Università di Genova | Dipartimento di Fisica

INFN GENOVA

# From Flavor Bounds to Charming Higgs Discoveries

— 07 / 05 / 2025 —

**MAURO VALLI**

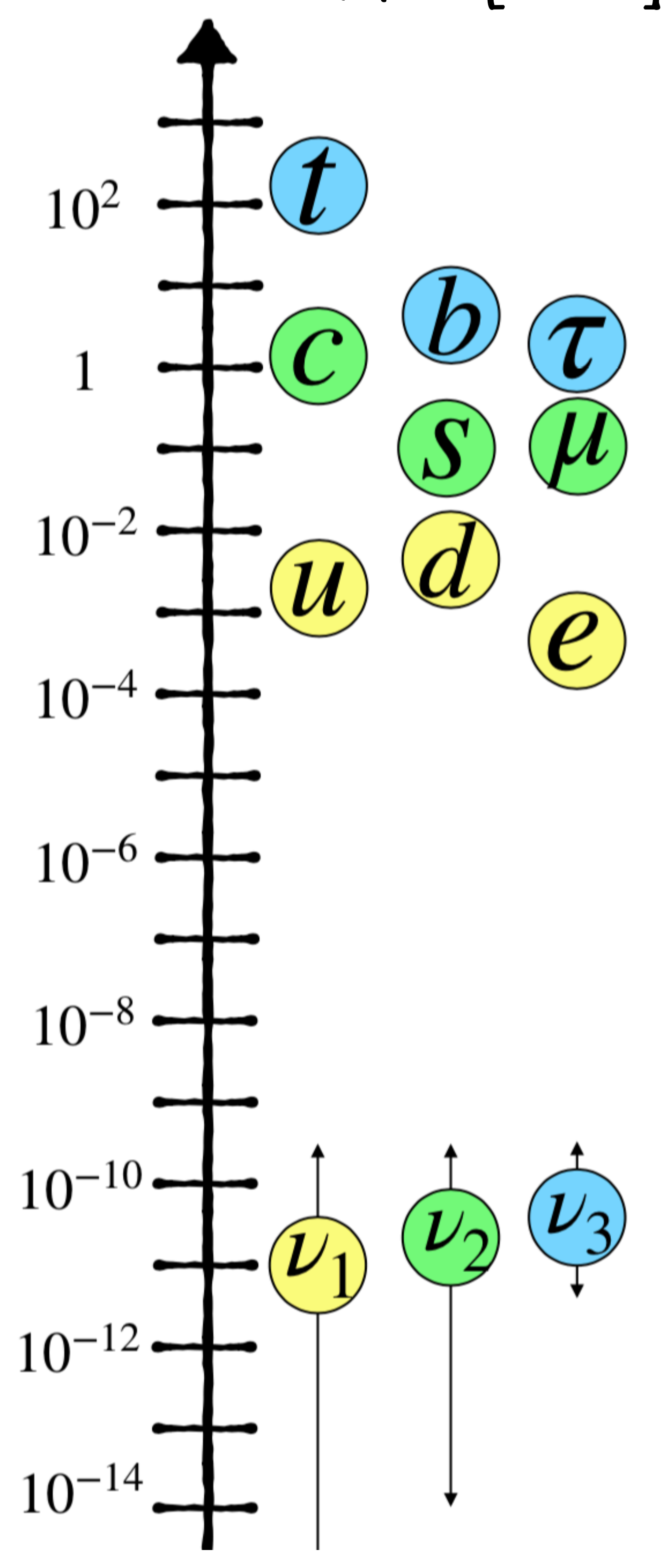
INFN Rome

INFN

**MANY THANKS TO** UTfit Collaboration + A.Giannakopoulou & P.Meade

# The Standard Model

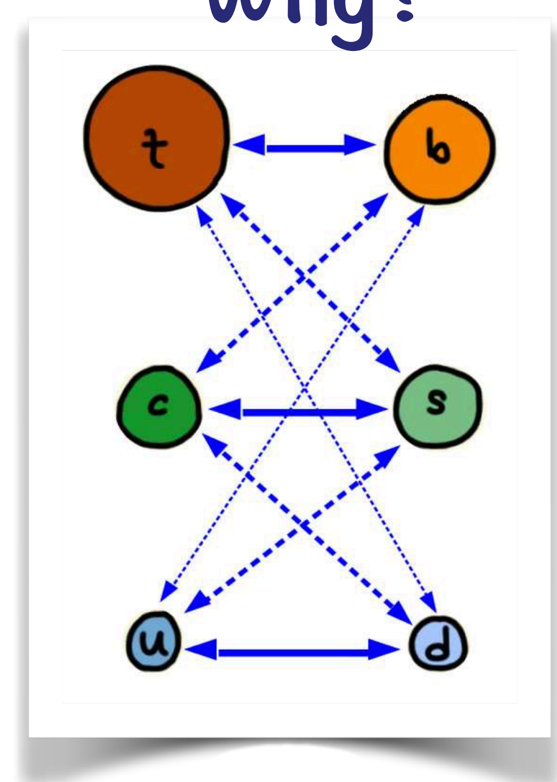
THE SM FLAVOR PUZZLE



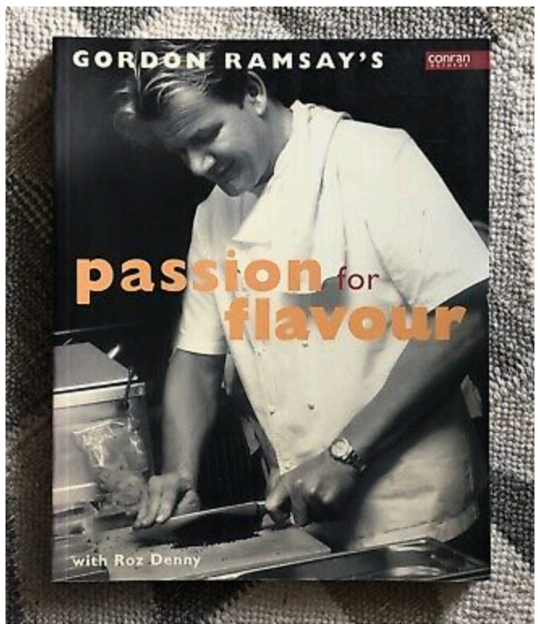

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{matrix} u \\ c \\ t \end{matrix}$$

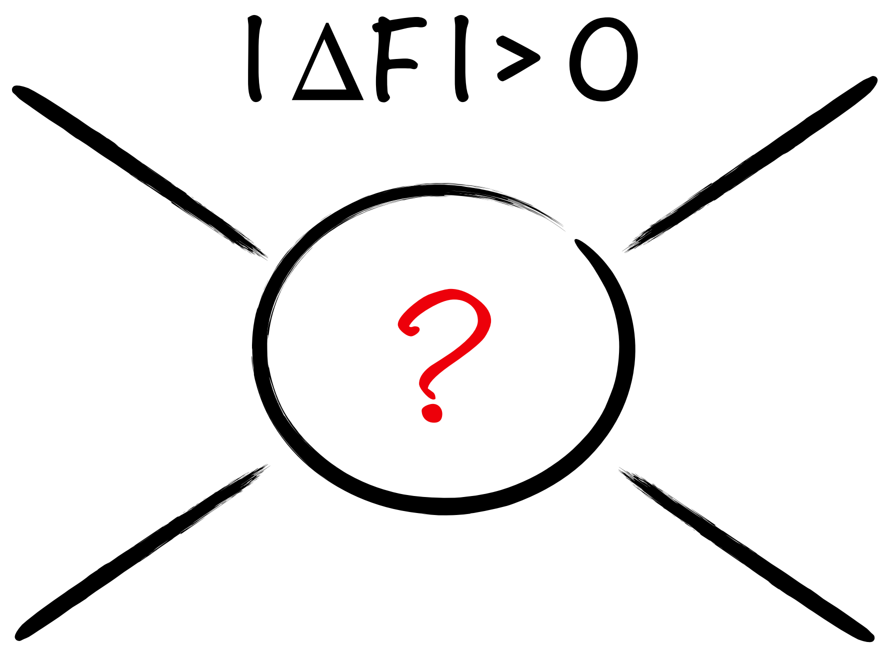
$$\begin{matrix} d & s & b \end{matrix}$$

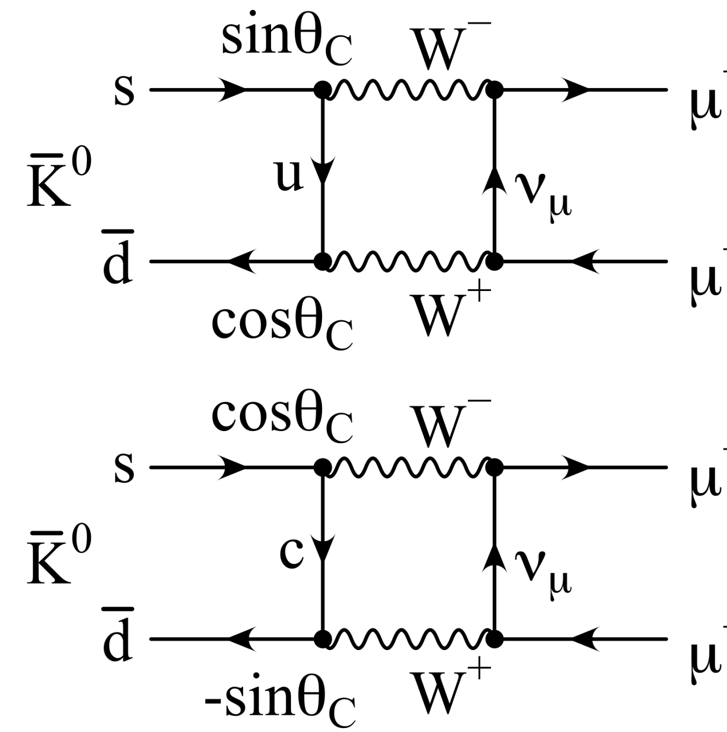
Why?



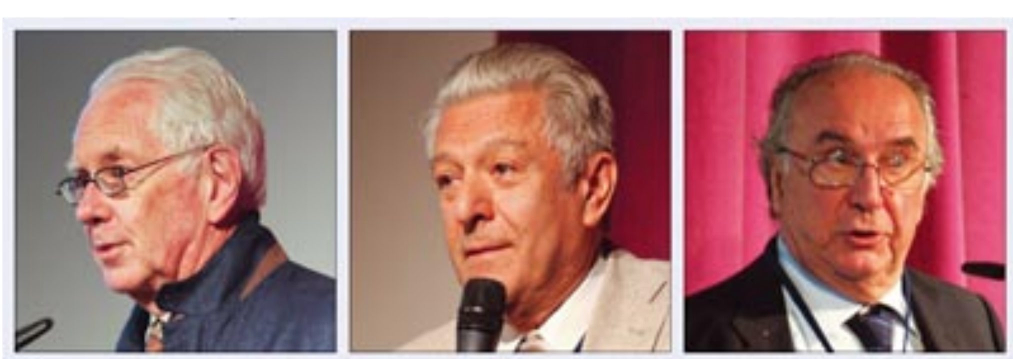
# Precision Tests: Flavor




## It led to "New Physics" (NP) !



https://agenda.infn.it/event/41258

- The 70th anniversary of CERN
- The 50th anniversary of $J/\Psi$

which marked the transition from

MANY MODELS to the STANDARD THEORY

2024

J.Iliopoulos @ **The Rise of Particle Physics**

# Flavor Metrology:

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

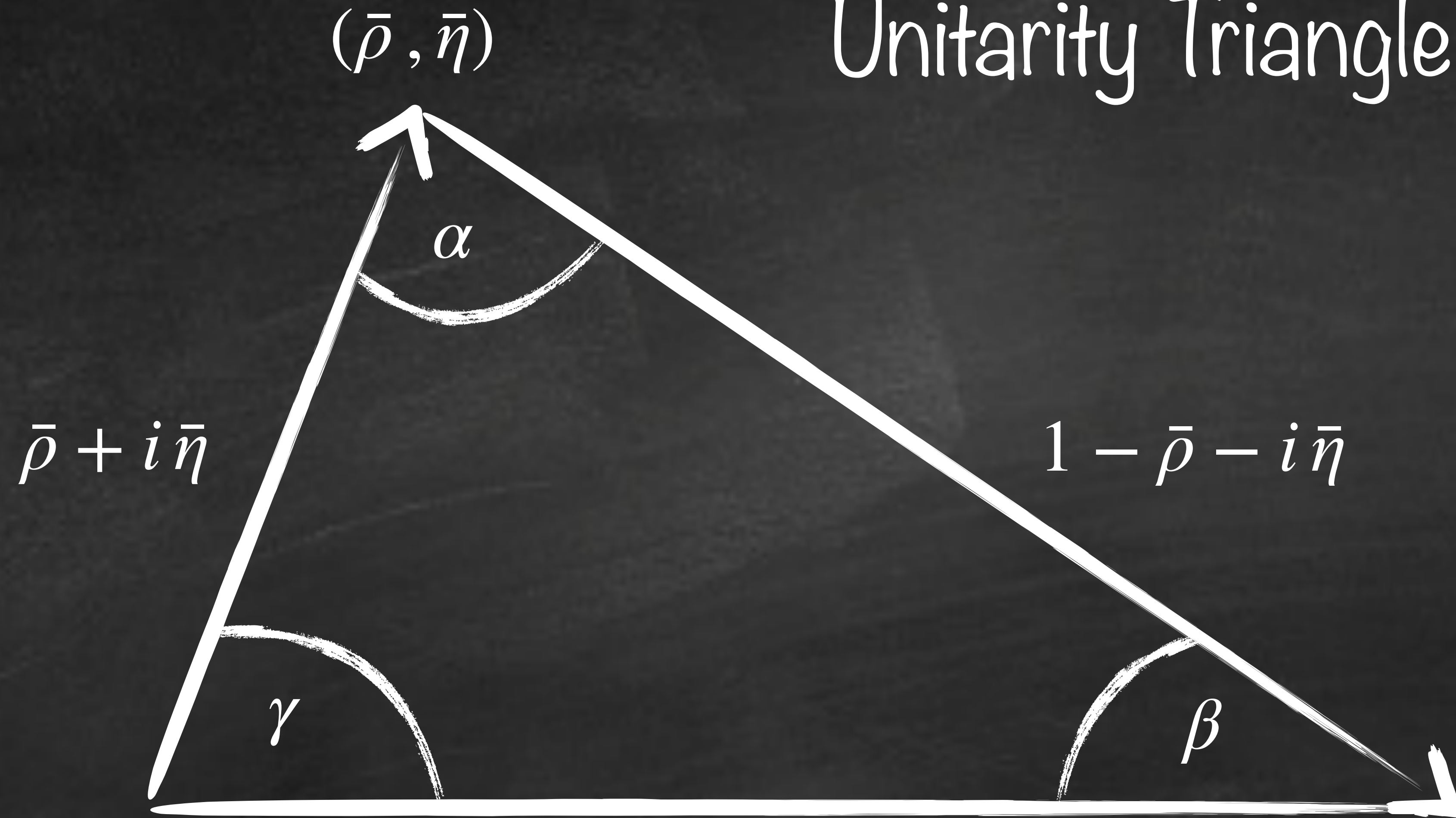
—> Flavor Changing Neutral Currents (FCNCs) **ONLY** @ one loop

- CKM matrix described by 4 params (3 angles + CP 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 $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

# Unitarity Triangle (UT)




$$-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} - \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = R_b\, e^{i\gamma} + R_t\, e^{-i\beta} = 1 \simeq (\bar{\rho} + i\bar{\eta}) + (1 - \bar{\rho} - i\bar{\eta})$$

UT*fit*


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

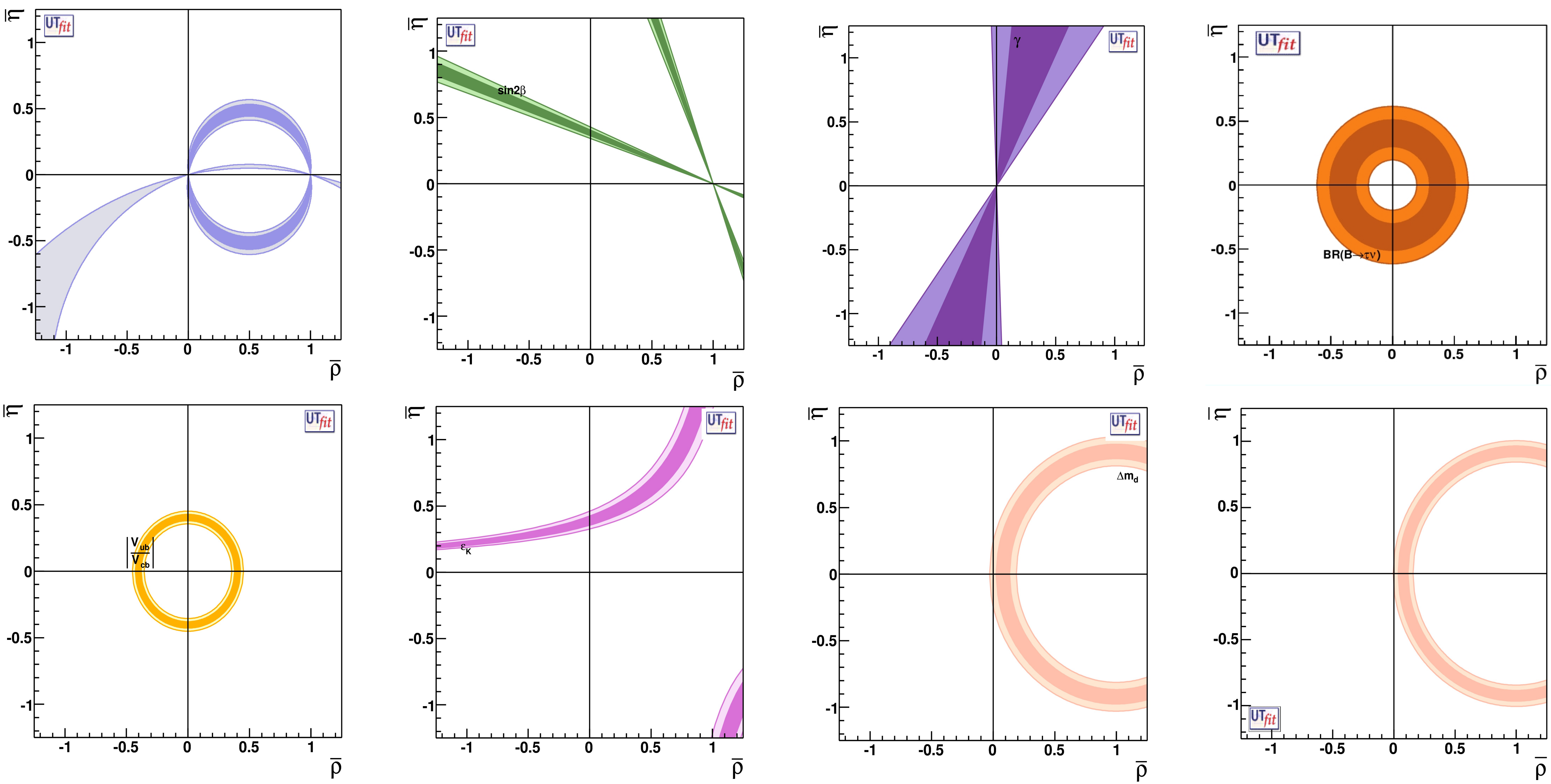
**New UT*fit* analysis of the unitarity triangle in the Cabibbo–Kobayashi–Maskawa scheme**

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**

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




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

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

# UTfit : Bayes aficionados

$$\mathcal{P}\left(\bar{\rho},\bar{\eta},\vec{p}\mid\vec{\mathcal{O}}\right)\sim\mathcal{P}\left(\vec{\mathcal{O}}\mid\bar{\rho},\bar{\eta},\vec{p}\right)\times\mathcal{P}_0(\bar{\rho},\bar{\eta},\vec{p})$$

$$\text{posterior}\ \sim\ \text{likelihood}\times\text{prior}$$

see, e.g., ***JHEP* 07 (2001) 013**

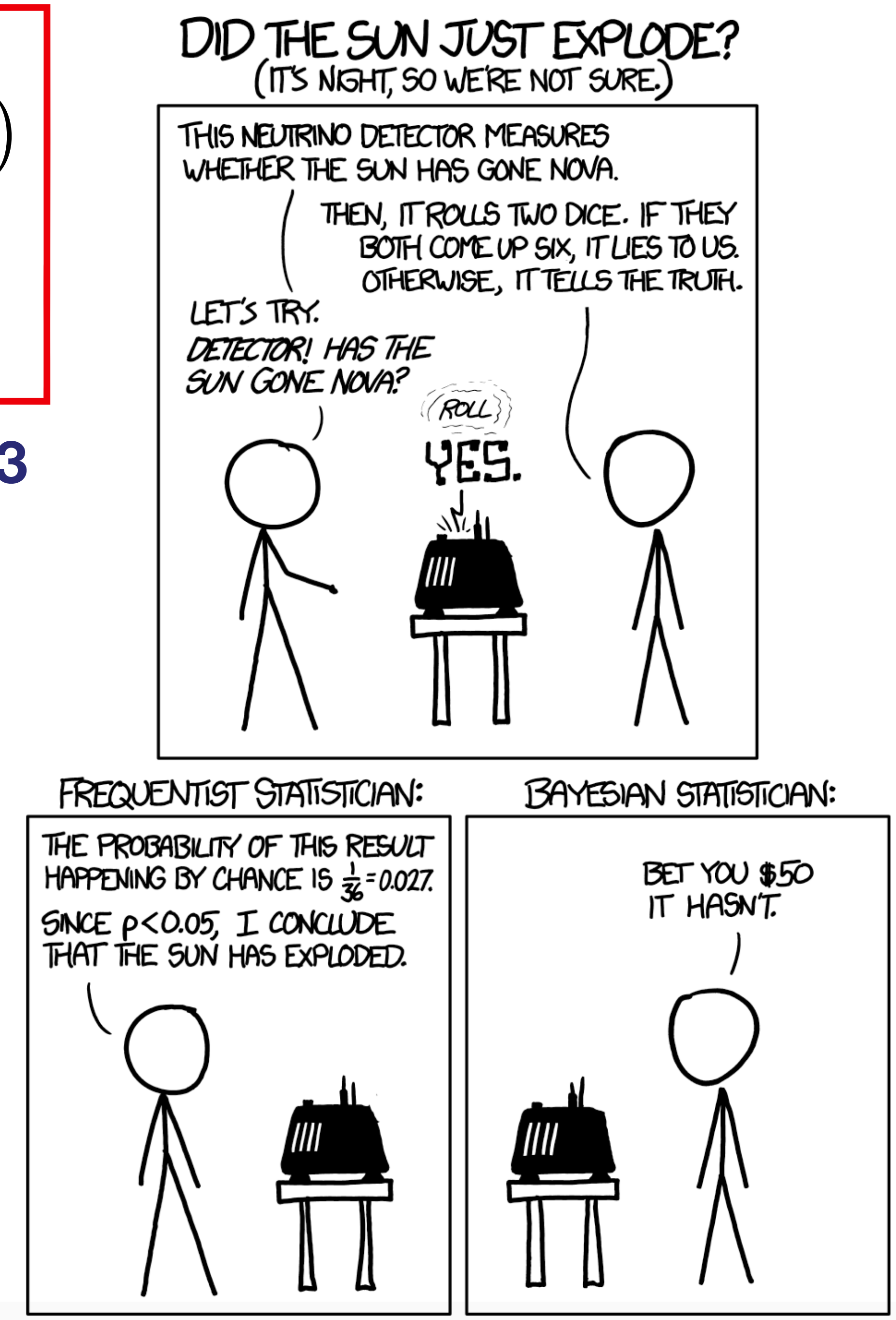
- $\vec{\mathcal{O}}=\{\epsilon_K,\Delta m_{d,s},\cdots\}$

  Observables <—> constraints in the fit

- $\vec{p}=\{f_{K,B},B_{K,B},\cdots\}$

  Parameters we can marginalize over

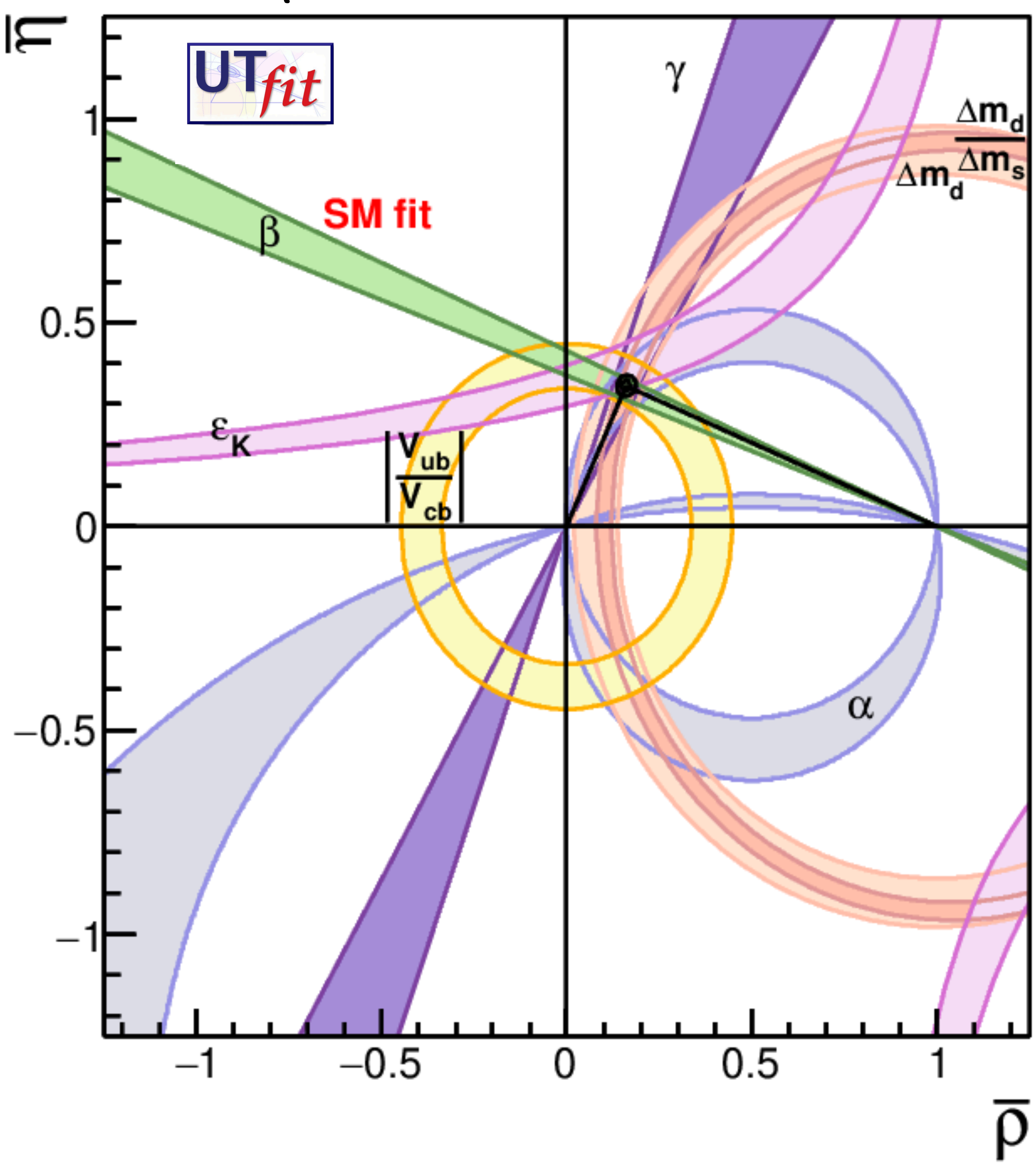
- $(\bar{\rho},\bar{\eta})$ <—> CKM pair to be inferred




@ https://xkcd.com/1132

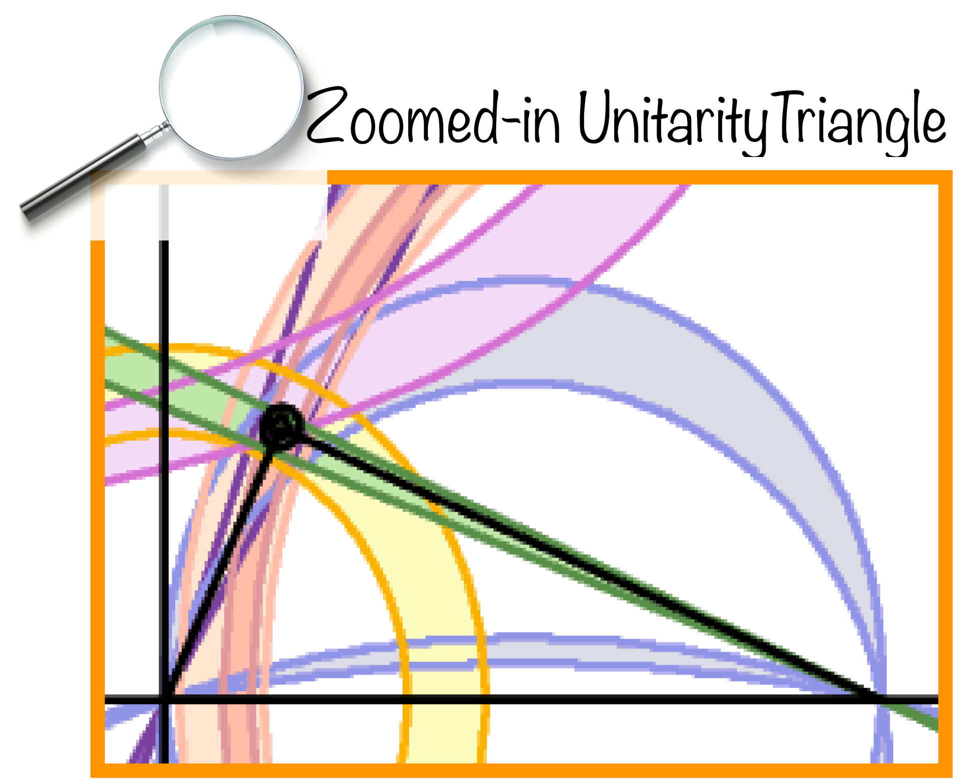
# UTA: Unitarity Triangle Analysis

@ 95% prob




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

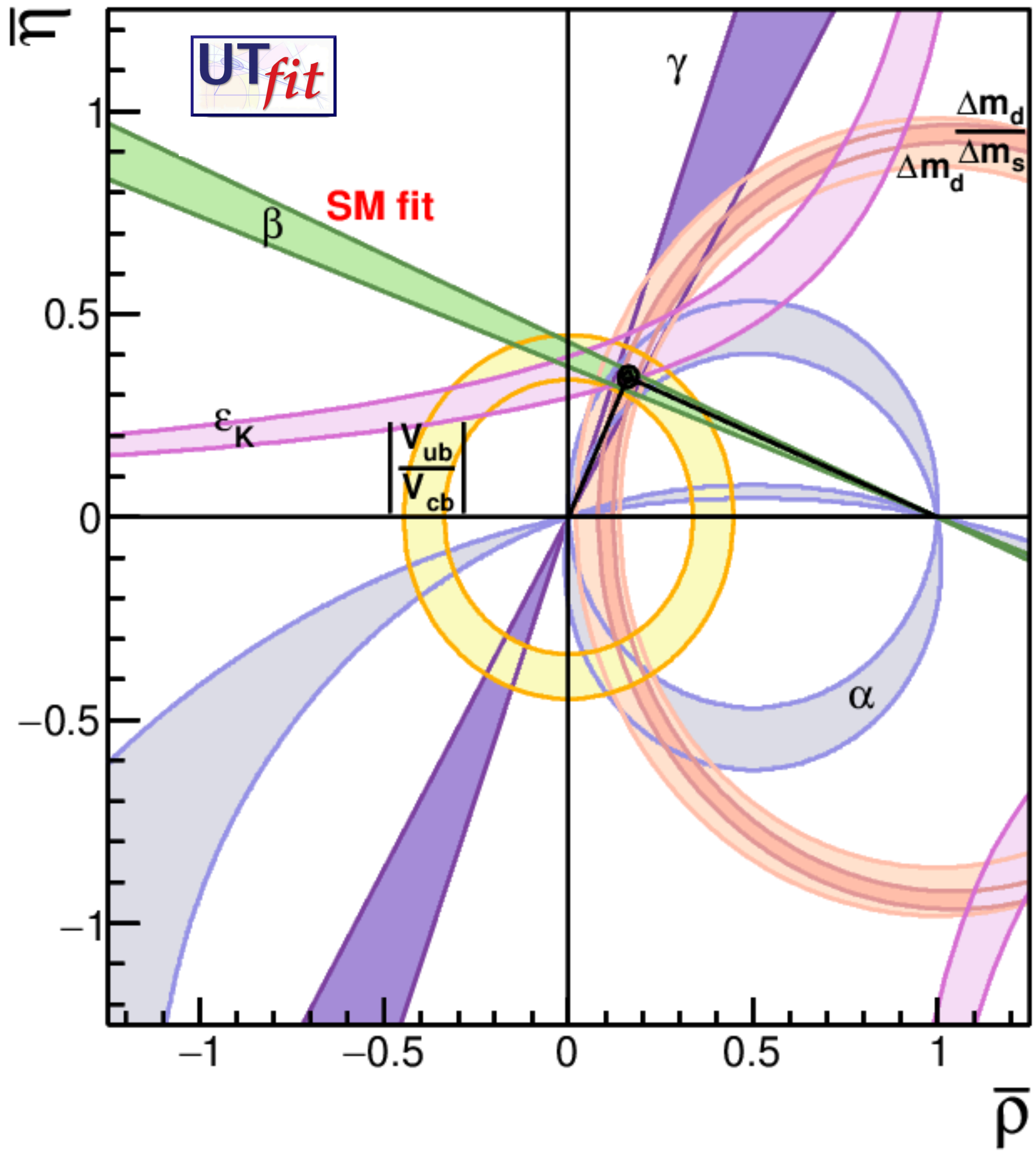
$$\lambda = 0.2251 \pm 0.0008$$
$$A = 0.827 \pm 0.010$$



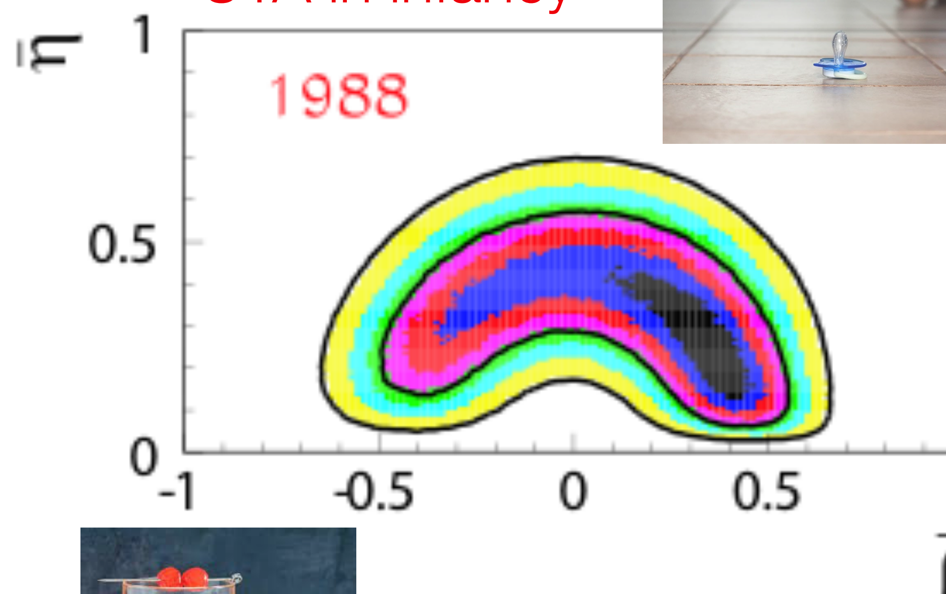

**PoS WIFAI2023 (2024) 007**

# few % determination = decades of tremendous EXP + TH progress!

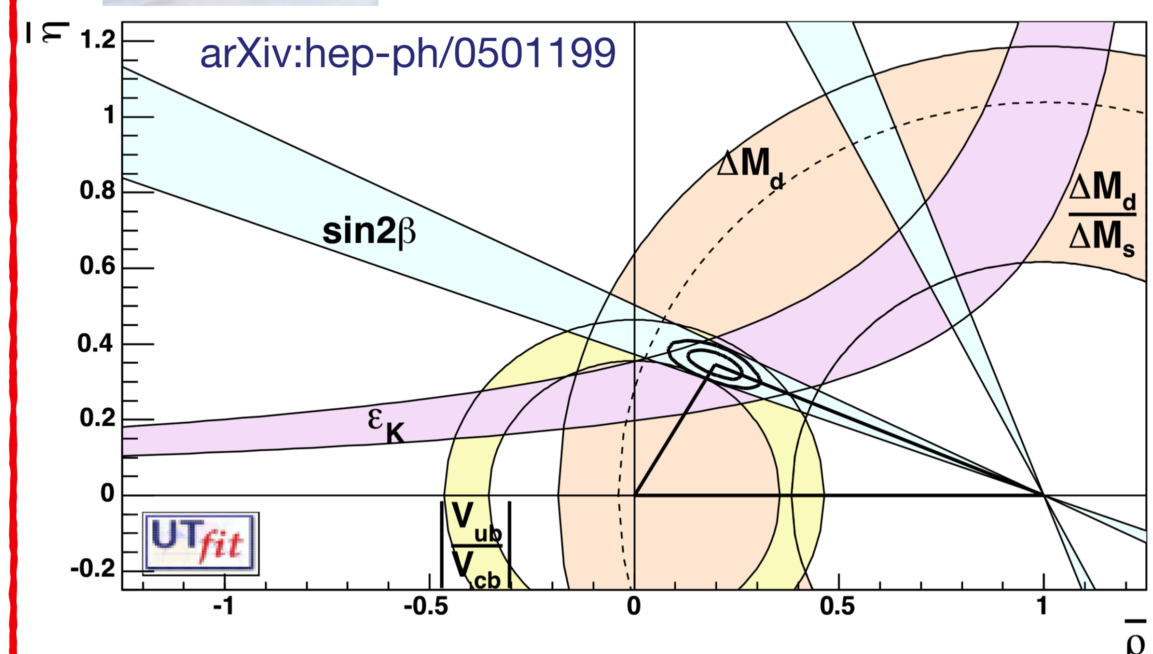
@ 95% prob




UTA in infancy




Old-Fashioned SM UTA




$$\bar{\rho} = 0.196 \pm 0.045 \sim 23\%$$
$$\bar{\eta} = 0.347 \pm 0.025 \sim 7\%$$

Compatibility plots

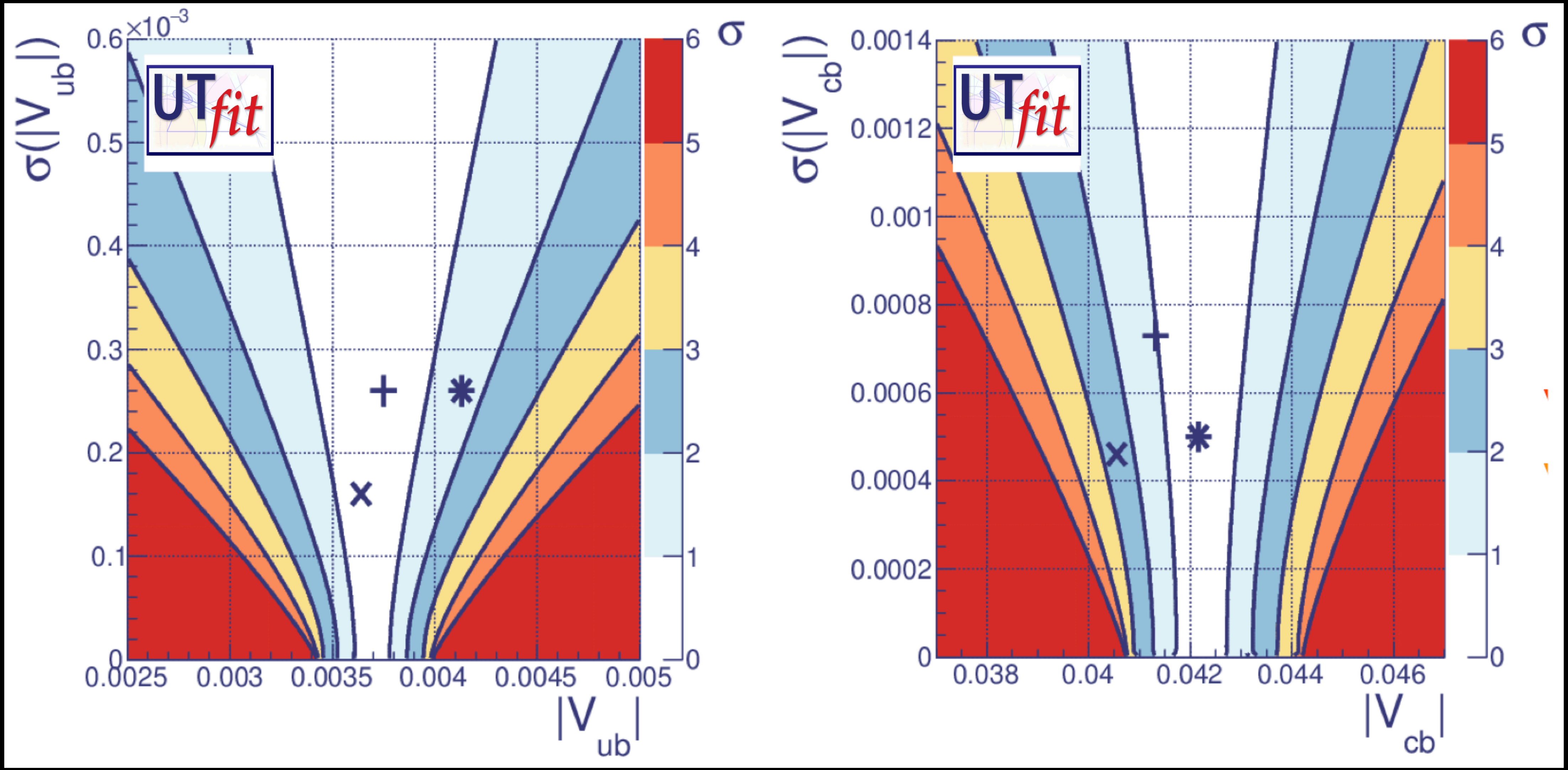
graphical pull of observables

# Tensions in the fit

+ <—> measurement

x <—> exclusive

* <—> inclusive



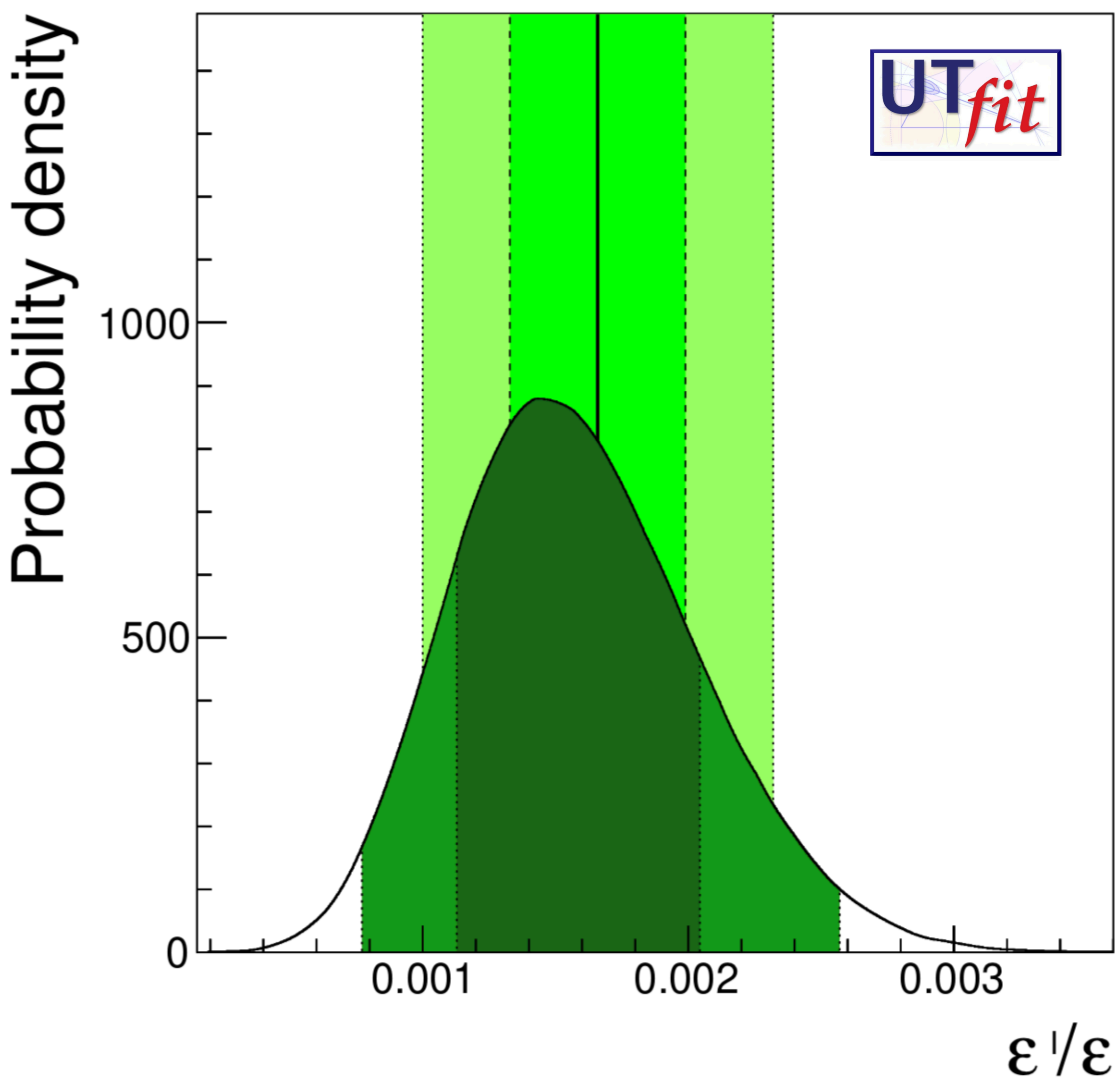

We find only a mild tension in the determination of $V_{cb}$ from exclusive modes ($< 3\sigma$).

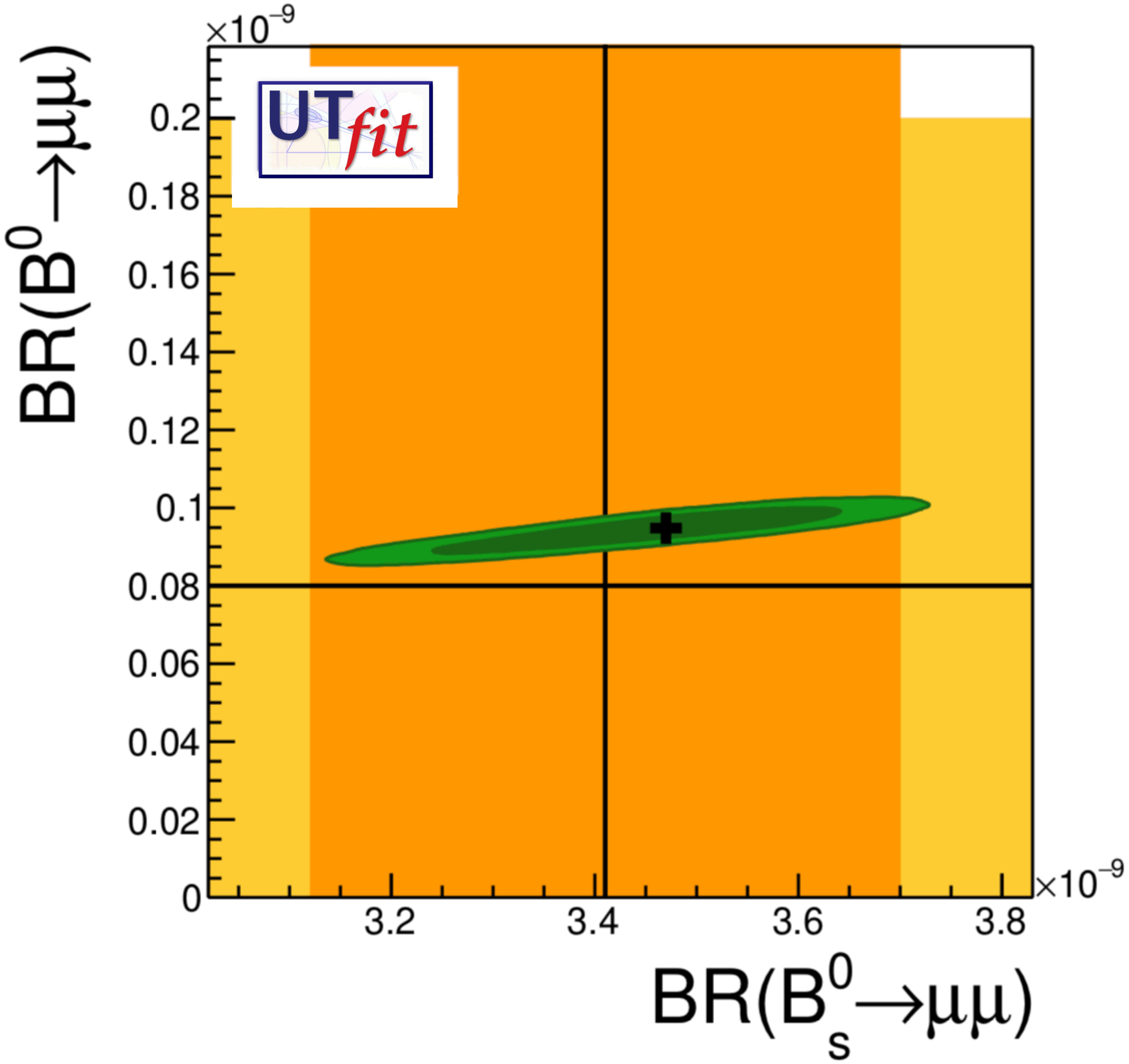
# UT Highlights: | ΔF | = 1

**UT now includes both indirect and direct CP from $K \to \pi\pi$**


to RBC/UKQCD Coll.

***PRD 102 (2020) 5, 054509***




**BR(s) in agreement w/ EXP data**

—> disfavoring NP for *B anomalies*

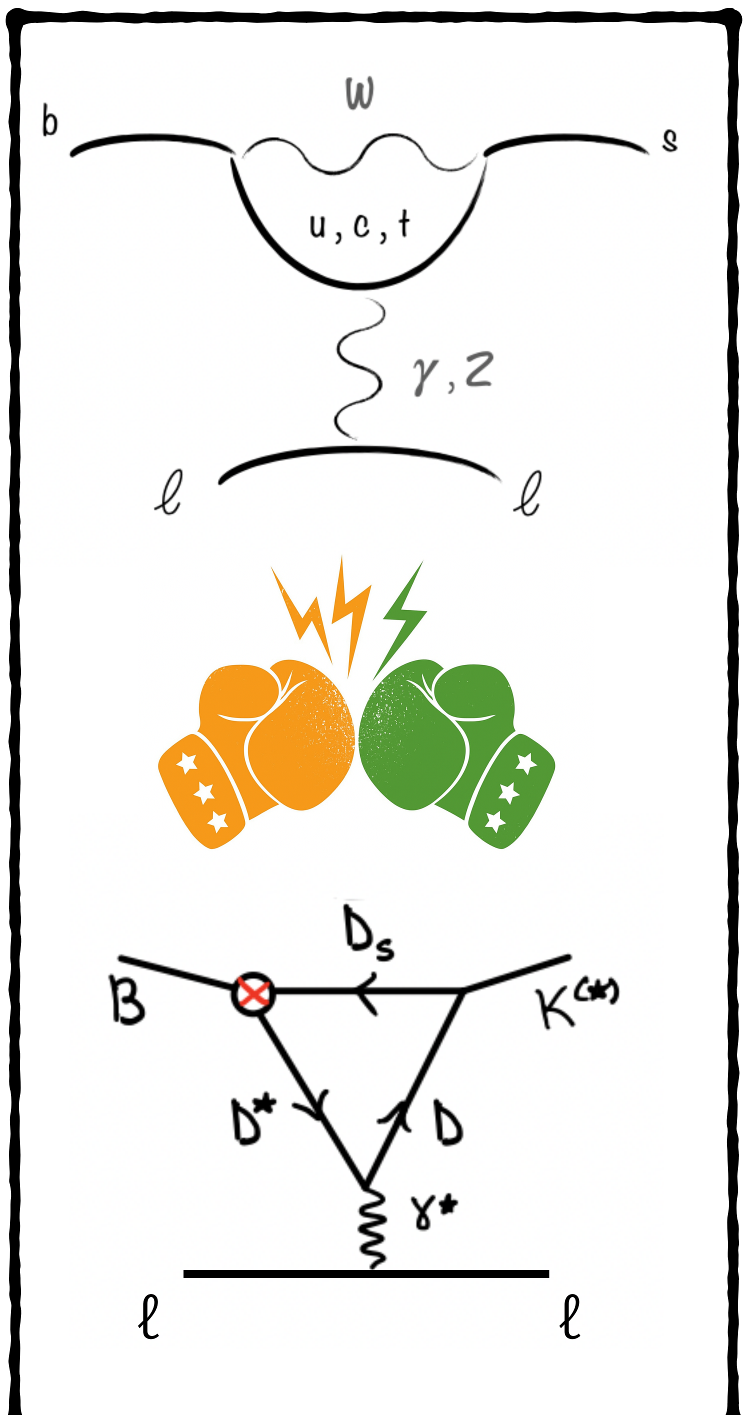
***PRD 107 (2023) 5, 055036***

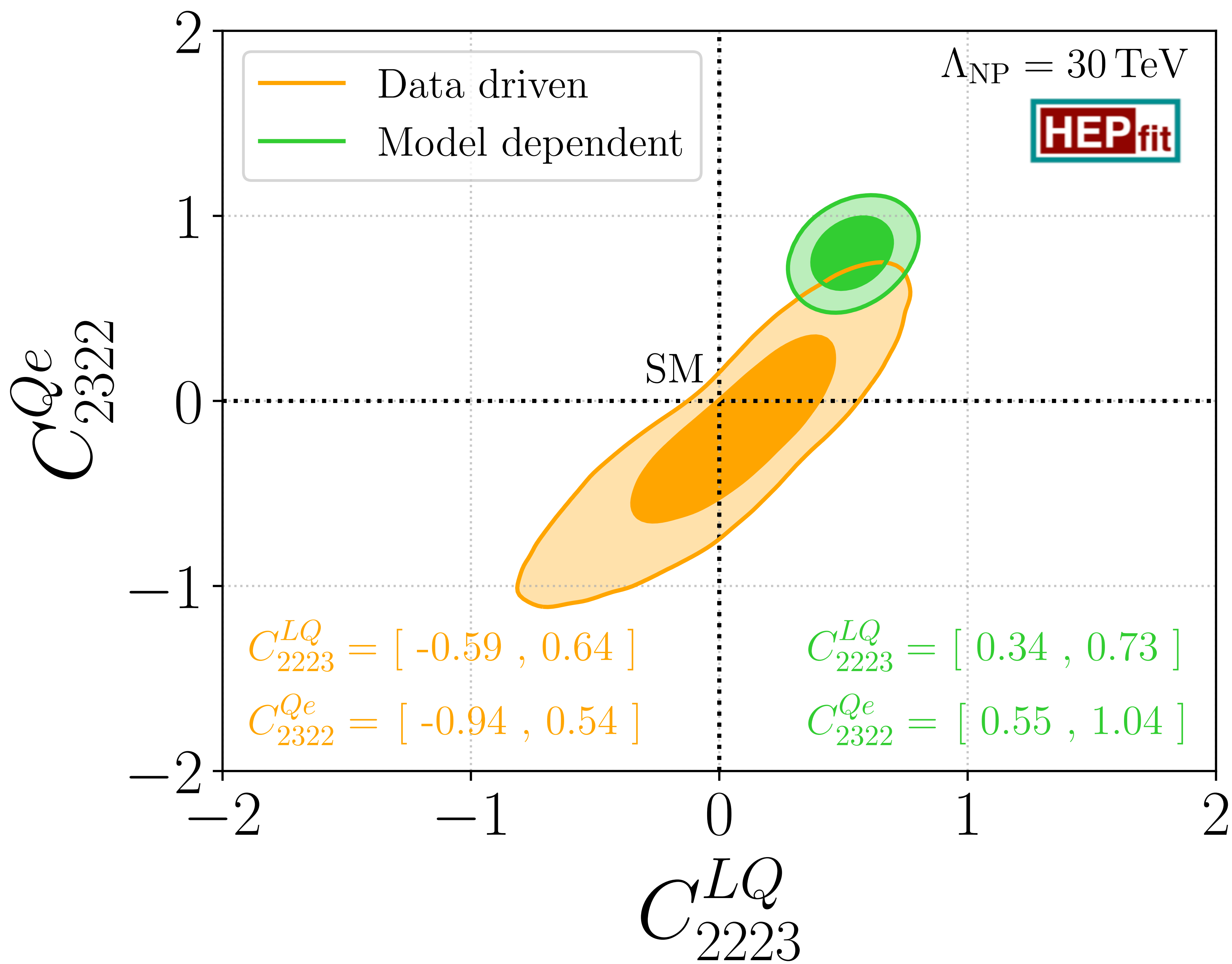
# B ANOMALIES : A GLIMPSE

***PRD 107 (2023) 5***
**SMEFT** GLOBAL ANALYSIS:
KEY **NP** OPERATORS

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

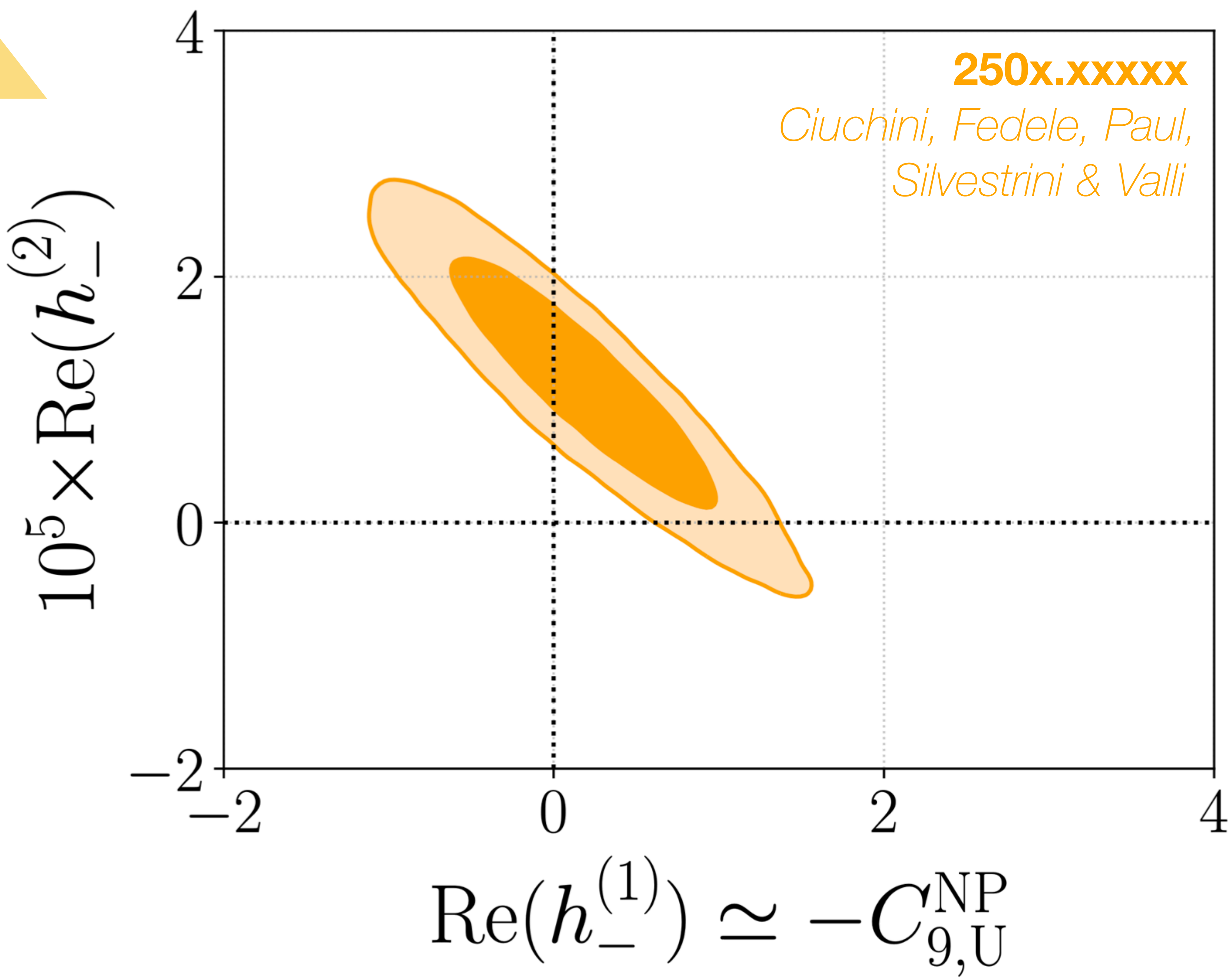
$$C_9 \propto C^{Qe} + C^{LQ}$$
$$C_{10} \propto C^{Qe} - C^{LQ}$$



# B ANOMALIES CIRCA 2025

QCD ONLY




New data from CMS and LHCb start to point to hadronic effects!

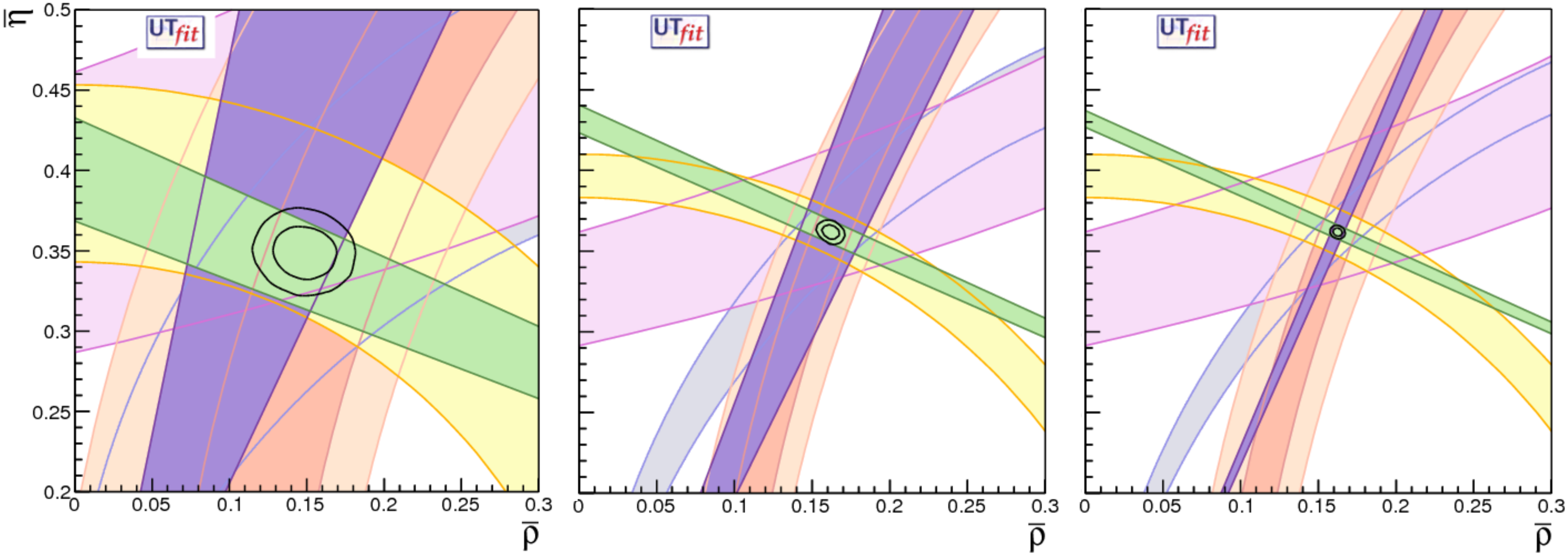
QCD ~ LEPTON UNIVERSAL NP

# UT Highlights: HL-LHC

**Ultimate upgrade of LHCb will possibly allow for < 1% in $(\bar{\rho}, \bar{\eta})$**

— arXiv:**1812.07638** —

**TODAY** **RUN 3** **HL-LHC**

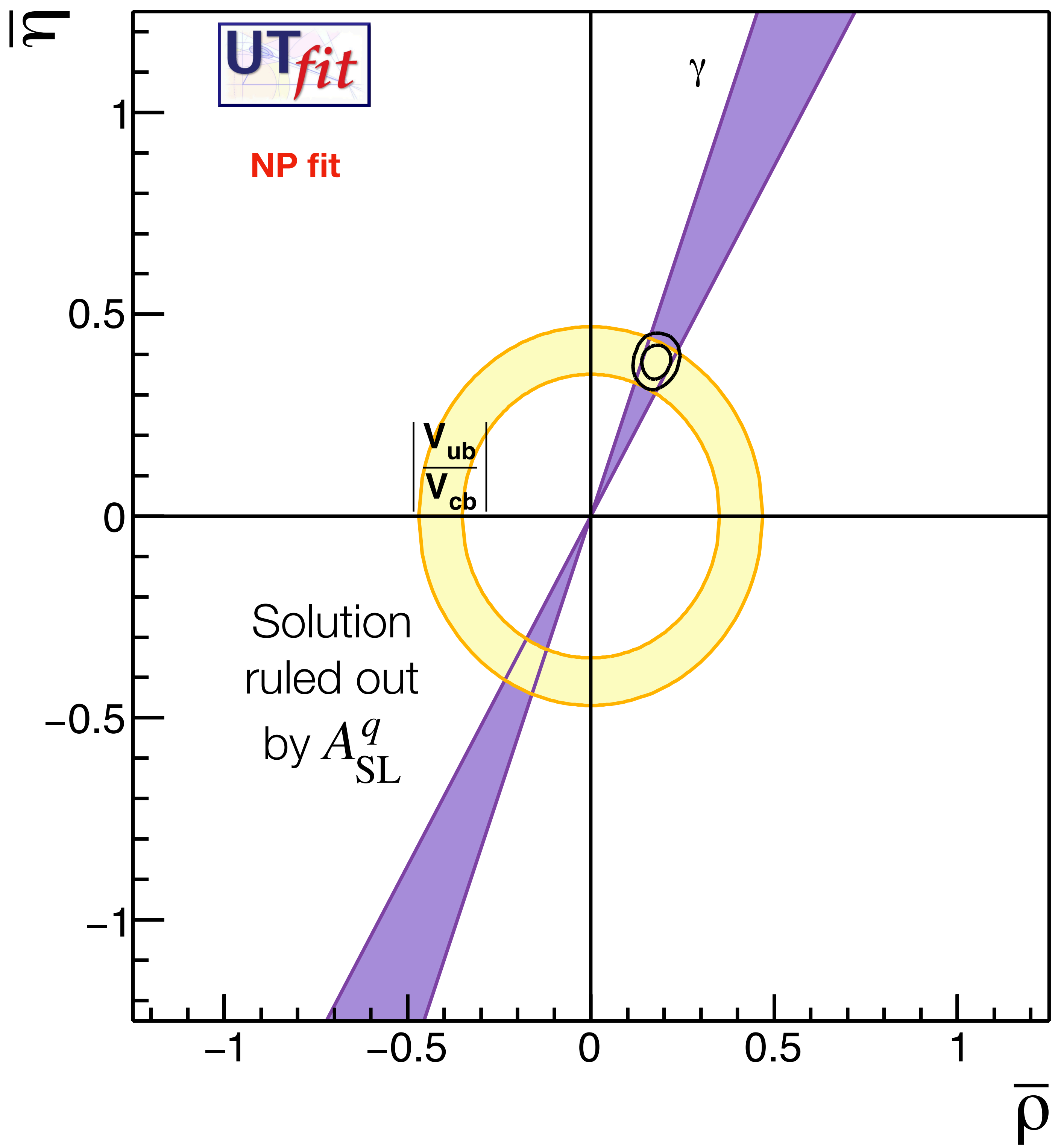



THIS IS W/O IMPACT OF BELLE II & RECENT B-PARKING OF CMS …

**HL-LHC EVEN MORE FLAVORFUL!**

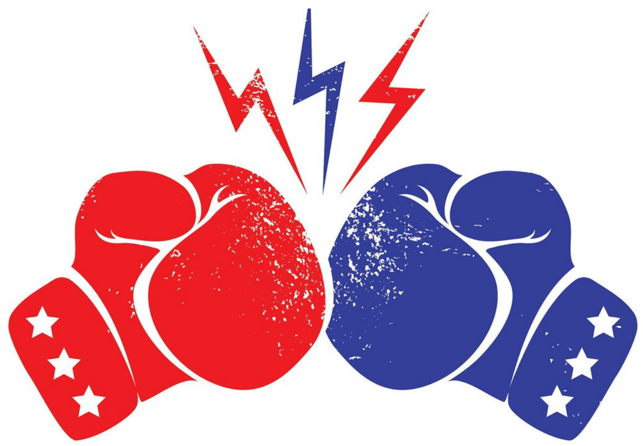
# NP UT Analysis

*** **Assumption:** only FCNC amplitudes affected by NP ***




**NP UT Analysis**

$$\bar{\rho} = 0.167 \pm 0.025 \sim 15\%$$
$$\bar{\eta} = 0.361 \pm 0.027 \sim 7.5\%$$



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

**SM UT Analysis**

# Flavour & BSM Physics

**PoS WIFAI2023 (2024) 007**

Most general $|\Delta F| = 2$ $H_{eff}$:

$$O_1^{q_iq_j} = \bar{q}^\alpha_{jL}\gamma_\mu q^\alpha_{iL}\,\bar{q}^\beta_{jL}\gamma^\mu q^\beta_{iL}$$

SM

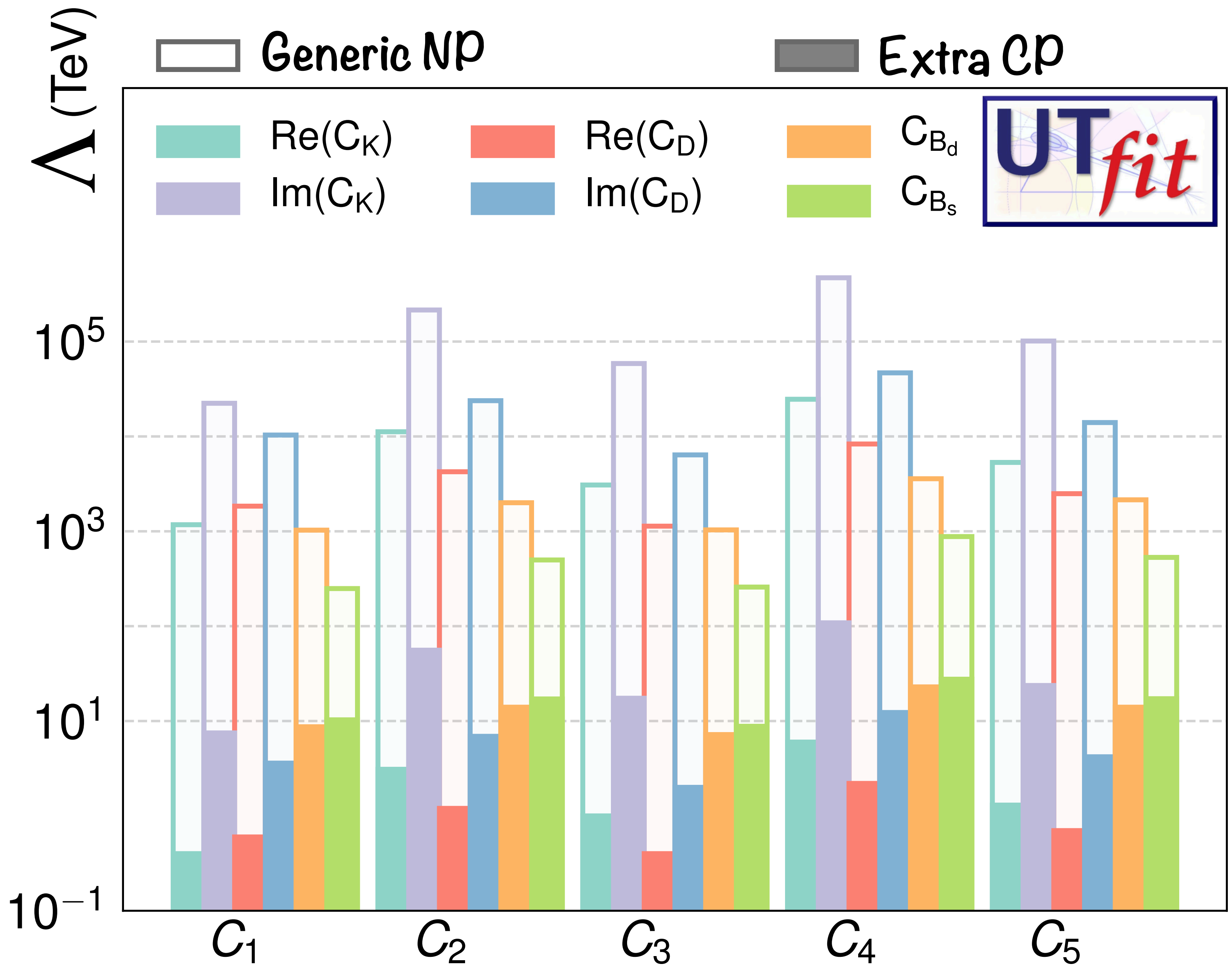
$$O_2^{q_iq_j} = \bar{q}^\alpha_{jR}q^\alpha_{iL}\,\bar{q}^\beta_{jR}q^\beta_{iL}$$

$$O_3^{q_iq_j} = \bar{q}^\alpha_{jR}q^\beta_{iL}\,\bar{q}^\beta_{jR}q^\alpha_{iL}$$

$$O_4^{q_iq_j} = \bar{q}^\alpha_{jR}q^\alpha_{iL}\,\bar{q}^\beta_{jL}q^\beta_{iR}$$

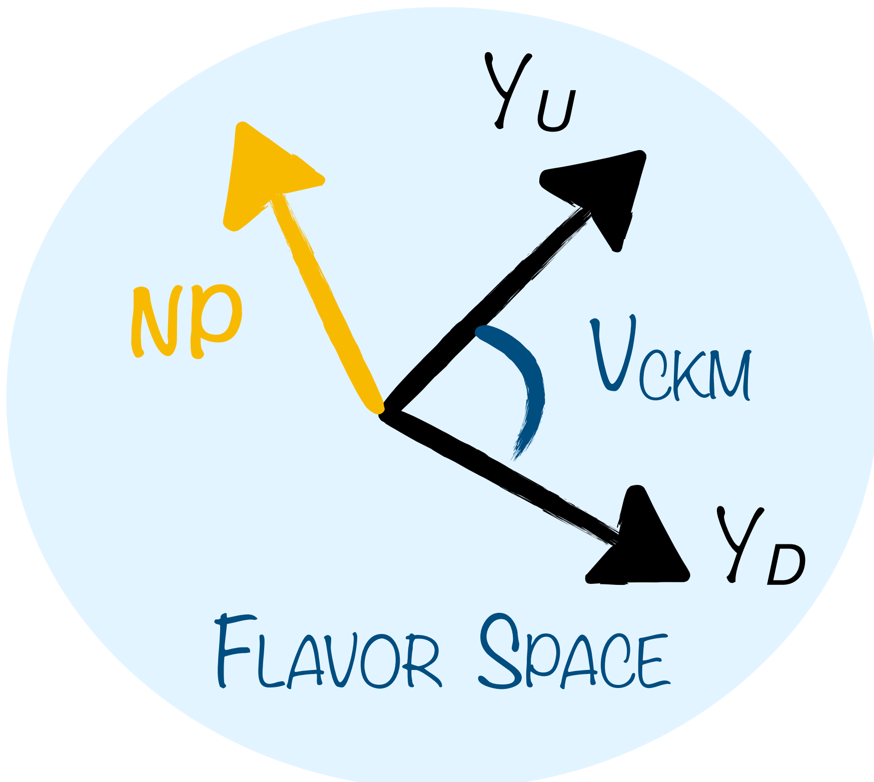
$$O_5^{q_iq_j} = \bar{q}^\alpha_{jR}q^\beta_{iL}\,\bar{q}^\beta_{jL}q^\alpha_{iR}$$

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

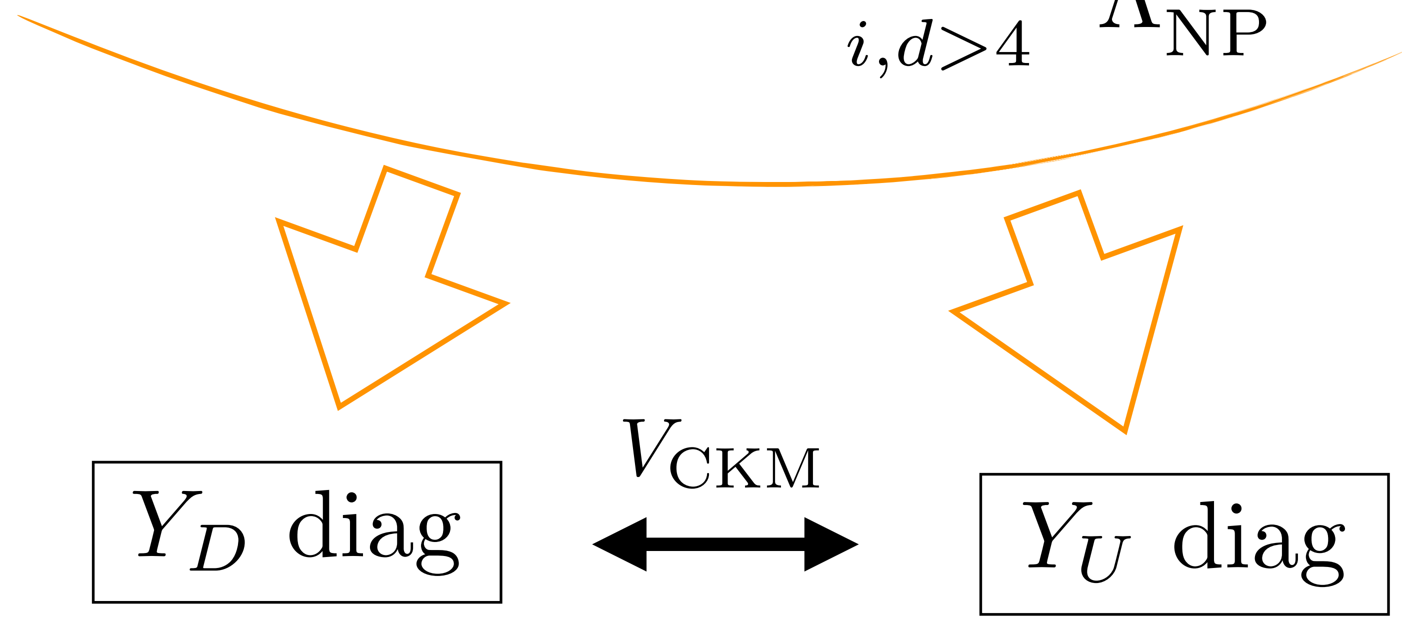



- **Generic NP** = no SM protection, i.e.: $C(\Lambda) \sim 1/\Lambda^2$ ⇨ $\Lambda > 4.7 \times 10^5$ TeV
- **Extra CP** = SM-like protection but new O(1) phases ➡ $\Lambda > 108$ TeV

# Going Beyond the Weak EFT




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




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

SMEFT RGE

| | | | | |
|---|---|---|---|---|
| $O^{HQ(1[3])}_{jk}$ $(H^\dagger i \overleftrightarrow{D}^{[A]}_\mu H)(\bar Q_j\gamma^\mu[\tau^A]Q_k)$ | $O^{LedQ}_{jjkl}$ $(\bar L_j e_j)(\bar d_k Q_l)$ | $O^{LeQu}_{jjkl}$ $(\bar L_j e_j)i\tau^2(\bar Q_k u_l)$ | $O^{ud(1[8])}_{jklm}$ $(\bar u_j\gamma_\mu[T^a]u_k)(\bar d_l\gamma^\mu[T^a]d_m)$ | $O^{QuQd(1[8])}_{jklm}$ $(\bar Q_j\gamma_\mu[T^a]u_k)i\tau^2(\bar Q_l\gamma^\mu[T^a]d_m)$ |
| $O^{QQ(1[3])}_{jklm}$ $(\bar Q_j\gamma_\mu[\tau^A]Q_k)(\bar Q_l\gamma^\mu[\tau^A]Q_m)$ | $O^{uu}_{jklm}$ $(\bar u_j\gamma_\mu u_k)(\bar u_l\gamma^\mu u_m)$ | $O^{dd}_{jklm}$ $(\bar d_j\gamma_\mu d_k)(\bar d_l\gamma^\mu d_m)$ | $O^{Qd(1[8])}_{jklm}$ $(\bar Q_j\gamma_\mu[T^a]Q_k)(\bar d_l\gamma^\mu[T^a]d_m)$ | $O^{Qu(1[8])}_{jklm}$ $(\bar Q_j\gamma_\mu[T^a]Q_k)(\bar u_l\gamma^\mu[T^a]u_m)$ |

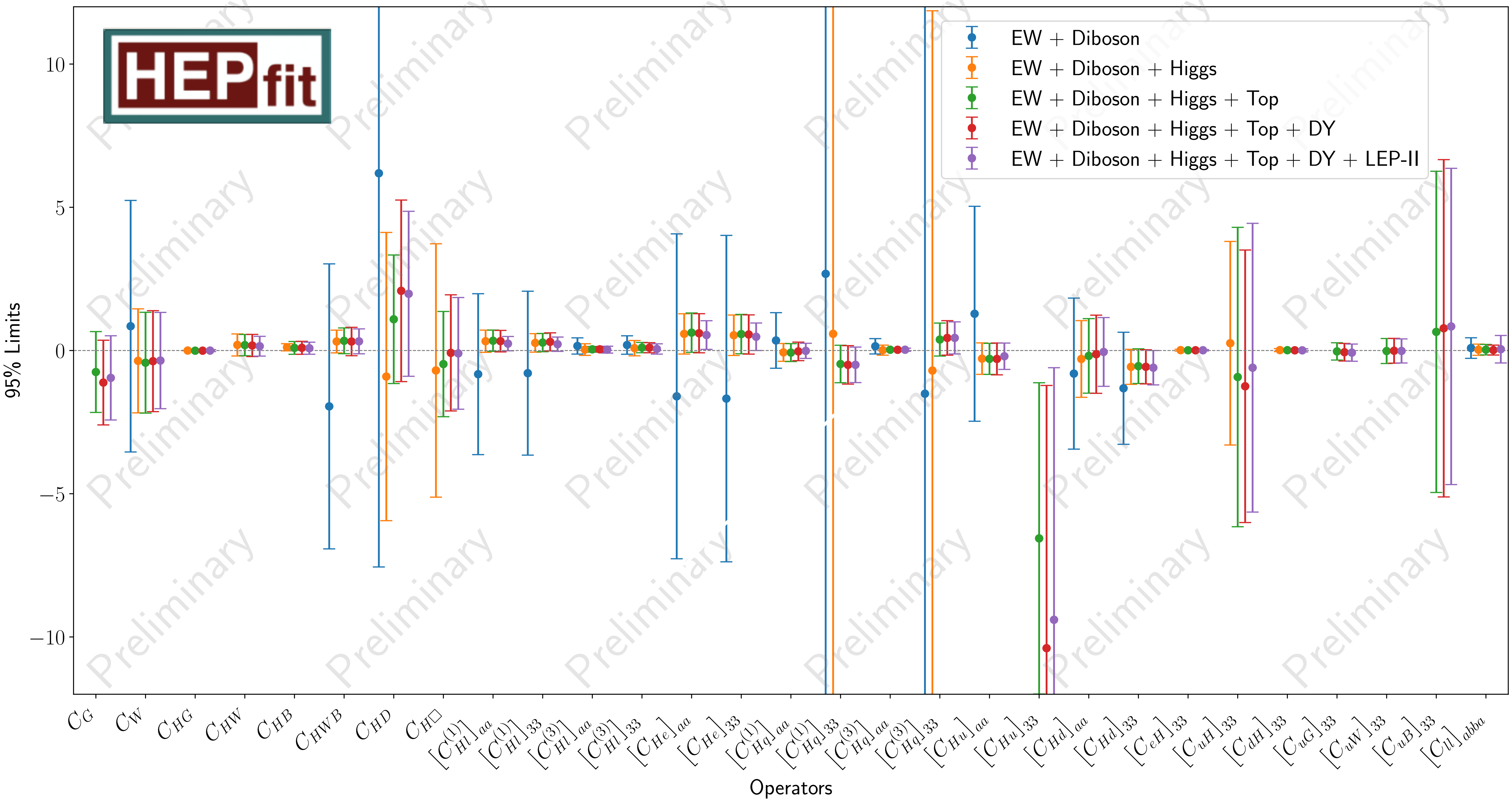
*poorly constrained*

FLAVOR MISALIGNMENT

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

# $U(2)^5$ 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

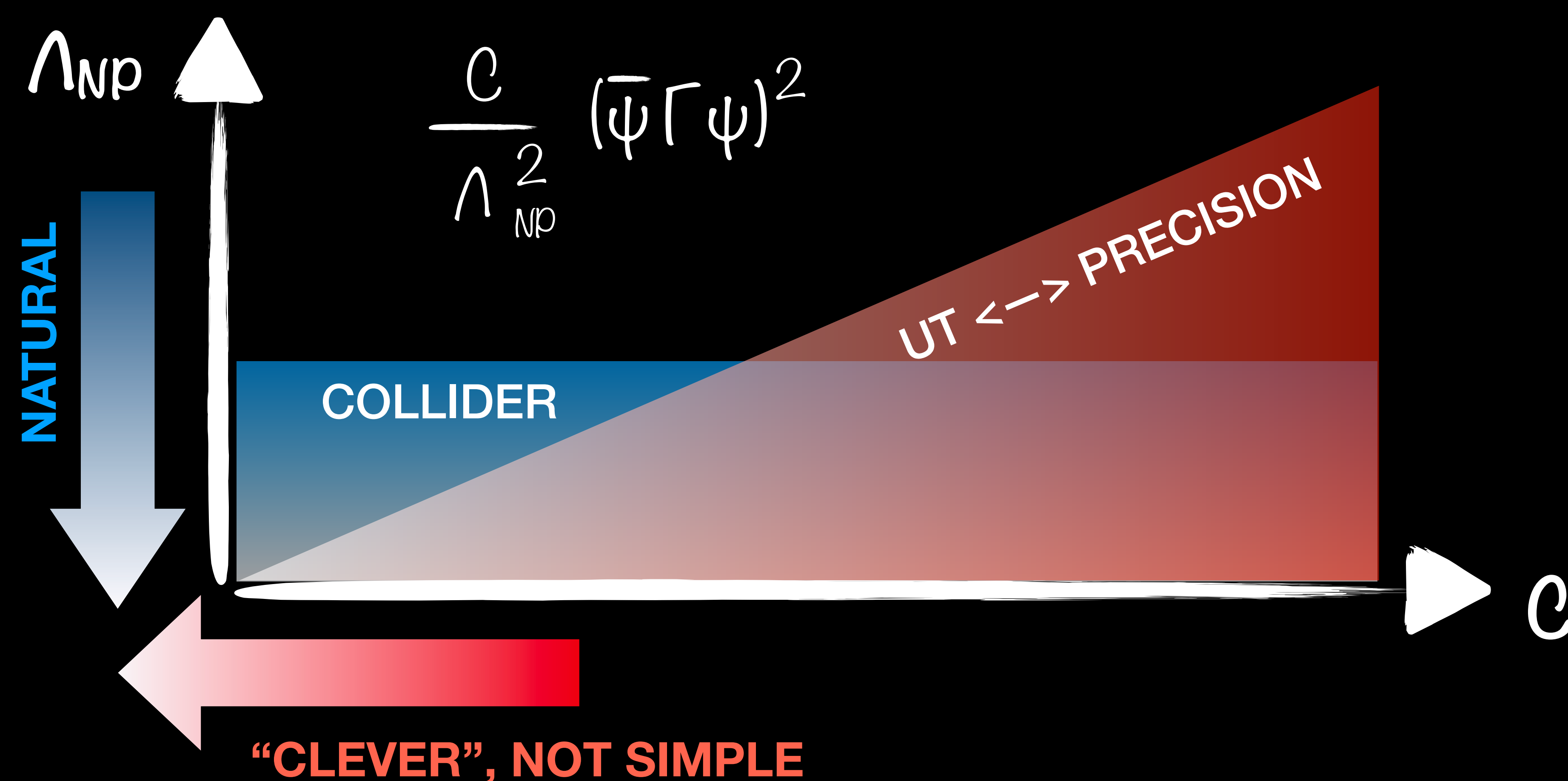

**SMEFT vs Precision.** Picture further constrained by Flavor . . .

[with J.de Blas, A.Goncalves, V.Miralles, L.Reina, L.Silvestrini]

# Lessons from Precision

- **SM UT:** Towards % precision … overall remarkable consistency!
  *—> in the HL-LHC era we might aim at a permil test*

- **NP UT:**




**BOTTOM LINE**

**A Theory of Flavor is either VERY CLEVER or "JUST" UNNATURAL**

# How To Be Clever ...

*SEIBERGOLOGY:* Yukawa are spurions breaking the **flavor group**

$$U(3)^5 = SU(3)_Q \times SU(3)_d \times SU(3)_u \times SU(3)_L \times SU(3)_e \times U(1)^5$$

$$U(1)^5 = U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{PQ} \times U(1)_e$$

E.g.: $-\mathcal{L}_{\rm SM} \supset Y^d_{ij}\,\overline{Q}_i H d_j + Y^u_{ij}\,\overline{Q}_i \widetilde{H} u_j + h.c.$

$$Y^d \sim (3,\bar{3},1) \qquad Y^u \sim (3,1,\bar{3})$$

under $SU(3)_Q \times SU(3)_d \times SU(3)_u$

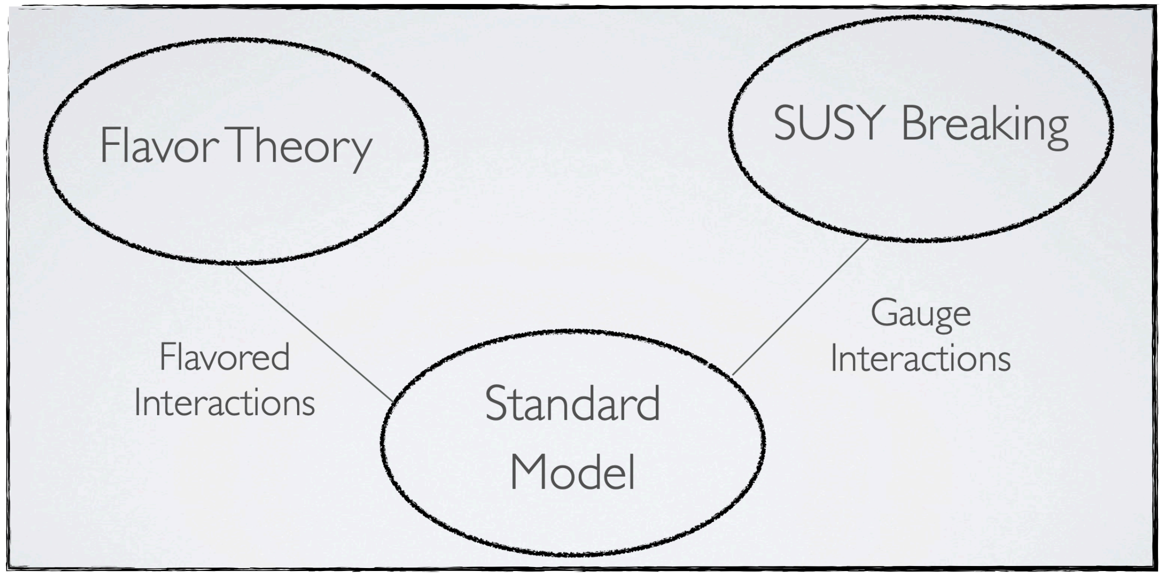
*ASSUMPTION:* **only spurions** that break **flavor** are **SM Yukawas**

**—> MINIMAL FLAVOR VIOLATION** [*Nucl.Phys.B* 645 (2002) 155]

# MFV is an Ansatz

**MFV** allows to push a full-fledged theory of flavor to very high energies.

$$\Lambda_{\text{NP flavor}} \gg \Lambda_{\text{BSM}} \gtrsim v_{\text{EW}}$$




Example: **GAUGE MEDIATION**

In models with gauge-mediated SUSY breaking, the sfermion sector becomes flavorful under SM RGE.

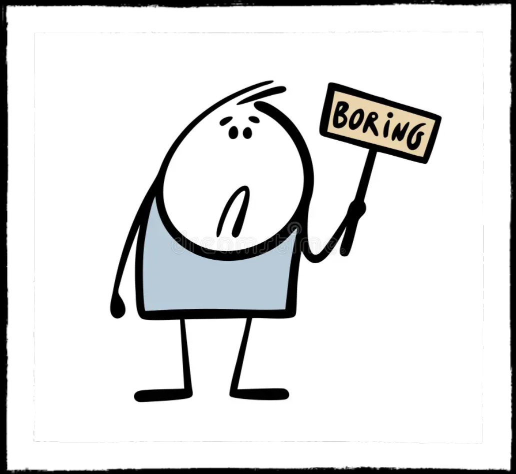
**The theory of Flavor is decoupled from the SUSY messenger sector.**

**FLAVOR BOUNDS GREATLY RELAXED UNDER THE MFV ANSATZ.**

"Minimal" for the # of spurions. Actually, **Maximal Flavor Conservation.**

arXiv:**2402.09503 — A. Glioti** ***et al.***

**MFV + SMEFT** leaves room x **New Physics** just above a **few TeV**.

MFV <—> 


Can we avoid large FCNCs

and have BSM with

radically different flavor 

# Alignment, a kind-of FCNC killer

Consider the SM Lagrangian in the up-quark diag basis:

$$-\mathcal{L}_{\rm SM} \supset (V y^d)_{ij}\, \overline{Q}_i H d_j + y^u_{ij}\, \overline{Q}_i \widetilde{H} u_j + h.c.$$

with $y^d = \mathrm{diag}(y_d, y_s, y_b)$ and $y^u = \mathrm{diag}(y_u, y_c, y_t)$

*ASSUMPTION:* new flavorful interactions **aligned** with $y^u$

E.g.: $\mathcal{L}_{\rm BSM} \supset \lambda^u_{ij} \overline{Q}_i H_2 u_j$ with $\lambda^u = \mathrm{diag}(\lambda_u, \lambda_c, \lambda_t)$

OLD BUT GOLD

Should squarks be degenerate? ☆

Yosef Nir *, Nathan Seiberg *

Physics Letters B
Volume 309, Issues 3–4, 15 July 1993, Pages 337-343

HOW TO FORMALLY JUSTIFY SUCH ASSUMPTION FOR BSM?

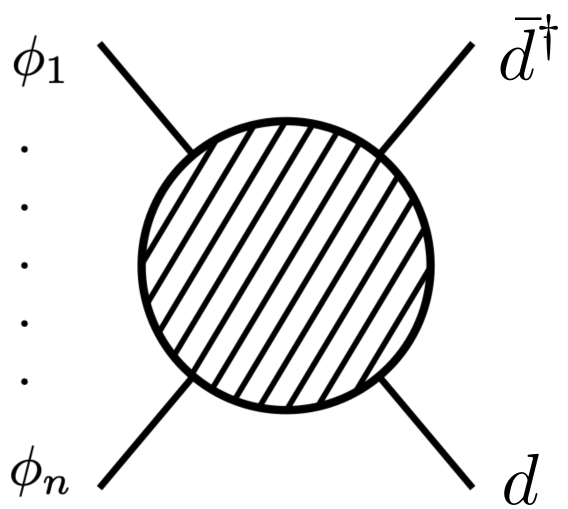
# Another Way to Be Clever: **Alignment!**

## — ANSATZ FOR ALIGNMENT IN THE UP-QUARK SECTOR —

**UV**

- **NO** breaking of the family number $U(1)_f^3$ and of $CP$ **other than** the wave-function renormalization $Z^d$ of $d$
- **NO** fields / spurions transforming under $U(3)_d$ **but** $d$ & $Z^d$

Mixing with Spontaneously Broken Flavor Vacuum




$$\mathcal{L} \supset i Z^d_{ij}\, \bar{d}_i^\dagger \bar{\sigma}^\mu d_j + i \bar{u}_i^\dagger \bar{\sigma}^\mu u_i + i \bar{Q}_i^\dagger \bar{\sigma}^\mu Q_i$$
$$+ \text{ Yukawa terms all flavor diagonal}$$

Canonical kinetic term implies: $(Z^d)^{-\frac{1}{2}} \sim V y^d$

**The up-quark sector remains aligned.**

**New spurions** allowed: $\lambda^u = \mathrm{diag}(\lambda_u, \lambda_c, \lambda_t)$

arXiv:**2410.05236 — *JHEP* 02 (2025) 067**

**How charming can the Higgs be?**

---

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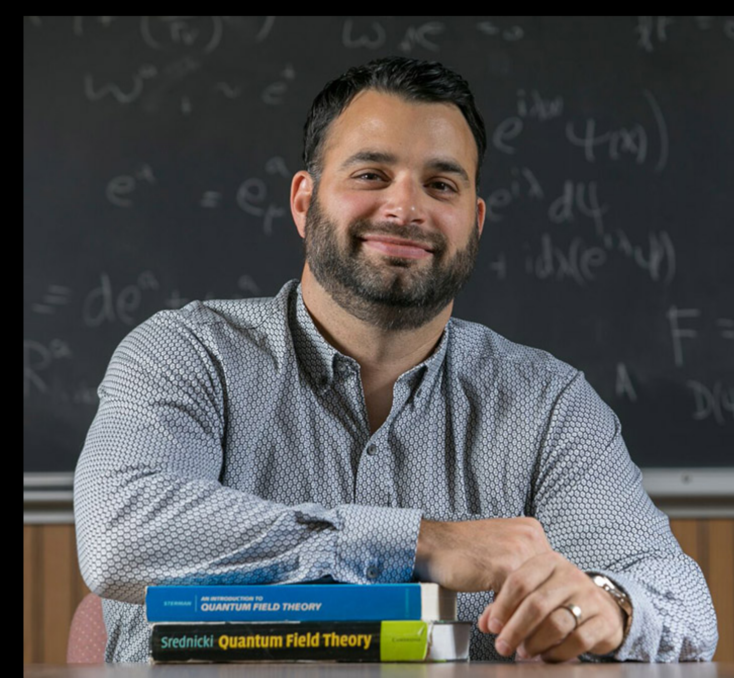
[b] *INFN Sezione di Roma, Piazzale Aldo Moro 2, I-00185 Rome, Italy*




Artemis Giannakopoulou

Mr. μUON COLLIDER

# SFV 2HDM

SFV physics may have generic family non-universal couplings to SM.

A simple framework: **SFV Two Higgs Doublet Models (2HDM).**

$$|D_\mu H_a|^2 - V(H_1, H_2) - \left(\mathcal{Y}^u_{aij}\overline{Q}_{Li} H_a U_{Rj} + \mathcal{Y}^d_{aij}\overline{Q}_{Li} H^c_a D_{Rj} + \mathcal{Y}^\ell_{aij}\overline{L}_{Li} H^c_a \ell_{Rj} + h.c.\right)$$

$(a = 1, 2\,;\; i, j = 1, 2, 3)$

2HDM features neutral 2 CP-even H:

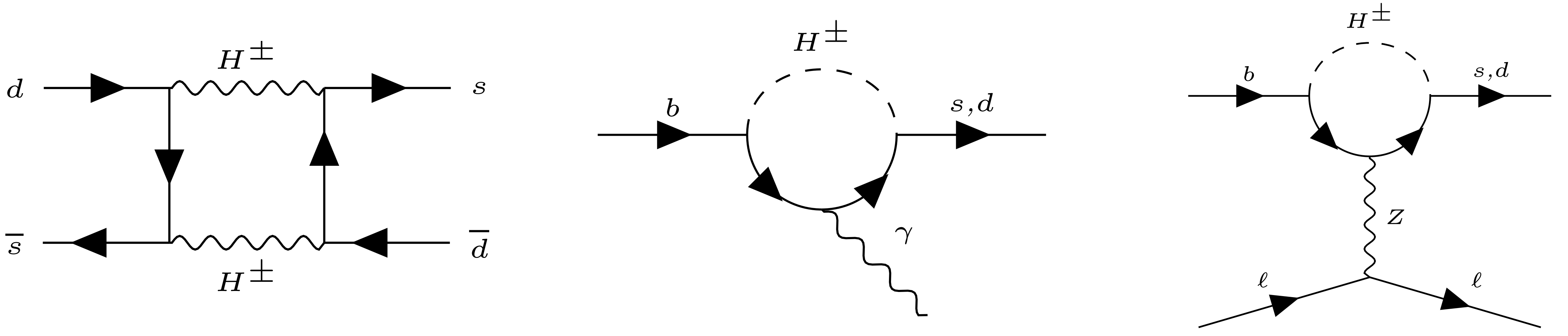
$\cos(\beta - \alpha) \neq 0$ **interesting!**

$$h = H^0_1 \sin(\beta - \alpha) + H^0_2 \cos(\beta - \alpha)$$
$$H = H^0_1 \cos(\beta - \alpha) - H^0_2 \sin(\beta - \alpha)$$

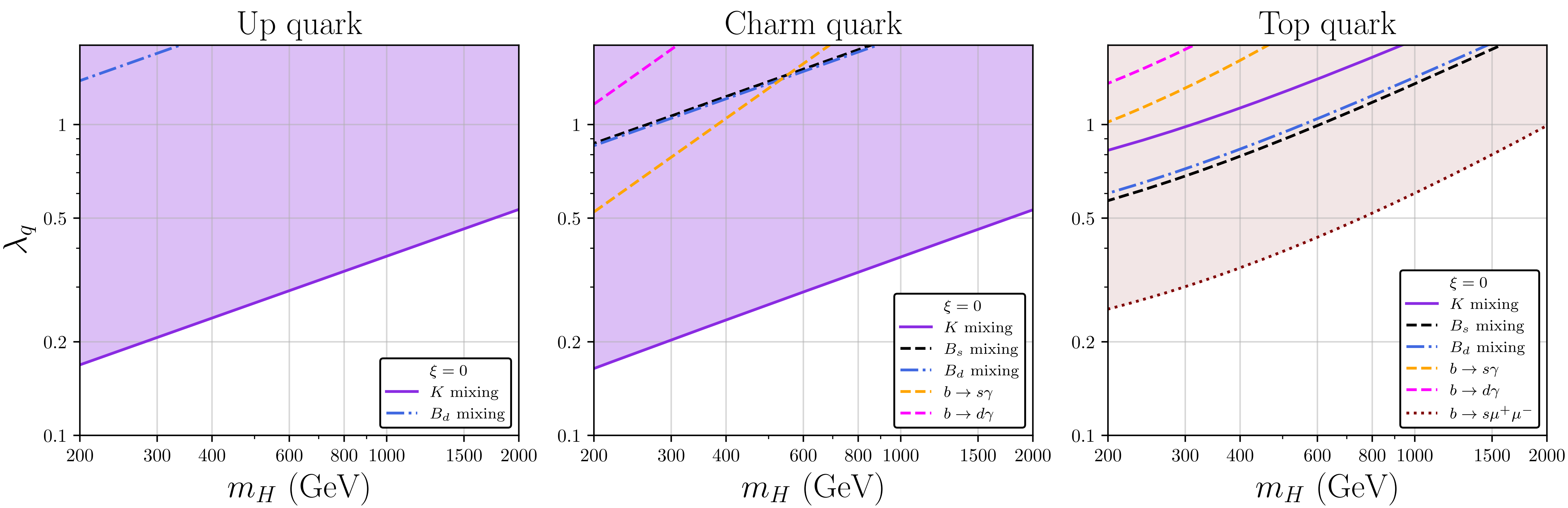
+ a CP-odd and charged ones … for simplicity: $m_H = m_{H^\pm} = m_A$

## DOWN-TYPE SFV ANSATZ ON 2HDM

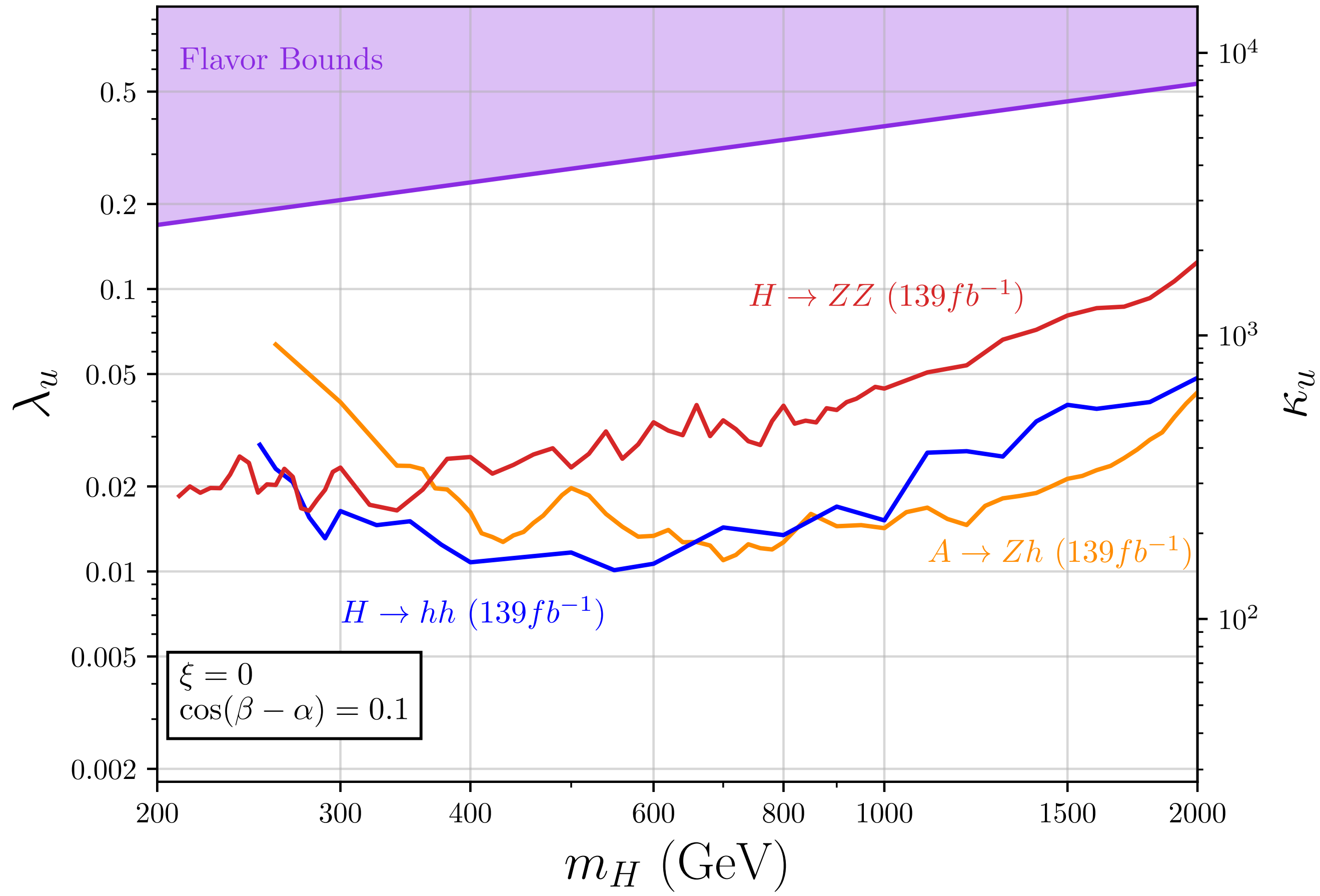
$$\mathcal{Y}^u_1 = y^u = \mathrm{diag}(y_u, y_c, y_t) \qquad \mathcal{Y}^d_1 = V y^d \qquad \mathcal{Y}^\ell_1 = y^\ell$$
$$\mathcal{Y}^u_2 = \lambda^u = \mathrm{diag}(\lambda_u, \lambda_c, \lambda_t) \qquad \mathcal{Y}^d_2 = \xi\, V y^d \qquad \mathcal{Y}^\ell_2 = \xi^\ell y^\ell$$

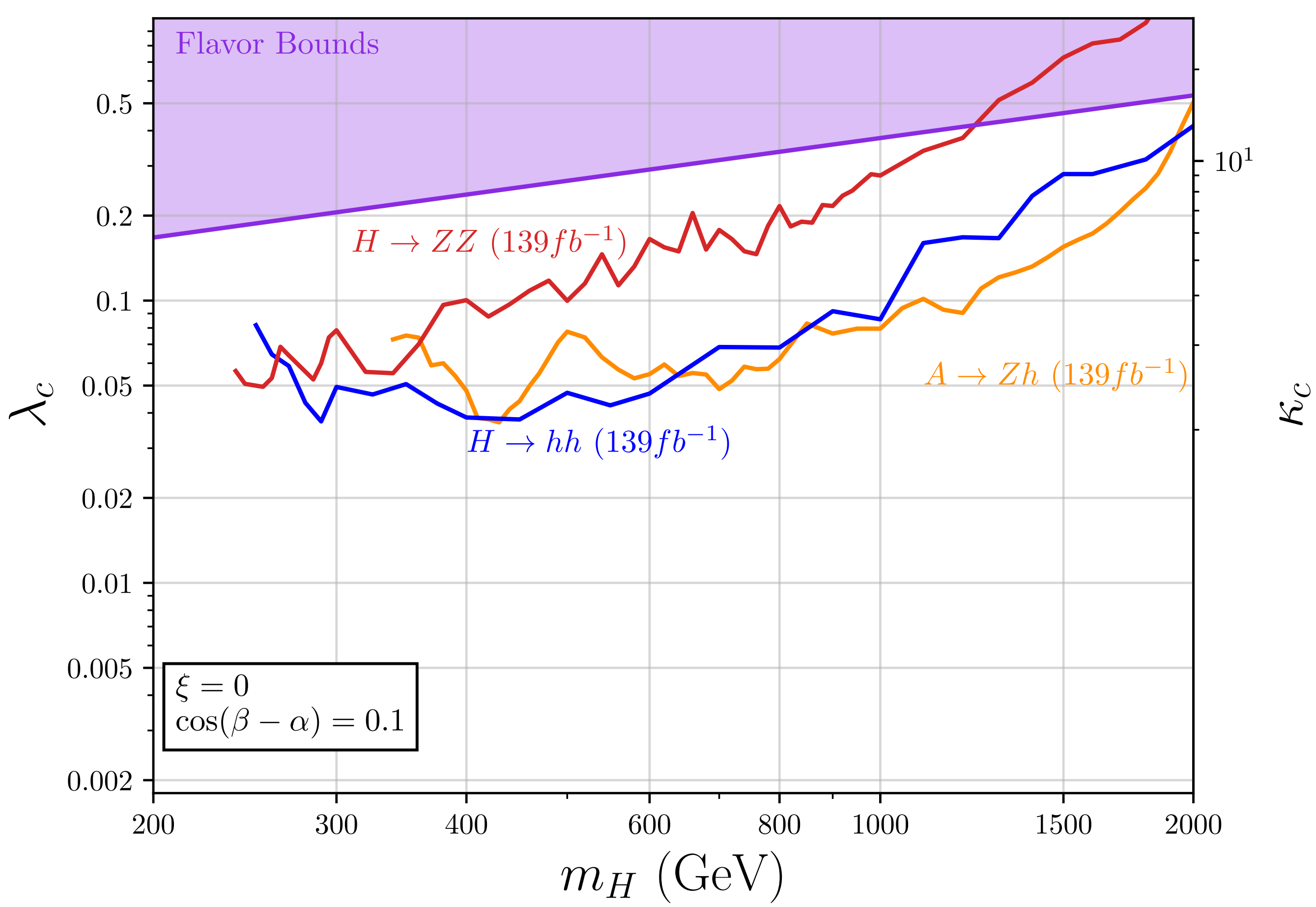



FLAVOR PROTECTION IN DOWN-TYPE SFV ALLOWS NEW HIGGSES @ TEV TO COUPLE TO UP-TYPE QUARKS WITH ~0.1 STRENGTH.

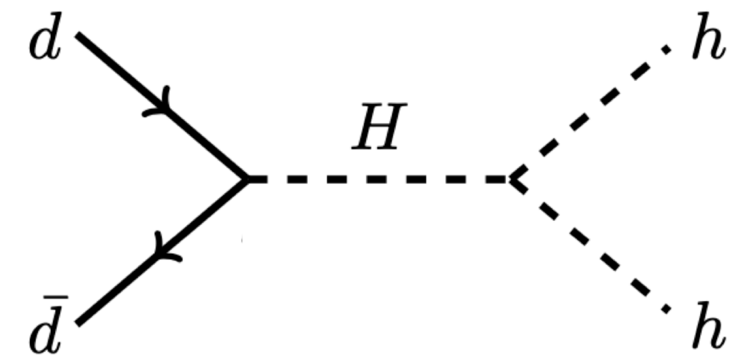



**Same outcome also for the up-type SFV 2HDM.**




**Di-Higgs production is a very sensitive probe of enhanced Higgs couplings to light quarks**




arXiv:**2101.04119**

# DOMINANT COLLIDER BOUNDS FROM SEARCH FOR NEW HIGGSES

- **Mainly from quark fusion, due to possibly large Yukawa**
- **Mostly into di-boson & di-Higgs due to non-zero mixing angle**

OBS.

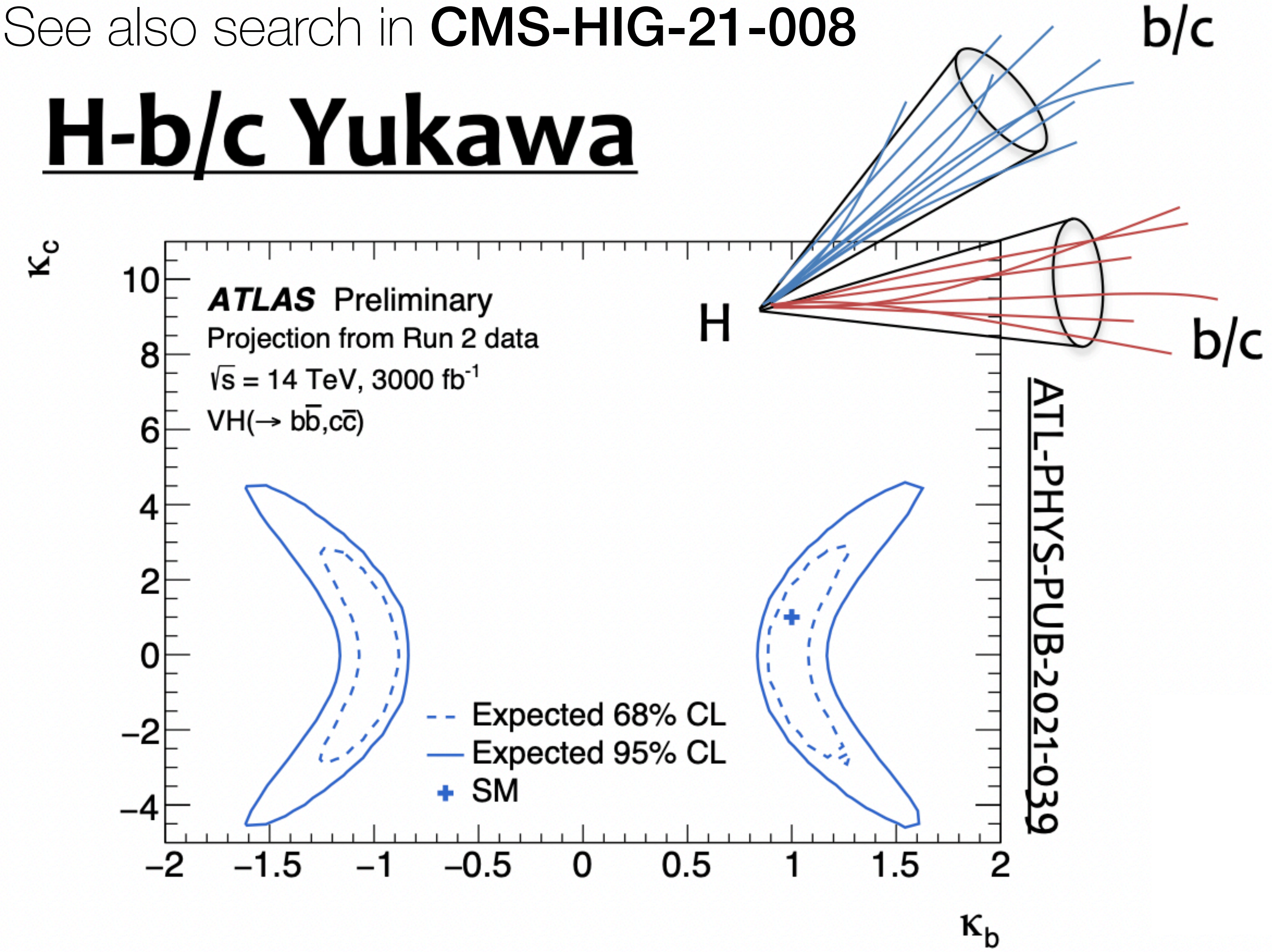
$\kappa_{u,c} \equiv y_{u,c}/y_{u,c}^{\rm SM}$ is the Yukawa modifier

# LHC probing Charm Yukawa!

Boosted topologies allow to disentangle rare signals from very large background ($H \to c\bar{c}$ 20x smaller than $H \to b\bar{b}$)

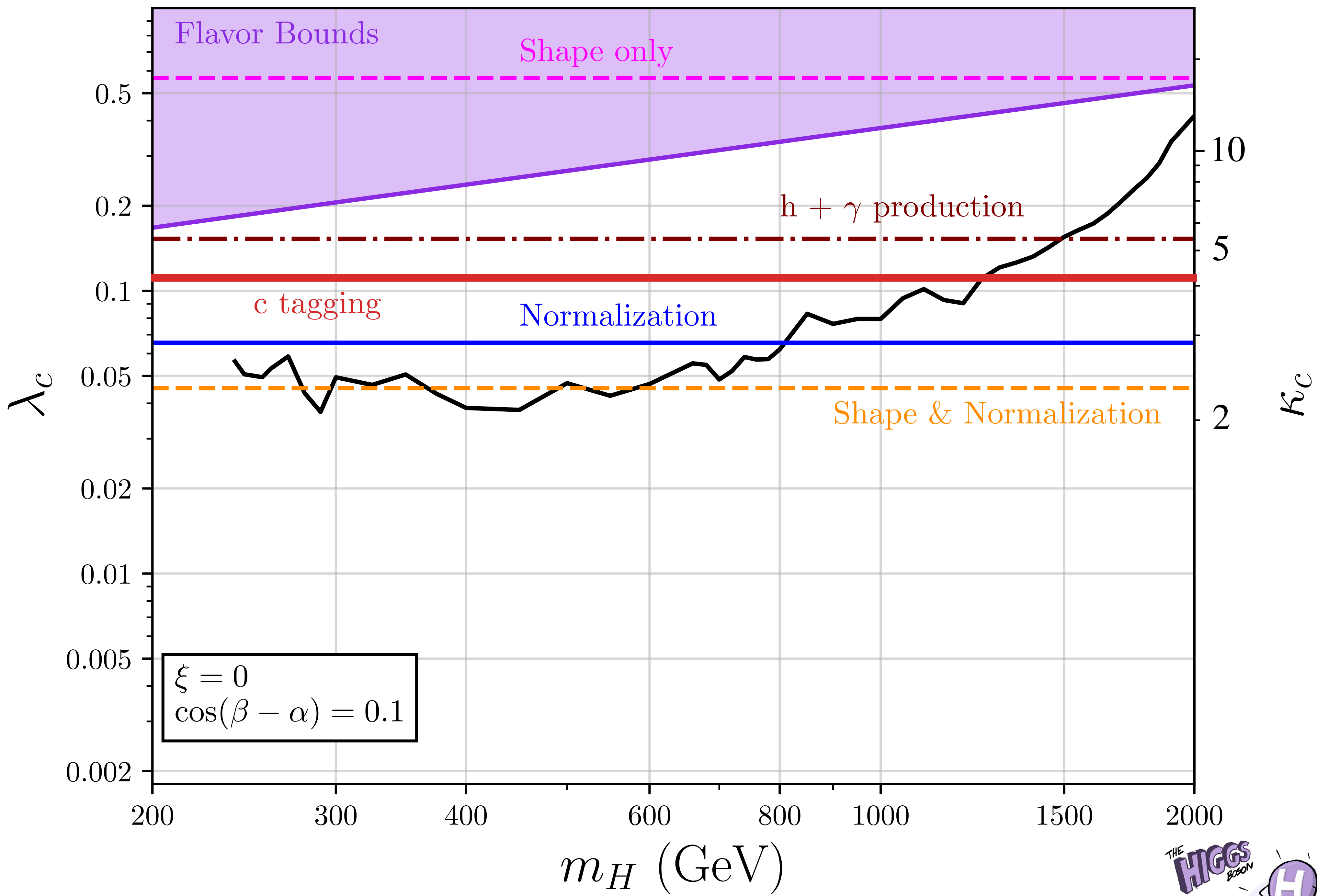
See also search in **CMS-HIG-21-008**

## H-b/c Yukawa



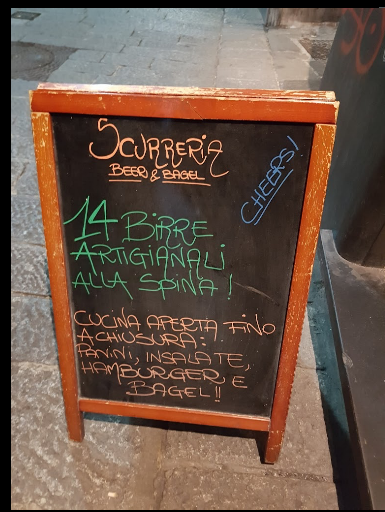

The advent of Deep Learning has been a game changer for ATLAS & CMS sensitivity to Yukawa coupling measurements.

# Charming Higgs @ LHC




arXiv:**2410.05236**

LHC **c tagging** turns out to be a remarkable probe of SFV ansatz





- **Program of precision with flavor is still very rich, but naively points to very high scales for NP.**

  No clear tension emerging from flavor data

- **In absence of evidence for NP, the main direction we pursued for BSM may need a paradigm shift.**

  E.g.: **MFV** hypothesis **—>** **SFV** ansatz

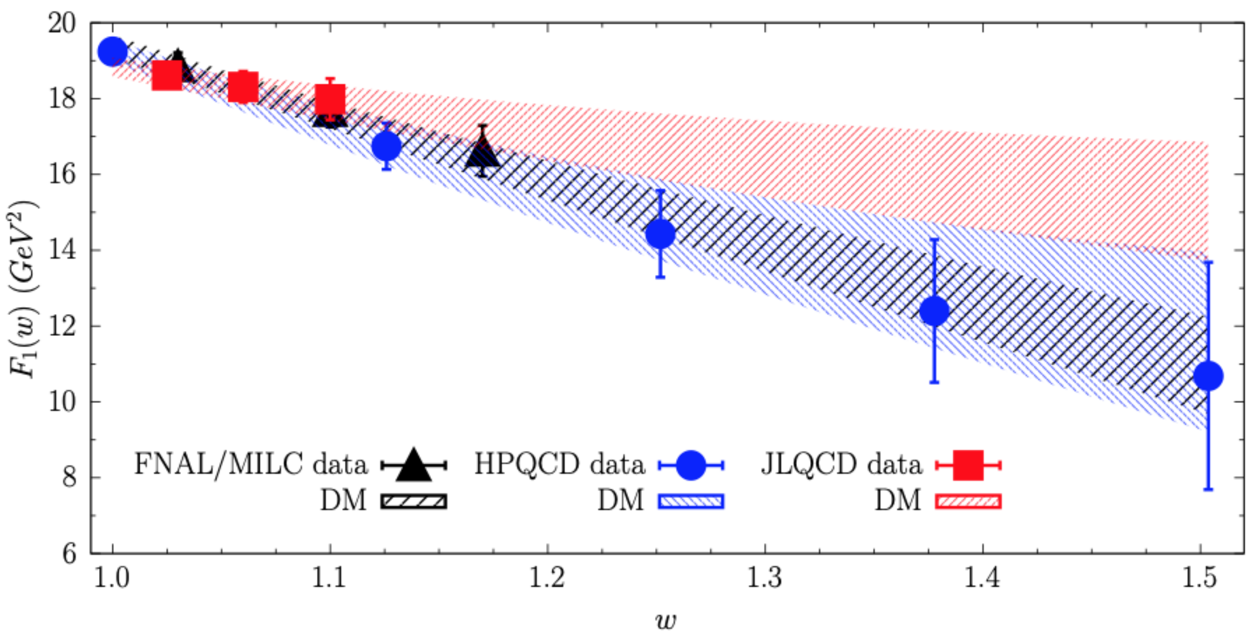
- **Theory + EXP progress can lead to new targets.**

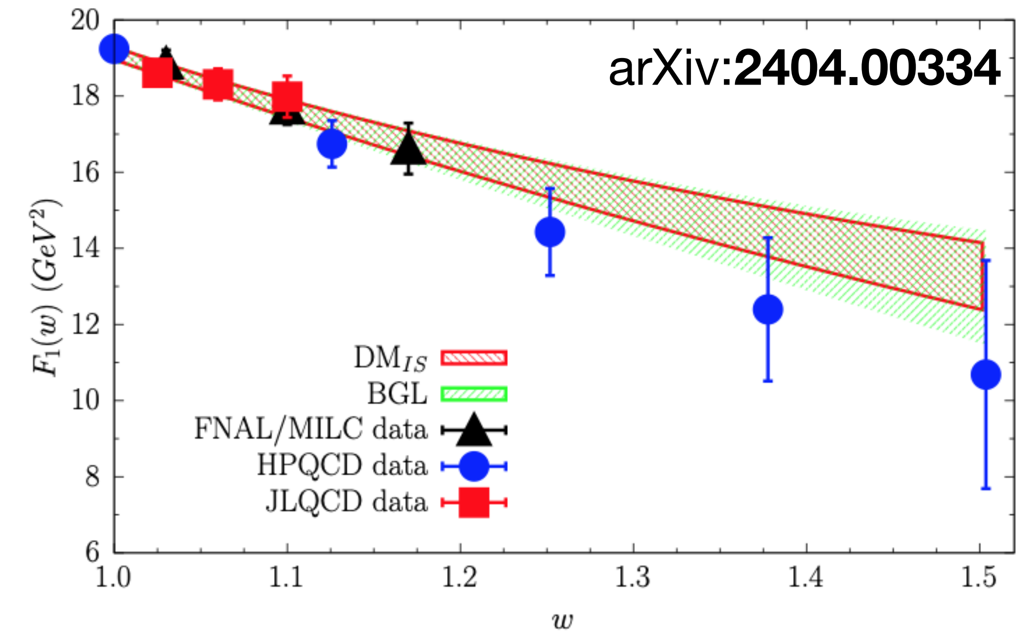
  Higgs Yukawa measurements insightful!

[ See 2410.05236 and also 2410.08272 ]

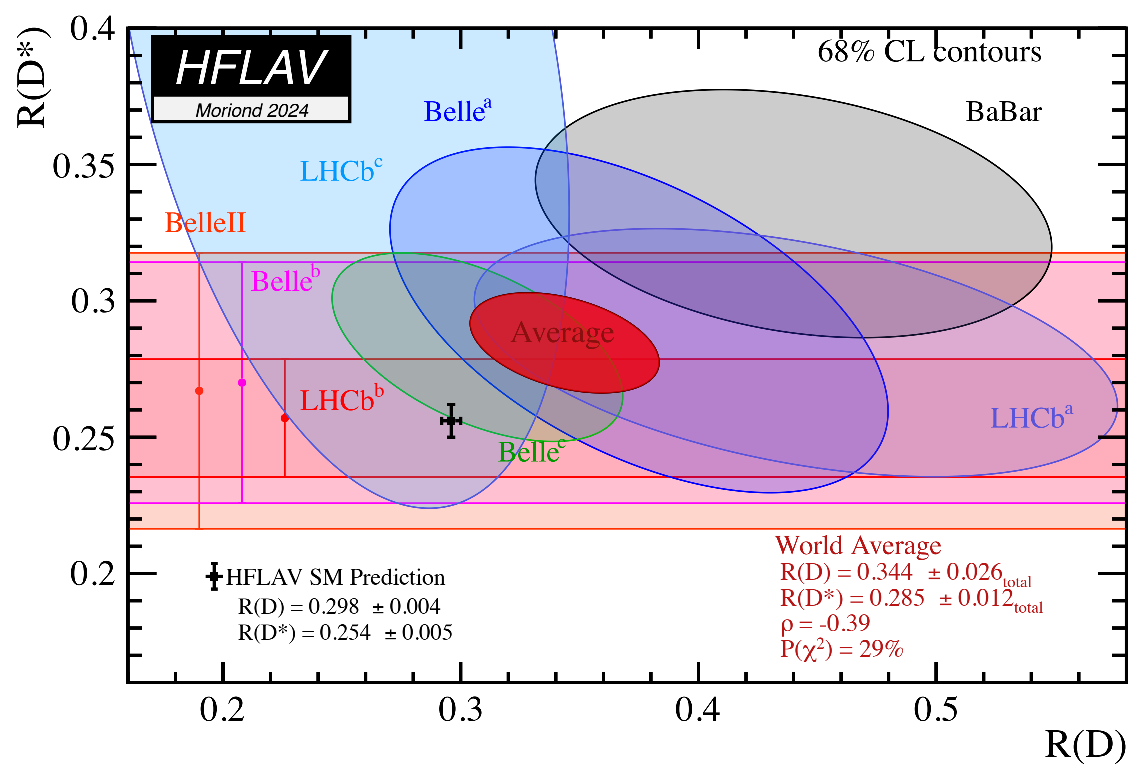
# BACKUP

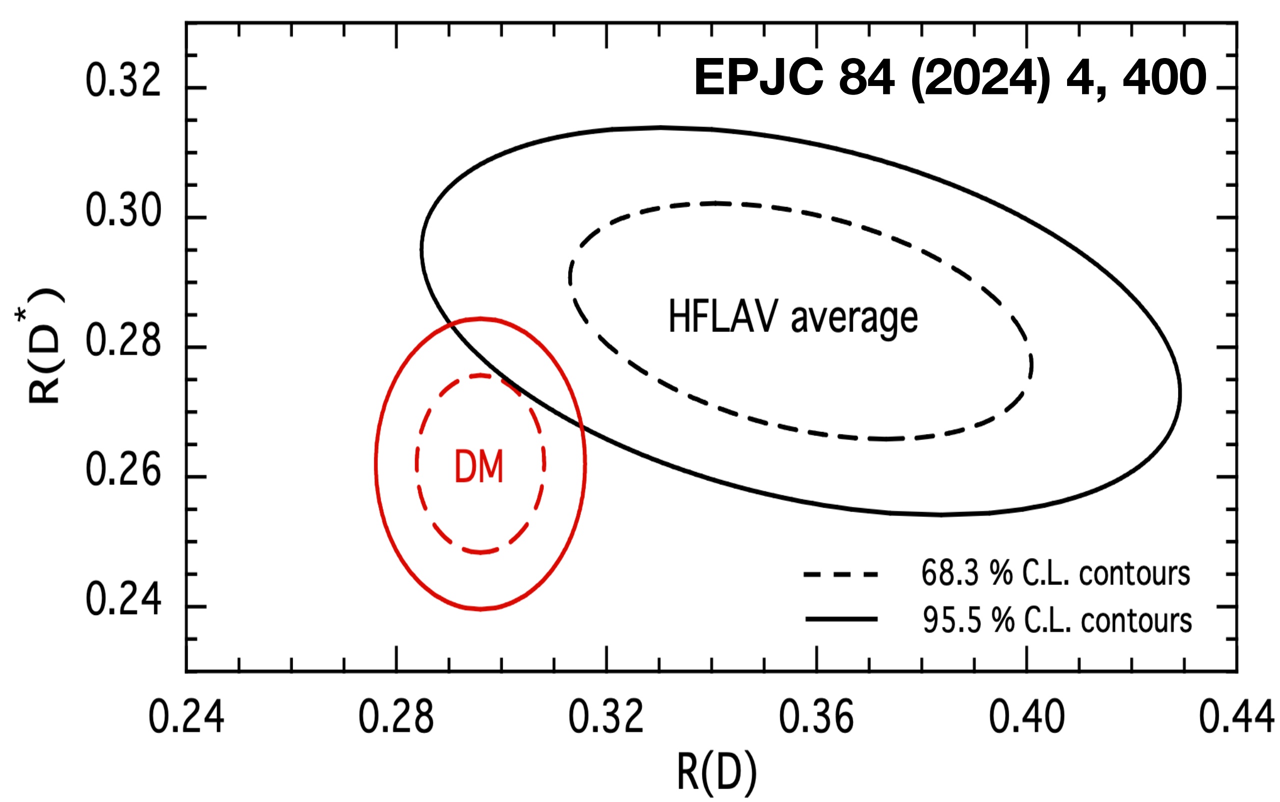
# A LOOk @ $V_{cb}$



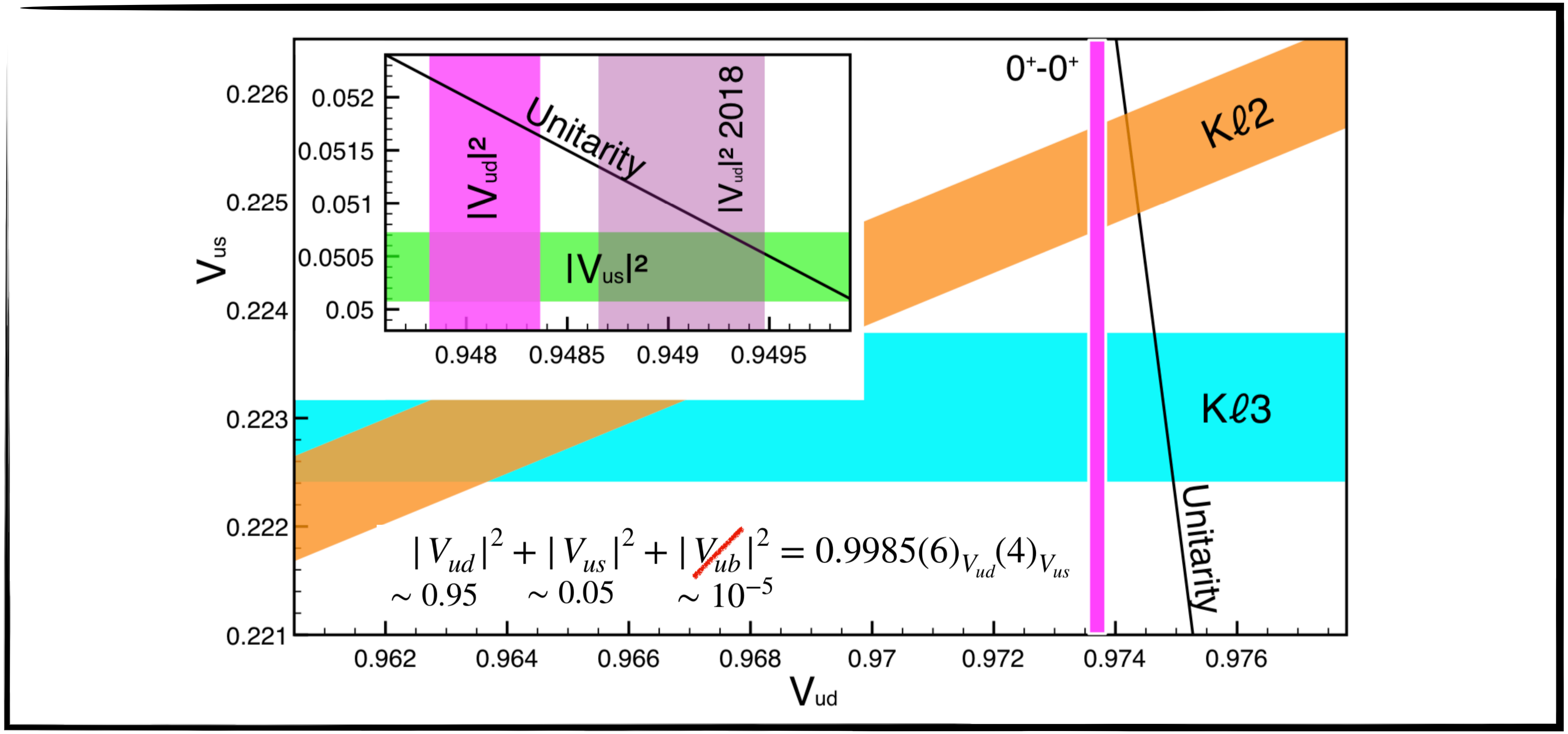

## THE OUTCOME FOR THE OTHER 3 FORM FACTORS IMPACT ALSO $R_{D^{(\star)}}$.



# A L👁👁k @ 1st row

Misha Gorshteyn @ CKM 23




- LQCD on (semi)leptonic decays : Beyond % precision —> **control of $\Delta I$ & 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*

# UT NP Analysis — Wiki How

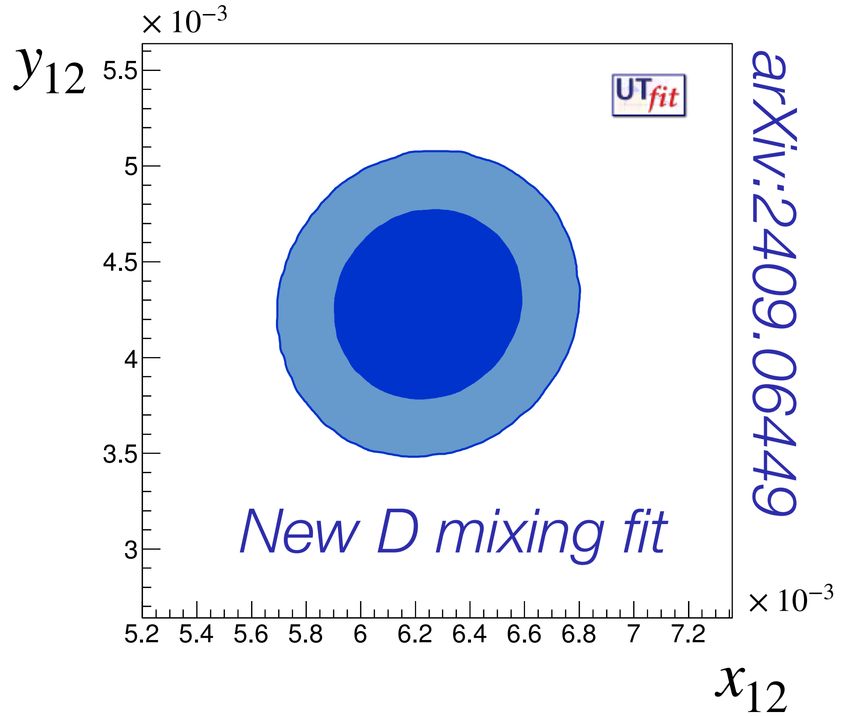
- Parametrize generic NP effects in | ΔF | = 2 transitions:

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

- Include an extended list of observables to study also NP:

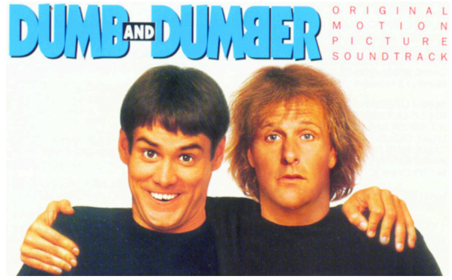
- **same-side dilepton charge asymmetry**
- **semileptonic asymmetries in $B^0$ and $B_s$**
- **lifetime $\tau^{FS}$ in flavour-specific final states**
- **$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$**

+




- Fit simultaneously CKM & NP —> bound on NP scale

O(10) new parameters



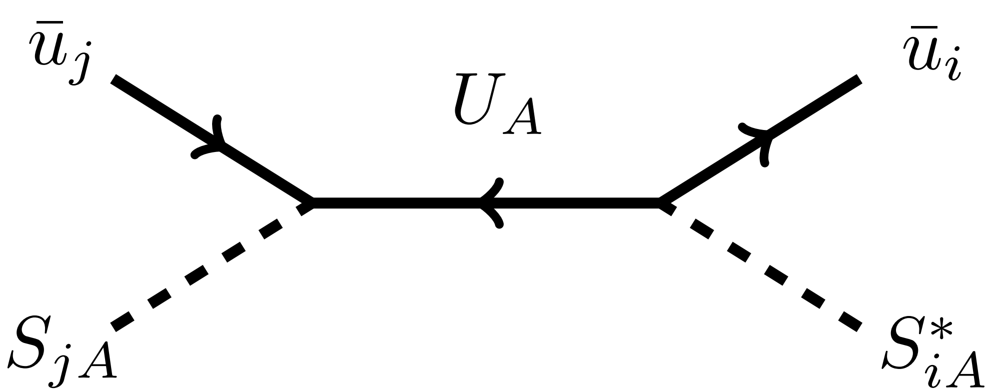

# : Vector-like quark

$$\mathcal{L} \supset M_{AB} U_A \bar{U}_B + \xi S_{iA} \bar{u}_i U_A$$
$$- \left[ \eta^u_{ij} \, Q_i \, H \, \bar{u}_j - \eta^d_{ij} \, Q_i \, H^c \, \bar{d}_j + \text{h.c.} \right] + \mathcal{L}_{\text{BSM}}$$

*No additional spurions/fields transforming under $U(3)_{\bar{u}}$*

Introduce mixing between up-quark and heavy VLQs in a flavor breaking vacuum

| | $U(3)_U$ | $U(3)_{\bar{U}}$ | $U(3)_{\bar{u}}$ | $U(1)_B$ | $\mathbb{Z}_2$ |
|---|---|---|---|---|---|
| $U$ | $3$ | | | $1/3$ | $-1$ |
| $\bar{U}$ | | $3$ | | $-1/3$ | $-1$ |
| $S$ | $\bar{3}$ | | $\bar{3}$ | | $-1$ |




Integrating out heavy quarks leads to wave-function renormalization of the SM up-quarks

$$Z^u_{ij} = \delta_{ij} + \frac{\xi^* \xi}{M^*_A M_A} S^*_{iA} S_{jA}$$

*The source of all flavor-breaking!*
*CKM matrix arises from returning to canonical basis*

S.Homiller@PPC2021

IN GENERAL, TWO CLASSES OF **SFV**: **UP-TYPE** AND **DOWN-TYPE**