Recent results in $b \to s\ell\ell$ transitions at LHCb

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On behalf of the LHCb collaboration

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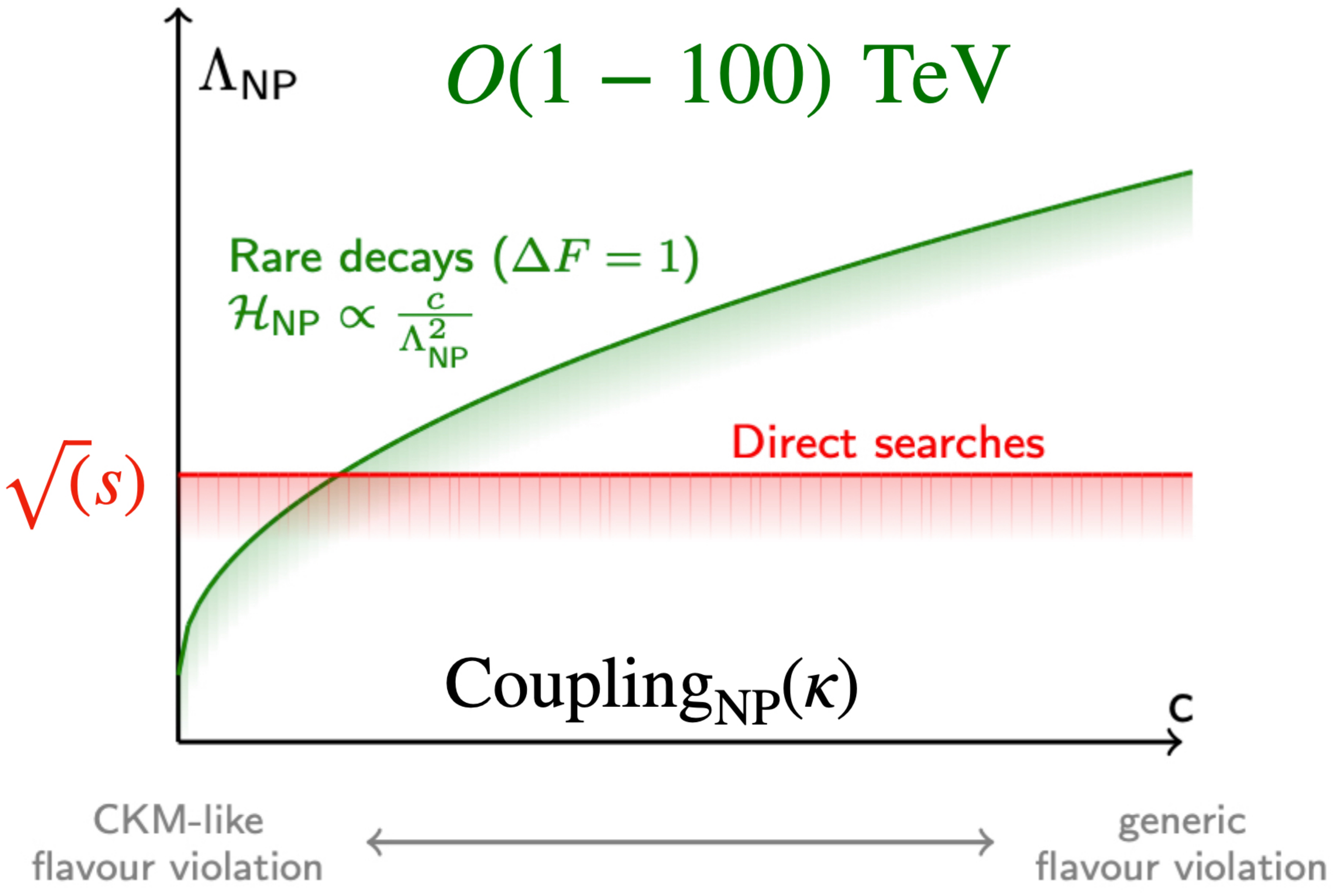
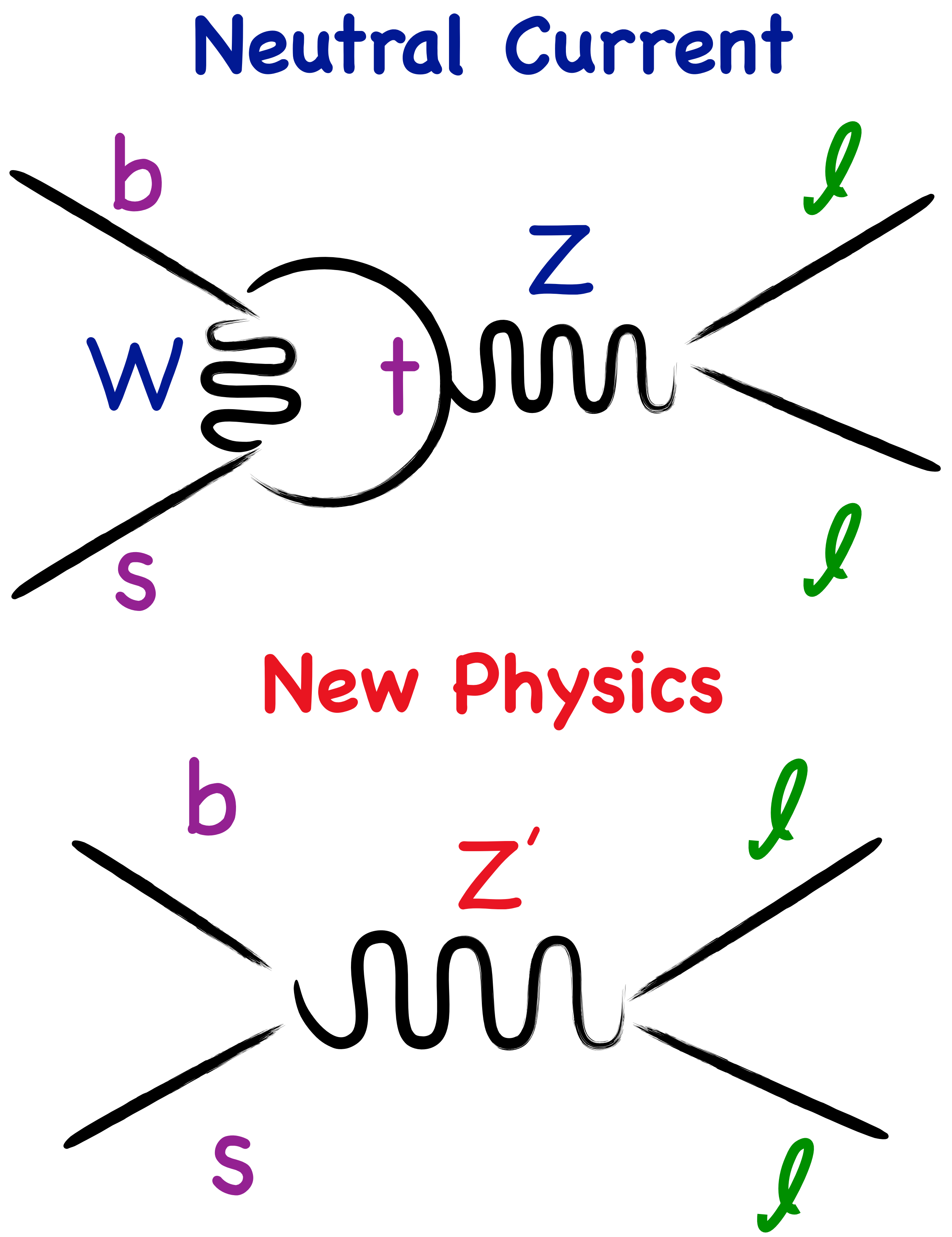
Outline

- Introduction
- Experimental observables using $b \to s\ell\ell$ transitions
  - Branching fractions
  - Angular observables
  - LFU ratios
- Searches for LFV decays
- Conclusion

Electroweak penguin decays

- Processes mediated by $b \to s\ell\ell$ transitions are sensitive to **New Physics (NP)**
  - Suppressed in the SM: $BR \sim 10^{-7} - 10^{-6}$
  - High energy mediators can modify the amplitudes





Electroweak penguin decays

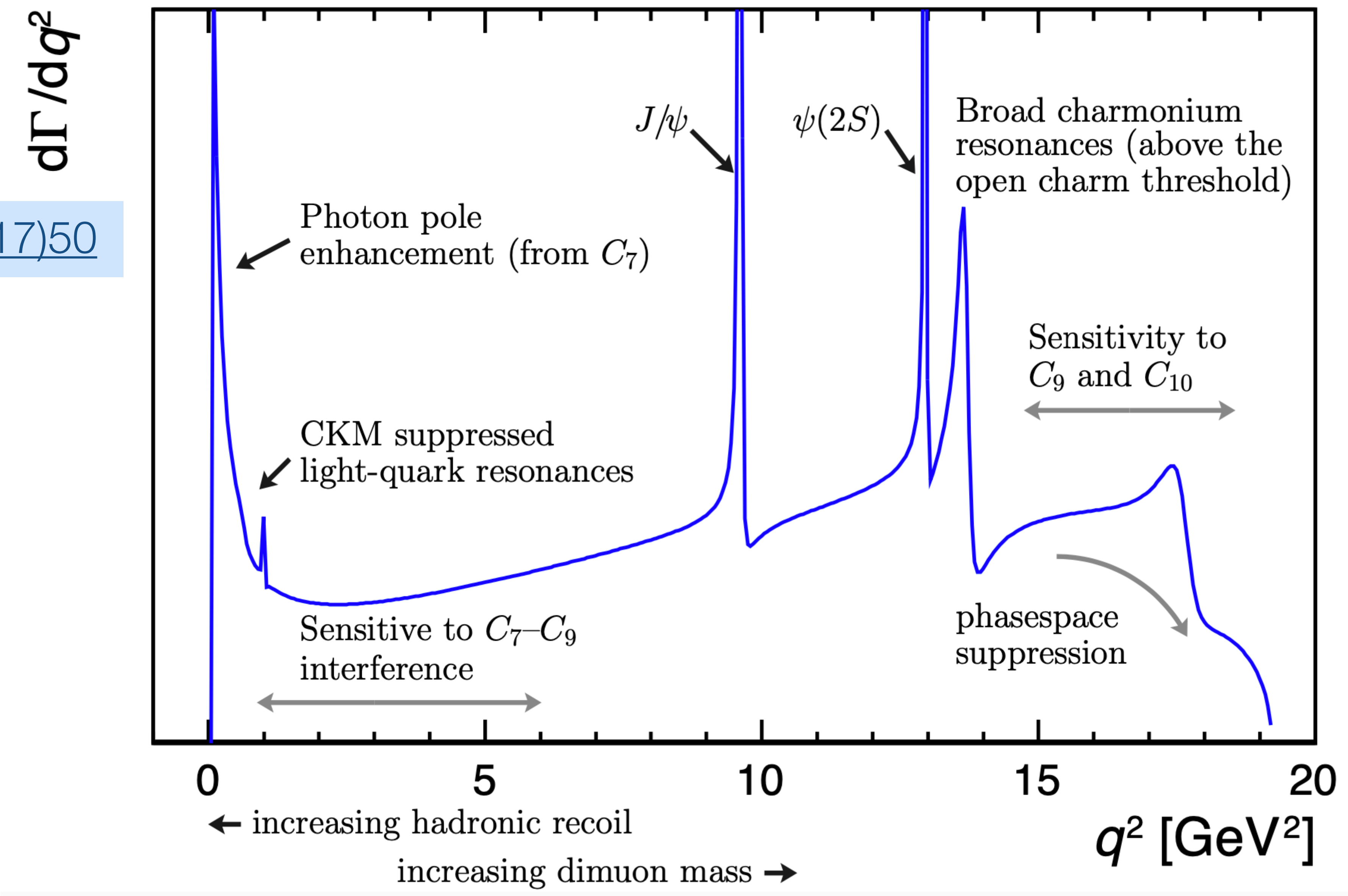
- Rare b decays can be described by an **effective theory**:

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

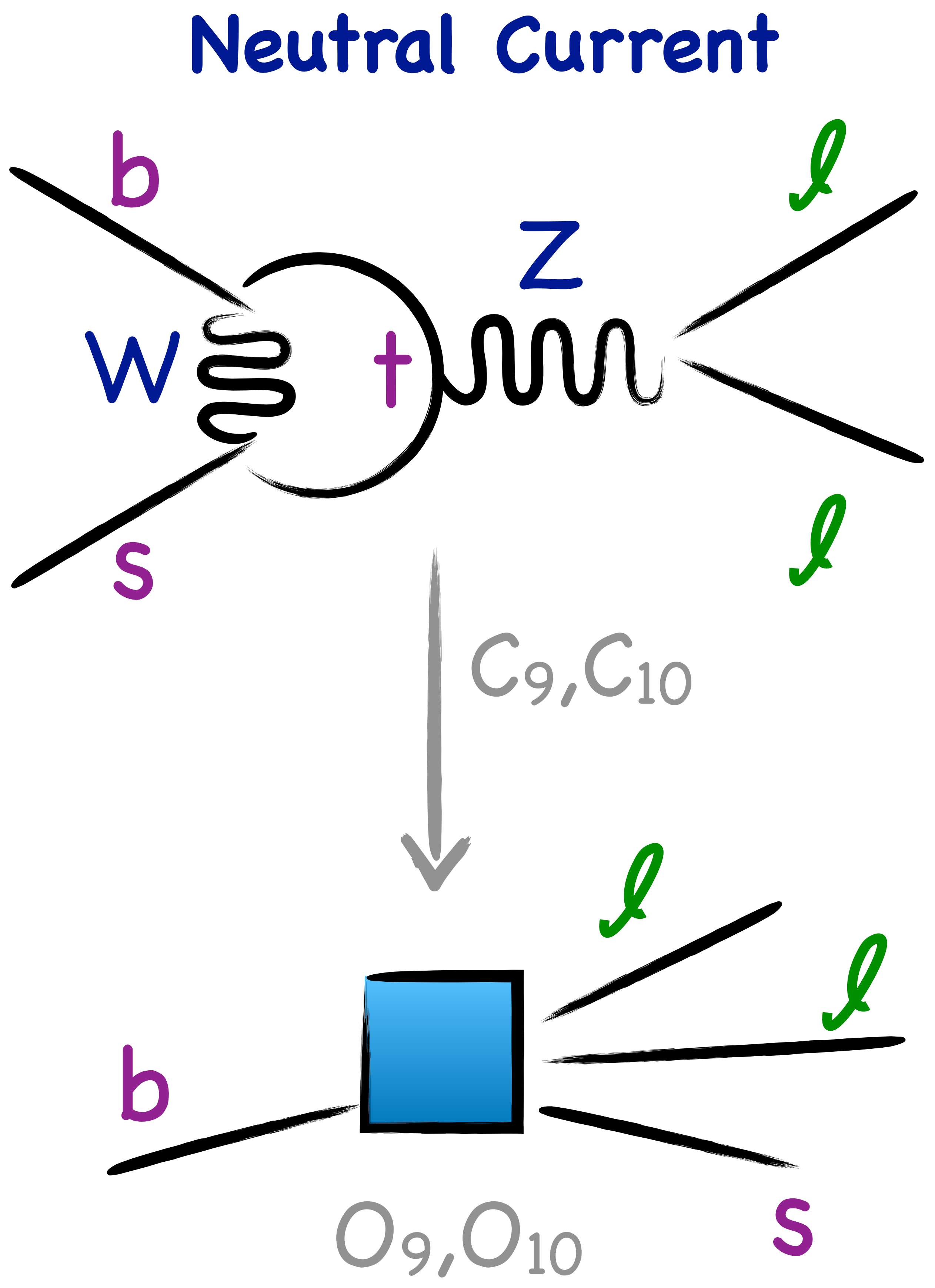
Effective coupling *Wilson Coefficients (WC)*

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: $C_i = C_i^{SM} + C_i^{NP}$

Experimental Observables

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- Large variety of observables available:
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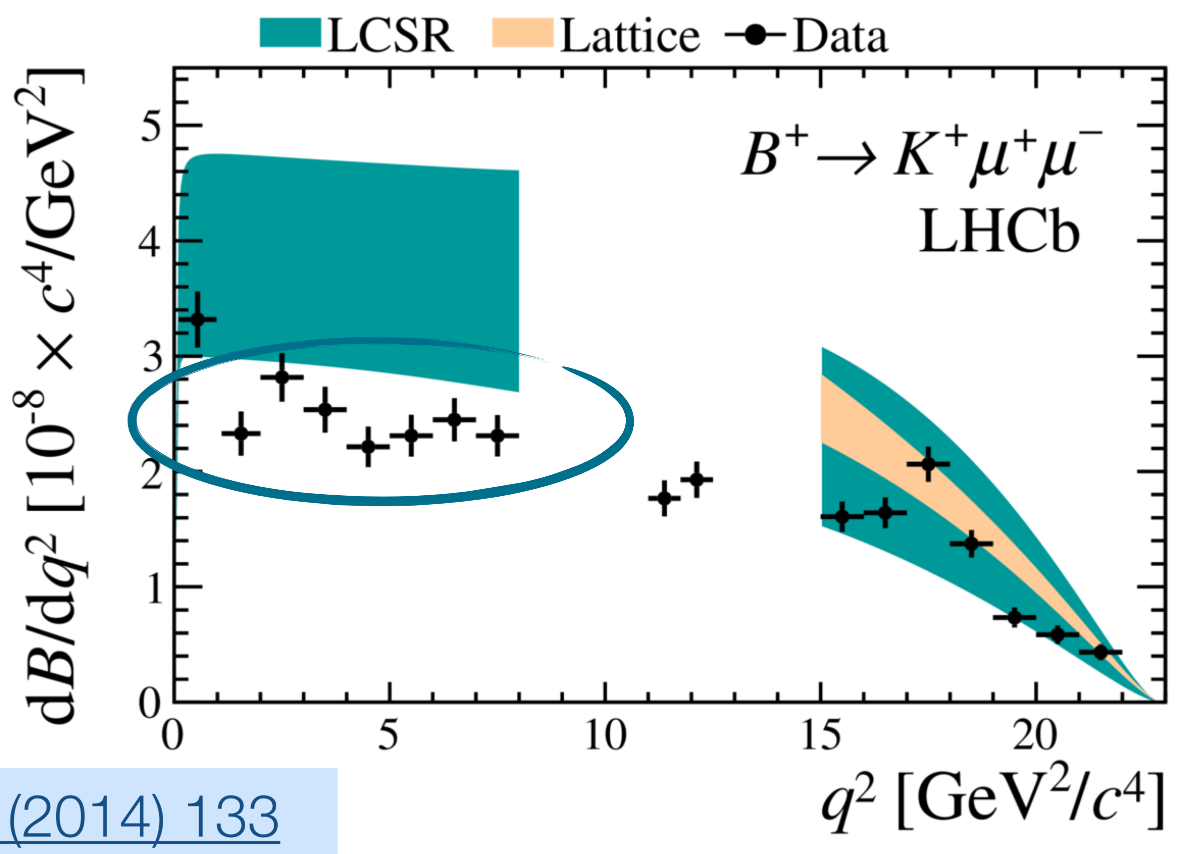
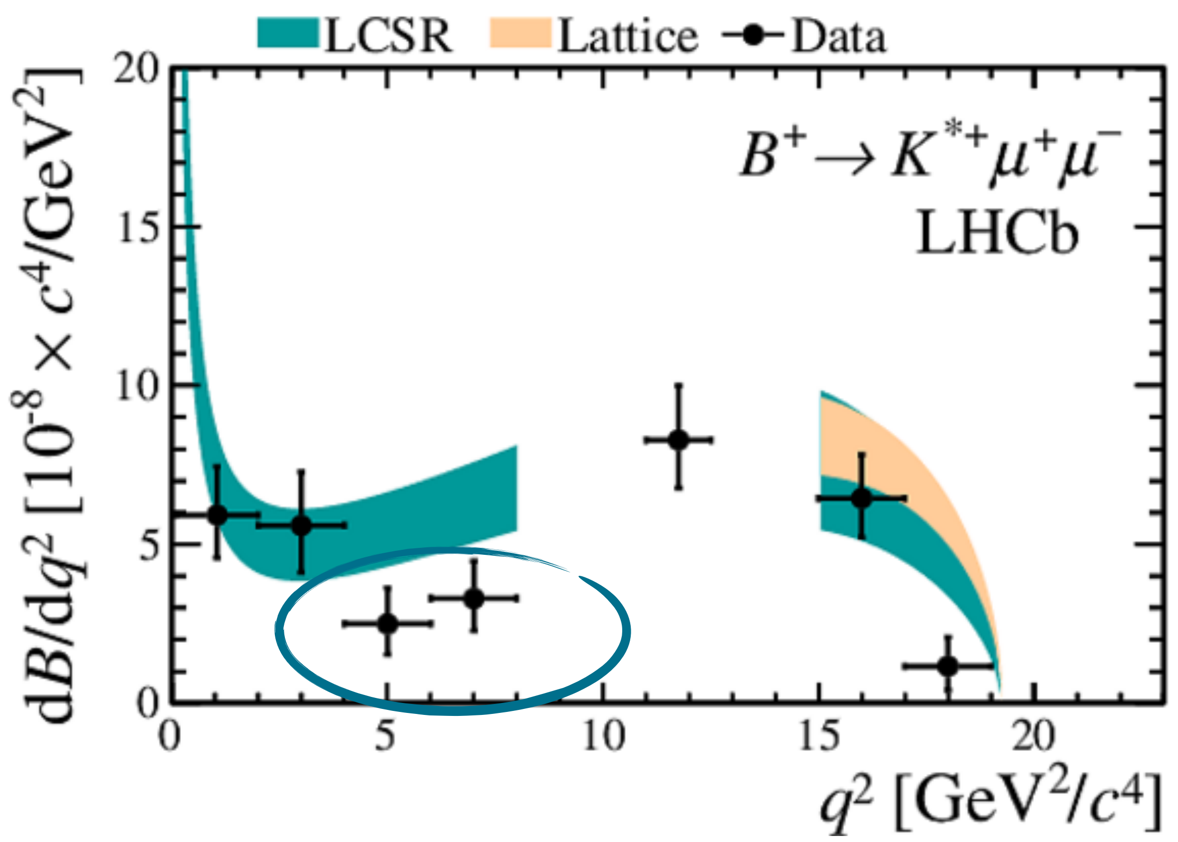
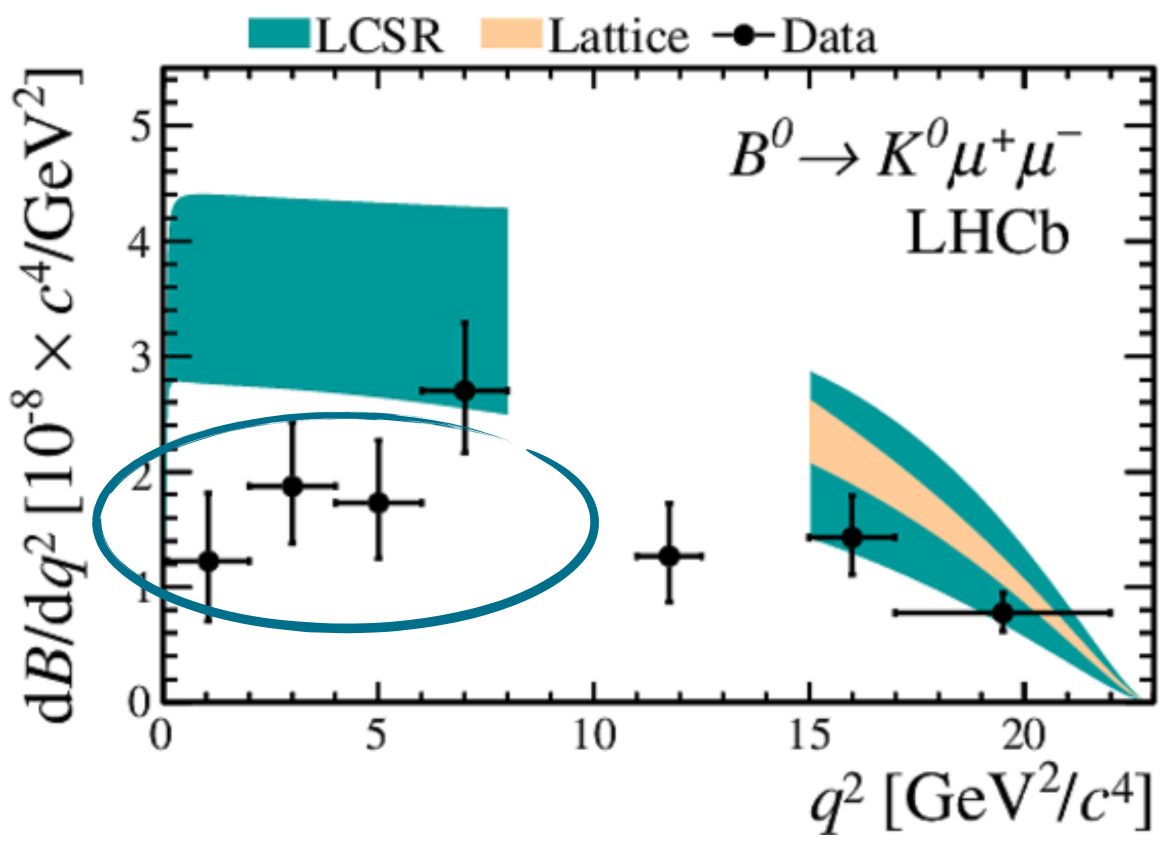
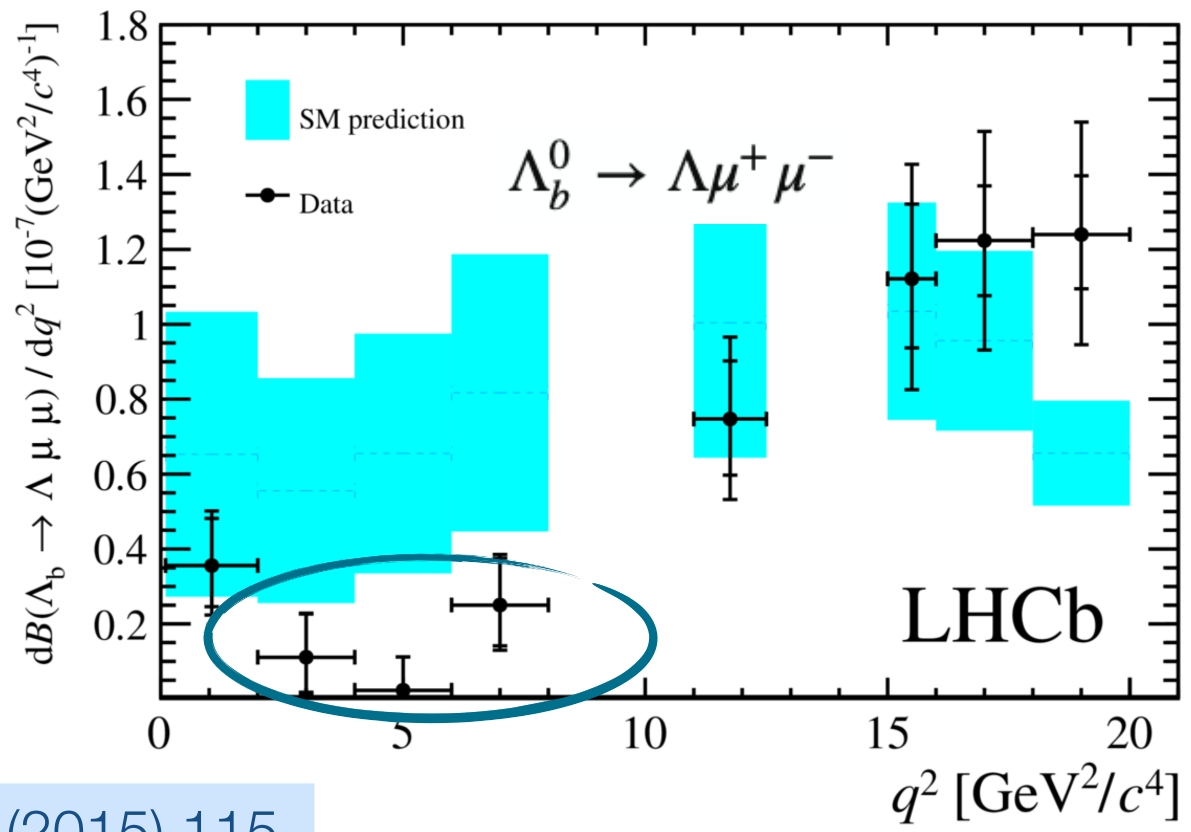


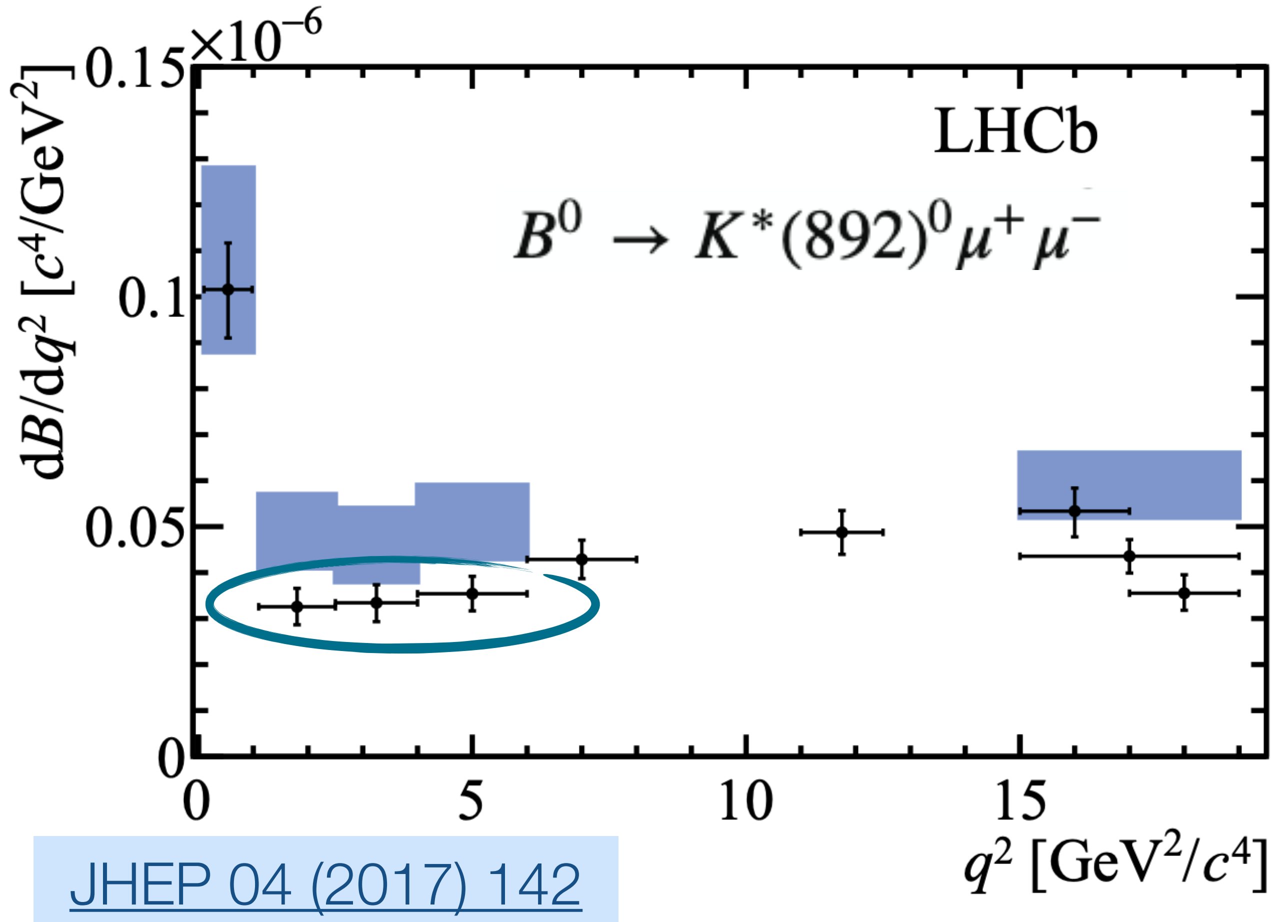


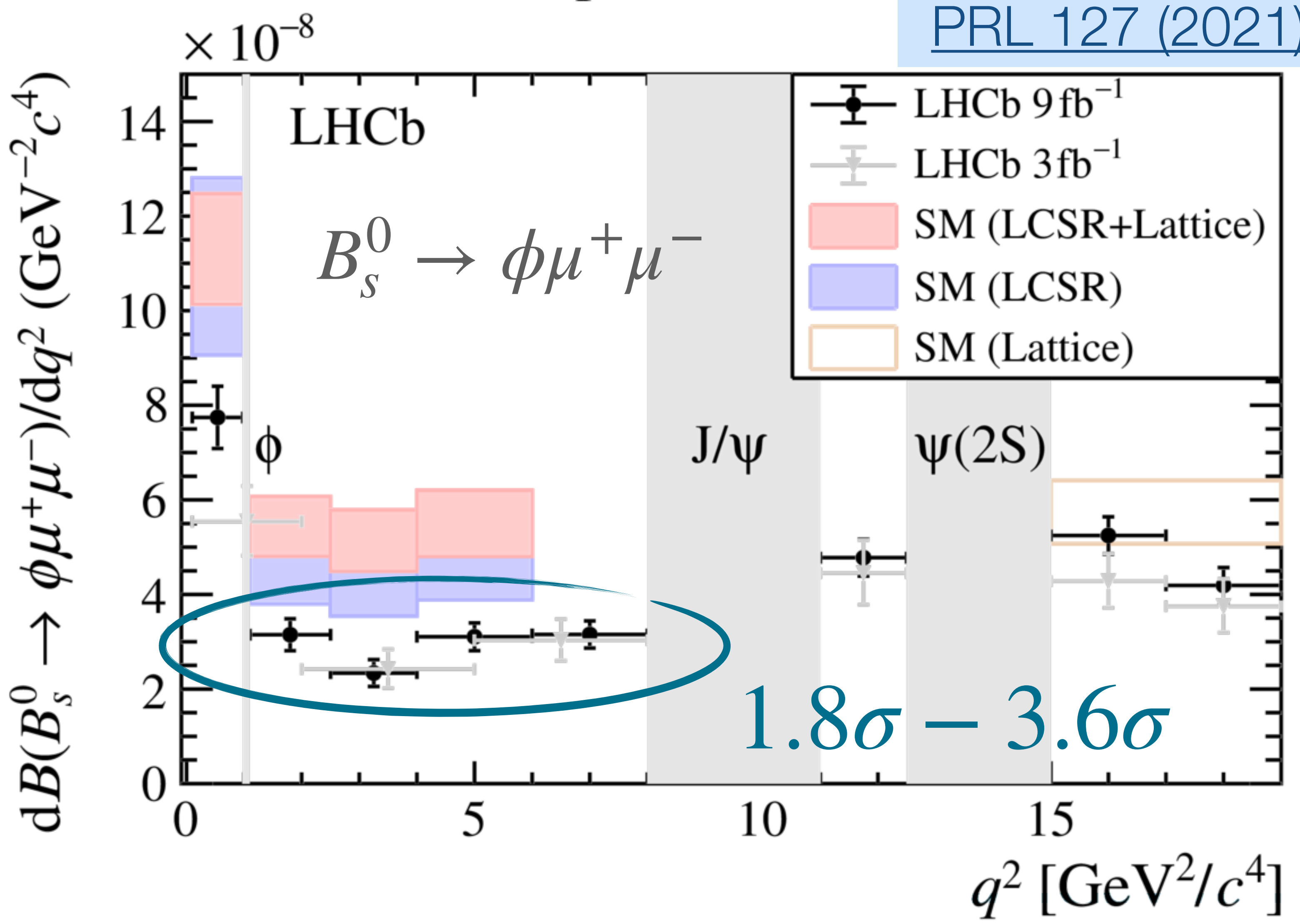


JHEP 06 (2014) 133

PRL 127 (2021) 151801







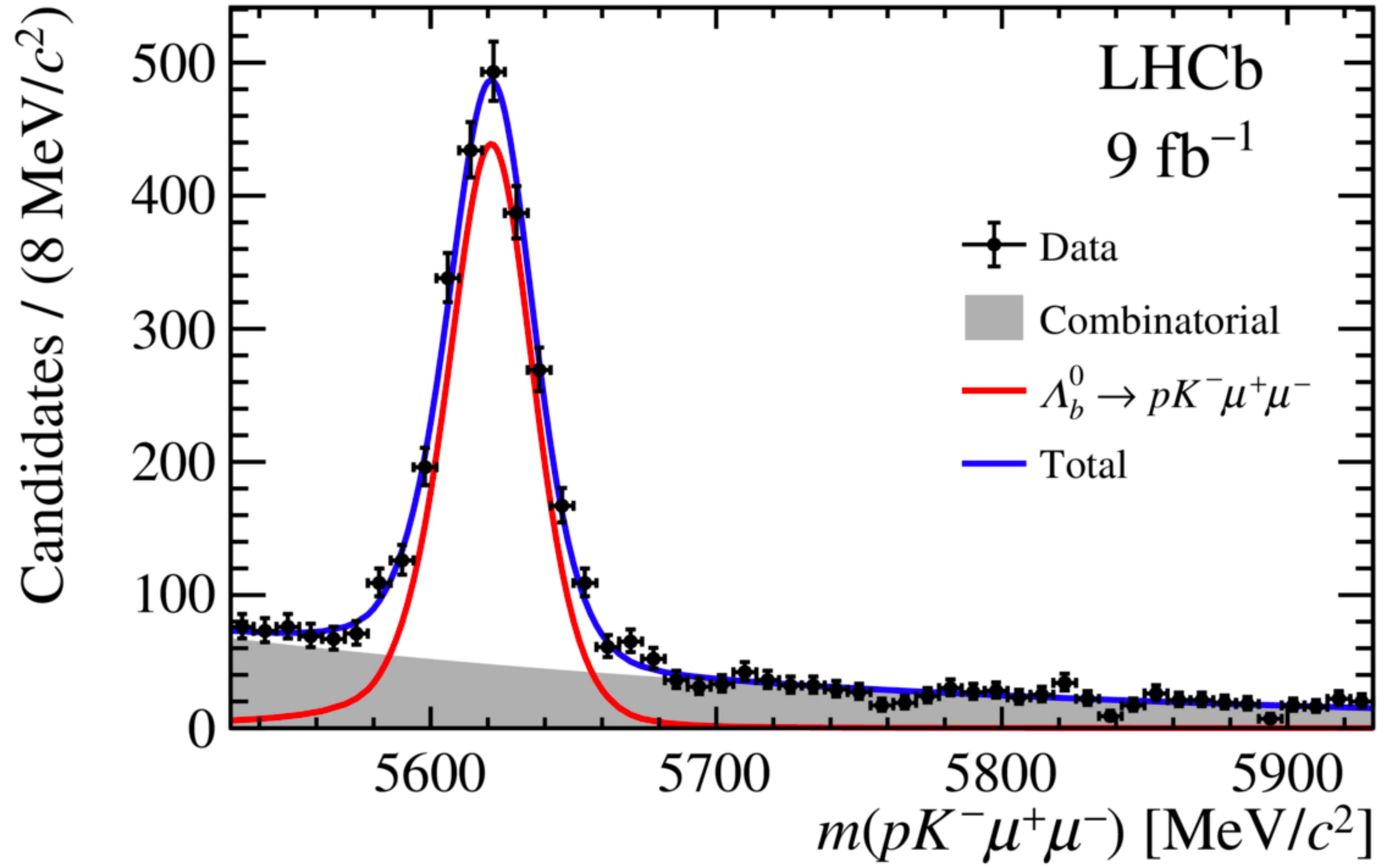
JHEP 06 (2015) 115

JHEP 04 (2017) 142

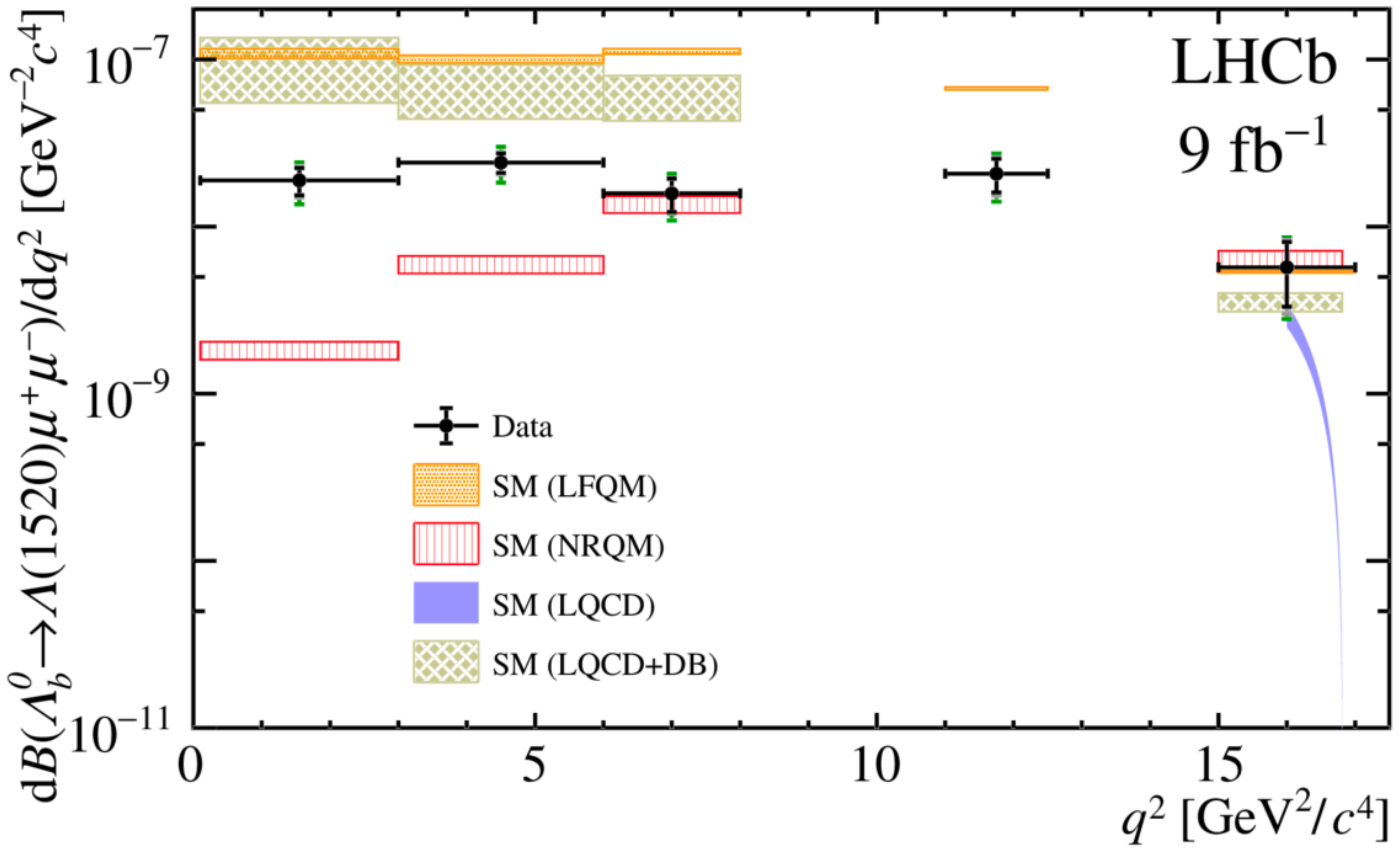
Differential branching fractions: $\Lambda_b \to \Lambda(1520)\mu^+\mu^-$

- Latest news from baryonic sector!
  - First measurement of differential $BF(\Lambda_b^0 \to \Lambda(1520)(\to pK^-)\mu^+\mu^-)$
  - $\Lambda_b \to pK^- J/\psi$ used to normalise and to correct the simulation
  - Difficult to estimate the agreement with the SM predictions

arXiv:2302.08262



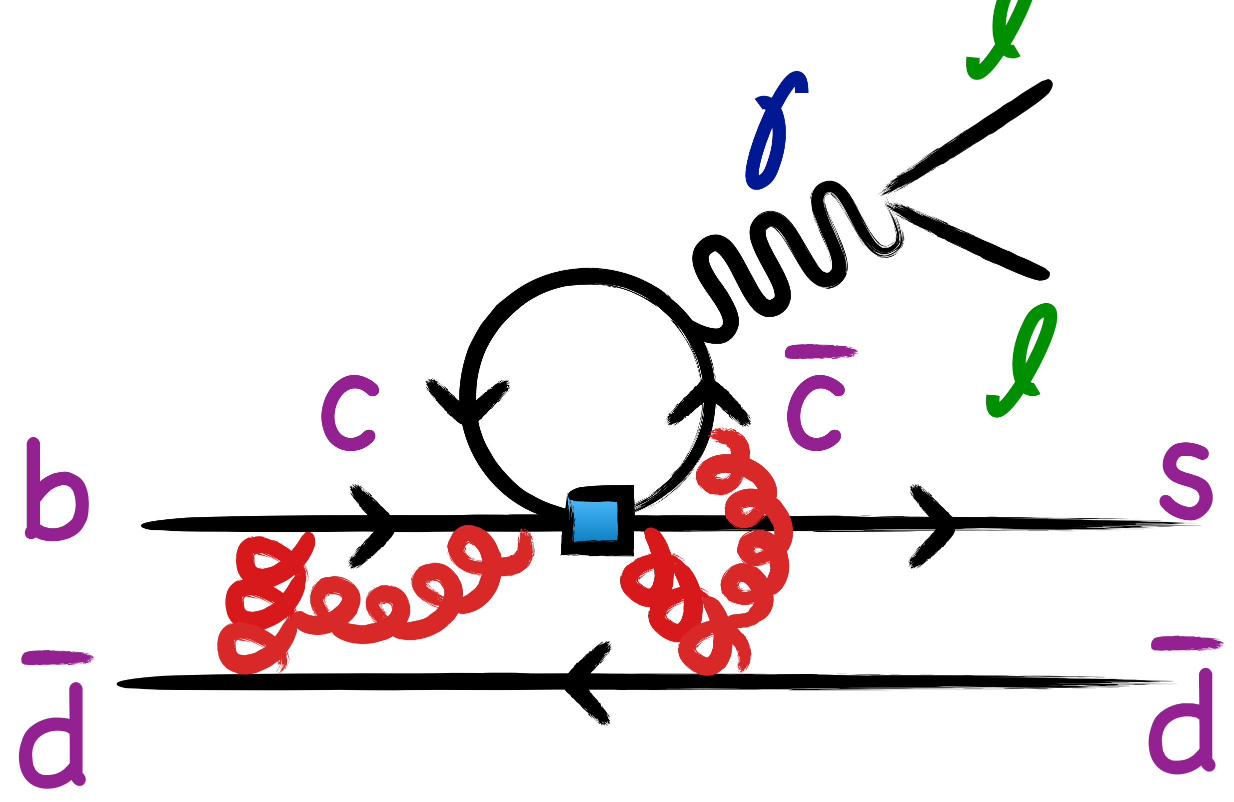
$N_{\Lambda_b \to pK^-\mu^+\mu^-} = 2250 \pm 57(\text{stat})$



Experimental Observables

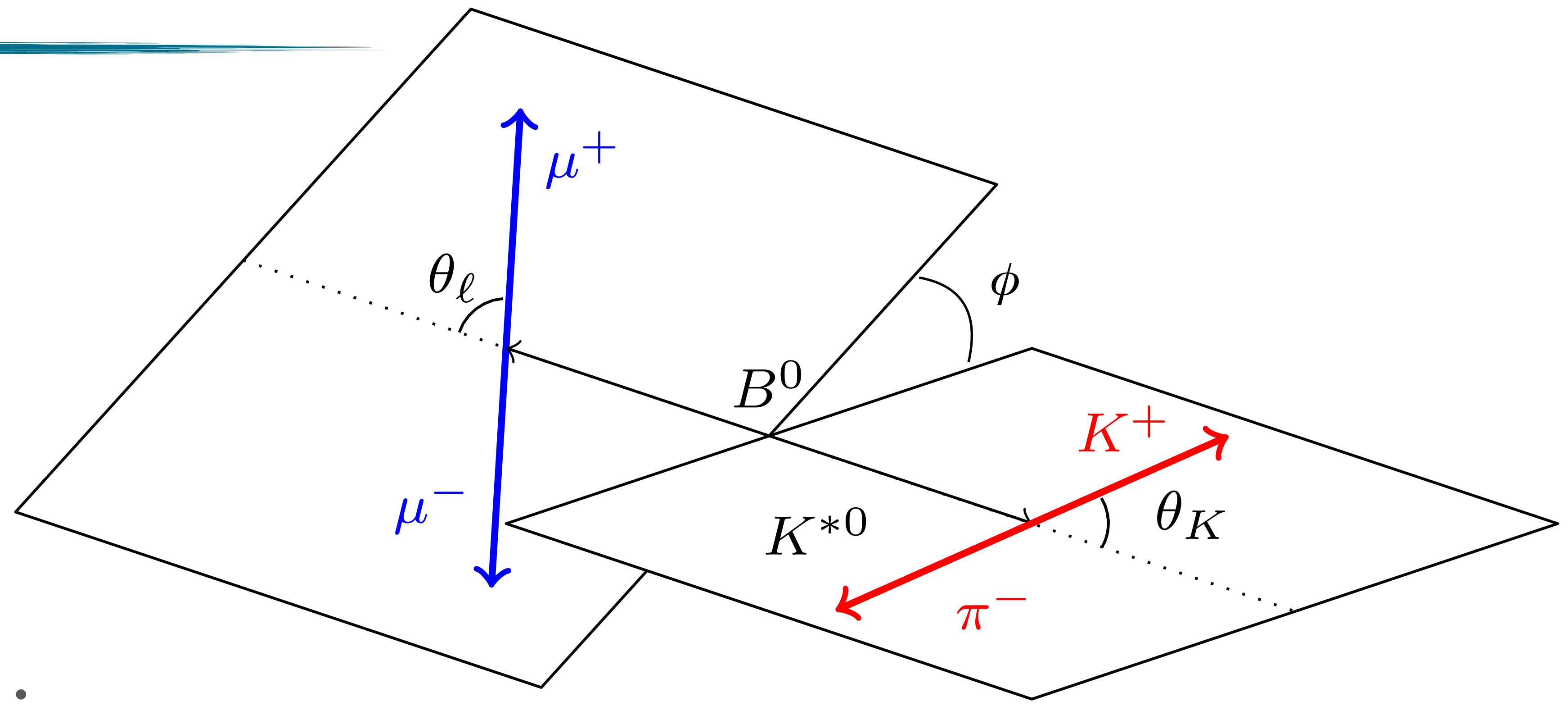
$q^2 = m^2(\ell^+\ell^-)$

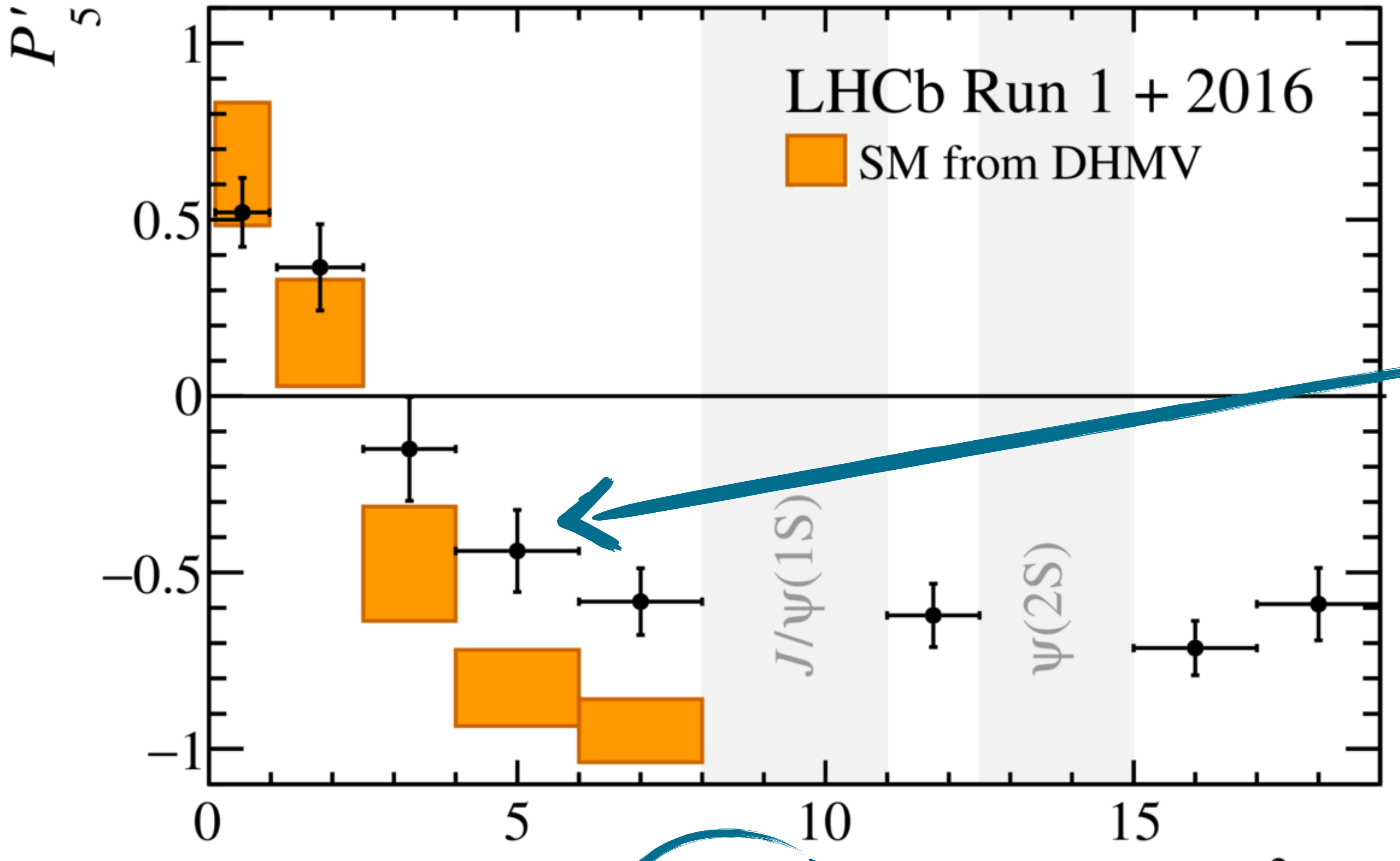
- Large variety of observables available:
  - Differential branching fractions: Large hadronic form factors uncertainties (20-30%)
  - Angular distributions of the final state particles:
    - Reduced form factor uncertainties
    - May be polluted by "charm loop" effects, hard to predict

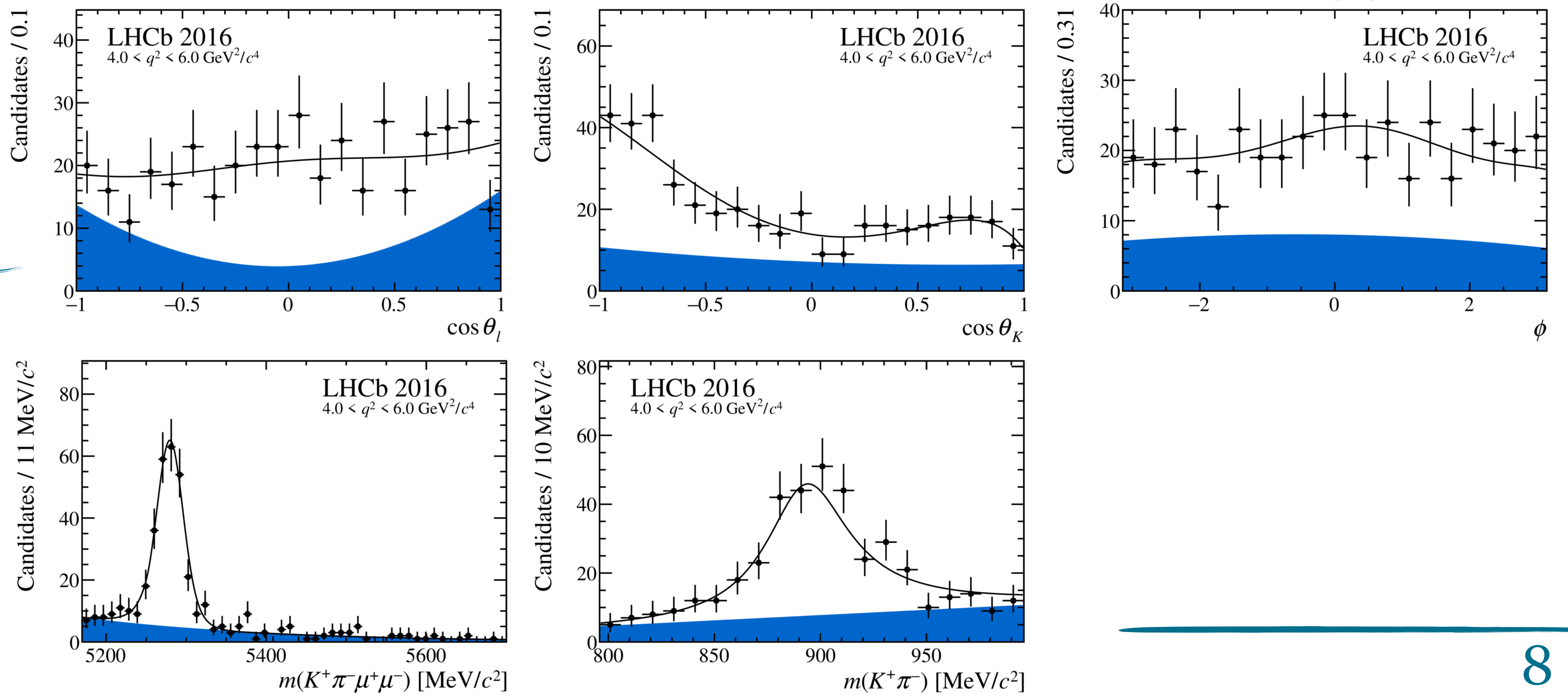


Angular distributions: $K^*\mu^+\mu^-$

- 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, $m(K\pi)$, $m(K\pi\mu\mu)$







PRL 125 (2020) 011802

3.3σ

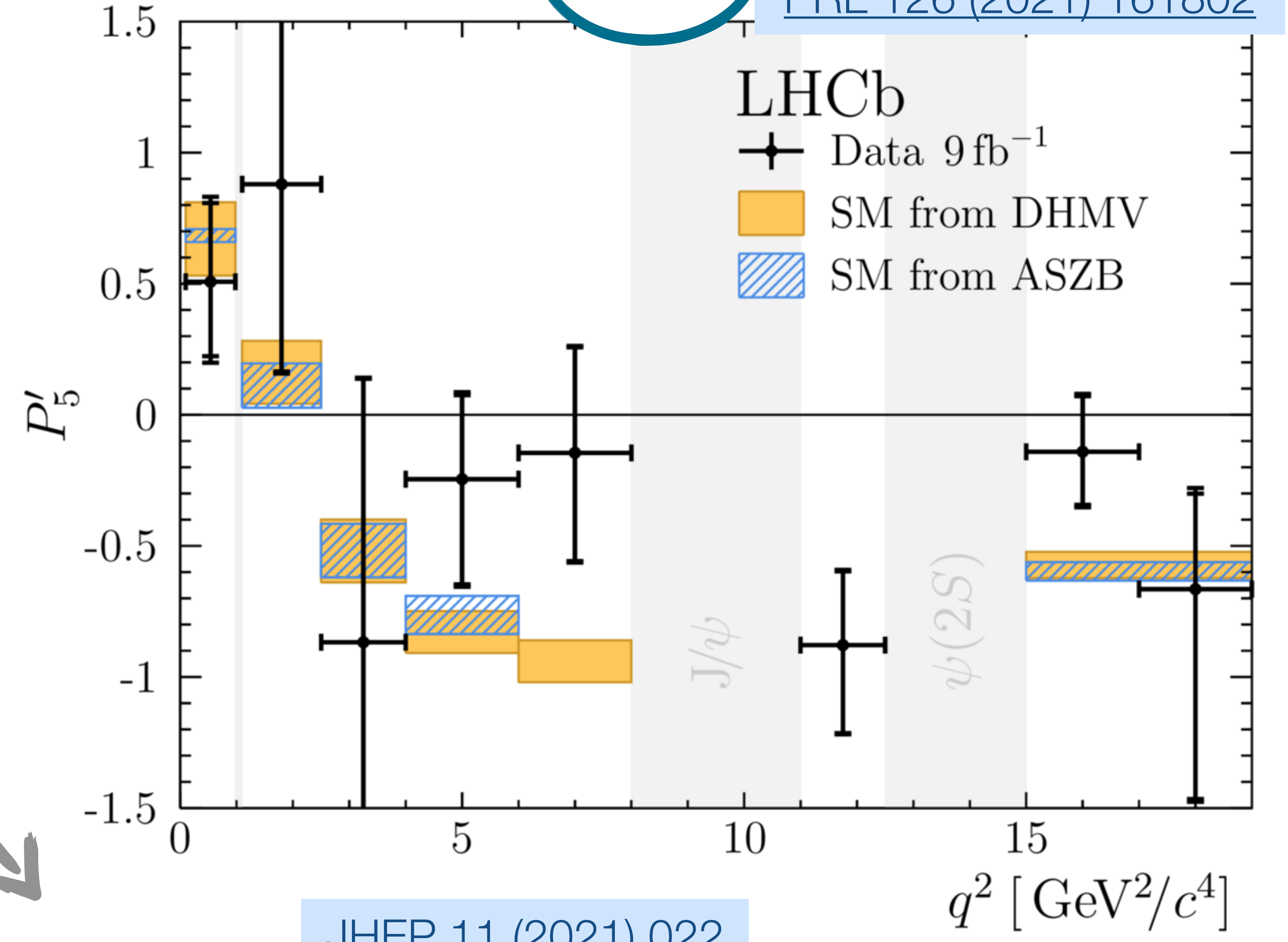
$q^2 = m^2(\ell^+\ell^-)$

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

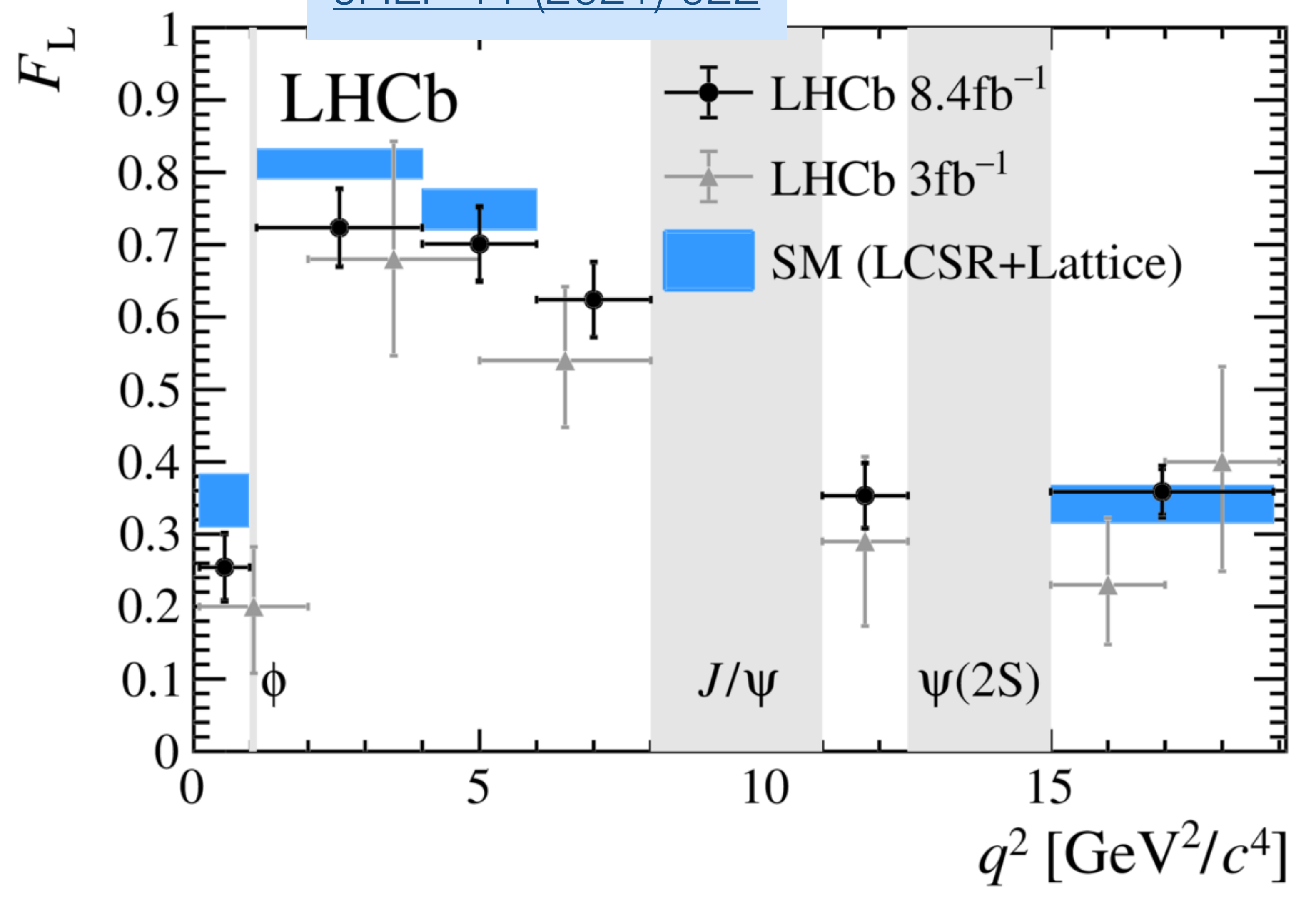
- Recent angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$ showed tension in the SM consistent with that found in $B^0 \to K^{*0}\mu^+\mu^-$
- Angular observables are also studied for $B_s^0 \to \phi\mu^+\mu^-$
  - Not all observables accessible (flavour symmetric final state)
  - Results found to be compatible 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



Experimental Observables

- Large variety of observables available:
  - Differential branching fractions: Large hadronic form factors uncertainties (20-30%)
  - Angular distributions of the final state particles:
    - Reduced form factor uncertainties
    - May be polluted by “charm loop” effects, hard to predict
  - Relative rates of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$, of the form

EPJ C76 (2016) 8 440

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

- are clean: QCD uncertainties cancels out in the ratio
- are predicted by the SM with very high precision
- Intriguing deviations observed in the past years

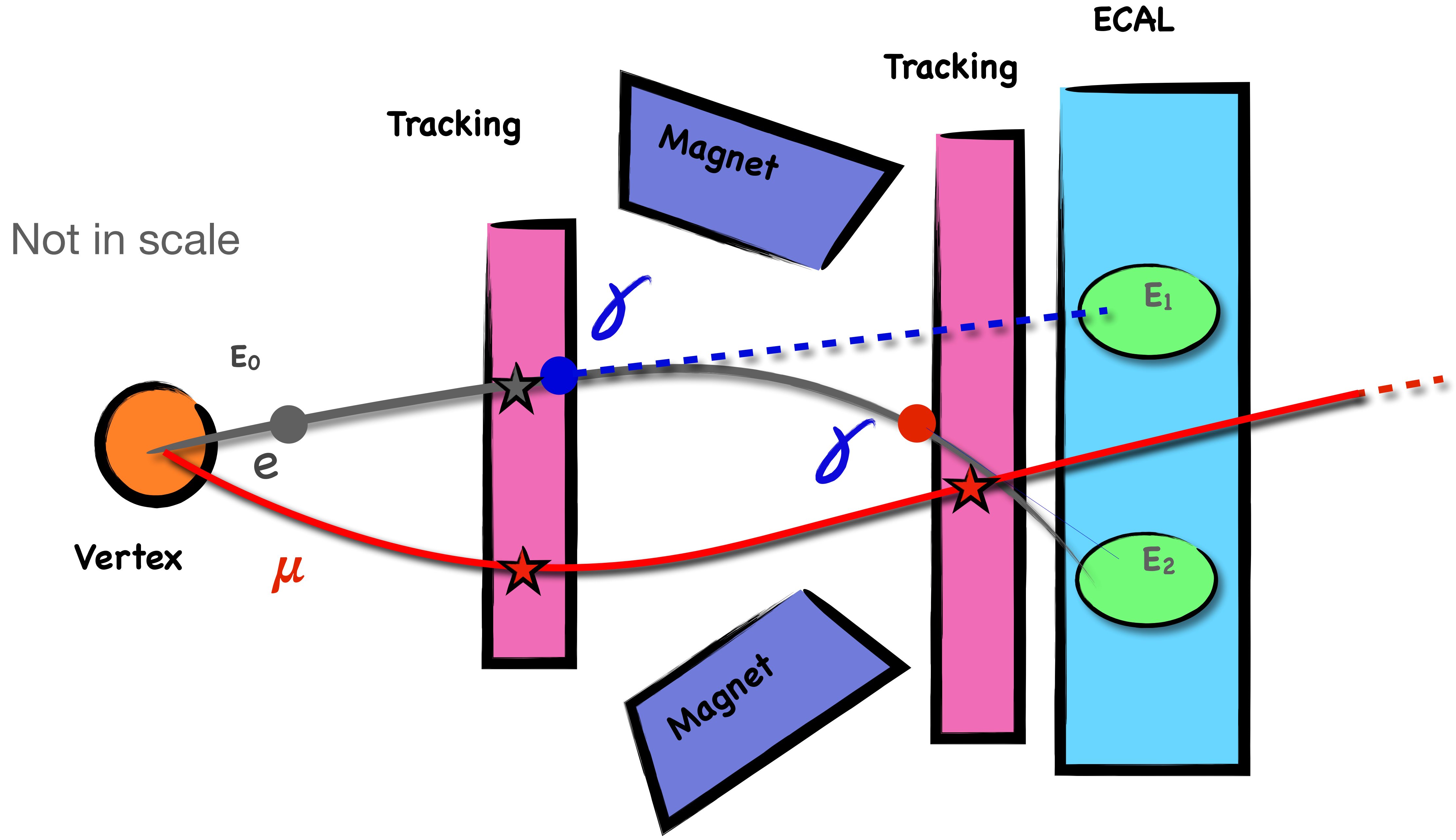
LFU ratios: Electron vs Muon

- Relative rates are sensitive to differences between leptons:

$$R_X = \frac{\mathcal{N}_{B^+\to X e^+ e^-}}{\mathcal{N}_{B^+\to X \mu^+ \mu^-}} \cdot \frac{\epsilon_{B^+\to X \mu^+ \mu^-}}{\epsilon_{B^+\to X e^+ e^-}}$$

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

- Most electrons emit **bremsstrahlung** photons:
  - Need to recover the photon cluster energy
- High occupancy in the ECAL
  - Higher energy thresholds ➞ lower statistics
- Worse p resolution, lower PID and tracking efficiencies than for muons



Crucial to control e/μ differences

LFU ratios: Electron vs Muon

arXiv:2212.09153v1

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- Most electrons emit **bremsstrahlung** photons:
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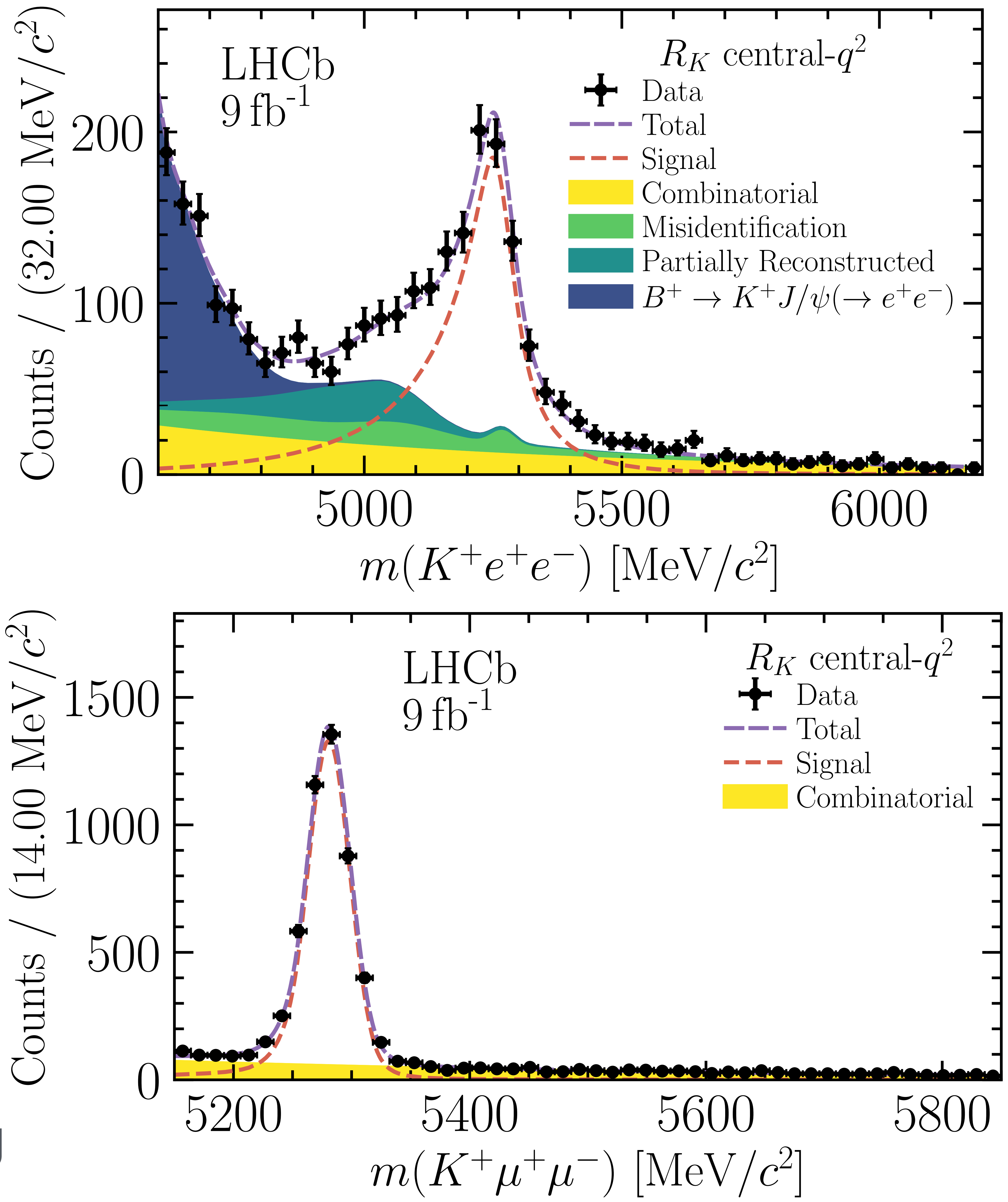
- Worse p resolution, lower PID and tracking efficiencies than for muons
- Additional backgrounds in the electron modes e.g misID $h \to e$



LFU ratio: Experimental strategy

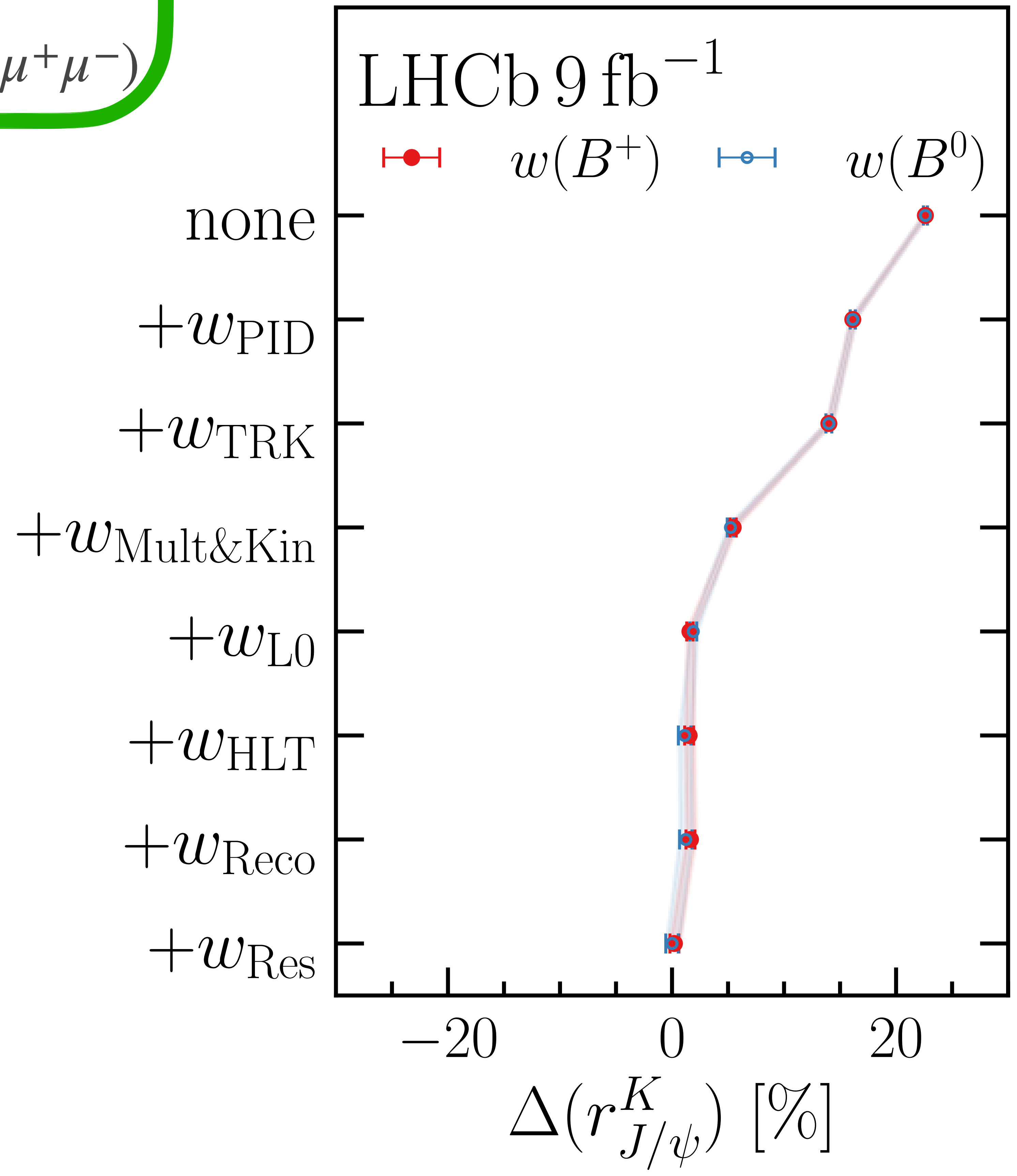
- R_X is measured as double ratios, to mitigate e/μ reconstruction differences

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

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

arXiv:2212.09153v1

- ▶ Yields: fits to the invariant mass
- ▶ Efficiencies: corrected simulation



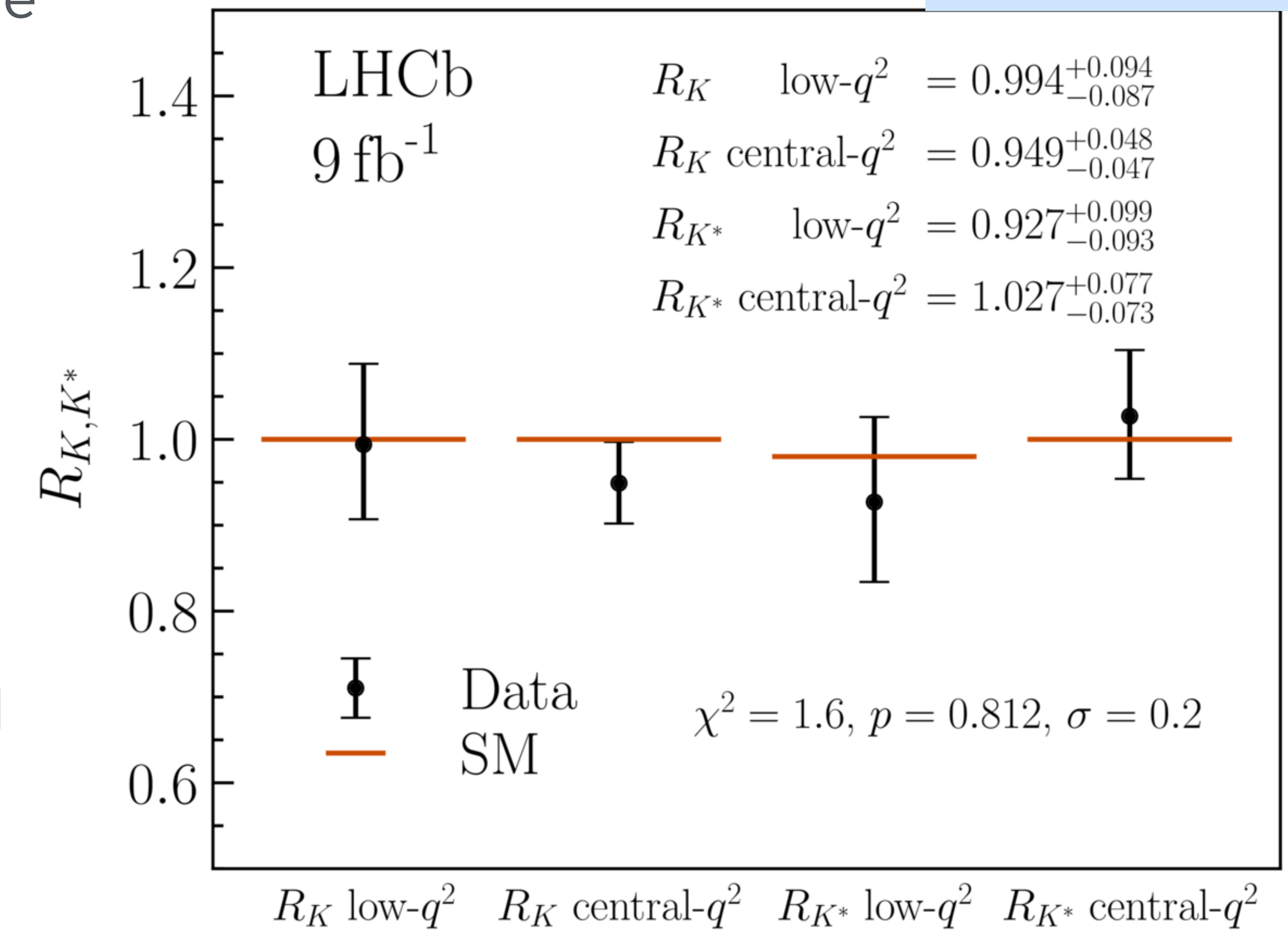
- J/ψ satisfy LFU at $\mathcal{O}(<1\%)$, not mediated by $b \to s\ell\ell$
- Intensive use of the resonant channels for checks/data driven studies

▶ $$r_{J/\psi} = \frac{\mathcal{B}(B \to XJ/\psi(\to \mu\mu))}{\mathcal{B}(B \to XJ/\psi(\to ee))} \equiv 1$$

R_K & R_{K*}

- Latest and most precise LFU ratios by measuring simultaneously R_K & R_{K*} with the full LHCb dataset
- Results in agreement with SM predictions within 0.2σ
- Shift wrt to previous measurements (superseded) due to
  - Tighter PID requirements
  - Addition of mis-identified background component in the fit
    - Main systematics
- Future: more decay channels: $R_\phi, R_{pK}, R_\Lambda, R_{K\pi\pi}\ldots$

arXiv:2212.09153v1



JHEP 06 (2023) 073

LFV

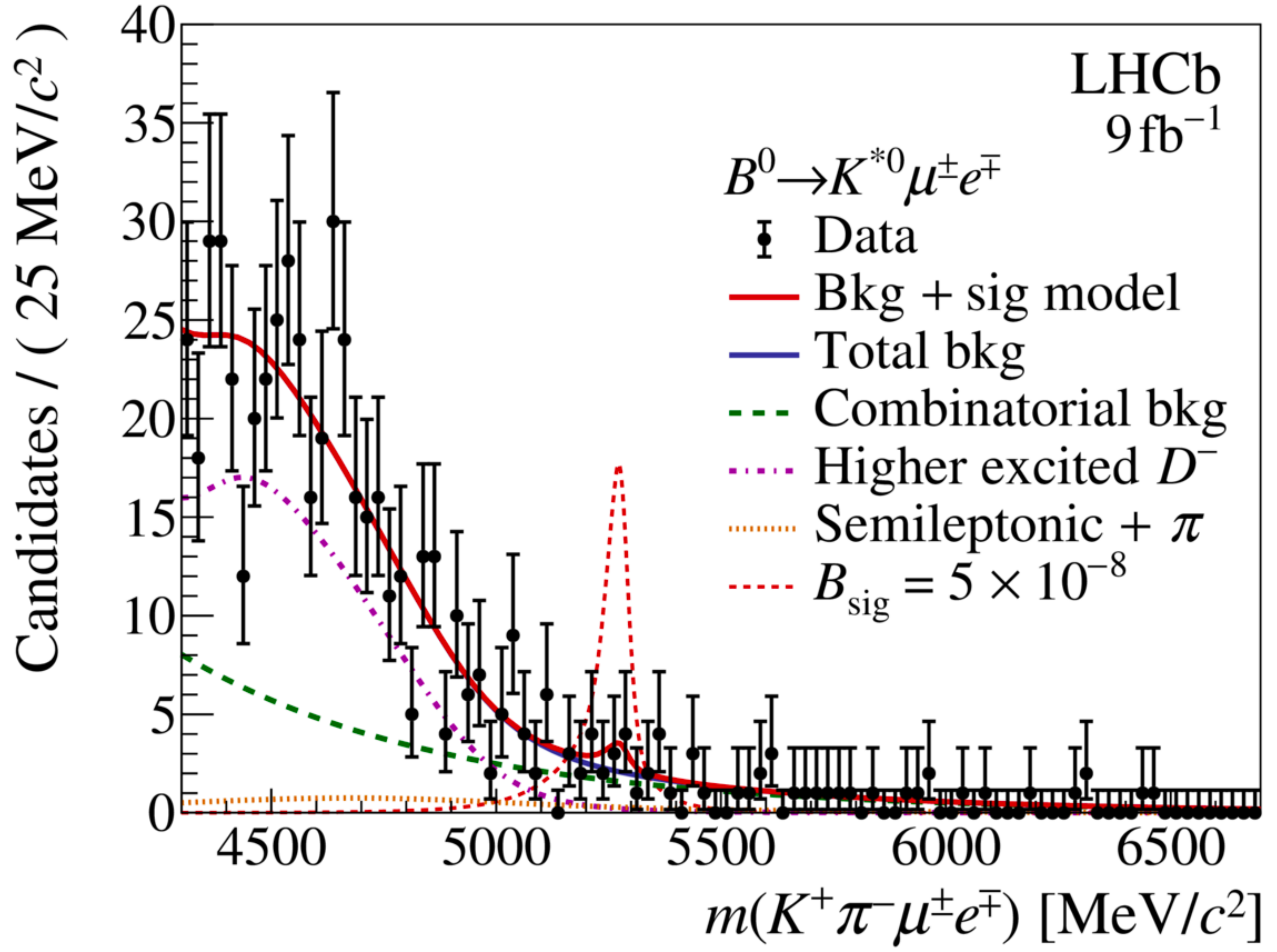
- $b \to s\ell\ell$ transitions also used to look for LFV decays
  - Related to possible LFUV
  - Can help constraining NP models
- Very recent search for $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$
  - Results also for $b \to s\mu^+e^-$ and $b \to s\mu^-e^+$ separately
  - No access found, best limits set

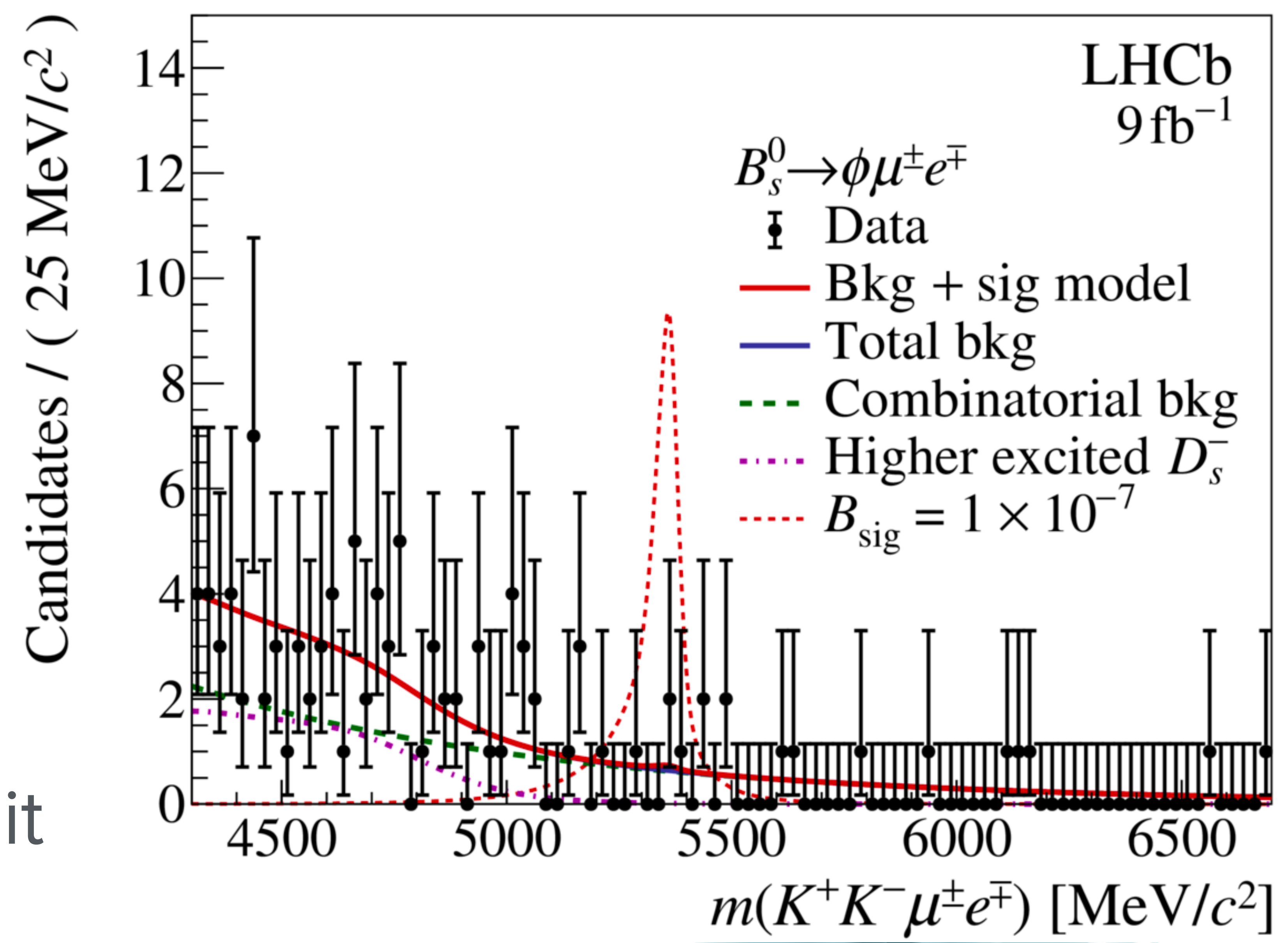
@90% (95%) CL

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9}\ (6.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8 \times 10^{-9}\ (7.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 10.1 \times 10^{-9}\ (11.7 \times 10^{-9}),$$
$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}e^{\mp}) < 16.0 \times 10^{-9}\ (19.8 \times 10^{-9})$$

World first limit

  - Provided limits on a scalar and left-handed NP scenario

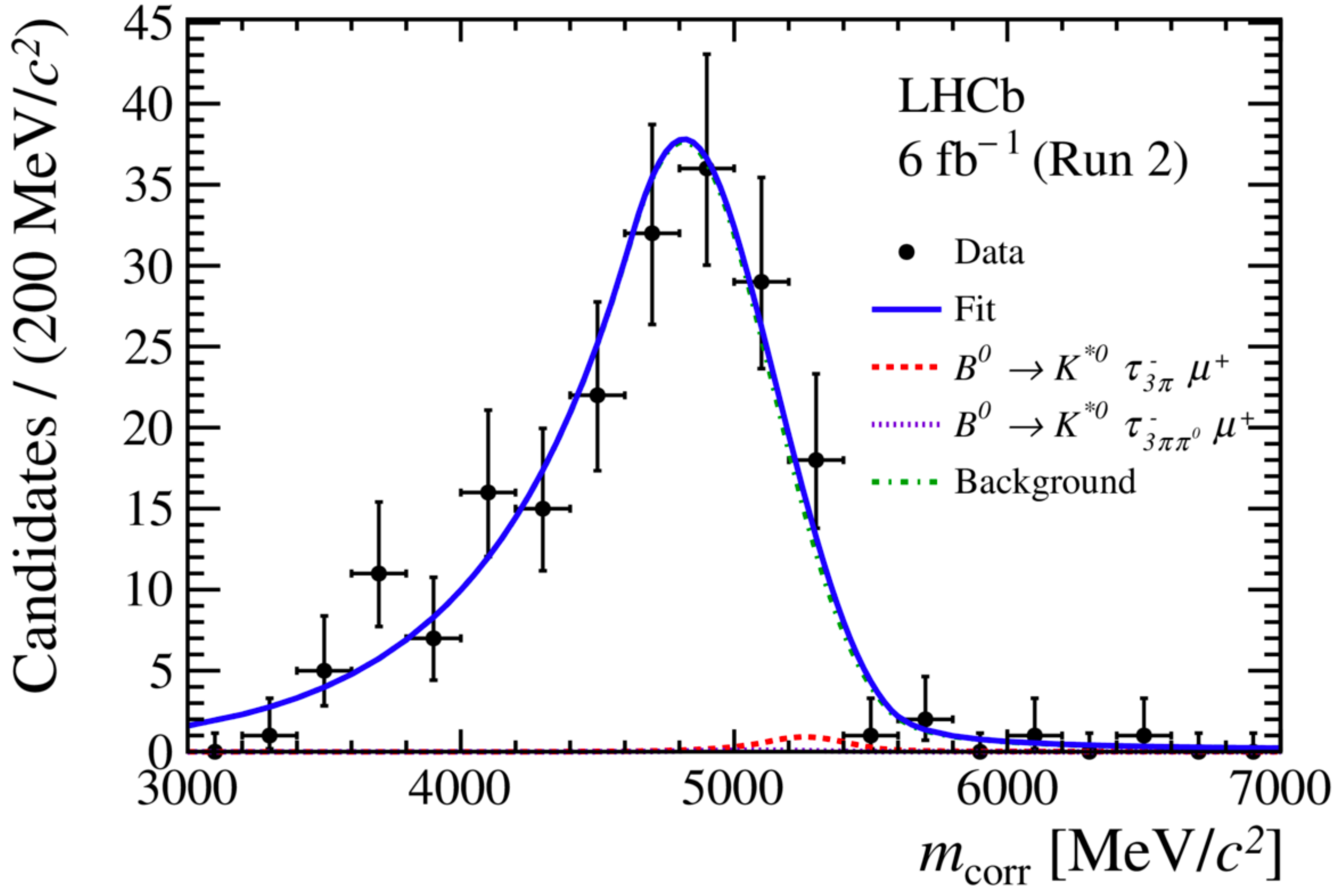


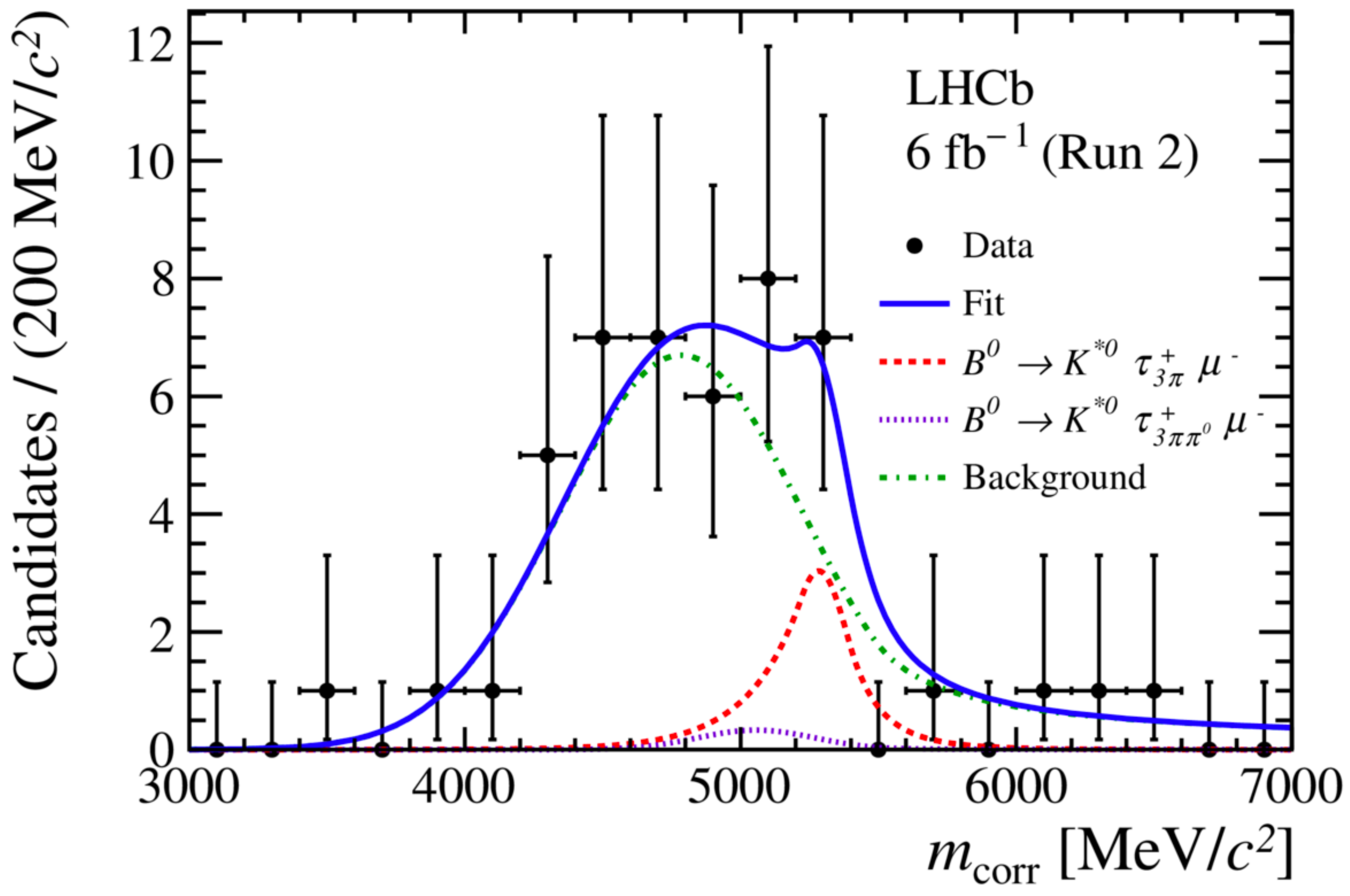


LFV with taus

arXiv:2209.09846

- First ever search for $B^+ \to K^{*0}\tau^\pm\mu^\mp$ recently published using full LHCb dataset
  - Use $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
  - Separated treatment for charges combinations
  - Corrected mass used to recover neutrinos energies: $m_{\text{corr}} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$
  - No significant access observed





World first limit on $b \to s\tau\mu$ @90% (95%) CL

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0\ (1.2) \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2\ (9.8) \times 10^{-6}$$

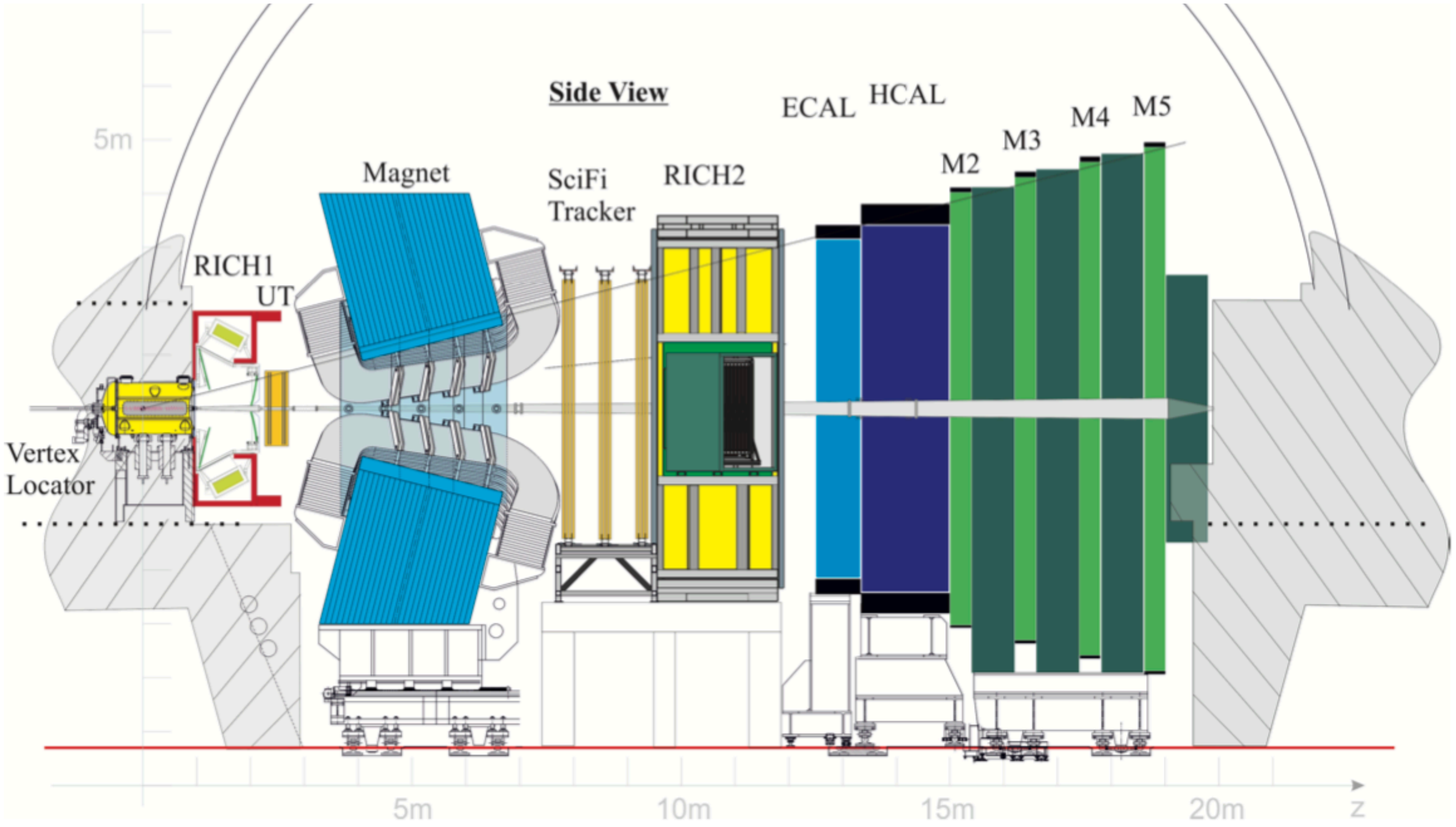
Conclusion & outlook

- $b \to s\ell\ell$ are ideal probes for New Physics
- LHCb intensively studied these processes over the years
  - Measurement precision limited by the statistics available
- Run3 started!
  - LHCb detector undergoing staged upgrades (see talk by Federica Oliva)
    - Replaced vertex, tracking detectors: Better vertex resolution
    - Removed hardware trigger: Better efficiency (especially for the electron modes)
- Measurements from other experiments (Belle II, CMS..) will be fundamental to solve the flavour puzzle

Thank you

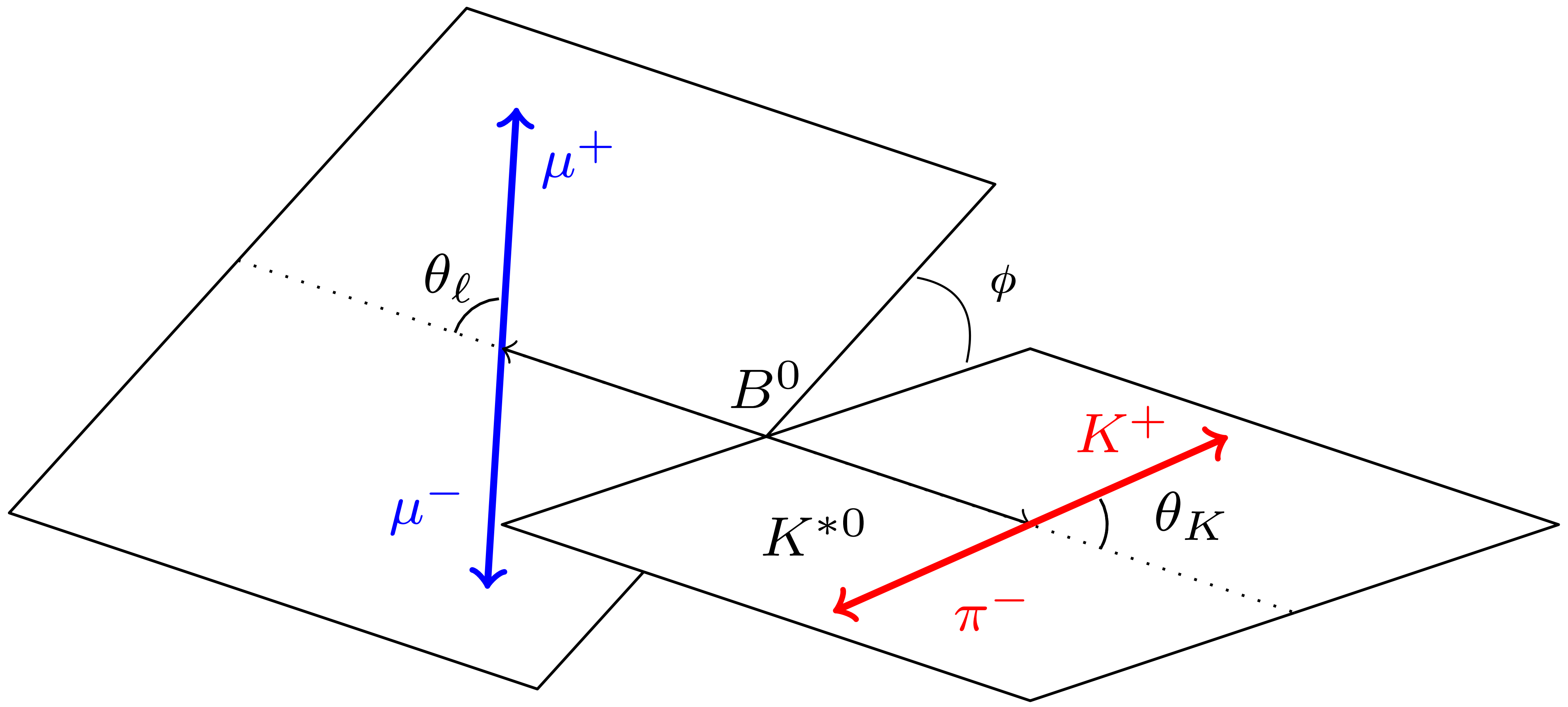
Backup

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

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



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

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

[PRL 128 (2021) 041801](PRL 128 (2021) 041801)

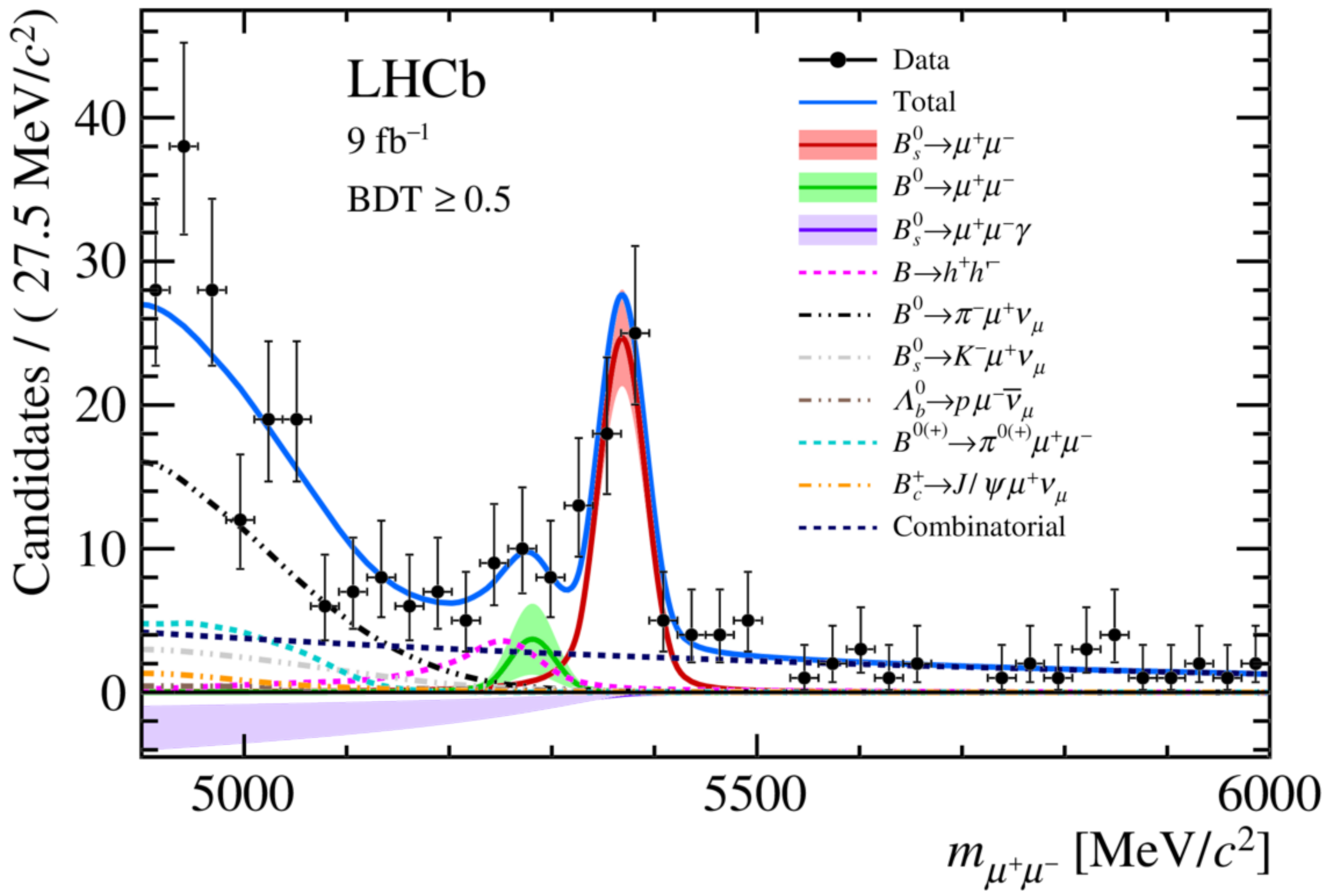
- Helicity suppressed, very rare decays
- Precise SM predictions

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

- Sensitive to axial-vector coupling C_{10}

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

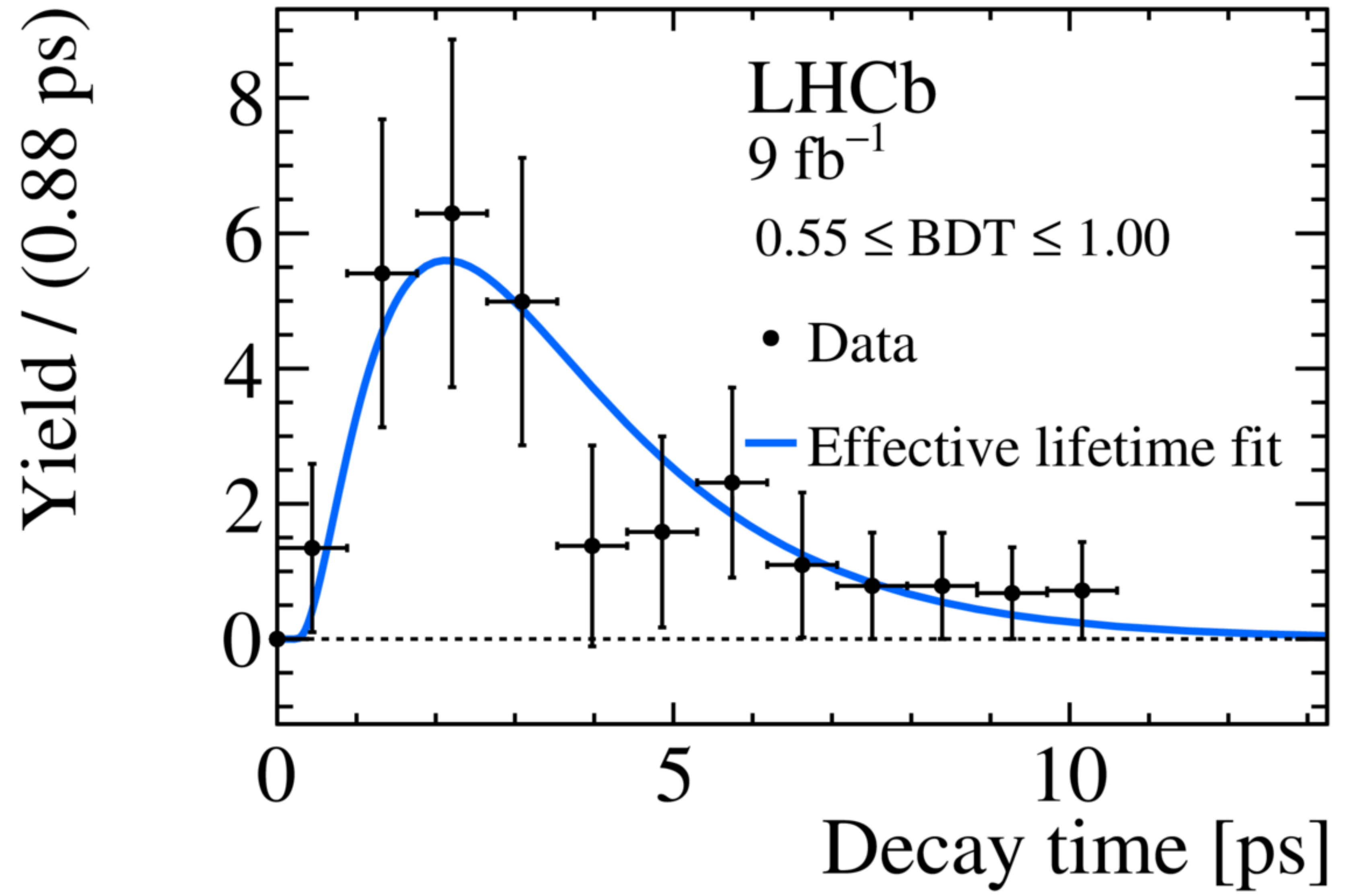
← **First limit**



- 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



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

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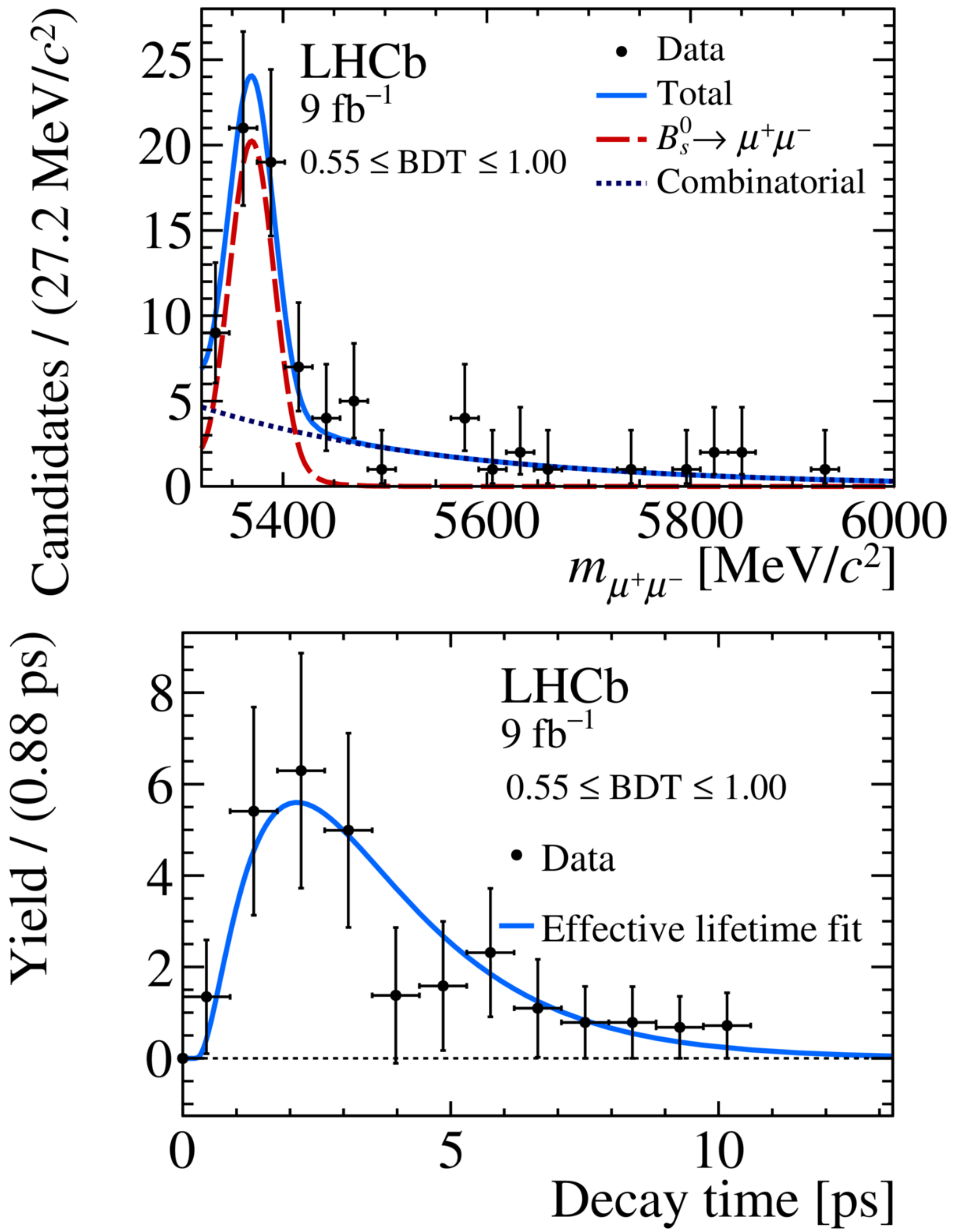


$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

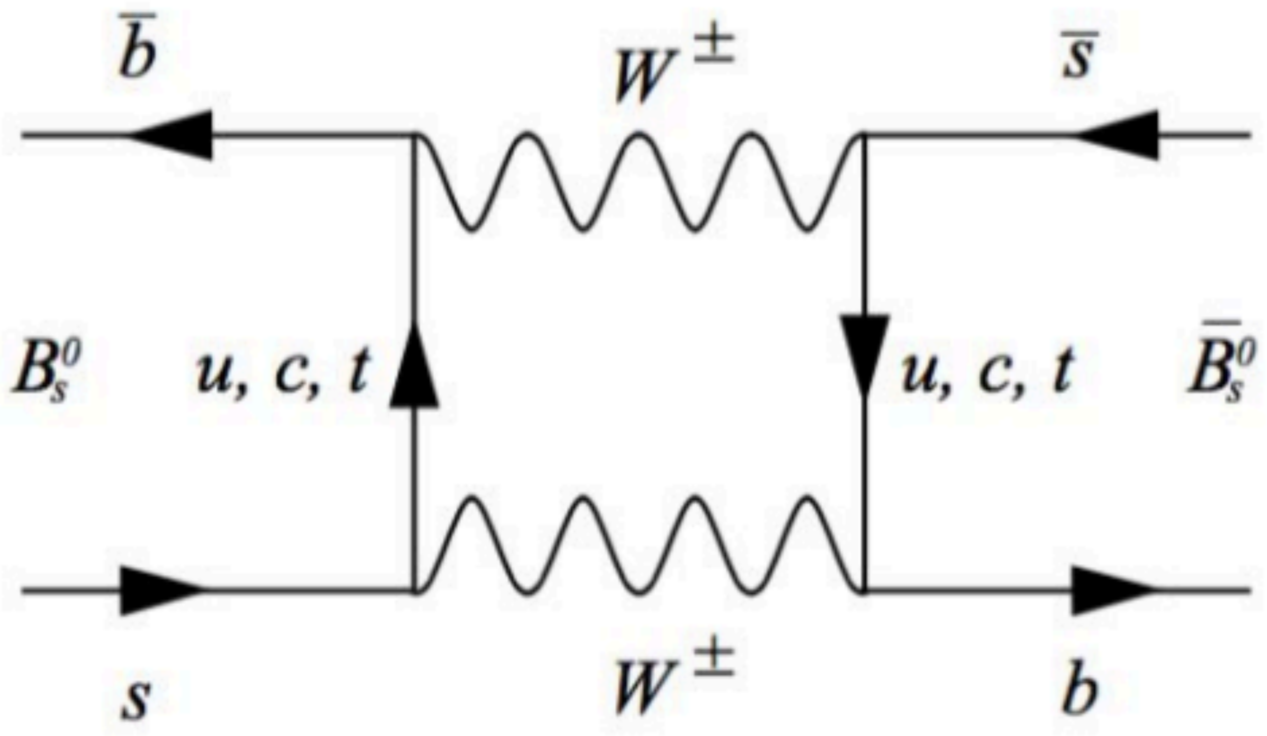
- Oscillations between flavour eigenstates $B_s^0, \bar{B}_s^0$
  - Two mass eigenstates B_H, B_L
  - For SM $B_s^0 \to \mu^+\mu^-$ only from heavy eigenstates
  - $A_{\Delta\Gamma_s}^{\mu\mu}$ sensitive to scalar or pseudo scalar NP contribution: $C_{10}^{(\prime)}, C_S^{(\prime)}, C_P^{(\prime)}$ WCs

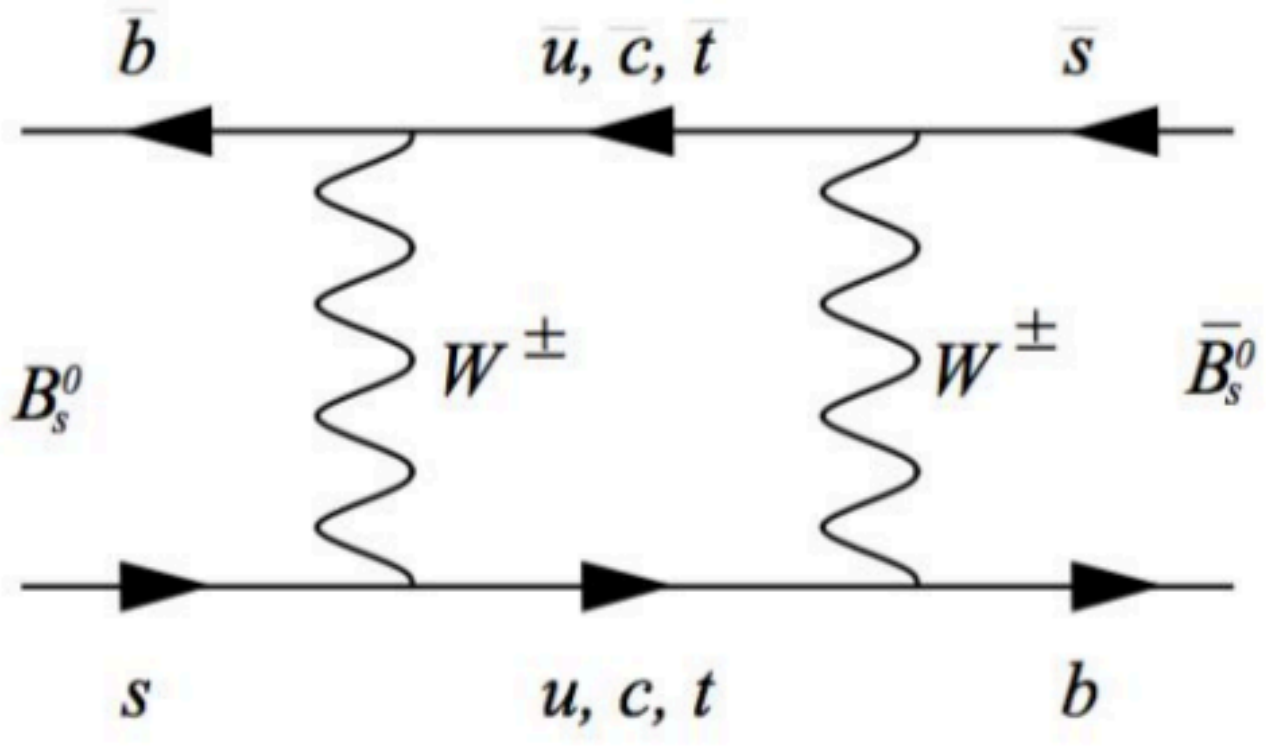
$$\mathcal{A}_{\Delta\Gamma} = \frac{R_H - R_L}{R_H + R_L} \stackrel{SM}{=} 1$$

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

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

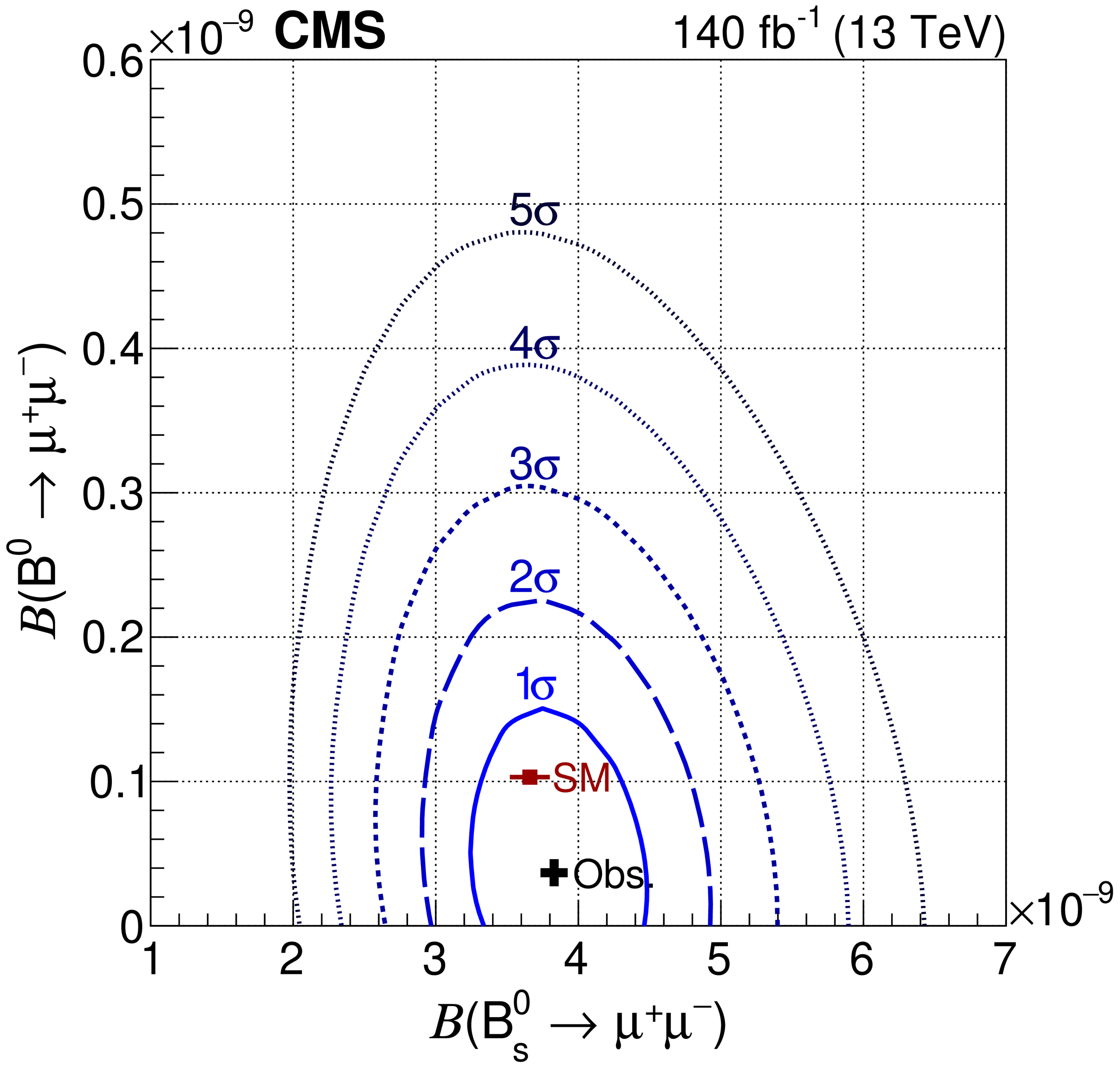
$$\text{with } \lambda = (q/p)(A(\bar{B}_s^0 \to \mu^+\mu^-)/A(B_s^0 \to \mu^+\mu^-)).$$



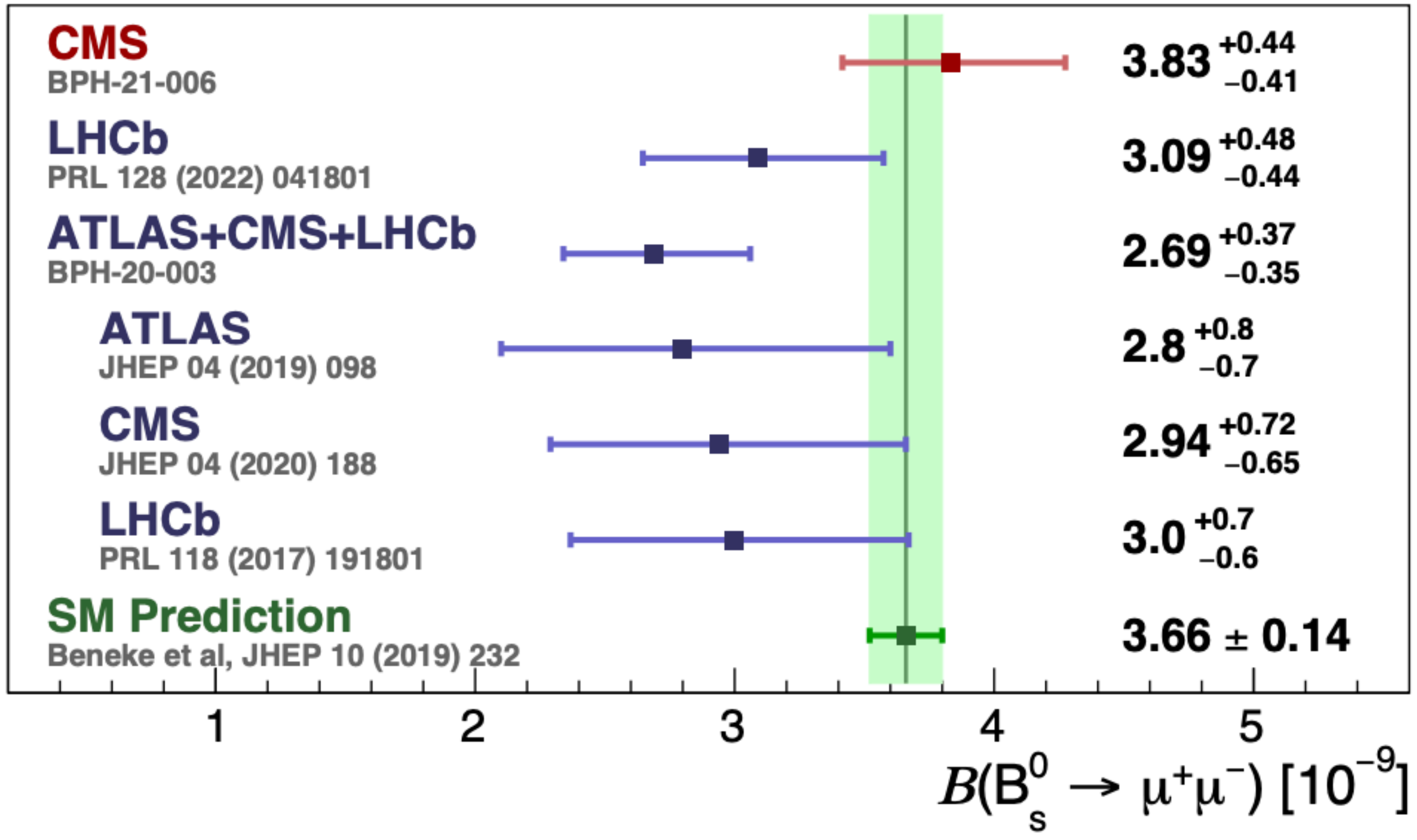


$B_s^0 \to \mu^+\mu^-$

- Helicity suppressed, very rare decay $\mathcal{O}(10^{-9})$
- Fully leptonic final state: Very clean SM predictions (few percent)

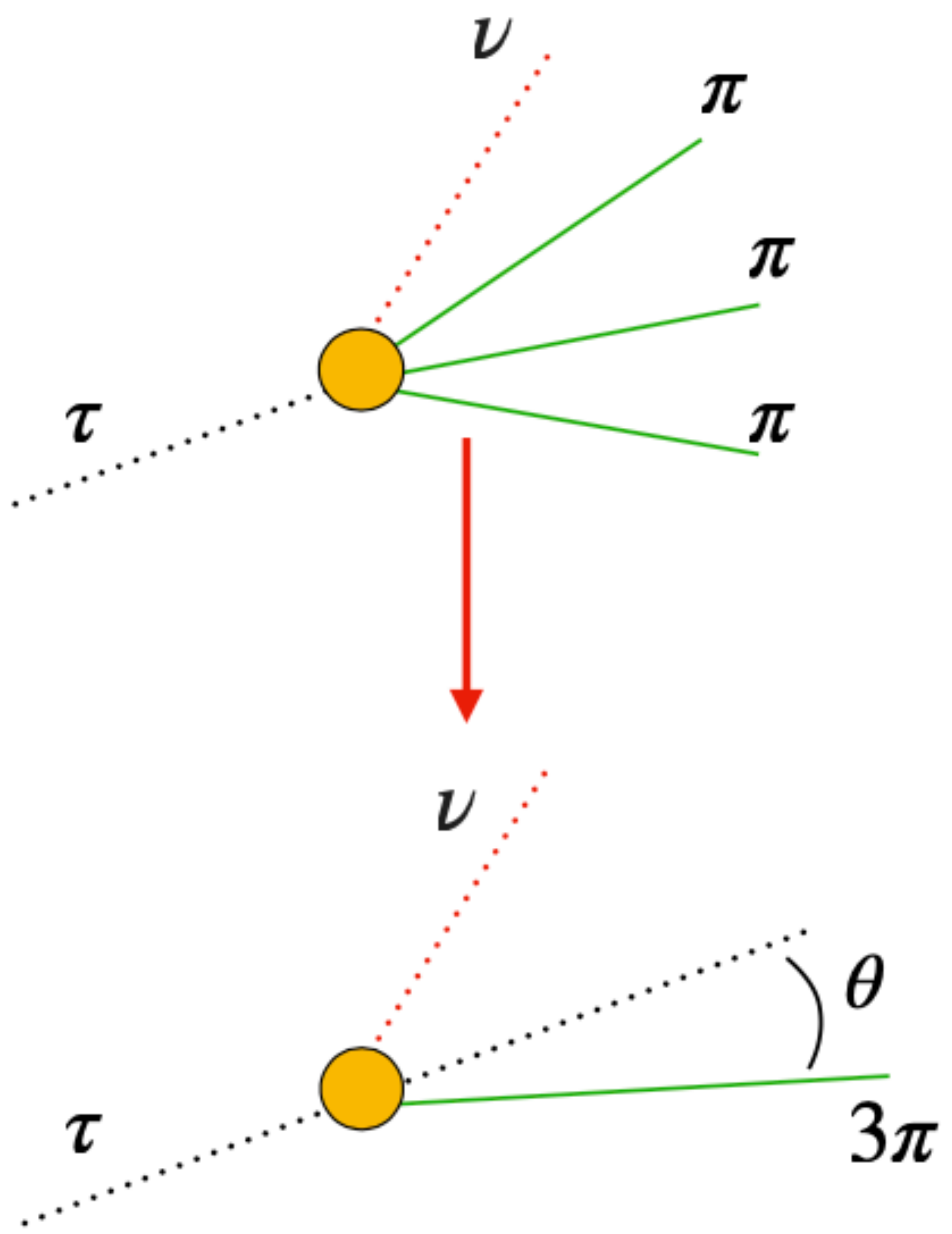


In agreement with the SM within 1σ



Why not $b \to s\tau^+\tau^-$?

- Decay vertex position reconstructed from pions tracks
  - **Minimally corrected mass**: $M_c = \sqrt{M_{vis}^2 + p_{vis}^2 \sin^2\theta} + p_{vis}\sin\theta$
- Hadronic decays can be reconstructed analytically
  - Impose the constraint $m_\tau = 1776.86$ MeV
  - $|\vec{p_\tau}| = \dfrac{(m_\tau^2 + m_{3\pi}^2)|\vec{p}_{3\pi}|\cos\theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p_{3\pi}}|^2\cos^2\theta)}$
- Momentum direction from tau and B decay vertices

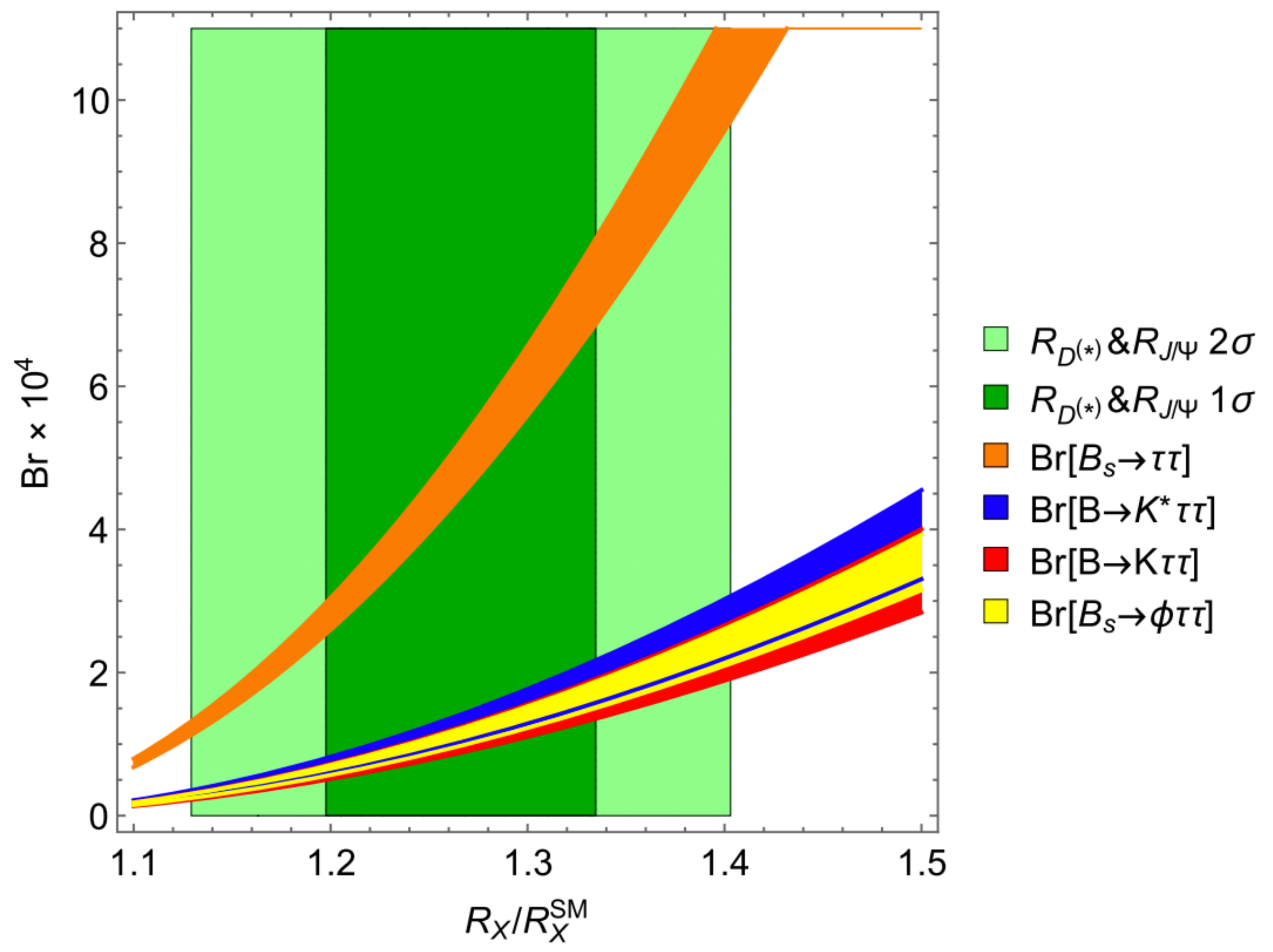


- Refit of the decay chain applying **mass constraints:**
  - Improve mass resolution
  - Need to initialize the fitter, analytic reconstruction can be used
  - Fitter can fail, reduced efficiency

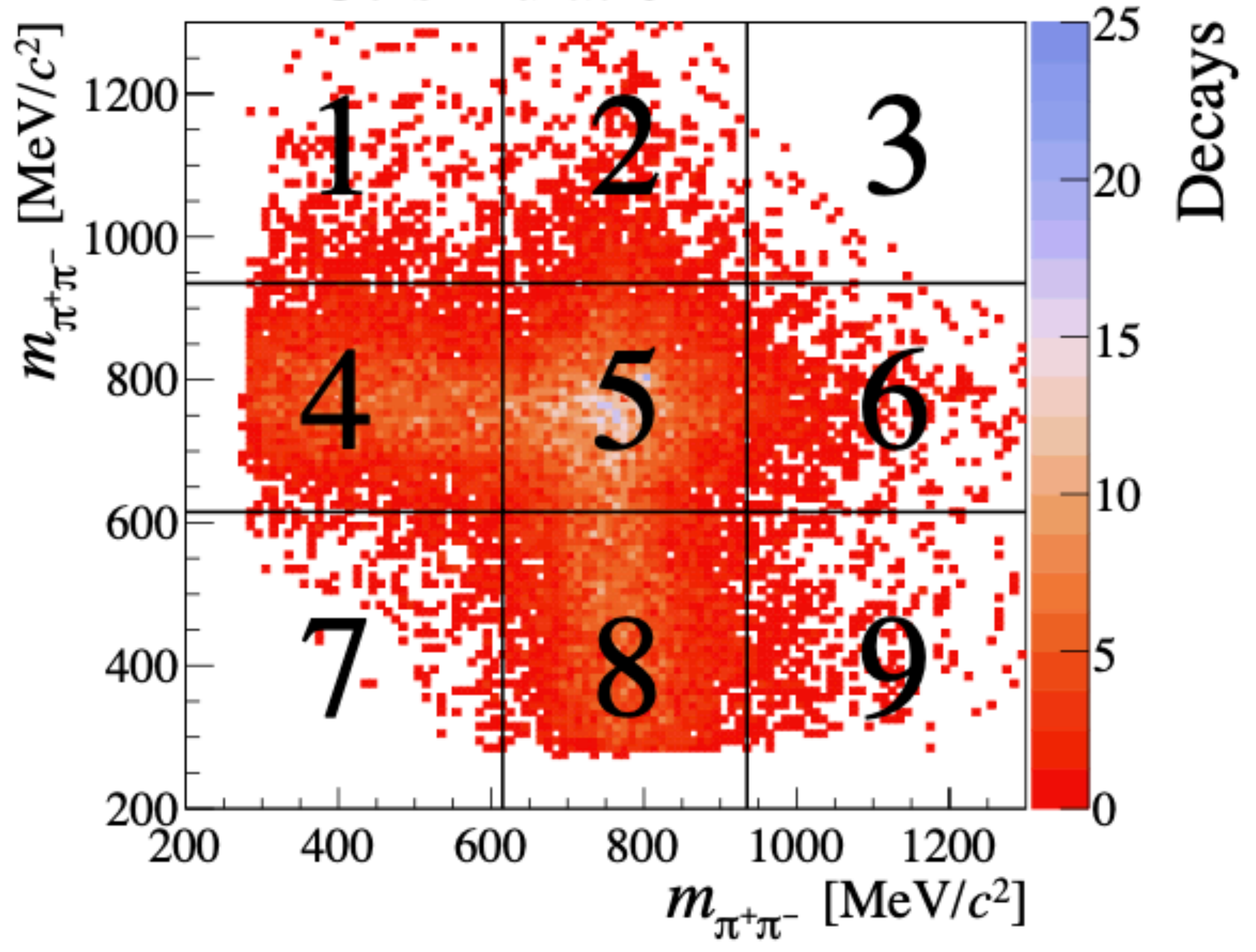
Why not $b \to s\tau^+\tau^-$?

- taus could be the most sensitive to NP, still largely unexplored
- More complex experimentally
  - Neutrinos in the final state, $m(\tau\tau)$ weak discriminant
  - No 4π coverage at LHCb
- Usually searched with : $\tau \to a_1(1260)^-\nu_\tau \to \rho(770)^0\pi^-\nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$
  - Study intermediate resonance forms cross-shape
- Exploit a large variety of MVA techniques
  - Isolation, selection and fit variables
- Difficult choice of control regions to model the background
  - Pseudo-Dalitz plane: define signal and background boxes

PRL 120 (2018) 181802



$B \to \tau\tau$



Decay	SM prediction	Limits @90% CL
$B^0 \to \tau\tau$	$(2.22 \pm 0.19)\cdot 10^{-8}$	$< 1.6 \cdot 10^{-3}$ (LHCb)
$B_s^0 \to \tau\tau$	$(7.73 \pm 0.49)\cdot 10^{-7}$	$< 5.2 \cdot 10^{-3}$ (LHCb)
$B^0 \to K^{*0}\tau\tau$	$(0.98 \pm 0.10)\cdot 10^{-7}$	Ongoing
$B^+ \to K^+\tau\tau$	$(1.20 \pm 0.12)\cdot 10^{-7}$	$< 2.3 \cdot 10^{-3}$ (BaBar)

LHC + LHCb upgrades → 2x yields for fully hadronic decays!

PRL 118 (2017) 251802 PRL 118 (2017) 031802

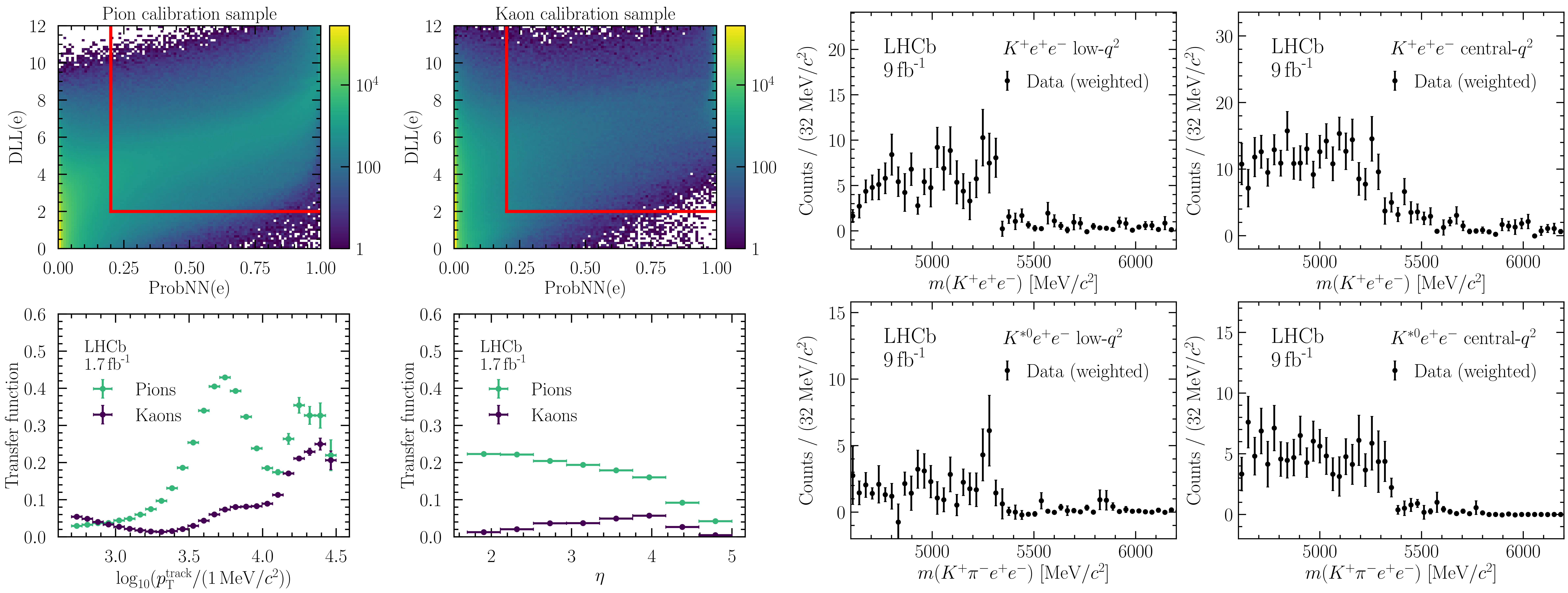
Upgrade

	R_X precision	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$
$b \to s\ell\ell$	R_K	0.043	0.025	0.017
	$R_{K^{*0}}$	0.052	0.031	0.020
	R_ϕ	0.130	0.076	0.050
	R_{pK}	0.105	0.061	0.041
$b \to d\ell\ell$	R_π	0.302	0.176	0.117

arXiv:1808.08865

Observables	Belle $0.71\,\text{ab}^{-1}$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (>14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (>14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (>14.4 GeV^2)	28%	11%	3.4%

Pass-Fail



Pion calibration sample
Kaon calibration sample
DLL(e)
ProbNN(e)
LHCb
1.7 fb-1
Pions
Kaons
Transfer function
$\log_{10}(p_{\mathrm{T}}^{\mathrm{track}}/(1\,\mathrm{MeV}/c^2))$
η
LHCb
9 fb-1
$K^+e^+e^-$ low-q^2
$K^+e^+e^-$ central-q^2
$K^{*0}e^+e^-$ low-q^2
$K^{*0}e^+e^-$ central-q^2
Data (weighted)
Counts / (32 MeV/c^2)
$m(K^+e^+e^-)$ [MeV/c^2]
$m(K^+\pi^-e^+e^-)$ [MeV/c^2]