A fresh l👀k @ the B anomalies

MAURO VALLI

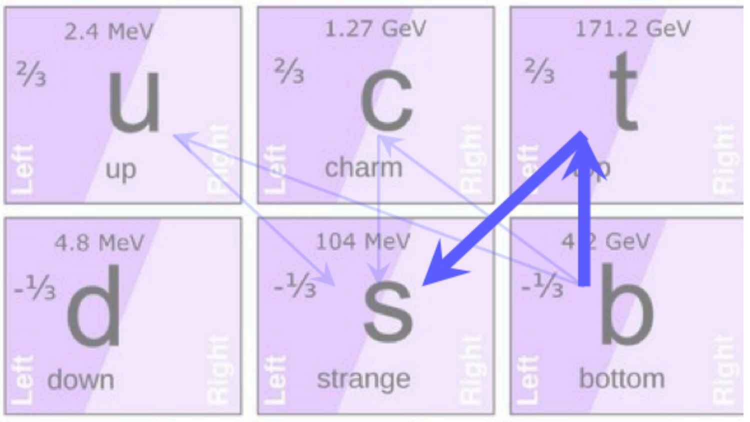
INFN Rome

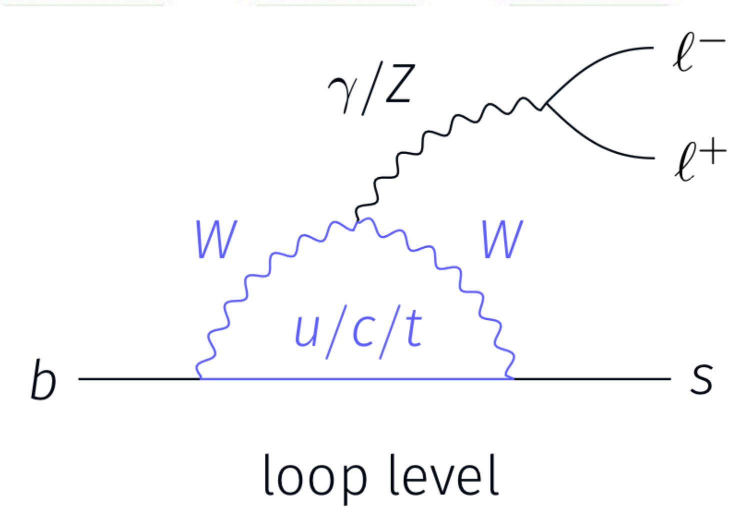
MANY THANKS TO: M.FEDELE, A.PAUL, L.SILVESTRINI & L.VITTORIO

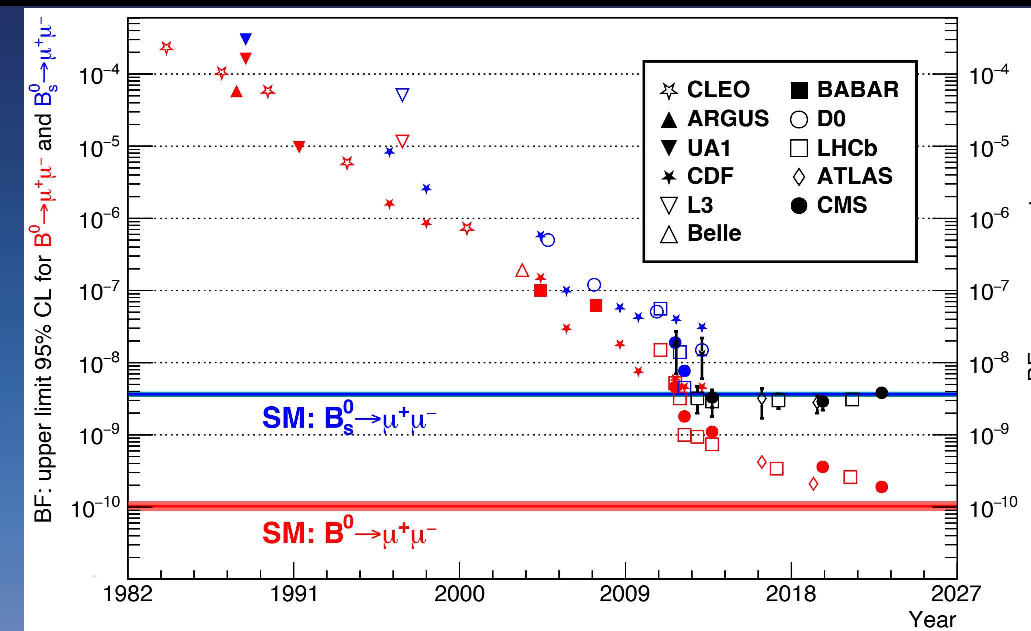
ChatGPT

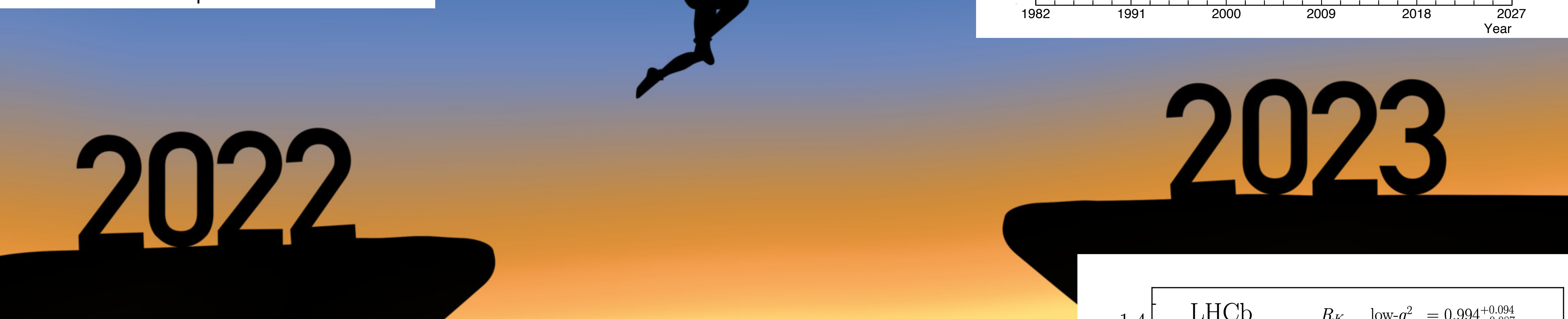
An anomaly refers to something that deviates from what is standard, normal, or expected. It can be a deviation from a pattern, behavior, or occurrence that stands out from the typical or anticipated norm. Anomalies can occur in various contexts, such as in data analysis, scientific observations, natural phenomena, or even in human behavior.

Semileptonic Rare B decays









nature physics

ARTICLES

https://doi.org/10.1038/s41567-021-01478-8

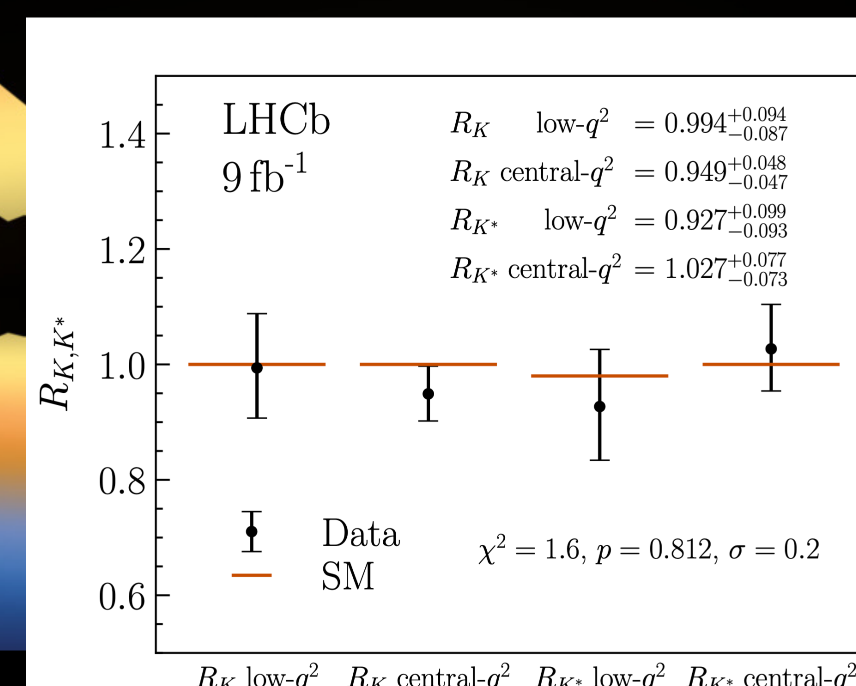
Check for updates

OPEN

Test of lepton universality in beauty-quark decays

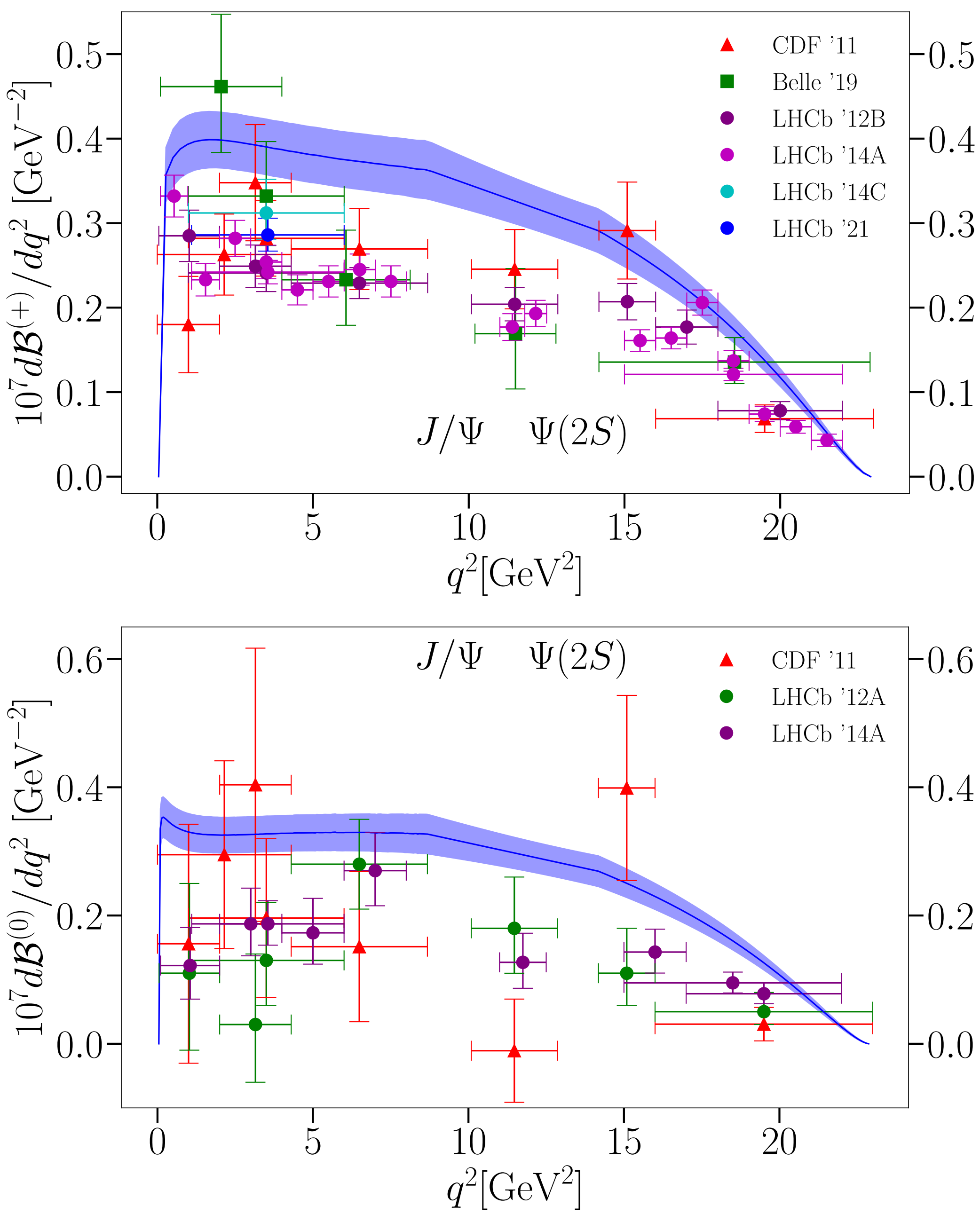
LHCb collaboration*

The standard model of particle physics currently provides our best description of fundamental particles and their interactions. The theory predicts that the different charged leptons, the electron, muon and tau, have identical electroweak interaction strengths. Previous measurements have shown that a wide range of particle decays are consistent with this principle of lepton universality. This article presents evidence for the breaking of lepton universality in beauty-quark decays, with a significance of 3.1 standard deviations, based on proton-proton collision data collected with the LHCb detector at CERN's Large Hadron Collider. The measurements are of processes in which a beauty meson transforms into a strange meson with the emission of either an electron and a positron, or a muon and an antimuon. If confirmed by future measurements, this violation of lepton universality would imply physics beyond the standard model, such as a new fundamental interaction between quarks and leptons.

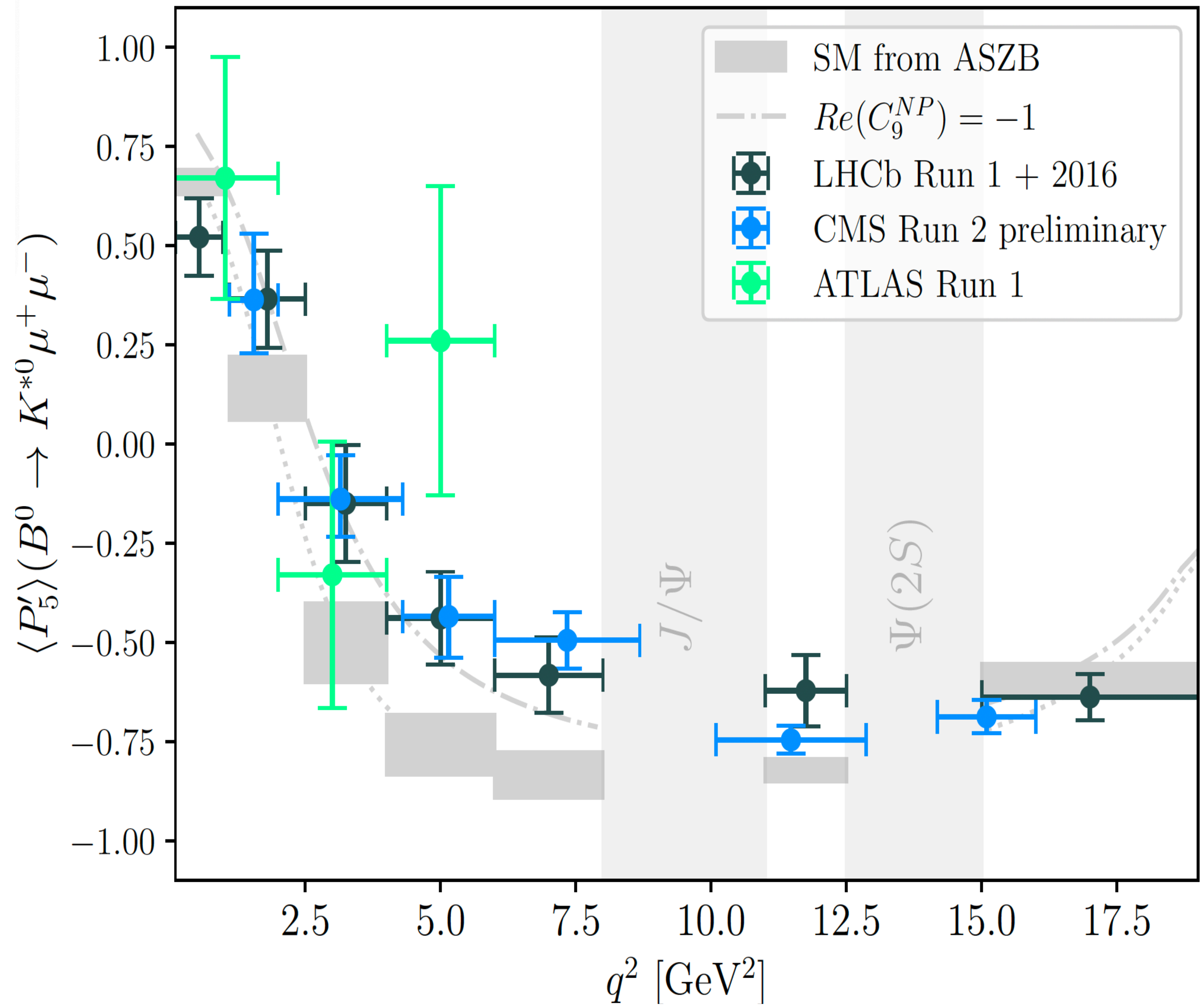


SHOULD WE STILL BE EXCITED TODAY?

Several BRs OFF (?)



Angular observables OFF (?)



see also D.Provenzano's talk

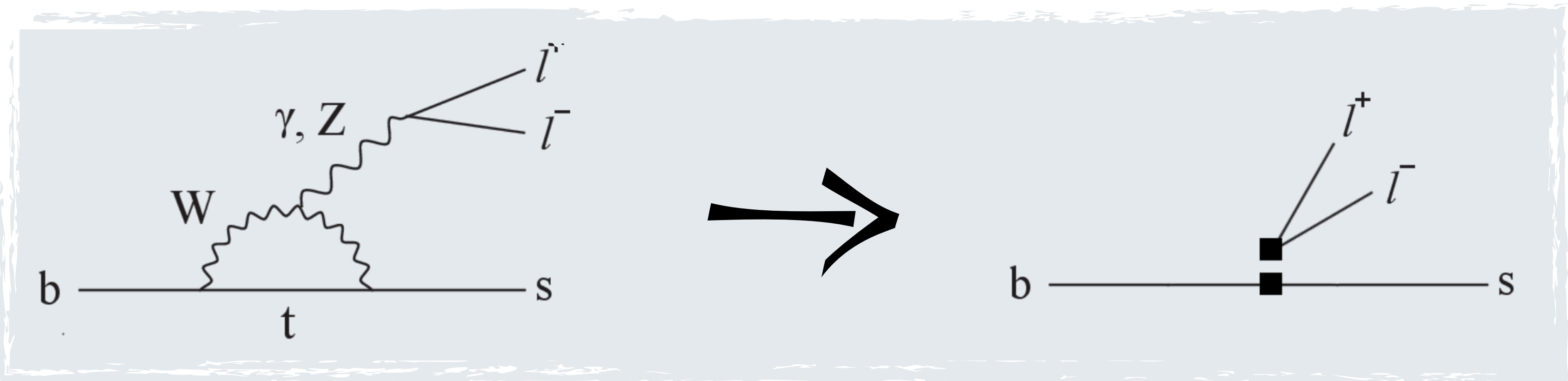
INTERLUDE: ANATOMY OF $B \to V(P)\, \ell^+\ell^-$

$$H_{eff}^{\Delta B=1} = H_{eff}^{had} + H_{eff}^{sl+\gamma}$$

$$H_{eff}^{had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 P_1^p + C_2 P_2^p + \sum_{i=3,\ldots,6} C_i P_i + C_{8g} Q_{8g} \right]$$

$$H_{eff}^{sl+\gamma} = \frac{4G_F}{\sqrt{2}} \lambda_t \left[C_7^{(\prime)} Q_{7\gamma}^{(\prime)} + C_9^{(\prime)} Q_{9V}^{(\prime)} + C_{10}^{(\prime)} Q_{10A}^{(\prime)} + C_S^{(\prime)} Q_S^{(\prime)} + C_P^{(\prime)} Q_P^{(\prime)} \right]$$

$$\begin{aligned}
P_1^p &= (\bar{s}_L \gamma_\mu T^a p_L)(\bar{p}_L \gamma^\mu T^a b_L) \\
P_2^p &= (\bar{s}_L \gamma_\mu p_L)(\bar{p}_L \gamma^\mu b_L) \\
P_3 &= (\bar{s}_L \gamma_\mu b_L) \textstyle\sum_q (\bar{q} \gamma^\mu q) \\
P_4 &= (\bar{s}_L \gamma_\mu T^a b_L) \textstyle\sum_q (\bar{q} \gamma^\mu T^a q) \\
P_5 &= (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} b_L) \textstyle\sum_q (\bar{q} \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} q) \\
P_6 &= (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} T^a b_L) \textstyle\sum_q (\bar{q} \gamma^{\mu 1} \gamma^{\mu 2} \gamma^{\mu 3} T^a q)
\end{aligned}$$



$$\begin{aligned}
Q_{7\gamma} &= \frac{e}{16\pi^2} \hat{m}_b \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b \\
Q_{8g} &= \frac{g_s}{16\pi^2} \hat{m}_b \bar{s} \sigma_{\mu\nu} P_R G^{\mu\nu} b \\
Q_{9V} &= \frac{\alpha_{em}}{4\pi} (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \ell) \\
Q_{10A} &= \frac{\alpha_{em}}{4\pi} (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \gamma^5 \ell) \\
Q_S &= \frac{\alpha_{em}}{4\pi} \frac{\hat{m}_b}{m_W} (\bar{s} P_R b)(\bar{\ell} \ell) \\
Q_P &= \frac{\alpha_{em}}{4\pi} \frac{\hat{m}_b}{m_W} (\bar{s} P_R b)(\bar{\ell} \gamma^5 \ell)
\end{aligned}$$

Process energy scale is $\mathcal{O}(m_b) \ll \mathcal{O}(v_{\rm EW})$ –> **EFT à la Fermi**

SM matching & QED+QCD RG effects @ NNLO [arXiv:**1102.5650**]

INTERLUDE: ANATOMY OF $B \to V(P)\,\ell^+\ell^-$

$$H_{eff}^{\Delta B=1} = H_{eff}^{had} + H_{eff}^{sl+\gamma}$$

$$H_{eff}^{had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 P_1^p + C_2 P_2^p + \sum_{i=3,\ldots,6} C_i P_i + C_{8g} Q_{8g} \right]$$

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Q_P &= \frac{\alpha_{em}}{4\pi} \frac{\hat{m}_b}{m_W} (\bar{s} P_R b)(\bar{\ell} \gamma^5 \ell)
\end{aligned}$$

Low-energy physics from two sets of contributions:

$$\mathcal{A} \sim \langle \ell^+ \ell^- | J_{\text{lep}} | 0 \rangle \langle V(P) | J_{had} | B \rangle$$

#1 Matrix elements of semi-leptonic & EM dipole operators naively factorize —> **form factors**

INTERLUDE: ANATOMY OF $B \to V(P)\, \ell^+\ell^-$

$$H_{eff}^{\Delta B=1} = H_{eff}^{had} + H_{eff}^{sl+\gamma}$$

$$H_{eff}^{had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 P_1^p + C_2 P_2^p + \sum_{i=3,\dots,6} C_i P_i + C_{8g} Q_{8g} \right]$$

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Q_P &= \frac{\alpha_{em}}{4\pi} \frac{\hat{m}_b}{m_W} (\bar{s} P_R b)(\bar{\ell} \gamma^5 \ell)
\end{aligned}$$

Low-energy physics from two sets of contributions:

$$\epsilon_{\lambda,\mu} \int d^4x\, e^{iqx} \langle V(P) | T\{ J_{had}^{\mu,e.m.}(x) \mathcal{H}_{had}^{eff}(0) \} | B \rangle$$

#2 Matrix elements of four-quark and QCD dipole operators —> *non-local* **hadronic** correlators h_λ

INTERLUDE: ANATOMY OF $B \to V(P)\, \ell^+ \ell^-$

Building blocks are helicity amplitudes, which generally read as:

$$H_\lambda^V(q^2) \propto (C_9 - C_9')\tilde{V}_\lambda(q^2) + \frac{2m_b m_B}{q^2}(C_7 - C_7')\tilde{T}_\lambda(q^2) - 16\pi^2 \frac{m_B^2}{q^2}\tilde{h}_\lambda(q^2)$$

$$H_\lambda^A(q^2) \propto (C_{10} - C_{10}')\tilde{V}_\lambda(q^2)$$

$$H^S(q^2) \propto \frac{m_b}{m_W}(C_S - C_S')\tilde{S}(q^2)$$

$$H^P(q^2) \propto \frac{m_b}{m_W}(C_P - C_P')\tilde{S}(q^2) + \frac{2m_\ell m_B}{q^2}(C_{10} - C_{10}')\left(1 + \frac{m_s}{m_b}\right)\tilde{S}(q^2)$$

polarizations: $\lambda = 0, \pm$

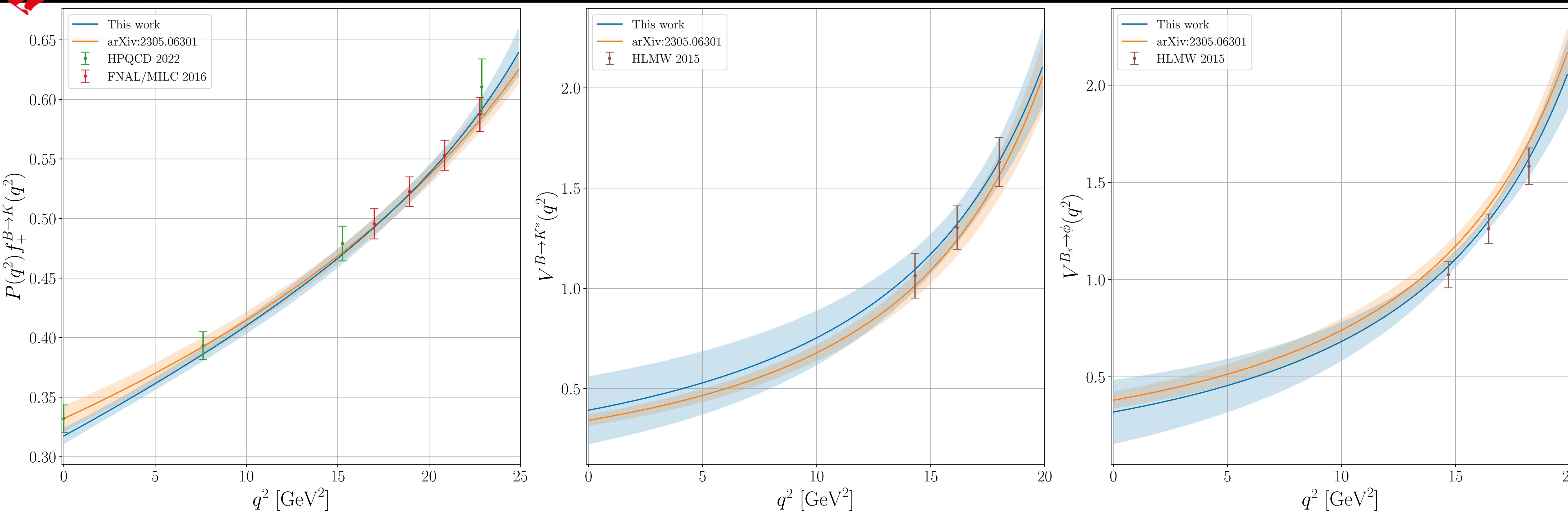
Short-distance order-of-magnitude: $C_{SM,7} \sim -1/3$, $C_{SM,9} \sim 4$, $C_{SM,10} \sim -4$

The main sources of uncertainties stem from form factors & long-distance effects encoded in such hadronic correlators.

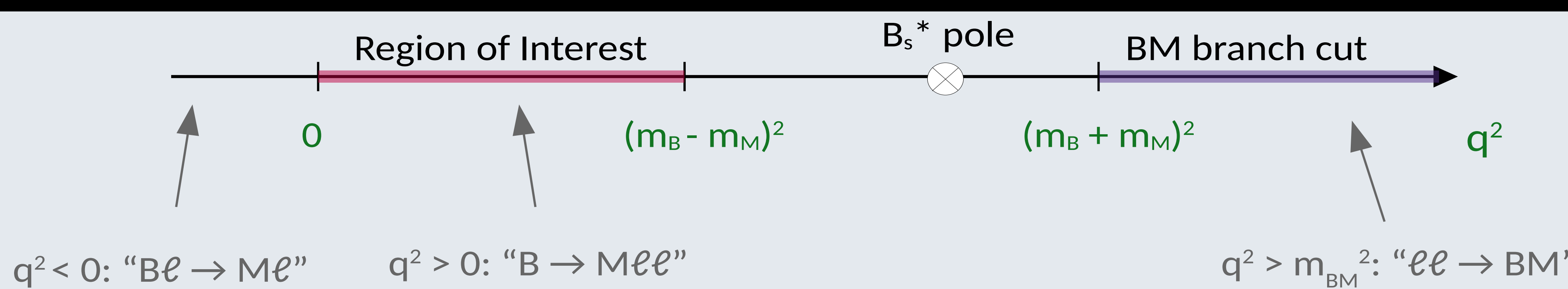
NEW

Form Factors for $B \to V(P)\, \ell^+\ell^-$

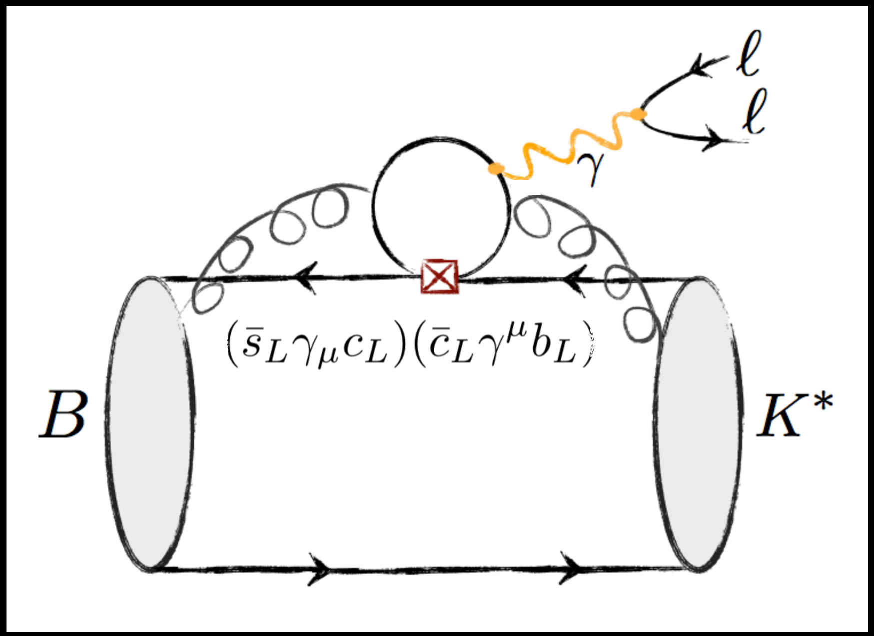
In preparation!



- **QCD Light-Cone Sum Rules (LCSR) —>** feasible @ low q^2, not first-principle
- **Lattice QCD —>** feasible @ high q^2, difficulties with unstable mesons (e.g., K*)

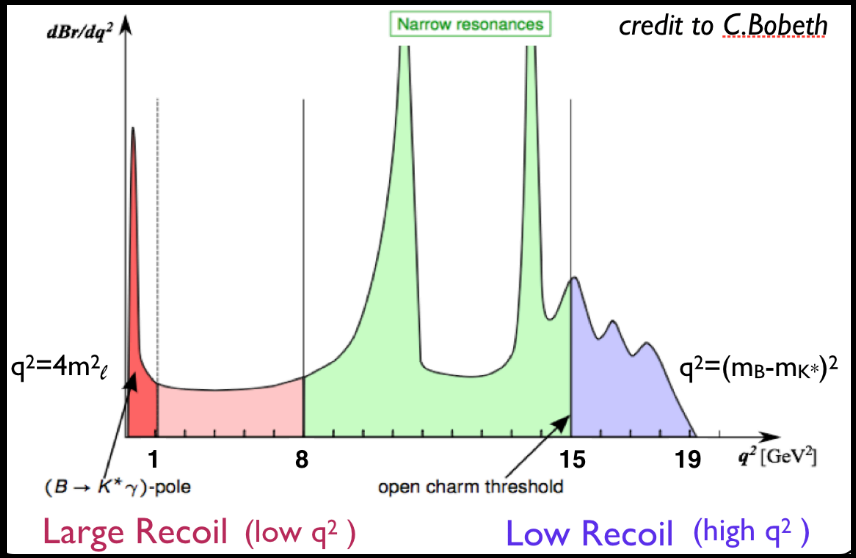


Known Unknowns in $B \to V(P)\, \ell^+\ell^-$



$\approx$

ESTIMATED IN *JHEP* 09 (2010) 089 ACCORDING TO:

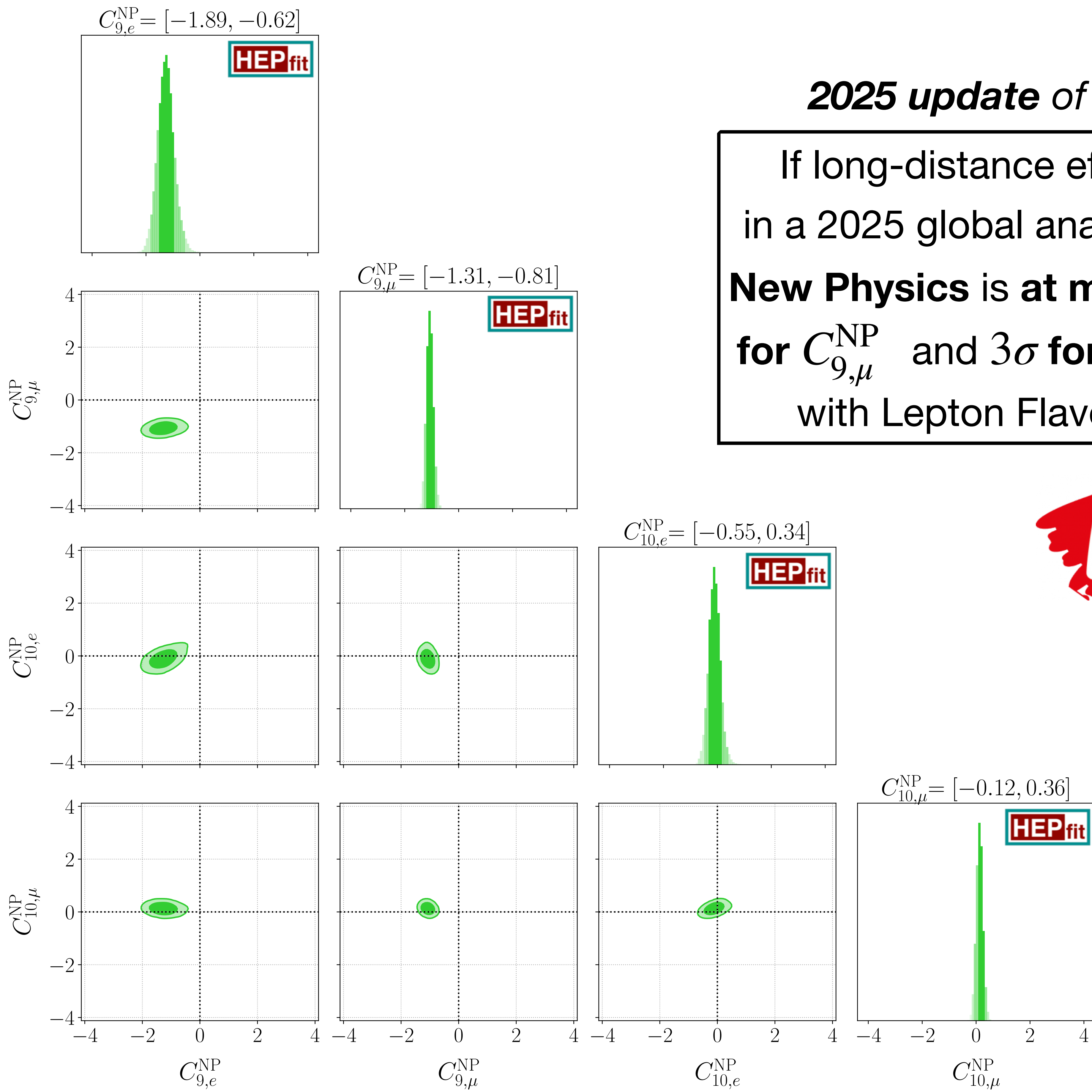


i) Light-cone sum rules (LCSR)

ii) Single soft gluon approximation

iii) Extrapolation to $c\bar{c}$ resonances

B ANOMALIES : “EVIDENCE” FOR NEW PHYSICS

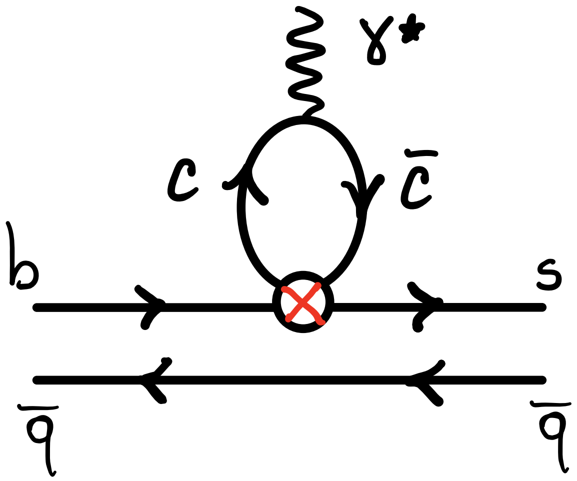


2025 update** of **PRD 107 (2023) 5

If long-distance effects are small,
in a 2025 global analysis of $b \to s\ell\ell$
New Physics is **at more than** 5σ **level**
for $C_{9,\mu}^{\rm NP}$ and 3σ **for** $C_{9,e}^{\rm NP}$, compatibly
with Lepton Flavor Universality.

In preparation!

In 2022, this class of charming penguins has been re-estimated
—> tiny contribution!
[*JHEP 09 (2022) 133*]



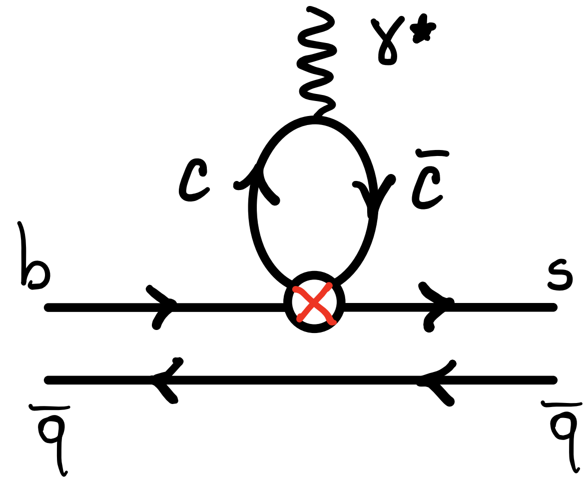
1) LCSR at $q^2 \leq 0$
2) z - expansion w/ $B \to M\, J/\psi$ data
3) dispersive bounds based on cuts in q^2

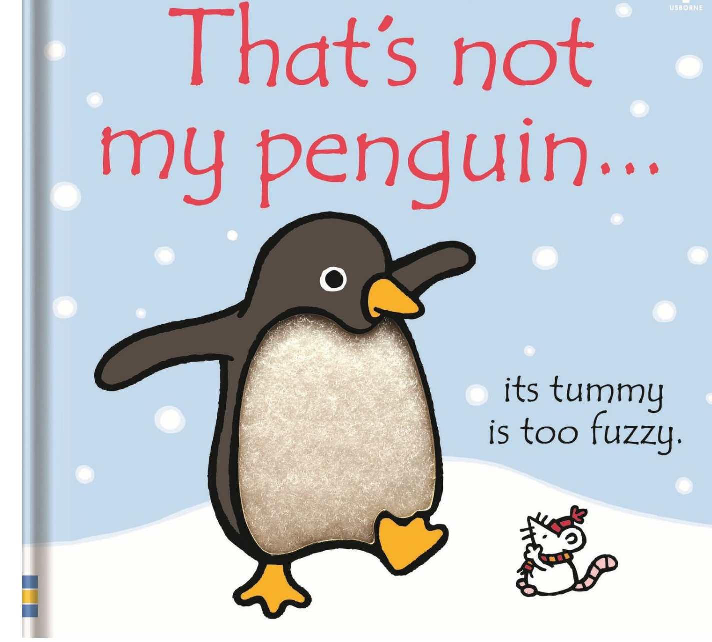
LHCb extracted non-local effects from data [*PRL132 (2024) 13*] likewise.

- Non-local function follows [JHEP 09 (2022) 133]

$$\mathcal{H}_\lambda(z) = \frac{1 - z z_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z), \qquad \hat{\mathcal{H}}_\lambda(z) = \phi_\lambda^{-1}(z) \sum_k a_{\lambda,k} z^k$$

In 2022, this class of charming penguins has been re-estimated —> tiny contribution**!** [*JHEP 09 (2022) 133*]

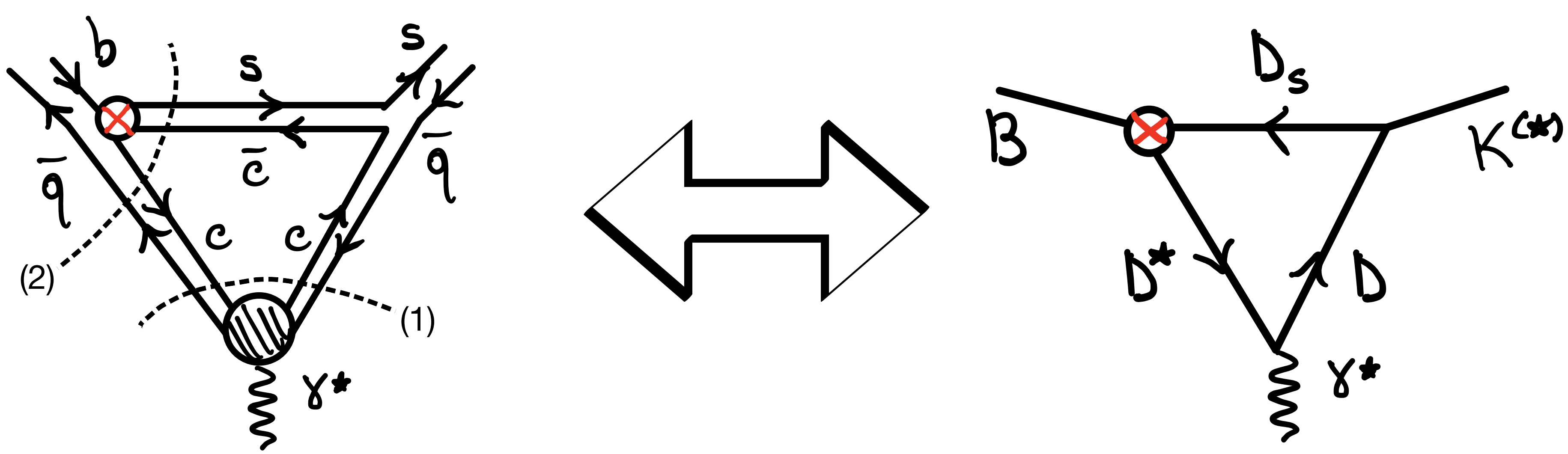




LHCb extracted non-local effects from data [*PRL132 (2024) 13*] likewise.

HOWEVER, WHAT ABOUT THOSE CHARMING PENGUINS?

[see discussion in *EPJC* 83 (2023) 1]



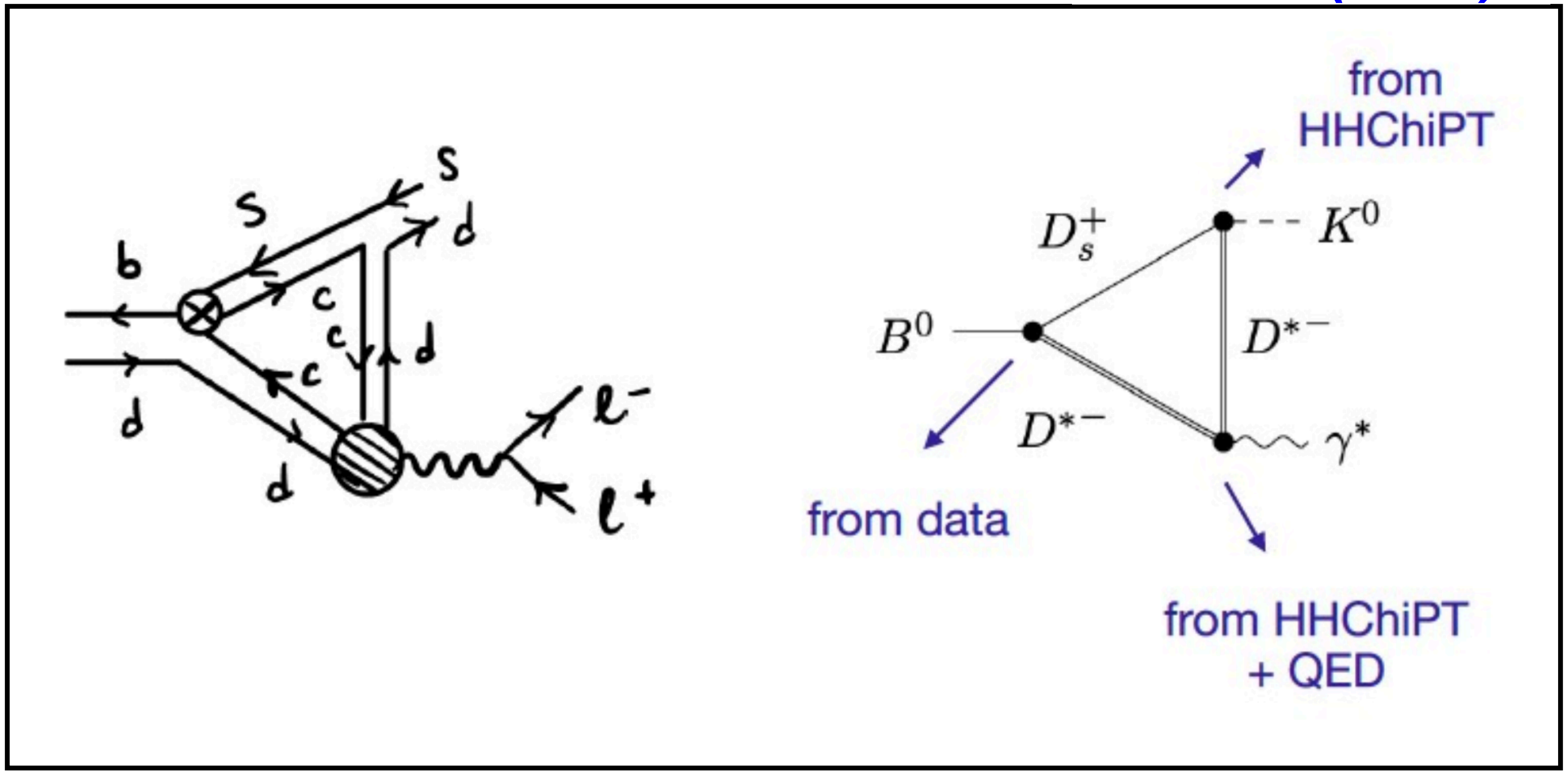
Rescattering from intermediate on-shell hadronic states.

These effects are NOT captured by analytic cuts solely in q^2.

[*i.e., anomalous thresholds, see* ***JHEP 07 (2024) 276*** **]**

TRIANGLES & ANOMALOUS THRESHOLDS

PRD 111 (2025) 9



Pheno estimates extrapolating Heavy Hadron ChiPT to region of low q^2 point to O(1%) effect at amplitude level, but could be larger, **2507.17824**!

Indeed, anomalous thresholds can yield O(10%) (and maybe more?)

— *distortion of the analytic structure implies "new" dispersion relations*

— $\bar{D}D,\ \bar{D}D^*,\ \bar{D}^*D^*,\ \bar{D}_sD_s,$ etc. *challenging for pheno analyses*

see ***JHEP 07 (2024) 276***

B ANOMALIES : A DATA DRIVEN APPROACH

Just Taylor-expand hadronic correlators $h_\lambda(q^2)$ and fit coeffs to data!

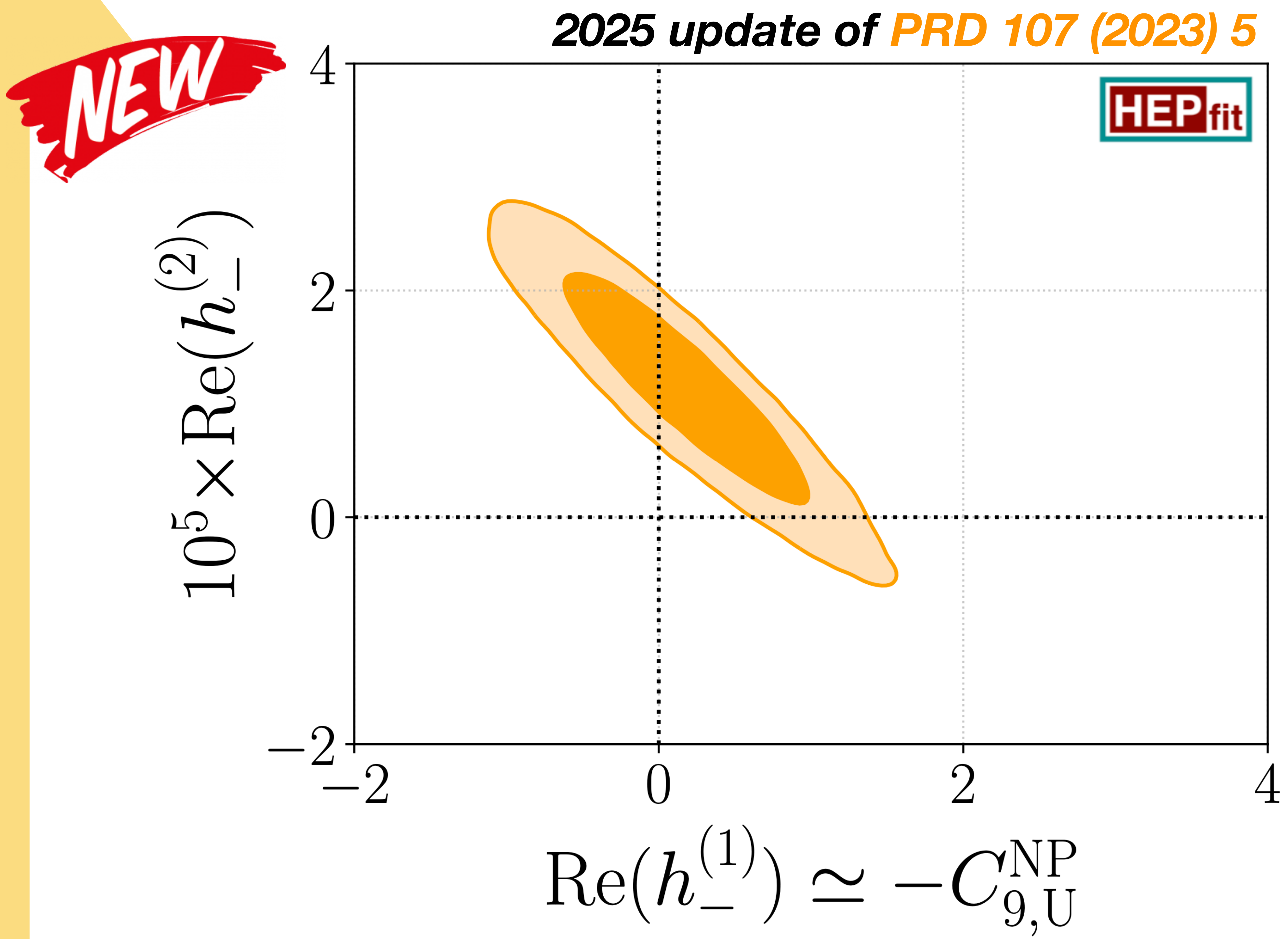
$$H_V^- \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right) \widetilde{V}_{L-} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm SM} + h_-^{(0)}\right)\widetilde{T}_{L-} - 16\pi^2 h_-^{(2)} q^4\right]\right\}$$

$$H_V^+ \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right) \widetilde{V}_{L+} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm SM} + h_-^{(0)}\right)\widetilde{T}_{L+} - 16\pi^2 \left(h_+^{(0)} + h_+^{(1)} q^2 + h_+^{(2)} q^4\right)\right]\right\}$$

$$H_V^0 \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right) \widetilde{V}_{L0} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm SM} + h_-^{(0)}\right)\widetilde{T}_{L0} - 16\pi^2 \sqrt{q^2}\left(h_0^{(0)} + h_0^{(1)} q^2\right)\right]\right\}$$

$h_-^{(1)}$ <—> Lepton Flavor Universal $C_{9,U}^{\rm NP}$

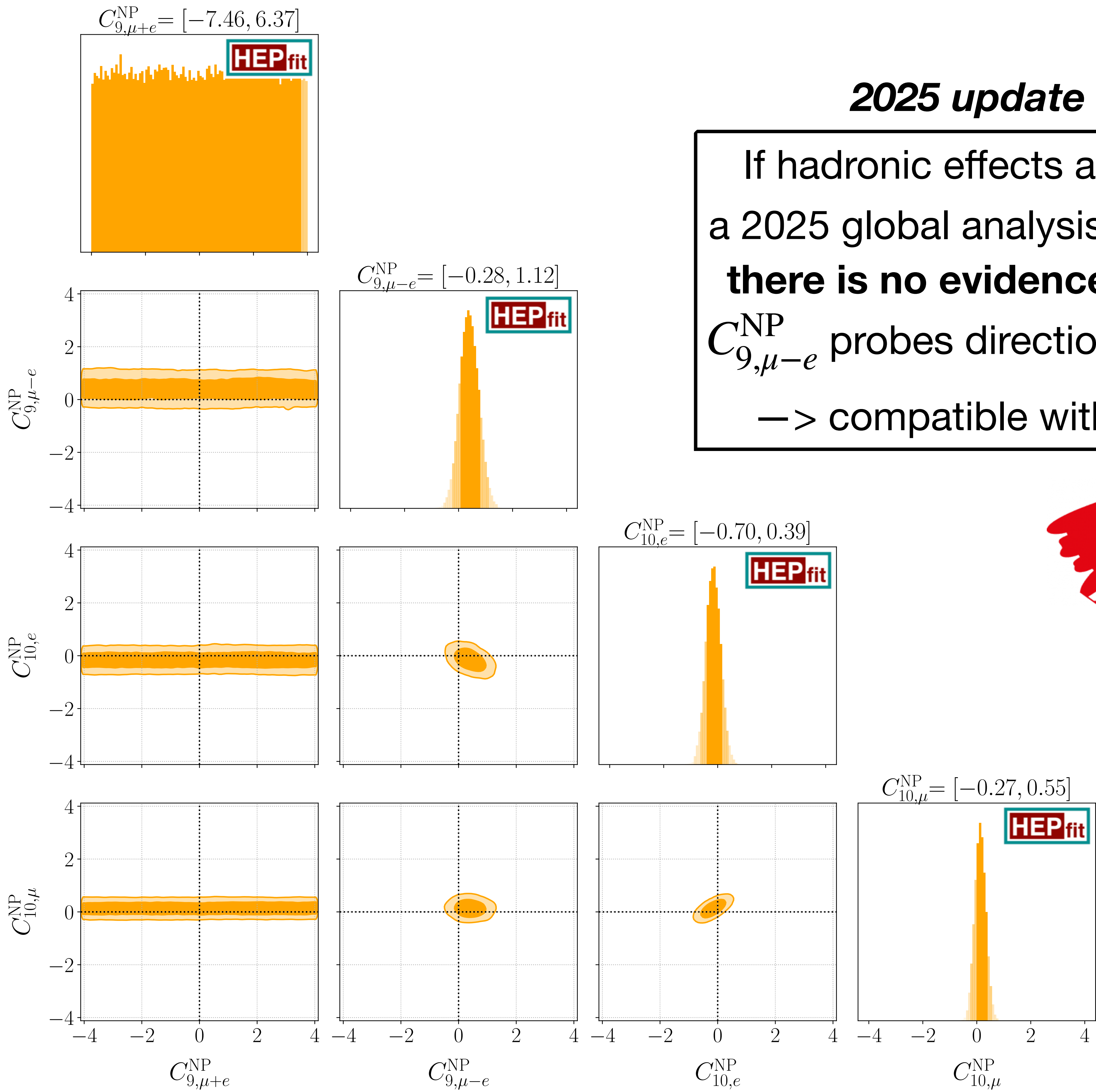
B ANOMALIES : WHERE WE ARE !



QCD ONLY

QCD ~ LEPTON UNIVERSAL NP

B ANOMALIES : "EVIDENCE" FOR NEW PHYSICS

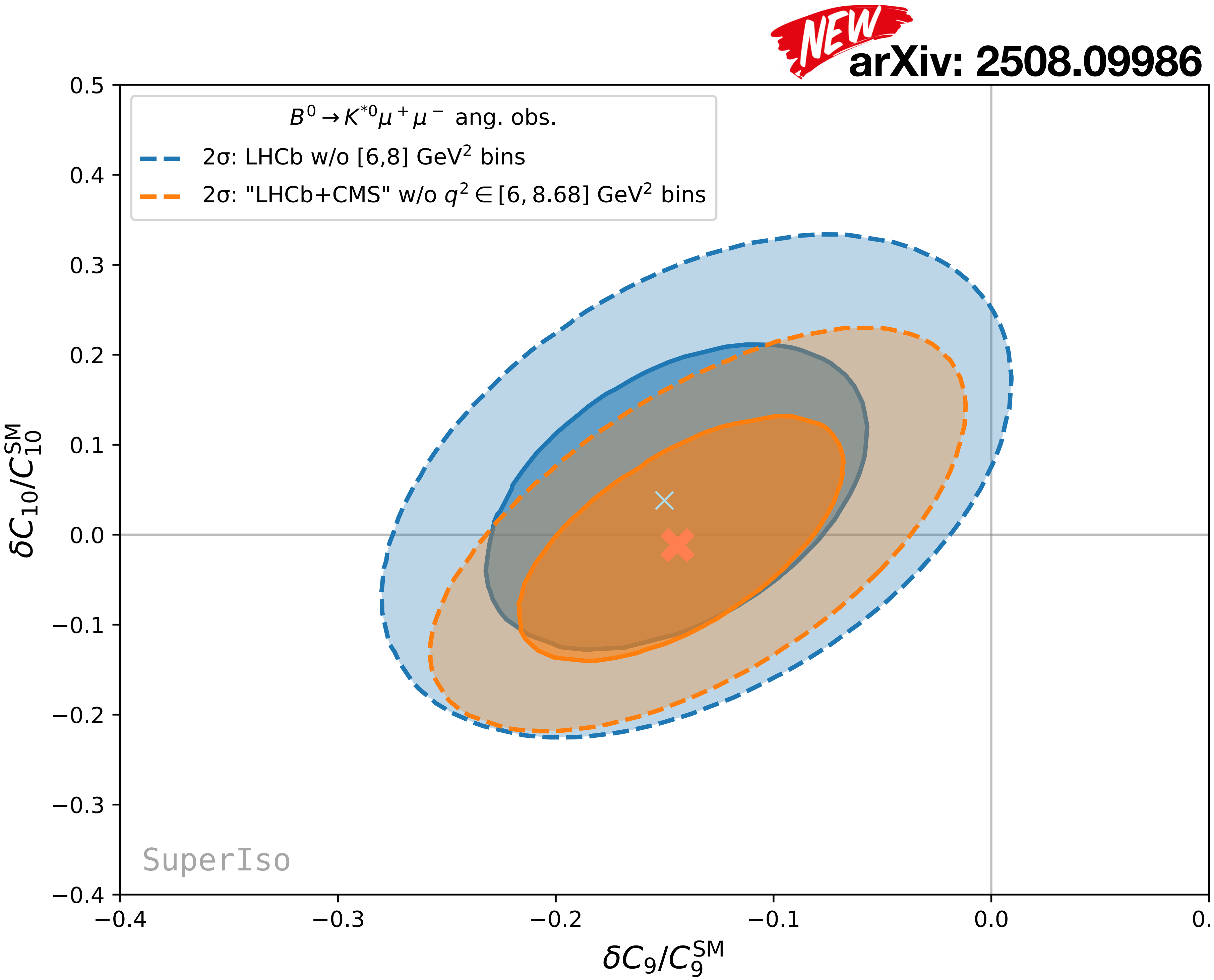


***2025 update** of PRD 107 (2023) 5*

If hadronic effects are actually sizable, a 2025 global analysis of $b \to s\ell\ell$ shows **there is no evidence for New Physics.**
$C^{NP}_{9,\mu-e}$ probes direction orthogonal to $C^{NP}_{9,U}$
—> compatible with 0 well within 2σ.

In preparation!

B ANOMALIES : A ZOOM ON CMS



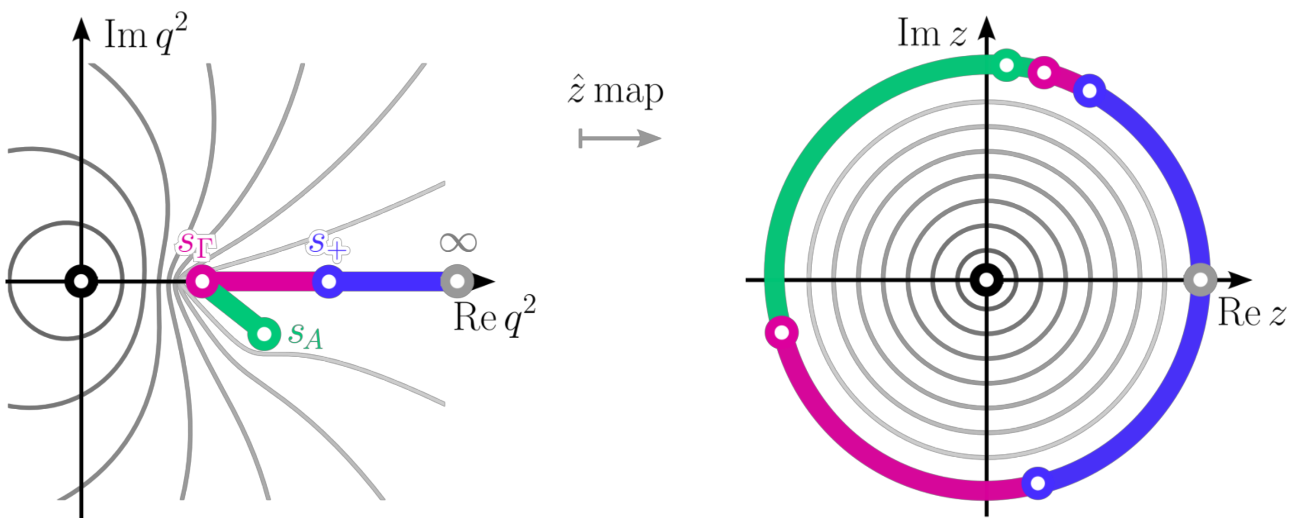
~10% uncertainty wrt leading amplitude due to unknown power corrections to QCD factorization (valid at low q^2) —> New Physics at ~3σ w/ CMS data.

B ANOMALIES : WHERE TO GO

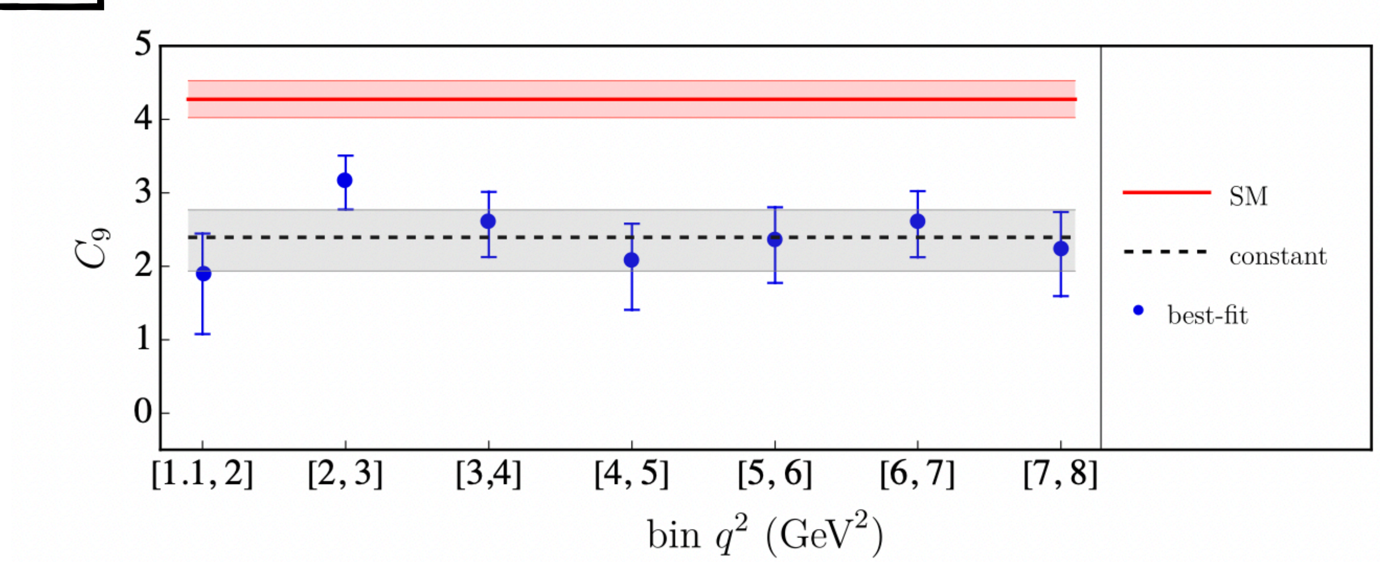
#1 TAME HADRONIC EFFECTS FROM FIRST PRINCIPLES

Charming penguins may be computed on the lattice at large q² via Spectral Function Reconstruction — ***arXiv: 2508.03655*** — see D.Becirevic's talk

Extrapolation to low q² region requires generalization of current dispersive bounds.
— see ***PRD* 111 (2025) 3** —

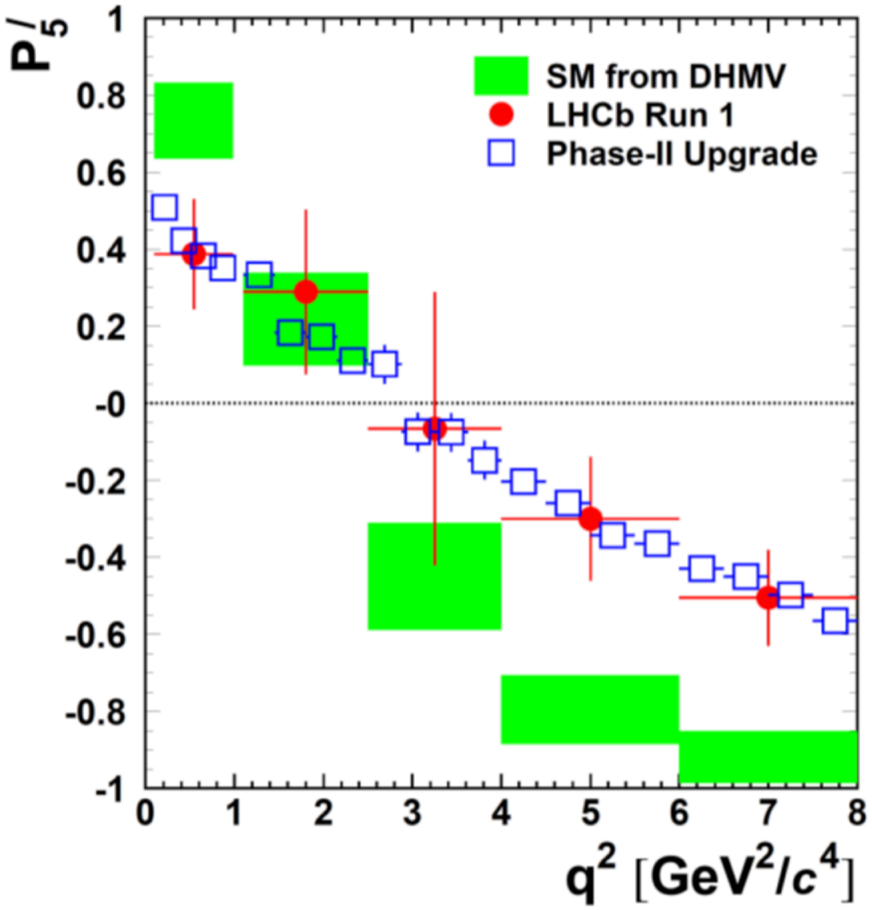


#2 MORE DATA , NEW OBSERVABLES (see E.Lunghi's talk)



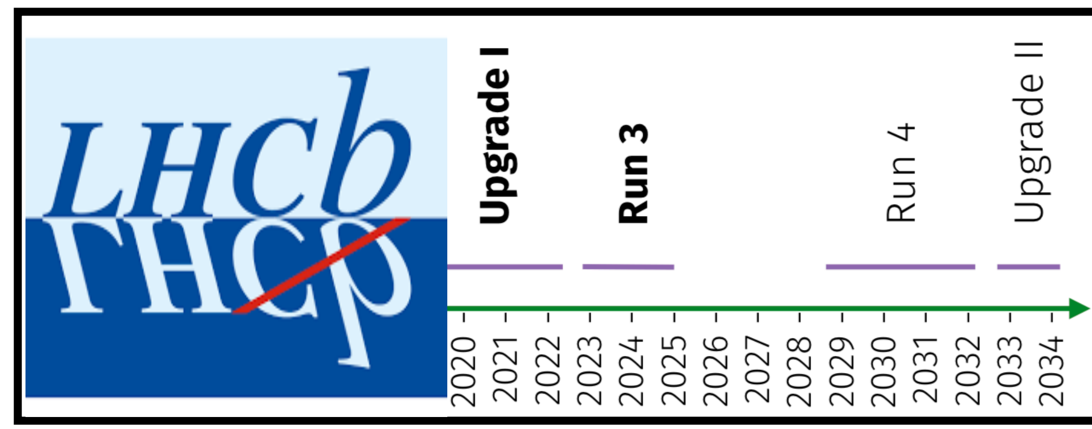
Test ΔC_9 dependence on q² binning, polarization of final state, for different channels.
— see ***EPJC 84 (2024) 5*** —

B ANOMALIES : A ☀ FUTURE



LHCb upgrade(s) will allow us to probe precisely the q^2 dependence in the angular analysis …

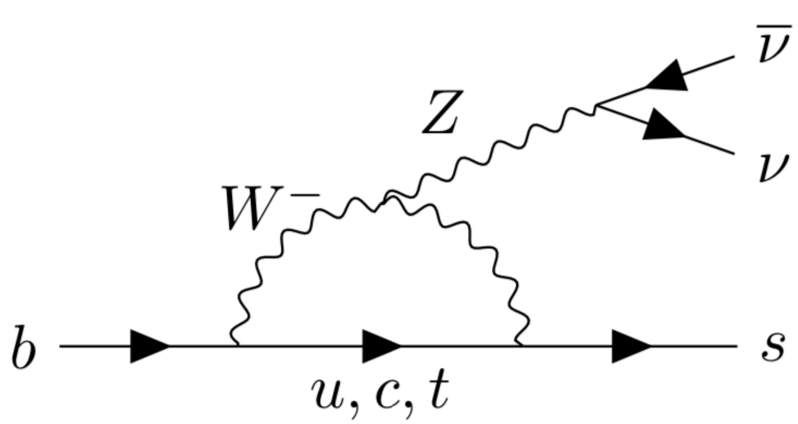
—> pin down effects from hadronic physics

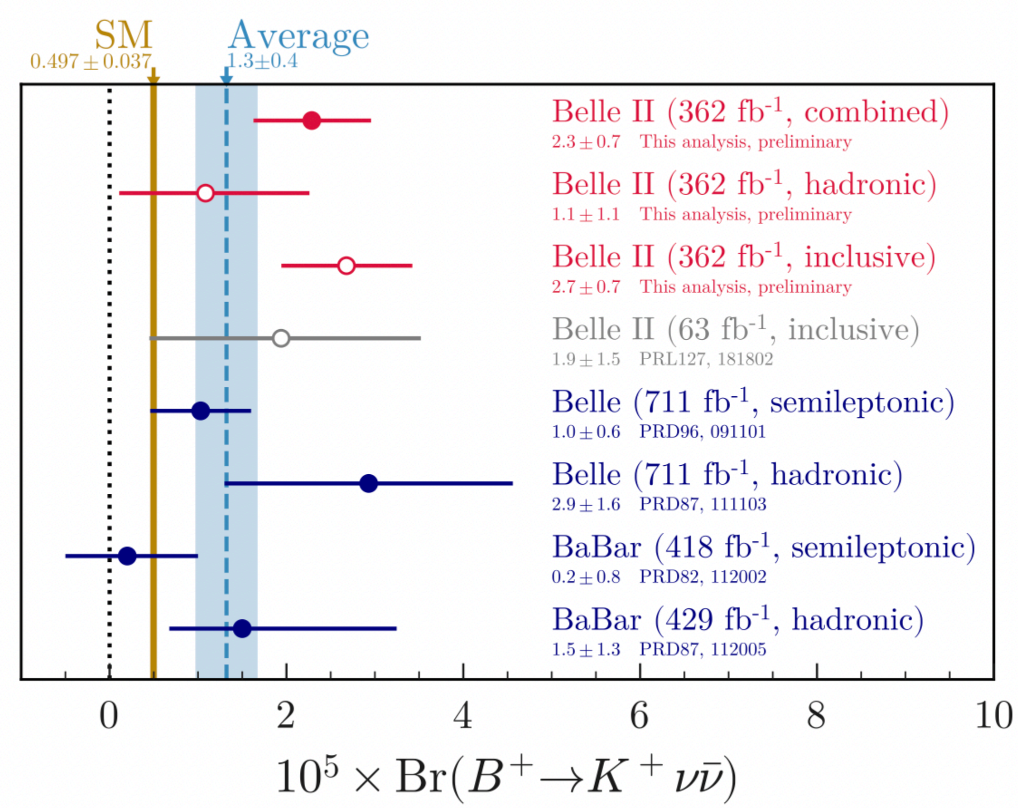


CMS & ATLAS are also going to play a role here!

Belle II is delivering interesting results as well!

MAYBE A NEW ANOMALY (see R.Volpe's talk)

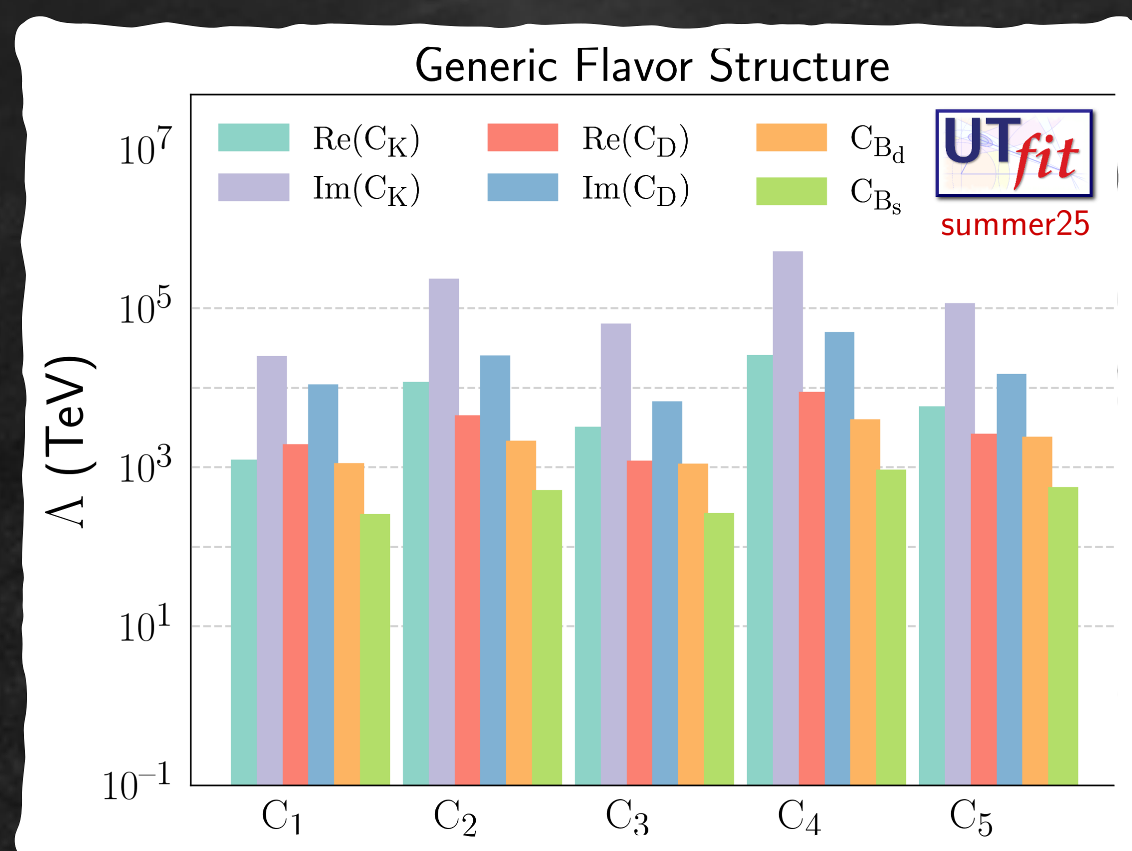




Take Home

I

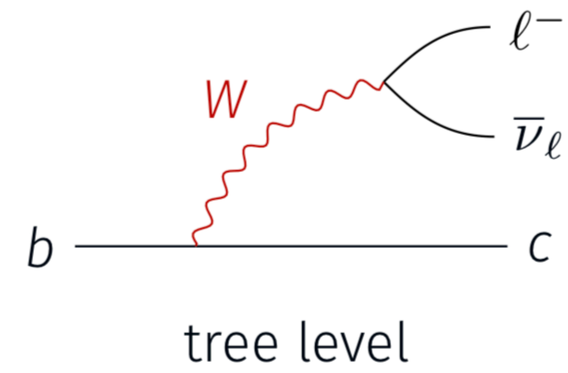
II

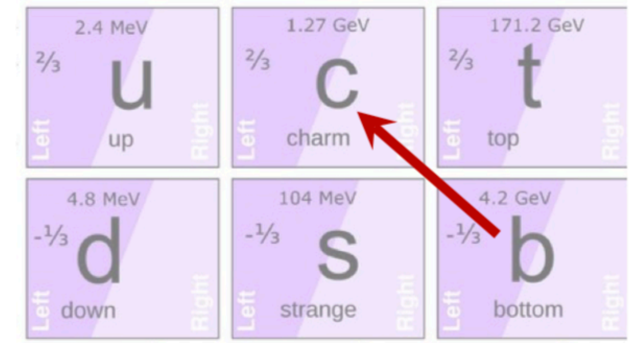


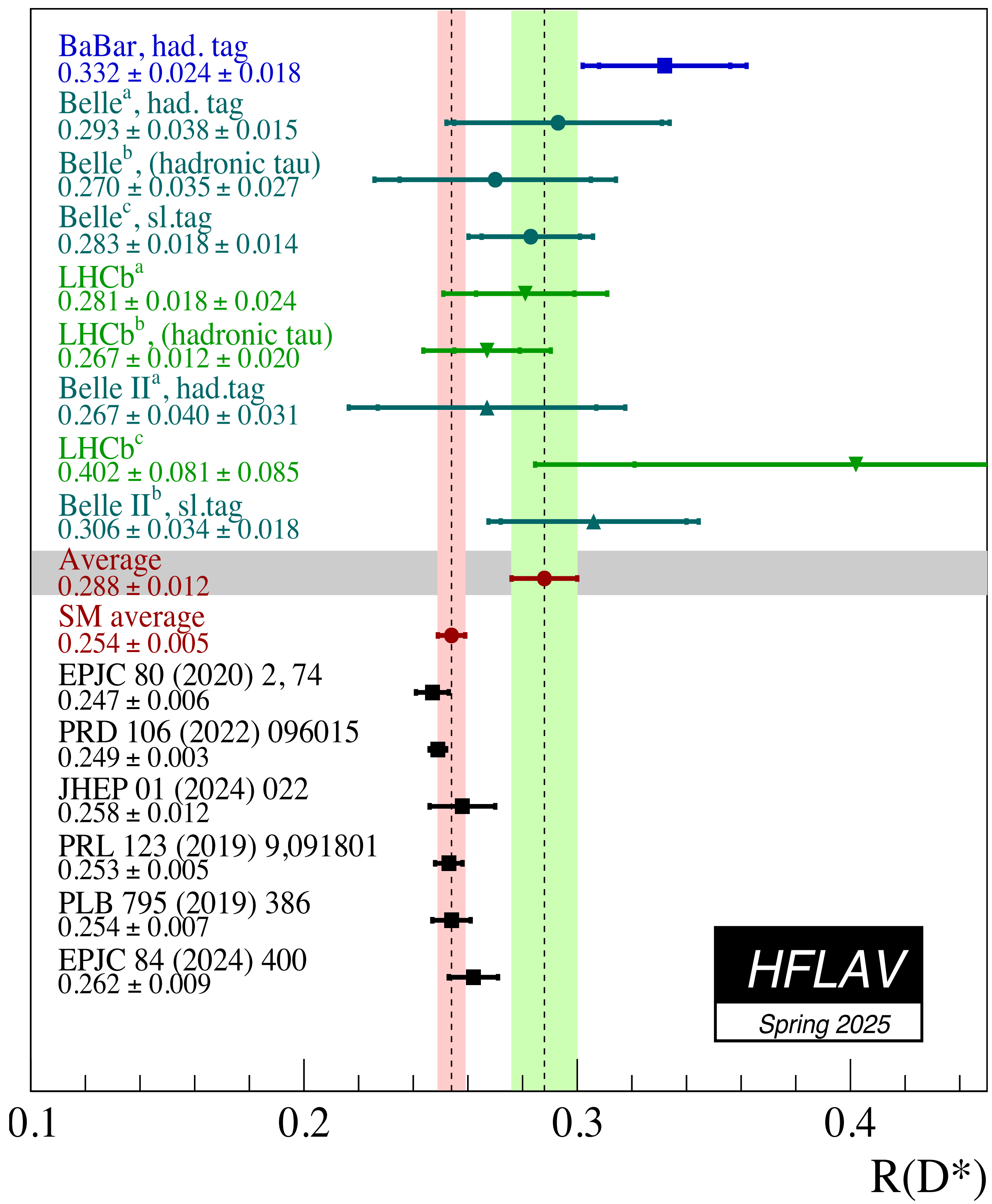
see UTfit (L.Vittorio) @ EPS25

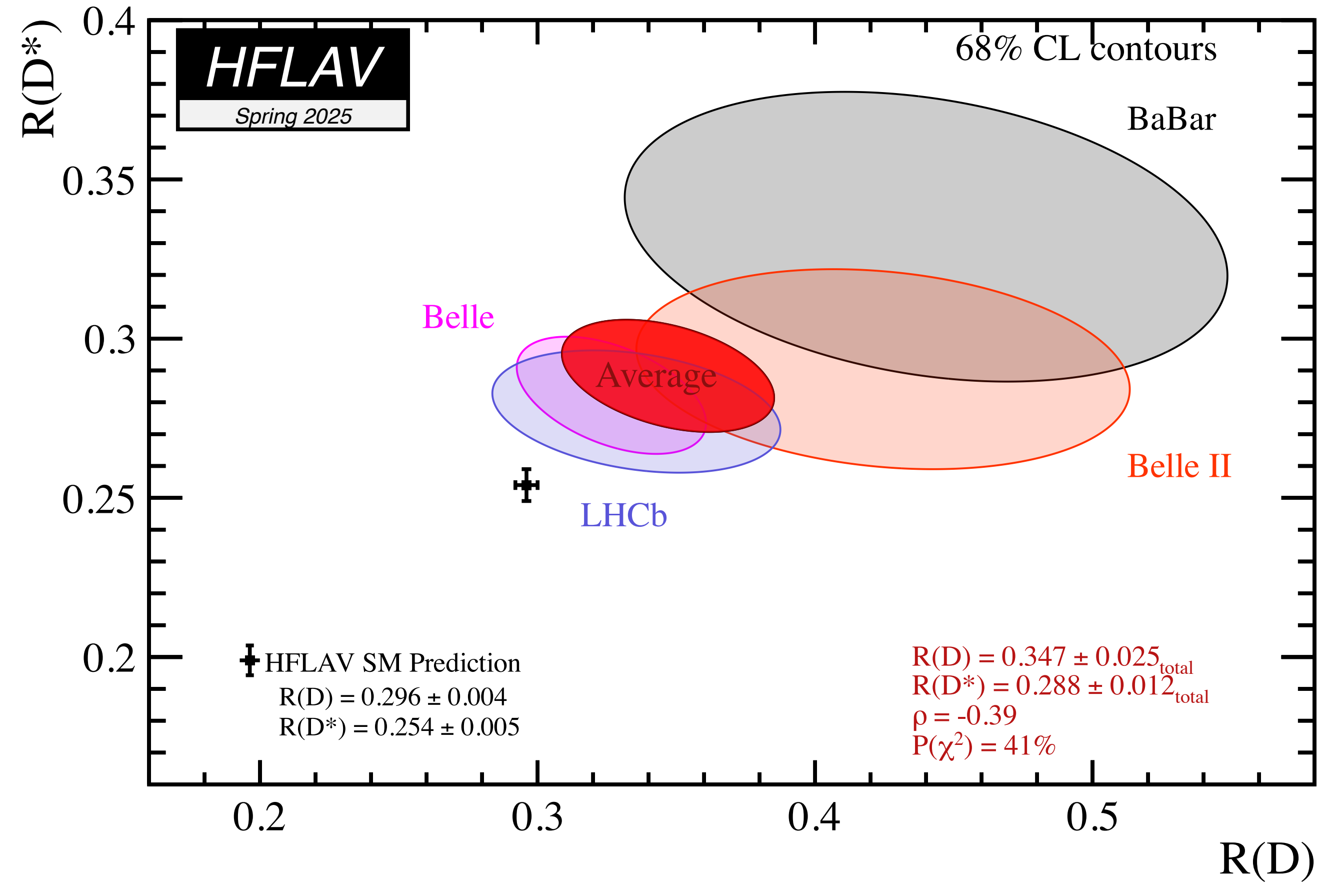
BACKUP

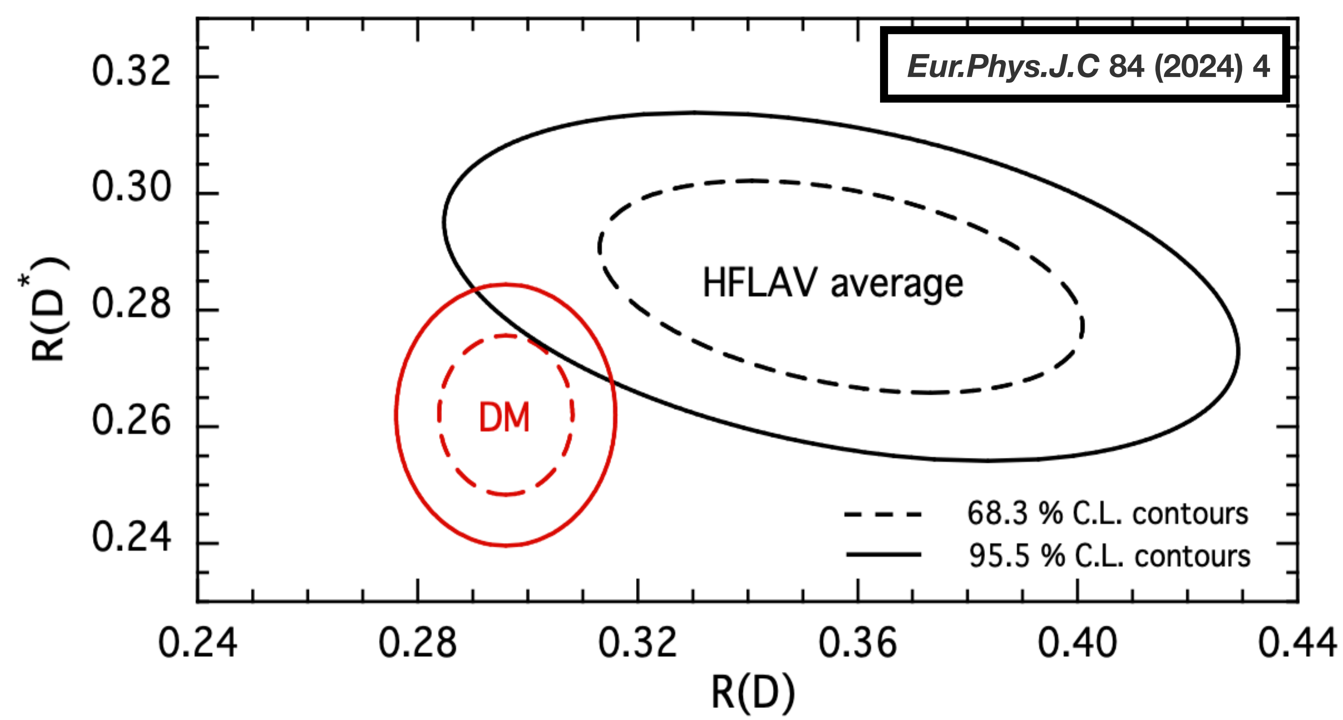
ARE THESE (INTERESTING) ANOMALIES? ...











Anomalies in $B \to K^* \mu\mu$?

[JHEP 06 (2016) 116]

$$h_{0,\pm}(q^2) = \sum_{k=0,1,2} h_{0,\pm}^{(k)} \left(\frac{q^2}{\mathrm{GeV}^2}\right)^k$$

Phenomenological Model Driven (PMD)

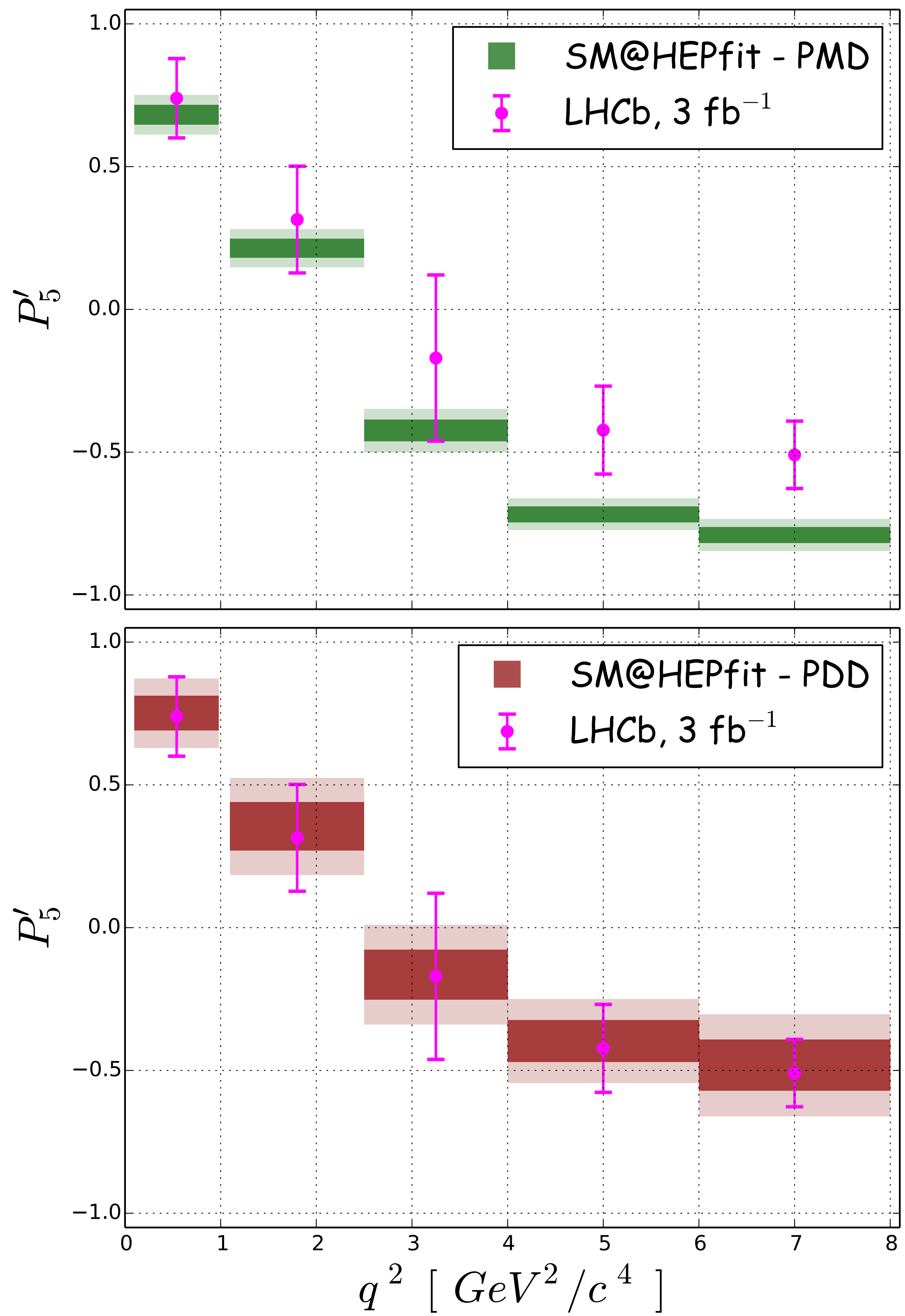
Enforce outcome of LCSR + dispersion relations in the entire range of q^2

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Descotes-Genon et al. 2013

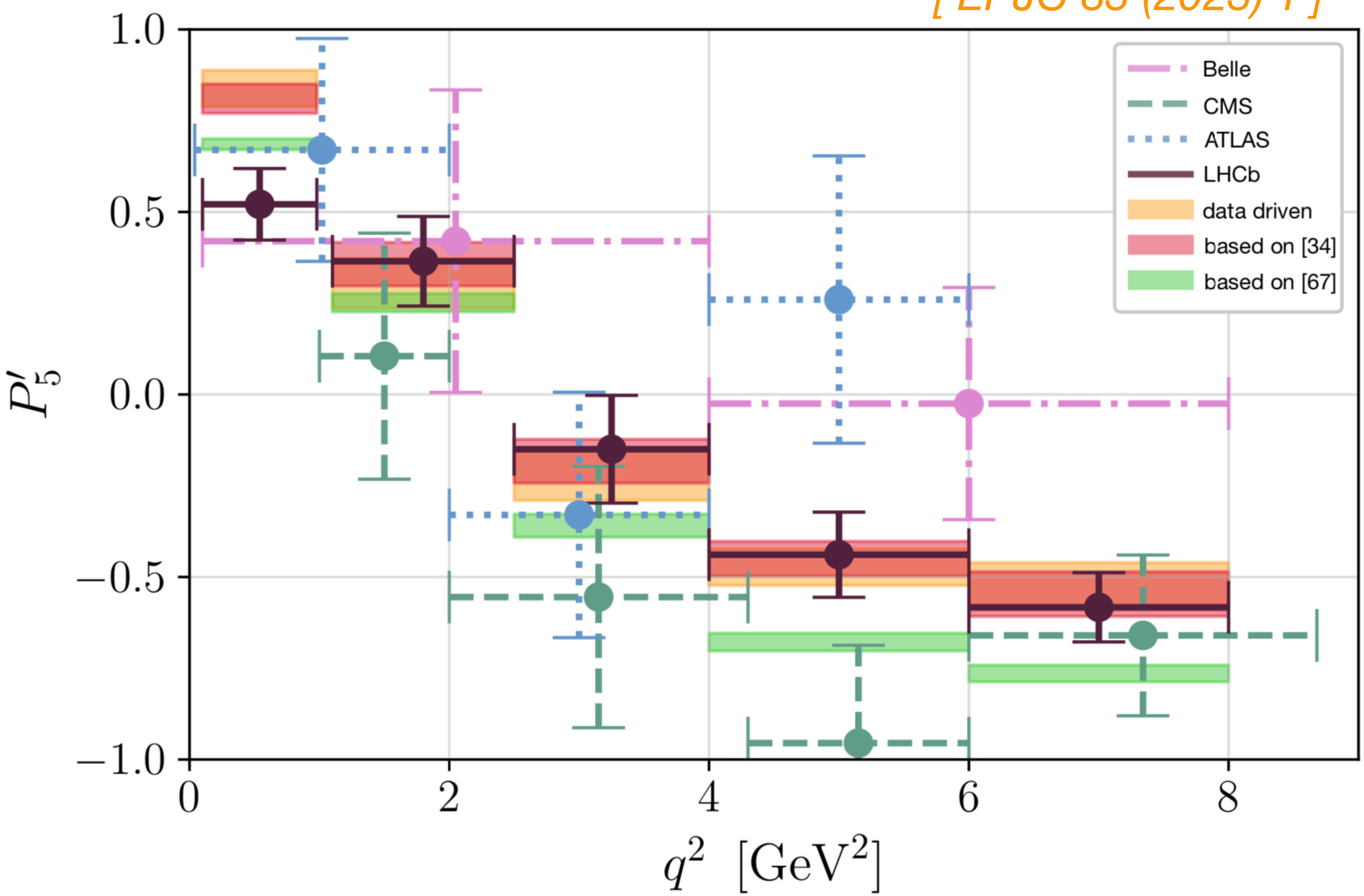
Phenomenological Data Driven (PDD)

Apply LCSR results only for $q^2 \lesssim \mathrm{GeV}^2$



B ANOMALIES : P_5'

[EPJC 83 (2023) 1]

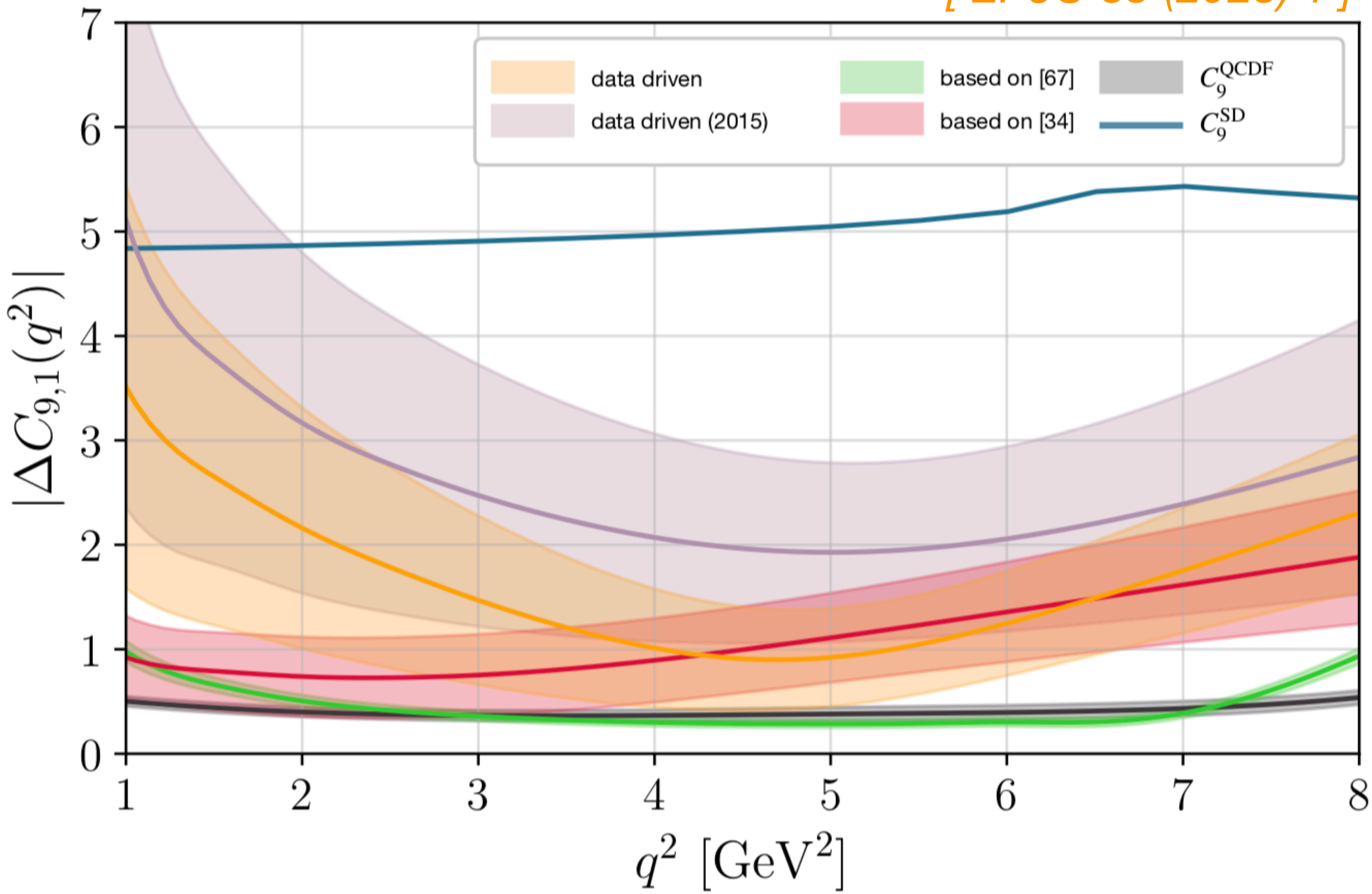


34. M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini et al., *Hadronic uncertainties in semileptonic $B \to K^* \mu^+ \mu^-$ decays*, *PoS* **BEAUTY2018** (2018) 044, [arXiv:1809.03789].

67. A. Khodjamirian, T. Mannel, A. Pivovarov and Y.-M. Wang, *Charm-loop effect in $B \to K^{(*)} \ell^+ \ell^-$ and $B \to K^* \gamma$*, *JHEP* **09** (2010) 089, [arXiv:1006.4945].

EXTRACTION OF HADRONIC EFFECTS

[EPJC 83 (2023) 1]



34. M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini et al., *Hadronic uncertainties in semileptonic $B \to K^* \mu^+ \mu^-$ decays*, *PoS* **BEAUTY2018** (2018) 044, [arXiv:1809.03789].

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Phenomenological Data Driven

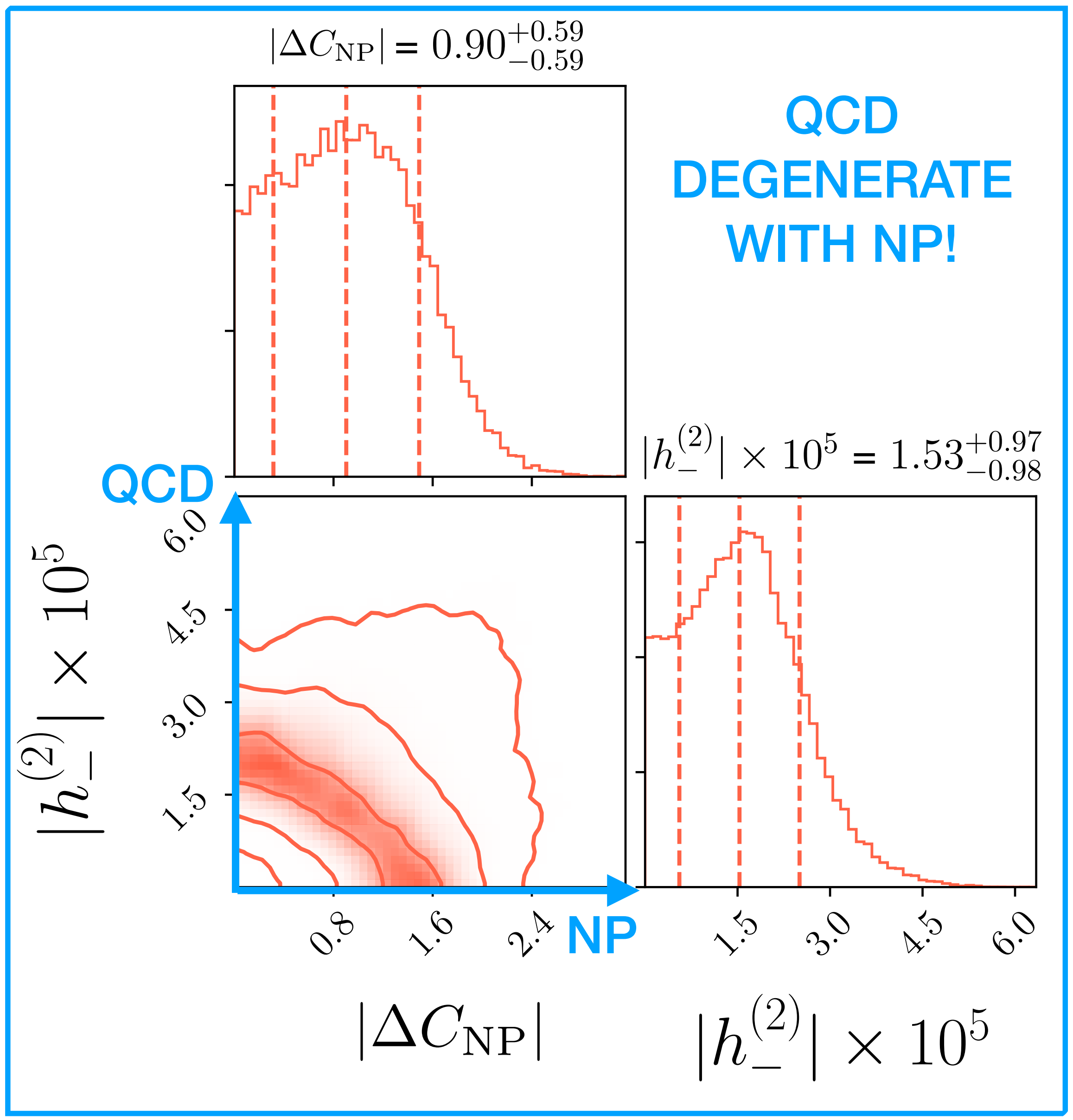
$$h_{0,\pm}\left(q^2\right) = \sum_{k=0,1,2} h_{0,\pm}^{(k)} \left(\frac{q^2}{\mathrm{GeV}^2}\right)^k$$

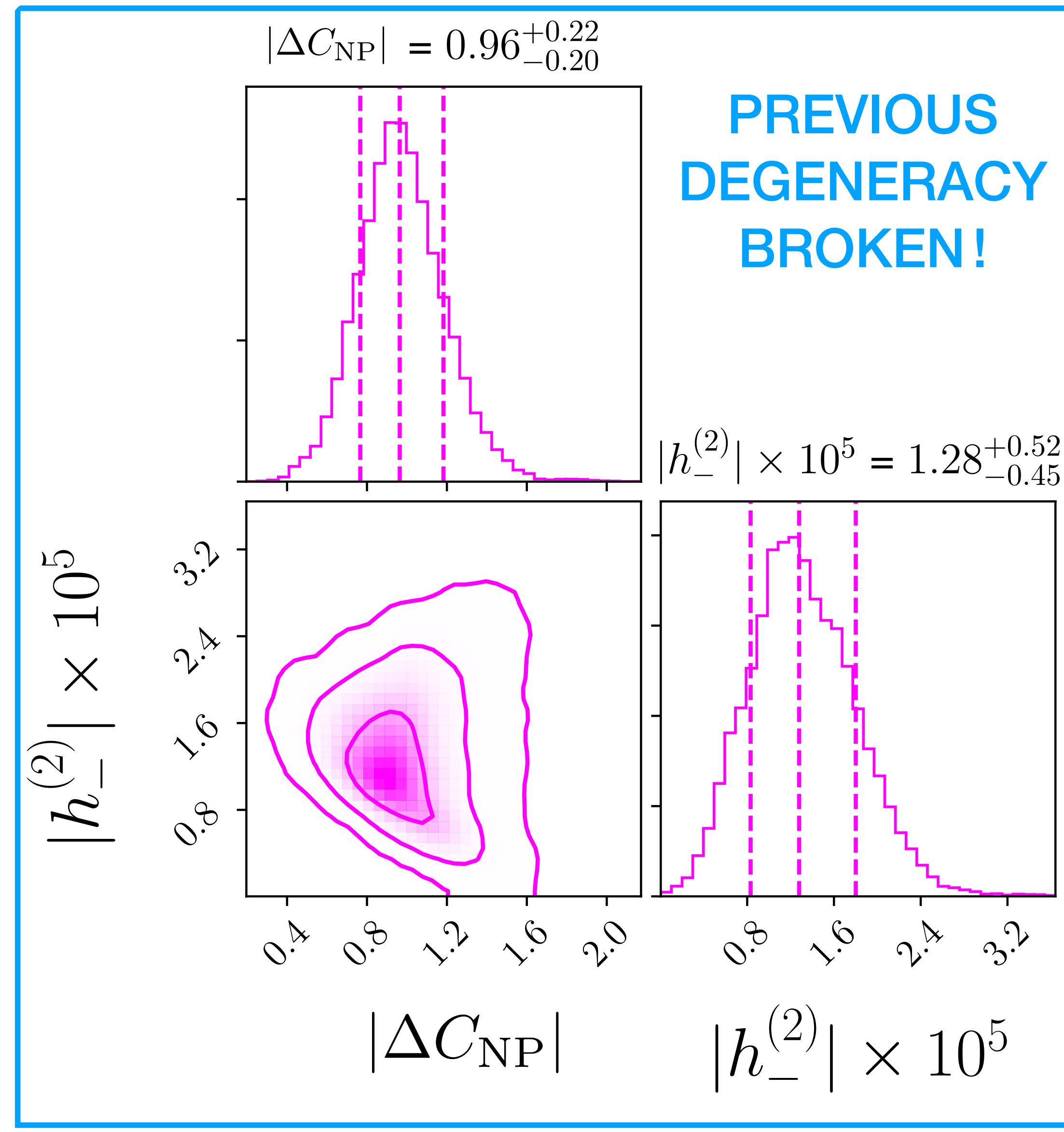
PROJECTIONS @ 50 fb^{-1}

(Hurth et al.`17 + Albrecht et al.`17)

RULE OF THUMB

Scaling LHCb stat errors roughly of 1/6





[*PoS BEAUTY2018 (2018) 044*]