Behind the Flavour Anomalies : Where do we stand?

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INFN Rome

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

EFTs & Precision : Flavour

Lagrangian:

Parameter

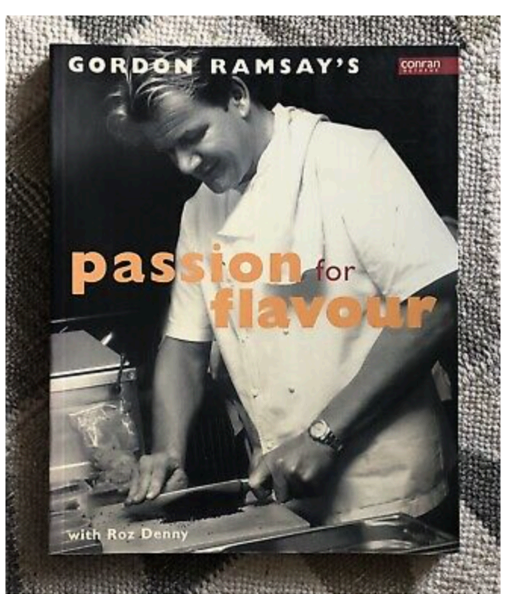
Cutoff scale

Local operator
- a monomial in fields and derivatives

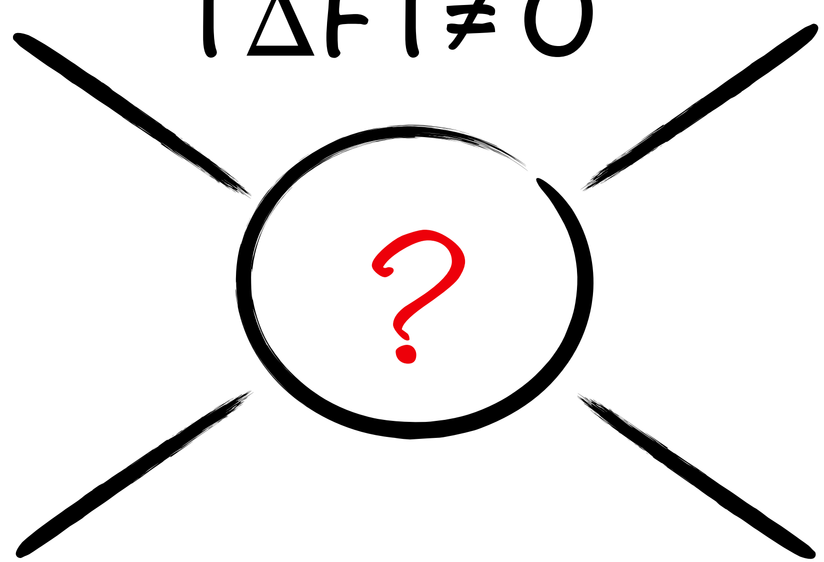
$$\mathscr{L}(x) = \sum c_{\mathcal{O}} \Lambda_{\mathcal{O}}^{4-\dim \mathcal{O}} \mathcal{O}(x)$$

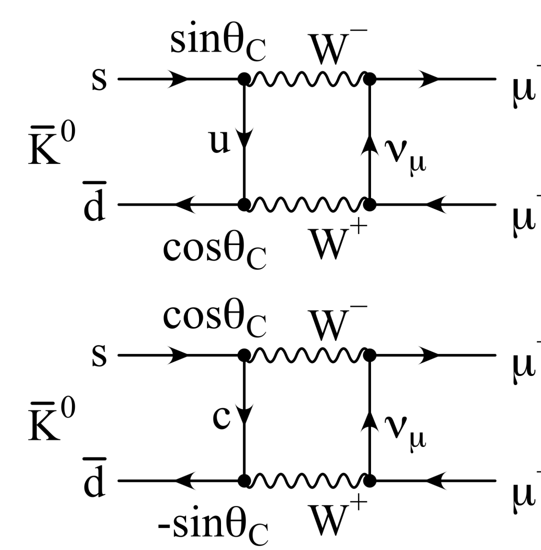
$$\text{Physical effects} \sim \left(\frac{E}{\Lambda_{\mathcal{O}}}\right)^{\dim \mathcal{O}-4}$$

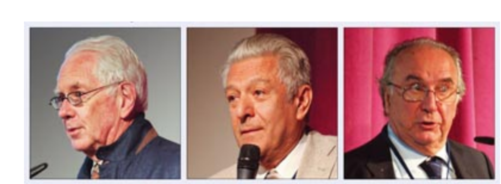
A. Greljo @ LHC Forum '23



$|\Delta F| \neq 0$

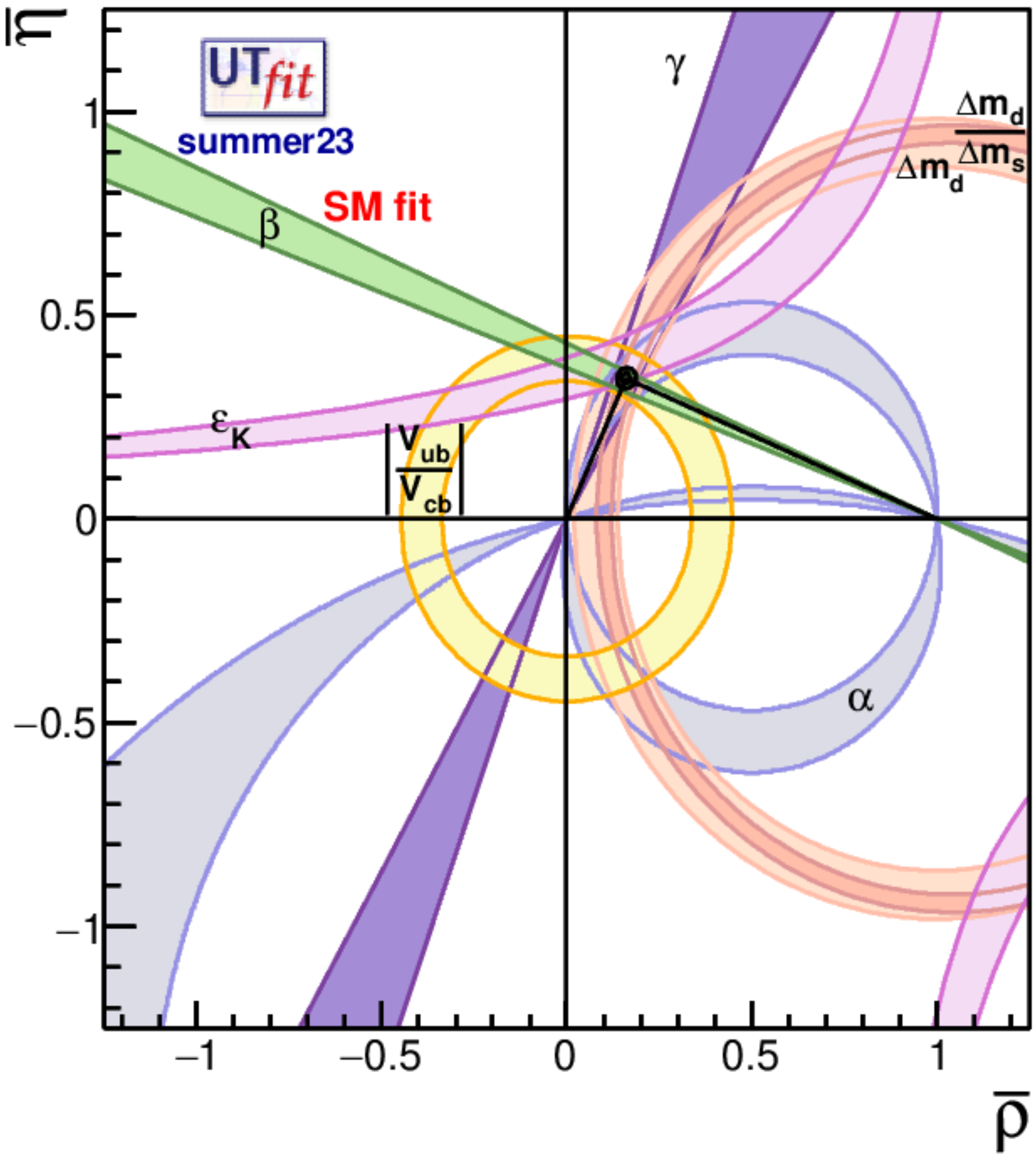






UTA: Unitarity Triangle Analysis

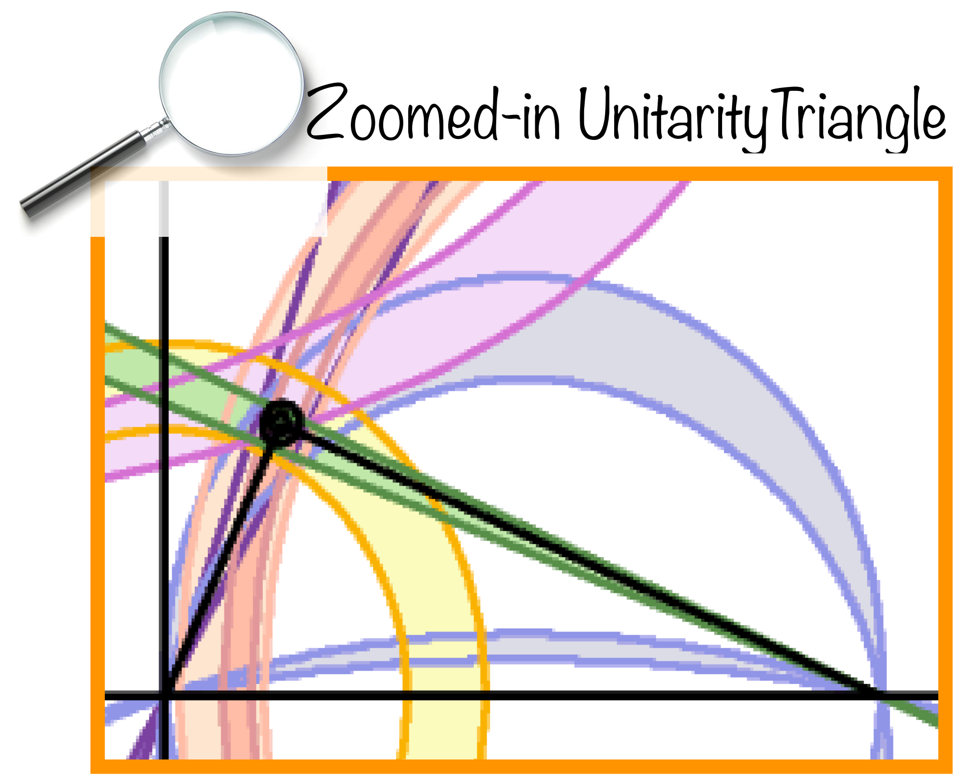
@ 95% prob



$$\bar{\rho} = 0.160 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.346 \pm 0.009 \sim 3\%$$

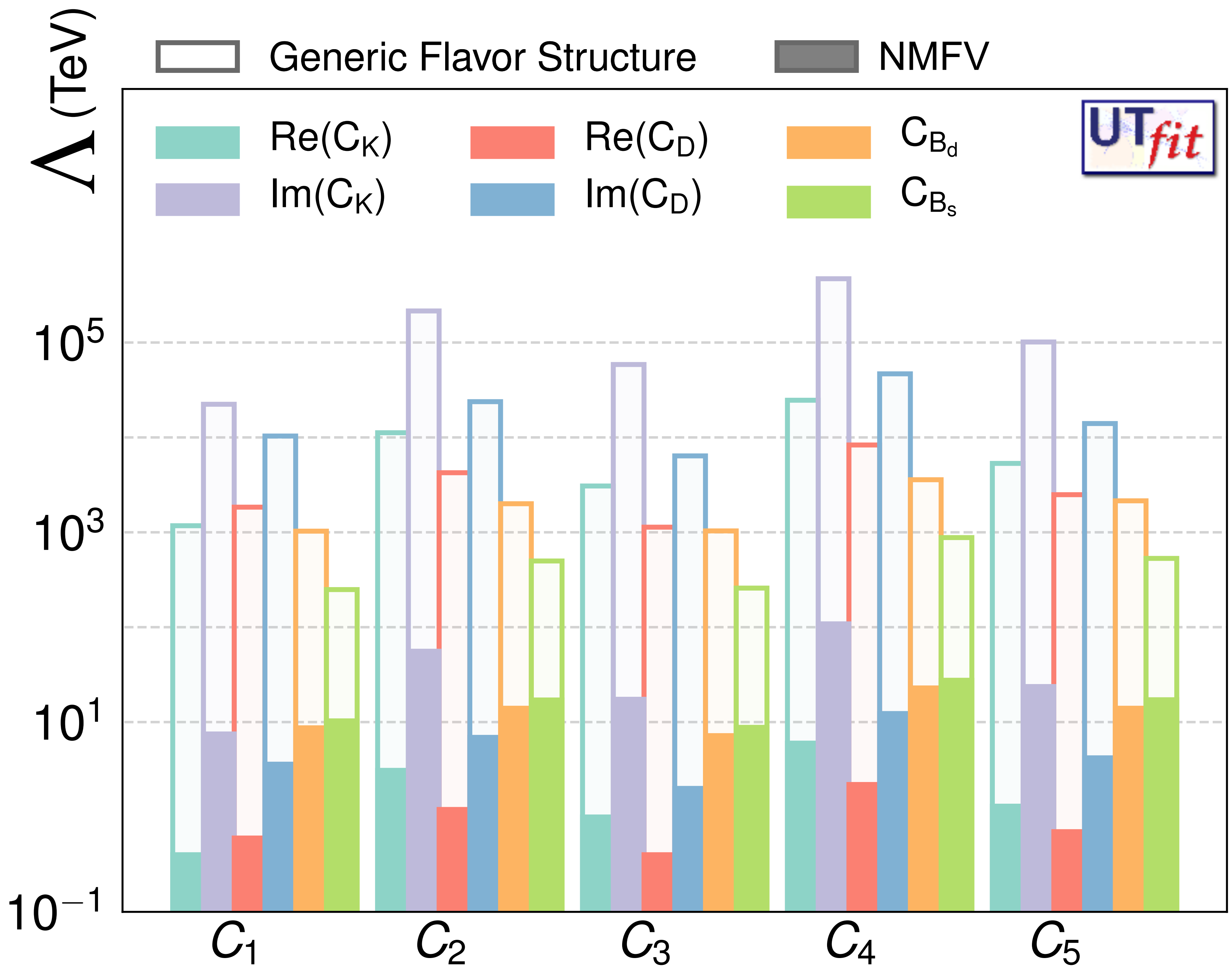
$$\lambda = 0.2251 \pm 0.0008$$
$$A = 0.827 \pm 0.010$$

Zoomed-in Unitarity Triangle



Rend. Lincei Sci. Fis. Nat. 34 (2023) 37

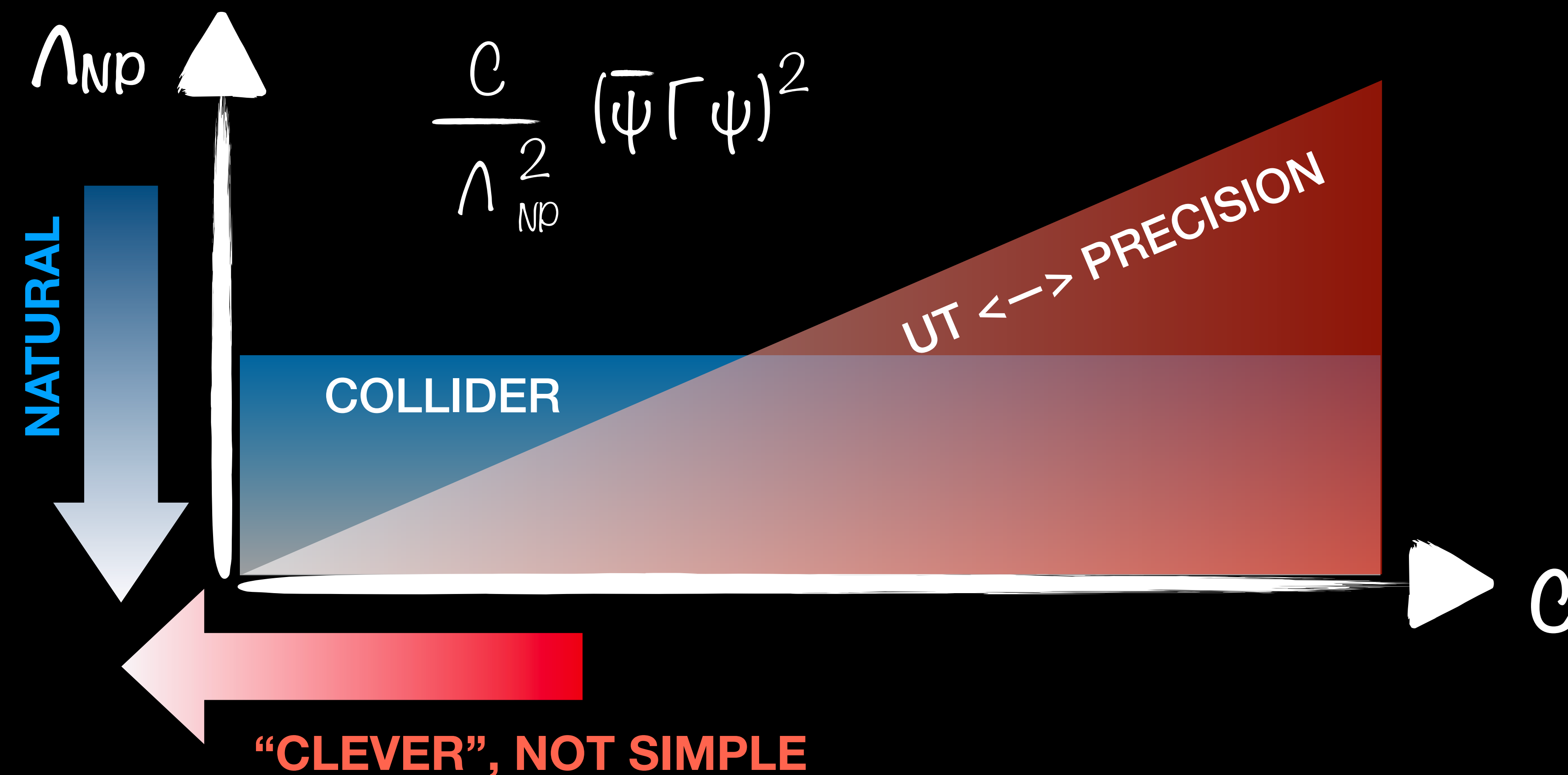
Flavour & BSM Physics



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

Lessons from UTA

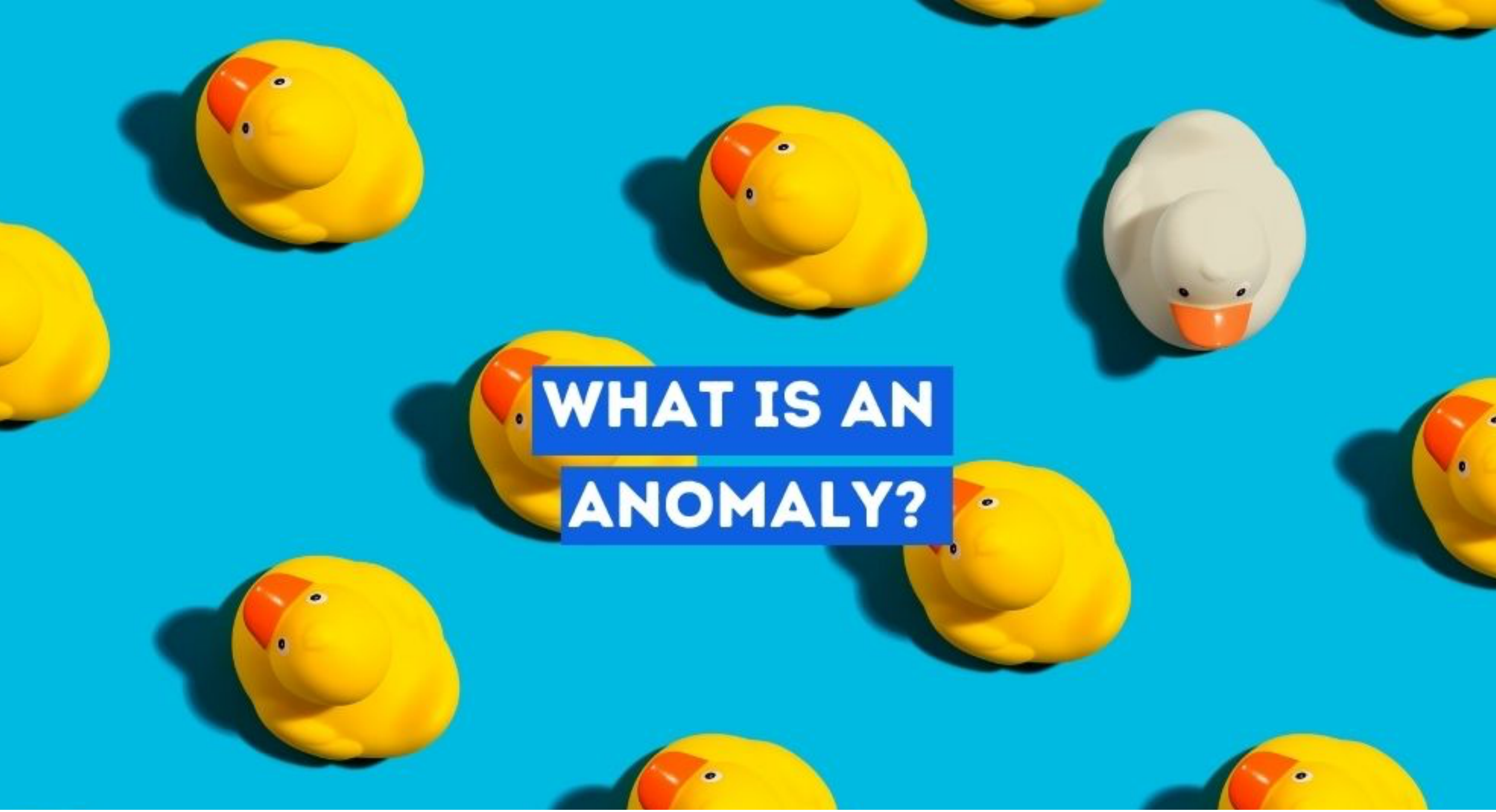
- SM UT : Towards % precision … Overall remarkable consistency.
- NP UT :



BOTTOM LINE

A theory of Flavour is either highly non-trivial or likely unnatural

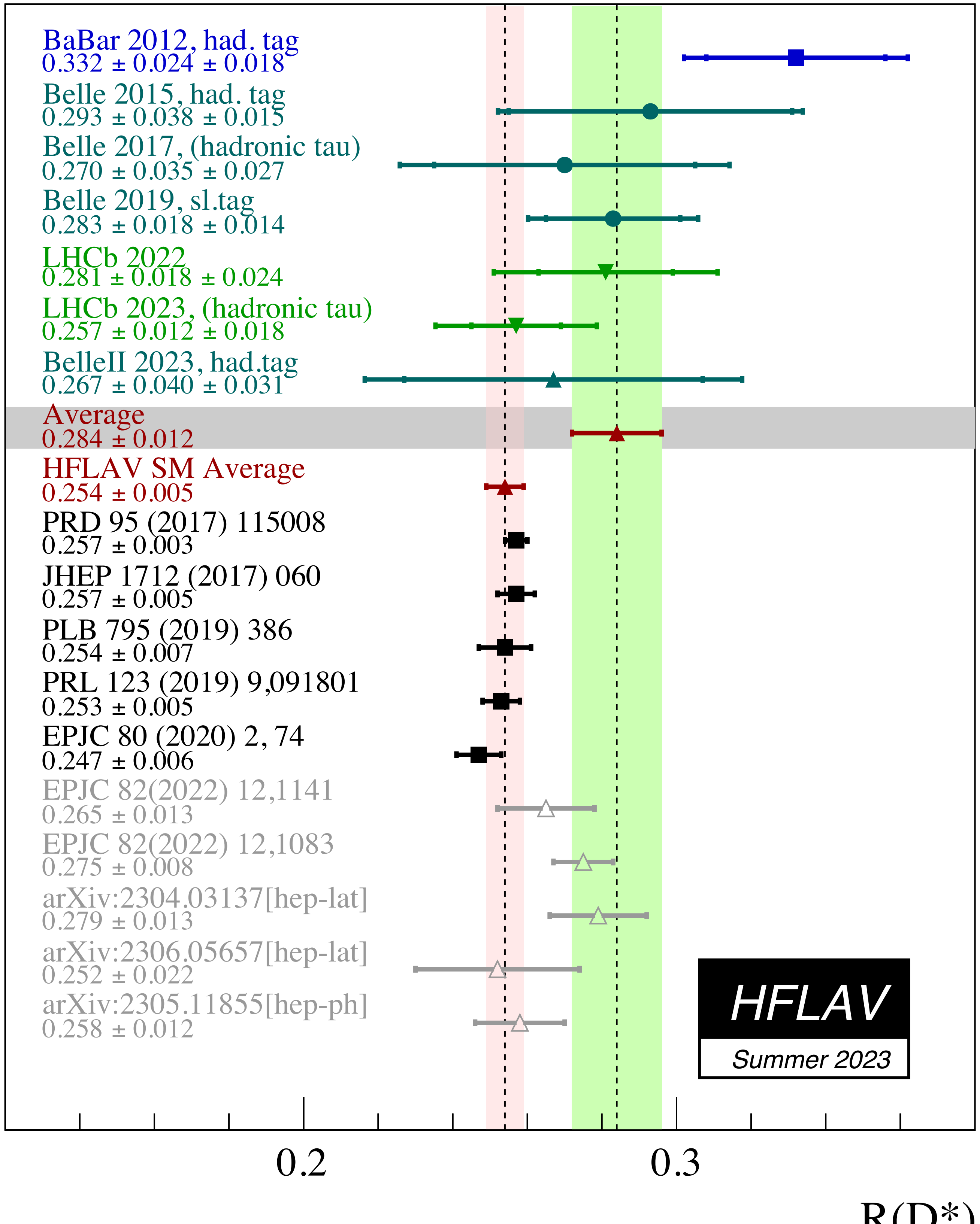
BEHIND THE FLAVOUR **ANOMALIES** THERE IS A PICTURE LIKE THAT !

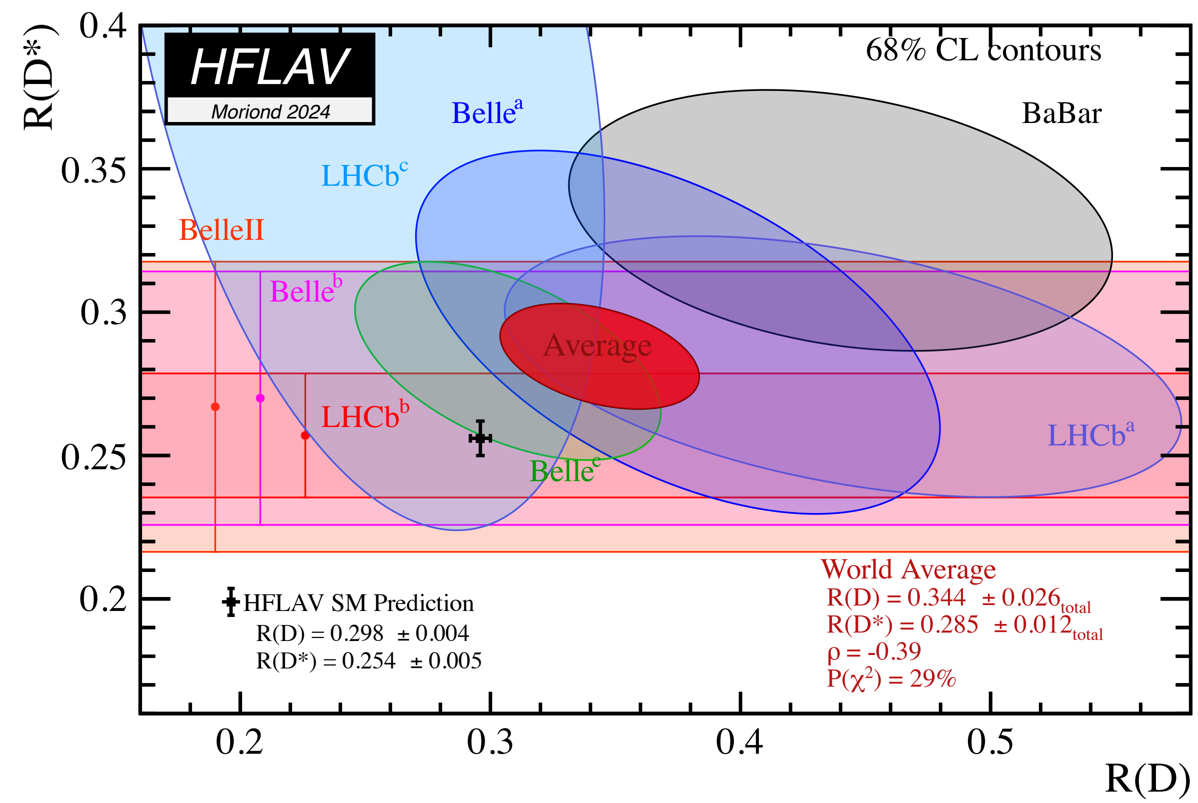


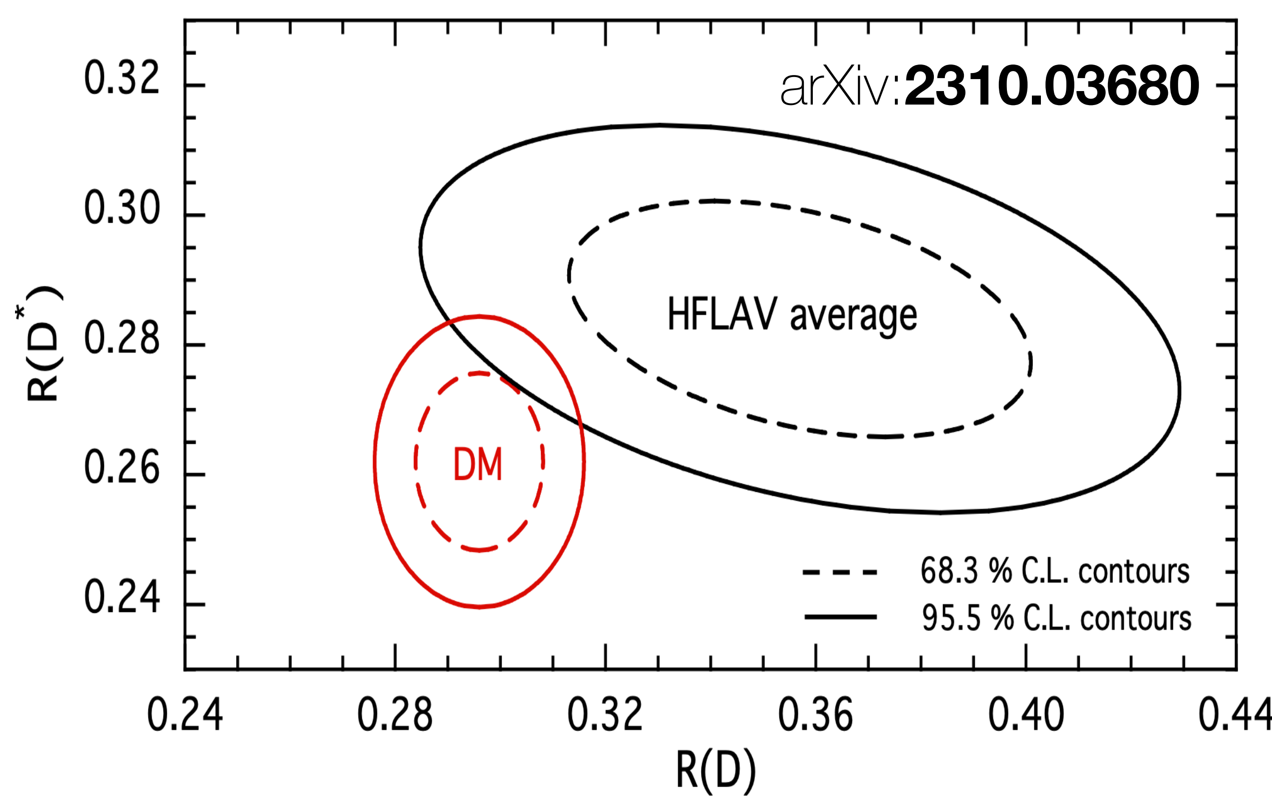
ChatGPT

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.

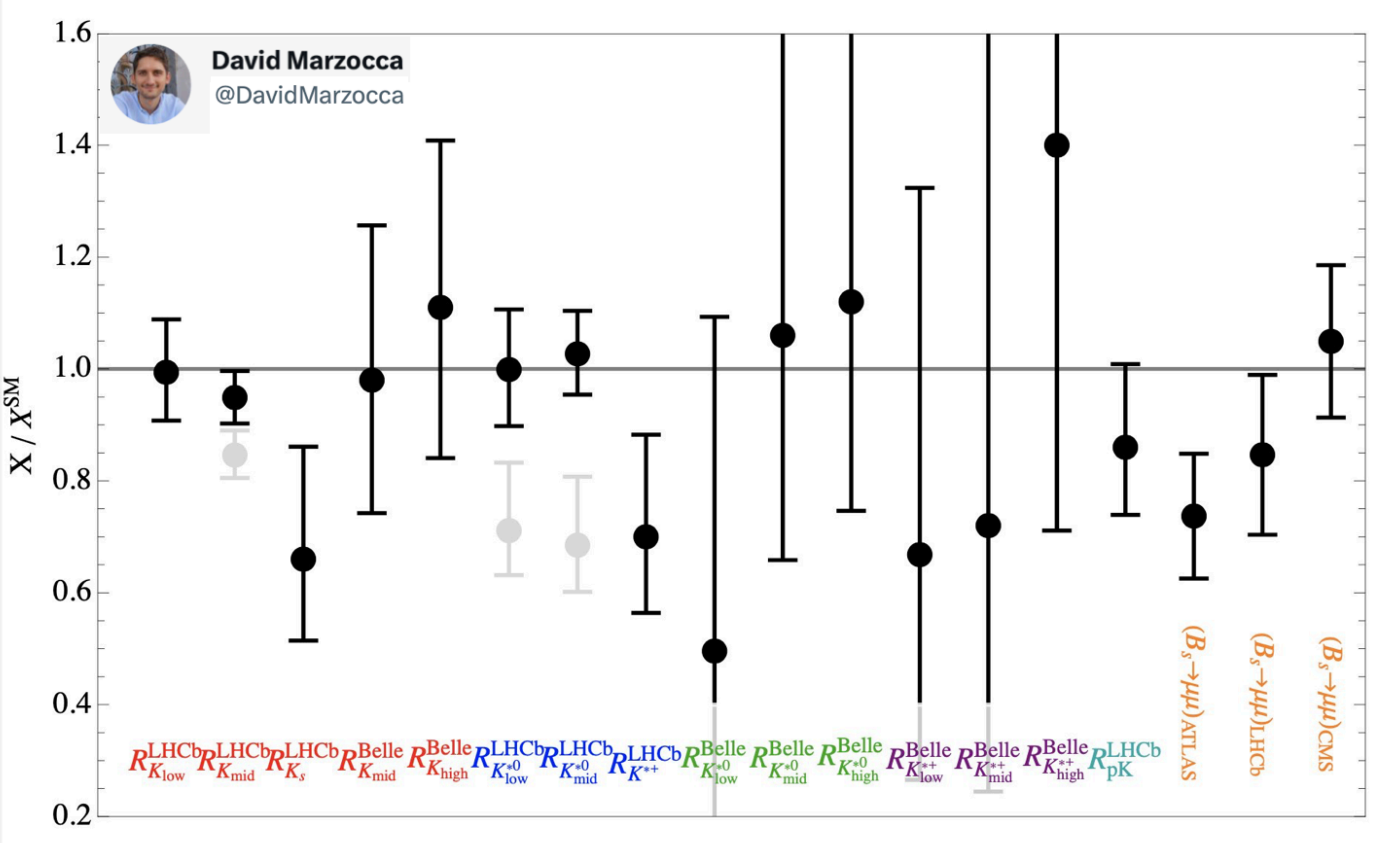
Are These (Exciting) Anomalies ? ...







... There Were Exciting Anomalies ...



B ANOMALIES : WHERE ARE WE STANDING

PRD 107 (2023) 5

SMEFT GLOBAL ANALYSIS:

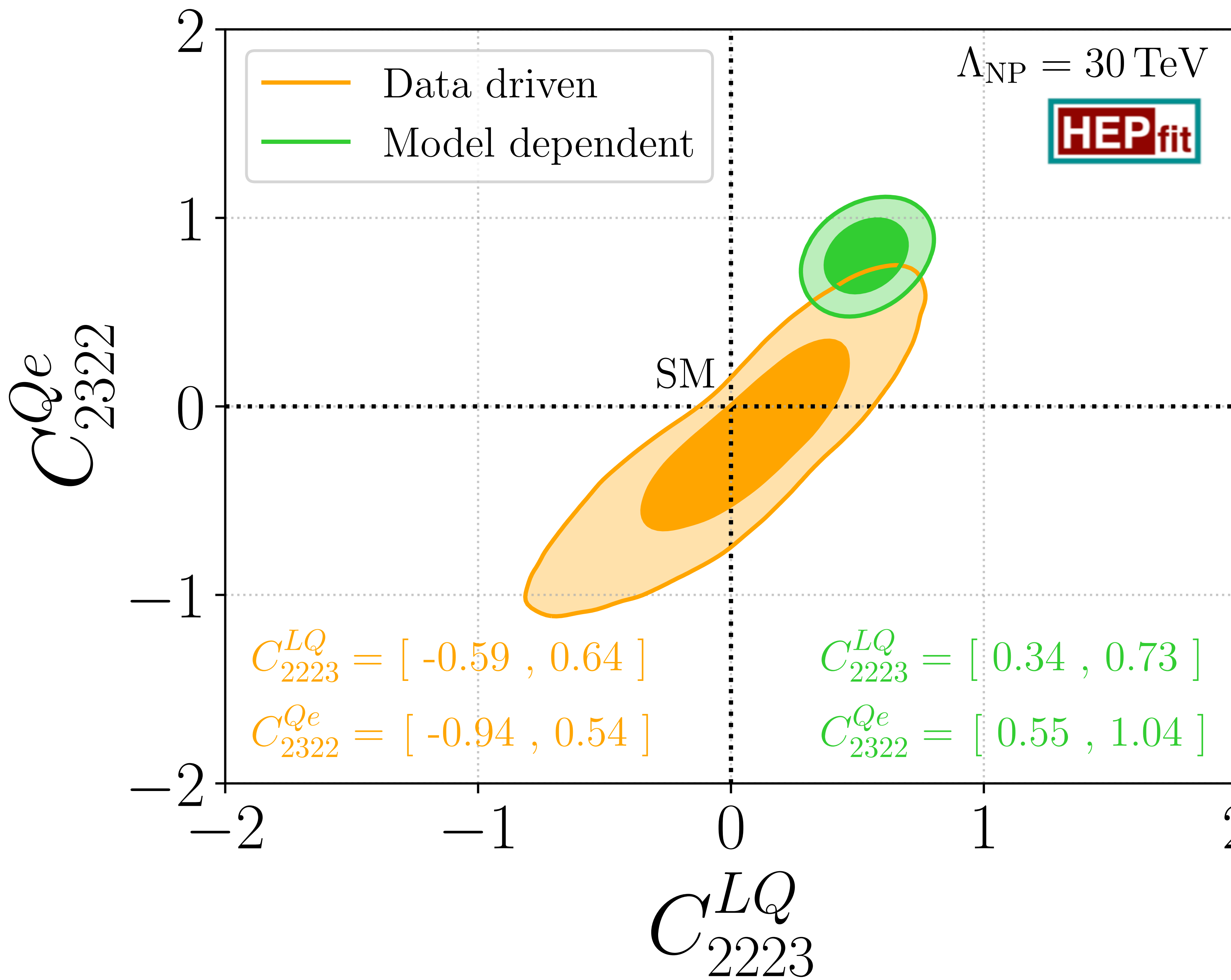
KEY **NP** OPERATORS

$$O^{LQ}_{2223} = \bar{L}_2\gamma_\mu L_2 \bar{Q}_2\gamma^\mu Q_3$$

$$O^{Qe}_{2322} = \bar{Q}_2\gamma_\mu Q_3 \bar{e}_2\gamma^\mu e_2$$

$$C_9 \propto C^{Qe} + C^{LQ}$$

$$C_{10} \propto C^{Qe} - C^{LQ}$$



B ANOMALIES : WHERE ARE WE STANDING

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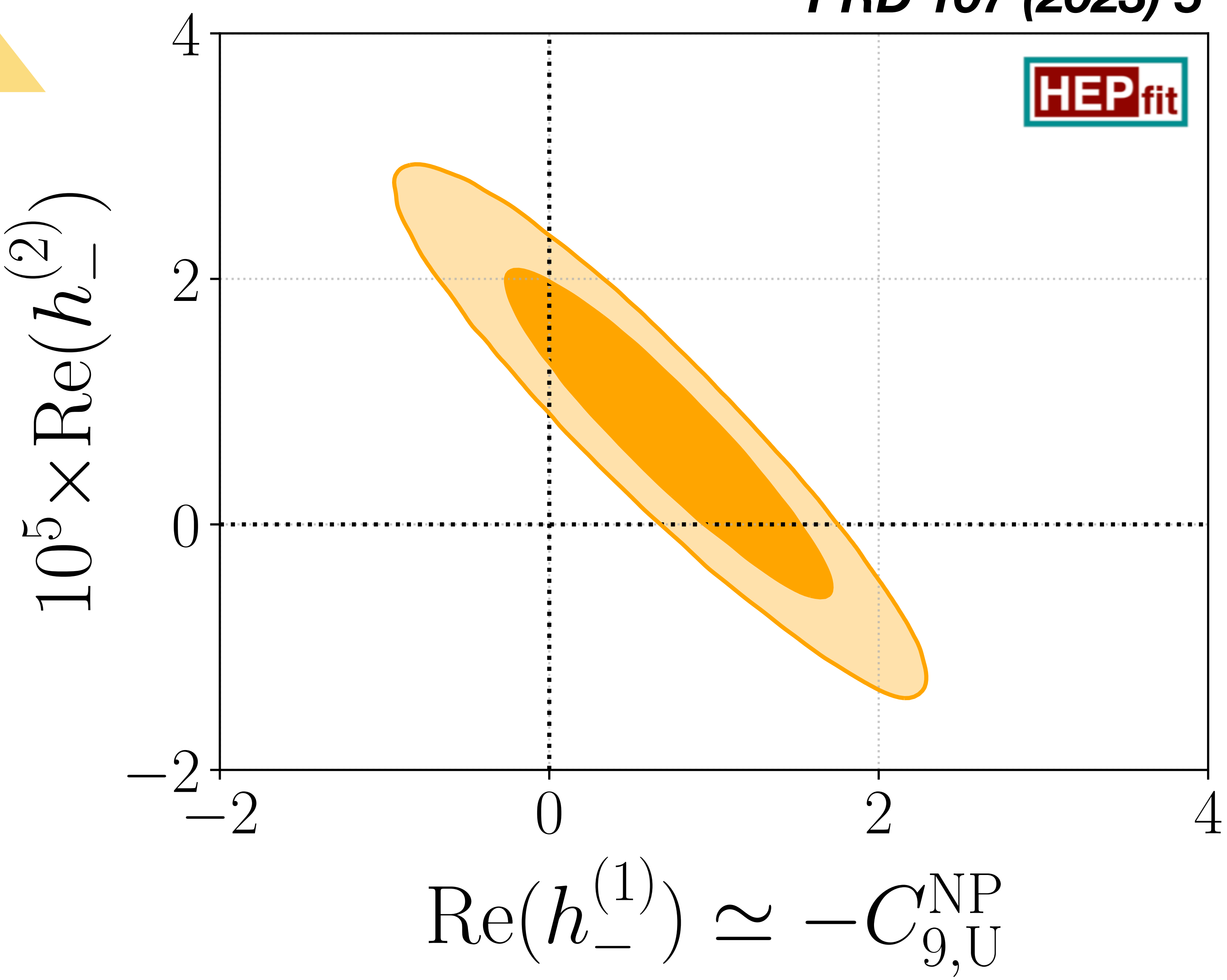
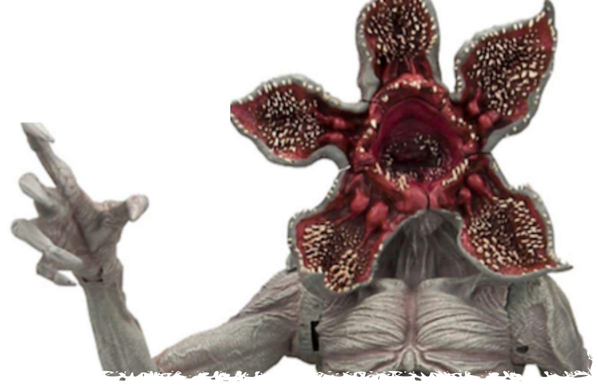


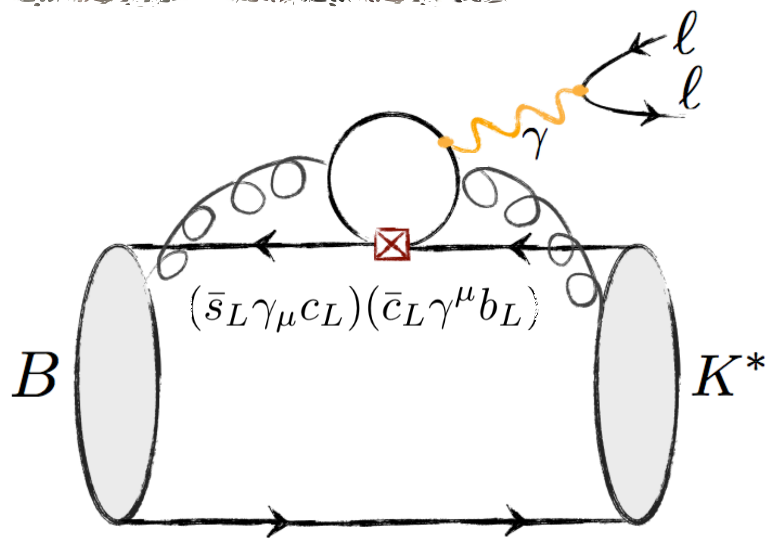
QCD ONLY

QCD ~ LEPTON UNIVERSAL NP



KNOWN UNKNOWNS IN $B \to K^* \ell\ell$

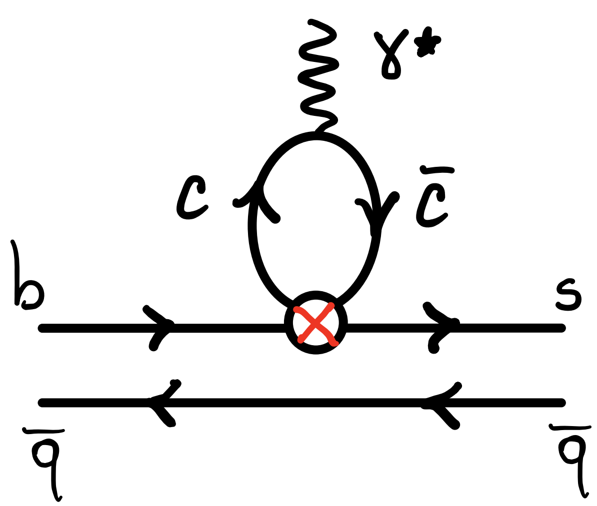
$$h_\lambda(q^2) = \frac{\epsilon^*_\mu(\lambda)}{m_B^2} \int d^4x e^{iqx} \langle \bar{K}^* | T\{ j^\mu_{\rm em}(x) \mathcal{H}^{\rm had}_{\rm eff}(0)\} | \bar{B} \rangle$$



***JHEP* 09 (2010) 089**
—> AS SMALL AS IN
QCD FACTORIZATION

1) Light-cone sum rules (LCSR)
2) Single soft gluon approx.
3) Pheno extrapolation to J/ψ

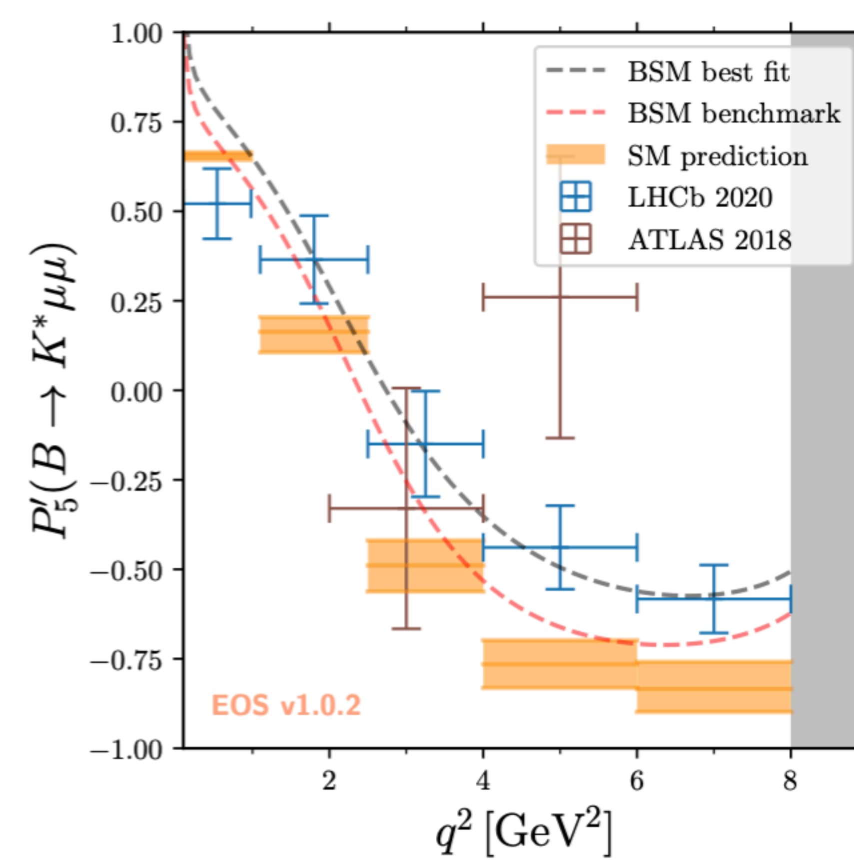
MORE RECENTLY RECOMPUTED IN [***JHEP* 02 (2021) 088**, ***JHEP* 09 (2022) 133**]



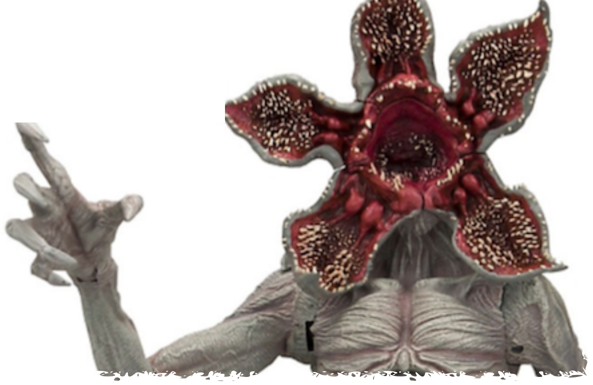
1) LCSR at $q^2 \leq 0$

*2) Szego polynomials **(!)***
to exploit analyticity
and B —> M J/ψ data

3) dispersive bounds



CHARMING PENGUINS VERY TINY (?)
NP REQUIRED TO ADDRESS DATA.



Known Unknowns in $B \to K^* \ell\ell$

JHEP 06 (2016) 116, *JHEP* 07 (2017) 025, EPJC 83 (2023) 1

A DATA DRIVEN APPROACH

$$\tilde{h}_\lambda(q^2) = \sum_k \tilde{h}_\lambda^{(k)} \left(\frac{q^2}{\mathrm{GeV}^2}\right)^k$$

up to *k = 2*, 16 real coeffs involved

ΔC_9 (semi-lep operator) ΔC_7 (e.m. dipole operator)

$$\left\{ \left(C_9^{\rm eff} + h_-^1\right) V_{L-} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) T_{L-} - 16\pi^2 h_-^2\, q^4\right]\right\}$$

$$\left\{ \left(C_9^{\rm eff} + h_-^1\right) \tilde{V}_{L0} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) \tilde{T}_{L0} - 16\pi^2 \left(\tilde{h}_0^0 + \tilde{h}_0^1\, q^2\right)\right]\right\}$$

$$\left\{ \left(C_9^{\rm eff} + h_-^1\right) V_{L+} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) T_{L+} - 16\pi^2 \left(h_+^0 + h_+^1\, q^2 + h_+^2\, q^4\right)\right]\right\}$$

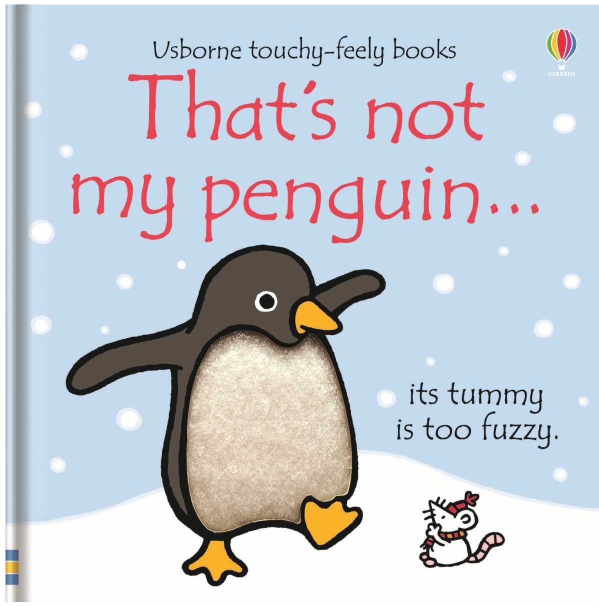
DO NOT HAVE $C_{7,9}$ SHORT-DISTANCE COUNTERPART!

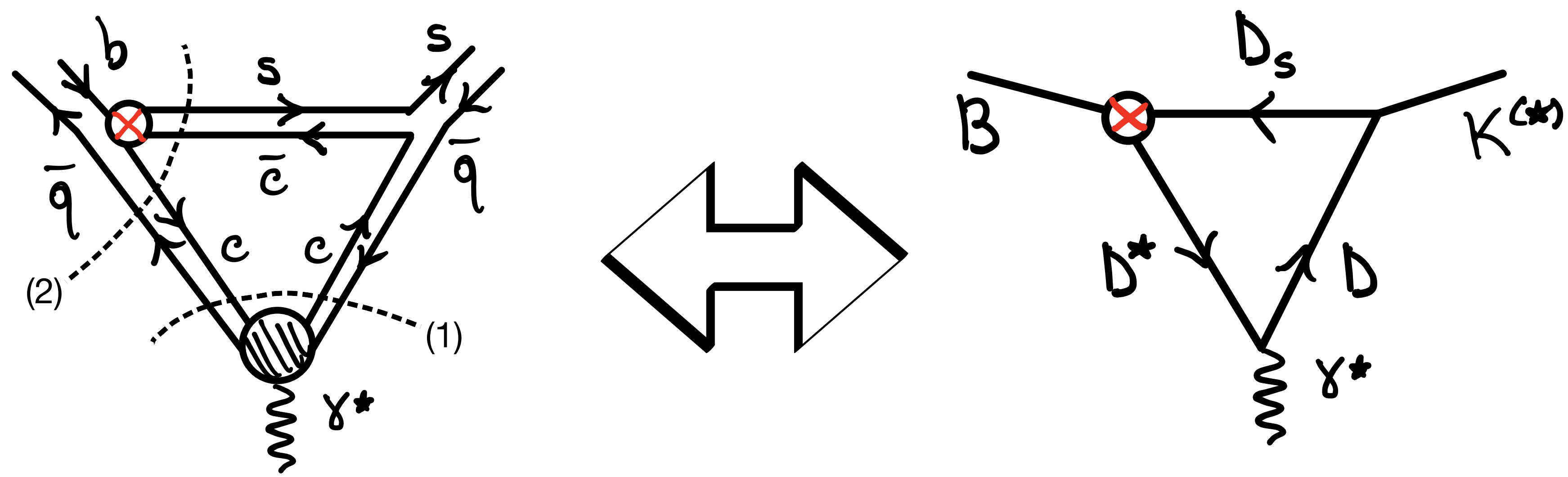
dislikes

(A) WHAT ABOUT ANALYTIC PROPERTIES OF AMPLITUDES ?

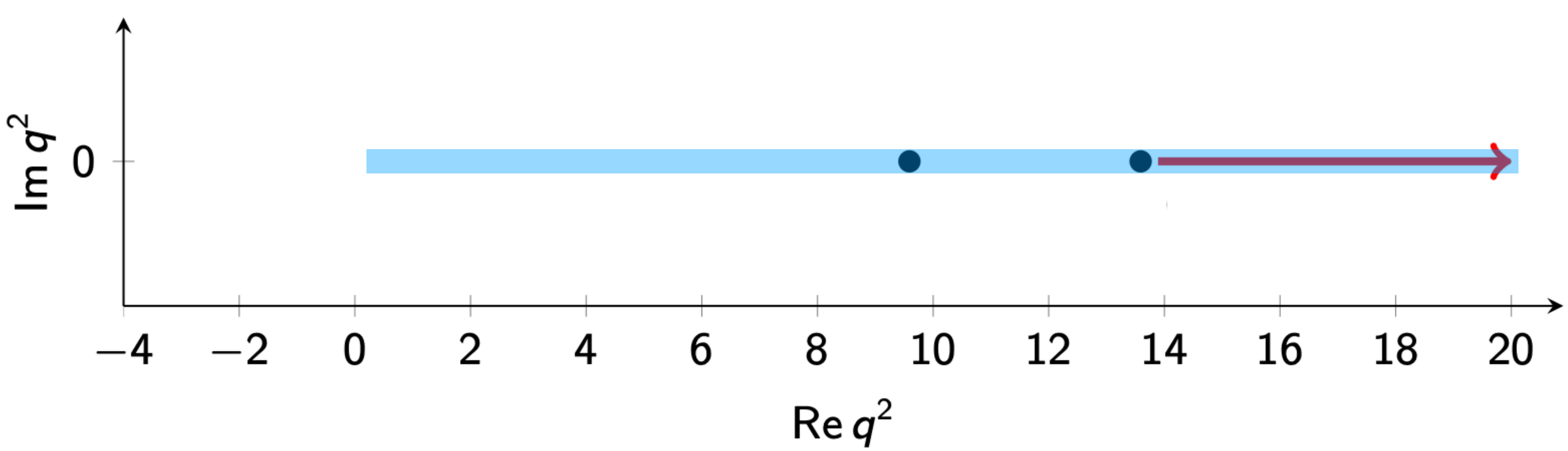
(B) HADRONIC PARAMETERIZATION HIDING NEW PHYSICS ?

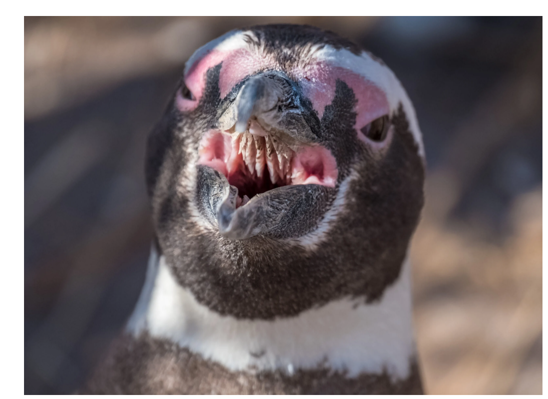
ANSWER TO (A): CHARMING PENGUINS





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

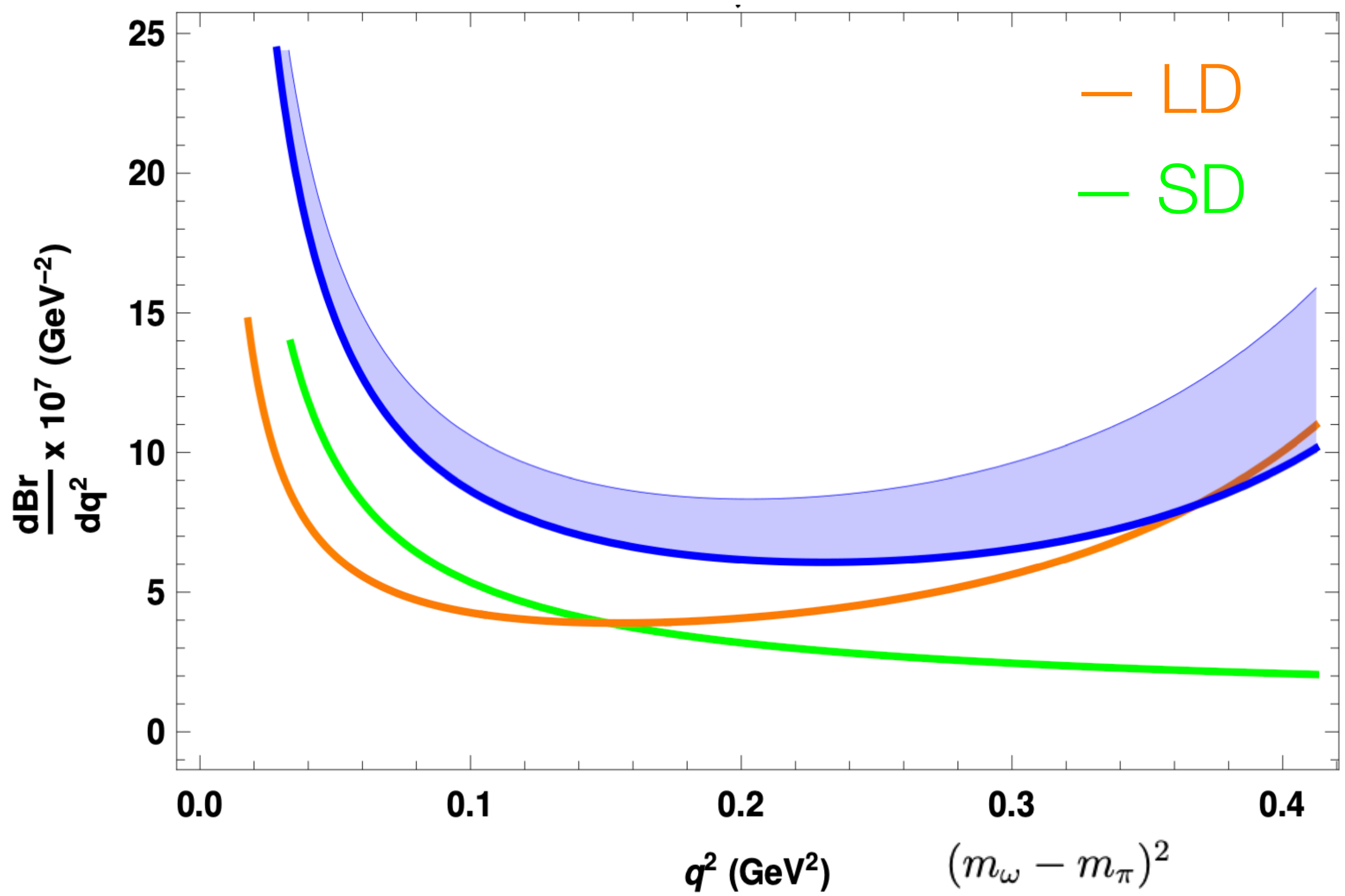


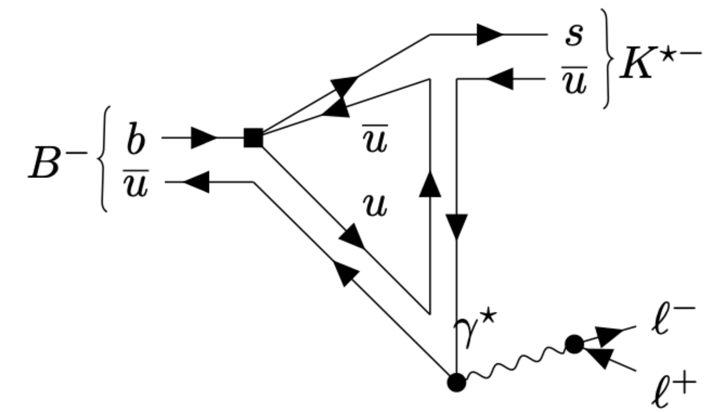


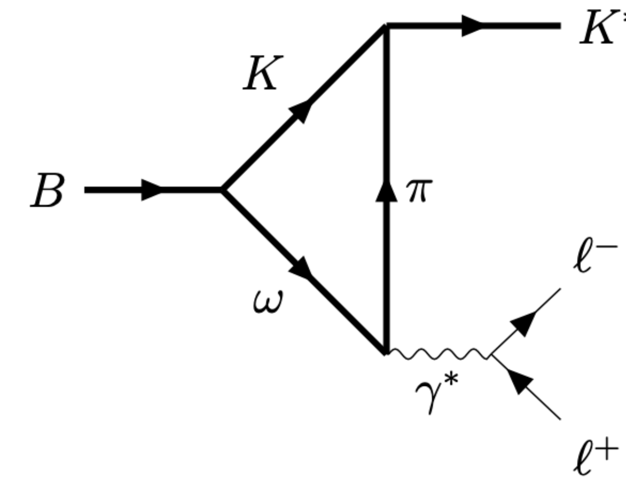
Analyticity <—> mapping into unit circle as done in ***EPJC* 78 (2018) 6**
only if *B* invariant mass would not allow for cut (2) (instead, it does!).

ANSWER TO (A): ANOMALOUS THRESHOLDS

PLB 840 (2023) 137877







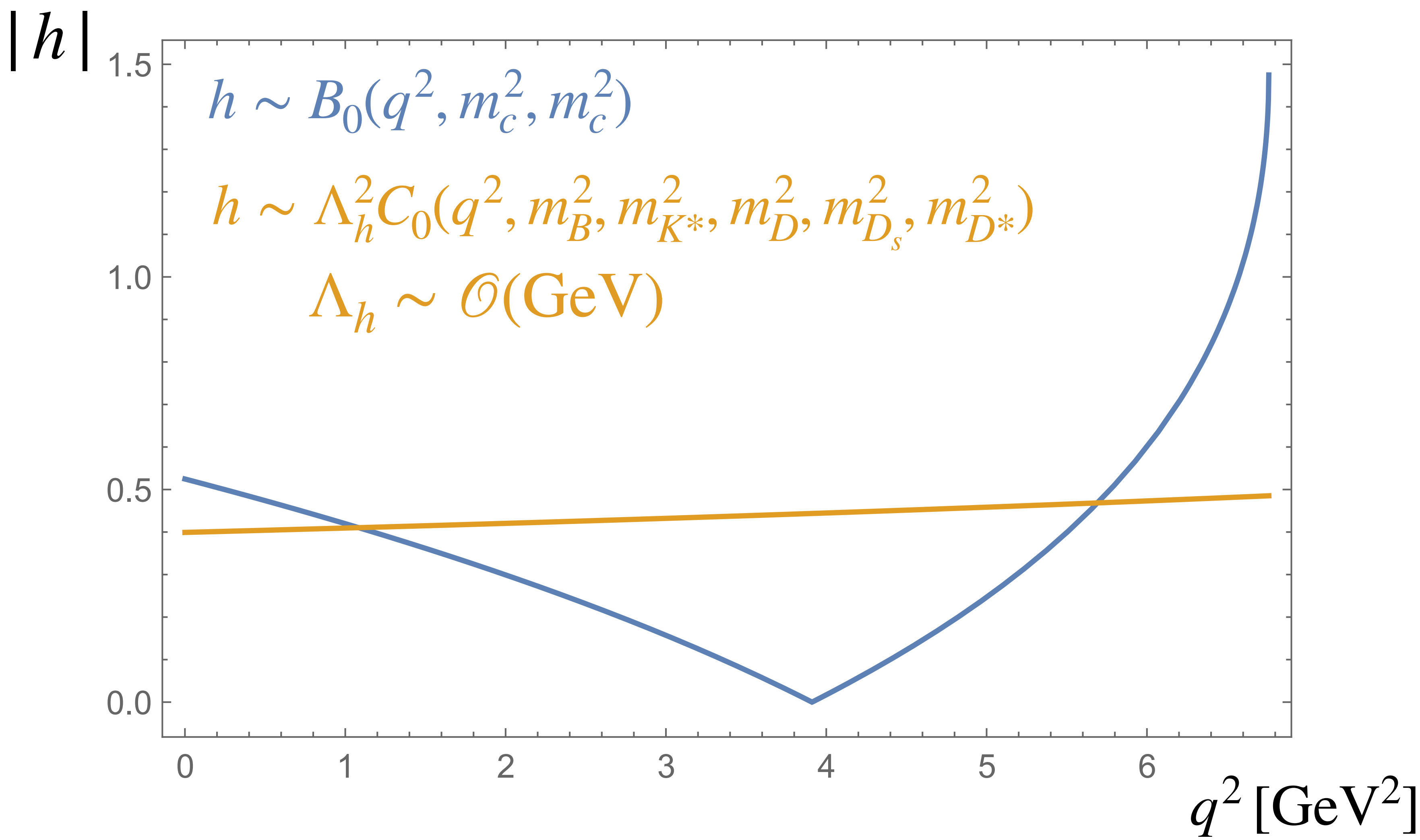
Bold estimate which highlighted the potential impact of these effects.

See talk of M. Hoferichter & S. Mutke on this!

— Anomalous thresholds depend on masses in the loop (Landau eq.s)

— Charming penguins not CKM suppressed, phenomenological impact?

ANSWER TO (A): A NAIVE CHECK

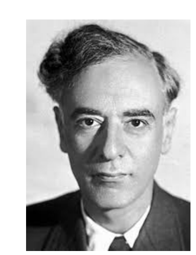


TRIANGLE DIAGRAMS DO NOT LOOK A PRIORI NEGLIGIBLE TO ME.

➡ **ANALYTICITY OF THE AMPLITUDES WAY MORE COMPLICATED THAN SINGLE DISPERSION RELATION LITERATURE RELIES ON.**

*Fronsdal & Norton — **J.Math.Phys. 5, 100 (1964)***

*Lucha, Melikhov & Simula — **PRD 75, 016001 (2007)***



ANSWER TO (B): ARE WE HIDING NEW PHYSICS?

SYMMETRIES OF THE AMPLITUDE DO NOT ALLOW TO DISENTANGLE ORIGIN OF A UNIVERSAL ΔC_9 IN CP-EVEN ANGULAR ANALYSIS & BRS.

— IF SHIFT INDEPENDENT OF HELICITY & q^2 [2401.18007] … VERY INTERESTING !

— WE MIGHT LEARN MORE WITH ADDITIONAL OBSERVABLES [2403.13056] …
… WISHLIST: A LATTICE BREAKTHROUGH [*Martinelli et al.*, work in progress]

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LHCb EXTRACTED RECENTLY NON-LOCAL EFFECTS FROM DATA [*PRL132 (2024) 13*]

See A. Mauri's talk

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

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

EVIDENCE FOR ΔC_9 AT 2 SIGMA LEVEL

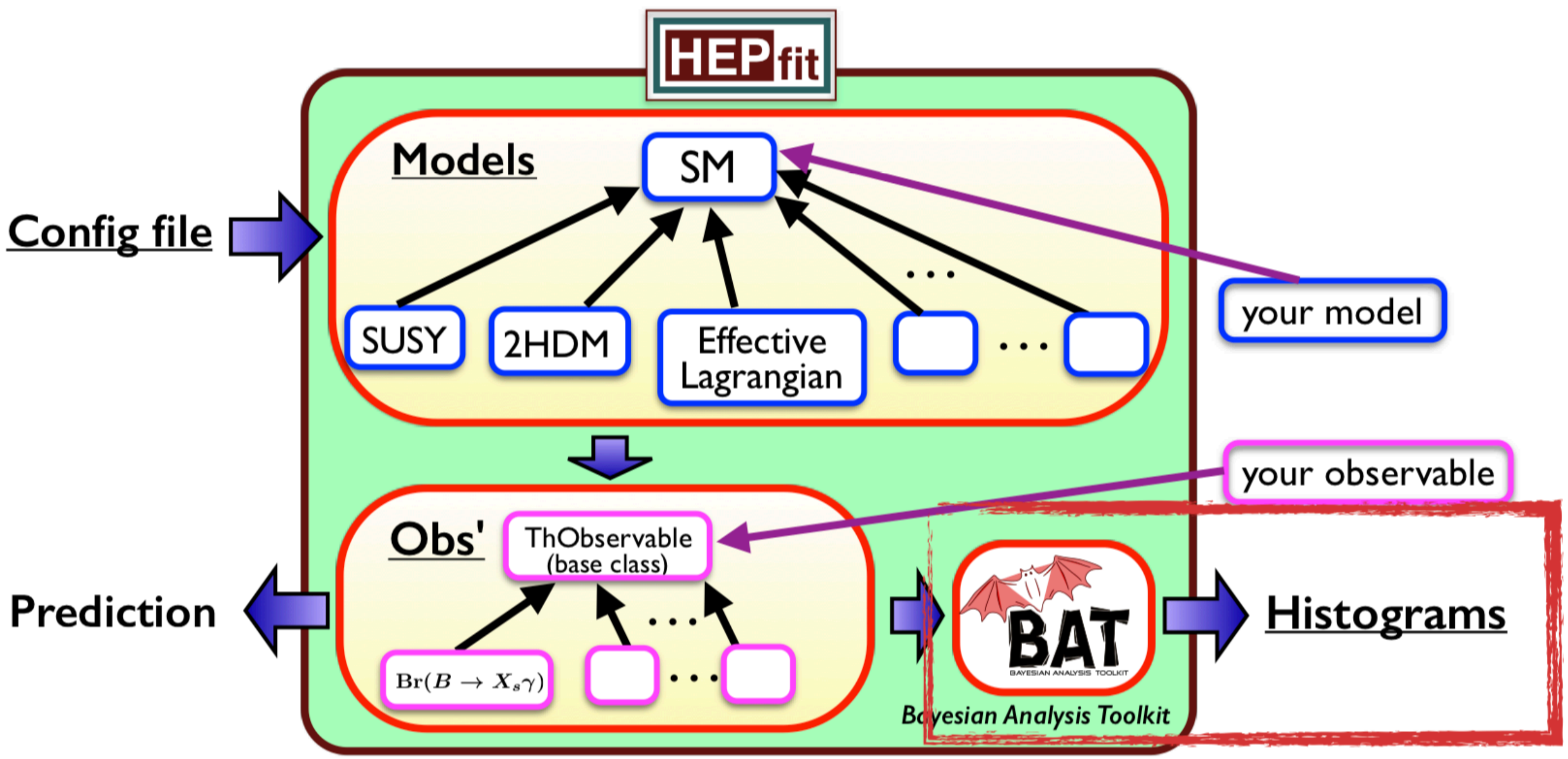
Eur. Phys. J. C (2020) 80:456
https://doi.org/10.1140/epjc/s10052-020-7904-z

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

HEPfit: a code for the combination of indirect and direct constraints on high energy physics models

J. de Blas[1,2], D. Chowdhury[3,4], M. Ciuchini[5], A. M. Coutinho[6], O. Eberhardt[7], M. Fedele[8], E. Franco[9], G. Grilli di Cortona[10], V. Miralles[7], S. Mishima[11], A. Paul[12,13,a], A. Peñuelas[7], M. Pierini[14], L. Reina[15], L. Silvestrini[9,16], M. Valli[17], R. Watanabe[5], N. Yokozaki[18]



[1910.14012]   https://hepfit.roma1.infn.it   https://github.com/silvest/HEPfit

Special Instructions

This ZIP file contains the Supplemetal Material for the publication LHCb-PAPER-2023-032.

The files are:

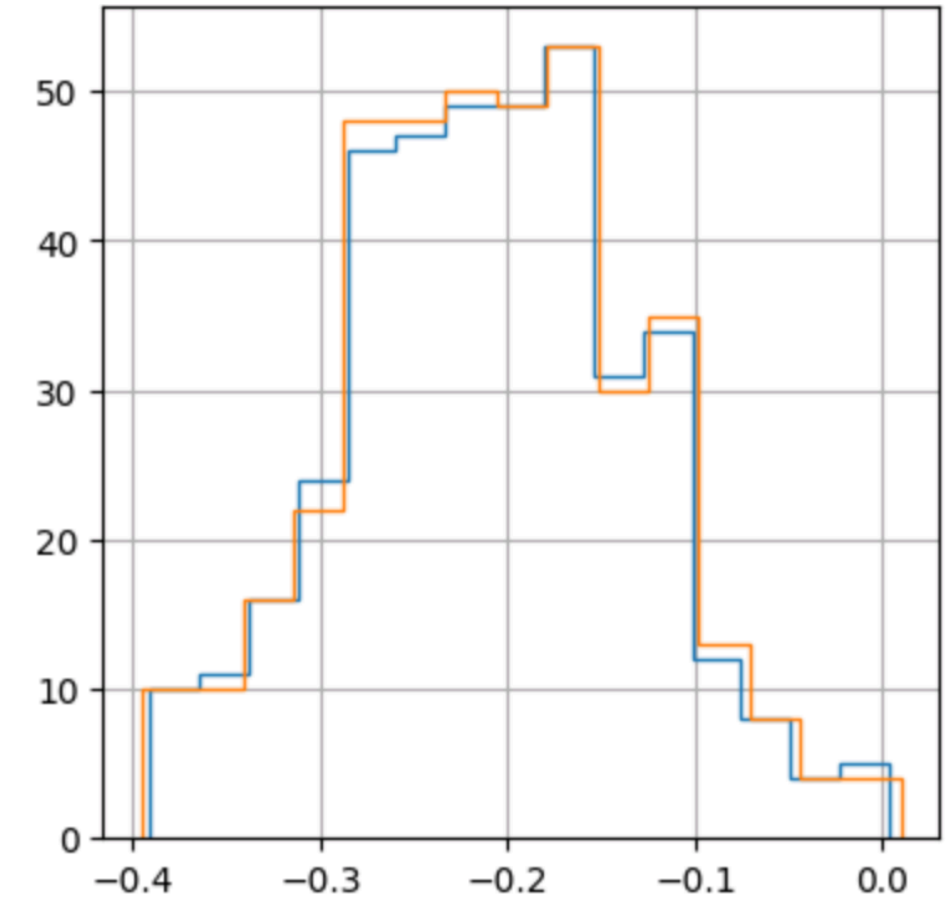
coefficients{}.json : - the fit results in form of a bootstrapped set of fit parameters

core/ : - a directory with the implementation of the signal amplitude model employed in the analysis

main.py : - main script with some instruction and examples on how to use the package

LHCb-PAPER-2023-032-Supplemental-Material.zip

P_5' : bin [2.5,4] GeV^2

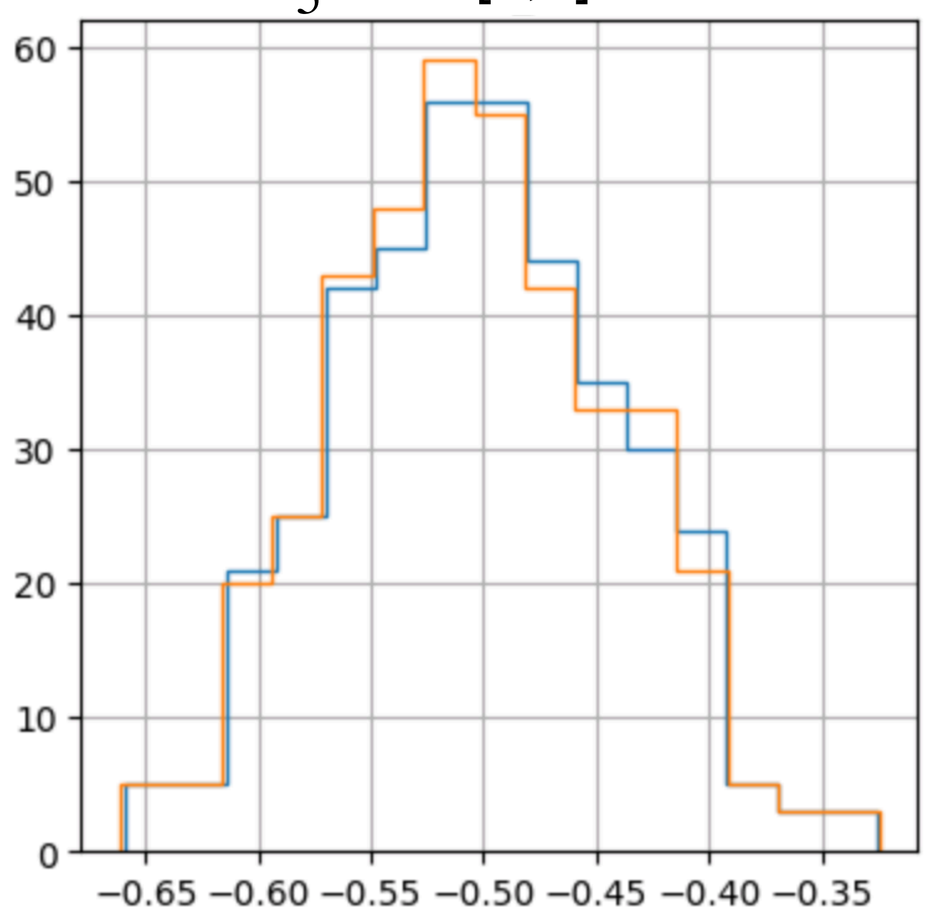


HEPfit

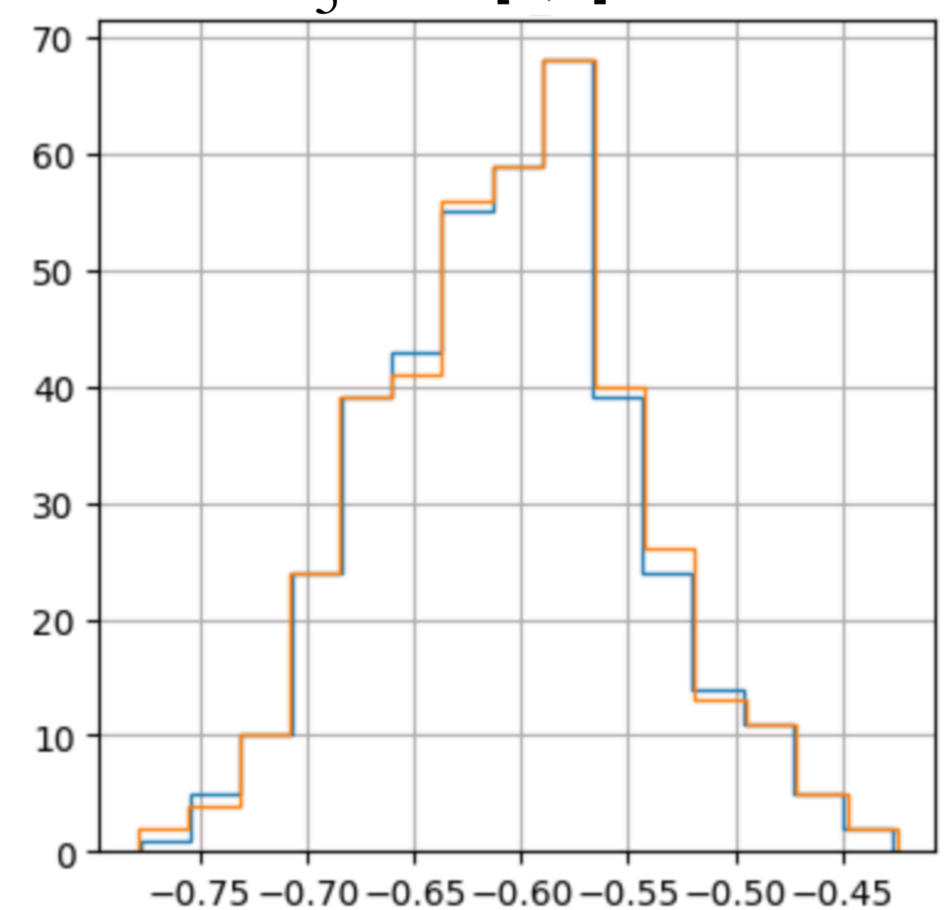
LHCb bootstrap

VERY GOOD AGREEMENT ACROSS ALL OBSERVABLES, INCLUDLING NARROW $c\bar{c}$

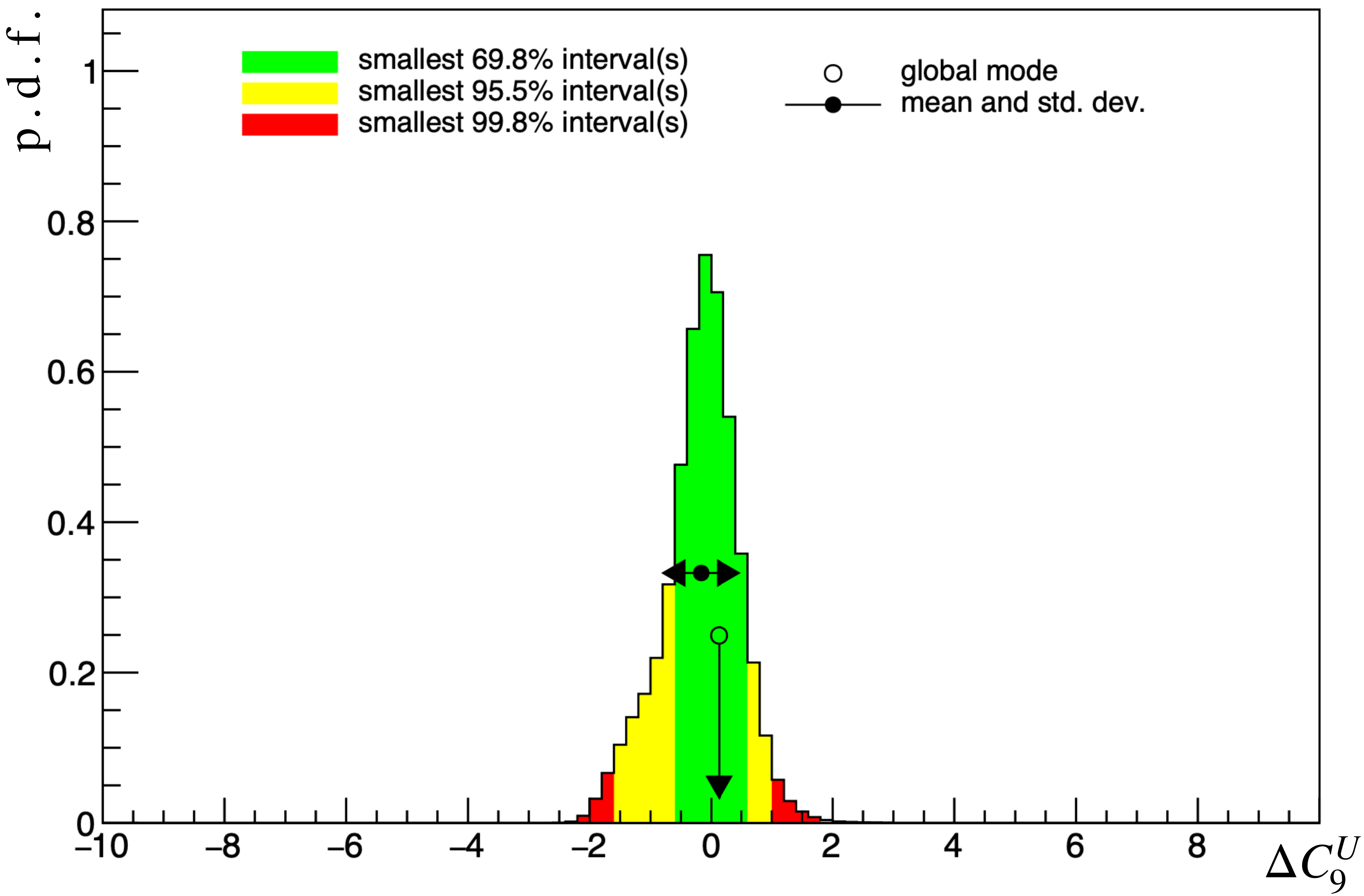
P_5' : bin [4,6] GeV^2



P_5' : bin [6,8] GeV^2

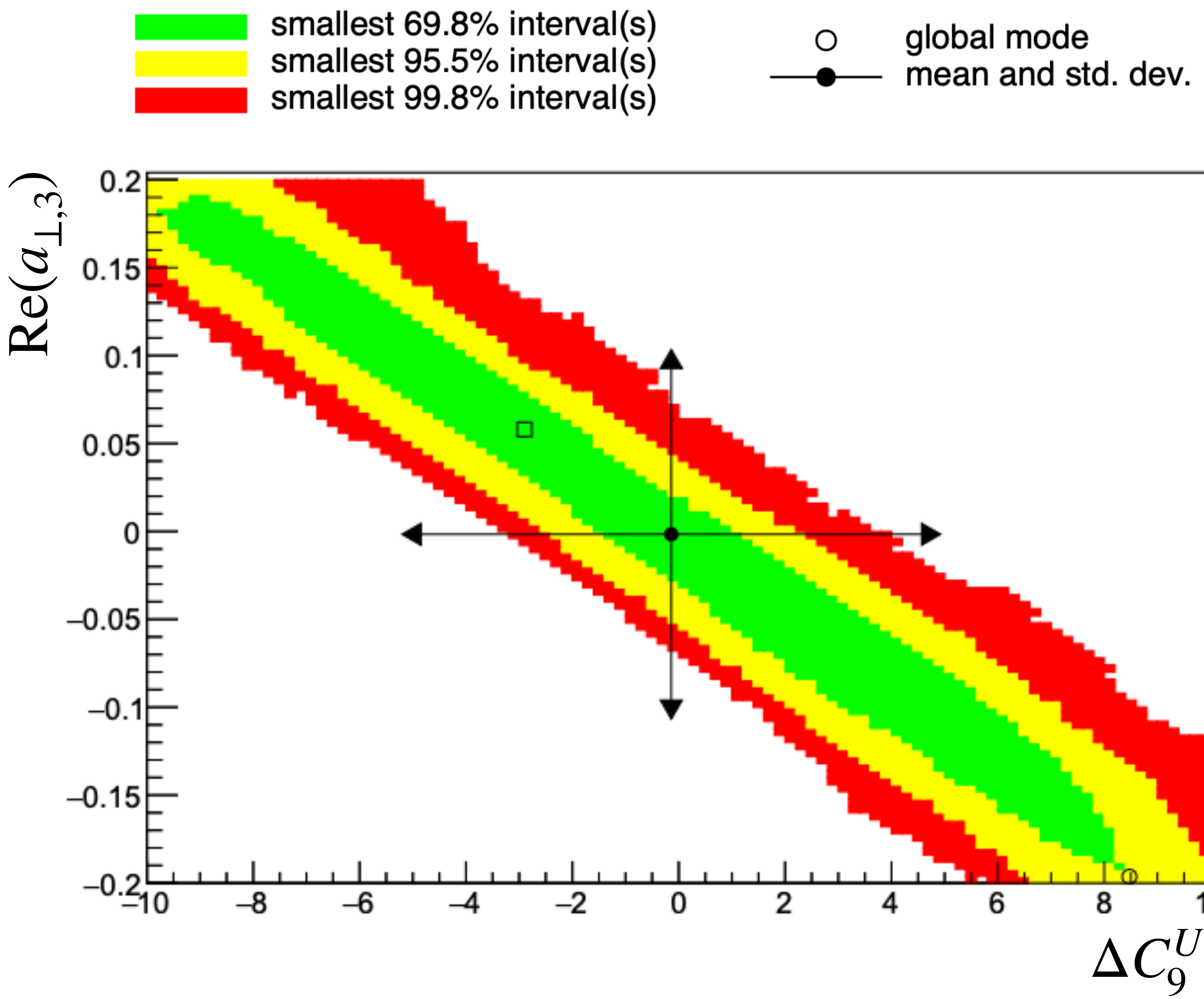


HEPfit MCMC results



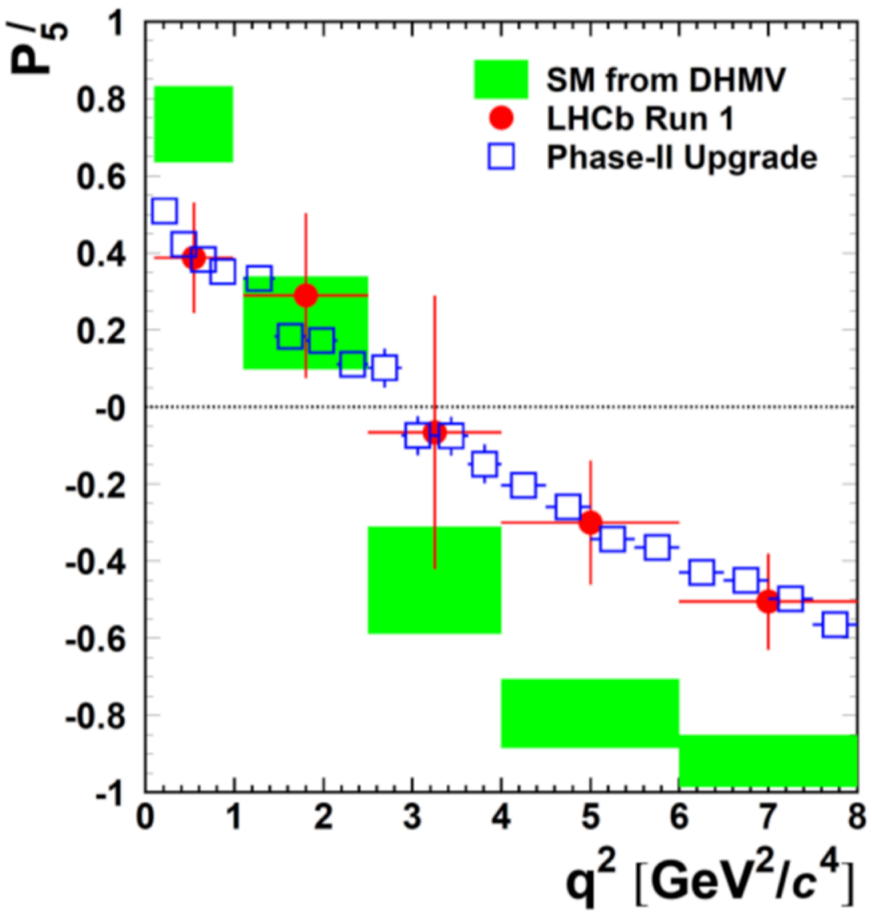
BAYESIAN INFORMATION CRITERION PENALIZES ADDITION OF UNIVERSAL ΔC_9.

HEPfit MCMC results



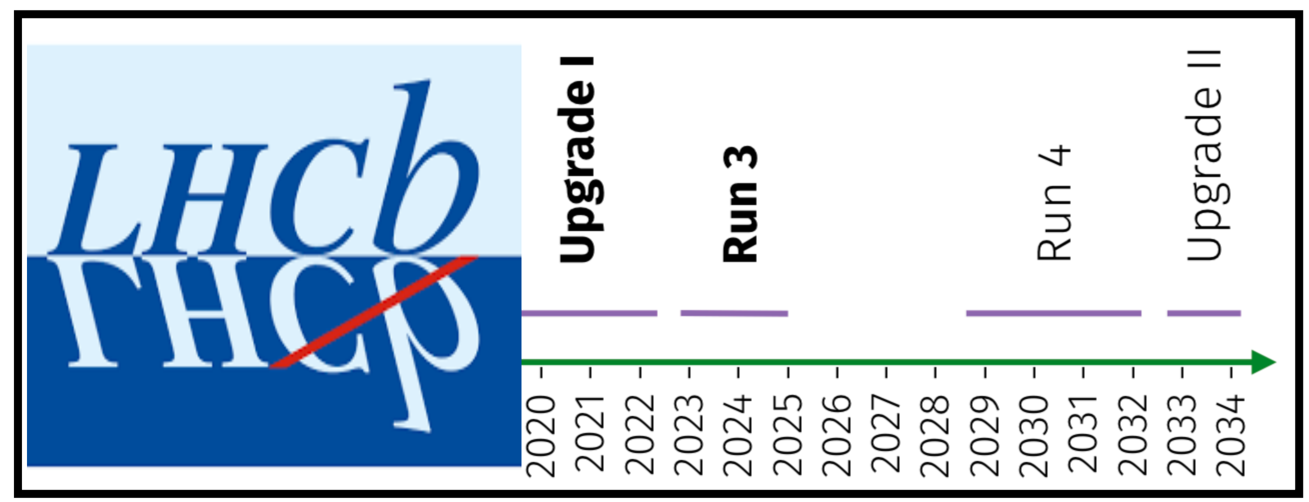
EXPANDING @ NEXT ORDER — INCLUDING $\mathcal{O}(z^3)$ — AFFECTS INFERENCE OF ΔC_9^U

B ANOMALIES : A ☀ FUTURE

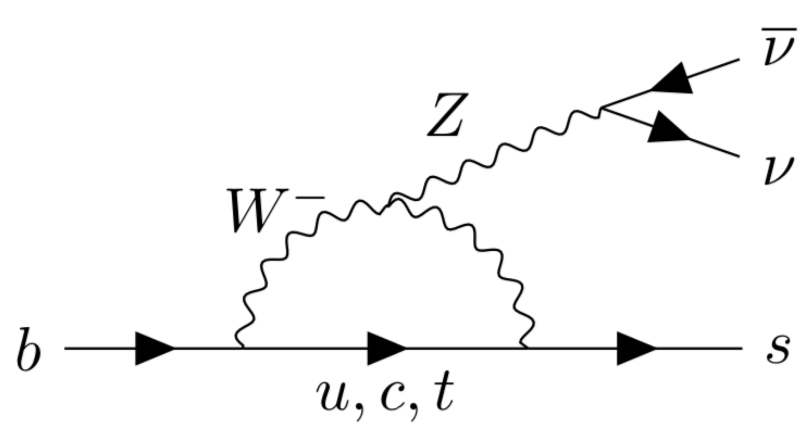


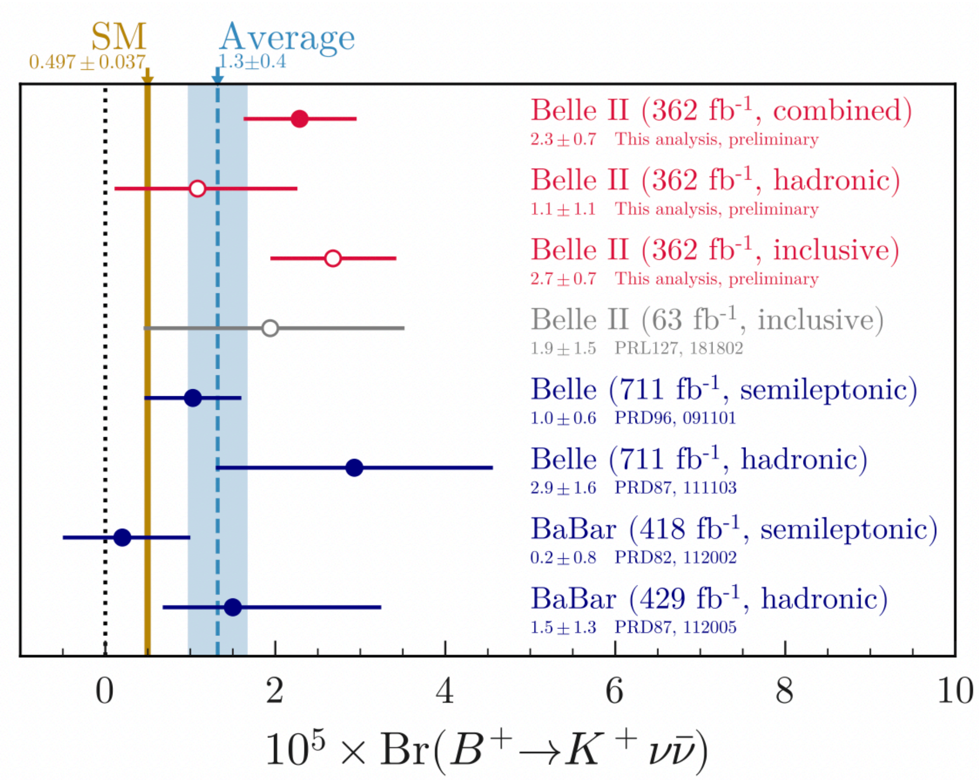
LHCb upgrade(s) will allow us to probe precisely the q² dependence in the angular analysis …

—> pin down effects from hadronic physics



Belle II is already delivering interesting results!





- NO WAY OF EXTRACTING UNIVERSAL SHORT DISTANCE IN B -> K* l l IF ONE IS AGNOSTIC ABOUT RESCATTERING

— IS THERE FULL AGREEMENT ON THIS? —

- IF TRIANGLE DIAGRAMS ARE NON-NEGLIGIBLE (WHY THEY WOULD BE?) , PRESENT DISPERSIVE BOUNDS ARE NOT OK

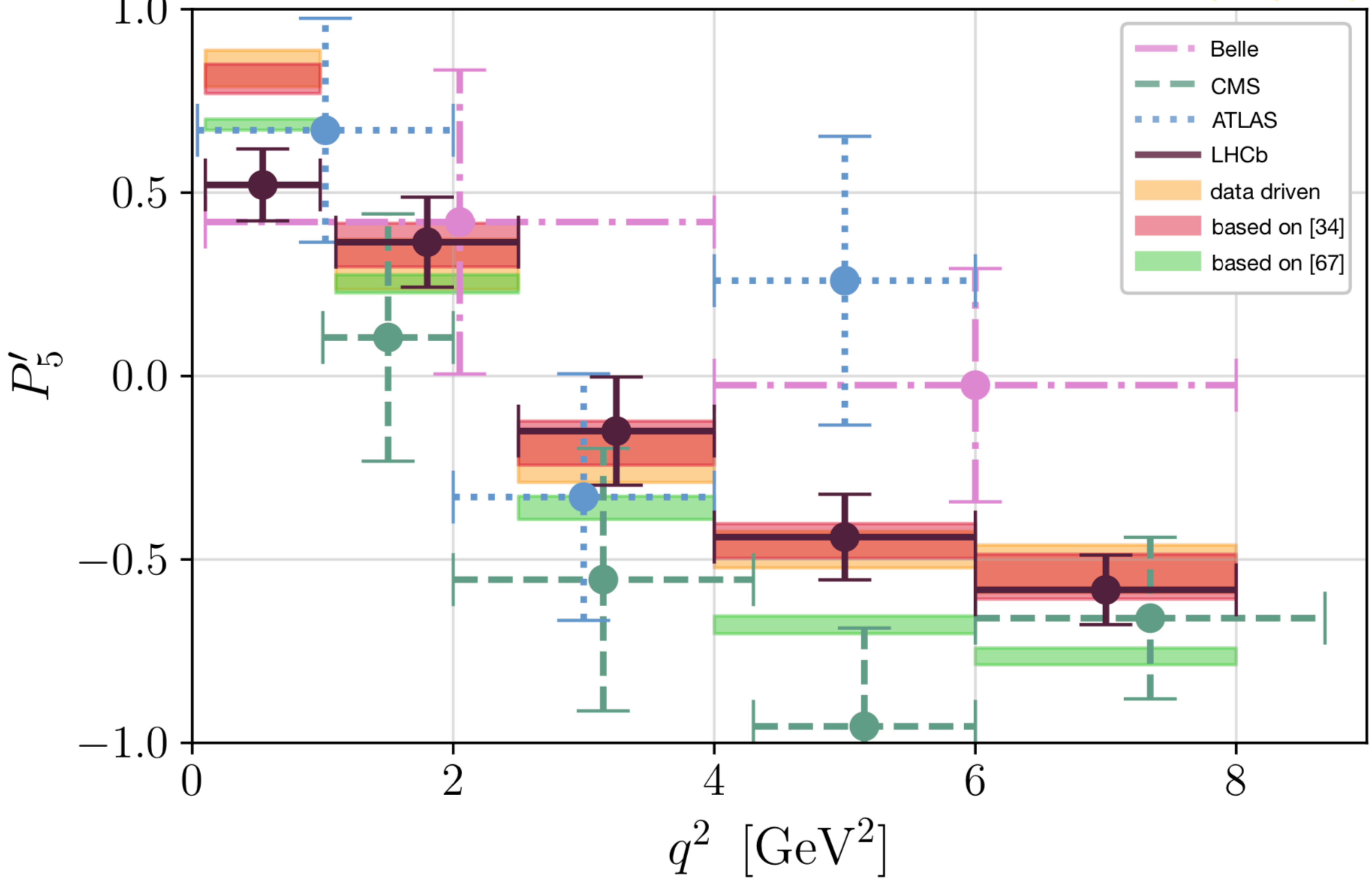
— IDEAS TO MAKE PROGRESS HERE ? —

- IF UNIVERSAL ΔC_9 GETS COMPATIBLE W/ HELICITY & q^2 INDEPENDENCE, LET'S NOT FORGET SAGAN'S LESSON:

BACKUP

B ANOMALIES : P_5'

2110.10126

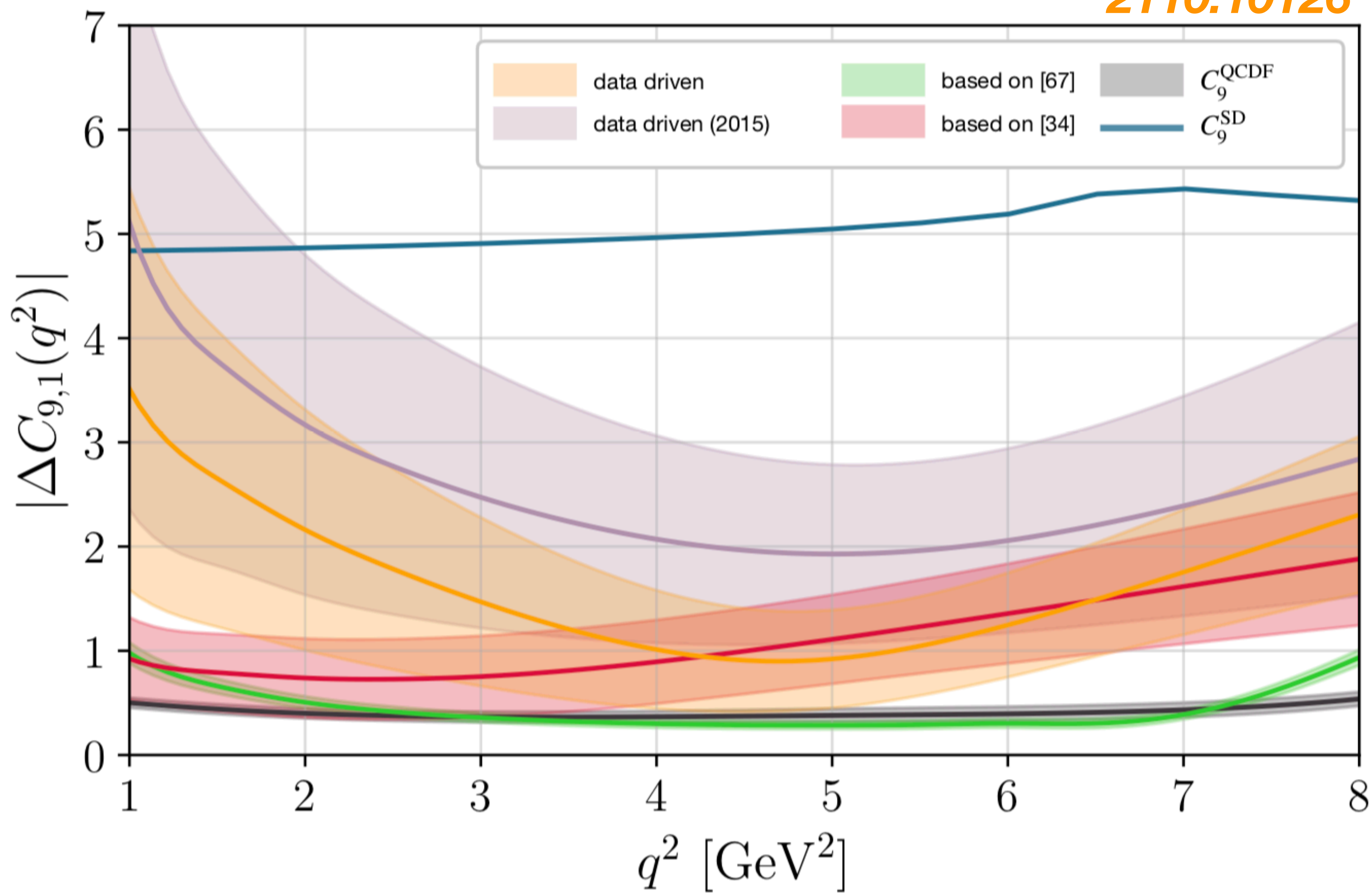


34. M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini et al., *Hadronic uncertainties in semileptonic $B \to K^* \mu^+ \mu^-$ decays*, *PoS* **BEAUTY2018** (2018) 044, [arXiv:1809.03789].

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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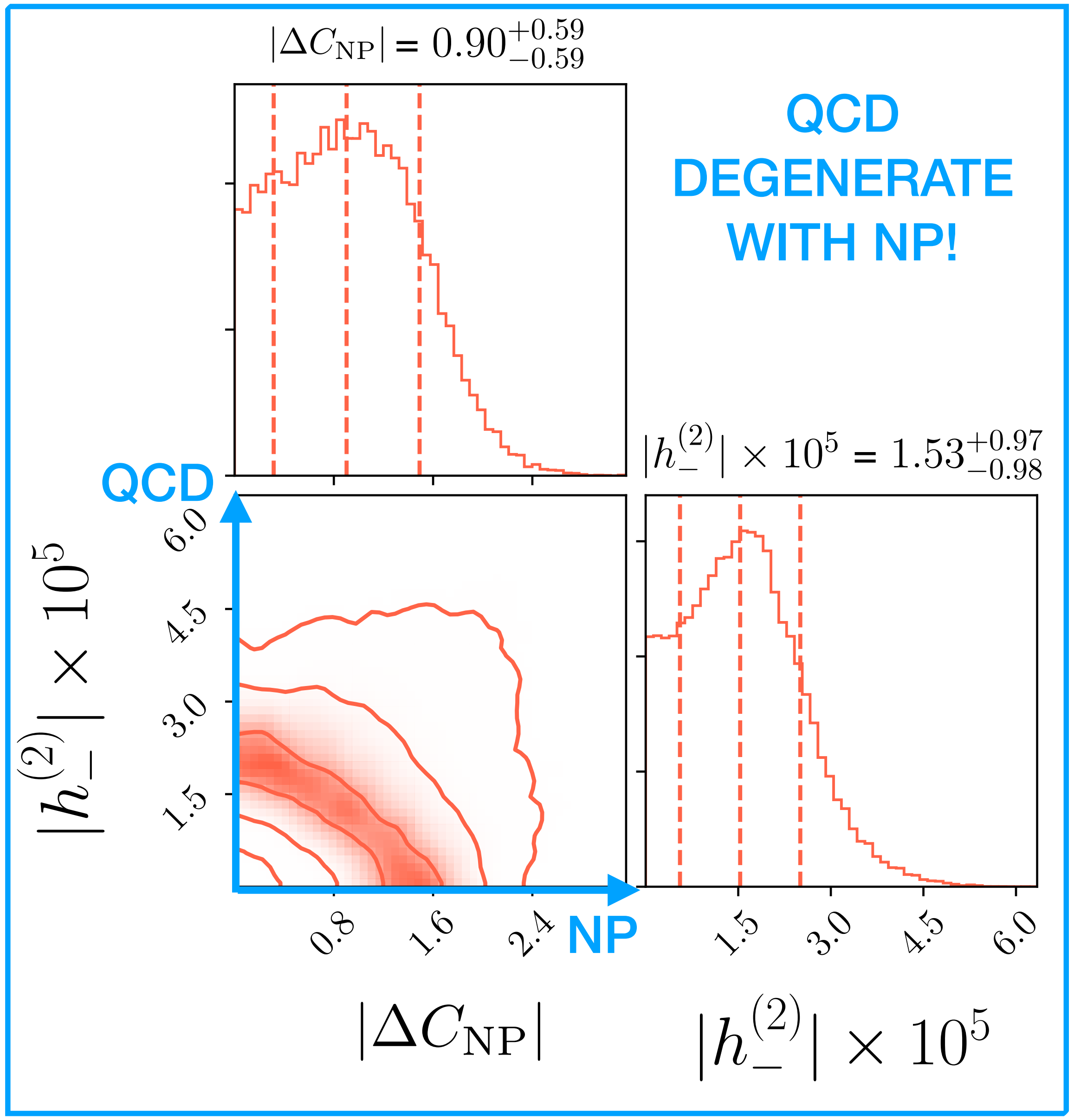
Phenomenological Data Driven

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

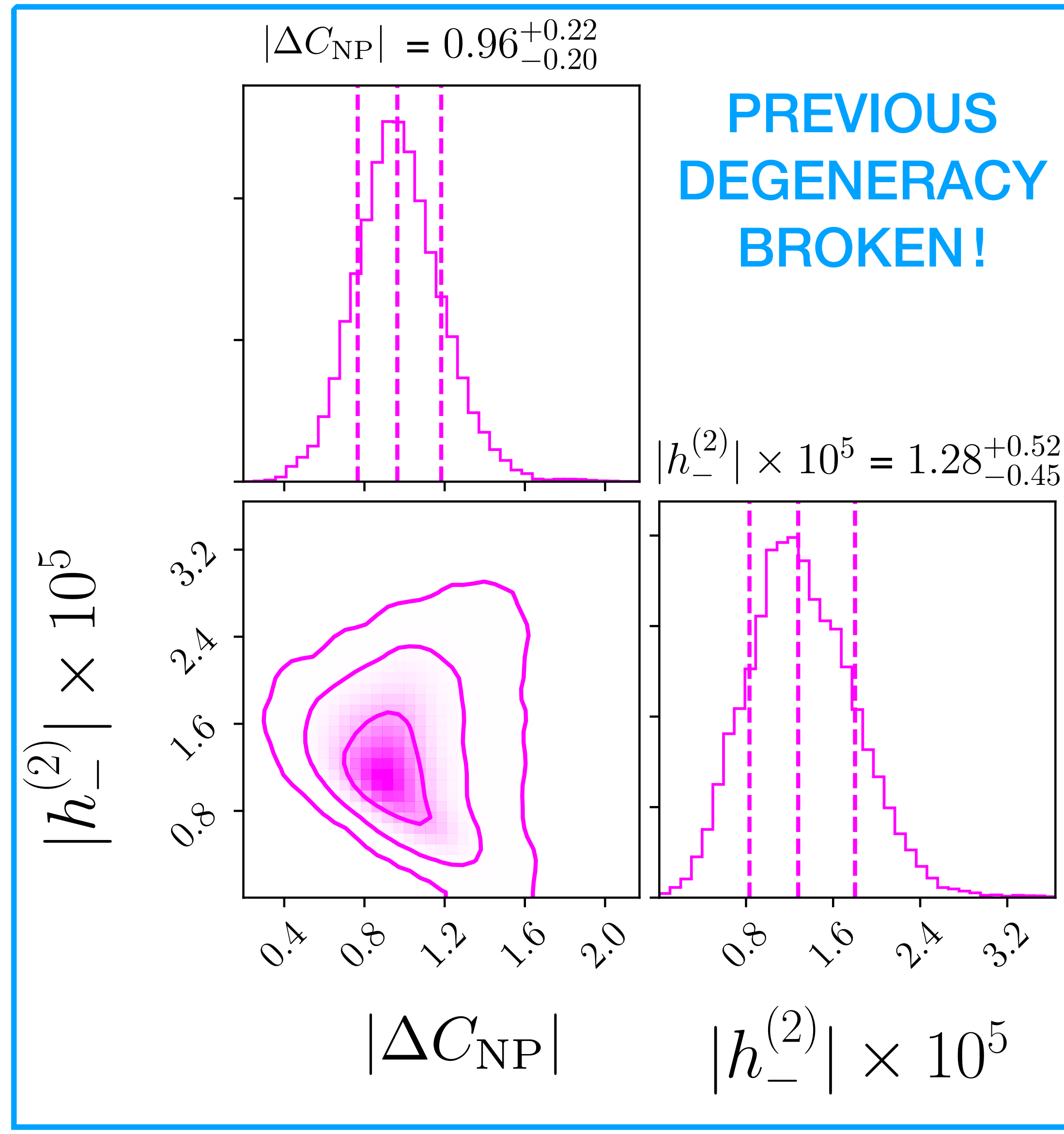


PROJECTIONS @ 50 fb^{-1}

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

RULE OF THUMB

Scaling LHCb stat errors roughly of 1/6



[*arXiv:**1809.03789***]