Exotic Higgs decays in models with natural neutrinos

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Outline

In the next 20 mins ..

1. Natural Neutrinos ?
2. Realisation in Composite Twin Higgs set up
    1. Gauge sector
    2. Top sector
    3. Neutrino sector
3. Higgs Decay
4. Summary/ Future Outlook

Natural Neutrinos ?

😞 LHC has placed significant pressure on the hypothesis of "natural" EWSB:

1. Measure properties of Higgs **consistent** with predictions of SM
2. Direct searches for new states responsible for softening the sensitivity of the Higgs mass eg. Colored Top partners not yet seen

Brings us to "Neutral Naturalnes"

1. Partner states responsible for cancellation of the quadratic divergence do not carry color charge
2. Such states have low cross-sections⇒difficult to see @LHC

Eg: Twin Higgs model [Chacki et. al. 2006….]

🤔 Plausible set up: Higgs to $\gamma\,\gamma$ and gg are SM like

⇒ maybe Higgs doesn't couple to light colored or charged fields

Natural Neutrinos

- Strong hints in nature for neutral states in BSM
  1. NP from disparate gravitational phenomenon pointing to Dark matter (DM)
  2. Need to generate neutrino mass

- Neutrino masses via introduction of right handed neutrinos (neutral states) which with ν_L via yukawa interaction

- What if – neutral fermionic top partner fields are simultaneously the right handed neutrinos (RHNs)? [Batell et. al. 2015]

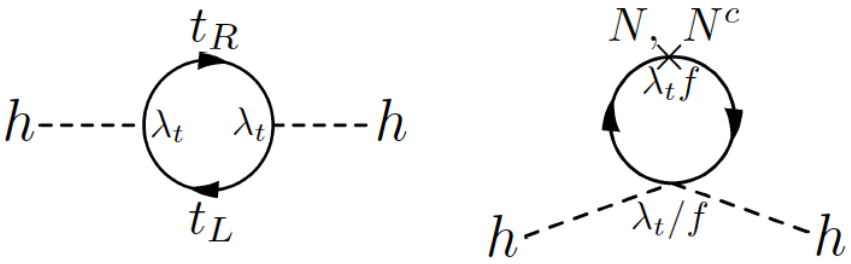
- These new neutral states, required to understand the empirical mystery of neutrino masses could also play a role in naturalness.

Natural Neutrinos

- **RHNs ↔ neutral top partners**

- Given that the RHNs are fermions, we are led to consider theories in which the Higgs arises as a pNGB, which provides a framework in which fermions can serve as top partners.

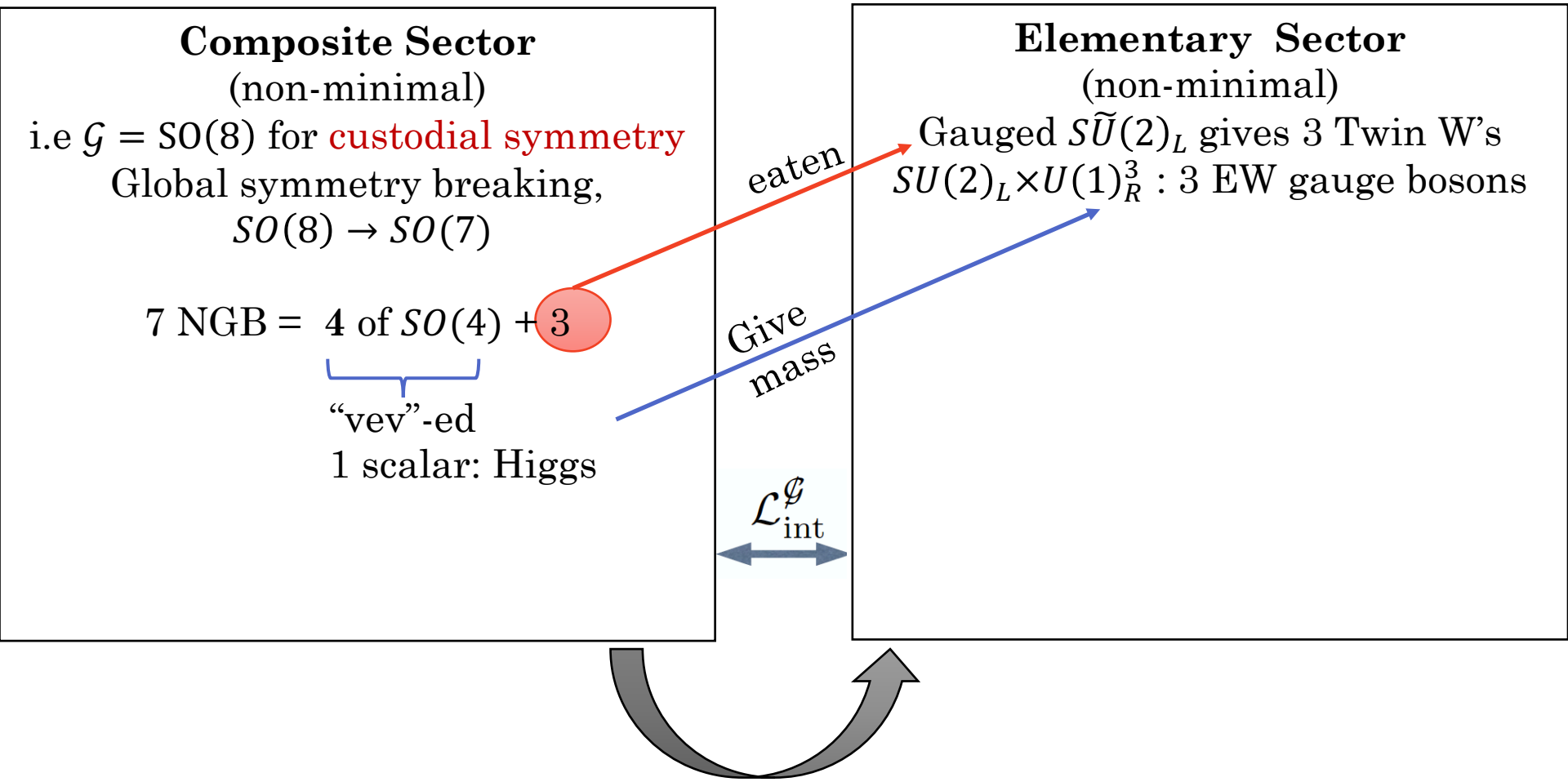
- For top partner to be neutral: $SU(3)_c$ should be **enlarged** to contain additional $SU(3)_N$ (for the right multiplicity of top partner loop)



- To enforce cancellation of quadratic divergences:
  1. Z_2 interchange symmetry, or
  2. $SU(6) \subset SU(3)_c \times SU(3)_N$

Explicit phenomenological model: composite Twin Higgs

2 site-Twin composite Higgs



$\frac{f^2}{4} Tr\left[\left(D_\mu \Sigma\right)^T D^\mu \Sigma\right]$, f is order parameter for $SO(8) \rightarrow SO(7)$

Gauge sector

Composite Sector
(non-minimal)
i.e $\mathcal{G} = \mathrm{SO}(8)$ for custodial symmetry
Global symmetry breaking,
$SO(8) \rightarrow SO(7)$

7 NGB = 4 of $SO(4)$ + 3

"vev"-ed
1 scalar: Higgs

Composite heavy resonances exist at mass scale $m^* \sim g^* f$

eaten

Give mass

$\mathcal{L}_{\text{int}}^{\not{G}}$

Elementary Sector
(non-minimal)
Gauged $S\tilde{U}(2)_L$ gives 3 Twin W's
$SU(2)_L \times U(1)_R^3$: 3 EW gauge bosons

ES: weakly coupled i.e $g_{1,2} \sim \tilde{g}_2 \ll g_\rho \sim g^*$

No $\tilde{B}_\mu$ - : Twin symmetry explicitly broken by not gauging twin Hypercharge
No massless twin photon

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$$M_W \sim g_2 f \sin\frac{\langle H\rangle}{f} = g_2 v$$

$$M_Z = M_W/\cos\theta_W \qquad M_\gamma = 0$$

$$M_{\widetilde{W}} \sim \tilde{g}_2 f \cos\frac{\langle H\rangle}{f} \sim \tilde{g}_2 f$$

Top sector

Composite Sector

Fermionic resonance,
Ψ *and* $\widetilde{\Psi}$ are $\mathbf{8}(\widetilde{\mathbf{8}})$ under SO(8)

They decompose under SO(7)
in $\mathbf{7}(\widetilde{\mathbf{7}})$ and $\mathbf{1}(\widetilde{\mathbf{1}})$

$\mathcal{L}_{int}$

Elementary Sector

Elementary $q_L(\widetilde{q_L})$ and
$t_R(\widetilde{t_R})$ mix with CS operators
in $\mathbf{8}(\widetilde{\mathbf{8}})$ and $\mathbf{1}(\widetilde{\mathbf{1}})$

ES: weakly coupled: $y_L, \widetilde{y_L} \ll g^*$

$\mathcal{G} = \mathrm{SO}(8) \times U(1)_X \times \widetilde{U(1)_X}$ to get right hypercharges for fermions; $Y = T_R^3 + X$
$SU(3)_c, \widetilde{SU(3)_c}$ global group introduced (ES and CS interact linearly)
Twin Parity is slightly different in the fermionic and gauge sectors.

$$\mathcal{L}_{int} = y_L^t\, \overline{q_L^t} \mathrm{U}\, \Psi_R^t + y_R^t \overline{t_R}\, \Psi_{L\mathbf{1}}^t + \widetilde{y_L^t}\, \overline{\widetilde{q_L^t}} \mathrm{U} \widetilde{\Psi_R^t} + \widetilde{y_R^t}\, \overline{\widetilde{t_R}}\, \widetilde{\Psi_{L\mathbf{1}}^t}$$

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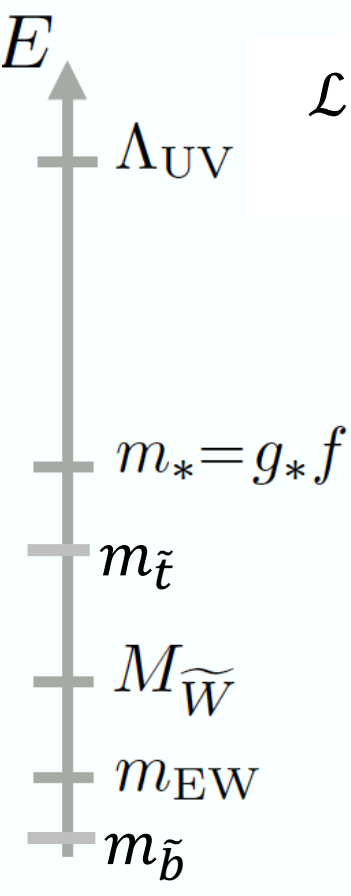
\# Mass e-state – top, bottom and it's twins

\# $m_t = \frac{y_t}{\sqrt{2}} \cdot v \sim \frac{y_L y_R}{g_*} \cdot v\,,\ m_{\tilde{t}} \sim \frac{\widetilde{y}_L \widetilde{y}_R}{g_*} \cdot f\,.$

\# CS resonances - heavy

Top/ Lepton sector

τ and ν embedded in similar fashion,
$L_l \leftrightarrow \widetilde{L_L}, \tau_R \leftrightarrow \widetilde{\tau_R}, \nu_R \leftrightarrow \widetilde{\nu_R}$ mix with CS operators in $\mathbf{8}(\widetilde{\mathbf{8}})$ and $\mathbf{1}(\widetilde{\mathbf{1}})$



$$\mathcal{L}_{int}^{lep} = \lambda_L^\tau \, \overline{L_L^\tau} \mathrm{U} \, \chi_R^\tau + \lambda_R^\tau \overline{\tau_R} \, \chi_{L\mathbf{1}}^\tau + \widetilde{\lambda_L^\tau} \, \overline{\widetilde{L_L^\tau}} \mathrm{U} \widetilde{\chi_R^\tau} + \widetilde{\lambda_R^\tau} \, \overline{\widetilde{\tau_R}} \, \widetilde{\chi_{L\mathbf{1}}^\tau}$$

$\widetilde{SU(3)}$:

1. Identified as flavor symmetry of RHNs
2. Assumed to be global symmetry $\Longrightarrow \mathcal{O}(10\%)$ tuning for $\Lambda \sim 5\ TeV$
3. $\widetilde{SU(3)}$ breaking terms crucial for neutrino mass generation - kept small to not affect tuning

Symmetries of fields below scale of $SU(3)\times \widetilde{SU(3)}$ breaking and after $SO(8) \to SO(7)$

Field	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$\widetilde{SU(3)}_c$	$\widetilde{SU(2)}_W$	$\boldsymbol{U(1)_X}$	$\boldsymbol{\widetilde{U(1)}_X}$
$q = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$	**3**	**2**	$1/6$	**1**	**1**	$2/3$	–
t_R	$\overline{\mathbf{3}}$	**1**	$-2/3$	**1**	**1**	$2/3$	–
b_R	$\overline{\mathbf{3}}$	**1**	$1/3$	**1**	**1**	$2/3$	$2/3$
$\tilde{q} = \begin{pmatrix} N \\ b_L \end{pmatrix}$	**1**	**1**	0	**3**	**2**	–	$2/3$
N_c	**1**	**1**	0	$\overline{\mathbf{3}}$	**1**	–	$2/3$
$\tilde{b}_R$	**1**	**1**	0	$\overline{\mathbf{3}}$	**1**	–	$2/3$
ν_L	**1**	**1**	0	**1**	**1**	–	–
H	**1**	**2**	$-1/2$	**1**	**1**	–	–

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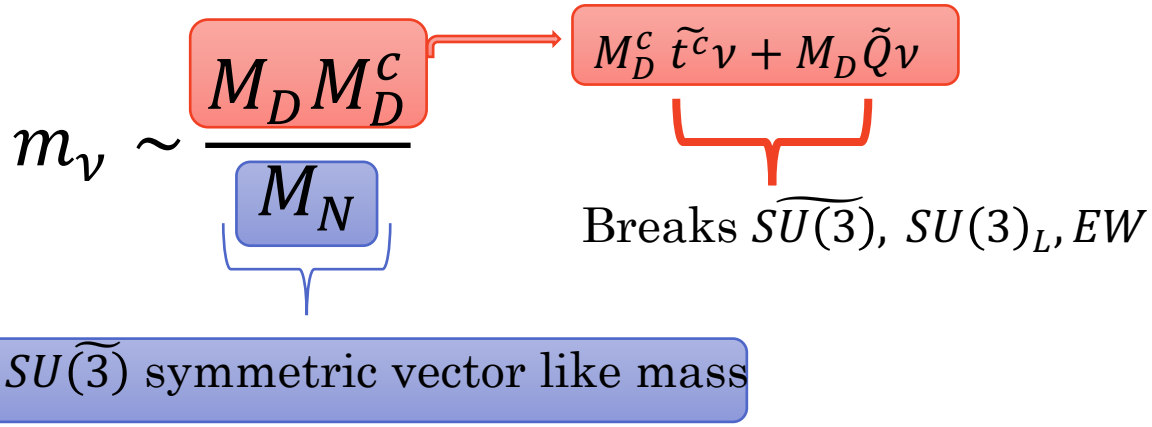
Neutrino Mass Generation

Mass matrix of neutrinos indicate:

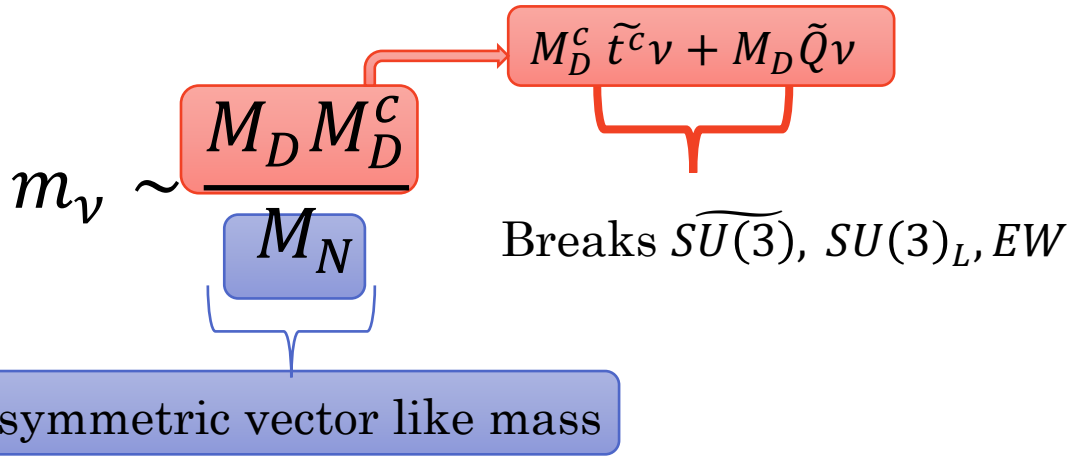
- In order to generate neutrino masses at least one of the Dirac mass terms has to be non zero
- Model's key idea: twin top plays the role of RHN



- Minimum pairs of mass matrices required for neutrino mass generation - Linear seesaw [Malinsky et. al. (2005)]
- It is a collective symmetry breaking which leads to the generation of non-zero light neutrino masses.

Neutrino Mass Generation

- The neutrino mass eigenvalues and mixing angles arise as the product of at least two seemingly unrelated matrices

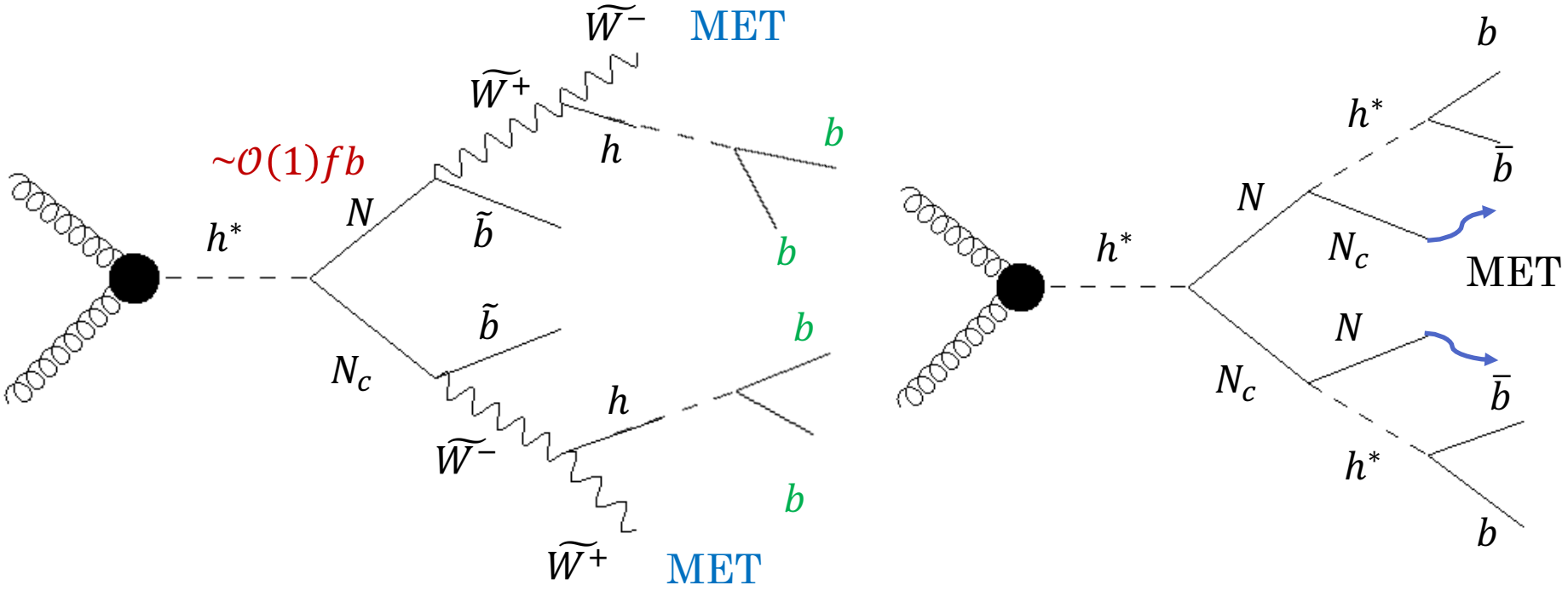


- $M_N \sim \widetilde{m_t} \Longrightarrow$linearizing mass terms about higgs, h yields tree level hNN_c vertex
- As N, N_c are twin tops they couple to $\widetilde{W}$ *and* $\tilde{b}$

Higgs decays

- Absence of confining $\widetilde{SU(3)}$ - different from Fraternal Twin Higgs
- Higgs can decay to light twin states
- Topology: $h \to 2 \to 4 \to 6$ [Curtin et al. (2013)]

$N \sim 500\ GeV, \widetilde{W} \sim 200\ GeV$



$Final\ state: 4b + MET$

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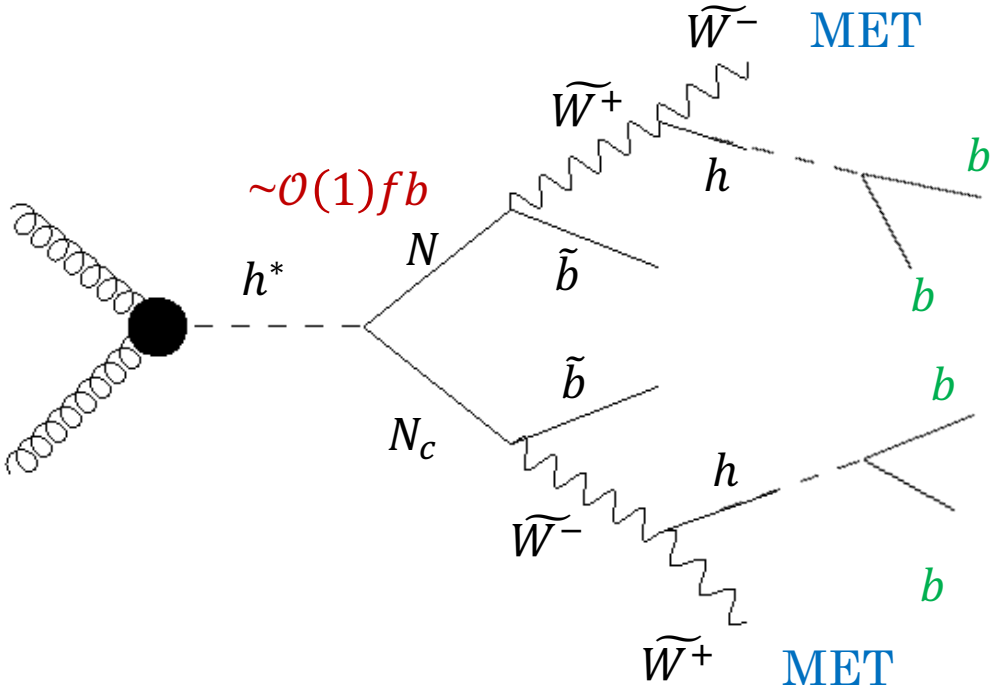

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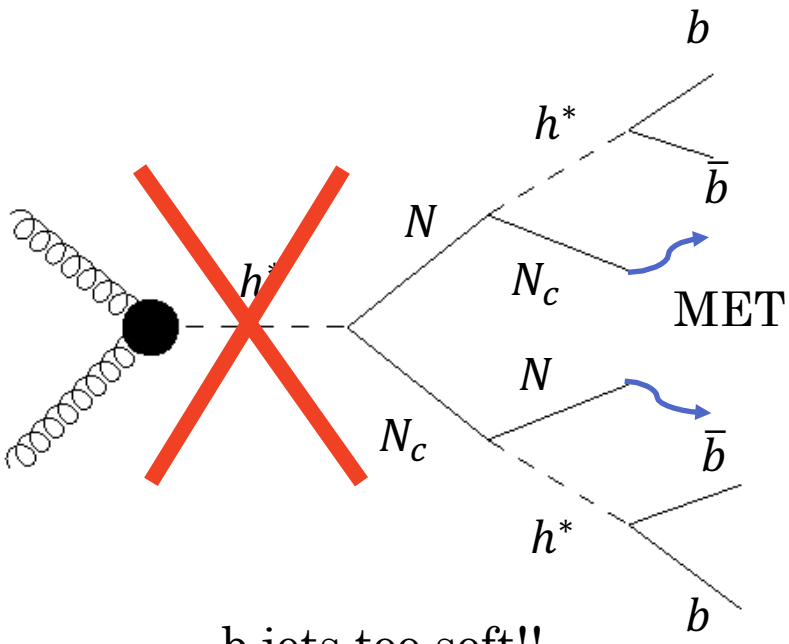

b jets too soft!!
Maybe < 10 GeV

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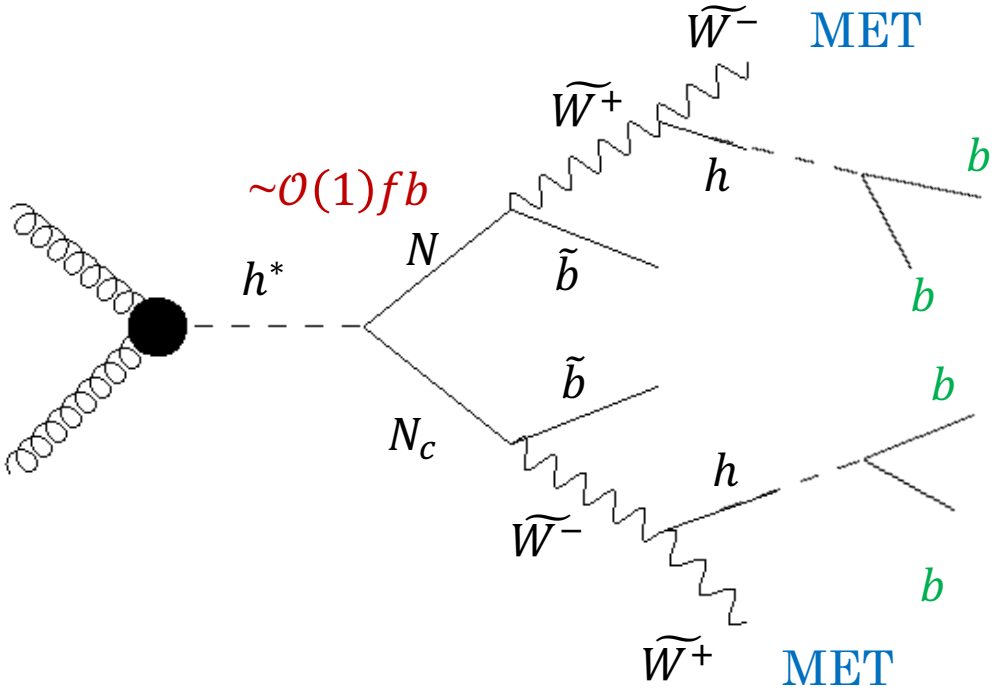

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Recast SUSY searches **for squarks and gluinos in final states with jets in** ATLAS-CONF-2016-078 for this set up

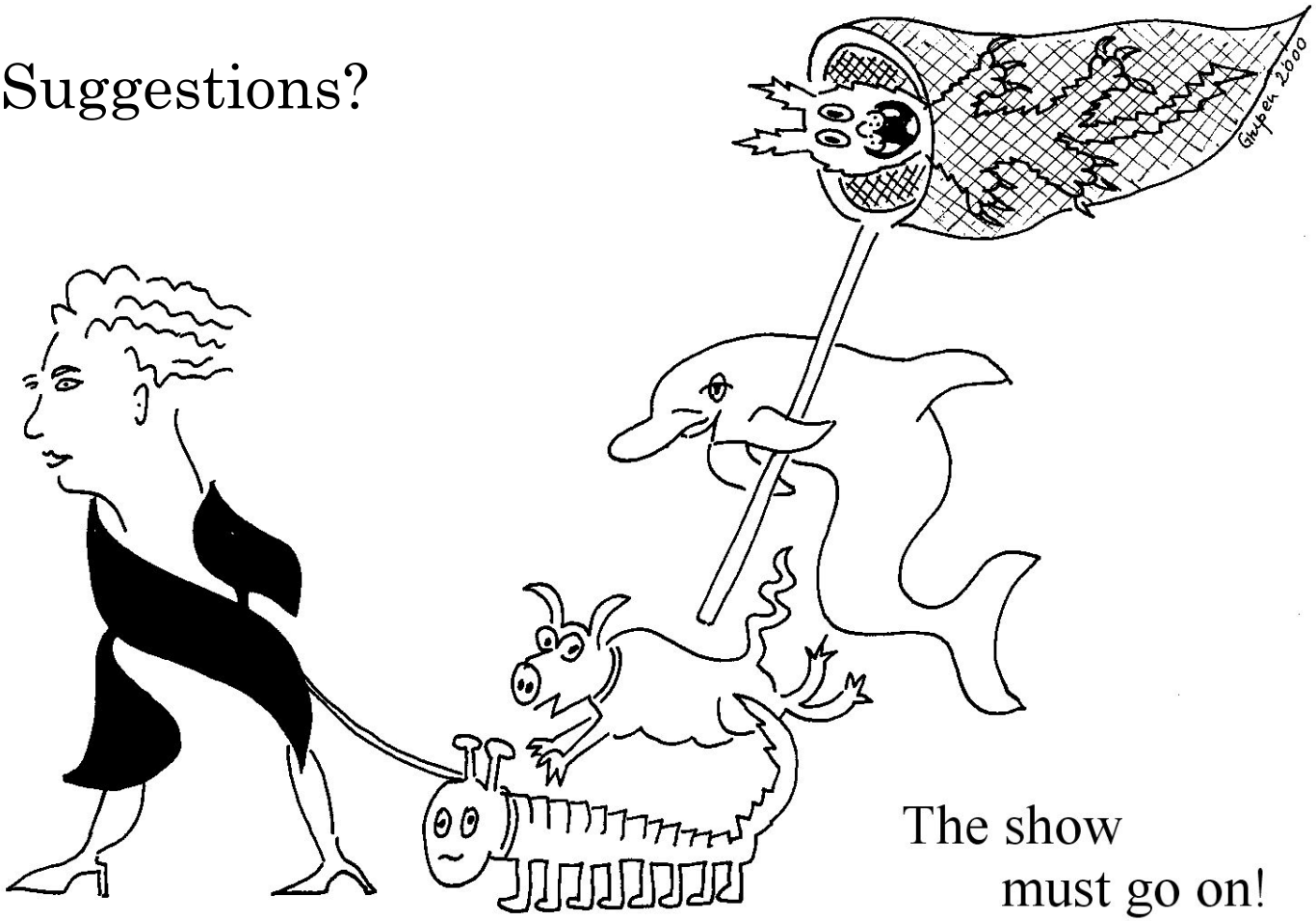
Explore the parameter space and provide projections for future colliders / high luminosity LHC (3000 fb^{-1})

Summary/ Future Outlook

- In composite Twin Higgs:– it is possible to use twin top as Right handed neutrinos.
- For neutrino mass generation the twin QCD needs to be broken (explicitly or spontaneously?) – needs theoretical investigation
- It is possible that the twin QCD does not confine.
- There is a great deal of Twin sector spectrum dependence on the possible decay chains
- For instance: study prompt decays of higgs to 4b's +jet
- Is it viable??? …Start by recasting SUSY search results to understand the parameter space….

THANK YOU!

Questions? Suggestions?

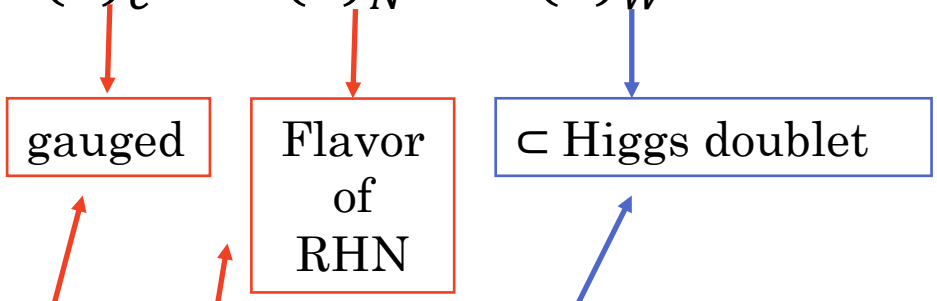


Backup

Explicit phenomenological models

Several "minimal" ways to implement:

- $SU(6)\times SU(3)_W \to SU(3)_c\times SU(3)_N\times SU(2)_W$



- $SU(6)\times SO(5) \to SU(3)_c\times SU(3)_N\times SO(4)$

Explicit embeddings of top partners require some "twisting" to protect pNGB higgs mass [Poland et. al. 2008]

Explicit phenomenological models

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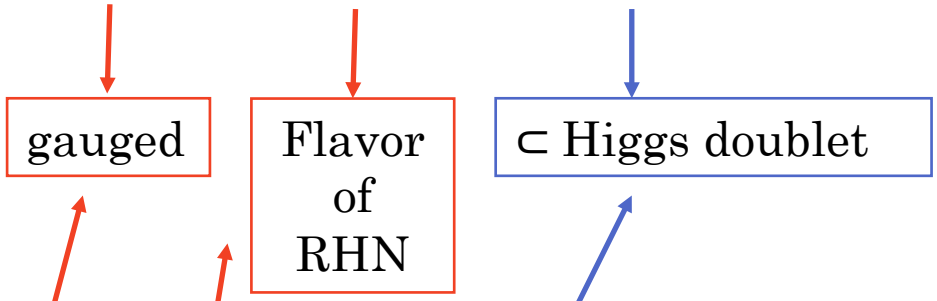
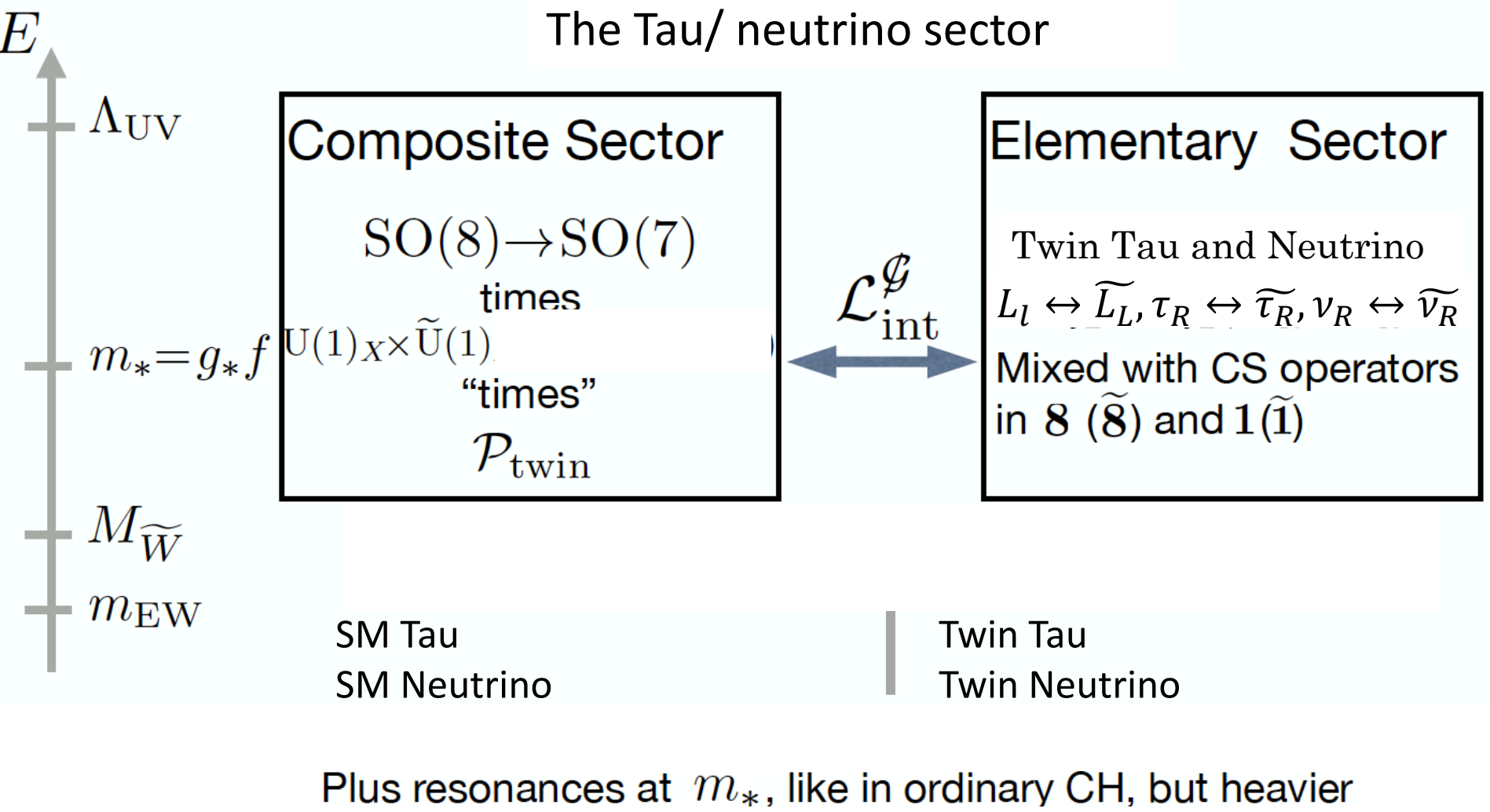
- ✖ $SU(6)\times SU(3)_W \to SU(3)_c\times SU(3)_N\times SU(2)_W$



- ✖ $SU(6)\times SO(5) \to SU(3)_c\times SU(3)_N\times SO(4)$

- Not clear if the setups contain gauge boson partners
- $\Longrightarrow$ quadratic divergence coming from $SU(2)_W$ gauge bosons is not cancelled !!! 😞

Lepton sector



Plus resonances at m_*, like in ordinary CH, but heavier

Ingredients of fermionic sector

- q_L and $t_R(\mathrm{b_R})$ embedded in Q_L^t and $T_R(\mathrm{B_R})$ which are **incomplete octet**
- $Q_L^t = \frac{1}{\sqrt{2}}\begin{pmatrix} i\,b_L \\ b_L \\ it_L \\ -t_L \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, T_R = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ t_R' \end{pmatrix}, Q_L^b = Q_L^t(t \leftrightarrow b\,), B_R = T_R\,(t \leftrightarrow b\,)$
- $\psi^t = \begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix} \oplus (S_{2/3}^1) \oplus (S_{2/3}^2) \oplus (S_{2/3}^3) \oplus (S_{2/3}^4)$

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Twin sector

- q_L and $t_R(\mathrm{b_R})$ embedded in Q_L^t and $T_R(\mathrm{B_R})$ which are **incomplete octet**
- $\widetilde{Q_L^t} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ i\,\widetilde{b_L} \\ \widetilde{b_L} \\ i\,\widetilde{t_L} \\ -\widetilde{t_L} \end{pmatrix}$, $\widetilde{T_R} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \widetilde{t_R'} \end{pmatrix}$, $\widetilde{Q_L^b} = \widetilde{Q_L^t}(\tilde{t} \leftrightarrow \tilde{b}\,)$, $\widetilde{B_R} = \widetilde{T_R}\,(\tilde{t} \leftrightarrow \tilde{b}\,)$

Identified with RHN

- $\widetilde{\psi^t} = \begin{pmatrix} \widetilde{D_o^1} & \widetilde{D_1} \\ \widetilde{D_{-1}} & \widetilde{D_o^2} \end{pmatrix} \oplus (\widetilde{U_o^1}) \oplus (\widetilde{U_o^2}) \oplus (\widetilde{U_o^3}) \oplus (\widetilde{U_o^4})$