University of Trieste, 10 / 06 / 2025

Cracks in the Standard Model? **A fresh look at the B anomalies**

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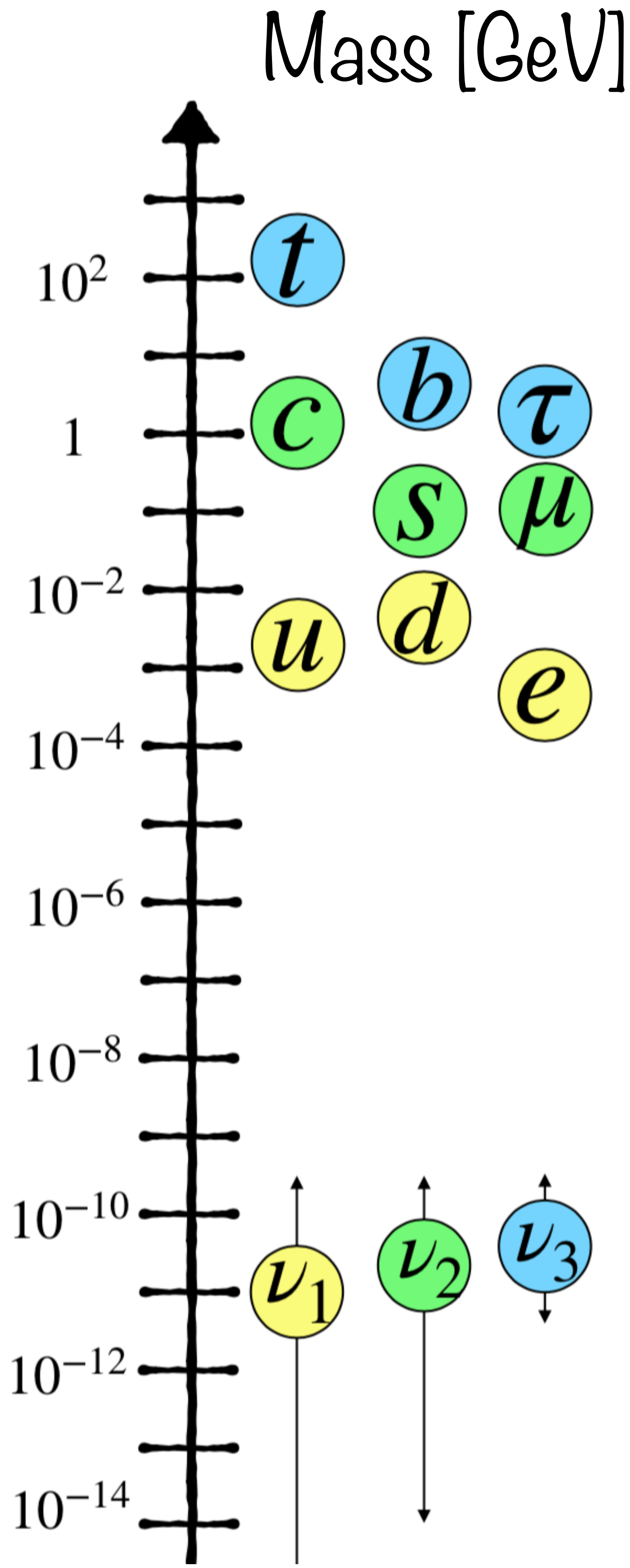
MANY THANKS TO: M.FEDELE, L.SILVESTRINI & L.VITTORIO

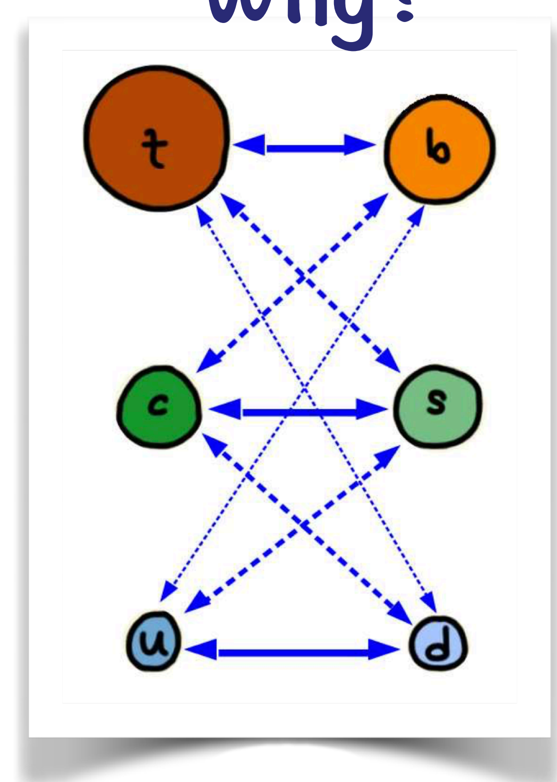
The Standard Model

THE SM FLAVOR PUZZLE



$$V_{\rm CKM} = \begin{array}{cc} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} & \begin{matrix} u \\ c \\ t \end{matrix} \\ \begin{matrix} d & \quad s & \quad b \end{matrix} & \end{array}$$

Why?



Effective Field Theories & Flavour

Lagrangian:

Parameter

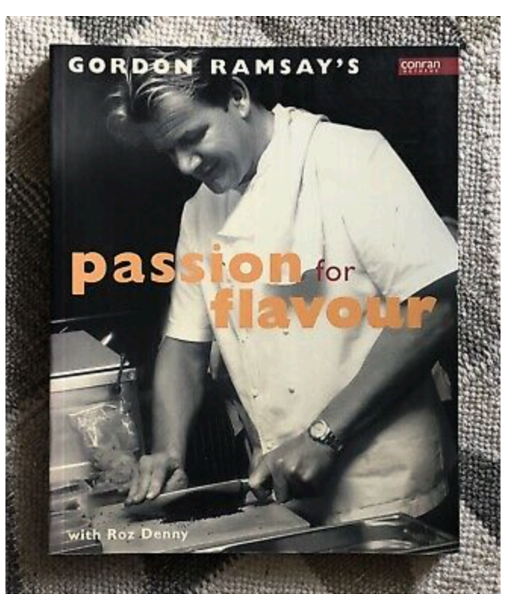
Cutoff scale

Local operator

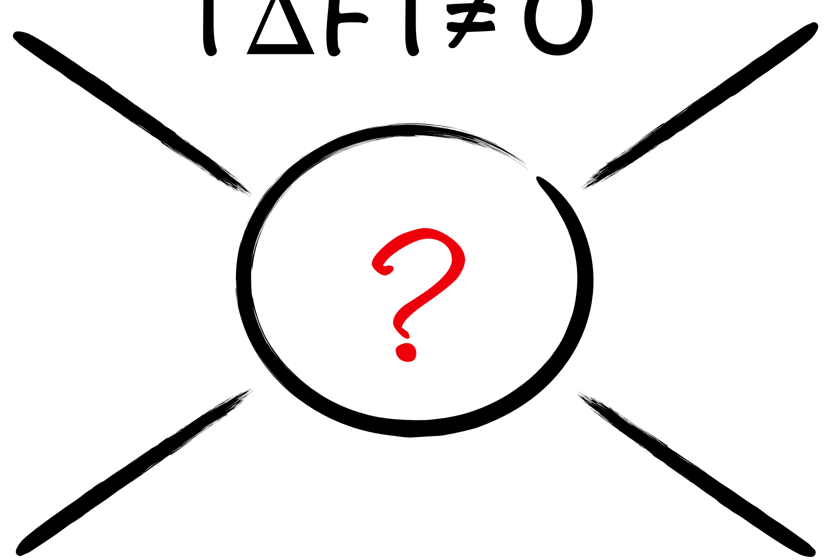
- a monomial in fields and derivatives

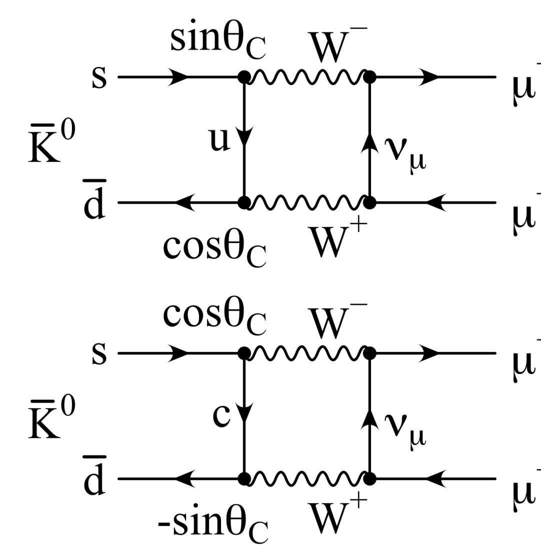
$$\mathscr{L}(x) = \sum c_{\mathcal{O}} \, \Lambda_{\mathcal{O}}^{4-\dim \mathcal{O}} \, \mathcal{O}(x)$$

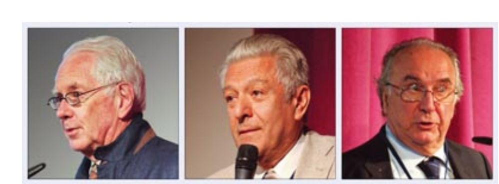
$$\text{Physical effects} \sim \left(\frac{E}{\Lambda_{\mathcal{O}}}\right)^{\dim \mathcal{O} - 4}$$



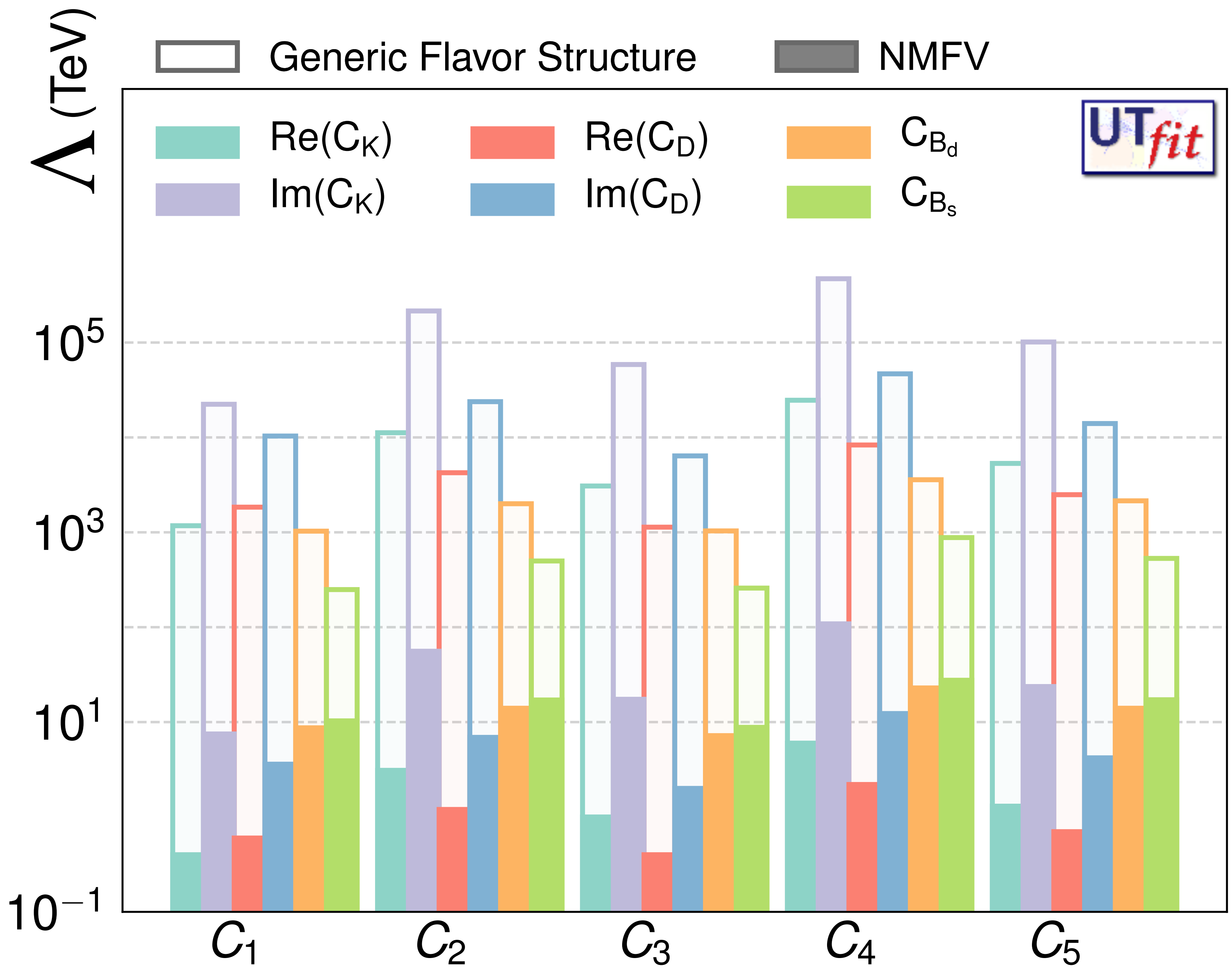
$|\Delta F| \neq 0$



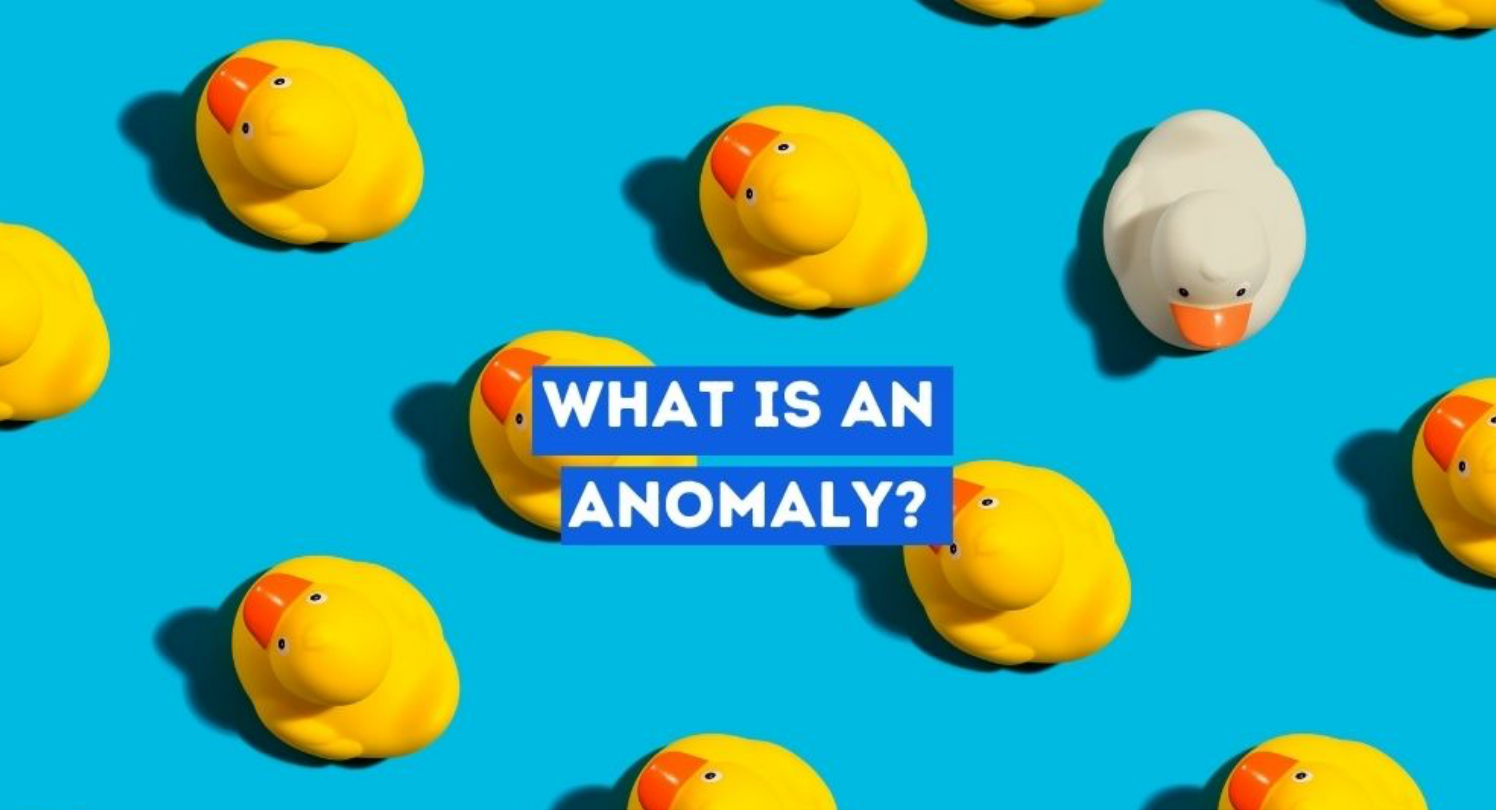




Flavour & BSM Physics



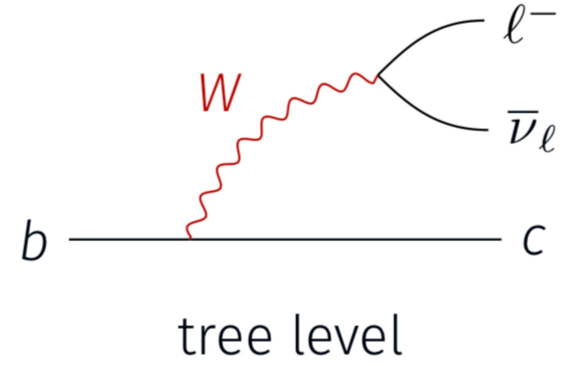
Generic source of Flavour / CP violation —> high NP scale

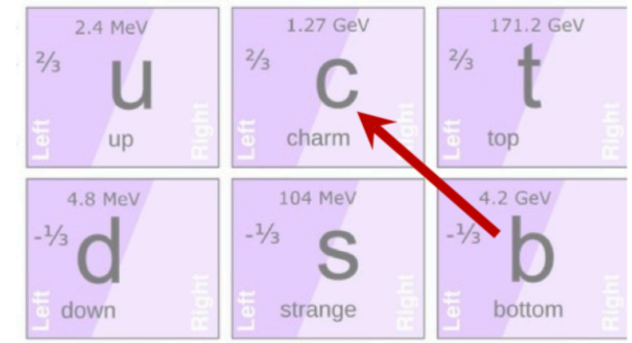


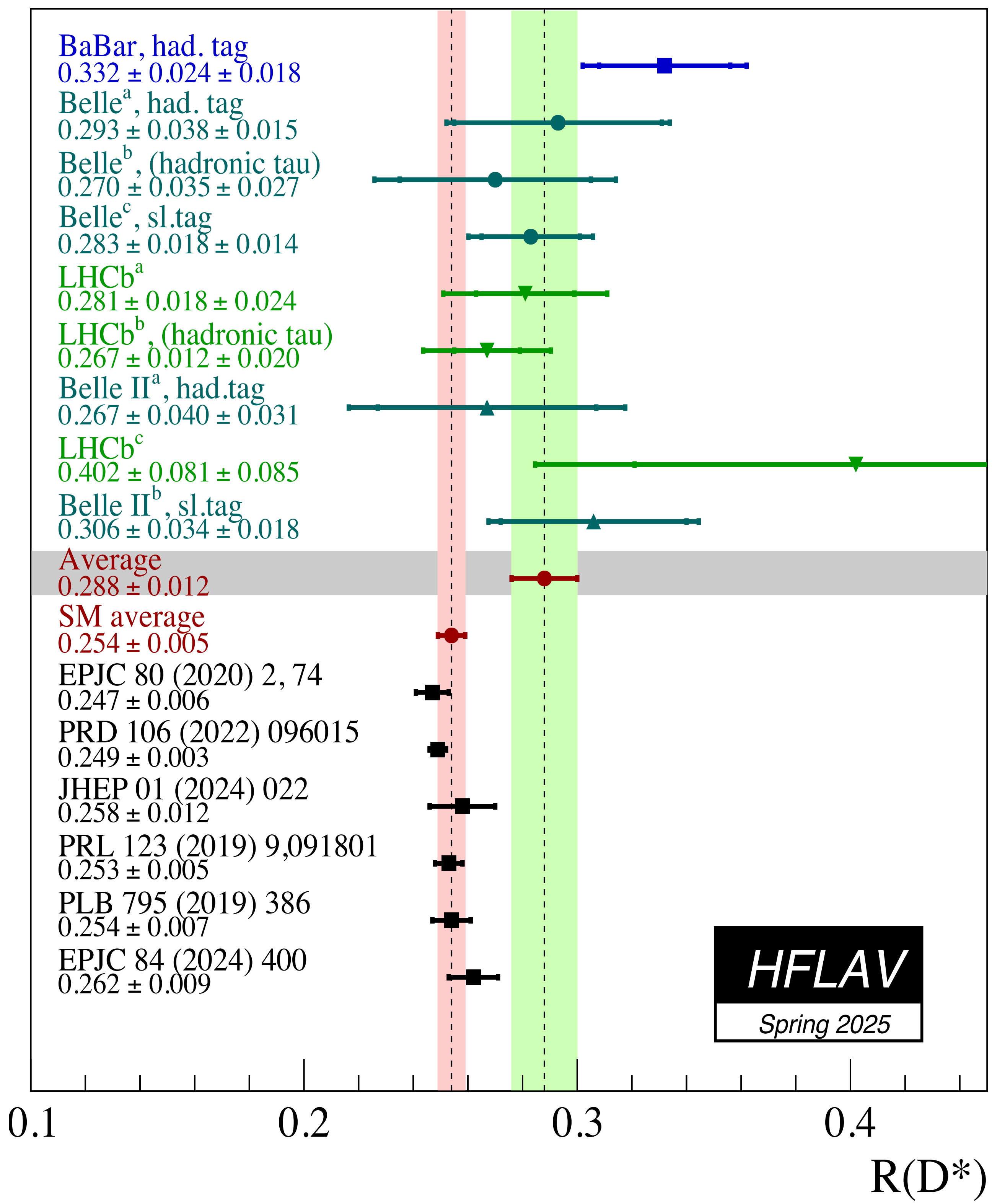
ChatGPT

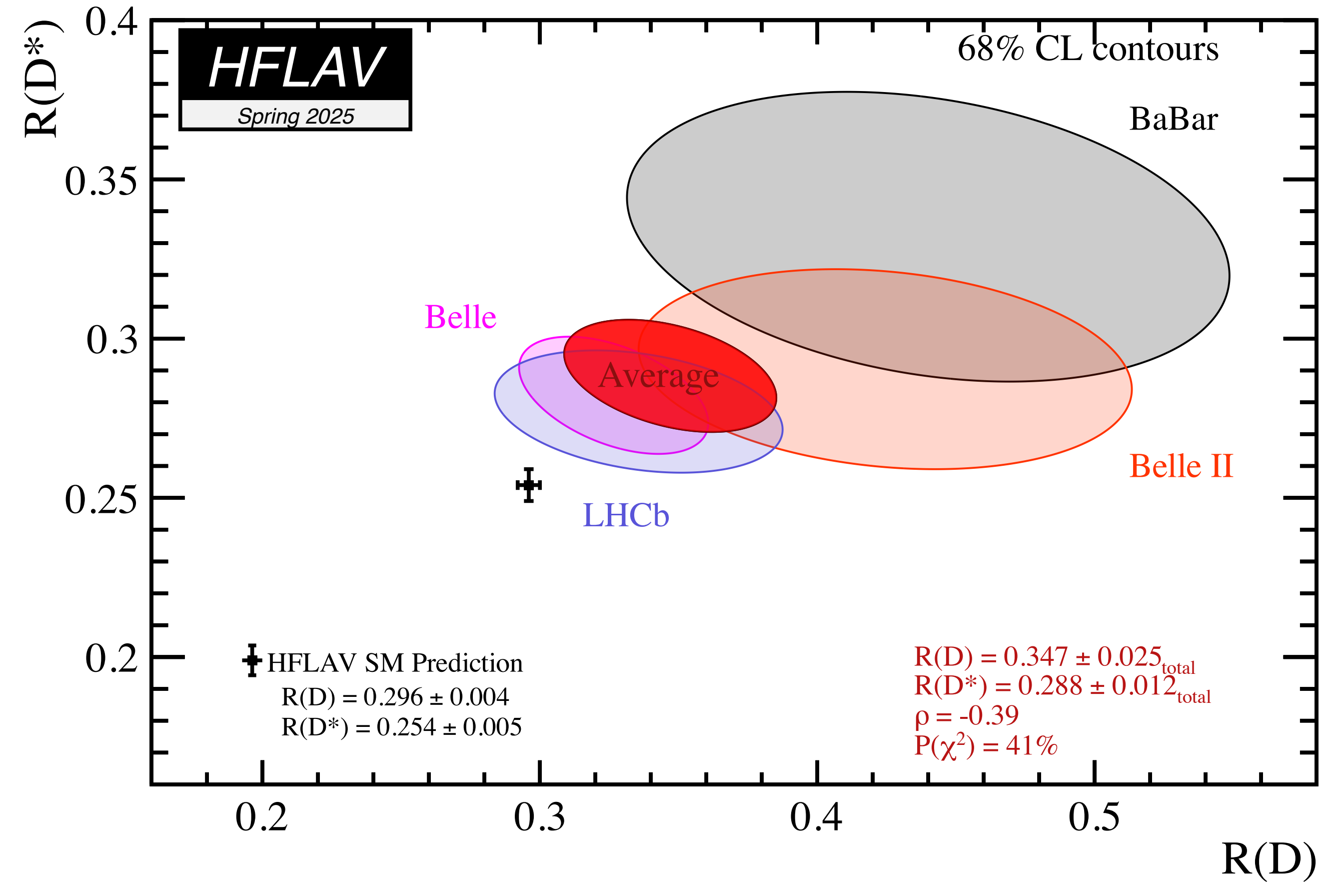
An anomaly refers to something that deviates from what is standard, normal, or expected. It can be a deviation from a pattern, behavior, or occurrence that stands out from the typical or anticipated norm. Anomalies can occur in various contexts, such as in data analysis, scientific observations, natural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

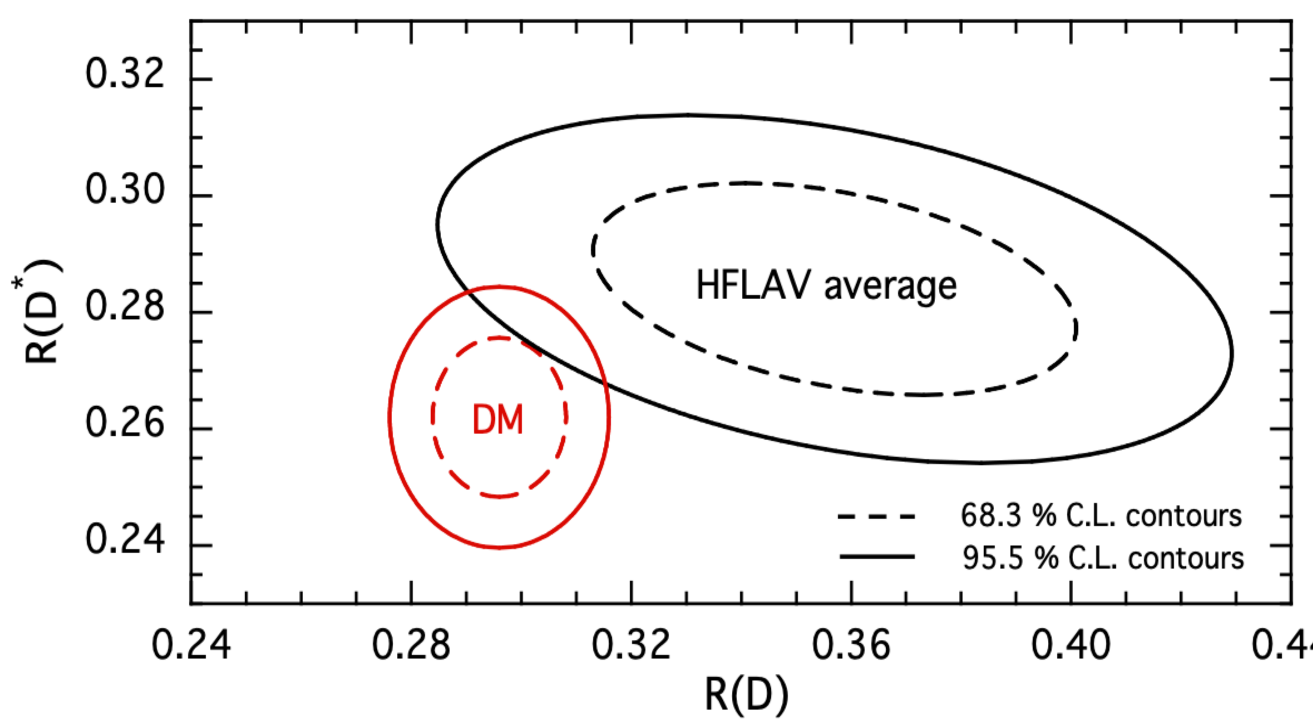
Are These (Interesting) Anomalies? ...



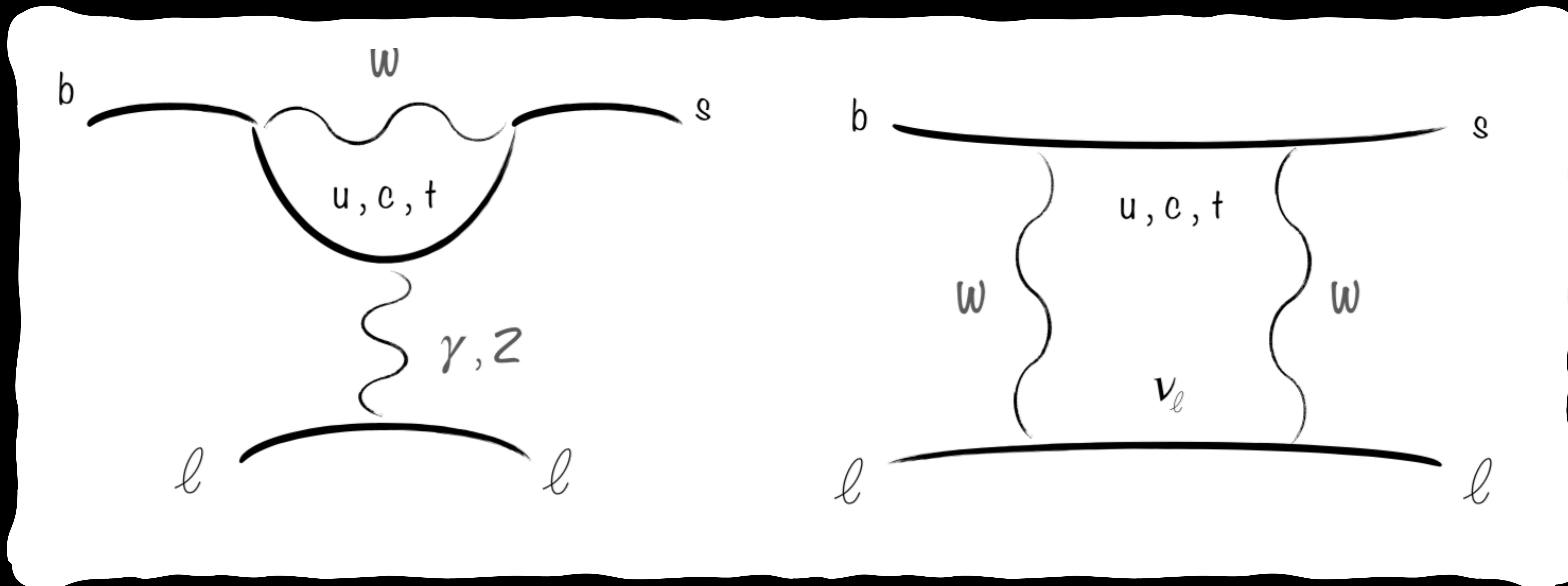








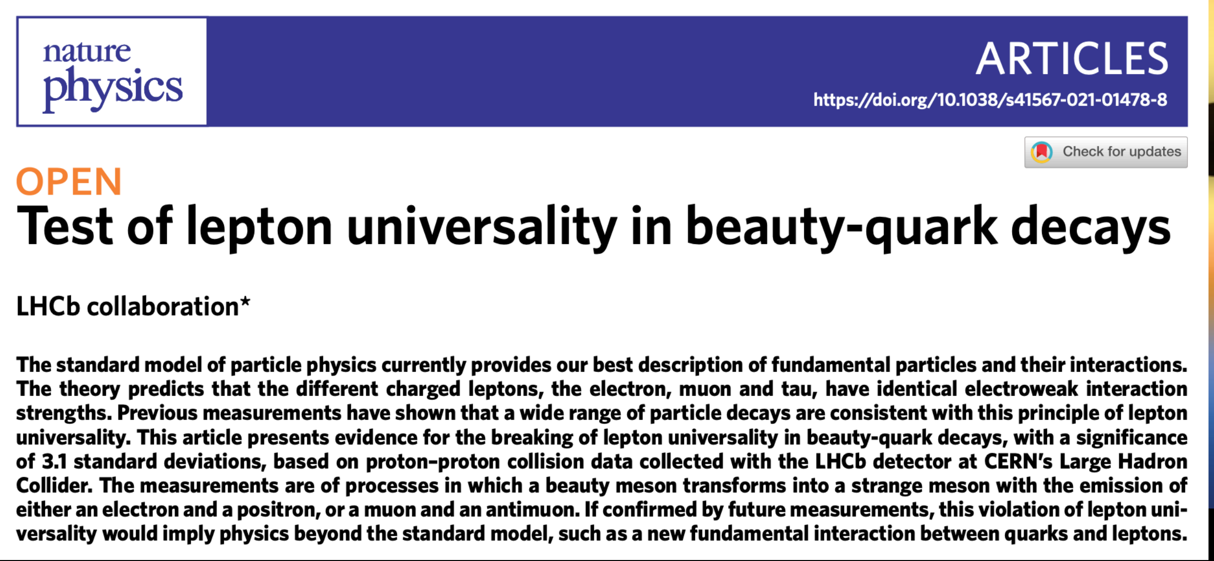
Semileptonic Rare B decays



- Flavor Changing Neutral Currents (FCNCs)
  - only @ loop level in the SM
  - GIM suppressed

for NP!

Semileptonic Rare B decays



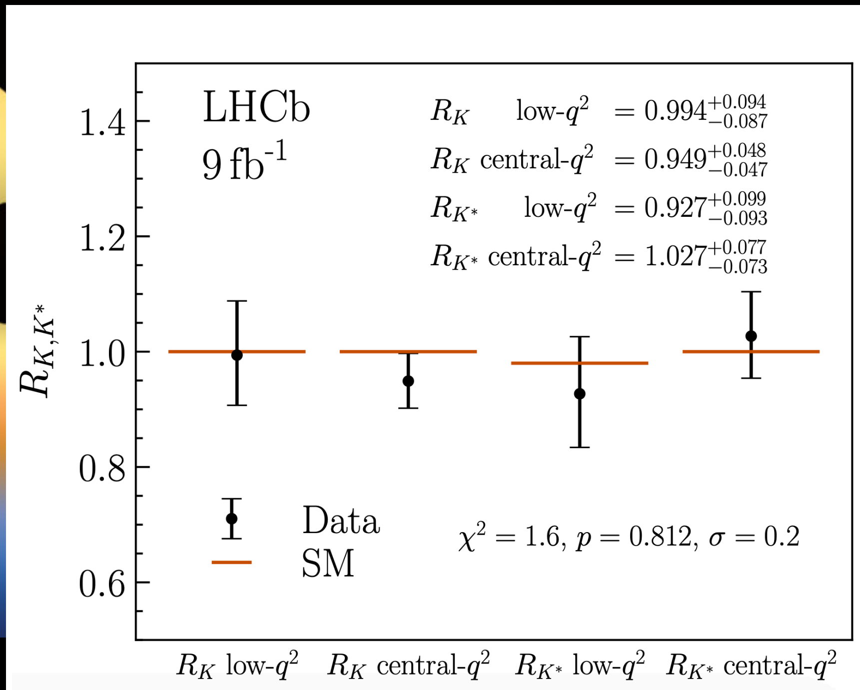
nature physics
ARTICLES
https://doi.org/10.1038/s41567-021-01478-8
Check for updates

OPEN

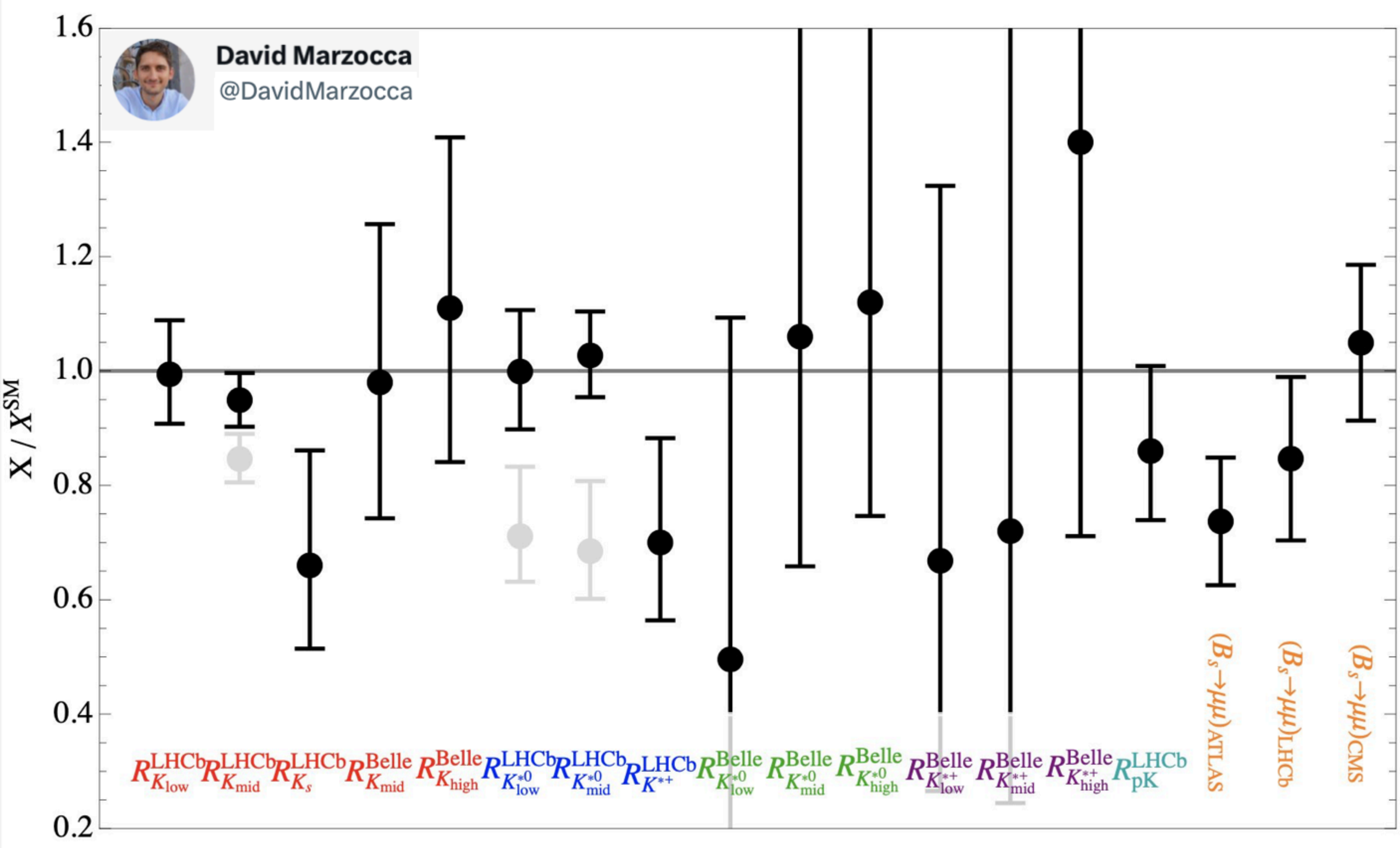
Test of lepton universality in beauty-quark decays

LHCb collaboration*

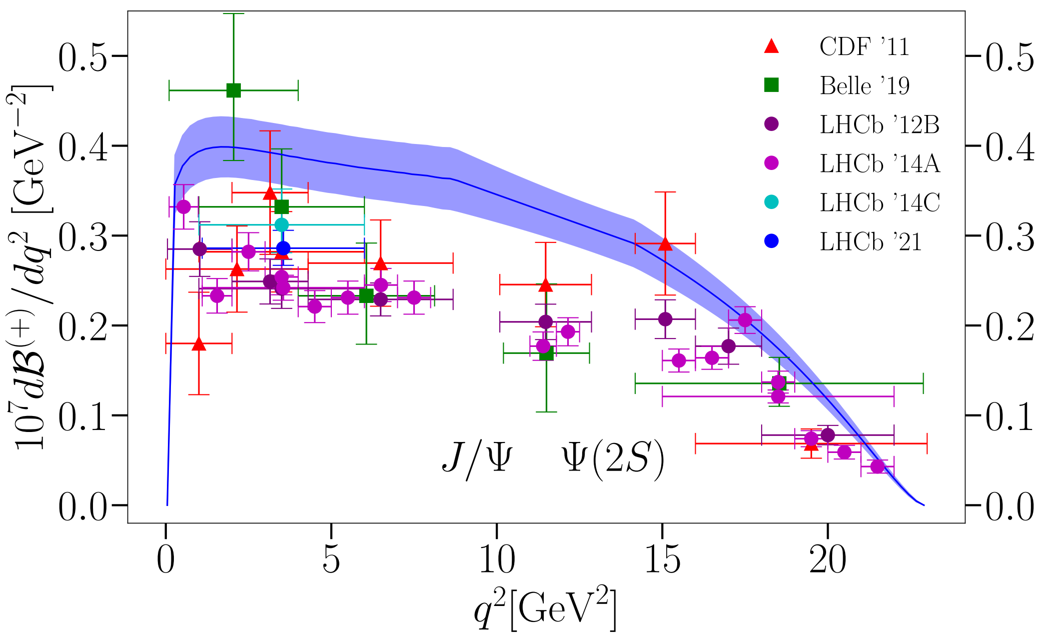
The standard model of particle physics currently provides our best description of fundamental particles and their interactions. The theory predicts that the different charged leptons, the electron, muon and tau, have identical electroweak interaction strengths. Previous measurements have shown that a 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.

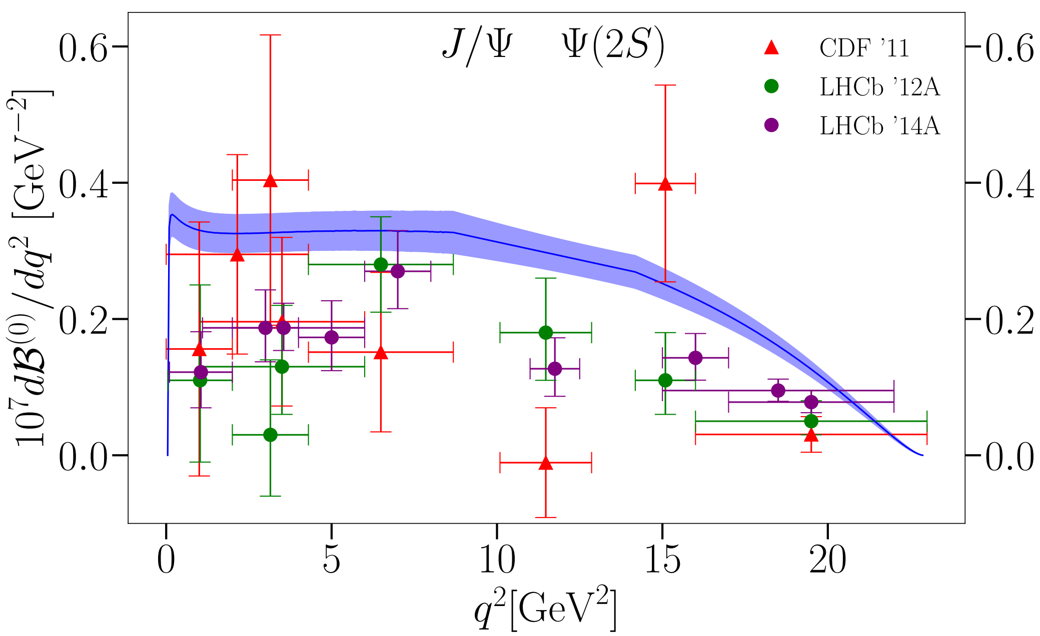


… There Were Exciting Anomalies …



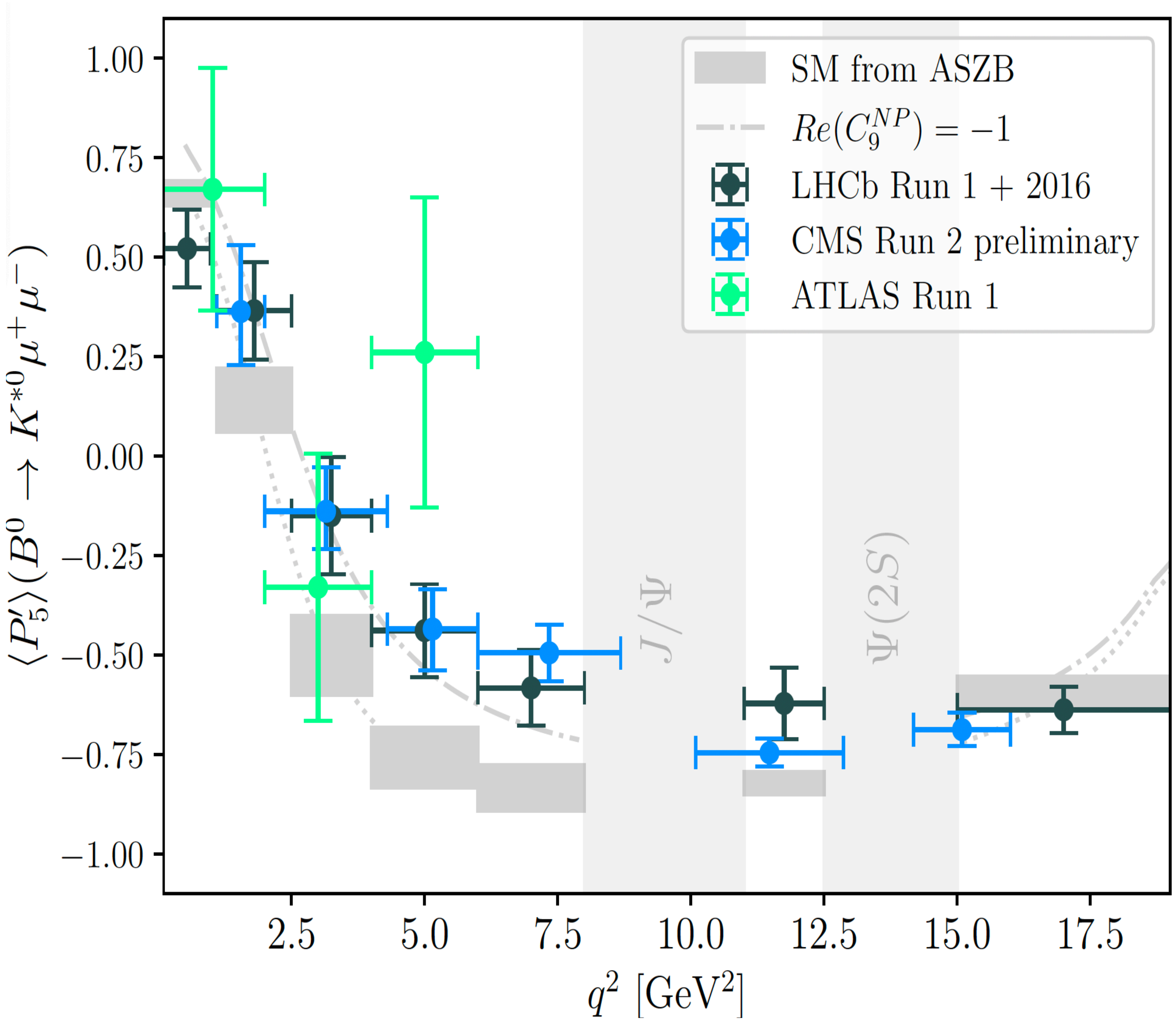
SHOULD WE (STILL) GET EXCITED?





Several BRs OFF (?)

Angular analyses OFF (?)



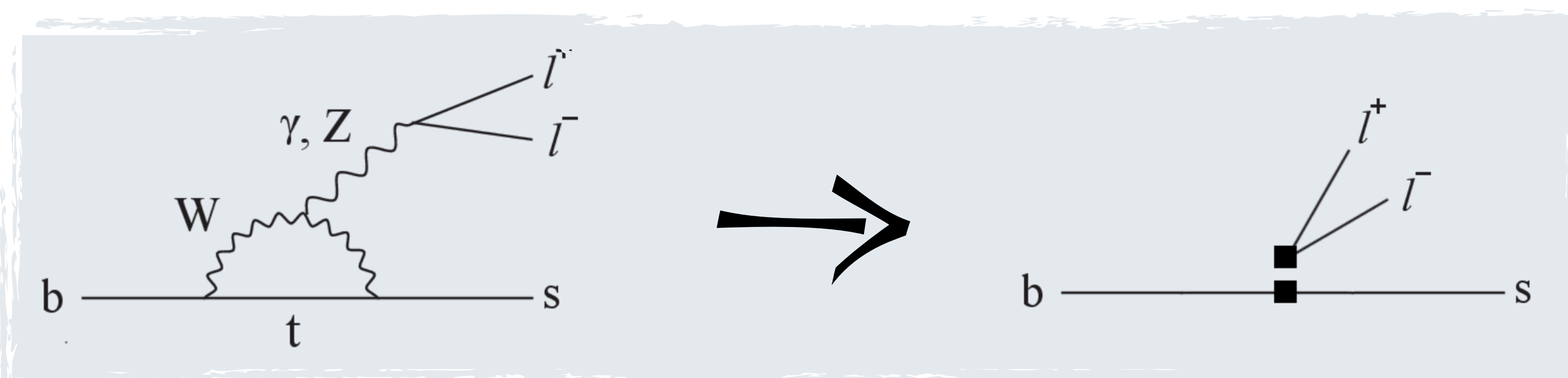
INTERLUDE: ANATOMY OF $B \to K^{(*)}\ \ell^+\ell^-$

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

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

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

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



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

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

SM matching & renormalization group effects known @ NNLO.

INTERLUDE: ANATOMY OF $B \to K^{(*)}\,\ell^+\ell^-$

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

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\end{aligned}$$

Low-energy physics from two sets of contributions:

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

$\boxed{\#1}$ Matrix elements of semi-leptonic & EM dipole operators naively factorize —> form factors

INTERLUDE: ANATOMY OF $B \to K^{(*)}\,\ell^+\ell^-$

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

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P_4 &= (\bar{s}_L \gamma_\mu T^a b_L) \textstyle\sum_q (\bar{q} \gamma^\mu T^a q) \\
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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)
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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}$$

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 & QCD dipole operators —> *non-local* hadronic correlators, h_λ

INTERLUDE: ANATOMY OF $B \to K^{(*)} \ell^+\ell^-$

Building blocks are helicity amplitudes, which generally read as:

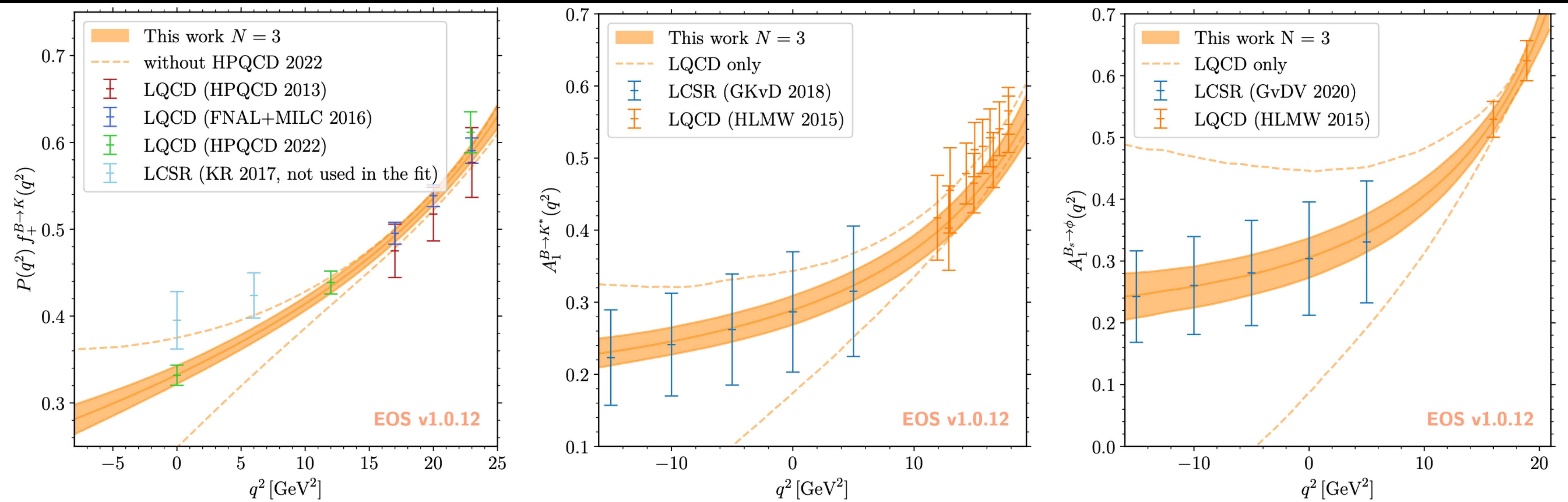
$$
\begin{aligned}
H_\lambda^V(q^2) &\propto (C_9 - C_9')\tilde{V}_\lambda(q^2) + \frac{2m_b m_B}{q^2}(C_7 - C_7')\tilde{T}_\lambda(q^2) - 16\pi^2\frac{m_B^2}{q^2}\tilde{h}_\lambda(q^2) \\
H_\lambda^A(q^2) &\propto (C_{10} - C_{10}')\tilde{V}_\lambda(q^2) \\
H^S(q^2) &\propto \frac{m_b}{m_W}(C_S - C_S')\tilde{S}(q^2) \\
H^P(q^2) &\propto \frac{m_b}{m_W}(C_P - C_P')\tilde{S}(q^2) + \frac{2m_\ell m_B}{q^2}(C_{10} - C_{10}')\left(1 + \frac{m_s}{m_b}\right)\tilde{S}(q^2)
\end{aligned}
$$

$\boxed{\text{polarizations: } \lambda = 0, \pm}$

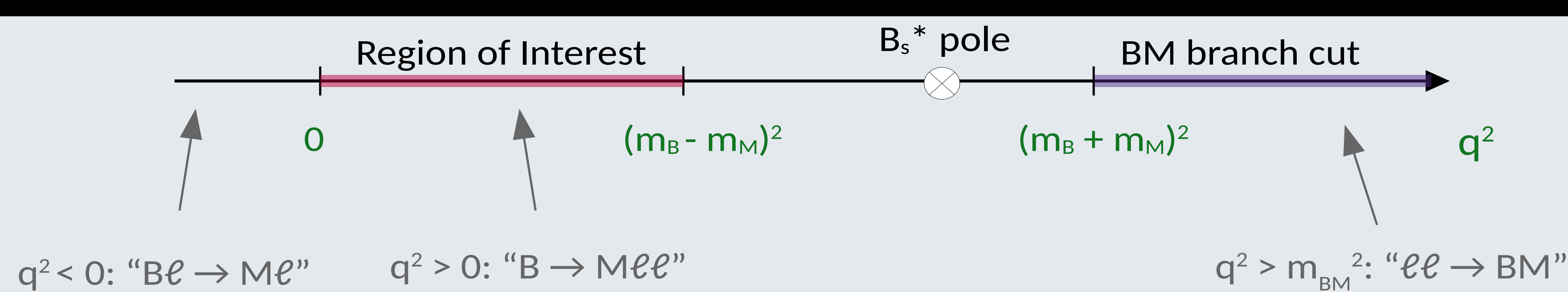
Short-distance order-of-magnitude: $C_{SM,7} \sim -1/3$, $C_{SM,9} \sim 4$, $C_{SM,10} \sim -4$

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

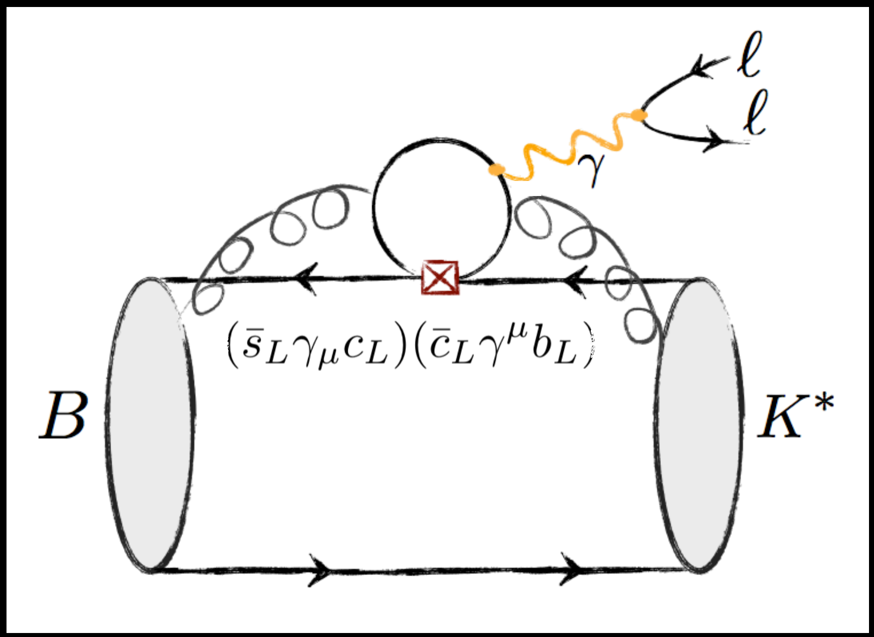
Form Factors for $B \to V(P)\, \ell^+\ell^-$



- **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*)

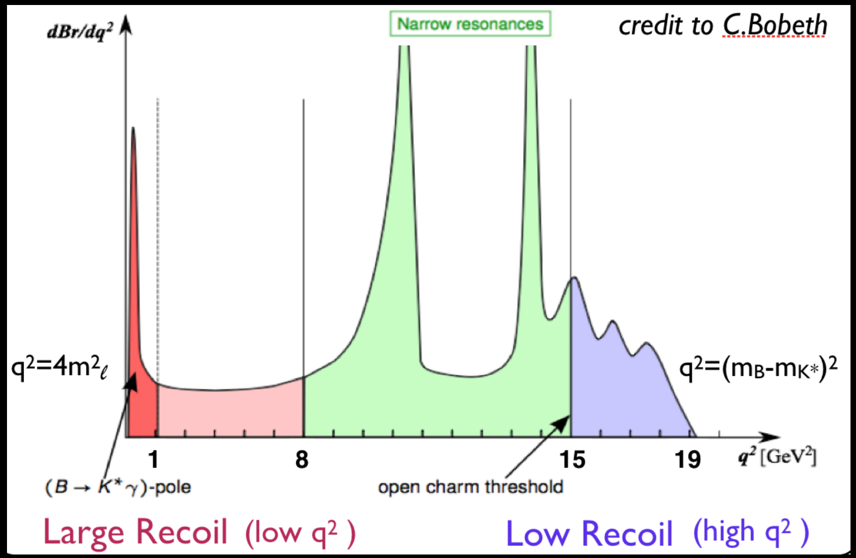


KNOWN UNKNOWNS IN $B \to K^{(*)} \ell^+\ell^-$



$\approx$

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

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)

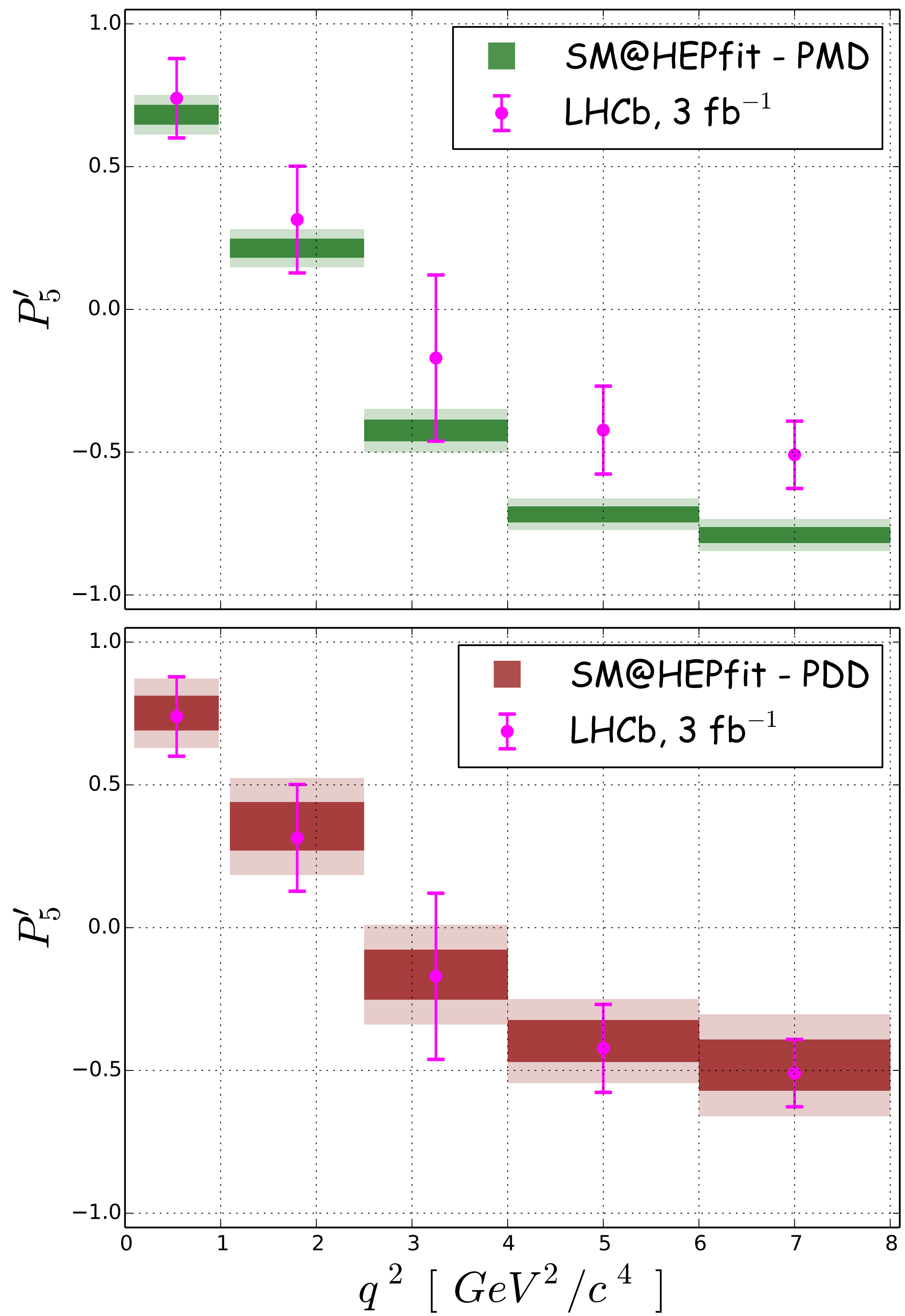
Enforce outcome of LCSR + dispersion relations in the entire range of q^2

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

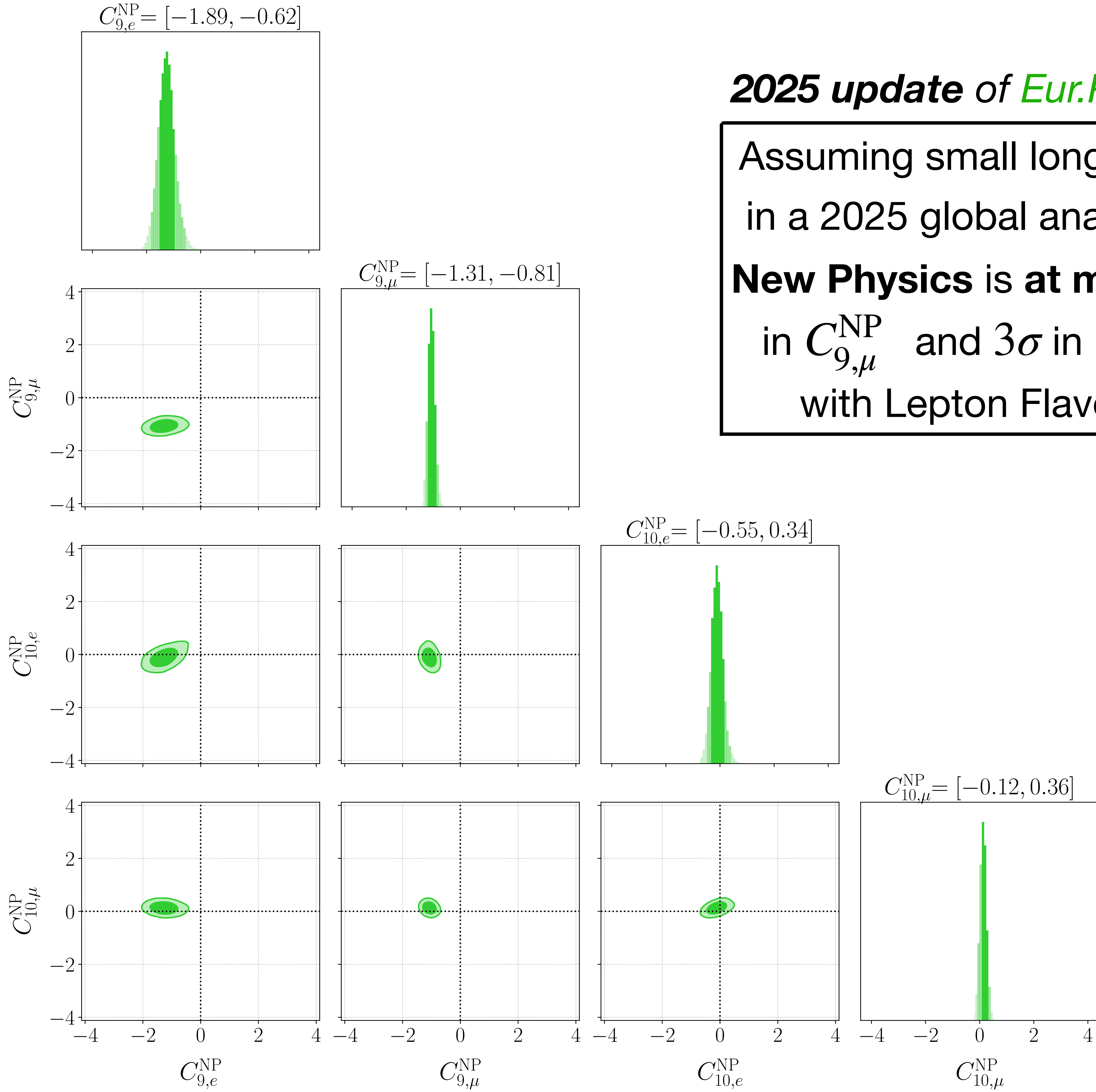
Descotes-Genon et al. 2013

Phenomenological Data Driven (PDD)

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

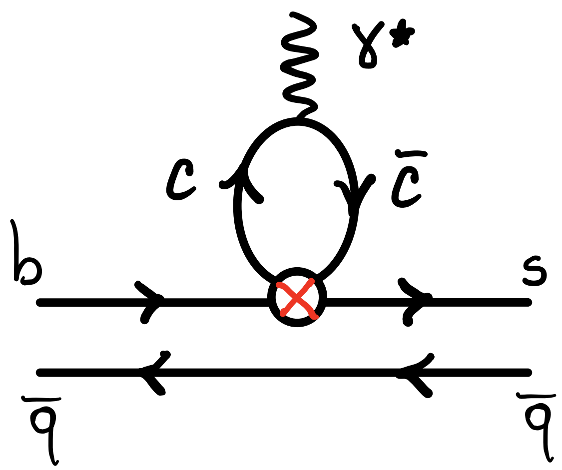


B ANOMALIES : “EVIDENCE” FOR NEW PHYSICS



***2025 update** of Eur.Phys.J.C 83 (2023)*

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



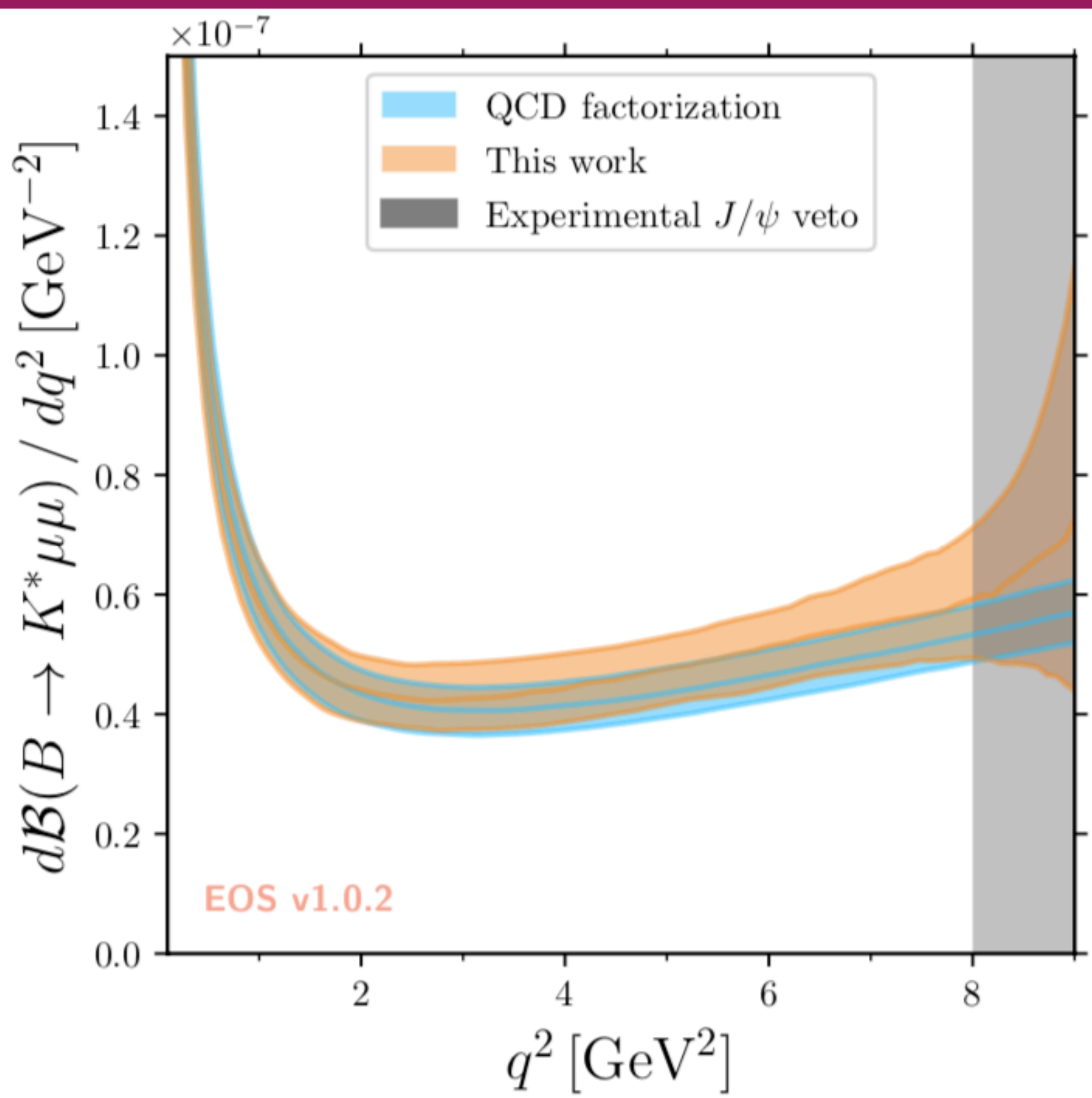
In 2022, this class of charming penguins has been re-estimated —> tiny contribution !

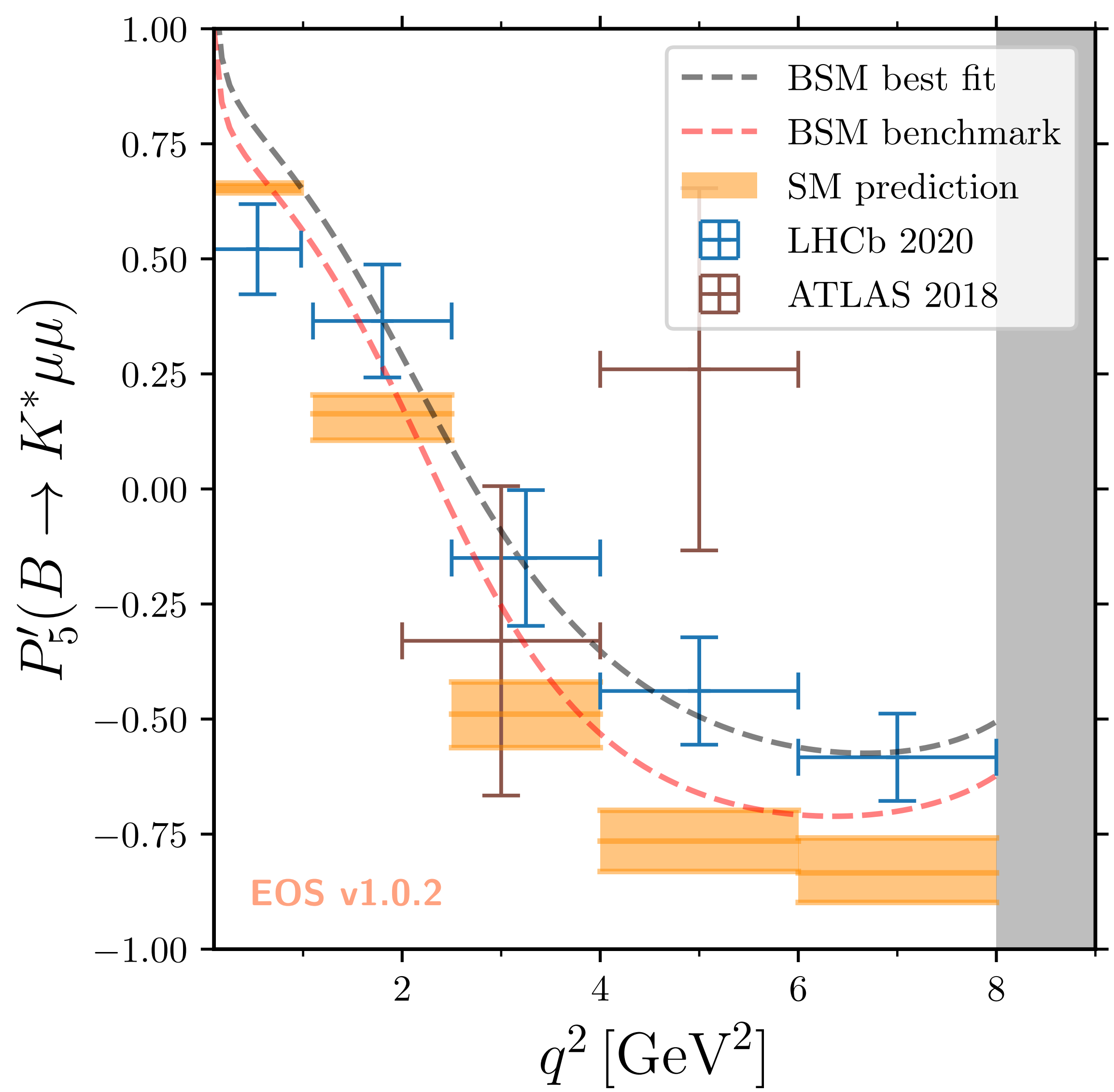
[*JHEP 09 (2022) 133*]

1) LCSR at $q^2 \leq 0$

2) z - expansion w/ $B \to M\, J/\psi$ data

3) dispersive bounds based on cuts in q²



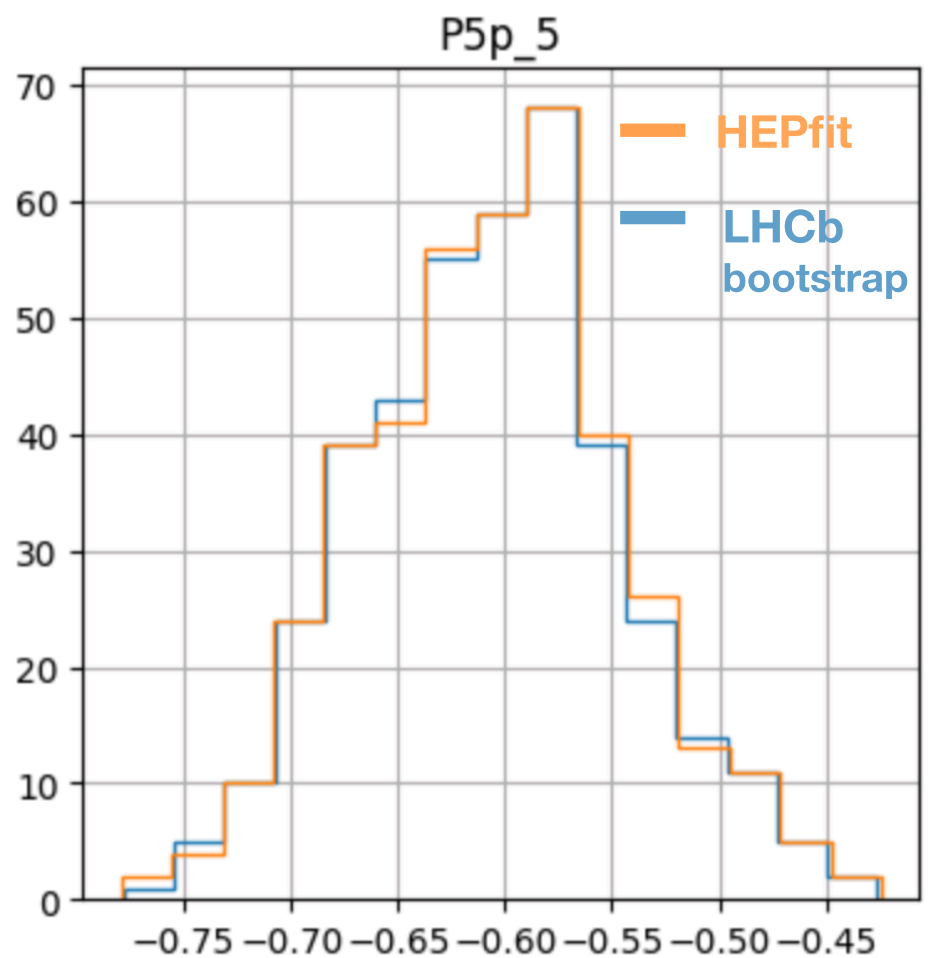


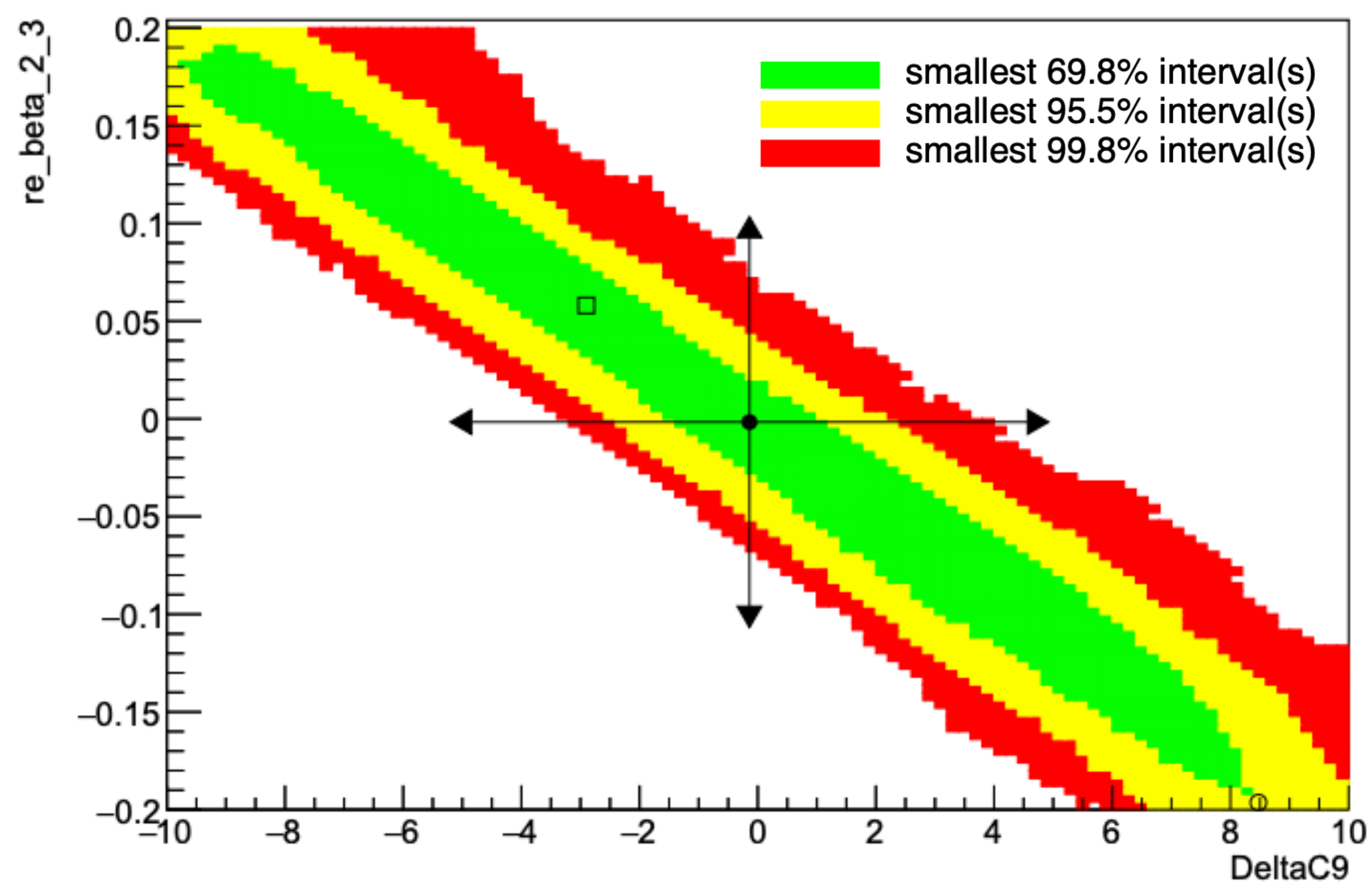
LHCb recently extracted non-local effects from data [*PRL132 (2024) 13*] using an ansatz based on the analytic structure in [*JHEP 09 (2022) 133*]

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

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

TRUNCATION AT $\mathcal{O}(z^2)$ —> EVIDENCE FOR $C_{9,U}^{\mathrm{NP}}$ AT 2 SIGMA LEVEL





EXPANDING AT NEXT ORDER — $\mathcal{O}(z^3)$ — AFFECTS INFERENCE OF $C_{9,U}^{\mathrm{NP}}$

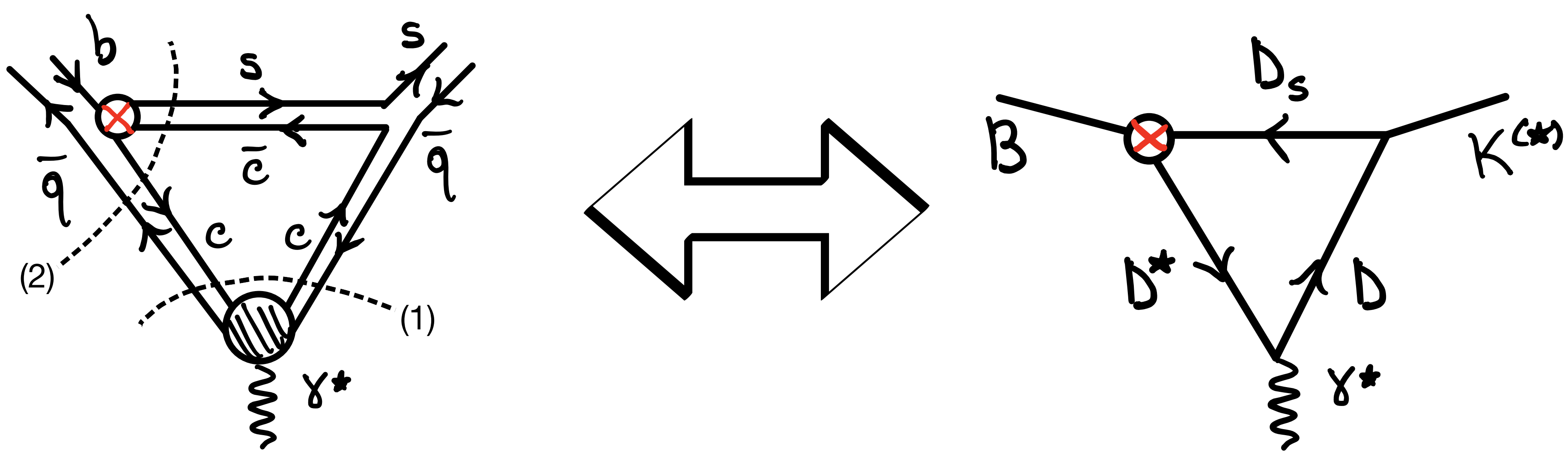
LHCb recently extracted non-local effects from data [*PRL132 (2024) 13*] using an ansatz based on the analytic structure in [*JHEP 09 (2022) 133*]

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

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

MOST IMPORTANTLY … WHAT ABOUT THOSE ?

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

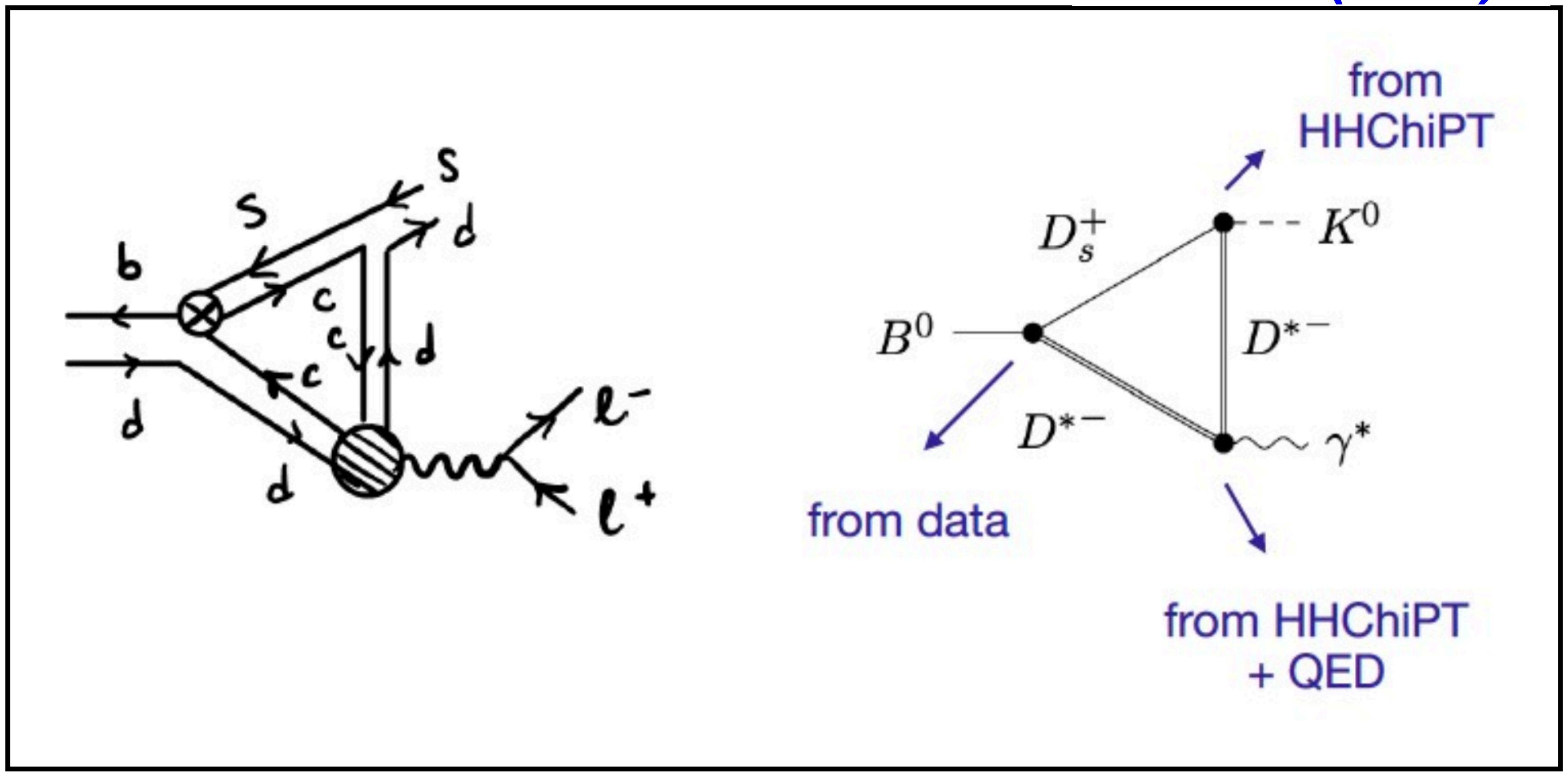


Rescattering from intermediate on-shell hadronic states.
These effects are NOT captured by analytic cuts solely in q^2.

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

TRIANGLES & ANOMALOUS THRESHOLDS

PRD 111 (2025) 9



Pheno estimate extrapolating Heavy Hadron ChiPT to region of low q^2 points to O(1%) effect at the amplitude level … but it could be way larger!

Anomalous thresholds easily yield O(10%) effects (maybe even O(1)?)

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

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

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

B ANOMALIES : A DATA DRIVEN APPROACH

Just Taylor-expand correlators h_λ and fit coeffs to data!

$$h_-(q^2) = -\frac{m_b}{8\pi^2 m_B}\widetilde{T}_{L-}(q^2)h_-^{(0)} - \frac{\widetilde{V}_{L-}(q^2)}{16\pi^2 m_B^2}h_-^{(1)}q^2 + h_-^{(2)}q^4 + \mathcal{O}(q^6)$$

$$h_+(q^2) = -\frac{m_b}{8\pi^2 m_B}\widetilde{T}_{L+}(q^2)h_-^{(0)} - \frac{\widetilde{V}_{L+}(q^2)}{16\pi^2 m_B^2}h_-^{(1)}q^2 + h_+^{(0)} + h_+^{(1)}q^2 + h_+^{(2)}q^4 + \mathcal{O}(q^6)$$

$$h_0(q^2) = -\frac{m_b}{8\pi^2 m_B}\widetilde{T}_{L0}(q^2)h_-^{(0)} - \frac{\widetilde{V}_{L0}(q^2)}{16\pi^2 m_B^2}h_-^{(1)}q^2 + h_0^{(0)}\sqrt{q^2} + h_0^{(1)}(q^2)^{\frac{3}{2}} + \mathcal{O}((q^2)^{\frac{5}{2}})$$

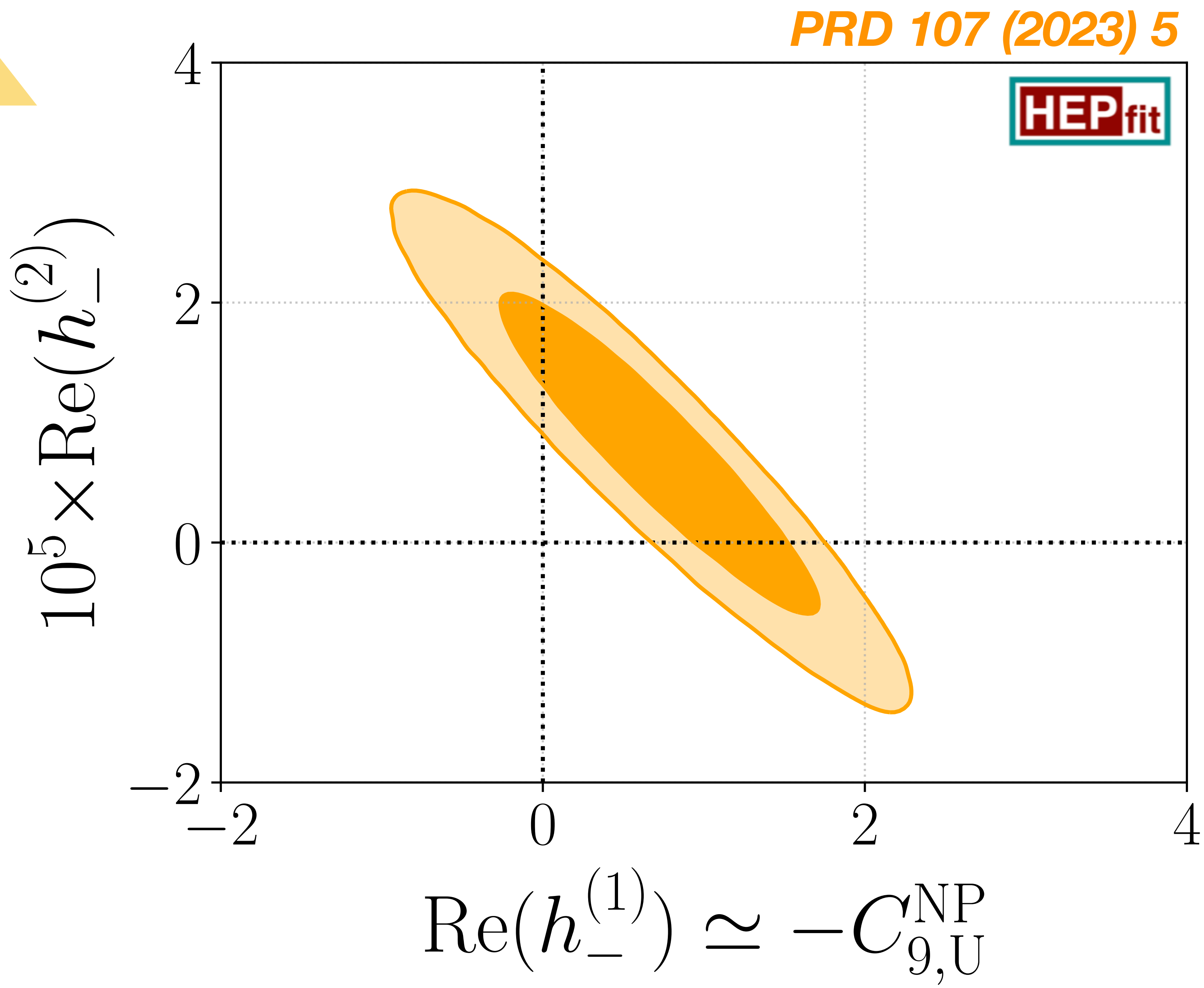
$$H_V^- \propto \left\{ \left(C_9^{\mathrm{SM}} + h_-^{(1)}\right)\widetilde{V}_{L-} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\mathrm{SM}} + h_-^{(0)}\right)\widetilde{T}_{L-} - 16\pi^2 h_-^{(2)}q^4\right]\right\}$$

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

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

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

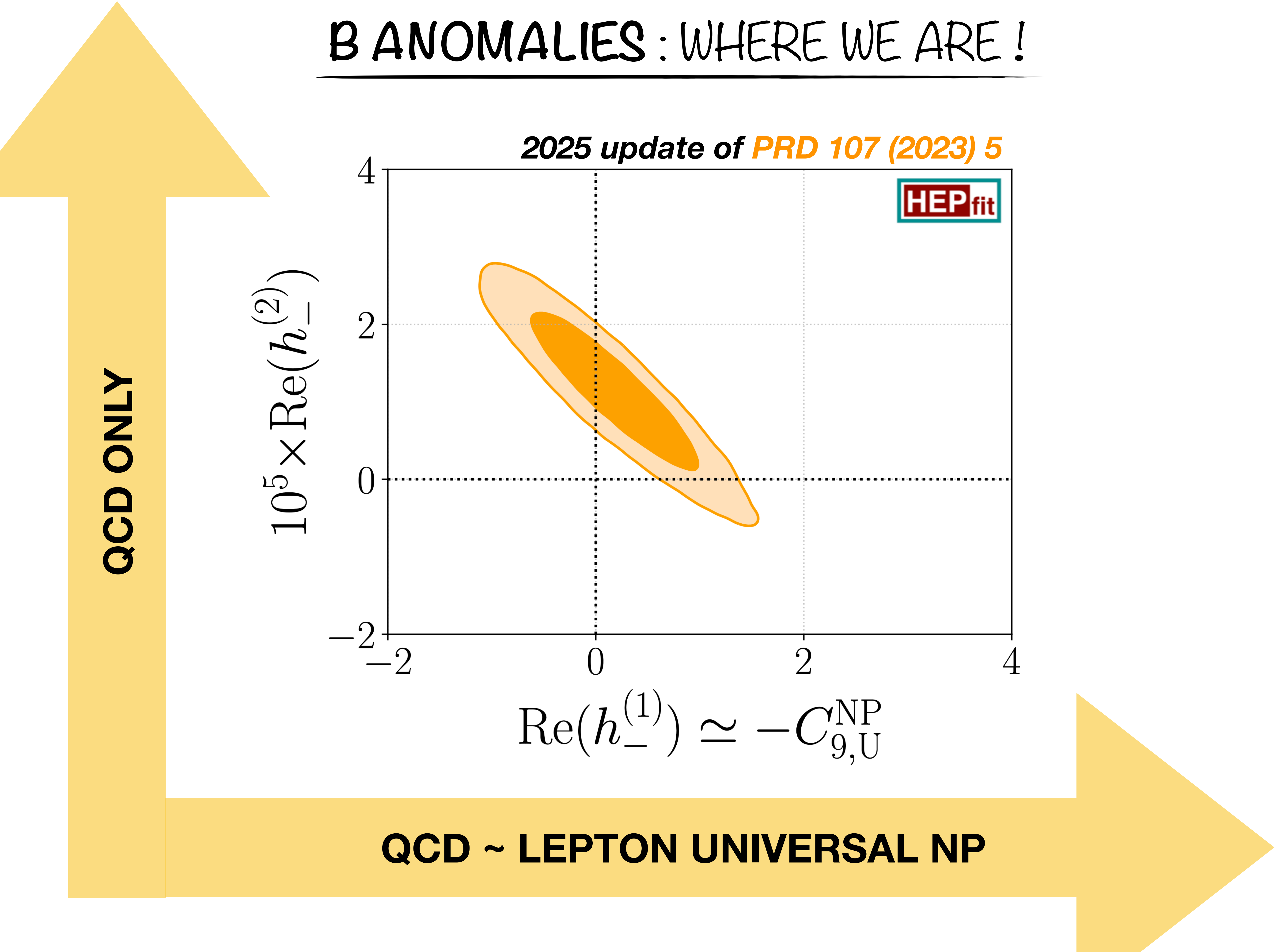
B ANOMALIES : ~ 2 YEARS AGO



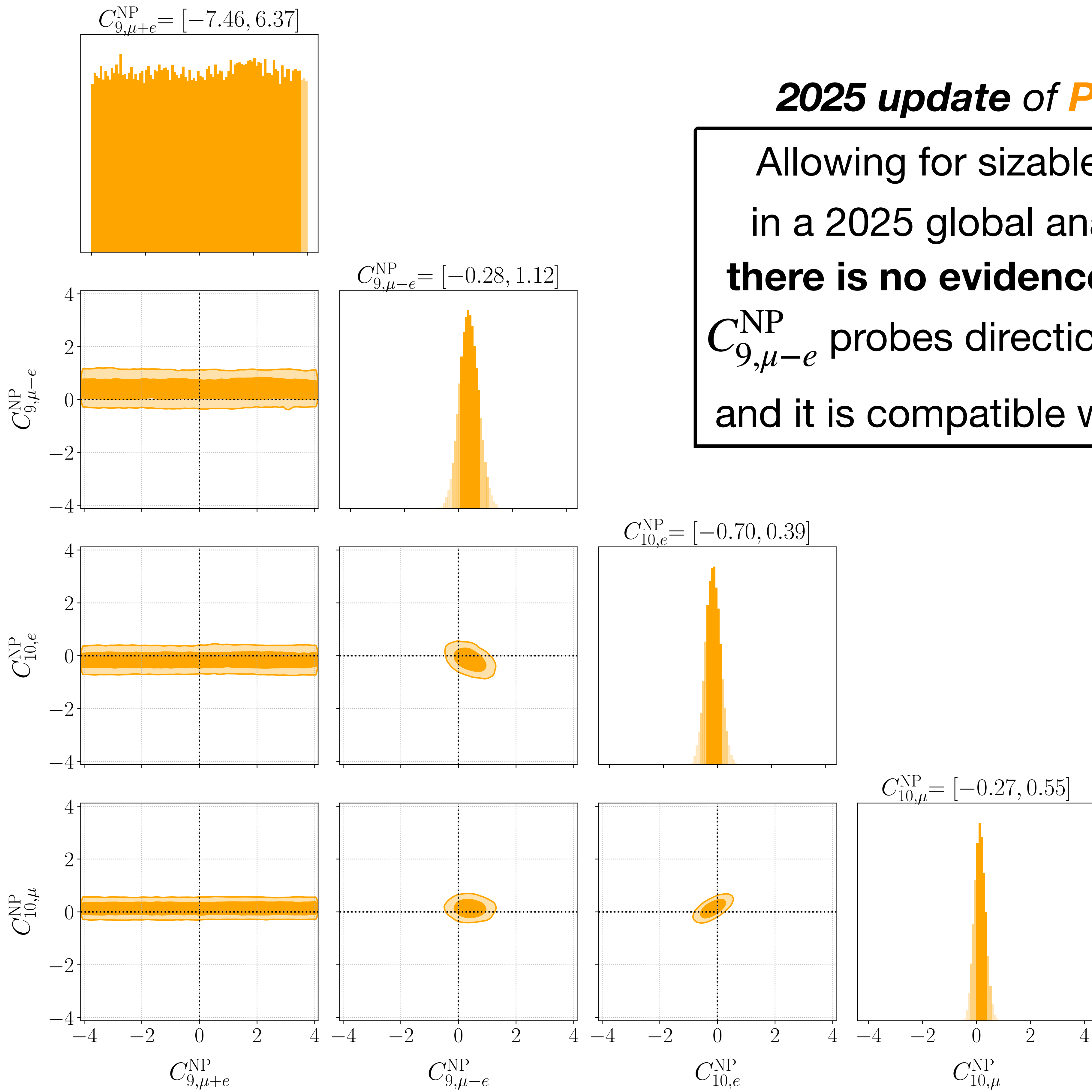
QCD ONLY

QCD ~ LEPTON UNIVERSAL NP

B ANOMALIES : WHERE WE ARE !



B ANOMALIES : "EVIDENCE" FOR NEW PHYSICS



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

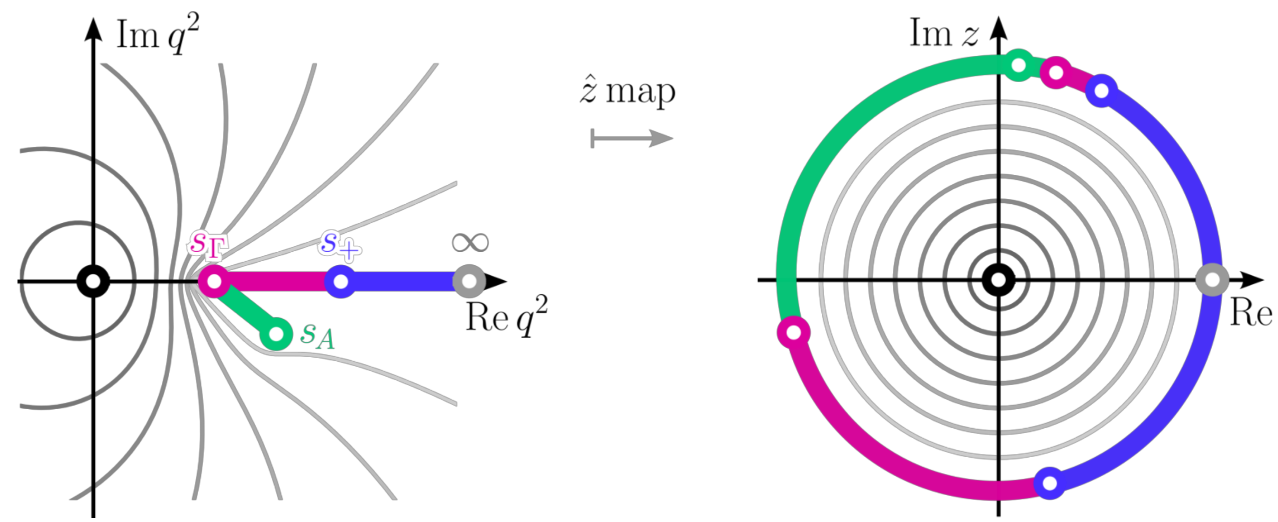
Allowing for sizable hadronic effects,
in a 2025 global analysis of $b \to s\ell\ell$
there is no evidence for New Physics.
$C^{NP}_{9,\mu-e}$ probes direction orthogonal to $C^{NP}_{9,U}$
and it is compatible with 0 well within 2σ.

B ANOMALIES : WHERE TO GO

#1 TAME HADRONIC EFFECTS FROM FIRST PRINCIPLES

Charming penguins may be computed on the lattice at large q² via the HLT method — ***PRD* 108 (2023) 7** — see **C.Sachrajda @ BFA 2025**.

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



B ANOMALIES : WHERE TO GO

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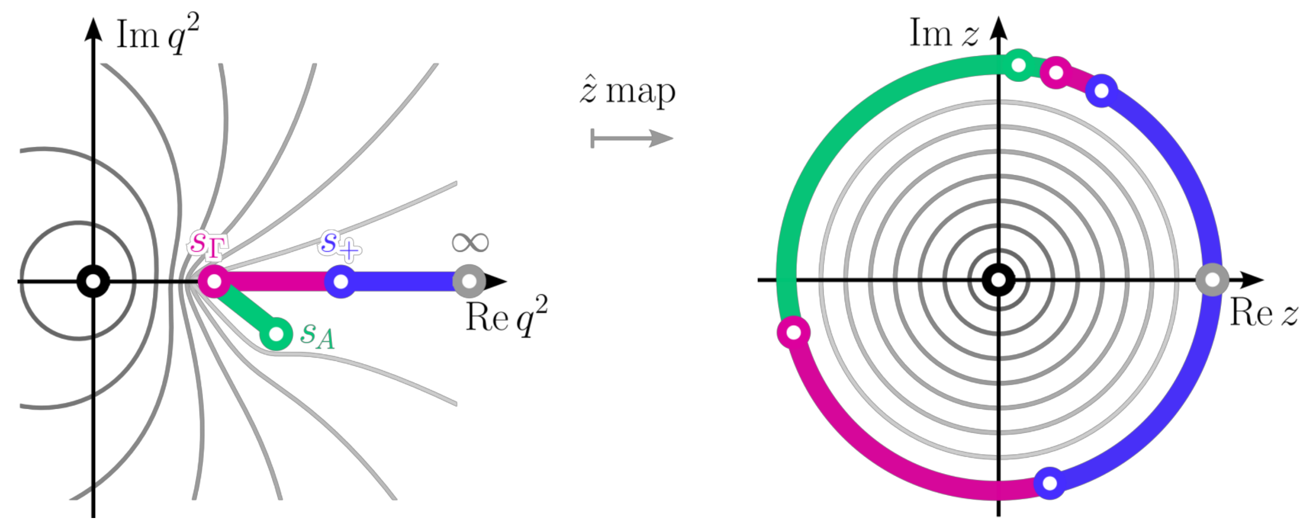
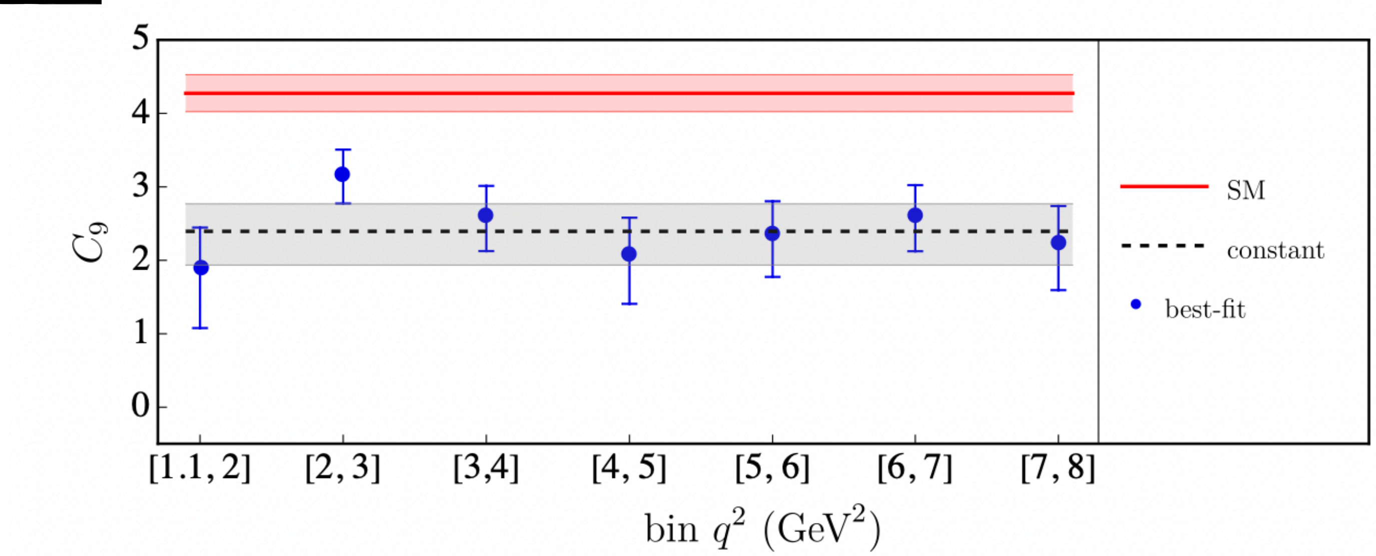
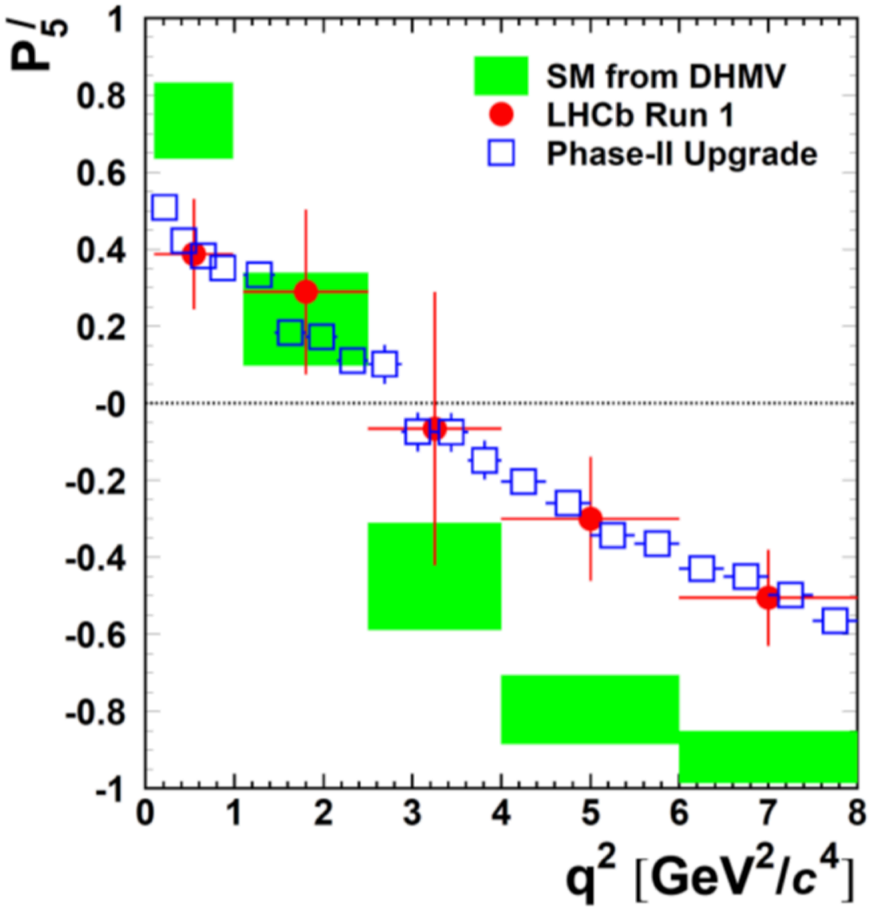


#2 COLLECT MORE DATA , MEASURE NEW OBSERVABLES



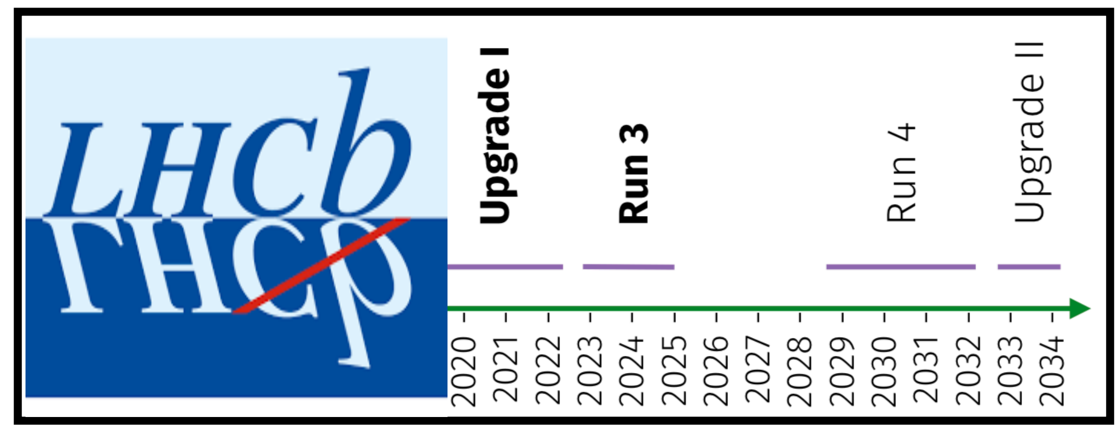
Test ΔC_9 dependence on q^2 binning, polarization of final state, for different channels.
— see ***EPJC 84 (2024) 5*** —

B ANOMALIES : A ☀ FUTURE



LHCb upgrade(s) will allow us to probe precisely the q² dependence in the angular analysis …

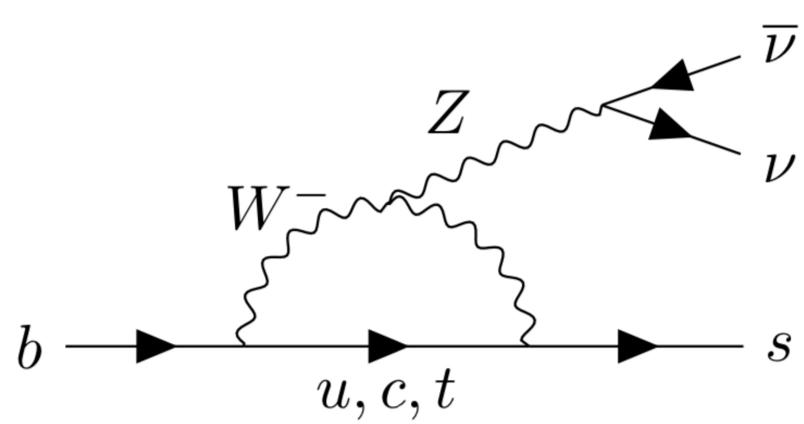
—> pin down effects from hadronic physics

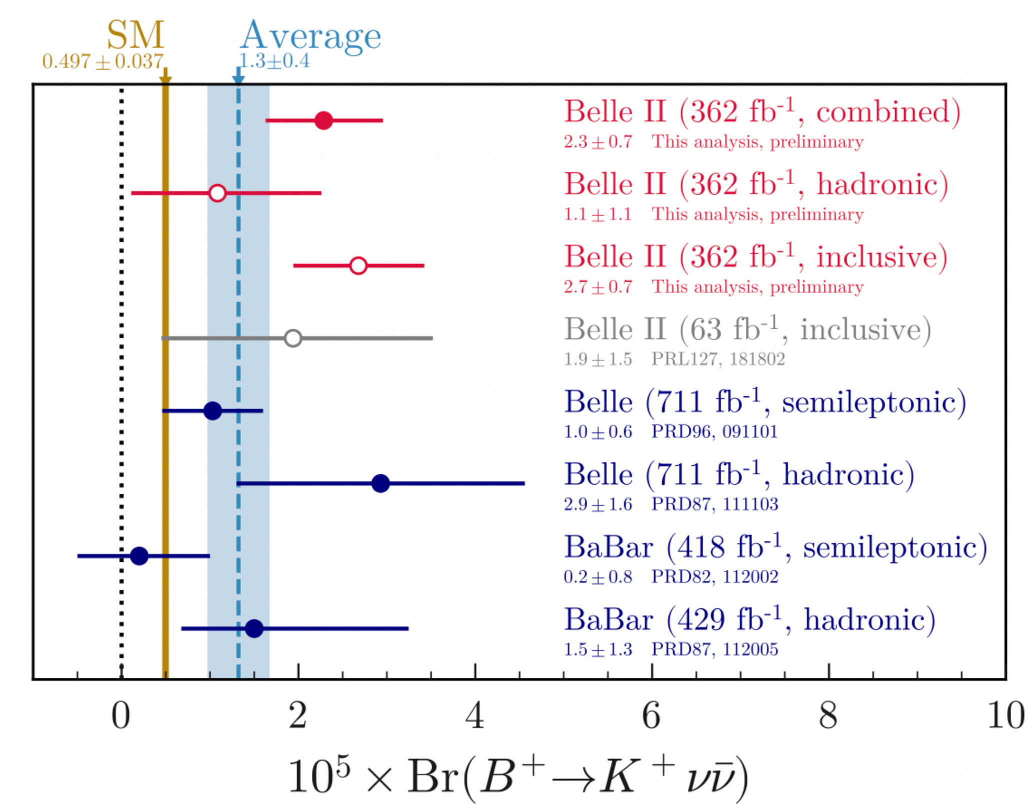


CMS & ATLAS are going to play a role as well!

Belle II is already delivering interesting results!

A POSSIBLE NEW INTERESTING ANOMALY …





Take Home

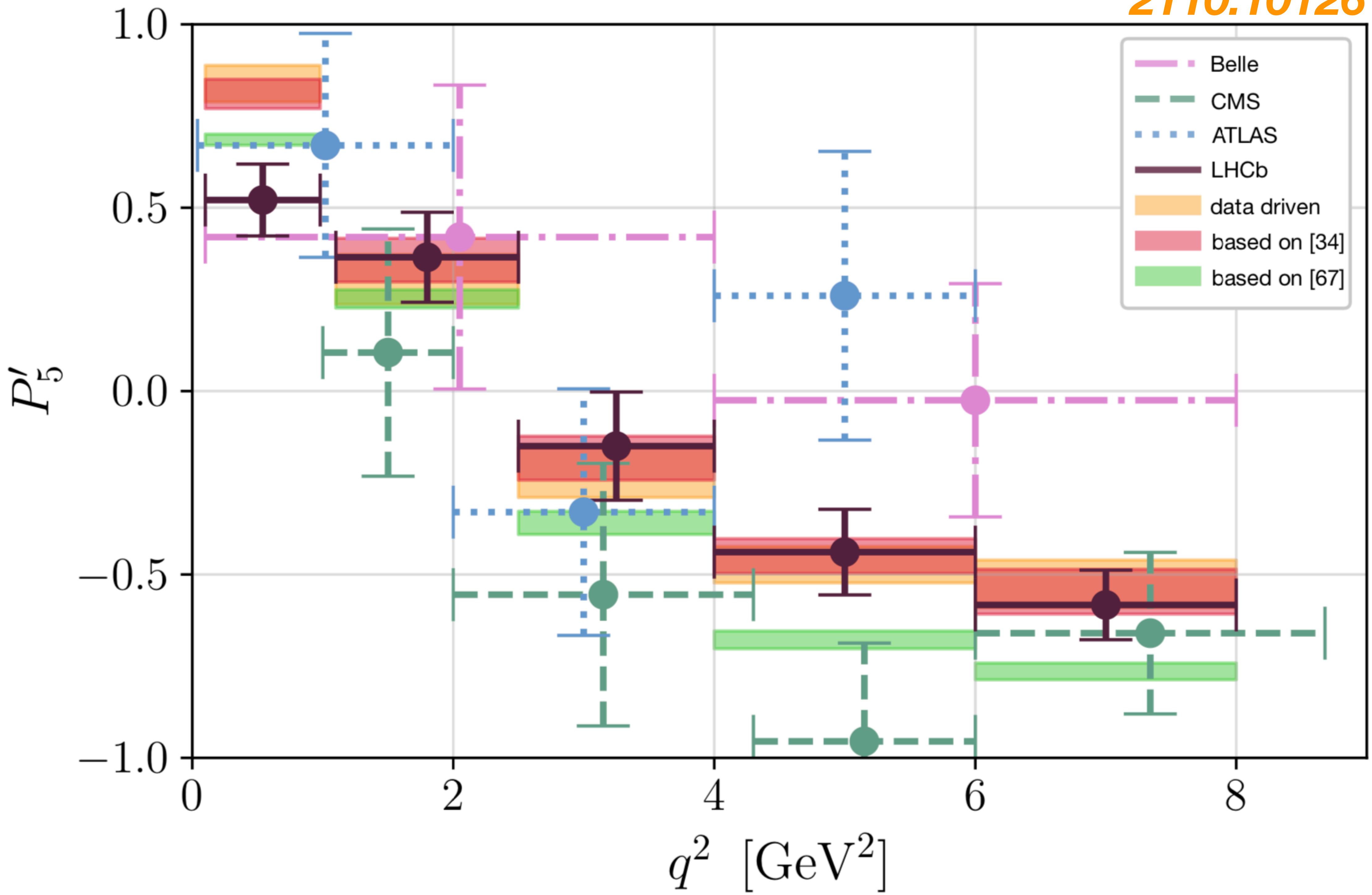
- 
WITH
GREAT ~~POWER~~ NP CLAIMS
COMES GREAT
RESPONSIBILITY
-~~SPIDERMAN~~ - M. Ciuchini

- 
ABSENCE
OF
EVIDENCE
IS NOT
EVIDENCE
OF
ABSENCE
CARL
SAGAN

BACKUP

B ANOMALIES : P_5'

2110.10126

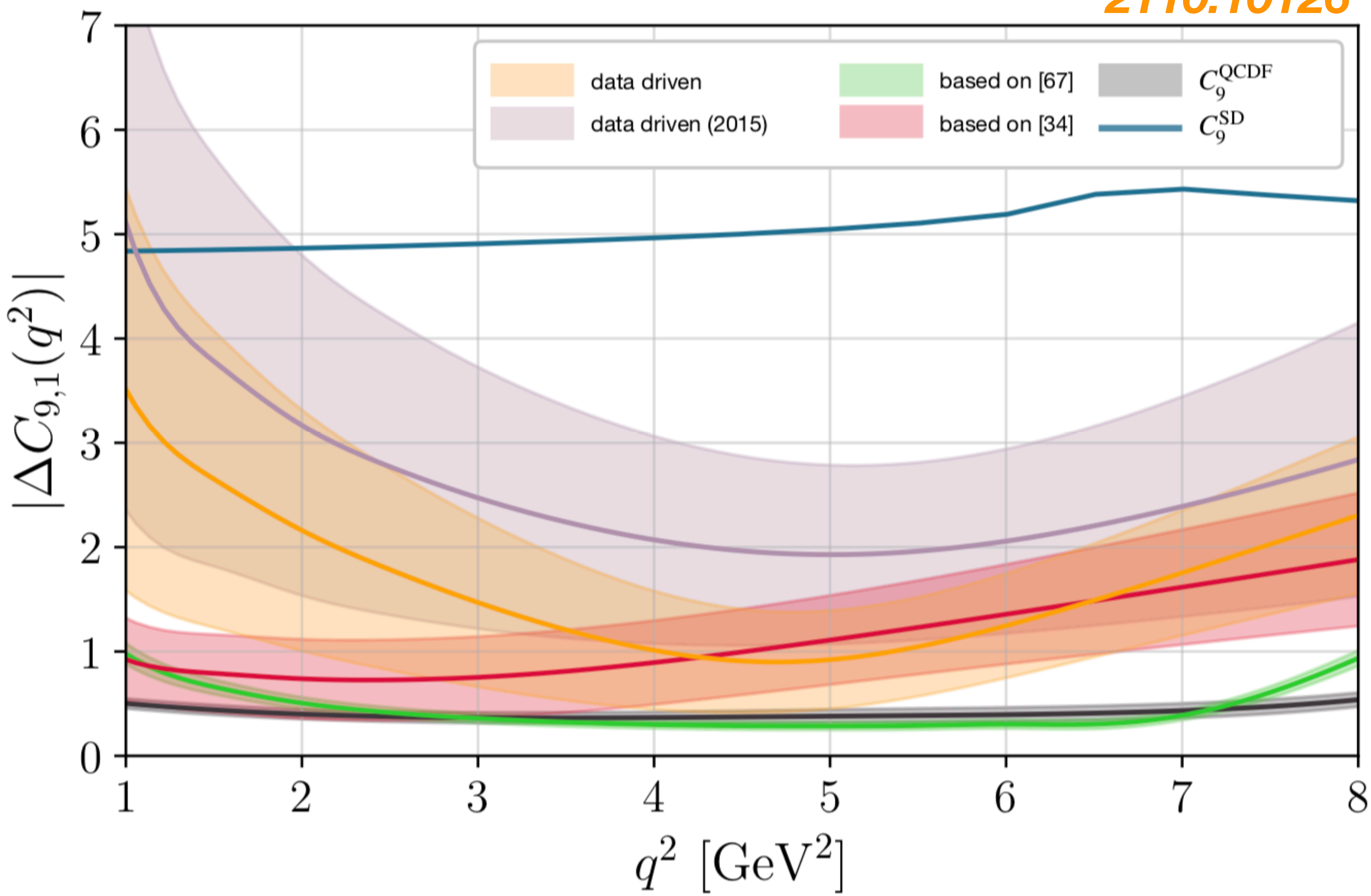


34. M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini et al., *Hadronic uncertainties in semileptonic $B \to K^* \mu^+ \mu^-$ decays*, *PoS* **BEAUTY2018** (2018) 044, [arXiv:1809.03789].

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

2110.10126



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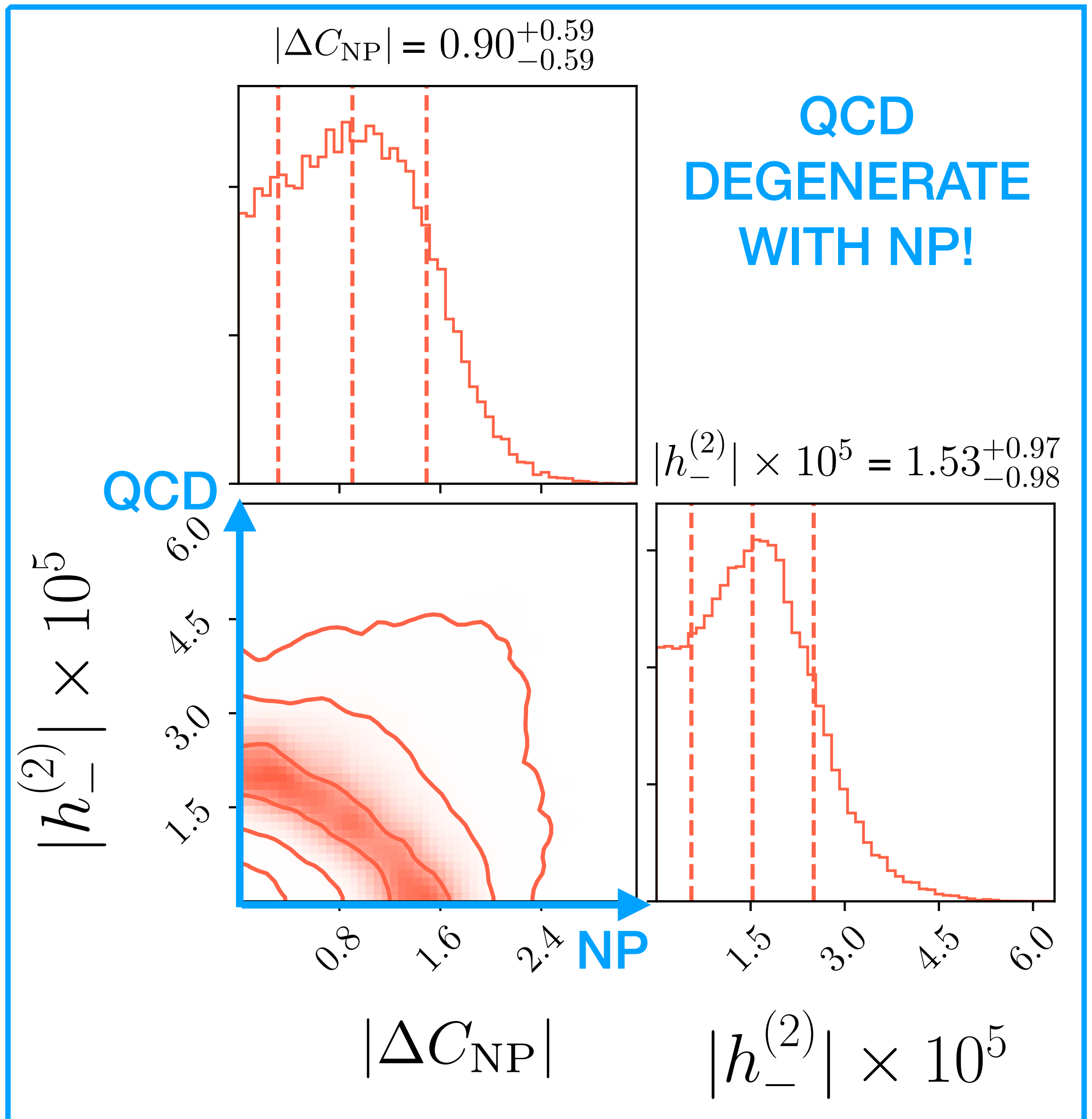
Phenomenological Data Driven

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

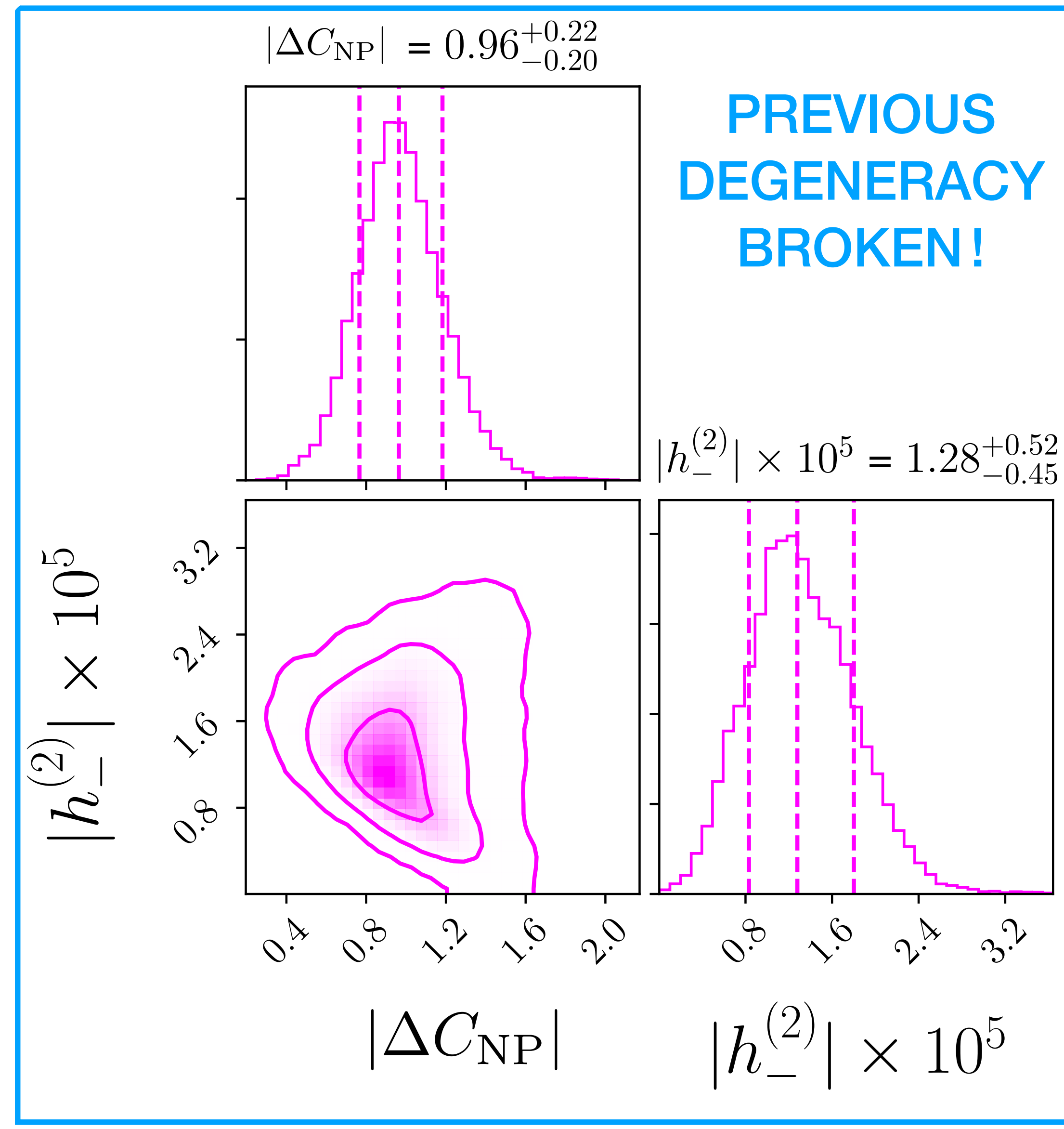


PROJECTIONS @ 50 fb^{-1}

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

RULE OF THUMB

Scaling LHCb stat errors roughly of 1/6



[*arXiv:**1809.03789***]