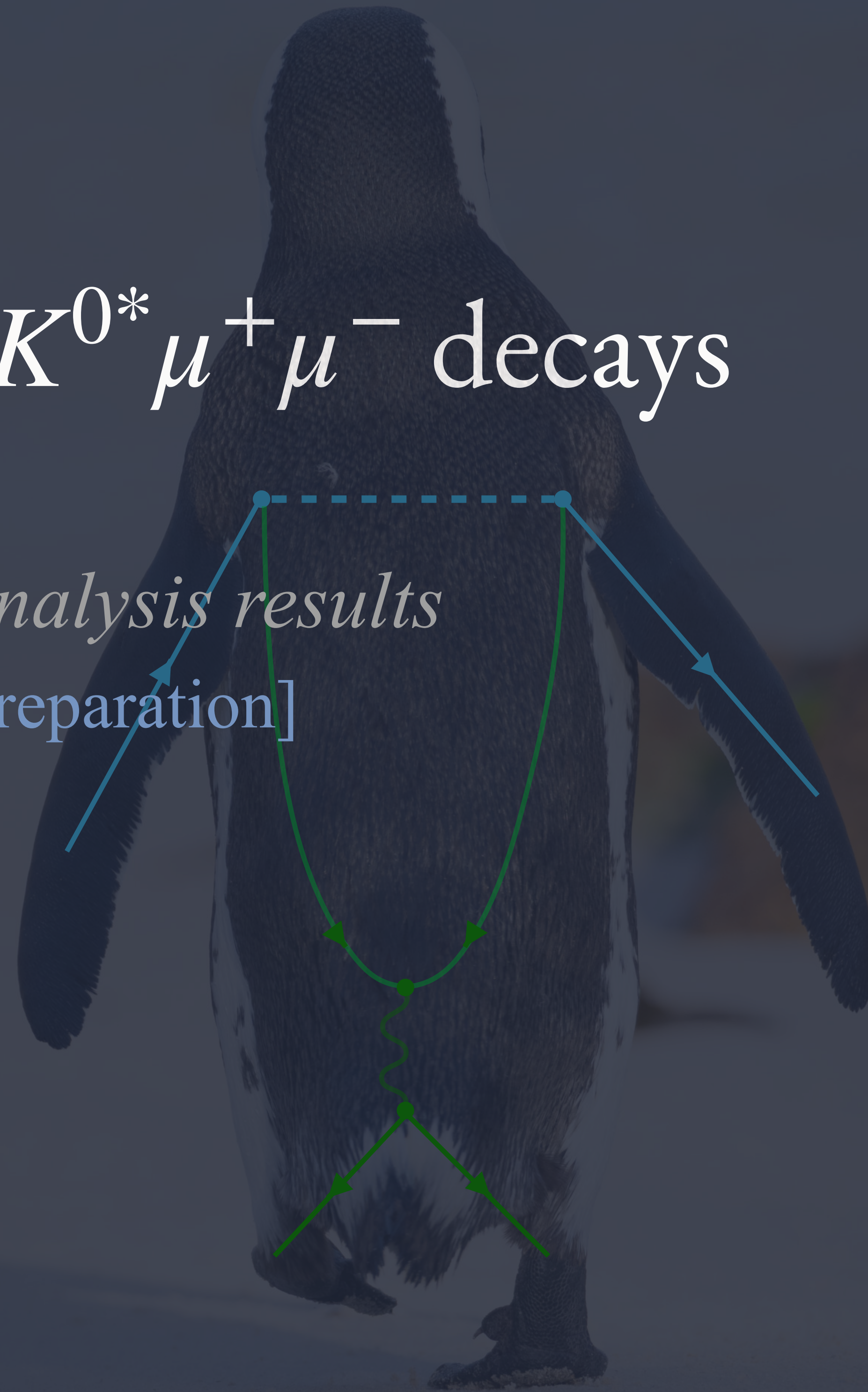
Effective couplings in $B^0 \to K^{0*}\mu^+\mu^-$ decays



On the recent LHCb amplitude analysis results

LHCb-PAPER-2023-32/33 [in preparation]

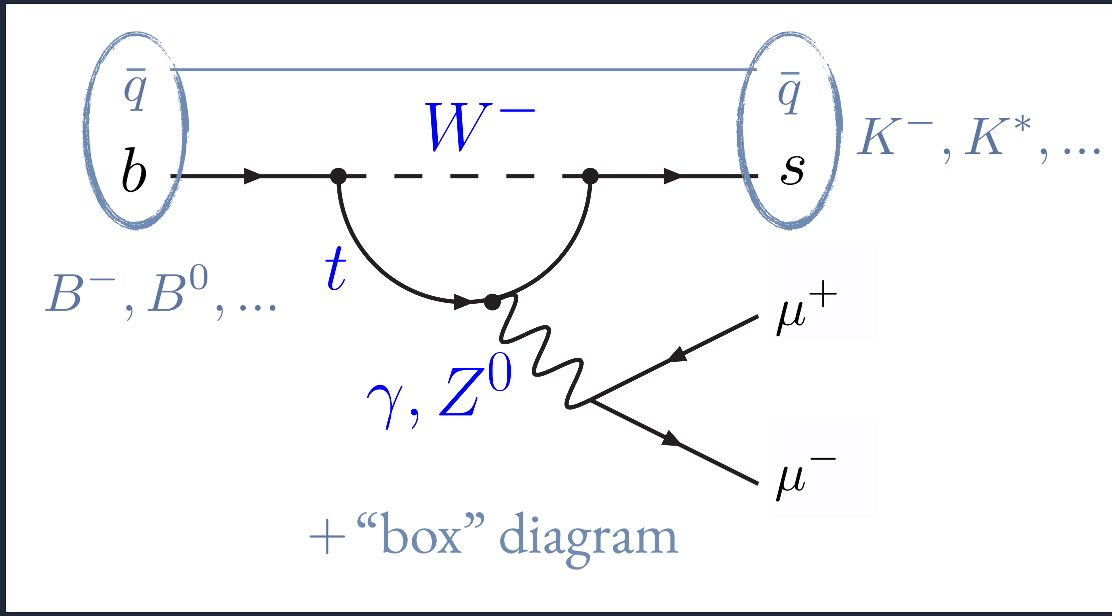
Rafael Silva Coutinho

Syracuse University

6th General Meeting of the LHC EFT Working Group
November 17th, 2023

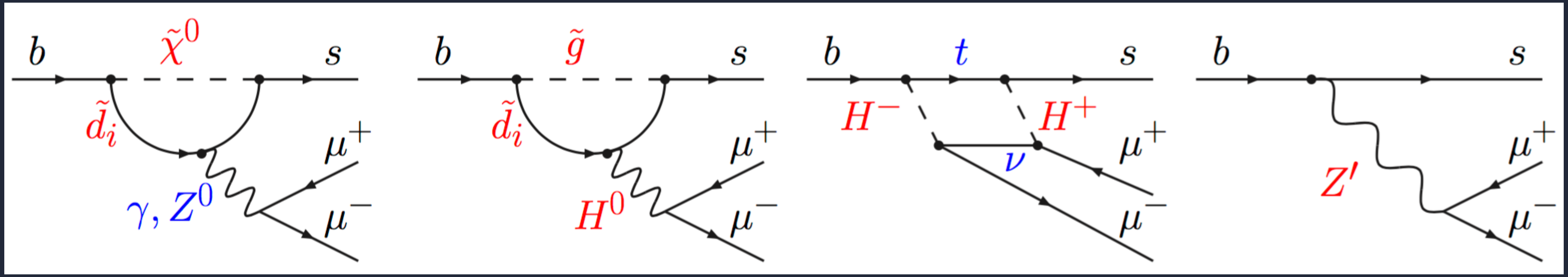
RARE DECAYS AS A PROBE OF NEW PHYSICS

FCNC: UNIQUE GLIMPSE TO HIGHER SCALE



[*E.G.* ENHANCEMENT/SUPPRESSION OF DECAY RATE, ANGULAR DISTRIBUTIONS AND NEW SOURCES OF ~~CP~~]

NEW PARTICLES CAN CONTRIBUTE AT LOOP AND/OR TREE LEVEL



Rare Decays as a Probe of New Physics

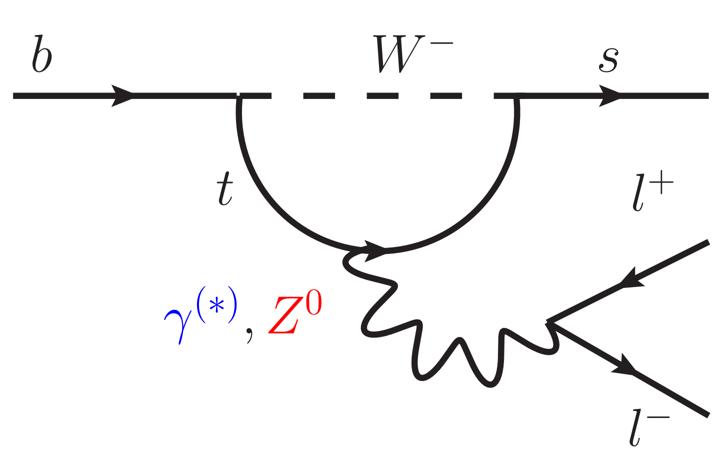
Rare B Decays are a Multi-Scale Problem: $\Lambda^2_{\rm NP} \gg m_W \gg m_b > \Lambda_{\rm QCD}$

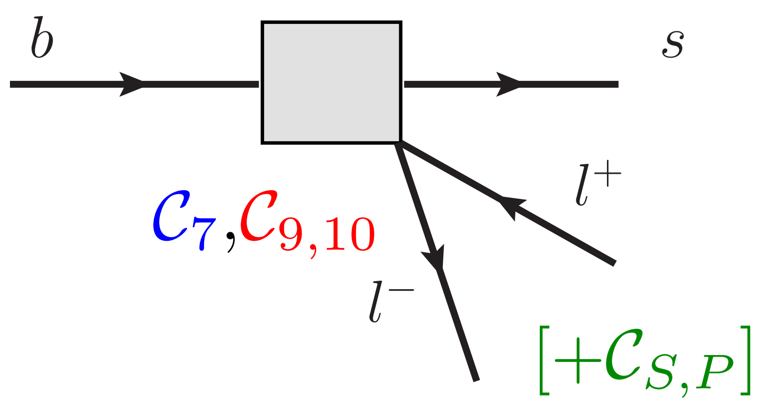
FCNC Effective Hamiltonian Described as OPE

Wilson coefficients ("effective coupling") **Local operator**

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

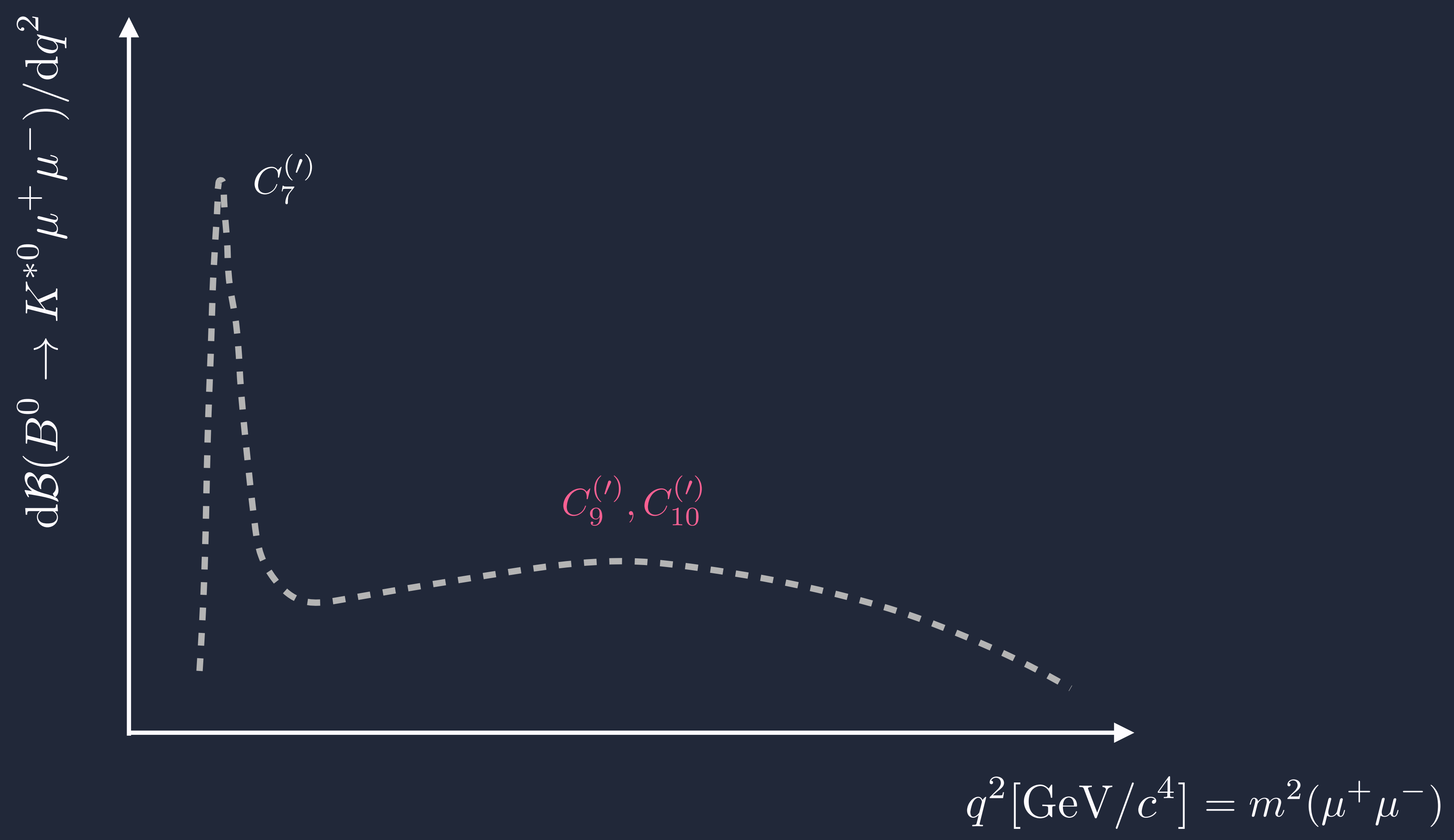




- $B^0_{(s)} \to l^+ l^-$
  $[\mathcal{C}_{10}, \mathcal{C}_S, \mathcal{C}_P]$
- $b \to s l^+ l^-$
  $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

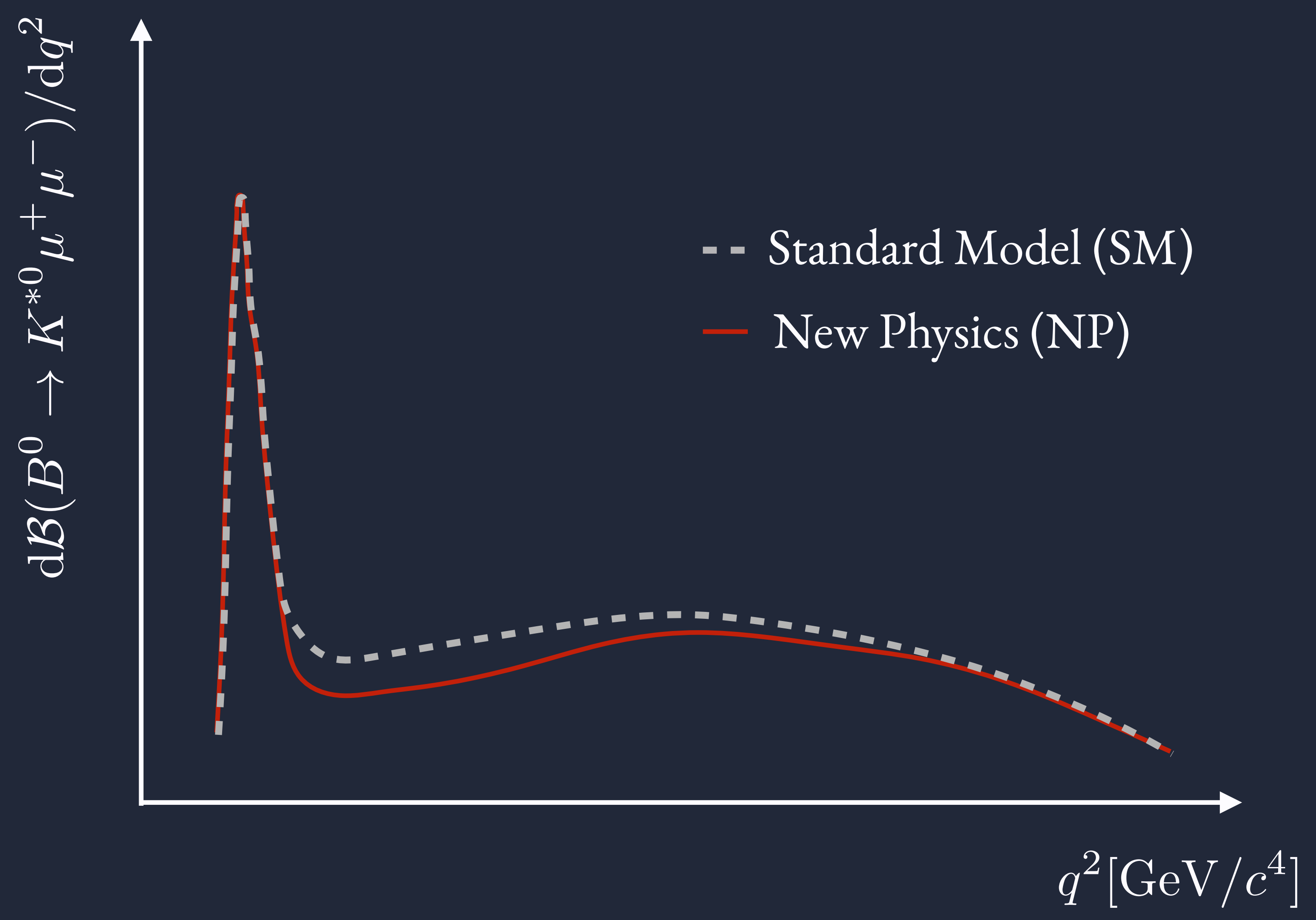
The $B^0 \to K^{*0}\mu^+\mu^-$ Decay Mode

Rich Phenomenology to Explore Experimentally



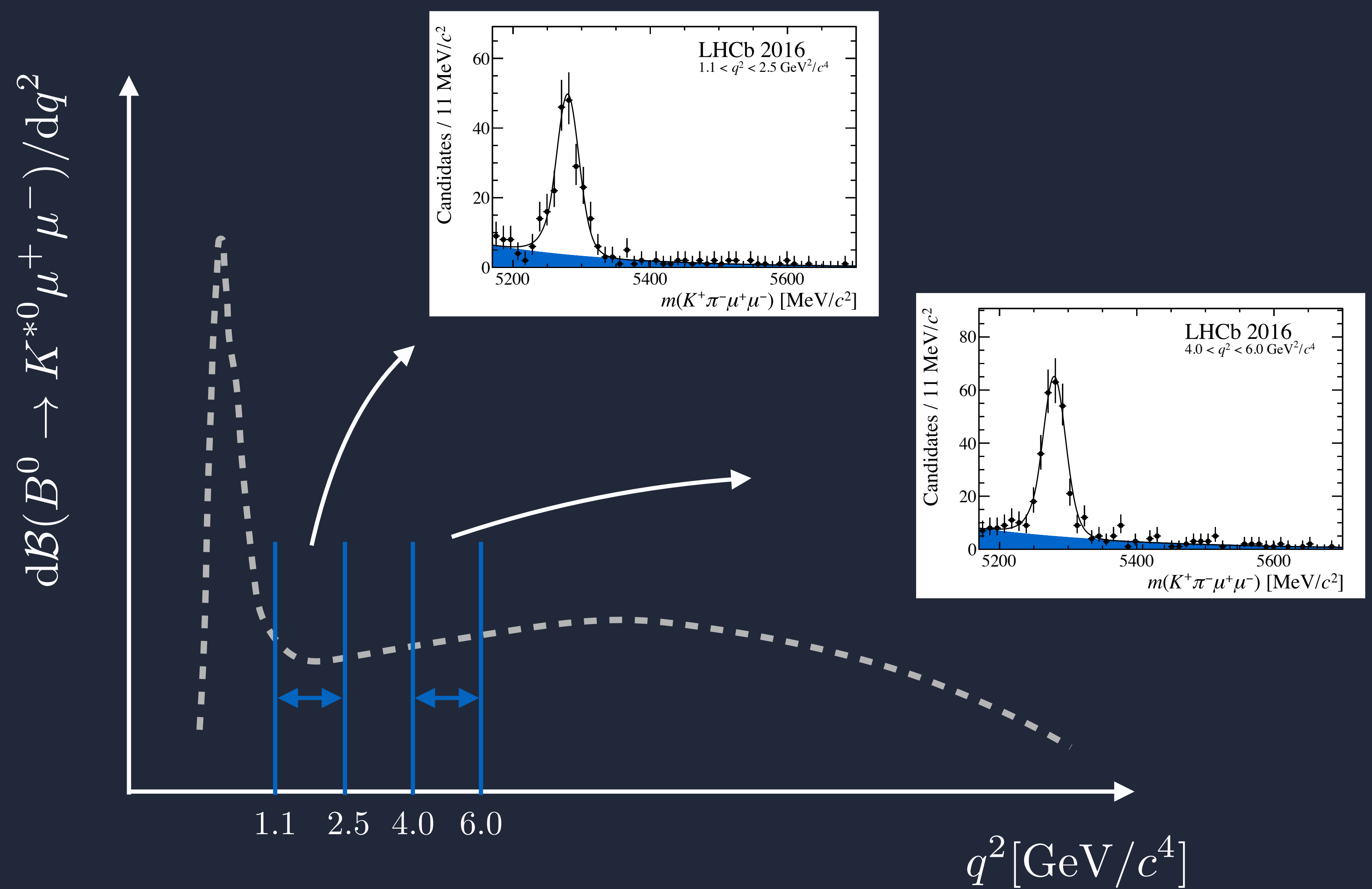
THE $B^0 \to K^{*0}\mu^+\mu^-$ DECAY MODE

RICH PHENOMENOLOGY TO EXPLORE EXPERIMENTALLY



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

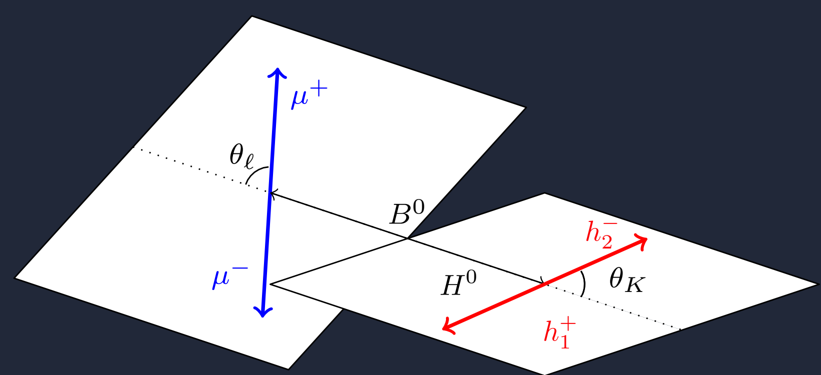
Rich Phenomenology to Explore Experimentally

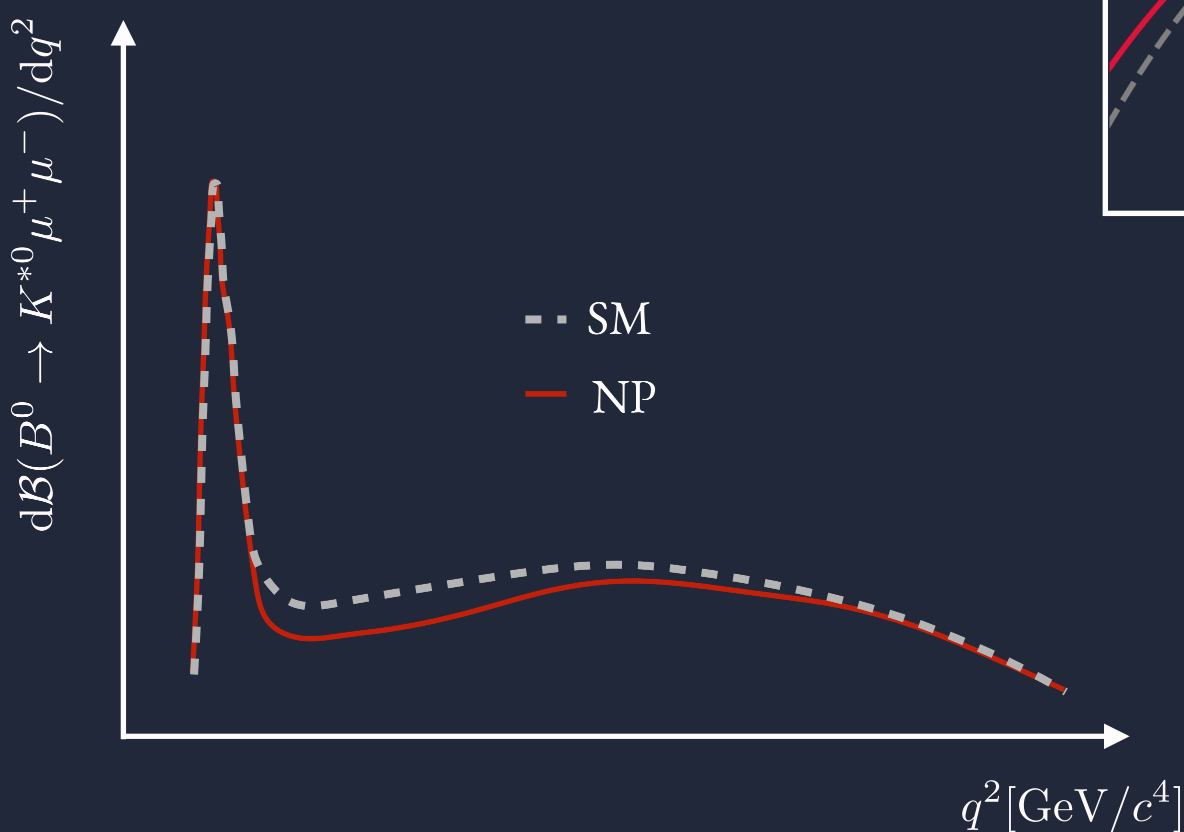


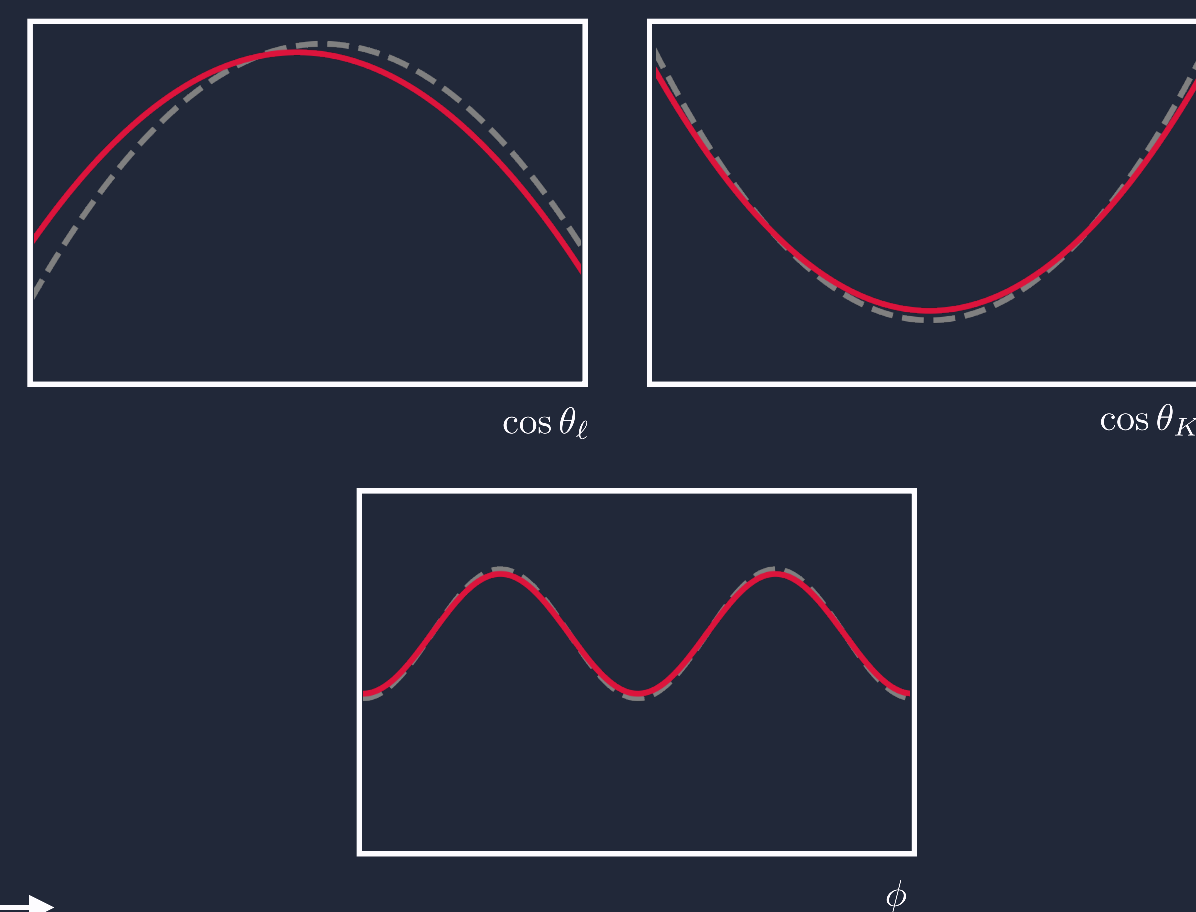
The $B^0 \to K^{*0}\mu^+\mu^-$ Decay Mode

spin-1

Rich Phenomenology to Explore Experimentally







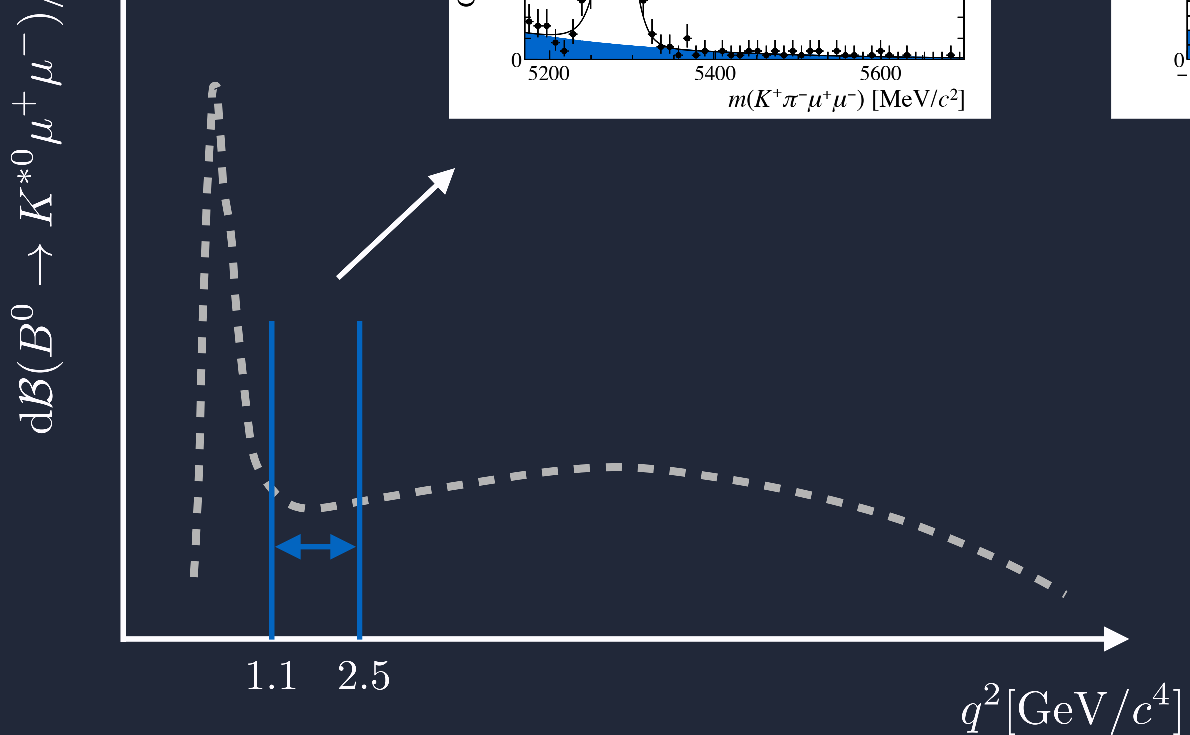
The $B^0 \to K^{*0}\mu^+\mu^-$ Decay Mode

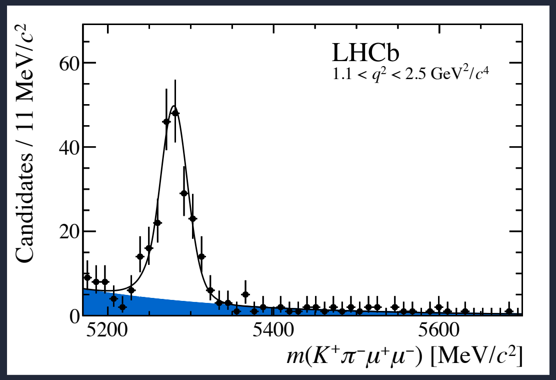
spin-1

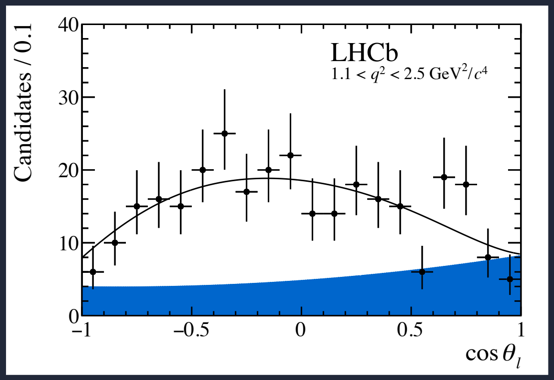
Rich Phenomenology to Explore Experimentally

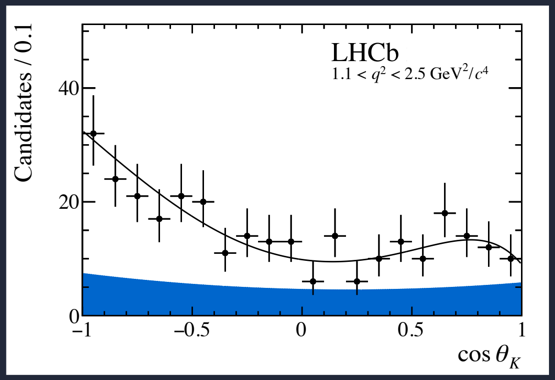
$$\frac{d\Gamma}{dq^2 d\vec{\Omega}} \propto \sum_i I_i(q^2) f_i(\vec{\Omega})$$

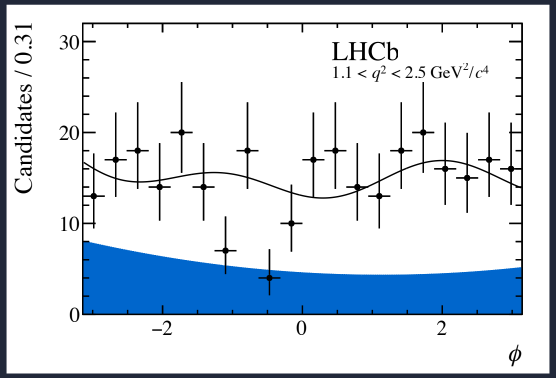
$\vec{\Omega} = \cos\theta_\ell, \cos\theta_K, \phi$









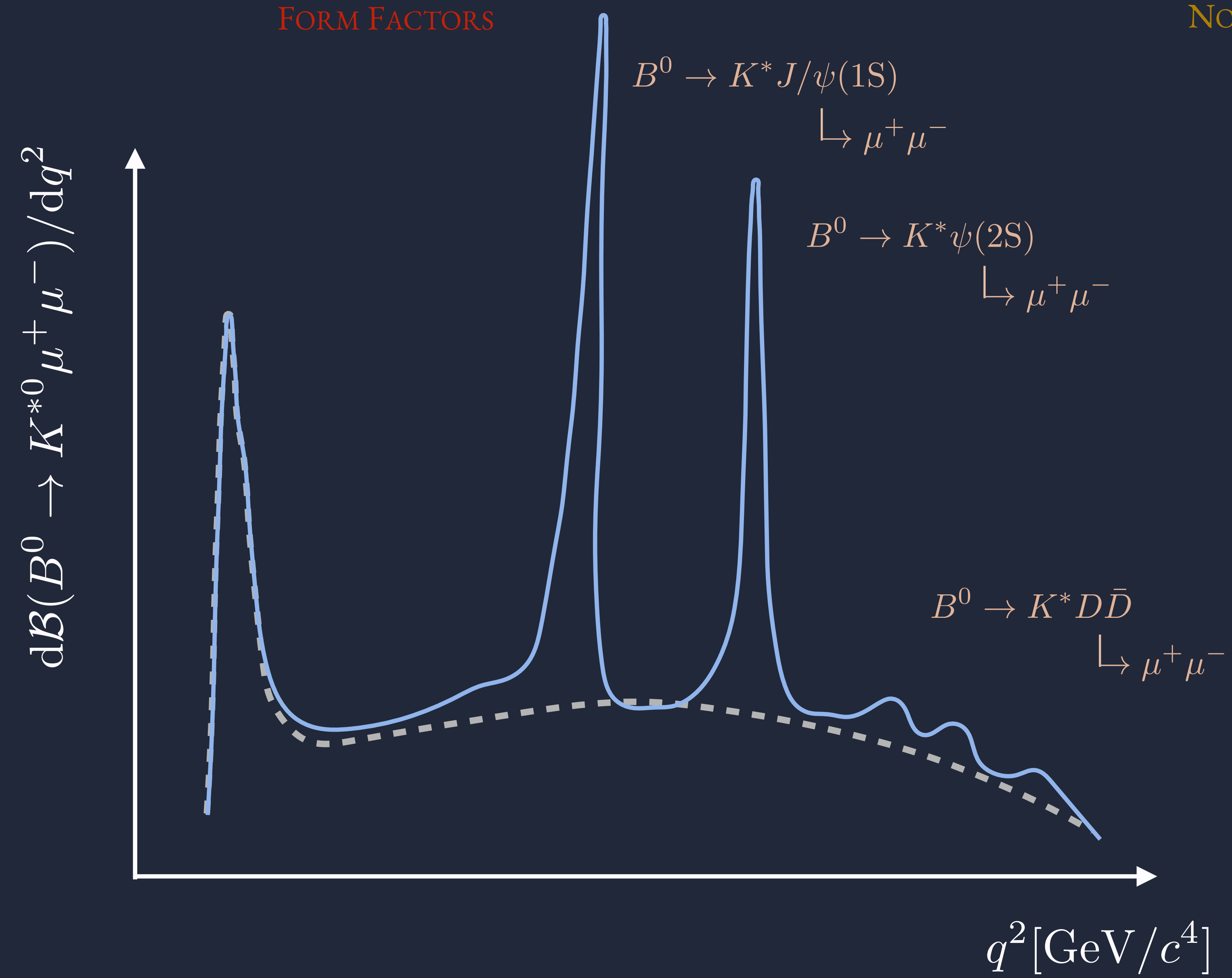


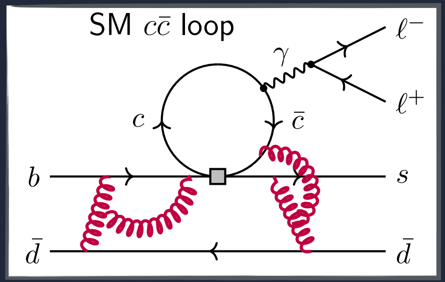
The $B^0 \to K^{*0}\mu^+\mu^-$ Decay Mode

$$\mathcal{A}_\lambda^{L,R} \propto \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')\right]\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[(C_7 \pm C_7')\mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]$$

Form Factors

Non-Local contributions
"Charm Loops"

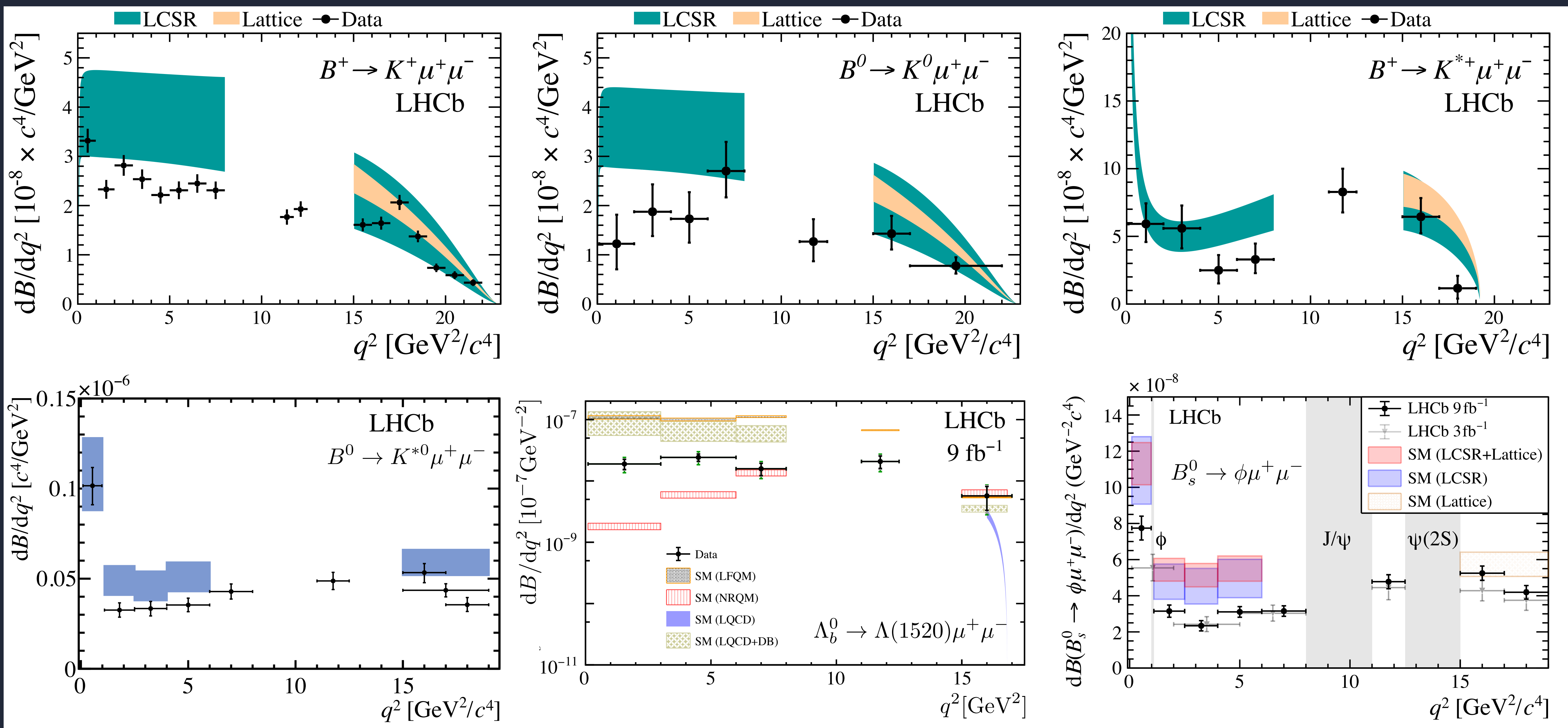




$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9^{\text{SM}} + \mathcal{C}_9^{c\bar{c}}$$

$b \to s\mu^+\mu^-$ Decay Rates

[LHCb, JHEP 06 (2014) 133, 11 (2016) 047, 06 (2015) 115, PRL 127 (2021) 151801]



Decay Rates Systematically Below the SM Predictions

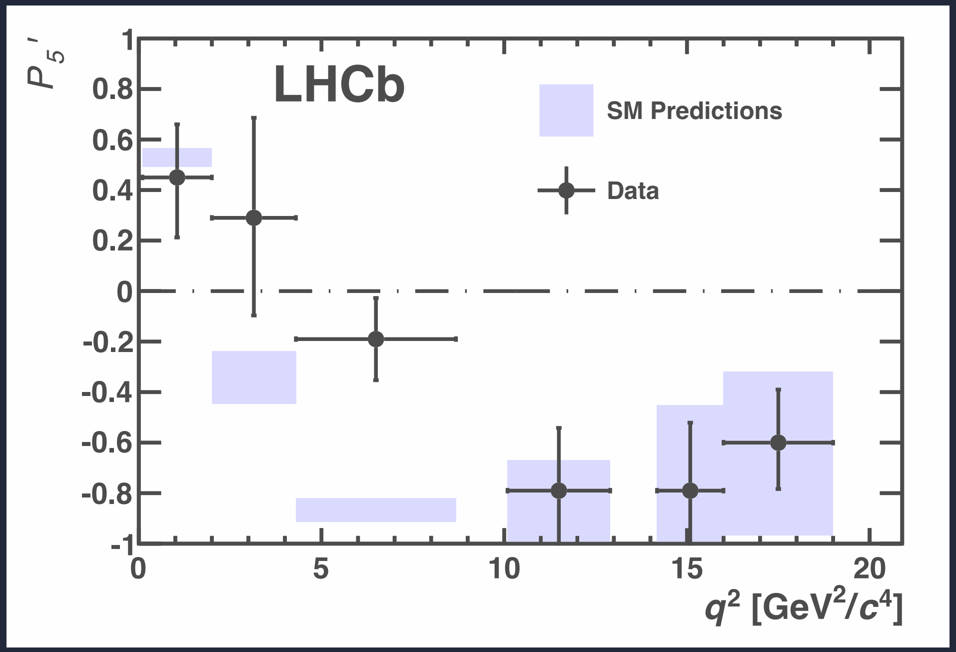
+

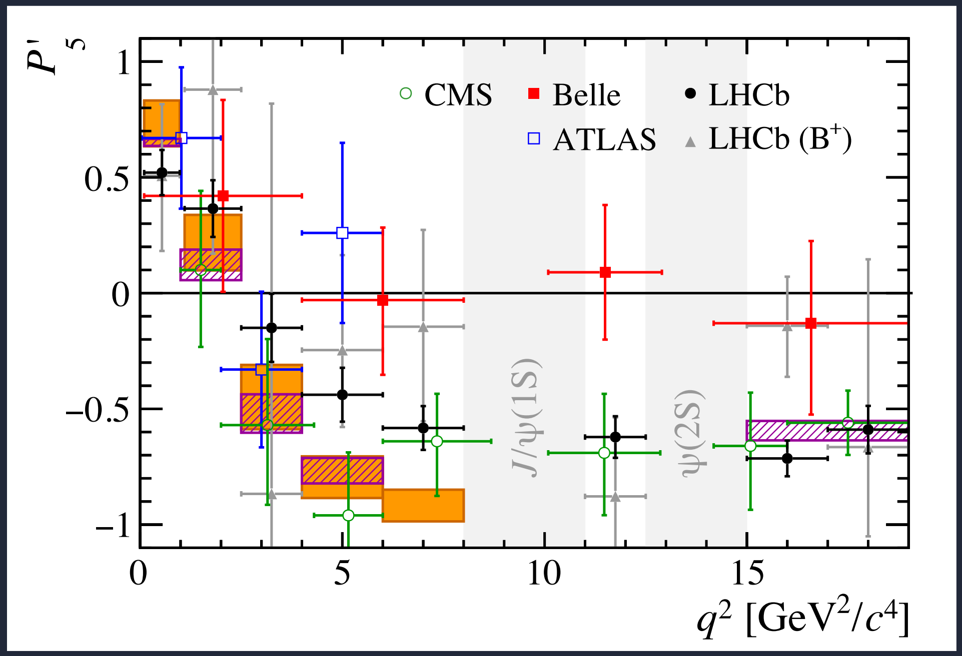
$b \to s\mu^+\mu^-$ Angular Analyses

[PRL 125 (2020) 011802, 126 (2021) 161802, JHEP 11 (2021) 043, 12 (2016) 065, 09 (2018) 146]

(In)Famous P_5'

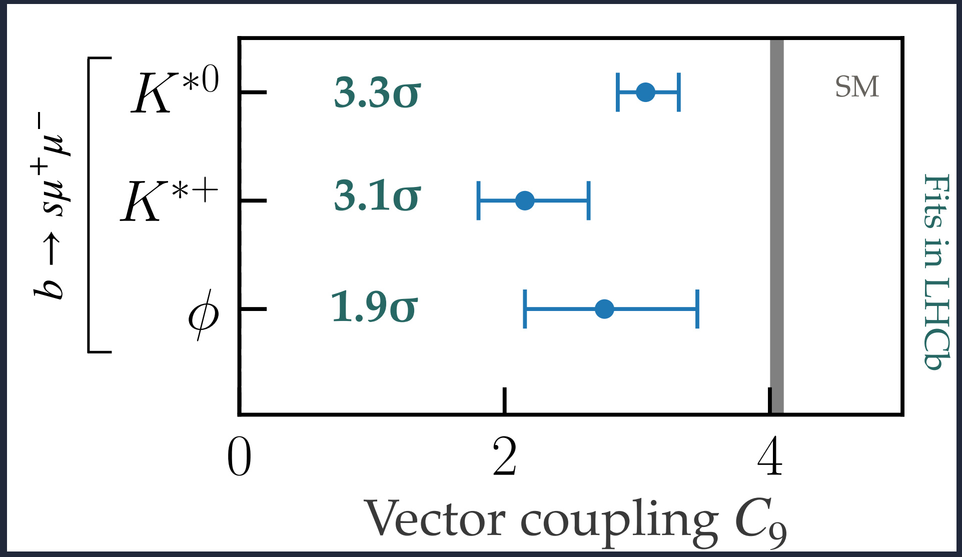
10th Year Anniversary!





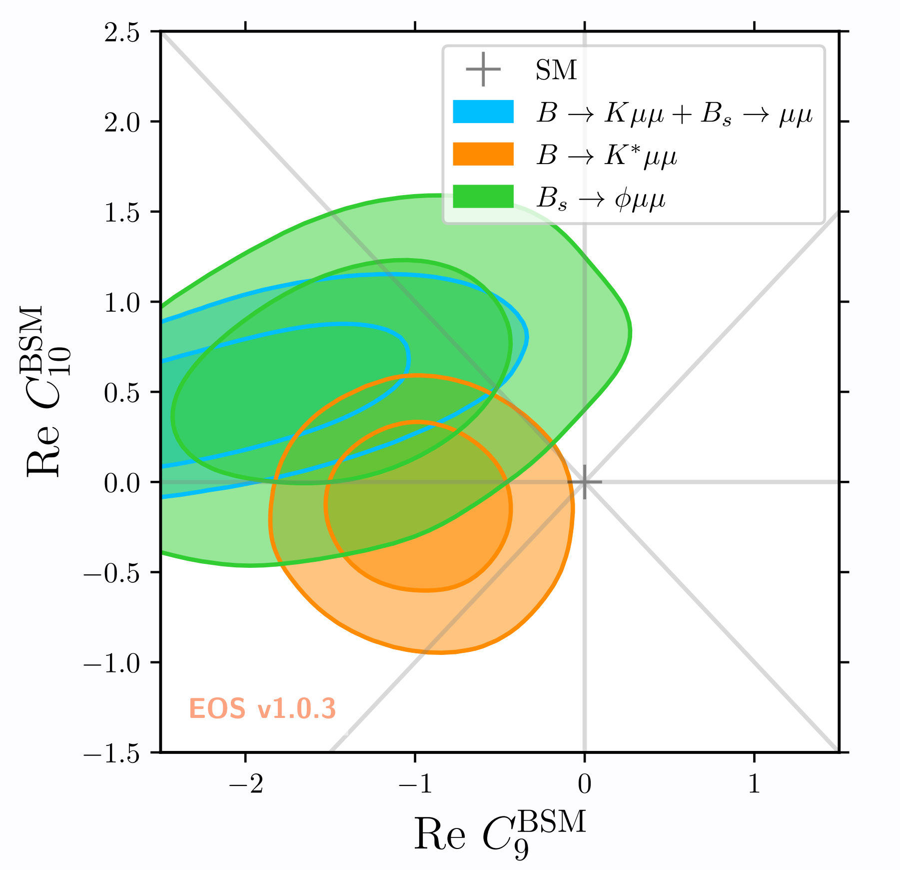
Leading Form Factors Uncertainties are Cancelled

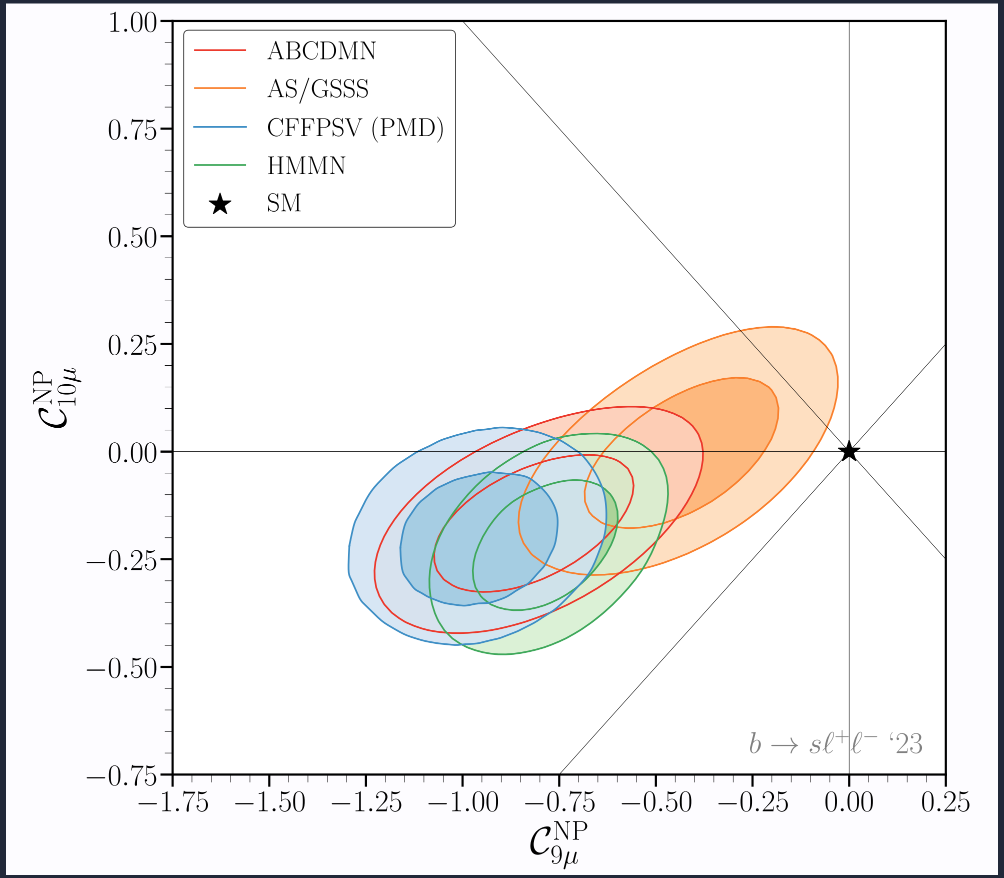
Similar Discrepancy wrt the SM Predictions



Global Analyses

Many Global Fits Available in the Literature, with Different Inputs, Statistical/Theory Assumptions ...





[Gubernari et al. JHEP 09 (2022) 133]
[Greljo et al. JHEP 05 (2023) 087]
[Alguero et al. EPJ C83 (2023) 648]
[Ciuchiniet et al. PRD 107 (2023) 055036]
[Hurth, Mahmoudi, Neshatpour arXiv:2310.05585]
[Capdevile, Crivellin, Matias arXiv:2309.01311]

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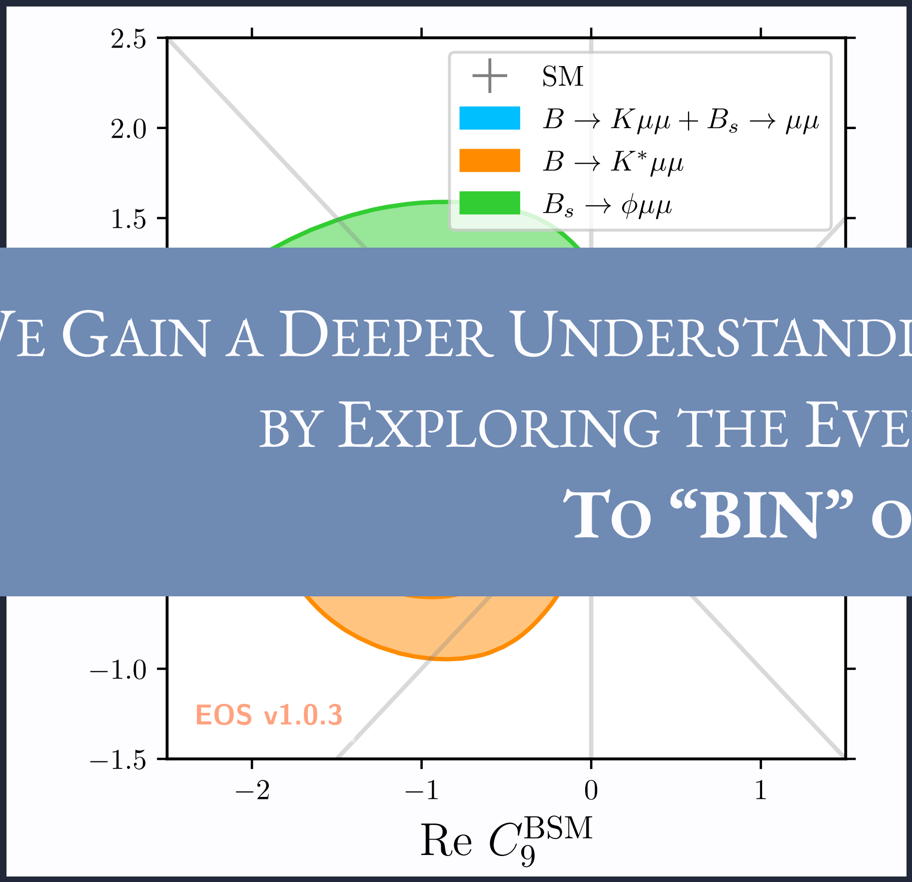
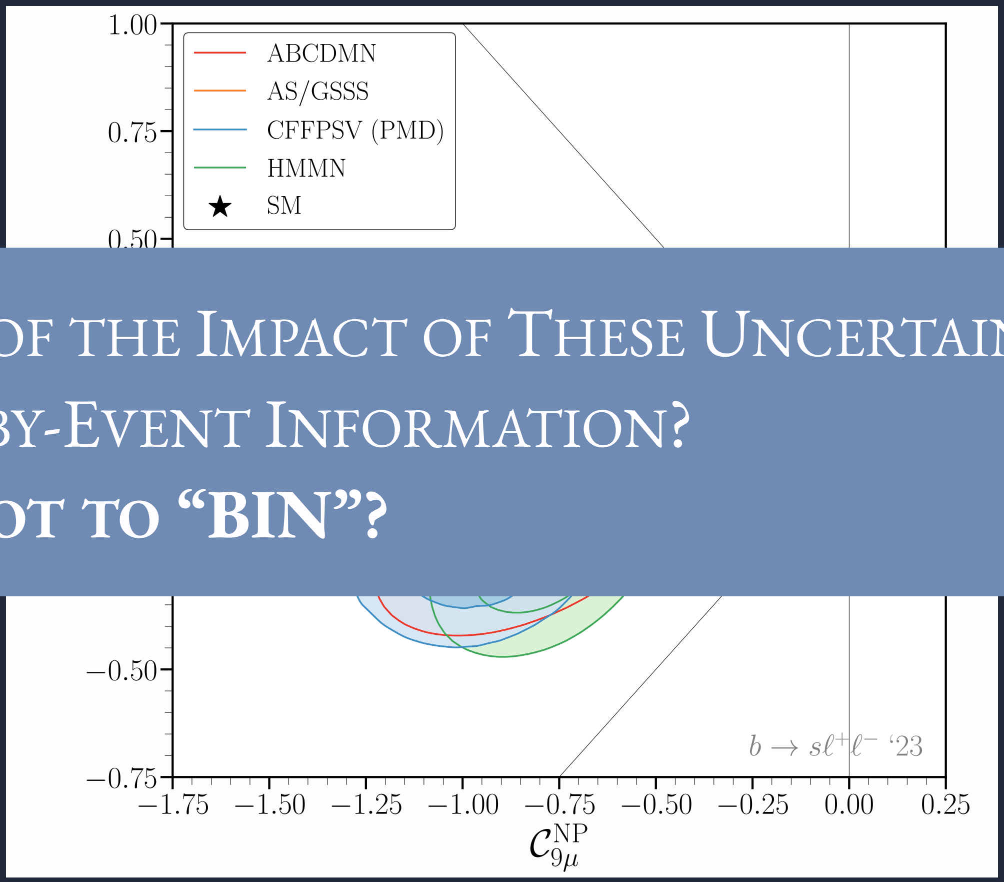




Can We Gain a Deeper Understanding of the Impact of These Uncertainties by Exploring the Event-by-Event Information?

To "BIN" or not to "BIN"?

[Gubernari et al. JHEP 09 (2022) 133]
[Greljo et al. JHEP 05 (2023) 087]
[Alguero et al. EPJ C83 (2023) 648]
[Ciuchiniet et al. PRD 107 (2023) 055036]
[Hurth, Mahmoudi, Neshatpour arXiv:2310.05585]
[Capdevile, Crivellin, Matias arXiv:2309.01311]

Analysis in a Nutshell

Perform a 5D Model-dependent Amplitude Fit $(q^2, \cos\theta_\ell, \cos\theta_k, \phi, m^2_{K\pi})$

Disentangle $(K\pi)^{*0}_0$ contributions

- Maximal Sensitivity to Non-local Hadronic Effects (and New Physics)

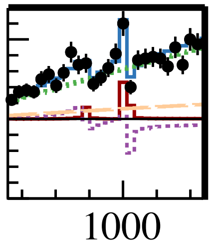
$$\mathcal{A}_\lambda^{L,R} \propto \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')\right]\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[(C_7 \pm C_7')\mathcal{F}_\lambda^T(q^2) - 16\pi^2\frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]$$

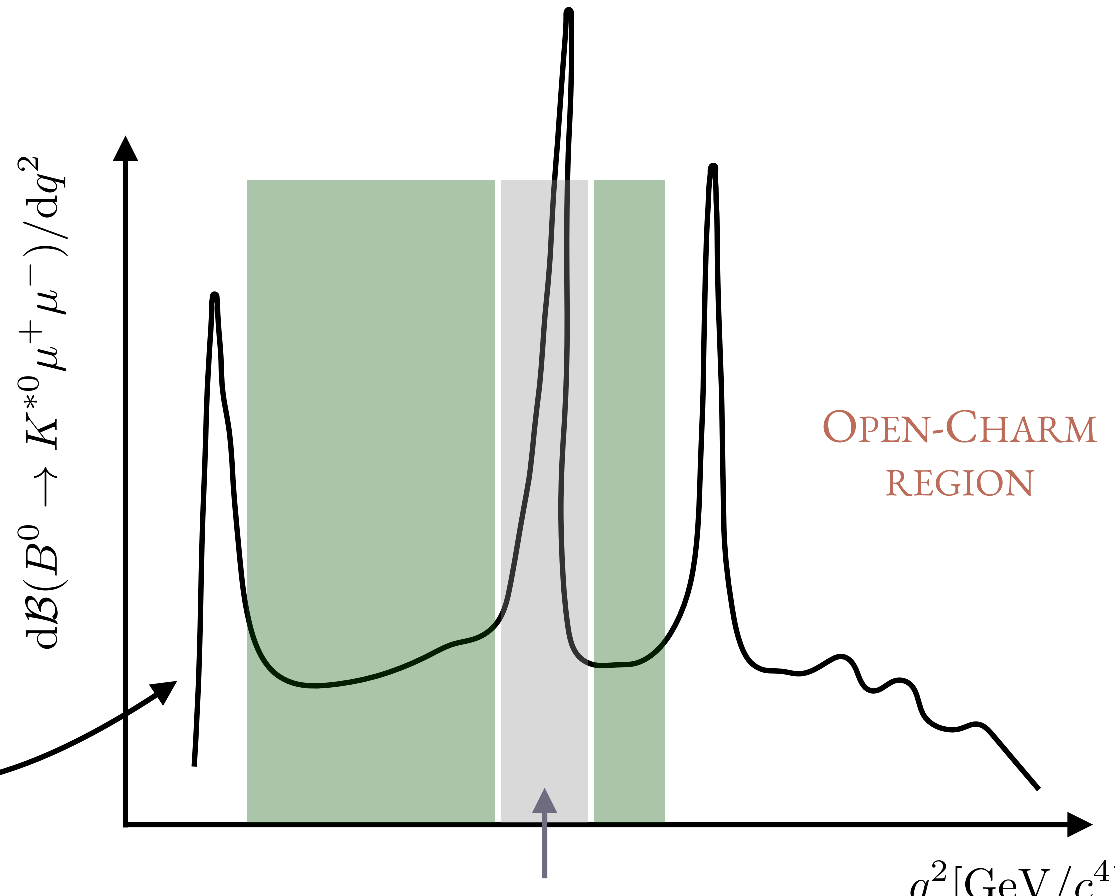
- Unbinned Dataset [Same as binned analysis PRL 125 (2020) 011802]

  [1.1, 8.0] GeV² and [11, 12.5] GeV²

- Avoid Light Resonances and Open Charm Regions

e.g. $B^+ \to K^+\mu^+\mu^-$ analysis [EPJC 77 (2017) 161]





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Local form factors (FFs) constrained to:

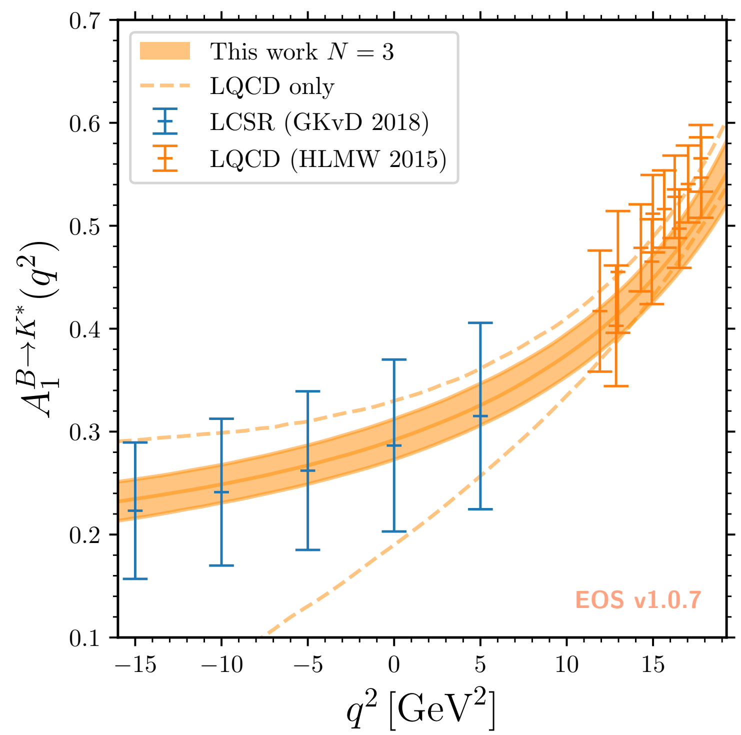
- Light-cone sum rules

[Gubernari, Kokulu, van Dyk; JHEP 01 (2019) 150]

- Lattice QCD

[Horgan, Liu, meinel, Wingate;
PRD 89 (2014) 094501
PoS LATTICE2014 (2015) 372]

[Gubernari, Reboud, van Dyk, Virto; arXiv:2305.06301]



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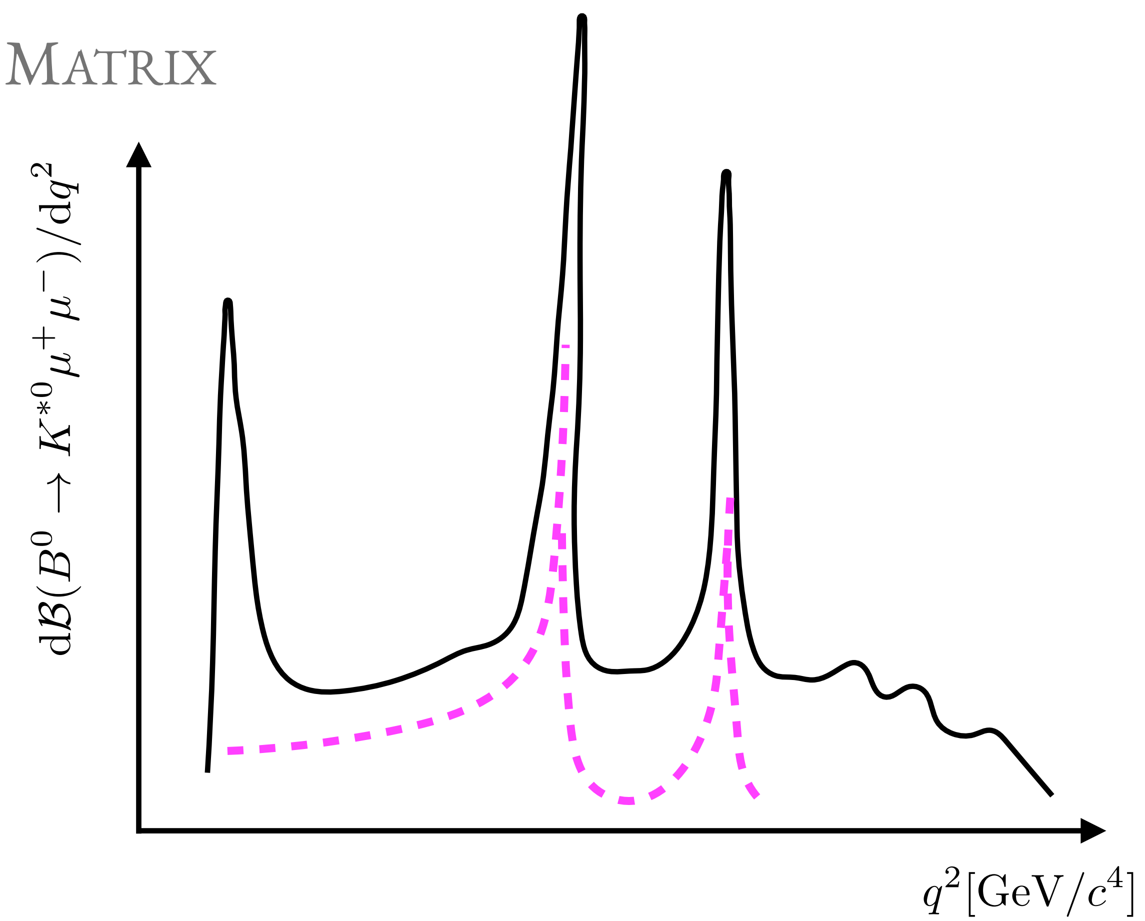
Exploit Analytical Properties of Hadronic Matrix

Bobeth, Chrzaszcz, van Dyk, Virto; EPJC 78 (2018) 451
Gubernari, van Dyk, Virto; JHEP 02 (2021) 088
Gubernari, Reboud, van Dyk, Virto; JHEP 09 (2022) 133

Determined from Data

$$\mathcal{H}_\lambda(z) = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \times \ldots \times \sum_n \alpha_{\lambda,n} z^n$$

Data Driven Determination of Truncation Order



Analysis in a Nutshell

Perform a 5D Model-dependent Amplitude Fit ($q^2, \cos\theta_\ell, \cos\theta_k, \phi, m^2_{K\pi}$)

- Maximal Sensitivity to Non-local Hadronic Effects (And New Physics)

$$\mathcal{A}_\lambda^{L,R} \propto \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')\right]\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[(C_7 \pm C_7')\mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]$$

Additional constraints on Non-local Terms

- Experimental Measurements on $B \to \psi_n K^*$

[PRD 76 (2007) 031102, 88 (2013) 074026, 90 (2014) 112009, 88 (2013) 052002, EPJC 72 (2012) 2118]

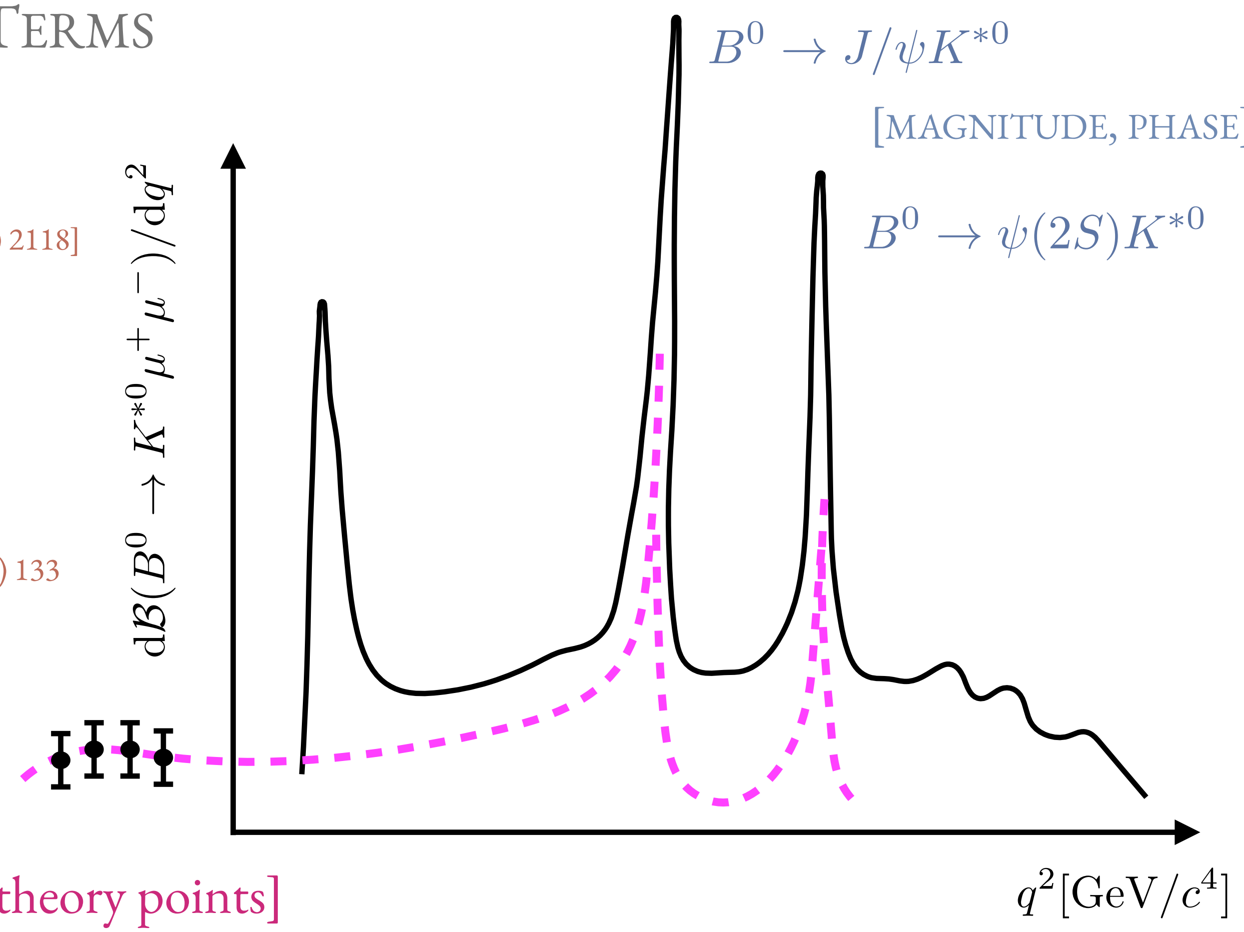
$$\underset{q^2 \to M^2_{\psi_n}}{\text{Res}} \frac{\mathcal{H}_\lambda(q^2)}{\mathcal{F}_\lambda(q^2)} = \frac{M_{\psi_n} f^*_{\psi_n} \mathcal{A}_\lambda^{\psi_n}}{M_B^2\, \mathcal{F}_\lambda(M^2_{\psi_n})}$$

- Reliable Theory Predictions at $q^2 \ll 4m_c^2$

Gubernari, Reboud, van Dyk, Virto; JHEP 09 (2022) 133

$q^2 < 0$ **constraints:** include points at $q^2 < 0$

$q^2 > 0$ **only:** exclude theory points at $q^2 < 0$



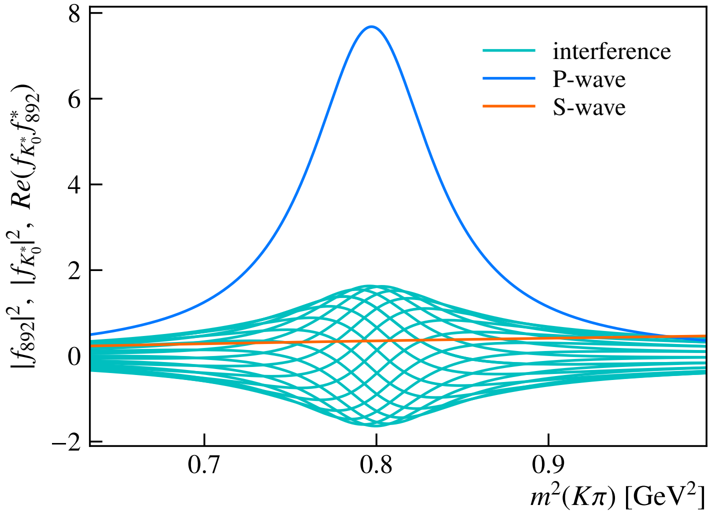
ANALYSIS IN A NUTSHELL

SIGNAL AMPLITUDE MODEL

- REAL $C_9, C_{10}, C'_9, C'_{10}$ [FLOAT]
- C_7, C'_7 [FIXED TO SM]
- 4 CKM PARAMETERS [CONSTRAIN TO CKMFITTER]
- 19 $B^0 \to K^{*0}$ FFS PARAMETERS [CONSTRAIN]
- 18-30 $\alpha_{\lambda,i}$ NON-LOCAL PARAMS [$q^2 < 0$ CONSTRAIN WITH z^4 AND $q^2 > 0$ ONLY WITH z^2 FLOAT]
- RELATIVE MAGNITUDE AND PHASE OF S-P WAVES [FLOAT]
- 9 $B \to K\pi|_{J=0}$ SCALAR FFS [CONSTRAIN]

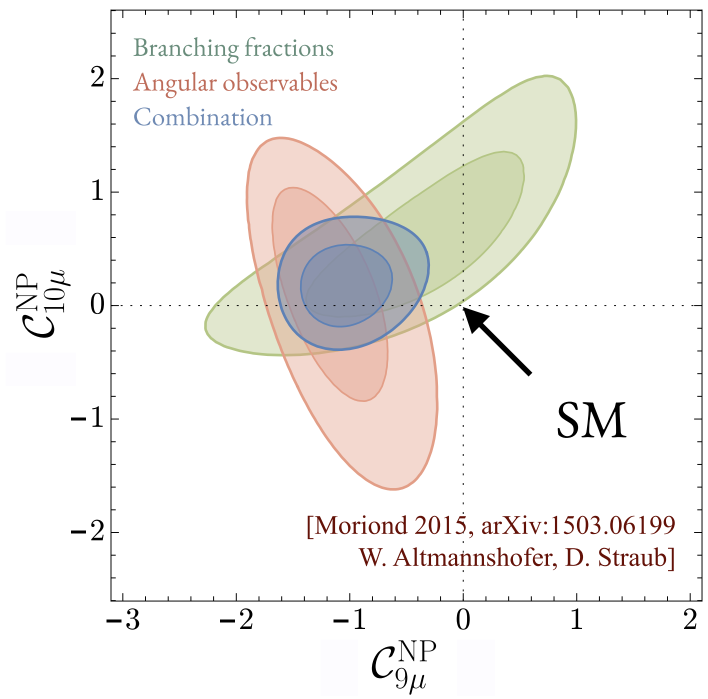
$$pdf_{\rm tot}(q^2,\vec{\Omega},m^2_{K\pi},m_{K\pi\mu\mu}) = P(m_{K\pi\mu\mu}) \times {\rm Acc}(q^2,\vec{\Omega}) \times \frac{{\rm d}^5\Gamma(B^0\to K^{*0}\mu^+\mu^-)}{{\rm d}q^2{\rm d}m^2_{K\pi}{\rm d}\vec{\Omega}} + pdf_{\rm bkg}(q^2,\vec{\Omega},m^2_{K\pi},m_{K\pi\mu\mu})$$

- FULL AMPLITUDE WITH $\mathcal{O}(10^2)$ PARAMETERS
- 6D EXTENDED FIT WITH $m_{K\pi\mu\mu}$ TO OBTAIN YIELDS
- $m^2_{K\pi}$ FIT TO SEPARATE S AND P WAVES
- MOST BKG PARAMS FLOATING IN THE FIT



Analysis in a Nutshell

Additional control over WCs by also using the BR information:



Differential decay rate and branching ratio have complementary information

- BR sets the scale of WCs

$$\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) = \frac{\tau_B}{\hbar}\int_{q^2_{\rm min}}^{q^2_{\rm max}}\int_{k^2_{\rm min}}^{k^2_{\rm max}} \boxed{\frac{d^2\Gamma}{dq^2dk^2}dq^2dk^2}$$

$$N_{\rm sig} = N_{J/\psi K\pi} \times \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) \times \frac{2}{3}}{\mathcal{B}(B^0 \to J/\psi K^+\pi^-) \times f^{J/\psi K\pi} \times \mathcal{B}(J/\psi \to \mu^+\mu^-)} \times R_\varepsilon$$

Mass fit to control channel (include exotica contribution)

Belle dedicated $B^0 \to J/\psi K^+\pi^-$ amplitude analysis

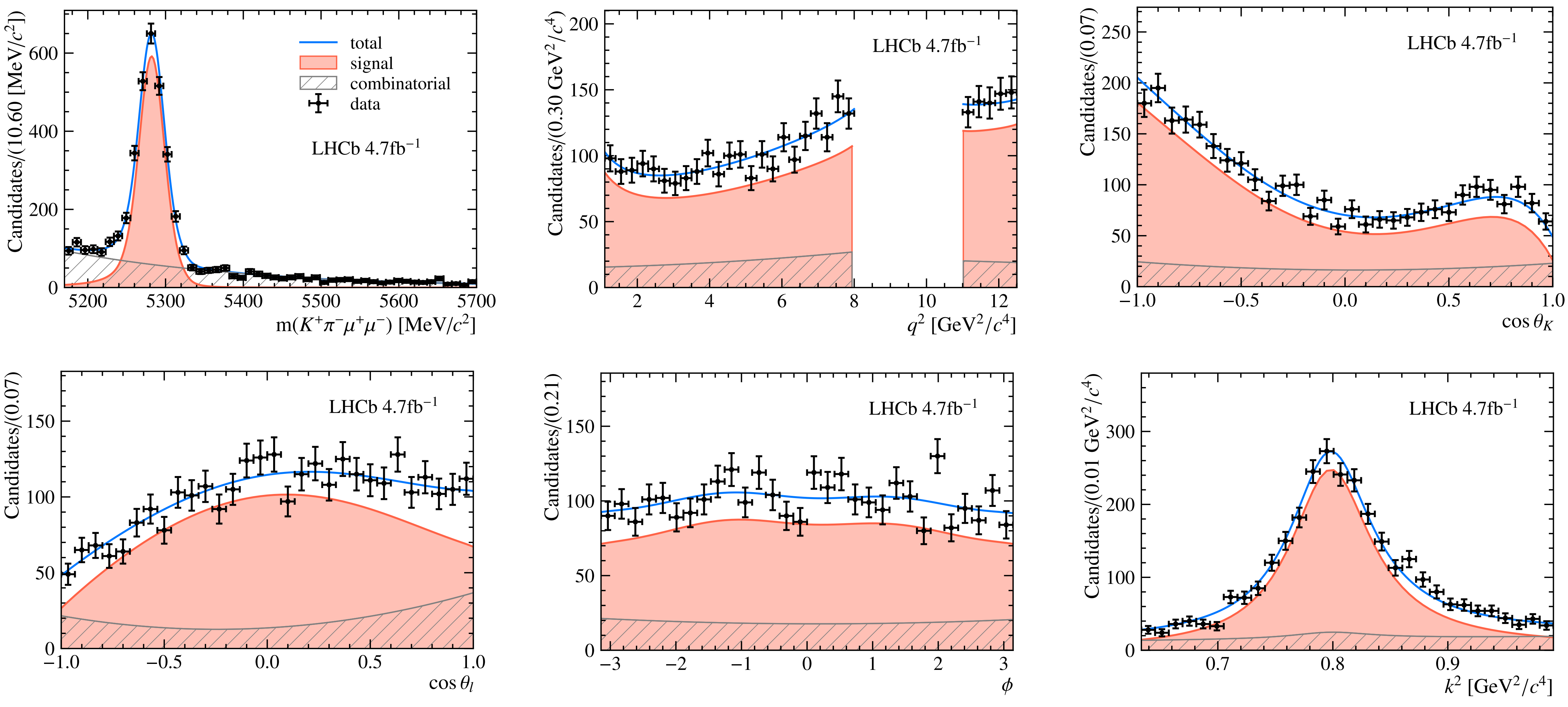
[Belle, PRD 90 (2014) 1122009]

Relative efficiencies from simulated samples

Fit Projections

[LHCb-PAPER-2023-032, LHCb-PAPER-2023-033, In preparation]

A total of 2568 ± 60 signal candidates are obtained

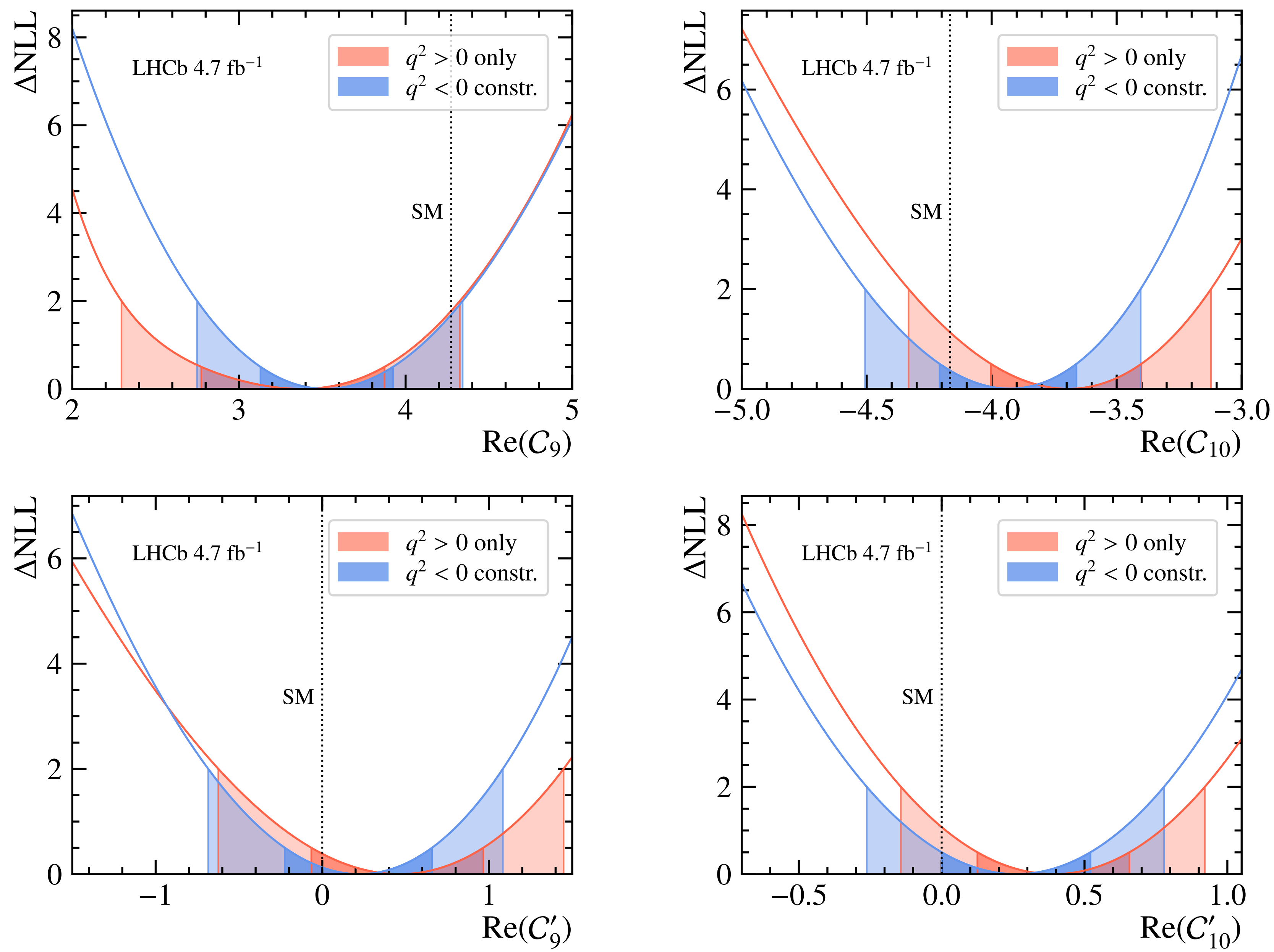


Wilson Coefficients

[LHCb-PAPER-2023-032, LHCb-PAPER-2023-033, In preparation]

Results Consistent with Global Fits

	$q^2 > 0$ only	deviation from SM
$\mathcal{C}_9$	$-0.93^{+0.53}_{-0.57}$	$1.9\ \sigma$
$\mathcal{C}_{10}$	$0.48^{+0.29}_{-0.31}$	$1.5\ \sigma$
$\mathcal{C}'_9$	$0.48^{+0.49}_{-0.55}$	$0.9\ \sigma$
$\mathcal{C}'_{10}$	$0.38^{+0.28}_{-0.25}$	$1.5\ \sigma$
	$q^2 < 0$ prior	
$\mathcal{C}_9$	$-0.68^{+0.33}_{-0.46}$	$1.8\ \sigma$
$\mathcal{C}_{10}$	$0.24^{+0.27}_{-0.28}$	$0.9\ \sigma$
$\mathcal{C}'_9$	$0.26^{+0.40}_{-0.48}$	$0.5\ \sigma$
$\mathcal{C}'_{10}$	$0.27^{+0.25}_{-0.27}$	$1.0\ \sigma$



Wilson Coefficients

[LHCb-PAPER-2023-032, LHCb-PAPER-2023-033, In preparation]

Results Consistent with Global Fits: [4 d.o.f.] with SM 1.3 (1.4) σ

	$q^2 > 0$ only	deviation from SM
$\mathcal{C}_9$	$-0.93^{+0.53}_{-0.57}$	$1.9\ \sigma$
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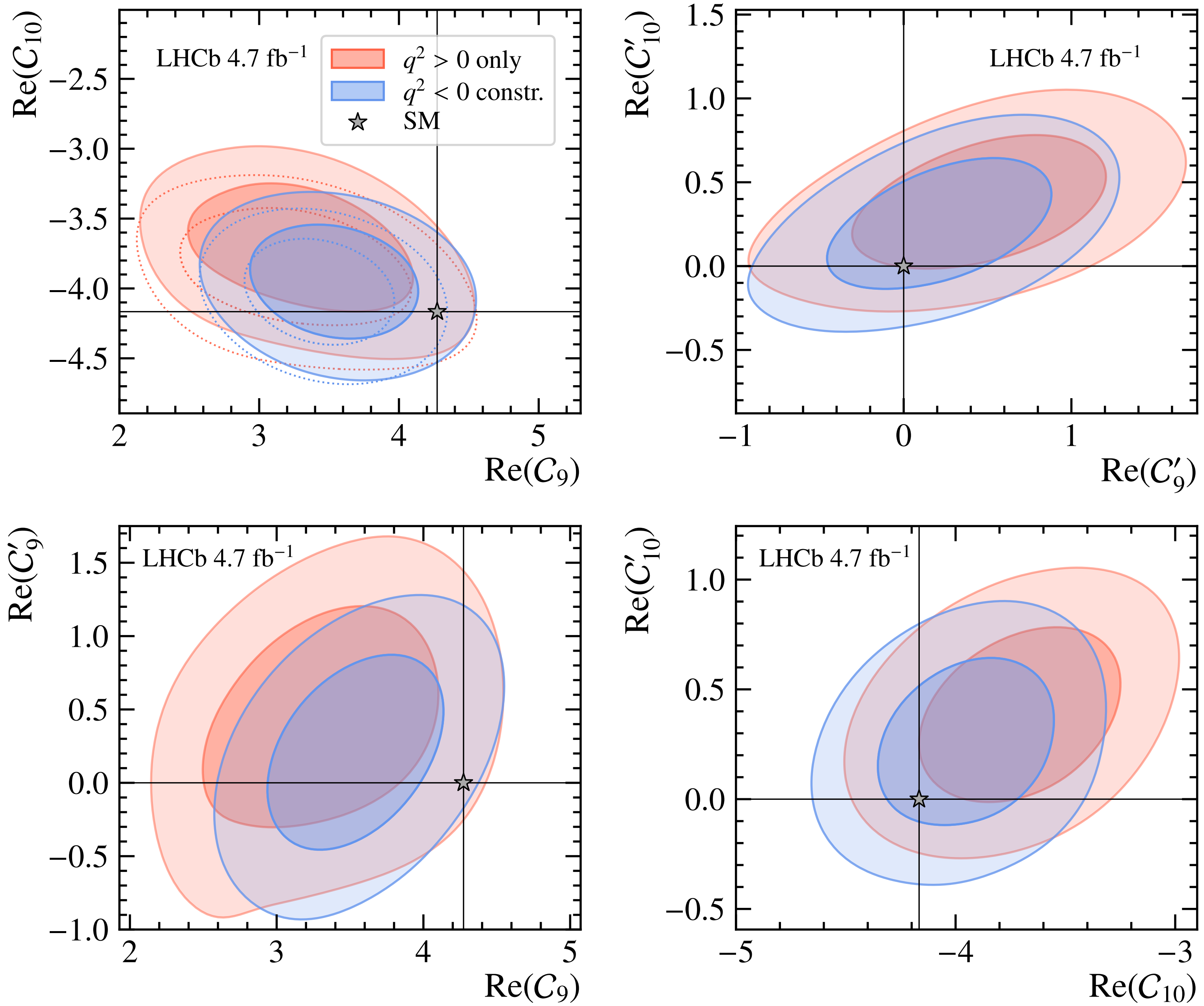
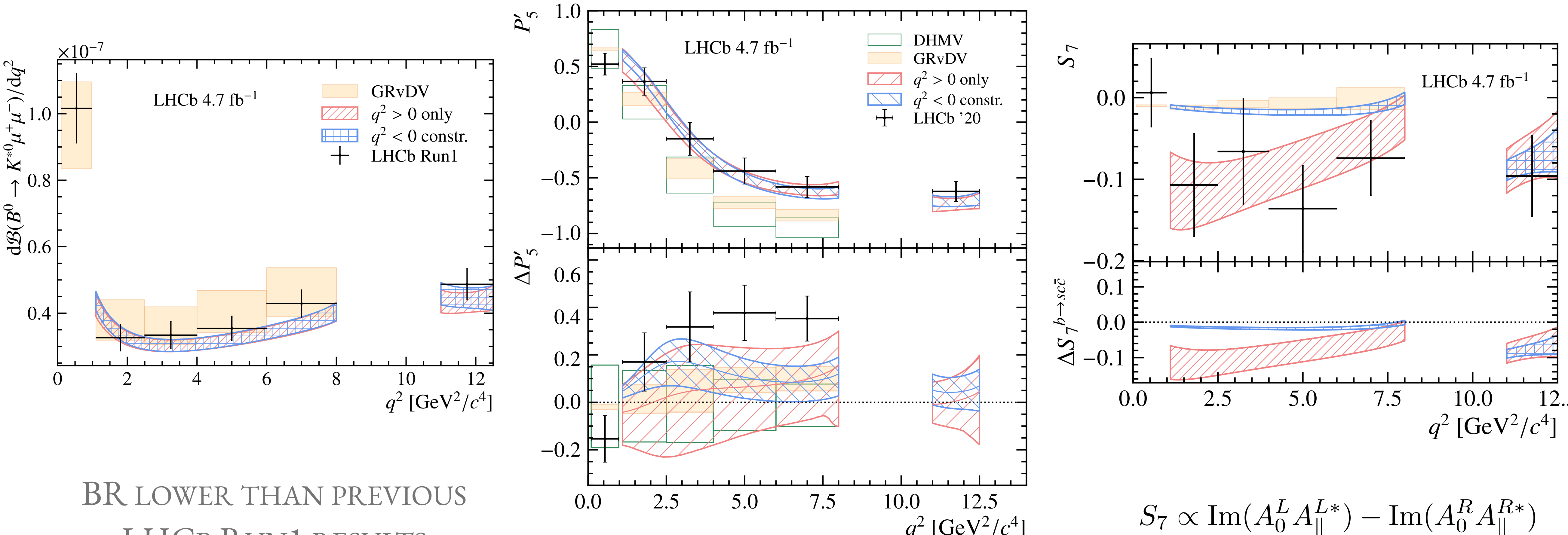


[LHCb-PAPER-2023-032, LHCb-PAPER-2023-033, In preparation]

Classical Binned Observables can be a-posteriori Retrieved



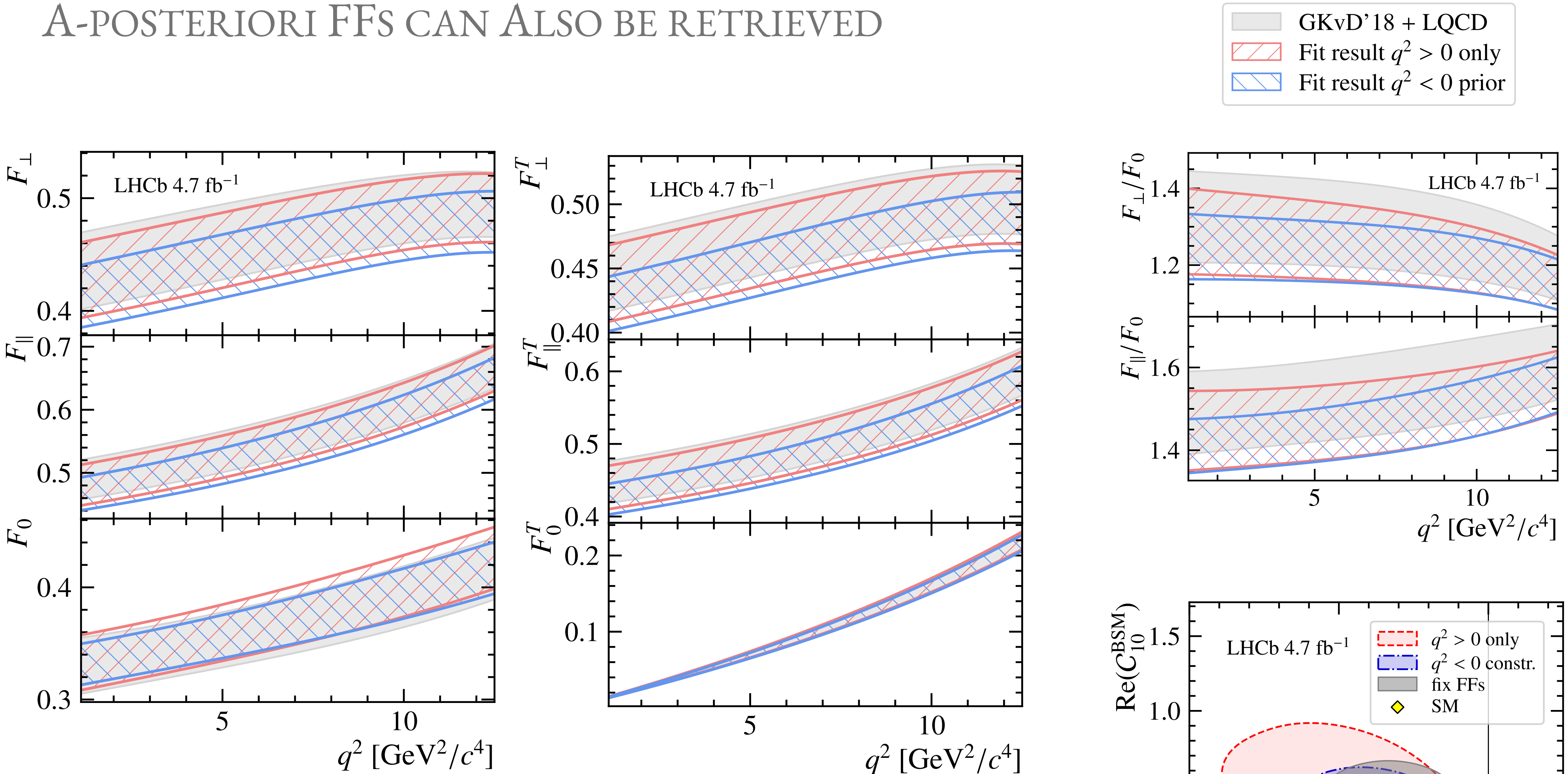
BR lower than previous LHCb Run1 results

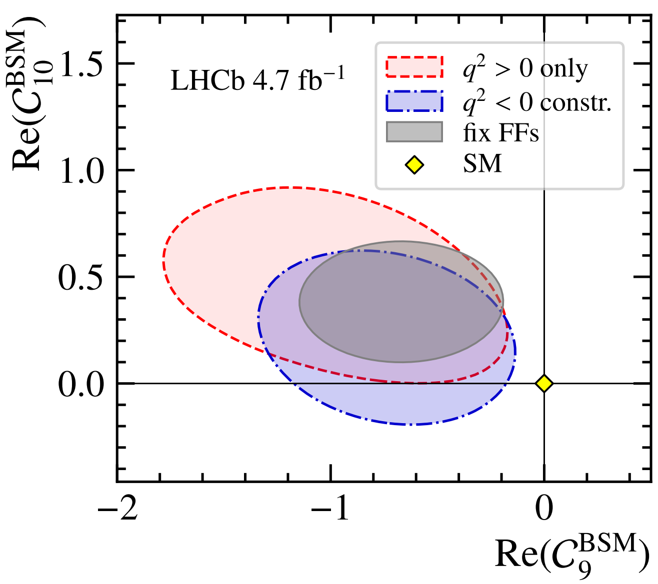
$$S_7 \propto \mathrm{Im}(A_0^L A_\parallel^{L*}) - \mathrm{Im}(A_0^R A_\parallel^{R*})$$

Form Factor results

[LHCb-PAPER-2023-032, LHCb-PAPER-2023-033, In preparation]

A-posteriori FFs can also be retrieved



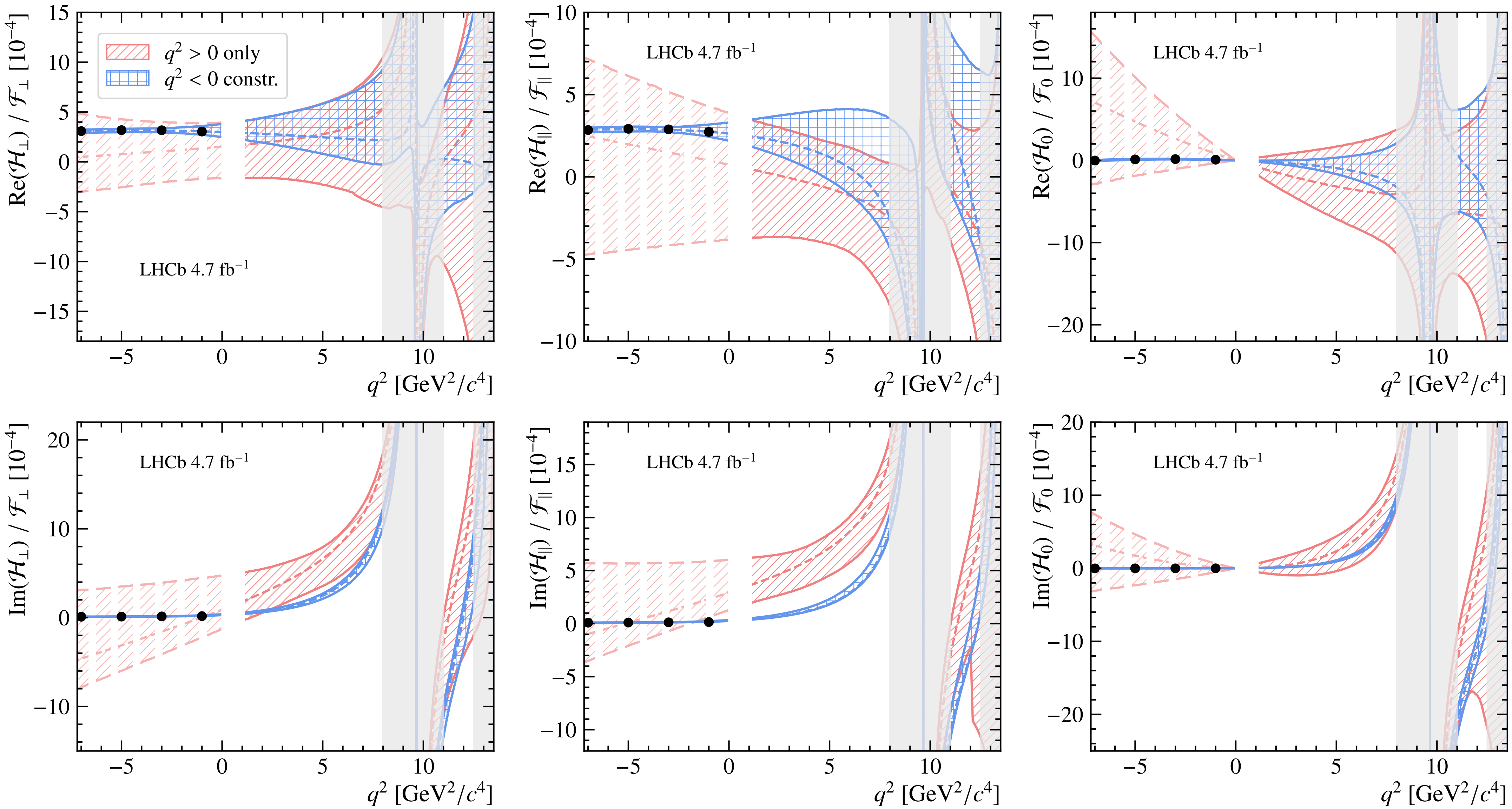


- Slight preference towards lower values
- Key information to help understanding these results

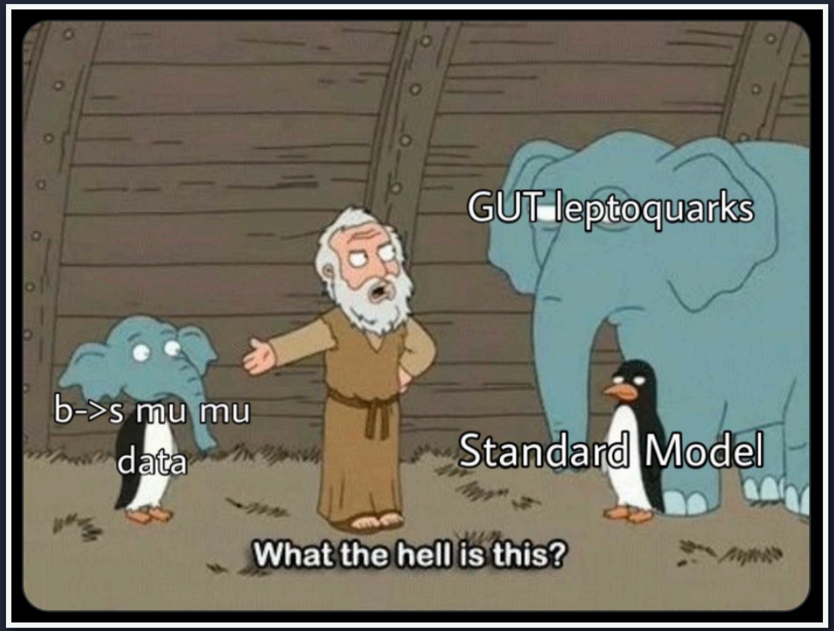
NON-LOCAL HADRONIC RESULTS

[LHCb-PAPER-2023-032, LHCb-PAPER-2023-033, In preparation]

OVERALL AGREEMENT BETWEEN TWO ALTERNATIVE FITS



SLIGHT TENSION ON IMAGINARY PART TO ACCOMMODATE VARIATION AT $q^2 = 0$



Summary

- Long-standing $b \to s\mu^+\mu^-$anomalies interpretation still hindered by SM hadronic uncertainties
- First q^2-unbinned analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays explores the full information in the data

Results are consistent with global picture pattern with significance at $\sim 2\,\sigma$

What Comes Next?

- Binned angular analysis and branching fraction with full LHCb Run 1+2 data
- More unbinned analysis with complementary non-local parametrisation

- A Precision Flavour Physics Era Ahead Of Us!

[New ideas, new channels, new observables ...]