BFA workshop — 17 / 04 / 2026 —

A Critical Look at Semileptonic (Rare) B Decays

Mauro Valli

INFN Rome

THANKS TO **M. Fedele**, **J.Scholze**, **L.Silvestrini**, **S.Simula** & **L.Vittorio**

Accidental Symmetries

1

At low energy, the SM reduces to QED x QCD

⇨ ACCIDENTAL SYMMETRY IN THE IR: $U(1)^{N_f}$

$$\frac{1}{\Lambda_{NP}^2}(\bar{s}\Gamma_{V-A}d)^2$$

$U(1)^{N_f}$ is violated by weak interactions: "NP" @ Λ_{EW}

2

At low energy, the SM features only 2 generations

⇨ ACCIDENTAL SYMMETRY IN THE IR: CP

$$\frac{e^{i\delta}}{\Lambda_{NP}^2}(\bar{s}\Gamma_{V-A}d)^2$$

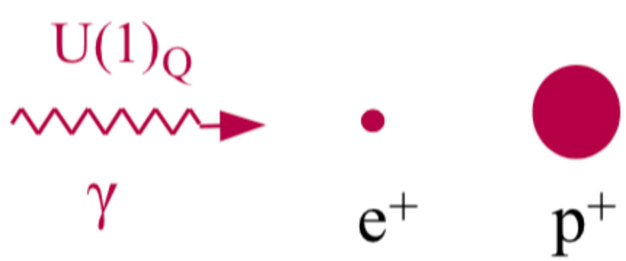
CP violation requires 3 generations & involves CKM hierarchy

ACCIDENTAL / APPROX SYMMETRIES SERVE AS A LAMPPOST FOR NP

Lepton Flavor Universality

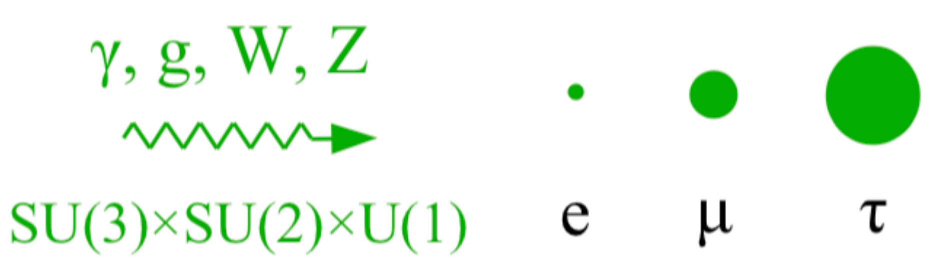
LFU <—> ACCIDENTAL in the SM gauge sector, broken by Yukawas

Suppose we could test matter only with long wave-length photons:



we would conclude that these two particles are "identical copies" but for their mass ...

This is exactly the same (*potentially misleading*) argument we use to infer flavor universality in the SM...

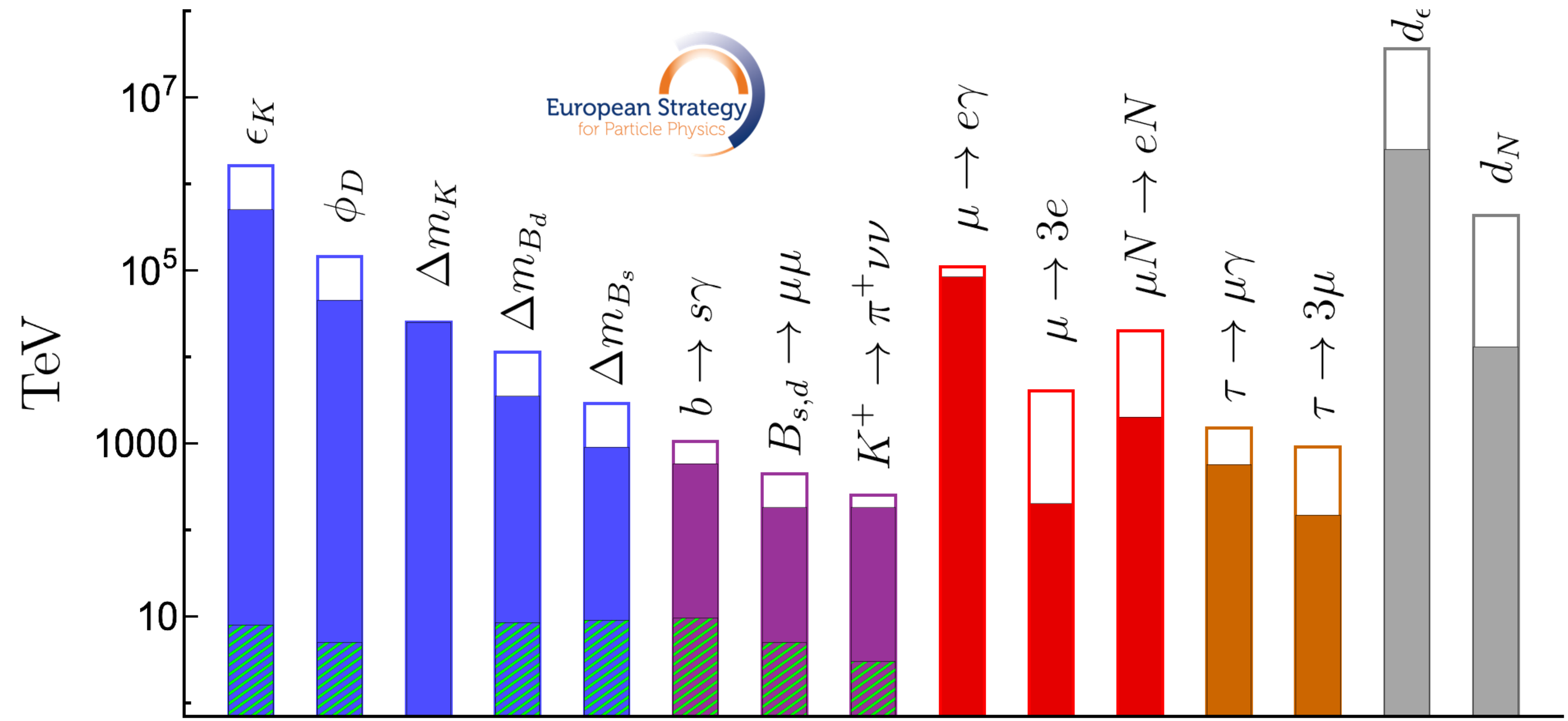


These three (families) of particles seems to be "identical copies" but for their mass ...

credit to G.Isidori

LFU NOT A FUNDAMENTAL SYMMETRY:
EXPECTED TO BE VIOLATED IN THE UV

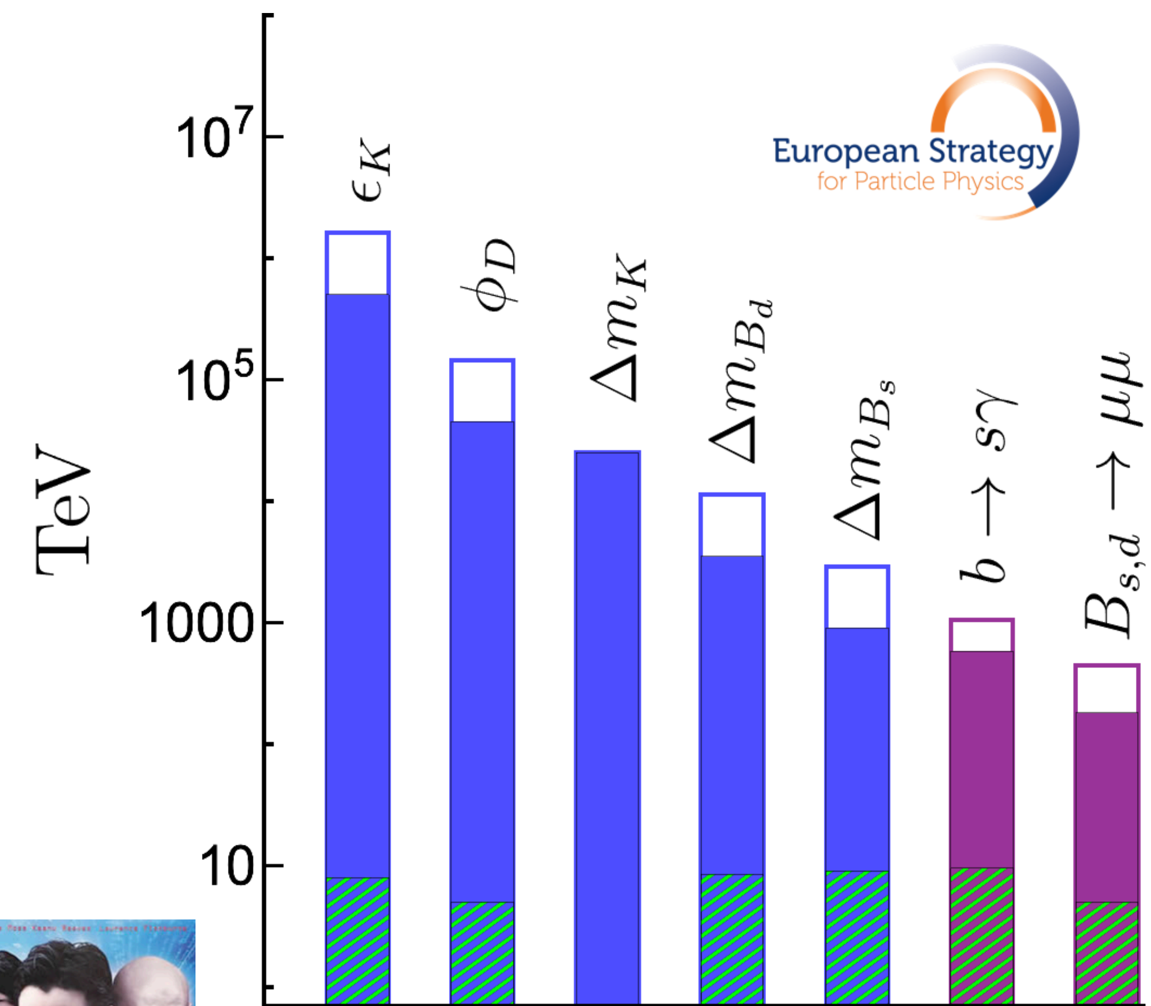
Flavor beyond the SM

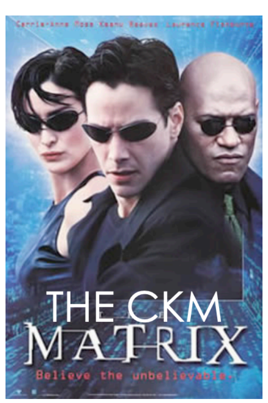


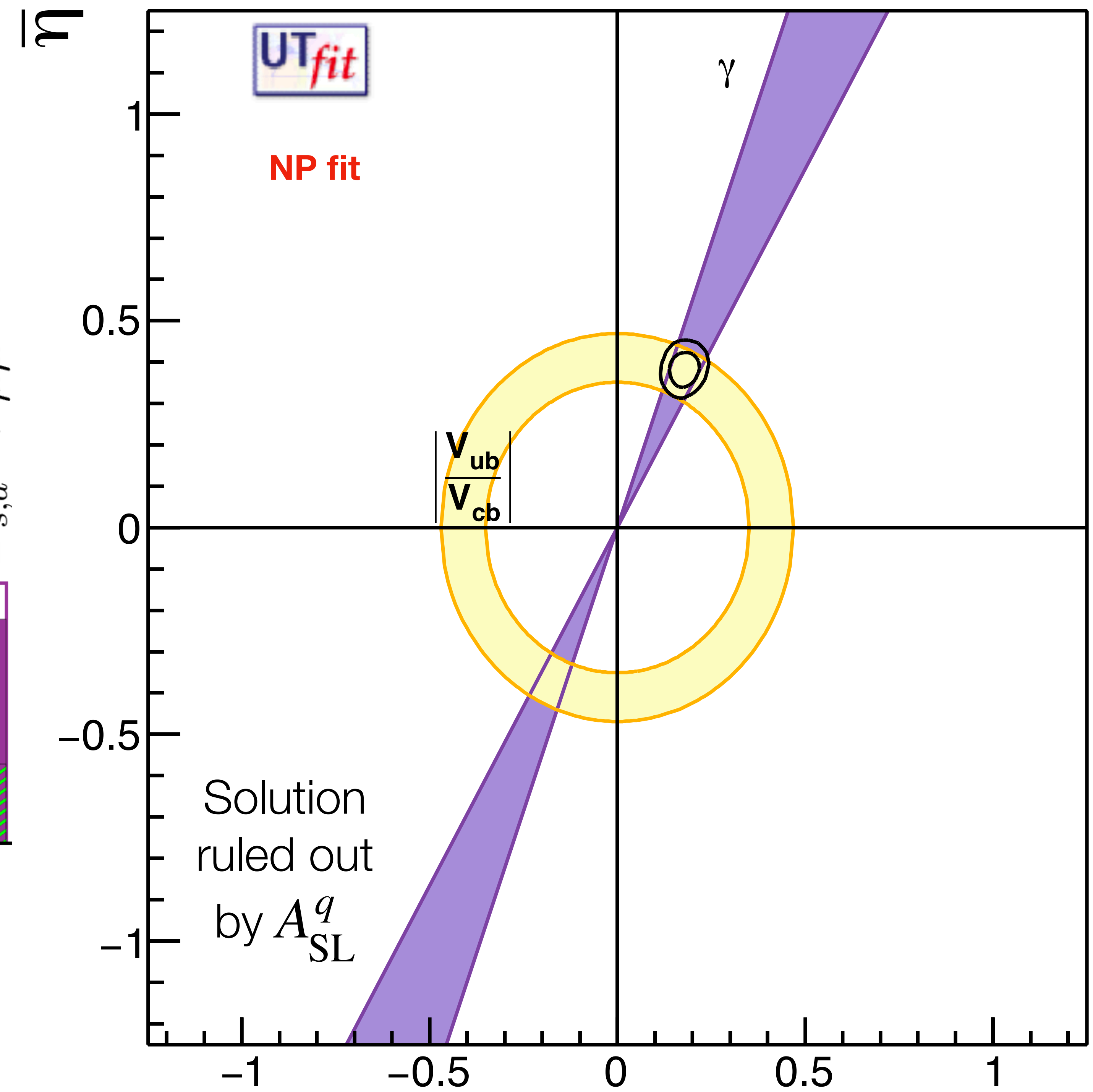
$$\sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

There is no reason why accidental symmetries should be respected in the UV —> **stringent bounds**

Flavor beyond the SM







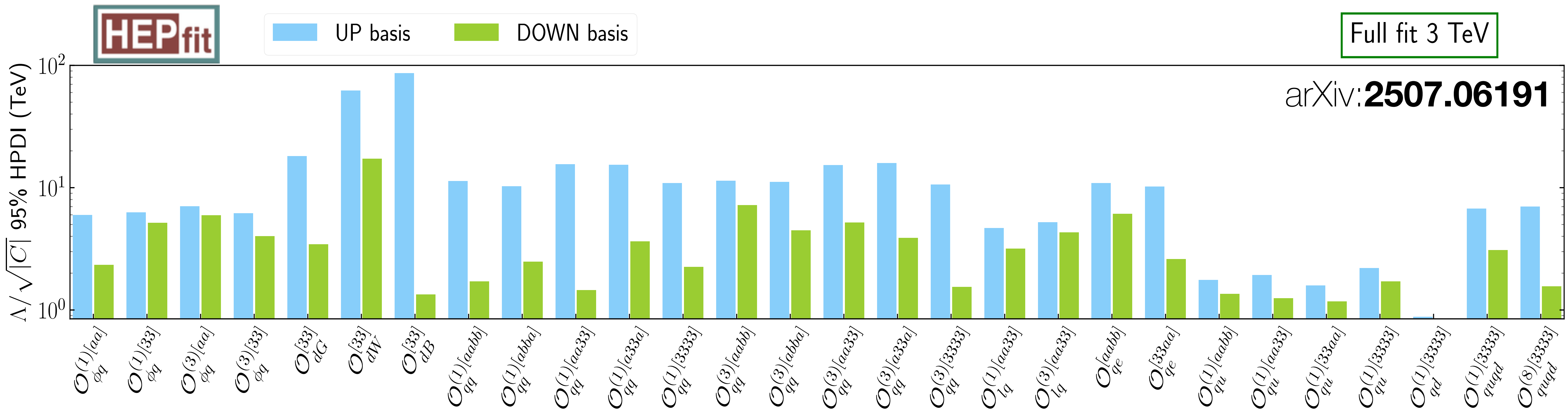
www.utfit.org

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

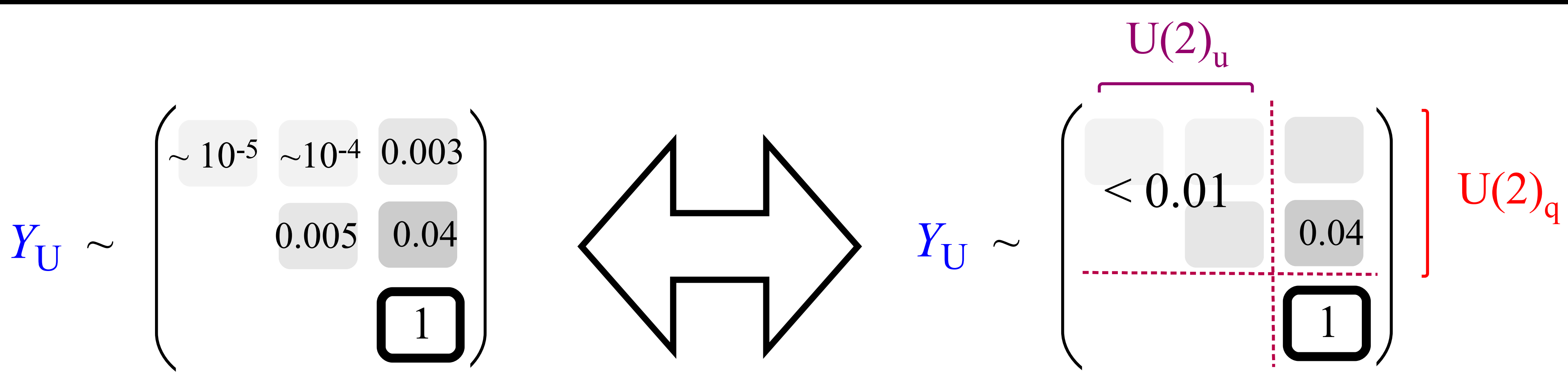
[*PoS* EPS-HEP2025 (2026) 302]

Is Flavor speaking loud?



$U(2)^5$ leaves room for NP in the Multi-TeV, not too far from the EW scale.

It is only approximate in the SM, but **insightful for the SM flavor puzzle.**

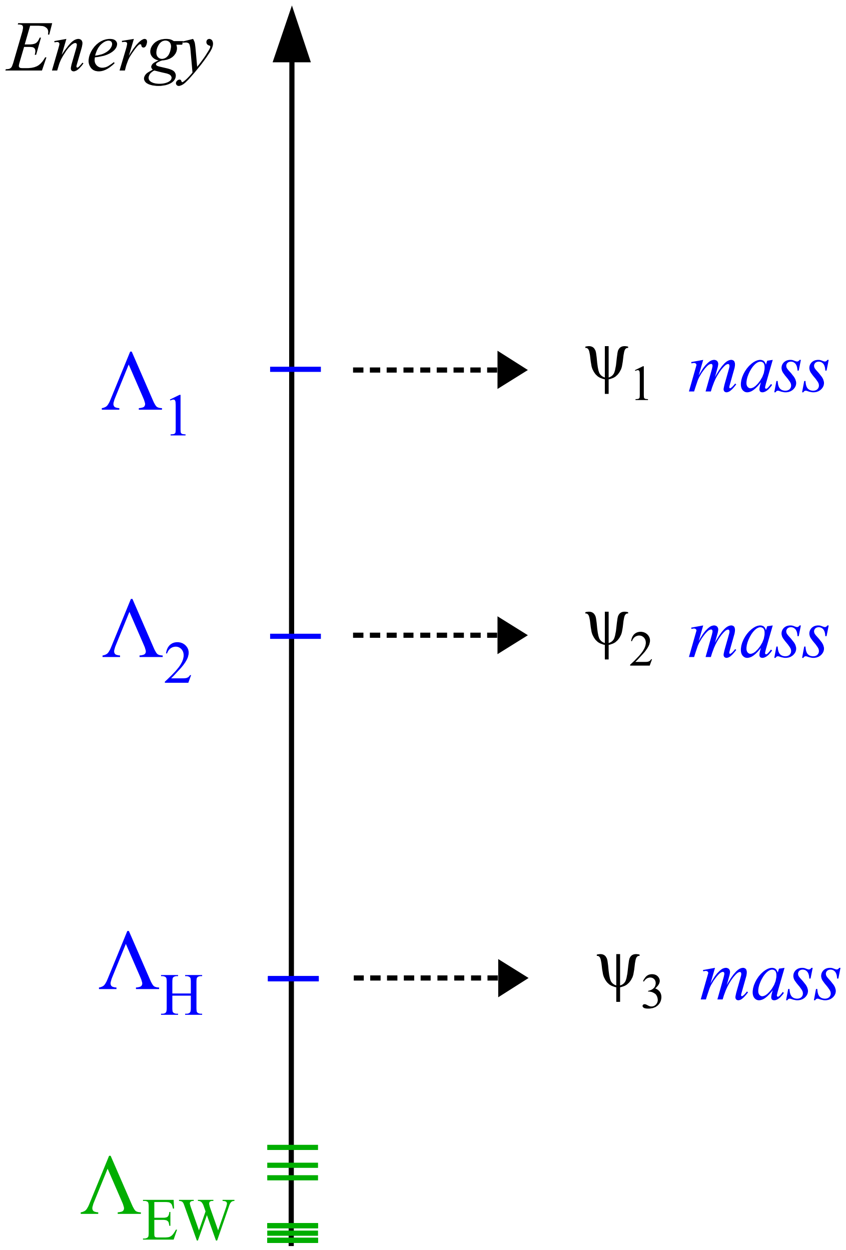


Y_U in the basis where Y_D is diagonal

Y_U in the basis where Y_D is diagonal

w/ or w/o U(2) ?

See, e.g.:
arXiv:**2312.14004**
arXiv:**2409.08657**
arXiv:**2503.14042**



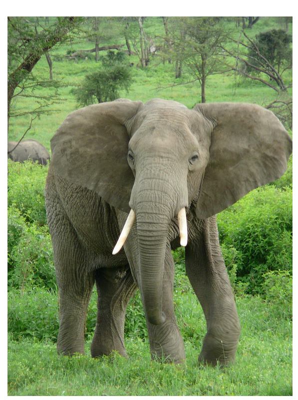
Extend the SM via a multi-scale UV w/ **flavor non-universal interactions**.

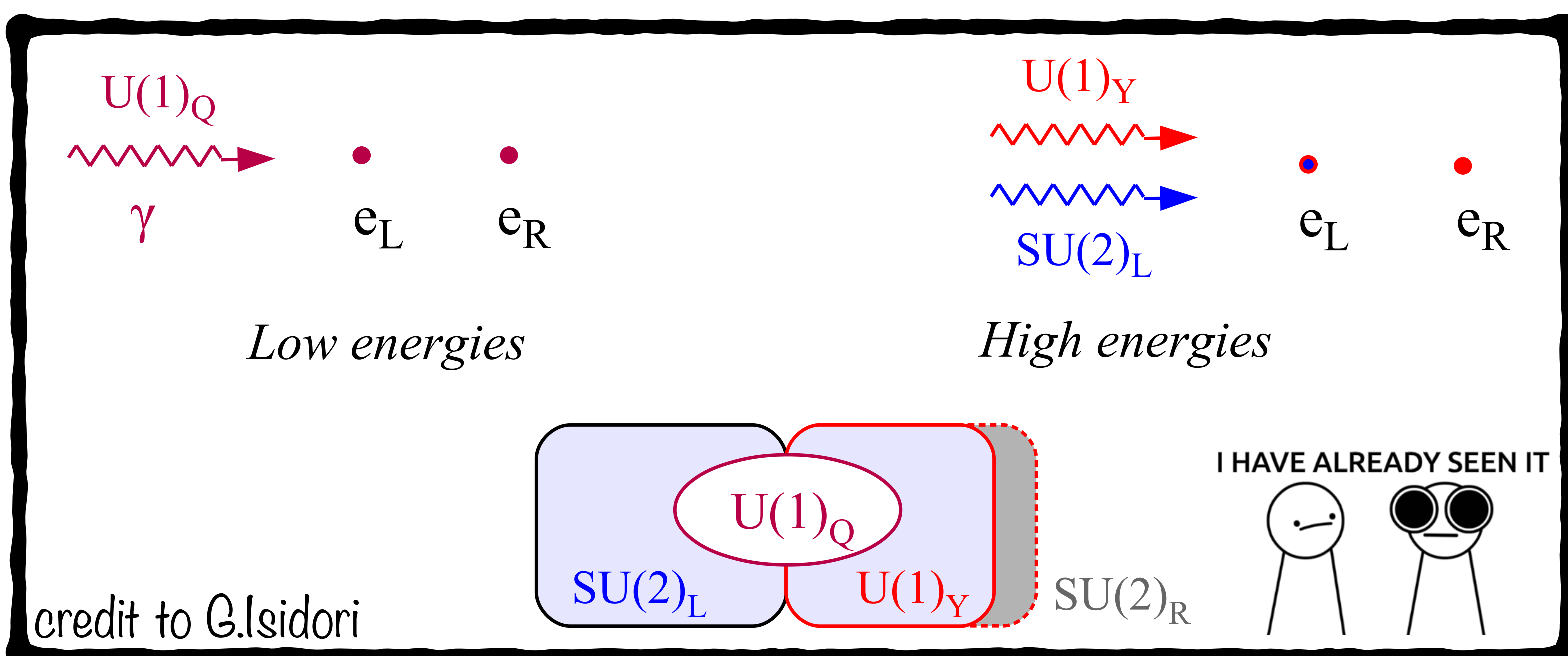
3 layers of heavy dynamics, accounting for fermion mass within a given generation.

$U(2)^5$ can emerge as an accidental symmetry if $\Lambda_{1,2} \gg \Lambda_3 \gtrsim \Lambda_{EW}$

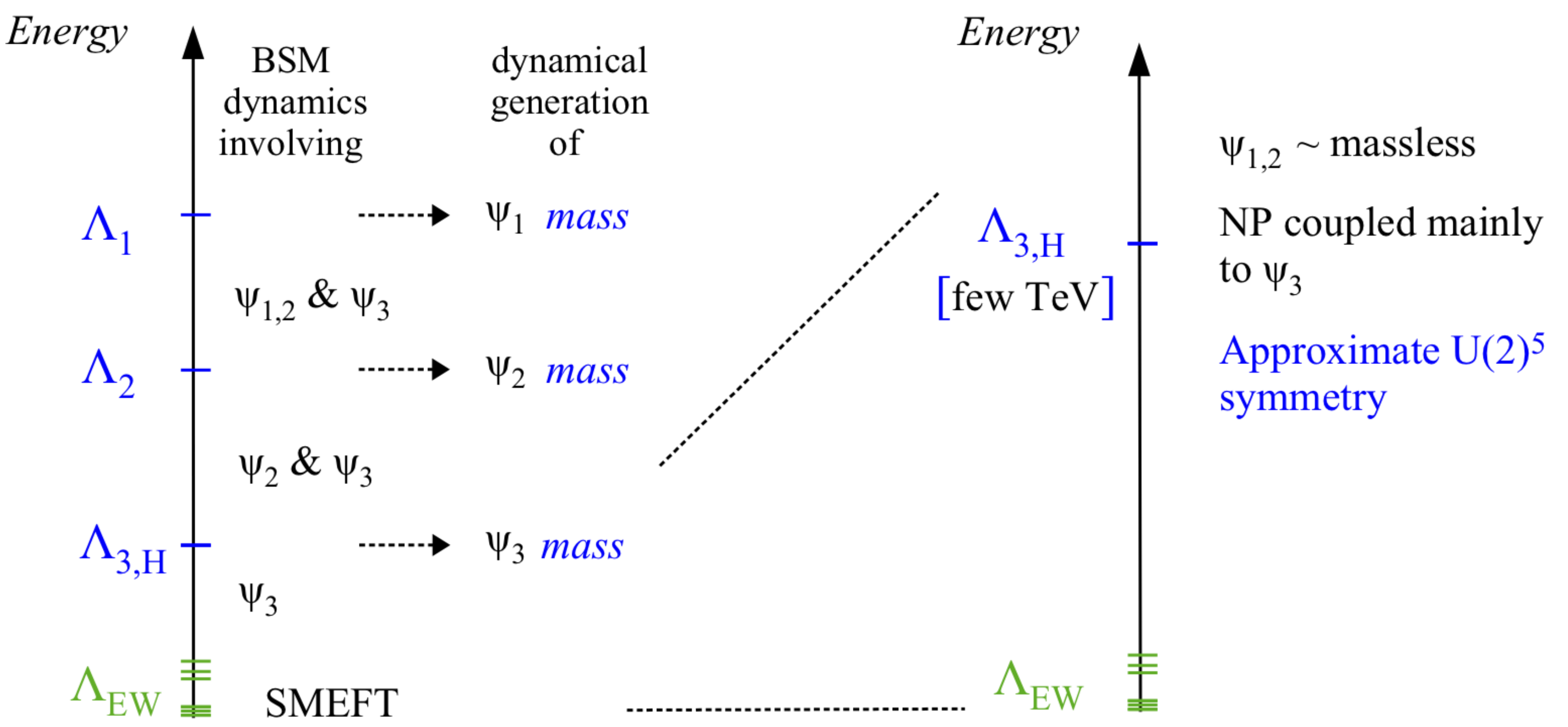
BONUS

EW hierarchy "natural"





signatures

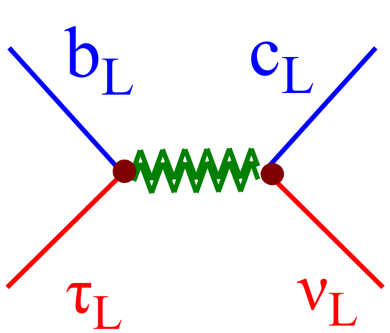


Pheno driver:

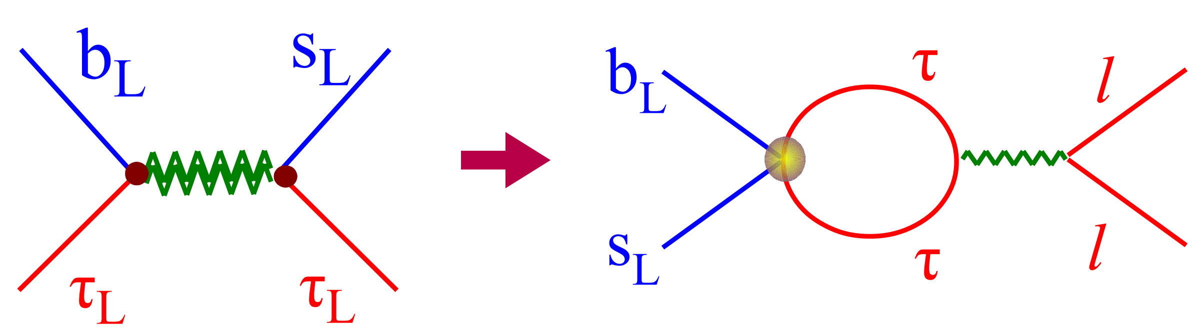
Leptoquark mainly coupled to 3rd gen., i.e. $U(2)^5$ friendly

$$U_1^\mu \sim (\mathbf{3},\, 1)_{2/3}$$

LFU tests in semileptonic B decays may be the smoking gun

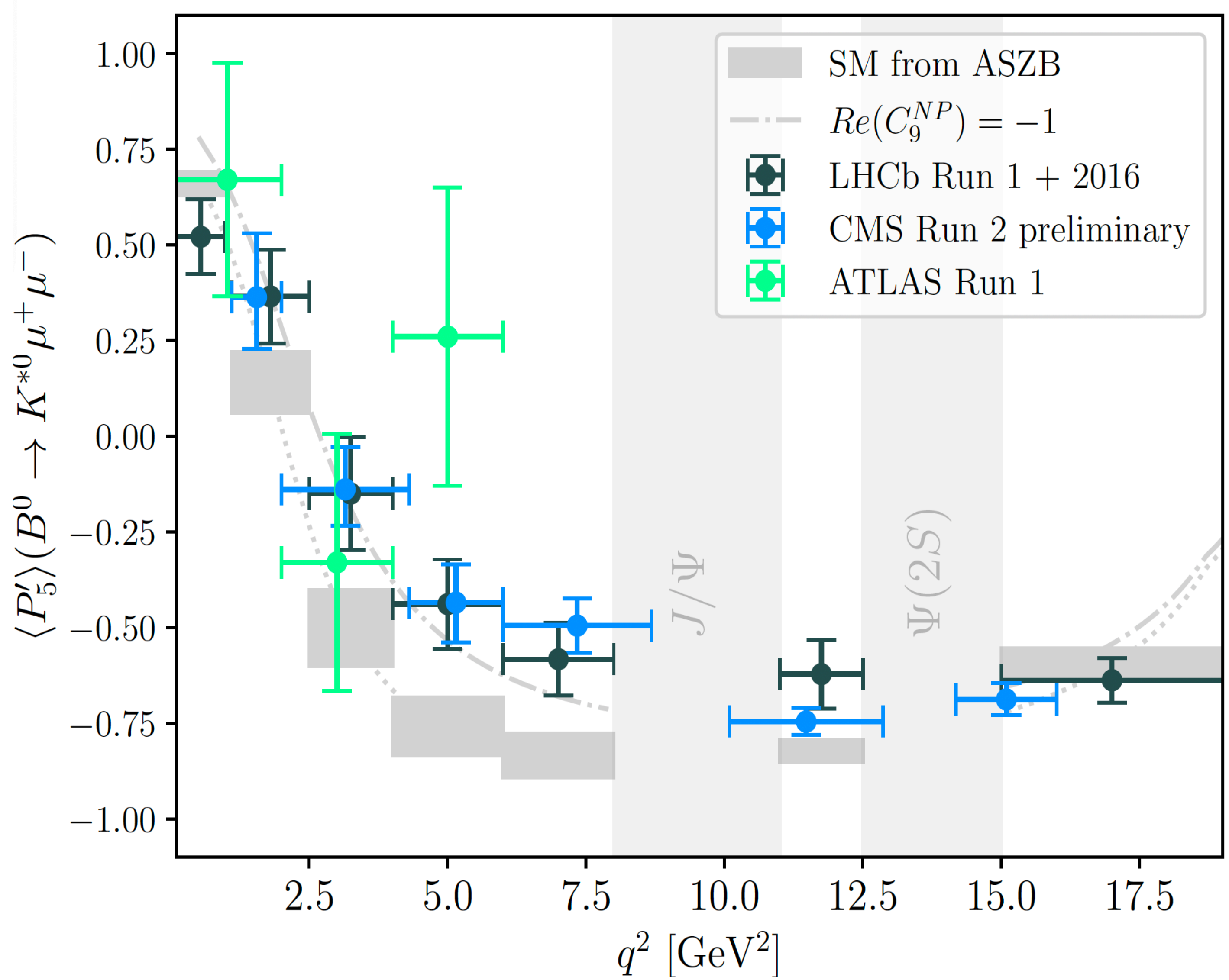


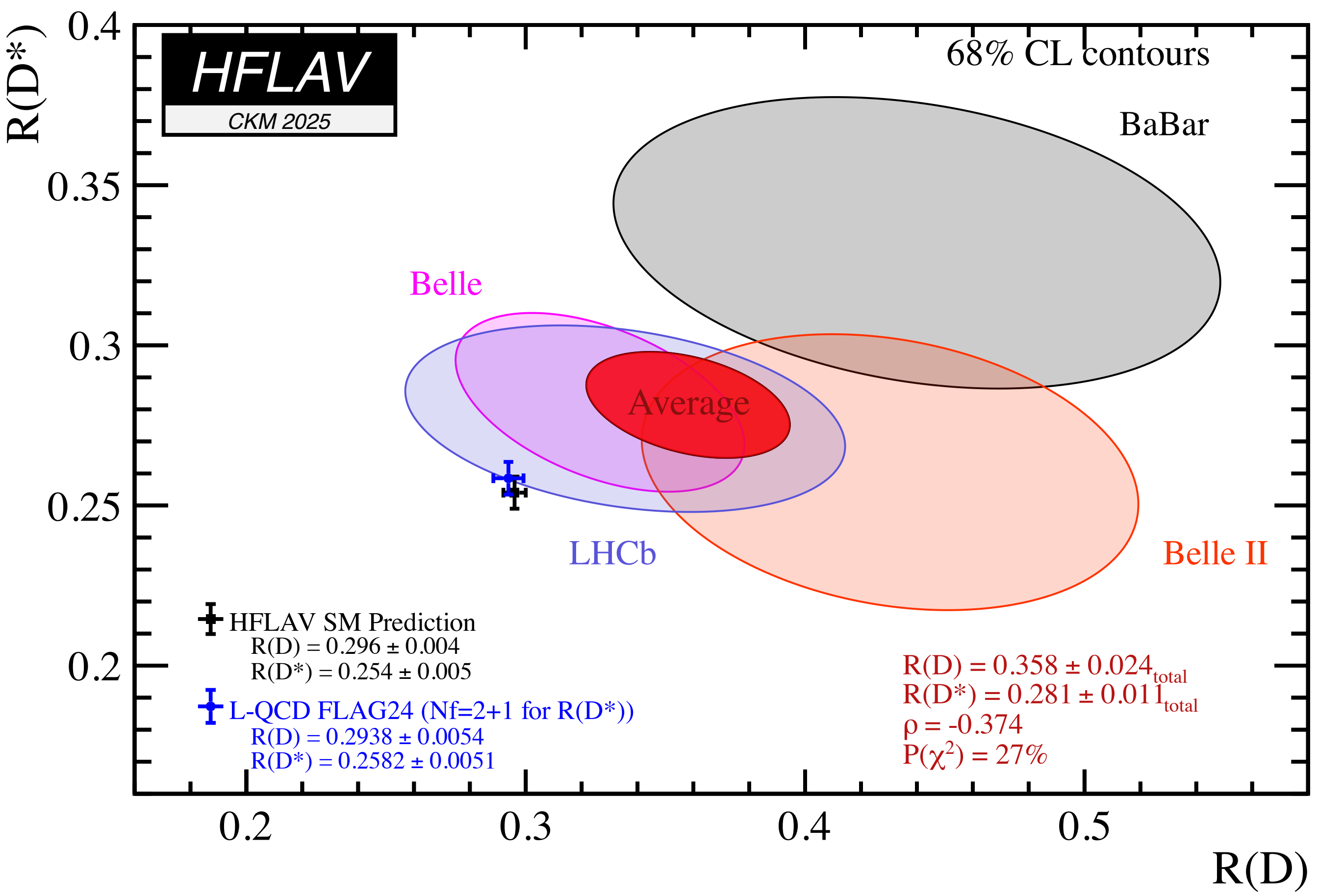
$$R(X)^{\tau/l} = \frac{\Gamma(B \to X\,\tau\nu)}{\Gamma(B \to X\,l\nu)}$$



LFU violation in b —> c, X = D,D*

LFU effects in measured b —> s obs





Do we have any evidence for such NP ?

ANATOMY OF SEMILEPTONIC RARE B DECAYS

Building blocks are helicity amplitudes, which generally read as:

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

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

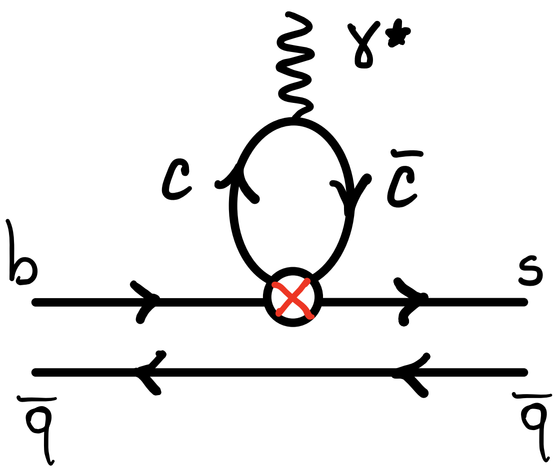
$$H^S(q^2) \propto \frac{m_b}{m_W}(C_S - C_S')\tilde{S}(q^2)$$

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

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.



In 2022, non-local effects — *charming penguins* — have been found to be a negligible contribution.

[arXiv:**2206.03797**]

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

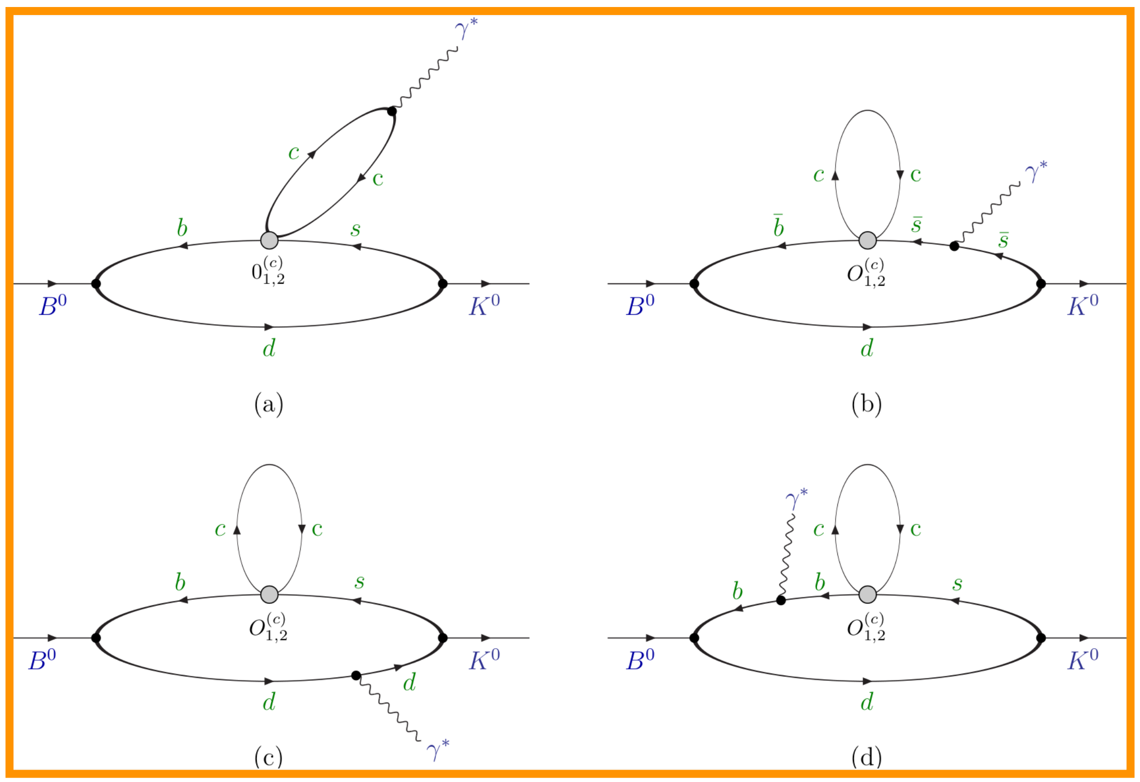
2) z - expansion w/ $B \to M\, J/\psi$ data

3) dispersive bounds based on cuts in q²

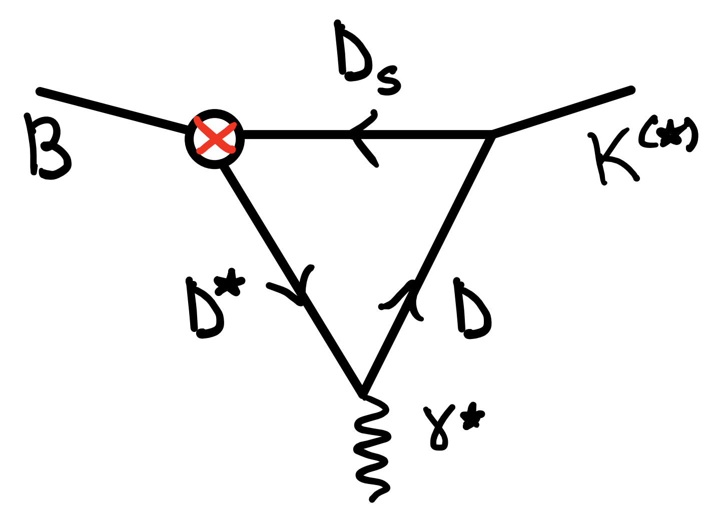
LHCb likewise, via an unbinned likelihood analysis [arXiv:**2312.09115**].

HADRONIC EFFECTS ABOVE DO NOT CAPTURE ALL THAT IS AT STAKE

arXiv:**2508.03655**



[arXiv:**2212.10516**]



artist's impression

Rescattering complicates analytic study of these amplitudes by A LOT.

See yesterday's talks on charming penguins

b-> s ll : A Data Driven Approach

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

Taylor-expand hadronic correlators $h_\lambda(q^2)$ and fit coefficients to data.

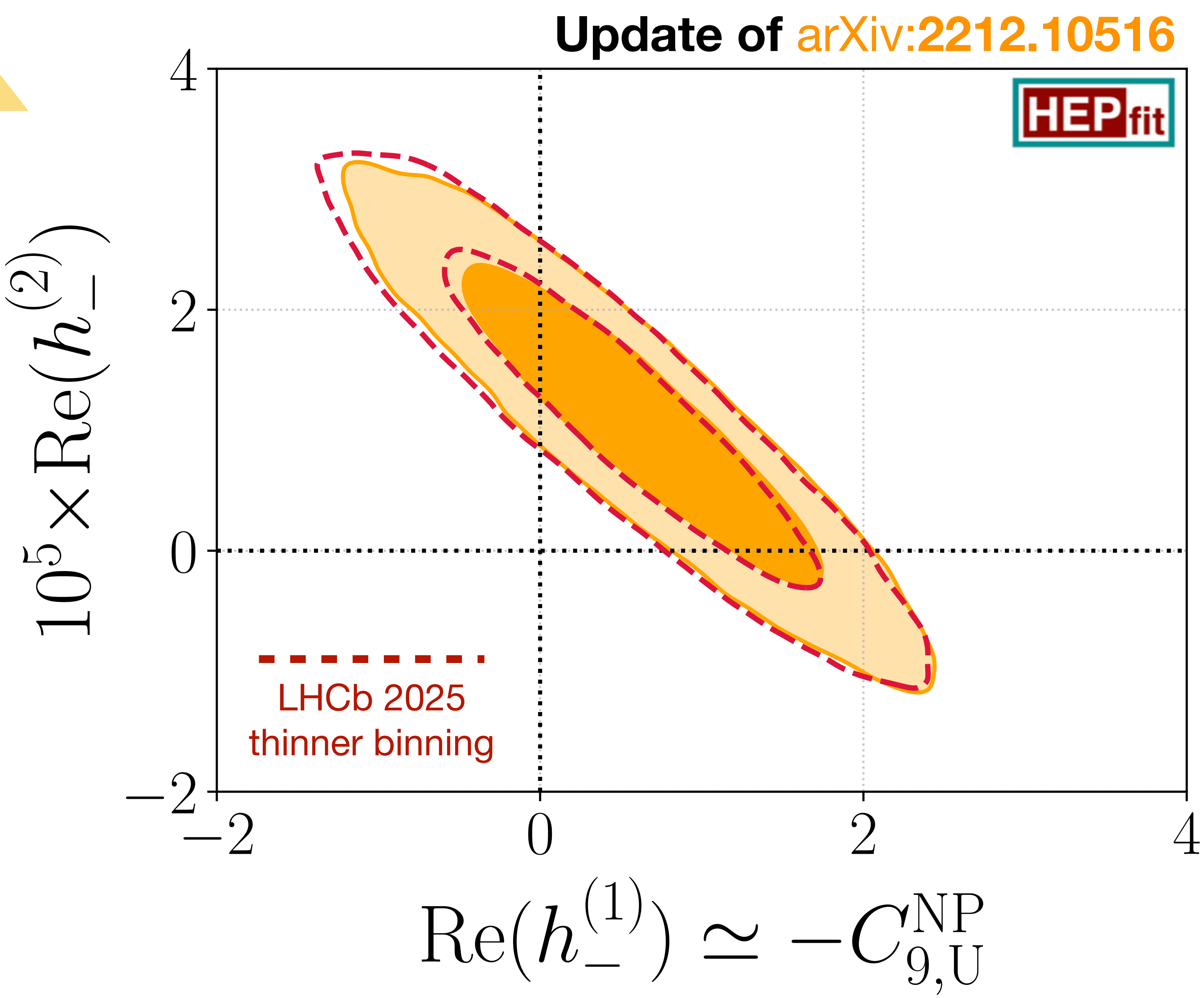
$$H_V^- \propto \left\{ \left(C_9^{\mathrm{SM}} + h_-^{(1)}\right) \widetilde{V}_{L-} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\mathrm{SM}} + h_-^{(0)}\right)\widetilde{T}_{L-} - 16\pi^2 h_-^{(2)} q^4\right]\right\}$$

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

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

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

b-> s ll : WHERE WE ARE NOW



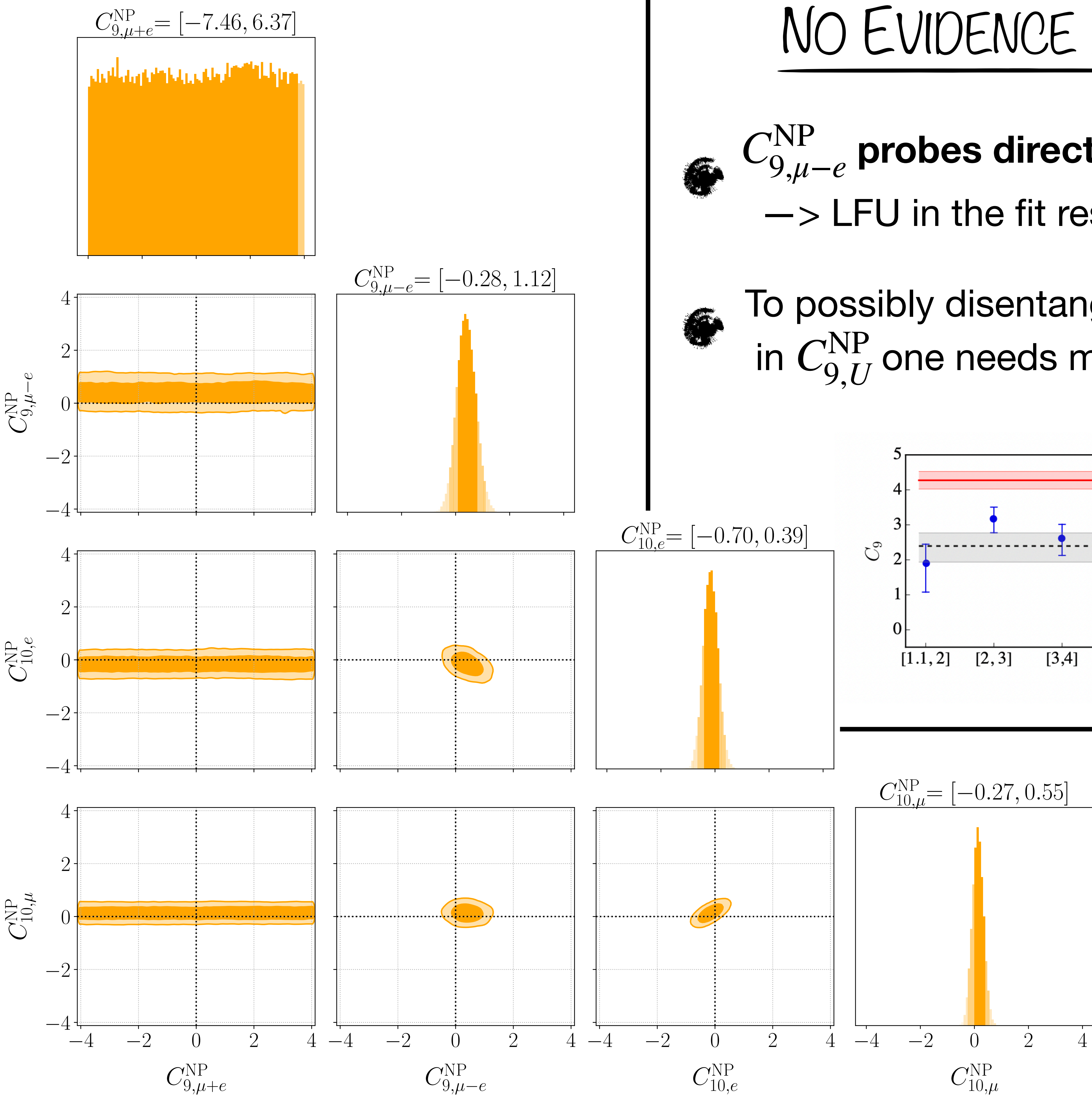
QCD ONLY

QCD ~ LEPTON UNIVERSAL NP

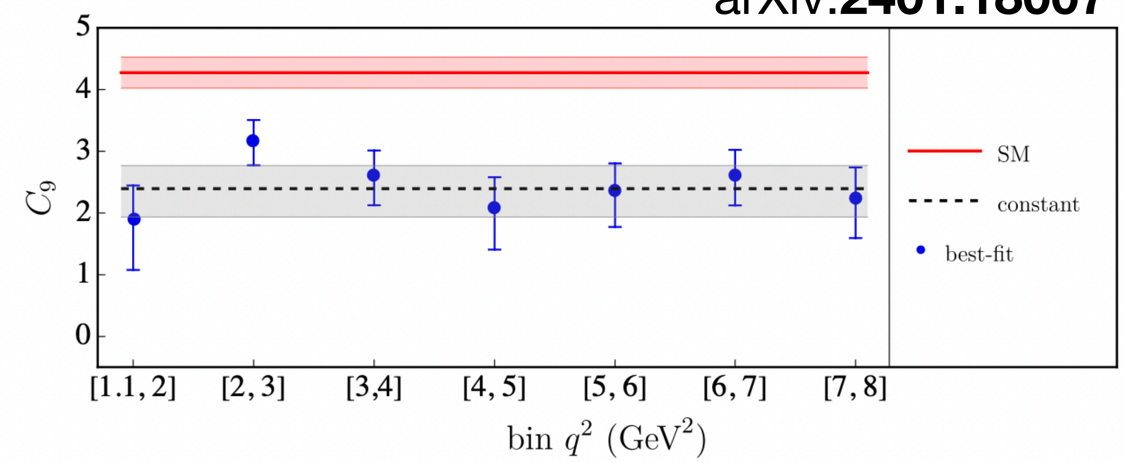
NO EVIDENCE X NEW PHYSICS

- $C_{9,\mu-e}^{\mathrm{NP}}$ **probes direction $\perp$ to** $C_{9,\mu+e}^{\mathrm{NP}} = C_{9,U}^{\mathrm{NP}}$
  —> LFU in the fit respected well within 2σ.

- To possibly disentangle genuine NP effects in $C_{9,U}^{\mathrm{NP}}$ one needs more data / TH progress

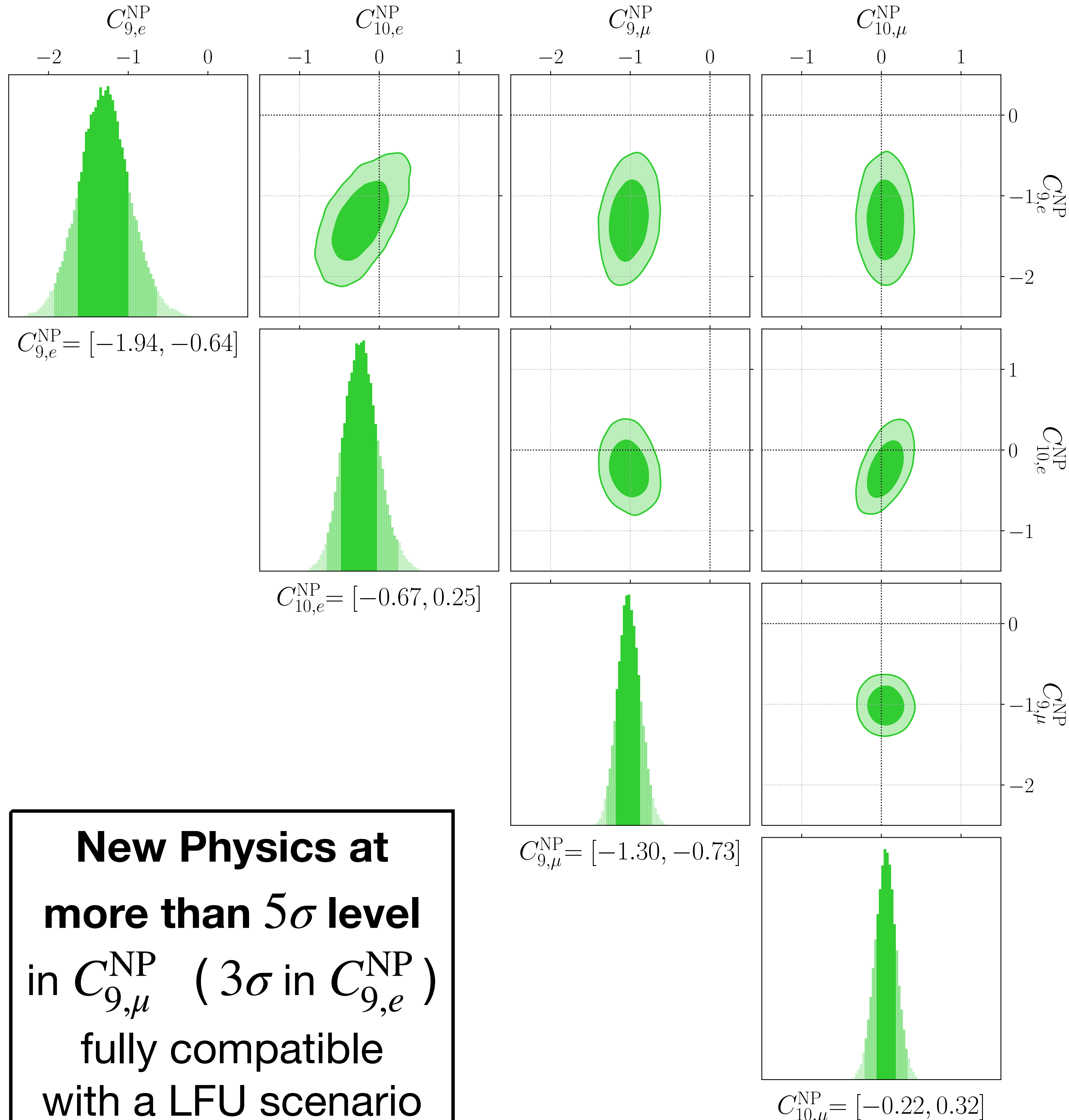


arXiv:**2401.18007**



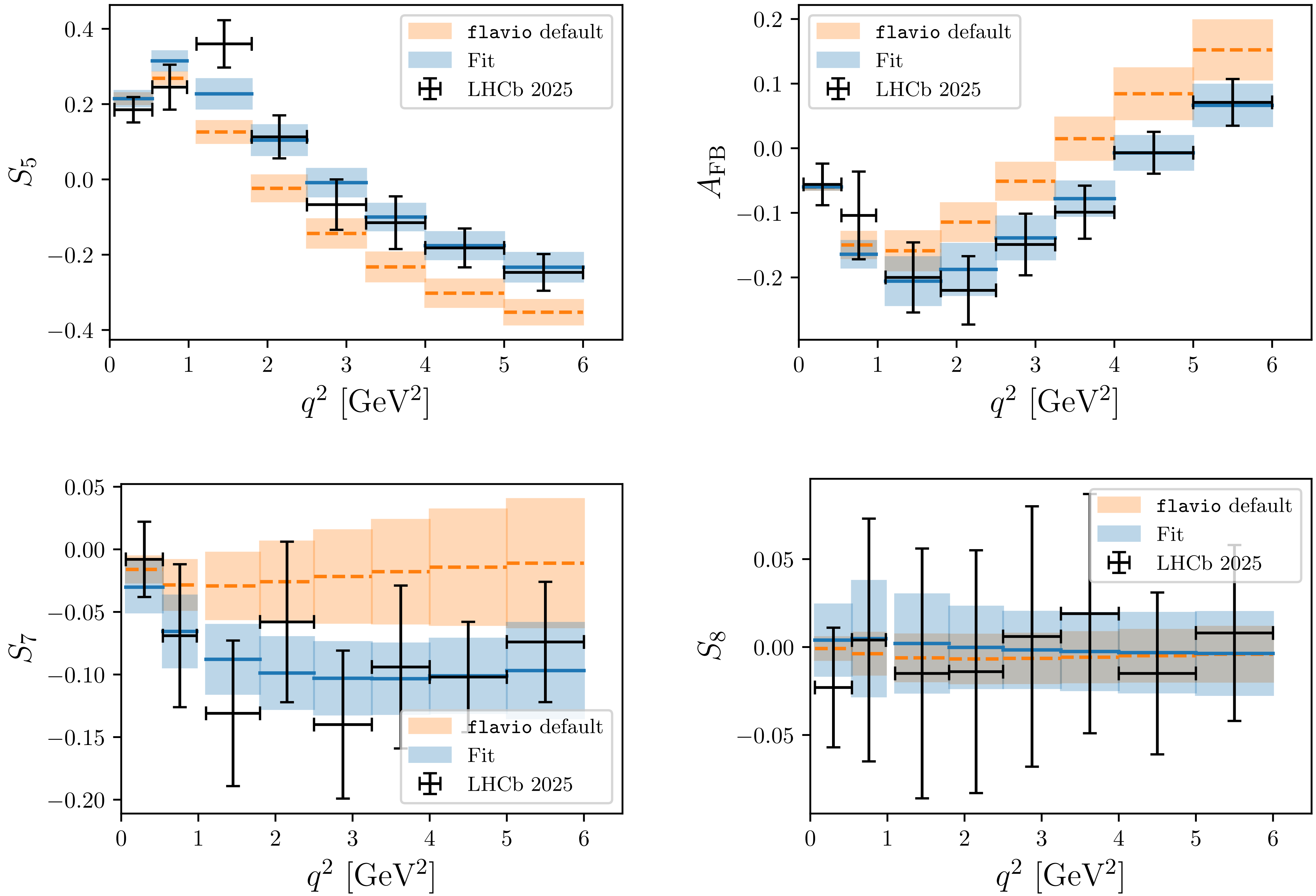
Update of
arXiv:**2212.10516**
HEPfit

WHAT IF CHARMING PENGUINS WERE ALL SMALL?



New Physics at more than 5σ level in $C^{NP}_{9,\mu}$ (3σ in $C^{NP}_{9,e}$) fully compatible with a LFU scenario

b-> s ll : $S_{7,8} \neq 0$ <—> HADRONICS



arXiv:**2603.27753**

S_7 measurements point to hadronic effects of ~ same size as required by **S_5** & **A_{FB}**

b-> s ll : ARE LOCAL FORM FACTORS OK?

QCD Light-Cone Sum Rules

low q^2 region

Quark-hadron duality — assumption that OPE matches hadronic spectral function, not first principles

No rigorous error budget — uncertainties estimated by naive parameter variation, no rock solid stat

In particular:
1) **Light-cone OPE truncation** — series cut at twist-3 or twist-4; convergence assumed, not guaranteed
2) **Borel parameter M^2** — results should be stable in a "window"; residual dependence is an error
3) **Continuum threshold s_0** — effective duality threshold fitted, not predicted; major systematic

A N A L I T I C I T Y + U N I T A R I T Y

1. Boyd-Grinstein-Lebed (BGL) parametrization: *the idea is to expand the FFs around z = 0. For the generic FF f(w)*

$$f(w) = \frac{1}{\phi_f(z) B_f(z)} \sum_{i=0}^{\infty} a_i^f z^i$$

Kinematical function * *B-factors* for resonances

Real parameters to be determined

PLB '95 [hep-ph/9504235]
NPB '96 [hep-ph/9508211]
PRD '97 [hep-ph/9705252]

See Nico's talk yesterday

2. Dispersive Matrix (DM) method: let us suppose to know a generic FF $f(q^2)$ at positions q^2_i (i=1, ..., N). We define (*here* $t = q^2$)

- inner product

$$\langle h_1 | h_2 \rangle = \int_{|z|=1} \frac{dz}{2\pi i z} \bar{h}_1(z) h_2(z)$$

- auxialiary function

$$g_t(z) \equiv \frac{1}{1 - \bar{z}(t) z}$$

$$z(t) = \frac{\sqrt{\frac{t_+ - t}{t_+ - t_-}} - 1}{\sqrt{\frac{t_+ - t}{t_+ - t_-}} + 1} \qquad t_\pm \equiv (m_B \pm m_D)^2$$

NPB 479 (1996) 353 ; NPB 189 (1981) 157 ; PRD 50 (1994) 373
New developments in M. Di Carlo et al, PRD '21 (2105.02497)

KEY POINT : since **M** contains only inner products, by construction its *determinant* is *semipositive definite*

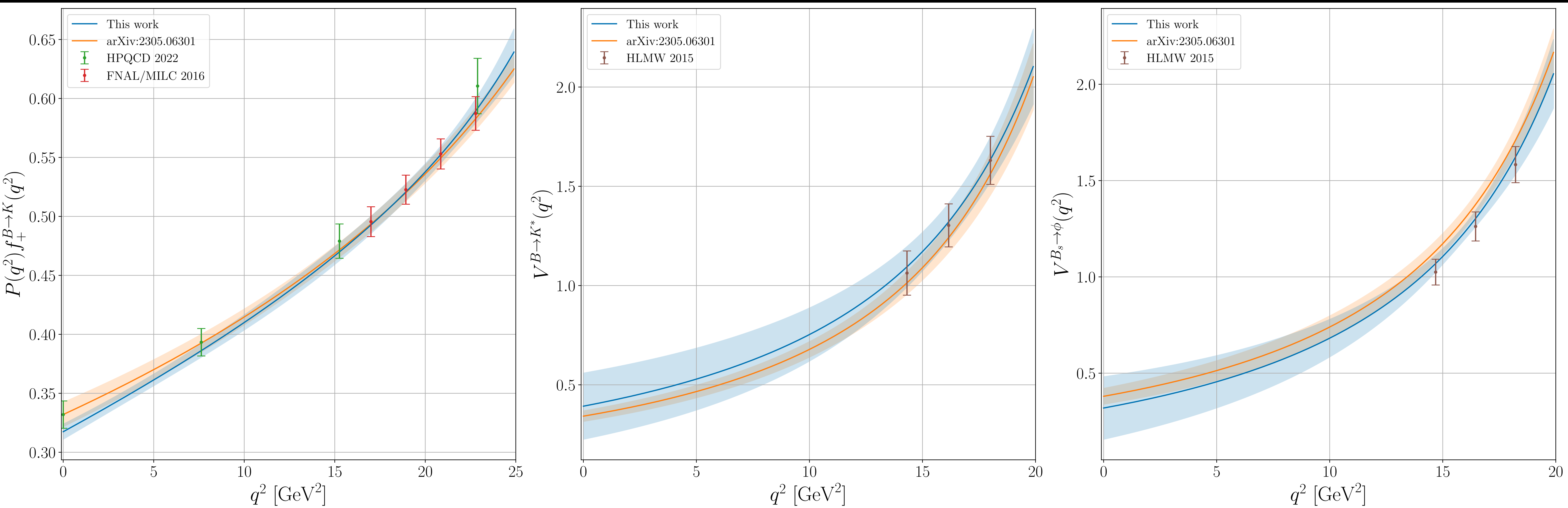
$$\mathbf{M} = \begin{pmatrix} \langle \phi f | \phi f \rangle & \langle \phi f | g_t \rangle & \langle \phi f | g_{t_1} \rangle & \cdots & \langle \phi f | g_{t_n} \rangle \\ \langle g_t | \phi f \rangle & \langle g_t | g_t \rangle & \langle g_t | g_{t_1} \rangle & \cdots & \langle g_t | g_{t_n} \rangle \\ \langle g_{t_1} | \phi f \rangle & \langle g_{t_1} | g_t \rangle & \langle g_{t_1} | g_{t_1} \rangle & \cdots & \langle g_{t_1} | g_{t_n} \rangle \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \langle g_{t_n} | \phi f \rangle & \langle g_{t_n} | g_t \rangle & \langle g_{t_n} | g_{t_1} \rangle & \cdots & \langle g_{t_n} | g_{t_n} \rangle \end{pmatrix}$$

$$\det \mathbf{M} \geq 0 \quad \Rightarrow \quad f_{lo}(z) \leq f(z) \leq f_{up}(z)$$

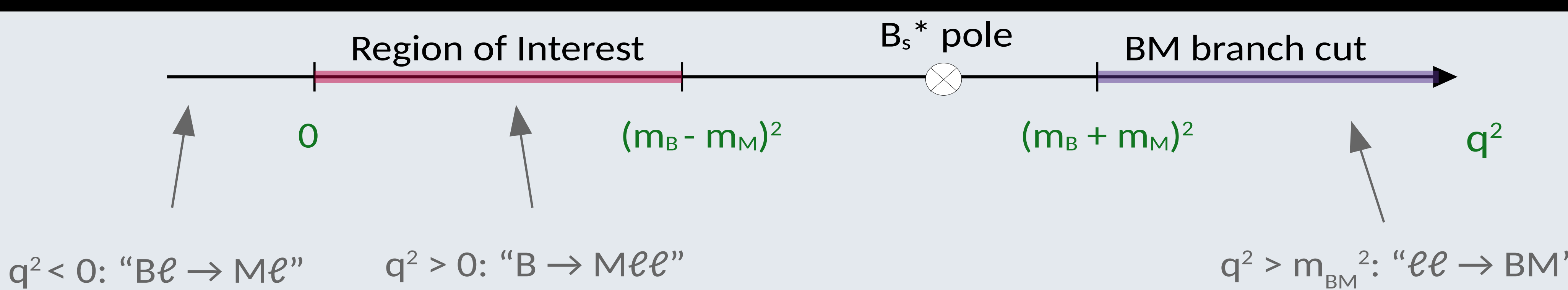
Form Factors for $B \to V(P)\, \ell^+\ell^-$

NEW

In preparation!



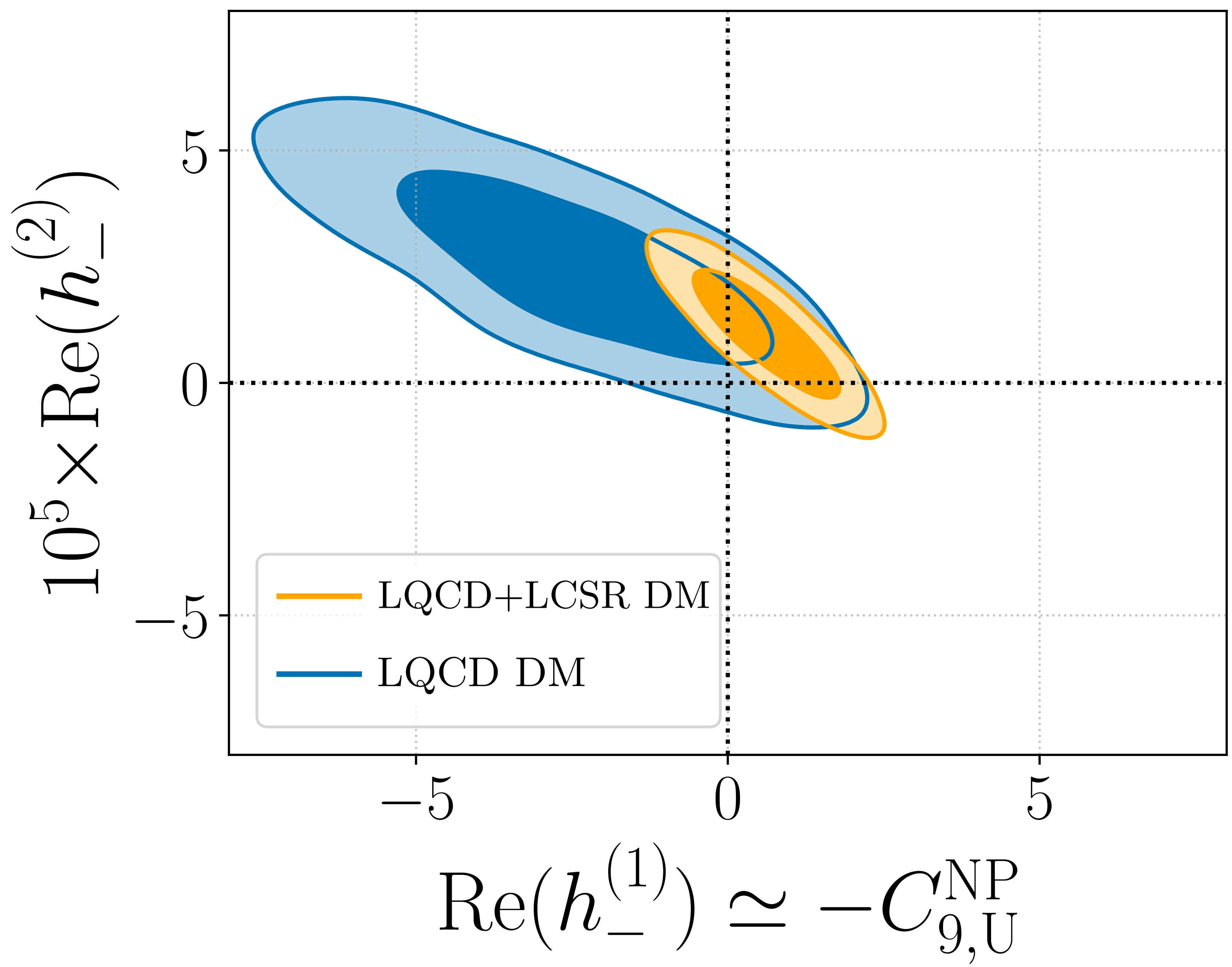
- **QCD Light-Cone Sum Rules (LCSR) —>** available @ $q^2 << 1$, not first-principle
- **Lattice QCD —>** typically reliable @ high q^2 with ~ stable mesons (i.e. K^* , ϕ_s ?)



b-> s ll : WERE WE DRIVEN BY LCSR?

NEW

In preparation!



QCD ONLY

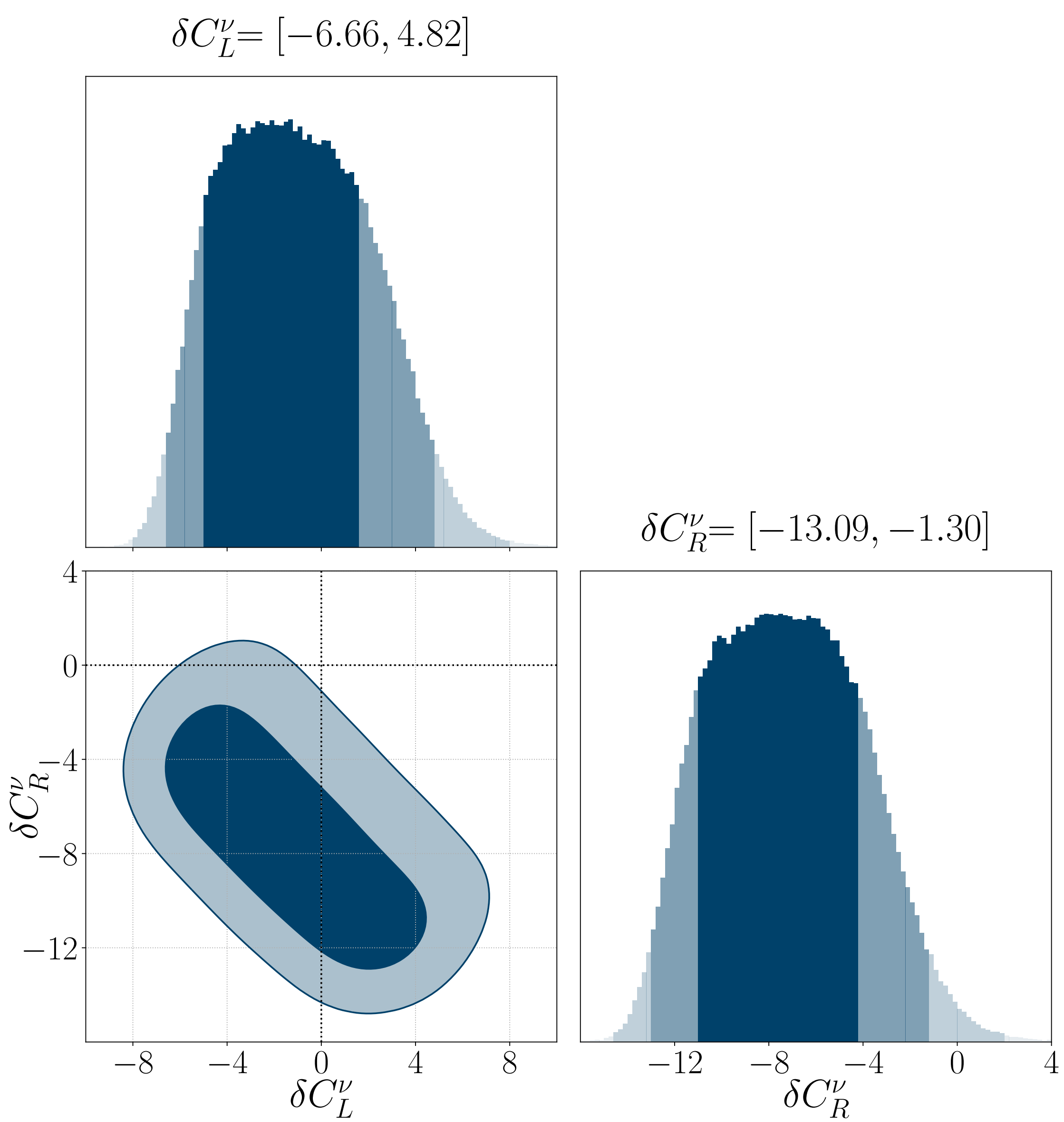
QCD ~ LEPTON UNIVERSAL NP

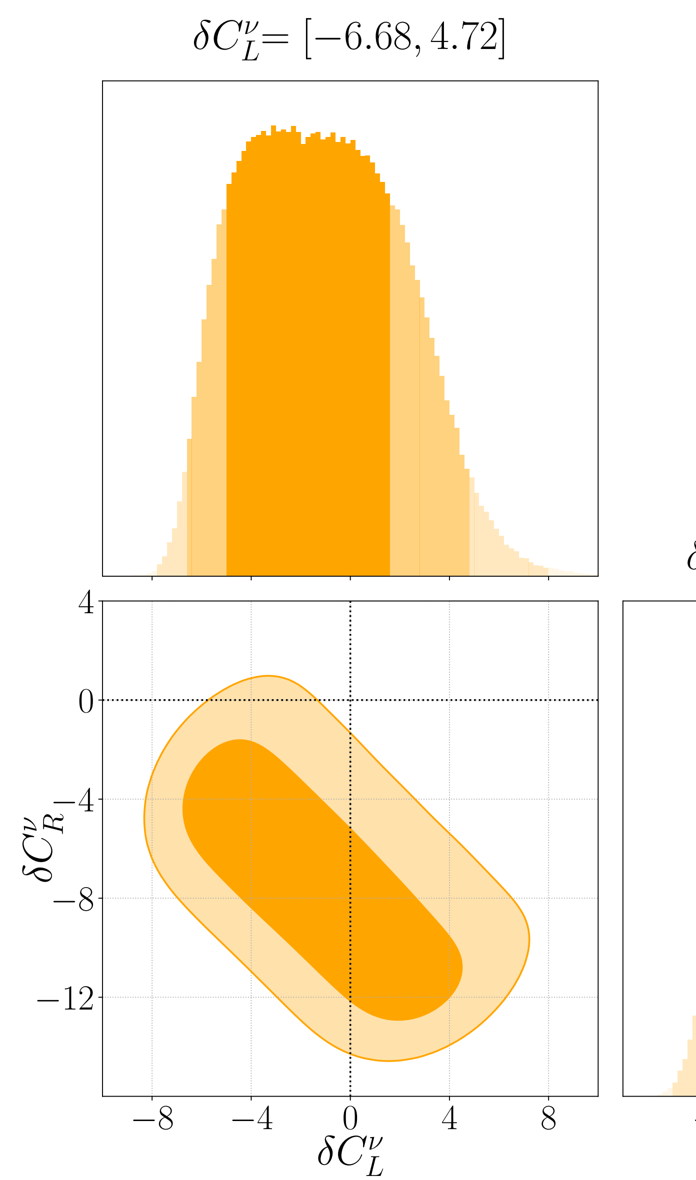
b-> s νν : WHAT ABOUT LCSR THERE?

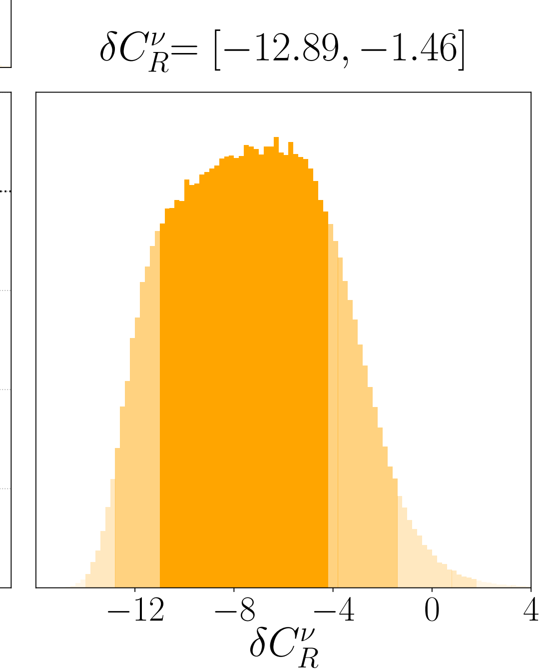
Channel	$\mathcal{B}$ w/ LQCD DM FFs	$\mathcal{B}$ w/ LQCD+LCSR DM FFs
$B^+ \to K^+ \nu\bar{\nu}$	$(3.96 \pm 0.22)\ \times 10^{-6}$	$(3.96 \pm 0.22)\ \times 10^{-6}$
$B^+ \to K^{*+} \nu\bar{\nu}$	$(9.9 \pm 1.8)\ \times 10^{-6}$	$(9.5 \pm 0.9)\ \times 10^{-6}$
$B^0 \to K^{*0} \nu\bar{\nu}$	$(9.3 \pm 1.7)\ \times 10^{-6}$	$(8.9 \pm 0.8)\ \times 10^{-6}$

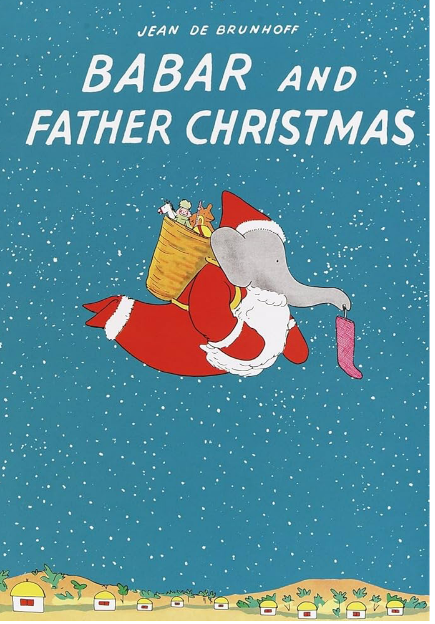
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}$$

2.7 σ from SM



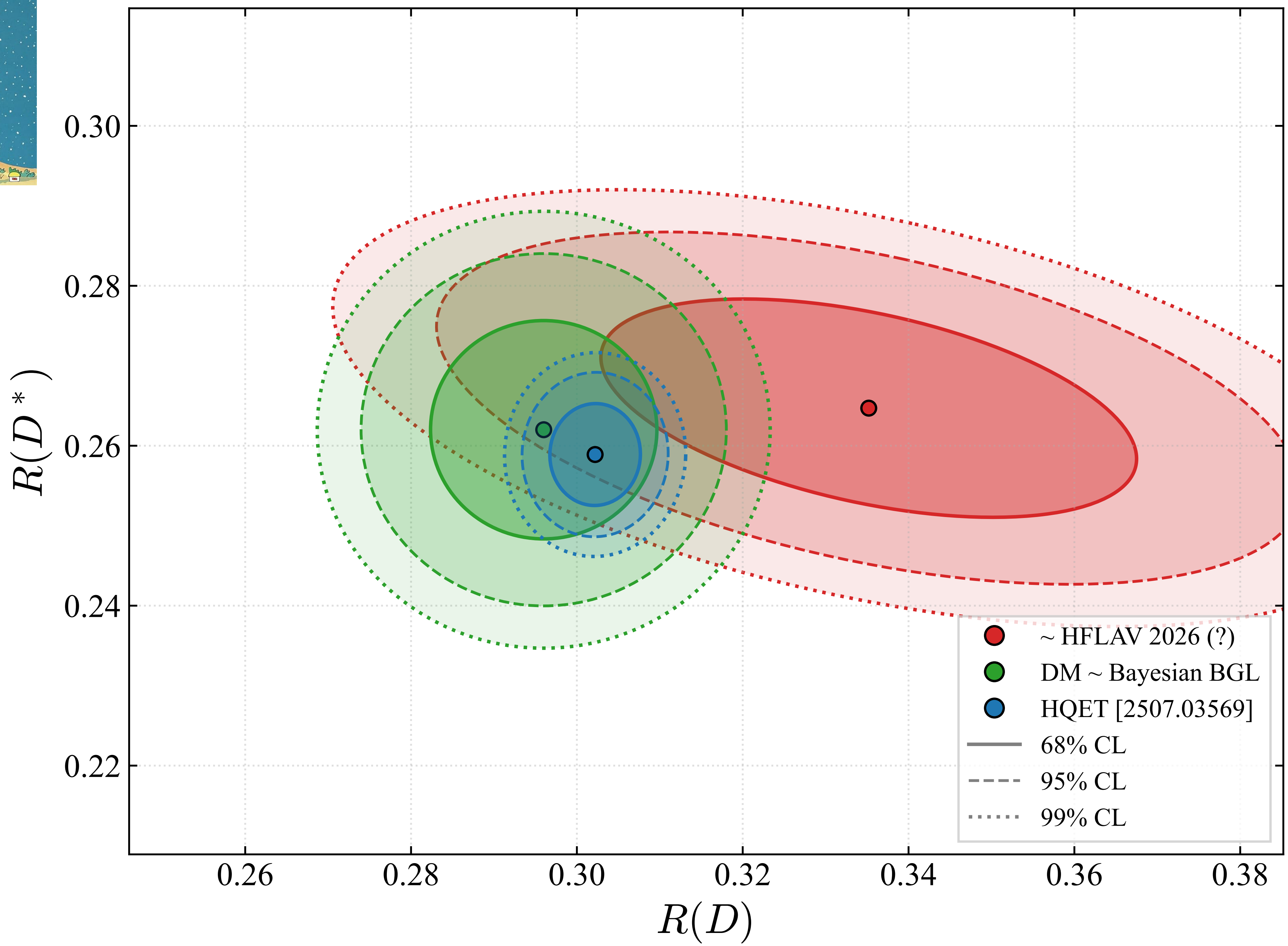






b-> c lν : New Sources of LFU Violation?

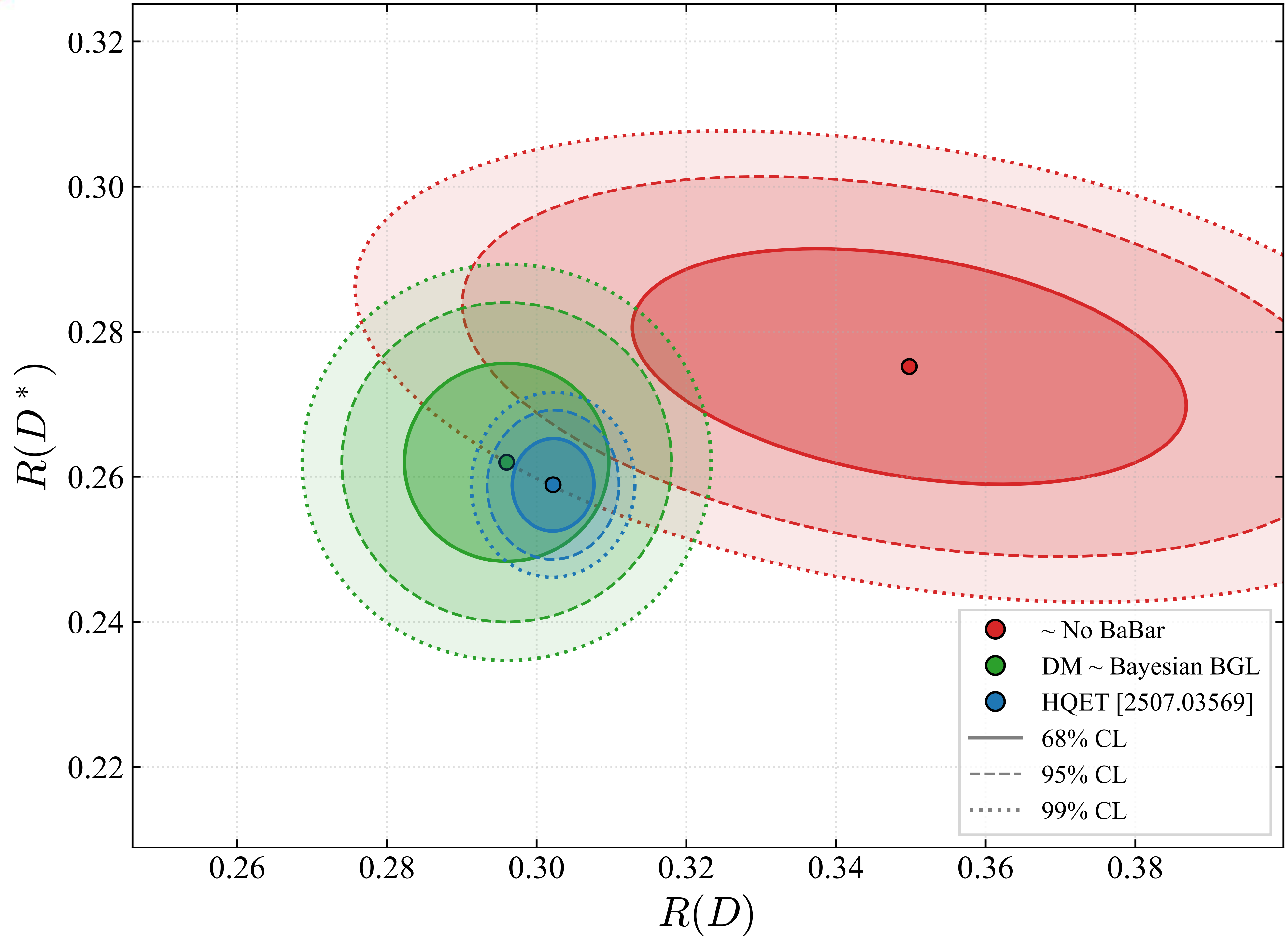
No!



No tension in current LFU tests, not even in b-> c lν.

b-> c l ν : New Sources of LFU Violation?

No!



No serious tension arises even when one leaves BaBar out!

- **Precision program with flavor physics is exciting: only a naive reading points to very high scales for NP.**

No 🔥 tension in *B* decays, **w/ more data** I am confident that **global analyses will clear out** the nature of $\Delta C_{9,U}$

- **Accidental symmetries such as LFU offer a unique way to stress-test the SM and serve as a lamppost for NP.**

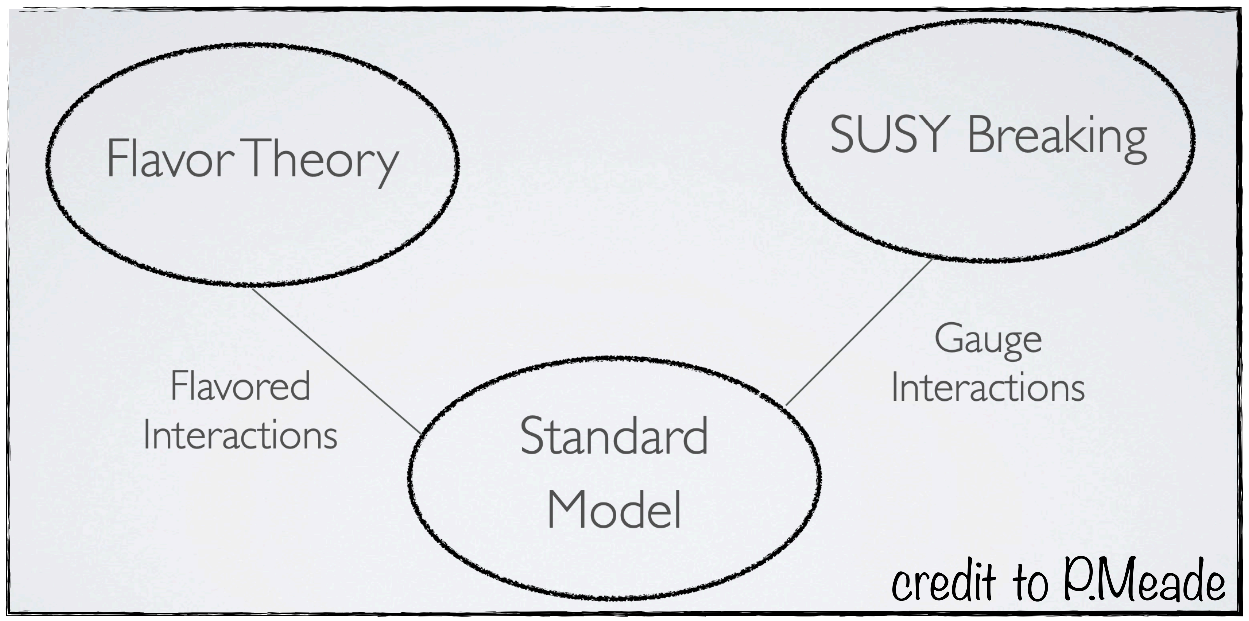
LFU looks “good”(as of today): **WHO ORDERED THAT?**

- **TH + EXP progress can lead to new paradigm shifts.**

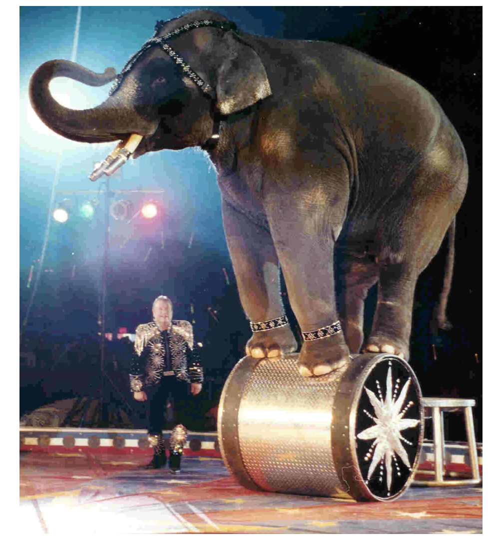
If a mass gap lies above the EW scale, SM EFT is our most powerful tool & **flavor remains** one of the **key** probes **for NP**.

Backup

Can we take Flavor apart?

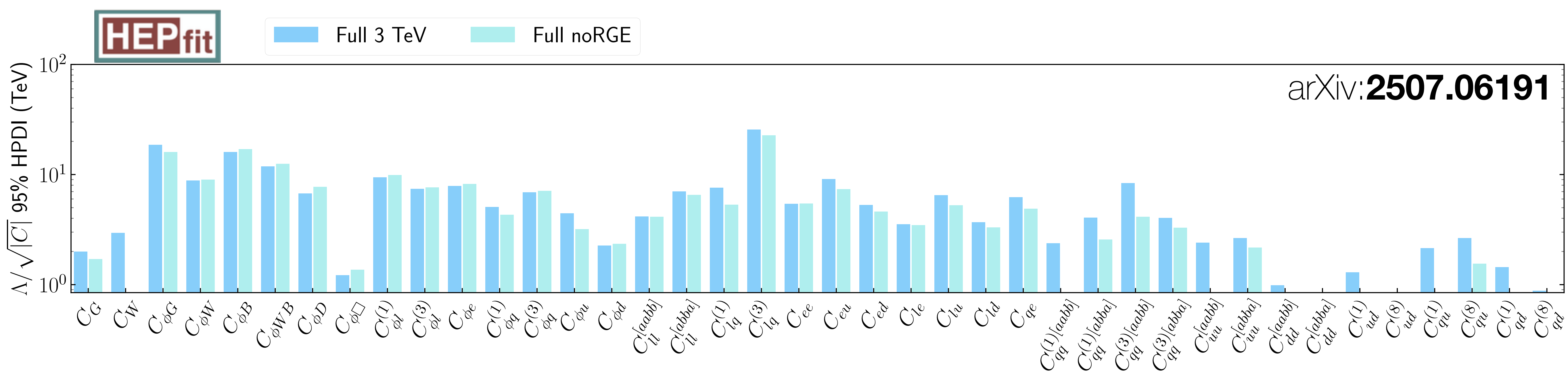


The SM Higgs



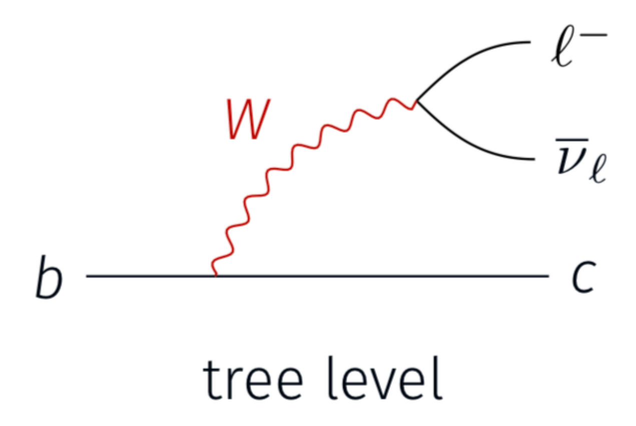
Bounds on flavor universal NP — **U(3)^5** — in the LHC era **point to ~ 30 TeV.**

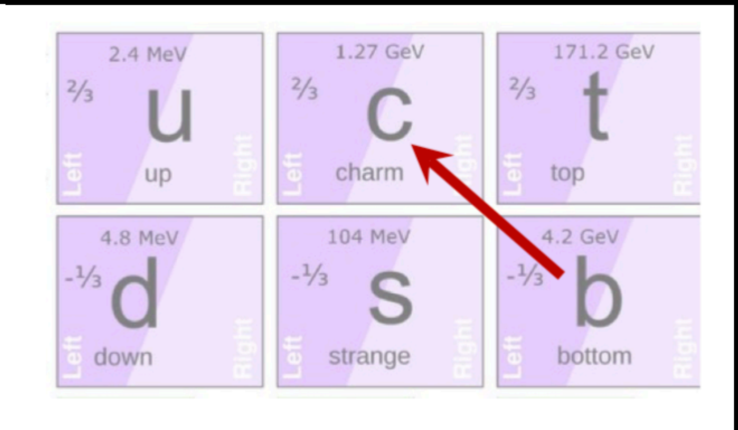
Flavor from SM RGE ✅ SM flavor puzzle postponed 😌 Higgs tuned 🤯



AND LAST BUT NOT LEAST

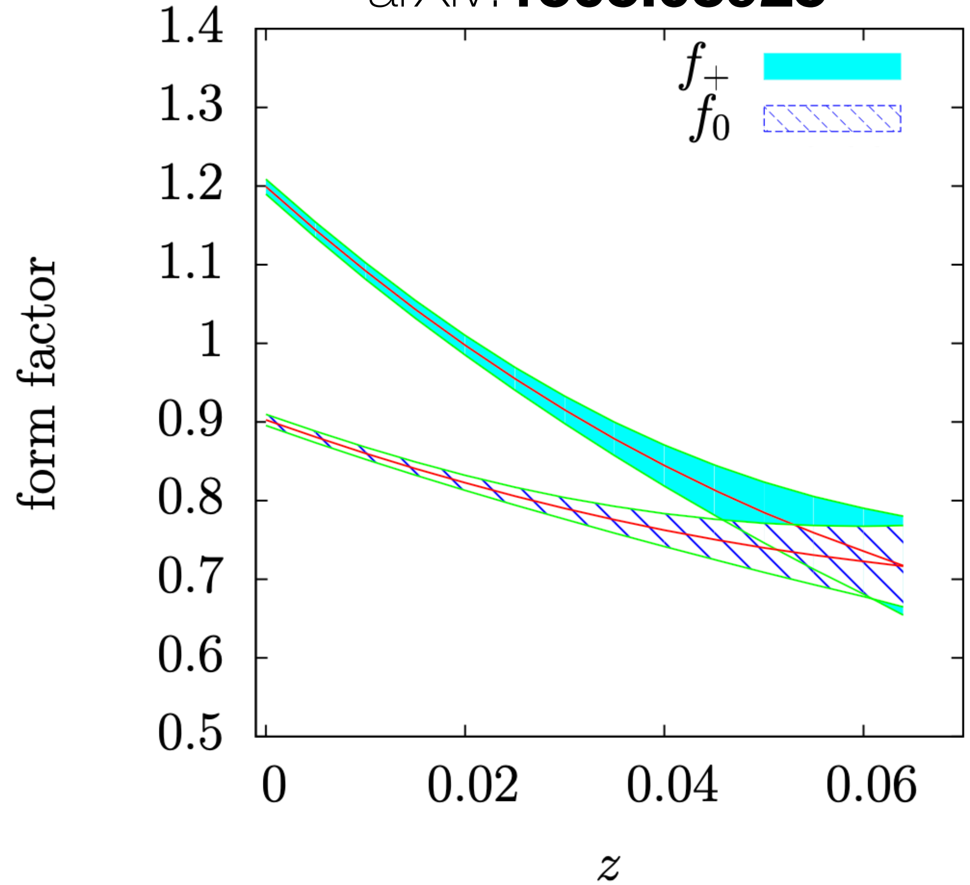
LFU & B DECAYS: NOT JUST A FCNC BUSINESS





- Charged-current semileptonic decays do not suffer from the non-local effects plaguing the study of some rare B decays.
- Lattice QCD provides non-perturbative determinations of the relevant matrix elements well beyond the zero-recoil limit.

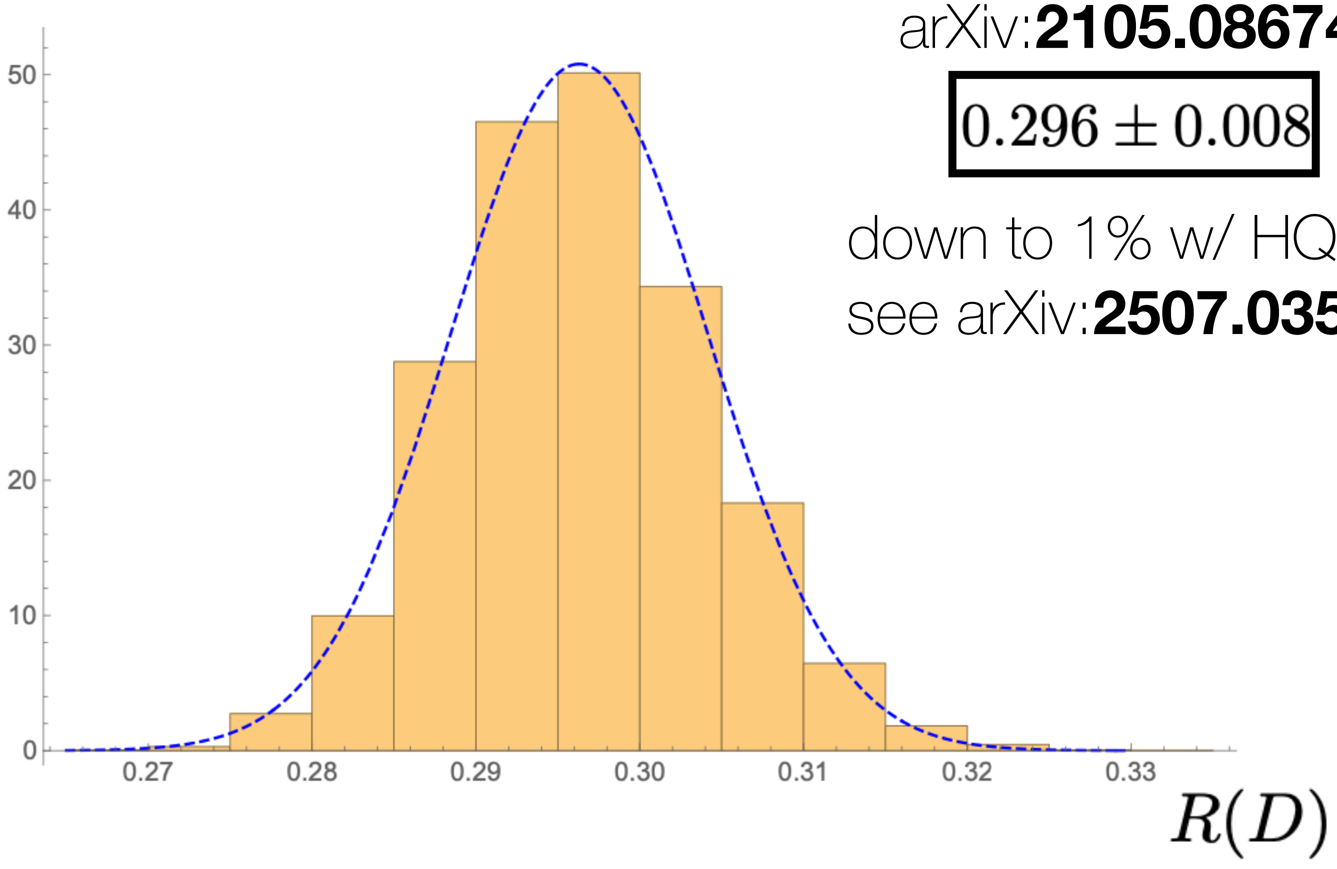
arXiv:**1505.03925**



arXiv:**2105.08674**

$\boxed{0.296 \pm 0.008}$

down to 1% w/ HQET, see arXiv:**2507.03569**



b-> c lν : FORM FACTORS FOR R_{D^*}

agenda.infn.it/event/44057/

2 APPROACHES IN VERY GOOD AGREEMENT HERE

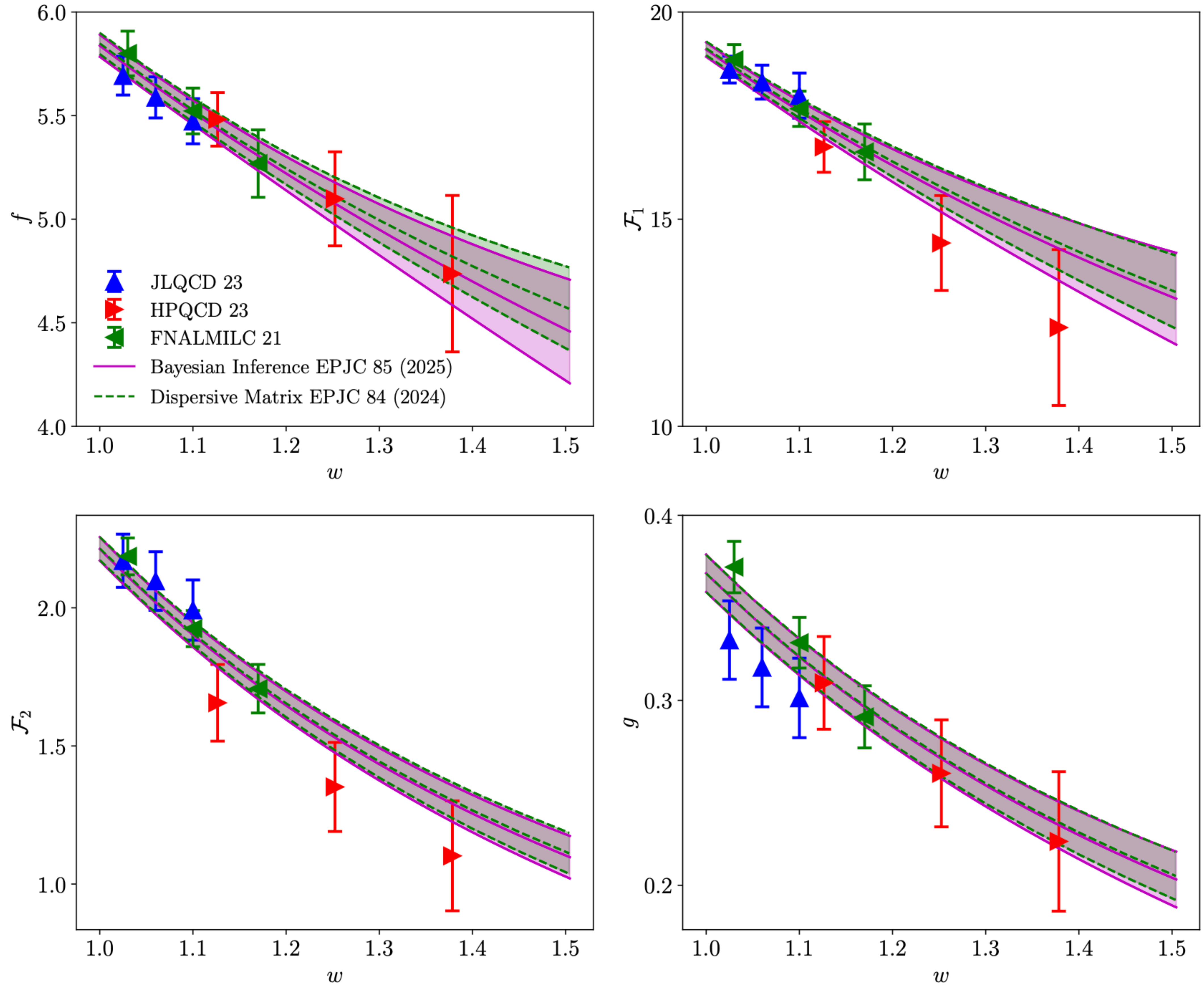
Ludovico Vittorio & Andreas Jüttner

SAPIENZA UNIVERSITÀ DI ROMA · INFN · University of Southampton

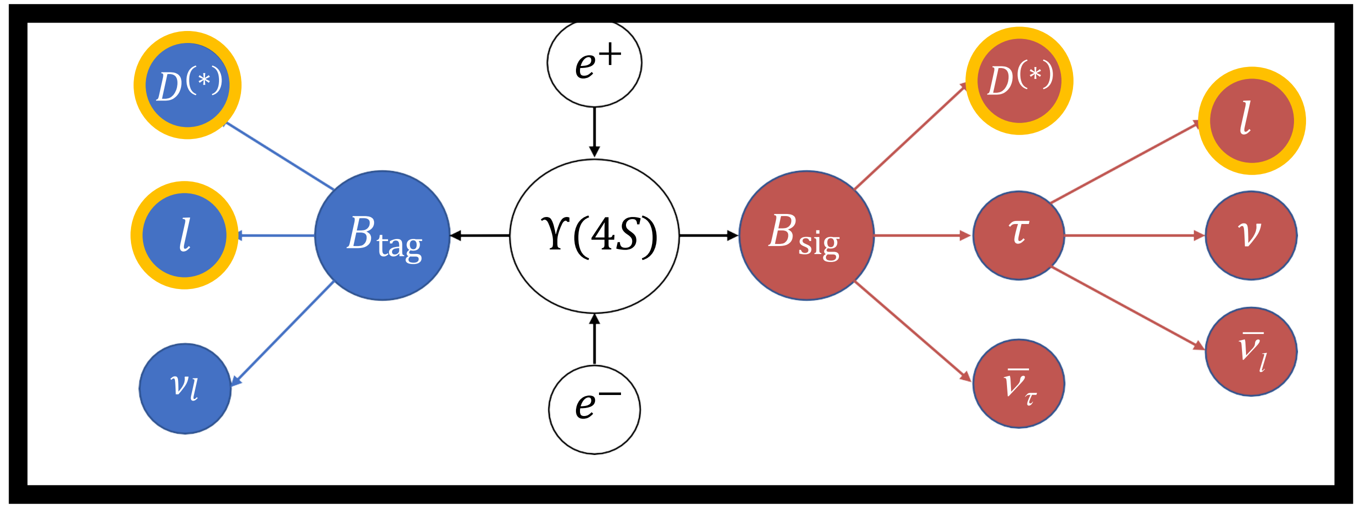
1) Filtering analysis of lattice QCD via dispersive matrix method

2) Bayesian fit to lattice QCD via BGL params w/ unitarity prior

See yesterday's talk by Simula, by Gubernari and by Vaquero



indico.fnal.gov/event/71119/



Particle identification requirements (usual *BABAR* criteria)

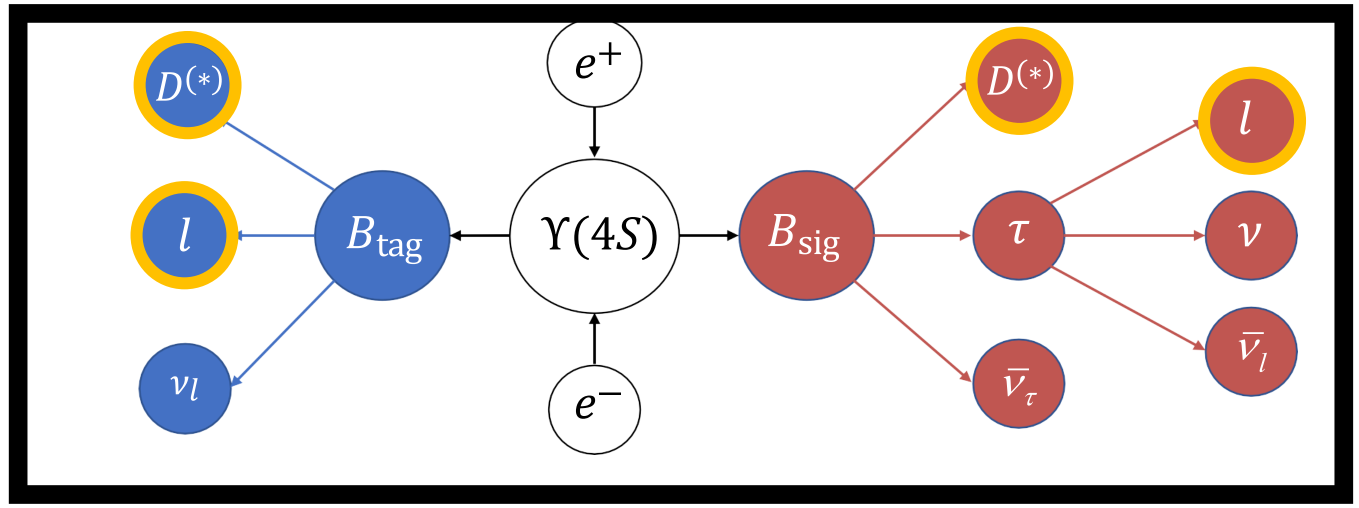
- The data sample is 426 fb^{-1} at the $\Upsilon(4S)$ resonance, taken with *BABAR* at PEP-II
- **Semileptonic tags** are used instead of hadronic tags that were employed in the 2012 measurement

Samples of the measurements with hadronic and semileptonic tags are essentially independent, so results can be individually included in world averages

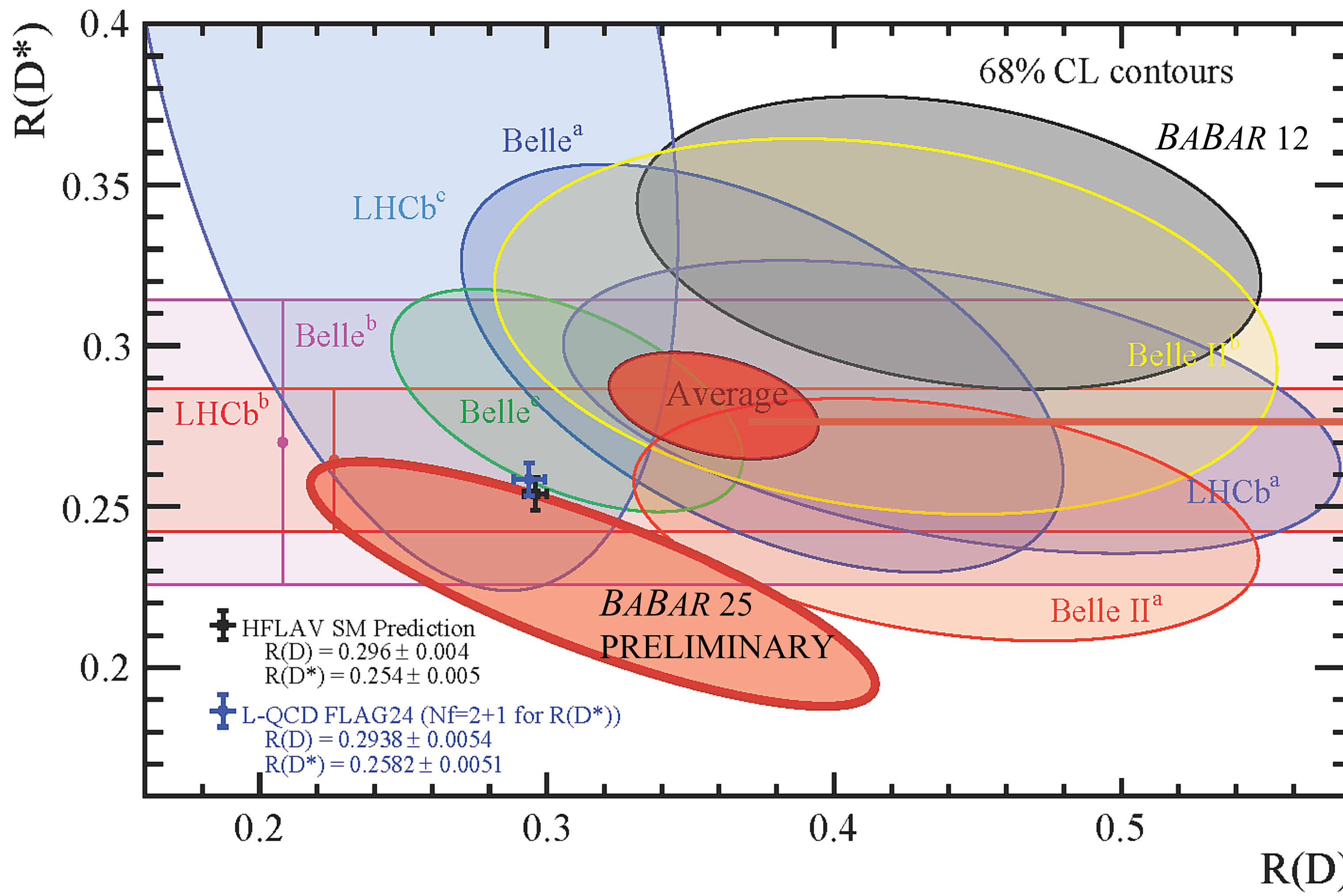
- $m(D)$: If final state has a π^0 require $m(D^0)$ *within* $[-45, 30]$ MeV of nominal D^0 mass
  require $m(D^+)$ *within* $[-36, 24]$MeV of nominal D^+ mass
  If final state does not have a π^0 require $m(D^0, D^+)$ within $[-15, +15]$ MeV of nominal mass
- $m(D^*) - m(D)$: For $D^{*+} \to D^0\pi^+$ within 2.5 MeV
  For $D^{*+} \to D^+\pi^0$ and $D^{*0} \to D^0\pi^0$ within 2.0 MeV

- $D^+ \to K^-\pi^+\pi^+, K_SK^+, K_S\pi^+, K_S\pi^+\pi^0, K_S\pi^+\pi^-\pi^+, K^-K^+\pi^+$ ~ 20%
- $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+, K_S\pi^+\pi^-, K_S\pi^0, K^-K^+$ ~ 30%
- $D^{*0} \to D^0\pi^0, D^{*+} \to D^0\pi^+, D^+\pi^0$

indico.fnal.gov/event/71119/



Experiment	$R(D)$	$R(D^*)$	Correlation
BABAR 12 (hadronic tag)	0.440 ± 0.058 ± 0.042	0.332 ± 0.024 ± 0.018	-0.27
HFLAV (CKM 2025 average)	0.358 ± 0.024	0.281 ± 0.011	-0.374
BABAR 25 (leptonic tag) **PRELIMINARY**	0.316 ± 0.062 ± 0.019	0.226 ± 0.022 ± 0.012	-0.82



This average does not include the *BABAR* 25 preliminary result