— 59th Rencontres de Moriond 2025 —

La Thuile, Italy - 29 / 03 / 25

Charming 

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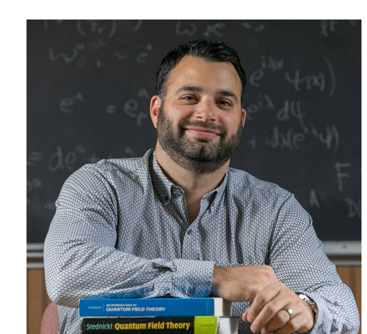
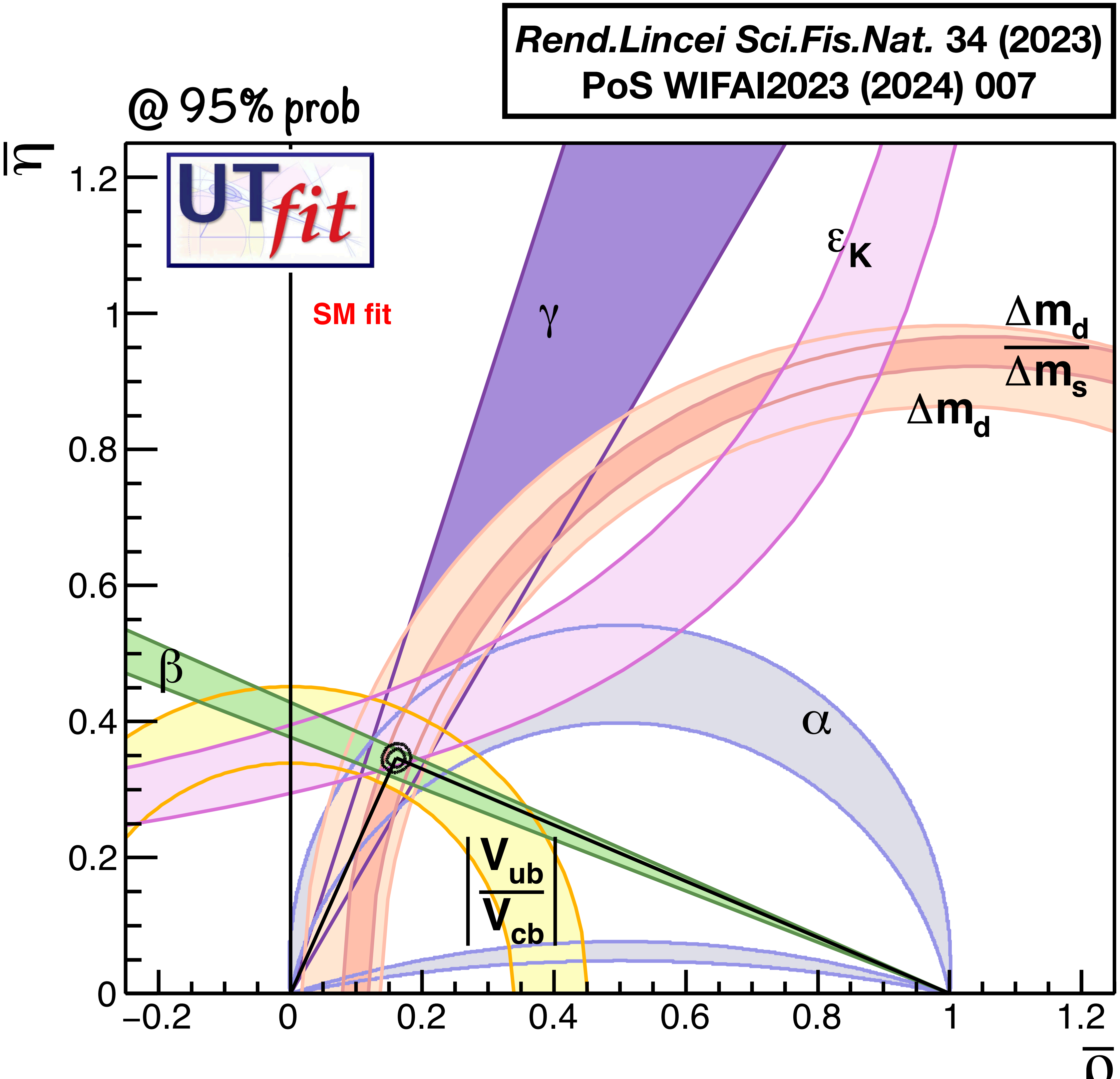
In collaboration w/: **Artemis Giannakopoulou** & **Patrick Meade**



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

UTA: Unitarity Triangle Analysis

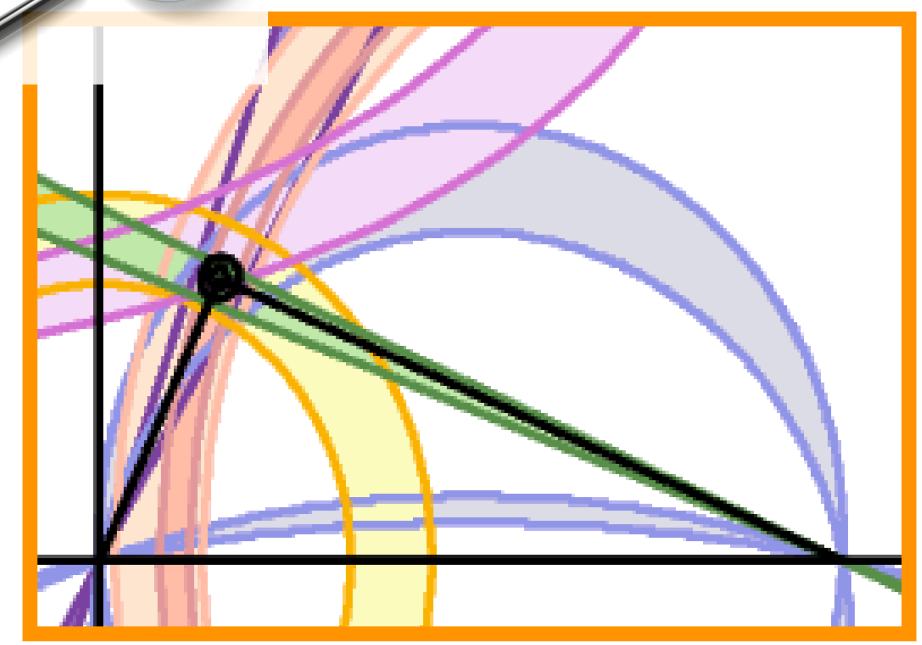


$$\bar{\rho} = 0.160 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.346 \pm 0.009 \sim 3\%$$

UT determination towards % precision

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

Zoomed-in Unitarity Triangle



Analogous results from the CKMfitter collaboration.

Flavor & BSM Physics

PoS WIFAI2023 (2024) 007

Most general |ΔF| = 2 H_{eff}:

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

SM

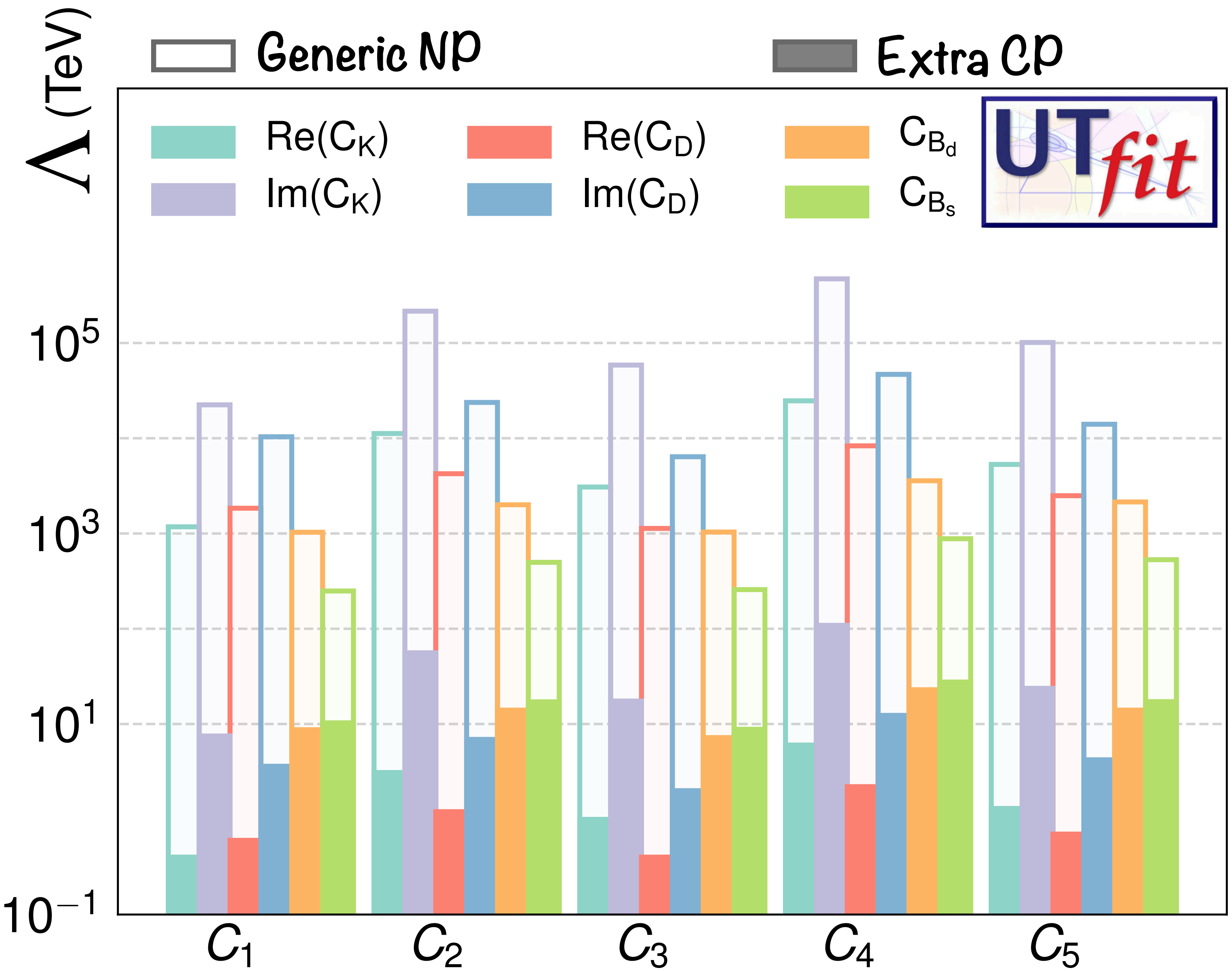
$$O_2^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\,\bar{q}_{jR}^{\beta} q_{iL}^{\beta}$$

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

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

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

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

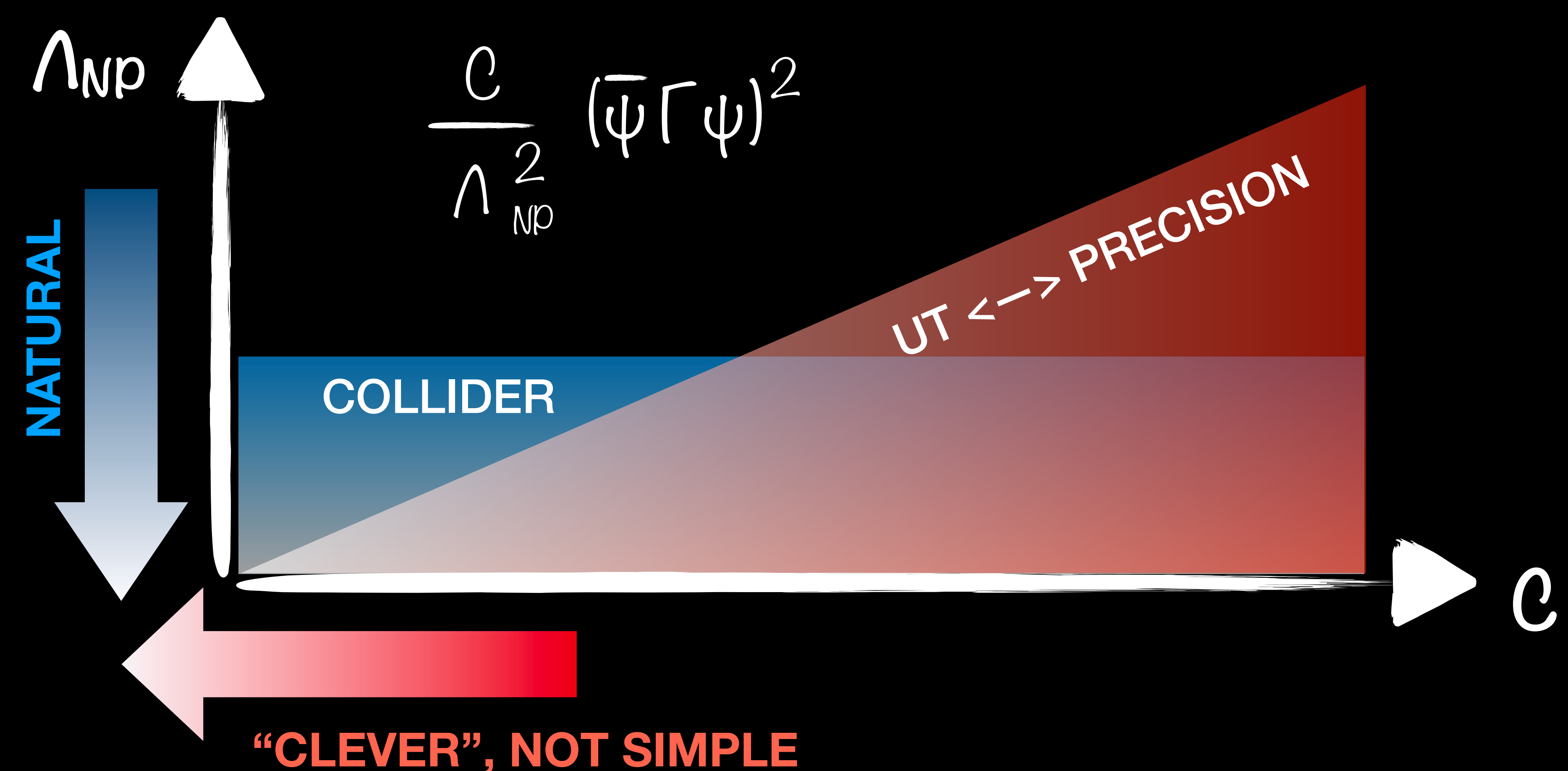


- **Generic NP** = no SM protection, i.e.: $C(\Lambda) \sim 1/\Lambda^2$ ⇨ $\Lambda > 4.7 \times 10^5$ TeV
- **Extra CP** = SM-like protection but new O(1) phases ➡ $\Lambda > 108$ TeV

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

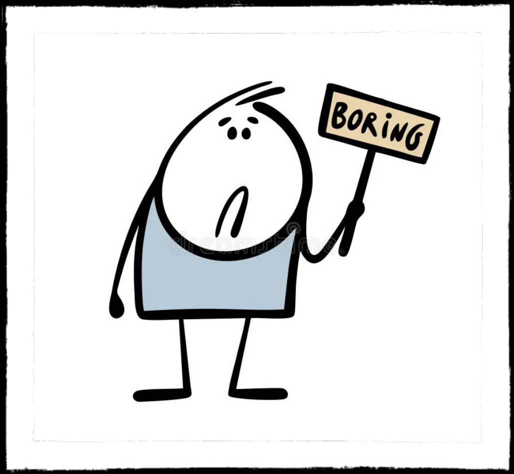
$\Rightarrow$ $Y^d \sim (3, \bar{3}, 1) \qquad Y^u \sim (3, 1, \bar{3})$

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

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

—> **M**INIMAL **F**LAVOR **V**IOLATION (*Nucl.Phys.B* 645 (2002) 155)

aka **M**AXIMAL **F**LAVOR **C**ONSERVATION (*see* ***arXiv:2402.09503***)

MFV <—> 

Can we avoid large FCNCs and have BSM with radically different flavor 

Another Way to Be Clever: Alignment!

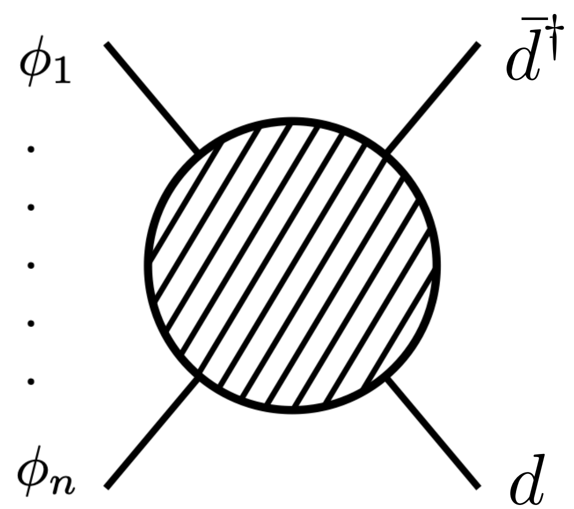
See also V. Miralles talk!

— 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

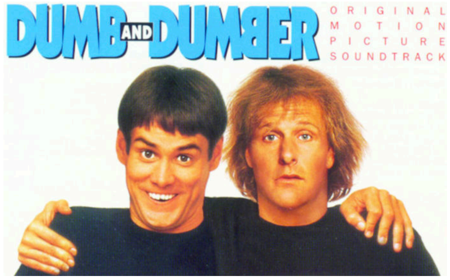


$$\mathcal{L} \supset iZ^d_{ij}\,\bar{d}_i^\dagger \bar{\sigma}^\mu d_j + i\bar{u}_i^\dagger \bar{\sigma}^\mu u_i + i\bar{Q}_i^\dagger \bar{\sigma}^\mu Q_i$$
$$+ \text{ Yukawa terms all flavor diagonal}$$

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

The up-quark sector remains aligned.

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



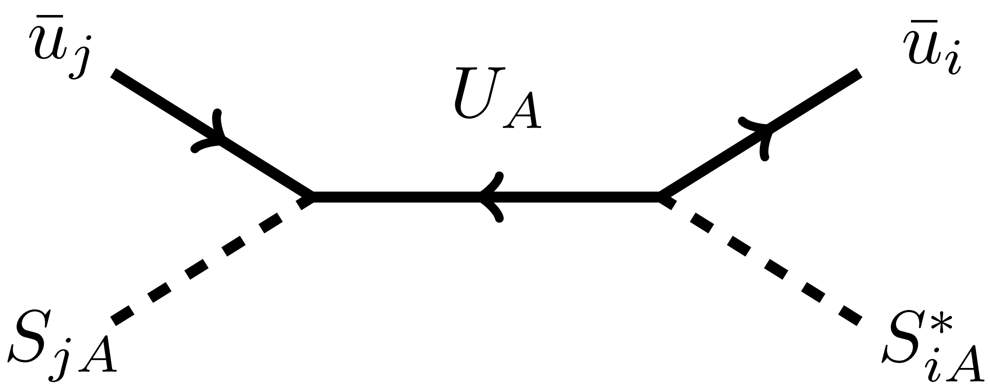
: Vector-like quark

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

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

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

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:

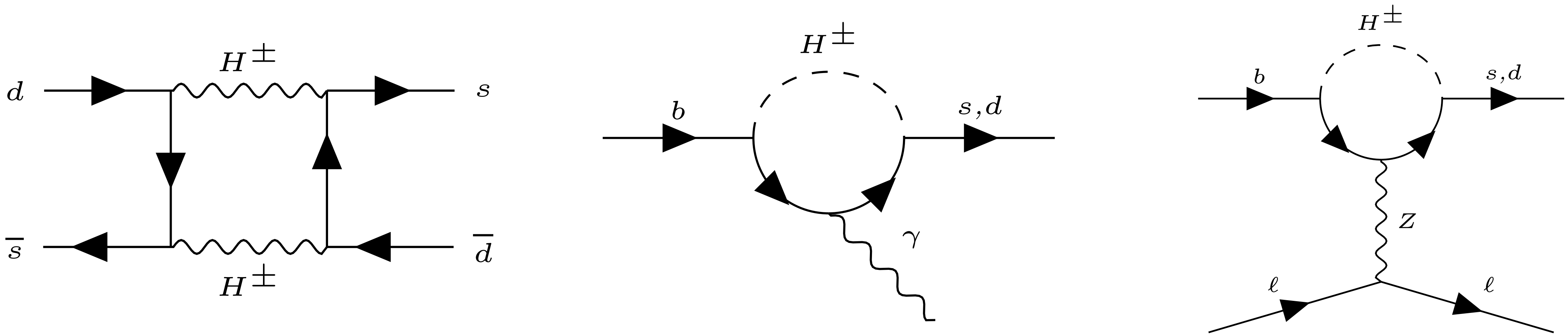
$\cos(\beta - \alpha) \neq 0$ **interesting!**

$$h = H_1^0 \sin(\beta - \alpha) + H_2^0 \cos(\beta - \alpha)$$
$$H = H_1^0 \cos(\beta - \alpha) - H_2^0 \sin(\beta - \alpha)$$

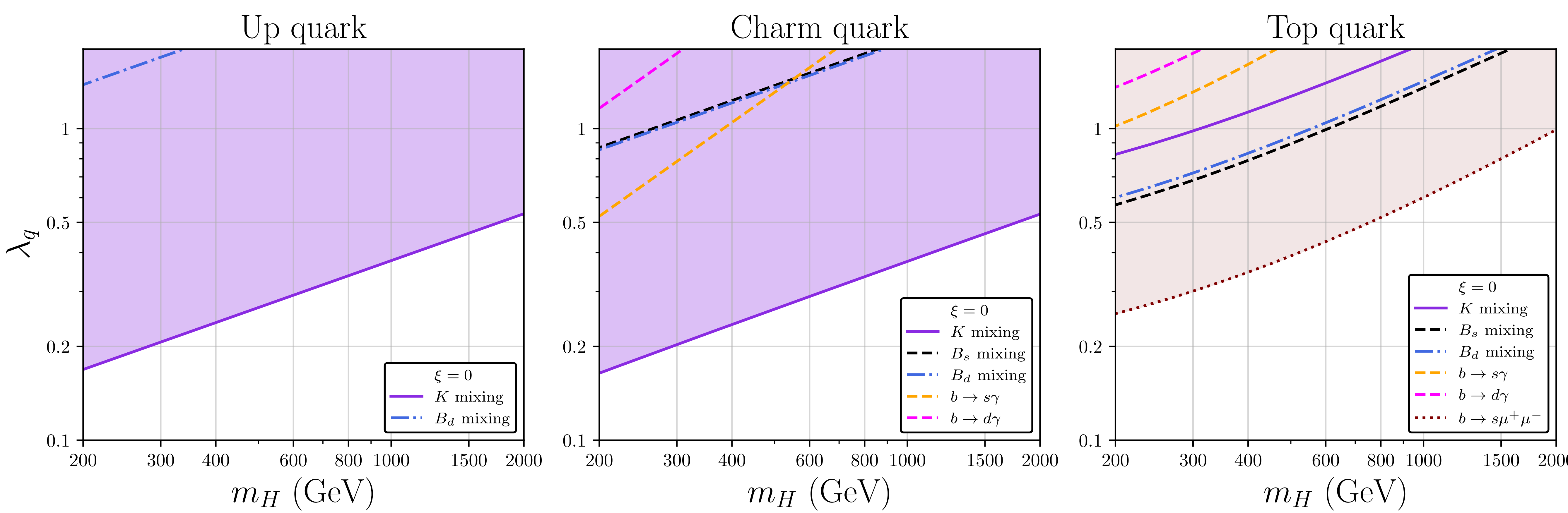
+ a CP-odd and charged ones … for simplicity: $m_H = m_{H^\pm} = m_A$

DOWN-TYPE SFV ANSATZ ON 2HDM

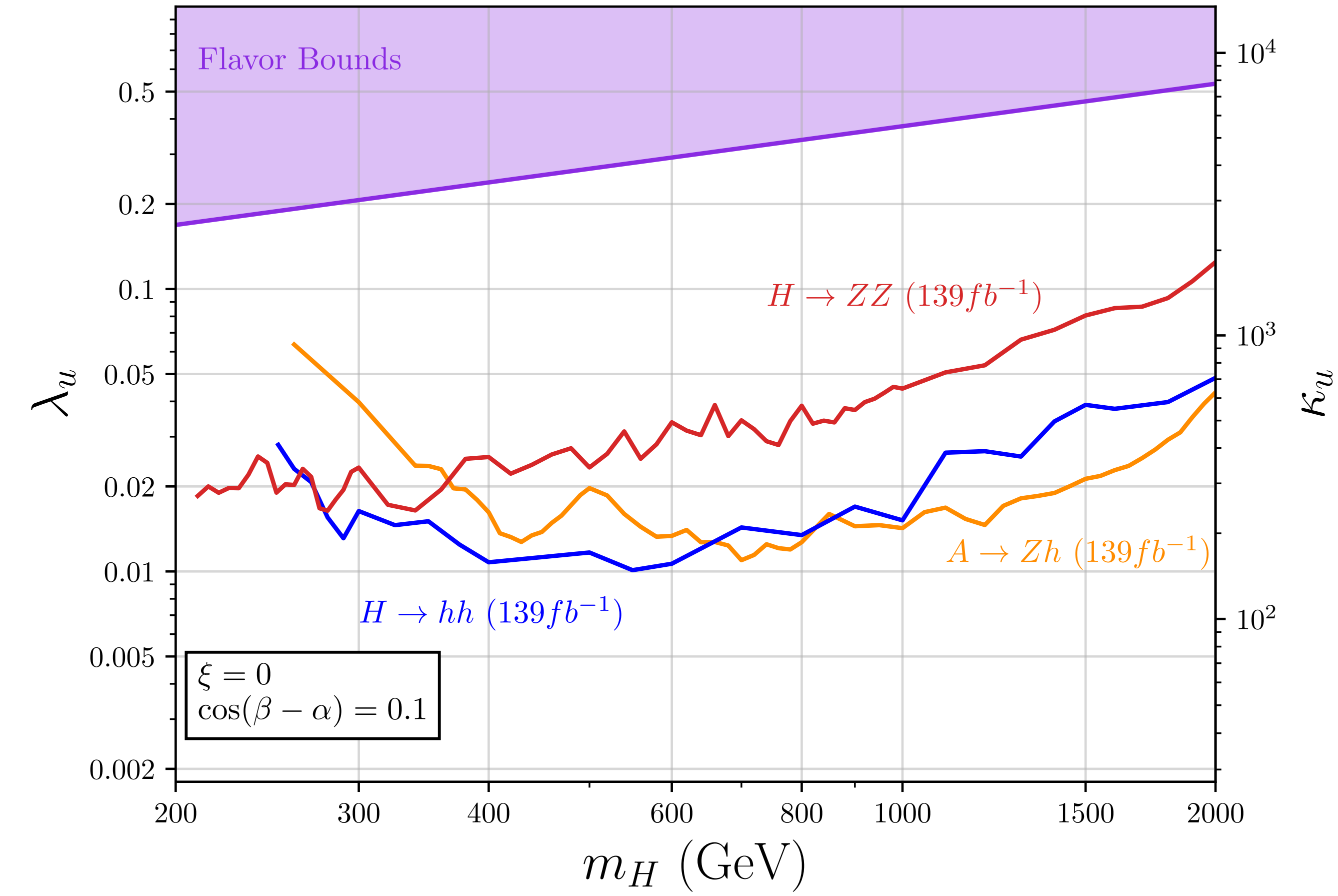
$$\mathcal{Y}^u_1 = y^u = \mathrm{diag}(y_u, y_c, y_t) \qquad \mathcal{Y}^d_1 = V y^d \qquad \mathcal{Y}^\ell_1 = y^\ell$$
$$\mathcal{Y}^u_2 = \lambda^u = \mathrm{diag}(\lambda_u, \lambda_c, \lambda_t) \qquad \mathcal{Y}^d_2 = \xi\, V y^d \qquad \mathcal{Y}^\ell_2 = \xi^\ell y^\ell$$

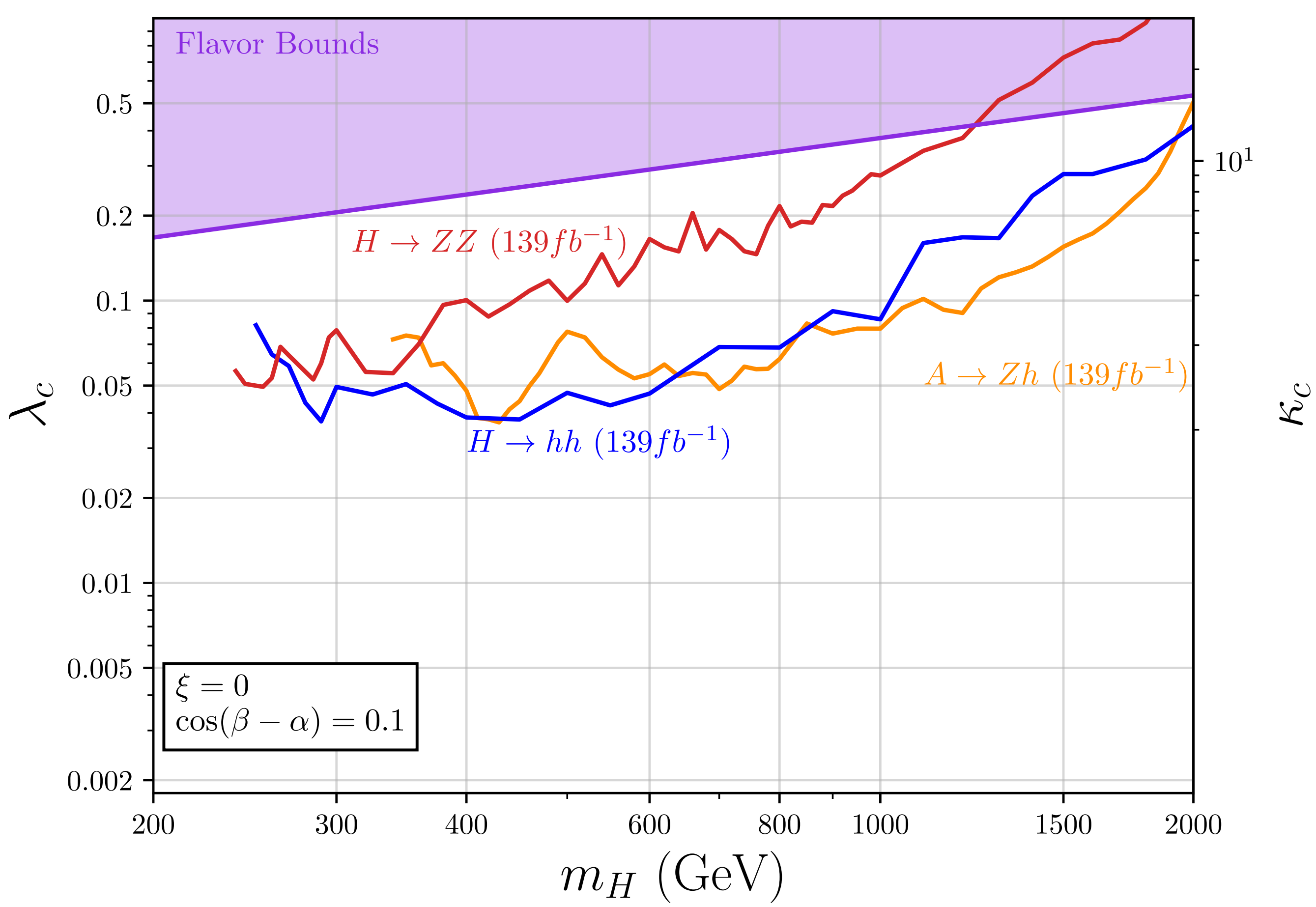


FLAVOR PROTECTION IN DOWN-TYPE SFV ALLOWS NEW HIGGSES @ TEV TO COUPLE TO UP-TYPE QUARKS WITH ~0.1 STRENGTH.

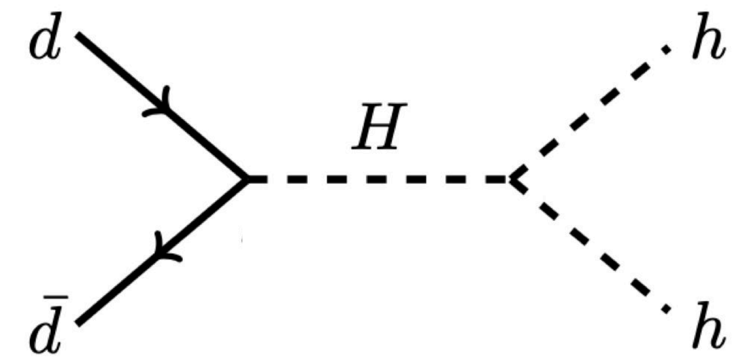


Same outcome also for the up-type SFV 2HDM.





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**

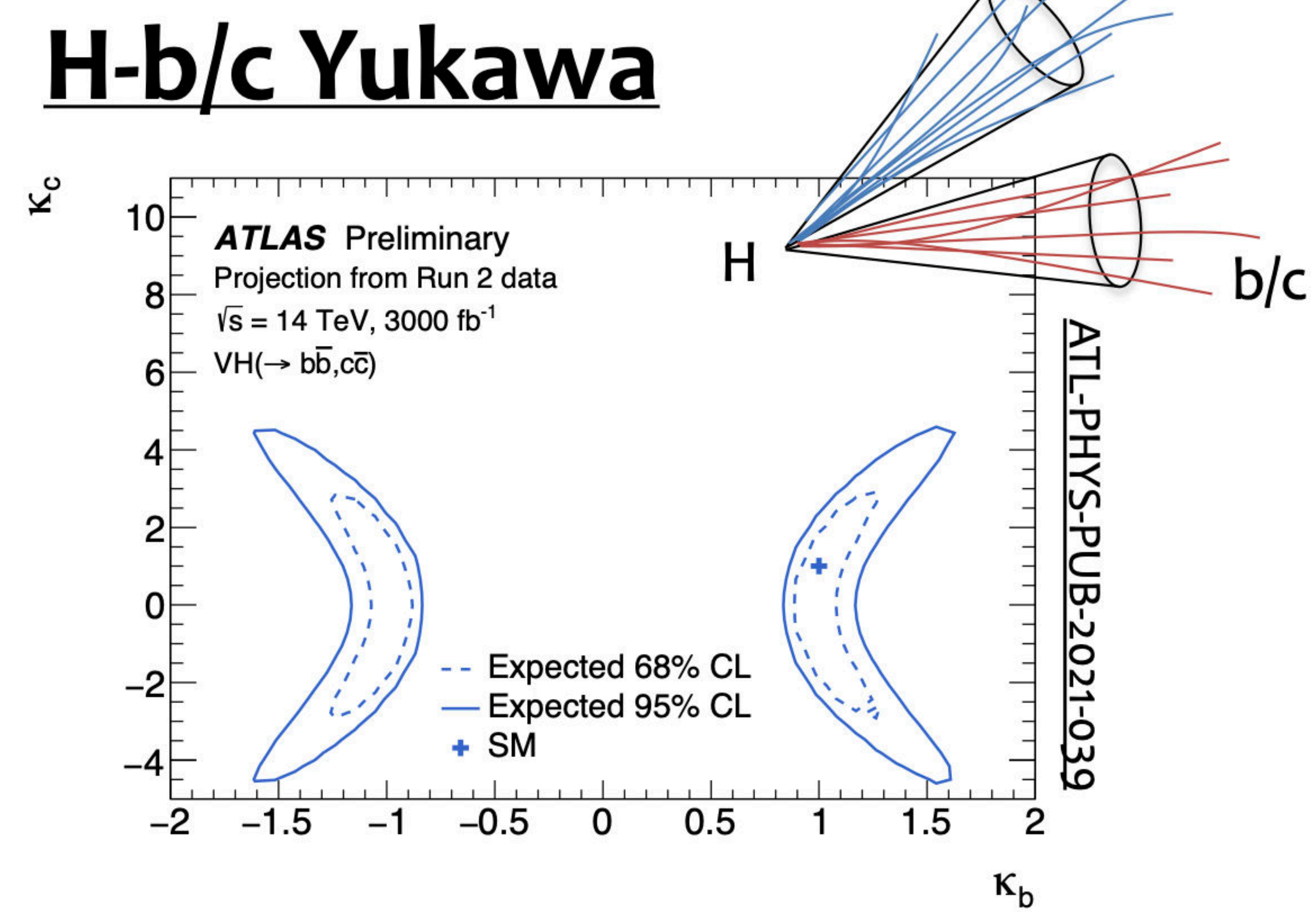
OBS.

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

LHC probing Charm Yukawa!

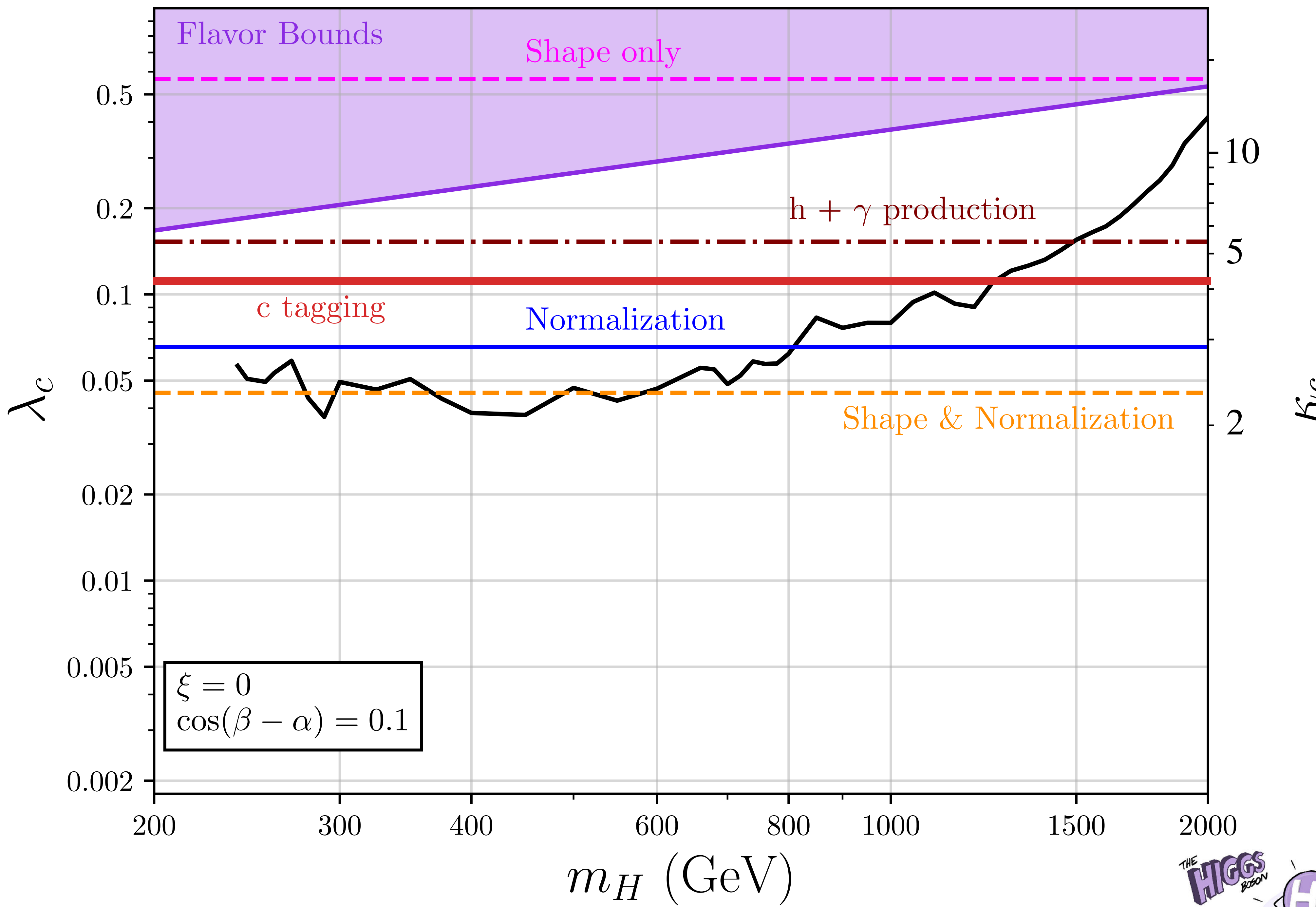
Boosted topologies allow to disentangle rare signals from very large background ($H \to c\bar{c}$ 20x smaller than $H \to b\bar{b}$)

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



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 scenarios!

- **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]