A BRIEF OVERVIEW OF NEXT-TO-MINIMAL COMPOSITE HIGGS MODEL

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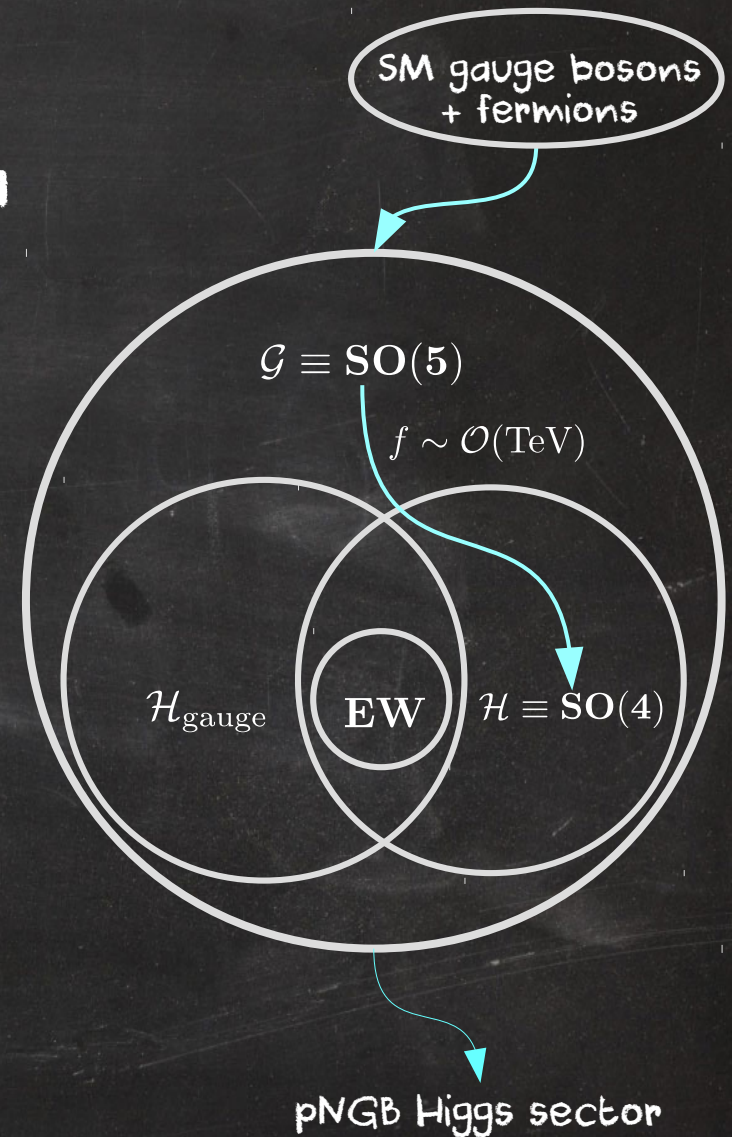Saha Institute of Nuclear Physics, HBNI
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SUSY 17
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Composite Higgs : Introduction

- Higgs : **composite bound state** of a strongly interacting sector

  Emerges as a **pNGB**

- Motivations: Hierarchy problem

  (Non-SUSY alternative)

- Minimal realization : **SO(5) / SO(4)**

- **Partial compositeness** paradigm: heavier quarks are more composite

SM gauge bosons
+ fermions

$\mathcal{G} \equiv \mathrm{SO}(5)$

$f \sim \mathcal{O}(\mathrm{TeV})$

$\mathcal{H}_{\mathrm{gauge}}$ **EW** $\mathcal{H} \equiv \mathrm{SO}(4)$

pNGB Higgs sector
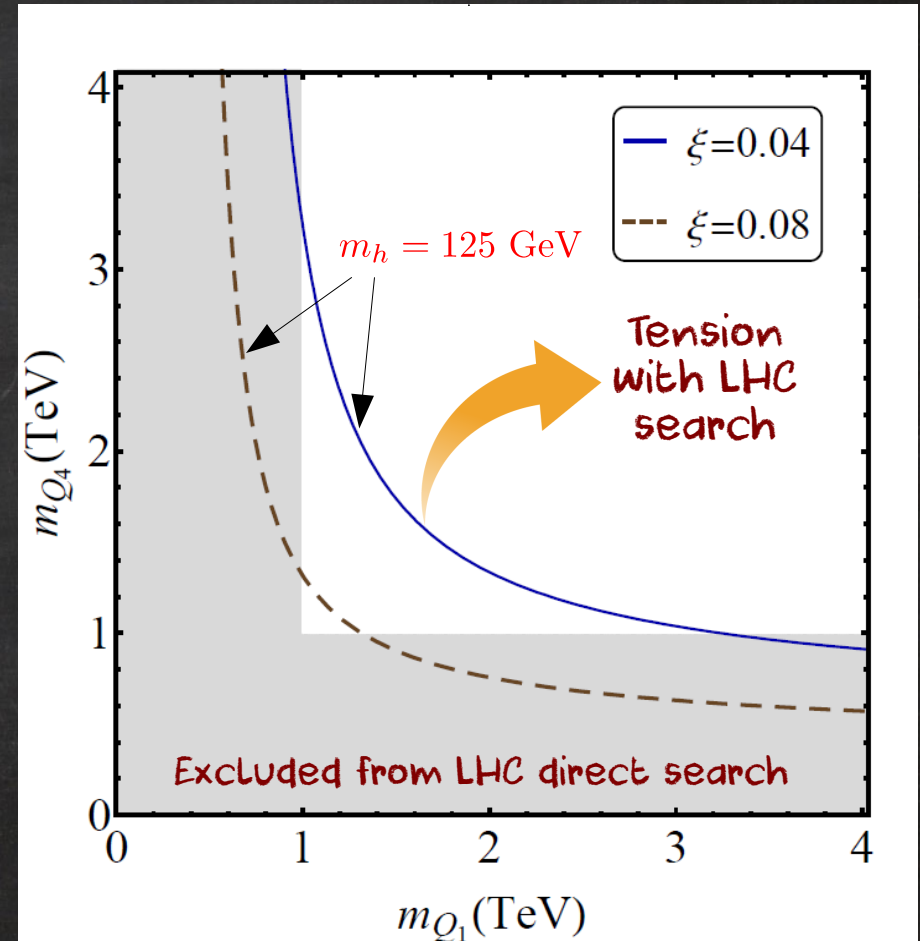
Higgs: too light to be composite ?

- Higgs mass scales as:

$$m_h^2 \sim \frac{N_c}{\pi^2} \frac{m_t^2 m_Q^2}{f^2}$$
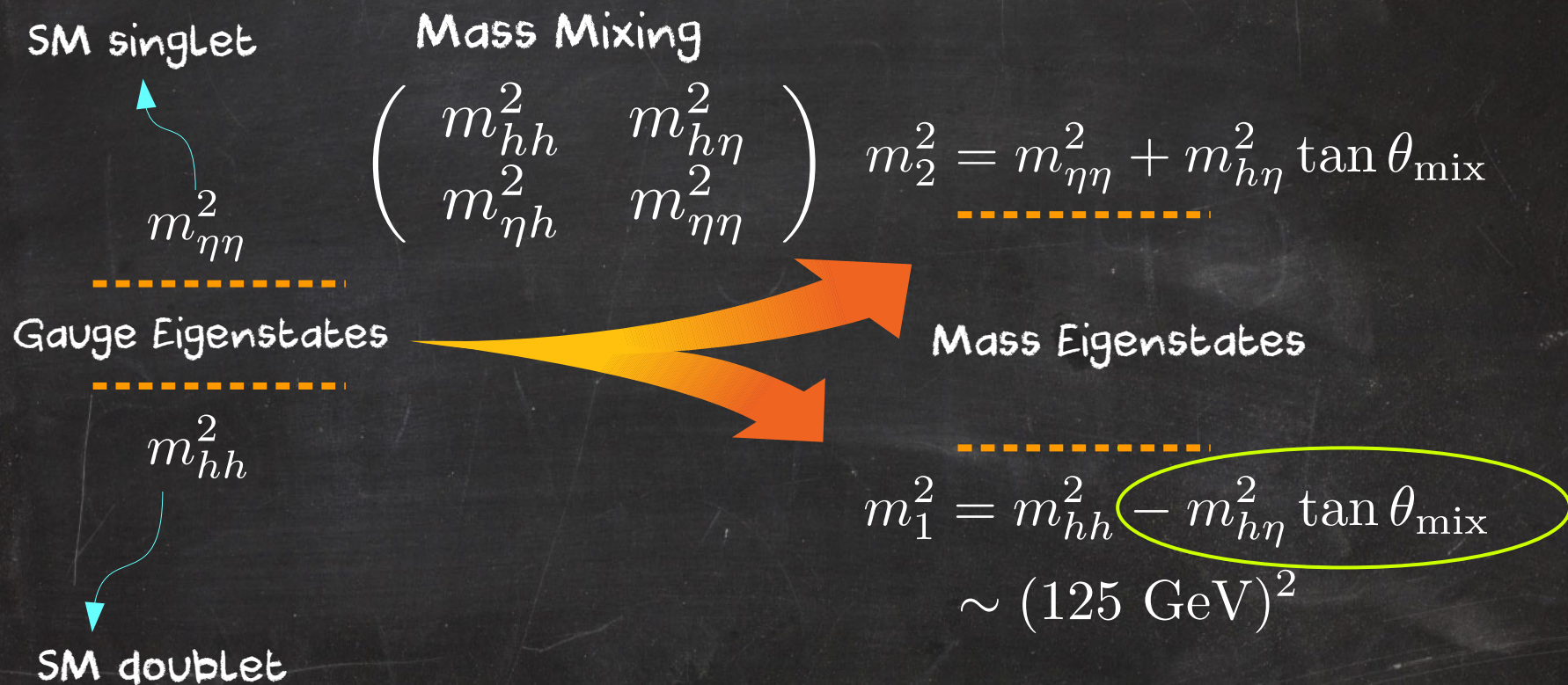
$$\xi = \frac{v^2}{f^2}$$

Light top-partners

Large Fine-tuning

Light Higgs

$m_h = 125$ GeV

Tension with LHC search

Excluded from LHC direct search

$\xi=0.04$

$\xi=0.08$

m_{Q_4}(TeV)

m_{Q_1}(TeV)

SO(5) / SO(4):
$$m_h^2 = \frac{N_c}{\pi^2} \frac{m_t^2}{f^2} \frac{m_{Q_1}^2 m_{Q_4}^2}{m_{Q_1}^2 - m_{Q_4}^2} \log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)$$

3

Pomarol, Riva; 12

Level Repulsion: improving fine-tuning

SM singlet

Mass Mixing

$$m^2_{\eta\eta}$$

$$\begin{pmatrix} m^2_{hh} & m^2_{h\eta} \\ m^2_{\eta h} & m^2_{\eta\eta} \end{pmatrix}$$

$$m^2_2 = m^2_{\eta\eta} + m^2_{h\eta} \tan\theta_{\mathrm{mix}}$$

- - - - - - - -

Gauge Eigenstates

- - - - - - - -

Mass Eigenstates

$$m^2_{hh}$$

- - - - - - - -

$$m^2_1 = m^2_{hh} - m^2_{h\eta} \tan\theta_{\mathrm{mix}}$$

$$\sim (125 \text{ GeV})^2$$

SM doublet

Enlarge the coset ! $\Longrightarrow$ SO(6) / SO(5)

Next-to-Minimal Model: SO(6) / SO(5)

- **5 NGBs :** $\Sigma(x) = \dfrac{1}{f}\left(h_1,\ h_2,\ h_3,\ h_4,\ \eta,\ \sqrt{f^2 - h_1^2 - h_2^2 - h_3^2 - h_4^2 - \eta^2}\right)^T$

- Radiative Potential :

$$V_{\text{eff}}(h,\eta) = -\frac{\mu_1^2}{2}h^2 + \frac{\lambda_1}{4}h^4 - \frac{\mu_2^2}{2}\eta^2 + \frac{\lambda_2}{4}\eta^4 - \frac{\lambda_m}{2}h^2\eta^2 \qquad \text{Mixing}$$
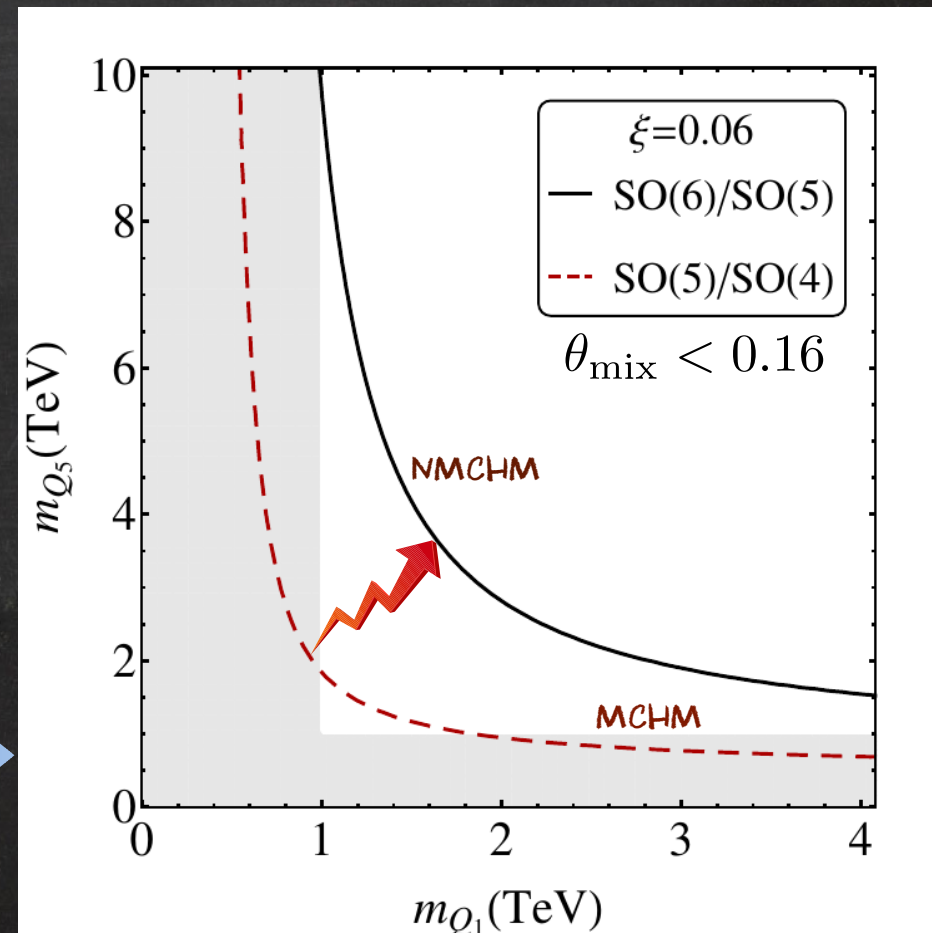
- Two possible minima :

$v_\eta = 0$
DM-candidate

$v_\eta \neq 0$
Doublet-singlet mixing

More breathing space for top-partners

$\xi = 0.06$

— SO(6)/SO(5)

-- SO(5)/SO(4)

$\theta_{\text{mix}} < 0.16$

NMCHM

MCHM

m_{Q_5}(TeV)

m_{Q_1}(TeV)

Modified Higgs Couplings : SO(5) /SO(4) case

$$\Delta\mathcal{L} \sim \frac{1}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) - \sum_{i=u,d}\Delta_i' y_i \frac{H^\dagger H}{f^2}\bar{q}_{L_i} H \psi_{R_i}$$

- hVV : uniquely determined by composite scale

$$k_V = \frac{g_{hVV}}{g_{hVV}^{SM}} = \sqrt{1-\xi}$$

- Yukawa : model dependent

$$k_t = 1 + \Delta_t \xi$$

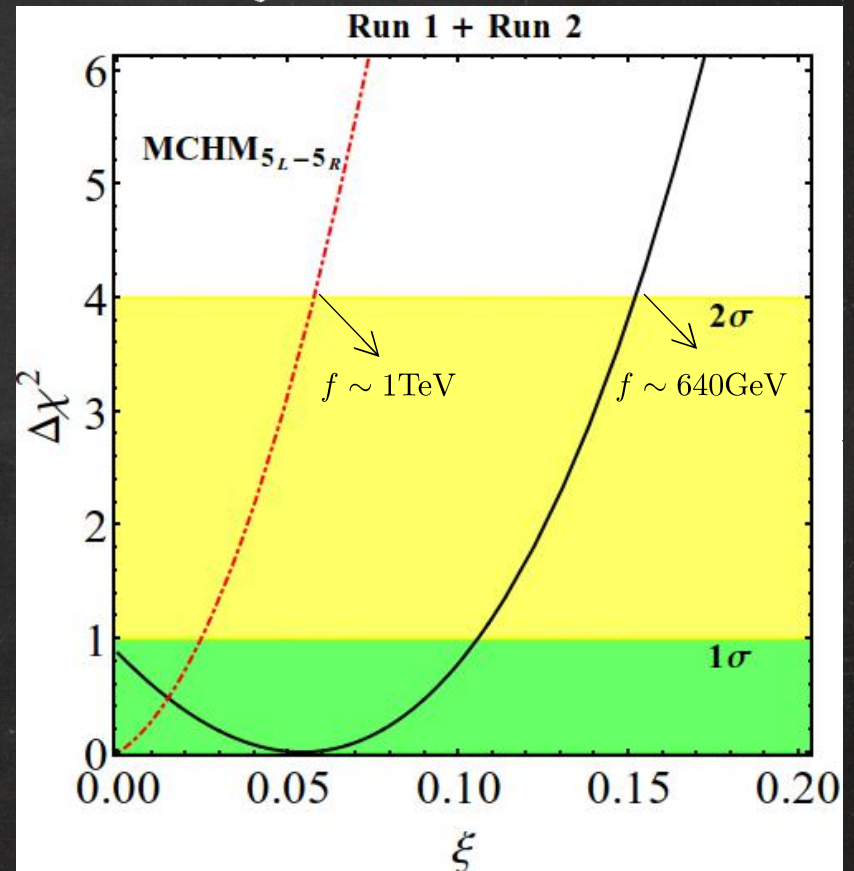MCHM$_{5L-5R}$

$$\Delta_t = -\frac{3}{2}$$

MCHM$_{14L-14R,\ 14L-5R,\ 5L-14R}$

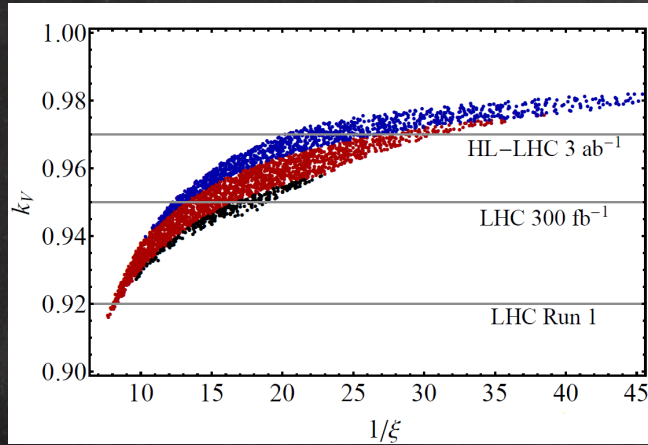$$\Delta_t = \Delta_t(F_Q, m_Q)$$

Riva et. al.; 13, Liu et.al.; 17

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

Run 1 + Run 2

MCHM$_{5_L-5_R}$

$f \sim 1\text{TeV}$ $f \sim 640\text{GeV}$

2σ

1σ

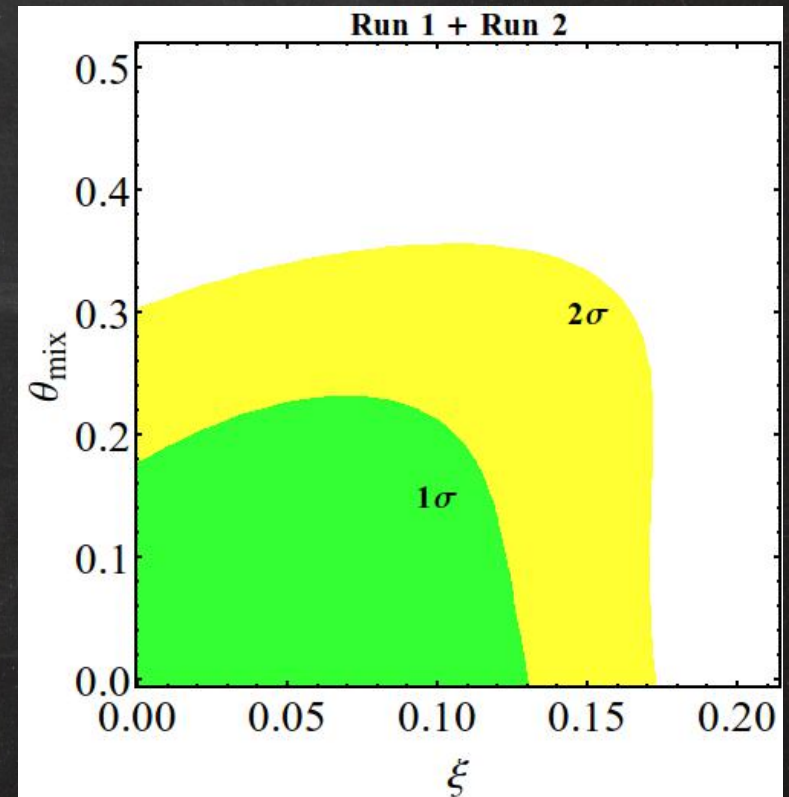AB, G Bhattacharyya, N Kumar, T S Ray
(in preparation)

SO(6)/SO(5) Case

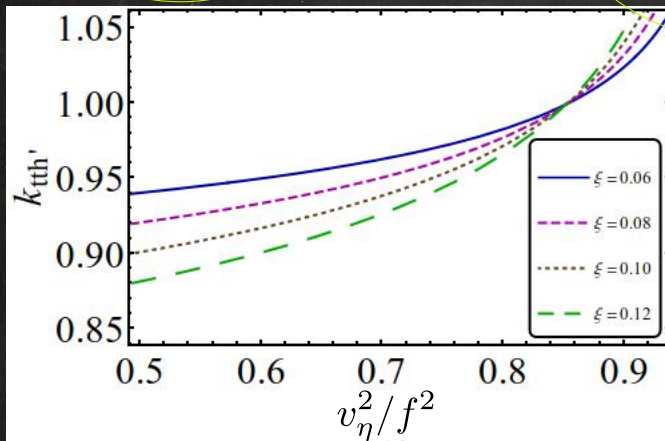$$k_V = \cos\theta_{\text{mix}}\sqrt{1-\xi}$$

$$\Delta\mathcal{L}_\eta \sim -\sum_{i=u,d} y_i(\Delta_i^\eta)'\frac{\eta^2}{f^2}\bar{q}_{L_i}H\psi_{R_i}$$

- LHC bounds on doublet-singlet mixing :

$$k_t = \cos\theta_{\text{mix}}(1+\Delta_t\xi) + \Delta_t^\eta\sin\theta_{\text{mix}}\sqrt{\frac{\xi v_\eta^2}{f^2-v_\eta^2}}$$
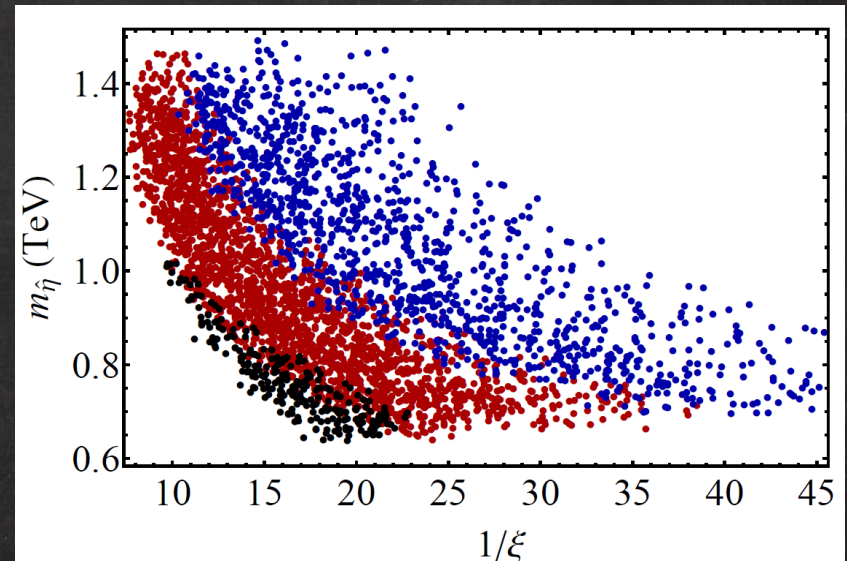
Singlet Phenomenology

- Non trivial couplings with gauge bosons and 3rd generation quarks

$$c_{\eta VV} \propto \sin\theta_{\text{mix}}\sqrt{1-\xi}$$

$$c_{\eta\bar{t}t} \propto -\cos\theta_{\text{mix}}\Delta_t^\eta\sqrt{\frac{\xi v_\eta^2}{f^2 - v_\eta^2}} + \sin\theta_{\text{mix}}(1+\Delta_t\xi)$$

- **Large mass** of η ➡

  Production modes and decay channels similar to Higgs, modulo suppressions due to large mass, small couplings

- **New search topologies:** $\eta \to hh$, $\eta \to t\bar{t}$ provided ($m_\eta > 2m_h, 2m_t$)

Niehoff et.al. 1611.09356

8

Summary

- Higgs as a composite pNGB: address hierarchy problem

- Minimal composite model : requires either large fine-tuning or light top-partners

- Next-to-minimal case extends the coset to $SO(6)/SO(5)$: Higgs doublet + SM singlet scalar

- Doublet-singlet mixing can give a handle to tame fine-tuning and accommodate heavier top-partners

- Phenomenological consequences include modified Higgs couplings : LHC data provide constraints on composite scale, doublet-singlet mixing
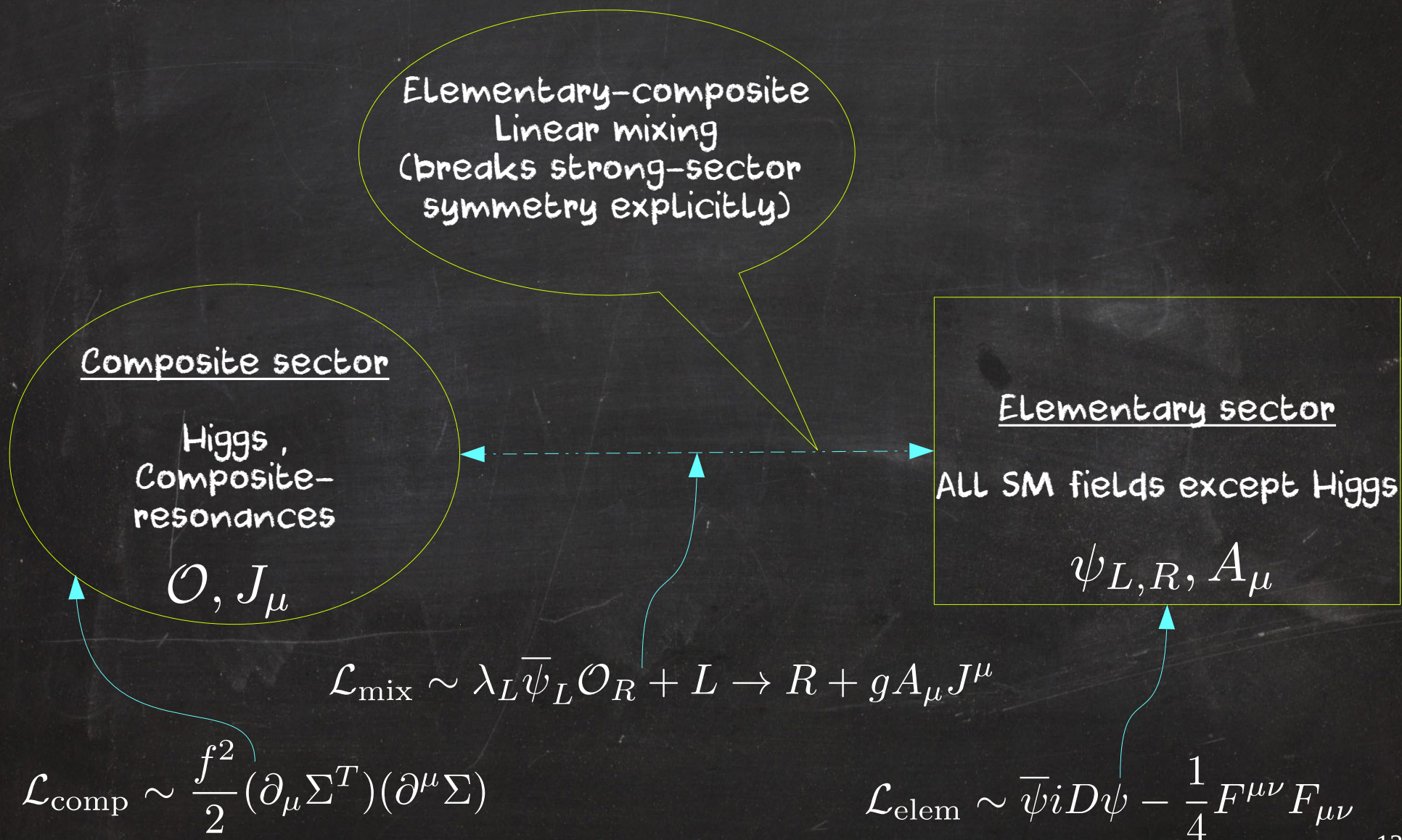
Collaborators:

Prof. Gautam Bhattacharyya (SINP)

Dr. Nilanjana Kumar (SINP)

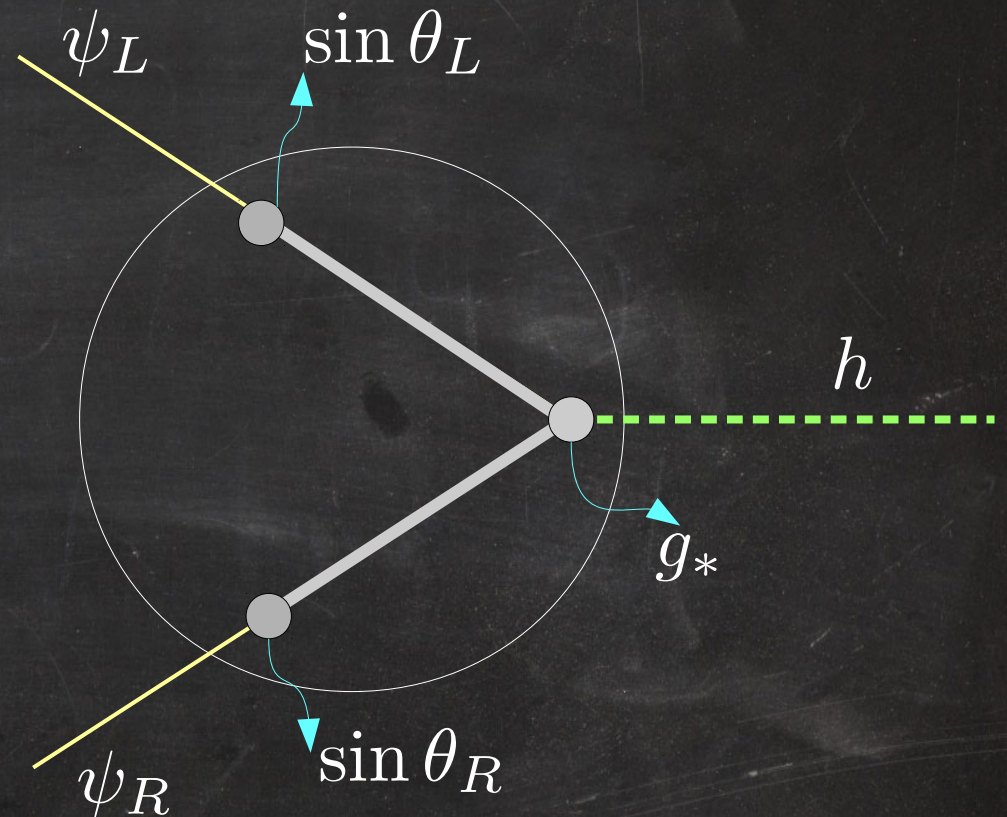Dr. Tirtha Sankar Ray (IIT Kharagpur)

THANK YOU !

Back up Slides

Partial Compositeness Paradigm

Elementary-composite
Linear mixing
(breaks strong-sector
symmetry explicitly)

Composite sector

Higgs ,
Composite-
resonances

$\mathcal{O}, J_\mu$

Elementary sector

ALL SM fields except Higgs

$\psi_{L,R}, A_\mu$

$$\mathcal{L}_{\mathrm{mix}} \sim \lambda_L \overline{\psi}_L \mathcal{O}_R + L \to R + g A_\mu J^\mu$$

$$\mathcal{L}_{\mathrm{comp}} \sim \frac{f^2}{2} (\partial_\mu \Sigma^T)(\partial^\mu \Sigma)$$

$$\mathcal{L}_{\mathrm{elem}} \sim \overline{\psi} i D \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

Yukawa Coupling

- SM fermions : massive after EWSB

- Interaction with Higgs

  ➡ via composite resonances

- Top can be substantially composite, while other light quarks are mostly elementary

ψ_L $\quad \sin\theta_L$

h

g_*

ψ_R $\quad \sin\theta_R$

Yukawa coupling :
$$y_\psi \simeq g_* \sin\theta_L \sin\theta_R$$

13

Lagrangian and EWSB Potential

- Gauge Contribution : similar to minimal model

$$\mathcal{L} = \frac{1}{2} P_T^{\mu\nu} \left[\left(\Pi_0(q^2) + \frac{\Pi_1(q^2)}{4} \frac{h^2}{f^2} \right) (B_\mu B_\nu + W_\mu^a W_\nu^a) + ... \right]$$

- Fermion contribution (top-quark) :

$$\mathcal{L} = \bar{t}_L p \left[\Pi_0^{t_L} + \frac{\Pi_1^{t_L}}{2} \frac{h^2}{f^2} \right] t_L + \bar{t}_R p \left[\Pi_0^{t_R} + \Pi_1^{t_R} \left(1 - \frac{h^2}{f^2} - \frac{\eta^2}{f^2} \right) \right] t_R$$

$$+ \bar{t}_L \left[\frac{\Pi^{t_L t_R}}{\sqrt{2}} \frac{h}{f} \sqrt{1 - \frac{h^2}{f^2} - \frac{\eta^2}{f^2}} \right] t_R + \text{h.c.}$$

- C-W Potential for h and η :

$$V_{\text{eff}} = \int \frac{d^4 q}{2\pi^4} \left[\frac{9}{2} \log \Pi_W(h) - 2N_c \log \left(q^2 \Pi_{t_L}(h,\eta) \Pi_{t_R}(h,\eta) + |\Pi_{t_L t_R}(h,\eta)|^2 \right) \right]$$