Rare decay measurements with the LHCb experiment

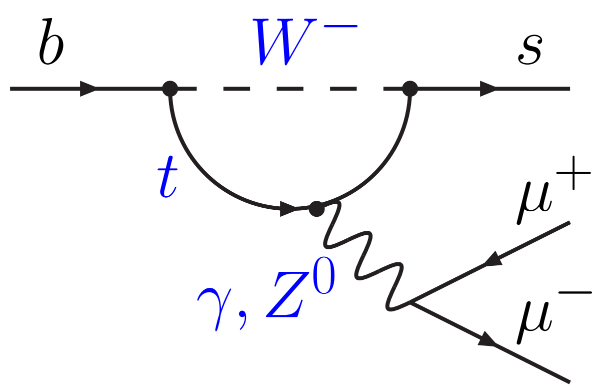
Titus Mombächer
IGFAE, Universidade de Santiago de Compostela

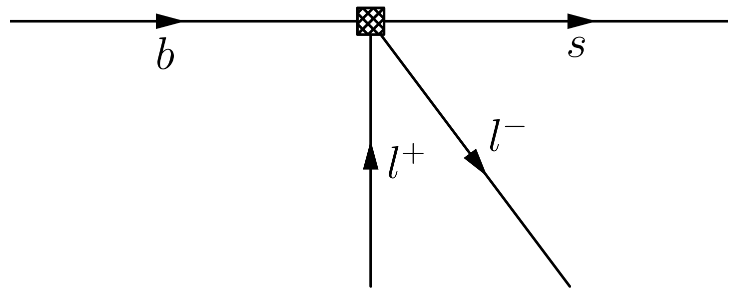
Red LHC workshop 2022
10.05.2022

titus.mombacher@cern.ch

Why rare decays?

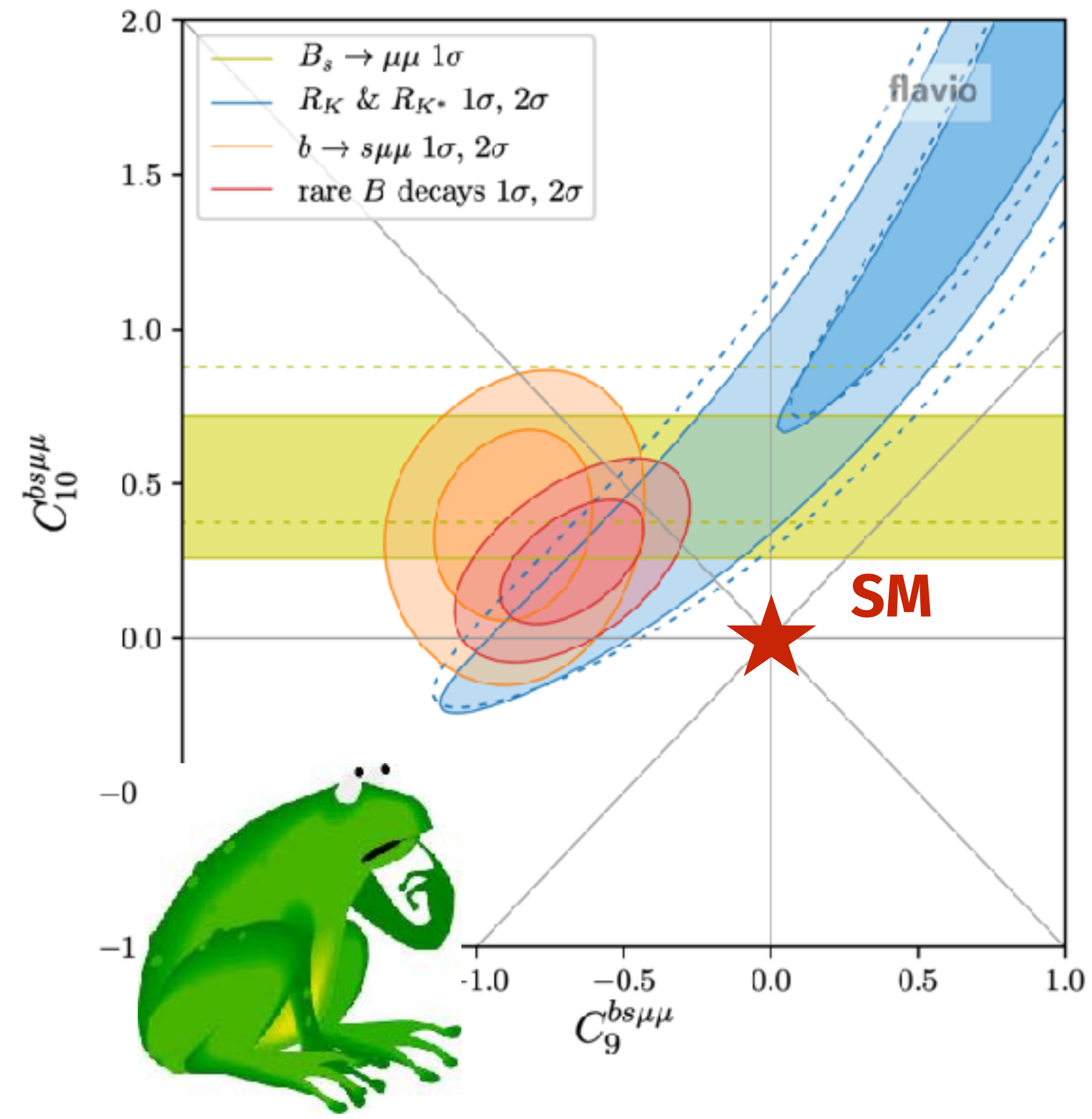
- Excellent probes for New Physics (NP)
  - Complementary to direct NP searches
    $\rightarrow$ explore higher energy scales
  - Standard Model (SM) background is small (even negligible)
  - NP might show sizeable effects
- Special interest in $b \rightarrow s\ell\ell$ transitions:
  Find deviations from SM in
  - (Differential) $b \rightarrow s\mu^+\mu^-$ branching fractions
  - $b \rightarrow s\mu^+\mu^-$ angular distributions
  - Lepton Flavour Universality ratios





See also talk by J. Virto

[Altmannshofer/Stangl, arXiv:2103.13370]

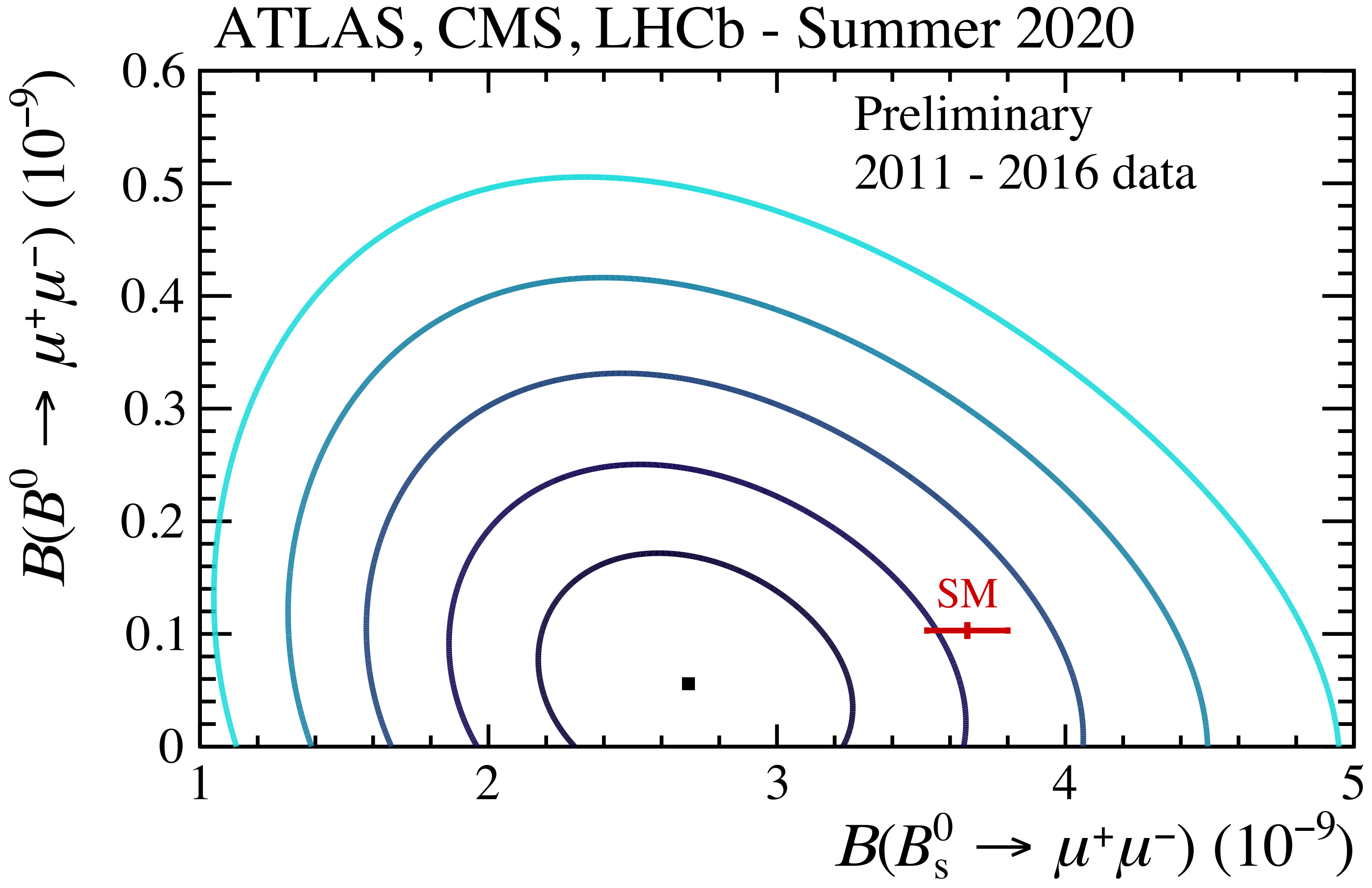


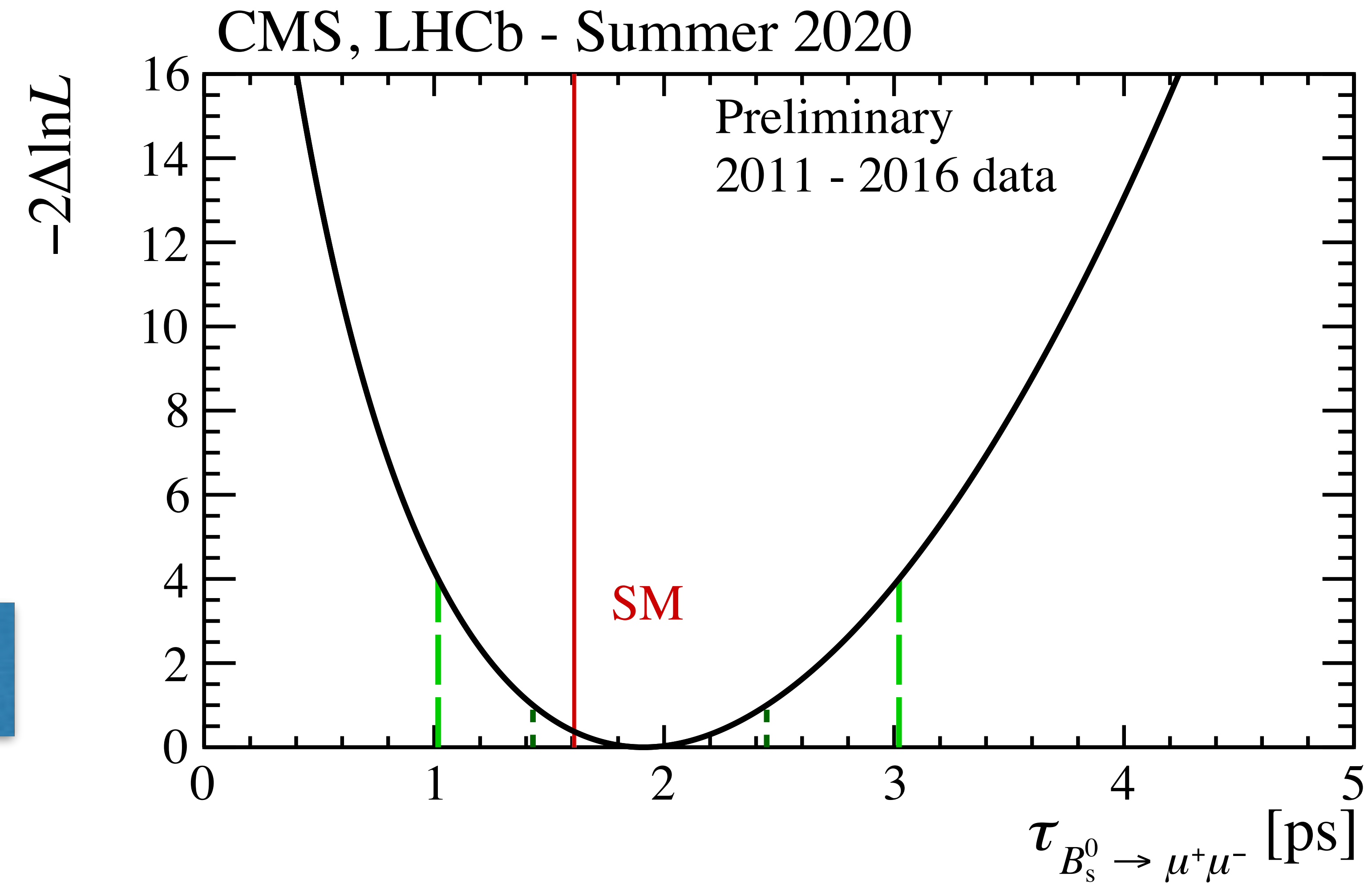
$B^0_{(s)} \to \mu^+\mu^-$ - the golden rare decays

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

- „High precision regime“ in branching fraction measurements with combination of LHC experiments:
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.69^{+0.37}_{-0.35} \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ @ 95 % CL
- Access to CP structure of $B^0_s \to \mu^+\mu^-$ decays via effective lifetime
  - Only the CP-odd eigenstate can decay to $\mu^+\mu^-$ in the SM
  - $\tau_{\mu^+\mu^-} = 1.62$ ps (CP-odd) vs. 1.42 ps (CP-even) [Particle Data Group]
  - Combinations of LHCb and CMS: $\tau_{\mu^+\mu^-} = 1.91^{+0.37}_{-0.35}$ ps

Measurements with ~half the available Run 1+2 data yet!



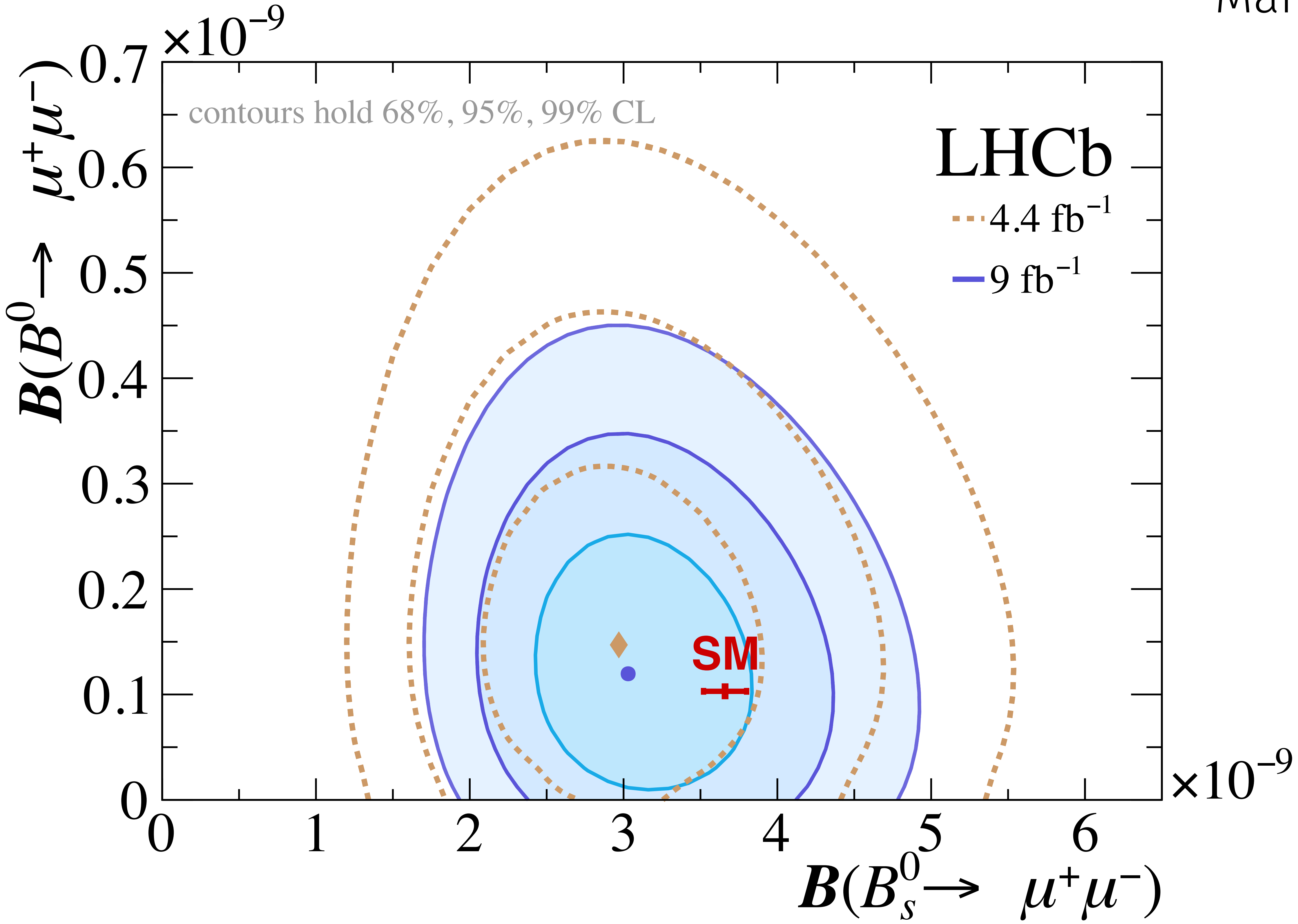


PRL 128 (2022) 041801
PRD 105 (2022) 012010

Update of the $B^0_{(s)} \to \mu^+\mu^-$ analysis with LHCb Run 1+2

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

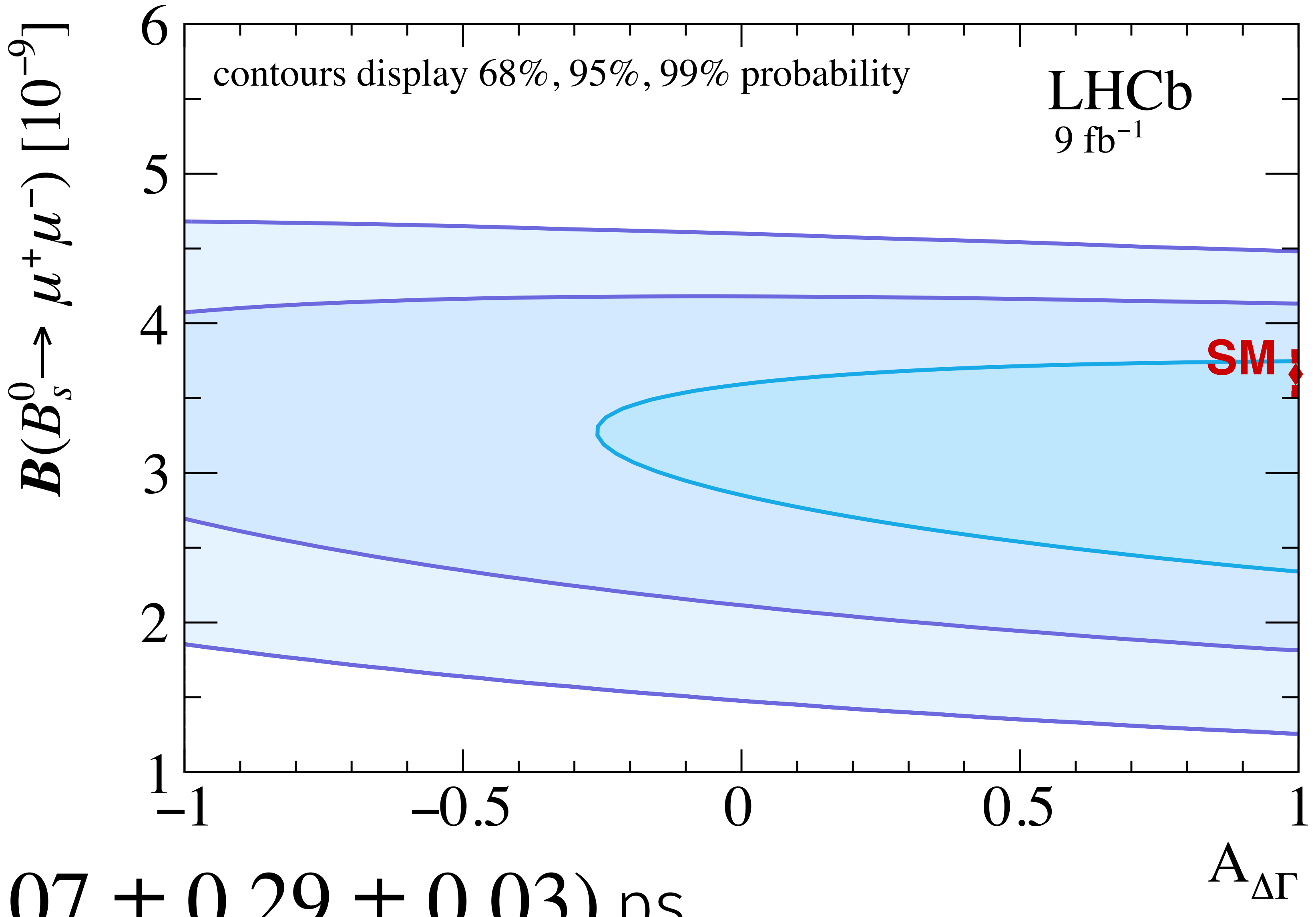
Similar precision as previous WA!



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

$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-} > 4.9\,\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$ @ 95 % CL

Main systematics from f_s/f_d (3%), normalisation $\mathcal{B}$ (3%), bkg description



$\tau_{\mu\mu} = (2.07 \pm 0.29 \pm 0.03)$ ps

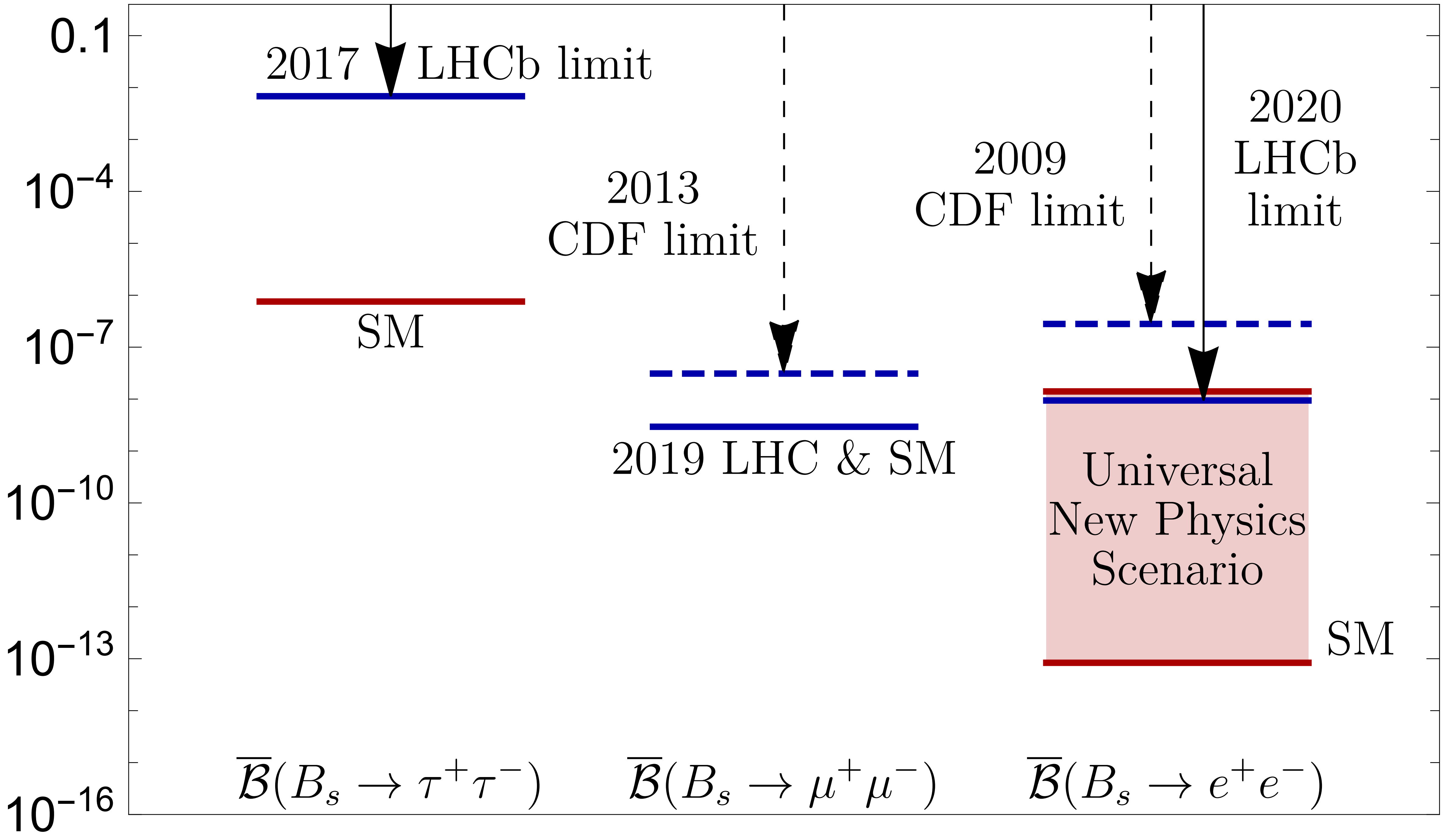
- Compatible at 1σ (2σ) with CP-odd/SM (CP-even) B^0_s eigenstate
- Systematic uncertainties negligible

PRL 124 (2020) 211802
PRD 118 (2017) 251802

Other $B^0_{(s)} \to \ell^+\ell^-$ decays

- Sensitivities for $B^0_{(s)} \to \tau^+\tau^-$ and $B^0_{(s)} \to e^+e^-$ significantly away from SM
  - $2 \times \tau$ (here hadronic) difficult to reconstruct
  - SM prediction for $B^0_{(s)} \to e^+e^-$ extremely small
  - Best limits from partial LHCb data set, probing New Physics scenarios
- At least 2x data set on tape, being analysed
- Hadronic and electronic final states profit vastly from new LHCb trigger strategy in Run 3

[Fleischer et al., JHEP 05 (2017) 156]



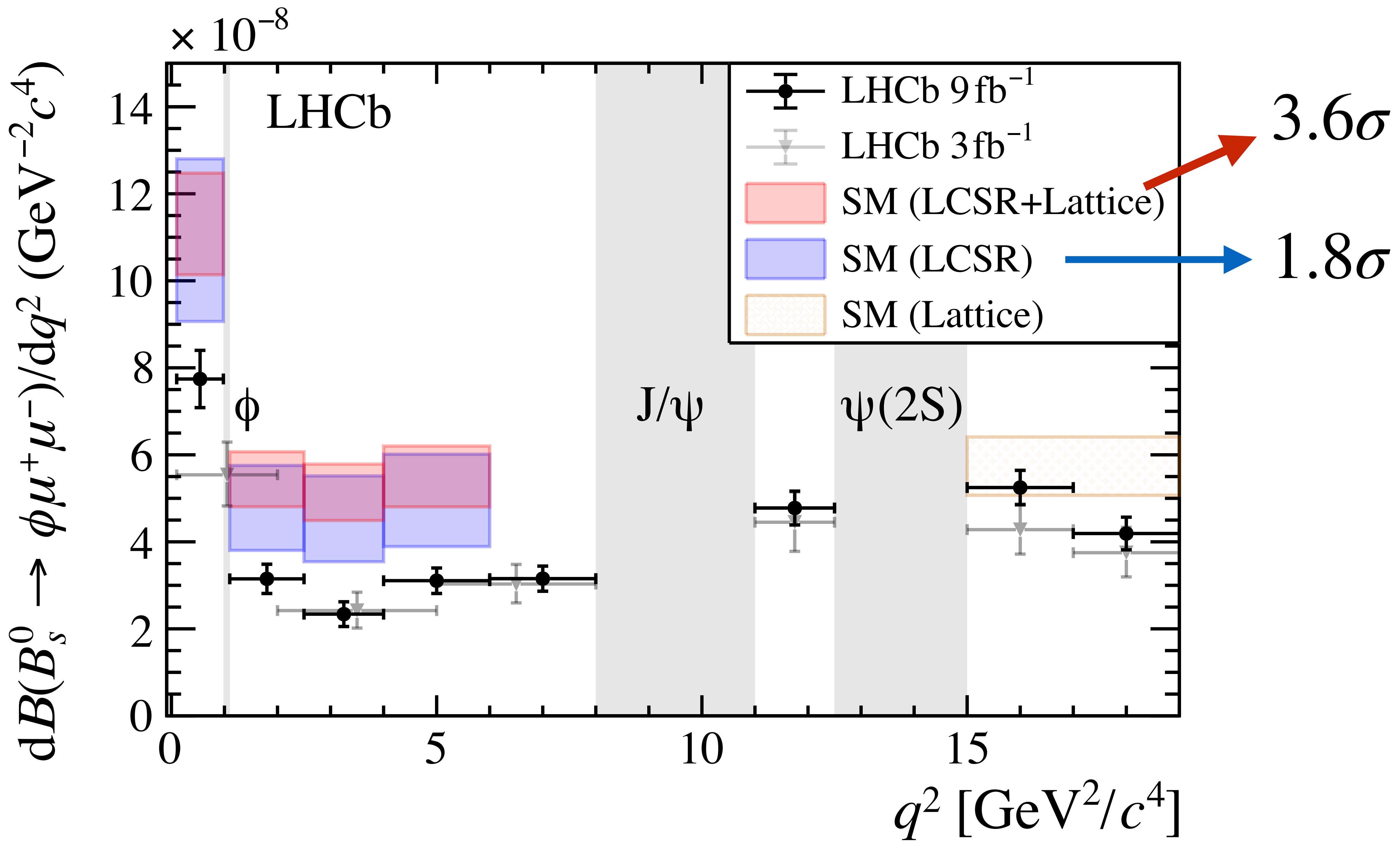
Limits at 95% CL

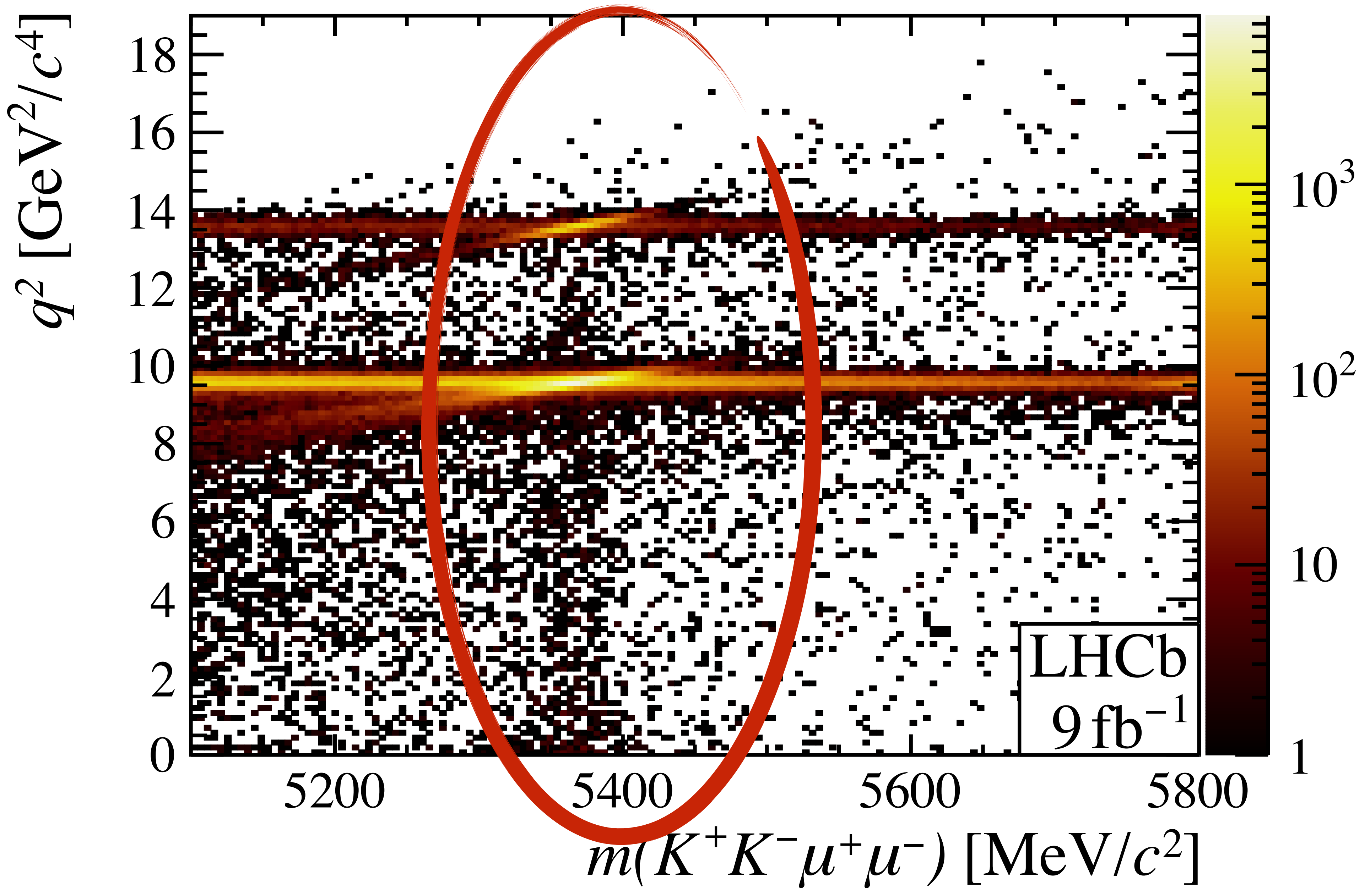
$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ $\mathcal{B}(B^0_s \to e^+e^-) < 11.2 \times 10^{-9}$

$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$ $\mathcal{B}(B^0 \to e^+e^-) < 3.0 \times 10^{-9}$

PRL 127 (2021) 151801

Differential branching fractions: $B_s^0 \to \phi\mu^+\mu^-$





$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (8.14 \pm 0.21 \pm 0.16 \pm 0.39 \pm 0.03) \times 10^{-7}$

syst norm q^2 extrap.

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

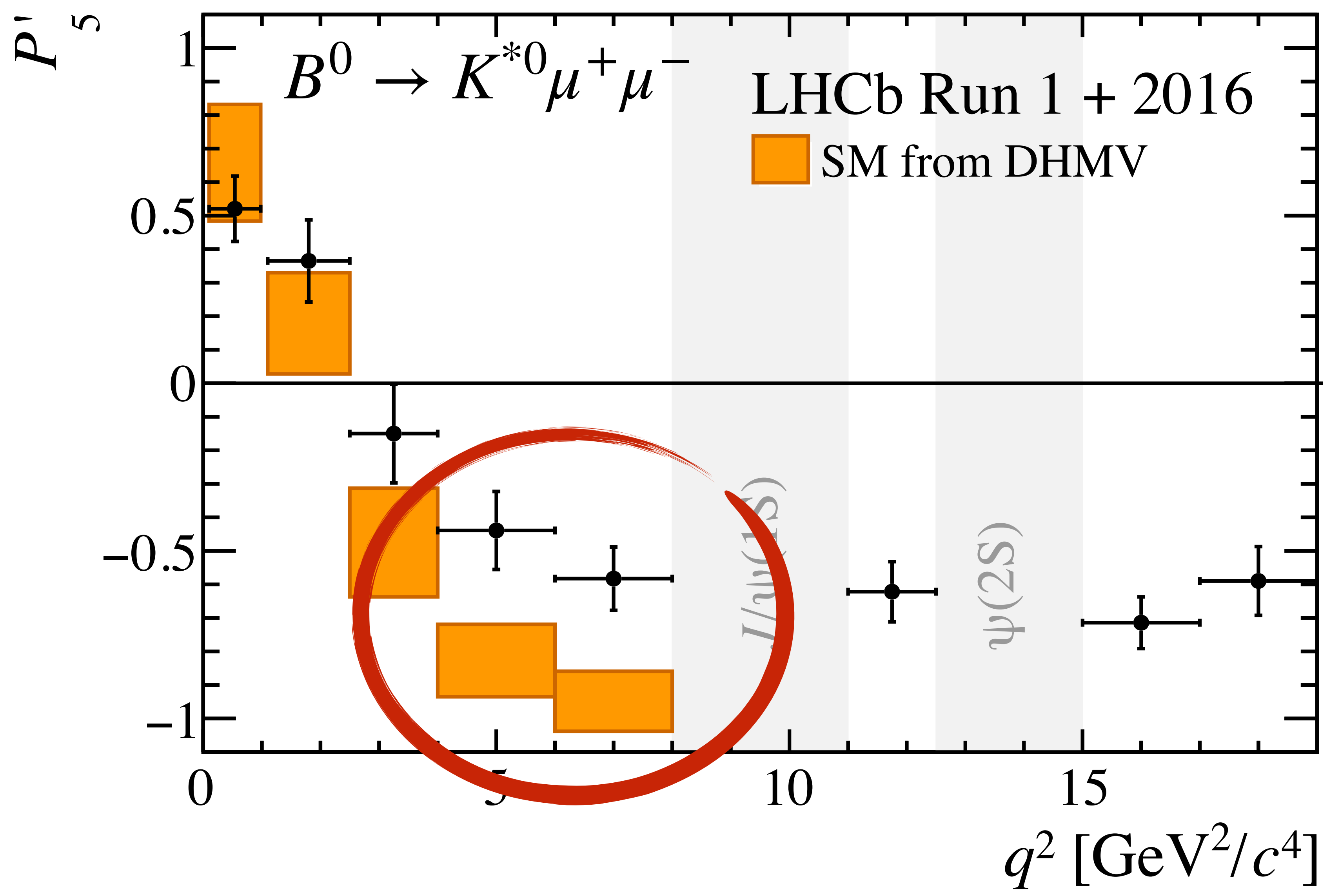
First observation of spin-2 FCNC: $> 9\sigma$

Similar trends in $B^0 \to K^{*0}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$, $B^0 \to K_S^0\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$

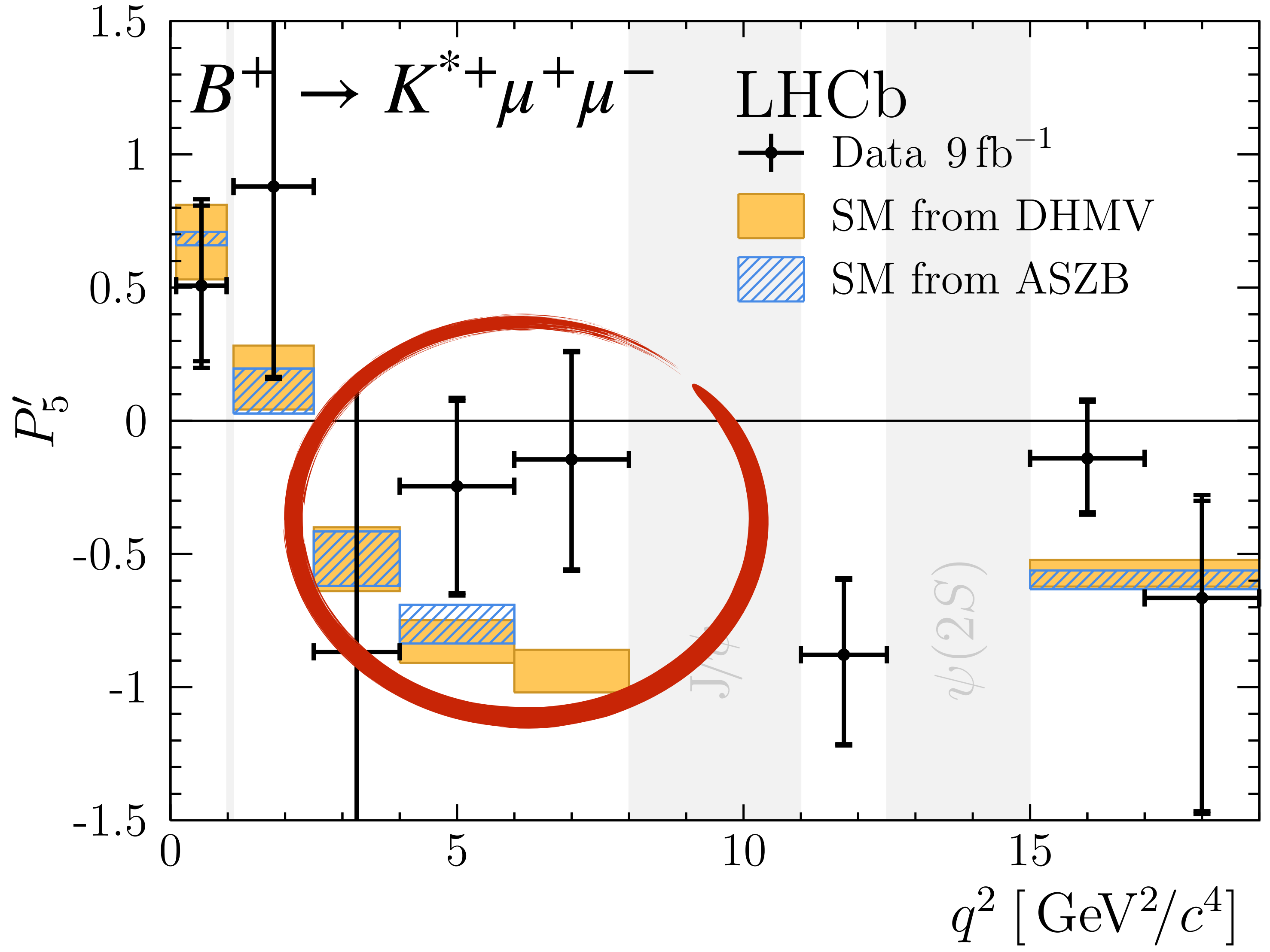
Angular analyses of $b \to s\ell^+\ell^-$ - type decays

- Multibody final states: possible NP effects in angular observables
- Observables ratio $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ less dependent on form factor uncertainties

  $\to$ only available for flavour-specific decays, for $B^0_s \to \phi\mu^+\mu^-$ flavour tagging might become available by end of Run 3
- Angular analyses show similar pattern

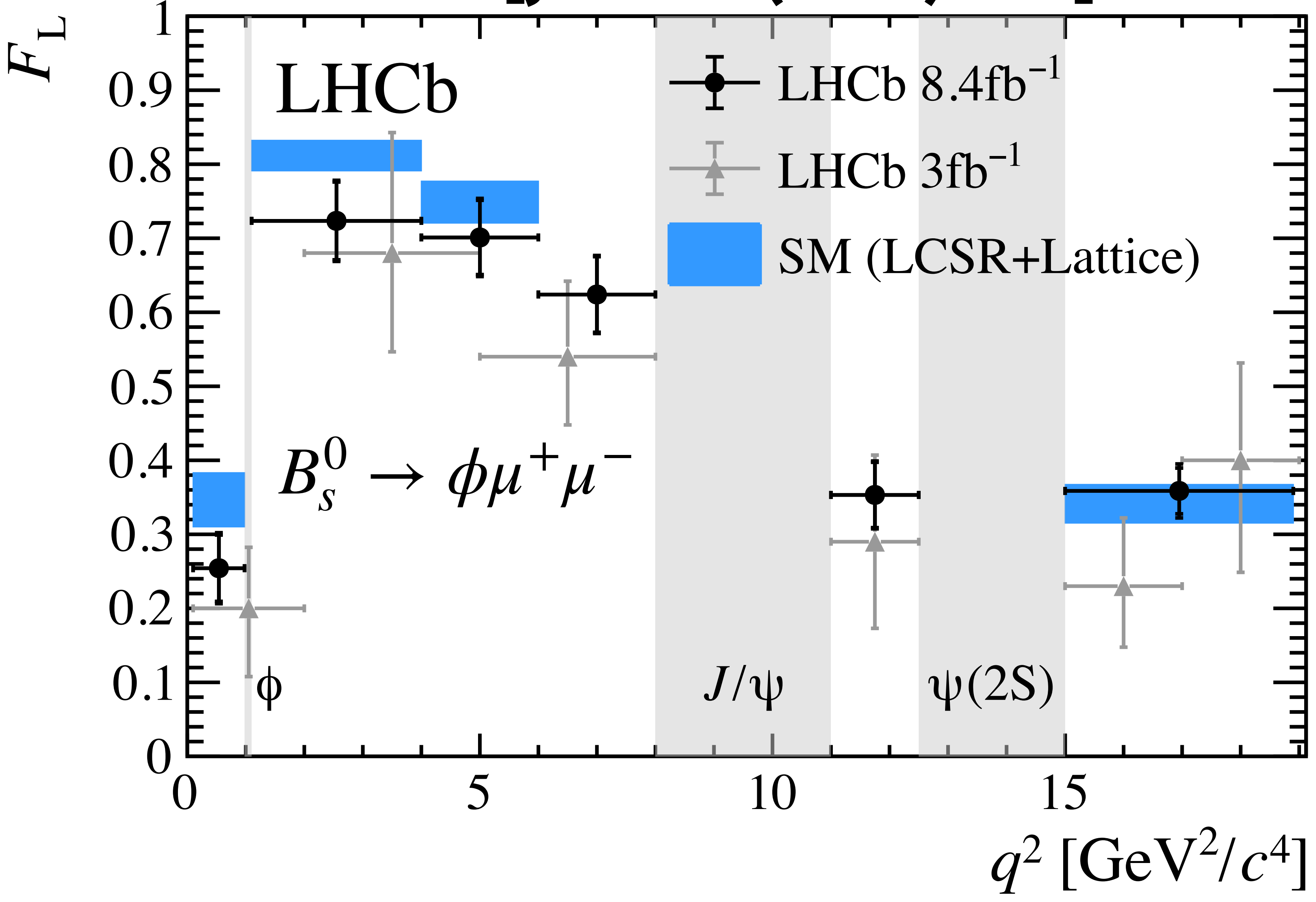


[PRL 125 (2020) 011802]



[PRL 126 (2021) 161802]

[JHEP 11 (2021) 043]



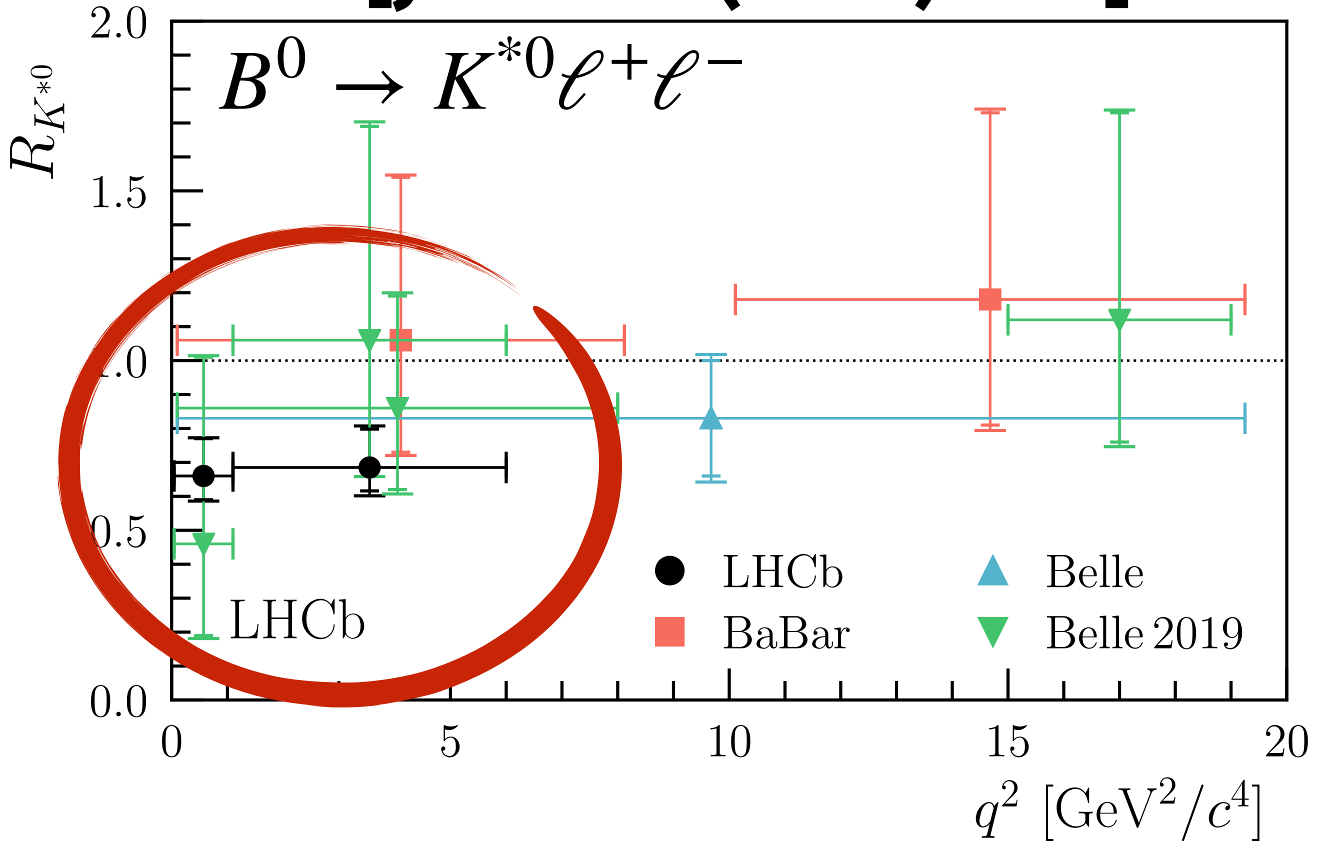
Lepton flavour universality ratios

- Double ratio to cancel experimental systematics and theoretical uncertainties:

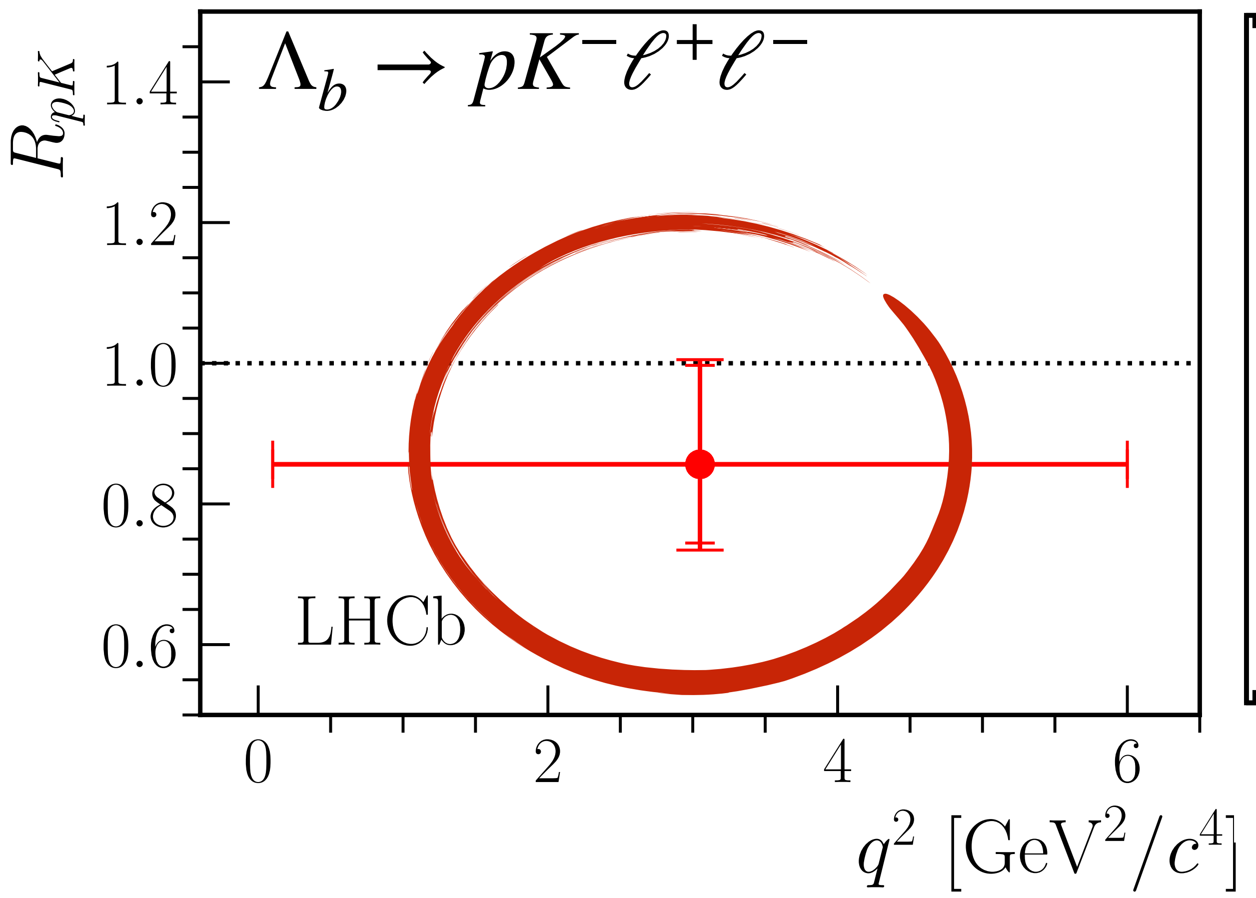
$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2} \times \frac{\mathcal{B}(B\to HJ/\psi(\to e^+e^-))}{\mathcal{B}(B\to HJ/\psi(\to \mu^+\mu^-))} = 1$$

- Stringent cross check of $r_{J/\psi} = \frac{\mathcal{B}(B\to HJ/\psi(\to e^+e^-))}{\mathcal{B}(B\to HJ/\psi(\to \mu^+\mu^-))}$ to test that electron and muon efficiencies are under control
- Also here consistent deviations from SM up to $3\sigma \to$ need closer investigation with more data and alternative experiments!

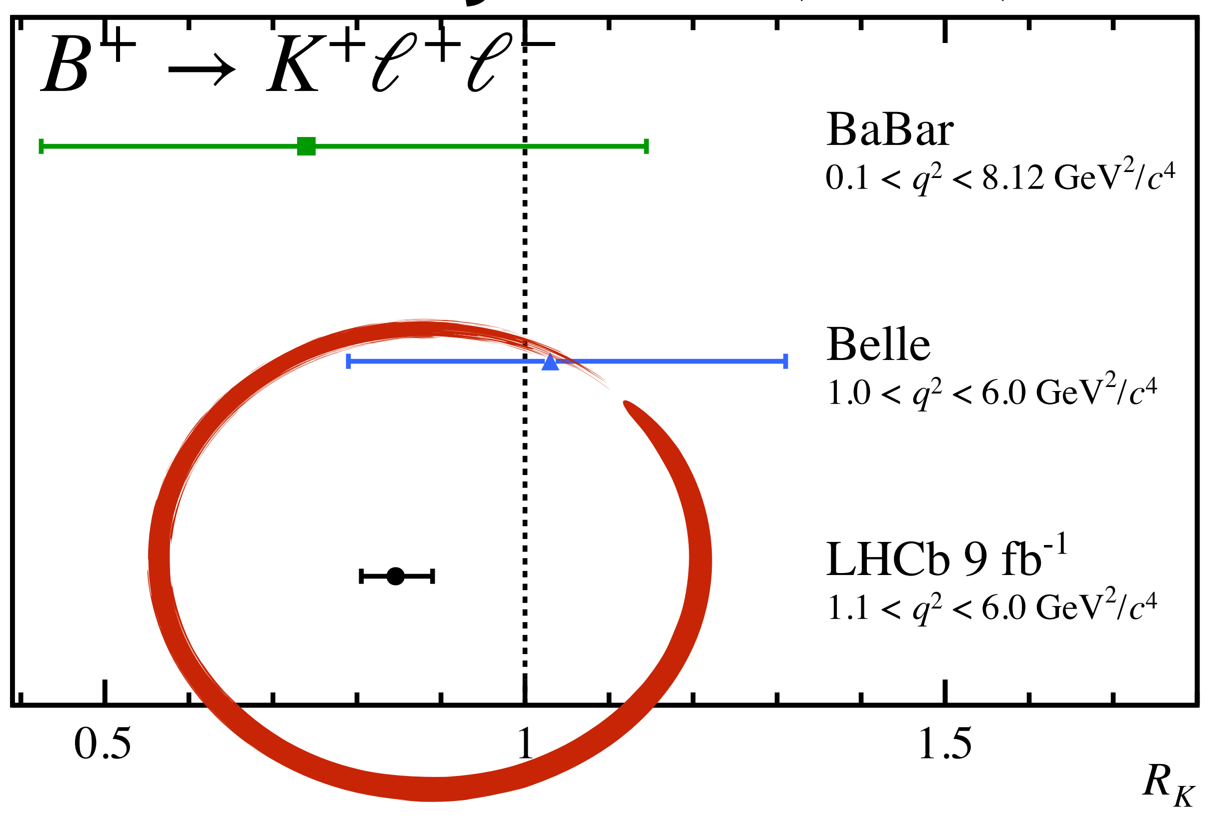
[JHEP 08 (2017) 055]



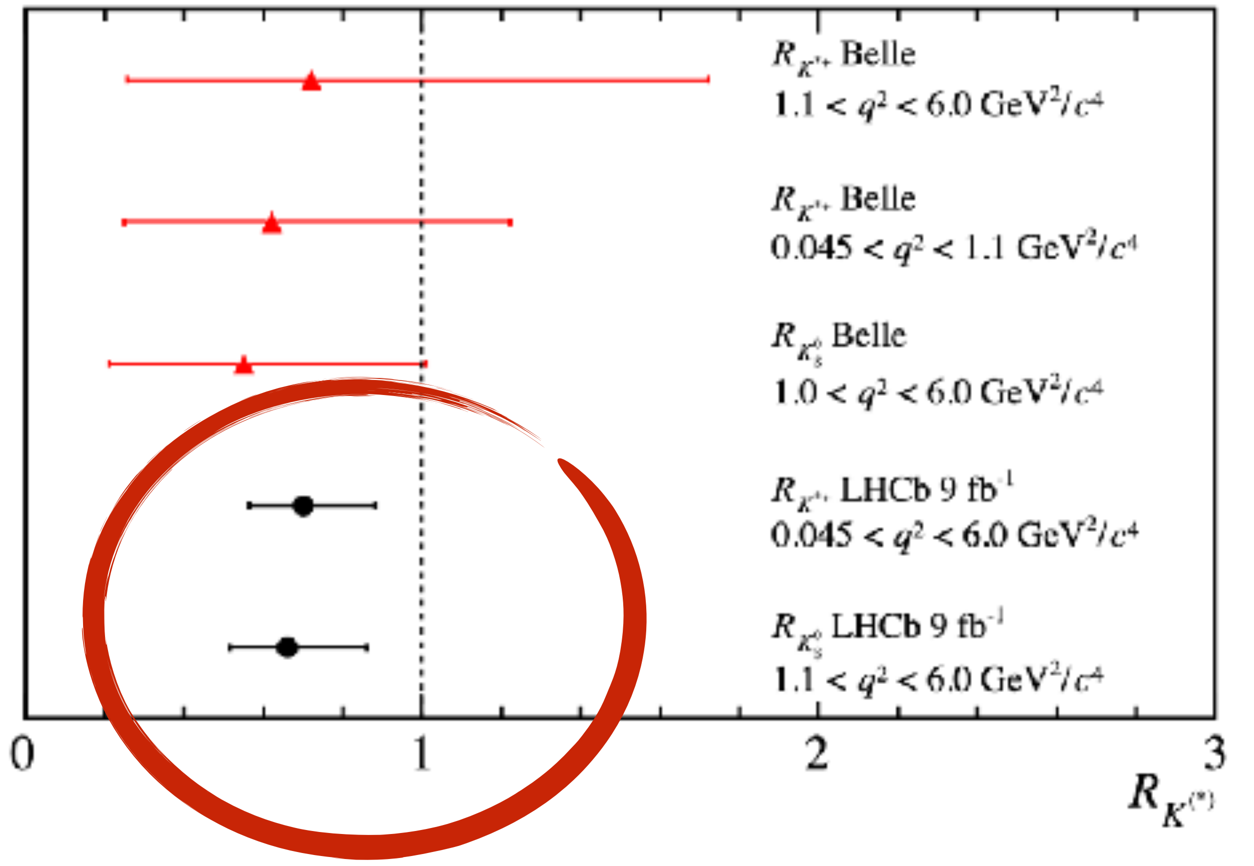
[JHEP 05 (2020) 040]



[Nature Physics 18 (2022) 272]



[arXiv:2110.09501]

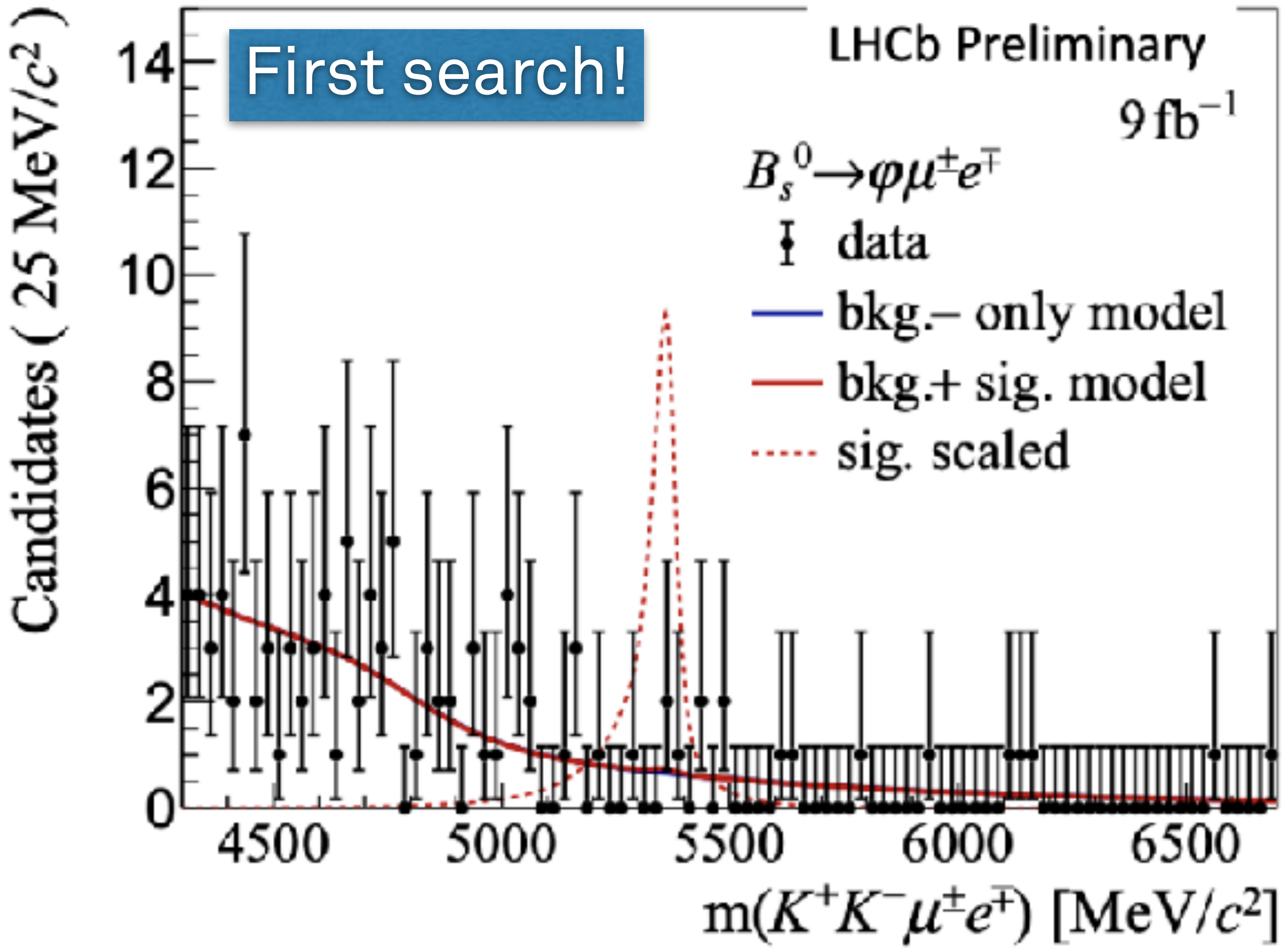


$B^0 \to K^0_S\ell^+\ell^-$
$B^+ \to K^{*+}\ell^+\ell^-$

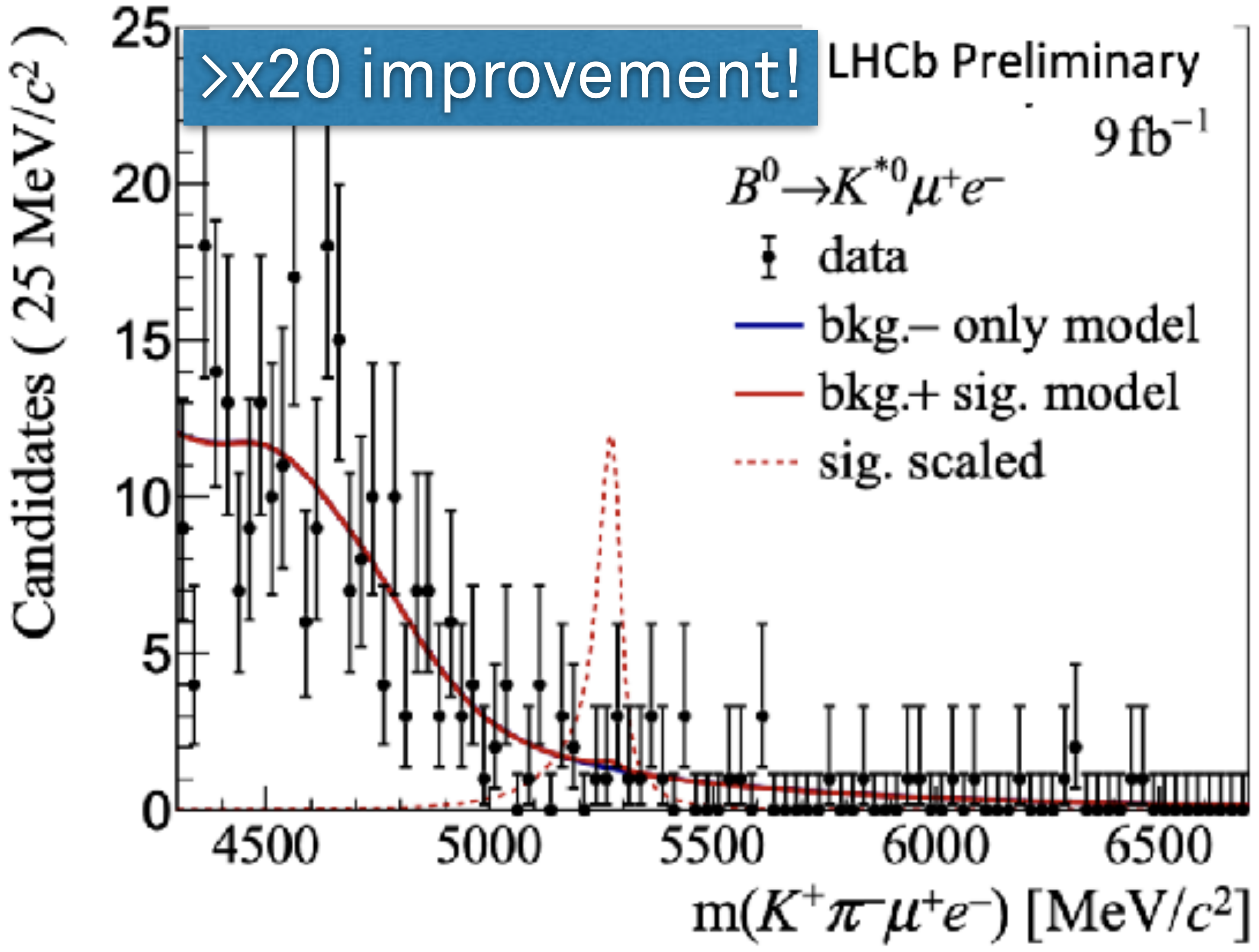
Searches for Lepton Flavour Violation

- Forbidden in the SM - but can have rates up to $\mathcal{O}(10^{-8})$ for $b \to s\mu e$-type decays in NP scenarios
- Especially in case of non-universality of lepton flavour couplings
- New LHCb search for $B_s^0 \to \phi\mu^\pm e^\mp$ and $B^0 \to K^{*0}\mu^\pm e^\mp$ → limits at 95% CL

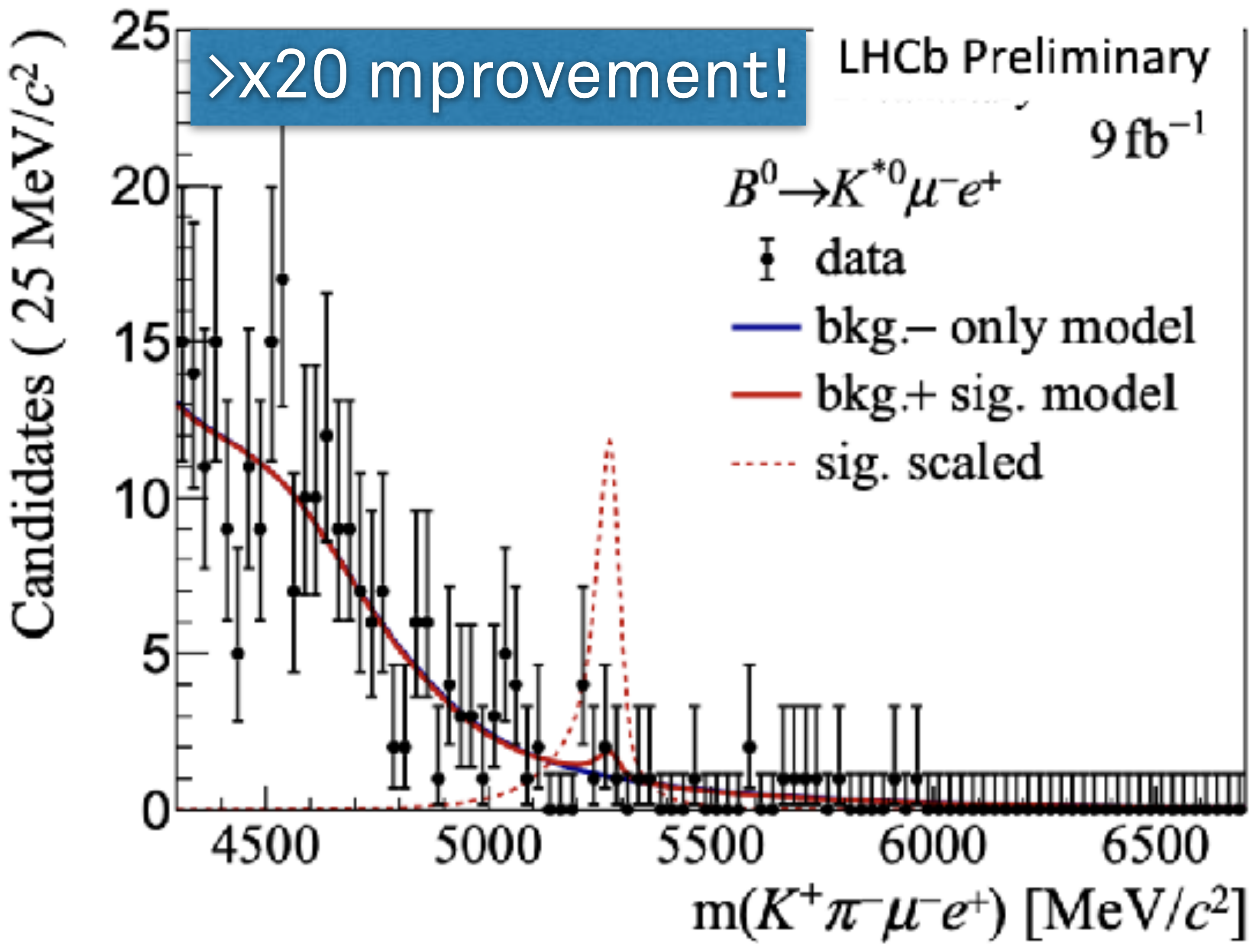
$\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 19.4 \times 10^{-9}$



$\mathcal{B}(B^0 \to K^{*0}\mu^+ e^-) < 5.7 \times 10^{-9}$



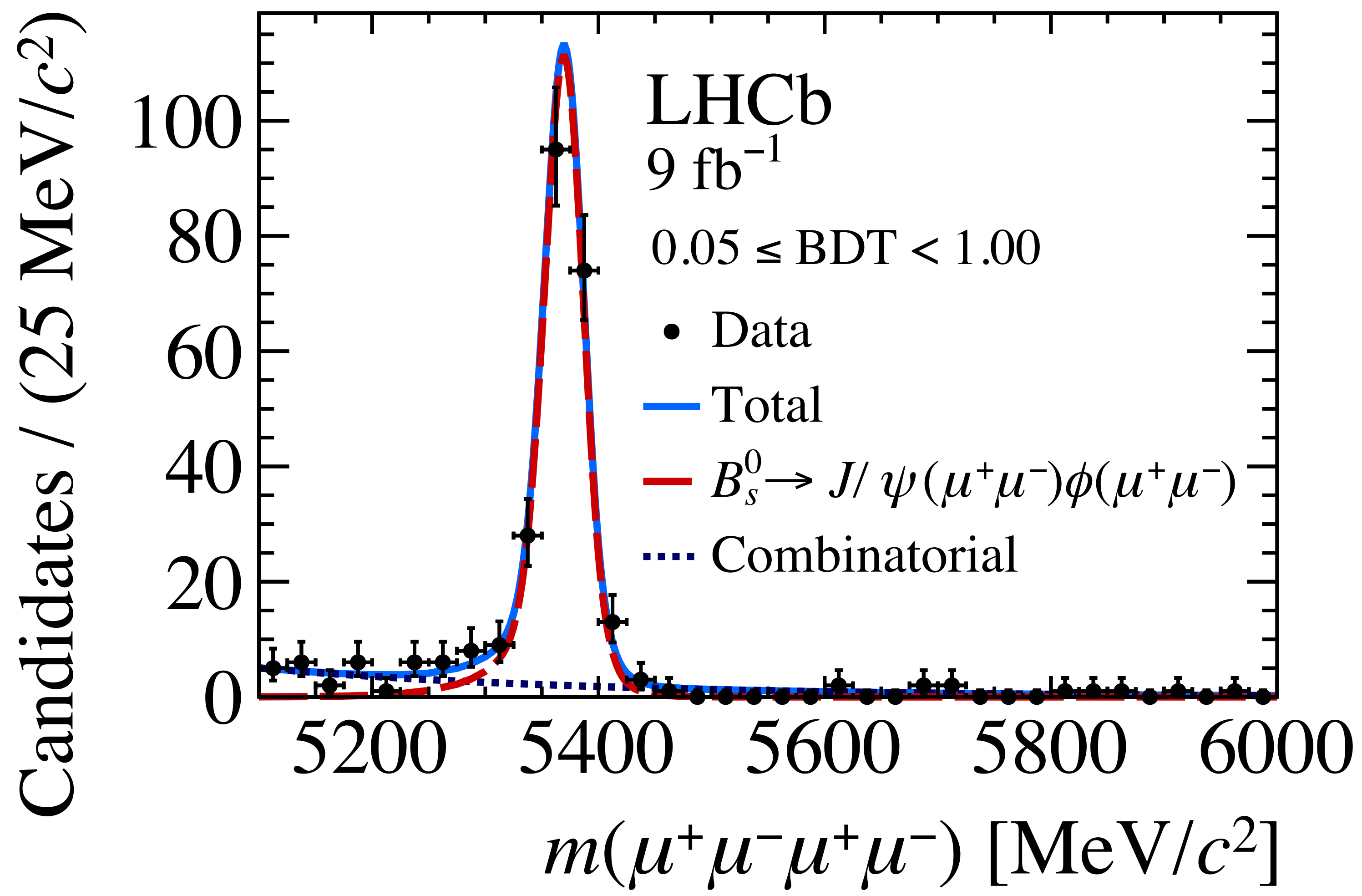
$\mathcal{B}(B^0 \to K^{*0}\mu^- e^+) < 6.7 \times 10^{-9}$

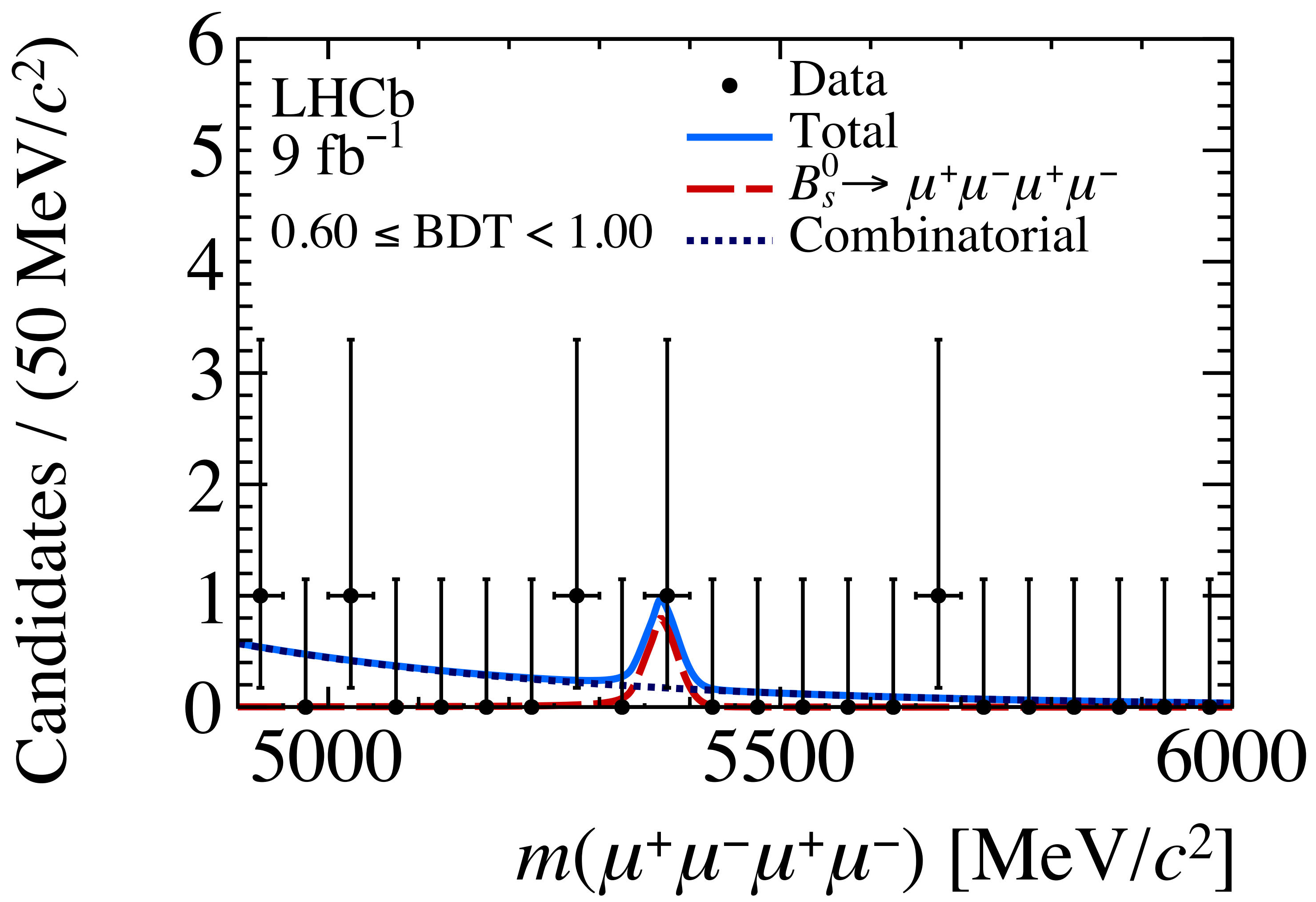


Searches for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays

- Very rare decay in SM, $\mathcal{O}(10^{-10})$ for B^0_s, $\mathcal{O}(10^{-12})$ for B^0
- Orders of magnitude enhancement possible
  - With e.g. MSSM [Demidov, Goburnov et al. arXiv:1112.5230]
  - With light scalars that could explain the g-2 anomaly → [Neubert et al. PRL 119 (2017) 031802] [Liu et al. JHEP 03 (2019) 008] [Chala et al. EPJC 79 (2019) 5, 431]
- First dedicated search for $B^0_{(s)} \to J/\psi\mu^+\mu^-$ and $B^0_{(s)} \to aa \to 4\mu$ ($m_a = 1\,\mathrm{GeV}$)
- Normalise to $B^0_s \to J/\psi\phi \to 4\mu$
- Extremely clean, no excess found
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 8.6 \times 10^{-10}$ (>2x improvement over previous search)
  - $\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.8 \times 10^{-10}$ (>2x improvement over previous search)
  - $\mathcal{B}(B^0_s \to aa) < 5.8 \times 10^{-10}$
  - $\mathcal{B}(B^0 \to aa) < 2.3 \times 10^{-10}$
  - $\mathcal{B}(B^0_s \to J/\psi\mu^+\mu^-) < 2.6 \times 10^{-9}$
  - $\mathcal{B}(B^0 \to J/\psi\mu^+\mu^-) < 1.0 \times 10^{-9}$

Now exploring non-minimal scenarios with more than 1 scalar

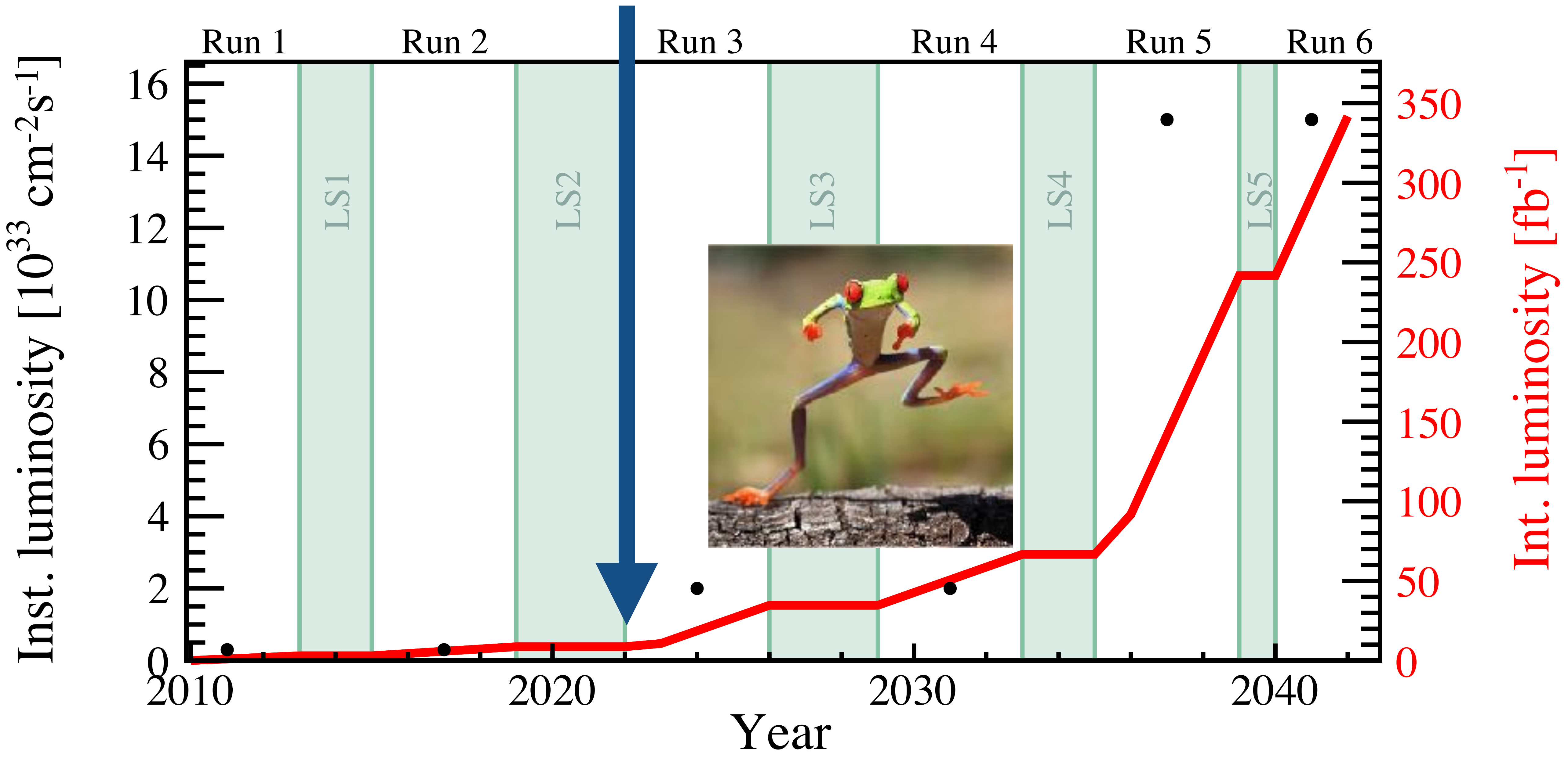




Summary

- Rare B decays are sensitive probes for NP
  - Stringent constraints on many models
  - Didn't even talk about rare charm and strange decays…
- LHCb measurements of $b \to s\ell\ell$ decays are in tension with SM predictions
  - Zeroing in from all possible angles
  - Confirmation from other experiments necessary
- Finishing analyses with full Run 1+2 data - now Run 3 is starting!

Modulo a little COVID shift



We're living in exciting times!