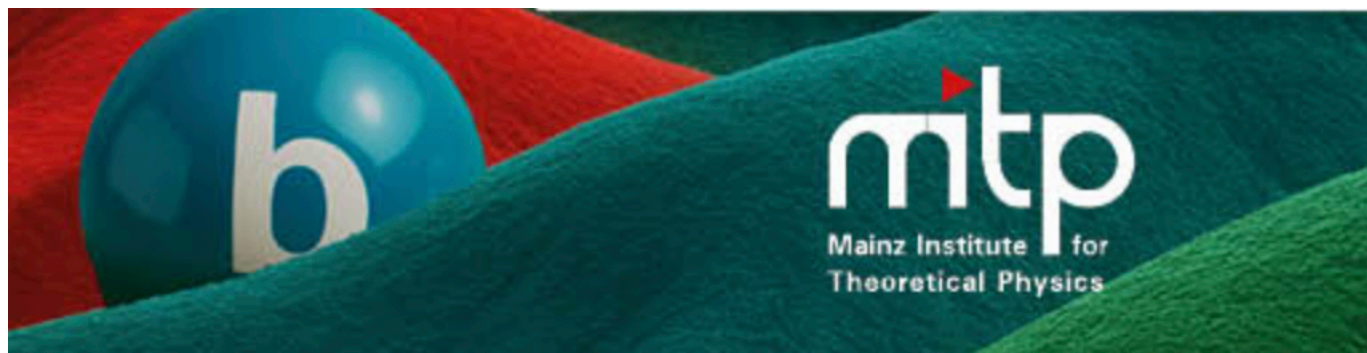




MITP Flavor Workshop — 14 / 07 / 2026 —

# TH Opportunities in Semileptonic (Rare) $B$ Decays

**MAURO VALLI**

---

INFN Rome

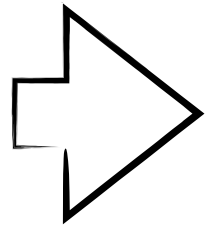


THANKS TO **M. Fedele, J.Scholze, L.Silvestrini, S.Simula & L.Vittorio**

# Accidental Symmetries

1

At low energy, the SM reduces to QED x QCD



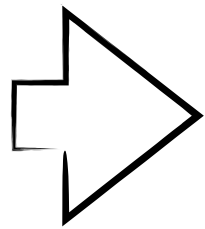
ACCIDENTAL SYMMETRY IN THE IR:  $U(1)^{N_f}$

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

$U(1)^{N_f}$  is violated by weak interactions: “NP” @  $\Lambda_{EW}$

2

At low energy, the SM features only 2 generations



ACCIDENTAL SYMMETRY IN THE IR: **CP**

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

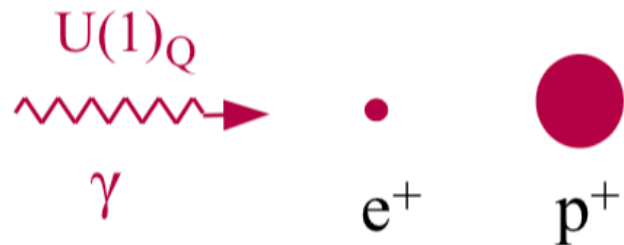
CP violation requires 3 generations & involves CKM hierarchy

ACCIDENTAL / APPROX SYMMETRIES SERVE AS A LAMPPOST FOR NP

# Lepton Flavor Universality

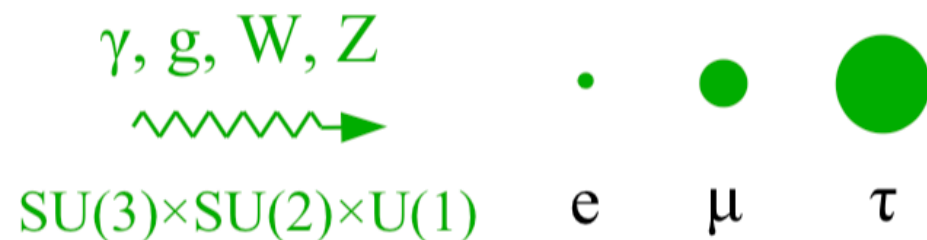
**LFU**  $\longleftrightarrow$  **ACCIDENTAL** in the SM gauge sector, broken by Yukawas

*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...

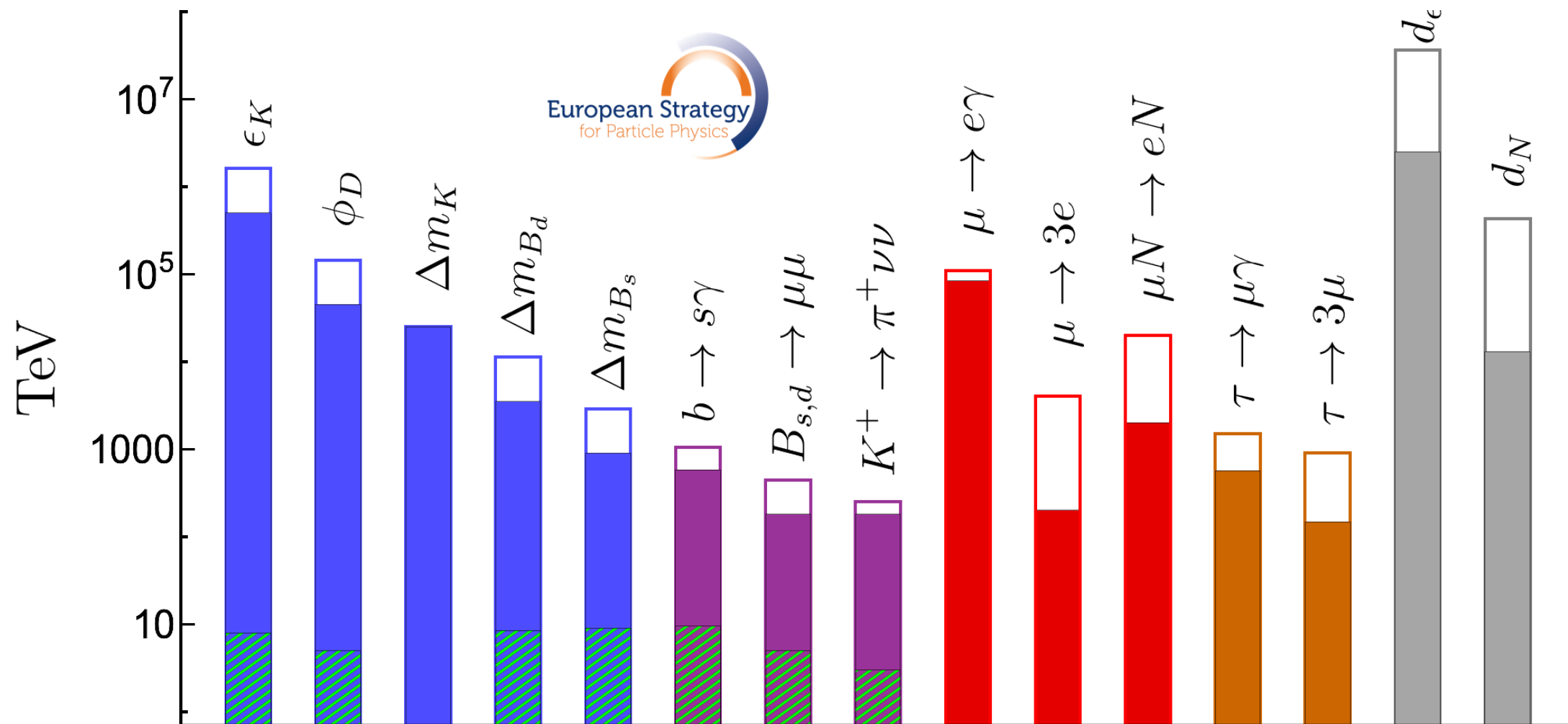


These three (families) of particles  
seems to be “identical copies”  
but for their mass ...

credit to G.Isidori

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

# Flavor beyond the SM

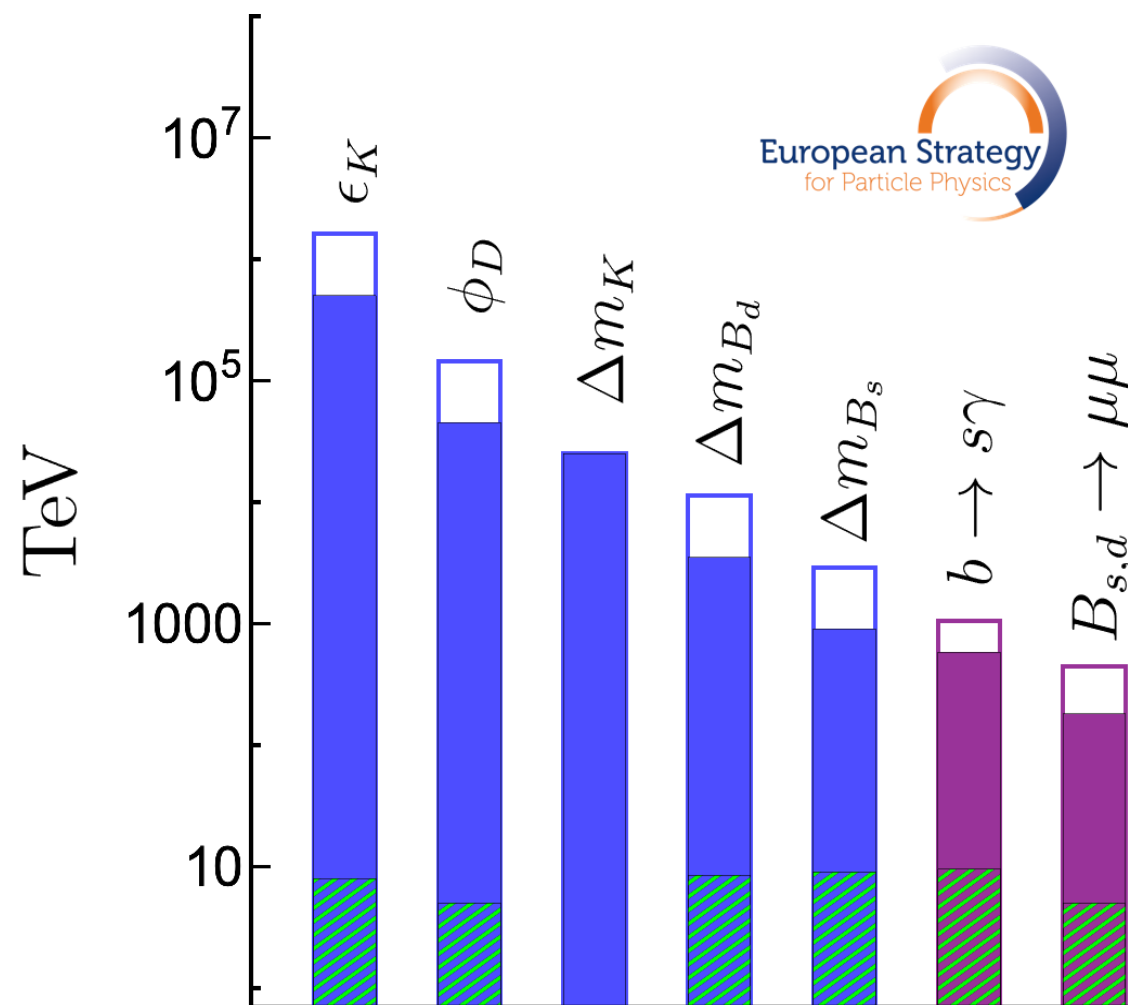


$$\sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} \mathcal{O}_i^{d \geq 5}$$

There is no reason why accidental symmetries should be respected in the UV  $\rightarrow$  **stringent bounds**

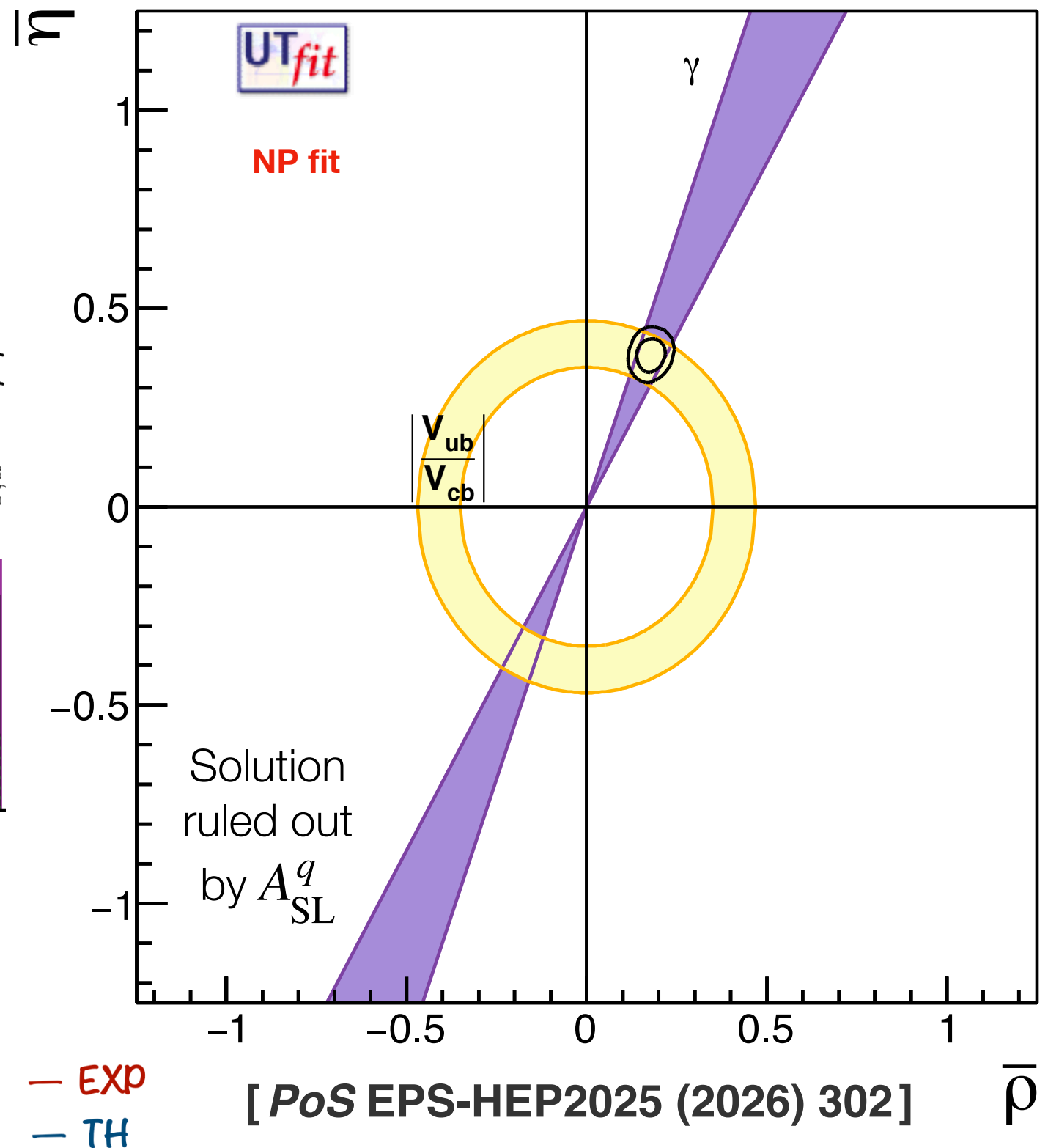


# Flavor beyond the SM



[www.utfit.org](http://www.utfit.org)

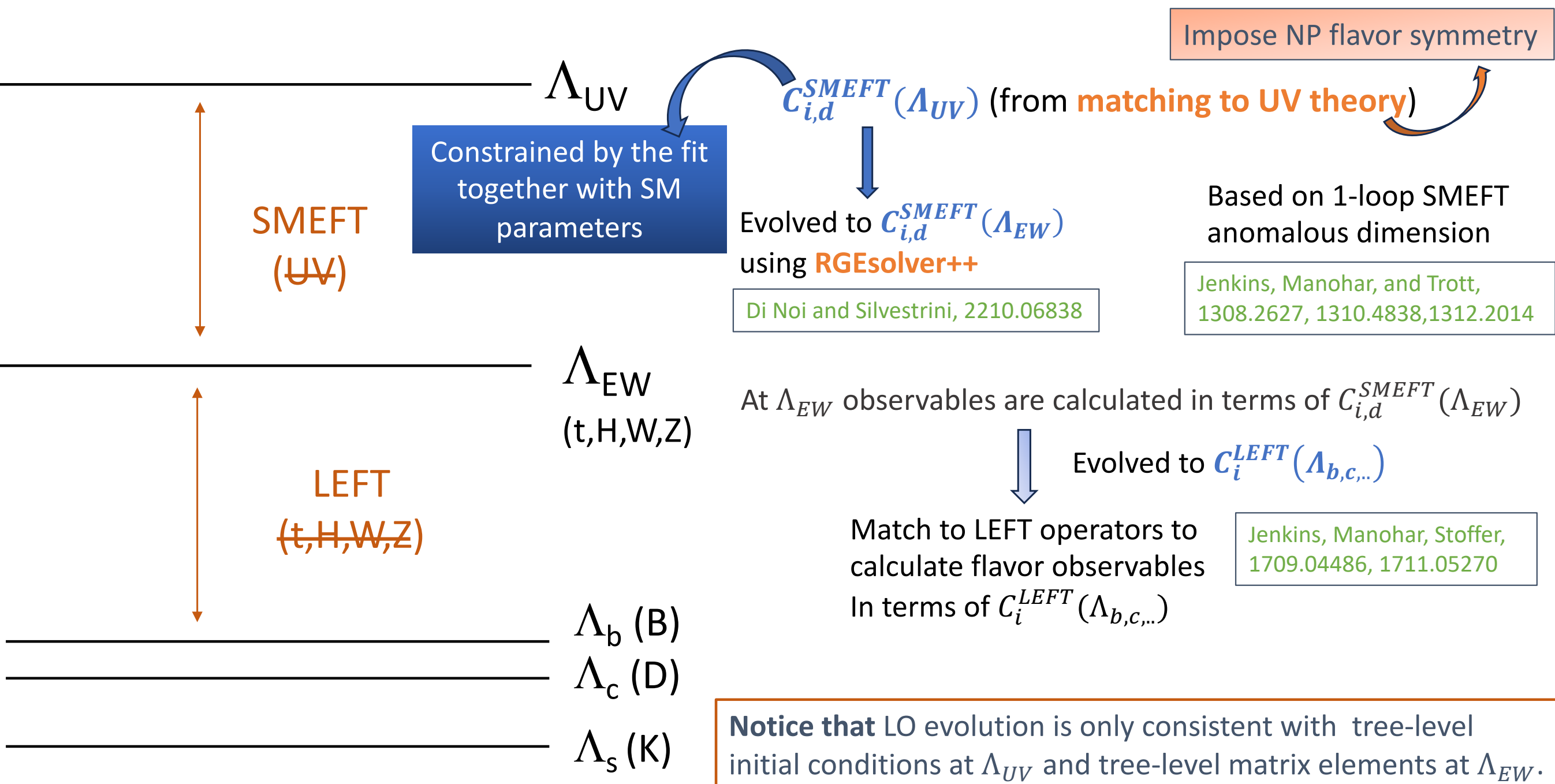
M. Bona, M. Ciuchini, D. Derkach, F. Ferrari, E. Franco,  
V. Lubicz, G. Martinelli, M. Pierini, L. Silvestrini, C.  
Tarantino, V. Vagnoni, M. Valli, and L. Vittorio



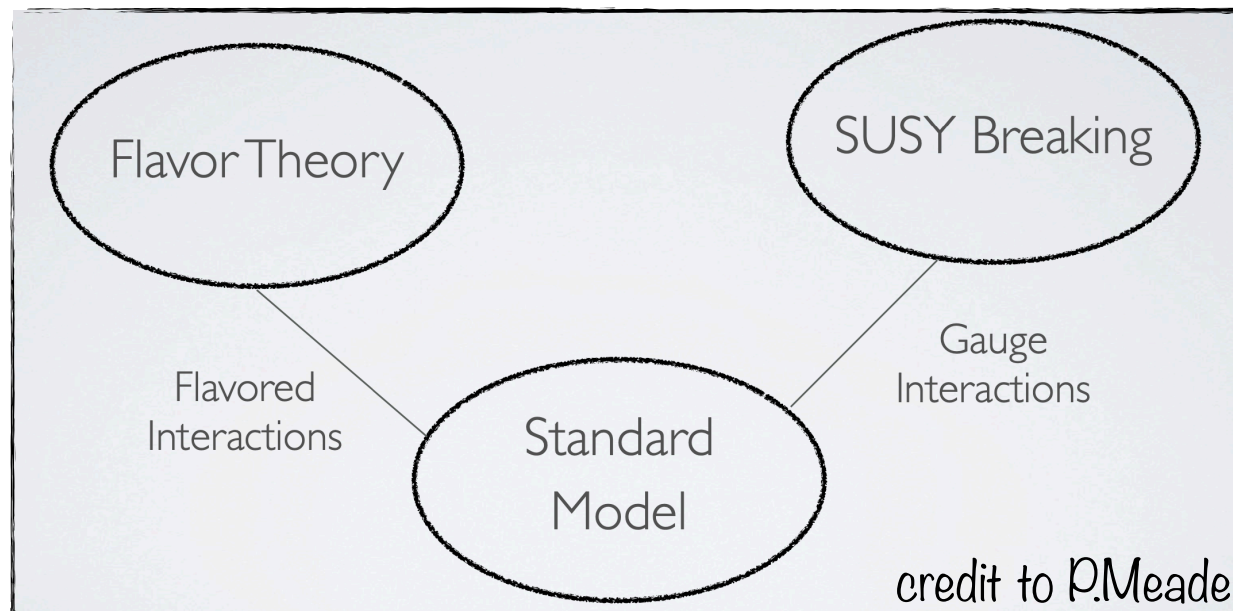
Exp: PDG, HFLAV  
Th: best available predictions



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



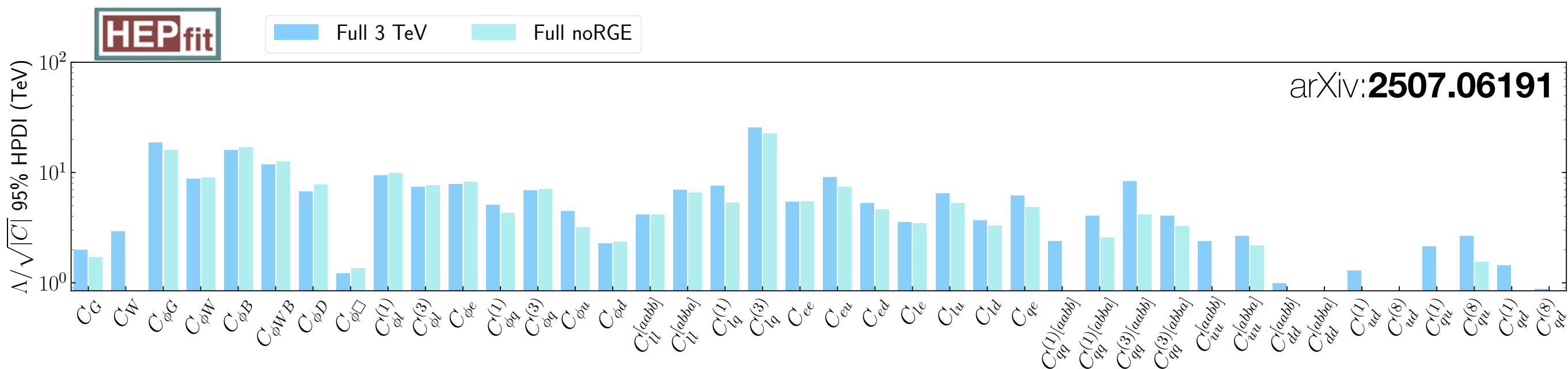
# Can we take Flavor apart?



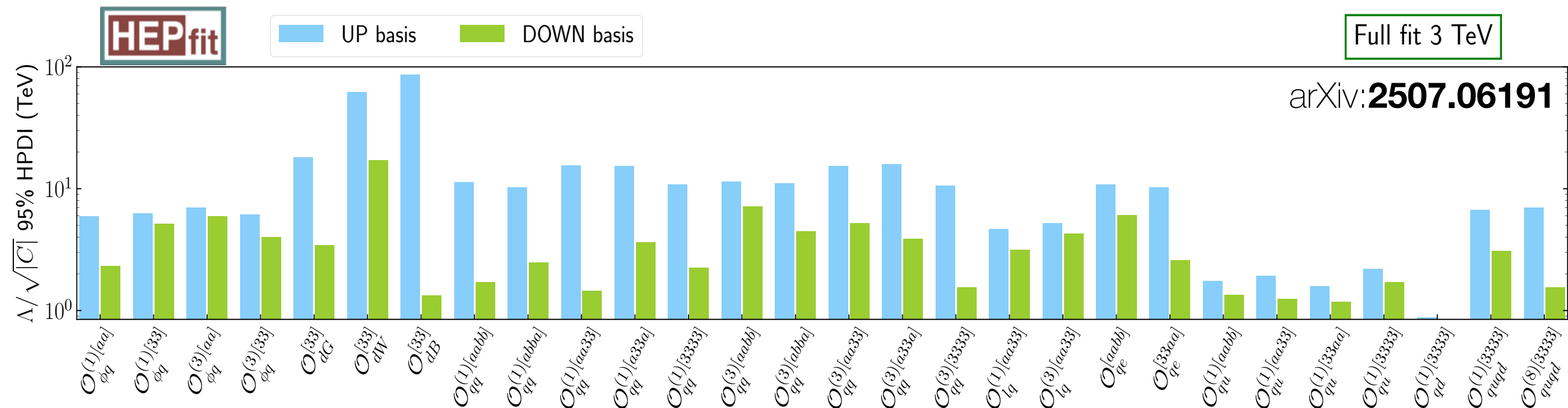
The SM Higgs

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



# 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.**

$$Y_U \sim \begin{pmatrix} \sim 10^{-5} & \sim 10^{-4} & 0.003 \\ & 0.005 & 0.04 \\ & & \boxed{1} \end{pmatrix} \longleftrightarrow Y_U \sim \begin{pmatrix} \overbrace{< 0.01}^{U(2)_u} & & \\ & \overbrace{0.04}^{U(2)_q} & \\ & & \boxed{1} \end{pmatrix}$$

$Y_U$  in the basis where  $Y_D$  is diagonal

$Y_U$  in the basis where  $Y_D$  is diagonal

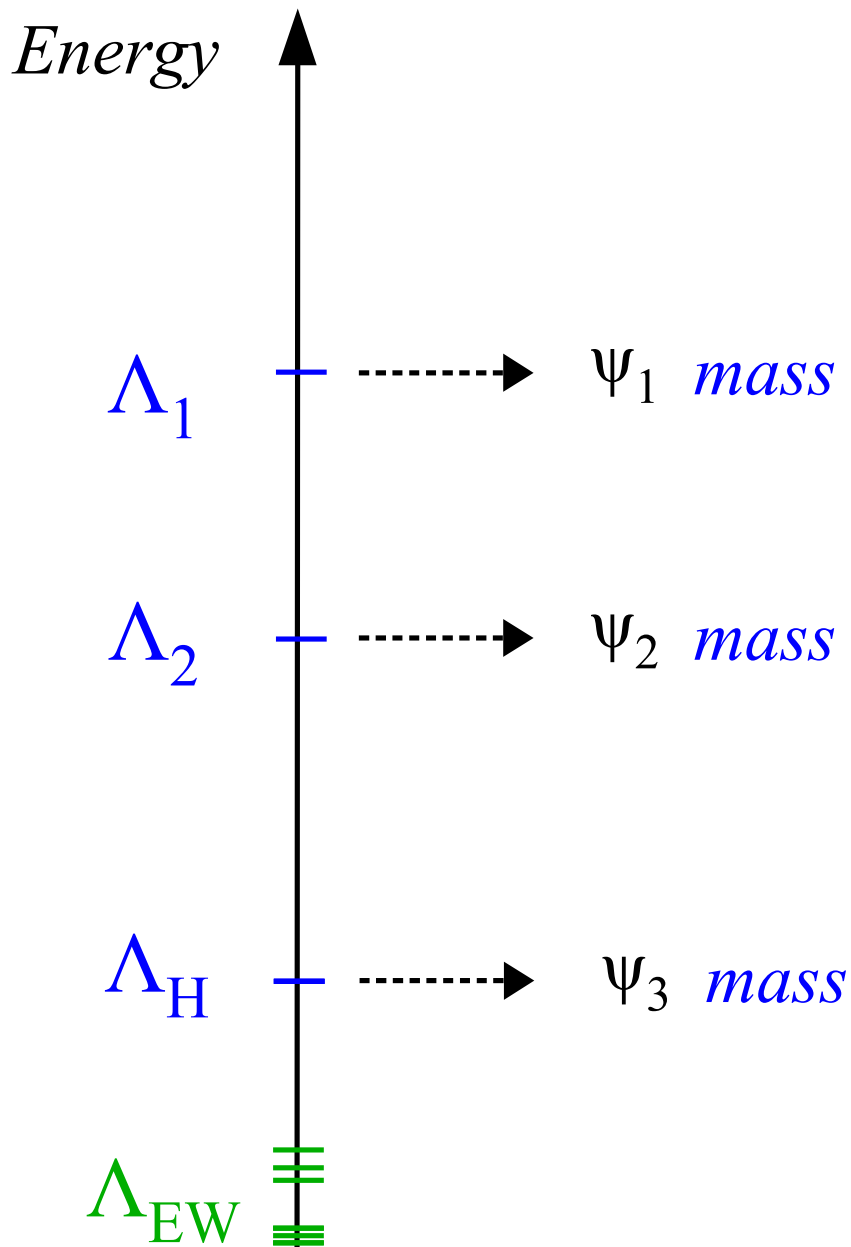
# w/ or w/o $U(2)$ ?

See, e.g.:

arXiv:**2312.14004**

arXiv:**2409.08657**

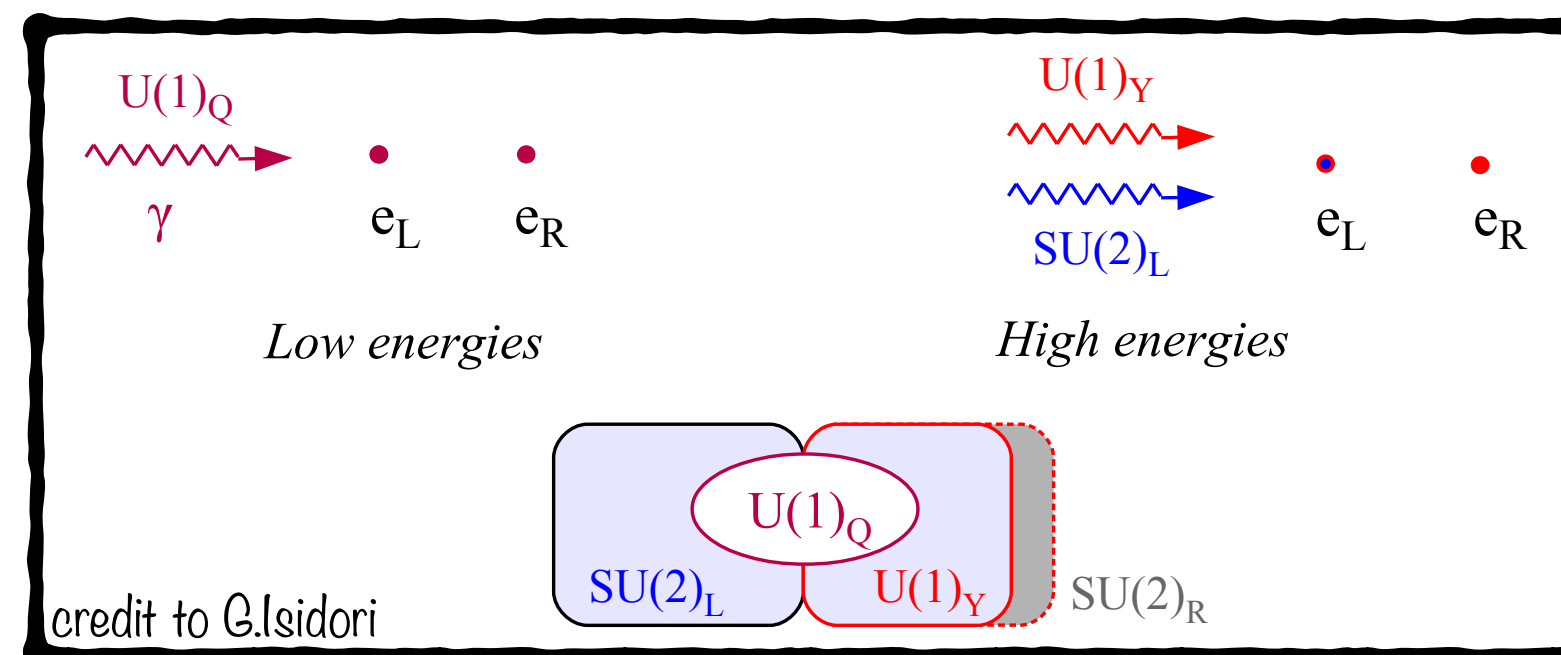
arXiv:**2503.14042**



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  $\Lambda_{1,2} \gg \Lambda_3 \gtrsim \Lambda_{EW}$



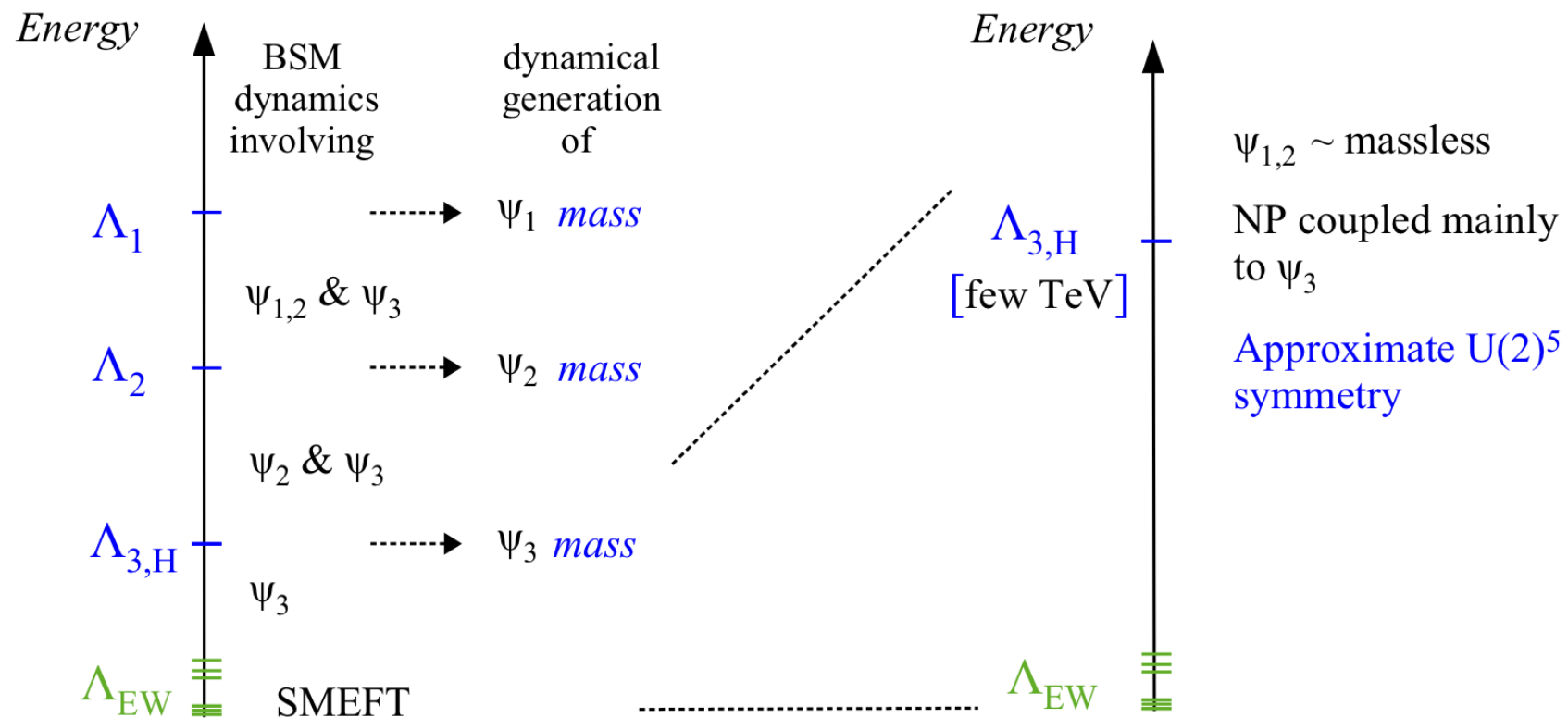
credit to G.Isidori

B  
O  
N  
U  
S

EW  
hierarchy  
"natural"



# signatures

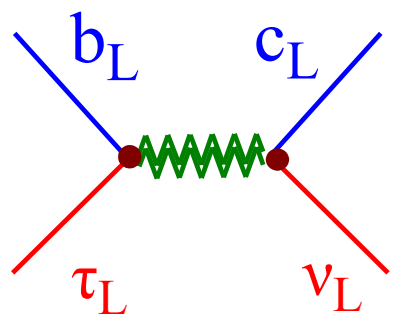


**Pheno driver:**

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

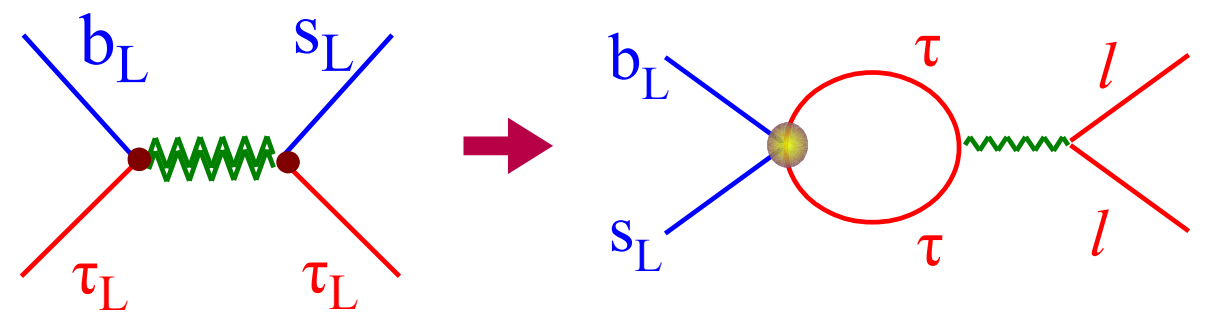
$U_1^\mu \sim (3, 1)_{2/3}$

LFU tests in semileptonic B decays may be the smoking gun

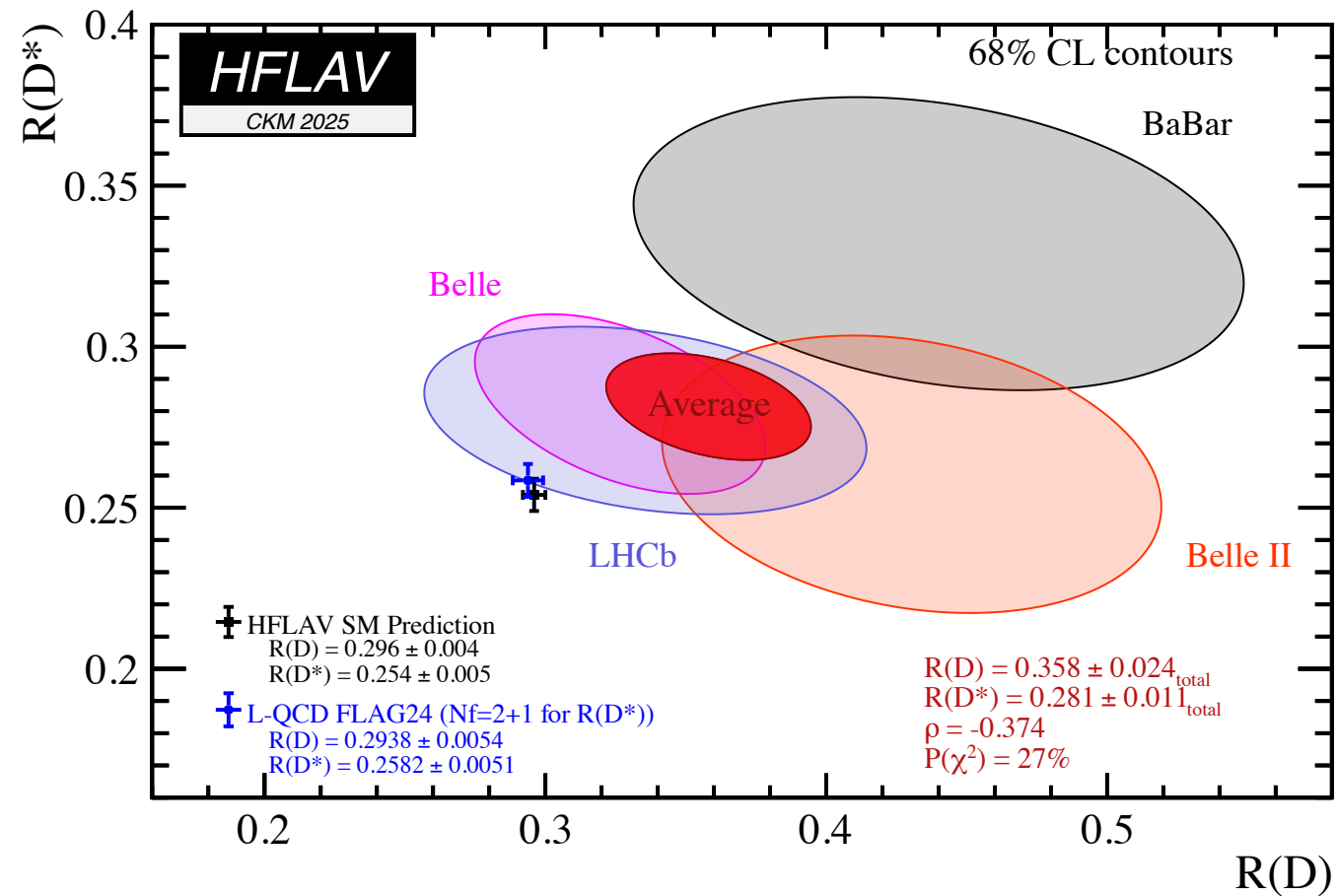
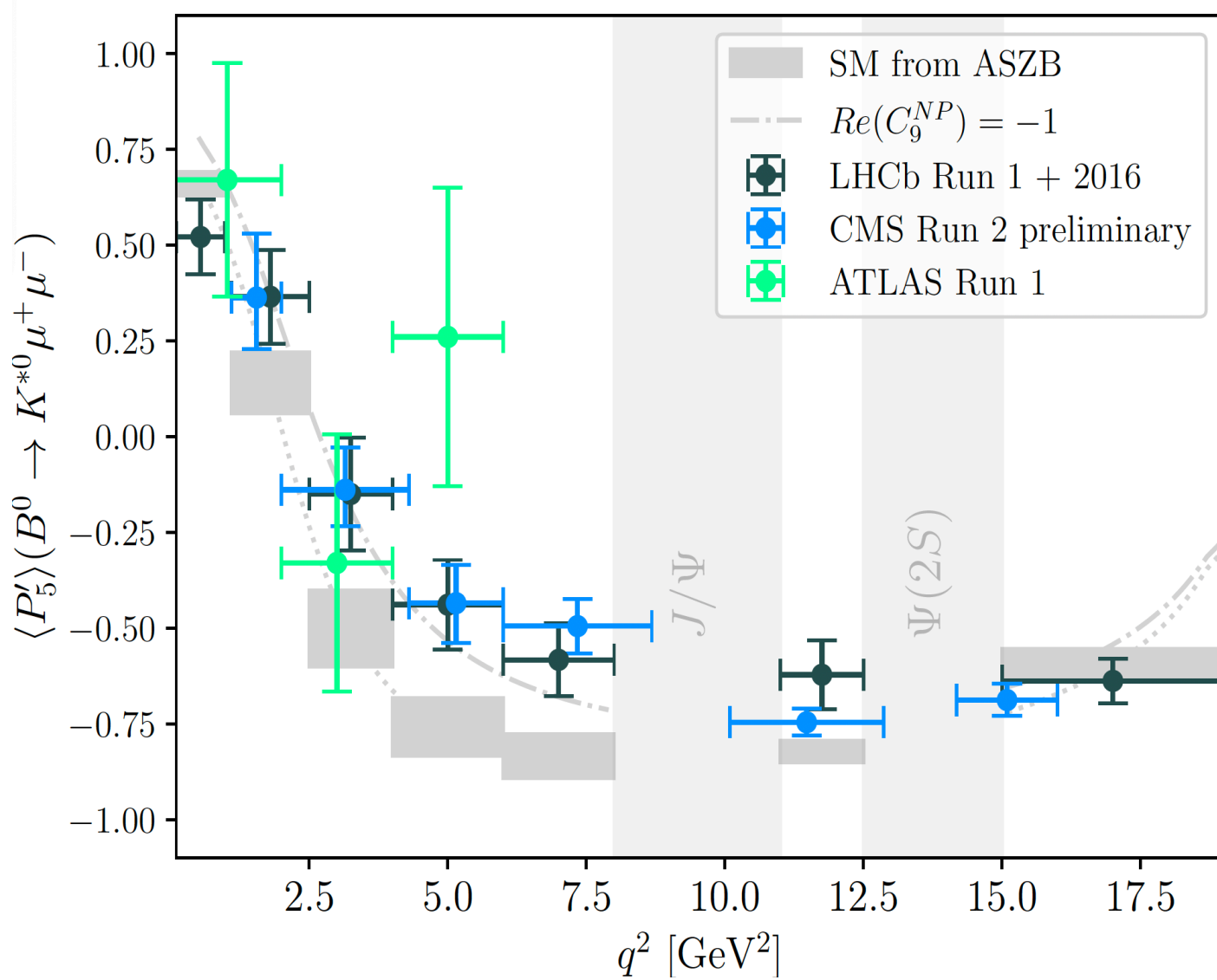


$$R(X)^{\tau/l} = \frac{\Gamma(B \rightarrow X \tau \nu)}{\Gamma(B \rightarrow X l \nu)}$$

LFU violation in  $b \rightarrow c$ ,  $X = D, D^*$



LFU effects in measured  $b \rightarrow s$  obs



Do we have  
any evidence for  
such NP ?

# ANATOMY OF SEMILEPTONIC RARE $B$ DECAYS

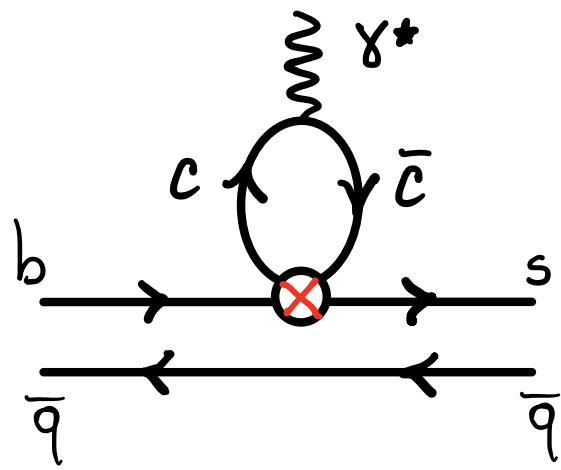
Building blocks are helicity amplitudes, which generally read as:

$$\begin{aligned} H_{\lambda}^V(q^2) &\propto (C_9 - C'_9) \tilde{V}_{\lambda}(q^2) + \frac{2m_b m_B}{q^2} (C_7 - C'_7) \tilde{T}_{\lambda}(q^2) - 16\pi^2 \frac{m_B^2}{q^2} \tilde{h}_{\lambda}(q^2) \\ H_{\lambda}^A(q^2) &\propto (C_{10} - C'_{10}) \tilde{V}_{\lambda}(q^2) \\ H^S(q^2) &\propto \frac{m_b}{m_W} (C_S - C'_S) \tilde{S}(q^2) \\ H^P(q^2) &\propto \frac{m_b}{m_W} (C_P - C'_P) \tilde{S}(q^2) + \frac{2m_{\ell} m_B}{q^2} (C_{10} - C'_{10}) \left(1 + \frac{m_s}{m_b}\right) \tilde{S}(q^2) \end{aligned}$$

polarizations:  $\lambda = 0, \pm$

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

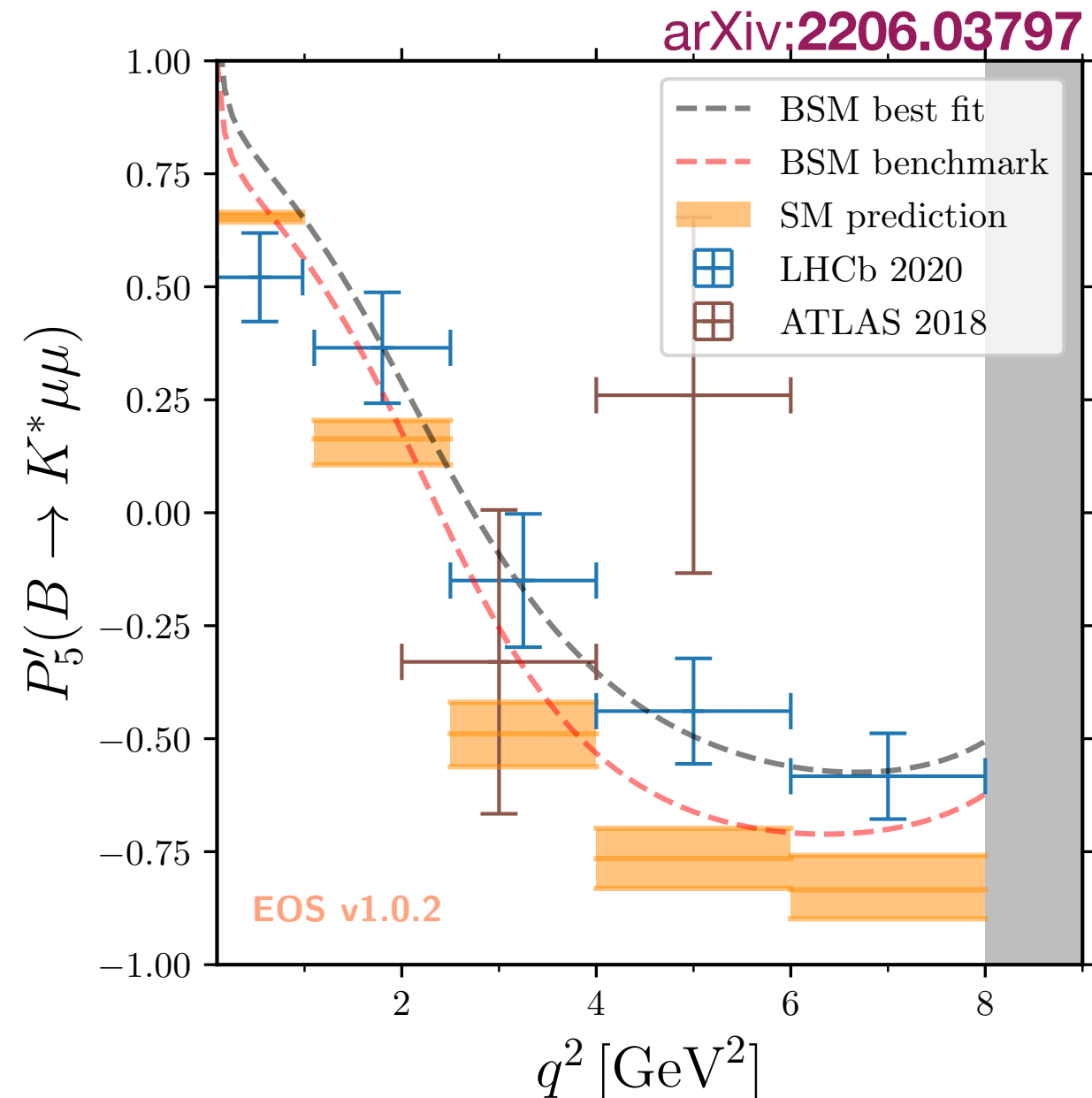
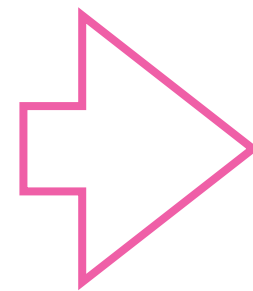
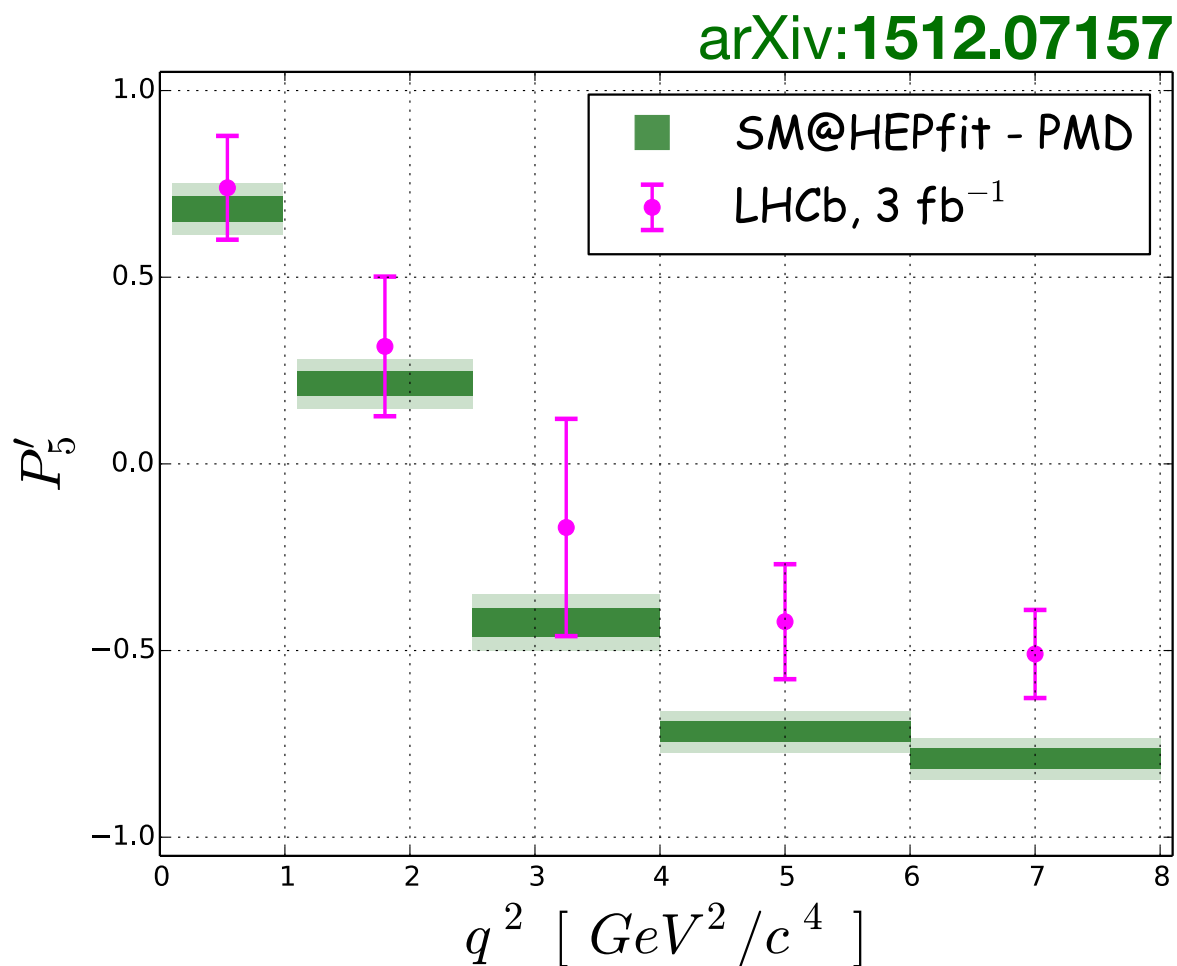
The main sources of uncertainties stem from **form factors** & **long-distance effects** encoded in such hadronic correlators.

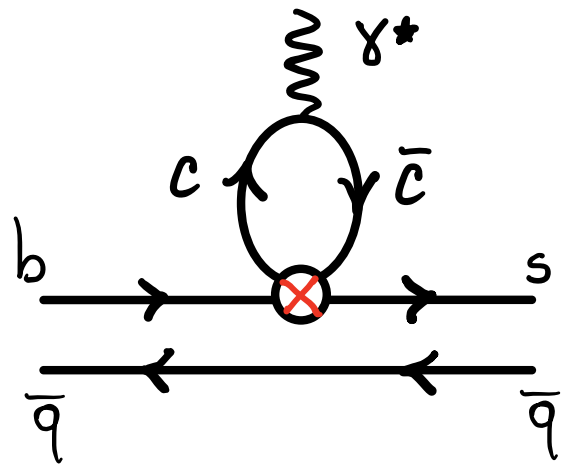


In 2022, non-local effects  
— *charming penguins* —  
have been found to be  
a negligible contribution.  
[ arXiv:2206.03797 ]

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

LHCb likewise, via unbinned likelihood analyses [e.g., arXiv:2312.09115].

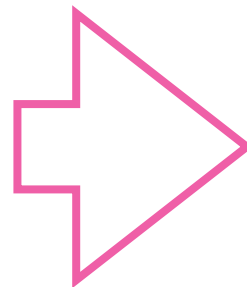




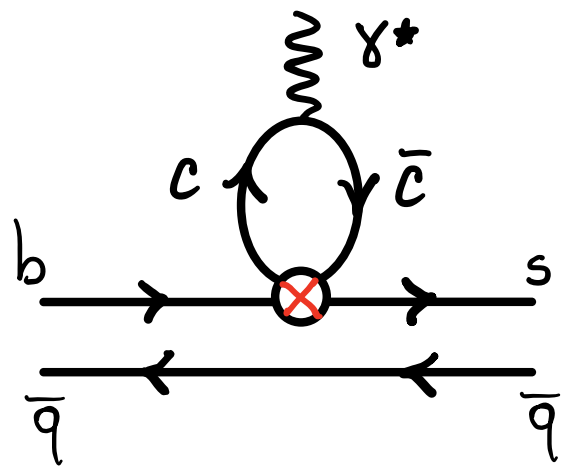
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**P'<sub>5</sub> ANOMALY AGING**



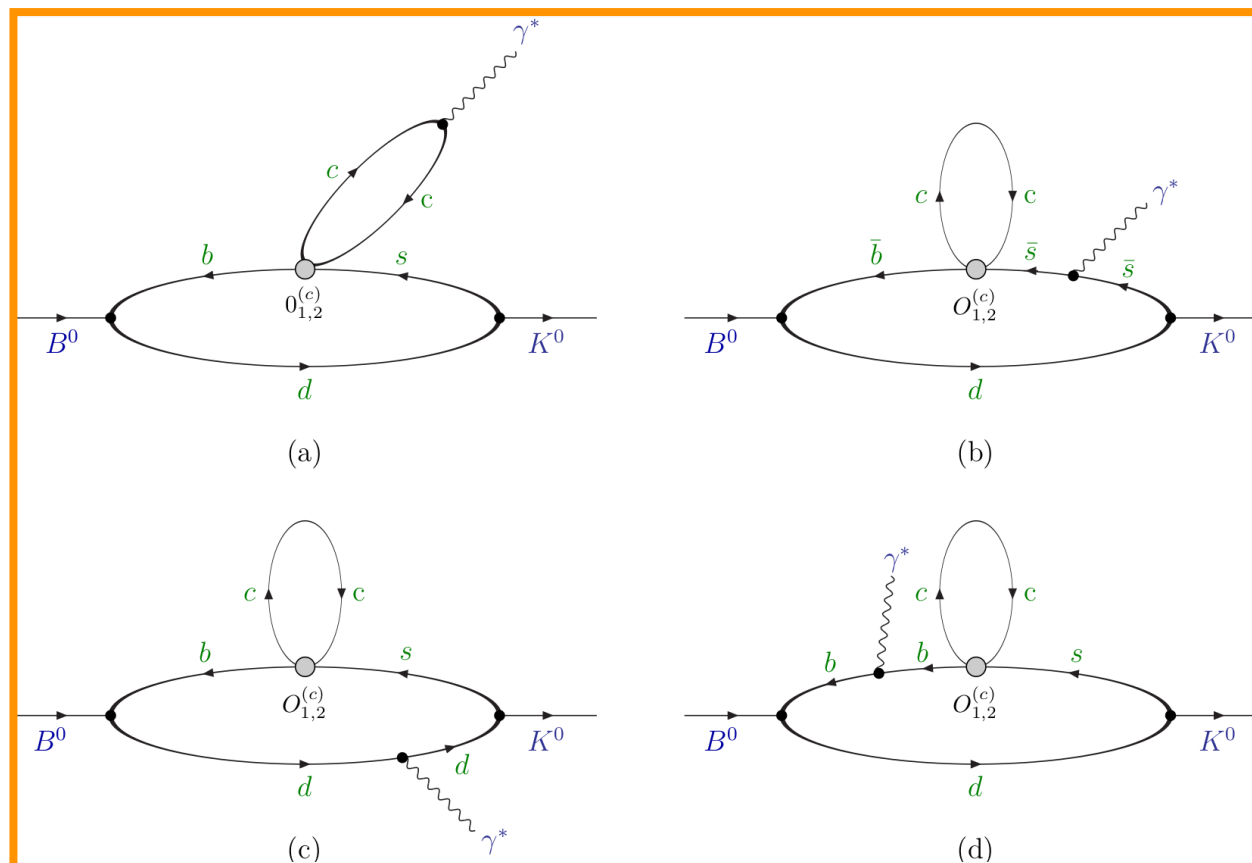
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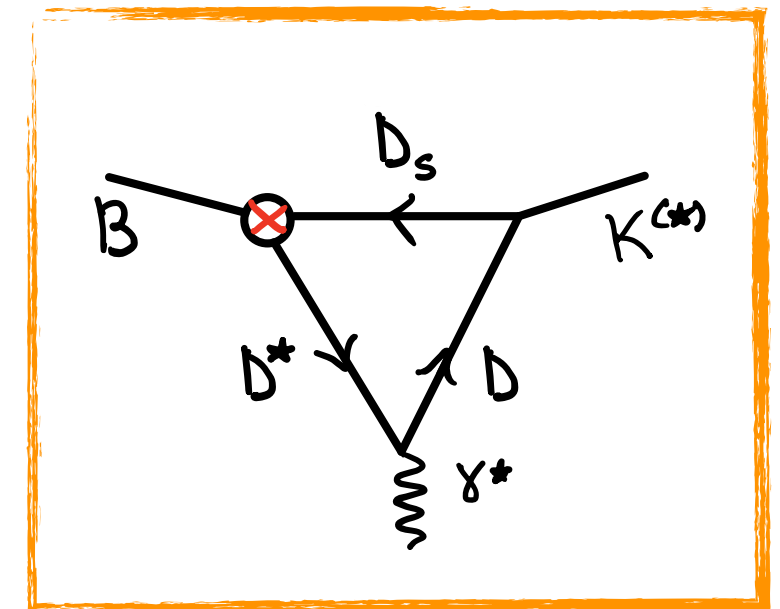
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HADRONIC EFFECTS ABOVE DO NOT CAPTURE ALL THAT IS AT STAKE

arXiv:2508.03655



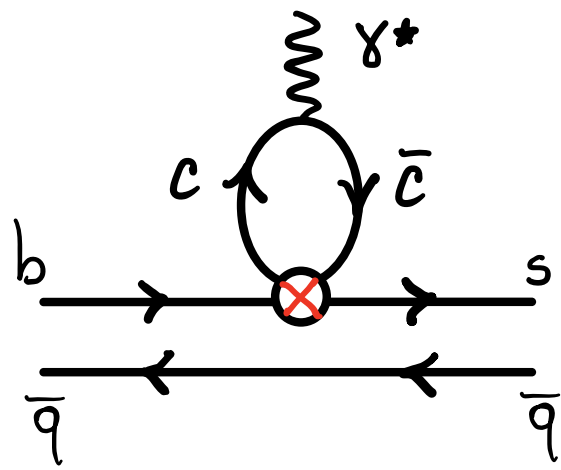
[ arXiv:2212.10516 ]



artist's impression

Rescattering complicates study of these amplitudes by A LOT.





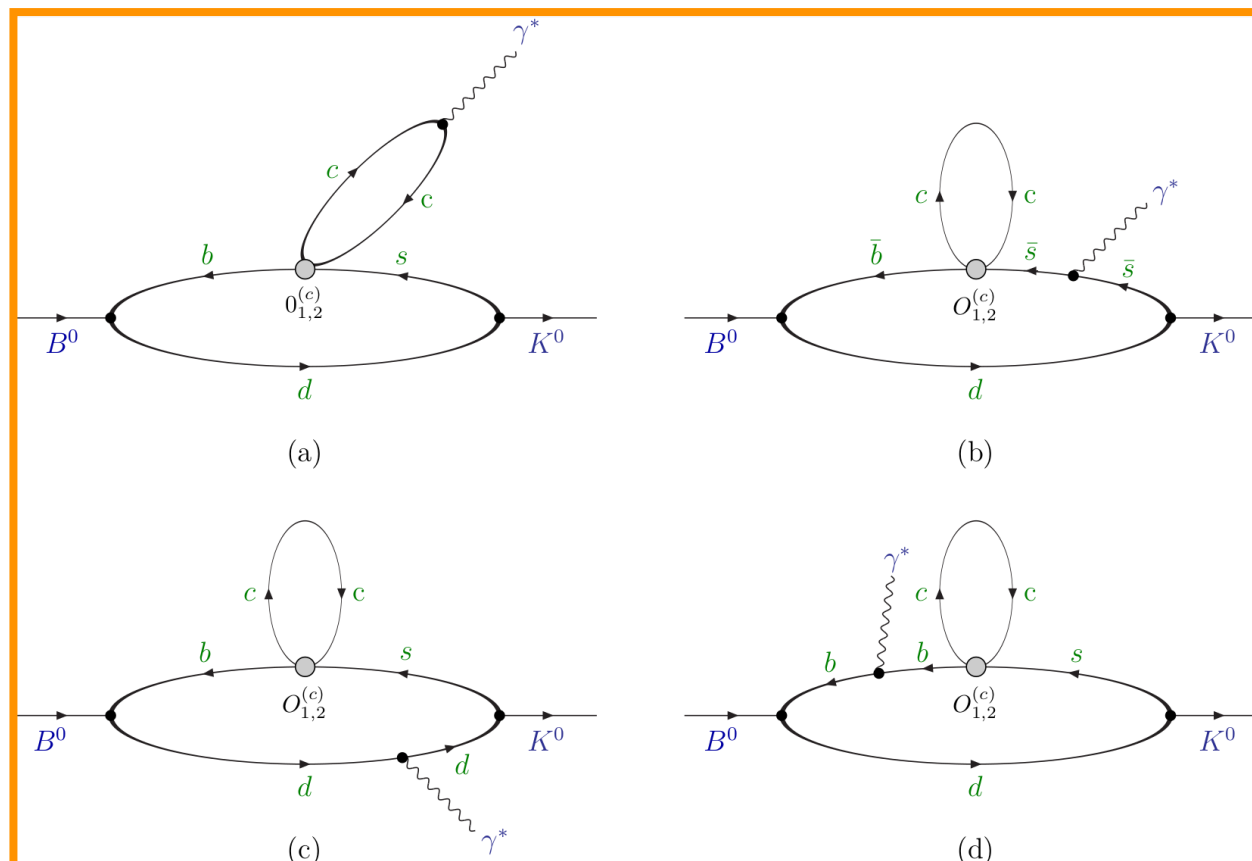
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HADRONIC EFFECTS ABOVE DO NOT CAPTURE ALL THAT IS AT STAKE

arXiv:2508.03655



artist's impression

Rescattering complicates study of these amplitudes by A LOT.

# The Spectral Function Reconstruction

- Lattice QCD provides a first-principles framework for the numerical calculation of correlation functions in Euclidean spacetime
- Analytic continuation from Euclidean to Minkowski problematic for amplitudes containing imaginary parts
- Maiani-Testa no-go theorem: for more than one incoming or outgoing hadron, correlation function always dominated by lowest-lying state

Maiani & Testa, PLB '90

# The Spectral Function Reconstruction

- Hadronic amplitudes with zero or one incoming and outgoing hadron can still develop imaginary parts if intermediate states have energy smaller than external states
- However, the problem of analytic continuation can be solved by writing the hadronic amplitude  $H$  as

$$H(E) = \lim_{\varepsilon \rightarrow 0} \int_{E^*}^{\infty} \frac{dE'}{2\pi} \frac{\rho(E')}{E' - E - i\varepsilon}$$

which is independent of time, and thus equal in Euclidean and Minkowski.

- If  $E^* > E$ , the  $\varepsilon \rightarrow 0$  limit is trivial; if  $E^* < E$ , the limit is highly nontrivial and can only be taken at the end of the calculation

# The Spectral Function Reconstruction

- Using SFR techniques, expect remarkable progress in the next few years in (in order of increasing difficulty):
  - inclusive semileptonic decays Gambino et al '22; De Santis et al '25; Kellermann et al '26
  - $CP$ -conserving  $D-\bar{D}$  mixing Di Carlo, Erben & Hansen '25
  - $CP$  violation in  $D-\bar{D}$  mixing
  - charming penguins in  $B \rightarrow K(^*) l^+ l^-$  decays Frezzotti et al '25
  - potentially any other channel with no more than one hadron in the initial and final state
  - New ideas on coping with more than one hadron in the final state are being put forward Patella & Tantalò '24

# $b \rightarrow s \ell \ell$ : A DATA DRIVEN APPROACH

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

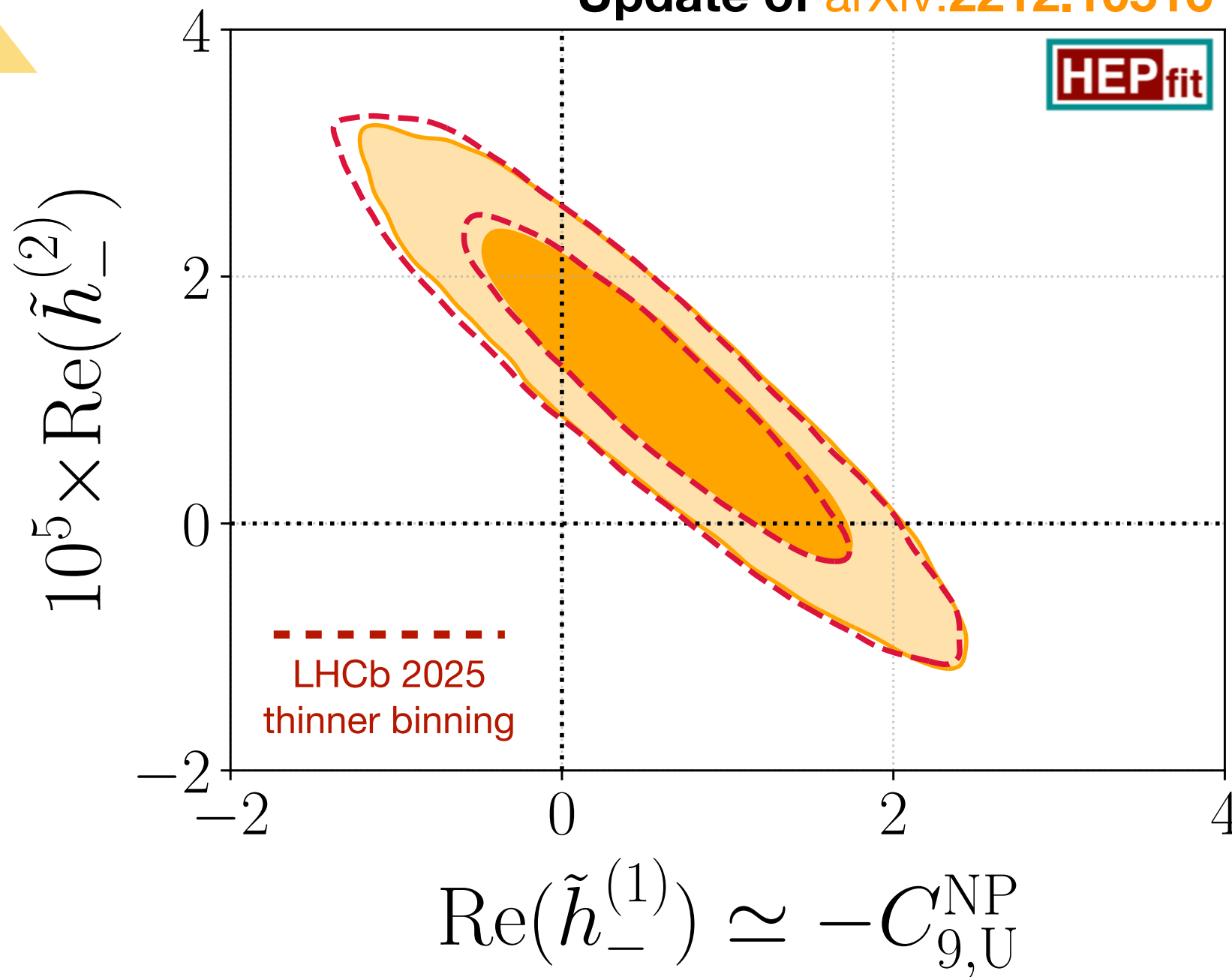
Taylor-expand hadronic correlators  
 $h_\lambda(q^2)$  and fit coefficients to data.

$$\begin{aligned} H_V^- &\propto \left\{ (C_9^{\text{SM}} + \tilde{h}_-^{(1)}) \widetilde{V}_{L-} + \frac{m_B^2}{q^2} \left[ \frac{2m_b}{m_B} (C_7^{\text{SM}} + \tilde{h}_-^{(0)}) \widetilde{T}_{L-} - 16\pi^2 h_-^{(2)} q^4 \right] \right\} \\ H_V^+ &\propto \left\{ (C_9^{\text{SM}} + \tilde{h}_-^{(1)}) \widetilde{V}_{L+} + \frac{m_B^2}{q^2} \left[ \frac{2m_b}{m_B} (C_7^{\text{SM}} + \tilde{h}_-^{(0)}) \widetilde{T}_{L+} - 16\pi^2 (h_+^{(0)} + h_+^{(1)} q^2 + h_+^{(2)} q^4) \right] \right\} \\ H_V^0 &\propto \left\{ (C_9^{\text{SM}} + \tilde{h}_-^{(1)}) \widetilde{V}_{L0} + \frac{m_B^2}{q^2} \left[ \frac{2m_b}{m_B} (C_7^{\text{SM}} + \tilde{h}_-^{(0)}) \widetilde{T}_{L0} - 16\pi^2 \sqrt{q^2} (h_0^{(0)} + h_0^{(1)} q^2) \right] \right\} \end{aligned}$$

$$\tilde{h}_-^{(1)} \longleftrightarrow \text{Lepton Flavor Universal } C_{9,U}^{\text{NP}}$$

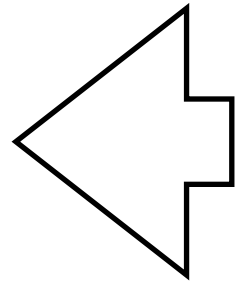
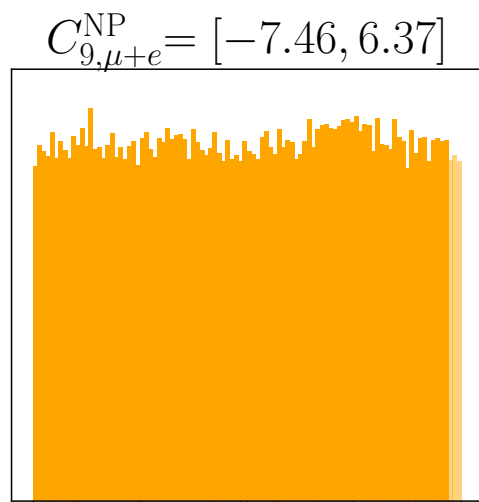
# $b \rightarrow s \ell \ell$ : WHERE WE ARE NOW

Update of [arXiv:2212.10516](#)

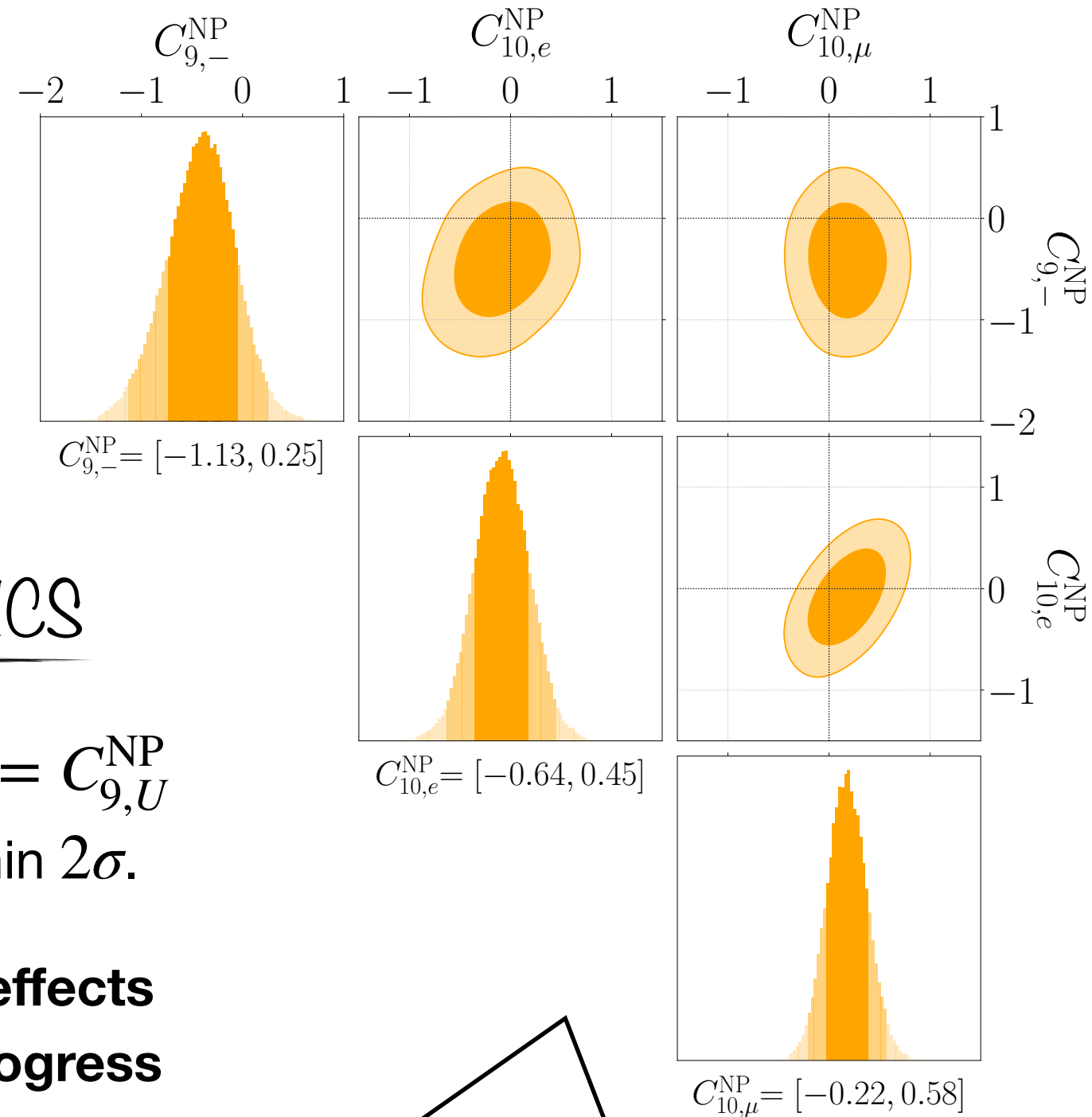


QCD ONLY

QCD ~ LEPTON UNIVERSAL NP



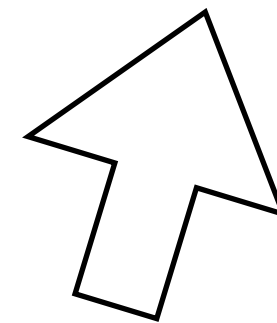
completely  
degenerate w/  
QCD effects



## NO EVIDENCE X NEW PHYSICS

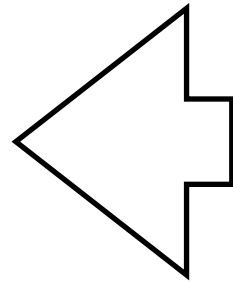
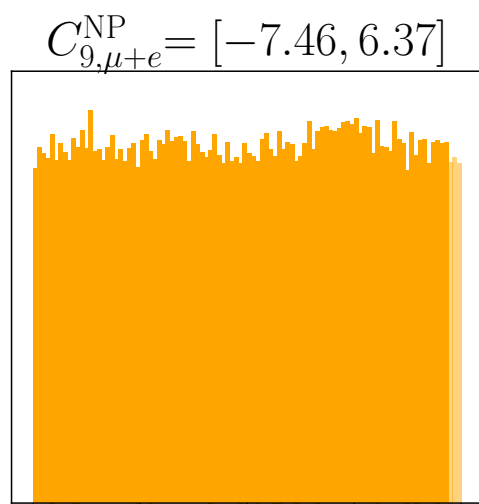
•  $C_{9,\mu-e}^{\text{NP}}$  probes direction  $\perp$  to  $C_{9,\mu+e}^{\text{NP}} = C_{9,U}^{\text{NP}}$   
 $\rightarrow$  LFU in the fit respected well within  $2\sigma$ .

• To possibly disentangle genuine NP effects  
 in  $C_{9,U}^{\text{NP}}$  one needs some solid TH progress

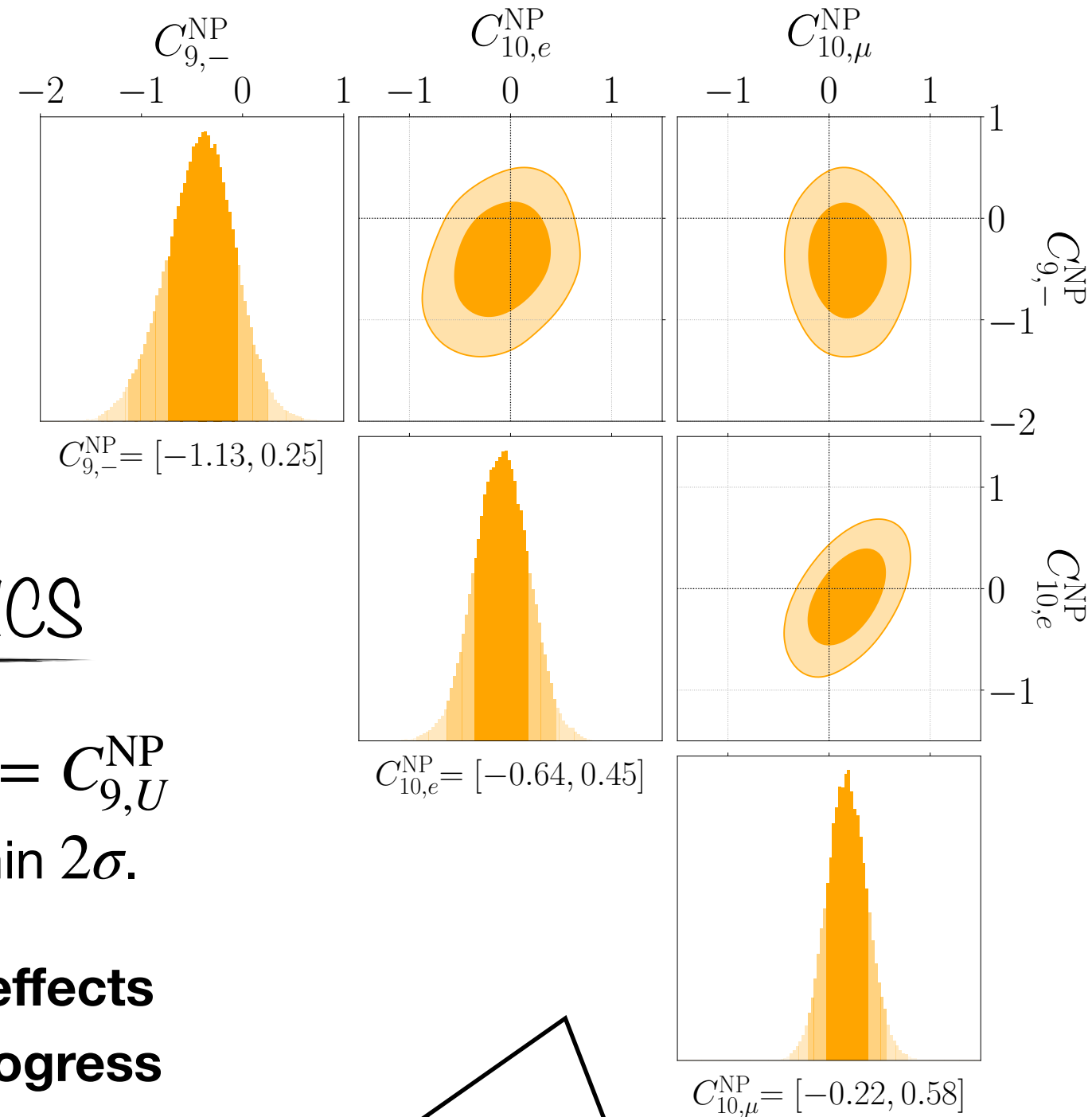


NP contributions very well compatible w/  
SM limit, in particular no significant LFUV





completely  
degenerate w/  
QCD effects



## NO EVIDENCE X NEW PHYSICS

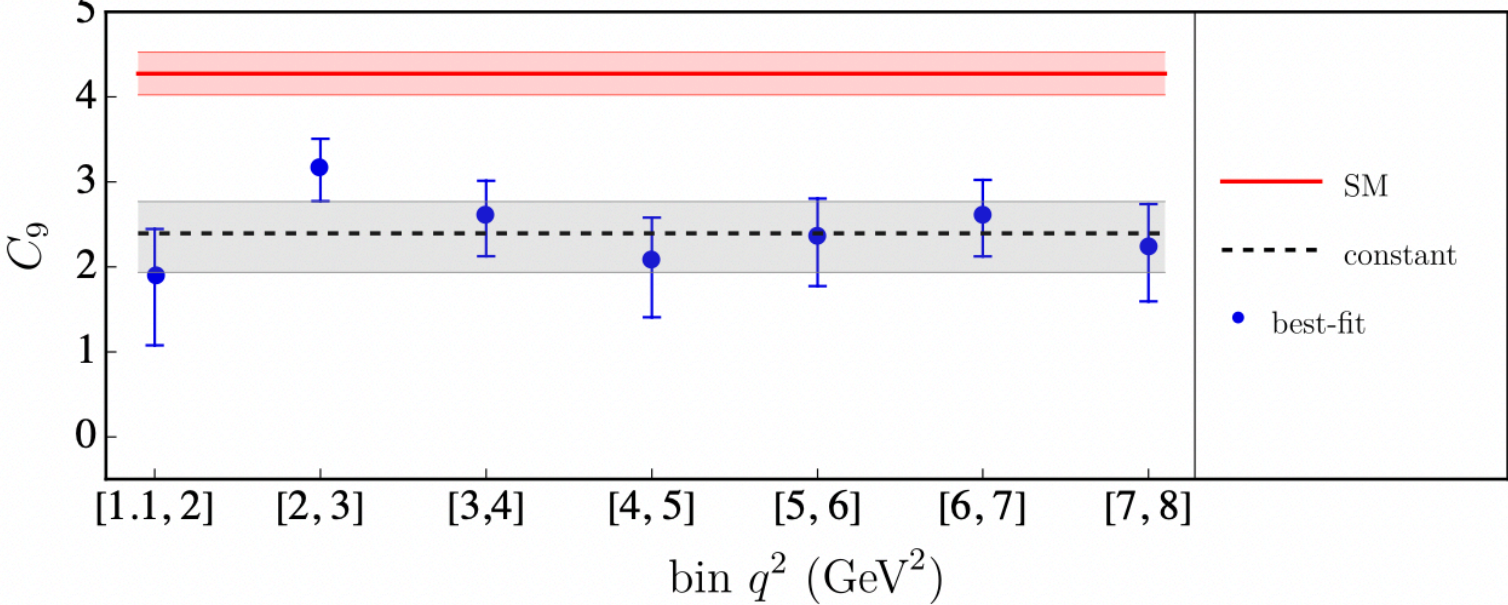
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 $\rightarrow$  LFU in the fit respected well within  $2\sigma$ .

• To possibly disentangle genuine NP effects  
 in  $C_{9,U}^{\text{NP}}$  one needs some solid TH progress

... however, one may  
 want to learn more from  
 current data, given the  
 wealth of EXP info ...

NP contributions very well compatible w/  
 SM limit, in particular no significant LFUV

Charming penguins  
 $\simeq c\bar{c}$  resonances



arXiv:2401.18007

More precisely, this shift includes:

Extracting resonance parameters with inputs from data by LHCb (1612.06764, 2405.17347)

$$C_9 \rightarrow C_9 + Y^\lambda(q^2)$$

$\lambda = K, \perp, //, 0$

$$C_9 \rightarrow C_9^\lambda(q^2) + Y_{q\bar{q}}^{[0]}(q^2) + Y_{b\bar{b}}^{[0]}(q^2) + Y_{c\bar{c}}^\lambda(q^2)$$

encodes (factorizable) **perturbative** contributions from 4-quark operators

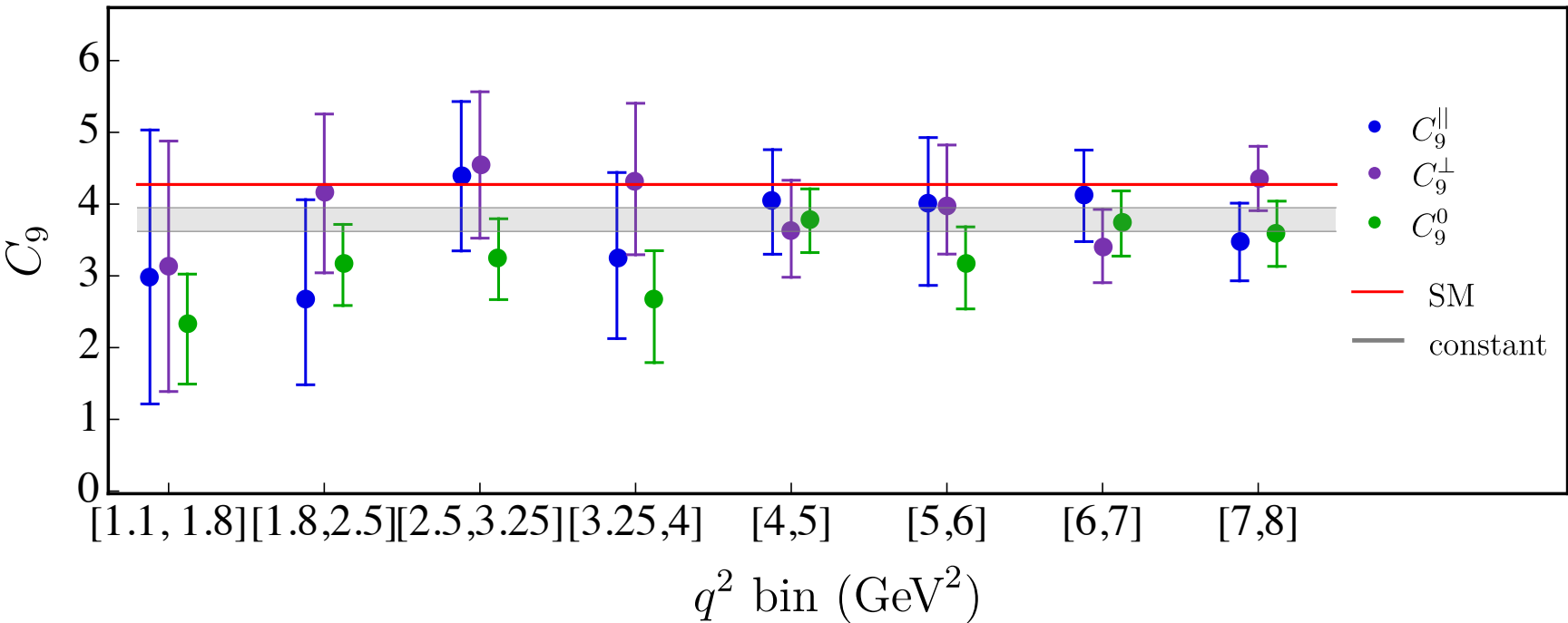
encodes the **perturbative** charm-loop contributions and  **$c\bar{c}$  resonances**

Dispersive relations:

$$Y_{c\bar{c}}^\lambda(q^2) = Y_{c\bar{c}}^\lambda(q_0^2) + \frac{16\pi^2}{\mathcal{F}_\lambda(q^2)} \Delta \mathcal{H}_{c\bar{c}}^\lambda(q^2), \quad q_0^2 = 0$$

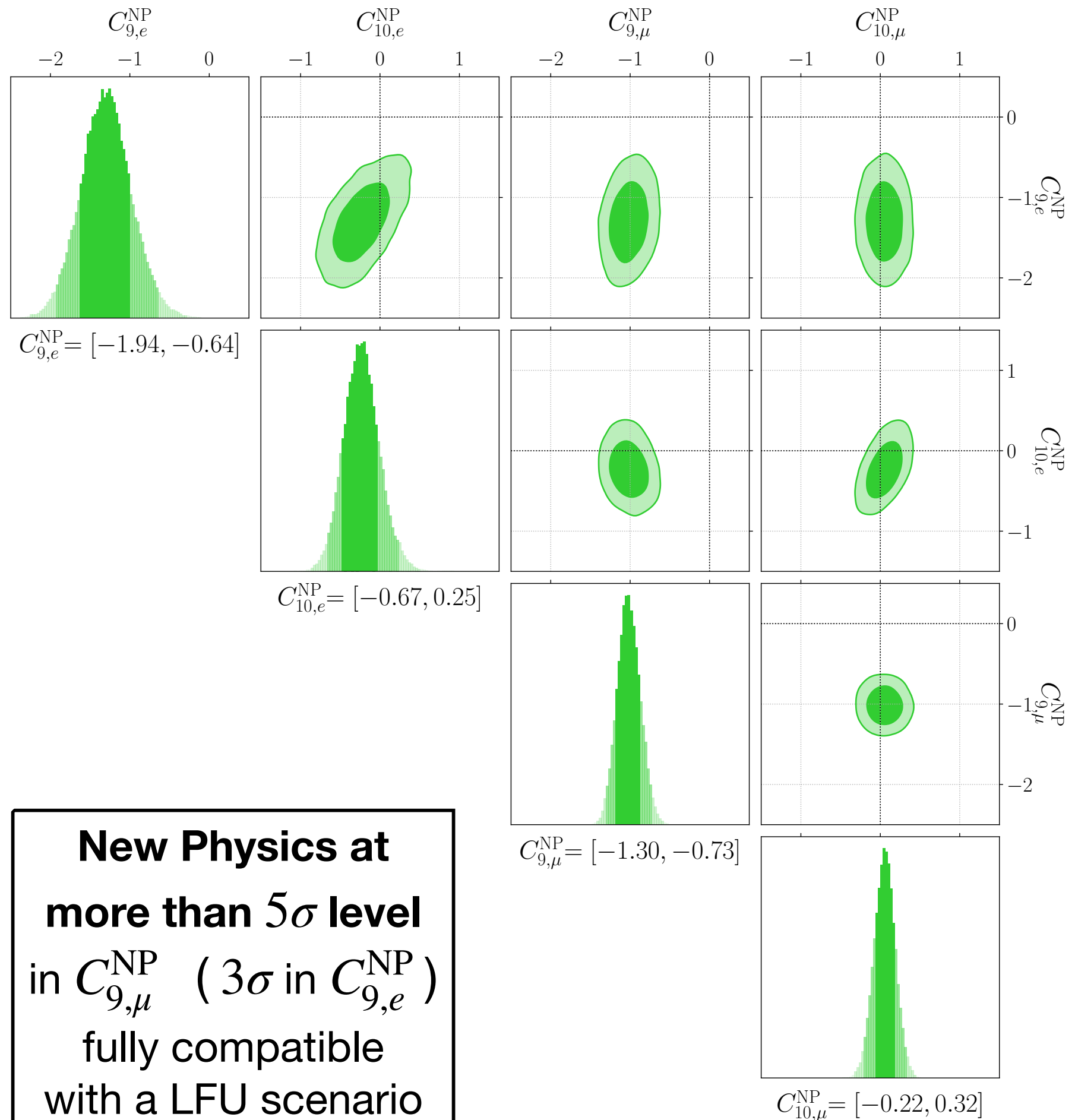
$$\Delta \mathcal{H}_{c\bar{c}}^{\lambda, 1P} = \sum_V \eta_V^\lambda e^{i\delta_V^\lambda} \frac{q^2}{m_V^2} A_V^{\text{res}}(q^2)$$

$$A_V^{\text{res}}(q^2) = \frac{m_V \Gamma_V}{m_V^2 - q^2 - im_V \Gamma_V}$$



arXiv:2607.09458

WHAT IF  
CHARMING  
PENGUINS  
WERE ALL  
SMALL?



**New Physics at  
more than  $5\sigma$  level  
in  $C_{9,\mu}^{\text{NP}}$  ( $3\sigma$  in  $C_{9,e}^{\text{NP}}$ )  
fully compatible  
with a LFU scenario**

???

# 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

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

$$f(w) = \frac{1}{\underbrace{\phi_f(z) B_f(z)}_{\text{Kinematical function} * B\text{-factors for resonances}}} \sum_{i=0}^{\infty} \underbrace{a_i^f}_{\text{Real parameters to be determined}} z^i$$

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

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

- inner product

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

- auxiliary function

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

$$z(t) = \frac{\sqrt{\frac{t_+ - t}{t_+ - t_-}} - 1}{\sqrt{\frac{t_+ - t}{t_+ - t_-}} + 1}$$

$$t_{\pm} \equiv (m_B \pm m_D)^2$$

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

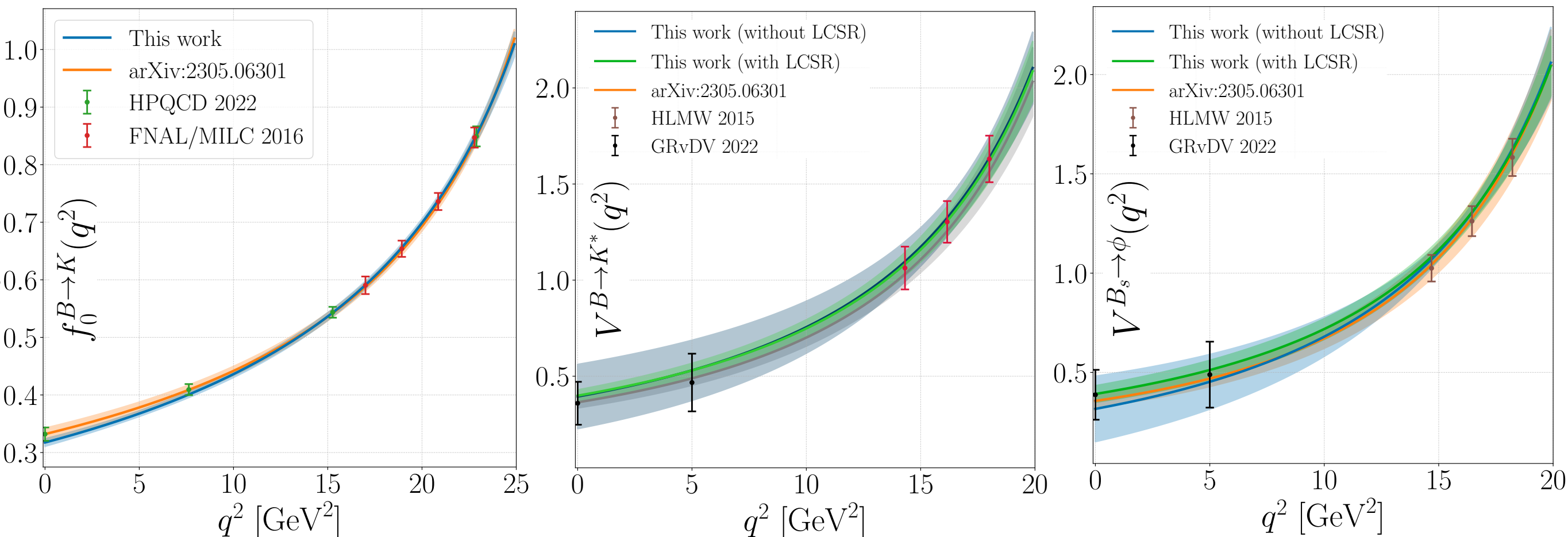
$$\det \mathbf{M} \geq 0 \quad \Rightarrow \quad f_{\text{lo}}(z) \leq f(z) \leq f_{\text{up}}(z)$$

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

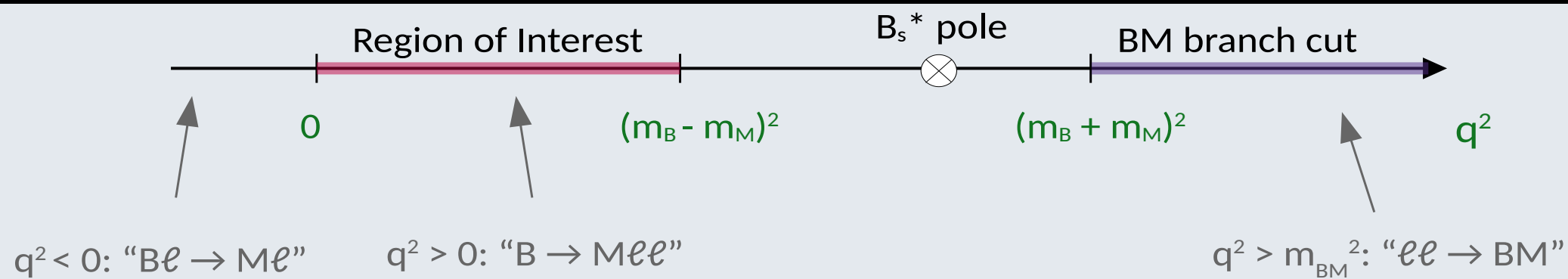
ANALYTICITY + UNITARITY

# FORM FACTORS FOR $B \rightarrow V(P) \ell^+ \ell^-$

arXiv:2607.03531

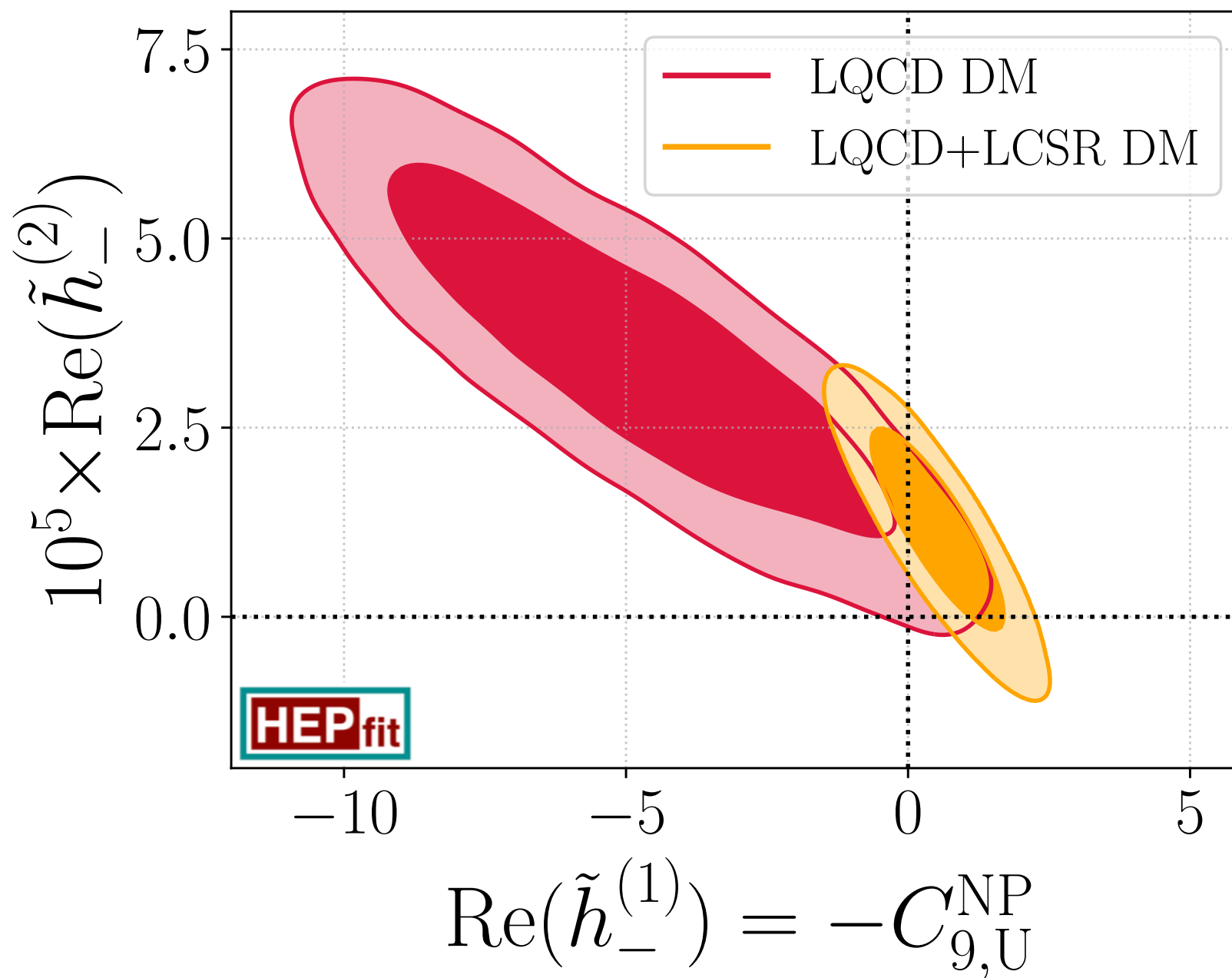


- **QCD Light-Cone Sum Rules (LCSR)** —> available @  $q^2 \ll 1$ , not first-principle
- **Lattice QCD** —> typically reliable @ high  $q^2$  with  $\sim$  stable mesons (...  $K^*$  vector?)



# $b \rightarrow s \ell \ell$ : WERE WE DRIVEN BY LCSR?

[arXiv:2607.03531](https://arxiv.org/abs/2607.03531)

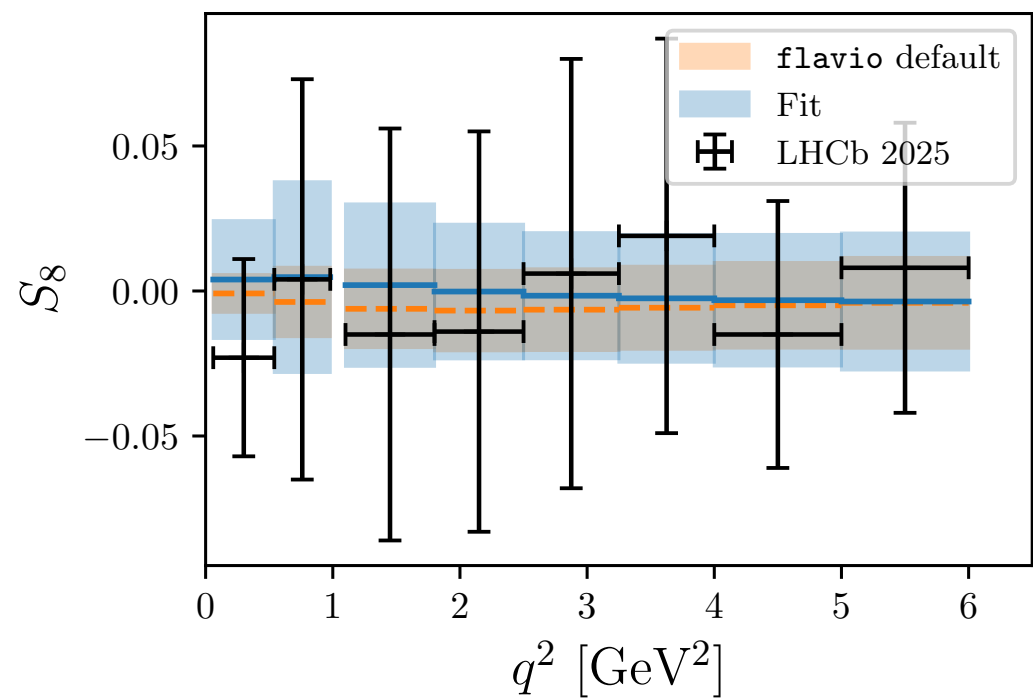
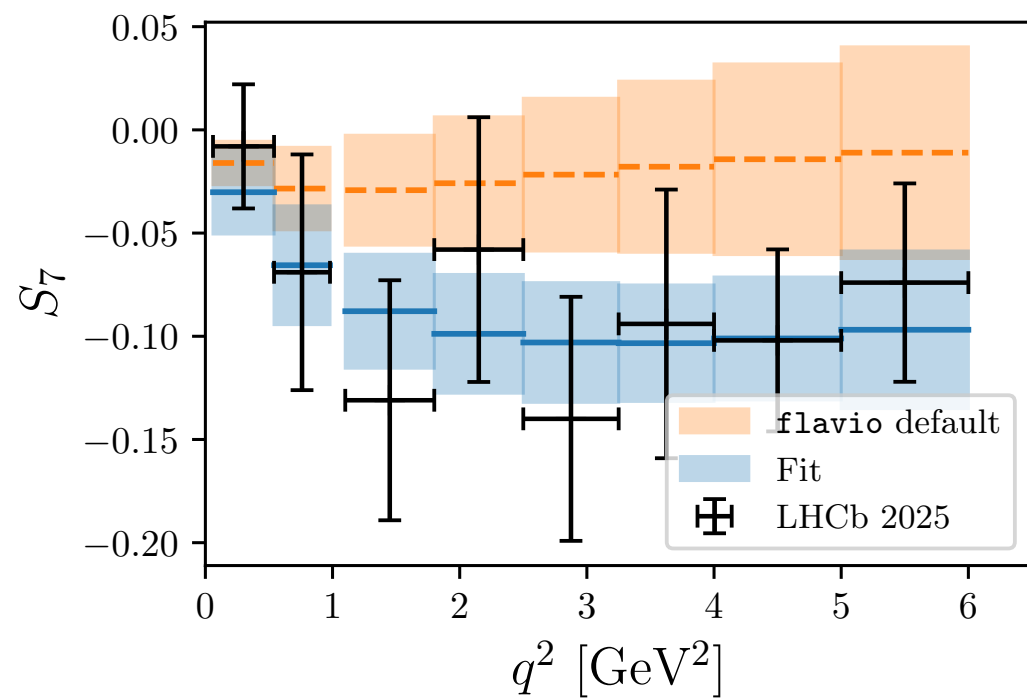
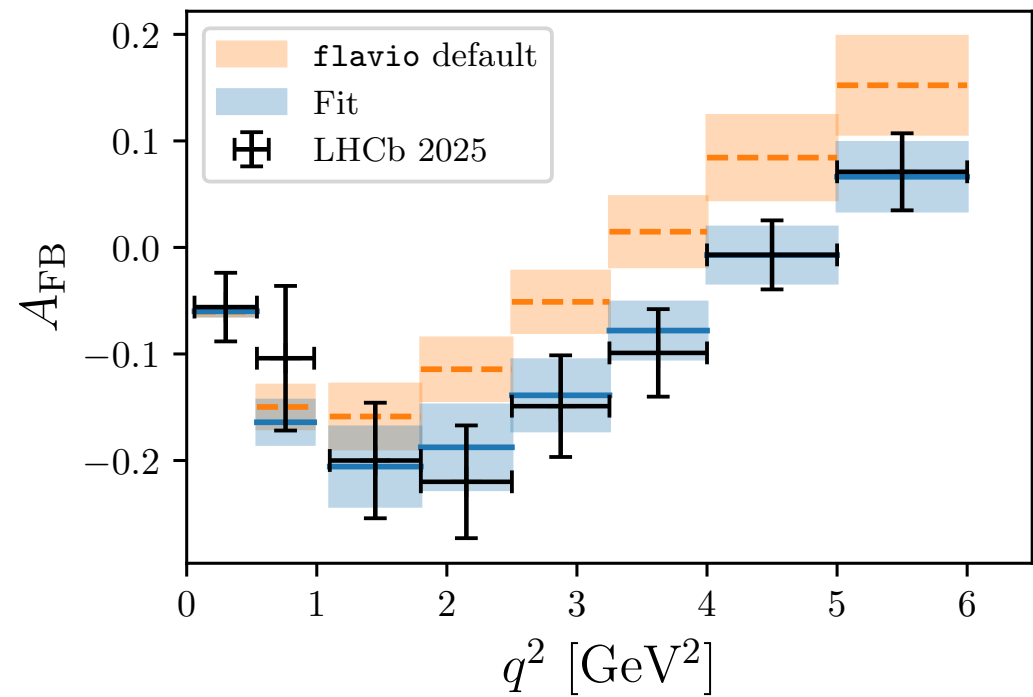
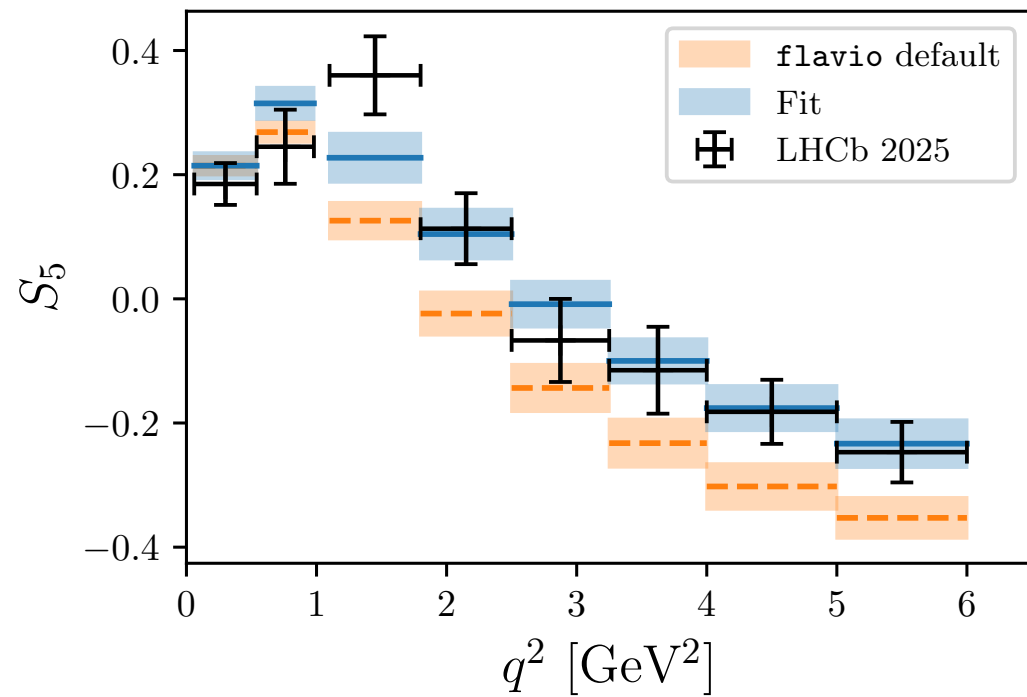


QCD ONLY

QCD ~ LEPTON UNIVERSAL NP



# $b \rightarrow s \ell \ell : S_{7,8} \neq 0 \longleftrightarrow \text{HADRONICS}$



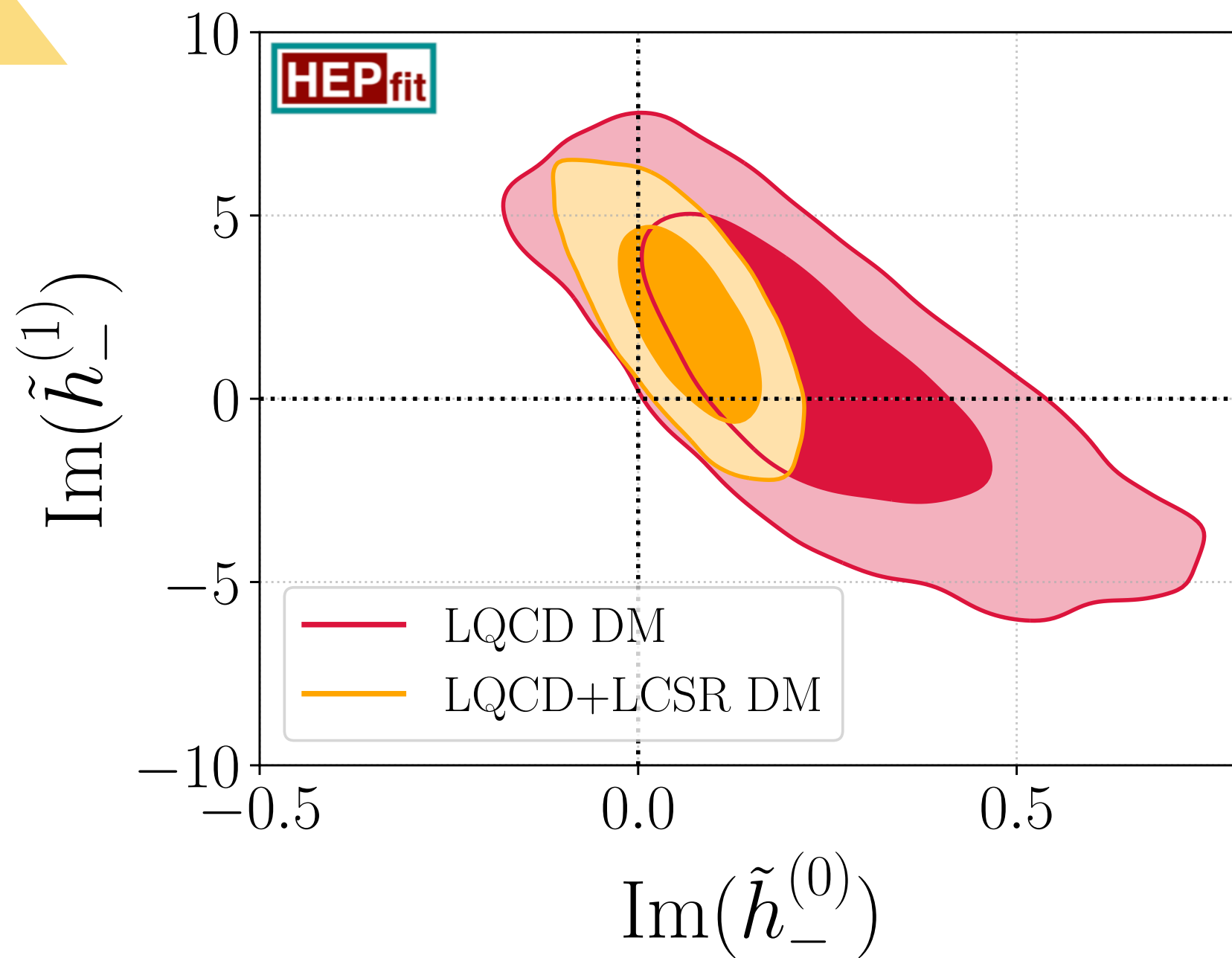
arXiv:**2603.27753**

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



# $b \rightarrow s \ell \ell$ : HINT FOR STRONG PHASES

[arXiv:2607.03531](https://arxiv.org/abs/2607.03531)



QCD ONLY

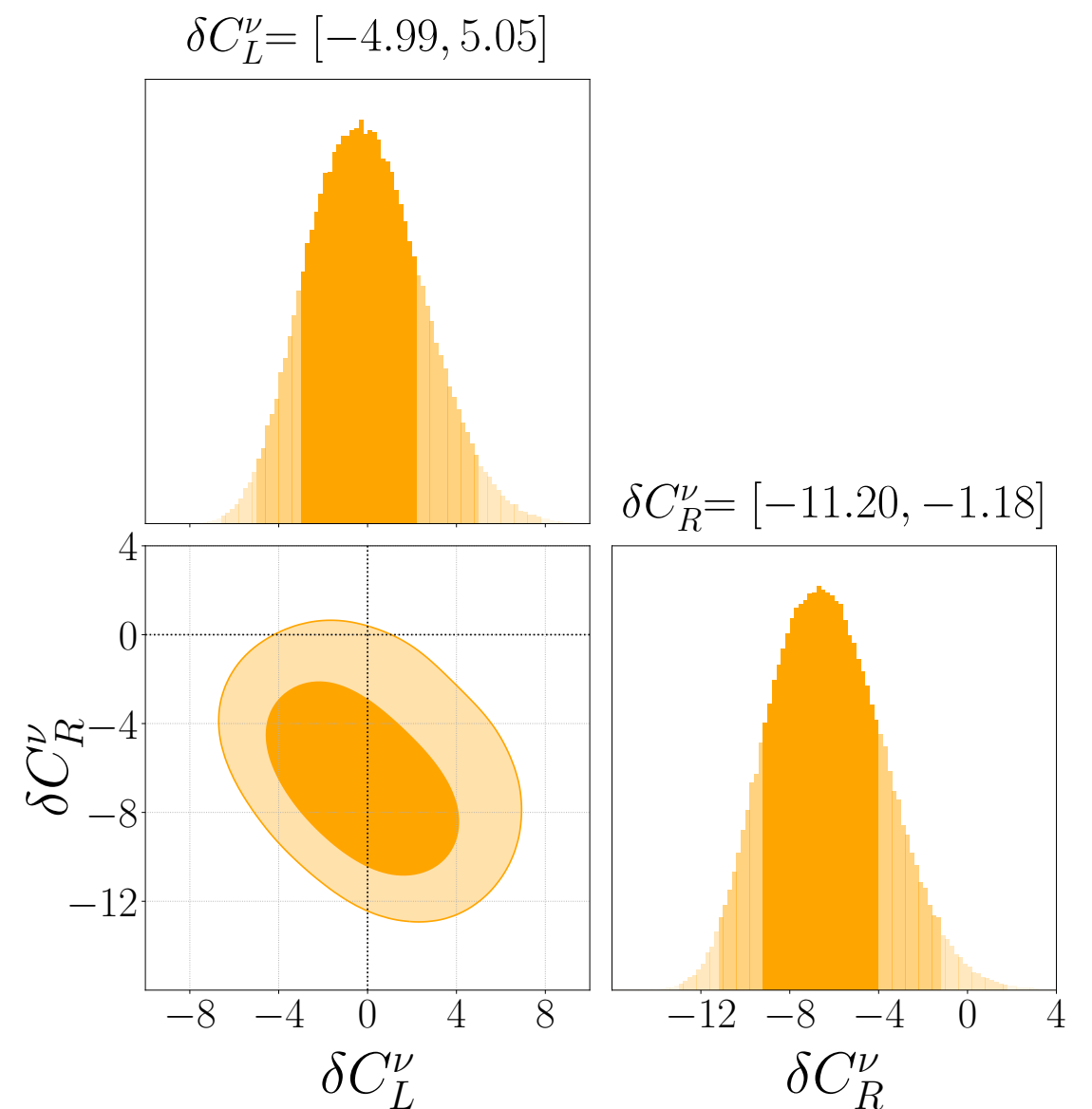
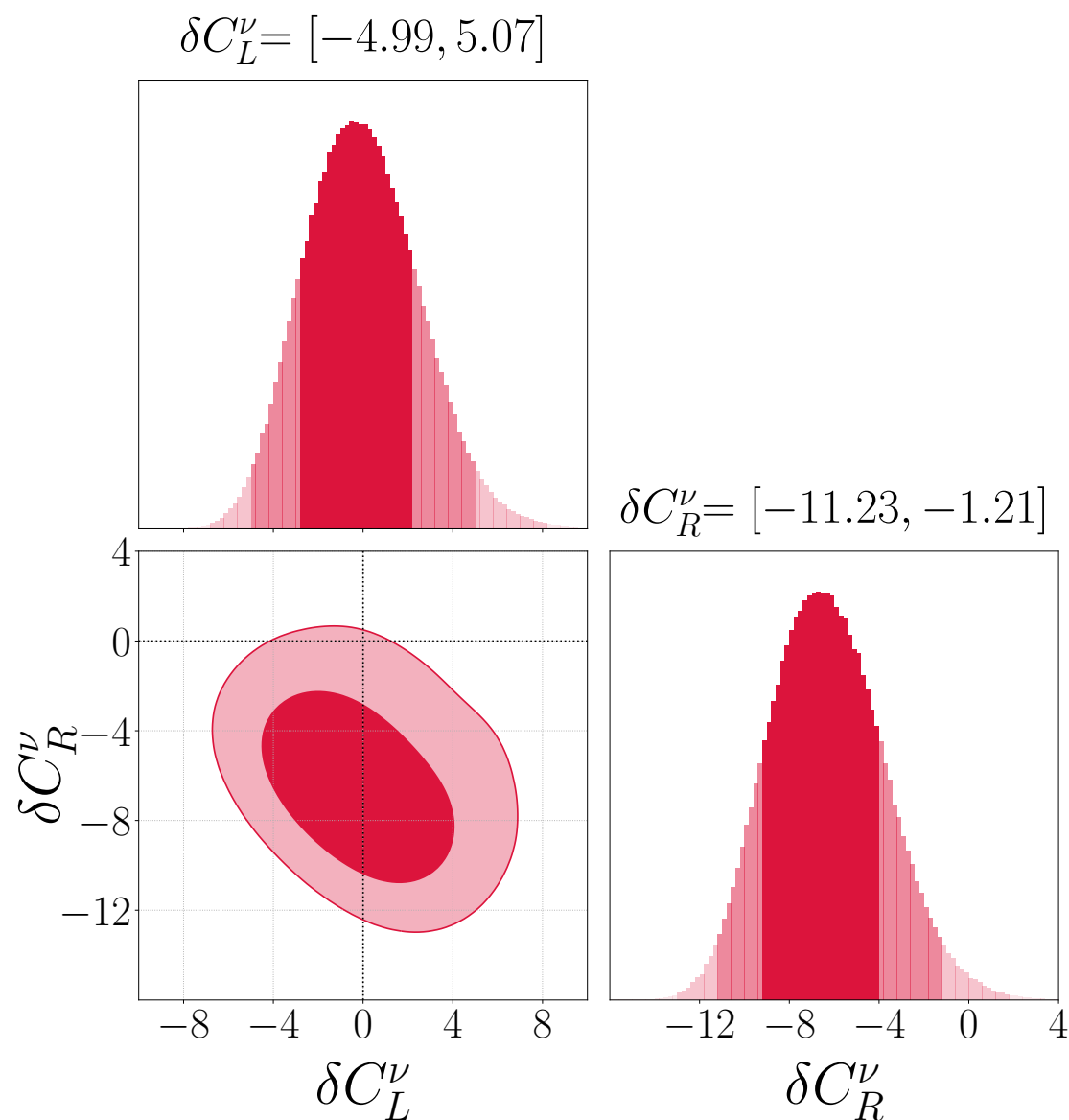
QCD ONLY

# $b \rightarrow s \nu \bar{\nu}$ : WHAT ABOUT LCSR THERE?

arXiv:2607.03531

| Channel                                | $\mathcal{B}$ w/ LQCD DM FFs     | $\mathcal{B}$ w/ LQCD+LCSR DM FFs |
|----------------------------------------|----------------------------------|-----------------------------------|
| $B^+ \rightarrow K^+ \nu \bar{\nu}$    | $(3.95 \pm 0.14) \times 10^{-6}$ | $(3.95 \pm 0.14) \times 10^{-6}$  |
| $B^0 \rightarrow K^0 \nu \bar{\nu}$    | $(3.71 \pm 0.13) \times 10^{-6}$ | $(3.71 \pm 0.13) \times 10^{-6}$  |
| $B^+ \rightarrow K^{*+} \nu \bar{\nu}$ | $(9.9 \pm 1.8) \times 10^{-6}$   | $(9.5 \pm 0.8) \times 10^{-6}$    |
| $B^0 \rightarrow K^{*0} \nu \bar{\nu}$ | $(9.3 \pm 1.7) \times 10^{-6}$   | $(8.9 \pm 0.7) \times 10^{-6}$    |

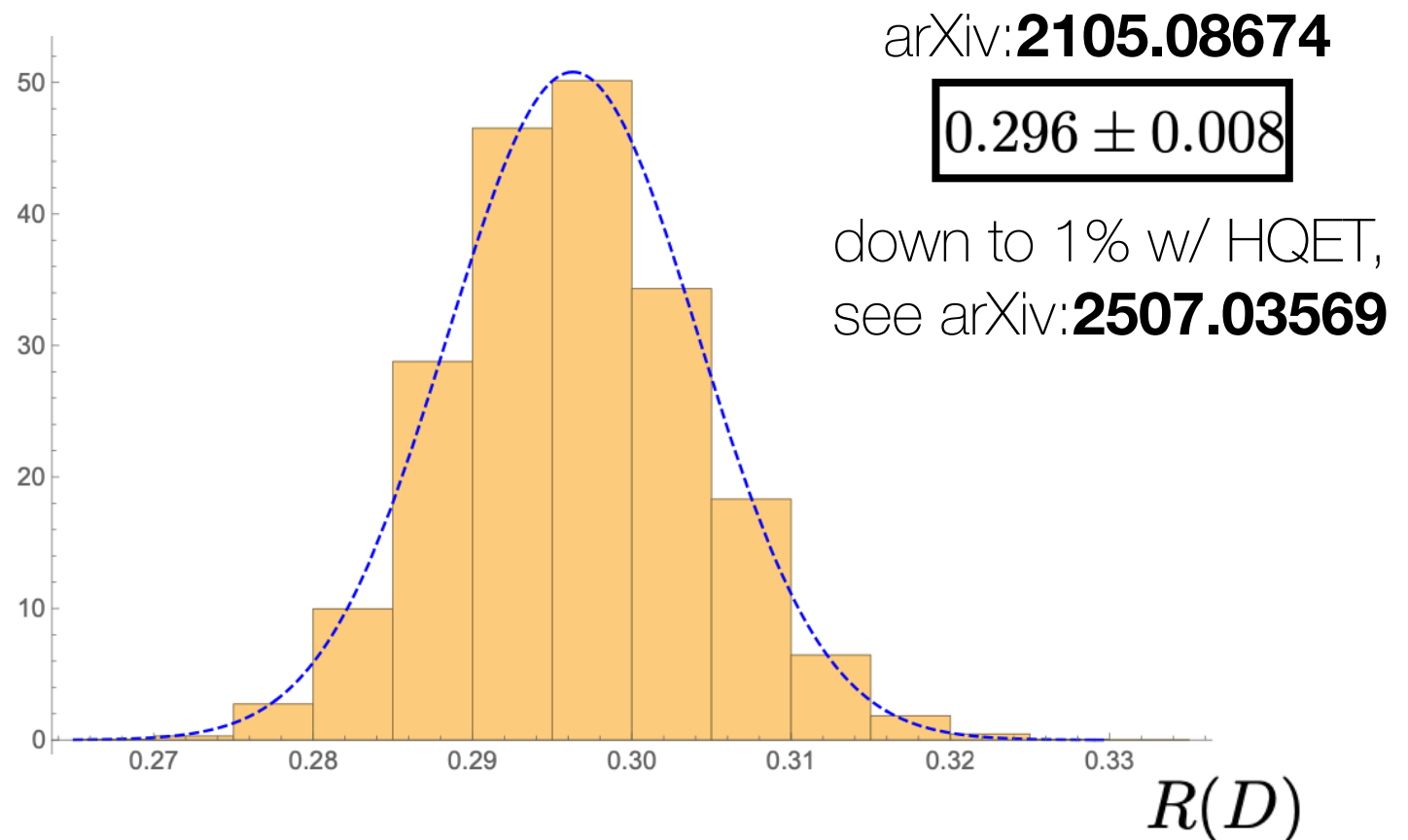
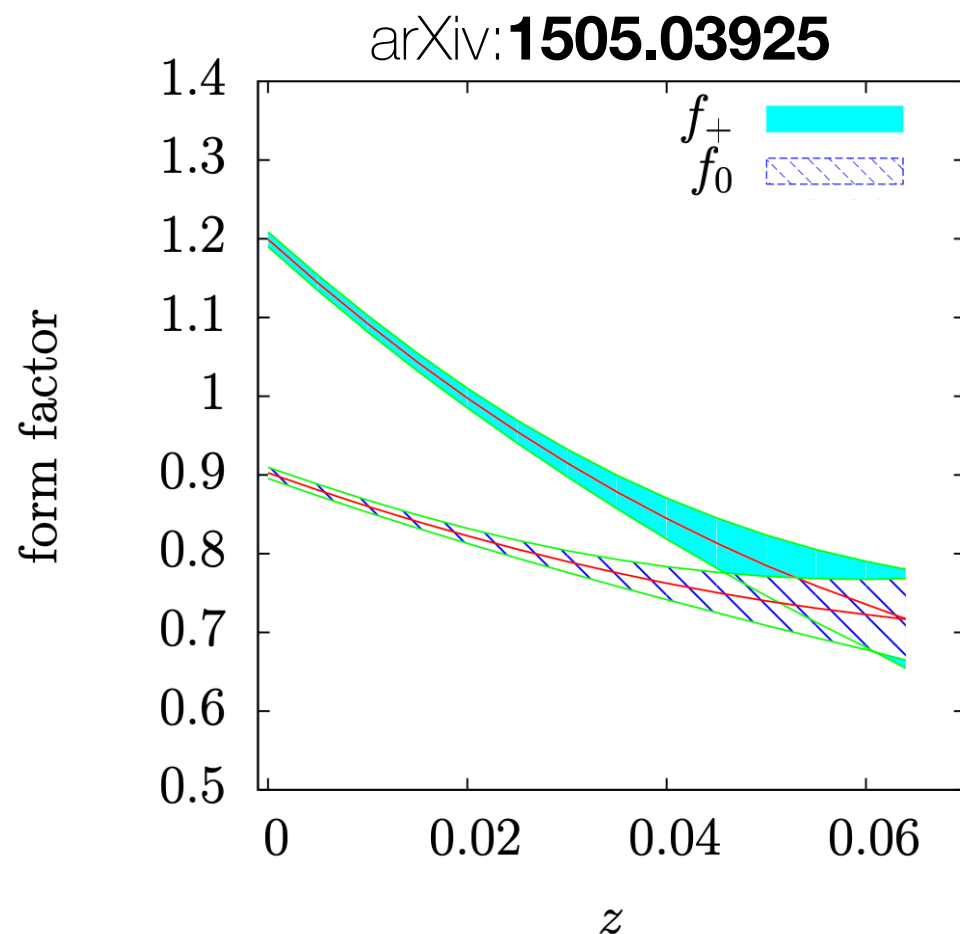
$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5} \quad \mathbf{2.7\sigma \text{ from SM}}$$



# 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.





BFA 2025

[agenda.infn.it/event/44057/](https://agenda.infn.it/event/44057/)

2 APPROACHES  
IN VERY GOOD  
AGREEMENT HERE

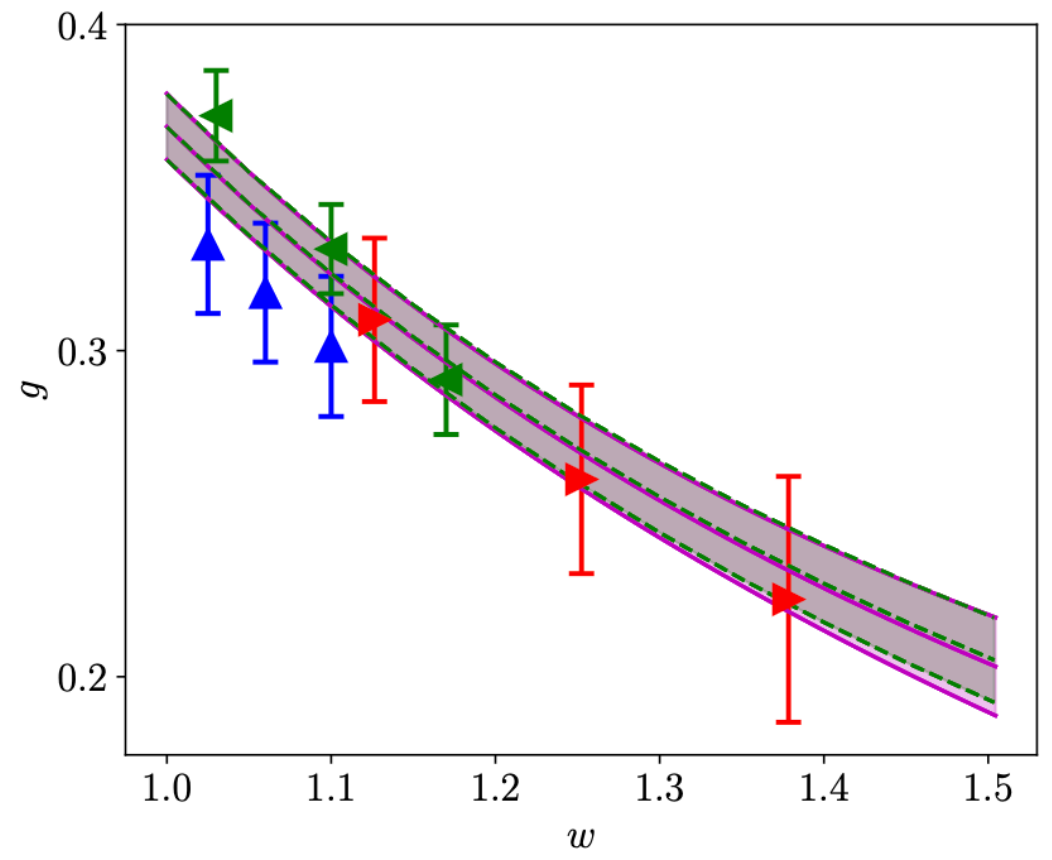
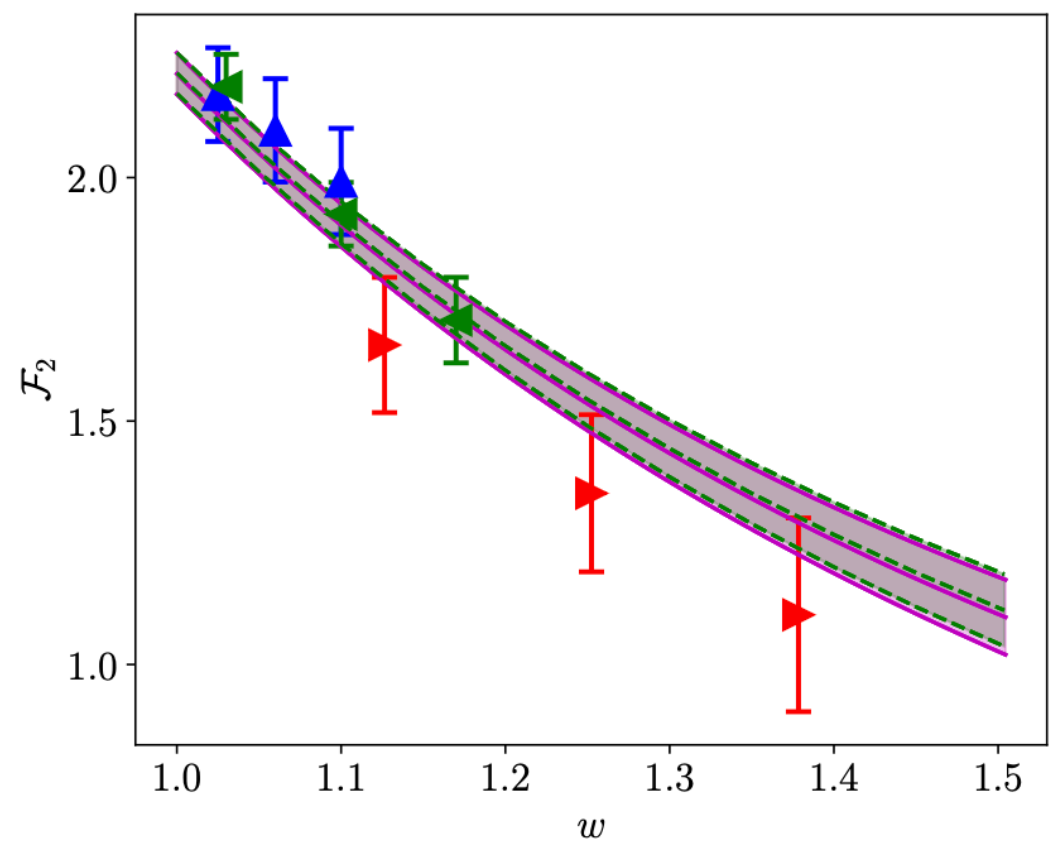
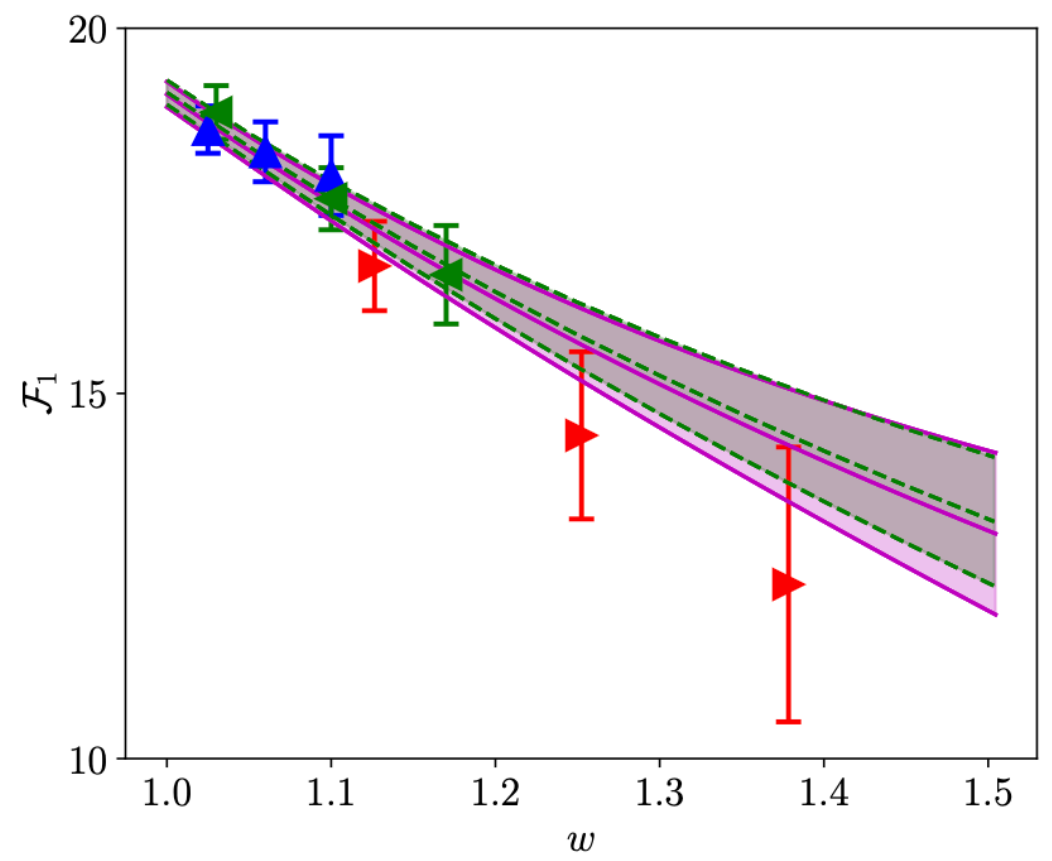
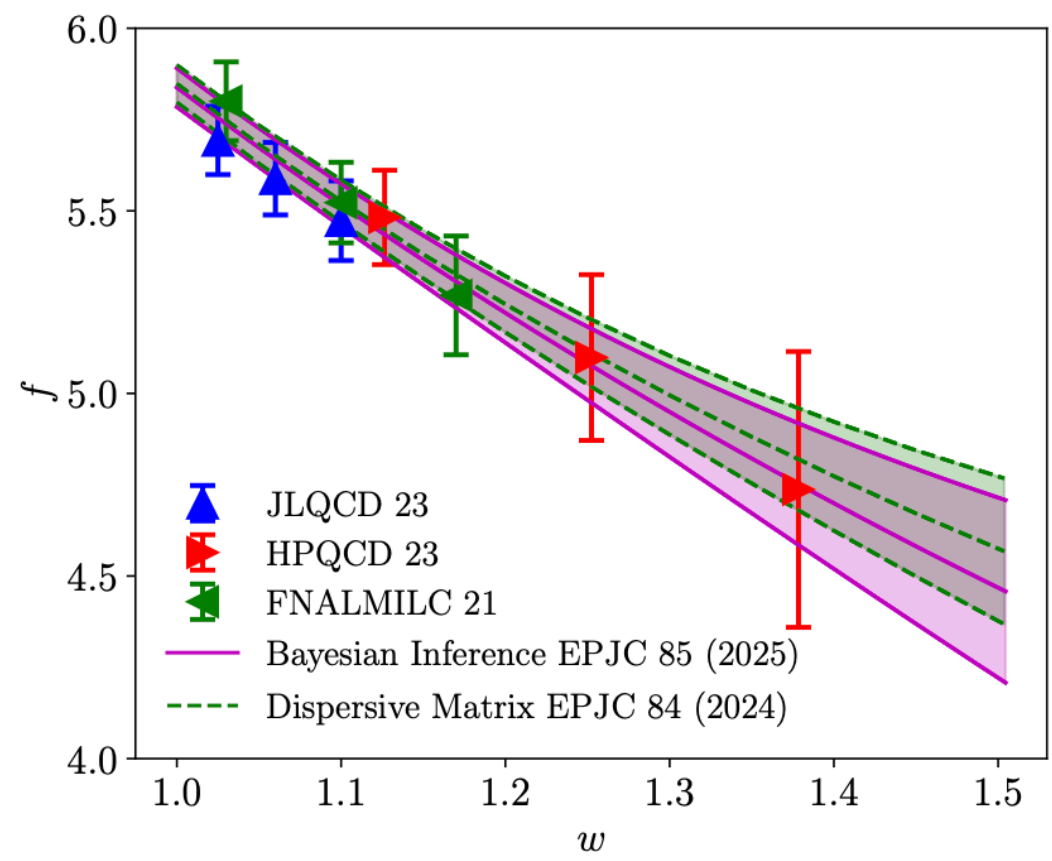
Ludovico Vittorio & Andreas Jüttner



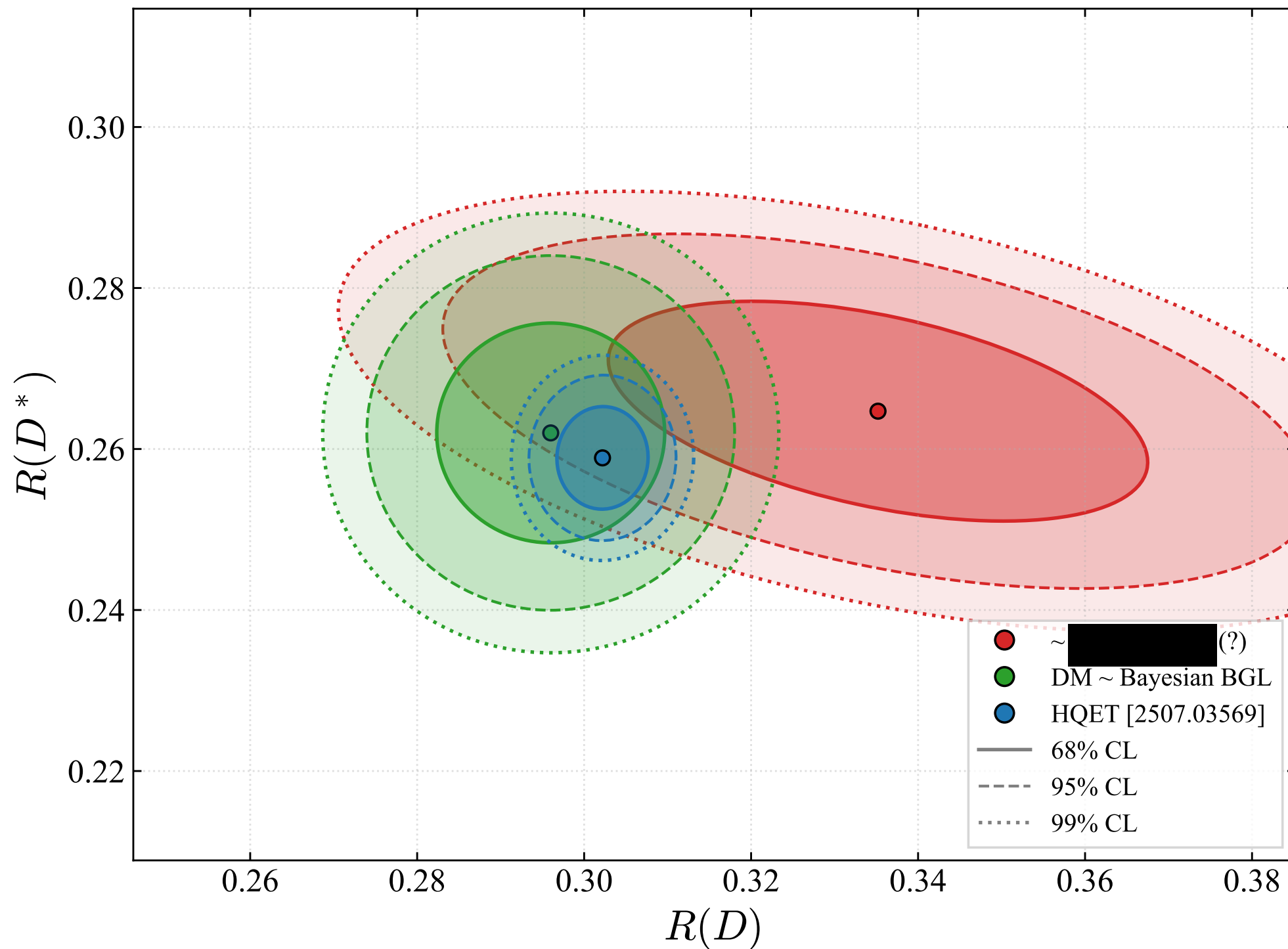
- 1) Filtering analysis of lattice QCD via dispersive matrix method
- 2) Bayesian fit to lattice QCD via BGL params w/ unitarity prior

See also  
**Nico's SOLO CLIMBING:**  
[arXiv:2605.26213](https://arxiv.org/abs/2605.26213)

# $b \rightarrow c l \nu$ : FORM FACTORS FOR $R_{D^*}$

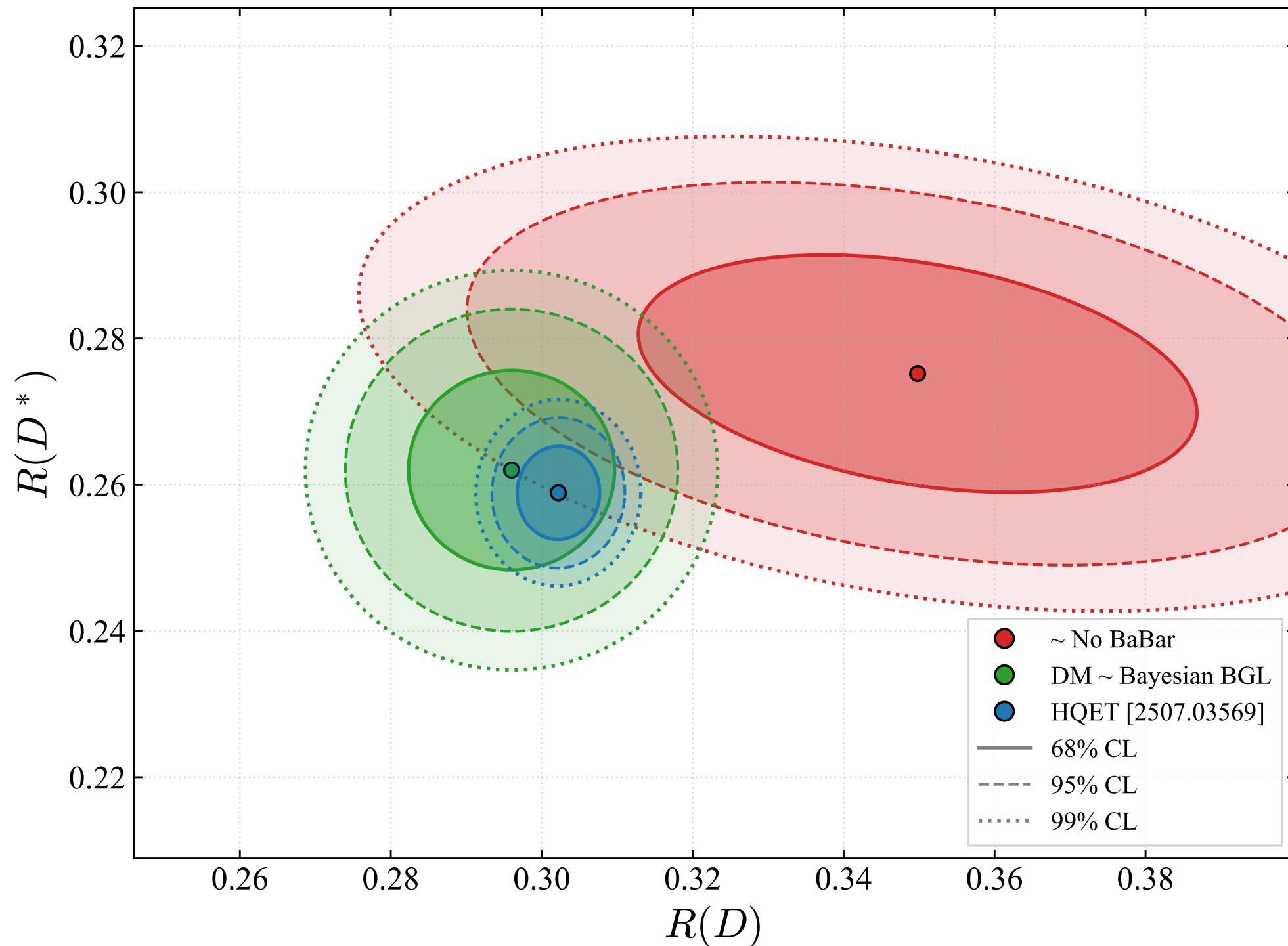


# $b \rightarrow c l \nu$ : NEW SOURCES OF LFU VIOLATION?



**No tension in current LFU tests, not even in  $b \rightarrow c l \nu$ .**

# $b \rightarrow c l \nu$ : NEW SOURCES OF LFU VIOLATION?



**No serious tension arises even when one leaves BaBar out!**

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

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

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

**2)** No 🔥 tension in rare  $B$  decays ... **do we all agree on:**  
*<<Classic QCD hallmarks are now emerging from data>>?*

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

**3) Flavor is a key probe for NP.** If  $R(D)$  &  $R(D^*)$  are “dead” as well, **what motivates flavorful BSM @ few TeV?**