Data-driven determination of charm loop effects in $B^0 \to K^{*0}\mu^+\mu^-$ decays

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On behalf of the LHCb collaboration

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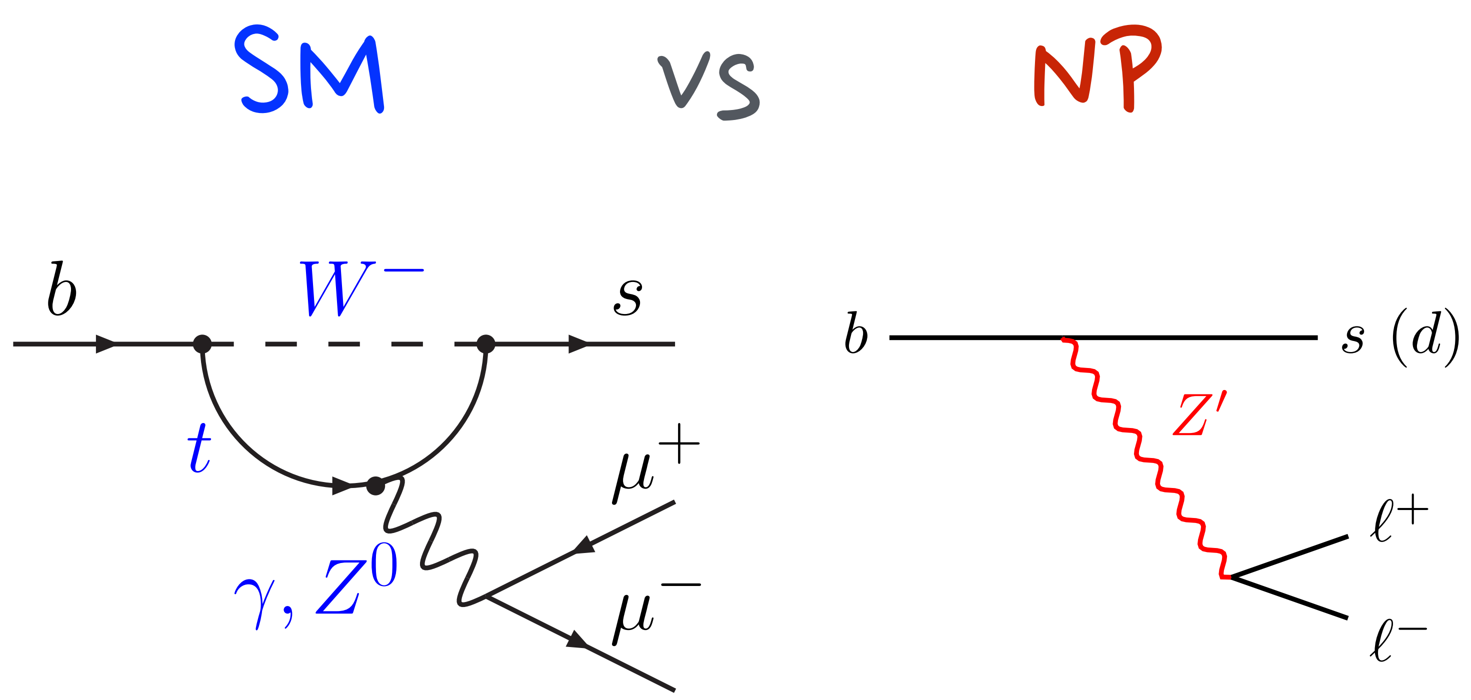
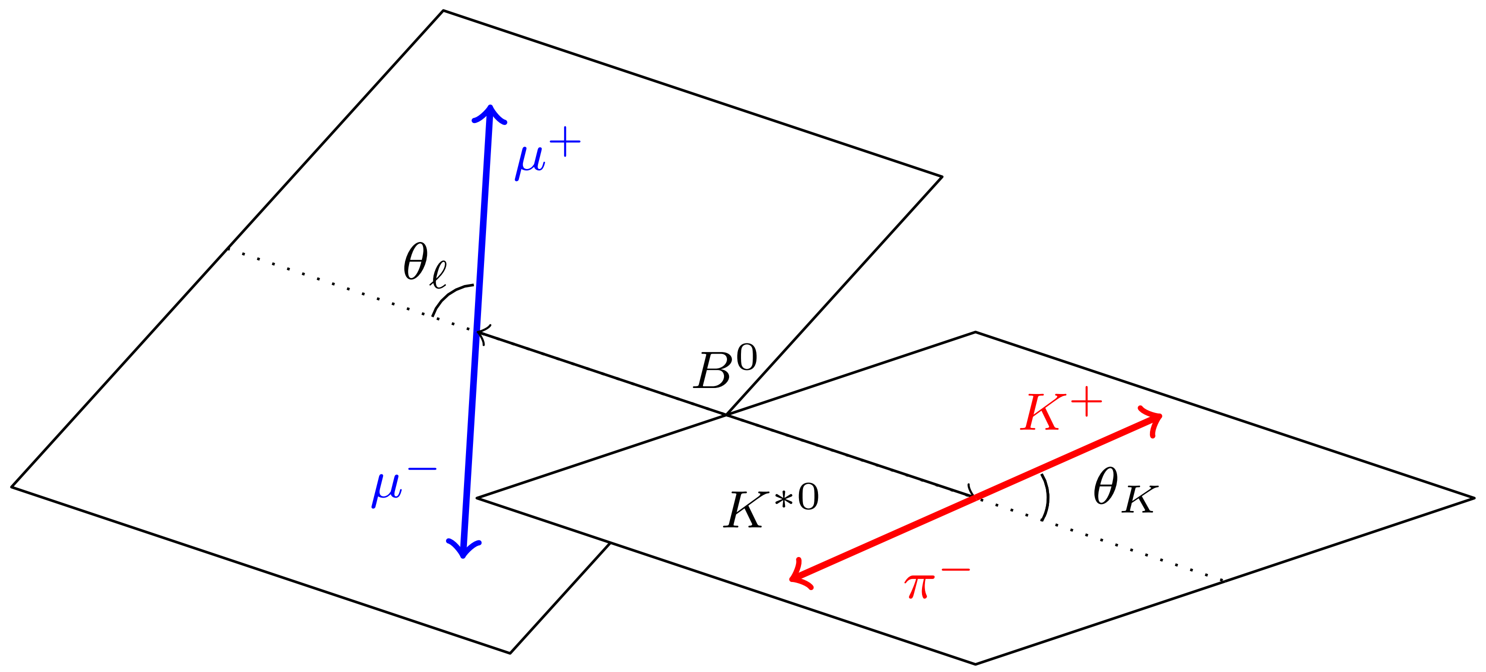
Motivation

- $B^0 \to K^{*0}\mu^+\mu^-$ mediated by FCNC
  - suppressed in the SM → sensitive to NP
  - rich angular structure
  - NP can alter branching ratio and ang. distributions



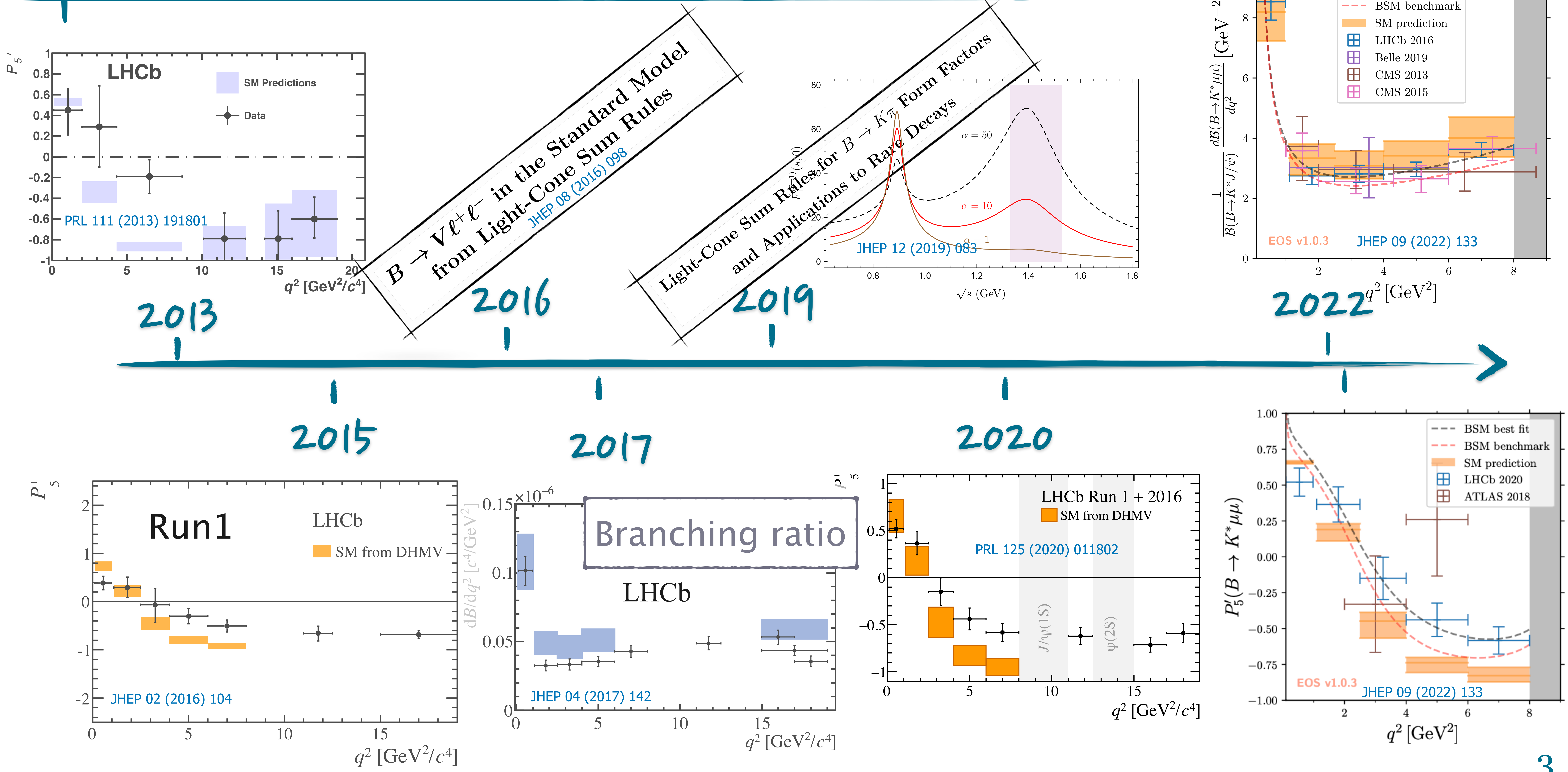


$$\frac{\mathrm{d}^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$= \frac{9}{32\pi}\Big[I_{1s}\sin^2\theta_K + I_{1c}\cos^2\theta_K + I_{2s}\sin^2\theta_K\cos 2\theta_\ell + I_{2c}\cos^2\theta_K\cos 2\theta_\ell + I_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + I_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + I_5\sin 2\theta_K\sin\theta_\ell\cos\phi + I_6\sin^2\theta_K\cos\theta_\ell + I_7\sin 2\theta_K\sin\theta_\ell\sin\phi + I_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + I_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \Big],$$

famous P_5' observable

Why we are here…a bit of history



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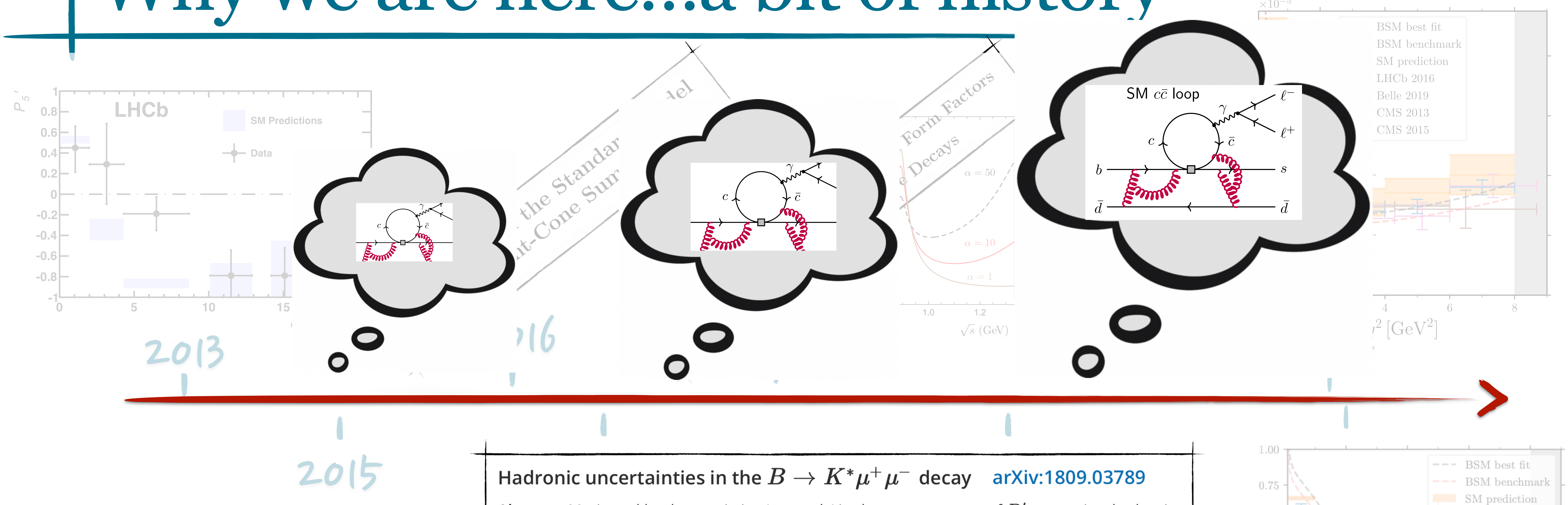


Hadronic uncertainties in the $B \to K^*\mu^+\mu^-$ decay arXiv:1809.03789

Abstract: Motivated by the persisting 'anomaly' in the measurement of P_5', we review hadronic uncertainties entering the angular observables of the decay $\bar{B} \to \bar{K}^*\mu^+\mu^-$. We argue that hadronic uncertainties could account for the present measurements. We discuss how to

Lessons from the $B^{0,+} \to K^{*0,+}\mu^+\mu^-$ angular analyses

arXiv:2011.01212 [pdf, other] hep-ph hep-ex doi 10.1103/PhysRevD.103.015030

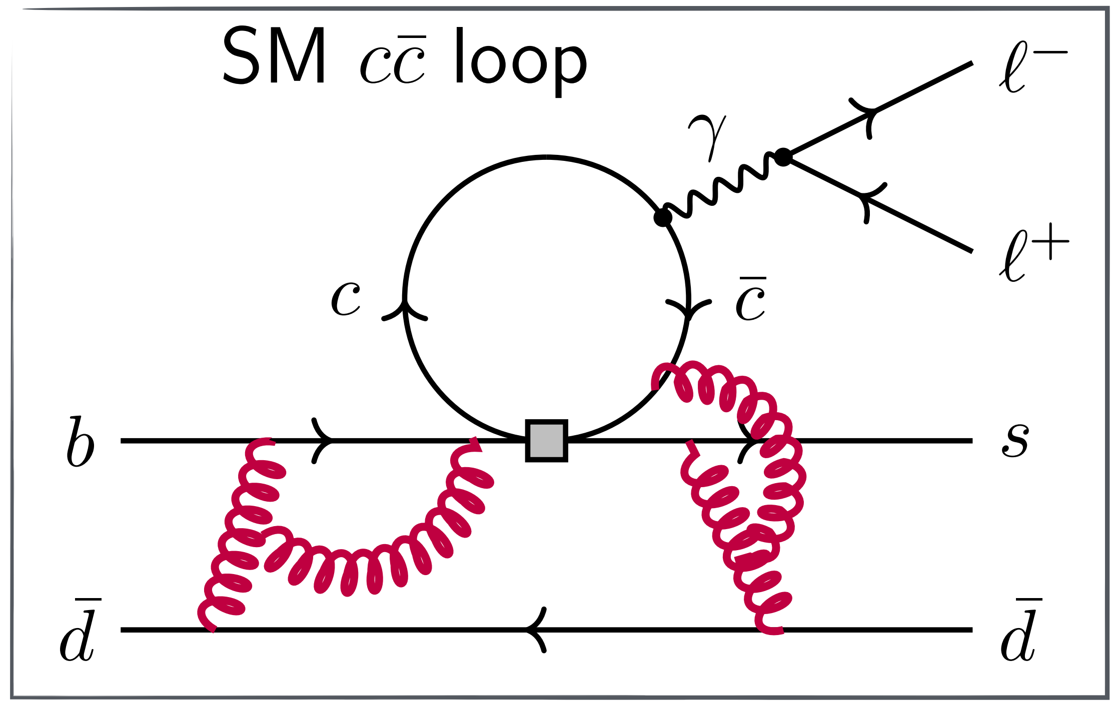
…cays in light of the recent measurements from the LHCb experiment, showing that new data strengthen the need for sizable hadronic contributions and correlations among them. We then

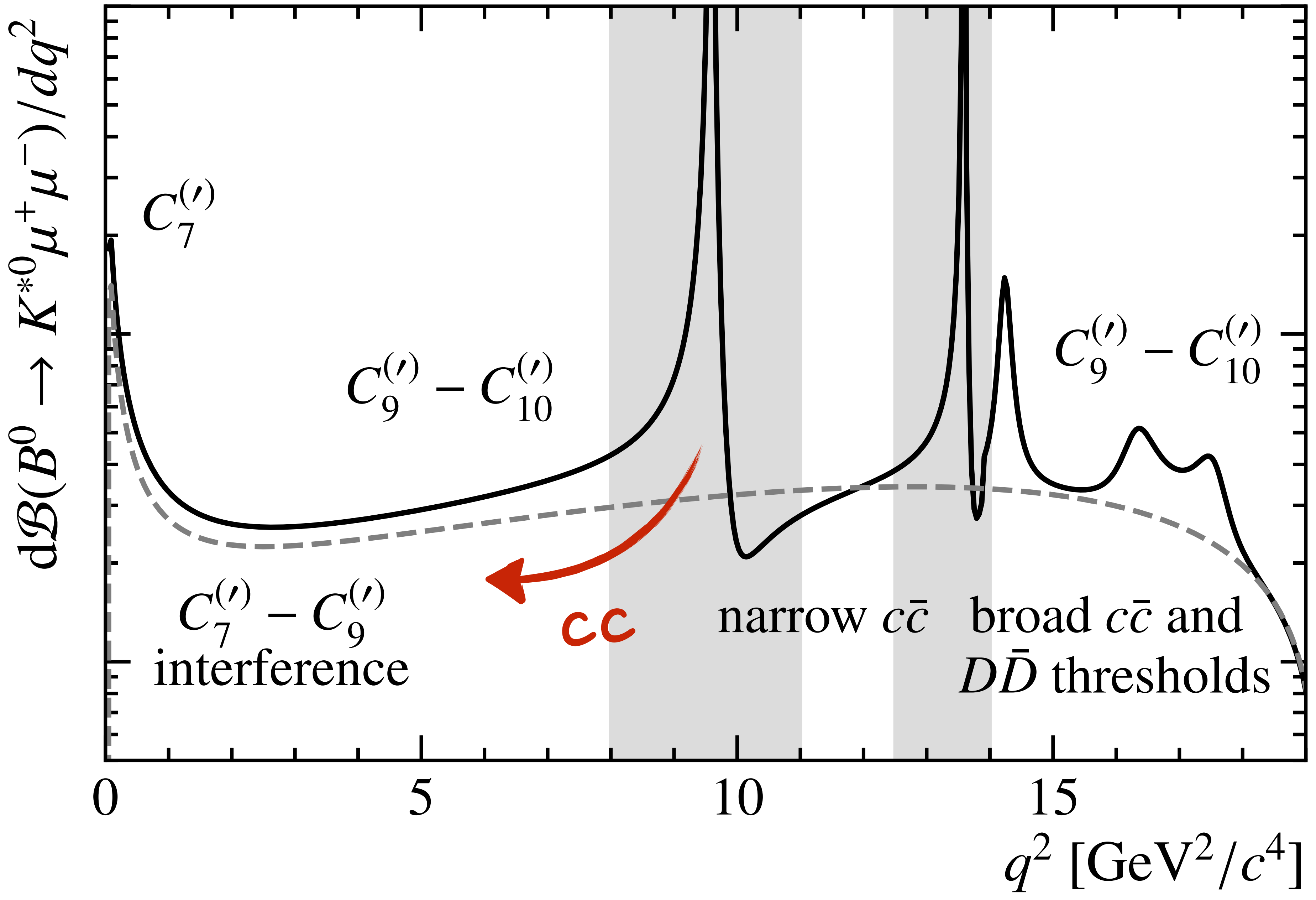
$B \to K^*\ell^+\ell^-$ decays at large recoil in the Standard Model: a theoretical reappraisal arXiv:1512.07157 [pdf, other] hep-ph doi 10.1007/JHEP06(2016)116

Abstract: We critically reassess the theoretical uncertainties in the Standard Model calculation of the $B \to K^*\ell^+\ell^-$ observables, focusing on the low q^2 region. We point out that even optimized observables are affected by sizable uncertainties, since hadronic contributions

Hadronic uncertainties…

- Non-local hadronic contribution "*charm-loop*"
  - Difficult to calculate reliably from first principles
  - Can mimic NP
  - Can we access it from data?





- Important developments on the theory side (see talk by Meril…)
- SM prediction available @$q^2 < 0$

Unbinned amplitude analysis

- Perform q^2 unbinned amplitude analysis
  - model *local* vs *non-local* contributions

non-local hadronic matrix elements "charm-loop"

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ \left[(\mathcal{C}_9 \pm \mathcal{C}_9') \mp (\mathcal{C}_{10} \pm \mathcal{C}_{10}') \right] \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[(\mathcal{C}_7 \pm \mathcal{C}_7') \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$\lambda = \perp, \parallel, 0$

Wilson coeff.

Form Factors

Polynomial expansion

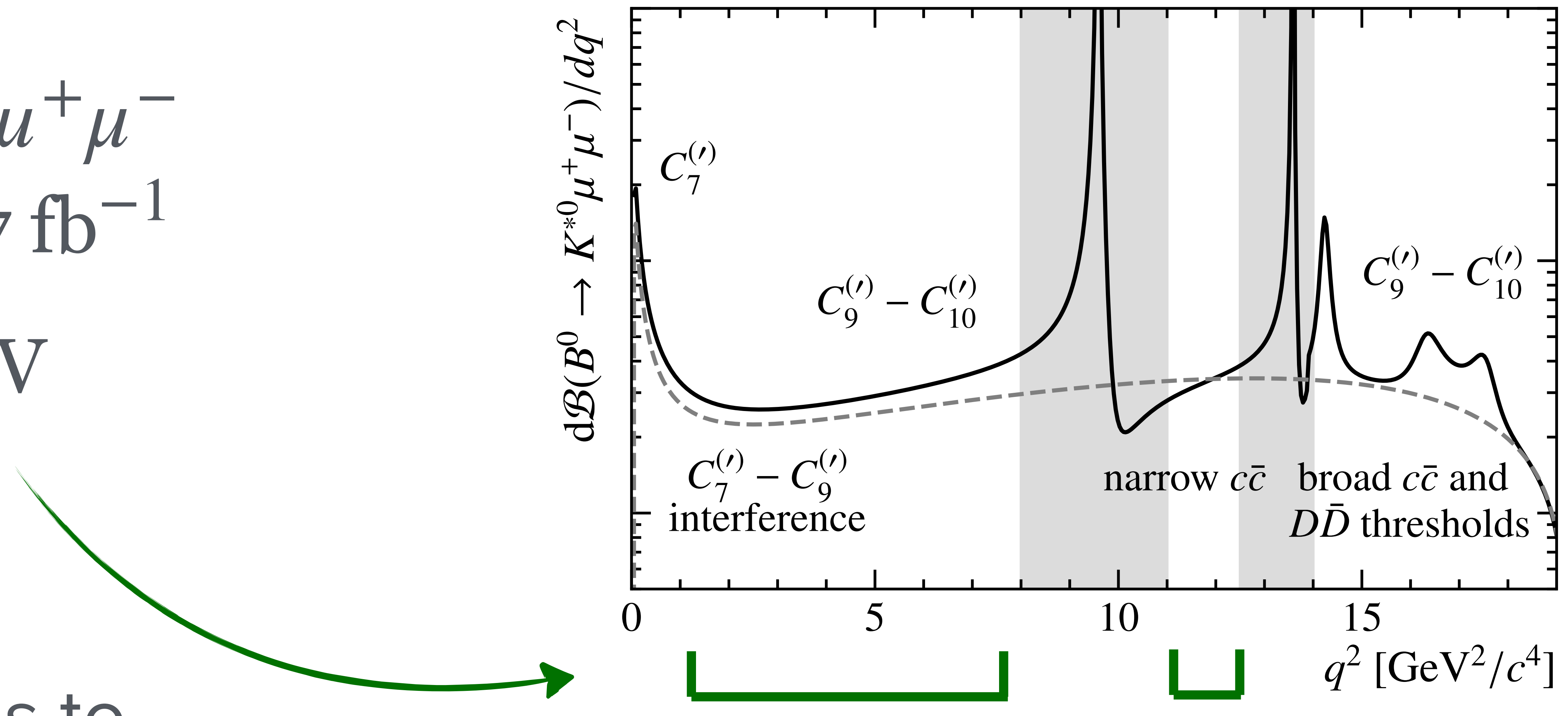
JHEP 09 (2022) 133

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

- **Fit 5-D differential decay rate!**
  - $q^2, m_{K\pi}^2, \cos\theta_\ell, \theta_K, \phi$

Analysis overview

- Same dataset of previous LHCb $B^0 \to K^{*0}\mu^+\mu^-$ binned angular analysis (Run-I + 2016) 4.7 fb^{-1}
  - two q^2 regions: [1.1, 8.0] & [11, 12.5] GeV



- Six-dimensional fit
  - `differential decay rate + invariant B mass to separate signal from combinatorial background

- Large number of signal parameters
  - Wilson coefficients: $\mathcal{C}_9, \mathcal{C}_{10}, \mathcal{C}_9', \mathcal{C}_{10}'$ [floated] + $\mathcal{C}_7, \mathcal{C}_7'$ [fixed to SM]
  - local FF : [constrained to LCSR + latticeQCD] JHEP 01 (2019) 150, *PoS* LATTICE2014 (2015) 372
  - non-local hadronic parameters $\mathcal{H}_\lambda(q^2)$ (see next slides)
  - S-wave (FFs + relative magnitude&phase)

Non-local contributions

- Combining theory & experimental information to constrain charm-loop parameters

Theory information

Value of charm-loop at $q^2 < 0$

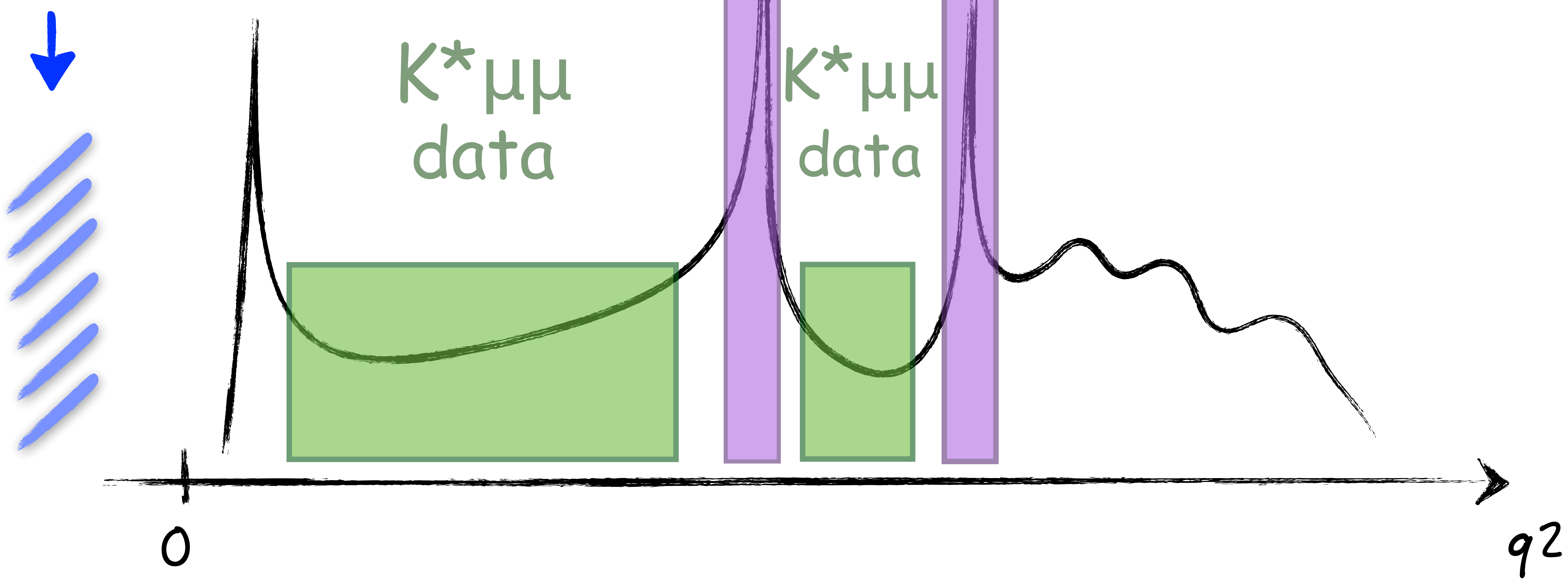
▶ reliable for $q^2 \ll 4m_c^2$

JHEP 09 (2022) 133

Experimental measurements

Branching ratio, polarization fraction and phase difference from $B^0 \to \psi_n K^{*0}$

PRD 76 031102(R) (2007)
PRD 88 052002 (2013)
PRD 88 074026 (2013)
PRD 90 112009 (2014)



Non-local contributions

- Combining ... parameters

- $q^2 < 0$ *prior:* include theory points @ q2<0
- $q^2 > 0$ *only:* exclude theory points @ q2<0

Theory inf...

Value of charm-loop at $q^2 < 0$

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JHEP 09 (2022) 133

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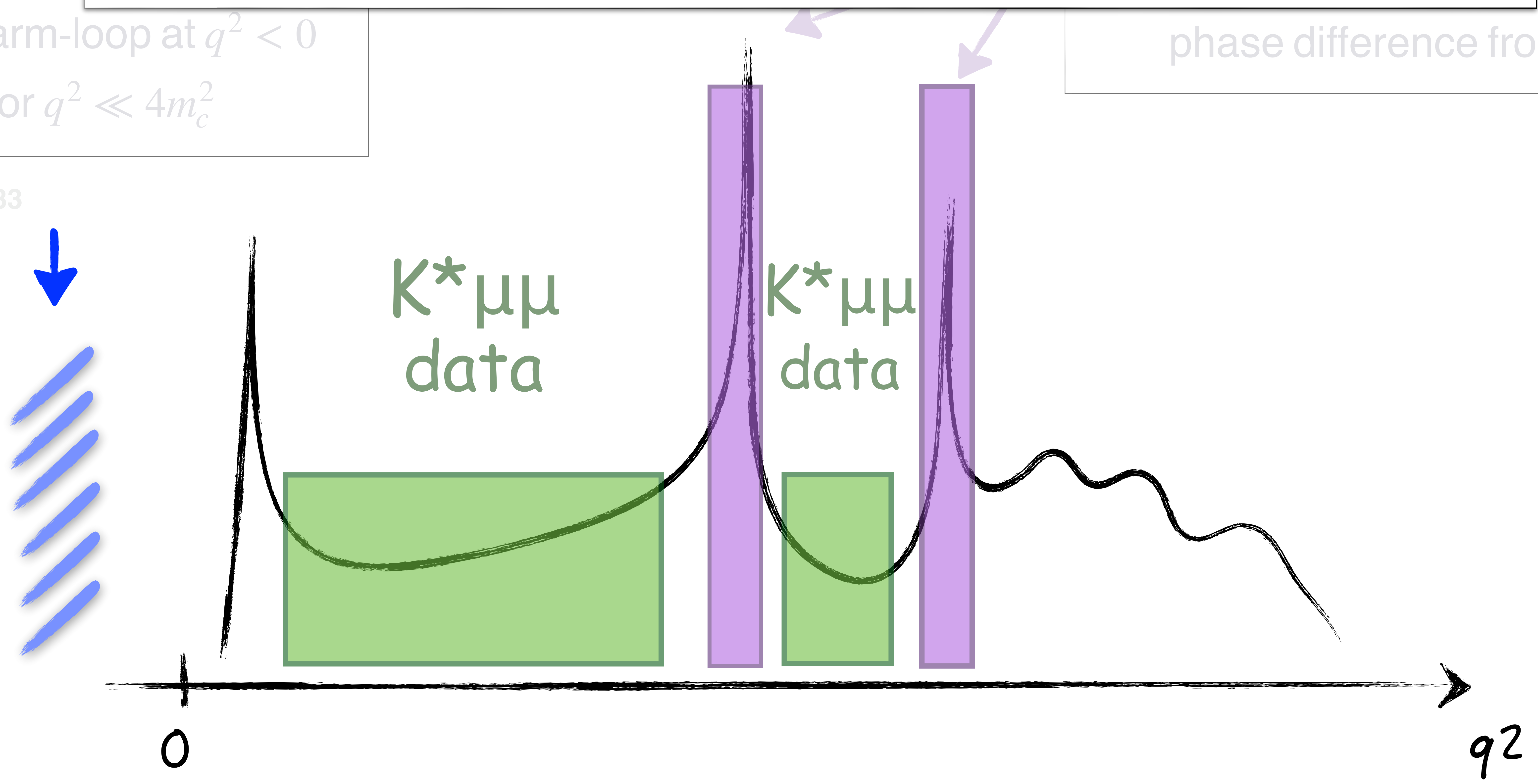
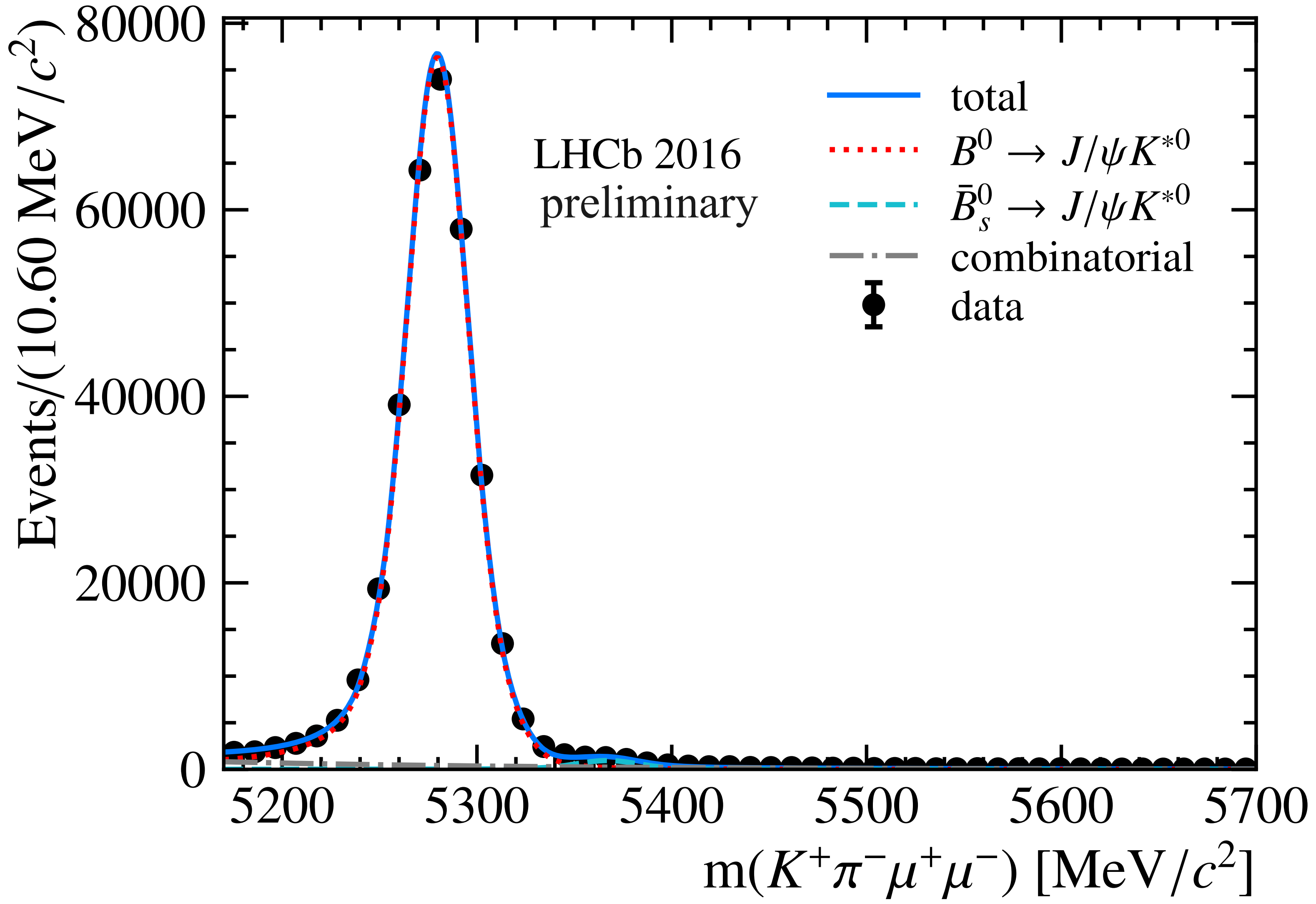


Branching ratio constraint

- Angular information can only access the relative size of Wilson coefficients
  - Scale of Wilson coeff. set by branching ratio

- Include branching ratio measurement in the analysis
  - Normalised to $B^0 \to J/\psi K^+\pi^-$ decays

$B^0 \to J/\psi K^+\pi^-$

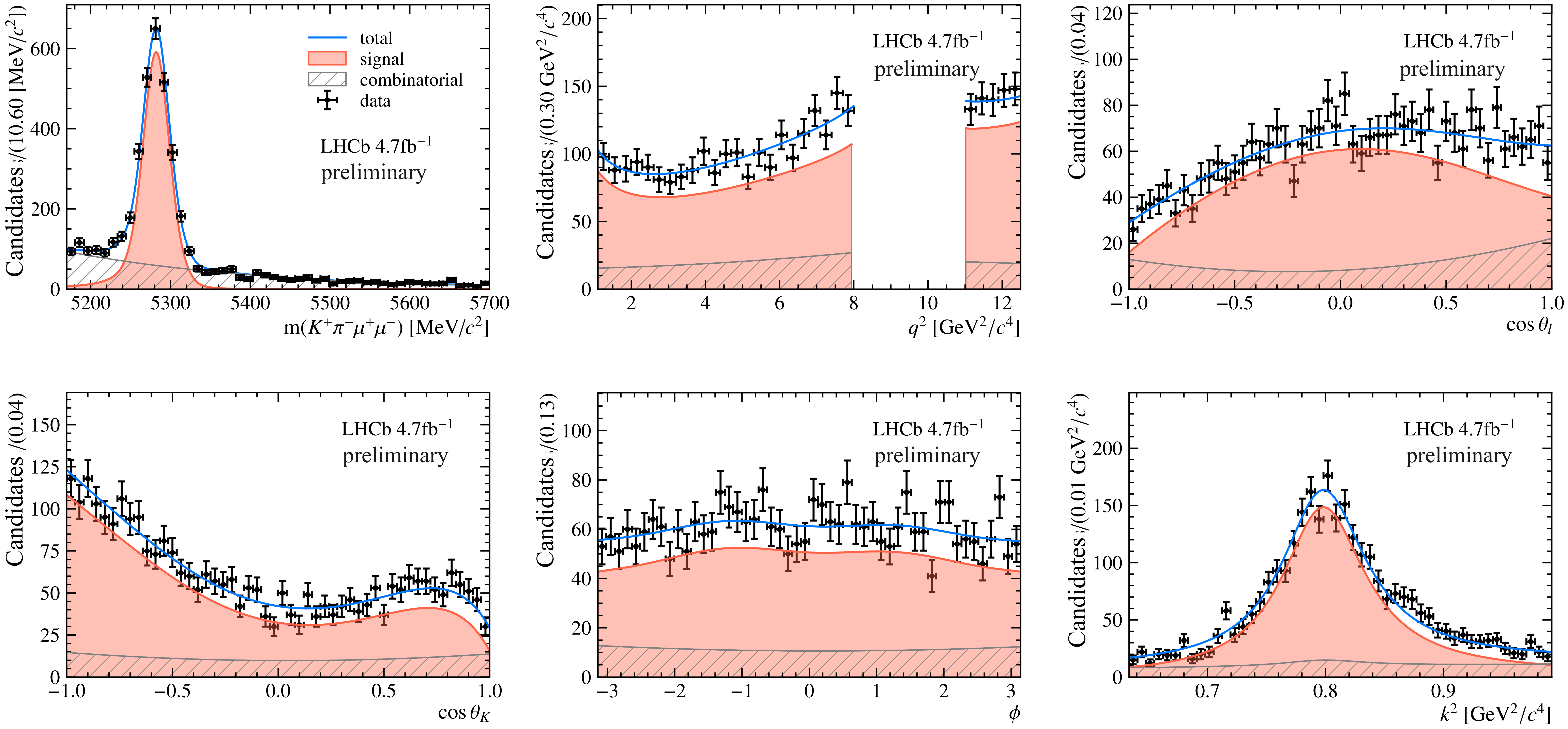


$$N_{sig} = N_{J/\psi K\pi} \times \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) \times \frac{2}{3}}{\mathcal{B}(B^0 \to J/\psi K^+\pi^-) \times f^{J/\psi K\pi} \times \mathcal{B}(J/\psi \to \mu^+\mu^-)} \times R_\varepsilon\,,$$

- Largest systematic uncertainties:
  - ❖ $\mathcal{B}(B^0 \to J/\psi K^+\pi^-) = (1.15 \pm 0.01 \pm 0.05) \cdot 10^{-3}$ PRD 90 (2014) 112009
  - ❖ $f^{B^0 \to J/\psi K\pi}_{\pm 100\mathrm{MeV}} = 0.644 \pm 0.010$

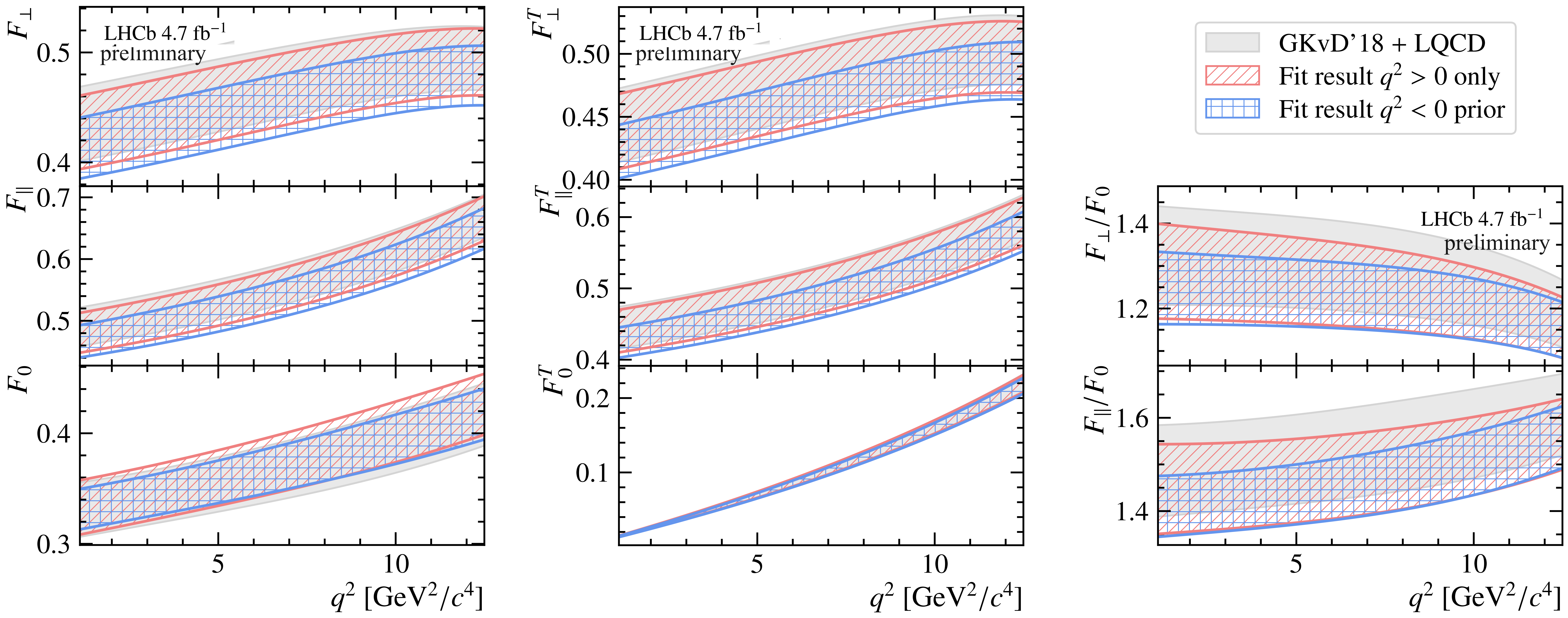
Fit projections

- Simultaneous fit to Run1 & 2016, $q^2 \in$ [1.1, 8.0] & [11, 12.5]



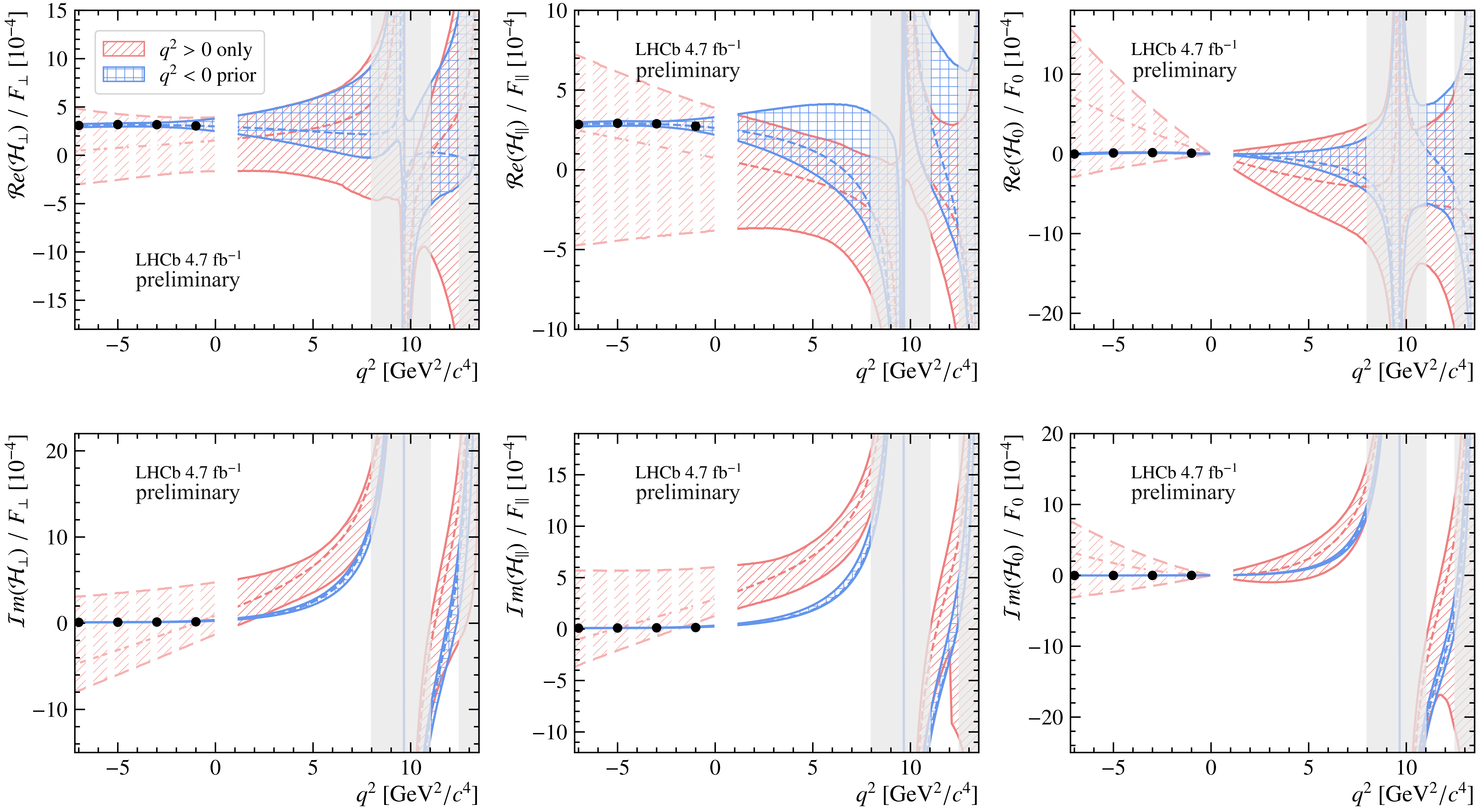
Form factor results

- Dominant uncertainty in $b \to s\ell\ell$ SM branching ratio prediction
- Fit results are found to require small adjustment in $\mathcal{F}_{\perp,\parallel}/\mathcal{F}_0$ ratio



Non-local hadronic results

- Good overall agreement between the two configurations
  - Small discrepancy in $Im\,\mathcal{H}_{\parallel}(q^2)$



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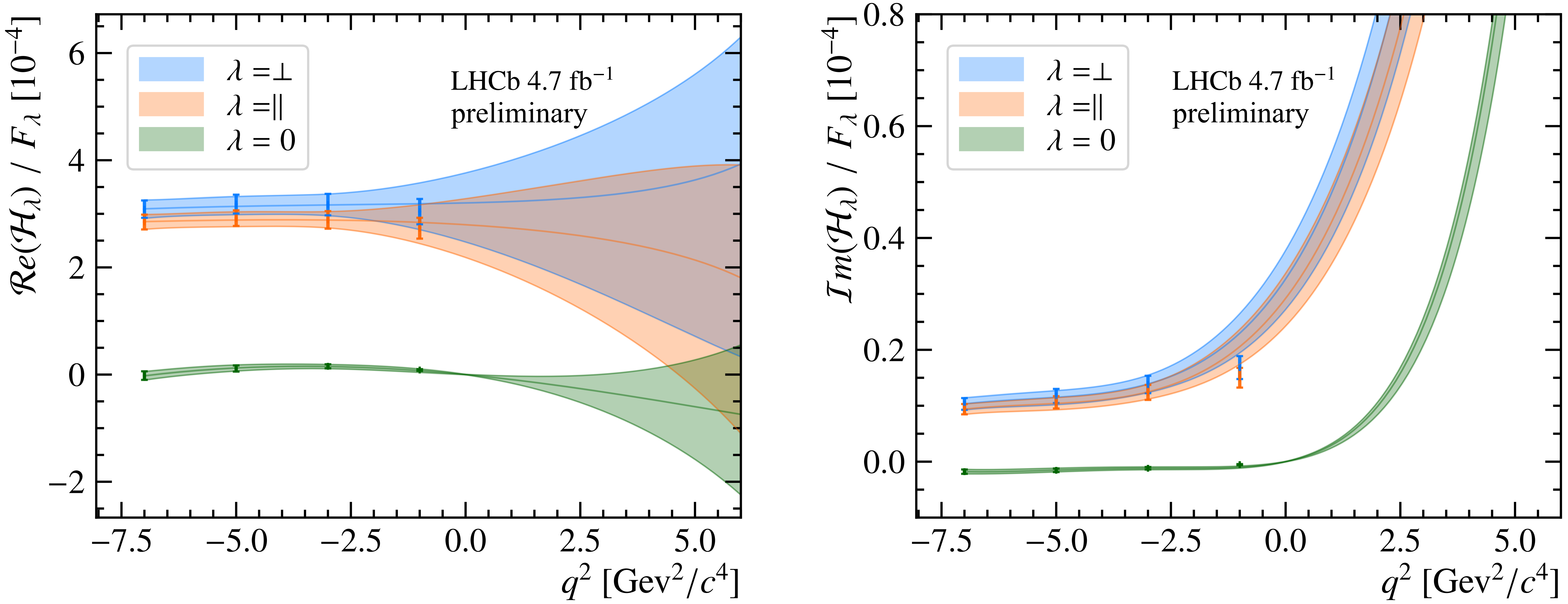

- $\mathcal{H}_\lambda(q^2)$ constrained from 3 theory points $q^2 \in [-7, -5, -3]$ GeV^2
- Result can be tested at $q^2 = -1$ GeV^2
  - Imaginary part tends to rise more rapidly than predictions

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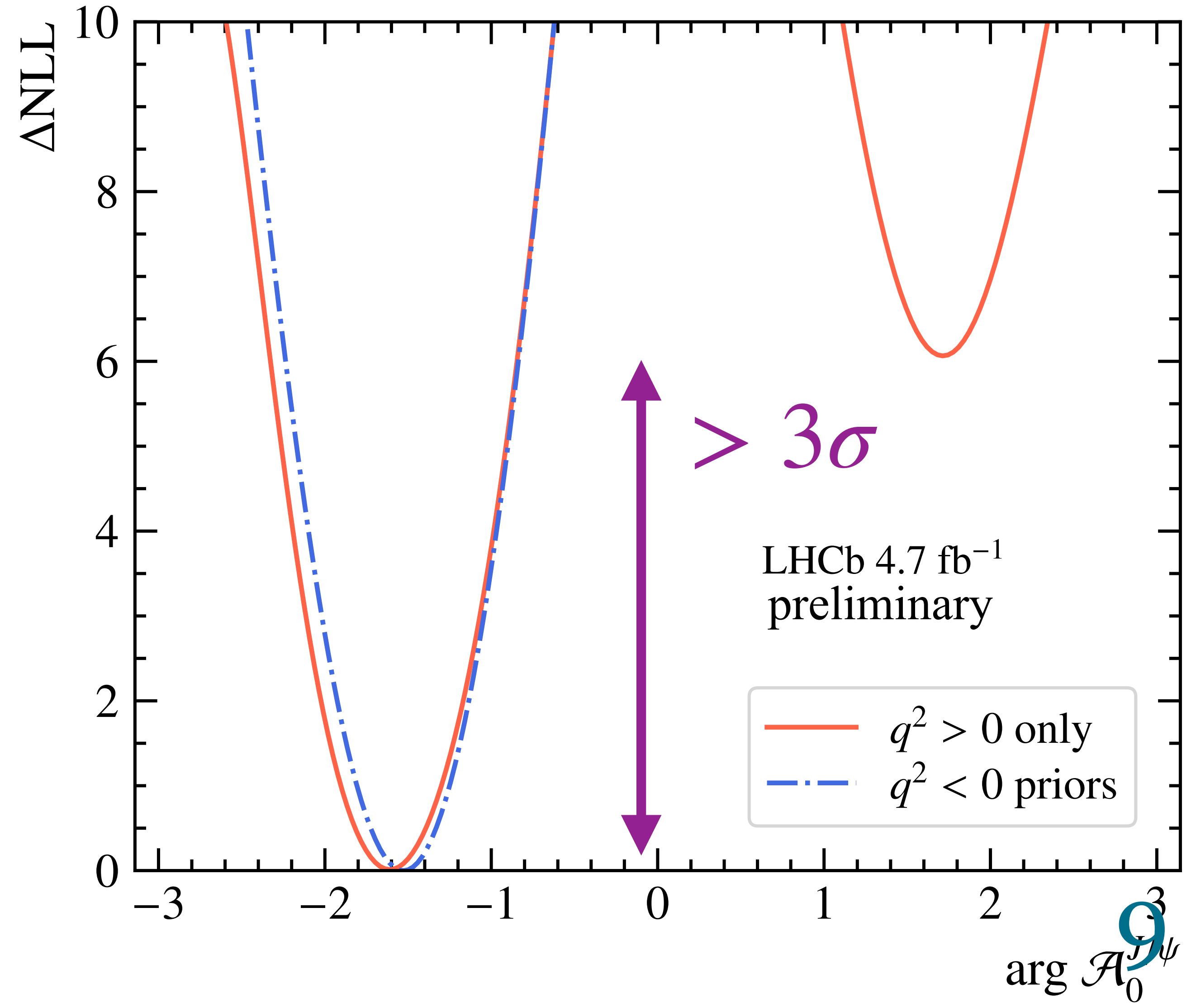
- $\mathcal{H}_\lambda(q^2)$ constrained from 3 theory points $q^2 \in [-7, -5, -3]$ GeV^2
- Result can be tested at $q^2 = -1$ GeV^2
  - Imaginary part tends to rise more rapidly than predictions
- Can measure phase difference between rare mode and Jpsi
  - $\arg A_0^{J/\psi} = \begin{array}{ll} -1.55^{+0.22}_{-0.18} & [q^2 < 0] \\ -1.61^{+0.22}_{-0.20} & [q^2 > 0] \end{array}$

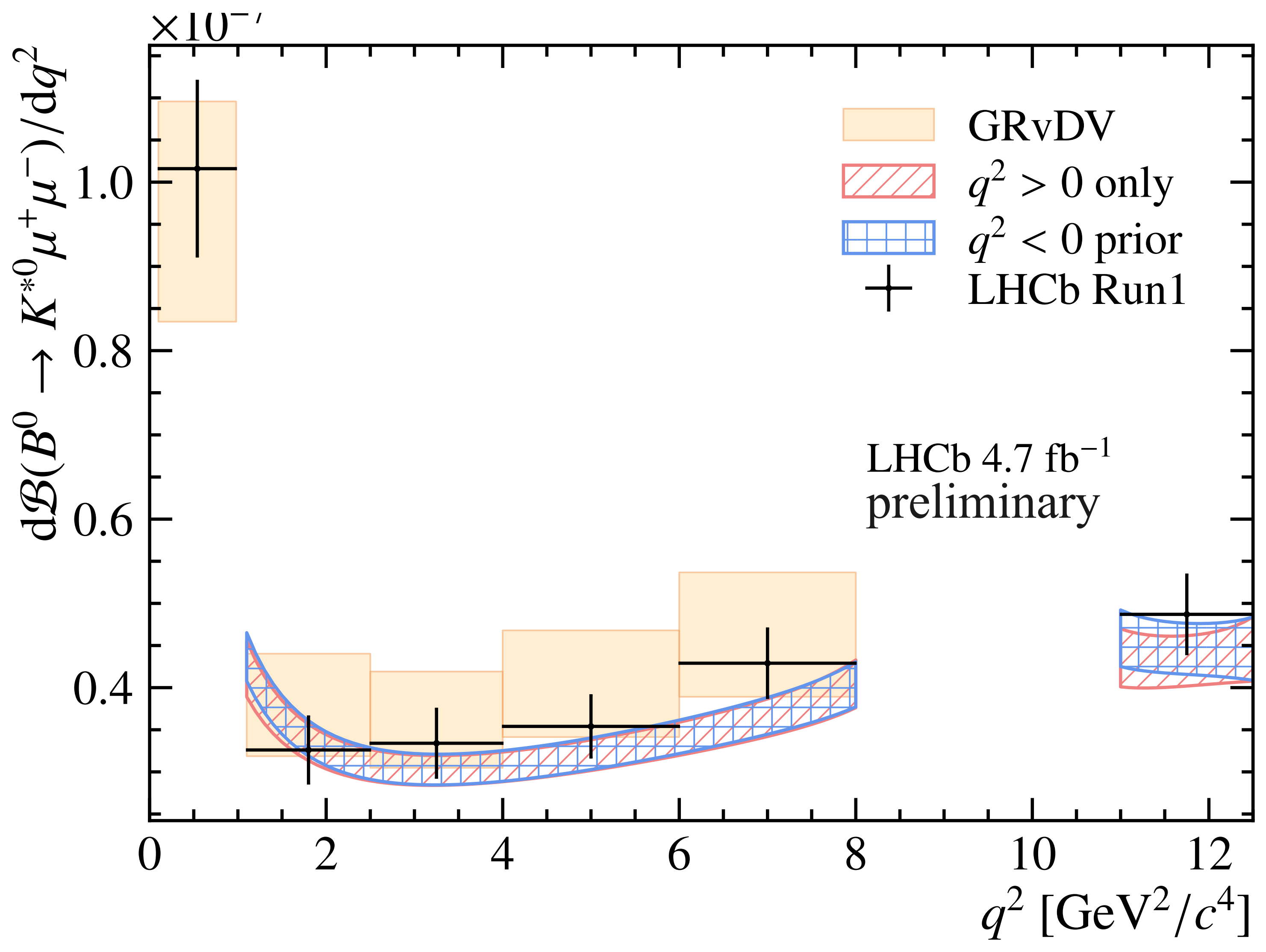
Compatible with what measured in $B^+ \to K^+\mu^+\mu^-$ decays

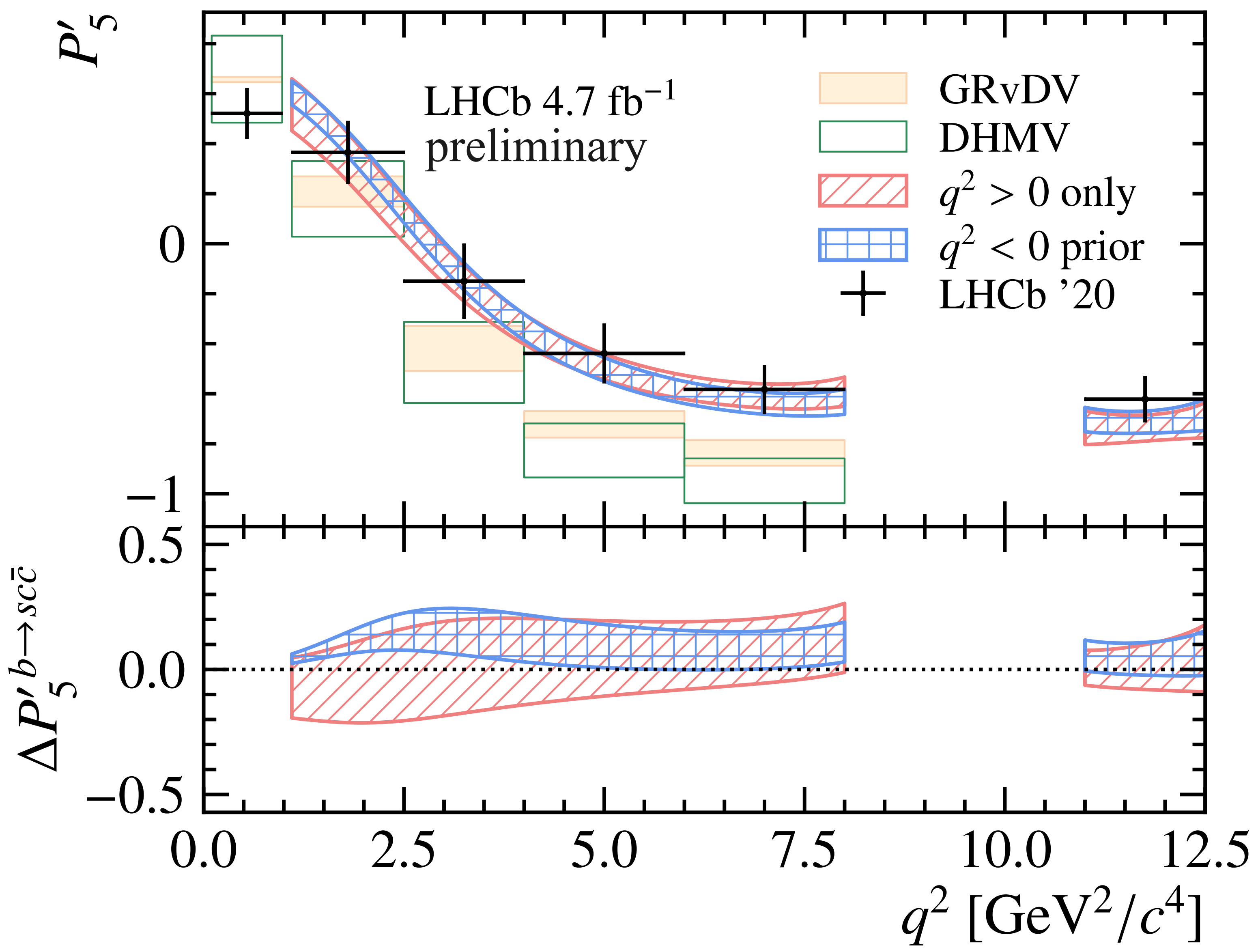
EPJ C77 (2017) 161

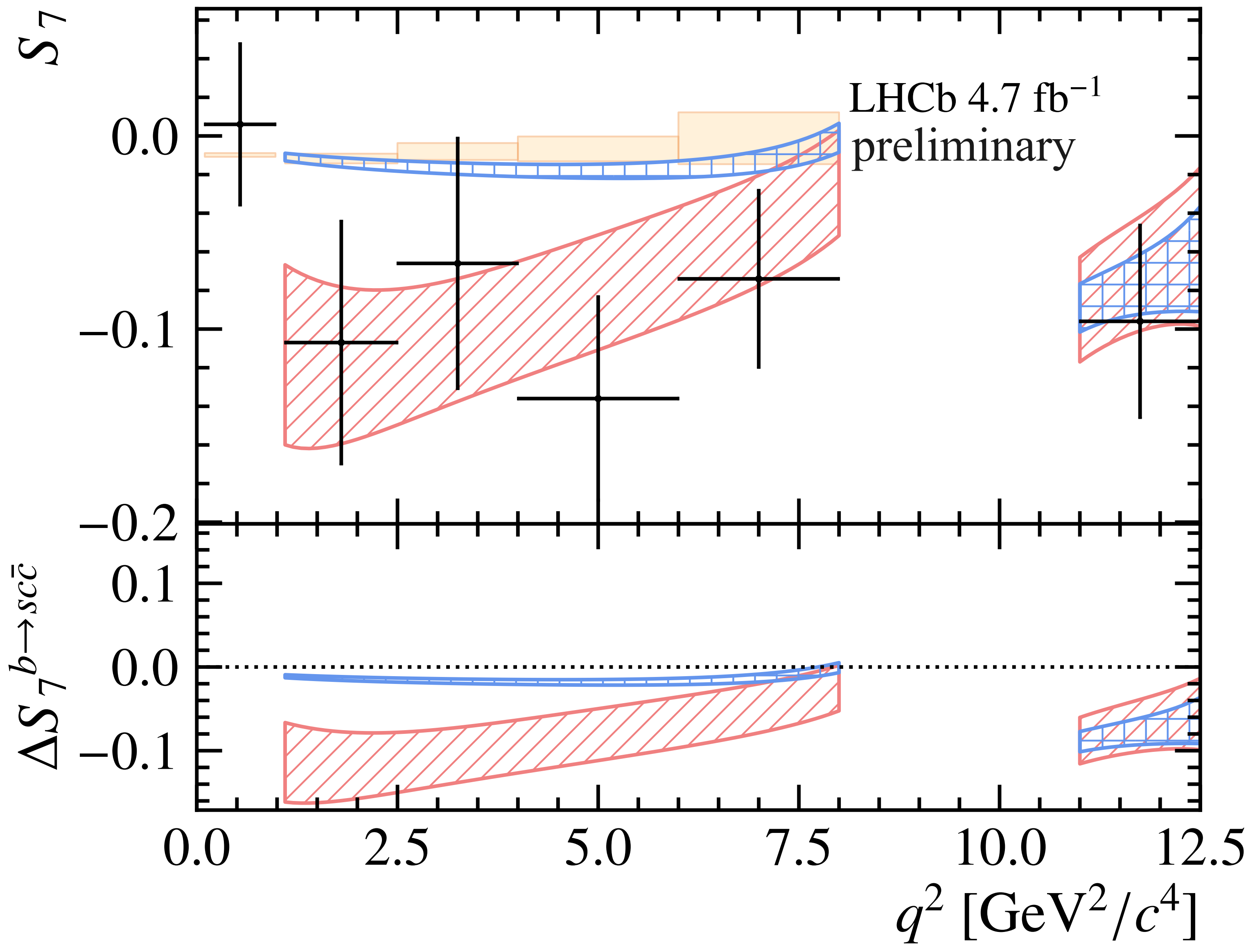


Retrieving the angular observables

- From the fit result we can reproduce the classic binned observables







- Lower BR compared to LHCb Run1 due to updated normalisation inputs
- Bottom: $c\bar{c}$ impact to P_5'

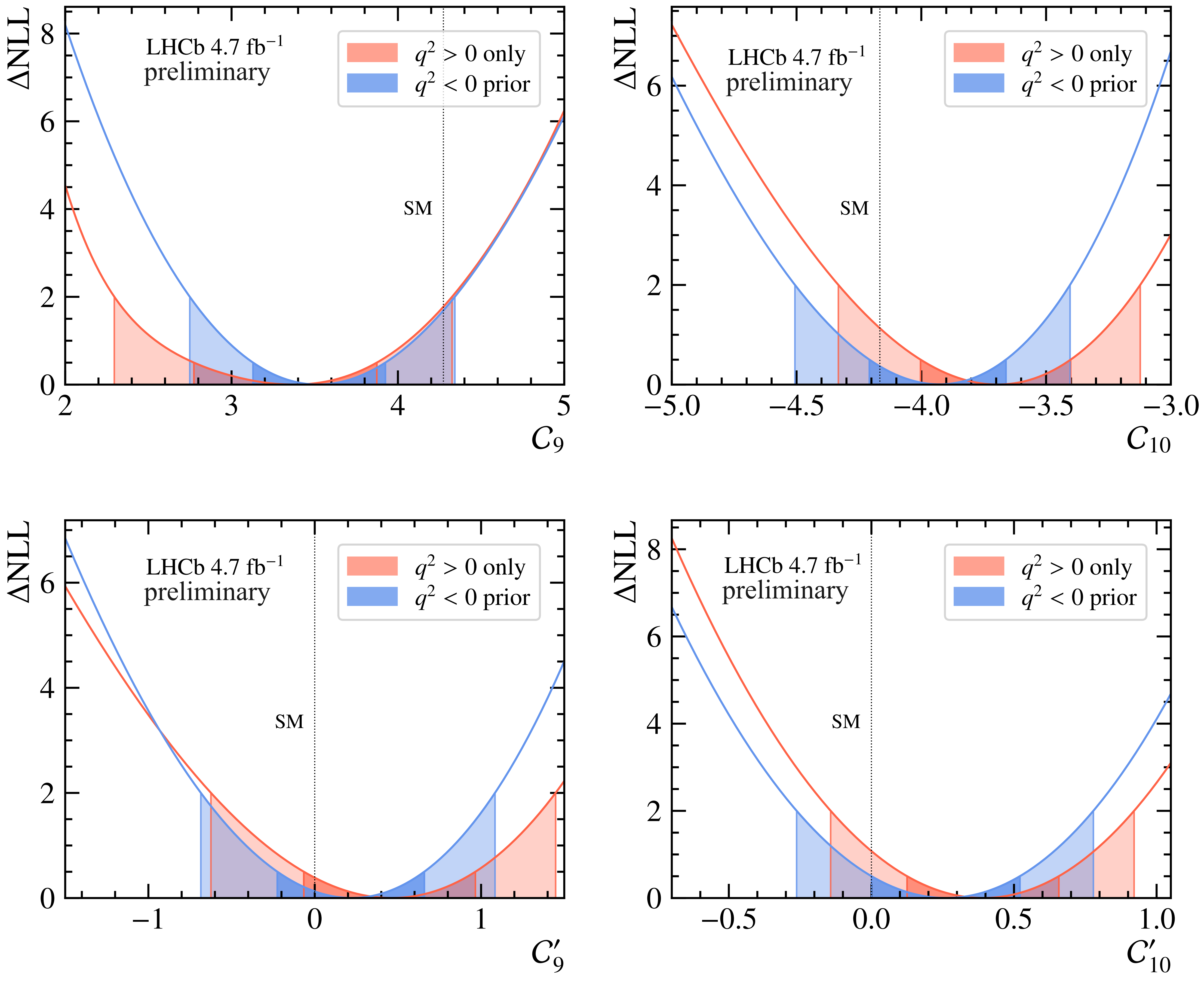
$$J_7 = \frac{3\sqrt{2}}{4}\beta_l \left[\mathrm{Im}(A_0^L A_\parallel^{L*}) - (L \to R) \right]$$

Wilson coefficients

- Uncertainty obtained from neg. log-likelihood profile

	$q^2 > 0$ only	
	Fit result	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	
$\mathcal{C}_9$	$-0.68^{+0.33}_{-0.46}$	$1.8\ \sigma$
$\mathcal{C}_{10}$	$0.24^{+0.27}_{-0.28}$	$0.9\ \sigma$
$\mathcal{C}'_9$	$0.26^{+0.40}_{-0.48}$	$0.5\ \sigma$
$\mathcal{C}'_{10}$	$0.27^{+0.25}_{-0.27}$	$1.0\ \sigma$

- Global compatibility [4 d.o.f.] with SM $1.3\,(1.4)\,\sigma$



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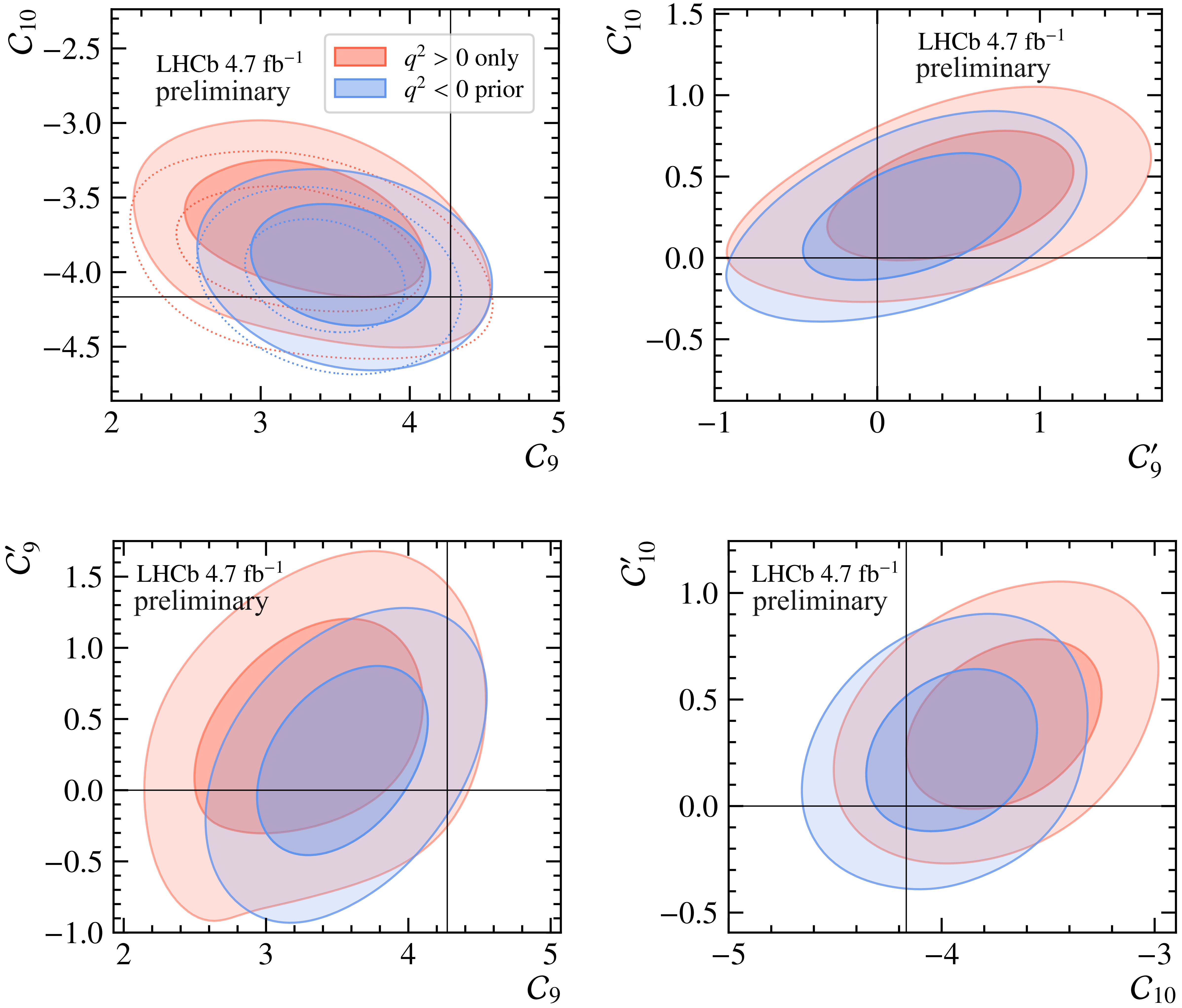

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Conclusion

- First unbinned amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays
- Complementary and more in dept set of information w.r.t. previous binned analyses
- Non-local hadronic determined from data under two assumptions
- Despite the extra freedom given by $c\bar{c}$ pars, fit still prefers to insert a shift in $\mathcal{C}_9$
- Tension reduced to $\sim 2\sigma$ in $\mathcal{C}_9$ and $\sim 1.4\sigma$ global

Backup

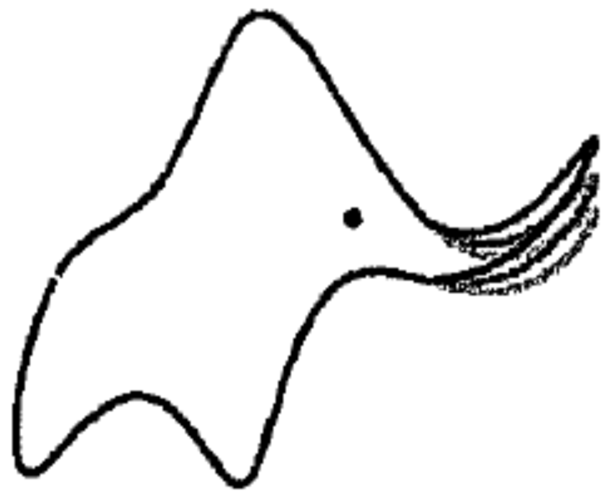
Results 68% 95% CL

	$q^2 > 0$ only			
	best fit value	68% CL	95% CL	deviation from SM
$\mathcal{C}_9$	3.34	[2.77, 3.87]	[2.30, 4.33]	1.9 σ
$\mathcal{C}_{10}$	−3.69	[−4.00, −3.40]	[−4.33, −3.12]	1.5 σ
$\mathcal{C}_9'$	0.48	[−0.07, 0.97]	[−0.62, 1.45]	0.9 σ
$\mathcal{C}_{10}'$	0.38	[0.13, 0.66]	[−0.14, 0.92]	1.5 σ
	$q^2 < 0$ prior			
$\mathcal{C}_9$	3.59	[3.13, 3.92]	[2.75, 4.34]	1.8 σ
$\mathcal{C}_{10}$	−3.93	[−4.21, −3.66]	[−4.51, −3.40]	0.9 σ
$\mathcal{C}_9'$	0.26	[−0.22, 0.66]	[−0.68, 1.08]	0.5 σ
$\mathcal{C}_{10}'$	0.27	[0.00, 0.52]	[−0.26, 0.78]	1.0 σ

Choice of the z order

- Truncation order of polynomial expansion chosen based on NLL improvement observed in data
  - $\mathcal{H}_\lambda[z^2]$ for fit @ $q^2 > 0$
  - $\mathcal{H}_\lambda[z^4]$ for fit with $q^2 < 0$ prior

	$2\Delta \log \mathcal{L}$	
	$q^2 < 0$ prior	$q^2 > 0$ only
$\mathcal{H}_\lambda[z^3] - \mathcal{H}_\lambda[z^2]$		3.6
$\mathcal{H}_\lambda[z^4] - \mathcal{H}_\lambda[z^3]$	21.22	-
$\mathcal{H}_\lambda[z^5] - \mathcal{H}_\lambda[z^4]$	8.64	-

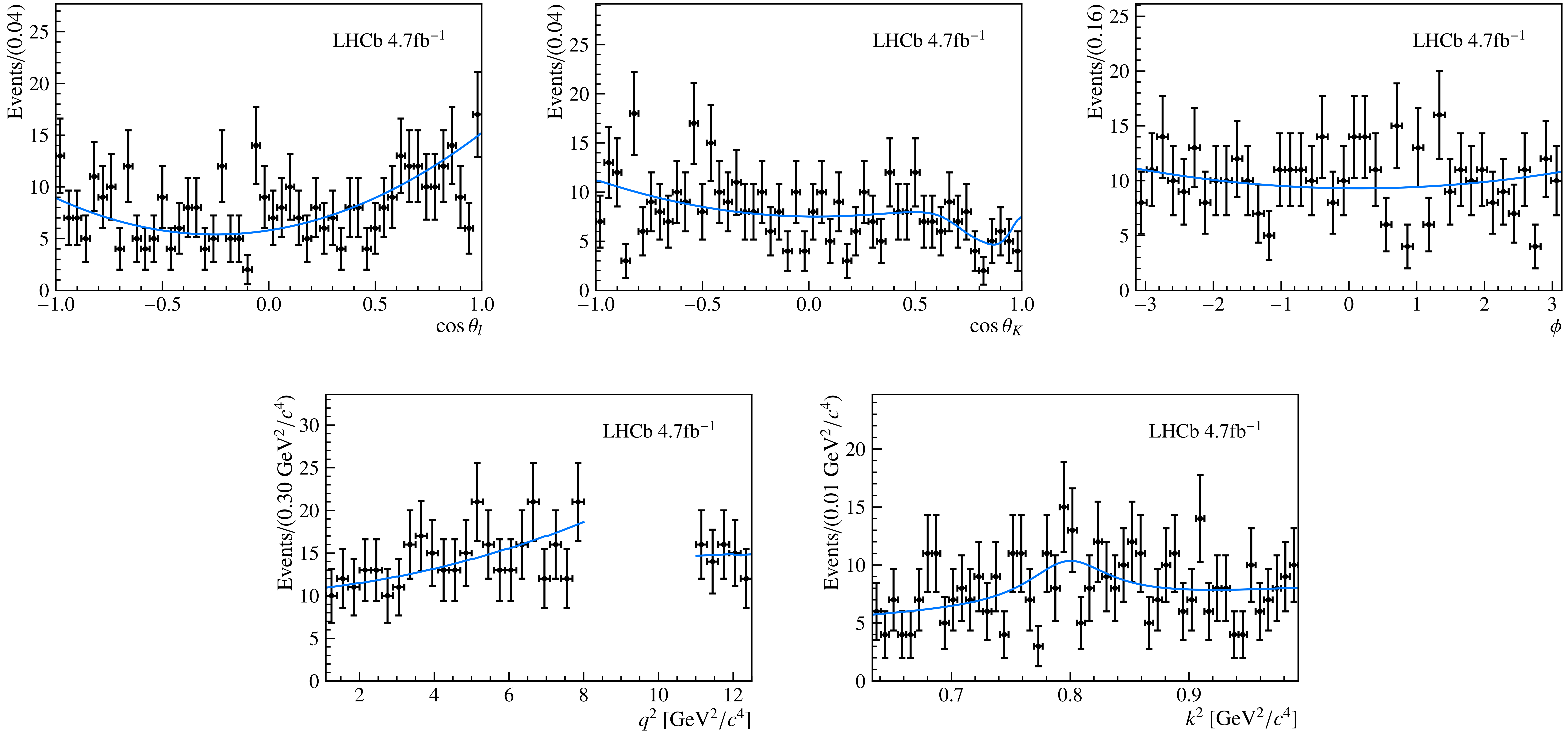


"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk." J. von Neumann

Systematics

	$\mathcal{C}_9$	$\mathcal{C}_{10}$	$\mathcal{C}'_9$	$\mathcal{C}'_{10}$
Amplitude model				
S-wave form factors	< 0.01	< 0.01	< 0.01	< 0.01
S-wave non-local hadronic	0.02	0.02	0.14	0.04
S-wave k^2 model	< 0.01	< 0.01	0.05	0.03
Subtotal	0.02	0.02	0.15	0.05
External inputs on BR				
$\mathcal{B}(B^0 \to J/\psi K^+\pi^-)$	0.05	0.08	0.02	0.01
$f_{\pm 100\mathrm{MeV}}^{B^0\to J/\psi K\pi}$	0.03	0.03	0.01	< 0.01
Others	0.03	0.04	0.03	0.01
Subtotal	0.07	0.09	0.04	0.01
Background model				
Chebyshev polynomial order	0.01	0.01	0.01	< 0.01
Combinatorial shape in k^2	0.02	< 0.01	0.02	< 0.01
Background factorisation	0.01	0.01	0.01	0.01
Peaking background	0.01	< 0.01	0.02	0.01
Subtotal	0.03	0.02	0.03	0.01
Experimental effects				
Acceptance parametrisation	< 0.01	< 0.01	< 0.01	< 0.01
Statistical uncertainty on acceptance	0.02	< 0.01	0.02	< 0.01
Subtotal	0.02	< 0.01	0.02	< 0.01
Total systematic uncertainty	0.08	0.10	0.16	0.05

Upper mass projections



Ang. obs (P-basis)

Ang. obs (S-basis)