Top partners in Same–Sign Dileptons: A Strong Sector at the LHC

Andrea Wulzer

Based on 0909.3977, with J. Mrazek

Why not a strong–sector EWSB ?
(which would solve the Hierarchy Problem)

- EWPT:
- Flavor:
- Predictivity:

Why not a strong–sector EWSB ?
(which would solve the Hierarchy Problem)

- EWPT: generically too large S from strong sector
  simplest TC is ruled out
  some (not huge) fine–tuning will be needed
- Flavor:
- Predictivity:

Why not a strong–sector EWSB ?
(which would solve the Hierarchy Problem)

- EWPT: generically too large S from strong sector
  simplest TC is ruled out
  some (not huge) fine–tuning will be needed
- Flavor: hard to avoid low–scale FCNC
  almost solved by partial compositeness
  so–called RS–GIM mechanism
- Predictivity:

Why not a strong–sector EWSB ?
(which would solve the Hierarchy Problem)

- EWPT: generically too large S from strong sector
  simplest TC is ruled out
  some (not huge) fine–tuning will be needed
- Flavor: hard to avoid low–scale FCNC
  almost solved by partial compositeness
  so–called RS–GIM mechanism
- Predictivity: frustrating not to have definite predictions
  5d models provide a predictive framework
  "reasonable" deformations of a strong sector

Partial Compositeness

(D. B. Kaplan; Contino, Sundrum,. . .)

In the “old times”: $$\mathcal{L}_q^{UV} = \frac{c}{\Lambda_{ETC}^{d-1}} \mathcal{O}_d \, \overline{q} q$$

In partial compositeness: $$\mathcal{L}_q^{UV} = \frac{\lambda}{\Lambda_{UV}^{d-5/2}} \, \overline{q} \, \mathcal{O}_d^{(q)}$$

Partial Compositeness

(D. B. Kaplan; Contino, Sundrum,. . .)

In the "old times": $\mathcal{L}_q^{UV} = \frac{c}{\Lambda_{ETC}^{d-1}} \mathcal{O}_d \, \overline{q} q$

In partial compositeness: $\mathcal{L}_q^{UV} = \frac{\lambda}{\Lambda_{UV}^{d-5/2}} \, \overline{q} \, \mathcal{O}_d^{(q)}$

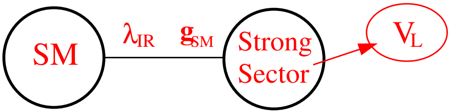
In the IR, ($M_* \sim$TeV) elementary/composite mixings:

$$\overline{q}_L \, i\not{\partial} q_L + \overline{Q} \, i\not{\partial} Q - M_* \overline{Q} Q + \lambda_{IR} M_* \overline{q}_L Q + \dots$$

The Partners:

Vector–like colored heavy fermions Q, B, T associated with $\mathcal{O}_d^{(q,b,t)}$

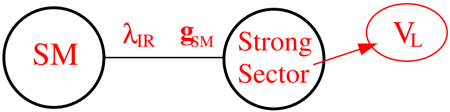
Pictorially:



Small masses from small mixings: $\lambda_{IR}^{1,2} \ll 1$

Light families are almost elementary

Pictorially:



Small masses from small mixings: $\lambda_{IR}^{1,2} \ll 1$

Light families are almost elementary

All non–universal effects from λ_{IR}, RS–GIM suppression of FCNC

Top partners strongly coupled to top quark

Specific (5d) Models:

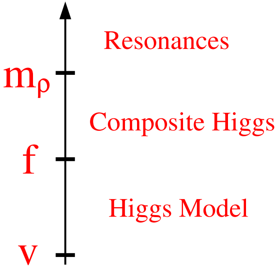
Higgsless: EWSB in the Strong Sector, 5d version of (large–N_c) TC, resonance scale $m_\rho \lesssim 2$ TeV, accidental cancellation in S

Specific (5d) Models:

Higgsless: EWSB in the Strong Sector, 5d version of (large–N_c) TC, resonance scale $m_\rho \lesssim 2$ TeV, accidental cancellation in S

Composite–Higgs: Strong Sector delivers "elementary–like" Higgs, $\xi = \dfrac{v^2}{f^2} \ll 1$

Fine–tune ξ for EWPT, $m_\rho \gtrsim 3$ TeV



A model for the Top Partners: (with Custodial $SO(4)$)

Same as in (Contino, Servant) where pair production was studied

$$Q = (\mathbf{2},\mathbf{2})_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix}, \quad \widetilde{T} = (\mathbf{1},\mathbf{1})_{2/3}, \quad \mathcal{L}_Y = Y_t^* \mathrm{Tr}\left[\overline{Q} H\right] \widetilde{T},$$

Describes a Composite–Higgs OR just the Goldstones:

$$H = \begin{bmatrix} h_d^\dagger & h_u \\ -h_u^\dagger & h_d \end{bmatrix} = \frac{v}{\sqrt{2}} U \simeq \begin{bmatrix} \frac{1}{\sqrt{2}}(v - i\varphi_0) & \varphi_+ \\ -\varphi_- & \frac{1}{\sqrt{2}}(v + i\varphi_0) \end{bmatrix}$$

A model for the Top Partners: (with Custodial $SO(4)$)

Same as in (Contino, Servant) where pair production was studied

$$Q = (\mathbf{2},\mathbf{2})_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix}\,, \quad \widetilde{T} = (\mathbf{1},\mathbf{1})_{2/3}\,, \quad \mathcal{L}_Y = Y_t^* \mathrm{Tr}\left[\overline{Q} H\right] \widetilde{T}\,,$$

Describes a Composite–Higgs OR just the Goldstones:

$$H = \begin{bmatrix} h_d^\dagger & h_u \\ -h_u^\dagger & h_d \end{bmatrix} = \frac{v}{\sqrt{2}} U \simeq \begin{bmatrix} \frac{1}{\sqrt{2}}(v - i\varphi_0) & \varphi_+ \\ -\varphi_- & \frac{1}{\sqrt{2}}(v + i\varphi_0) \end{bmatrix}$$

Mixing:
$$\begin{pmatrix} q_L \\ Q_L \end{pmatrix} \to \begin{pmatrix} \cos\varphi_q q_L + \sin\varphi_q Q_L \\ \cos\varphi_q Q_L - \sin\varphi_q q_L \end{pmatrix}$$
(same for t_R–$\widetilde{T}_R$)

We find the Top Yukawa: $y_t = Y_t^* \sin\varphi_q \sin\varphi_t$

And verteces with t and W_L:

$$\mathcal{L} \subset -\lambda_B \varphi_+ \bar{t}_R B + \lambda_T \varphi_- \bar{t}_R T_{5/3}$$

$$\lambda_B = \sin\varphi_t \cos\varphi_q Y_t^* \qquad \lambda_T = \sin\varphi_t Y_t^* > y_t$$

We find the Top Yukawa: $y_t = Y_t^* \sin\varphi_q \sin\varphi_t$

And verteces with t and W_L:

$$\mathcal{L} \subset -\lambda_B \varphi_+ \overline{t}_R B + \lambda_T \varphi_- \overline{t}_R T_{5/3}$$

$$\lambda_B = \sin\varphi_t \cos\varphi_q Y_t^* \qquad \lambda_T = \sin\varphi_t Y_t^* > y_t$$

Available parameter space is model–dependent. However:

1. N_c will have to be small, $\widehat{S} \simeq \dfrac{m_w^2}{16\pi^2 v^2}\xi N_c$
2. $\sin\varphi_q$ affects b_L couplings (not $Z\overline{b}b$), *e.g.* Δm_B, better small

We find the Top Yukawa: $y_t = Y_t^* \sin\varphi_q \sin\varphi_t$

And verteces with t and W_L:

$$\mathcal{L} \subset -\lambda_B \varphi_+ \bar{t}_R B + \lambda_T \varphi_- \bar{t}_R T_{5/3}$$

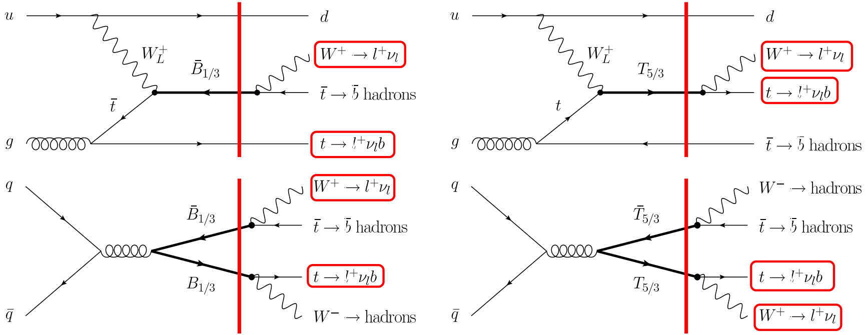
$$\lambda_B = \sin\varphi_t \cos\varphi_q Y_t^* \quad \lambda_T = \sin\varphi_t Y_t^* > y_t$$

Available parameter space is model–dependent. However:

1. N_c will have to be small, $\widehat{S} \simeq \frac{m_w^2}{16\pi^2 v^2} \xi N_c$
2. $\sin\varphi_q$ affects b_L couplings (not $Z\bar{b}b$), *e.g.* Δm_B, better small

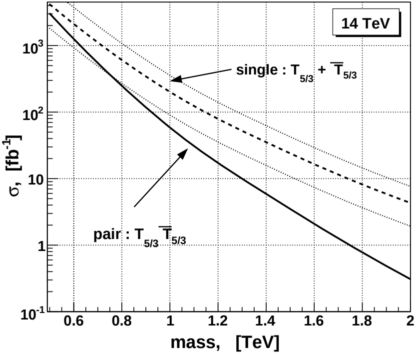
Reasonable: $\left\{ \begin{array}{l} N_c \leq 10 \Rightarrow Y_t^* = \frac{4\pi}{\sqrt{N_c}} \geq 4 \\ \sin\varphi_q \leq \sin\varphi_t \end{array} \right. \Rightarrow \lambda_{B,T} \geq \sqrt{3}, 2$

Production:



For Single: $\sigma(+,+) \simeq 2\,\sigma(-,-)$ (measure $\lambda_{T,B}$)

Production Xsect:



Signal: $pp \to l^{\pm} l^{\pm} + \not{E}_T + \text{jets}$

- Hard Isolated $l^{\pm} l^{\pm}$: $p_T > 10$ GeV, $\Delta R(LJ) > 0.4$ $(\eta < 2.5)$
- One very hard $l^{\pm}$ (harder for $T_{5/3}$ than for $B_{1/3}$)
- $\not{E}_T$ from neutrinos (more for $B_{1/3}$)
- Large $H_T = \sum_{J,L,\not{E}_T} |P_T|$

Signal: $pp \to l^\pm l^\pm + \not{E}_T + \text{jets}$

- Hard Isolated $l^\pm l^\pm$: $p_T > 10$ GeV, $\Delta R(LJ) > 0.4$ $(\eta < 2.5)$
- One very hard $l^\pm$ (harder for $T_{5/3}$ than for $B_{1/3}$)
- $\not{E}_T$ from neutrinos (more for $B_{1/3}$)
- Large $H_T = \sum_{J,L,\not{E}_T} |P_T|$

Only relevant for $M \lesssim 2$TeV (pay leptonic BR of $\frac{2}{9} \cdot \frac{2}{9} \cdot \frac{6}{9} \simeq 0.03$)

Backgrounds:

- The $l^\pm l^\pm$ Background:
  1. $W^\pm W^\pm$
  2. $W^\pm W^\pm W^{\rm any}$ (enhanced by $W^\pm H$)
  3. $W^\pm t\bar{t}$
  4. $W^\pm W^\mp t\bar{t}$ (again enhanced by Higgs)

Backgrounds:

- The $l^\pm l^\pm$ Background:
    1. $W^\pm W^\pm$
    2. $W^\pm W^\pm W^{\mathrm{any}}$ (enhanced by $W^\pm H$)
    3. $W^\pm t\bar{t}$
    4. $W^\pm W^\mp t\bar{t}$ (again enhanced by Higgs)
- The $l^\pm l^\pm l^{\mathrm{any},lost}$ Background: $(p_T(l) < 5$ GeV, $\eta(l) > 2.5)$
    1. $W^\pm Z$ (1/20 to lose the lepton, but bigger that $W^\pm W^\pm$)
    2. $(H > W^\pm W^\mp)Z$ (subdominant w.r.t. $W^\pm H$)

Backgrounds:

- The $l^{\pm} l^{\pm}$ Background:
  1. $W^{\pm}W^{\pm}$
  2. $W^{\pm}W^{\pm}W^{\rm any}$ (enhanced by $W^{\pm}H$)
  3. $W^{\pm}t\bar{t}$
  4. $W^{\pm}W^{\mp}t\bar{t}$ (again enhanced by Higgs)
- The $l^{\pm} l^{\pm} l^{{\rm any},lost}$ Background: $(p_T(l) < 5$ GeV, $\eta(l) > 2.5)$
  1. $W^{\pm}Z$ (1/20 to lose the lepton, but bigger that $W^{\pm}W^{\pm}$)
  2. $(H > W^{\pm}W^{\mp})Z$ (subdominant w.r.t. $W^{\pm}H$)
- The $l^{\pm} l^{\mp}$ Background (ch. misid 10^{-2}):
  1. $W^{\pm}W^{\mp}$
  2. $t\bar{t}$
  3. $Z^{*}/\gamma*$ (invariant mass cut $m_{ll} > 120$GeV, killed by $\not{E}_T$)

Simulation:

MadGraph/MadEvent with MLM matching, showering with Pythia.

Discovery results from Parton Level (plus hard jets) calculation.

Simulation:

MADGRAPH/MADEVENT with MLM matching, showering with PYTHIA.

Discovery results from Parton Level (plus hard jets) calculation.

One detector disturbance included (crucial for $Z^*/\gamma*$):

$$\sigma(\vec{\not{E}}_T) = \kappa \sqrt{\sum_{J,L} |p_T|}$$

$\kappa_{\mathrm{ATLAS}} = 0.47$, $\kappa_{\mathrm{CMS}} = 0.97$, we take $\kappa = 1.0$

Optimized Cuts:

Cut	Mass, [TeV]	$p_T(L1)$, [GeV]	H_T, [GeV]	$\not{E}_T$, [GeV]
soft	0.5	60	500	50
medium	1.0	100	1000	50
hard	1.5	200	1200	100
max	2.0	250	1600	100

For B and $T_{5/3}$, $\lambda_{T,B} = 3$:

Mass, [TeV]	$L_{\mathrm{discovery}}$, [fb^{-1}]	# signal	# background
0.5	0.024	5	0
1.0	1.103	8	2
1.5	26.40	17	11
2.0	326.7	28	31

For only B, $\lambda_B = 3$:

Mass, [TeV]	$L_{\mathrm{discovery}}$, [fb^{-1}]	# signal	# background
0.5	0.076	8	2
1.0	4.3	16	11
1.5	82	30	37
2.0	637	39	61

For B and $T_{5/3}$, $\lambda = 2$: $\quad 90\text{fb}^{-1}$ for 1.5 TeV

For B and $T_{5/3}$, $\lambda = 2$: 90fb^{-1} for 1.5 TeV

Most pessimistic case (in our model):

$$\frac{M_T}{M_B} = \frac{\lambda_B}{\lambda_T} = \cos\varphi_q \quad \Rightarrow \quad B \text{ heavy and decoupled if } \sin\varphi_q \text{ large}$$

As if $T_{5/3}$ only, $\lambda = 2$: 470fb^{-1} for 1.5 TeV

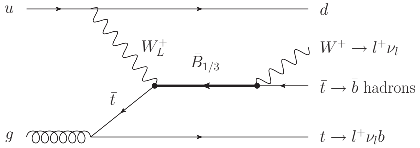
Maximum reach around 1.3 TeV, 90fb^{-1}

Discovering Top Partners in the excess:

- Identify SM particles: leptonic W's by m_{T2}, had. t (eff. 60%)
- Measure $(+,+)$ — $(-,-)$ Asymmetry

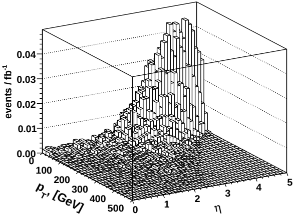
Discovering Top Partners in the excess:

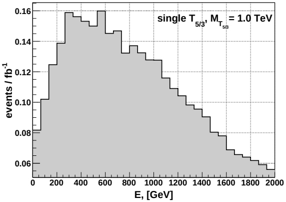
- Identify SM particles: leptonic W's by m_{T2}, had. t (eff. 60%)
- Measure $(+,+)$ — $(-,-)$ Asymmetry
- Tag a Forward Jet:

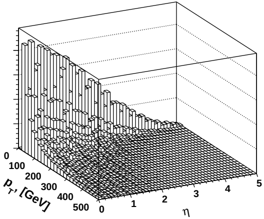


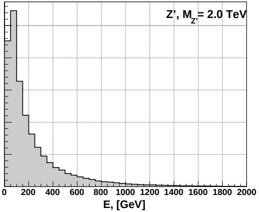
W of low virtuality, $p_T(J) \lesssim m_W$, $E \gtrsim 1$ TeV $\Rightarrow \eta \sim 3$

Main background to Forward Jet is ISR, (eff. of 65%, fake of 20%)





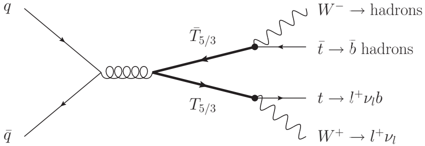




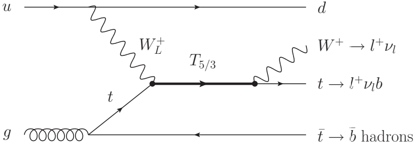
Measure the Mass:

For the $T_{5/3}$:

- If pair produced reconstruct the hadronic $T_{5/3}$:

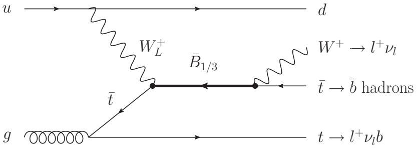


- If singly produced use m_T: $\not{E}_T$ for ν's transv. energies

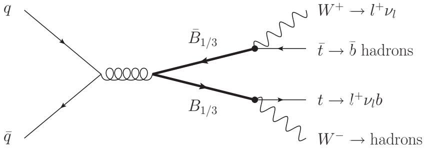


For the B:

- If singly produced use m_{T2} for t and B

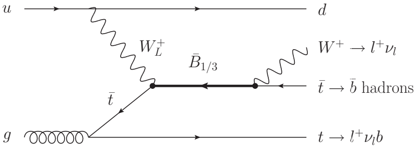


- If pair produced ?

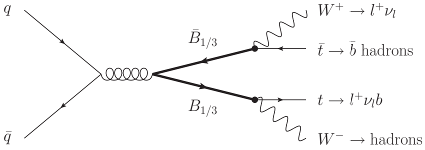


For the B:

- If singly produced use m_{T2} for t and B



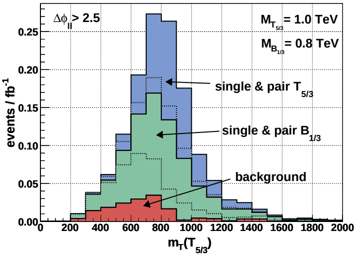
- If pair produced ?



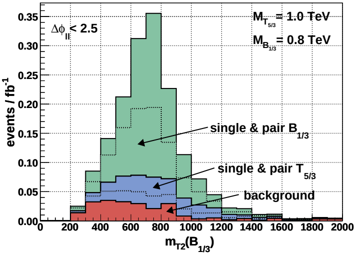
Alternative: reconstruct ν's with MAOS (Cho,Choi,Kim,Park)

Example:

$$M_T = 1.0 \text{ TeV}, \ M_{B_{1/3}} = 0.8 \text{ TeV}$$



(a) $m_T(T_{5/3})$ for $\Delta\varphi_{ll} > 2.5$



(b) $m_{T2}(B_{1/3})$ for $\Delta\varphi_{ll} < 2.5$

Conclusions

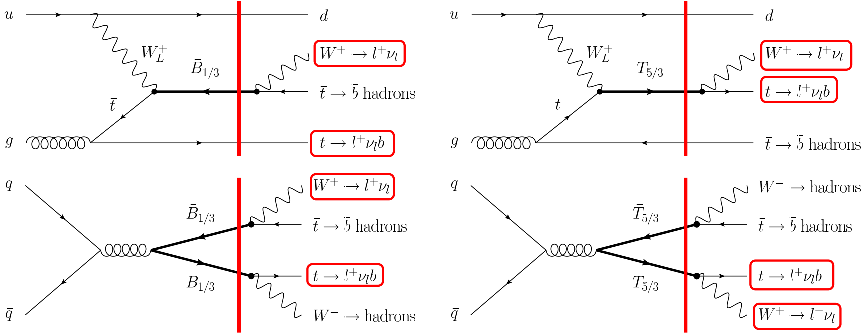
- Top Partners are signatures of Partial Compositeness
- Discovered in same–sign dileptons for $M \lesssim 1.5$ TeV
- Possible to measure couplings and masses

Conclusions

- Top Partners are signatures of Partial Compositeness
- Discovered in same–sign dileptons for $M \lesssim 1.5$ TeV
- Possible to measure couplings and masses
- Relevant for Higgsless where the resonance scale is low

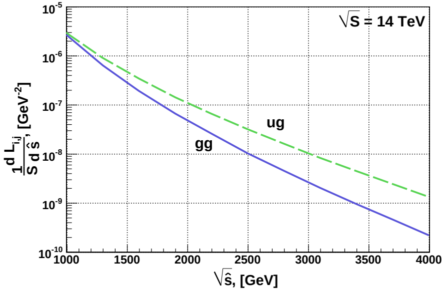
  Also for Composite–Higgs (Contino, Da Rold, Pomarol) :

  Partners in $[0.5, 1.5]$ are the best signature of the scenario.



$$\text{Single}/\text{Pair} \simeq \frac{\lambda^2}{4\pi} \cdot \alpha_W/\alpha_S(\text{phase space}) \simeq 1/10$$

Compensated by parton lumionsities



$$\frac{d\mathcal{L}_{i,j}}{d\widehat{s}} = \frac{1}{S}\int_{\widehat{s}/S}^{1} \frac{dx}{x}\, F_i(x)\, F_j(\widehat{s}/(Sx))\,,$$

LHC @ 10 TeV:

Mass, [TeV]	$L_{\text{discovery}}$, [fb^{-1}]	# signal	# background
0.5	0.072	5	0
1.0	5.5	9	3
1.5	210	22	19

To be compared with 7 TeV:

Mass, [TeV]	$L_{\text{discovery}}$, [fb^{-1}]	# signal	# background
0.5	0.024	5	0
1.0	1.103	8	2
1.5	26.40	17	11
2.0	326.7	28	31