Searching for highly boosted new physics signatures: moving from LHC run I to higher energies

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C. Delaunay, TF, J. Gonzales-Fraile, S.J. Lee, G. Panico, G. Perez [JHEP 02 (2014) 055]

TF, J.H. Kim, S.J. Lee, S.H. Lim [JHEP 1405 (2014) 123]

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

M. Backović, TF, J.H. Kim, S.J. Lee [arXiv: 1410.8131]

M. Backović, TF, J.H. Kim, S.J. Lee [arXiv: 1501.07456]

Flavor and top physics @ 100 TeV
IHEP

Outline

- Motivation
- A sample model: minimal composite Higgs from $SO(5)/SO(4)$ breaking
  - The Lagrangian
  - Overview on quark partner phenomenology
- Constraints on composite quark partners from run I
- Prospects for composite quark partners at higher energies
- Conclusions and Outlook

Motivation / Overview

☺ 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 $m_h, v \ll M_{pl}$.

$\rightarrow$ requires new particle content "near" the EW scale.
To evade detection until today, the new sector needs to be

1. hidden (mainly interacting with the SM through the Higgs)
2. and/or heavy (charged under SM but avoiding copious production by mass)

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

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

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

A sample model: Composite Higgs

- 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 $v \sim m_h < f \lll M_{pl}$.

Simplest realization:

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

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

- The Goldstone bosons live in $SO(5)/SO(4) \rightarrow$ 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^3_R assigns hyper charge to it. Later: Include a global $U(1)_X$ and gauge $Y = T^3_R + X$.
  $\Rightarrow$ Correct quantum numbers for the Goldstone bosons to be identified as a non-linear realization of the Higgs doublet.

A sample model: Composite Higgs

We use the CCWZ construction to construct the low-energy EFT.
Coleman, Wess, Zumino [1969], Callan, Coleman [1969]
Central element: the Goldstone boson matrix $U(\Pi) = \exp\left(\frac{i}{f}\Pi_i T^i\right)$, where $\Pi = (0, 0, 0, \overline{h})$ with $\overline{h} = < h > + h$ and T^i are the broken $SO(5)$ generators.

From it, one can construct the CCWZ d^i_μ and e^a_μ symbols (see e.g. talk by Juan Jose Sanz-Cillero)
E.g. kinetic term for the "Higgs":

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

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

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 (← implementation in CHM?).

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:

$$q_L^5 = \frac{1}{\sqrt{2}} \begin{pmatrix} i d_L \\ d_L \\ i u_L \\ -u_L \\ 0 \end{pmatrix}, \quad u_R^5 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ u_R \end{pmatrix}, \quad \psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}.$$

BSM particle content (per u-type quark):

	U	$X_{2/3}$	D	$X_{5/3}$	$\tilde{U}$
$SO(4)$	**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:

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

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

Derivation of Feynman rules:

- expand d_μ, e_μ, U_{gs} around $\langle h \rangle$,
- diagonalize the mass matrices,
- match the lightest mass eigenvalue with the SM quark mass
  $\rightarrow$ this fixes y_L in terms of the other parameters
  (light quarks: $m_q \ll v/\sqrt{2}$; if $y_R \sim 1 \Rightarrow y_L \ll 1$)
  (top quark: $m_t \sim v/\sqrt{2}$; requires $y_R \sim 1$ and $y_L \sim 1$)
- calculate the couplings in the mass eigenbasis.

Masses and couplings

The SM like quark:

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

Partners in the **4**:

$$\begin{aligned} M_{X5/3} &= \quad M_4 &&= M_{Uf1} + \mathcal{O}(\epsilon^2) \\ M_D &= \sqrt{M_4^2 + y_L^2 f^2} &&= M_{Uf2} + \mathcal{O}(\epsilon^2) \end{aligned}$$

Singlet Partner:

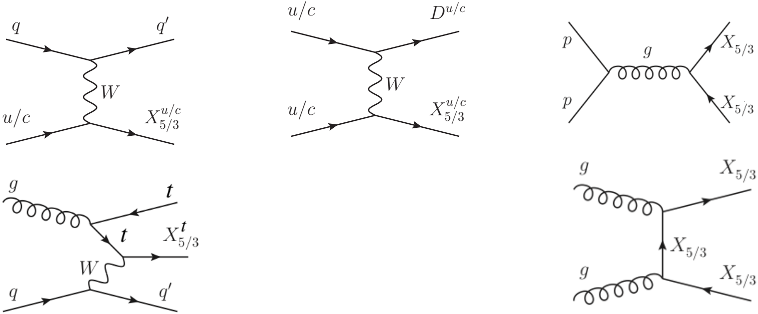
$$M_{Us} = \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2)$$

Couplings (examples):

$$\begin{aligned} \left|g^R_{XWu}\right| &= \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left| \frac{y_R f\, M_1}{M_4 M_{Us}} - \sqrt{2} c_R \frac{y_R f}{M_{Us}} \right| + \mathcal{O}(\epsilon^3) \\ \left|g^L_{UsWd}\right| &= \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left(\frac{y_L f\,(M_1 M_4 + y_R^2 f^2)}{M_{Uf2} M_{Us}^2} - \frac{\sqrt{2} c_L y_L f}{M_{Uf2}} \right) + \mathcal{O}(\epsilon^3) \end{aligned}$$

Production and decays

Production mechanisms (shown here: $X_{5/3}$ production)



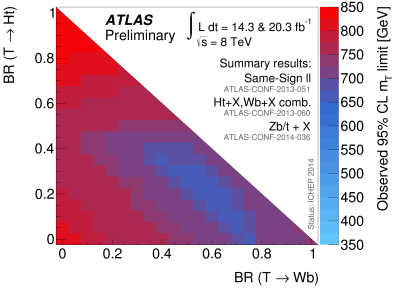
(a) EW single production (b) EW pair production (c) QCD pair production

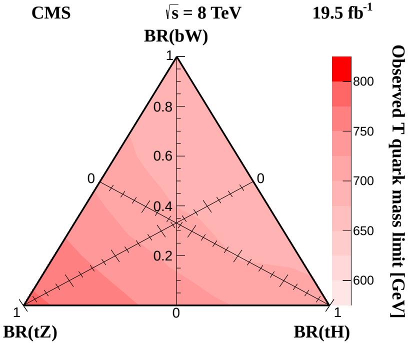
Decays:

- $X_{5/3} \to W^+ u$ (100%),
- $D \to W^- u$ ($\sim$ 100%),
- $U_{f1} \to Zu$ (dominant),
- $U_{f2} \to hu$ (dominant),
- light quark partner: $U_s \to hu$, top partner: also $U_s \to Zu$, $U_s. \to Wb$

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 [1409.5500] , $M_{X_{5/3}} > 800\,\mathrm{GeV}$ 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]



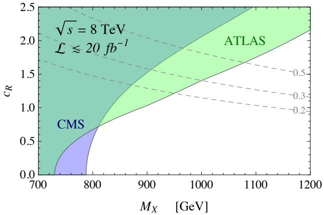


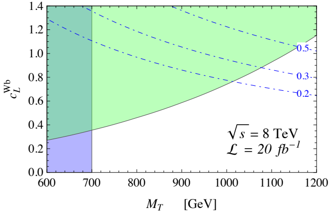
CMS [PLB 729, 149 (2014)]

Bounds on top partners from run I

- Bounds including single-production channels: Matsedonskyi, Panico, Wulzer [2014]

  for earlier work, see also Li, Liu, Shu [2013]





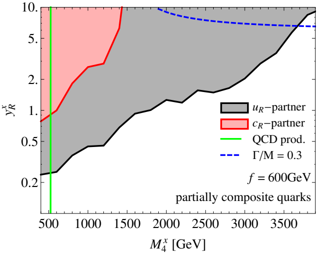
Note: In the above plots $c_R = 2g^R_{XWu}/g$ and $c_L^{Wb} = 2g^L_{UsWd}/g$ as compared to the coupling formulae given earlier.

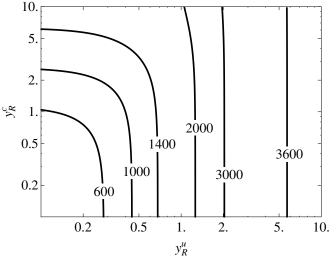
Determining bounds on partners of light quarks from run I

- Bounds on partners of light quarks in the **4**

  Delaunay, TF, Gonzales-Fraile, S.J. Lee, Panico, Perez [JHEP 02 (2014) 055]

  - From QCD pair production: $M_4^{u,d,s,c} > 530\,\mathrm{GeV}$
    (from ATLAS and CMS searches applicable to $WWjj$, $ZZjj$ final states)
  - Single production:
    (from ATLAS and CMS searches applicable to Wjj, Zjj final states)





- Bounds on partners of light quarks in the singlet

  TF, J. H. Kim, S. J. Lee, S. H. Lim [JHEP 1405 (2014) 123]

$$pp \to U_s \overline{U}_s \to jjhh \to \gamma\gamma X \quad \Rightarrow \quad M_1^{u,d,s,c} > 310\,\mathrm{GeV}$$

Prospects for composite quark partners at higher energiesI

At run II, we have more energy
$\Rightarrow$ 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 $\Rightarrow$ 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 optimized search strategy for top partners in the **4**.

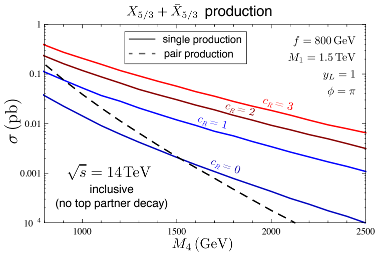
   M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]
2. $T \to tZ$: leptonic Z vs. $Z \to \nu\bar{\nu}$. Who wins?

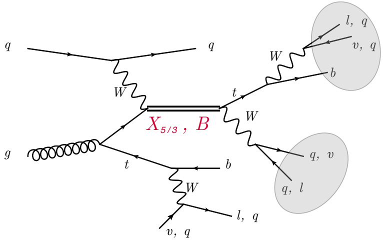
   M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1501.07456]
3. Maximizing the sensitivity for the "least visible" quark partner: An optimized search strategy for singlet partners of light quarks.

   M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1410.8131]

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)

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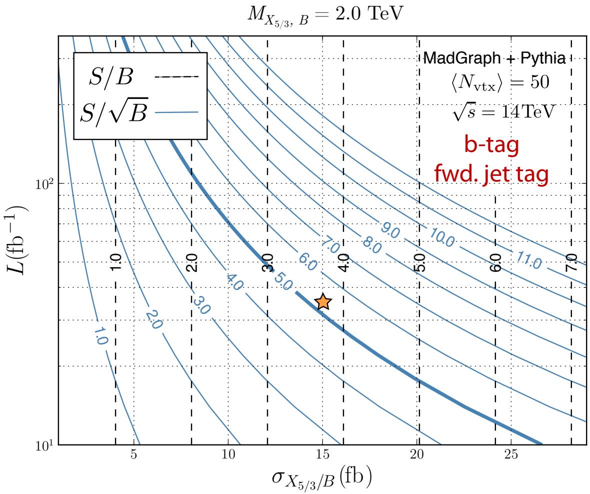
$M_{X_{5/3}/B} = 2.0$ TeV, $\sigma_{X_{5/3}+B} = 15\,\text{fb}$, $L = 35\,\text{fb}^{-1}$, $\langle N_{\text{vtx}}\rangle = 50$

$X_{5/3}+B$	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

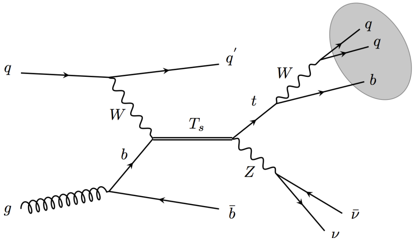


M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

Prospects for composite quark partners at LHC run II

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

M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1501.07456]



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 at LHC run II

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.

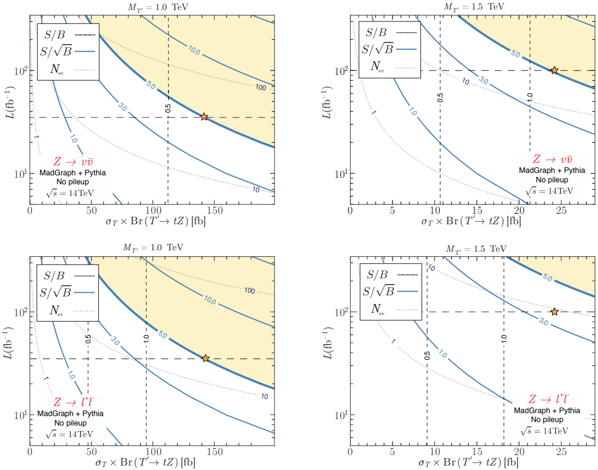
For the $\not{E}_T$ channel, we instead demand:

- 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 at LHC run II

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



M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1501.07456]

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.

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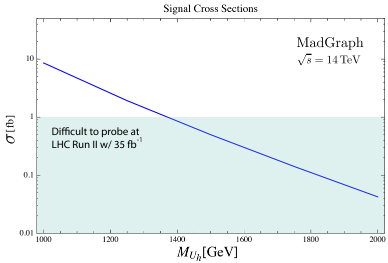
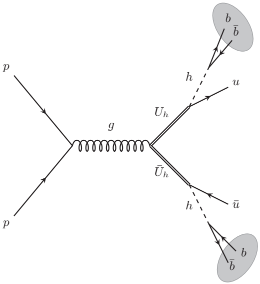




<table>
<tr><td rowspan="4">Cut Scheme</td><td rowspan="3">Basic Cuts</td><td>Demand at least four fat jets ($R = 0.7$) with
$p_T > 300$ GeV, $|\eta| < 2.5$</td></tr>
<tr><td>Declare the two highest p_T fat jets
satisfying $Ov_2^h > 0.4$ and $Ov_3^t < 0.4$
to be Higgs candidate jets.
At least 1b-tag on both Higgs candidate jets.</td></tr>
<tr><td>Select the two highest p_T light jets ($r = 0.4$), with $p_T > 25$ GeV
to be the u quark candidates.</td></tr>
<tr><td>Complex Cuts</td><td>$|\Delta_h| < 0.1$
$|\Delta_{U_h}| < 0.1$
$m_{U_{h1,2}} > 800$ GeV</td></tr>
</table>

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 [arXiv: 1410.8131]

	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}

Conclusions and Outlook

- 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 $M_X \gtrsim 800\,\mathrm{GeV}$.
- The phenomenology of light quark partners strongly differs from top-partner phenomenology.
  - For partially composite quarks with partners in the fourplet, we find a flavor and y_R independent bound of $M_4^{u/c} \gtrsim 525$ GeV as well as stronger flavor and y_R dependent bounds (*e.g.* $M_4^u \gtrsim 1.8$ TeV, $M_4^c \gtrsim 610$ GeV for $y_R^{u/c} = 1$).
  - For partially composite quarks with partners in the singlet, we find a flavor- and $\lambda_{\mathrm{mix}}^{\mathrm{eff}}$ independent bound of $M_{U_h} > 310\,\mathrm{GeV}$ as well as increased flavor-and $\lambda_{\mathrm{mix}}^{\mathrm{eff}}$-dependent bounds.
- For run II, single-production channels and strongly boosted top and Higgs searches become important.
  - Performing dedicated searches for boosted tops, the $X_{5/3}$ can be discovered even at masses beyond $2\,\mathrm{TeV}$.
  - Even the (currently weakest constraint) singlet partners of light quarks can be discovered at masses beyond $1\,\mathrm{TeV}$.

Qualitative Conclusions and Outlook

- When very heavy new particles are produced and decay into SM particles, the decay products are highly boosted.
- The reducible SM backgrounds (typically) decrease faster with increasing p_T than the signal $\Rightarrow$ for 'sufficiently high" M_X (high $\sqrt{s}$) one is left mainly with irreducible backgrounds.
- In this limit, searches including boosted tops, Z, W, Higgs, ... are most promising in the "most probable" channel (hadronic channels or $b\bar{b}$) ($S \propto B \propto BR \Rightarrow S/\sqrt{B} \propto \sqrt{BR}$)
- For low M_X (low $\sqrt{s}$), the best search channels are "clean" channels ($Z_{ll}, W_{lep}, t_{lep}, h_{\gamma\gamma}, h_{4l}$).
- The $M_X, \sqrt{s}$ at which "most probable" channels start dominating "clean" channels crucially depends on the efficiencies of identifying (hadronic / $b\bar{b}$) top (see talk by Michele Selvaggi), Z, W, Higgs.
  $\Rightarrow$ requires improved jet sub-structure techniques ("software")
  and depends on detector resolution/performance ("hardware").

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:

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

$$e^a_\mu = -A^a_\mu + 4\,i\,\frac{\sin^2\left(\Pi/2f\right)}{\Pi^2}\vec{\Pi}^t t^a \nabla_\mu\vec{\Pi}$$

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

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

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

$$A_\mu = \frac{g}{\sqrt{2}}W^+_\mu\left(T^1_L + iT^2_L\right) + \frac{g}{\sqrt{2}}W^-_\mu\left(T^1_L - iT^2_L\right) + g\left(c_w Z_\mu + s_w A_\mu\right)T^3_L + g'\left(c_w A_\mu - s_w Z_\mu\right)T^3_R\,.$$

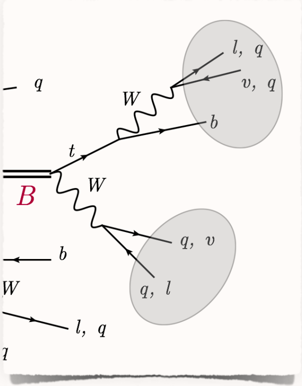
Explicit form in unitary gauge:

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

and

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

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:

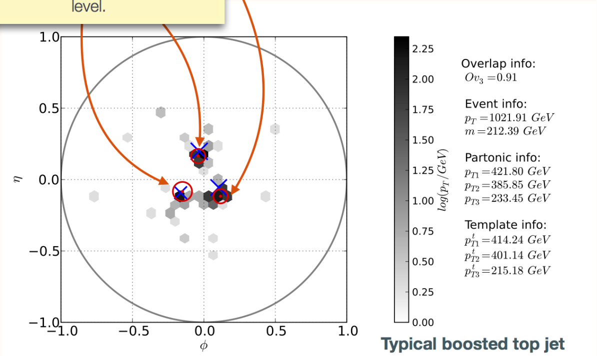
Almeida, Lee, Perez, Sterman, Sung - Phys.Rev. D82 (2010) 054034
MB, Juknevich, Perez - JHEP 1307 (2013) 114
Almeida, Erdogan, Juknevich, Lee, Perez, Sterman - Phys.Rev. D85 (2012) 114046
MB, Gabizon, Juknevich, Perez, Soreq - JHEP 1404 (2014) 176

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

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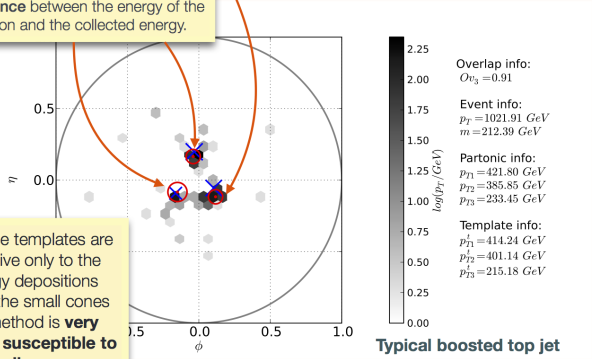
Tagging of **Boosted Objects**

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.**

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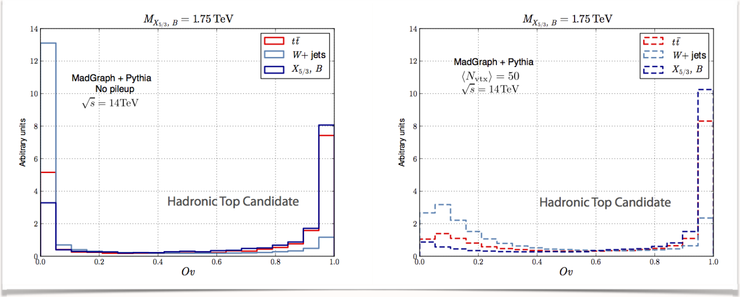
Tagging of **Boosted Objects**

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

No Pileup | 50 avg. pileup



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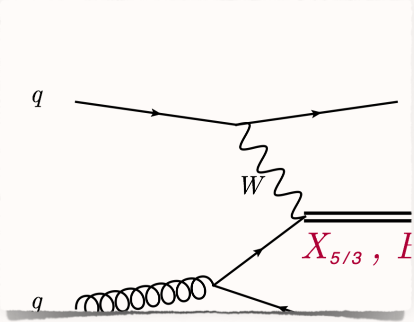
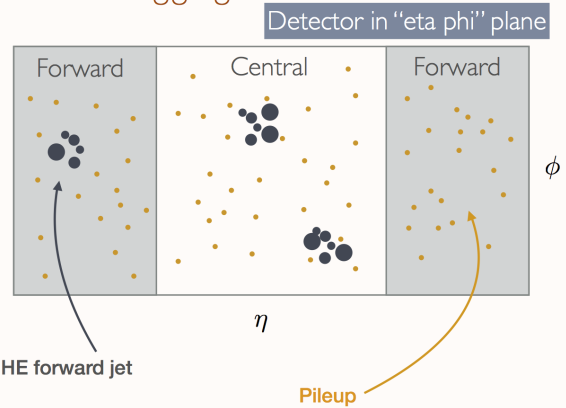
Forward Jet Tagging



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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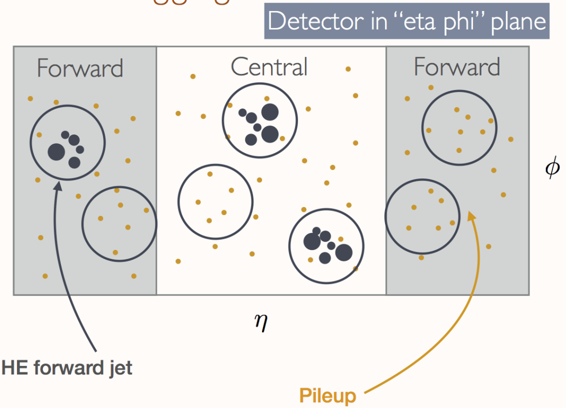
Forward Jet Tagging



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

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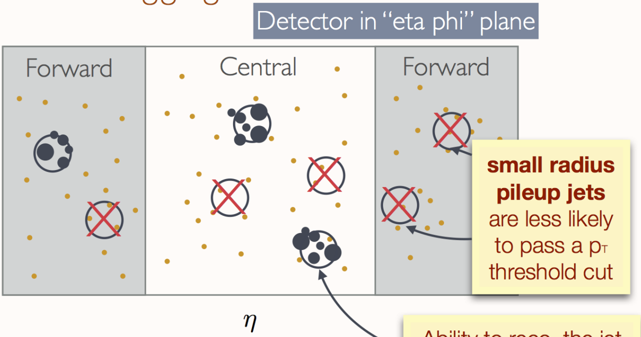
Forward Jet Tagging



(Simple) Solution:

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

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

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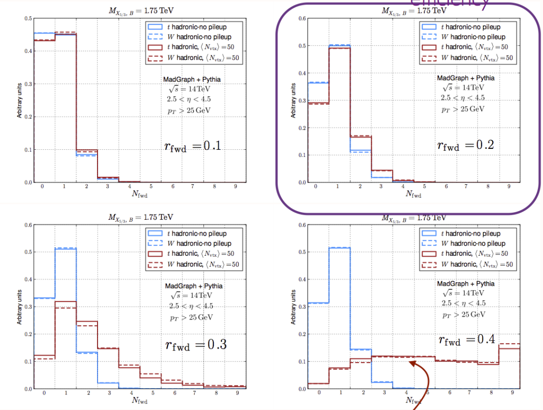
Forward Jet Tagging

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!**)

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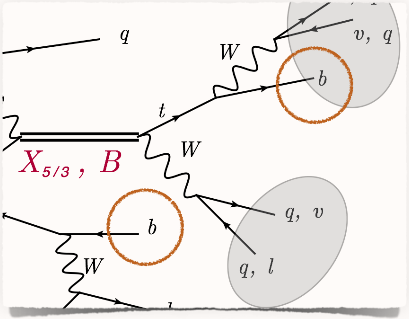
b-tagging Strategy



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b-tagging Strategy

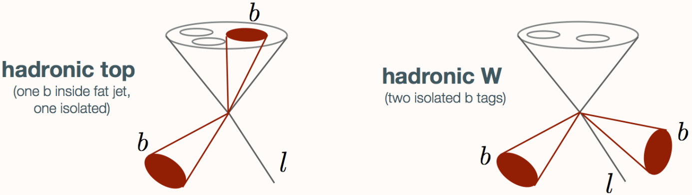
Full simulation of b-tagging requires consideration of complex detector effects (e.g. tracking info).

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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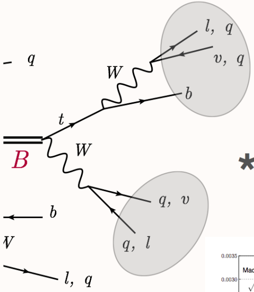
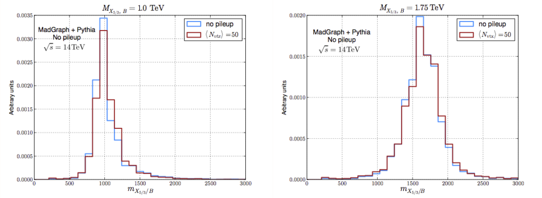
We can reconstruct the **resonance mass**



- 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**!

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