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Recent hints of lepton universality violation in rare B decays

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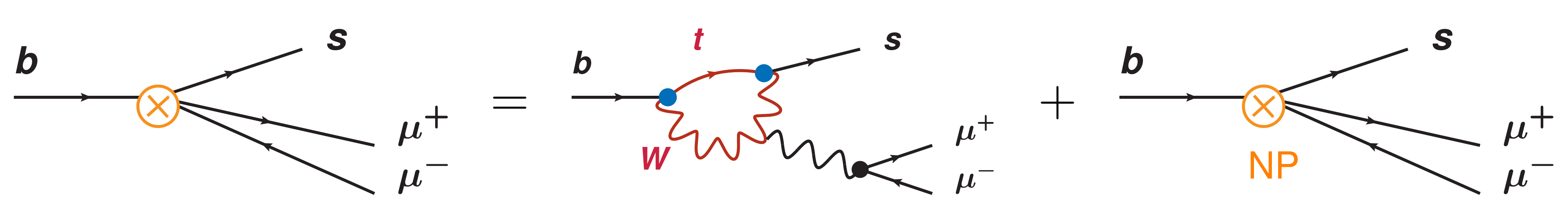
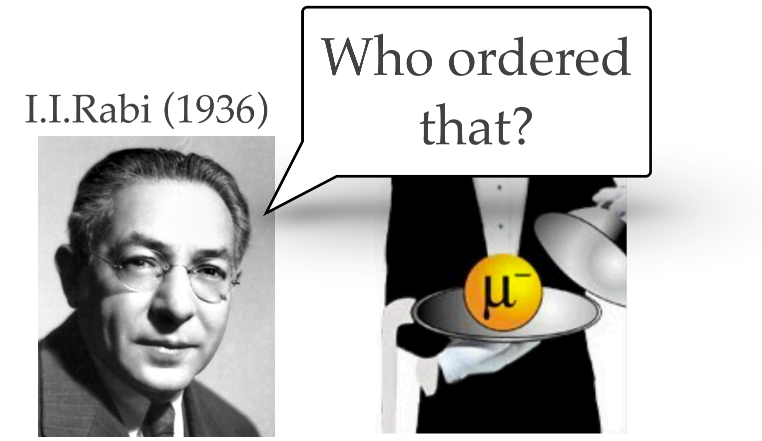
July 15th 2021 - BNL particle physics seminar

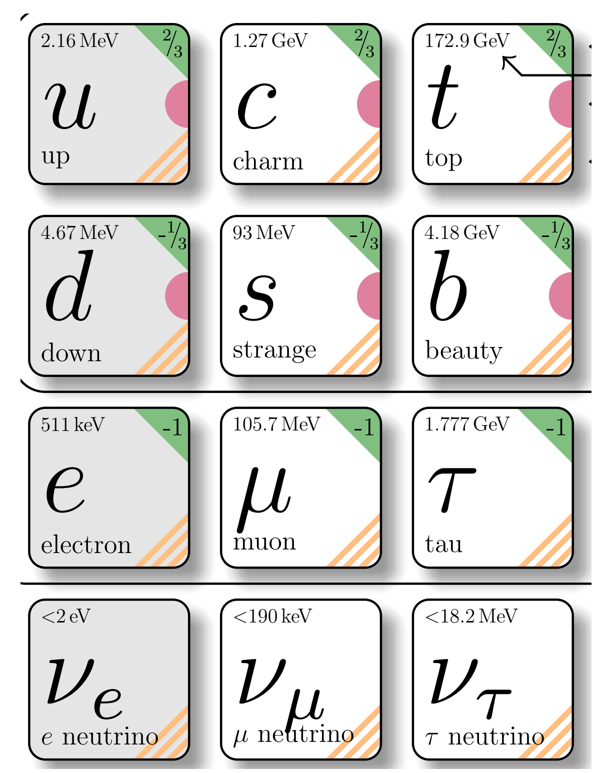


Flavour anomalies = Standard Model + New Physics?

The big picture



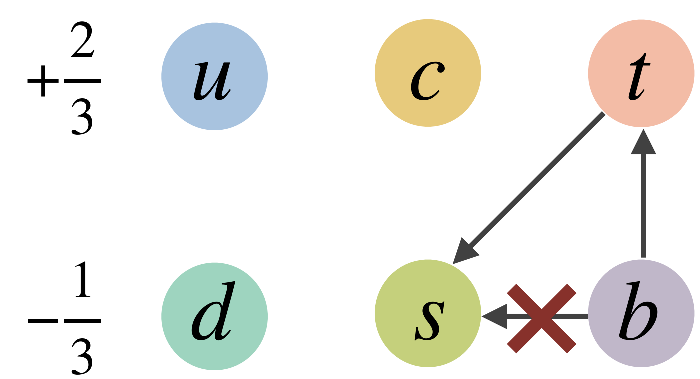
- We have evidence that there is physics beyond the SM
  - Neutrino masses, Dark Matter, BAU, Gravity
  - Also, the **flavour sector** is unexplained!



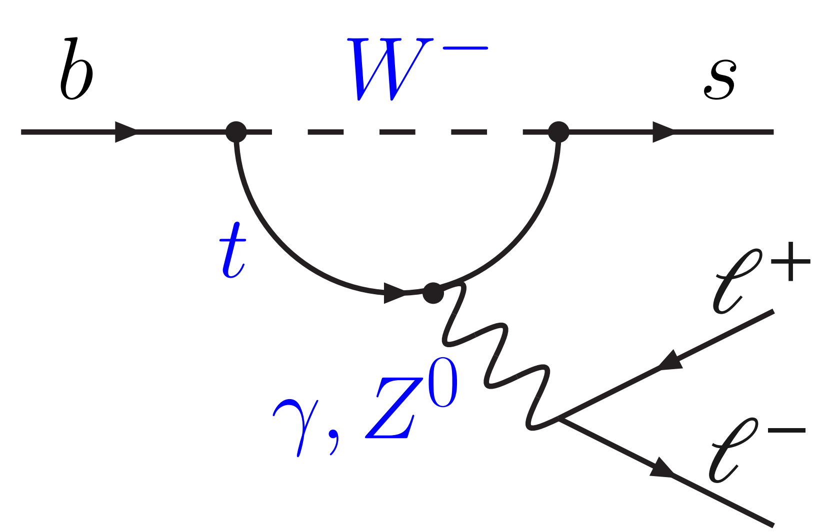
- New physics energy scale could be higher than the LHC collision energy
- **We might see new physics indirectly first**
  - Vast program of precision SM measurements
  - The LHC can greatly contribute (EW, Higgs, flavour)
  - Several particles we know were first seen indirectly!

Rare beauty-quark decays

- Rare $b \to s\ell^+\ell^-$ provide an excellent NP probe
  - Flavour-changing $b \to s$ neutral current
    - Forbidden at tree-level, proceeds through loop
    - Small CKM matrix elements and GIM mechanism
    - SM branching ratio below 10^{-6}
    - **TeV-scale NP can contribute at the same order**!



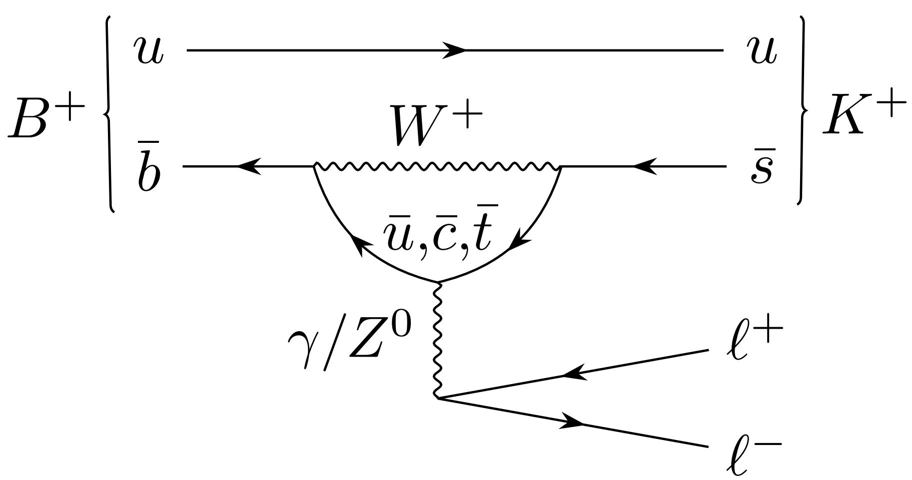
  - **(Semi)-leptonic** beauty $b \to s\ell^+\ell^-$ transitions
    - Long-distance contributions under control ($m_b \gg \Lambda_{QCD}$)
    - Sensitive to lepton-flavour, additional Z or lepto-quarks



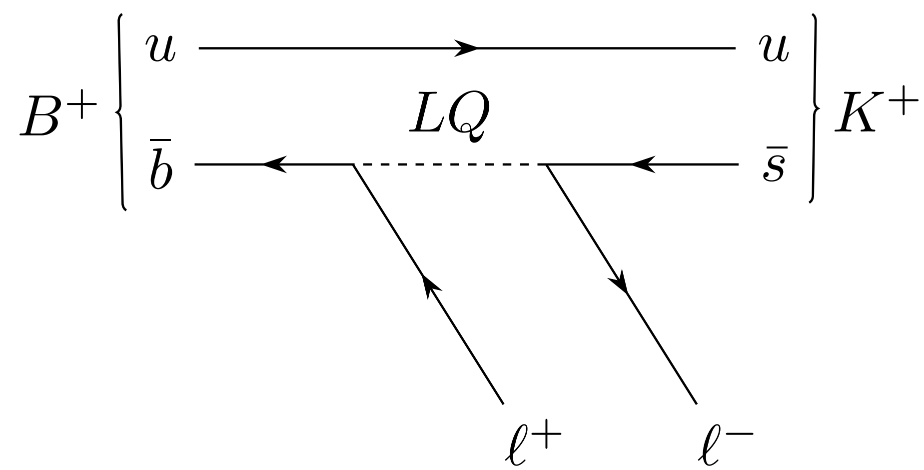
  - **Examples** of hadron decays involving $b \to s\ell^+\ell^-$:
    - $B_s \to \ell^+\ell^-$, $B \to K\ell^+\ell^-$, $B_s \to \phi\ell^+\ell^-$, $\Lambda_b \to \Lambda\ell^+\ell^-$
    - Spectator quark of $b \to s\ell^+\ell^-$ changes (similar physics probe)
    - Lorentz structure of physics probed depends on hadrons spins

Rare beauty-quark decays

SM process

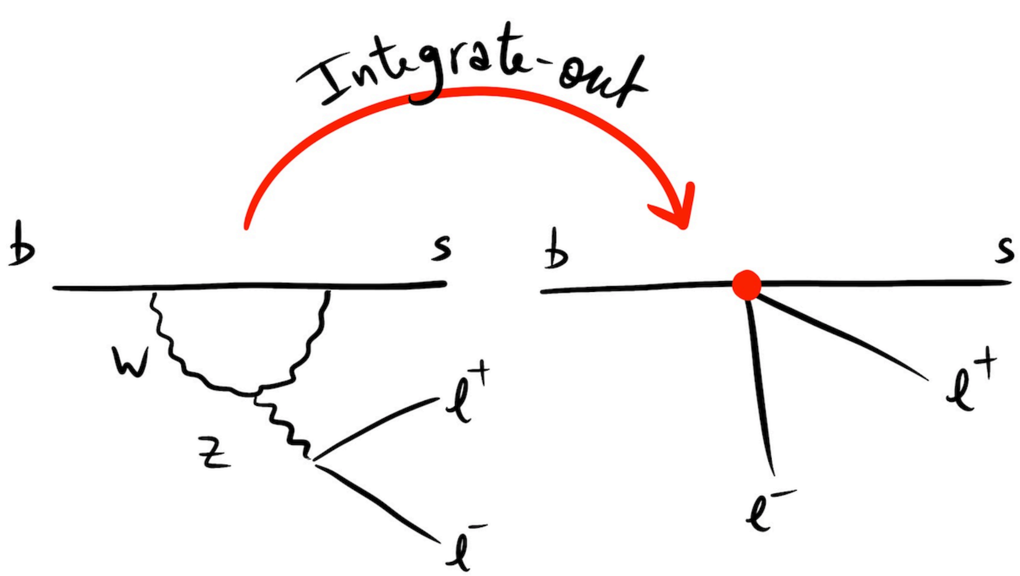


NP example



Weak effective theory

- $m_B \ll m_W \to$ Integrate out electroweak scale and above
  - Includes Higgs, W, Z, top quark or any heavier NP particle
  - Basically the good old Fermi theory of weak interaction
  - Describe $b \to s\ell^+\ell^-$ process with dimension-6 operators
  - NP enters in effective couplings (Wilson coefficients)



Fermi constant · CKM elements · Wilson coefficients · Dimension-6 $bs\ell\ell$ operators

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

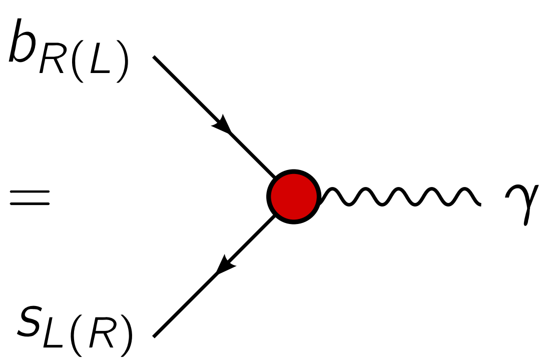
$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

What we measure · SM prediction · New heavy particle?

Weak effective theory

dipole operator

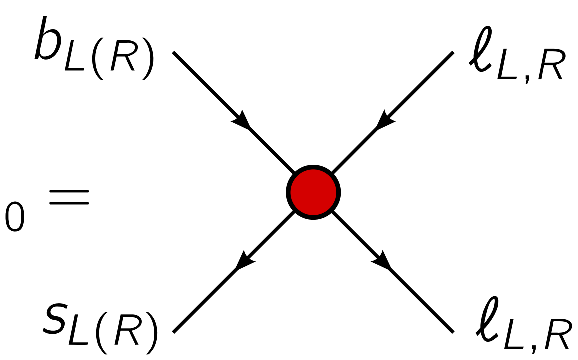
$\mathcal{O}_7^{(\prime)} =$



$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{\mathrm{R(L)}}b)F^{\mu\nu}$$

vector, axial-vector

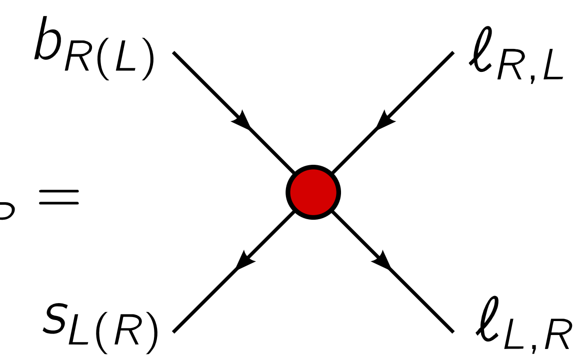
$\mathcal{O}_{9,10}^{(\prime)} =$



$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{L(R)}}b)(\bar{\ell}\gamma^\mu\ell)$$
$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{L(R)}}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

scalar, pseudo-scalar

$\mathcal{O}_{S,P}^{(\prime)} =$



$$\mathcal{O}_{\mathrm{S}}^{(\prime)} = \bar{s}P_{R(L)}b\,\bar{\ell}\ell$$
$$\mathcal{O}_{\mathrm{P}}^{(\prime)} = \bar{s}P_{R(L)}b\,\bar{\ell}\gamma_5\ell$$

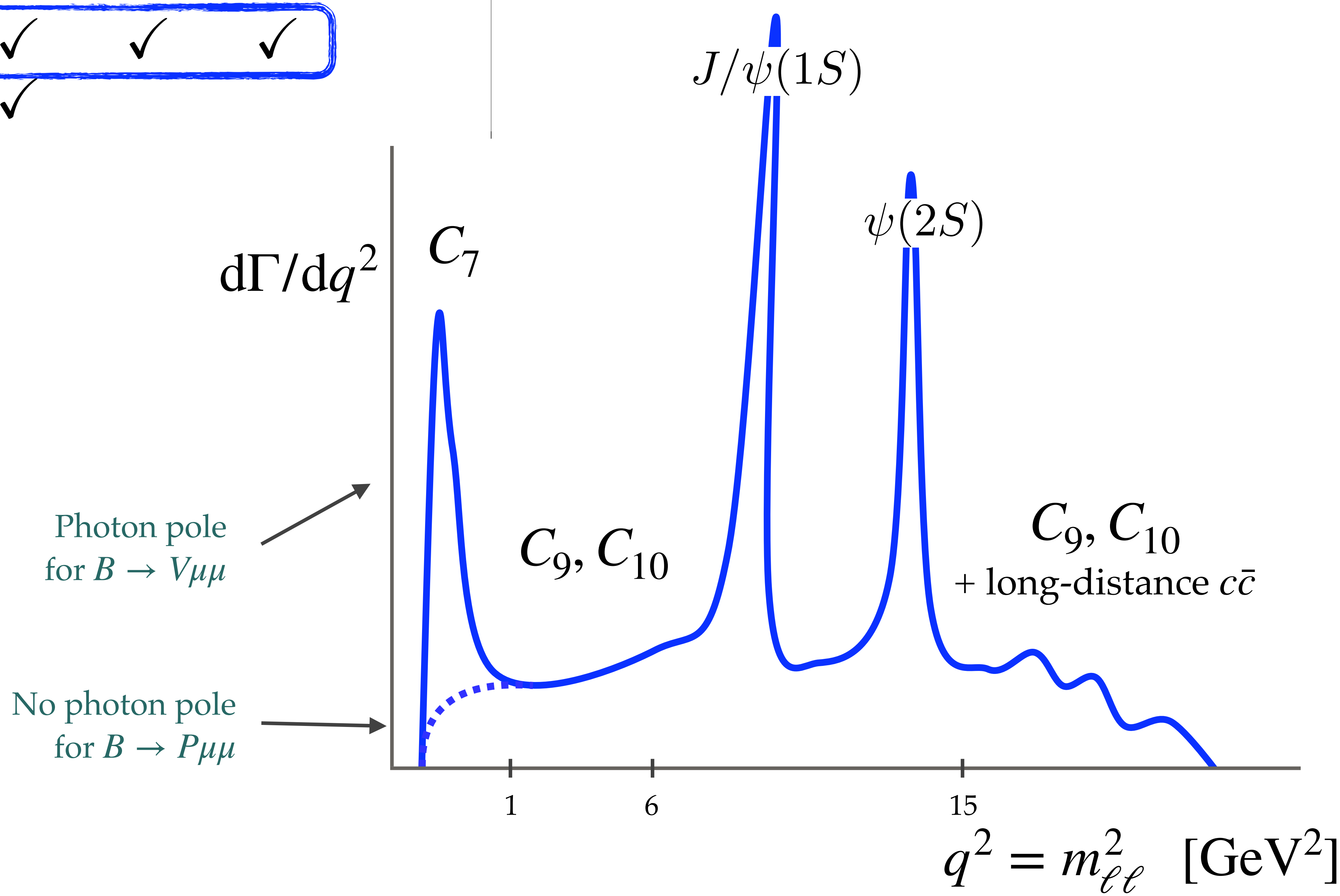
	$\mathcal{C}_7^{(\prime)}$	$\mathcal{C}_9^{(\prime)}$	$\mathcal{C}_{10}^{(\prime)}$	$\mathcal{C}_{\mathrm{S,P}}^{(\prime)}$
leptonic			✓	✓
semileptonic	✓	✓	✓	
radiative	✓			

in the SM:

- $\mathcal{C}_{\mathrm{S,P}} \propto \mathrm{m}_\ell \mathrm{m_b}/\mathrm{m_W^2} \sim 0$
- $\mathcal{C}_i^{\prime} \propto m_s/m_b \sim 0.02$

q^2 for semileptonic $b \to s\ell\ell$

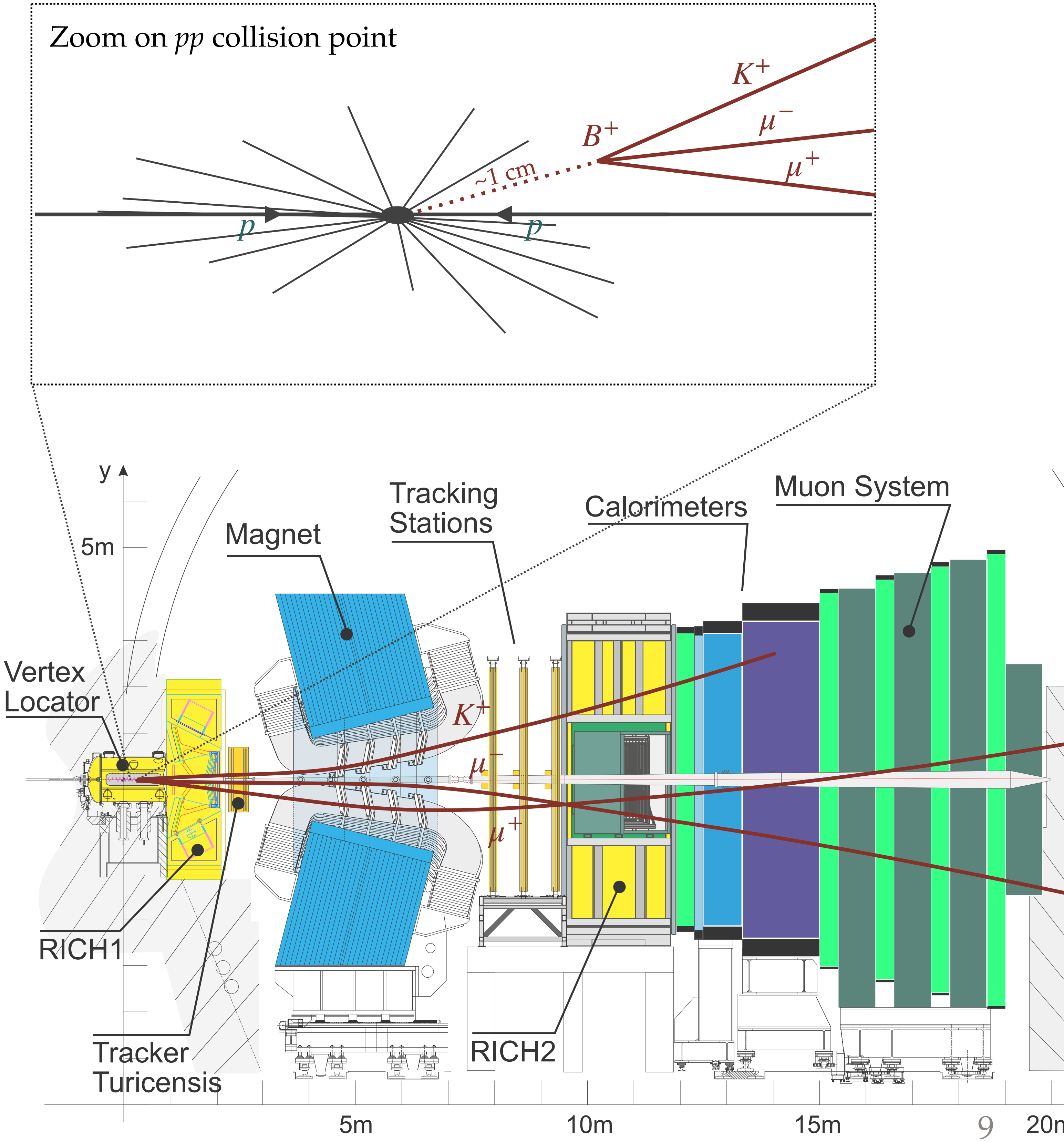
	$\mathcal{C}_7^{(\prime)}$	$\mathcal{C}_9^{(\prime)}$	$\mathcal{C}_{10}^{(\prime)}$	$\mathcal{C}_{\mathrm{S,P}}^{(\prime)}$
leptonic			✓	✓
semileptonic	✓	✓	✓	
radiative	✓			



The LHCb experiment

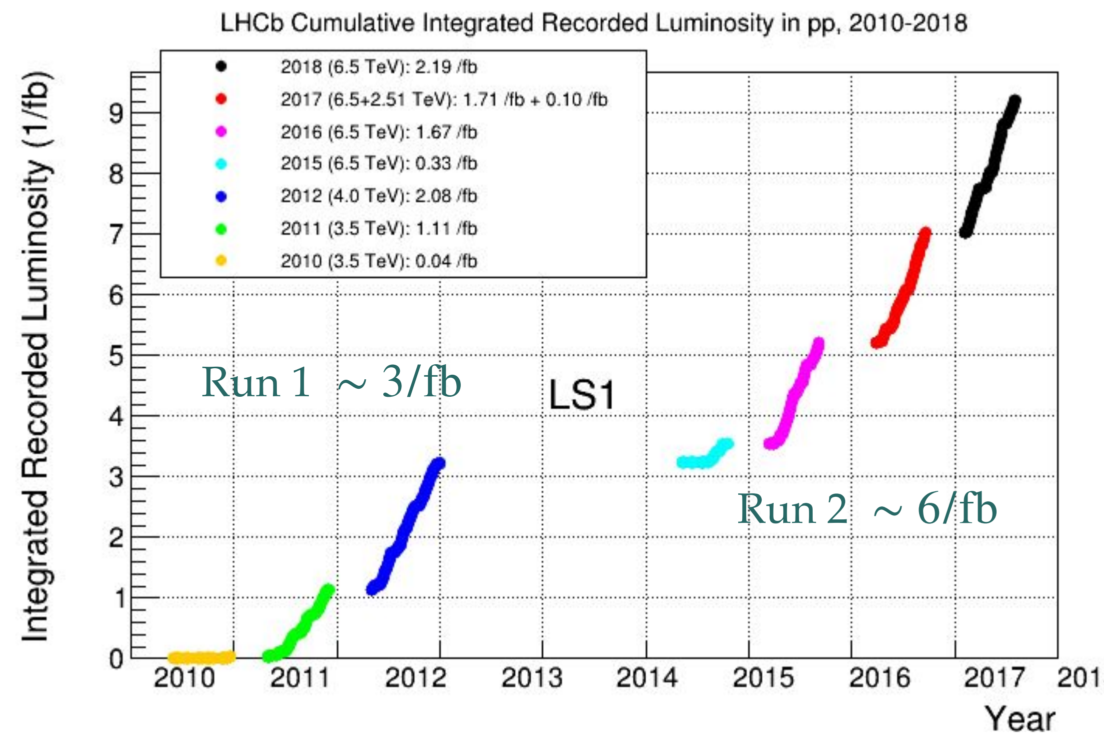
The LHCb experiment

- **LHC pp collisions at 7-13 TeV**
  - Huge $pp \to b\bar{b}X$ cross-section
  - Also large background $\sigma(\text{inelastic}) \simeq 200\sigma(b\bar{b})$
- **LHCb designed for b-hadrons:**
  - In the forward region of pp collisions where most of $b\bar{b}$ pairs are produced
  - Running at lower luminosity and one pp collision per bunch crossing
  - Low-$p_{\rm T}$ triggers (few GeV)
  - Identify displaced b-hadron vertex leveraging large boost
  - Momentum measurement with spectrometer $\sigma_p/p \sim 0.5\,\%$
  - PID with calorimeters, muon system and Cherenkov detectors (RICH)

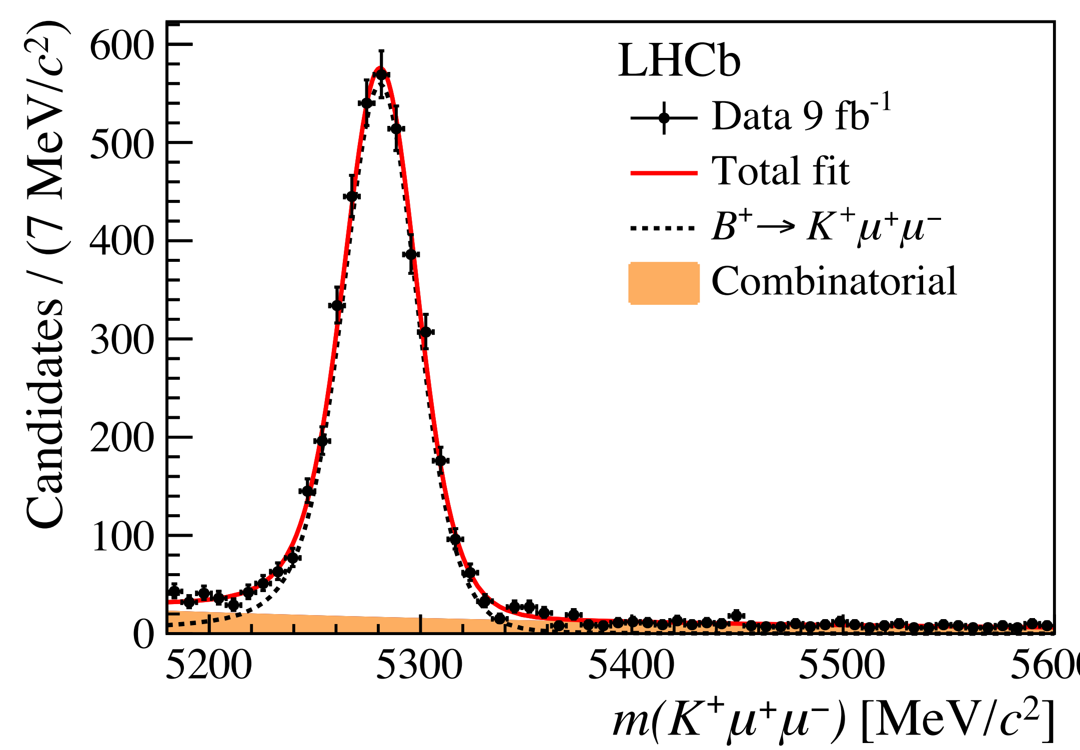


The LHCb experiment

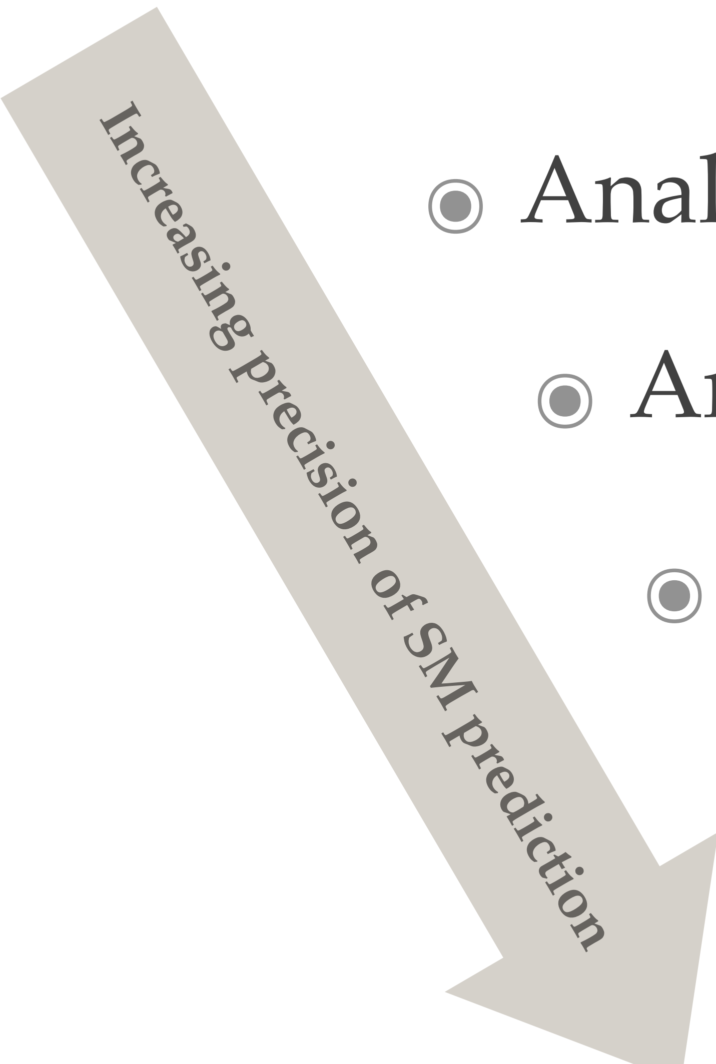
- **Excellent performance in LHC Run 1 and 2**
  - About 10^{12} $b\bar{b}$ in the acceptance
  - Recorded world-largest sample of $b \to s\ell\ell$ decays
  - About 50 times more $B \to K^*\mu\mu$ events than the Belle experiment
  - Statistics of $\mathcal{O}(10^3)$ events per channel e.g. $N(B^+ \to K^+\mu^+\mu^-) = 3850 \pm 70$ for a BR of about 1.2×10^{-7}
  - Best performance for fully-charged final states with muons



arXiv:2103.11769



LHCb results



- Analysis of semileptonic $b \to s\mu\mu$
  - Analysis of leptonic $B_s \to \mu\mu$
    - Test of lepton universality in $b \to s\ell\ell$

BR of semileptonic $b \to s\mu\mu$

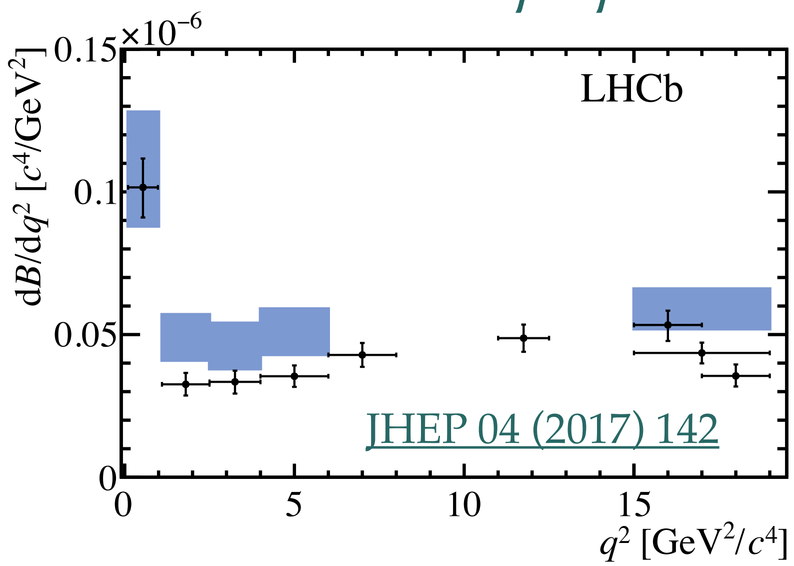
dB/dq^2 in exclusive $b \to s\mu\mu$ seems to undershoot SM

- Theory uncertainties ~20-30% (hadronic form factors)
- Coherent undershooting, but predictions uncertainties are correlated

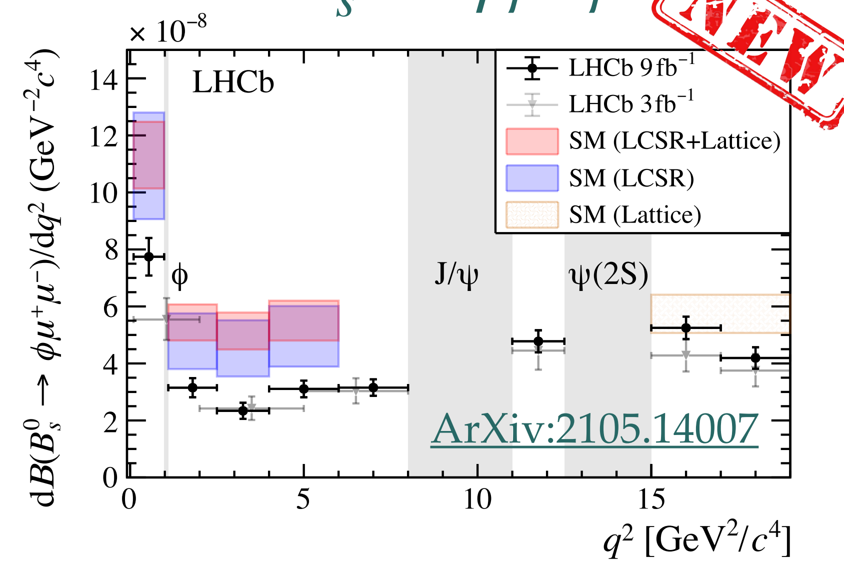
Inclusive $B \to X_s\mu\mu$ has smaller (10%) theory uncertainty

- very hard at LHCb but will try with sum of exclusive channels (assume isospin symmetry)

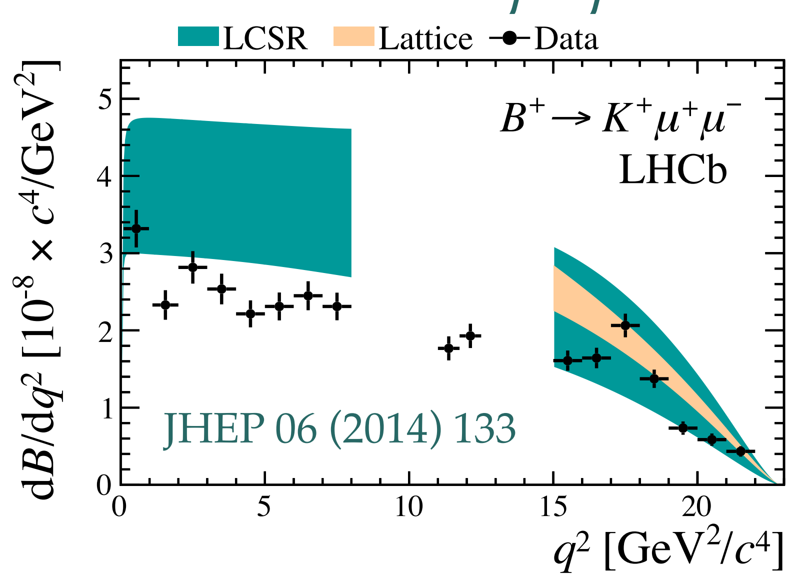
$B^0 \to K^{*0}\mu^+\mu^-$



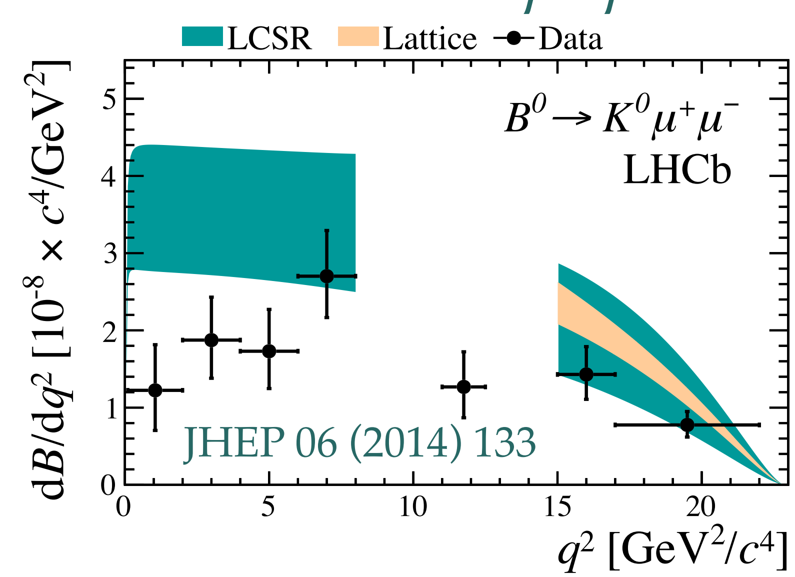
$B_s \to \phi\mu^+\mu^-$



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



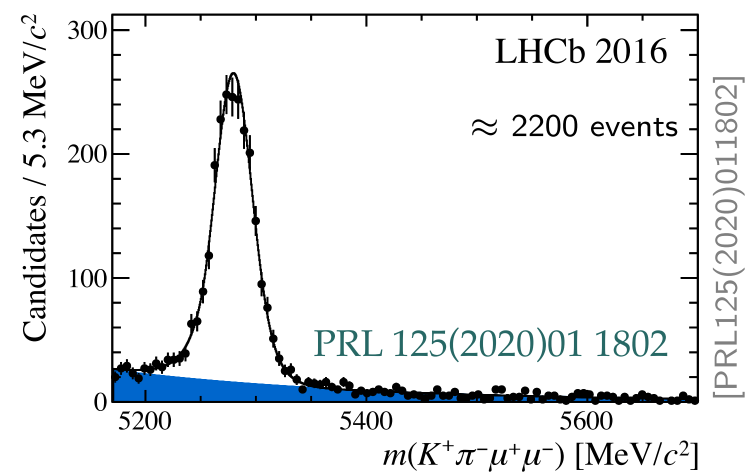
$B^0 \to K^0\mu^+\mu^-$



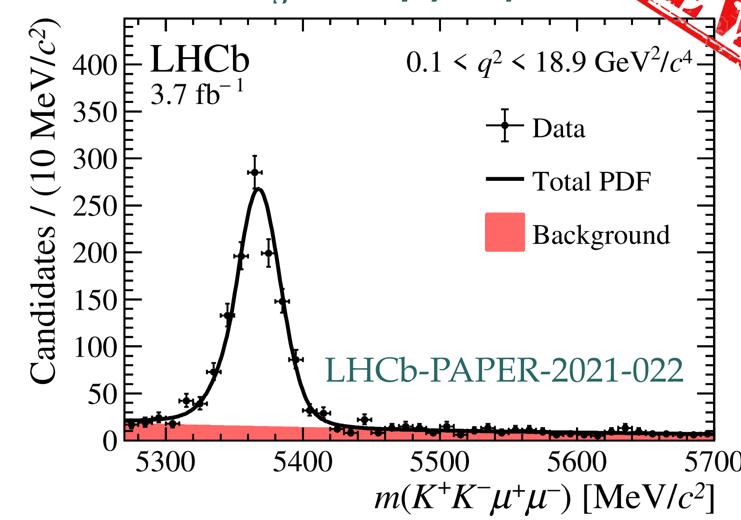
$b \to s\mu\mu$ angular analysis

- $B \to V(hh)\mu^+\mu^-$ gives 4-particle final state
  - 3D angular analysis in bins of q^2
- Kinematics defined by 3 angles
  - Described by spherical harmonics
  - Measure a set of ang. observables S_i (some have clear physical meaning)
- Current results:
  - $B^0 \to K^{*0}\mu^+\mu^-$with 6/fb (~4600 events)
  - $B^+ \to K^{*+}\mu^+\mu^-$ with 9/fb (~700 events)
  - $B_s \to \phi\mu^+\mu^-$ with 9/fb (~1900 candidates)

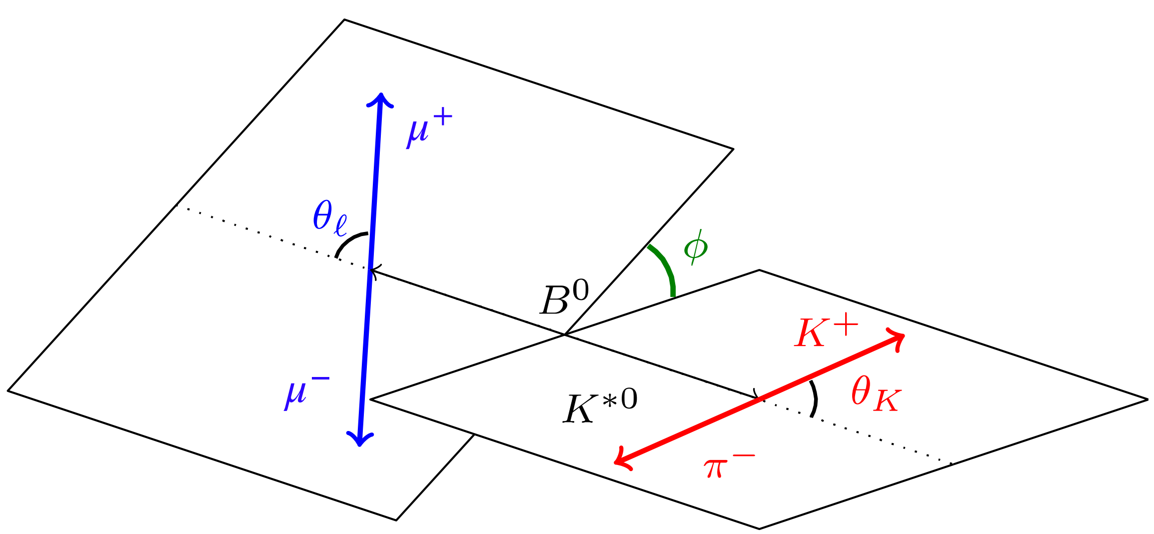
$B^0 \to K^{*0}\mu^+\mu^-$



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



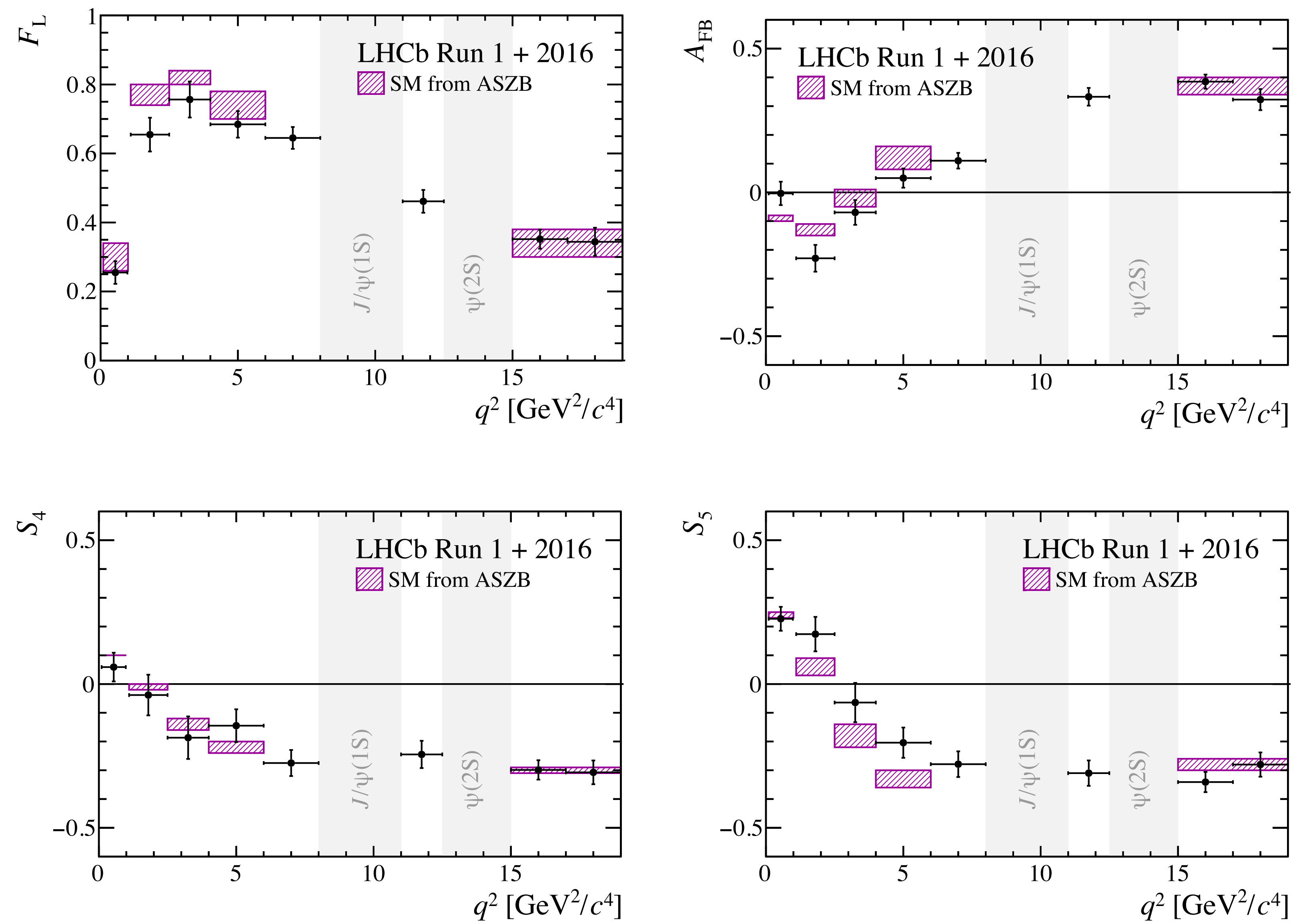
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\,d\cos\theta_K\,d\cos\theta_L\,d\phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L - F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi + \tfrac{3}{4}A_{FB}\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi + S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]$$



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

PRL 125(2020)01 1802

- Measure 8 CP-averaged angular observables in 8 q^2 bins (64 numbers!)
- Deviations at 1-2 sigma level observed in some observables
  → is it simply look-elsewhere effect?

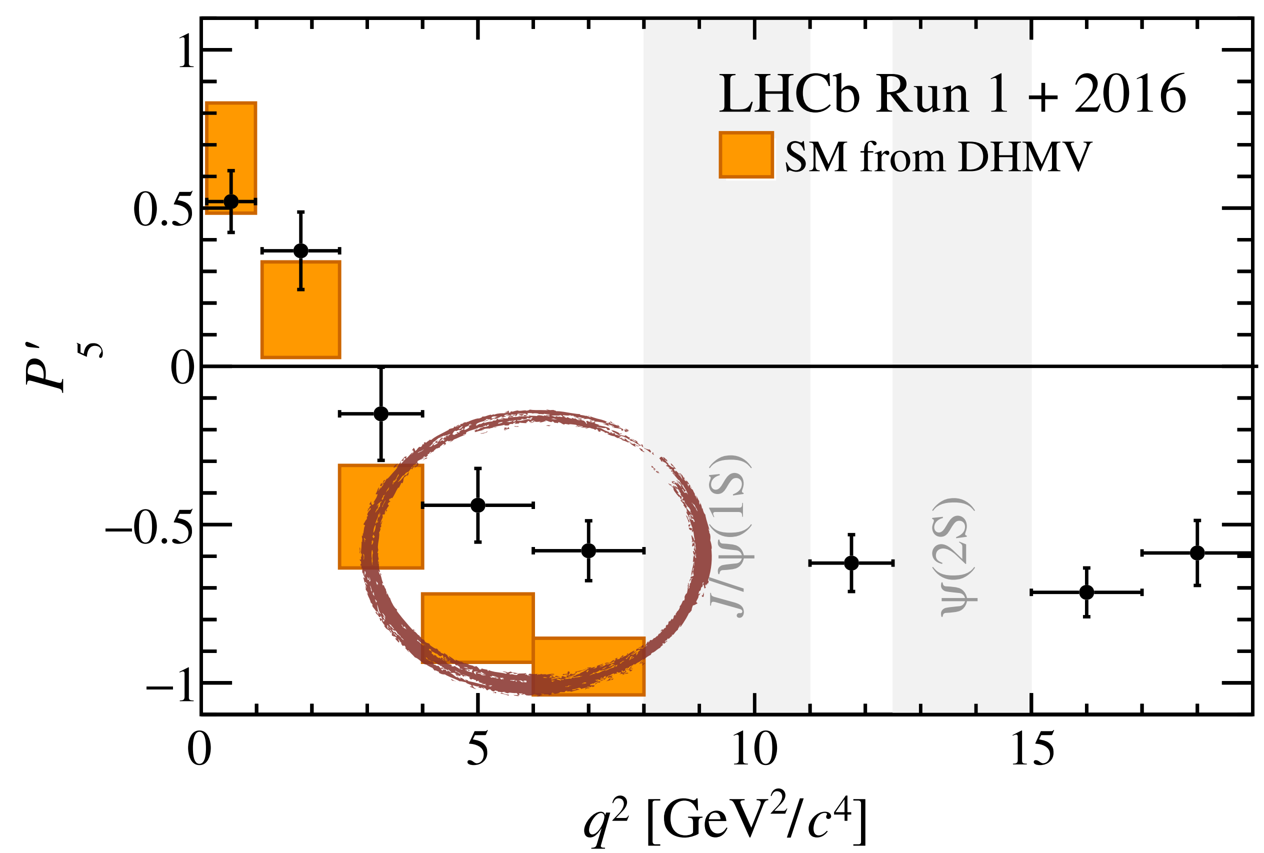


…4 more observables not shown here

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

PRL 125(2020)01 1802

- Can construct theoretically cleaner angular observables such as
$$P'_5 = \frac{S_5}{F_L\sqrt{1-F_L}}$$
where hadronic uncertainties cancel out at first order
- If NP contributes to C_9 and C_{10} expect large deviations in P'_5
- Observed local discrepancies:
  - 2.5σ for $q^2 = [4.0 - 6.0]$ GeV^2
  - 2.9σ for $q^2 = [6.0 - 8.0]$ GeV^2
- Easier stat interpretation using global EFT fits → see later

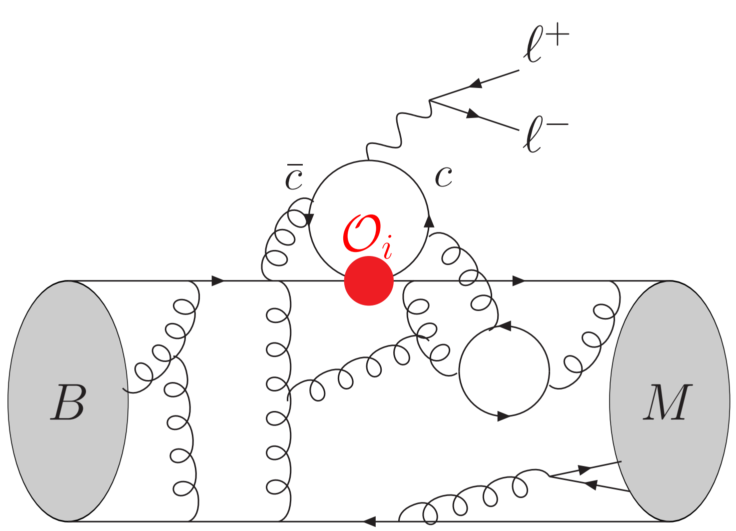


SM predictions by [JHEP12(2014)125] and [JHEP09(2010)089]

WET fit

Similar fits from other groups:
Algueró et al., arXiv:1903.09578
Kowalska et al., arXiv:1903.10932
Ciuchini et al., arXiv:2011.01212
Datta et al., arXiv:1903.10086
Arbey et al., arXiv:1904.08399
Geng et al., arXiv:2103.12738

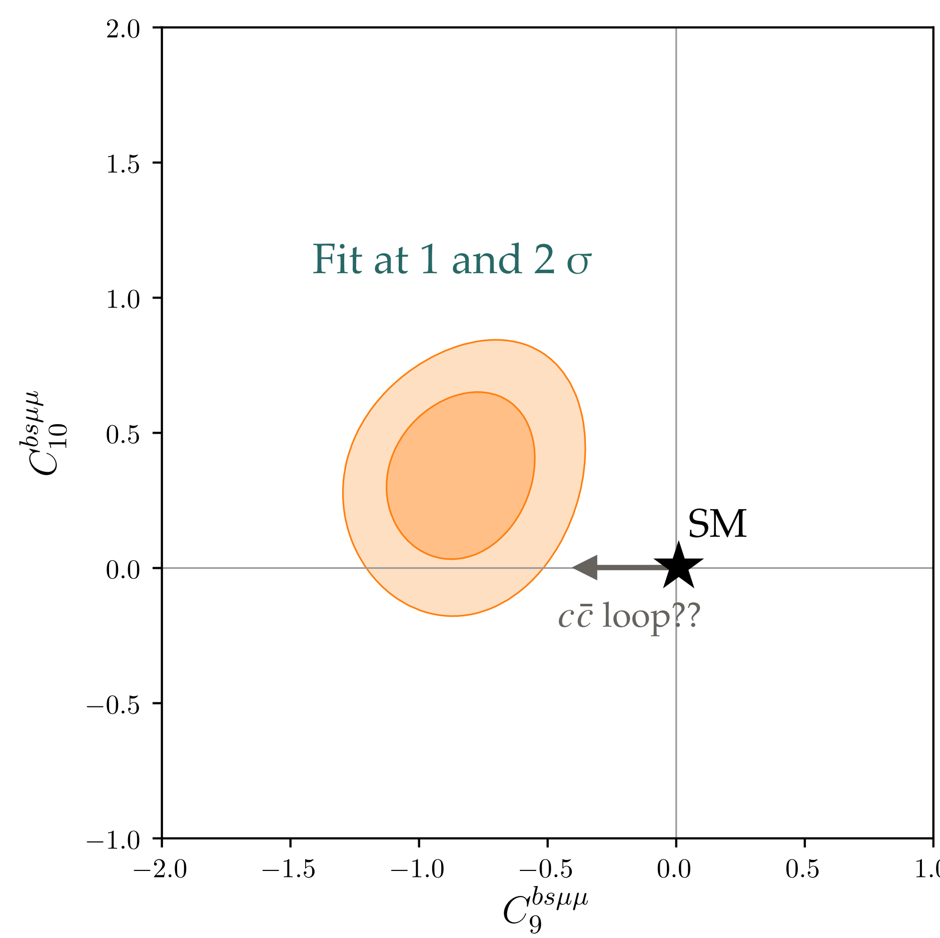
- Can fit Wilson coeffs to all semileptonic $b \to s\mu\mu$ (BR and angular observables)
  - Most relevant are $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$
  - Taking into account th. and exp. uncertainties and correlations
- Theory uncertainties under scrutiny
  - A shift in C_9 could be mimicked by hadronic effects (charm loop)
  - LHCb working to get experimental handles to pin this down



$c\bar{c}$ loop diagram

Fit from W. Altmannshofer and P. Stangl arXiv:2103.13370

	Wilson coefficient	$b \to s\mu\mu$ best fit	pull
	$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ
	$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ
	$C_9^{\prime bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ
	$C_{10}^{\prime bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ
	$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ
V-A	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ

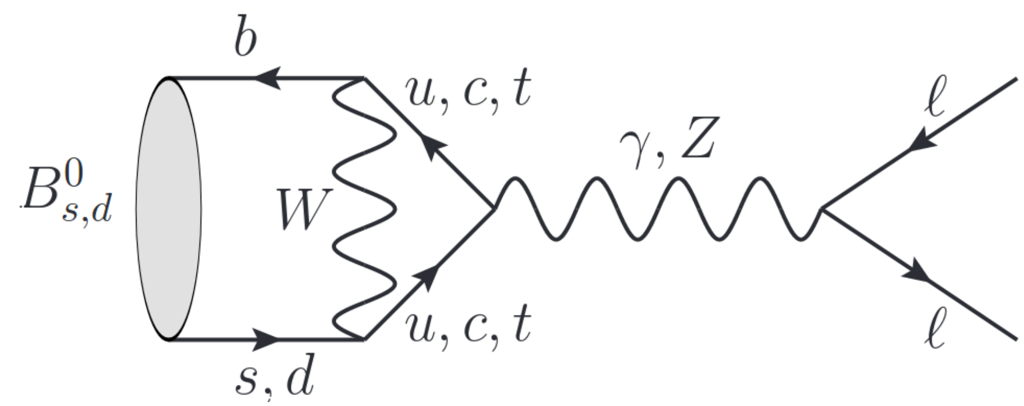


Leptonic $B_s \to \mu\mu$

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

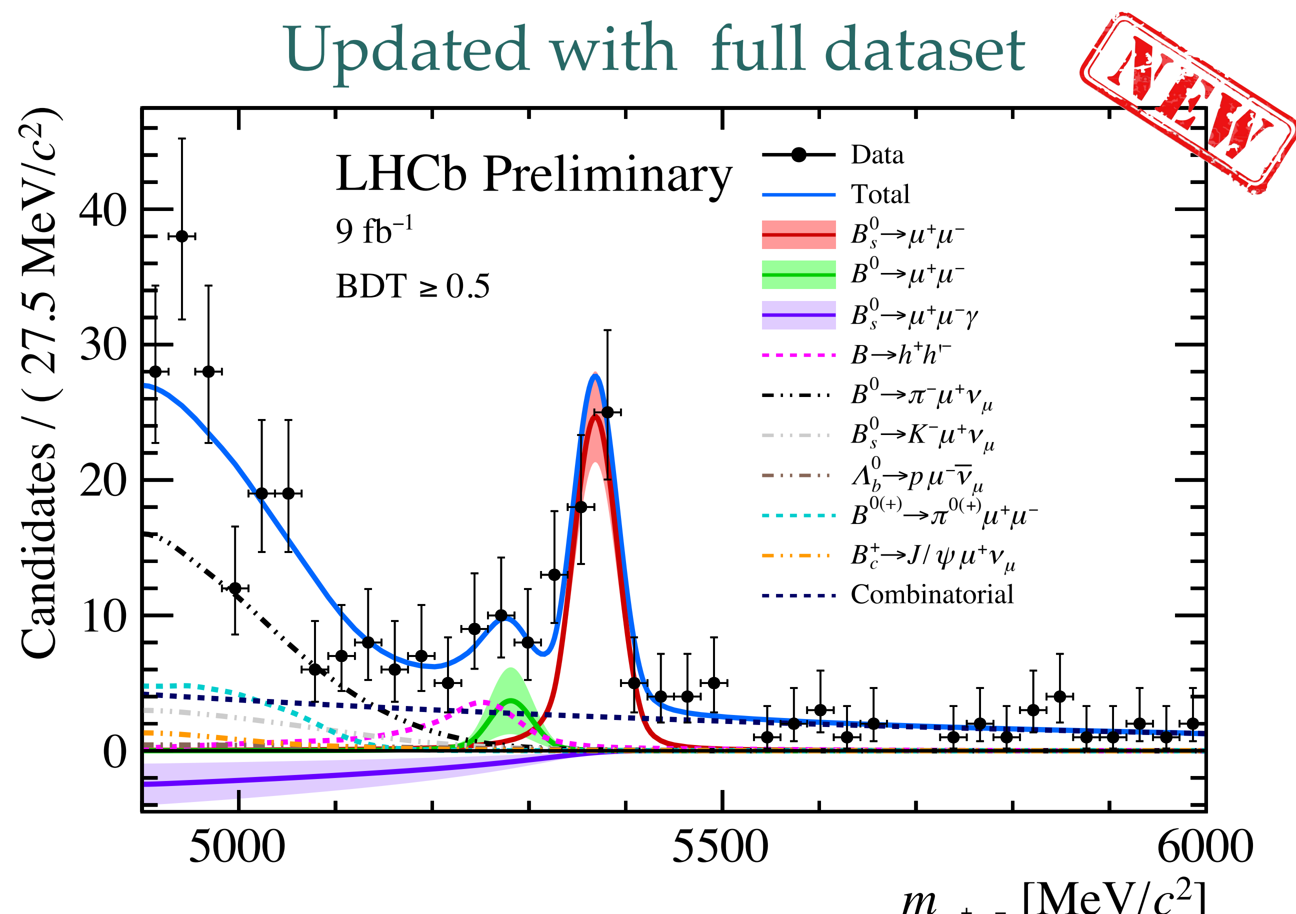
- Purely leptonic $B_{(s)} \to \mu^+\mu^-$ decay
  - Same diagrams as $b \to s\mu\mu$
  - Much smaller BR because of helicity suppression ($B_{(s)}$ pseudoscalar)
  - More precise predictions because of leptonic final state
    $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
    $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$
    [Beneke et al. JHEP 10 (2019) 232](#)
    [Kozachuk et al., PRD 97 (2018) 053007](#)
  - Sensitive to (pseudo-)scalar $C^{(\prime)}_{S,P}$ and axial-vector C_{10} couplings

	$\mathcal{C}_7^{(\prime)}$	$\mathcal{C}_9^{(\prime)}$	$\mathcal{C}_{10}^{(\prime)}$	$\mathcal{C}_{\mathrm{S,P}}^{(\prime)}$
leptonic			✓	✓
semileptonic	✓	✓	✓	
radiative	✓			



+ box diagram with neutrinos

Updated with full dataset



LHCB-PAPER-2021-007

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

LHCB-PAPER-2021-007

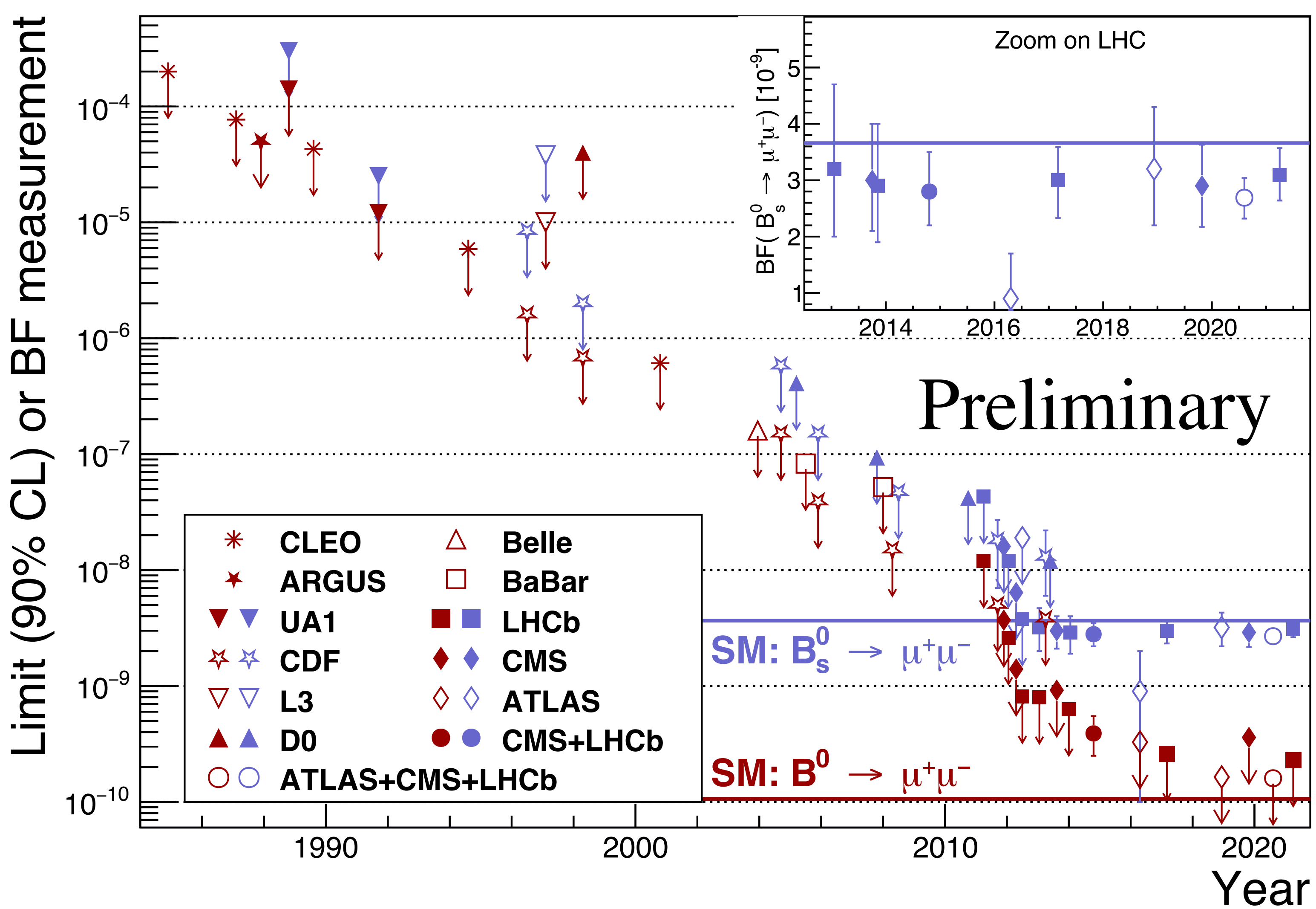
$$BR(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

16% uncertainty!

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

$BR(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$ at 95 % CL

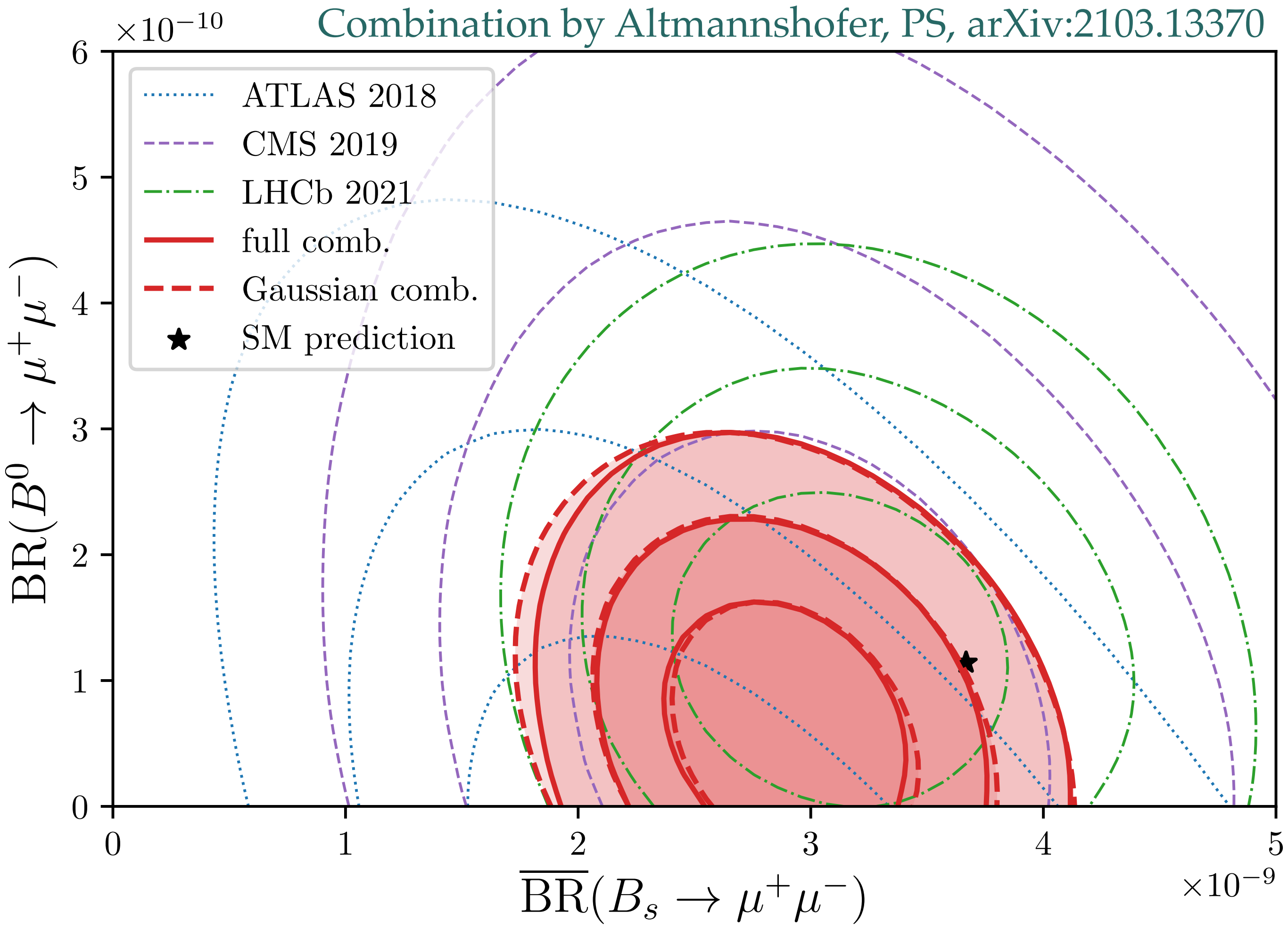
$\tau(B_s^0 \to \mu^+\mu^-) = (2.07 \pm 0.29 \pm 0.03)$ ps



LHC combination

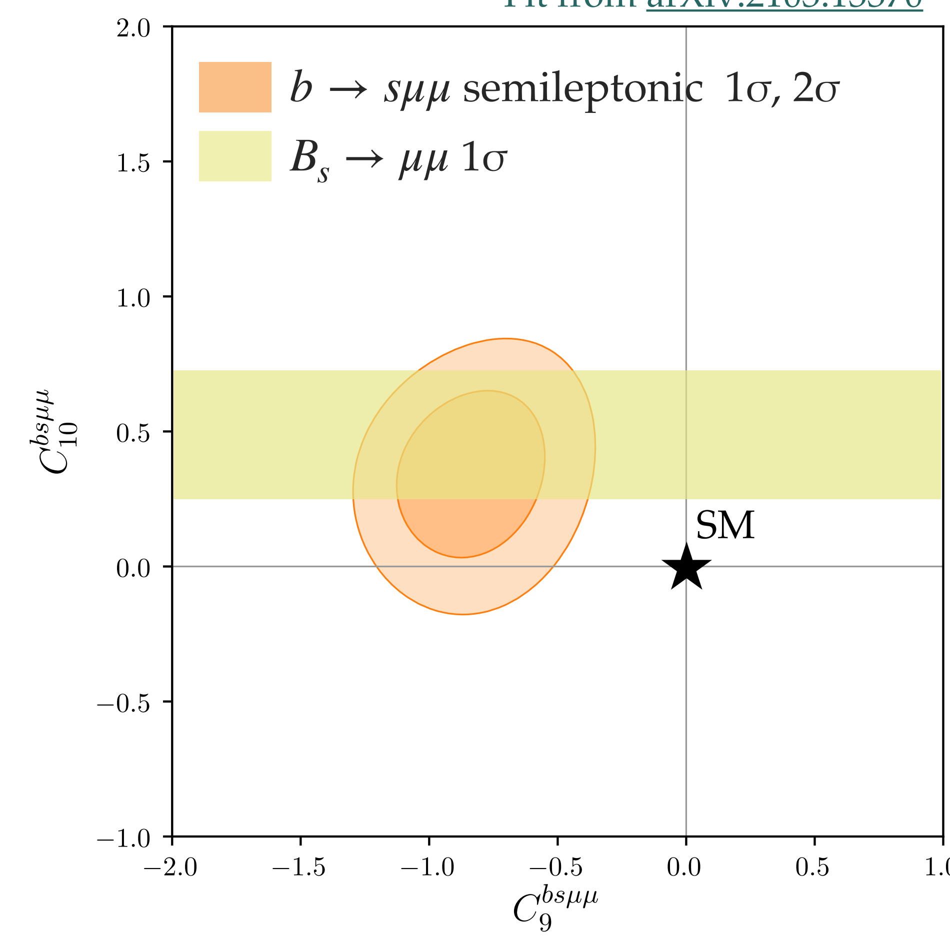
- Combining results $B_{(s)} \to \mu\mu$ results from ATLAS, CMS and LHCb
- Uncertainty on $BR(B_s \to \mu\mu)$ reduced to about 12%
- Measurement undershoots SM by about 2σ
  → Compatible with C_{10} shift that could explain $b \to s\mu\mu$!

Combination by Altmannshofer, PS, arXiv:2103.13370



Official combination not yet updated with 2021 LHCb in LHCb-CONF-2020-002

Fit from arXiv:2103.13370

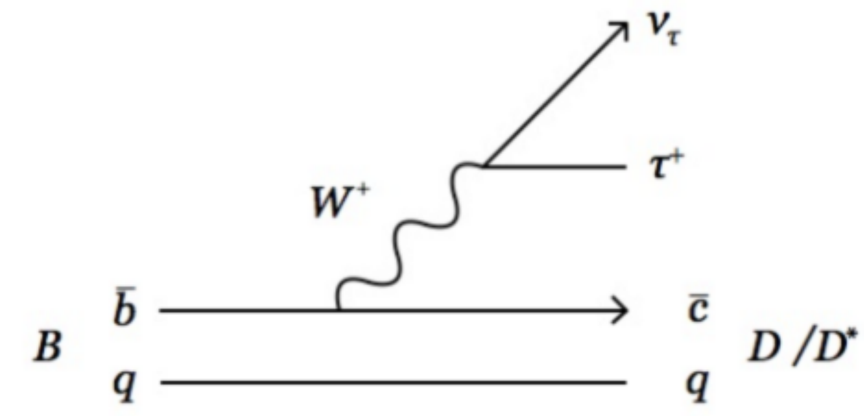


Lepton Flavour Universality tests

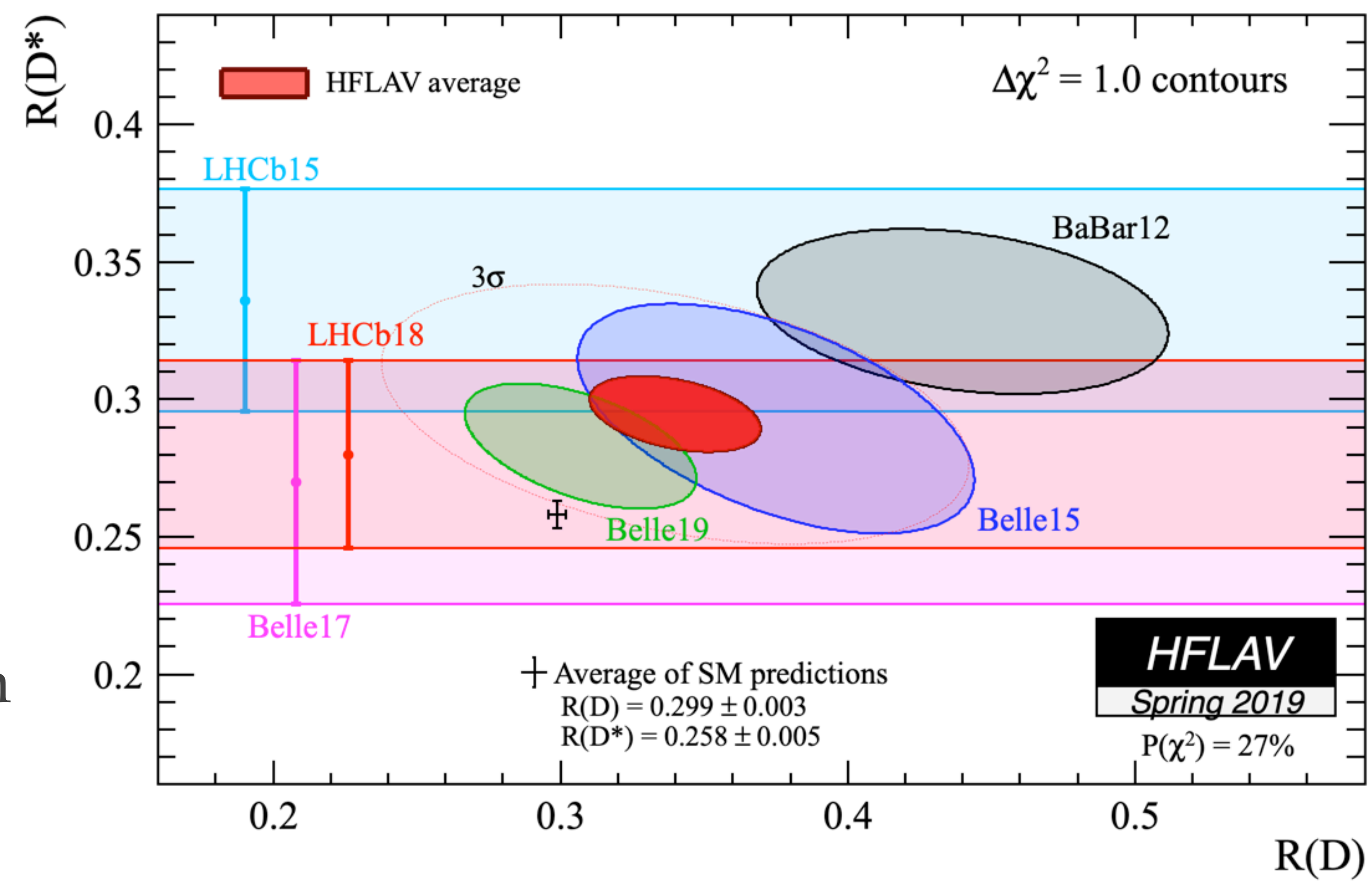
A word on tree-level B decays

- LFU has been tested intree-level $b \to c\ell\nu$ transitions
  - Comparing τ decay to $\ell = \mu(,e)$

$$\mathscr{R}\left(D^{(*)}\right) = \frac{\mathscr{B}\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathscr{B}\left(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$$



- LHCb, Belle and BaBar have comparable sensitivity
  - Measurements complicated by missing neutrino(s)
  - **Combined** result deviates about 3σ from the SM



- Not the subject of this talk, but something to keep an eye on

LFU test in b→$s\ell\ell$: μ vs e

- Can use semileptonic $b \to s\ell\ell$ to search for LFU-violation due to New Physics
- Rare $b \to s\ell\ell$ with $\ell=\tau$ are not observed yet
- Can compare BR with $\ell=\mu$ and e :

$$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \stackrel{\mathrm{SM}}{\cong} 1$$

  - LFU QCD uncertainties ~completely cancel in the ratio
  - Largest uncertainty remaining is 1% due to QED corrections (taken into account with PHOTOS, but with approximations)

Bordone, Isidori, Pattori EPJC(2016)76:440

- Previous tests at B-factories limited by statistics
- LHCb has much higher statistics, but electrons more challenging than muons
  - Trigger, PID, background, bremsstrahlung

e^+e^- at LHCb: Selection

- Electrons at LHCb:
  - Being light, they are produced in a plethora of decay channels
  - **Trigger** on large $e^{\pm}/h^{\pm}$ energy deposit on calorimeters
  - **Electron ID** relies on calorimeter for suppression of π mis-ID
  - Large **combinatorial background**: machine-learning based classification using kinematics info and isolation
- Muons trigger and ID is easier
  - Selection more efficient

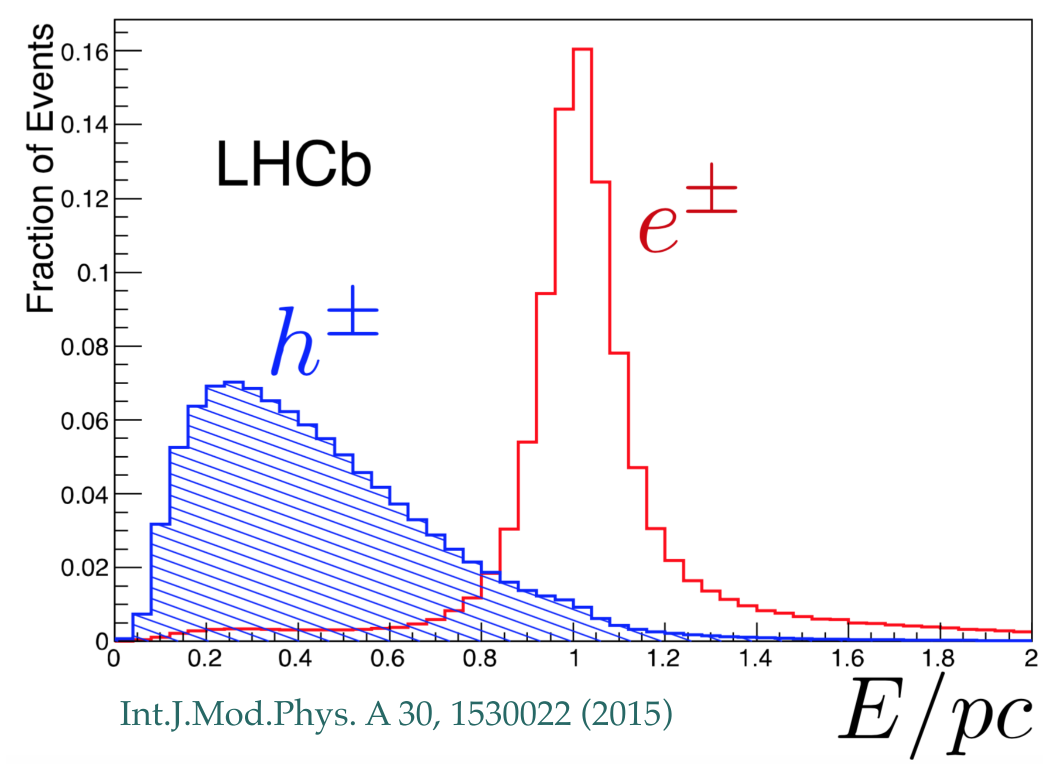
$$\frac{\epsilon\left(B^+ \to K^+\mu^+\mu^-\right)}{\epsilon\left(B^+ \to K^+e^+e^-\right)} \simeq 3$$

Phys. Rev. Lett. 122 (2019) 191801

Hardware trigger at LHCb:

- $p_{\mathrm{T}}(\mu^{\pm}) > 1.5 - 1.8$ GeV
- $E_{\mathrm{T}}(e^{\pm}) > 2.5 - 3.0$ GeV

Electron ID at LHCb

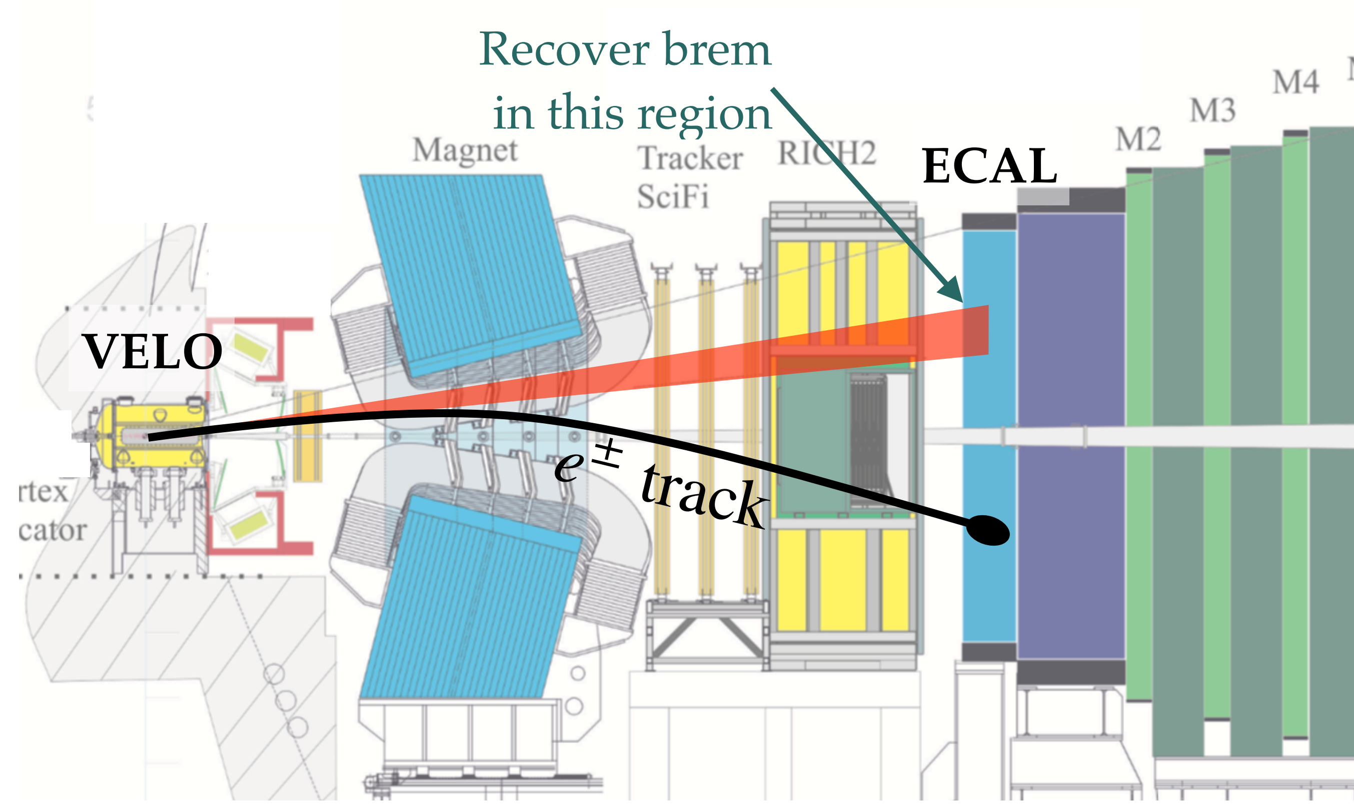


Int.J.Mod.Phys. A 30, 1530022 (2015)

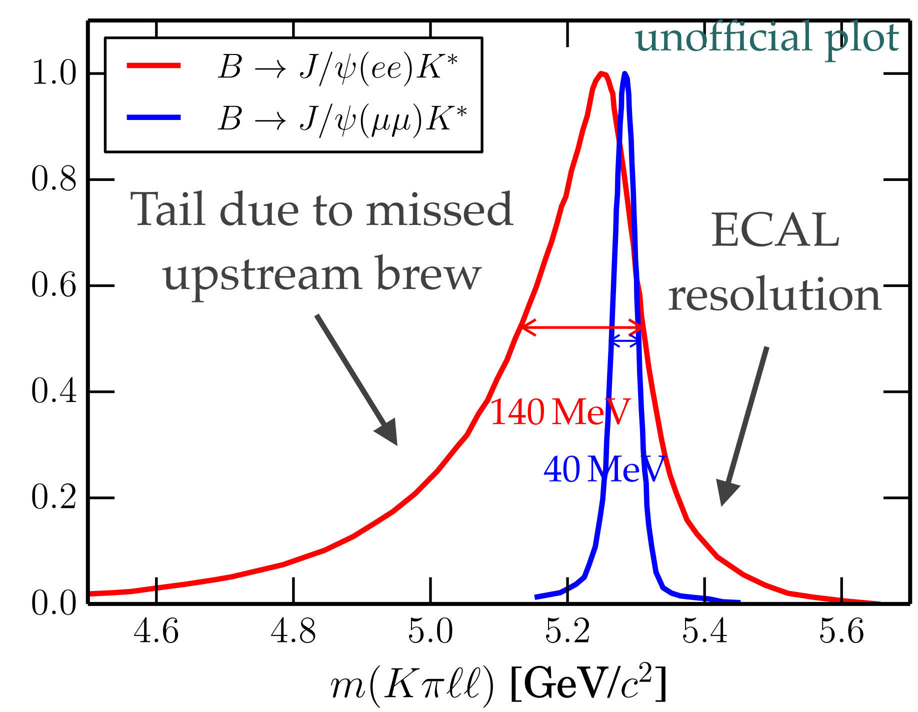
e^+e^- at LHCb: Bremsstrahlung

- Boosted B from LHC collision
  - Most electrons emit hard **bremsstrahlung** photon
  - If emitted **before the magnet it** affects the momentum measurement
- Brem-recovery algorithm searches for compatible deposits in the calorimeter
  - Recovery efficiency is limited (but well reproduced in simulation)
  - **ECAL resolution** is worse than spectrometer (1-2% vs 0.5%)

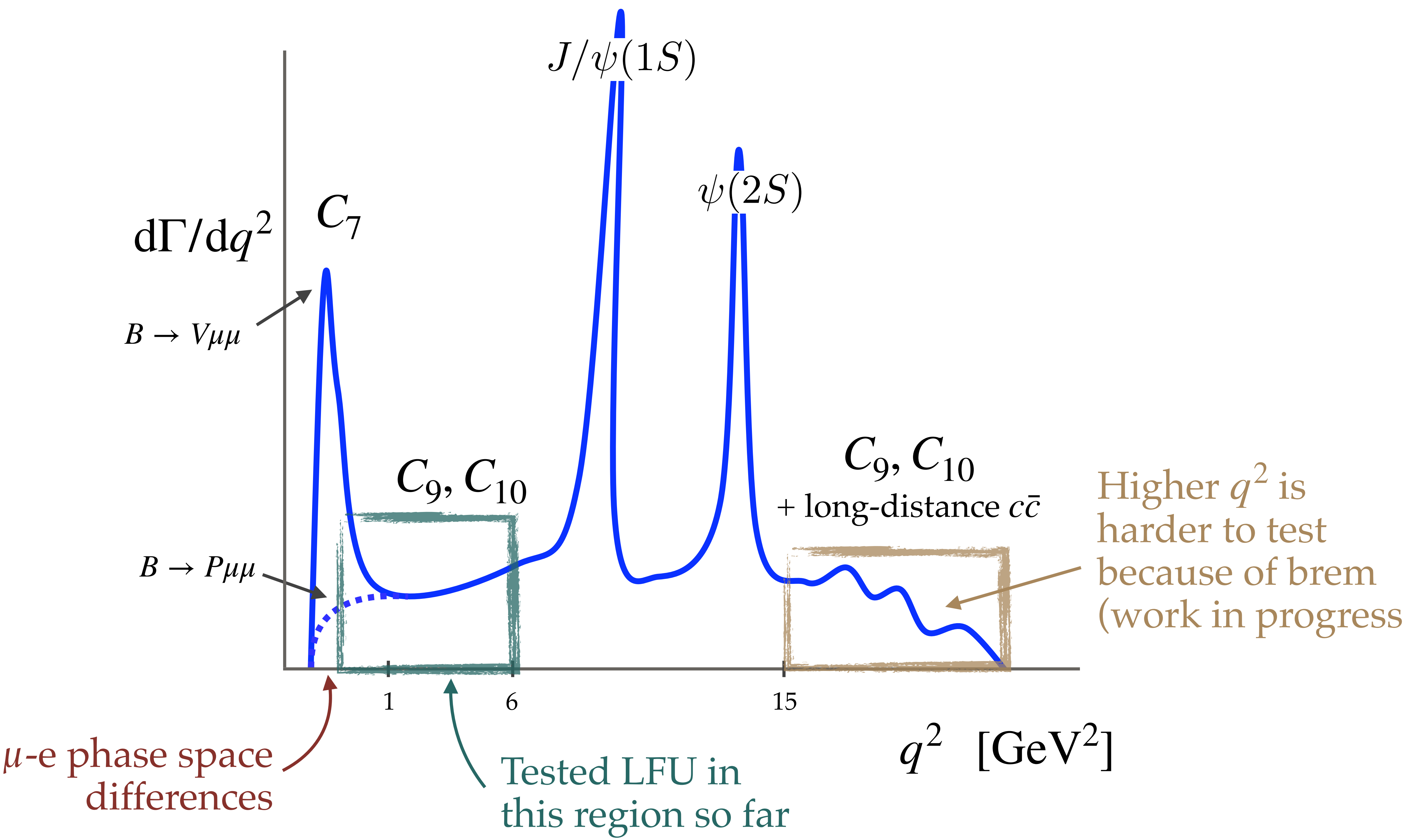
LHCb, JHEP 08 (2017) 055



Int.J.Mod.Phys. A 30, 1530022 (2015)

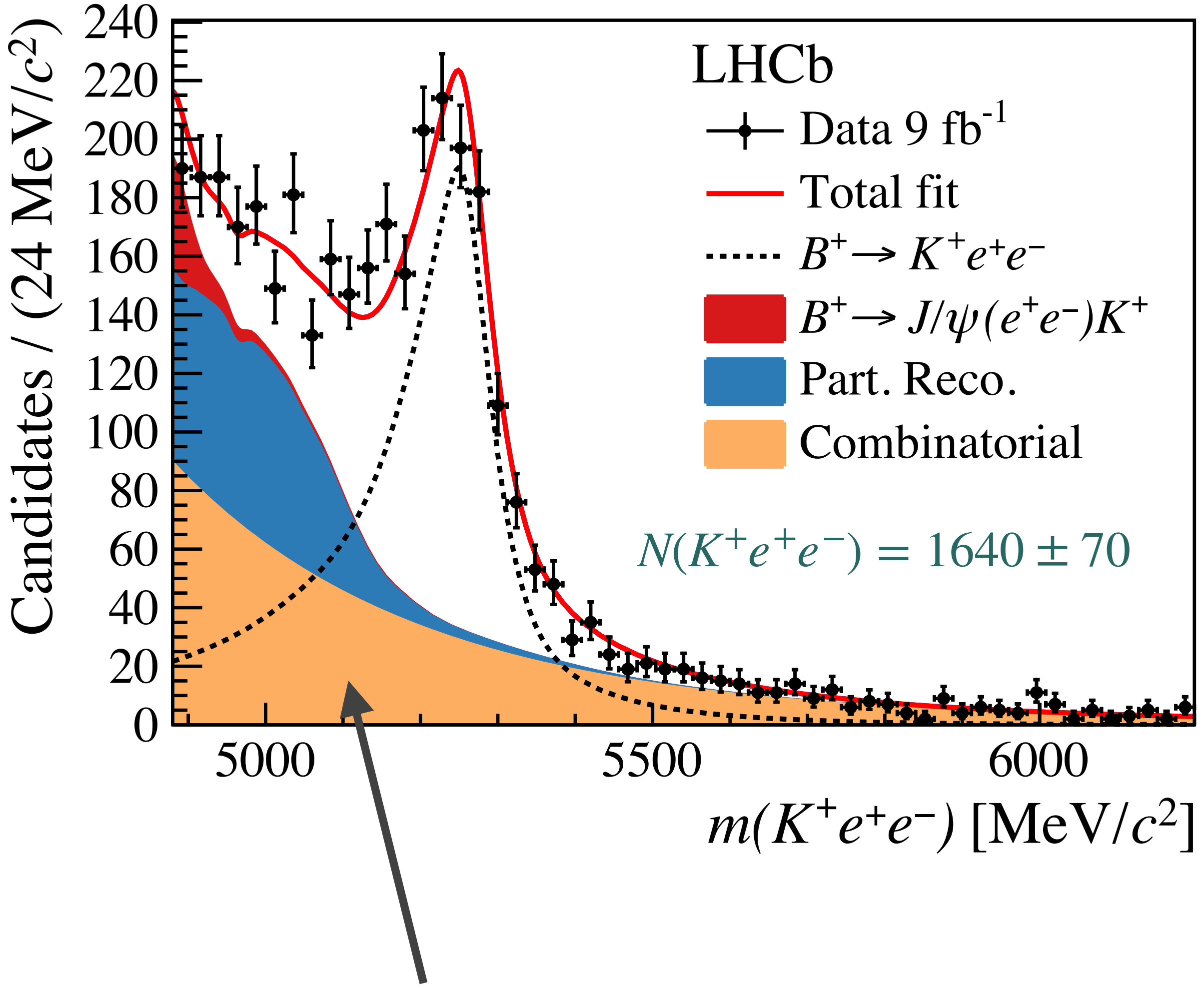


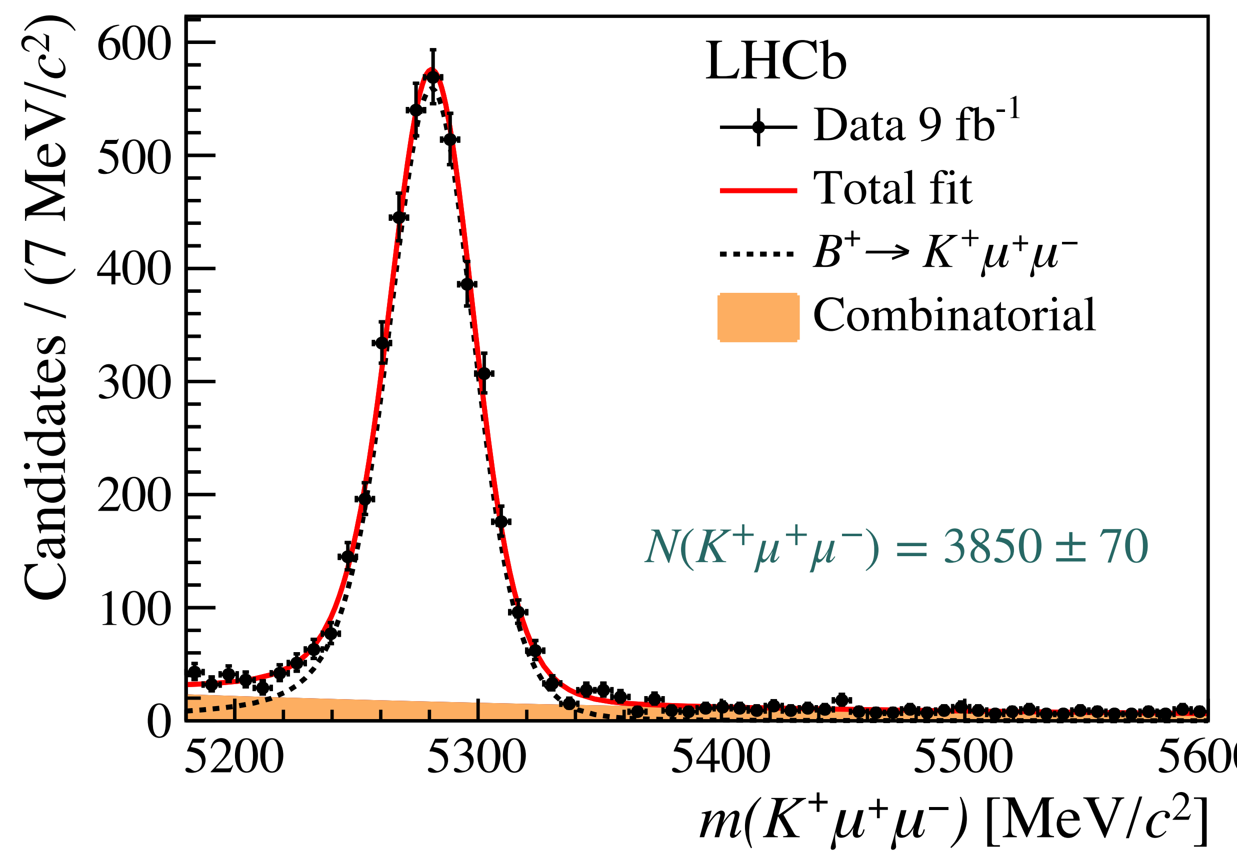
q^2 for semileptonic $b \to s\ell\ell$



e^+e^- at LHCb: Resolution

LHCb arXiv:2103.11769

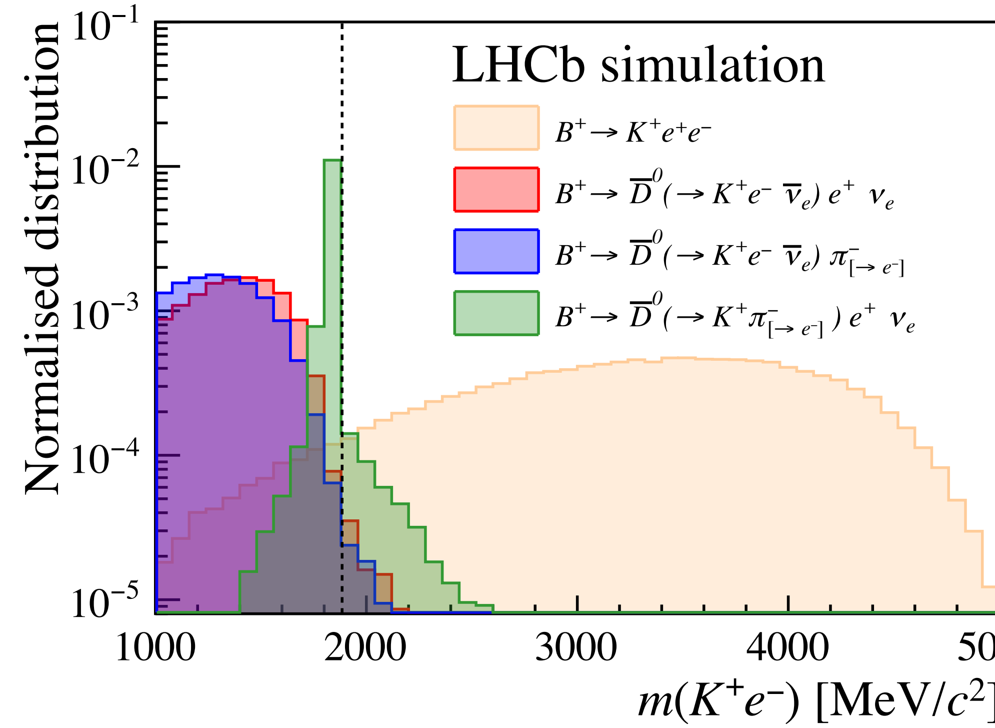


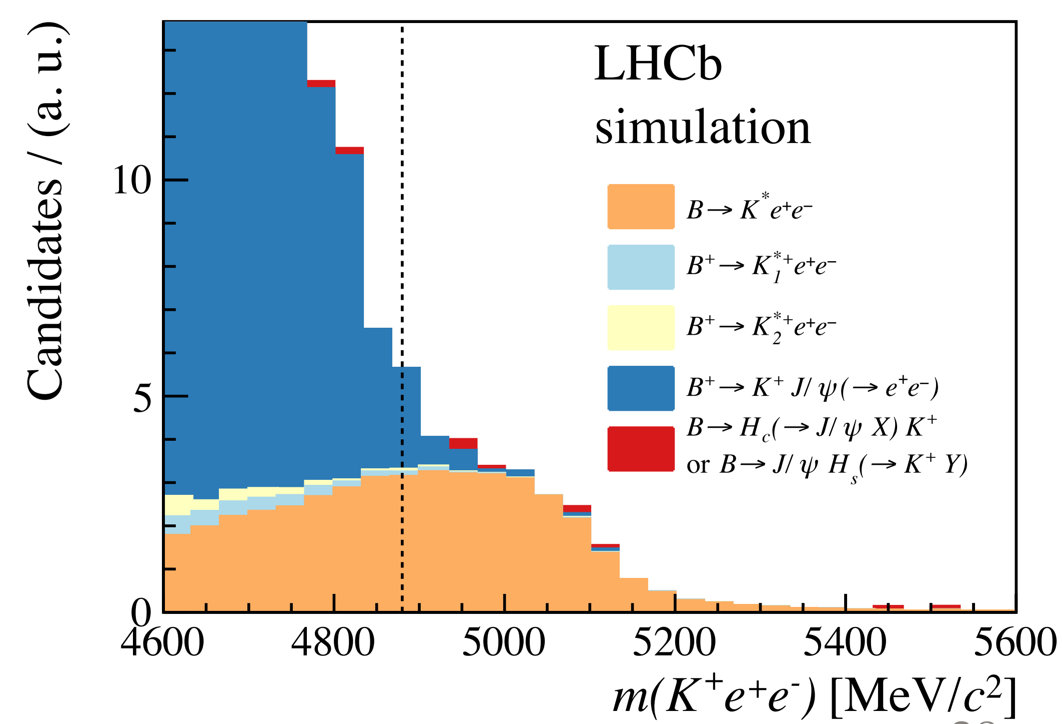


- Background with missing pion (Part. Reco.) due to mass resolution
- Combinatorial background is much larger
- Signal mass shape controlled with $J/\psi \to e^+e^-$ channel

Backgrounds in electrons

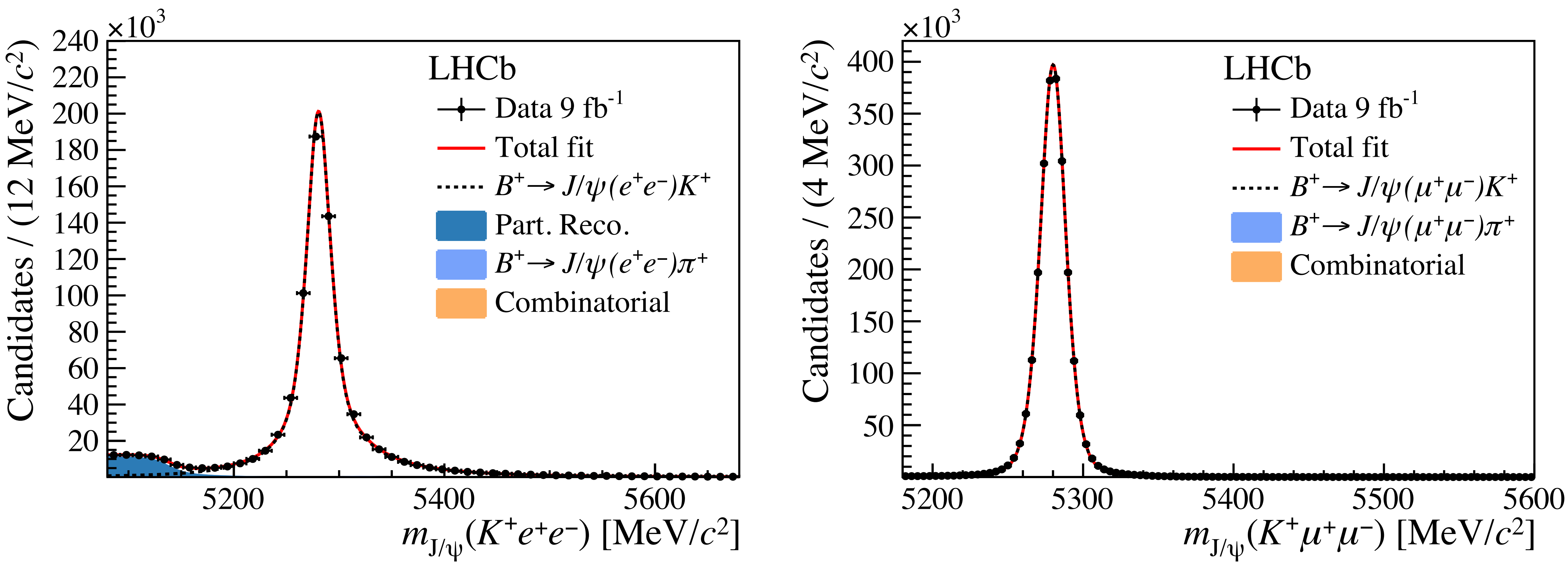
- Particle ID and mass vetoes to suppress bkg e.g:
    - cascade $B \to D \to K$ with $m(K^+e^-) > m_{D^0}$
    - remove $B^+ \to K^+\pi^+\pi^-$ with tight electron ID
- Reduce combinatorial background with multivariate analysis (Boosted Decision Tree)
- Choose $m(K^+e^+e^-)$ window to suppress other backgrounds





Charmonium control channel

LHCb arXiv:2103.11769



- $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ decays are known (and expected) to respect LFU at 0.4% level
- Excellent control channel: samples of 750k electrons and 2.3M muons
- Can be isolated from background using J/ψ mass constrain

e^+e^- at LHCb: Modelling

LHCb arXiv:2103.11769

- Use **double ratio:**

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

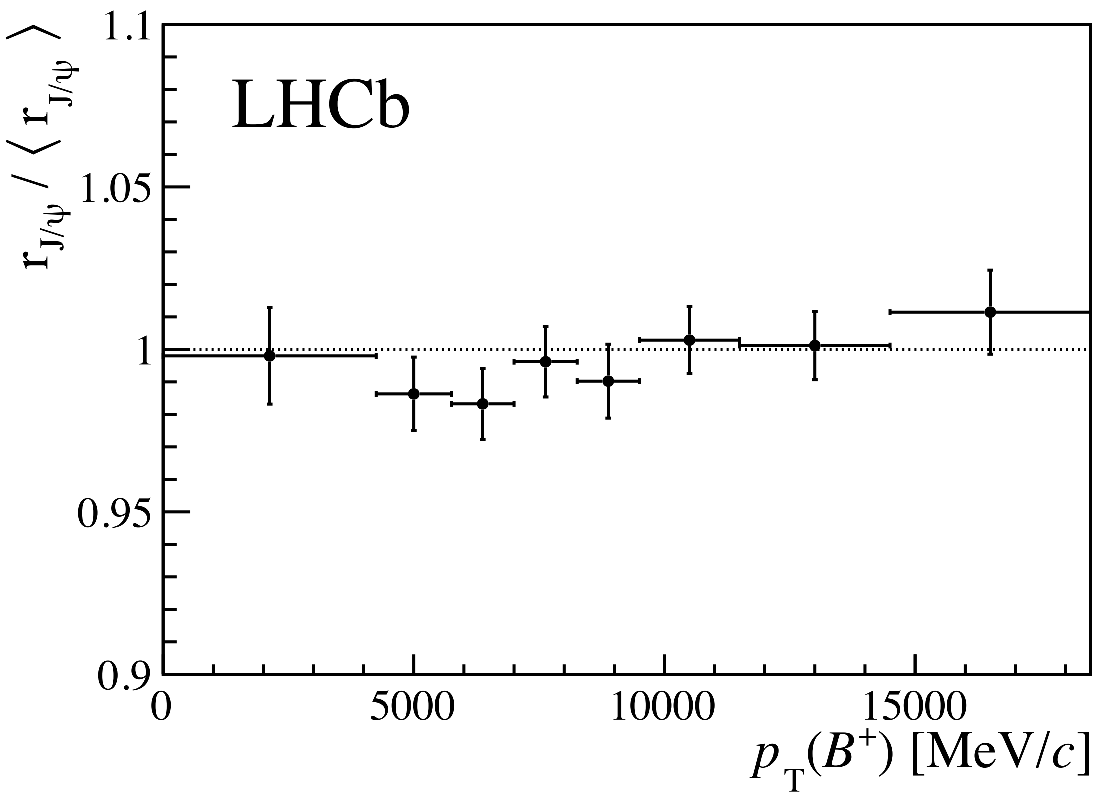
$$= \frac{N_{K^+\mu^+\mu^-}}{N_{K^+ J/\psi\,(\mu^+\mu^-)}}\frac{N_{K^+ J/\psi\,(e^+e^-)}}{N_{K^+e^+e^-}}\frac{\epsilon_{K^+ J/\psi\,(\mu^+\mu^-)}}{\epsilon_{K^+\mu^+\mu^-}}\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+ J/\psi\,(e^+e^-)}}$$

$\to$ cancel systematics

- **Crosschecks using** universality in $c\bar{c}$ resonances

$$r_{J/\psi} = \frac{B\left(B^+ \to J/\psi\,(\to \mu^+\mu^-)\,K^+\right)}{B\left(B^+ \to J/\psi\,(\to e^+e^-)\,K^+\right)} = 0.981 \pm 0.020$$

- Can also check $r_{J/\psi}$ **differentially** to insure efficiency is modelled correctly as a function of the relevant kinematic variables



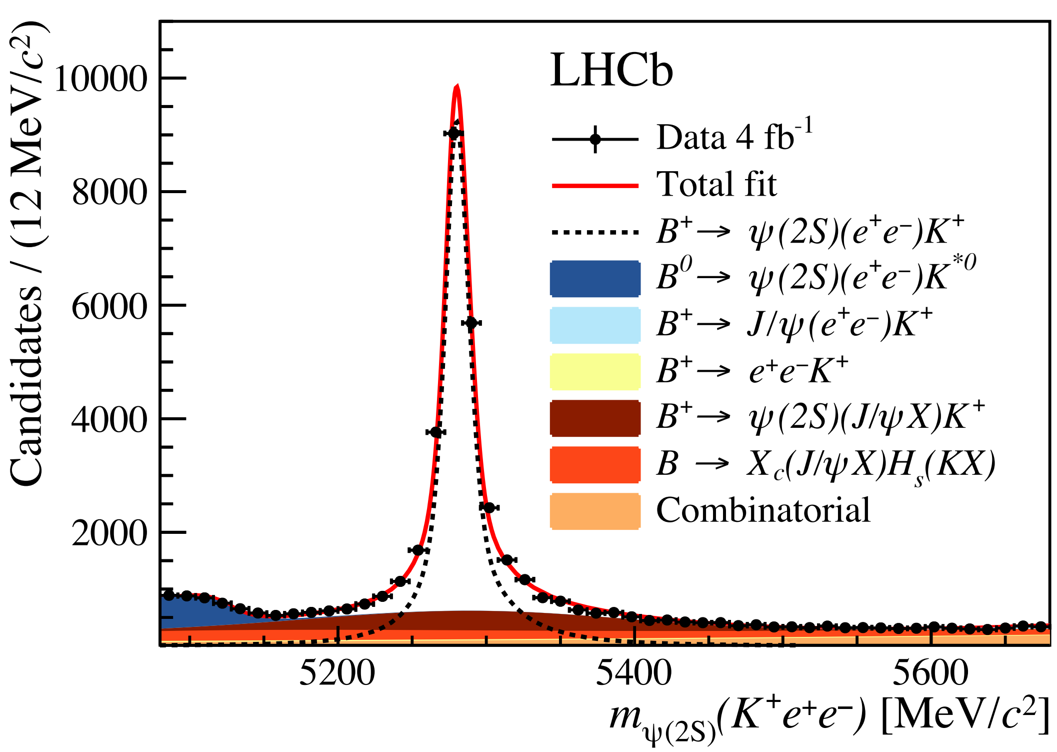
e^+e^- at LHCb: Modelling

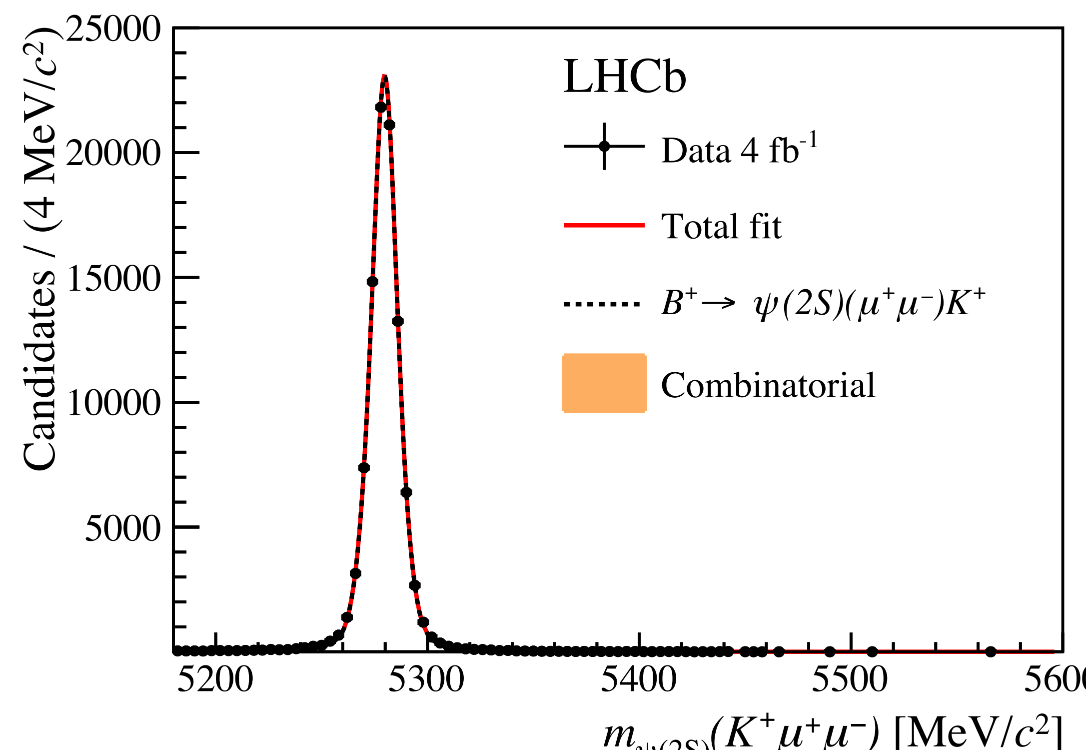
- Can also test that R_K measured at the $\psi(2S)$ is 1

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

- Validation of q^2 dependence of efficiency correction

- Compatible with unity to 1% precision:
  $R_{\psi(2S)} = 0.997 \pm 0.011(\text{ stat } + \text{ syst })$





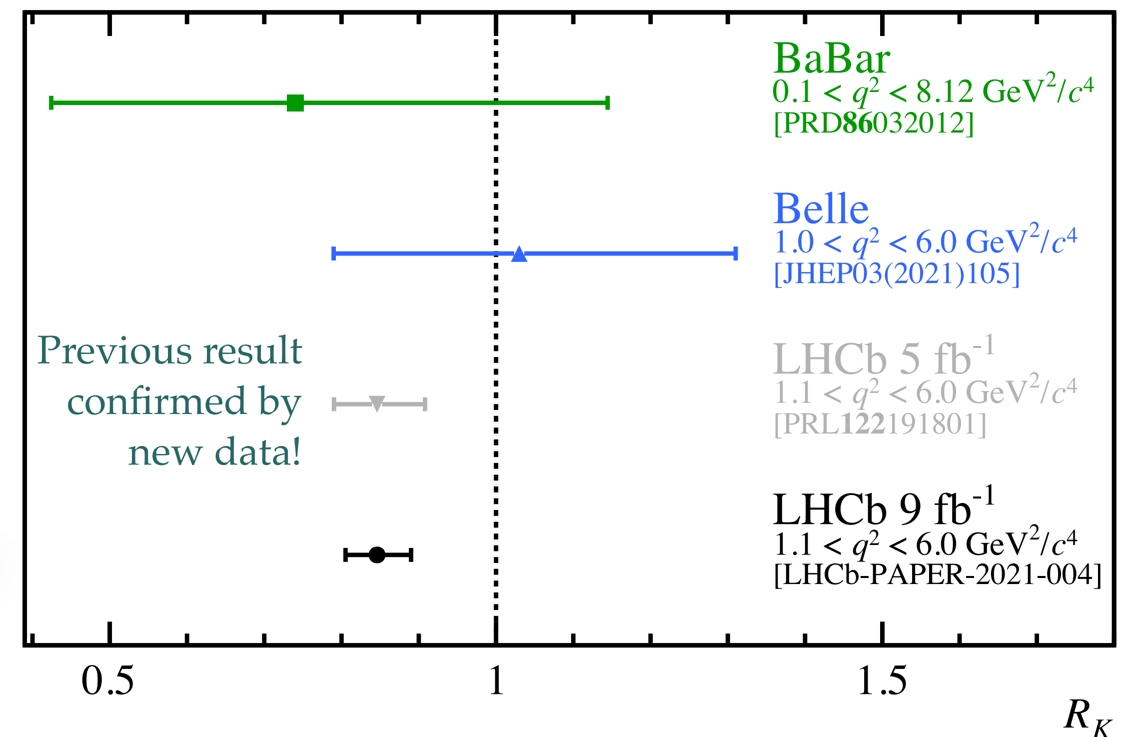
R_K result

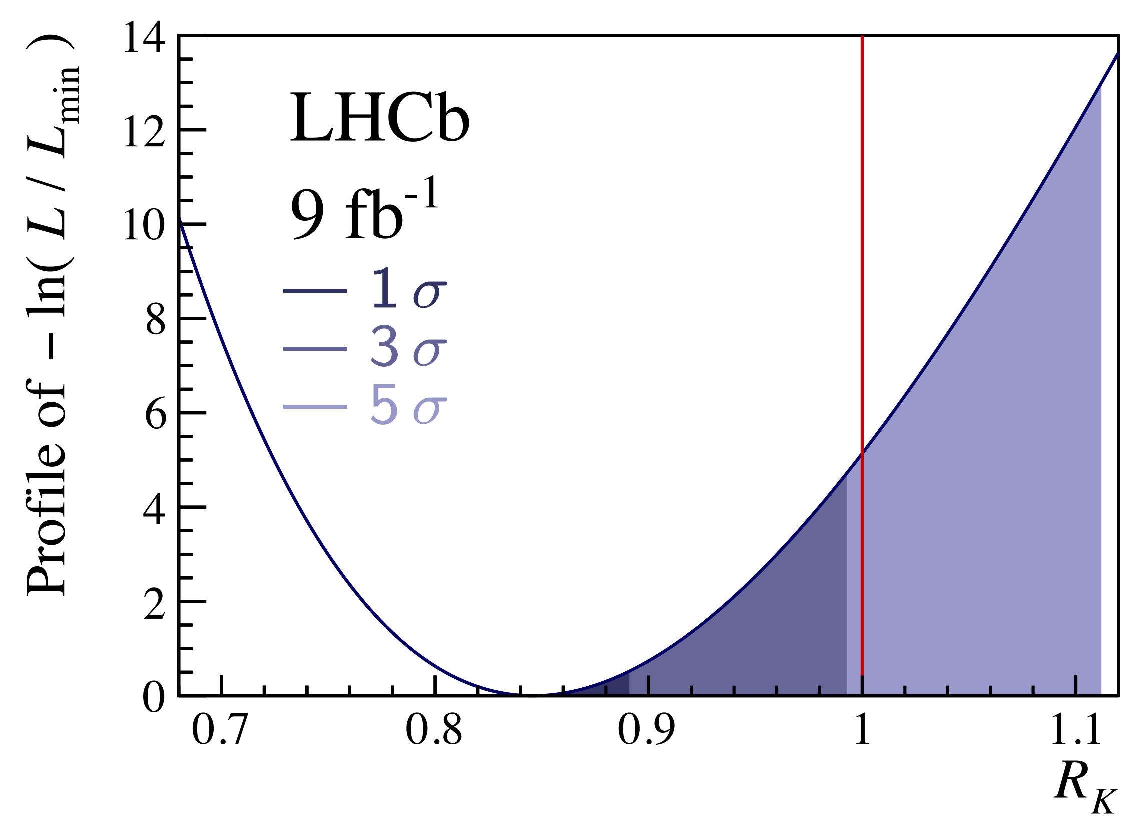
LHCb arXiv:2103.11769

- Measured with full Run 1+2 dataset (9/fb at √s=7, 8 and 13 TeV)

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

- Yield of ~1640 $B^+ \to K^+e^+e^-$ events (vs ~3850 in $B^+ \to K^+\mu^+\mu^-$) driving the total uncertainty:
  - 5% statistical error vs 1.5% systematic
- **R_K is found to be lower than unity by ~15% with a significance of 3.1σ**

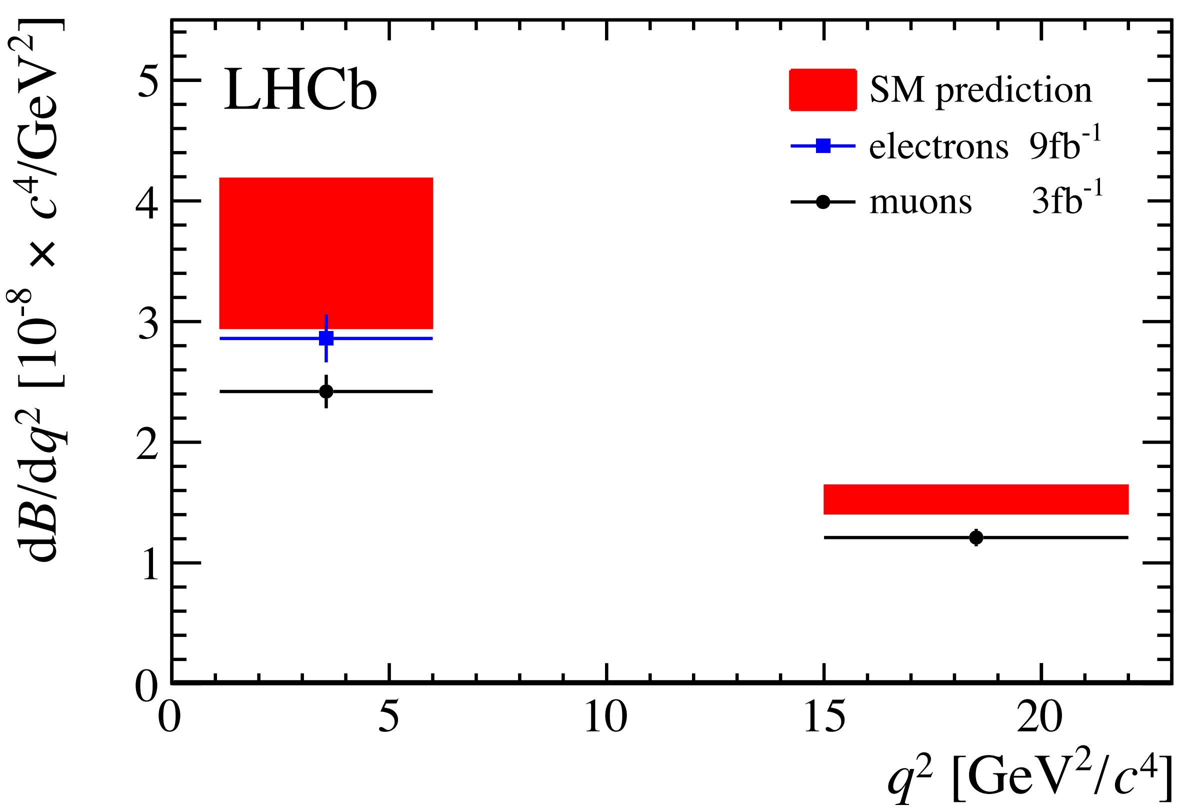




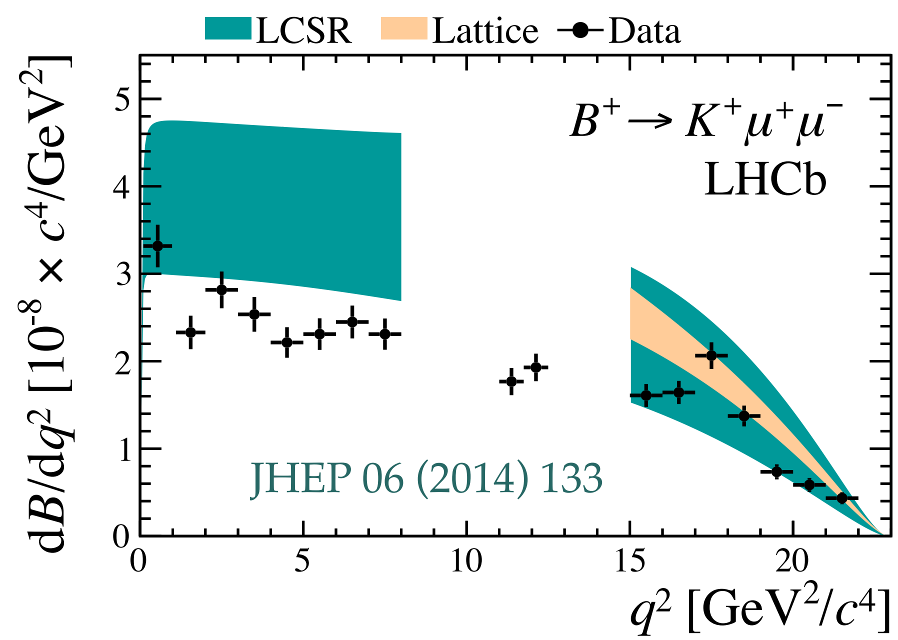
R_K result

- Also measured electrons BR and compared to previous result on muons:

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



$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ from 3/fb paper:

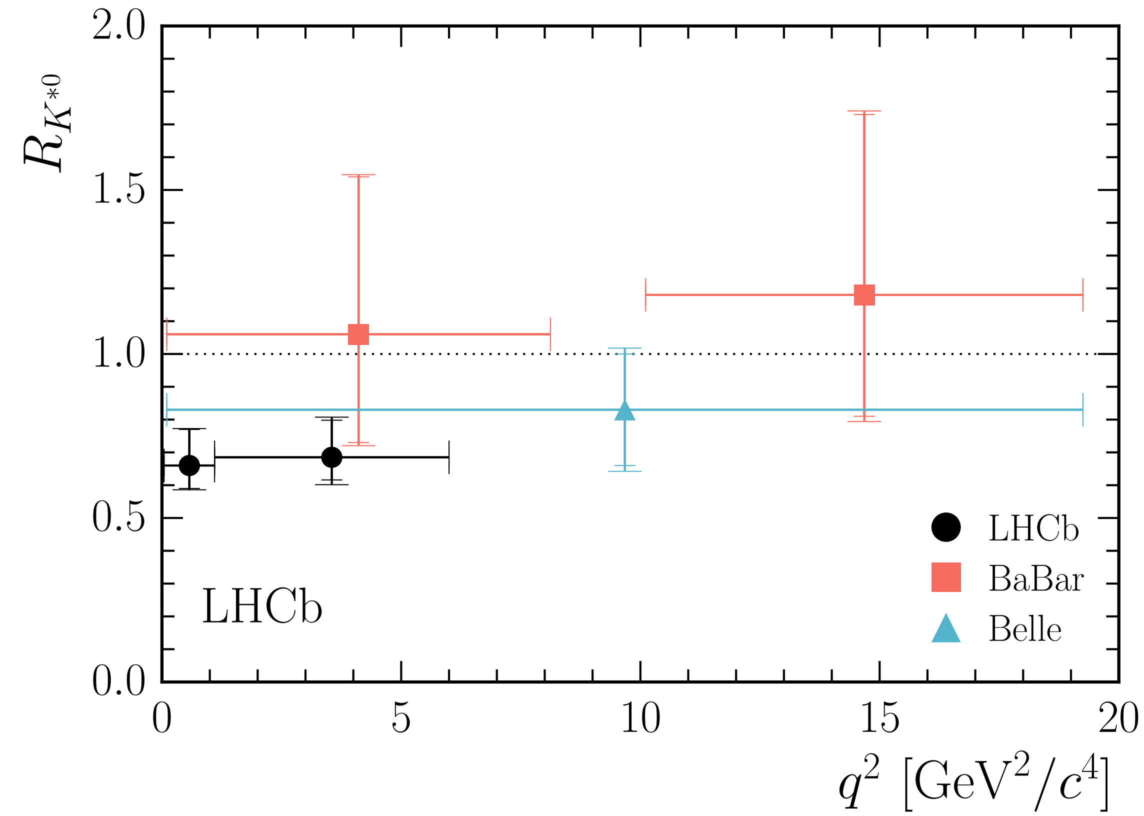


→ Electrons BR closer to SM prediction (but both compatible)

R_{K^*} result

LHCb, JHEP 08 (2017) 055

- Similar deviation was observed in R_{K^*} using Run 1 data
- Precision of ~17% in both bins, statistically dominated
- Upcoming Run 1 + Run 2 update expected to reduce uncertainty by factor ~2



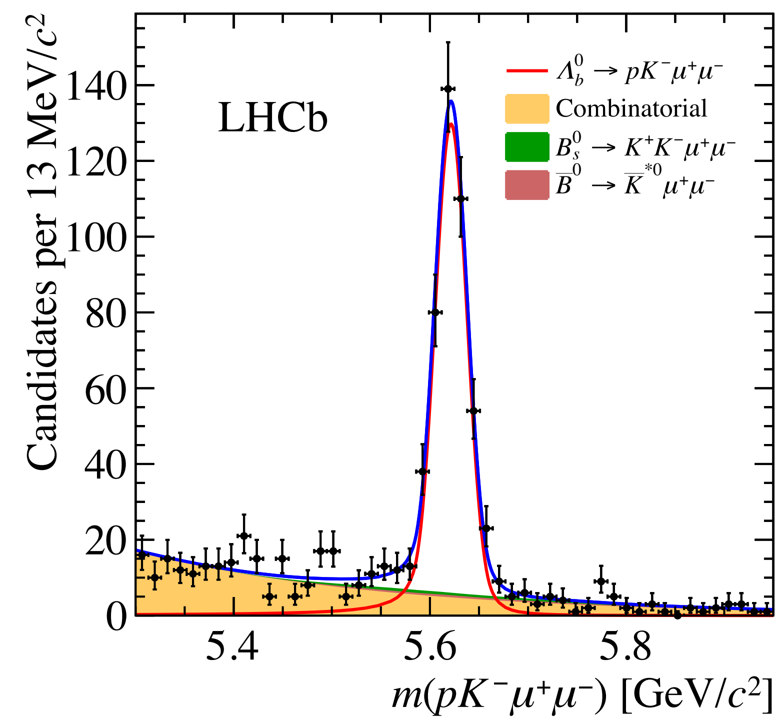
$$R_{K^{*0}} = \begin{cases} 0.66\ ^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \ \text{GeV}^2/c^4 \\ 0.69\ ^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \ \text{GeV}^2/c^4 \end{cases}$$

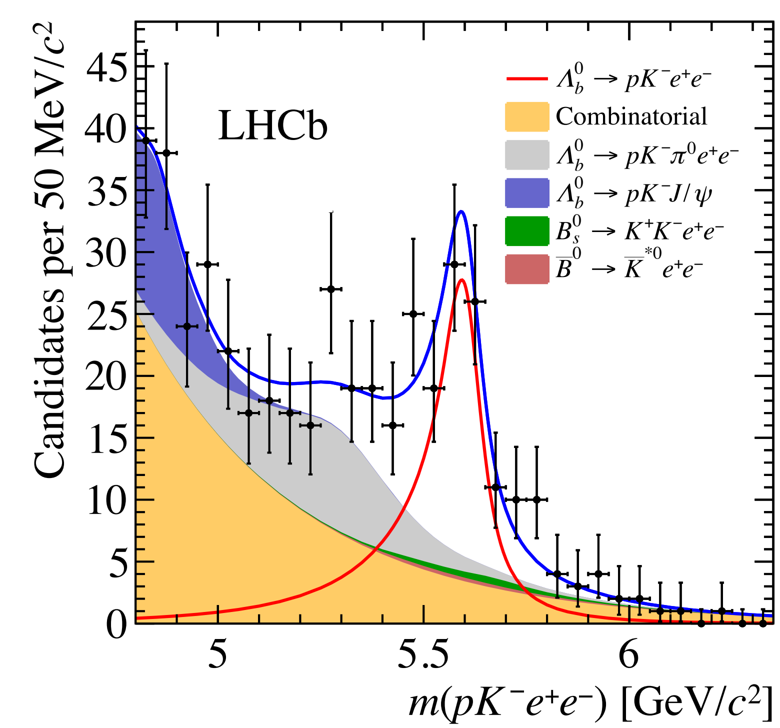
LFU test in baryons

LHCb, JHEP 05 (2020) 040

- New test of LFU in $\Lambda_b \to pK^-\ell^+\ell^-$
  - Using Run 1 + 2016 dataset (4.7/fb)
- Similar physics as R_K and
  - Different final state and selection
  - Different backgrounds and systematic uncertainties
- Crosscheck using $\Lambda_b \to pK^- J/\psi$
- Measured phase space region:
  - $m(pK^-) > 2.6$ GeV
  - $0.1 < q^2 < 6.0\ \mathrm{GeV}^2$

$$R_{pK}\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86^{+0.14}_{-0.11} \pm 0.05$$





Global fits

Weak effective theory fits

- Fit all $b \to s\ell\ell$ data with Weak Effective Theory
  - Semileptonic $b \to s\mu\mu$ (BR and angular)
  - $BR(B_s \to \mu\mu)$ measurement
  - LFU tests $b \to se^+e^-$ vs $b \to s\mu^+\mu^-$

  } **Theoretically cleaner**

- $bs\mu\mu$ NP contribution give large pull from SM (>5σ)
  - Objection 1: semileptonic $b \to s\mu\mu$ predictions are hard
  - Objection 2: you cherry picked the coefficient to fit!

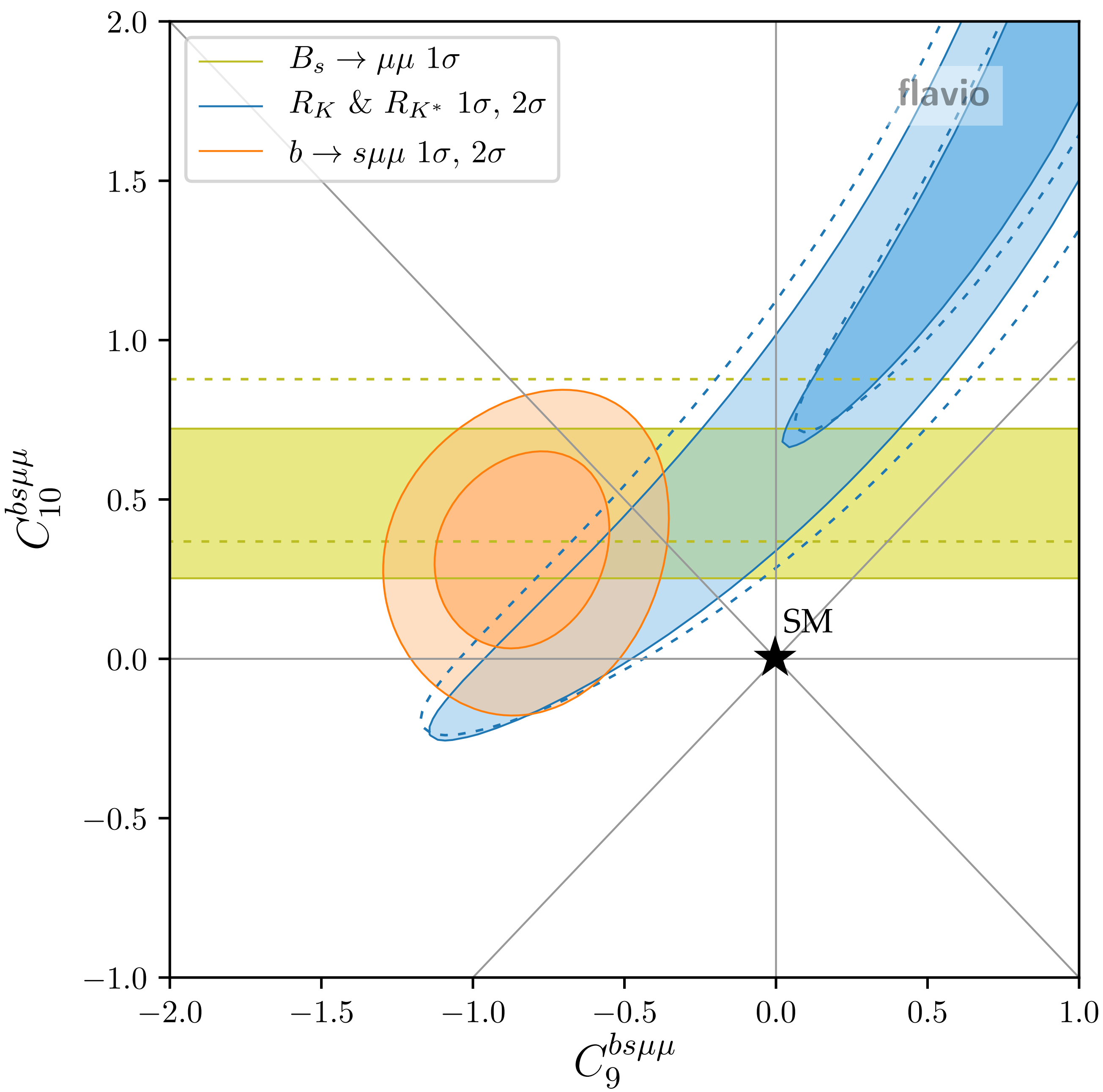
Fit from W. Altmannshofer and P. Stangl arXiv:2103.13370

Wilson coefficient	$b \to s\mu\mu$ best fit	pull	LFU, $B_s \to \mu\mu$ best fit	pull	all rare B decays best fit	pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}^{\prime bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

Similar fits from other groups:
Algueró et al., arXiv:1903.09578
Kowalska et al., arXiv:1903.10932
Ciuchini et al., arXiv:2011.01212
Datta et al., arXiv:1903.10086
Arbey et al., arXiv:1904.08399
Geng et al., arXiv:2103.12738

WET fits

Fit from W. Altmannshofer and P. Stangl arXiv:2103.13370



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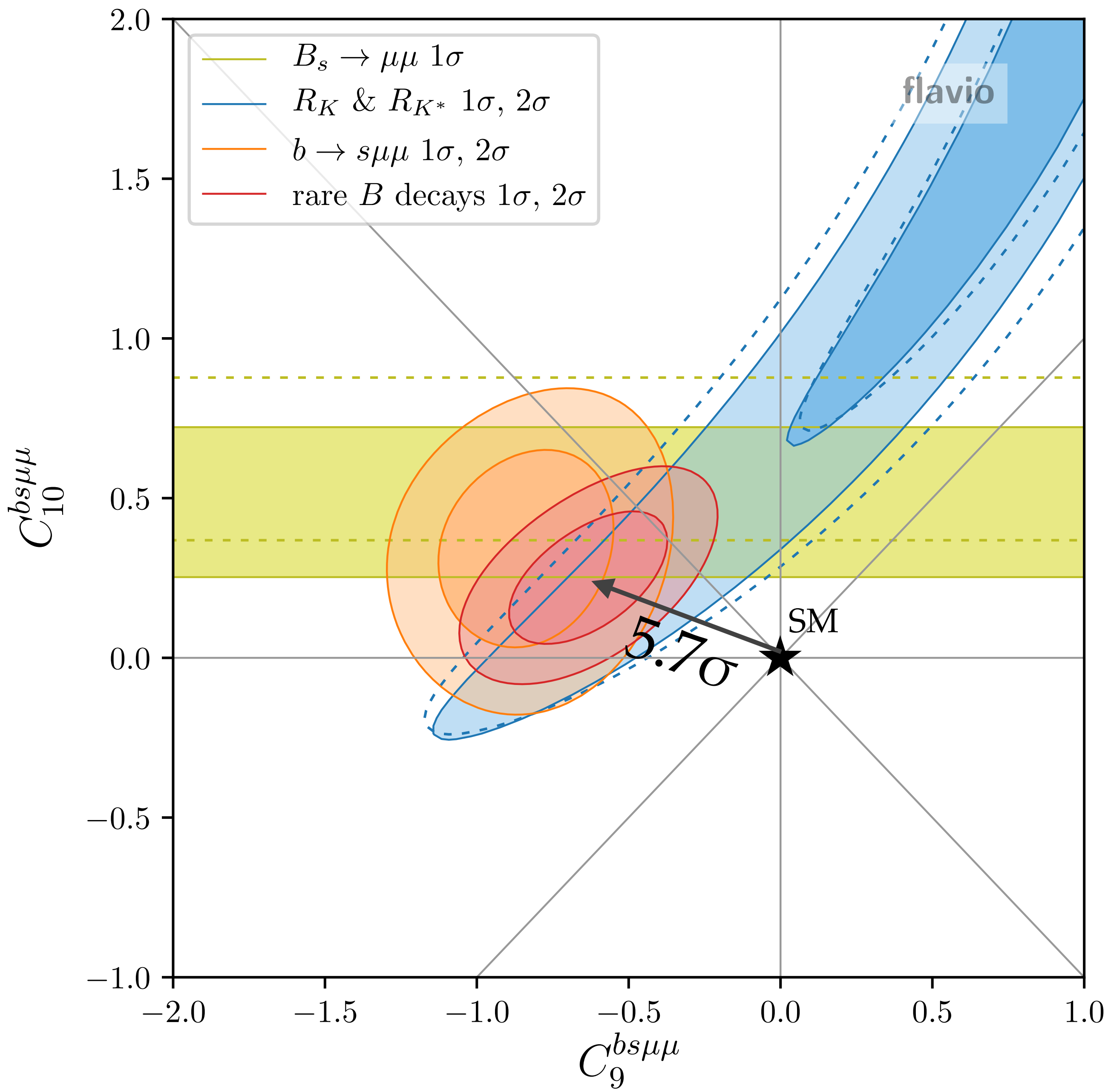
WET fits

Fit from W. Altmannshofer and P. Stangl arXiv:2103.13370



$C_9^{bs\mu\mu}$, $C_{10}^{bs\mu\mu}$ fit gives 5.7σ pull w.r.t. SM

Similar fits from other groups:
Algueró et al., arXiv:1903.09578
Kowalska et al., arXiv:1903.10932
Ciuchini et al., arXiv:2011.01212
Datta et al., arXiv:1903.10086
Arbey et al., arXiv:1904.08399
Geng et al., arXiv:2103.12738

Prospects

Upcoming Run 2 analyses

Prospects for muons

- Updates with full Run 2:
  - $B^0 \to K^*\mu^+\mu^-$
  - $B_s \to \phi\mu^+\mu^-$
- New analyses:
  - Search for $B \to K^*\tau^+\tau^-$

Prospects for LU tests

CERN-LHCC-2018-027

R_X precision	9fb^{-1}
~~R_K~~	~~0.043~~
$R_{K^{*0}}$	0.052
R_ϕ	0.130
R_{pK}	0.105
R_π	0.302

We got 0.042!

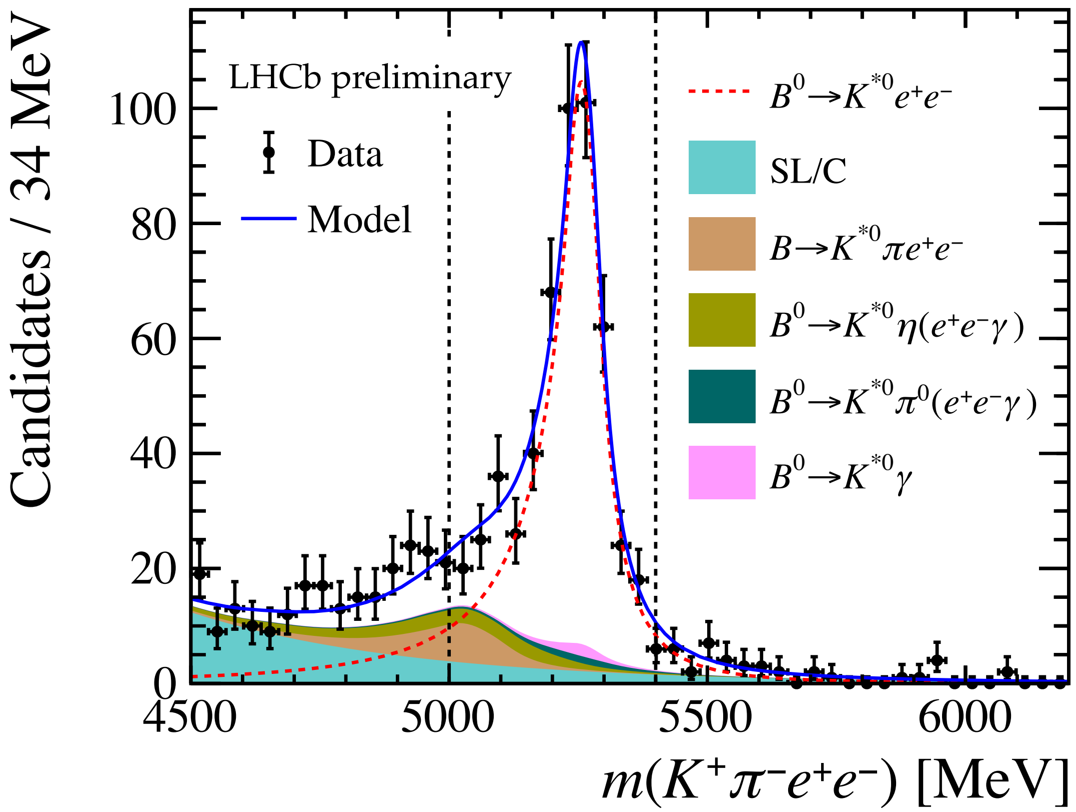
+ we are exploring high q^2

S.Glashow et al Phys.Rev.Lett. 114 (2015) 091801

- LFU violation implies LFV
  $\to$ several LFV searches: $e^+\mu^-$, $\mu^+\tau^-$

$B^0 \to K^*e^+e^-$ angular analysis

- If $b \to s\mu\mu$ angular anomalies and $b \to s\ell\ell$ anomalies have the same NP origin, then$b \to see$ angular observables should be SM!
- $B^0 \to K^*ee$ angular analysis was performed only at very low q^2 to measure $b \to s\gamma^*$
- **Next step is to extend the analysis to higher q^2 values and compare to muons**

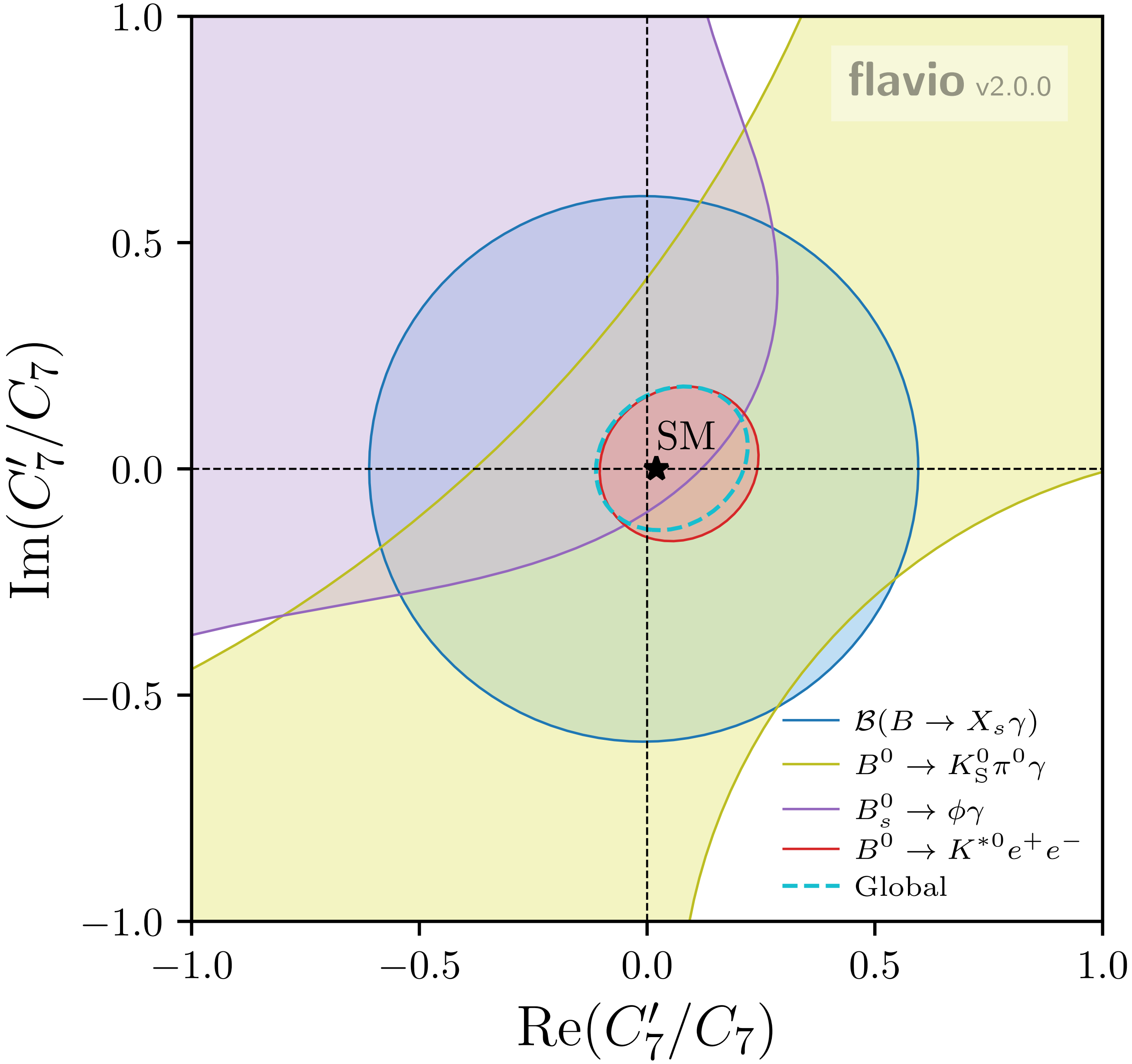


JHEP 12 (2020) 081

$B^0 \to K^* e^+ e^-$ angular analysis

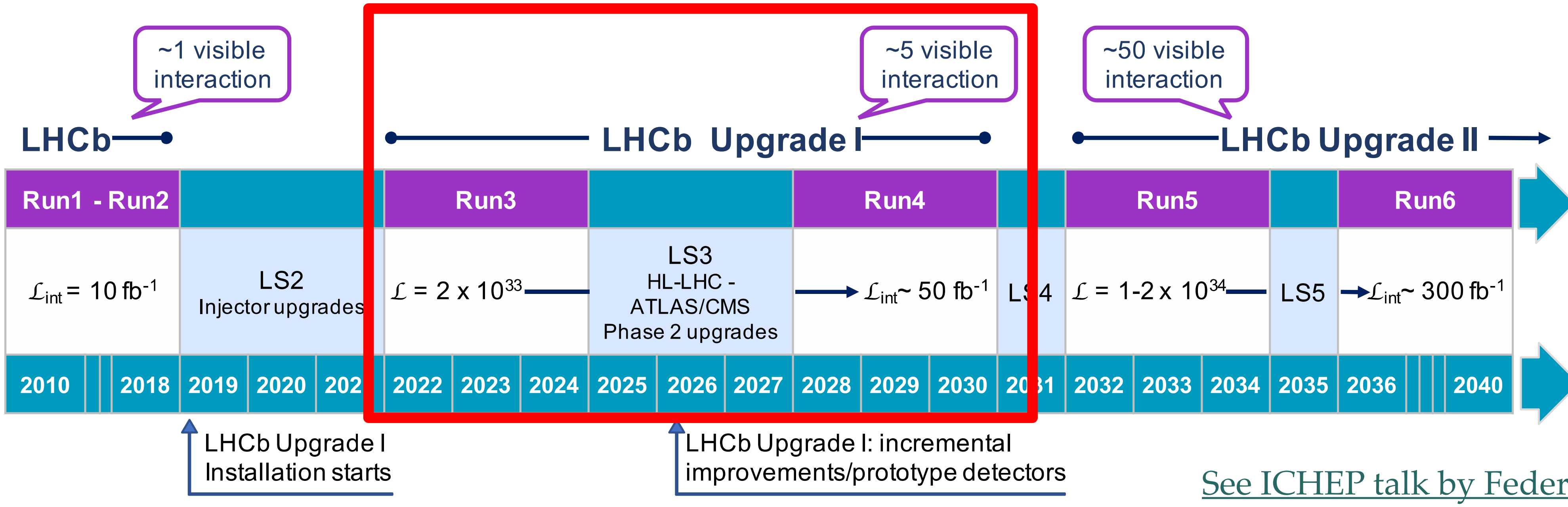
By the way, …

the $B^0 \to K^* e^+ e^-$ angular analysis at low q^2 just placed world best limit on $b \to s\gamma$ photon polarisation, a golden flavour physics parameter



JHEP 12 (2020) 081

LHCb upgrade I

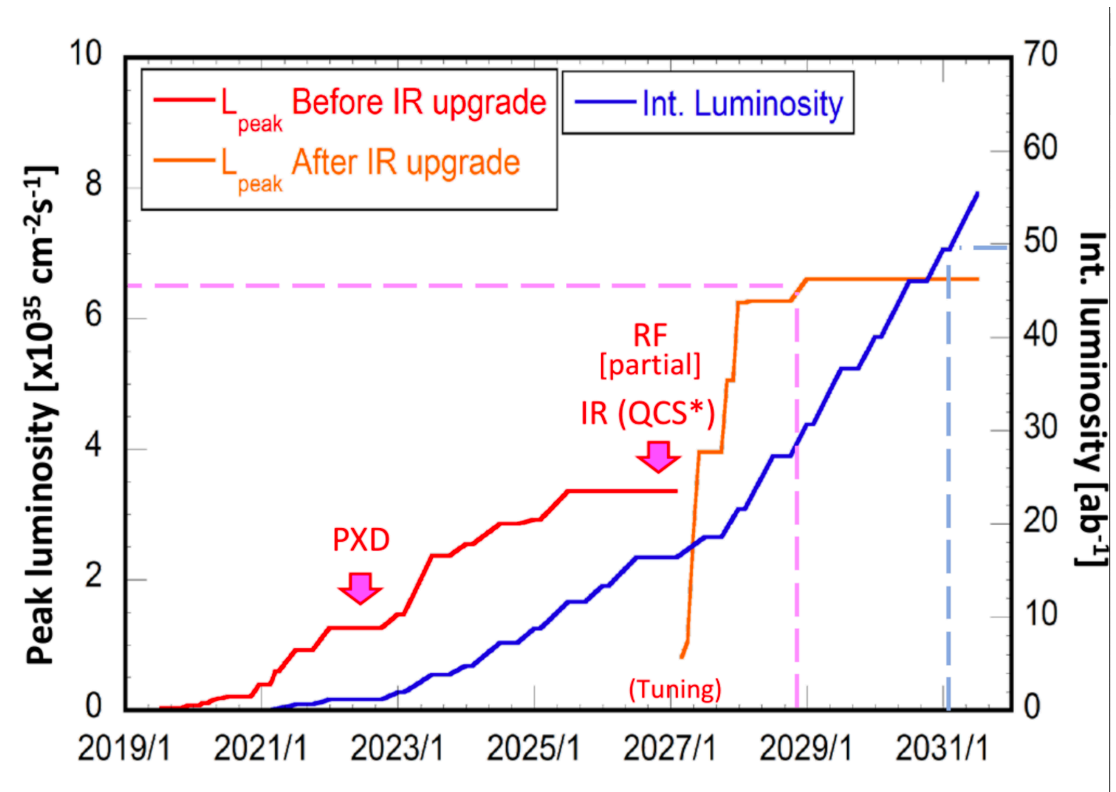


See ICHEP talk by Federico

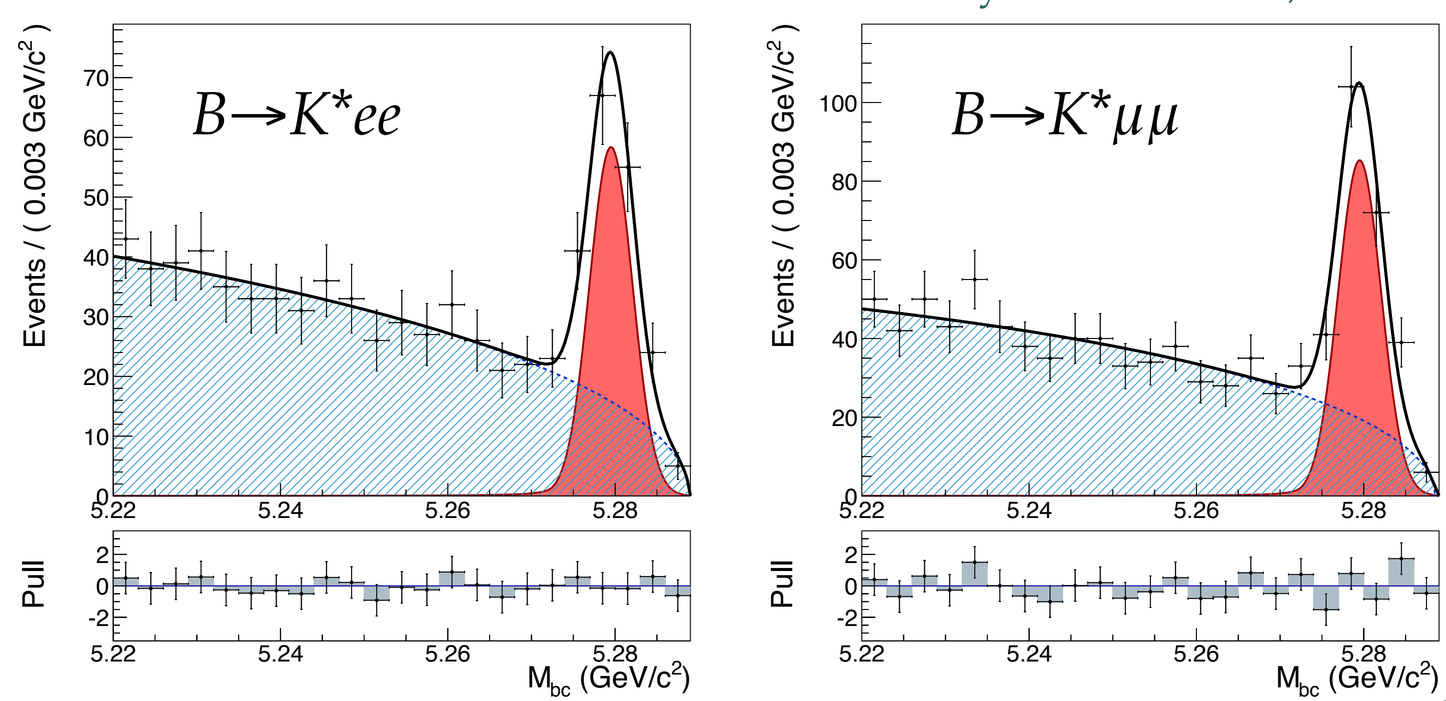
- Preparing upgrade for LHC Run 3 and 4
  - Higher luminosity → collect 50/fb by the end of Run 4
  - Upgrade to maintain performance and improve trigger capabilities
- LHCb detector Upgrade I in a nutshell:
  - More precise vertexing and tracking systems
  - Completely new readout system: throughput of 32 Tbps
  - Full software trigger on 500 modern GPUs

Few words on Belle II

- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - Much cleaner than LHC environment
  - Cross-section $\mathcal{O}$(nb): need huge luminosity
- Belle II is ramping up
  - Aim at collecting 50 ab^{-1} around 2031
  - Not as much stat as LHCb in charged modes:
    $K^+\mu\mu$: 1 fb^{-1} LHCb $\simeq$ 2.5 ab^{-1} Belle II
    $K^+e^+e^-$: 1 fb^{-1} LHCb $\simeq$ 1 ab^{-1} Belle II
- But Belle II can measure channels with neutral hadrons and neutrinos → great complementarity
- + Essential validation of the anomalies from experiment with very different environment and challenges



Belle: Phys. Rev. Lett. 118, 111801

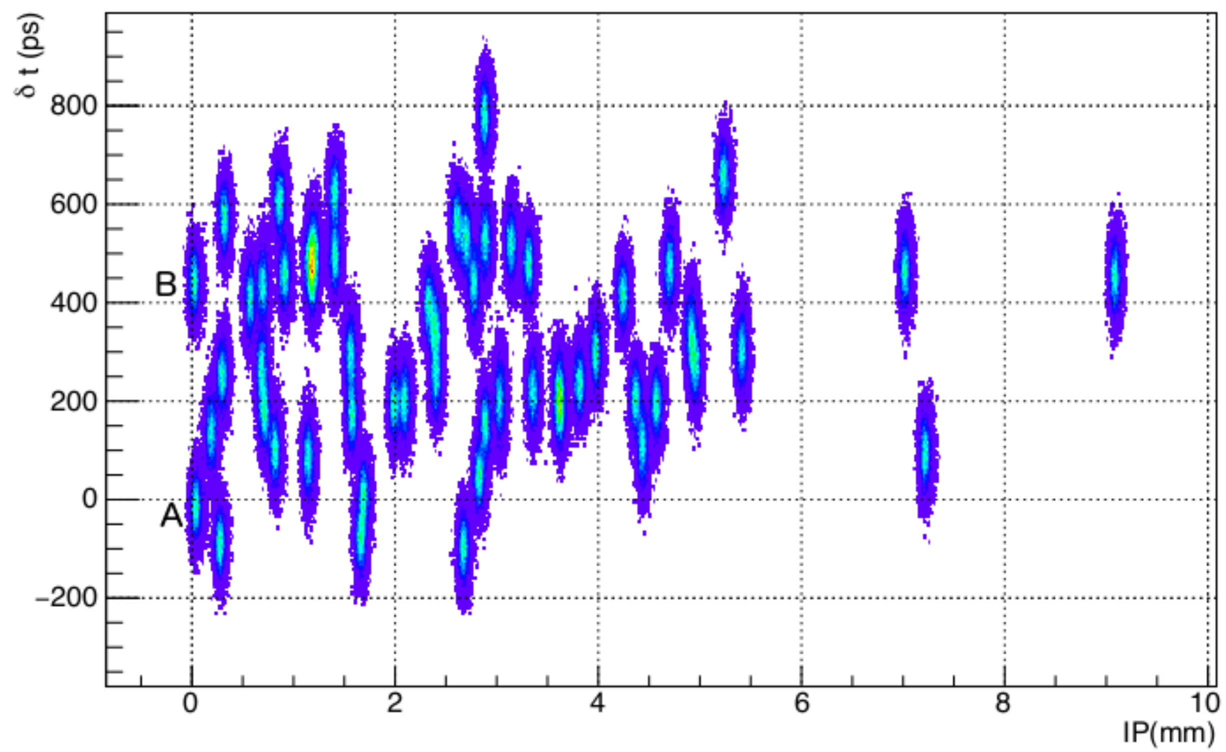


Response to muons and electrons is very similar!

LHCb Upgrade II

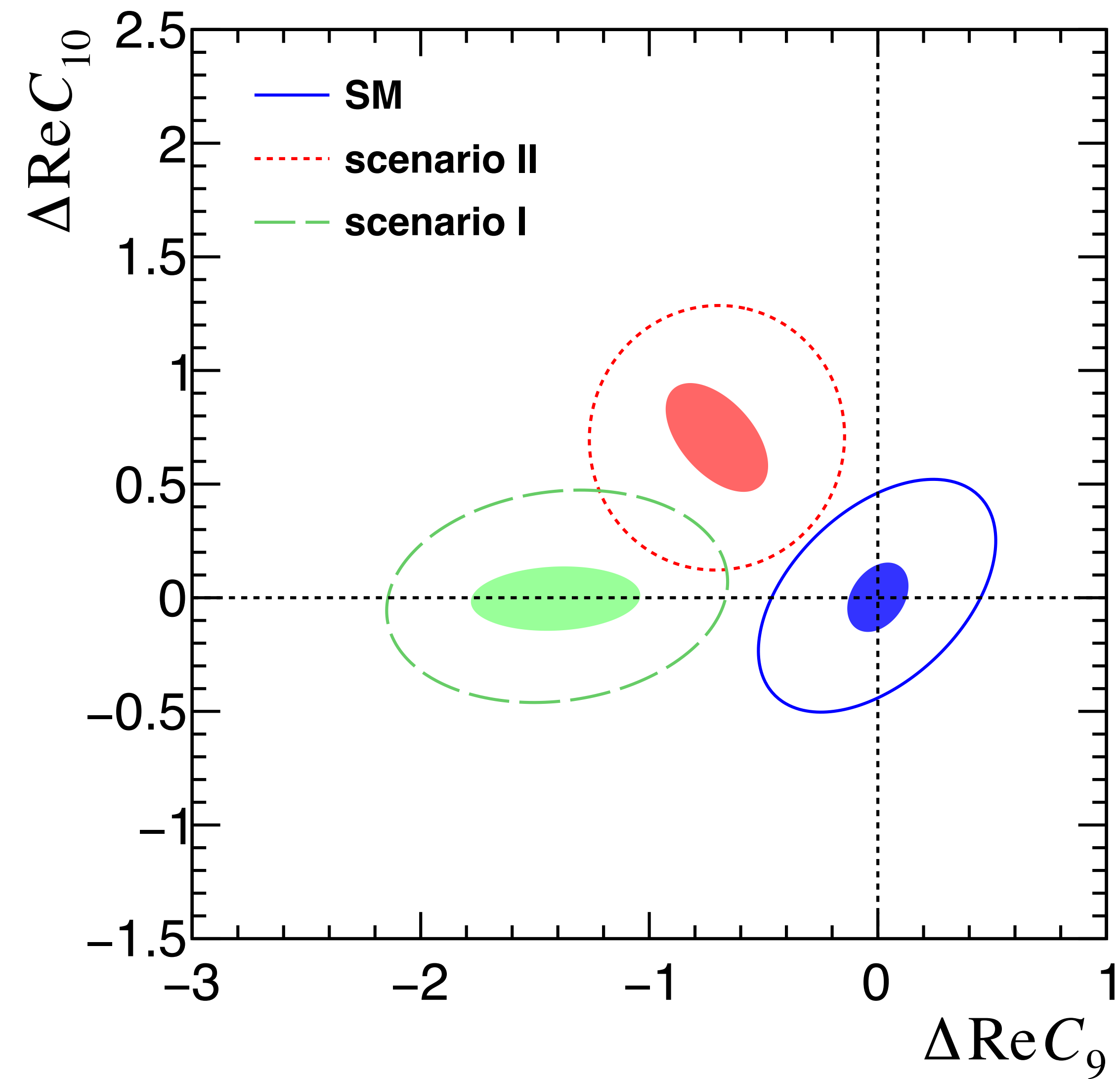
- Plan to crank up luminosity by another factor 10 in Run 5-6 (2030s)
  - Aim at collecting 300/fb by 2040
- Need to deal with the collision pile-up of about 50
  - Higher granularity
  - Lower material budget
  - Better radiation hardness
  - Tracking detectors with precise timing (200ps/hit in VELO, 20-50ps in ECAL)
  - Hardware accelerators for online reconstruction

Timing is crucial to find origin vertex of *B* decay



Rare decays in Upgrade II

- $B_{(s)} \to \mu\mu$, LFU tests and LFV searches will directly profit from the higher statistics
- Withh 400k events, the $B^0 \to K^*\mu\mu$ angular analysis will enter a new precision era, where sophisticated amplitude analyses will allow to disentangle NP and SM effects
- If anomalies are confirmed:
  - The Upgrade II will allow to precisely pin down their structure and possibly discover related effects in $b \to d\ell\ell$, $b \to se\mu$
- If anomalies are not confirmed:
  - The Upgrade II will give a unique chance to probe NP effects at an energy scale about twice as large as the current one



Summary

- Flavour anomalies in the $b \to s\ell\ell$ sector were reinforced by recent measurements
  - Are we seeing a coherent pattern?
- More data needed to solve the puzzle
  - Upcoming analyses of Run 2 data (on tape)
  - Upcoming LHCb upgrade (starting data-taking next year)
  - Other experiments: Belle II, CMS, ATLAS
- Upgrade II as the ultimate precision flavour factory

"Extraordinary claims require extraordinary evidence"
Carl Sagan

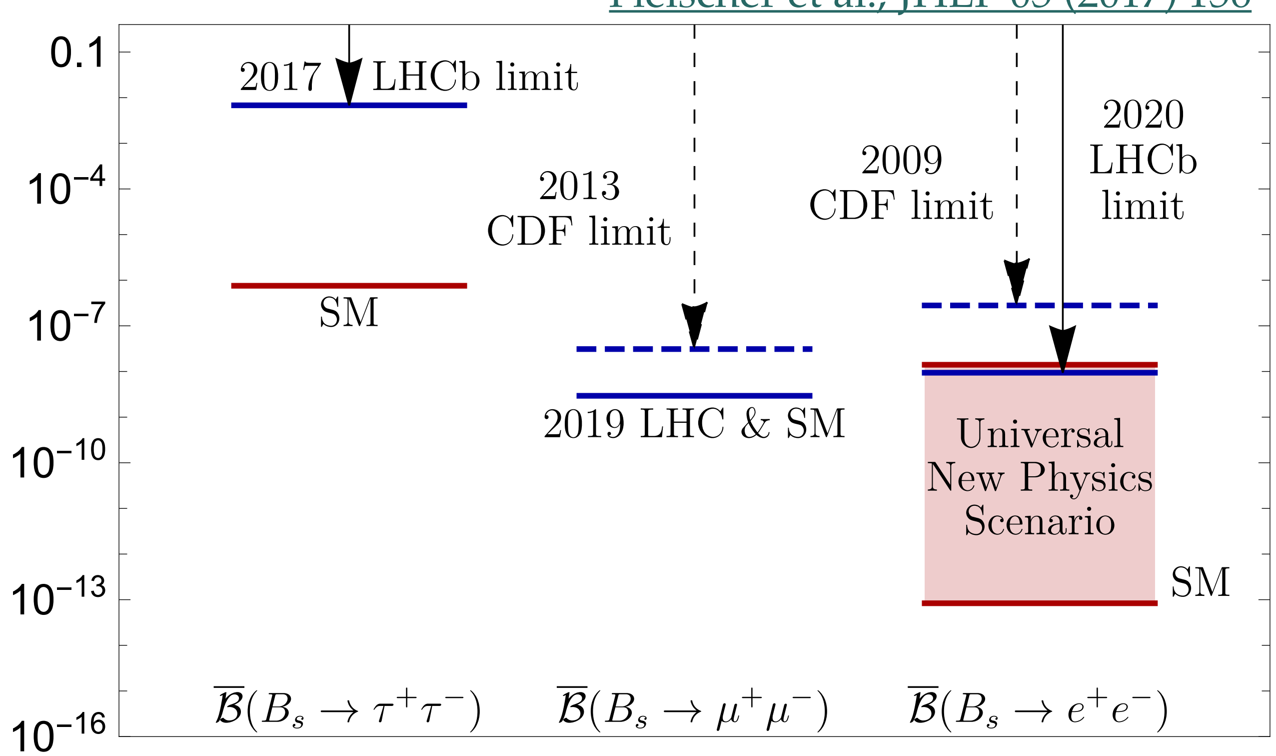
"Discovery commences with the awareness of anomaly"
Thomas Kuhn

BACKUP

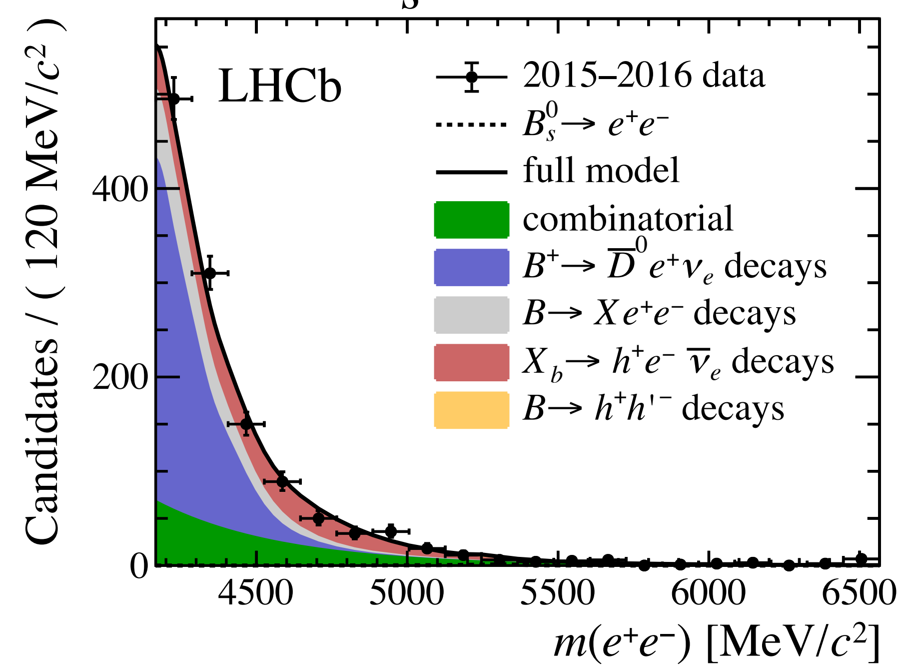
$B_s \to e^+e^-$ and $B_s \to \tau^+\tau^-$

- Not lepton universal in the SM
  - Very different levels of helicity suppression depending on the lepton mass
- Electrons and taus present additional experimental challenges
- LHCb has search for both and has set upper limits
  $BR(B_s^0 \to e^+e^-) < 11.2 \times 10^{-9}$ at 95 % CL
  $BR(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95 % CL

Fleischer et al., JHEP 05 (2017) 156

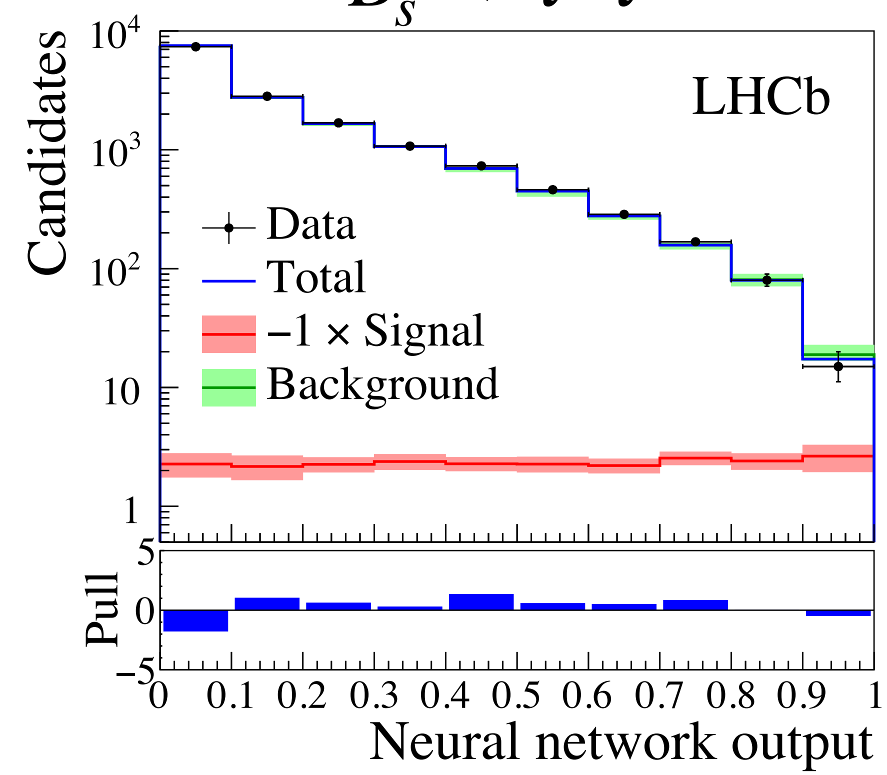


$B_s \to e^+e^-$



Phys. Rev. Lett. 124 (2020) 211802

$B_s \to \tau^+\tau^-$

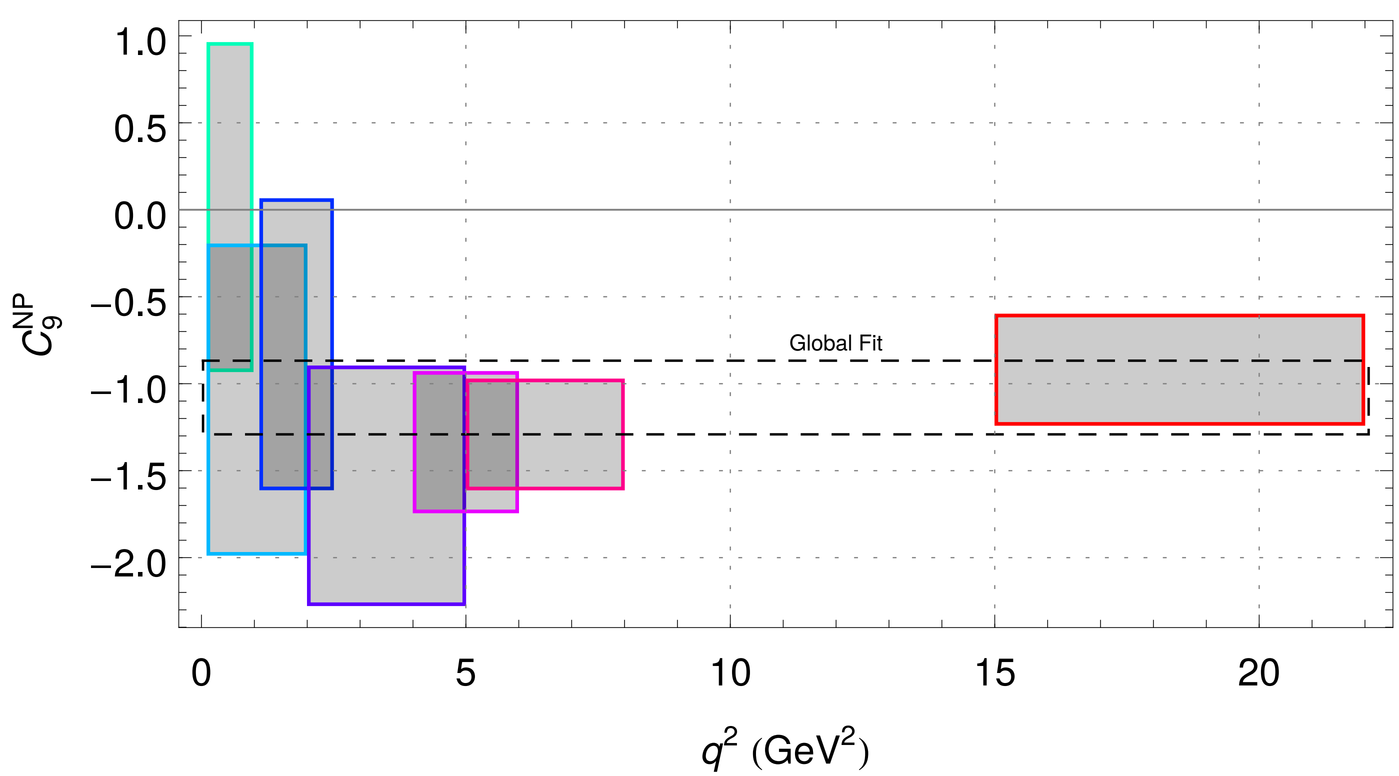


Phys. Rev. Lett. 118 (2017) 251802

A handle on the $c\bar{c}$ loop

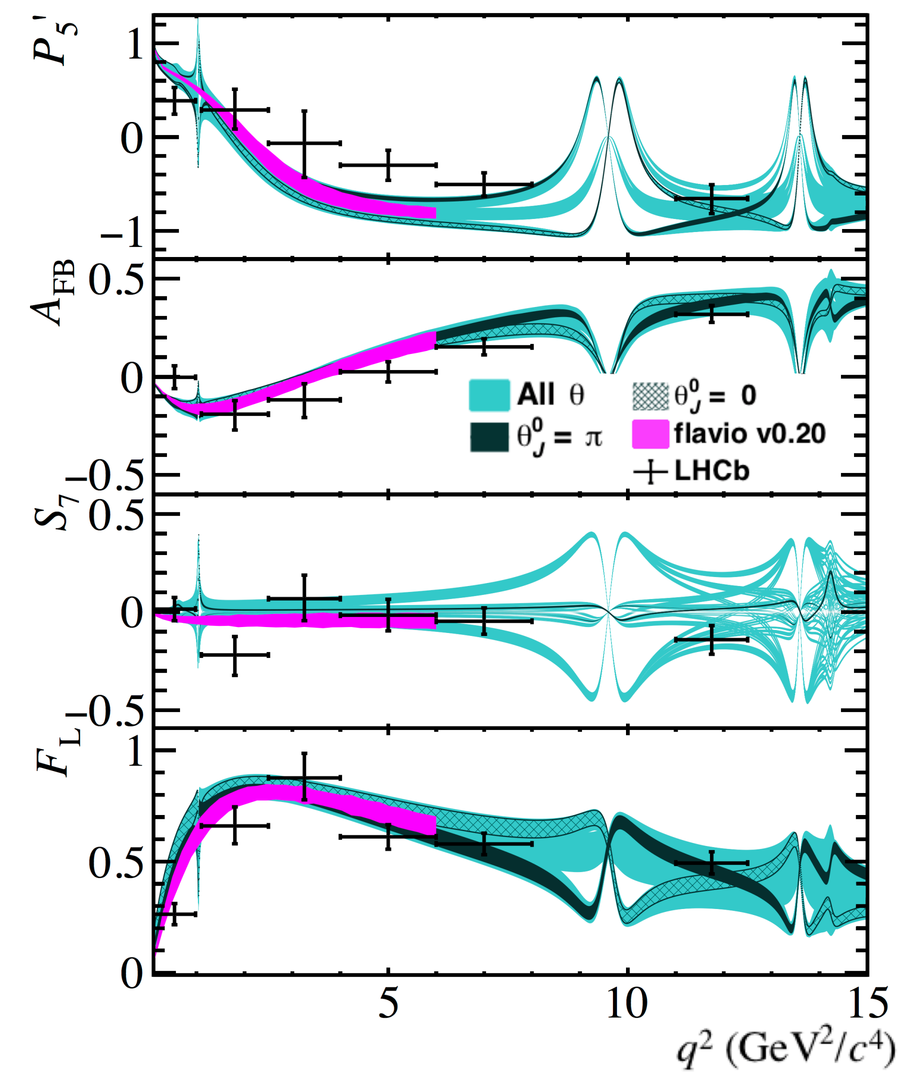
- NP in C9 would give helicity and q^2 independent effect while hadronic effects **could** be helicity and q^2 dependent

W.Altmannshofer et al Eur.Phys.J. C77 (2017) no.6, 377
B.Capdevilla et al PoS LHCP2016 (2016) 073



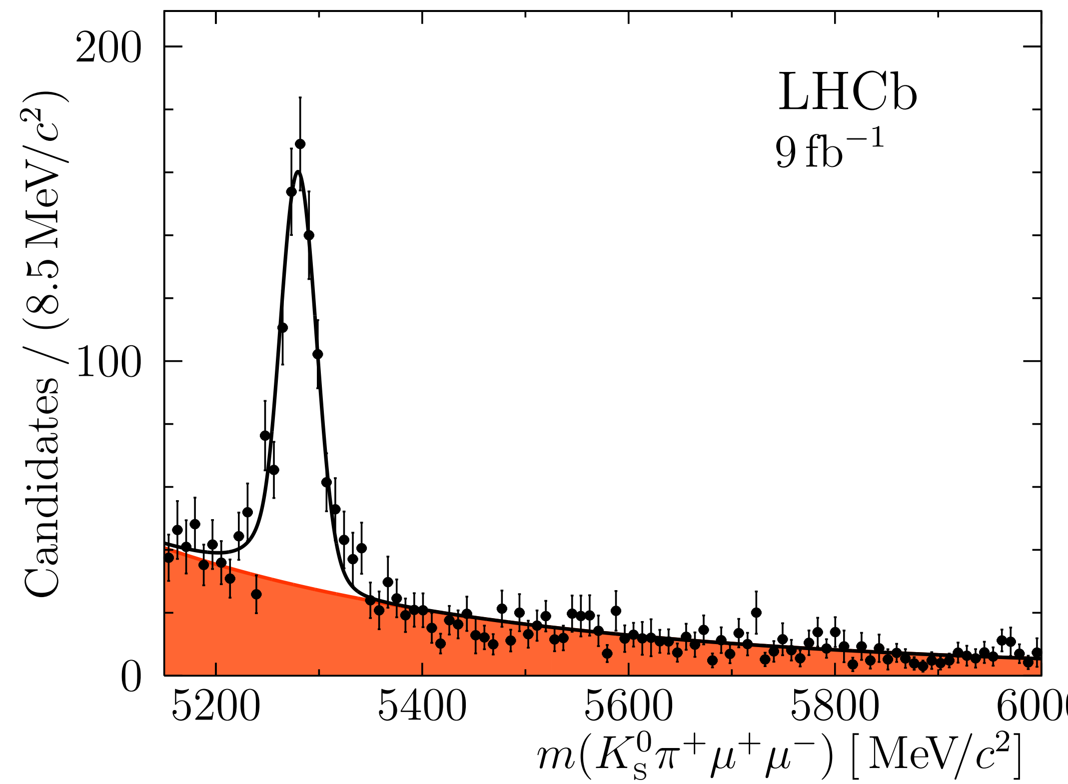
- Perform full angular analysis of $B \to K^* \mu\mu$ including cc resonances and measure interference phases

Blake et al., arXiv:1709.03921



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

- Recently analysed also isospin partner $B^+ \to K^{*+}(K_S\pi^+)\mu^+\mu^-$
- Challenging reconstruction of long-lived $K_S \to \pi^+\pi^-$
- Signal yield of 737 ± 34 events split in 8 q^2 bins for angular fit
- Angular folding technique used to reduce dimensionality of the fit



folding 0:

$$\phi \to \phi + \pi \quad \text{for } \phi < 0$$

folding 1:

$$\phi \to -\phi \quad \text{for } \phi < 0$$
$$\phi \to \pi - \phi \quad \text{for } \cos\theta_L < 0$$
$$\cos\theta_L \to -\cos\theta_L \quad \text{for } \cos\theta_L < 0$$

folding 2:

$$\phi \to -\phi \quad \text{for } \phi < 0$$
$$\cos\theta_L \to -\cos\theta_L \quad \text{for } \cos\theta_L < 0$$

folding 3:

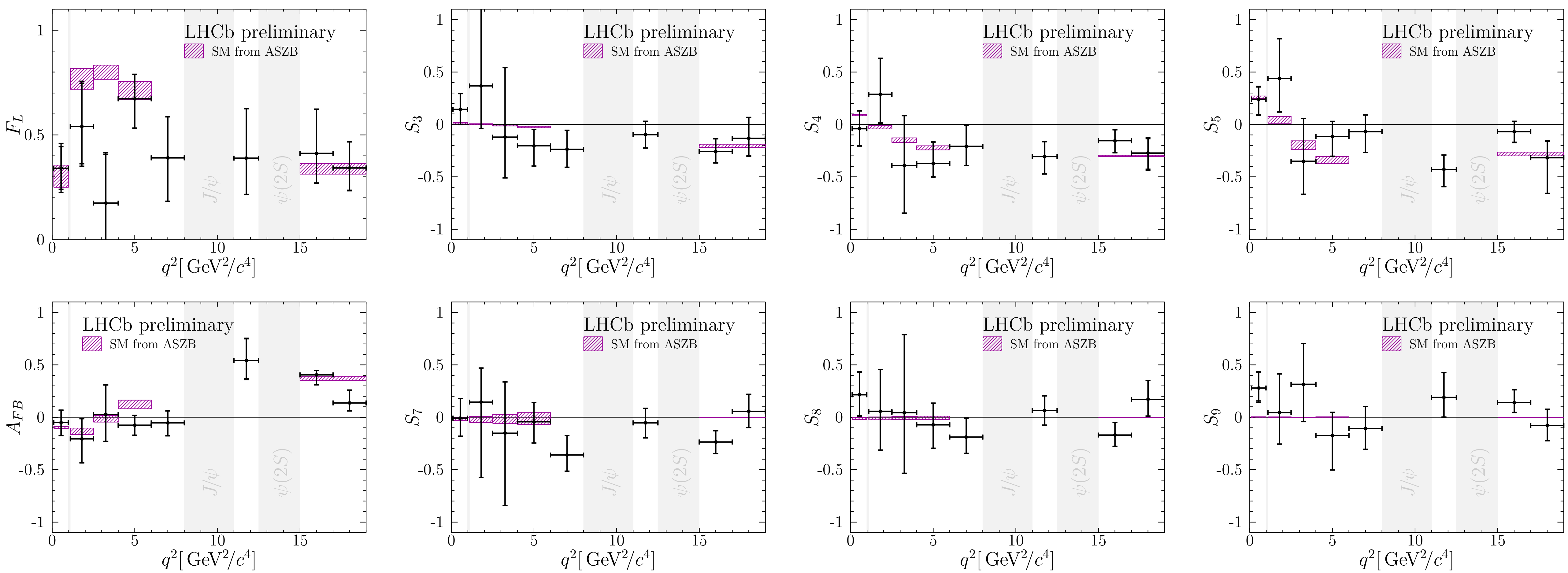
$$\cos\theta_L \to -\cos\theta_L \quad \text{for } \cos\theta_L < 0$$
$$\phi \to \pi - \phi \quad \text{for } \phi > \tfrac{\pi}{2}$$
$$\phi \to -\pi - \phi \quad \text{for } \phi < -\tfrac{\pi}{2}$$

folding 4:

$$\cos\theta_L \to -\cos\theta_L \quad \text{for } \cos\theta_L < 0$$
$$\phi \to \pi - \phi \quad \text{for } \phi > \tfrac{\pi}{2}$$
$$\phi \to -\pi - \phi \quad \text{for } \phi < -\tfrac{\pi}{2}$$
$$\cos\theta_K \to -\cos\theta_K \quad \text{for } \cos\theta_L < 0$$

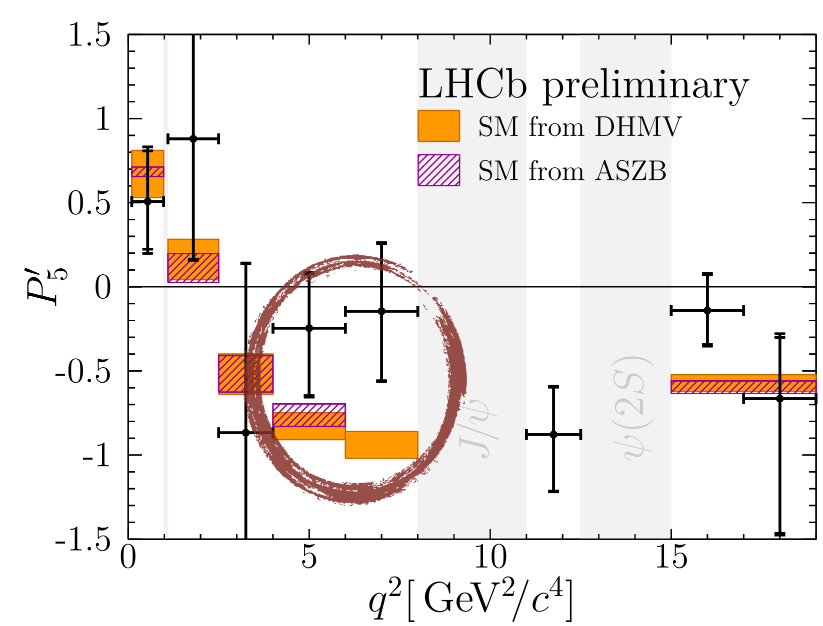
observable	moment	0	1	2	3	4
F_L	$\cos^2\theta_K$	(✓)	(✓)	(✓)	(✓)	✓
S_3	$\sin^2\theta_K \sin^2\theta_L \cos 2\phi$	(✓)	(✓)	(✓)	(✓)	✓
S_4	$\sin 2\theta_K \sin 2\theta_L \cos\phi$		✓			
S_5	$\sin 2\theta_K \sin\theta_L \cos\phi$			✓		
A_{FB}	$\sin^2\theta_K \cos\theta_L$	✓				
S_7	$\sin 2\theta_K \sin\theta_L \sin\phi$				✓	
S_8	$\sin 2\theta_K \sin 2\theta_L \sin\phi$					✓
S_9	$\sin^2\theta_K \sin^2\theta_L \sin 2\phi$	✓				

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



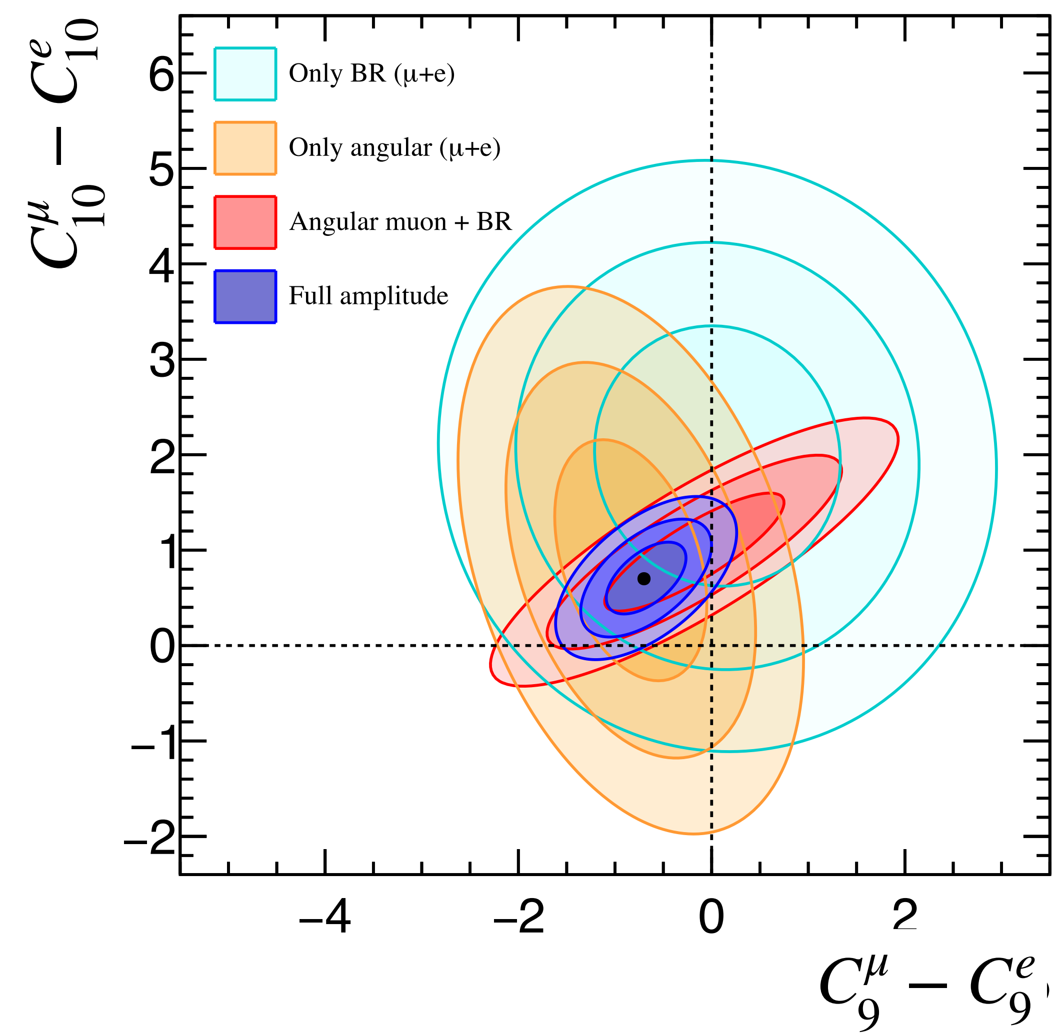
DHMV SM predictions by [JHEP06(2016)092] and [JHEP01(2018)093]
ASZB SM predictions by [JHEP08(2016)098] and [Eur.Phys.J.C75(2015)382]

- Results compatible with observations in B^0 channel
  - Similar pattern of deviations in P_5'
  - Uncertanties are much larger, but global EFT fit confirms same trend



$B^0 \to K^* e^+ e^-$ angular analysis

A.Mauri et al Phys. Rev. D 99, 013007 (2019)



- Combined angular analysis of $B \to K^* ee$ and $B \to K^* \mu\mu$
  - Most sensitive approach is full amplitude analysis
  - Local and non-local hadronic uncertainties are LFU and cancel in the combined fit

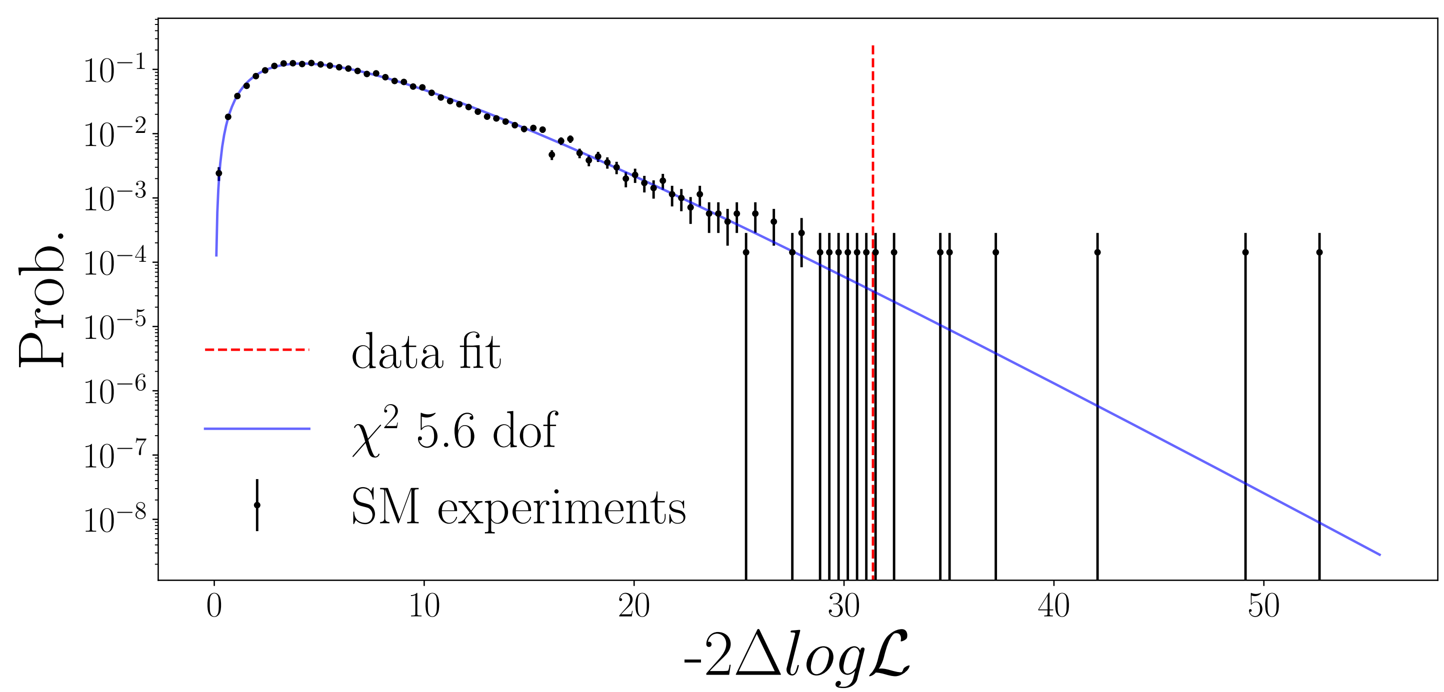
$$\mathcal{A}_{\lambda}^{L,R} = \mathcal{N}_{\lambda} \left\{ (C_9 \mp C_{10}) \mathcal{F}_{\lambda}(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_{\lambda}^{T}(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_{\lambda}(q^2) \right] \right\}$$

Local form factors **Non local ($c\bar{c}$)**

Look-elsewhere effect?

- How about the other Wilson coefficients?
  - The dipole $b \to s\gamma$ C_7 and C_7' are very constrained
  - (Pseudo-)scalar operators only affect $B_s \to \mu\mu$
- Recent attempt at taking Look-elsewhere effect into account by fitting all WC together (both e and μ)
  - Running pseudo-experiments to evaluate trial factor
  - Marginalising over $C_9^{\text{univ.}}$ to be conservative
  - **Global significance of 3.9σ**

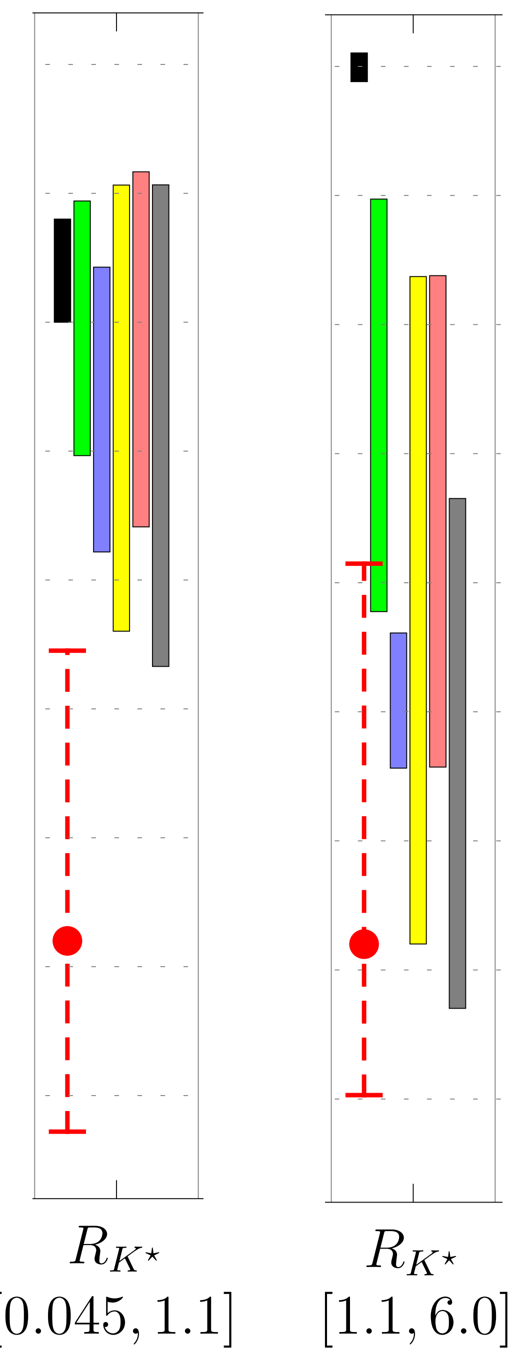
arXiv:2104.05631



The first R_{K^*} bin

B.Capdevilla et al arXiv:1704.05340

- Favoured region of q^2 is [1.1-6]
  - Far from photon pole and from J/ψ tail
  - Sensitive to New Physics in C_9 and C_{10}
- Thanks to photon pole the [$4m_\mu^2$ - 1.1] bin has enough statistics for a measurement
  - Dominated by dipole operator O_7
    - C_7 already very constrained by $b \to s\gamma$
    - Deviation pointing to underestimated systematic?
  - SM LU is broken close to threshold
  - LUV breaks cancellation of form factors



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

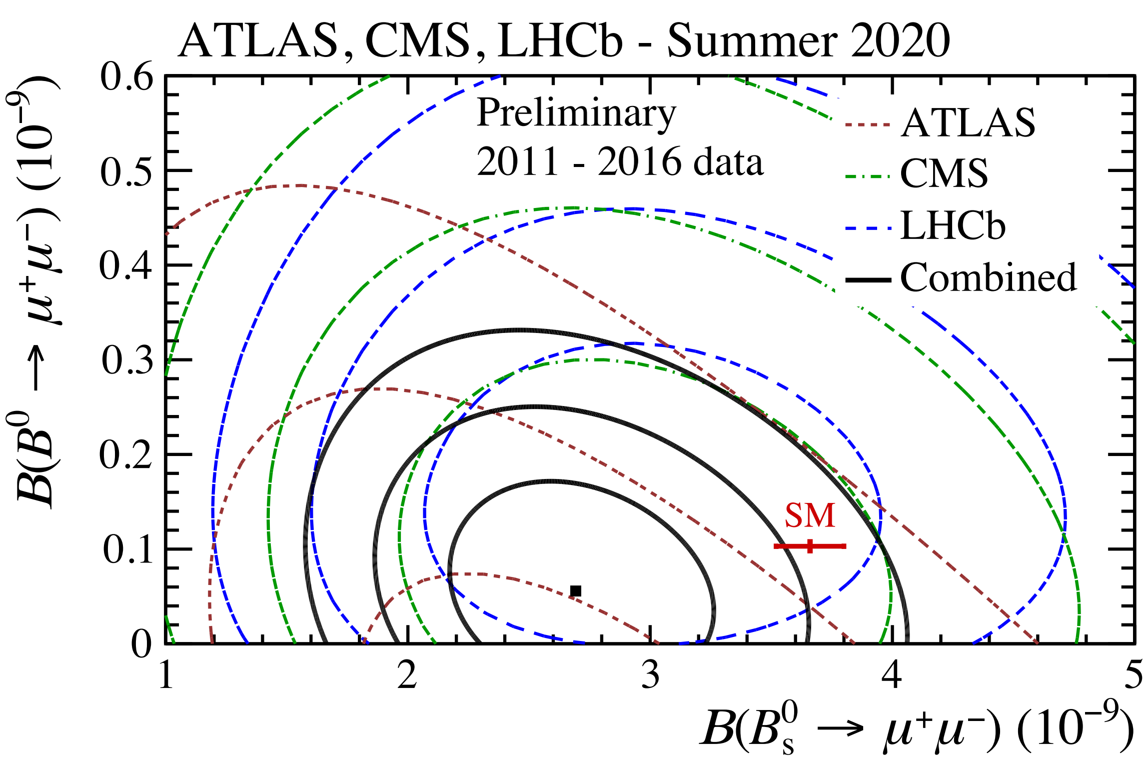
LHCb-CONF-2020-002

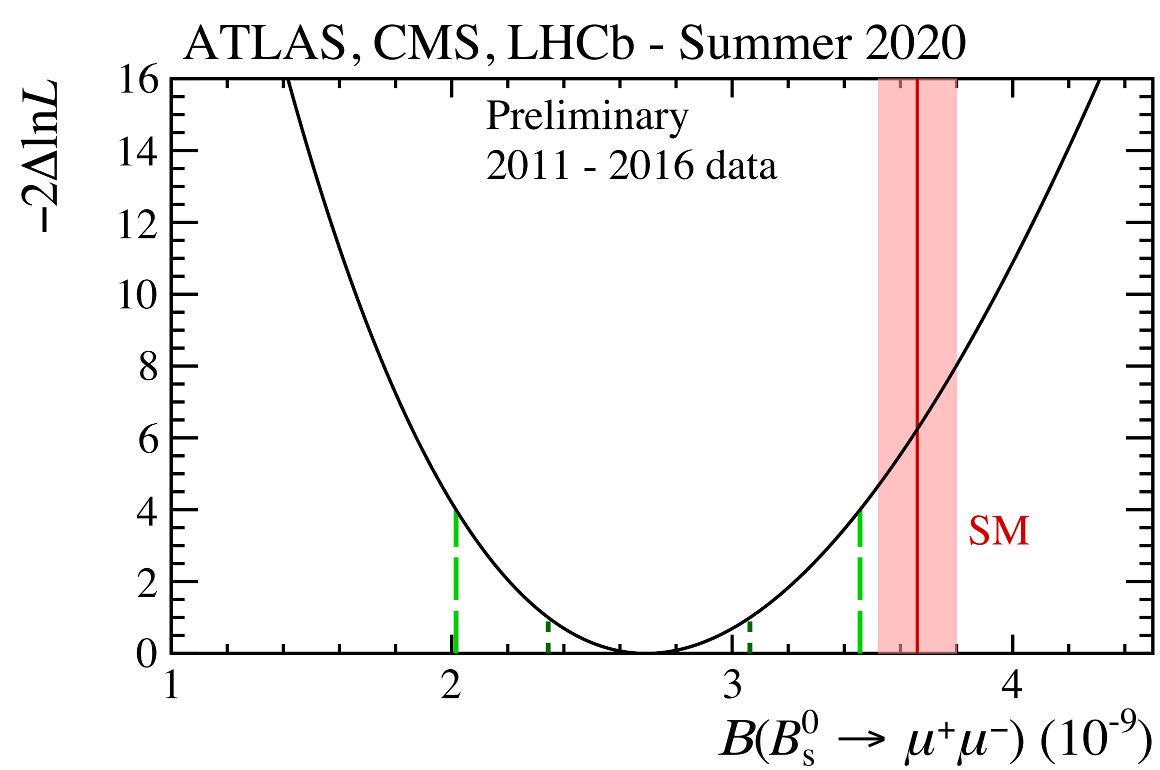
- Latest BR predictions have precision at 4-5% level:
  $\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = \left(3.66 \pm 0.14\right) \times 10^{-9}$
  $\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) = \left(1.03 \pm 0.05\right) \times 10^{-10}$

Beneke et al JHEP 10 (2019) 232

- ATLAS+CMS+LHCb combination:
  $\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$
  $\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) < 1.9 \times 10^{-10}$ at 95% CL

2.1σ deviation compatible with other anomalies





$B_s \to \mu\mu$ lifetime

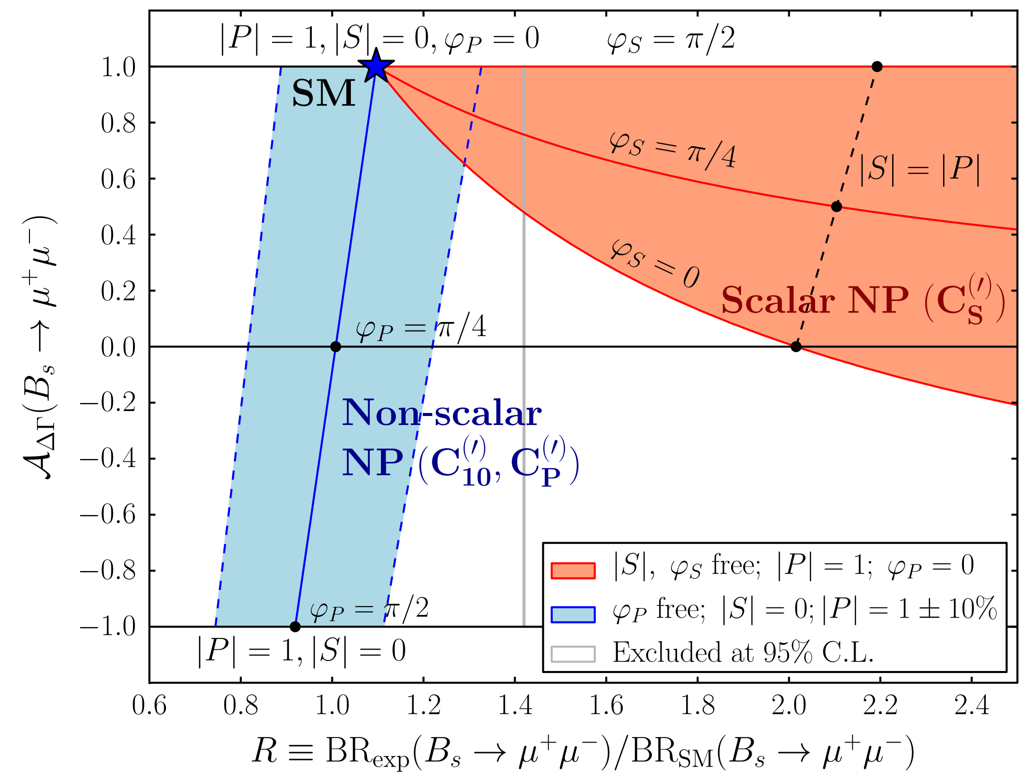
JHEP 1307 (2013) 77

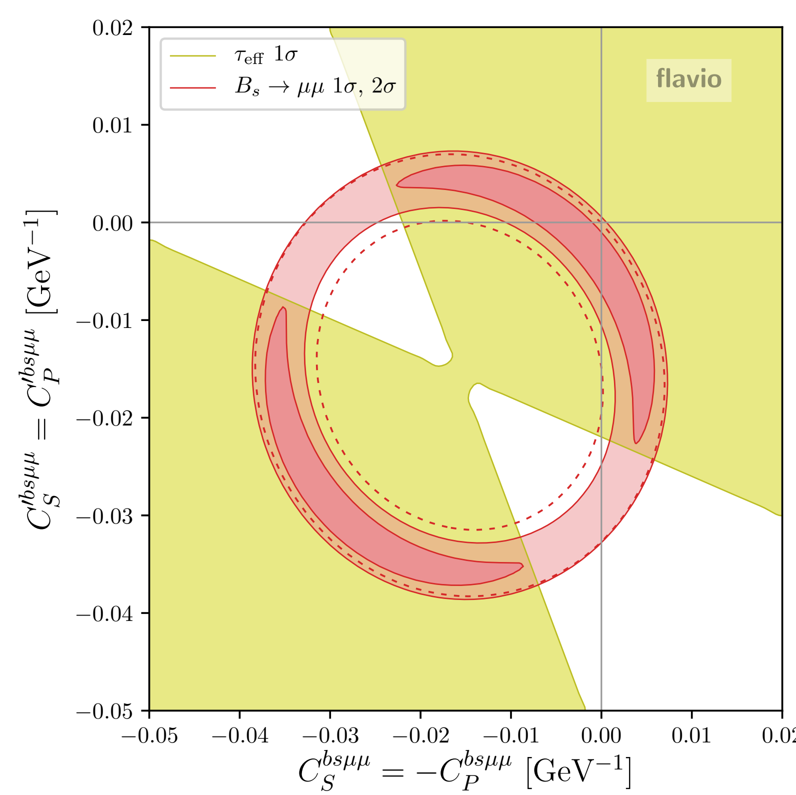
- Amplitude asymmetry can reveal new (pseudo)scalars contributions even if $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ is SM-like

$$A^{\mu\mu}_{\Delta\Gamma} = \frac{\Gamma_{B_{s,H}\to\mu^+\mu^-} - \Gamma_{B_{s,L}\to\mu^+\mu^-}}{\Gamma_{B_{s,H}\to\mu^+\mu^-} + \Gamma_{B_{s,L}\to\mu^+\mu^-}} \overset{\text{SM}}{=} +1$$

$$\tau_{\mu\mu} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2A^{\mu\mu}_{\Delta\Gamma}y_s + y_s^2}{1+A^{\mu\mu}_{\Delta\Gamma}y_s}\right]$$

$$y_s = \tau_{B_s}\Delta\Gamma/2 = 0.062 \pm 0.006$$





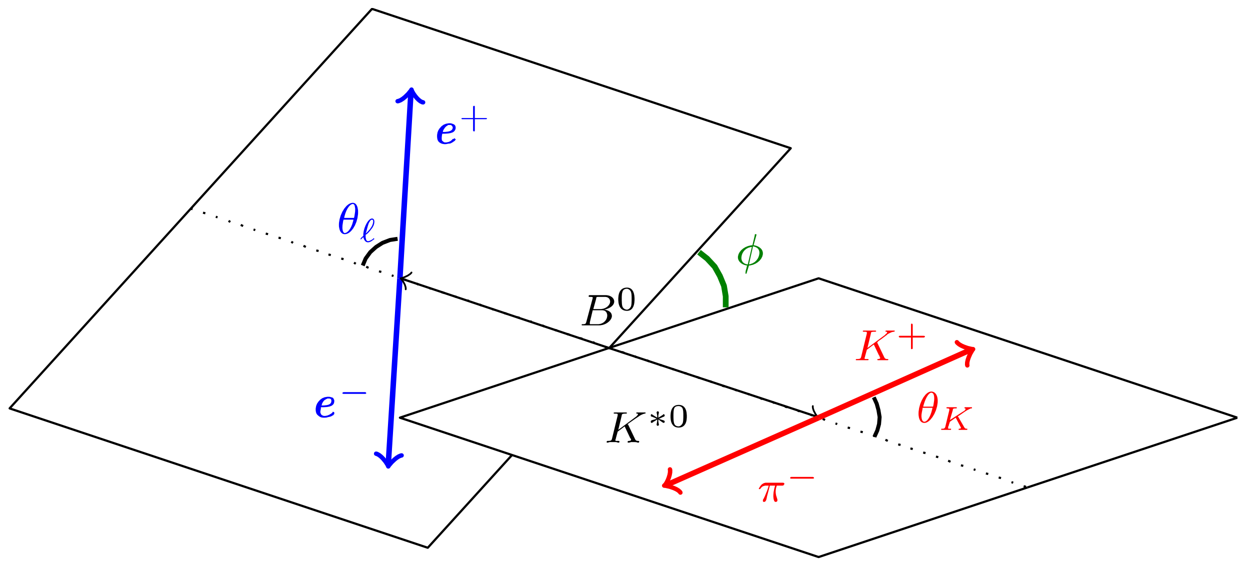
$B_{(s)} \to \mu\mu$ projections

		current			
LHCb			9fb^{-1}	23fb^{-1}	300fb^{-1}
	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\pm 0.6^{+0.3}_{-0.2} \times 10^{-9}$	$^{+0.46}_{-0.43}{}^{+0.15}_{-0.11} \times 10^{-9}$	$\pm 0.30 \times 10^{-9}$	$\pm 0.16 \times 10^{-9}$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$	90 %	70 %	34 %	10 %
	$\tau_{\mu^+\mu^-}$ (ps)	$\pm 0.44 \pm 0.05$	$\pm 0.29 \pm 0.03$	± 0.16	± 0.04
CMS			150fb^{-1}	300fb^{-1}	3000fb^{-1}
	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$^{+0.7}_{-0.6} \pm 0.2 \times 10^{-9}$		$\pm(0.43 - 0.46) \times 10^{-9}$	$\pm(0.39) \times 10^{-9}$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$			50 %	21 %
	$\tau_{\mu^+\mu^-}$ (ps)	$^{+0.61}_{-0.44}$		± 0.15	± 0.05
ATLAS	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$^{+0.8}_{-0.7} \times 10^{-9}$	$\pm 0.83 \times 10^{-9}$		$\pm(0.46 - 0.55) \times 10^{-9}$
	$\mathcal{B}(B^0 \to \mu^+\mu^-)$	$< 2.1 \times 10^{-10}$	$\pm 1.43 \times 10^{-10}$		$\pm(0.28 - 0.54) \times 10^{-10}$

[LHCB-PUB-2018-009] [ATL-PHYS-PUB-2018-005] [CMS PAS FTR-14-013/-015]

$B^0 \to K^*e^+e^-$: Angular analysis

JHEP 12 (2020) 081



- Folding ϕ angle to simplify the 3D angular expression:

$$\tilde{\phi} \equiv \begin{cases} \phi \text{ if } \phi \geq 0 \\ \phi + \pi \text{ if } \phi < 0 \end{cases}$$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} = \frac{9}{16\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell$$
$$+(1-F_\mathrm{L})A_T^{Re}\sin^2\theta_K\cos\theta_\ell$$
$$+\tfrac{1}{2}(1-F_\mathrm{L})A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi}$$
$$+\tfrac{1}{2}(1-F_\mathrm{L})A_T^{Im}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Big].$$

$B^0 \to K^*\gamma$ photon polarisation:

$$A_{\mathrm{R(L)}} \equiv |A_{\mathrm{R(L)}}|\,e^{i\phi_{\mathrm{R(L)}}}, \quad \tan\chi \equiv \left|A_\mathrm{R}/A_\mathrm{L}\right|$$

$$A_\mathrm{T}^{(2)} \simeq \sin(2\chi)\cos(\phi_\mathrm{L}-\phi_\mathrm{R}),$$
$$A_\mathrm{T}^{\mathrm{Im}} \simeq \sin(2\chi)\sin(\phi_\mathrm{L}-\phi_\mathrm{R}),$$

$B^0 \to K^* e^+ e^-$ angular analysis

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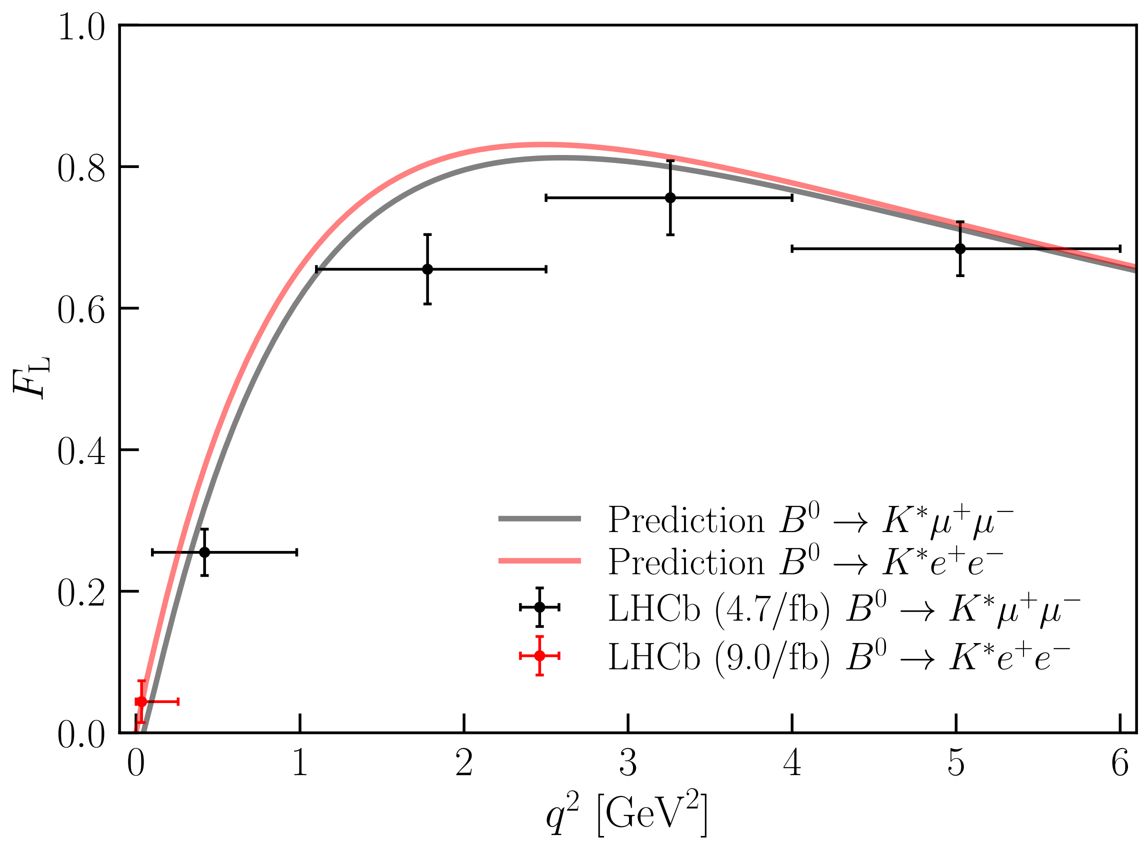
Measurement of $b \to see$ angular observables at very low q^2 (**red point**)



Most precise measurement (**red area**) of $b \to s\gamma$ photon polarisation