Modified Higgs couplings in minimal composite Higgs models
(and beyond)

Avik Banerjee
Saha Institute of Nuclear Physics, HBNI
Kolkata

(w/ Gautam Bhattacharyya, Nilanjana Kumar, Tirtha Sankar Ray)

PRD 96 (2017) 035040, JHEP 1803 (2018) 062

23rd DAE-BRNS HEP Symposium, 2018
IIT Madras, Chennai
13.12.2018

Composite Higgs : Introduction

- Higgs : composite bound state of a strongly interacting sector

  Emerges as a pNGB

- Motivations: Hierarchy problem

  (Non-SUSY alternative)

Composite Higgs : Introduction

- Higgs : composite bound state of a strongly interacting sector

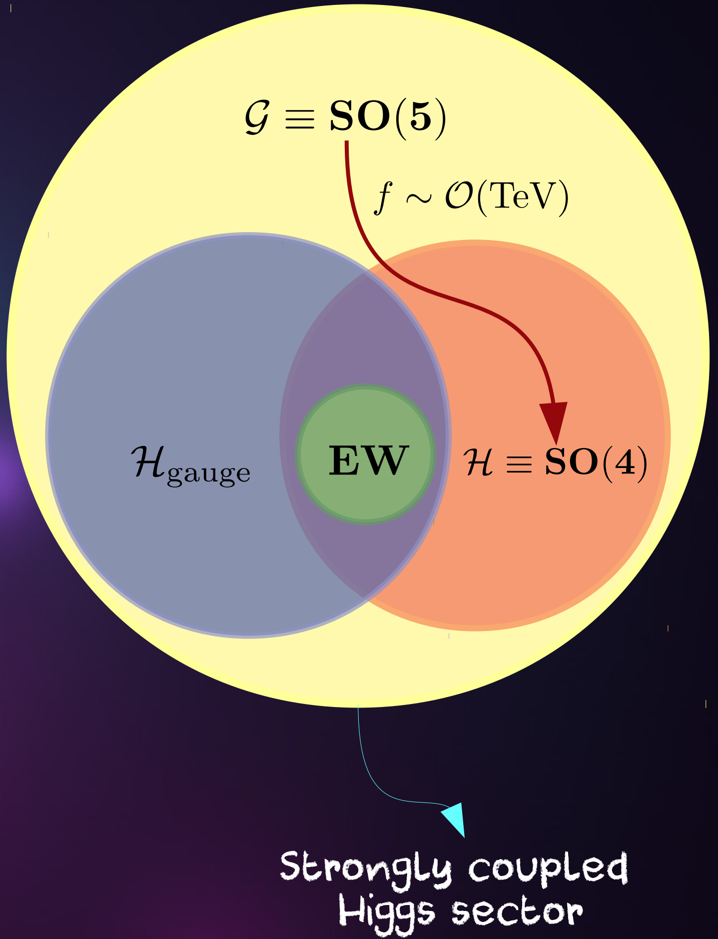
  Emerges as a pNGB

- Motivations: Hierarchy problem

  (Non-SUSY alternative)

- Minimal realization (MCHM) :

  SO(5) / SO(4)



Composite Higgs : Introduction

- Higgs : composite bound state of a strongly interacting sector

  Emerges as a pNGB

- Motivations: Hierarchy problem

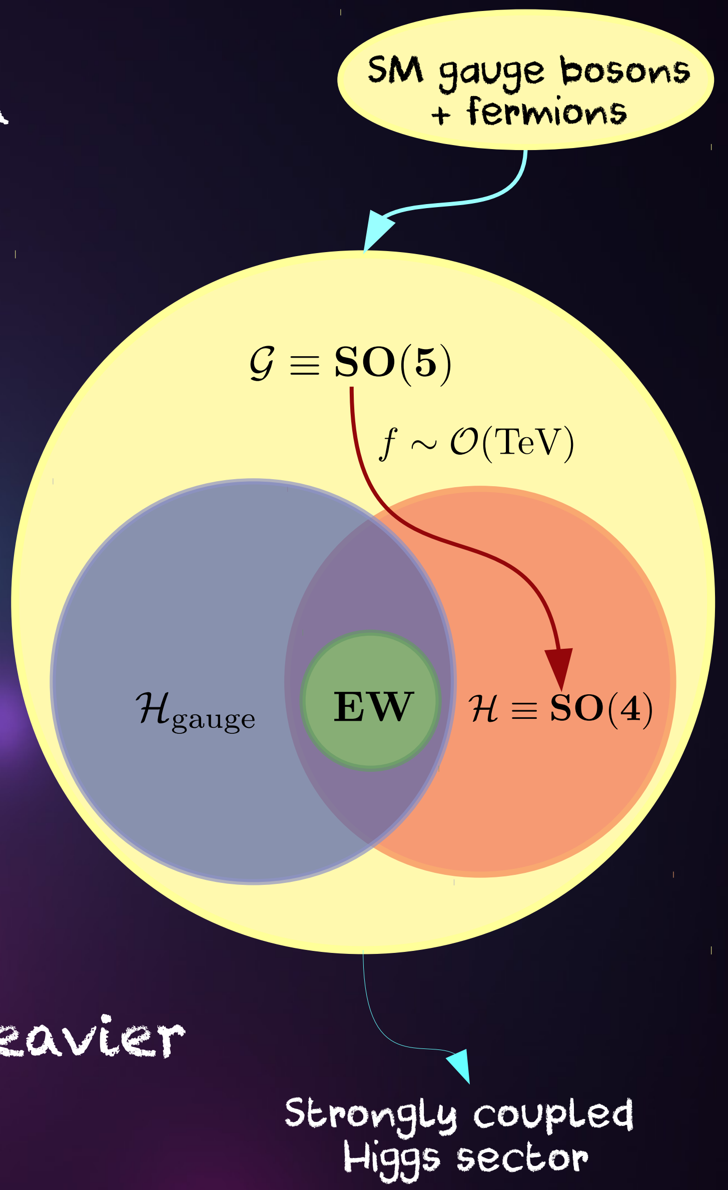
  (Non-SUSY alternative)

- Minimal realization (MCHM) :

  SO(5) / SO(4)

- Partial compositeness paradigm: heavier quarks are more composite

$$|\mathrm{SM}\rangle = \cos\theta|\mathrm{elem}\rangle + \sin\theta|\mathrm{comp}\rangle$$



Strongly Interacting Light Higgs (SILH)

Higher dimensional operators

$$\mathcal{L}_{\text{kin}} = |D_\mu H|^2 + \frac{c_H}{2f^2}|\partial_\mu (H^\dagger H)|^2 + \ldots$$

$$\mathcal{L}_{\text{Yuk}} = -y_u \bar{q}_L H^c u_R - y_u \Delta_u \frac{H^\dagger H}{f^2} \bar{q}_L H^c u_R + \ldots$$

*Giudice et. al. 0703164 hep-ph

Strongly Interacting Light Higgs (SILH)

Higher dimensional operators

$$\mathcal{L}_{\text{kin}} = |D_\mu H|^2 + \frac{c_H}{2f^2}|\partial_\mu (H^\dagger H)|^2 + \dots$$

$$\mathcal{L}_{\text{Yuk}} = -y_u \bar{q}_L H^c u_R - y_u \Delta_u \frac{H^\dagger H}{f^2} \bar{q}_L H^c u_R + \dots$$

After EWSB

$$\mathcal{L}_{\text{gauge}} = M_W^2 \left(|W|^2 + \frac{1}{2c_W^2} Z^2 \right) \left[1 + k_V \frac{h}{v} + k_V^{(2)} \frac{h^2}{v^2} + \dots \right]$$

$$\mathcal{L}_{\text{Yuk}} = -m_u \bar{u} u \left[1 + k_u \frac{h}{v} + k_u^{(2)} \frac{h^2}{v^2} + \dots \right]$$

$$k_V = \frac{g_{hVV}}{g_{hVV}^{SM}} = \sqrt{1 - c_H \frac{v^2}{f^2}} \qquad k_u = \frac{g_{h\bar{u}u}}{g_{h\bar{u}u}^{SM}} = 1 + \left(\Delta_u - \frac{c_H}{2} \right) \frac{v^2}{f^2}$$

*Giudice et. al. 0703164 hep-ph

Modified Higgs Couplings in MCHM

$$\Delta\mathcal{L} \sim \frac{1}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) - y\Delta_u \frac{H^\dagger H}{f^2}\bar{q}_L H^c u_R$$

- hVV: uniquely determined by composite scale (f)

$$k_V = \frac{g_{hVV}}{g_{hVV}^{SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

Modified Higgs Couplings in MCHM

$$\Delta\mathcal{L} \sim \frac{1}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) - y\Delta_u \frac{H^\dagger H}{f^2}\bar{q}_L H^c u_R$$

- hVV : uniquely determined by composite scale (f)

$$k_V = \frac{g_{hVV}}{g_{hVV}^{SM}} = \sqrt{1 - \frac{v^2}{f^2}}$$

- Yukawa : model dependent

$$k_t = 1 + \left(\Delta_t - \frac{1}{2}\right)\frac{v^2}{f^2}$$

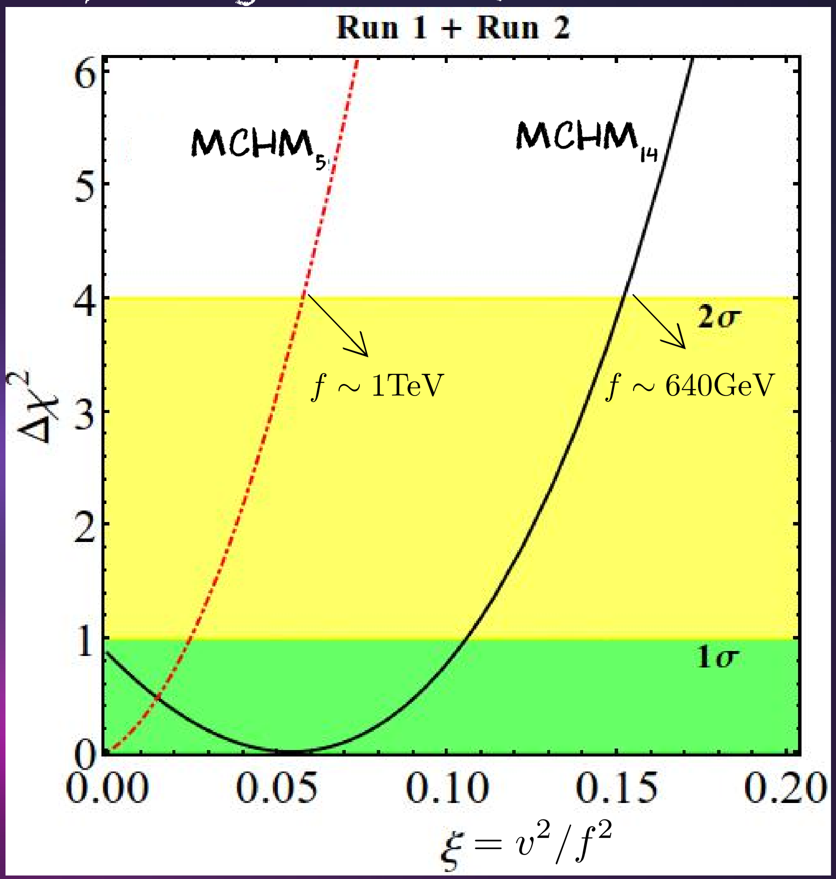
MCHM$_5$

$$\Delta_t = -1$$

MCHM$_{14}$

$$\Delta_t = \Delta_t(F_Q, m_Q)$$

Confronting LHC data (7-8 TeV + 13TeV)



AB, G Bhattacharyya, N Kumar, T S Ray; 1712.07494

Beyond MCHM...

- Additional scalar pNGBs can exist : dark matter candidate / fine-tuning / collider phenomenology

Beyond MCHM…

- Additional scalar pNGBs can exist : dark matter candidate / fine-tuning / collider phenomenology

Examples:

- Doublet + Singlet : $SO(6)/SO(5)$
- 2HDM : $SO(6)/SO(4)\times SO(2)$
- Doublet + Triplet : $SU(5)/SO(5)$

Beyond MCHM...

- Additional scalar pNGBs can exist : dark matter candidate / fine-tuning / collider phenomenology

Examples:

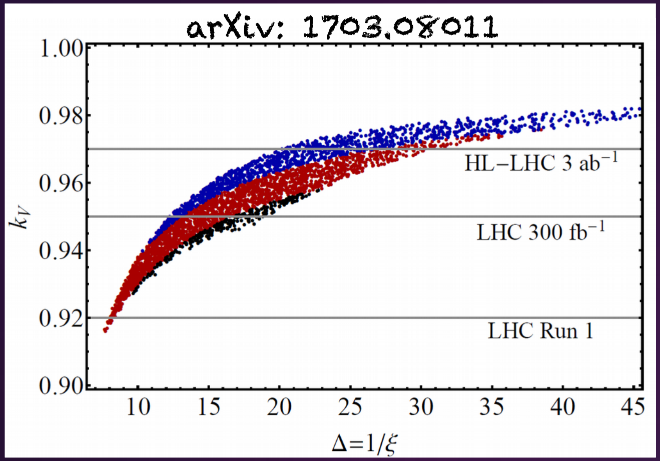
- Doublet + Singlet : SO(6)/SO(5)
- 2HDM : SO(6)/SO(4)xSO(2)
- Doublet + Triplet : SU(5)/SO(5)

SILH description:

- Doublet + Singlet : Chala et al. 1703.10624
- 2HDM : Karmakar et al. 1707.00716
- Doublet + Triplet : Not yet done

Next-to-minimal : SO(6)/SO(5) Case

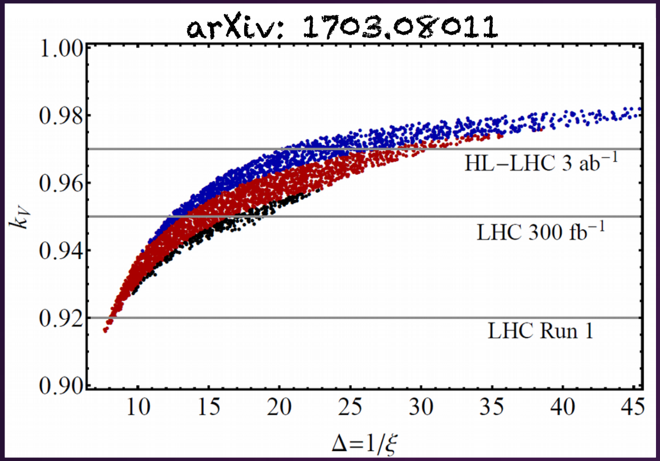
$$k_V = \cos\theta_{\rm mix}\sqrt{1-\frac{v^2}{f^2}}$$



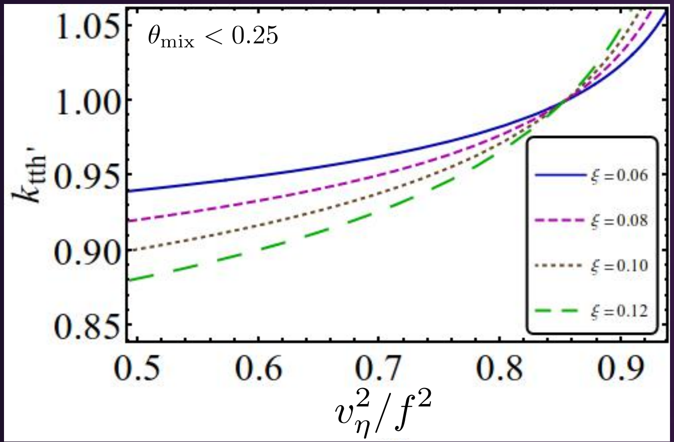
Next-to-minimal : SO(6)/SO(5) Case

$$k_V = \cos\theta_{\rm mix}\sqrt{1-\frac{v^2}{f^2}}$$

$$\Delta\mathcal{L}_\eta \sim -y\Delta_u^\eta \frac{\eta^2}{f^2}\bar{q}_L H^c u_R$$



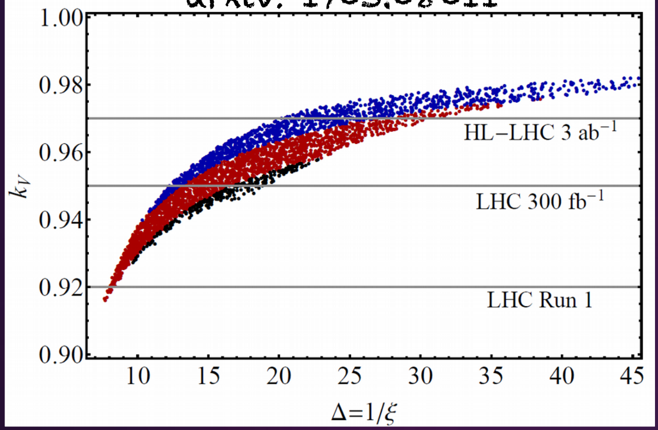
$$k_t = \cos\theta_{\rm mix}\left[1+\left(\Delta_t-\frac{1}{2}\right)\frac{v^2}{f^2}\right]+\Delta_t^\eta\sin\theta_{\rm mix}\sqrt{\frac{v^2v_\eta^2}{f^2(f^2-v_\eta^2)}}$$



Next-to-minimal : SO(6)/SO(5) Case

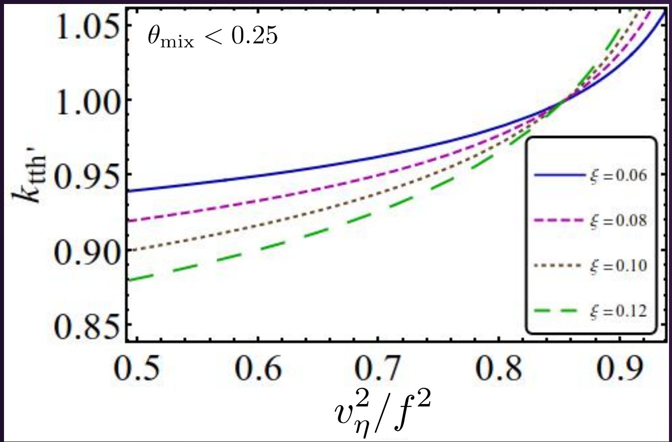
$$k_V = \cos\theta_{\rm mix}\sqrt{1-\frac{v^2}{f^2}}$$

arXiv: 1703.08011

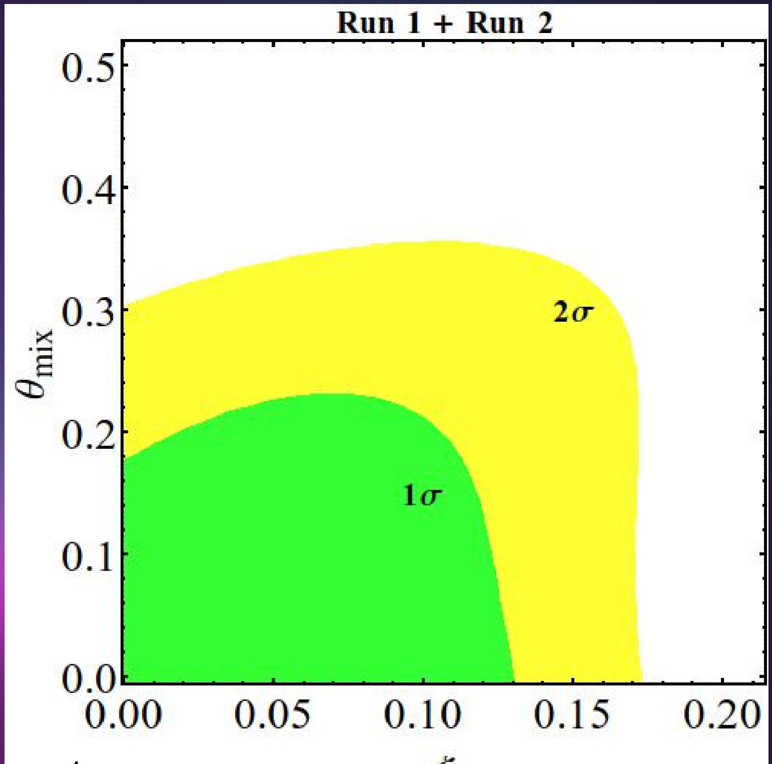


$$\Delta\mathcal{L}_\eta \sim -y\Delta_u^\eta \frac{\eta^2}{f^2}\bar{q}_L H^c u_R$$

$$k_t = \cos\theta_{\rm mix}\left[1+\left(\Delta_t-\frac{1}{2}\right)\frac{v^2}{f^2}\right]+\Delta_t^\eta \sin\theta_{\rm mix}\sqrt{\frac{v^2 v_\eta^2}{f^2(f^2-v_\eta^2)}}$$



- LHC bounds on doublet-singlet mixing :



arXiv: 1712.07494

Doublet + Triplet : Georgi-Machacek model

Custodial symmetry protected by scalar potential at tree level

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_L \to \mathrm{SU}(2)_V$$

$$(2,2) \to 1 \oplus 3$$

$$(3,3) \to 1 \oplus 3 \oplus 5$$

$$(h_{125}, H) \quad (H_3^\pm, H_3^0) \quad (H_5^{\pm\pm}, H_5^\pm, H_5^0)$$

$$(G^\pm, G^0)$$

VEVS:

$$\langle \phi^0 \rangle = \frac{v_d}{\sqrt{2}}, \quad \langle \xi^0 \rangle = \langle \chi^0 \rangle = v_t$$

$$\tan\beta = \frac{2\sqrt{2} v_t}{v_d}$$

Doublet + Triplet : Georgi-Machacek model

Custodial symmetry protected by scalar potential at tree level

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_L \to \mathrm{SU}(2)_V$$

$$(2,2) \to 1 \oplus 3$$

$$(3,3) \to 1 \oplus 3 \oplus 5$$

(h_{125}, H) $(H_3^\pm, H_3^0)$ $(G^\pm, G^0)$ $(H_5^{\pm\pm}, H_5^\pm, H_5^0)$

VEVS:

$$\langle \phi^0 \rangle = \frac{v_d}{\sqrt{2}}, \quad \langle \xi^0 \rangle = \langle \chi^0 \rangle = v_t$$

$$\tan\beta = \frac{2\sqrt{2} v_t}{v_d}$$

Toy scenario : dimension-6 operators in Yukawa sector only

$$\mathcal{L}_{\mathrm{Yuk}} = -y^u \bar{q}_L \phi^c u_R - \frac{\Delta_u}{f} y^u \bar{q}_L \chi^\dagger \phi u_R - \frac{\Delta'_u}{f} y^u \bar{q}_L \xi \phi^c u_R + \text{down-type}$$

Y=1/2 Y=1 Y=0

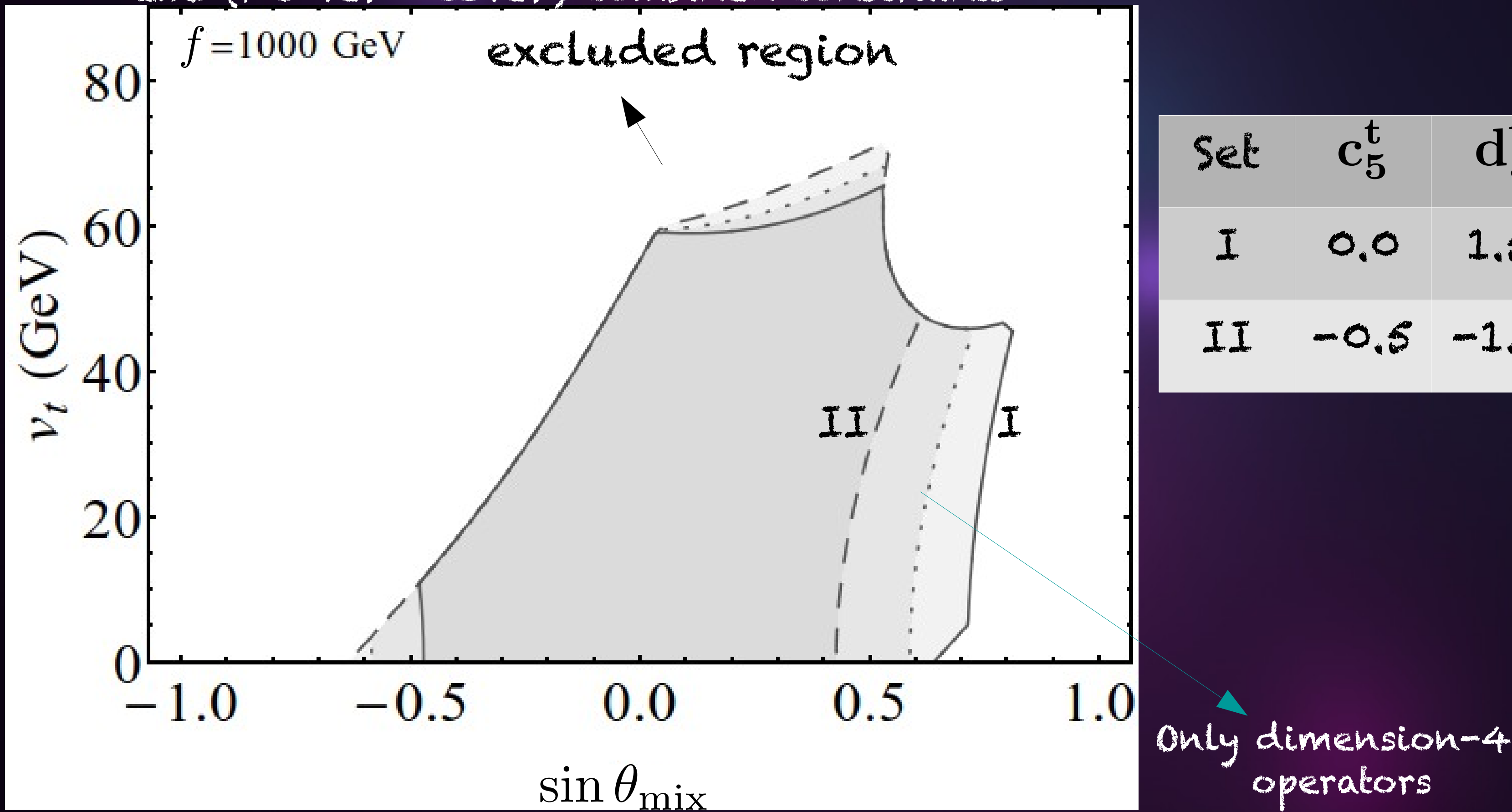
*AB, G Bhattacharyya, N Kumar (in preparation)

125 GeV Higgs at LHC

$$k_V = \cos\theta_{\rm mix}\cos\beta + 2\sqrt{\frac{2}{3}}\sin\theta_{\rm mix}\sin\beta$$

$$k_{t,b} = \frac{\cos\theta_{\rm mix}}{\cos\beta} + \sin\theta_{\rm mix}\left(\frac{c_5^{t,b}}{\sqrt{3}} \pm \frac{d_5^{t,b}}{\sqrt{6}}\right)\frac{v}{f}$$

LHC (7-8 TeV + 13TeV) combined constraints

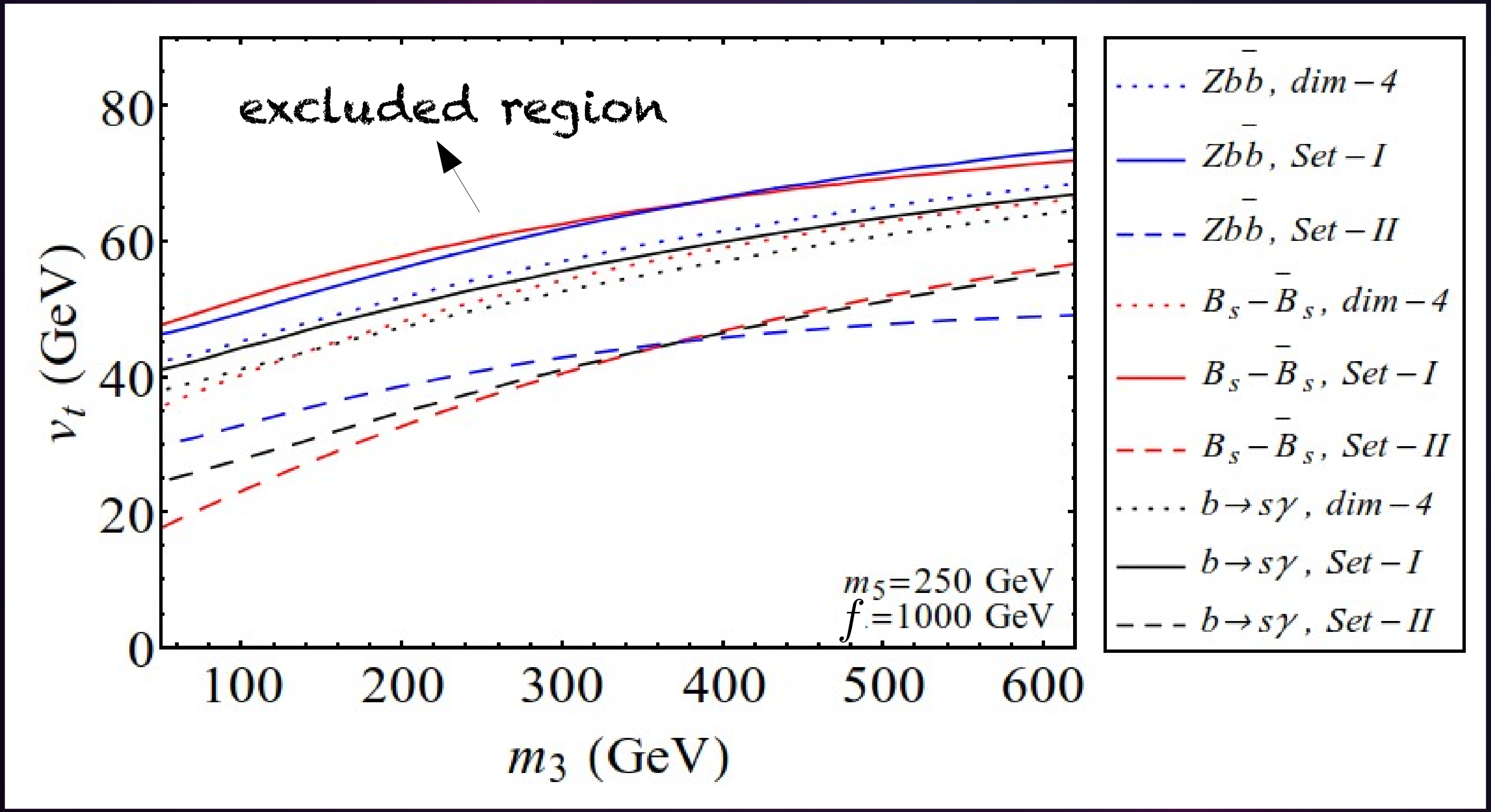


Set	c_5^t	d_5^t	c_5^b	d_5^b
I	0.0	1.5	0.5	1.5
II	-0.5	-1.5	0.5	1.5

Charged Higgs

$$g_{H_3^\pm \bar{u} d} = -i\frac{\sqrt{2}}{v}V_{ud}\left[\left(t_\beta - \frac{1}{c_\beta}\left(\frac{c_5^u}{2\sqrt{2}} + \frac{d_5^u}{2}\right)\frac{v}{f}\right)m_u P_L - \left(t_\beta - \frac{1}{c_\beta}\left(\frac{c_5^d}{2\sqrt{2}} - \frac{d_5^d}{2}\right)\frac{v}{f}\right)m_d P_R\right]$$

$$g_{H_5^\pm \bar{u} d} = i\frac{\sqrt{2}}{v}V_{ud}\left[\left(\frac{c_5^u}{2\sqrt{2}} - \frac{d_5^u}{2}\right)\frac{v}{f}m_u P_L - \left(\frac{c_5^d}{2\sqrt{2}} + \frac{d_5^d}{2}\right)\frac{v}{f}m_d P_R\right]$$



Take home...

- Composite Higgs: interesting non-SUSY alternative to address hierarchy problem
- Experimental consequences: new colored particles, modifications in Higgs couplings
- Higher dimensional operators capture nonlinearity of pNGBs (e.g. SILH framework)
- MCHM: hVV modifications universal, hff depends on reps.
- Next-to-minimal: additional modifications due to neutral scalar mixing, constrained by LHC data
- Triplet extended models (e.g. GM model): significant impact of dimension-6 operators, constraints from flavour physics observables on charged Higgs sector
- Future direction: Full SILH description of triplet Higgs models

Thank you!