LHC resonance searches in $t\bar{t}Z$ final state

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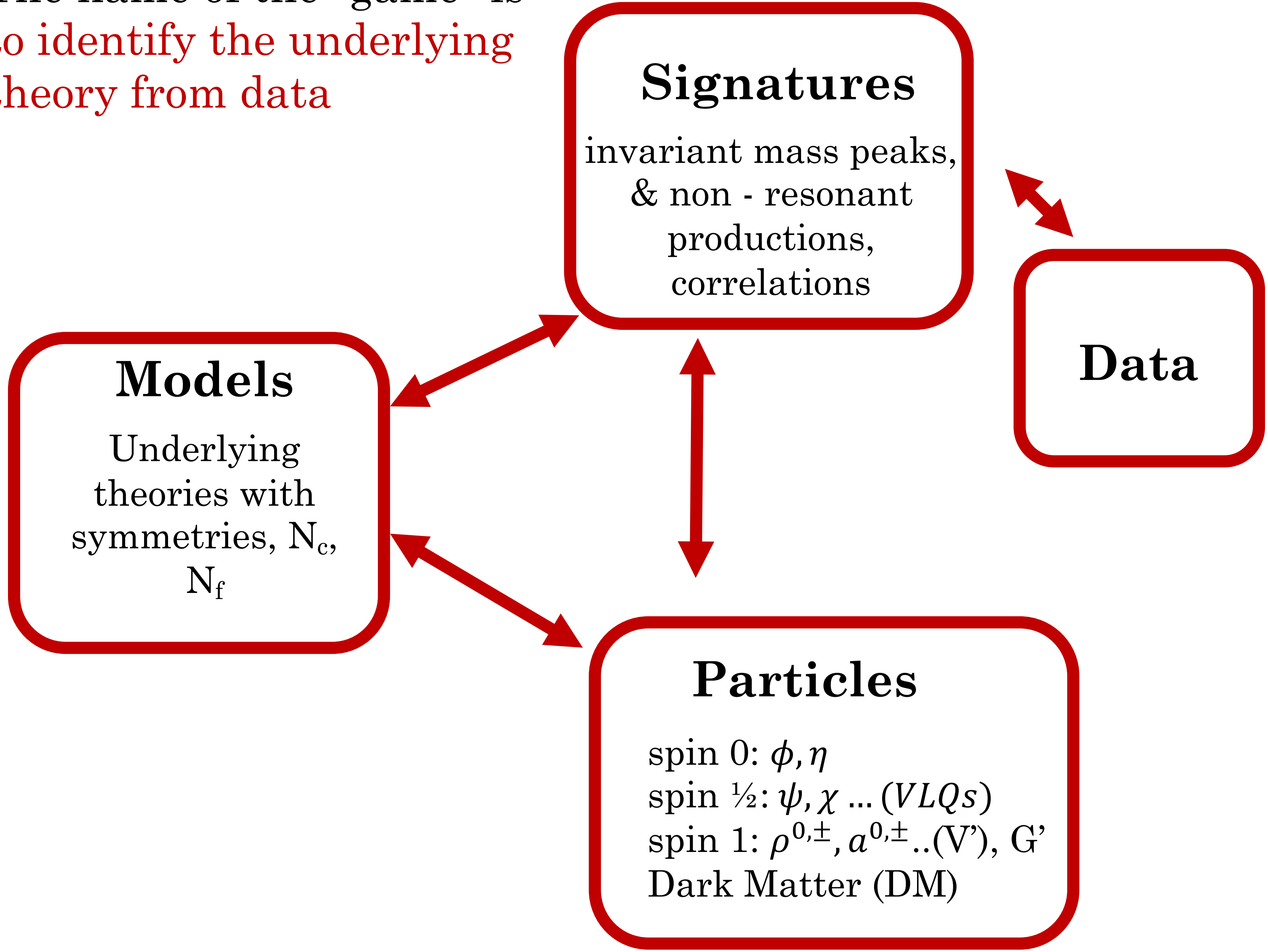
KOREA UNIVERSITY

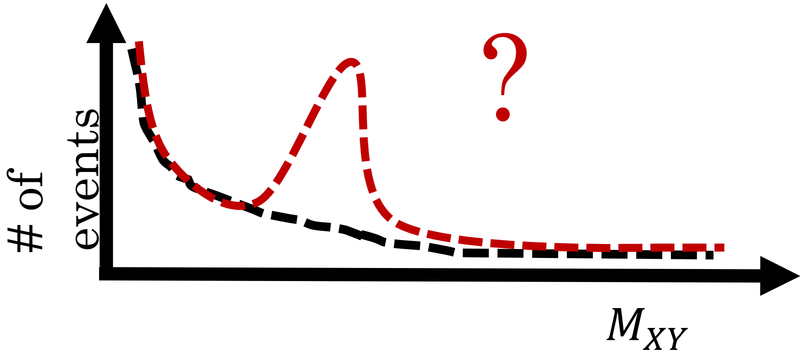
KIAS Workshop, 2016

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



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$\Longrightarrow$ $m_{\text{vectors}} \sim \mathcal{O}(few\ TeV)$ 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, $\rho_o \rightarrow X_{5/3}X_{5/3} \rightarrow SS2l$ @ LHC Run II (recast of QCD top partner pair production@CMS)[Barducci et al (2015)]

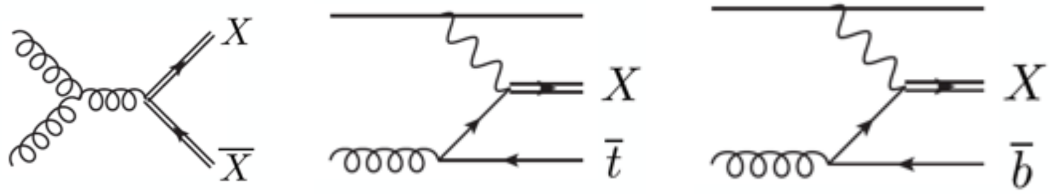
- **EW resonance**, $W' \rightarrow X_{5/3}\,X_{2/3}$ (@$SS2l$)and $T'b$ [Vignaroli (2014)]

Disclaimer: not a comprehensive list

Status of heavy resonances

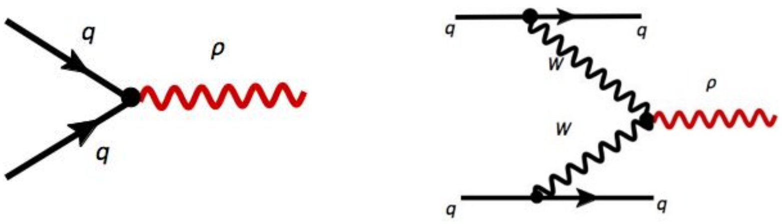
[comprehensive review see Panico, Wulzer '15 , Csaki, Grojean, Terning'15]

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



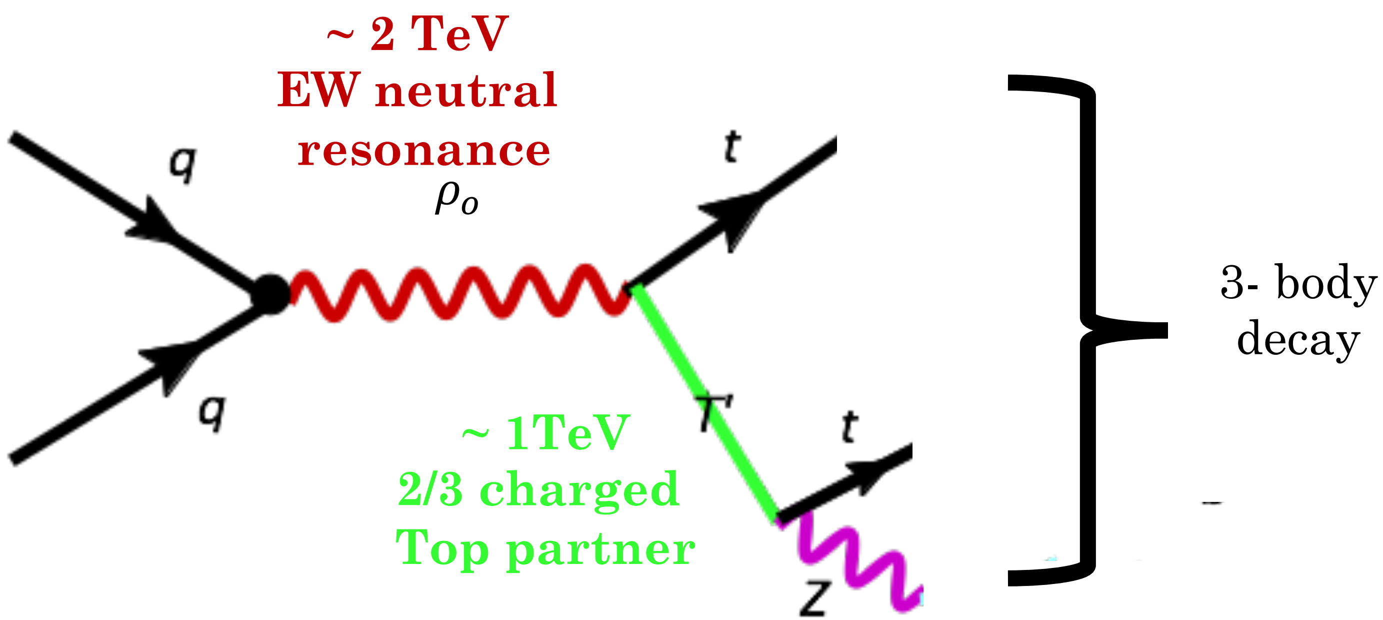
[Matsedonskyi et al. '12]

- 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

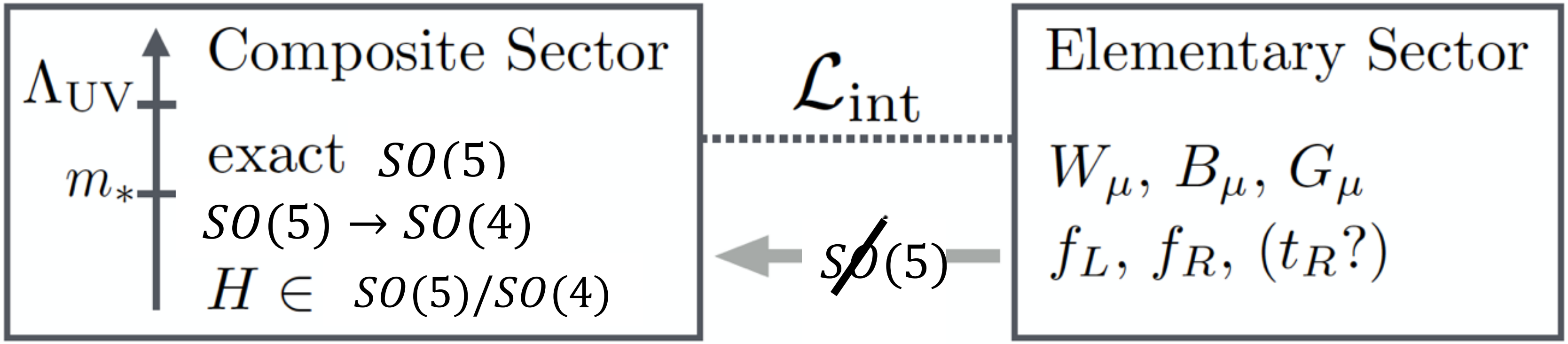
Search Strategy @ LHC run II



- T' decays into a top (bottom) quark and a h (W boson) also possible
- Complementary probes of new physics scenarios.

Sample model:
2-site Composite Higgs Model

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



- Simplified version of a 5D model with $SO(5) \rightarrow SO(4)$ 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, ρ_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**, $T_{f,1}$

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

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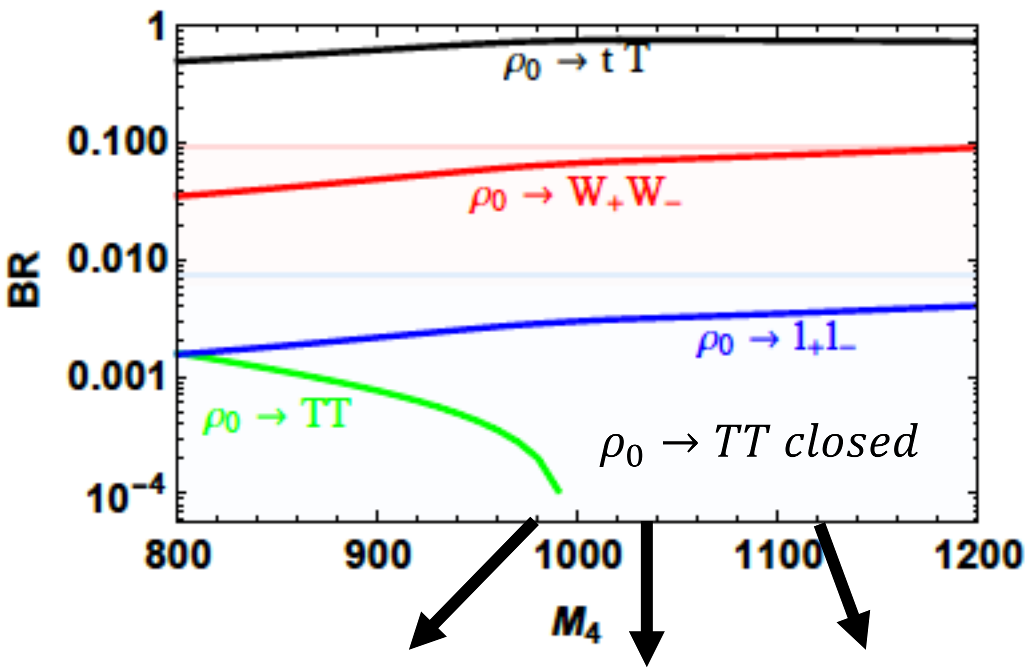


SP2

$\rho_0 \rightarrow TT$ *open*

SP1

$\rho_0 \rightarrow tT(max)$

SP3

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

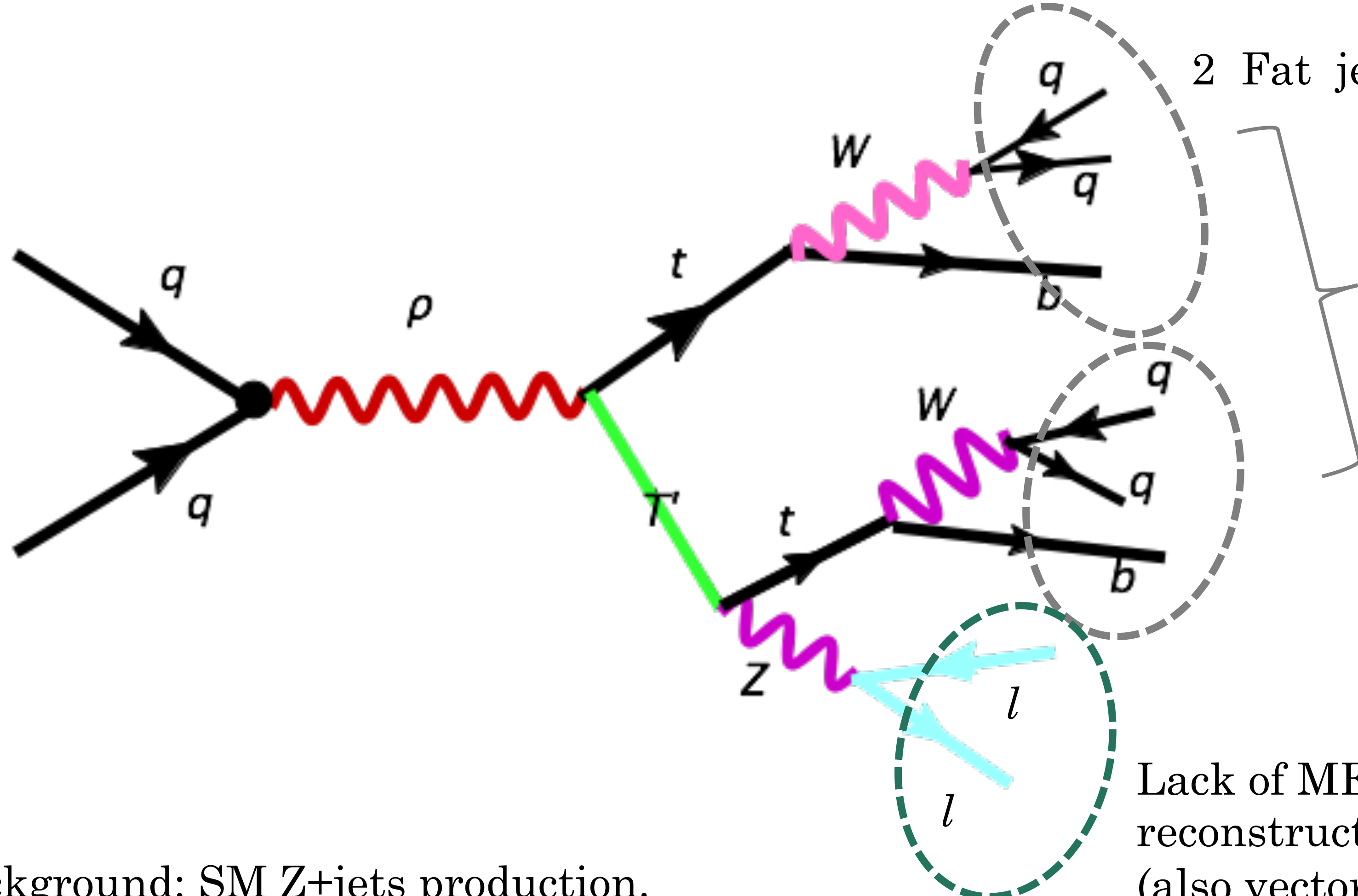
Diboson bound - 4.16 fb ,
SP(1,2,3) σ is 3.55, 3,26 and 3.59 fb

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

Final States with 2 Leptons and no MET



2 Fat jets in an event

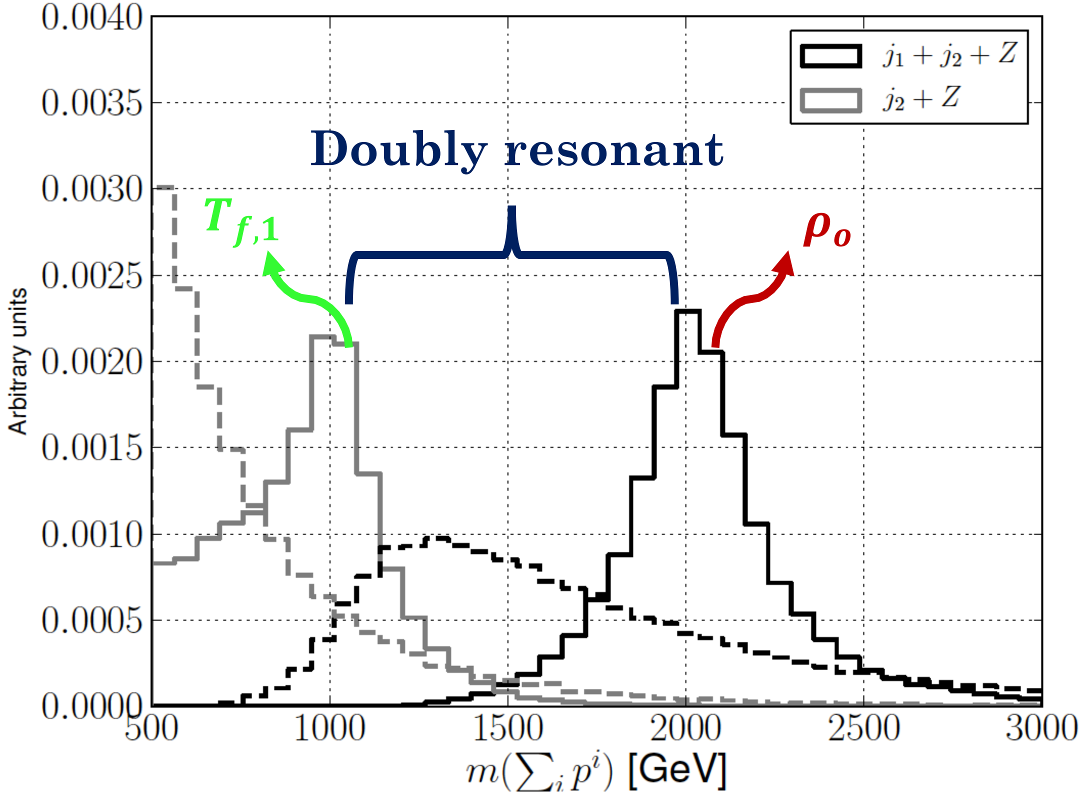
b-tagging

Lack of MET ⟹ full reconstruction of event (also vector resonance and top partner mass)

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

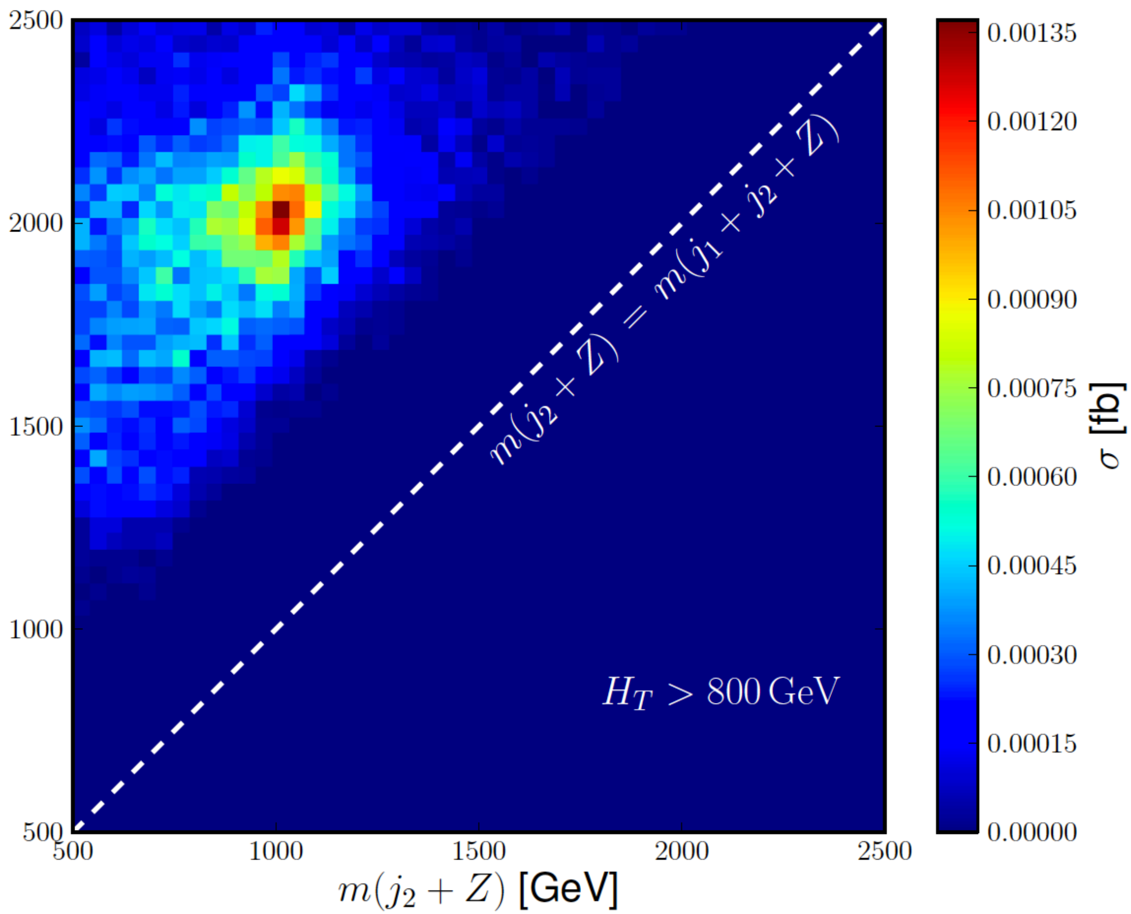
$S/\sqrt{B}$ (30 fb^{-1}) – 6.5
$S/\sqrt{B}$ (100 fb^{-1}) – 11.8

- 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

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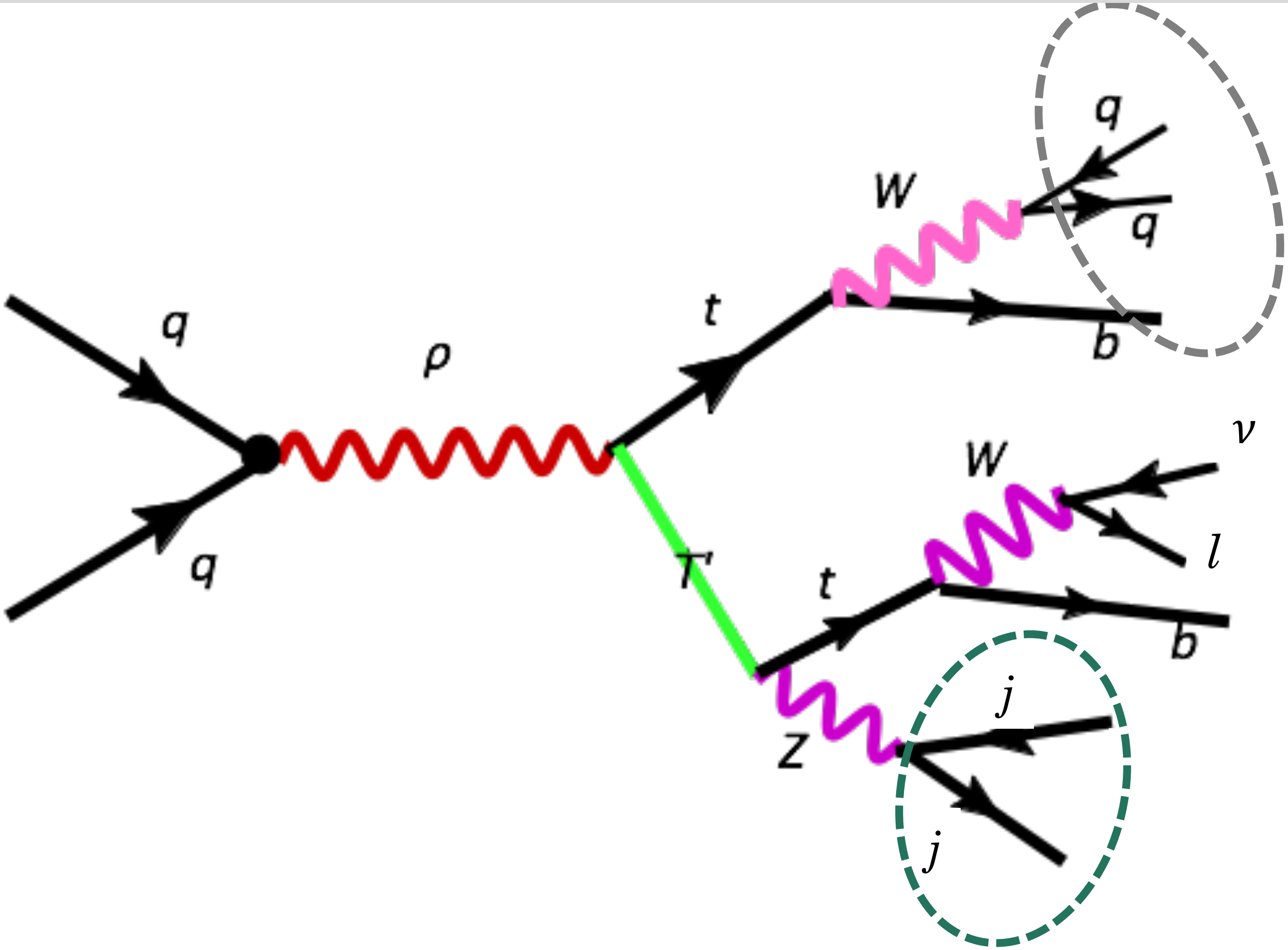
$m_{23} > 800\,\text{GeV}$	0.074	0.074	0.074	3.5×10^{-3}
$m_{123} > 1.8\,\text{TeV}$	0.066	0.066	0.066	2.9×10^{-3}
S/B	20	20	20	
$S/\sqrt{B}(30\,\text{fb}^{-1})$	6.5	6.5	6.5	
$S/\sqrt{B}(100\,\text{fb}^{-1})$	11.8	11.8	11.8	

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 $H_T > 800\,\text{GeV}$ 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 $Z \to ll$

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.

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**
- $Z \rightarrow l^+ l^-$ 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.

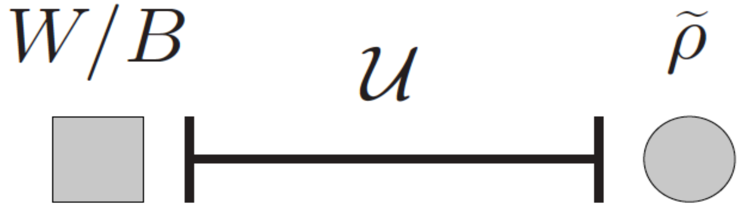
THANK YOU!

Backup

Features of Gauge sector

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

gauge subgroup $SU(2)_L \times U(1)_Y \subset \mathcal{G}$



gauging $SO(4) \subset \mathcal{G}_e$

$\mathcal{G}$ $[Eg.\, SO(5)_L]$

$\mathcal{G}_e$ $[Eg.\, SO(5)_R]$

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

$\mathcal{U}$: Goldstone matrix

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)]

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**

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

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

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

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

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

Partially Composite vectors : Mass and couplings

Masses

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

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

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

Post EWSB:
Physical vectors in mass basis

Couplings (examples)

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

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

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

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

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**

$$M_{Tf1} = M_4$$

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

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

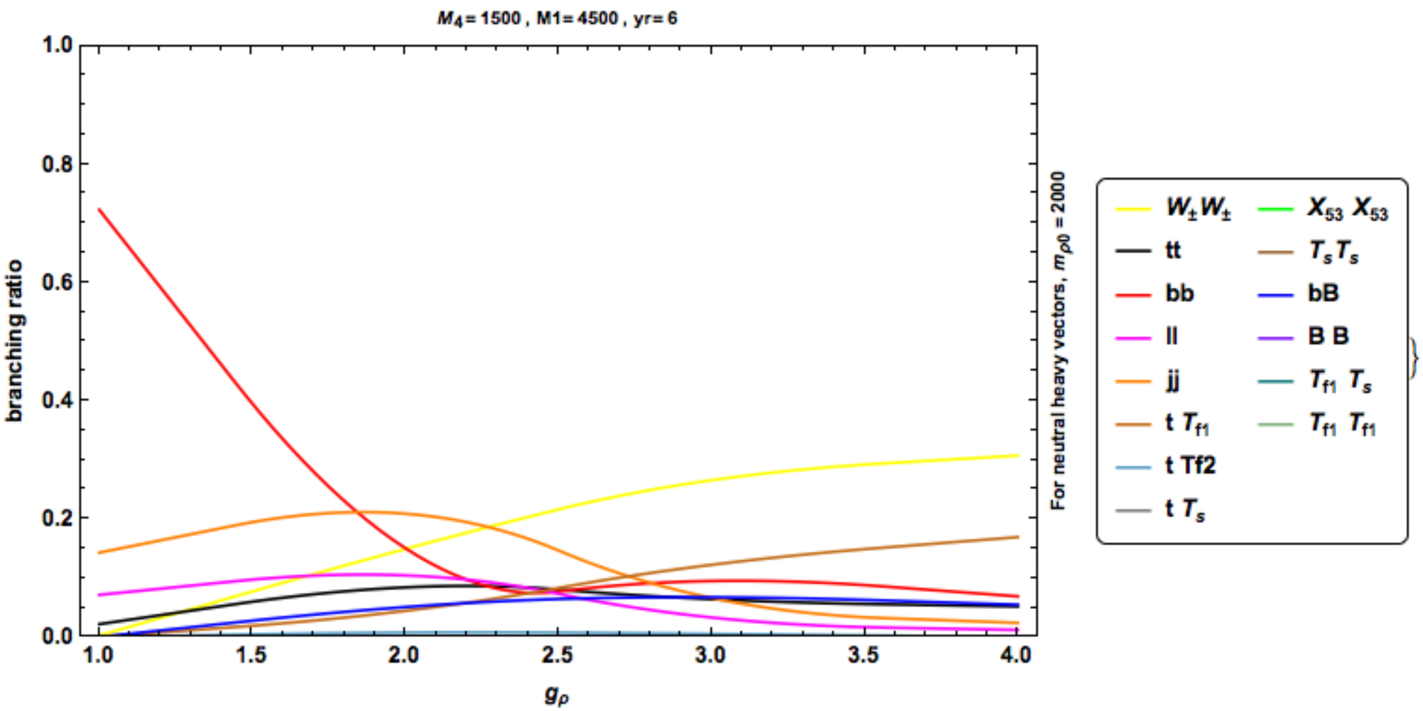
Singlet Partner

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

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

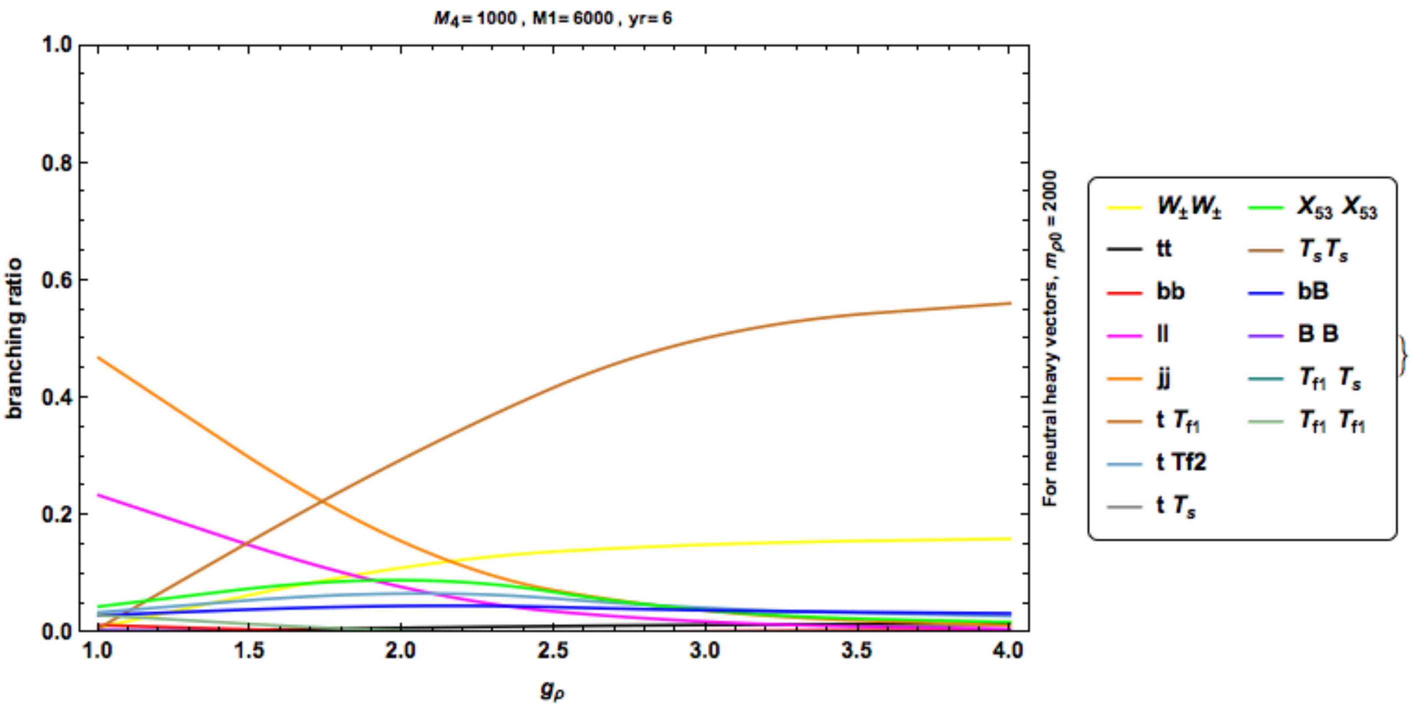
SM vs non SM decay

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



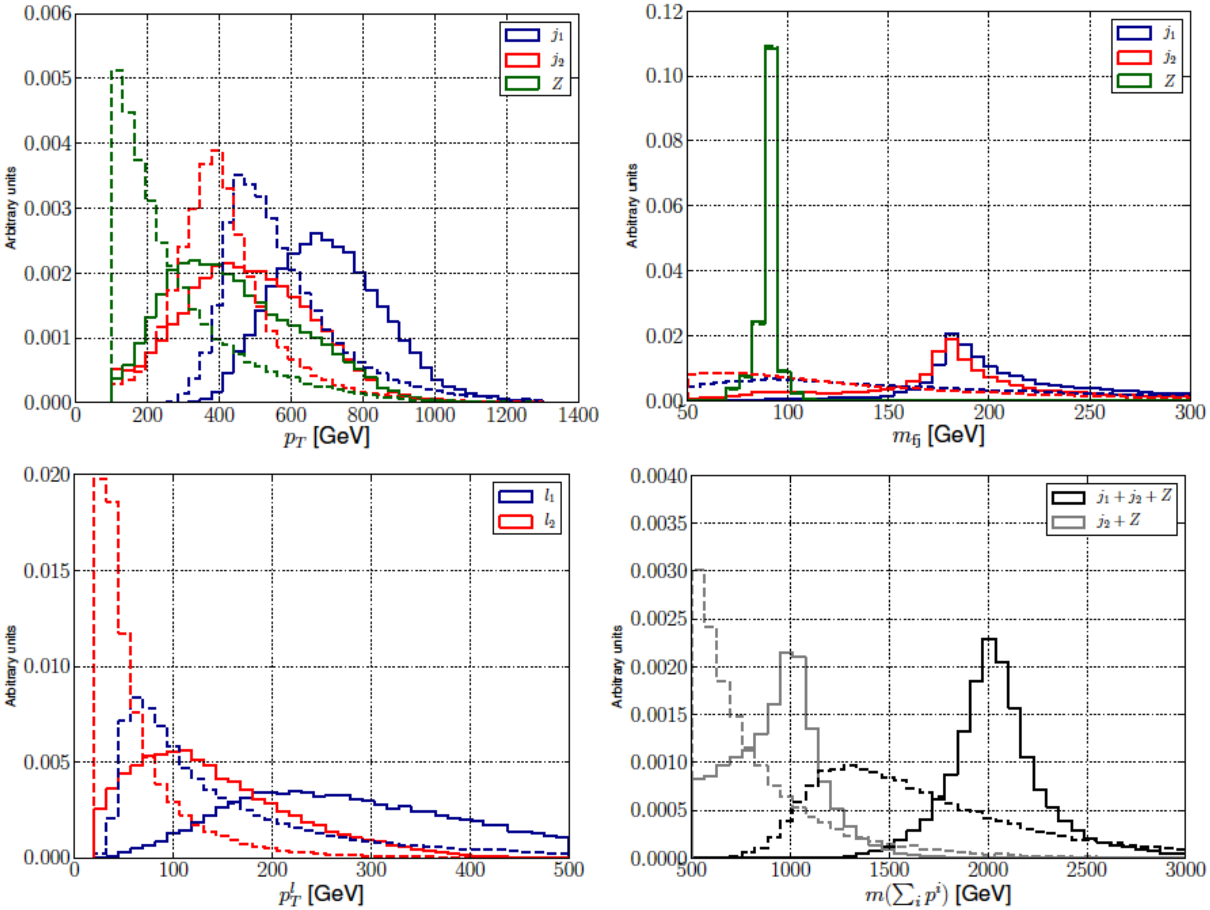
SM vs non SM decay

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



Final States with 2 Leptons and no MET

kinematic distributions of the signal and background events for SP3



70 GeV < m_{ll} < 110 GeV.

- Background: SM Z+jets
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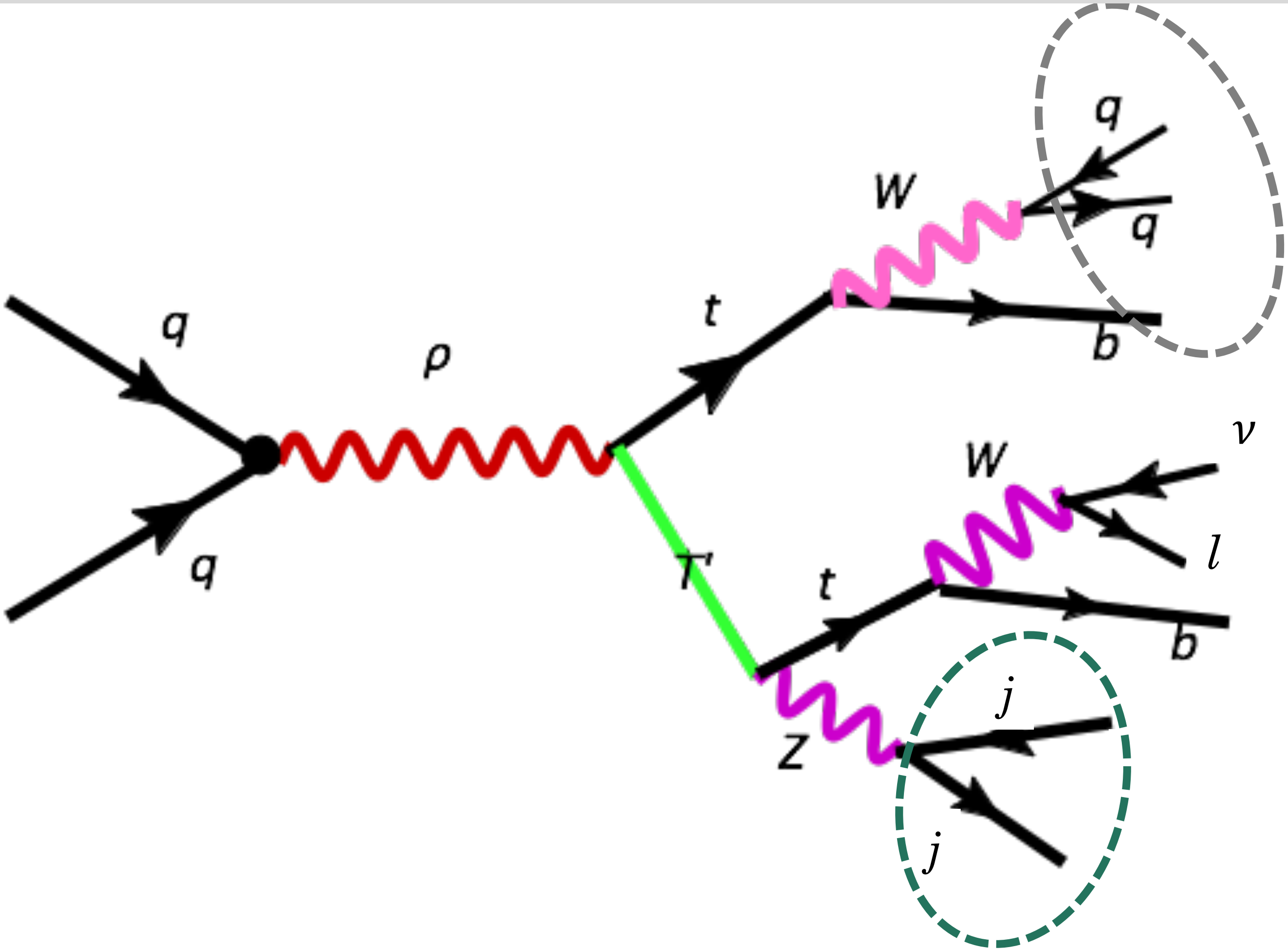

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Tagging efficiencies

- 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

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

- Z boson tagging

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

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.