Composite Higgs Models:
On top partners, UV embeddings and collider phenomenology

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M. Backović, TF, S. J. Lee, G. Perez [JHEP 1509,022]

M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082, Phys.Rev. D92 (2015) 011701, arXiv: 1507.06568]

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Outline

- Motivation for composite Higgs models
- A low-energy effective setup: minimal composite Higgs from $SO(5)/SO(4)$ breaking
- Constraints on composite quark partners from run I
- Prospects for composite quark partners at LHC run II
- A potential UV embedding and its collider phenomenology
- Conclusions and Outlook

Motivation

☺ Atlas and CMS found a Higgs-like resonance with a mass $m_h \sim 125$ GeV and couplings to $\gamma\gamma$, WW, ZZ, bb, and $\tau\tau$ compatible with the Standard Model (SM) Higgs.

☹ The Standard Model suffers from the hierarchy problem.

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

One possible solution: Composite Higgs Models (CHM)

- Consider a model which gets strongly coupled at a scale $f \sim \mathcal{O}(1\,\mathrm{TeV})$.
  $\rightarrow$ Naturally obtain $f \lll M_{pl}$.
- Assume a global symmetry which is spontaneously broken by dimensional transmutation $\rightarrow$ strongly coupled resonances at f and Goldstone bosons (to be identified with the Higgs sector).
- Assume that the only source of explicit symmetry breaking arises from Yukawa-type interactions.
  $\rightarrow$ The Higgs-like particles become pseudo-Goldstone bosons
  $\Rightarrow$ Naturally generates a scale hierarchy $v \sim m_h < f \lll M_{pl}$.

Composite Higgs model: general setup

Simplest realization:

The minimal composite Higgs model (MCHM) Agashe, Contino, Pomarol [2004]

Effective field theory based on $SO(5) \to SO(4)$ global symmetry breaking.

- The Goldstone bosons live in $SO(5)/SO(4) \to 4$ d.o.f.
- $SO(4) \simeq SU(2)_L \times SU(2)_R$
  Gauging $SU(2)_L$ yields an $SU(2)_L$ Goldstone doublet.
  Gauging T_R^3 assigns hyper charge to it. Later: Include a global $U(1)_X$ and gauge $Y = T_R^3 + X$.
  $\Rightarrow$ Correct quantum numbers for the Goldstone bosons
  to be identified as a non-linear realization of the Higgs doublet.

We use the CCWZ construction to construct the low-energy EFT.
Coleman, Wess, Zumino [1969], Callan, Coleman [1969]

Central element: the Goldstone boson matrix

$$U(\Pi) = \exp\left(\frac{i}{f}\Pi_i T^i\right) = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos \bar{h}/f & \sin \bar{h}/f \\ 0 & 0 & 0 & -\sin \bar{h}/f & \cos \bar{h}/f \end{pmatrix},$$

where $\Pi = (0, 0, 0, \bar{h})$ with $\bar{h} =< h > + h$
and T^i are the broken $SO(5)$ generators.

How to include the quarks?

In the SM, the Higgs multiplet

- induces EWSB (✓ in CHM),
- provides a scalar degree of freedom (✓ in CHM),
- generates fermion masses via Yukawa terms ($\leftarrow$ implementation in CHM?).

How to include quarks and quark masses?
One solution Kaplan [1991]: Include elementary fermions q as incomplete linear representations of $SO(5)$ which couple to the strong sector via

$$\mathcal{L}_{mix} = y \bar{q}_{I_\mathcal{O}} \mathcal{O}^{I_\mathcal{O}} + \text{h.c.}\,,$$

where $\mathcal{O}$ is an operator of the strongly coupled theory in the representation $I_\mathcal{O}$.
Note: The Goldstone matrix $U(\Pi)$ transforms non-linearly under $SO(5)$, but linearly under the $SO(4)$ subgroup $\rightarrow \mathcal{O}^{I_\mathcal{O}}$ has the form $f(U(\Pi))\mathcal{O}'_{fermion}$.

Simplest choice for quark embedding:

$$q_L^5 = \frac{1}{\sqrt{2}} \begin{pmatrix} ib_L \\ b_L \\ it_L \\ -t_L \\ 0 \end{pmatrix}, \quad t_R^5 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}, \quad \psi = \begin{pmatrix} Q \\ \tilde{T} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ iT + iX_{2/3} \\ -T + X_{2/3} \\ \sqrt{2}\tilde{T} \end{pmatrix}.$$

BSM particle content (per u-type quark):

	T	$X_{2/3}$	B	$X_{5/3}$	$\tilde{T}$
$SO(4)$	**4**	**4**	**4**	**4**	**1**
$SU(3)_c$	**3**	**3**	**3**	**3**	**3**
$U(1)_X$ charge	$2/3$	$2/3$	$2/3$	$2/3$	$2/3$
EM charge	$2/3$	$2/3$	$-1/3$	$5/3$	$2/3$

Fermion Lagrangian:

$$\mathcal{L}_{comp} = i\,\overline{Q}(D_\mu + ie_\mu)\gamma^\mu Q + i\bar{\tilde{T}}\not{D}\tilde{T} - M_4\overline{Q}Q - M_1\bar{\tilde{T}}\tilde{T} + \left(ic\overline{Q}^i\gamma^\mu d^i_\mu\tilde{T} + \text{h.c.}\right),$$

$$\mathcal{L}_{el,mix} = i\,\bar{q}_L\not{D}q_L + i\,\bar{t}_R\not{D}t_R - y_L f\bar{q}^5_L U_{gs}\psi_R - y_R f\bar{t}^5_R U_{gs}\psi_L + \text{h.c.}$$

Masses and couplings

Expanding in $\epsilon = v/h$ yields Feynman rules in the mass eigenbasis.
The SM like quark:

$$m_t = \frac{v}{\sqrt{2}} \frac{|M_1 - M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3)$$

Partners in the **4**:

$$\begin{aligned} M_{X5/3} &= \quad M_4 &&= M_{Tf1} + \mathcal{O}(\epsilon^2) \\ M_B &= \sqrt{M_4^2 + y_L^2 f^2} &&= M_{Tf2} + \mathcal{O}(\epsilon^2) \end{aligned}$$

Singlet Partner:

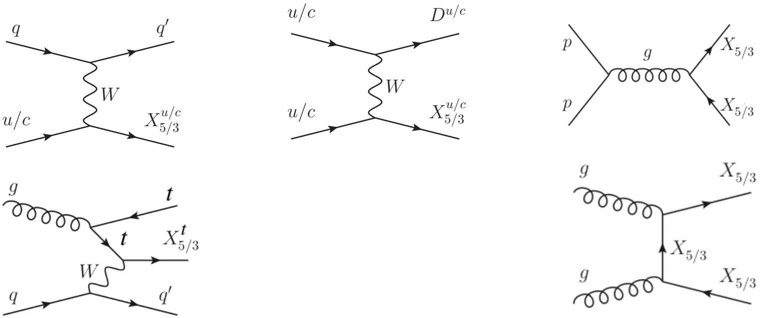
$$M_{Ts} = \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2)$$

Couplings (examples):

$$\begin{aligned} \left|g_{XWt}^R\right| &= \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left| \frac{y_R f\, M_1}{M_4 M_{Ts}} - \sqrt{2} c_R \frac{y_R f}{M_{Ts}} \right| + \mathcal{O}(\epsilon^3) \\ \left|g_{TsWb}^L\right| &= \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left(\frac{y_L f \left(M_1 M_4 + y_R^2 f^2\right)}{M_{Tf2} M_{Ts}^2} - \frac{\sqrt{2} c_L y_L f}{M_{Tf2}} \right) + \mathcal{O}(\epsilon^3) \end{aligned}$$

Production and decays

Production mechanisms (shown here: $X_{5/3}$ prod. for partners of up-type quarks)



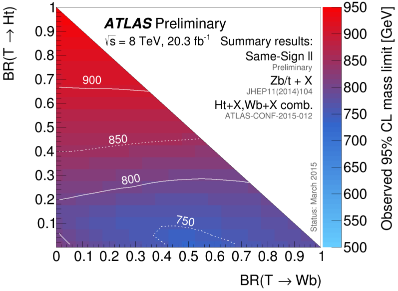
(a) EW single production (b) EW pair production (c) QCD pair production

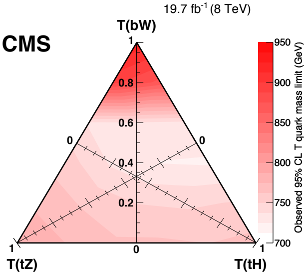
Decays:

- $X_{5/3} \to W^+ t$ (100%),
- $B \to W^- t$ ($\sim$ 100%),
- $T_{f1}, T_{f2}, T_s \to W^- b, Zt, ht$ (with parameter-dependent BRs)

Bounds on top partners from run I

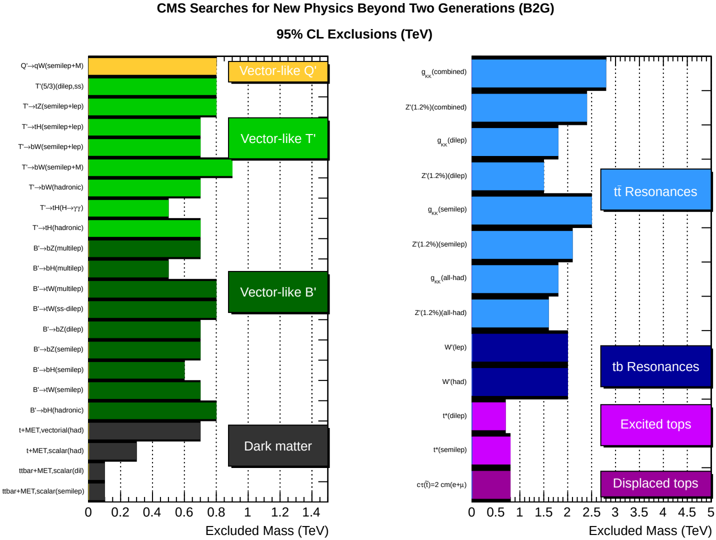
- ATLAS and CMS determined bounds on (QCD) pair-produced top partners with charge $5/3$ (the $X_{5/3}$) in the same-sign di-lepton channel.
  $M_{X_{5/3}} > 770\,\mathrm{GeV}$ ATLAS [JHEP 1411 (2014) 104] , $M_{X_{5/3}} > 800\,\mathrm{GeV}$ CMS [PRL 112 (2014) 171801]
- ATLAS and CMS determined a bound 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]

Bounds on top partners from run I



Prospects for composite quark partners at LHC run II

At run II, we have more energy
⇒ searches are sensitive to higher quark partner masses.

However, for composite quark partners there are two additional genuine aspects:

1. Single-production channels (if present) will become more important as compared to QCD pair production channels.
2. For heavier quark partners, their decay products become strongly boosted ⇒ we need dedicated search strategies for boosted tops, Higgses, EW gauge bosons.

Three examples:

1. Maximizing the sensitivity for the "most visible" quark partner: An alternative search strategy for $X_{5/3}$.
   M. Backović, TF, S. J. Lee, G. Perez [JHEP 1509, 022]
2. * Maximizing the sensitivity for charge 2/3 top partners: A comprehensive survey on single produced T' and its decay channels.
   M. Backović, TF, J. H. Kim, S. J. Lee [Phys.Rev. D92 (2015) 011701, arXiv: 1507.06568]
3. * Maximizing the sensitivity for "the illusive Q_h " quark partner:
   M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082]

Prospects for composite quark partners: charge 2/3 partner(s)

Searching for top quark partner(s) with charge 2/3:

M. Backović, TF, J. H. Kim, S. J. Lee [Phys.Rev. D92 (2015) 011701, arXiv: 1507.06568]

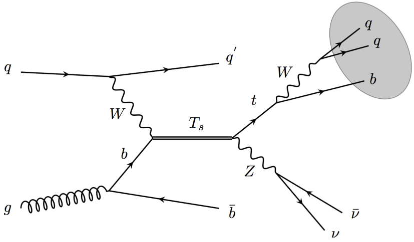
- Charge $2/3$ partners can decay into ht, Zt, or Wb.
- The resulting t, h, W, Z have various decay channels
  W and t: leptonic ($l\nu$) or hadronic (jj)
  Z: leptonic (l^+l^-), invisible ($\nu\bar{\nu}$), hadronic jj, or ($b\bar{b}$)
  h: $\gamma\gamma$, ZZ^*, WW^*, $b\bar{b}$, ...
- The cleanest channels (typically) come with the smallest branching fractions.

Hence there are many final states, it is a priory not clear which channel performs best, and this can depend on M_T and $\sqrt{s}$.
We performed a comprehensive overview as well as detailed studies on the six channels most promising channels. M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1507.06568]

Here, just one example:

Prospects for composite quark partners: charge 2/3 partner(s)

Search for top quark singlet partners in the $j\bar{b}tZ$ final state:



Similar topology to the previous signature. We again use:

- high H_T-cut [500 (750) GeV for 1 (1.5) TeV search],
- Ov_3^t top-template with b tag,
- forward-jet-tag,
- this time no additional b tag,

...and the Z: $Z \to ll$ or $Z \to \not{E}_T$?

Prospects for composite quark partners: charge 2/3 partner(s)

Search for top quark singlet partners in the $j\bar{b}tZ$ final state:

The $\not{E}_T$ has a big advantage ($BR(Z \to \not{E}_T)/BR(Z \to \not{E}_T) \approx 3$)
...and a big disadvantage ($t + \not{E}_T$ has $t\bar{t}$ background).

For a "fair" comparison between the channels,
we use the same cuts on both channels w.r.t the "$j\bar{b}t$ - part" of the event.

For the di-lepton channel, we apply "typical" cuts.

For the $\not{E}_T$ channel, we instead demand:

- No isolated lepton in the event,
- $\not{E}_T > 500\ (750)\,\text{GeV}$ for the $1\ (1.5)\,\text{TeV}$ search,
- "isolated" $\not{E}_T$ (meaning: $\Delta\phi_{\not{E}_T,j} > 1.0$).

...so what wins??

Prospects for composite quark partners: charge 2/3 partner(s)

Search for top quark singlet partners in the $j\bar{b}tZ$ final state:

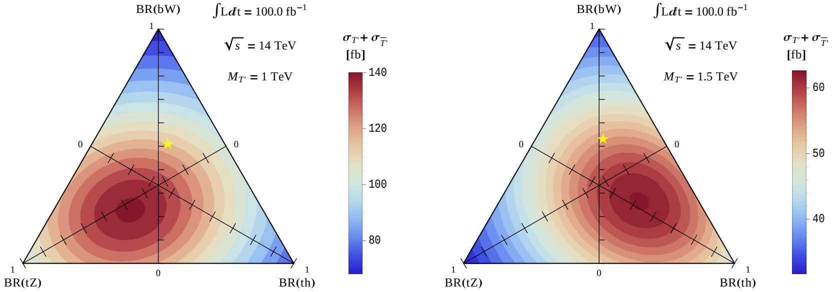
$T' \to Z_{\text{inv}} t_{\text{had}}$	$M_{T'} = 1.0$ TeV search						$M_{T'} = 1.5$ TeV search					
	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}$ (100 fb^{-1})	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}$ (100 fb^{-1})
preselection	4.9	26000	21000	44	0.00011	0.23	1.3	5200	5300	12	0.00012	0.12
Basic Cuts	3.5	900	6100	11	0.00050	0.42	1.0	140	1200	2.4	0.00074	0.27
$Ov_3^t > 0.6$	2.7	510	840	6.5	0.0020	0.75	0.87	81	230	1.6	0.0028	0.49
b-tag	1.8	300	28	4.1	0.0055	1.0	0.51	42	6.7	0.9	0.010	0.72
$\not{E}_T > 400\,(600)$ GeV	1.2	13	8.3	0.84	0.055	2.6	0.39	0.95	1.4	0.13	0.16	2.5
$N_{\text{fwd}} \geq 1$	0.75	2.5	1.2	0.25	0.19	3.8	0.26	0.19	0.23	0.039	0.58	3.9
$\lvert\Delta\phi_{\not{E}_T,j}\rvert > 1.0$	0.62	0.89	0.91	0.21	0.31	4.4	0.21	0.072	0.17	0.031	0.78	4.1

$T' \to Z_{ll} t_{\text{had}}$	$M_{T'} = 1.0$ TeV search					$M_{T'} = 1.5$ TeV search				
	signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}$	signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}$
preselection	1.6	4800	13	3.3×10^{-4}	0.23	0.42	1300	3.5	3.3×10^{-4}	0.12
Basic Cuts	1.1	750	1.3	0.0014	0.39	0.30	170	0.36	0.0018	0.23
$Ov_3^t > 0.6$	0.71	71	0.61	0.010	0.85	0.24	19	0.14	0.012	0.54
b-tag	0.49	2.6	0.40	0.16	2.8	0.14	0.64	0.082	0.19	1.7
$\Delta R_{ll} < 1.0$	0.49	2.6	0.39	0.16	2.8	0.14	0.64	0.081	0.20	1.7
$\lvert m_{ll} - m_Z\rvert < 10$ GeV	0.44	2.4	0.35	0.16	2.7	0.13	0.58	0.074	0.19	1.6
$N_{\text{fwd}} \geq 1$	0.28	0.38	0.10	0.58	4.0	0.084	0.098	0.018	0.72	2.5

M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1507.06568]

Prospects for composite quark partners: charge 2/3 partner(s)

We also did detailed analyses of the $W_{\rm lep}b$, $W_{\rm had}b$, $h_{bb}t_{\rm had}$, and $h_{bb}t_{\rm lep}$ channels, and found best results for $Z_{\rm inv}t_{\rm had}$, $W_{\rm lep}b$ and $h_{bb}t_{\rm had}$.

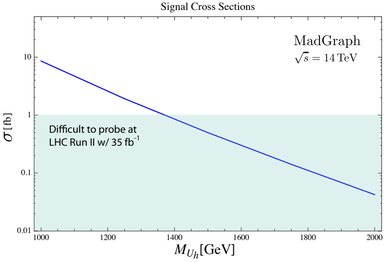


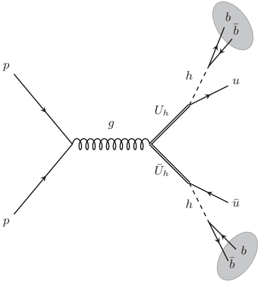
Expected discovery reach for a T' with mass of 1 TeV (left) and 1.5 TeV (right) in terms of T' production cross section for the LHC at 14 TeV with 100 fb^{-1} of data. The yellow star marks the branching ratios at the sample model point used for simulation.

Prospects for composite quark partners at LHC run II

Search for light quark singlet partners in the *hhjj* final state with $h \to b\bar{b}$ decays.

M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082]





Cut Scheme	Basic Cuts	Demand at least four fat jets ($R = 0.7$) with $p_T > 300$ GeV, $\lvert\eta\rvert < 2.5$
		Declare the two highest p_T fat jets satisfying $Ov_2^h > 0.4$ and $Ov_3^t < 0.4$ to be Higgs candidate jets. At least 1b-tag on both Higgs candidate jets.
		Select the two highest p_T light jets ($r = 0.4$), with $p_T > 25$ GeV to be the u quark candidates.
	Complex Cuts	$\lvert\Delta_h\rvert < 0.1$ $\lvert\Delta_{U_h}\rvert < 0.1$ $m_{U_{h1,2}} > 800$ GeV

Table III: Summary of the Event Selection Cut Scheme

Prospects for composite quark partners at LHC run II

Search for light quark singlet partners in the *hhjj* final state with $h \to b\bar{b}$ decays.

M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082]

	σ_s [fb]	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{b\bar{b}}$ [fb]	$\sigma_{\text{multi-jet}}$ [fb]	S/B	$S/\sqrt{B}$
Preselection Cuts	6.8	4.6×10^{2}	8.4×10^{3}	2.8×10^{5}	2.4×10^{-5}	7.5×10^{-2}
Basic Cuts	1.2	4.6	16.0	6.8×10^{2}	1.7×10^{-3}	2.7×10^{-1}
$\lvert\Delta_{mh}\rvert < 0.1$	8.2×10^{-1}	1.7	6.5	2.8×10^{2}	2.9×10^{-3}	2.9×10^{-1}
$\lvert\Delta_{mU}\rvert < 0.1$	5.6×10^{-1}	5.5×10^{-1}	2.0	87.0	6.3×10^{-3}	3.5×10^{-1}
$m_{U_{h1,2}} > 800$ GeV	5.0×10^{-1}	3.6×10^{-1}	1.6	67.0	7.3×10^{-3}	3.6×10^{-1}
b-tag	3.4×10^{-1}	4.4×10^{-2}	1.1×10^{-2}	1.5×10^{-2}	**4.8**	**7.5**

Table IV: $M_{U_h} = 1$ TeV , $\sigma_s = 6.8$ fb , $\mathcal{L} = 35$ fb^{-1}

	σ_s [fb]	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{b\bar{b}}$ [fb]	$\sigma_{\text{multi-jet}}$ [fb]	S/B	$S/\sqrt{B}$
Preselection Cuts	2.4	4.6×10^{2}	8.4×10^{3}	2.8×10^{5}	8.15×10^{-6}	2.6×10^{-2}
Basic Cuts	6.0×10^{-1}	4.6	16.0	6.8×10^{2}	8.6×10^{-4}	1.4×10^{-1}
$\lvert\Delta_{mh}\rvert < 0.1$	3.9×10^{-1}	1.7	6.5	2.8×10^{2}	1.4×10^{-3}	1.4×10^{-1}
$\lvert\Delta_{mU}\rvert < 0.1$	2.7×10^{-1}	5.5×10^{-1}	2.0	87.0	3.0×10^{-3}	1.7×10^{-1}
$m_{U_{h1,2}} > 1000$ GeV	2.2×10^{-1}	1.9×10^{-1}	1.0	45.0	4.8×10^{-3}	1.9×10^{-1}
b-tag	1.34×10^{-1}	2.2×10^{-2}	8.5×10^{-3}	1.2×10^{-2}	**3.1**	**3.8**

Table V: $M_{U_h} = 1.2$ TeV , $\sigma_s = 2.4$ fb , $\mathcal{L} = 35$ fb^{-1}

Towards a CH UV embedding

The above approaches Composite Higgs models in terms of a low-energy EFT.

Are there candidates for a UV embeddings (and what is the confining group, what are the Higgs and quark partner constituents ("preons"))?

Ferretti, Karateev [JHEP 1403 (2014) 077] classified candidate models which

- contain no elementary scalars (to not re-introduce a hierarchy problem),
- have a simple hyper-color group G_{HC},
- have a Higgs candidate amongst its Goldstone bosons,
- have a top partner candidate amongst its bound states,
- satisfy other consistency conditions (asymptotic freedom, no anomalies, ...),
- (no SM gauge group Landau pole near the EW scale).

...they find only few models satisfying this wish-list, with the minimal co-sets $SU(5)/SO(5)$ c.f. Ferretti [JHEP 1406 (2014) 142], $SU(4)/Sp(4)(\sim SO(6)/SO(5))$ c.f. Barnard, Gherghetta, Ray [JHEP 1402 (2014) 002] or $SU(4) \times SU(4) \to SU(4)_D$ Vecchi [arXiv:1506.00623].

The model: SU(4)/Sp(4) coset based on $G_{\mathrm{HC}} = \mathrm{Sp}(2N_c)$

Field content of the microscopic fundamental theory and property transformation under the gauged symmetry group $Sp(2N_c) \times SU(3)_c \times SU(2)_L \times U(1)_Y$, and under the global symmetries $SU(4) \times SU(6) \times U(1)$.

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{SU}(4)$	$\mathrm{SU}(6)$	$\mathrm{U}(1)$
Q_1 Q_2	$\square$	$\mathbf{1}$	$\mathbf{2}$	0	$\mathbf{4}$	$\mathbf{1}$	$-3(N_c-1)q_\chi$
Q_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	$1/2$			
Q_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-x$			

The model: SU(4)/Sp(4) coset based on $G_{\rm HC} = \mathrm{Sp}(2N_c)$

Bound states of the model:

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
QQ	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	σ π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{1},\mathbf{20})$	σ_c π_c
χQQ	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\overline{QQ}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$Q\overline{\chi}\overline{Q}$	1/2	$(\mathbf{1},\overline{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$Q\overline{\chi}\overline{Q}$	1/2	$(\mathbf{15},\overline{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\overline{Q}\sigma^\mu Q$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$ $(\mathbf{10},\mathbf{1})$	a ρ
$\overline{\chi}\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$ $(\mathbf{1},\mathbf{15})$	a_c ρ_c

"Higgs": π transforms as $\mathbf{4}\oplus\mathbf{1}$ under $SO(4)$ $\rightarrow$ identify $\pi \equiv (H,\eta)$.
top partners: $(3,2,2)_{2/3}$ states (for t_L) in $\psi^5_{1,2}, \psi^5_4, \psi^{10}$ and
$(3,1,1)_{2/3}$ or $(3,1,3)_{2/3}$ (for t_R) in $\psi^1_{1,2}, \psi^5_{1,2}, \psi_3, \psi^5_4, \psi^{10}_4$.

The model: $SU(4)/Sp(4)$ coset based on $G_{\rm HC} = {\rm Sp}(2N_c)$

Key-observations:

- Before gauging $SU(3)_c$ the model exhibits an $SU(6)$ global symmetry which is broken to $SO(6)$ by the condensate $\langle\chi\chi\rangle$, leading to $35 - 15 = 20$ colored Goldstone bosons $\pi_c = (\mathbf{8},\mathbf{1},\mathbf{1})_0 \oplus (\mathbf{6},\mathbf{1},\mathbf{1})_{2x} \oplus (\bar{\mathbf{6}},\mathbf{1},\mathbf{1})_{-2x}$.
- The global $SU(6)$ is explicitly broken by gauging $SU(3)_c$, couplings to the top, and an overall $SU(6)$ breaking (but $SO(6)$ preserving) mass term. The former two induce a (small) mass splitting between π_6 and π_8.
- As π_6 and π_8 are pseudo-Goldstone bosons, they are expected to be the lighter than other bound states (vector-resonances, top-partners).

Upshot:

- The "wish-list" strongly constrains potential UV completions in terms of the hyper-color gauge group and the global symmetry group breaking pattern.
- The model under consideration ($SU(4)/Sp(4)$ coset based on $G_{\rm HC} = Sp(2N_c)$) predicts additional light states which can affect the LHC phenomenology of composite Higgs models with a perspective for a UV completion.

Effective description and phenomenology

With the gained insight on the $SU(4)/Sp(4)$ coset based on $G_{\rm HC} = Sp(2N_c)$, we set up an effective model to describe novel aspects of its LHC phenomenology.

$$\mathcal{L}_{eff} = |D_\mu \pi_6|^2 - m^2_{\pi_6}|\pi_6|^2 + \frac{1}{2}(D_\mu \pi_8)^2 - \frac{1}{2}m^2_{\pi_8}(\pi_8)^2 - V_{\rm scalar}(\pi_6, \pi_8)$$
$$+a_R\, \pi_6 t^c_R t^c_R + a_L\, \pi^c_6 t_L t_L + b\, \pi_8 t^c_R t_L + h.c.,$$

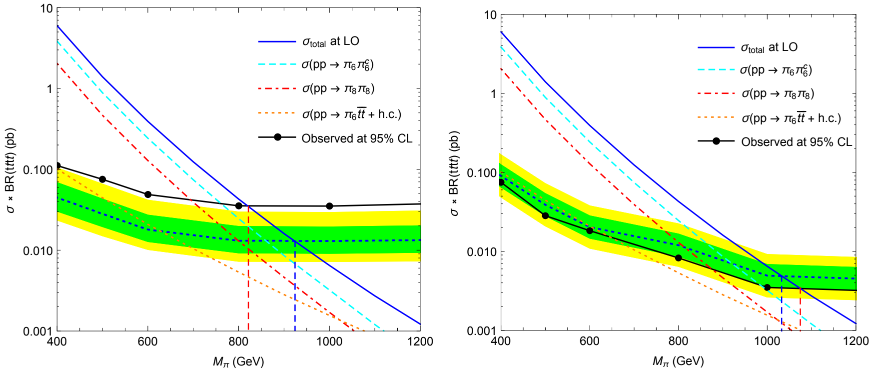
The coupling term $\propto a_R$ is gauge invariant while the terms $\propto a_L, b$ can only be generated via EW symmetry breaking, which implies

$$\frac{a_L}{a_R} \sim \mathcal{O}(v^2/\Lambda^2)\,, \quad \frac{b}{a_R} \sim \mathcal{O}(v/\Lambda)\,.$$

Therefore, the π_6 can be QCD pair produced or single produced via the a_R coupling while π_8 is always dominantly QCD pair produced. π_6 decays to tt while π_8 decays to $t\bar{t}$.

$\Rightarrow$ The model predicts BSM excesses in the $t\bar{t}t\bar{t}$ final state with $t\bar{t}$ and tt resonances.

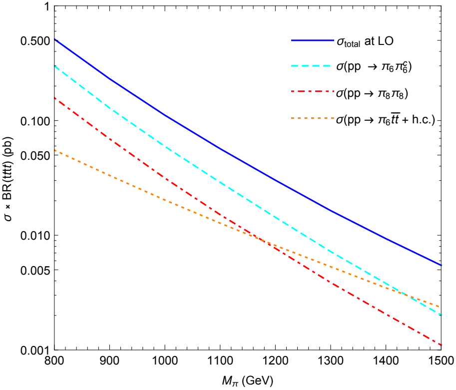
Effective description and phenomenology



G. Cacciapaga, H. Cai, A. Deandrea, TF, S. J. Lee, A. Parolini [JHEP11(2015)201]

Cross sections for the sextet and octet scalars at the LHC at 8 TeV, with $a_R = 1$. Left panel: comparison with the ATLAS 2SSL search [ATLAS, arXiv:1504.04605], where the green (yellow) band is for 1σ (2σ) expected limit and the solid black curve is the observed limit. Right panel: comparison with the ATLAS 1-lepton search observed limit [ATLAS, arXiv:1505.04306].

Effective description and phenomenology



G. Cacciapaga, H. Cai, A. Deandrea, TF, S. J. Lee, A. Parolini [JHEP11(2015)201]

Cross sections for the sextet and octet scalar production at the LHC 13 TeV, with $a_R = 1$.

Effective description and phenomenology

Determination of signal- and an estimate for background acceptance at 13 TeV:

	$t\bar{t}W^+jj$	$t\bar{t}Zjj$	$t\bar{t}W^+W^-$	$t\bar{t}t\bar{t}$	M_π (TeV)		
					0.9	1.0	1.2
no cut	800	787	11.4	7.40	192	85.0	19.1
basic cuts	85.1	107	1.60	2.05	64.5	26.7	5.16
$p_T^{j1} > 100$ GeV, $p_T^{j2} > 50$ GeV ($p_T^{\ell^-} < 10$ GeV, or $\lvert\eta_{\ell^-}\rvert > 2.5$)	36.4	2.03	0.72	1.83	63.4	26.1	5.0
$H_T > 650$ GeV	28.1	1.36	0.51	1.68	63.2	26.0	4.99
Acceptance	3.5%	0.17%	4.5%	23%	33%	31%	26%

Number of events and final acceptance for the main SM backgrounds (not including fakes and charge mis-id) and for the signal from single and pair productions of $p\,p \to \overline{tt}\pi_6$, $tt\pi_6^c$, $\pi_6\pi_6^c$, $\pi_8\pi_8$ in an effective model with $a_R = 1$. Numbers are given for an integrated luminosity of $\int Ldt = 100$ fb^{-1} at a $\sqrt{s} = 13$ TeV LHC.

G. Cacciapaga, H. Cai, A. Deandrea, TF, S. J. Lee, A. Parolini [JHEP11(2015)201]

Effective description and phenomenology

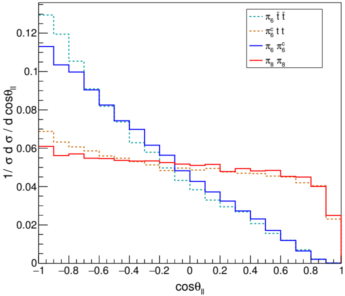
	M_π	0.9 TeV	1.0 TeV	1.1 TeV	1.2 TeV	1.3 TeV	1.4 TeV	1.5 TeV
	$\pi_8\pi_8$	18.6	7.60	3.06	1.25	0.55	0.23	0.10
$a_R = 1$	$\pi_6\pi_6^c$	35.3	13.1	4.99	1.99	0.81	0.32	0.14
	$\pi_6\bar{t}\bar{t}$	4.89	2.93	1.75	1.01	0.60	0.36	0.22
	$\pi_6^c tt$	4.38	2.40	1.35	0.74	0.42	0.25	0.15
$a_R = 2$	$\pi_6\pi_6^c$	24.2	9.67	4.02	1.76	0.80	0.36	0.18
	$\pi_6\bar{t}\bar{t}$	16.8	10.5	6.47	4.02	2.62	1.72	1.14
	$\pi_6^c tt$	15.1	8.76	5.30	3.38	2.08	1.35	0.94

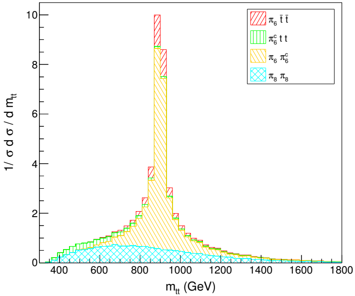
Number of events for each channel with an integrated luminosity $\int Ldt = 100\ \text{fb}^{-1}$ at Run II after cuts. For the sextet, we used $a_R = 1$ (upper block) and $a_R = 2$ (lower block).

G. Cacciapaga, H. Cai, A. Deandrea, TF, S. J. Lee, A. Parolini [JHEP11(2015)201]

Effective description and phenomenology

Are π_6 and π_8 resonances distinguishable? Yes!





G. Cacciapaga, H. Cai, A. Deandrea, TF, S. J. Lee, A. Parolini [JHEP11(2015)201]

- A heavy $\pi_6 \to tt$ resonance yields a large opening angle between the same-sign dileptons, while for a π_8 resonance, the same-sign dileptons are only weakly correlated (left plot).
- Performing an invariant mass reconstruction of the $(l^+\nu b)(l^+\nu b)$ system yields a peak for a π_6 resonance but not for π_8 (right plot).

Conclusions

- Composite Higgs models provide a viable solution to the hierarchy problem. Realizing quark masses via partial compositeness requires quark partners.
- Top partners (in the MCHM) are constraint from run I to $M_X \gtrsim 800\,\mathrm{GeV}$.
- For run II, single-production channels and strongly boosted top, W, Higgs, and Z searches become important.
  Examples:
  - For $X_{5/3}$, the semi-leptonic decay channel has good discovery reach.
  - For charge 2/3 top partners, we presented a comprehensive analysis of the most promising final states from T' decays.
    Shown here: $T' \to Z_{\mathrm{inv}}\, t_{\mathrm{had}}$. Please see [arXiv:1507.06568] for many other channels and simulation details.
- EFT descriptions of composite Higgs models are only a part of the story. UV embeddings need to be studied and will lead to novel LHC signatures.

Backup

Composite Higgs Model, background

The Goldstone boson matrix (in unitary gauge)

$$U(\Pi) = \exp\left(\frac{i}{f}\Pi_i T^i\right) = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos \overline{h}/f & \sin \overline{h}/f \\ 0 & 0 & 0 & -\sin \overline{h}/f & \cos \overline{h}/f \end{pmatrix},$$

where $\Pi = (0, 0, 0, \overline{h})$ with $\overline{h} =< h > +h$
and T^i are the broken $SO(5)$ generators.

Definition of d and e symbols:

$$d_\mu^i = \sqrt{2}\left(\frac{1}{f} - \frac{\sin \Pi/f}{\Pi}\right)\frac{\vec{\Pi}\cdot\nabla_\mu\vec{\Pi}}{\Pi^2}\Pi^i + \sqrt{2}\frac{\sin\Pi/f}{\Pi}\nabla_\mu\Pi^i$$

$$e_\mu^a = -A_\mu^a + 4\,i\,\frac{\sin^2(\Pi/2f)}{\Pi^2}\vec{\Pi}^t t^a \nabla_\mu \vec{\Pi}$$

d_μ symbol transforms as a fourplet under the unbroken $SO(4)$ symmetry, while e_μ belongs to the adjoint representation.
$\nabla_\mu\Pi$ is the "covariant derivative" of the Goldstone field Π

$$\nabla_\mu\Pi^i = \partial_\mu\Pi^i - iA_\mu^a\left(t^a\right)^i{}_j\,\Pi^j\,,$$

A_μ: gauge fields of the gauged subgroup of $SO(4) \simeq SU(2)_L \times SU(2)_R$

$$A_\mu = \frac{g}{\sqrt{2}}W_\mu^+\left(T_L^1 + iT_L^2\right) + \frac{g}{\sqrt{2}}W_\mu^-\left(T_L^1 - iT_L^2\right) + g\left(c_w Z_\mu + s_w A_\mu\right)T_L^3 + g'\left(c_w A_\mu - s_w Z_\mu\right)T_R^3\,.$$

Explicit form in unitary gauge:

$$\begin{cases} e_L^{1,2} = -\cos^2\left(\frac{\overline{h}}{2f}\right) W_L^{1,2} \\ e_L^3 = -\cos^2\left(\frac{\overline{h}}{2f}\right) W^3 - \sin^2\left(\frac{\overline{h}}{2f}\right) B \end{cases}, \begin{cases} e_R^{1,2} = -\sin^2\left(\frac{\overline{h}}{2f}\right) W_L^{1,2} \\ e_R^3 = -\cos^2\left(\frac{\overline{h}}{2f}\right) B - \sin^2\left(\frac{\overline{h}}{2f}\right) W^3 \end{cases}$$

and

$$\begin{cases} d_\mu^{1,2} = -\sin(\overline{h}/f)\frac{W_\mu^{1,2}}{\sqrt{2}} \\ d_\mu^3 = \sin(\overline{h}/f)\frac{B_\mu - W_\mu^3}{\sqrt{2}} \\ d_\mu^4 = \frac{\sqrt{2}}{f}\partial_\mu h, \end{cases} .$$

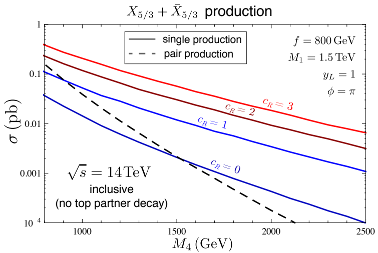
Example/Application: kinetic term for the "Higgs" using CCWZ:

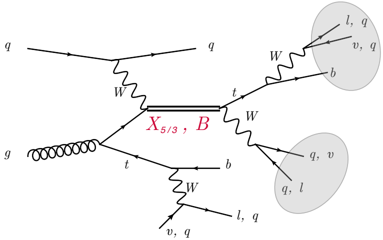
$$\mathcal{L}_{\Pi} = \frac{f^2}{4} d^i_\mu d^{i\mu} \quad = \quad \frac{1}{2}(\partial_\mu h)^2 + \frac{g^2}{4} f^2 \sin^2\left(\frac{\bar{h}}{f}\right)\left(W_\mu W^\mu + \frac{1}{2c_w} Z_\mu Z^\mu\right)$$

$$\Rightarrow v = 246 \text{ GeV } = f \sin\left(\frac{< h >}{f}\right) \equiv f \sin(\epsilon).$$

Prospects for composite quark partners at LHC run II

Search for top partners in the $q\bar{t}tW$ final state with semi-leptonic decay of tW.





The final state is characterized by		We use this by
- a high energy forward jet	$\rightarrow$	used as a tag
- two b's	$\Rightarrow$	demand two b-tags
- a highly boosted tW system with:		
– one hard lepton,	$\rightarrow$	$p_T^l > 100\,\mathrm{GeV}$ cut
– missing energy,		
– "fat jets",	$\rightarrow$	reconstruct boosted t/W using Template Overlap Method (TOM)

Prospects for composite quark partners at LHC run II

Search for top partners in the $q\bar{t}tW$ final state with semi-leptonic decay of tW.

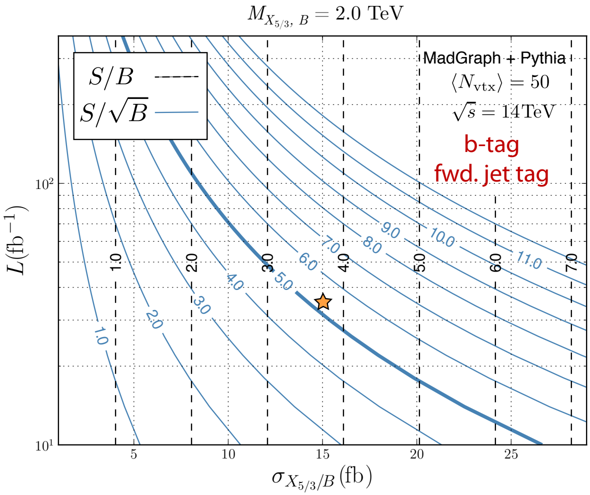
M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

$M_{X_{5/3}/B} = 2.0$ TeV, $\sigma_{X_{5/3}+B} = 15$ fb, $L = 35\,\text{fb}^{-1}$, $\langle N_{\text{vtx}}\rangle = 50$

$X_{5/3}+B$	σ_s [fb]		$\sigma_{t\bar{t}}$ [fb]		$\sigma_{W+\text{jets}}$ [fb]		ϵ_s		$\epsilon_{t\bar{t}}$		$\epsilon_{W+\text{jets}}$		S/B		$S/\sqrt{B}$	
Fat jet candidate	t	W	t	W	t	W	t	W	t	W	t	W	t	W	t	W
Basic Cuts	1.6	2.3	76.0	556.0	5921.0	3879.0	0.36	0.51	0.06	0.46	0.19	0.12	3×10^{-4}	4×10^{-4}	0.1	0.1
$p_T > 700$ GeV	1.3	2.0	60.0	506.0	1322.0	1082.0	0.28	0.45	0.05	0.42	0.04	0.04	9×10^{-4}	8×10^{-4}	0.2	0.2
$p_T^l > 100$ GeV	1.2	1.9	23.0	349.0	912.0	733.0	0.27	0.41	0.02	0.29	0.03	0.02	0.001	0.001	0.2	0.2
$Ov > 0.5$	1.0	1.3	12.0	170.0	354.0	254.0	0.23	0.30	0.01	0.14	0.01	0.008	0.003	0.002	0.3	0.3
$M_{X_{5/3}/B} > 1.5$ TeV	0.9	1.2	0.7	106.0	168.0	160.0	0.20	0.26	6×10^{-4}	0.09	0.006	0.005	0.005	0.003	0.4	0.3
$m_{jl} > 300$ GeV	0.8	0.4	0.5	12.0	111.0	27.0	0.17	0.08	4×10^{-4}	0.01	0.004	9×10^{-4}	0.007	0.02	0.4	0.7
b-tag & no fwd. tag	**0.3**	0.1	**0.08**	2.7	**0.2**	0.5	0.07	0.03	7×10^{-5}	0.002	5×10^{-6}	2×10^{-5}	**1.3**	0.09	**3.7**	1.0
fwd. tag & no b-tag	**0.5**	0.3	**0.2**	3.7	**32.0**	7.8	0.10	0.06	2×10^{-4}	0.003	0.001	3×10^{-4}	**0.02**	0.05	**0.6**	0.9
b-tag and fwd. tag	**0.2**	0.1	**0.03**	0.9	**0.03**	0.1	0.05	0.02	2×10^{-5}	7×10^{-4}	1×10^{-6}	4×10^{-6}	**3.7**	0.2	**5.3**	1.3

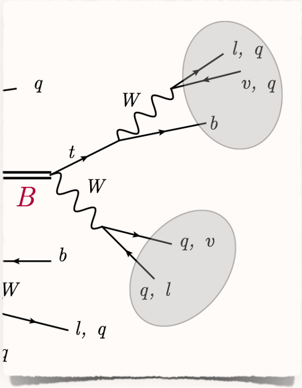
Table 5. Example cutflow for signal and background events **in the presence of** $\langle N_{\text{vtx}}\rangle = 50$ **interactions per bunch crossing**, for $M_{X_{5/3}/B} = 2.0$ TeV and inclusive cross sections $\sigma_{X_{5/3}/B}$. No pileup subtraction/correction techniques have been applied to the samples. $\sigma_{s,t\bar{t},W+\text{jets}}$ are the signal/background cross sections including all branching ratios, whereas ϵ are the efficiencies of the cuts relative to the generator level cross sections. The results for $M_{X_{5/3}/B} = 2.0$ TeV assume both $X_{5/3}$ and B production.

Prospects for composite quark partners at LHC run II



M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

Tagging of **Boosted Objects**



from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Tagging of **Boosted Objects**

- We use the **Template Overlap Method (TOM)**
  - Low susceptibility to pileup.
  - Good rejection power for light jets.
  - Flexible Jet Substructure framework
    (**can tag tops, Higgses, Ws ...**)

For a gruesome amount of detail on TOM see:

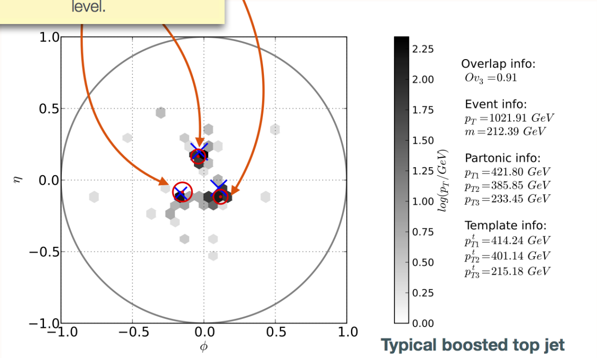
Almeida, Lee, Perez, Sterman, Sung - Phys.Rev. D82 (2010) 054034
MB, Juknevich, Perez - JHEP 1307 (2013) 114
Almeida, Erdogan, Juknevich, Lee, Perez, Sterman - Phys.Rev. D85 (2012) 114046
MB, Gabizon, Juknevich, Perez, Soreq - JHEP 1404 (2014) 176

from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Tagging of **Boosted Objects**

The red dots with circles are **peak template momenta.** They represent the "most likely" top decay configuration at a parton level.

Blue - positions of truth level top decay products.
Gray - Calorimeter energy depositions.
Red - Peak template positions.



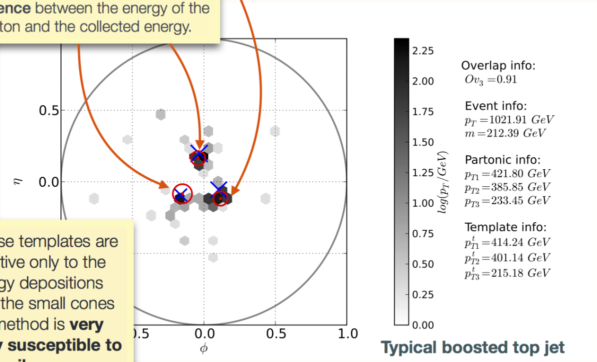
Typical boosted top jet

from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Tagging of **Boosted Objects**

Blue - positions of truth level top decay products.
Gray - Calorimeter energy depositions.
Red - Peak template positions.

Templates are matched to jet energy distribution **by collecting radiation within some small cone around each parton and minimizing the difference** between the energy of the parton and the collected energy.



Typical boosted top jet

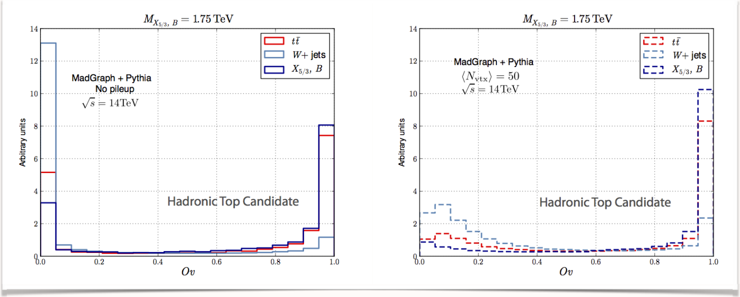
Because templates are sensitive only to the energy depositions within the small cones the method is **very weakly susceptible to pileup.**

from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Tagging of **Boosted Objects**

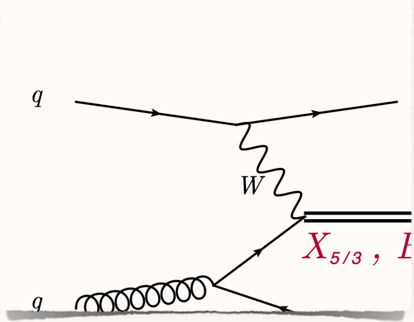
- **Template Overlap Method**
  - Good rejection power for light jets.
  - Flexible Jet Substructure framework (**can tag t, h, W ...**)

No Pileup **50 avg. pileup**



from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

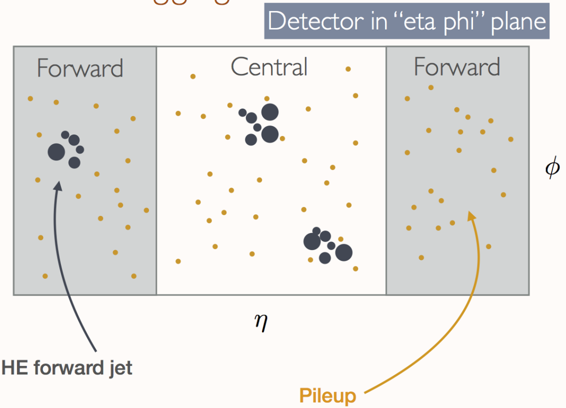
Forward Jet Tagging



Forward Jets as useful tags of top partner production also proposed in:
De Simone, Matsedonskyi, Rattazzi Wulzer JHEP 1304 (2013) 004

from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Forward Jet Tagging



Seems easy, but actually quite difficult!

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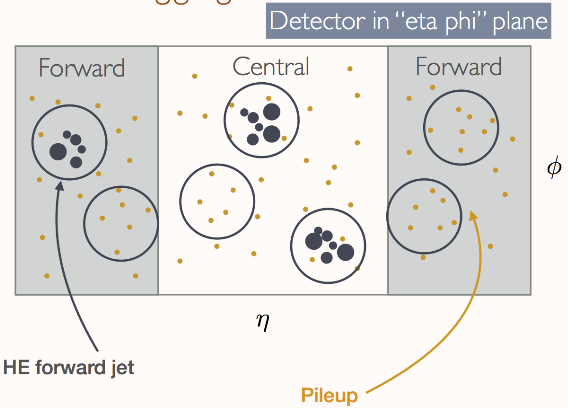
Forward Jet Tagging



Complicated at high pileup (**fake jets appear**)

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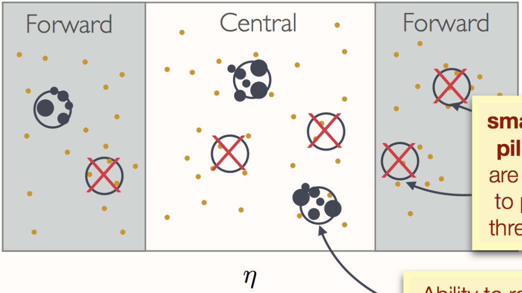
Forward Jet Tagging

Detector in "eta phi" plane



small radius pileup jets are less likely to pass a p_T threshold cut

Ability to reco. the jet energy/p_T is diminished, by we are interested **in tagging the forward jet, not measuring it**

(Simple) Solution:

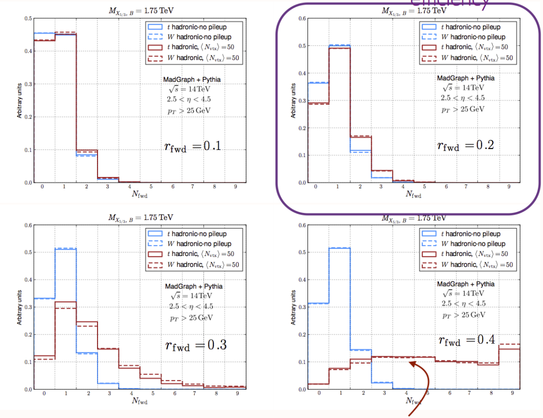
Define forward jets as (say) r = 0.2 jets with

$$p_T^{\rm fwd} > 25\ {\rm GeV}, \quad 2.5 < \eta^{\rm fwd} < 4.5\,,$$

from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Forward Jet Tagging

r = 0.2 - good compromise between pileup insensitivity and signal efficiency



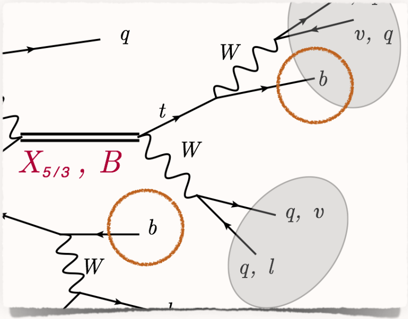
Blue - No Pileup

Red - 50 Pileup Events

Standard ATLAS r = 0.4 **forward jet will not work** without some aggressive pileup subtraction technique (**open problem!**)

from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

b-tagging Strategy



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b-tagging Strategy

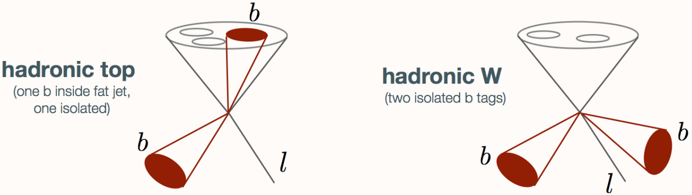
Full simulation of b-tagging requires consideration of complex detector effects (e.g. tracking info).

We use a **simplified approach**:

Assign a "b-tag" to every r = 0.4 jet which has a truth level b or c jet within dr = 0.4 from the jet axis.

For each "b-tag" we use the benchmark efficiencies:

$$\epsilon_b = 0.75, \ \epsilon_c = 0.18, \ \epsilon_l = 0.01$$



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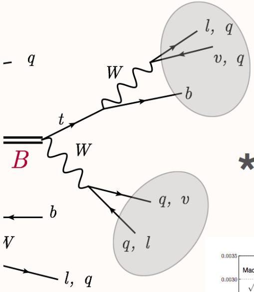
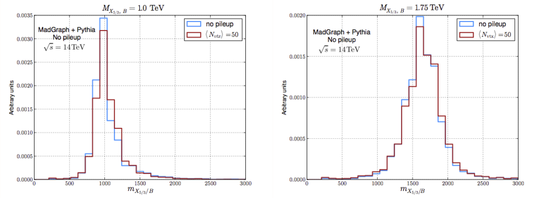
We can reconstruct the **resonance mass**



- Use the peak template (pileup insensitive)*:
  - **hadronic top:** $m_X^2 = (p^{\text{temp}} + p^l + p^\nu)^2$
  - **hadronic W:** $m_X^2 = (p^{\text{temp}} + p^l + p^\nu + p^b)^2$

* because of a **boosted topology**, assigning $\eta_\nu = \eta_l$ works well for the purpose of resonance reconstruction.

red - pileup   blue - no pileup



Note: very **difficult to reconstruct the resonance mass** with same sign **di-leptons**!

from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Composite Higgs models and flavor

Why is flavor a problem in CHM?
The Lagrangian up-sector Lagrangian (for Q, q, t in **5**)

$$\mathcal{L}_{comp} = i\overline{Q}_{L,R}\left(D+E\right)Q_{L,R} + i\overline{\tilde{T}}_{L,R}D\tilde{T}_{L,R} - M_4\left(\overline{Q}_L Q_R + \overline{Q}_R Q_L\right) - M_1\left(\overline{\tilde{T}}_L\tilde{T}_R + \overline{\tilde{T}}_R\tilde{T}_L\right) + ic_L\overline{Q}^i_L\gamma^\mu d^i_\mu\tilde{T}_L + ic_R\overline{Q}^i_R\gamma^\mu d^i_\mu\tilde{T}_R + \text{h.c.}$$

$$-\mathcal{L}_{mix} = y_{L4,1}f\overline{q}^5_{3L}U\psi_R + y_{R4,1}f\overline{t}^5_R U\psi_L + \text{h.c.}$$
$$= y_{L4}f\left(\overline{b}_L B_R + c^2_{\theta/2}\overline{t}_L T_R + s^2_{\theta/2}\overline{t}_L X_{2/3R}\right) - \frac{y_{L1}f}{\sqrt{2}}s_\theta\overline{t}_L\tilde{T}_R + y_{R4}f\left(\frac{s_\theta}{\sqrt{2}}\overline{t}_R T_L - \frac{s_\theta}{\sqrt{2}}\overline{t}_R X_{2/3L}\right) + y_{R1}fc_\theta\overline{t}_R\tilde{T}_L + h.c.\,,$$

(where $\theta = \frac{h+\langle h\rangle}{f}$).
...plus a similar down-sector lagrangian
... plus additional composite resonances (scalars, vectors, ...).
All quarks obtain mass from PC $\Rightarrow$ promote all M, y, c to matrices in flavor space.
$\Rightarrow$ many (!!) angles and phases $\Rightarrow$ FCNCs from Z, h, and resonance exchange.

Composite Higgs models and flavor

First solution: Minimally Flavor violating composite Higgs setup.

Redi, Weiler [JHEP 1111 (2011) 108]

- Assume fully flavor symmetric strong sector.
- Assume $\lambda_R \propto \mathbb{1}$.
- Adjust λ_L to reproduce quark masses and CKM matrix.

This produces a scenario in which RH quarks are mostly composite, and all quark partners have similar mass.
Other solutions:

- Avoid large FCNC's by postulating flavor symmetries on all (or only the light) families Barbieri *et al.* [JHEP 1207,181], Niehoff, Stangl, Straub [arXiv:1508.00569]
- "RS / 5D inspired" *c.f. e.g.* Csaki etal. [JHEP 0804, 006 (2008)], Csaki, Falkowski, Weiler [JHEP 0809, 008], Csaki, Perez, Surujon, Weiler [PRD81 (2010) 075025

All these approaches yield partners to all quarks at a similar scale.

Question: Can a model with only 3rd generation partners pass flavor bounds?

The setup

- Realize one up-type quark ("the top") as partially composite.
- Realize one down-type quark ("the bottom") as partially composite.
  [One economic way: Embed the b_R into **14**. This allows PC mixing term:

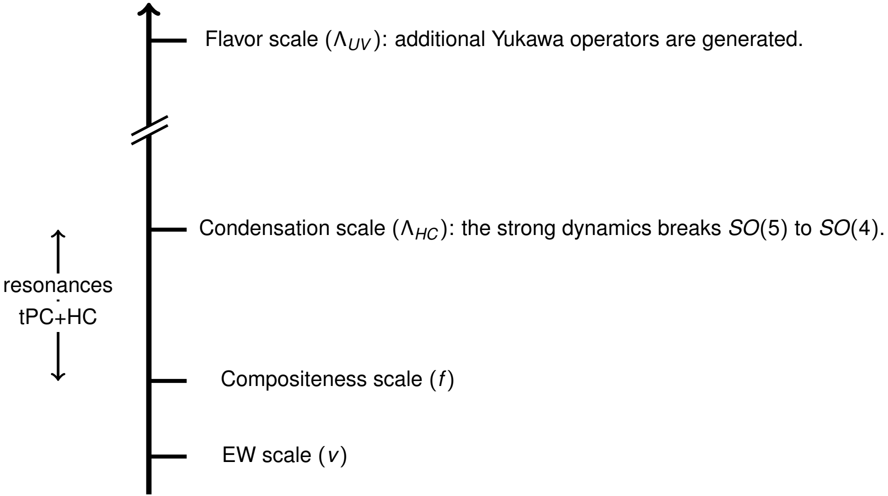
$$\mathcal{L} = y_R f \,\overline{\psi}_L U^t d^{14}_{3R} \Sigma + h.c. = \frac{1}{2} y_R f s_\theta \overline{B}_L b_R + h.c. \,.$$

  where $\Sigma = U \cdot (0,0,0,0,1)^T$.]
- Assume that new high-scale physics ($\sim 10^5\,\mathrm{TeV}$) induces "light" masses for quark bilinears (mass à la technicolor):

$$\begin{aligned}
\mathcal{L}_Y &= \overline{q}_{L,\alpha} \lambda^u_{\alpha,\beta} u_{R,\beta}\, \mathcal{O}_u + \bar{\tilde{q}}_{L,\alpha} \lambda^d_{\alpha,\beta} d_{R\beta}\, \mathcal{O}_d + h.c. \\
&\to \sqrt{2}\, (\overline{q}_{\alpha L}{}^5 \Sigma) m^u_{\mathrm{UV}\alpha\beta} (\Sigma^T u^5_{\beta R}) + \sqrt{2}\, (\bar{\tilde{q}}^5_{\alpha L} \Sigma) m^d_{\mathrm{UV}\alpha\beta} (\Sigma^T d^5_{\beta R}) + h.c. \\
&= \frac{s_{2\theta}}{2} \left[\overline{u}_{\alpha L} m^u_{\mathrm{UV}\alpha\beta} u_{\beta R} + \overline{d}_{\alpha L} m^d_{\mathrm{UV}\alpha\beta} d_{\beta R} \right] + h.c.
\end{aligned}$$

where $\tilde{m}^{u,d}_{\alpha\beta} \equiv s_{2\epsilon} m^{u,d}_{\mathrm{UV}} \sim O(m_c, m_s)$.

The setup


Flavor scale (Λ_{UV}): additional Yukawa operators are generated.
Condensation scale (Λ_{HC}): the strong dynamics breaks $SO(5)$ to $SO(4)$.
resonances
tPC+HC
Compositeness scale (f)
EW scale (v)

Such a setup yields mass matrices

$$M_{\rm up} = \begin{pmatrix} \tilde{m}[\epsilon]_{11} & \tilde{m}[\epsilon]_{12} & \tilde{m}[\epsilon]_{13} & 0 & 0 & 0 \\ \tilde{m}[\epsilon]_{21} & \tilde{m}[\epsilon]_{22} & \tilde{m}[\epsilon]_{23} & 0 & 0 & 0 \\ \tilde{m}[\epsilon]_{31} & \tilde{m}[\epsilon]_{32} & \tilde{m}[\epsilon]_{33} & f y_{L4} \cos^2\frac{\epsilon}{2} & f y_{L4} \sin^2\frac{\epsilon}{2} & -f\frac{y_{L1}}{\sqrt{2}}\sin\epsilon \\ 0 & 0 & f\frac{y_{R4}^*}{\sqrt{2}}\sin\epsilon & M_4 & 0 & 0 \\ 0 & 0 & -f\frac{y_{R4}^*}{\sqrt{2}}\sin\epsilon & 0 & M_4 & 0 \\ 0 & 0 & f y_{R1}^*\cos\epsilon & 0 & 0 & M_1 \end{pmatrix}.$$

and Yukawa matrices

$$Y_{\rm up}^{mix} = \begin{pmatrix} \tilde{y}[\epsilon]_{11} & \tilde{y}[\epsilon]_{12} & \tilde{y}[\epsilon]_{13} & 0 & 0 & 0 \\ \tilde{y}[\epsilon]_{21} & \tilde{y}[\epsilon]_{22} & \tilde{y}[\epsilon]_{23} & 0 & 0 & 0 \\ \tilde{y}[\epsilon]_{31} & \tilde{y}[\epsilon]_{32} & \tilde{y}[\epsilon]_{33} & -\frac{y_{L4}}{2}\sin\epsilon & \frac{y_{L4}}{2}\sin\epsilon & -\frac{y_{L1}}{\sqrt{2}}\cos\epsilon \\ 0 & 0 & \frac{y_{R4}^*}{\sqrt{2}}\cos\epsilon & 0 & 0 & 0 \\ 0 & 0 & -\frac{y_{R4}^*}{\sqrt{2}}\cos\epsilon & 0 & 0 & 0 \\ 0 & 0 & -y_{R1}^*\sin\epsilon & 0 & 0 & 0 \end{pmatrix},$$

where $\tilde{y}[\epsilon]_{\alpha\beta} \equiv c_{2\epsilon}\frac{m^u_{\mathrm{UV}\alpha\beta}}{f}$ (and analogous for the down-sector).

Block-diagonalizing the mass matrix yields:

$$m_U \simeq \frac{s_{2\epsilon}}{2} m^u_{\rm UV} + m_t \delta_{33}$$

$$y_u \simeq \frac{m_U}{f s_{2\epsilon}/2}\left(1 - \frac{1}{2} s^2_{2\epsilon}\right) + B_u\,, \quad \text{where} \quad B_u \sim \frac{\Sigma_u}{M_*^2}\,,$$

with

$$\Sigma_u \sim \begin{pmatrix} m_c^2 & m_c^2 & m_c m_t \\ m_c^2 & m_c^2 & m_c m_t \\ m_c m_t & m_c m_t & m_t^2 \end{pmatrix}.$$

...and analogous for the down-type sector.
Charged and neutral currents are also proportional to $B_{u,d}$.
Finally, diagonalizing the light sector fully yields

$$m_U = V_{uL} M_U^{diag} V_{uR}^\dagger \quad \text{where} \quad V_{uL,R} \sim \begin{pmatrix} O(1) & O(1) & O(\frac{m_c}{m_t}) \\ O(1) & O(1) & O(\frac{m_c}{m_t}) \\ O(\frac{m_c}{m_t}) & O(\frac{m_c}{m_t}) & 1 \end{pmatrix}.$$

Key point: Flavor changing observables with light quarks are suppressed by additional powers of m_c/m_t and/or m_s/m_b as compared to the “standard ” calculation.

One can go through the standard list of constraints. We looked at

- effects from h, Z, W exchange,
- effects from heavy resonance exchange,
- UV contributions from heavy flavor scale physics

on

- $Z \to b\bar{b}$,
- CKM unitarity,
- $\Delta F = 2$ FCNCs,
- $\Delta F = 1$ FCNCs.

Resulting bounds on V_{dL} (setting $V_{uR,L}$ to the values from above)

$$\begin{aligned}
\text{Z boson FCNCs} \quad &\Rightarrow \quad |V^*_{dL33} V_{dL13}| < 10^{-1}\,, \ |V^*_{dL33} V_{dL23}| < 10^{-1/2}\,, \ |V^*_{dL13} V_{dL23}| < 10^{-5/2}\,, \\
\text{CKM unitarity} \quad &\Rightarrow \quad |V_{dL13}| < 10^{-1}\,, \quad |V_{dL23}| < 10^{-1/2}\,, \\
\text{Scalar resonance} \quad &\Rightarrow \quad |z_4^{db}| < 1 \div 10^{-2}\,, \quad |z_4^{sb}| < 1 \div 10^{-1/2}\,, \quad |z_4^{ds}| < 10^{-4} \div 10^{-6}\,, \\
\text{Vector resonance} \quad &\Rightarrow \quad |V^*_{dL33} V_{dL31}| < 10^{-1} \div 10^{-3}\,, \quad |V^*_{dL33} V_{dL32}| < 1 \div 10^{-2}\,, \\
&\qquad |V^*_{dL32} V_{dL31}| < 10^{-3} \div 10^{-5}\,.
\end{aligned}$$

where

$$z_4^{d_\alpha d_\beta} = V^*_{dL3\alpha} V_{dL3\beta} \sum_{\gamma\delta} V_{dR\gamma\beta} V^*_{dR\delta\alpha}\,.$$

... in good accord with m_s/m_b suppressions in expected form of V_{dL}.

Problems:

- To fully reproduce the CKM matrix, the UV flavor scale mass matrix needs to be specified.
- Neutron EDM (requires knowledge of UV flavor scale mass matrix).

Virtues:

- We looked at generalizations to other quark and quark partner embeddings into $SO(5)$, and find that the key point (suppression of FCNCs by powers of m_c/m_t) occurs for generic quark embeddings.
- We looked at generalizations to larger cosets. The suppressions mainly depend on the $SU(2) \times U(1)$ quantum numbers of the partners. Therefore the concept still applies. The only thing that needs to be checked individually: Interactions with / FCNCs from additional Goldstone Bosons.