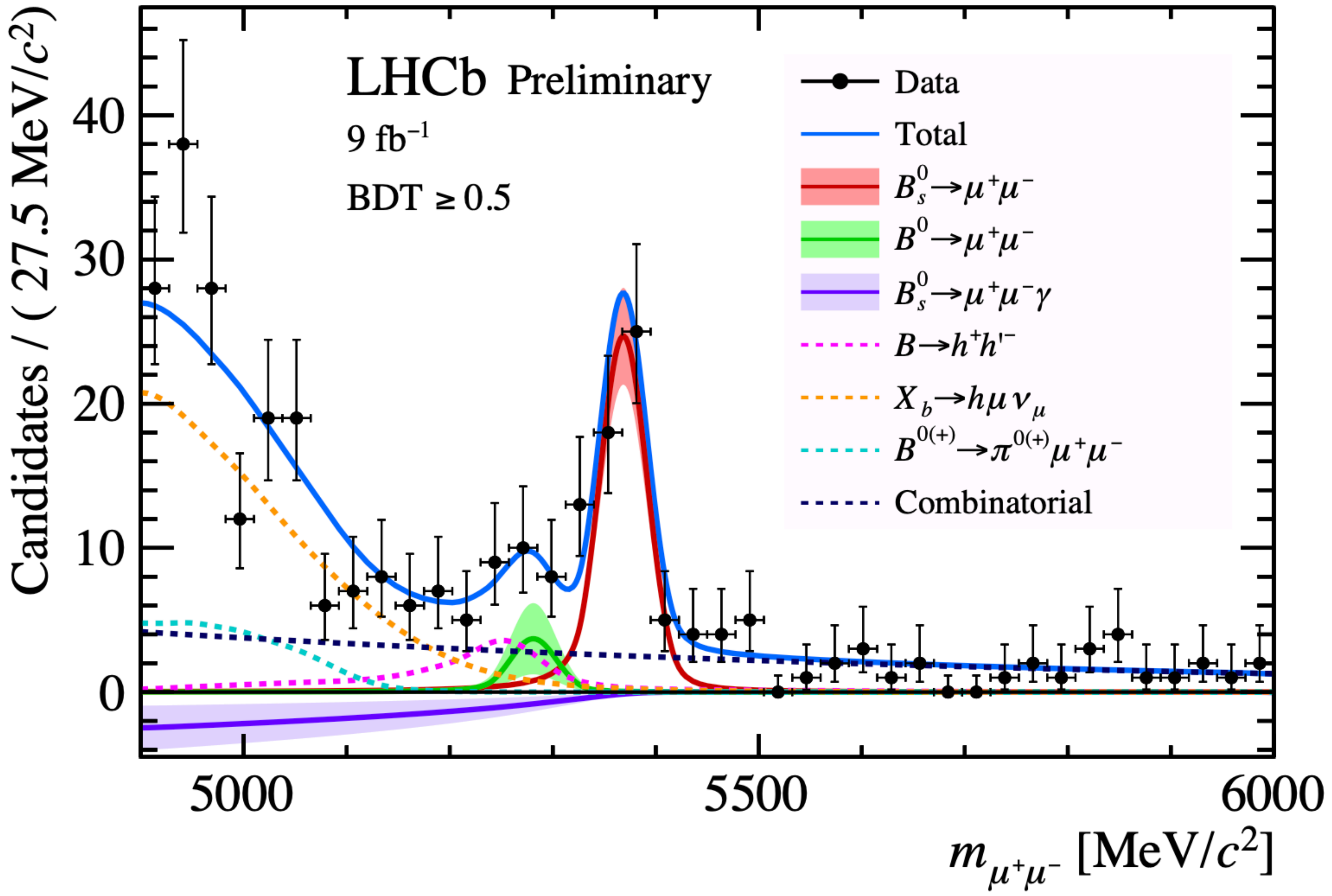
- First observation of $B^0_s \to f_2'(1525)\ \mu^+\mu^-$ [9σ]

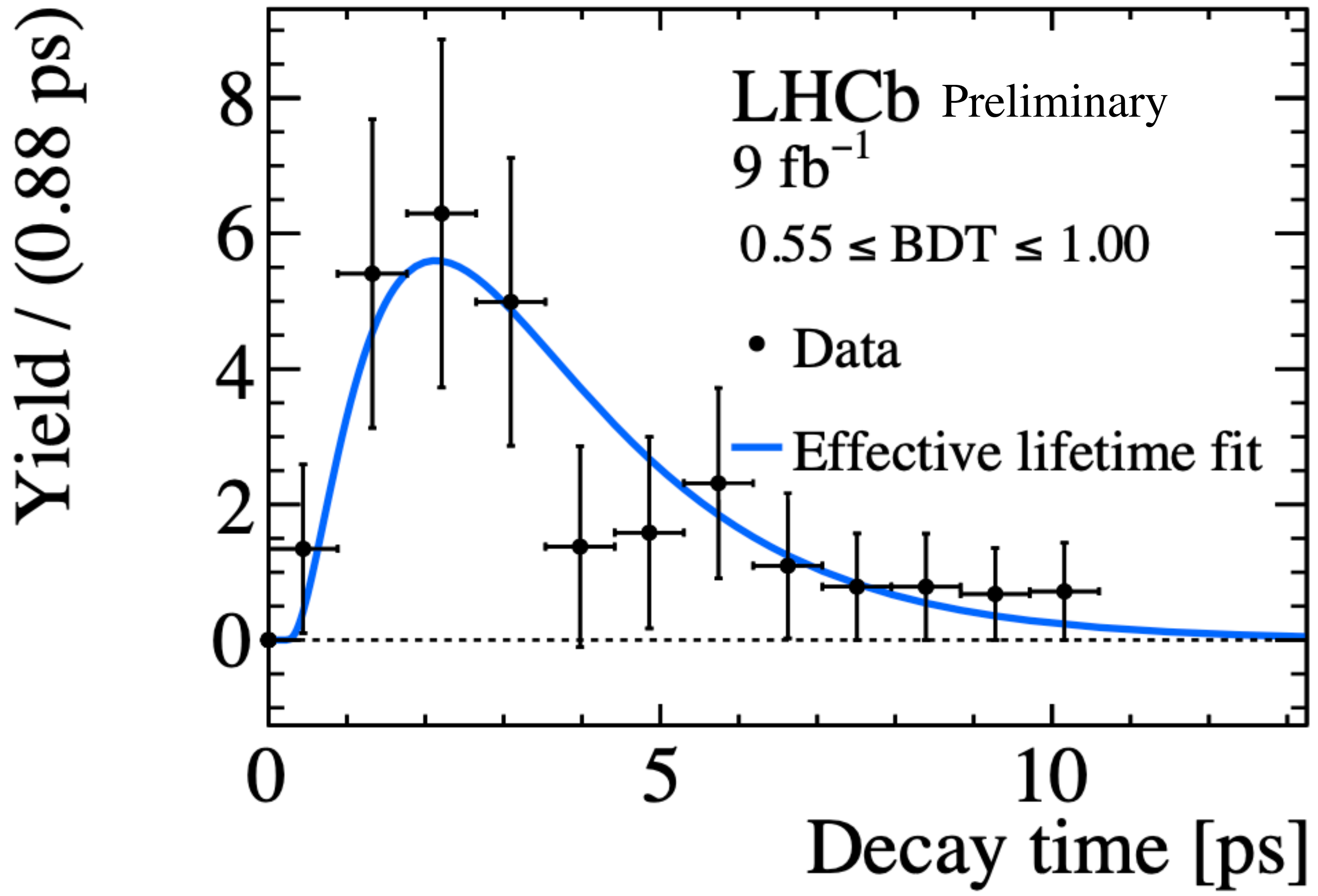
$$\mathcal{B}(B^0_s \to f_2'\mu^+\mu^-) = (1.57 \pm 0.19\ (\mathrm{stat}) \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$$



$B^0_{(S)} \to \mu^+\mu^-$: New LHCb result

[LHCb-PAPER-2021-007]
[LHCb-PAPER-2021-008]
in preparation





- Full Run1+2 LHCb sample
- Find $B_s \to \mu^+\mu^-$ with significance >10σ, but no evidence yet for $B^0 \to \mu^+\mu^-$ (1.7σ)

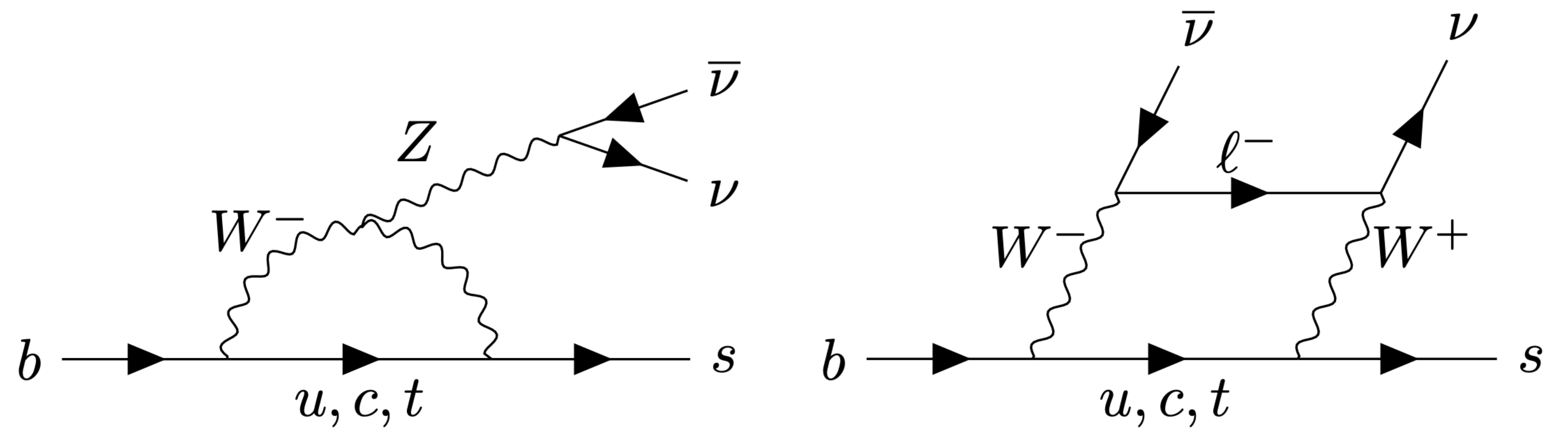
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09\ ^{+0.46}_{-0.43}\ ^{+0.15}_{-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\ (95\,\%\,\text{CL})$$

- Set a limit also for the radiative decay (ISR) $\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-}>4.9\text{GeV}} < 2.0 \times 10^{-10}\ (95\,\%\,\text{CL})$
- Updated effective lifetime $\tau_{\text{eff}}(B^0_s \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03$ ps
- Main BR systematics from f_s/f_d (3%) improved from an updated hadronisation fraction [LHCb, arXiv:2103.06810]

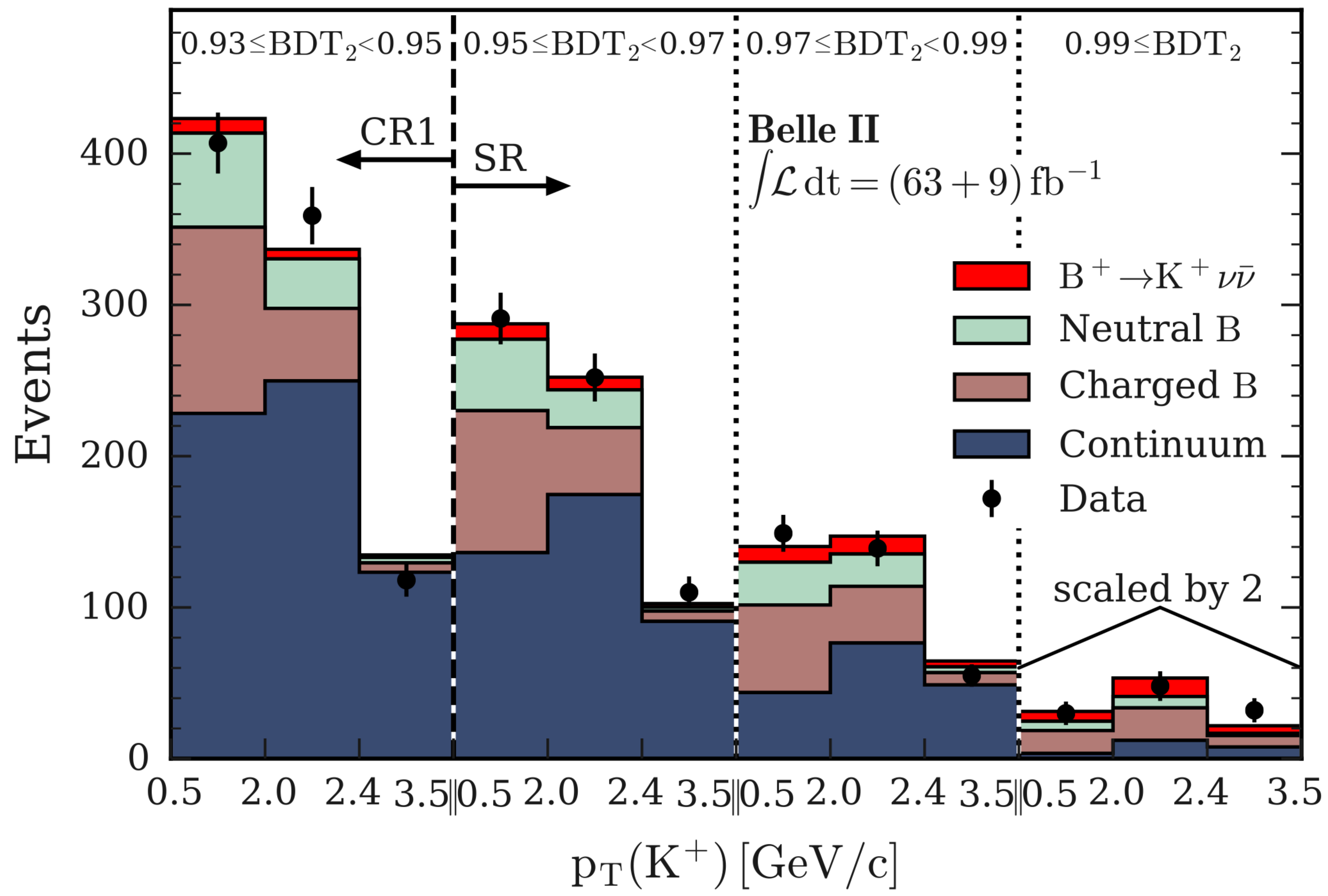
Search for $B^+ \to K^+\nu\bar{\nu}$

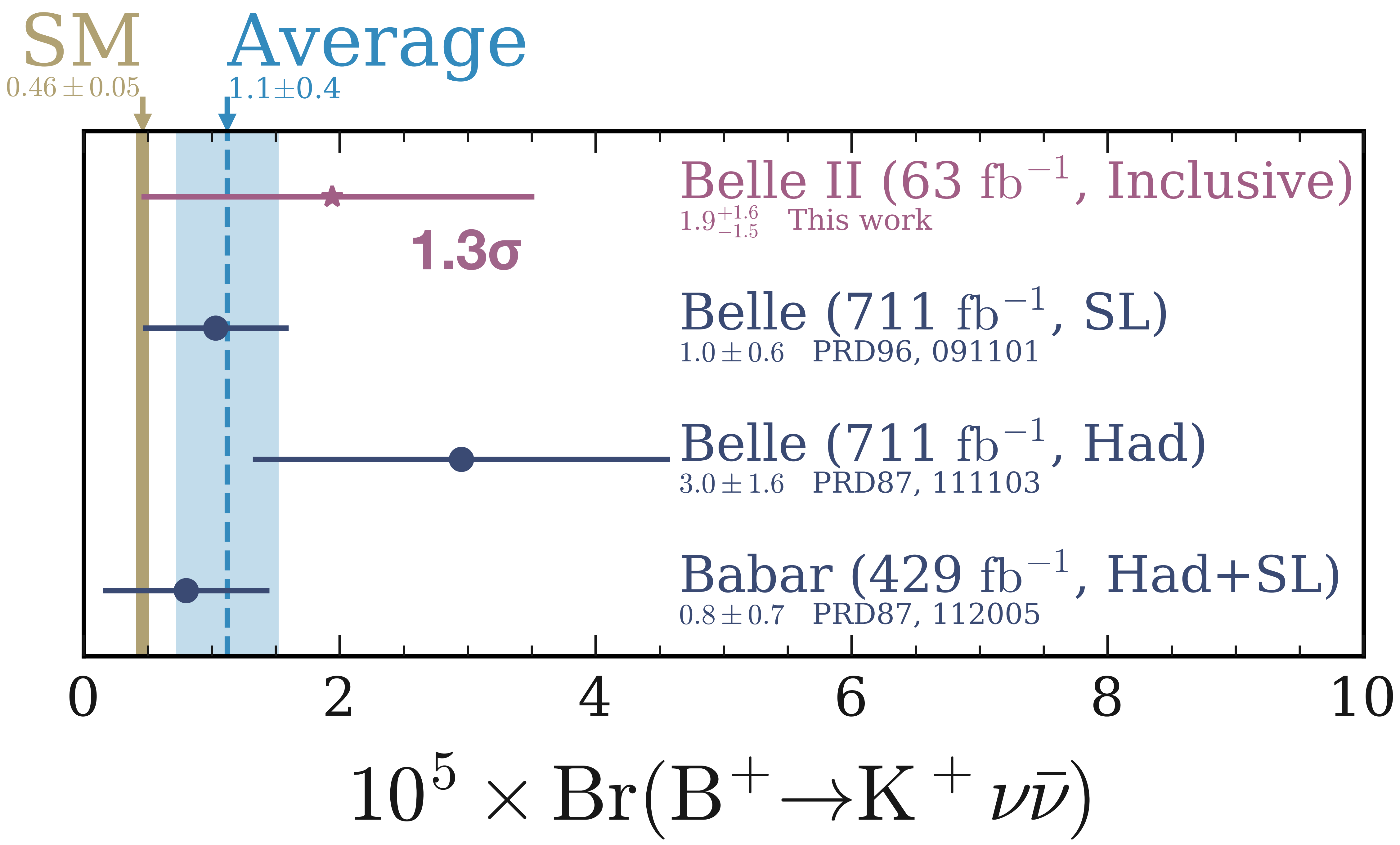
[Belle II, arXiv:2104.12624]

- Purely weak penguin
  - $\mathscr{B}^{SM} = (4.6 \pm 0.5) \times 10^{-6}$ [Blake et al, PPNP 92 (2017) 50]
  - Very challenging experimentally



- New Belle II analysis, reaches competitive sensitivity using just 63/fb of integrated luminosity





Lepton Flavour Non-Universal effects in the SM? [Phys. Rev. D105 (2022) L031903]

- It was recently proposed that the photons from decays of the kind:

$$B \to K\pi^0(\to e^+e^-\gamma)\gamma$$

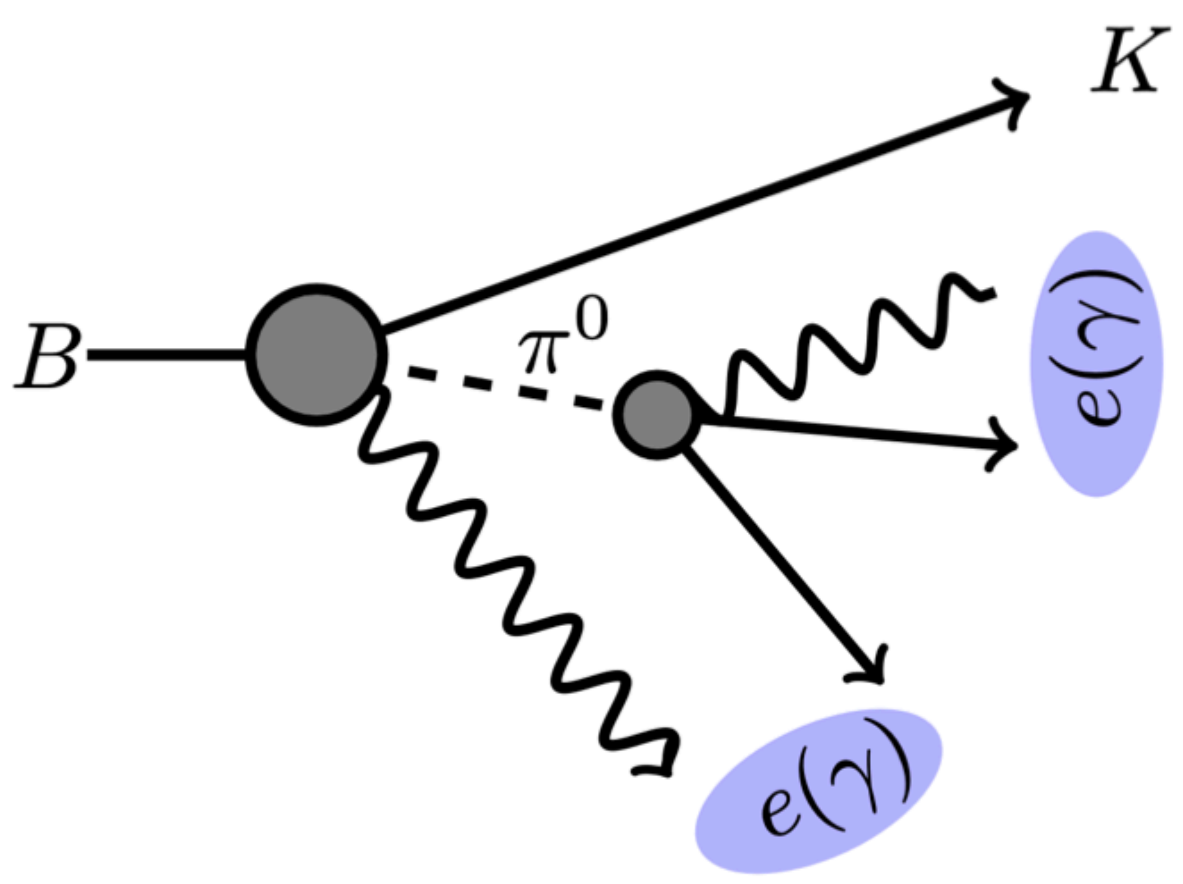
could be added to the electrons as bremsstrahlung photons mimicking the rare modes $B \to Ke^+e^-$ and emulate an excess of the electrons

- Effect was estimated in [arXiv:2110.11209] to be at 4% order

- If this was the case we would observe an accumulation of events below $q^2_{\rm TRACK} = m^2_{\pi^0}$ where

$$q^2_{\rm TRACK} = (p_{\rm TRACK}(e^+) + p_{\rm TRACK}(e^-))^2$$

Is the dilepton invariant mass computed using only track information (and no bremsstrahlung recovery)



Number of fully selected events with $q^2_{\rm TRACK} < m^2_{\pi^0}$ that enter the R_K result are < 1 per-mille