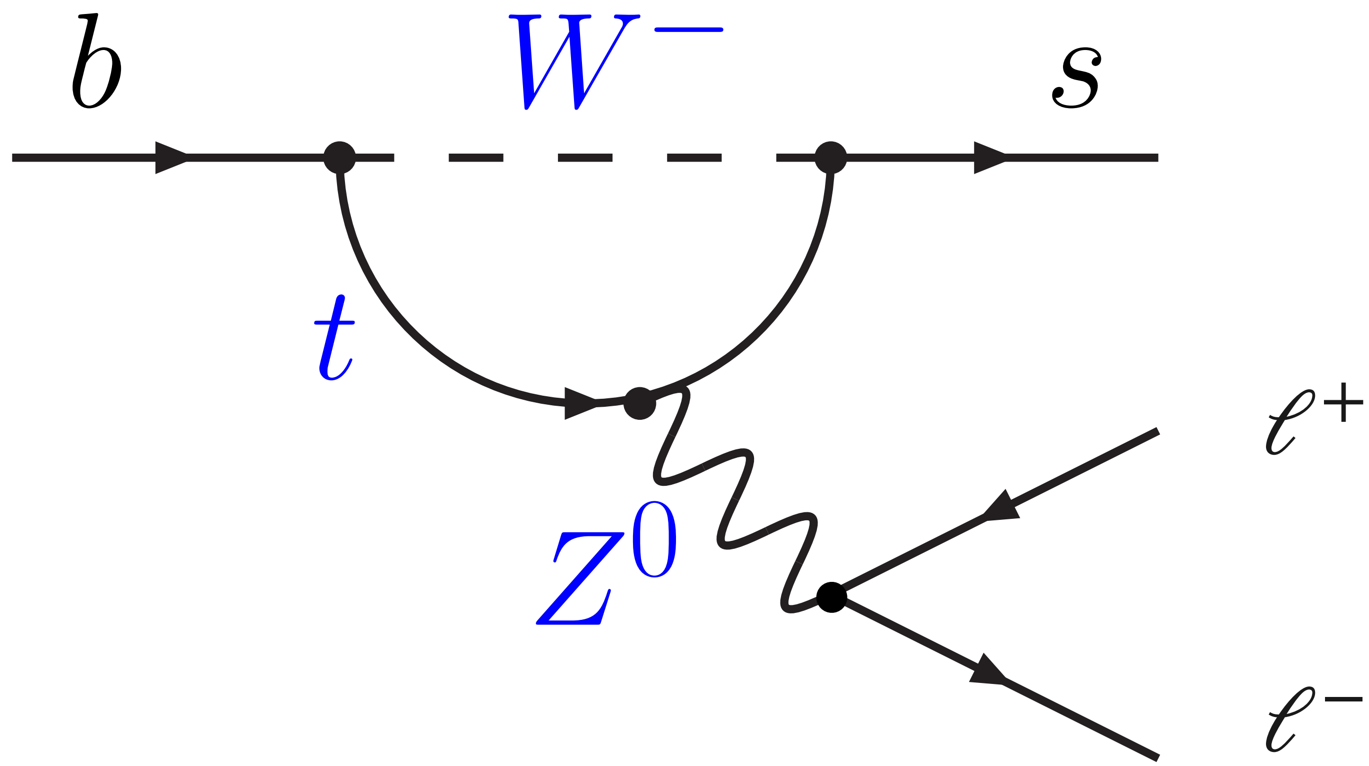


Physics at the LHC - WS 2021-2022

Rare B decays and Lepton Universality

Martino Borsato

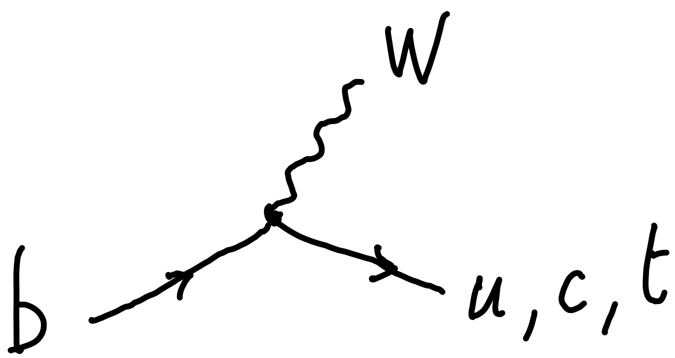
Credits/references

- P.Owen lecture at HCPSS2021
- M.Williams LHCb StarterTalk
- LHCb detector performance paper

Lecture 2/4 - Monday Jan 17th 2022

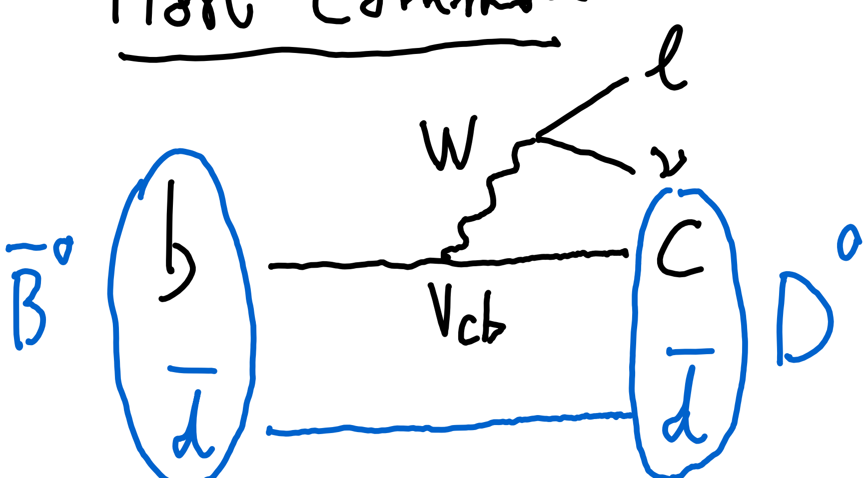
Rare B decays

- B decays weakly



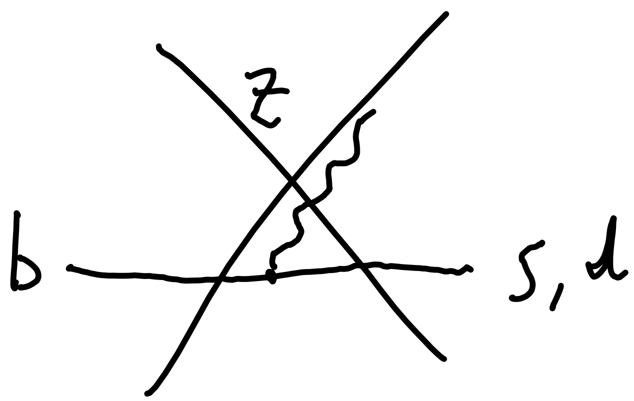
$$\propto V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \cancel{V_{tb}} \end{bmatrix} = \begin{bmatrix} 1 & 0.1 & 0.001 \\ 0.1 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{bmatrix}$$

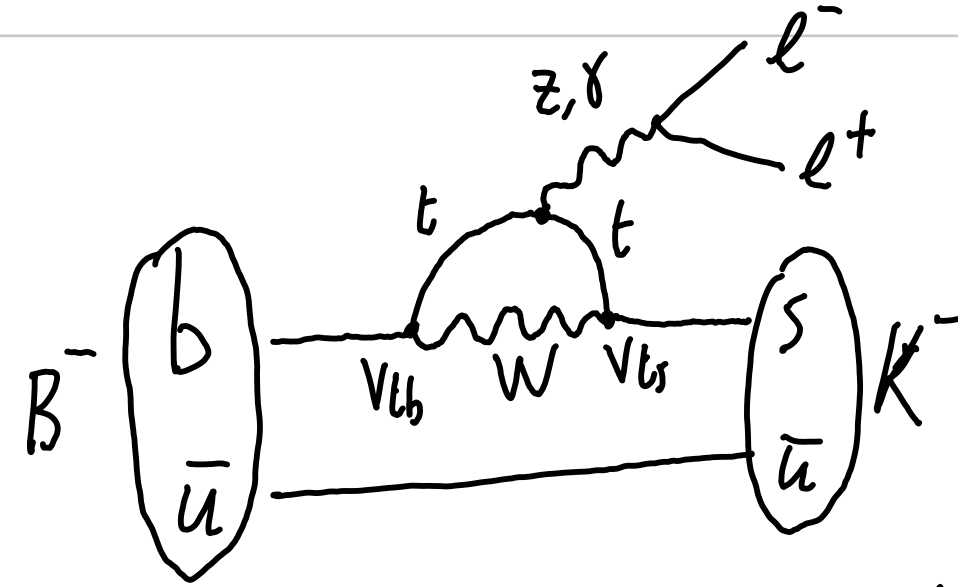
Most common



$BR(\bar{B}^0 \to D^0 \ell \nu) \sim 2\%$ $\Longrightarrow$ Rare B decay $< 10^{-4}$

Flavour-Changing Neutral Currents





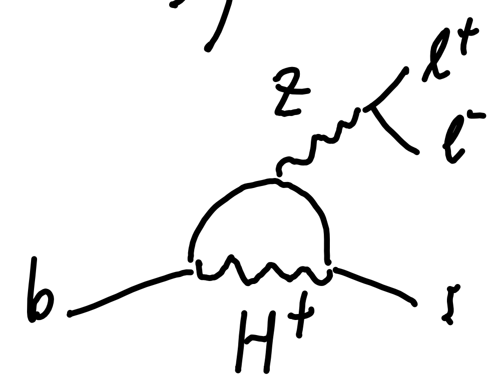
$10^{-5} \div 10^{-10}$

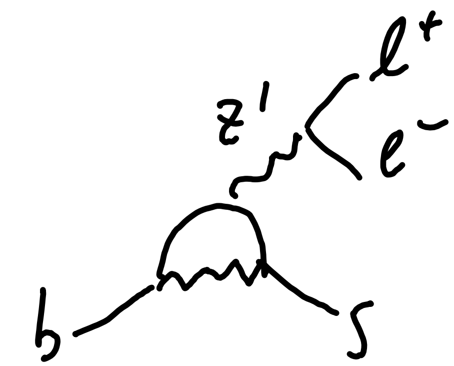
SUPPRESSED: 1) CKM V_{ts} 2) LOOP 3) GIM

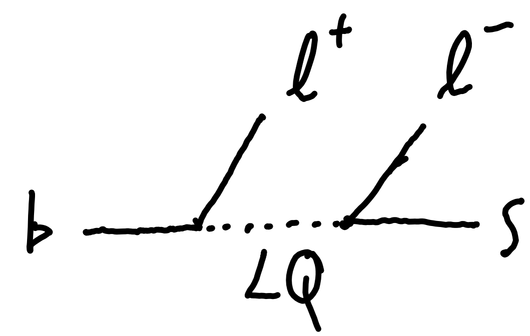
WHY INTERESTING?

- TEST the flav. structure of the SM
- SEARCH FOR NEW PARTICLES
- WORKED IN THE PAST

$K \to \mu\mu \Rightarrow$ charm

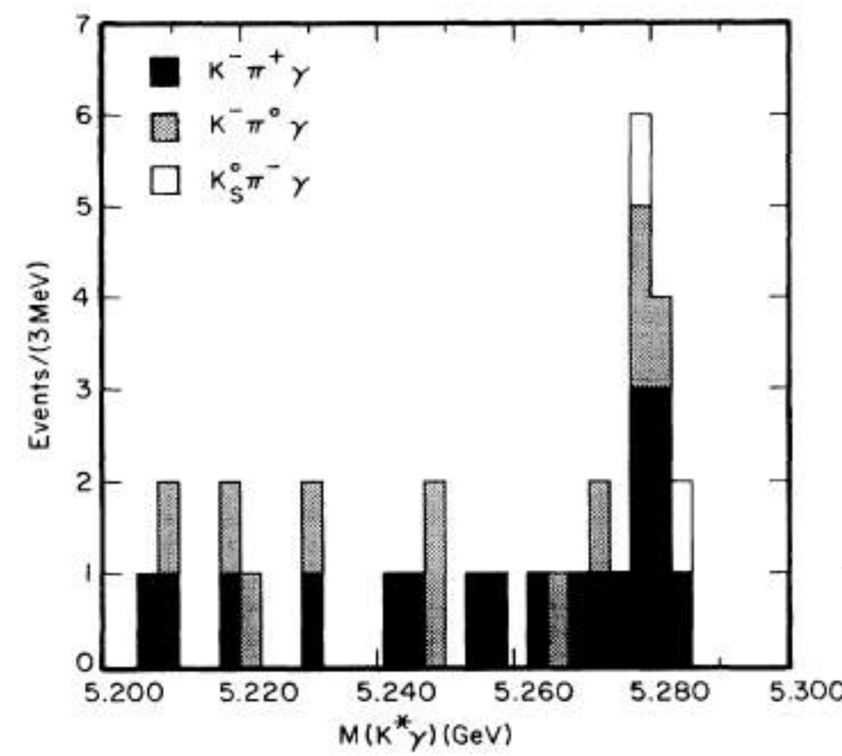






First $b \to s$ FCNC: $b \to s\gamma$

- Discovered in 1993 at CLEO
  - $\mathrm{BR}(B \to K^*\gamma) \simeq 4 \times 10^{-5}$
  - Quark transition $b \to s\gamma$
- Nowadays $b \to s\gamma$ well known
  - Many decays studied $\to$
  - Measured CP violation, mixing, polarisation of the emitted γ
- All measurements agree with SM
  - Great constraints on e.g. SUSY
  - Still space for improvement
- $b \to s\gamma$ hard at LHCb (neutral γ)



[Phys.Rev.Lett. 71 (1993) 674 - Cited by 605 records
Phys.Rev.Lett. 74 (1995) 2885 - Cited by 836 records
Phys.Rev.Lett. 87 (2001) 251807 - Cited by 565 records]

$B^+ \to K^{*+}\gamma$

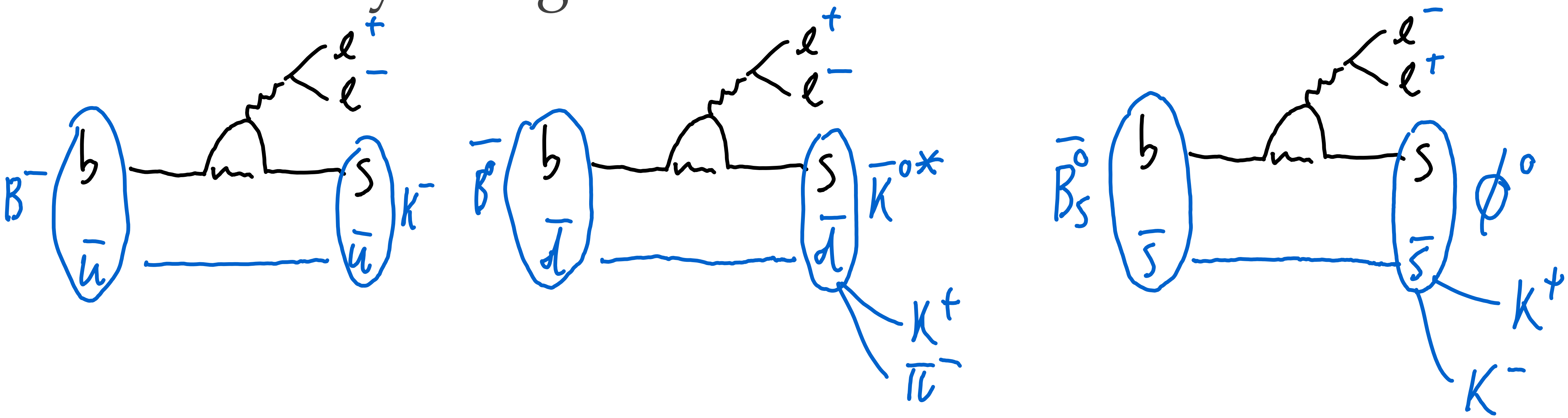
↳ $K^+\pi^0$, $K^0\pi^+$

$B^0 \to K^{*0}\gamma$

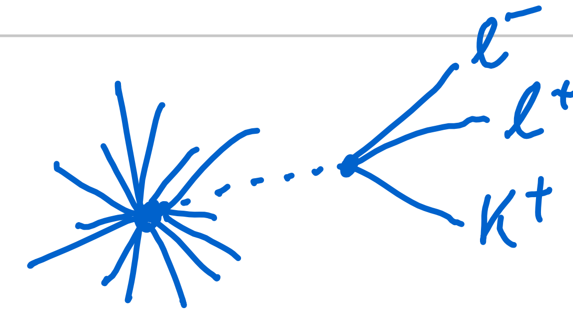
↳ $K^+\pi^-$, ~~$K^0\pi^0$~~

$b \to s\ell^+\ell^-$ at LHCb

- Several fully charged final states



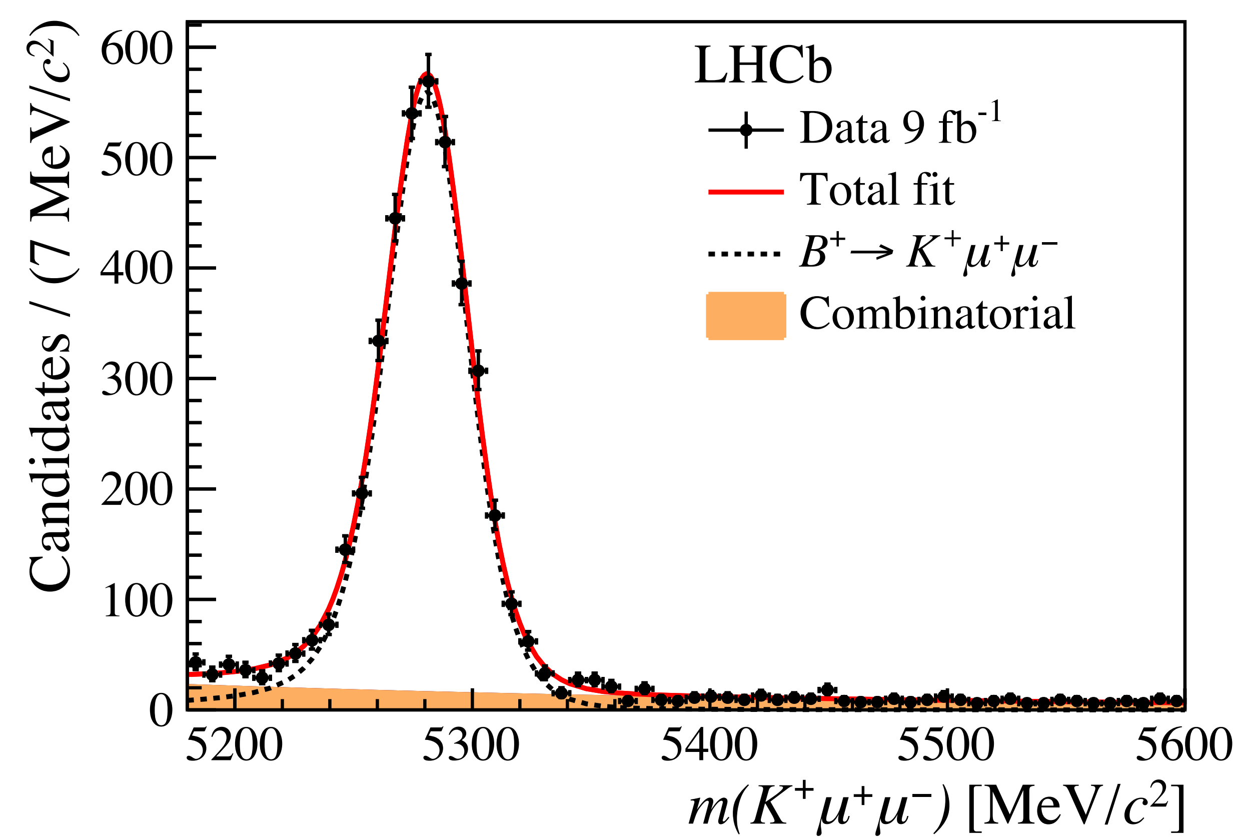
Selecting $b \to s\mu\mu$



- Hardware trigger: μ, $\mu\mu$
- Software trigger: displaced charged tracks forming vertex
- Muon and charged-hadron identification
- Machine Learning classifier to label events that are more likely to contain signal
- Fit to B invariant mass to subtract background
  - Mostly combinatorial combination of tracks

~4k $B^+ \to K^+\mu^+\mu^-$

BR of about 1.2×10^{-7}



Measuring the BR

- Decay amplitude gets contribution from NP
  → Decay Branching Ratio can be different
- **Measuring BR at LHCb**
  - Hard to know how many B are produced
  - Always normalise to other decay channel
- $b \to s\ell^+\ell^-$ have excellent normalisation channels

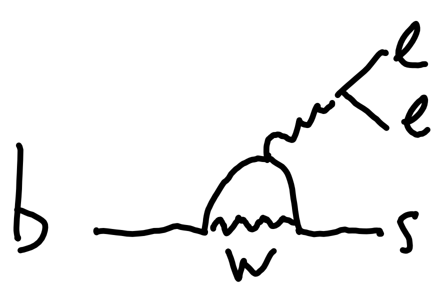
SIGNAL DECAY

B factories

$$BR(S) = \frac{N_S}{N_N} \frac{\varepsilon_N}{\varepsilon_S} BR(N)$$

$\frac{\varepsilon_N}{\varepsilon_S} \sim 1$

NORMALISATION DECAY



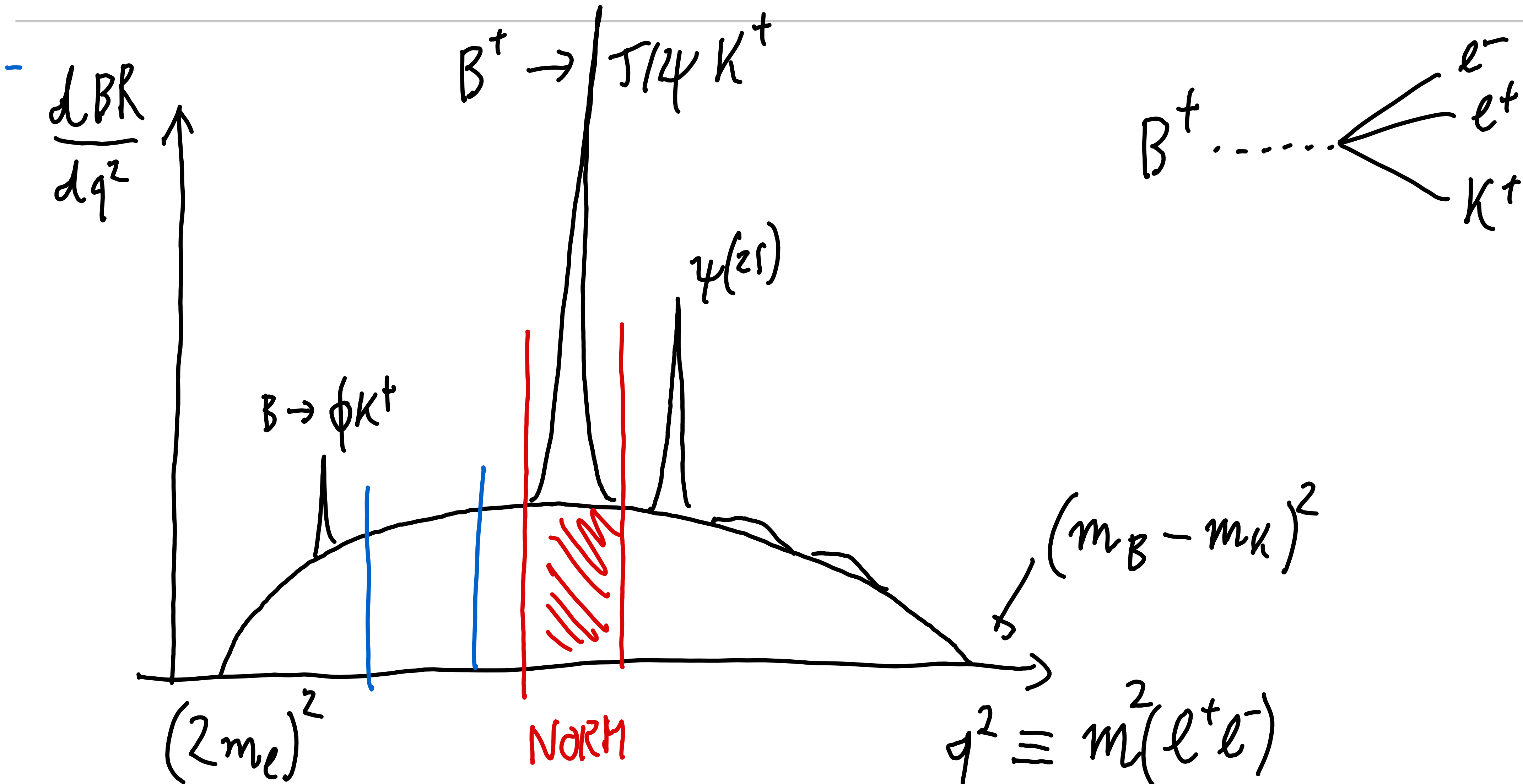
$BR(B^+ \to K^+\ell^+\ell^-) \sim 10^{-7}$

$BR(B^+ \to J/\psi K^+) \sim 10^{-3}$

$BR(J/\psi \to \ell^+\ell^-) \sim 6 \times 10^{-2}$

$BR(B^+ \to K^+ J/\psi \to \ell^+\ell^-) \sim 6 \times 10^{-5}$

A function of q^2

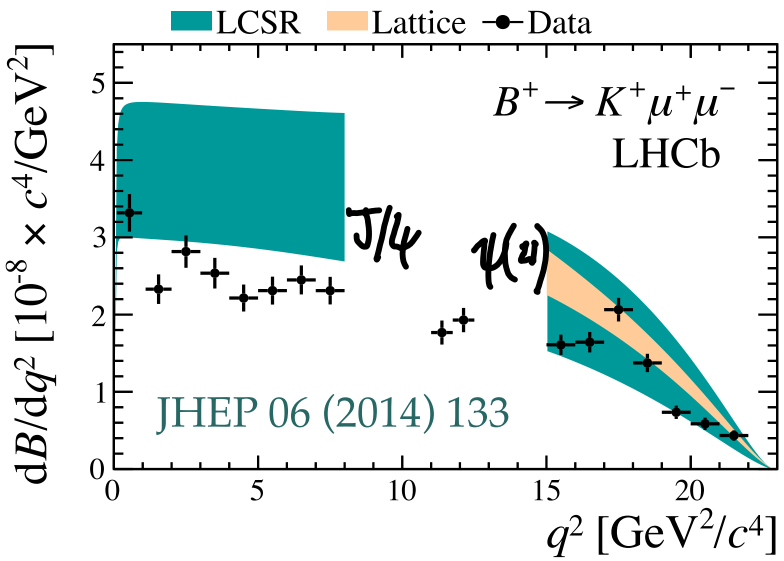


$$\frac{dBR(B \to K\ell\ell)}{dq^2} = \frac{N_S^{q^2\,\mathrm{cut}}}{N_N} \, \frac{\varepsilon_N}{\varepsilon_S} \, \frac{BR(N)}{\Delta q^2}$$

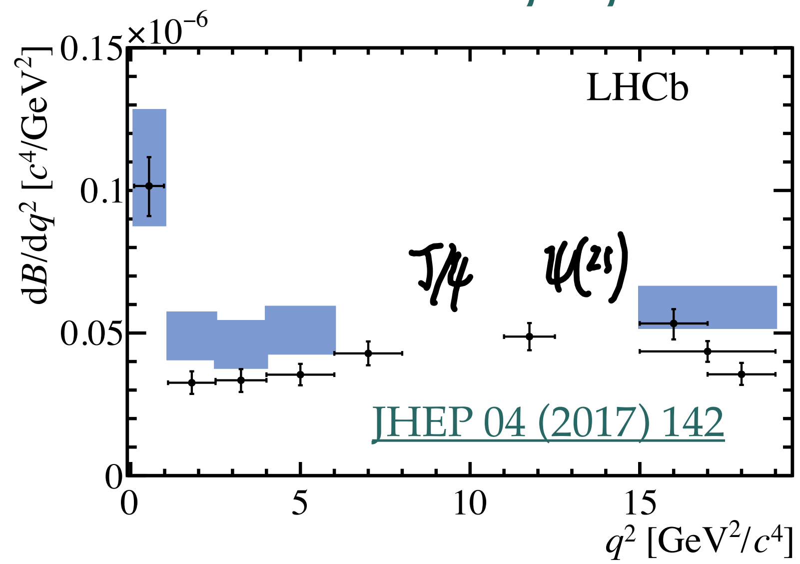
← bin width

BR results

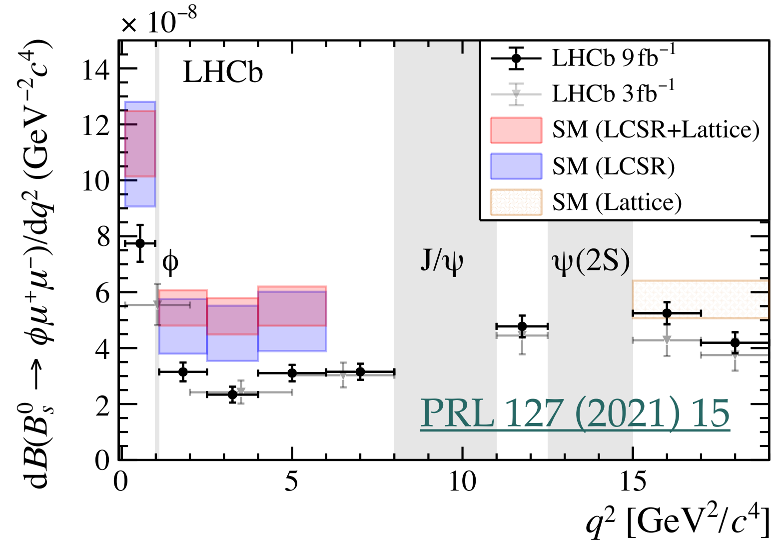
$B^+ \to K^+\mu^+\mu^-$



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



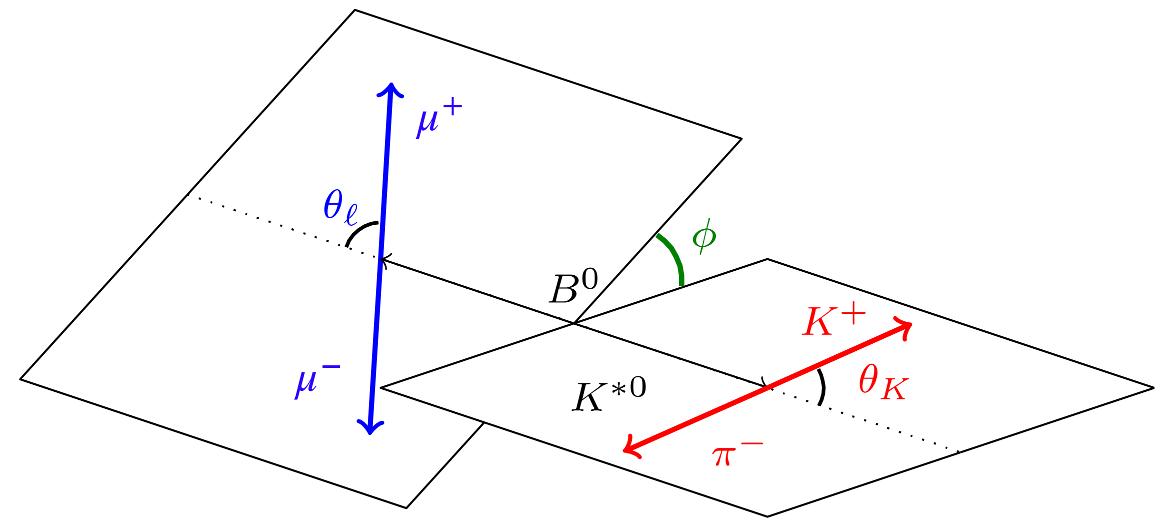
$B_s \to \phi\mu^+\mu^-$



- Measured dBR/dq^2 in various decay modes
- Predictions have large uncertainties (10-20%)
- All rates lower than SM predictions
  - Is this a sign of NP contributions (negative interference with SM)
  - Or is this just a sign that these SM predictions are hard to do?

Angular analyses

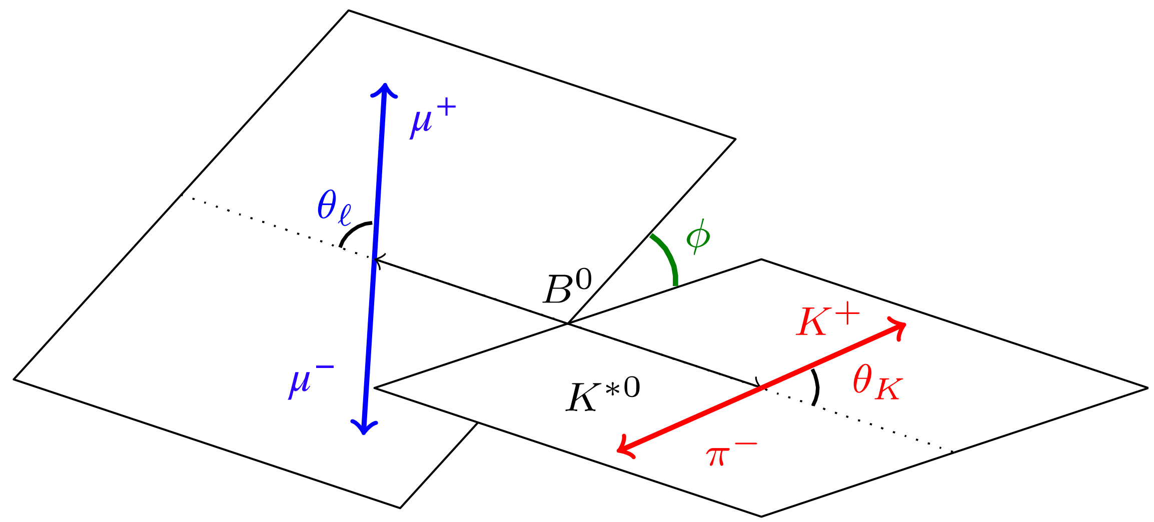
- Can study other properties of the B decay
  - e.g. $B^0 \to K^{*0}\ell^+\ell^-$ has rich structure
- Full decay kinematic described as function of q^2 and three angles



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

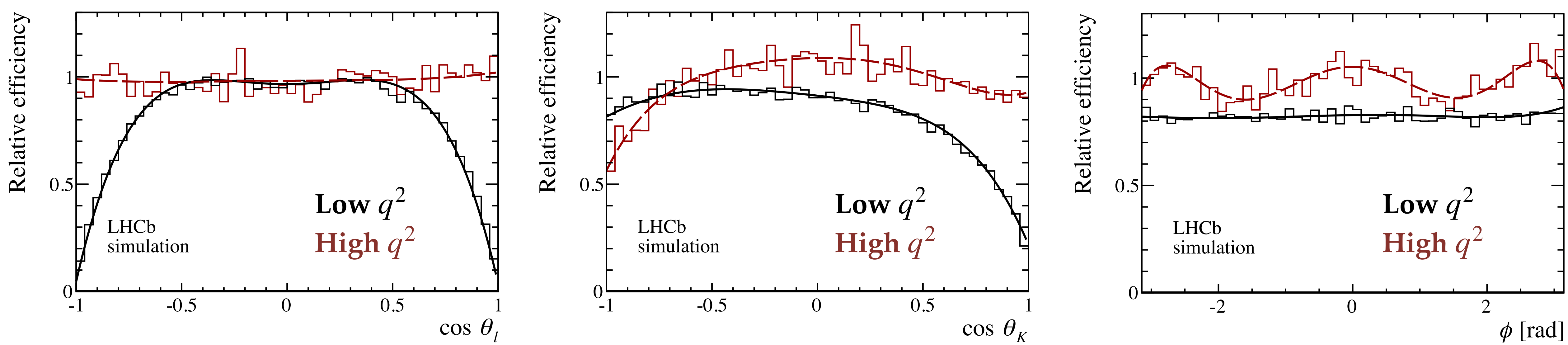
$d\cos\theta_\ell \, d\cos\theta_K \, d\phi$

Correcting acceptance effects



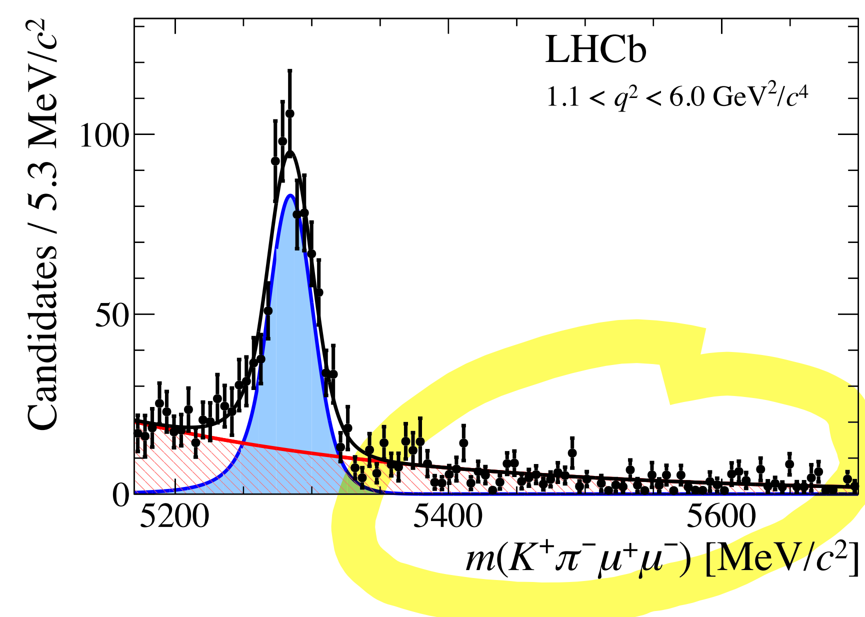
$$\cos\theta_\ell \sim \frac{E_{\ell^+} - E_{\ell^-}}{E_{\ell^+} + E_{\ell^-}}$$

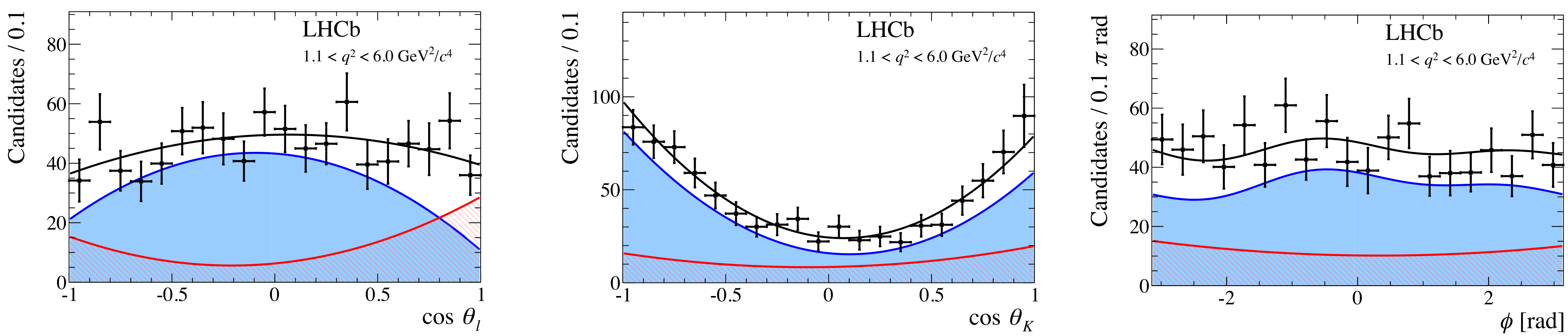
$$\cos\theta_K \sim \frac{E_{K^+} - E_{\pi^-}}{E_{K^+} + E_{\pi^-}}$$



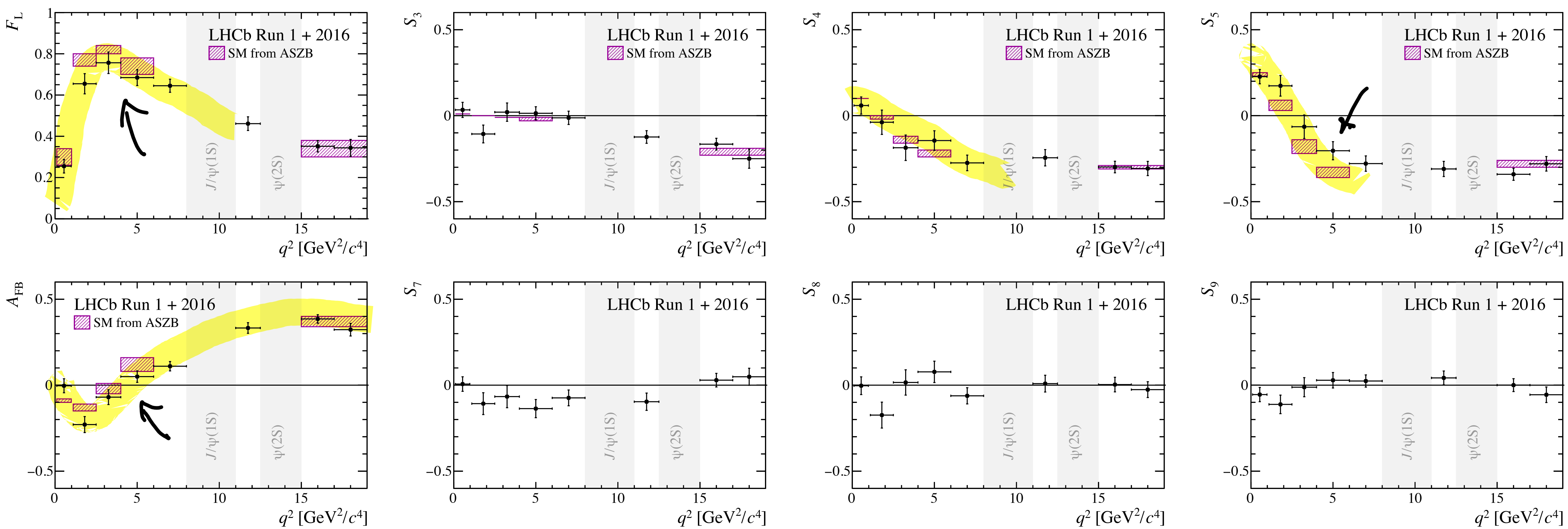
Multidimensional fit

- Fit physical probability density function (PDF) to acceptance-corrected data
- Use *B* mass fit to substract background and to model it in the angular dimensions
- Fit three angles simultaneously and extract **angular observables** in bins of q^2





Results angular analysis



[PRL125(2020)011802]

- Measure 8 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?

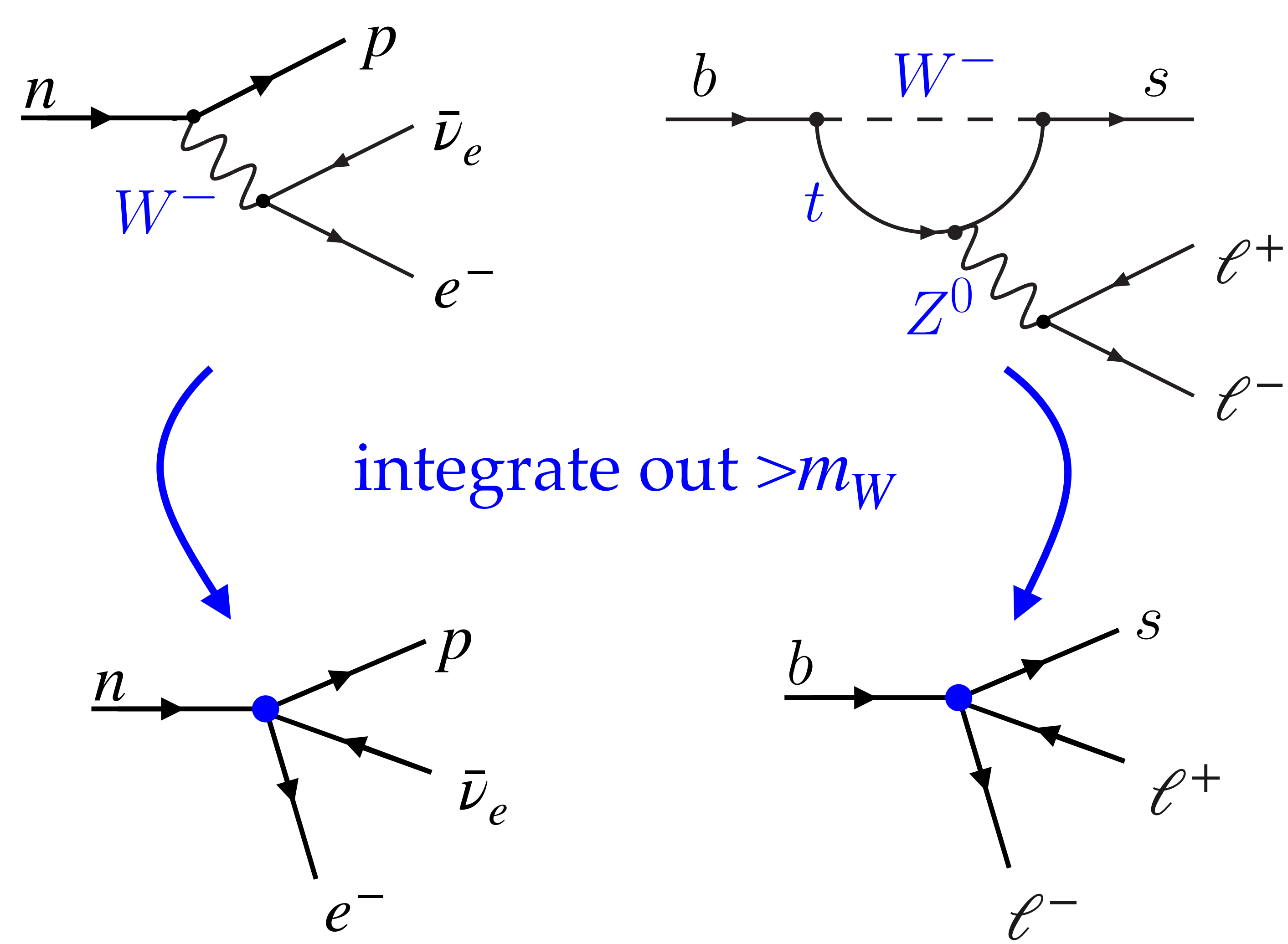
Interpretation

- Integrate out $> m_W$
- four-fermion interaction described by effective couplings

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

- Main SM contributions:
  - **Vector** (C_9) and **Axial-vector** (C_{10}) leptonic currents
  - $b \to s\gamma^*$ contribution in (C_7) → very well constrained by radiative decays

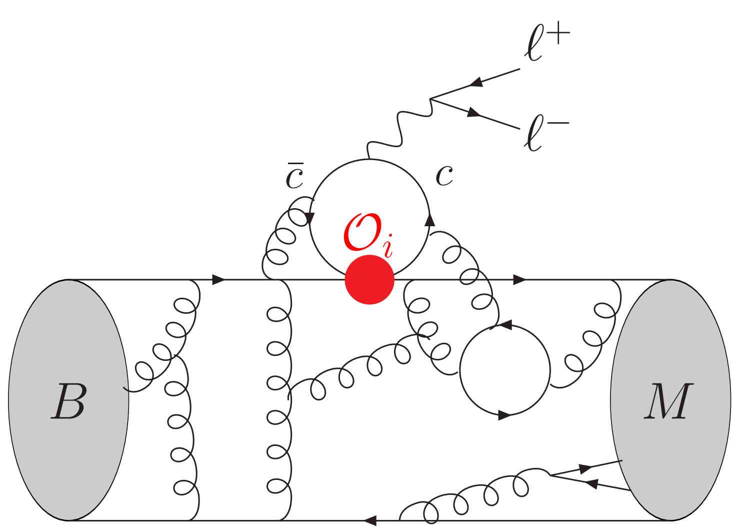
β decay $\qquad\qquad b \to s\ell\ell$



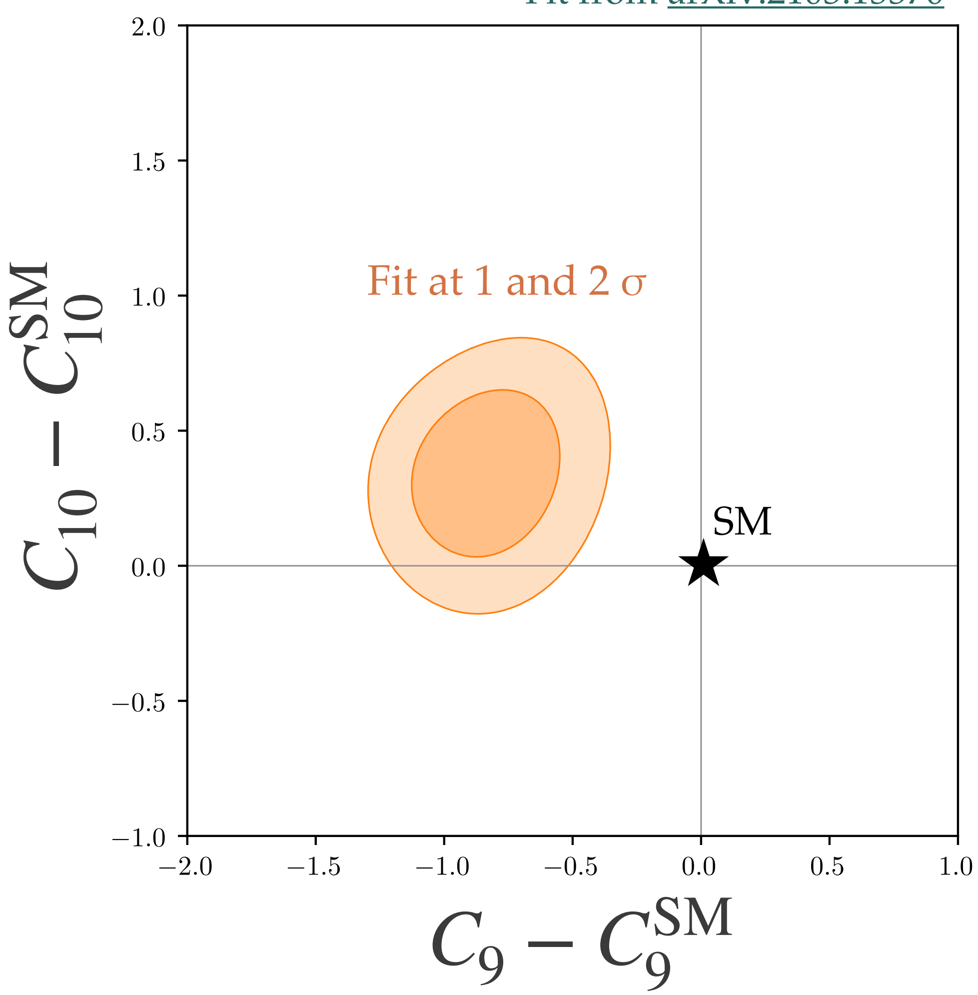
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

Interpretation

- Fit most relevant effective couplings C_9 and C_{10} to data
- Use all $b \to s\mu\mu$ measurements
  - Branching ratios
  - Angular analyses
- Fitted couplings do not match SM expectation (**anomaly**!)
  - Coherent picture from BR and angular analyses
  - SM predictions still under scrutiny



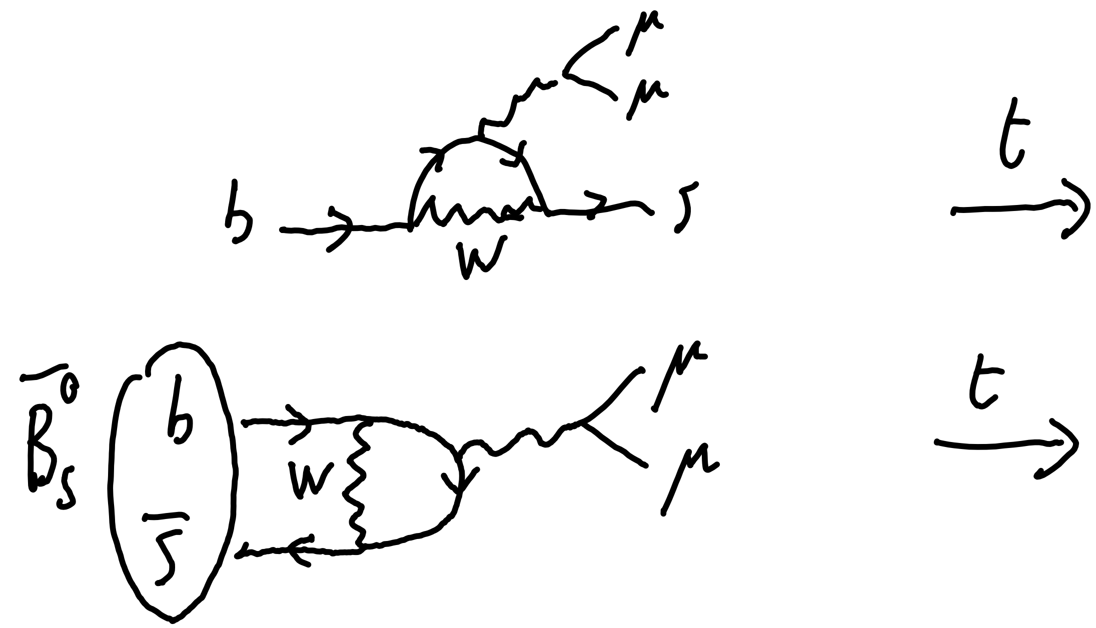
Fit from arXiv:2103.13370



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

The very rare $B_s \to \mu\mu$

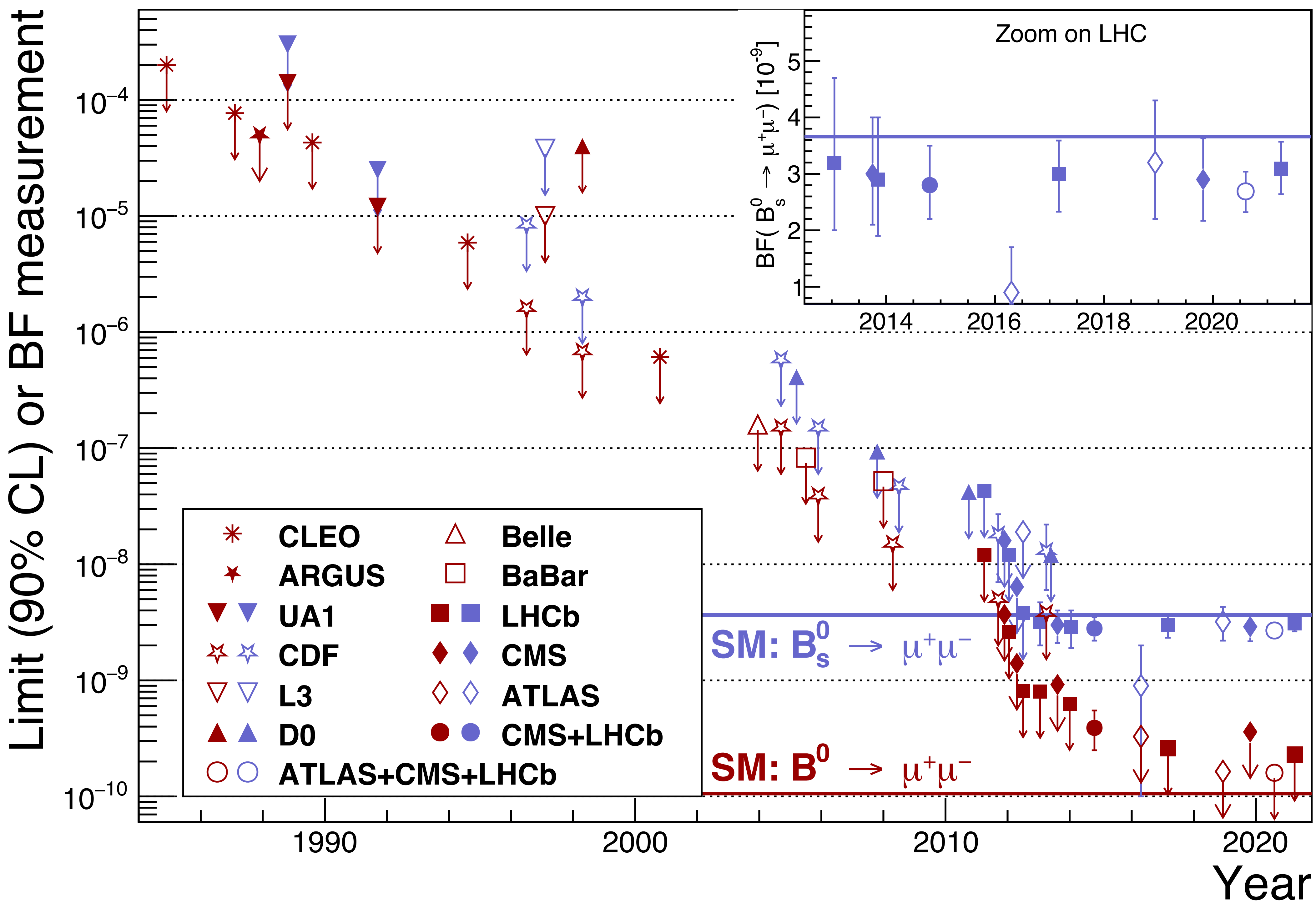
- Purely leptonic $B_{(s)} \to \mu^+\mu^-$ decay
  - Same diagrams as $b \to s\mu\mu$ (spectator quark in initial state)
  - More precise predictions because of leptonic final state
  - Much smaller BR because of helicity suppression ($B_{(s)}$ pseudoscalar)



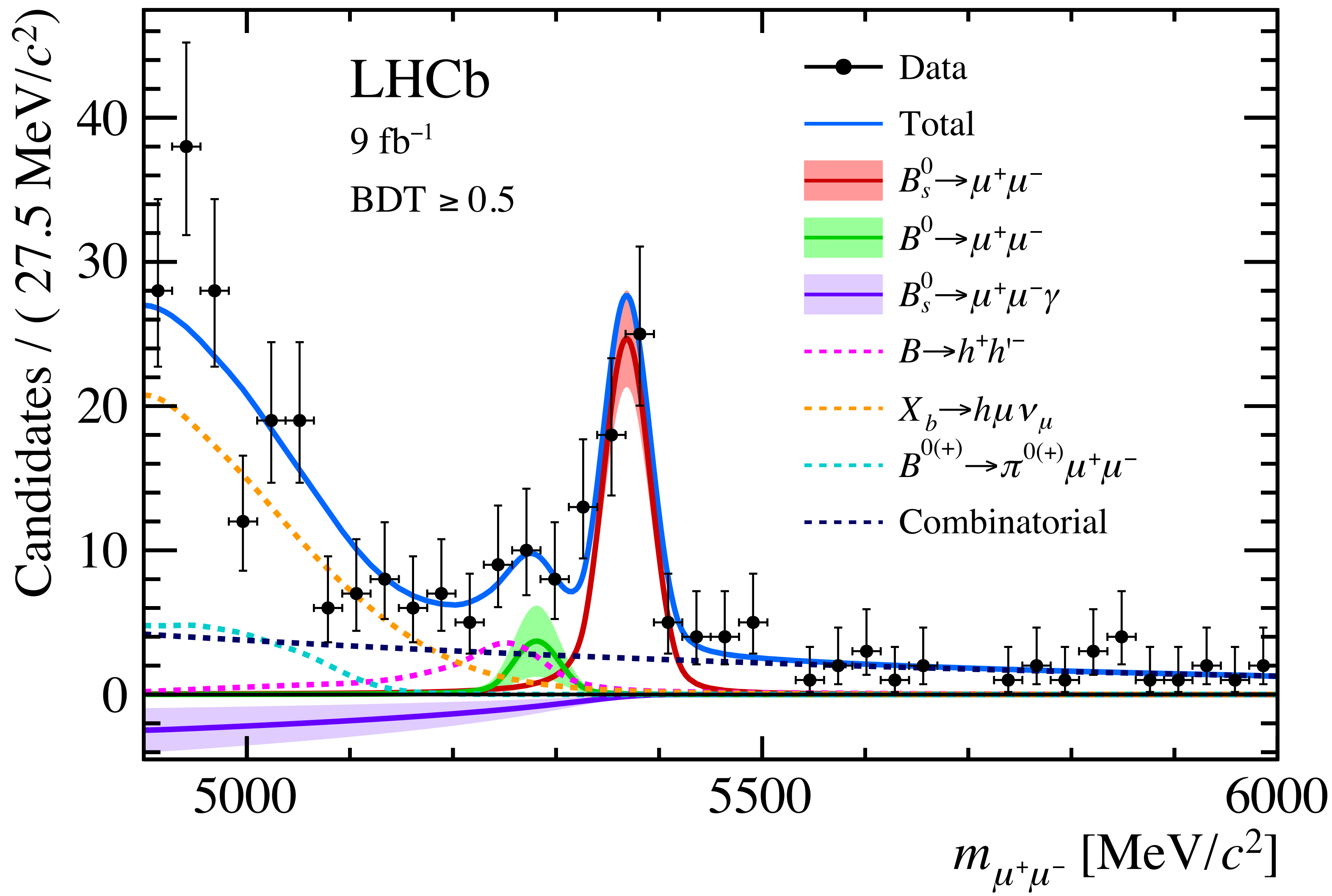
- SM branching fractions prediction: $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$ with only 4% uncertainty

The very rare $B_s \to \mu\mu$

LHCB-PAPER-2021-007



The very rare $B_s \to \mu\mu$



Latest LHCb result

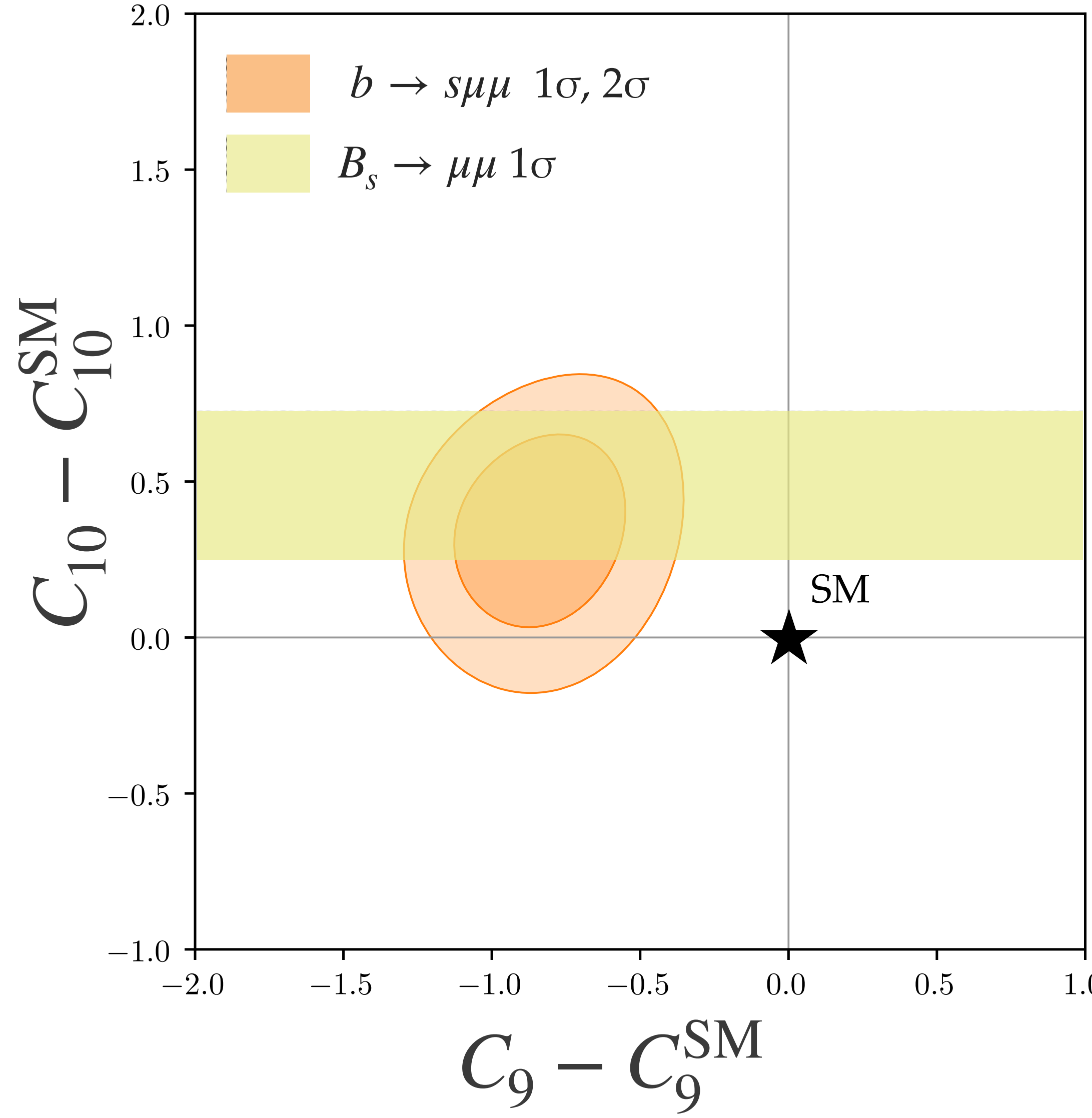
$$BR(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

16% uncertainty!

Interpretation

- 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 below SM by about 2σ
  → Compatible with C_{10} shift that could explain $b \to s\mu\mu$!

Fit from arXiv:2103.13370



Tests of Lepton Universality

$b \to s\ell^+\ell^-$ tests of LU

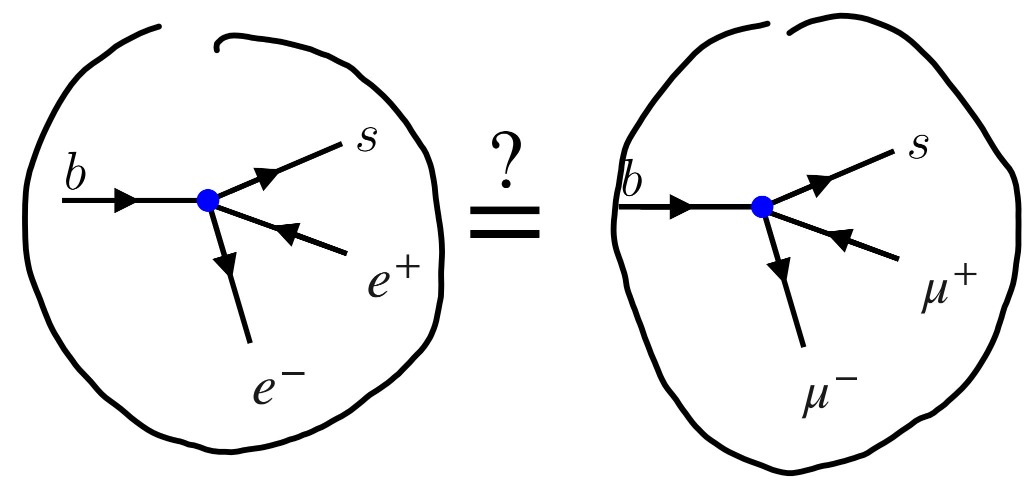
- $b \to s\ell^+\ell^-$ is lepton universal in the SM
  → can identify LU violating NP contribution

Hiller & Kruger arXiv:hep-ph/0310219

- $b \to s\tau\tau$ not observed yet → compare μ and e
- Predictions are extremely precise
  - QCD uncertainty cancels to 10^{-4}
  - Up to ~1% QED corrections

Bordone et al arXiv:1605.07633

- Main challenge at LHCb is e/μ differences in the detector response



$$R_H = \frac{\int_{q^2_{\min}}^{q_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2}{\int_{q^2_{\min}}^{q_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to He^+e^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2} \overset{\text{SM}}{\cong} 1$$

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

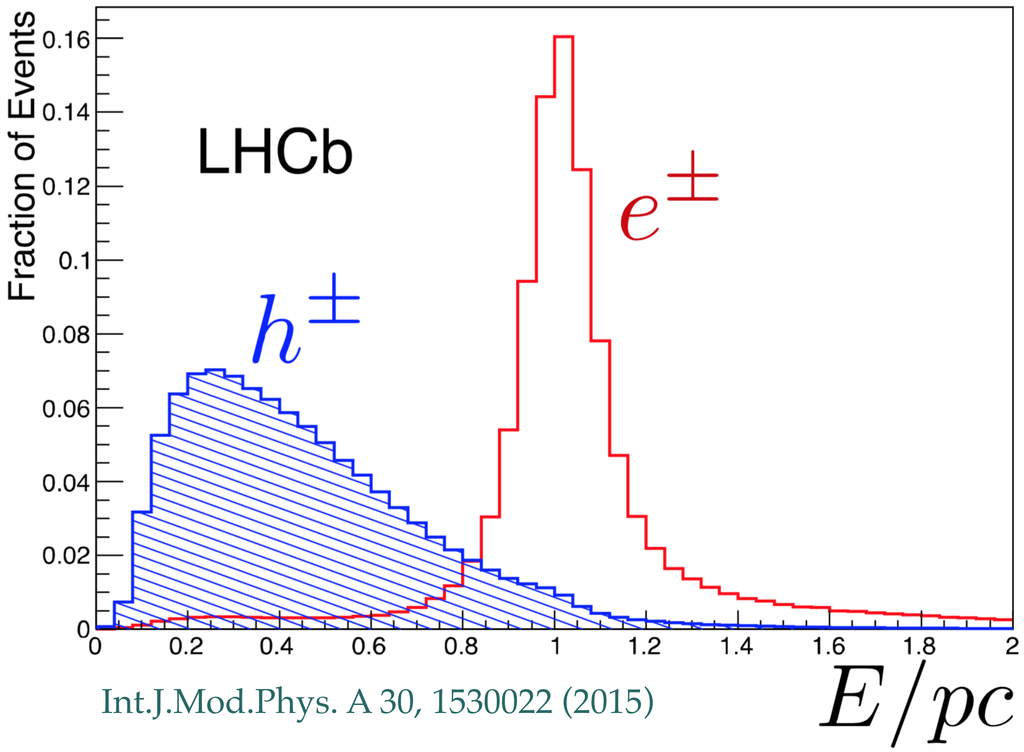
$$\frac{\epsilon\left(B^+ \to K^+\mu^+\mu^-\right)}{\epsilon\left(B^+ \to K^+e^+e^-\right)} \simeq 3$$

Phys. Rev. Lett. 122 (2019) 191801

Hardware trigger at LHCb:

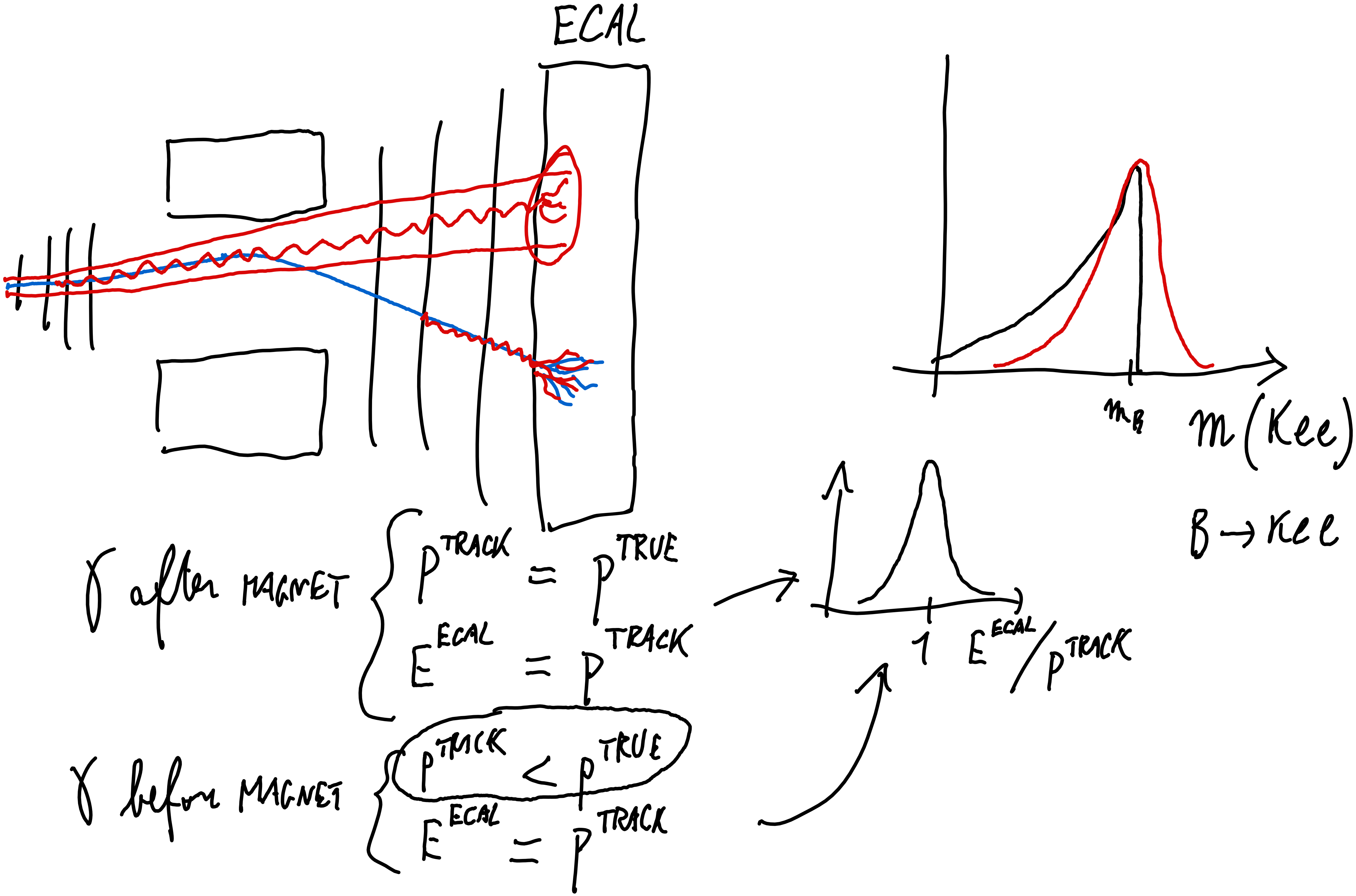
- $p_T(\mu^\pm) > 1.5 - 1.8$ GeV
- $E_T(e^\pm) > 2.5 - 3.0$ GeV

Electron ID at LHCb



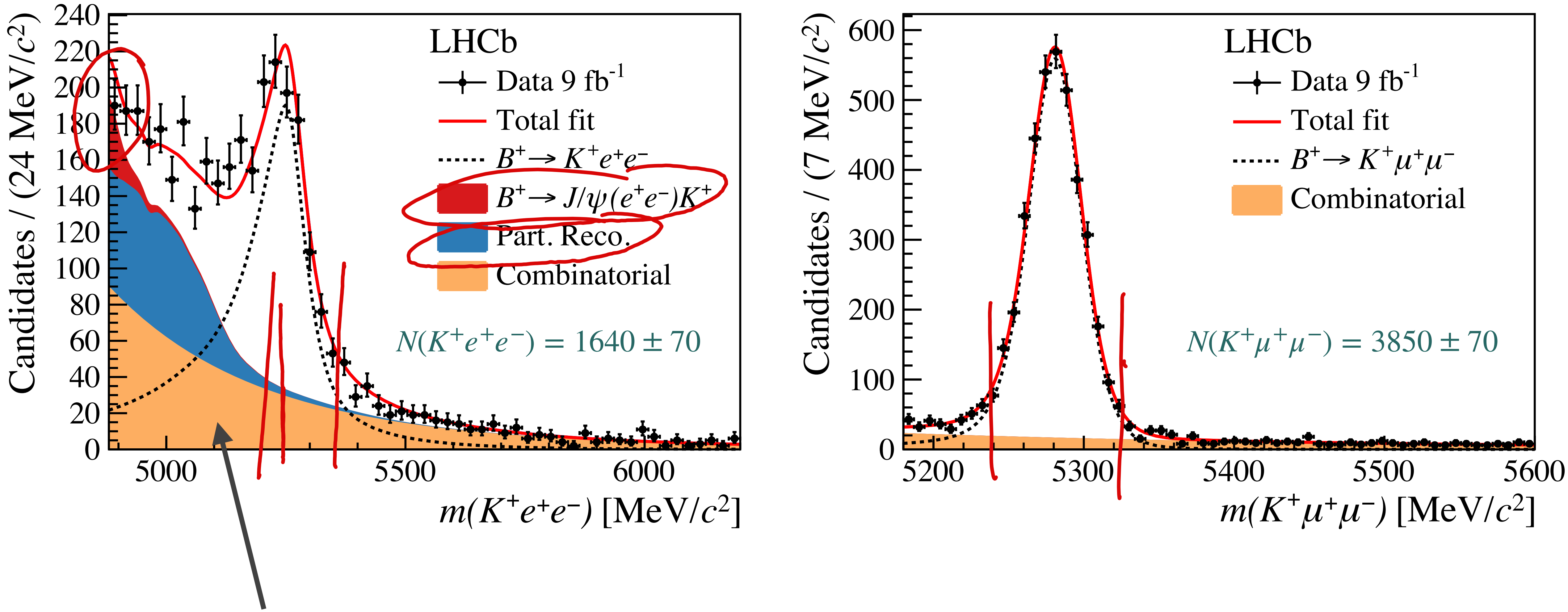
Int.J.Mod.Phys. A 30, 1530022 (2015)

Bremsstrahlung



Mass resolution

LHCb arXiv:2103.11769



- Background with missing pion (Part. Reco.) due to mass resolution
- Combinatorial background is much larger

Backgrounds in electrons

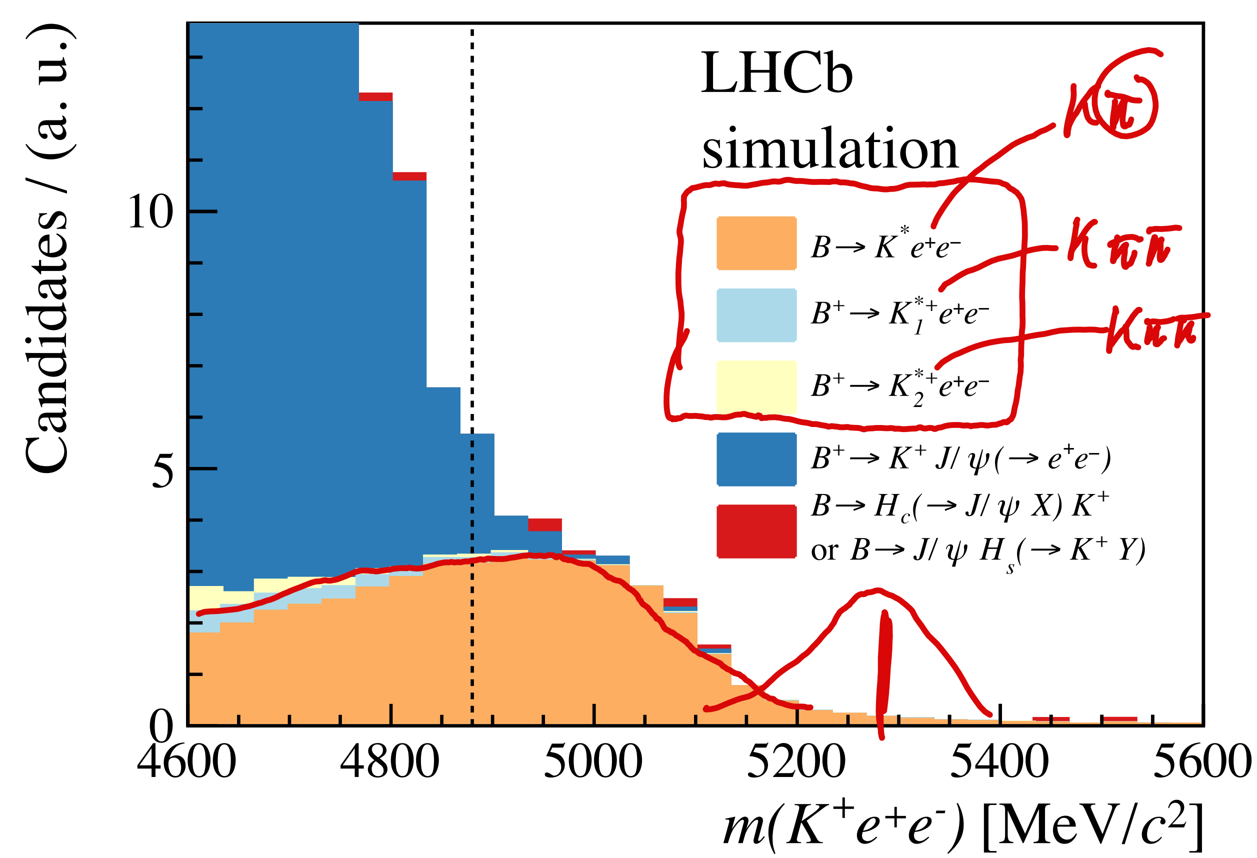
- Particle ID and mass vetoes to suppress peaking bkg
  - Remove $B^+ \to \bar{D}^0(\to K^+e^-\nu)e^+\bar{\nu}$ by requiring $m(K^+e^-) > m_{D^0}$
  - Remove $B^+ \to K^+\pi^+\pi^-$ with electron ID
- Reduce combinatorial background with multivariate analysis (Boosted Decision Tree)
- Choose $m(K^+e^+e^-)$ window to suppress other backgrounds
  - Cross-check using control regions and changing $m(K^+e^+e^-)$ window

$P(\pi \to e) \sim 1\%$

$P(K\pi\pi \to Kee) \sim 10^{-4}$

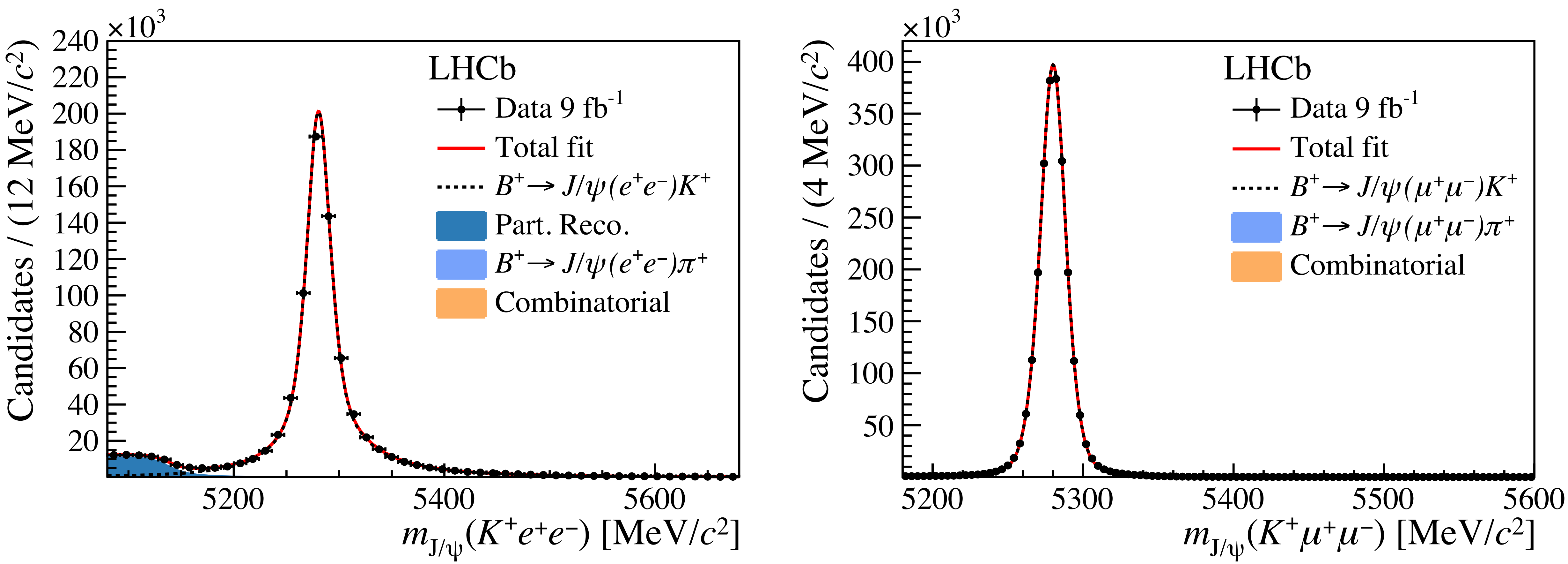
$1.1 < q^2 < 6.0$ GeV^2

$m^2_{J/\psi} = 9.5$ GeV^2



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

$B \to K J/\psi$ $\qquad$ $\mathcal{B}(J/\psi \to \mu\mu) \overset{\text{L.U.}}{=} \mathcal{B}(J/\psi \to ee)$

Double ratio

$$R_K = \left.\frac{BR(B \to K\mu\mu)}{BR(B \to Kee)}\right|_{q^2 \in [1.1,\, 6.0]\, GeV^2}$$

$$R_K = \frac{N_S^{\mu\mu}}{N_S^{ee}} \frac{\varepsilon_S^{ee}}{\varepsilon_S^{\mu\mu}} \sim \frac{1}{3}$$

$$R_{J/\psi} = \frac{BR(B \to K\, J/\psi(\mu\mu))}{BR(B \to K\, J/\psi(ee))} = 1$$

$$= \frac{R_K}{R_{J/\psi}} = \frac{N_S^{\mu\mu}}{N_S^{ee}} \frac{\varepsilon_S^{ee}}{\varepsilon_S^{\mu\mu}} \cdot \frac{N_N^{ee}}{N_N^{\mu\mu}} \frac{\varepsilon_N^{\mu\mu}}{\varepsilon_N^{ee}}$$

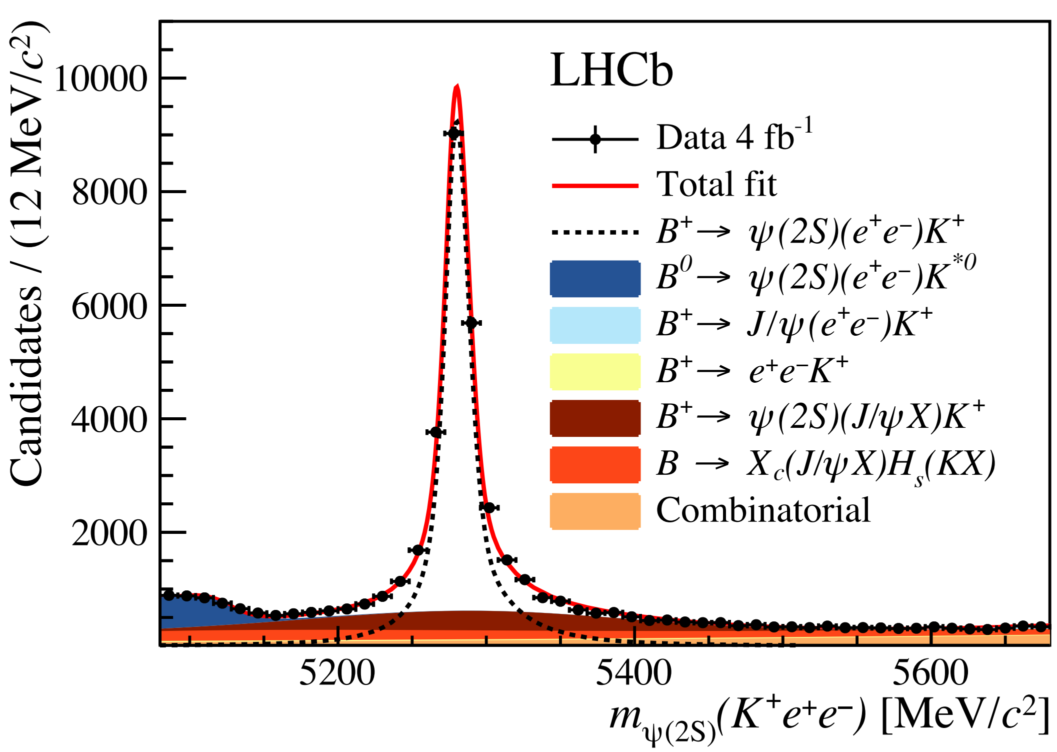
Double ratio with $\psi(2S)$

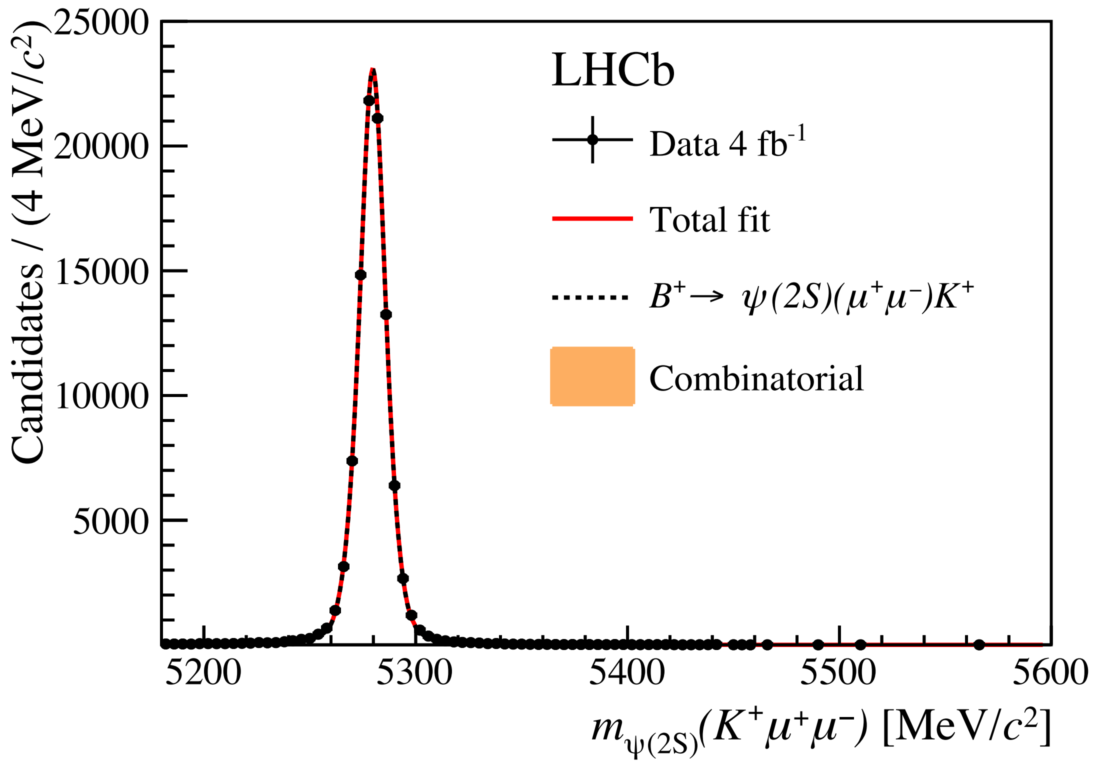
- Can also test that R_K measured at the $\psi(2S)$ is 1

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = 1$$

- Validation of q^2 dependence of efficiency correction

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





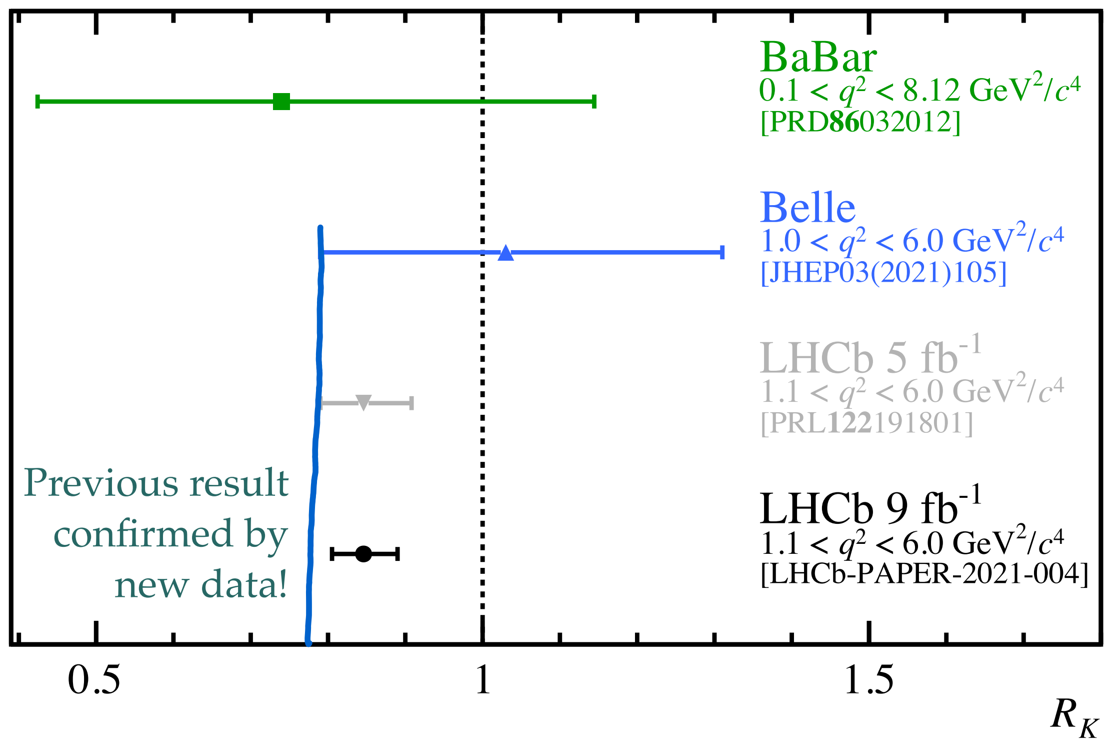
R_K result

LHCb arXiv:2103.11769

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

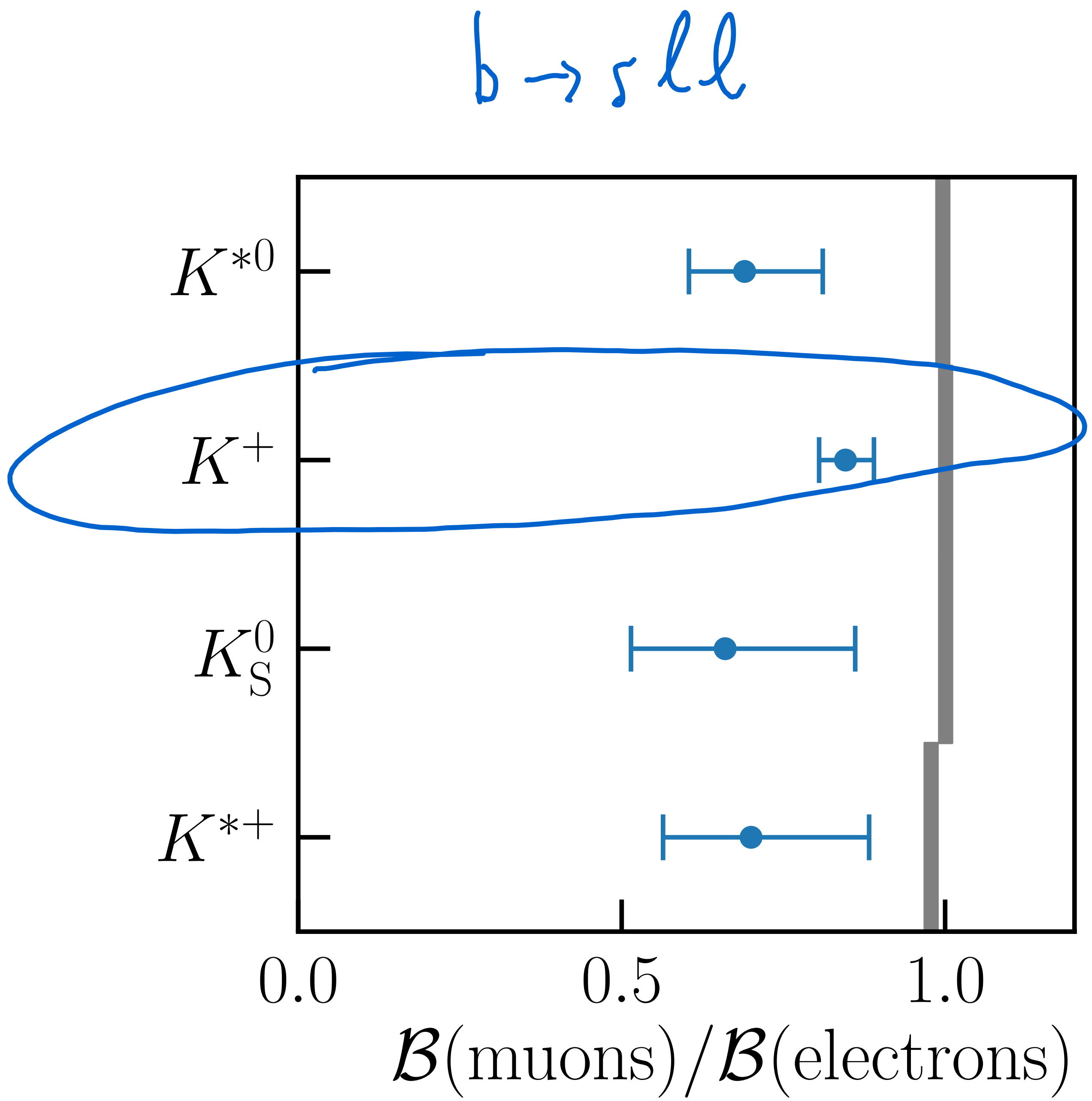
$$R_K = 0.846^{+0.042}_{-0.039}(\text{ stat })^{+0.013}_{-0.012}\,(\text{syst})$$

- 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 1 by ~15% with a significance of 3.1σ**



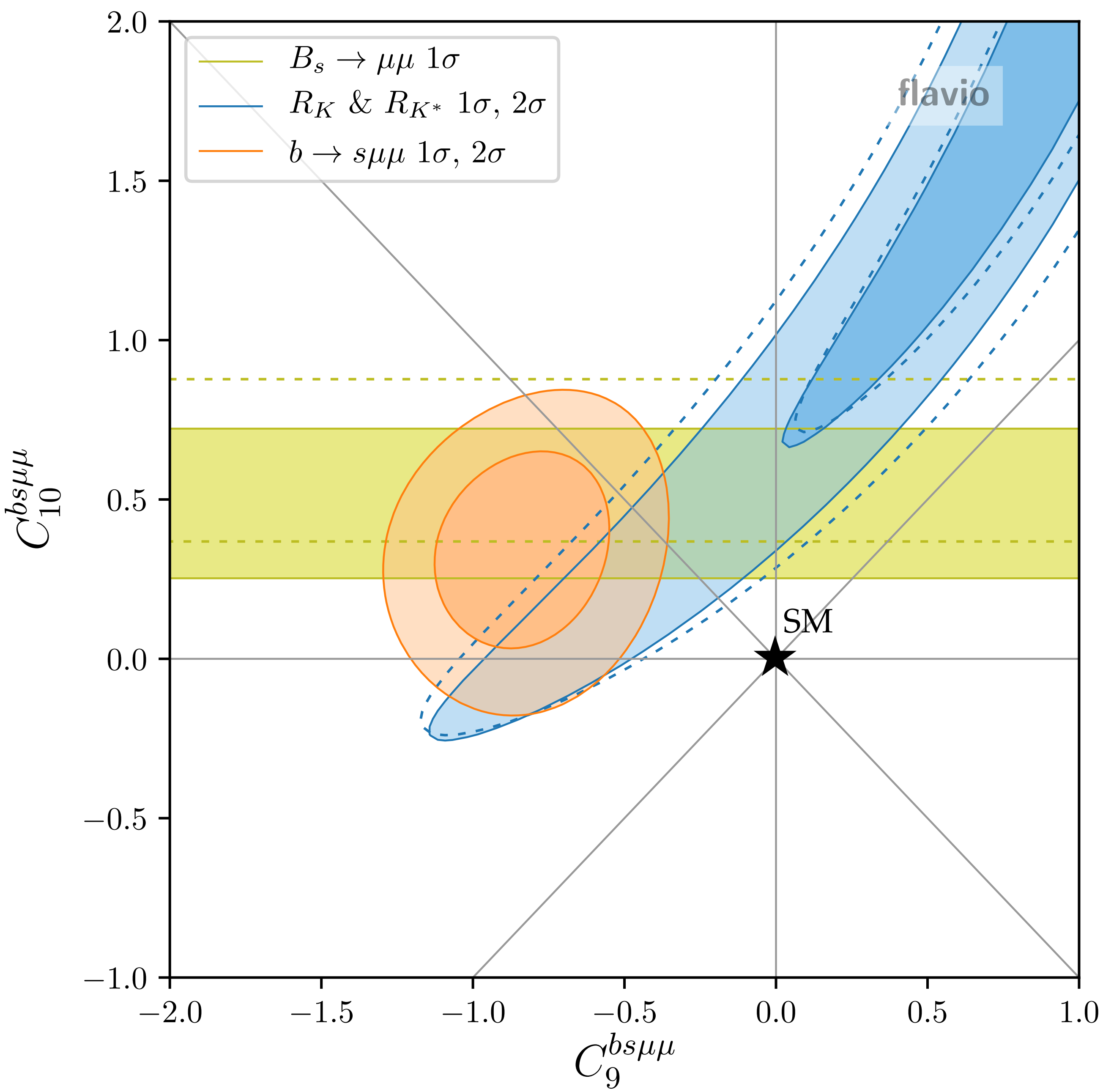
Other LU tests

- Tested LU in other decay channels
- Precision limited, but coherent results
- Combination not trivial (cannot simply average)



Intepretation

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



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
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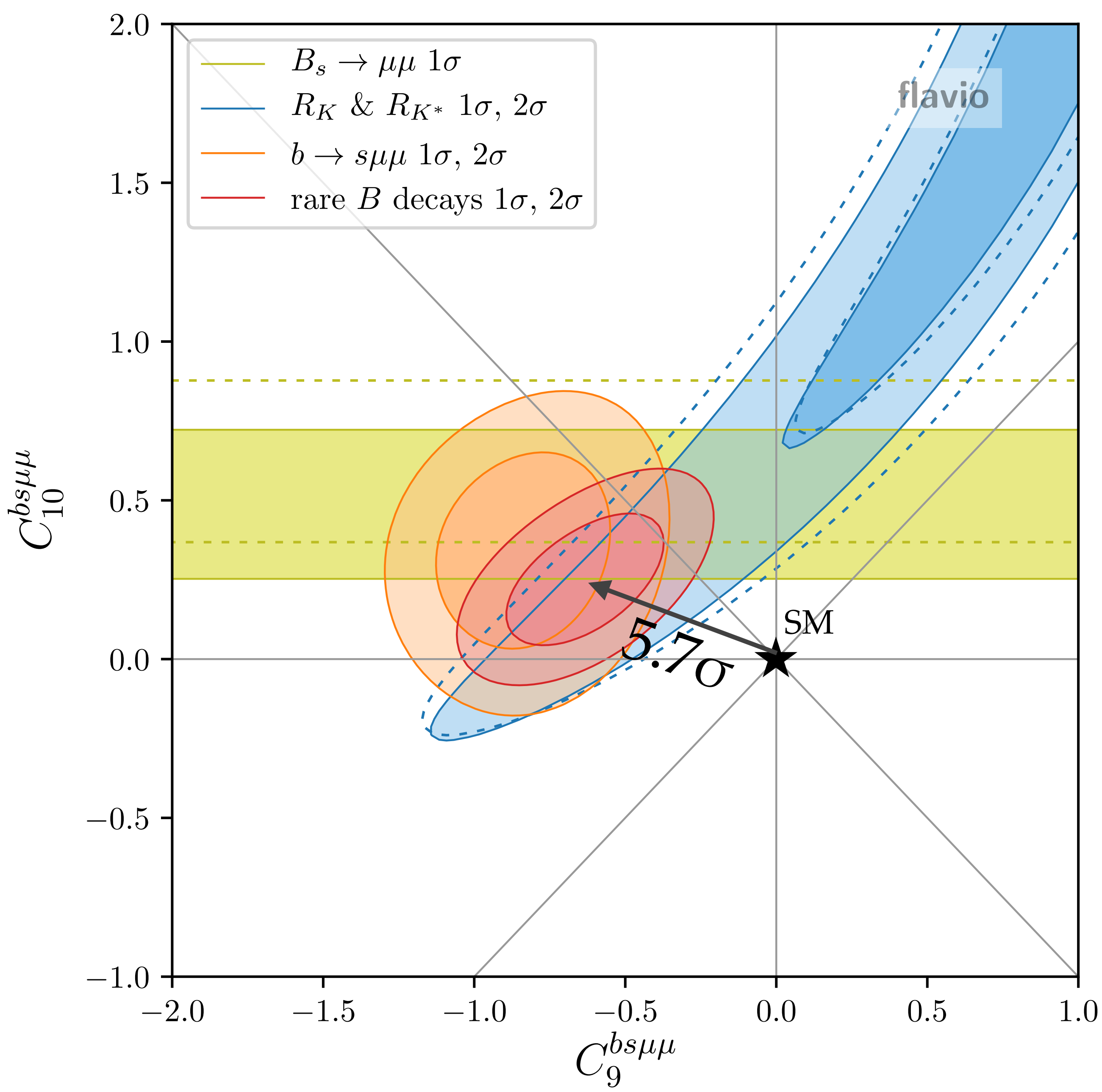

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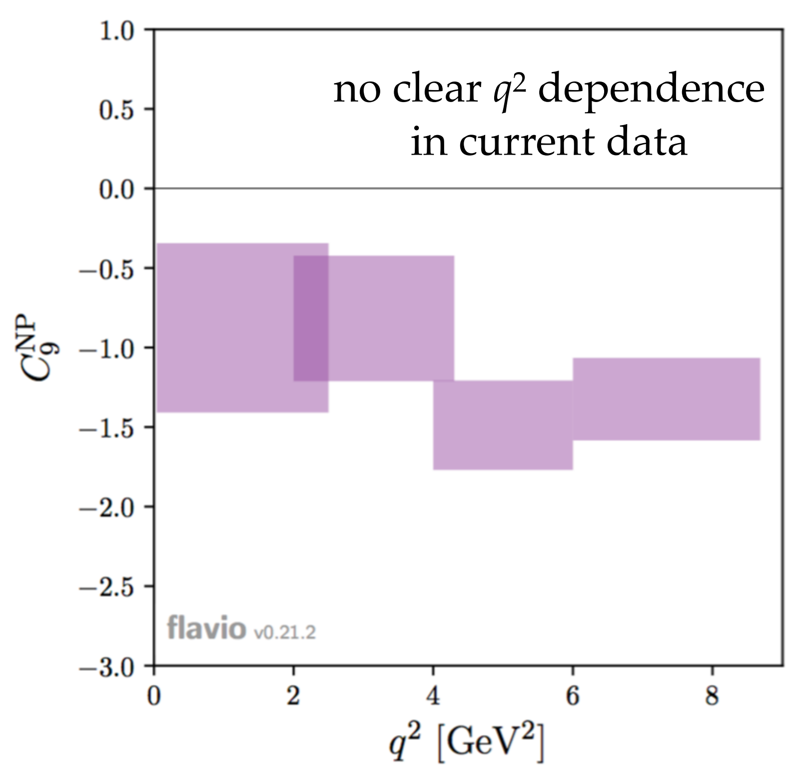
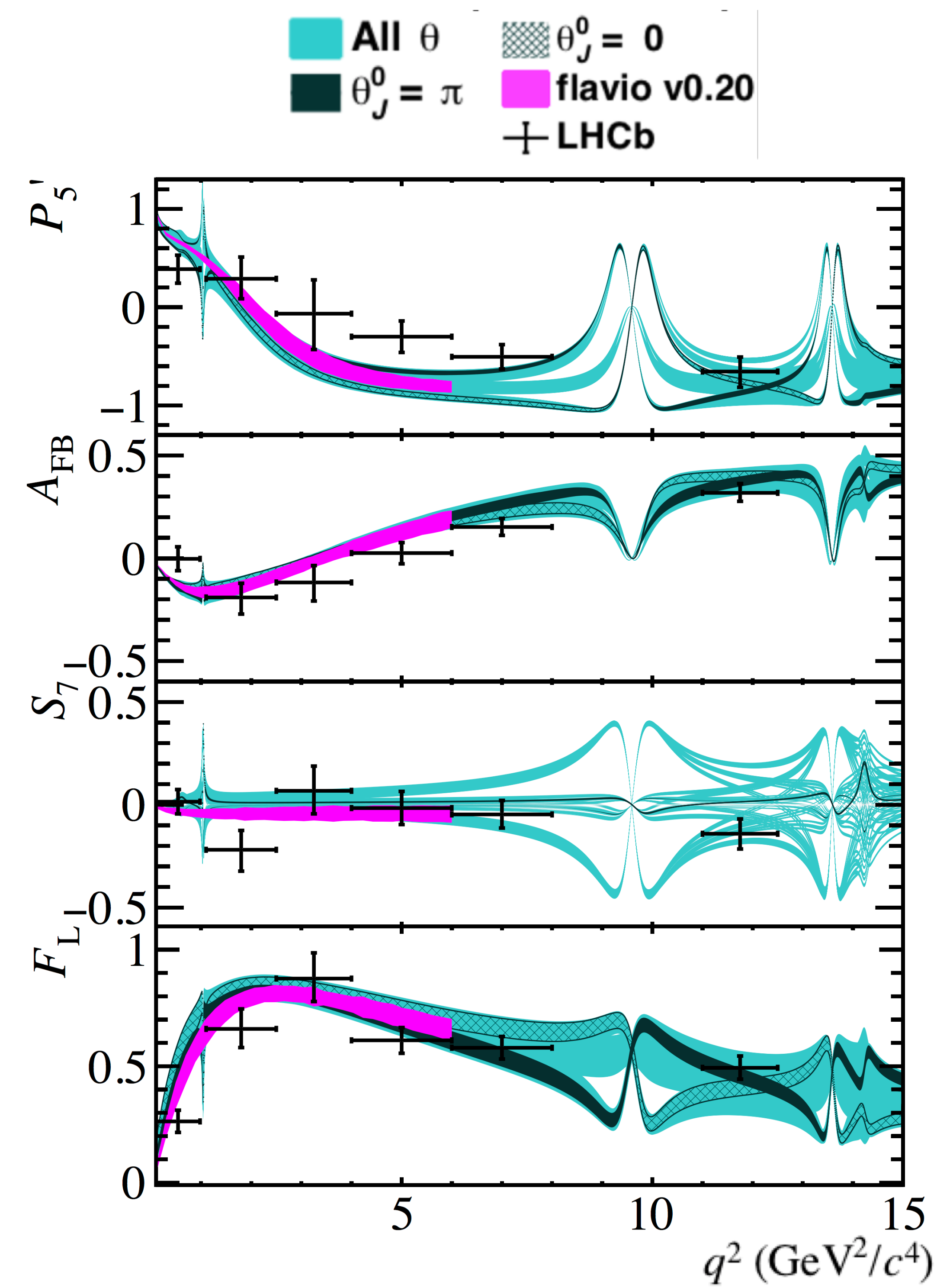
Backup

A handle on the cc loop

- Experimental handles on $c\bar{c}$ 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
  - Perform full angular analysis of $B \to K^* \mu\mu$ including *cc* resonances and measure interference phases
    Blake et al., arXiv:1709.03921

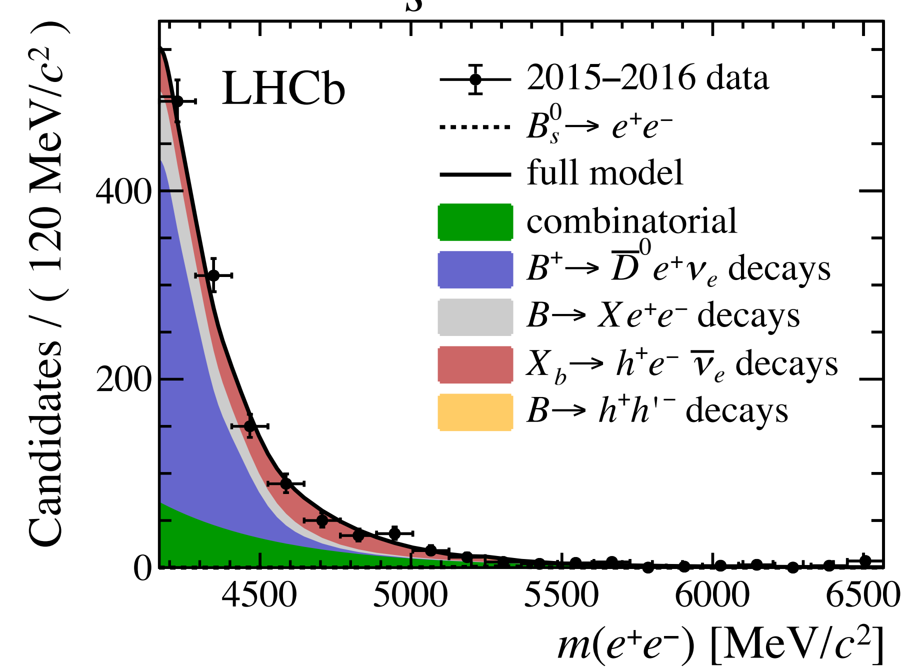




$B_s \to e^+e^-$ and $B_s \to \tau^+\tau^-$

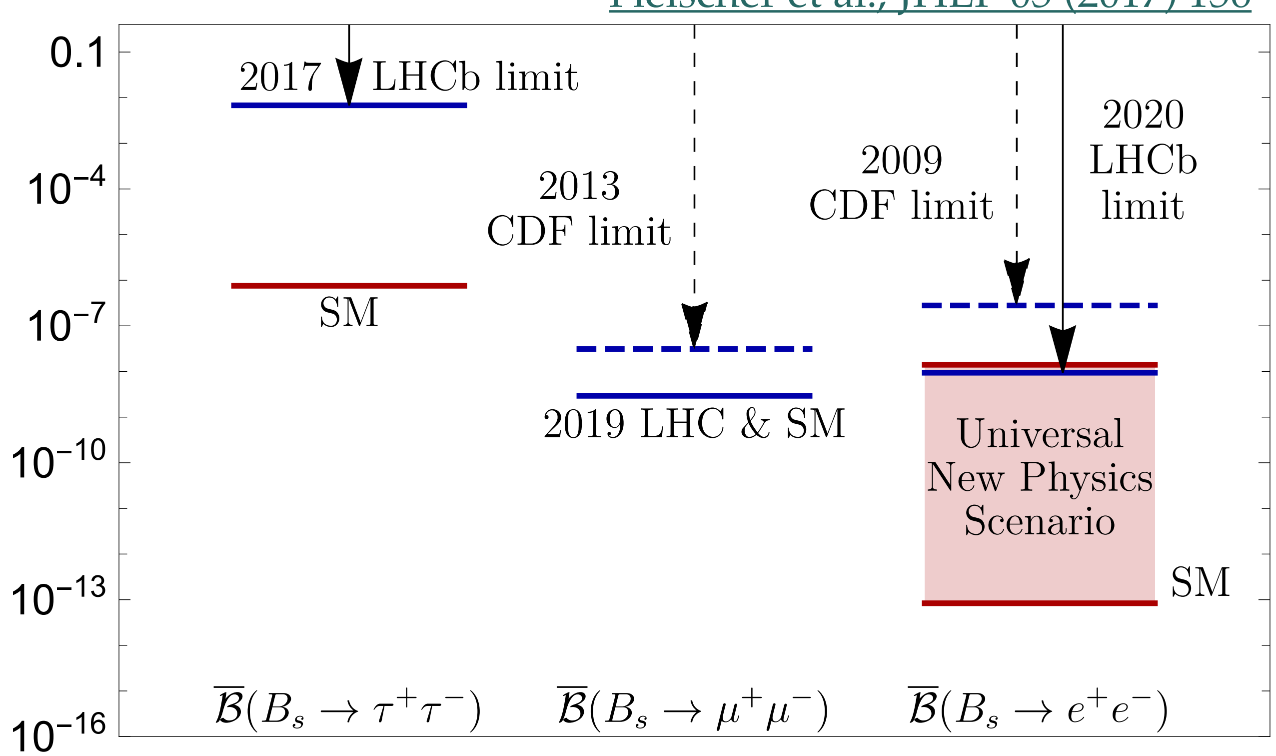
- Different levels of helicity suppression depending on the lepton mass
- Electrons and taus present additional experimental challenges
- LHCb has search for both and has set upper limits
  $BR(B_s^0 \to e^+e^-) < 11.2 \times 10^{-9}$ at 95 % CL
  $BR(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95 % CL

$B_s \to e^+e^-$

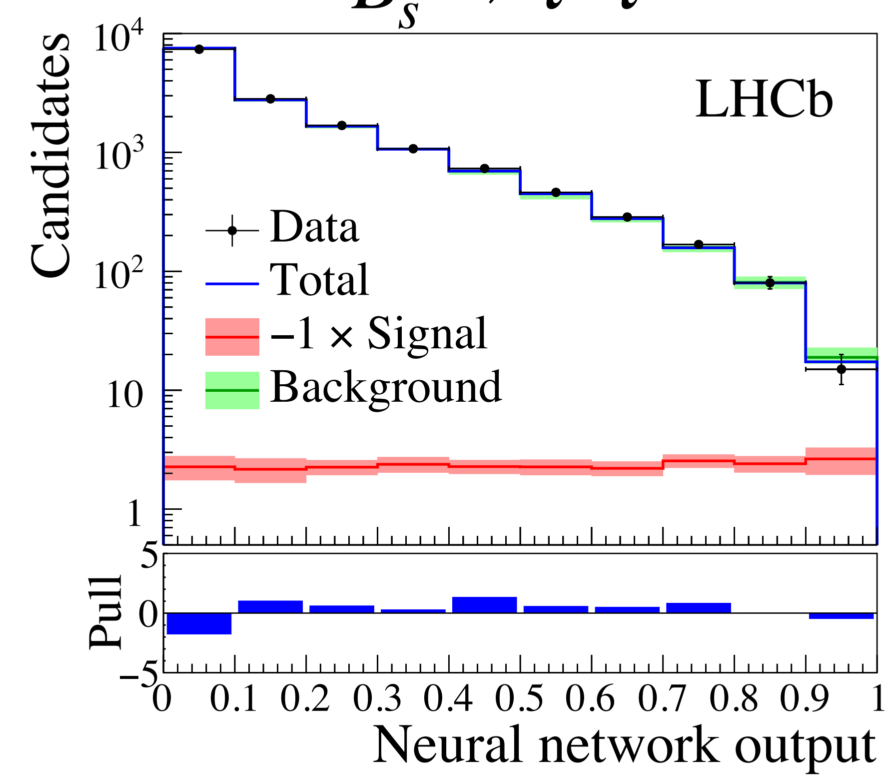


Phys. Rev. Lett. 124 (2020) 211802

Fleischer et al., JHEP 05 (2017) 156



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



Phys. Rev. Lett. 118 (2017) 251802