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

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On behalf of the LHCb Collaboration

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

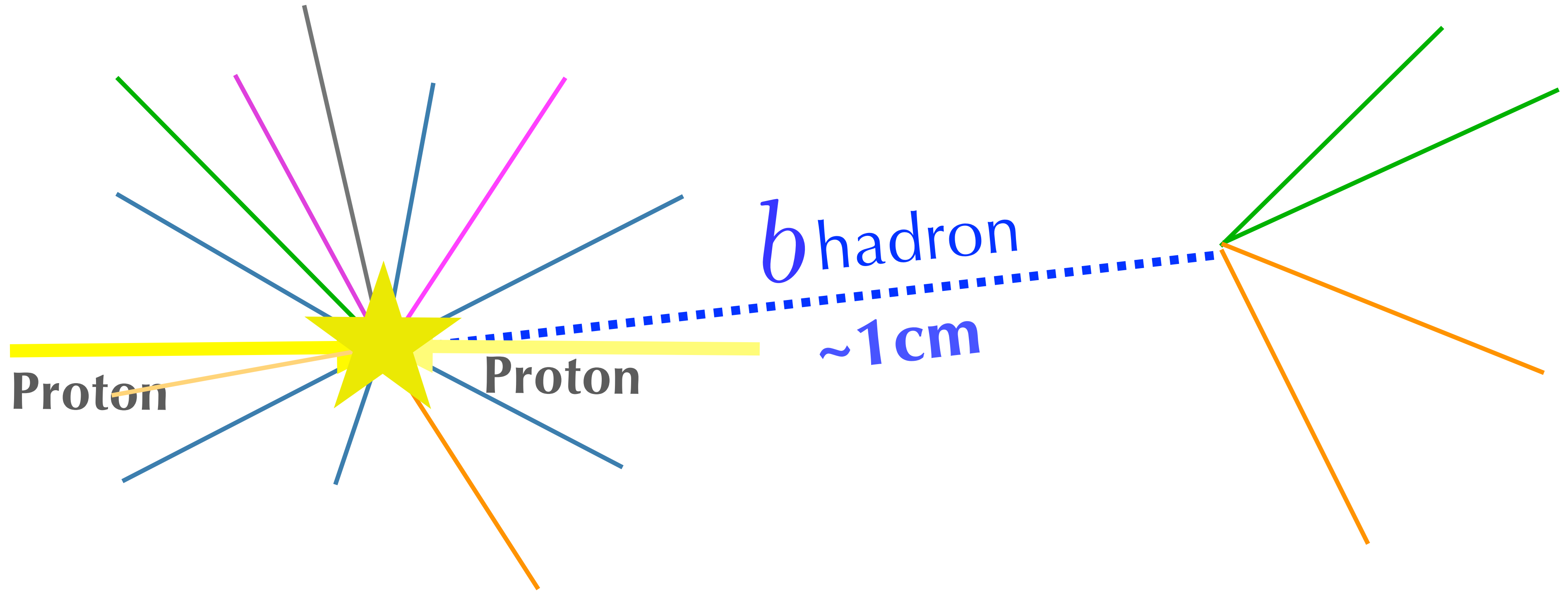
Universität Zürich[UZH]

LHCb

19th July 2024

The LHCb experiment

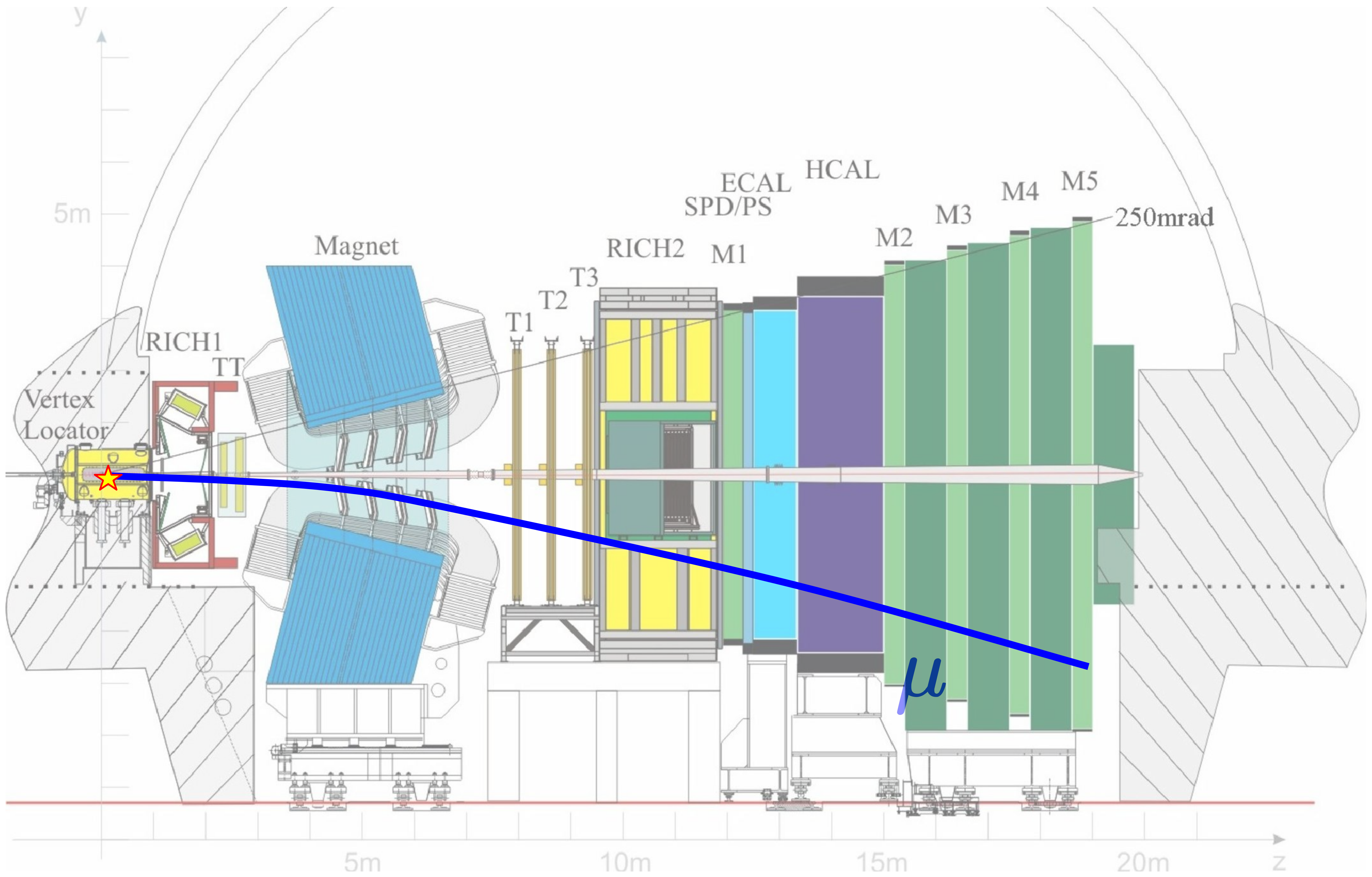
Boost of b-hadrons is exploited to separate signal and background



$B^0 \to K^+\pi^-\mu^+\mu^-$ has a clean signal

- Efficient hadron and muon particle identification
- Precise tracking

Largest collection of $b\bar{b}$-pairs in the world



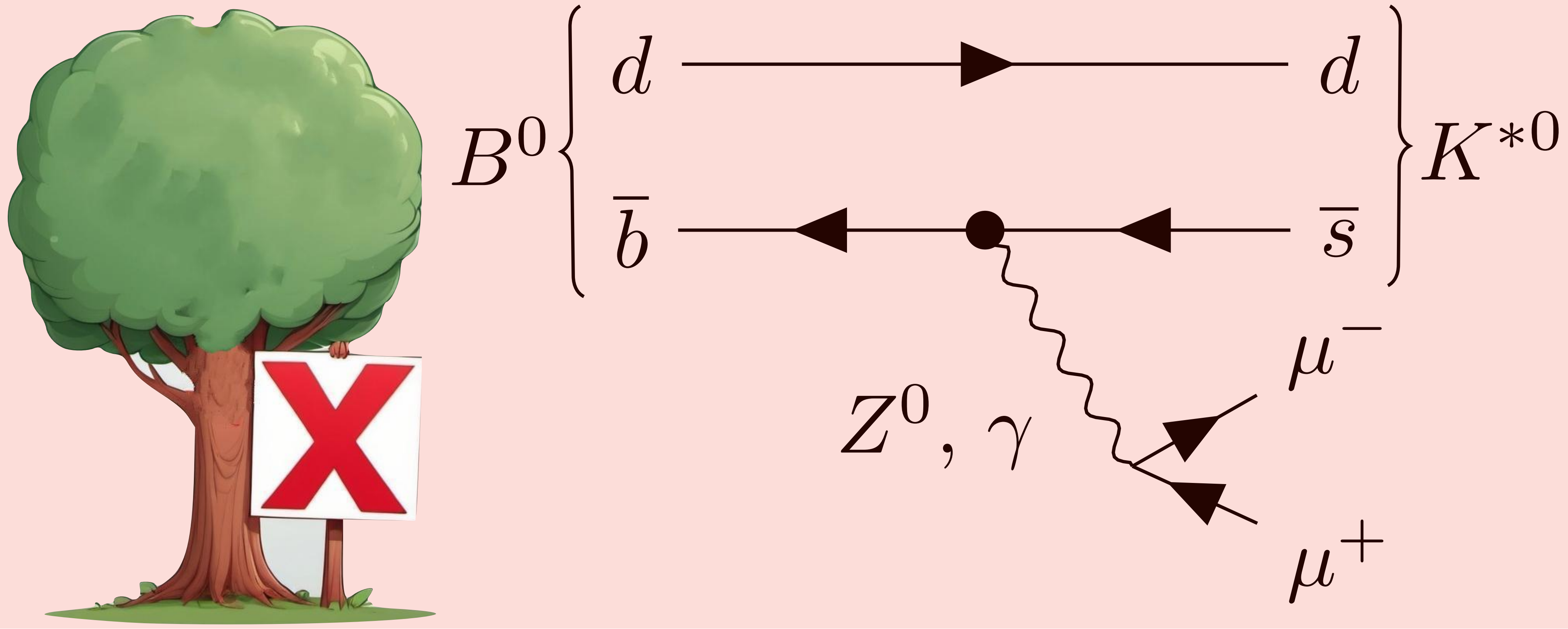
Int. J. Mod. Phys. A 30 (2015) 1530022

Rare decays

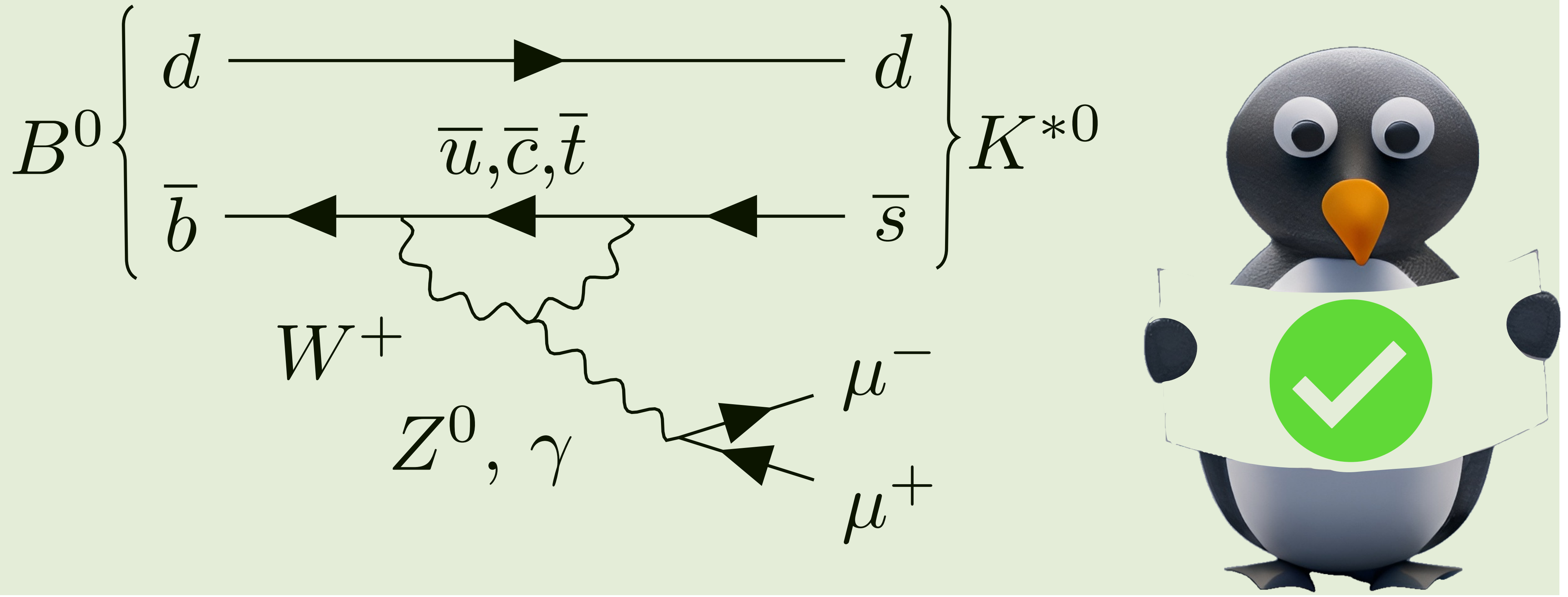
$$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$$

Rare decays provide a great environment to search for New Physics

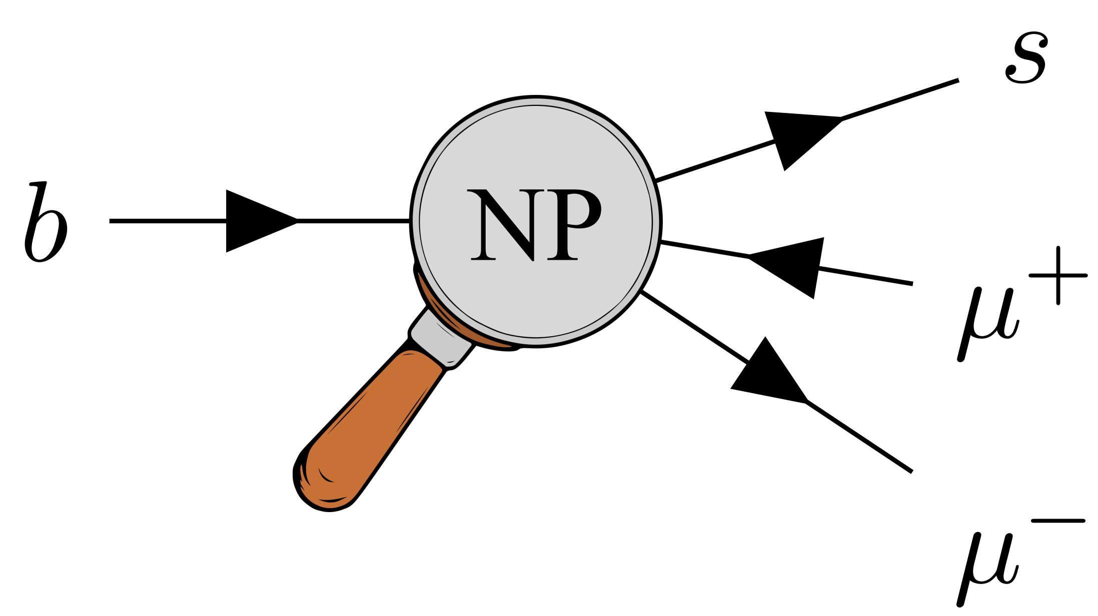
Not allowed at tree level



Suppressed in the SM



Precision measurements allow for indirect searches for NP contributions of competitive order in e.g. $b \to s\ell^+\ell^-$



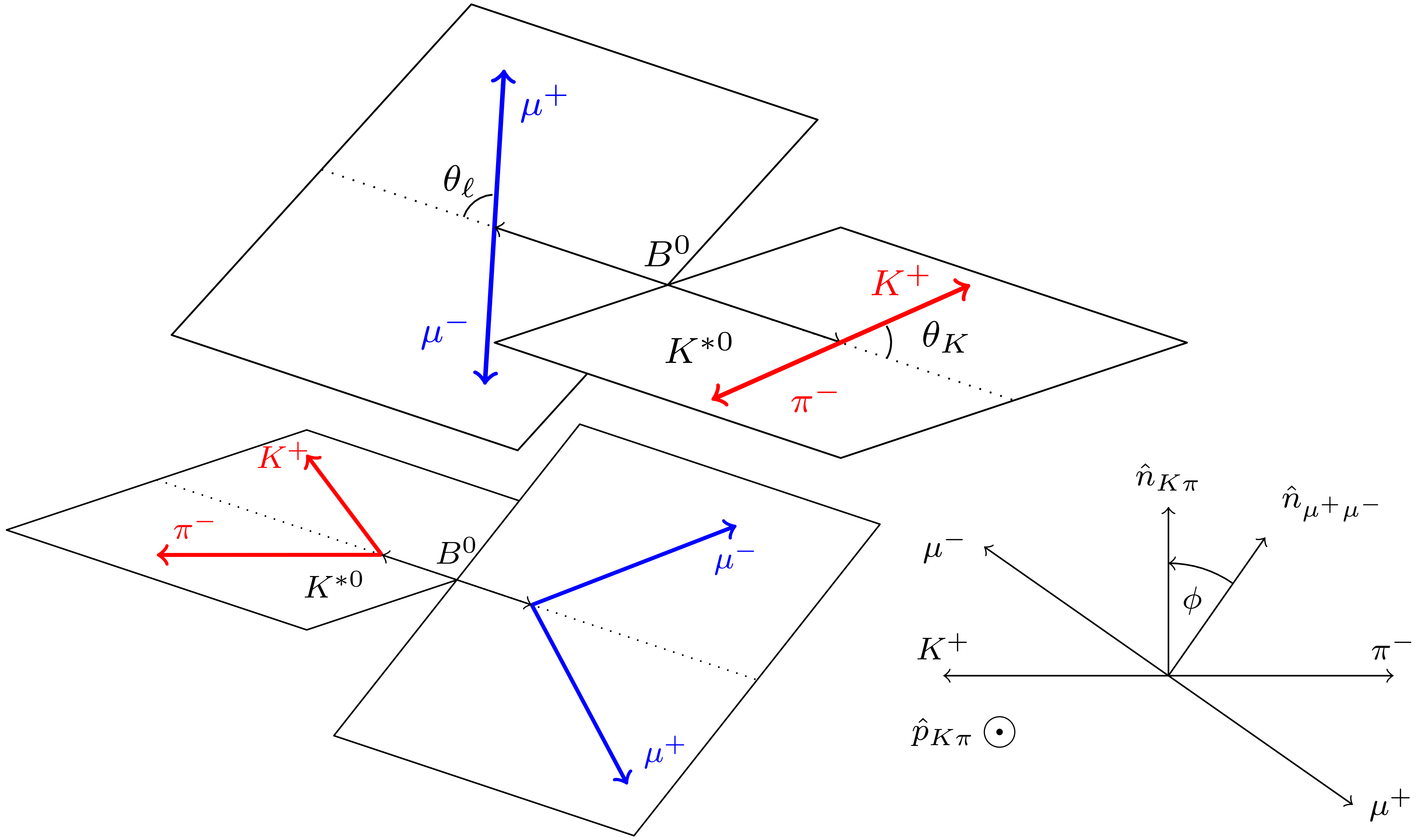
$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

The phase space is fully described by θ_ℓ, θ_K, ϕ, $m_{K\pi}$ and $q^2 \equiv m(\mu^+\mu^-)^2$

Angular observables

$$\frac{d\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2 d\vec{\Omega} dm^2_{K\pi}} = \frac{9}{32\pi}\sum_i J_i(q^2) f_i(\cos\theta_\ell, \cos\theta_K, \phi) g_i(m^2_{K\pi})$$

Angular distributions



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The phase space is fully described by θ_ℓ, θ_K, ϕ, $m_{K\pi}$ and $q^2 \equiv m(\mu^+\mu^-)^2$

Angular observables → Decay amplitudes

$$\frac{d\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2 d\vec{\Omega} dm^2_{K\pi}} = \frac{9}{32\pi}\sum_i J_i(q^2) f_i(\cos\theta_\ell, \cos\theta_K, \phi) g_i(m^2_{K\pi})$$

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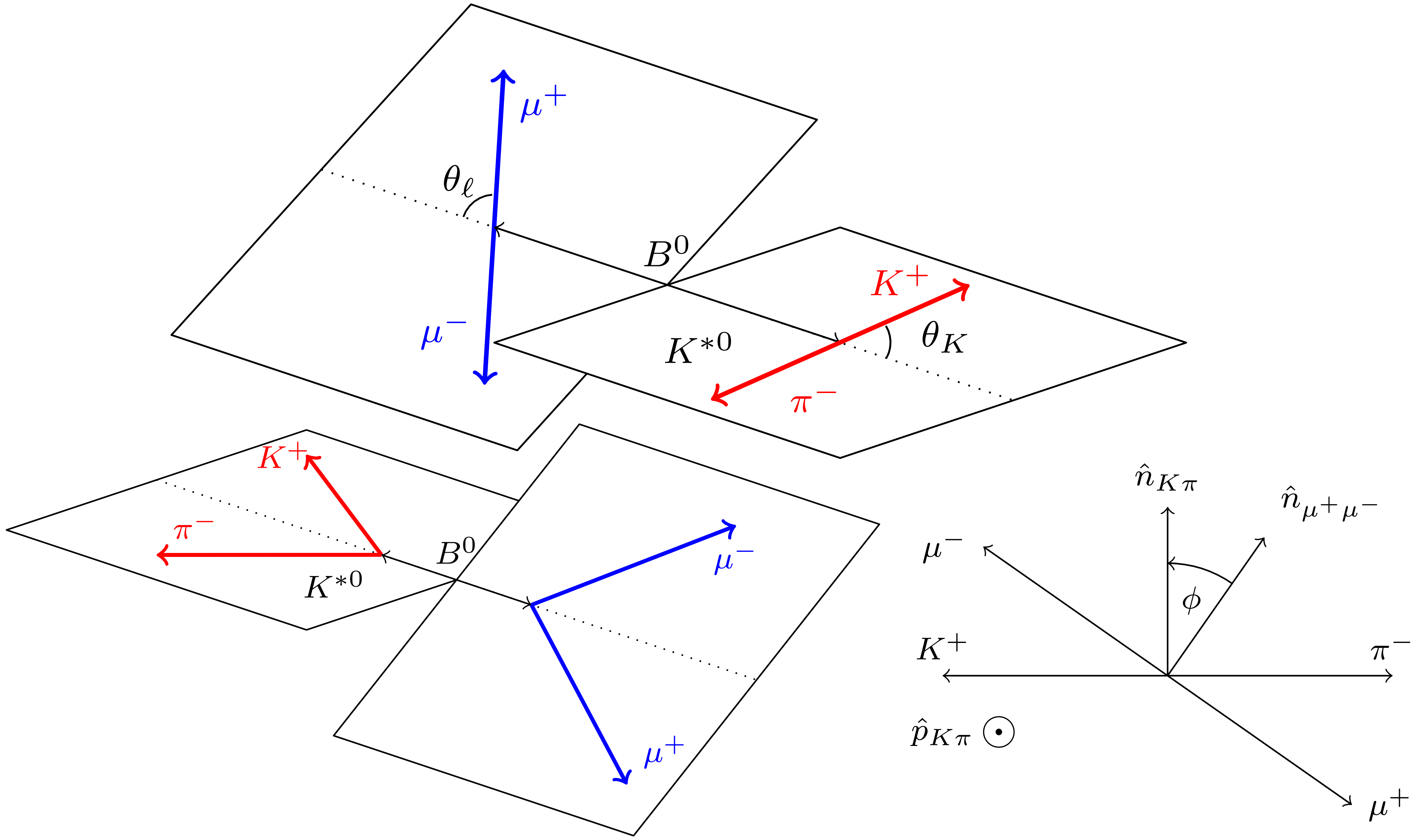
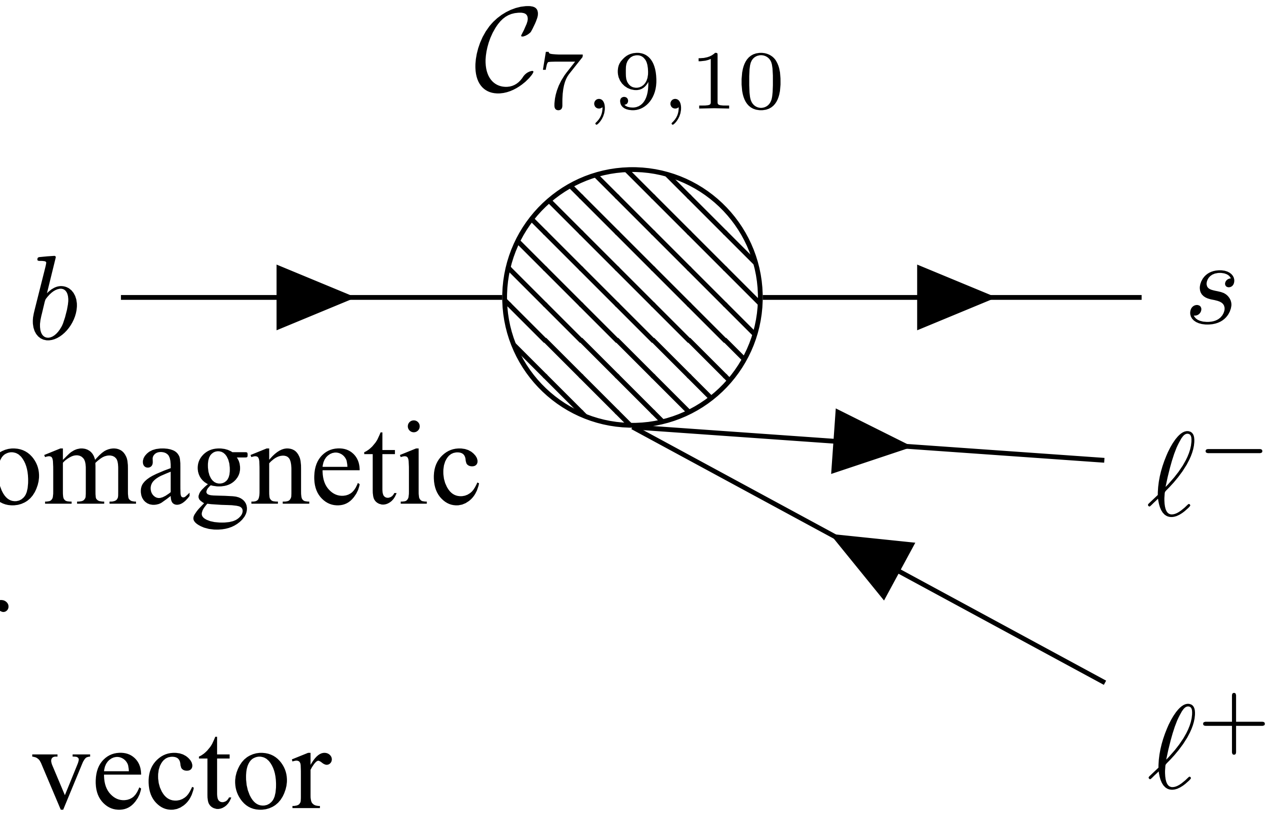


$b \to s\ell^+\ell^-$

in Weak effective theory



C_7: Electromagnetic

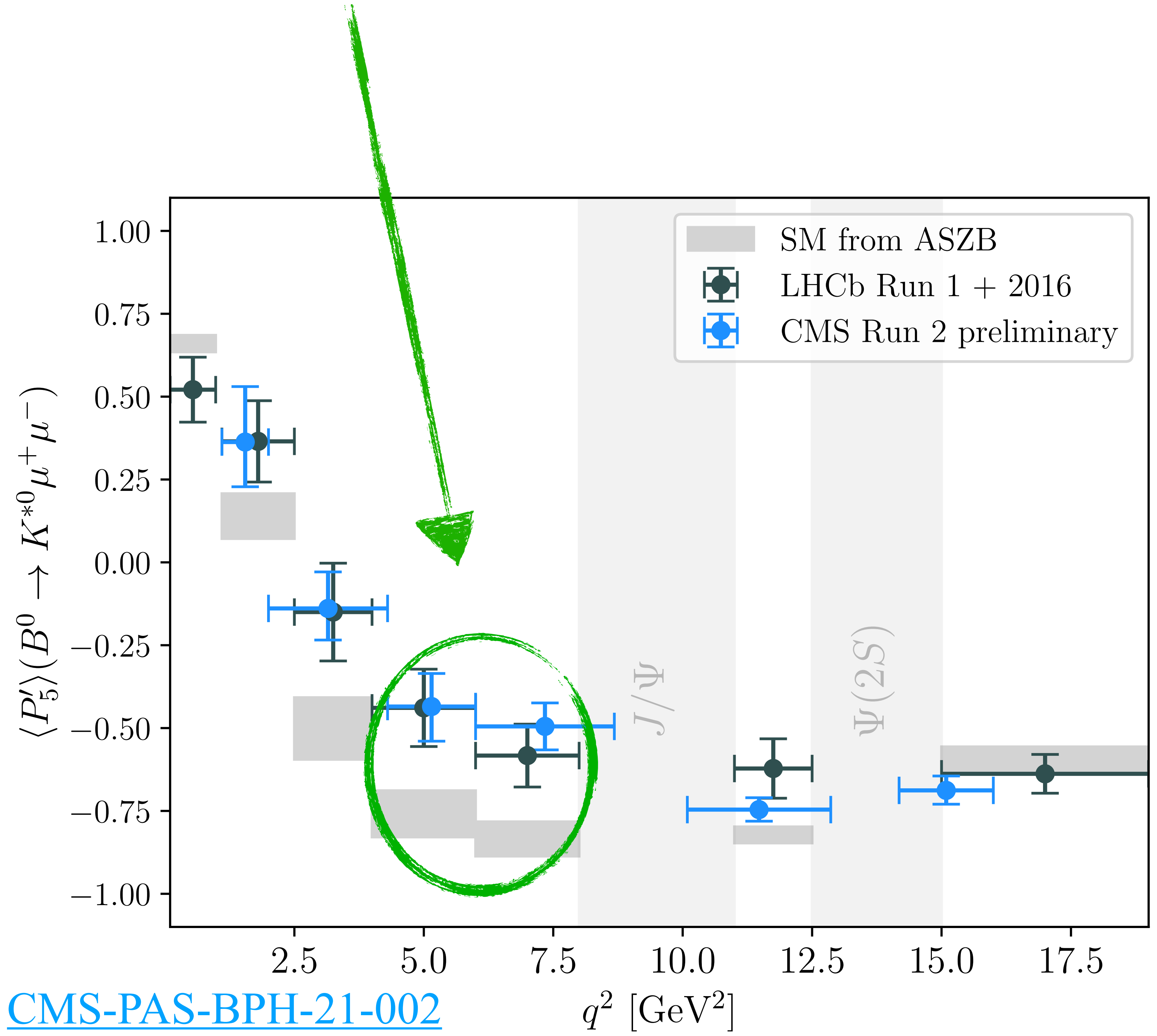
C_9: Vector

C_{10}: Axial vector

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

Long standing tensions with the Standard Model

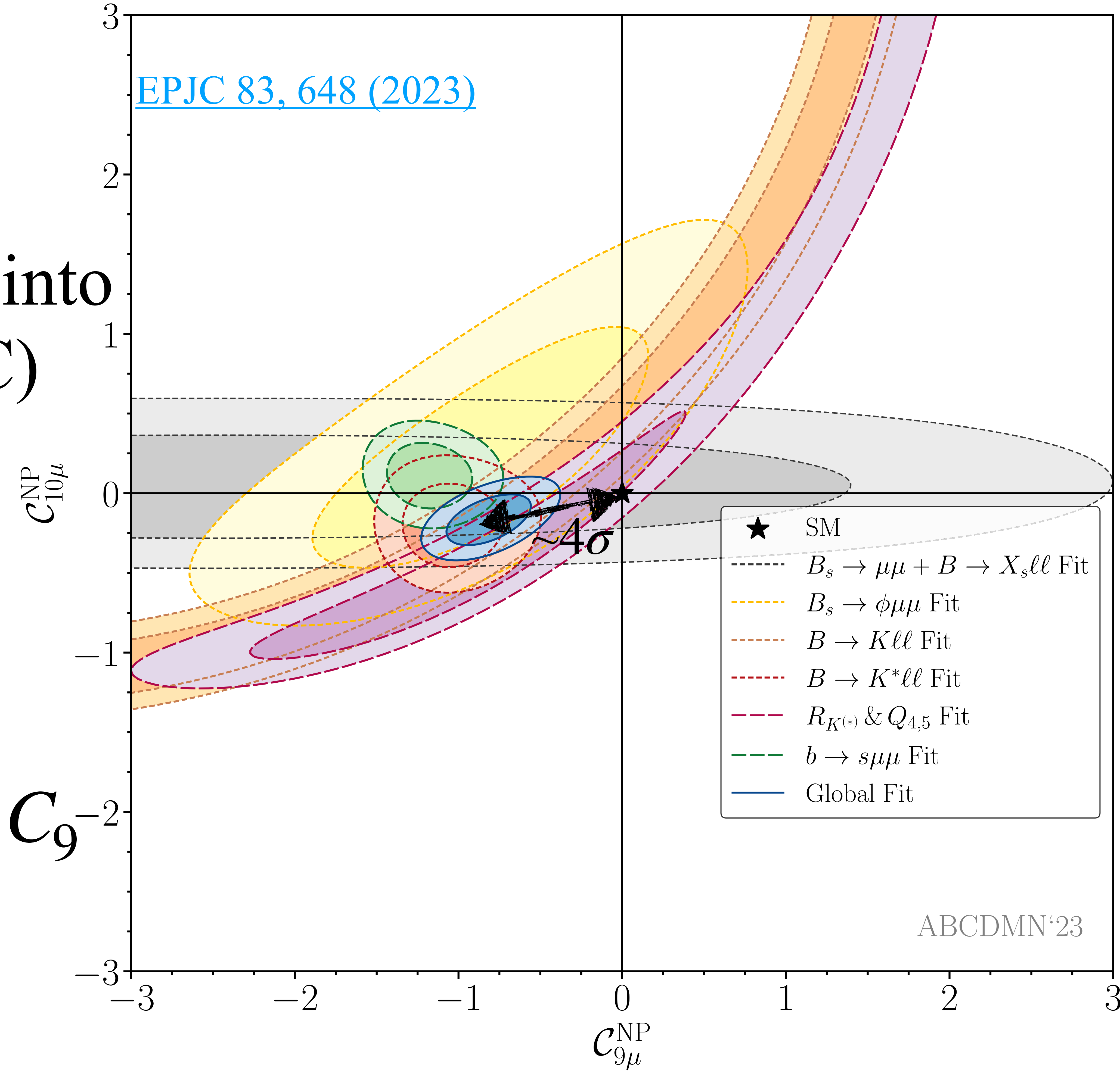
Tension seen in the observable P_5'



[CMS-PAS-BPH-21-002](#)
[PRL. 125 (2020) 011802](#)

All observables translated into effective couplings (WC)

Shift in vector coupling C_9 is favoured!

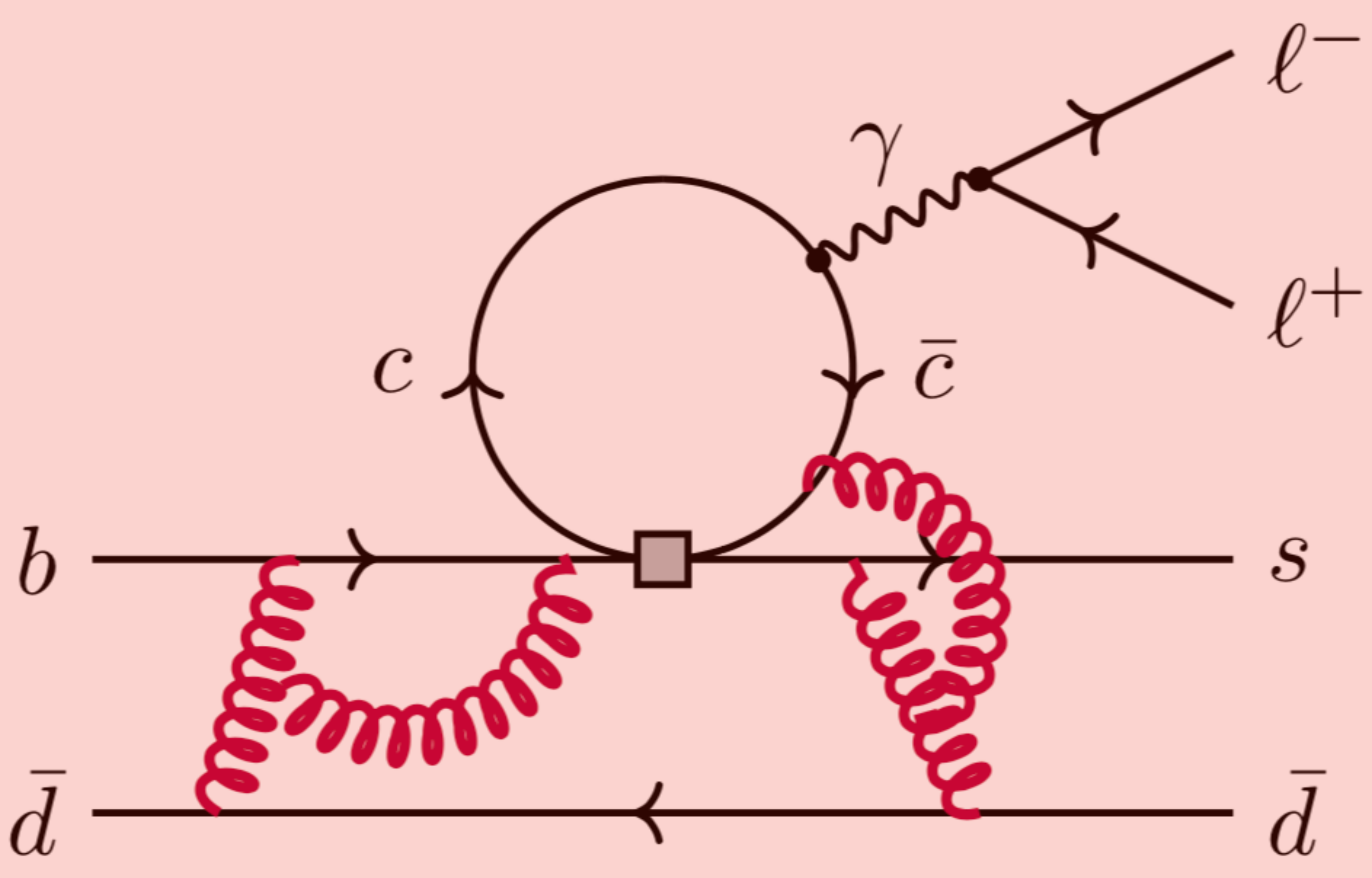


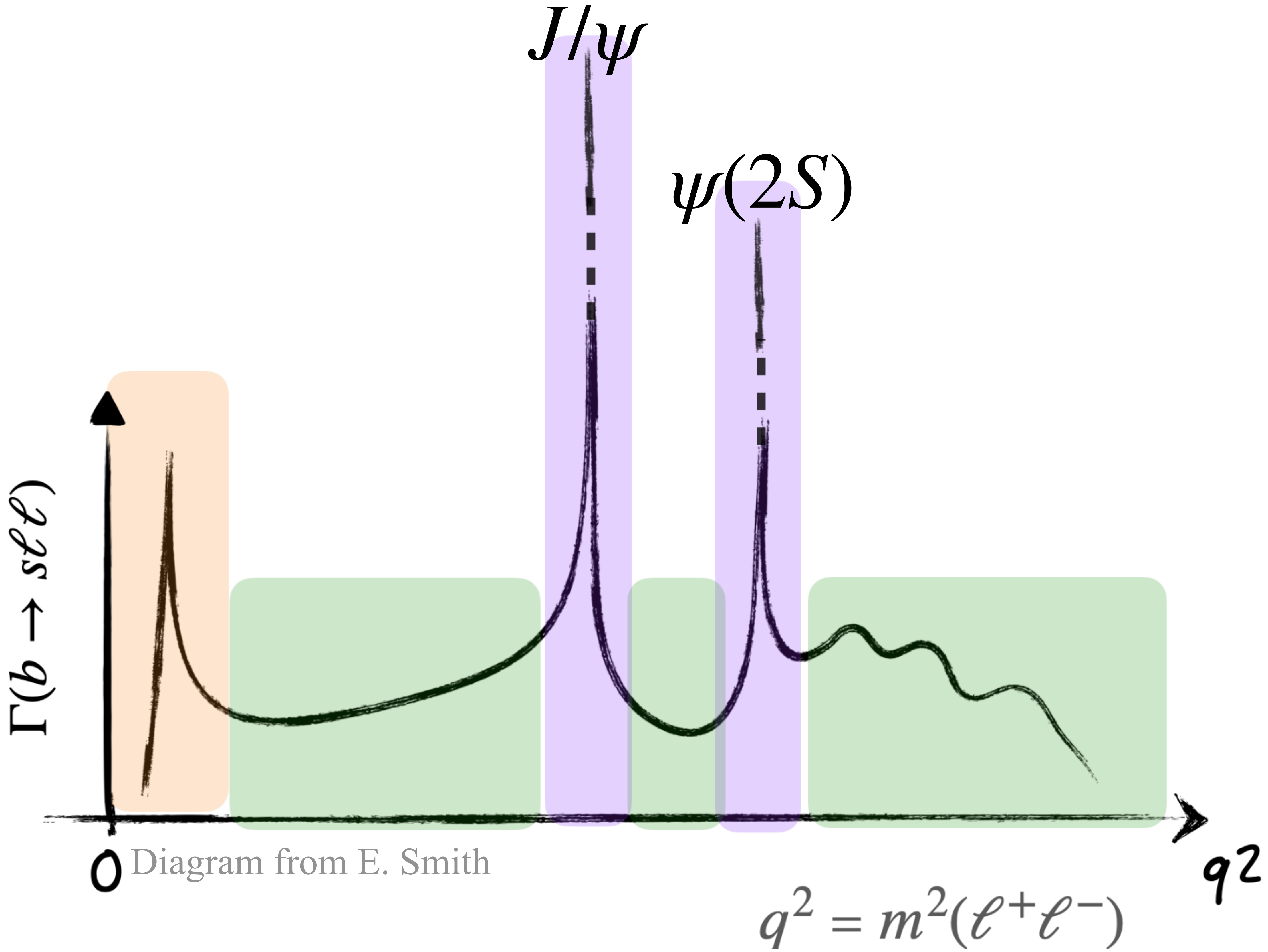
Not including CMS Run 2 result

Interpretation of the anomaly

Non-local contributions from the $c\bar{c}$ resonances impact the rare mode regions

SM QCD effects

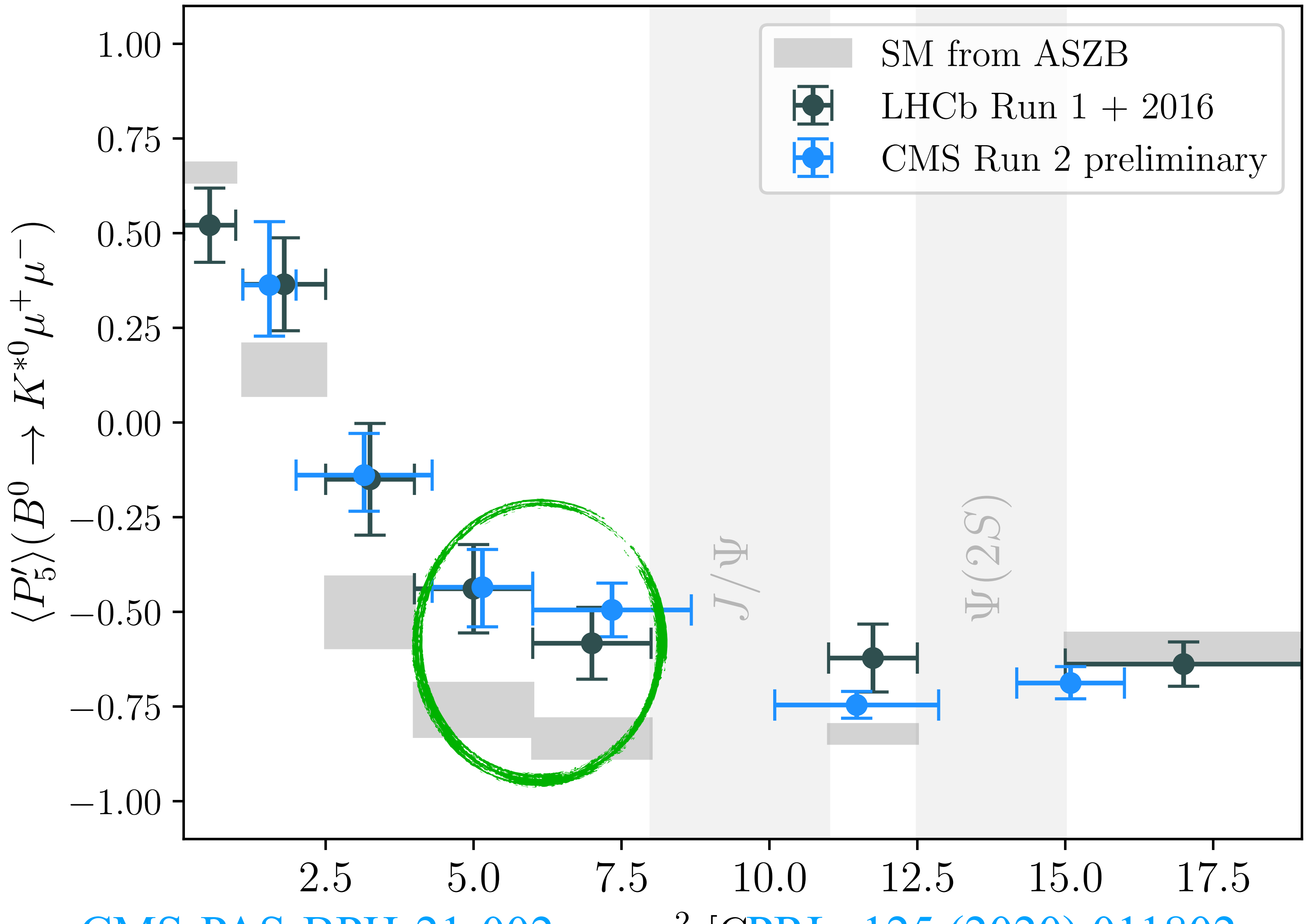




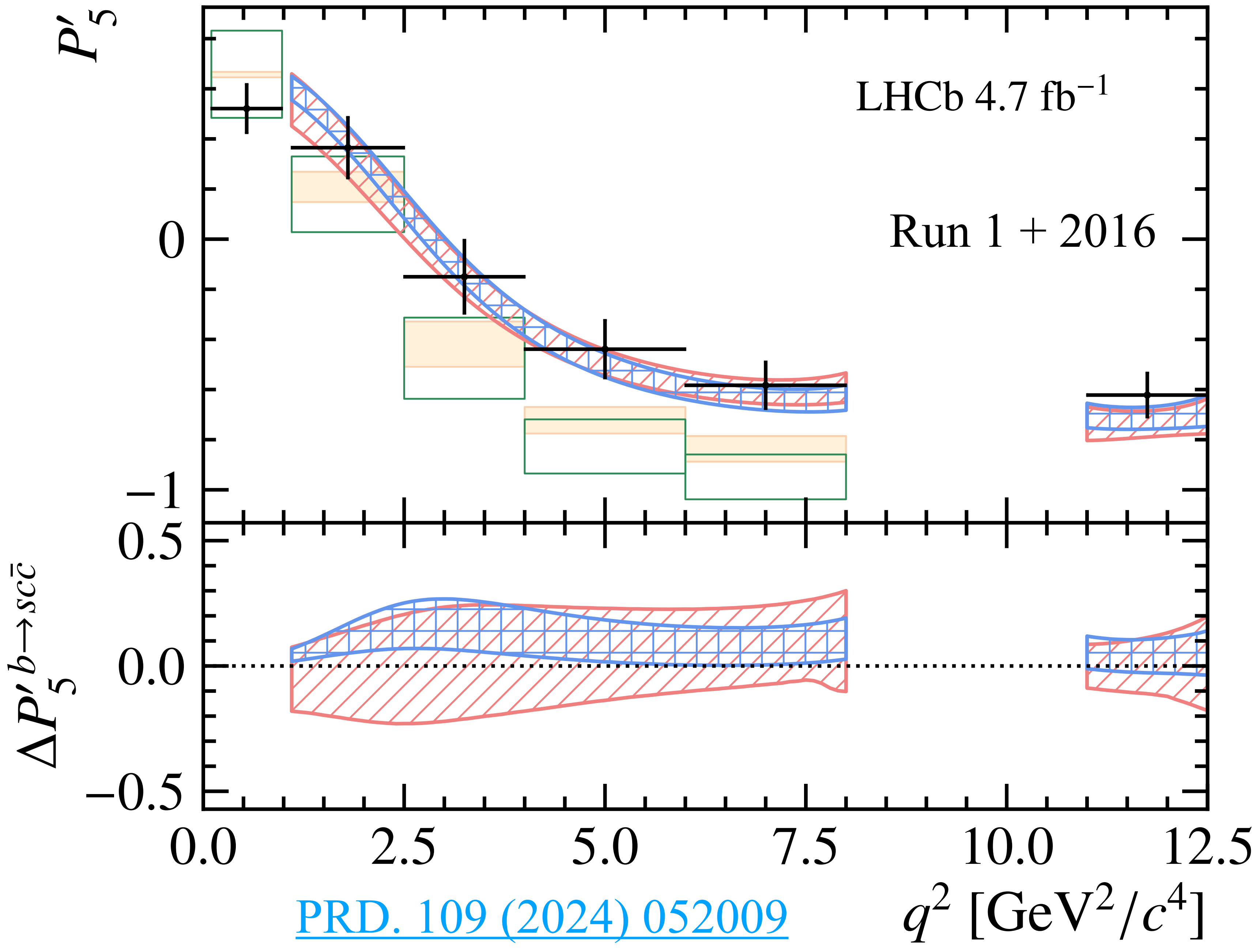
NP or underestimated SM QCD?

Amplitude analysis to separate local and non-local contributions

Previous measurement strategies



CMS-PAS-BPH-21-002 PRL. 125 (2020) 011802



PRD. 109 (2024) 052009

Model-independence

Model-dependence

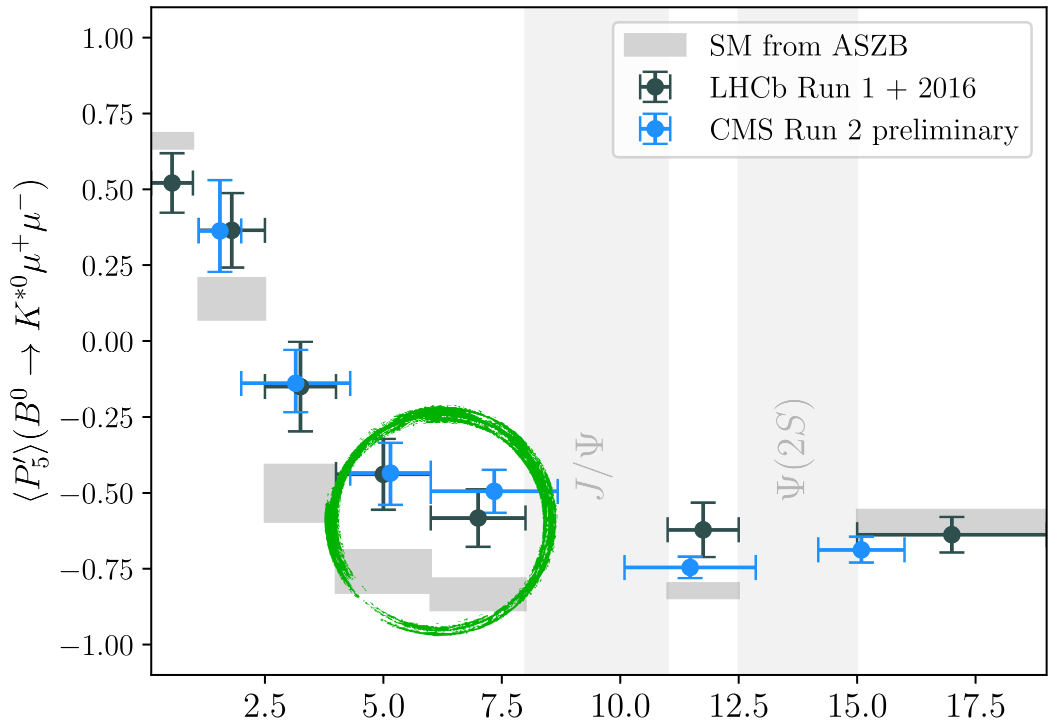
Measures observables in bins of q^2

Uses polynomial expansion to **model** non-local contributions and extracts Wilson coefficients directly

Analysis strategy

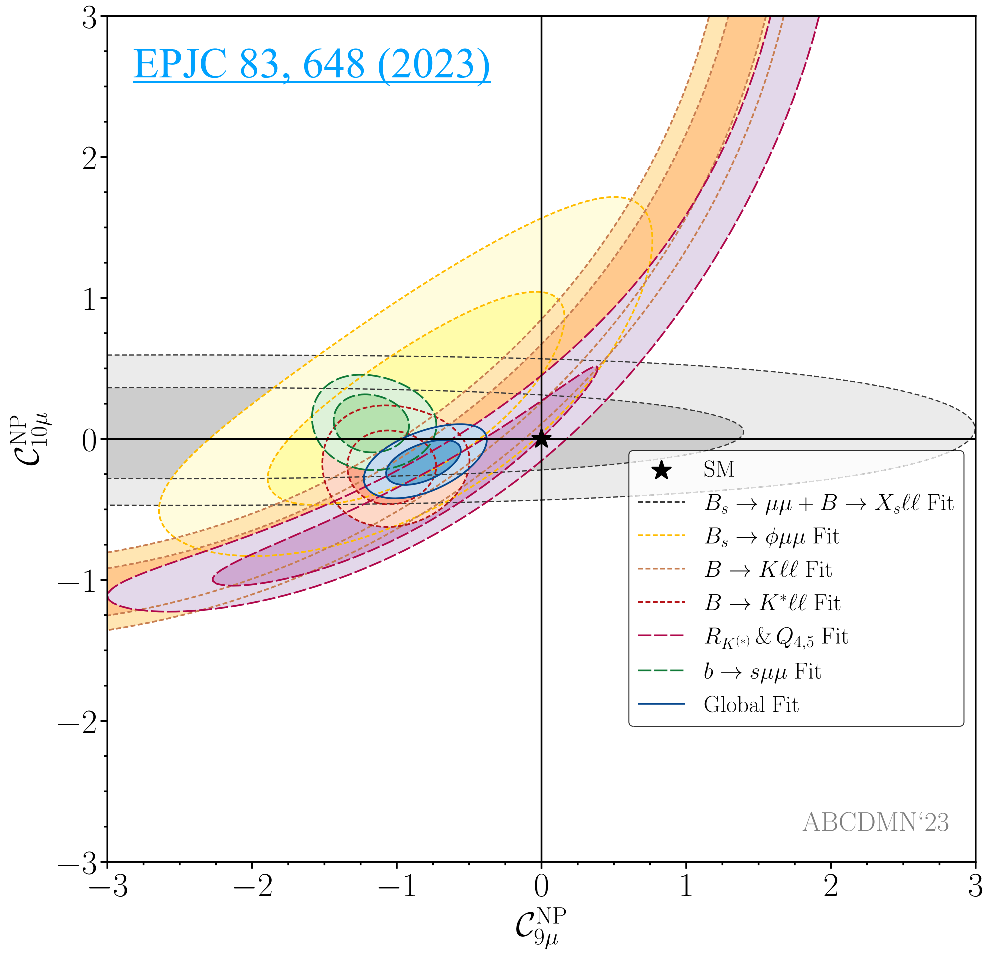
Instead of the binned approach (similar to Run 1+2016 measurement PRD. 109 (2024) 052009)

$$\frac{d\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2 d\overrightarrow{\Omega} dm^2_{K\pi}}$$



CMS-PAS-BPH-21-002 PRL. 125 (2020) 011802

Model-dependence



Model-dependence
(No loss of information within bins)

First analysis of $B^0 \to K^{*0}\mu^+\mu^-$ using full Run 1 + Run 2 data:
Parameterise the **full q^2 spectrum** of the decay in terms of Wilson coefficients, Form Factors, and non-local contributions

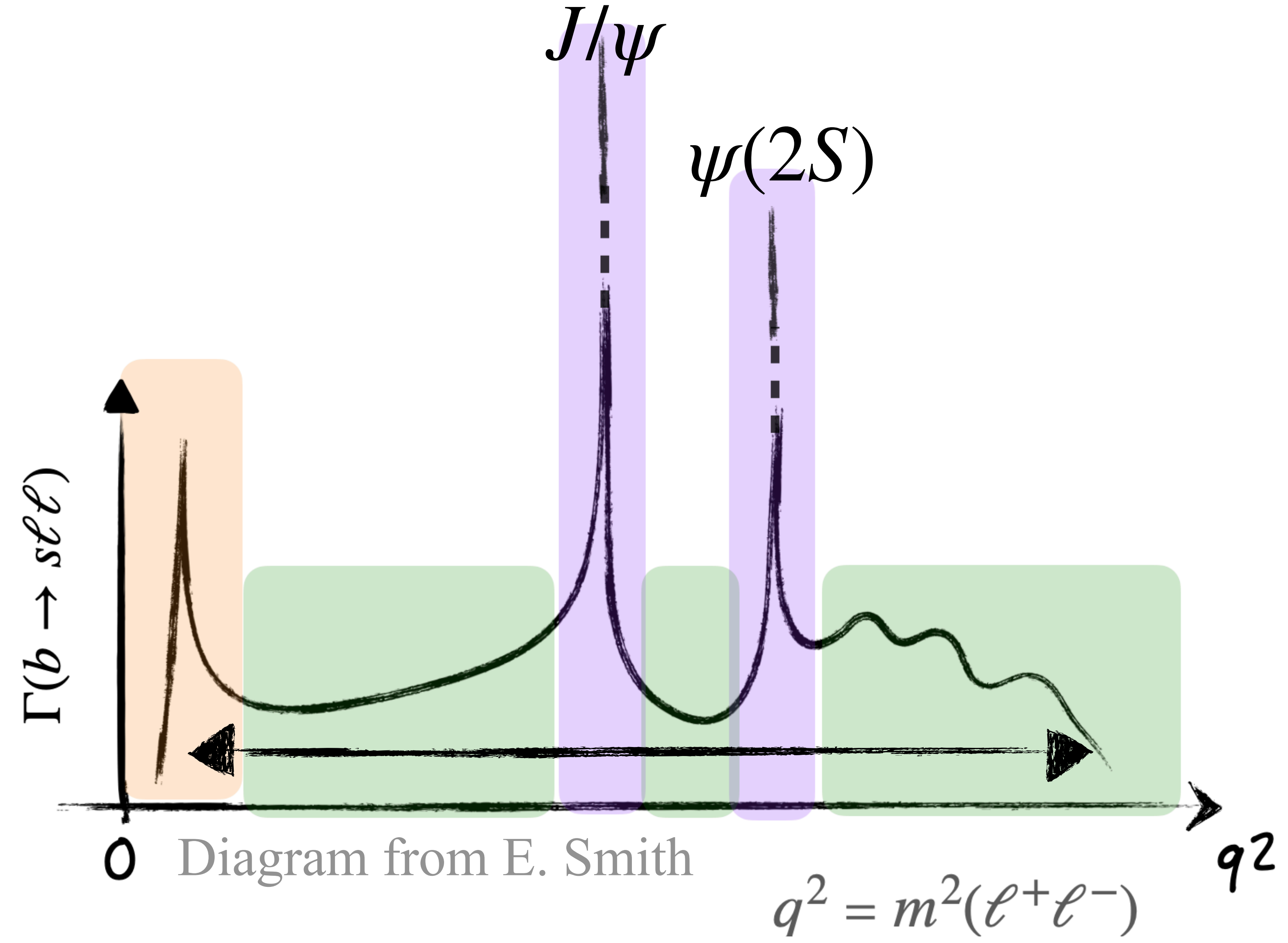


Diagram from E. Smith

Analysis strategy

Contributions to the differential decay rate:

$$C_9^{eff,\lambda}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0)}(q_0^2) + Y_{c\bar{c}}^{1P,\lambda}(q^2) + Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

$$C_7^{eff,\lambda} = C_7 + \zeta^{\lambda} e^{i\omega^{\lambda}}$$

Cornella et al. [EPJC 80 (2020) 12, 1095]

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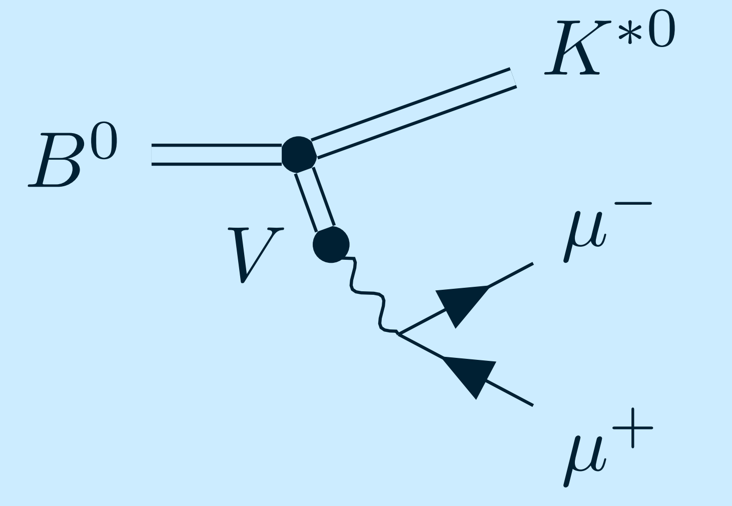

1-particle contributions

$\rho(770)$, $\omega(782)$,

$\phi(1020)$, J/ψ,
$\psi(2S)$, $\psi(3770)$,

$\psi(4040)$, $\psi(4160)$

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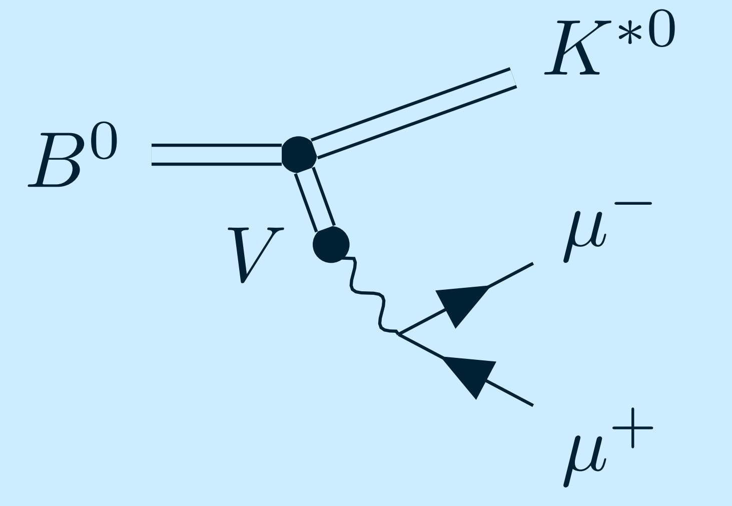

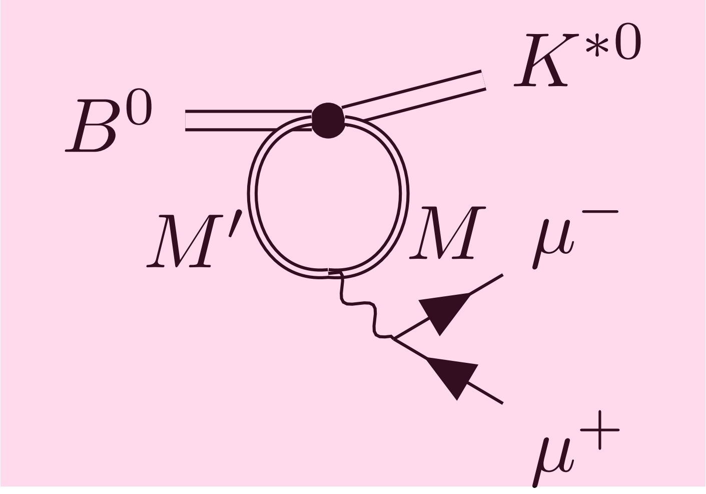

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2-particle contributions

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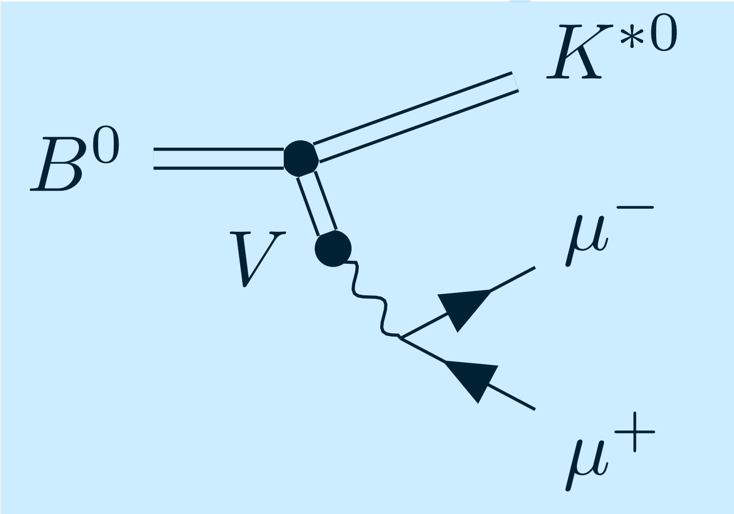

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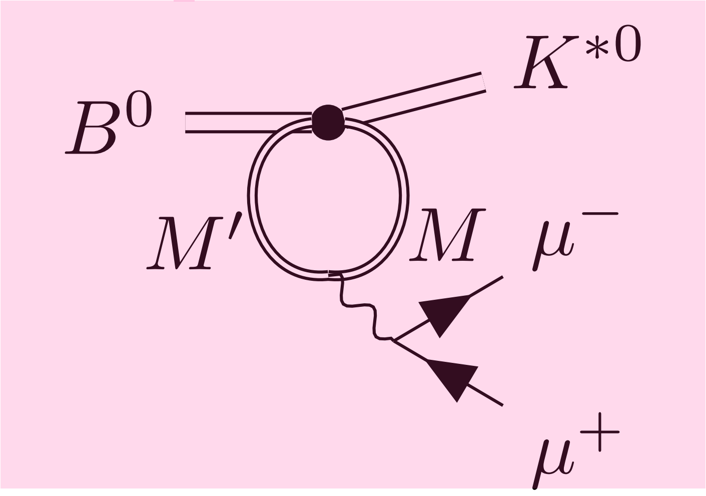

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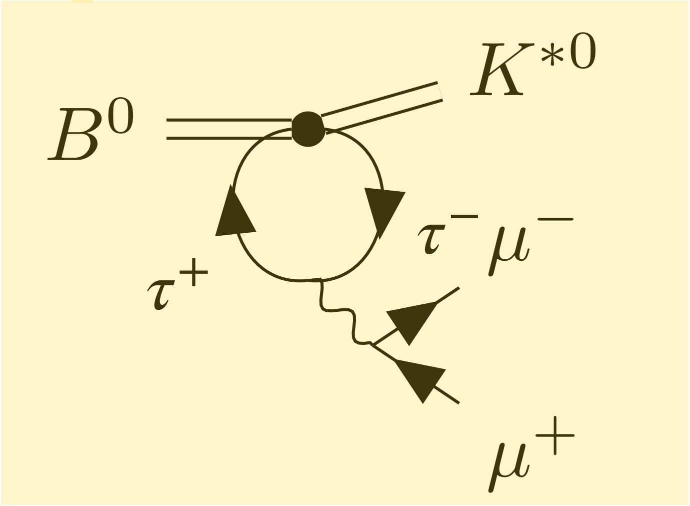

$B^0 \to K^{*0}\tau^+\tau^-$ contribution

Sensitive to C_9^{τ}

Cornella et al. [EPJC 80 (2020) 12, 1095]

Analysis strategy

Contributions to the differential decay rate:

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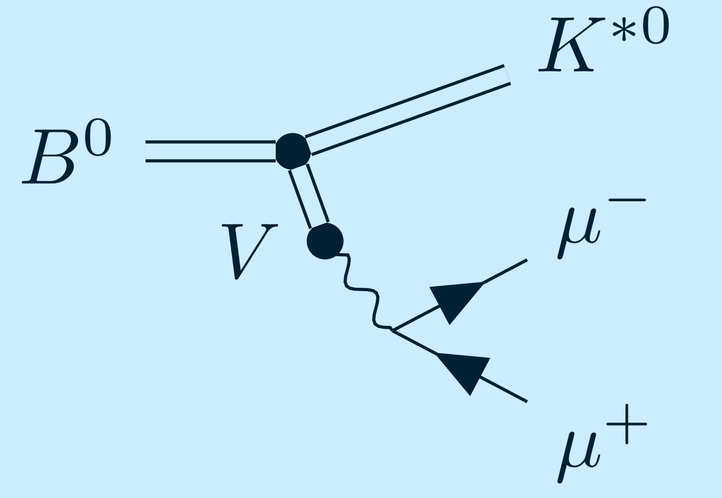
$$C_7^{eff,\lambda} = C_7 + \zeta^{\lambda} e^{i\omega^{\lambda}}$$

Determined theoretically at negative q^2

Constant term

Negligible impact from light quarks

Asatrian, Greub, Virto [JHEP 04 (2020) 012]



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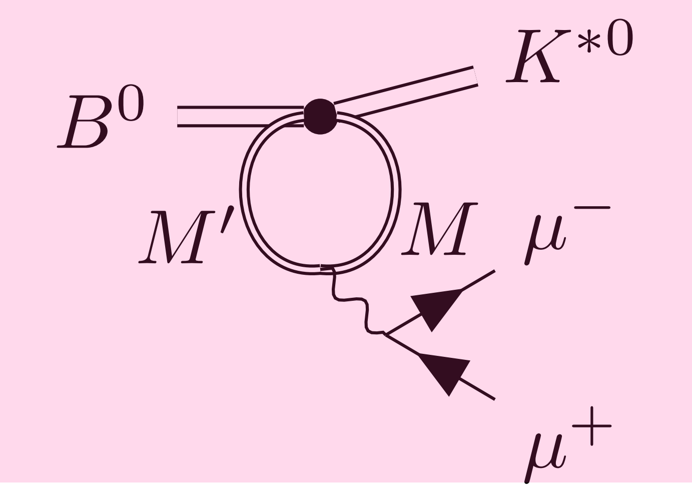

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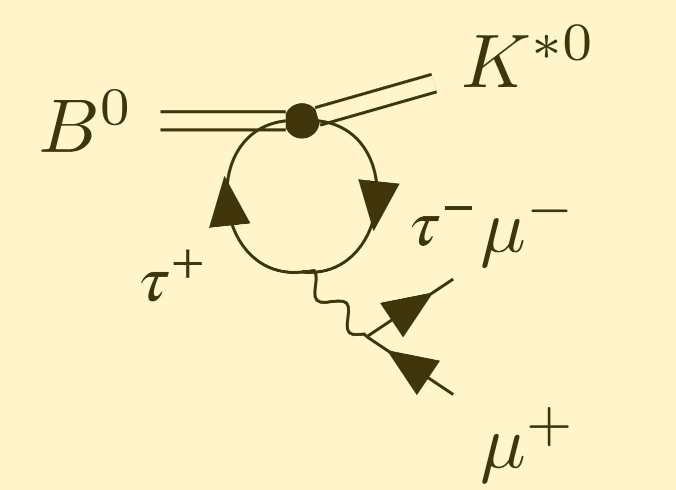

$B^0 \to K^{*0}\tau^+\tau^-$ **contribution**

Sensitive to C_9^{τ}

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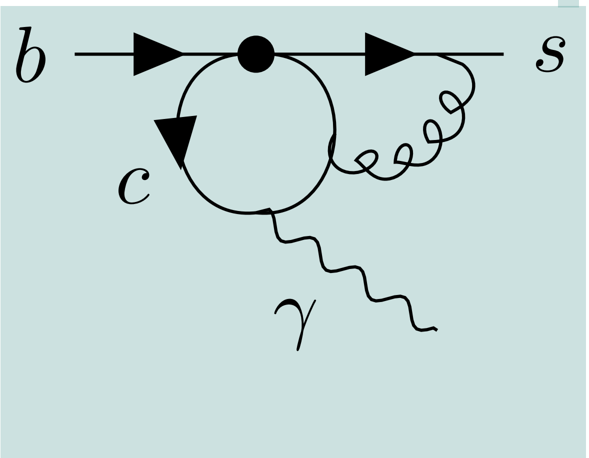


C_7 vertex correction

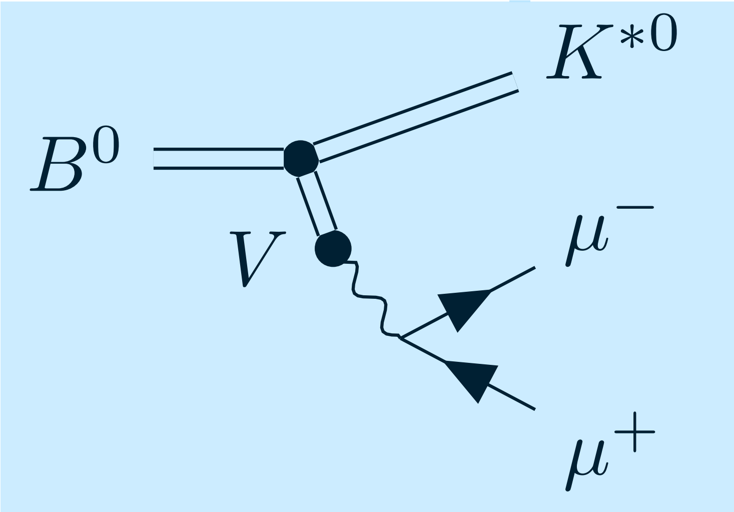
Polarisation dependent shift to C_7

Determined theoretically at negative q^2

Constant term

Negligible impact from light quarks

Asatrian, Greub, Virto [JHEP 04 (2020) 012]



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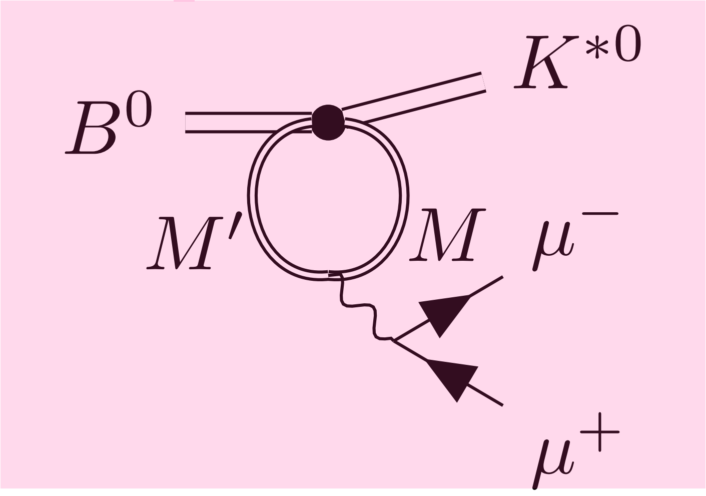

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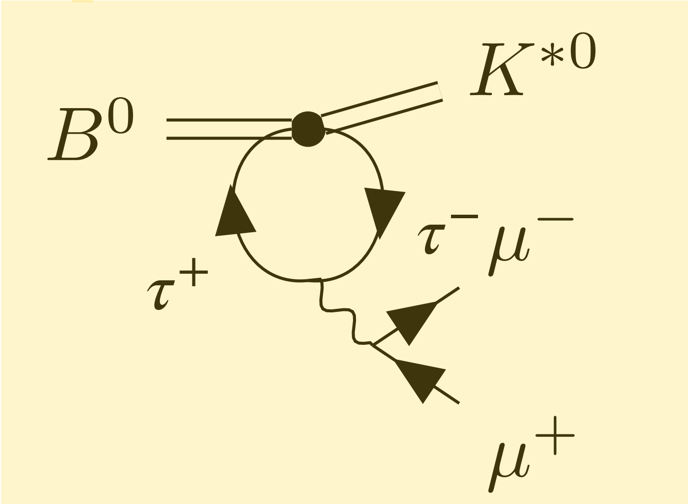


$B^0 \to K^{*0}\tau^+\tau^-$ contribution

Sensitive to C_9^{τ}

Cornella et al. [EPJC 80 (2020) 12, 1095]

Analysis strategy

LHCb-PAPER-2024-011

Signal fractions — Differential decay rate — Acceptance — Resolution — Combinatorial background

$$\mathcal{P}^i_{Tot}(\overline{\Omega}, q^2) = f^i_{sig}\left((\mathcal{P}_{sig}(\overline{\Omega}, q^2) \times \epsilon(\overline{\Omega}, q^2)) \circledast R^i(q^2)\right) + (1 - f^i_{sig})\mathcal{P}_{bkg}(\overline{\Omega}, q^2)$$

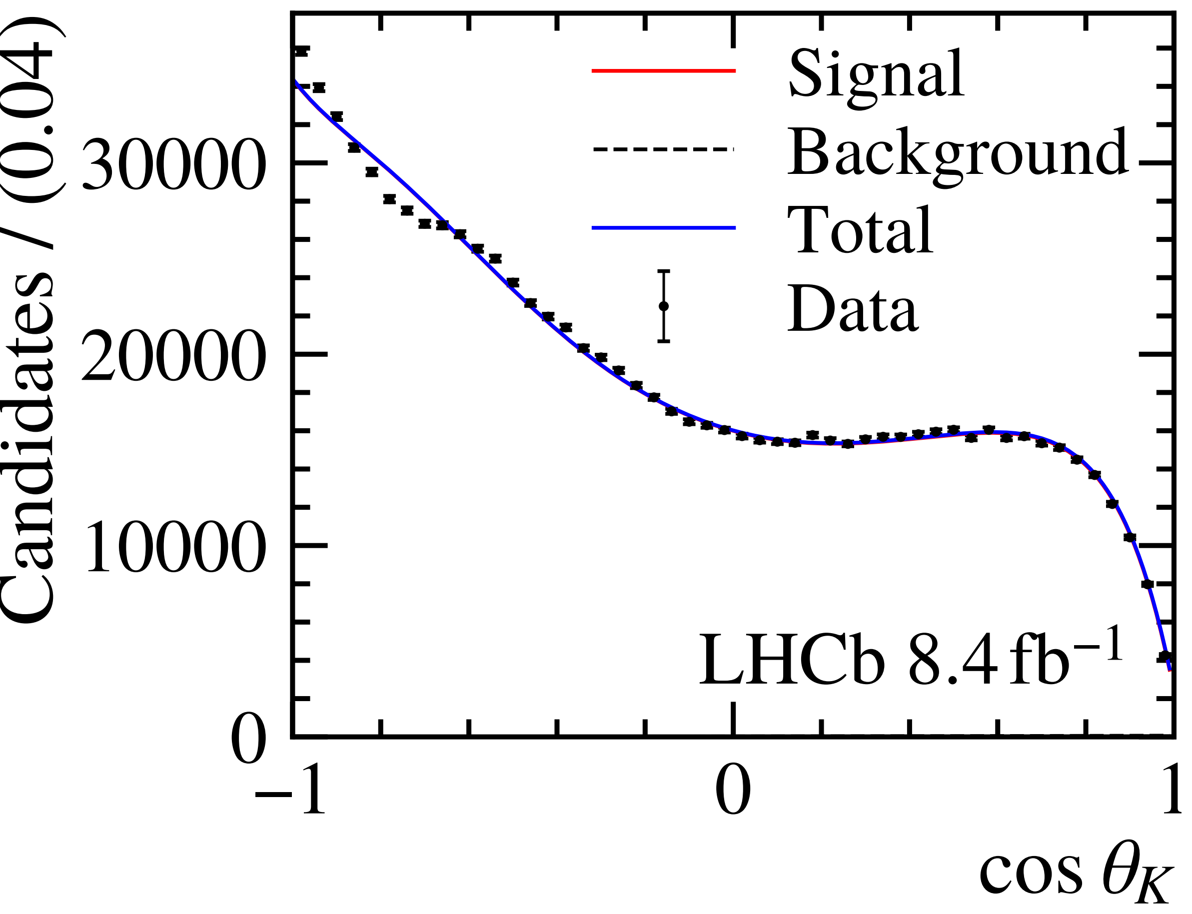
Simulation
- Acceptance

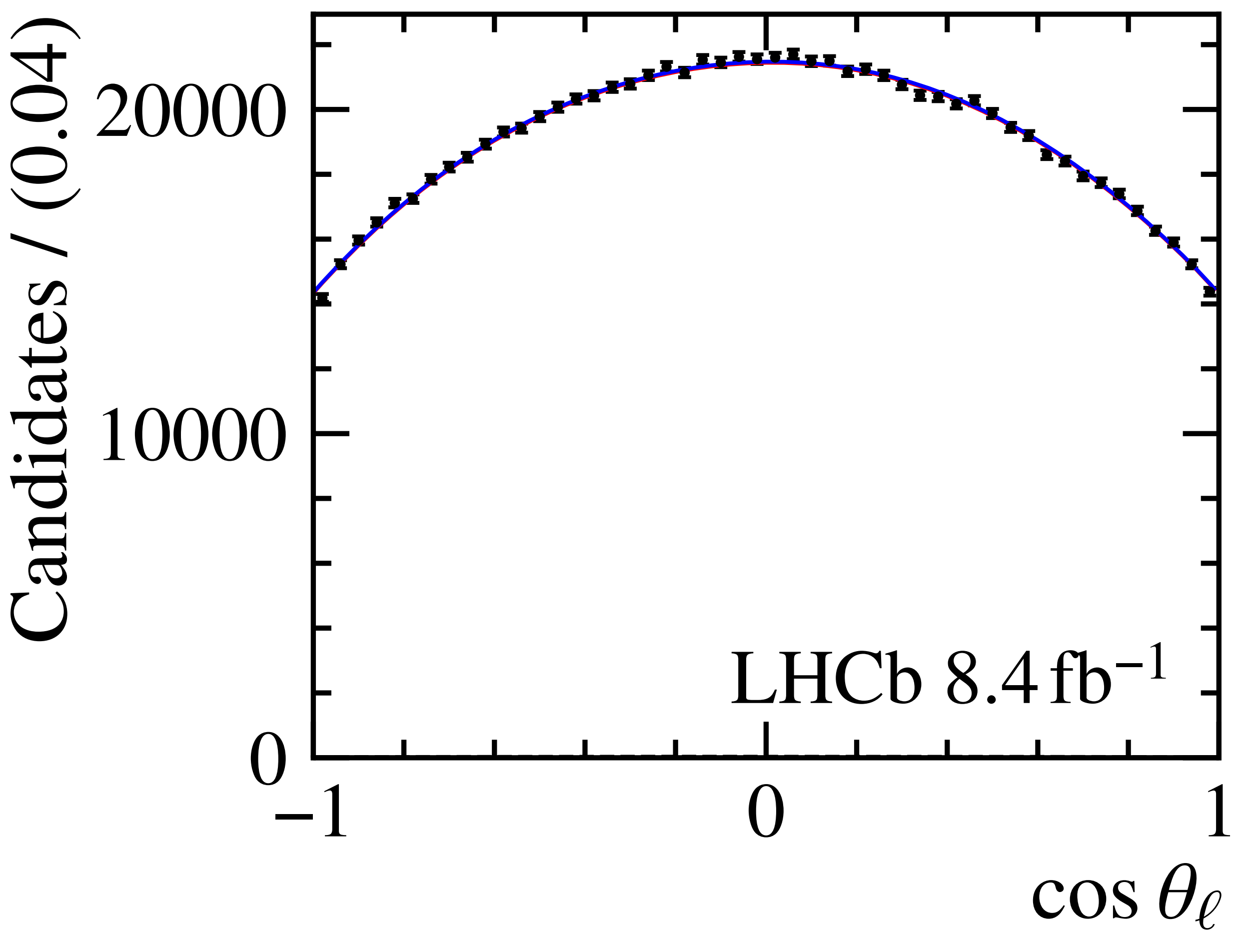
Data
- Resolution
- Background model

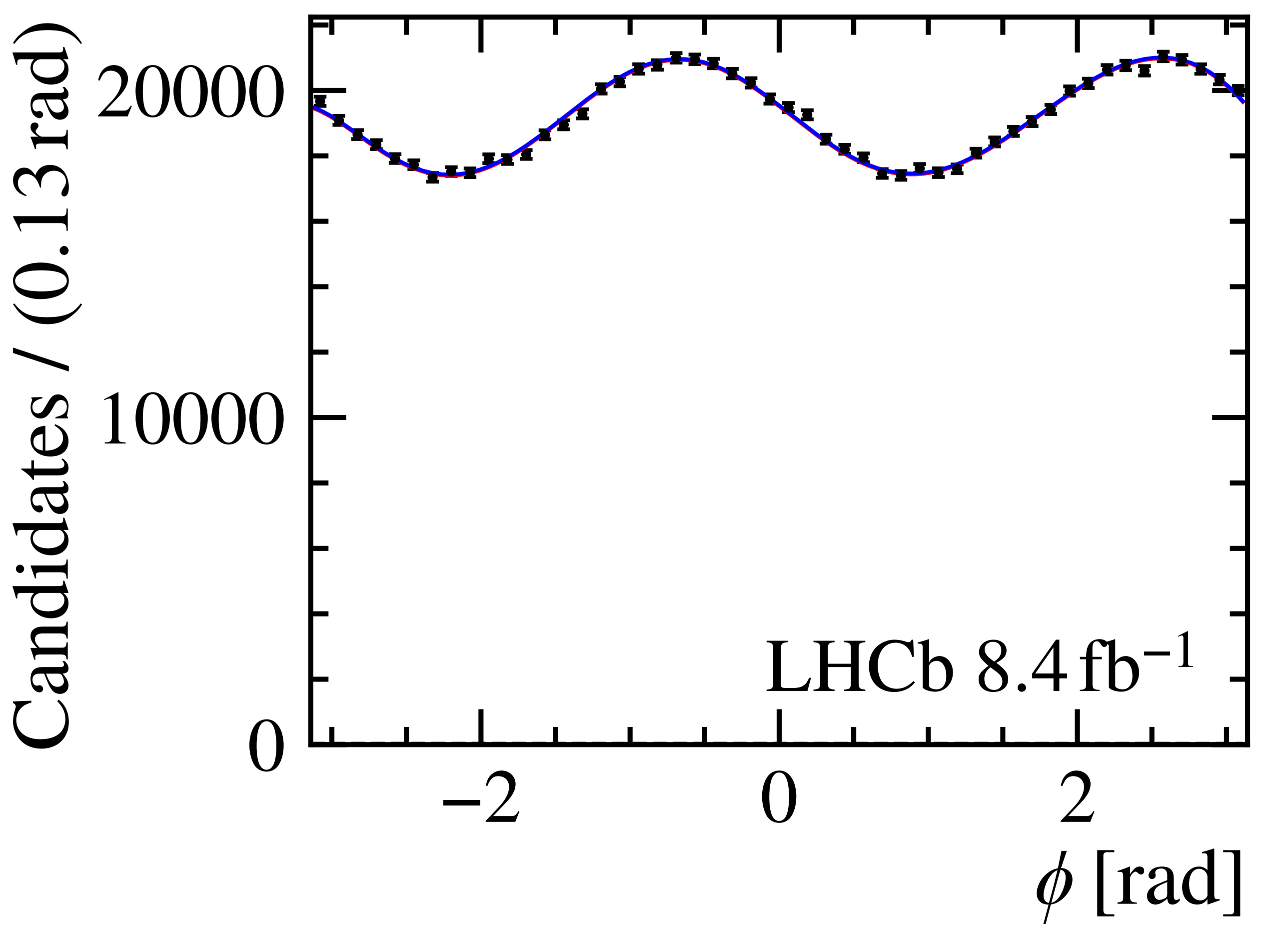
Theory JHEP 09, 133 (2022)
- Local $B^0 \to K^{*0}$ form factors (Gaussian constrained)

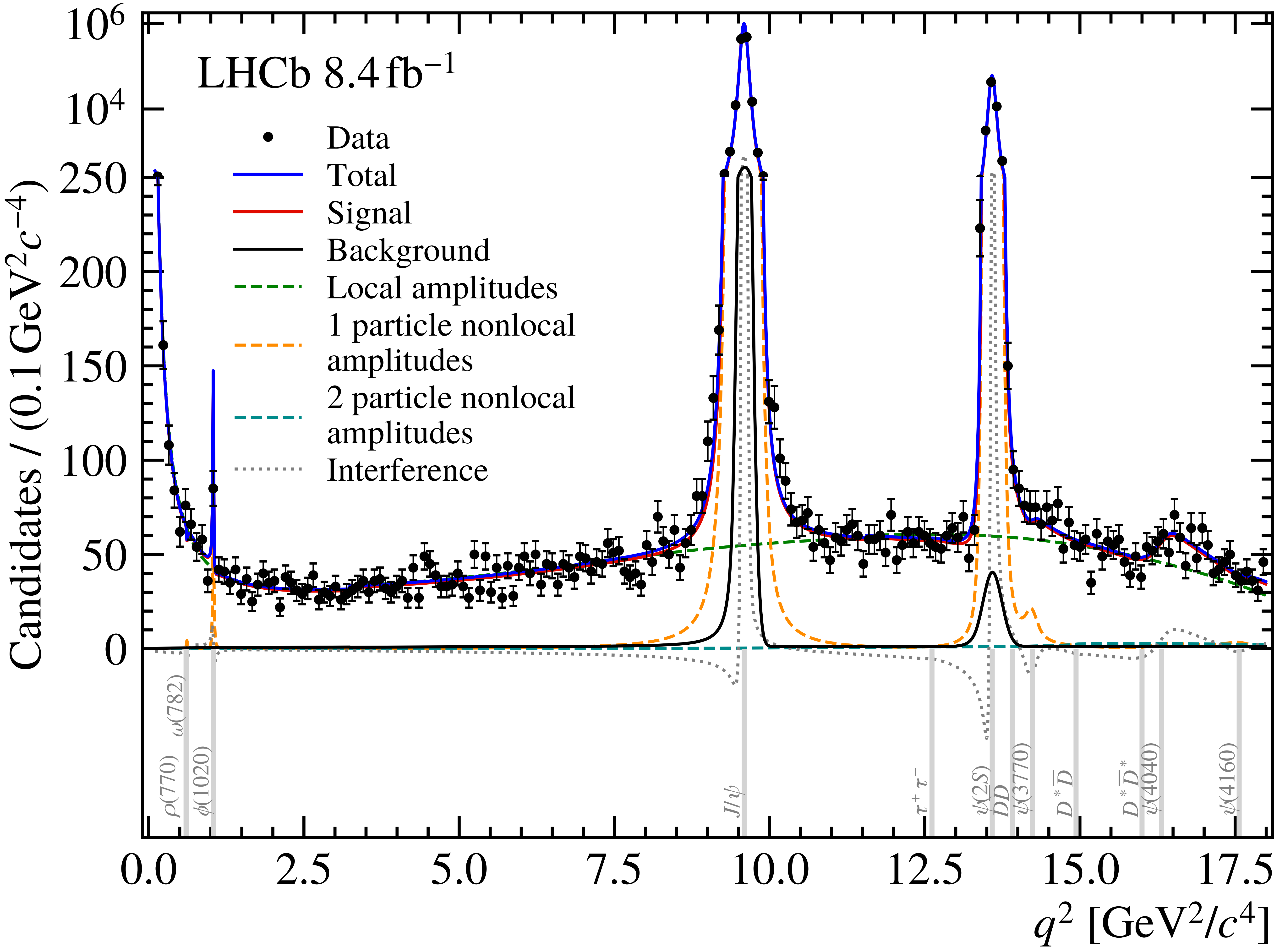
150 parameters determined in fit
- $\mathcal{R}(C_9)$, $\mathcal{R}(C_{10})$, $\mathcal{R}(C_9')$, $\mathcal{R}(C_{10}')$, $\mathcal{R}(C_9^\tau)$
- Mag. & phase of 1P contributions
- Real & Imag. of $D^{(*)}\bar{D}^{(*)}$ per helicity
- ΔC_7 per helicity
- Form Factors

Results - Fit projections









Results - Non-local contributions

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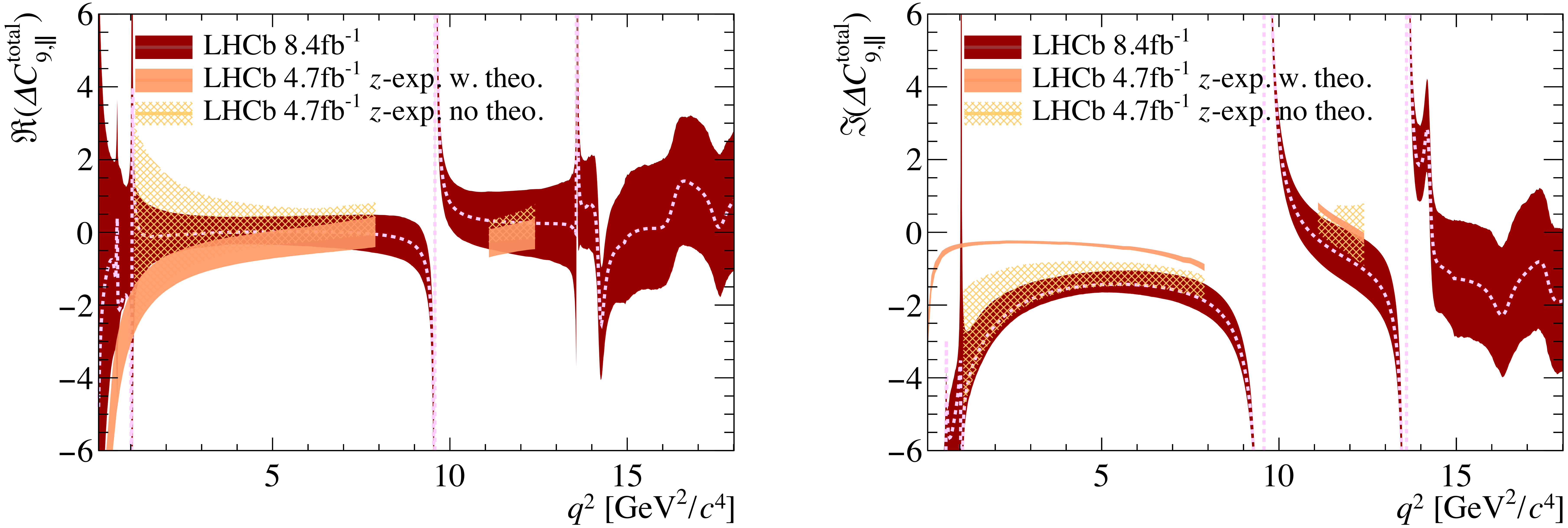
Clear impact from non-local contributions on WCs (per helicity)

Good agreement with Run 1 + 2016 analysis, which models non-local contributions with polynomial expansion

PRD. 109 (2024) 052009



Results - Observables

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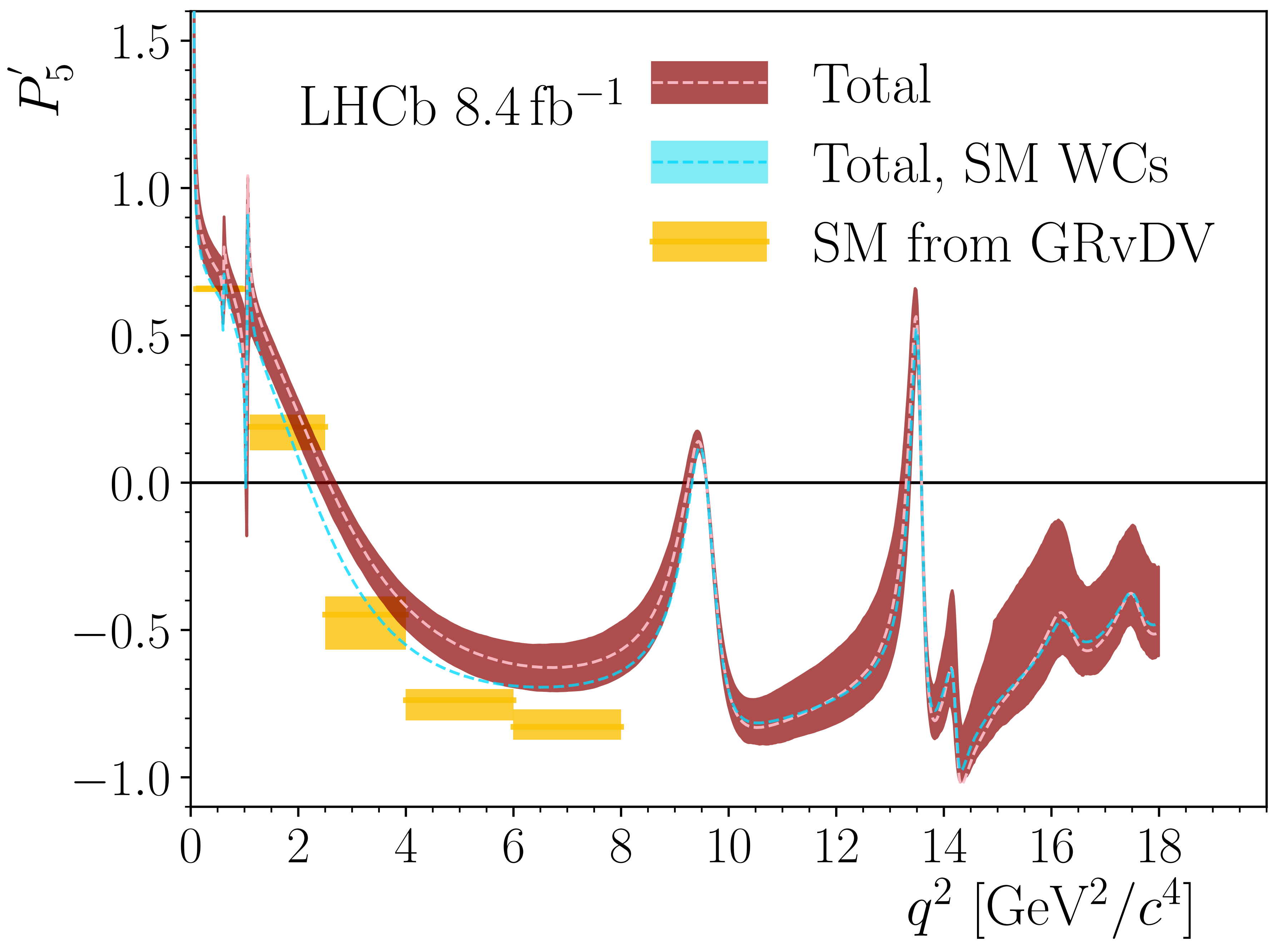
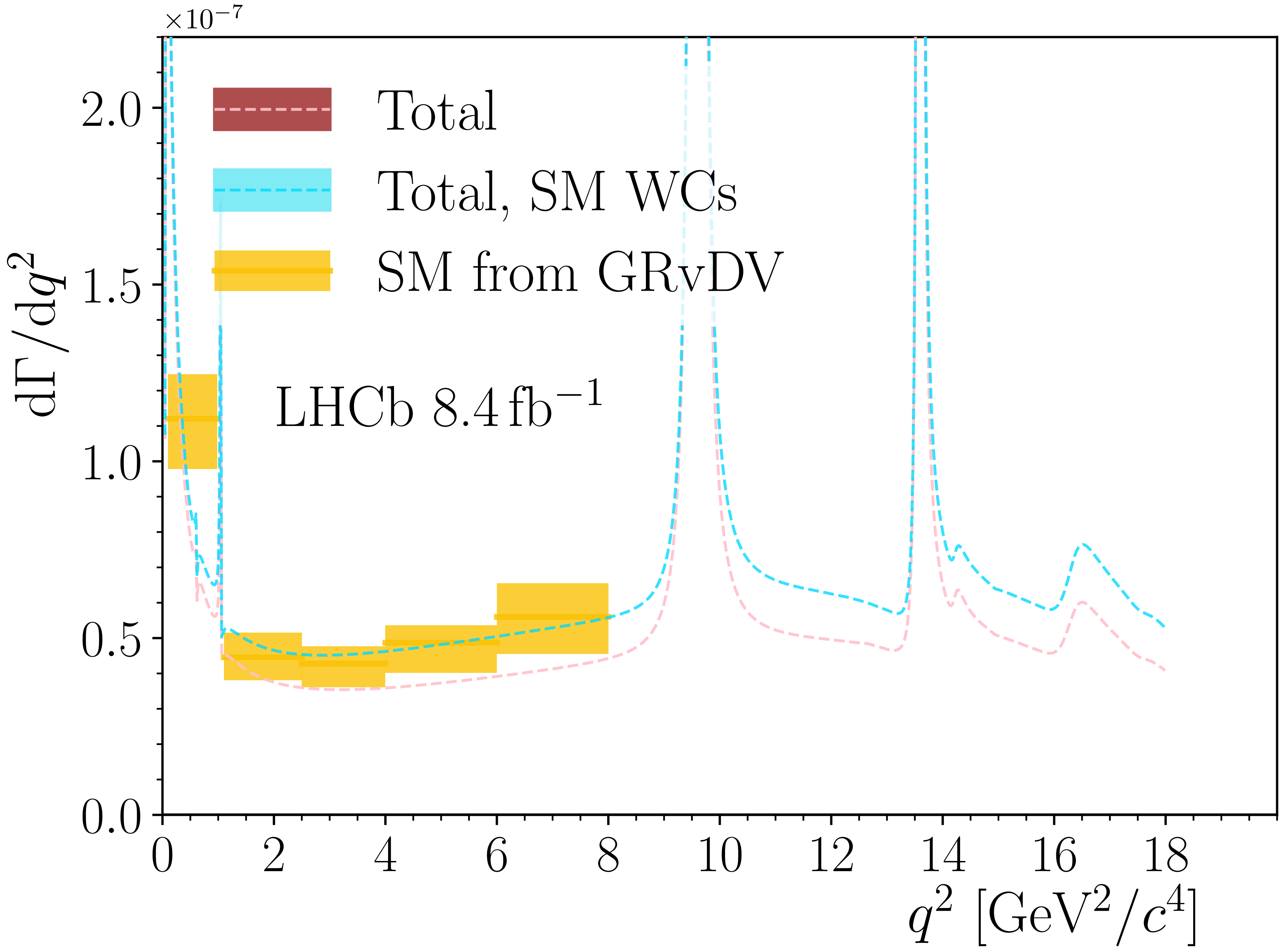
Tension in observables persist





Results - Wilson coefficients

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C_9	$3.56 \pm 0.28 \pm 0.18$
C_{10}	$-4.02 \pm 0.18 \pm 0.16$
C_9'	$0.28 \pm 0.41 \pm 0.12$
C_{10}'	$-0.09 \pm 0.21 \pm 0.06$
C_9^τ	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

First direct measurement of C_9^τ

Global significance of 1.5σ

Largest local deviation is in C_9 at 2.1σ

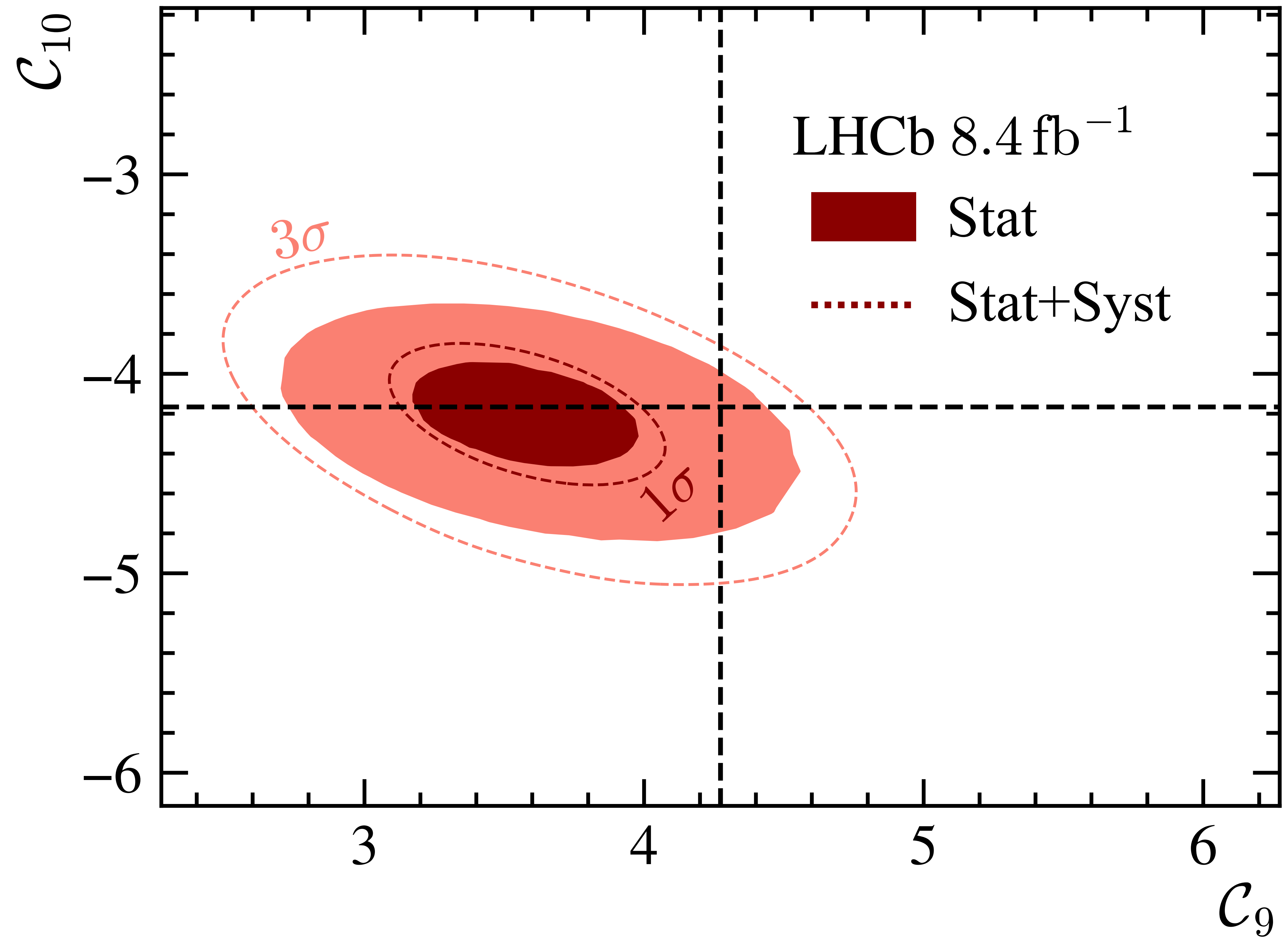
Systematic uncertainty dominated by $\mathscr{B}(B^0 \to J/\psi K^{*0})$

Phys. Rev. D 90 (2014), 112009

Non-local contributions are larger than what has been assumed so far

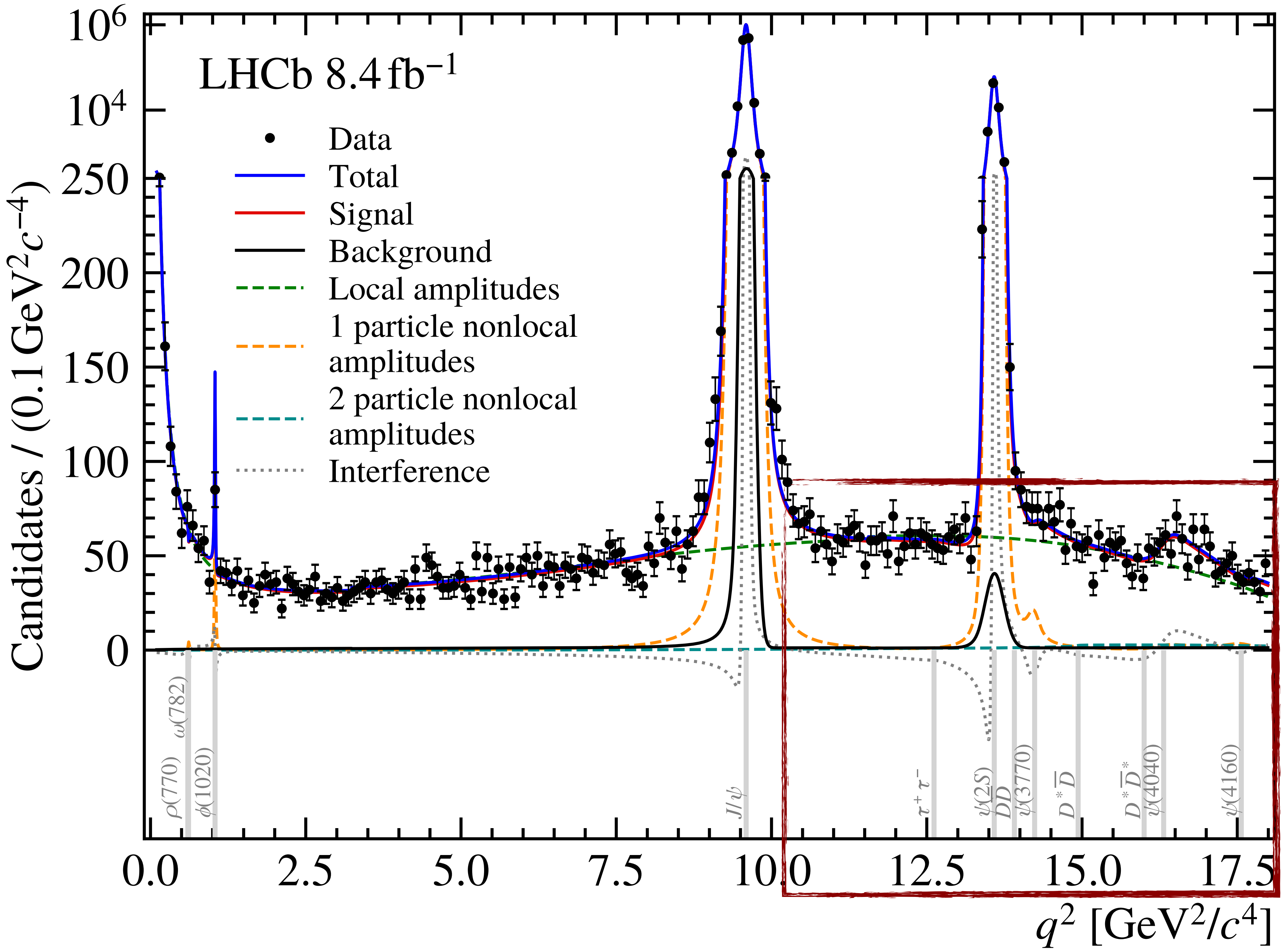
Value of C_9 still shifted down from C_9^{SM}

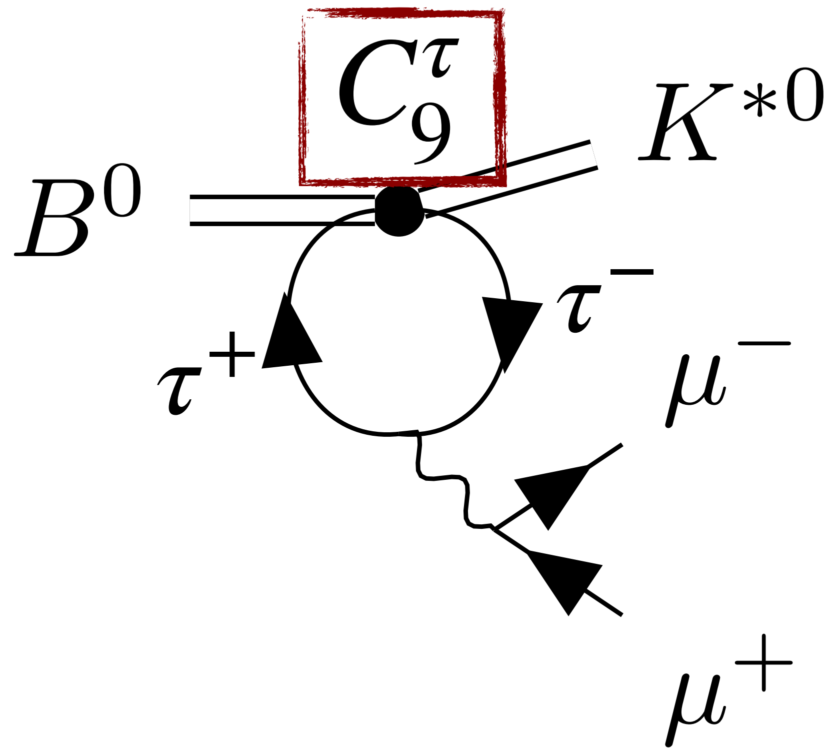
More data needed



Results - Direct measurement of C_9^τ

LHCb-PAPER-2024-011





Many NP models expect large enhancements in the third generation

$C_9^\tau \quad (-1.0 \pm 2.6 \pm 1.0) \times 10^2$

From measurement of C_9^τ, assuming value of C_{10}^τ

Converted to 90% limit on

$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) \sim [0.8 - 2.5] \times 10^{-3}$

Using Flavio

Best 90% limit from direct measurements

$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) \sim 3.1 \times 10^{-3}$

Belle, Phys. Rev. D108 (2023) L011102

Summary

- Rare decays is a promising area to search for New Physics
  - ~4σ tension in global fits to $b \to s\ell^+\ell^-$

- Binned (model independent) measurements of angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ are deviating from the SM - most clearly visible in P_5' by CMS and LHCb

- Non-local contributions are larger than what has been assumed so far
  - Value of C_9 still shifted down from C_9^{SM} - more data needed

- First direct determination of C_9^τ
  - Competitive sensitivity to $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-)$ with direct measurements!

Thank you for listening!

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SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

LHCb

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