Measurements of $B^0 \to K^{*0}\mu^+\mu^-$ and $C_{9,\tau}$ at LHCb

Quirks in Quark Flavour, June 2024

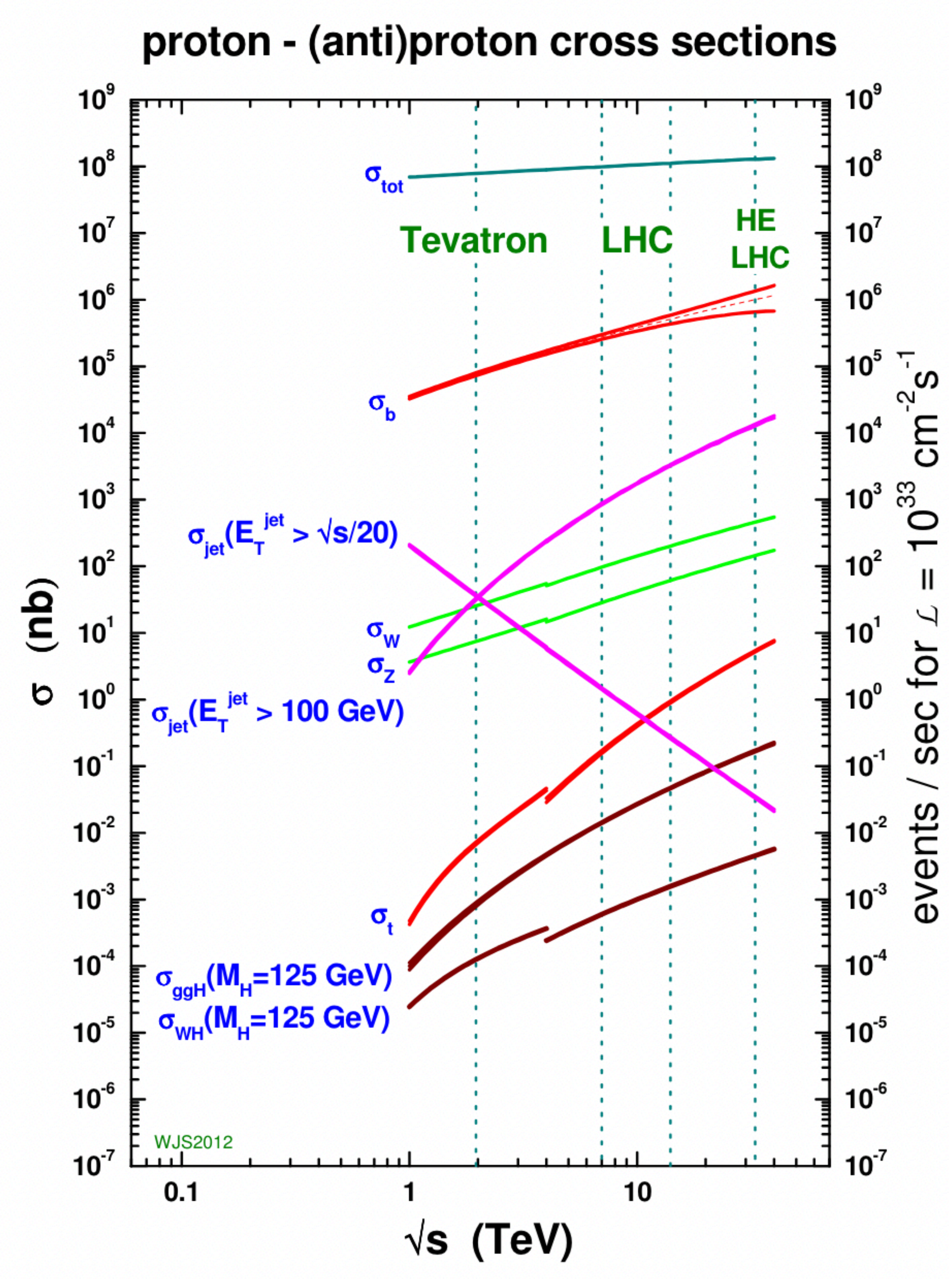
Eluned Smith

eluned@mit.edu

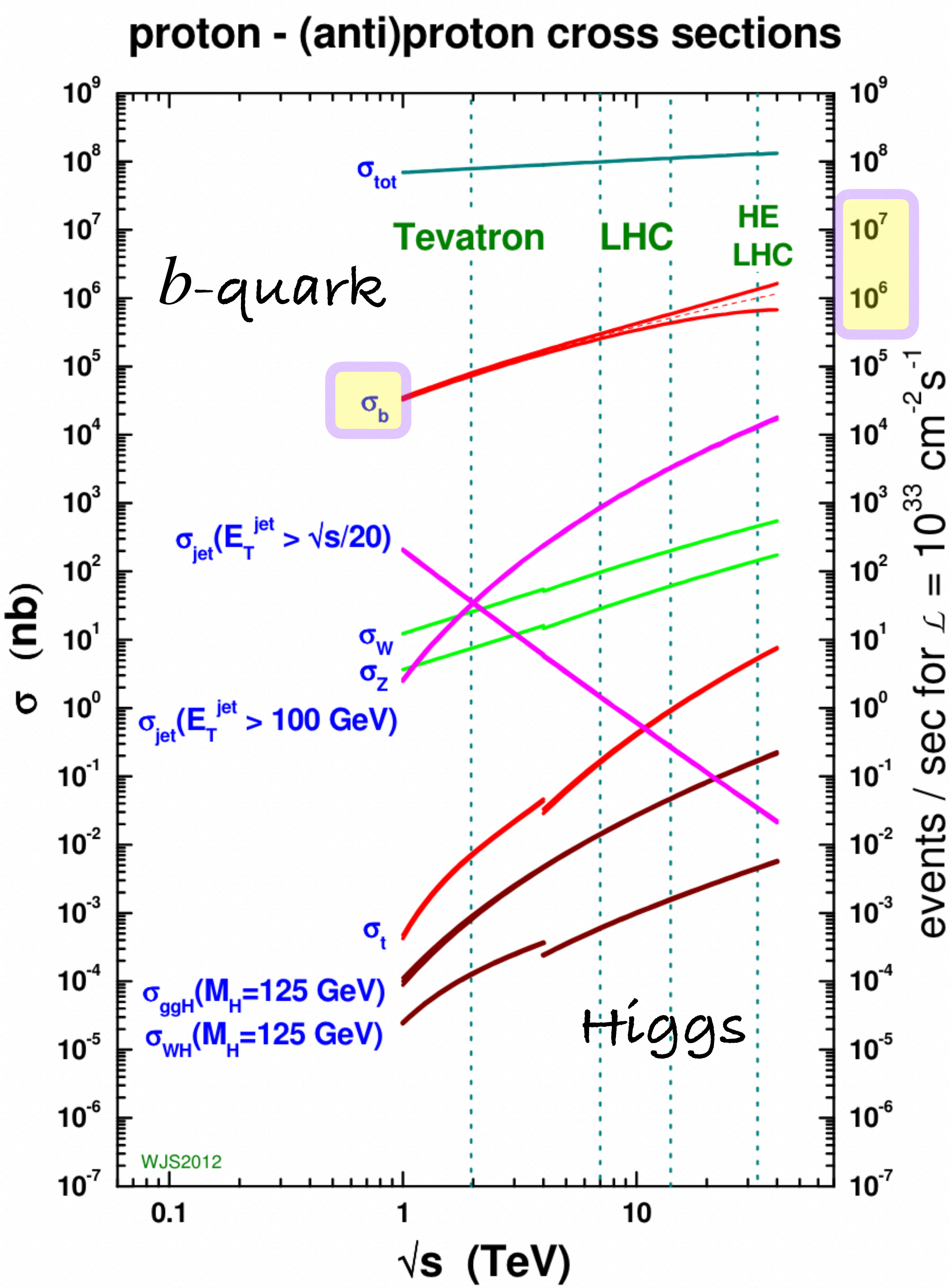
On behalf of LHCb

Massachusetts Institute of Technology

b-quarks at the LHC



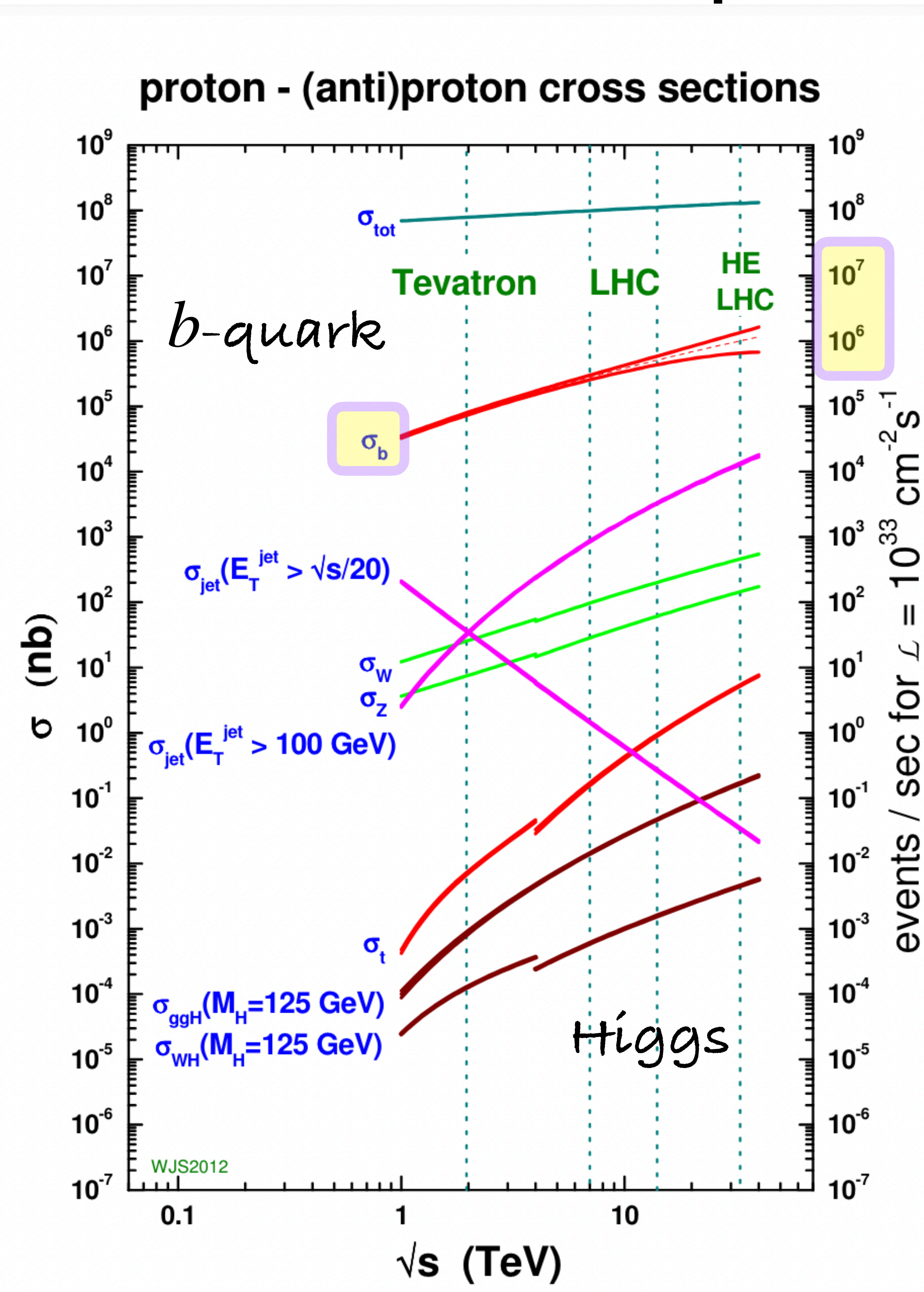
b-quarks at the LHC



We have a lot…

- Cross-section $\mathcal{O}(100)\,\mu b$
- Millions of $b\bar{b}$ pairs produced per second

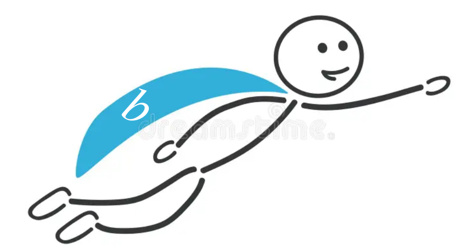
b-quarks at the LHC

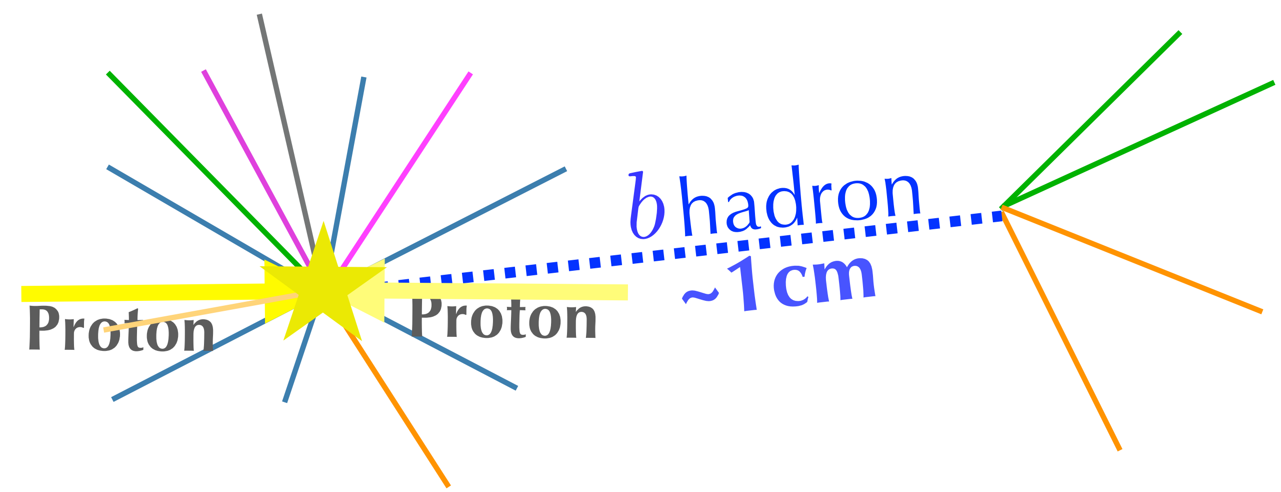


We have a lot…

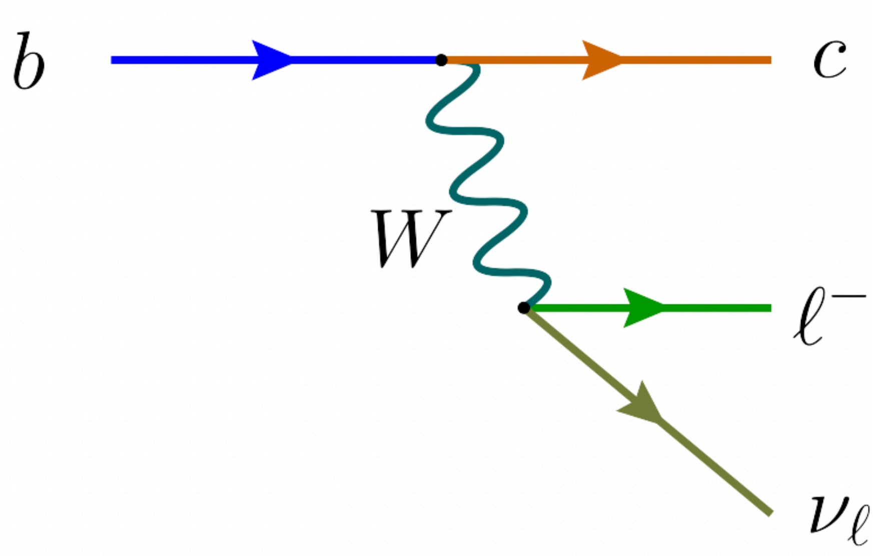
- Cross-section $\mathcal{O}(100)\,\mu b$
- Millions of $b\bar{b}$ pairs produced per second

And they fly…

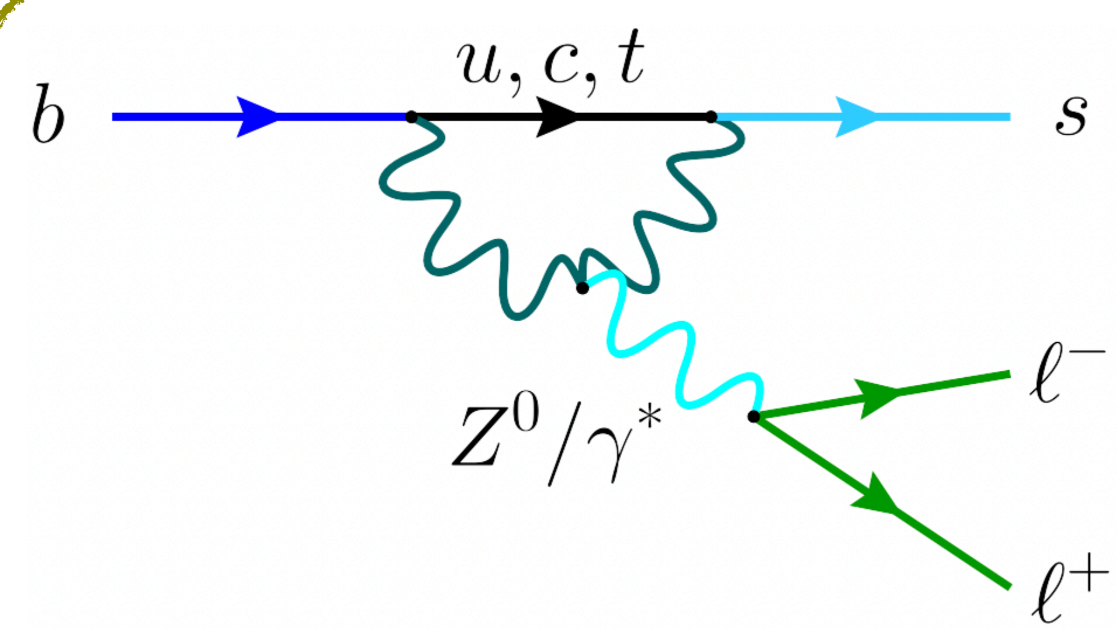




The B-anomalies



Charged current $\sim 3\sigma$

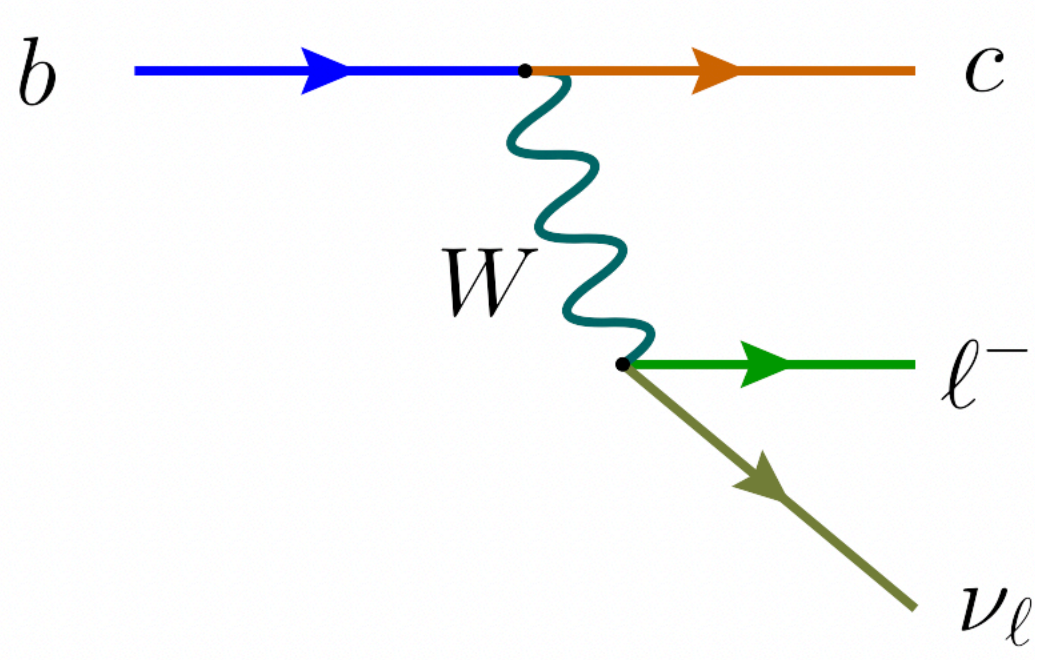


Neutral current $\sim 4 - 5\sigma$

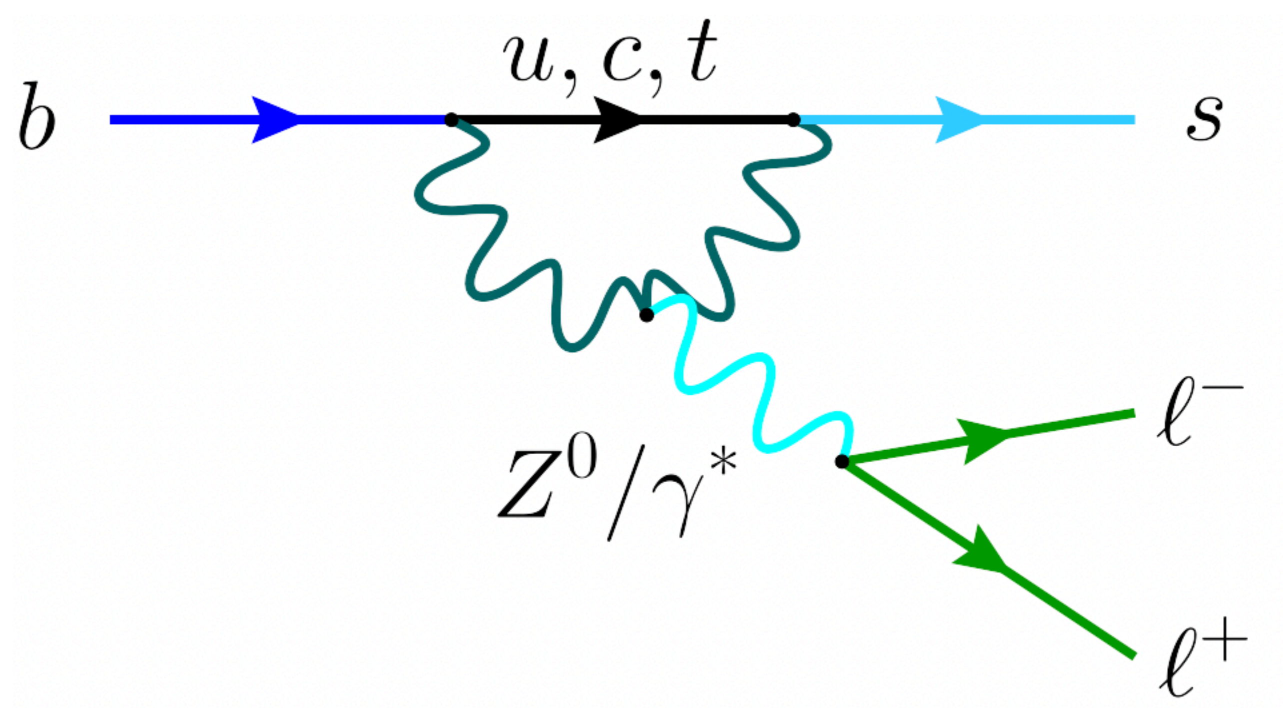
The B-anomalies

$b \to c\ell\nu$

$b \to s\ell\ell$



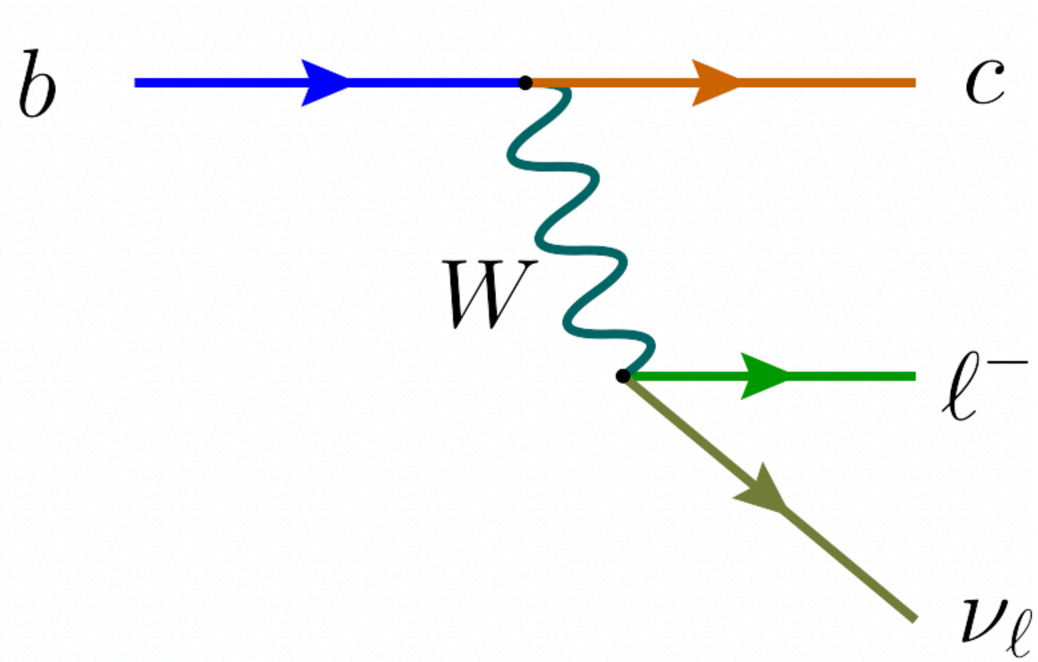
Charged current:



Neutral current:

The B-anomalies

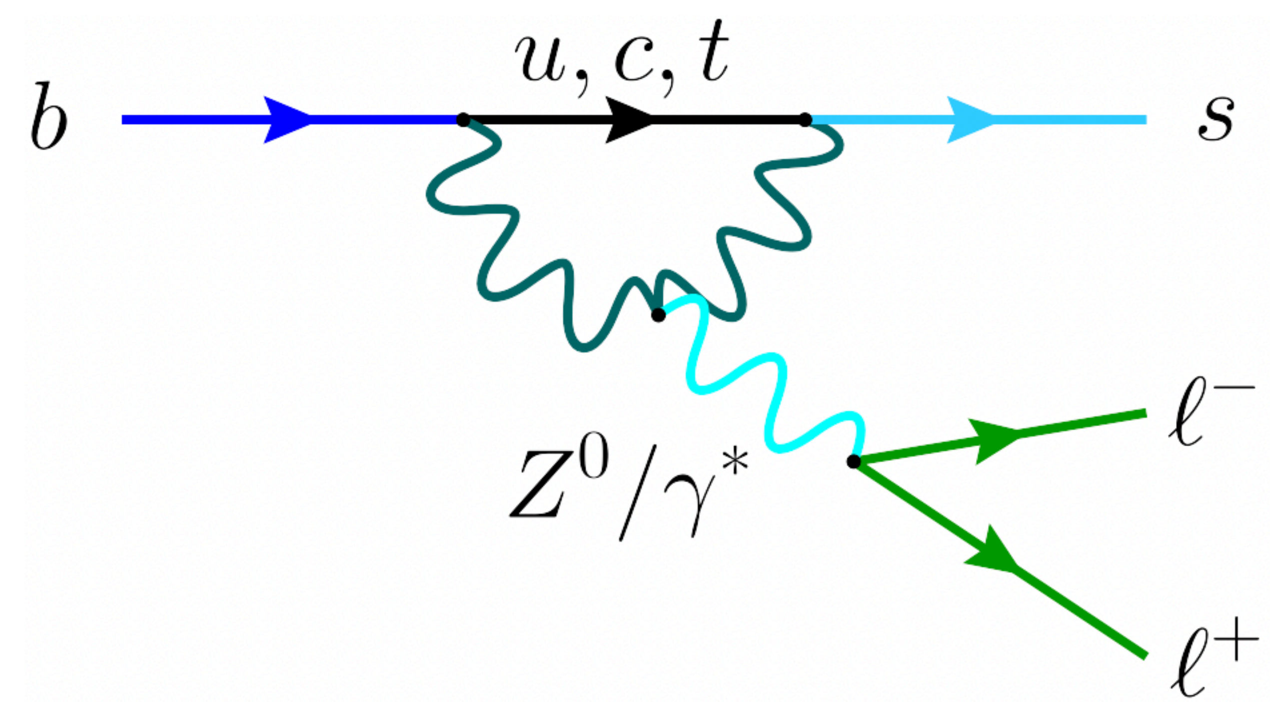
$b \to c\ell\nu$



Charged current:

- Tree-level
  - $\mathscr{B}$ order %
- Neutrino in final state (invisible)

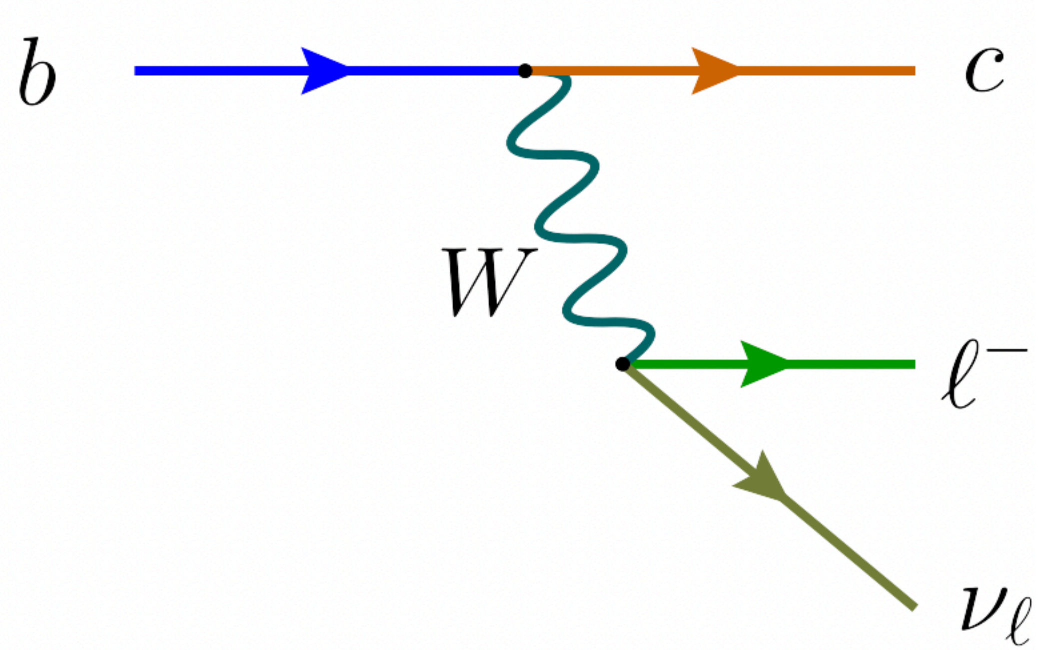
$b \to s\ell\ell$

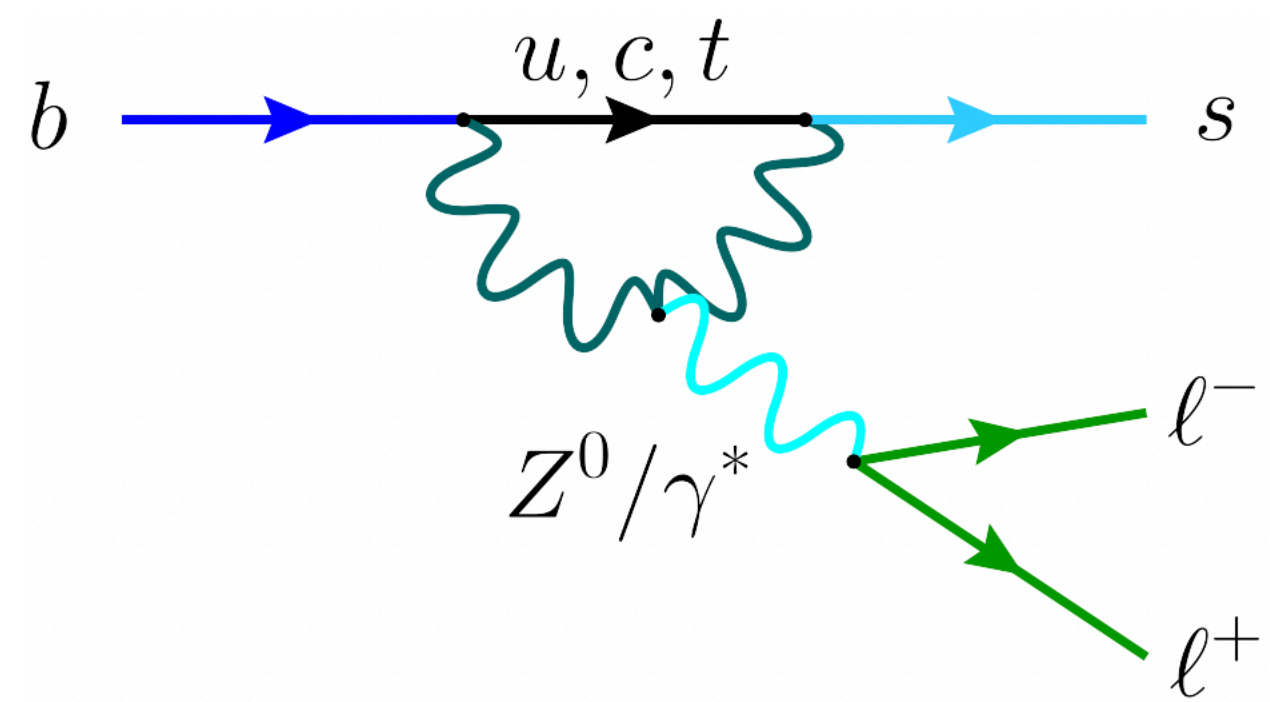


Neutral current:

The B-anomalies

$b \to c\ell\nu$ $b \to s\ell\ell$





Charged current:

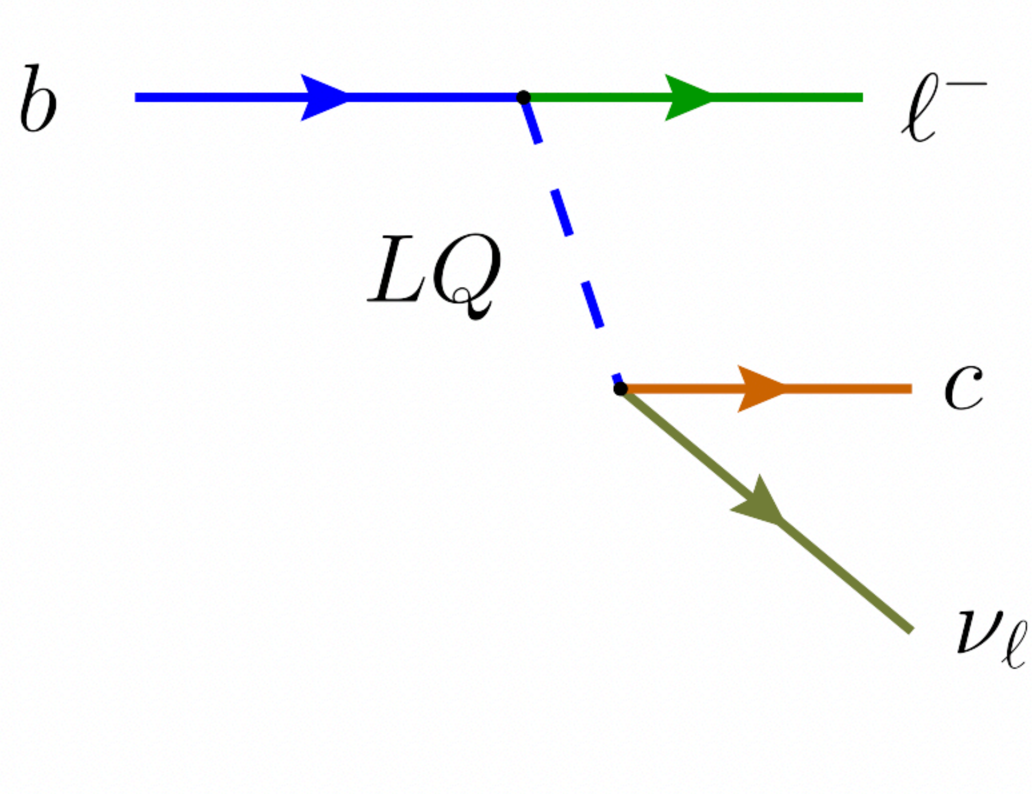
- Tree-level
  - $\mathscr{B}$ order %
- Neutrino in final state (invisible)

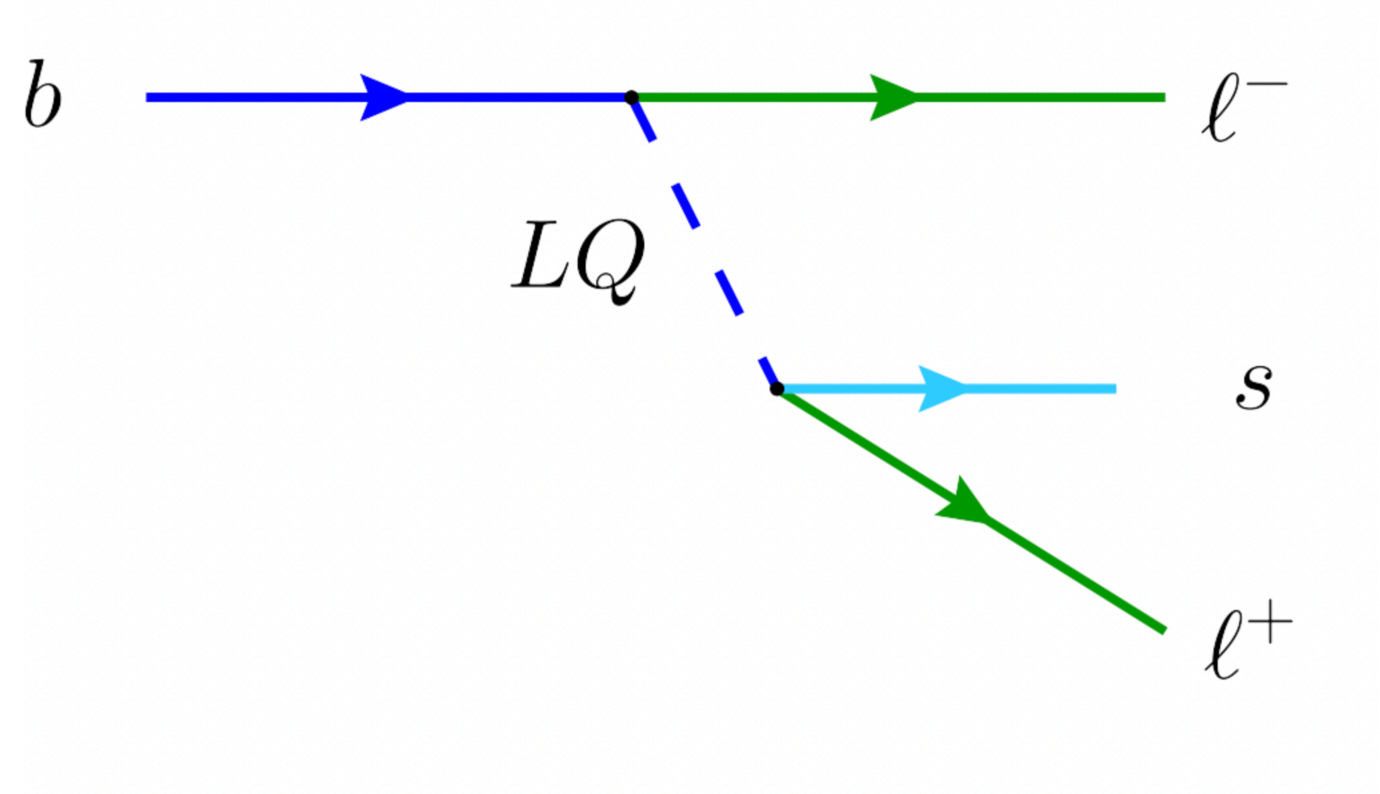
Neutral current:

- Loop-suppressed:
  - $\mathscr{B}$ order $10^{-7} - 10^{-9}$
- Full reconstructed final state

The B-anomalies

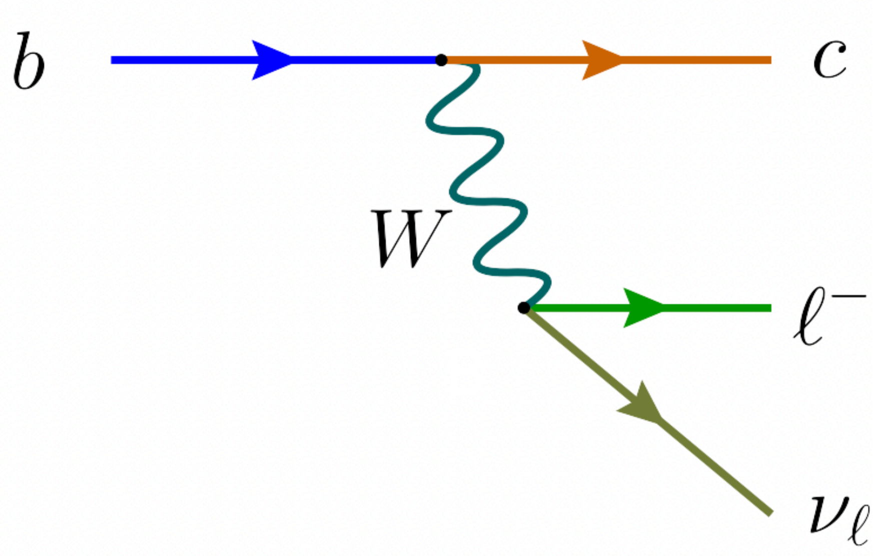
$b \to c\ell\nu$ $b \to s\ell\ell$



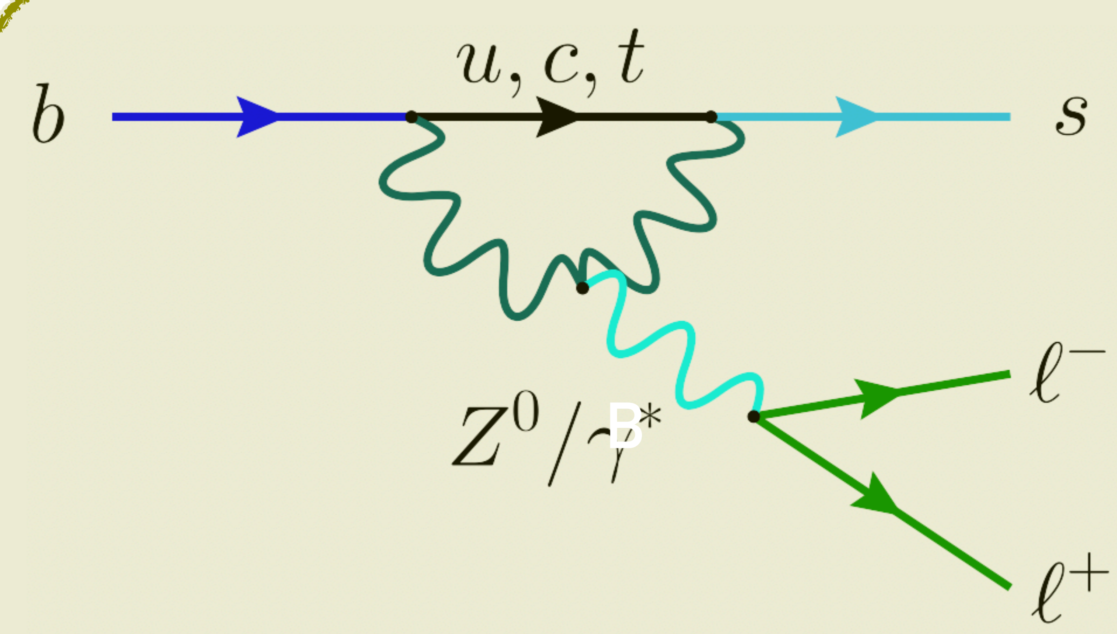


Could be joint explanation…motivates $b \to s\tau\tau$ measurements

The B-anomalies

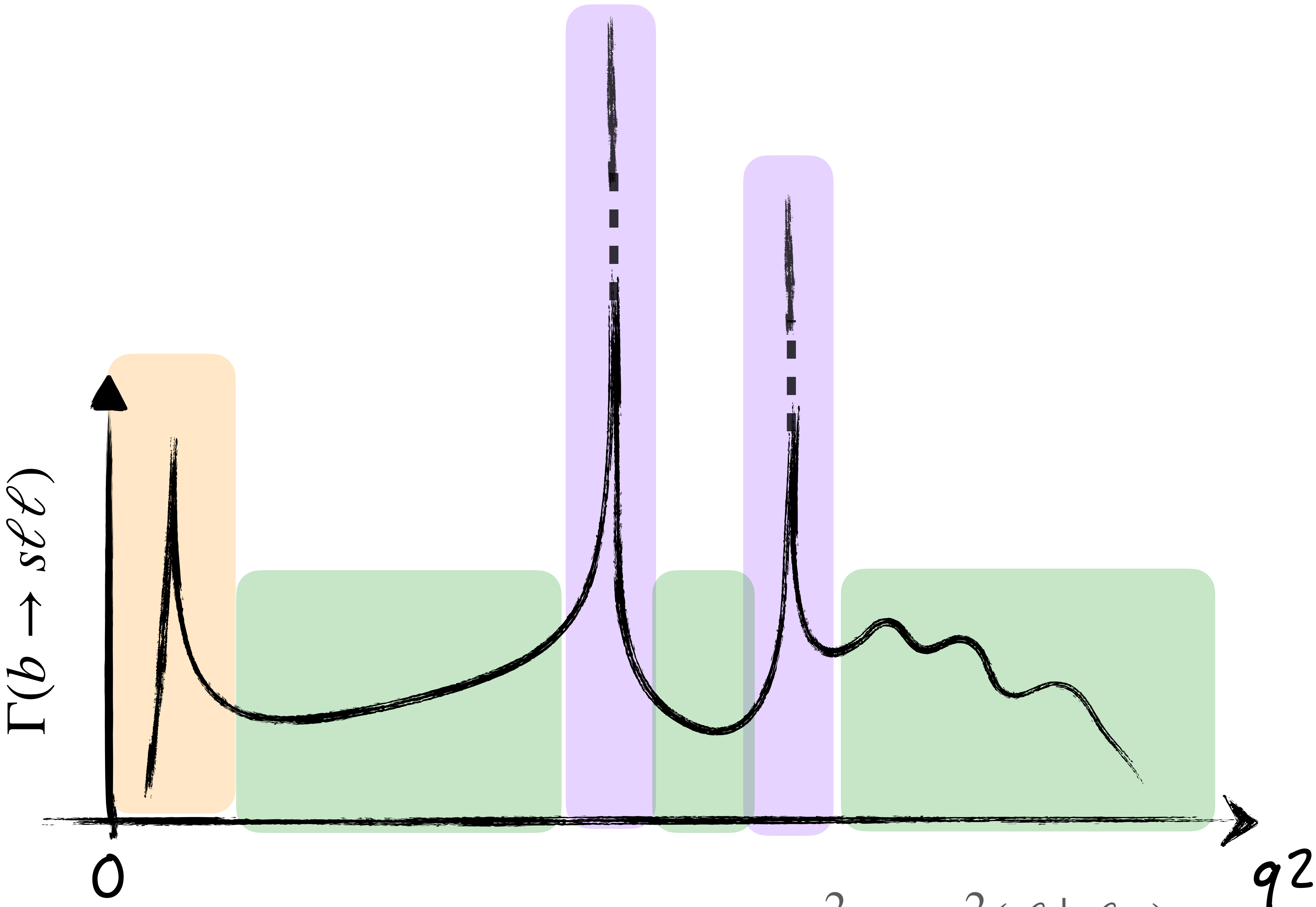


Charged current $\sim 3\sigma$



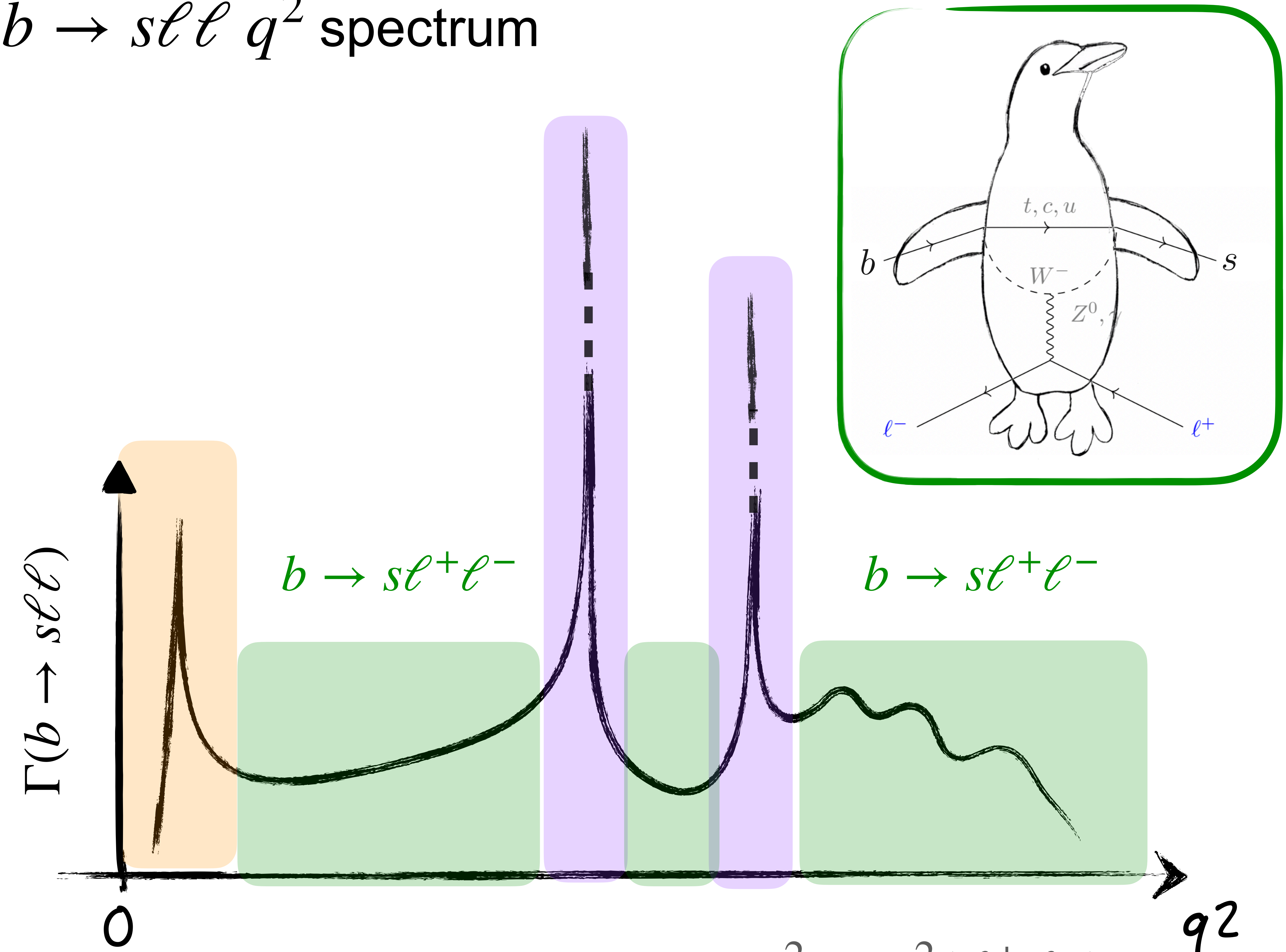
Neutral current $\sim 4-5\sigma$

The $b \to s\ell\ell$ q^2 spectrum



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

The $b \to s\ell\ell$ q^2 spectrum



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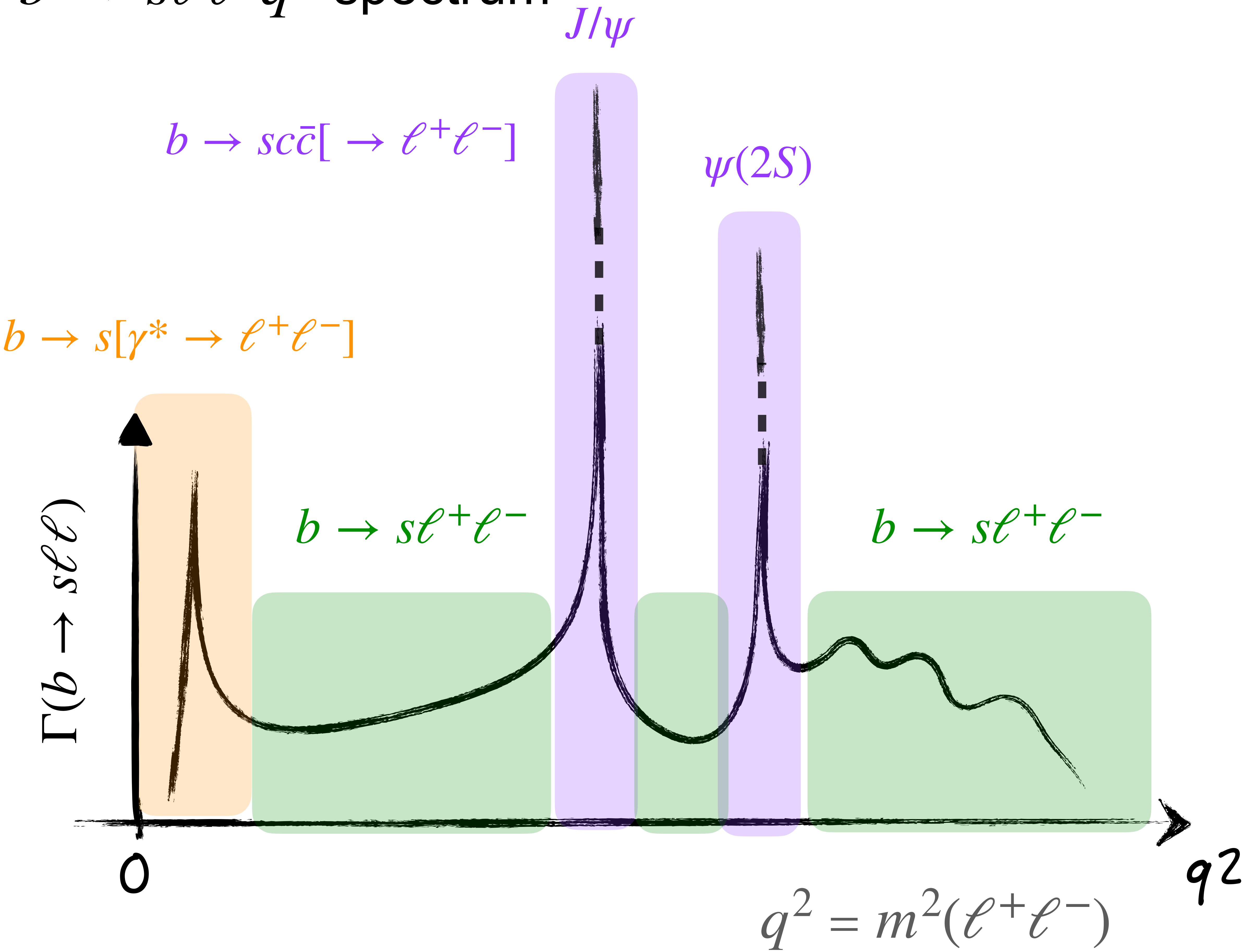
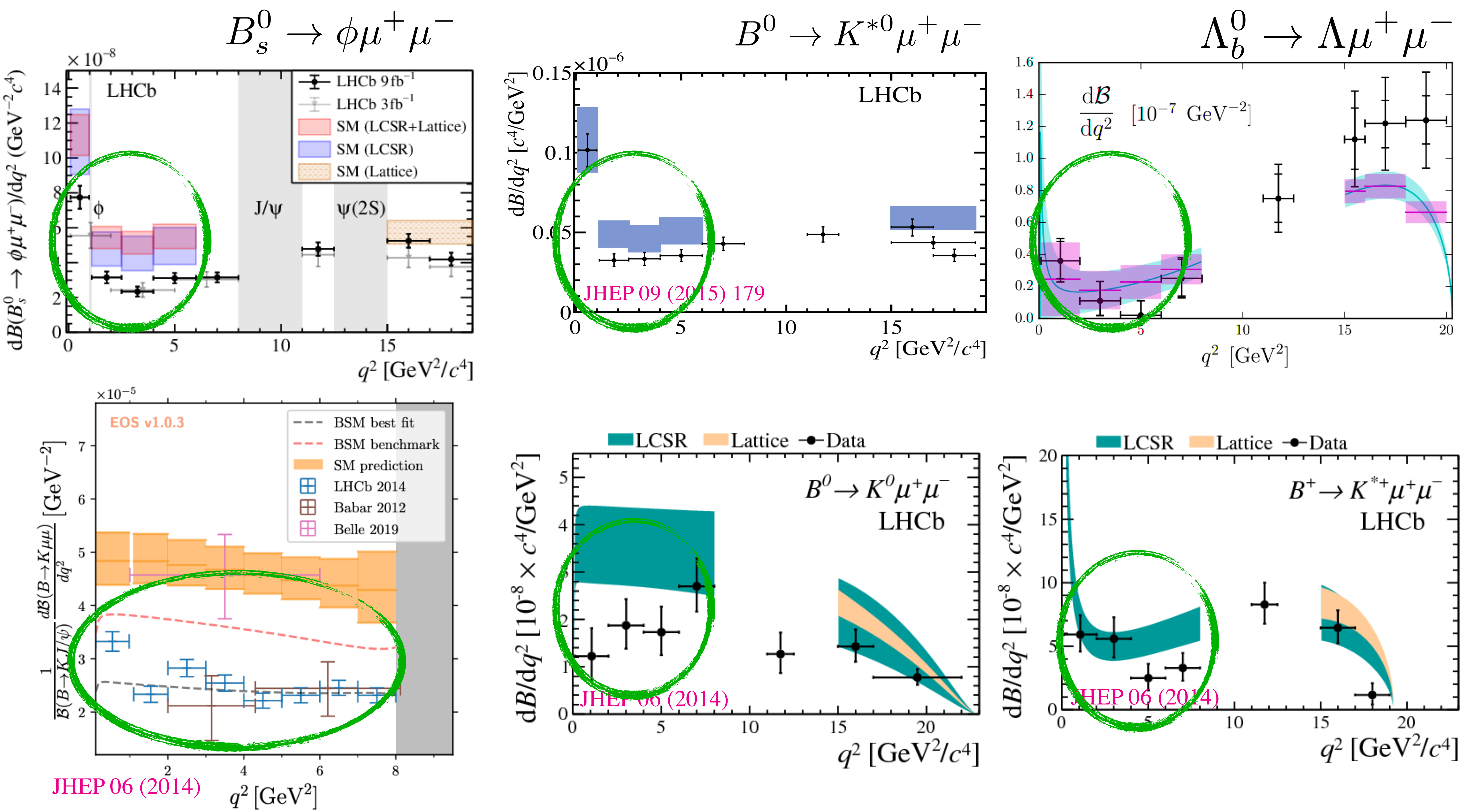
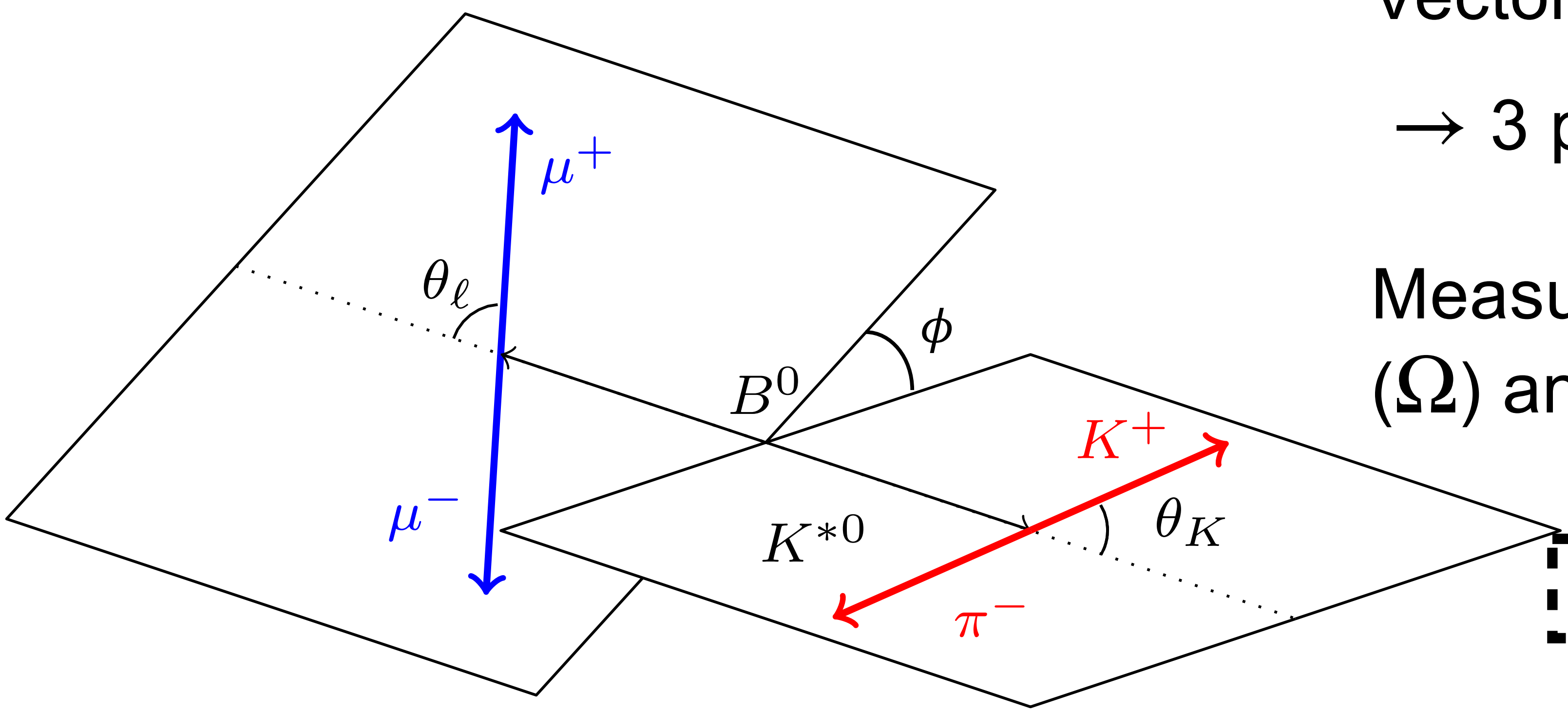


Branching fractions



Same pattern, decay rate too low!!

Angular analysis of $B \to V(\to h^+h^-)\mu^+\mu^-$



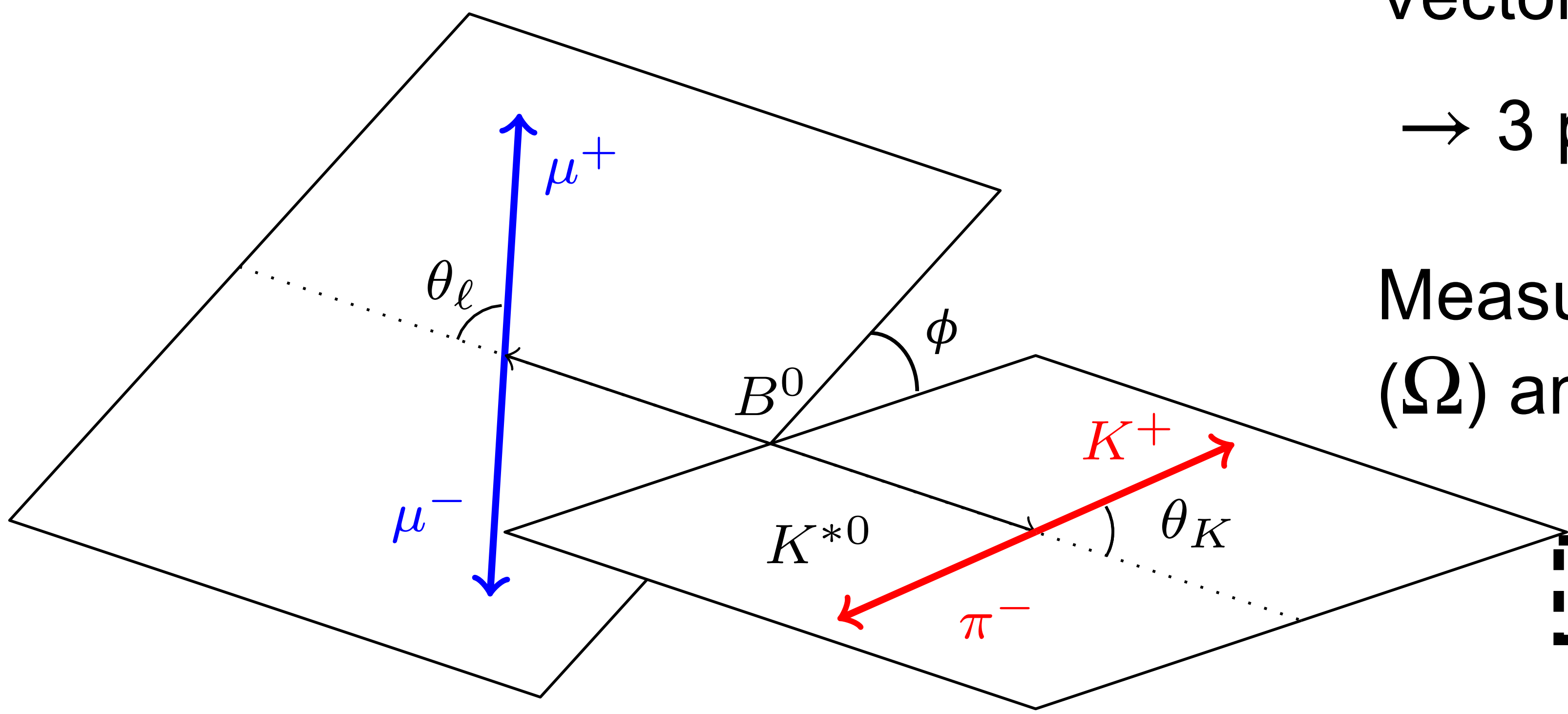
Vector = spin 1 = P-wave

→ 3 polarisation amplitudes

Measure decay rate across 3 angles (Ω) and q^2

"Traditionally" perform in bins of q^2

Angular analysis of $B \to V(\to h^+h^-)\mu^+\mu^-$



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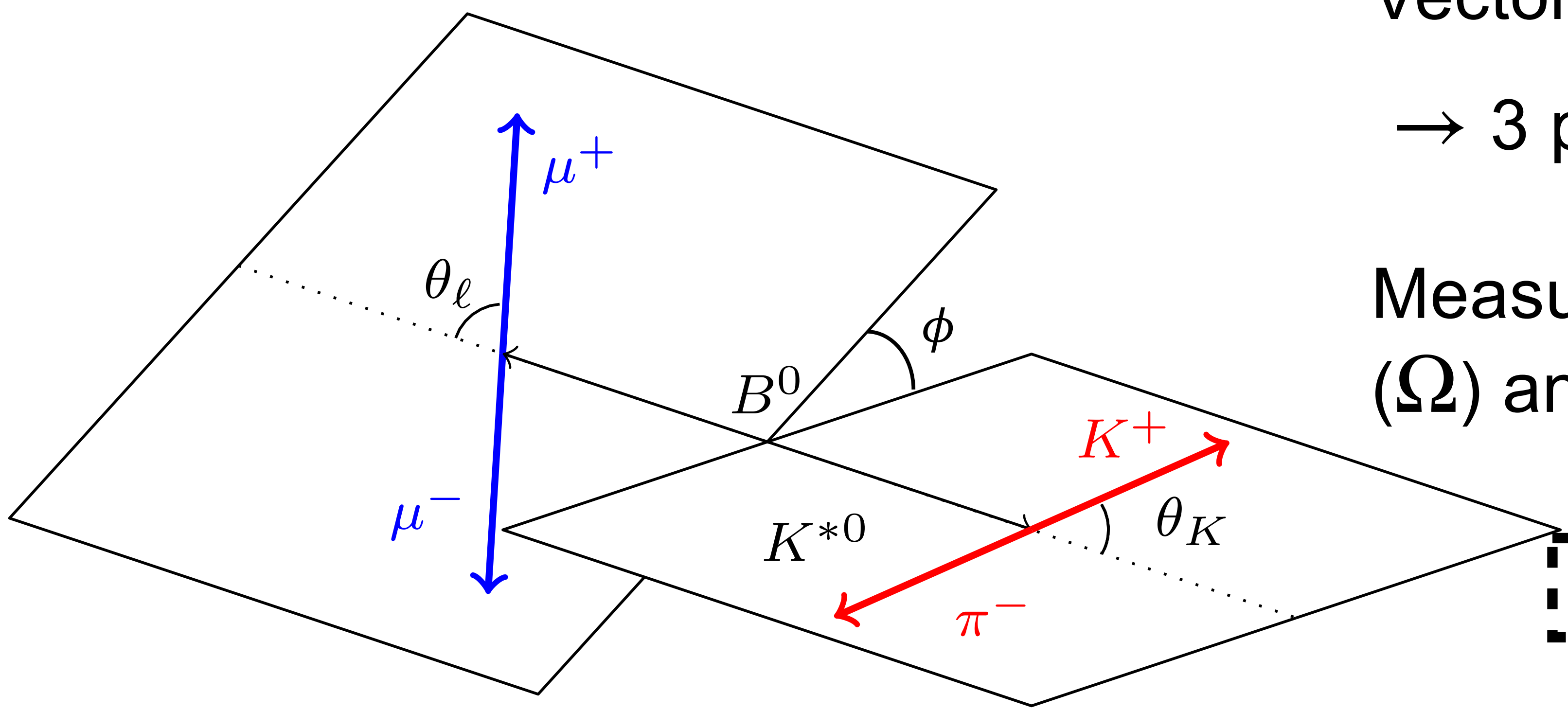
angular coefficients - function of amplitudes

$$\frac{\mathrm{d}^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{d}\hat{\Omega}\mathrm{d}q^2} = \sum_i I_i(q^2) f_i(\Omega)$$

Spherical harmonics

Angular analysis of $B \to V(\to h^+h^-)\mu^+\mu^-$



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Spherical harmonics

CP-averaged + averaged over q^2 = S_i or P'_i

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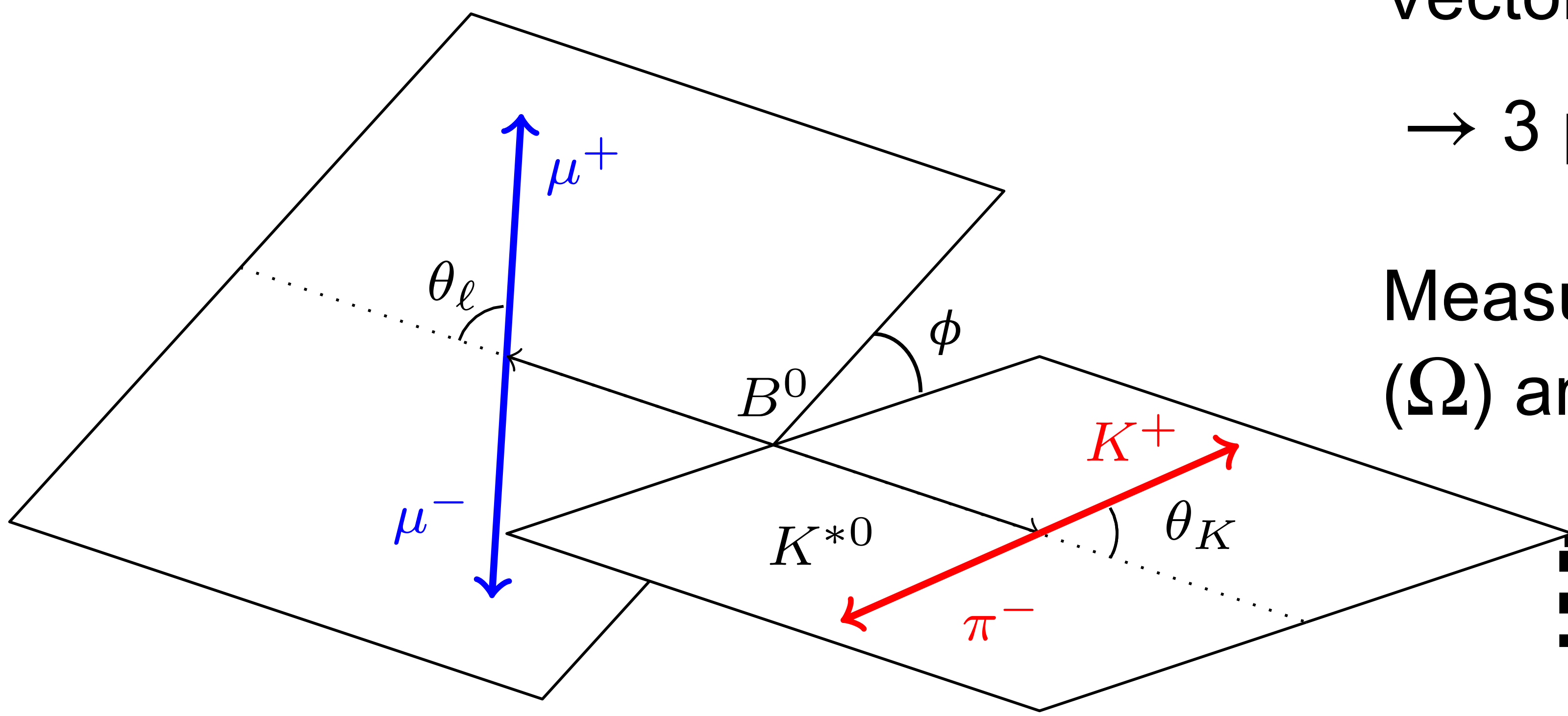

Vector = spin 1 = P-wave

$\to$ 3 polarisation amplitudes

Measure decay rate across 3 angles (Ω) and q^2

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angular coefficients - function of amplitudes

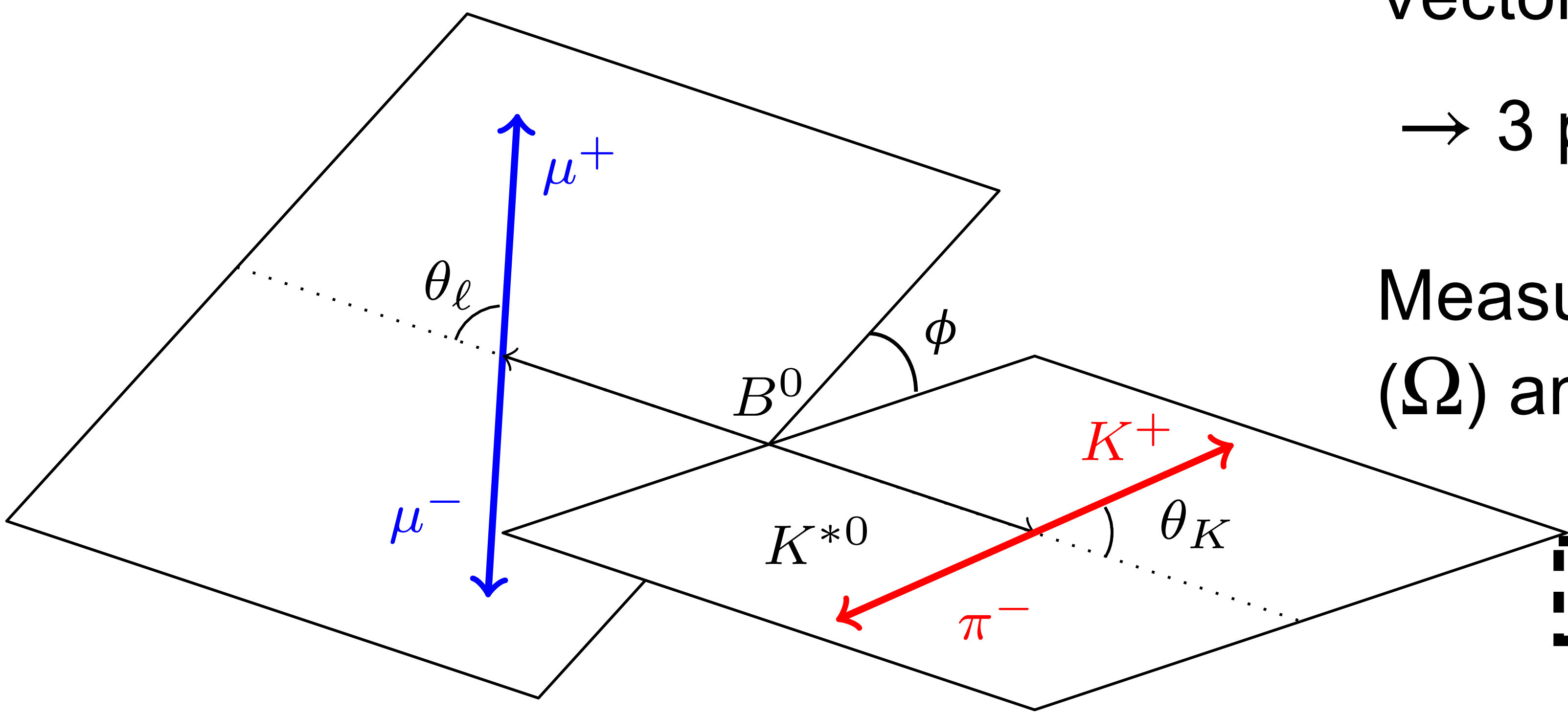
$$\frac{d^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{d\hat{\Omega}dq^2} = \sum_i I_i(q^2) f_i(\Omega)$$

Spherical harmonics

CP-averaged + averaged over q^2 = S_i or P'_i

S_i divided by either $\propto |A_0|^2$ or $|A_T|^2$ to reduce uncert.

Angular analysis of $B \to V(\to h^+h^-)\mu^+\mu^-$

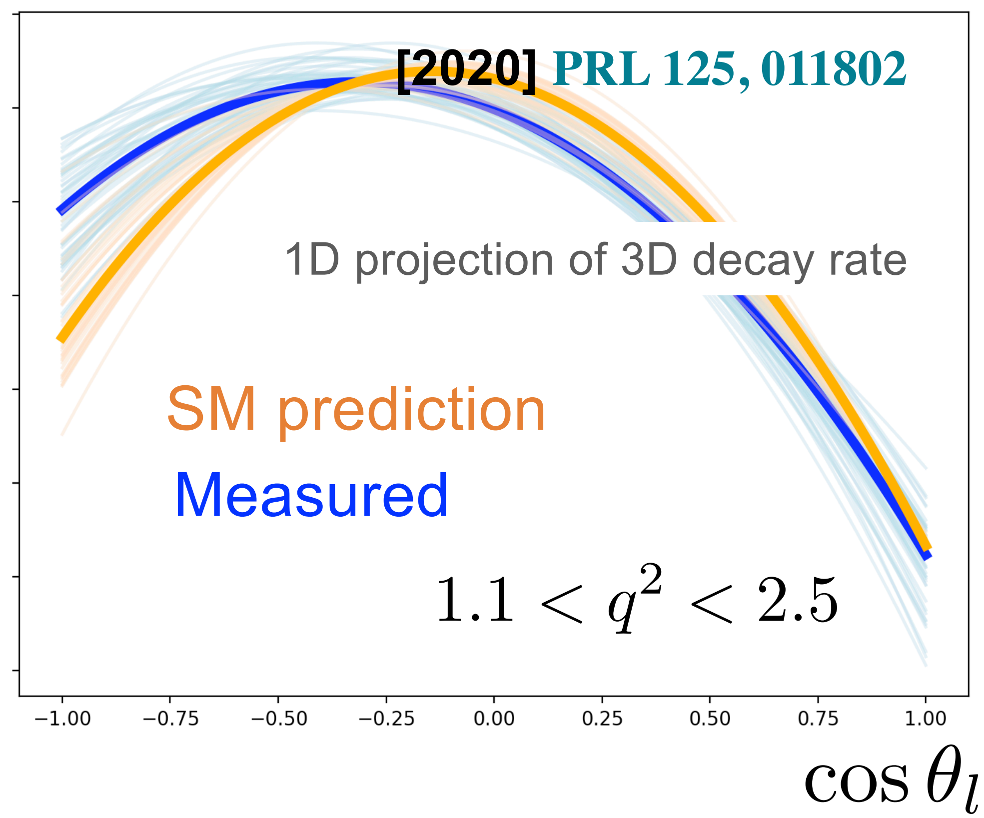


Vector = spin 1 = P-wave

$\to$ 3 polarisation amplitudes

Measure decay rate across 3 angles (Ω) and q^2

"Traditionally" perform in bins of q²



angular coefficients - function of amplitudes

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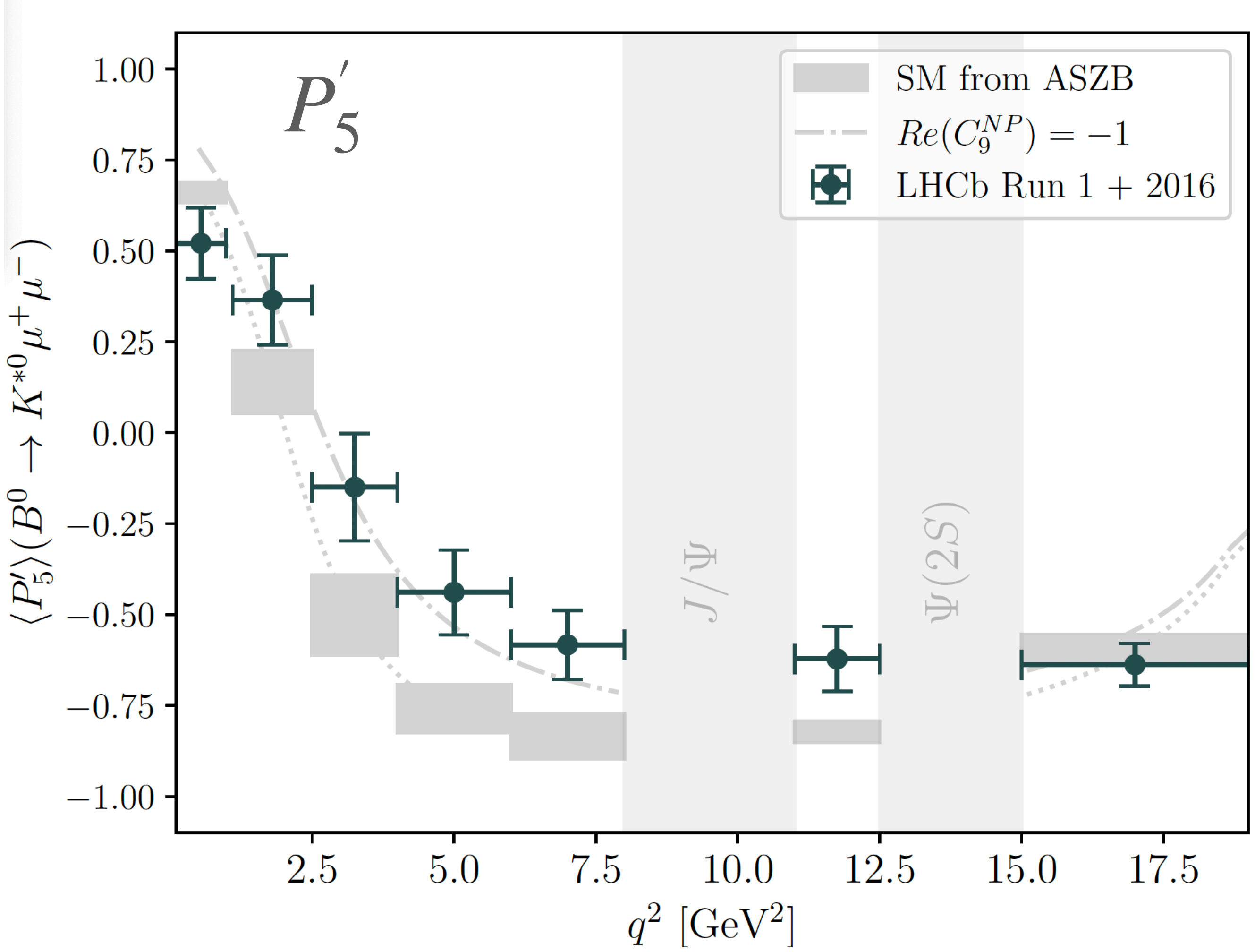
Spherical harmonics

Example: analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$

LHCb B0 PRL 125, 011802 (2020) . LHCb B+ PRL 161802 (2021) ATLAS: JHEP 10 (2018) 047

Belle: PRL 118 (2017), CMS:PLB 781 (2018) 517541



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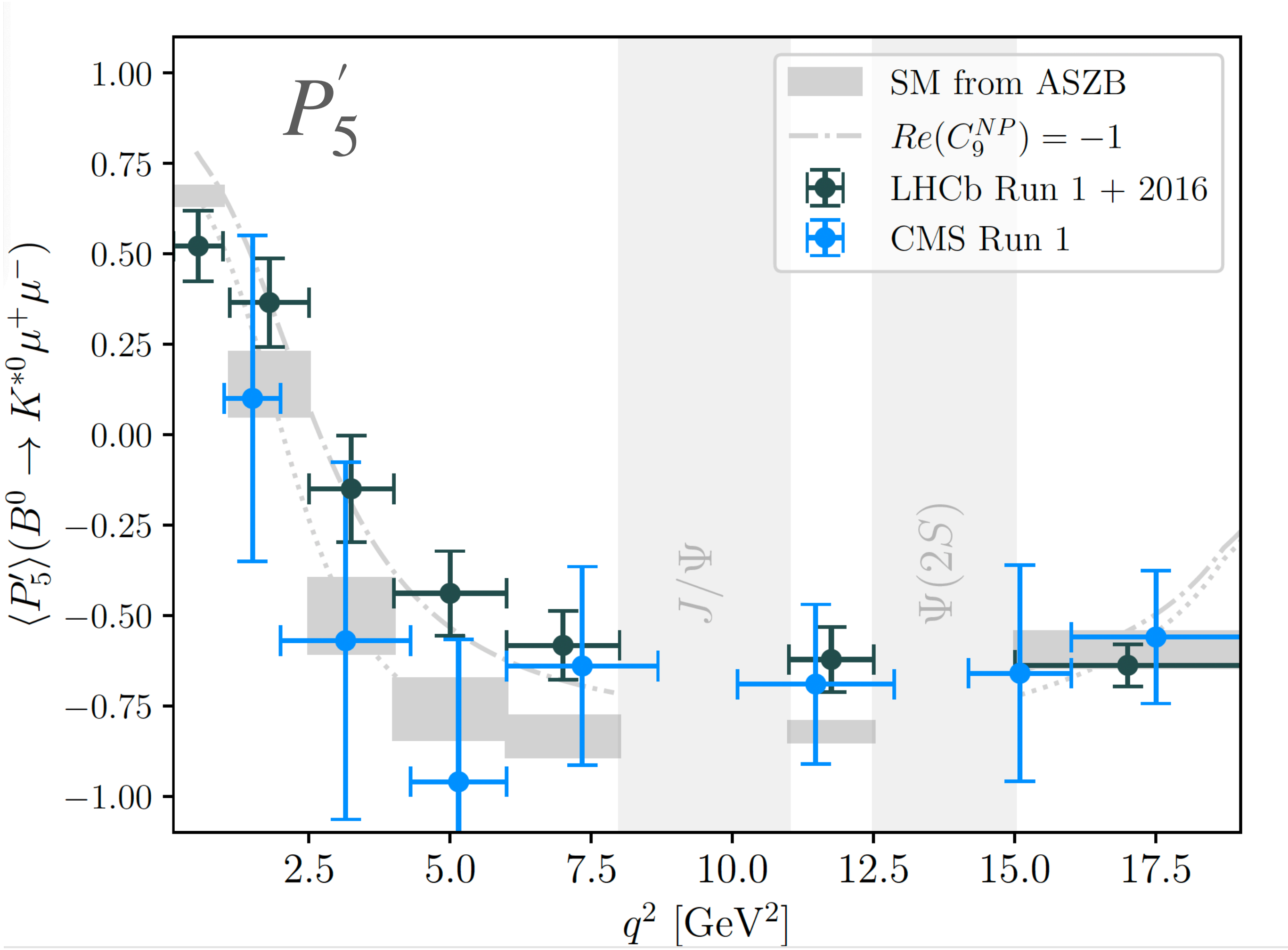

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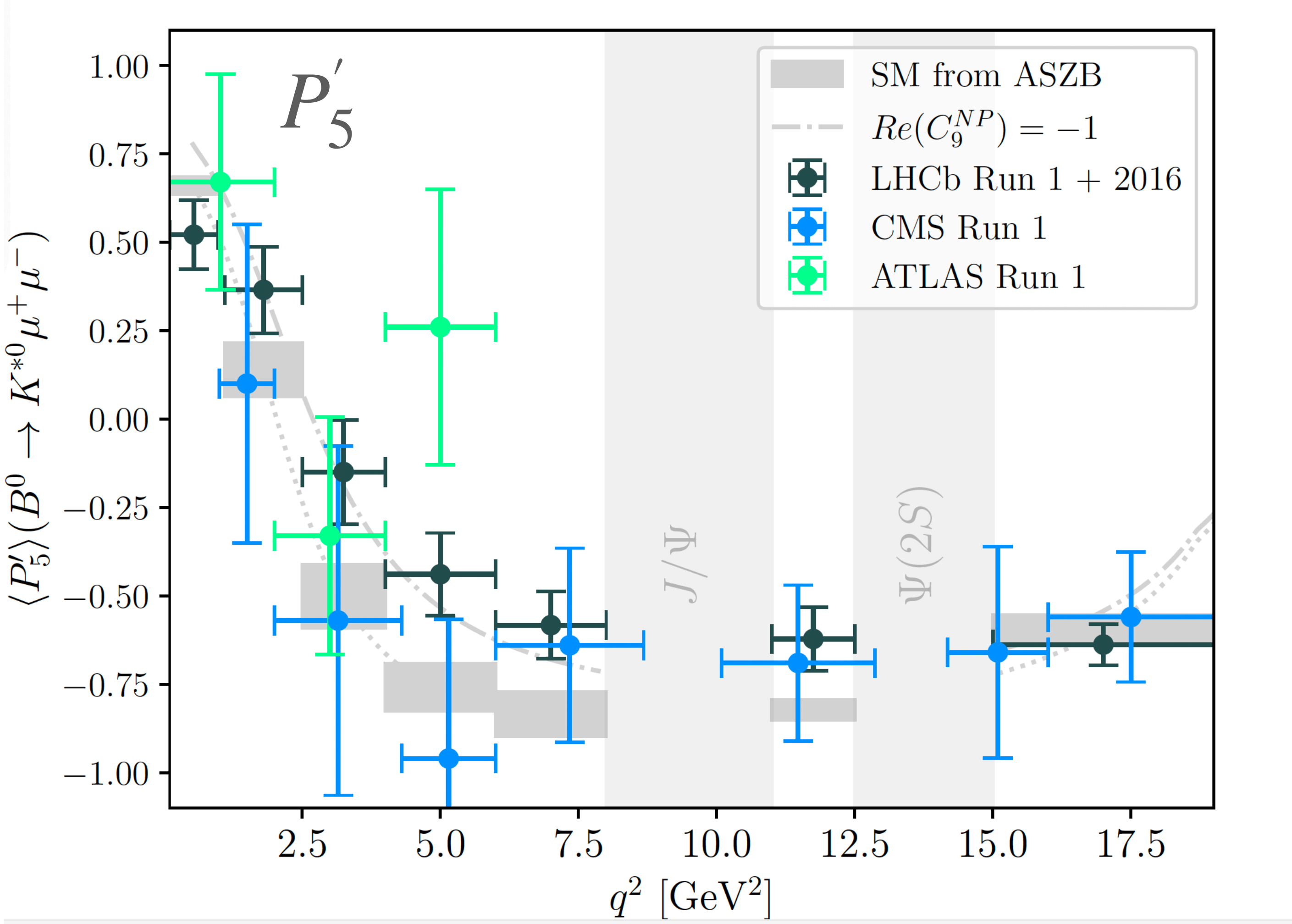

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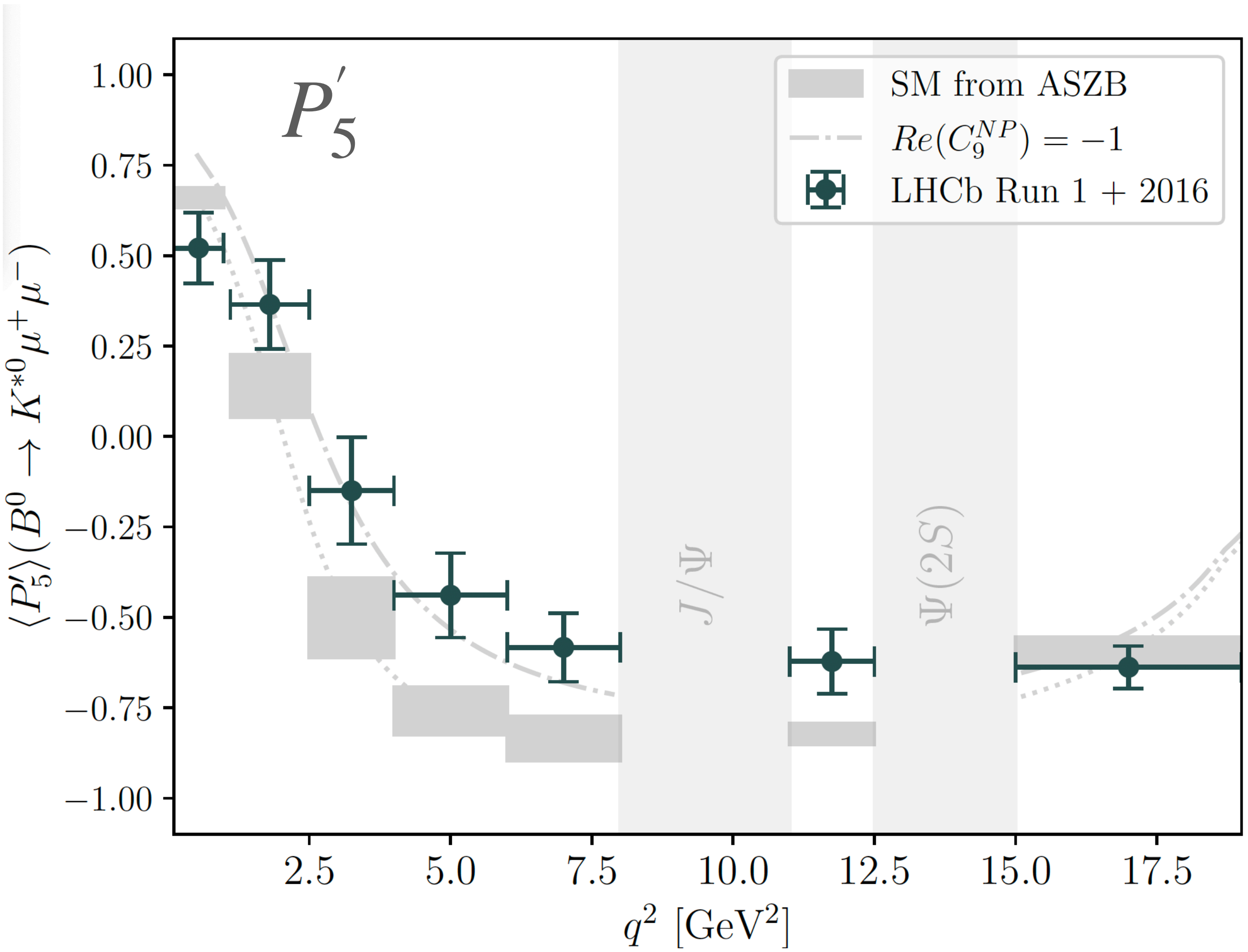

One angular observable of 8 (or 12) P-wave observables in total

$$
\begin{aligned}
\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\
&+ (\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l \\
&+ \frac{1}{2}P_1(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\
&+ \sqrt{(1-F_L)F_L}(\frac{1}{2}P_4'\sin 2\theta_K\sin 2\theta_l\cos\phi + P_5'\sin 2\theta_K\sin\theta_l\cos\phi) \\
&- \sqrt{(1-F_L)F_L}(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P_8'\sin 2\theta_K\sin 2\theta_l\sin\phi) \\
&+ 2P_2(1-F_L)\sin^2\theta_K\cos\theta_l - P_3(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]
\end{aligned}
$$

Example: analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$

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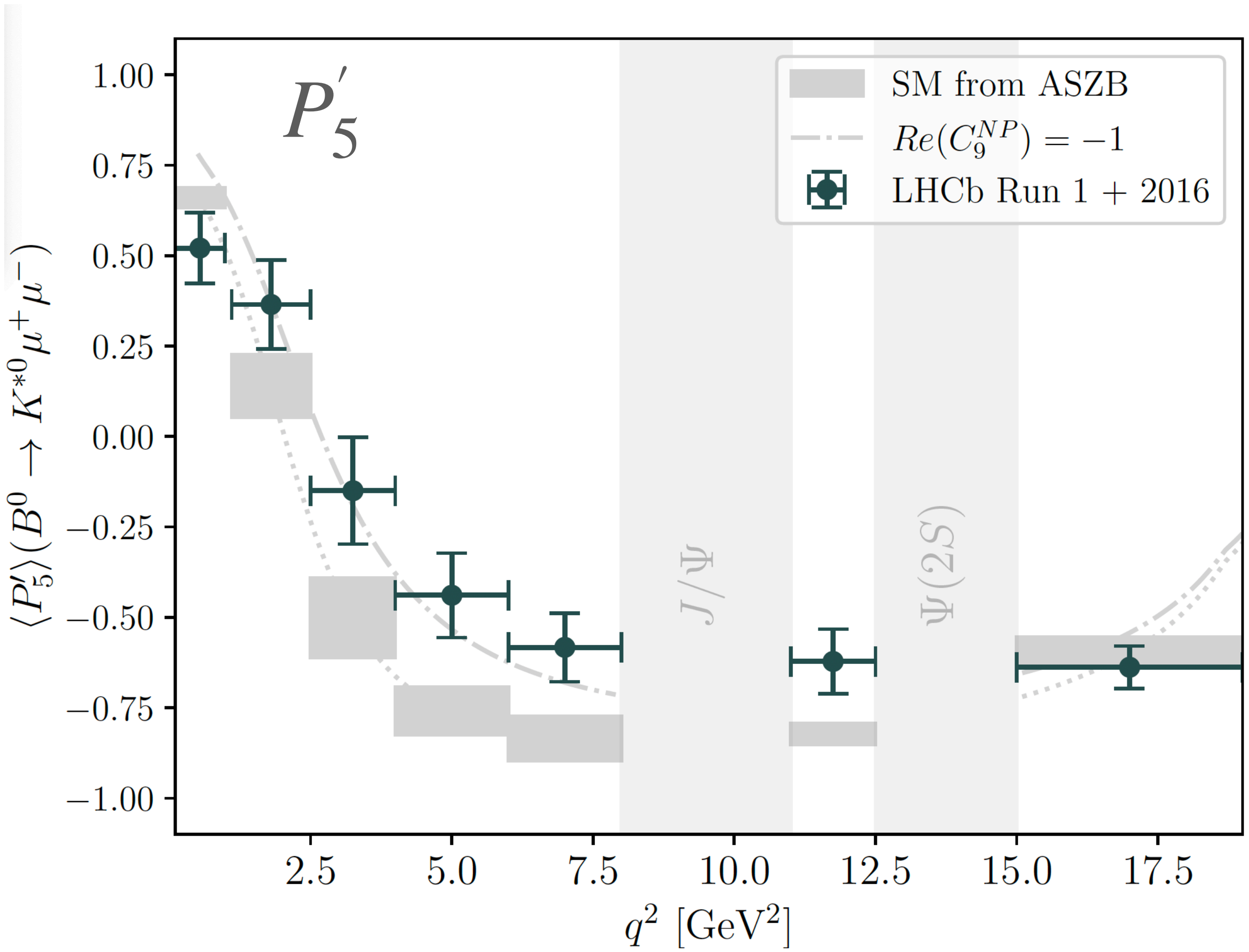
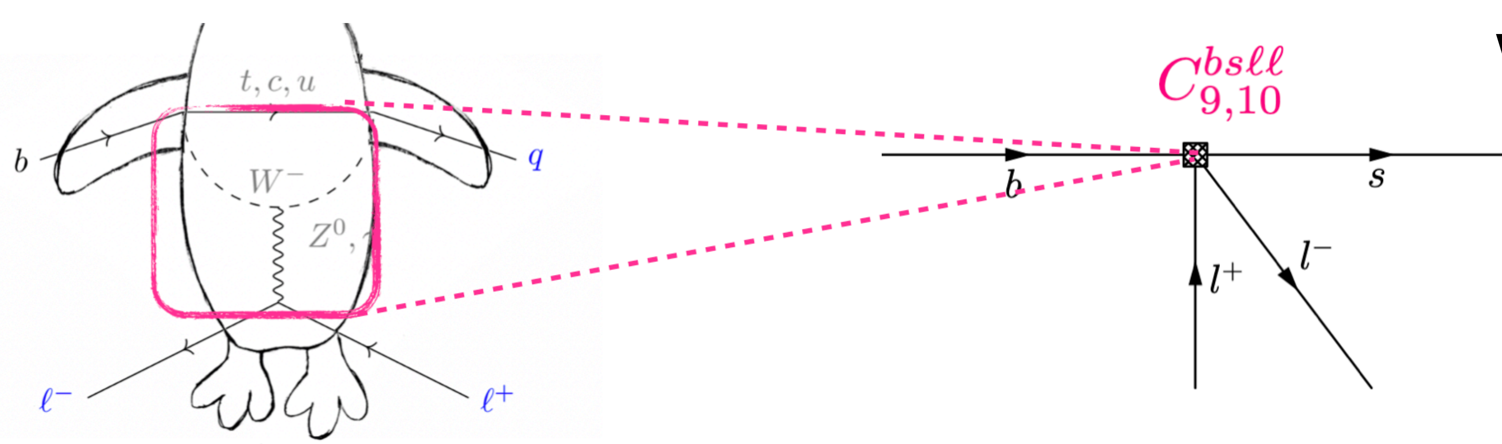
Global agreement with SM?



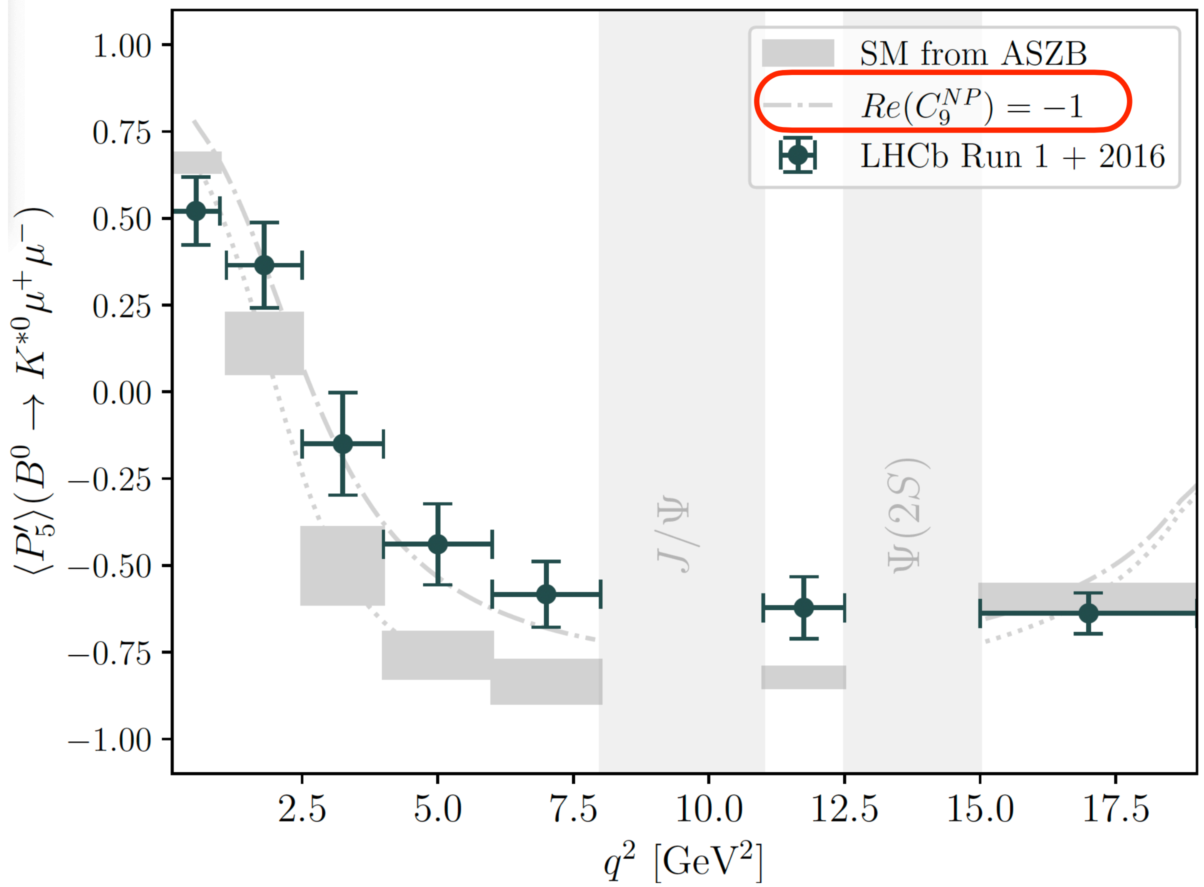
EW scale >> m_b, replace loop with effective couplings



C_9 = $bs\ell\ell$ vector current

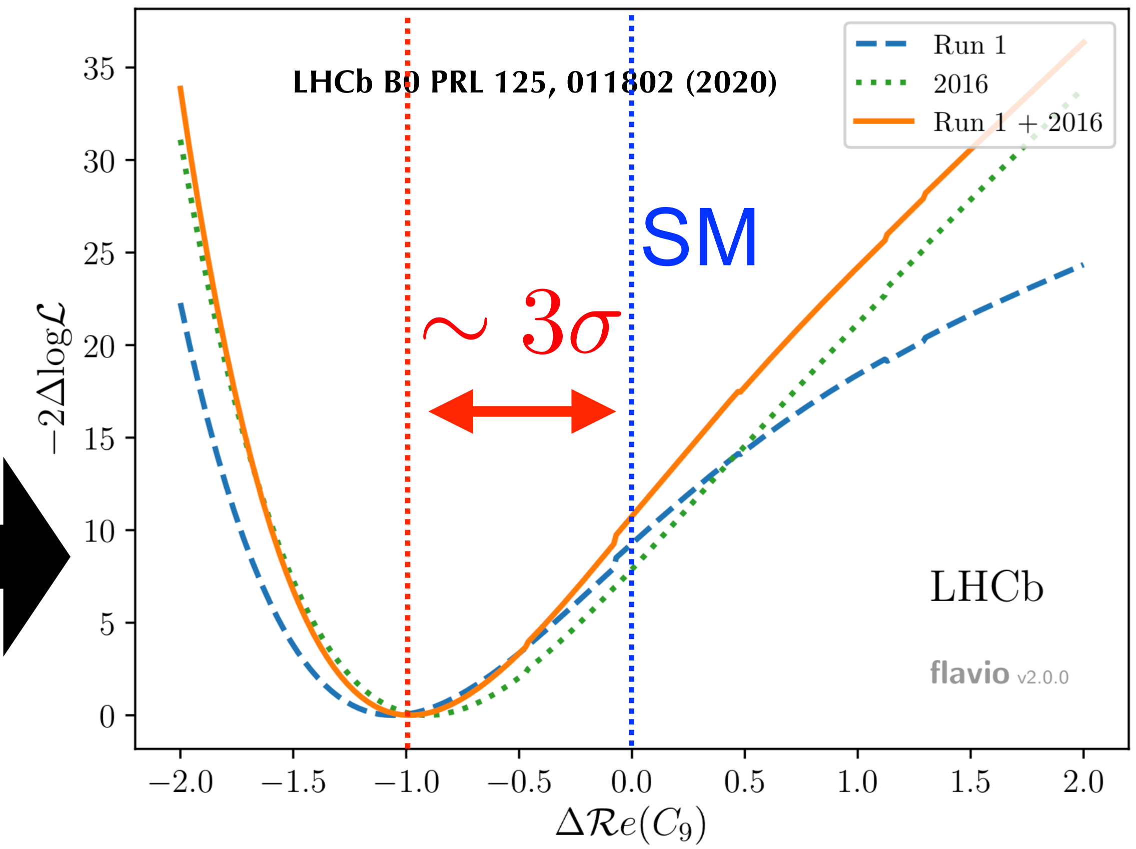
C_{10} = $bs\ell\ell$ axial-vector current

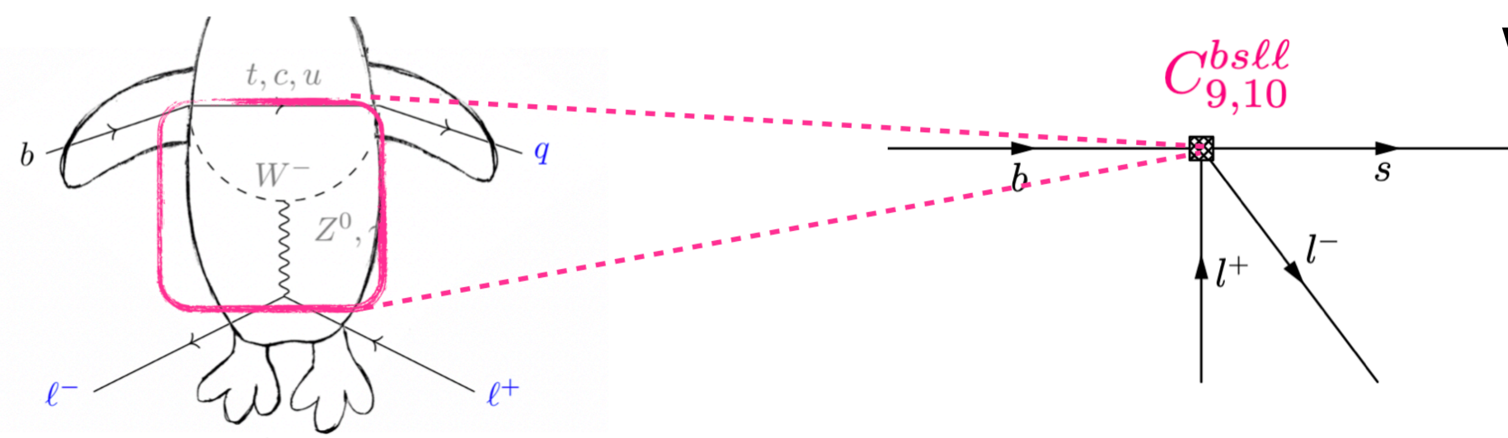
Example: analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$



+ 7 other observables (S_i basis!!)

Global agreement with SM?





EW scale >> m_b, replace loop with effective couplings

C_9 = $bs\ell\ell$ vector current

C_{10} = $bs\ell\ell$ axial-vector current

Summary of angular analysis

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

$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.3\,^{+0.7}_{-0.6}$

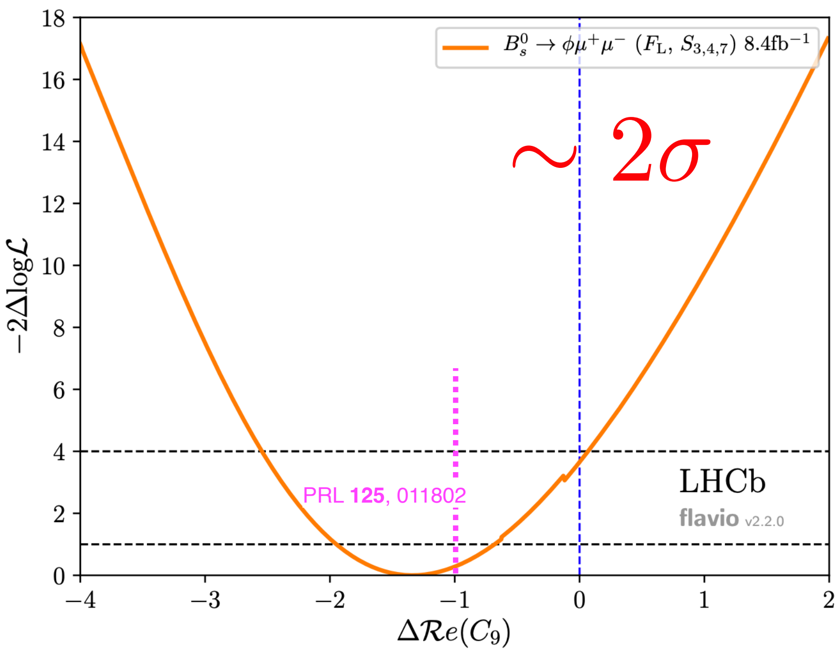
JHEP 11 (2021) 043

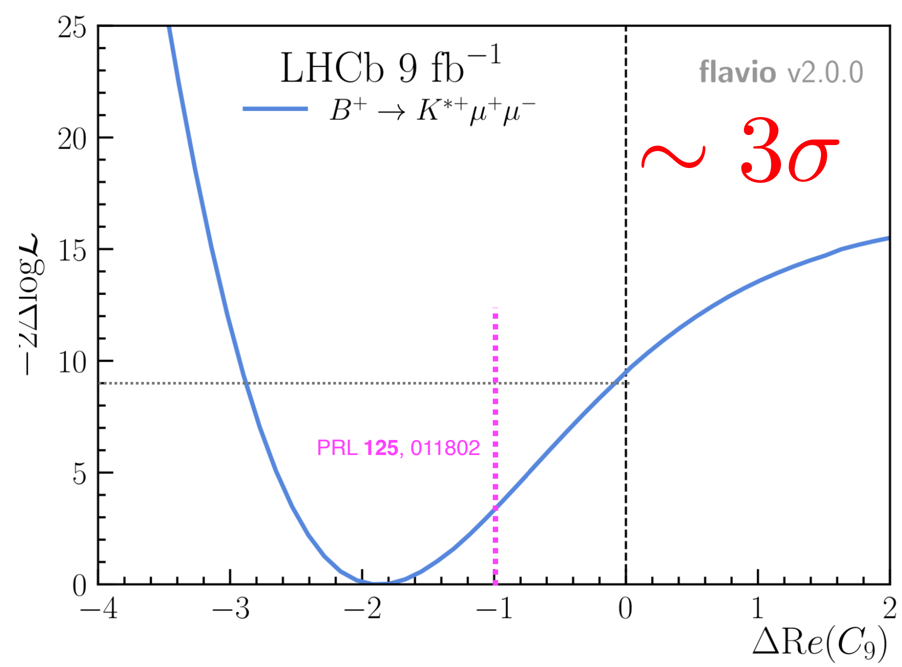
$\Delta\mathcal{R}e(\mathcal{C}_9) = -1.9$

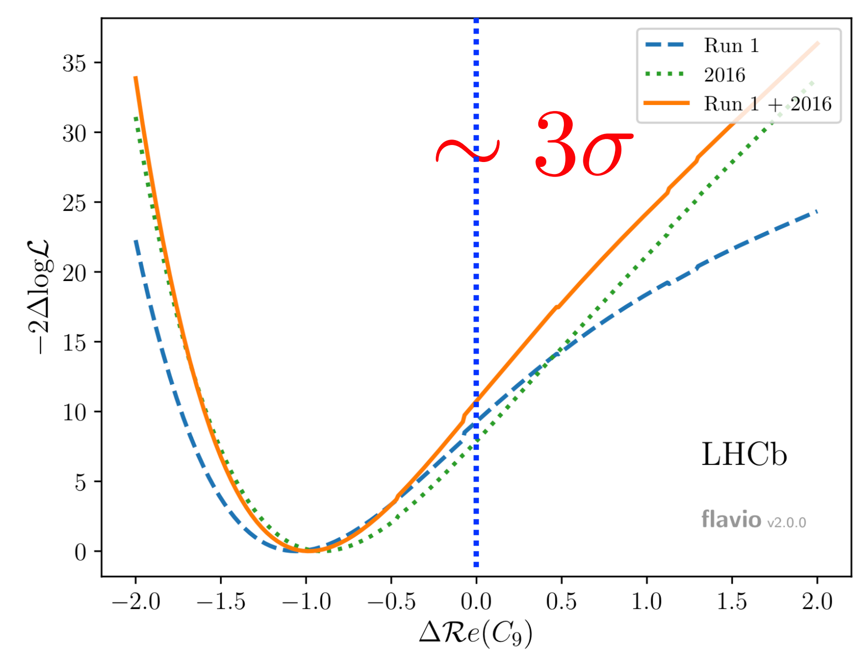
Phys. Rev. Lett. **126**, 161802

$\Delta\mathcal{R}e(\mathcal{C}_9) = -0.99^{+0.25}_{-0.21}$

Phys. Rev. Lett. **125**, 011802







Same pattern, negative definitions in effective coupling

New!! $B^0 \to K^{*0}\mu^+\mu^-$ with 140 fb^{-1} from CMS

Increase in data:

- fit full angular distribution (no angular folding, in contrast to Run 1)
- Full parameterisation of $[K\pi]$ spin-0 partial wave (S-wave)

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Identifying kaons from pions..

- Take the hypothesis which gives $m(K\pi)$ closest to pole mass

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Identifying kaons from pions..

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Assumptions

- Massless leptons and no scalar or tensor amplitudes

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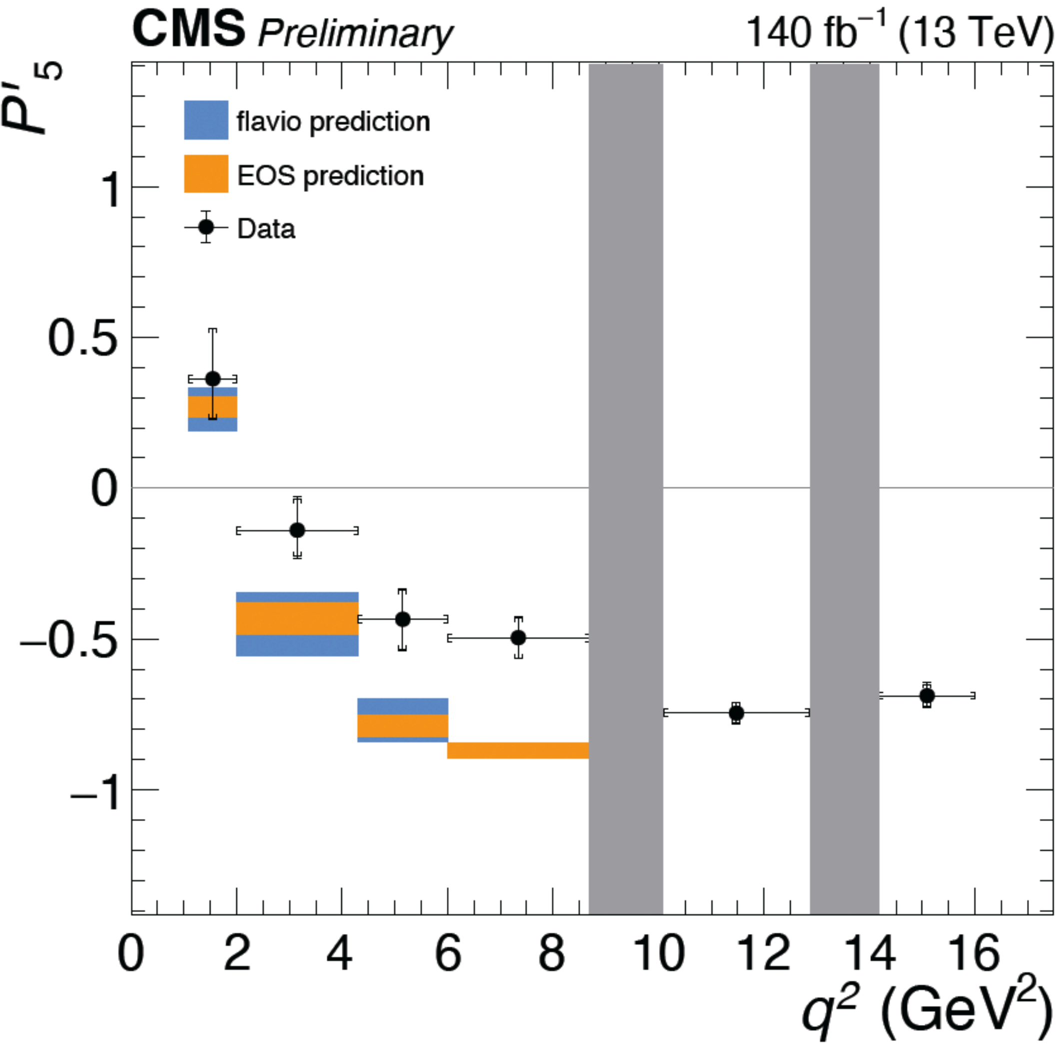
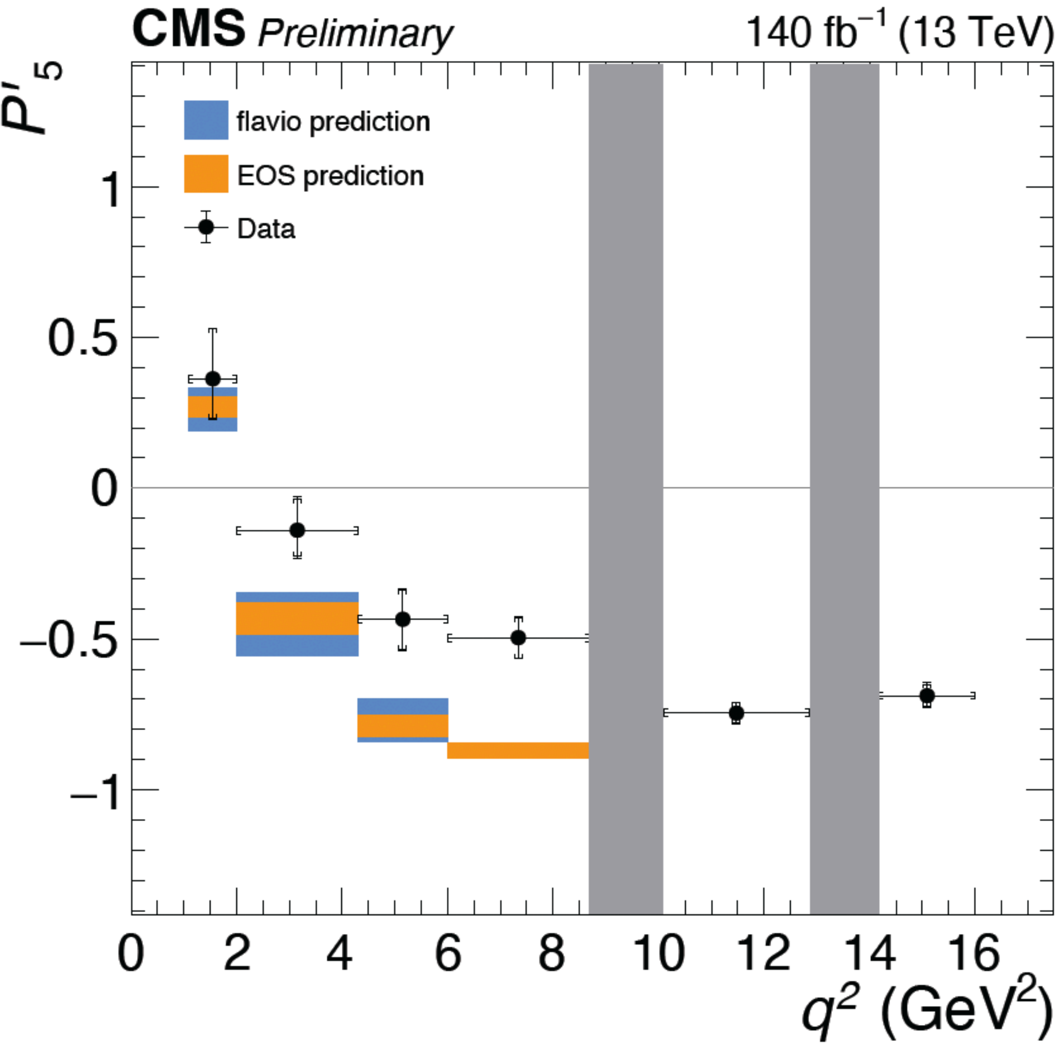


Table 1: Preliminary results, CMS Run 2

	$1.1 < q^2 < 2$ GeV^2	$2 < q^2 < 4.3$ GeV^2	$4.3 < q^2 < 6$ GeV^2
F_L	$0.709^{+0.073}_{-0.054} \pm 0.021$	$0.810^{+0.036}_{-0.030} \pm 0.016$	$0.714^{+0.032}_{-0.030} \pm 0.012$
P_1	$0.089^{+0.234}_{-0.204} \pm 0.040$	$-0.285^{+0.187}_{-0.208} \pm 0.051$	$-0.297^{+0.153}_{-0.168} \pm 0.038$
P_2	$-0.374^{+0.173}_{-0.125} \pm 0.095$	$-0.244^{+0.094}_{-0.077} \pm 0.039$	$0.121^{+0.080}_{-0.076} \pm 0.030$
P_3	$-0.045^{+0.209}_{-0.216} \pm 0.044$	$-0.187^{+0.196}_{-0.218} \pm 0.089$	$-0.027^{+0.143}_{-0.143} \pm 0.081$
P'_4	$-0.436^{+0.289}_{-0.323} \pm 0.111$	$-0.431^{+0.160}_{-0.185} \pm 0.075$	$-0.717^{+0.154}_{-0.158} \pm 0.074$
P'_5	$0.363^{+0.165}_{-0.132} \pm 0.028$	$-0.139^{+0.103}_{-0.087} \pm 0.039$	$-0.435^{+0.096}_{-0.101} \pm 0.027$
P'_6	$0.000^{+0.094}_{-0.097} \pm 0.021$	$0.108^{+0.075}_{-0.071} \pm 0.018$	$0.129^{+0.074}_{-0.071} \pm 0.011$
P'_8	$-0.157^{+0.368}_{-0.369} \pm 0.113$	$-0.727^{+0.193}_{-0.184} \pm 0.056$	$0.007^{+0.215}_{-0.216} \pm 0.036$
	$6 < q^2 < 8.68$ GeV^2	$10.09 < q^2 < 12.86$ GeV^2	$14.18 < q^2 < 16$ GeV^2
F_L	$0.627^{+0.016}_{-0.016} \pm 0.011$	$0.474^{+0.011}_{-0.013} \pm 0.009$	$0.394^{+0.012}_{-0.012} \pm 0.009$
P_1	$-0.056^{+0.101}_{-0.102} \pm 0.046$	$-0.439^{+0.051}_{-0.047} \pm 0.030$	$-0.465^{+0.037}_{-0.037} \pm 0.025$
P_2	$0.188^{+0.039}_{-0.040} \pm 0.014$	$0.386^{+0.021}_{-0.019} \pm 0.018$	$0.440^{+0.008}_{-0.010} \pm 0.008$
P_3	$0.099^{+0.092}_{-0.090} \pm 0.014$	$0.013^{+0.041}_{-0.043} \pm 0.007$	$-0.034^{+0.037}_{-0.038} \pm 0.010$
P'_4	$-0.949^{+0.102}_{-0.101} \pm 0.058$	$-1.025^{+0.064}_{-0.066} \pm 0.059$	$-1.159^{+0.042}_{-0.038} \pm 0.041$
P'_5	$-0.495^{+0.067}_{-0.067} \pm 0.023$	$-0.746^{+0.033}_{-0.032} \pm 0.014$	$-0.688^{+0.038}_{-0.036} \pm 0.021$
P'_6	$0.010^{+0.052}_{-0.052} \pm 0.016$	$0.080^{+0.037}_{-0.041} \pm 0.011$	$0.121^{+0.040}_{-0.039} \pm 0.011$
P'_8	$-0.061^{+0.143}_{-0.143} \pm 0.042$	$-0.093^{+0.104}_{-0.094} \pm 0.029$	$-0.011^{+0.086}_{-0.089} \pm 0.022$

New!! $B^0 \to K^{*0}\mu^+\mu^-$ with 140 fb^{-1} from CMS



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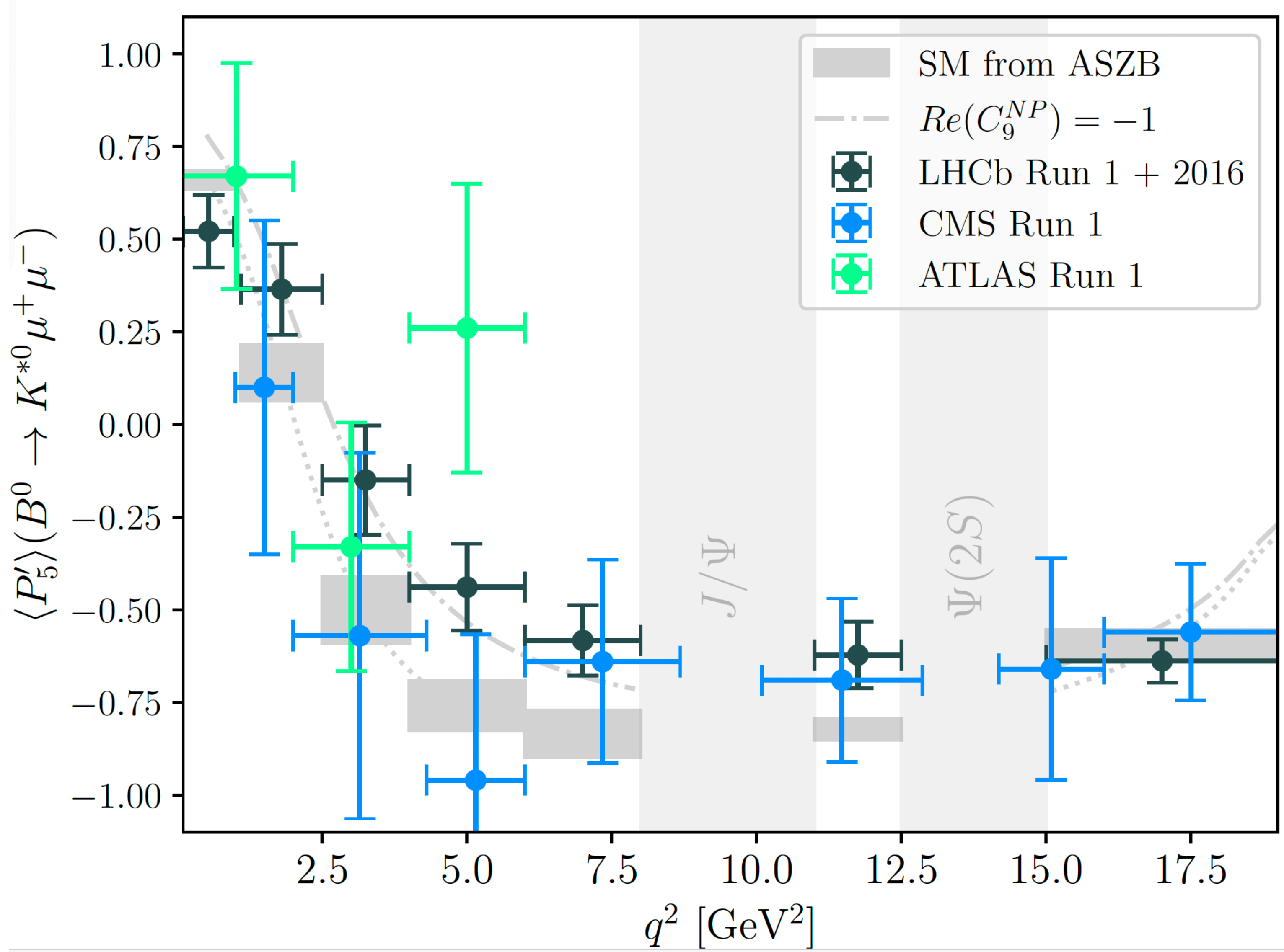

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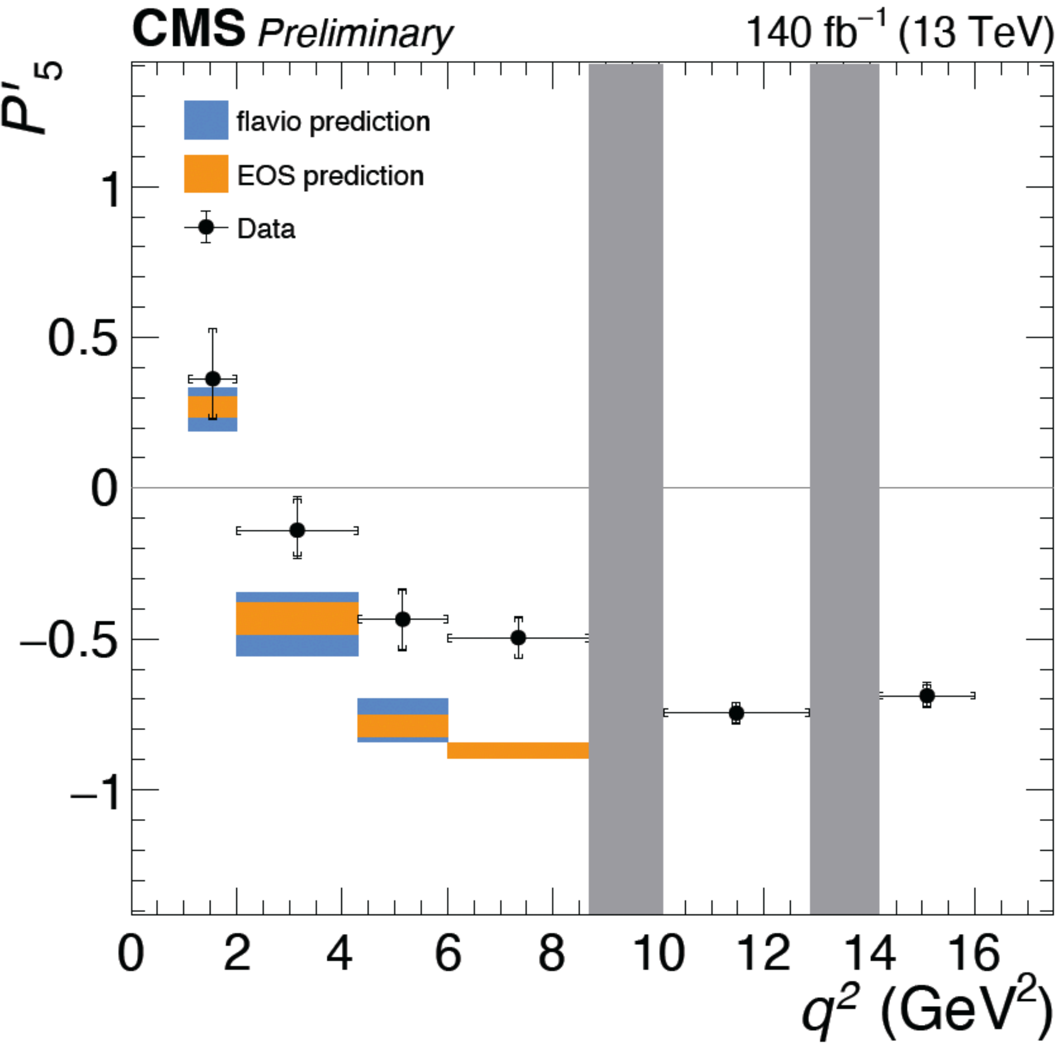

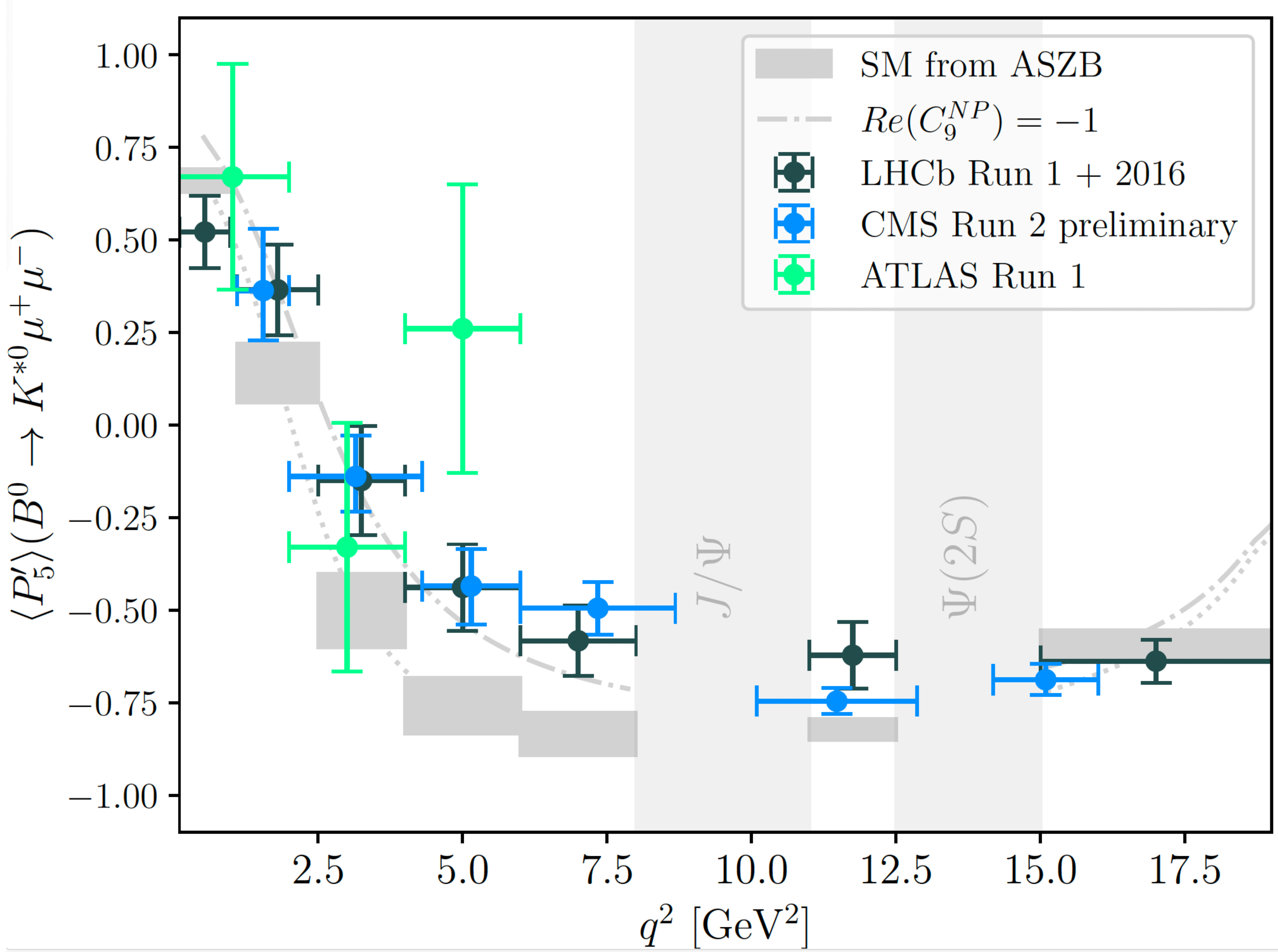

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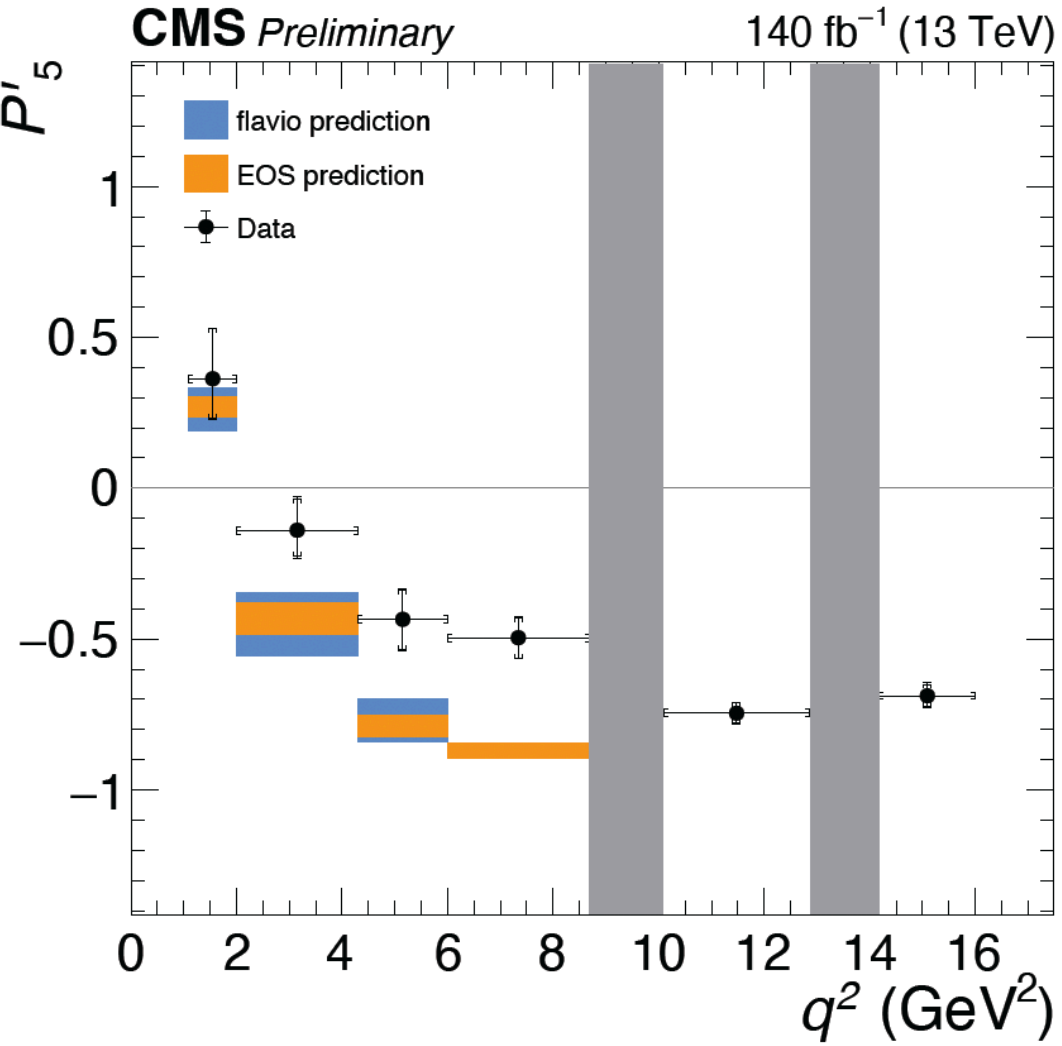
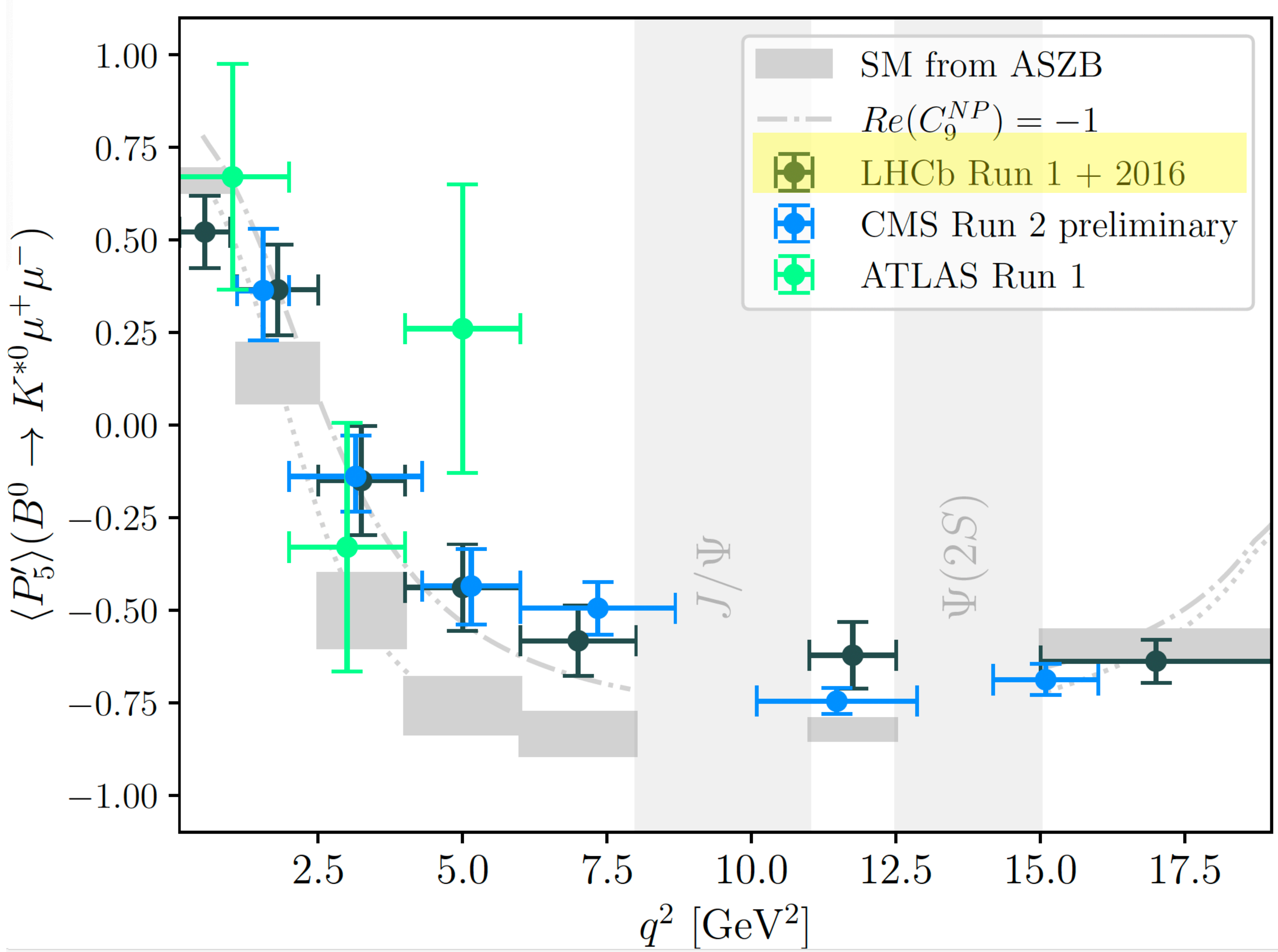


What about LHCb Run 1 and 2?



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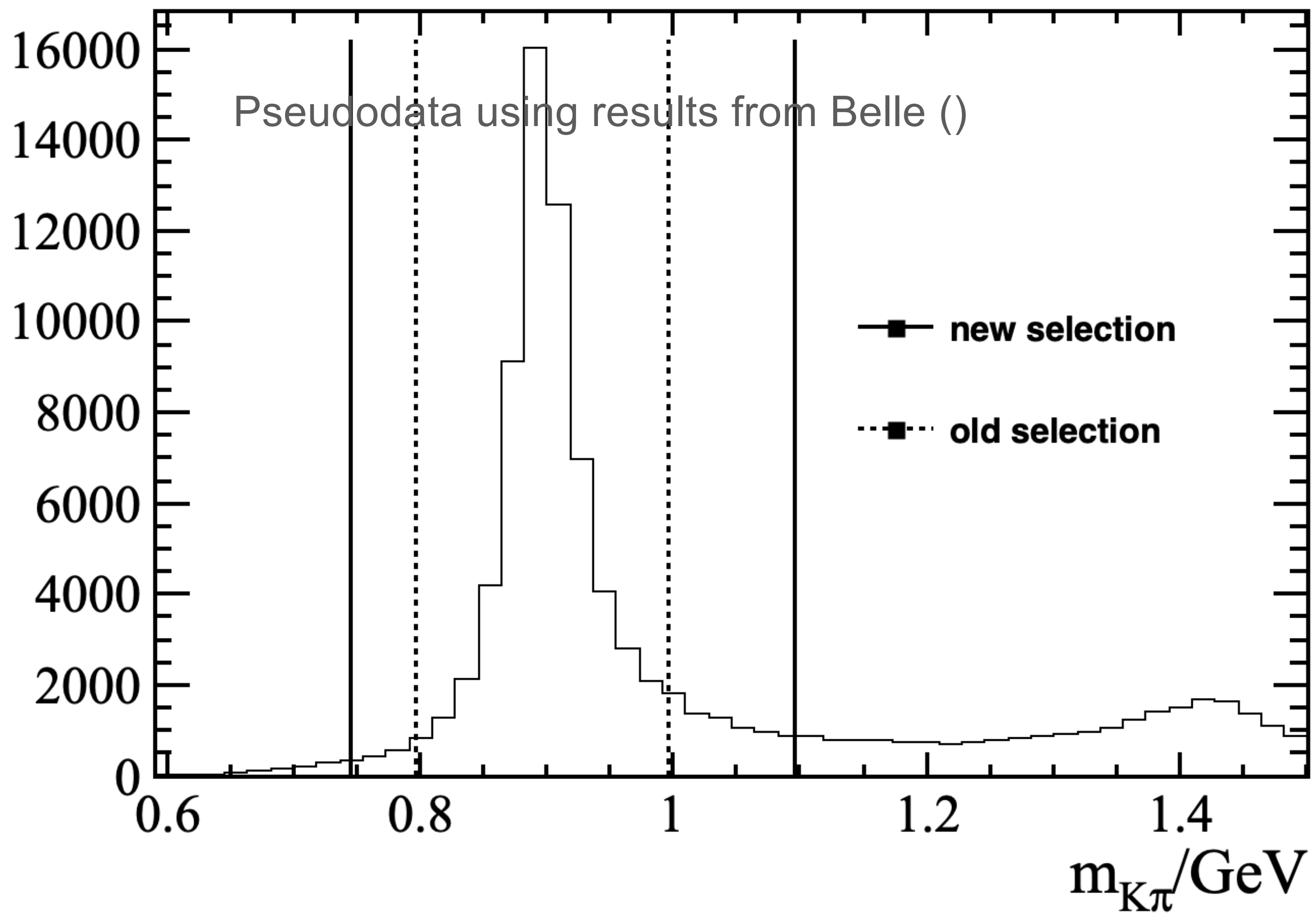
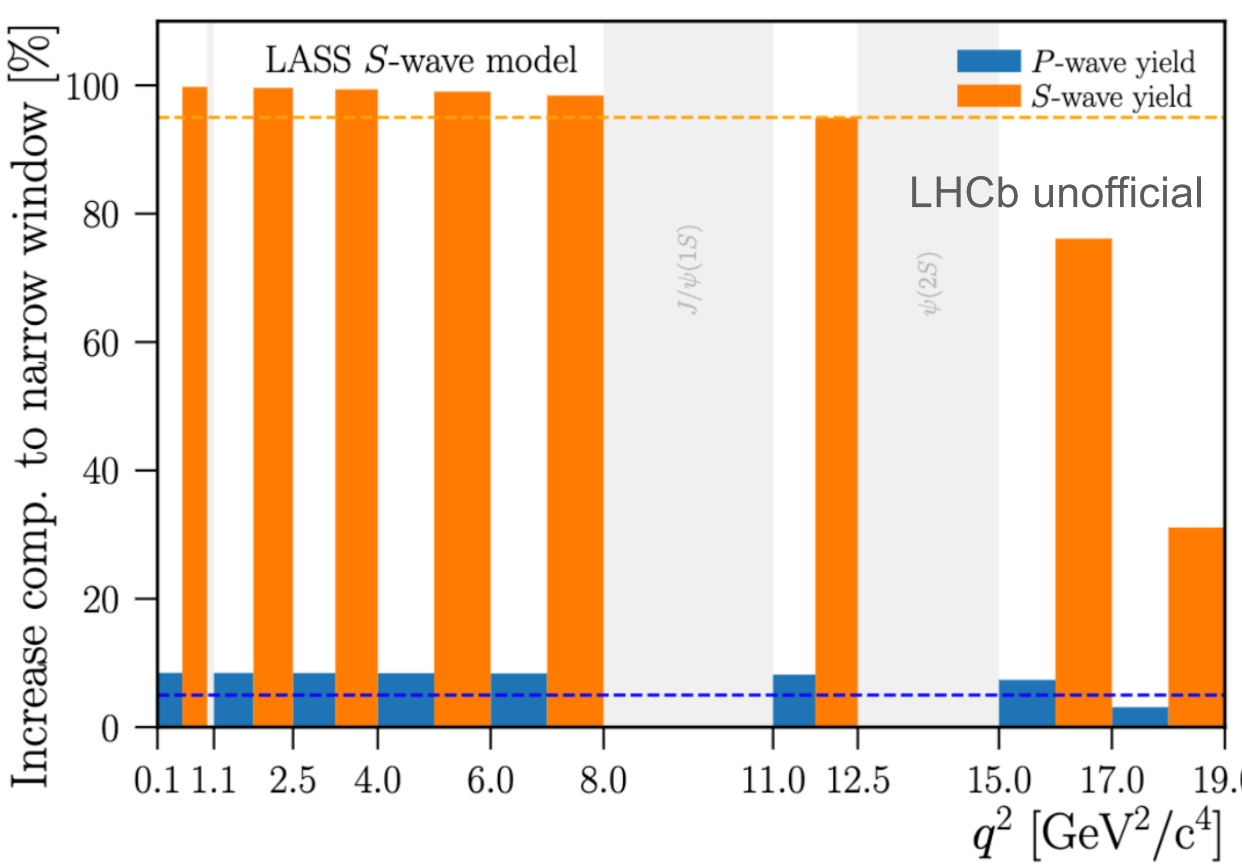
Published Run 1 + 2016 vs upcoming Run 1 +2

Add 17+18 data → roughly double number of $b\bar{b}$ pairs based on $pp \to b\bar{b}X$ cross section and lumi.

Increase width of $m_{K\pi}$ window → further increase in events





Published Run 1 + 2016 vs upcoming Run 1 +2

Fit full 5D PDF (i.e. $m_{K\pi}$, Ω in bins of q^2), and CP-averages and CP-asymmetries simultaneously

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{\overleftrightarrow{\Gamma}}{d\vec{\Omega}\ dq^2\ dm_{K\pi}} = \frac{9}{64\pi}\sum_{i\in\mathcal{P}}(S_i \pm A_i)f_i(\theta_l,\theta_K,\phi)\,|\mathcal{BW}_{\mathcal{P}}(m_{K\pi})|^2 + \sum_{i\in\mathcal{S}}(S_i \pm A_i)f_i(\theta_l,\theta_K,\phi)\,|\mathcal{BW}_{\mathcal{S}}(m_{K\pi})|^2 + \sum_{i\in\mathcal{S}/\mathcal{P}}(S_i \pm A_i)f_i(\theta_l,\theta_K,\phi)\,g(\mathcal{BW}_{\mathcal{S}}(m_{K\pi})\mathcal{BW}^{\star}_{\mathcal{P}}(m_{K\pi}))$$

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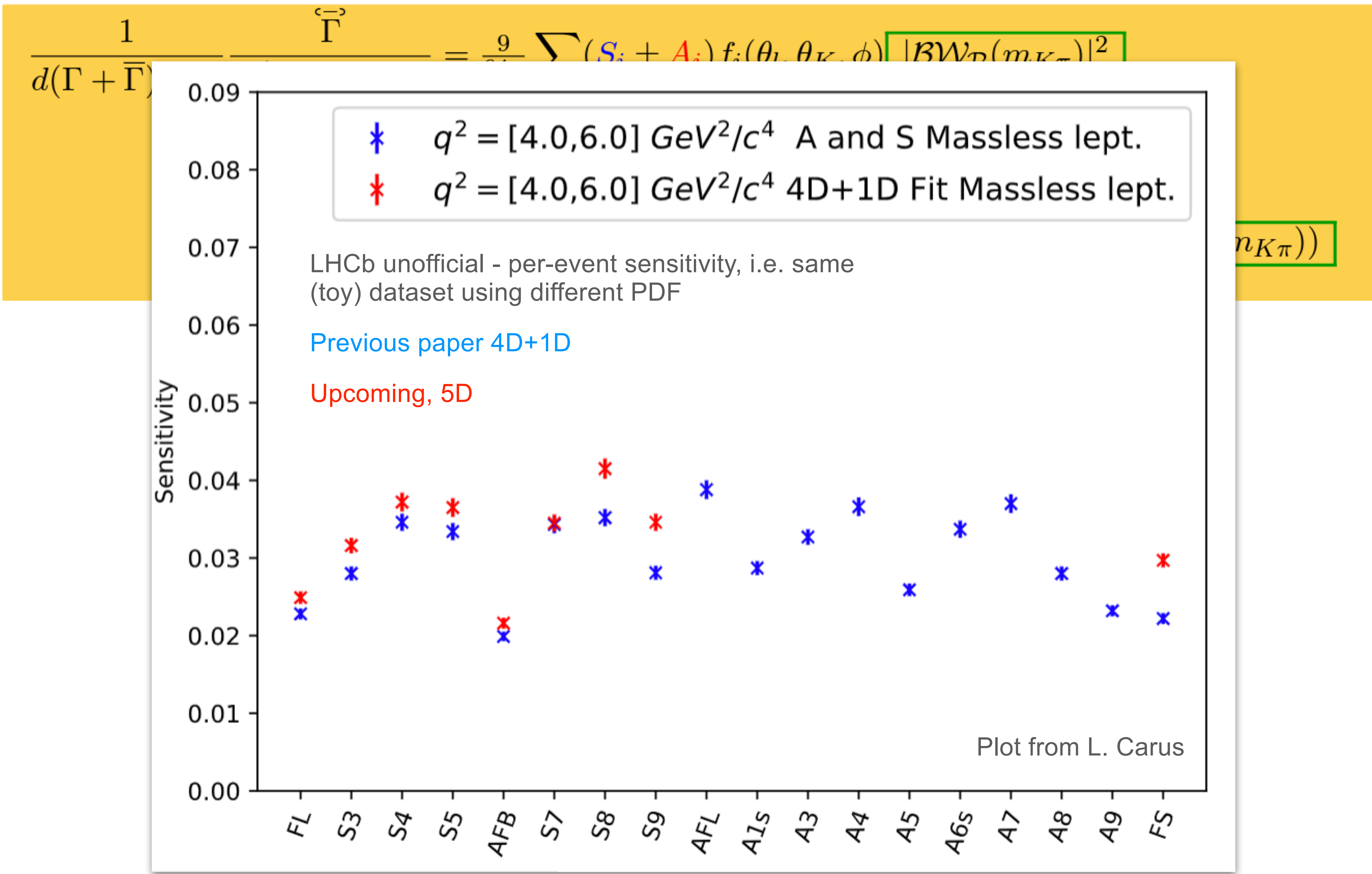

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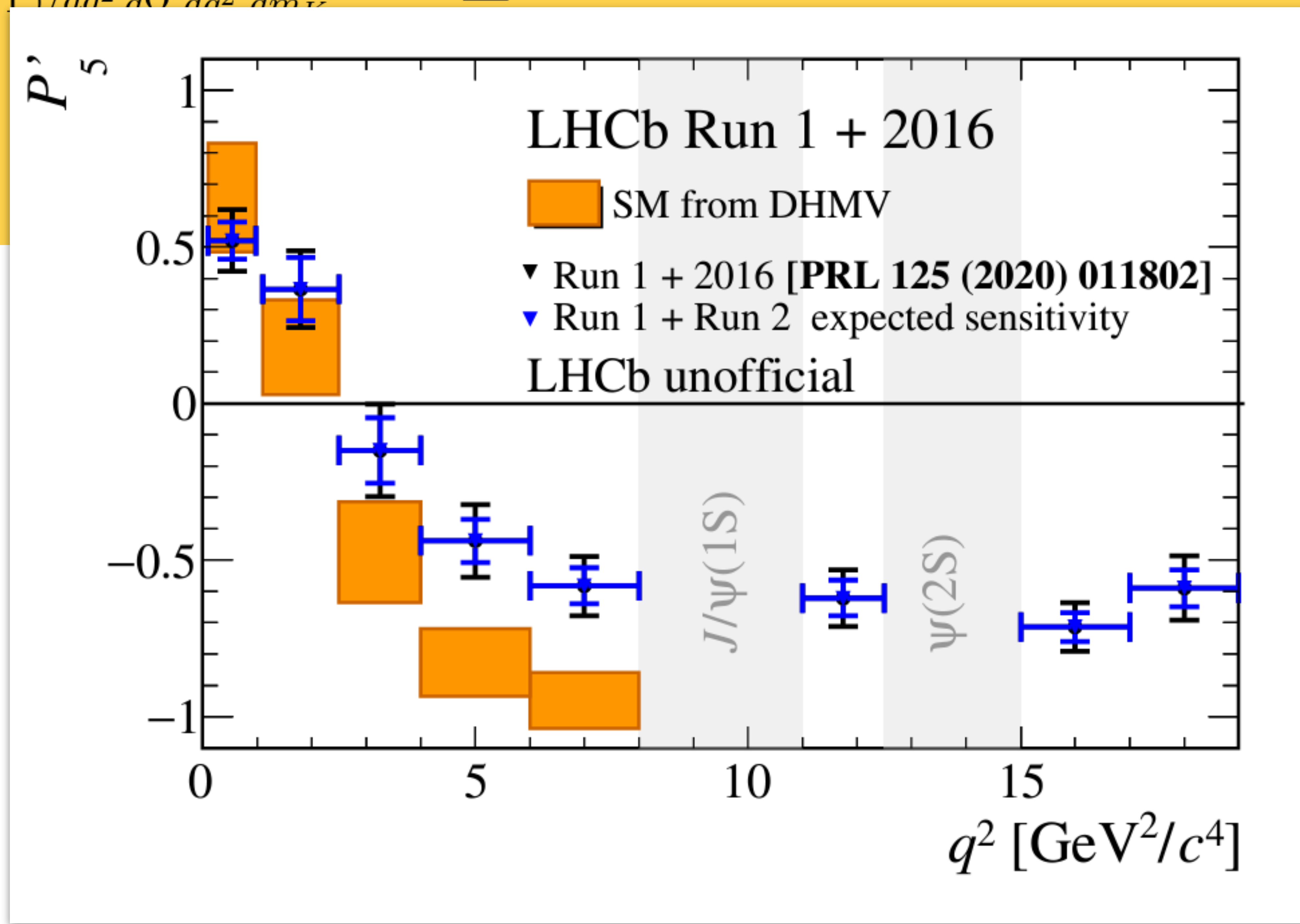
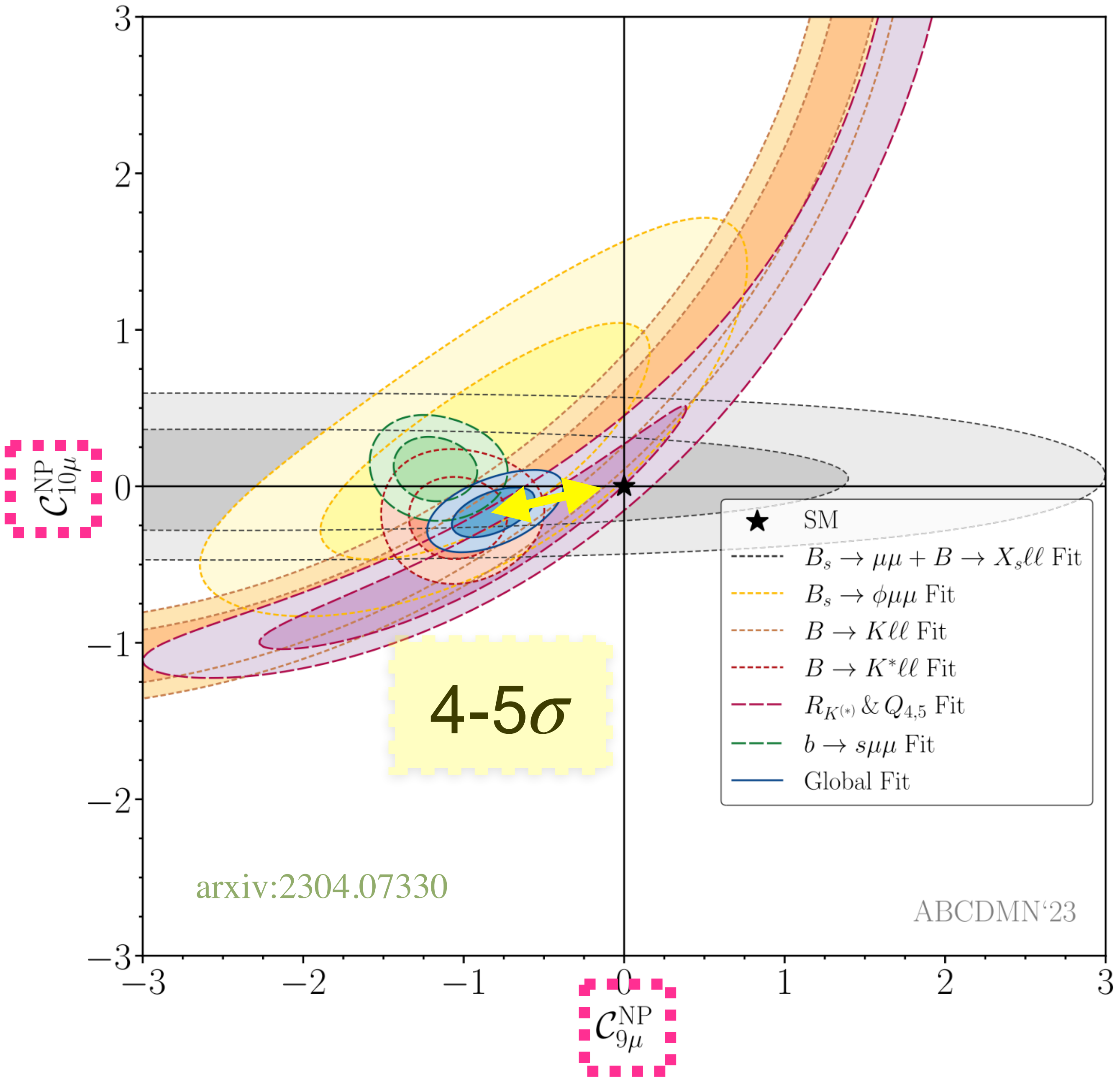


Global deviation from SM over all $b \to s\ell\ell$?



Highest experimental precision in $b \to s\mu^+\mu^-$ decays

Combine branching fraction and angular information for all experiments and measured $b \to s\mu^+\mu^-$ modes

Disagreement with SM at level of 4-5σ

Long-standing discrepancy- why aren't we claiming new physics?

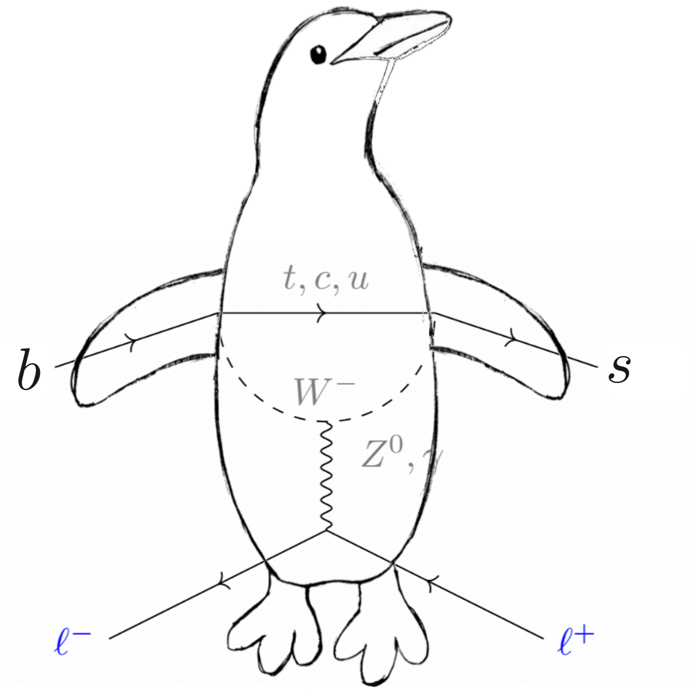
Hadronic cleanliness

Lepton Flavour Universality and $B_s \to \mu^+\mu^-$

Angular analyses

Branching fractions

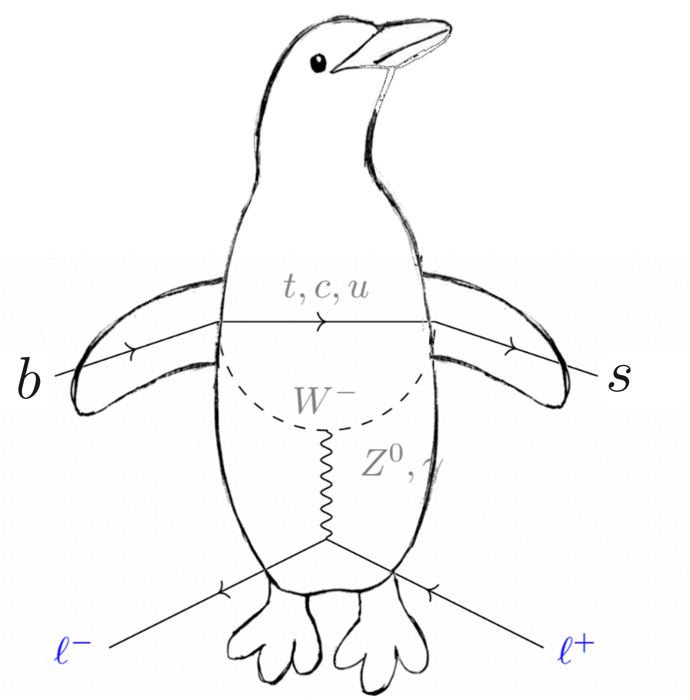
Cause of anomalies?



$+$? $=$ deviations

Cause of anomalies?

Option 1 - New Physics



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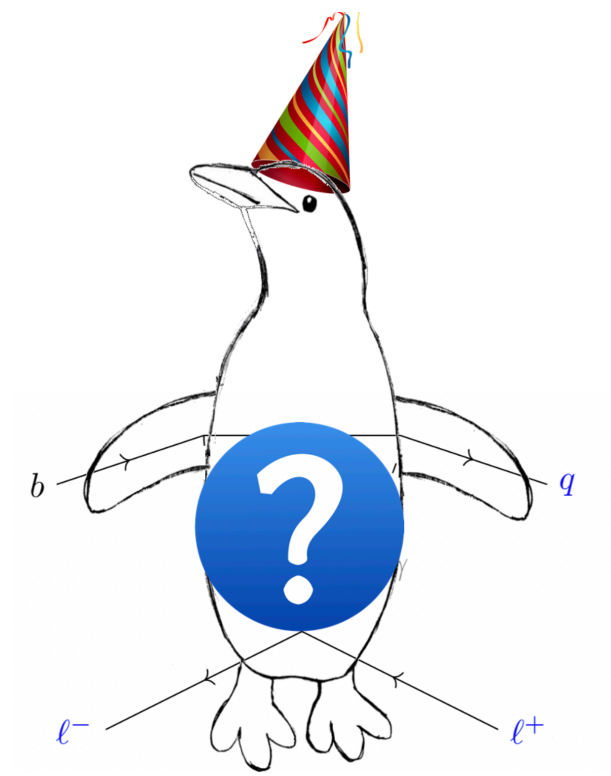
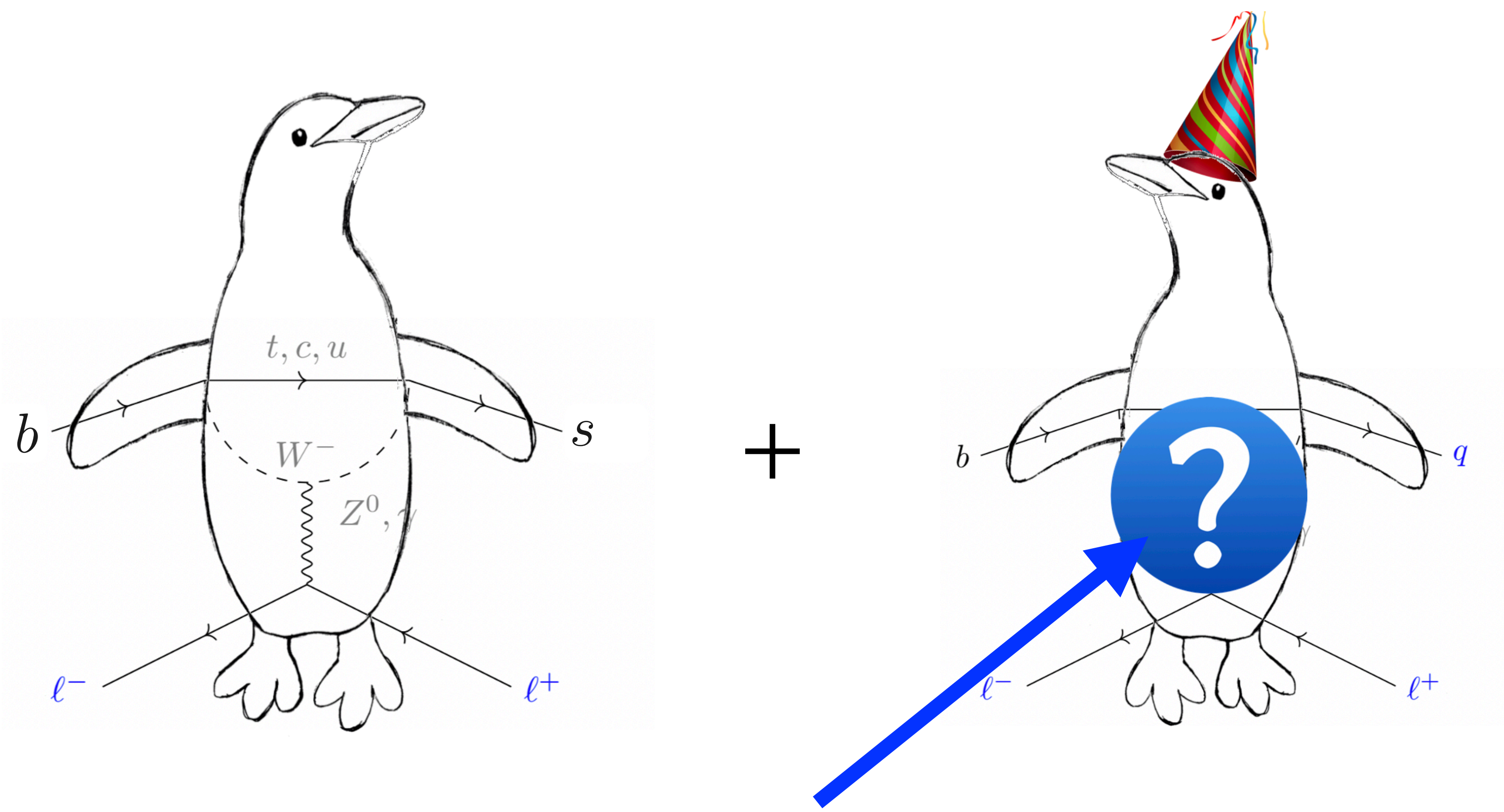


= deviations

Cause of anomalies?

Option 1 - New Physics

- e.g. enhancements in $b \to s\tau^+\tau^-$ gives combined explanation for B-anomalies

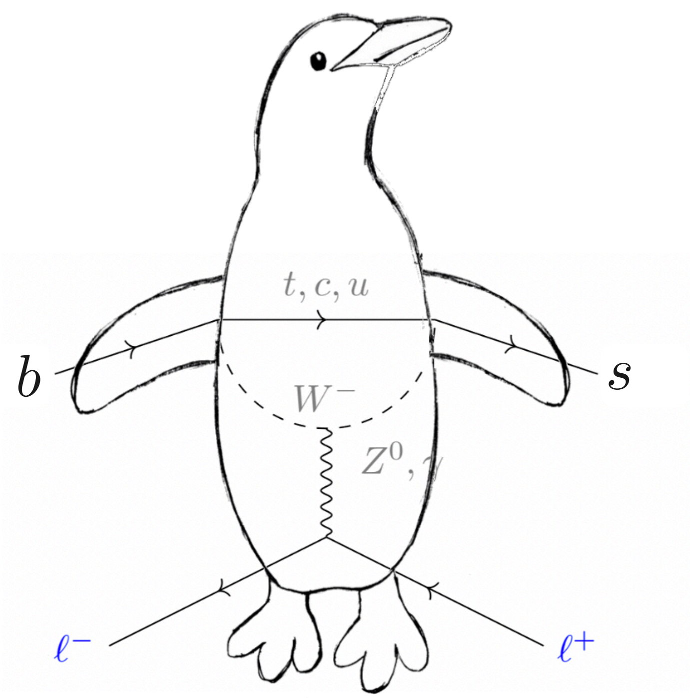


= deviations

CP violating? Leptoquark? $b \to s\tau^+\tau^-$?

Cause of anomalies?

Option 2 - misunderstood QCD processes



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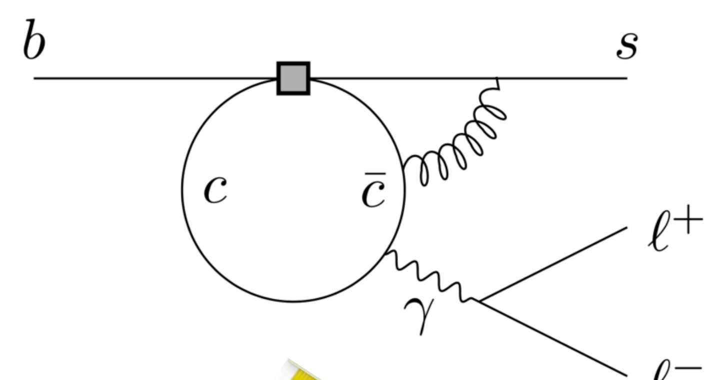
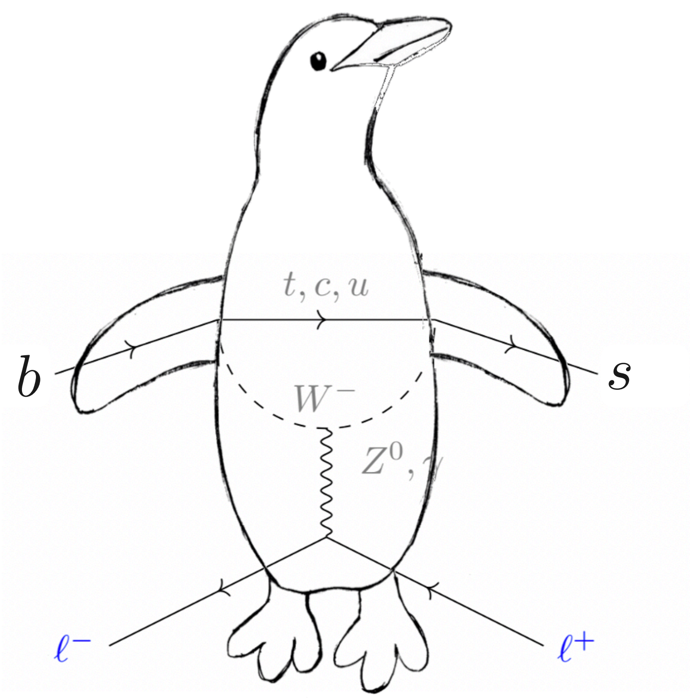


= deviations

Cause of anomalies?

Option 2 - misunderstood QCD processes

- $b \to sc\bar{c}[c\bar{c} \to \gamma^* \to \mu^+\mu^-]$ (charm-loops) can mimic deviations in C_9



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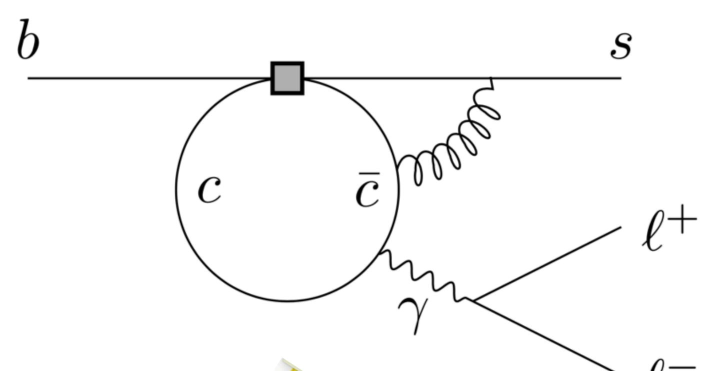
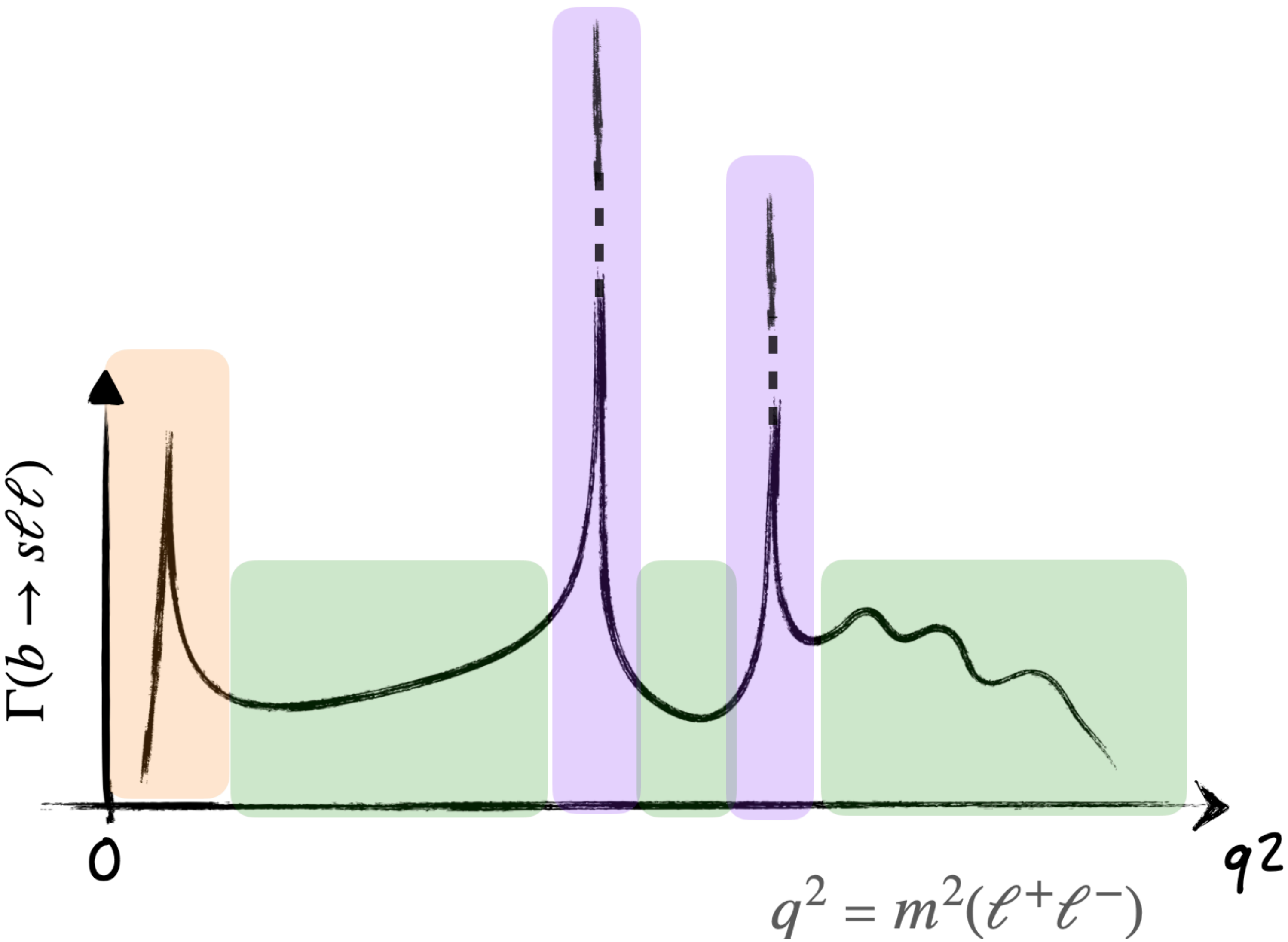


= deviations

q^2 dependence, fit models to data to further constrain amplitudes

Fit q^2 spectrum continuously to disentangle long (non-local) and short distance contributions to $B^0 \to K^{*0}\mu^+\mu^-$



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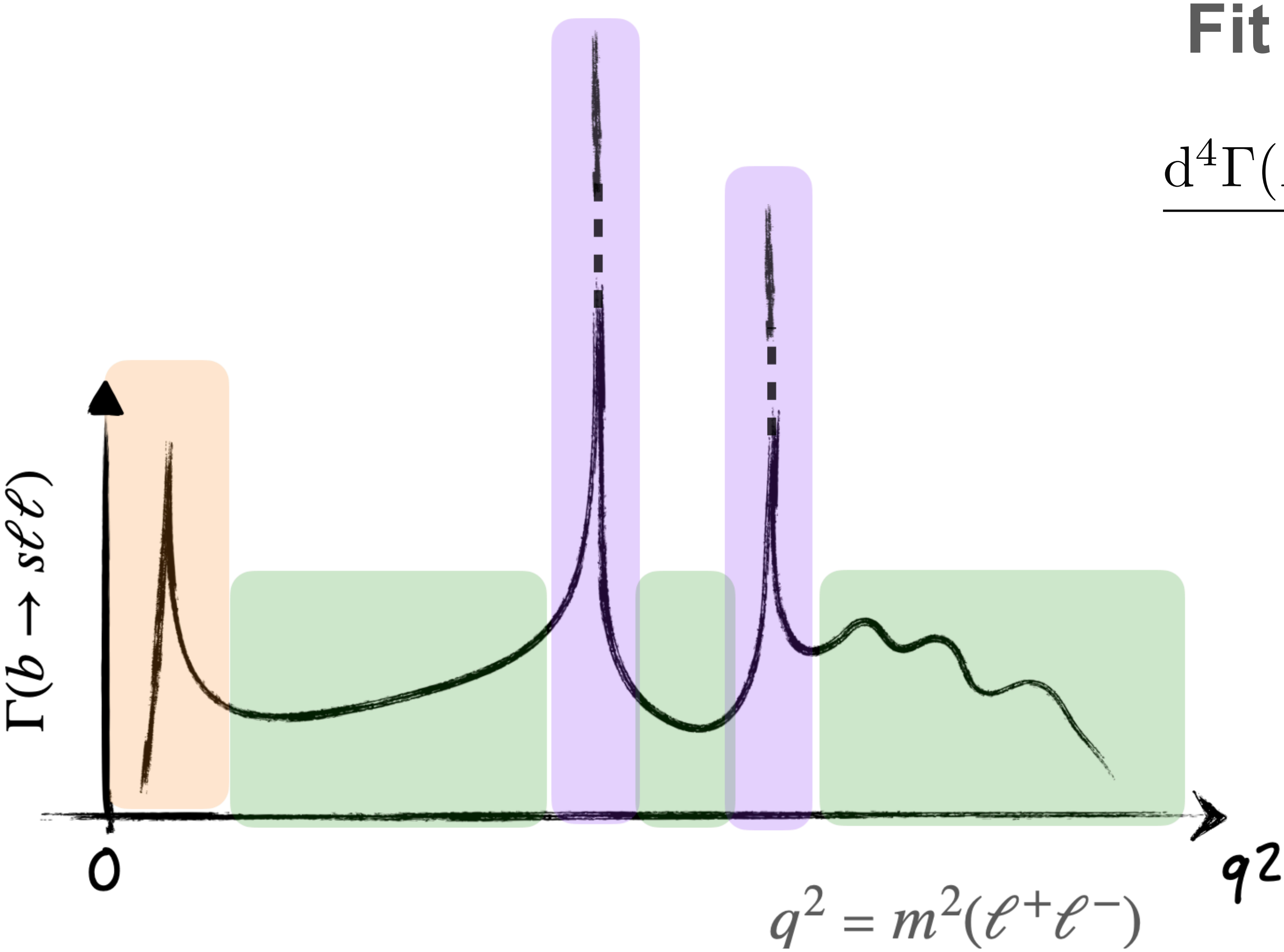

Fit the angular *and* q^2 spectrum

$$\frac{d^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{d\hat{\Omega}dq^2} = \sum_i I_i(q^2) f_i(\Omega)$$

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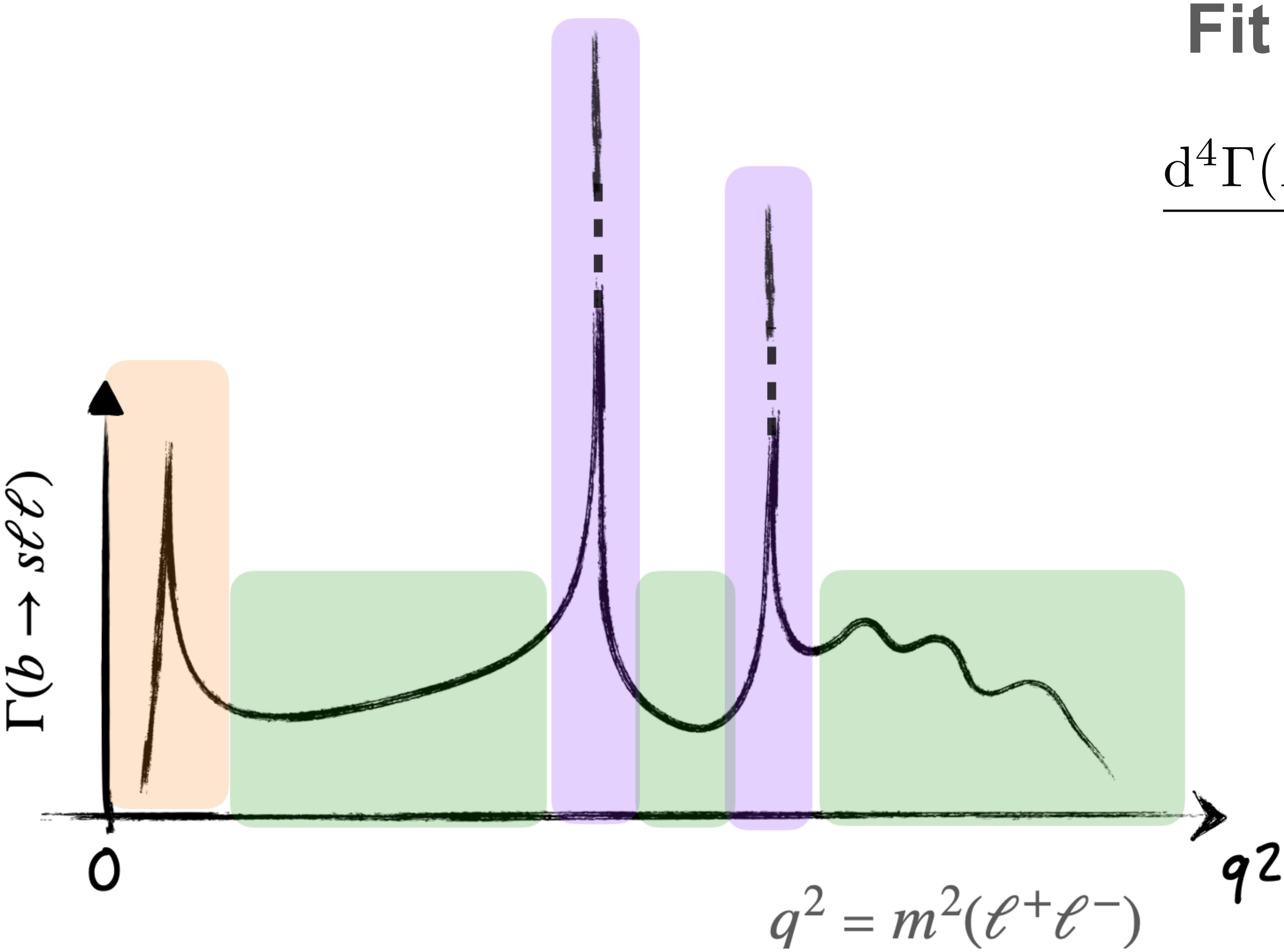

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Combinations of $\mathscr{A}^\lambda(q^2)$

$\lambda \in 0, ||, \perp, t$

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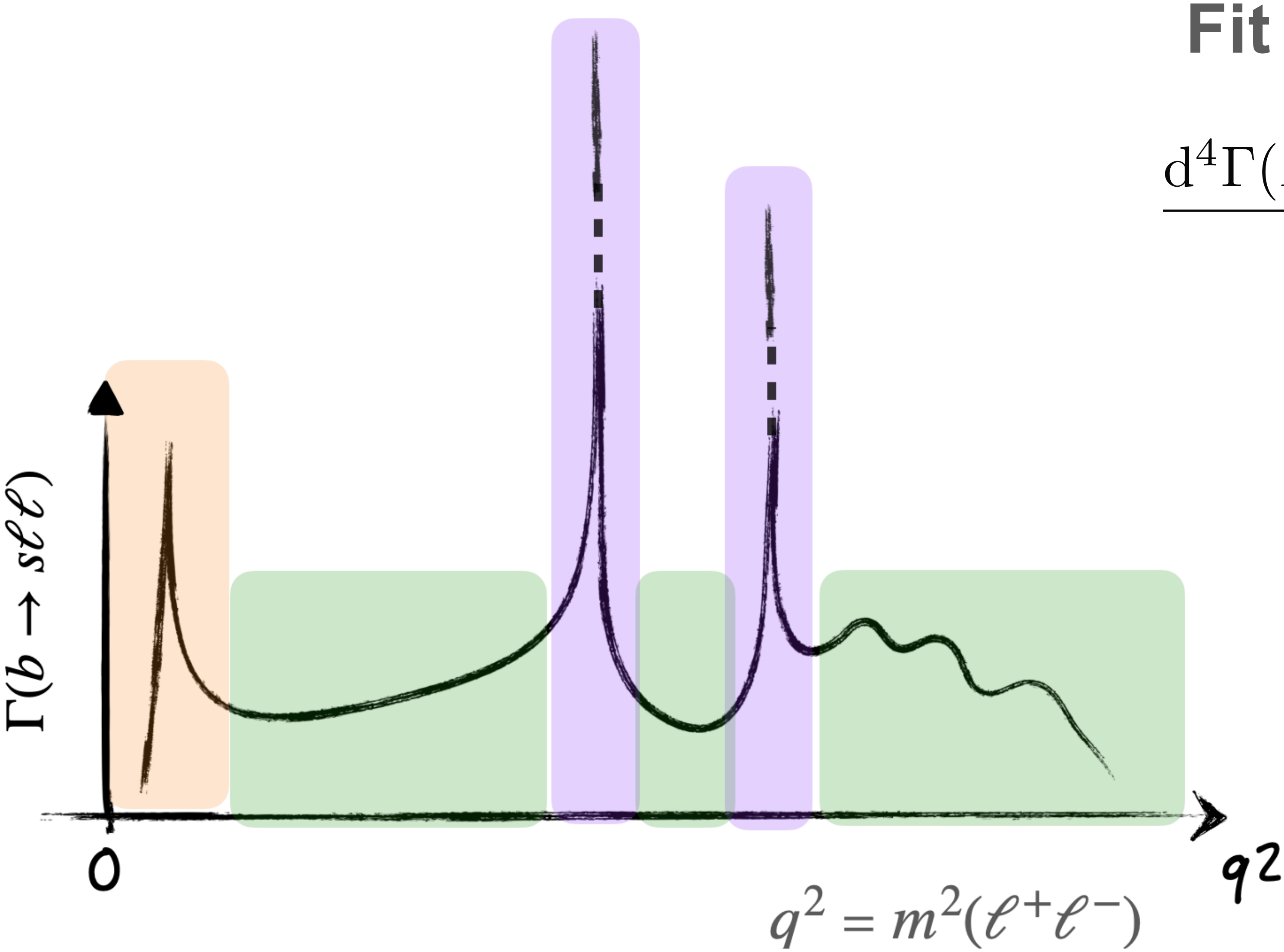

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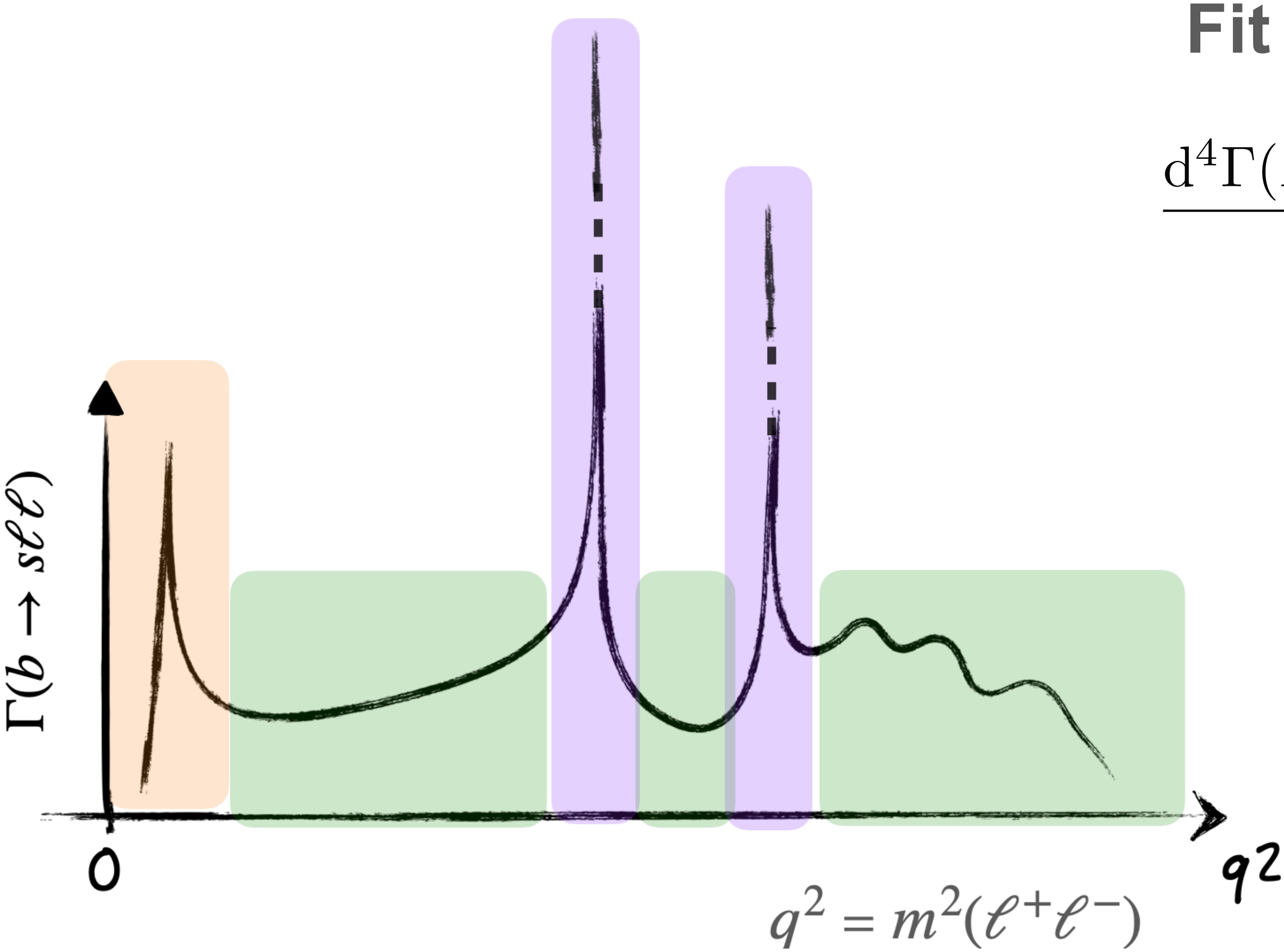

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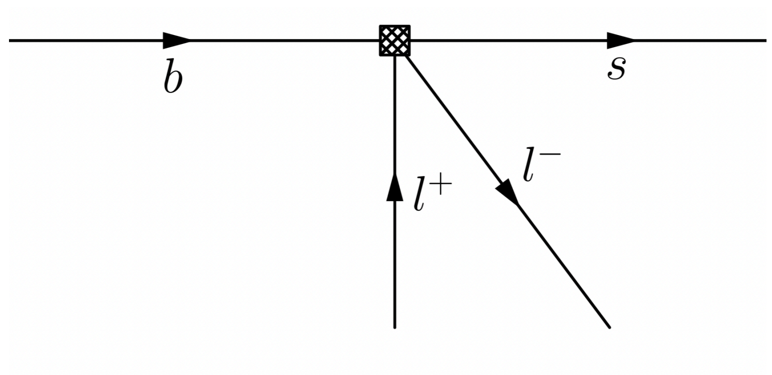
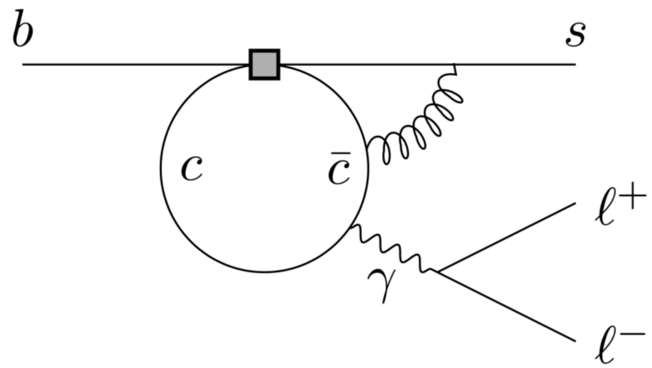
C_9 (vector) is altered by non-local charm-loop

Parameterising non-local form-factors

$\lambda \in 0, ||, \perp$

$C_{9,\lambda}^{eff}(q^2) =$  $+$ 

$$C_{9,\lambda}^{eff}(q^2) = C_9 + H_\lambda(q^2)$$

Parameterising non-local form-factors

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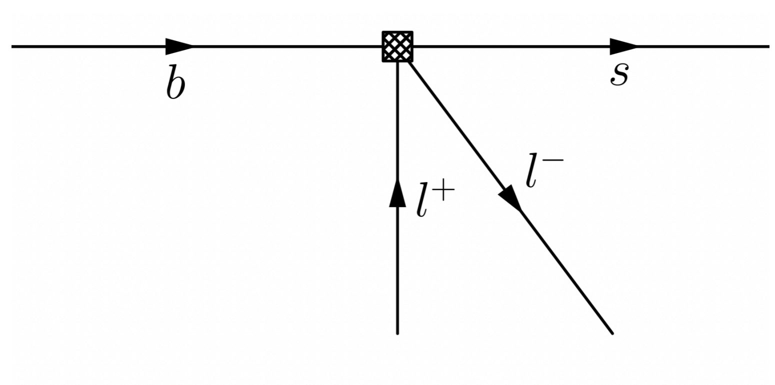
$C^{eff}_{9,\lambda}(q^2) =$



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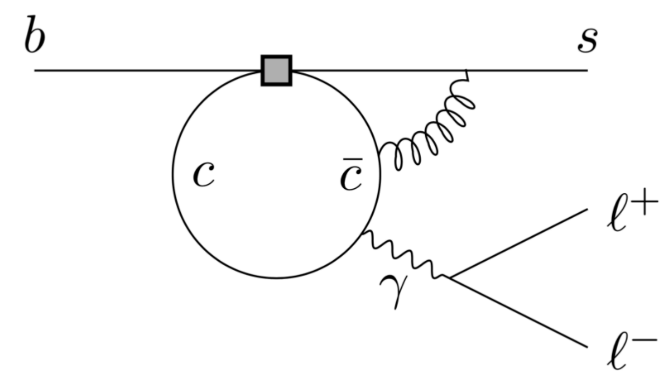


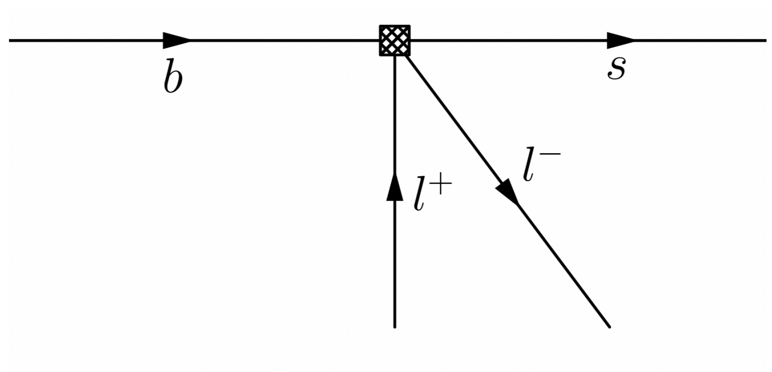
$$C^{eff}_{9,\lambda}(q^2) = C_9 + H_\lambda(q^2)$$

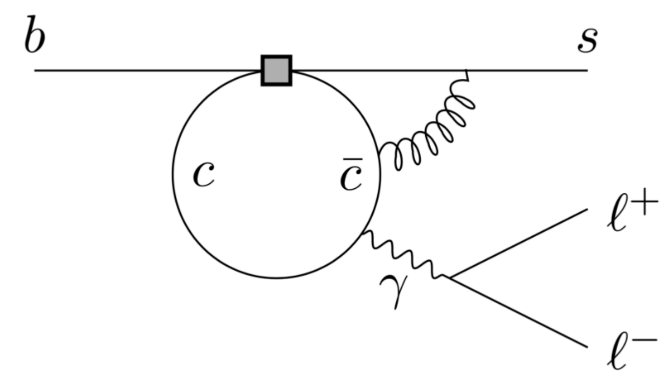
Two different analyses done, with different models for $H_\lambda(q^2)$:

- Z-expansion (LHCb-PAPER-2023-033,032), partial q^2
- Amplitude analysis over full q^2 (LHCb-PAPER-2024-011)

Parameterising non-local form-factors

$\lambda \in 0, ||, \perp$

$C_{9,\lambda}^{eff}(q^2) =$ 

$+$ 

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Matts talk
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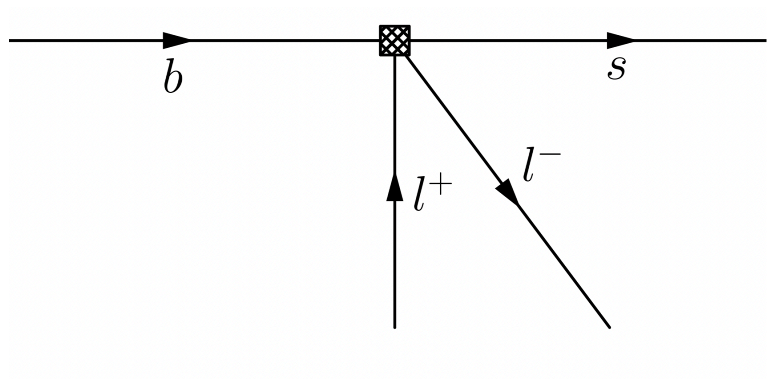
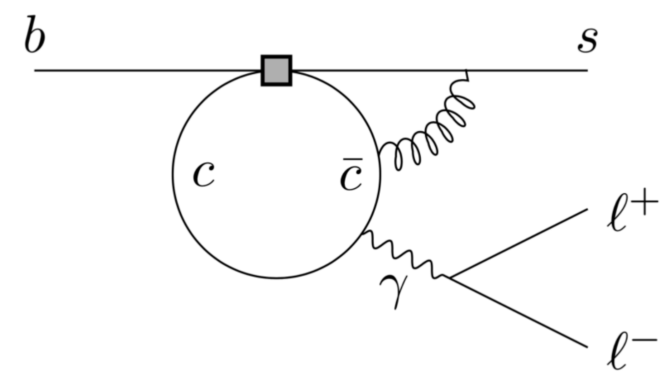
$C^{eff}_{9,\lambda}(q^2) =$ 

$+$ 

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Parameterising non-local form-factors

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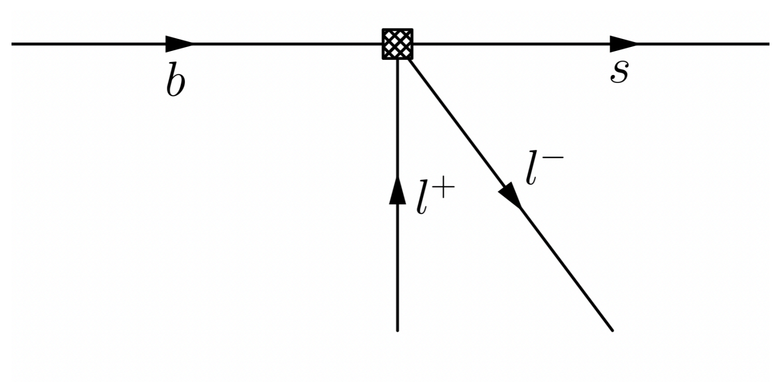
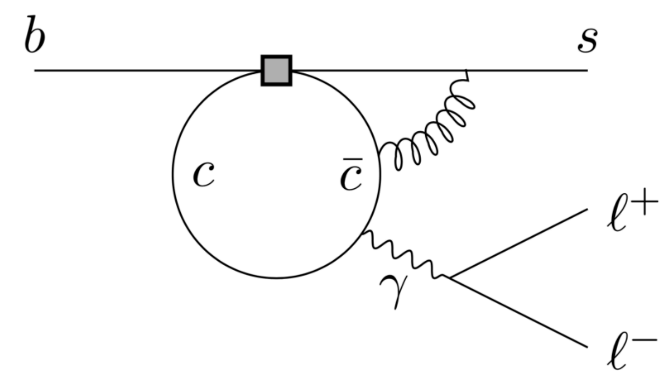
$$C_{9,\lambda}^{eff}(q^2) =$$ 

$+$ 

$$C_{9,\lambda}^{eff}(q^2) = C_9 + H_\lambda(q^2)$$

Two different analyses done, with different models for $H_\lambda(q^2)$:

This talk

- ➤ Z-expansion (LHCb-PAPER-2023-033,032), partial q^2
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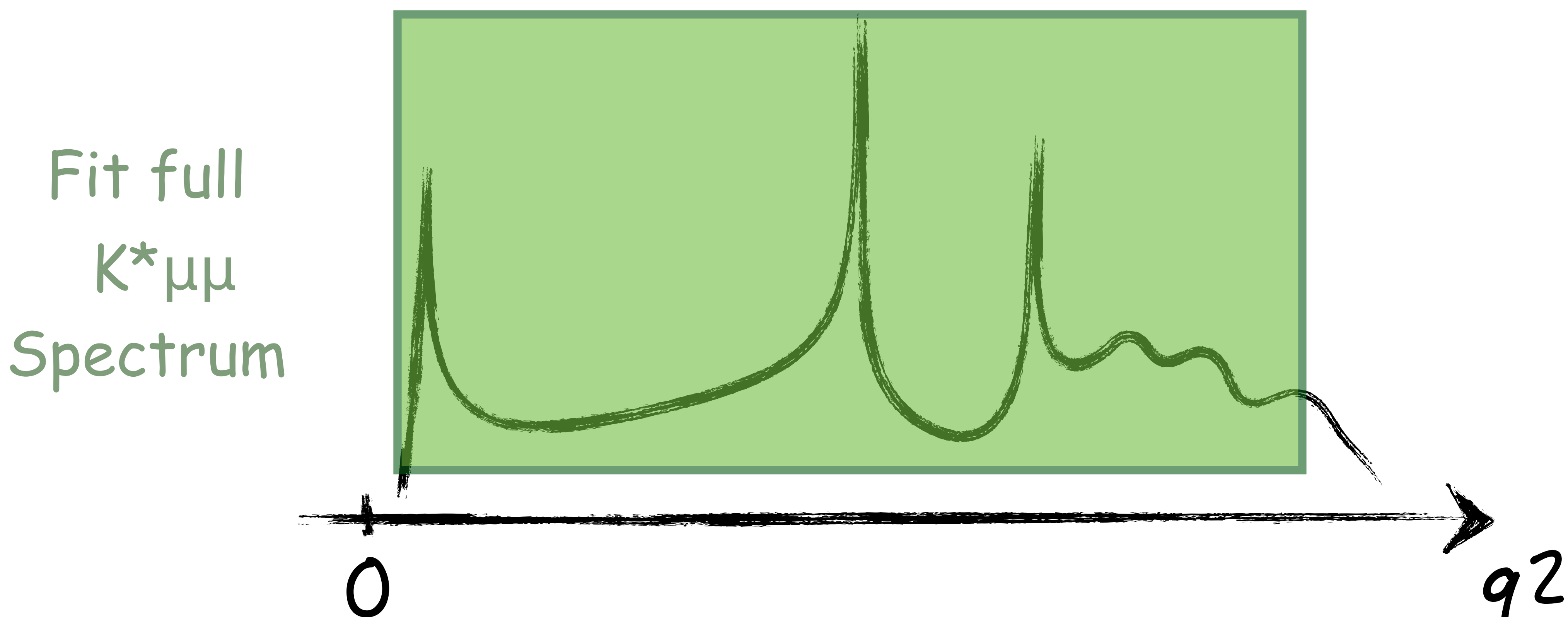
Note, C_7 fixed, but $\mathcal{C}_7^{(\text{eff}),\lambda} = \mathcal{C}_7 + \Delta\mathcal{C}_7^{\lambda}$, degenerate with 0th order tensor FF

Amplitude parameterisation

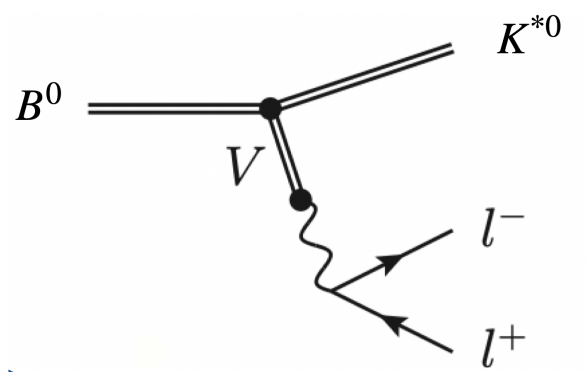
$$H_\lambda(q^2) = \sum_{j=all\,possible\,resonances} A_{\lambda,j}\mathscr{L}(q^2) = |A_{\lambda,j}|\, e^{i\delta_{j,\lambda}}\mathscr{L}(q^2)$$



Amplitude analysis over all q^2 - new!

$$H_\lambda(q^2) = \sum_{j=\text{all possible resonances}} A_{\lambda,j}\mathscr{L}(q^2) = |A_{\lambda,j}|\, e^{i\delta_{j,\lambda}}\mathscr{L}(q^2)$$

$H_\lambda(q^2) =$



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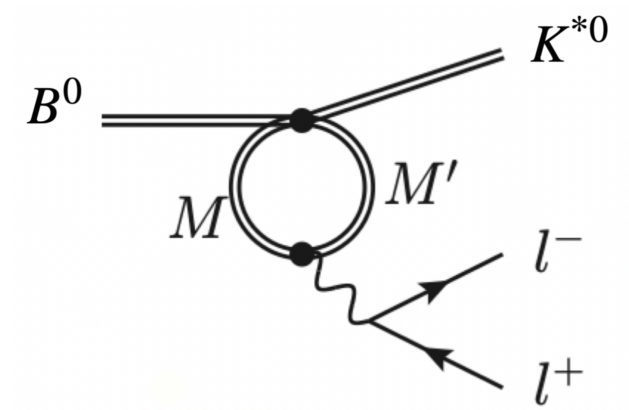

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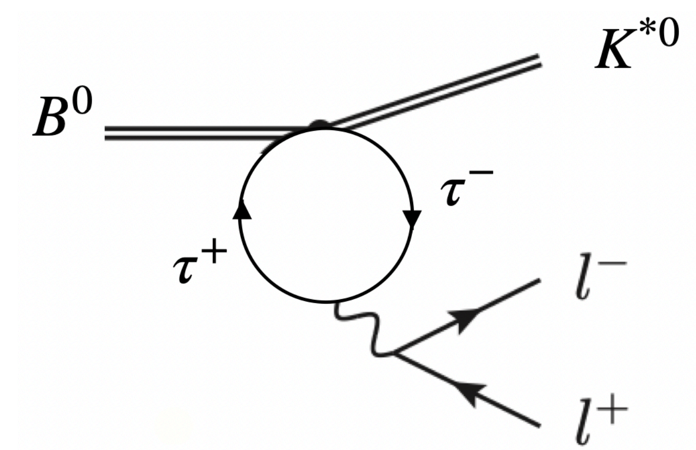


1-particle contributions

Includes:
$\omega(782)$, $\rho(770)$, $\phi(1020)$, J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$

2-particle contributions

Includes:
$D\overline{D}$,
$D^*\overline{D}$,
$D^*\overline{D}^*$

Tau loop contribution

Sensitive to C_9^τ

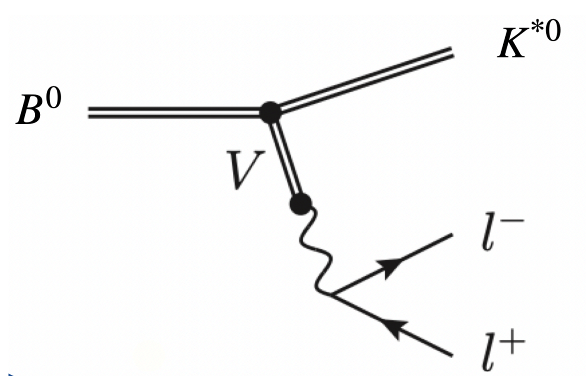
$\mathscr{L} = Breit - Wigner$

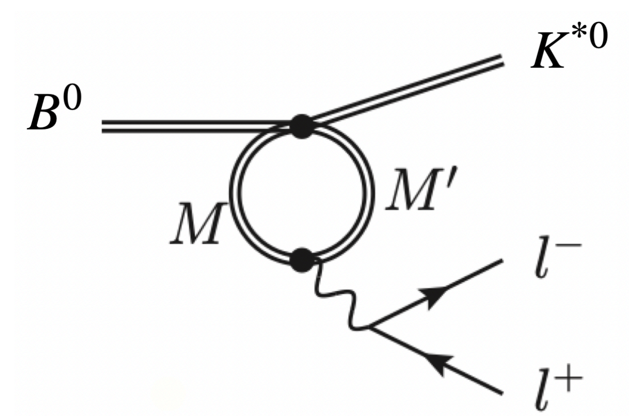
$\mathscr{L} = Dispersion - relation$

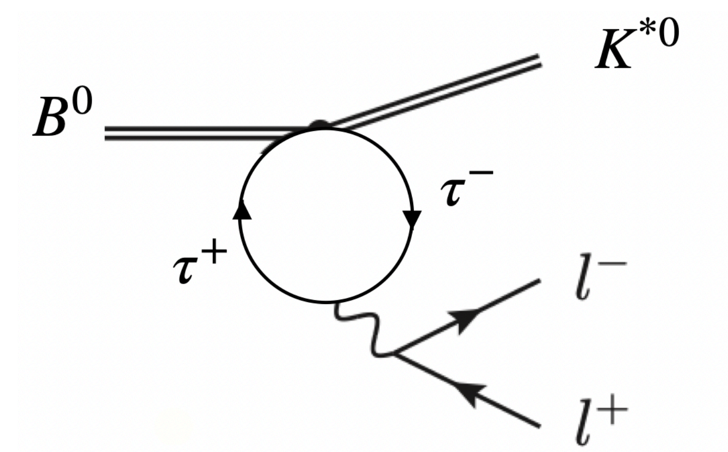
JHEP 02 (2013) 010 JHEP 1009:089,2010 Eur. Phys. J. C78 (2018) 453 *Eur.Phys.J.C* 80 (2020) 12, 1095

Amplitude analysis over all q^2 - new!

$$H_\lambda(q^2) = \sum_{j=\text{all possible resonances}} A_{\lambda,j}\mathcal{L}(q^2) = |A_{\lambda,j}|\, e^{i\delta_{j},\lambda}\mathcal{L}(q^2)$$

$H_\lambda(q^2) =$ 

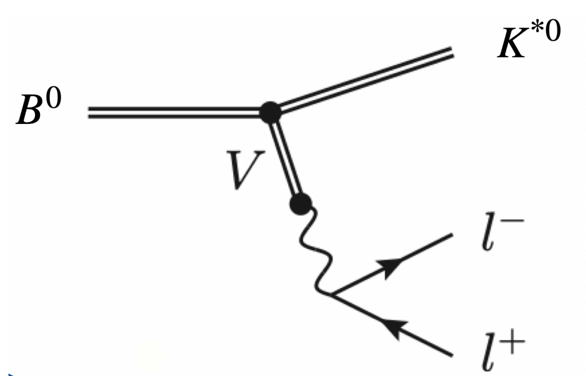
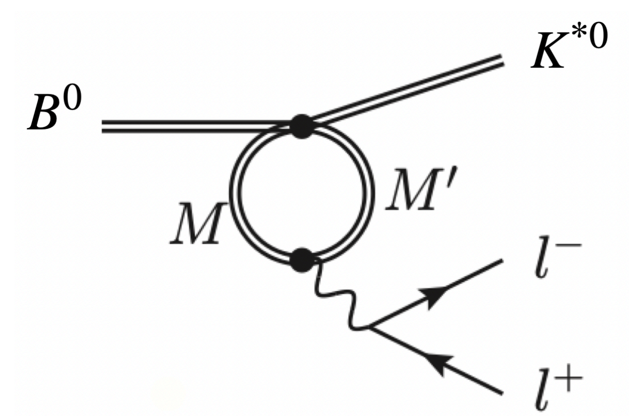
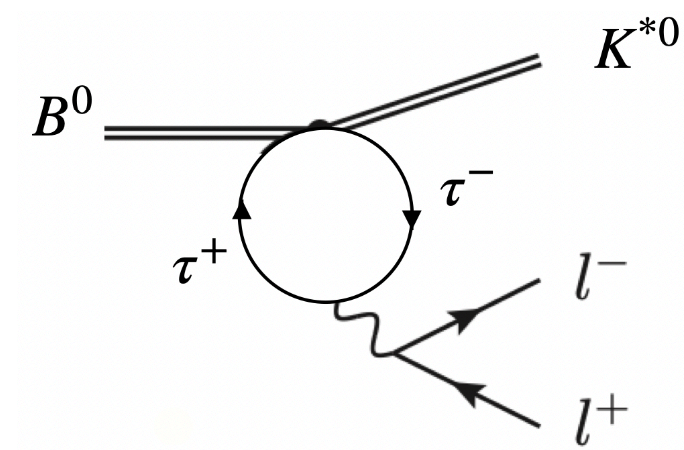
+ 

+ 

$$\Delta Y^{1\mathrm{P}}_{q\bar{q},\lambda}(q^2) = \sum_j |A_j^\lambda| e^{i\delta_j^\lambda} \frac{(q^2 - q_0^2)}{m_j^2 - q_0^2} BW_j(q^2);$$

Amplitude analysis over all q^2 - new!

$$H_\lambda(q^2) = \sum_{j=all\ possible\ resonances} A_{\lambda,j}\mathscr{L}(q^2) = |A_{\lambda,j}|\, e^{i\delta_{j,\lambda}}\mathscr{L}(q^2)$$

$H_\lambda(q^2) =$  +  + 

$$\Delta Y^{1P}_{q\bar{q},\lambda}(q^2) = \sum_j |A_j^\lambda| e^{i\delta_j^\lambda} \frac{(q^2 - q_0^2)}{m_j^2 - q_0^2} BW_j(q^2),$$

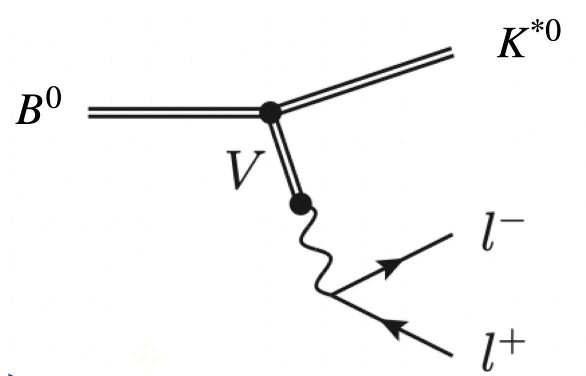
$$\rho^{2P}_{q\bar{q}}(q^2) = \sum_k \left[\frac{\lambda(q^2, m_{k_1}^2, m_{k_2}^2)}{q^2}\right]^{\frac{2L+1}{2}}$$

JHEP 02 (2013) 010 JHEP 1009:089,2010 Eur. Phys. J. C78 (2018) 453 *Eur.Phys.J.C* 80 (2020) 12, 1095

Amplitude analysis over all q^2 - new!

$$H_\lambda(q^2) = \sum_{j=\text{all possible resonances}} A_{\lambda,j}\mathscr{L}(q^2) = |A_{\lambda,j}|\, e^{i\delta_{j,\lambda}}\mathscr{L}(q^2)$$

$H_\lambda(q^2) =$



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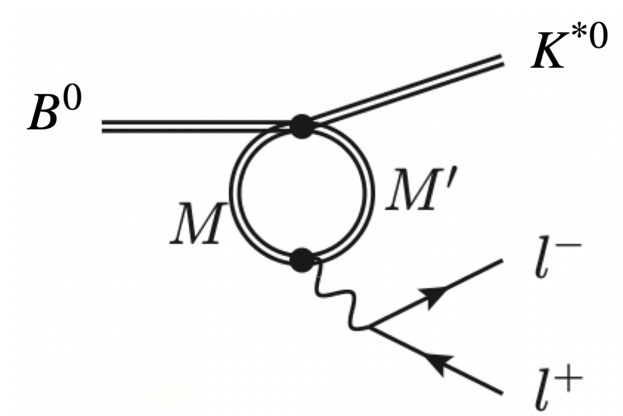

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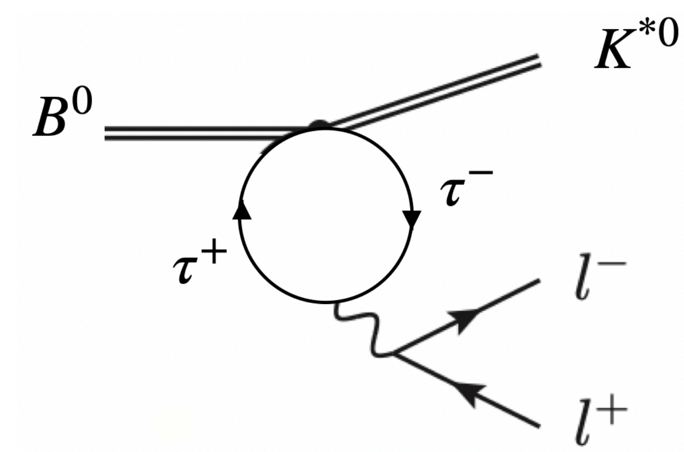

$$\Delta Y^{1P}_{q\bar{q},\lambda}(q^2) = \sum_j |A_j^\lambda| e^{i\delta_j^\lambda} \frac{(q^2 - q_0^2)}{m_j^2 - q_0^2} BW_j(q^2),$$

$$\Delta Y^{2P}_{q\bar{q},\lambda}(q^2) = \equiv |A^\lambda_{D^*\bar{D}}| e^{i\delta^\lambda_{D^*\bar{D}}} h_S(m_{D^*\bar{D}}, q^2) + \sum_{n=D\bar{D},D^*\bar{D}^*} |A_n^\lambda| e^{i\delta_n^\lambda} h_P(m_n, q^2),$$

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Fit projections

Amplitude model

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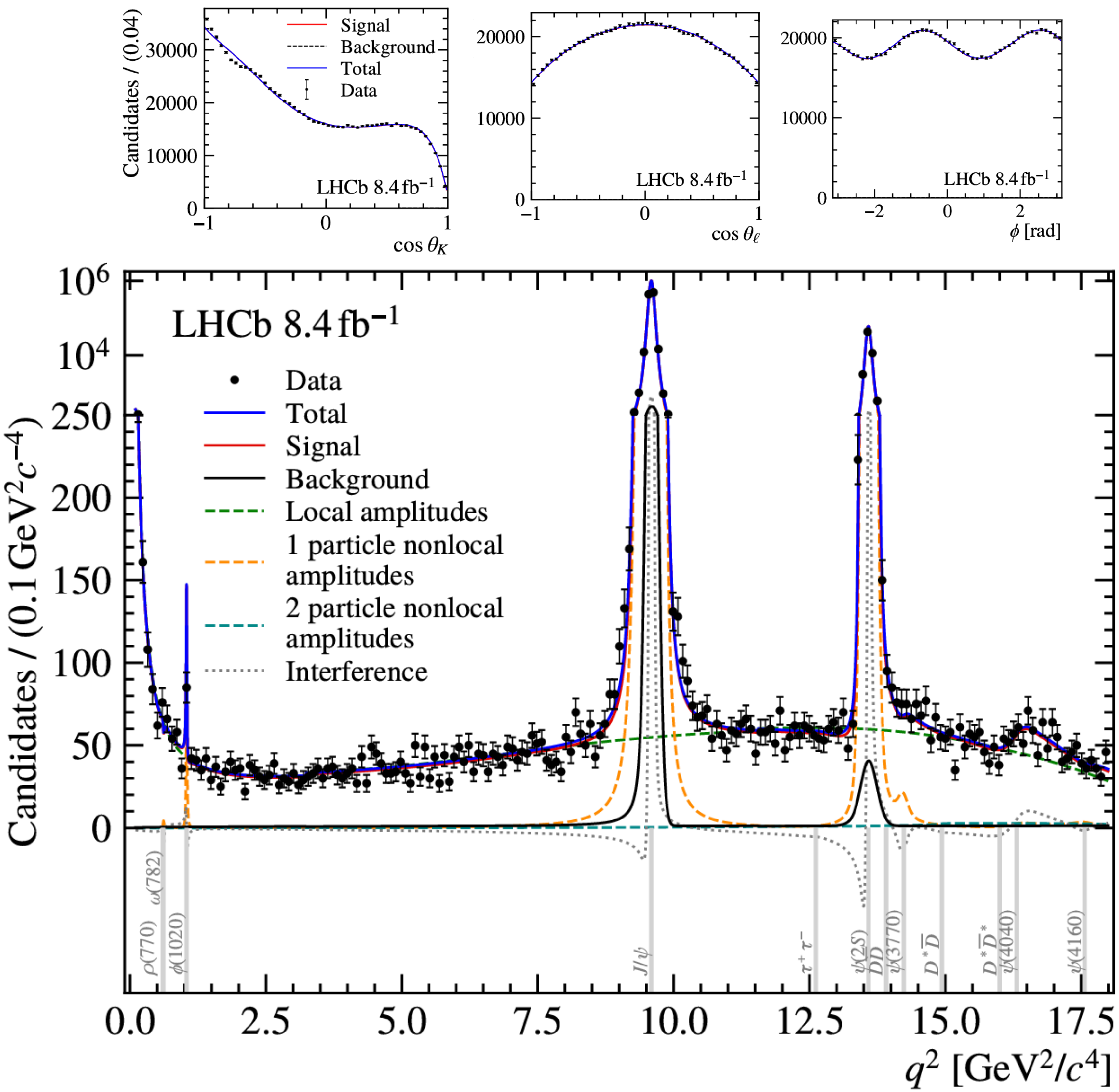
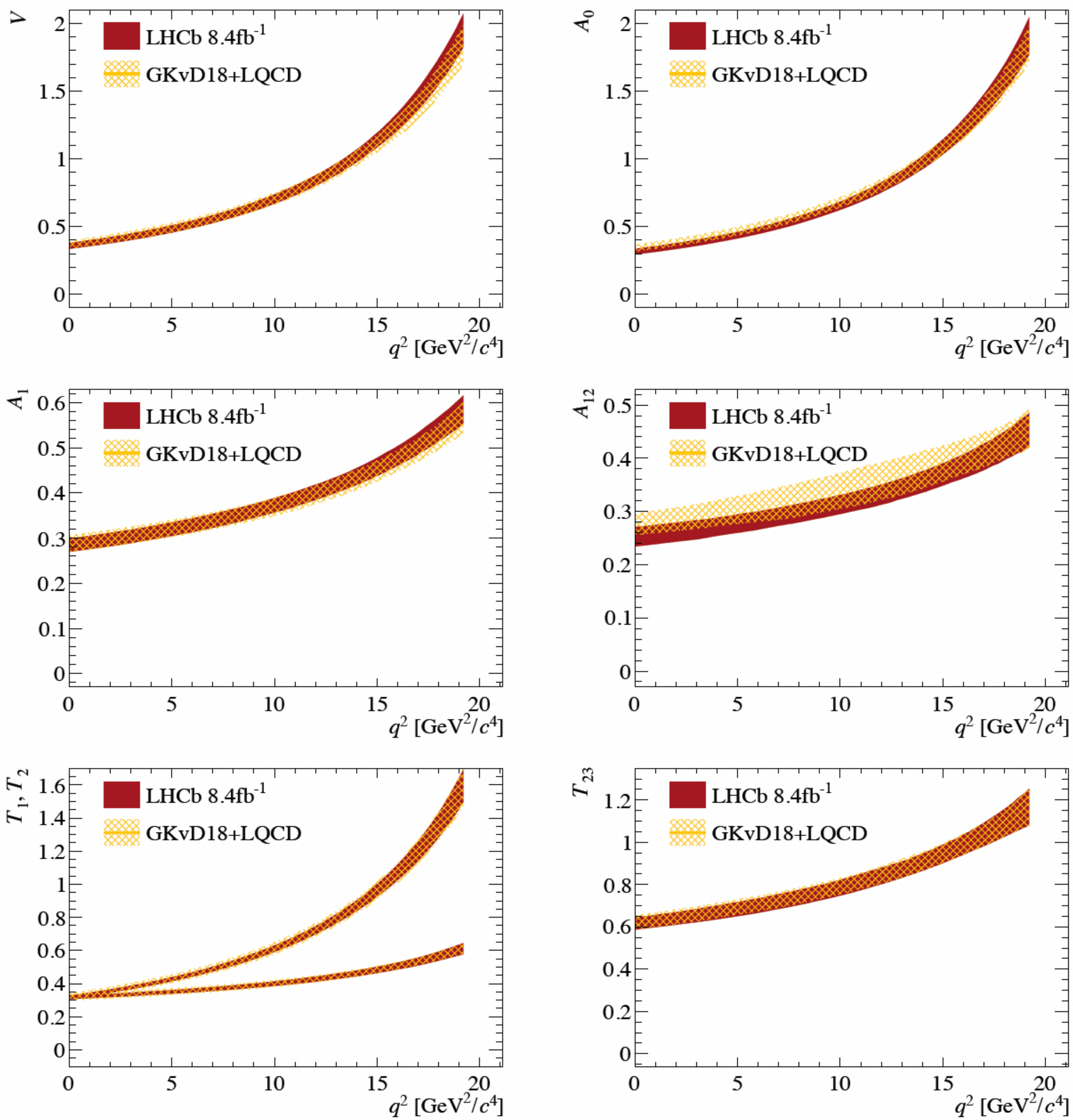


Amplitude analysis over all q^2 : results



Local form factors

arXiv:2206.03797

$$F_i(q^2) = \frac{1}{1 - q^2/m_{R,i}^2} \sum_{k=0}^{2} \alpha_{i,k} [z(q^2) - z(0)]^k,$$

Local form-factor results

Parameter	Prior [34]	Posterior
$\alpha_1^{A_0}$	-1.12 ± 0.20	$-1.21 \pm 0.19 \pm 0.02$
$\alpha_2^{A_0}$	2.18 ± 1.76	$3.23 \pm 1.69 \pm 0.18$
$\alpha_0^{A_1}$	0.29 ± 0.02	$0.29 \pm 0.01 \pm 0.00$
$\alpha_1^{A_1}$	0.46 ± 0.13	$0.40 \pm 0.10 \pm 0.01$
$\alpha_2^{A_1}$	1.22 ± 0.73	$1.21 \pm 0.69 \pm 0.10$
$\alpha_0^{A_{12}}$	0.28 ± 0.02	$0.26 \pm 0.02 \pm 0.00$
$\alpha_1^{A_{12}}$	0.55 ± 0.34	$0.47 \pm 0.22 \pm 0.04$
$\alpha_2^{A_{12}}$	0.58 ± 2.08	$0.53 \pm 1.26 \pm 0.17$
α_0^{V}	0.36 ± 0.03	$0.36 \pm 0.02 \pm 0.00$
α_1^{V}	-1.09 ± 0.17	$-1.09 \pm 0.17 \pm 0.01$
α_2^{V}	2.73 ± 1.99	$3.93 \pm 1.74 \pm 0.25$
$\alpha_1^{T_1}$	-0.95 ± 0.14	$-0.94 \pm 0.14 \pm 0.01$
$\alpha_2^{T_1}$	2.11 ± 1.28	$2.07 \pm 1.16 \pm 0.05$
$\alpha_0^{T_2}$	0.32 ± 0.02	–
$\alpha_1^{T_2}$	0.60 ± 0.18	$0.61 \pm 0.16 \pm 0.01$
$\alpha_2^{T_2}$	1.70 ± 0.99	$1.78 \pm 0.98 \pm 0.03$
$\alpha_0^{T_{23}}$	0.62 ± 0.03	–
$\alpha_1^{T_{23}}$	0.97 ± 0.32	$0.95 \pm 0.30 \pm 0.01$
$\alpha_2^{T_{23}}$	1.81 ± 2.45	$1.68 \pm 2.15 \pm 0.04$

Size of $H_\lambda(q^2)$?

$$H_\lambda(q^2) = \sum_{j=\text{all possible resonances}} A_{\lambda,j}\mathscr{L}(q^2) = |A_{\lambda,j}|\, e^{i\delta_{j,\lambda}}\mathscr{L}(q^2)$$

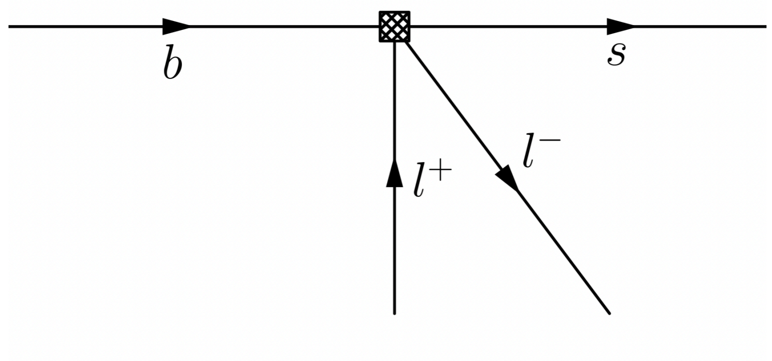
Nonlocal parameter results			
$\lvert A^{\parallel}_{J/\psi}\rvert$	$(3.98 \pm 0.01 \pm 0.15) \times 10^{-3}$	$\delta^{\parallel}_{J/\psi}$	$0.23 \pm 0.01 \pm 0.01$
$\lvert A^{\perp}_{J/\psi}\rvert$	$(3.85 \pm 0.01 \pm 0.14) \times 10^{-3}$	$\delta^{\perp}_{J/\psi}$	$-0.21 \pm 0.00 \pm 0.01$
$\lvert A^{0}_{J/\psi}\rvert$	–	$\delta^{0}_{J/\psi}$	$-1.92 \pm 0.05 \pm 0.02$
$\lvert A^{\parallel}_{\psi(2S)}\rvert$	$(9.59 \pm 0.28 \pm 0.82) \times 10^{-4}$	$\delta^{\parallel}_{\psi(2S)}$	$0.84 \pm 0.02 \pm 0.19$
$\lvert A^{\perp}_{\psi(2S)}\rvert$	$(8.38 \pm 0.27 \pm 0.62) \times 10^{-4}$	$\delta^{\perp}_{\psi(2S)}$	$-0.44 \pm 0.02 \pm 0.11$
$\lvert A^{0}_{\psi(2S)}\rvert$	$(13.4 \pm 0.4 \pm 1.1) \times 10^{-4}$	$\delta^{0}_{\psi(2S)}$	$-2.54 \pm 0.13 \pm 0.12$
$\lvert A^{0}_{\rho(770)}\rvert$	–	$\delta^{0}_{\rho(770)}$	$1.38 \pm 0.53 \pm 0.65$
$\lvert A^{0}_{\omega(782)}\rvert$	–	$\delta^{0}_{\omega(782)}$	$-0.49 \pm 0.92 \pm 0.53$
$\lvert A^{0}_{\phi(1020)}\rvert$	–	$\delta^{0}_{\phi(1020)}$	$0.10 \pm 0.82 \pm 0.78$

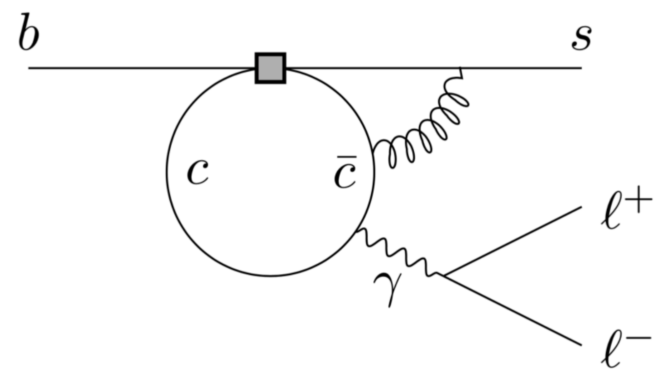
Nonlocal parameter results ($\times 10^{-5}$)			
$\Re(A^{\parallel}_{\psi(3770)})$	$3.68 \pm 1.34 \pm 0.73$	$\Im(A^{\parallel}_{\psi(3770)})$	$2.87 \pm 1.88 \pm 0.49$
$\Re(A^{\perp}_{\psi(3770)})$	$-3.53 \pm 1.45 \pm 0.47$	$\Im(A^{\perp}_{\psi(3770)})$	$-0.86 \pm 1.56 \pm 0.53$
$\Re(A^{0}_{\psi(3770)})$	$-3.14 \pm 1.39 \pm 0.60$	$\Im(A^{0}_{\psi(3770)})$	$1.67 \pm 1.54 \pm 0.62$
$\Re(A^{\parallel}_{\psi(4040)})$	$-2.39 \pm 1.53 \pm 0.96$	$\Im(A^{\parallel}_{\psi(4040)})$	$-0.71 \pm 1.80 \pm 1.11$
$\Re(A^{\perp}_{\psi(4040)})$	$-2.01 \pm 1.47 \pm 0.59$	$\Im(A^{\perp}_{\psi(4040)})$	$0.35 \pm 1.49 \pm 0.82$
$\Re(A^{0}_{\psi(4040)})$	$-5.62 \pm 1.71 \pm 1.07$	$\Im(A^{0}_{\psi(4040)})$	$1.32 \pm 1.87 \pm 0.99$
$\Re(A^{\parallel}_{\psi(4160)})$	$0.04 \pm 1.72 \pm 0.56$	$\Im(A^{\parallel}_{\psi(4160)})$	$1.91 \pm 1.98 \pm 1.45$
$\Re(A^{\perp}_{\psi(4160)})$	$-2.81 \pm 1.75 \pm 0.61$	$\Im(A^{\perp}_{\psi(4160)})$	$0.32 \pm 0.15 \pm 0.09$
$\Re(A^{0}_{\psi(4160)})$	$1.03 \pm 1.77 \pm 0.39$	$\Im(A^{0}_{\psi(4160)})$	$-1.66 \pm 1.67 \pm 1.04$

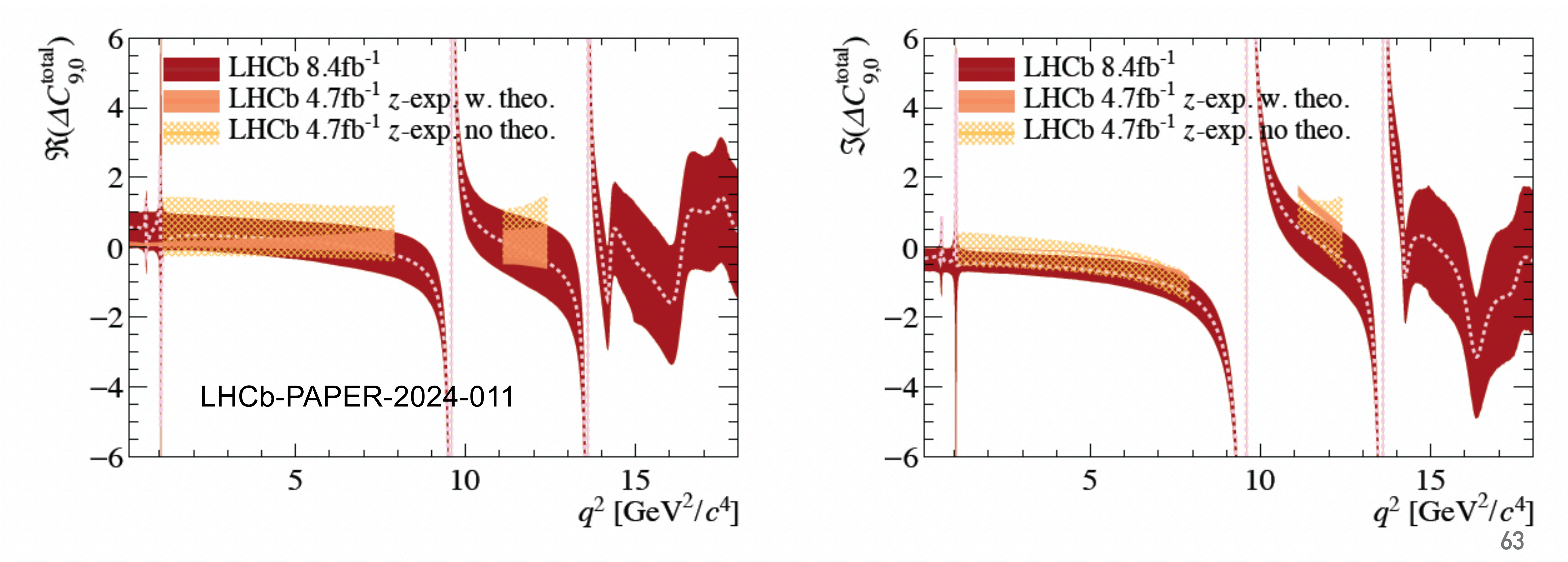
Nonlocal parameter results			
$\Re(A^{\parallel}_{D^0\bar{D}^0})$	$-0.07 \pm 0.93 \pm 0.69$	$\Im(A^{\parallel}_{D^0\bar{D}^0})$	$-0.44 \pm 0.71 \pm 0.73$
$\Re(A^{\perp}_{D^0\bar{D}^0})$	$-0.12 \pm 0.83 \pm 0.71$	$\Im(A^{\perp}_{D^0\bar{D}^0})$	$0.02 \pm 0.80 \pm 0.74$
$\Re(A^{0}_{D^0\bar{D}^0})$	$-0.33 \pm 0.91 \pm 0.70$	$\Im(A^{0}_{D^0\bar{D}^0})$	$-0.27 \pm 0.77 \pm 0.81$
$\Re(A^{\parallel}_{D^{*0}\bar{D}^{*0}})$	$-0.06 \pm 0.96 \pm 0.63$	$\Im(A^{\parallel}_{D^{*0}\bar{D}^{*0}})$	$-0.25 \pm 0.79 \pm 0.67$
$\Re(A^{\perp}_{D^{*0}\bar{D}^{*0}})$	$-0.16 \pm 0.91 \pm 0.66$	$\Im(A^{\perp}_{D^{*0}\bar{D}^{*0}})$	$-0.03 \pm 0.85 \pm 0.70$
$\Re(A^{0}_{D^{*0}\bar{D}^{*0}})$	$-0.17 \pm 0.95 \pm 0.66$	$\Im(A^{0}_{D^{*0}\bar{D}^{*0}})$	$-0.28 \pm 0.85 \pm 0.78$
$\Re(A^{\parallel}_{D^{*0}\bar{D}^0})$	$0.02 \pm 0.42 \pm 0.66$	$\Im(A^{\parallel}_{D^{*0}\bar{D}^0})$	$-0.46 \pm 0.32 \pm 0.58$
$\Re(A^{\perp}_{D^{*0}\bar{D}^0})$	$-0.24 \pm 0.42 \pm 0.70$	$\Im(A^{\perp}_{D^{*0}\bar{D}^0})$	$-0.11 \pm 0.39 \pm 0.61$
$\Re(A^{0}_{D^{*0}\bar{D}^0})$	$-0.51 \pm 0.41 \pm 0.68$	$\Im(A^{0}_{D^{*0}\bar{D}^0})$	$0.12 \pm 0.35 \pm 0.58$
$\Re(\Delta\mathcal{C}^{\parallel}_7)$	$0.00 \pm 0.03 \pm 0.02$	$\Im(\Delta\mathcal{C}^{\parallel}_7)$	$-0.10 \pm 0.03 \pm 0.01$
$\Re(\Delta\mathcal{C}^{\perp}_7)$	$-0.05 \pm 0.03 \pm 0.02$	$\Im(\Delta\mathcal{C}^{\perp}_7)$	$-0.04 \pm 0.04 \pm 0.01$
$\Re(\Delta\mathcal{C}^{0}_7)$	$0.33 \pm 0.33 \pm 0.09$	$\Im(\Delta\mathcal{C}^{0}_7)$	$-0.19 \pm 0.20 \pm 0.09$

Size of $H_\lambda(q^2)$?

$$C_{9,\lambda}^{eff}(q^2) = C_9 + H_\lambda(q^2)$$







Size of $H_\lambda(q^2)$?

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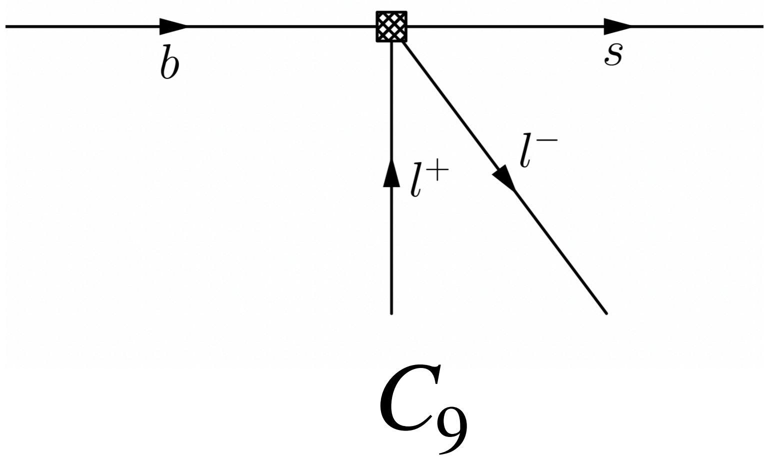
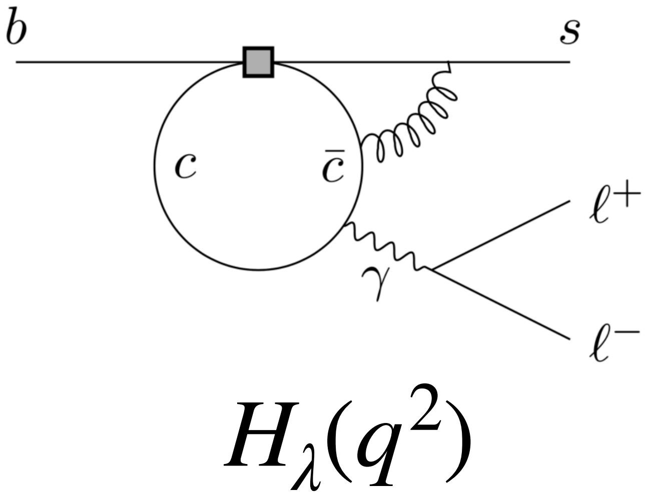
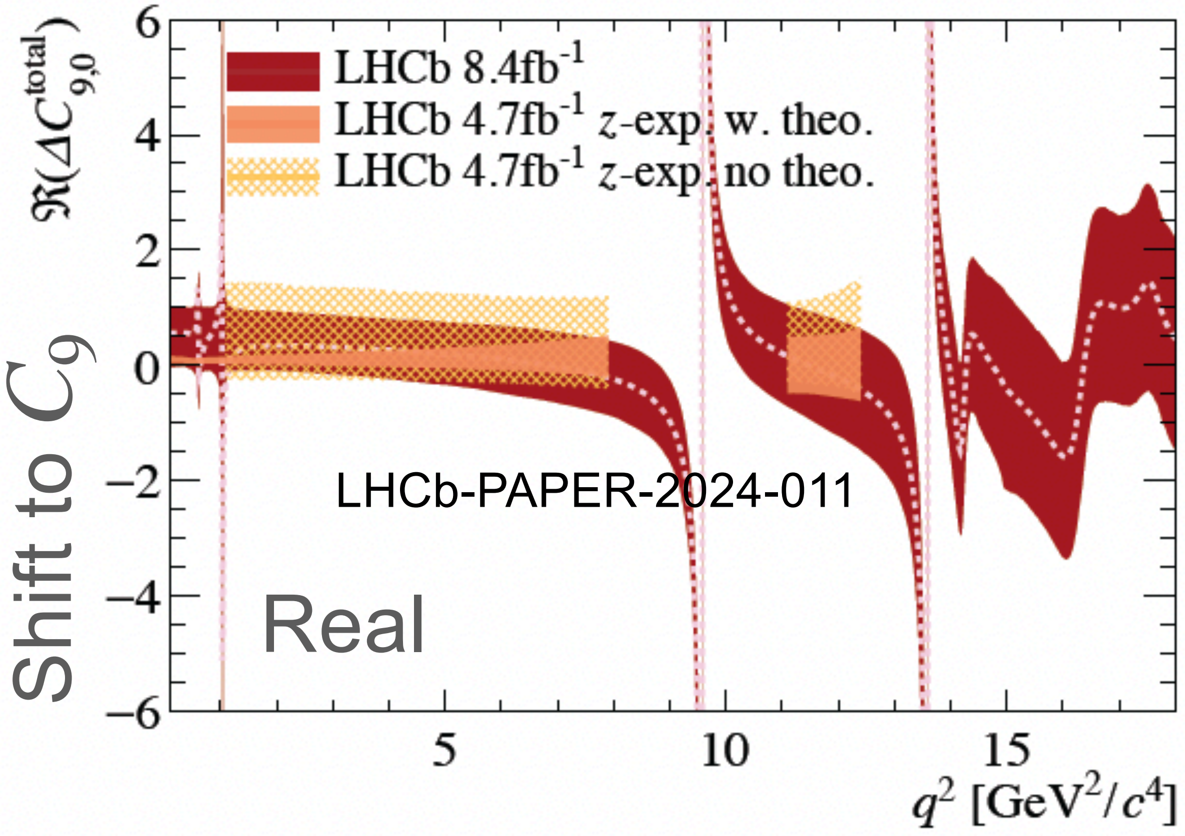
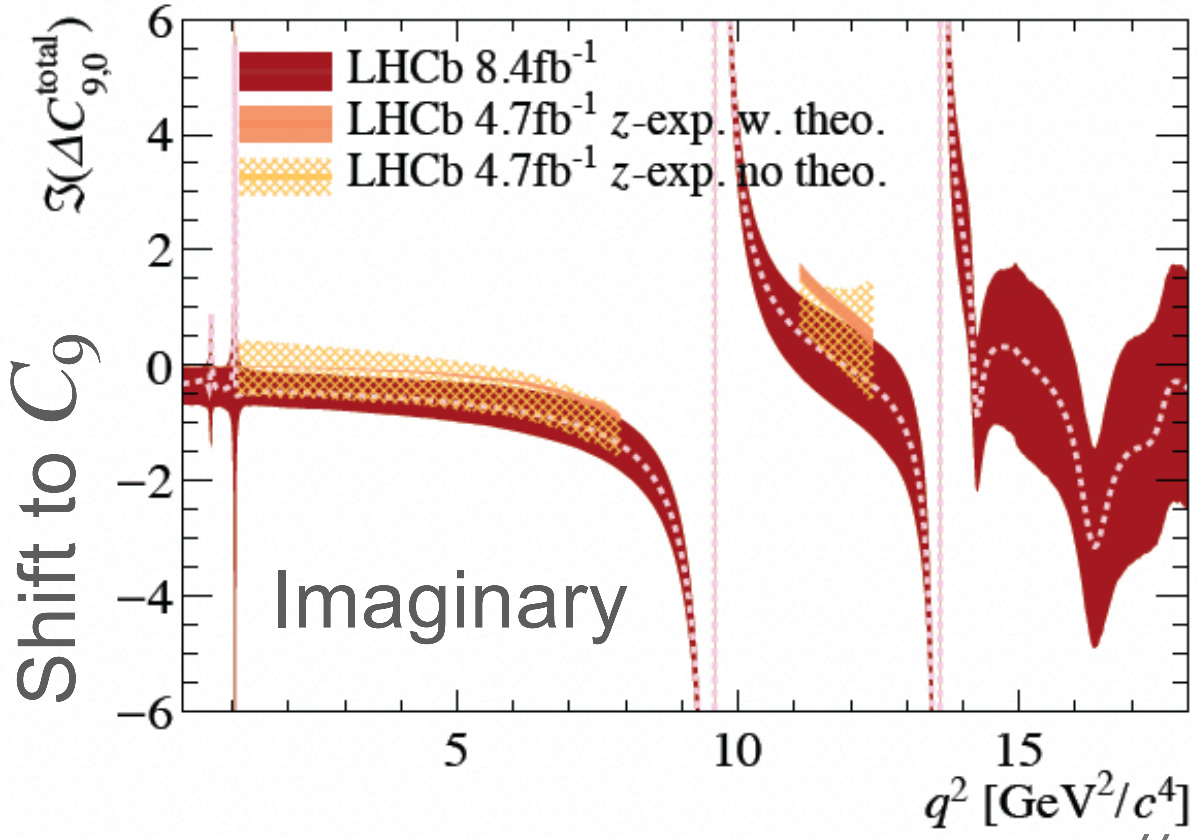




Z-expansion Amplitude

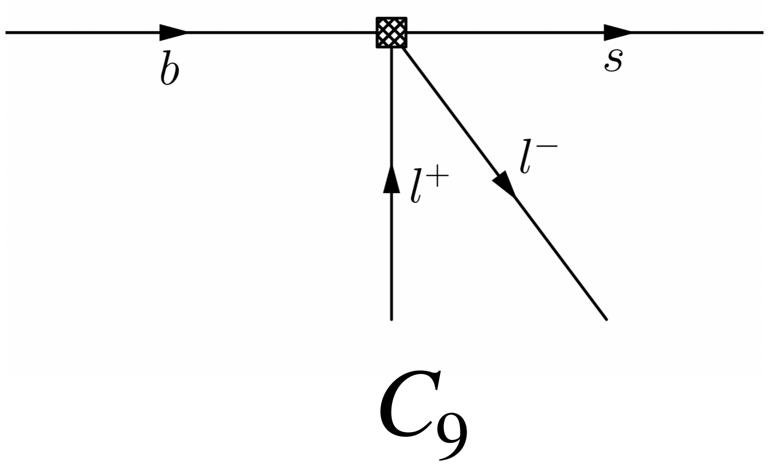
Example $\lambda = 0$

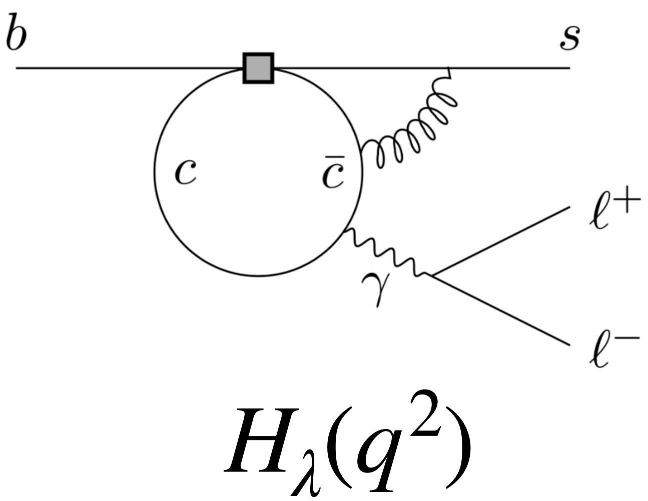




Size of $H_\lambda(q^2)$?

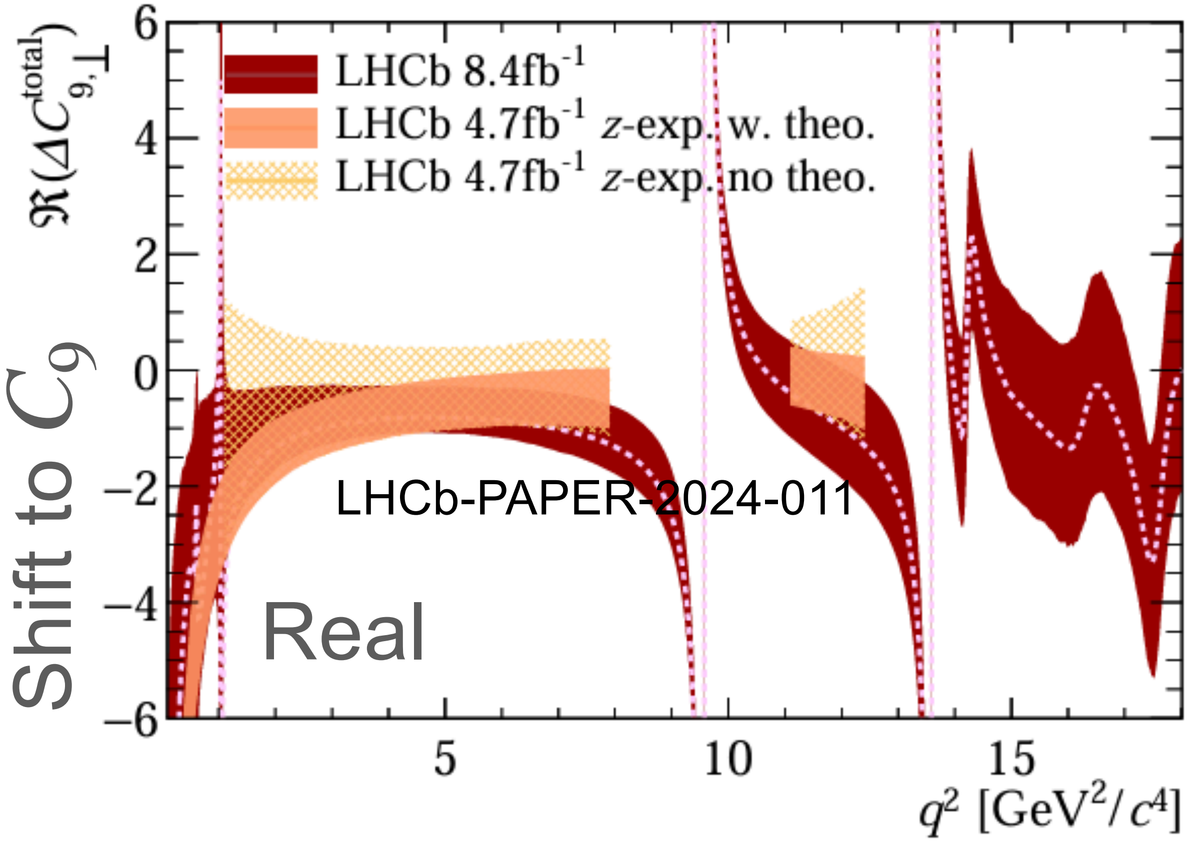
$$C^{eff}_{9,\lambda}(q^2) = C_9 + H_\lambda(q^2)$$

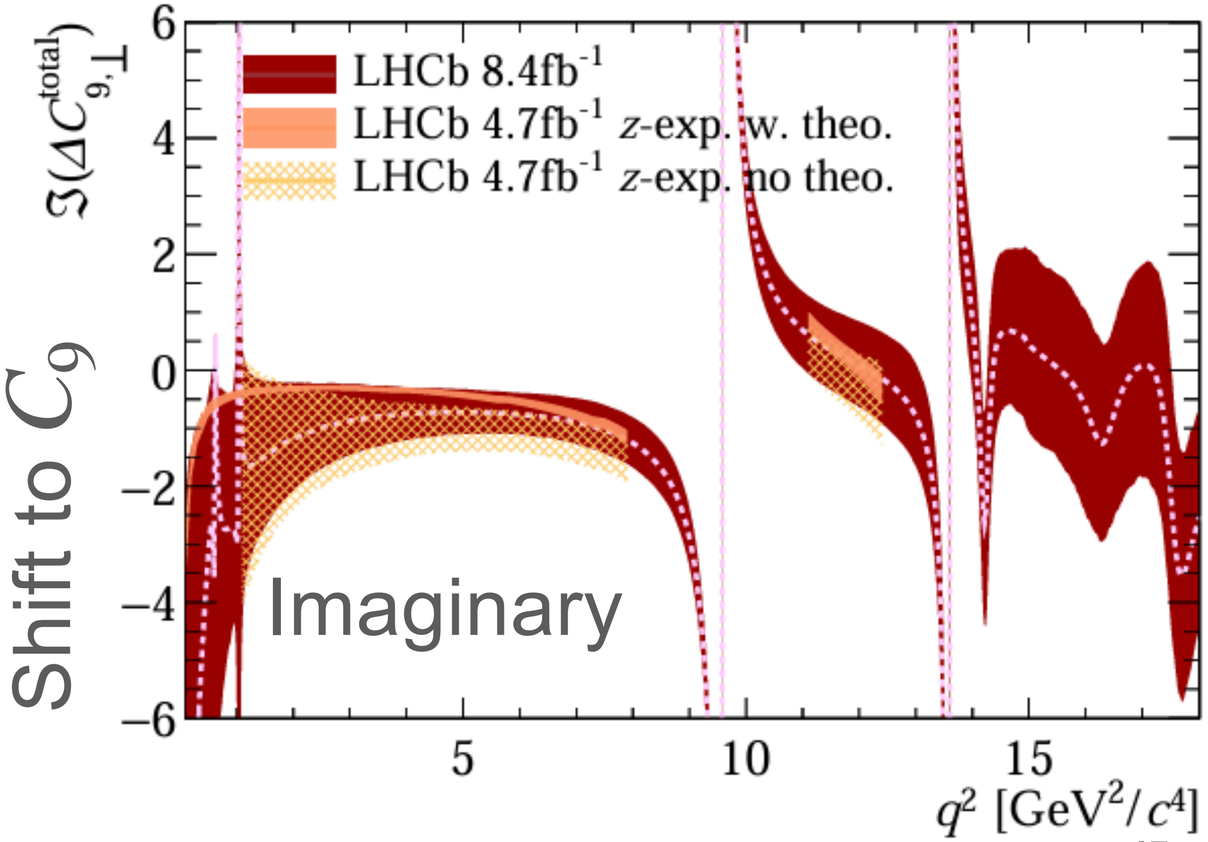




Z-expansion Amplitude

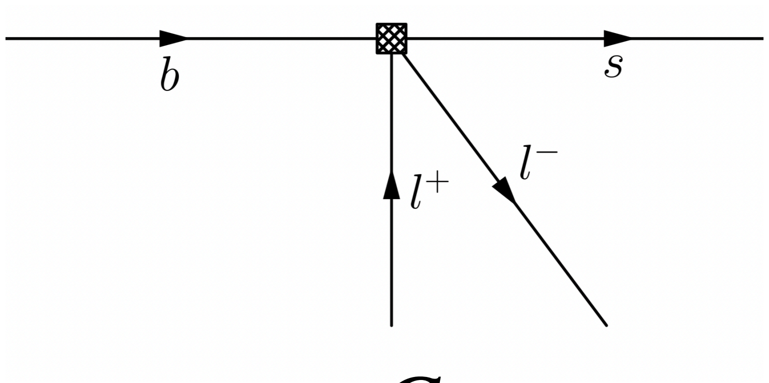
Example $\lambda = \perp$





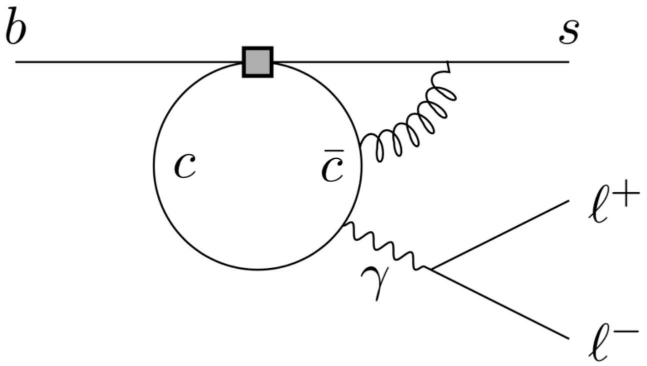
Size of $H_\lambda(q^2)$?

$$C^{eff}_{9,\lambda}(q^2) =$$



C_9

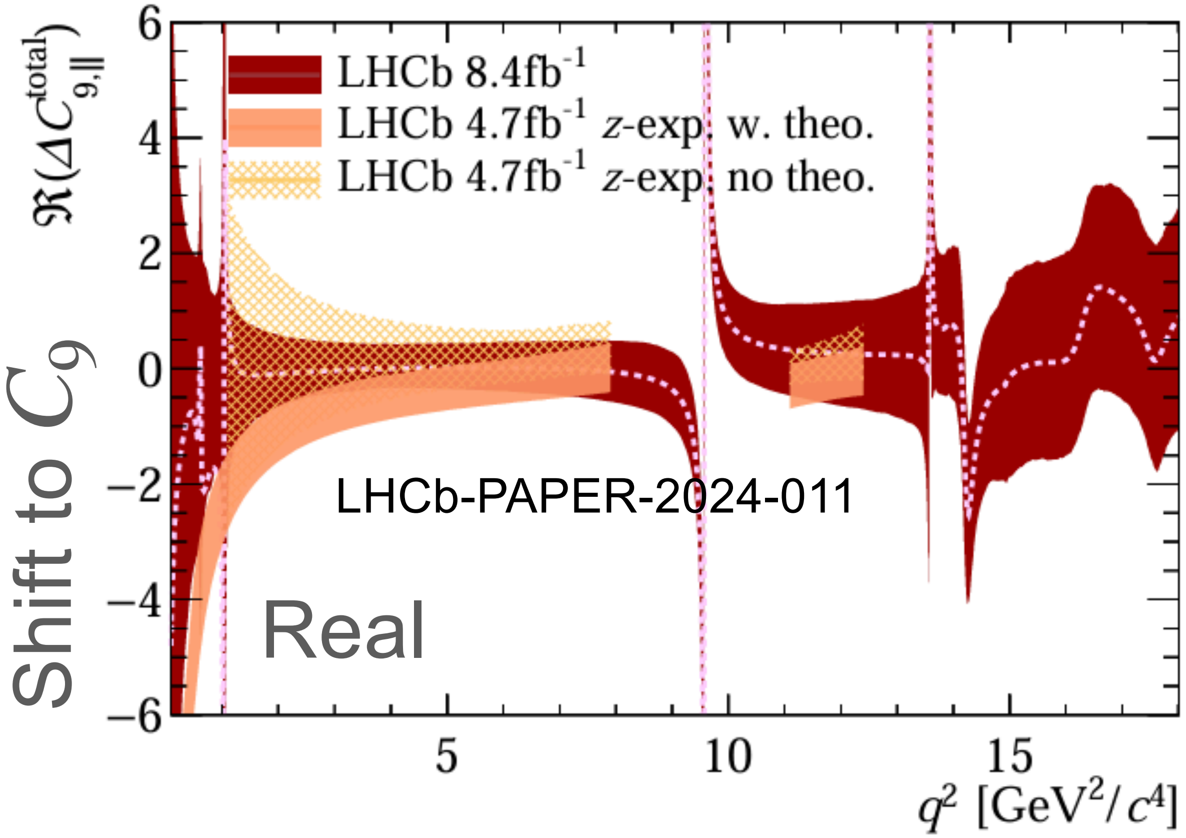
$+$

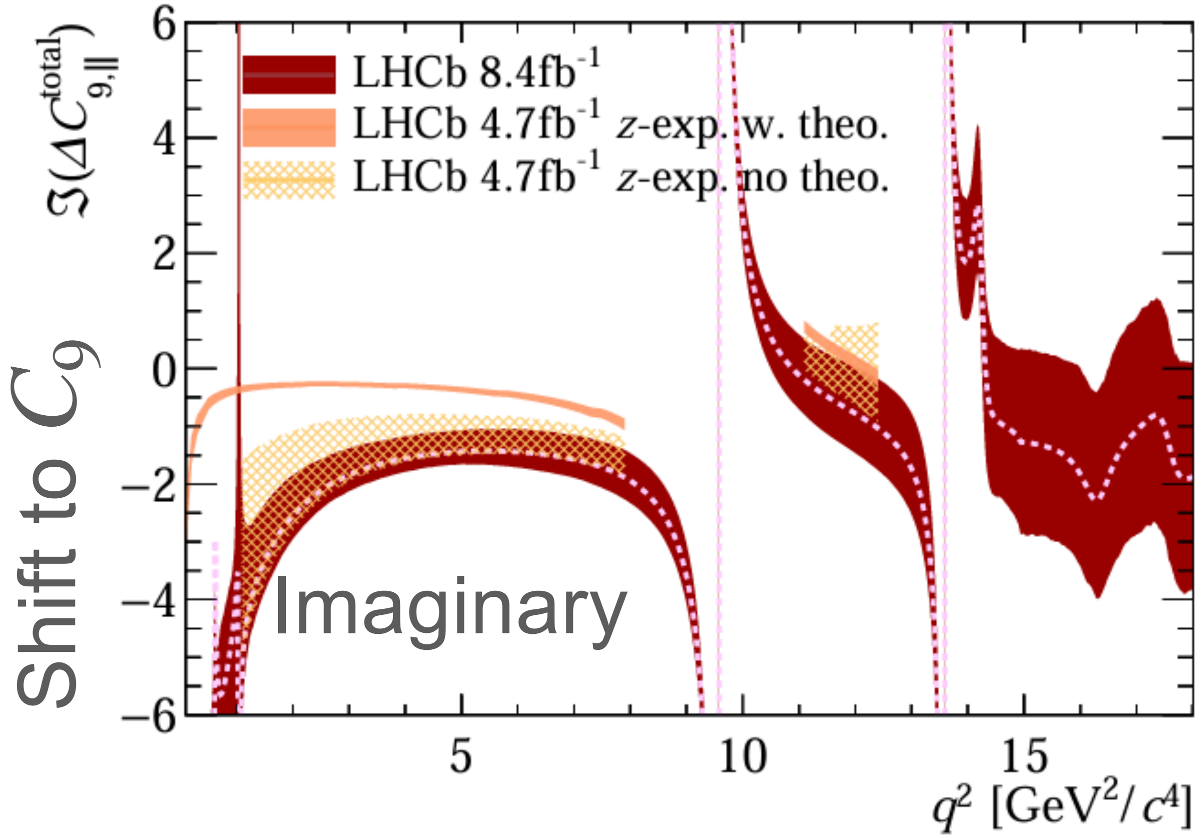


$H_\lambda(q^2)$

Z-expansion   Amplitude

Example $\lambda = ||$





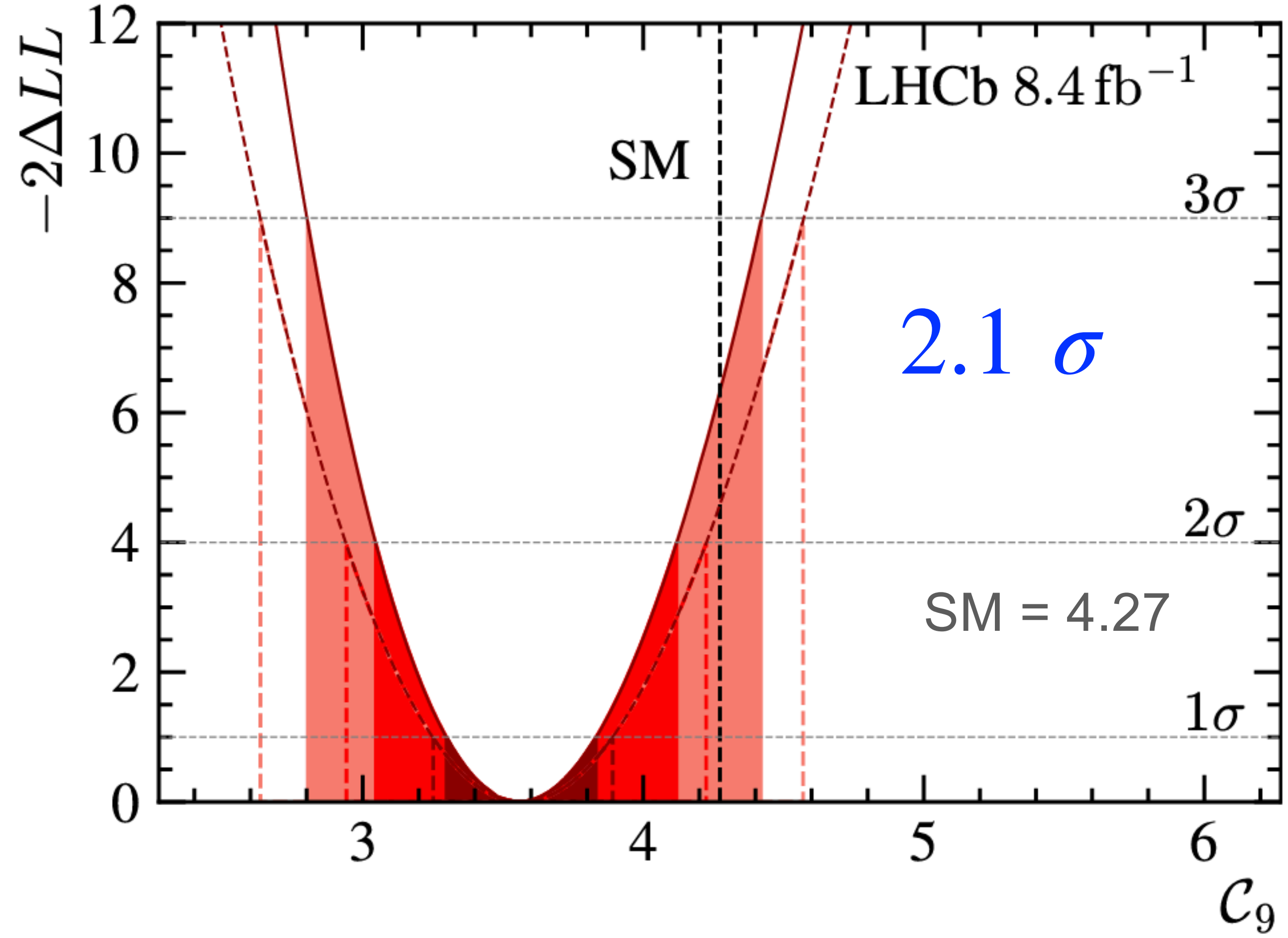
Measured values of C_9 ?

Measured values of C_9 ?

LHCb-PAPER-2023-032

LHCb-PAPER-2024-011

Amplitude model



$$\Delta C_9^{NP} = -0.71 \pm 0.33$$

Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}_9'$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}_{10}'$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

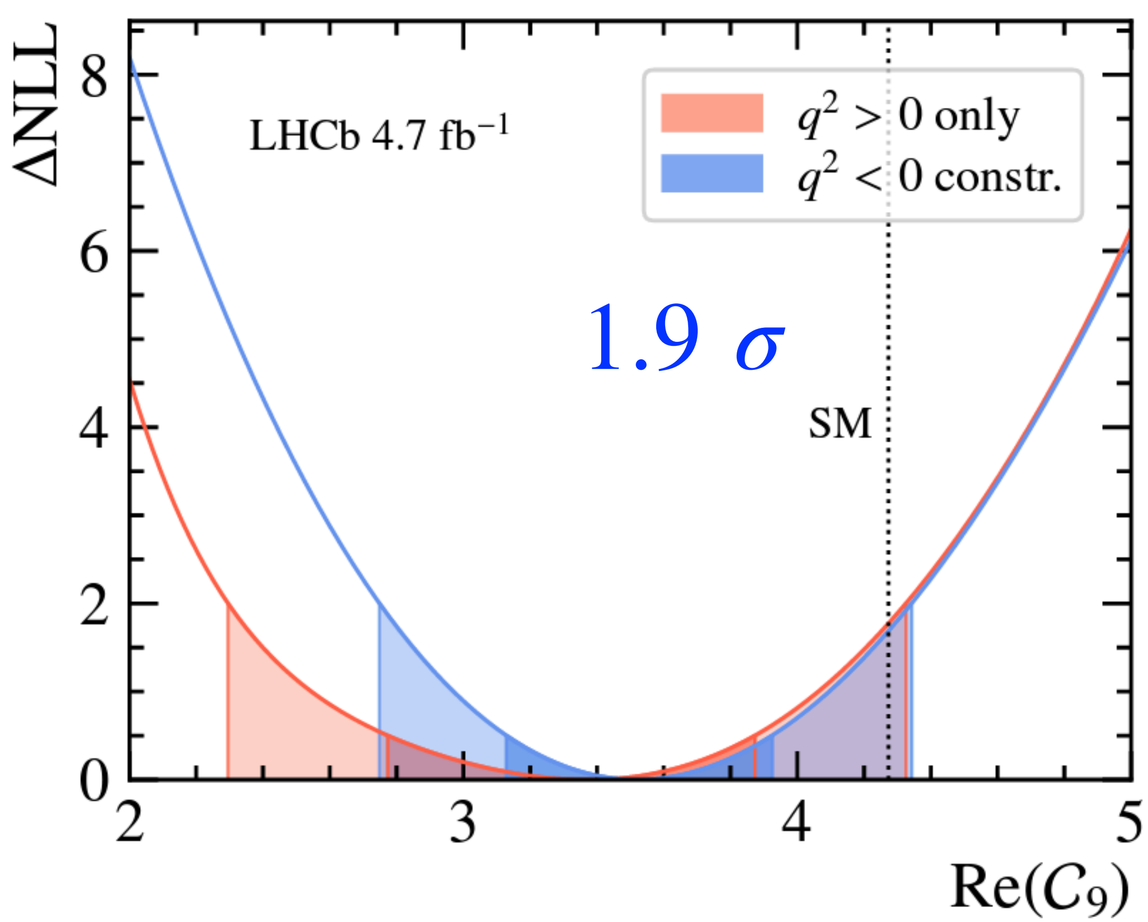
Measured values of C_9 ?

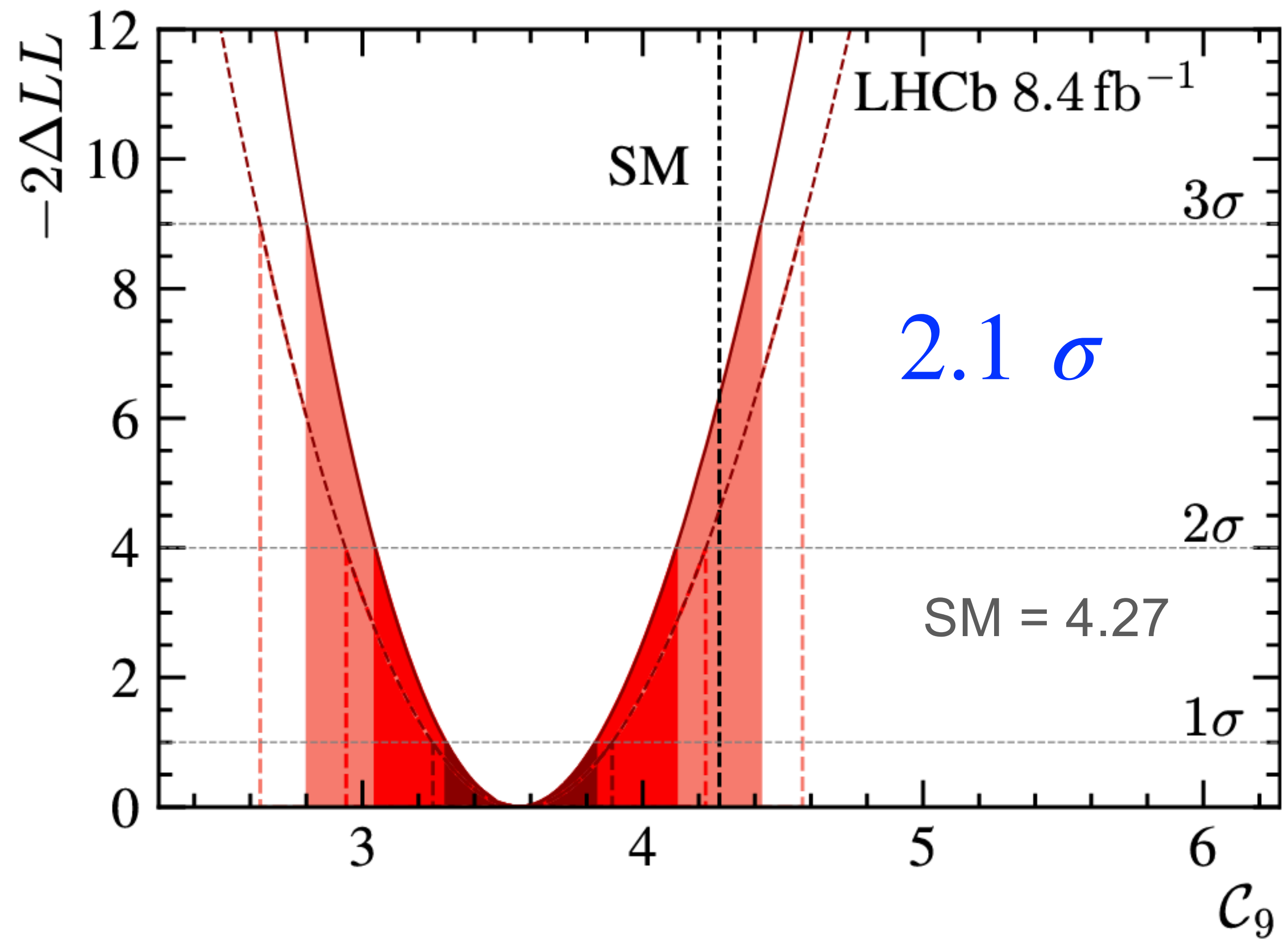
LHCb-PAPER-2023-032

LHCb-PAPER-2024-011

Z-expansion

Amplitude model





$$\Delta C_9^{NP} = -0.93^{+0.53}_{-0.57}$$

$$\Delta C_9^{NP} = -0.71 \pm 0.33$$

	$q^2 > 0$ only				
	best fit value	68% C.I.	95% C.I.	SM value	deviation from SM
$\mathcal{C}_9$	3.34	[2.77, 3.87]	[2.30, 4.33]	4.27	1.9 σ
$\mathcal{C}_{10}$	−3.69	[−4.00, −3.40]	[−4.33, −3.12]	−4.17	1.5 σ
$\mathcal{C}_9'$	0.48	[−0.07, 0.97]	[−0.62, 1.45]	0	0.9 σ
$\mathcal{C}_{10}'$	0.38	[0.13, 0.66]	[−0.14, 0.92]	0	1.5 σ

Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
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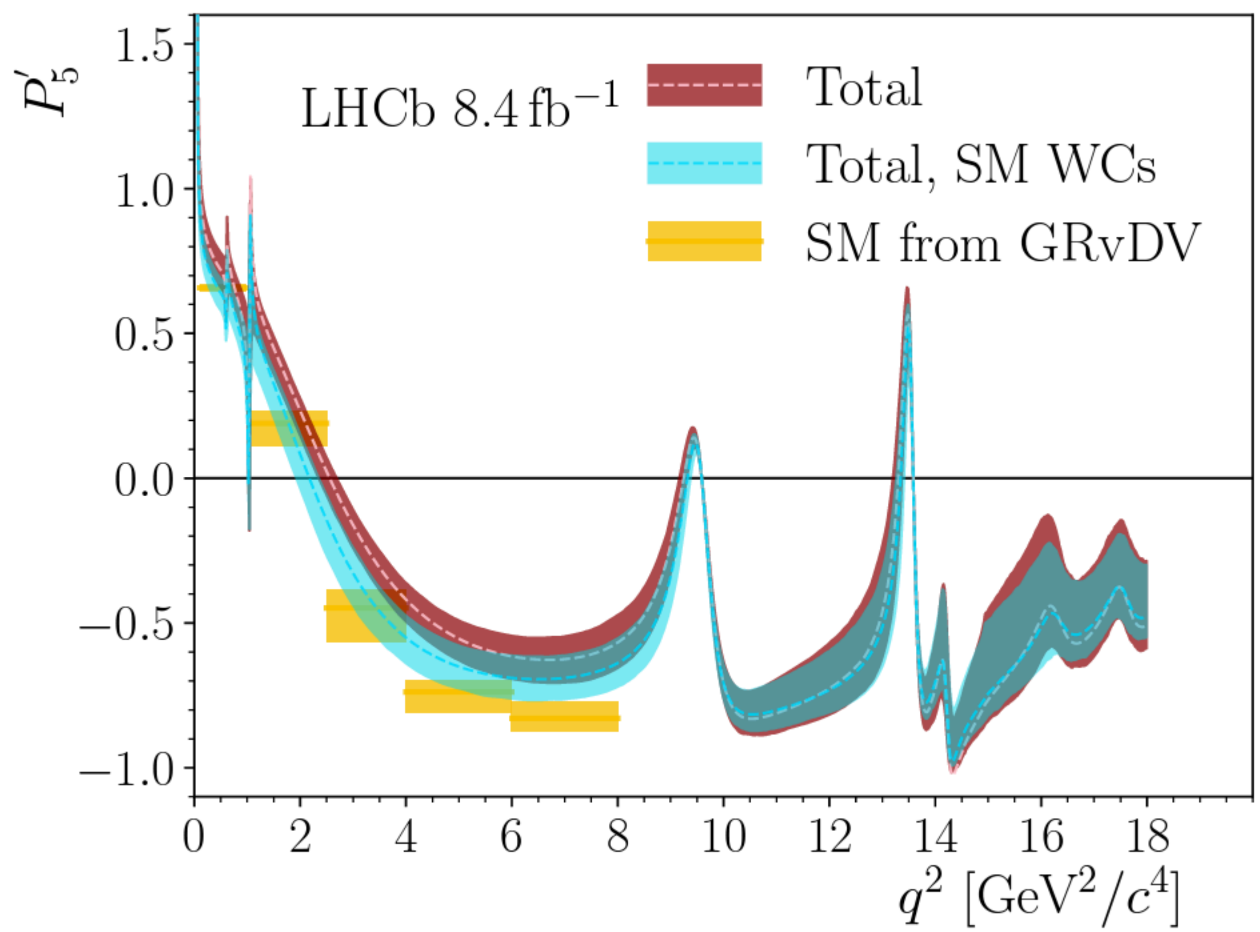
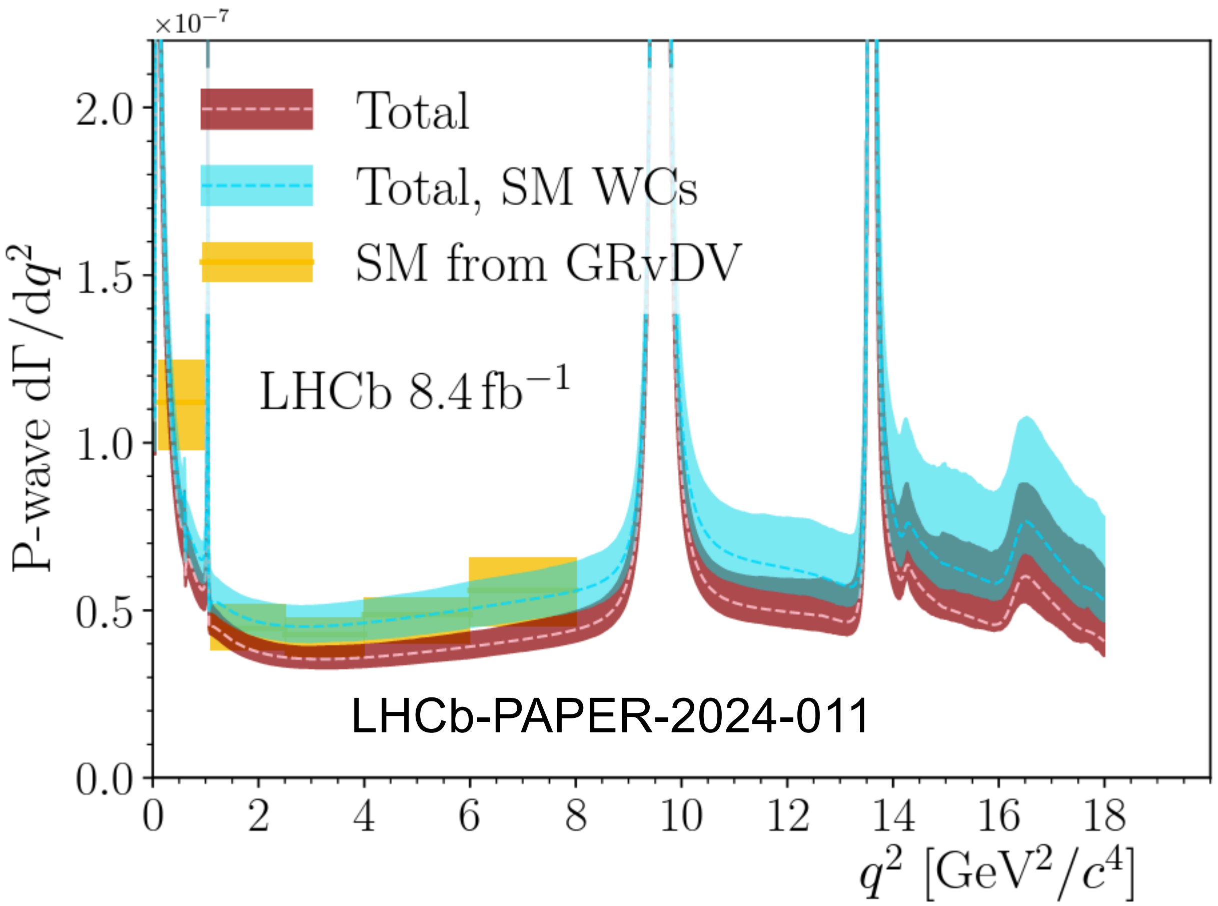
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

Affect of non-local contributions on branching fractions?

Amplitude model

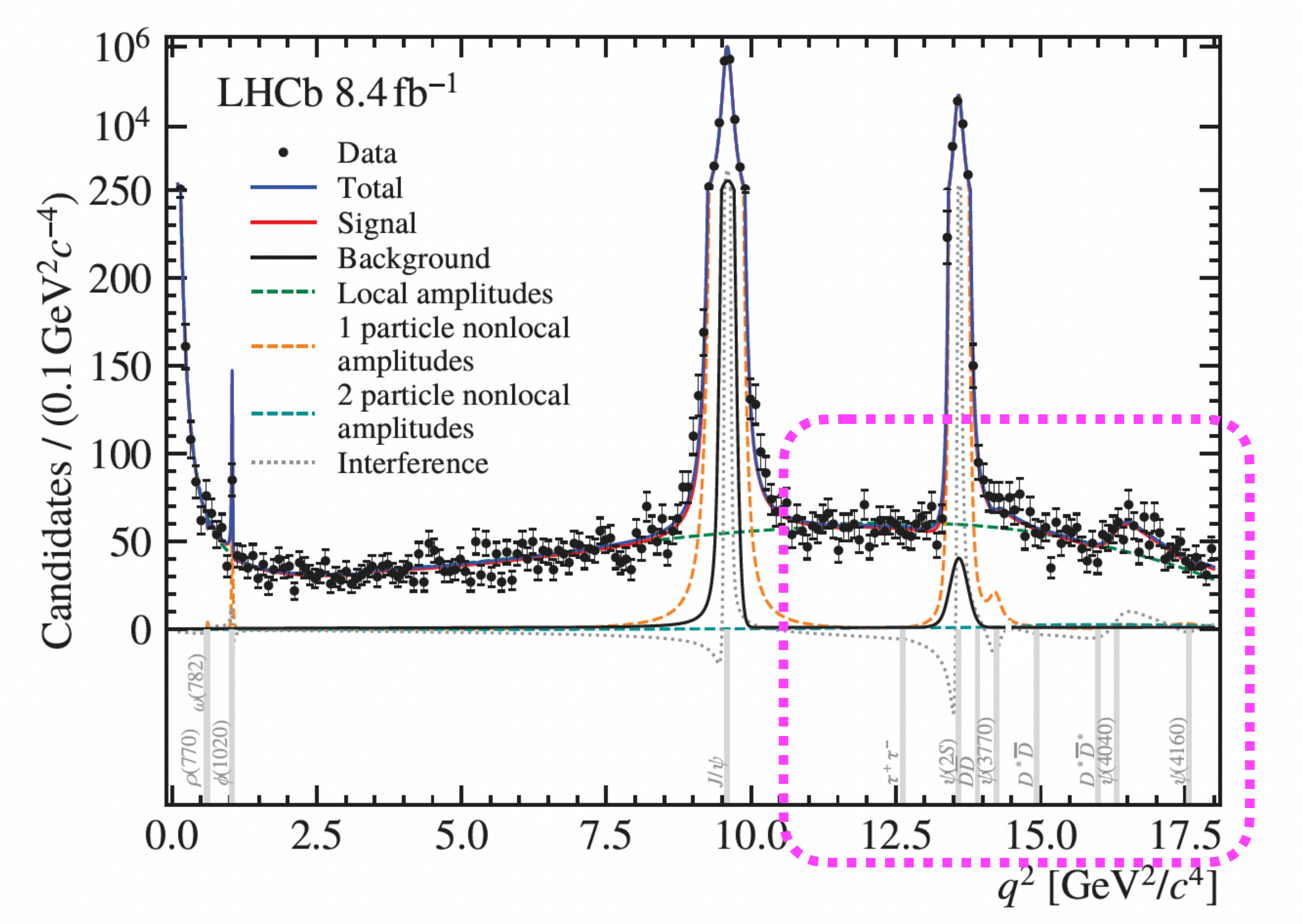
- affect on SM predictions





Small modification to SM predictions, but tension remains

Worlds first direct measurement of $C_{9\tau}$



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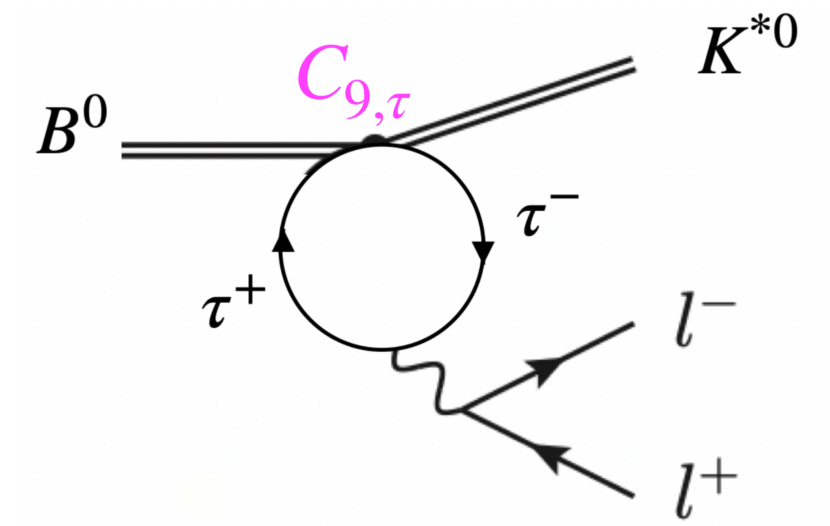


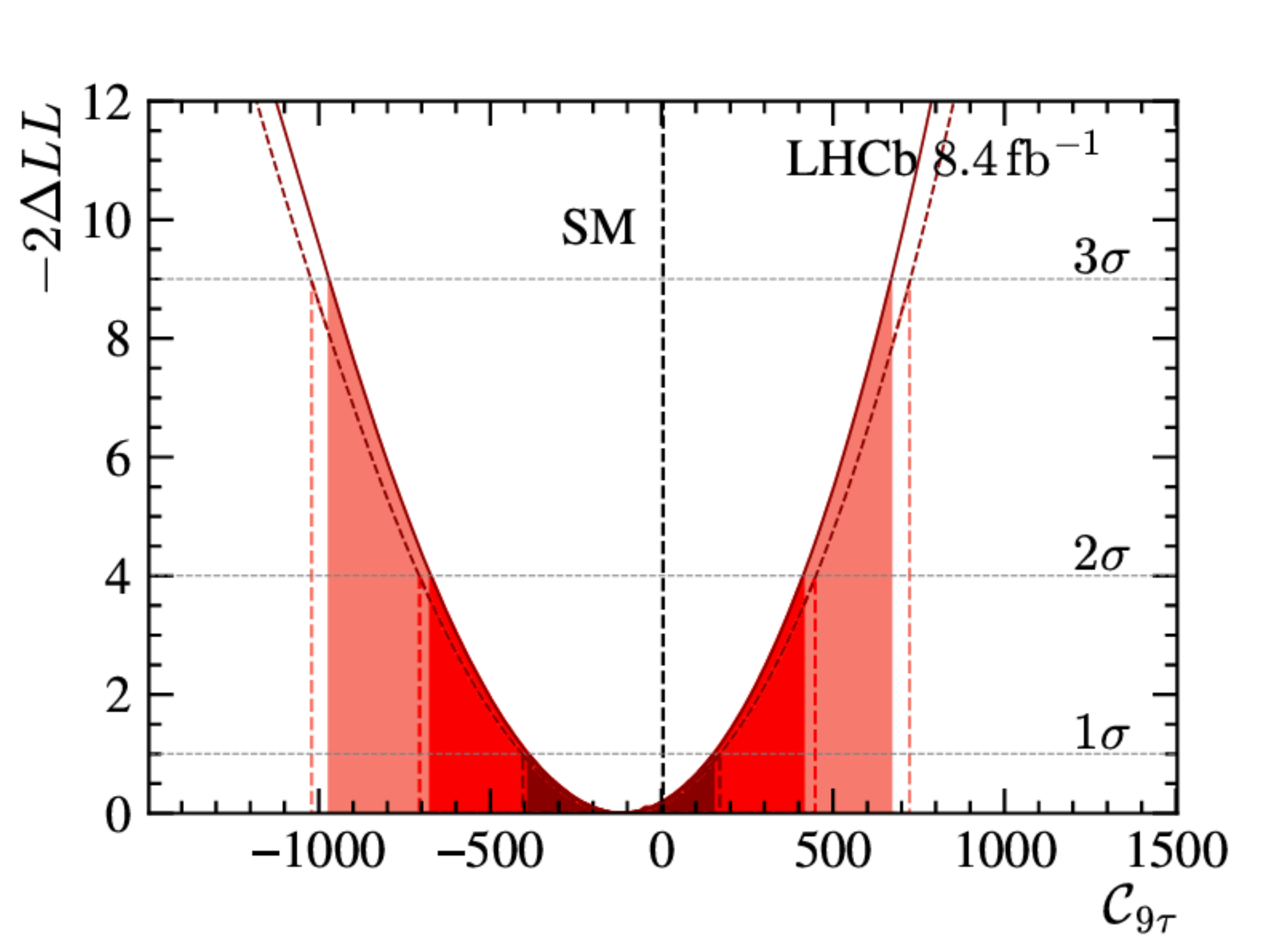
Muon analysis is sensitive to $C_{9,\tau}$ via

$B^0 \to K^{*0}[\tau^+\tau^- \to \gamma^* \to \mu^+\mu^-]$

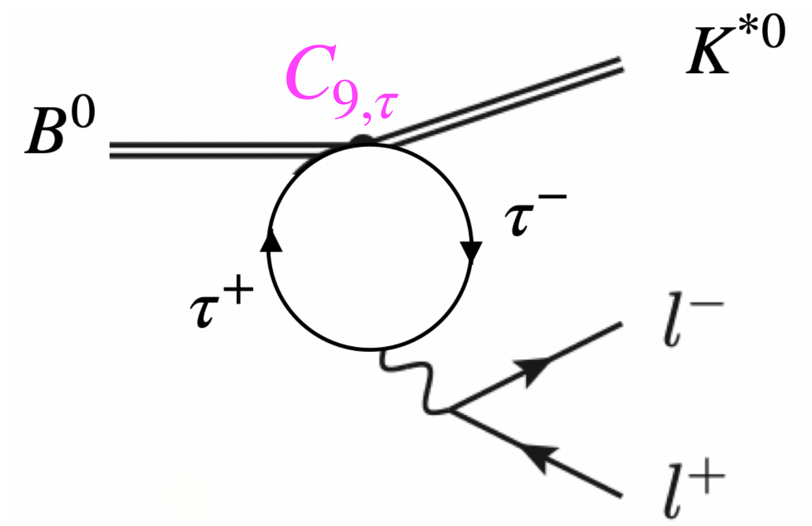
$\propto C_{9,\tau}$

Worlds first direct measurement of $C_{9,\tau}$

Worlds first direct measurement of $C_{9\tau}$



LHCb-PAPER-2024-011



Muon analysis is sensitive to $C_{9,\tau}$ via

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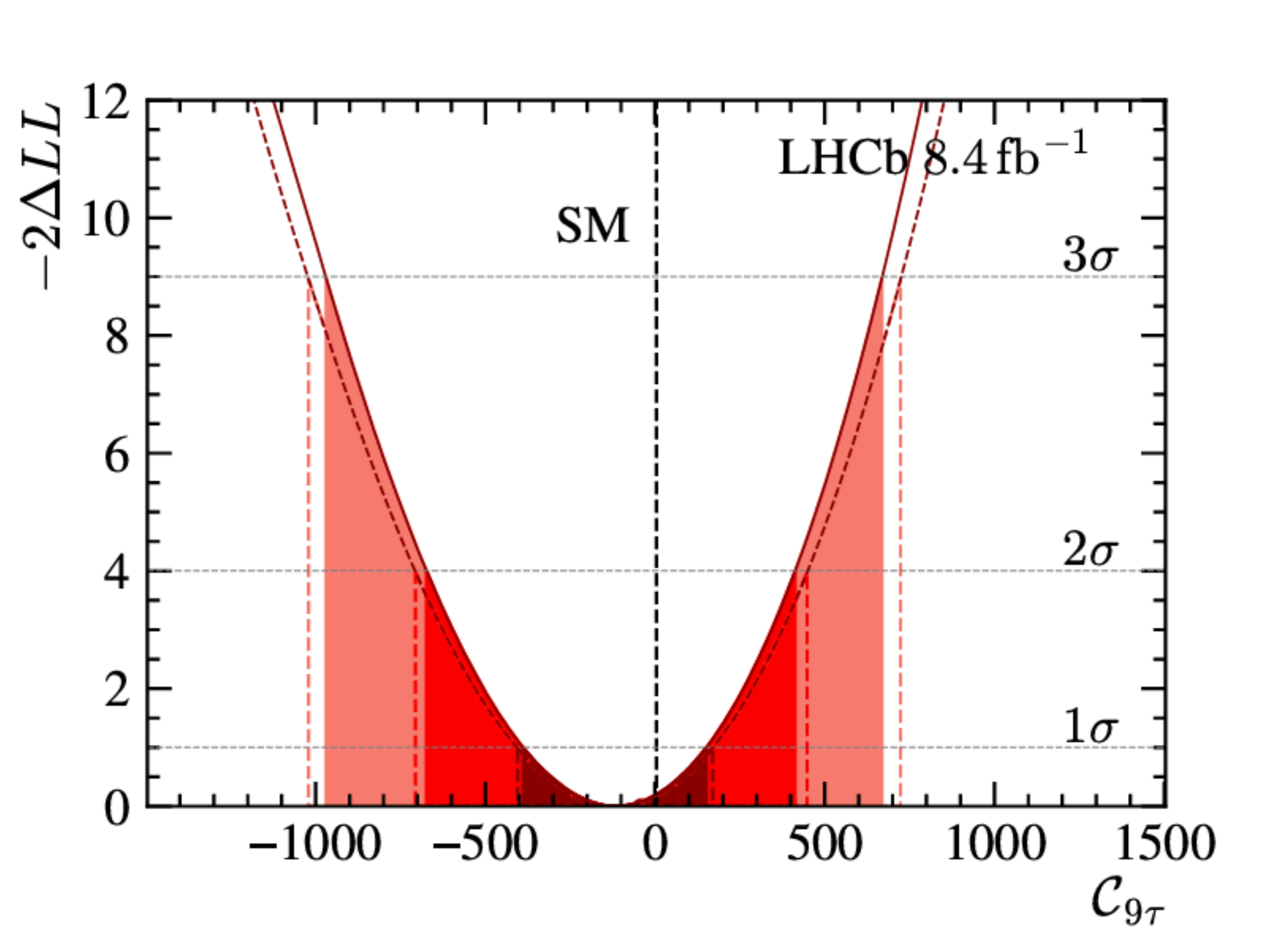
$\propto C_{9,\tau}$

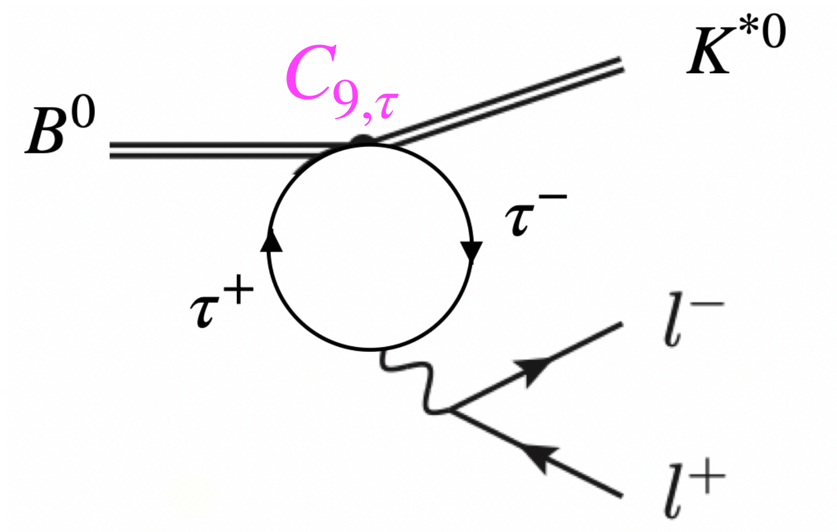
Worlds first direct measurement of $C_{9,\tau}$

$$C_{9,\tau} = (-1.0 \pm 2.6 \pm 1.0) \times 10^2$$

Worlds first direct measurement of $C_{9\tau}$



LHCb-PAPER-2024-011



Convert to 90% CL on
$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) \sim [1.7 - 2.2] \times 10^{-3}$

Best direct measurement of $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) =$
3.1×10^{-3} 90% CL Belle, Phys. Rev. D108 (2023) L011102

SM prediction $\mathscr{O}(10^{-7})$, NP models $\mathscr{O}(10^{-4})$

Muon analysis is sensitive to $C_{9,\tau}$ via

$B^0 \to K^{*0}[\tau^+\tau^- \to \gamma^* \to \mu^+\mu^-]$

$\propto C_{9,\tau}$

Worlds first direct measurement of $C_{9,\tau}$

$$C_{9,\tau} = (-1.0 \pm 2.6 \pm 1.0) \times 10^2$$

Cross-checks

$$Y_{q\bar{q},\lambda}(q^2) = Y_{q\bar{q},\lambda}(q_0^2) + \frac{(q^2 - q_0^2)}{\pi} \int_{4m_\mu^2}^{\infty} \frac{\rho_{q\bar{q},\lambda}(s)}{(s - q_0^2)(s - q^2 - i\epsilon)} \mathrm{d}s,$$

JHEP 1009:089,2010

JHEP 02 (2013) 010

Perturbatively calculable via OPE at $q^2 < 0$

- Pick subtraction point q_0^2
- Extrapolate to rest of q^2

$q_0^2 = -10, -4.6\,(nom)\,, -1\,\mathrm{GeV}$

Pick different subtraction points in q^2, max change in C_9 $\sim 35\,\%$ stat. uncertainty

Cross-checks

Local form-factors:

- **Nominal** GKDvD18 used (LCSR + Lattice) JHEP 09 (2022) 133, arXiv:2206.03797.
- **Alternative** BSZ (LCSR + Lattice) JHEP 08 (2016) 098, arXiv:1503.05534.

$$A_0^{L,R}(q^2) = -8N\frac{m_B m_{K^*}}{\sqrt{q^2}}\left(([C_9^{\mathrm{eff},0}(q^2) - C_9'] \mp [C_{10} - C_{10}'])A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}} C_7^{\mathrm{eff},0} T_{23}(q^2)\right), \quad (39)$$

$$A_\parallel^{L,R}(q^2) = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left(([C_9^{\mathrm{eff},\parallel}(q^2) - C_9'] \mp [C_{10} - C_{10}'])\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7^{\mathrm{eff},\parallel} T_2(q^2)\right), \quad (40)$$

$$A_\perp^{L,R}(q^2) = N\sqrt{2\lambda}\left(([C_9^{\mathrm{eff},\perp}(q^2) + C_9'] \mp [C_{10} + C_{10}'])\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7^{\mathrm{eff},\perp} T_1(q^2)\right), \quad (41)$$

$$A_t(q^2) = \frac{N}{\sqrt{q^2}}\sqrt{\lambda}\left(2[C_{10} - C_{10}']A_0(q^2)\right) \quad (42)$$

Cross-checks

Local form-factors:

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- **Alternative** BSZ (LCSR + Lattice) JHEP 08 (2016) 098, arXiv:1503.05534.

Coefficient	GKDvD	BSZ	Coefficient	GKDvD	BSZ
$\alpha_0^{A_0}$	0.34 ± 0.03	0.37 ± 0.03	$\alpha_0^{T_1}$	0.32 ± 0.02	0.31 ± 0.03
$\alpha_1^{A_0}$	-1.12 ± 0.20	-1.37 ± 0.26	$\alpha_1^{T_1}$	-0.95 ± 0.14	-1.01 ± 0.19
$\alpha_2^{A_0}$	2.18 ± 1.76	0.13 ± 1.63	$\alpha_2^{T_1}$	2.11 ± 1.28	1.53 ± 1.64
$\alpha_0^{A_1}$	0.29 ± 0.02	0.30 ± 0.03	$\alpha_0^{T_{23}}$	0.62 ± 0.03	0.67 ± 0.06
$\alpha_1^{A_1}$	0.46 ± 0.13	0.39 ± 0.19	$\alpha_1^{T_{23}}$	0.97 ± 0.32	1.32 ± 0.22
$\alpha_2^{A_1}$	1.22 ± 0.73	1.19 ± 1.03	$\alpha_2^{T_{23}}$	1.81 ± 2.45	3.82 ± 2.20
$\alpha_1^{A_{12}}$	0.55 ± 0.34	0.53 ± 0.13	$\alpha_1^{T_2}$	0.60 ± 0.18	0.50 ± 0.17
$\alpha_2^{A_{12}}$	0.58 ± 2.08	0.48 ± 0.66	$\alpha_2^{T_2}$	1.70 ± 0.99	1.61 ± 0.80
α_0^{V}	0.36 ± 0.03	0.38 ± 0.03			
α_1^{V}	-1.09 ± 0.17	-1.17 ± 0.26			
α_2^{V}	2.73 ± 1.99	2.42 ± 1.53			

- Adapted from arXiv:2206.03797

Table 10: Posteriors of the $B \to K^*$ local FFs fit. We used the exact relations (A.24)-(A.25) to reduce the number of parameters to 19. The posterior distribution is accurately described with a single multivariate Gaussian distribution, whose parameters are given in the ancillary file `BToKstar-local.yaml`. We compare our results to those of Ref. [29].

Cross-checks

Local form-factors:

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Coefficient	GKDvD	BSZ	Coefficient	GKDvD	BSZ
$\alpha_0^{A_0}$	0.34 ± 0.03	0.37 ± 0.03	$\alpha_0^{T_1}$	0.32 ± 0.02	0.31 ± 0.03
$\alpha_1^{A_0}$	1.12 ± 0.20	1.37 ± 0.26	$\alpha_1^{T_1}$	0.95 ± 0.14	1.01 ± 0.10
$\alpha_1^{A_{12}}$	0.55 ± 0.34	0.53 ± 0.13	$\alpha_1^{T_2}$	0.60 ± 0.18	0.50 ± 0.17
$\alpha_2^{A_{12}}$	0.58 ± 2.08	0.48 ± 0.66	$\alpha_2^{T_2}$	1.70 ± 0.99	1.61 ± 0.80
α_0^{V}	0.36 ± 0.03	0.38 ± 0.03			
α_1^{V}	-1.09 ± 0.17	-1.17 ± 0.26			
α_2^{V}	2.73 ± 1.99	2.42 ± 1.53			

Causes a $\sim 1\sigma$ deviation in C_{10}
(in data but also just using toys generating with one set of FFs and fitting back with another)

- Adapted from arXiv:2206.03797

Table 10: Posteriors of the $B \to K^*$ local FFs fit. We used the exact relations (A.24)-(A.25) to reduce the number of parameters to 19. The posterior distribution is accurately described with a single multivariate Gaussian distribution, whose parameters are given in the ancillary file BToKstar-local.yaml. We compare our results to those of Ref. [29].

Cross-checks

Wilsons should be constant in q^2 if good goodness of fit

Fit around q^2 mid-point

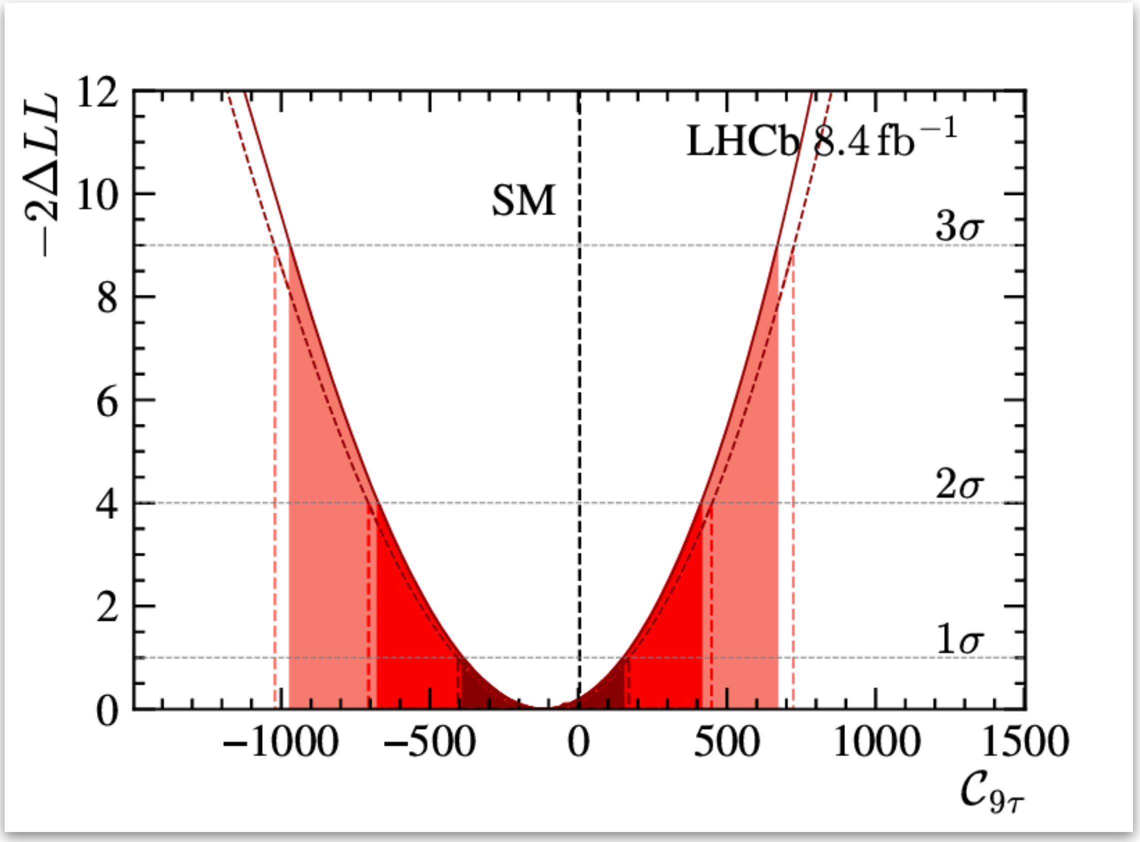
$$
\begin{aligned}
C_9^{q^2} &= C_9 + \alpha(q^2 - 8.95) \\
C_{10}^{q^2} &= C_{10} + \beta(q^2 - 8.95).
\end{aligned}
$$

$$\alpha = 0.029 \pm 0.082,\ \beta = -0.058 \pm 0.026$$

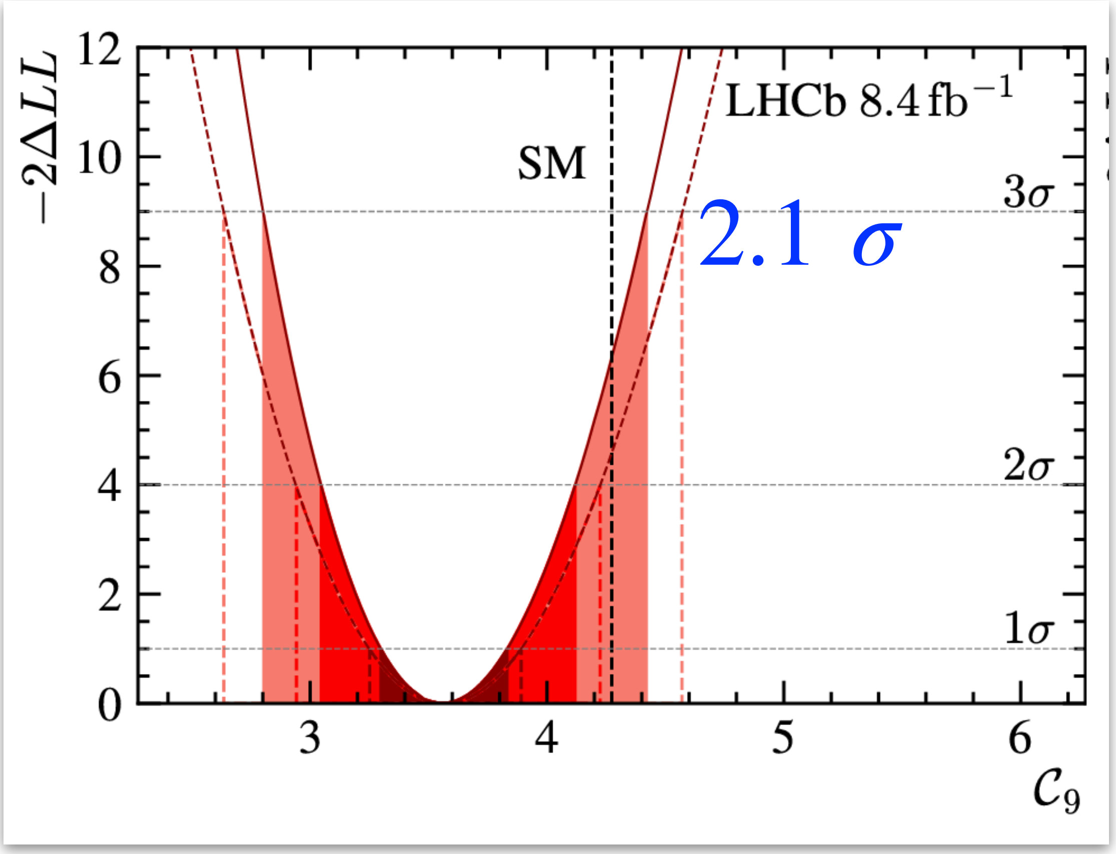
C_9 is consistent with 0, C_{10} has a 2.2σ deviation

Conclusions

- Non-local analyses suggest **small non-local** FFs affect
  - Plus **worlds best measurement of** $C_{9\tau}$



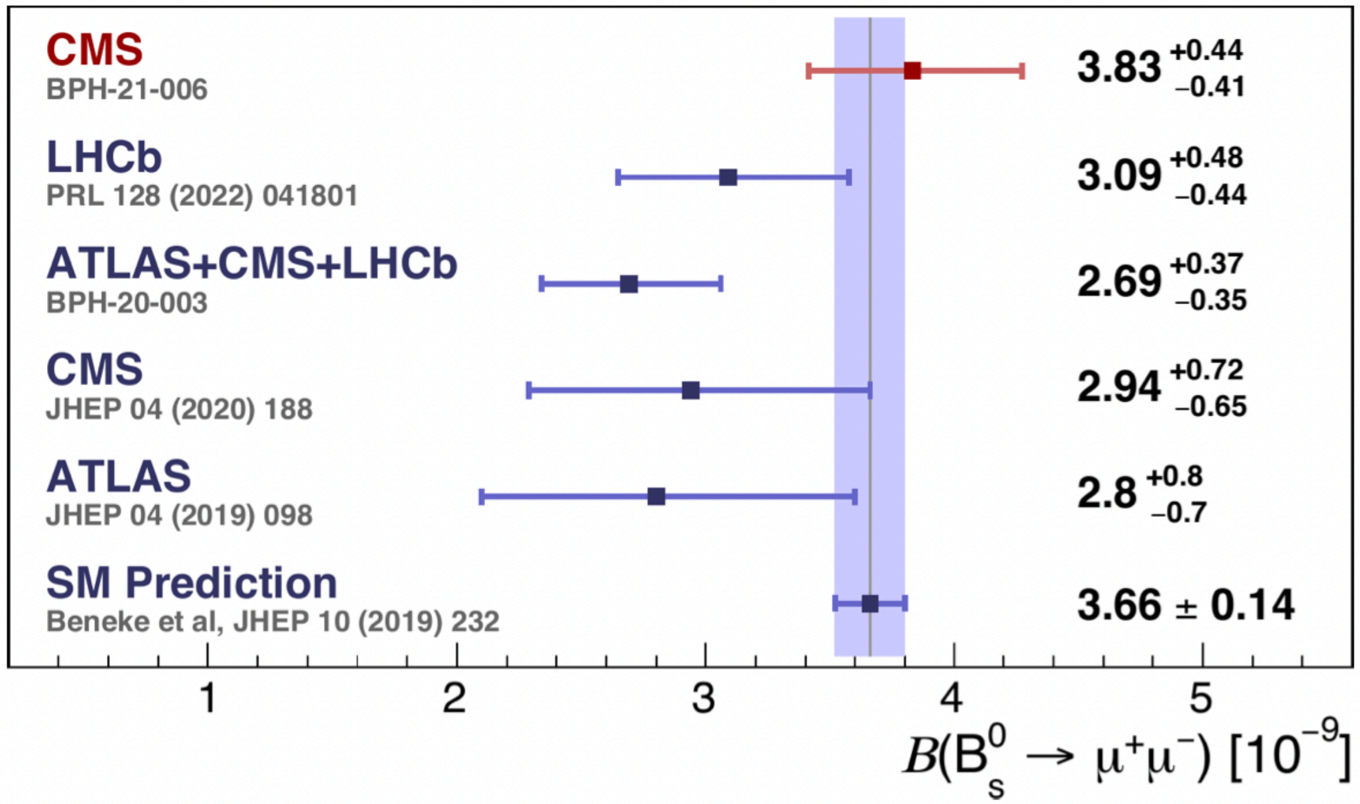
- **Inputs useful for future non-local ana:**
  - Better theory knowledge of $D\bar{D}$ states
  - Belle II measurements of $B \to K^{*0} J\psi$
  - S-wave….

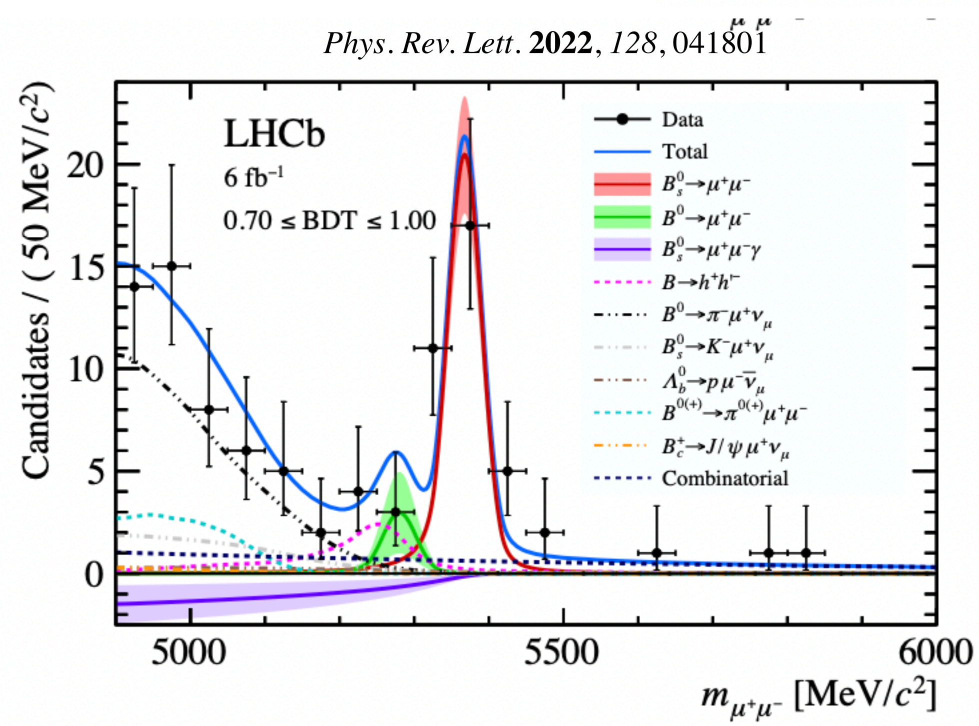


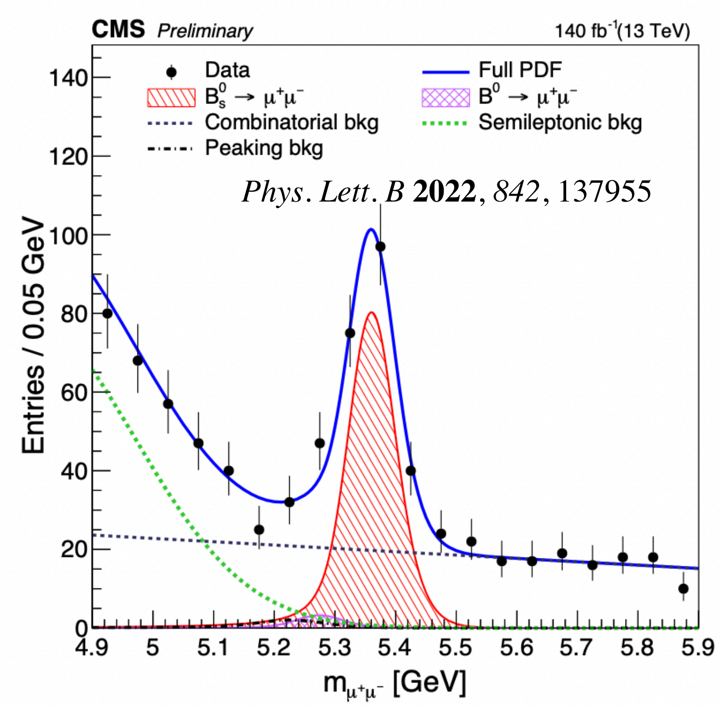
Back-ups

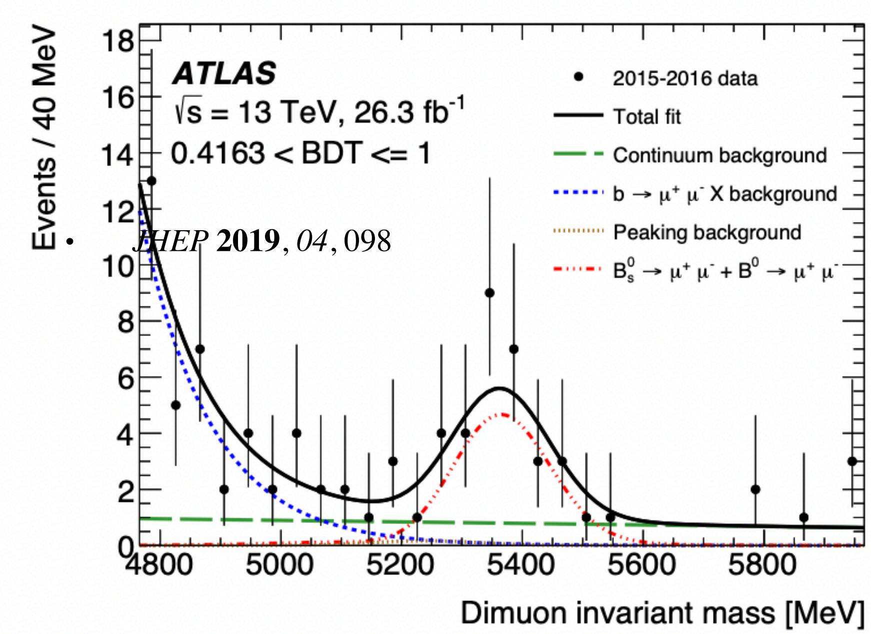
$B_s \to \mu^+\mu^-$: branching fraction

Clean observable, sensitive to C_{10}









$B_s \to \mu^+\mu^-$: effective lifetime

In the SM, just the heavy mass eigenstate B_H decays to $\mu^+\mu^-$

CP-averaged lifetime more sensitive to (NP) contributions from light mass eigenstate than branching fraction

$$\tau_{\mu\mu} \equiv \frac{\int_0^\infty t\langle\Gamma(B_s^0 \to \mu^+\mu^-)\rangle dt}{\int_0^\infty \langle\Gamma(B_s^0 \to \mu^+\mu^-)\rangle dt} = \frac{\tau_{B_s^0}}{1-y_s^2}\left[\frac{1+2\mathcal{A}_{\Delta\Gamma}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma}y_s}\right]$$

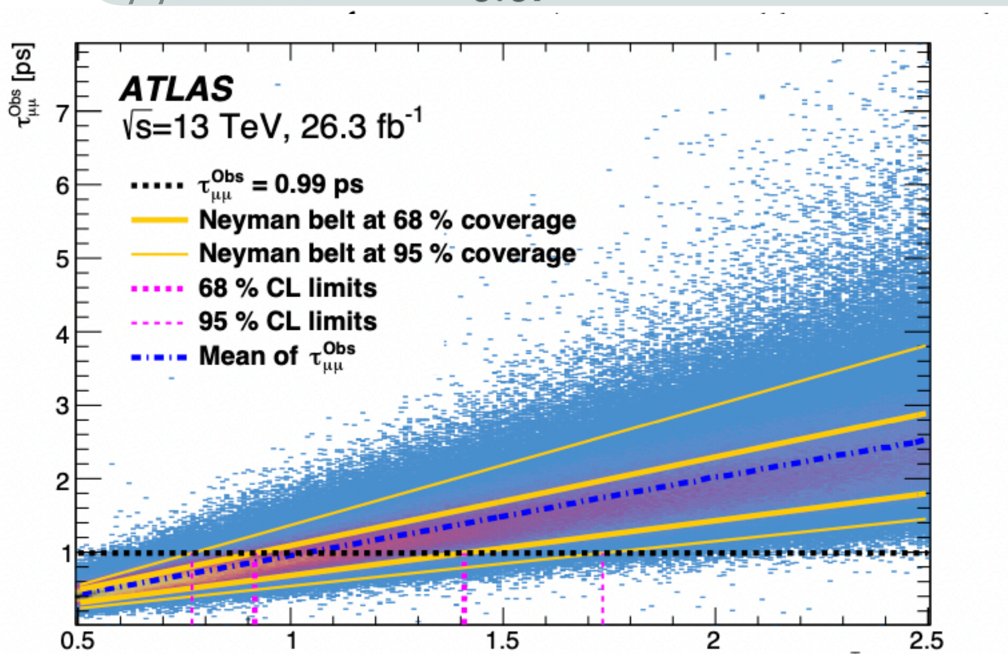
$$\mathcal{A}_{\Delta\Gamma} \equiv \frac{R_H^{\mu^+\mu^-} - R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-} + R_L^{\mu^+\mu^-}}$$

$y_s \sim 0.1$

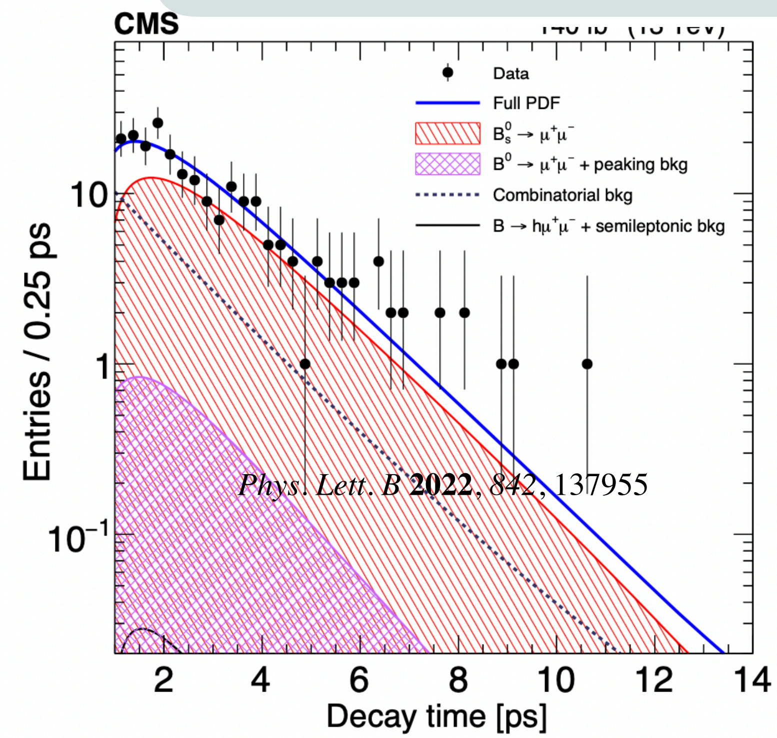
$B_s \to \mu^+\mu^-$: effective lifetime

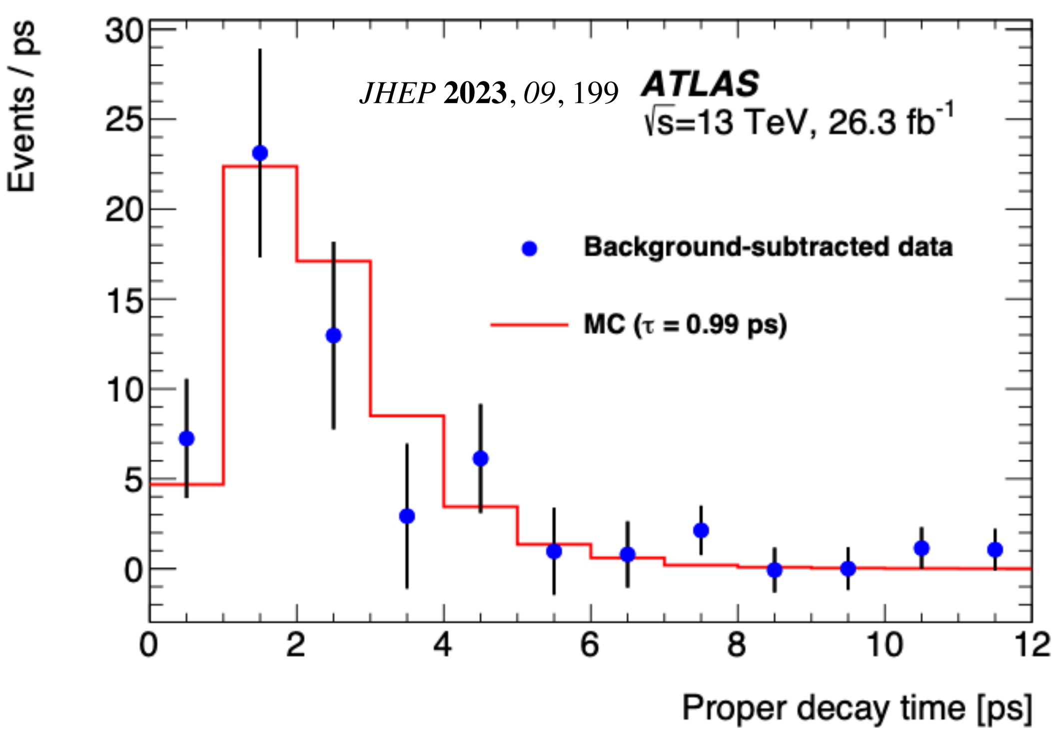
$$\tau_{\mu\mu}^{SM} = 1.624 \pm 0.009\,\mathrm{ps}$$

$$\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})$$

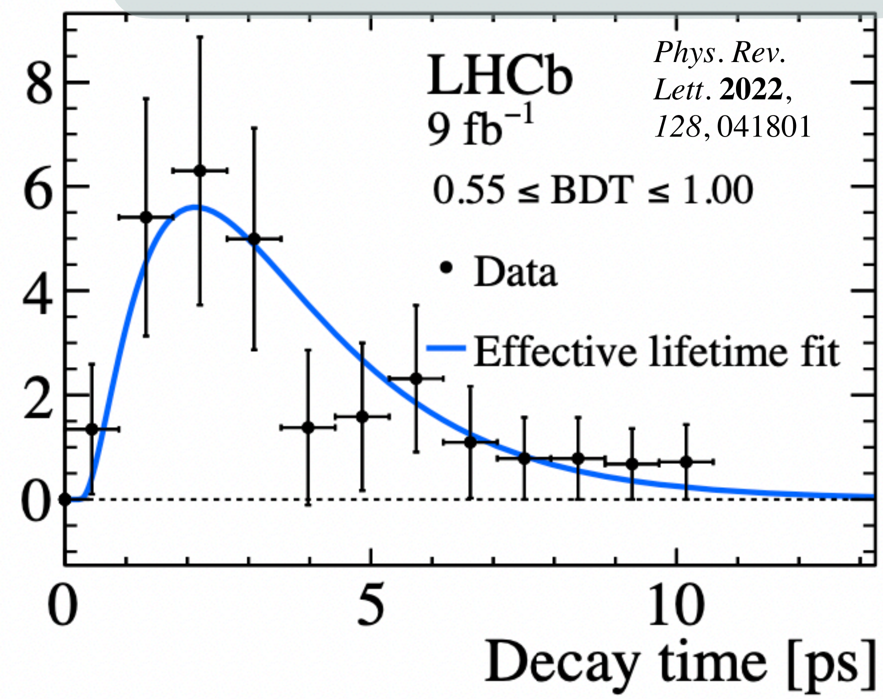


$$\tau_{\mu\mu} = 1.83^{+0.23}_{-0.20}\,(\mathrm{stat})^{+0.04}_{-0.04}\,(\mathrm{syst})\ \mathrm{ps},$$





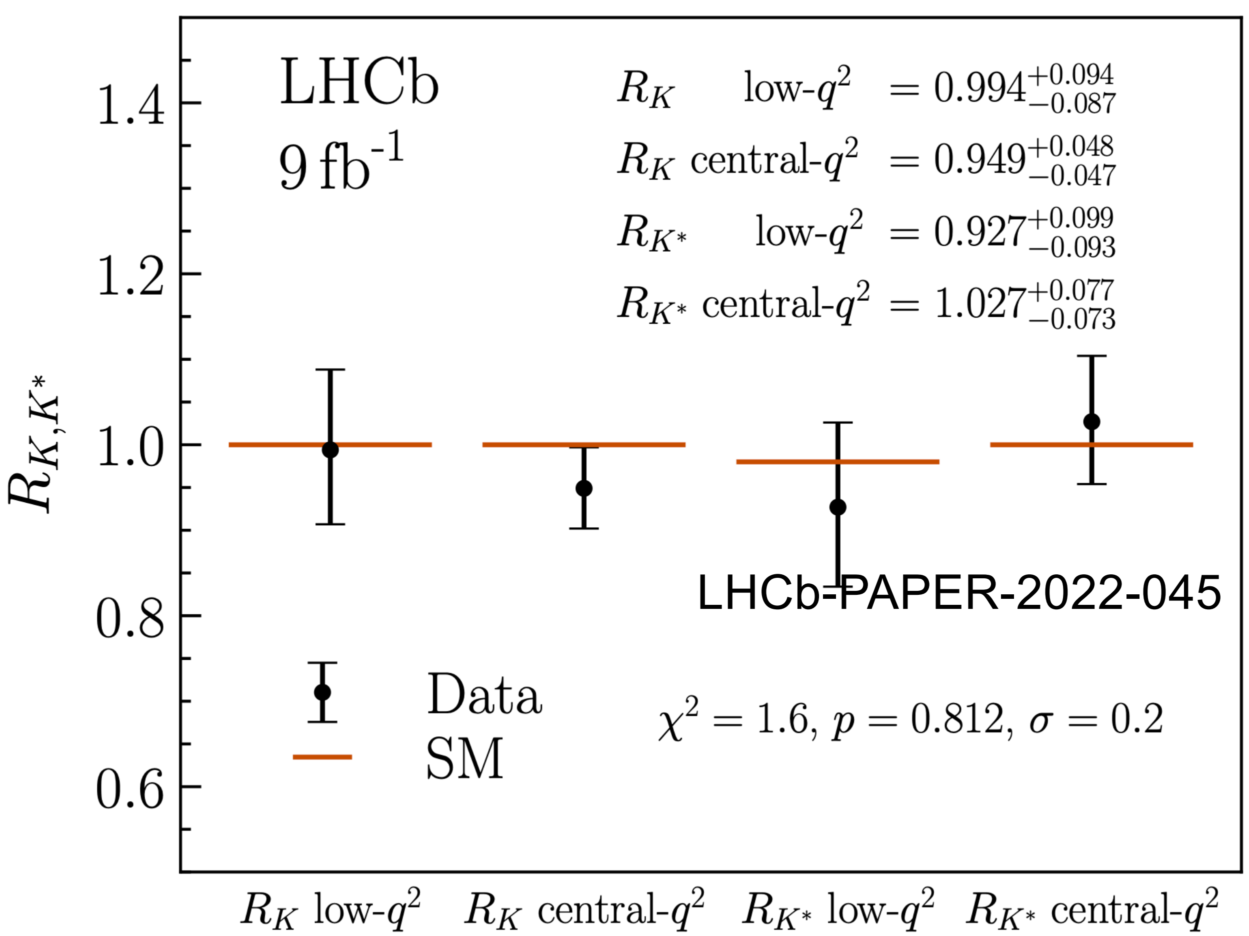
$$\tau_{\mu^+\mu^-} = 2.07 \pm 0.29 \pm 0.03\,\mathrm{ps},$$



Lepton flavour universality tests

$$R(X) = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)}$$

Precisely predicted to be ~1 in SM



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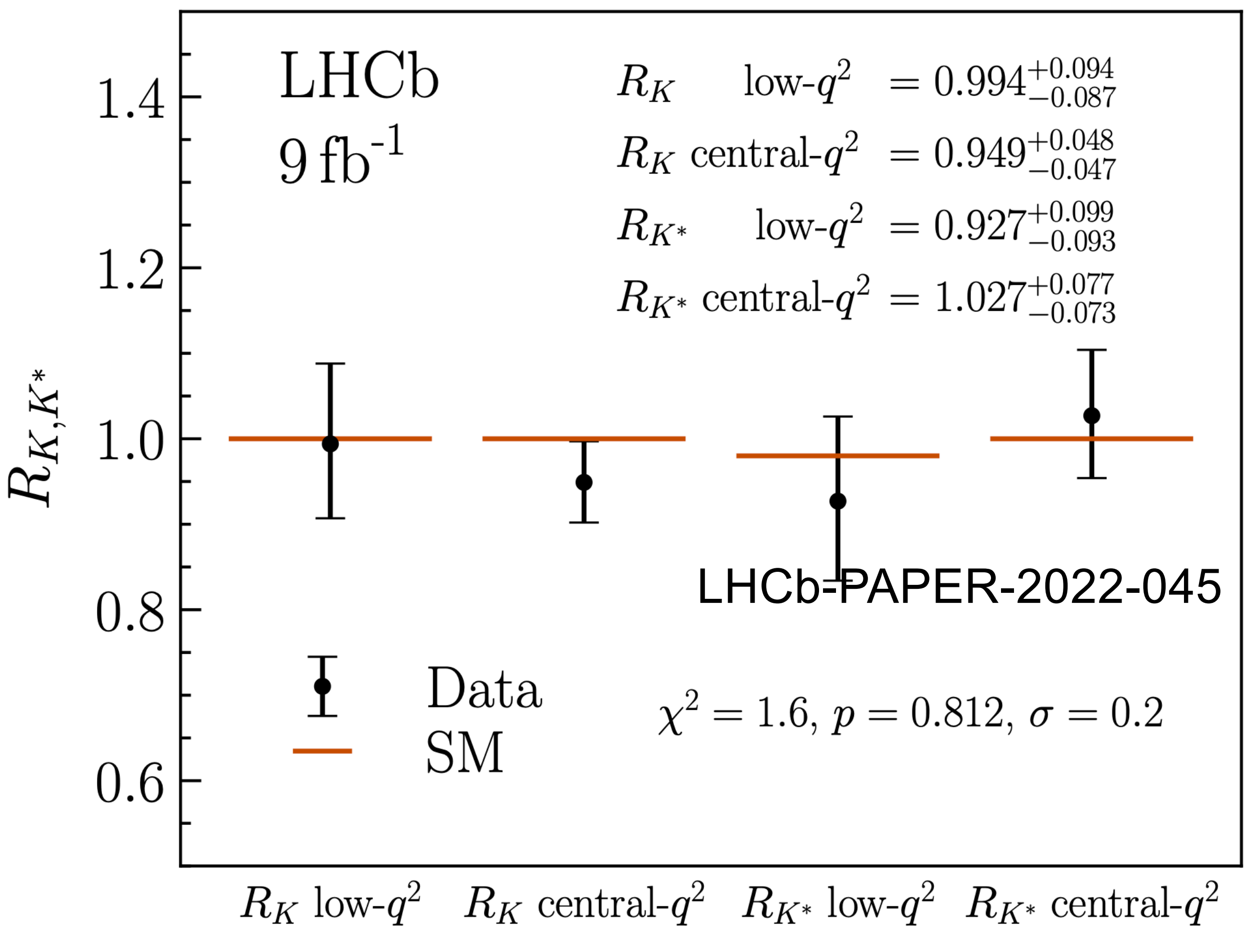
Lepton flavour universality tests

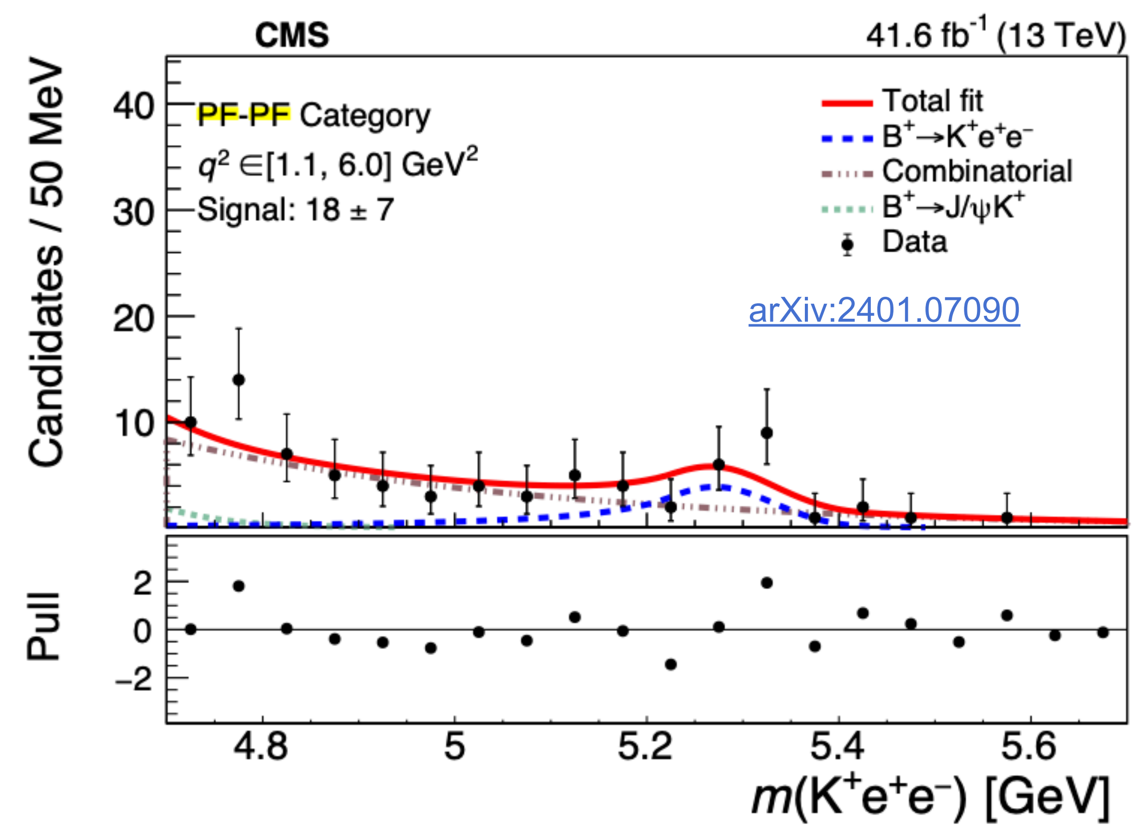
$$R(X) = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to X e^+ e^-)}$$

Precisely predicted to be ~1 in SM

New CMS result

$$R(K) = 0.78^{+0.47}_{-0.23}$$





Precisely predicted to be ~1 in SM

Amplitude analysis over all q^2 : results

Nonlocal parameter results			
$\|A^{\parallel}_{J/\psi}\|$	$(3.98 \pm 0.01 \pm 0.15) \times 10^{-3}$	$\delta^{\parallel}_{J/\psi}$	$0.23 \pm 0.01 \pm 0.01$
$\|A^{\perp}_{J/\psi}\|$	$(3.85 \pm 0.01 \pm 0.14) \times 10^{-3}$	$\delta^{\perp}_{J/\psi}$	$-0.21 \pm 0.00 \pm 0.01$
$\|A^{0}_{J/\psi}\|$	–	$\delta^{0}_{J/\psi}$	$-1.92 \pm 0.05 \pm 0.02$
$\|A^{\parallel}_{\psi(2S)}\|$	$(9.59 \pm 0.28 \pm 0.82) \times 10^{-4}$	$\delta^{\parallel}_{\psi(2S)}$	$0.84 \pm 0.02 \pm 0.19$
$\|A^{\perp}_{\psi(2S)}\|$	$(8.38 \pm 0.27 \pm 0.62) \times 10^{-4}$	$\delta^{\perp}_{\psi(2S)}$	$-0.44 \pm 0.02 \pm 0.11$
$\|A^{0}_{\psi(2S)}\|$	$(13.4 \pm 0.4 \pm 1.1) \times 10^{-4}$	$\delta^{0}_{\psi(2S)}$	$-2.54 \pm 0.13 \pm 0.12$
$\|A^{0}_{\rho(770)}\|$	–	$\delta^{0}_{\rho(770)}$	$1.38 \pm 0.53 \pm 0.65$
$\|A^{0}_{\omega(782)}\|$	–	$\delta^{0}_{\omega(782)}$	$-0.49 \pm 0.92 \pm 0.53$
$\|A^{0}_{\phi(1020)}\|$	–	$\delta^{0}_{\phi(1020)}$	$0.10 \pm 0.82 \pm 0.78$

Nonlocal parameter results $(\times 10^{-5})$			
$\Re(A^{\parallel}_{\psi(3770)})$	$3.68 \pm 1.34 \pm 0.73$	$\Im(A^{\parallel}_{\psi(3770)})$	$2.87 \pm 1.88 \pm 0.49$
$\Re(A^{\perp}_{\psi(3770)})$	$-3.53 \pm 1.45 \pm 0.47$	$\Im(A^{\perp}_{\psi(3770)})$	$-0.86 \pm 1.56 \pm 0.53$
$\Re(A^{0}_{\psi(3770)})$	$-3.14 \pm 1.39 \pm 0.60$	$\Im(A^{0}_{\psi(3770)})$	$1.67 \pm 1.54 \pm 0.62$
$\Re(A^{\parallel}_{\psi(4040)})$	$-2.39 \pm 1.53 \pm 0.96$	$\Im(A^{\parallel}_{\psi(4040)})$	$-0.71 \pm 1.80 \pm 1.11$
$\Re(A^{\perp}_{\psi(4040)})$	$-2.01 \pm 1.47 \pm 0.59$	$\Im(A^{\perp}_{\psi(4040)})$	$0.35 \pm 1.49 \pm 0.82$
$\Re(A^{0}_{\psi(4040)})$	$-5.62 \pm 1.71 \pm 1.07$	$\Im(A^{0}_{\psi(4040)})$	$1.32 \pm 1.87 \pm 0.99$
$\Re(A^{\parallel}_{\psi(4160)})$	$0.04 \pm 1.72 \pm 0.56$	$\Im(A^{\parallel}_{\psi(4160)})$	$1.91 \pm 1.98 \pm 1.45$
$\Re(A^{\perp}_{\psi(4160)})$	$-2.81 \pm 1.75 \pm 0.61$	$\Im(A^{\perp}_{\psi(4160)})$	$0.32 \pm 0.15 \pm 0.09$
$\Re(A^{0}_{\psi(4160)})$	$1.03 \pm 1.77 \pm 0.39$	$\Im(A^{0}_{\psi(4160)})$	$-1.66 \pm 1.67 \pm 1.04$

Nonlocal parameter results			
$\Re(A^{\parallel}_{D^0\bar{D}^0})$	$-0.07 \pm 0.93 \pm 0.69$	$\Im(A^{\parallel}_{D^0\bar{D}^0})$	$-0.44 \pm 0.71 \pm 0.73$
$\Re(A^{\perp}_{D^0\bar{D}^0})$	$-0.12 \pm 0.83 \pm 0.71$	$\Im(A^{\perp}_{D^0\bar{D}^0})$	$0.02 \pm 0.80 \pm 0.74$
$\Re(A^{0}_{D^0\bar{D}^0})$	$-0.33 \pm 0.91 \pm 0.70$	$\Im(A^{0}_{D^0\bar{D}^0})$	$-0.27 \pm 0.77 \pm 0.81$
$\Re(A^{\parallel}_{D^{*0}\bar{D}^{*0}})$	$-0.06 \pm 0.96 \pm 0.63$	$\Im(A^{\parallel}_{D^{*0}\bar{D}^{*0}})$	$-0.25 \pm 0.79 \pm 0.67$
$\Re(A^{\perp}_{D^{*0}\bar{D}^{*0}})$	$-0.16 \pm 0.91 \pm 0.66$	$\Im(A^{\perp}_{D^{*0}\bar{D}^{*0}})$	$-0.03 \pm 0.85 \pm 0.70$
$\Re(A^{0}_{D^{*0}\bar{D}^{*0}})$	$-0.17 \pm 0.95 \pm 0.66$	$\Im(A^{0}_{D^{*0}\bar{D}^{*0}})$	$-0.28 \pm 0.85 \pm 0.78$
$\Re(A^{\parallel}_{D^{*0}\bar{D}^0})$	$0.02 \pm 0.42 \pm 0.66$	$\Im(A^{\parallel}_{D^{*0}\bar{D}^0})$	$-0.46 \pm 0.32 \pm 0.58$
$\Re(A^{\perp}_{D^{*0}\bar{D}^0})$	$-0.24 \pm 0.42 \pm 0.70$	$\Im(A^{\perp}_{D^{*0}\bar{D}^0})$	$-0.11 \pm 0.39 \pm 0.61$
$\Re(A^{0}_{D^{*0}\bar{D}^0})$	$-0.51 \pm 0.41 \pm 0.68$	$\Im(A^{0}_{D^{*0}\bar{D}^0})$	$0.12 \pm 0.35 \pm 0.58$
$\Re(\Delta\mathcal{C}^{\parallel}_7)$	$0.00 \pm 0.03 \pm 0.02$	$\Im(\Delta\mathcal{C}^{\parallel}_7)$	$-0.10 \pm 0.03 \pm 0.01$
$\Re(\Delta\mathcal{C}^{\perp}_7)$	$-0.05 \pm 0.03 \pm 0.02$	$\Im(\Delta\mathcal{C}^{\perp}_7)$	$-0.04 \pm 0.04 \pm 0.01$
$\Re(\Delta\mathcal{C}^{0}_7)$	$0.33 \pm 0.33 \pm 0.09$	$\Im(\Delta\mathcal{C}^{0}_7)$	$-0.19 \pm 0.20 \pm 0.09$

Amplitude analysis over all q^2 : results

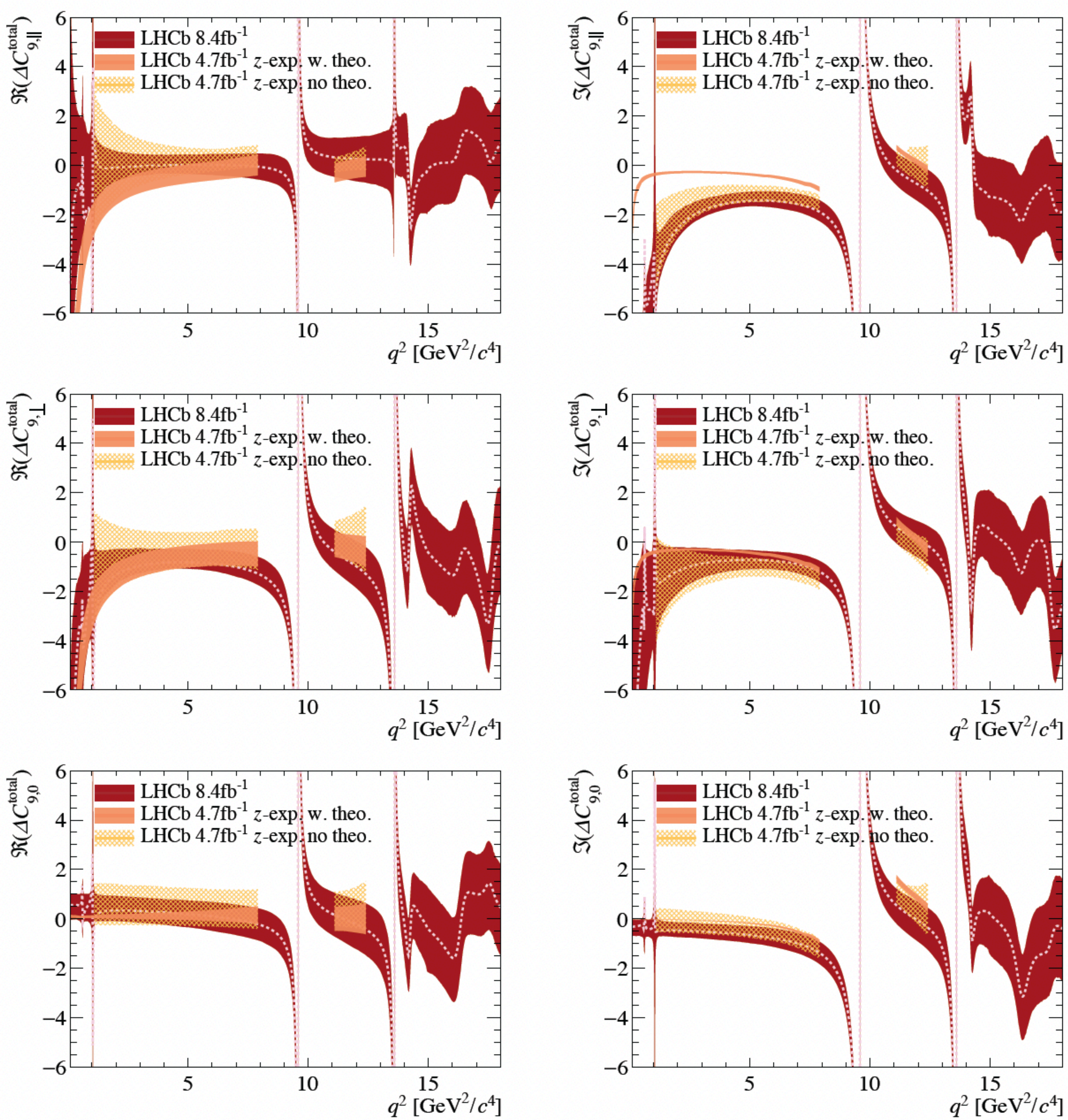
Nonlocal parameter results			
$\|A^{\parallel}_{J/\psi}\|$	$(3.98 \pm 0.01 \pm 0.15) \times 10^{-3}$	$\delta^{\parallel}_{J/\psi}$	$0.23 \pm 0.01 \pm 0.01$
$\|A^{\perp}_{J/\psi}\|$	$(3.85 \pm 0.01 \pm 0.14) \times 10^{-3}$	$\delta^{\perp}_{J/\psi}$	$-0.21 \pm 0.00 \pm 0.01$
$\|A^{0}_{J/\psi}\|$	–	$\delta^{0}_{J/\psi}$	$-1.92 \pm 0.05 \pm 0.02$
$\|A^{\parallel}_{\psi(2S)}\|$	$(9.59 \pm 0.28 \pm 0.82) \times 10^{-4}$	$\delta^{\parallel}_{\psi(2S)}$	$0.84 \pm 0.02 \pm 0.19$
$\|A^{\perp}_{\psi(2S)}\|$	$(8.38 \pm 0.27 \pm 0.62) \times 10^{-4}$	$\delta^{\perp}_{\psi(2S)}$	$-0.44 \pm 0.02 \pm 0.11$
$\|A^{0}_{\psi(2S)}\|$	$(13.4 \pm 0.4 \ \pm 1.1 \ ) \times 10^{-4}$	$\delta^{0}_{\psi(2S)}$	$-2.54 \pm 0.13 \pm 0.12$
$\|A^{0}_{\rho(770)}\|$	–	$\delta^{0}_{\rho(770)}$	$1.38 \pm 0.53 \pm 0.65$
$\|A^{0}_{\omega(782)}\|$	–	$\delta^{0}_{\omega(782)}$	$-0.49 \pm 0.92 \pm 0.53$
$\|A^{0}_{\phi(1020)}\|$	–	$\delta^{0}_{\phi(1020)}$	$0.10 \pm 0.82 \pm 0.78$

Nonlocal parameter results ($\times 10^{-5}$)			
$\Re(A^{\parallel}_{\psi(3770)})$	$3.68 \pm 1.34 \pm 0.73$	$\Im(A^{\parallel}_{\psi(3770)})$	$2.87 \pm 1.88 \pm 0.49$
$\Re(A^{\perp}_{\psi(3770)})$	$-3.53 \pm 1.45 \pm 0.47$	$\Im(A^{\perp}_{\psi(3770)})$	$-0.86 \pm 1.56 \pm 0.53$
$\Re(A^{0}_{\psi(3770)})$	$-3.14 \pm 1.39 \pm 0.60$	$\Im(A^{0}_{\psi(3770)})$	$1.67 \pm 1.54 \pm 0.62$
$\Re(A^{\parallel}_{\psi(4040)})$	$-2.39 \pm 1.53 \pm 0.96$	$\Im(A^{\parallel}_{\psi(4040)})$	$-0.71 \pm 1.80 \pm 1.11$
$\Re(A^{\perp}_{\psi(4040)})$	$-2.01 \pm 1.47 \pm 0.59$	$\Im(A^{\perp}_{\psi(4040)})$	$0.35 \pm 1.49 \pm 0.82$
$\Re(A^{0}_{\psi(4040)})$	$-5.62 \pm 1.71 \pm 1.07$	$\Im(A^{0}_{\psi(4040)})$	$1.32 \pm 1.87 \pm 0.99$
$\Re(A^{\parallel}_{\psi(4160)})$	$0.04 \pm 1.72 \pm 0.56$	$\Im(A^{\parallel}_{\psi(4160)})$	$1.91 \pm 1.98 \pm 1.45$
$\Re(A^{\perp}_{\psi(4160)})$	$-2.81 \pm 1.75 \pm 0.61$	$\Im(A^{\perp}_{\psi(4160)})$	$0.32 \pm 0.15 \pm 0.09$
$\Re(A^{0}_{\psi(4160)})$	$1.03 \pm 1.77 \pm 0.39$	$\Im(A^{0}_{\psi(4160)})$	$-1.66 \pm 1.67 \pm 1.04$

Nonlocal parameter results			
$\Re(A^{\parallel}_{D^0\bar{D}^0})$	$-0.07 \pm 0.93 \pm 0.69$	$\Im(A^{\parallel}_{D^0\bar{D}^0})$	$-0.44 \pm 0.71 \pm 0.73$
$\Re(A^{\perp}_{D^0\bar{D}^0})$	$-0.12 \pm 0.83 \pm 0.71$	$\Im(A^{\perp}_{D^0\bar{D}^0})$	$0.02 \pm 0.80 \pm 0.74$
$\Re(A^{0}_{D^0\bar{D}^0})$	$-0.33 \pm 0.91 \pm 0.70$	$\Im(A^{0}_{D^0\bar{D}^0})$	$-0.27 \pm 0.77 \pm 0.81$
$\Re(A^{\parallel}_{D^{*0}\bar{D}^{*0}})$	$-0.06 \pm 0.96 \pm 0.63$	$\Im(A^{\parallel}_{D^{*0}\bar{D}^{*0}})$	$-0.25 \pm 0.79 \pm 0.67$
$\Re(A^{\perp}_{D^{*0}\bar{D}^{*0}})$	$-0.16 \pm 0.91 \pm 0.66$	$\Im(A^{\perp}_{D^{*0}\bar{D}^{*0}})$	$-0.03 \pm 0.85 \pm 0.70$
$\Re(A^{0}_{D^{*0}\bar{D}^{*0}})$	$-0.17 \pm 0.95 \pm 0.66$	$\Im(A^{0}_{D^{*0}\bar{D}^{*0}})$	$-0.28 \pm 0.85 \pm 0.78$
$\Re(A^{\parallel}_{D^{*0}\bar{D}^{0}})$	$0.02 \pm 0.42 \pm 0.66$	$\Im(A^{\parallel}_{D^{*0}\bar{D}^{0}})$	$-0.46 \pm 0.32 \pm 0.58$
$\Re(A^{\perp}_{D^{*0}\bar{D}^{0}})$	$-0.24 \pm 0.42 \pm 0.70$	$\Im(A^{\perp}_{D^{*0}\bar{D}^{0}})$	$-0.11 \pm 0.39 \pm 0.61$
$\Re(A^{0}_{D^{*0}\bar{D}^{0}})$	$-0.51 \pm 0.41 \pm 0.68$	$\Im(A^{0}_{D^{*0}\bar{D}^{0}})$	$0.12 \pm 0.35 \pm 0.58$
$\Re(\Delta\mathcal{C}^{\parallel}_7)$	$0.00 \pm 0.03 \pm 0.02$	$\Im(\Delta\mathcal{C}^{\parallel}_7)$	$-0.10 \pm 0.03 \pm 0.01$
$\Re(\Delta\mathcal{C}^{\perp}_7)$	$-0.05 \pm 0.03 \pm 0.02$	$\Im(\Delta\mathcal{C}^{\perp}_7)$	$-0.04 \pm 0.04 \pm 0.01$
$\Re(\Delta\mathcal{C}^{0}_7)$	$0.33 \pm 0.33 \pm 0.09$	$\Im(\Delta\mathcal{C}^{0}_7)$	$-0.19 \pm 0.20 \pm 0.09$

A lot of numbers describing non-local effects…easier to see graphically

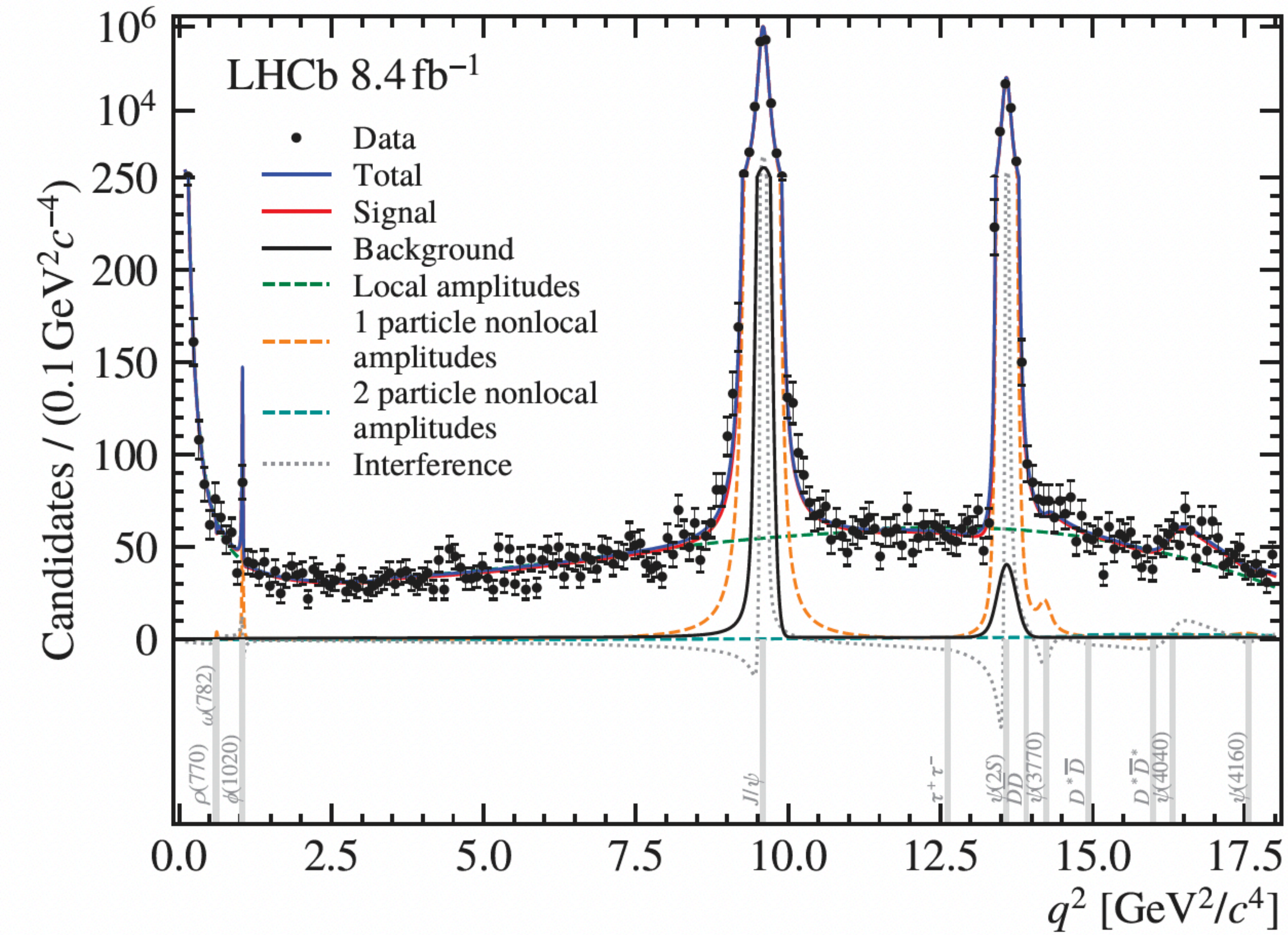
Amplitude analysis over all q^2 : results



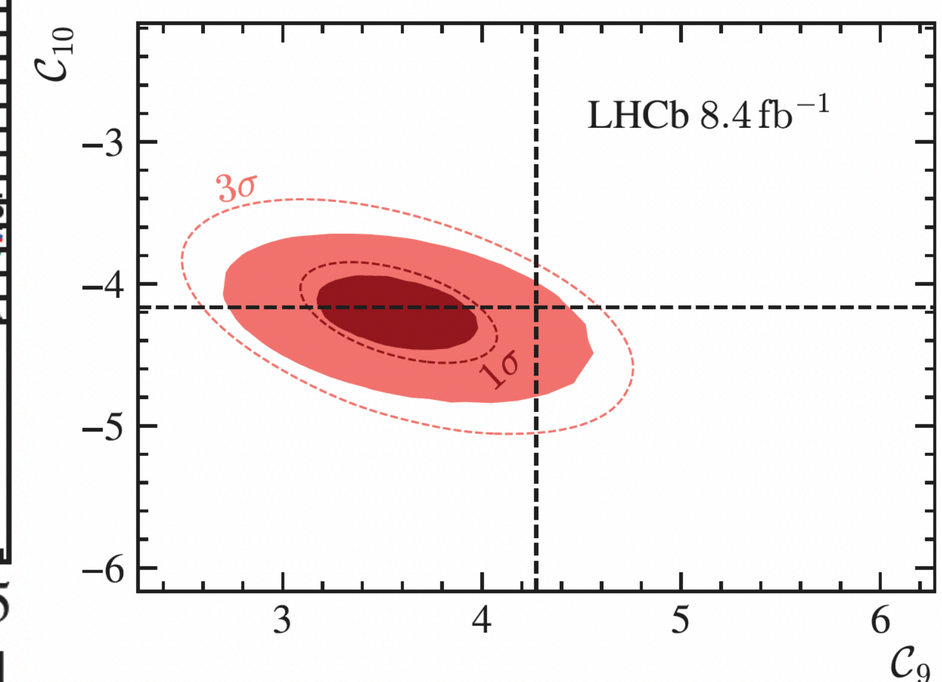
Non-local form factors (amplitude analysis + z-expansion)

Amplitude analysis over all q^2 : results

$$\Delta\mathcal{C}_9^{\mathrm{NP}} = -0.71 \pm 0.33$$



Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}'_9$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}'_{10}$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

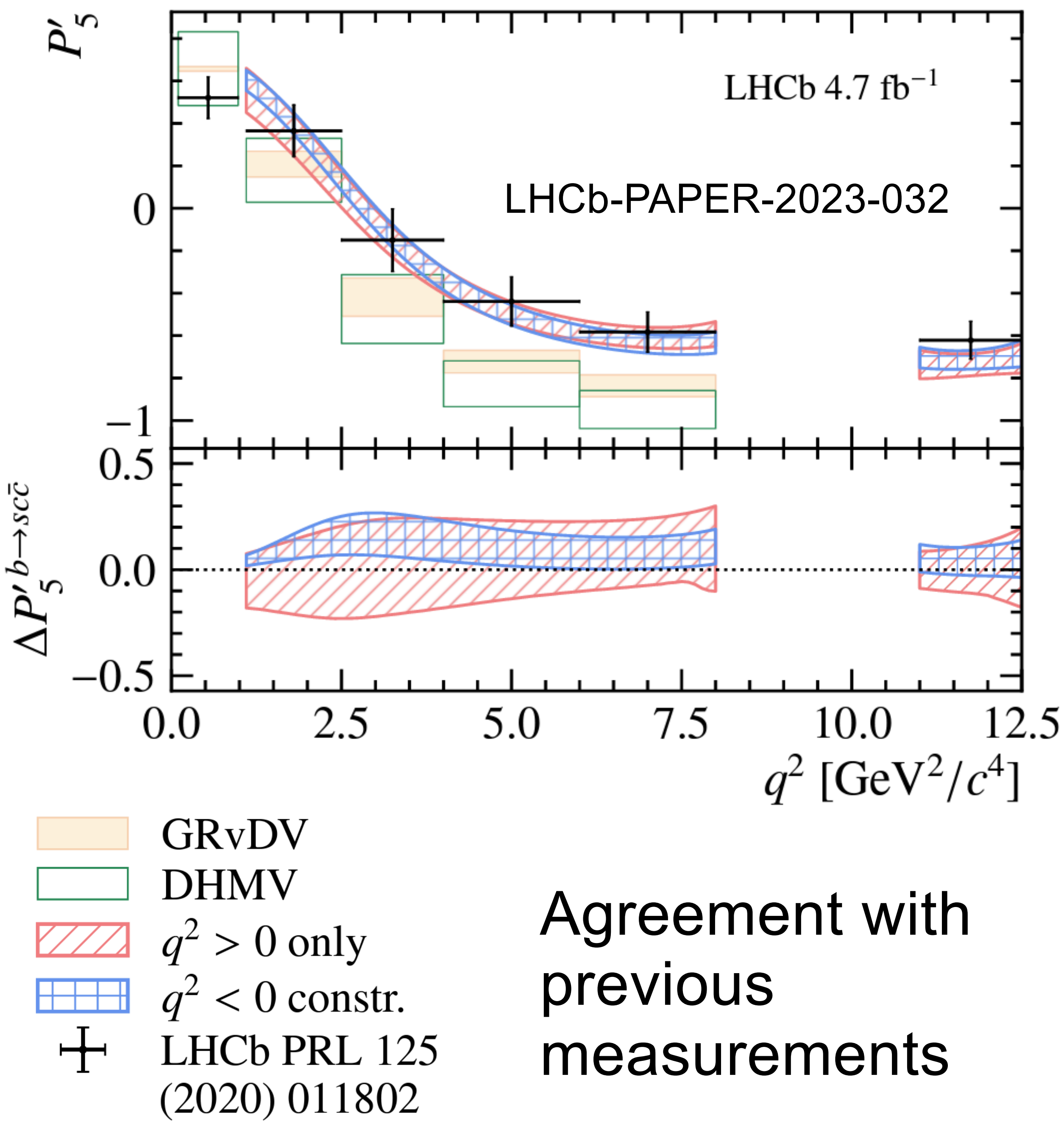


Central value for C_9 remains consistent with anomalies, but larger uncertainty reduces tension to 2.1σ

Affect of non-local contributions on angular observables?

Z-expansion

-comparison with previous measurements

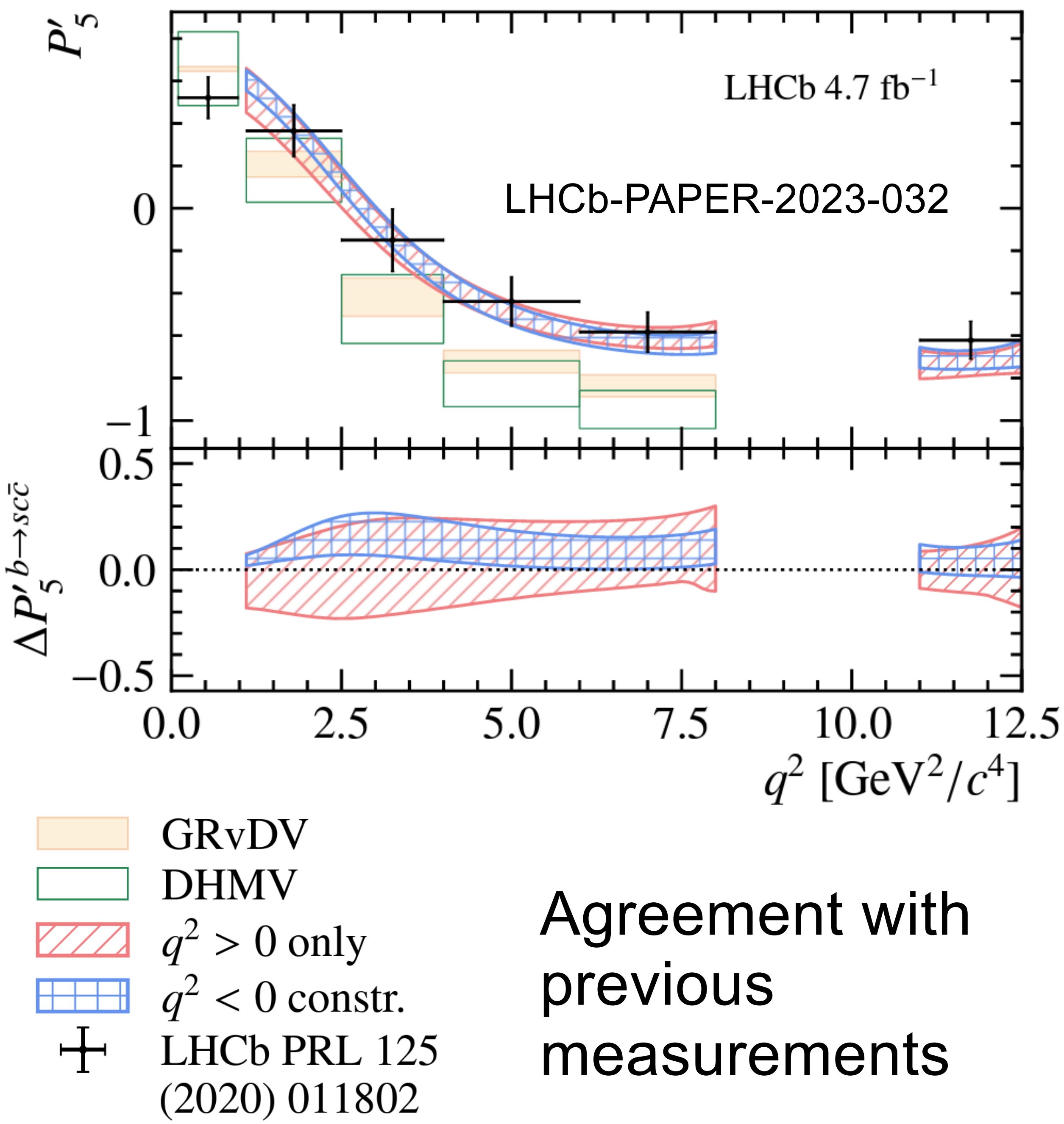


Agreement with previous measurements

Affect of non-local contributions on angular observables?

Z-expansion

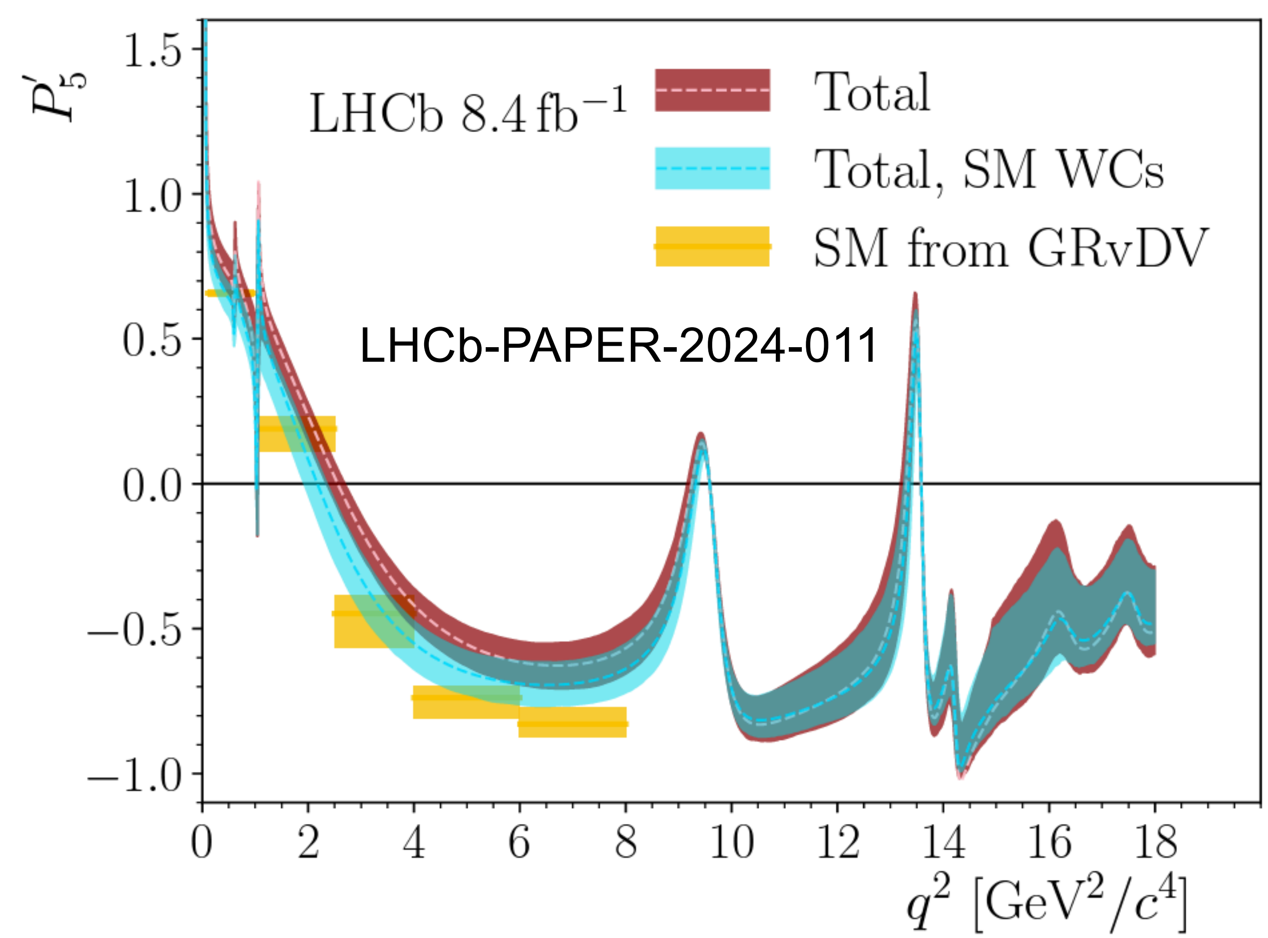
-comparison with previous measurements



Agreement with previous measurements

Amplitude model

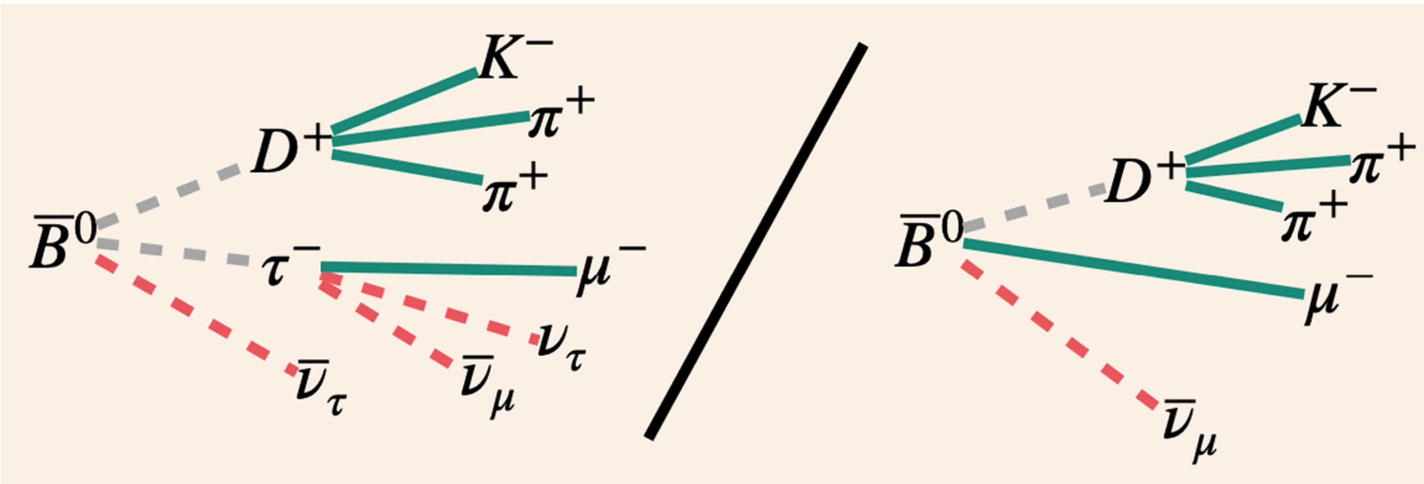
- affect on SM predictions



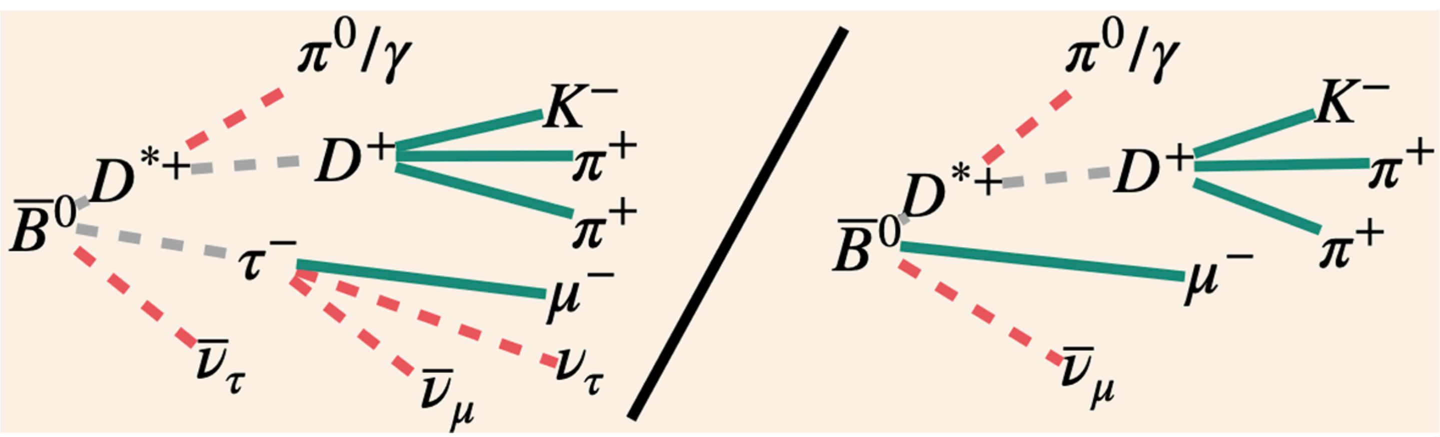
Small modification to SM predictions, but still a shift wrt data

Measurement of $R(D^{*+})$ and $R(D^{+})$ at LHCb

$R(D^{+}) =$



$R(D^{*+}) =$



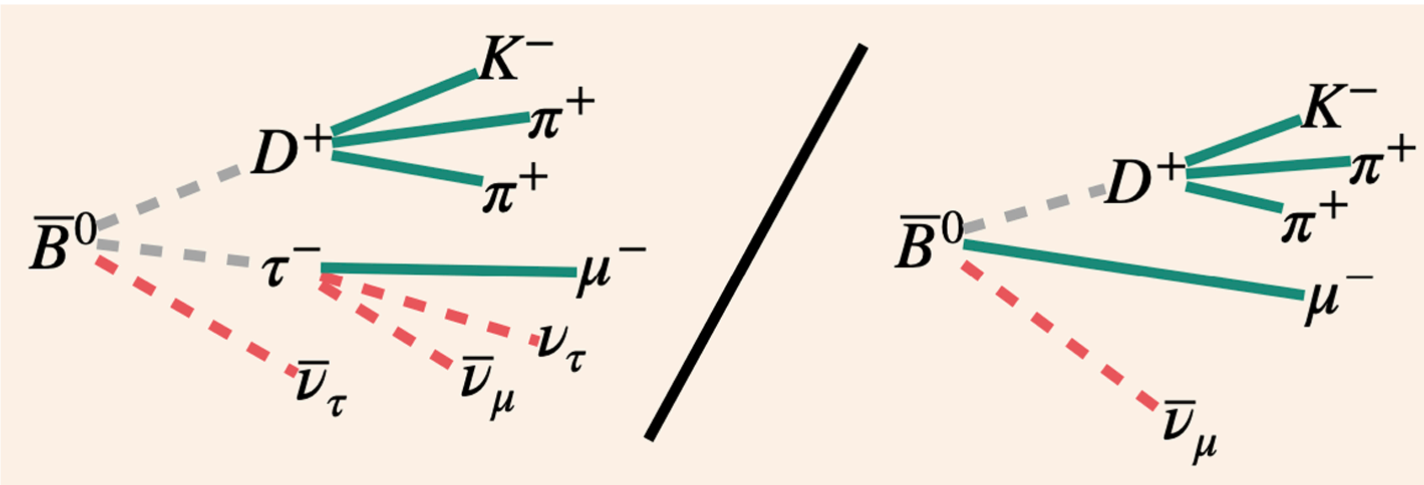
Reconstruct only $D^+(\to K^-\pi^+\pi^+)$ and μ^-

Simulation *Fits to data*

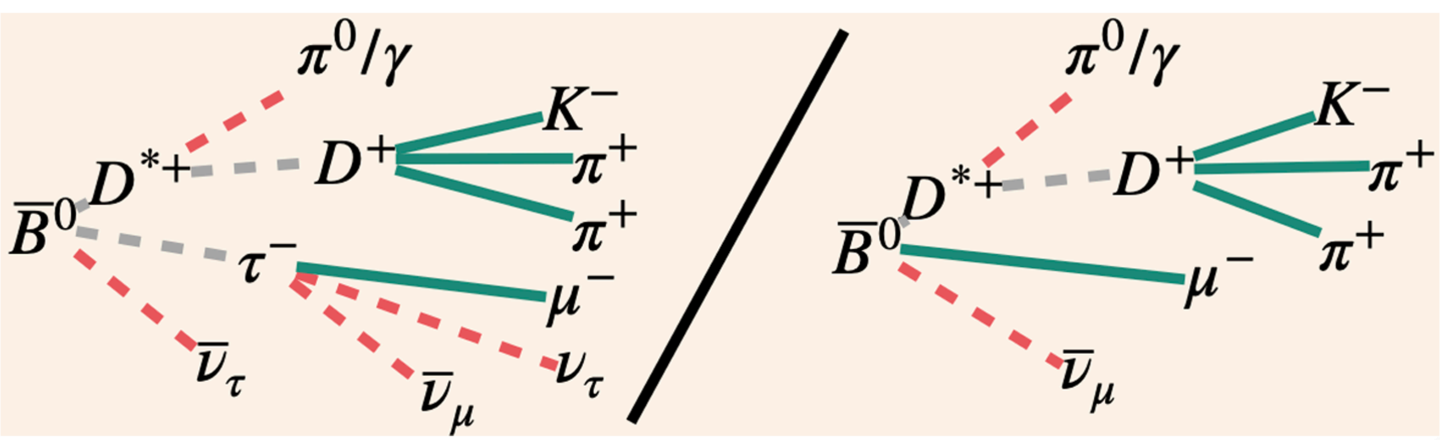
$$R(D^{(*)+}) = \frac{\epsilon_\mu^{D^{(*),+}}}{\epsilon_\tau^{D^{(*),+}}} \frac{N_\tau^{D^{(*),+}}}{N_\mu^{D^{(*),+}}} \frac{1}{\mathscr{B}(\tau^- \to \mu^-\nu_\tau)}$$

Measurement of $R(D^{*+})$ and $R(D^{+})$ at LHCb

$R(D^{+}) =$



$R(D^{*+}) =$



Reconstruct only $D^+(\to K^-\pi^+\pi^+)$ and μ^-

Simulation *Fits to data*

$$R(D^{(*)+}) = \frac{\epsilon_\mu^{D^{(*),+}}}{\epsilon_\tau^{D^{(*),+}}} \frac{N_\tau^{D^{(*),+}}}{N_\mu^{D^{(*),+}}} \frac{1}{\mathcal{B}(\tau^- \to \mu^- \nu_\tau)}$$

Perform simultaneous fit to **3 kinematic variables** across **4 samples** to constrain background

Samples defined by candidate isolation

- only $D^+\mu^-$? — Signal
- $D^+\mu^-\pi^-$? — $B \to D^{**}\ell^-\nu_\ell$
- $D^+\mu^-\pi^-\pi^+$? — $B \to D^{**}\ell^-\nu_\ell$
- $D^+\pi^-K^+$? — $B \to D^+H_cX$

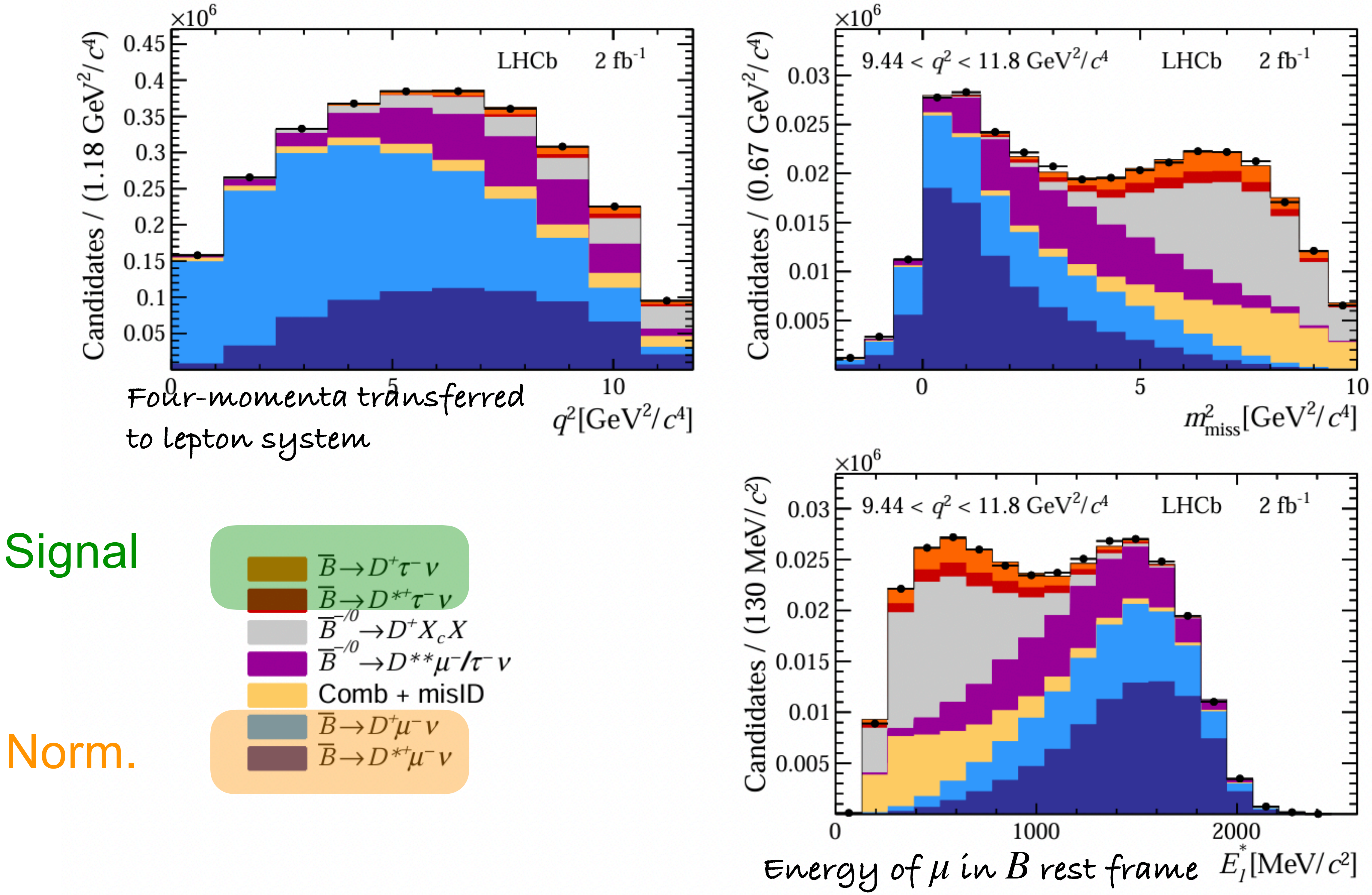
Form-factors dictate **shape** of signal and yields

- Use BGL parameterisation
  Phys.Rev.D 56 (1997) 6895-6911
- Float in fit, with constrains from lattice predictions

Measurement of $R(D^{*+})$ and $R(D^{+})$ at LHCb

LHCb-PAPER-2024-007

Fits for signal-sample



Measurement of $R(D^{*+})$ and $R(D^{+})$ at LHCb

LHCb-PAPER-2024-007

$$R(D^+) = 0.249 \pm 0.043(\text{stat}) \pm 0.047(\text{syst})$$
$$R(D^*) = 0.402 \pm 0.081(\text{stat}) \pm 0.085(\text{syst})$$
$$\rho = -0.39$$

Systematics-led analysis

Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$B \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$B \to D^+X_cX$ fractions	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.086

Main systematics:

- Background modelling/ branching fractions
- Form factor parameterisation

Measurement of $R(D^{*+})$ and $R(D^+)$ at LHCb

LHCb-PAPER-2024-007

$$R(D^+) = 0.249 \pm 0.043(\text{stat}) \pm 0.047(\text{syst})$$
$$R(D^*) = 0.402 \pm 0.081(\text{stat}) \pm 0.085(\text{syst})$$
$$\rho = -0.39$$

Systematics-dominated analysis

Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$B \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$B \to D^+X_cX$ fractions	0.020	0.034
Misidentification	0.019	0.012
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Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.086

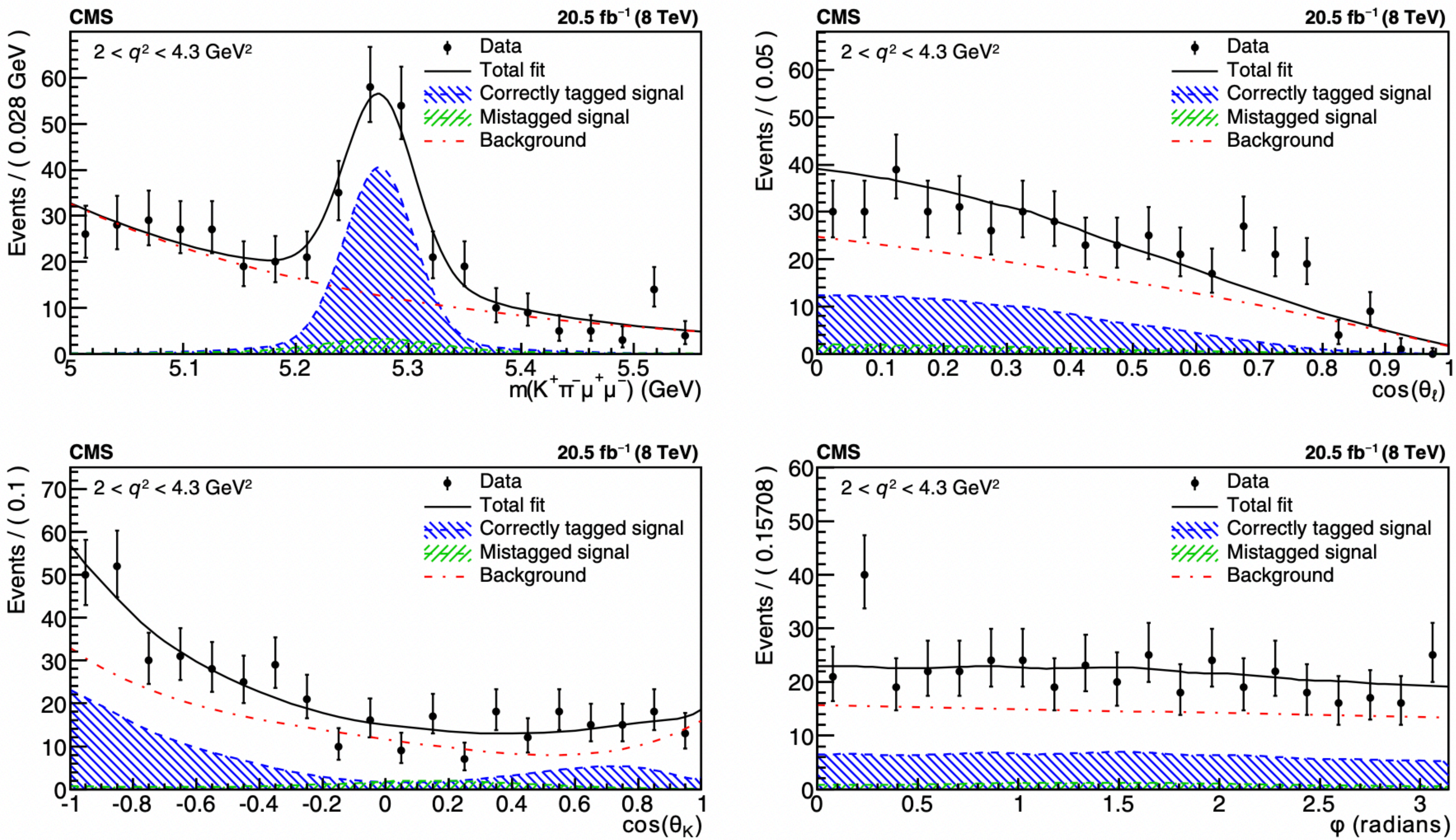
Main systematics:

- Background modelling/ branching fractions
- Form factor parameterisation

New: *systematic due to simulation size no longer leading systematic, due to new approaches to speed up MC, see details in G. Pietrzyk's talk*

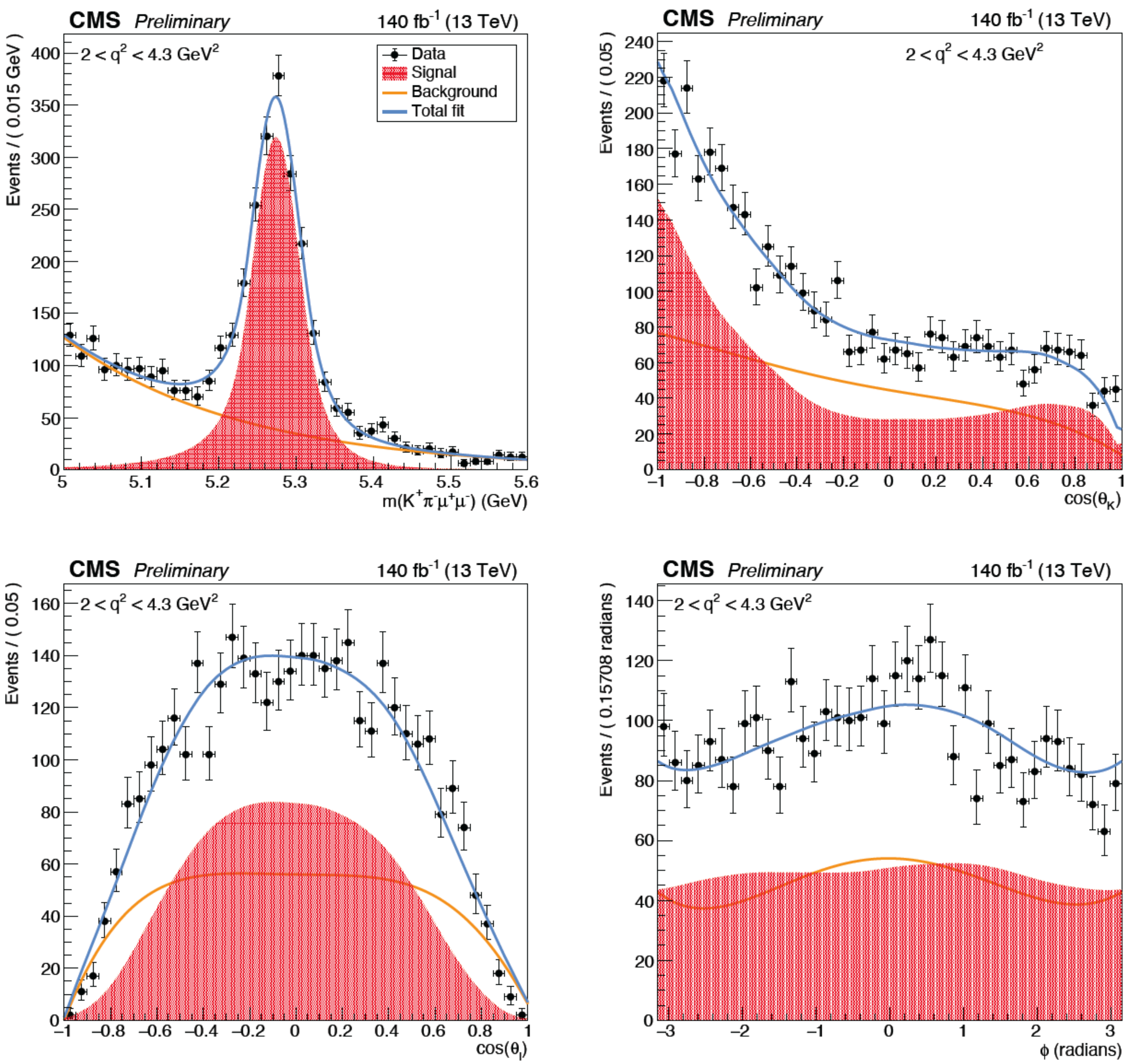
New!! $B^0 \to K^{*0}\mu^+\mu^-$ with 140 fb^{-1} from CMS

Previous Run 1 only result



New!! $B^0 \to K^{*0}\mu^+\mu^-$ with 140 fb^{-1} from CMS

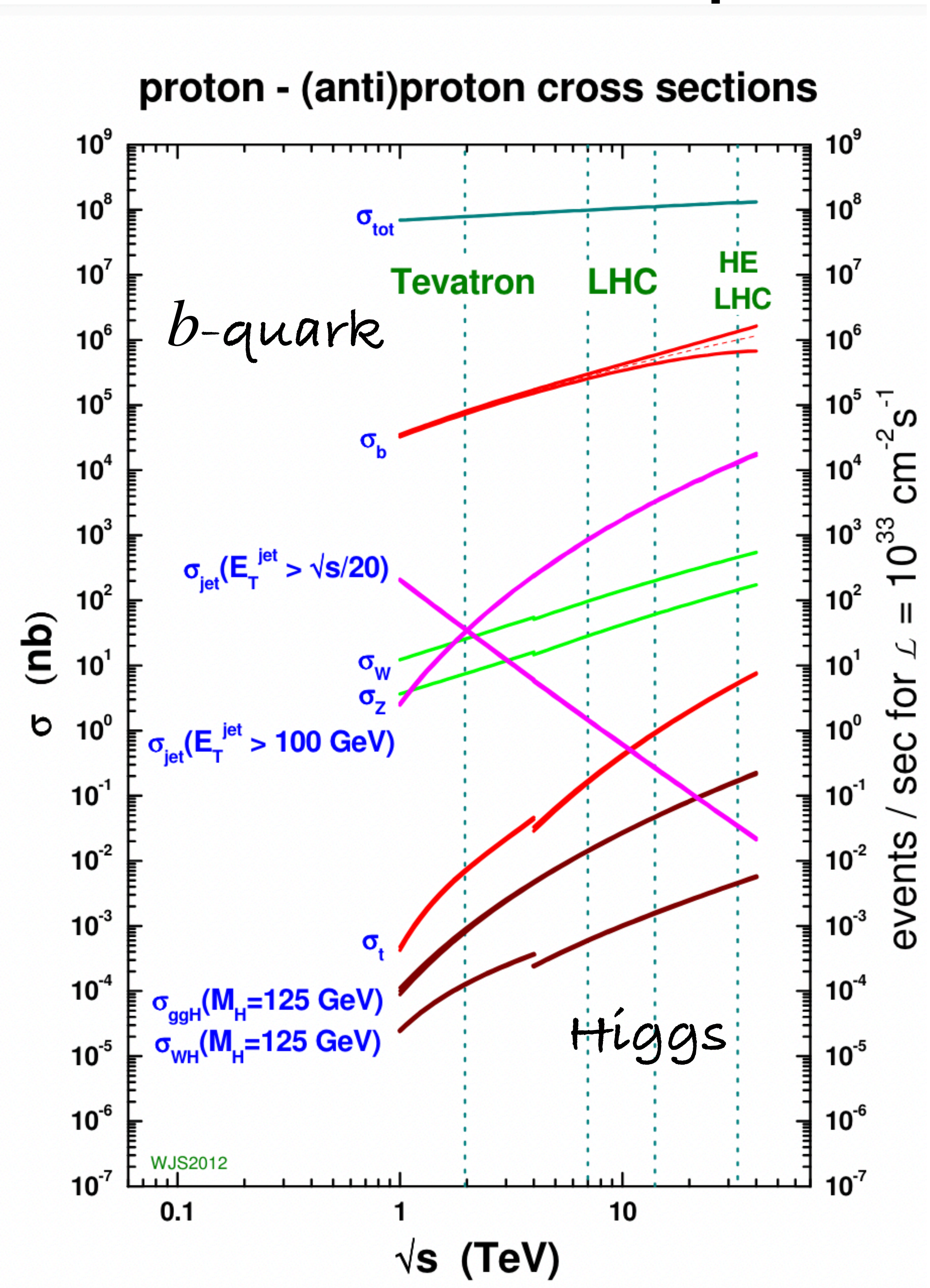
New Run 2 results



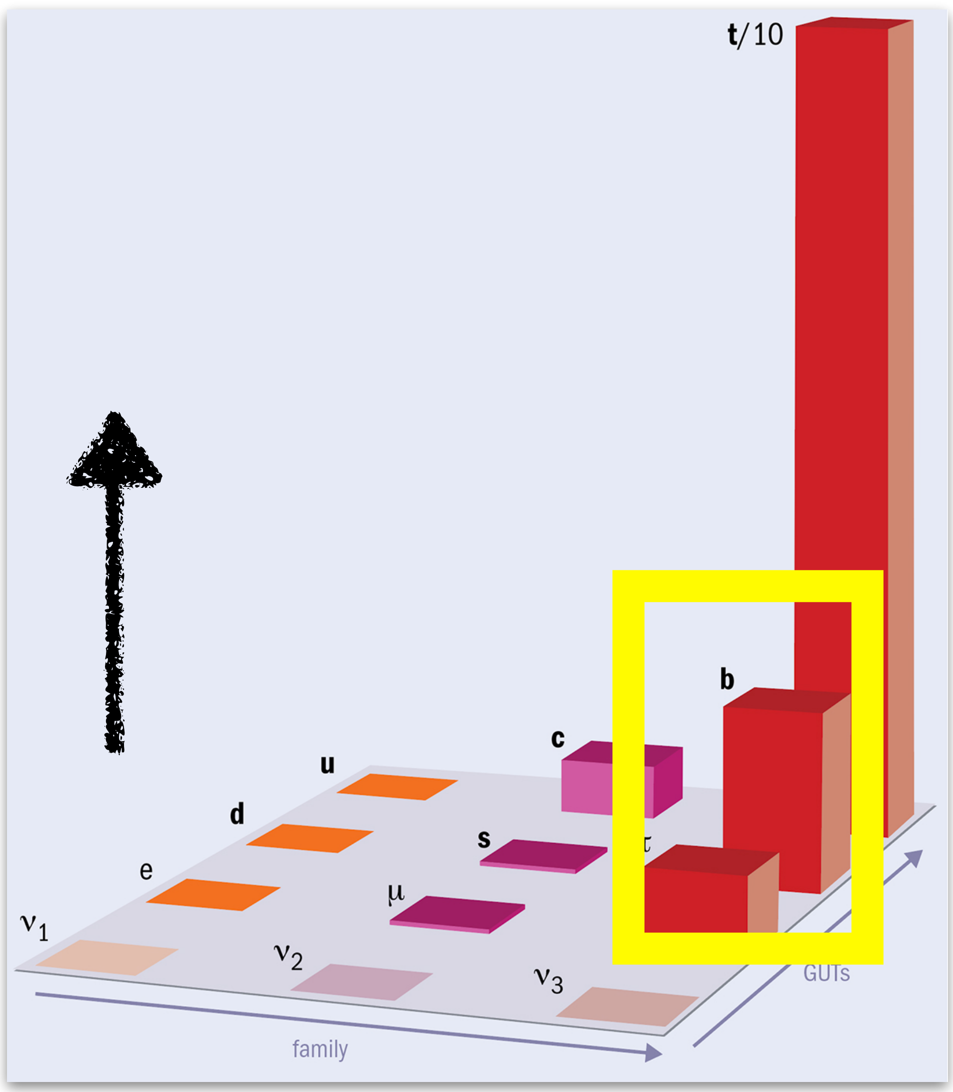
Result is still statistically dominated

Effect on P_5' ?

b-quarks at the LHC



heaviest stable quark

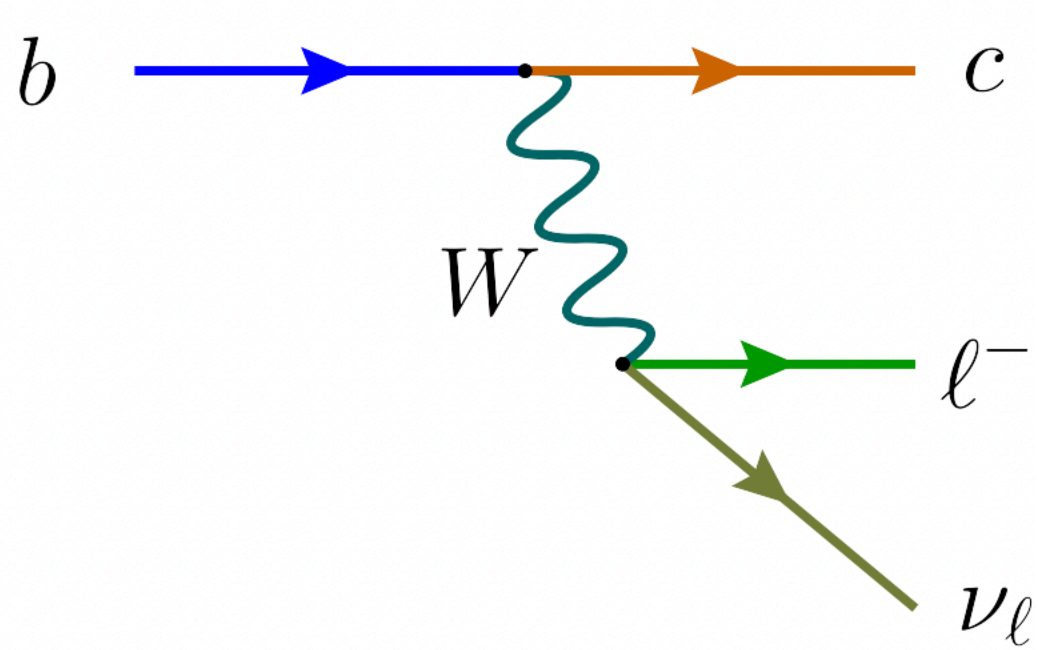


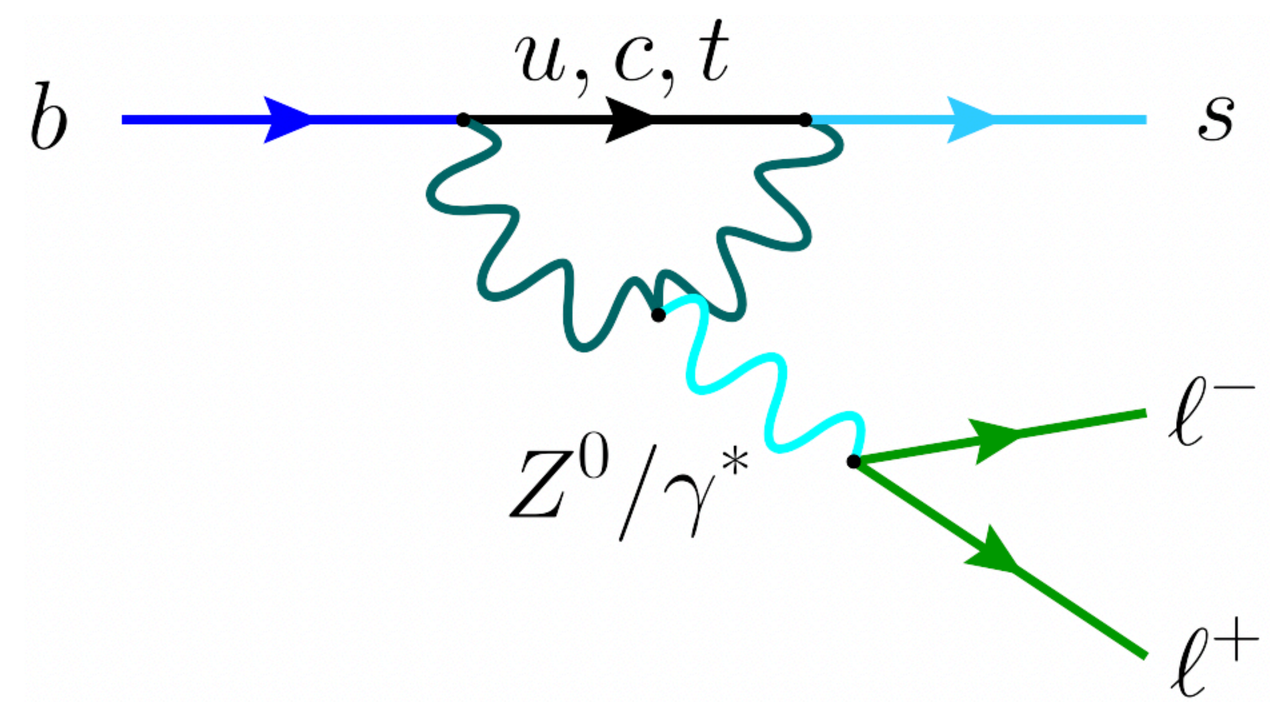
3rd generation - sensitivity to BSM

Semi-leptonic b quark decays

$b \to c\ell\nu$

$b \to s\ell\ell$



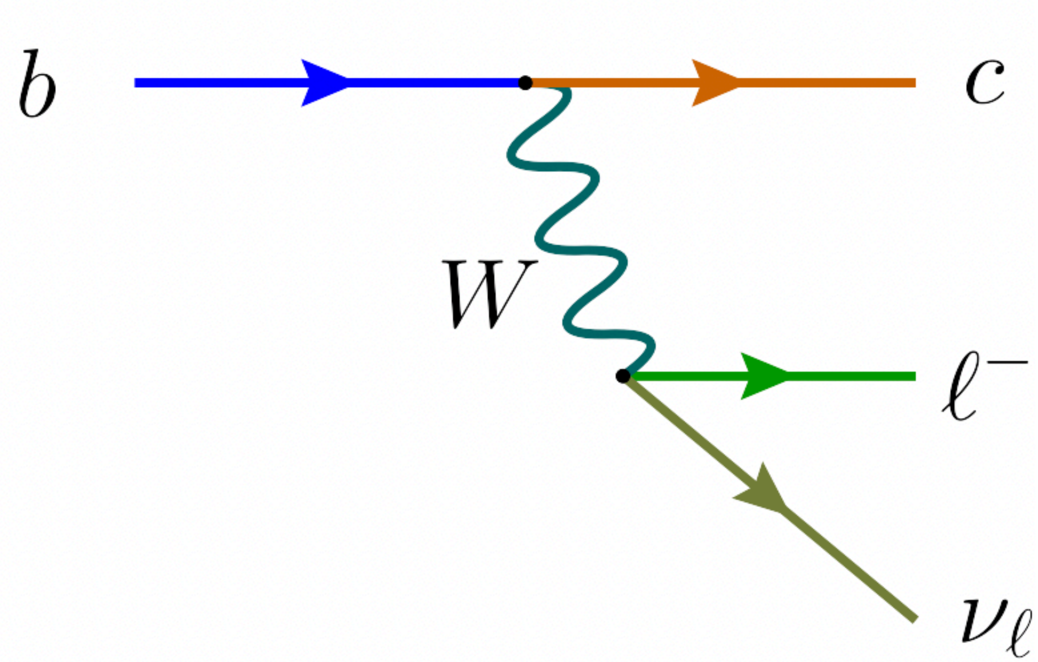


Charged current:

Neutral current:

Semi-leptonic b quark decays

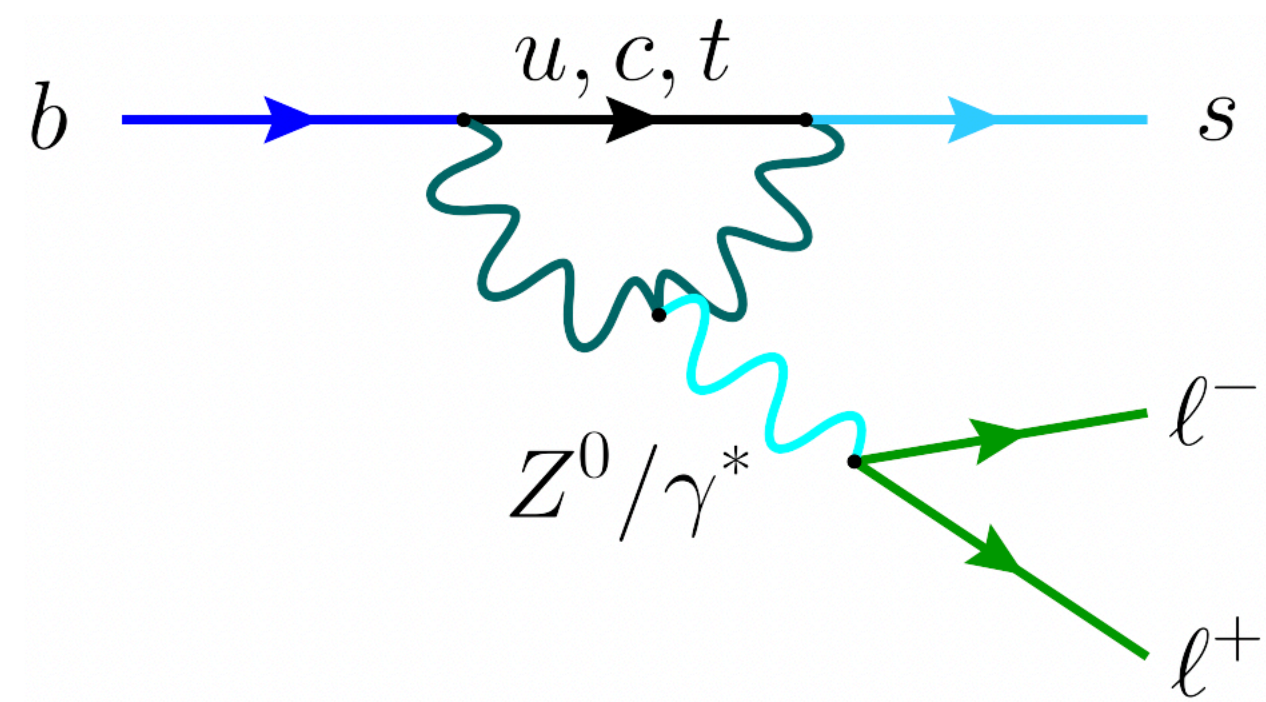
$b \to c\ell\nu$



Charged current:

- Tree-level
  - $\mathscr{B}$ order %

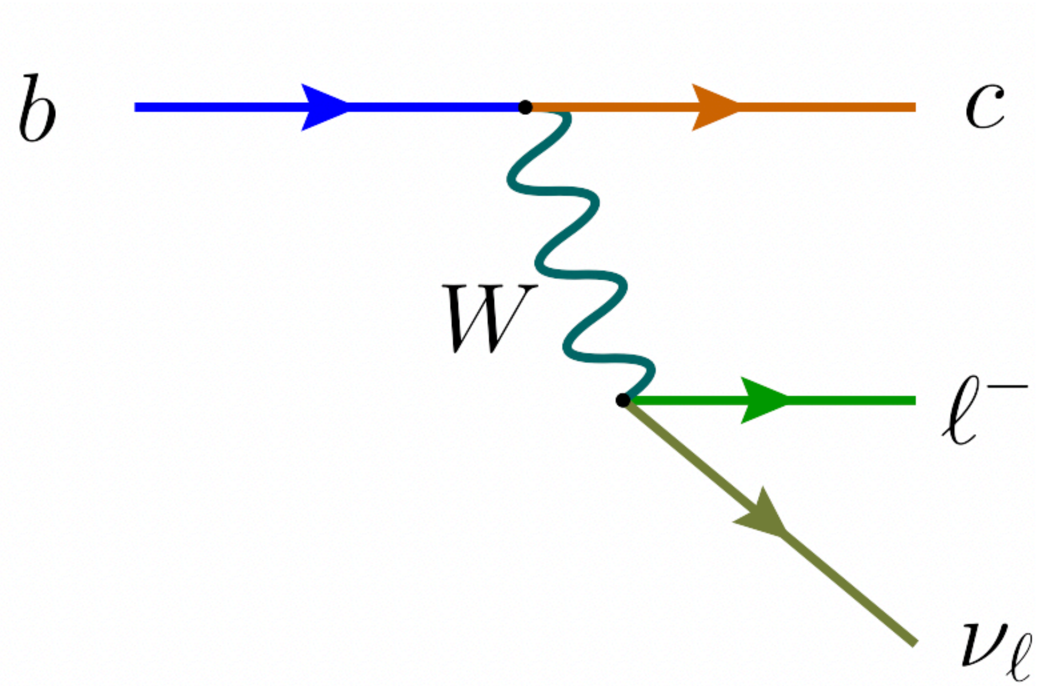
$b \to s\ell\ell$



Neutral current:

Semi-leptonic b quark decays

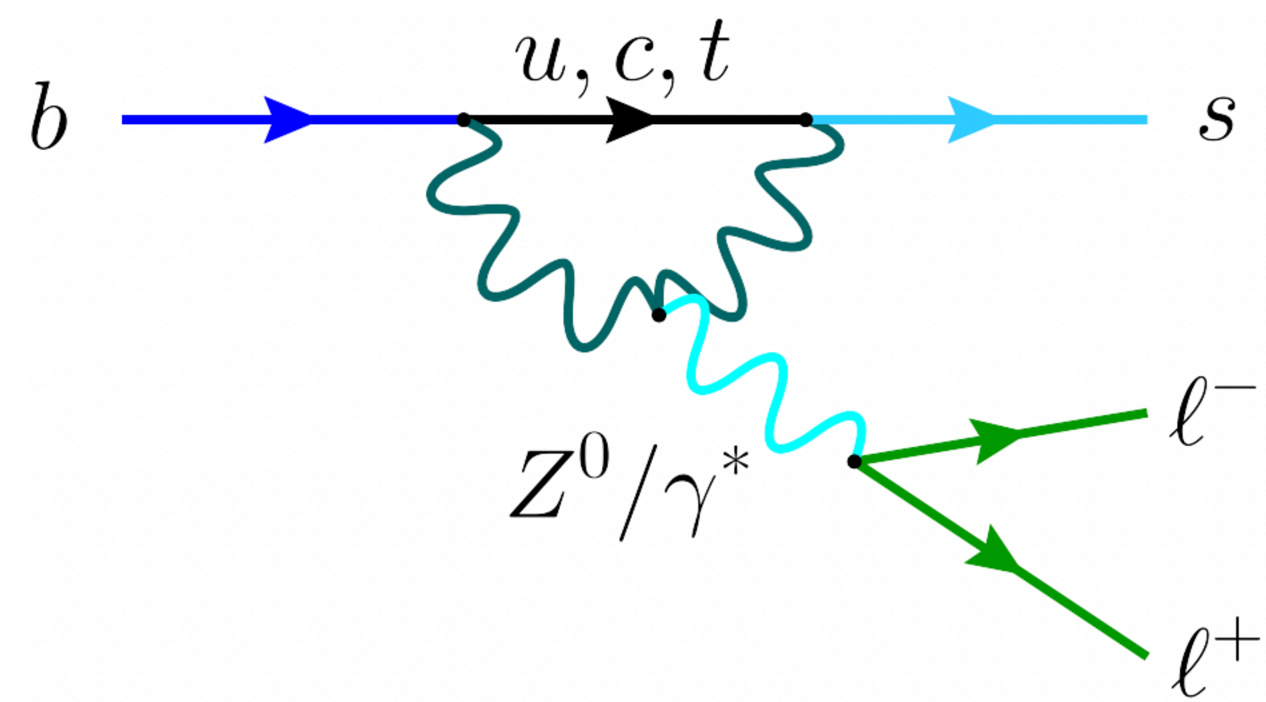
$b \to c\ell\nu$



Charged current:

- Tree-level
  - $\mathscr{B}$ order %
- Neutrino in final state (invisible)

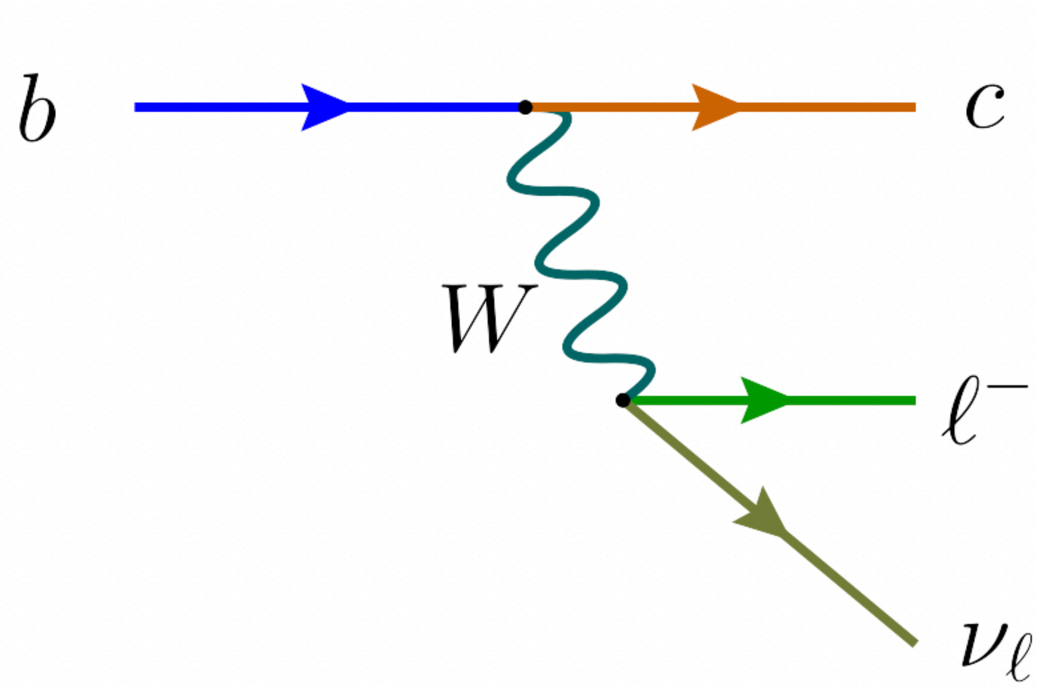
$b \to s\ell\ell$



Neutral current:

Semi-leptonic b quark decays

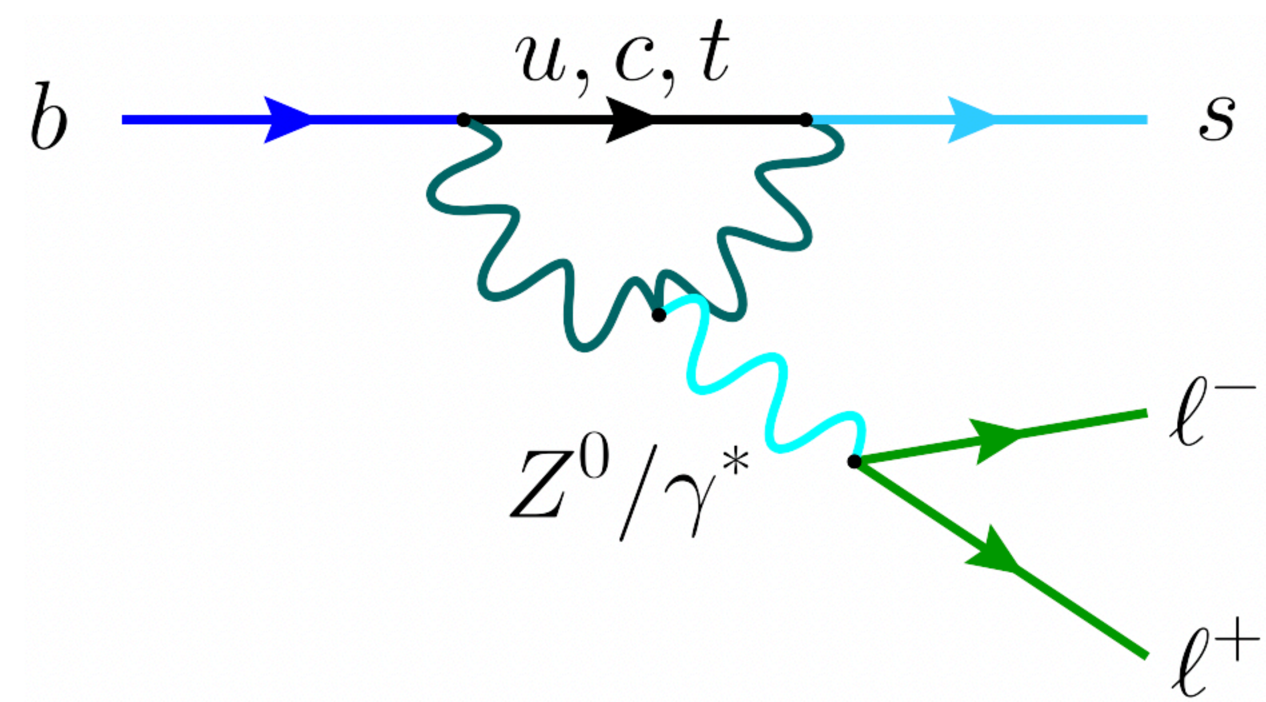
$b \to c\ell\nu$



Charged current:

- Tree-level
  - $\mathscr{B}$ order %
- Neutrino in final state (invisible)

$b \to s\ell\ell$

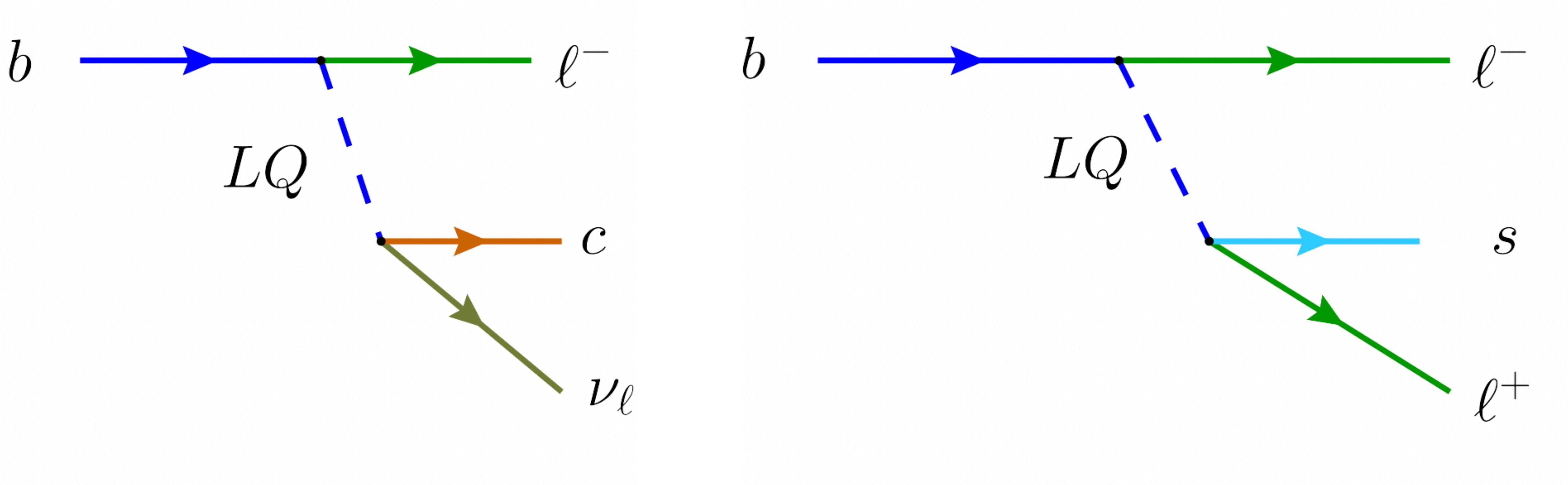


Neutral current:

- Loop-suppressed:
  - $\mathscr{B}$ order $10^{-7} - 10^{-9}$
- Full reconstructed final state

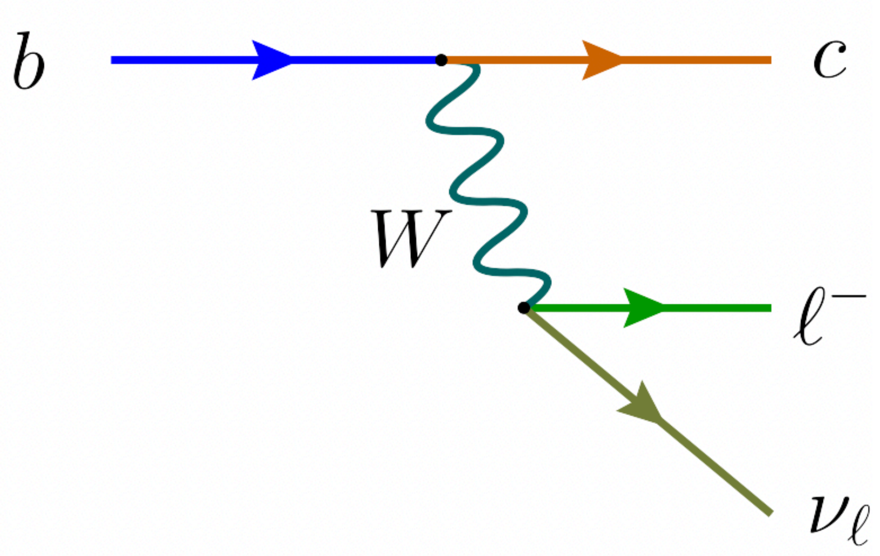
Semi-leptonic b quark decays

$b \to c\ell\nu$ $\qquad$ $b \to s\ell\ell$

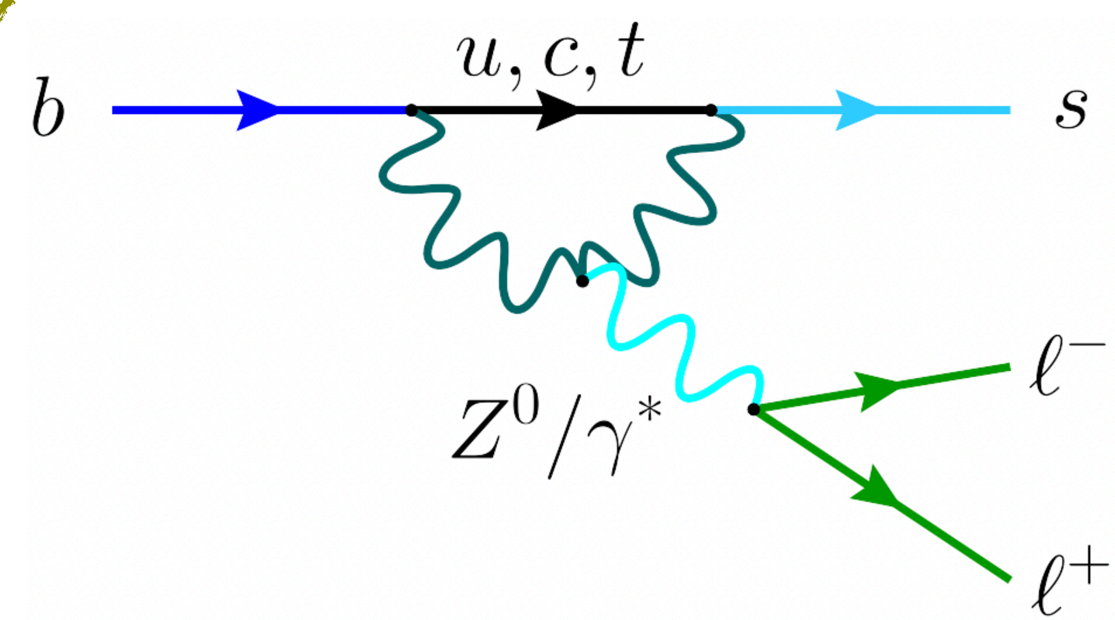


Could be joint explanation…motivates $b \to s\tau\tau$ measurements

The B-anomalies

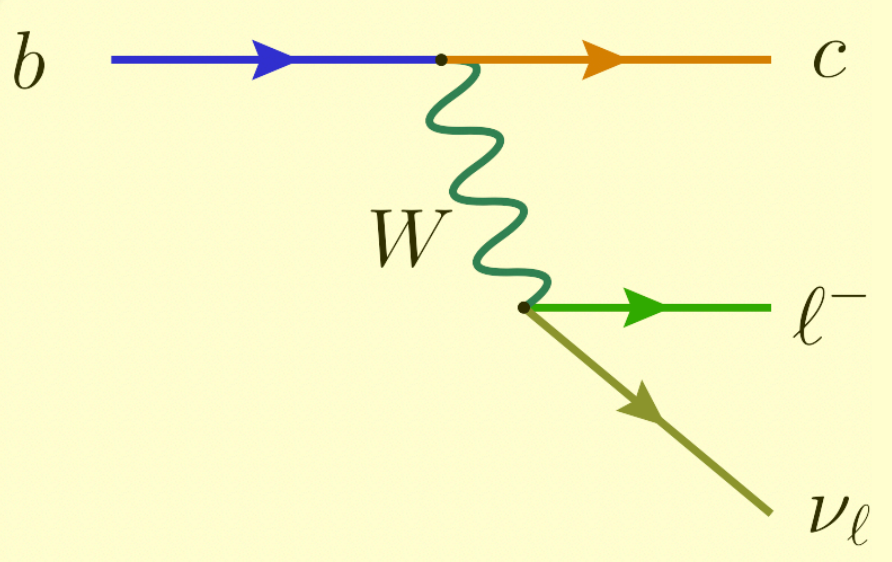


Charged current $\sim 3\sigma$

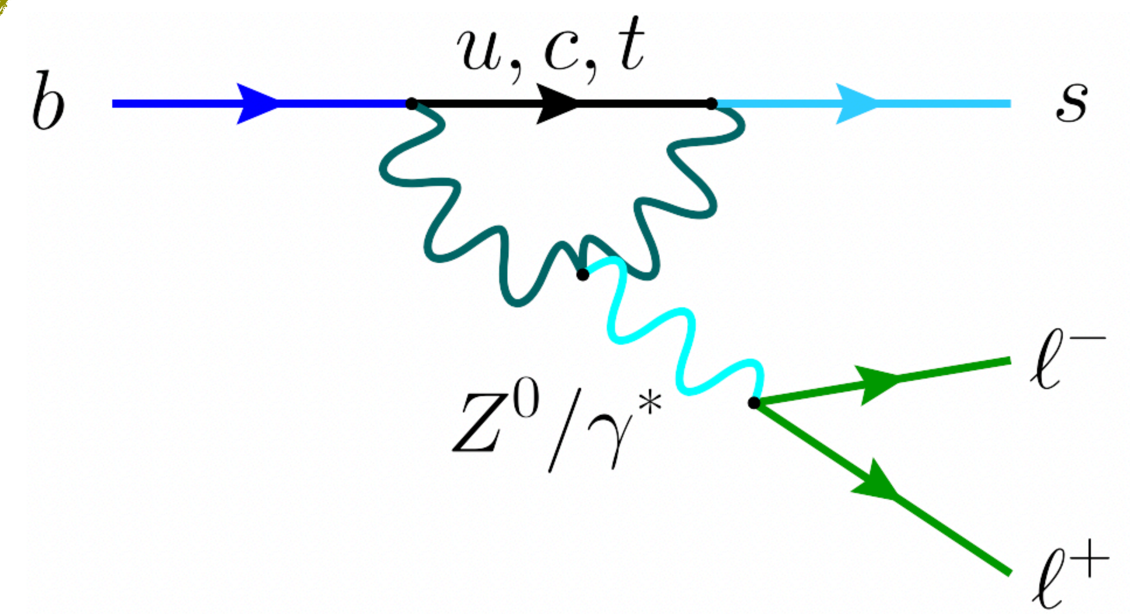


Neutral current $\sim 4 - 5\sigma$

The B-anomalies



Charged current $\sim 3\sigma$



Neutral current $\sim 4-5\sigma$

Charged current anomalies

$$R(D^{(*,+)}) = \frac{\mathscr{B}(B^{(+)} \to D^{(*,+)}\tau\nu_\tau)}{\mathscr{B}(B^{(+)} \to D^{(*,+)}\ell\nu_\ell)}$$

$\ell \in \mu, e$, *(LHCb only μ)*

Isospin

$$R(D^0) = R(D^+)$$

$$R(D^{*0}) = R(D^{*+})$$

Hadronic

$$\tau \to \nu_\tau \pi X$$

Semi-leptonic (SL)

$$\tau \to \nu_\tau \ell \nu_\ell$$

Charged current anomalies

$$R(D^{(*,+)}) = \frac{\mathscr{B}(B^{(+)} \to D^{(*,+)}\tau\nu_\tau)}{\mathscr{B}(B^{(+)} \to D^{(*,+)}\ell\nu_\ell)}$$

$\ell \in \mu, e$, (LHCb only μ)

Isospin

$R(D^0) = R(D^+)$

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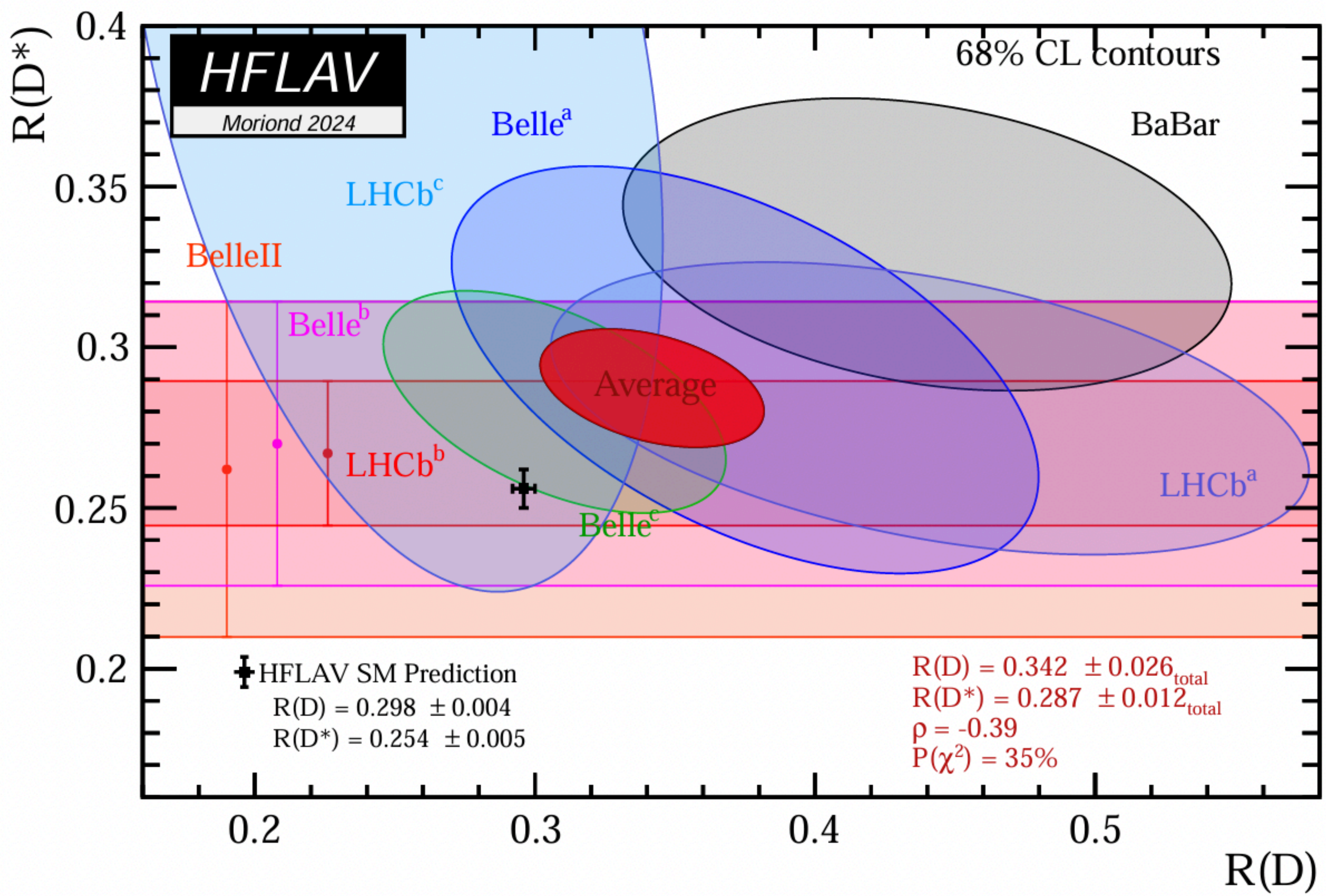
Semi-leptonic (SL)

$\tau \to \nu_\tau \ell \nu_\ell$



Charged current anomalies

$$R(D^{(*,+)}) = \frac{\mathscr{B}(B^{(+)} \to D^{(*,+)}\tau\nu_\tau)}{\mathscr{B}(B^{(+)} \to D^{(*,+)}\ell\nu_\ell)}$$

$\ell \in \mu, e$, (LHCb only μ)

Isospin

$R(D^0) = R(D^+)$

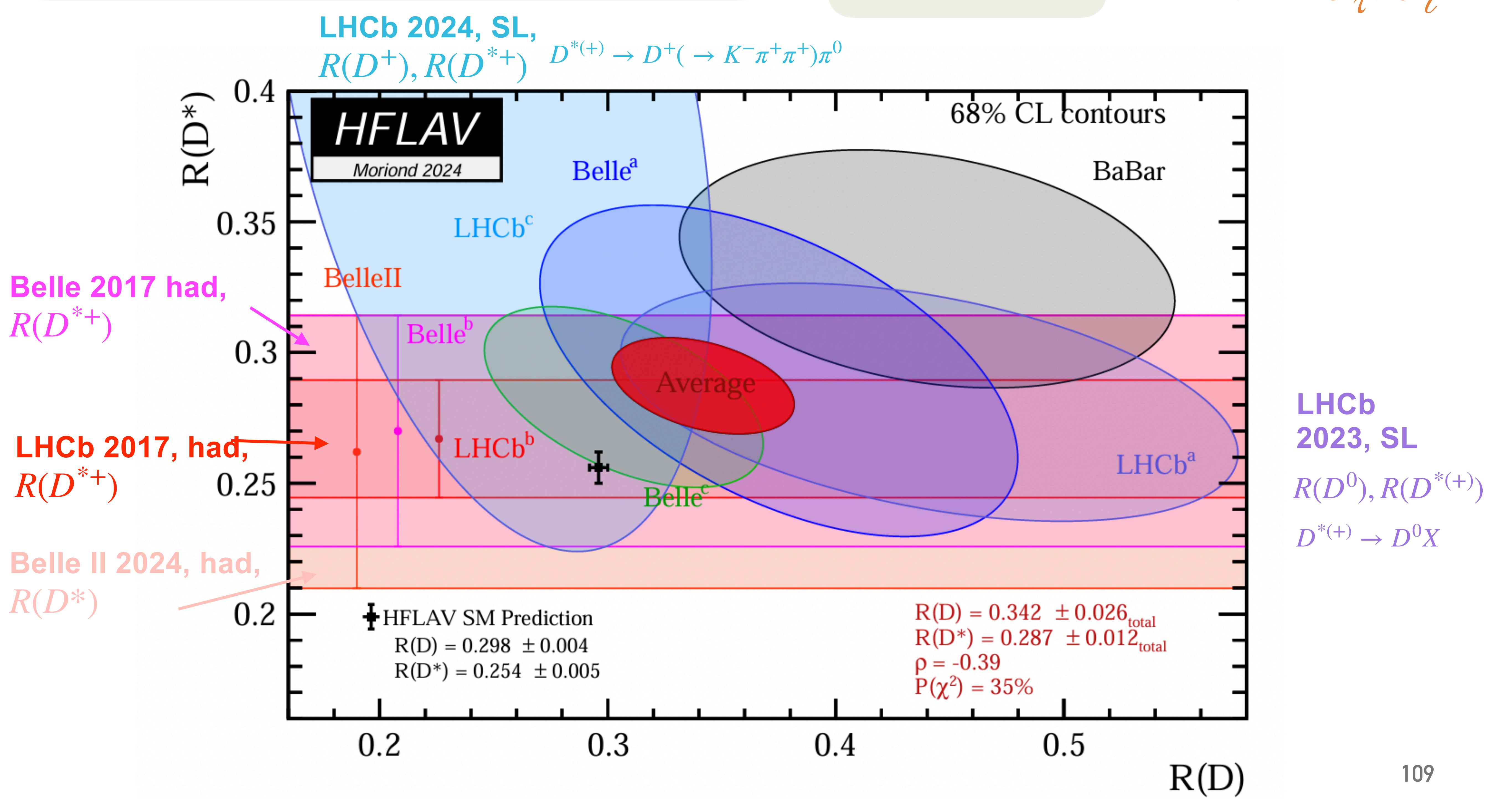
$R(D^{*0}) = R(D^{*+})$

Hadronic

$\tau \to \nu_\tau \pi X$

Semi-leptonic (SL)

$\tau \to \nu_\tau \ell \nu_\ell$



Charged current anomalies

$$R(D^{(*,+)}) = \frac{\mathcal{B}(B^{(+)} \to D^{(*,+)}\tau\nu_\tau)}{\mathcal{B}(B^{(+)} \to D^{(*,+)}\ell\nu_\ell)}$$

$\ell \in \mu, e$, *(LHCb only* μ*)*

Isospin

$R(D^0) = R(D^+)$

$R(D^{*0}) = R(D^{*+})$

Hadronic

$\tau \to \nu_\tau \pi X$

Semi-leptonic (SL)

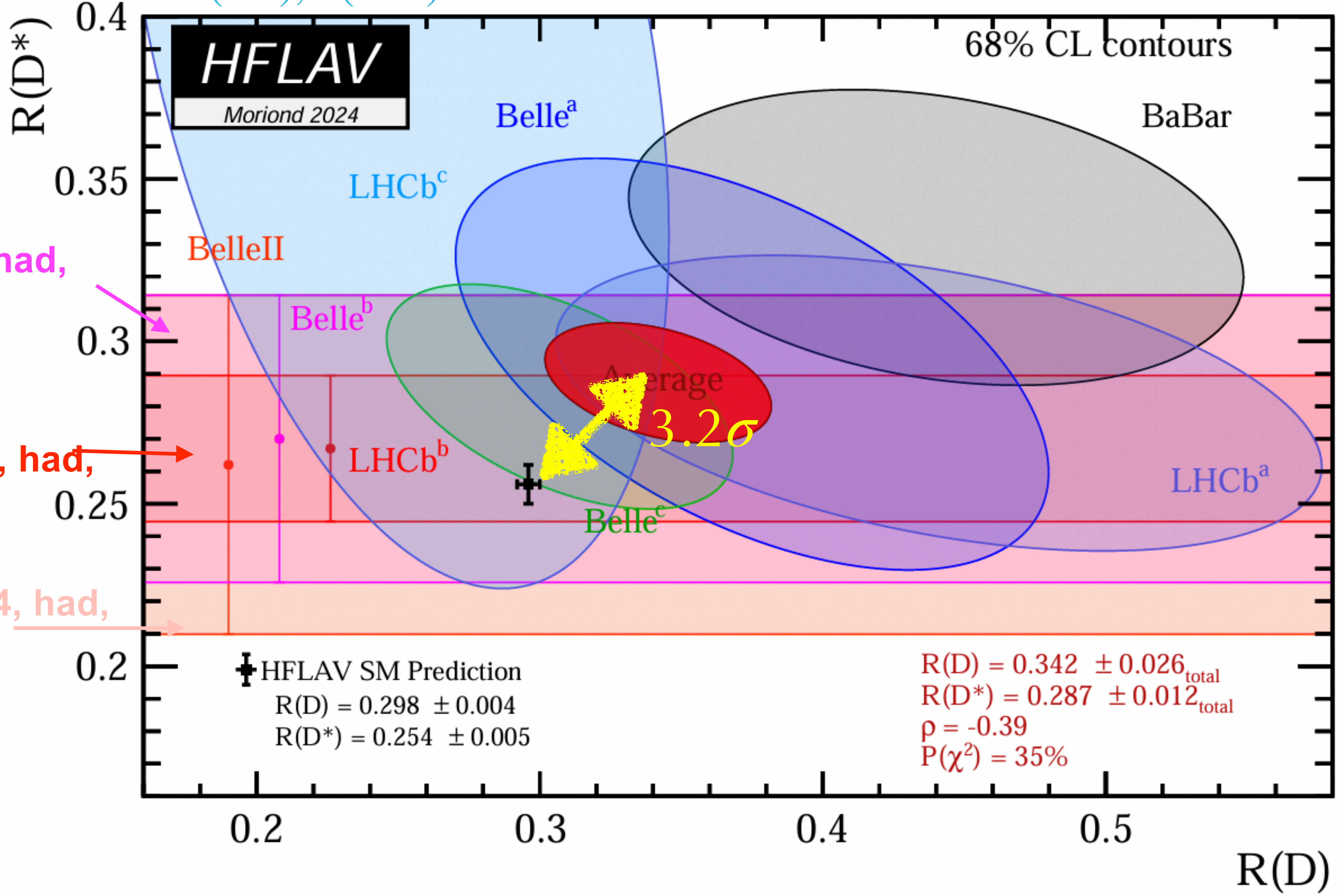
$\tau \to \nu_\tau \ell \nu_\ell$

LHCb 2024, SL,
$R(D^+), R(D^{*+})$ $D^{*(+)} \to D^+(\to K^-\pi^+\pi^+)\pi^0$

Belle 2017 had,
$R(D^{*+})$

LHCb 2017, had,
$R(D^{*+})$

Belle II 2024, had,
$R(D^*)$



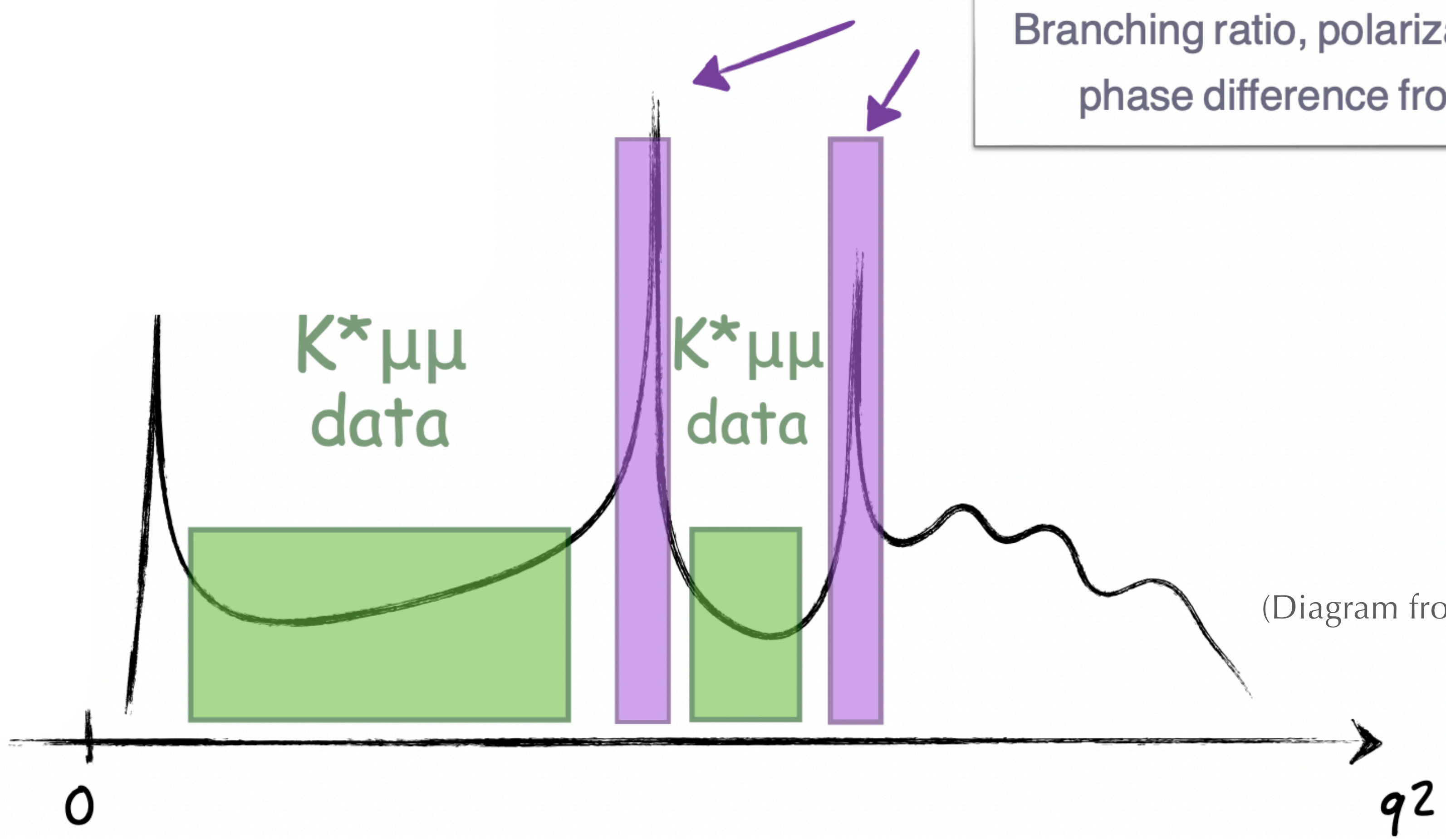
LHCb 2023, SL
$R(D^0), R(D^{*(+)})$
$D^{*(+)} \to D^0 X$

Z-expansion

Polynomial-expansion

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

z = remapping of q^2



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)

(Diagram from A. Mauri)

Polynomial-expansion

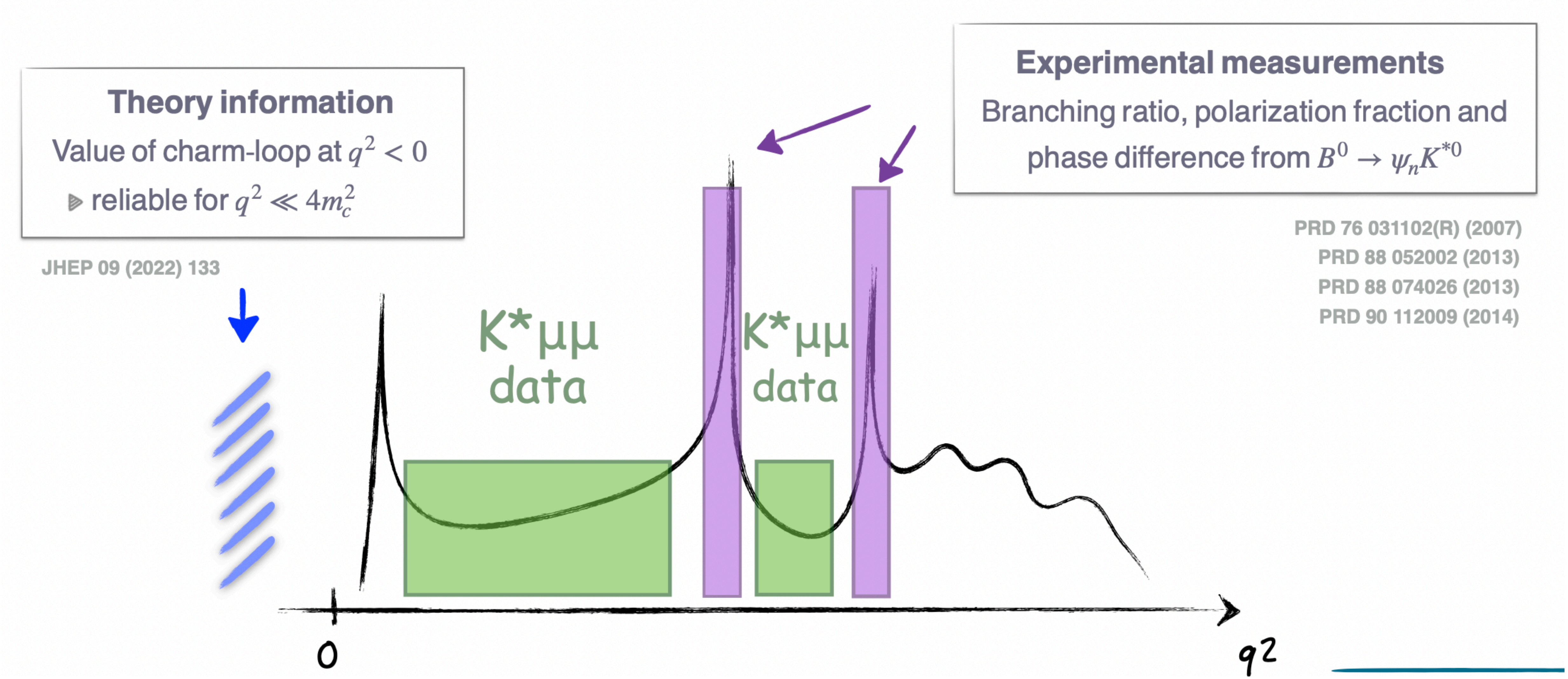
Z-expansion

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

z = remapping of q^2

2 models used:

- With theory info from $<q^2$ (n = 4)
- With no theory info (n = 2)



Charged current anomalies

$$R(D^{(*,+)}) = \frac{\mathscr{B}(B^{(+)} \to D^{(*,+)}\tau\nu_\tau)}{\mathscr{B}(B^{(+)} \to D^{(*,+)}\ell\nu_\ell)}$$

$\ell \in \mu, e,$ (LHCb only μ)

Isospin

$R(D^0) = R(D^+)$

$R(D^{*0}) = R(D^{*+})$

Hadronic

$\tau \to \nu_\tau \pi X$

Semi-leptonic (SL)

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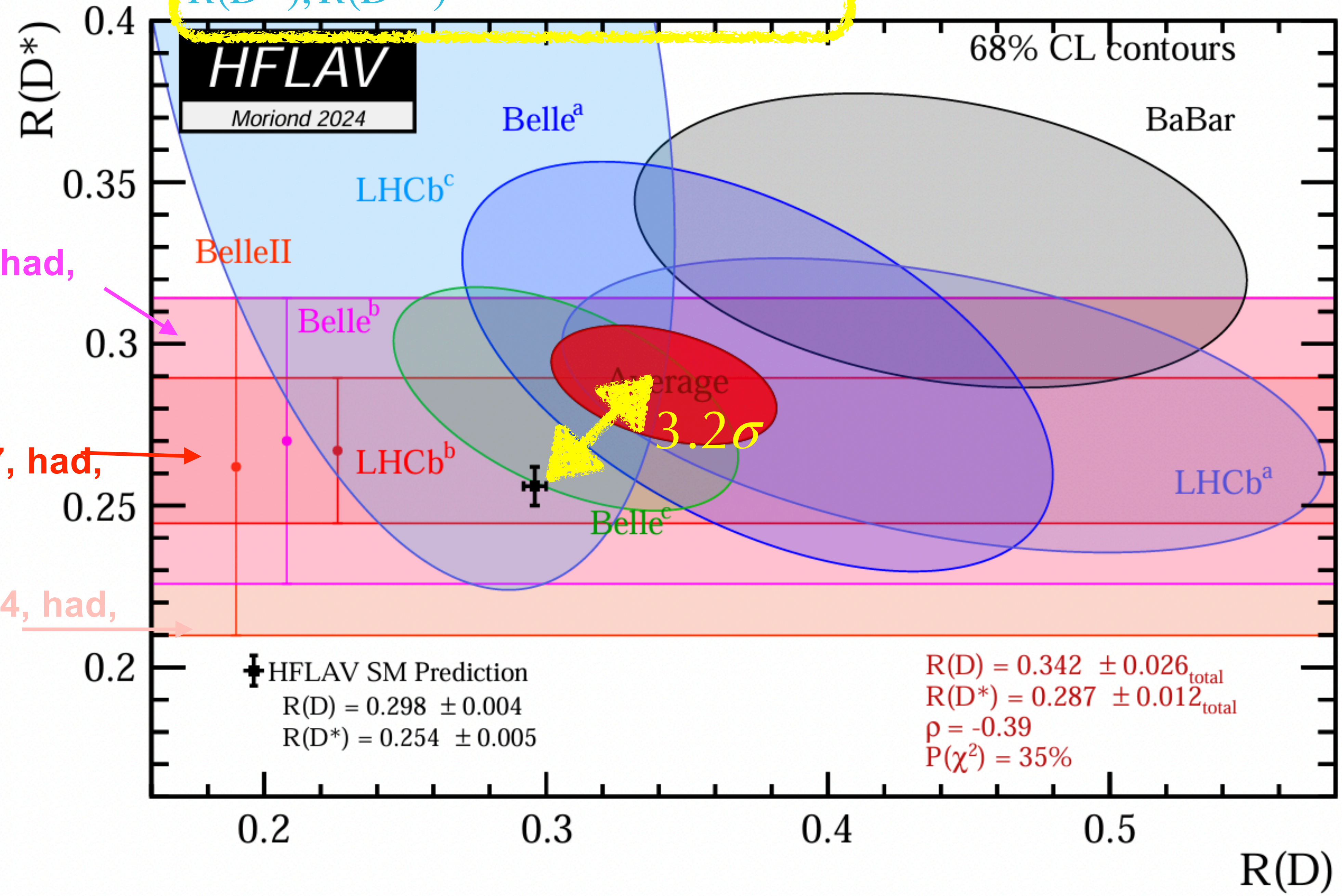
LHCb 2024, SL, $R(D^+), R(D^{*+})$ $D^{*(+)} \to D^+(\to K^-\pi^+\pi^+)\pi^0$

Belle 2017 had, $R(D^{*+})$

LHCb 2017, had, $R(D^{*+})$

Belle II 2024, had, $R(D^*)$

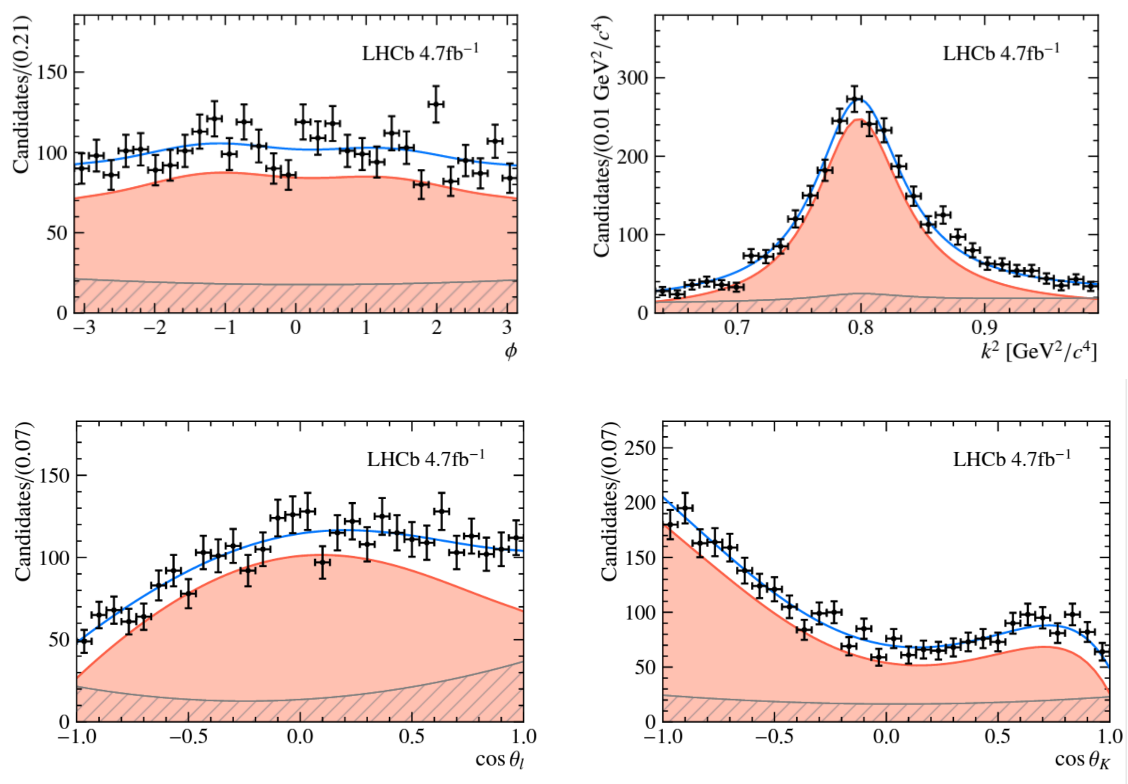
LHCb 2023, SL, $R(D^0), R(D^{*(+)})$ $D^{*(+)} \to D^0 X$

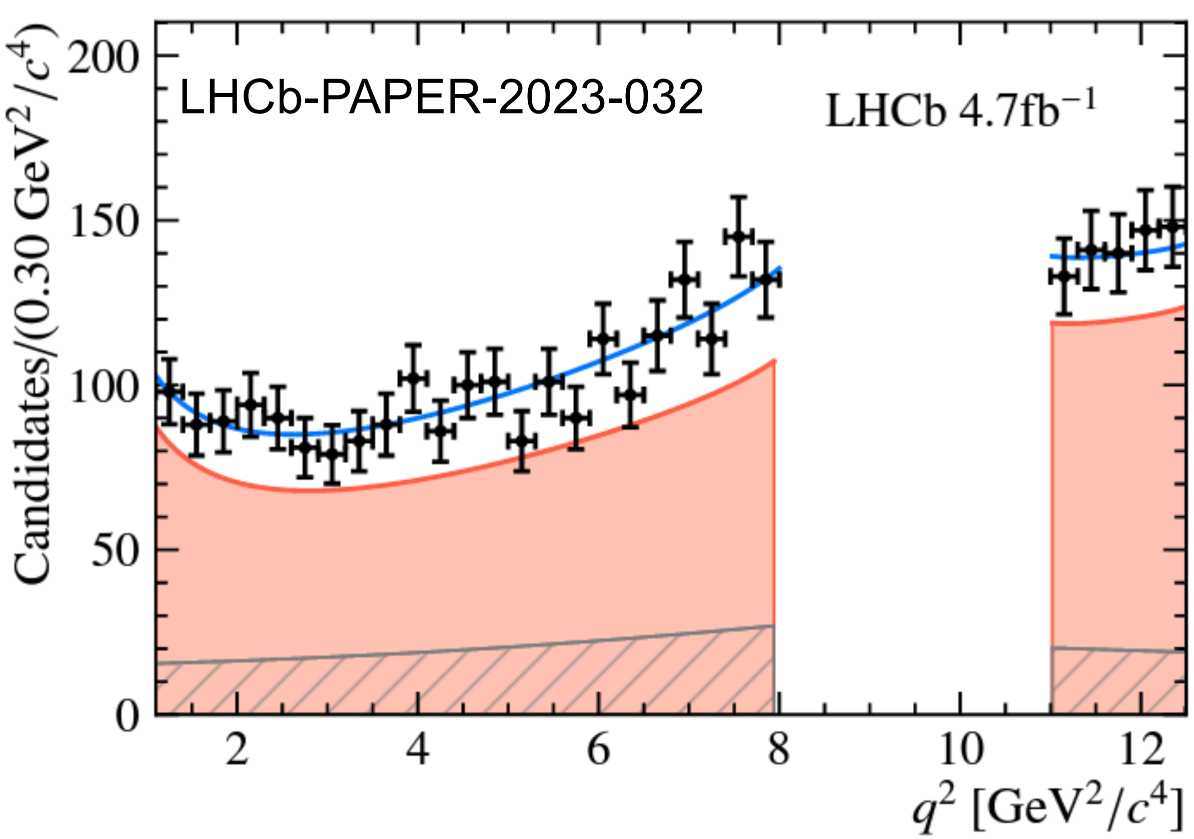


Fit projections

Z-expansion

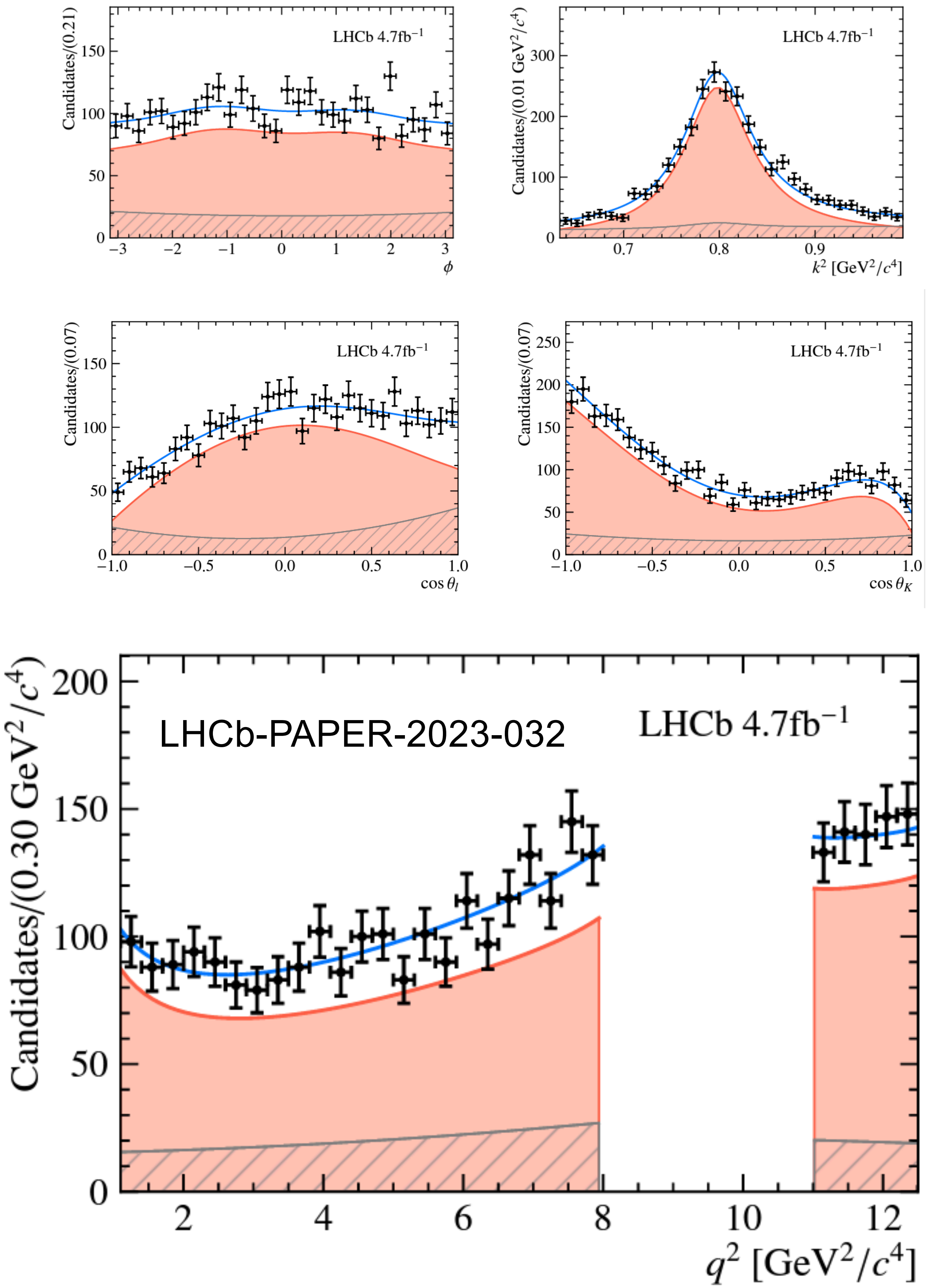
Amplitude model





Fit projections

Z-expansion



Amplitude model