LHC vector resonance searches

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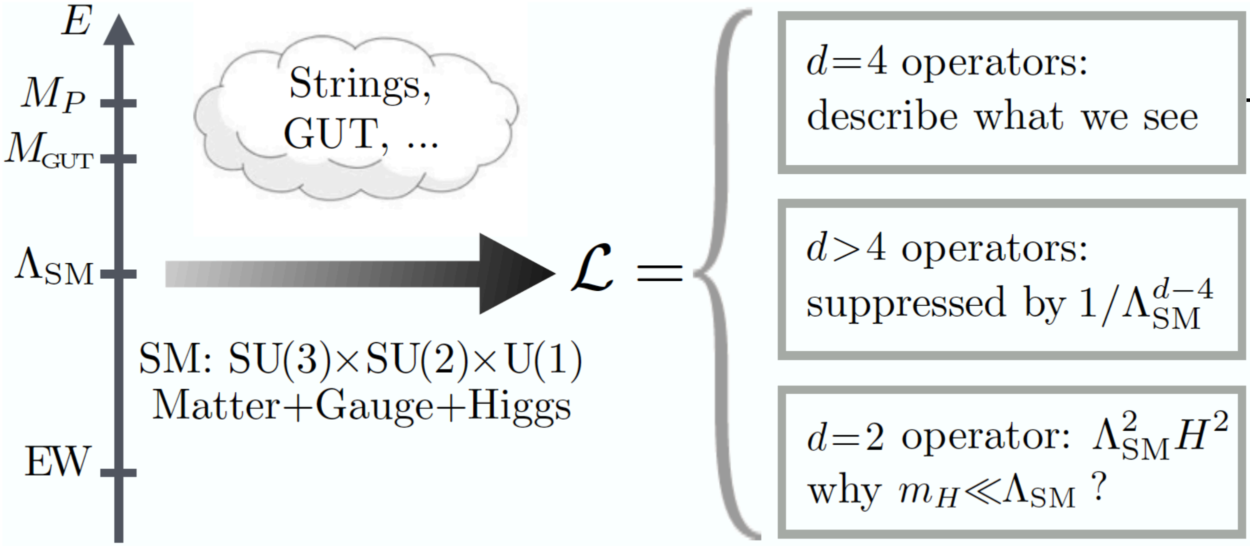
Outline

- SM
- BSM
- Composite Higgs
- 2-site CHM
- Heavy vector & Top partner production
- Direct/Indirect Constraints
- Search strategy
- Summary and Outlook

SM is an EFT



$$-\frac{1}{4}\mathcal{F}^2 - i\bar{q}Hq + |DH|^2 + \lambda|H|^4$$

$$+\frac{(\bar{q}q)^2}{\Lambda_{SM}^2} + \cdots$$

$$-\epsilon\Lambda_{SM}^2|H|^2$$

Wulzer, Panico '15

- d>4 operators like Weinberg operator for neutrino mass or bounds on proton decay push Λ_{SM}>>100 GeV
- Hierarchy among Yukawa couplings points to a highly non generic BSM theory

Why BSM?

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

$\Longrightarrow \mu^2 \sim (90\ GeV)^2 \Longrightarrow \epsilon \sim -\frac{(90\ \text{GeV})^2}{\Lambda_{SM}^2} \ll 1$ (naturalness problem)

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

😱 But BSM physics exists!

Experimental Facts: Neutrino masses, baryon asymmetry , Dark matter, Inflation, Dark energy

Theoretical inconsistencies: Strong CP problem, flavor hierarchies, gauge coupling unification, **EW Hierarchy**

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

Why BSM?

🤔 Requires new particle content "near" the EW scale

To evade detection until today, the new sector needs to be

1. Hidden (mainly interacting with the SM through the Higgs)
2. And/or heavy (charged under SM but avoiding copious production)

Following option 2): If the new particles(s) can decay into SM particles, the decay products are highly boosted

- For high p_T decay products, the backgrounds are low 😊
- Signal efficiencies are altered (top, Z, W identification, b-tagging)
- For high M_X, the production cross section is reduced 😞

$\Longrightarrow$ "Golden" channels for new particle searches depend on M_X (and $\sqrt{s}$).

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

Signatures

invariant mass peaks, & non - resonant productions, correlations

Data

Models

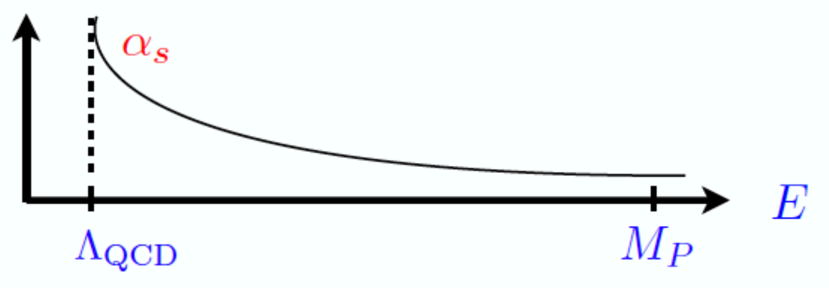
Underlying theories with symmetries, N_c, N_f

Particles

spin 0: ϕ, η
spin ½: ψ, χ ... $(VLQs)$
spin 1: $\rho^{0,\pm}, a^{0,\pm}$..(V'), G'
Dark Matter (DM)

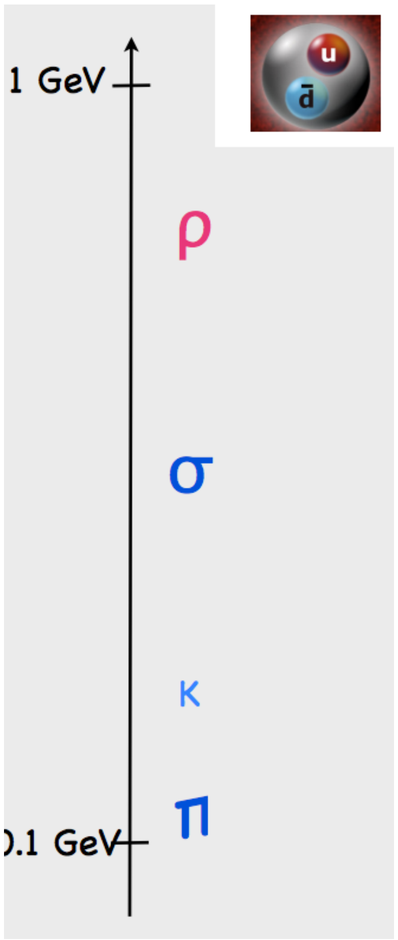
Composite Scalars in QCD

- Spectrum of low-energy QCD contains scalars with $m \sim GeV \ll M_P$ without any hierarchy problem. That's because they are composite states, and quantum correction to their masses are naturally cut off at 1 GeV.



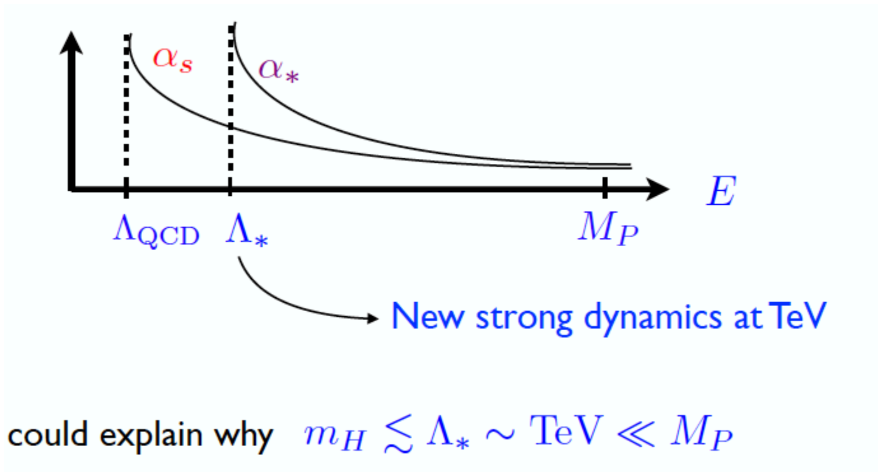
- Moreover, it contains pions and kaons who are (pseudo-)scalar with $m \ll 1$ GeV. That's because they are pseudo-Goldstone bosons of approximate SU(3)xSU(3) symmetry of QCD rotating left- and right-handed light quarks, which is then spotaneously broken to SU(3) by vacuum condensate

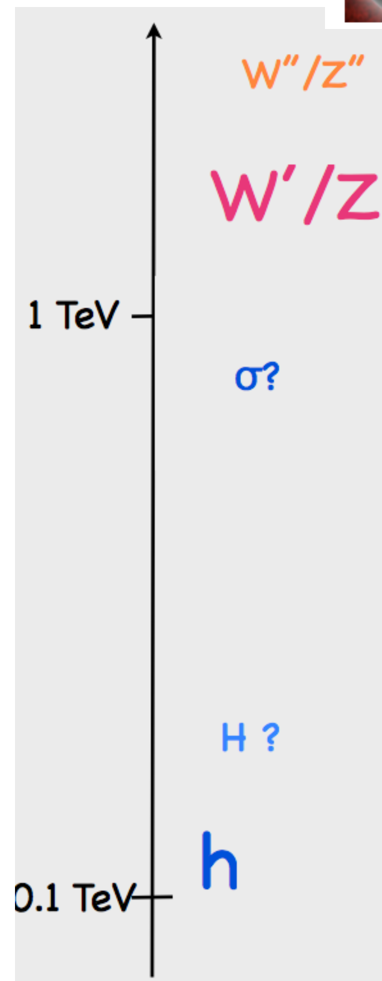
- Technically, pions are protected by shift symmetry $\pi \to \pi + \alpha$ in the effective Lagrangian below 1 GeV



Composite Higgs

- This or similar structure can be carried over to a strongly interacting gauge sector confining near the TeV scale

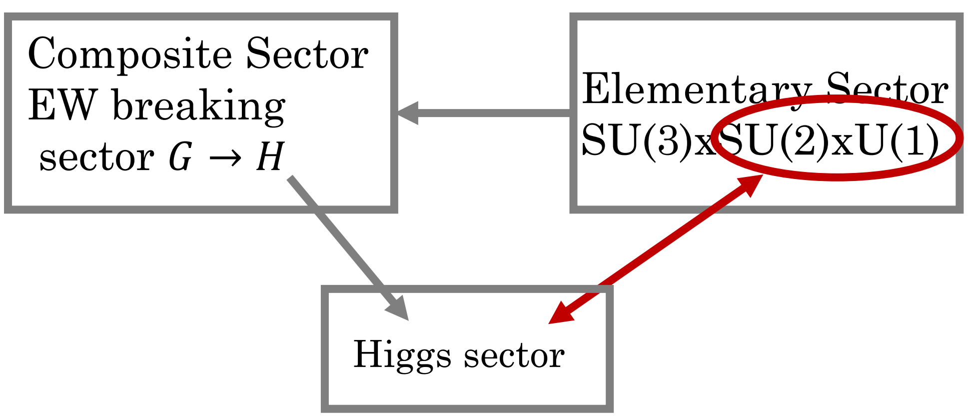


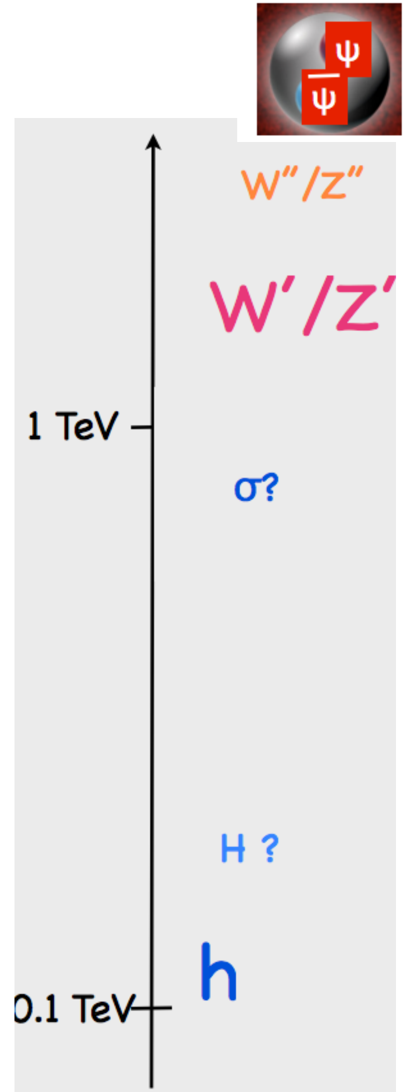


- σ-like scalars are not attractive candidates for the 125 GeV Higgs, as the latter should be narrow and much lighter than cut-off
- Therefore, the 125 GeV Higgs should be pion-like, that is it should be a pseudo-Goldstone boson
- Optionally, depending on the global symmetry of the strongly interacting sector, there may be additional light pGB scalars (kaon-like) forming an extended Higgs sector
- Near the TeV scale there should be a tower of spin-1 and other resonances

Composite (PGB) Higgs

- Assume the existence of a strongly coupled sector charged under the SM local symmetry at a scale $f \sim \mathcal{O}(1\text{ TeV}) \rightarrow f \ll M_p$
- Furthermore, the strong sector has a global symmetry, $\mathcal{G}$ that is larger than the SM gauge group
- Spontaneous breaking of that global symmetry, $\mathcal{G} \rightarrow \mathcal{H}$ gives rise to a set of Goldstone boson, some of which are identified with the SM Higgs doublet
- The global symmetry is softly broken by Yukawa-type interactions, allowing the Higgs to acquire mass (becoming a pseudo Goldstone boson) but still protecting the Higgs mass from quadratically divergent loop corrections $\Longrightarrow v \sim m_h < f \ll M_p$





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

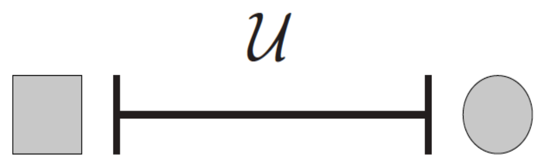
- **Little Higgs**: collective symmetry breaking [Arkani-Hamed, Cohen, Georgi '00s]
  - Higgs is GB under multiple symmetries
  - Two or more explicit symmetry breaking terms are needed to break all symmetries protecting the Higgs mass.
  - No quadratic divergences at one-loop.

- **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]

Phenomenological CHMs

- Aim: obtain phenomenological model in which relevant physical observables like Higgs potential, EW parameters can be reliably predicted
- Focus on a class of explicit implementations of CHMs based on fully 4-D constructions.
- Provide simplified description of holographic theories in which only few KK levels i.e limited set of composite **resonances** are included.
- Starting point: **Nonlinear $\boldsymbol{\sigma}$- model** with coset: $SO(5)_L \times SO(5)_R \,/SO(5)_V$



2 site model

$SO(5)_L$ — Elementary sector

$SO(5)_R$ — Composite sector

- SO(5) Goldstone matrix, $\mathcal{U} = \exp(i\frac{\sqrt{2}}{f}\Pi_A \, T^A)$

  Broken SO(5) generators (T^A)

  $SO(5)\times SO(5)\,/SO(5)$ GB (Π_A)
- Gives 10 GBs in adjoint of $SO(5)_V$

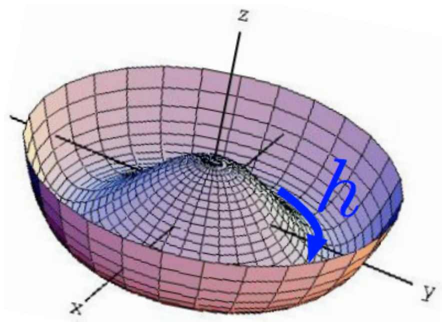
[Panico, Wulzer'11, Matsedonskyi, Wulzer'12]

pNGB Higgs

- The Higgs is a Goldstone with respect to $SO(5)_V$

- **4** under $SO(4)_V \subset SO(5)_V$ identified with Higgs doublet (minimal Higgs sector)

- Higgs can be thought of as an angular variable along the valley of unbroken $SO(4)_V$, while the radial direction corresponds to heavy excitations which are integrated out in effective description



- We need to **break all the symmetries** ($S0(5)_L$ *and* $SO(5)_R$) to generate a term which depends on the Higgs VEV

⇓

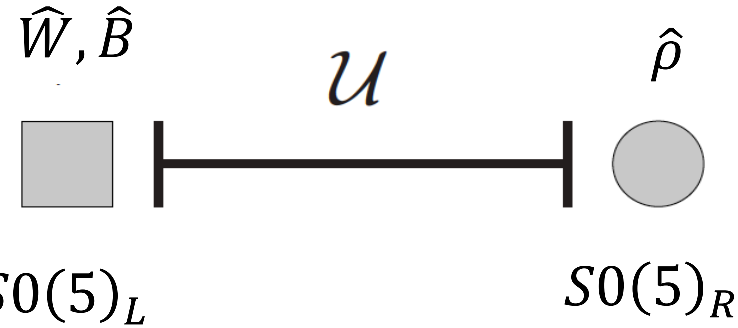
- Higgs potential and also all EWSB effects through **collective breaking** i.e breaking of both symmetries

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

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

Matsedonskyi et al. (2004)

Gauge sector



$\widehat{W_\mu}, \widehat{B_\mu}$ gauge subgroup of 1st site, $SU(2)_L \times U(1)_Y \subset SO(5)_L$

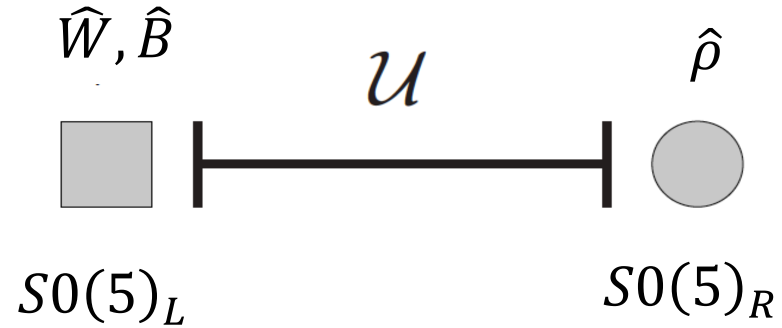
$\hat{\rho}_\mu$ comes from gauging 2nd site **6** of $SO(4) \subset SO(5)_R$

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

interactions of SM gauge bosons and other heavy vector resonances with the Goldstones

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

Gauge sector



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SM gauge fields → **combination of elementary**, $\widehat{W_\mu}, \widehat{B_\mu}$ and **composite** $\hat{\rho}_\mu$ - **partial compositeness**

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

Partially Composite vectors : Mass and couplings

Masses

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

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

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

Post EWSB:
Physical vectors in mass basis

Focus on neutral state in the $SU(2)_L$ triplet

Couplings (examples)

SM electroweak couplings are related to 2-site model

$$\frac{1}{g^2} = \frac{1}{\widehat{g}^2} + \frac{1}{g_\rho^2},$$

$$\frac{1}{g_y^2} = \frac{1}{\widehat{g}'^2} + \frac{1}{g_\rho^2}.$$

$$g^L_{\rho_0 q \bar{q}} = -\frac{\widehat{g}^2}{g_\rho}\left(1 - \frac{g_\rho^2 \; s_{L,q}^2}{\widehat{g}^2}\right)$$

$$g^{L,R}_{\rho T_{f,1} T_{f,1}} = \frac{3 g_\rho c_y - 4 \widehat{g}_y s_y}{6}$$

$$g^R_{\rho_0 T_{f,1} t} = c_y \; s_{R,t} \; \frac{v}{f} \; \frac{g_\rho}{2\sqrt{2}} \frac{M_1}{M_4}$$

$$g^R_{T_{f,1} t Z} = s_y \; s_{R,t} \; \frac{v}{f} \; \frac{g_\rho}{2\sqrt{2}} \frac{M_1}{M_4}$$

Ingredients of Top sector

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

q_L, t_R ⊢――――――⊣ ψ

- q_L and t_R embedded in Q_L and T_R which are **incomplete fiveplets**

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

- $\psi \in (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{1}) = \begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix} \oplus (\tilde{T})$
- Elementary and composite sector kinetic Lagrangians is

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

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

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

where

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

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

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

Top 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

Partially Composite fermions : Mass and couplings

SM like top

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

$\frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \rightarrow s_{L,t}$ $\quad \frac{y_R f}{\sqrt{M_1^2 + y_R^2 f^2}} \rightarrow s_{R,t}$

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

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

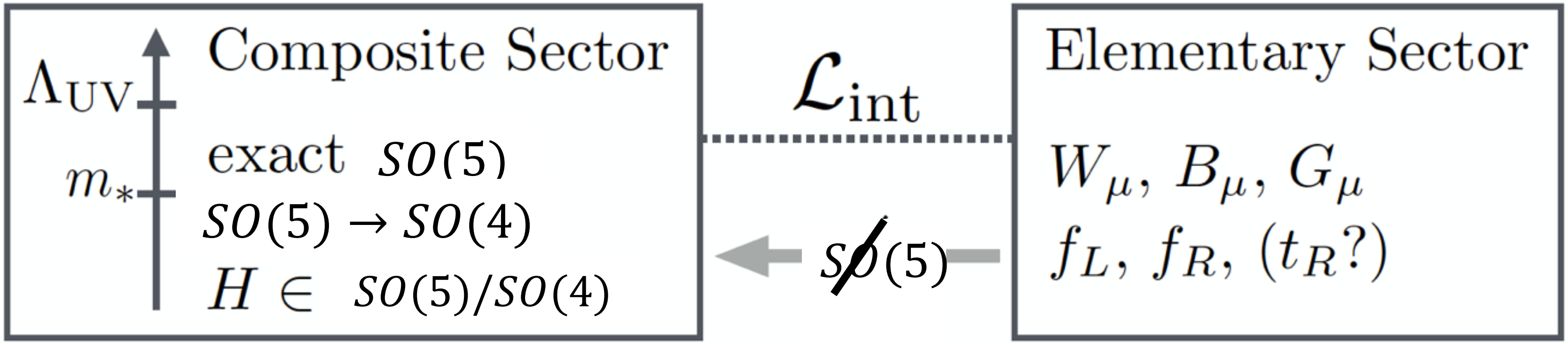
} Post EWSB: Top sector in mass basis @ leading order in v/f

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

Summary
2-site Composite Higgs Model

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



- Simplified version of a 5D model with $SO(5) \to SO(4)$ breaking
- EW SM gauge fields - linear combination of the elementary group $SU(2)_L \times U(1)_Y \subset SO(5)_L$ and the analogous subgroup inside $SO(5)_R$
- Heavy vector bosons contain the **neutral state, $\boldsymbol{\rho_o}$**, in the $SU(2)_L$ triplet.
- Elementary fermions q_L and t_R embedded in Q_L and T_R which are **incomplete fiveplets** of $SO(5)_L$
- Top partners implemented in a fiveplet of $SO(5)_R$, we focus on **lightest 2/3 charged top partner, $\boldsymbol{T_{f,1}}$**

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 -
4. Dark Matter (DM)

} Non minimal cosets

Higgs sector is modified

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

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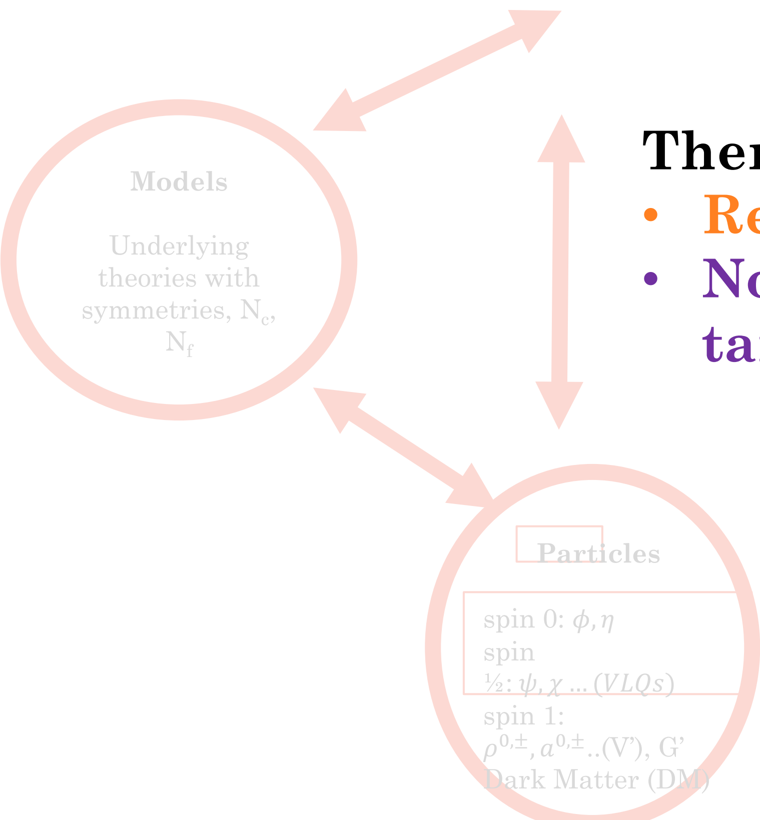
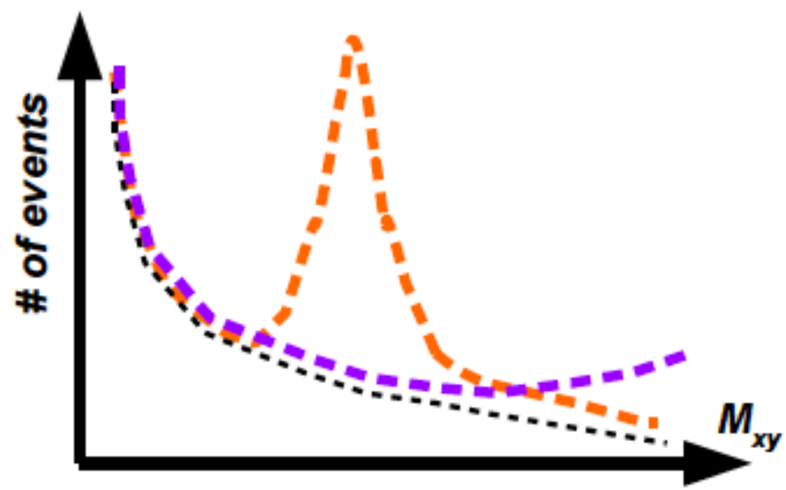
Signatures and Strategies

Data



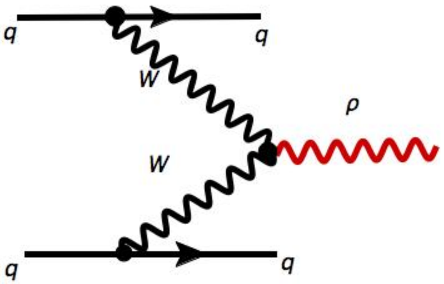
There are two main classes of signatures

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



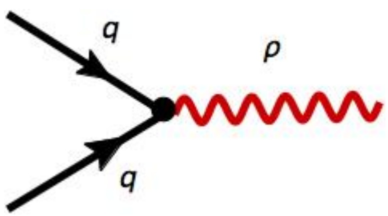
Production rates of ρ

VBF

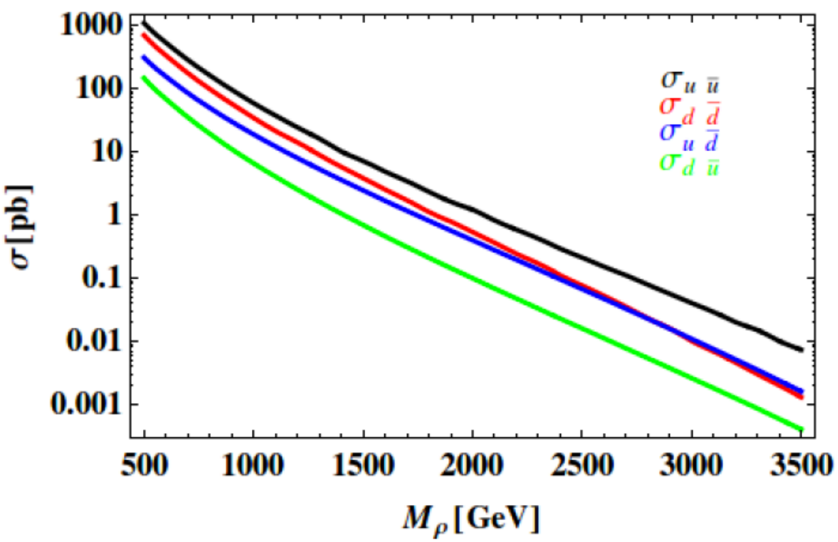


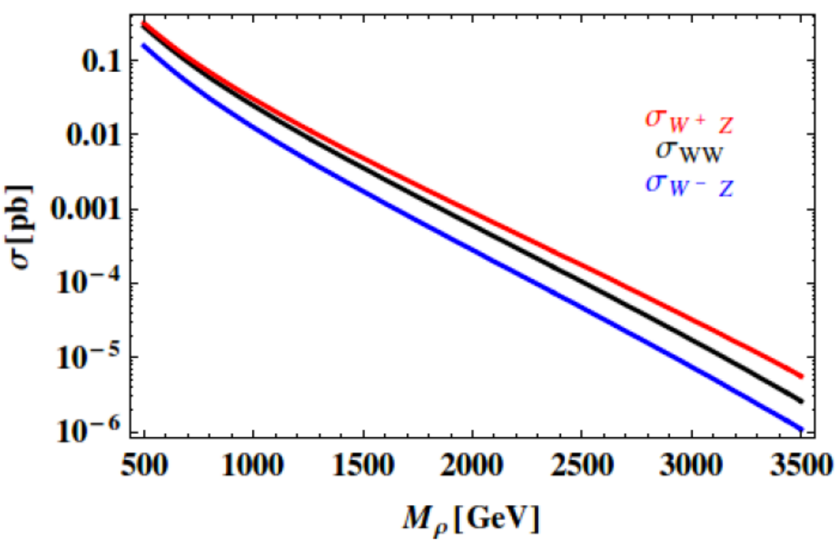
$$\sigma(pp \to \rho^0 + X) = g^2_{\rho^0 WW} \cdot \sigma_{WW}$$

DY



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





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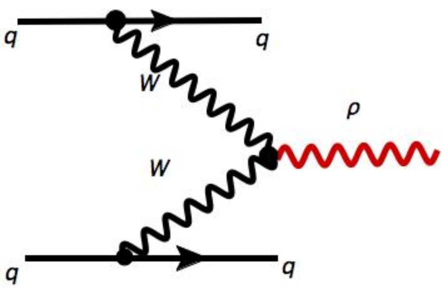

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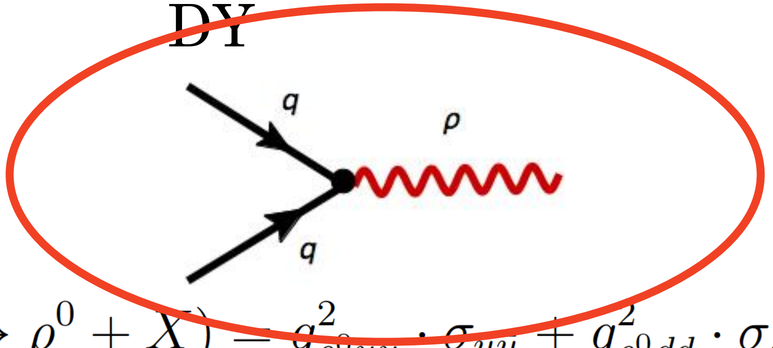

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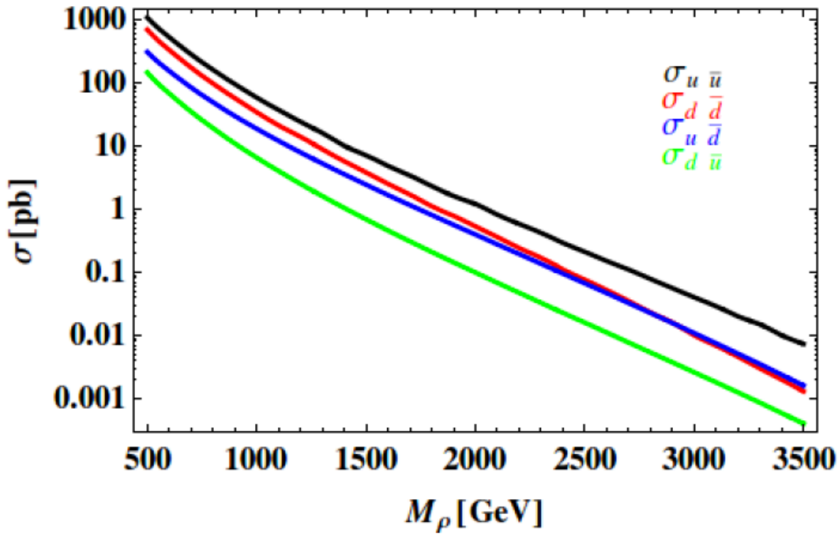
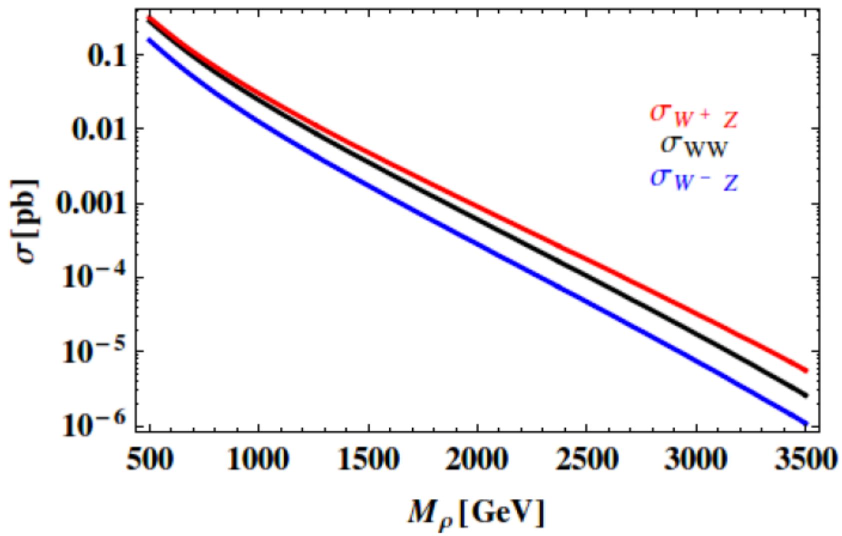


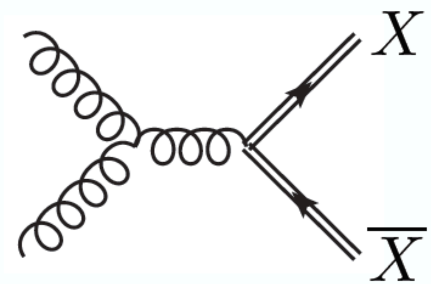


VBF **subleading** in motivated part of parameter space

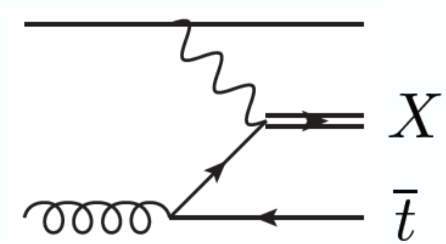
Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012)

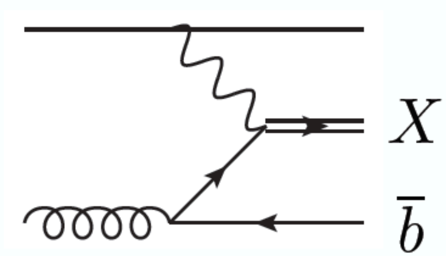
Three possible production mechanisms



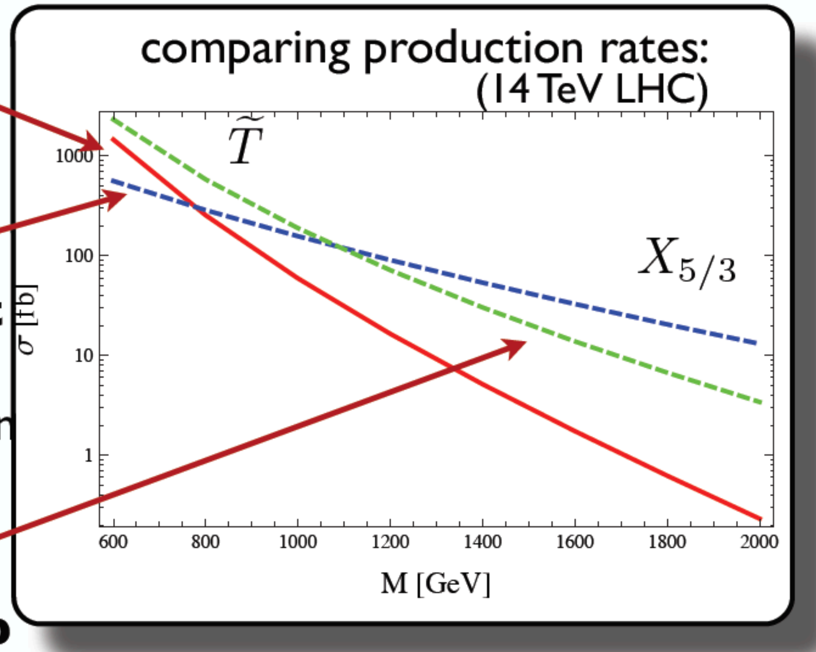
QCD **pair prod**.
model indep.,
relevant at low mass



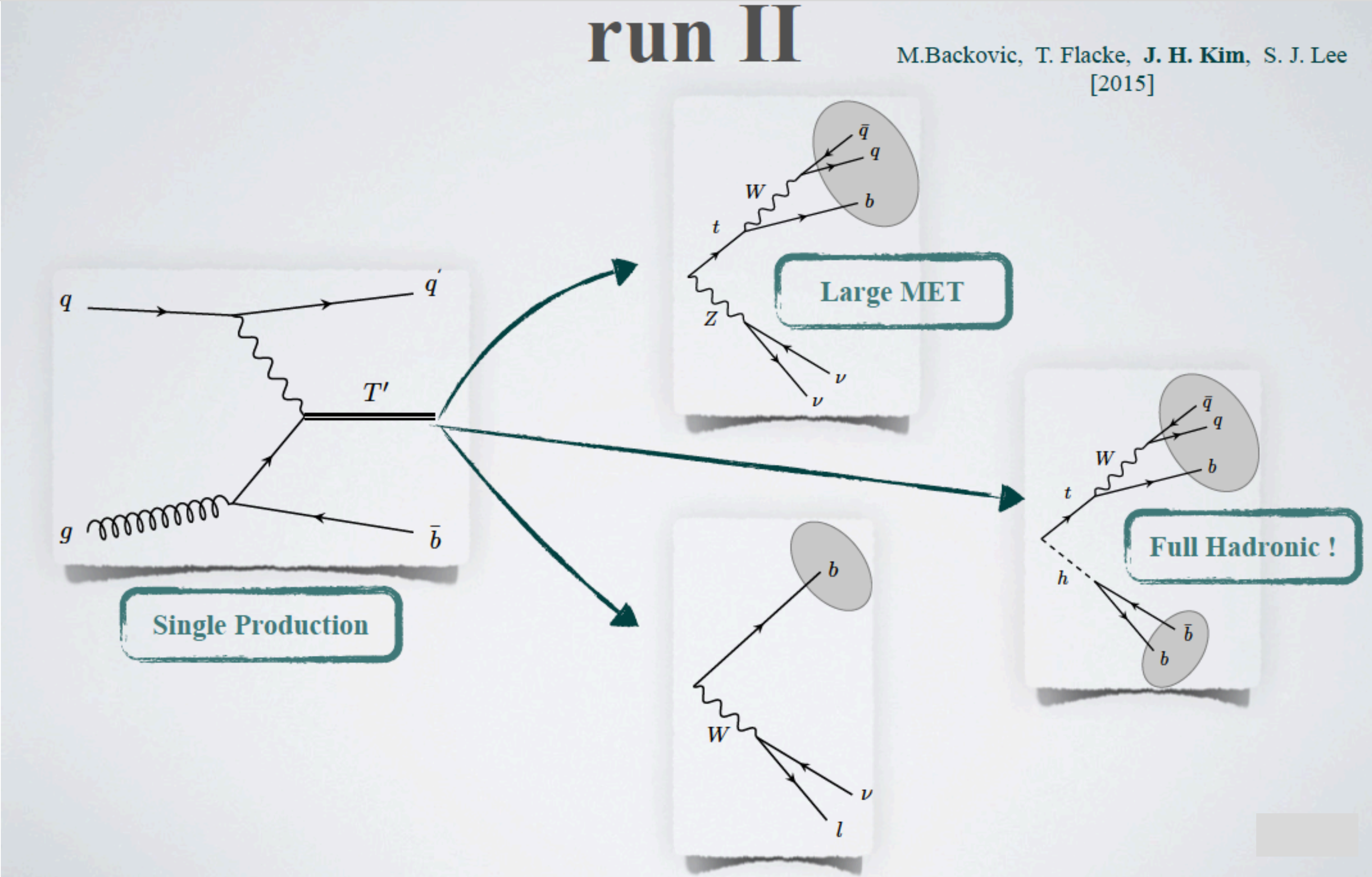
single prod. with **t**
model dep. coupling
pdf-favoured at high m



single prod. with **b**
favoured by small b mass
dominant when allowed



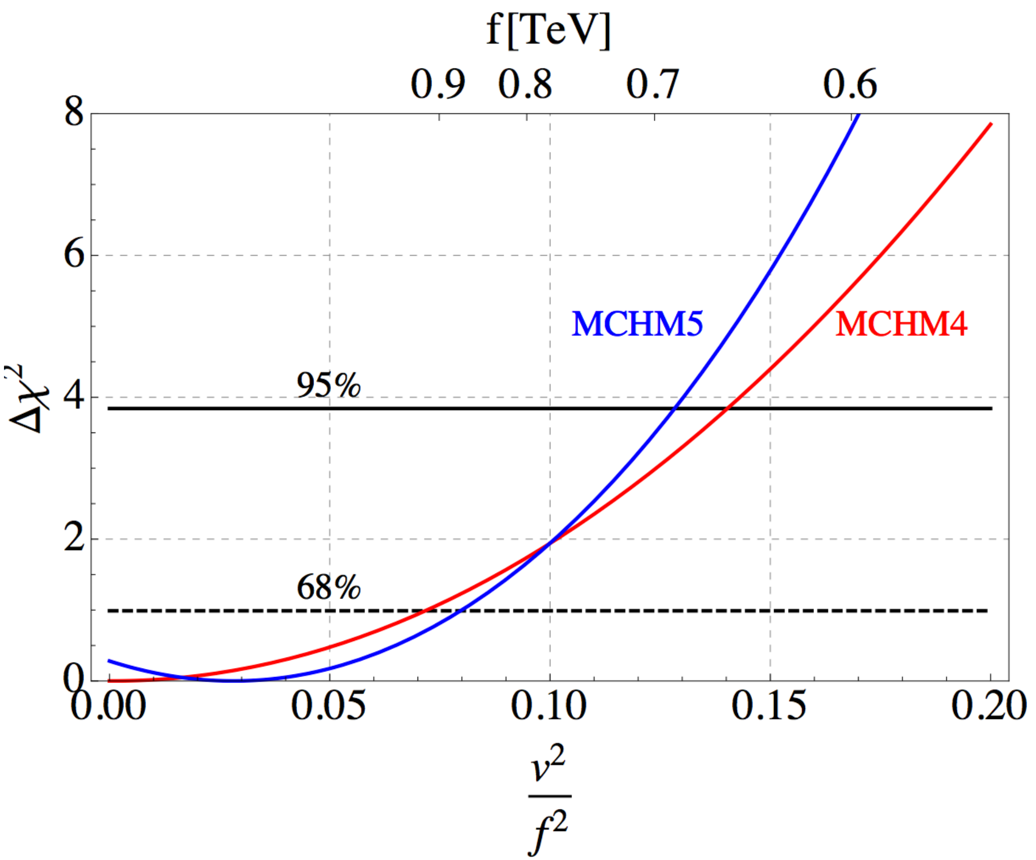
Top partners @ LHC



Collider Constraints

- Precise bound on global symmetry breaking scale depends a bit on realization of fermion sector
- However typical bound is in the 800 GeV ballpark (High Luminosity LHC Run
-)

Channel	Production	Run-1	ATLAS Run-2	CMS Run-2
$\gamma\gamma$	ggh	$1.10^{+0.23}_{-0.22}$	$0.62^{+0.30}_{-0.29}$ [4]	$0.77^{+0.25}_{-0.23}$ [5]
	VBF	$1.3^{+0.5}_{-0.5}$	$2.25^{+0.75}_{-0.75}$ [4]	$1.61^{+0.90}_{-0.80}$ [5]
	Wh	$0.5^{+1.3}_{-1.2}$	-	-
	Zh	$0.5^{+3.0}_{-2.5}$	-	-
	Vh	-	$0.30^{+1.21}_{-1.12}$ [4]	-
	$t\bar{t}h$	$2.2^{+1.6}_{-1.3}$	$-0.22^{+1.26}_{-0.99}$ [4]	$1.9^{+1.5}_{-1.2}$ [5]
$Z\gamma$	incl.	$1.4^{+3.3}_{-3.2}$	-	-
ZZ^*	ggh	$1.13^{+0.34}_{-0.31}$	$1.34^{+0.39}_{-0.33}$ [4]	$0.96^{+0.40}_{-0.33}$ [6]
	VBF	$0.1^{+1.1}_{-0.6}$	$3.8^{+2.8}_{-2.2}$ [4]	$0.67^{+1.61}_{-0.67}$ [6]
WW^*	ggh	$0.84^{+0.17}_{-0.17}$	-	-
	VBF	$1.2^{+0.4}_{-0.4}$	$1.7^{+1.2}_{-0.9}$	-
	Wh	$1.6^{+1.2}_{-1.0}$	$3.2^{+4.4}_{-4.2}$	-
	Zh	$5.9^{+2.6}_{-2.2}$	-	-
	$t\bar{t}h$	$5.0^{+1.8}_{-1.7}$	-	-
	incl.	-	-	0.3 ± 0.5 [7]
$\tau^+\tau^-$	ggh	$1.0^{+0.6}_{-0.6}$	-	-
	VBF	$1.3^{+0.4}_{-0.4}$	-	-
	Wh	$-1.4^{+1.4}_{-1.4}$	-	-
	Zh	$2.2^{+2.2}_{-1.8}$	-	-
	$t\bar{t}h$	$-1.9^{+3.7}_{-3.3}$	-	-
$b\bar{b}$	VBF	-	$-3.9^{+2.8}_{-2.9}$ [8]	$-3.7^{+2.4}_{-2.5}$ [9]
	Wh	$1.0^{+0.5}_{-0.5}$	-	-
	Zh	$0.4^{+0.4}_{-0.4}$	-	-
	Vh	-	$0.21^{+0.51}_{-0.50}$ [10]	-
	$t\bar{t}h$	$1.15^{+0.99}_{-0.94}$	$2.1^{+1.0}_{-0.9}$ [11]	$-0.19^{+0.80}_{-0.81}$
$\mu^+\mu^-$	incl.	$0.1^{+2.5}_{-2.5}$	$-0.8^{+2.2}_{-2.2}$ [13]	-
multi-ℓ	cats.	-	$2.5^{+1.3}_{-1.1}$ [14]	$2.3^{+0.9}_{-0.8}$ [15]

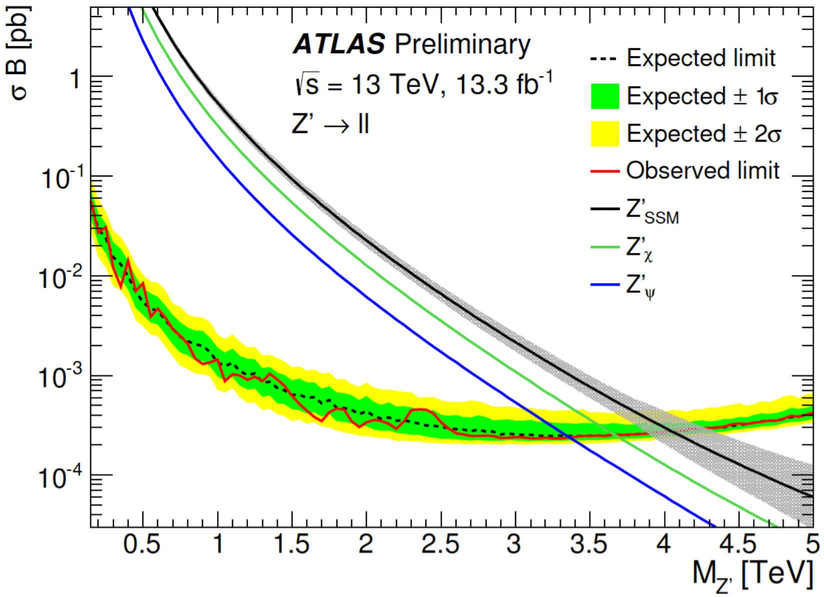


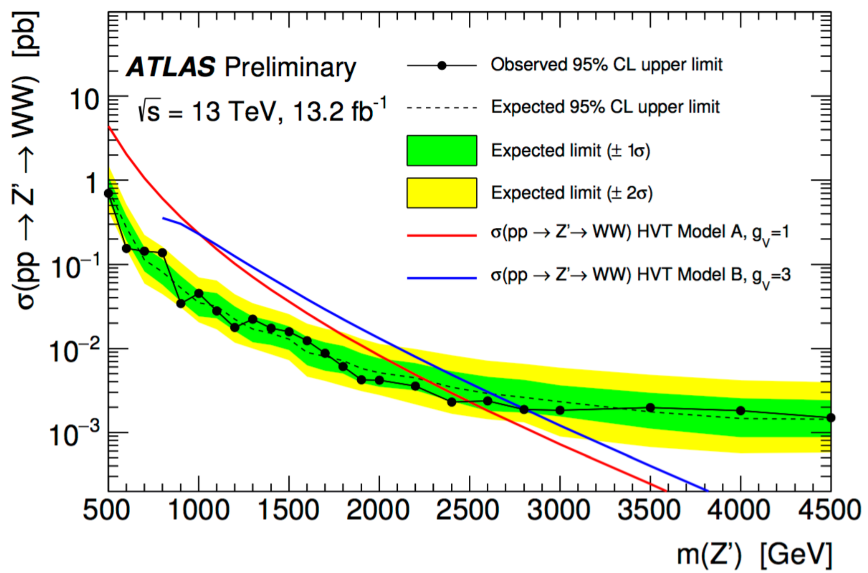
Electroweak Precision constraints

- New resonances give a positive contribution to S parameter
- Moreover, modifications of Higgs couplings effectively yield positive contribution to S and negative contribution to T
- Finally, there can be a new large contribution to Zbb vertex
- Constraints on symmetry breaking scale f are generically somewhat stronger than from LHC Higgs data, although they are much more model dependent
- Constraints on measurements of total hadronic higgs width and CKM unitarity allow for left handed mixing, $s_{L,q} < 0.15$
- Flavor constraints on top sector, impose a bound: $s_{L,t} \lesssim 0.95 \left(\frac{3}{g_\rho}\right)^{1/2}$

Direct Search for Vector Resonances

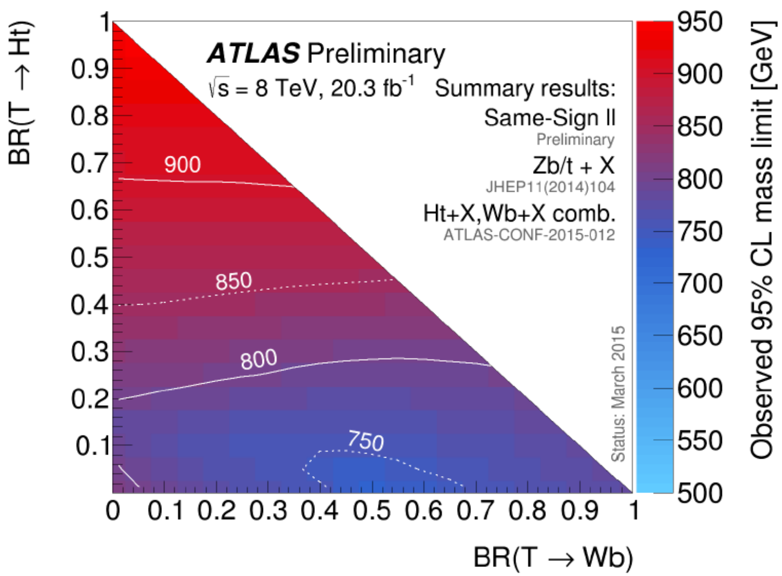
- Heavy vector resonances W' and Z' coupled most strongly to the heaviest SM particles. One should search for resonances in the t-tbar, and W+W-, WZ, and Wh invariant mass spectrum
- Couplings to quarks and to lepton is more model dependent. Some wiggle room to control production cross section. Depending on parameters dilepton signatures may be the leading ones.
- Current limits typically around 2-3 TeV, but can be evaded by tweaking parameters. For 2 TeV : σB < 0.34 fb (dileptons) and < 4.16 fb (dibosons)

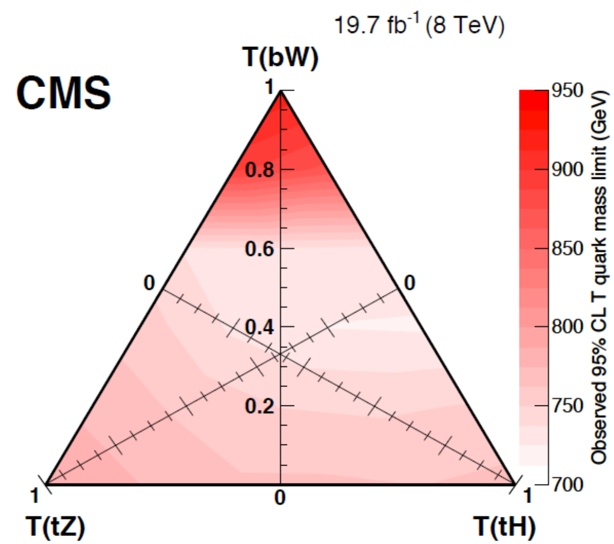




Vector-like quarks: exp limits

- 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]

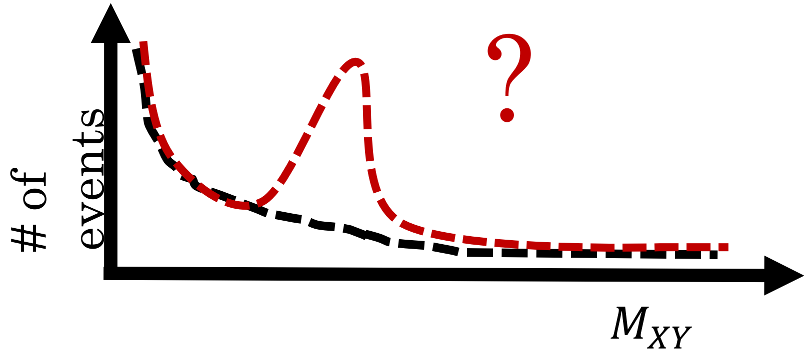




CMS [hep-ex:1509.04177]

Why $t\bar{t}Z$ final state?

- Exotic Searches at ATLAS and CMS look for BSM vector resonances.
- Main focus on signatures of "bumps" in invariant mass spectra of two SM final states (pairs of leptons, jets, top quarks, γ,W, Z)



- Absence of excess$\Longrightarrow$ $m_{vectors} \sim \mathcal{O}(few\ TeV)$ for models where BR to SM pairs dominate.
- What if – decay into non SM pairs dominates?
- Search strategy chosen so far by LHC experiments might be incomplete and can potentially be improved in an essential manner

Phenomenological models with non standard decay modes

- Models with $t' + G'_{\mu}$ @ Tevatron [Dobrescu et. al (2009), Kong et. al (2011)] with $(Wj)(Wj)$, $t\bar{t}h$ and multi-lepton final states

- CHMs with non-standard G' signals i.e $t\bar{t}$ +X @ early LHC [Chala et. al. (2014)] elude existing search strategies aimed at the RS-like KK gluon, composite Higgs models or their close variants.

- Broad **Neutral EW** resonance in CHMs, $\rho_o \to X_{5/3}X_{5/3} \to SS2l$ @ LHC Run II (recast of QCD top partner pair production@CMS)[Barducci et al (2015)]

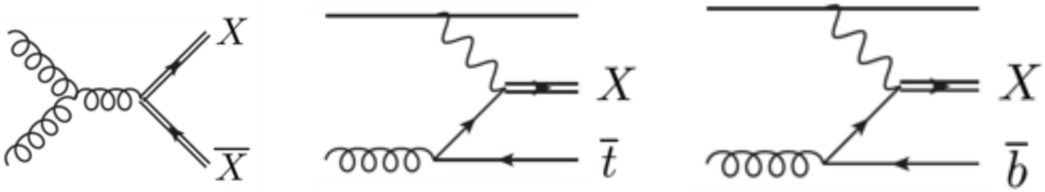
- **EW resonance**, $W' \to X_{5/3}\,X_{2/3}$ (@$SS2l$)and $T'b$ [Vignaroli (2014)]

Disclaimer: not a comprehensive list

Status of heavy resonances

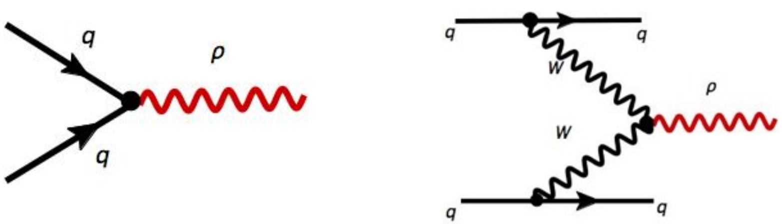
[comprehensive review see Panico, Wulzer '15 , Csaki, Grojean, Terning'15]

- QCD pair and single production of **top partners**



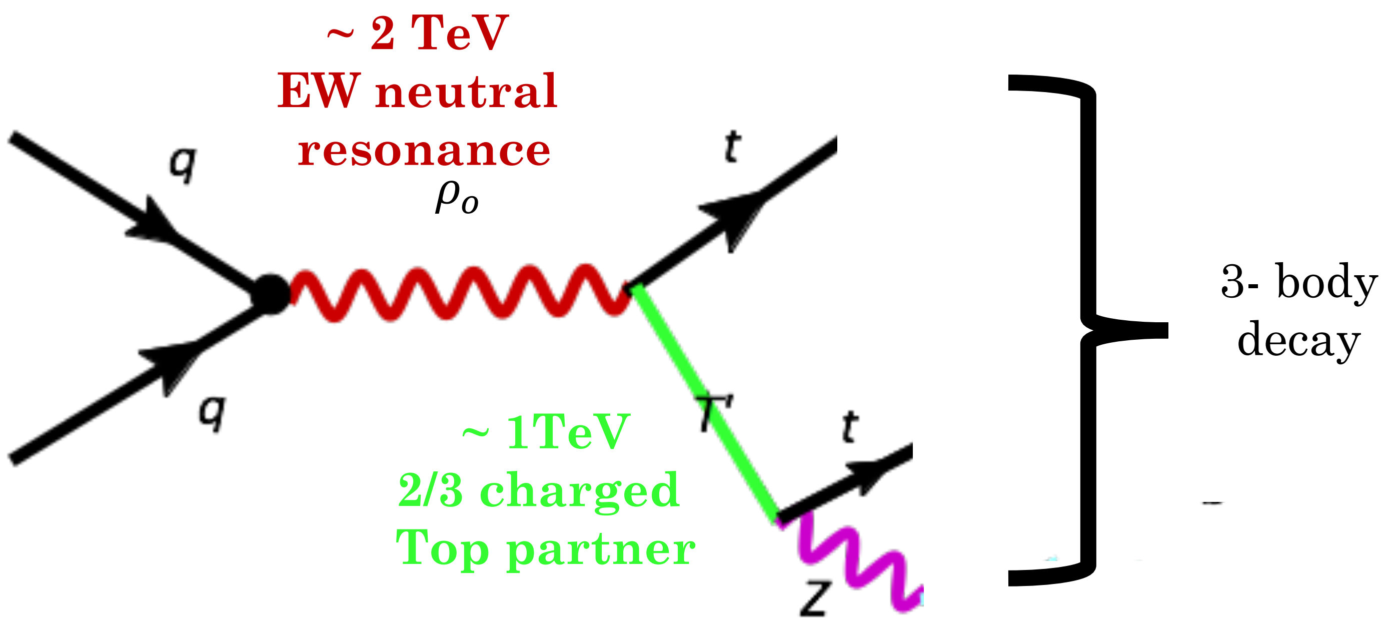
[Matsedonskyi et al. '12]

- a reasonably tuned composite Higgs generically requires, $M_{T'} \sim$ TeV
- ATLAS, CMS – ICHEP '16 exotic results push, $M_{T'} \sim 950$ GeV
- DY and VBF (subleading) production of vector resonances (ρ's)



- EWPT pushes $M_\rho > 2\text{-}3$ TeV [Contino and Salvarezza '15]
- If kinematically allowed ***ρ*** **decays to top partners become dominant**
- Top partner production processes via ρ_0 (celebratred Z') become viable

Search Strategy @ LHC run II



- T' decays into a top (bottom) quark and a h (W boson) also possible

- Complementary probes of new physics scenarios.

Details of benchmark models

$$g_\rho = 3.5, \quad f = 808 \text{ GeV}, \quad m_\rho = 2035 \text{ GeV}, \quad M_1 = 20 \text{ TeV}, \quad s_{L,q} = 0.1$$

- Choice of f satisfies bound $f > 800$ GeV from higgs couplings (High Lumi LHC projections)
- *with* $g_\rho = 3.5 \Longrightarrow m_\rho = 2035$ GeV ~ 2 TeV
- $s_{L,q}$= 0.1 (bound on light-quark compositeness)
- $M_1 = 20$ TeV → simplifies the 2/3 top partner mass spectra, decouples the 3rd partner

	SP1	SP2	SP3
M_4 [GeV]	1000	970	1030
y_R	10	11	11
$M_{T_{f1}}$[GeV]	1020	990	1050

- 3 different choices of $M_4$and y_R illustrate 3 scenarios
  i. $M_{T_{f1}} \sim \frac{m_{\rho_0}}{2}$
  ii. $M_{T_{f1}} < \frac{m_{\rho_0}}{2}$
  iii. $M_{T_{f1}} > \frac{m_{\rho_0}}{2}$

Benchmark Models

$$g_\rho = 3.5, \quad f = 808 \text{ GeV}, \quad m_\rho = 2035 \text{ GeV}, \quad M_1 = 20 \text{ TeV}, \quad s_{L,q} = 0.1$$

	SP1	SP2	SP3
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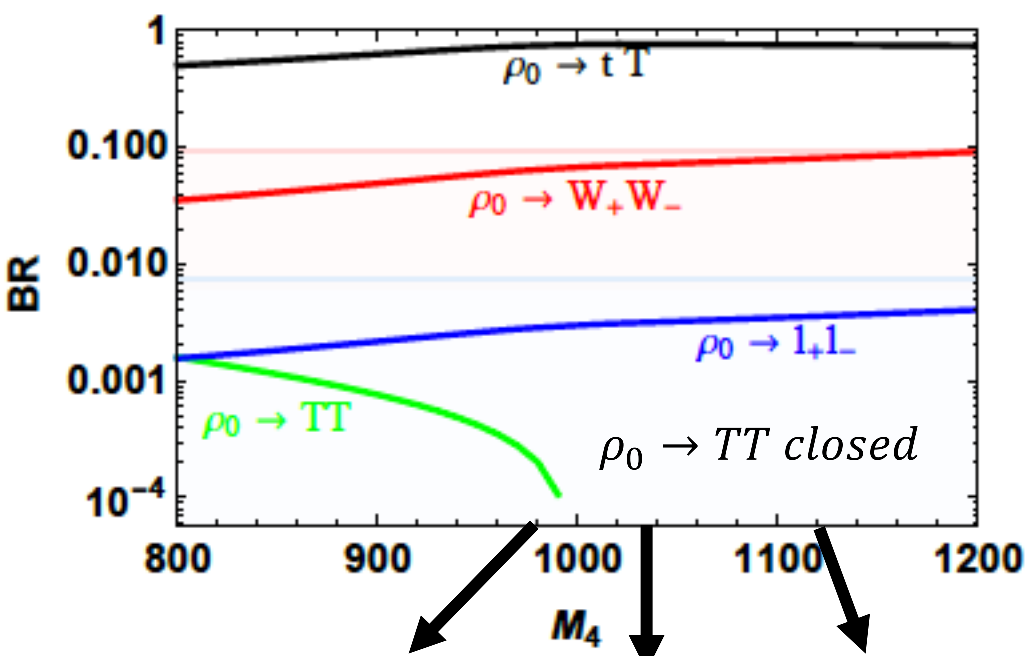


SP2

$\rho_0 \to TT$ open

SP1

$\rho_0 \to tT(max)$

SP3

SP(1,2,3) safe from dilepton bounds
σ ~0.15 fb (0.34 fb - exp)

Diboson bound - 4.16 fb ,
SP(1,2,3) σ is 3.55, 3,26 and 3.59 fb

Top partner produced dominantly decays into t Z **~ 40 fb @ 13TeV**

Collider Phenomenology

- $t\bar{t}$Z final state is highly boosted – easy reconstruction
- MG_aMC for event generation at parton level
- PYTHIA 6 to shower the events
- Impose cut of $H_T > 800$ GeV on the hard processes level to increase statistics in background event samples.
- Cluster showered events using FASTJET implementation of anti-k_T algorithm
  - R= 1.5 jet cone for "fat jet" (CMS top tagging)
  - r= 0.4 for b-tagging
- Simplified b, Z and top tagging weighted by appropriate tagging efficiencies

Tagging efficiencies

- b-tagging benchmark of

$$\epsilon_b = 0.70\,, \quad \epsilon_c = 0.18\,, \quad \epsilon_j = 0.017\,,$$

where $\epsilon_{b,c,j}$ are the probabilities that a b, c or light jet will be tagged as a b-jet.

- Boosted top tagging from CMS benchmark point

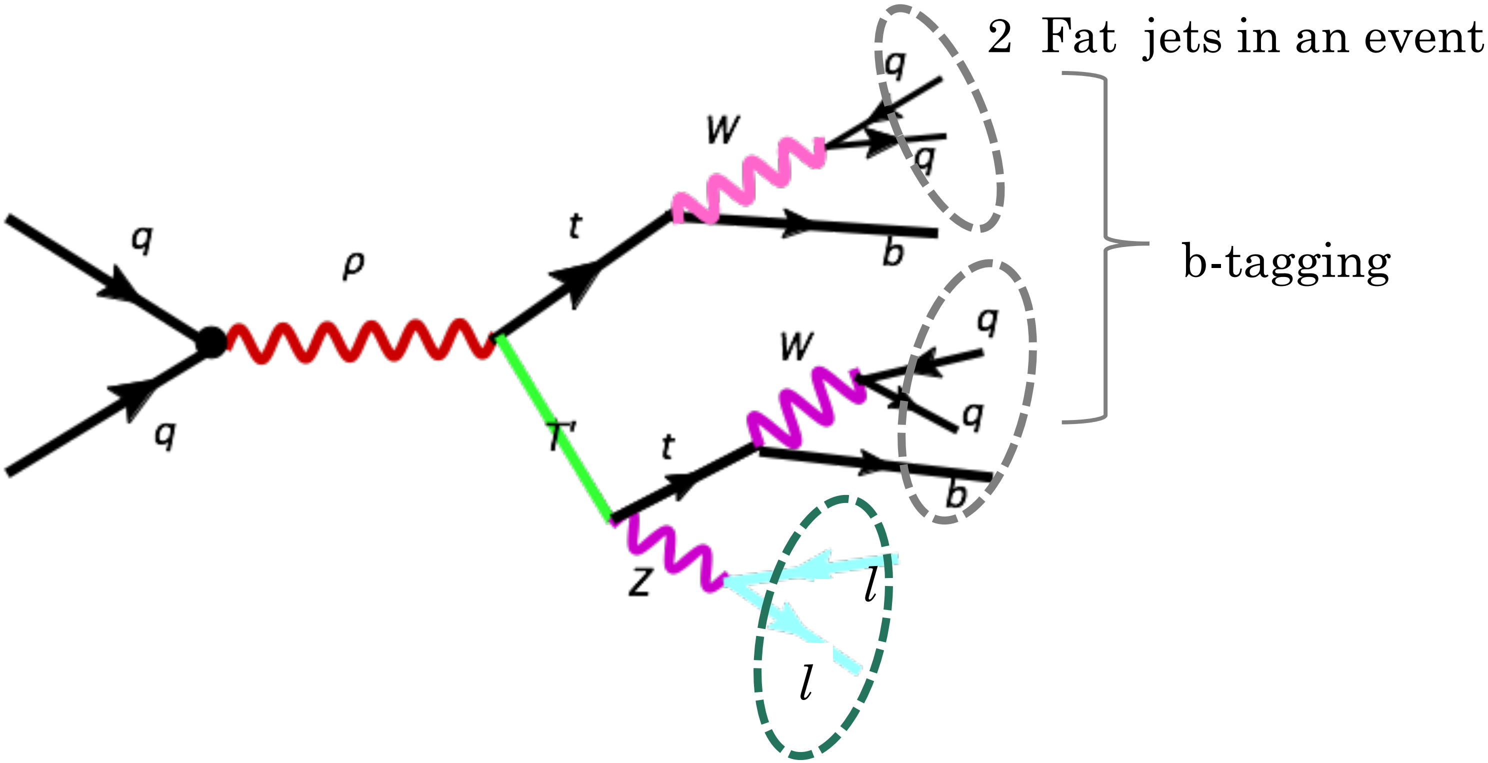
$$\epsilon_t = 0.5\,, \quad \epsilon_j = 0.005\,,$$

- Z boson tagging CMS benchmark point

$$\epsilon_Z = 0.5, \quad \epsilon_j = 0.03$$

where $\epsilon_{Z,j}$ are the probabilities that a Z boson or a light jet will be tagged as Z boson respectively. Note that the top tagging efficiencies include fat jet b-tagging.

Final States with 2 Leptons and no MET

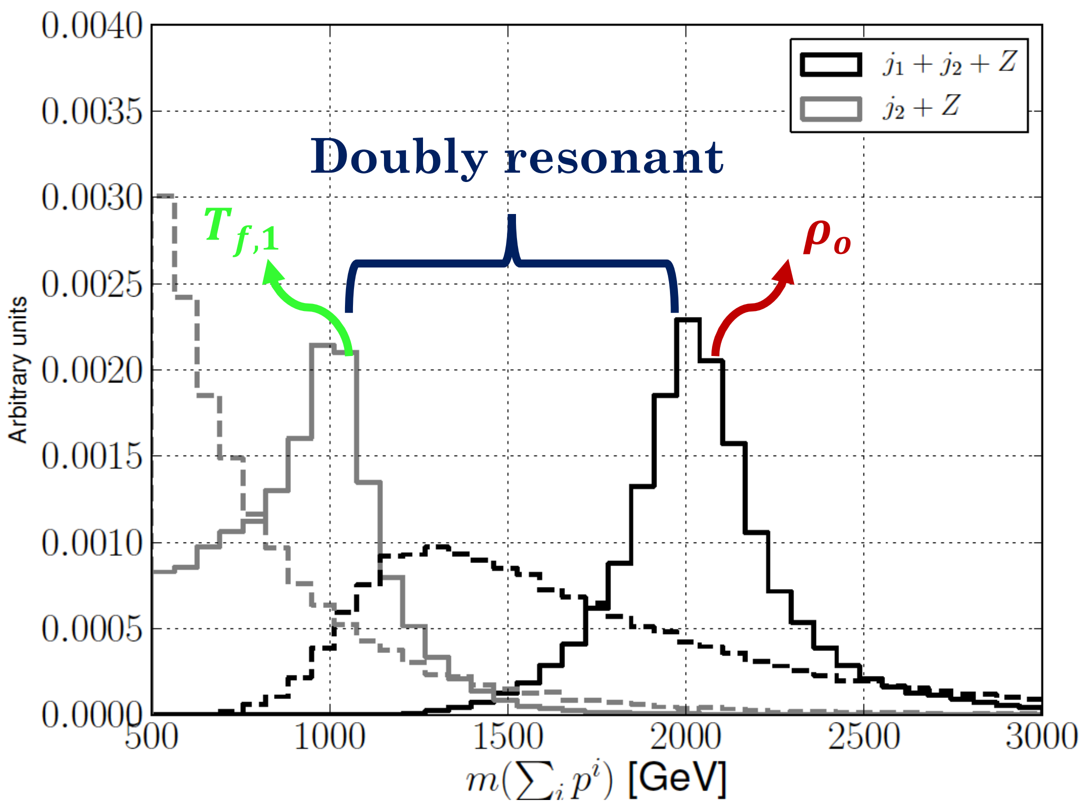


Leptonic Z final state does suffer from smaller ~ 7% BR compared to fully hadronic channel but also comes with important advantages :

1. Lack of MET $\Longrightarrow$ full reconstruction of event (also vector resonance and top partner mass)
2. Background: SM Z+jets production. SM $t\bar{t}$ (10%) ; SM $t\bar{t}$Z (negligible at high event H_T)

Final States with 2 Leptons and no MET

kinematic distributions of the signal events for SP1



discoverable @ LHC13 in the $Z \to ll$ channel

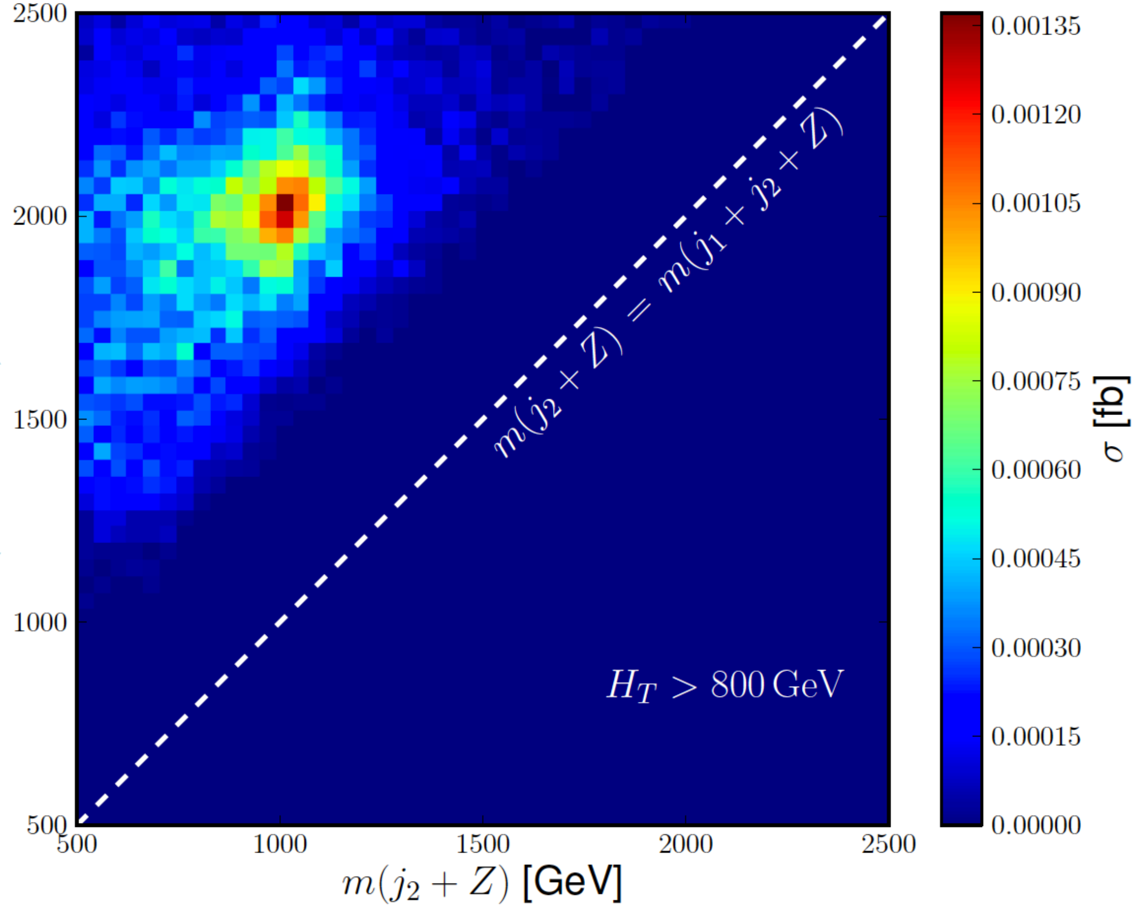
$S/\sqrt{B}$ (30 fb^{-1}) – 6.5
$S/\sqrt{B}$ (100 fb^{-1}) – 11.8

- Background: SM Z+jets
- $j_{1,2}$ – hardest and second hardest R=1.5 jets
- Z – sum of 2 hardest leptons ($l_{1,2}$)
- Assumptions: no pileup, detector simulation or top tagging

Final States with 2 Leptons and no MET

Distribution of signal and background in m_{23}, m_{123} plane

m_{123}
(invariant mass of both tops and Z boson)



m_{23} (invariant mass of second hardest top and Z)

Bulk of background in $m_{23} \sim 500 - 1000\ GeV$, $m_{123} \sim 1 - 2\ TeV$

Signal appears as a **"blip"** at $m_{23} \sim 1\ TeV$, $m_{123} \sim 2\ TeV$

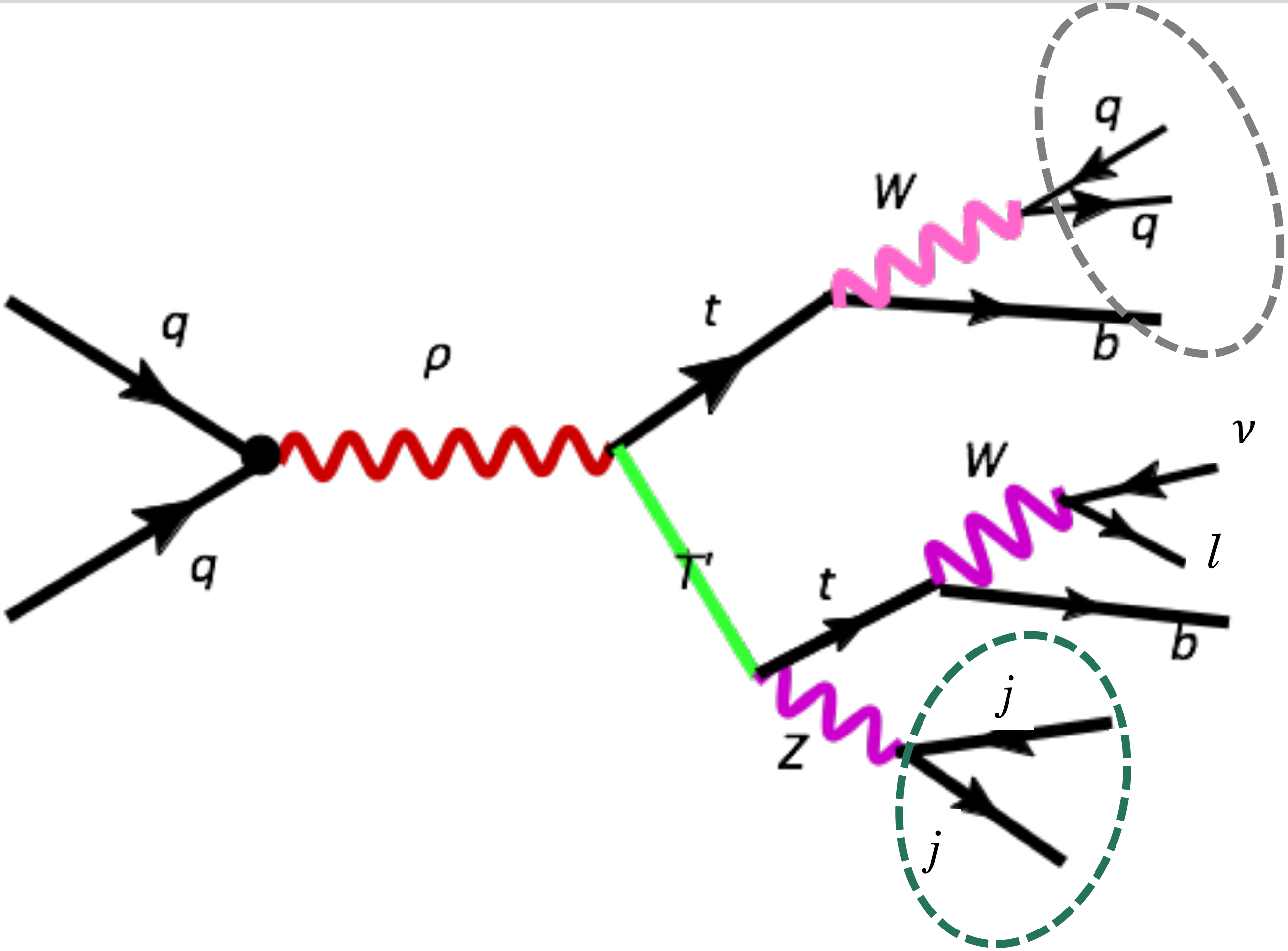
Unique feature:
correlation between mass of tZ and $t\bar{t}Z$ system

Final States with 2 Leptons and no MET

$Z \to l^+ l^-$	$\sigma(\mathrm{SP1})$	$\sigma(\mathrm{SP2})$	$\sigma(\mathrm{SP3})$	$\sigma(Z+\mathrm{jets})$
Preselection	0.64	0.64	0.64	326
$p_T^Z > 300\,\mathrm{GeV}$	0.48	0.46	0.49	254
$p_T^{j_{1,2}} > 400, 300\,\mathrm{GeV}$	0.38	0.36	0.39	38
CMS top tag	0.098	0.090	0.098	9.5×10^{-3}
$m_{23} > 800\,\mathrm{GeV}$	0.074	0.074	0.074	3.5×10^{-3}
$m_{123} > 1.8\,\mathrm{TeV}$	0.066	0.066	0.066	2.9×10^{-3}
S/B	20	20	20	
$S/\sqrt{B}(30\,\mathrm{fb}^{-1})$	6.5	6.5	6.5	
$S/\sqrt{B}(100\,\mathrm{fb}^{-1})$	11.8	11.8	11.8	

Table 2. Example cutflow for the $t\bar{t}Z$ resonance search in the $Z \to l^+ l^-$ channel, assuming the $t, \bar{t}$ quarks decay hadronically. All samples assume a $H_T > 800\,\mathrm{GeV}$ cut at the event generator level. All cross section values are in fb. The background cross section includes an NLO K-factor of 1.3.

Final States with 1 Lepton and MET



Event cross section is 8 times bigger than $Z \rightarrow ll$

Background: SM $t\bar{t}$+jets, W+jets (more background than previous search)

$S/\sqrt{B}$ $(100\ fb^{-1})$ – 2.5
$S/\sqrt{B}$ $(300\ fb^{-1})$ – 4.3

Poor performance!
($t\bar{t}$+jets rejection power low because of inferior Z boson tagging)

Final States with 1 Lepton and MET

$(Z \to jj), 1l, \not{E}_T$	σ(SP1)	σ(SP2)	σ(SP3)	$\sigma(t\bar{t}$+jets)	$\sigma(W$+jets)
Preselection	0.99	0.99	0.99	197	2.0
$p_T^{t_{1,2}} > 500, 400\,\text{GeV}$	0.57	0.56	0.56	23	0.45
$\not{E}_T > 100\,\text{GeV}$	0.46	0.46	0.46	18	0.23
$p_T^Z > 300\,\text{GeV}$	0.38	0.37	0.37	10	0.14
CMS top tag	0.19	0.18	0.19	4.8	< 0.01
CMS Z tag	0.094	0.091	0.094	0.14	< 0.01
$m_{23} > 800\,\text{GeV}$	0.088	0.087	0.087	0.13	< 0.01
$m_{123} > 1.8\,\text{TeV}$	0.086	0.084	0.086	0.12	< 0.01
S/B	0.72	0.72	0.72		
$S/\sqrt{B}(100\,\text{fb}^{-1})$	2.5	2.5	2.5		
$S/\sqrt{B}(300\,\text{fb}^{-1})$	4.3	4.3	4.3		

Table 3. Example cutflow for channels with 1 hard lepton and missing energy. All samples assume a $H_T > 800\,\text{GeV}$ cut at the event generator level. All cross section values are in fb. We use conservative K-factors of 2 and 1.3 respectively for the $t\bar{t}$ and W+jets background.

Other channels

Final states other than two boosted jets and two leptons can be utilized in searches for $\rho \rightarrow t\ T_{f1} \rightarrow \bar{t}tZ$

- $2l^{+}2l^{-} + 2b + MET$: clean final state but BR(Z→ $l^{+}l^{-}$)×BR (t → $l\nu b)^{2}$= $0.07\times0.11^{2} = 8\times10^{-4}$!!! Useful at high luminosity

- 2fj+MET: Fully reconstructing the event and the resonance mass is significantly more difficult in this case due to the more complex composition of MET. Use of kinematic edge or transverse variables could provide useful information on the heavy particle masses

- 3fj: highest BR but large backgrounds from SM multi-jet, $\bar{t}t$ and W/Z+jet processes

Summary

- Past LHC searches for neutral vector resonances have mainly focused on two body resonance decays
- **Absence of signal in resonance searches** & **mass limits** $\sim \mathcal{O}(TeV)$

- **Low resonance decay BR into two body final states** (@LHC)
- **Vector resonance, ρ_0 decay to $t\bar{t}Z$** can **dominate**
- $Z \to l^+l^-$ scenario is very promising (other final states also explored).
- **Benchmark model points** we consider could be **discovered** at LHC13 with as little as **30 fb^{-1} of integrated luminosity.**
- **New search strategies** can aid in **hunting** heavy vector resonances and top partners.

Future outlook

- Apply these results to other three body resonance searches, such as $t\bar{t}$H final states
- If the search would trigger on a single hard lepton in the event, situation similar to $t\bar{t}$Z with $Z \rightarrow had$.
- Higgs tagging algorithm can exploit the presence of two b-jets inside the fat jet – better than had Z search discussed previously.
- Searches for charged vector resonances where similar three body final states could be considered.
- Future studies would benefit from inclusion of detector effects, more realistic boosted object tagging algorithms, as well as studies of high pileup environment on the results

THANK YOU!