Composite vector resonances and Top partners @ LHC

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Outline

- BSM & Hierarchy Problem
- Composite Higgs
- Nonlinear σ- model
- Discrete Composite Higgs models
- Status of Heavy vector & Top partner searches
- Search strategy
- Summary

Why BSM?

- **Higgs discovery** is already old news

- Since 2012 - main focus has been to measure Higgs boson properties:
  - Couplings , Mass , Spin/CP ….

- **125 GeV Higgs boson** seems **consistent with SM** expectations[1].

[1] 1412.8662

- But BSM physics exists!
  - **Experimental Facts:** Neutrino masses, Dark matter, Inflation, baryon asymmetry, Dark energy
  - **Theoretical inconsistencies:** Strong CP problem, flavor hierarchies, gauge coupling unification, **EW Hierarchy**

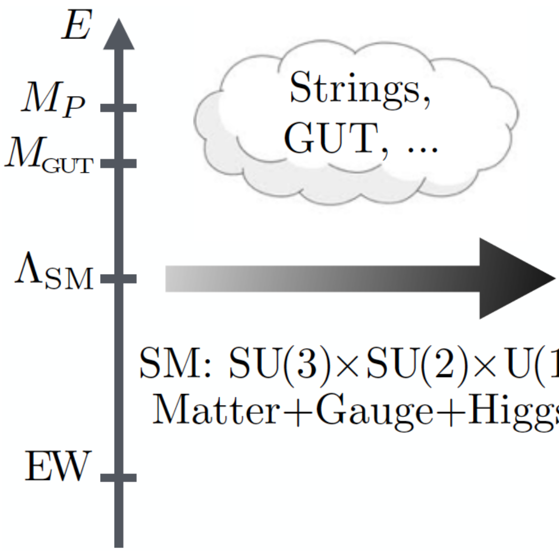
- With all the LHC data – we still DO NOT have a strong front-runner BSM model

BSM World now??

We face the **Lonely Higgs Problem**:-

Higgs discovered but no sight of New physics.

SM is an EFT



$\mathcal{L} =$

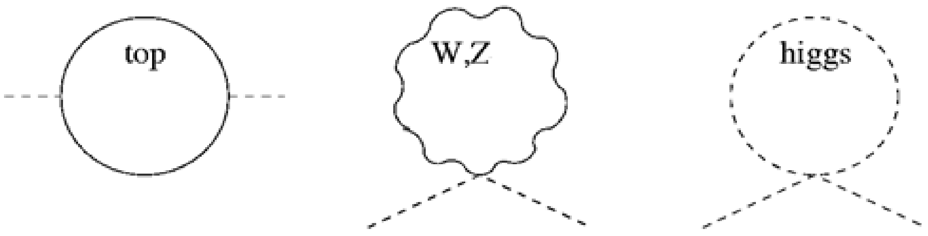
- $d{=}4$ operators: describe what we see — $-\frac{1}{4}\mathcal{F}^2 - i\bar{q}Hq + |DH|^2 + \lambda|H|^4$
- $d{>}4$ operators: suppressed by $1/\Lambda_{\rm SM}^{d-4}$ — $+\frac{(\bar{q}q)^2}{\Lambda^2} + \cdots$
- $d{=}2$ operator: $\Lambda_{\rm SM}^2 H^2$ why $m_H \ll \Lambda_{\rm SM}$? — $-\epsilon\Lambda^2|H|^2$

- $\Lambda \gtrsim$ few Tev from Electro-weak data
- But also pretty small ….
  - $\epsilon \sim -(100\ \mathrm{GeV})^2/\Lambda^2$ (naturalness problem)

- **A strong motivation to look for non-SM physics.**

Hierarchy problem

- In SM, m_h^2 receives quadratically divergent corrections from interactions with other SM fields.
- The largest contributions come from the:



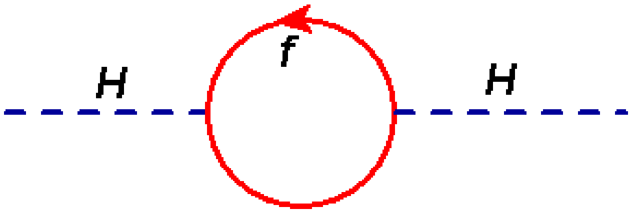
- For ~10% fine-tuning, $m_h = 125$ GeV, requires that

$$\Lambda_{top} \lesssim 2 \text{ TeV} \qquad \Lambda_{gauge} \lesssim 5 \text{ TeV} \qquad \Lambda_{Higgs} \lesssim 10 \text{ TeV}$$

- So, SM has to break down at scale, $\Lambda \sim O(1)$ TeV

Typical solutions to Hierarchy Problem

- We have met the enemy and it is this loop :



- **A possible resolution of Hierarchy Problem via weakly coupled physics.**

- This solution invariably **involves a top partner .**

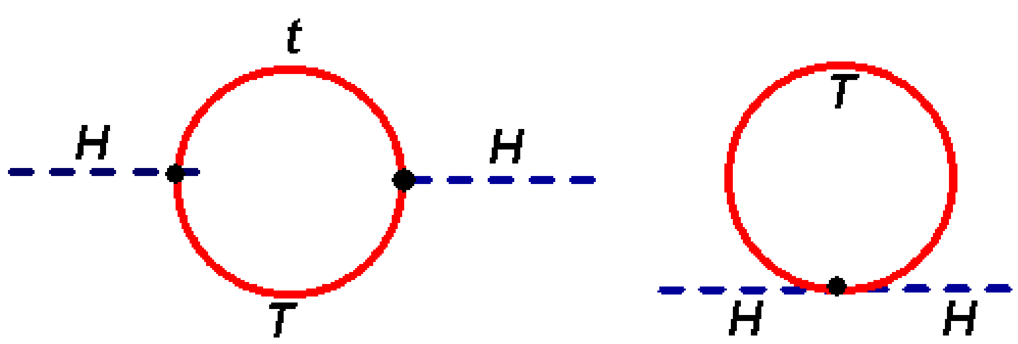
- They help **in cancelling the effects of SM loop contributions**. The current lore has:
  - **Supersymmetric extensions**
  - Shift symmetry or other gauge extensions

1 possibility

- **Shift symmetry or other gauge extensions** $\Rightarrow$ Spin-1/2 top partner (little Higgs models, twin Higgs models)

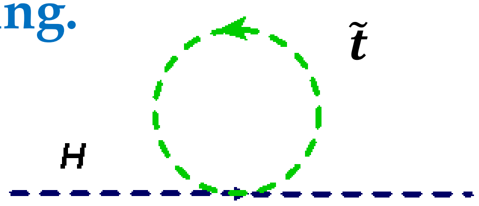
  - Higgs field(s) are pseudo Nambu-Goldstone bosons

  - The quadratic divergences are canceled by the **same-spin partners** of **the SM top quark, gauge bosons and Higgs**



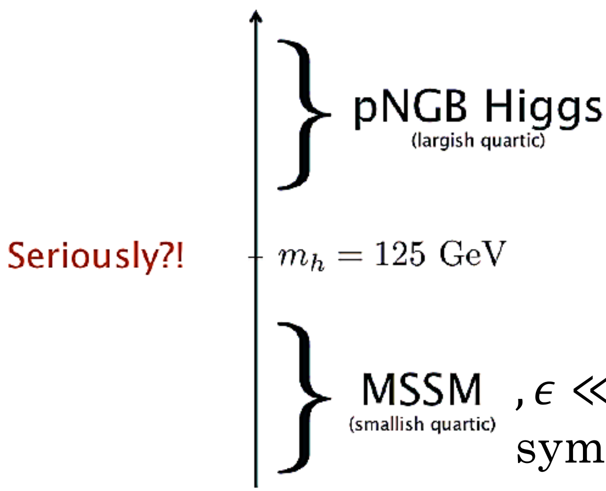
2nd possibility

- **Supersymmetric extensions** ⇒ Spin-0 top partner ("stop")
  - There is a superpartner for each SM particle with opposite spin statistics.
  - Quadratic radiative corrections – cancelled between fermions and bosons
  - **The superpartners of the top are scalar particles in MSSM**, and they are required to be around **~TeV to avoid excessive fine-tuning.**



BSM models

- Natural explanations of 125 GeV Higgs



, $\epsilon \ll 1$ by shift symmetry

, $\epsilon \ll 1$ by chiral symmetry

- Minimal Composite Higgs models ($MCHM_5$) have tuning $\lesssim 10\%$ [2]

[2] 1307.4778, 1210.7114

- "Natural" SUSY models with elaborate structure: tuning $\lesssim 5\%$ [3]

[3] 1209.2115, 1212.5243

- LHC run 2 hope: a resonance or superpartner shows up!

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Composite Higgs

- Suppose Higgs is composite (Dugan, Kaplan, Georgi – 1980s)

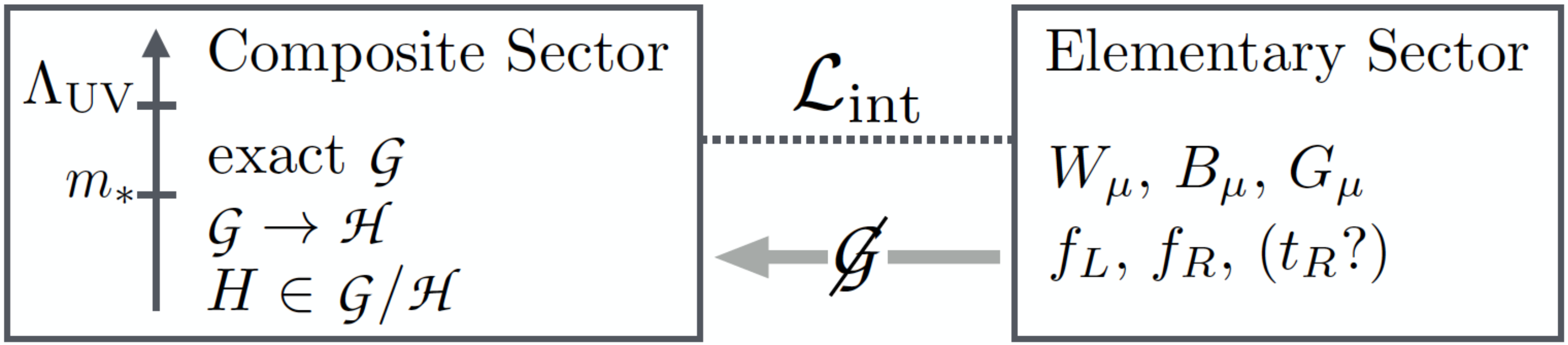
$$l_H \sim \frac{1}{\text{TeV}}$$

- Hierarchy problem is resolved

- Corrections to m_H screened above $1/l_H$

- At low energies, Higgs behaves like an elementary particle

Composite Higgs Models



- **Higgs** as a **Goldstone** of a spontaneously broken global symmetry , $\mathcal{G} \to \mathcal{H}$
- Elementary sector induces a **small** (explicit) **breaking** of $\mathcal{G}$
- Higgs becomes a **pseudo-Goldstone**
- EW symmetry breaking is **radiatively induced**

Composite Higgs Models

Striking **phenomenological features**

Higgs sector is modified

- Modification of the Higgs couplings
  - Growth of WW scattering
  - Change in Higgs productions: $\kappa_{Z,W} = \sqrt{1 - v^2/f^2}$
- Double Higgs production- contributions grow with energy squared [Contino, Dolan….]

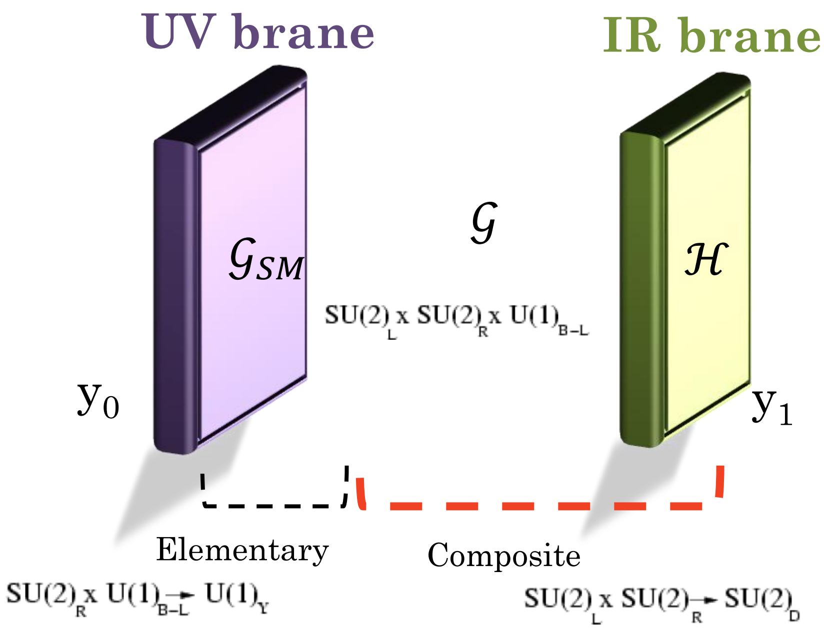
The **strong sector** gives rise to **tower of resonances**

- Fermionic resonances
- Gauge resonances

Description of CH

Specific implementations: **Extra dimensions** through **Holography**

[Contino, Nomura, Pomarol, Agashe, ...]



Elementary Sector	↔	UV
Composite Sector	↔	Bulk +IR
Global Symmetry	↔	Local symm. in XDim

- Extradimensional gauge theory
- Higgs comes from the 5^{th} component of gauge fields (Gauge Higgs Unification)

Description of CH

- Warped extra dimensions can be useful
- **hep-ph/0612180**
    - **calculable** and **predictive** framework
    - full description of the **resonances**

- But..
    - **Calculations** in warped EFT , while doable, **are not easy**, and
    - Its **not** really **suited** for the **LHC collider phenomenology - difficult to automate** by computer
    - several parameters (also ‘hidden’ like the **metric**)
    - includes many states **not accessible at LHC**

Description of CH

Need for a **simplified** framework:
effective description inspired by deconstruction

- Simplified version of 5D model – as 4D EFT
- Description of **resonances**
  - One set of resonances of the strong sector are included
  - Small number of “measurable” parameters
  - parametrize many extra-dim. models (eg. different metric)

- **Computable** and **predictable**
  - Higgs potential, EWP

- Important tool to analyze **LHC phenomenology**

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The non-linear σ –model

- “minimal" description of a composite Higgs with custodial symmetry
  - Contains pNGB Higgs and SM gauge fields and no composite sector
- non-linear σ -model of the SO(5)/SO(4) coset
- Parameterize the Goldstone by a Σ- field

$$\Sigma_I = U_{I5}\,, \qquad U = \exp\left[i\frac{\sqrt{2}}{f}\,\Pi_{\widehat{a}}T^{\widehat{a}}\right]$$

Transforming in the fundamental representation of SO(5).

The non-linear σ −model

Elementary (SM) gauge fields are introduced by weak gauging

$$SU(2)_L \times U(1)_Y \subset SO(4) \simeq SU(2)_L \times SU(1)_R$$

Covariant derivative of the Goldstone matrix is

$$D_\mu \Sigma = \left(\partial_\mu - iA_\mu\right)\Sigma, \qquad \mathrm{A}_\mu = g\, W_\mu^\alpha T_L^\alpha + g' B_\mu T_R^3$$

The leading order Lagrangian is

$$\mathcal{L}_0 = \underbrace{\frac{f^2}{2}\sum_I D_\mu \Sigma_I D^\mu \Sigma^I}_{\mathcal{L}_\pi} - \underbrace{\frac{1}{4}\mathrm{Tr}\left[\mathrm{W}_{\mu\nu}\mathrm{W}^{\mu\nu}\right] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}}_{\mathcal{L}_g}$$

The non- linear σ −model

Power counting to estimate size of terms in Lagrangian

$$\mathcal{L}_i = \Lambda^2 f^2 \left(\frac{\Lambda}{4\pi f}\right)^{2L} \left(\frac{\Pi}{f}\right)^{E_\pi} \left(\frac{gW}{\Lambda}\right)^{E_W} \left(\frac{\partial}{\Lambda}\right)^{d} \left(\frac{gf}{\Lambda}\right)^{2\eta}$$

Keeping cut-off Λ free we count the **degree of divergence**

The NDA estimate is obtained by putting

$$\left(\frac{g}{4\pi}\right)^{2\eta}$$

$$\Lambda = \Lambda_{Max} = 4\,\pi f$$

The non- linear σ −model

- $\hat{S}$ and $\hat{T}$ parameters are **logarithmically divergent**
- **Calculable** but not **predictable** within the σ −model
- **Description of the resonances** (in particular, of the fermionic resonances which give the dominant contribution) would be **needed**.
- m_H too beyond the reach of σ −model
- **Higgs potential diverges quadratically** at one loop

The non- linear σ −model

- $\hat{S}$ and $\hat{T}$ parameters are **logarithmically divergent**

- **Calculable** but not **predictable** within the σ −model

- **Desc** … of the
  fermi … minant
  contr …

Key observables are **not calculable**

$\Downarrow$

We must introduce **more symmetries**

- m_H too beyond the reach of σ −model

- **Higgs potential diverges quadratically** at one loop

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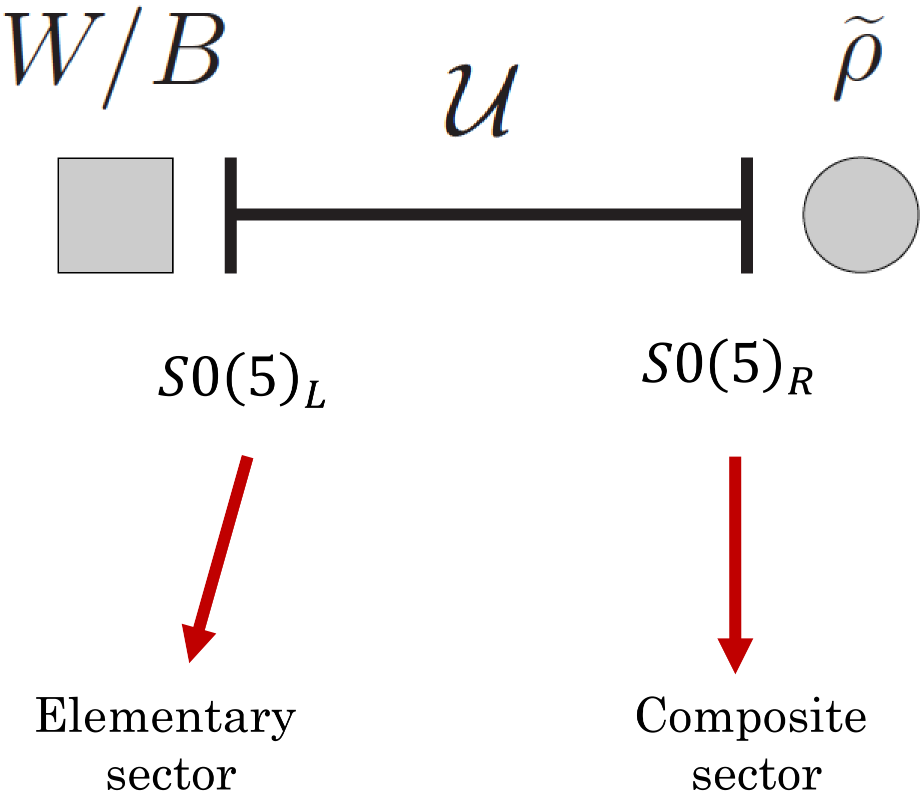
2-site model

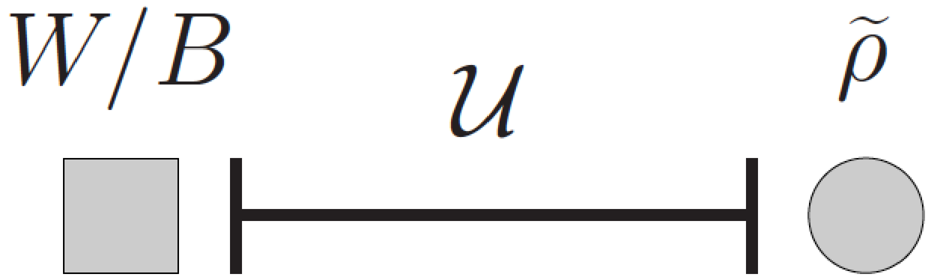
- Nonlinear σ- model
- $\mathcal{L}_\pi = \frac{f^2}{2} Tr\left[\left(D_\mu \mathcal{U}\right)^T D^\mu \mathcal{U}\right]$

  where $\mathcal{U}$ is Goldstone matrix of $SO(5)_L \times SO(5)_R\ /SO(5)_V$
- $\mathcal{U}[\Pi] = \exp\left(i \frac{\sqrt{2}}{f} \Pi_A T^A\right)$ which transforms linearly under $SO(5)_L \times SO(5)_R$
- Gives 10 d.o.f s in adjoint of $SO(5)_V$



2-site model: gauge sector

The extra **symmetries** are related to the resonances of the composite sector



W_μ, B_μ gauge subgroup of 1st site, $SU(2)_L \times U(1)_Y \subset SO(5)_L$

$\tilde{\rho}_\mu$ comes from gauging 2nd site $SO(4) \subset SO(5)_R$ - 3 fold purpose

1. Eats 6 Goldstones
2. Breaks extra $SO(5)_R$ invariance
3. a description of the massive vector resonances

SM gauge fields → **combination of elementary**, W_μ, B_μ and **composite** $\tilde{\rho}_\mu$ - **partial compositeness**

[Kaplan (1991), Contino, Kramer, Son and Sundrum (2006)]

2-site model: Higgs

The Higgs is a Goldstone with respect to $SO(5)_L \times SO(5)_R$

We need to **break all the symmetries** to generate a term which depends on the Higgs VEV

$\Downarrow$

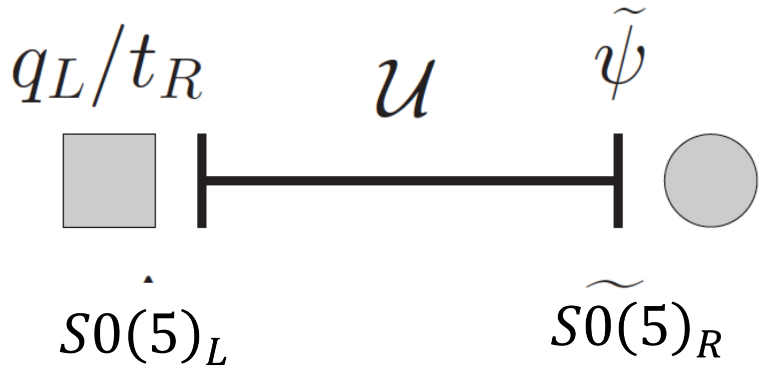
EWSB effects through **collective breaking**: cancellation of divergences

[Arkani-Hamed et al. (2001), ...]

$\hat{S}$, $\hat{T}$ and Higgs mass are calculable(finite)

Matsedonskyi et al. (2004)

2-site model: top sector

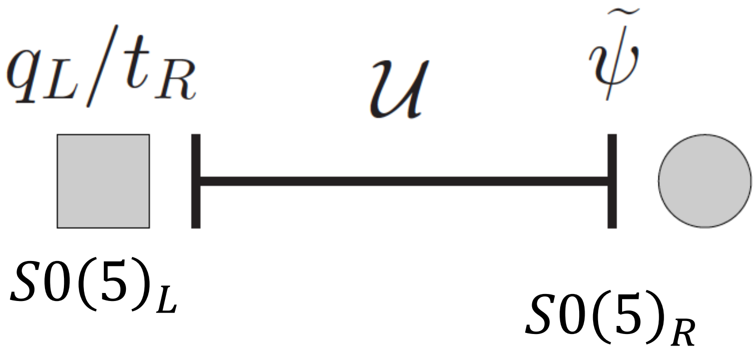


- q_L and t_R embedded in Q_L and T_R which are **incomplete** $S0(5)_L$ **fiveplets**

$$Q_L = \frac{1}{\sqrt{2}}\begin{bmatrix} -\,i\,b_L \\ -b_L \\ -it_L \\ t_L \\ 0 \end{bmatrix},\ T_R = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{bmatrix}$$

- $\psi \in (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1}) = \begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix} \oplus (\tilde{T})$

2-site model: top sector



Elementary sector

Composite sector

$$D_\mu q_L = \left(\partial_\mu - i\,\frac{\hat{g}}{2} W_\mu^\alpha \sigma_\alpha - i\,\frac{\hat{g}'}{2} B_\mu\right) q_L$$

$$D_\mu t_R = \left(\partial_\mu - i\,\frac{\widehat{2g}'}{3} B_\mu - i g_s\, G_\mu\right) t_R$$

$$D_\mu \tilde{\psi} = \left(\partial_\mu - i\,\frac{\widehat{2g}'}{3} B_\mu - i \widetilde{g_\rho} \tilde{\rho}_\mu\right) \tilde{\psi}$$

Elementary and composite sector kinetic Lagrangians is

$$\mathcal{L}^f_{el} = i\bar{q}_L \gamma^\mu D_\mu q_L + i\bar{t}_R \gamma^\mu D_\mu t_R \,,$$

$$\mathcal{L}^f_{cs} = i\bar{\tilde{\psi}} \gamma^\mu D_\mu \tilde{\psi} + \widetilde{m}^{IJ} \bar{\tilde{\psi}}_I \tilde{\psi}_J \,,$$

Mass term $\widetilde{m} = \mathrm{diag}(\widetilde{m}_Q, \widetilde{m}_T)$

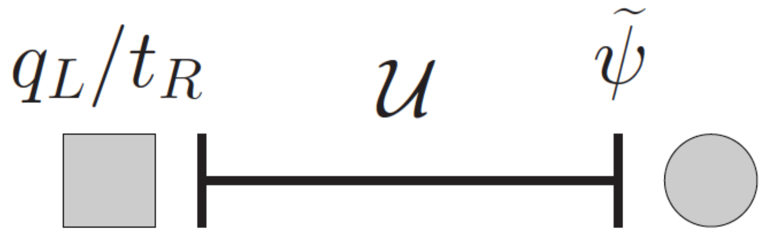
4plet singlet

2-site model: fermionic sector

	$\begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$	t'_R	b'_R	$\begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}$	$\begin{pmatrix} T' \\ B' \end{pmatrix}$	$\tilde{T}$
$SU(3)_c$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$
$SO(5)$	$\mathbf{5}^\star$	$\mathbf{5}^\star$	$\mathbf{5}^\star$	$\mathbf{5}$		
$SO(4)$	$\mathbf{4}^\star$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{4}$		$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_X$	$2/3$	$2/3$	$2/3$	$2/3$	$2/3$	$2/3$
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$7/6$	$1/6$	$2/3$

$\star$ indicates incomplete representations

2-site model: top sector



Invoking partial compositeness via y's

$$\mathcal{L}_{mix} = y_L f\, \overline{Q_L^I}\,\mathcal{U}_{IJ}\widetilde{\psi^J} + y_R f\, \overline{T_R^I}\,\mathcal{U}_{IJ}\widetilde{\psi^J}$$

For correct hypercharges, B_μ comes out of gauging $S0(5)_L \times U(1)_X$

$\widetilde{W}_\mu$ and $\tilde{\rho}_\mu$ come from gauging $SU(2)_L \subset SU(5)_L$ and $SO(4) \subset SU(5)_R$

2-site model: top sector

$$\mathcal{L}_{\rm top} = i\overline{q_L}\not{D}q_L + i\overline{t_R}\not{D}t_R + i\overline{\psi_4}(\not{D} - M_4)\psi_4 + i\overline{\psi_1}(\not{D} - M_1)\psi_1$$
$$+ y_L f \overline{q_L}(U\psi) + y_R f \overline{t_R}(U\psi) + h.c \cdots$$

The leading order Lagrangian contains four parameters

- the fourplet and singlet mass scales M_4 and M_1 and
- the left and right-handed pre- Yukawa couplings $y_{L,R}$
- y_L fixed to reproduce the correct top mass

Partially Composite vectors : Mass and couplings

Masses

$$m_W^2 = \frac{v^2 \widehat{g}^2 \widehat{g_\rho}^2}{4\left(\widehat{g_\rho}^2 + \widehat{g}^2\right)},$$

$$m_Z^2 = \frac{1}{4} v^2 \widehat{g_\rho}^2 \left(\frac{\widehat{g'}^2}{\widehat{g'}^2 + \widehat{g_\rho}^2} + \frac{\widehat{g}^2}{\widehat{g_\rho}^2 + \widehat{g}^2} \right),$$

$$\mathbf{3}_0 : m_{\rho_L}^2 = \frac{1}{2} f^2 \left(\widehat{g_\rho}^2 + \widehat{g}^2\right) - \frac{\widehat{g}^2 v^2 \widehat{g_\rho}^2}{4\left(\widehat{g_\rho}^2 + \widehat{g}^2\right)},$$

$$\mathbf{1}_0 : m_{\rho_B}^2 = \frac{1}{2} f^2 \left(\widehat{g'}^2 + \widehat{g_\rho}^2\right) - \frac{v^2 \widehat{g_\rho}^2 \widehat{g'}^2}{4\left(\widehat{g'}^2 + \widehat{g_\rho}^2\right)},$$

$$\mathbf{1}_\pm : m_{\rho_C}^2 = \frac{1}{2} f^2 \widehat{g_\rho}^2.$$

Post EWSB:
Physical vectors in mass basis

Couplings (examples)

	VV, Vh	$\bar{q}_L \gamma^\mu q_L$	$\bar{u}_R \gamma^\mu u_R$	$\bar{d}_R \gamma^\mu d_R$	$\bar{\ell}_L \gamma^\mu \ell_L$	$\bar{e}_R \gamma^\mu e_R$
$\rho^{0,\pm}$	g_ρ	$-\frac{g^2}{g_\rho}(1 - a_L \frac{g_\rho^2}{g^2} s_{L,q}^2)\tau^a$	–	–	$-\frac{g^2}{g_\rho}\tau^a$	–

Partially Composite fermions : Mass and couplings

SM like top

$$m_t = \frac{v}{\sqrt{2}} \frac{|M_1 - M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{M_1^2 + y_R^2 f^2}}$$

Partners in 4

$$M_{Tf1} = M_4$$

$$M_{Tf2} = \sqrt{M_4^2 + y_L^2 f^2}$$

$$M_{X_{5/3}} = M_4$$

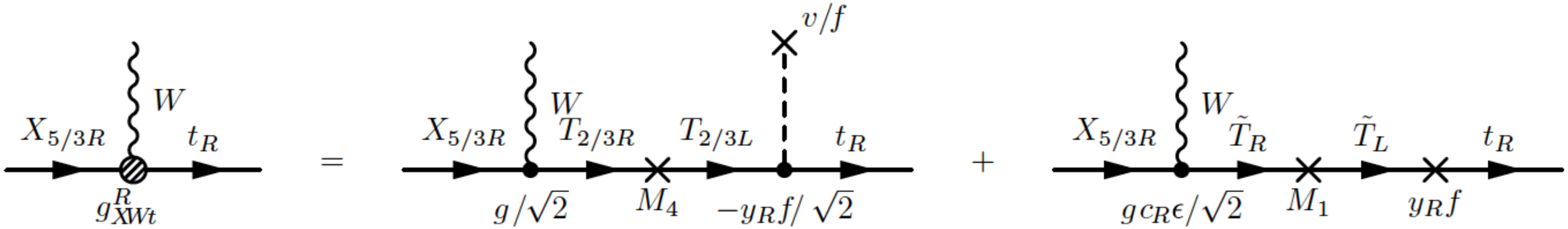
Singlet Partner

$$M_{Ts} = \sqrt{M_1^2 + y_R^2 f^2}$$

Post EWSB: Top sector in mass basis @ leading order in v/f

Partially Composite fermions : Mass and couplings

How to (qualitatively) understand the "mixing" couplings:



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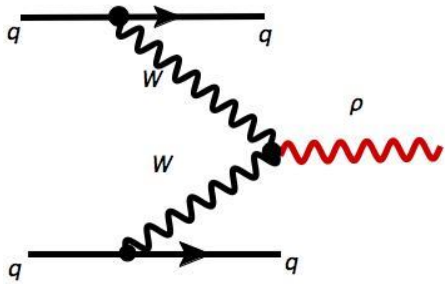
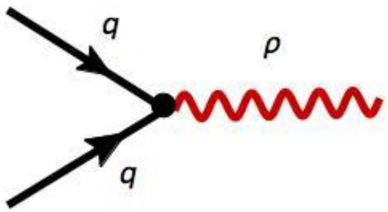
Production rates of ρ

VBF

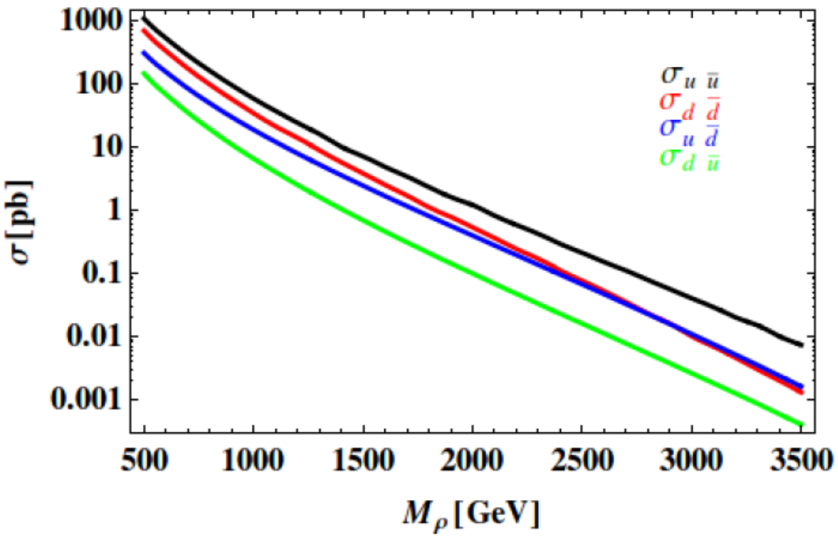


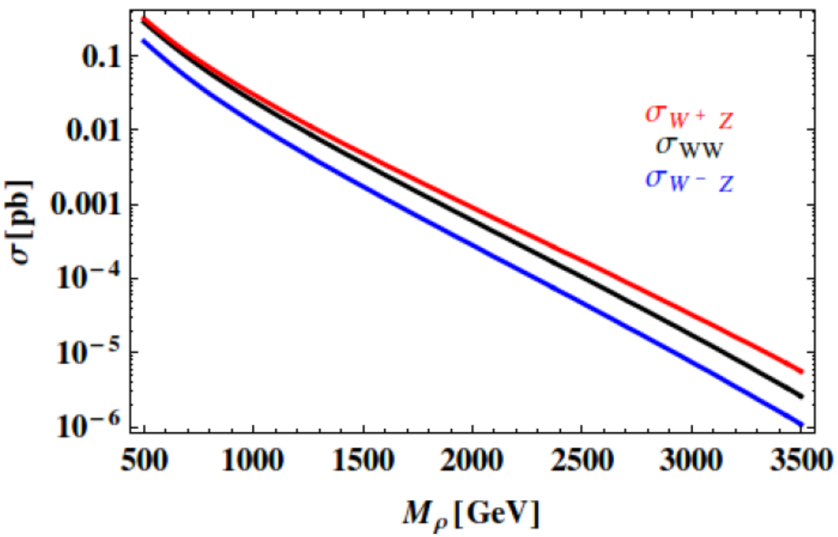
$$\sigma(pp \to \rho^0 + X) = g^2_{\rho^0 WW} \cdot \sigma_{WW}$$

DY



$$\sigma(pp \to \rho^0 + X) = g^2_{\rho^0 uu} \cdot \sigma_{u\bar{u}} + g^2_{\rho^0 dd} \cdot \sigma_{d\bar{d}}$$





Production rates of ρ

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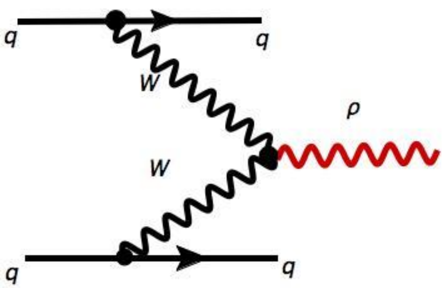

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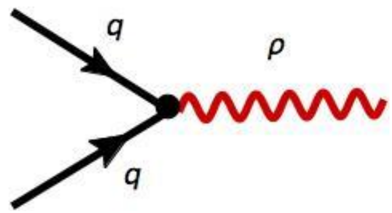

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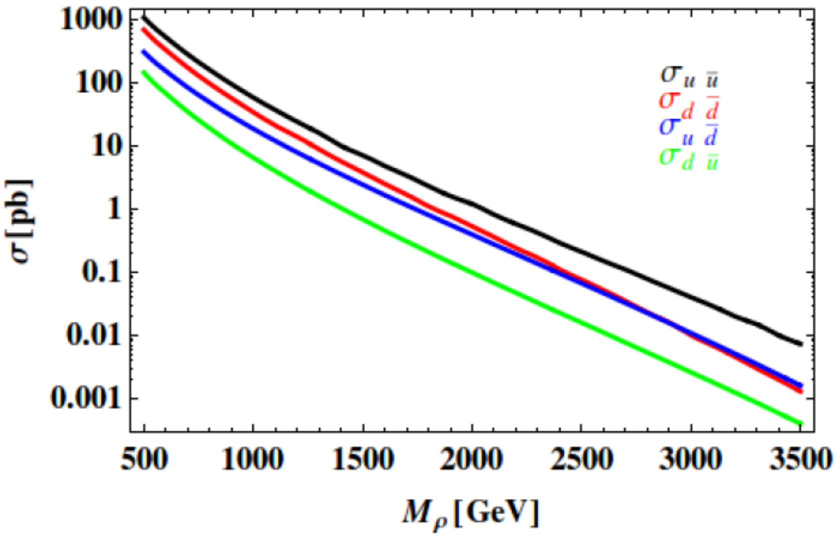
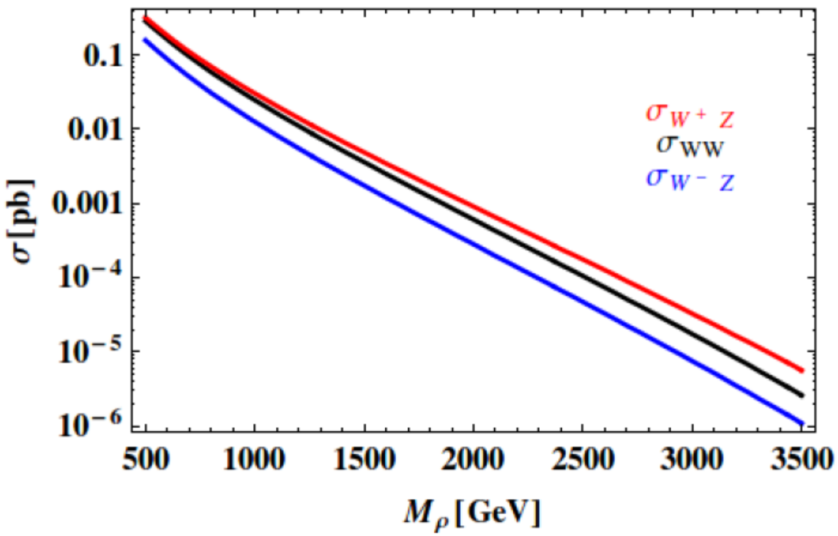
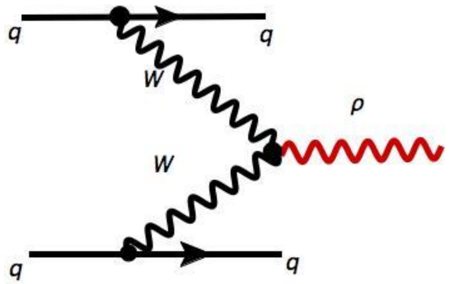




VBF **subleading** in motivated part of parameter space

Production rates of ρ

VBF



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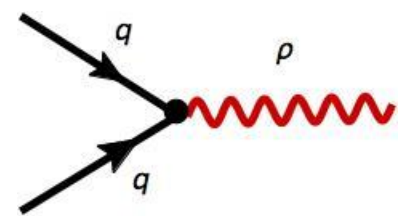
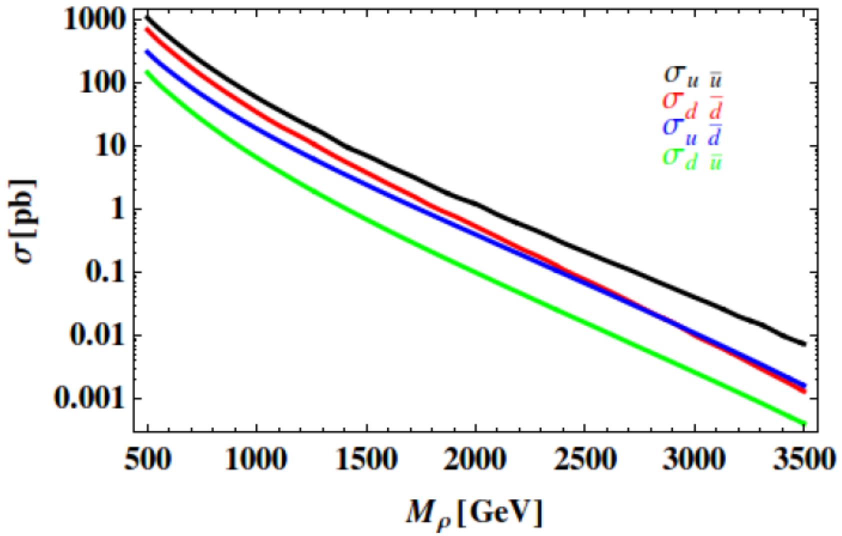
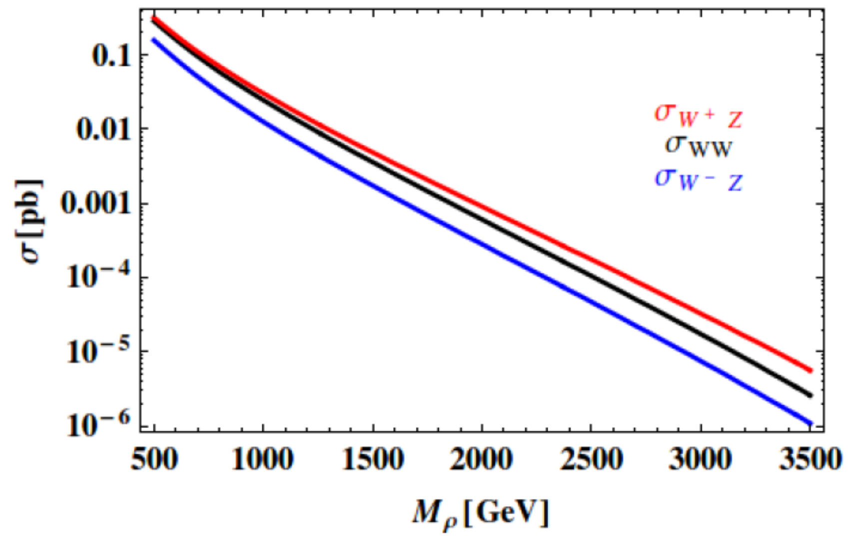
DY



$$\sigma(pp \to \rho^0 + X) = g^2_{\rho^0 uu} \cdot \sigma_{u\bar{u}} + g^2_{\rho^0 dd} \cdot \sigma_{d\bar{d}}$$



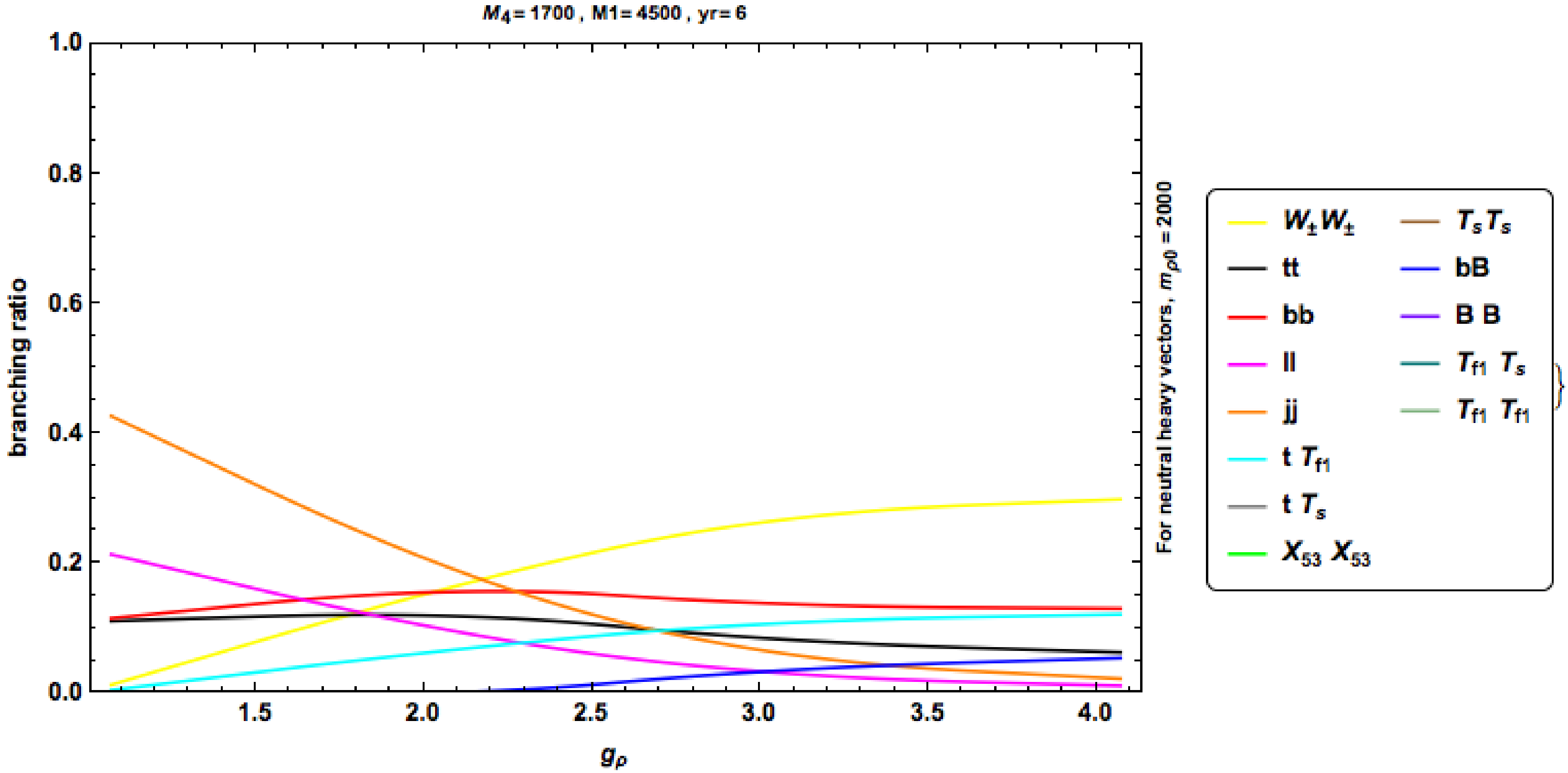


VBF subleading in motivated part of parameter space

Decay widths

- Relevant decay channels:
  - SM (di-quark, di-lepton, di-boson)
  - Exotics (t T, TT) – Top partner production channels

1.07,



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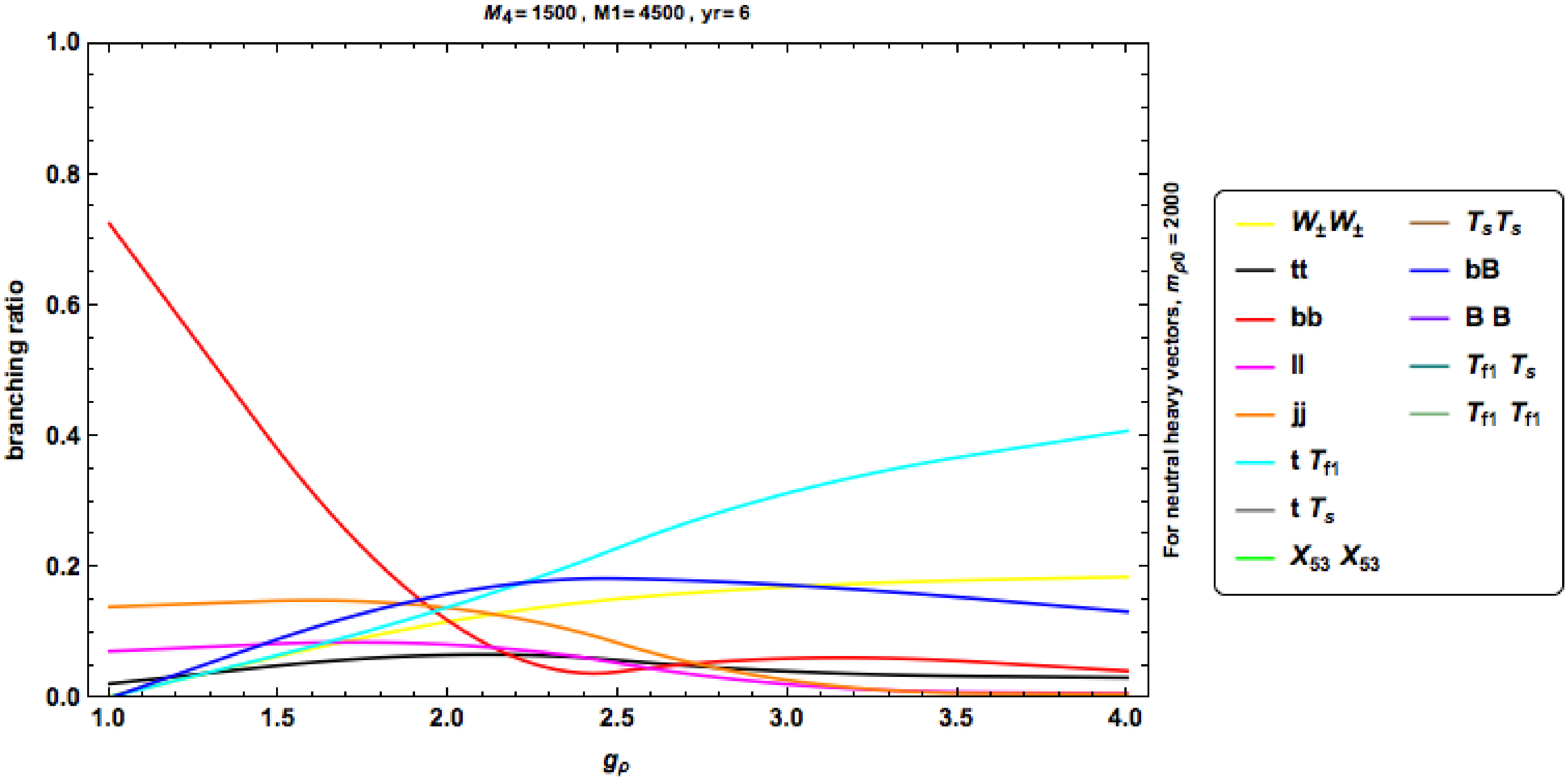
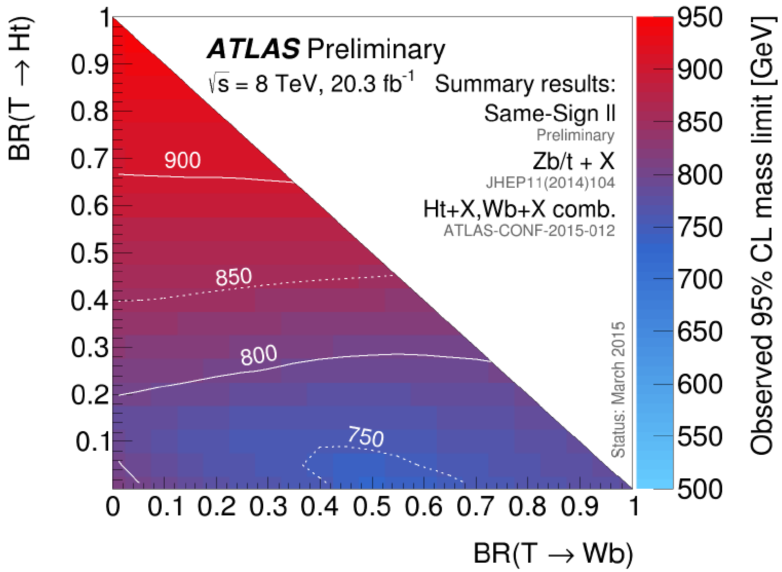
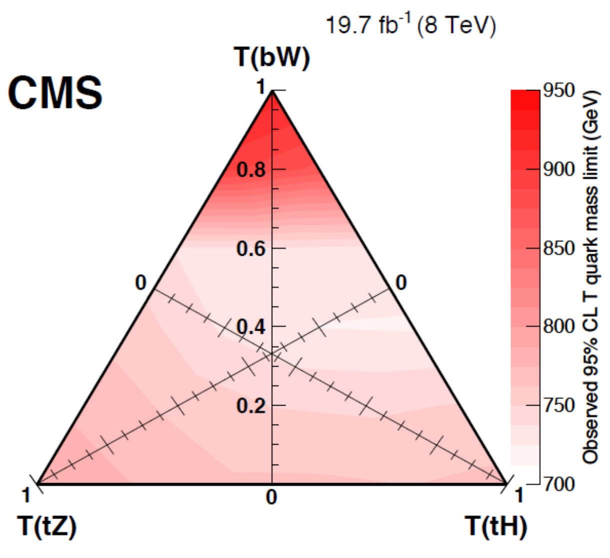


Vector-like quarks: exp limits

- ATLAS and CMS determined bounds on (QCD) pair-produced top partners with charge $5/3$ (the $X_{5/3}$) in the same-sign di-lepton channel.
  $M_{X_{5/3}} > 770\,\mathrm{GeV}$ ATLAS [JHEP 1411 (2014) 104] , $M_{X_{5/3}} > 800\,\mathrm{GeV}$ CMS [PRL 112 (2014) 171801]
  Run II: $M_{X_{5/3}} > 940(960)\,\mathrm{GeV}$ CMS [B2G-15-006]
- ATLAS and CMS determined a bound on (QCD) pair-produced top partners with charge $2/3$ (applicable for the T_s, T_{f1}, T_{f2}). [Similar bounds for B]

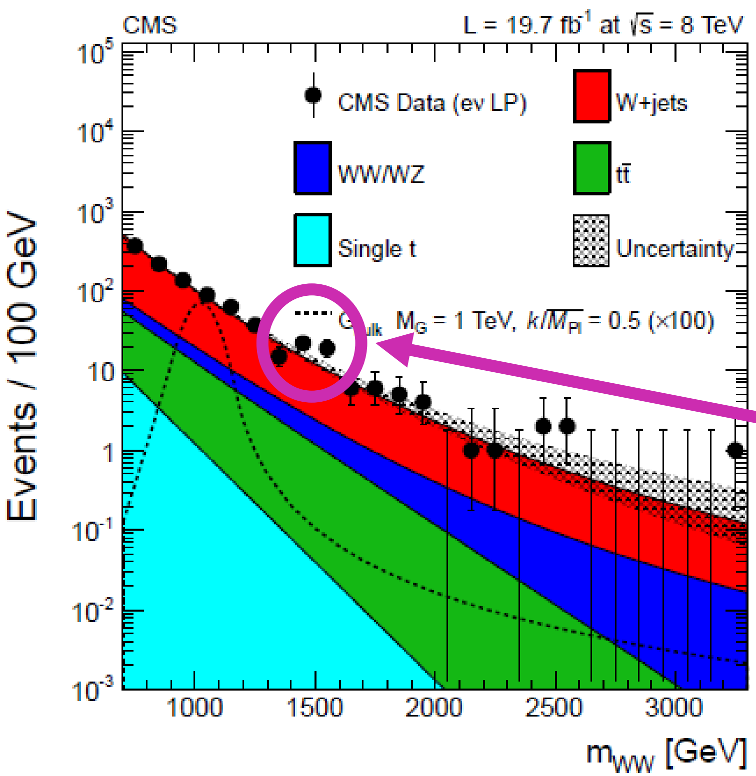


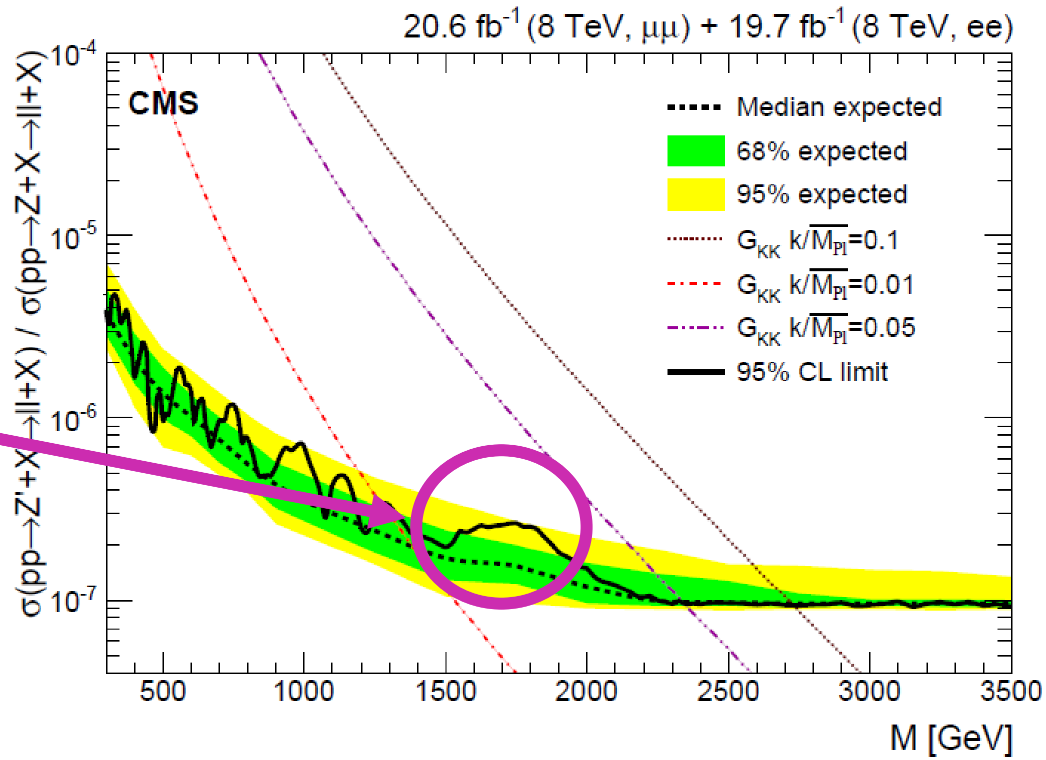


CMS [hep-ex:1509.04177]

Heavy vector resonances

- di-lepton signature- $M_{Z'} > 3.5$ TeV @ 13 TeV [CMS-PAS-EXO-15-005]
- $M_{W'} > 2$ TeV @ 13 TeV in di-boson channel [CMS-PAS-EXO-15-002]
- … do not forget hints from 8 TeV data from ATLAS … and CMS



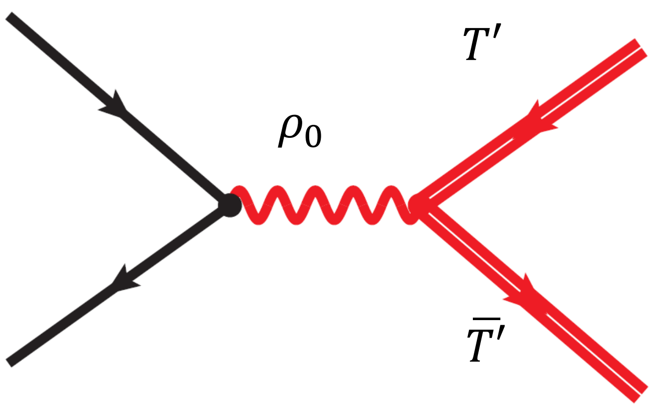


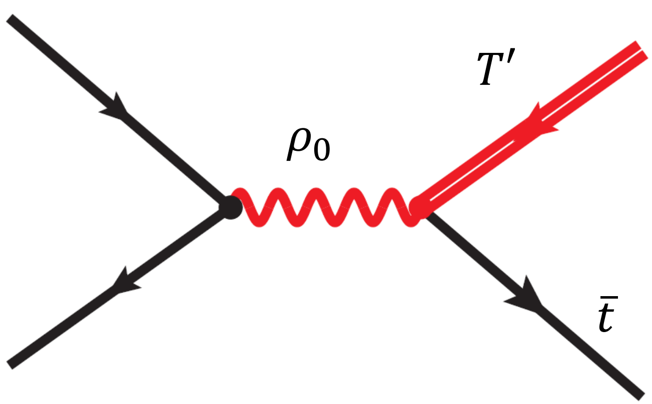
Outline

- BSM & Hierarchy Problem
- Composite Higgs
- Nonlinear σ- model
- Discrete Composite Higgs models
- Status of Heavy vector & Top partner searches
- Search strategy
- Summary

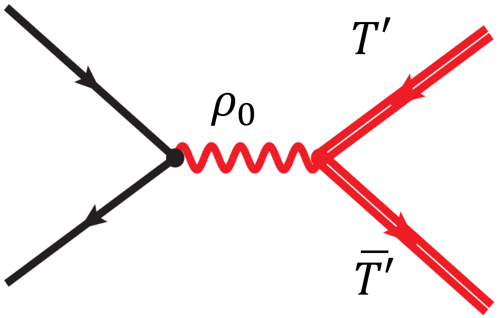
Status of natural CHMs

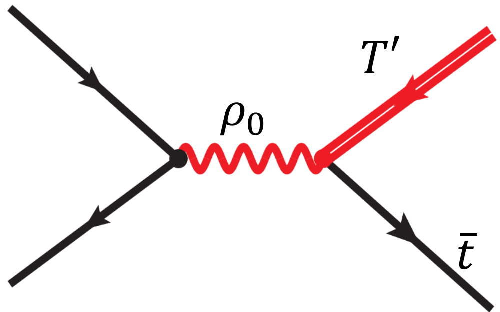
- a reasonably tuned pNGB Higgs generically requires, $M_T \sim$ TeV
- EWPT pushes $M_\rho >$ 2-3 TeV
- If kinematically allowed ρ decays to VLQs become dominant
- VLQ production processes via ρ_0(Z') become viable

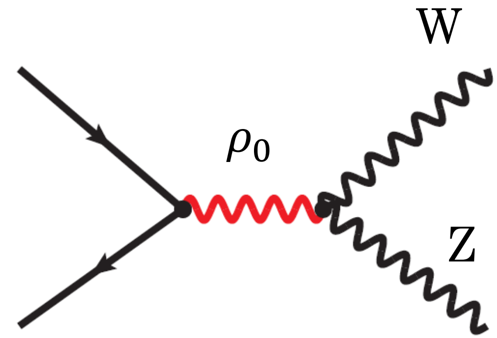




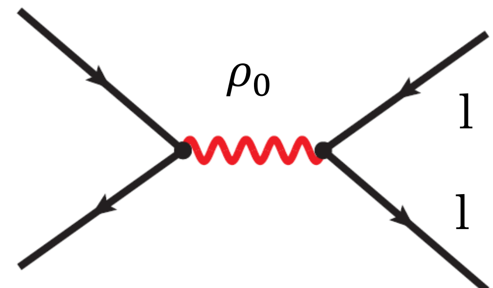
“No loose” strategy for Z’

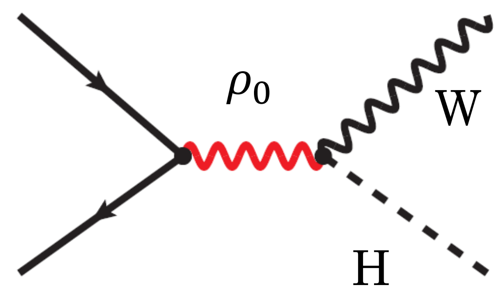






- Additional signatures to be added to support the **“no loose” strategy for Z**’ (neutral heavy resonances)
- Can be combined with di-lepton, VV, VH
- resonance searches **if some excess is observed**
- Bounds on $\rho_{\pm}$ – using X5/3’s





Barducci, Delauney – 1511.01101

2 site: Phenomenological Lagrangian

$$\begin{aligned}
\mathcal{L}_\rho &= ig_{\rho+WZ}\left[(\partial_\mu\rho^+_\nu - \partial_\nu\rho^+_\mu)W^{\mu-}Z^\nu - (\partial_\mu W^+_\nu - \partial_\nu W^+_\mu)\rho^{\mu-}Z^\nu + (\partial_\mu Z_\nu - \partial_\nu Z_\mu)\rho^{\mu-}W^{\nu+} + h.c.\right] \\
&+ ig_{\rho 0WZ}\left[(\partial_\mu W^+_\nu - \partial_\nu W^+_\mu)W^{\mu-}\rho^{0\nu} + (\partial_\mu\rho^0_\nu - \partial_\nu\rho^0_\mu)W^{\mu+}W^{\nu-} + h.c.\right] \\
&+ g_{\rho+Wh}\left(h\rho^+_\mu W^{\mu-} + h.c.\right) + g_{\rho 0Zh}\left(h\rho^0_\mu Z^\mu\right) \\
&+ \sqrt{2}\sum_{X,Y}\left[\left(g^L_{\rho_o XY}X_L\not\rho_0\bar{Y_L} + g^R_{\rho 0XY}X_R\not\rho_0\bar{Y_R}\right) + \left(g^L_{\rho+XY}X_L\not\rho^+\bar{Y_L} + h.c.\right) + \left(g^R_{\rho+XY}X_R\not\rho^+\bar{Y_R} + h.c.\right)\right] \\
&+ \sqrt{2}\sum_{l,l}\left[g^L_{\rho_o qq}\ \ q_L\not\rho_0\bar{q_L} + g^L_{\rho+qq}\left(q_L\not\rho^+\bar{q_L} + h.c.\right)\right] \\
&+ \sqrt{2}\sum_{l,l}\left[g^L_{\rho_o ll}\ \ l_L\not\rho_0\bar{l_L} + g^L_{\rho+ll}\left(l_L\not\rho^+\bar{l_L} + h.c.\right)\right]
\end{aligned}$$

$g\rho_0WW$	0.00244019
$g\rho_+WZ$	0.00276068
$g\rho_0Zh$	88.8538
$g\rho_+Wh$	88.8538

$g\rho_0tt^L$	0.202911
$g\rho_0tt^R$	0.0471
$g\rho_0tT^L_{f1}$	0.225294
$g\rho_0tT^R_{f1}$	0.991918
$g\rho_0tT^R_{f2}$	0.398755
$g\rho_0tT^L_{f2}$	1.04598
$g\rho_0bb^L$	0.257927
$g\rho_0bB^L$	1.16253

$\lambda ht_RT_{f1,L}$	1.36804
$\lambda ht_LT_{f1,R}$	0.169354
$\lambda ht_RT_{f1,L}$	1.36804
$\lambda ht_LT_{f1,R}$	0.169354
$gW_+bT^L_{f1}$	0.0113745
$gZtTf1L$	0.0640996
$gZtTf1R$	0.308658

2-site: Benchmark points

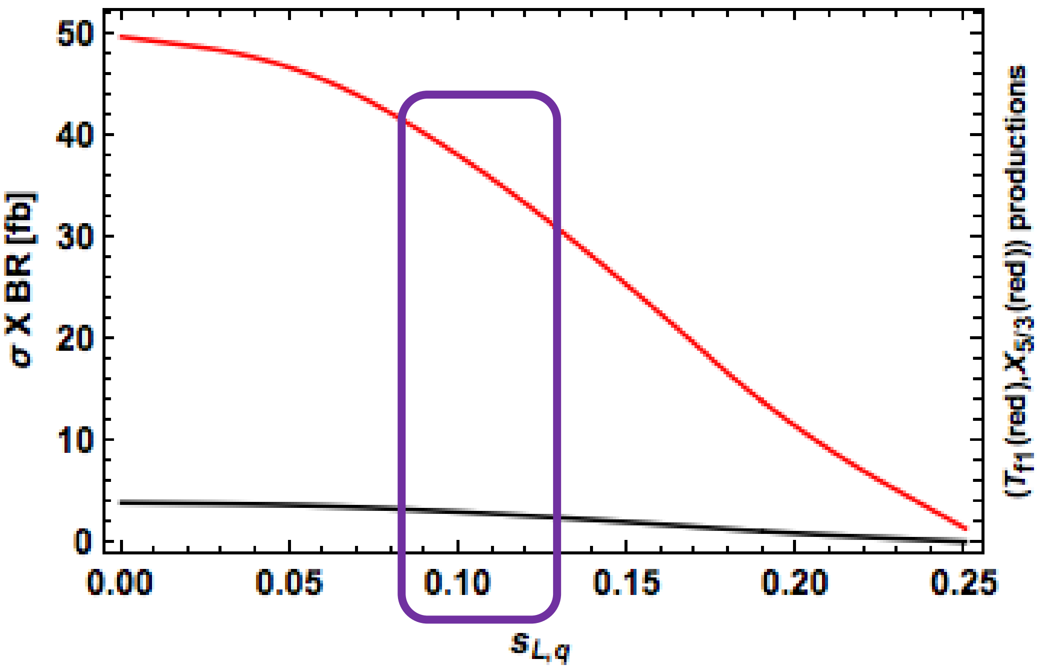
for f = 1.3 TeV ,M_4 = 1.5 TeV, M_1 = 4.5 TeV , y_R = 6 and g_ρ = 2:5

Partially composite light quarks

BR	$s_{L,q} = 0$	$s_{L,q} = 0.1$
$\mathrm{BR}(\rho^0 \to W^\pm W^\pm)$	14.8528	15.1532
$\mathrm{BR}(\rho^0 \to \mathrm{tt})$	4.9727	5.07327
$\mathrm{BR}(\rho^0 \to \mathrm{bb})$	7.86043	8.0194
$\mathrm{BR}(\rho^0 \to \mathrm{ll})$	3.95841	4.0384
$\mathrm{BR}(\rho^0 \to \mathrm{jj})$	7.91682	6.0545
$\mathrm{BR}(\rho^0 \to \mathrm{t}\ T_{\mathrm{f1}})$	22.8233	23.2849
$\mathrm{BR}(\rho^0 \to \mathrm{bB})$	18.1072	18.4735

BR	$s_{L,q} = 0$	$s_{L,q} = 0.1$
$\mathrm{BR}(\rho^\pm \to W^\pm \mathrm{h})$	19.7267	20.2601
$\mathrm{BR}(\rho^\pm \to W^\pm \mathrm{Z})$	19.7267	20.2601
$\mathrm{BR}(\rho^\pm \to tb)$	16.5903	17.0389
$\mathrm{BR}(\rho^\pm \to l)$	3.5049	3.59967
$\mathrm{BR}(\rho^\pm \to jj)$	10.5147	8.09498
$\mathrm{BR}(\rho^\pm \to bT_{\mathrm{f1}})$	2.49319	2.56061
$\mathrm{BR}(\rho^\pm \to tX_{5/3})$	13.9152	14.2915
$\mathrm{BR}(\rho^\pm \to tb)$	6.33486	6.50616
$\mathrm{BR}(\rho^\pm \to T_{\mathrm{f2}}\ \mathrm{B})$	5.441	5.58812

2-site: Benchmark points



Production of T' from ρ_0~ 40 fb @ 14TeV

Production of $X_{5/3}$ from $\rho_{\mp}$ ~ 4 fb @ 14TeV

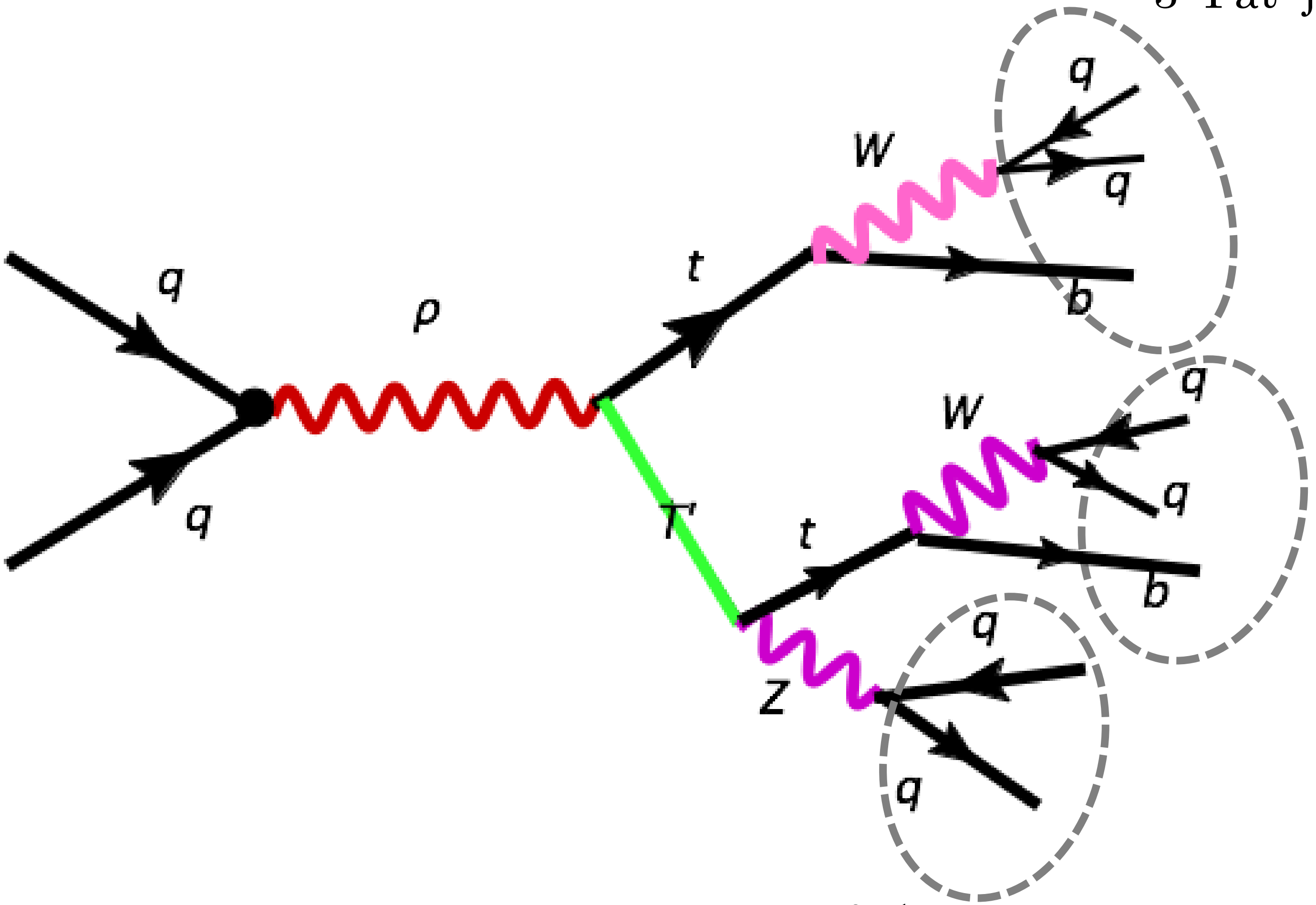
Top partner decays

- Dominant couplings to W;Z; h and an SM quark are chiral (either left- or right-handed coupling dominates).

$$\left.\begin{aligned}\Gamma(F \to W f) &= M_F \frac{M_F^2}{m_W^2} \frac{|g|^2_{\text{eff}}}{32\pi} \Gamma_W\,,\\ \Gamma(F \to Z f) &= M_F \frac{M_F^2}{m_W^2} \frac{|g|^2_{\text{eff}}}{32\pi} \Gamma_Z\,,\\ \Gamma(F \to h f) &= M_F \frac{|\lambda|^2_{\text{eff}}}{32\pi} \Gamma_h\,,\end{aligned}\right\}\ \text{Kinematic functions}$$

Search Strategy @ LHC run II

3 Fat jets in an event



Boosted
Top tagging
+
B-tagging

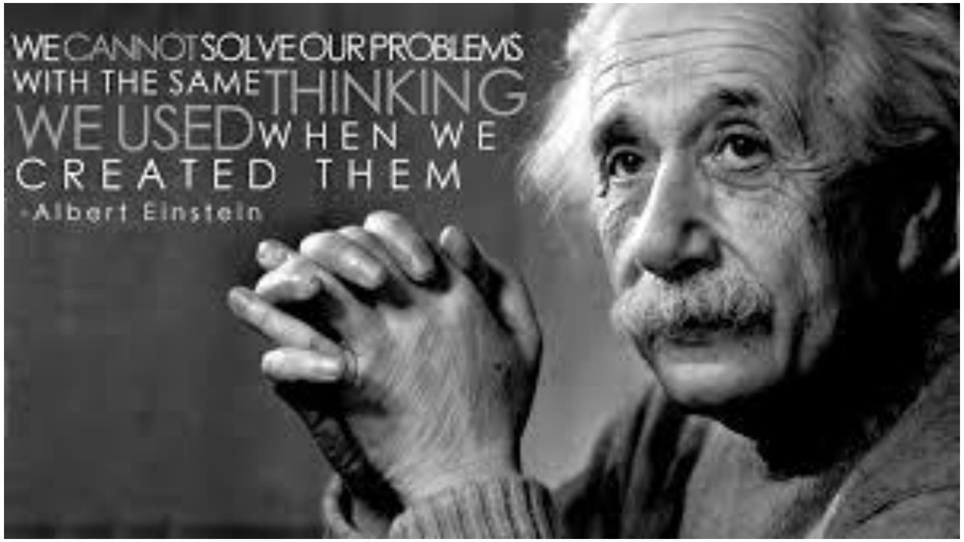
10 signal events expected with $L = 100\ fb^{-1}$

Summary

- **Composite Higgs model** (with H as PGB) provides **a viable solution to the hierarchy problem** and generically predict partner states to the fermions
- **Top partner will be probed beyond the 1 TeV mass region at the Run 2 of LHC**
- **mass of top partners < mass of heavy vector resonances**.
- **vector resonances decay to top partners** instead of pure Standard Model final states start can **dominate**
- For run II, **single-top partner production channels and strongly boosted top searches** become **important.**

- **New search strategies** can aid in **hunting Top partners** and also put more **accurate bounds on heavy vector resonances**

THANK YOU!


WE CANNOT SOLVE OUR PROBLEMS
WITH THE SAME THINKING
WE USED WHEN WE
CREATED THEM
-Albert Einstein