New search strategies for composite quark partners at the LHC Run II

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

TF, Jeong Han Kim,
S. J. Lee, Sung Hak Lim [JHEP 1405 (2014) 123]

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

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

DESY Theory seminar
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Outline

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^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.

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.

From it, one can construct the CCWZ d^i_μ and e^a_μ symbols
E.g. kinetic term for the "Higgs":

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

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

Note: In the above, the Higgs multiplet is parameterized as a Goldstone multiplet and it is *assumed* that a Higgs potential is induced which leads to EWSB.

Concrete realizations *c.f. e.g.* Review by Contino [2010], Panico *et al.* [2012], ...:
Couplings of the Higgs to the quark sector (most importantly to the top)*
explicitly break the $SO(5)$ symmetry.
$\Rightarrow$ Couplings to the top sector induce an effective potential for the Higgs which induces EWSB.

* *c.f.* Delaunay, Grojean, Perez [2013] for the influence of other quark partners on Higgs physics

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:

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

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:

$$\begin{aligned}\mathcal{L}_{comp} &= i\,\overline{Q}(D_\mu + ie_\mu)\gamma^\mu Q + i\overline{\tilde{U}}\not{D}\tilde{U} - M_4\overline{Q}Q - M_1\overline{\tilde{U}}\tilde{U} + \left(ic\overline{Q}^i\gamma^\mu d^i_\mu \tilde{U} + \text{h.c.}\right),\\ \mathcal{L}_{el,mix} &= i\,\overline{q}_L\not{D}q_L + i\,\overline{u}_R\not{D}u_R - y_L f\overline{q}^5_L U_{gs}\psi_R - y_R f\overline{u}^5_R U_{gs}\psi_L + \text{h.c.}\end{aligned}$$

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**:

$$M_{X5/3} = M_4 = M_{Uf1} + \mathcal{O}(\epsilon^2)$$

$$M_D = \sqrt{M_4^2 + y_L^2 f^2} = M_{Uf2} + \mathcal{O}(\epsilon^2)$$

Singlet Partner:

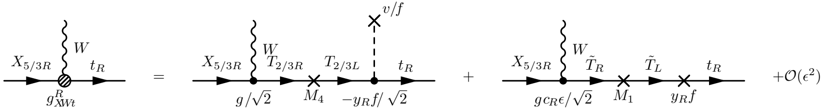
$$M_{Us} = \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2)$$

Couplings (examples):

$$\left|g^R_{XWu}\right| = \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left| \frac{y_R f M_1}{M_4 M_{Us}} - \sqrt{2} c_R \frac{y_R f}{M_{Us}} \right| + \mathcal{O}(\epsilon^3)$$

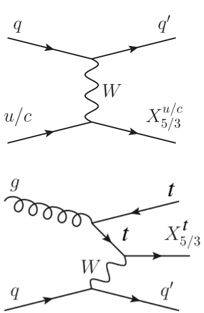
$$\left|g^L_{UsWd}\right| = \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left(\frac{y_L f \left(M_1 M_4 + y_R^2 f^2\right)}{M_{Uf2} M_{Us}^2} - \frac{\sqrt{2} c_L y_L f}{M_{Uf2}} \right) + \mathcal{O}(\epsilon^3)$$

How to (qualitatively) understand the “mixing” couplings:

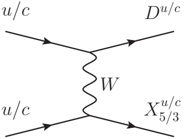


Production and decays

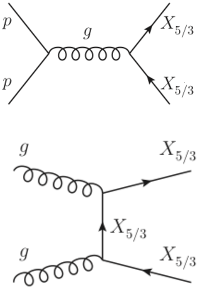
Production mechanisms (shown here: $X_{5/3}$ production)



(a) EW single production



(b) EW pair production



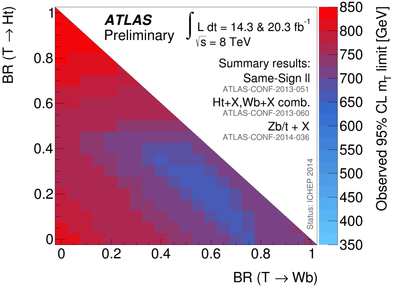
(c) QCD pair production

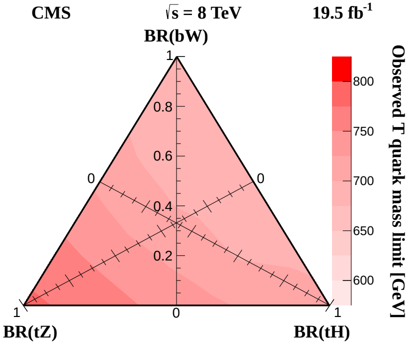
Decays:

- $X_{5/3} \to W^+ u$ (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]

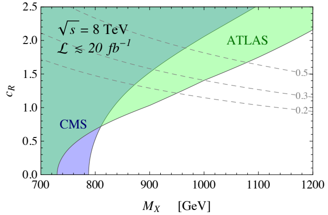


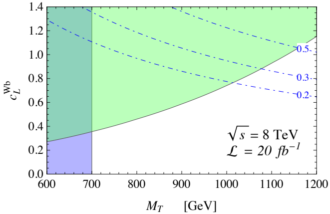


CMS [PLB 729, 149 (2014)]

Bounds on top partners from run I

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





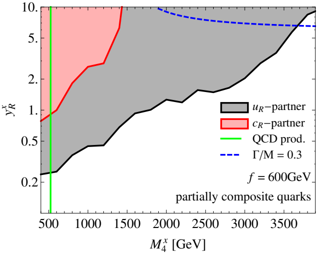
Note: In the above plots $c_R = 2g^R_{XWu}/g$ and $c_L^{Wb} = 2g^L_{UsWd}/g$ as compared to the coupling formulae given earlier.

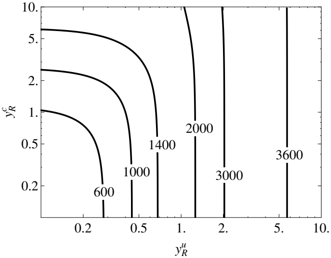
Determining bounds on partners of light quarks from run I

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



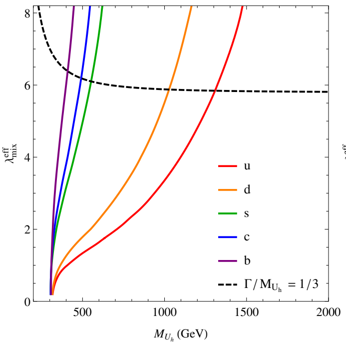


Determining bounds on partners of light quarks from run I

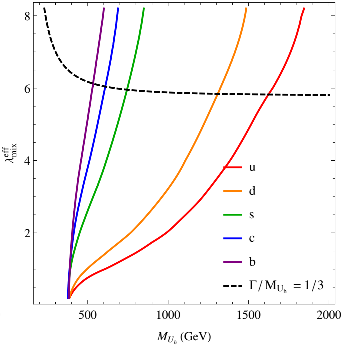
- Bounds on partners of light quarks in the singlet

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

  - From QCD pair production: $M_4^{u,d,s,c} > 310\,\text{GeV}$
    (using $p_T^{\gamma\gamma}$, N_{jet}, p_T^{jet} from the $h \to \gamma\gamma$ search in [ATLAS-CONF-2013-072])
  - Single production:



Constraints neglecting events with $p_T^{\gamma\gamma} > 200$ GeV
(conservative; ignoring overflow bins)



Constraints including events with $p_T^{\gamma\gamma} > 200$ GeV
(projection; including overflow bins)

Prospects for composite quark partners at LHC run II

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.

Two examples:

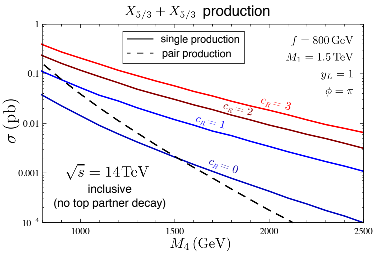
1. Maximizing the sensitivity for the "most visible" quark partner:
   An optimized search strategy for top partners in the **4**.

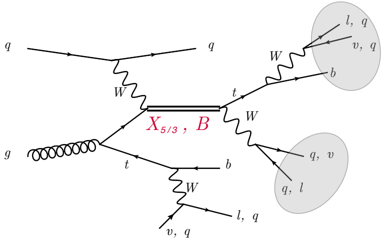
   M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]
2. Maximizing the sensitivity for the "least visible" quark partner:
   An optimized search strategy for singlet partners of light quarks.

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

Prospects for composite quark partners at LHC run II

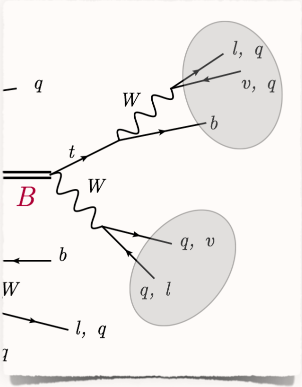
Search for top partners in the $q\bar{t}tW$ final state with semi-leptonic decay of tW.





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)

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:

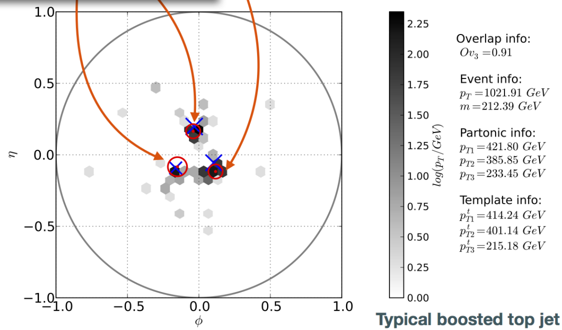
Almeida, Lee, Perez, Sterman, Sung - Phys.Rev. D82 (2010) 054034
MB, Juknevich, Perez - JHEP 1307 (2013) 114
Almeida, Erdogan, Juknevich, Lee, Perez, Sterman - Phys.Rev. D85 (2012) 114046
MB, Gabizon, Juknevich, Perez, Soreq - JHEP 1404 (2014) 176

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.



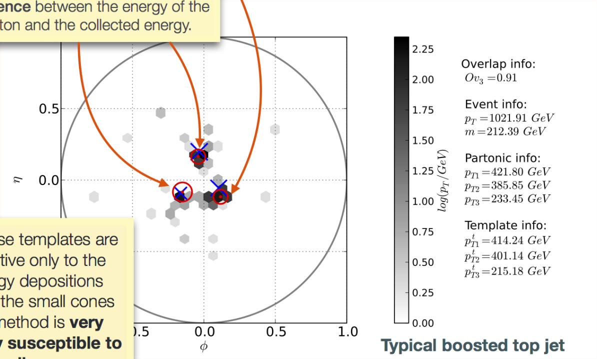
Typical boosted top jet

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

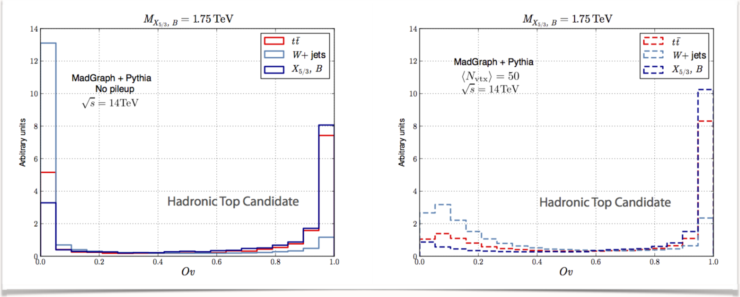
Because templates are sensitive only to the energy depositions within the small cones the method is **very weakly susceptible to pileup.**

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



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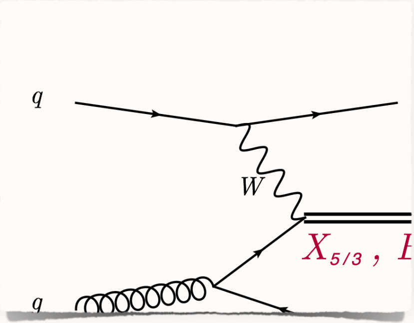
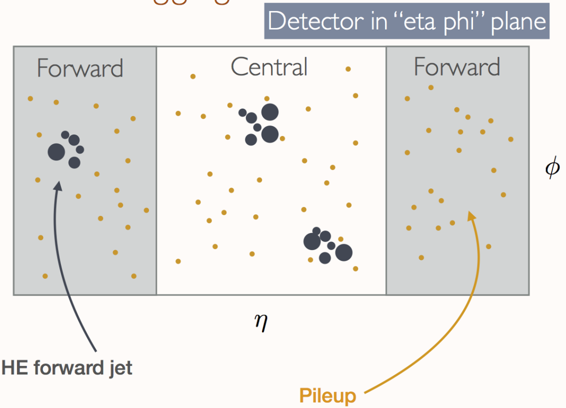
Forward Jet Tagging



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

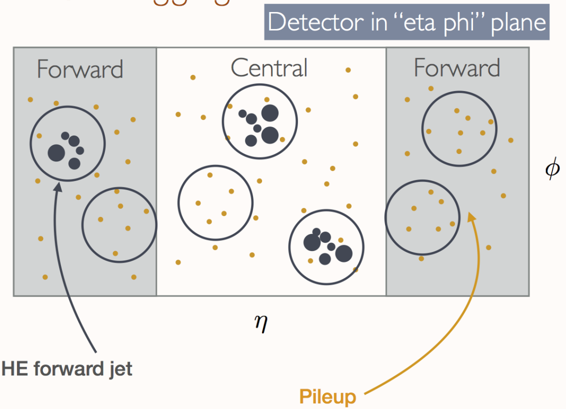
Forward Jet Tagging



Seems easy, but actually quite difficult!

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

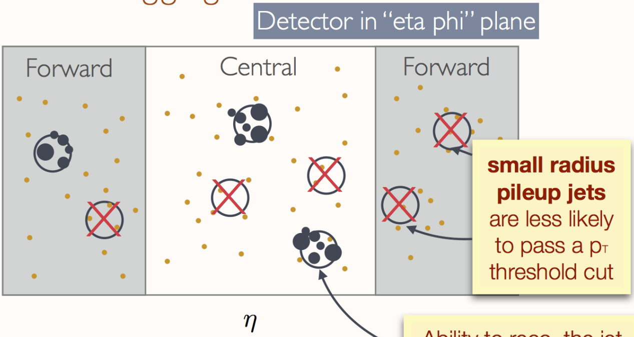
Forward Jet Tagging



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

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

Forward Jet Tagging



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

(Simple) Solution:

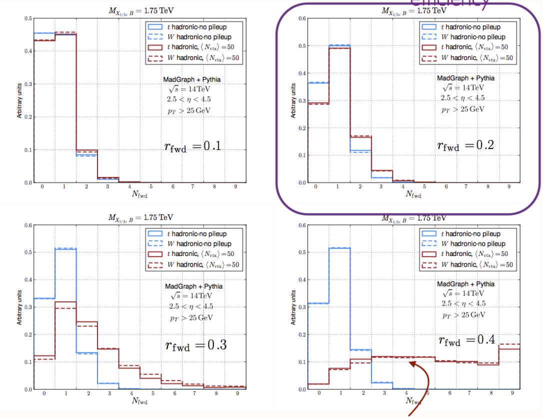
Define forward jets as (say) r = 0.2 jets with

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

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

Forward Jet Tagging

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



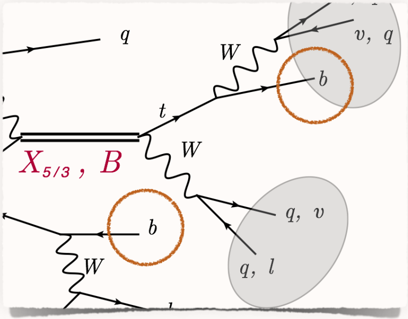
Blue - No Pileup

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).

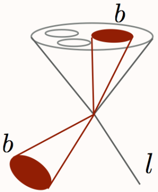
We use a **simplified approach**:

> **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.**

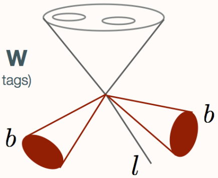
For each "**b**-tag" we use the benchmark efficiencies:

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

hadronic top
(one b inside fat jet, one isolated)

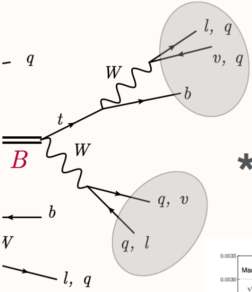


hadronic W
(two isolated b tags)



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

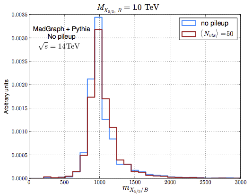
We can reconstruct the **resonance mass**

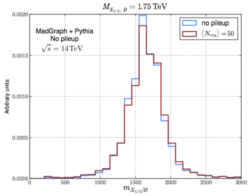


- Use the peak template (pileup insensitive)$\star$:
  - **hadronic top:** $m_X^2 = (p^{\text{temp}} + p^l + p^\nu)^2$
  - **hadronic W:** $m_X^2 = (p^{\text{temp}} + p^l + p^\nu + p^b)^2$

$\star$ 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

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.

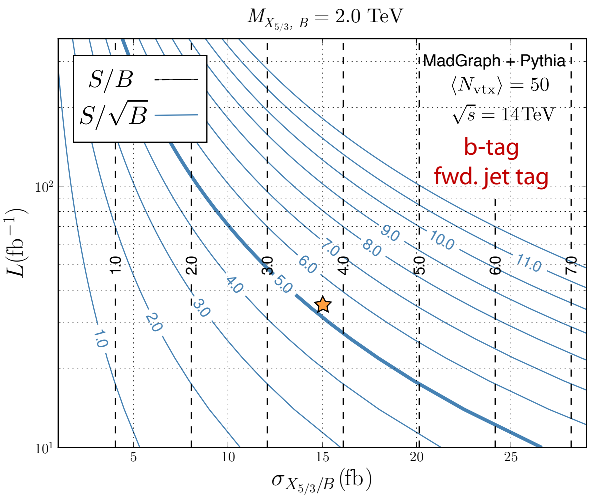
M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

$M_{X_{5/3}/B} = 2.0$ 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



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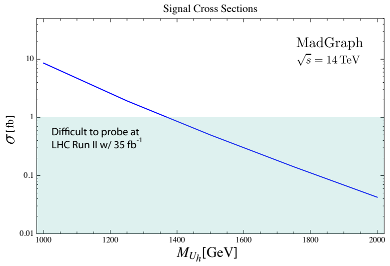
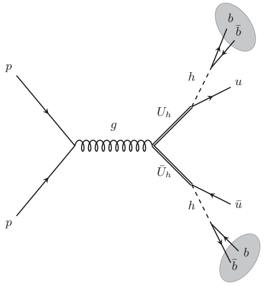
Prospects for composite quark partners at LHC run II

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]





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

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	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 $1\,\mathrm{TeV}$.