Probing the interplay between composite vector/fermionic resonances @ LHC

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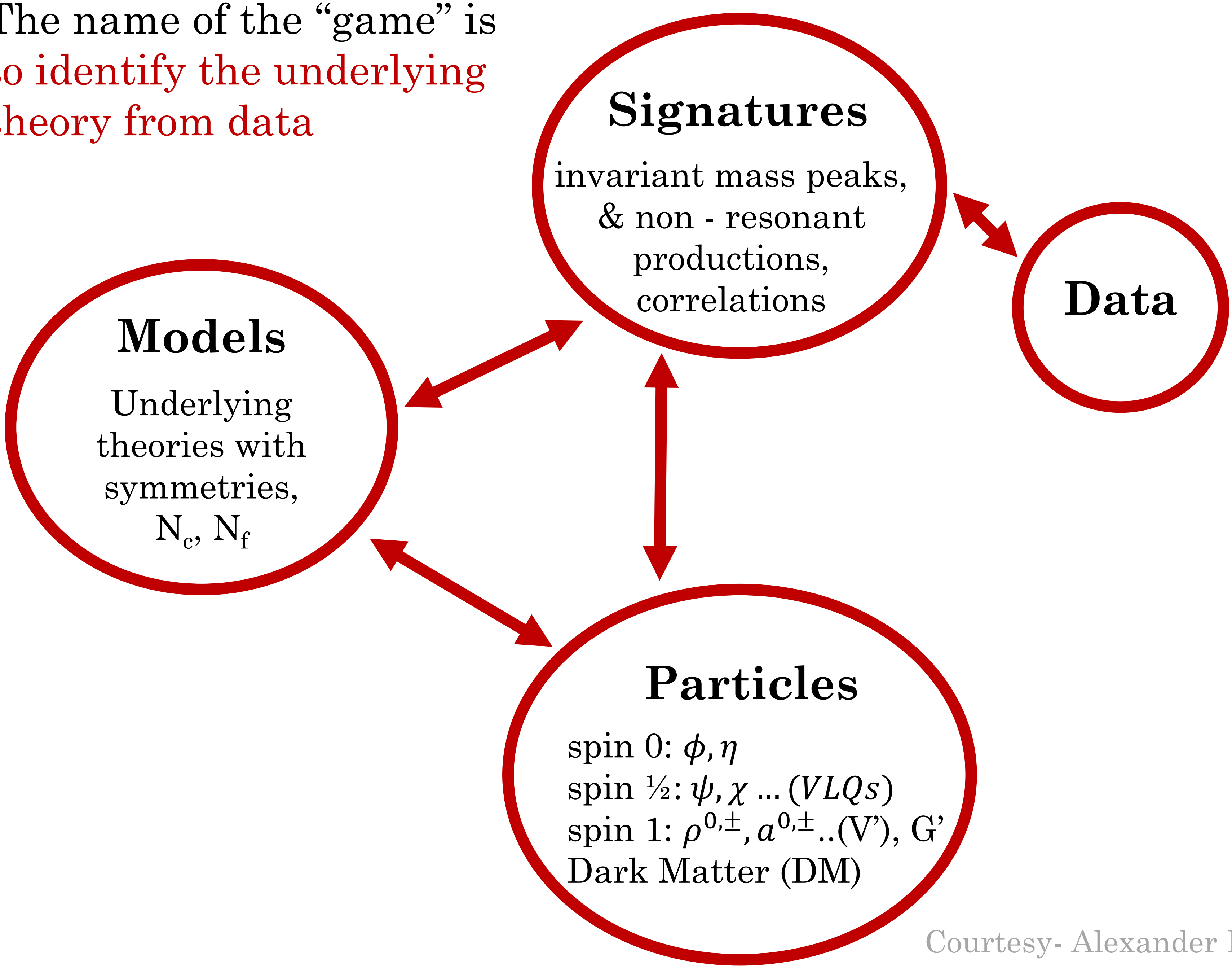
The name of the "game" is to identify the underlying theory from data



Courtesy- Alexander Belyaev

Models

☺ LHC circa 2012 – Higgs Discovery , $m_h \sim 125$ GeV

☹ But its couplings to $\gamma\,\gamma$, WW, ZZ, bb, and $\tau\tau$ are **compatible with the Standard Model (SM) Higgs.**

☹ Standard Model suffers from the **hierarchy problem**.

⟹Search for an SM extension with a Higgs-like state which provides an explanation for why $m_h, v \ll M_{pl}$.

One possible solution**: Composite Higgs Models (CHM)**

- Consider a model which gets strongly coupled at a scale $f \sim \mathcal{O}\,(1\,TeV\,)$
  → Naturally obtain $f \ll M_{pl}$.

- Assume a global symmetry which is spontaneously broken by dimensional transmutation → **strongly coupled resonances** at f and **Goldstone bosons** (to be identified with the **Higgs sector**).

- Assume that the only source of **explicit symmetry breaking** arises from **Yukawa-type interactions**.
  → The Higgs-like particles become pseudo-Goldstone bosons
  ⟹Naturally generates a scale hierarchy $v \sim m_h < f \ll M_{pl}$.

Signatures and Strategies

Data

Models

Underlying theories with symmetries, N_c, N_f

Particles

spin 0: ϕ, η

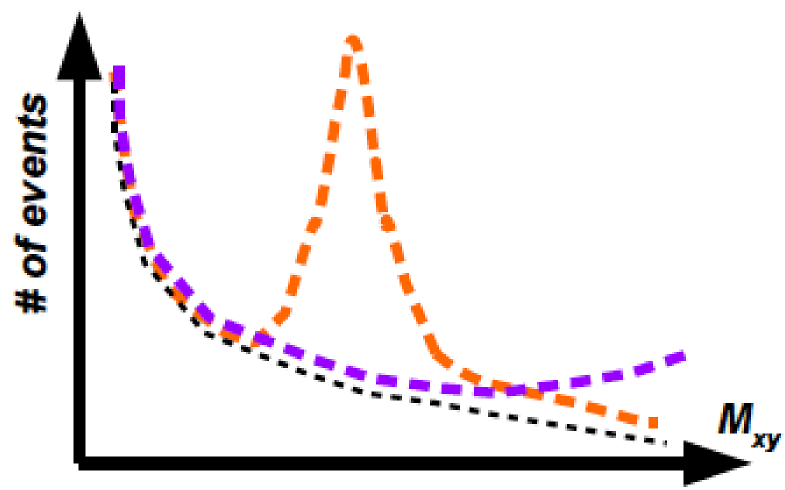
spin ½: ψ, χ ... $(VLQs)$

spin 1: $\rho^{0,\pm}, a^{0,\pm}$..(V'), G'

Dark Matter (DM)

There are two main classes of signatures

- **Resonant – single or several bumps**
- **Non-resonant typically effects in the tails of the distributions**



[see Alex Pomarol's Talk]

Particles

Striking **phenomenological features**

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

1. Fermionic resonances: spin ½ - ψ, χ ...**Vector like quarks (B, $T_{2/3}$, $X_{5/3}$)**
2. Gauge resonances : spin 1: $\rho^{0,\pm}, a^{0,\pm}$..(V' commonly called **W' , Z'),** G'
3. spin 0: ϕ, η - [see Alex Pomarol's Talk]
4. Dark Matter (DM) – [see Alexander M Wijanco's Talk]

} Non minimal cosets

Status of natural CHMs

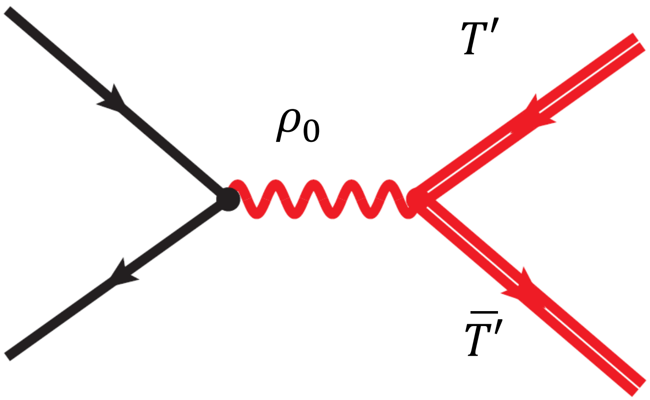
[comprehensive review see Panico, Wulzer '15 , Csaki, Grojean, Terning'15]

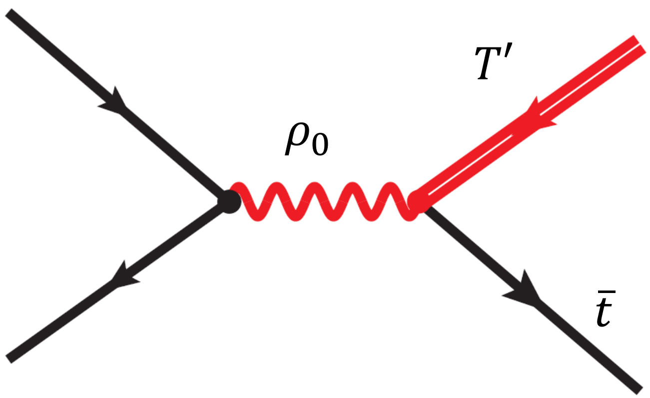
- Pair and single production of VLQs
- a reasonably tuned pNGB Higgs generically requires, $M_T \sim$ TeV

[Matsedonskyi et al. '12]

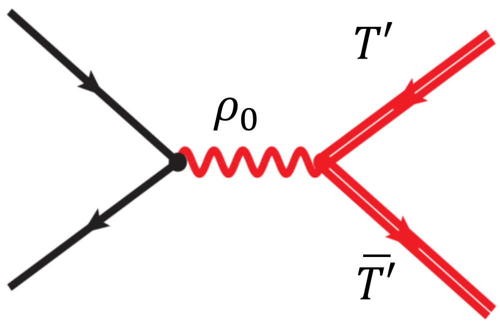
- DY and diboson production of vector resonances (ρ's)
- ρ decay channels: SM (di-quark, di-lepton, di-boson) and

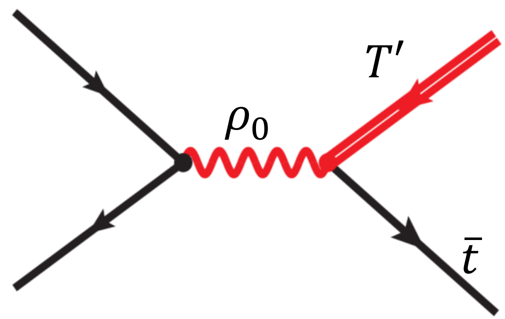
  Exotics (t T, TT) – Top partner production channels
- EWPT pushes $M_\rho > 2$-3 TeV [Contino and Salvarezza '15]
- If kinematically allowed **ρ decays to VLQs become dominant**
- VLQ production processes via ρ_0(Z') become viable

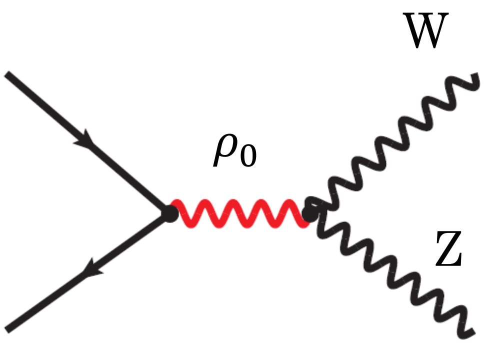


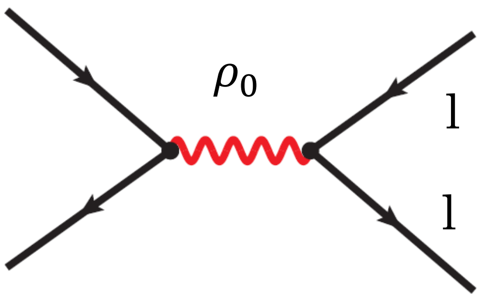


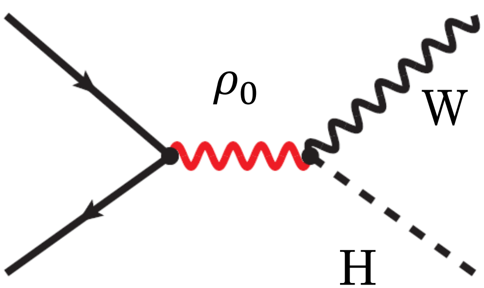
"No lose" strategy for ρ's











- Additional signatures to be added to support the **"no lose" 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 $X_{5/3}$'s

[Barducci, Delauney – 1511.01101]

Composite Higgs

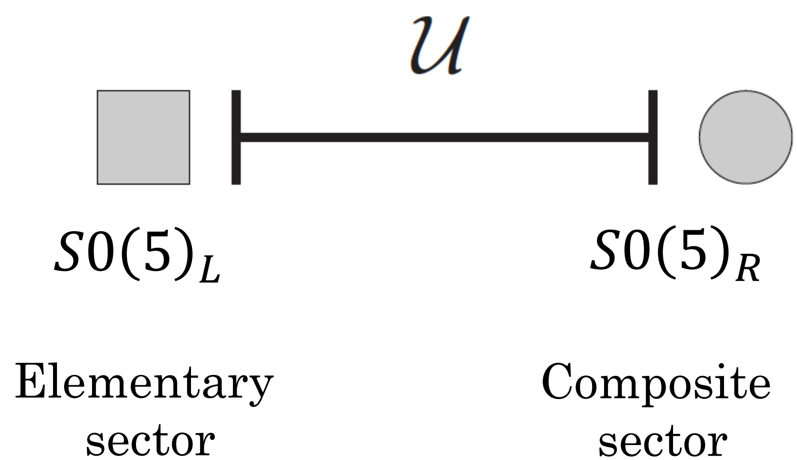
- **Warped XD models**: 5D dual (AdS/CFT correspondence) of Composite Higgs: [Randall & Sundrum,... ’90s]

  nice frame work, providing explicit realization of 4D composite Higgs model

- **Little Higgs**: collective symmetry breaking [Arkani-Hamed, Cohen, Georgi ’00s]
  - Higgs is GB under multiple symmetries
  - Two or more explicit symmetry breaking terms are needed to break all symmetries protecting the Higgs mass.
  - No quadratic divergences at one-loop.
- **Holographic Higgs**: Higss as a component of GB (A5)[Contino, Nomura, Pomarol; Agashe, Contino, Pomarol; Hosotani,...]
- Simple 4D effective description (**Strongly-Interacting Light Higgs**) [Giudice, Grojean, Pomarol, Rattazzi ’07]
- NB: **Higgs** does not need to be a usual PGB; it can arise from other mechanisms, i.e. it can be a light **dilaton** [Bellazzini, Csaki, Hubisz, Serra, Terning ’12, ’13]

2 site Composite Higgs model

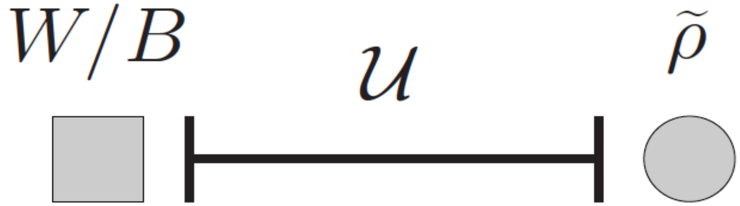
- Simplified version of 5D model – as 4D EFT
- Description of **resonances**
  - One set of resonances of the strong sector are included
  - parametrize many extra-dim. models (eg. different metric)
- Useful tool to analyze **LHC phenomenology**
- **Nonlinear σ- model**
- $\mathcal{U}$: Goldstone matrix of
  $SO(5)_L \times SO(5)_R / SO(5)_V$
- Gives 10 d.o.f s in adjoint of $SO(5)_V$



[Panico, Wulzer'11, Matsedonskyi, Wulzer'12]

2-site model: gauge sector

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



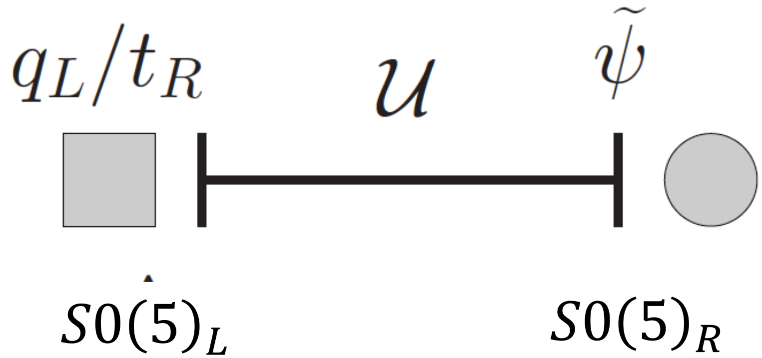
W_μ, B_μ gauge subgroup of 1st site, $SU(2)_L \times U(1)_Y \subset SO(5)_L$
$\tilde{\rho}_\mu$ comes from gauging 2nd site $SO(4) \subset SO(5)_R$

$$\mathcal{L}_0 = \underbrace{\frac{f^2}{2} Tr\left[\left(D_\mu \mathcal{U}\right)^T D^\mu \mathcal{U}\right]}_{\mathcal{L}_\pi} - \underbrace{\frac{1}{4} \mathrm{Tr}\left[\tilde{\rho}_{\mu\nu}\tilde{\rho}^{\mu\nu}\right]}_{\mathcal{L}_{g,strong}} \underbrace{- \frac{1}{4} \mathrm{Tr}\left[\mathrm{W}_{\mu\nu}\mathrm{W}^{\mu\nu}\right] - \frac{1}{4} B_{\mu\nu}B^{\mu\nu}}_{\mathcal{L}_{g,elementary}}$$

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: top sector



- q_L and t_R embedded in Q_L and T_R which are **incomplete** $SO(5)_L$ **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 and composite sector kinetic Lagrangians is

$$\mathcal{L}^f_{el} = i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{t}_R\gamma^\mu D_\mu t_R\,,$$
$$\mathcal{L}^f_{cs} = i\bar{\widetilde{\psi}}\gamma^\mu D_\mu\widetilde{\psi} + \widetilde{m}^{IJ}\bar{\widetilde{\psi}}_I\widetilde{\psi}_J\,,$$

Mass term, $\widetilde{m} = diag(M_4, M_1)$

Invoking partial compositeness via y's

$$\mathcal{L}_{mix} = y_L f\,\overline{Q^I_L}\mathcal{U}_{IJ}\widetilde{\psi^J} + y_R f\,\overline{T^I_R}\mathcal{U}_{IJ}\widetilde{\psi^J}$$

Parameters of the leading order lagrangian:

- f and gauge couplings: g, g', g_ρ
- 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
- g, g' fixed to reproduce the correct W and Z mass

Partially Composite vectors : Mass and couplings

Masses

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

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

$$\mathbf{3}_0 : m_{\rho_{0,\pm}}^2 = \frac{1}{2} f^2 \left(\widehat{g_\rho}^2 + \widehat{g}^2\right) - \frac{\widehat{g}^2 v^2 \widehat{g_\rho}^2}{4\left(\widehat{g_\rho}^2 + \widehat{g}^2\right)},$$

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

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

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	$-\frac{g^2}{g_\rho}\left(1 - a_L \frac{g_\rho^2}{g^2} s_{L,q}^2\right)\tau^a$	–	–	$-\frac{g^2}{g_\rho}\tau^a$	–

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

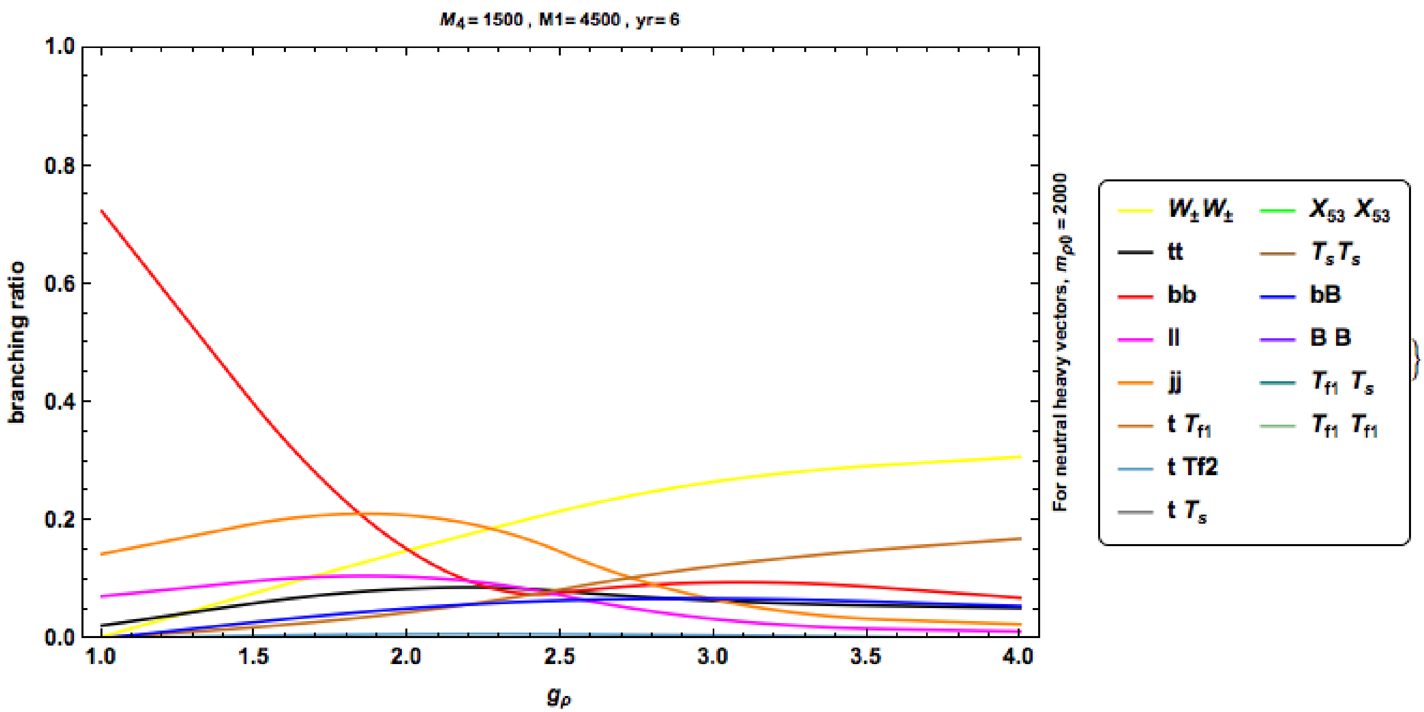
$$M_{Ts} = \sqrt{M_1^2 + y_R^2 f^2}$$

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

2-site: Benchmark points

1. Set 1: For $f = 1.1$ TeV, $M4 = 1.5$ TeV, $M1 = 4.5$ TeV, $y_R = 6$ and $g_\rho = 2.5$
2. Set 2: For $f = 942$ GeV, $M4 = 1$ TeV, $M1 = 5.5$ TeV, $y_R = 4$ and $g_\rho = 3$
3. Set 3: For $f = 942$ GeV, $M4 = 1$ TeV, $M1 = 6$ TeV, $y_R = 3$ and $g_\rho = 3$

$\boldsymbol{m_\rho \sim 2\, TeV,\, m_T \geq 1.5\, \mathrm{TeV}\ (\mathrm{Set\ 1})}$ $\Longrightarrow$ Single Top partner production occurs but SM like final states (diboson) dominates



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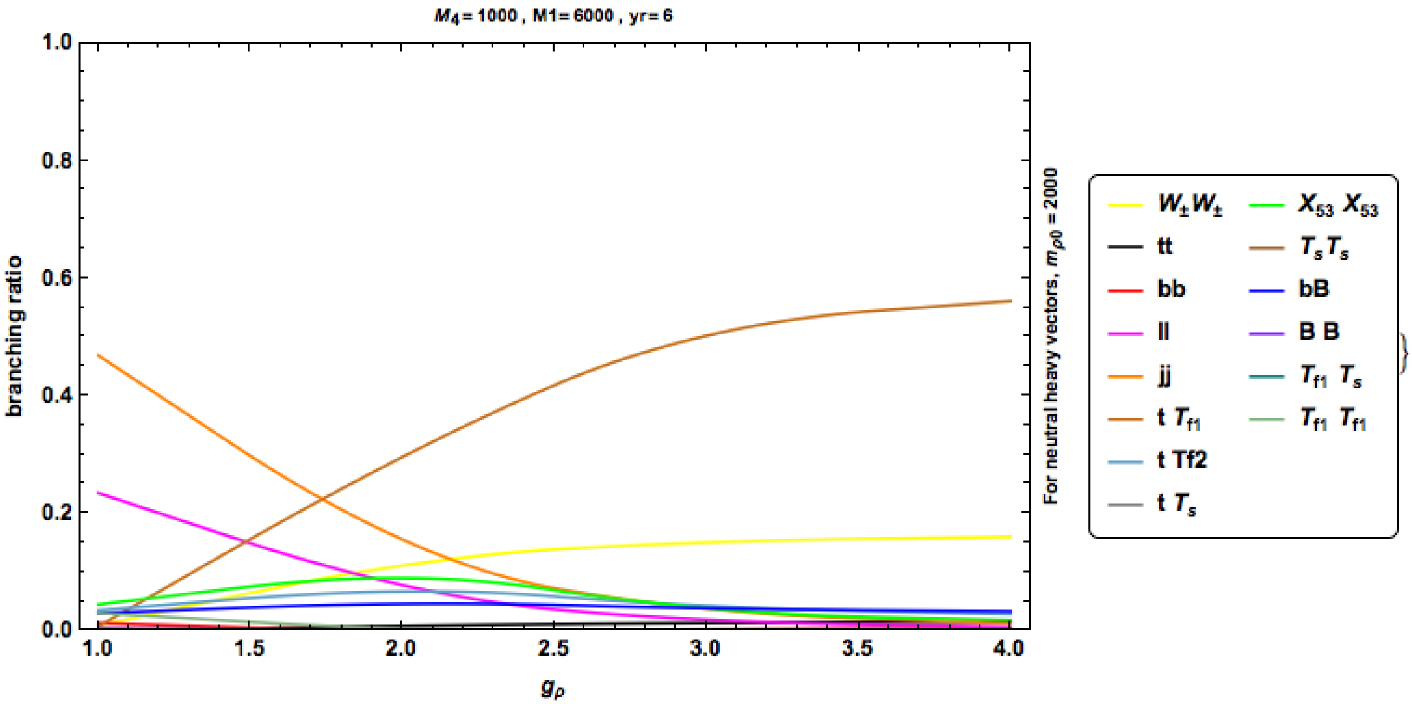
3. Set 3: For $f = 942$ GeV, $M4 = 1$ TeV, $M1 = 6$ TeV, $y_R = 3$ and $g_\rho = 3$

$\boldsymbol{m_\rho \sim 2\ TeV\ , m_T \geq 1}$ **TeV (Set 2,3)** $\Longrightarrow$ Top partner pair production allowed, single top partner production dominates

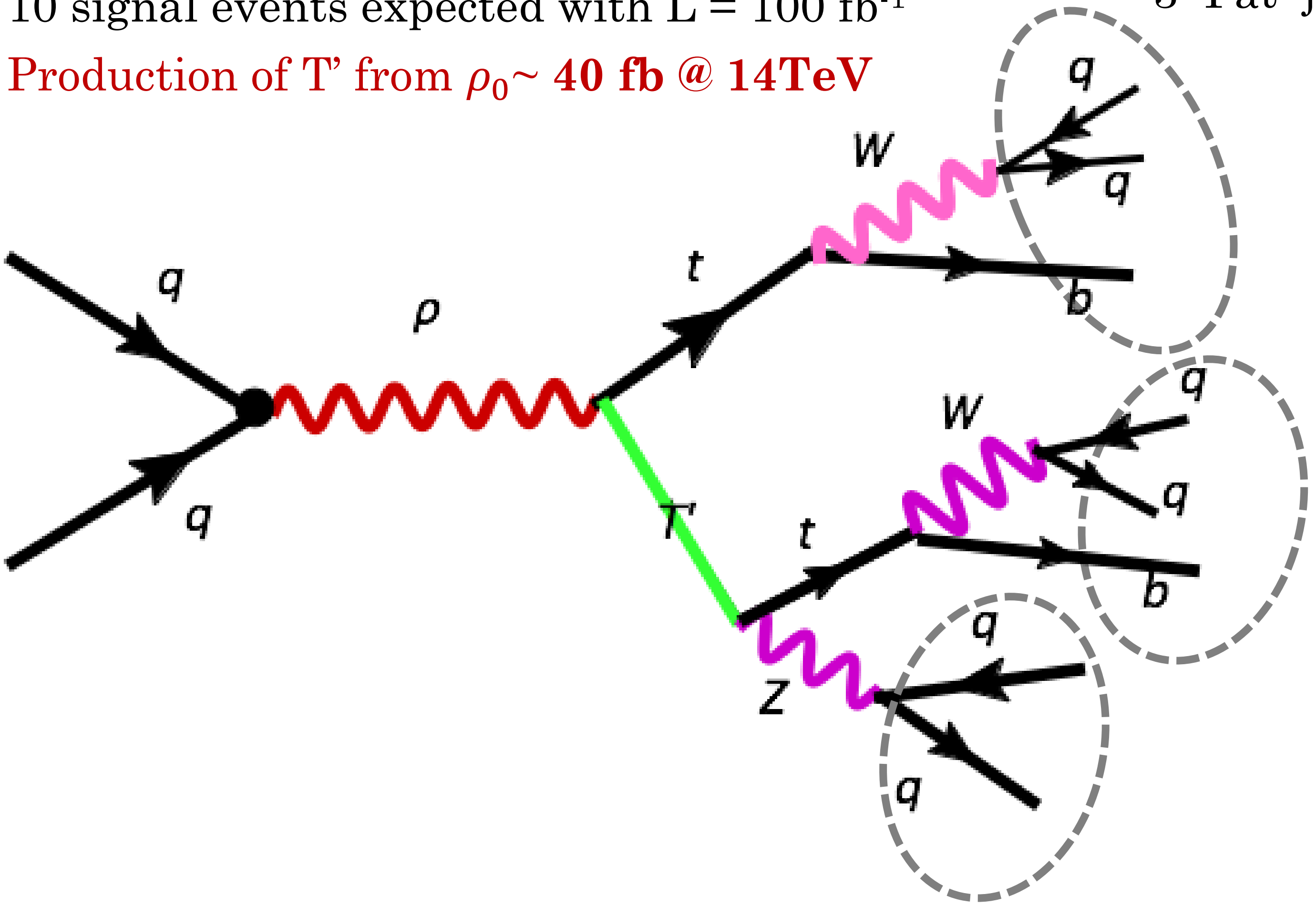


Search Strategy @ LHC run II

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

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

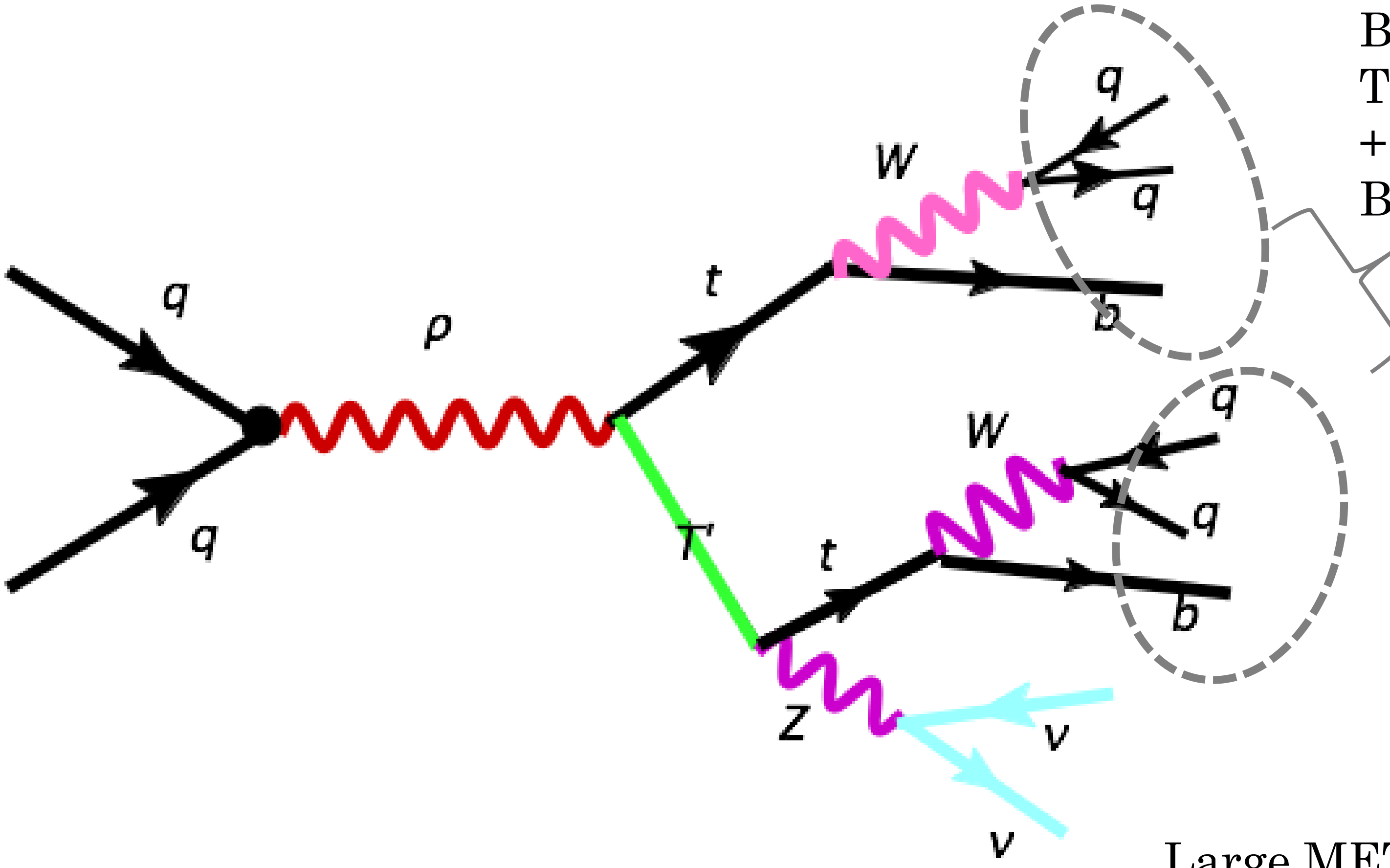
3 Fat jets in an event



Boosted
Top tagging
+
B-tagging

Madgraph 5 with Feynrules model implementation of a toy model with a Z-prime , interfaced with VLQ model and an effective Higgs model

Search Strategy @ LHC run II



Boosted
Top tagging
+
B-tagging

Large MET ($\nu's$)

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!