Electroweak Penguin Decays at LHCb

Sara Celani
On behalf of the
LHCb collaboration

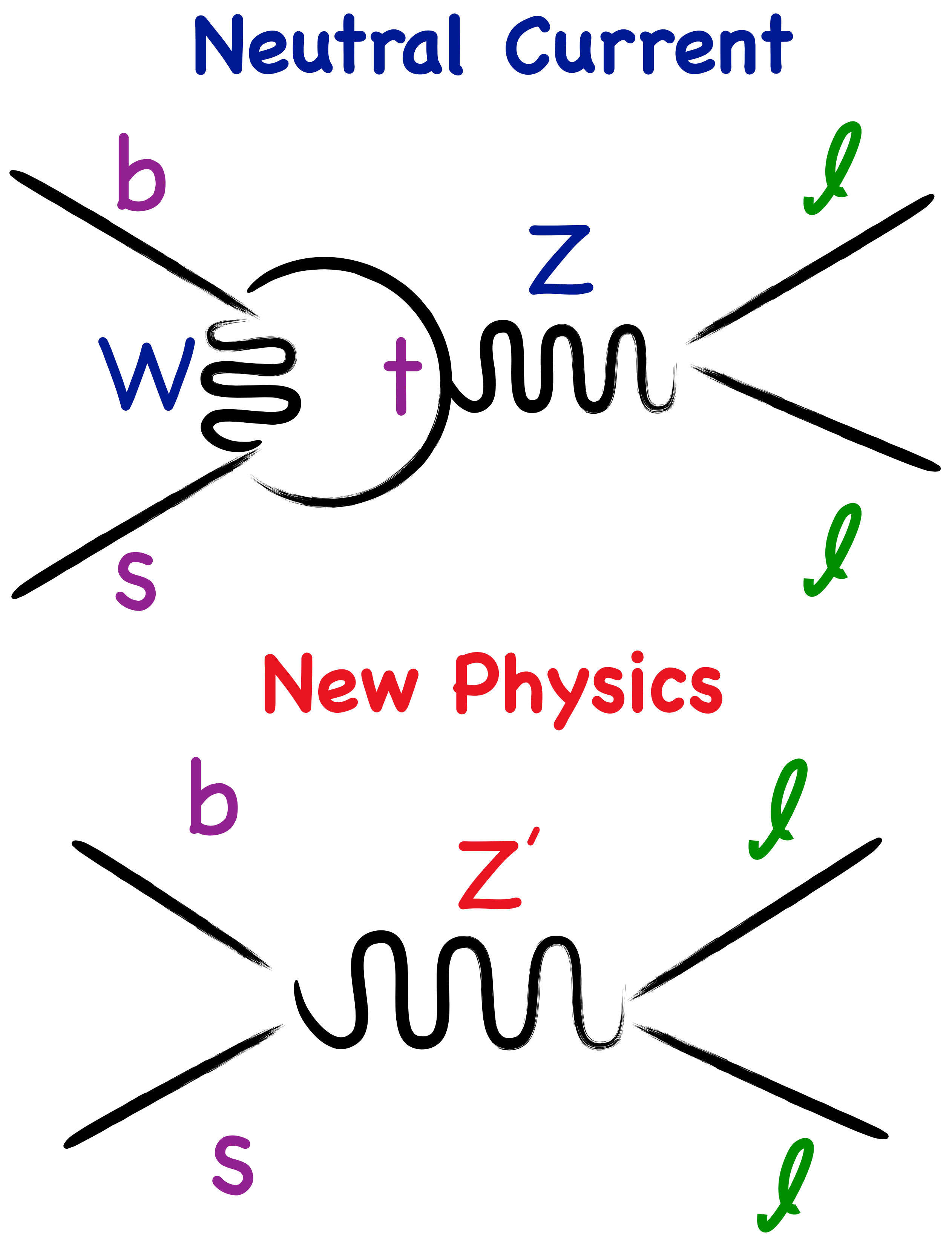
LHCb
EPFL

International Conference
of High Energy Physics
Bologna 6-13 July 2022

Electroweak penguin decays

- Processes including $b \to s\ell\ell$ transition are sensitive to **New Physics (NP)** contribution
  - Suppressed in the SM (they can happen only via loop or boxes): small BR ~10^{-7} - 10^{-6}
  - New physics mediators can enter in the loops and modify the amplitudes

- SM gauge interactions have the same amplitude for all the families: **Lepton Flavour Universality (LFU)**



Electroweak penguin decays

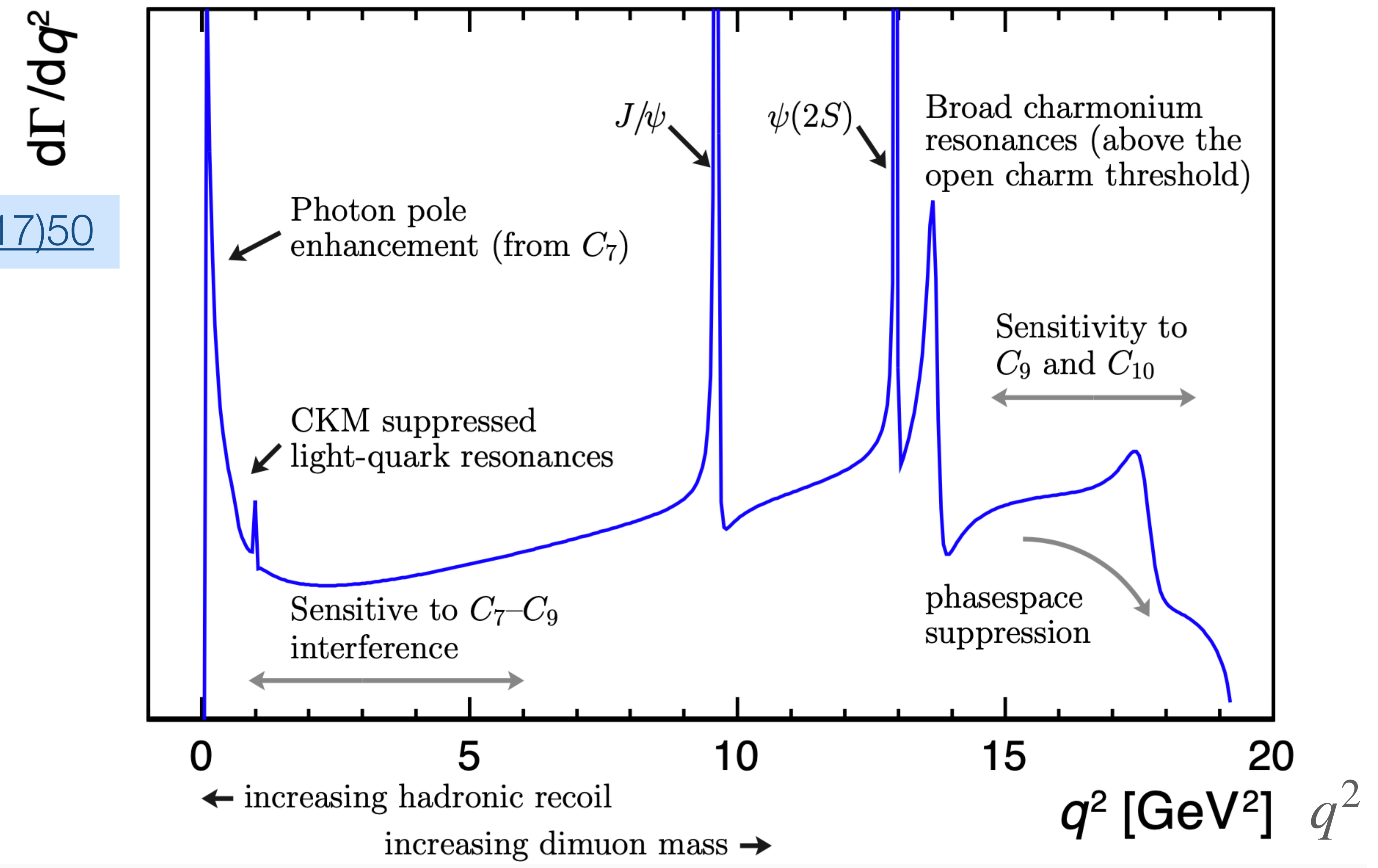
- Rare b decays can be described by an **effective theory**:

$$\mathrm{H_{eff}} \propto \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum C_i O_i$$

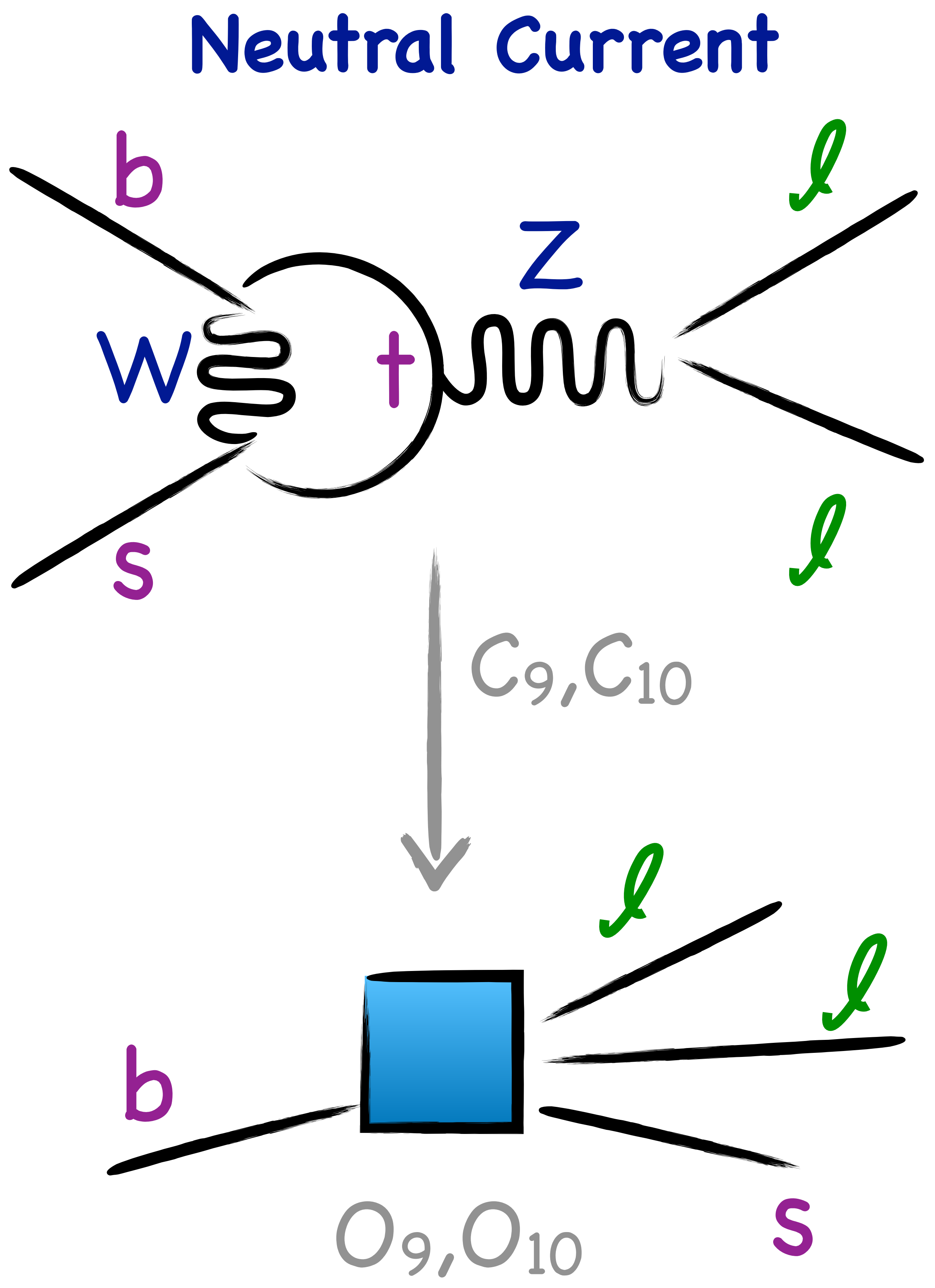
Effective coupling
Wilson Coefficients (WC)

Local Operators

Prog.Part.Nucl.Phys.02(2017)50



$q^2 = m^2(\ell^+\ell^-)$



- NP can introduce new operators or modify the WCs depending on its structure: $C_i = C_i^{SM} + C_i^{NP}$

Electroweak penguin decays

- Large variety of observables available:
  - **Relative rates** of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$, of the form

EPJ C76 (2016) 8 440

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

Sebastian's **talk**

- are clean: QCD uncertainties cancels out in the ratio
- are predicted by the SM with very high precision

Electroweak penguin decays

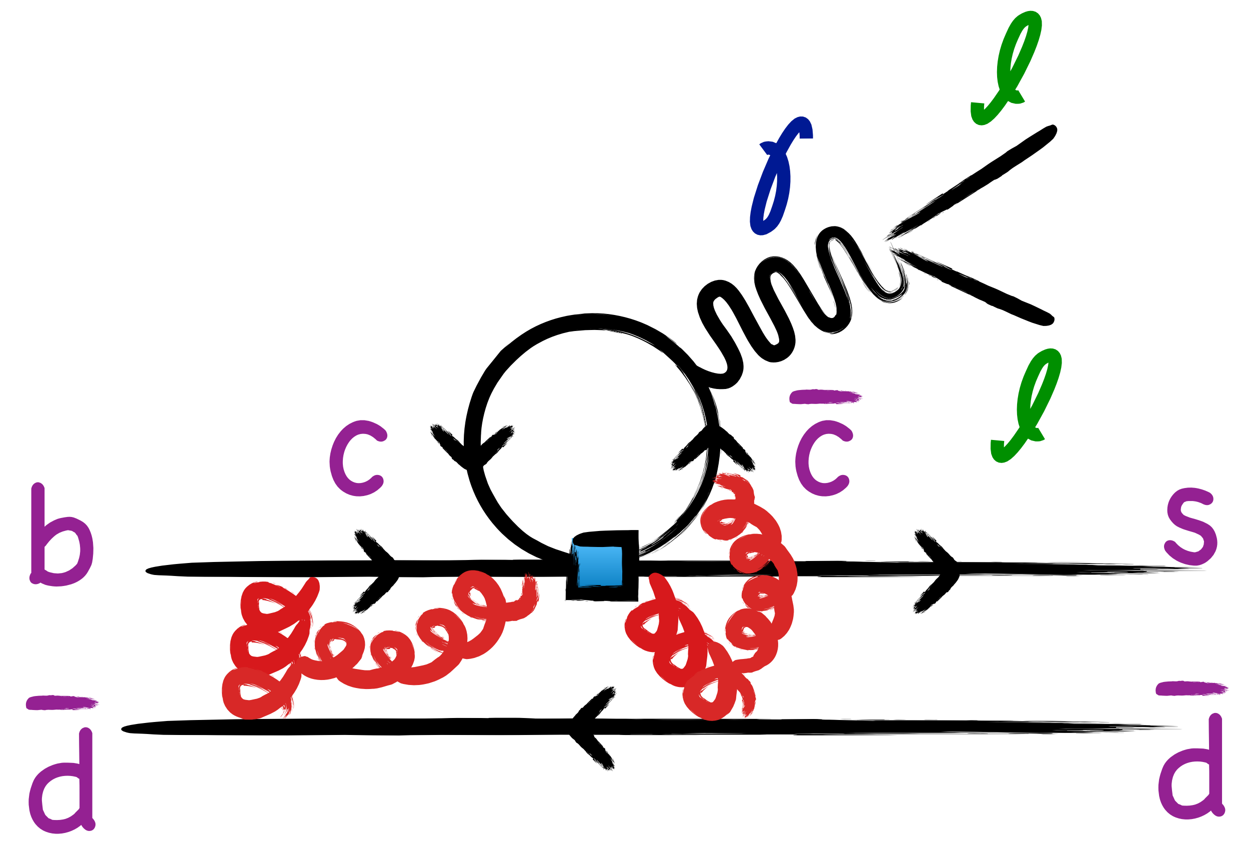
- Large variety of observables available:
  - **Relative rates** of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$, of the form

EPJ C76 (2016) 8 440

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

    - ❖ are clean: QCD uncertainties cancels out in the ratio
    - ❖ are predicted by the SM with very high precision
  - **Angular distributions** of the final state particles:
    - ❖ Reduced form factor uncertainties
    - ❖ May be polluted by "charm loop" effects, hard to predict

Sebastian's talk



Electroweak penguin decays

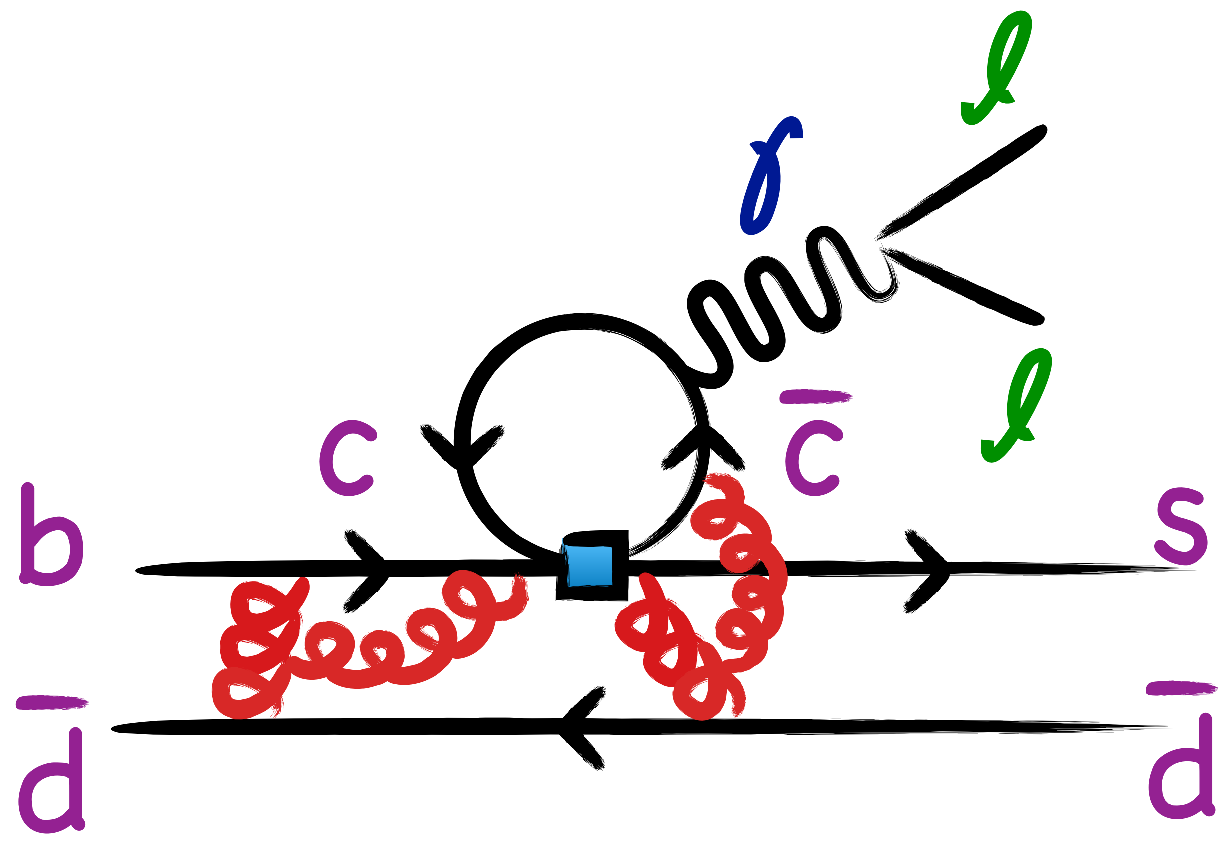
- Large variety of observables available:
  - **Relative rates** of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$, of the form

EPJ C76 (2016) 8 440

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \stackrel{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

Sebastian's **talk**

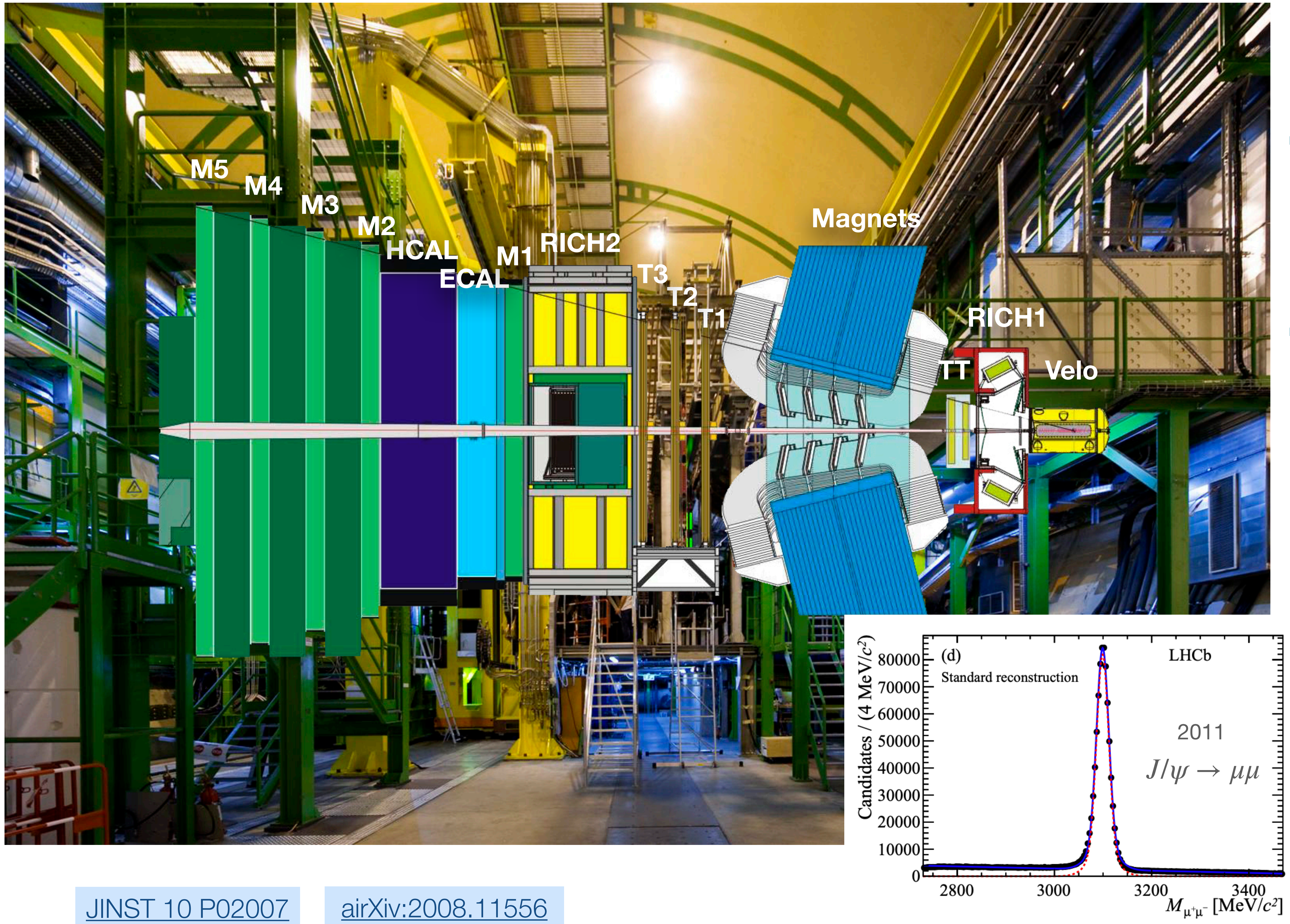
    - are clean: QCD uncertainties cancels out in the ratio
    - are predicted by the SM with very high precision
  - **Angular distributions** of the final state particles:
    - Reduced form factor uncertainties
    - May be polluted by "charm loop" effects, hard to predict



  - **Branching fractions:**
    - $B_s^0 \to \mu^+\mu^-$ very clean SM predictions $\sim \mathcal{O}(4\%)$ Maarten's **talk**
    - $B \to K^*\mu^+\mu^-, B_s \to \phi\mu^+\mu^-..$ Suffer the most from theory uncertainties

b decays @LHCb

LHCb detector in Runs 1-2 (2010-2018)



JINST 10 P02007 airXiv:2008.11556

- LHCb forward detector: 27% of b hadrons produced from pp collision inside **acceptance** $(B^+, B^0, B_s, B_c, \Lambda_b \ldots)$
- Good **trigger** on displaced tracks especially for di-muons channel ($\sim 90\,\%$ efficiency)
- Good **PID** performances from RICH 1,2 , CALO and Muon Stations
  - Electron ID $\sim 90\,\%$ for $\sim 5\,\%$ $h \to e$
  - Kaon ID $\sim 95\,\%$ for $\sim 5\,\%$ $\pi \to K$
  - Muon ID $\sim 97\,\%$ for $\sim 1-3\,\%$ $\pi \to \mu$
- Excellent **tracking** performances ($\sim 96\,\%$ efficiency)
  - Δ p / p = 0.5(1.0)% at low(high) momentum
  - Impact parameter resolution: (15 +29/ pT[GeV]) µm

LFU ratio status

See Sebastian's **talk**

- Relative rates are measured as double ratios: $R_X = \frac{BF(B \to X\mu^+\mu^-)}{BF(B \to XJ/\psi(\to \mu^+\mu^-))} \cdot \frac{BF(B \to XJ/\psi(\to e^+e^-))}{BF(B \to Xe^+e^-)}$

$X = K, K^*, \Lambda_b \ldots$

Run1 $3fb^{-1}$ JHEP 08 (2017) 055

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2 \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2 \end{cases}$$

2.1σ, 2.4σ

Run1 + 2016 $4.7fb^{-1}$ JHEP 05 (2020) 040

$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

1σ

Run1+2 $9fb^{-1}$ Nat.Phys.18, 277-282 (2022)

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

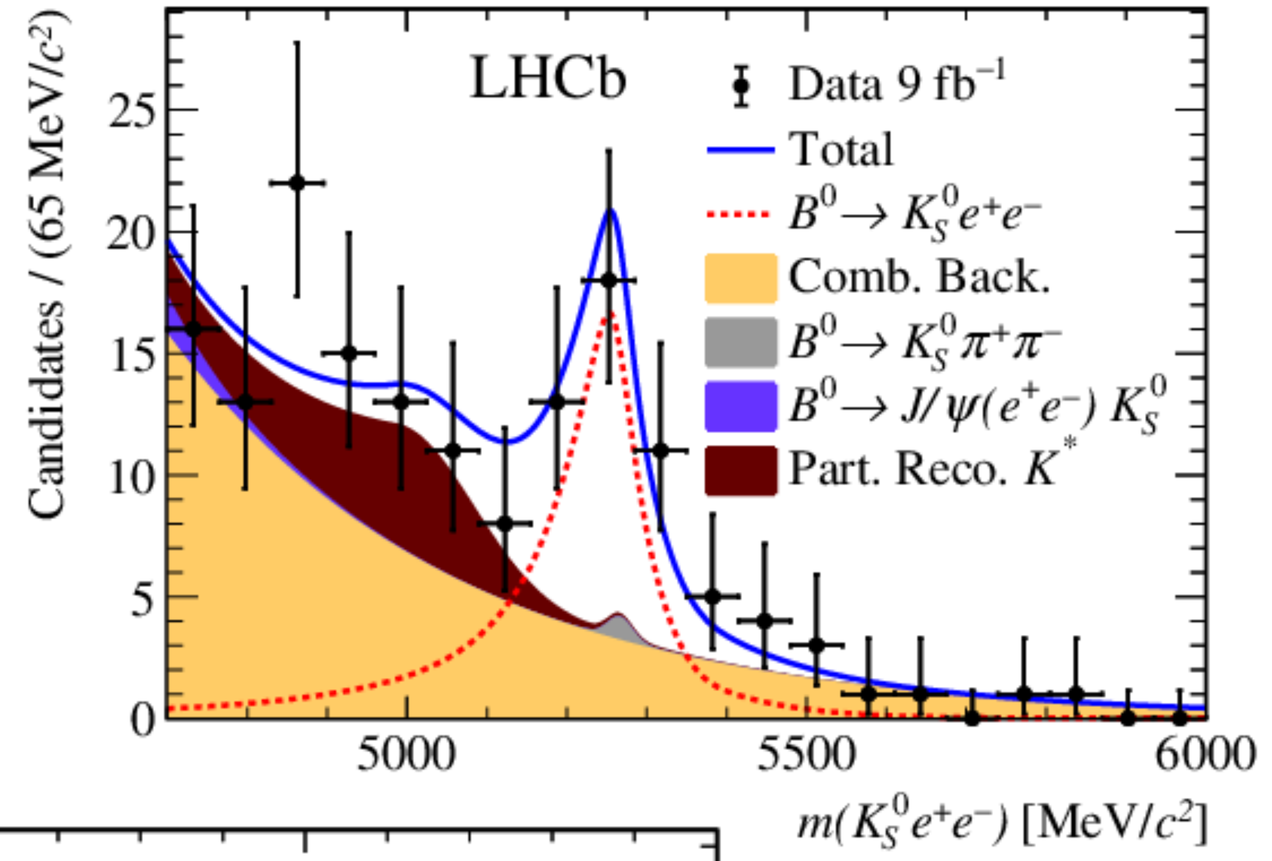
3.1σ

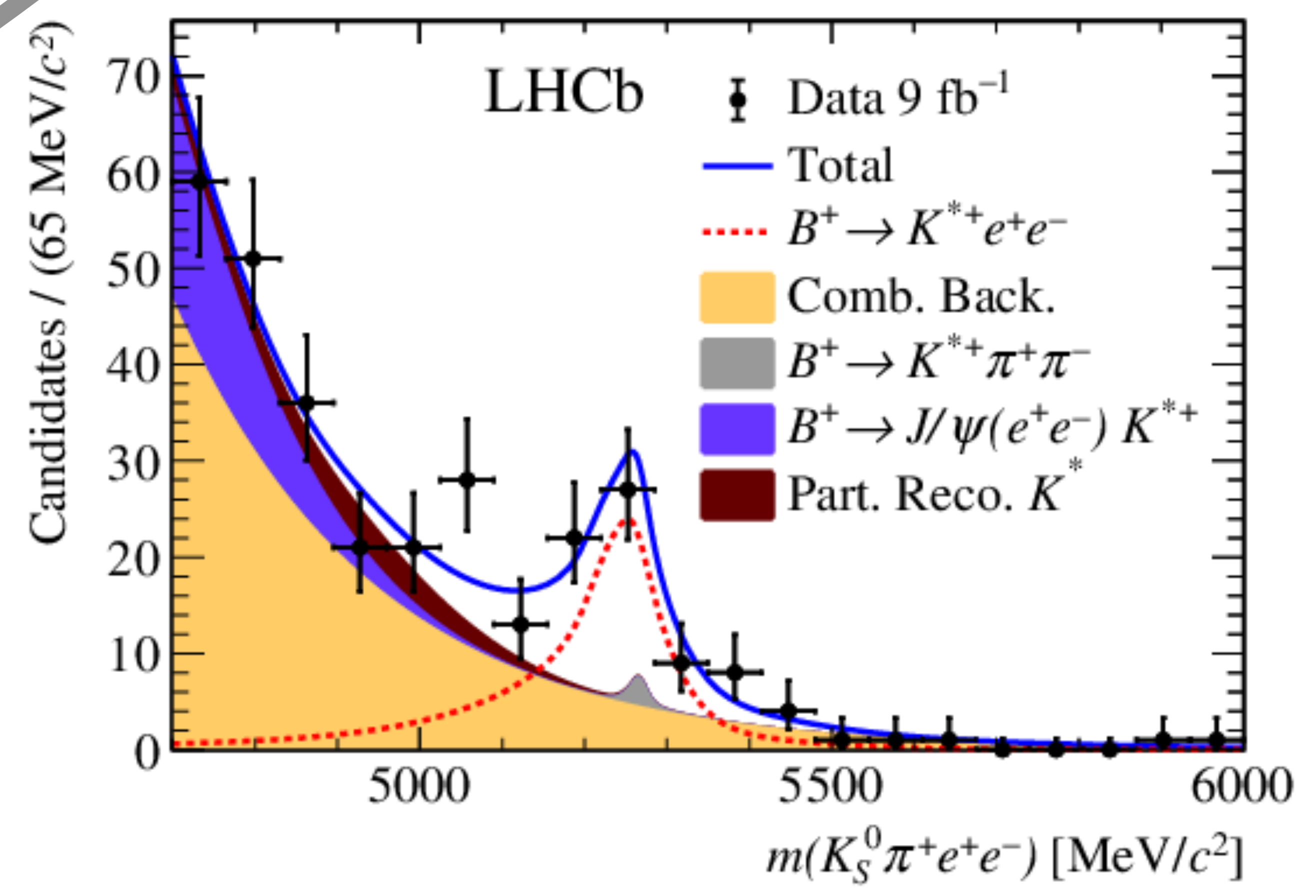
Run1+2 $9fb^{-1}$ PRL 128 (2022) 191802

$$R_{K^0_S} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})^{+0.02}_{-0.04}\,(\text{syst.})\,,$$
$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})^{+0.03}_{-0.04}\,(\text{syst.})$$

1.5σ, 1.6σ

+ first observation of electron modes

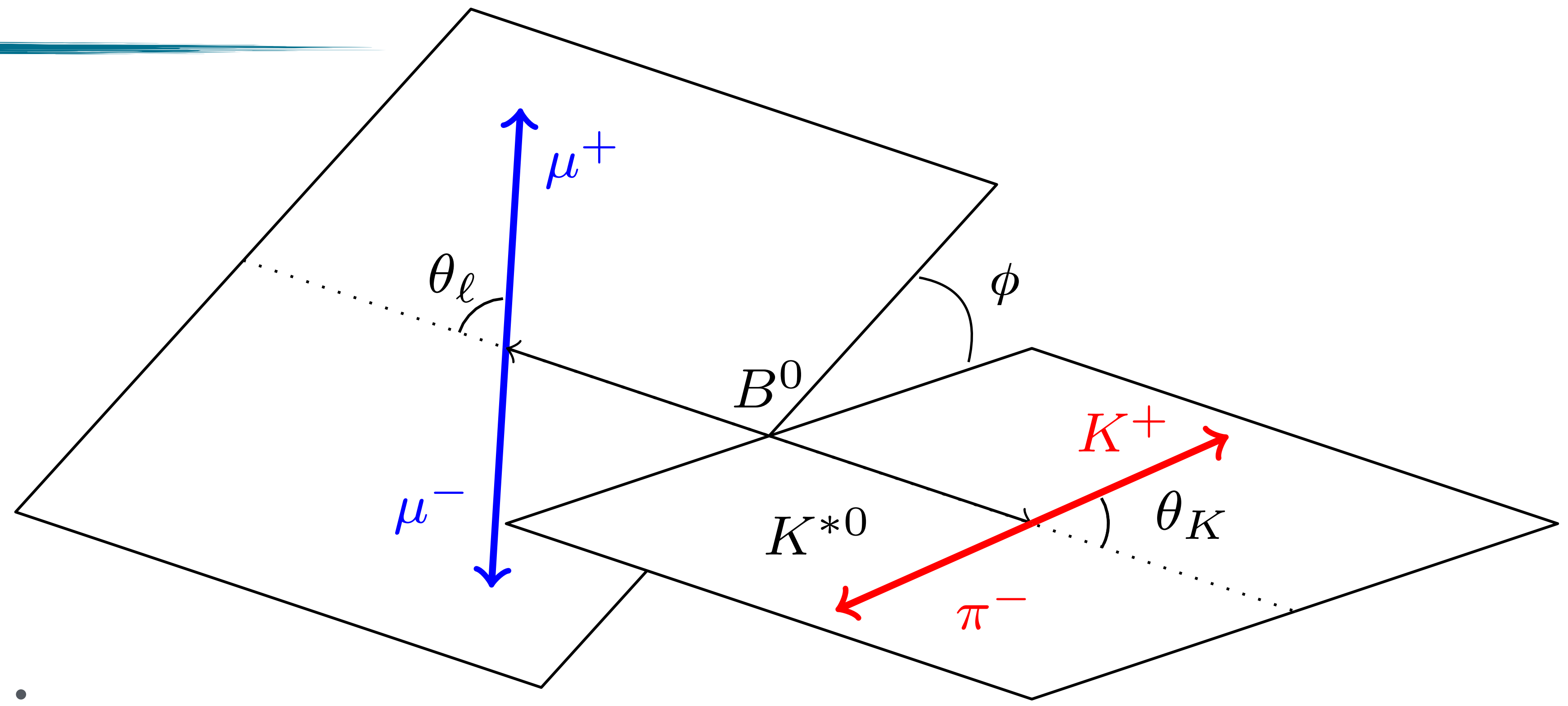


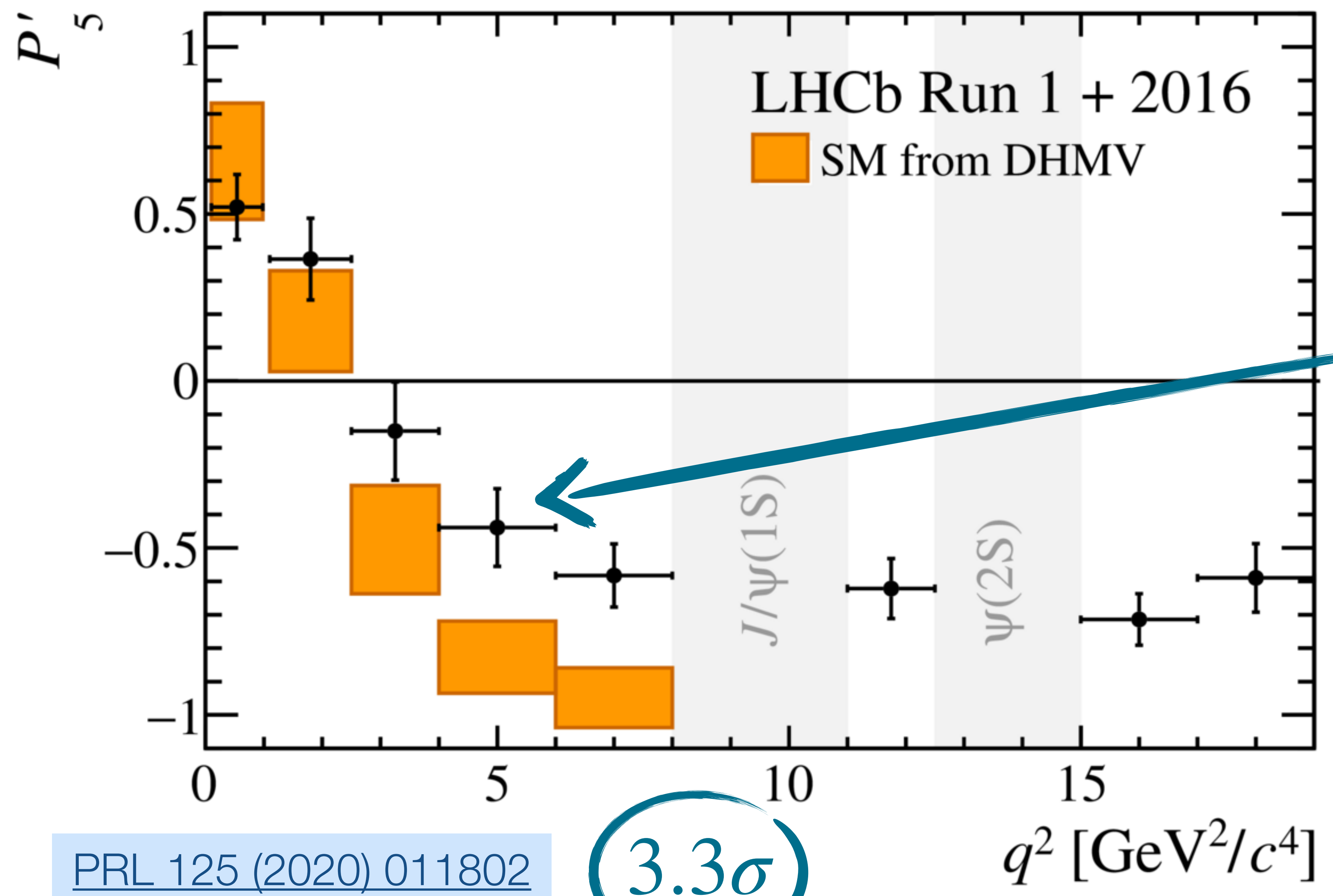


- Near future:
  - ▶ Update of R_{pK} and combined $R_K - R_{K^*}$ analysis with the full dataset
  - ▶ Ratio measurements with many more decay channels: $R_\phi, R_{K\pi\pi} \ldots$

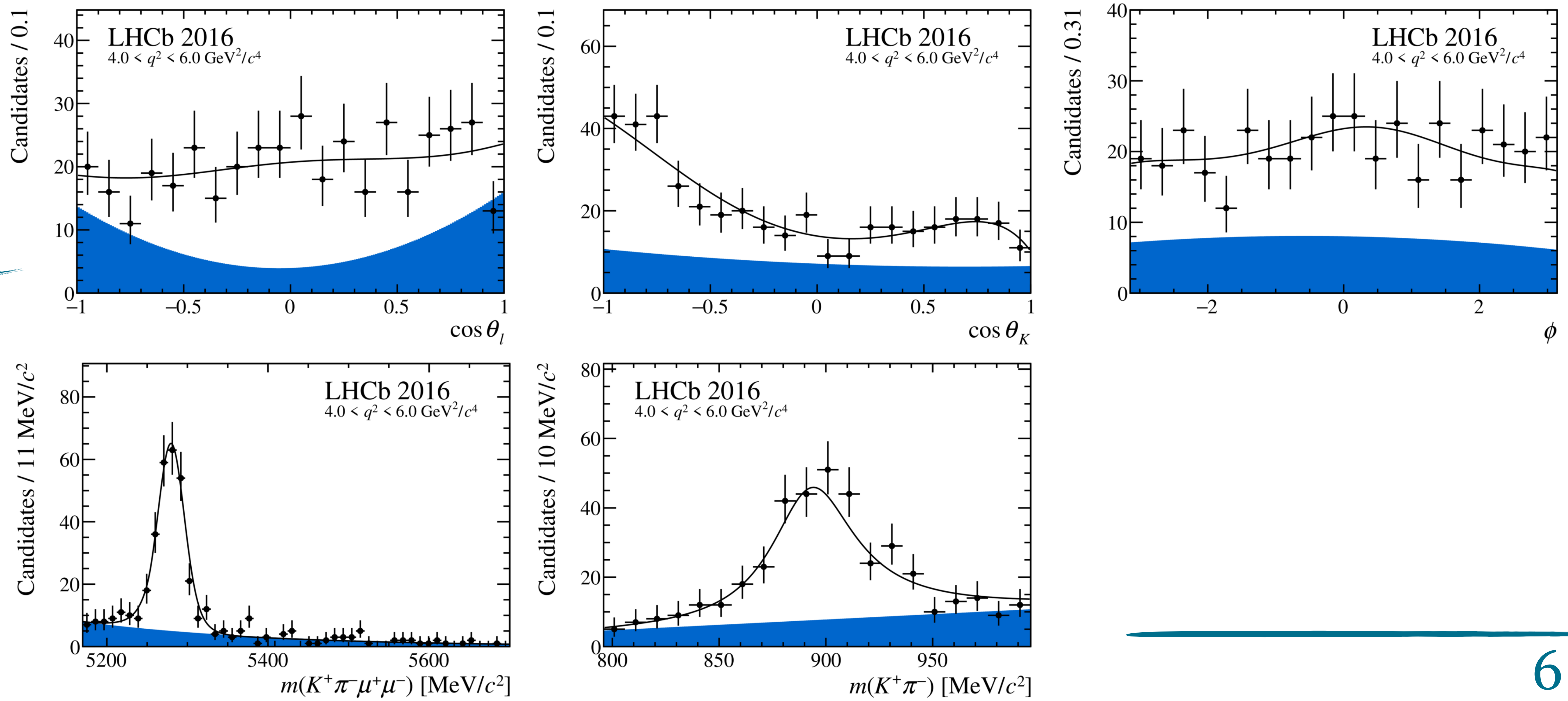
Angular distributions: $K^*\mu^+\mu^-$

- The angular distributions of the $B^0 \to K^*\mu^+\mu^-$ decay is described by $\Omega = (\theta_\ell, \theta_K, \phi)$
- The coefficients F_L, A_{FB}, S_i are related to WCs
- New basis of P_i' operator to reduce form factors uncertainties: e.g. $P_5' = S_5/\sqrt{F_L(1-F_L)}$
- Observables are extracted from a multidimensional fits in the angles, $m(K\pi)$, $m(K\pi\mu\mu)$





$q^2 = m^2(\ell^+\ell^-)$



3.3σ

PRL 125 (2020) 011802

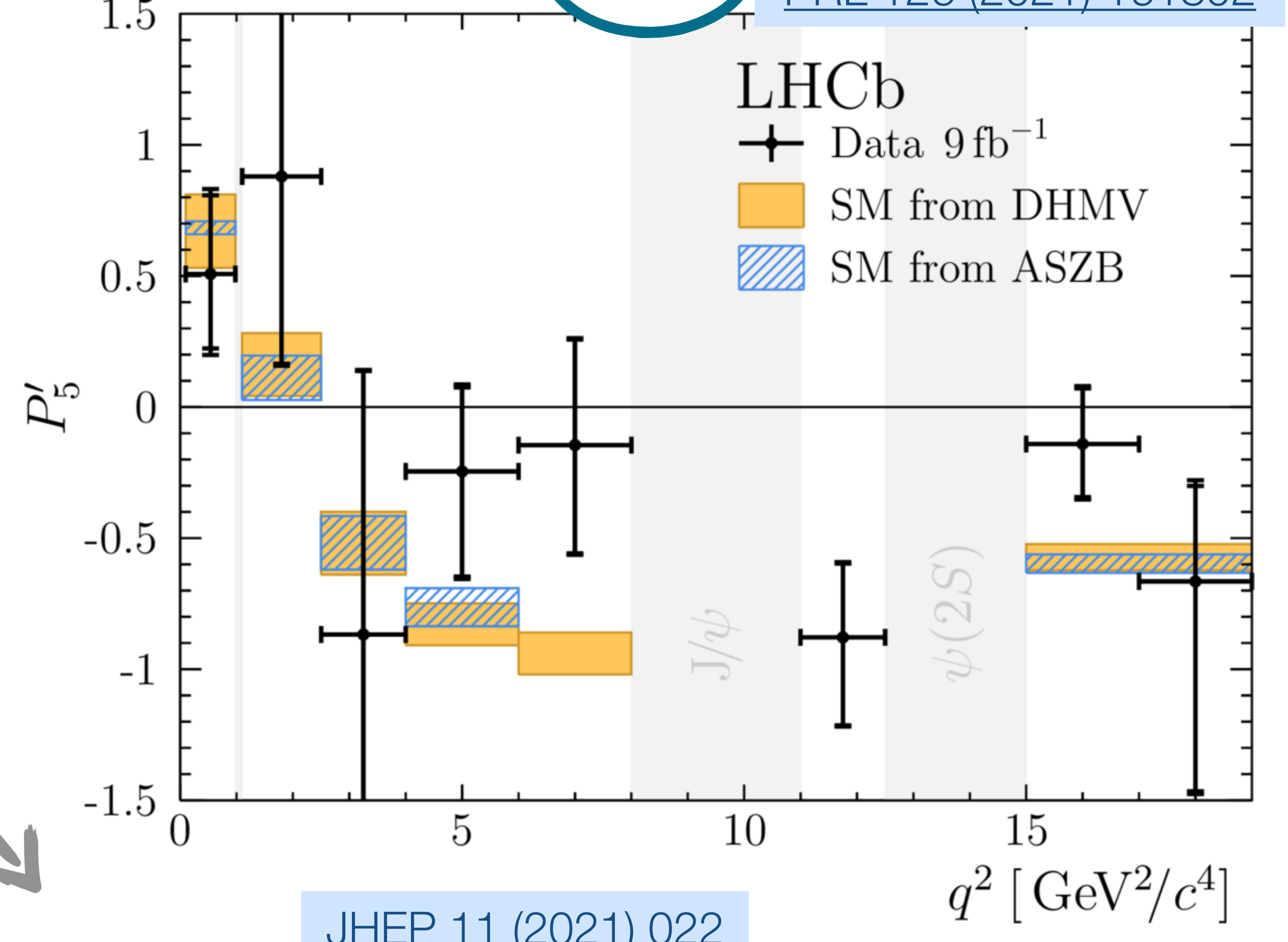
Sara Celani

Angular distributions: $K^{*+}\mu^+\mu^-, \phi\mu^+\mu^-$

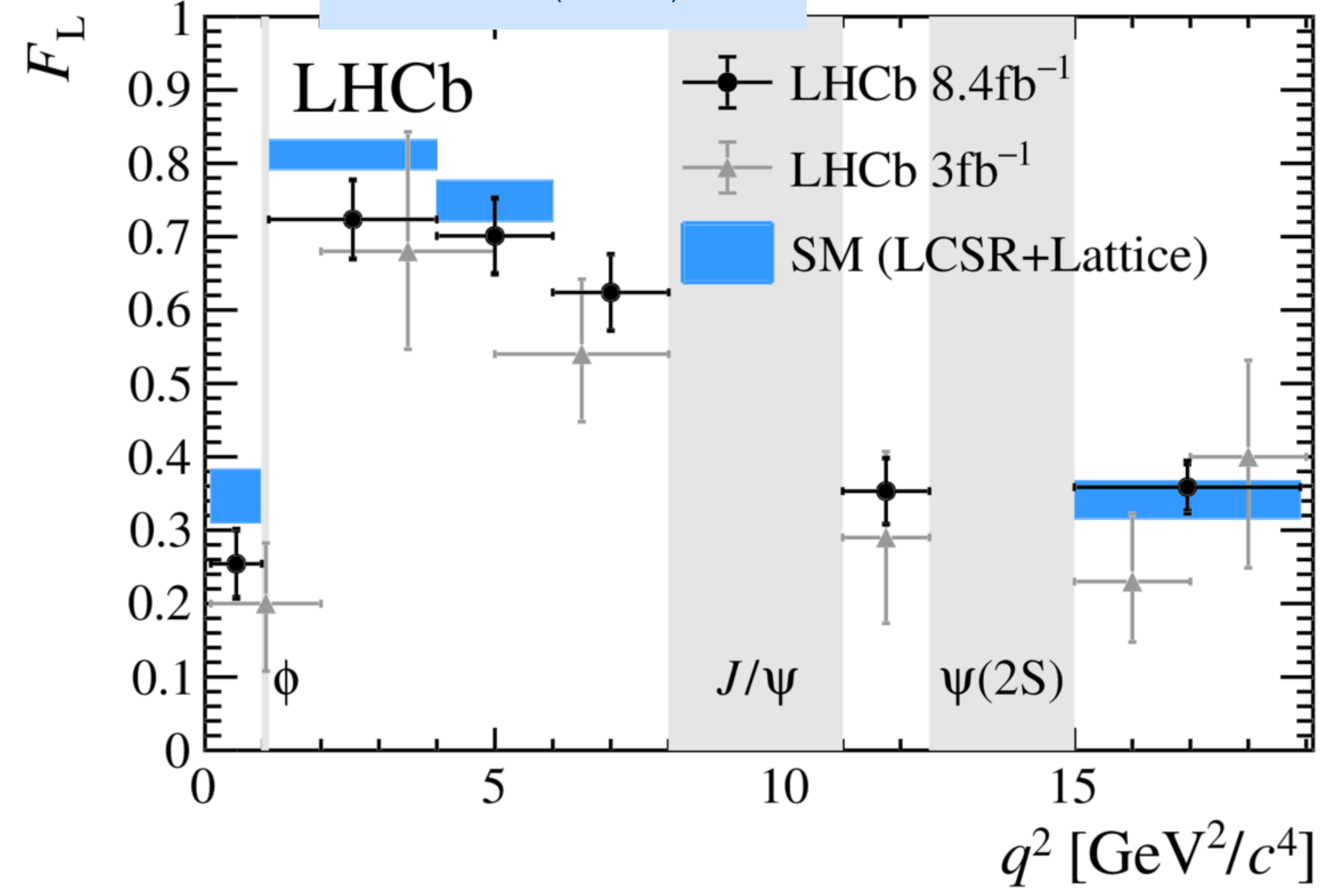
- Recent angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$ showed tension in the SM consistent with that found in $B^0 \to K^{*0}\mu^+\mu^-$
- Angular observables are also studied for $B_s^0 \to \phi\mu^+\mu^-$
  - Not all observable accessible (flavour symmetric final state)
  - Results found to be compatible with SM predictions
- Near future:
  - Update of $B^0 \to K^*\mu^+\mu^-$ with the full 9 fb^{-1} dataset
  - Angular analysis with electrons: $B^0 \to K^*e^+e^-$, $B^+ \to K^+e^+e^-$
  - Direct fits to WCs via amplitude analysis

3.1σ

PRL 126 (2021) 161802



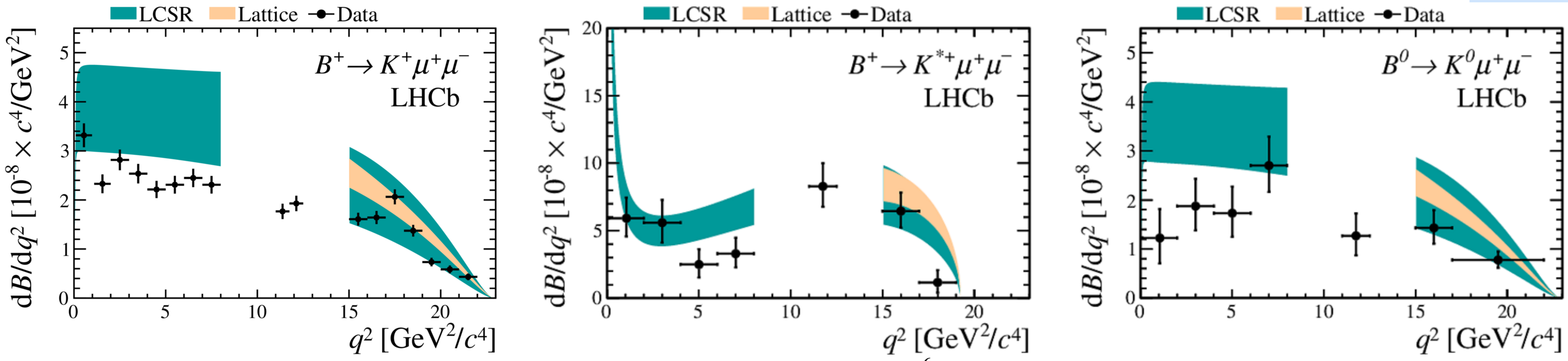
JHEP 11 (2021) 022



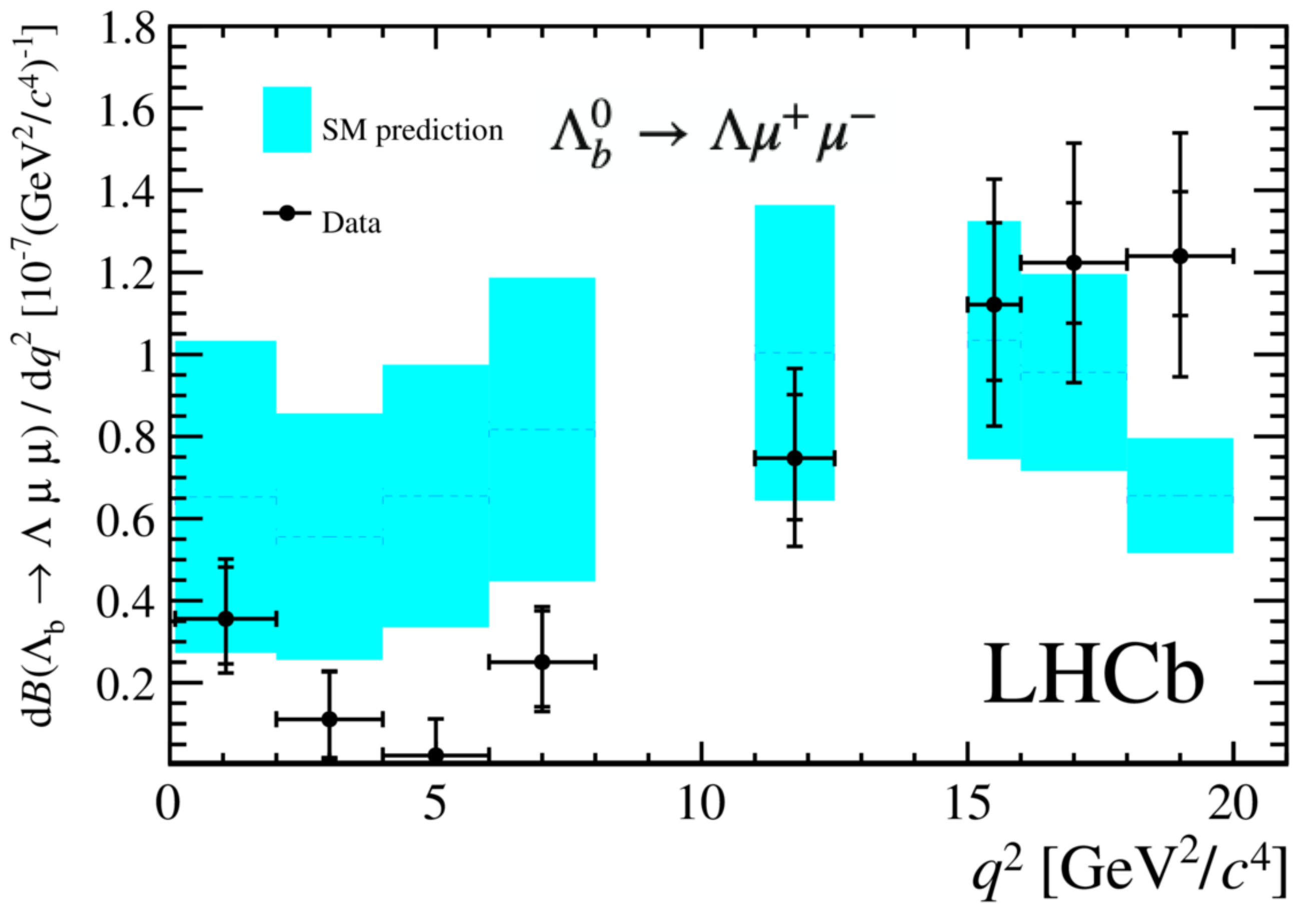
Differential branching fractions

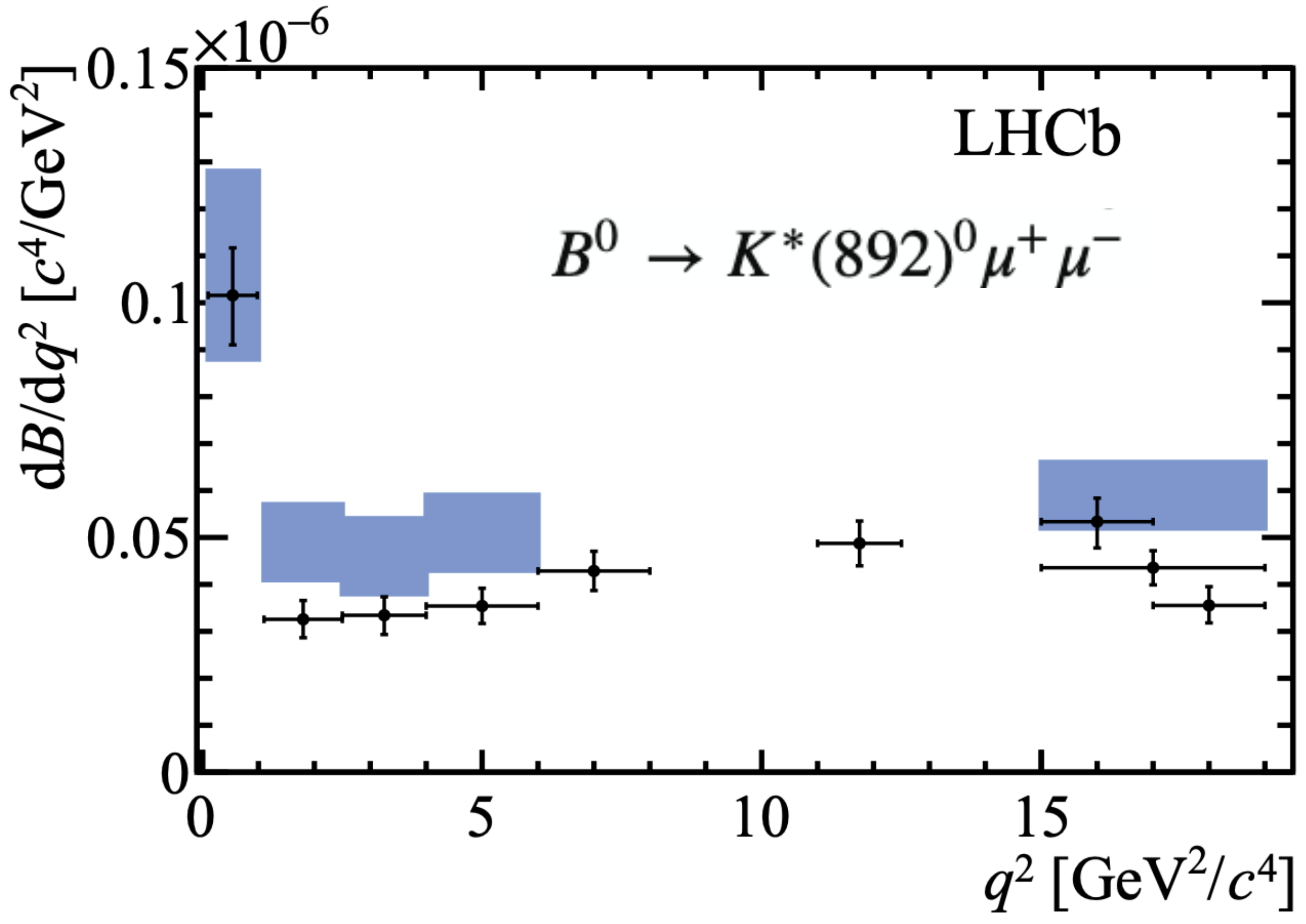
- $b \to s\mu\mu$ BF are measured to be consistently lower than the SM prediction
  - Large hadronic form factors uncertainties (20-30%)

JHEP 06 (2014) 133



JHEP 06 (2015) 115



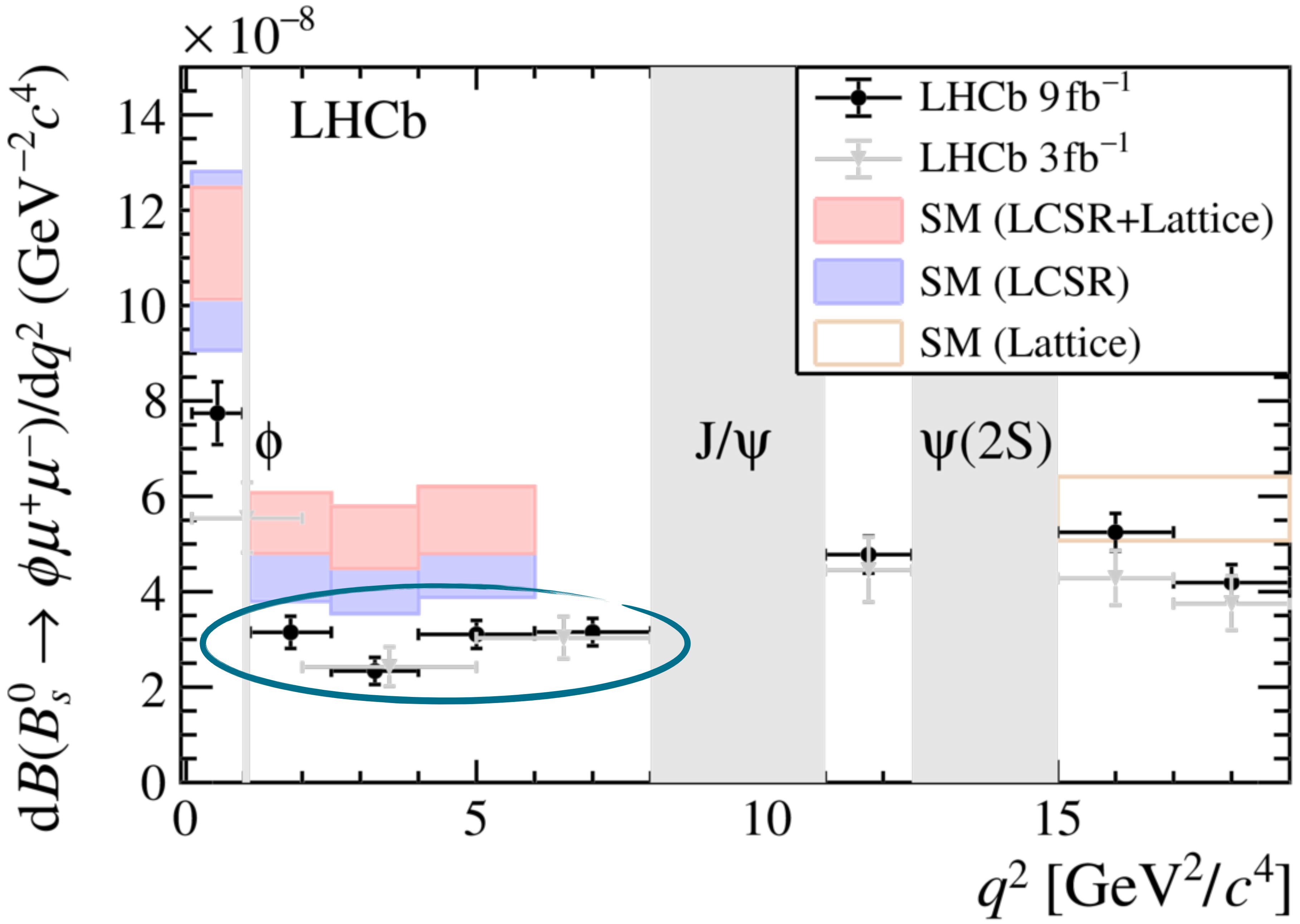


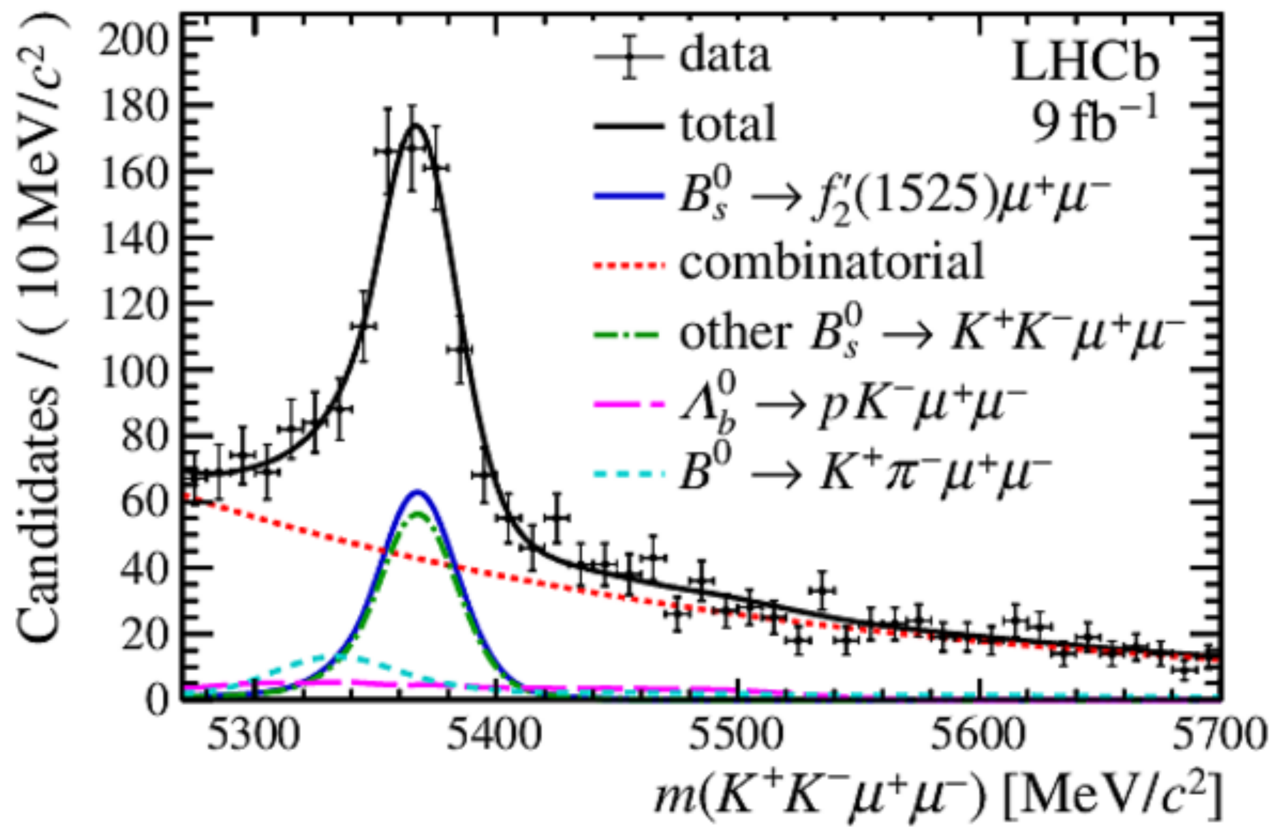
JHEP 04 (2017) 142

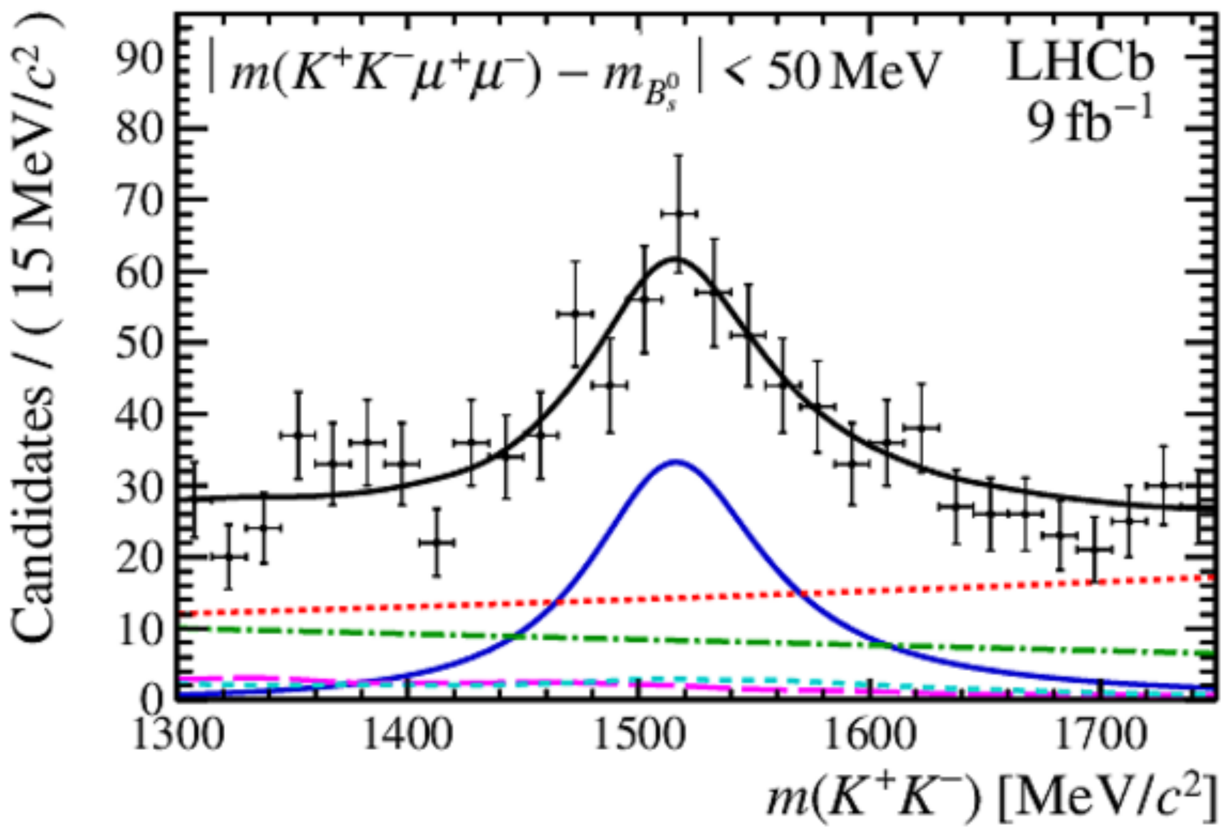
Differential branching fractions: $B_s^0 \to \phi\mu^+\mu^-$

PRL 127 (2021) 151801

- Recent update of differential $BF(B_s^0 \to \phi(\to KK)\mu^+\mu^-)$
  - Relative to $B_s^0 \to J/\psi\phi$
  - Main systematics
    - Model of the simulation sample (depending on $\Delta\Gamma_s$ and form factors)
    - Normalisation BF
  - In $1.1 < q^2 < 6.$ GeV, 3.6σ below the SM







- **First observation** of $B_s^0 \to f_2'(1525)\mu^+\mu^-$ (9σ)
- Consistent with SM

$$BF(B_s^0 \to f_2'(1525)\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$$

$B^0_{s,d} \to \mu^+\mu^-(\gamma)$

See Maarten's **talk**

PRL 128 (2021) 041801

- Helicity suppressed, very rare decays
- Precise SM predictions

$$BF(B^0_s \to \mu^+\mu^-) \overset{SM}{=} (3.66 \pm 0.14) \times 10^{-9}$$
$$BF(B^0 \to \mu^+\mu^-) \overset{SM}{=} (1.03 \pm 0.05) \times 10^{-10}$$

- Sensitive to axial-vector coupling C_{10}

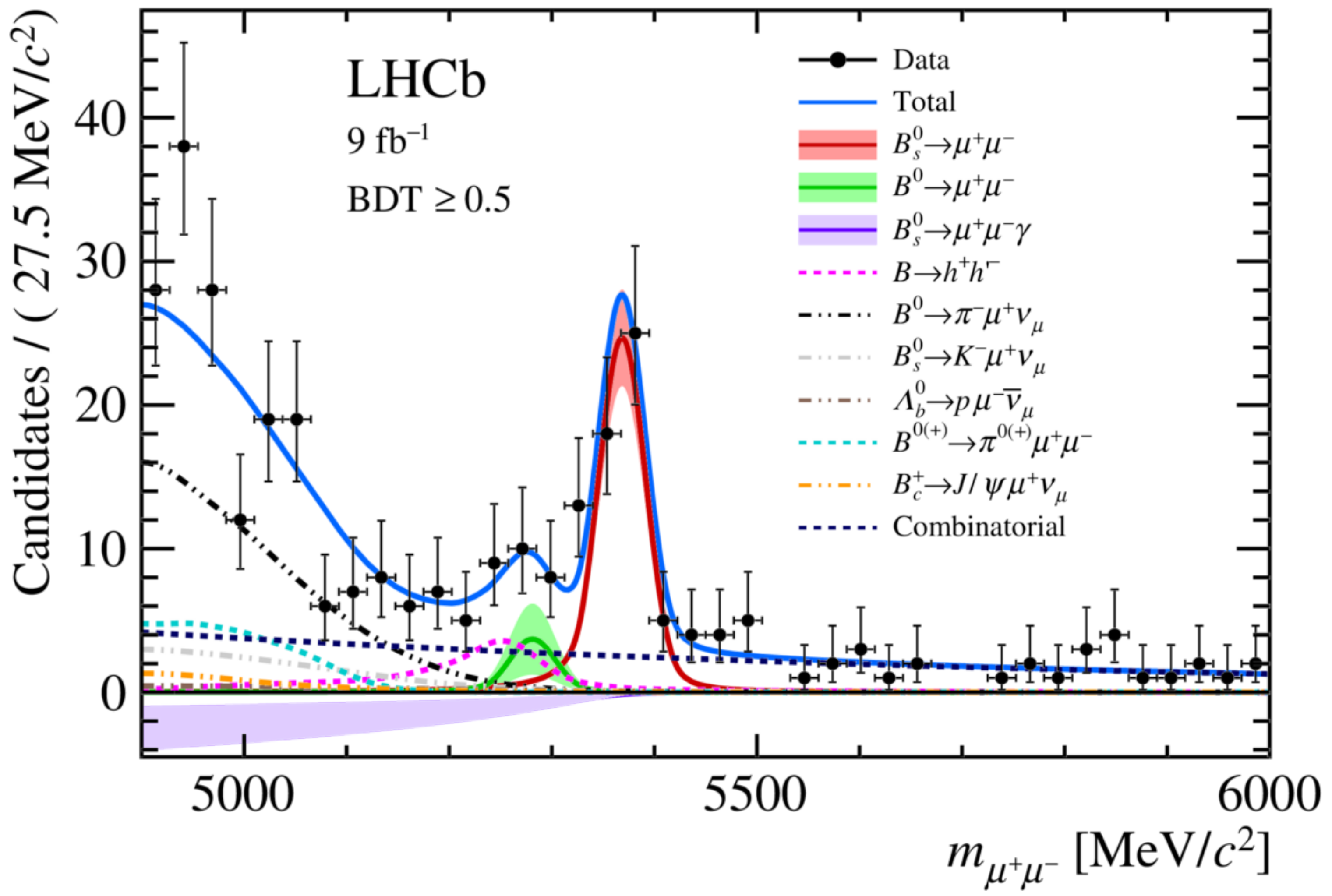
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.3(2.6) \times 10^{-10},$$
$$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma) < 1.5(2.0) \times 10^{-9} \quad \text{with} \quad m_{\mu\mu} > 4.9\ \text{GeV}/c^2.$$

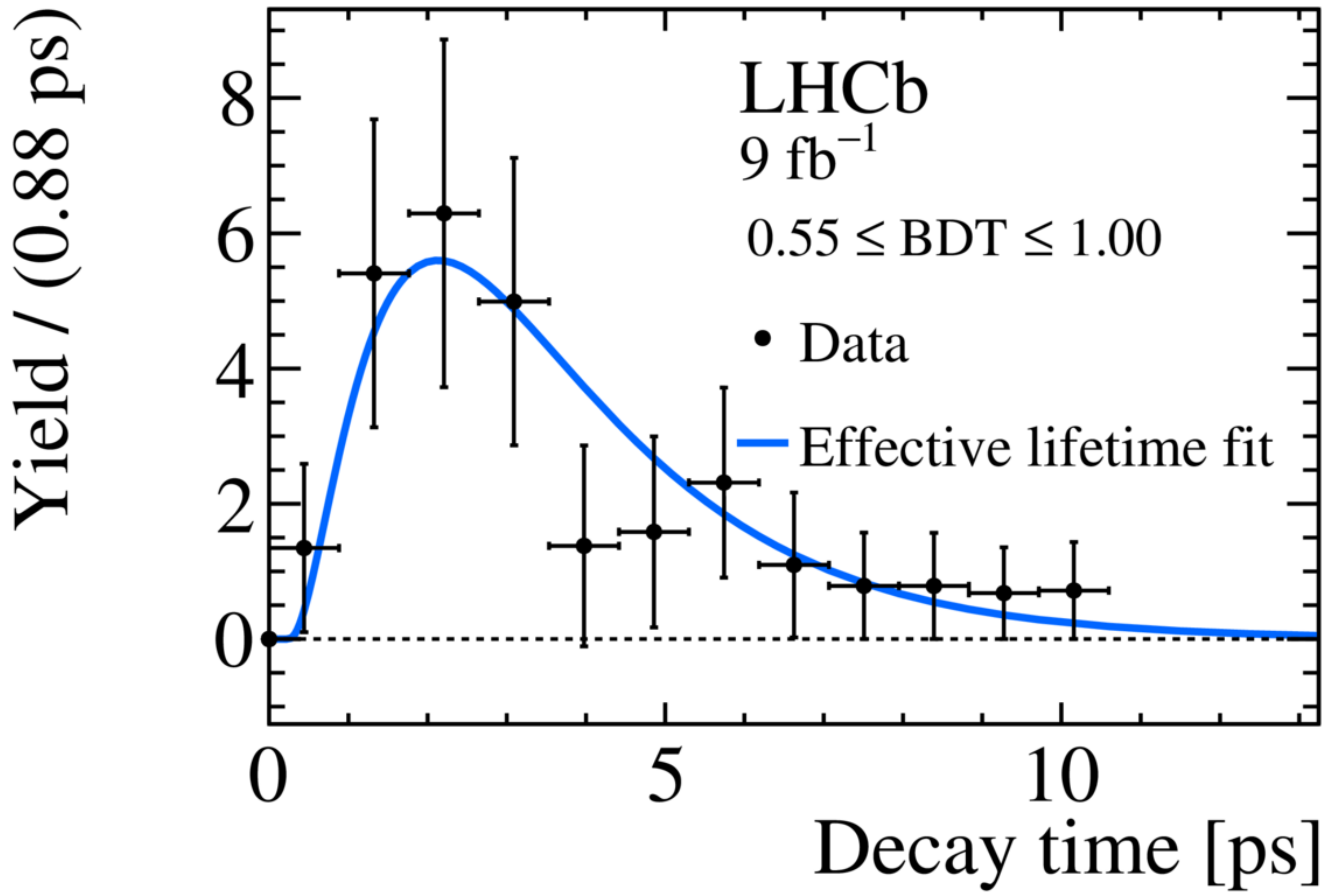
← First limit

- B^0_s lifetime is sensitive to NP

$$\tau_{\mu^+\mu^-} = 2.07 \pm 0.29 \pm 0.03\ \text{ps}$$

Consistent with the SM at 1.5σ





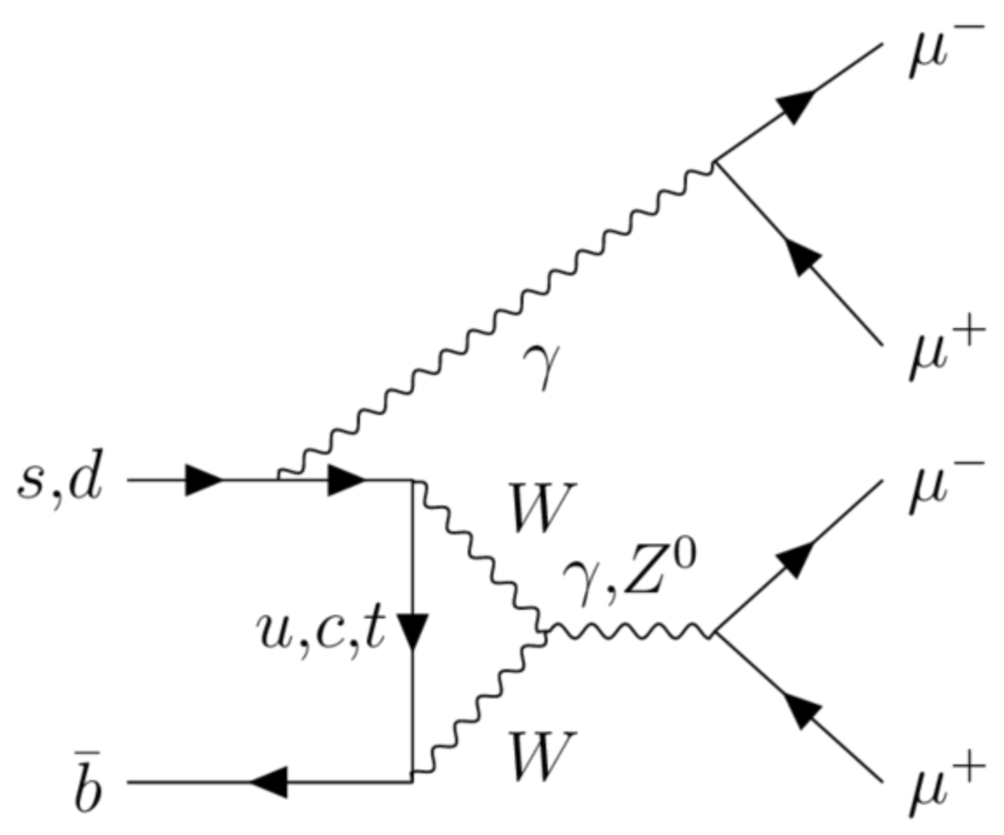
Searches: $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

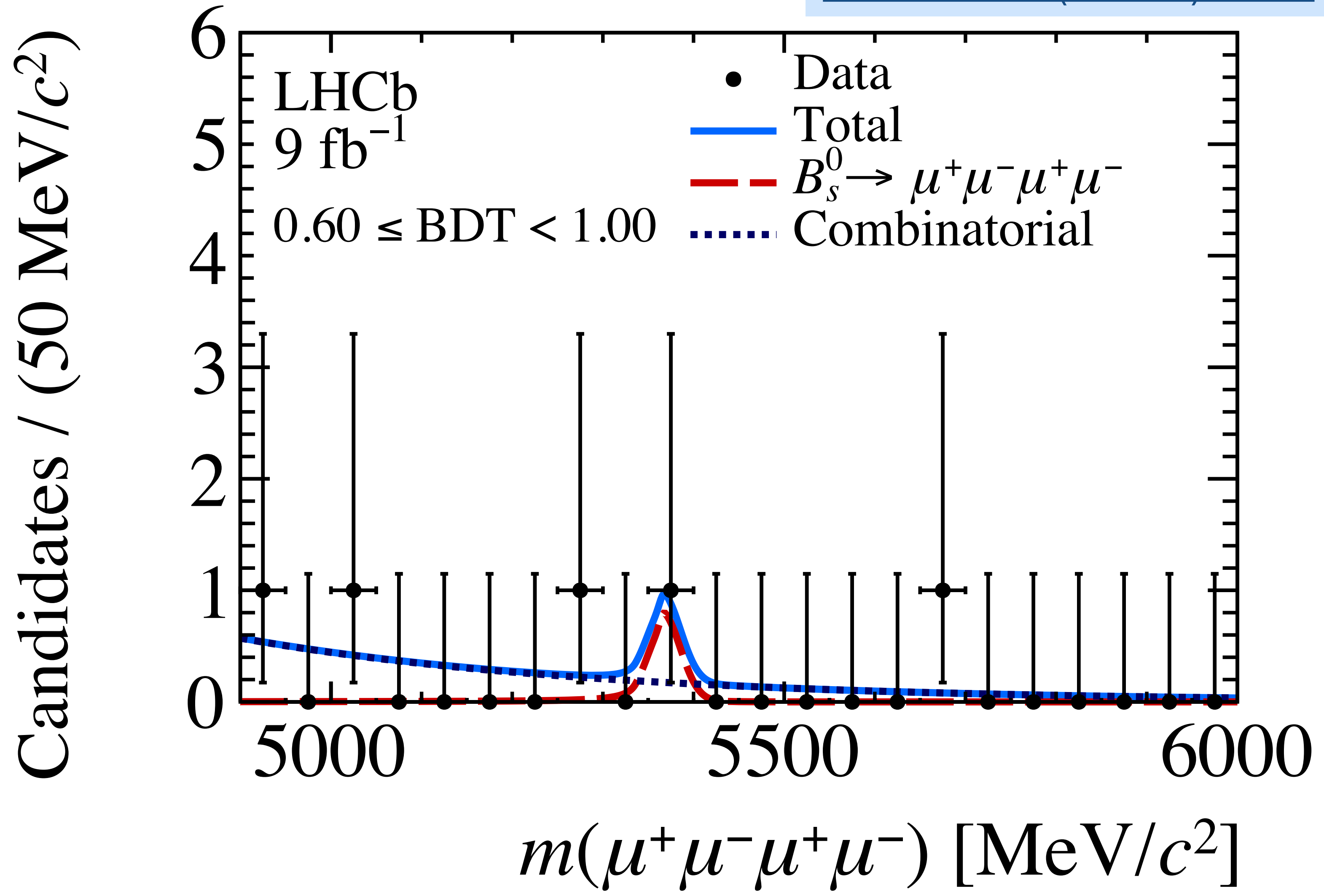
See Maarten's **talk**

JHEP 03 (2022) 109

- Helicity suppressed

$$BF(B^0_s \to \mu^+\mu^-\mu^+\mu^-) \overset{SM}{=} (0.9 - 1.0) \times 10^{-10}$$
$$BF(B^0 \to \mu^+\mu^-\mu^+\mu^-) \overset{SM}{=} (0.4 - 4.0) \times 10^{-12}$$





- Strategy:
  - Six Signal modes: non resonant, BSM scalar resonance ($m_a = 1$ GeV), resonant $b \to c$
  - $B \to J/\psi(\to \mu\mu)\phi(\to \mu\mu)$ as normalisation channel
  - Negligible background from misID
  - Main systematic from simulation model (no theoretical description of the decay's dynamic)
  - No signal observed, most stringent limits up to date!

@95% CL

$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\mu^+\mu^-\right) < 8.6 \times 10^{-10},$$
$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 1.8 \times 10^{-10},$$
$$\mathcal{B}\left(B^0_s \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) < 5.8 \times 10^{-10},$$
$$\mathcal{B}\left(B^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) < 2.3 \times 10^{-10},$$
$$\mathcal{B}\left(B^0_s \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) < 2.6 \times 10^{-9},$$
$$\mathcal{B}\left(B^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) < 1.0 \times 10^{-9}.$$

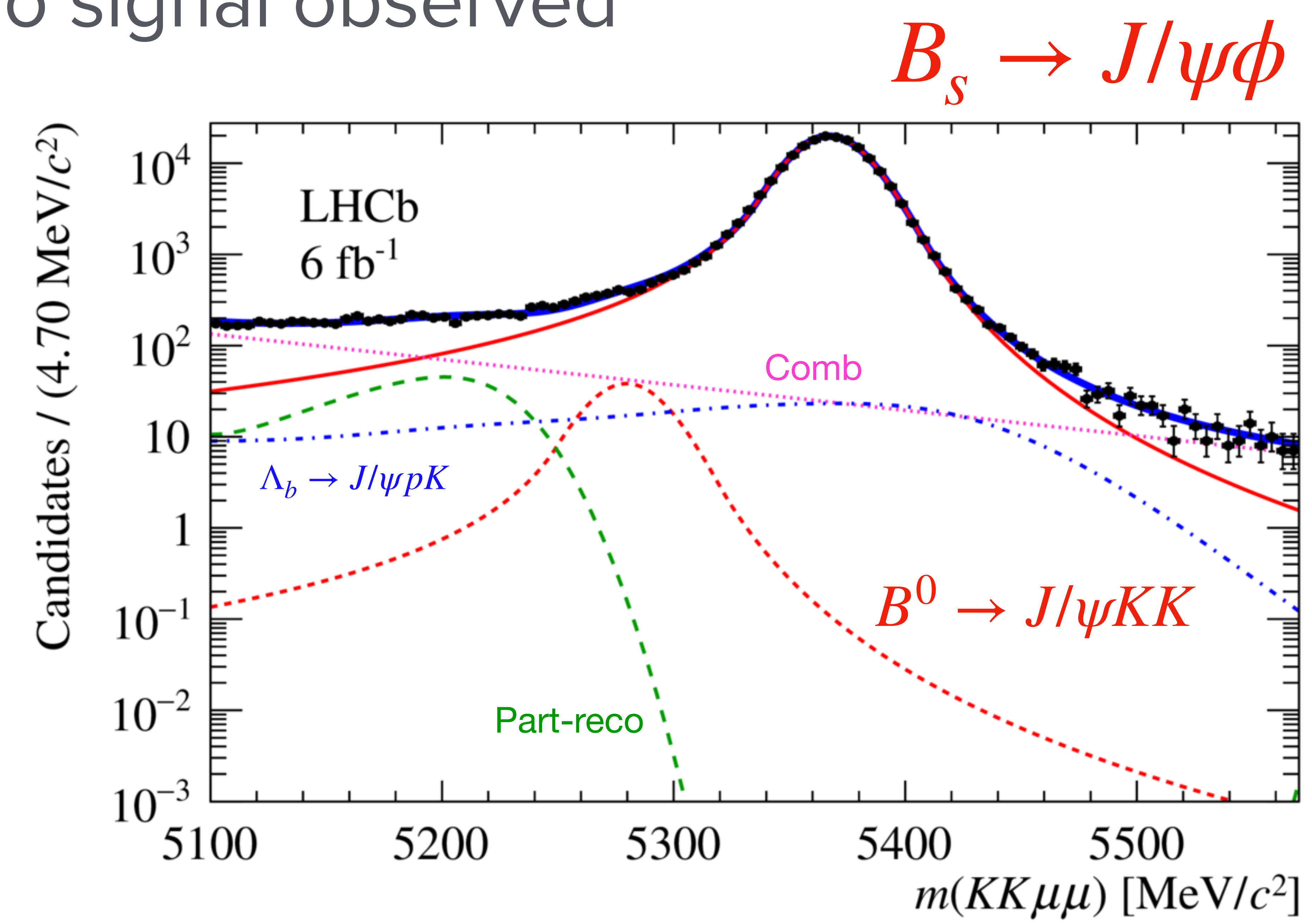
Searches: $B^0 \to \phi\mu^+\mu^-$

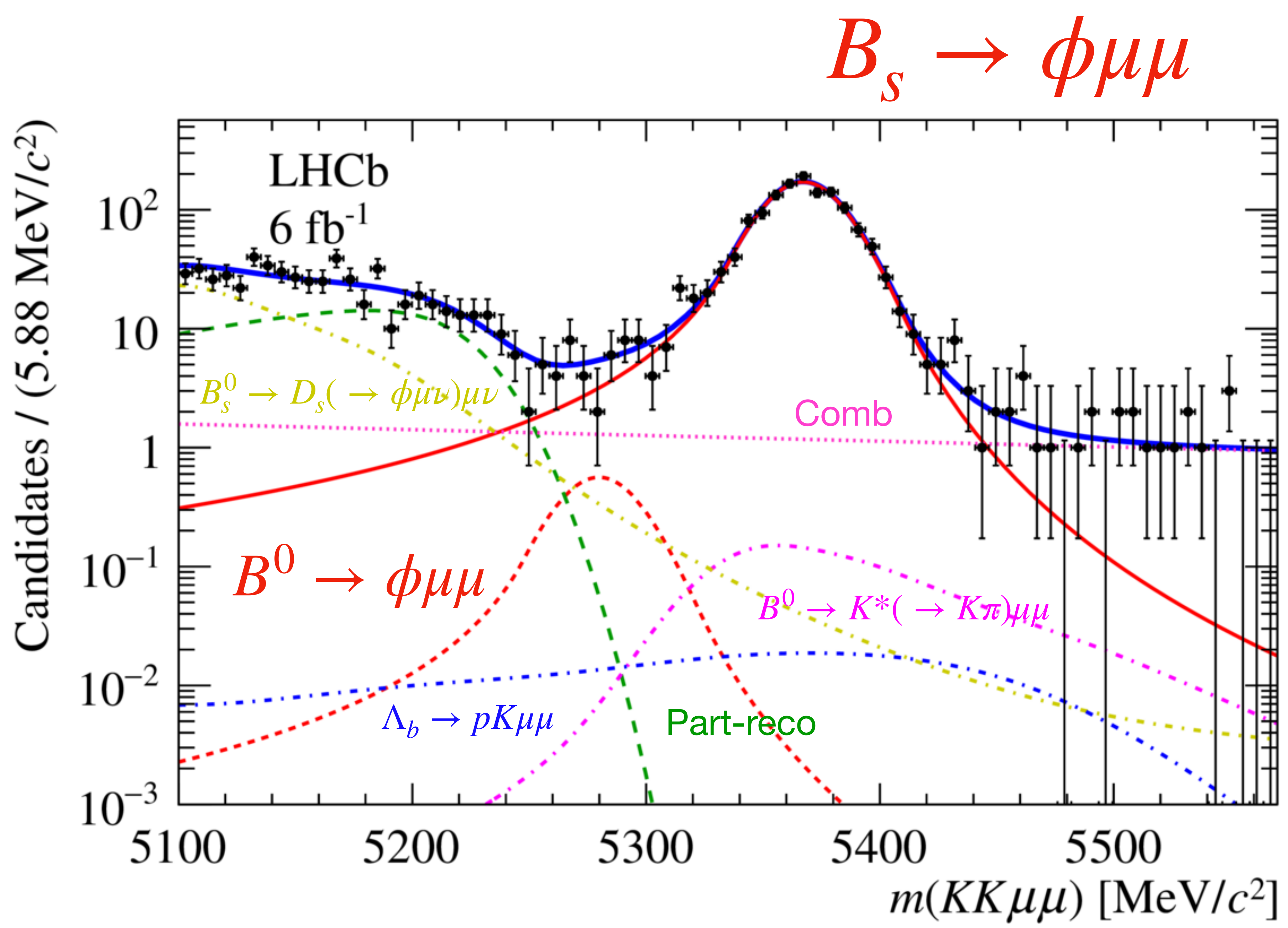
JHEP 05 (2022) 67

- $BF \sim \mathcal{O}(10^{-11})$, sensitive to new mediators
- Strategy:
  - Measure the ratio $R = BF(B^0 \to \phi\mu\mu)/BF(B_s^0 \to \phi\mu\mu)$
  - $B_s^0 \to J/\psi\phi$ employed for BDT training and mass modelling
  - No signal observed

$$\mathcal{R} < 4.4 \times 10^{-3} \text{ at a } 90\% \text{ (CL)}$$
$$\mathcal{B}(B^0 \to \phi\mu^+\mu^-) < 3.2 \times 10^{-9} \text{ at a } 90\% \text{ CL}$$

First limit





Conclusion & outlook

- Electroweak penguin decays are ideal probes for New Physics
- LHCb intensively studied these processes over the years
  - Several measurements to be updated with the full dataset
- Run3 is starting!
  - ~3 times Run1+2 dataset collected in 3 years
  - LHCb detector undergoing staged upgrades
    - Replaced vertex, tracking detectors: Better vertex resolution
    - Removed hardware trigger: Better efficiency

Reduce statistical + data-driven models uncertainties

Reduce background from charged and neutral tracks
Electron modes more accessible

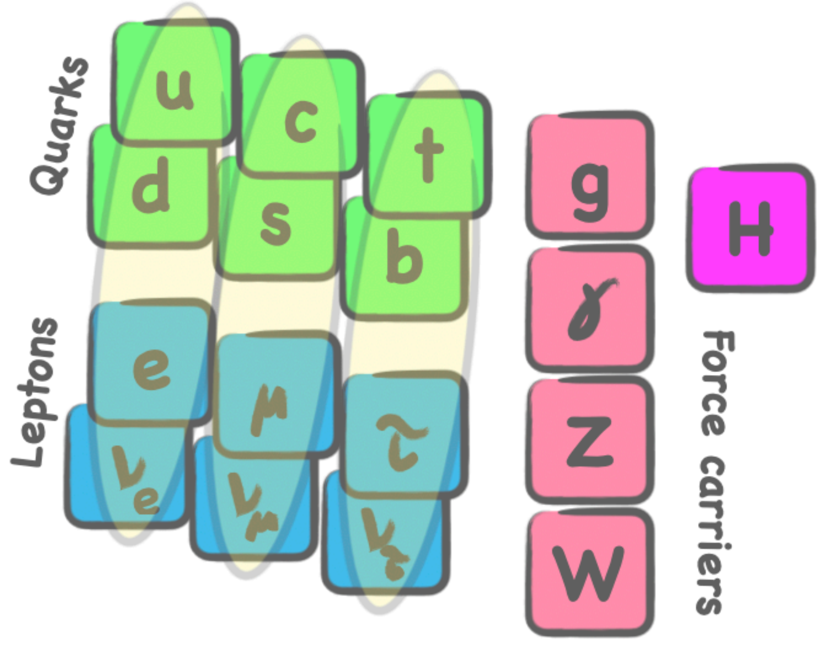
Thank you

Backup

The flavour puzzle

$\psi = Q_L, u_r, d_r, L_L, e_r$

$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$



$$\mathscr{L}_{SM} = \mathscr{L}_{gauge}(\psi_i, A_a) + \mathscr{L}_{Higgs}(\psi_i, A_a, H)$$

$$\mathscr{L}_{gauge} = \sum_a \frac{-1}{4g_a^2}(F_{\mu\nu})^2 + \sum_{i=1}^{3} \bar{\psi}_i i \not{D} \psi_i$$

3 identical replica ($i = 1,2,3$) of the same family differing only in mass

Gauge interactions have the same amplitude for all the families: **Lepton Flavour Universality (LFU)**

Flavour is conserved: stringent limits on **Lepton Flavour Violating (LFV)** decays

- **Why 3 generations?**
- **What is the origin of their different mass?**
- **What is the origin of the hierarchy in quark-mixing?**

$$\mathscr{L}_{Higgs} = \mathscr{L}_H + \mathscr{L}_{Yukawa}$$

Only Yukawa interaction distinguishes the families

Quark sector:

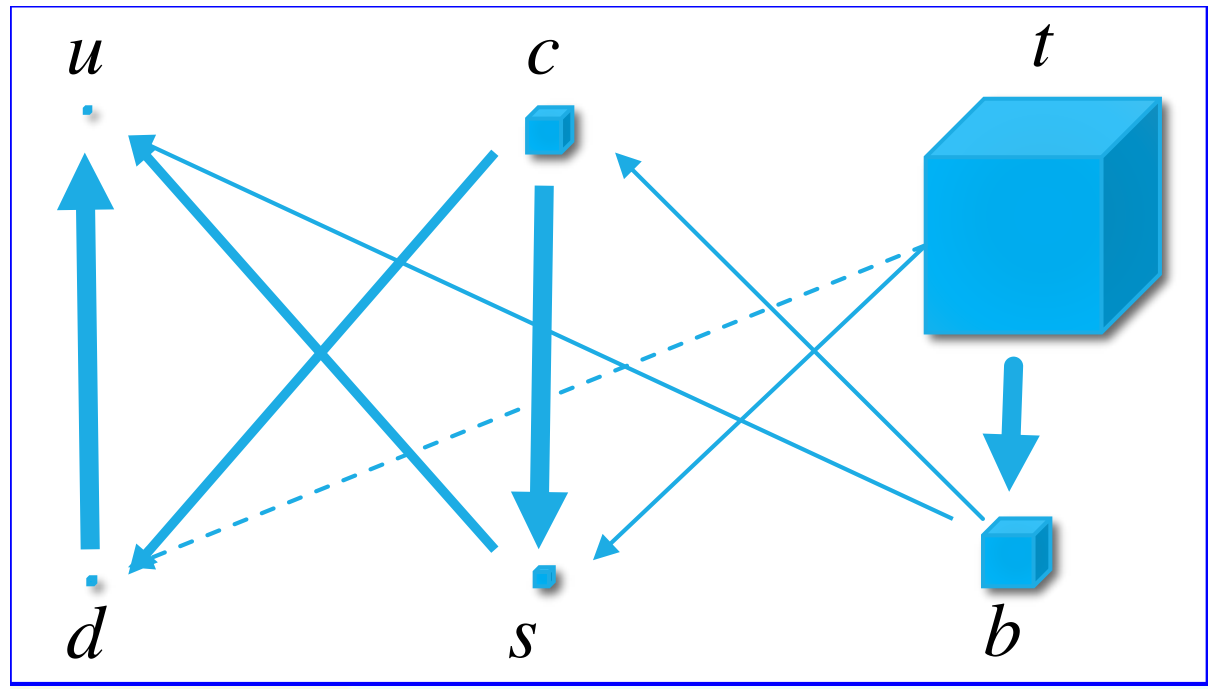
$$\bar{Q}_L{}^i\, Y_D{}^{ik}\, d_R{}^k\, \mathrm{H} + h.c. \rightarrow \bar{d}_L{}^i\, M_D{}^{ik}\, d_R{}^k + \ldots$$

$$\bar{Q}_L{}^i\, Y_U{}^{ik}\, u_R{}^k\, \mathrm{H_c} + h.c. \rightarrow \bar{u}_L{}^i\, M_U{}^{ik}\, u_R{}^k + \ldots$$

Only one mass matrix at time can be diagonalised (for gauge flavour invariance)

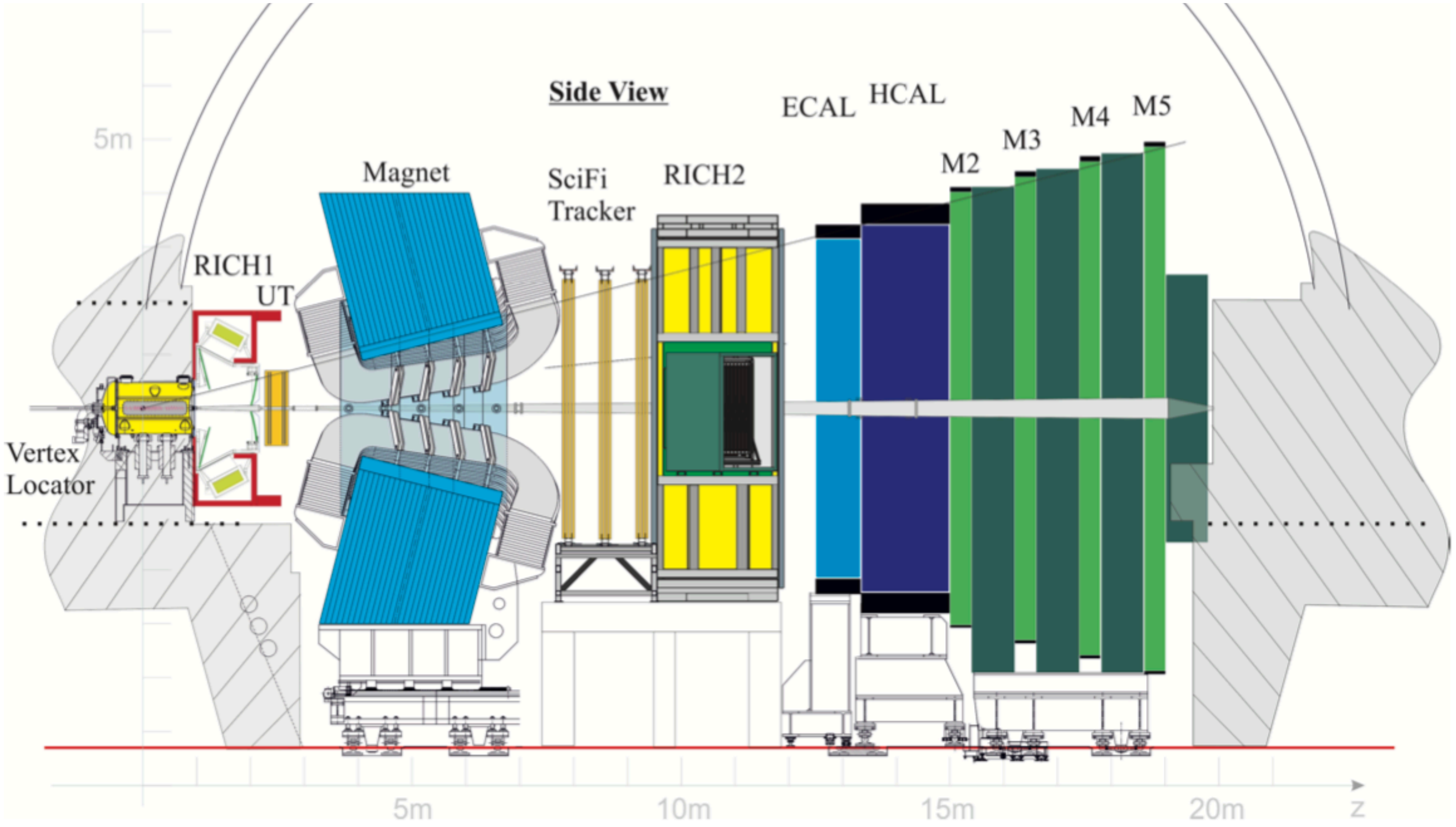
$M_D = \mathrm{diag}(m_d, m_s, m_b)$

$M_U = V^+ \times \mathrm{diag}(m_u, m_c, m_t)$



V_CKM appears in charged-current gauge interaction (mixing u and d)

LHCb upgrade - Phase I



- New Vertex Detector
  - Pixel silicon detector
- Trigger-less readout
  - Software HLT on GPU
- New tracking stations:
  - Scintillating Fibers (SciFi) and Silicon micro-strips (UT)
- RICH: New PMTs + new electronics
- Calorimeters
  - PMT gain reduced by a factor 5, FEE redeveloped
- Muon system
  - FEE redeveloped

LFU ratios: Electron vs Muon

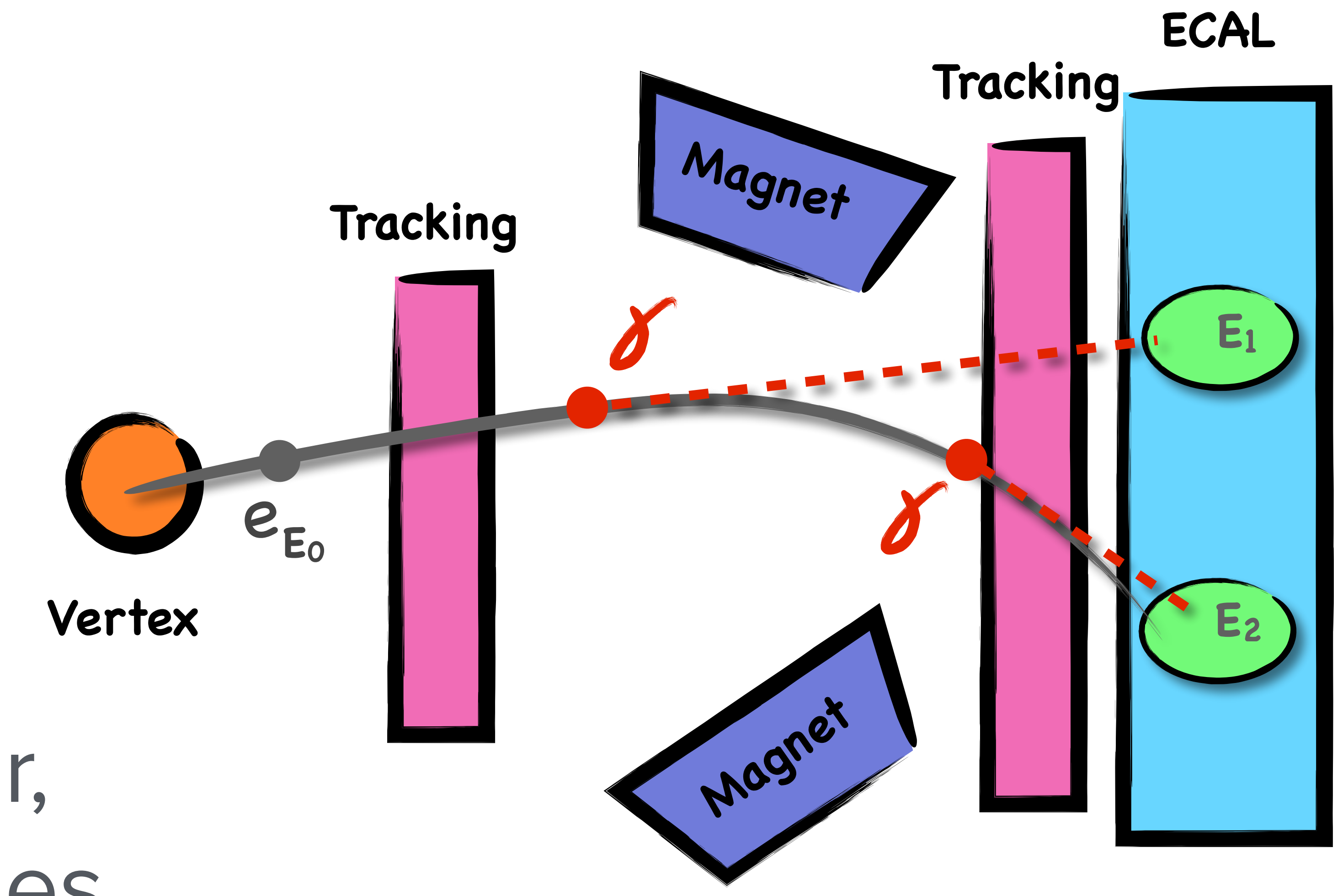
See Sebastian's **talk**

- Relative rates are measured as double ratios

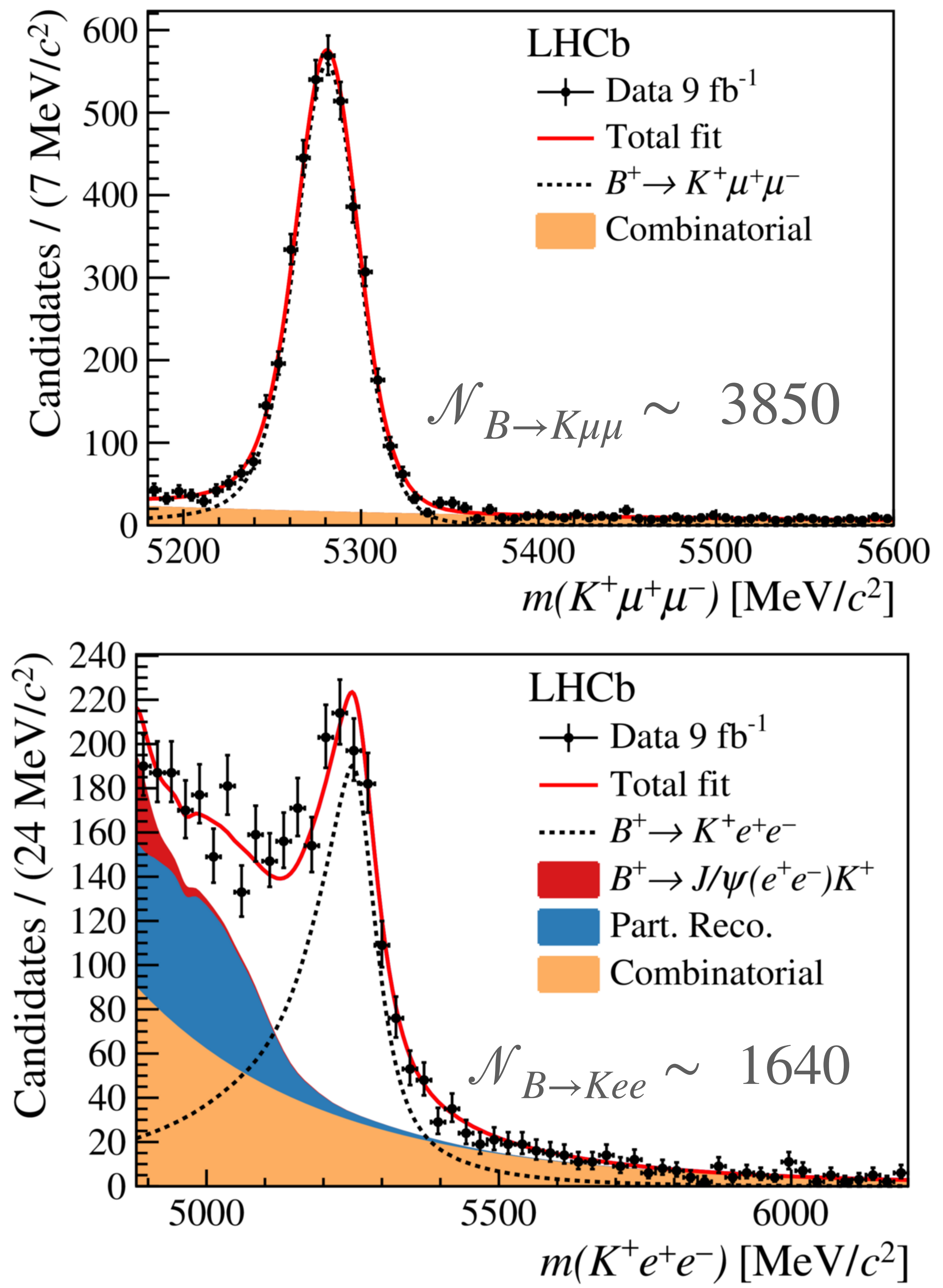
$$R_X = \frac{\mathcal{N}_{B\to X\mu^+\mu^-}}{\mathcal{N}_{B\to X(J/\psi\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B\to X(J/\psi\to e^+e^-)}}{\mathcal{N}_{B\to Xe^+e^-}} \cdot \frac{\epsilon_{B\to X(J/\psi\to\mu^+\mu^-)}}{\epsilon_{B\to X\mu^+\mu^-}} \cdot \frac{\epsilon_{B\to Xe^+e^-}}{\epsilon_{B\to X(J/\psi\to e^+e^-)}}$$

$X = K, K^*, \Lambda_b \dots$

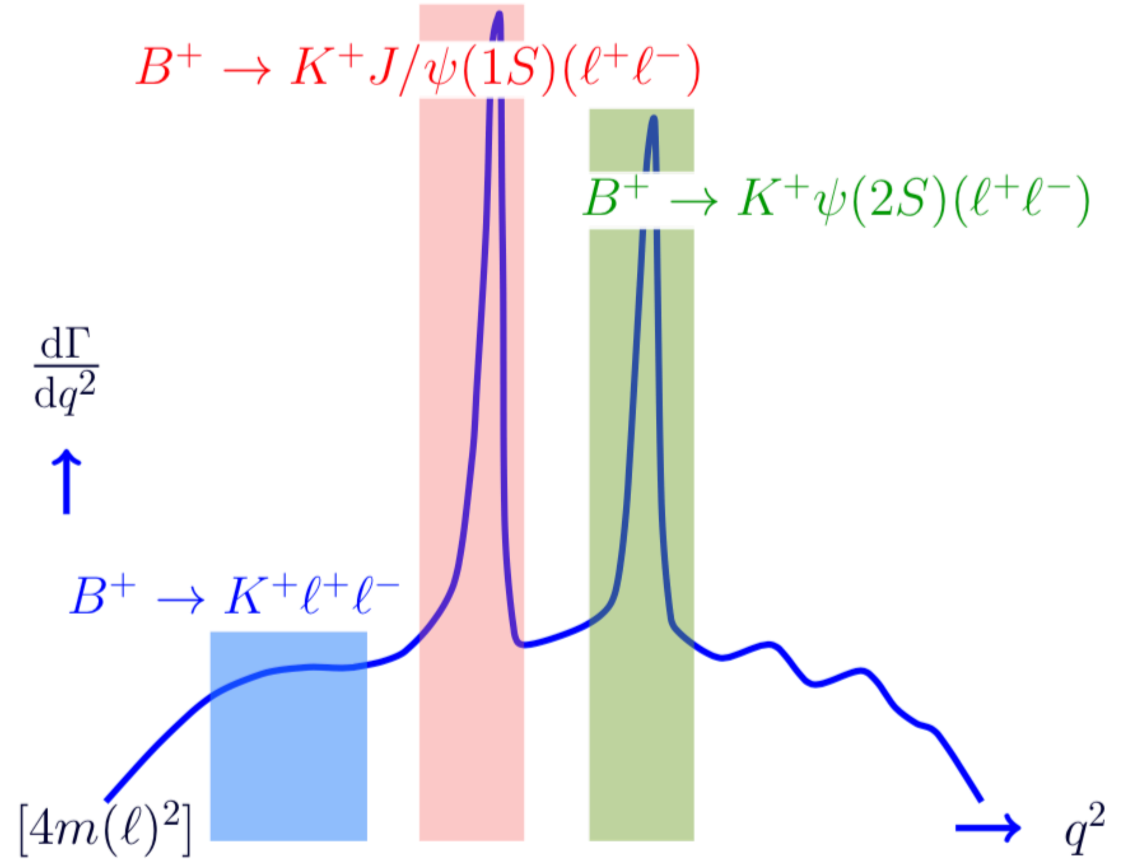
- $J/\psi \to \ell\ell$ satisfies lepton universality at 0.4% precision (PDG)
- Reduced systematics due to leptons reconstruction differences:
  - Most electrons emit **bremsstrahlung** photons
  - Electrons has worse p resolution
  - Electrons has lower trigger, PID and tracking efficiencies



Nat.Phys.18, 277-282 (2022)



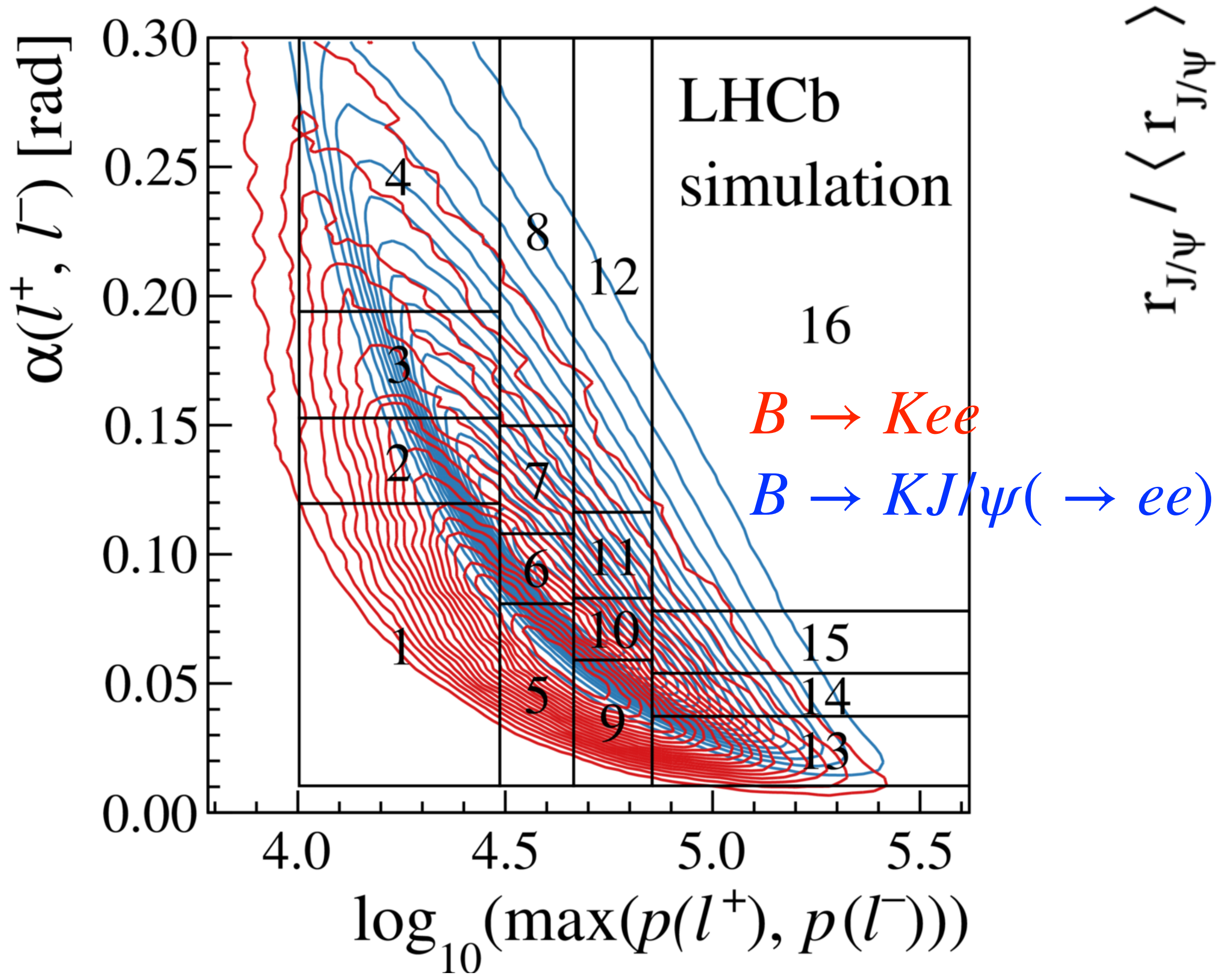
Cross-checks: $r_{J/\psi}$ and $R_{\psi(2S)}$

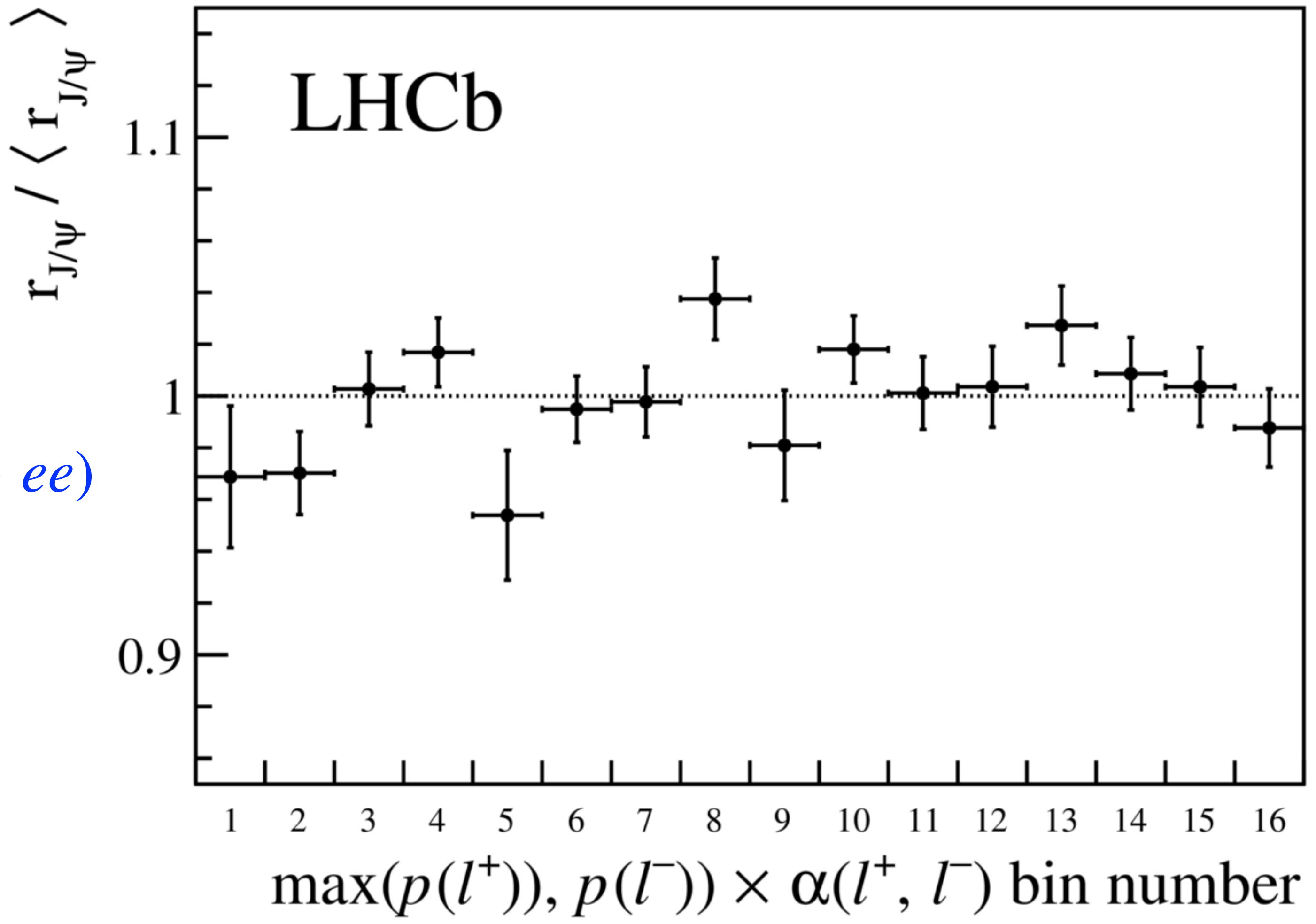


- Extensive use of $B \to X_s(J/\psi \to \ell^+\ell^-)$ and $B \to X_s(\psi(2S) \to \ell^+\ell^-)$ to check that efficiencies are under control

▶ Check: $r_{J/\psi} \equiv \frac{\mathcal{B}(B \to X\, J/\psi\,(\to \mu^+\mu^-))}{\mathcal{B}(B \to X\, J/\psi\,(\to e^+e^-))} \overset{SM}{=} 1$ [0.4% precision (PDG)]

+ absence of trends on any kinematics variables



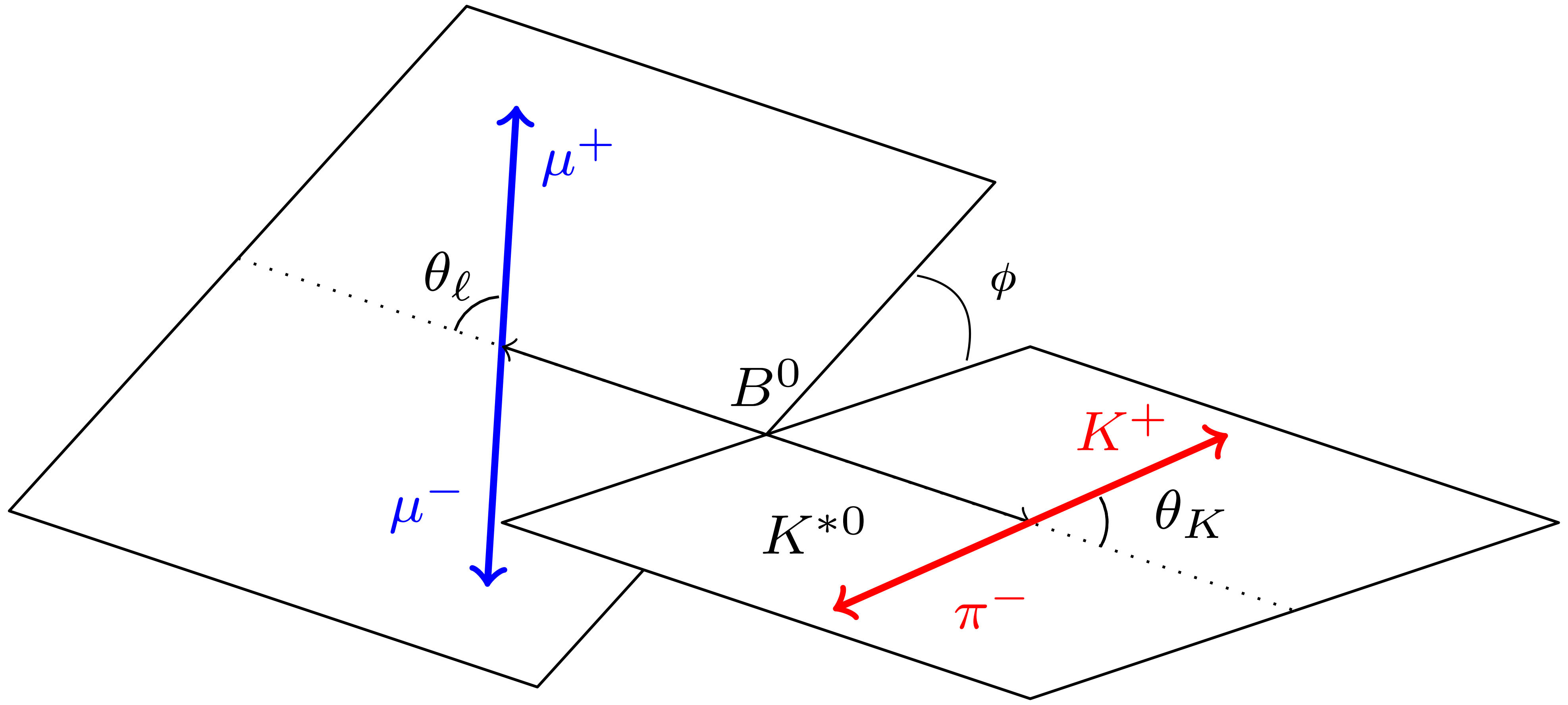


arXiv:2103.11769

▶ Check: $R_{\psi(2S)} = \frac{\mathcal{B}(B \to X(\psi(2S) \to \mu\mu))}{\mathcal{B}(B \to X(J/\psi \to \mu\mu))} \cdot \frac{\mathcal{B}(B \to X(J/\psi \to ee))}{\mathcal{B}(B \to X(\psi(2S) \to ee))} \overset{SM}{=} 1$ [~ 1% precision (PDG)]

Validation of the double ratio procedure (effective cancelation of syst uncertainties)

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

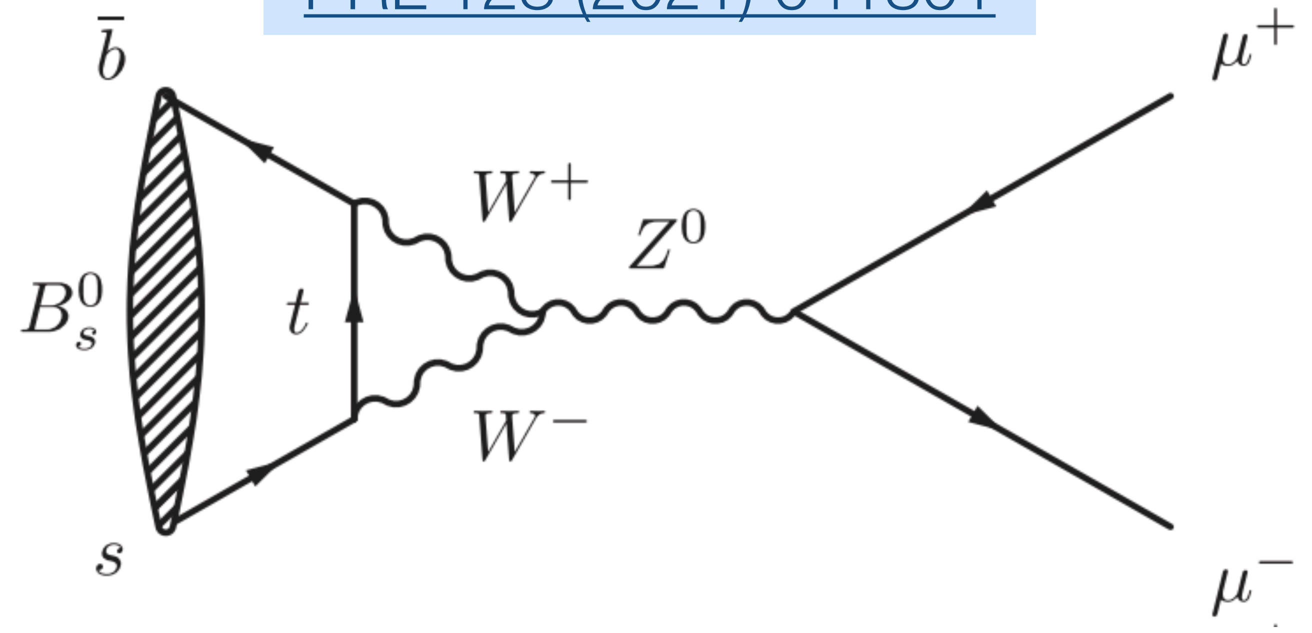


$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \\
&+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l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

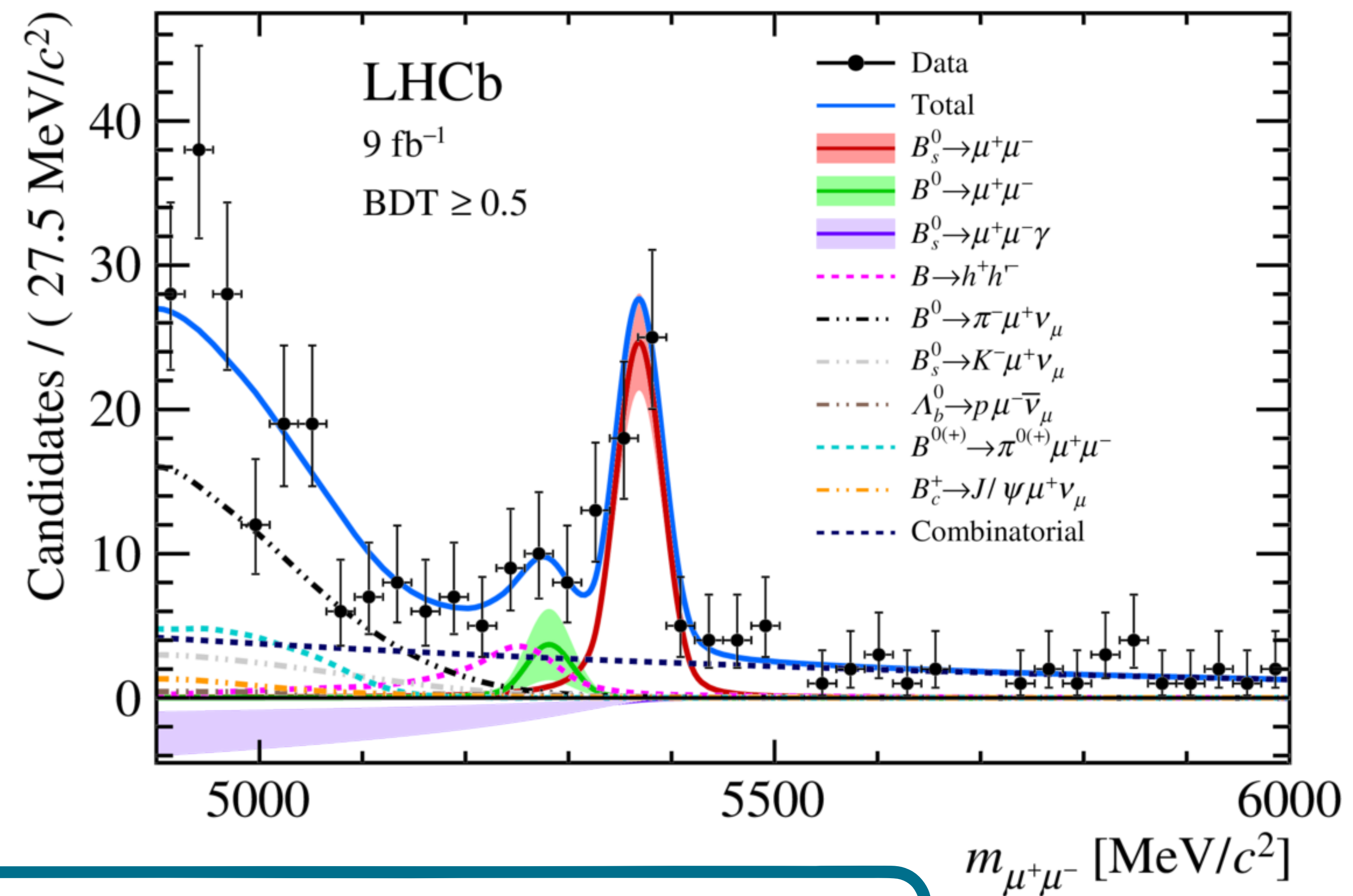
$B^0_{s,d} \to \mu^+\mu^-(\gamma)$

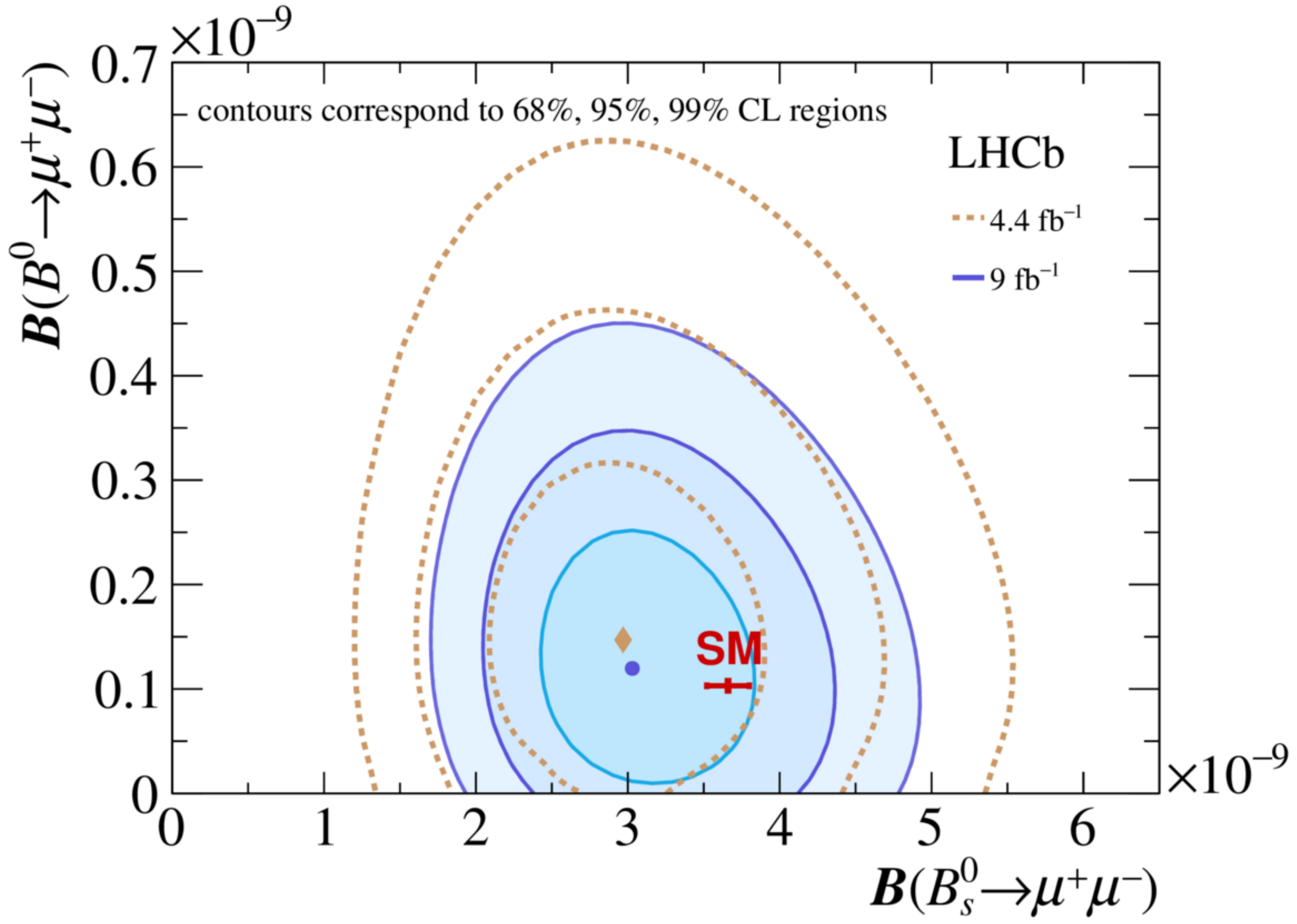
See Maarten's **talk**

PRL 128 (2021) 041801



- Helicity suppressed, very rare decays $BF \sim \mathcal{O}(10^{-9}, 10^{-10})$
- Precise SM predictions $\sim \mathcal{O}(4\%)$
- Sensitive to axial-vector coupling C_{10}
- Strategy:
  - Two opposite charged tracks from a displaced vertex
  - BDT vs combinatorial, stringent PID vs $\mu \leftrightarrow K, \pi$ misID
  - Yields normalised to $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi K^+$





$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.3(2.6) \times 10^{-10},$$
$$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma) < 1.5(2.0) \times 10^{-9}$$
$$\text{with} \quad m_{\mu\mu} > 4.9\ \text{GeV}/c^2.$$

First limit

$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

PRL 128 (2021) 041801

- The B_s^0 lifetime is sensitive to NP

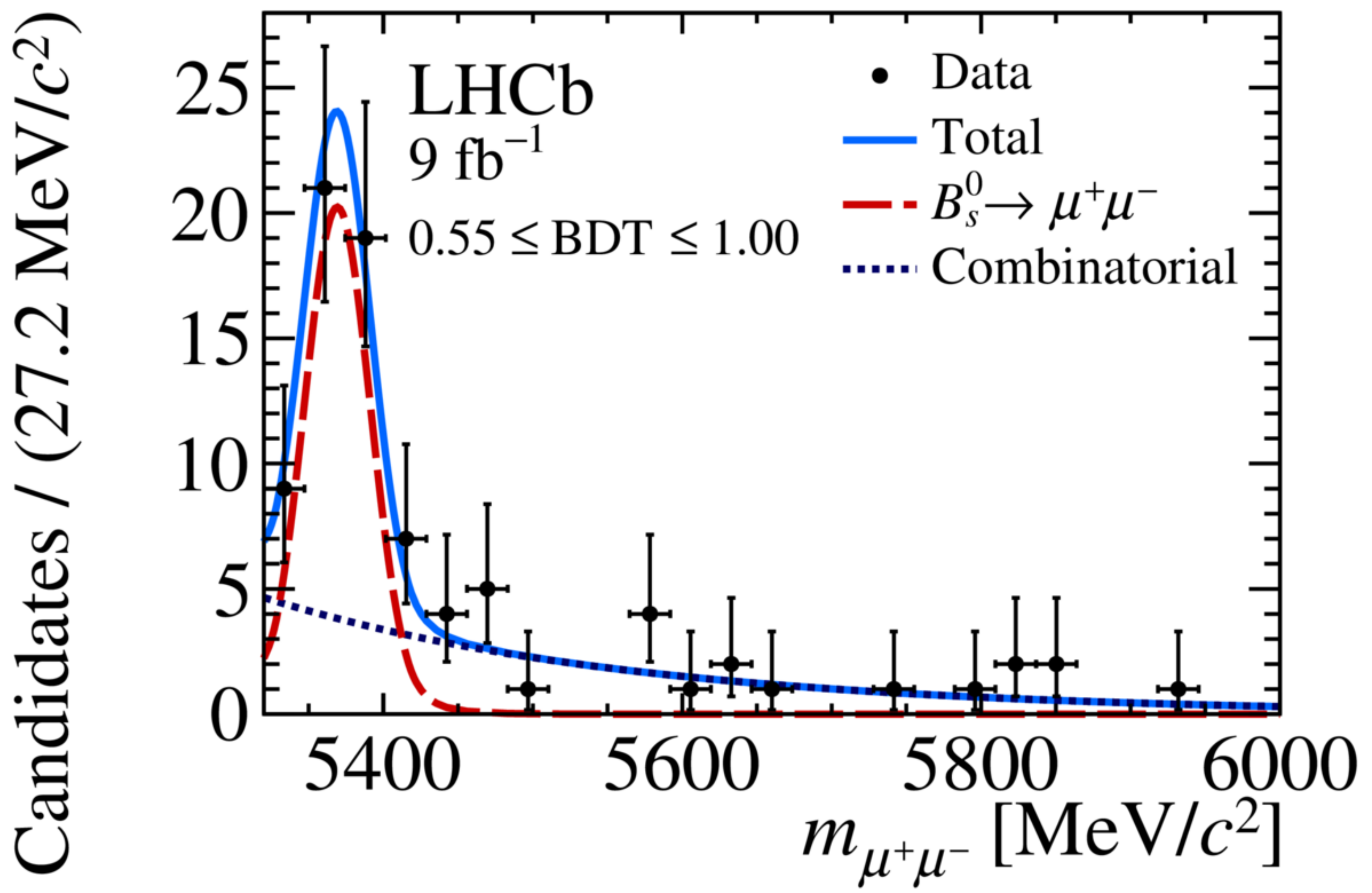
$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1 - y_s^2}\left[\frac{1 + 2A^{\mu\mu}_{\Delta\Gamma_s} y_s + y_s^2}{1 + A^{\mu\mu}_{\Delta\Gamma_s} y_s}\right]$$

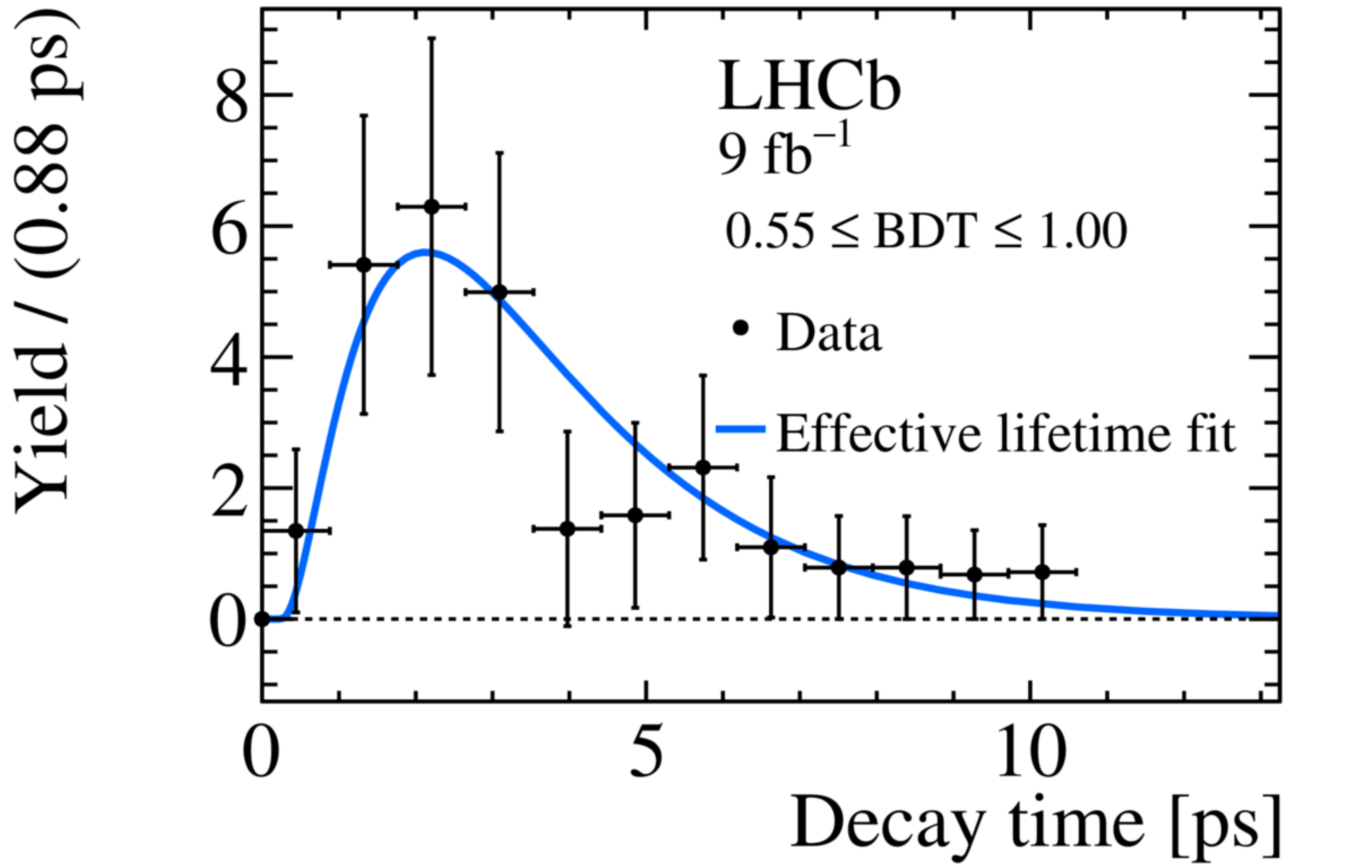
  - $A^{\mu\mu}_{\Delta\Gamma_s} = 1$ for the SM
    - $B_s^0 \to \mu\mu$ only from heavy mass eigenstate
    - Access to the CP structure of the interaction

- Strategy:
  - Dataset split into two BDT bins
  - Fit to background-subtracted $\tau_{\mu\mu}$ distribution via the *sPlot* technique

$$\tau_{\mu^+\mu^-} = 2.07 \pm 0.29 \pm 0.03 \text{ ps}$$

Consistent with the SM at 1.5σ





$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

- Oscillations between flavour eigenstates $B_s^0, \bar{B}_s^0$
  - Two mass eigenstates B_H, B_L
  - For SM $B_s^0 \to \mu^+\mu^-$ only from heavy eigenstates
  - $A^{\mu\mu}_{\Delta\Gamma_s}$ sensitive to scalar or pseudo scalar NP contribution: $C^{(\prime)}_{10}, C^{(\prime)}_{S}, C^{(\prime)}_{P}$ WCs

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2}\left[\frac{1+2A^{\mu\mu}_{\Delta\Gamma_s}y_s+y_s^2}{1+A^{\mu\mu}_{\Delta\Gamma_s}y_s}\right]$$

$$y_s \equiv \Delta\Gamma_s/(2\Gamma_s) \qquad A^{\mu\mu}_{\Delta\Gamma_s} \equiv -2\Re(\lambda)/(1+|\lambda|^2),$$

with $\lambda = (q/p)(A(\bar{B}_s^0 \to \mu^+\mu^-)/A(B_s^0 \to \mu^+\mu^-))$.

$$\mathcal{A}_{\Delta\Gamma} = \frac{R_H - R_L}{R_H + R_L} \overset{SM}{=} 1$$