FLASY 2024: the 10th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology

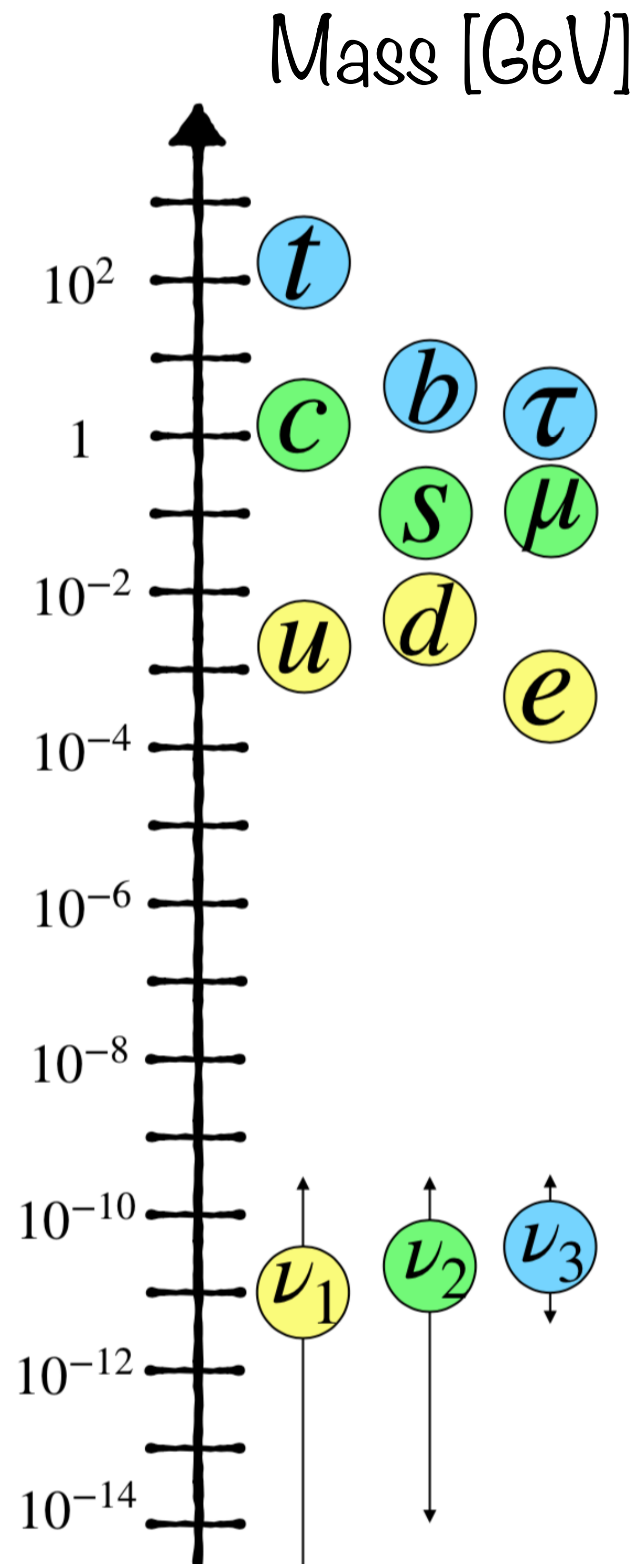
Flavour Anomalies : Where do we stand?

Mauro Valli

INFN Rome

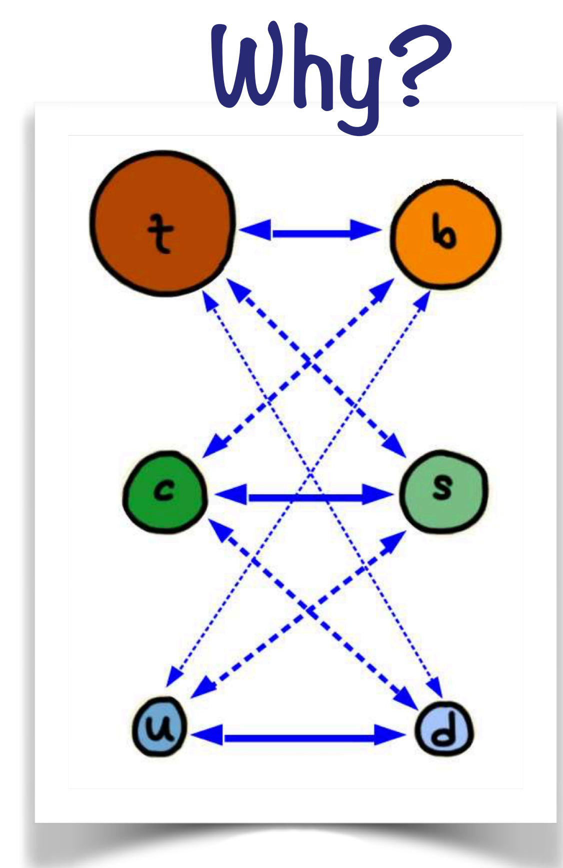
MANY THANKS TO: M.FEDELE, V.MIRALLES, L.SILVESTRINI & L.VITTORIO

The Standard Model



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{matrix} u \\ c \\ t \end{matrix}$$

$$\quad d \quad s \quad b$$



EFTs & Precision : Flavour

Lagrangian:

Parameter

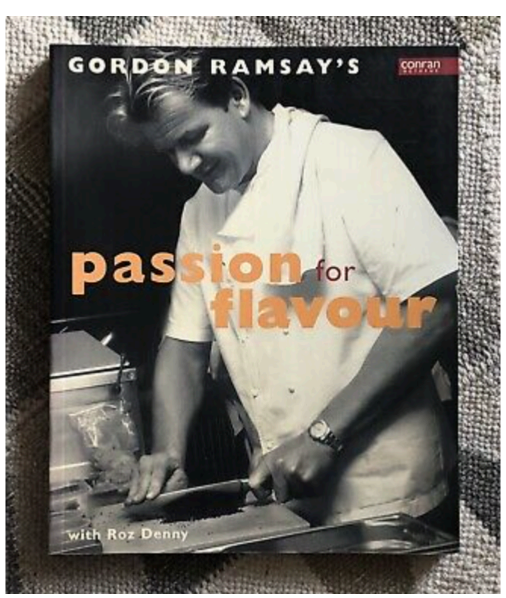
Cutoff scale

Local operator
- a monomial in fields and derivatives

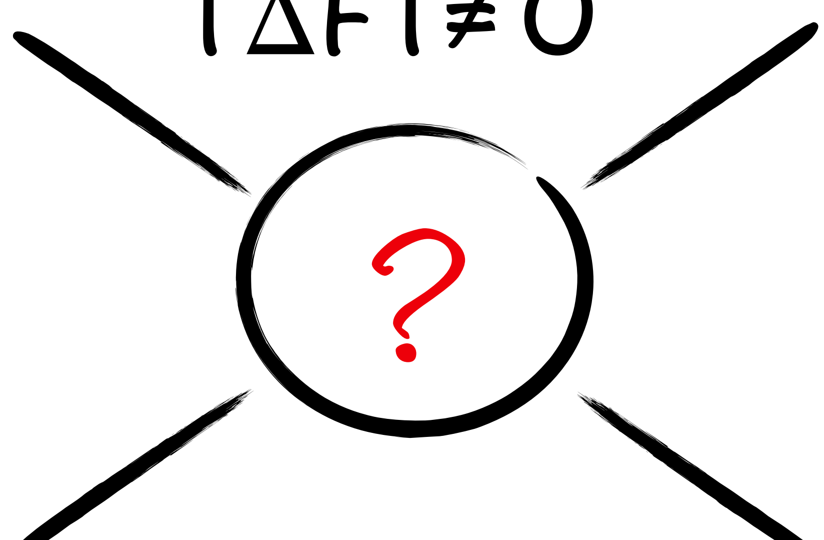
$$\mathscr{L}(x) = \sum c_{\mathcal{O}} \, \Lambda_{\mathcal{O}}^{4-\dim \mathcal{O}} \, \mathcal{O}(x)$$

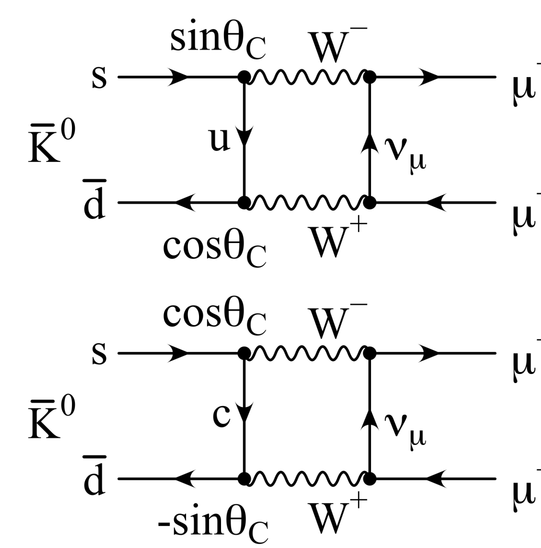
Physical effects $\sim \left(\frac{E}{\Lambda_{\mathcal{O}}}\right)^{\dim \mathcal{O} - 4}$

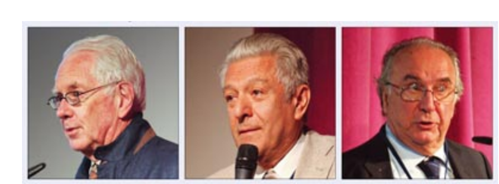
A. Greljo @ LHC Forum '23



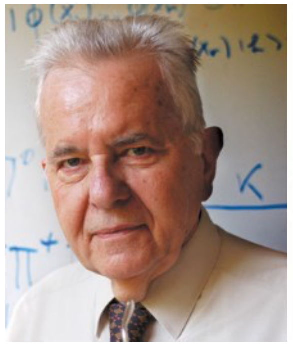
$|\Delta F| \neq 0$







Flavor Metrology :



- Flavor violation in SM in charged weak-current <—> V_{CKM}

—> Flavor Changing Neutral Currents (FCNCs) **ONLY** @ one loop

- CKM matrix described by 4 params (3 angles and a C~~P~~ phase)

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$(\bar\rho, \bar\eta)$ apex of $V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$

UTfit

www.utfit.org

M.Bona, M. Ciuchini, D. Derkach, F. Ferrari, E. Franco, V. Lubicz, G. Martinelli, M. Pierini, L. Silvestrini, C. Tarantino, V. Vagnoni, M. Valli, and L.Vittorio

— EXP

— TH

LINCEI CELEBRATIVE ESSAYS

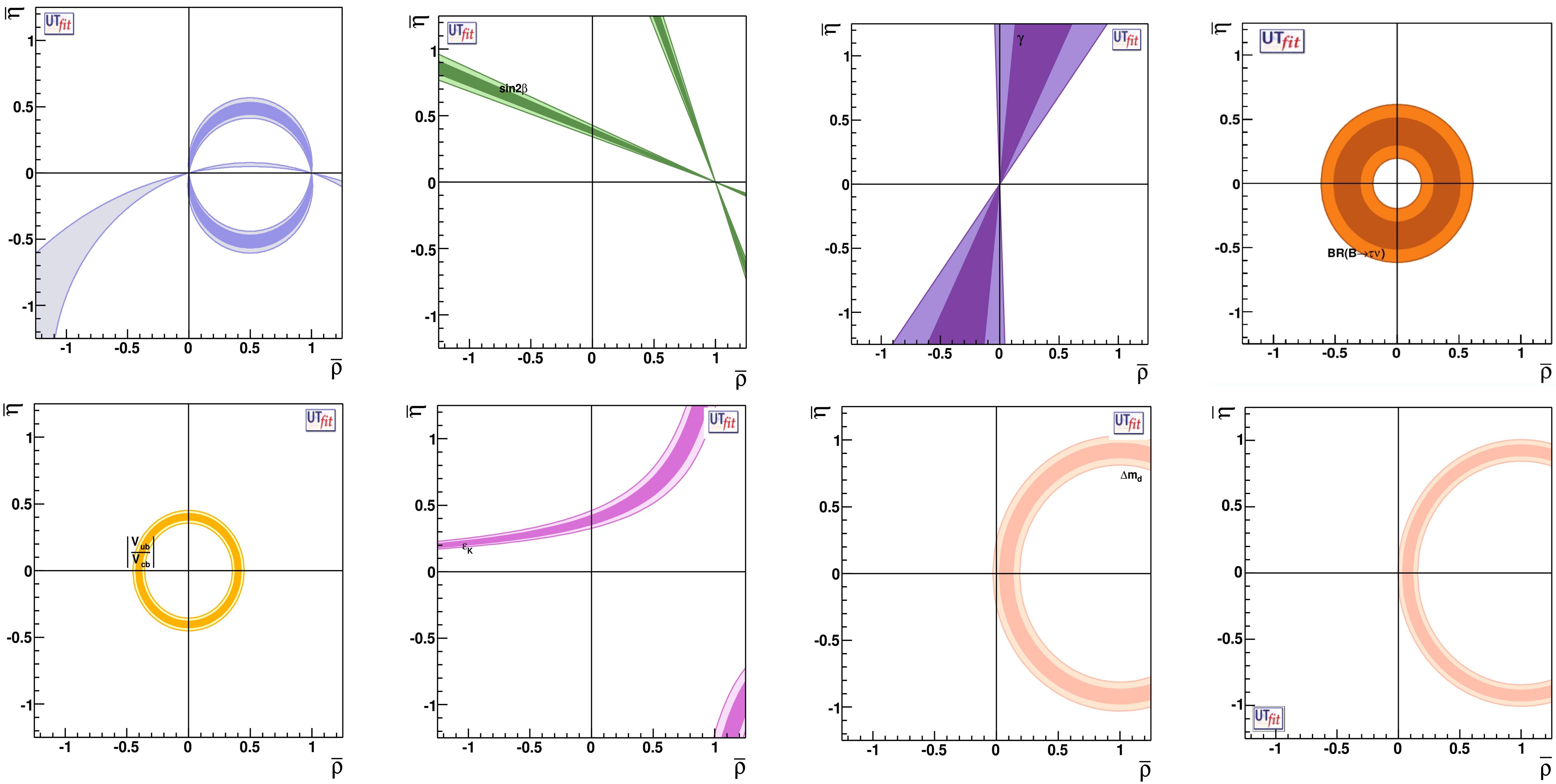
New UT*fit* analysis of the unitarity triangle in the Cabibbo–Kobayashi–Maskawa scheme

arXiv: **2212.03894** — *Rend.Lincei Sci.Fis.Nat. 34 (2023) 37-57*

The Power of Redundancy

see, e.g., ***Les Houches Lect.Notes 108 (2020)* - L.Silvestrini**

$\alpha\ (B \to \pi\pi, \rho\rho)$ $\beta\ (B \to J/\psi K^{(*)})$ $\gamma\ (B \to D^{(*)}K)$ $\mathrm{BR}(B \to \tau\nu)$

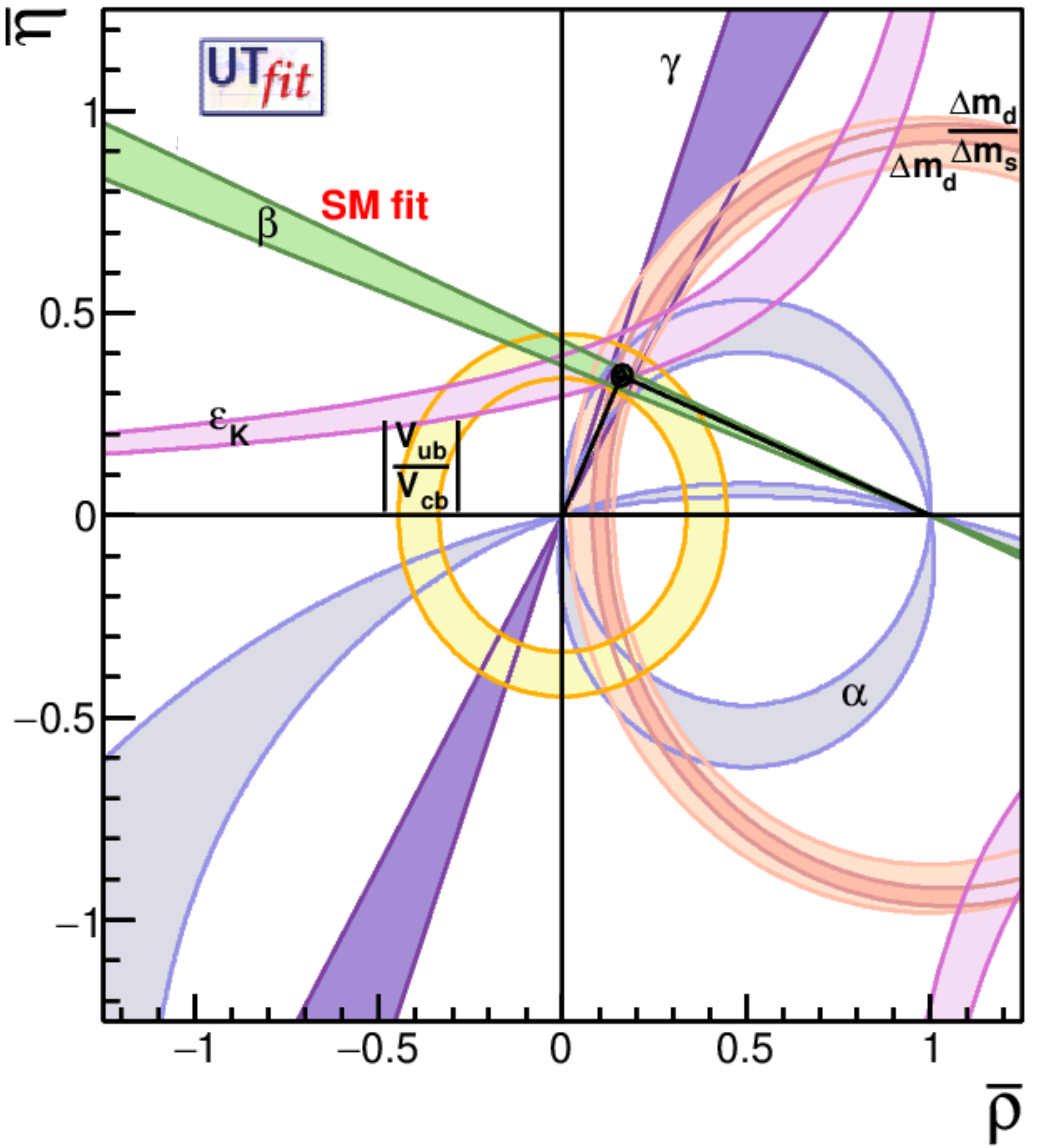


$|V_{ub}/V_{cb}|$ ϵ_K Δm_d $\Delta m_d/\Delta m_s$

(semileptonic decays) (CPV in $K - \bar{K}$) $(B_{d,s} - \bar{B}_{d,s})$

UTA: Unitarity Triangle Analysis

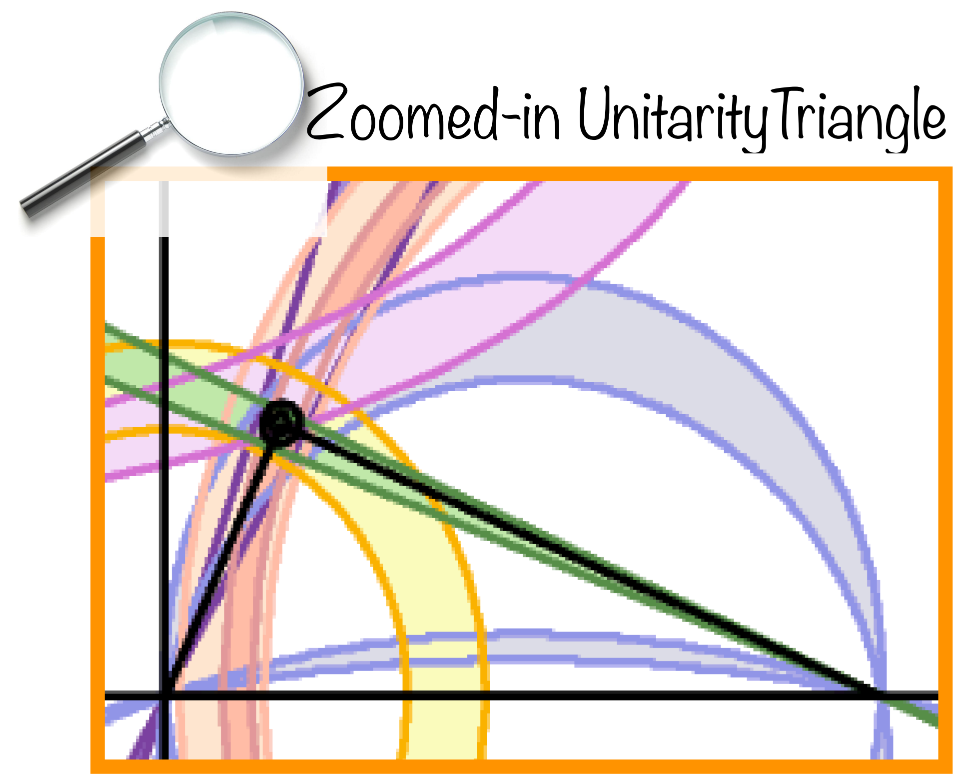
@ 95% prob



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

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

Zoomed-in Unitarity Triangle



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

Flavour & BSM Physics

SM

$$O_1^{q_i q_j} = \bar{q}_{jL}^{\alpha}\gamma_\mu q_{iL}^{\alpha}\,\bar{q}_{jL}^{\beta}\gamma^\mu q_{iL}^{\beta}$$

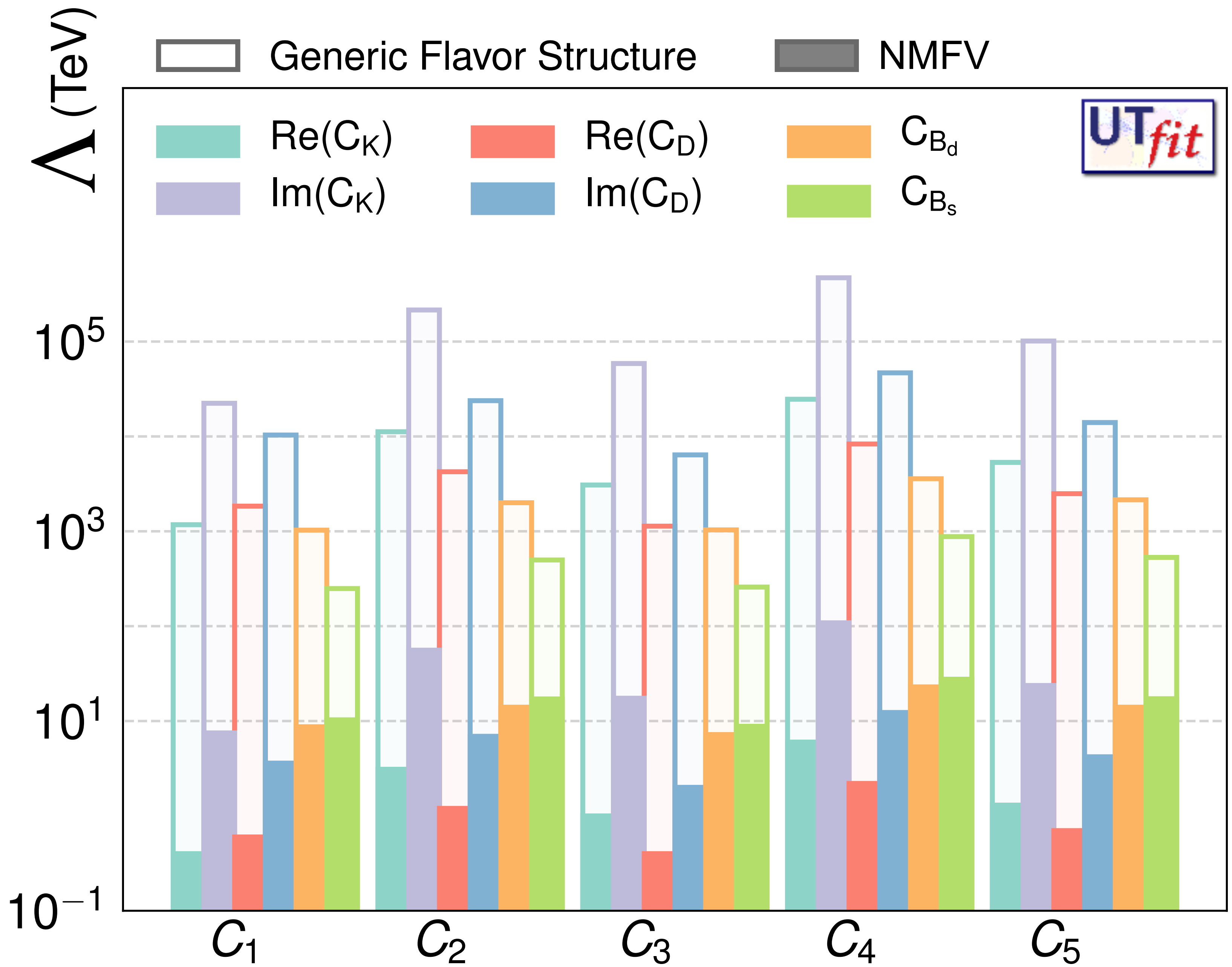
$$O_2^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\,\bar{q}_{jR}^{\beta} q_{iL}^{\beta}$$

$$O_3^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\,\bar{q}_{jR}^{\beta} q_{iL}^{\alpha}$$

$$O_4^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\,\bar{q}_{jL}^{\beta} q_{iR}^{\beta}$$

$$O_5^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\,\bar{q}_{jL}^{\beta} q_{iR}^{\alpha}$$

$+$ chirally flipped $\widetilde{O}_{1,2,3}^{q_i q_j}$

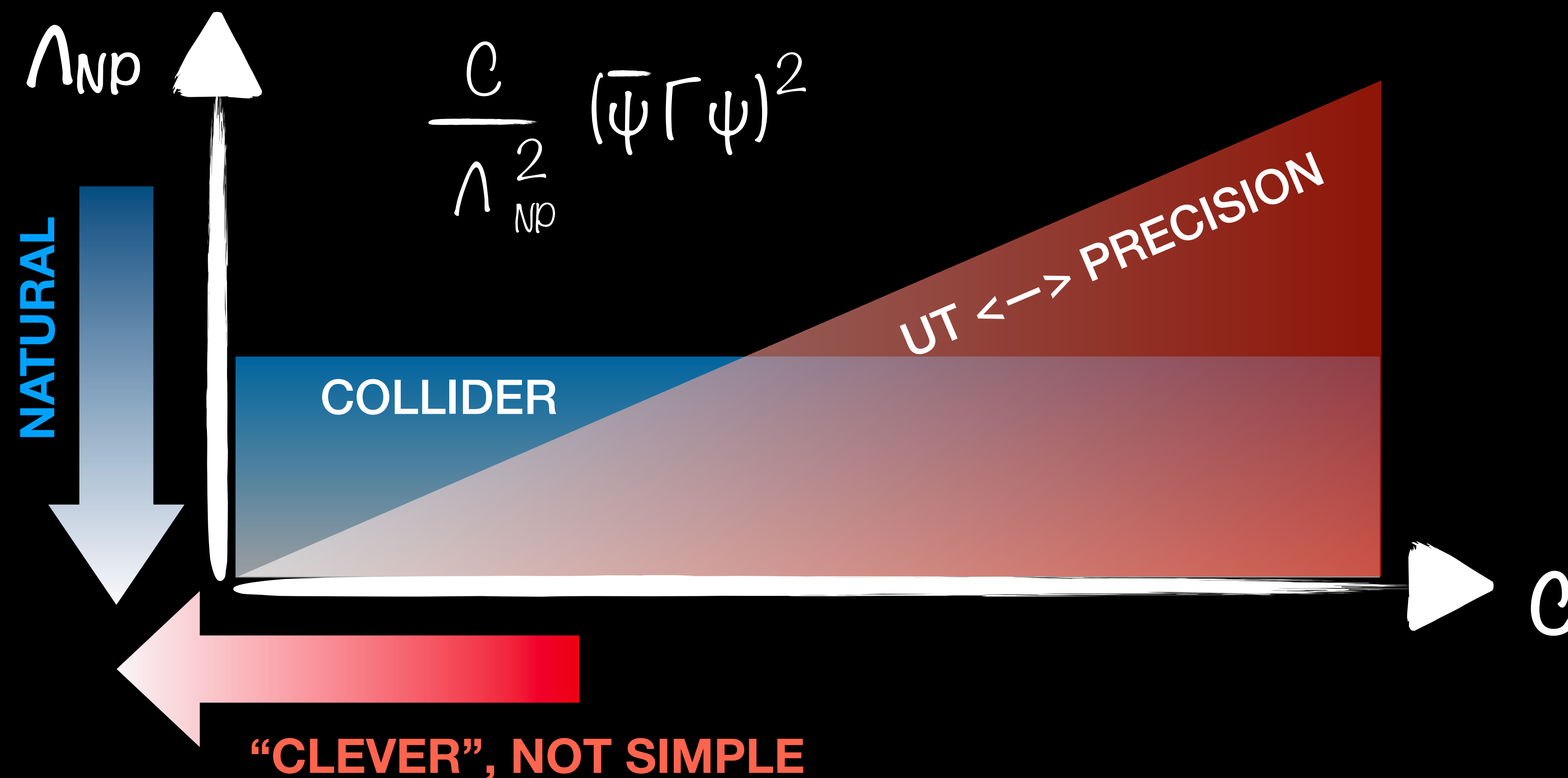


- **Generic NP** = no SM protection, i.e.: $C(\Lambda) \sim 1/\Lambda^2$ ⇨ $\Lambda > 4.7 \times 10^5$ TeV
- **Next-to-MFV** = SM-like protection + O(1) phases ➡ $\Lambda > 108$ TeV

Lessons from UTA

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

- NP UT :

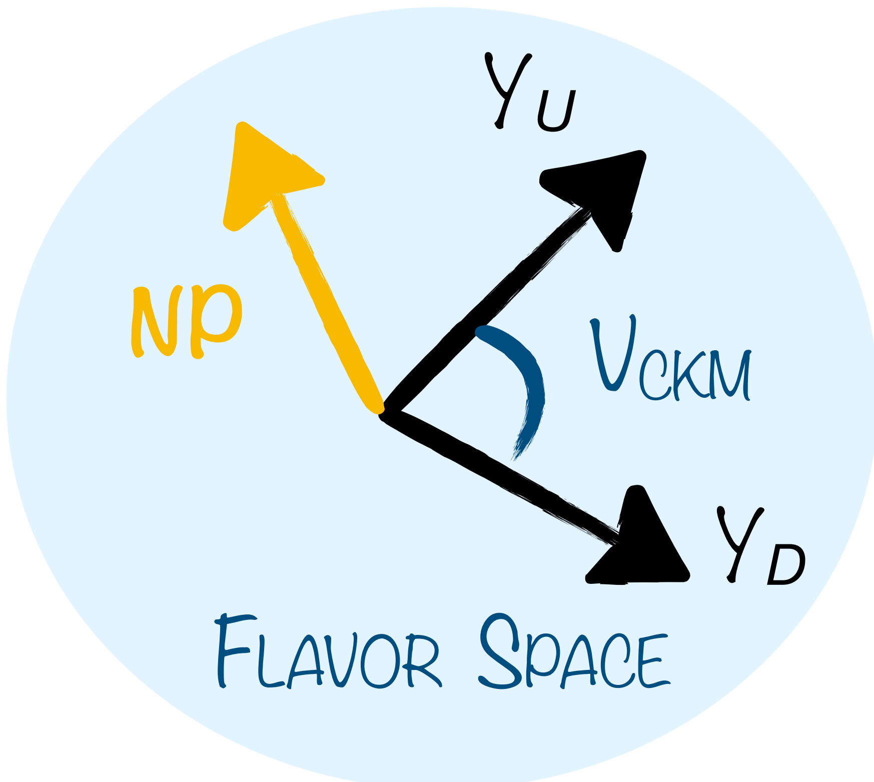


BOTTOM LINE

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

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

NP: Going Beyond the Weak EFT



$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i,d>4} \frac{C_i \mathcal{O}_i^{(d)}}{\Lambda_{\rm NP}^{d-4}}$$

Y_D diag $\xleftrightarrow{V_{\rm CKM}}$ Y_U diag

$|\Delta F| = 2$ bounds in the SMEFT — ***Phys. Lett. B 799 (2019) 135062***

SMEFT RGE

$O_{jk}^{HQ(1[3])}$ $(H^\dagger i \overset{\leftrightarrow}{D}{}_\mu^{[A]} H)\,(\bar{Q}_j \gamma^\mu [\tau^A]\, Q_k)$	O_{jjkl}^{LedQ} $(\bar{L}_j e_j)\,(\bar{d}_k Q_l)$	O_{jjkl}^{LeQu} $(\bar{L}_j e_j) i\tau^2\,(\bar{Q}_k u_l)$	$O^{ud(1[8])}_{jklm}$ $(\bar{u}_j \gamma_\mu [T^a] u_k)\,(\bar{d}_l \gamma^\mu [T^a] d_m)$	$O^{QuQd(1[8])}_{jklm}$ $(\bar{Q}_j \gamma_\mu [T^a] u_k) i\tau^2\,(\bar{Q}_l \gamma^\mu [T^a] d_m)$
$O^{QQ(1[3])}_{jklm}$ $(\bar{Q}_j \gamma_\mu [\tau^A] Q_k)\,(\bar{Q}_l \gamma^\mu [\tau^A] Q_m)$	O^{uu}_{jklm} $(\bar{u}_j \gamma_\mu u_k)\,(\bar{u}_l \gamma^\mu u_m)$	O^{dd}_{jklm} $(\bar{d}_j \gamma_\mu d_k)\,(\bar{d}_l \gamma^\mu d_m)$	$O^{Qd(1[8])}_{jklm}$ $(\bar{Q}_j \gamma_\mu [T^a] Q_k)\,(\bar{d}_l \gamma^\mu [T^a] d_m)$	$O^{Qu(1[8])}_{jklm}$ $(\bar{Q}_j \gamma_\mu [T^a] Q_k)\,(\bar{u}_l \gamma^\mu [T^a] u_m)$

poorly constrained

FLAVOR MISALIGNMENT

… UT IN THE SMEFT: A LOT OF WORK YET TO BE DONE !

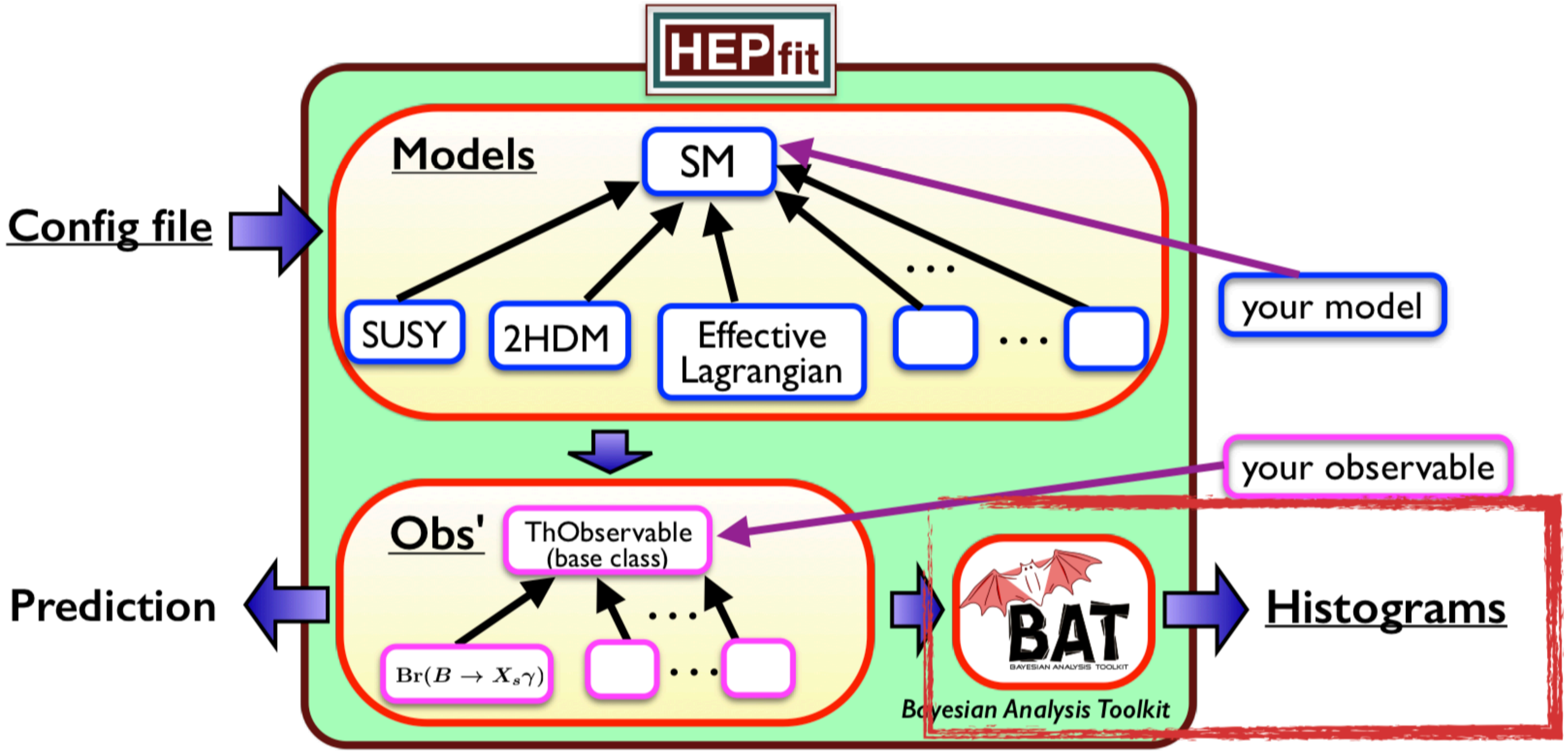
Eur. Phys. J. C (2020) 80:456
https://doi.org/10.1140/epjc/s10052-020-7904-z

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

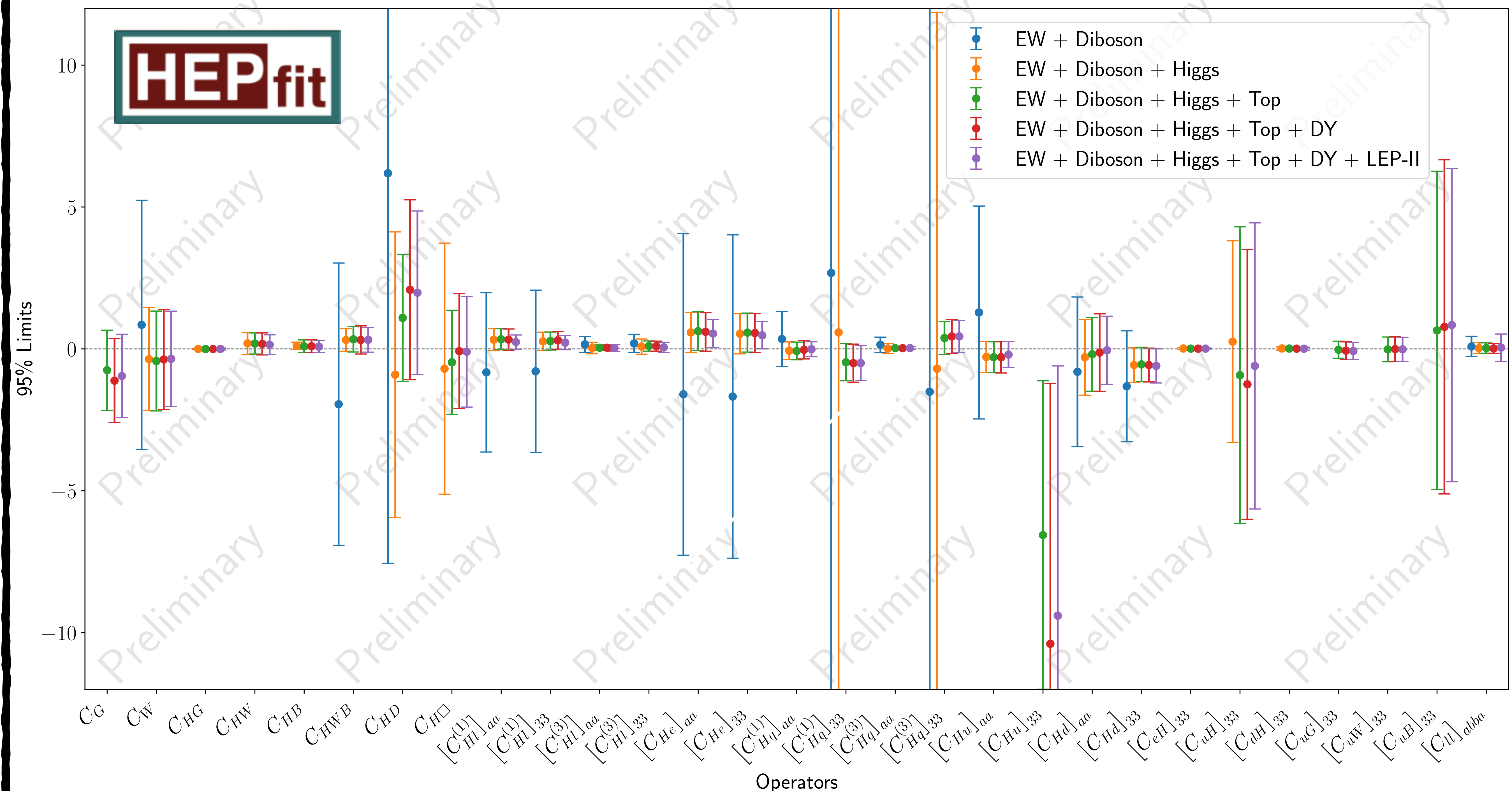
J. de Blas[1,2], D. Chowdhury[3,4], M. Ciuchini[5], A. M. Coutinho[6], O. Eberhardt[7], M. Fedele[8], E. Franco[9], G. Grilli di Cortona[10], V. Miralles[7], S. Mishima[11], A. Paul[12,13,a], A. Peñuelas[7], M. Pierini[14], L. Reina[15], L. Silvestrini[9,16], M. Valli[17], R. Watanabe[5], N. Yokozaki[18]



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

$U(2)^5$ flavour symmetry: 2-Fermion

Limits for WC at the scale $\Lambda_{UV} = 1$ TeV

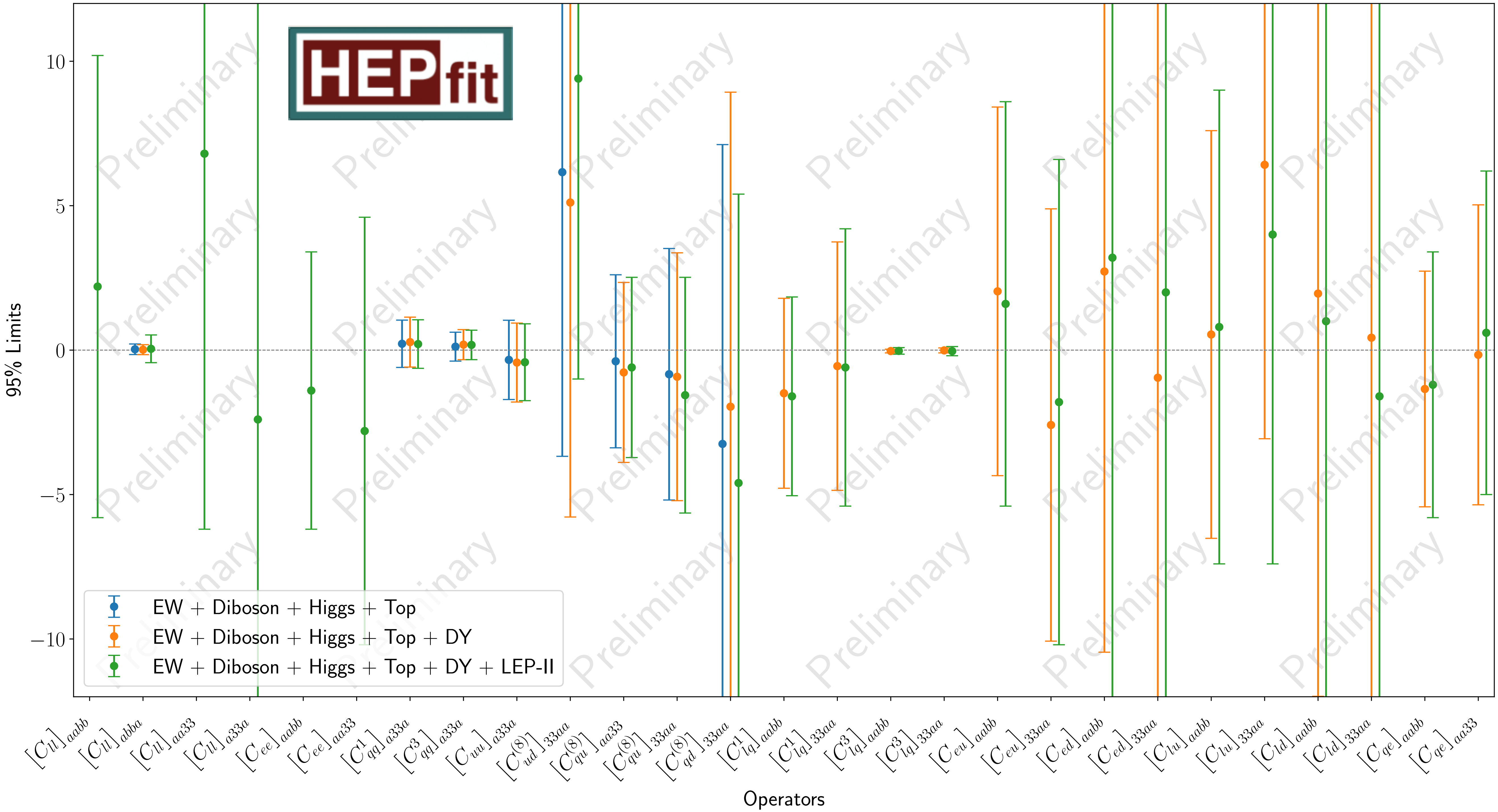


Víctor Miralles New physics constraints via global fits Higgs and Effective Field Theory 2024

Picture even more constrained by Flavor (ongoing analysis w/ J. De Blas, A. Goncalves, V. Miralles, L.Reina, L. Silvestrini)

$U(2)^5$ flavour symmetry: 4-Fermion

Limits for WC at the scale $\Lambda_{UV} = 1$ TeV



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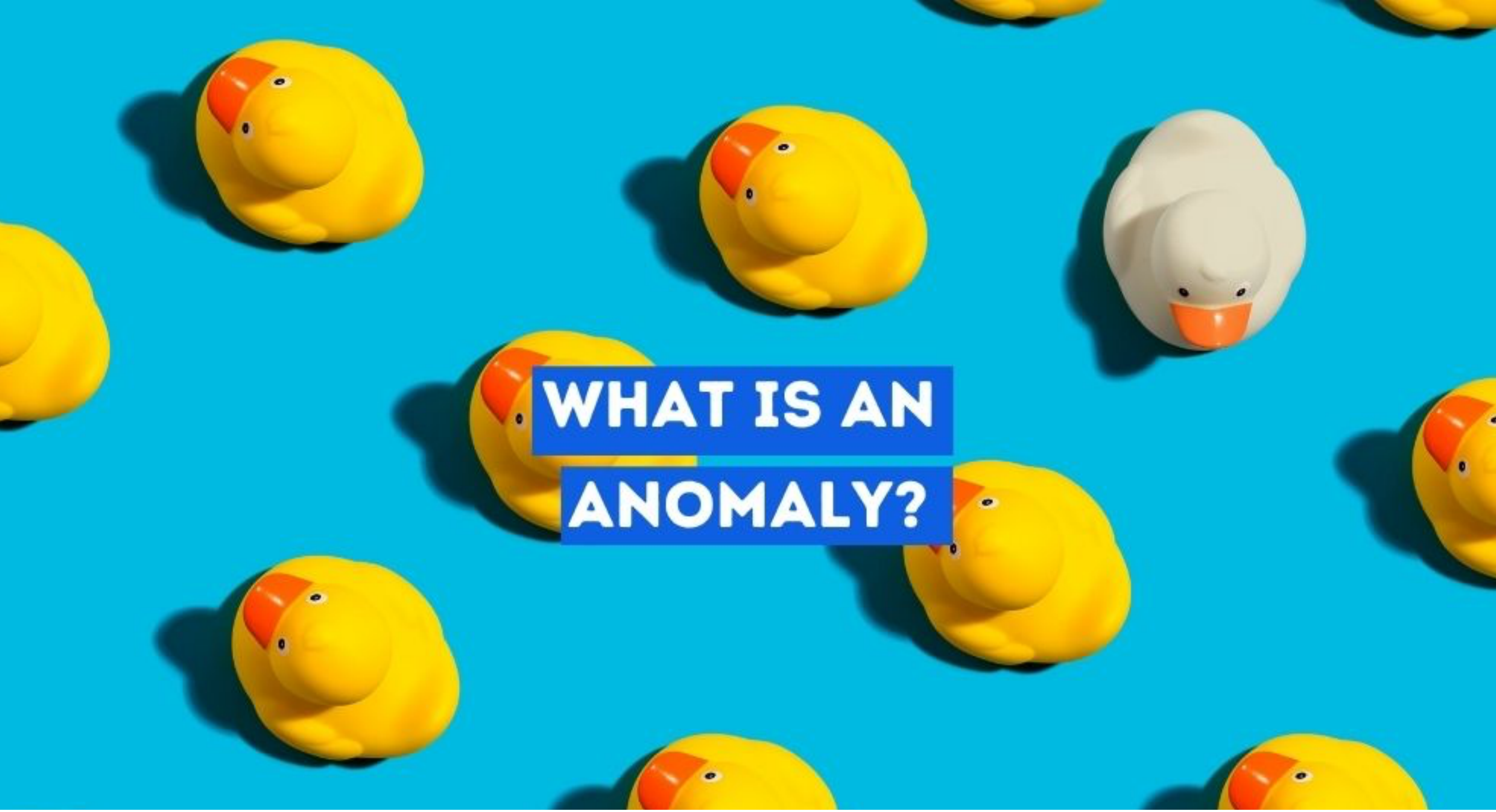
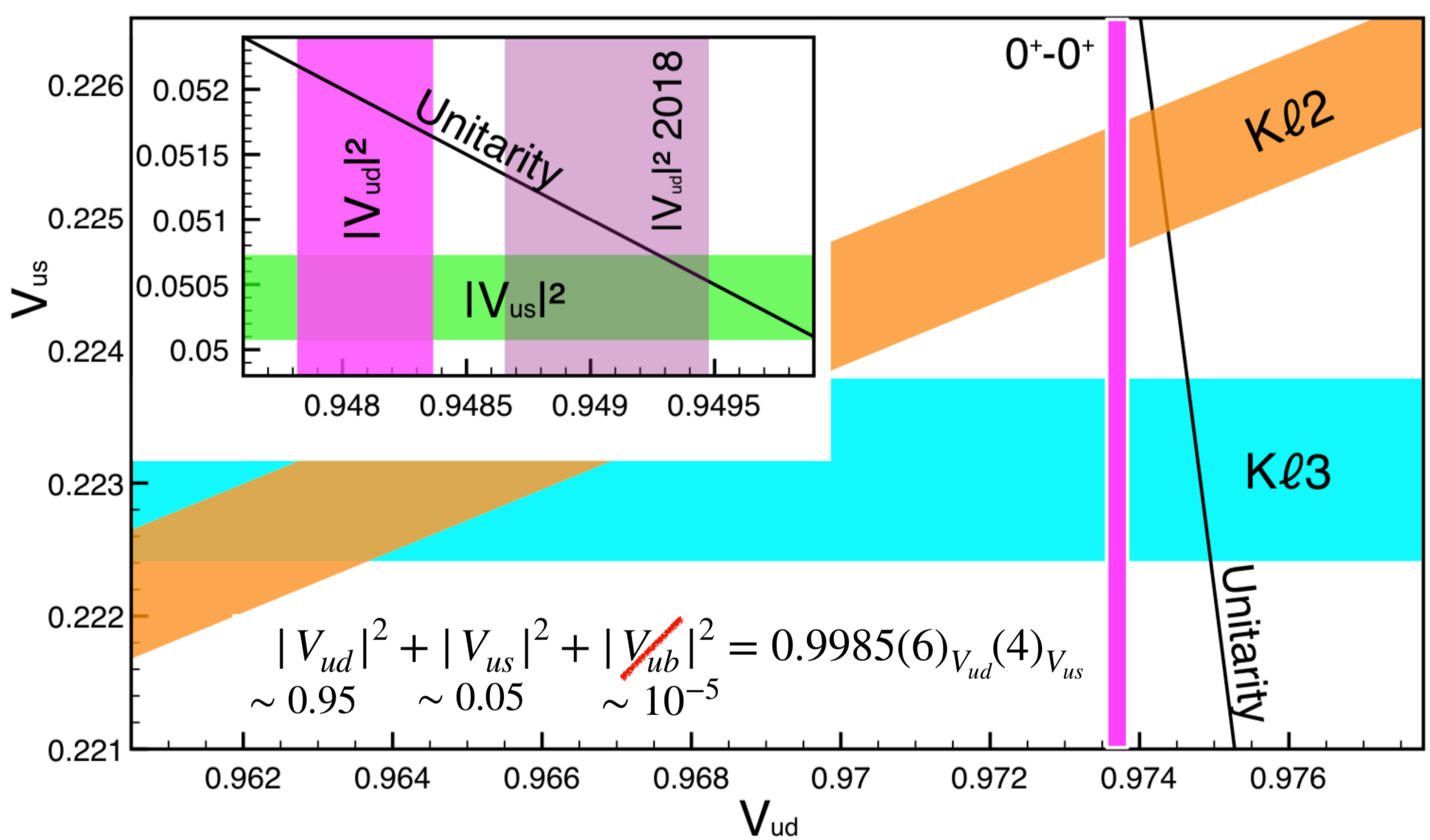


ChatGPT

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.

A L👁👁k @ 1st row

Misha Gorshteyn @ CKM 23



- LQCD on (semi)leptonic decays : Beyond % precision —> **control of ΔI & QED**

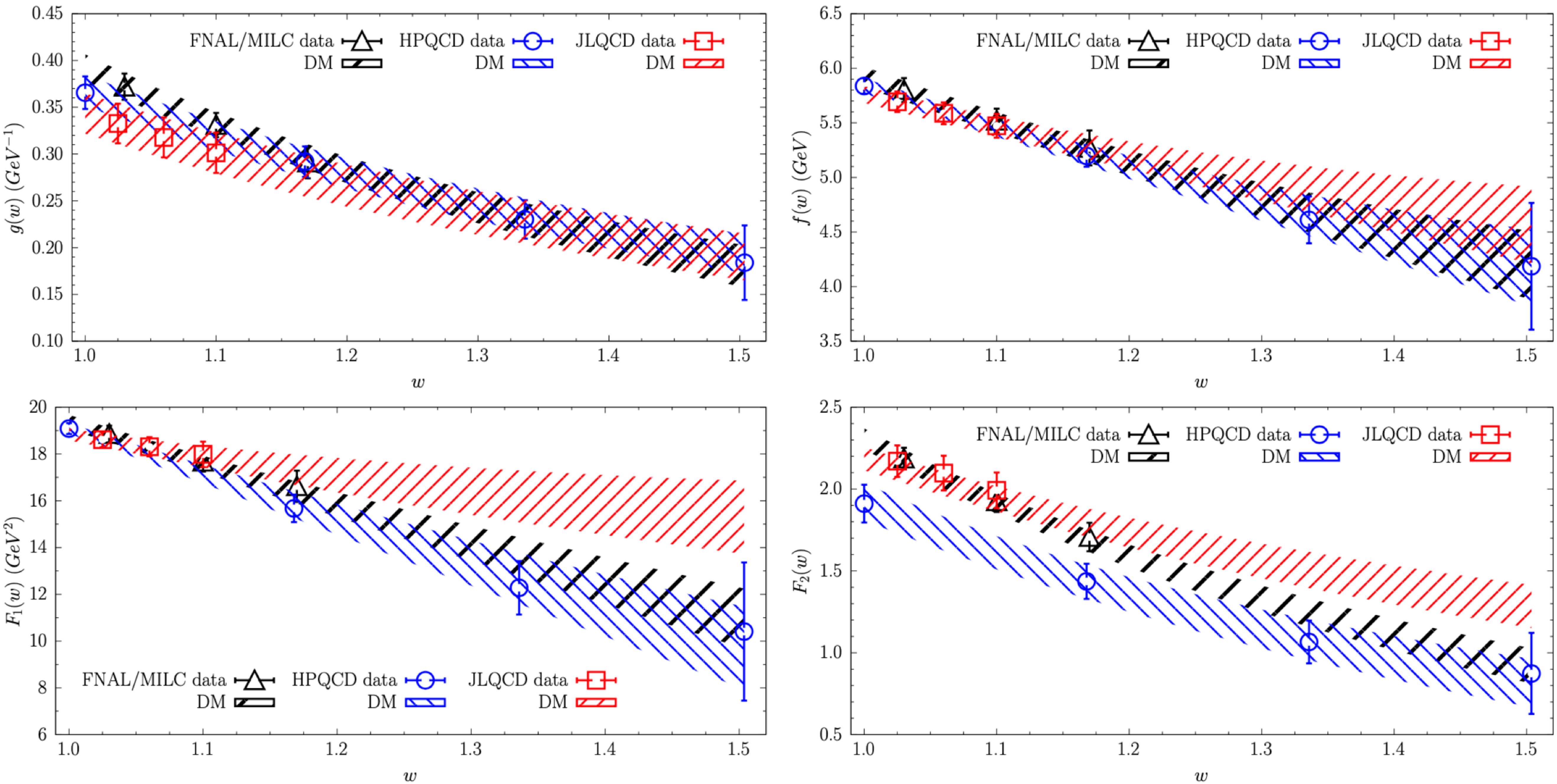
  See , e.g., Phys.Rev.D 105 (2022) 11, 114507

- 0+ —> 0+ transitions "better" than neutron decay, **but $\pi^+ \rightarrow \pi^0 e^+ \nu$ cleanest though**

  Interesting proposal: PIONEER — *arXiv:2203.01981*

A LOOK @ V_{cb}

Ludovico Vittorio @ CKM 23

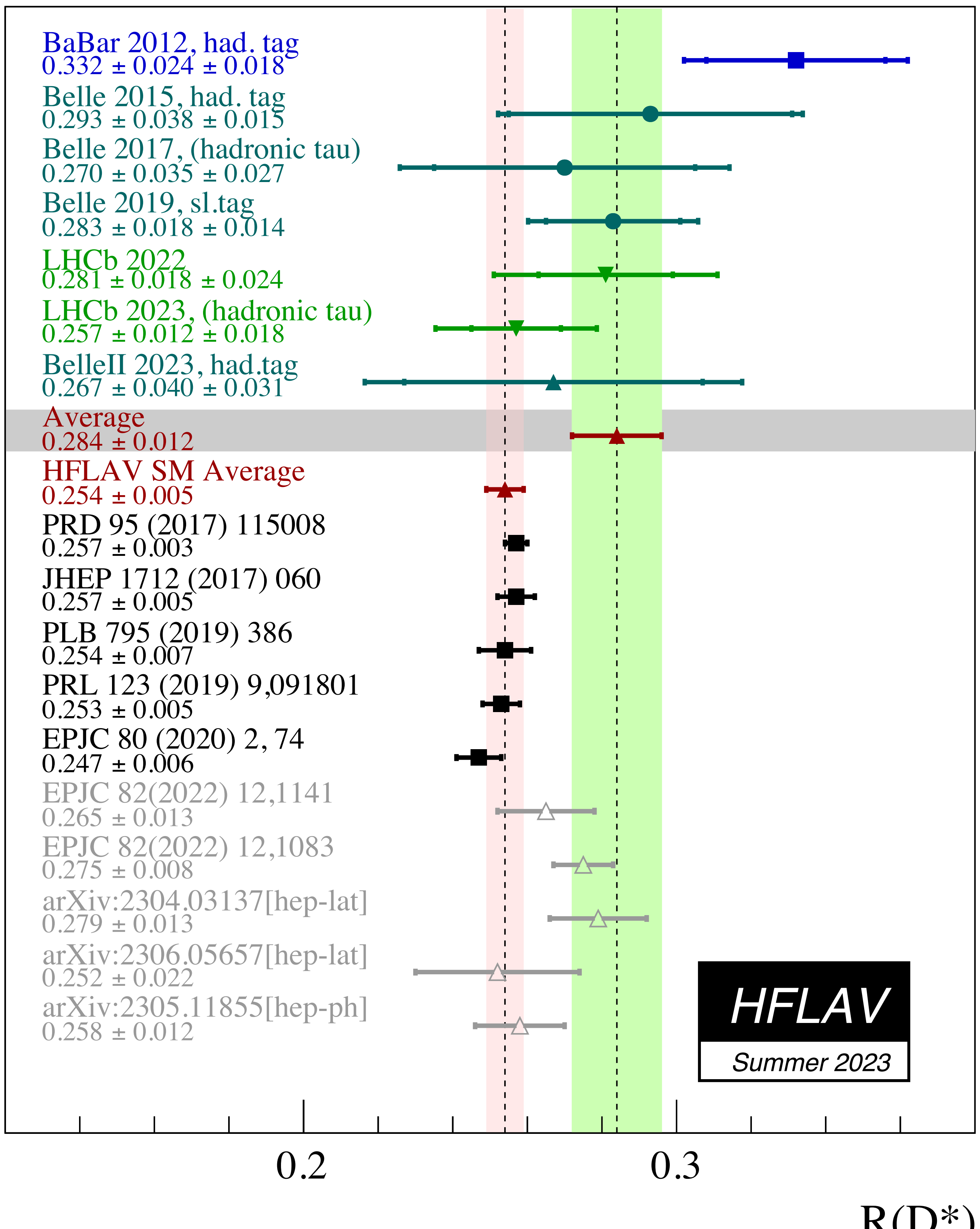


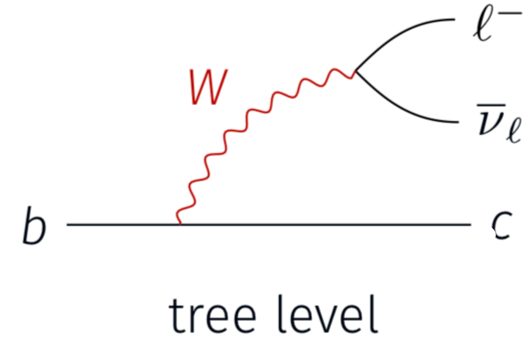
JLQCD:
arXiv:2306.05657

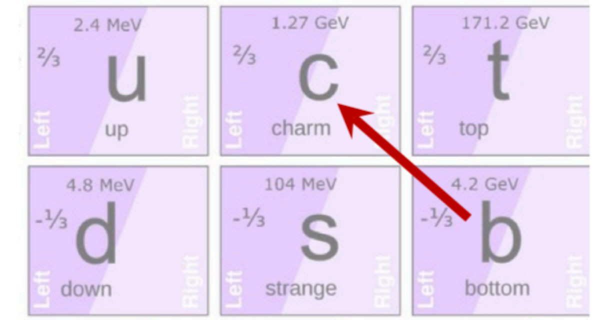
FNAL/MILC:
EPJC '22
(arXiv:2105.14019)

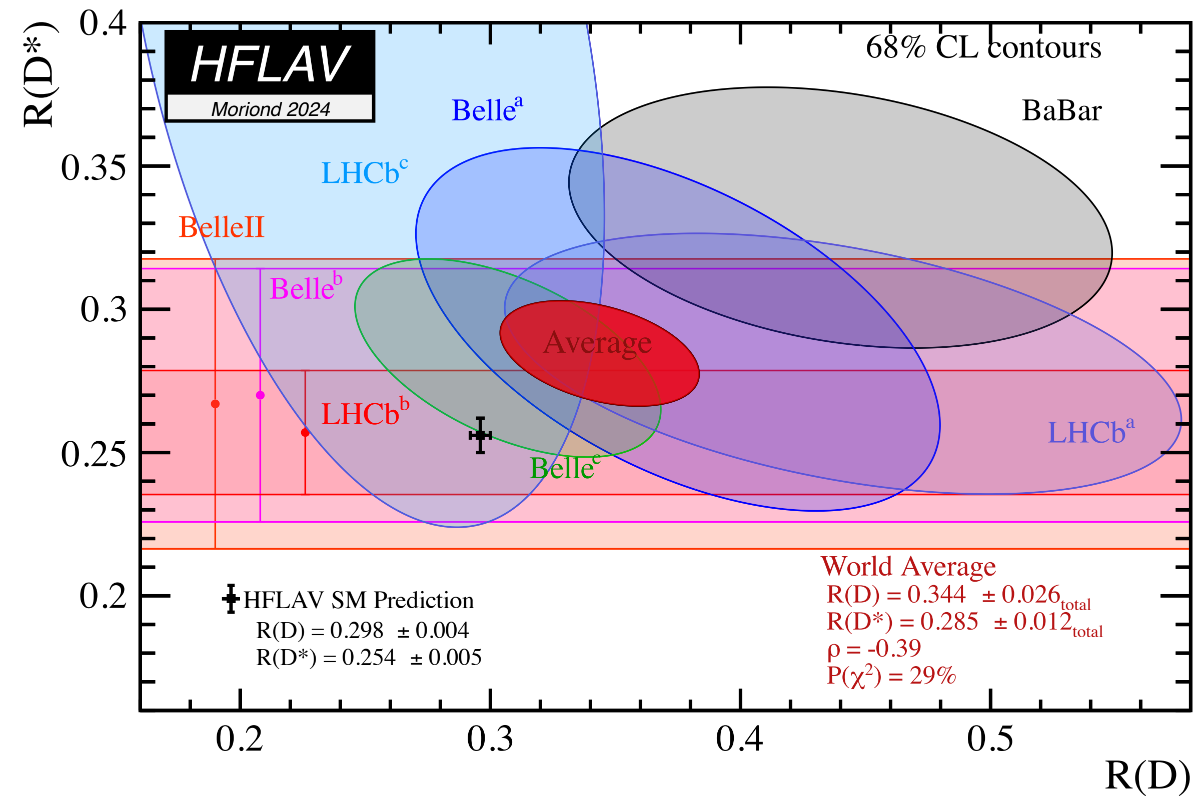
HPQCD:
arXiv:2304.03137

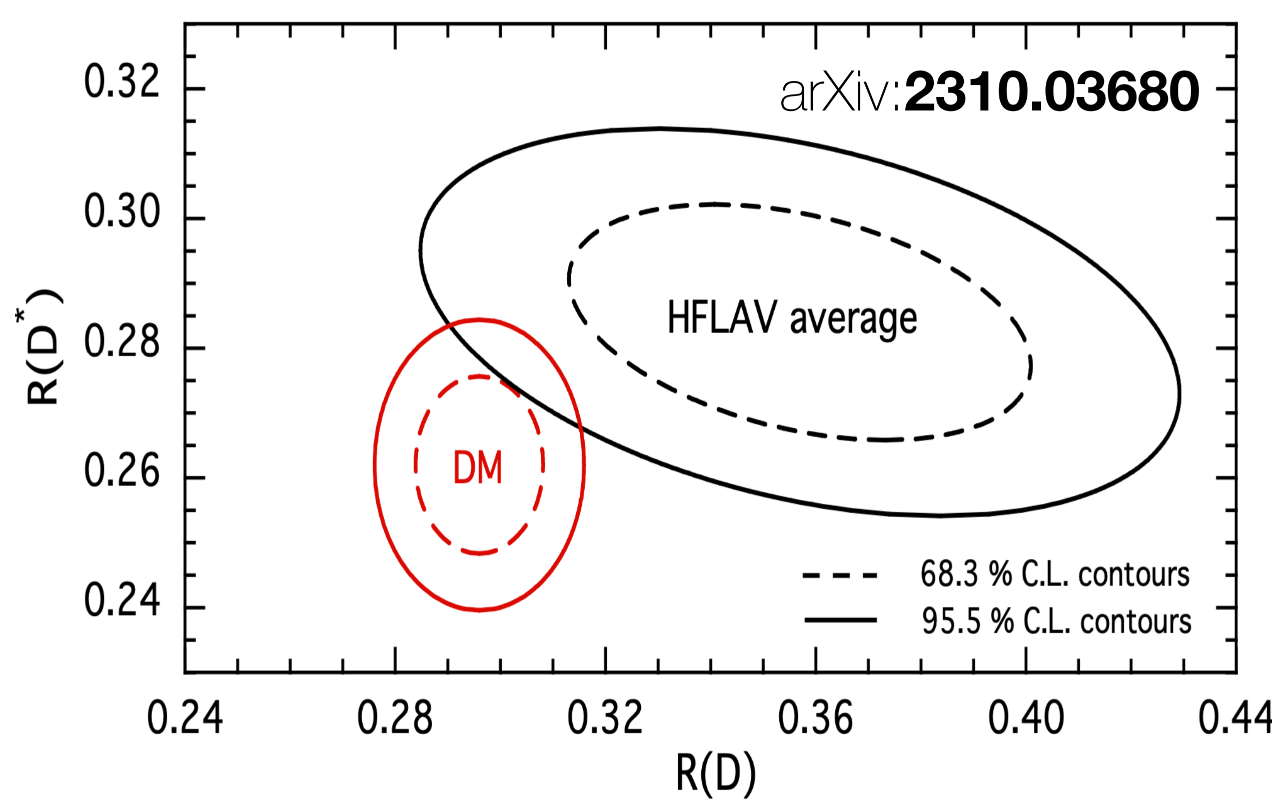
Are These (Exciting) Anomalies? ...



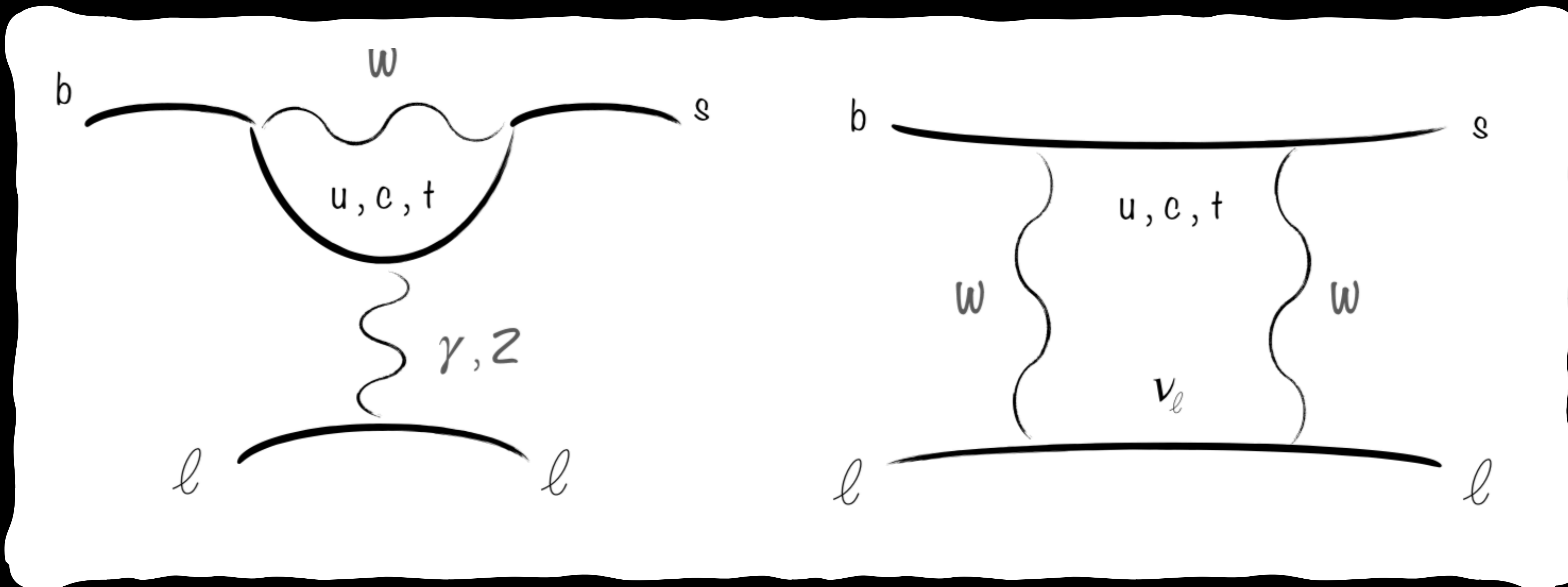








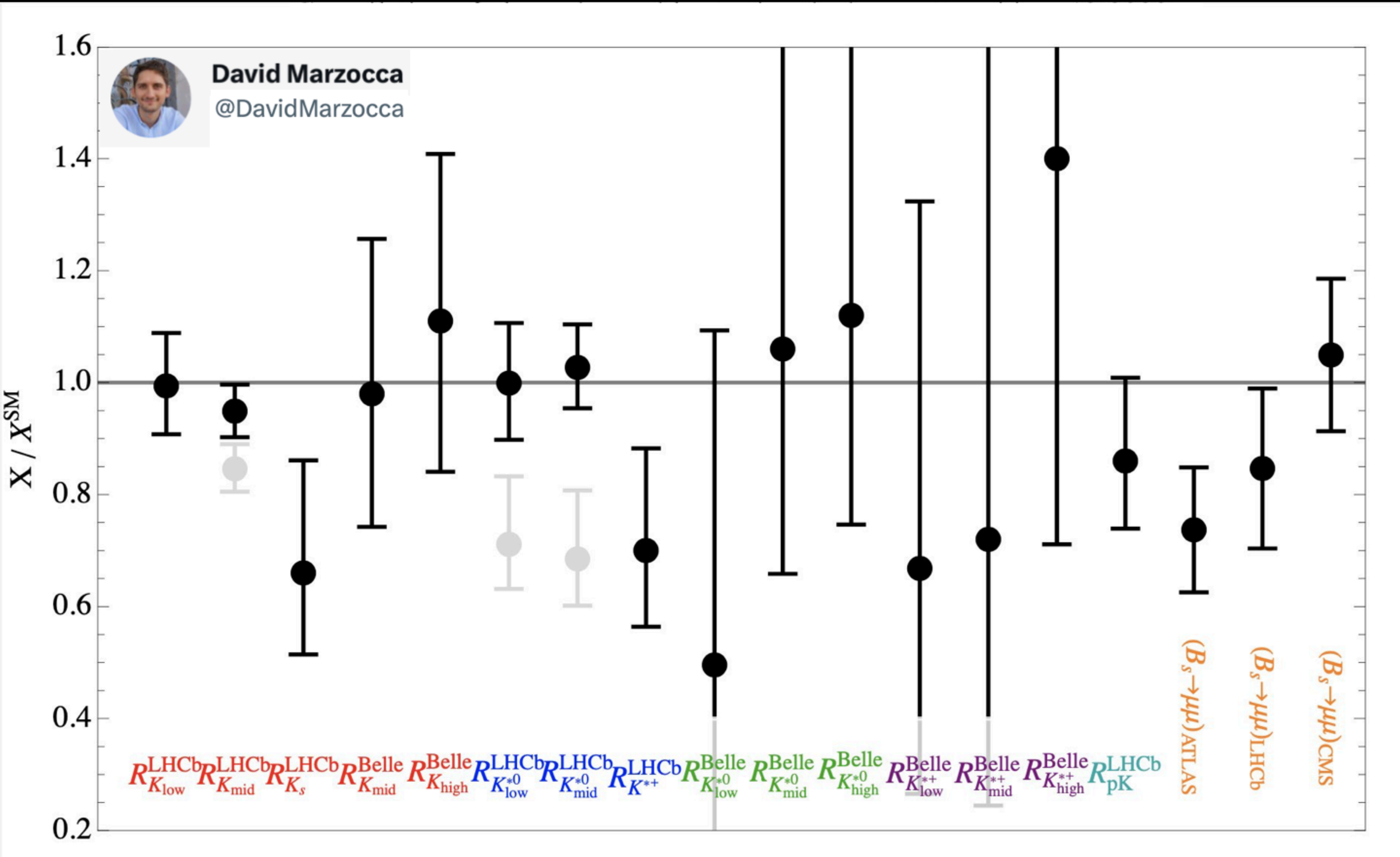
Semileptonic Rare B decays



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

for NP!

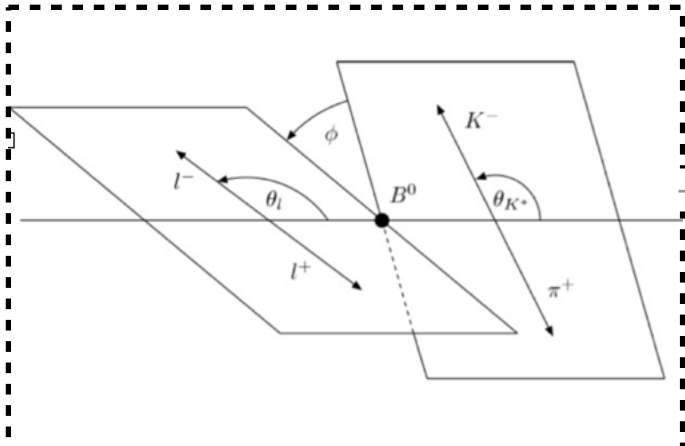
… There Were Exciting Anomalies …

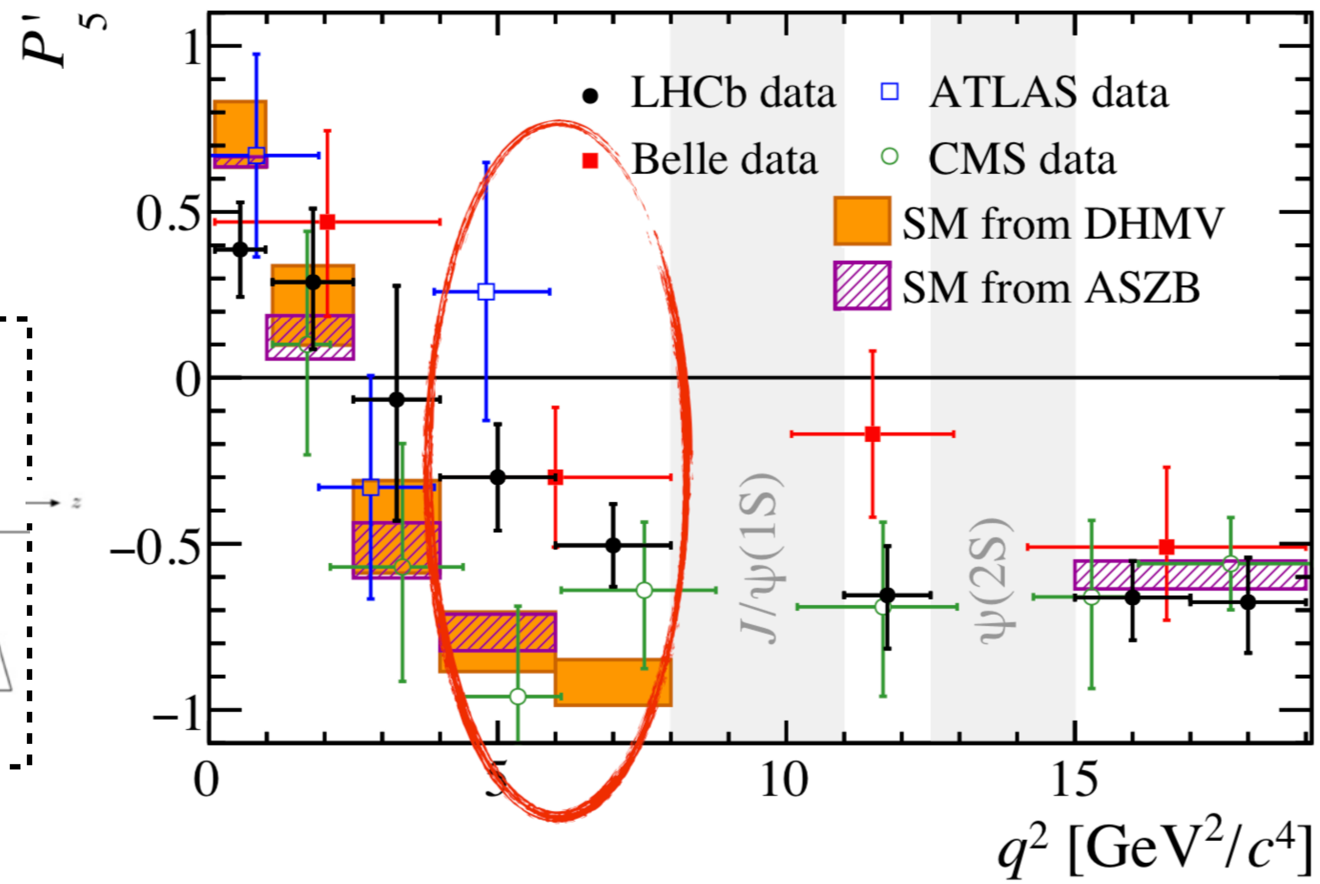


Hints for **NP effects** in the same class of FCNCs

ANGULAR ANALYSIS OF $M \longrightarrow V \mu\mu$

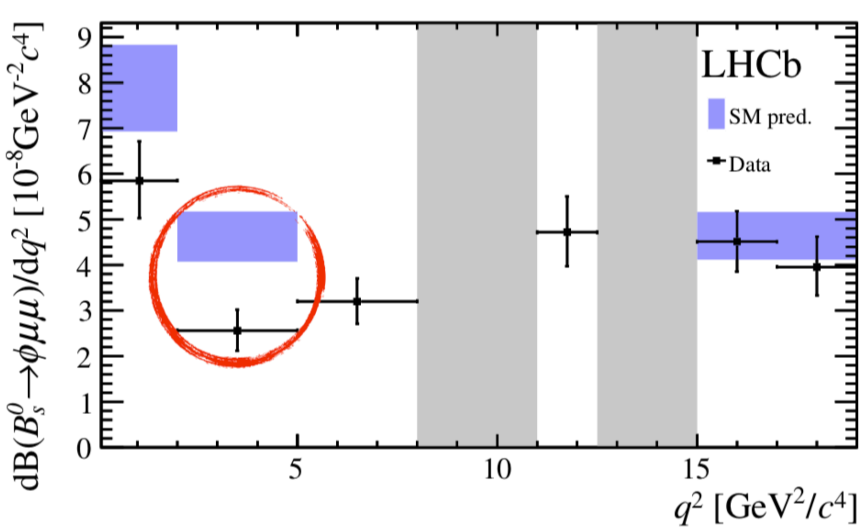
[$M = B_{(s)}$, $V = K^{*0,+}$ (ϕ)]

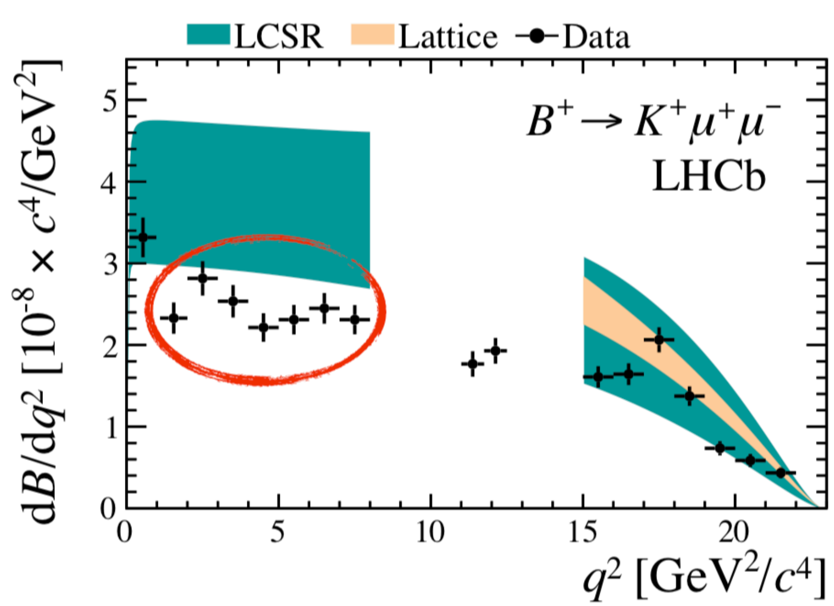




- LHCb
- $4.0 < q^2 / GeV^2 < 6.0$
- $6.0 < q^2 / GeV^2 < 8.0$
- 3.4 σ
- ATLAS
- $4.0 < q^2 / GeV^2 < 6.0$
- 2.7 σ
- BELLE
- $4.0 < q^2 / GeV^2 < 8.0$
- 2.6 σ
- CMS
- No discrepancies!

BRs , same range in q^2





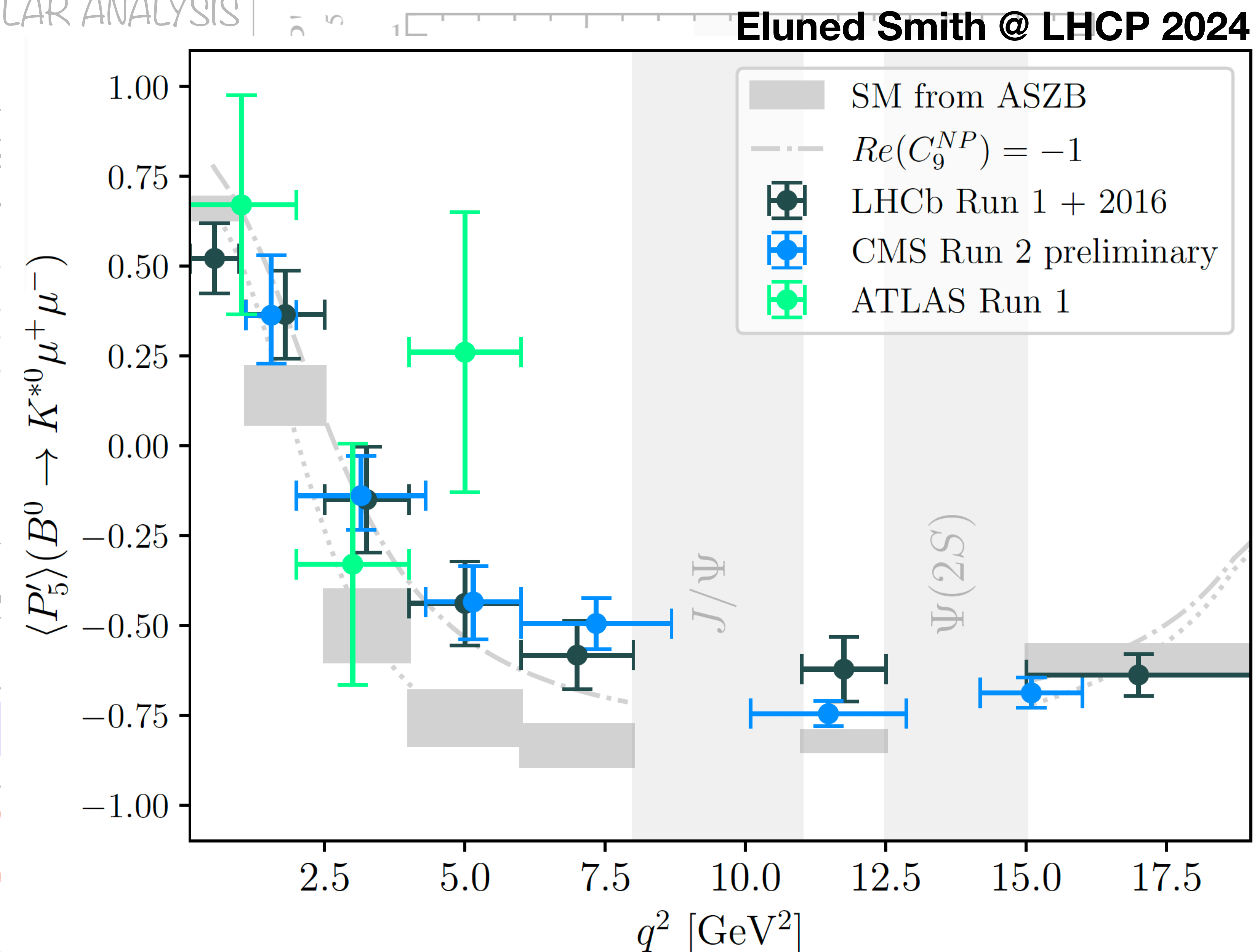
- $2.0 < q^2 / GeV^2 < 5.0$
- Low q^2

CONSISTENT vs TIME

Tension in muons @ LHCb

PRL 25, 011802 (2020)

Hints for **NP effects** in the same class of FCNCs



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

$$H_\lambda^{(V)}(q^2) \propto 2\frac{m_b m_B}{q^2}\left(C_7^{\rm eff} + \Delta C_{7,\lambda}^{\rm QCDf}(q^2)\right)\boxed{\tilde{T}_\lambda(q^2)} + C_9^{\rm eff}(q^2)\boxed{\tilde{V}_\lambda(q^2)}$$

$$+\Delta C_{9,\lambda}^{\rm QCDf}(q^2) + 16\pi^2\frac{m_B^2}{q^2}\boxed{\tilde{h}_\lambda(q^2)}\,,$$

HELICITY AMPLITUDES : $\lambda = \pm, 0\,.$

$$H^{(P)}(q^2) \propto 2\frac{m_\ell m_B}{q^2}C_{10}\left(1+\frac{m_s}{m_b}\right)\boxed{\tilde{S}(q^2)}\,, \qquad H_\lambda^{(A)}(q^2) \propto C_{10}\boxed{\tilde{V}_\lambda(q^2)}\,.$$

- SHORT DISTANCE @ DIM 6

  SM Wilson coeffs @ ~ m_b : C_7 ~ -1/3 , C_9 ~ 4 , C_{10} ~ -4

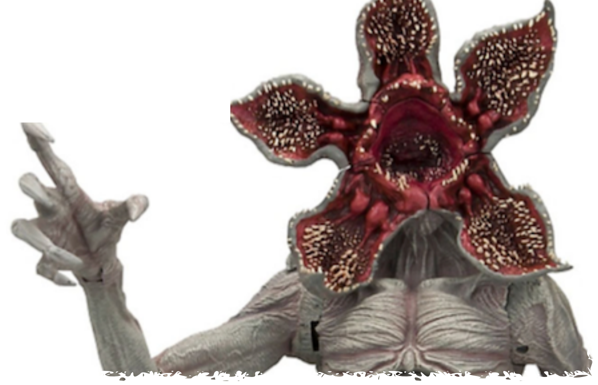
- FORM FACTORS FOR $B \to K^{(*)}$

  state-of-the-art from LQCD & LCSR computations

- QCD CONTRIBUTIONS FROM C x C & PENGUINS

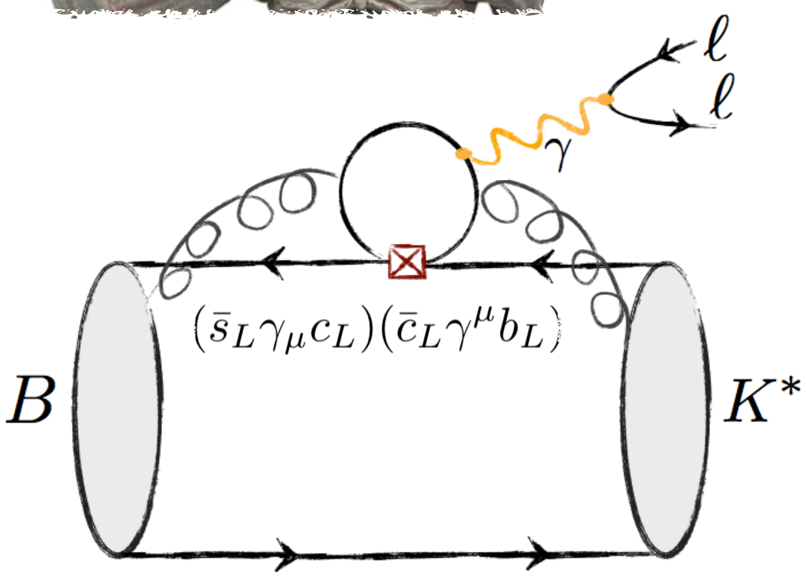
  QCD factorization for leading effects of $O(\Lambda_{QCD}/m_b)$,

  but non-factorizable power corrections also present.



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

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

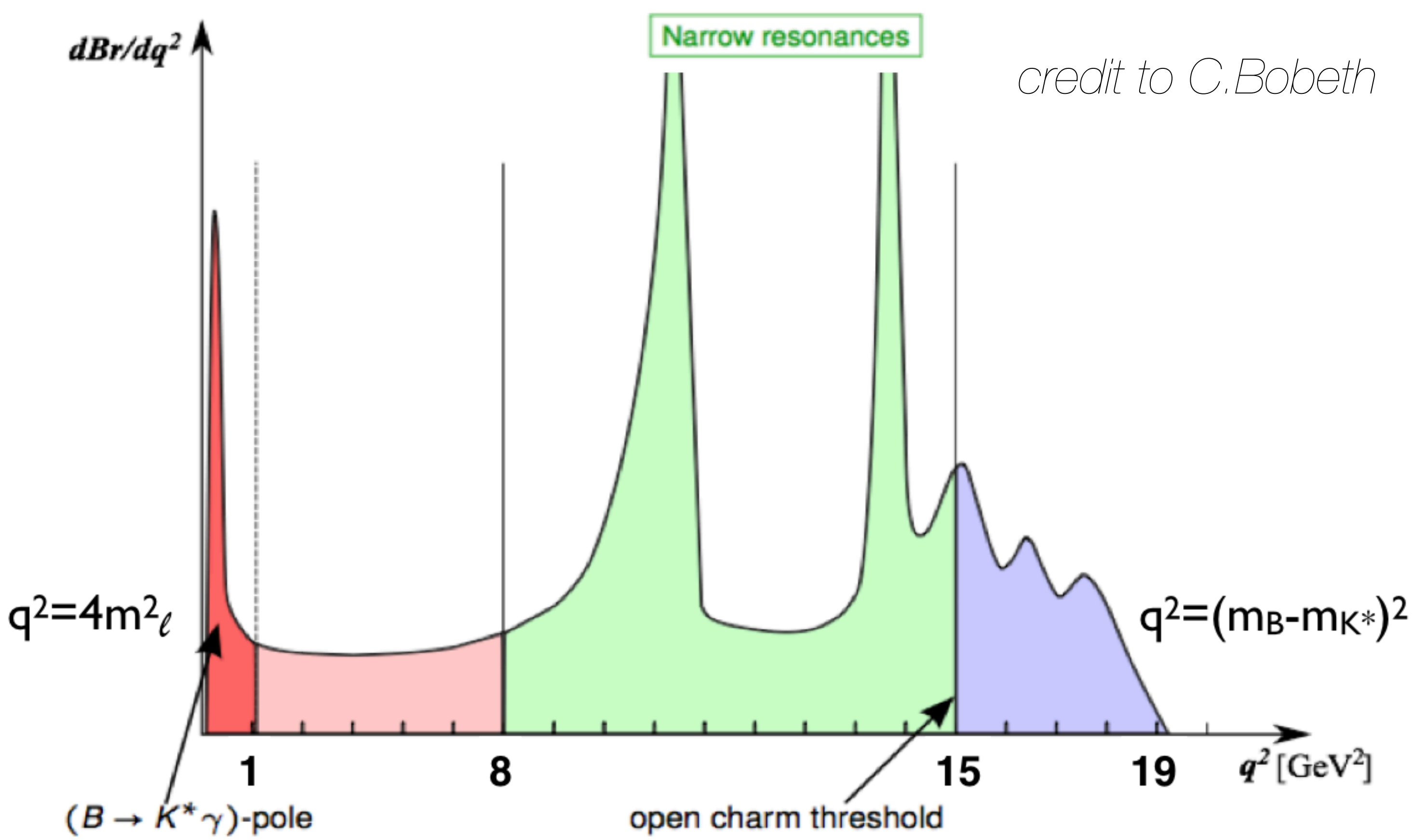


COMPUTED IN
***JHEP* 09 (2010) 089**
ACCORDING TO:

i) Light-cone sum rules (LCSR)

ii) Single soft gluon approximation

iii) Extrapolation via dispersion rel.



Large Recoil (low q^2)   Low Recoil (high q^2)

“OPTIMISTIC” =
TRUST THIS COMPLETELY!
Pheno - Model - Driven (PMD)

“CONSERVATIVE” =
TRUST THIS PARTIALLY!
Pheno - Data - Driven (PDD)

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

[JHEP 06 (2016) 116]

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

Phenomenological Model Driven (PMD)

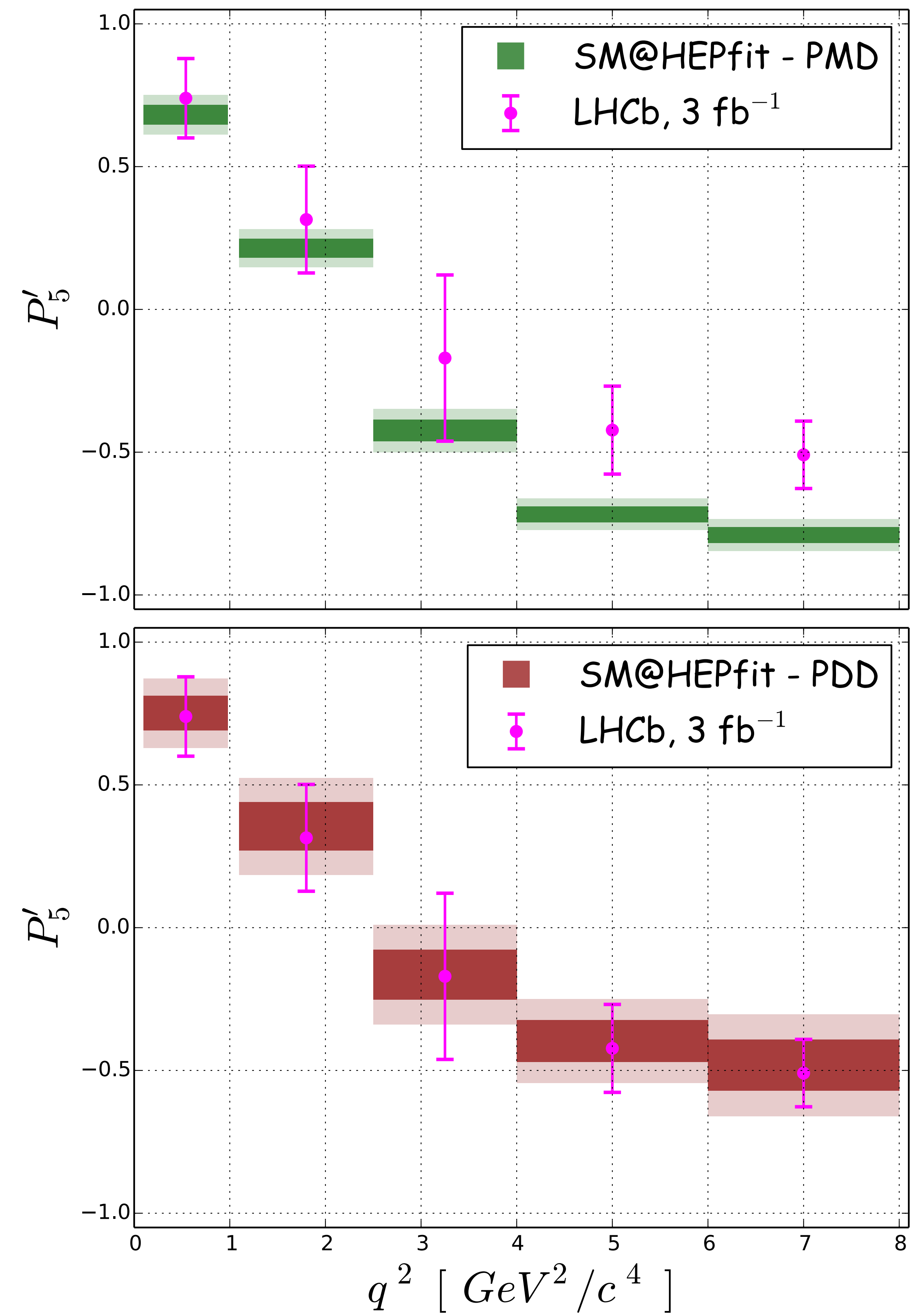
Enforce outcome of LCSR + dispersion relations in the entire range of q^2

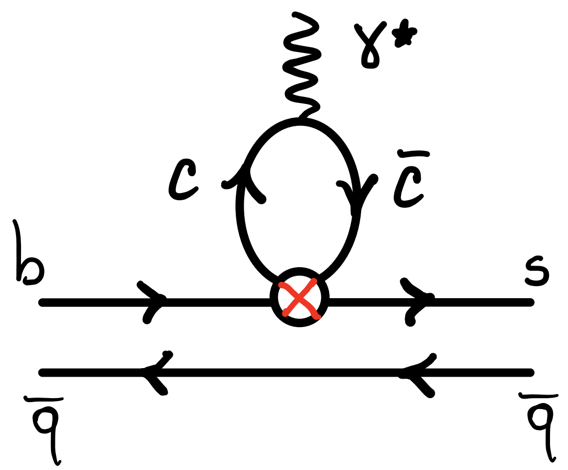
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Descotes-Genon et al. 2013

Phenomenological Data Driven (PDD)

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





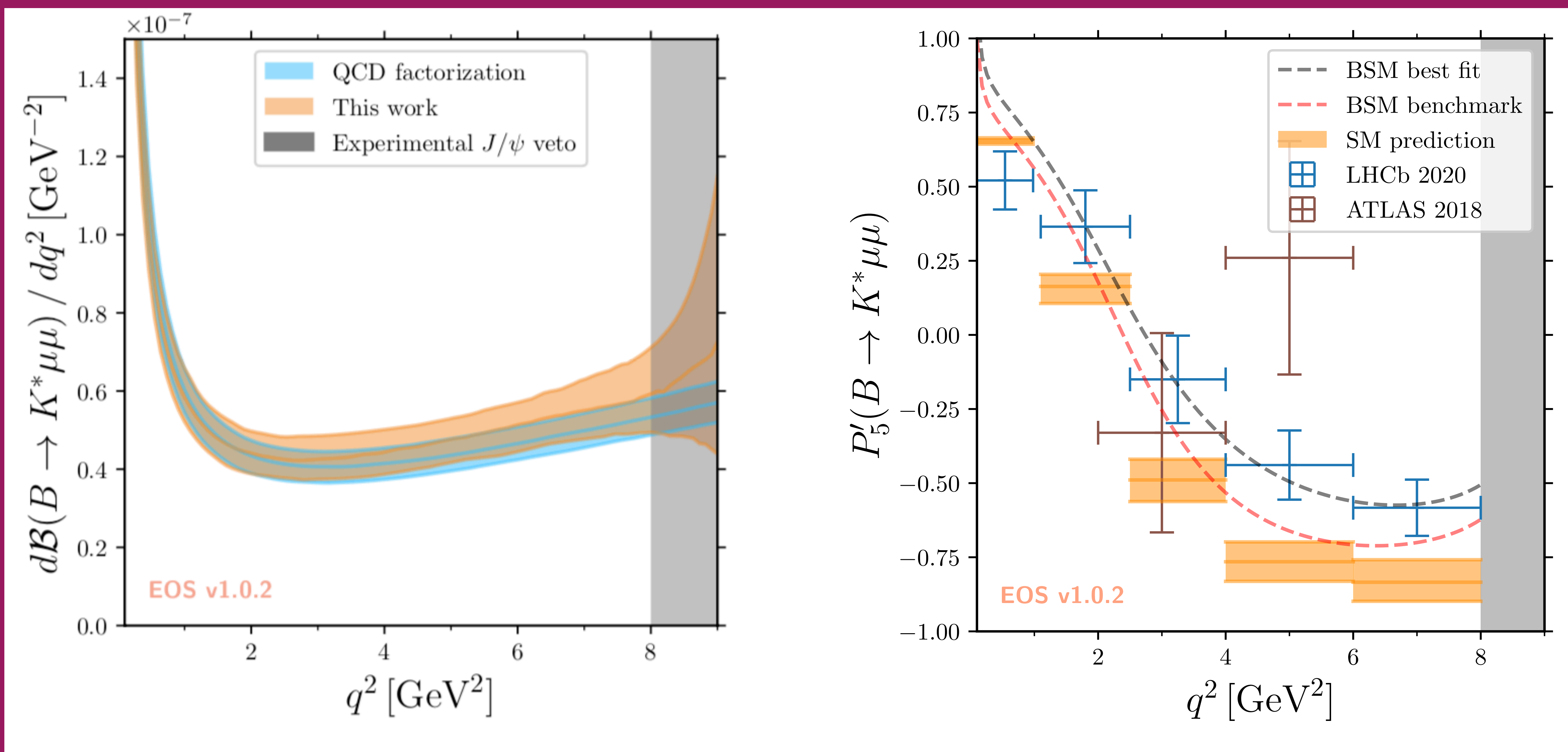
In 2022, this class of charming penguins has been re-estimated —> tiny contribution !

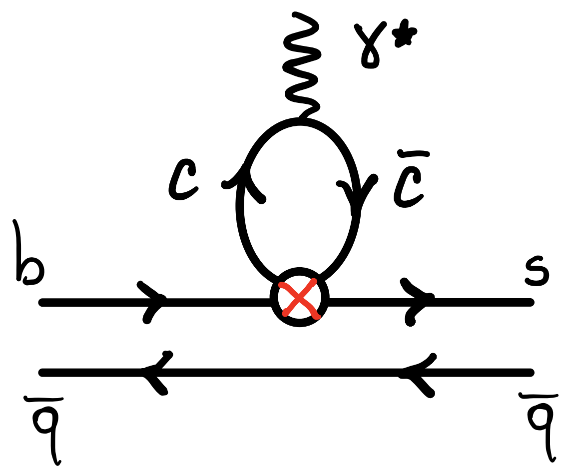
[*JHEP 09 (2022) 133*]

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

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

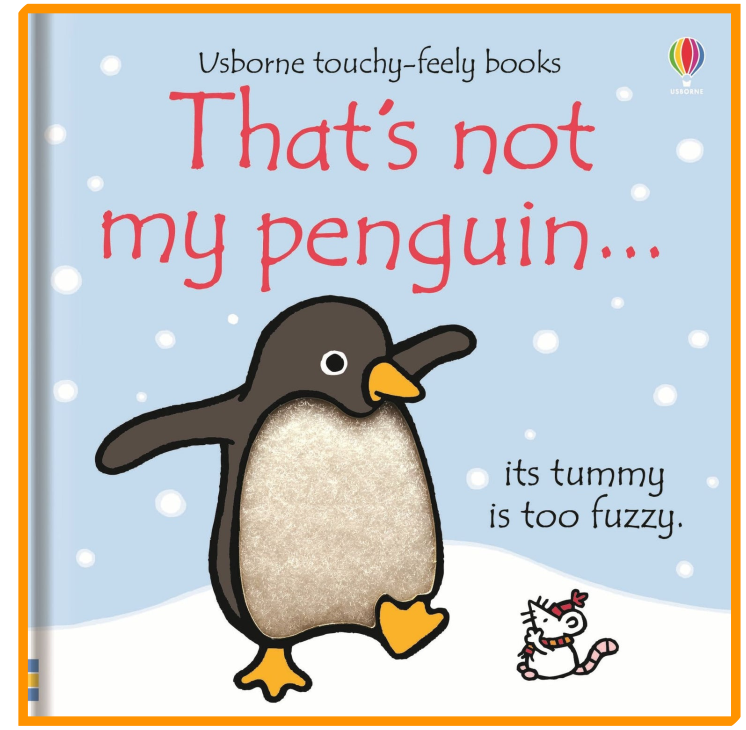
3) dispersive bounds





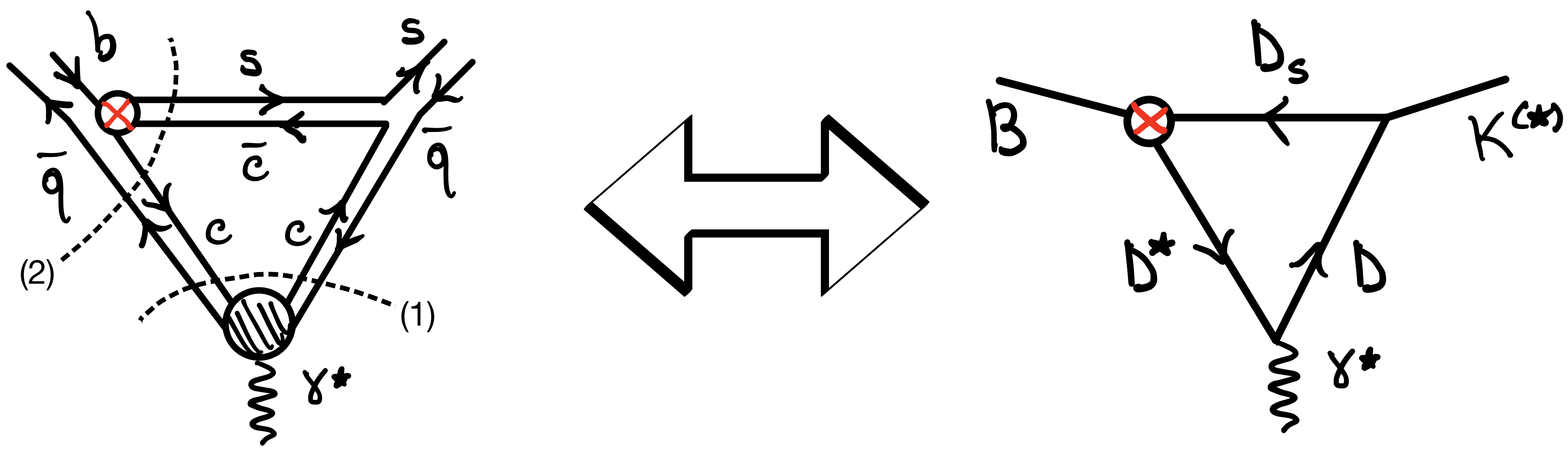
In 2022, this class of charming penguins has been re-estimated —> tiny contribution**?**

[*JHEP 09 (2022) 133*]



... BUT WHAT ABOUT THOSE ?

[*Eur.Phys.J.C 83 (2023)*]



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

[*i.e., anomalous thresholds, see* ***arXiv:2406.14608*** **]**

NEW data driven approach: no theory input on $h_\lambda^{(k)}$

B ANOMALIES : WHERE ARE WE STANDING

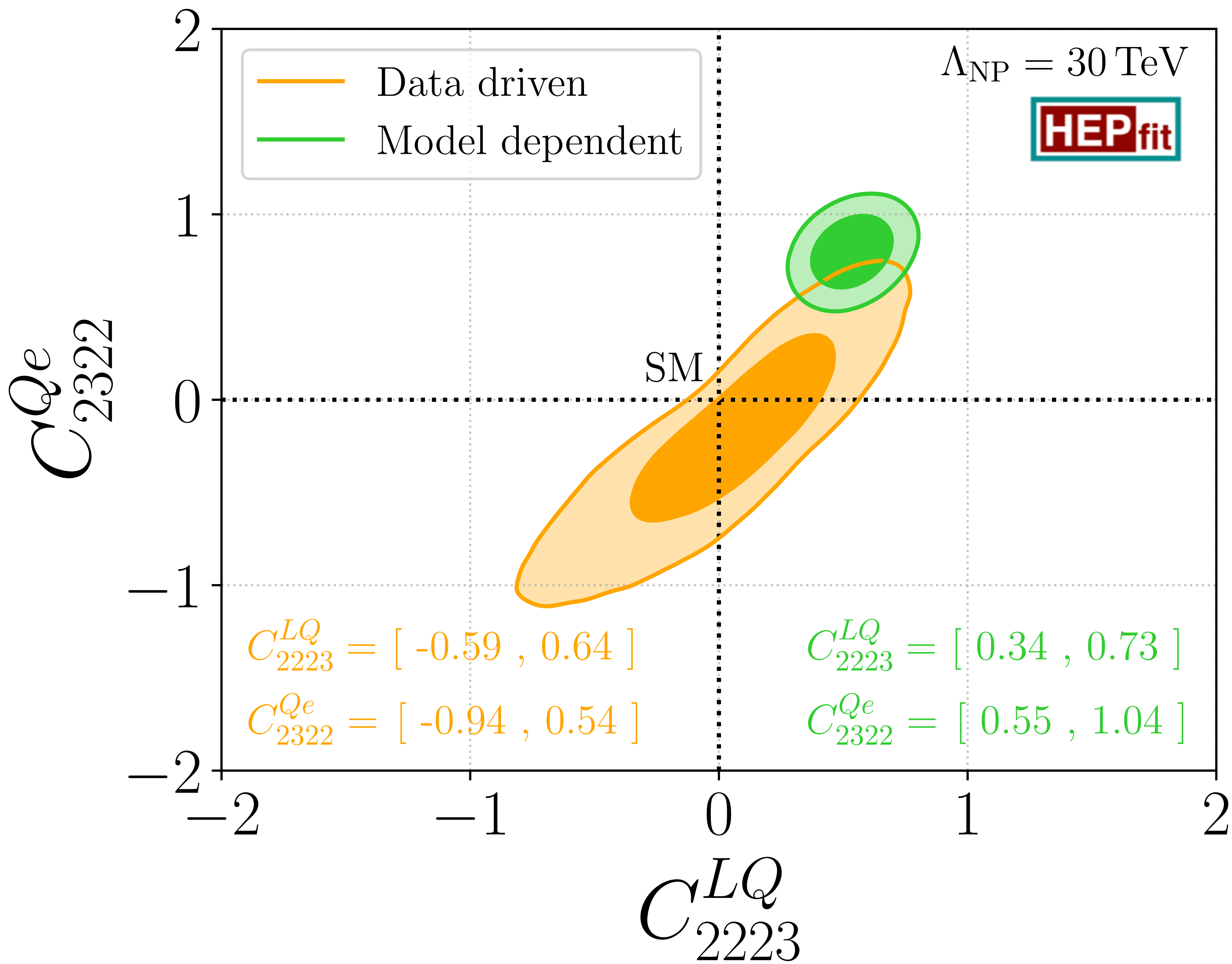
PRD 107 (2023) 5

SMEFT GLOBAL ANALYSIS:

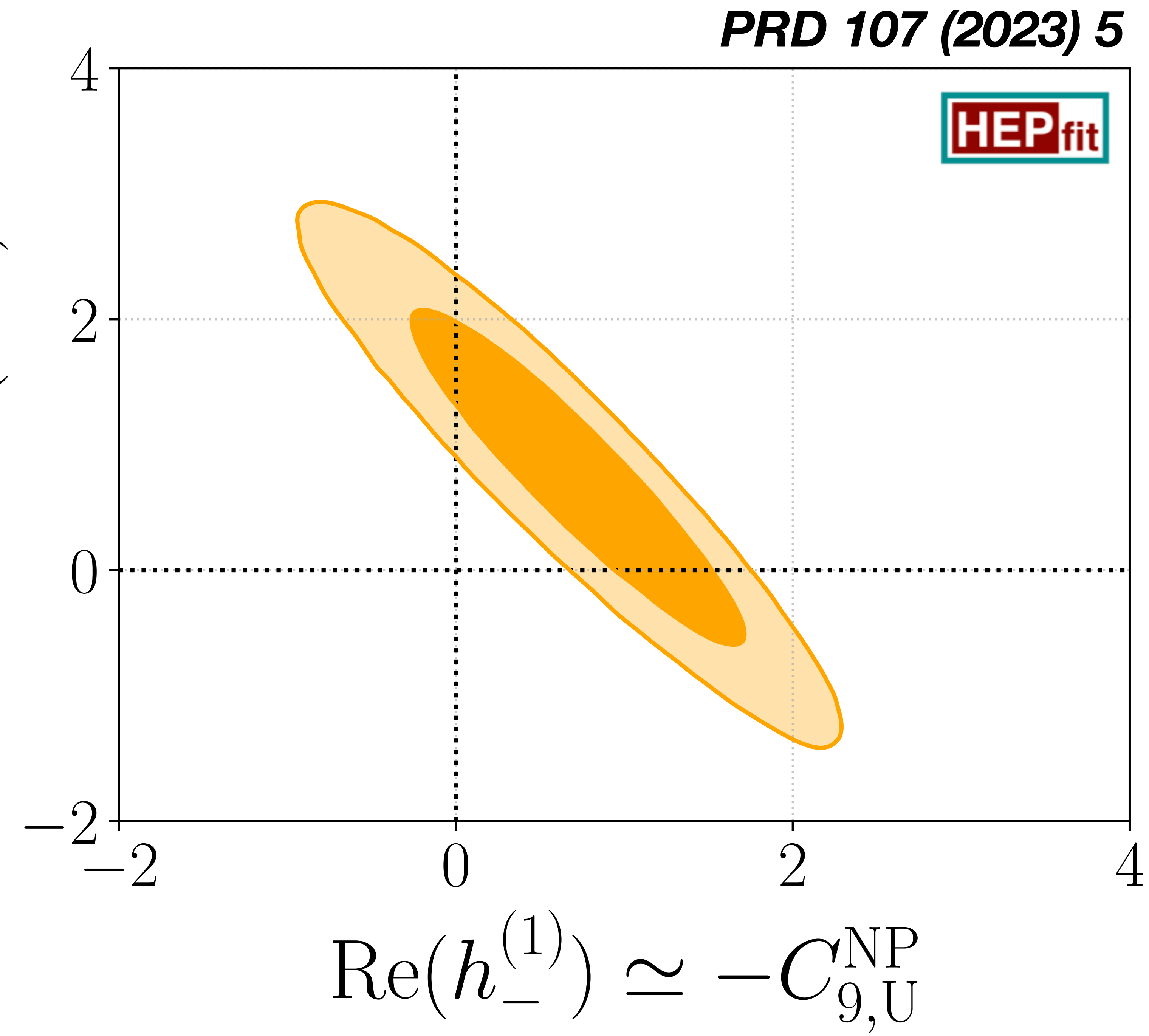
KEY **NP** OPERATORS

$$O^{LQ}_{2223} = \bar{L}_2\gamma_\mu L_2\bar{Q}_2\gamma^\mu Q_3$$
$$O^{Qe}_{2322} = \bar{Q}_2\gamma_\mu Q_3\bar{e}_2\gamma^\mu e_2$$

$$C_9 \propto C^{Qe} + C^{LQ}$$
$$C_{10} \propto C^{Qe} - C^{LQ}$$



B ANOMALIES : WHERE ARE WE STANDING



QCD ONLY

QCD ~ LEPTON UNIVERSAL NP

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*]

- 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

Special Instructions

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

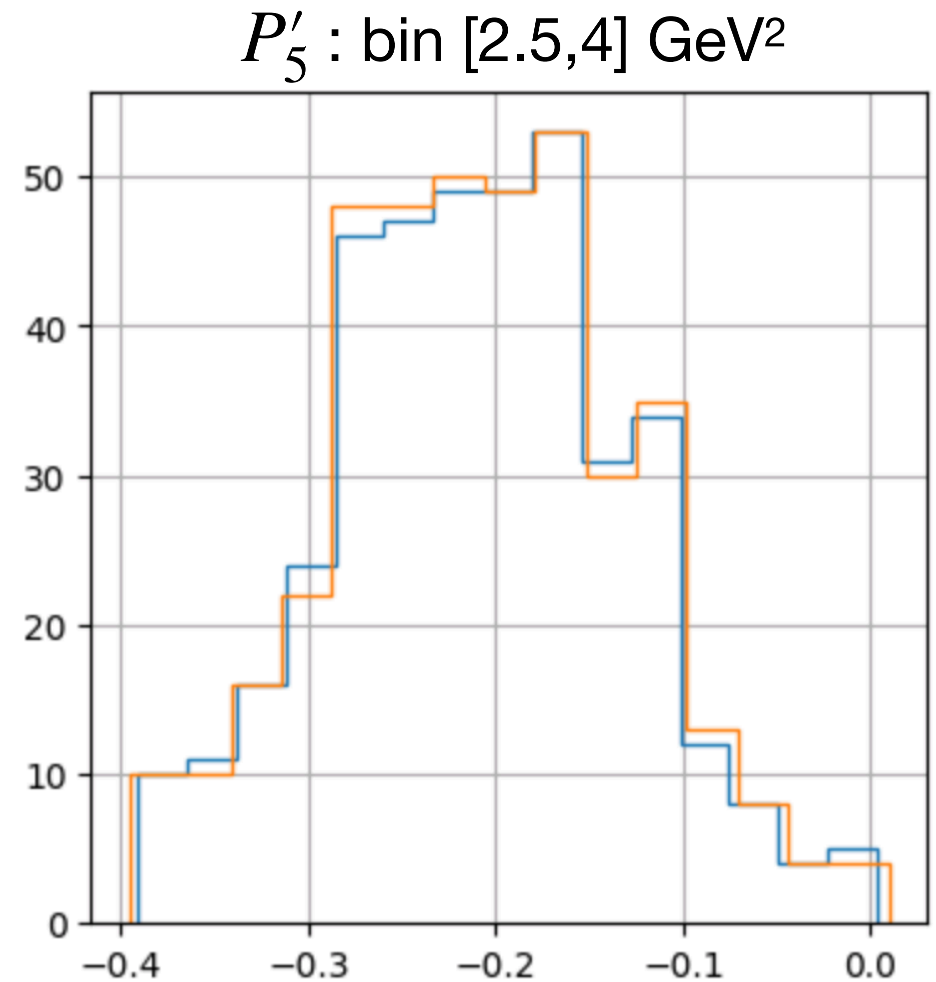
The files are:

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

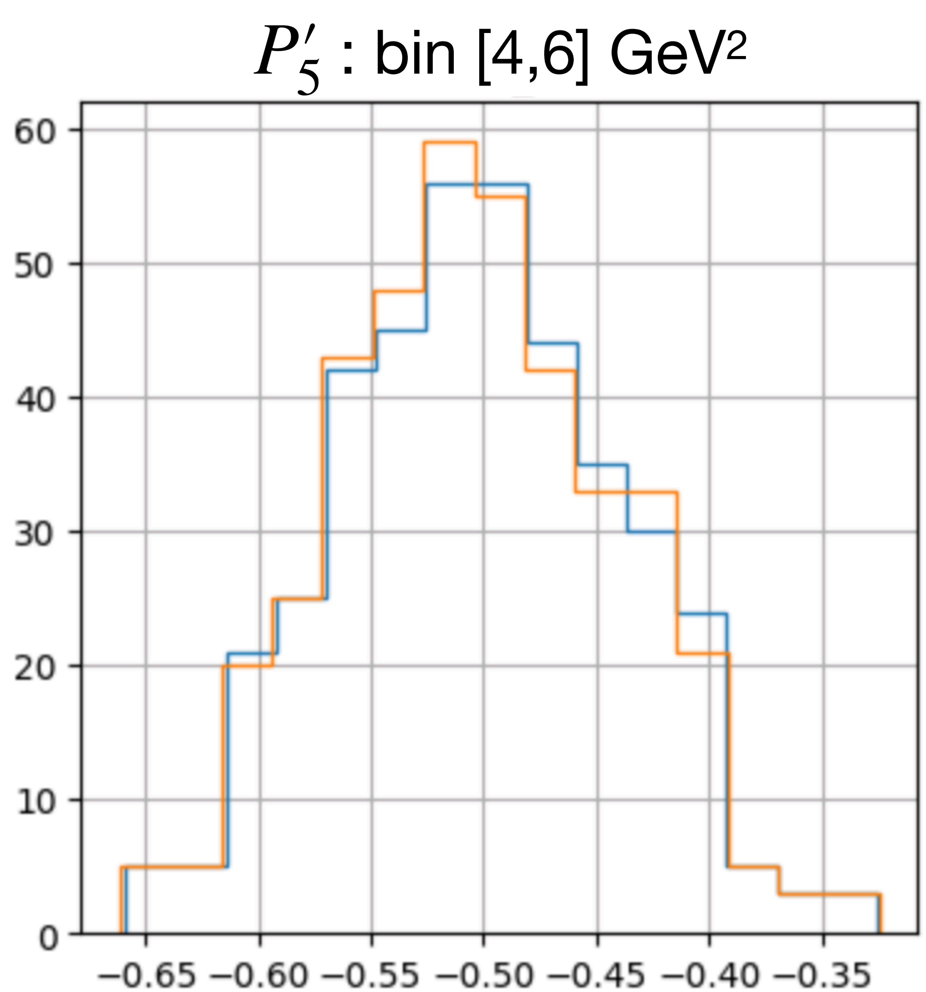
LHCb-PAPER-2023-032-Supplemental-Material.zip

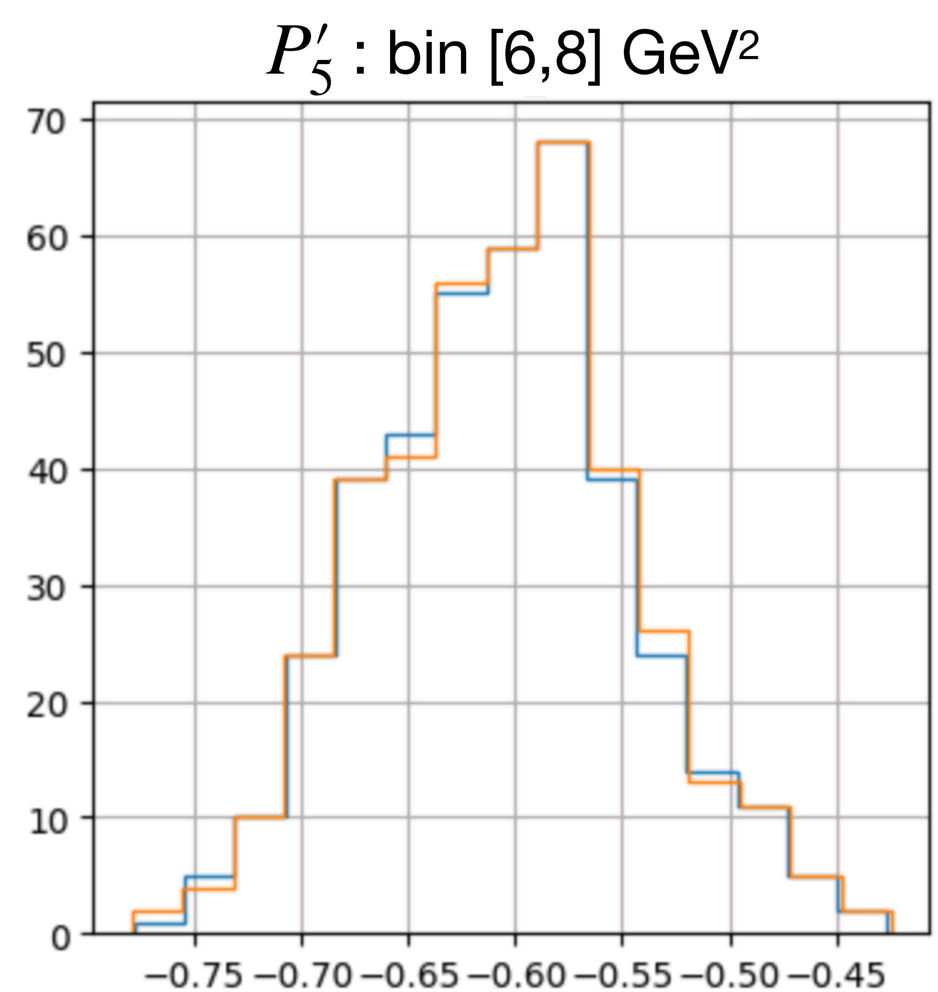


HEPfit

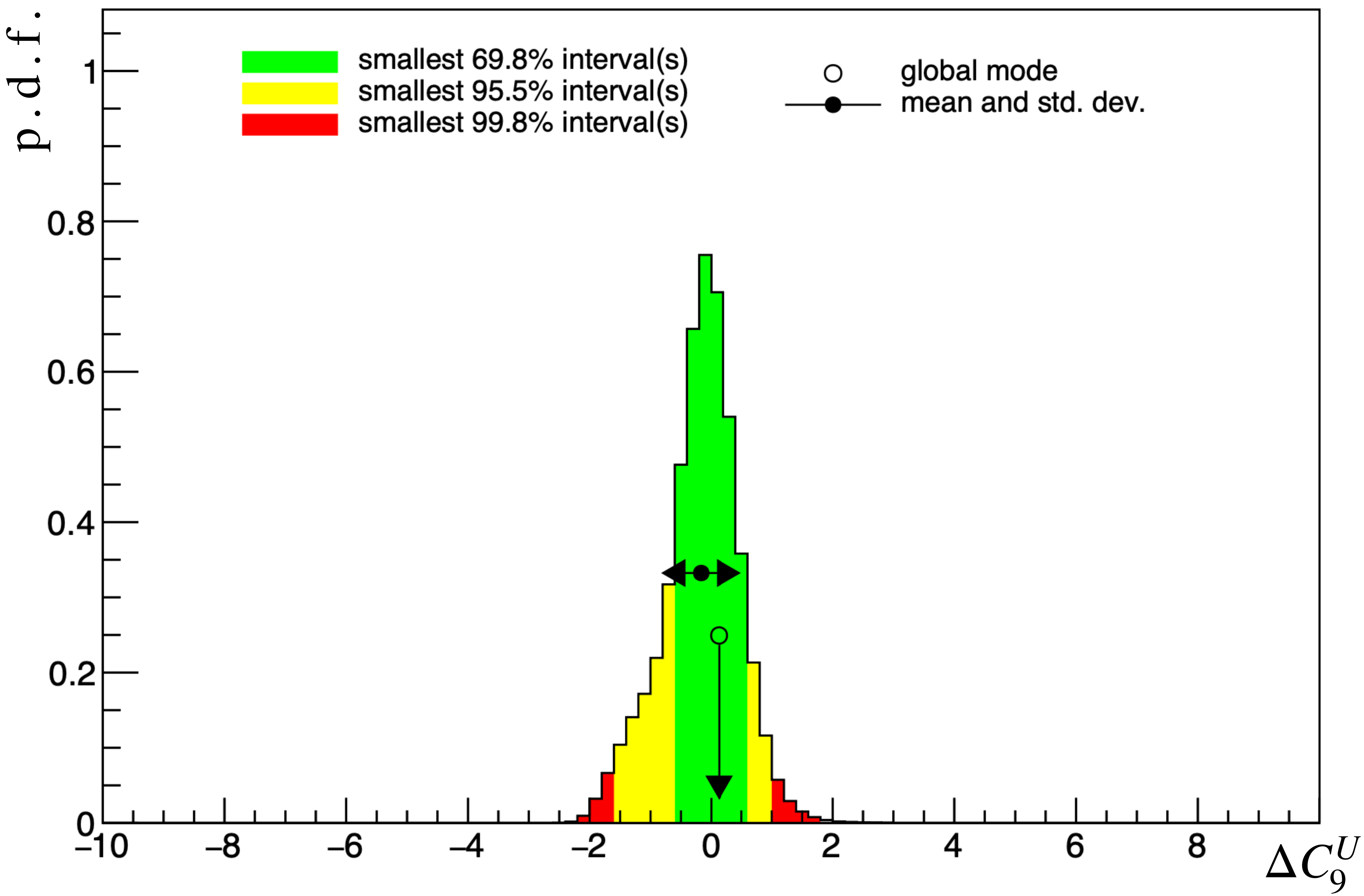
LHCb bootstrap

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



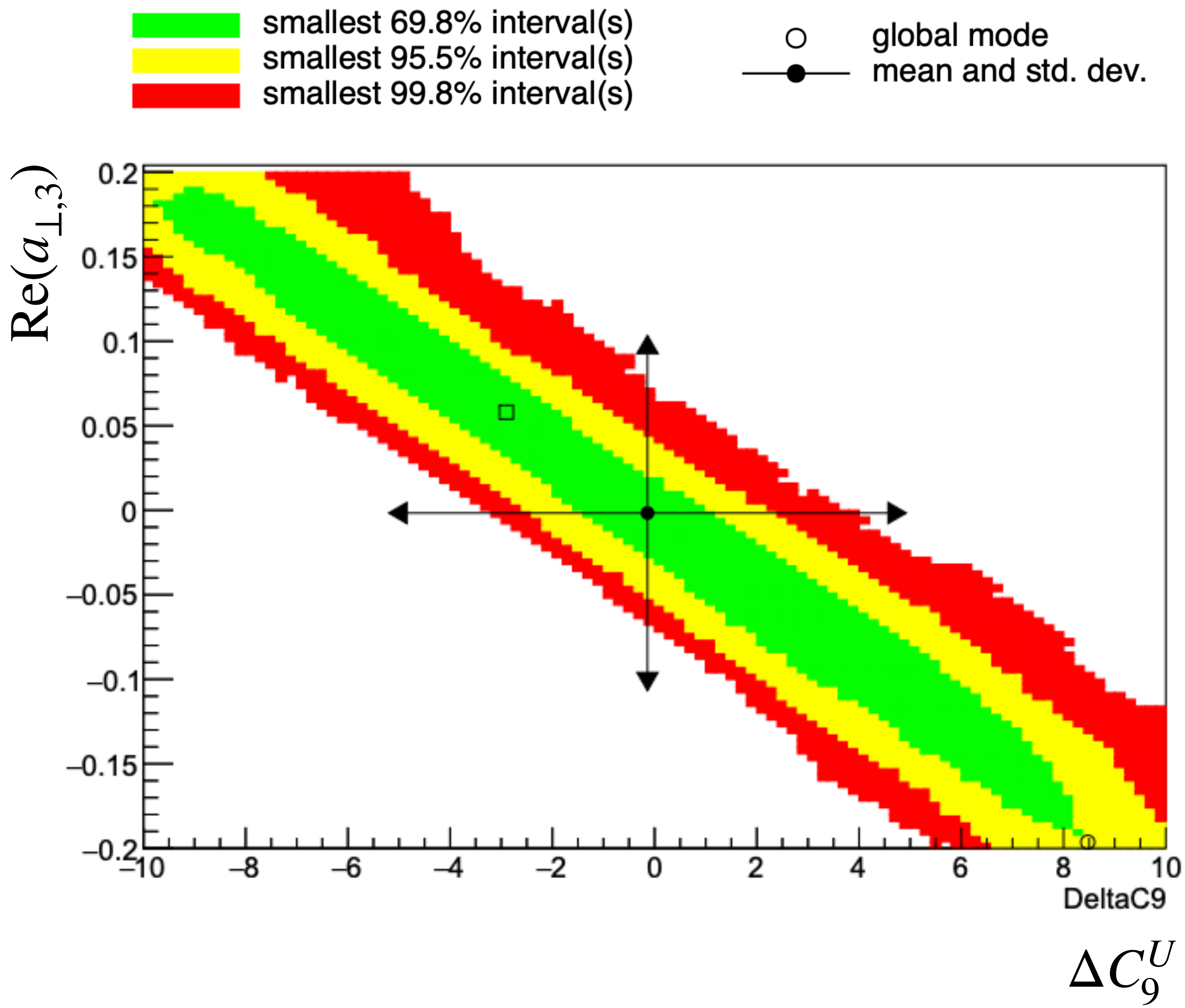


HEPfit MCMC results



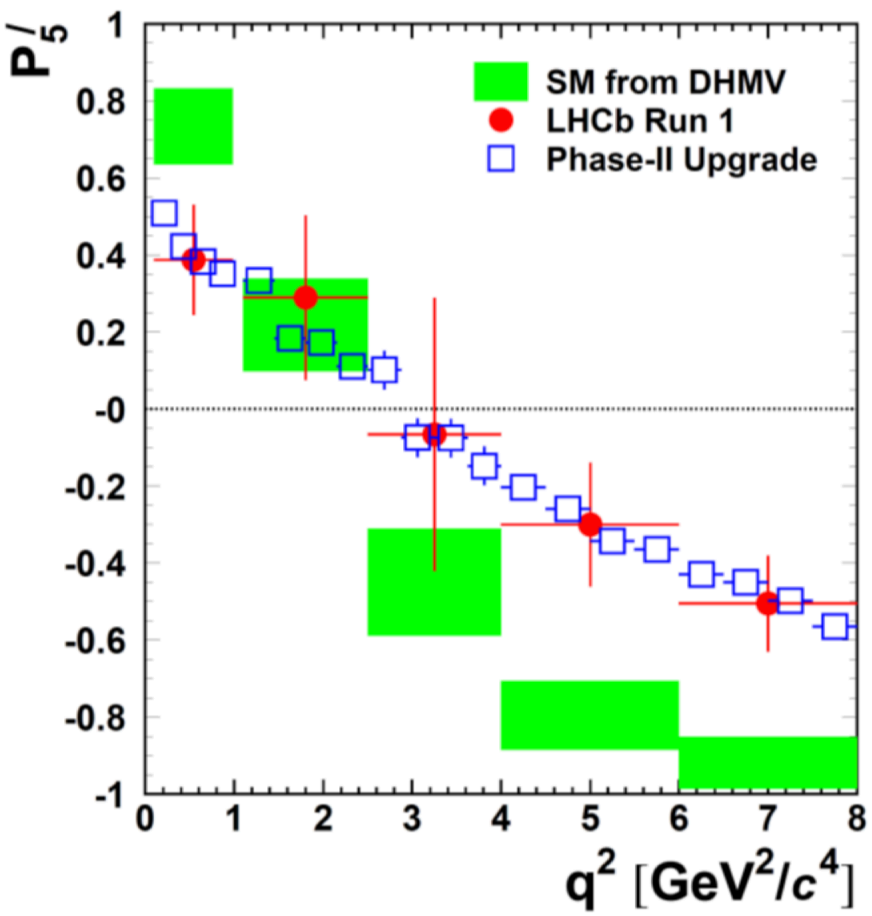
BAYESIAN INFORMATION CRITERION PENALIZES ADDITION OF UNIVERSAL ΔC_9.

HEPfit MCMC results



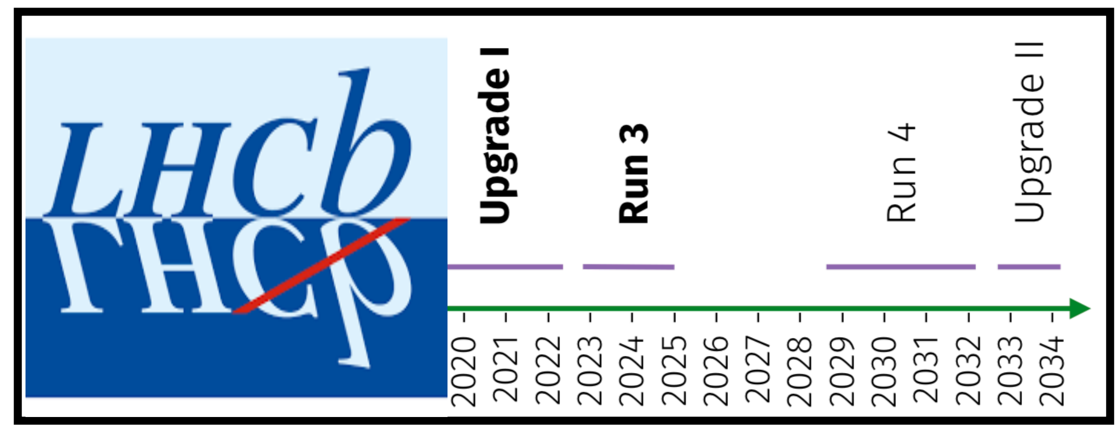
EXPANDING @ NEXT ORDER — INCLUDING $\mathcal{O}(z^3)$ — AFFECTS INFERENCE OF ΔC_9^U

B ANOMALIES : A FUTURE



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

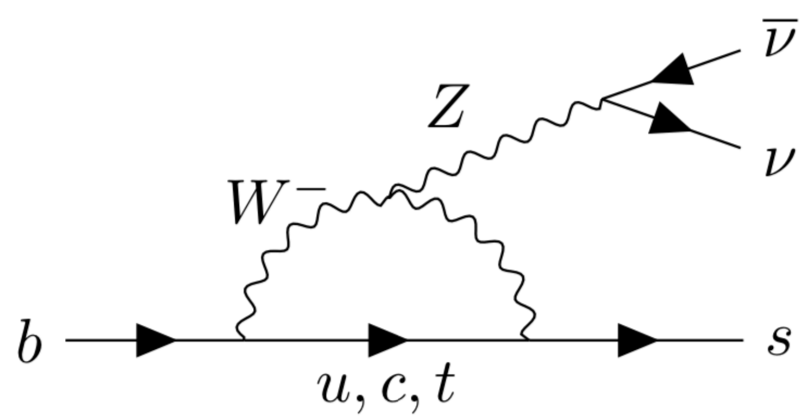
—> pin down effects from hadronic physics

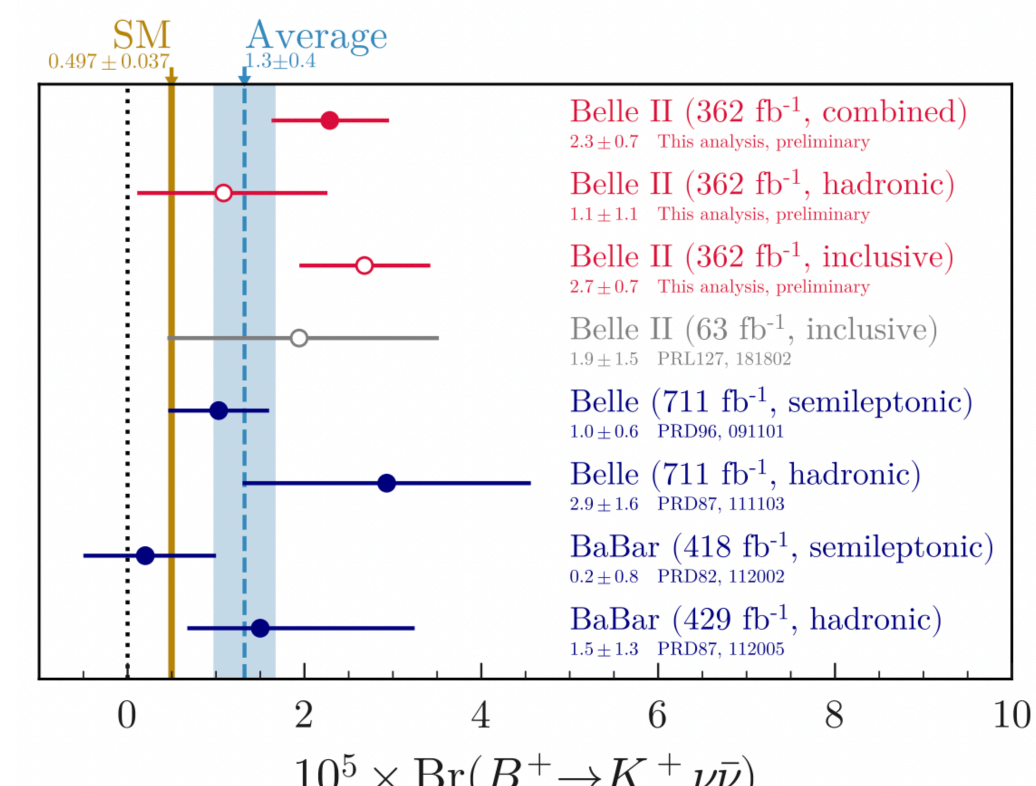


CMS & ATLAS are going to play a role as well!

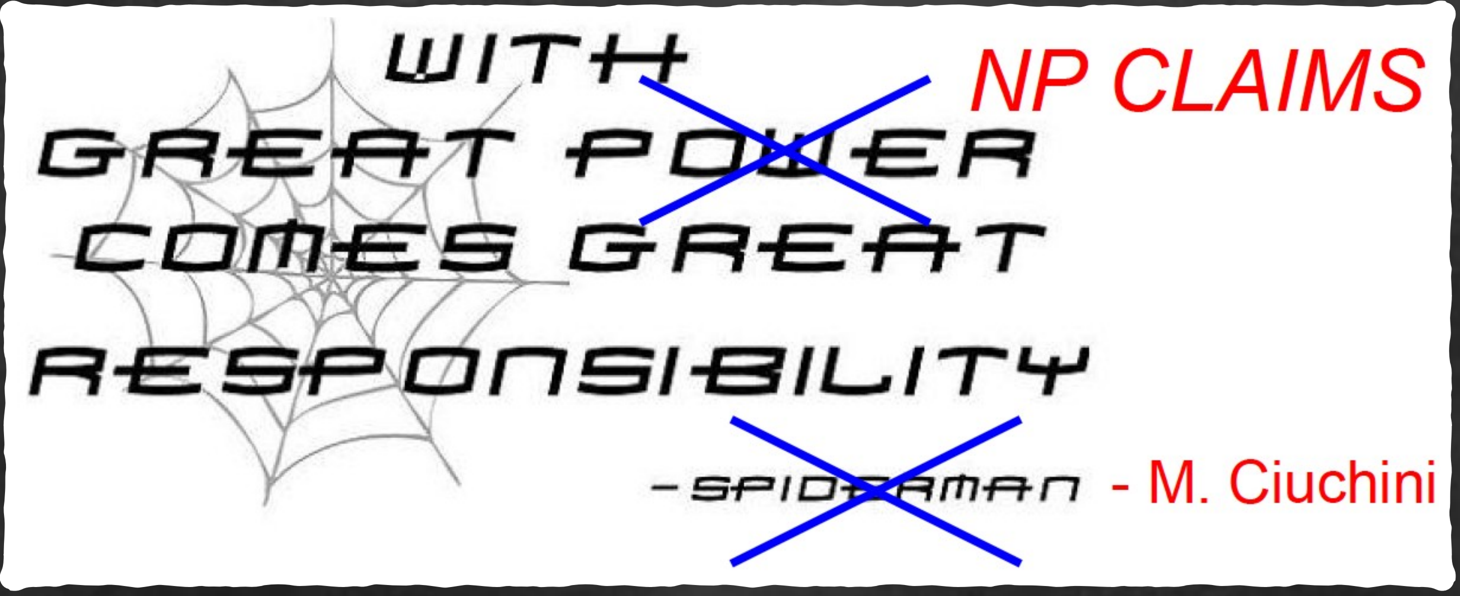
Belle II is already delivering interesting results!

A POSSIBLE NEW INTERESTING ANOMALY …





FLASY
2024
@ UCI

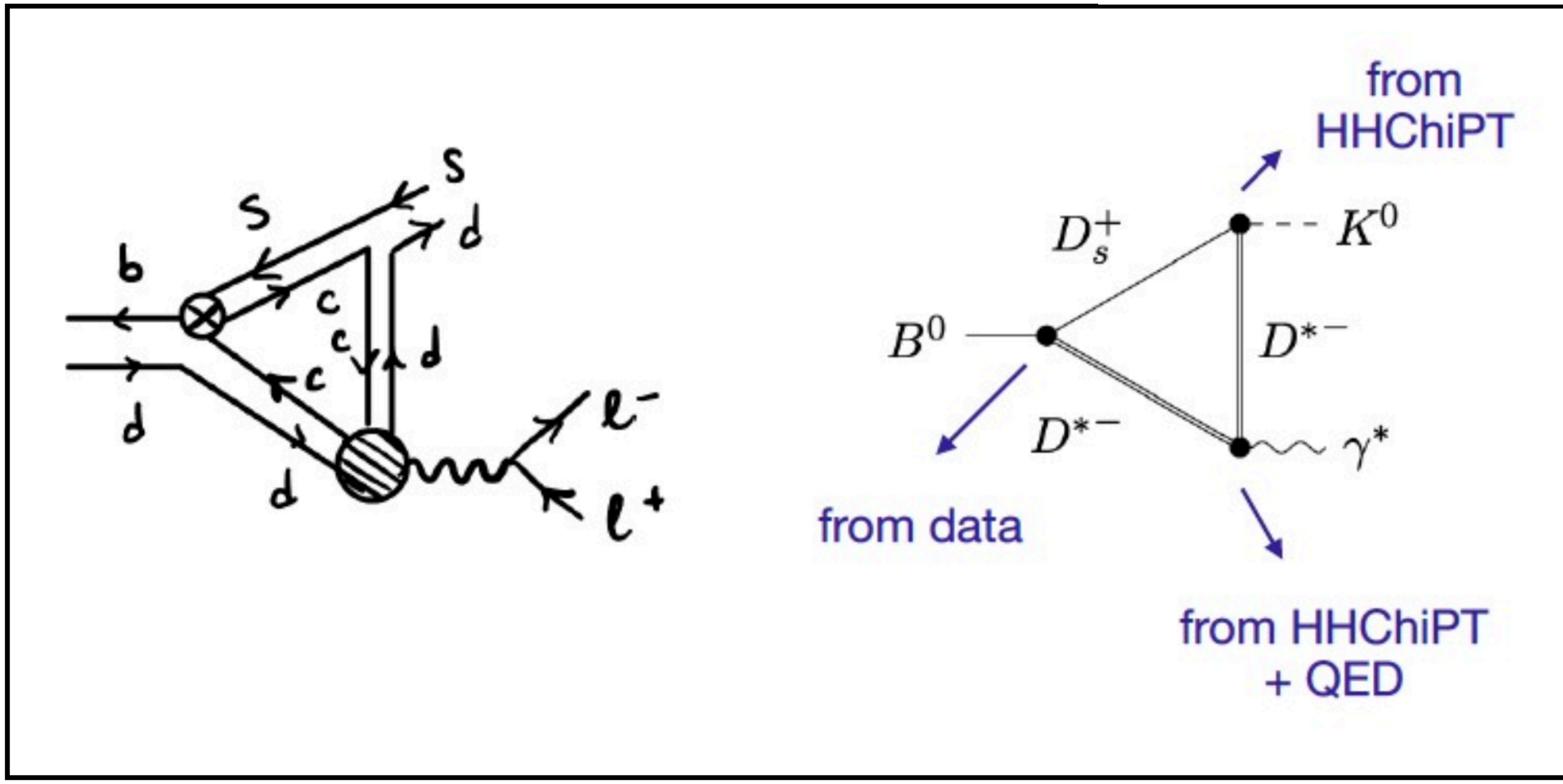


Special Thanks to M + M x the organization & the invitation!

BACKUP

TRIANGLES & ANOMALOUS THRESHOLDS

*arXiv:**2405.17551***



Pheno estimate extrapolating Heavy Hadron ChiPT to region of low q2 points to an effect of few percent … but see recent *arXiv:**2406.14608***

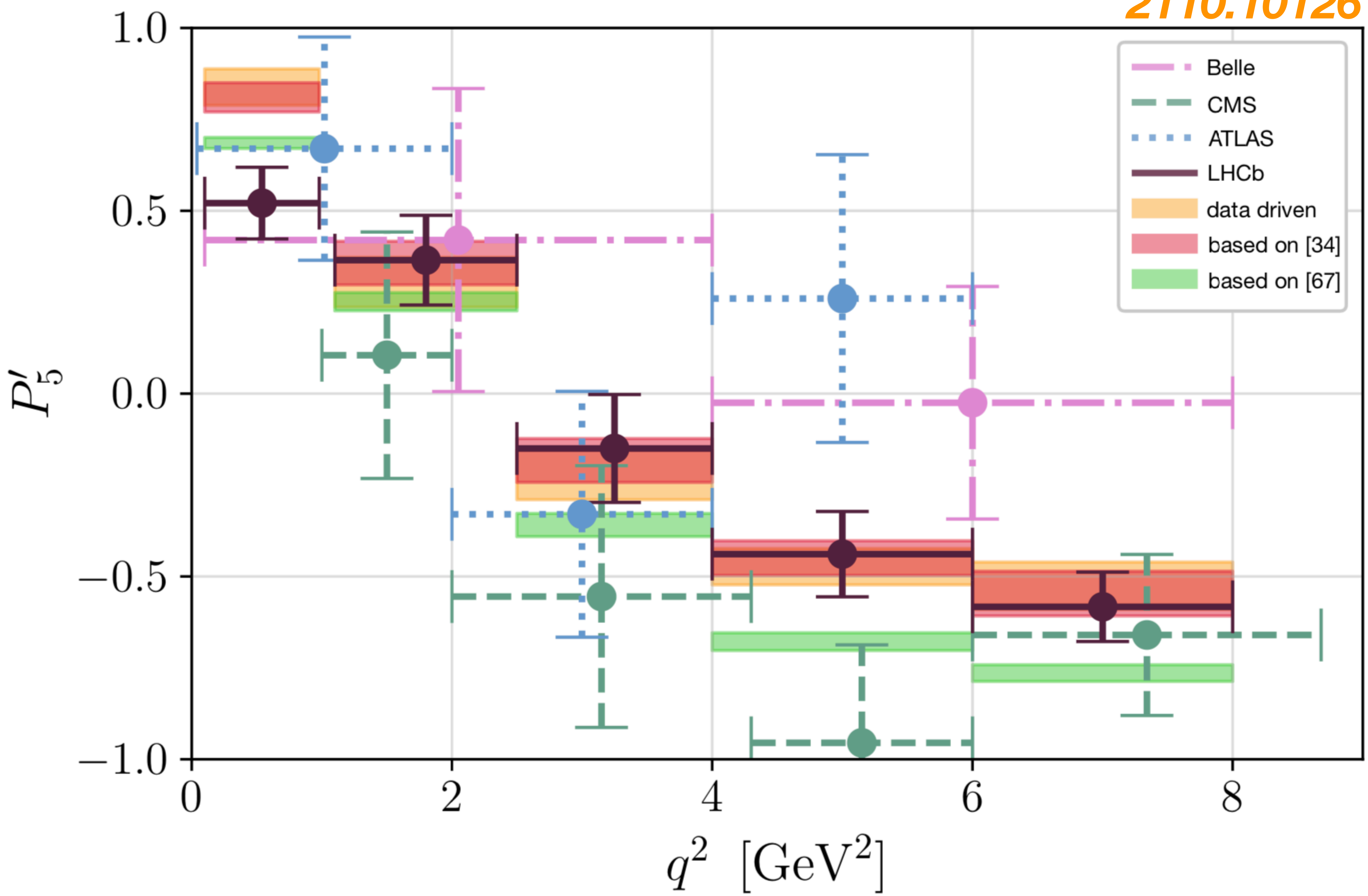
Anomalous thresholds easily yield O(10%) effects (maybe even O(1)?)

– *distortion of the analytic structure implies “new” dispersion relations*

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

B ANOMALIES : P_5'

2110.10126

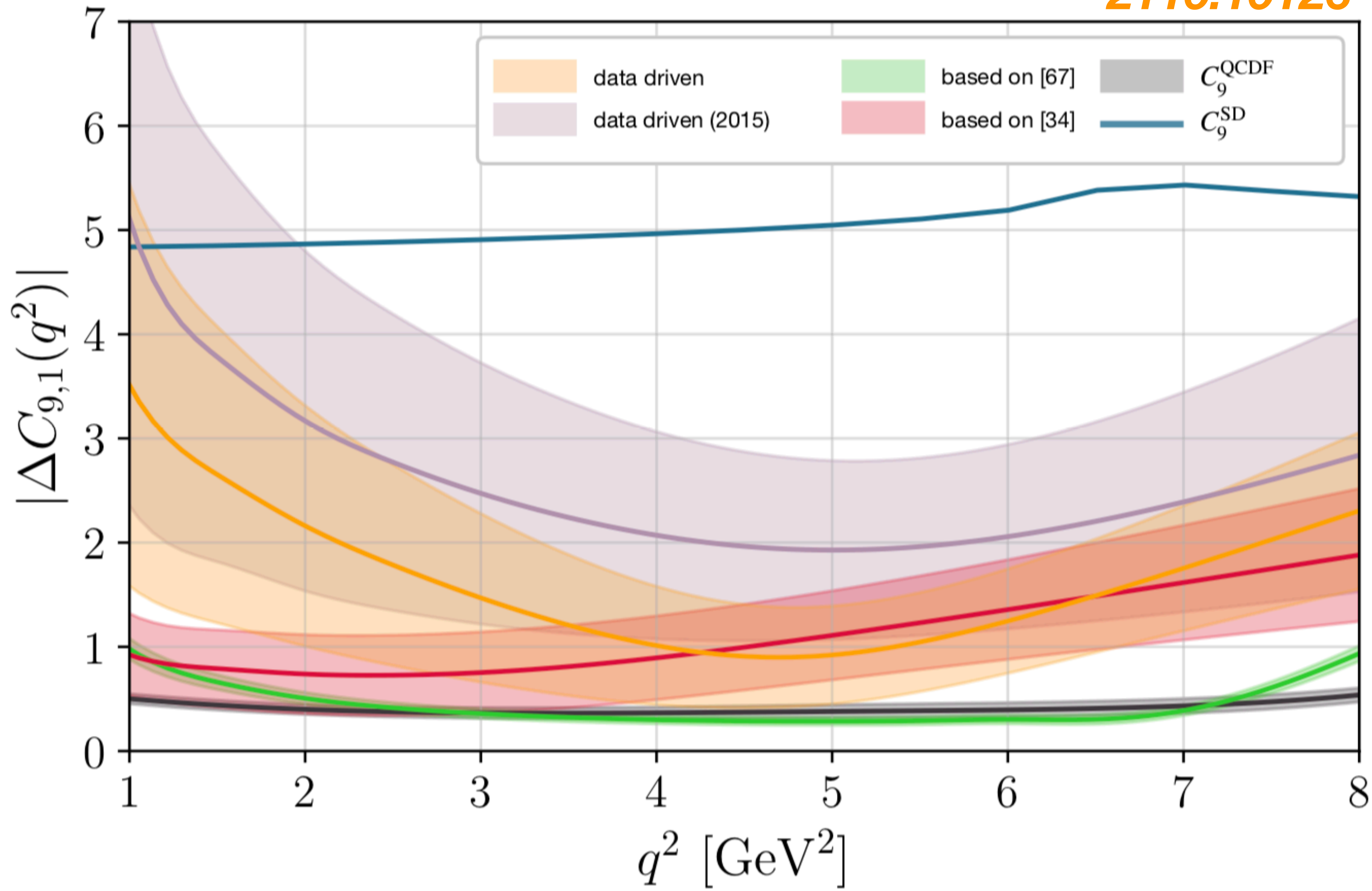


34. M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini et al., *Hadronic uncertainties in semileptonic $B \to K^* \mu^+ \mu^-$ decays*, *PoS* **BEAUTY2018** (2018) 044, [arXiv:1809.03789].

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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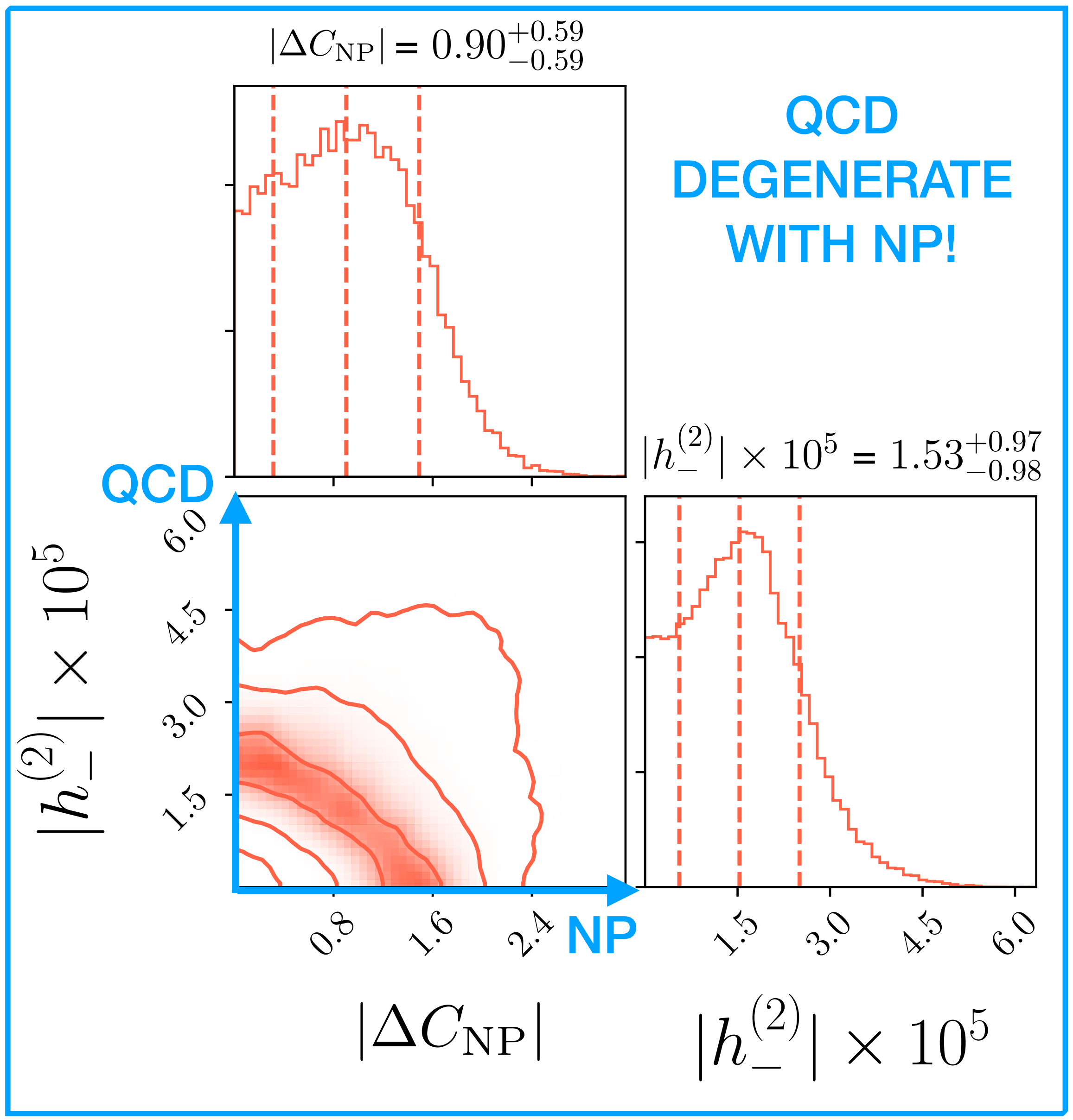
Phenomenological Data Driven

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

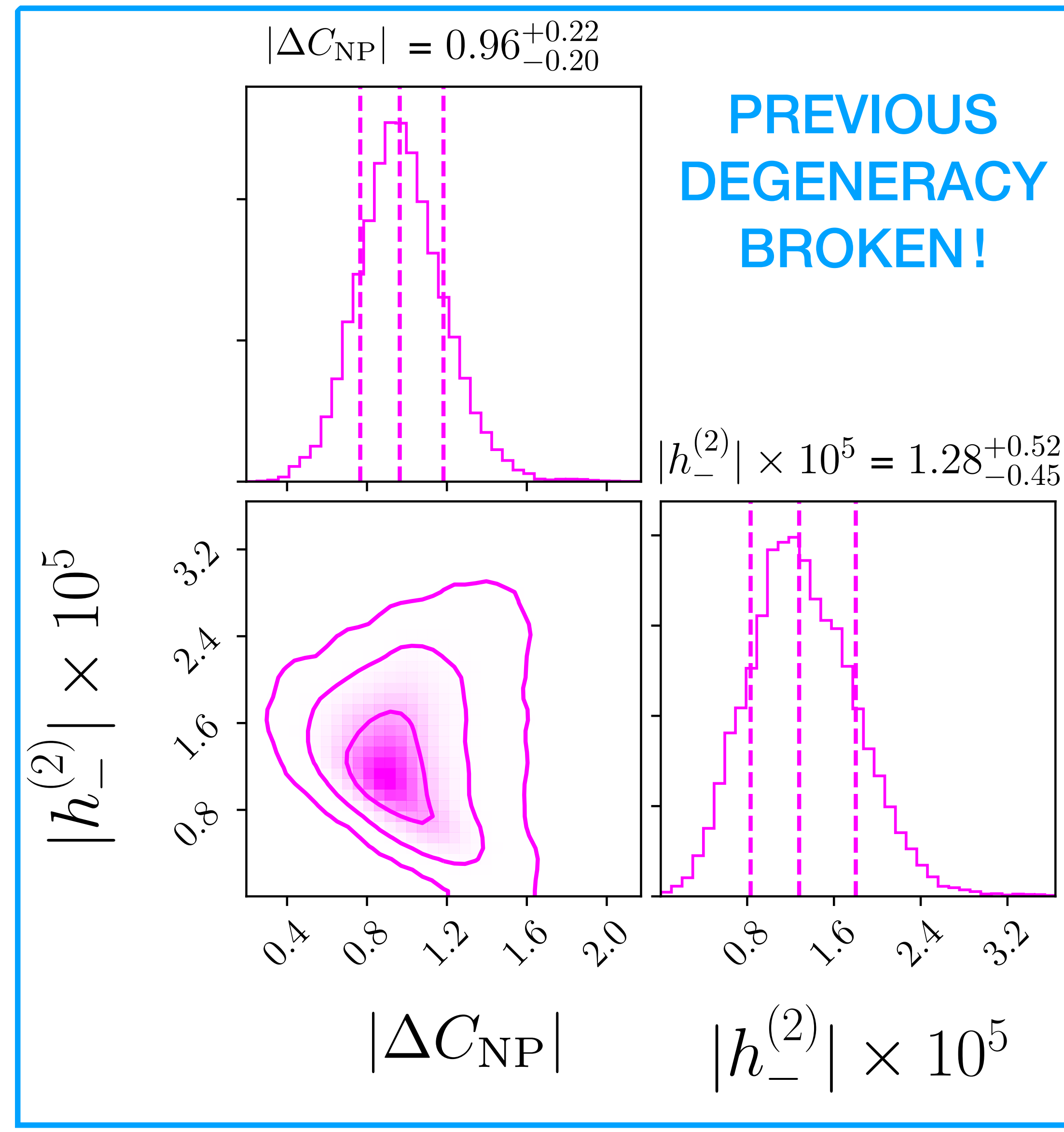


PROJECTIONS @ 50 fb^{-1}

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

RULE OF THUMB

Scaling LHCb stat errors roughly of 1/6



[*arXiv:**1809.03789***]