Amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays at LHCb

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On behalf of the LHCb collaboration

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LHCb-PAPER-2023-033
in preparations

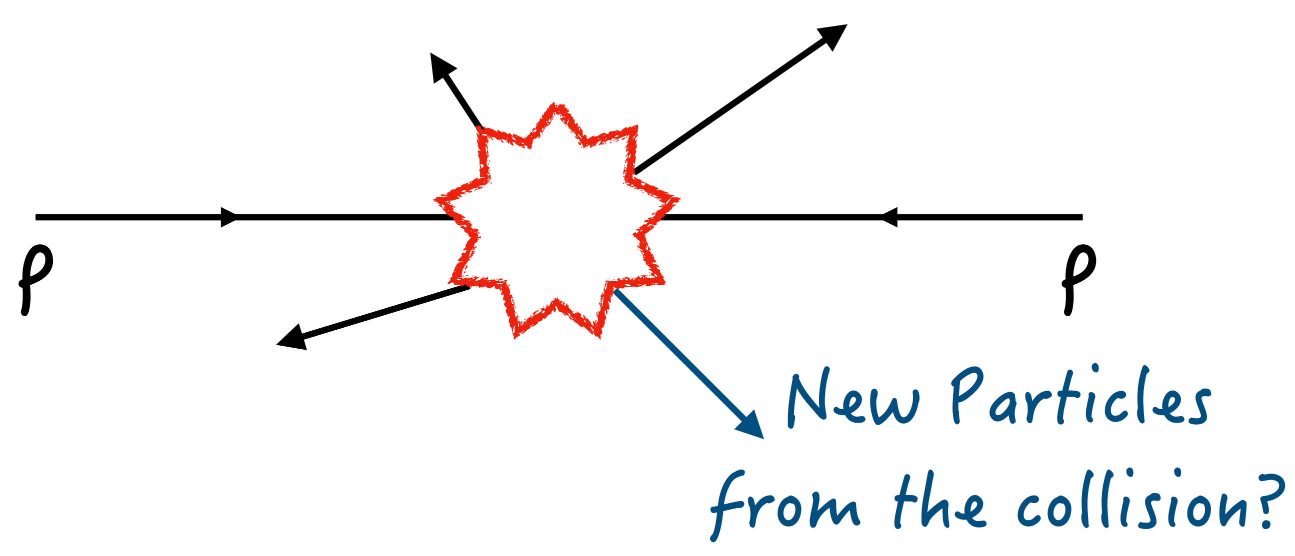
LHC seminar, CERN, 14 November 2023

Outline

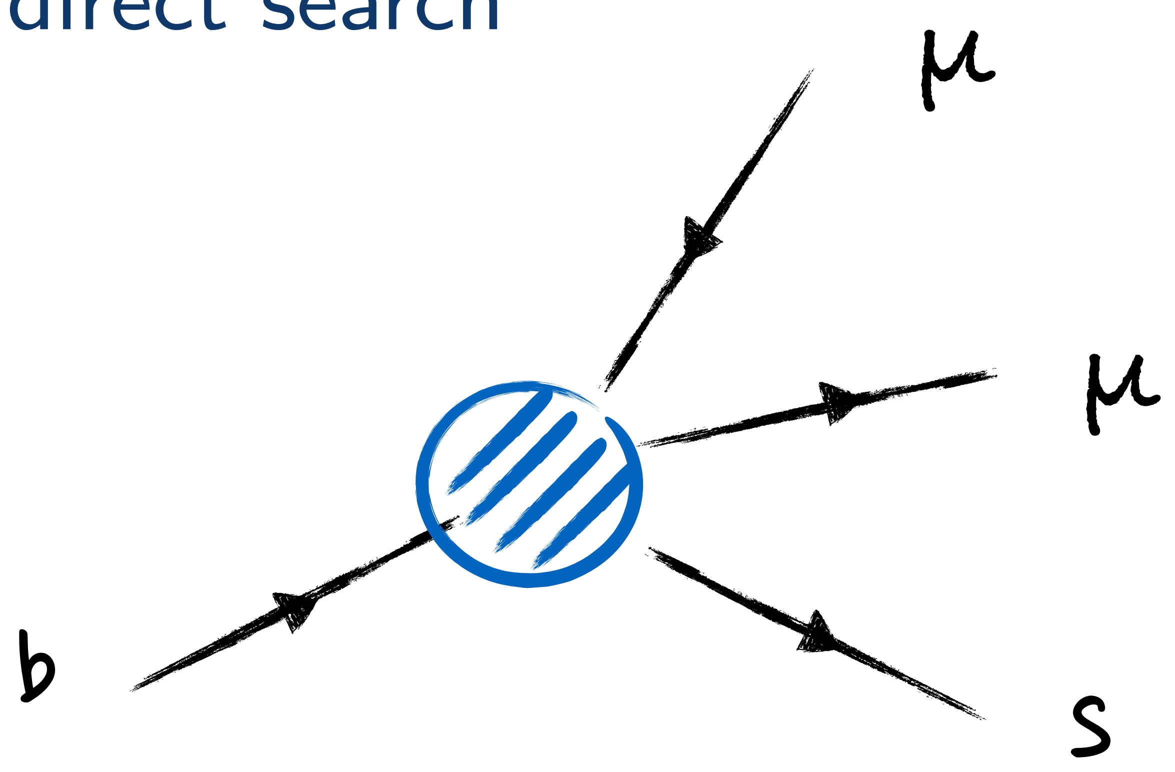
- Introduction to $b \to s\ell\ell$ decays
- Status of the field
- Amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays
  - Methodology
  - LHCb detector & selected dataset
  - Results
- Future prospects & conclusions

The indirect search for NP

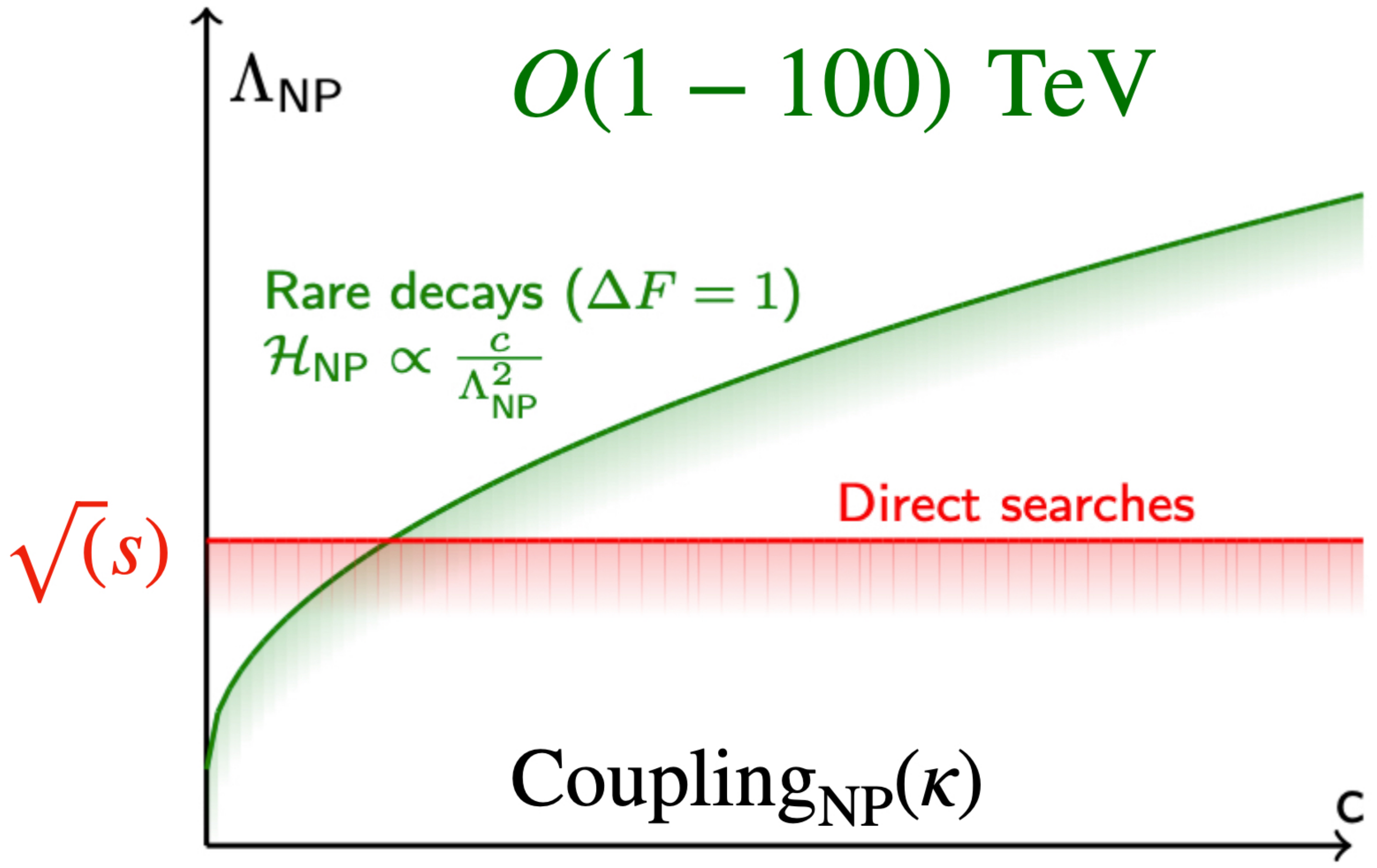
Direct search



Indirect search

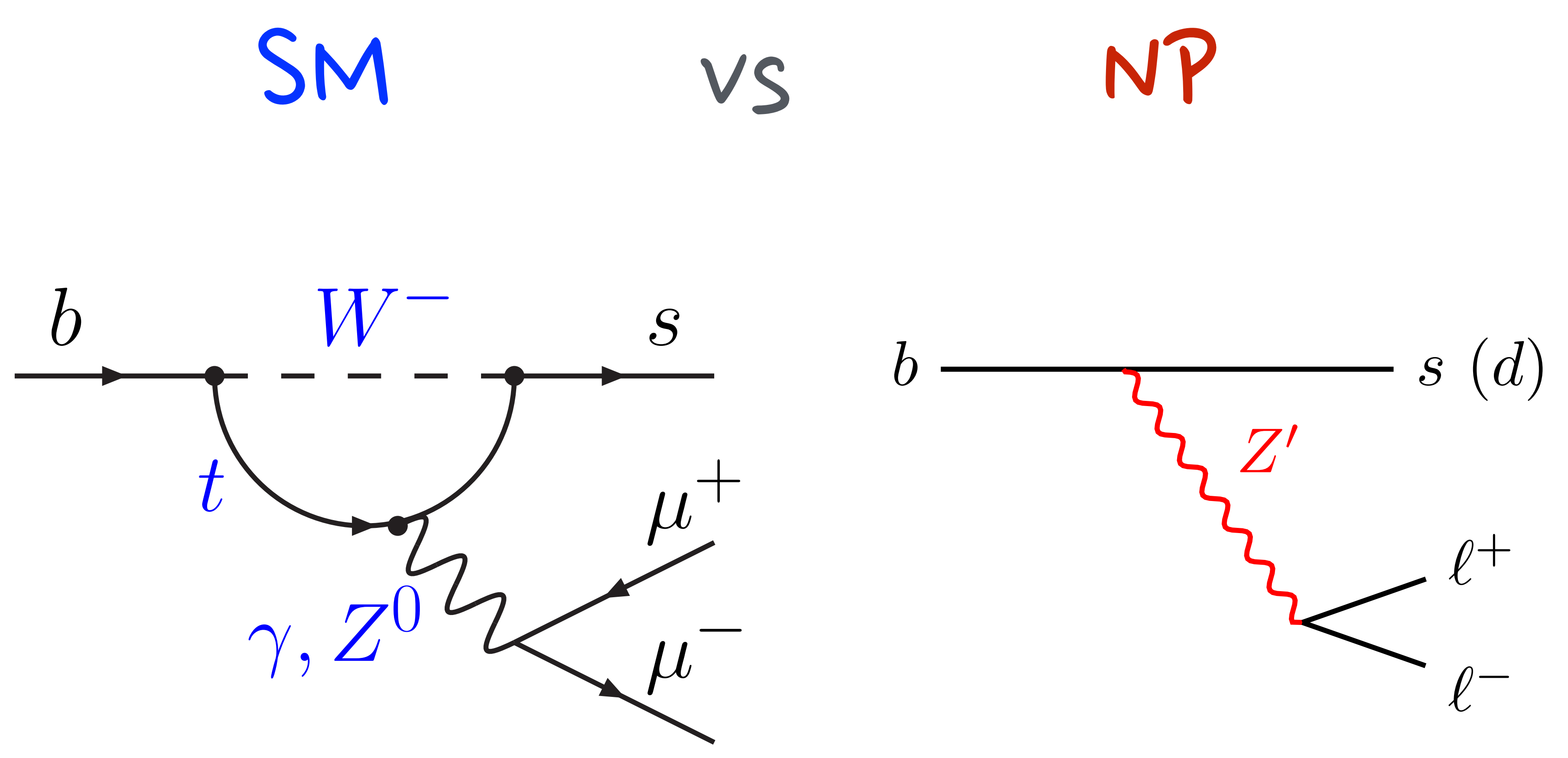


- So far, no direct evidence of physics beyond the SM
- Indirect searches
  - Study processes that are suppressed or even forbidden in the SM → NP can be relatively large
  - Precision measurement of observables → compare with (precise) SM predictions
  - Access higher mass scales (virtual contribution)



Why $b \to s\mu\mu$

- Flavour Changing Neutral Currents such as $b \to s\mu\mu$ are excellent candidates for indirect NP searches
  - Strongly suppressed in the SM: $\mathscr{B} \sim \mathcal{O}(10^{-6})$
    - arise only at loop level
    - quark mixing is so hierarchical
    - GIM mechanism
    - only left-handed chirality participates in the SM



- NP particles can compete with the SM process and modify the properties of the decay

The SM as an Effective Field Theory

- Low energy processes (B decays) can be described by an effective theory by integrating out the heavy fields

$$\mathscr{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i (C_i^{SM} + \Delta C_i^{NP}) \mathscr{O}_i$$

Wilson coefficients (*effective couplings*)

Local operators

- NP particles can modify the effective couplings of the different types of interaction

- SM operators contributing to $b \to s\ell^+\ell^-$ transitions

$$\mathcal{O}_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_R^{\alpha} \sigma^{\mu\nu} F_{\mu\nu} s_L^{\alpha}\,, \qquad \textit{photon}$$

$$\mathcal{O}_{9V} = \frac{1}{2} \bar{b}_L^{\alpha} \gamma^{\mu} s_L^{\alpha} \bar{\ell} \gamma_{\mu} \ell\,, \qquad \textit{vector}$$

$$\mathcal{O}_{10A} = \frac{1}{2} \bar{b}_L^{\alpha} \gamma^{\mu} s_L^{\alpha} \bar{\ell} \gamma_{\mu} \gamma_5 \ell\,, \qquad \textit{axial-vector}$$

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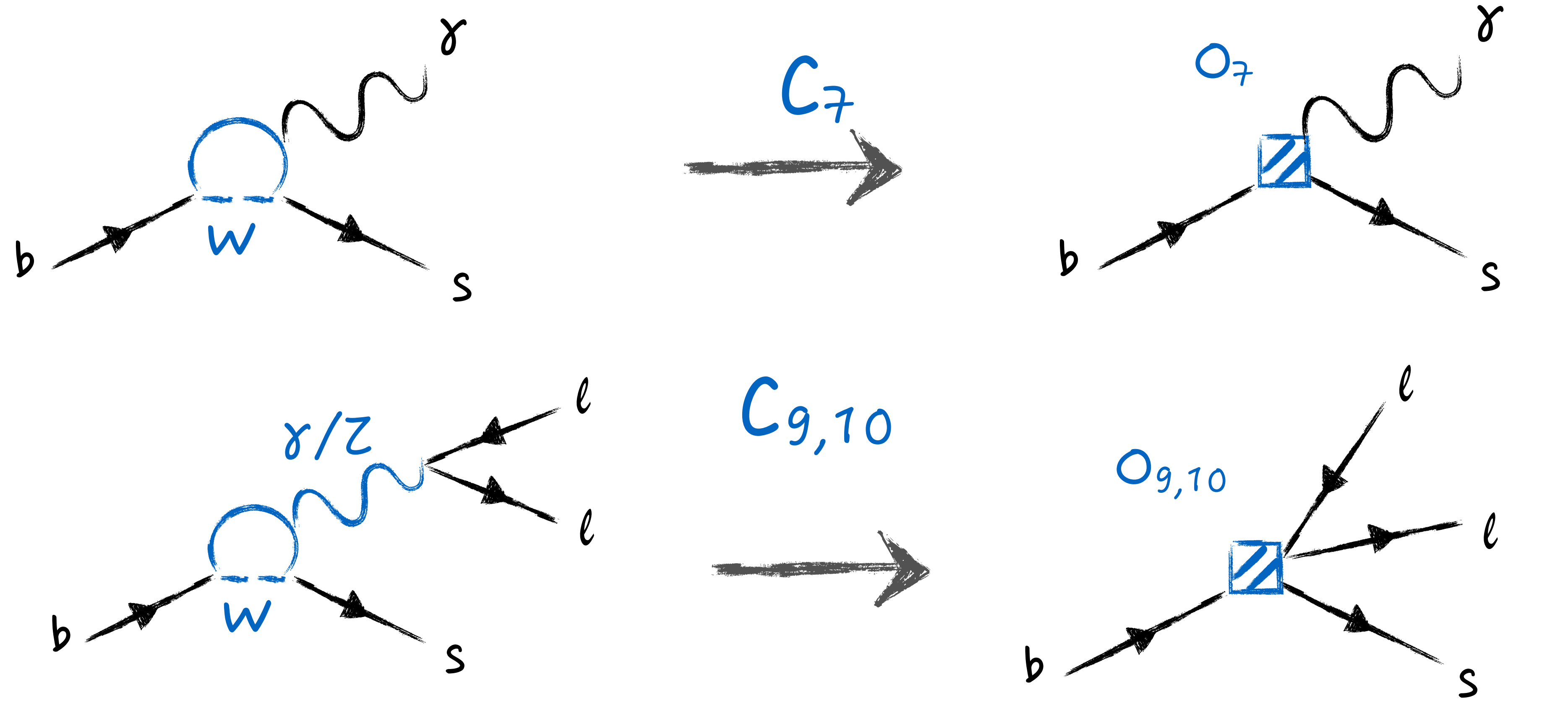
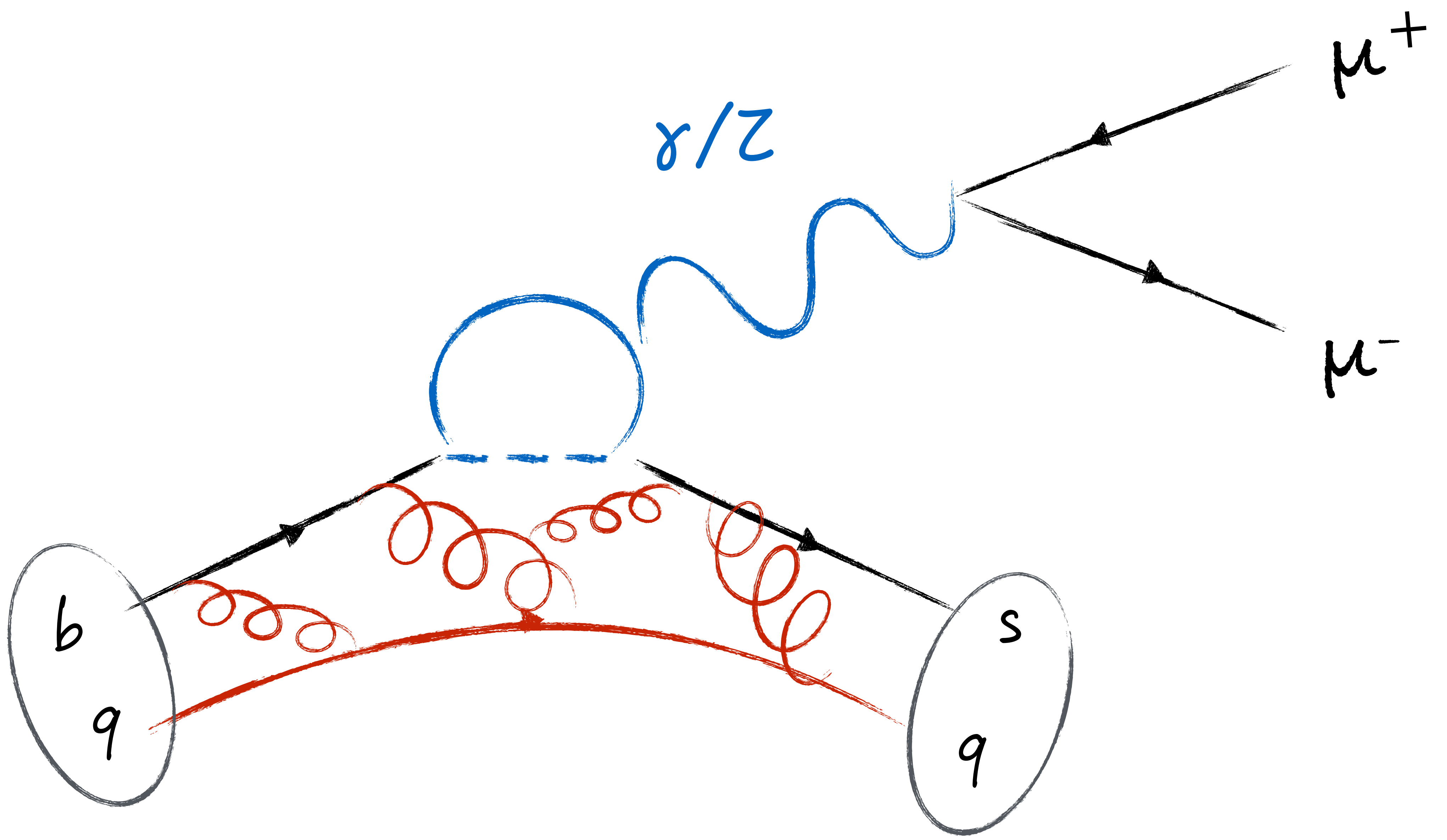


Exclusive decays

- In the real world, we do not observe the quark transition, but the hadron decay

$$b \to s\mu^+\mu^- \longrightarrow \begin{cases} B^+ \to K^+\mu^+\mu^- \\ B^0 \to K^{*0}\mu^+\mu^- \\ B_s \to \phi\mu^+\mu^- \\ \dots\ \dots\ \dots \end{cases}$$



- Need to compute hadronic matrix elements (form-factors, decay constant, etc.)
  - non-perturbative QCD $\longrightarrow$ difficult calculations!
  - main uncertainty in the SM predictions

Status of the field: experiments

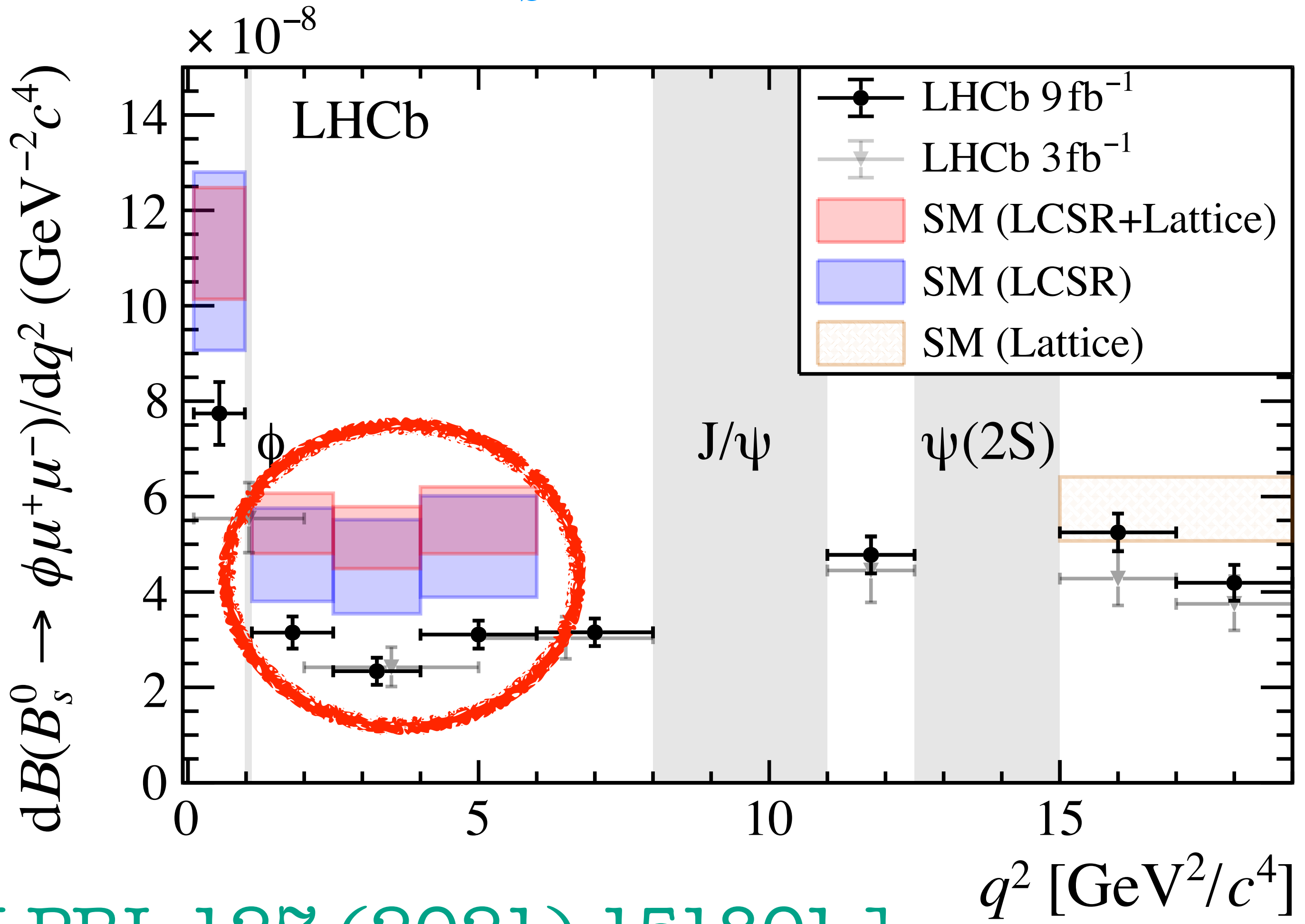
q^2: dimuon invariant mass squared

Branching fraction measurements

- Measured to be lower than SM in several $b \to s\mu^+\mu^-$ decays
  - SM prediction largely affected by form-factors uncertainties

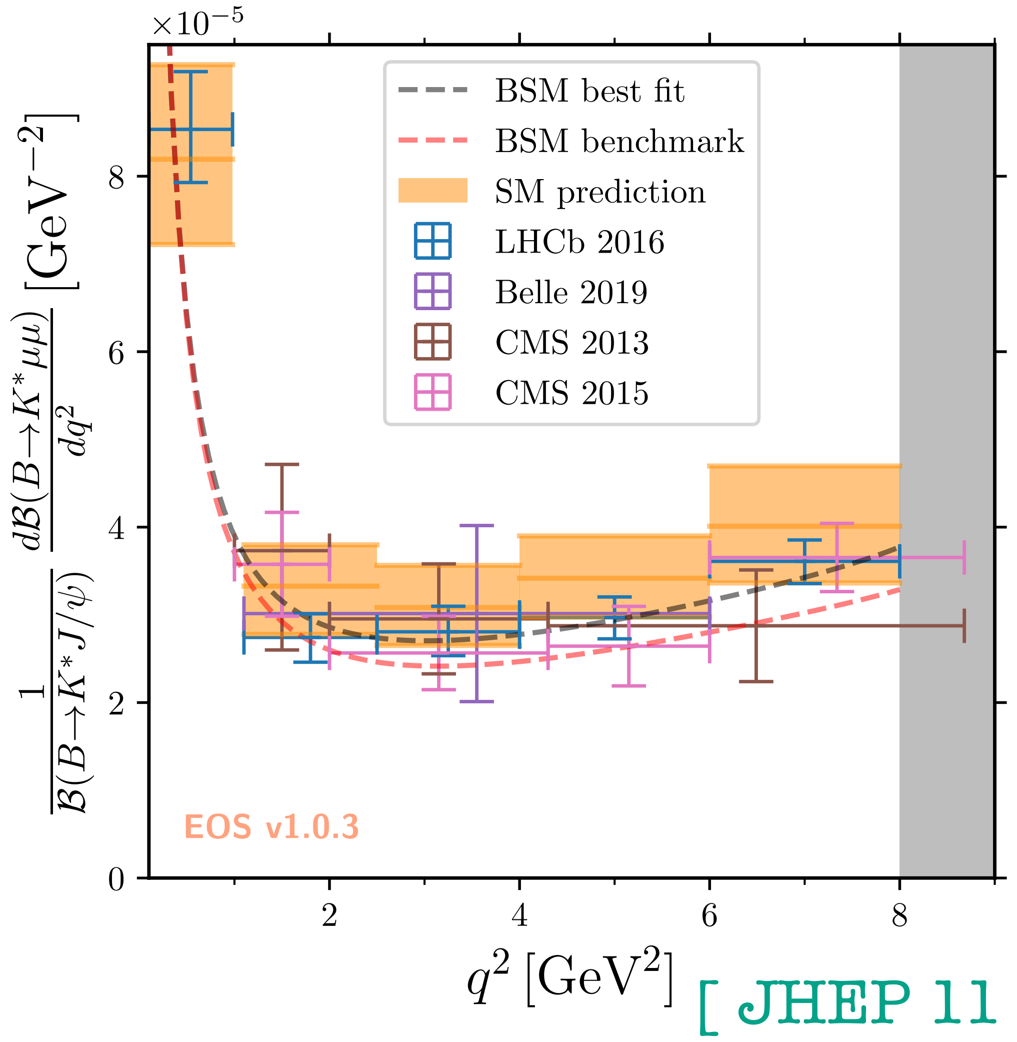
Anomaly **or common issue with form factors from SM?**

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



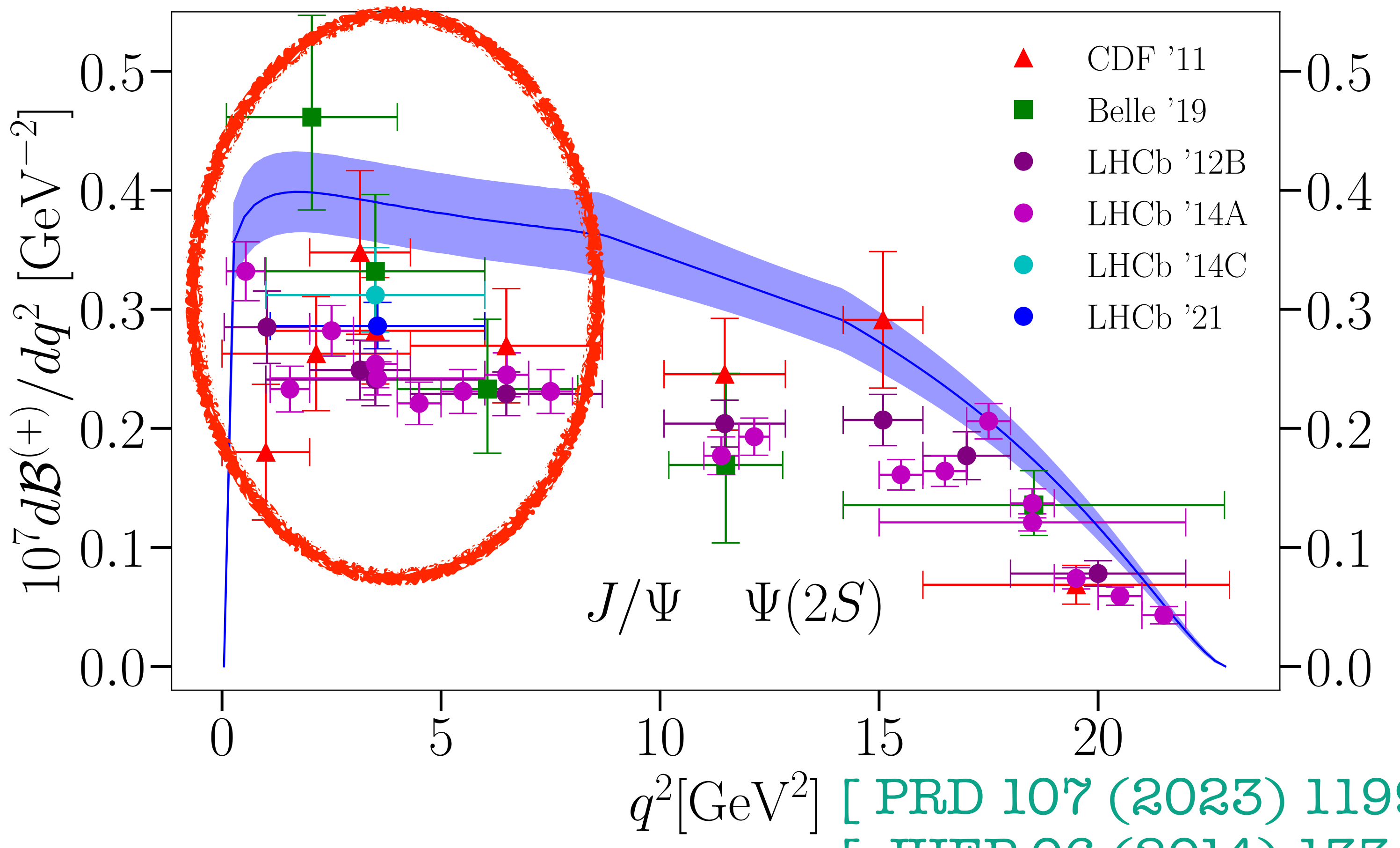
[PRL 127 (2021) 151801]

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



[JHEP 11 (2016) 047]
[JHEP 04 (2017) 142]
[JHEP 09 (2022) 133]

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

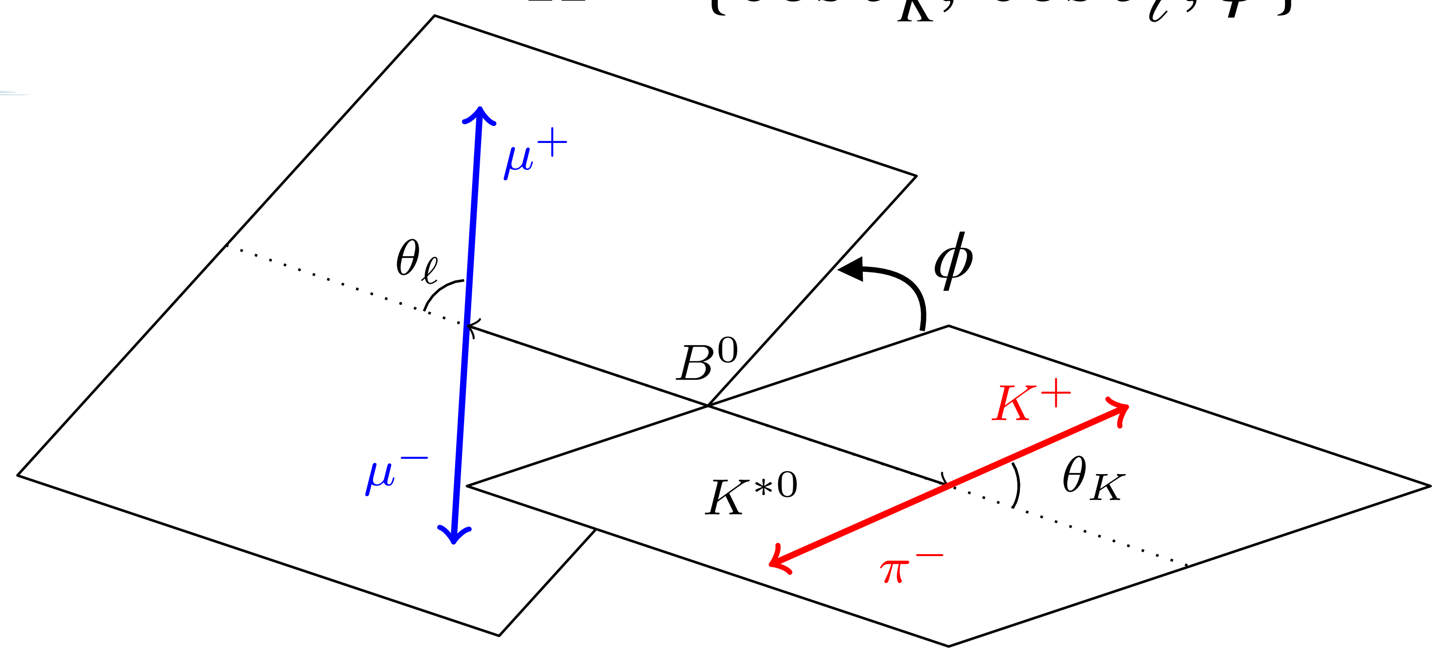


[PRD 107 (2023) 119903]
[JHEP 06 (2014) 133]

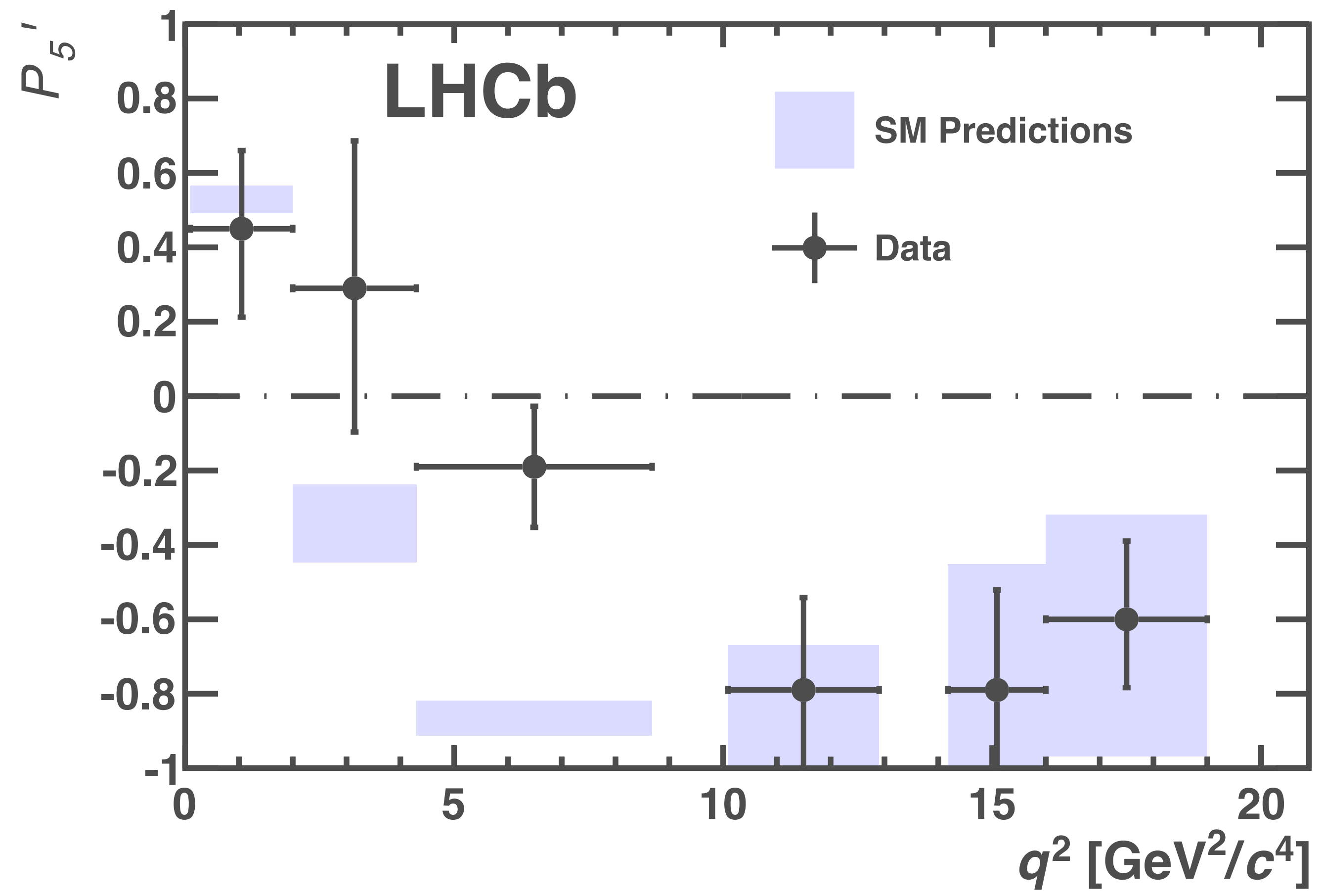
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

- *Optimised* P'_5 observable: reduced form-factor uncertainties
  - long standing discrepancy (since first measurement in 2013)

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

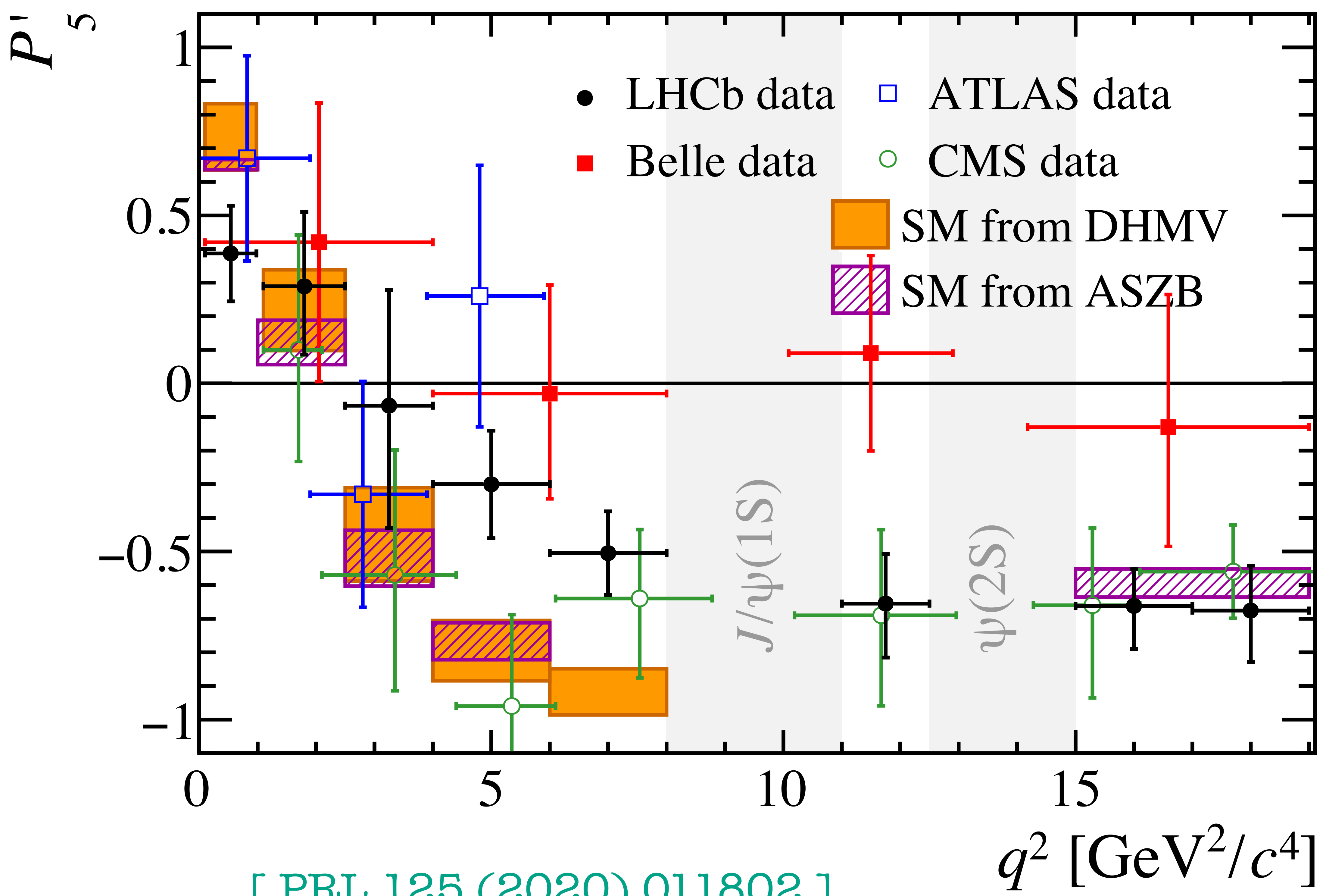


(2013) 1 fb^{-1}



[PRL 111 (2013) 191801]

(2020) 4.7 fb^{-1}



[PRL 125 (2020) 011802]

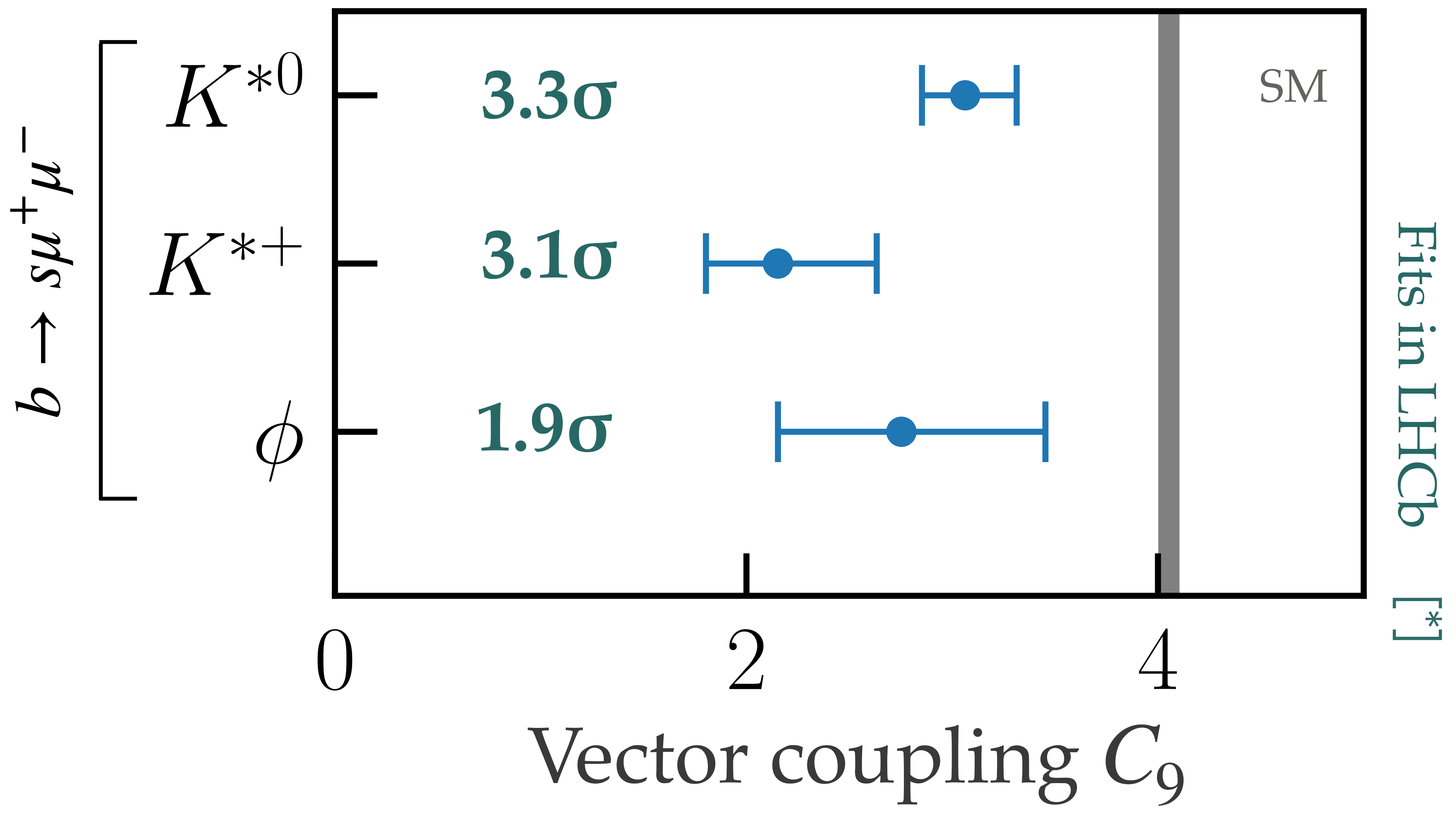
More angular analyses…

- LHCb performed angular analysis on other exclusive $b \to s\mu^+\mu^-$ decays

PRL 125 (2020) 011802
- $B^0 \to K^{*0}\mu^+\mu^-$ with 4.7 fb-1 (~4600 events)

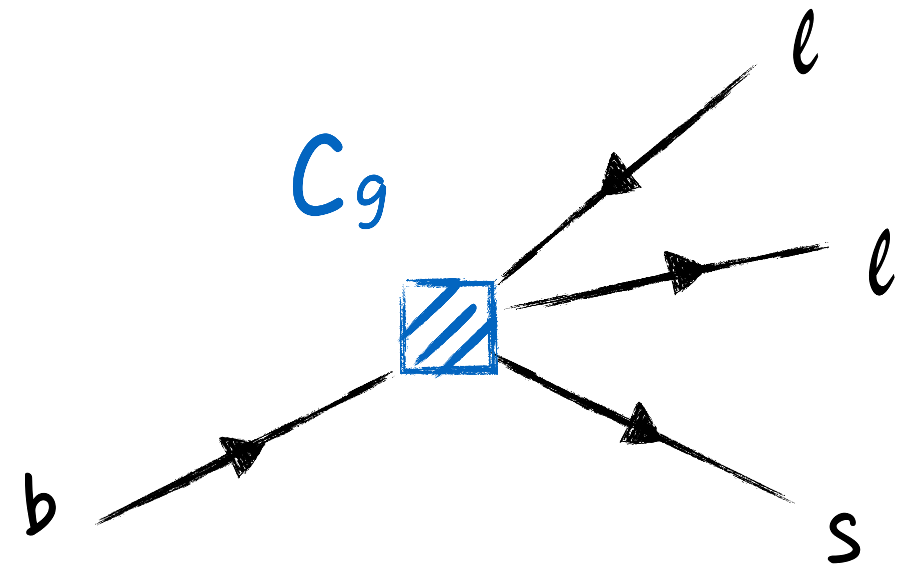
PRL 126 (2021) 161802
- $B^+ \to K^{*+}\mu^+\mu^-$ with 9 fb-1 (~700 events)

JHEP 11 (2021) 043
- $B_s \to \phi\mu^+\mu^-$ with 9 fb-1 (~1900 events)



Intriguing coherent pattern…

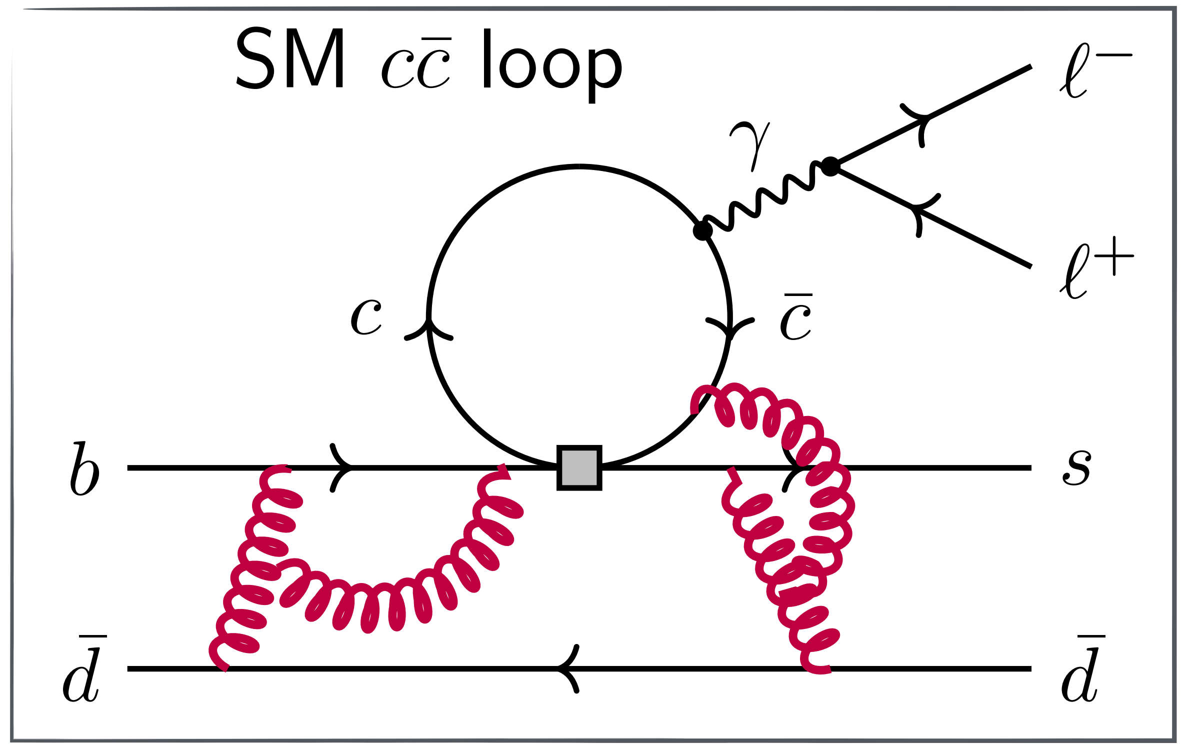
Is it New Physics or *charm-loop*…?



[*] based on Flavio software, only C9 floated

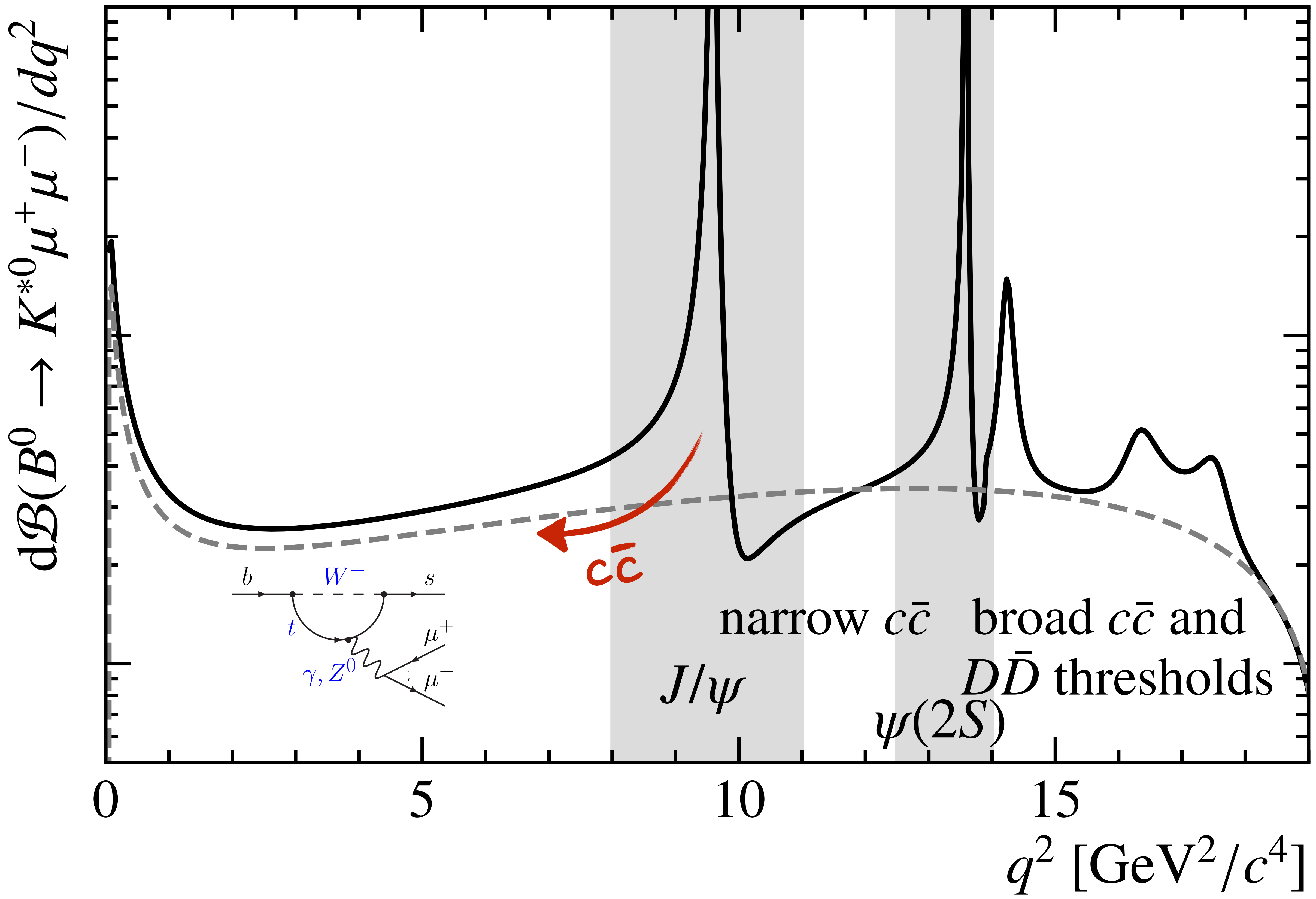
Long-distance QCD effects (charm-loop)

- Long-distance hadronic contribution "*charm-loop*"
  - Difficult to calculate reliably from first principles
  - Can mimic NP



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

Resonance magnitudes and phases chosen arbitrarily for illustration purpose



Motivation to the analysis

- A deeper comprehension of the impact of these hadronic contributions is crucial for a final understanding of the $b \to s\mu^+\mu^-$ anomalies

- Perform an amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays
  - Fit the full 5D differential decay rate unbinned in q^2
    - maximal sensitivity to non-local hadronic effects (and New Physics)

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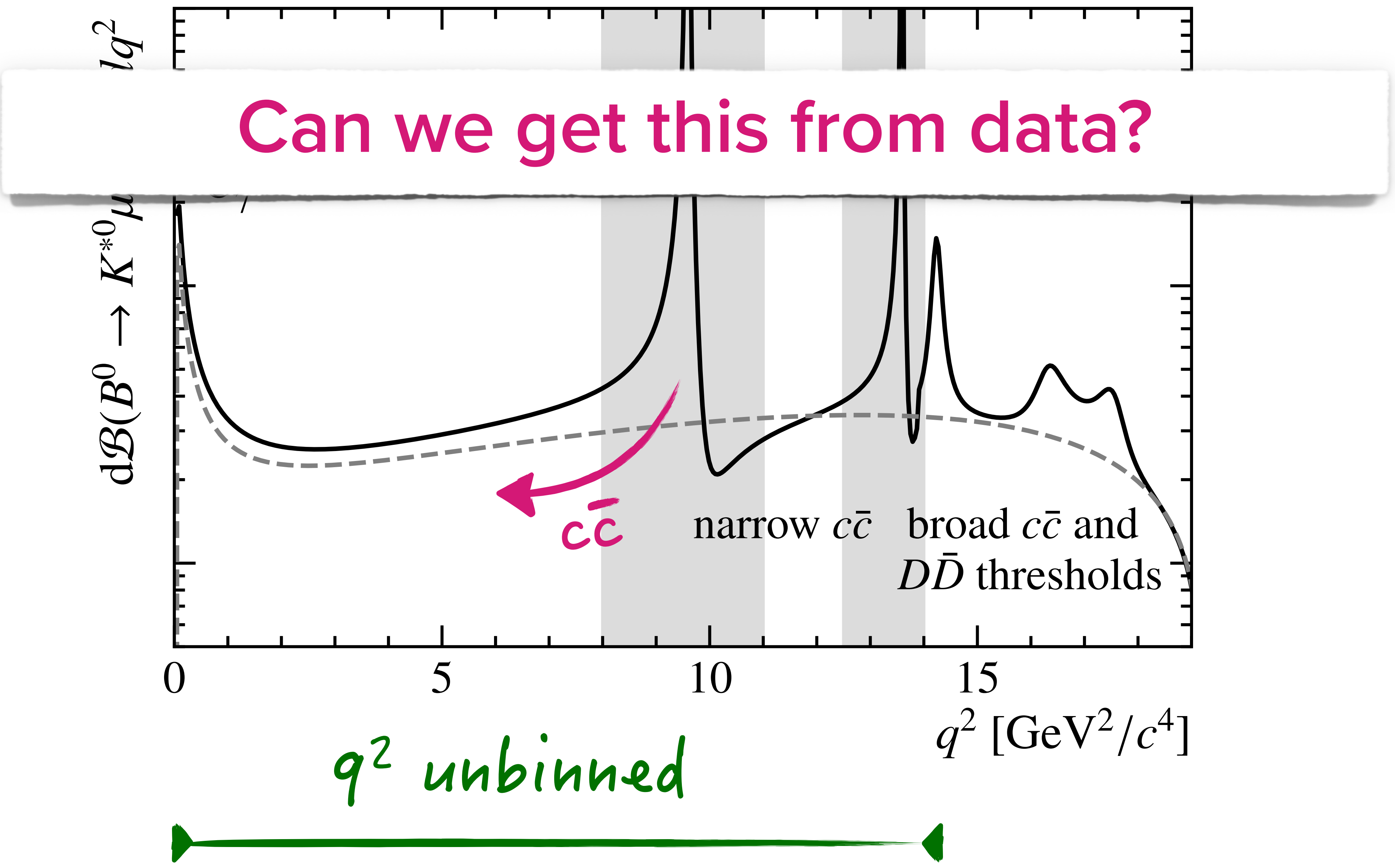

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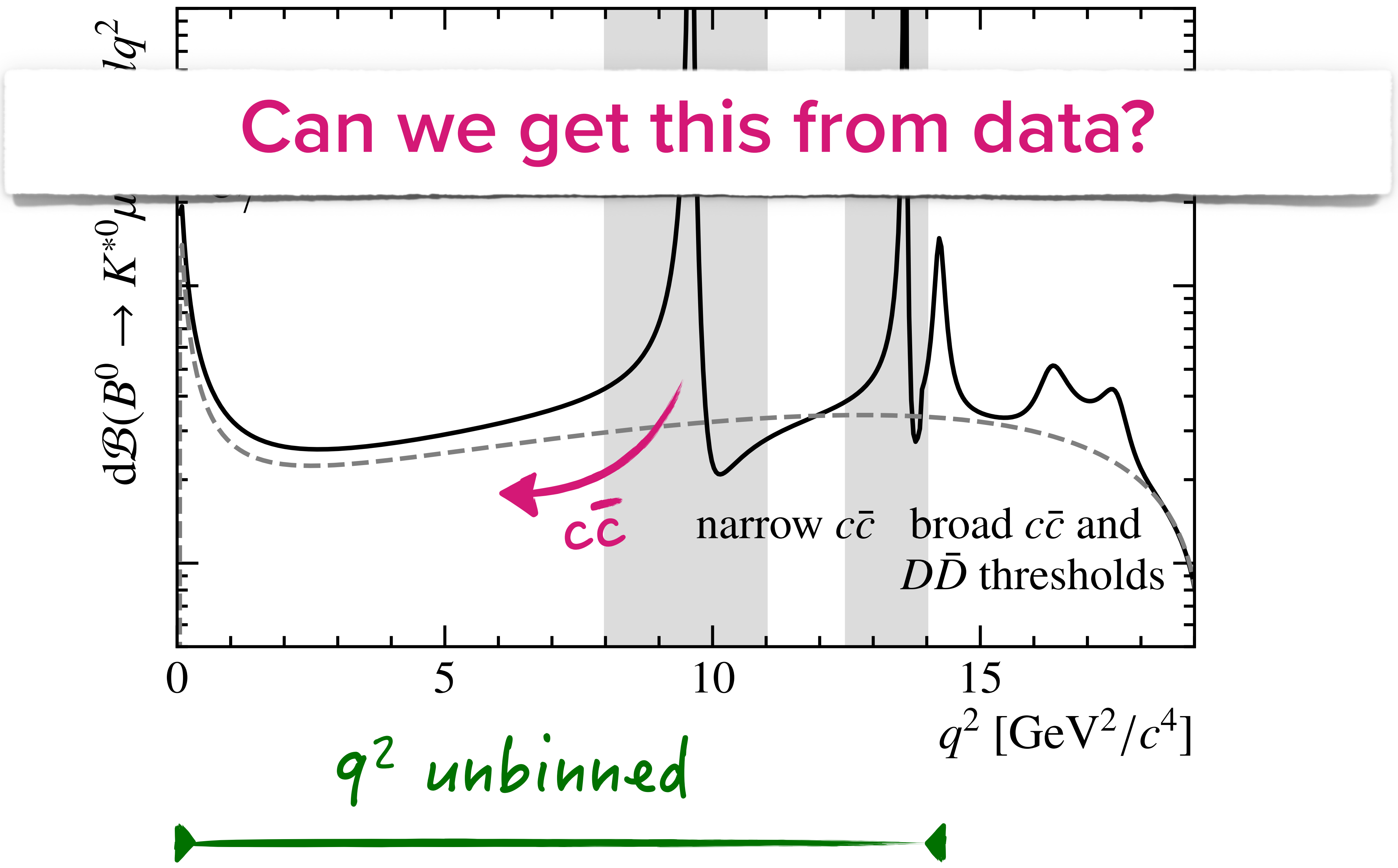
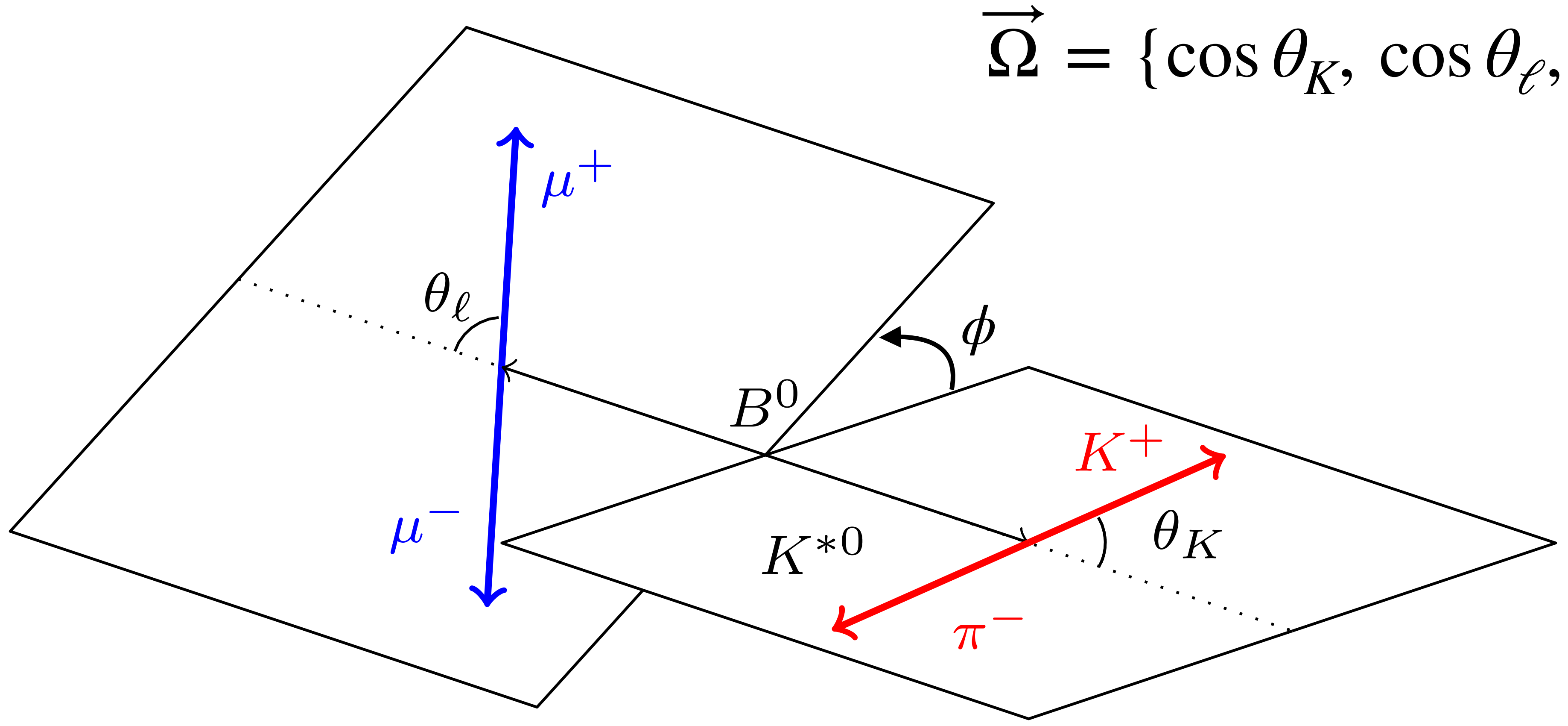


- Perform a (model dependent) amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays
  - Fit the full 5D differential decay rate unbinned in q^2
    - maximal sensitivity to non-local hadronic effects (and New Physics)

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

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



- K^{*0} meson has spin-1 (P-wave)
  - reconstructed through $K^{*0} \to K^+\pi^-$
  - 3 polarisations: $\lambda = \perp, \parallel, 0$
    ↳ rich angular structure

$$\frac{d^5\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, dk^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2,k^2) f_i(\vec{\Omega})$$

Angular coeffs   Angular terms (11)

bilinear combination of decay amplitudes [*]

$$I_i \propto \left(\mathcal{A}_{\lambda_1}\mathcal{A}^*_{\lambda_2}\right)$$

difference w.r.t. binned approach ↔

$$< S_i >= \frac{\int_a^b I_i(q^2)\mathrm{d}q^2}{\int_a^b \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}\mathrm{d}q^2}$$

[*] Full definition in the backup

The decay amplitudes

- Need to parametrise the decay amplitudes
  - model *local* vs *non-local* contributions
  - choice of parametrisation introduces a model dependence

non-local hadronic matrix elements "charm-loop"

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

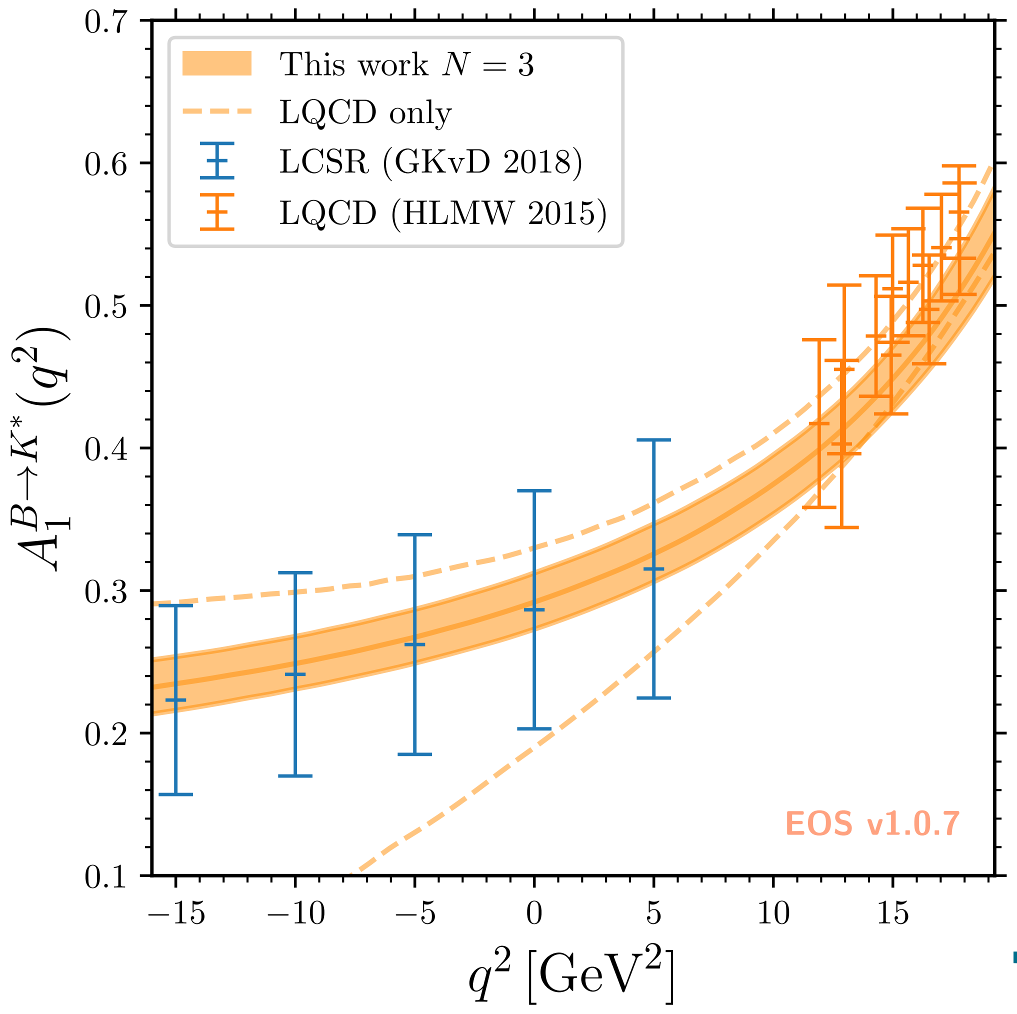
Wilson coeff.

Form Factors

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]



Non-local hadronic terms (I)

- Based on the parametrisation proposed in Refs.
  - 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

  - exploit analytic properties of the hadronic matrix elements

1. Map q^2 into *conformal* variable $z(q^2)$:

$$q^2 \mapsto z(q^2) \equiv \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

2. Remove J/ψ and $\psi(2S)$ poles
3. Taylor-expand the remaining function

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

These are the parameters we want to measure

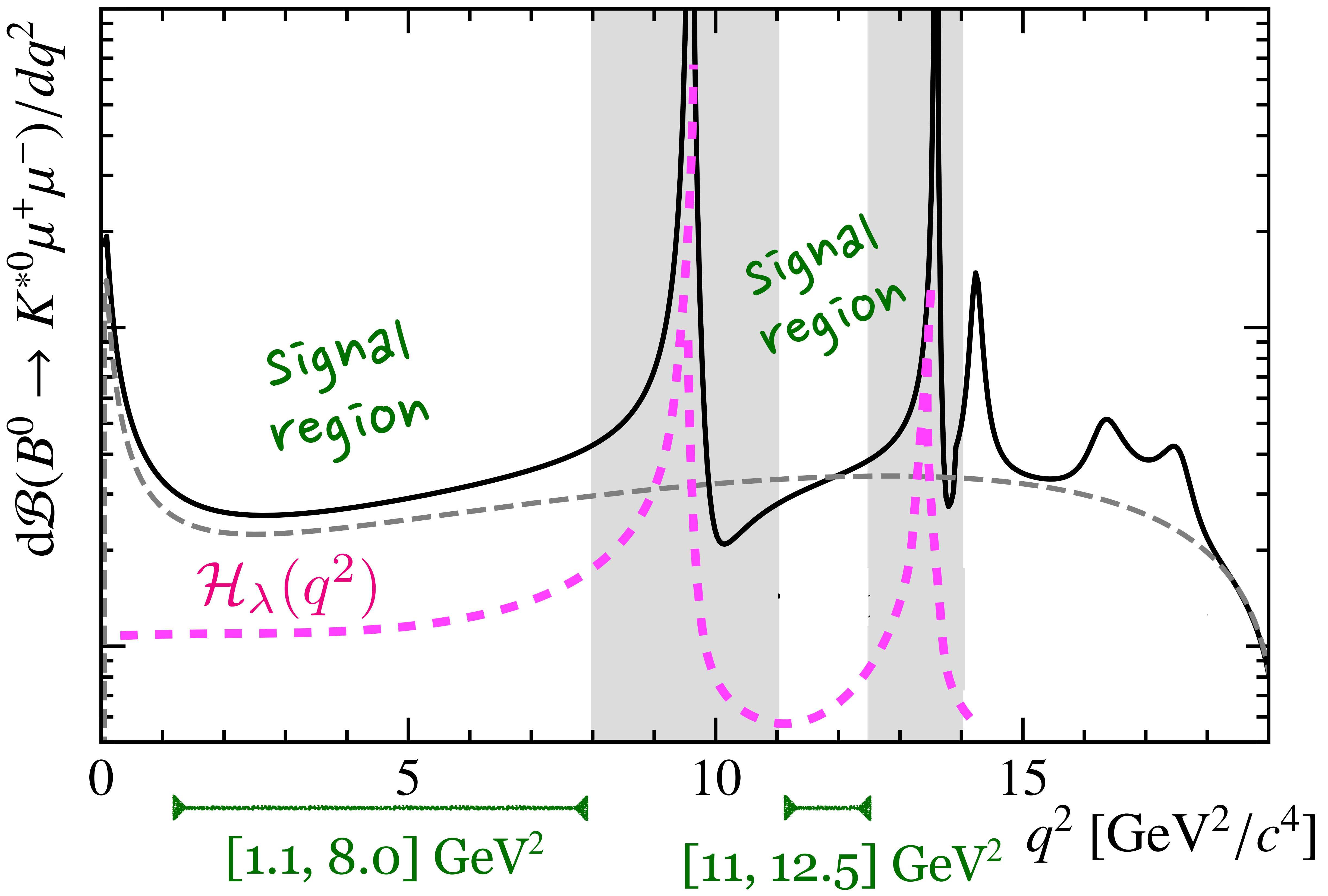
Poles

some known functions [GvDV 2021]

polynomial expansion

Non-local hadronic terms (II)

- Add information to constrain charm-loop parameters



Non-local hadronic terms (II)

- Add information to constrain charm-loop parameters

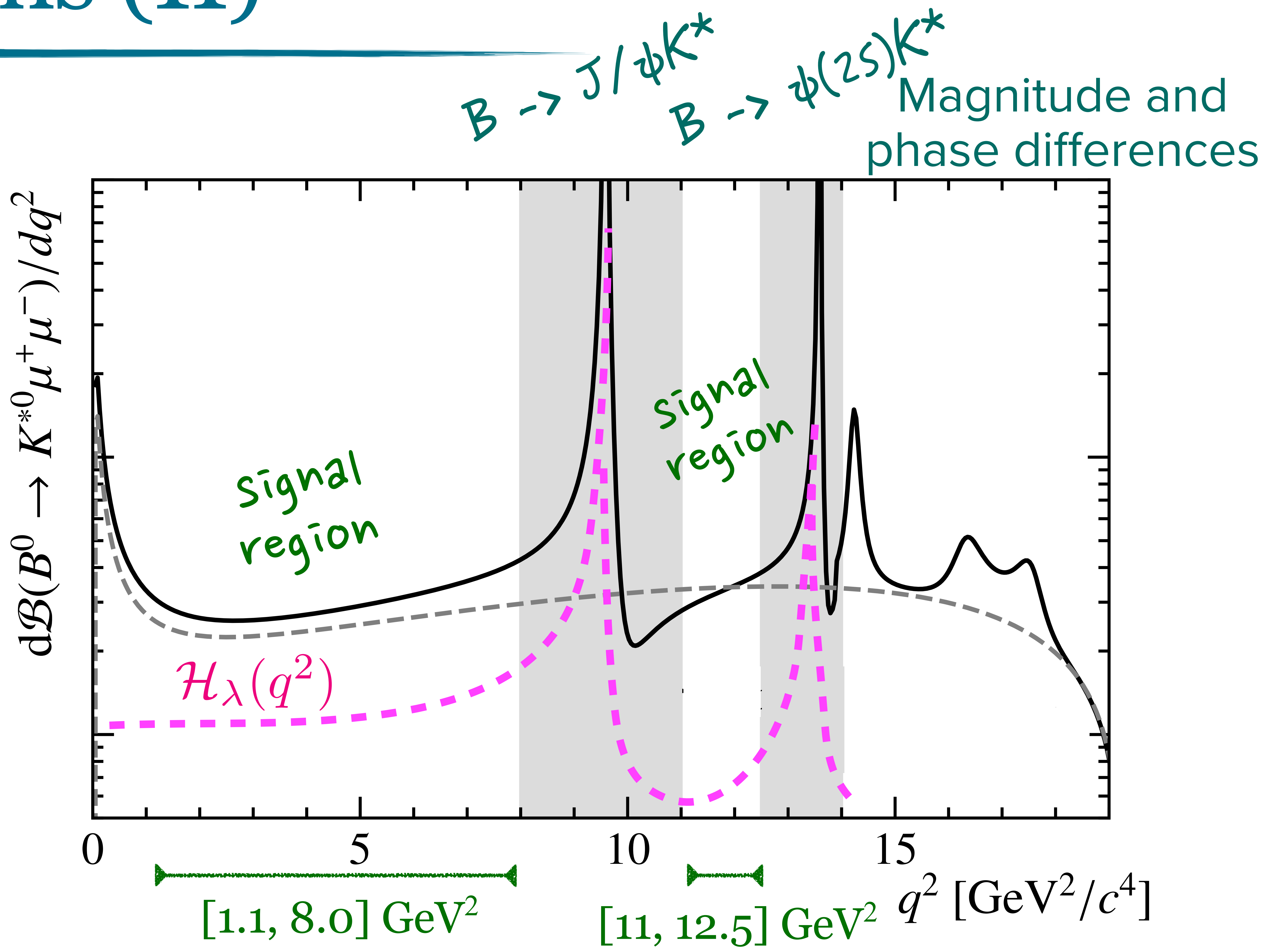
  ① experimental measurements on $B^0 \to \psi_n K^{*0}$ decays

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

[BCvDV 2018]

  - Branching fraction, polarisation fraction and phase differences

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



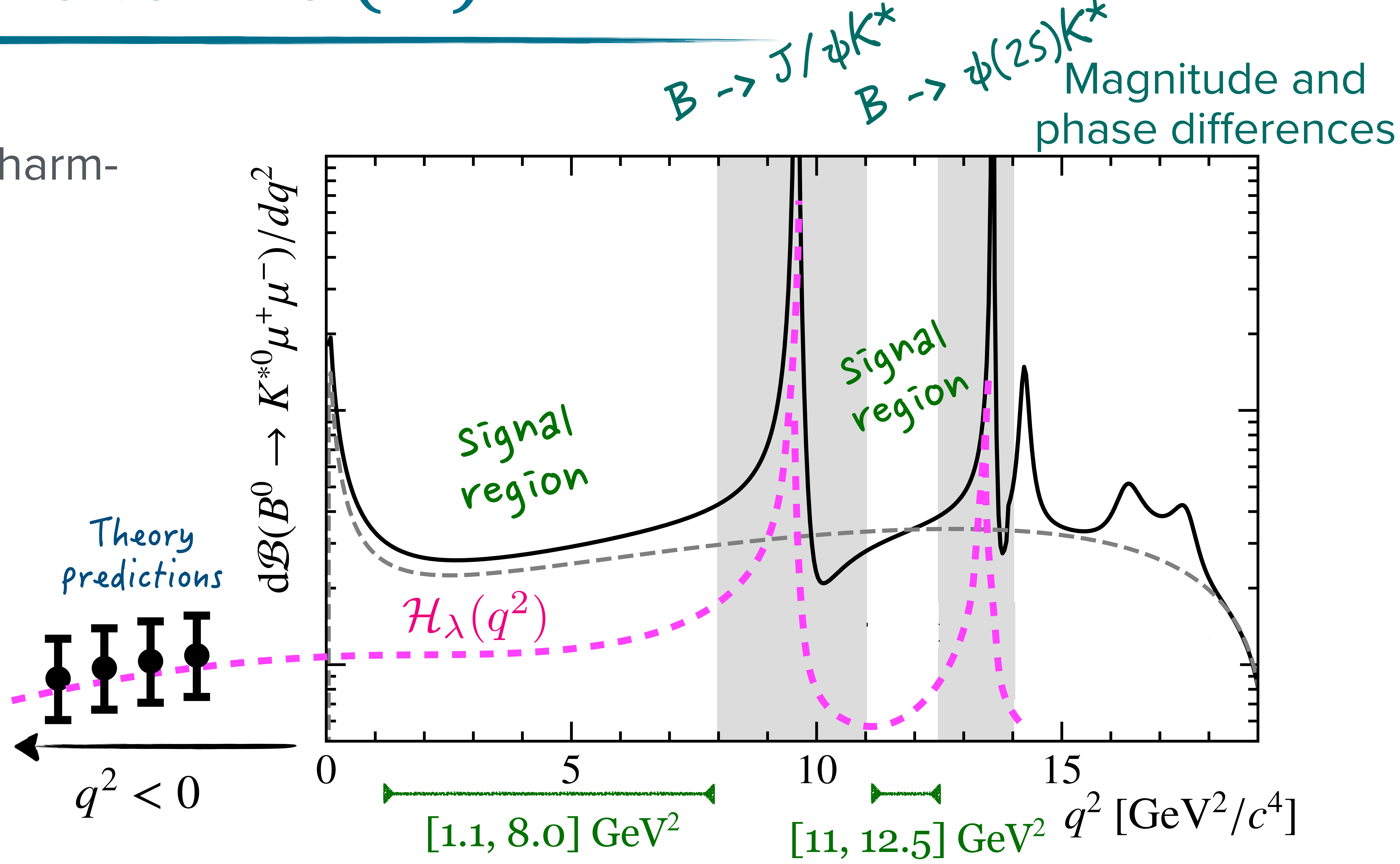
Non-local hadronic terms (II)

- Add information to constrain charm-loop parameters

  1. experimental measurements on $B^0 \to \psi_n K^{*0}$ decays

  2. theory predictions at $q^2 < 0$
     - reliable for $q^2 \ll 4m_c^2$

[GRvDV 2022]



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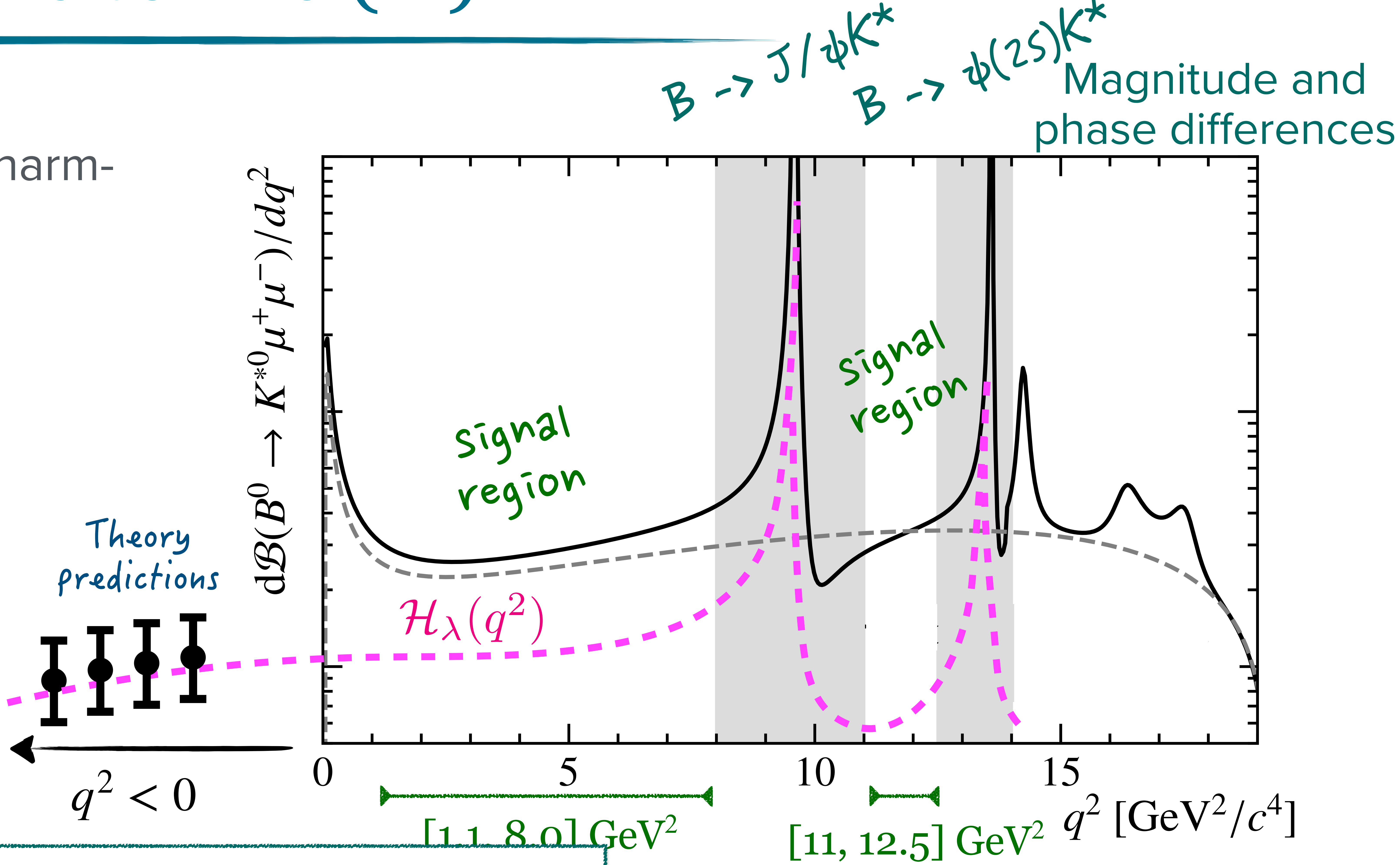
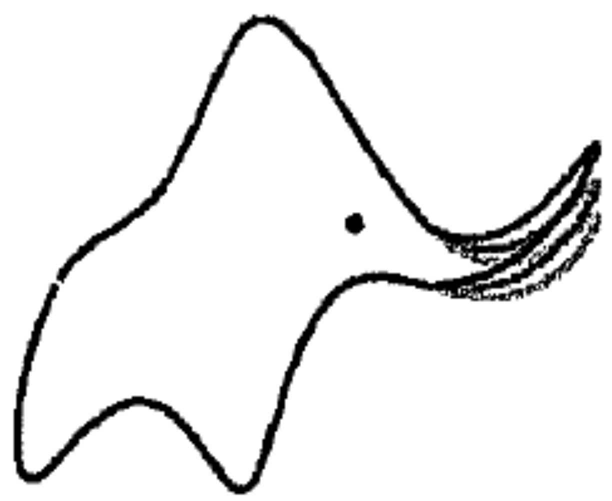


Two studied configurations:

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

Choice of the z order

- Data driven determination of the truncation order:
  - fit repeated with increasing polynomial order $\mathcal{H}_\lambda[z^2, z^3, z^4, \dots]$
  - till no significant improvement in the likelihood is found



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

$$2\Delta \log \mathcal{L} > 2\Delta N_{\text{pars}}$$

(each z-order brings six additional parameters)

	$2\Delta \log \mathcal{L}$ $q^2 < 0$ constr.	$2\Delta \log \mathcal{L}$ $q^2 > 0$ 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	-

- $\mathcal{H}_\lambda[z^2]$ for $q^2 > 0$ only fit
- $\mathcal{H}_\lambda[z^4]$ for $q^2 < 0$ constr. fit

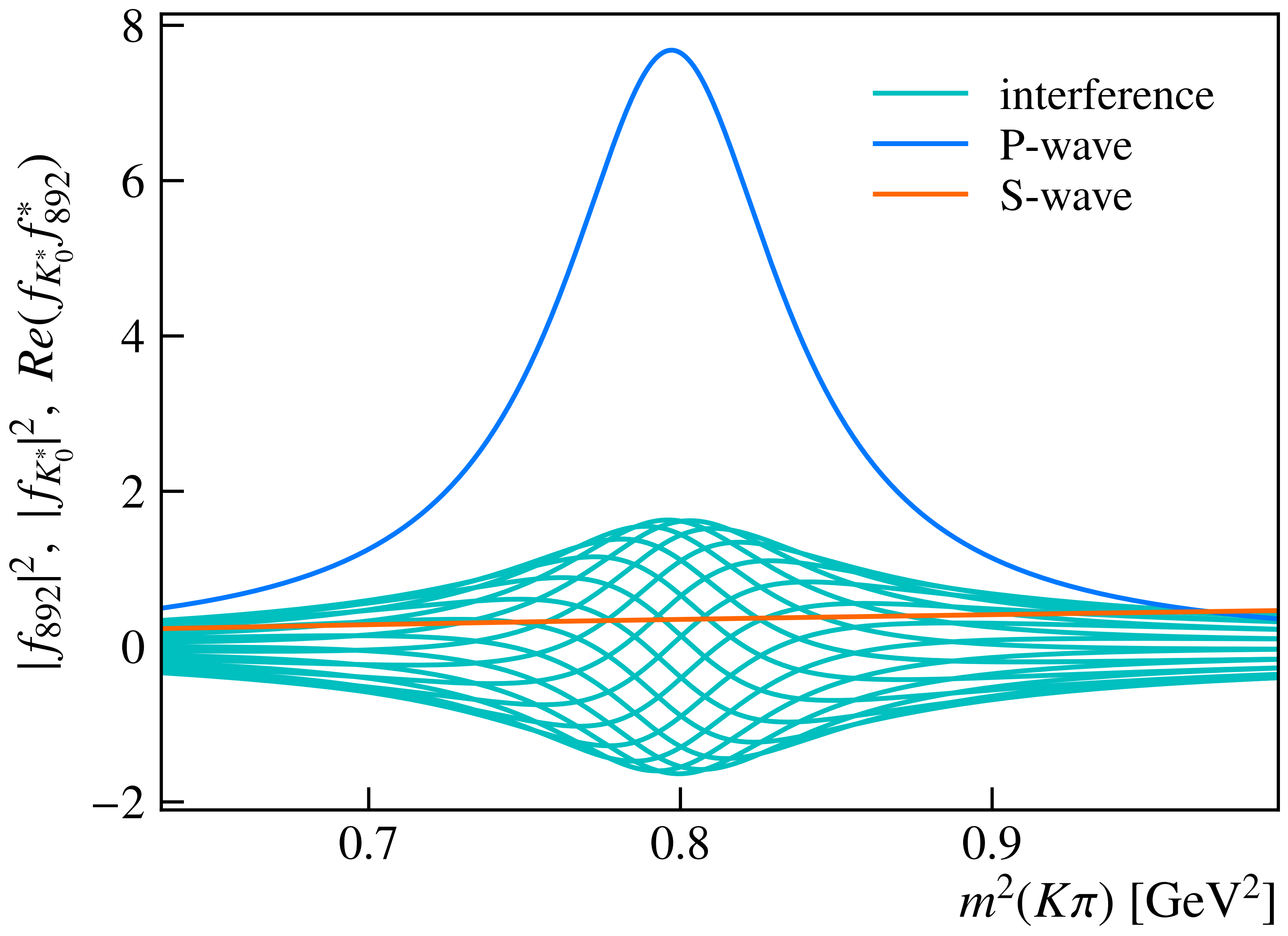
S-wave

- $B^0 \to K^+\pi^-\mu^+\mu^-$ decays can also proceed though a scalar $K^+\pi^-$ configuration (S-wave)
  - require additional scalar amplitudes $\mathcal{A}_{S0}^{L,R} = -\mathcal{N}\frac{\sqrt{\lambda(M_B^2,q^2,k^2)}}{M_B\sqrt{q^2}}\left\{\left[(\mathcal{C}_9-\mathcal{C}_9')\mp(\mathcal{C}_{10}-\mathcal{C}_{10}')\right]f_+(q^2,k^2)+\frac{2m_bM_B}{q^2}(\mathcal{C}_7-\mathcal{C}_7')f_T(q^2,k^2)\right\}$
  - extend the fit to $k^2 = m^2(K^+\pi^-)$ [Descontes-Genon, Khodjamirian, Virto; JHEP 12 (2019) 083]

P-wave: $\mathcal{A}^{L,R}_{0,\perp,\|,t} \mapsto \mathcal{A}^{L,R}_{0,\perp,\|,t} \times \hat{f}_{\mathrm{BW}}(k^2)\,,$

S-wave: $\mathcal{A}^{L,R}_{S0,\,St} \mapsto \mathcal{A}^{L,R}_{S0,\,St} \times \boxed{|g_S|\, e^{i\delta_S}}\, \hat{f}_{\mathrm{LASS}}(k^2)$

relative magnitude and phase between P and S-wave →



Total signal amplitude model

- Five-dimensional P- and S-wave total $B^0 \to K^+\pi^-\mu^+\mu^-$ decay rate
  - expressed in terms of decay amplitudes
  - Fit this to data!

$$pdf_{\text{sig}} \propto \frac{\mathrm{d}^5\Gamma}{\mathrm{d}q^2\,\mathrm{d}k^2\,\mathrm{d}\vec{\Omega}}$$

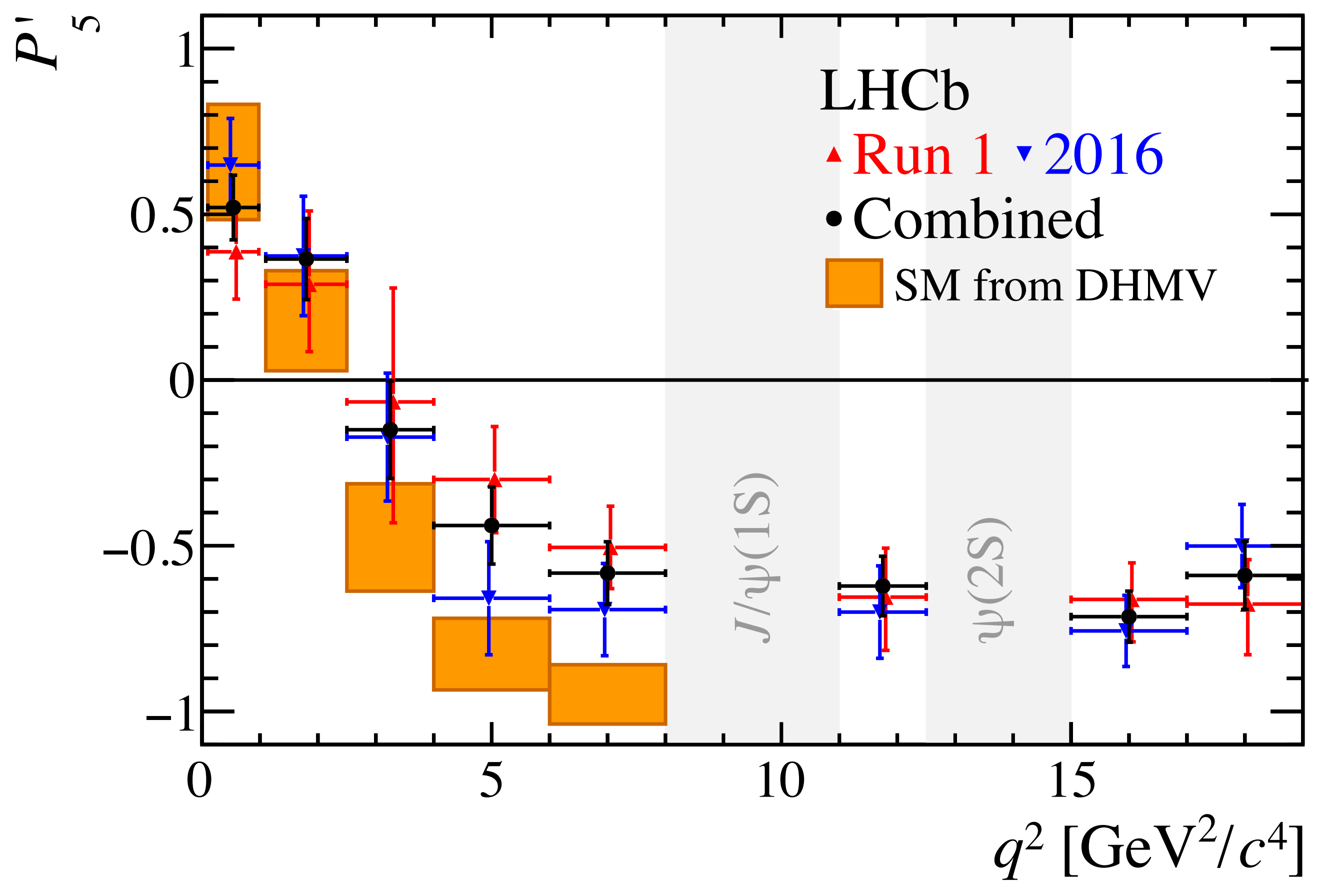
- Large number of signal parameters:
  - $\mathcal{C}_9, \mathcal{C}_{10}, \mathcal{C}_9', \mathcal{C}_{10}'$ [floated]
  - $\mathcal{C}_7, \mathcal{C}_7'$ [fixed to SM(*) $\mathcal{C}_7^{\text{SM}} = -0.337, \mathcal{C}_7'^{\text{SM}} = 0$]
  - 4 CKM pars (in $\mathcal{A}_\lambda$'s norm.) [constrained to CKMfitter]
  - 19 $B^0 \to K^{*0}$ FFs pars [constrained to LCSR+LQCD]
  - 18-30 non-local pars $\alpha_{\lambda,i}$ [constrained via $\mathcal{H}_\lambda$]
    - depending on the order of $\mathcal{H}_\lambda[z^n]$
  - g_S, δ_S relative magnitude and phase [floated]
  - 9 $B \to K\pi|_{J=0}$ scalar FFs (nuisance) [constrained]

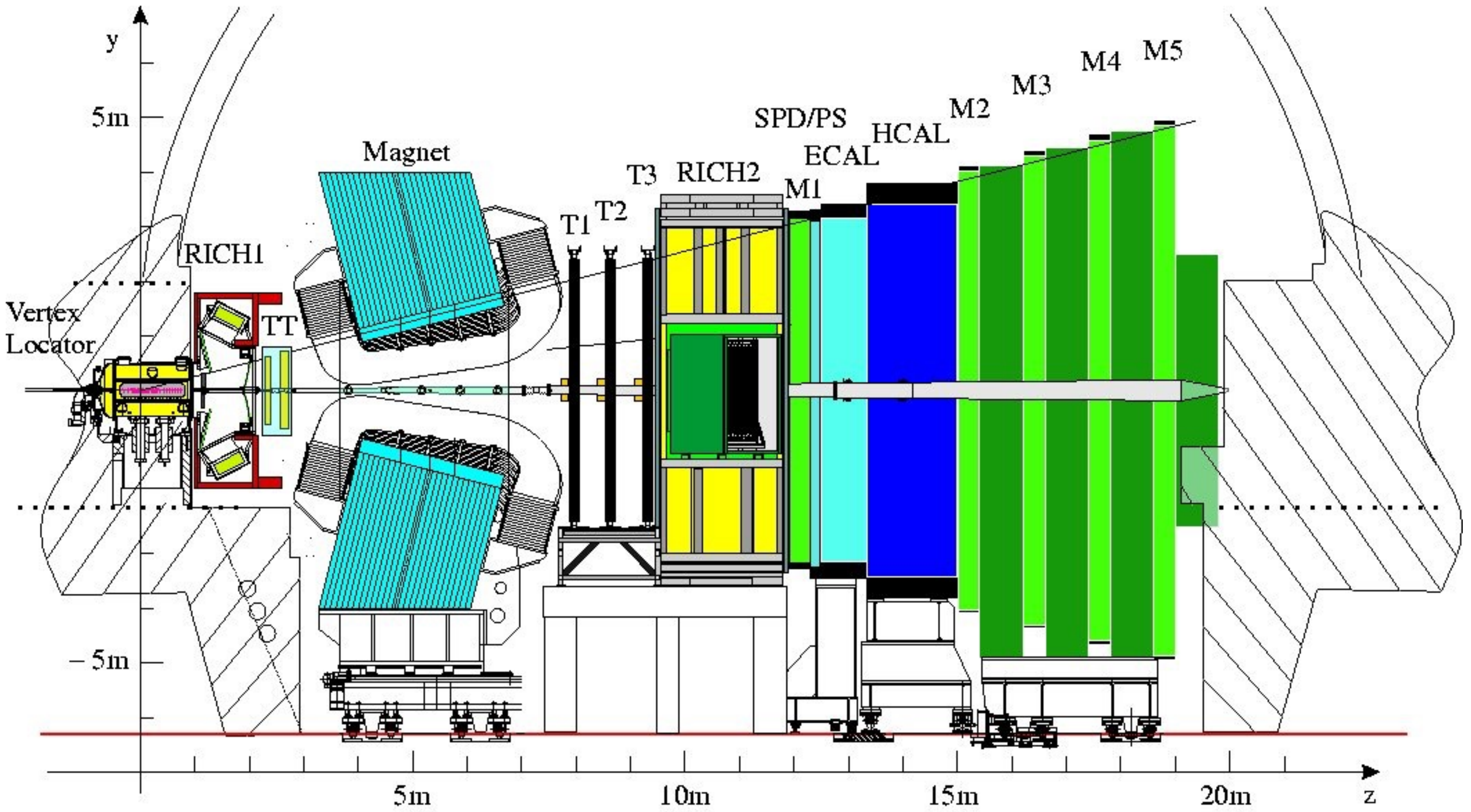
(*) Strongly constrained by radiative decays
[Paul, Straub; JHEP 04 (2017) 027]

The LHCb detector

- Analysis performed with 4.7 fb^{-1} of *pp* data collected by the LHCb detector between 2011 and 2016
  - same dataset of previous binned $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

PRL 125 (2020) 011802





- LHCb is a forward arm spectrometer to study *b*- and *c*-hadron decays ($2 < \eta < 5$)

[JINST 3 (2008) S080005]
[Int. J Mod. Phys A 30 (2015) 1530022]

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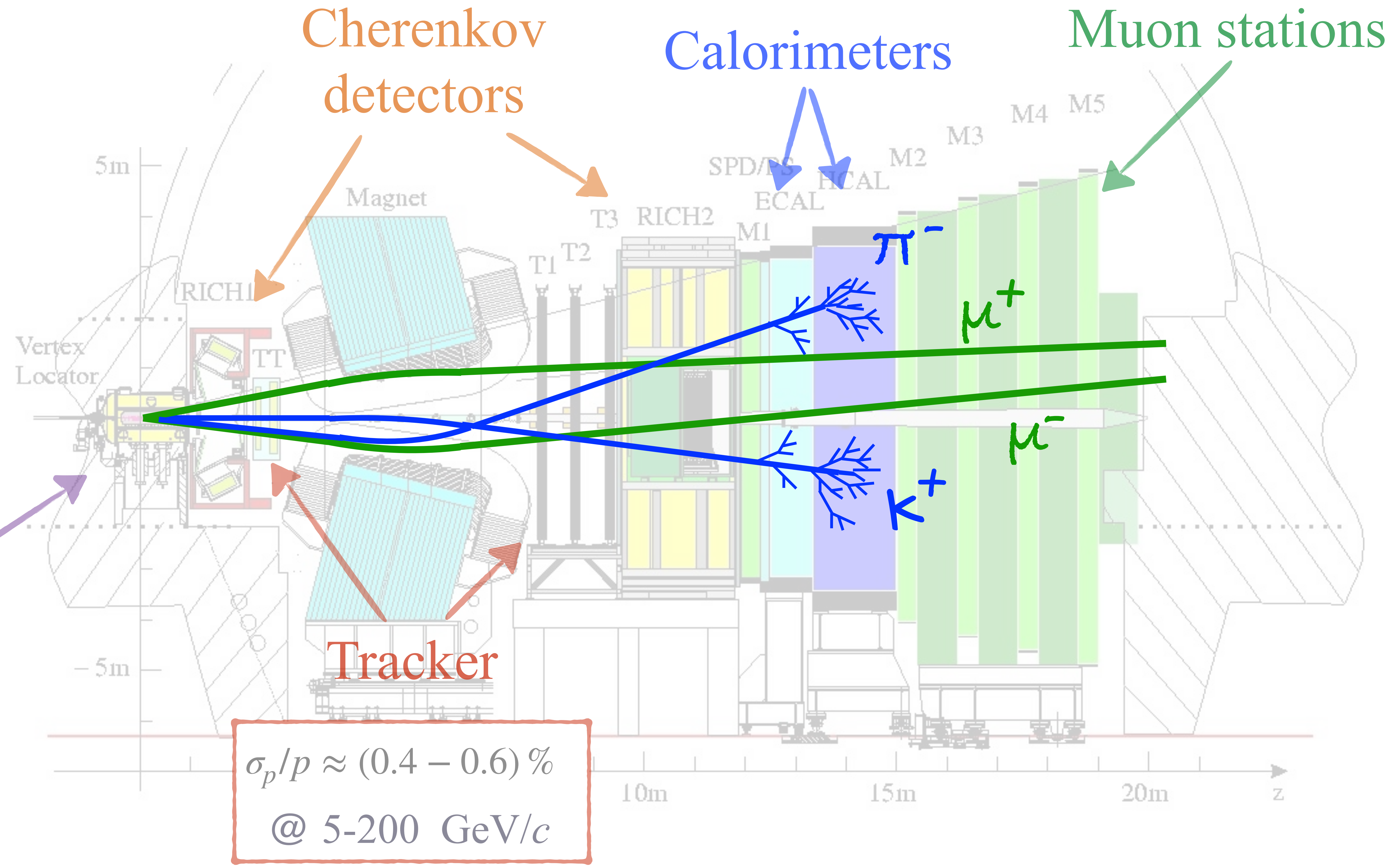
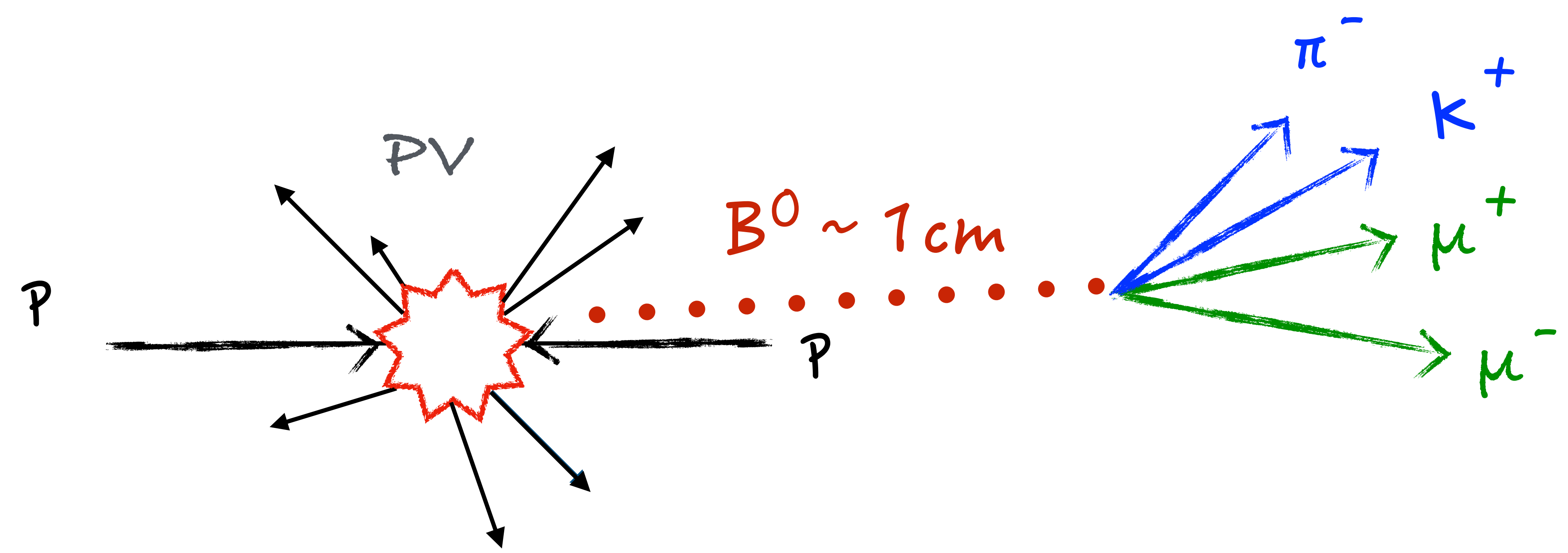


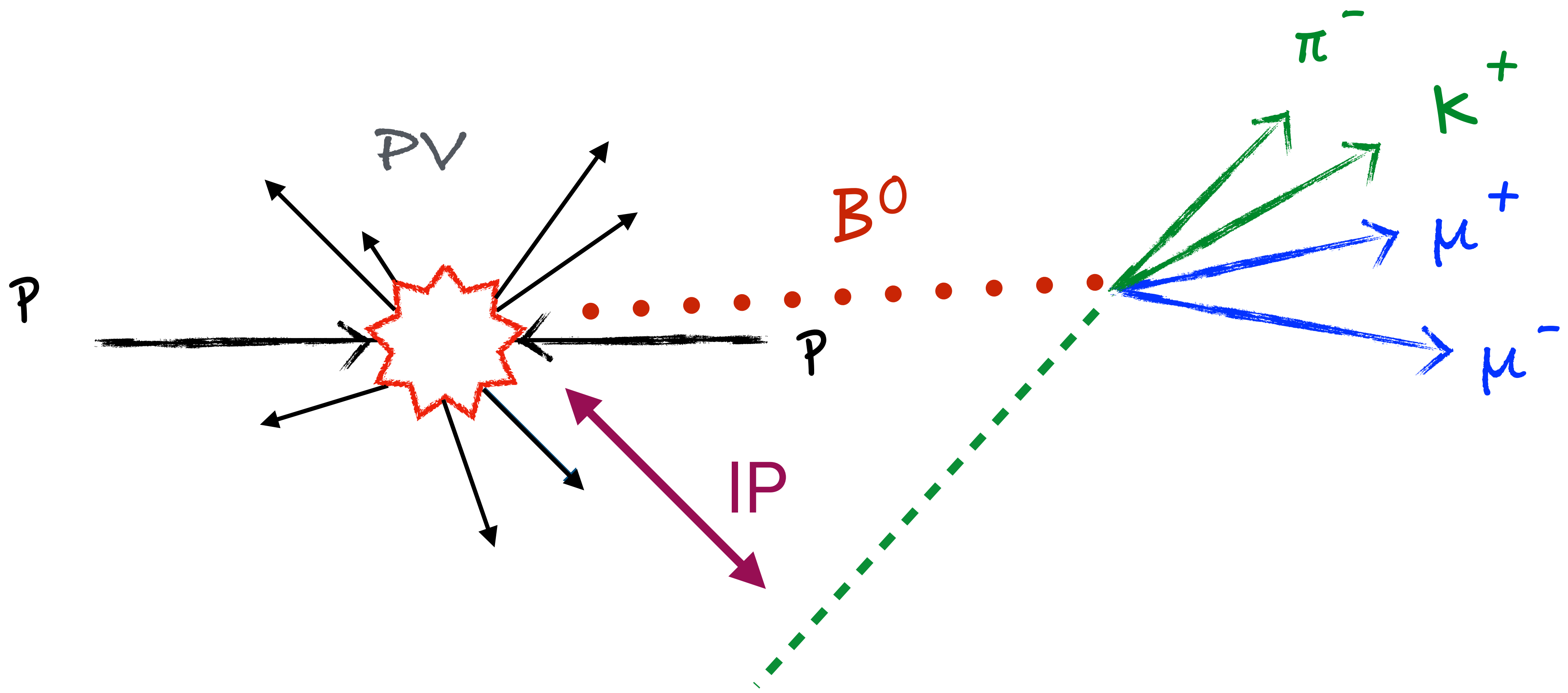


- LHCb is a forward arm spectrometer to study *b*- and c-hadron decays $(2 < \eta < 5)$

[JINST 3 (2008) S08005]
[Int. J Mod. Phys A 30 (2015) 1530022]

Selection of the candidates

- Require large impact parameter (IP) for final-state particles and small IP + good vertex for B^0

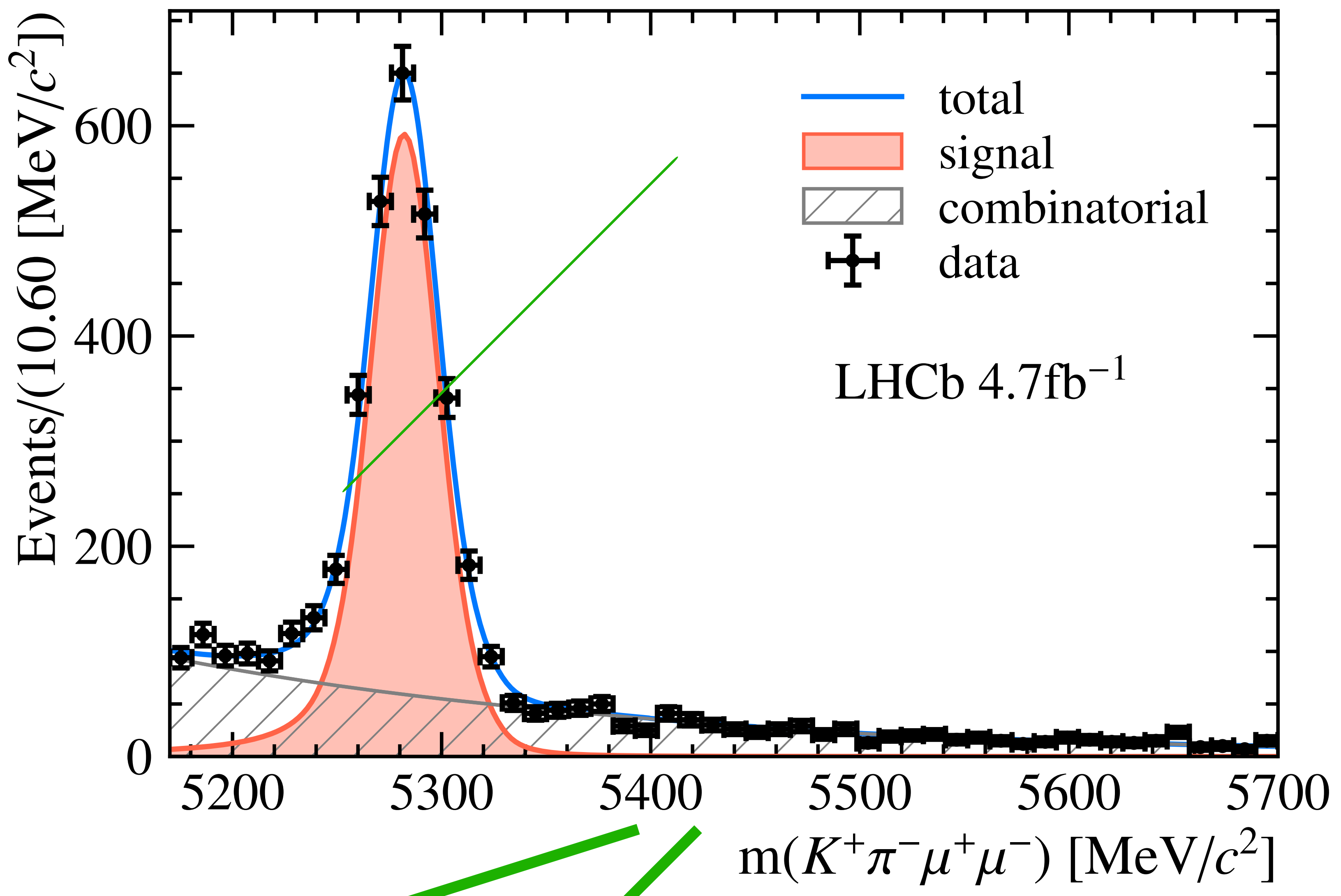


- Peaking backgrounds suppressed below 1% by dedicated vetoes based on mass and PID requirements
  - $B_s^0 \to \phi(1020)(\to K^+K^-)\mu^+\mu^-$
  - $\Lambda_b^0 \to pK^-\mu^+\mu^-$
  - $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$

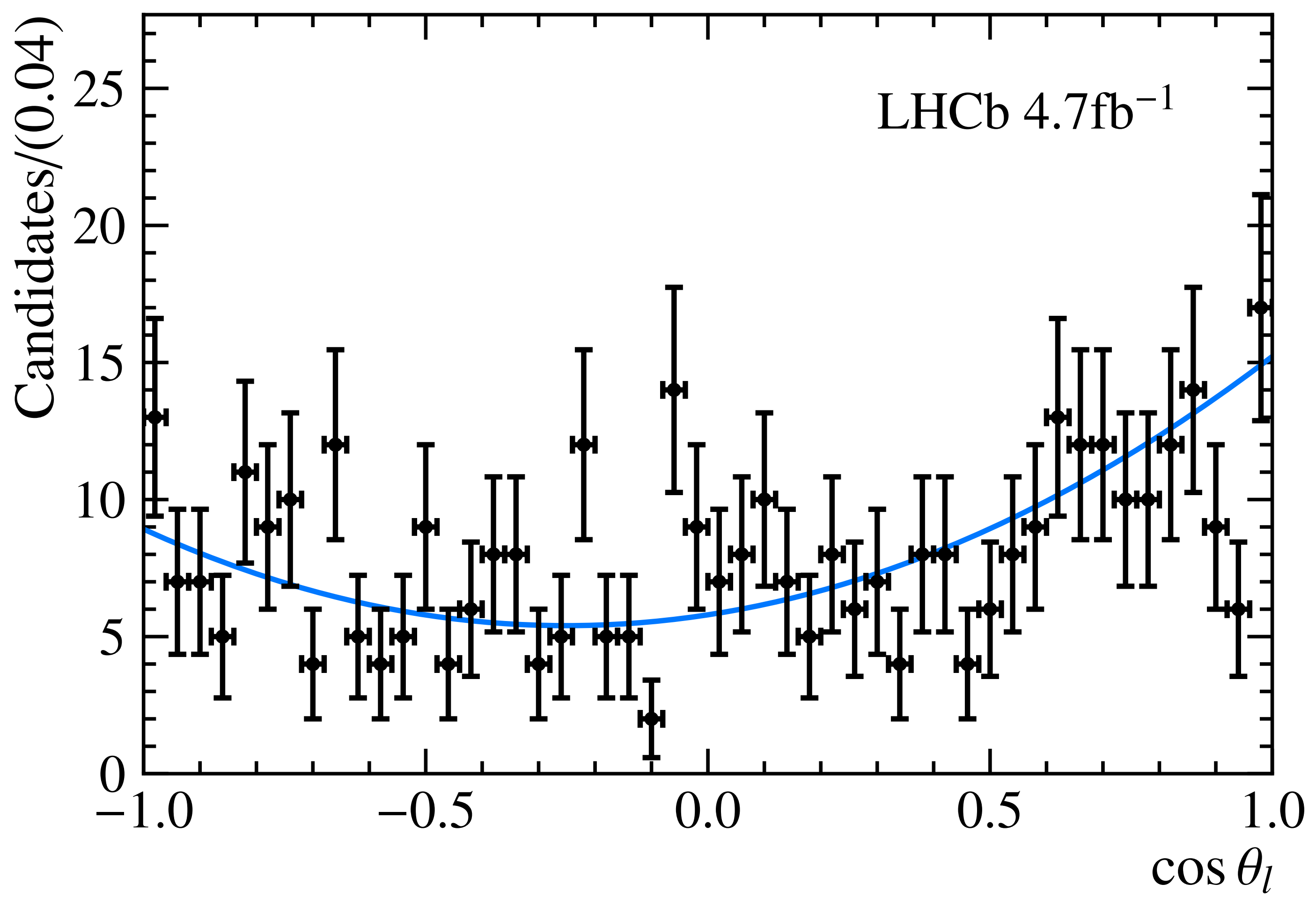
- BDT trained against combinatorial background
  - 85% efficient on signal
  - reject 97% of background

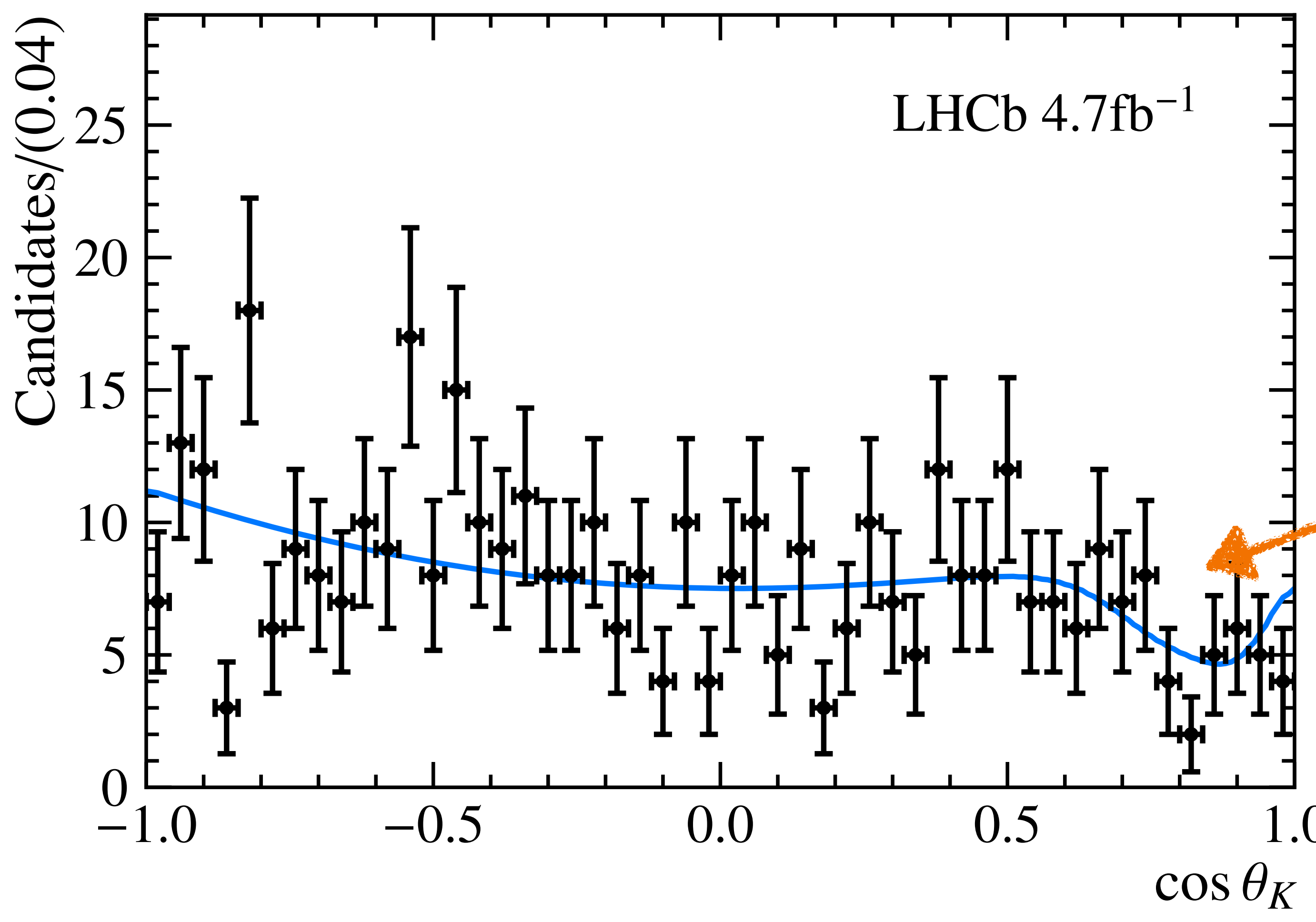
Combinatorial background

- Surviving combinatorial background must be modelled in the fit
  - Added reconstructed $m(K^+\pi^-\mu^+\mu^-)$ invariant mass
  - double CB (signal) + exponential (background)
  - background q^2, k^2 and angles modelled with 2nd order Chebichev polynomials (free parameters)



Fit projections in the high mass sideband

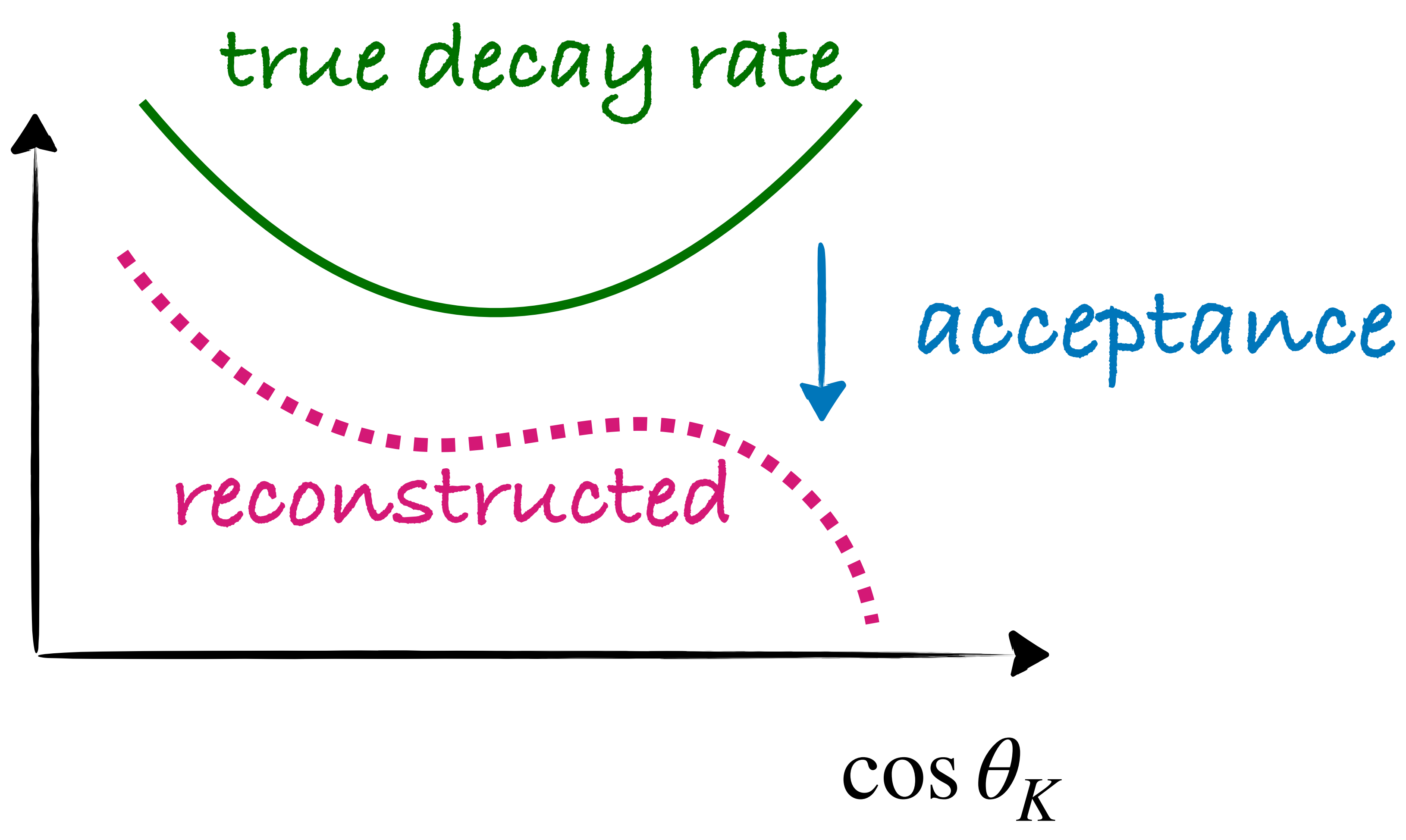




Sculpting due to the $B^+ \to K^+\mu^+\mu^-$ veto, included in the background model

Sig + bkg total pdf

- Trigger, reconstruction and selection requirement distorts the signal distributions: acceptance effect
  - studied with simulated samples
  - parametrised by Legendre polynomials



$$\mathrm{Acc}(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \sum_{k,l,m,n} c_{klmn}\, L(\cos\theta_\ell, k)\, L(\cos\theta_K, l)\, L(\phi, m)\, L(q^2, n)$$

- Extended 6D maximum likelihood fit

Detector

Physics

$$pdf_{sig}(q^2, k^2, \vec{\Omega}, m_{K\pi\mu\mu}) = doubleCB(m_{K\pi\mu\mu}) \times \mathrm{Acc}(q^2, \vec{\Omega}) \times \frac{\mathrm{d}^5\Gamma(B^0 \to K^+\pi^-\mu^+\mu^-)}{\mathrm{d}q^2\,\mathrm{d}k^2\,\mathrm{d}\vec{\Omega}}$$

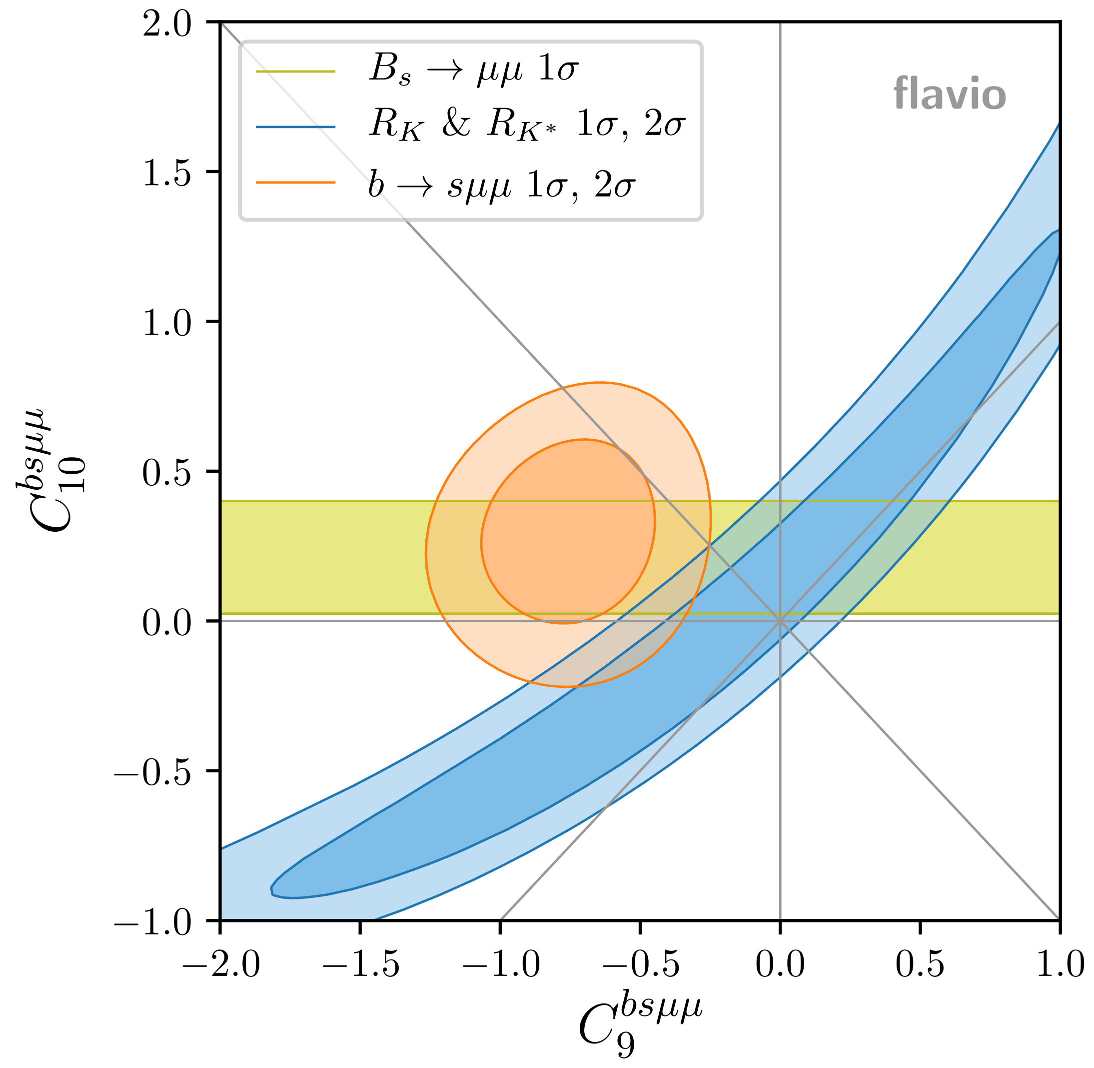
$$pdf_{bkg}(q^2, k^2, \vec{\Omega}, m_{K\pi\mu\mu}) = e^{-\lambda m_{K\pi\mu\mu}} \times (1 - \varepsilon^{3D}_{veto}(\vec{x})) \times \prod_x \left(\sum c_i T_i(x)\right)$$

Signal mass pars., acceptance, and background pars. allowed to be different between Run1 and 2016

(different beam energy and condition)

Branching ratio constraint

[Greljo, Salko, Smolkovic, Stangl; JHEP 05 (2023) 087]



- Differential decay rate can only access the relative size of the Wilson coefficients
  - Scale of Wilson coeff. set by branching ratio

- Extended fit allows to link the observed yield to the signal branching fraction

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

Wilson coefficients enter here

$$N_{sig} = N_{J/\psi K\pi} \times \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) \times \frac{2}{3}}{\mathcal{B}(B^0 \to J/\psi K^+\pi^-) \times f^{J/\psi K\pi}_{\pm 100\mathrm{MeV}} \times \mathcal{B}(J/\psi \to \mu^+\mu^-)} \times R_\varepsilon$$

Normalised to $B^0 \to J/\psi K^+\pi^-$ control channel to reduce systematic

Input for BR determination

- BR determination requires several external inputs:

$$N_{sig} = N_{J/\psi K\pi} \times \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) \times \frac{2}{3}}{\mathcal{B}(B^0 \to J/\psi K^+\pi^-) \times f^{J/\psi K\pi}_{\pm 100\mathrm{MeV}} \times \mathcal{B}(J/\psi \to \mu^+\mu^-)} \times R_\varepsilon$$

$K^{*0} \to K^+\pi^-$

from mass fit to control channel (include exotica contribution)

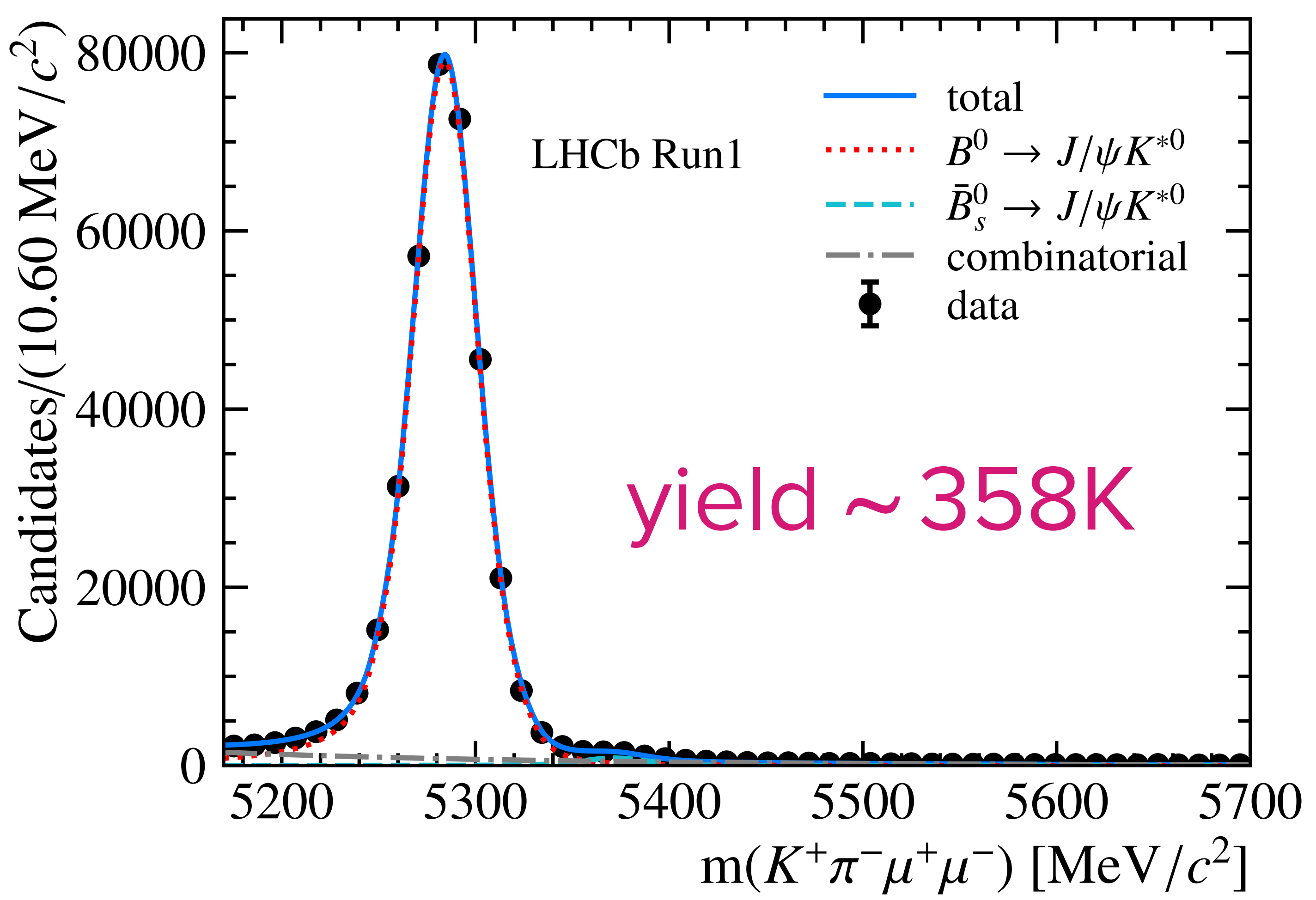
from Belle dedicated $B^0 \to J/\psi K^+\pi^-$ amplitude analysis

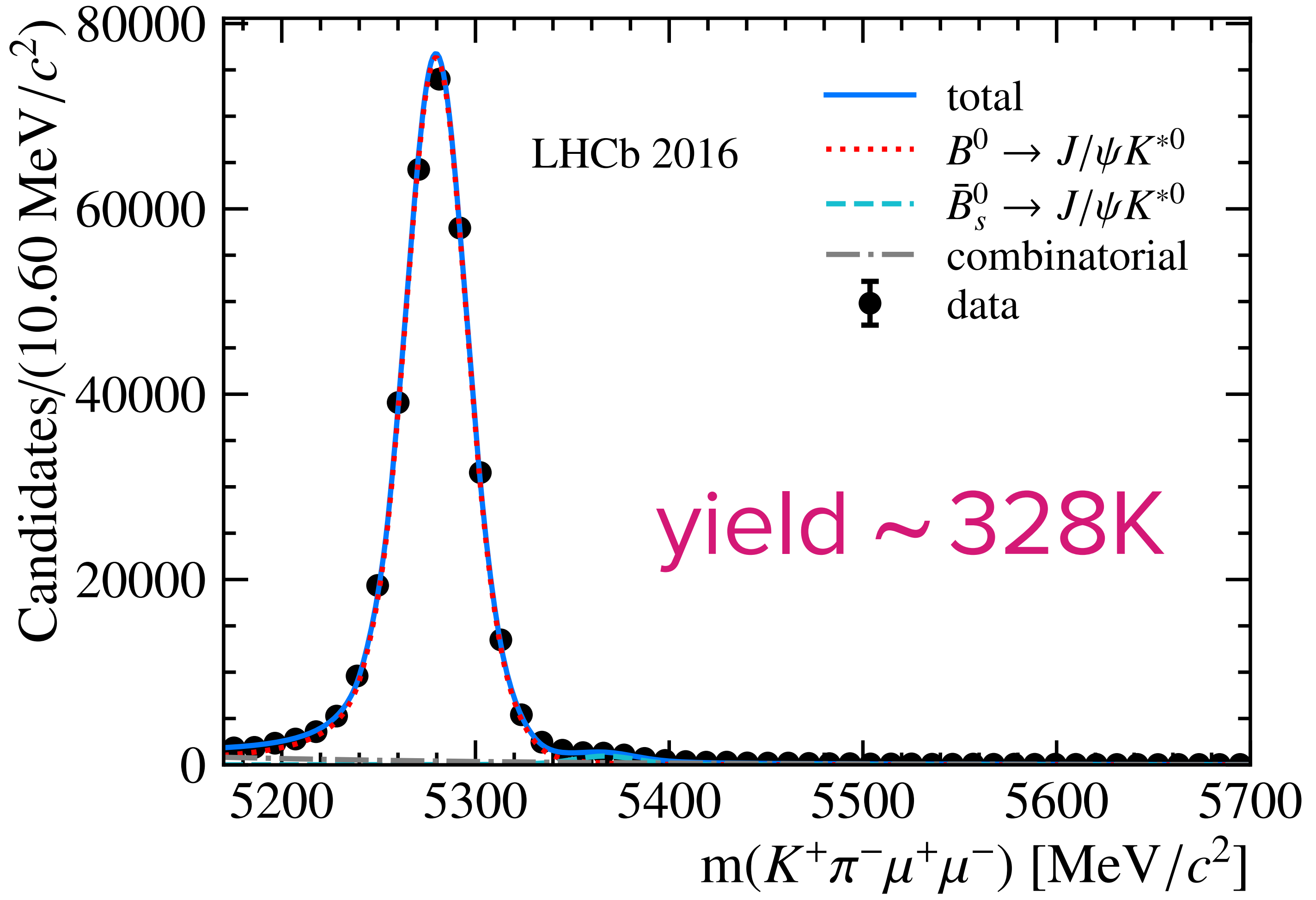
[PRD 90 (2014) 1122009]

PDG

Ratio of efficiency: from simulations

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





- $\mathcal{B}(B^0 \to J/\psi K^+\pi^-) = (1.15 \pm 0.01 \pm 0.05) \cdot 10^{-3}$ → inclusive norm. BR
- $f^{B^0 \to J/\psi K\pi}_{\pm 100\mathrm{MeV}} = 0.644 \pm 0.010$ → fraction of events in the $m(K^+\pi^-)$ window of the analysis (determined from Belle model assuming *conservative* uncorrelated uncertainties)

Systematic uncertainties

Systematics due to the amplitude model

Largest systematic for $\mathcal{C}_9$, $\mathcal{C}_{10}$ comes from BR external inputs

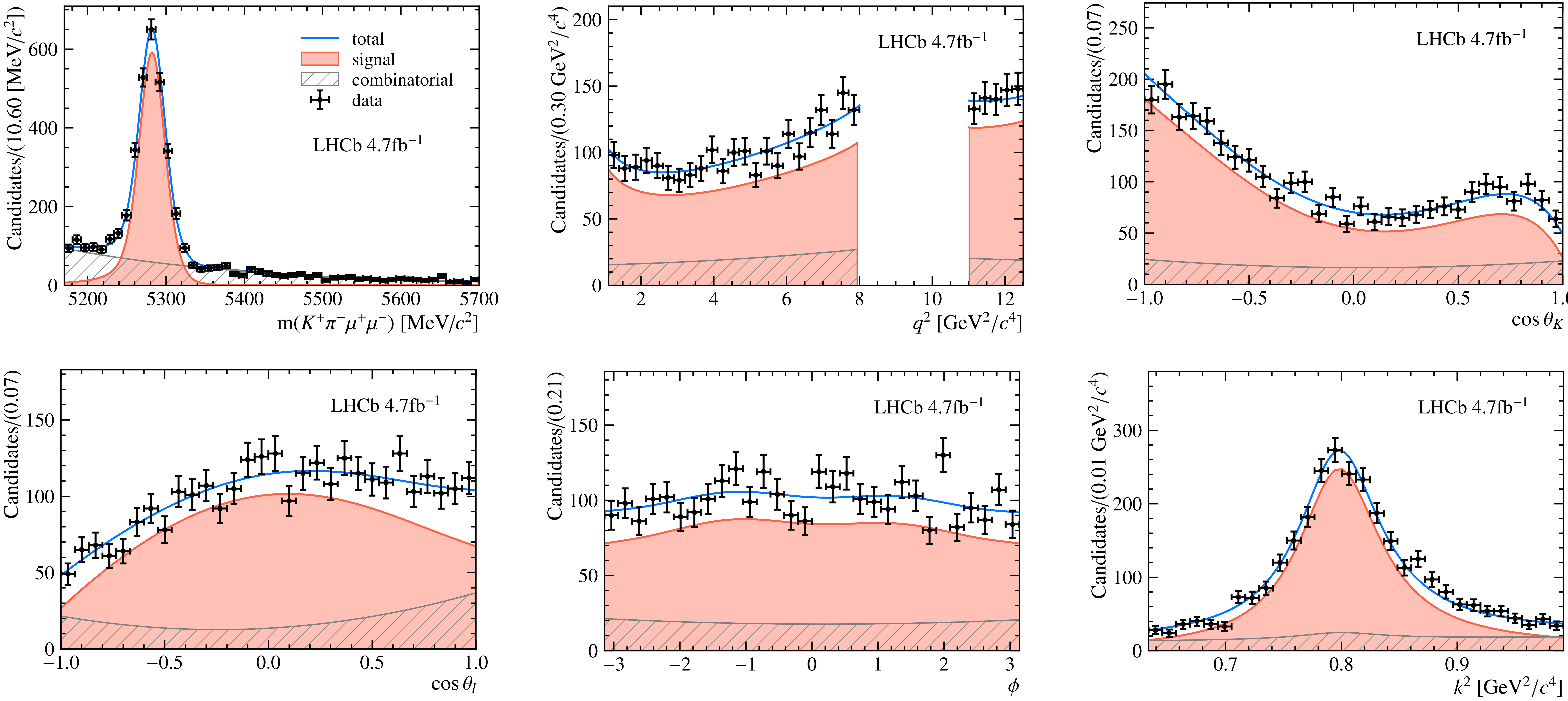
Systematics related to exp. effects are in common with binned BR/angular analyses

Total syst. negligible w.r.t. statistical uncertainty

	$\mathcal{C}_9$	$\mathcal{C}_{10}$	$\mathcal{C}_9'$	$\mathcal{C}_{10}'$
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
$f^{B^0\to J/\psi K\pi}_{\pm 100\mathrm{MeV}}$	0.03	0.03	0.01	< 0.01
Others (R_ε)	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
Statistical uncertainty ($q^2 < 0$ constr.)	0.40	0.28	0.40	0.24

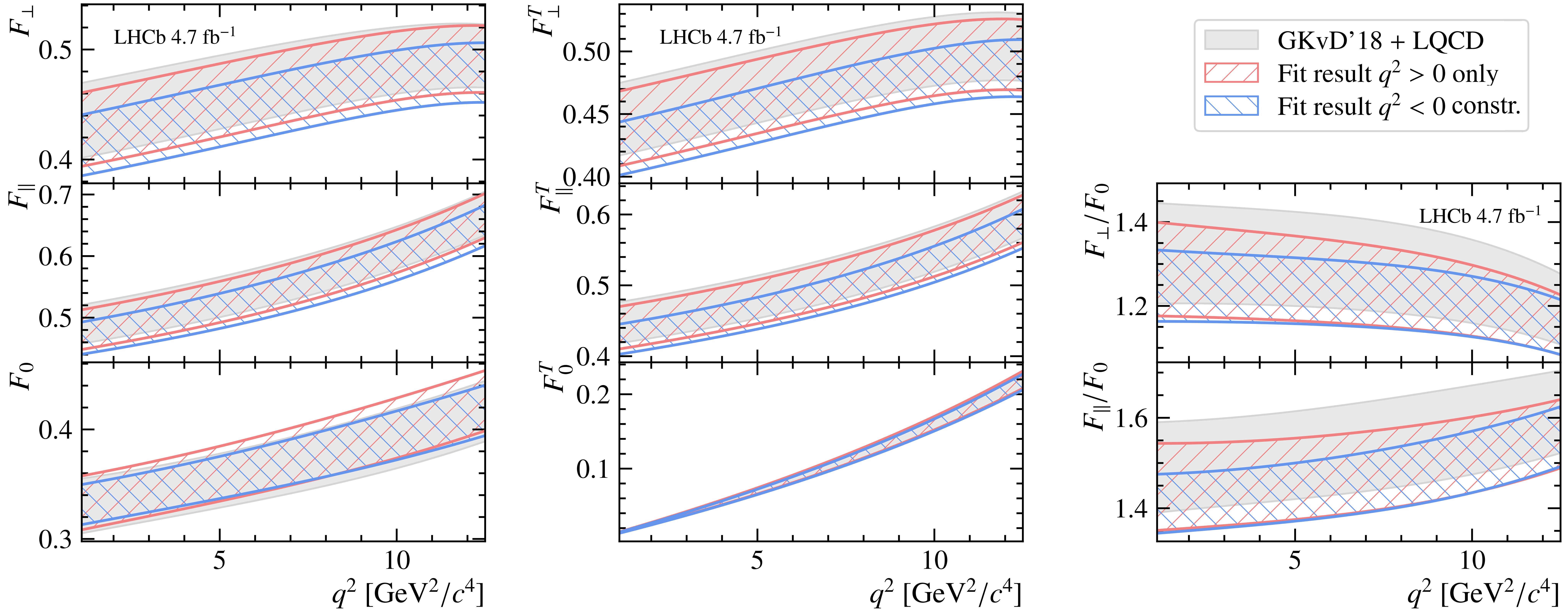
Fit projections

- Observed 2568 ± 60 signal decays



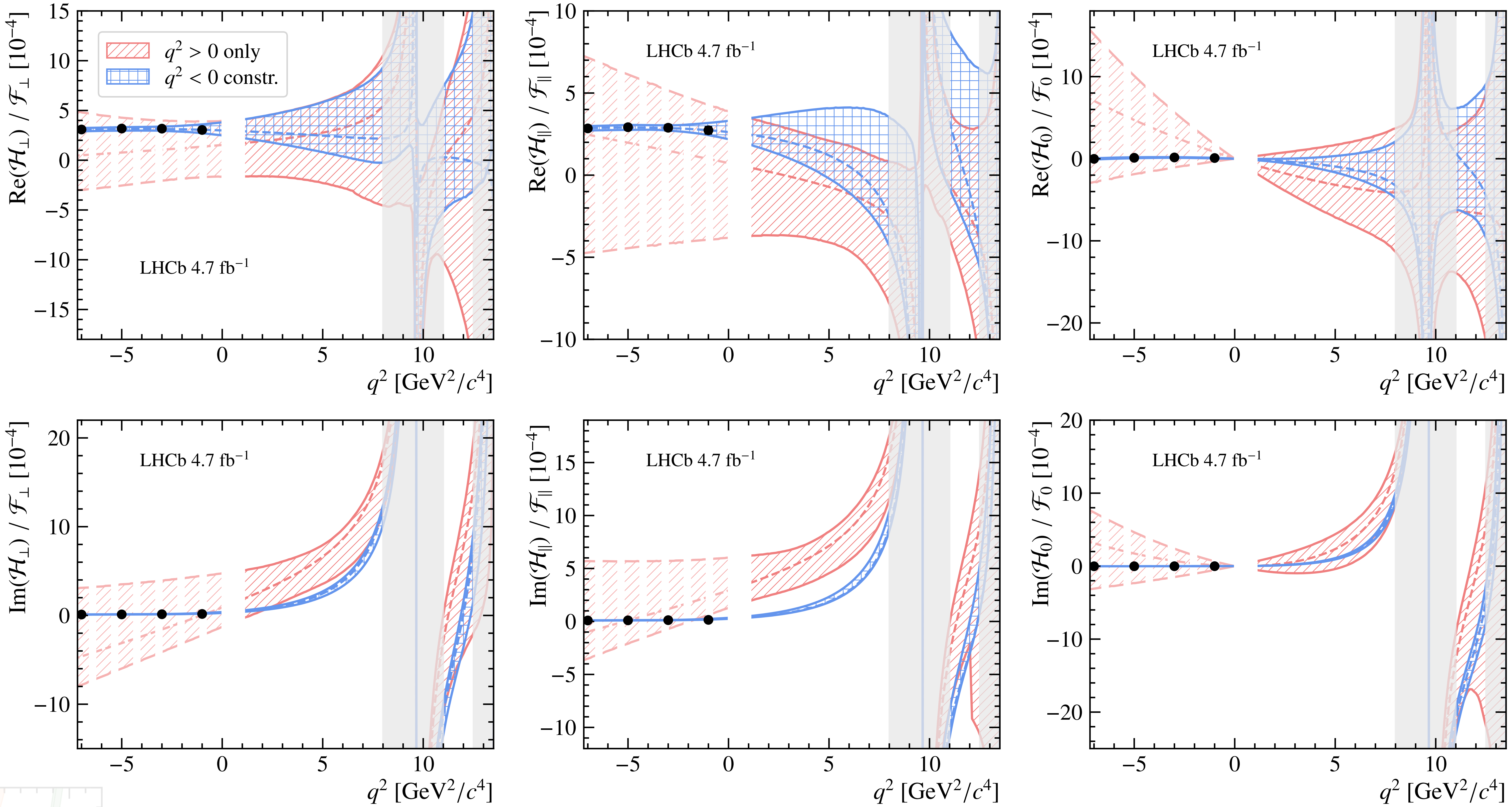
Form factor results

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



Zoom at $q^2 < 0$

- Sharp variation in $Im\,\mathcal{H}_\lambda(q^2)$ between $q^2 < 0$ and $q^2 > 0$
  - require high polynomial order $\mathcal{H}_\lambda[z^4]$

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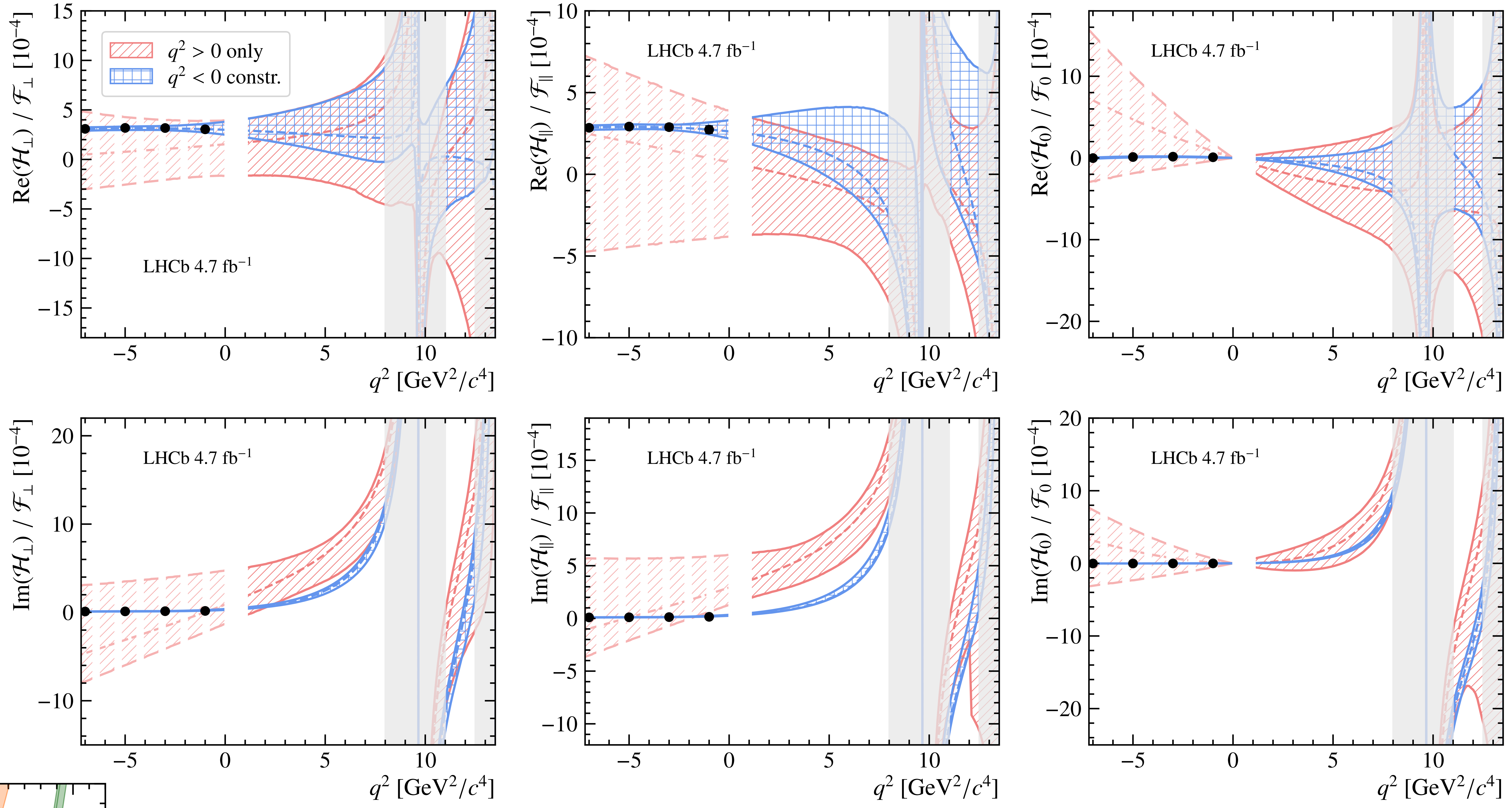
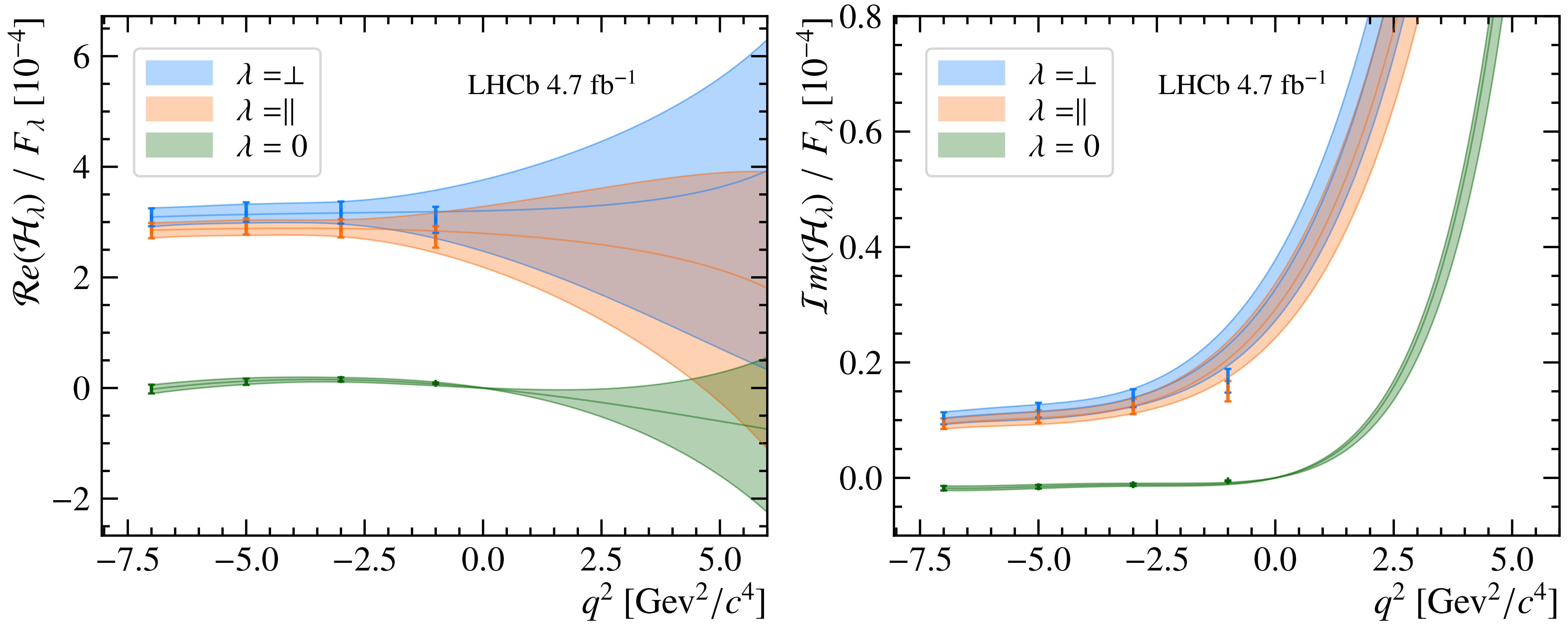


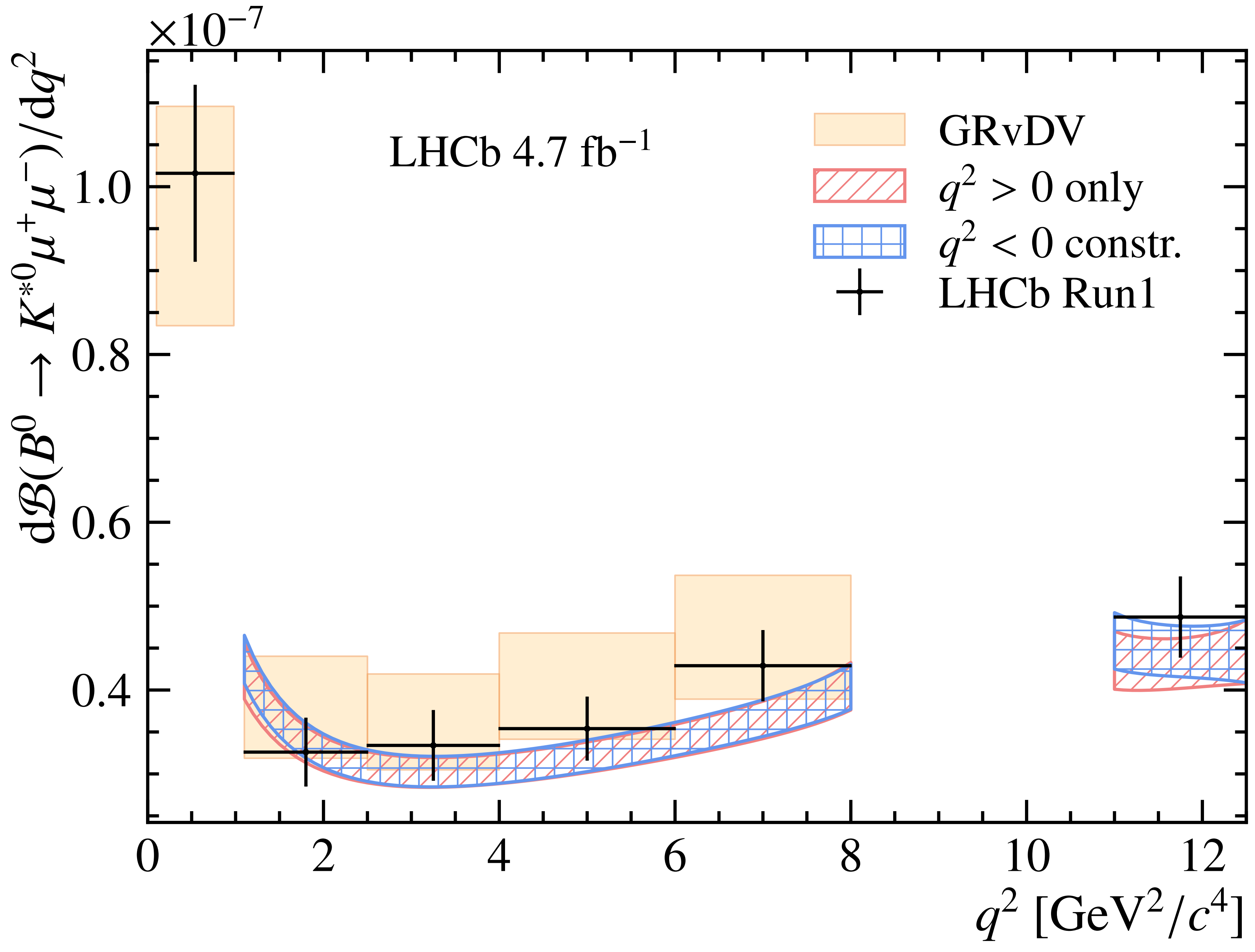
Zoom at $q^2 < 0$

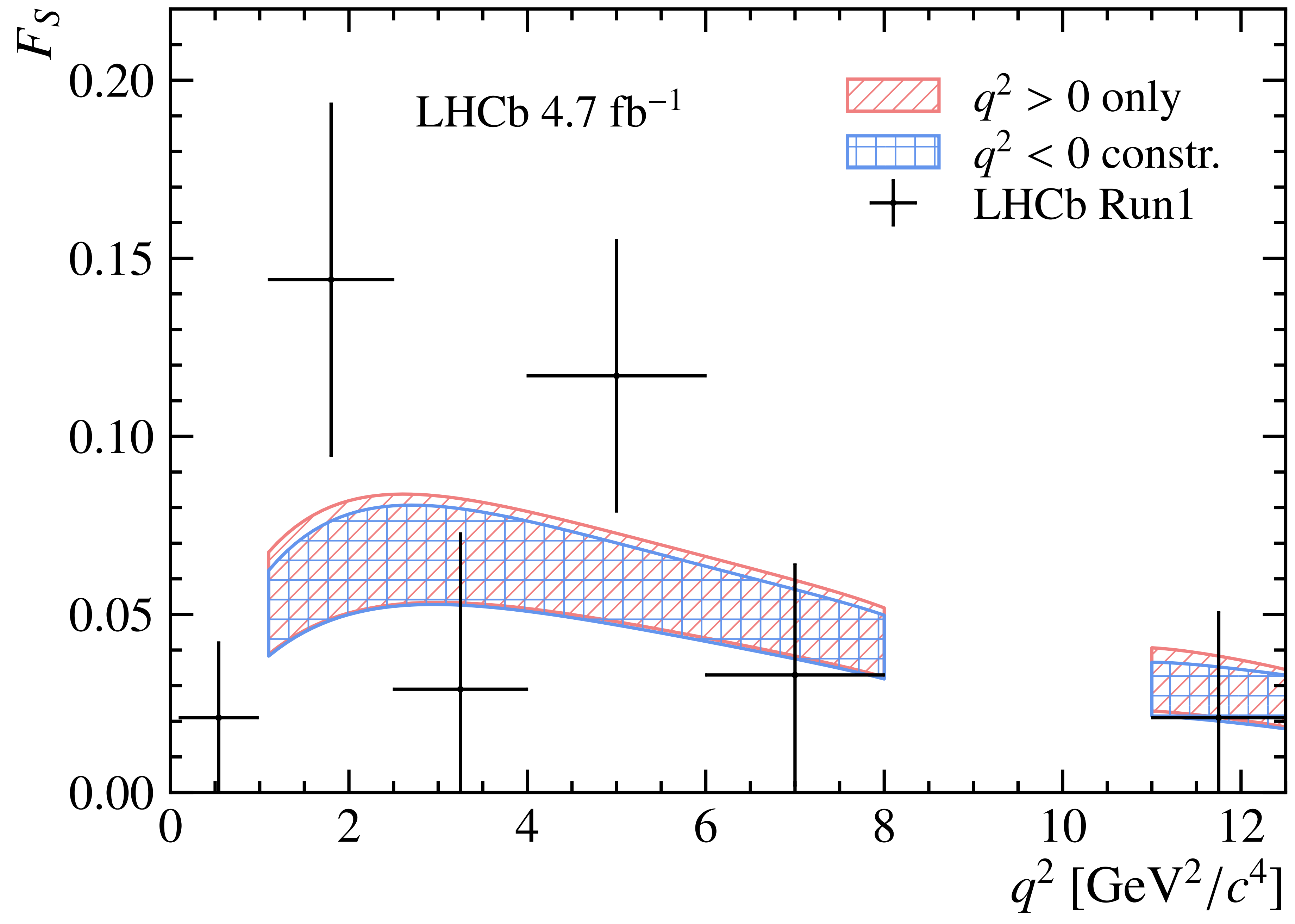


- Sharp variation in $Im\,\mathcal{H}_\lambda(q^2)$ between $q^2 < 0$ and $q^2 > 0$
  - require high polynomial order $\mathcal{H}_\lambda[z^4]$

Br & Fs

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

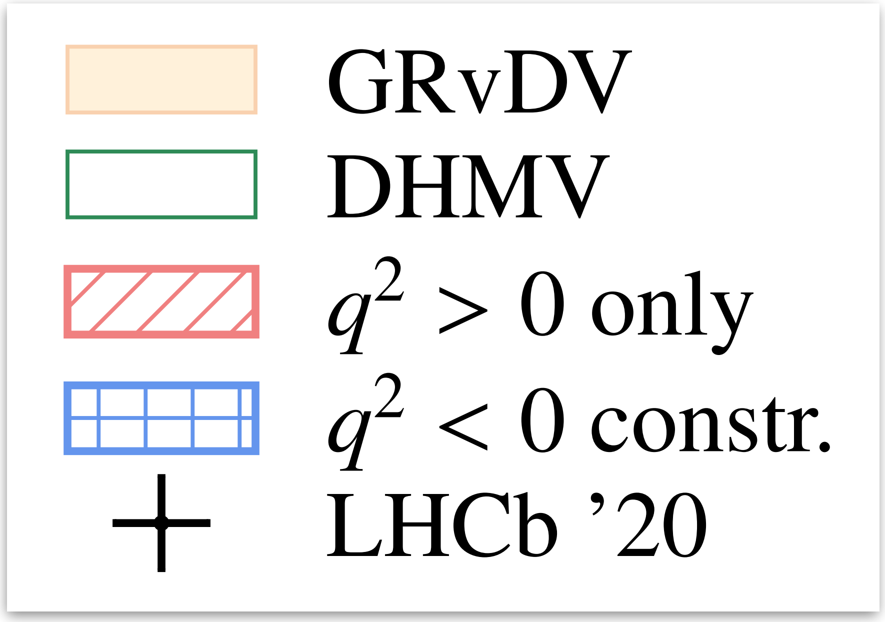


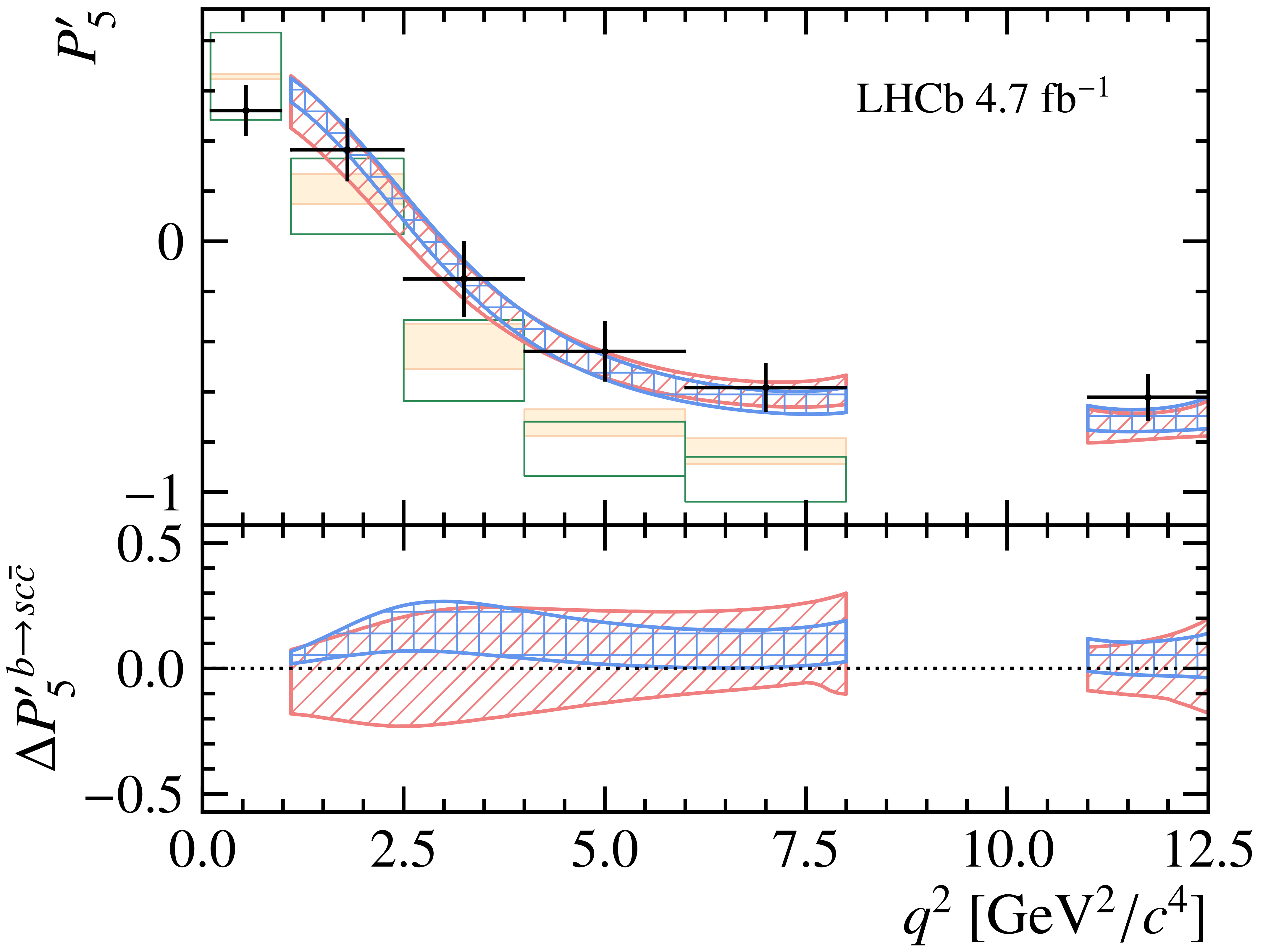


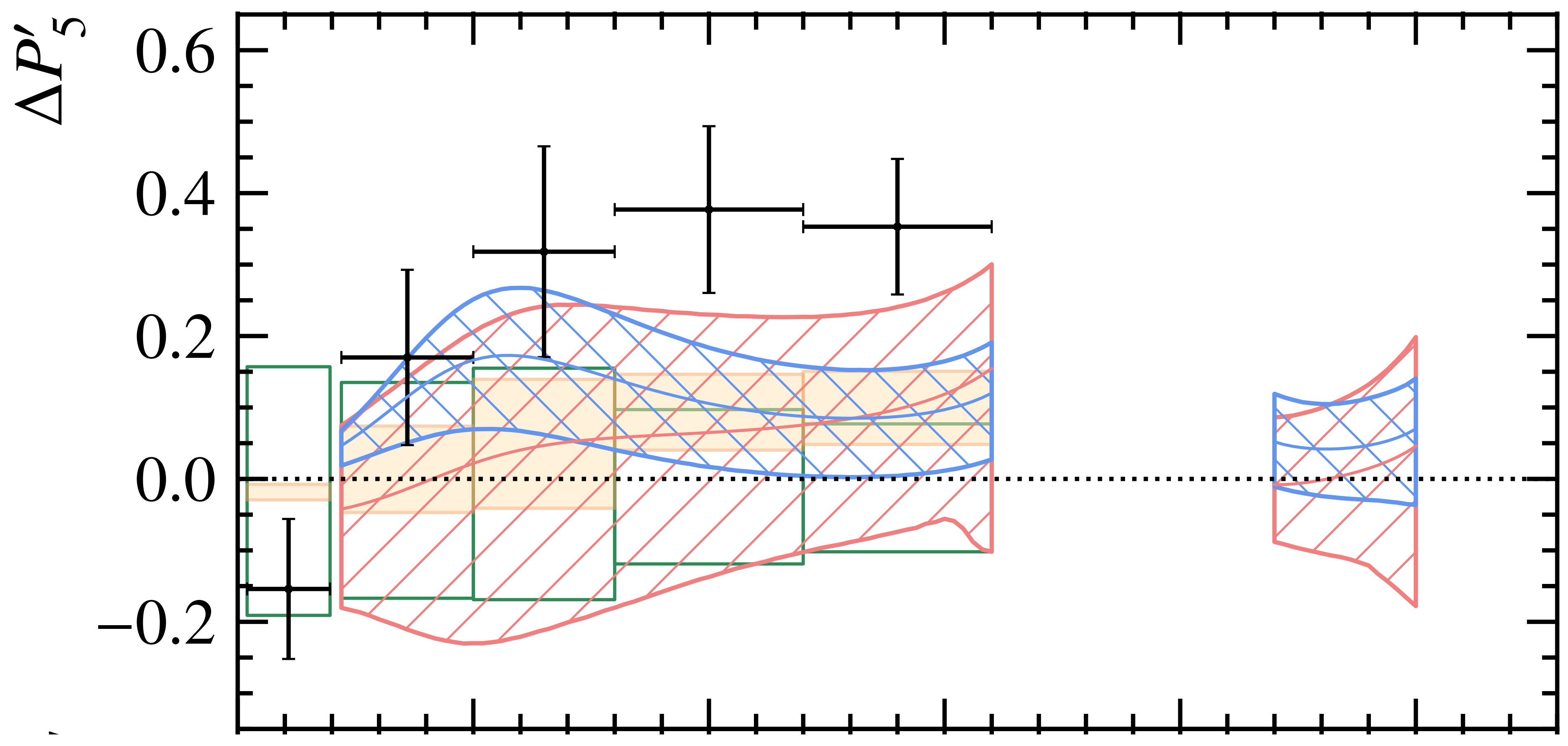
- Lower BR compared to LHCb Run1 due to updated normalisation inputs

P5’ angular observable

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







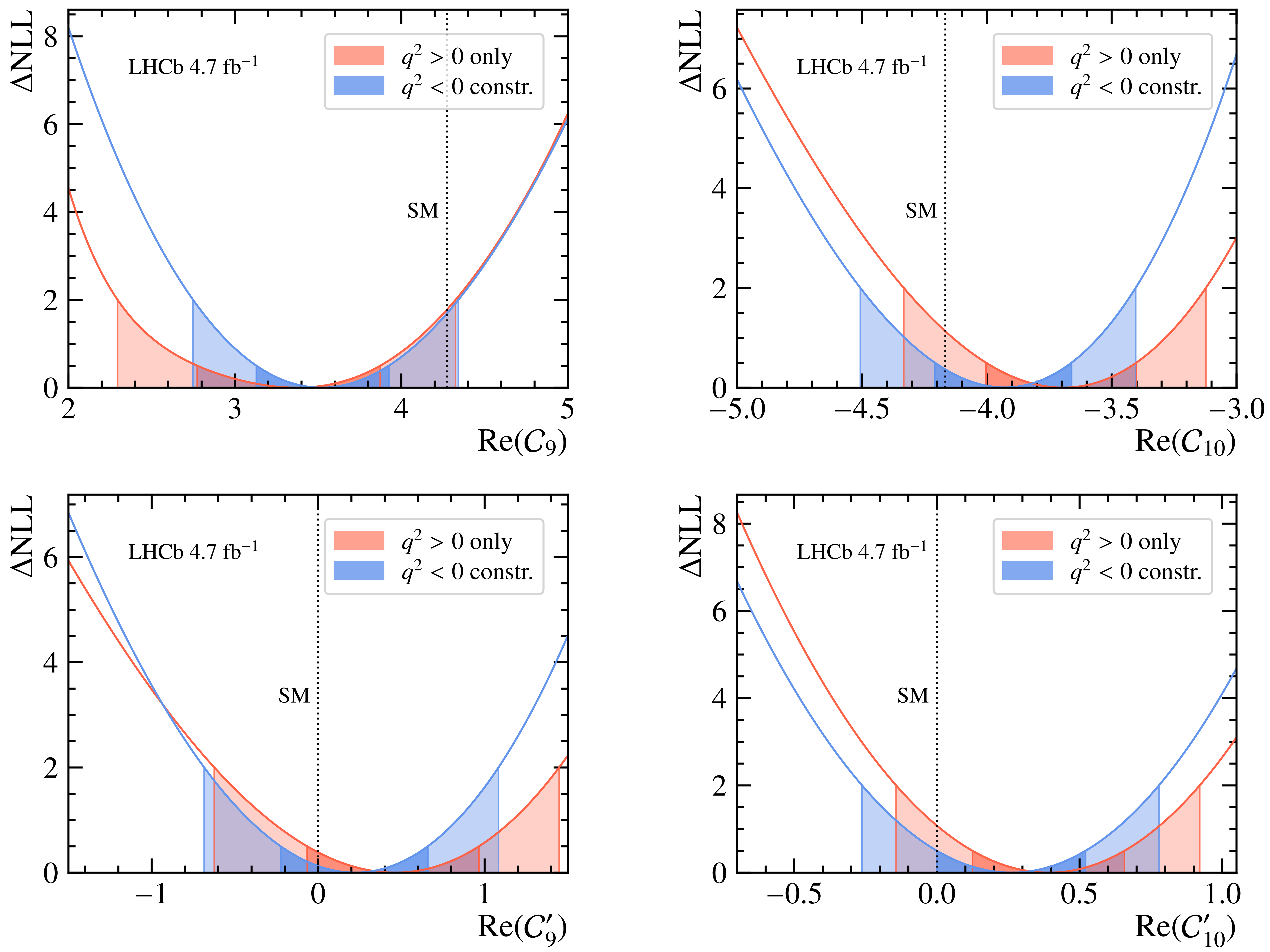
- Note: non-gaussian uncertainties

$\Delta P_5'^{\,b\to s c\bar{c}}$ isolates contribution due to $c\bar{c}$

Wilson coefficients 1D

- Uncertainty obtained from neg. log-likelihood profile

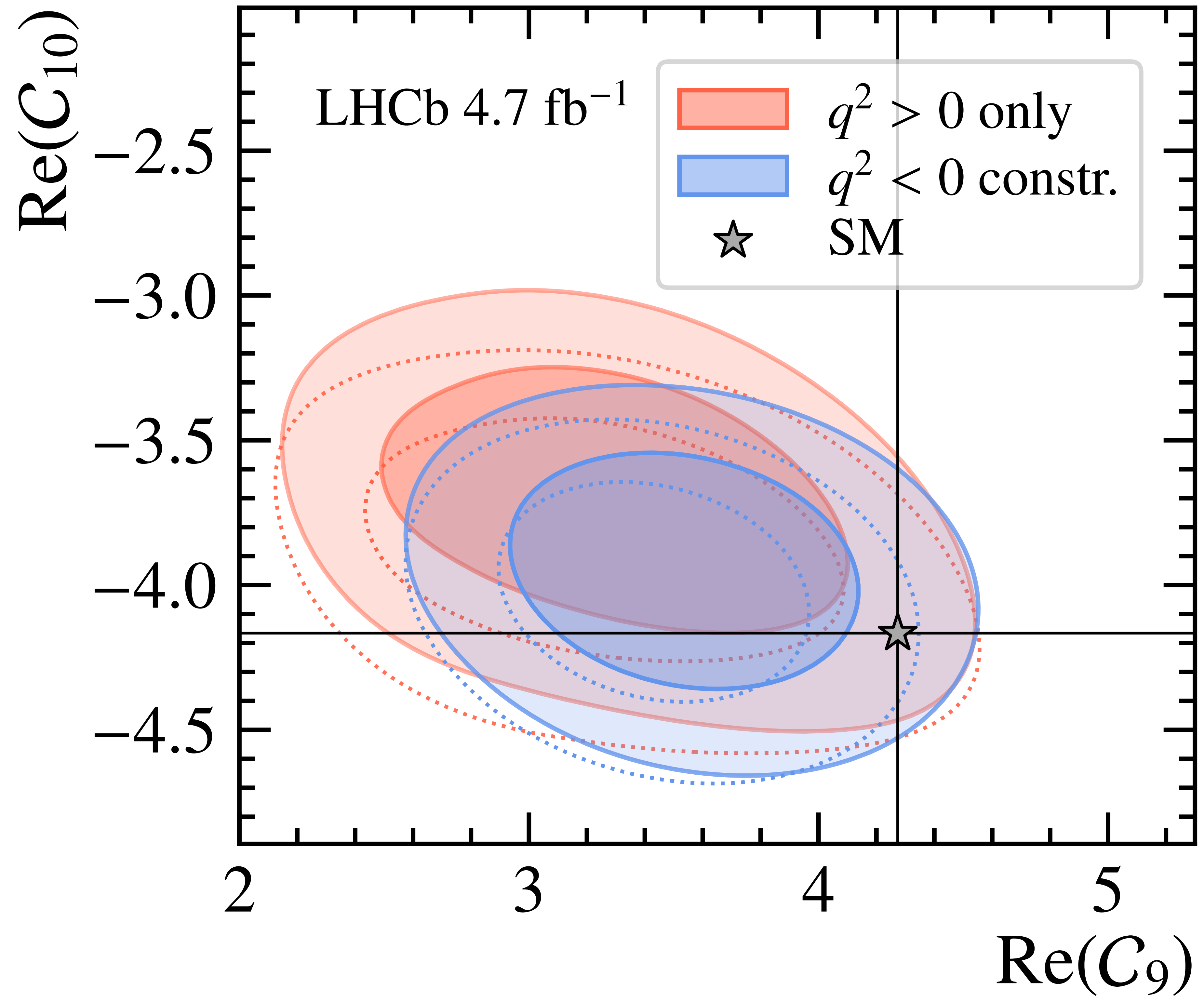
	$q^2 > 0$ only	
	Fit result	deviation from SM
$\Delta\mathcal{C}_9$	$-0.93^{+0.53}_{-0.57}$	$1.9\ \sigma$
$\Delta\mathcal{C}_{10}$	$0.48^{+0.29}_{-0.31}$	$1.5\ \sigma$
$\Delta\mathcal{C}'_9$	$0.48^{+0.49}_{-0.55}$	$0.9\ \sigma$
$\Delta\mathcal{C}'_{10}$	$0.38^{+0.28}_{-0.25}$	$1.5\ \sigma$
	$q^2 < 0$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

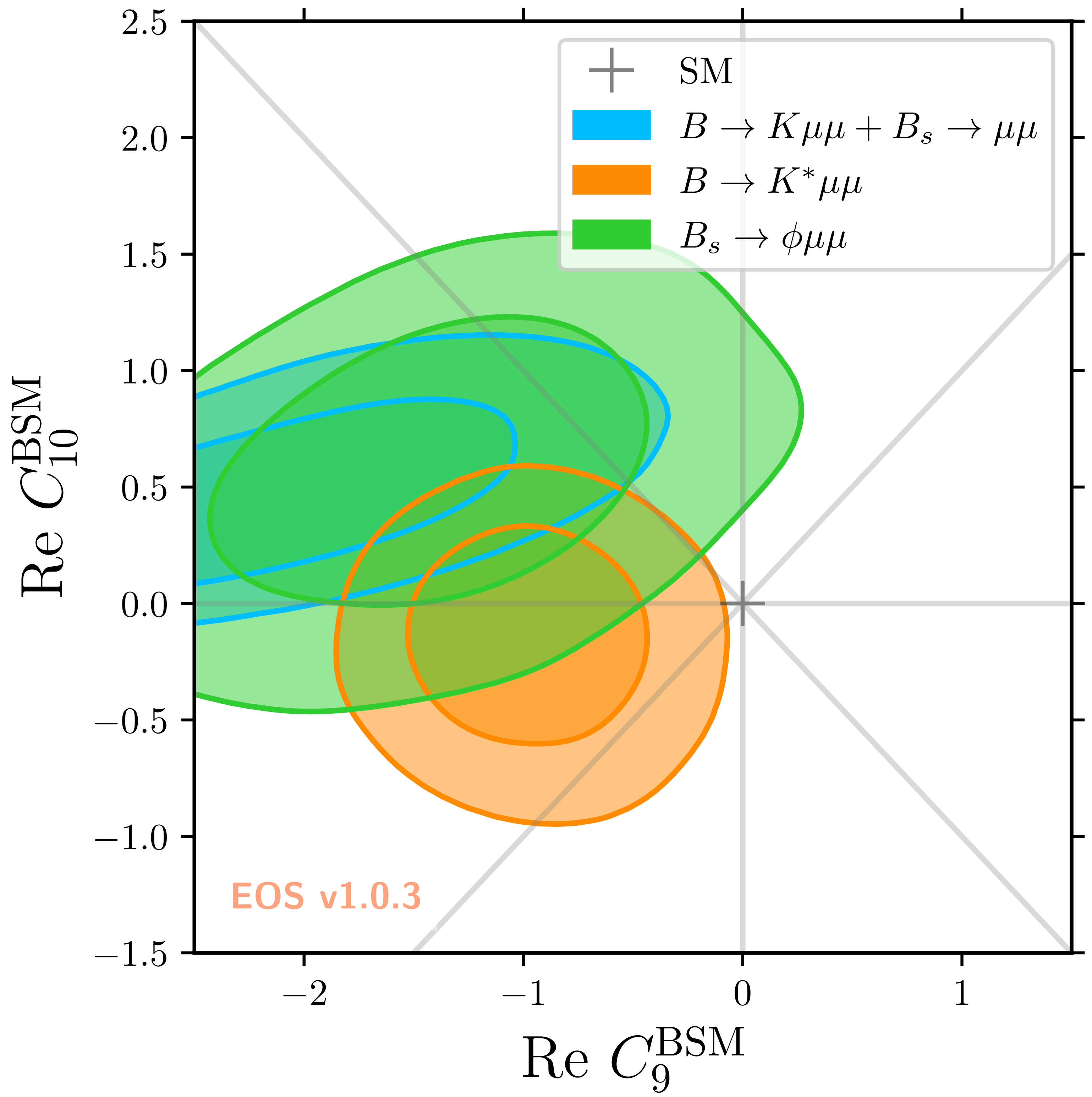


Wilson coefficients 2D

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

- Results consistent with global analyses of $b \to s\mu^+\mu^-$ decays



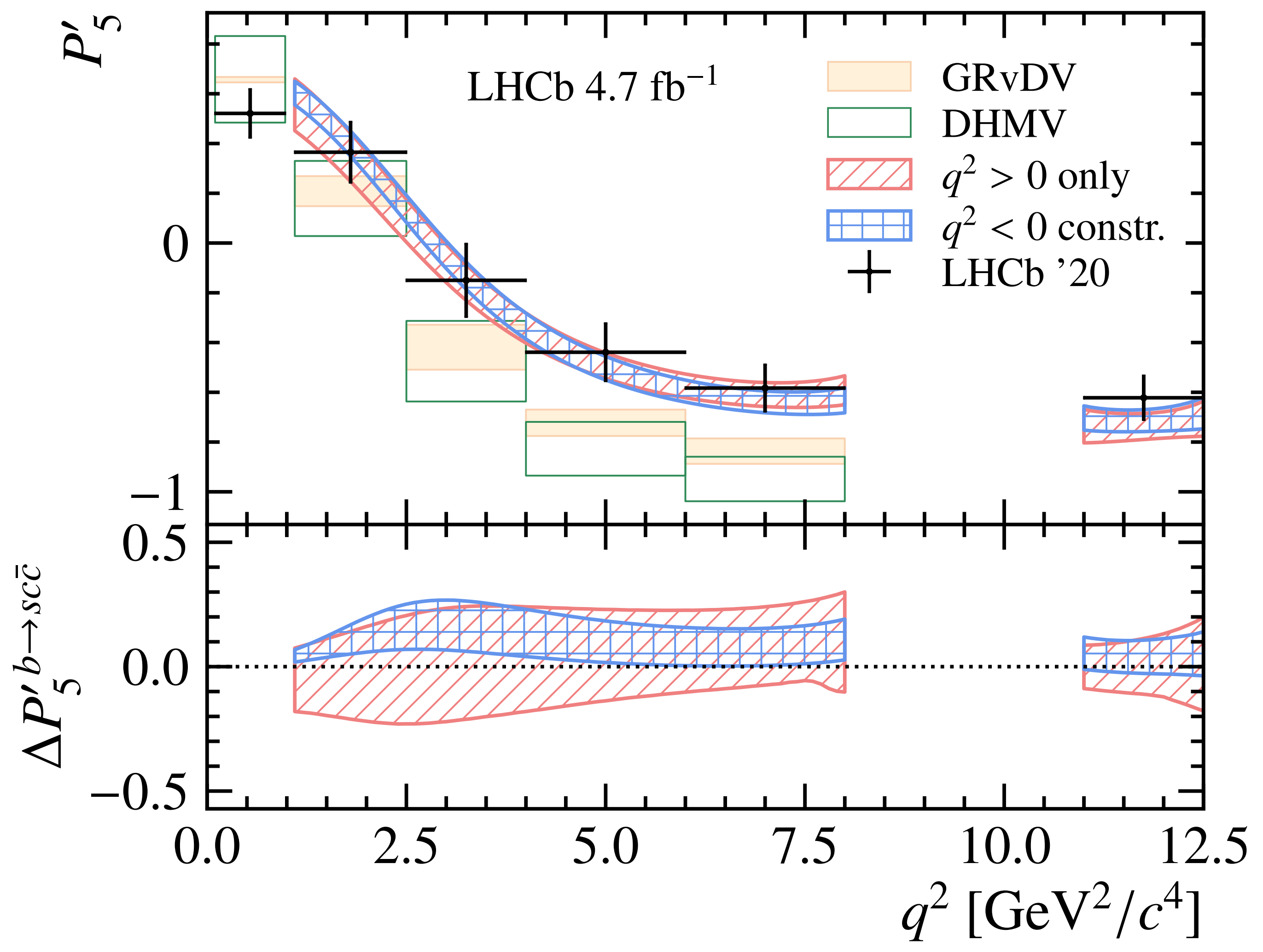


Global compatibility [4 d.o.f.] with SM $1.3\ (1.4)\ \sigma$

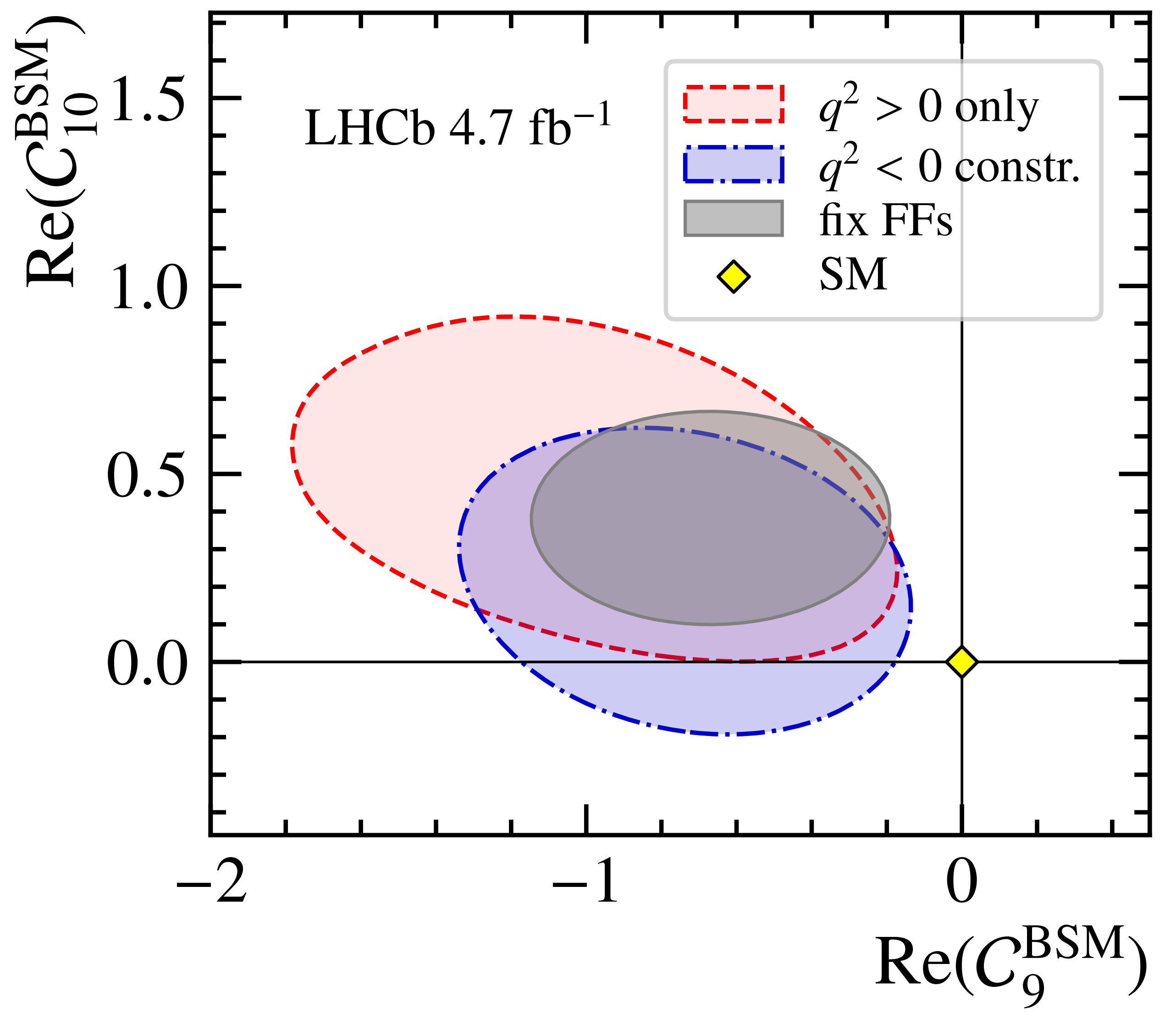
- Many global fits available in the literature
- sub-sets of inputs, different statistical tools/theory assumptions, etc...

Results overview

- New analysis method to determine hadronic contributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays
  - choice of parametrisation ⟶ model dependence
- Impact of $c\bar{c}$ on P_5' found to be consistent with predictions →

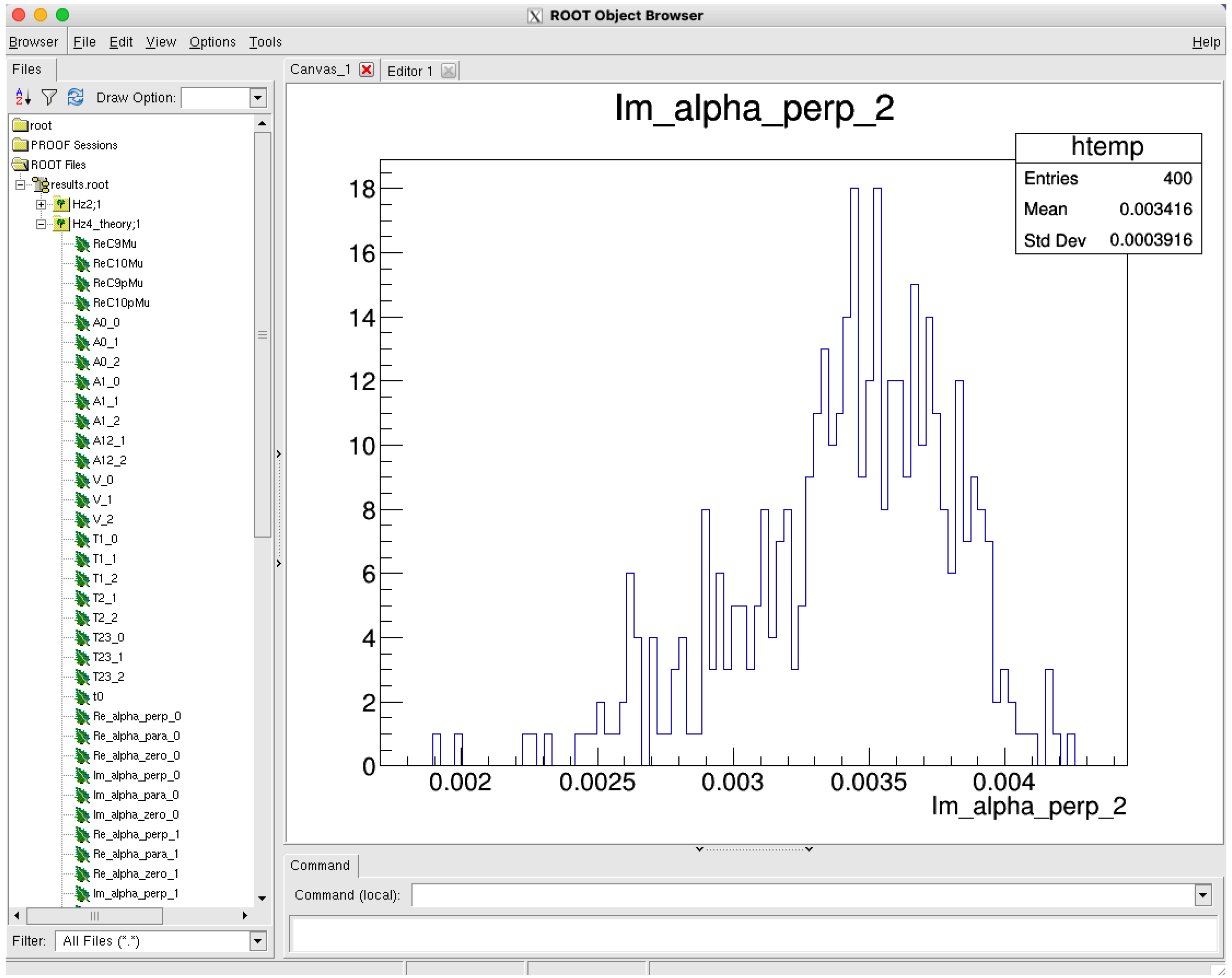


- Despite the extra freedom given by $c\bar{c}$ pars, fit still prefers to insert a shift in $\mathcal{C}_9$
  - Result consistent with pattern of anomalies seen in $b \to s\mu^+\mu^-$ decays
  - compatibility w.r.t. SM: 1.8σ in $\mathcal{C}_9$ and 1.4σ global
- Should not forget the importance of the form-factors! →



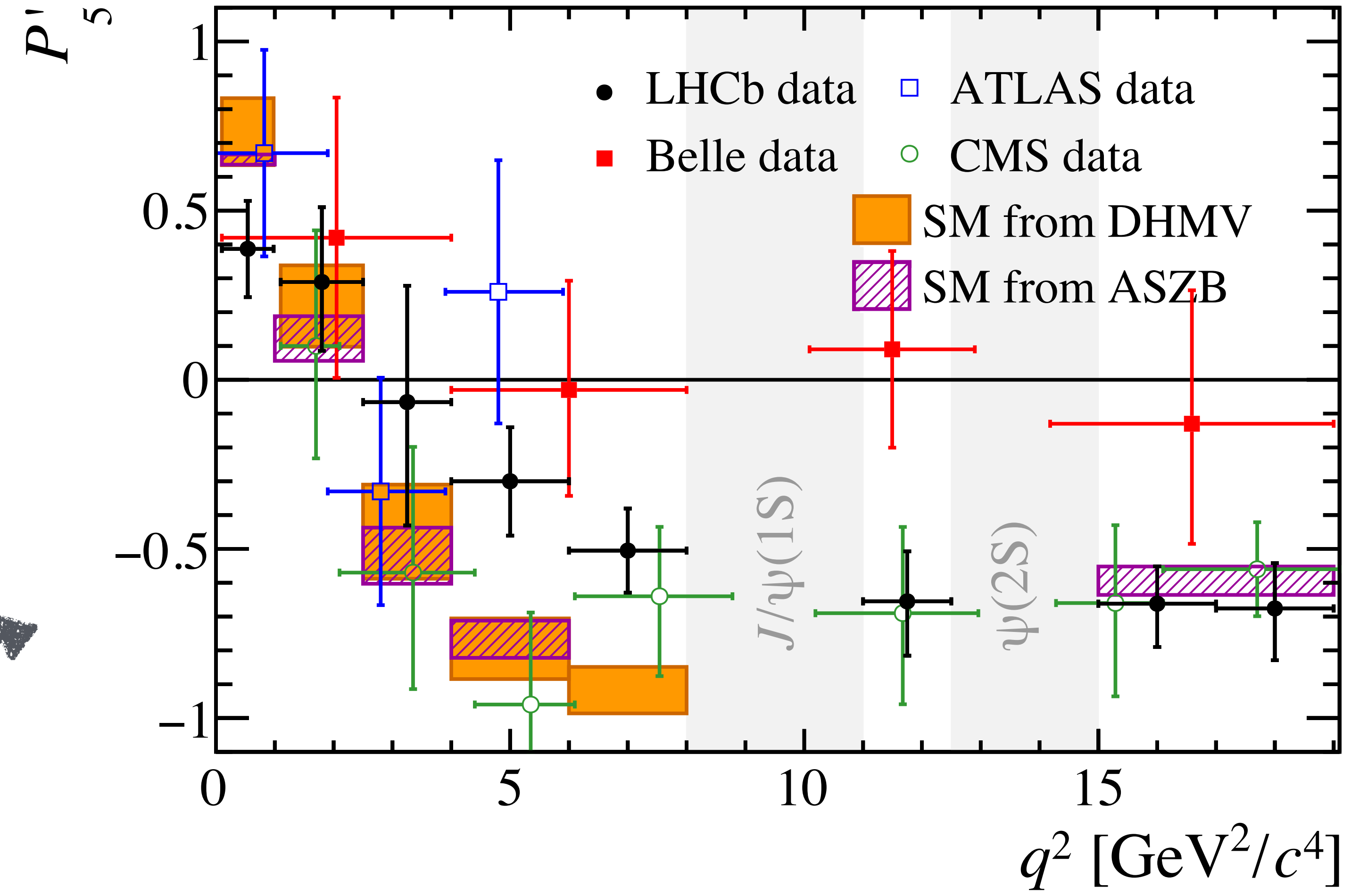
Auxiliary files

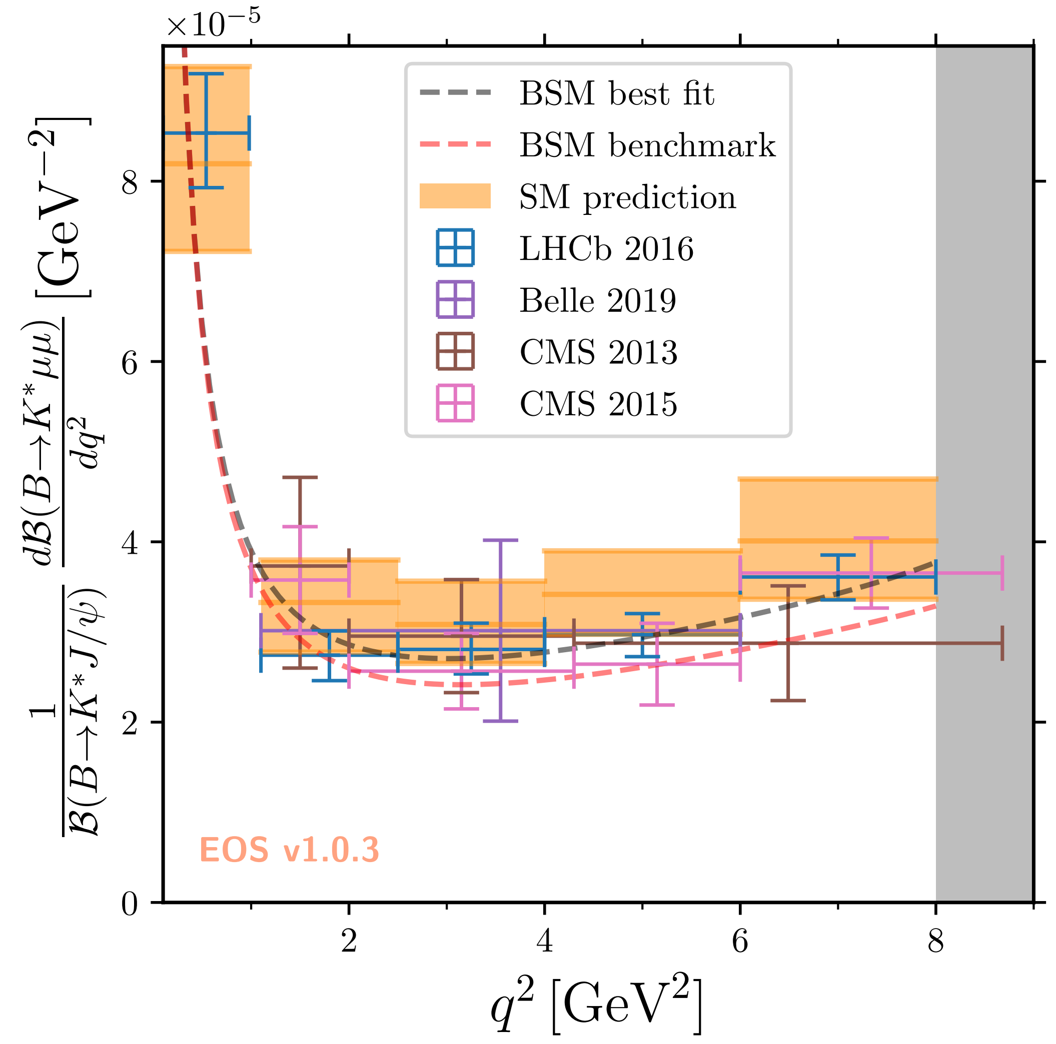
- Analysis offers a large set of results
- Strong interplay between theory and experiment
- Publish set of bootstrapped fit parameters to favour future reinterpretation of the analysis
  - non-trivial correlations
  - allow to reproduce confidence intervals for any desired quantity
  - can transform fit results to different models



A look to the future

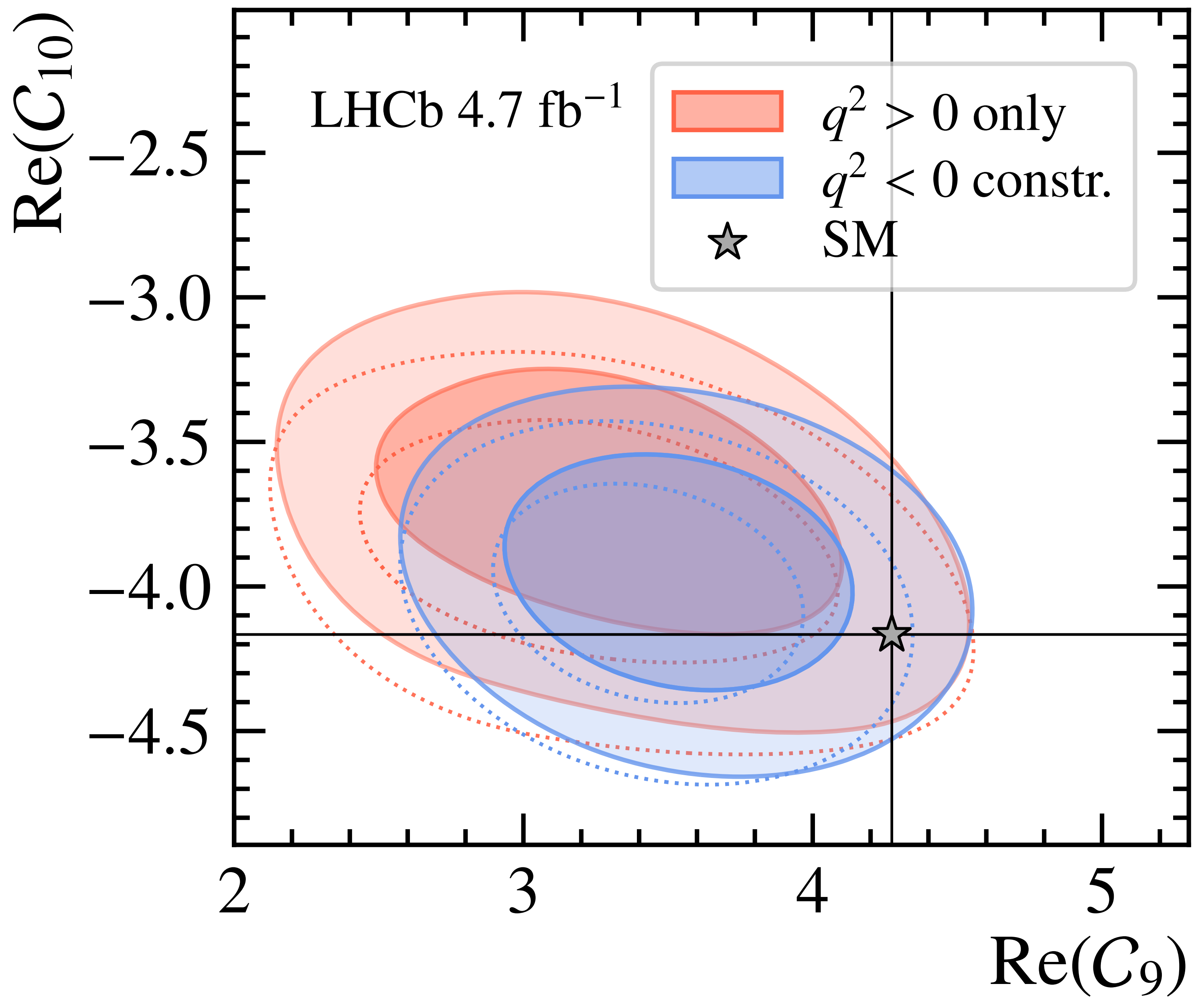
- Important step towards a better understanding of $B^0 \to K^{*0}\mu^+\mu^-$ decays....
  - but this is not the end of the story!
- Need to update with the full Run2 dataset
  - Binned angular analysis coming soon
  - Binned branching fraction too
  - More unbinned analyses
    - different long-distance parametrisations
      - ↳ complementary info
- Run3 dataset will boost the precision of these measurements
  - also allow to study even more suppressed decays





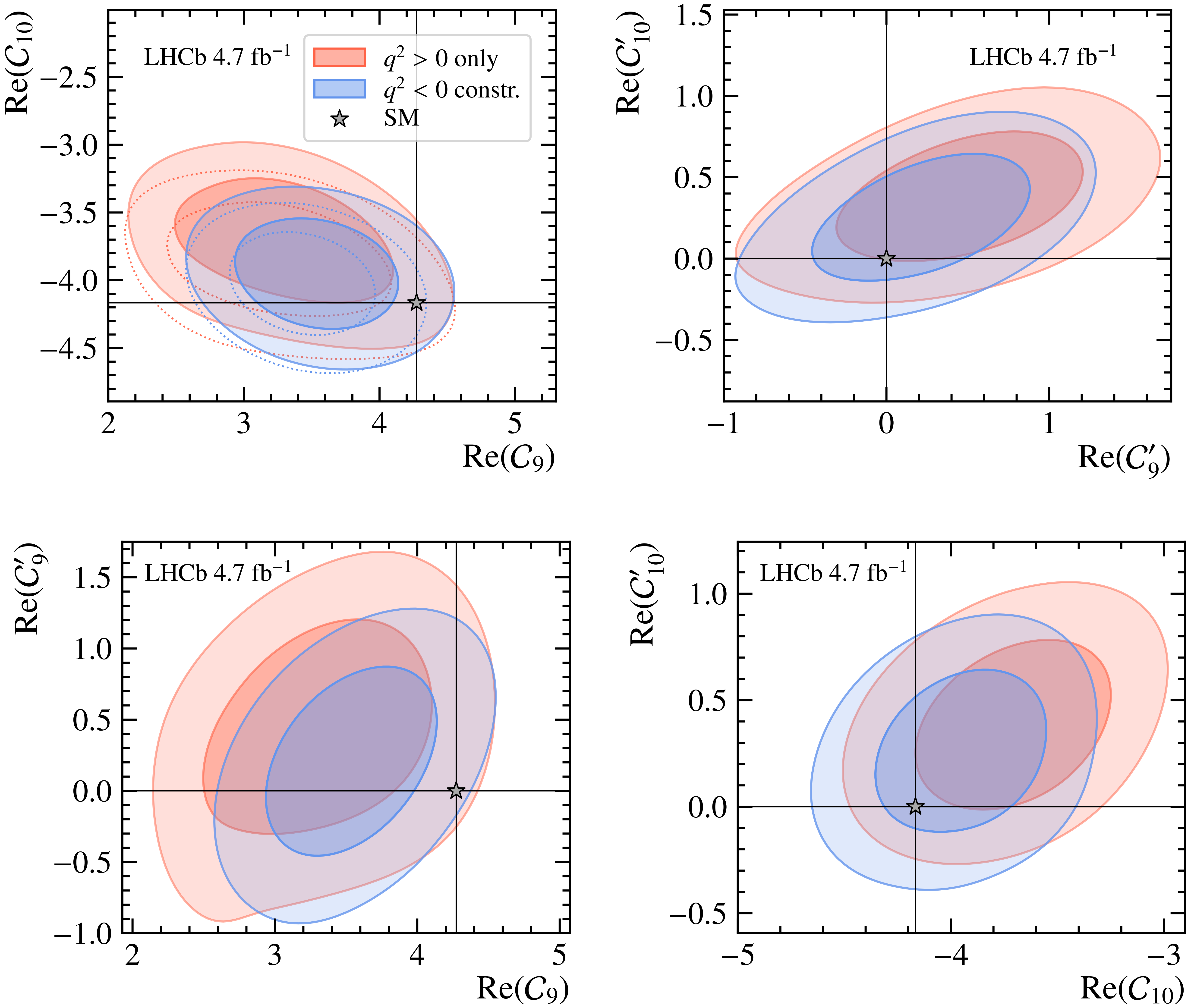
Conclusion

- Set of anomalies in different measurements of $b \to s\mu^+\mu^-$ processes
  - Difficult interpretation due to SM hadronic uncertainties
- First q^2-unbinned amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$
  - Complementary and more in-dept set of information w.r.t. previous binned analyses
  - Non-local hadronic contributions determined from data under two assumptions
- Result consistent with pattern of anomalies seen in $b \to s\mu^+\mu^-$ decays with significance of 1.8σ in $\mathcal{C}_9$ and 1.4σ global



Backup

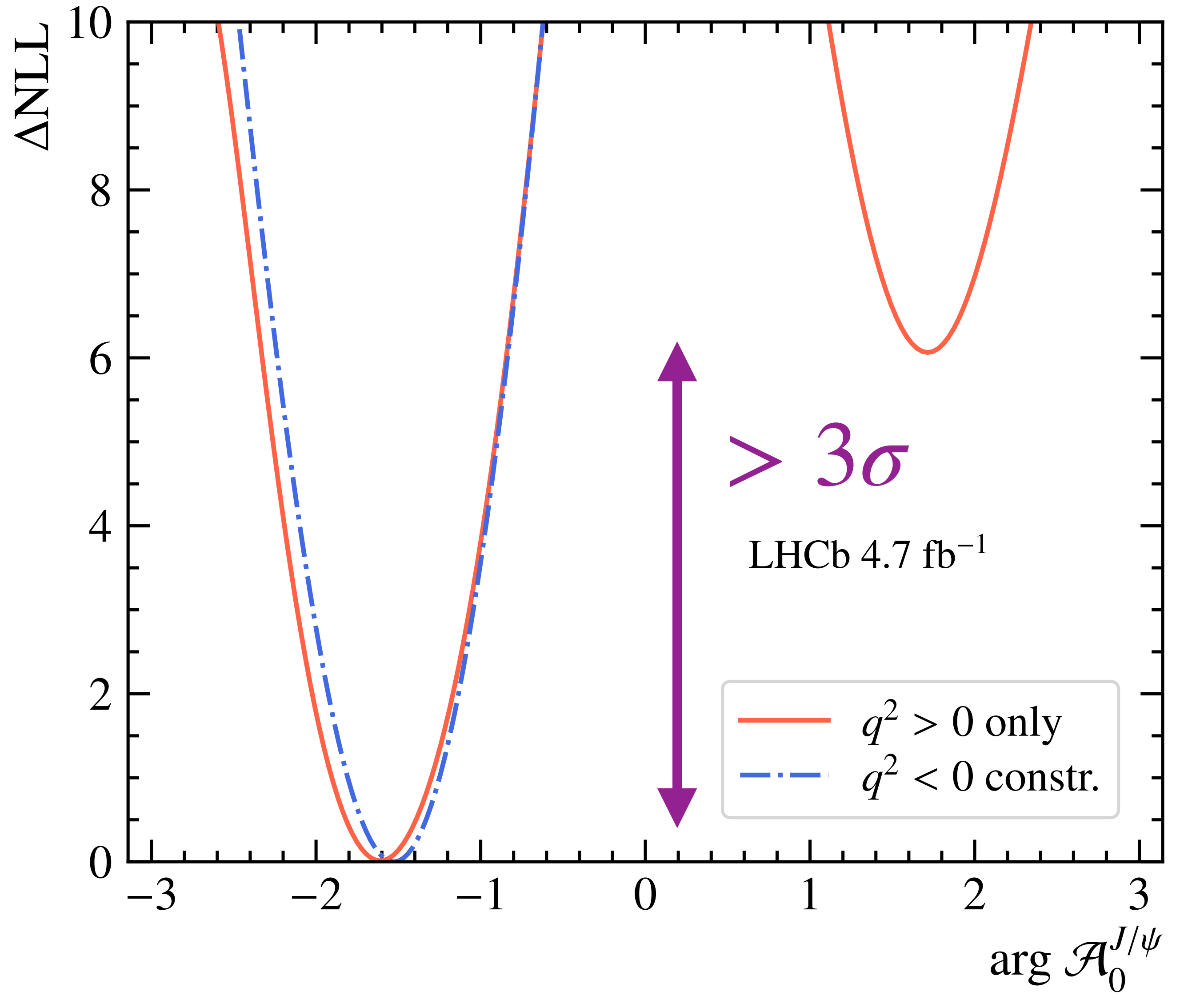
Wilson coefficients 2D



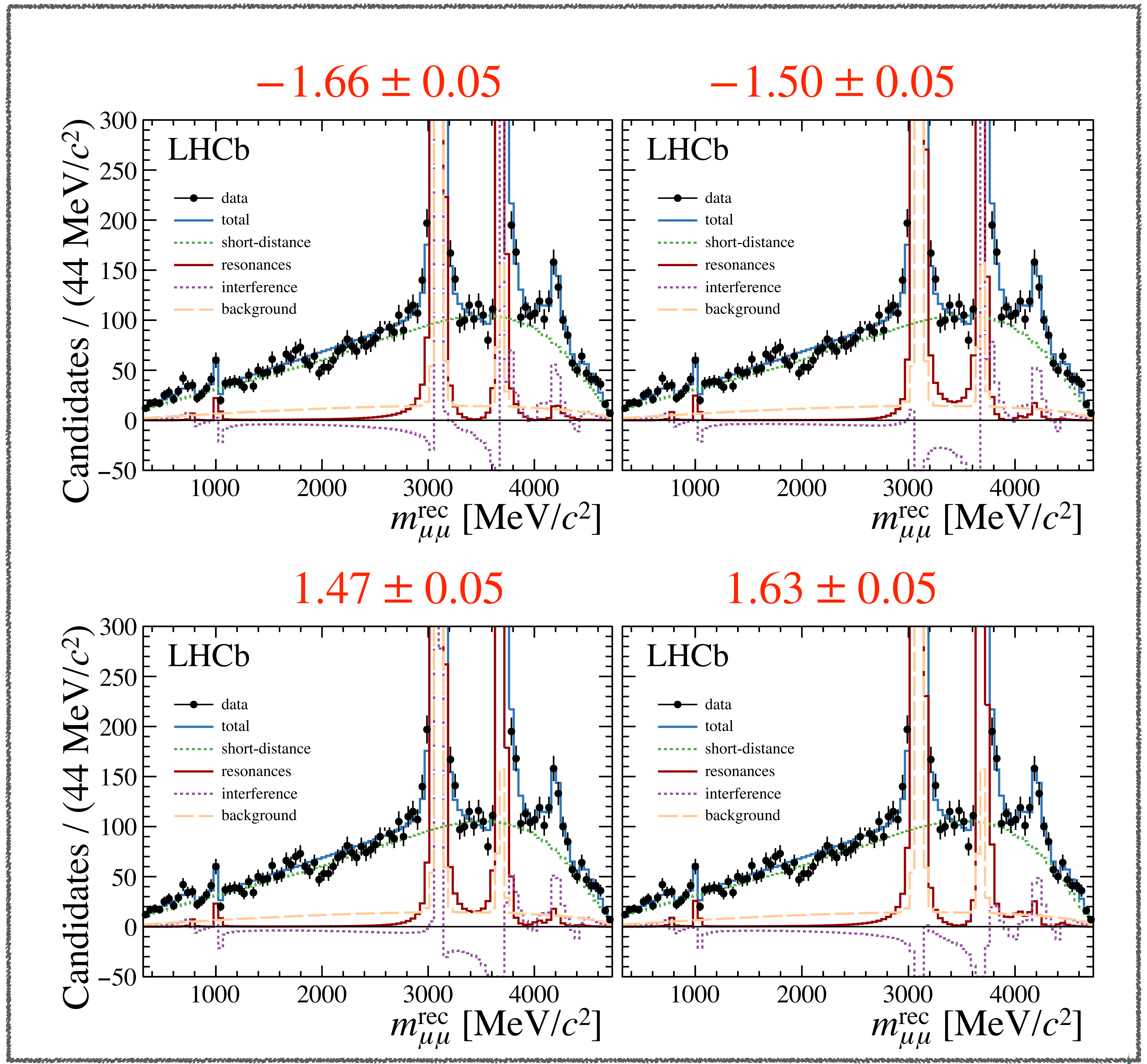
Non-local hadronic results (J/ψ)

- Phase difference between rare mode and $B^0 \to J/\psi K^{*0}$ decays
  - $\arg \mathcal{A}_0^{J/\psi} = \begin{cases} -1.55^{+0.22}_{-0.18} & [q^2 < 0] \\ -1.61^{+0.22}_{-0.20} & [q^2 > 0] \end{cases}$

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



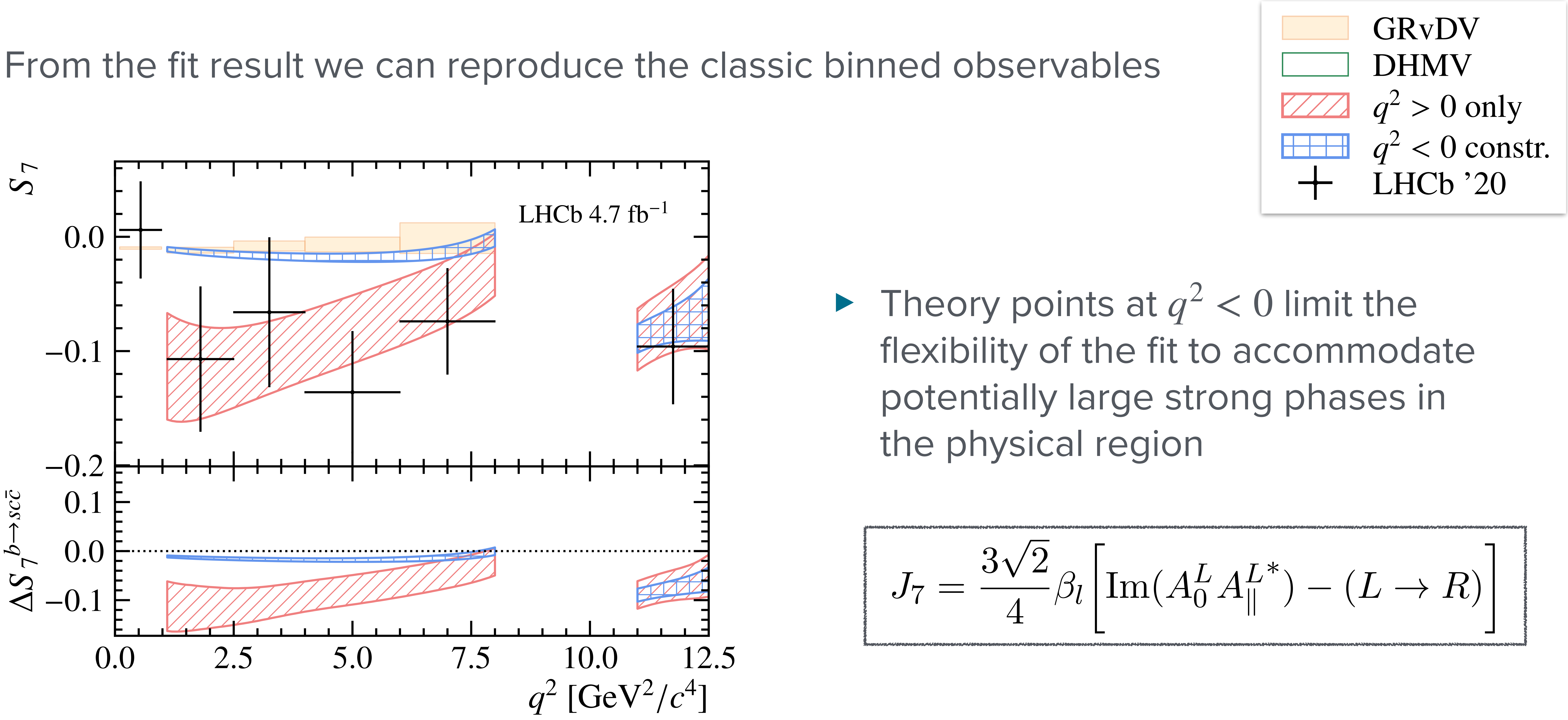
$B^+ \to K^+\mu^+\mu^-$ EPJ C77 (2017) 161



  - No sensitivity to $\arg \mathcal{A}_0^{\psi(2S)}$

S7 angular observable

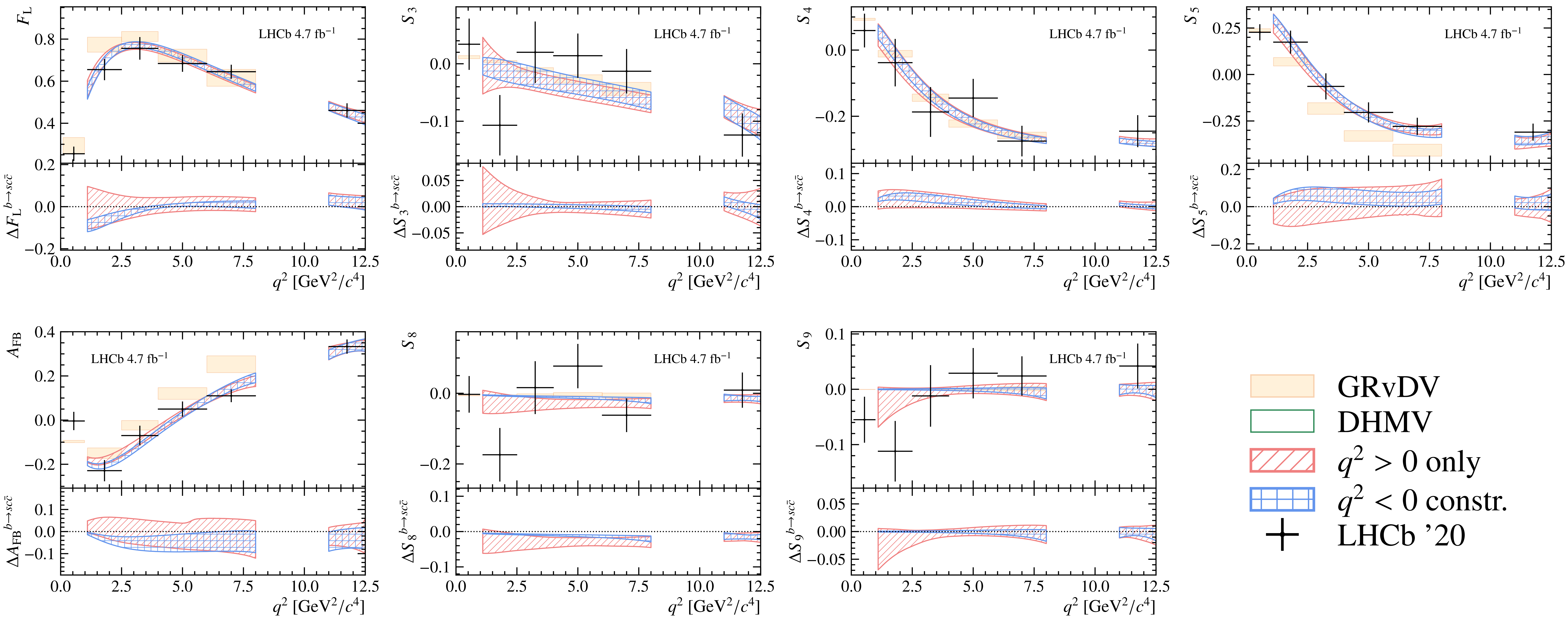
- From the fit result we can reproduce the classic binned observables



- Theory points at $q^2 < 0$ limit the flexibility of the fit to accommodate potentially large strong phases in the physical region

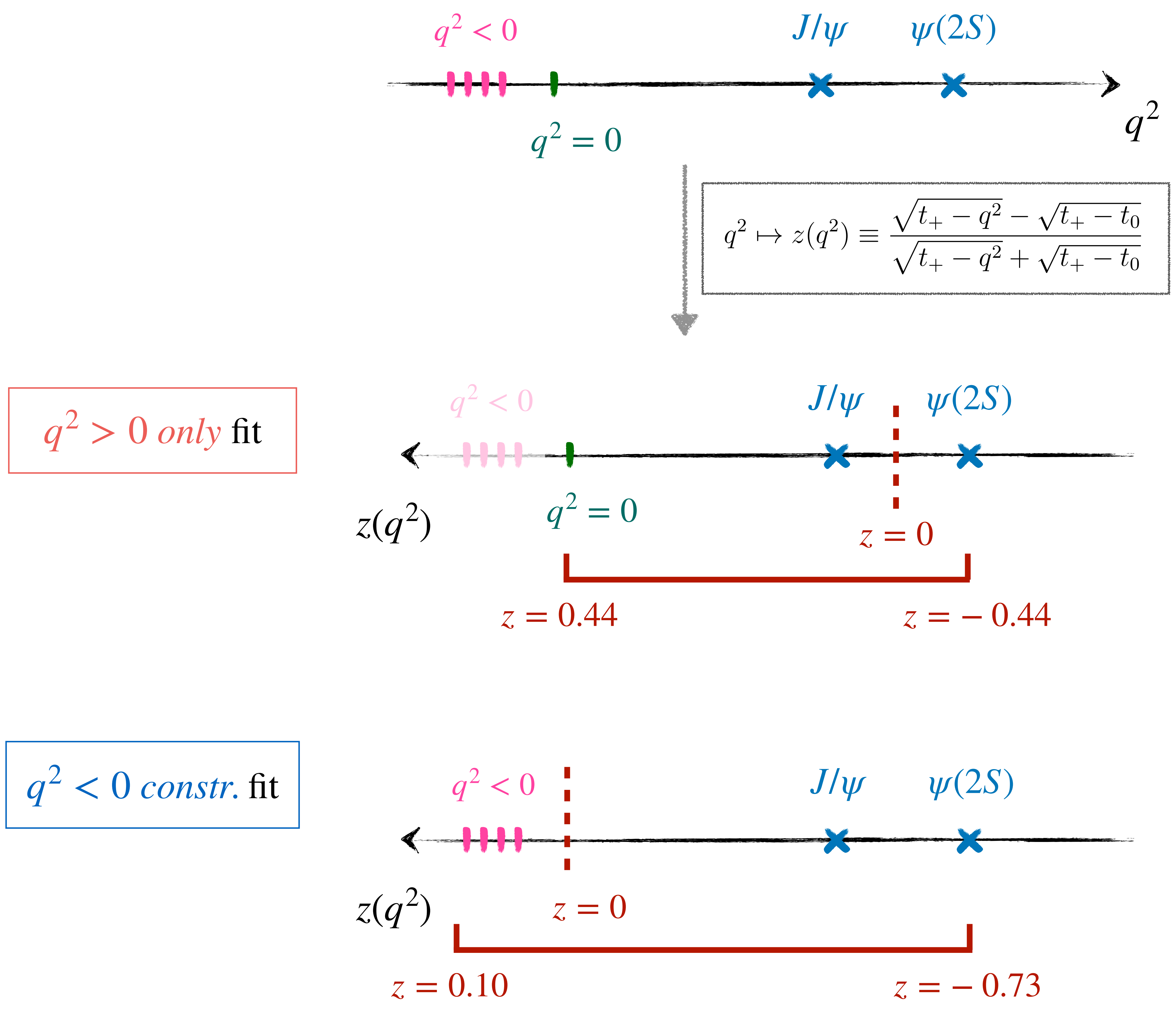
$$J_7 = \frac{3\sqrt{2}}{4}\beta_l\left[\mathrm{Im}(A_0^L A_\parallel^{L*}) - (L \to R)\right]$$

Other angular observables: S-basis



Choice of t_0 and the z order

- Choice of t_0 impacts the convergency of the series



- Data driven determination of the truncation order:
  - fit repeated with increasing polynomial order $\mathcal{H}_\lambda[z^2, z^3, z^4, \ldots]$
  - till no significant improvement in the likelihood is found

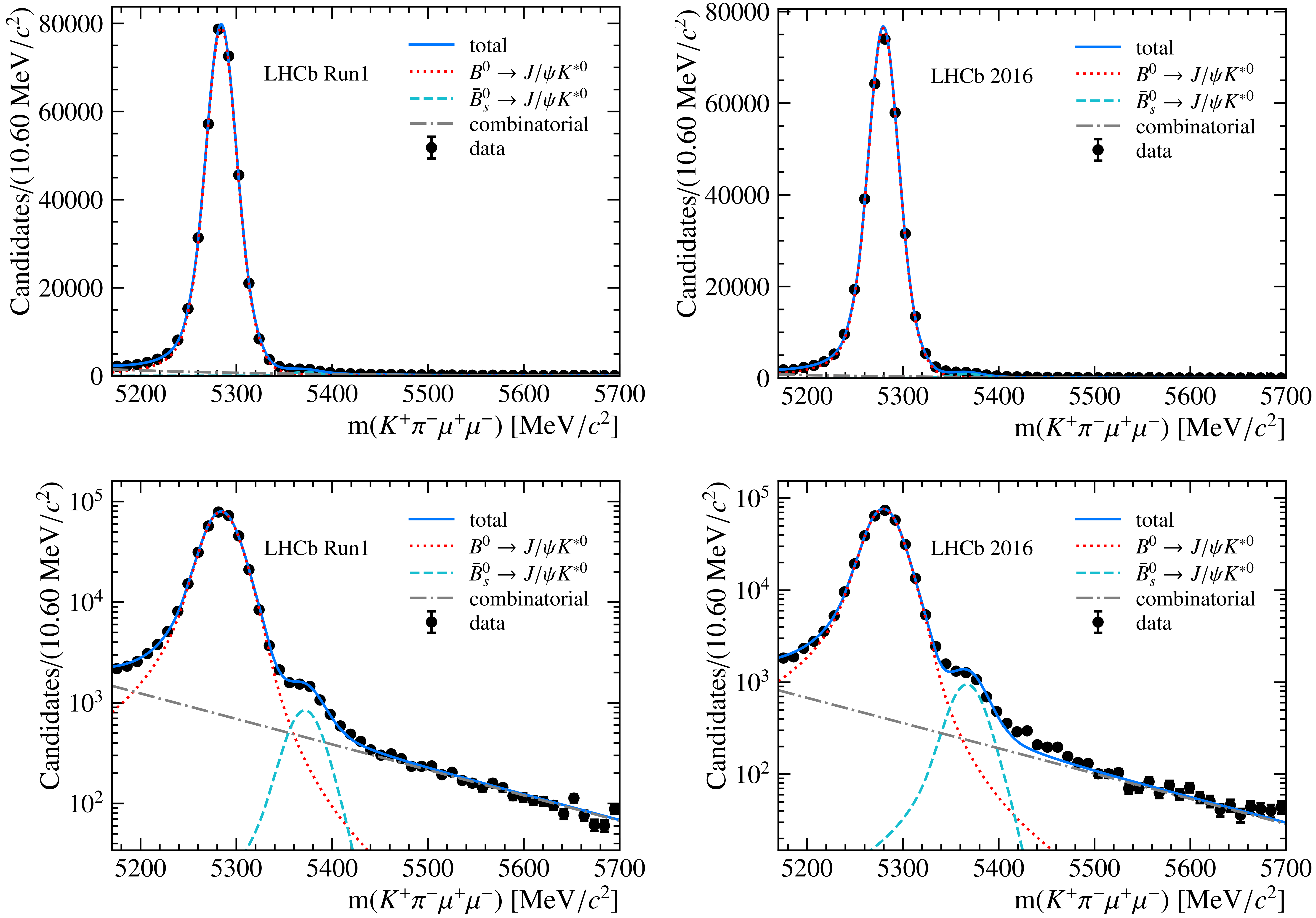
$$2\Delta \log \mathcal{L} > 2\Delta N_{\text{pars}}$$

(each *z*-order brings six additional parameters)

	$2\Delta \log \mathcal{L}$	
	$q^2 < 0$ constr.	$q^2 > 0$ 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	-

- $\mathcal{H}_\lambda[z^2]$ for $q^2 > 0$ only fit
- $\mathcal{H}_\lambda[z^4]$ for $q^2 < 0$ constr. fit

Control channel mass fits



Results 68% 95% CL

	best fit value	68% CL	95% CL	deviation from SM
	$q^2 > 0$ only			
$\mathcal{C}_9$	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

External constraints

CKM parameters	CKMfitter Summer19
A	0.8235 ± 0.0145
λ	0.224837 ± 0.000251
$\bar{\eta}$	0.3499 ± 0.0079
$\bar{\rho}$	0.1569 ± 0.0102

	$B^0 \to J/\psi K^{*0}$		$B^0 \to \psi(2S) K^{*0}$	
f_0	-		0.455 ± 0.057	[65]
$f_{\parallel}$	0.227 ± 0.006	[64, 66, 67]	0.22 ± 0.06	[64]
$f_{\perp}$	0.209 ± 0.005	[64, 66, 67]	0.30 ± 0.06	[64]
$\delta_{\parallel}$	0.20 ± 0.03	[64, 66, 67]	0.34 ± 0.4	[64]
$\delta_{\perp}$	-0.21 ± 0.03	[64, 66, 67]	-0.34 ± 0.3	[64]
$\mathcal{B}(B^0 \to \psi_n K^{*0})$	$(1.19 \pm 0.08) \times 10^{-3}$	[66]	$(5.55 \pm 0.87) \times 10^{-4}$	[65]
$\frac{\mathcal{B}(B^0 \to \psi(2S) K^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})}$	0.487 ± 0.021 [68]			

	$\mathcal{R}e[\mathcal{H}_\perp]/\mathcal{F}_\perp$				$\mathcal{R}e[\mathcal{H}_\parallel]/\mathcal{F}_\parallel$				$\mathcal{R}e[\mathcal{H}_0]/\mathcal{F}_0$			
q^2	-7.0	-5.0	-3.0	-1.0	-7.0	-5.0	-3.0	-1.0	-7.0	-5.0	-3.0	-1.0
μ	3.087	3.182	3.172	3.041	2.846	2.919	2.886	2.731	-0.019	0.113	0.154	0.085
σ	0.162	0.175	0.200	0.237	0.138	0.146	0.164	0.194	0.080	0.057	0.038	0.016
	$\mathcal{I}m[\mathcal{H}_\perp]/\mathcal{F}_\perp$				$\mathcal{I}m[\mathcal{H}_\parallel]/\mathcal{F}_\parallel$				$\mathcal{I}m[\mathcal{H}_0]/\mathcal{F}_0$			
q^2	-7.0	-5.0	-3.0	-1.0	-7.0	-5.0	-3.0	-1.0	-7.0	-5.0	-3.0	-1.0
μ	0.103	0.117	0.138	0.168	0.094	0.106	0.124	0.15	-0.018	-0.015	-0.012	-0.005
σ	0.010	0.013	0.016	0.021	0.009	0.011	0.013	0.018	0.004	0.003	0.002	0.001

The angular functions

$$
\begin{aligned}
I_{1s} &= \frac{2+\beta_l^2}{4}\Big[|\mathcal{A}_\perp^L|^2 + |\mathcal{A}_\parallel^L|^2 + (L\to R)\Big] \\
&\quad + \frac{4m_l^2}{q^2}\,\mathcal{R}e\Big(\mathcal{A}_\perp^L\mathcal{A}_\perp^{R*} + \mathcal{A}_\parallel^L\mathcal{A}_\parallel^{R*}\Big), \\
I_{1c} &= \Big[|\mathcal{A}_0^L|^2 + |\mathcal{A}_0^R|^2\Big] + \frac{4m_l^2}{q^2}\Big[|\mathcal{A}_t|^2 + 2\,\mathcal{R}e(\mathcal{A}_0^L\mathcal{A}_0^{R*})\Big], \\
I_{2s} &= \frac{\beta_l^2}{4}\Big[|\mathcal{A}_\perp^L|^2 + |\mathcal{A}_\parallel^L|^2 + (L\to R)\Big], \\
I_{2c} &= -\beta_l^2\Big[|\mathcal{A}_0^L|^2 + |\mathcal{A}_0^R|^2\Big], \\
I_3 &= \frac{\beta_l^2}{2}\Big[|\mathcal{A}_\perp^L|^2 - |\mathcal{A}_\parallel^L|^2 + (L\to R)\Big], \\
I_4 &= -\frac{\beta_l^2}{\sqrt{2}}\,\mathcal{R}e\Big[\mathcal{A}_0^L\mathcal{A}_\parallel^{L\,*} + (L\to R)\Big], \\
I_5 &= \sqrt{2}\beta_l\,\mathcal{R}e\Big[\mathcal{A}_0^L\mathcal{A}_\perp^{L\,*} - (L\to R)\Big], \\
I_{6s} &= -2\beta_l\,\mathcal{R}e\Big[\mathcal{A}_\parallel^L\mathcal{A}_\perp^{L\,*} - (L\to R)\Big], \\
I_7 &= -\sqrt{2}\beta_l\,\mathcal{I}m\Big[\mathcal{A}_0^L\mathcal{A}_\parallel^{L\,*} - (L\to R)\Big], \\
I_8 &= \frac{\beta_l^2}{\sqrt{2}}\,\mathcal{I}m\Big[\mathcal{A}_0^L\mathcal{A}_\perp^{L\,*} + (L\to R)\Big], \\
I_9 &= -\beta_l^2\,\mathcal{I}m\Big[\mathcal{A}_\perp^L\mathcal{A}_\parallel^{L\,*} + (L\to R)\Big],
\end{aligned}
$$

$$
\begin{aligned}
I_{1c}^S &= \frac{1}{3}\Big\{\Big[|\mathcal{A}_{S0}^L|^2 + |\mathcal{A}_{S0}^R|^2\Big] + \frac{4m_l^2}{q^2}\Big[|\mathcal{A}_{St}|^2 + 2\,\mathrm{Re}(\mathcal{A}_{S0}^L\mathcal{A}_{S0}^{R\,*})\Big]\Big\}, \\
I_{2c}^S &= -\frac{1}{3}\beta_l^2\Big[|\mathcal{A}_{S0}^L|^2 + |\mathcal{A}_{S0}^R|^2\Big], \\
\tilde{I}_{1c} &= \frac{2}{\sqrt{3}}\mathrm{Re}\Big[\mathcal{A}_{S0}^L\mathcal{A}_0^{L\,*} + \mathcal{A}_{S0}^R\mathcal{A}_0^{R*} + \frac{4m_l^2}{q^2}\Big(\mathcal{A}_{S0}^L\mathcal{A}_0^{R*} + \mathcal{A}_0^L\mathcal{A}_{S0}^{R\,*} + \mathcal{A}_{St}\mathcal{A}_t^{\,*}\Big)\Big], \\
\tilde{I}_{2c} &= -\frac{2}{\sqrt{3}}\beta_l^2\,\mathrm{Re}\Big[\mathcal{A}_{S0}^L\mathcal{A}_0^{L\,*} + \mathcal{A}_{S0}^R\mathcal{A}_0^{R*}\Big], \\
\tilde{I}_4 &= -\sqrt{\frac{2}{3}}\beta_l^2\,\mathrm{Re}\Big[\mathcal{A}_{S0}^L\mathcal{A}_\parallel^{L\,*} + (L\to R)\Big], \\
\tilde{I}_5 &= \sqrt{\frac{8}{3}}\beta_l^2\,\mathrm{Re}\Big[\mathcal{A}_{S0}^L\mathcal{A}_\perp^{L\,*} - (L\to R)\Big], \\
\tilde{I}_7 &= -\sqrt{\frac{8}{3}}\beta_l^2\,\mathrm{Im}\Big[\mathcal{A}_{S0}^L\mathcal{A}_\parallel^{L\,*} - (L\to R)\Big], \\
\tilde{I}_8 &= \sqrt{\frac{2}{3}}\beta_l^2\,\mathrm{Im}\Big[\mathcal{A}_{S0}^L\mathcal{A}_\perp^{L\,*} + (L\to R)\Big],
\end{aligned}
$$

Form factors

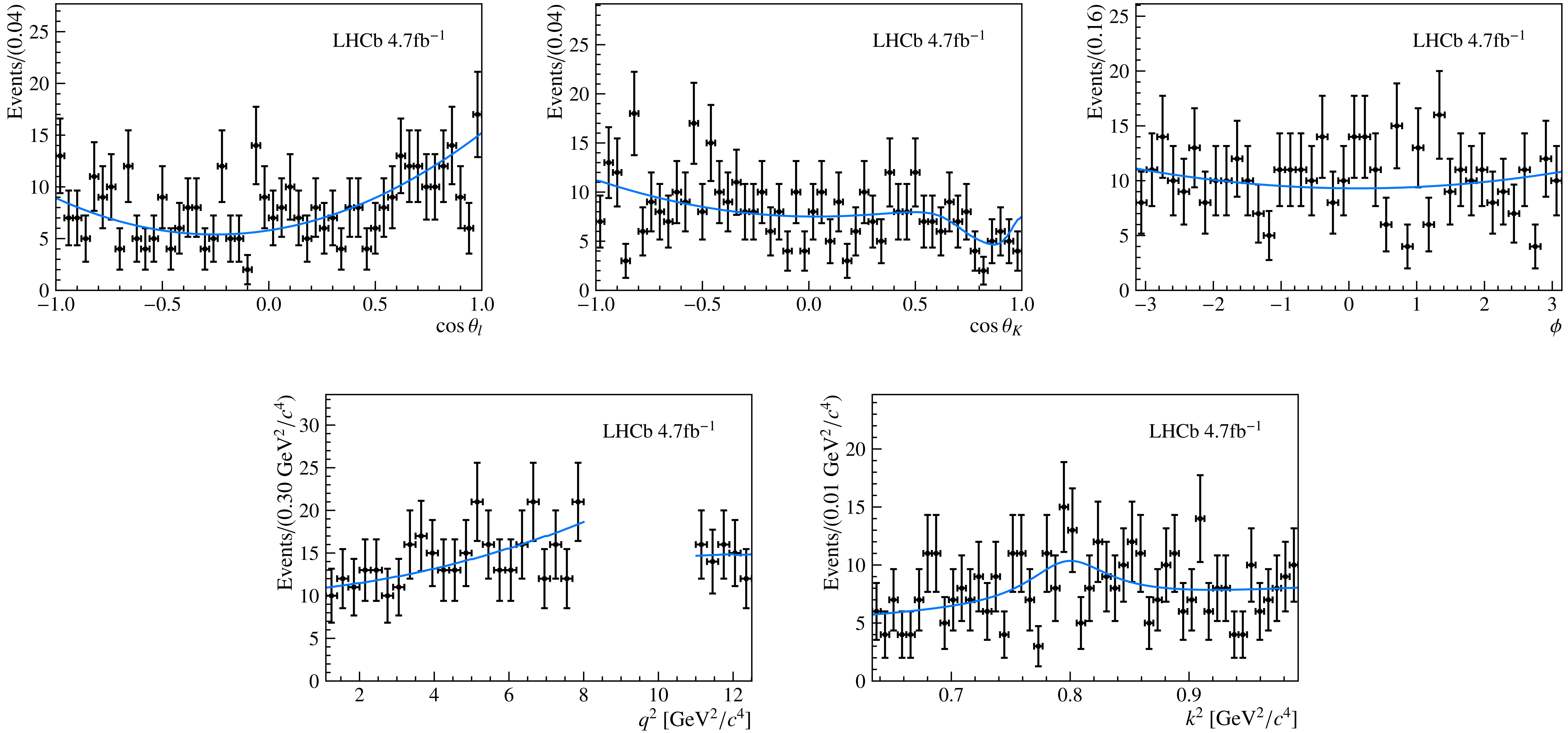
$$
\begin{aligned}
\mathcal{F}_\perp &\mapsto \frac{\sqrt{2\lambda(M_B^2, q^2, k^2)}}{M_B(M_B + M_{K^{*0}})} V \,, \\
\mathcal{F}_\parallel &\mapsto \frac{\sqrt{2}(M_B + M_{K^{*0}})}{M_B} A_1 \,, \\
\mathcal{F}_0 &\mapsto \frac{(M_B^2 - q^2 - M_{K^{*0}}^2)(M_B + M_{K^{*0}})^2 A_1 - \lambda(M_B^2, q^2, k^2) A_2}{2 M_{K^{*0}} M_B^2 (M_B + M_{K^{*0}})} \,, \\
\mathcal{F}_\perp^T &\mapsto \frac{\sqrt{2\lambda(M_B^2, q^2, k^2)}}{M_B^2} T_1 \,, \\
\mathcal{F}_\parallel^T &\mapsto \frac{\sqrt{2}(M_B^2 - M_{K^{*0}}^2)}{M_B^2} T_2 \,, \\
\mathcal{F}_0^T &\mapsto \frac{q^2(M_B^2 + 3M_{K^{*0}}^2 - q^2)}{2 M_B^3 M_{K^{*0}}} T_2 - \frac{q^2 \lambda(M_B^2, q^2, k^2)}{2 M_B^3 M_{K^{*0}} (M_B^2 - M_{K^{*0}}^2)} T_3 \,, \\
\mathcal{F}_t &\mapsto \frac{\sqrt{\lambda(M_B^2, q^2, k^2)}}{M_B \sqrt{q^2}} A_0 \,.
\end{aligned}
$$

S-wave amplitude

$$\mathcal{A}_{S\,0}^{L,R} = -\mathcal{N}\frac{\sqrt{\lambda(M_B^2, q^2, k^2)}}{M_B\sqrt{q^2}}\Big\{\Big[(\mathcal{C}_9 - \mathcal{C}_9') \mp (\mathcal{C}_{10} - \mathcal{C}_{10}')\Big] f_+(q^2, k^2) + \frac{2m_b M_B}{q^2}(\mathcal{C}_7 - \mathcal{C}_7') f_T(q^2, k^2)\Big\},$$

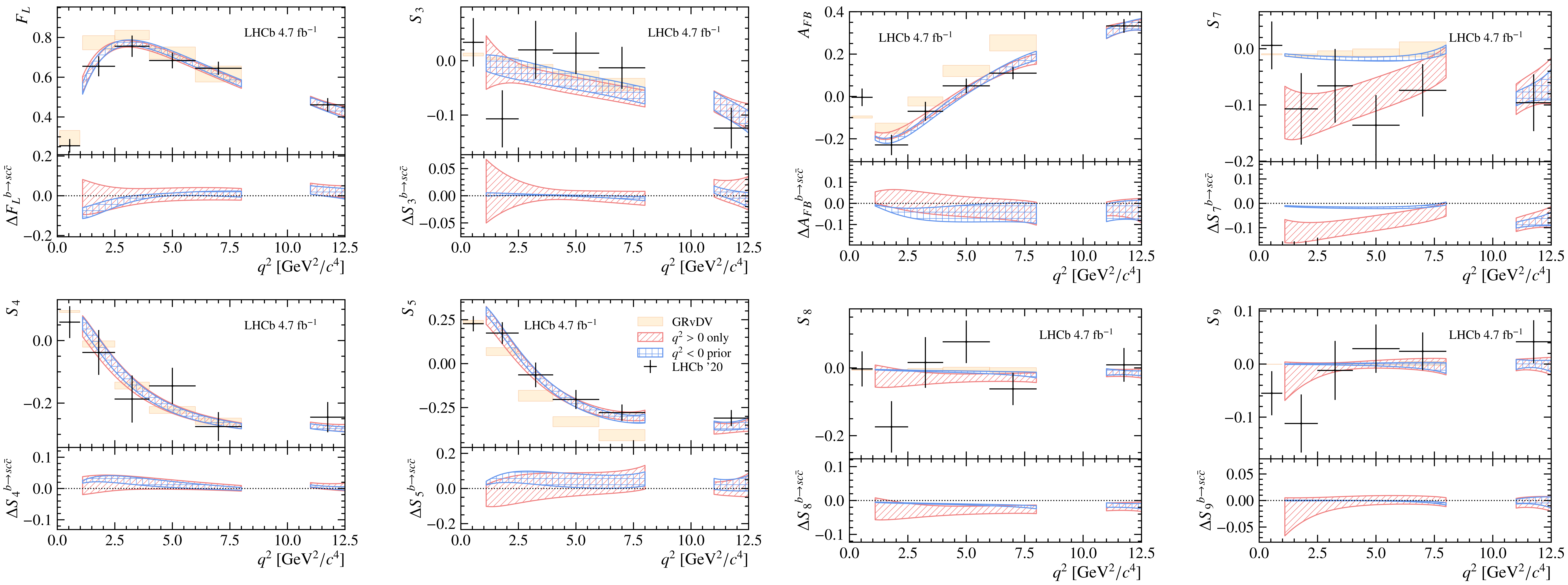
$$\mathcal{A}_{S\,t} = -2\mathcal{N}\frac{M_B^2 - k^2}{M_B\sqrt{q^2}}(\mathcal{C}_{10} - \mathcal{C}_{10}') f_0(q^2, k^2),$$

Upper mass projections



Ang. obs (P-basis)

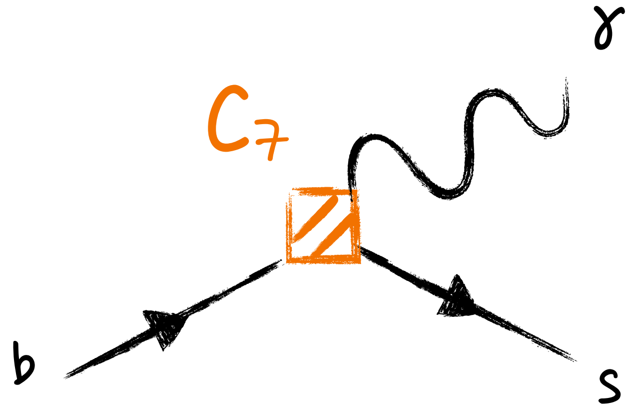
Ang. obs (S-basis)



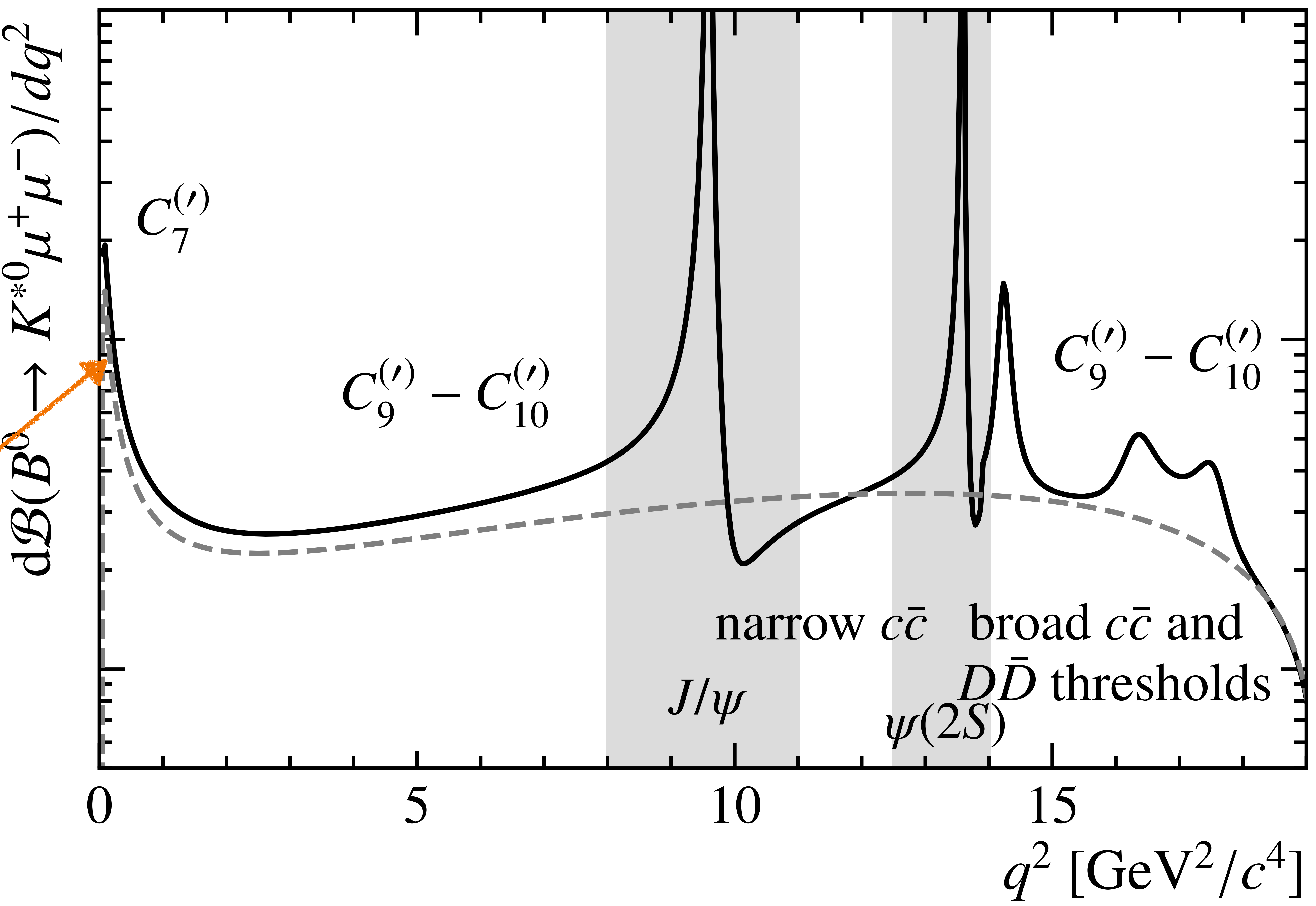
q^2 spectrum

photon pole

Well known by radiative decays e.g. $B \to K^{*0}\gamma$



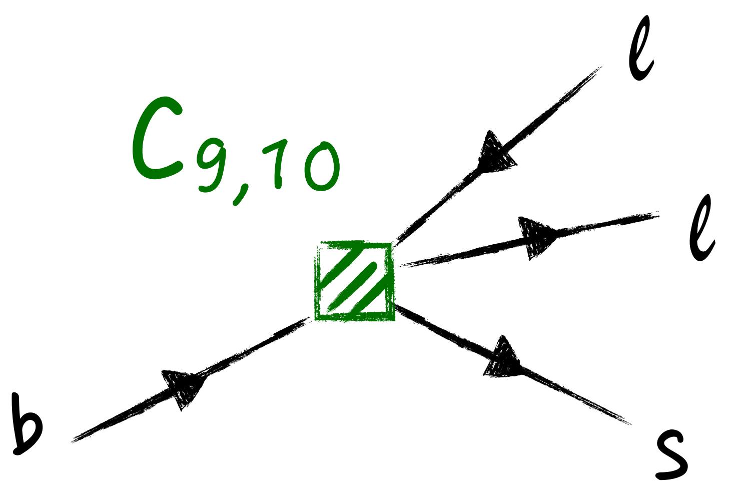
[Paul, Straub; JHEP 04 (2017) 027]

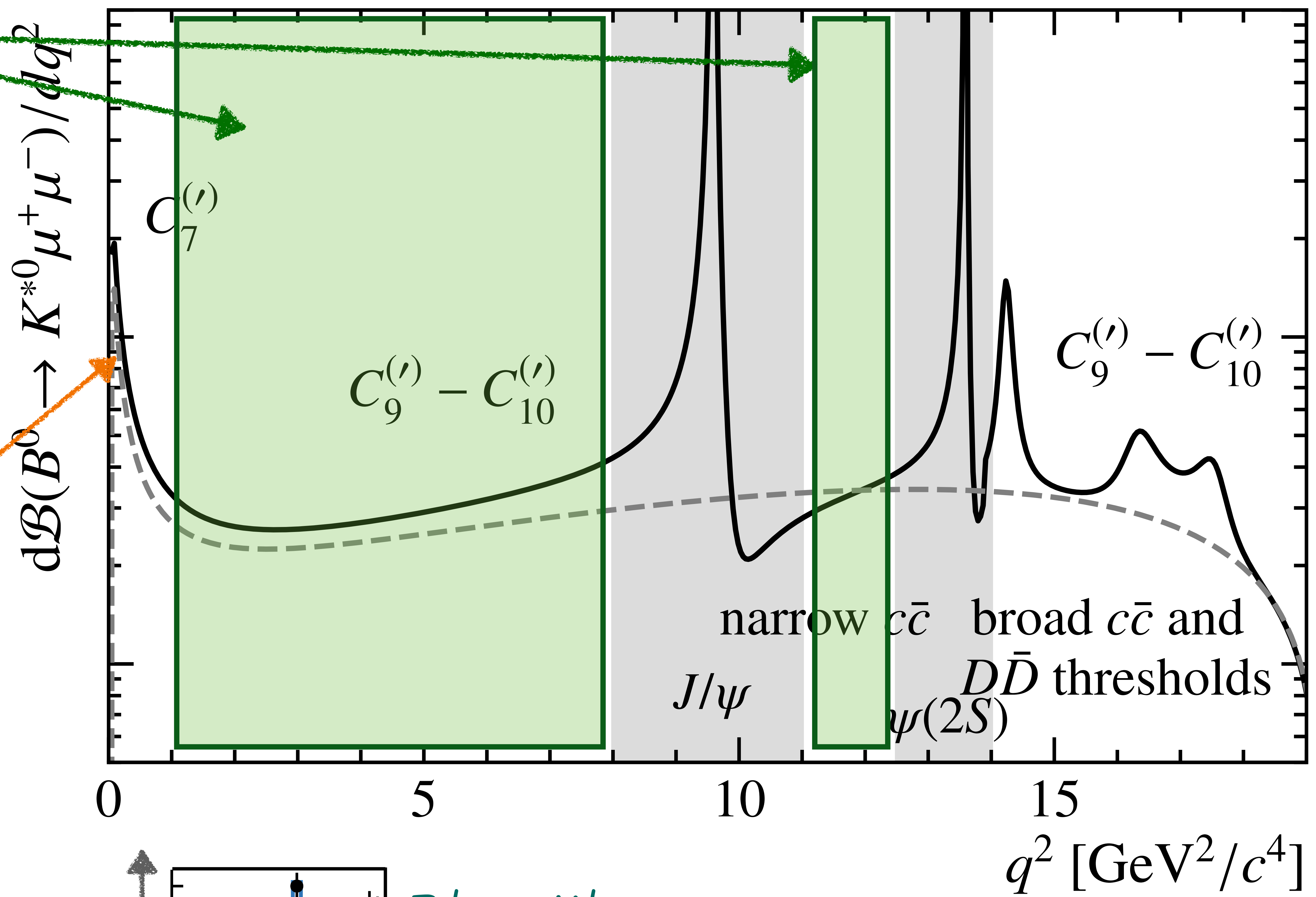


q^2 spectrum

2 signal regions

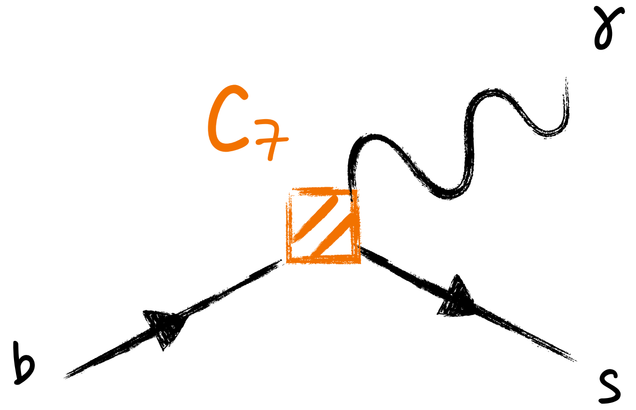
[1.1, 8.0] & [11, 12.5] GeV^2





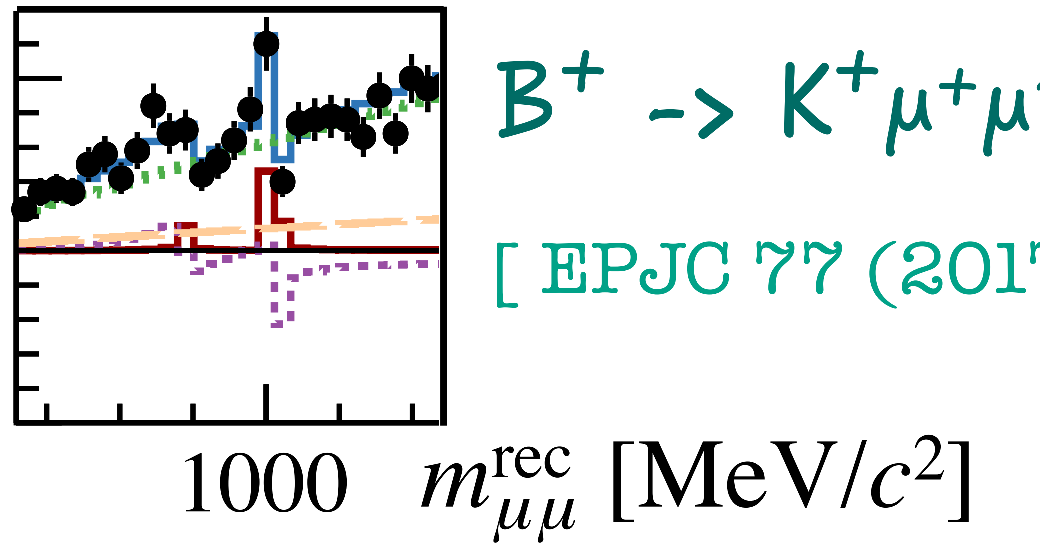
photon pole

Well known by radiative decays e.g. $B \to K^{*0}\gamma$



[Paul, Straub; JHEP 04 (2017) 027]

- light resonances: $\rho^0(770), \omega(792), \phi(1020)$
- extra complications without real benefit



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

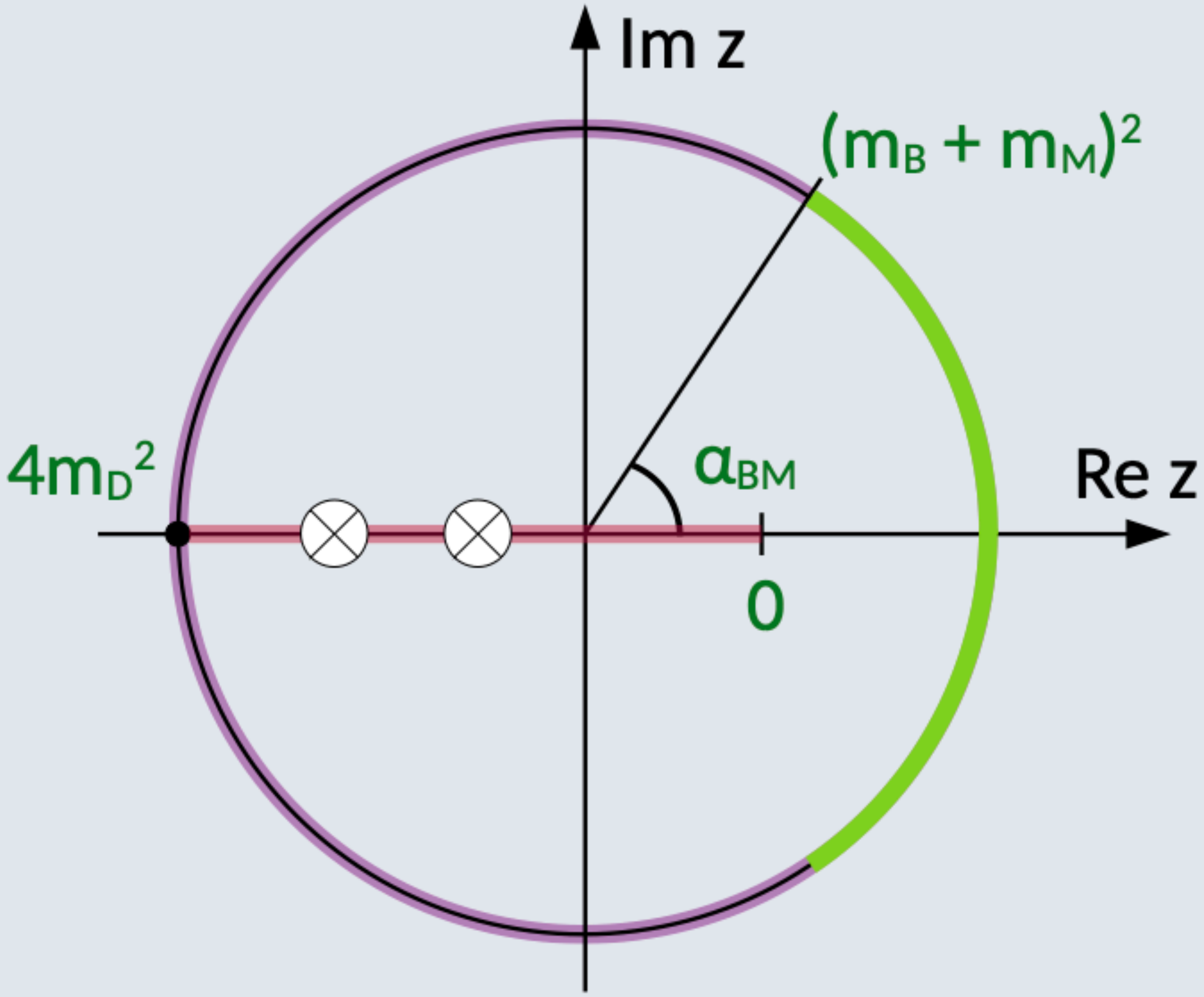
[EPJC 77 (2017) 161]

GRvDV parametrization

- The bound can be "**diagonalized**" with **orthonormal polynomials** of the arc of the unit circle [Gubernari, van Dyk, Virto '20]

$$z(s) = \frac{\sqrt{4m_D^2 - s} - \sqrt{4m_D^2 - s_0}}{\sqrt{4m_D^2 - s} + \sqrt{4m_D^2 - s_0}}$$

$$\mathcal{H}_\lambda(z) = \frac{1}{\phi(z)\mathcal{P}(z)} \sum_{k=0}^{N} a_{\lambda,k}\, p_k(z)$$



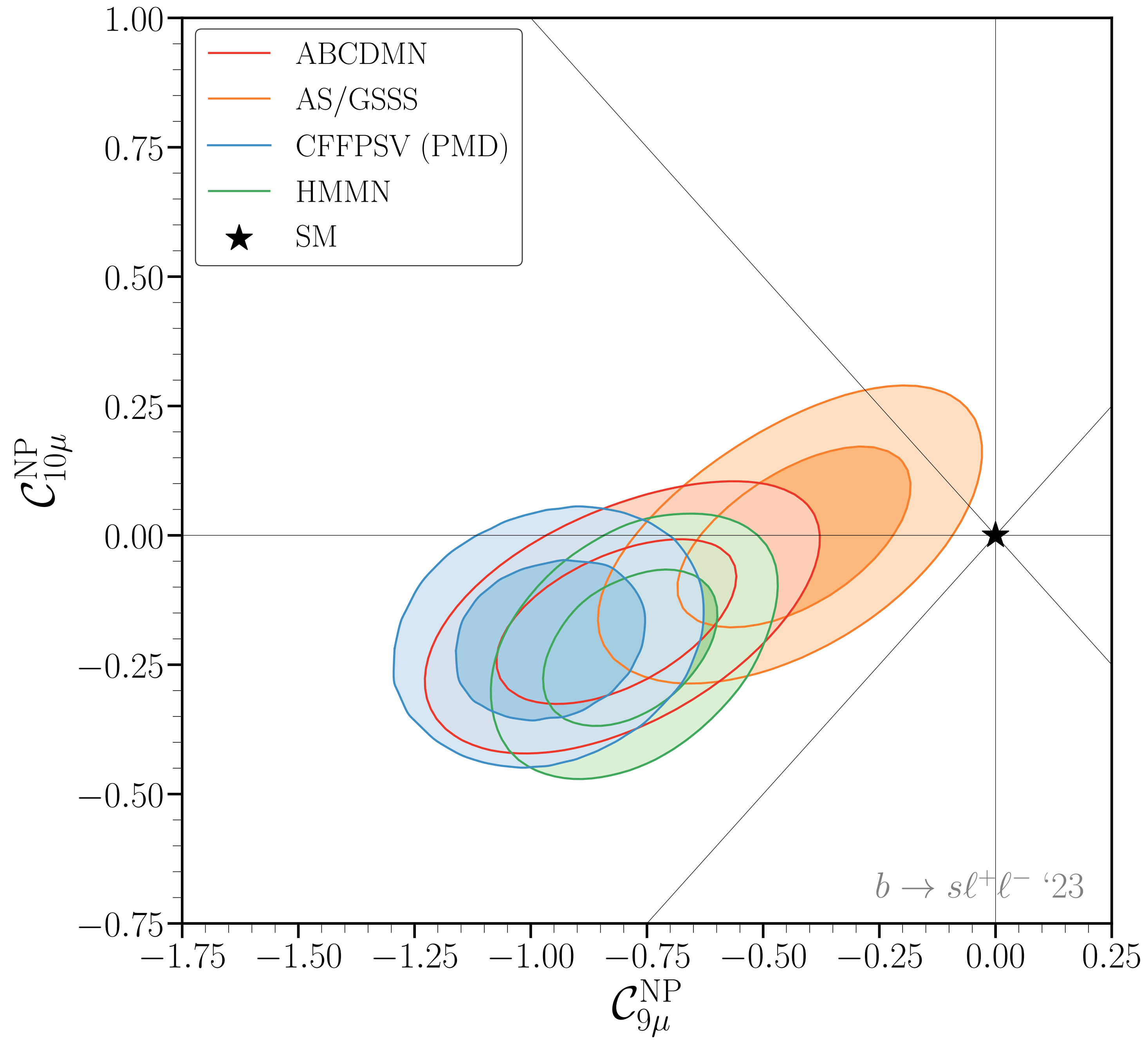
- The coefficients respect the **simple bound**:

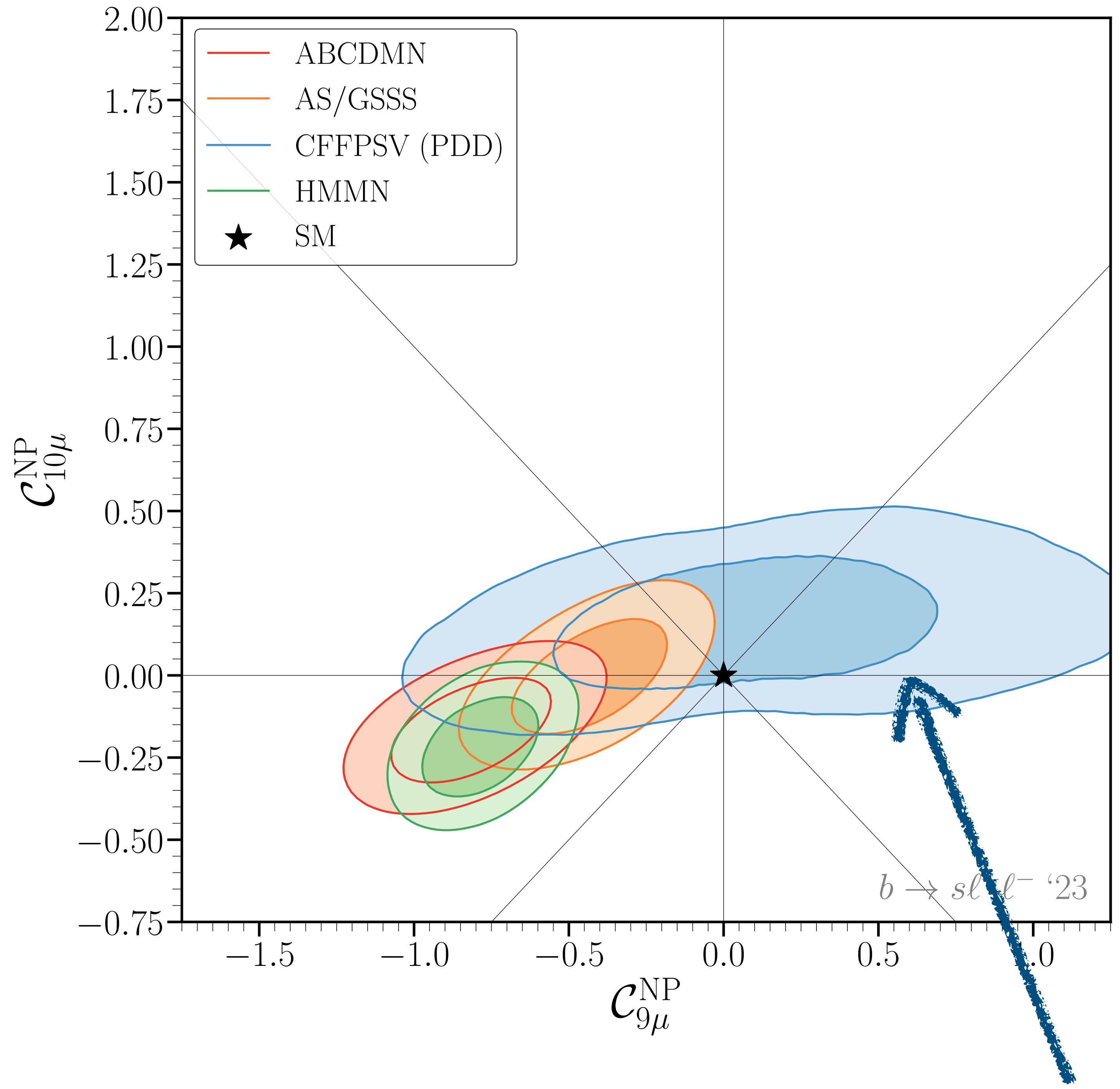
$$\sum_{n=0}^{\infty} \left\{ 2\left|a_{0,n}^{B\to K}\right|^2 + \sum_{\lambda=\perp,\parallel,0} \left[2\left|a_{\lambda,n}^{B\to K^*}\right|^2 + \left|a_{\lambda,n}^{B_s\to\phi}\right|^2 \right] \right\} < 1$$

Global fits to $b \to s\ell\ell$ observables

- Many global fits produced in the literature
  - suggest a flavour universal shift in C9

arXiv:2309.01311





JHEP 09 (2022) 133
JHEP 05 (2023) 087
EPJ C83 (2023) 648
PRD 107 (2023) 055036
arXiv:2310.05585

- global fits from different groups use sub-sets of inputs, different statistical tools/theory assumptions, etc...
- constant long-distance QCD allowed

What about LFU?

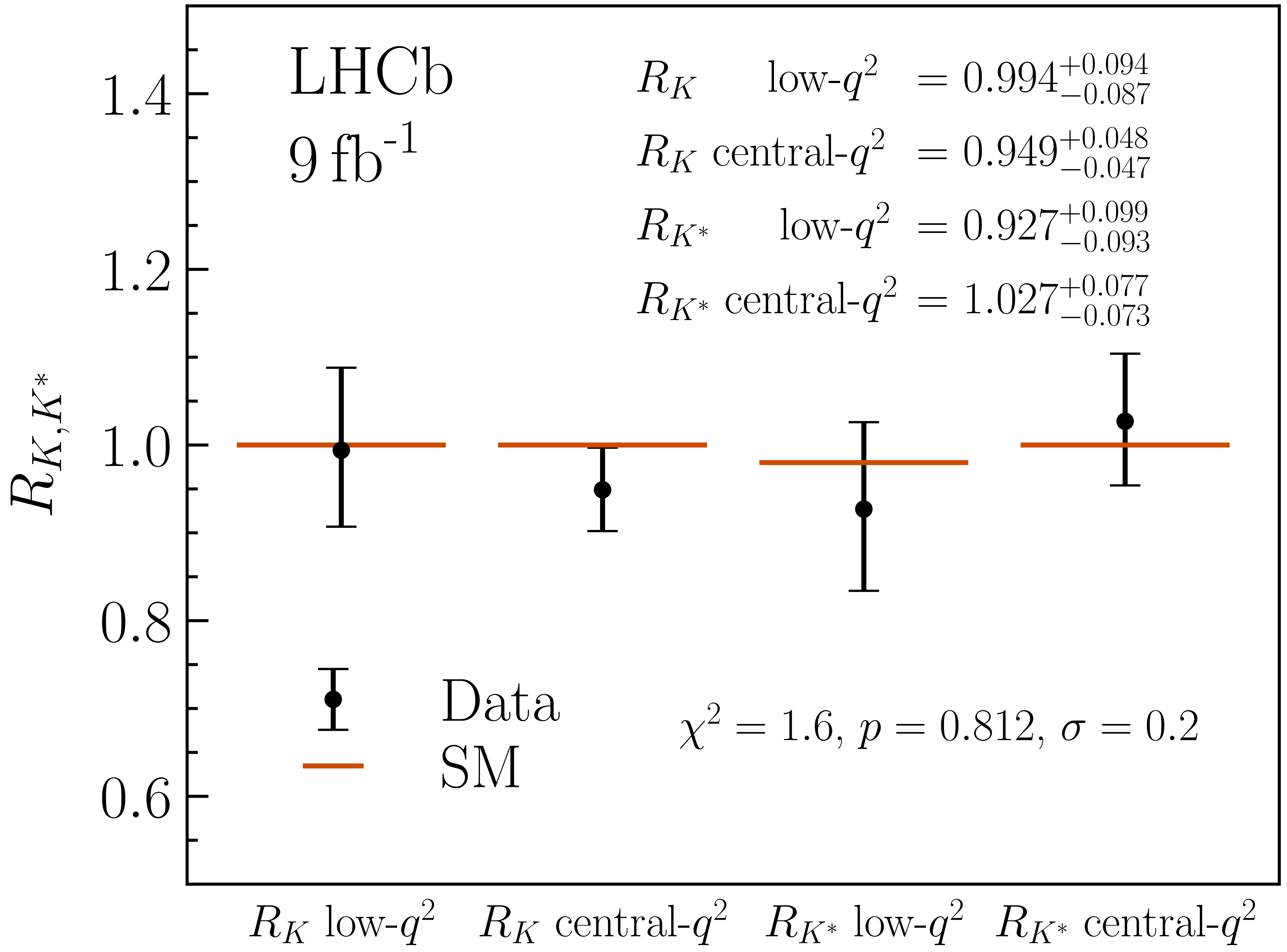
- Measuring ratios of branching fraction between $b \to s\mu^+\mu^-$ and $b \to se^+e^-$

$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to se^+e^-)}$$

  - hadronic uncertainties cancels at $\mathcal{O}(10^{-4})$
  - QED correction at $\mathcal{O}(10^{-2})$

- Latest LHCb results from December 2022
  - Compatible with SM within 5%

PRL 131 (2023) 051803
PRD 108 (2023) 032002



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