

A warped extra dimensions search strategy for LHC@14TeV motivated by LEP & Tevatron 3rd generation anomalies

J.I. Sanchez Vietto^{1(*)} E. Alvarez¹ L. Da Rold²

¹IFIBA, Conicet, Argentina

²CAB, Conicet, Argentina

Workshop on Beyond the Standard Model
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Outline

1 Introduction

- Experimental results on 3rd generation anomalies

2 A warped/composite model

- Equivalence between WED and a composite model
- Model building: designing the embeddings of the fermions
- The model addresses the anomalies $Zb\bar{b}$ and A_{FB}

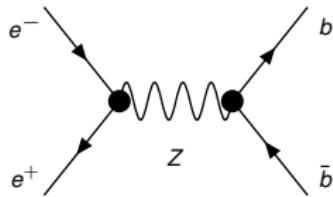
3 Phenomenology

- Spectrum
- Signal features
- Backgrounds
- Designed cuts and expected discovery/exclusion reach

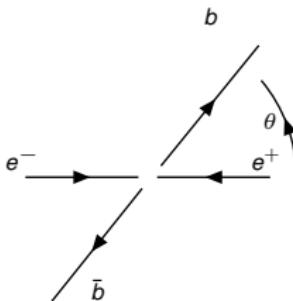
4 Conclusions

Experimental results for 3rd generation

LEP & SLC $Z b\bar{b}$ anomalies

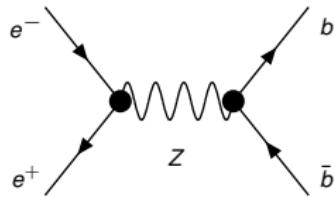


$$A_{FB}^b = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

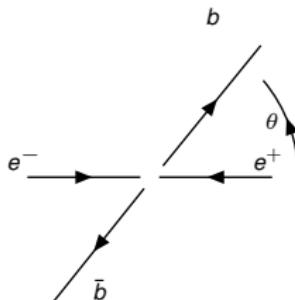


	$R_b = \frac{\Gamma(Z \rightarrow b\bar{b})}{\Gamma(Z \rightarrow \text{hadrons})}$	A_{FB}^b
Exp	0.21629 ± 0.00066	0.0992 ± 0.0016
SM	0.21586	0.1037 ± 0.0008

LEP & SLC Zbb anomalies



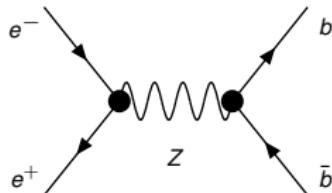
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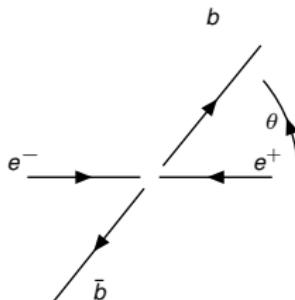
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⇒ good agreement in R_b

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⇒ good agreement in R_b

...but 2.9σ deviation in A_{FB}^b

LEP & SLC $Zb\bar{b}$ anomalies

A_{FB}^b anomaly \Rightarrow shift g_L^b and g_R^b

$$R_b \simeq \frac{g_L^{b^2} + g_R^{b^2}}{\sum_q (g_L^{q^2} + g_R^{q^2})}$$

$$A_{FB}^b|_{m_Z^2} \simeq \frac{3}{4} \frac{g_L^{\ell^2} - g_R^{\ell^2}}{g_L^{\ell^2} + g_R^{\ell^2}} \frac{g_L^{b^2} - g_R^{b^2}}{g_L^{b^2} + g_R^{b^2}}$$

LEP & SLC $Zb\bar{b}$ anomalies

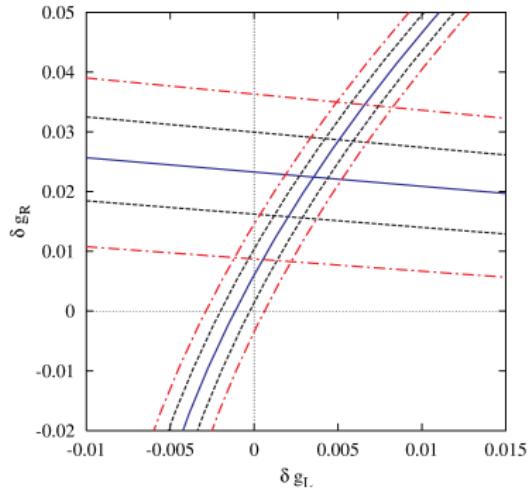
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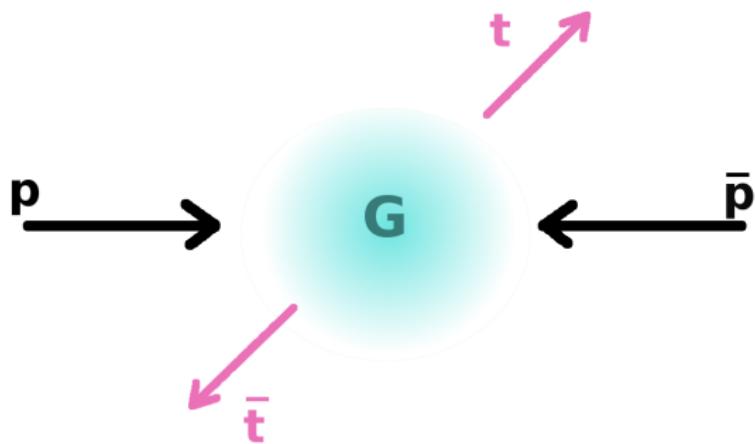
	Exp	SM $_{m_h \simeq 100 \text{ GeV}}$	pull	$\delta g/g$
g_L^b	-0.373	-0.376	0.003	1%
g_R^b	± 0.0966	0.0798	$\begin{cases} +0.02 \\ -0.17 \end{cases}$	$\begin{cases} +20\% \\ -220\% \end{cases}$

LEP & SLC $Zb\bar{b}$ anomalies

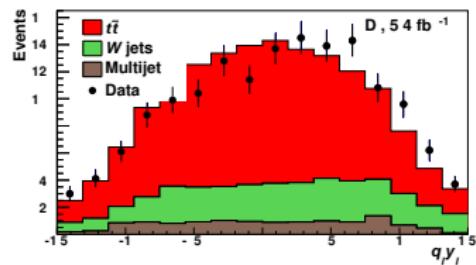
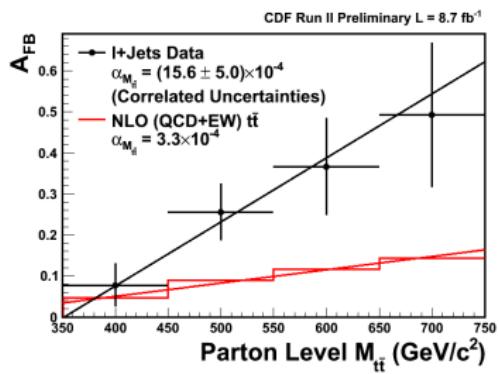


(Wagner et al 2001)

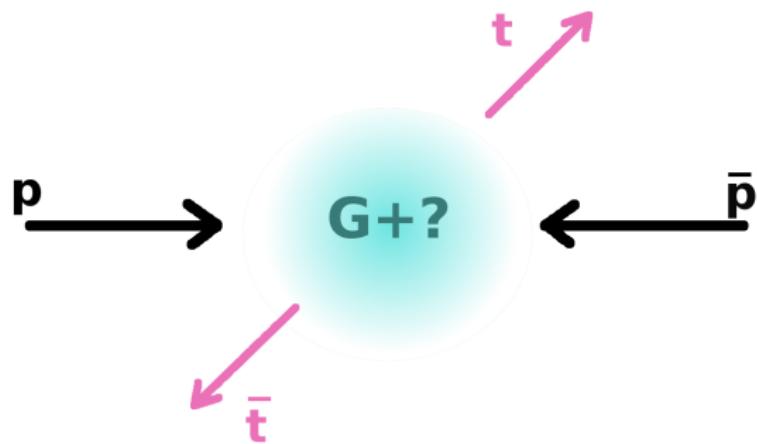
TEVATRON $t\bar{t}$ Forward-Backward asymmetry



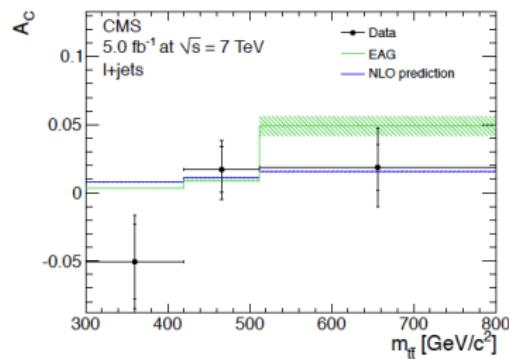
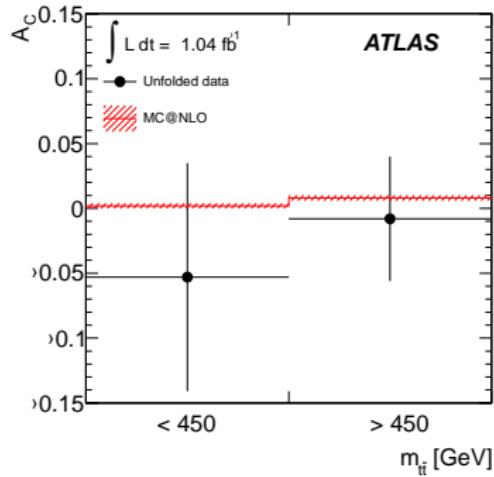
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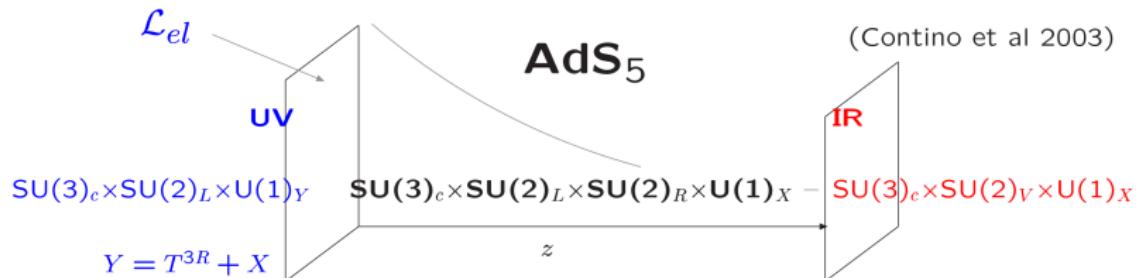


LHC $t\bar{t}$ Charge asymmetry



A Warped/Composite model with the embeddings designed to address the problem

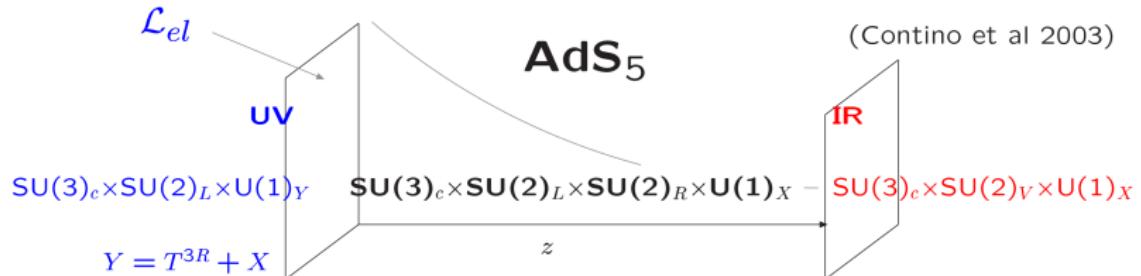
A 5D warped model



Set-up:

- bulk gauge symmetry
- broken explicitly at **UV** by boundary conditions
- broken spontaneously at **IR** by **H**

A 5D warped model



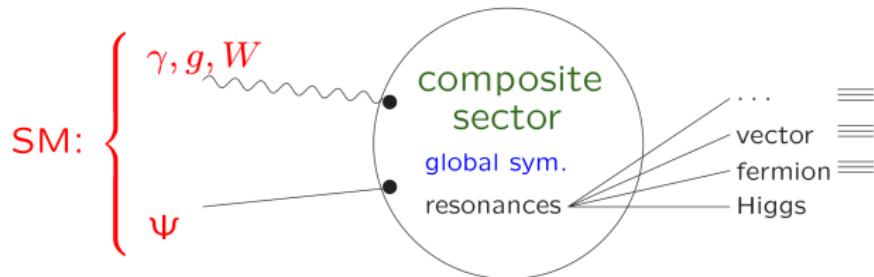
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Fermions:

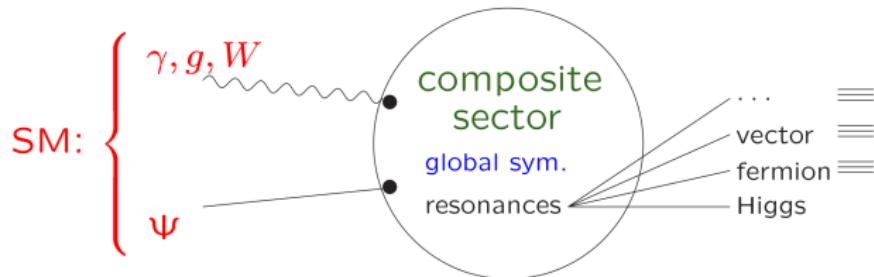
- for every SM fermion \Rightarrow a full 5D fermion
- choose representations for fermions: ex: $\psi_{5D}^{q1} = (3, 2, 2)_{2/3}$
- 4D fermion mixings depending on $M_\psi^{5D} \Rightarrow$ successful pheno. naturally!

The low energy equivalent 2-sector model



- bulk local symmetry \Rightarrow global composite symmetry
- UV local symmetry \Rightarrow elementary local symmetry
- IR symmetry \Rightarrow Higgs sector symmetry

The low energy equivalent 2-sector model



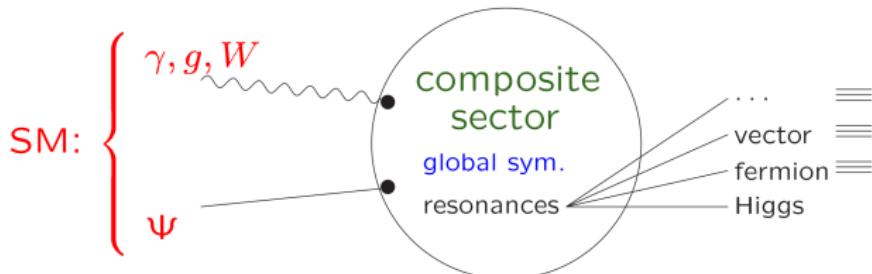
$$\mathcal{L} = \mathcal{L}_{el} + \mathcal{L}_{cp} + \mathcal{L}_{mix}$$

- Elementary Sector

$$\mathcal{L}_{el} = \mathcal{L}_{SM}(\psi_L^{el}, \tilde{\psi}_R^{el}, A_\mu^{el})$$

- G_{SM} local symmetry & massless fermions
- no elementary Higgs \Rightarrow no EW breaking

The low energy equivalent 2-sector model



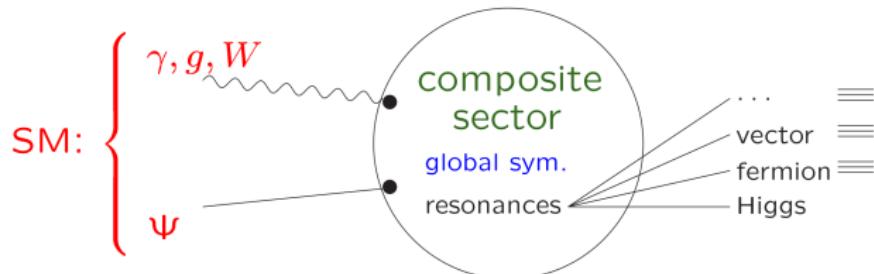
$$\mathcal{L} = \mathcal{L}_{el} + \mathcal{L}_{cp} + \mathcal{L}_{mix}$$

- Effective description of composite dynamics: ψ^{cp}, H, A_μ^{cp}

$$\mathcal{L}_{cp}^{eff} = -\frac{1}{4} F_{\mu\nu}^{cp}{}^2 + \frac{M^2}{2} A_\mu^{cp}{}^2 + |D_\mu^{cp} H|^2 - V(H) + \bar{\psi}^{cp} (\not{D}^{cp} - M) \psi^{cp} - y_{cp} \bar{\psi}^{cp} H \tilde{\psi}^{cp}$$

- SM-field \rightarrow cp-fields + G_{cp} global sym. + composite H
- cp-sector characterized by a cp scale M and coupling $y_{cp} \gg g_{SM}$

The low energy equivalent 2-sector model



$$\mathcal{L} = \mathcal{L}_{el} + \mathcal{L}_{cp} + \mathcal{L}_{mix}$$

- Linear mixings

$$\mathcal{L}_{mix}^{eff} \supset \bar{\psi}_L^{el} \Delta \mathcal{P}_\psi \psi_R^{cp} + \bar{\tilde{\psi}}_R^{el} \tilde{\Delta} \mathcal{P}_{\tilde{\psi}} \tilde{\psi}_L^{cp} + \text{gauge-mix}$$

The mixings preserve a local G_{SM} and provide massless ψ_{SM}

all the small numbers arise from small mixings (e.g.: light fermions)

2-site model: Choosing the global symmetry

- Preserve SM gauge sym.: $G_{cp} \supset G_{SM}$
- Custodial symmetry of the SM:

$V(H)$ has a $SU(2)_L \times SU(2)_R$ global symmetry

$$\Sigma = (\tilde{H}, H) = (2, 2) \rightarrow U_L \Sigma U_R^\dagger$$

$\Rightarrow G_{cp} \supset SU(2)_L \times SU(2)_R$ to protect the T parameter

$$G_{cp} = [SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X]^{cp}, \text{ with } Y = T^{3R} + X$$

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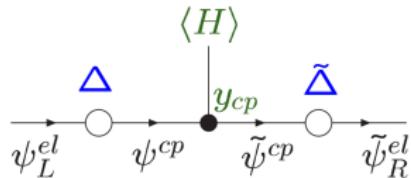
- Symmetry breaking

$$\downarrow \langle \Sigma \rangle$$

$$[SU(3)_c \times SU(2)_V \times U(1)_X]^{cp}$$

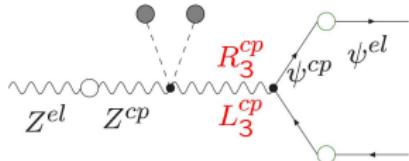
- Choose ψ^{cp} embedding \Rightarrow correct phenomenology

2-site model: Fermion spectrum



$$m_\psi = y_{cp} \langle H \rangle \frac{\Delta}{M_\psi} \frac{\tilde{\Delta}}{\tilde{M}_\psi}$$

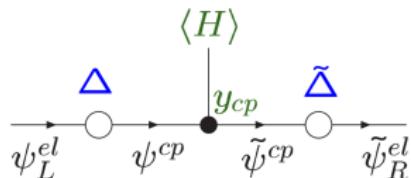
SM Mass controlled by two mixings



$$\delta g^\psi \sim \frac{\Delta_\psi^2}{M^2}$$

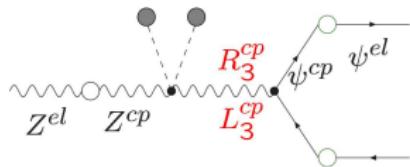
$Z b\bar{b}$ controlled by one mixing

2-site model: Fermion spectrum



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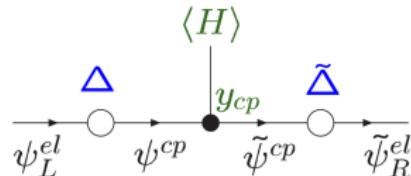
$$\delta g^\psi \sim \frac{\Delta_\psi^2}{M^2}$$

$Z b \bar{b}$ controlled by one mixing

- Heavy top & $Z b \bar{b}$ vs. light bottom

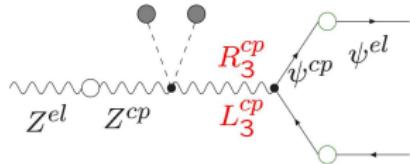
$$q_L^{el} = \begin{bmatrix} t_L^{el} \\ b_L^{el} \end{bmatrix} \Rightarrow \begin{cases} \Delta_q \text{ large} & \xleftarrow{\quad} m_t \text{ heavy top} \\ \tilde{\Delta}_b \text{ large} & \xleftarrow{\quad} \delta g_R^b \text{ large} \end{cases}$$

2-site model: Fermion spectrum



$$m_\psi = y_{cp} \langle H \rangle \frac{\Delta}{M_\psi} \frac{\tilde{\Delta}}{\tilde{M}_\psi}$$

SM Mass controlled by two mixings



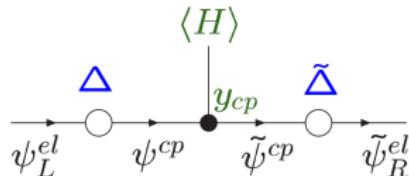
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$Z b\bar{b}$ controlled by one mixing

- Heavy top & $Z b\bar{b}$ vs. light bottom

$$q_L^{el} = \begin{bmatrix} t_L^{el} \\ b_L^{el} \end{bmatrix} \Rightarrow \left\{ \begin{array}{l} \Delta_q \text{ large} \\ \tilde{\Delta}_b \text{ large} \end{array} \right. \xleftarrow{\quad} \begin{array}{l} m_t \text{ heavy top} \\ \delta g_R^b \text{ large} \end{array} \xrightarrow{\quad} \boxed{m_b \text{ too large} \times}$$

2-site model: Fermion spectrum



$$m_\psi = y_{cp} \langle H \rangle \frac{\Delta}{M_\psi} \frac{\tilde{\Delta}}{\tilde{M}_\psi}$$

SM Mass controlled by two mixings

- Associate 2 resonances with q_L^{el} : $\mathcal{L}_{mix}^{eff} \supset \bar{q}_L^{el} (\Delta_1 \mathcal{P}_q q_R^{1cp} + \Delta_2 \mathcal{P}_q q_R^{2cp})$
- decouple Yukawas: $\mathcal{L}_{cp}^{eff} \supset y_{cp}^t \bar{q}^{1cp} H t^{cp} + y_{cp}^b \bar{q}^{2cp} H b^{cp}$

$$\left\{ \begin{array}{l} m_t = y_{cp}^t \langle H \rangle \frac{\Delta_1}{M_1} \frac{\tilde{\Delta}_t}{\tilde{M}_t} \\ m_b = y_{cp}^b \langle H \rangle \frac{\Delta_2}{M_2} \frac{\tilde{\Delta}_b}{\tilde{M}_b} \end{array} \right. \Rightarrow \text{different Left-mixings } \checkmark$$

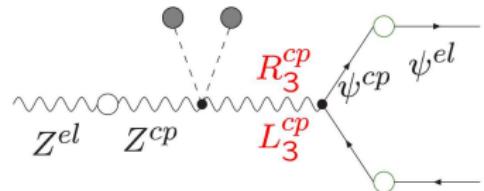
\Rightarrow choose a small Δ_2 to obtain a light bottom

Summary: $t_{L,R}$ and b_R almost composite, whereas b_L partially composite

2-site model: $Z b\bar{b}$ corrections

- Gauge contribution to δg

$$\delta g^\psi \sim \frac{\Delta_\psi^2}{M^2} [\mathcal{T}^{3R}(\psi^{cp}) - \mathcal{T}^{3L}(\psi^{cp})]$$



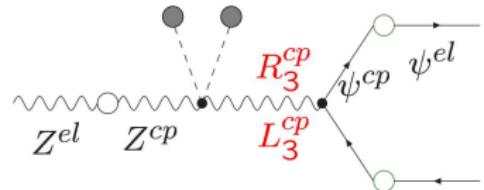
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- P_{LR} ($L \leftrightarrow R$) symmetry to protect $Z\psi\bar{\psi}$ couplings

for $\mathcal{P}_\psi \psi^{cp}$ mixing with ψ , if: $\mathcal{T}^{3R} = \mathcal{T}^{3L} \Rightarrow$ Symmetry protection



$Zb\bar{b}$ corrections: top & bottom embedding

- Large m_t and small m_b
- Large and positive δg_R^b and small positive δg_L^b
- Demand \mathcal{L}_Y be singlet of G_{CP} and $Y = T^{3R} + X$

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$$q^{1cp} = (\mathbf{2}, \mathbf{2})_{2/3}, \quad t^{cp} = (\mathbf{1}, \mathbf{1})_{2/3} \quad \text{(top embedding)}$$

$$q^{2cp} = (\mathbf{2}, \mathbf{3})_{-5/6}, \quad b^{cp} = (\mathbf{1}, \mathbf{2})_{-5/6} \quad \text{(bottom embedding)}$$

(ArXiv: 1009.2392 and 1011.6557)

Summarizing

- warped/composite model
- auxiliary resonance required to address large δg_R^b and small m_b
- embedding addresses: m_t , m_b and $A_{FB}(b\bar{b})$

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From here:

- scan parameter space for good points
- compute spectrum
- search for not excluded parameter space

Phenomenology and search strategy

Top and bottom embedding - Minimal particle content

- Top & bottom embeddings

q , t , b , (*SM*)

$$q^{1cp} = (\mathbf{2}, \mathbf{2})_{2/3} = \begin{bmatrix} X_1^{cp'} & U_1^{cp} \\ U_1^{cp'} & D_1^{cp} \end{bmatrix} , \quad t^{cp} = (\mathbf{1}, \mathbf{1})_{2/3} = U_t^{cp}$$

$$q^{2cp} = (\mathbf{2}, \mathbf{3})_{-5/6} = \begin{bmatrix} U_2^{cp} & D_2^{cp'} & V_2^{cp''} \\ D_2^{cp} & V_2^{cp'} & S_2^{cp'} \end{bmatrix} , \quad b^{cp} = (\mathbf{1}, \mathbf{2})_{-5/6} = \begin{bmatrix} D_b^{cp} & V_b^{cp'} \end{bmatrix} .$$

Top and bottom embedding - Minimal particle content

- Top & bottom embeddings

$$q, \quad t, \quad b, \quad (\text{SM})$$

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- Mass eigenstates

- SM-like:

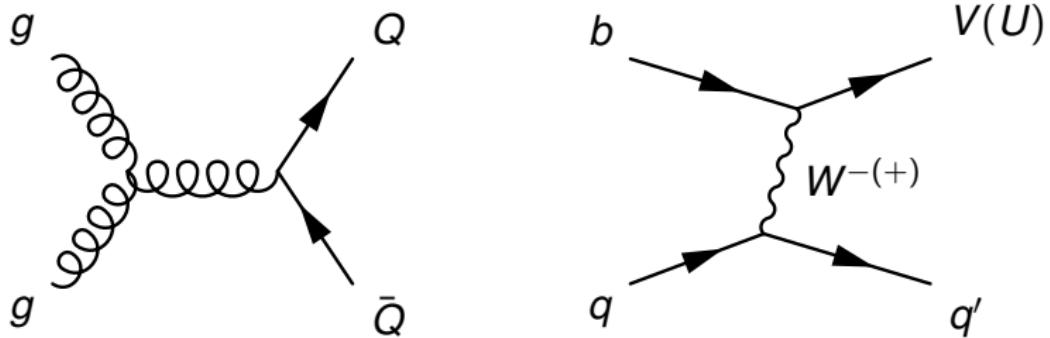
$$\begin{aligned} U_1, U_2, U_3, U_4, U_5 \quad (Q = 2/3), \\ D_1, D_2, D_3, D_4, D_5 \quad (Q = -1/3) \end{aligned}$$

- Exotic charges:

$$\begin{aligned} X \quad (Q = 5/3), \\ S \quad (Q = -7/3), \\ V_1, V_2, V_3 \quad (Q = -4/3) \end{aligned}$$

Production at the LHC

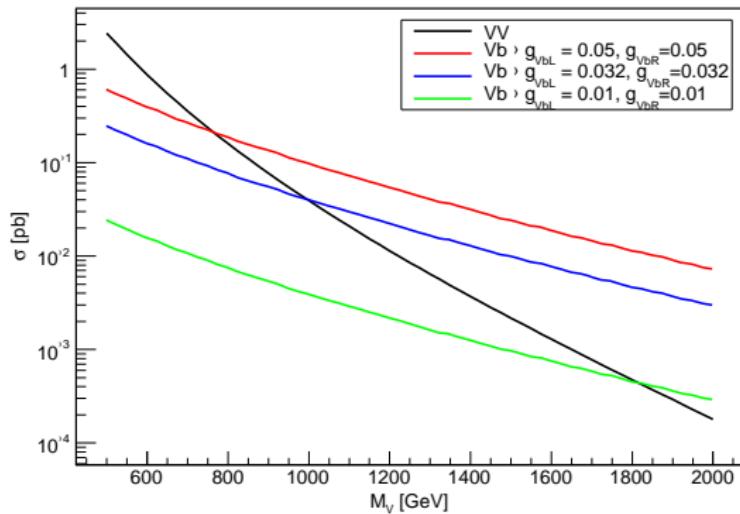
- QCD pair production (model independent): $gg \rightarrow Q\bar{Q}(V\bar{V})$
- EW single production $qb \rightarrow q'V$



arXiv: 1209.0471 $M_U > 570$ GeV @ 95 % CL

arXiv: 1204.1088 $M_D > 611$ GeV @ 95 % CL

Pair and single V production at the LHC 14 TeV

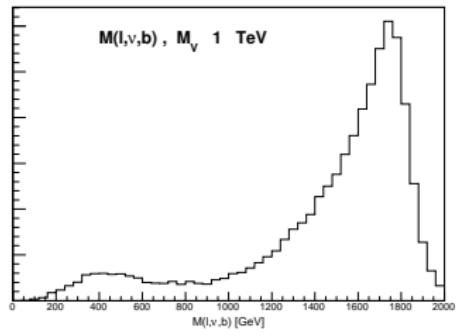
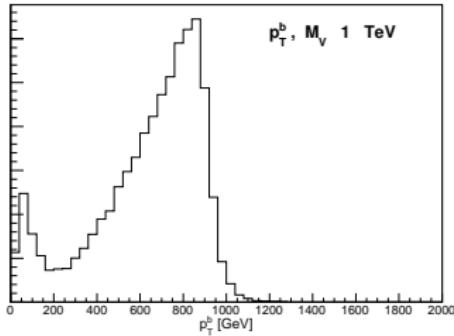
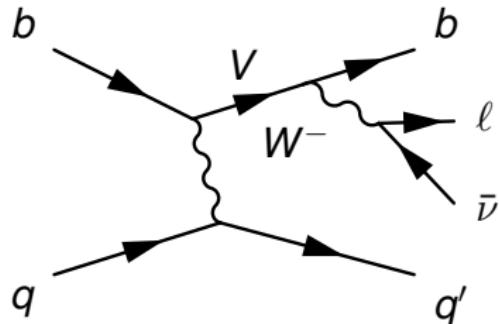


A Benchmark point

- $M_V = 1.8 \text{ TeV}$ and $g_{Wb} = 0.065$
- Besides solving hierarchy problem and providing light Higgs, this specific model provides this benchmark point and:
 - Correct third generation fermion masses.
 - Solves LEP/SLC $Zb\bar{b}$ anomaly
 - Addresses Tevatron+LHC top puzzle (arXiv:1011.6557 requires update)
 - At the price of adding an extra q^2 resonance.

Signal features

Signal: 1 lepton, 1 b-tag + mE_T



Main backgrounds

Main backgrounds for the channel 1-lepton, 1 b-tag and mE_t

- $W + nj$ with $W \rightarrow \ell\nu$ and exactly one jet mistagged as a b-jet

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Other backgrounds

- $t \rightarrow W^+ b$, with $W \rightarrow \ell\nu$

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Other backgrounds

- $t \rightarrow W^+ b$, with $W \rightarrow \ell\nu$
- $Wb + nj$, $Wc + nj$, with $W \rightarrow \ell\nu$ and one b-tag

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- $t \rightarrow W^+ b$, with $W \rightarrow \ell\nu$
- $Wb + nj$, $Wc + nj$, with $W \rightarrow \ell\nu$ and one b-tag
- $Wb\bar{b} + nj$, $Wc\bar{c} + nj$, with $W \rightarrow \ell\nu$, one b-tag and one missed heavy quark

Main backgrounds

Main backgrounds for the channel 1-lepton, 1 b-tag and mE_t

- $W + nj$ with $W \rightarrow \ell\nu$ and exactly one jet mistagged as a b-jet
- $t\bar{t}$, with exactly one top decaying leptonically

Other backgrounds

- $t \rightarrow W^+ b$, with $W \rightarrow \ell\nu$
- $Wb + nj$, $Wc + nj$, with $W \rightarrow \ell\nu$ and one b-tag
- $Wb\bar{b} + nj$, $Wc\bar{c} + nj$, with $W \rightarrow \ell\nu$, one b-tag and one missed heavy quark
- $Z + nj$ with $Z \rightarrow \ell\bar{\ell}$, exactly one jet mistagged as a b-jet and one missed lepton
- $Zb, Zb\bar{b}, Zc, Zc\bar{c}, \dots$
- ...
- QCD multijet with one jet mistagged as a b-jet and one jet mistagged as a lepton

Simulations

- We generated signal and backgrounds with MadGraph/MadEvent 5 + PYTHIA + PGS
- In cases when it was necessary, the MLM matching procedure was used.

process	cross section
$Vq, (V \rightarrow \ell\nu b)$	0.0026 pb
$W, Wj, Wjj (W \rightarrow \ell\nu)$	36000 pb
$t\bar{t} (t \rightarrow \ell\nu b)$	136 pb

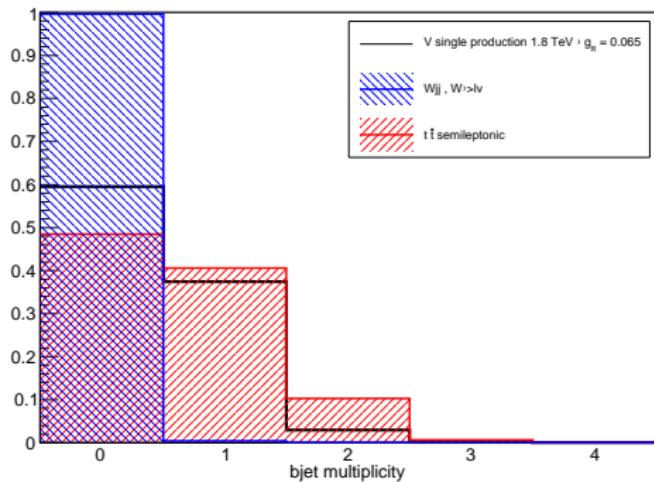
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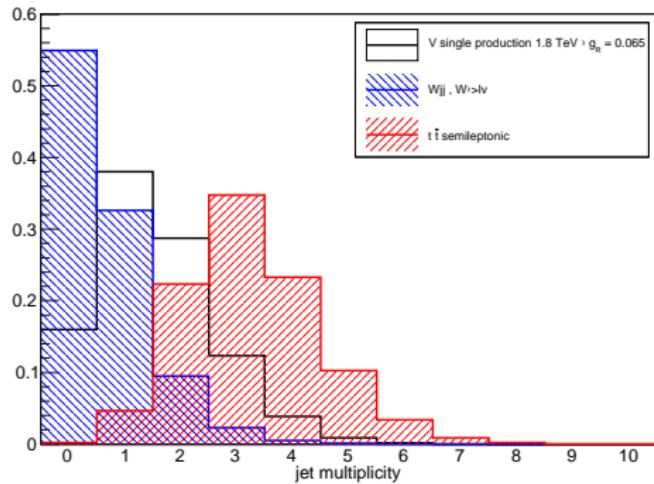
⇒ tiny signal

b-tagged jet multiplicity



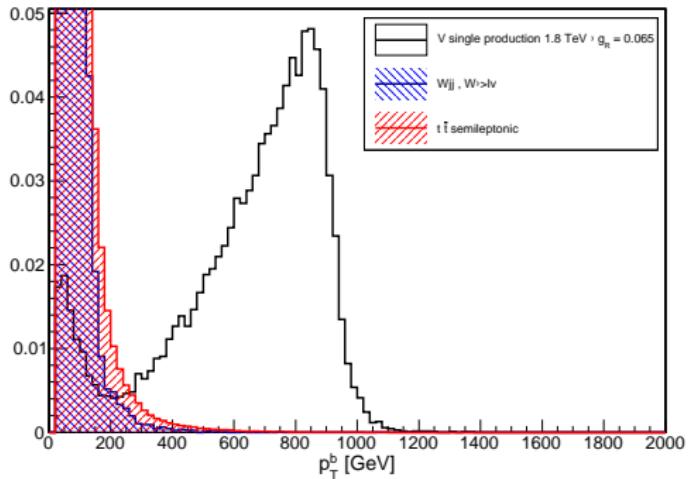
- Today single production searches use the two b-tagged jets channel (for instance: 1209.1062).
- In order to increase the reach of the search we require one b-tagged jet.

Jet multiplicity



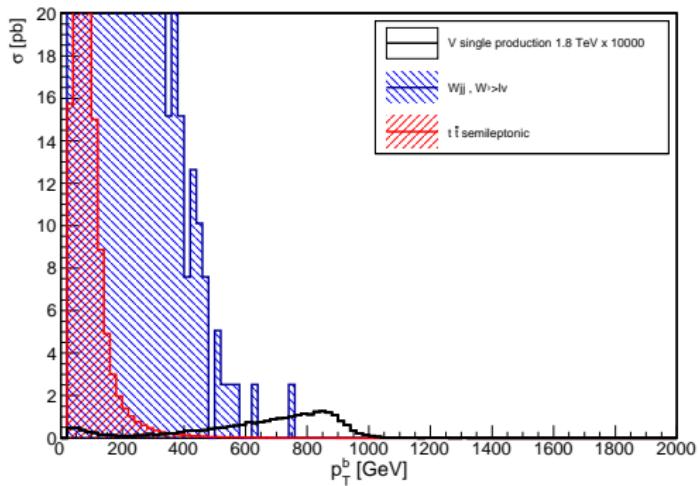
- We suppress Wj background asking for $N_{jet} \geq 1$ and $t\bar{t}$ requiring $N_{jet} \leq 2$.

b-jet transversal momentum ($p_T(b)$)



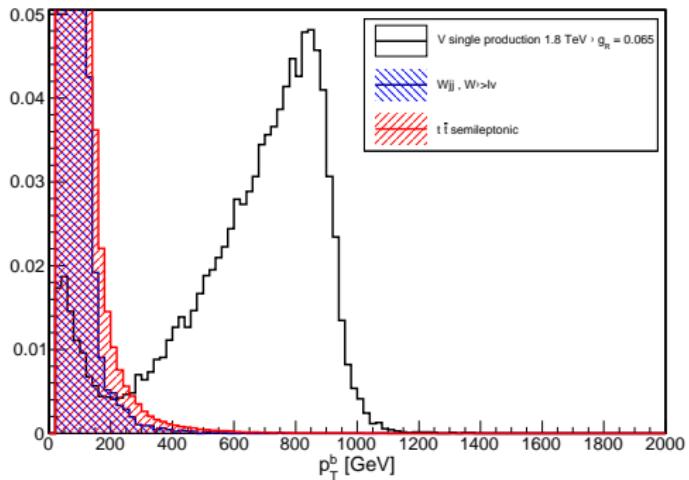
- $p_T(b)$ is peaked at low values for the background whereas for the signal is at $\sim M_V / 2$.
- We ask for $p_T^b > 500$ GeV.

b-jet transversal momentum ($p_T(b)$)



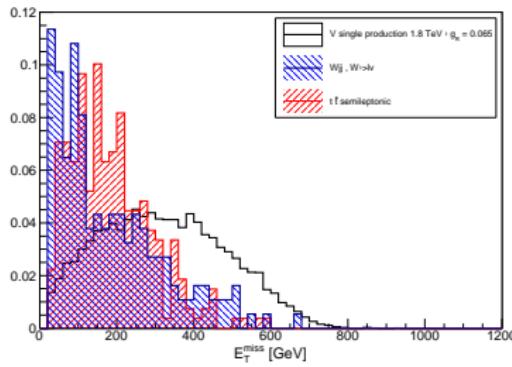
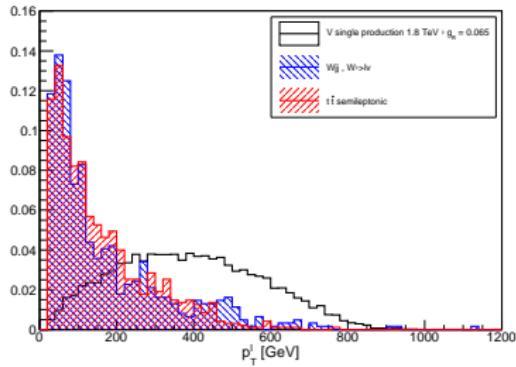
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b-jet transversal momentum ($p_T(b)$)



- $p_T(b)$ is peaked at low values for the background whereas for the signal is at $\sim M_V / 2$.
- We ask for $p_T^b > 500$ GeV.

Lepton p_T and E_T^{miss}



- Again backgrounds are peaked at small p_T and the signal is spread around $\sim M_V/4$
- We ask for p_T^ℓ and $E_T^{miss} > 250$ GeV.

Search strategy

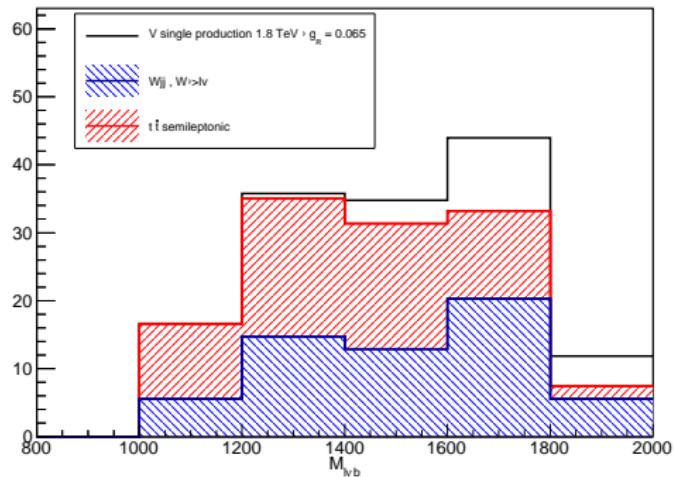
Summarizing, we require:

- $N_j \geq 1$ to suppress W background.
- $N_j \leq 2$ to suppress $t\bar{t}$ background.
- Exactly one b-tagged jet.
- high p_T for the b-tagged jet: $p_T^b > 500$ GeV.
- high p_T for the lepton and the E_T^{miss} : p_T^ℓ and $E_T^{miss} > 250$ GeV.

CUT FLOW

N_{bjet}	N_{jet}	$p_T^{min}(b)$ (GeV)	$p_T^{min}(\ell)$ (GeV)	E_T^{min} (GeV)	$\sigma * A(t\bar{t})$ (pb)	$\sigma * A(Wjj)$ (pb)	$\sigma * A(S)$ (pb)	significance 100 fb^{-1}	significance 300 fb^{-1}
-	-	-	-	-	53.9×10^3	14106×10^3	2.27	0.006	0.010
1	-	-	-	-	21.9×10^3	56.2×10^3	0.85	0.030	0.05
1	1 or 2	-	-	-	5.9×10^3	23.7×10^3	0.57	0.033	0.06
1	1 or 2	500	-	-	17.6	11.4	0.44	0.81	1.40
1	1 or 2	500	250	250	0.70	0.68	0.19	1.66	2.87

Invariant mass spectrum after cuts



Conclusions

Conclusions

- Besides solving the hierarchy problem and provide a light Higgs, WED/Composite models can also accommodate bottom and top A_{FB} asymmetries.
- The correct fermion embedding for third generation puzzles predicts a light exotic quark V that can be reached at the LHC Run II.
- Failure of searches at 1 TeV changes the topology of the search strategy: Single production instead of pair production.
- Searches in the channel with one lepton, 1 b-tag and mE_T can probe single production of the $Q = -4/3$ exotic quark.
- We designed a search strategy and presented expected discovery/exclusion reach.

Work in progress

- Search strategy for the intermediate region: Single and pair production.
- Cuts scanning to maximize reach.
- Include b-jet charge measurement to suppress $t\bar{t}$ background and differentiate V from up-like resonances.

Back-up slides

$Zb\bar{b}$ corrections: top embedding

Choose the quantum numbers of the top partners

- heavy top (large mixings) \Rightarrow induce large $\delta g_L^b \gtrsim \mathcal{O}(10)[\delta g_L^b]_{exp}$
- invoke P_{LR} : q_L^{el} mixes with $q^{1cp} \supset b_1^{cp}$,

$$\begin{array}{c} \text{SU(2)}_L \times \text{SU(2)}_R \times \text{U(1)}_X \\ \searrow \downarrow \quad \swarrow \\ T^{3L}(b_1^{cp}) = -1/2 = T^{3R}(b_1^{cp}) \Rightarrow q^{1cp} = (\mathbf{2}, \mathbf{2})_{2/3} \end{array}$$

- demand \mathcal{L}_Y to be a singlet of G_{cp} \Rightarrow $t^{cp} = \begin{cases} (\mathbf{1}, \mathbf{1})_{2/3} \\ (\mathbf{1}, \mathbf{3})_{2/3} + (\mathbf{3}, \mathbf{1})_{2/3} \end{cases}$

$Zb\bar{b}$ corrections: bottom embedding

- exp. prefer $\delta g_L^b > 0$: (remember $\delta g^\psi \sim T^{3L}(\psi^{cp}) - T^{3R}(\psi^{cp})$)

since $T^{3L}(b_2^{cp}) = T^{3L}(b_L^{el}) = -1/2 \Rightarrow T^{3R}(b_2^{cp}) > -1/2$

- exp. prefer $\delta g_R^b > 0$:

since $T^{3L}(\tilde{b}^{cp}) = 0 \Rightarrow T^{3R}(\tilde{b}^{cp}) > 0$

- demand \mathcal{L}_Y to be a singlet of G_{cp} and $Y = T^{3R} + X$

$$\left\{ \begin{array}{l} q^{2cp} = (\mathbf{2}, \mathbf{3})_{-5/6}, \quad b^{cp} = (\mathbf{1}, \mathbf{2})_{-5/6} \Rightarrow T^{3L}(b_2^{cp}) = 1, \quad T^{3R}(\tilde{b}^{cp}) = \frac{1}{2} \\ q^{2cp} = (\mathbf{2}, \mathbf{4})_{-4/3}, \quad b^{cp} = (\mathbf{1}, \mathbf{3})_{-4/3} \Rightarrow T^{3L}(b_2^{cp}) = \frac{3}{2}, \quad T^{3R}(\tilde{b}^{cp}) = 1 \end{array} \right.$$

and larger representations