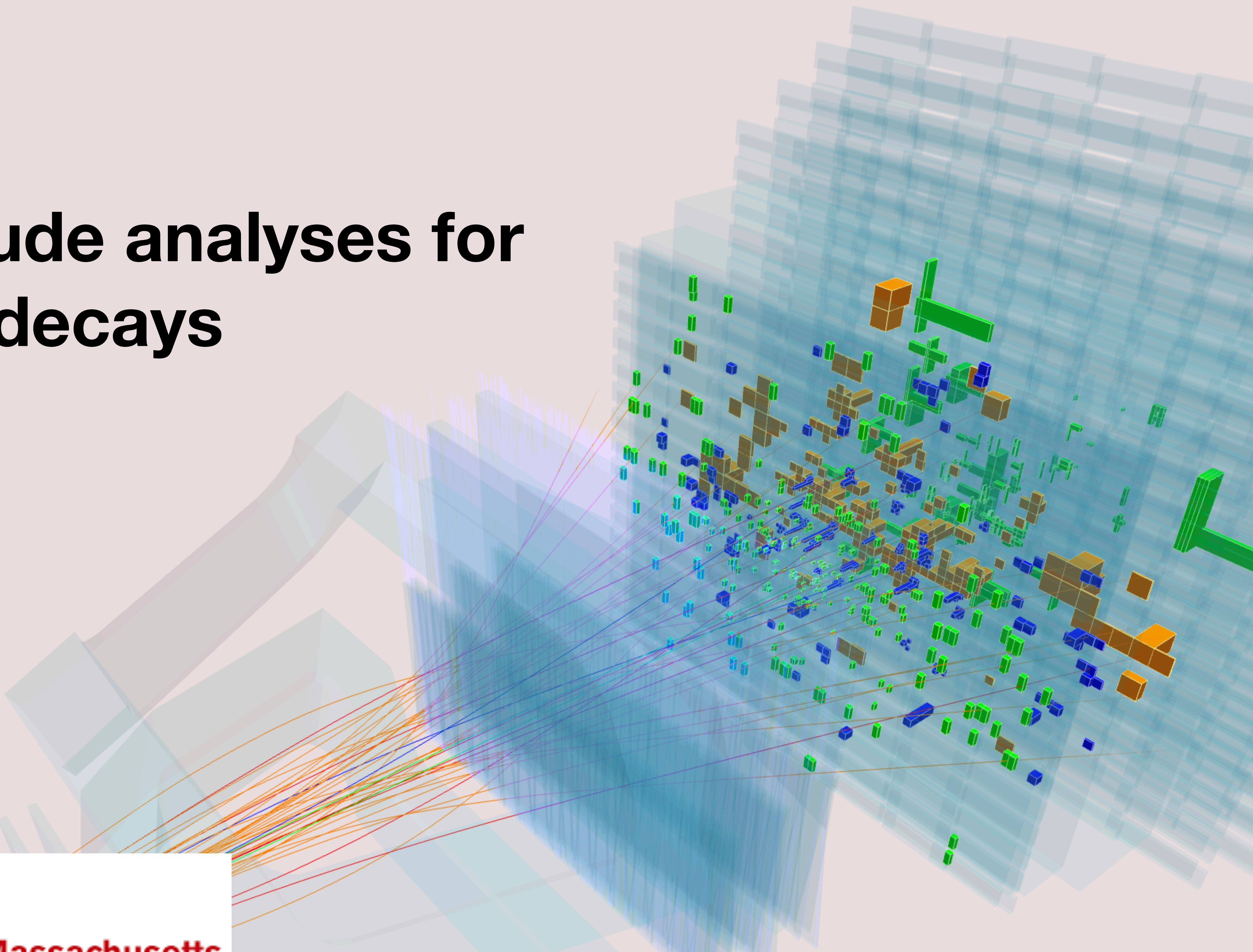
Amplitude analyses for rare B decays



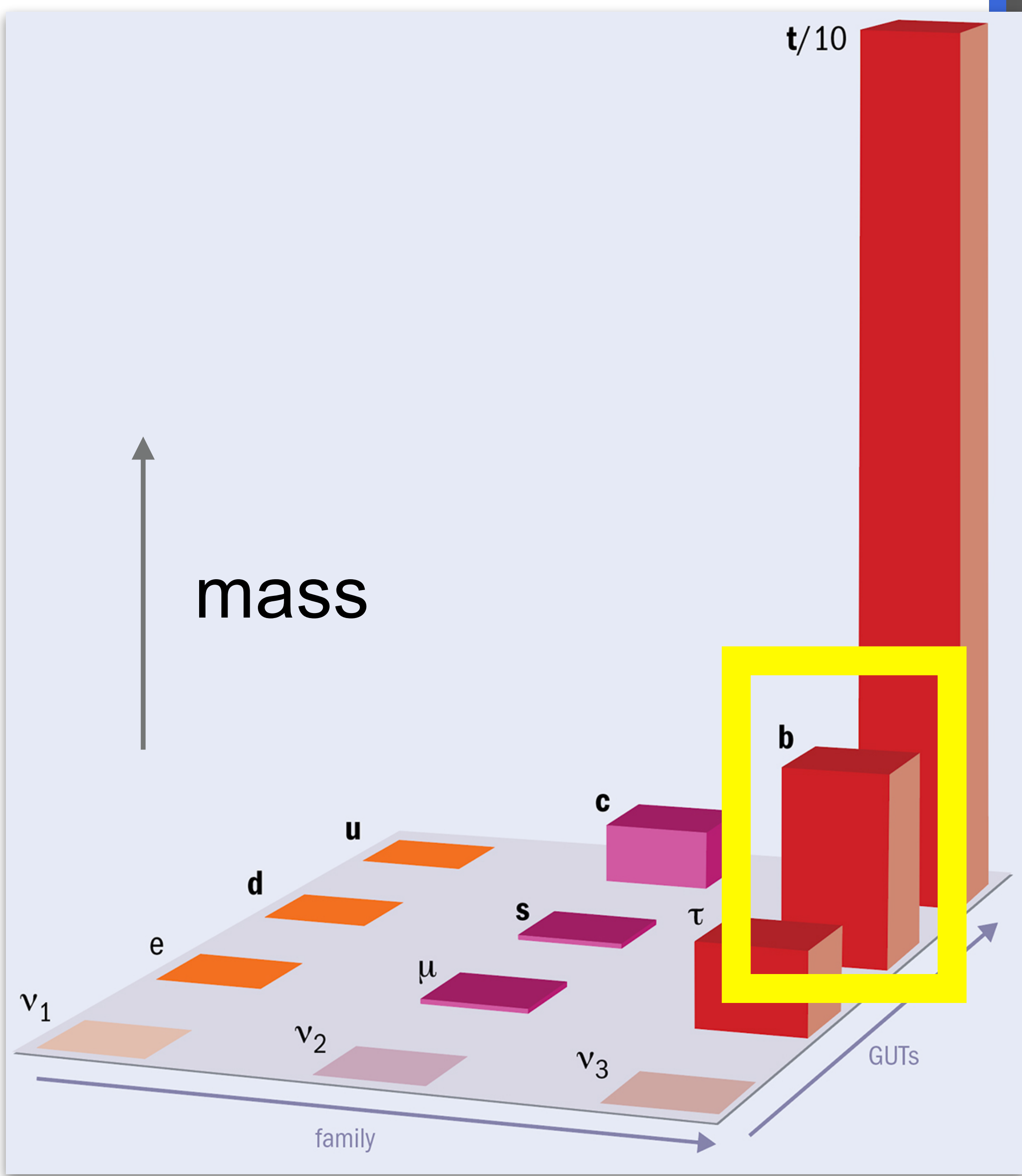
Eluned Smith

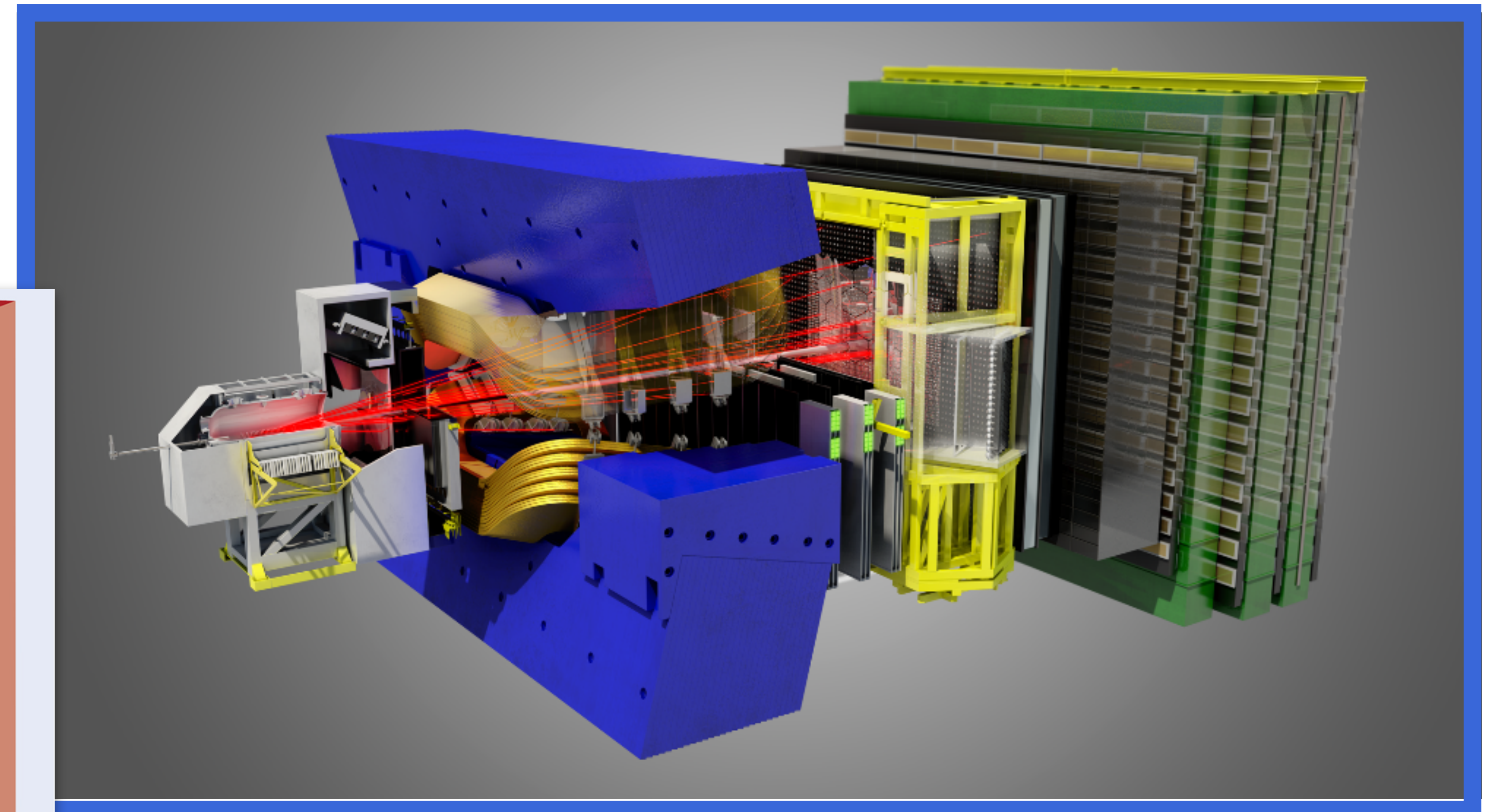
Massachusetts Institute of Technology

05/29/2024

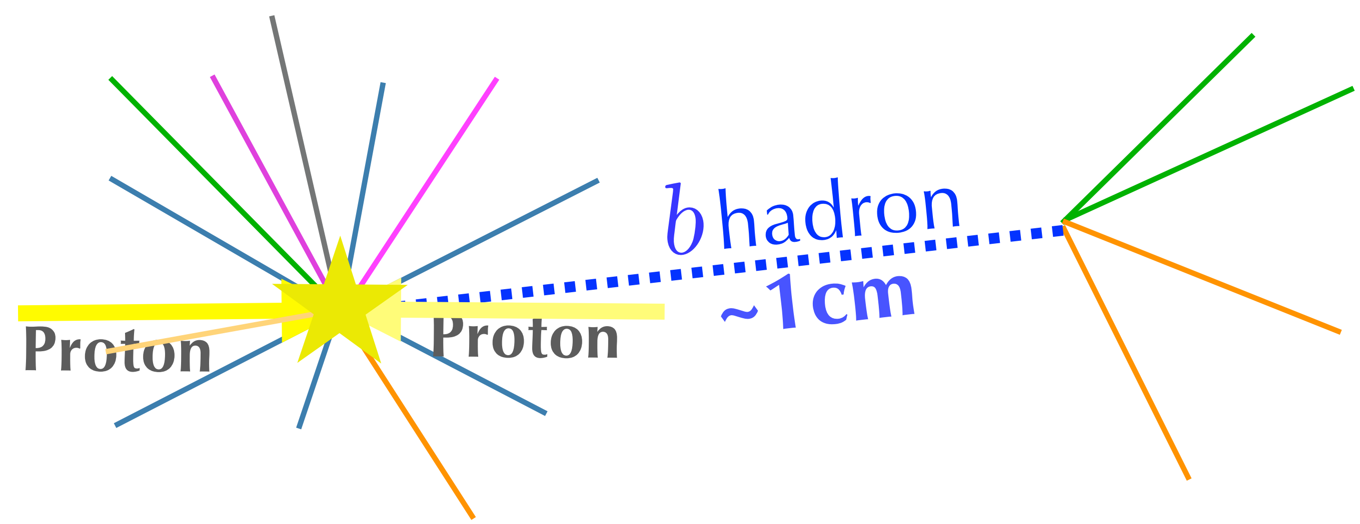
PWA13/Athos8

LHCb experiment



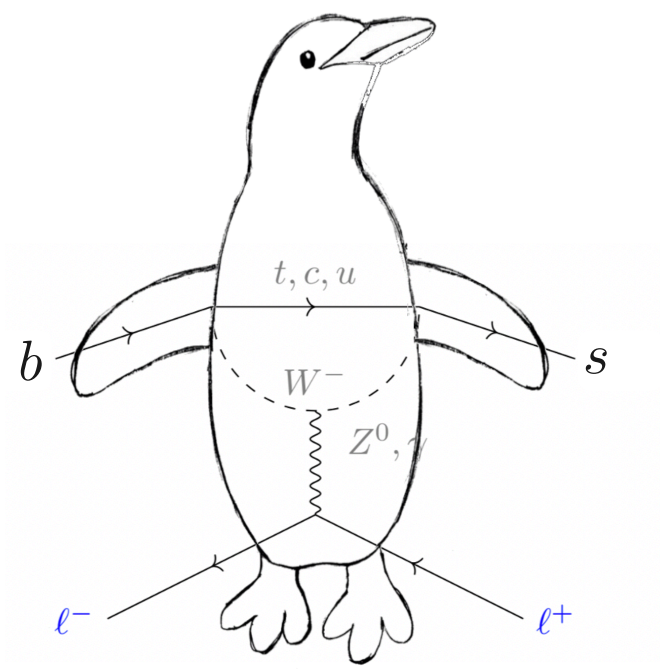


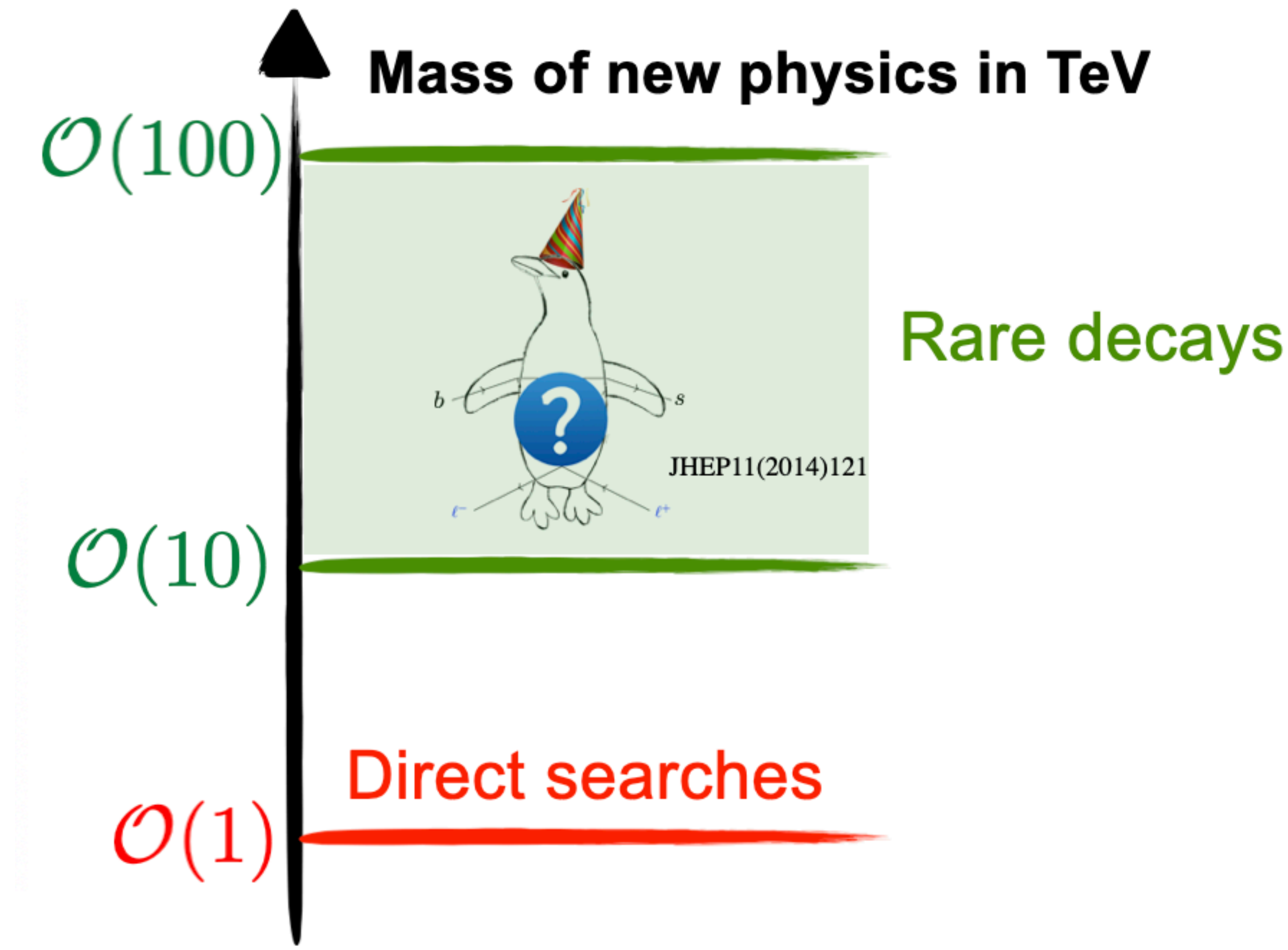
b quark: heaviest stable quark



Rare B decays at LHCb

Electroweak penguin (EWP)





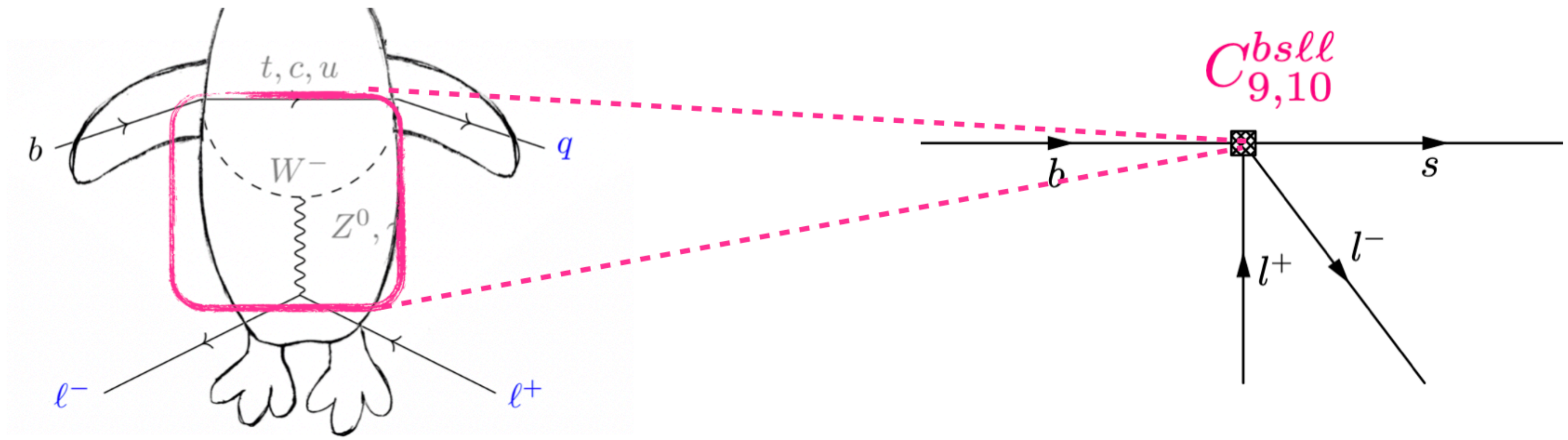
$b \to s\ell\ell$: flavour-changing neutral current,

branching fraction in SM $\mathcal{O}(10^{-6} - 10^{-9})$

Suppression makes rare decays particularly sensitive to New Physics

Rare B decays at LHCb

EWP in effective field theory



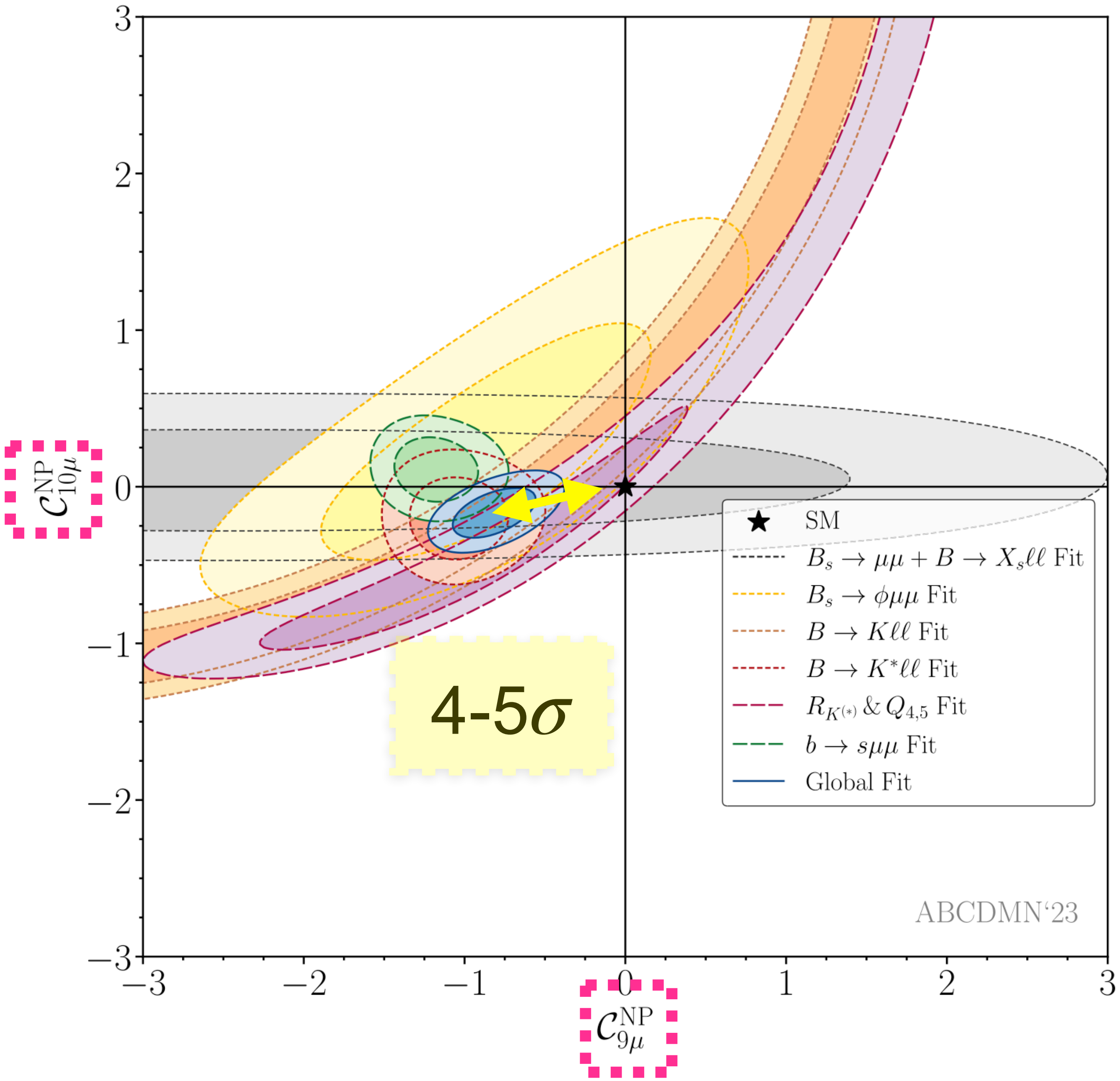
EW scale >> m_b, replace loop with effective couplings

C_9 = $bs\ell\ell$ vector current

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

C_7 = $bs\gamma$ (less-relevant)

Rare B decays at LHCb



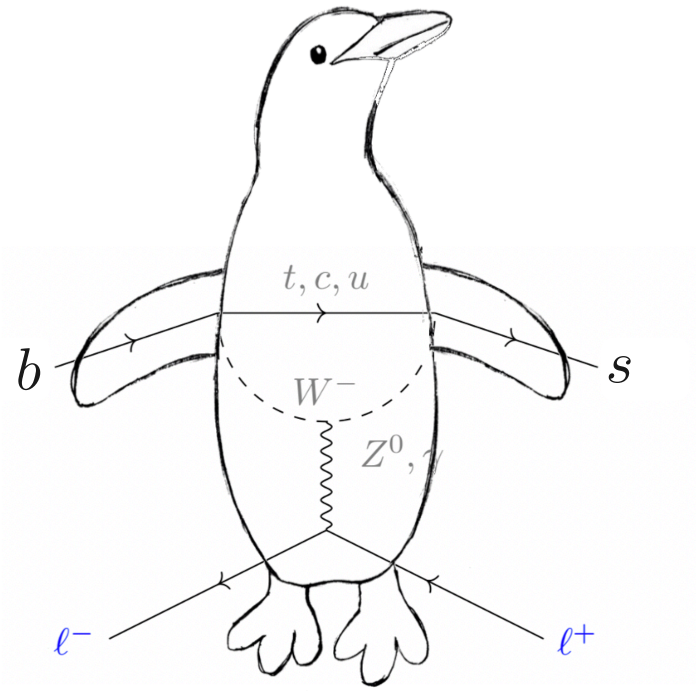
Highest experimental precision in $b \to s\mu^+\mu^-$ decays

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- what causes anomalies in rare electroweak penguin decays?

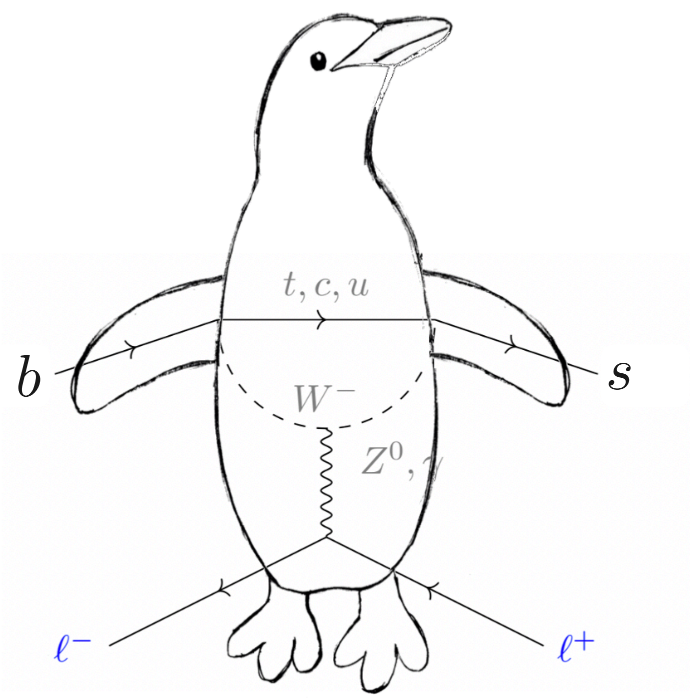
Cause of anomalies?



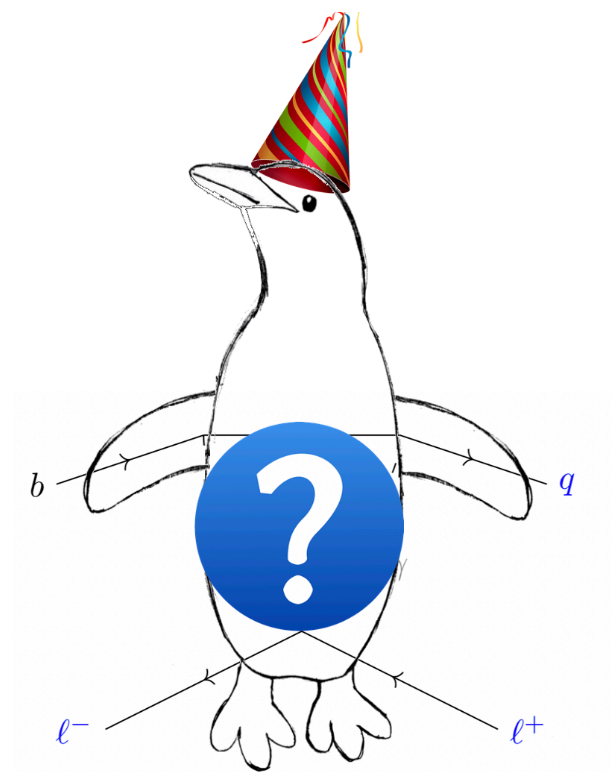
+ ? = deviations

Cause of anomalies?

Option 1 - New Physics



$+$

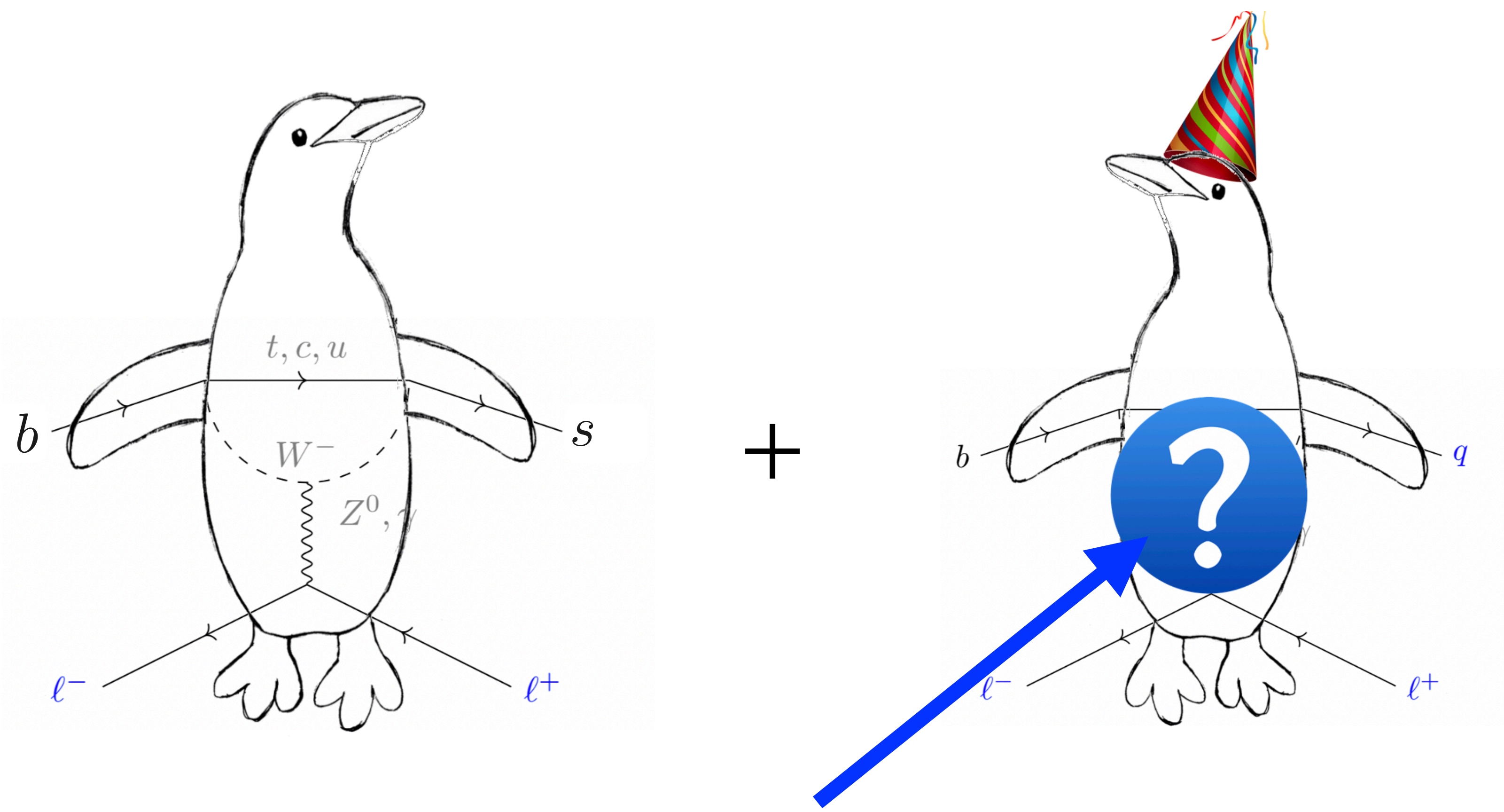


= deviations

Cause of anomalies?

Option 1 - New Physics

- Many new physics scenarios highly predictive for certain observables, e.g. enhancements in $b \to s\tau^+\tau^-$

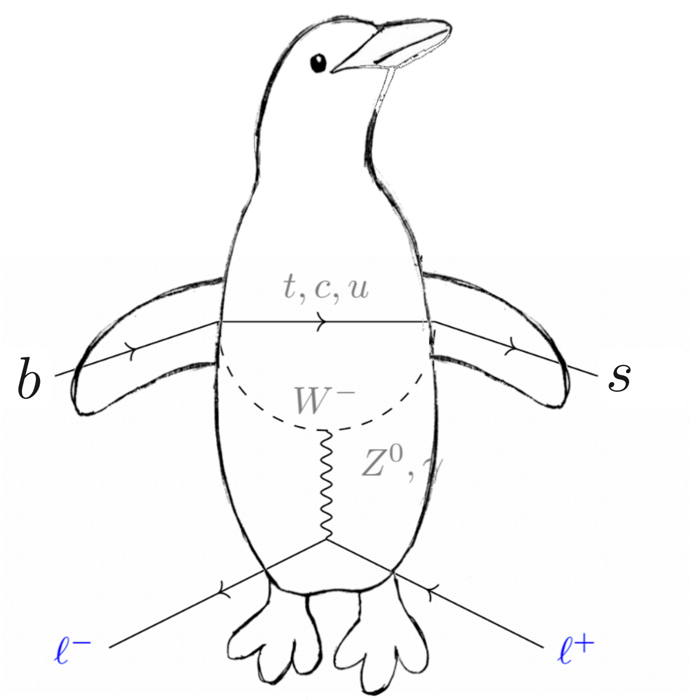


= deviations

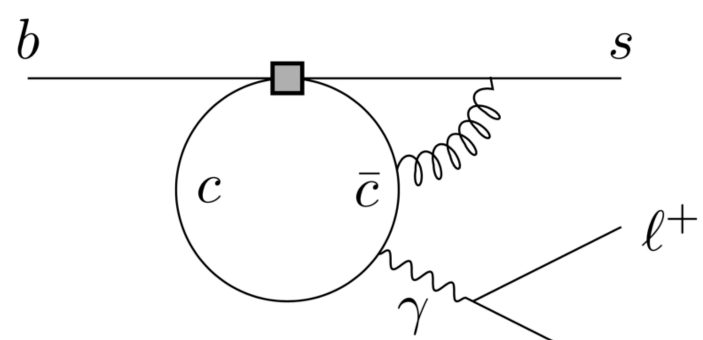
CP violating? Leptoquark? $b \to s\tau^+\tau^-$?

Cause of anomalies?

Option 2 - misunderstood QCD processes



+

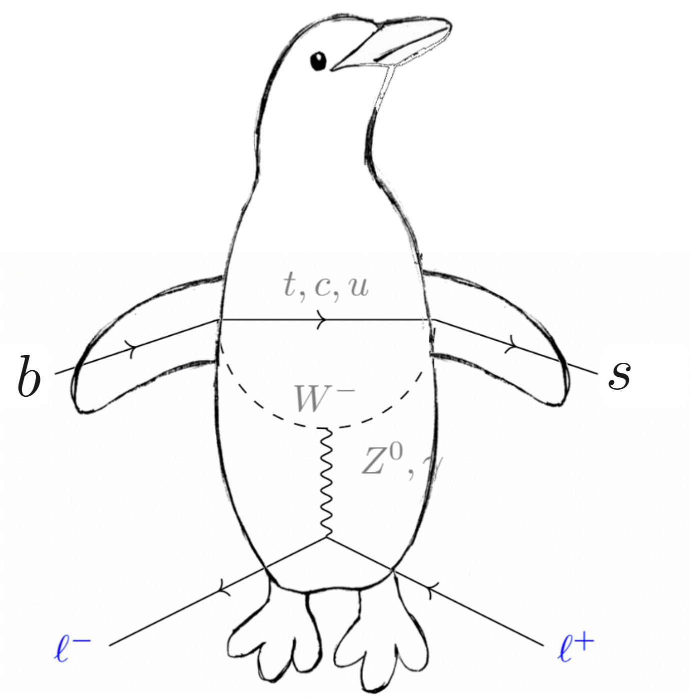


= deviations

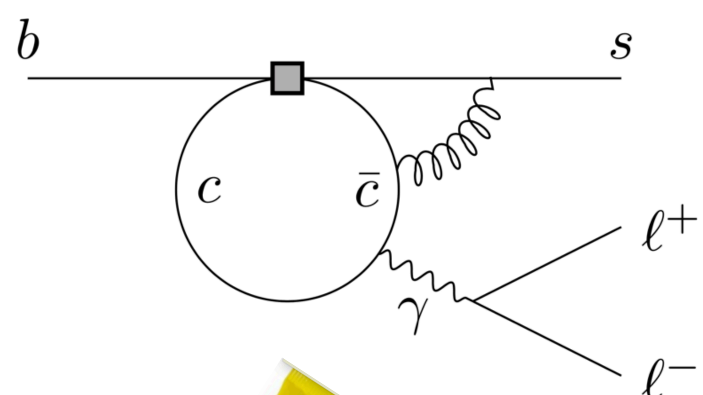
Cause of anomalies?

Option 2 - misunderstood QCD processes

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



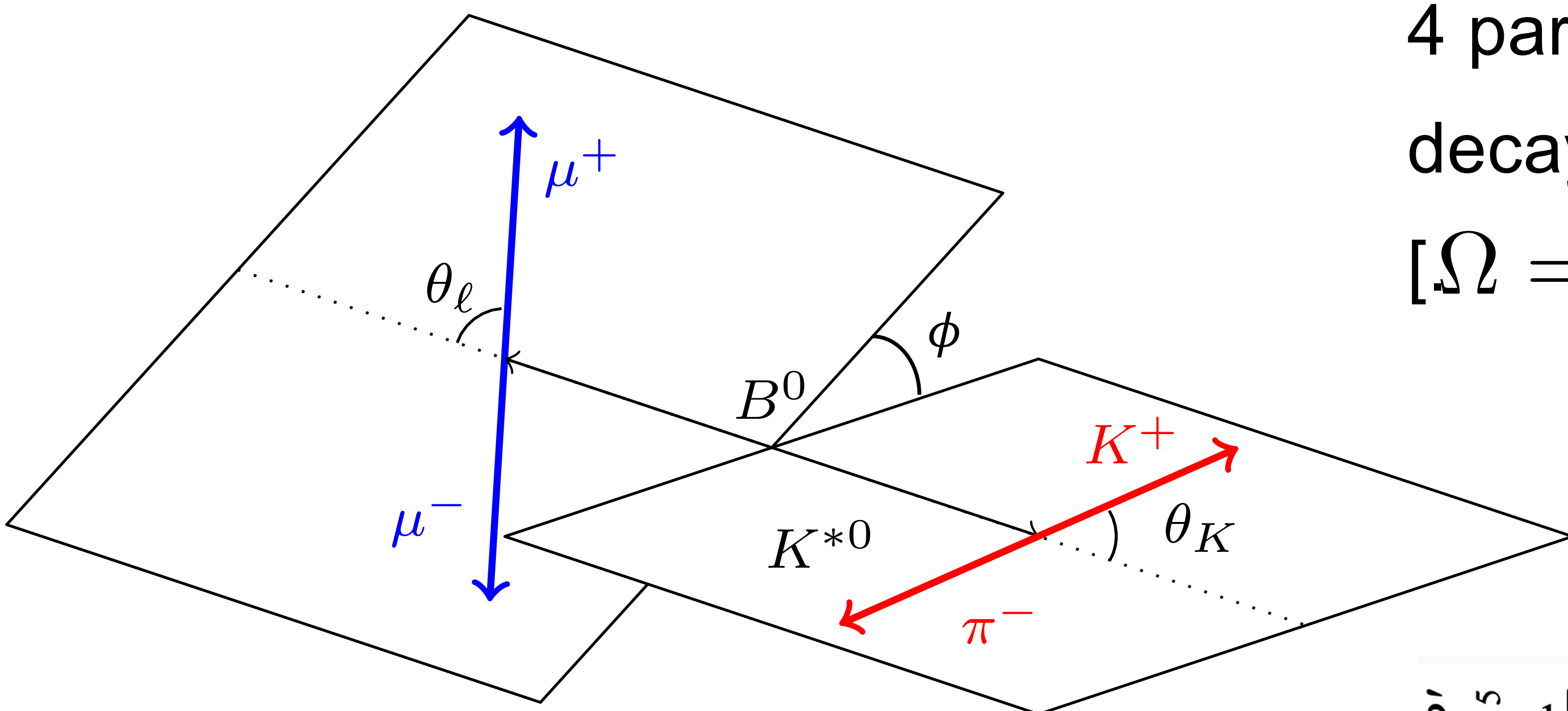
+



= deviations

Fit theory models to data to constrain amplitudes

Measuring $\Gamma(B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-)$

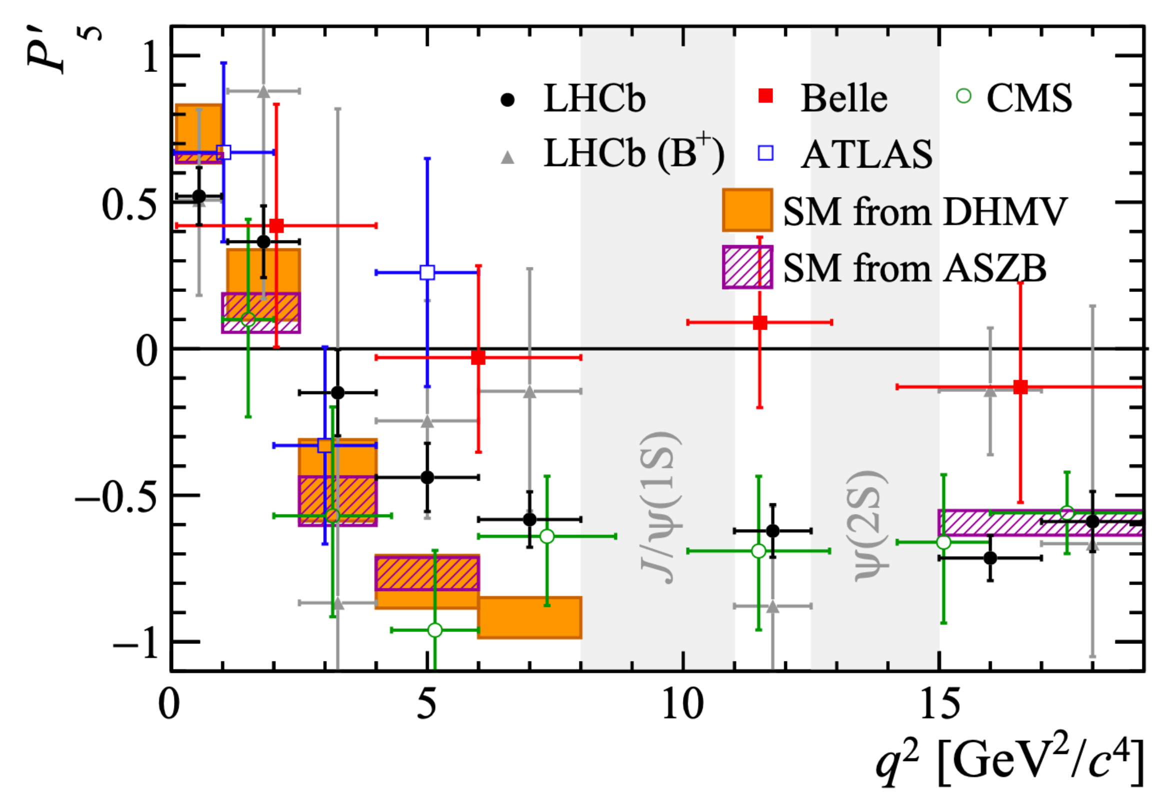


4 particles in final-state:

decay described by 3 angles

$[\Omega = \cos\theta_l, \cos\theta_k, \phi]$ and q²

$q^2 = m^2(\mu\mu)$



angular coefficients - 12 **in total**

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

angular functions

$\cos\theta_l$

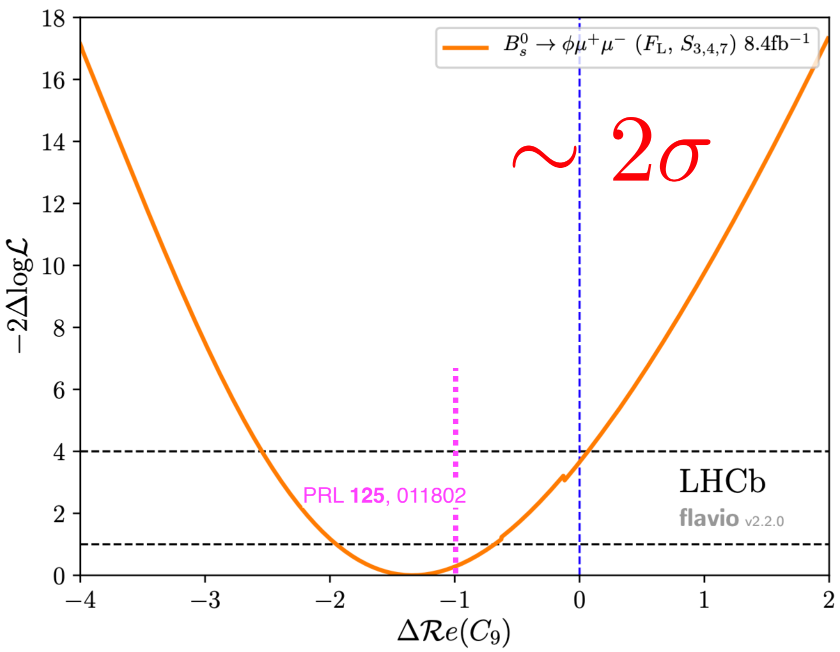
Averaged over q^2: model independent but lose information

Summary of $b \to s\mu^+\mu^-$ angular analysis

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

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

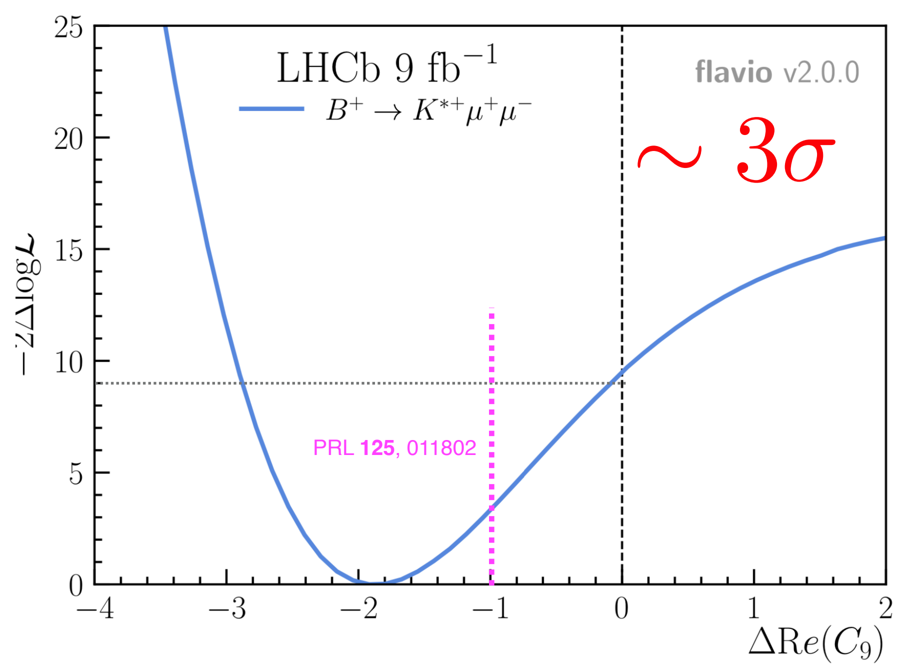
JHEP 11 (2021) 043



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

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

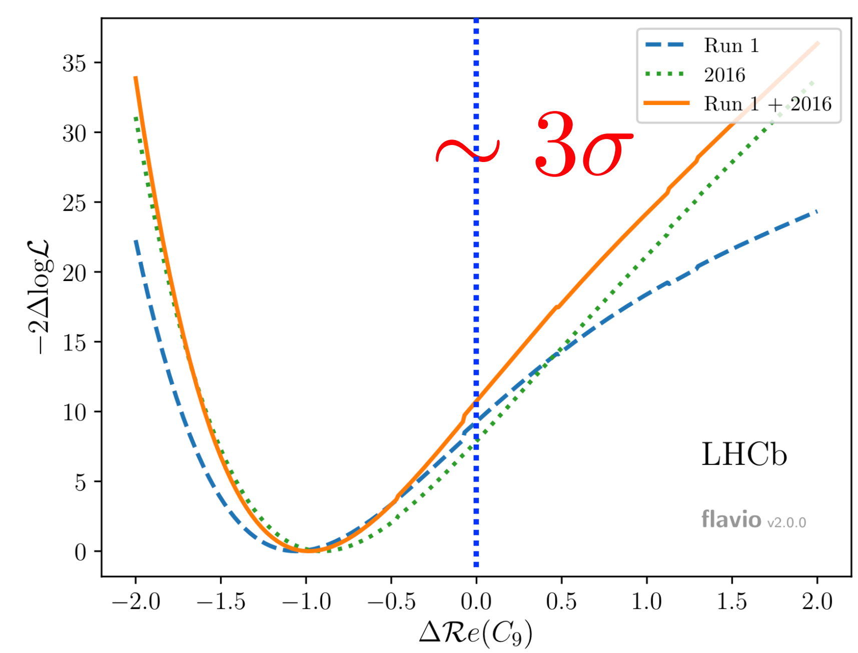
Phys. Rev. Lett. **126**, 161802



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

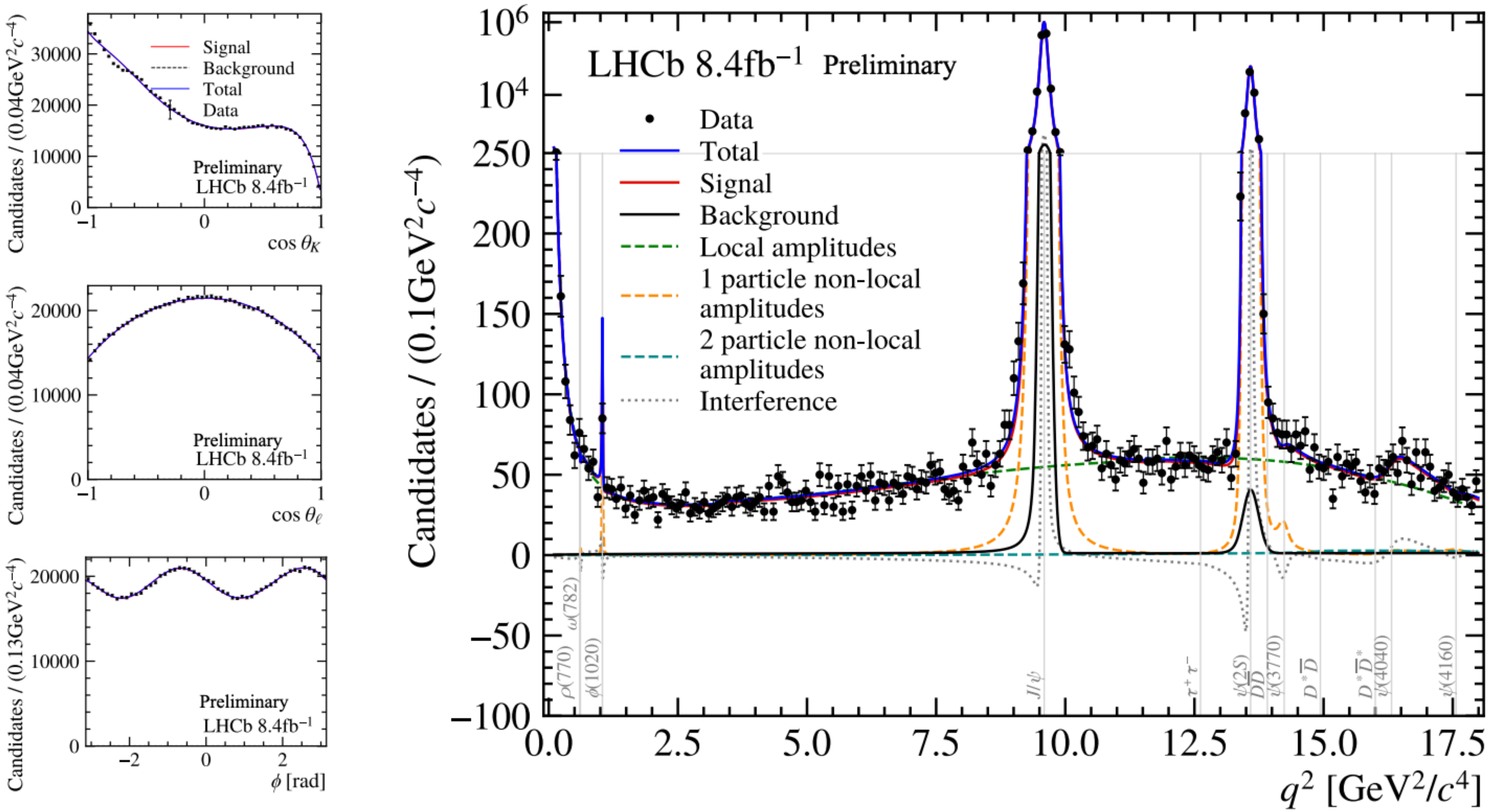
$\Delta\mathcal{R}e(\mathcal{C}_9) = -0.99^{+0.25}_{-0.21}$

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



Same pattern, negative definitions in effective coupling

Using amplitude analysis to disentangle long and short distance contributions to $B^0 \to K^{*0}\mu^+\mu^-$



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

i	I'_i	f_i
$1s$	$\left(\frac{(2+\beta_\mu^2)}{4}(\lvert A_\perp^L\rvert^2 + \lvert A_\parallel^L\rvert^2 + \lvert A_\perp^R\rvert^2 + \lvert A_\parallel^R\rvert^2) + \frac{4m_\mu^2}{q^2}\ \mathrm{Re}[A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}]\right) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K$
$1c$	$\left((\lvert A_0^L\rvert^2 + \lvert A_0^R\rvert^2) + \frac{4m_\mu^2}{q^2}(\lvert A_t\rvert^2 + 2\ \mathrm{Re}[A_0^L A_0^{R*}]) + \beta_\mu^2\lvert A_\mathrm{scalar}\rvert^2\right) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\cos^2\theta_K$
$2s$	$\frac{\beta_\mu^2}{4}(\lvert A_\perp^L\rvert^2 + \lvert A_\parallel^L\rvert^2 + \lvert A_\perp^R\rvert^2 + \lvert A_\parallel^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K \cos 2\theta_\ell$
$2c$	$-\beta_\mu^2(\lvert A_0^L\rvert^2 + \lvert A_0^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\cos^2\theta_K \cos 2\theta_\ell$
3	$\frac{1}{2}\beta_\mu^2(\lvert A_\perp^L\rvert^2 - \lvert A_\parallel^L\rvert^2 + \lvert A_\perp^R\rvert^2 - \lvert A_\parallel^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K \sin^2\theta_\ell \cos 2\phi$
4	$\frac{1}{\sqrt{2}}\beta_\mu^2\ \mathrm{Re}[A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin 2\theta_K \sin 2\theta_\ell \cos\phi$
5	$\sqrt{2}\beta_\mu\left(\mathrm{Re}[A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}] - \frac{m_\mu}{\sqrt{q^2}}\mathrm{Re}[A_\parallel^L A_\mathrm{scalar}^* + A_\parallel^R A_\mathrm{scalar}^*]\right) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin 2\theta_K \sin\theta_\ell \cos\phi$
$6s$	$2\beta_\mu\ \mathrm{Re}[A_\parallel^L A_\perp^{L*} - A_\parallel^R A_\perp^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K \cos\theta_\ell$
$6c$	$4\beta_\mu\frac{m_\mu}{\sqrt{q^2}}\ \mathrm{Re}[A_0^L A_\mathrm{scalar}^* + A_0^R A_\mathrm{scalar}^*] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\cos^2\theta_K \cos\theta_\ell$
7	$\sqrt{2}\beta_\mu\left(\mathrm{Im}[A_0^L A_\parallel^{L*} - A_0^R A_\parallel^{R*}] + \frac{m_\mu}{\sqrt{q^2}}\mathrm{Im}[A_\perp^L A_\mathrm{scalar}^* + A_\perp^R A_\mathrm{scalar}^*]\right) \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin 2\theta_K \sin\theta_\ell \sin\phi$
8	$\frac{1}{\sqrt{2}}\beta_\mu^2\ \mathrm{Im}[A_0^L A_\perp^{L*} + A_0^R A_\perp^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin 2\theta_K \sin 2\theta_\ell \sin\phi$
9	$\beta_\mu^2\ \mathrm{Im}[A_\parallel^L A_\perp^{L*} + A_\parallel^R A_\perp^{R*}] \times \lvert\mathcal{BW}_\mathrm{P}\rvert^2$	$\sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$
κ		
10	$\frac{1}{2}\left(\lvert A_\mathrm{S}^L\rvert^2 + \lvert A_\mathrm{S}^R\rvert^2 + \frac{4m_\mu^2}{q^2}(\lvert A_t\rvert^2 + 2\mathrm{Re}[A_\mathrm{S}^L A_\mathrm{S}^{R*}])\right) \times \lvert\mathcal{BW}_\mathrm{S}\rvert^2$	1
11	$\sqrt{3}\left(\ \mathrm{Re}[(A_\mathrm{S}^L A_0^{L*} + A_\mathrm{S}^R A_0^{R*} + \frac{4m_\mu^2}{q^2}(A_\mathrm{S}^L A_0^{R*} + A_{\mathrm{scalar},t}A_t^*)) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*] + \mathrm{Re}[\frac{4m_\mu^2}{q^2}A_0^L A_\mathrm{S}^{R*} \times \mathcal{BW}_\mathrm{P}\mathcal{BW}_\mathrm{S}^*]\right)$	$\cos\theta_K$
12	$-\frac{1}{2}\beta_\mu^2\ (\lvert A_\mathrm{S}^L\rvert^2 + \lvert A_\mathrm{S}^R\rvert^2) \times \lvert\mathcal{BW}_\mathrm{S}\rvert^2$	$\cos 2\theta_\ell$
13	$-\sqrt{3}\beta_\mu^2\ \mathrm{Re}[(A_\mathrm{S}^L A_0^{L*} + A_\mathrm{S}^R A_0^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\cos\theta_K \cos 2\theta_\ell$
14	$\sqrt{\frac{3}{2}}\beta_\mu^2\ \mathrm{Re}[(A_\mathrm{S}^L A_\parallel^{L*} + A_\mathrm{S}^R A_\parallel^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\sin\theta_K \sin 2\theta_\ell \cos\phi$
15	$2\sqrt{\frac{3}{2}}\beta_\mu\ \mathrm{Re}[(A_\mathrm{S}^L A_\perp^{L*} - A_\mathrm{S}^R A_\perp^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\sin\theta_K \sin\theta_\ell \cos\phi$
16	$2\sqrt{\frac{3}{2}}\beta_\mu\ \mathrm{Im}[(A_\mathrm{S}^L A_\parallel^{L*} - A_\mathrm{S}^R A_\parallel^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\sin\theta_K \sin\theta_\ell \sin\phi$
17	$\sqrt{\frac{3}{2}}\beta_\mu^2\ \mathrm{Im}[(A_\mathrm{S}^L A_\perp^{L*} + A_\mathrm{S}^R A_\perp^{R*}) \times \mathcal{BW}_\mathrm{S}\mathcal{BW}_\mathrm{P}^*]$	$\sin\theta_K \sin 2\theta_\ell \sin\phi$

P-wave ($K^{*0}(892)$)

S-wave (spin-0 $K\pi$ state) +S-P interference

Parameterising amplitudes as a function of q^2

Wilson Coefficients

Local $B \to K^{*0}$ form-factors, q^2 dependent

$$\mathcal{A}_0^{L,R}(q^2) = N_0 \left\{ \left[\left(\mathcal{C}_9^{(\text{eff}),0}(q^2) - \mathcal{C}_9' \right) \mp \left(\mathcal{C}_{10} - \mathcal{C}_{10}' \right) \right] A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}} \left(\mathcal{C}_7^{(\text{eff}),0} - \mathcal{C}_7' \right) T_{23}(q^2) \right\},$$

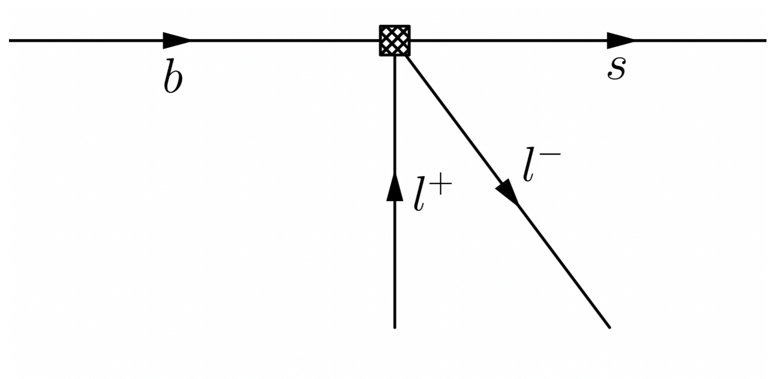
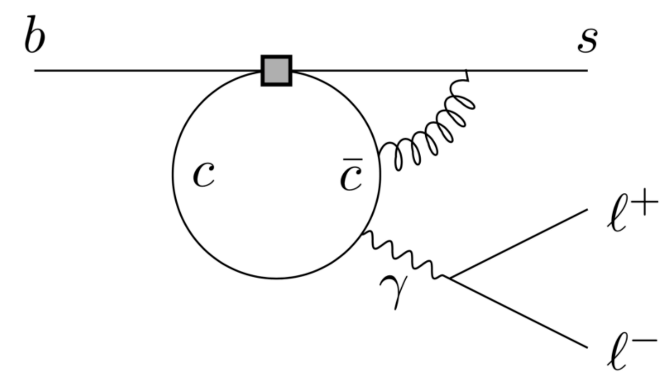
$$\mathcal{A}_\parallel^{L,R}(q^2) = N_\parallel \left\{ \left[\left(\mathcal{C}_9^{(\text{eff}),\parallel}(q^2) - \mathcal{C}_9' \right) \mp \left(\mathcal{C}_{10} - \mathcal{C}_{10}' \right) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} \left(\mathcal{C}_7^{(\text{eff}),\parallel} - \mathcal{C}_7' \right) T_2(q^2) \right\},$$

$$\mathcal{A}_\perp^{L,R}(q^2) = N_\perp \left\{ \left[\left(\mathcal{C}_9^{(\text{eff}),\perp}(q^2) + \mathcal{C}_9' \right) \mp \left(\mathcal{C}_{10} + \mathcal{C}_{10}' \right) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} \left(\mathcal{C}_7^{(\text{eff}),\perp} - \mathcal{C}_7' \right) T_1(q^2) \right\},$$

$$\mathcal{A}_t(q^2) = N_t \left\{ 2 \left[\mathcal{C}_{10} - \mathcal{C}_{10}' \right] A_0(q^2) \right\},$$

Parameterising non-local form-factors

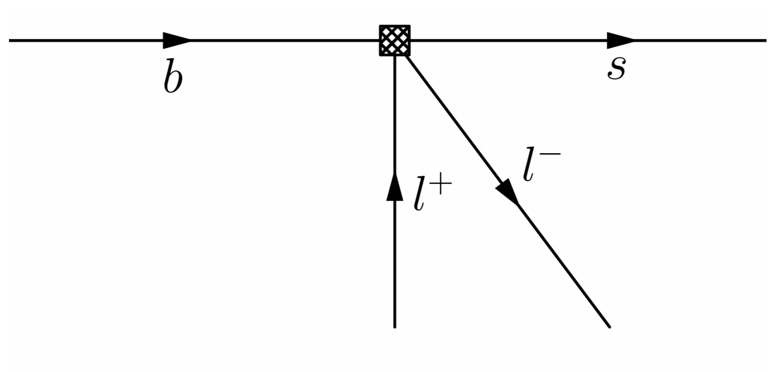
$\lambda \in 0, ||, \perp$

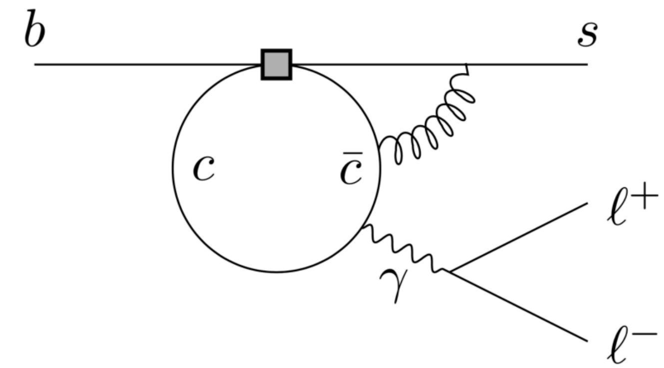
$C_{9,\lambda}^{eff}(q^2) =$  $+$ 

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

Parameterising non-local form-factors

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

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

$+$ 

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

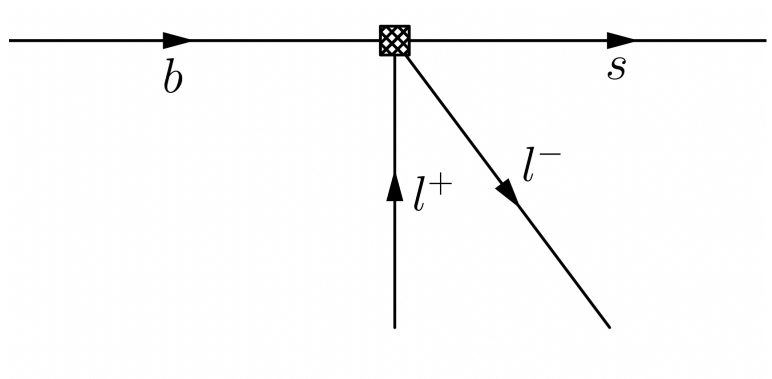
Two different analyses done, with different models for $H_\lambda(q^2)$:

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

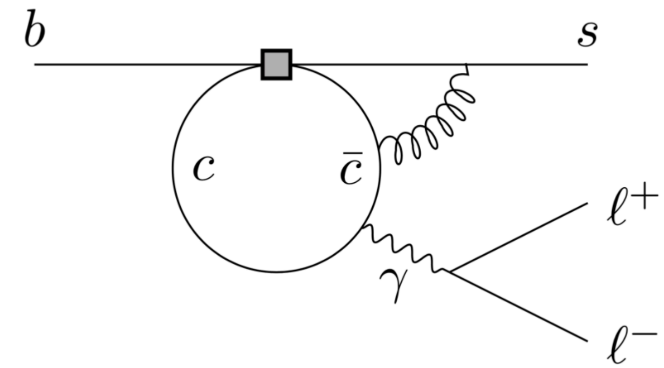
Parameterising non-local form-factors

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

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



$+$



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

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)

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

Theory information

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

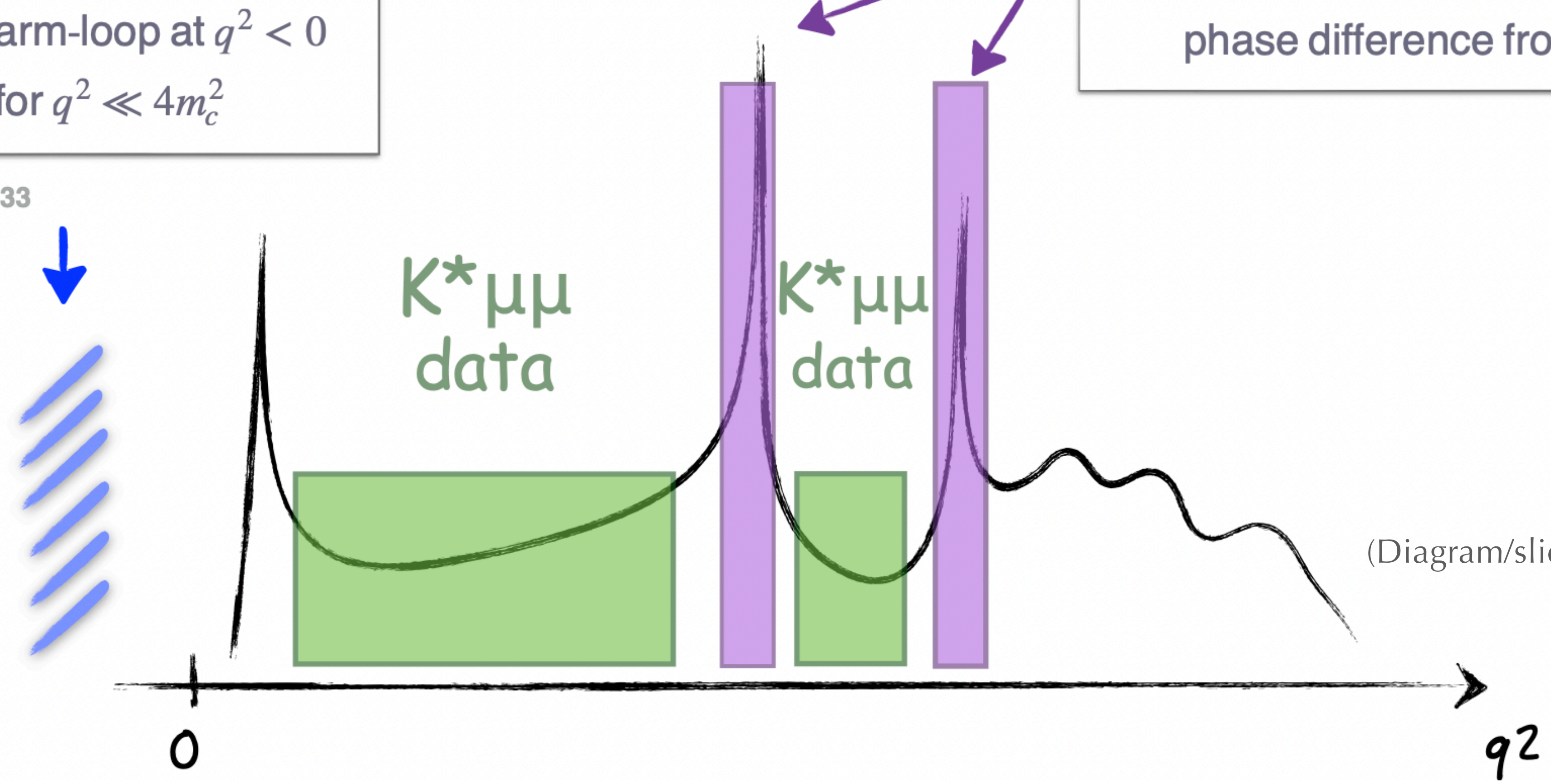
▸ reliable for $q^2 \ll 4m_c^2$

JHEP 09 (2022) 133

Experimental measurements

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

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



(Diagram/slide from A. Mauri)

Z-expansion

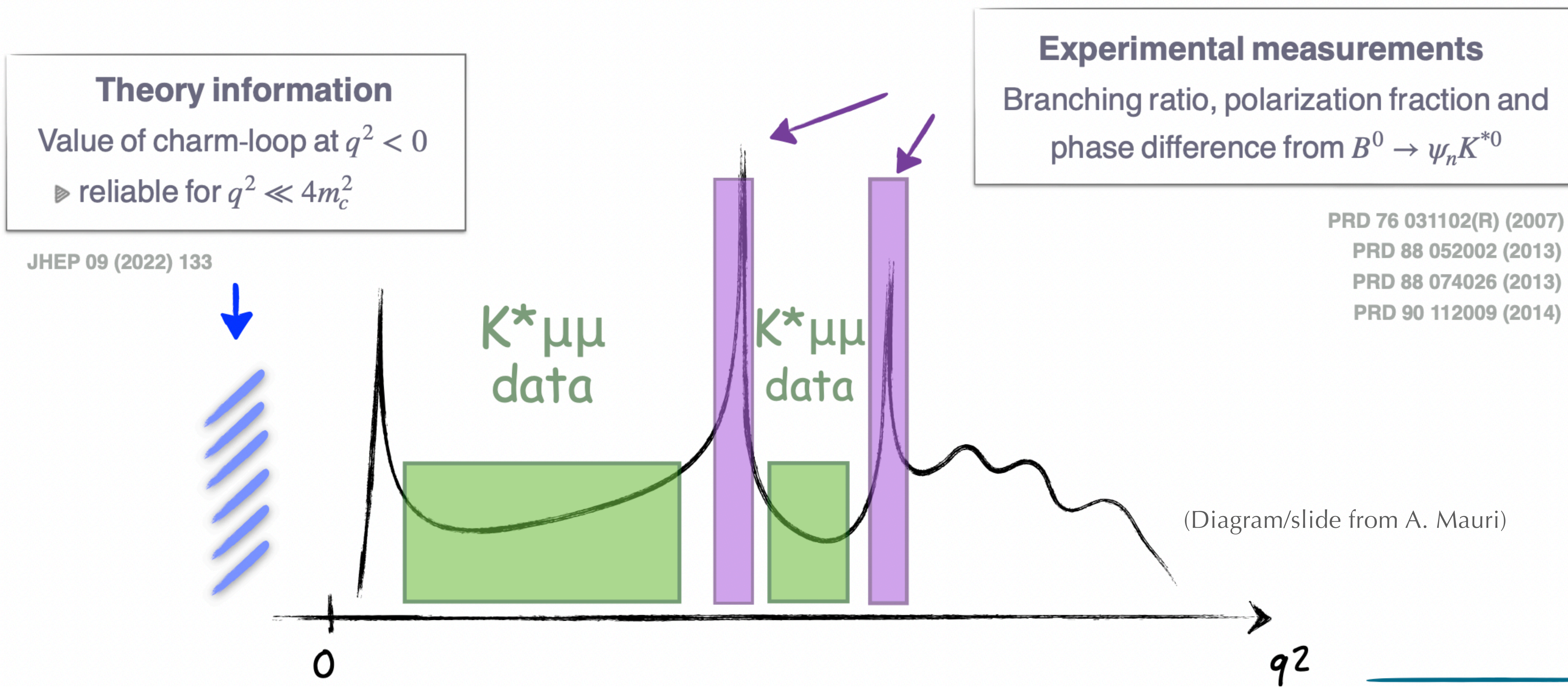
Polynomial-expansion

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

z = *remapping* of q^2

2 models used:

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



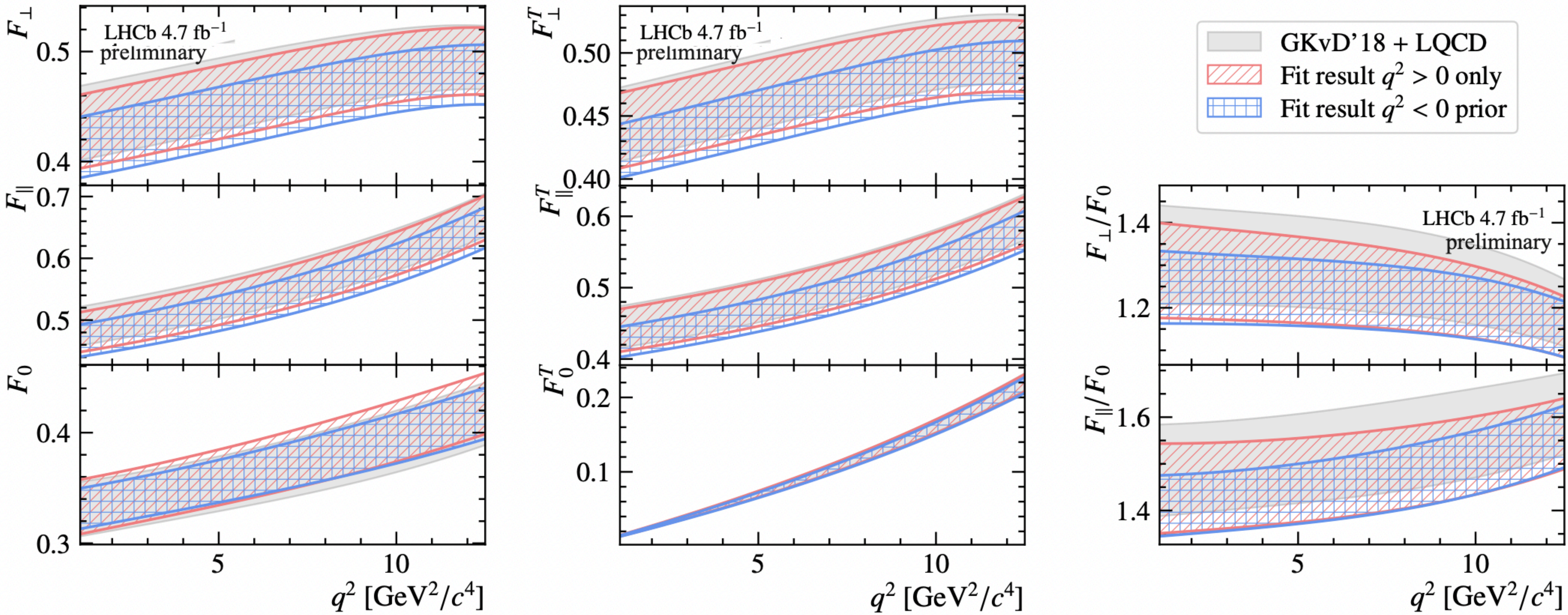
(Diagram/slide from A. Mauri)

Z-expansion: results

Results for local $B \to K^*$ form-factors

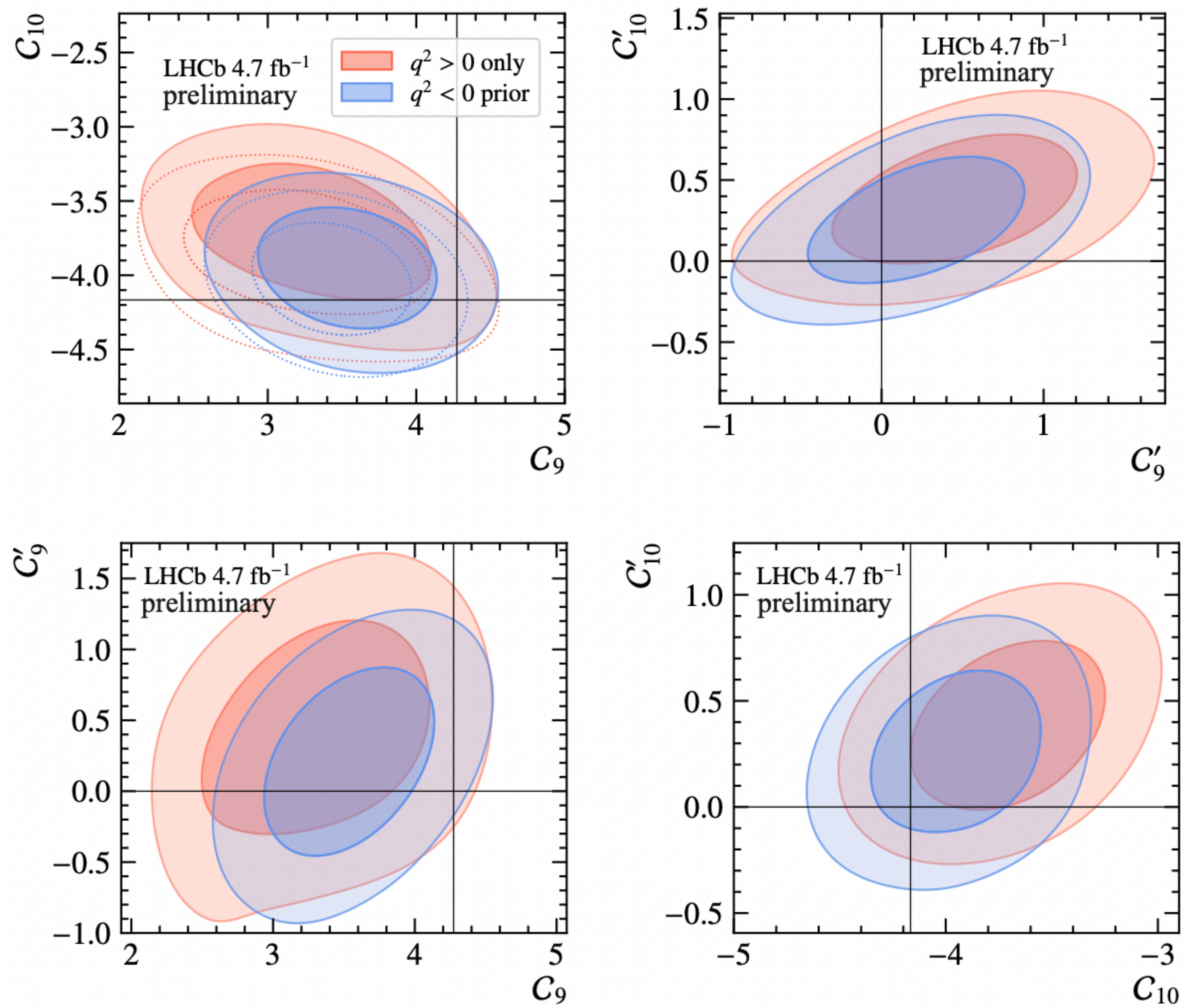
$$F_i(q^2) = \frac{1}{1 - q^2/m^2_{R,i}} \sum_{k=0}^{2} \alpha_{i,k}[z(q^2) - z(0)]^k,$$

$\alpha_{i,k}$ coefficients constrained from LCSR + LQCD



Z-expansion: results

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

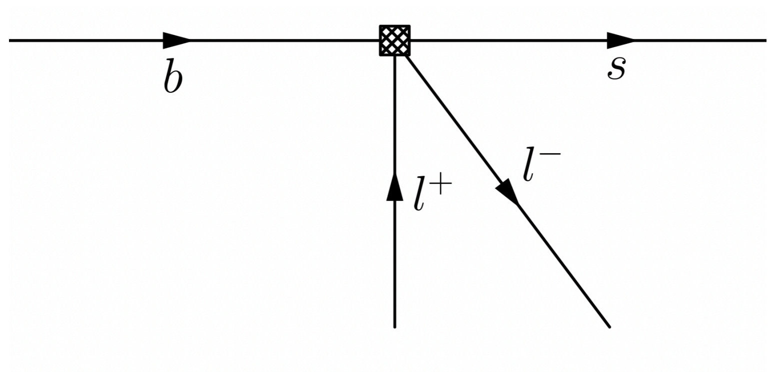


Central value for C_9 remains consistent with anomalies, but larger uncertainty reduces tension to 1.8σ

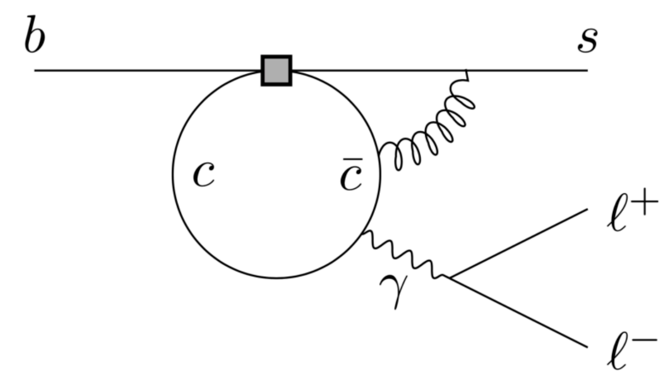
Parameterising non-local form-factors

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

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



$+$



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

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)**

Amplitude analysis over all q^2 - new!

arXiv > hep-ex > arXiv:2405.17347

High Energy Physics – Experiment

[Submitted on 27 May 2024]

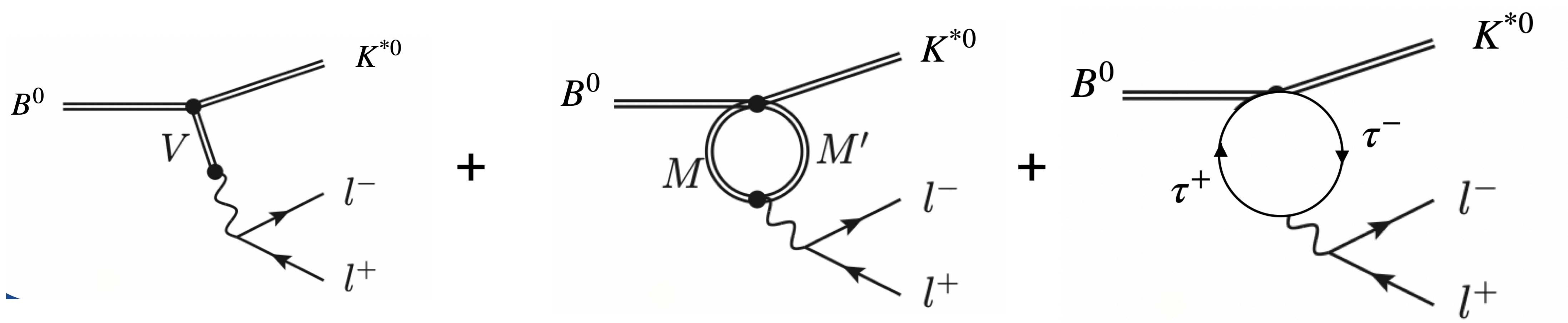
Comprehensive analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

LHCb collaboration: R. Aaij, A.S.W. Abdelmotteleb, C. Abellan Beteta, F. Abudinén, T. Ackernley, A. A. Ade
B. Adeva, M. Adinolfi, P. Adlarson, C. Agapopoulou, C.A. Aidala, Z. Ajaltouni, S. Akar, K. Akiba, P. Albicoc
Albrecht, F. Alessio, M. Alexander, Z. Aliouche, P. Alvarez Cartelle, R. Amalric, S. Amato, J.L. Amey, Y. Am
An, L. Anderlini, M. Andersson, A. Andreianov, P. Andreola, M. Andreotti, D. Andreou, A. Anelli, D. Ao, F.
M. Argenton, S. Arguedas Cuendis, A. Artamonov, M. Artuso, E. Aslanides, R. Ataide Da Silva, M. Atzeni,
Audurier, D. Bacher, I. Bachiller Perea, S. Bachmann, M. Bachmayer, J.J. Back, P. Baladron Rodriguez, V. Ba
W. Baldini, H. Bao, J. Baptista de Souza Leite, M. Barbetti, I. R. Barbosa, R.J. Barlow, M. Barnyakov, S. Barsu
Barter, M. Bartolini, J. Bartz, J.M. Basels, G. Bassi, B. Batsukh, A. Bay, A. Beck, M. Becker, F. Bedeschi, I.B. B
S. Belin, V. Bellee, K. Belous, I. Belov, I. Belyaev, G. Benane, G. Bencivenni, E. Ben-Haim, A. Berezhnoy, R.
Bernet Andres, A. Bertolin, C. Betancourt, F. Betti, J. Bex, Ia. Bezshyiko, J. Bhom, M.S. Bieker, N.V. Biesuz,
A. Biolchini, M. Birch, F.C.R. Bishop, A. Bitadze, A. Bizzeti, T. Blake, F. Blanc, J.E. Blank, S. Blusk, V. Bochar
J.A. Boelhauve et al. (995 additional authors not shown)

Amplitude analysis over all q^2 - new!

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

$H_\lambda(q^2) =$



1-particle contributions

Includes:

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

2-particle contributions

Includes:

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

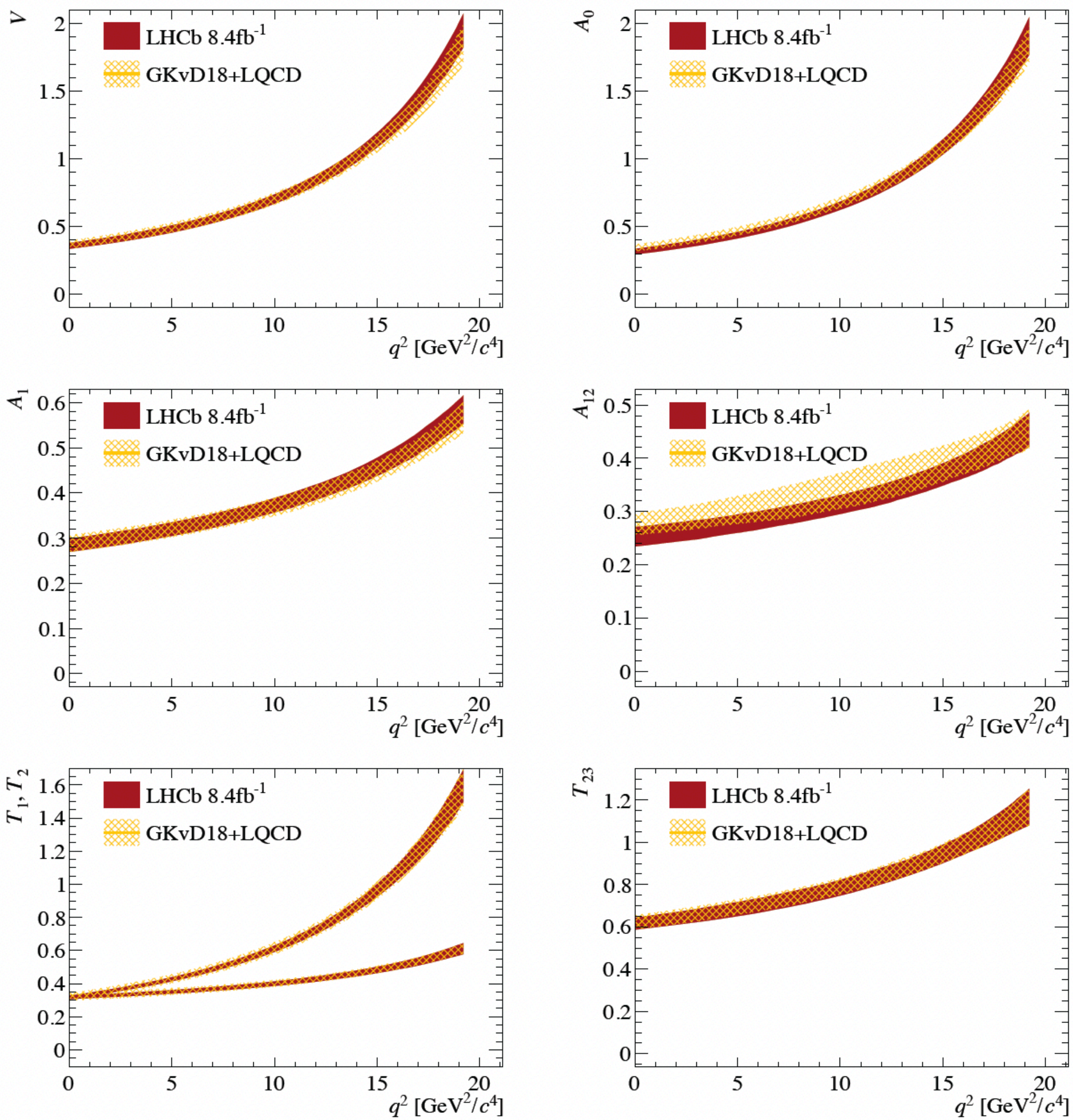
Tau loop contribution

Sensitive to C_9^τ

$\mathcal{L}$ = Breit – Wigner

$\mathcal{L}$ = Dispersion – relation

Amplitude analysis over all q^2 : results



Local form factors

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	$1.68 \pm 2.15 \pm 0.04$

Amplitude analysis over all q^2 : results

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

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

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

Amplitude analysis over all q^2 : results

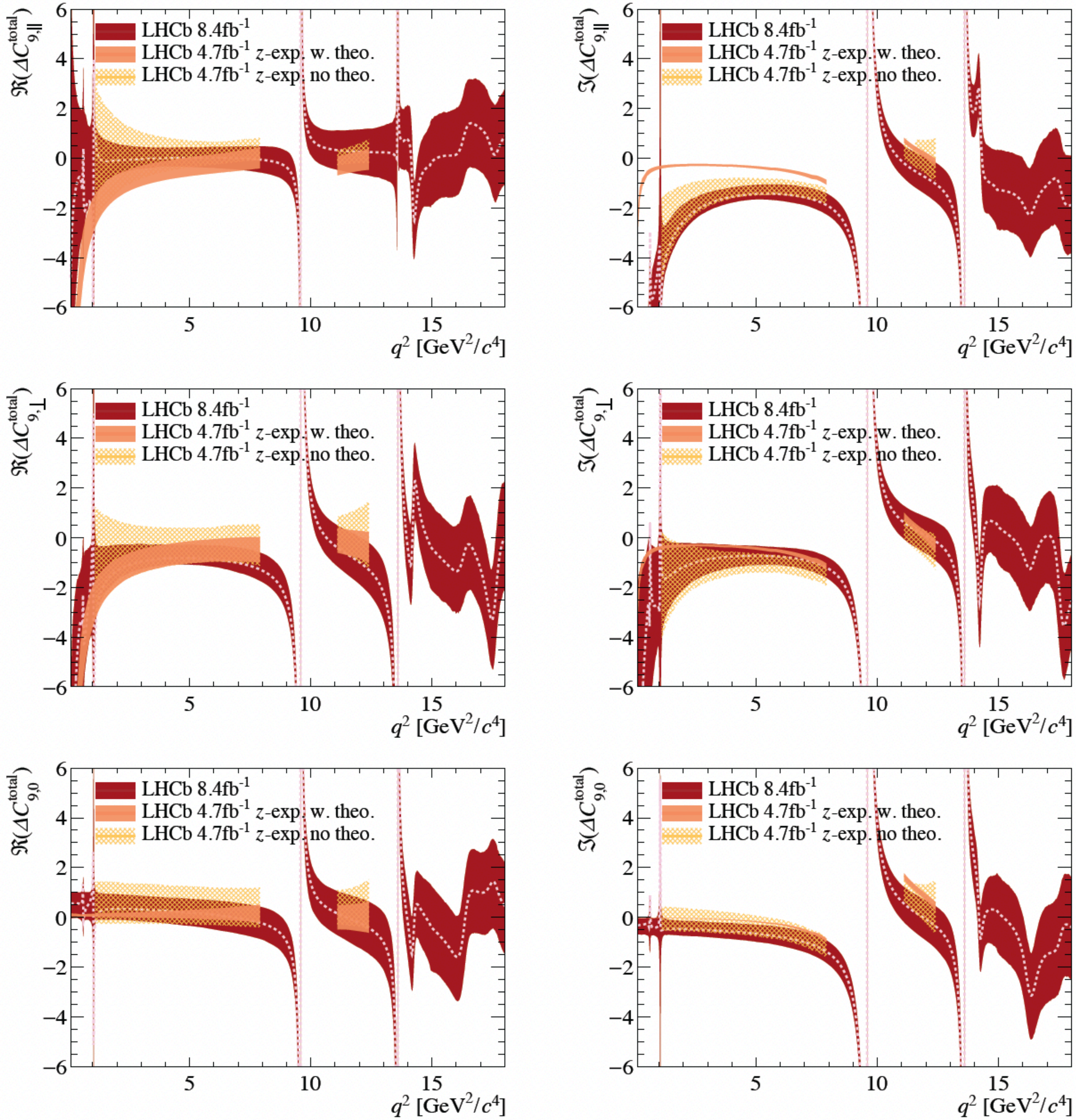
Nonlocal parameter results			
$\|A^{\parallel}_{J/\psi}\|$	$(3.98 \pm 0.01 \pm 0.15) \times 10^{-3}$	$\delta^{\parallel}_{J/\psi}$	$0.23 \pm 0.01 \pm 0.01$
$\|A^{\perp}_{J/\psi}\|$	$(3.85 \pm 0.01 \pm 0.14) \times 10^{-3}$	$\delta^{\perp}_{J/\psi}$	$-0.21 \pm 0.00 \pm 0.01$
$\|A^{0}_{J/\psi}\|$	–	$\delta^{0}_{J/\psi}$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

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

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

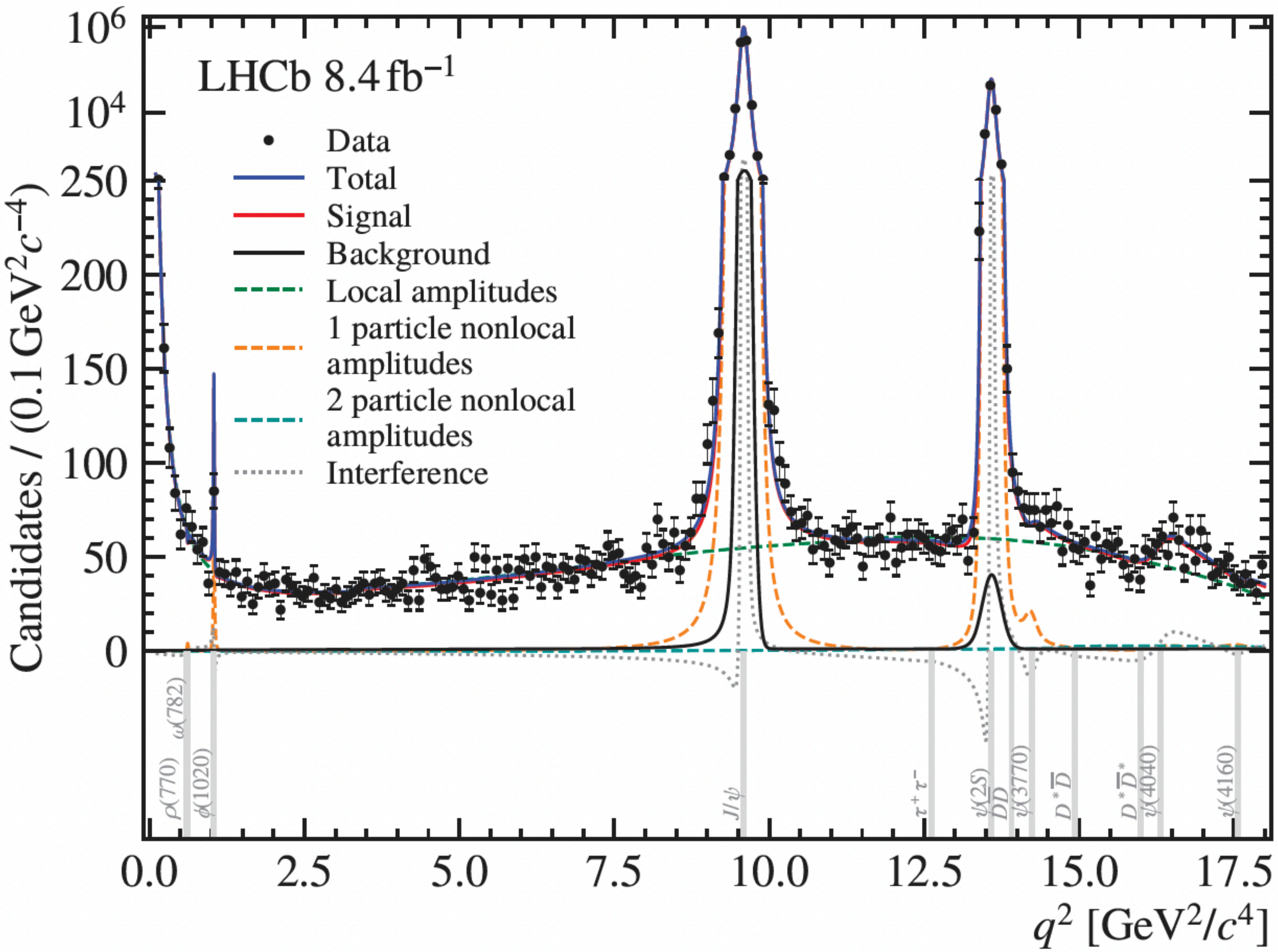
Amplitude analysis over all q^2 : results



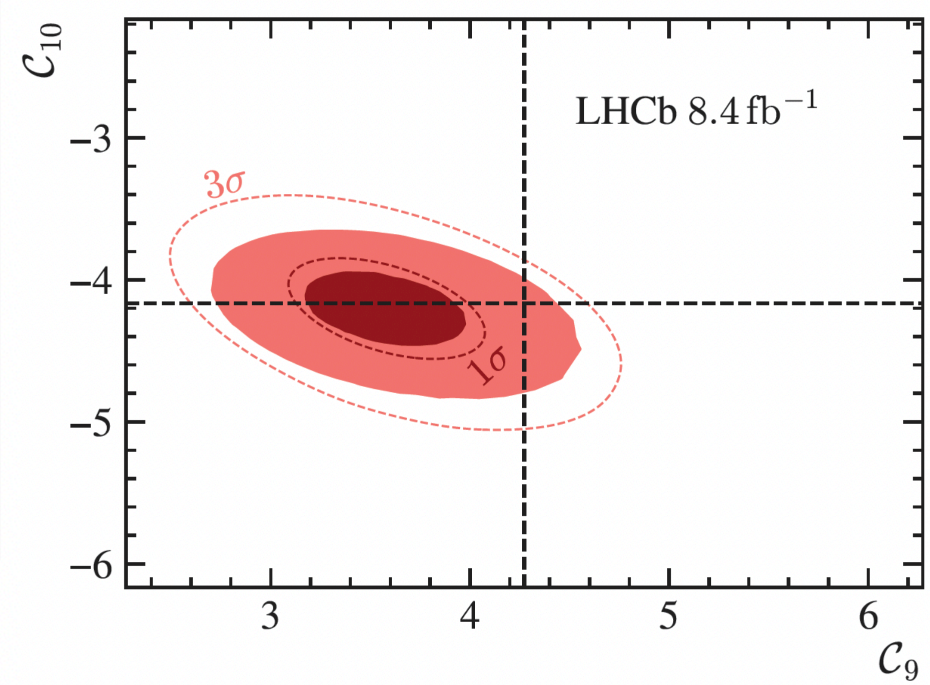
Non-local form factors (amplitude analysis + z-expansion)

Amplitude analysis over all q^2 : results

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

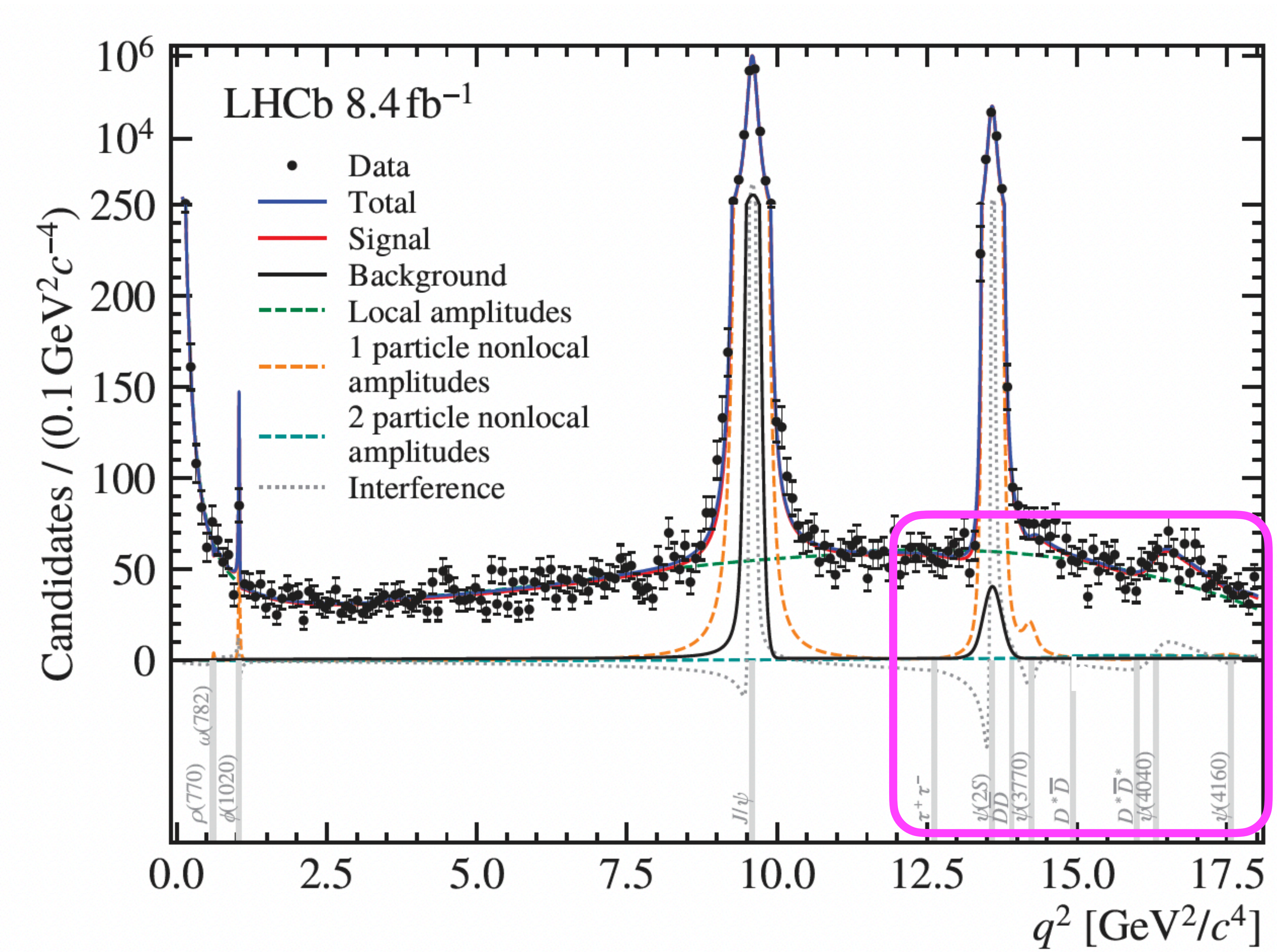


Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}_9'$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}_{10}'$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$



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

Amplitude analysis over all q^2 : results



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

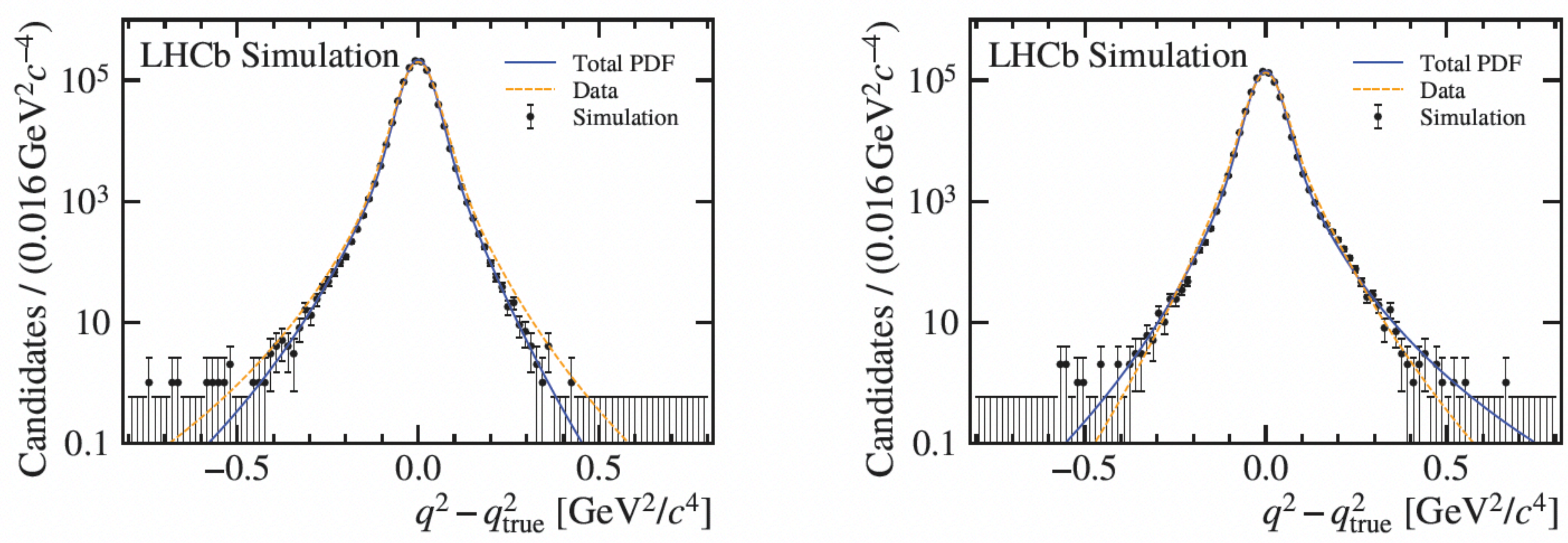
First direct measurement of $C_{9,\tau}$

Corresponds to 90% CL on $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-)$ of $\sim 1.7 - 2.2e^{-3}$

Best direct measurement of $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-)$ = $1e^3$ 90%CL

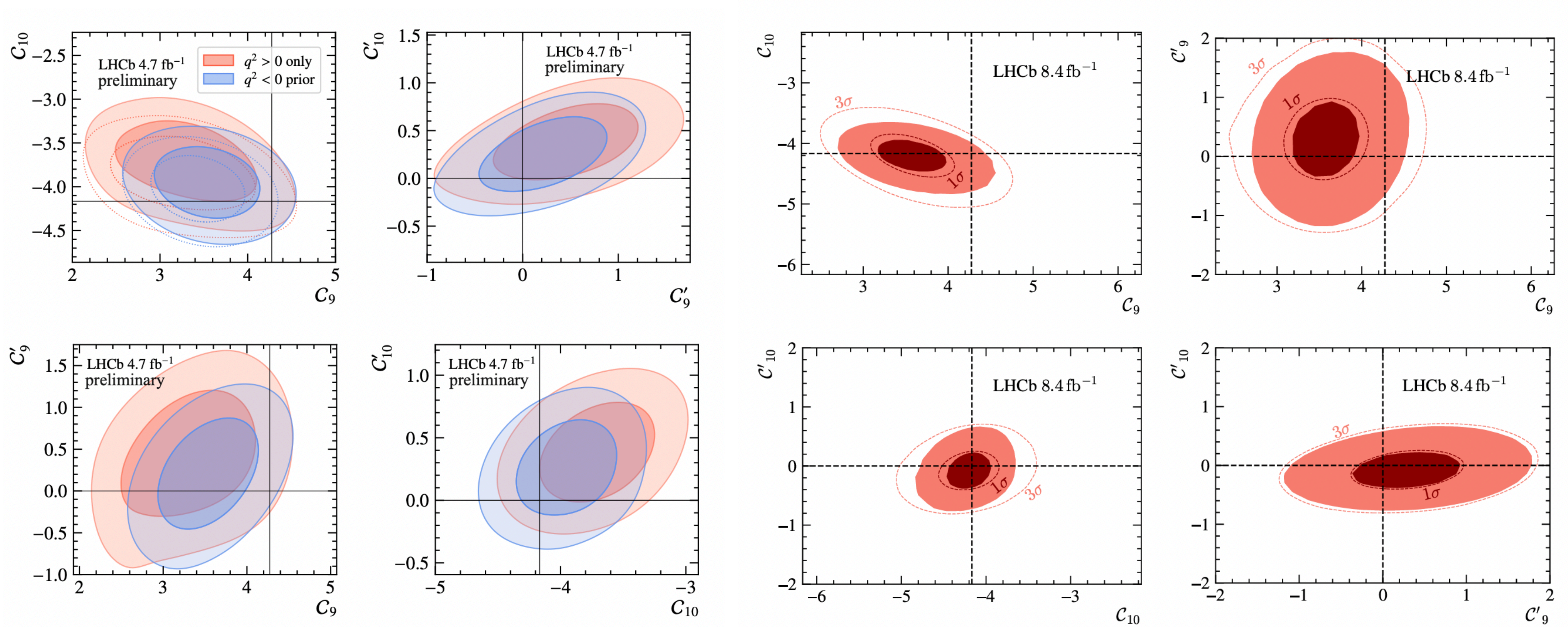
Some thoughts on challenges

- Scale difference between short and long distance amplitudes
- Incorporating resolution into fit: q^2 dependent + care about the tails
- Computational time for unbinned ML + res. convolution on ~ 1.5 million events
- Incorporating exotica
- Presenting fit info to theorists - pseudo data?
- Knowledge of open charm-states/fit stability (mainly affects $C_{9\tau}$)



Summary

- First amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$
- Challenging but necessary to leverage data to separate short and long-distance
- Two analyses performed so far, using different models/data
- Future analyses will include CP-violating affects (strong phase variation)
- Measurements of $B^0 \to K^{*0}J/\psi$ from Belle II wanted :)



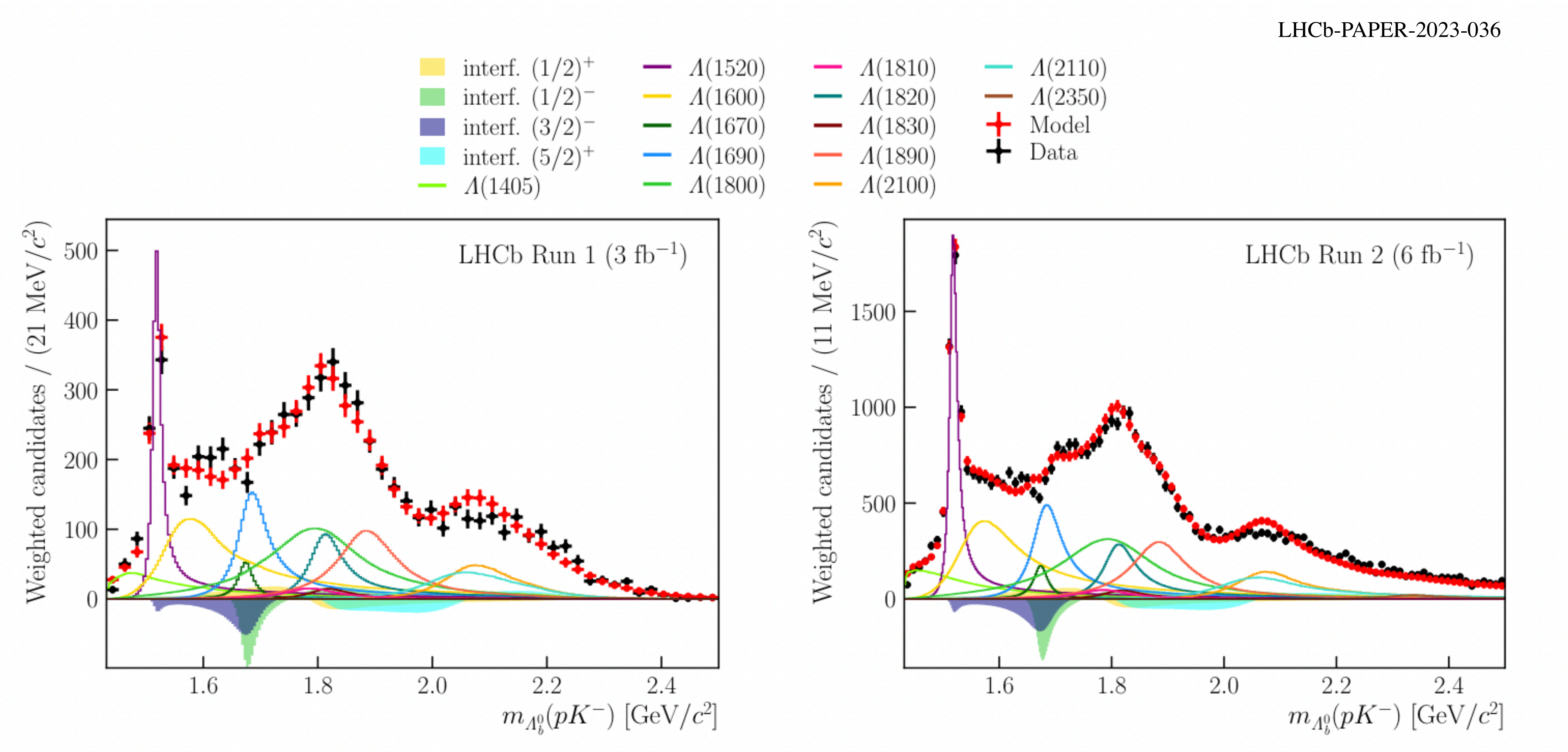
$b \to s\gamma$ amplitude analyses

- $B_s \to \phi\gamma, B^0 \to K^{*0}\gamma, B^+ \to K^+\pi^+\pi^-\gamma, \Lambda_b \to pK\gamma \ldots$

$b \to s\gamma$ amplitude analyses

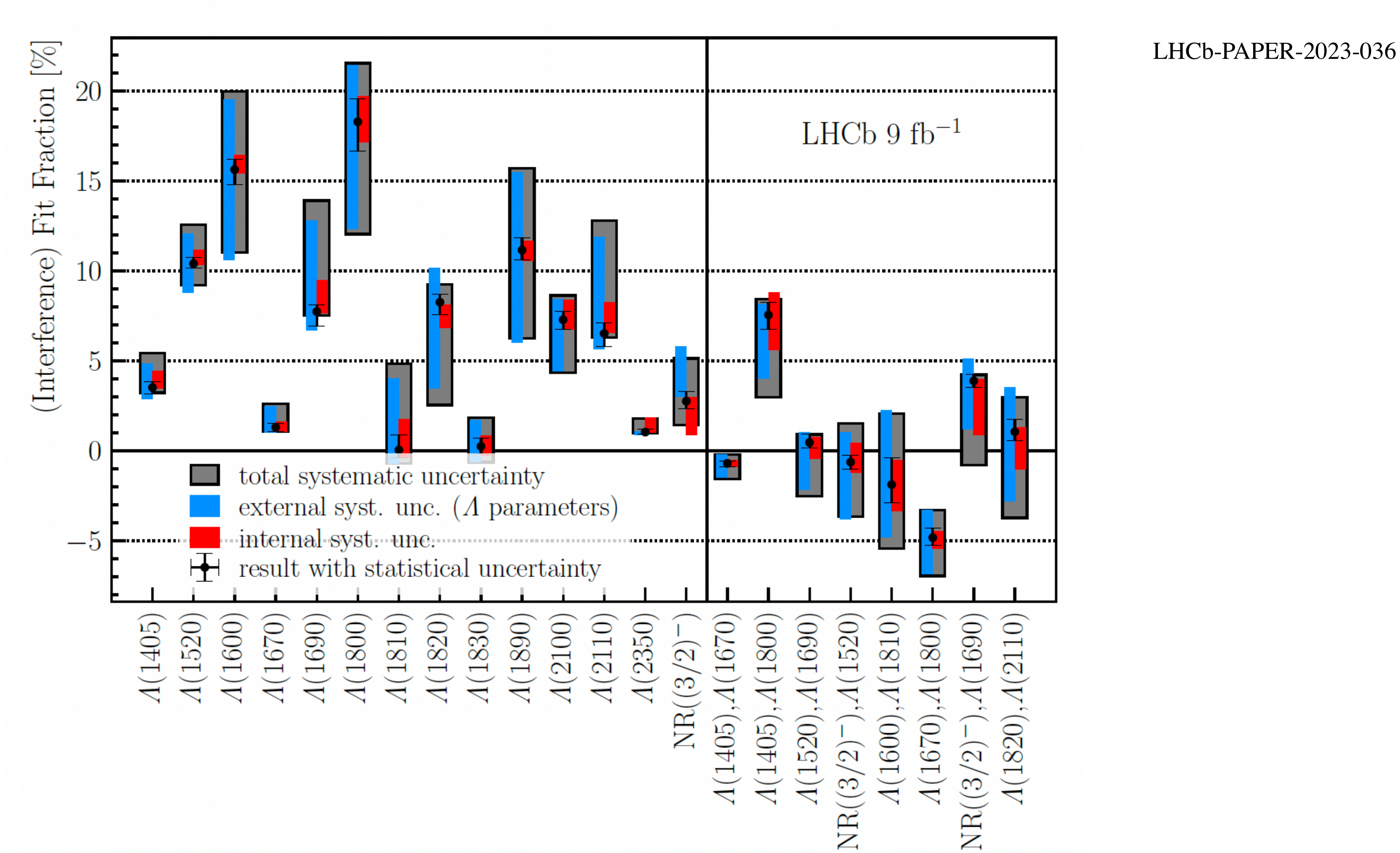
- $B_s \to \phi\gamma, B^0 \to K^{*0}\gamma, B^+ \to K^+\pi^+\pi^-\gamma, \Lambda_b \to pK\gamma \ldots$

Amplitude analysis of $\Lambda_b^0 \to pK\gamma$ - new !



- Largest contributions to $m(pK)$ spectrum from $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1800)$ and $\Lambda(1890)$ states

Amplitude analysis of $\Lambda_b^0 \to pK\gamma$ - new !



- Comparison to $\Lambda_b \to pKJ/\psi$ tricky as no pentaquark, heavier resonances enhanced in radiative case