A universally enhanced light-quarks Yukawa couplings paradigm

(A UEHiggsY paradigm)

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Based on:

PRD98 (2018) no.5, 055001, SBS & Amarjit Soni (arXiv:1804.02400)

PRD97 (2018) no.5, 055014, Jonathan Cohen, SBS, Gad Eilam, Amarjit Soni (arXiv:1705.09295)

Outline

- Universally Enhanced light quark Higgs Yukawa (UEHiggsY):

  the case of $Y_q(q=u,d,s,c) \sim O(Y_b^{SM})$ …

  what's so special about $Y_q \sim O(Y_b^{SM})$? …

- Is this excluded ? ⇒ CONSTRAINTS ⇒ NO!

- Can it (the UEHiggsY) be NATURALLY realized in BSM scenarios? YES!
  - EFT description √
  - BSM physics with TeV-scale vector-like quarks √

- Can it be detected? ⇒ "SMOKING GUN" signals ⇒ YES!

- Summary & outlook (LHC sensitivities)

Constraints ?

$Y_q(q=u,d,s,c) \sim O(Y_b^{SM})$ not excluded !

It is consistent with all available Higgs data:

- **125 GeV Higgs signals measurements**

  SBS, Soni PRD2018 (arXiv:1804.02400 + updated analysis)

- **Higgs p_T distributions & rare Higgs decays**

  Kagan, Perez, Petriello, Soreq, Stoynev, Zupan, PRL2015 (arXiv:1406.1722); Perez, Soreq, Stamou, Tobioka, PRD2015 (arXiv:1503.00290); Soreq, Zhu, Zupan, JHEP2016 (arXiv:1606.09621); Bishara, Haisch, Monni, Re, PRL2017 (arXiv:1606.09253); Bonner, Logan arXiv:1608.04376; F. Yu, JHEP2017 (arXiv:1609.06592)

Is it natural ?

b-quark Yukawa ⇔ NP paradigm

If TeV-scale NP is responsible for light-quark Yukawa's Y_q,

then on general grounds (at leading order from the EFT …):

$$Y_q \sim g_{NP} \cdot \frac{EW^2}{\Lambda^2}$$

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then on general grounds (at leading order from the EFT …):

$$Y_q \sim g_{NP} \cdot \frac{EW^2}{\Lambda^2} \sim 0.025 \sim Y_b(SM)$$

with $\Lambda \sim 1.5$ TeV & $g_{NP} \sim O(1)$ (natural NP)

@ the current bounds on heavy scalars and fermions …

The UEHiggsY setup: an EFT description

dim.6 EFT operators that can generate non-SM Yukawa-like terms:

$$\Delta\mathcal{L}_{qH} = \frac{H^\dagger H}{\Lambda^2} \cdot \left(f_{uH} \bar{q}_L \tilde{H} u_R + f_{dH} \bar{q}_L H d_R \right) + h.c.$$

+ dim.4 SM Yukawa's:

$$\mathcal{L}_{SM}^{Y} = -Y_u \bar{q}_L \tilde{H} u_R - Y_d \bar{q}_L H d_R + h.c.$$

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$\Rightarrow$ Yukawa couplings are modified:

$$y_q^{ij} = \frac{m_q}{v} \delta_{ij} - \frac{\epsilon}{\sqrt{2}} \left(\hat{f}_{qH}^{ij} R + \hat{f}_{qH}^{ji\star} L \right)$$

$$\epsilon \equiv \frac{v^2}{\Lambda^2}$$

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For Λ ~ 1.5 TeV & f_{qH} ~ O(1) $\Rightarrow$ (natural TeV-scale NP)

$$y_q \sim \frac{\epsilon}{\sqrt{2}}\hat{f}_{qH} \sim 0.025 \sim y_b^{SM}$$

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For all light-quark q=u,d,c,s
& also for the b-quark …

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For all light-quark q=u,d,c,s
& also for the b-quark …

Light quarks Yukawa couplings of the size of the b-quark Yukawa are the natural choice for TeV-scale NP !!!

Two Potential problems

fine-tuning

required to accommodate the light quark masses m_q << m_b with the enhanced Yukawa's $Y_q \sim O(Y_b^{SM})$

flavor

Yukawa couplings & Wilson coefficients cannot be simultaneously diagonalized

FCNC may appear, e.g.

$$y_d^{12} = y(\bar{d}sh) \sim \frac{\epsilon \hat{f}_{dH}^{12}}{\sqrt{2}} \sim \mathcal{O}(y_b^{SM})$$

Λ ~ 1.5 TeV

Fine-tuning of the UEHiggsY paradigm - how bad is it ?

- Consider a single light-quark (e.g., the u-quark) :

$$\mathcal{L} = -Y_u \bar{q}_L \tilde{H} u_R + \frac{f_{uH}}{\Lambda^2} \bar{q}_L \tilde{H} u_R (H^\dagger H)$$

- u-quark mass & Yukawa coupling:

require

$$m_u = \frac{v}{\sqrt{2}} \left(Y_u - \frac{1}{2} \epsilon f_{uH} \right) \sim 2\ MeV$$

$$y_u = \frac{1}{\sqrt{2}} \left(Y_u - \frac{3}{2} \epsilon f_{uH} \right) \sim y_b^{SM} \sim 0.025$$

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- The fine-tuned solution:

$$Y_u = -\frac{y_b^{SM}}{\sqrt{2}} \left(1 - \frac{3}{\sqrt{2}} \frac{m_u}{m_b} \right)$$

$$\epsilon f_{uH} = -\sqrt{2} y_b^{SM} \left(1 - \frac{1}{\sqrt{2}} \frac{m_u}{m_b} \right)$$

Λ ~ O(1 TeV) → f_{uH} ~ O(1)

with a natural Wilson coefficient !

fine-tuning $\sim \frac{m_u}{m_b} \sim 10^{-3}$ ⇛ O(0.1%) technical fine-tuning

In fact, not worst than the flavor fine-tuning problem in the SM – the small off-diagonal CKM elements …

Flavor in the UEHiggsY paradigm: Underlying physics …

- **<u>Taking care of flavor</u>:**

  SYMMETRIES from the underlying theory …

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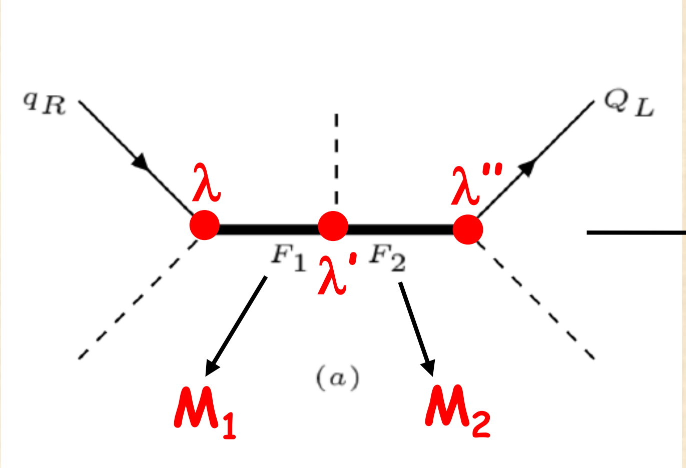
e.g. heavy Vector-Like-Quarks (VLQ):

the dim.6 effective operators are generated with:



matching

$$\Delta\mathcal{L}_{qH} = \frac{H^\dagger H}{\Lambda^2} \cdot \left(f_{uH} \bar{q}_L \tilde{H} u_R + f_{dH} \bar{q}_L H d_R \right)$$

$$\Lambda = \sqrt{M_1 M_2}$$

$$\hat{f}_{qH} = \lambda \lambda' \lambda''$$

e.g., the SM-like VLQ (F_1,F_2)=(doublet,singlet): $Q_i=(U,D)_i$, U_i, D_i

Q=(3,2,1/6) , U=(3,1,2/3) , D=(3,1,-1/3)

$$y_q^{ij} \sim \frac{v^2}{M^2} (\lambda\lambda'\lambda'')^{ij} \overset{M\sim 1.5\ \mathrm{TeV}}{\underset{\lambda\sim\mathcal{O}(1)}{\longrightarrow}} y_b^{SM}$$

Flavor in the UEHiggsY paradigm: Underlying physics …

- Taking care of flavor:

SYMMETRIES from the underlying theory …

e.g., consider a simple/minimal Z_3 flavor symmetry:

$$\psi^k = e^{i\alpha(\psi^k)\tau_3}\psi^k \ , \quad \tau_3 = \frac{2\pi}{3}$$

$\psi = q_L, u_R, d_R, Q_L, U_R, D_R$ & $\alpha(\psi^k)$ *are the* Z_3 charges of ψ^k

Q=(3,2,1/6) , U=(3,1,2/3) , D=(3,1,-1/3)

Flavor in the UEHiggsY paradigm: Underlying physics …

$$\psi^k \to e^{i\alpha(\psi^k)\tau_3}, \tau_3 \equiv \frac{2\pi}{3}$$

Simplest Z_3 symmetry: $\alpha(\psi^k)$ = k (k = generation index)

$\Rightarrow$ consistent with the UEHiggsY setup with no tree-level FCNC (all Yukawa-like VLQ couplings are diagonal …)

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More interesting examples of allowed Z_3 symmetries with non-diagonal textures:

Z_3 symmetry 1: $\alpha(q_L^k) = \alpha(u_R^k) = \alpha(d_R^k) = (1,2,3)$, $\alpha(Q_L^k) = \alpha(D_R^k) = (1,2,0)$, $\alpha(U_R^k) = (1,2,1)$

$$\hat{Y}_d, \hat{Y}_u, \hat{\lambda}_{QD} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad \hat{\lambda}_{QU}, \hat{\lambda}_{Uq} \in \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \hat{\lambda}_{Qd}, \hat{\lambda}_{Qu}, \hat{\lambda}_{Dq} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\hat{f}_{dH}, \hat{f}_{uH} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Z_3 symmetry 2: $\alpha(q_L^k) = \alpha(u_R^k) = \alpha(d_R^k) = (1,2,3)$, $\alpha(Q_L^k) = \alpha(U_R^k) = (1,2,1)$, $\alpha(D_R^k) = (1,2,0)$

$$\hat{Y}_d, \hat{Y}_u \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad \hat{\lambda}_{QD}, \hat{\lambda}_{Qu}, \hat{\lambda}_{Qd} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ \times & 0 & 0 \end{pmatrix} \quad \hat{\lambda}_{QU} \in \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix} \quad \hat{\lambda}_{Uq} \in \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \hat{\lambda}_{Dq} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\hat{f}_{dH},\ \hat{f}_{uH} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

No tree-level FCNC

Z_3 symmetry 3: $\alpha(q_L^k) = \alpha(d_R^k) = (1,2,3)$, $\alpha(Q_L^k) = \alpha(U_R^k) = \alpha(u_L^k) = (1,2,1)$, $\alpha(D_R^k) = (1,2,0)$

$$\hat{Y}_d, \hat{\lambda}_{Dq} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad \hat{Y}_u, \hat{\lambda}_{Uq} \in \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \hat{\lambda}_{QD}, \hat{\lambda}_{Qd} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ \times & 0 & 0 \end{pmatrix} \quad \hat{\lambda}_{QU}, \hat{\lambda}_{Qu} \in \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

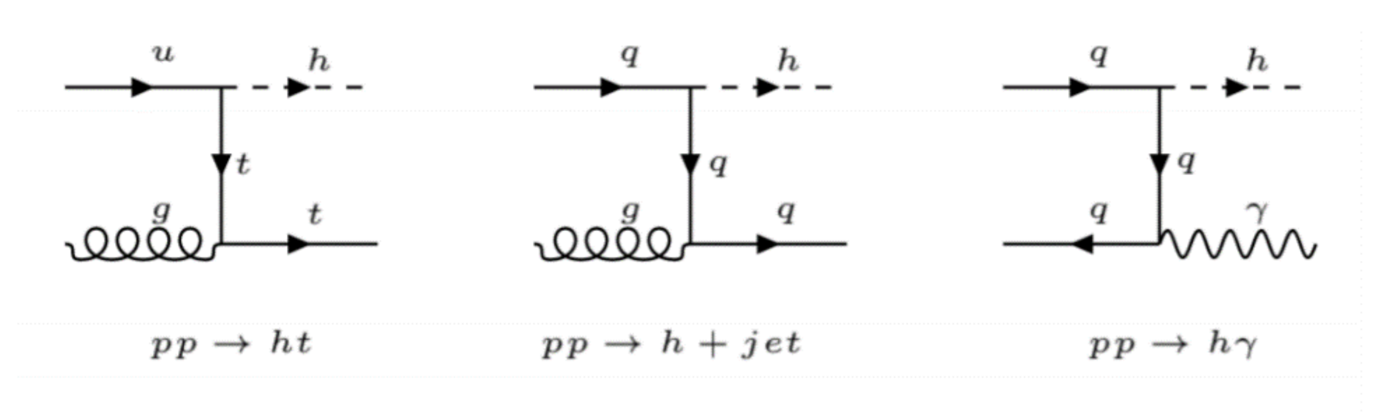
$$\hat{f}_{dH} \in \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \hat{f}_{uH} \in \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$tree-level$ $\bar{u}_L t_R h$ FC coupling

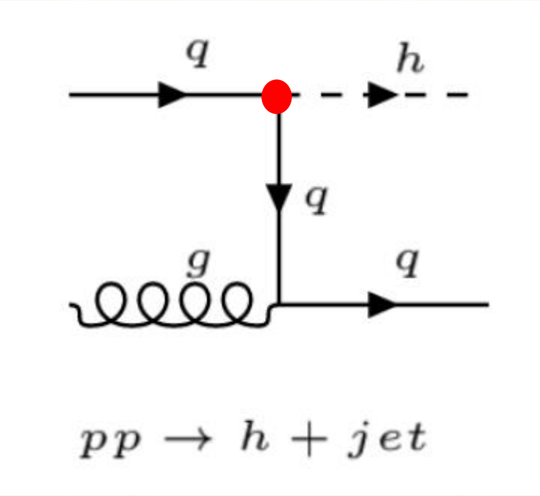
(no FCNC elsewhere …)

signals of the UEHiggsY paradigm

Single Higgs (high p_T) production



Higgs + high p_T jet : $pp \to h+j$



+ s-channel …

(J. Cohen, SBS, G. Eilam, A. Soni, PRD2018 arxiv:1705.09295)

see also: Soreq, Zhu, Zupan, JHEP2016 (arXiv:1606.09621); Bishara, Haisch, Monni, Re, PRL2017 (arXiv:1606.09253); Bonner, Logan, arXiv:1608.04376

$$R_{hj\to f\bar{f}j} = \frac{\hat{\sigma}(pp \to hj \to f\bar{f} + j)}{\hat{\sigma}(pp \to hj \to f\bar{f} + j)_{SM}}$$

$f = b,\ \tau,\ \gamma,\ W,\ Z$

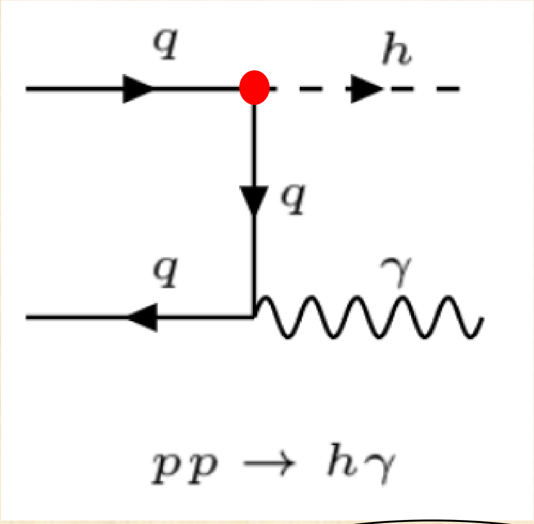
$y_q \sim y_b^{SM}$ →

$$R_{hj\to f\bar{f}j} \sim 0.3 - 0.4$$

$p_T(h) > 200$ GeV

For more studies of NP in pp → h+j, see: Brein, Hollik, PRD2003 (hep-ph/0305321); Dittmaier, Kramer, Spira, PRD2004 (hep-ph/0309204); Dawson, Jackson, Reina, Wackeroth, PRD2004 (hep-ph/0311067) + PRL2005 (hep-ph/0408077) + MPL2006 (hep-ph/0508293); Campbell, hep-ph/0405302; Banfi, Martin, Sanz, JHEP2014 (arxiv:1308.4771); Grojean, Salvioni, Schlaffer, Weiler, JHEP2014 (arxiv:1312.3317); Ghosh, Wienbusch, PRD2015 (arxiv:1411.2029); Dawson, Lewis, Zeng, PRD2014 (arxiv:1409.6299); Harlander, Neumann, PRD2013 (arxiv:1308.2225); Bramante, Delgado, Lehman, Martin, PRD2016 (arxiv:1410.2484).

Higgs + high p_T photon : $pp \to h+\gamma$



+ crossed …

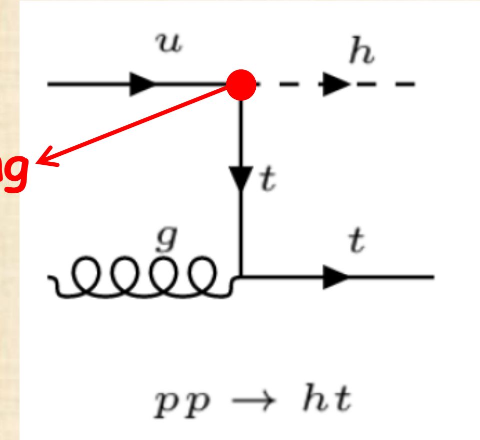
UEHiggsY:

- **tree-level:** $qq \to h\gamma \Rightarrow \sigma(pp \to h\gamma) \sim O(1000\ \text{fb})$ [$p_T(\gamma) > 30$ GeV]
  (80% from $uu \to h\gamma$)

$\Rightarrow$ **For the exclusive $\sigma(pp \to h\gamma \to bb\gamma, \tau\tau\gamma, \gamma\gamma\gamma)$ a factor of ~ 3000 enhancement:**

$$R_{h\gamma \to bb\gamma/\tau\tau\gamma/\gamma\gamma\gamma} \equiv \frac{\sigma(pp \to h\gamma \to b\bar{b}\gamma/\tau^+\tau^-\gamma/\gamma\gamma\gamma)}{\sigma(pp \to h\gamma \to b\bar{b}\gamma/\tau^+\tau^-\gamma/\gamma\gamma\gamma)_{SM}} \sim 10000 \times 0.3 \sim 3000$$

Flavor changing Higgs + single top: $pp \to ht + h.c.$



FC tuh coupling

+ s-channel

SM tree-level Higgs+ single top production channels:

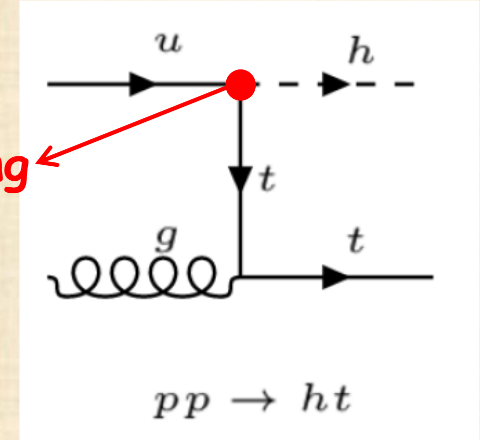
- bW → ht + jet (the dominant t-channel hard process)
  * $\sigma_{SM}(pp \to ht + jet) \sim 75$ fb (LO) (sensitive to the sign of the htt Yukawa coupling …)
- qq' → W* → ht + b-jet (sub-dominant s-channel hard process)
  * $\sigma_{SM}(pp \to ht + b\text{-}jet) \sim \sigma_{SM}(pp \to ht + jet)/25 \sim 3$ fb (LO)

exclusive pp → ht (+h.c.) ∝ vanishingly small 1-loop tuh/tch couplings …

Flavor changing Higgs + single top:

pp → ht + h.c.

FC tuh coupling



+ s-channel

$\hat{f}^{13}_{uH} \sim \mathcal{O}(1)$ & $\Lambda \sim 1.5$ TeV

UEHiggsY framework: $\mathcal{L}_{tuh} = \xi_{tu} \bar{t} u h + h.c. \quad , \quad \xi_{tu} = \frac{1}{\sqrt{2}} \frac{v^2}{\Lambda^2} \hat{f}^{13}_{uH}$ → y_b^{SM}

- Isolating the exclusive ht + h.c. rates:
- Also, different asymmetric production rates h+t vs. h+t(bar) than in SM …

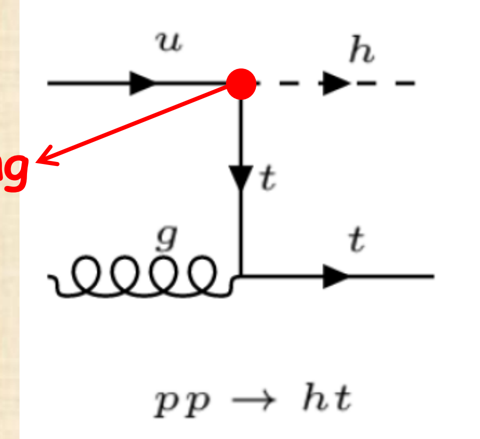
$$R_{th/thj} \equiv \frac{\sigma(pp \to th)}{\sigma(pp \to th + j)_{SM}} \sim 2$$

$$\bar{R}_{\bar{t}h/\bar{t}hj} \equiv \frac{\sigma(pp \to \bar{t}h)}{\sigma(pp \to \bar{t}h + j)_{SM}} \sim 0.8$$

in the SM: $R_{th/thj}, \bar{R}_{\bar{t}h/\bar{t}hj} \to 0$

Flavor changing Higgs + single top:

pp → ht + h.c.



FC tuh coupling

+ s-channel

- **Current sensitivity** from CMS recent dedicated search for the exclusive single top + Higggs signal:

A.M. Sirunyan et al, CMS collab. , arxiv:1712.02399

$$\sigma(pp \to th + \bar{t}h) \lesssim 16 \times \sigma(pp \to th + \bar{t}h)_{UEHiggsY}$$

- **Current best direct bound** by ATLAS (from t→uh,ch):

M. Aaboud et al, CMS collab. , arxiv:1707.01404

Still "room" for the UEHiggsY: $\xi_{tu/tc} = \frac{1}{\sqrt{2}} \frac{v^2}{\Lambda^2} \hat{f}_{uH}^{13/23} \lesssim 3 y_b^{SM}$

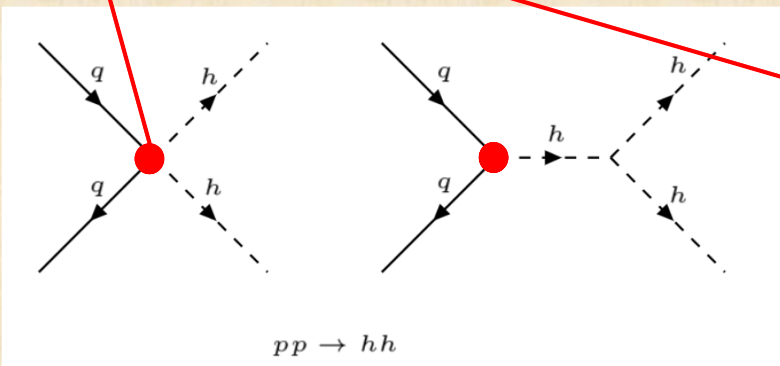
Multi Higgs production

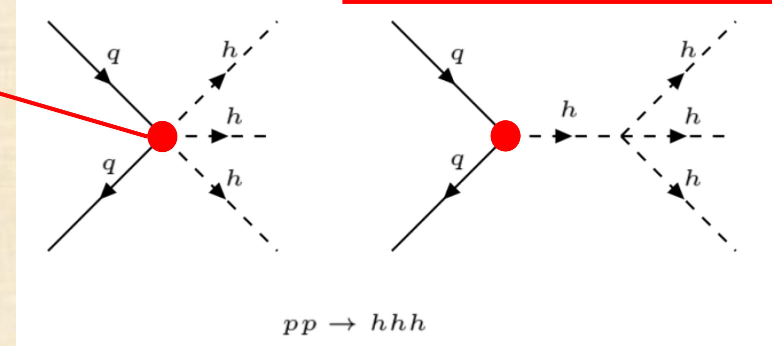
$pp \rightarrow hh, hhh$

Multi Higgs production: pp → hh, hhh

New qqhh & qqhhh contact terms from the UEHiggsY dim.6 Opts:

$$\Delta\mathcal{L}_{qH} = \frac{H^\dagger H}{\Lambda^2} \cdot \left(f_{uH} \bar{q}_L \tilde{H} u_R + f_{dH} \bar{q}_L H d_R \right)$$





UEHiggsY framework

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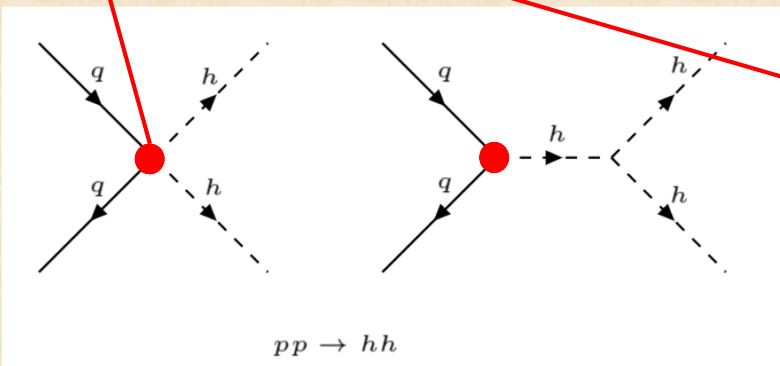
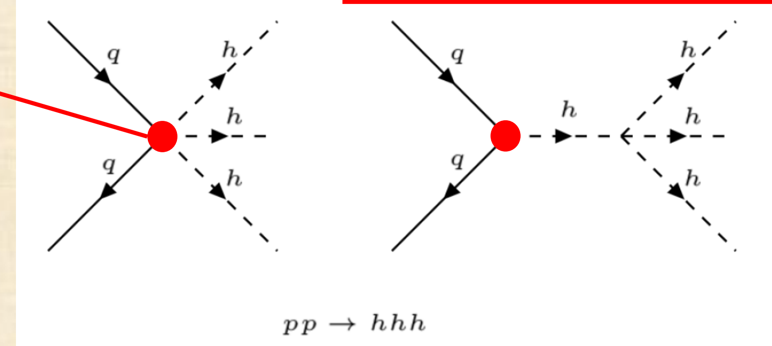
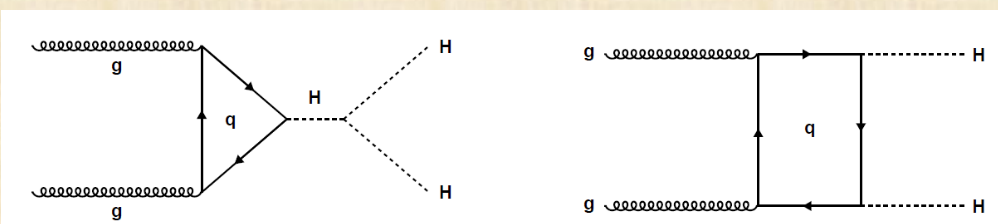
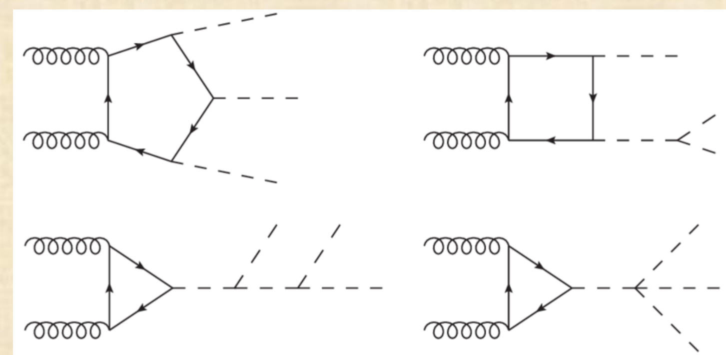




UEHiggsY framework

Recall SM leading diagrams for hh & hhh production:





Multi Higgs production: $pp \to hh,\ hhh$

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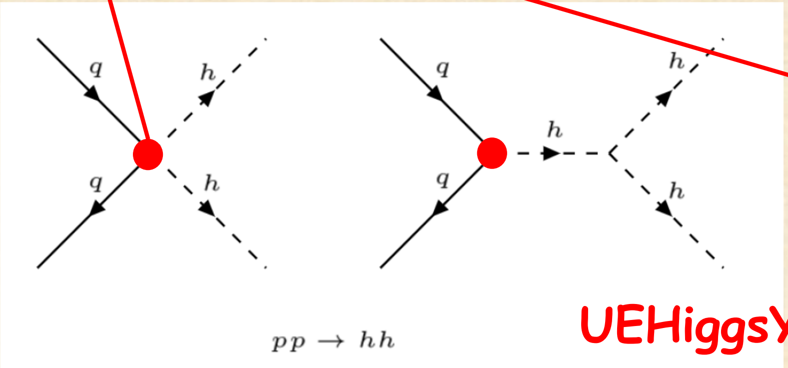
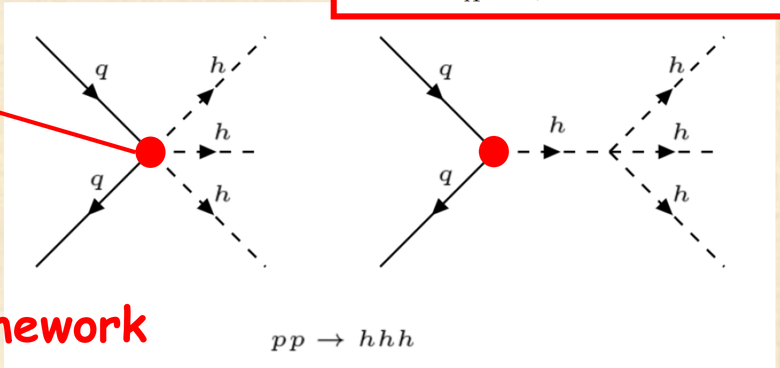


UEHiggsY framework



$$\sigma(pp \to hh)_{UEHiggsY} \sim 1.5\ [pb]$$

$$R_{hh} \equiv \frac{\sigma(pp \to hh)}{\sigma(pp \to hh)_{SM}} \sim 100$$

$$R_{hh \to b\bar{b}b\bar{b}/b\bar{b}\gamma\gamma} \sim 0.3^2 \cdot R_{hh} \sim 10$$

$$\sigma(pp \to hhh)_{UEHiggsY} \sim 10\ [fb]$$

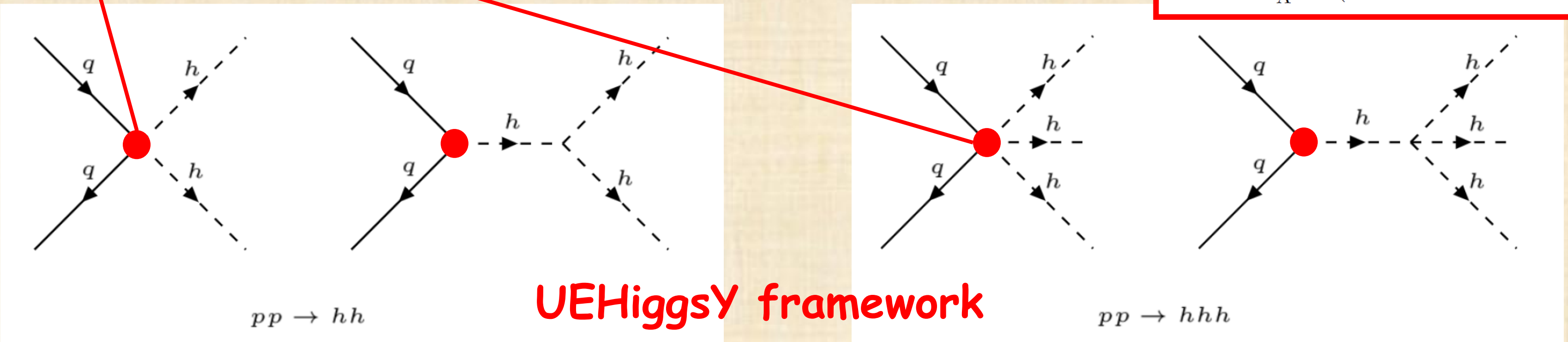
$$R_{hhh} \equiv \frac{\sigma(pp \to hhh)}{\sigma(pp \to hhh)_{SM}} \sim 300$$

$$R_{hhh \to b\bar{b}b\bar{b}b\bar{b}} \sim 0.3^3 \cdot R_{hhh} \sim 10$$

Multi Higgs production: pp → hh, hhh

New qqhh & qqhhh contact terms from the UEHiggsY dim.6 Opts:

$$\Delta\mathcal{L}_{qH} = \frac{H^\dagger H}{\Lambda^2}\cdot\left(f_{uH}\bar{q}_L\tilde{H}u_R + f_{dH}\bar{q}_L H d_R\right)$$



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$$\sigma(pp\to hh)_{UEHiggsY} \sim 1.5\ [pb]$$

$$R_{hh} \equiv \frac{\sigma(pp\to hh)}{\sigma(pp\to hh)_{SM}} \sim 100$$

$$R_{hh\to b\bar{b}b\bar{b}/b\bar{b}\gamma\gamma} \sim 0.3^2\cdot R_{hh} \sim 10$$

$$\sigma(pp\to hhh)_{UEHiggsY} \sim 10\ [fb]$$

$$R_{hhh} \equiv \frac{\sigma(pp\to hhh)}{\sigma(pp\to hhh)_{SM}} \sim 300$$

$$R_{hhh\to b\bar{b}b\bar{b}b\bar{b}} \sim 0.3^3\cdot R_{hhh} \sim 10$$

Current best bounds (ATLAS):

$$R_{hh\to b\bar{b}\gamma\gamma} \lesssim 20$$
$$R_{hh\to b\bar{b}b\bar{b}} \lesssim 13$$
$$R_{hh\to b\bar{b}\tau^+\tau^-} \lesssim 13$$

UEHiggsY prod. CSX probably too small:

$$\sigma(pp\to hhh\to b\bar{b}b\bar{b}b\bar{b}) \sim 60\ [\text{ab}]$$

SUMMARY

CONCLUSION

- Light quarks Yukawa couplings of the size of the b-quark Yukawa
  are the natural choice for TeV-scale NP
  - useful EFT parameterizations of the NP …

- This scenario is naturally realized with new heavy TeV-scale Vector-like-quarks (VLQ) and/or scalars that have O(1) couplings with the SM fields

- "smoking gun" signals are expected @ the LHC in exclusive single high-p_T Higgs production

$$pp \to h+\gamma\ ,\ h+j\ ,\ h+top$$

as well as in multi-Higgs production

$$pp \to hh\ ,\ hhh$$

SUMMARY

CONCLUSION

LHC signals: expectations/predictions of the UEHiggsY framework & current search status

	$\sqrt{s} = 13$ TeV (RUN2)		
Higgs signal	SM prediction	our UEHiggsY prediction	Current limit/sensitivity
$R_{hV\to b\bar{b}V} = \frac{\sigma(pp\to hV\to b\bar{b}V)}{\sigma(pp\to hV\to b\bar{b}V)_{SM}}$ $V = Z, W$	1	~ 0.33	$\sim 0.9 \pm 0.3$ (ATLAS [30]) $\sim 1.06 \pm 0.3$ (CMS [31])
$R_{hj\to f\bar{f}j} = \frac{\sigma(pp\to hj\to f\bar{f}+j)}{\sigma(pp\to hj\to f\bar{f}+j)_{SM}}$ $f = b, \tau, \gamma, Z, W$ $p_T(h) > 200$ GeV	1	$\sim 0.3 - 0.4$	None
$\sigma(pp \to h\gamma)$ $p_T(\gamma) > 30$ GeV	~ 0.1 [fb]	~ 1.25 [pb]	None
$\sigma(pp \to ht)$	~ 0	~ 100 [fb]	$\lesssim 1.5$ [pb] (CMS [50])
$R_{hh} = \frac{\sigma(pp\to hh)}{\sigma(pp\to hh)_{SM}}$	1	~ 100	None
$R_{hh\to b\bar{b}\gamma\gamma}$	1	~ 10	$\lesssim 19$ (CMS [43])
$R_{hh\to b\bar{b}b\bar{b}}$	1	~ 10	$\lesssim 29$ (ATLAS [44])
$R_{hhh} = \frac{\sigma(pp\to hhh)}{\sigma(pp\to hhh)_{SM}}$	1	~ 300	None
$R_{hhh\to b\bar{b}b\bar{b}b\bar{b}}$	1	~ 10	None

backups

Contribution of light quarks in ggh & γγh loops

In particular, the contribution of each light-quark (i.e., in the limit that $m_h^2 \gg m_q^2$) to the 1-loop ggh amplitude is (see e.g., [31]):

$$A_q \propto y_q \cdot \frac{m_q \cdot v}{m_h^2} \cdot \log^2\left(\frac{m_h^2}{m_q^2}\right) , \quad (23)$$

and their leading effect to the overall 1-loop gluon-fusion Higgs production channel arises from their interference with the top-quark loop (similar to the case of the leading b-quark contribution in the SM). Thus, the relative size of any light-quark contribution to the ggh coupling with respect to that of the b-quark one is:

$$\frac{A_q}{A_b} \sim \frac{y_q}{y_b} \cdot \frac{m_q}{m_b} \cdot \frac{\log^2\left(\frac{m_h^2}{m_q^2}\right)}{\log^2\left(\frac{m_h^2}{m_b^2}\right)} , \quad (24)$$

so that the contribution to $gg \to h$ from a $c(s)$-quark with $y_c(y_s) \sim y_b^{SM}$ is about 50%(20%) of the SM b-quark one, i.e., $A_c(A_s) \sim 0.5(0.2)A_b$. Furthermore, the effect of the light-quarks of the 1st generation is about a hundred times smaller than the SM b-quark one. Therefore, since the b-quark contribution to the 1-loop ggh production cross-section is less than 10% (and is included below), the overall UEHiggsY effect on the $gg \to h$ cross-section is around 5% if all the light-quarks have Yukawa couplings $y_q \sim y_b^{SM}$ and is, therefore, neglected in the analysis below.

Note that, in the decay $h \to \gamma\gamma$, the dominant contribution arises from the W-boson loop and, as a consequence, the relative effect of the light-quarks loops in our UEHiggsY scenario with $y_q \sim y_b^{SM}$ is much smaller. In particular, the top-quark loop contributes about 30% of $\Gamma(h \to \gamma\gamma)$, mostly from its interference with the W loop [28]. Thus, for example, the c-quark loop with $y_c \sim y_b^{SM}$ which is $A_c \sim 0.03 A_t$ (see Eqs. 23 and 24), will be negligibly small for our purpose.

UEHiggs total effect on gg→h CSX is O(5%)

UEHiggs total effect on h→γγ width is O(1%)

Why UEHiggsY ?

- Natural & "conventional" TeV-scale NP
  can generate enhanced light-quarks Yukawa of $O(Y_b^{SM})$
  - Natural: having O(1) couplings to the SM-fields
  - Conventional: heavy vector-like quarks, heavy scalars …
    $\Rightarrow$ building blocks of many BSM constructions …

- $Y_q(q=u,d,s,c) \sim O(Y_b^{SM})$ not excluded !

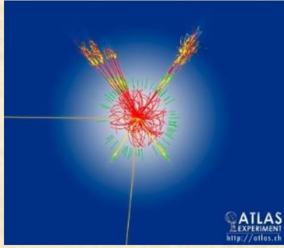
Any sign of these couplings being significantly enhanced w.r.t SM will undermine the SM prediction:

$$y_f \propto m_f/v$$

Besides, light quarks Yukawa may play an important role in BSM physics:

Partially composite 1st-2nd gen quarks: enhanced Yukawa's from mixing with the strong dynamics (mixing with heavy VLQ …)
Delaunay, Grojean, Perez, JHEP2013 (arXiv:1303.5701);
Delaunay, Flacke, Gonzalez-Fraile, Lee, Panico, Perez, JHEP2014 (arXiv:1311.2072)
Modified Y_q may have important implications for Higgs portal DM pheno (DM annihilation altered …)
Bishara, Brod, Uttayarat, Zupan, JHEP2016 (arXiv:1504.04022)

What do we currently know? CONSTRAINTS …



- **Sensitivity to light-quarks Yukawa:**

mostly constrained by 125 GeV Higgs signals:

$$\mu^F = \frac{\sigma(pp \to h \to F)}{\sigma(pp \to h \to F)_{SM}}$$

–Currently, rather weak bounds on 1st & 2nd generations Yukawa's:

- F= bb,$\tau\tau$,ZZ*,WW*,$\gamma\gamma$

  F= hV$\to$bbV (V=W,Z)

Consistent with $Y_q \sim O(Y_b^{SM})$ @ 1-2σ (q=u,d,s,c,b)

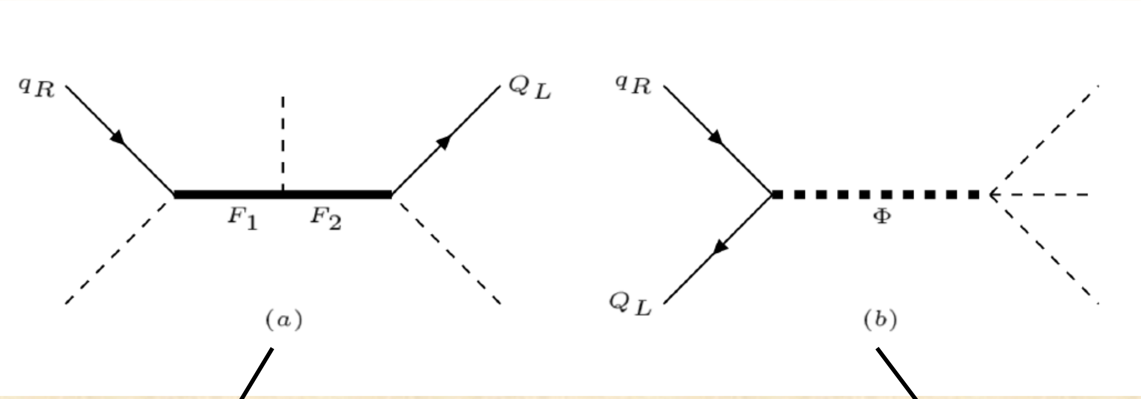
(SBS & Amarjit Soni, PRD2018, arxiv:1804.02400)

–Also from Higgs p_T distribution & rare Higgs decays :

Kagan, Perez, Petriello, Soreq, Stoynev, Zupan, PRL2015 (arXiv:1406.1722); Perez, Soreq, Stamou, Tobioka, PRD2015 (arXiv:1503.00290); Soreq, Zhu, Zupan, JHEP2016 (arXiv:1606.09621); Bishara, Haisch, Monni, Re, PRL2017 (arXiv:1606.09253); Bonner, Logan arXiv:1608.04376; F. Yu, JHEP2017 (arXiv:1609.06592)

Flavor in the UEHiggsY paradigm: Underlying physics …

- The effective UEHiggsY dim 6 opts can be generated by various types of heavy underlying NP (that couples to the SM fields):



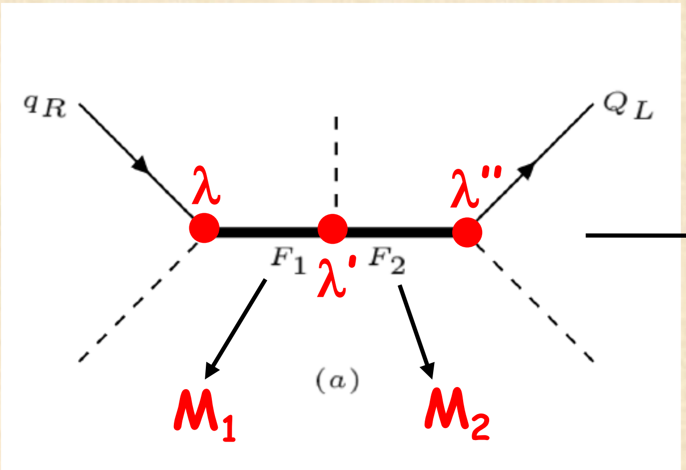
Heavy Vector-like quarks (VLQ) F_1 & F_2

Heavy scalars Φ

(F_1,F_2)=(doublet,singlet)
and/or
(F_1,F_2)=(doublet,triplet)

Flavor in the UEHiggsY paradigm: Underlying physics …

VLQ: the dim.6 effective operators are generated with:



$$\Delta\mathcal{L}_{qH} = \frac{H^\dagger H}{\Lambda^2} \cdot \left(f_{uH} \bar{q}_L \tilde{H} u_R + f_{dH} \bar{q}_L H d_R \right)$$

$$\Lambda = \sqrt{M_1 M_2}$$

$$\hat{f}_{qH} = \lambda\lambda'\lambda''$$

- If VLQ have masses $M = M_1 \sim M_2 \sim O(1)$ TeV and natural couplings $\lambda \sim O(1)$, then Yukawa couplings of all light-quarks are enhanced, with a typical size of the b-quark Yukawa:

But,
also generates potentially "dangerous" $q_i q_j h$ FCNC: $y_q^{ij} \sim O(y_b^{SM})$ …

$$y_q^{ij} \sim \frac{v^2}{M^2} (\lambda\lambda'\lambda'')^{ij} \xrightarrow[\lambda\sim\mathcal{O}(1)]{M\sim 1.5\text{ TeV}} y_b^{SM}$$

UEHiggsY paradigm: Underlying physics and flavor

- Assume VLQ are in their mass basis: $M_F(\bar{F}_L F_R + \bar{F}_R F_L)$

- With: $M_{F=Q,U,D} \sim 1-2~\mathrm{TeV}$ (typical bounds: M_F > 1-1.5 TeV, depending on their mixing with SM quarks and on their decay pattern)

- In general, VLQ will also have Yukawa-like couplings:

Pure VLQ Yukawa-like couplings in the underlying theory:

$$-\mathcal{L}_V^Y = \hat{\lambda}_{QU} \bar{Q}_L \tilde{\phi} U_R + \hat{\lambda}_{QD} \bar{Q}_L \phi D_R + h.c. ~,$$

Yukawa-like interactions - mixing VLQ with SM-quarks:

In general: all $\hat{\lambda}_{QU,QD,Uq,Dq,Qu,Qd}$ are 3X3 matrices in VLQ-SM flavor space

$$\begin{aligned} -\mathcal{L}_{Vq}^Y &= \hat{\lambda}_{Uq} \bar{q}_L \tilde{\phi} U_R + \hat{\lambda}_{Dq} \bar{q}_L \phi D_R ~, \\ &+ \hat{\lambda}_{Qu} \bar{Q}_L \tilde{\phi} u_R + \hat{\lambda}_{Qd} \bar{Q}_L \phi d_R + h.c. \end{aligned}$$

The dim.6 effective operators are generated with:

$$\Delta \mathcal{L}_{qH} = \frac{H^\dagger H}{\Lambda^2} \cdot \left(f_{uH} \bar{q}_L \tilde{H} u_R + f_{dH} \bar{q}_L H d_R \right)$$

$$\begin{aligned} \hat{f}_{uH} &= \hat{\lambda}_{Uq} \hat{\lambda}_{QU}^\dagger \hat{\lambda}_{Qu} \quad , \quad \Lambda = \sqrt{M_U M_Q} \\ \hat{f}_{dH} &= \hat{\lambda}_{Dq} \hat{\lambda}_{QD}^\dagger \hat{\lambda}_{Qd} \quad , \quad \Lambda = \sqrt{M_D M_Q} \end{aligned}$$

UEHiggsY paradigm: Underlying physics and flavor

- **Taking care of flavor:**
  FCNC in down-quark sector and among 1st & 2nd generation up-quark sector are severely constrained, typically:

$$Y_d^{12,21} \leq 10^{-5}\ ,\ Y_d^{13,31,23,32} \leq 10^{-4}\ ,\ Y_u^{12,21} \leq 10^{-5}$$

⇒ Any viable underlying UV completion of the SM should have a mechanism which stronglu suppresses (or forbids) the Higgs mediated FCNF couplngs:

⇒ in our TeV-scale VLQ case: $f_{dH}^{i \neq j}, f_{uH}^{12,21} \leq 10^{-4}$!

e.g., consider a simple/minimal Z_3 flavor symmetry:

$$\psi^k \to e^{i\alpha(\psi^k)\tau_3}\ , \tau_3 \equiv \frac{2\pi}{3}$$

$\psi = q_L, u_R, d_R, Q_L, U_R, D_R$ & $\alpha(\psi^k)$ are the Z_3 charges of ψ^k

Notation & BR's in the UEHiggsY framework

For given final state, F(h), that includes one or more Higgs bosons, define:

$$R_{F(h)} \equiv \frac{\sigma(pp \to F(h))}{\sigma(pp \to F(h))_{SM}}$$

For h → ff, f= b,τ,γ,W,Z - ratio of BR's :

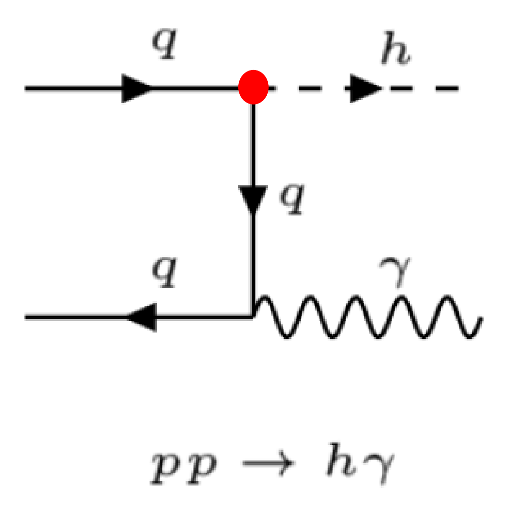
$$\mu^{decay}_{UEHiggsY} \equiv \frac{BR(h \to f\bar{f})_{UEHiggsY}}{BR(h \to f\bar{f})_{SM}} = \frac{1}{1 + 4\kappa_q^2 BR(h \to b\bar{b})_{SM}} \sim 0.3$$

$$\kappa_q \equiv \frac{y_q}{y_b^{SM}} \to 1$$

⇒ For n Higgs bosons in the final state & including the Higgs decays h → ff:

$$R_{F(h \to f\bar{f})} = R_{F(h)} \cdot \left(\mu^{decay}_{UEHiggsY}\right)^n \sim 0.3^n \cdot R_{F(h)}$$

Higgs + high p_T photon : $pp \to h+\gamma$



+ crossed …

SM:

- tree-level: $cc, bb \to h\gamma \Rightarrow \sigma_{SM}(pp \to h\gamma) \sim O(0.1\ fb)$ [$p_T(\gamma) > 30$ GeV]
- **No *gg* → hγ (Furry's theorem)**
- **SM inclusive hγ production @ 13TeV LHC:**

  $\sigma_{SM}(pp \to h\gamma + j\ ,\ h\gamma + W/Z\ ,\ h\gamma + tt\ ,\ h\gamma + t + j) \sim O(1\ fb)$
  $\sigma_{SM}(pp \to h\gamma + 2j) \sim O(20\ fb)$

Gabrielli, Mele, Piccinini, Pittau, JHEP2016 (arxiv:1601.03635);
Gabrielli, Maltoni, Mele, Moretti, Piccinini, Pittau, NPB2007, (hep-ph/0702119)