

# How Charming Can  Be?



**Mauro Valli**

INFN Rome

INFN

arXiv:**2410.05236** (about to appear in **JHEP**)

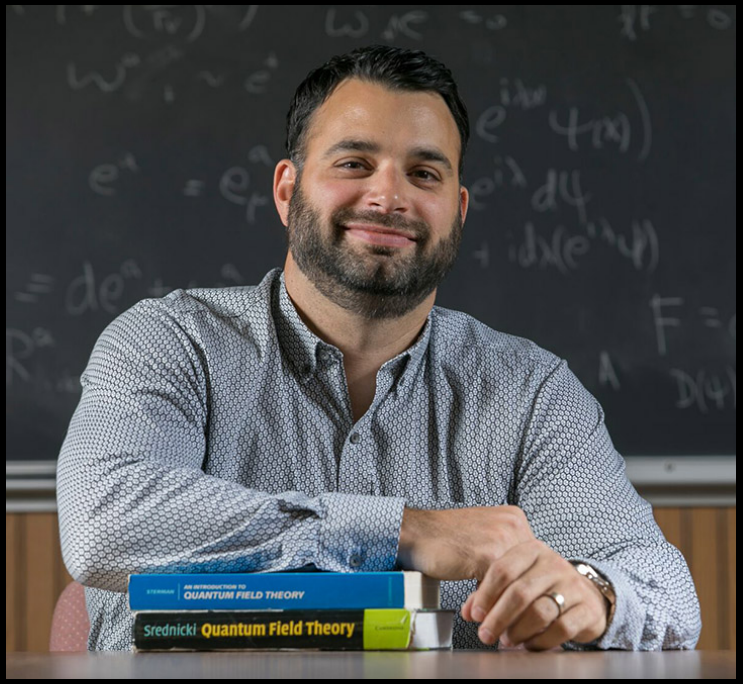
## How charming can the Higgs be?

---


**Artemis Sofia Giannakopoulou,[a] Patrick Meade[a] and Mauro Valli[b]**

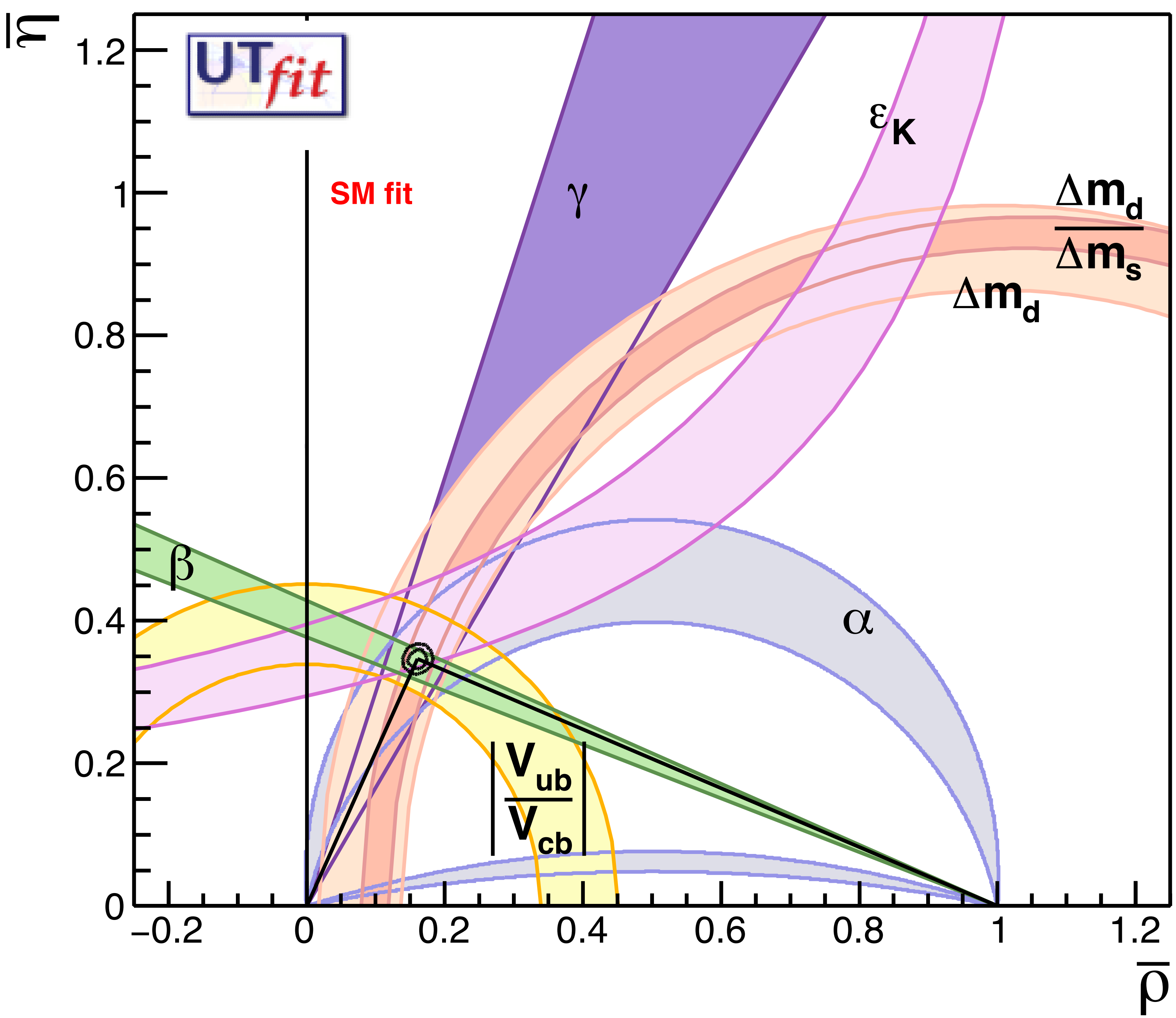
[a] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA*
[b] *INFN Sezione di Roma, Piazzale Aldo Moro 2, I-00185 Rome, Italy*


Artemis Giannakopoulou




*Mr.* μUON COLLIDER

# UTA: Unitarity Triangle Analysis

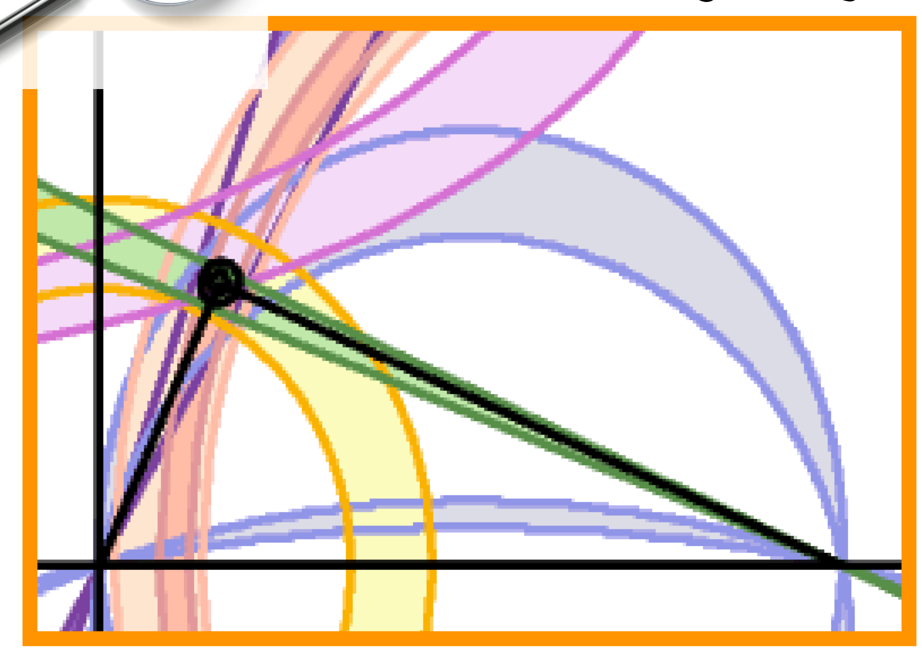



$$\bar{\rho} = 0.160 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.346 \pm 0.009 \sim 3\%$$

UT determination towards % precision

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

Zoomed-in Unitarity Triangle



# Flavor & BSM Physics

PoS WIFAI2023 (2024) 007

SM

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

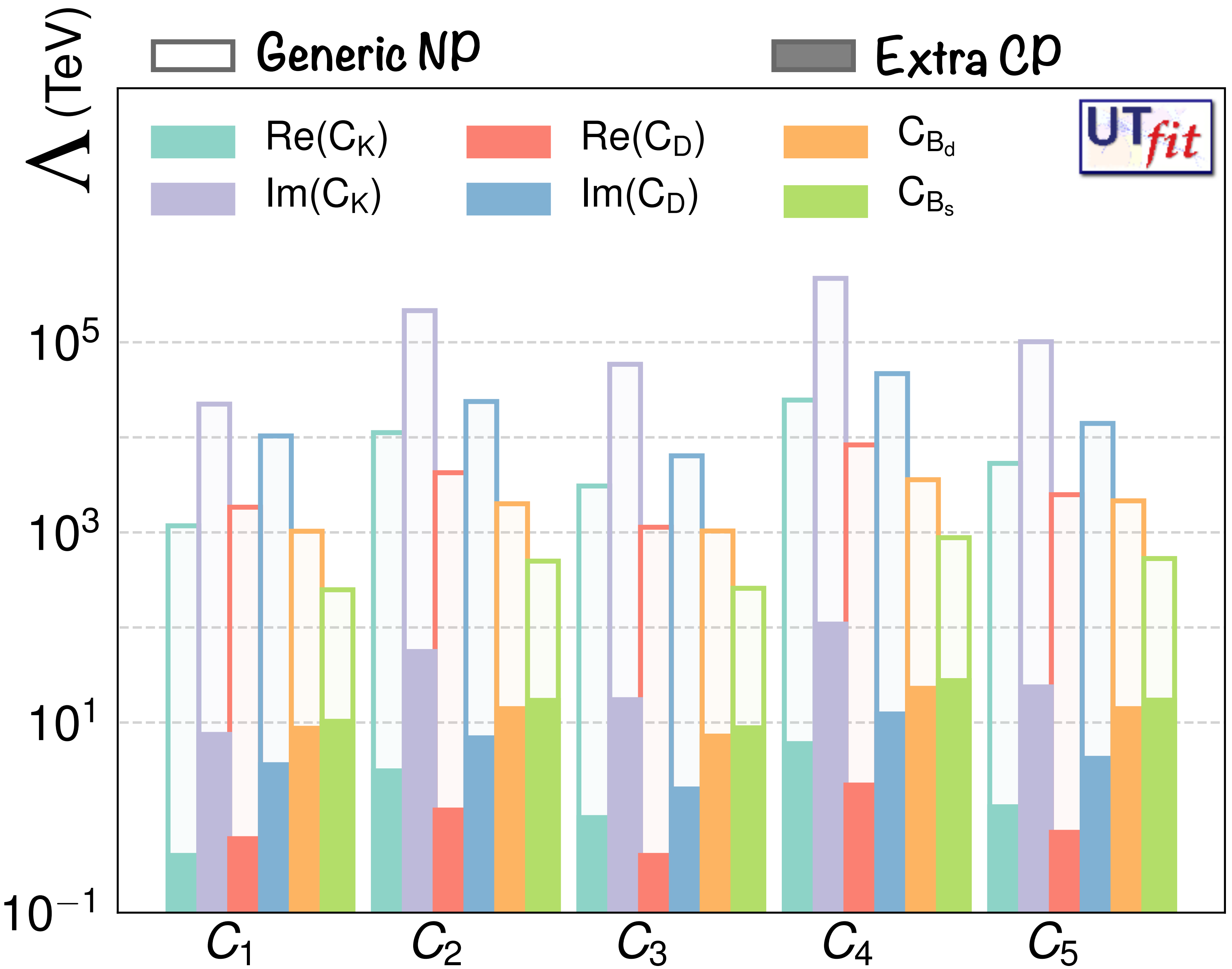
$$O_2^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \, \bar{q}_{jR}^{\beta} q_{iL}^{\beta}$$

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

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

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

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

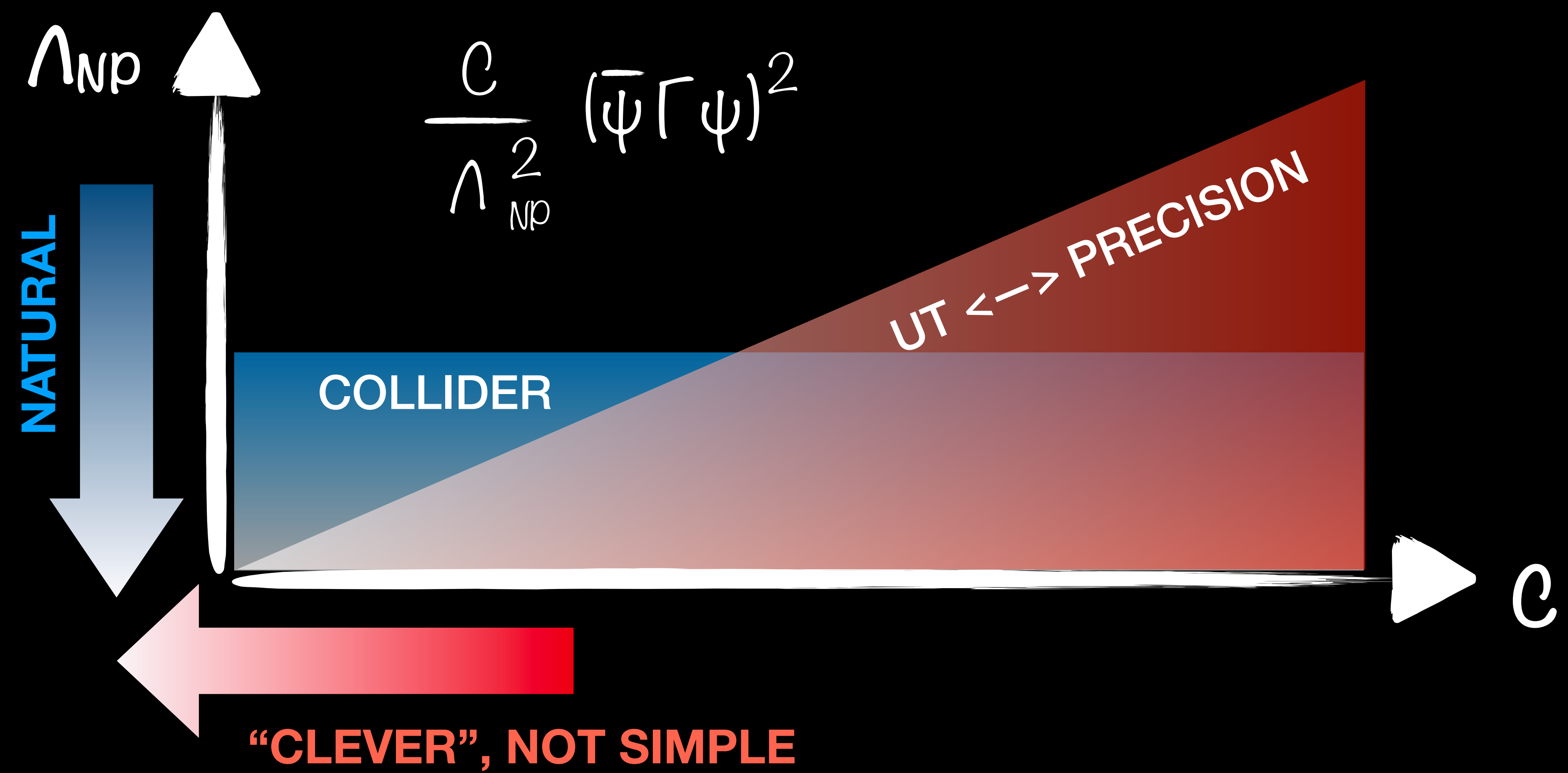



- **Generic NP** = no SM protection, i.e.: $C(\Lambda) \sim 1/\Lambda^2$ ⇨ $\Lambda > 4.7 \times 10^5$ TeV
- **Extra CP** = SM-like protection but new O(1) phases ➡ $\Lambda > 108$ TeV

# Lessons from Precision

- **SM UT:** Towards % precision … overall remarkable consistency!
  *—> in the HL-LHC era we can hope for 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.: $-\mathcal{L}_{\rm SM} \supset Y^d_{ij}\,\overline{Q}_i H d_j + Y^u_{ij}\,\overline{Q}_i \widetilde{H} u_j + h.c.$

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

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]

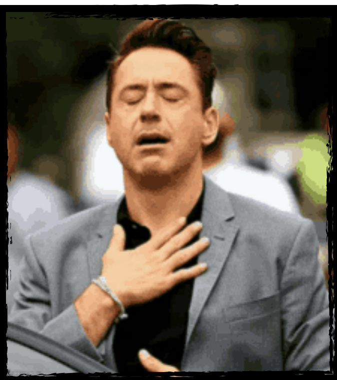
*aka* **M**AXIMAL **F**LAVOR **C**ONSERVATION (*in Lausanne)*

# MFV leaves room for New Physics just above a few TeV.

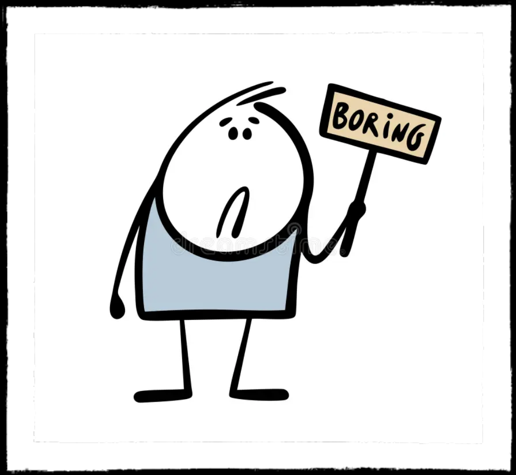
| Model-independent bounds on the standard model effective theory from flavour physics | Physics Letters B<br>Volume 799, 10 December 2019, 135062 |
|---|---|

# **MFV** leaves room for **New Physics** just above a **few TeV**.

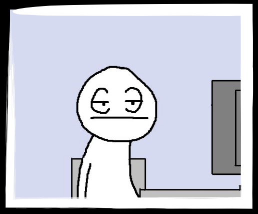
| Model-independent bounds on the standard model effective theory from flavour physics | Physics Letters B<br>Volume 799, 10 December 2019, 135062 |
|---|---|



Little Hierarchy problem possibly not too bad …

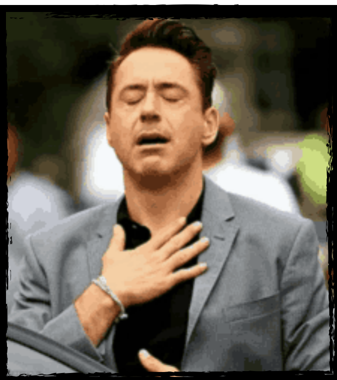
But … isn't MFV … 

, though?

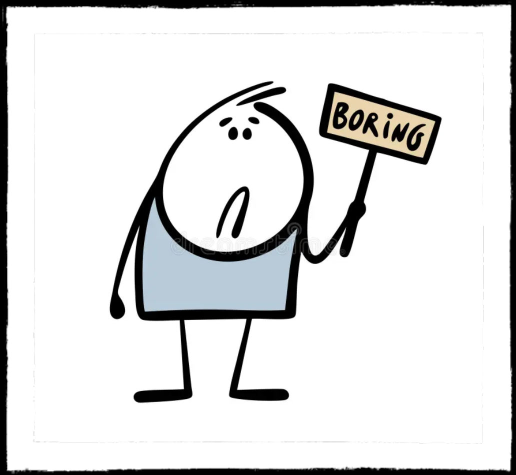
BSM pheno driven by couplings to 3rd gen 

# **MFV** leaves room for **New Physics** just above a **few TeV**.

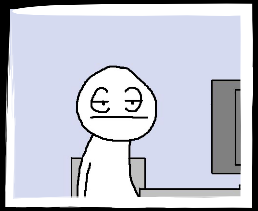
| Model-independent bounds on the standard model effective theory from flavour physics | Physics Letters B<br>Volume 799, 10 December 2019, 135062 |
| --- | --- |



Little Hierarchy problem possibly not too bad …

But … isn't MFV … 

, though?

BSM pheno driven by couplings to 3rd gen 

Can we avoid large FCNCs effects & have BSM with a radically different flavor than the SM one ?

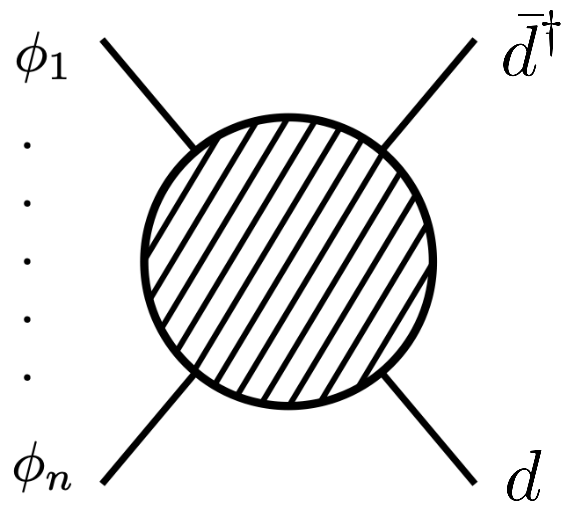
# Another Way to Be Clever: Alignment!

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

Require (at least at the renormalizable level) the UV theory to be such that:

- **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 non-trivial under $U(3)_d$ **but** $d$ and $Z^d$

Mixing with Spontaneously Broken Flavor Vacuum




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

Getting the kinetic term canonical one gets: $(Z^d)^{-\frac{1}{2}} \sim V\, y^d$

**The up-quark sector** is unaffected and **remains aligned.**

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

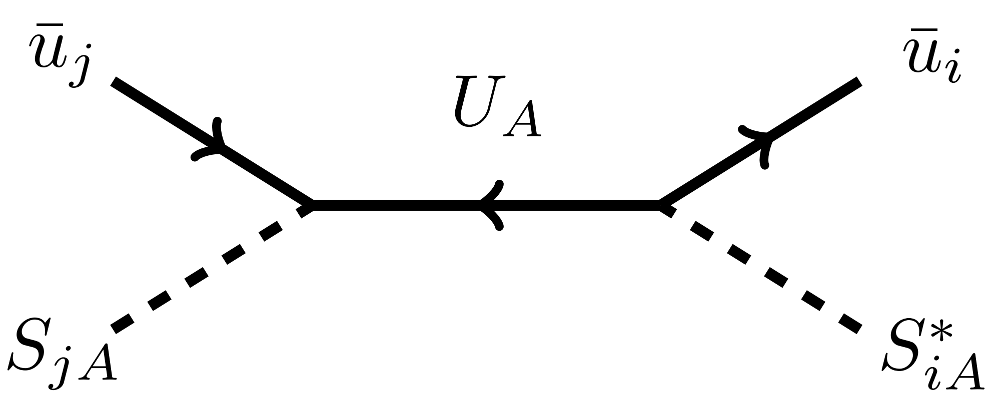
# EXAMPLE: VECTOR-LIKE QUARK

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

*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**

# 2HDM SFV

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:

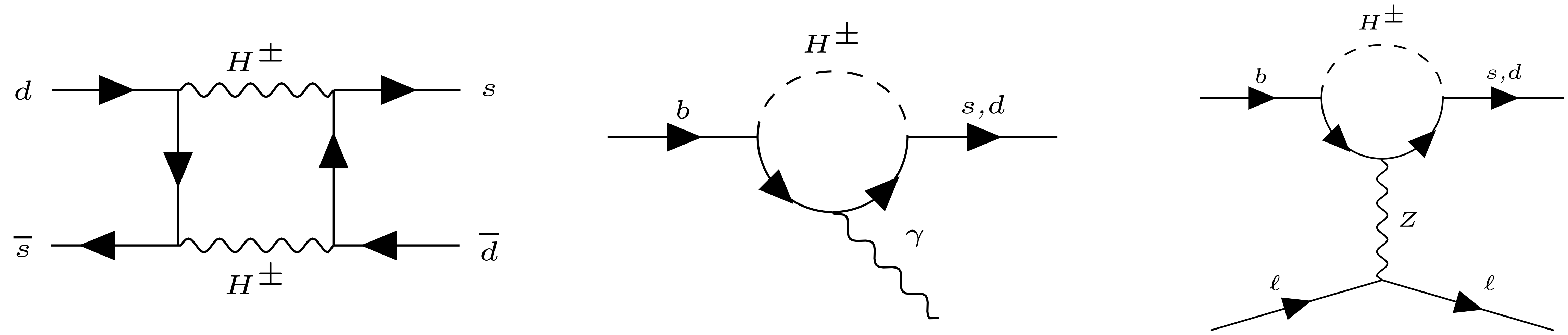
$\cos(\beta - \alpha) \neq 0$ **interesting!**

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

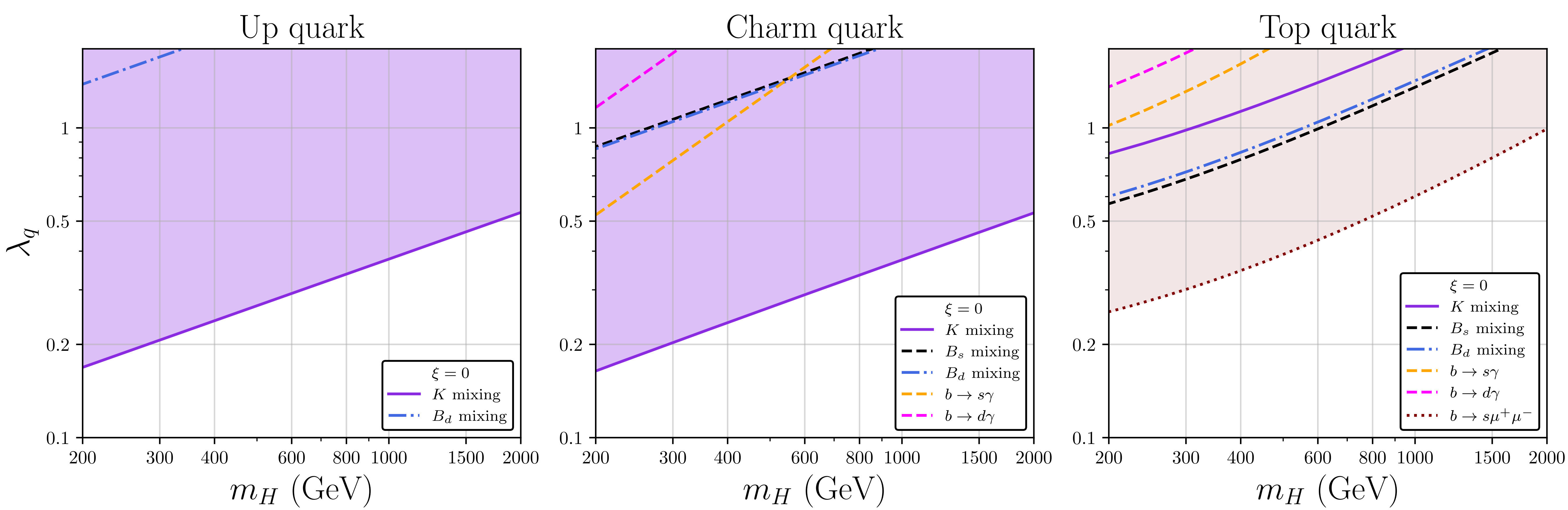
+ a CP-odd and charged ones … for simplicity: $m_H = m_{H^\pm} = m_A$

DOWN-TYPE SFV ANSATZ ON 2HDM

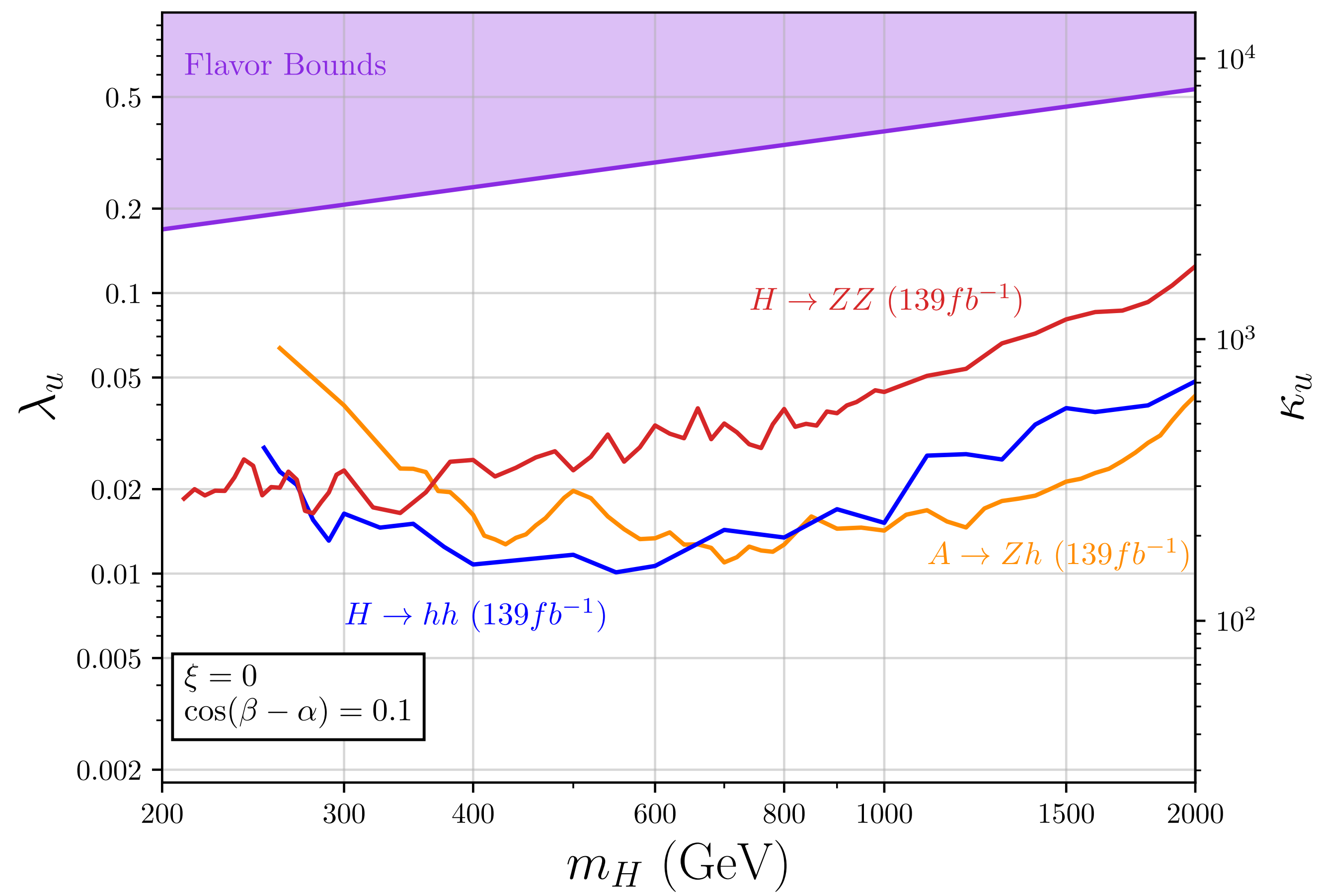
$$\mathcal{Y}^u_1 = y^u = \mathrm{diag}(y_u, y_c, y_t) \qquad \mathcal{Y}^d_1 = V y^d \qquad \mathcal{Y}^\ell_1 = y^\ell$$
$$\mathcal{Y}^u_2 = \lambda^u = \mathrm{diag}(\lambda_u, \lambda_c, \lambda_t) \qquad \mathcal{Y}^d_2 = \xi\, V y^d \qquad \mathcal{Y}^\ell_2 = \xi^\ell y^\ell$$

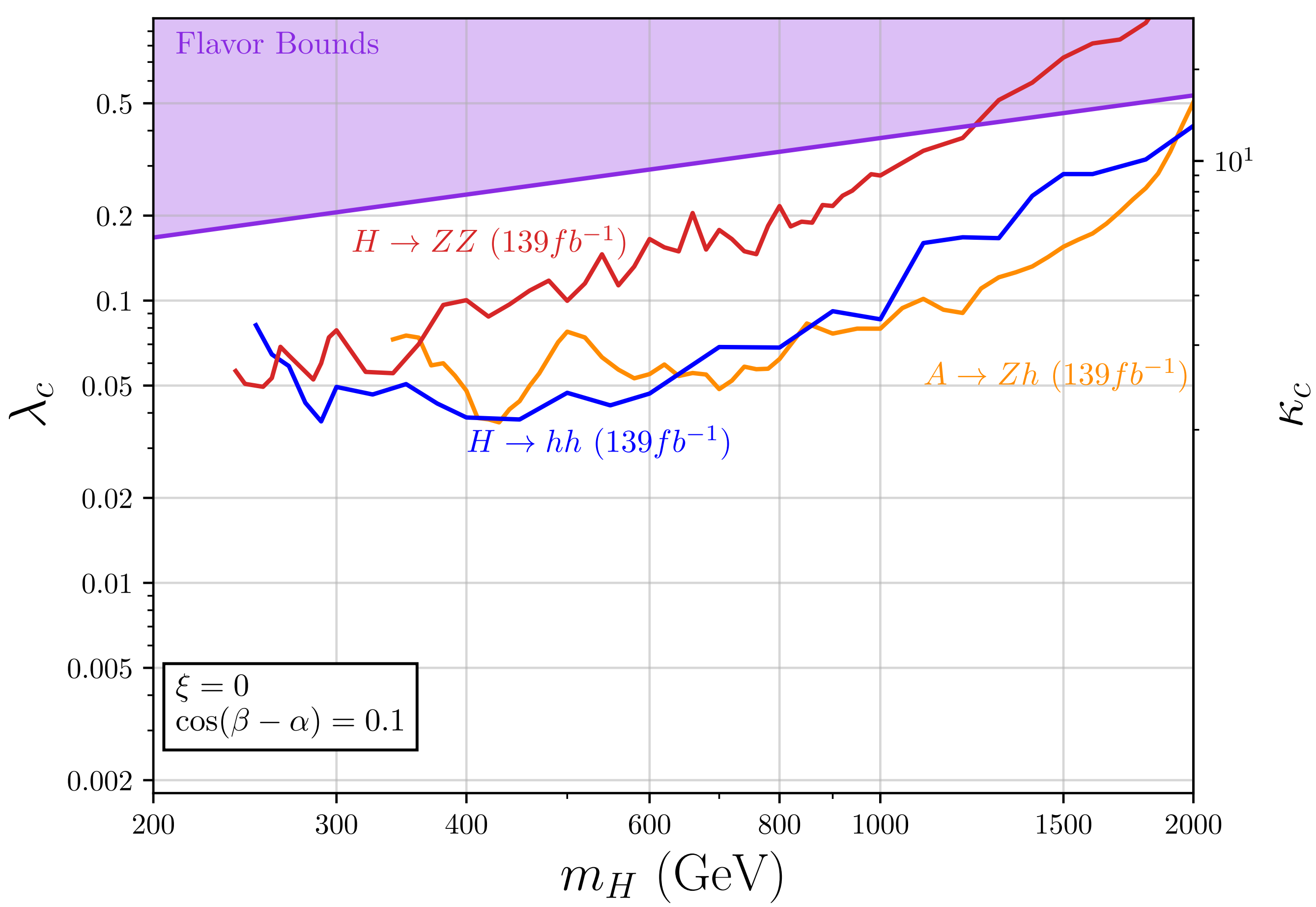



FLAVOR PROTECTION IN DOWN-TYPE SFV ALLOWS NEW HIGGSES @ THE TEV TO COUPLE TO UP-TYPE QUARKS WITH ~0.1 STRENGTH.

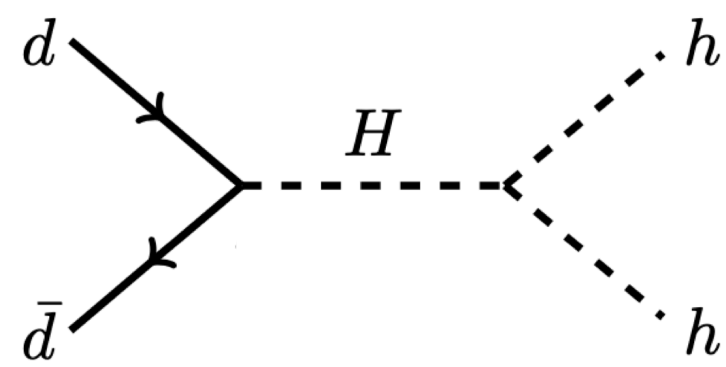



An analogous message holds for the up-type SFV 2HDM as well.




**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 starting to probe Charm Yukawa!

N. Berger @ ICHEP 24

## ATLAS and CMS VH→cc

More in Andrea Cardini's talk and Maarten de Coen's poster

### ATLAS VH→cc

New

Simultaneous fit with VH→bb

$\mu_{VH\to cc}$ **< 11.3 @ 95% CL** (10.4 exp.)

Best limit to date

Factor 2.5 improvement over previous limit !

More in Francesco Di Bello's talk

**⇒ $|\kappa_c|$ < 4.2** @ 95% CL

Factor 2 improvement over previous

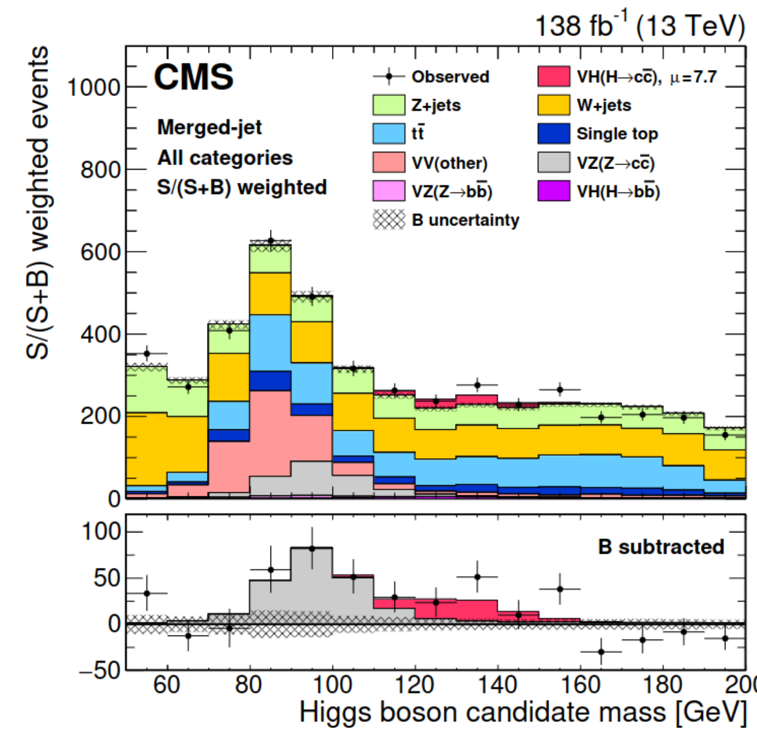
### CMS VH→cc :

Includes boosted H→cc ($p_T^H$ > 300 GeV)

$\mu_{VH\to cc}$ **< 14 (7.6)** @ 95% CL **best sensitivity**

**⇒ 1.1 < $|\kappa_c|$ < 5.5**

**First observation of Z→cc in hadronic collisions.**

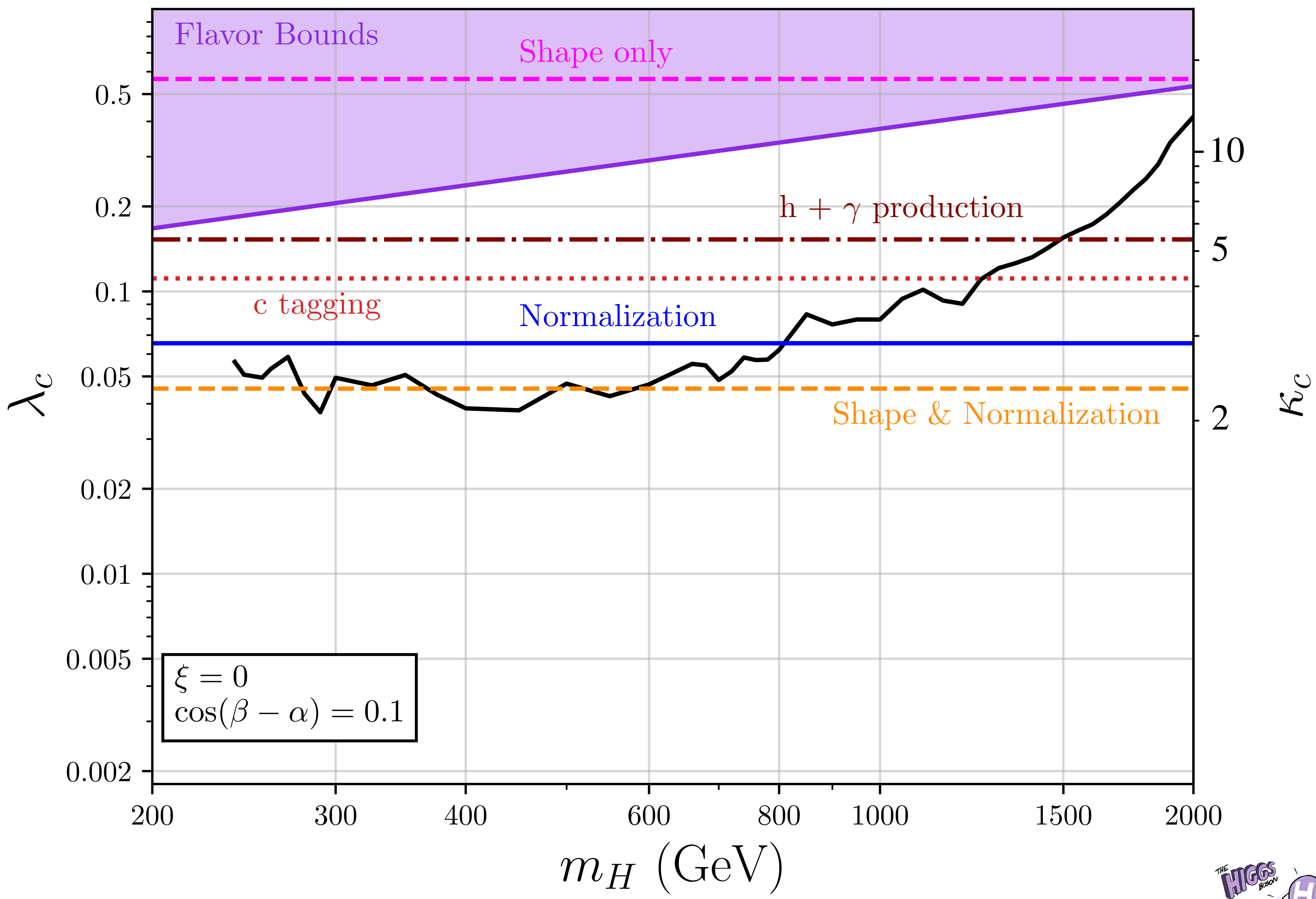



PRL 131 (2023) 041801,
PRL 131 (2023) 061801



The advent of Deep Learning has been a game changer for ATLAS & CMS sensitivity to 2nd gen Yukawa couplings.

# Charming Higgs @ LHC




arXiv:**2410.05236**

**Program of precision with flavor is still very rich, but keeps pointing to very high scales for NP.**

No clear tension emerging from flavor data

**In absence of signs of NP, the leading paradigms we relied on for BSM should be reconsidered.**

MFV ansatz ***vs*** SFV models

**TH + EXP progress can lead to interesting new targets.** *E.g., This Charming ~~Man~~*

[See also 2410.08272] *Higgs!*

TPPC