Search strategies for vector-like quark partners at LHC run-II

Thomas Flacke
Korea University & IBS CTPU

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, JHEP 1604, 014]

M. Backović, TF, B. Jain, S. J. Lee [work in progress]

ISMD2016, 08/30/2016

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 (and run II)
- Prospects for composite quark partners at LHC run II
- 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^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.

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 $\to \mathcal{O}^{I_\mathcal{O}}$ 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:

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

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

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**:

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

Singlet Partner:

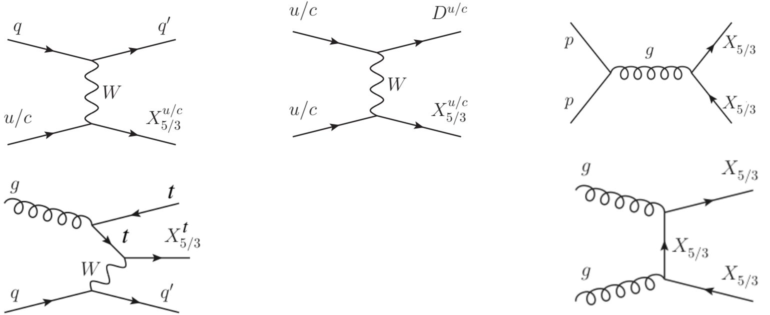
$$M_{Ts} = \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2)$$

Couplings (examples):

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

Production and decays

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



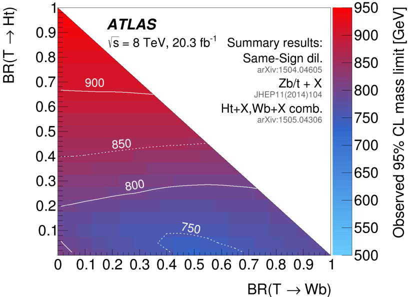
(a) EW single production (b) EW pair production (c) QCD pair production

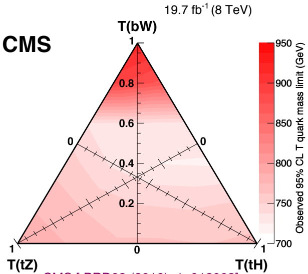
Decays:

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

- 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]
  Run II: $M_{X_{5/3}} > 940\,\mathrm{GeV}$ CMS [CMS-PAS-B2G-15-006]
- 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]

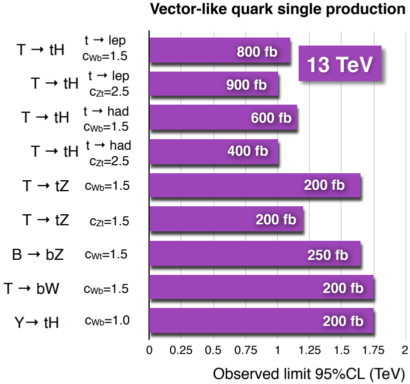




CMS [PRD93 (2016), 1, 012003]

Bounds on top partners

CMS single-T' summary



CMS-PAS-B2G-15-008: $T' \to h_{bb} t_{\rm lep}$
CMS-PAS-B2G-16-001: $T'/B' \to Z_{ll} X$
CMS-PAS-B2G-16-005: $T' \to h_{bb} t_{\rm had}$
CMS-PAS-B2G-16-006: $T' \to W_{\rm lep} b$

ATLAS-CONF-2016-072: $T' \to W_{\rm lep} b$

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:

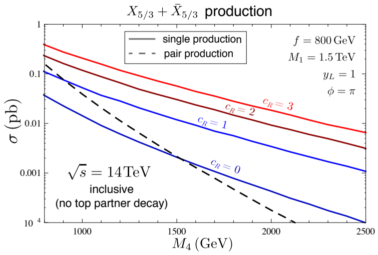
1. Single-production channels (if present) will become more important as compared to QCD pair production channels.
2. For heavier quark partners, their decay products become strongly boosted ⇒ we need dedicated search strategies for boosted tops, Higgses, EW gauge bosons.

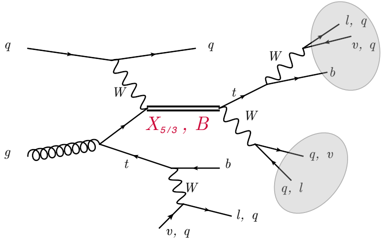
Two/Three examples:

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, JHEP 1604, 014]
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 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,	$\rightarrow$	$p_T^l > 100\,\text{GeV}$ 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.

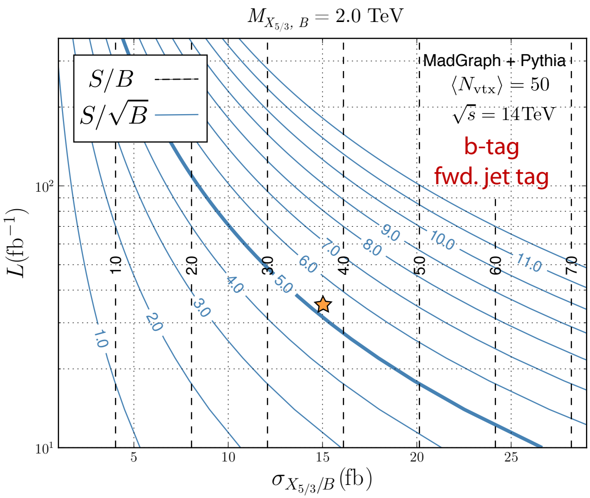
M. Backović, TF, S. J. Lee, G. Perez [JHEP 1509, 022]

$M_{X_{5/3}/B} = 2.0$ 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 [JHEP 1509, 022]

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, JHEP 1604, 014]

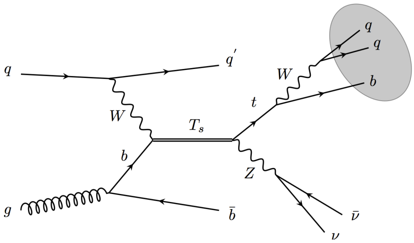
- Charge $2/3$ partners can decay into ht, Zt, or Wb.
- The resulting t, h, W, Z have various decay channels
  W and t: leptonic ($l\nu$) or hadronic (jj)
  Z: leptonic (l^+l^-), invisible ($\nu\overline{\nu}$), hadronic jj, or ($b\overline{b}$)
  h: $\gamma\gamma$, ZZ^*, WW^*, $b\overline{b}$, ...
- 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 [JHEP 1604, 014]

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,
- $\not{E}_T > 500\ (750)\,\mathrm{GeV}$ for the $1\ (1.5)\,\mathrm{TeV}$ 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:

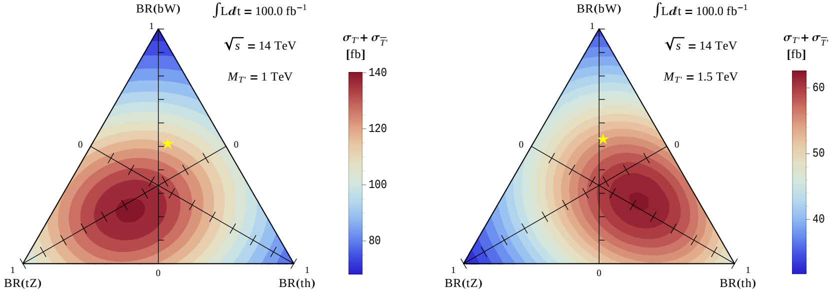
$T' \to Z_{\rm inv} t_{\rm had}$	$M_{T'} = 1.0$ TeV search						$M_{T'} = 1.5$ TeV search					
	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(100\,{\rm fb}^{-1})$	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(100\,{\rm fb}^{-1})$
preselection	4.9	26000	21000	44	0.00011	0.23	1.3	5200	5300	12	0.00012	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
$N_{\rm fwd} \geq 1$	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

$T' \to Z_{ll} t_{\rm had}$	$M_{T'} = 1.0$ 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
$N_{\rm fwd} \geq 1$	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 [JHEP 1604, 014]

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

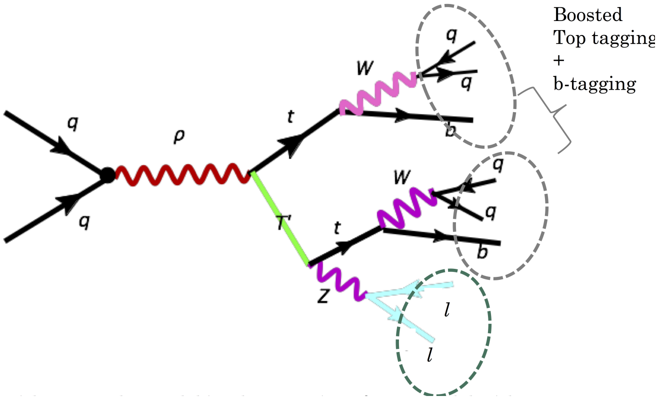
We also did detailed analyses of the $W_{\text{lep}}b$, $W_{\text{had}}b$, $h_{bb}t_{\text{had}}$, and $h_{bb}t_{\text{lep}}$ channels, and found best results for $Z_{\text{inv}}t_{\text{had}}$, $W_{\text{lep}}b$ and $h_{bb}t_{\text{had}}$.



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: charge 2/3 partner(s)

Outlook: Another potentially interesting production mechanism of top partners is via production and decay of vector-resonances:



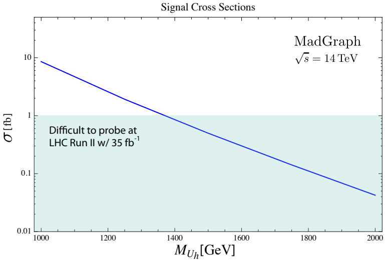
This yields different final states / kinematics (e.g. $\rho \rightarrow T\bar{t} \rightarrow Zt\bar{t}$).

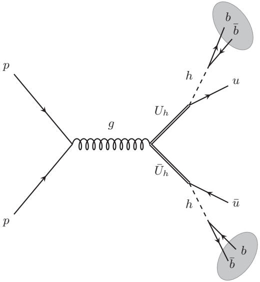
M. Backović, TF, B. Jain, S. J. Lee [work in progress]

Prospects for quark partners at LHC run II: boosted Higgs(es)

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 fo quark partners at LHC run II

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

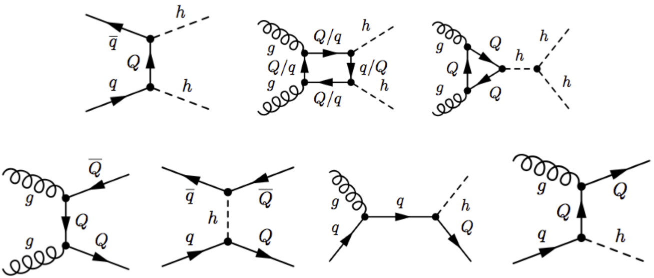
Table V: $M_{U_h} = 1.2$ TeV , $\sigma_s = 2.4$ fb , $\mathcal{L} = 35$ fb^{-1}

Prospects for quark partners at LHC run II: : boosted Higgs(es)

Outlook: If VLQs couple to a light quark and the Higgs, there are additional Higgs single- and pair production channels (beyond $hhq\overline{q}$).

LesHouches proceedings arXiv:1605.02684 and work in progress:

H Cai, G. Cacciapaglia, A. Carvalho, A. Deandrea, TF, B. Fuks, D. Majumder, H.-S. Shao.



Spectacular new physics signatures. Final states with highly boosted h_{bb} have QCD as a background, but as shown before, jet-substructure techniques combined with $b - tagging$ can help. Work in progress.

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 (and early run II) to $M_X \gtrsim 750 - 950\,\mathrm{GeV}$.
- 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 [JHEP 1604, 014] for many other channels and simulation details.
- For partners of light quarks, new Higgs single- and pair production mechanisms can arise. Combining jet-substructure techniques and b-tagging is vital to separate the signal from QCD background.

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:

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

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

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

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

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:

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

and

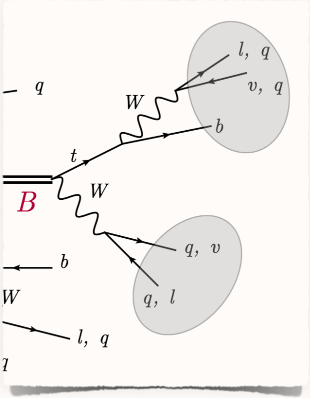
$$\begin{cases} d_\mu^{1,2} = -\sin(\bar{h}/f)\frac{W_\mu^{1,2}}{\sqrt{2}} \\ d_\mu^3 = \sin(\bar{h}/f)\frac{B_\mu - W_\mu^3}{\sqrt{2}} \\ d_\mu^4 = \frac{\sqrt{2}}{f}\partial_\mu h, \end{cases} .$$

Example/Application: kinetic term for the “Higgs” using CCWZ:

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

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

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:

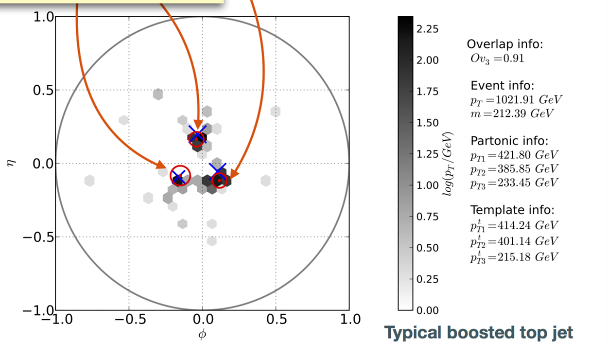
Almeida, Lee, Perez, Sterman, Sung - Phys.Rev. D82 (2010) 054034
MB, Juknevich, Perez - JHEP 1307 (2013) 114
Almeida, Erdogan, Juknevich, Lee, Perez, Sterman - Phys.Rev. D85 (2012) 114046
MB, Gabizon, Juknevich, Perez, Soreq - JHEP 1404 (2014) 176

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.



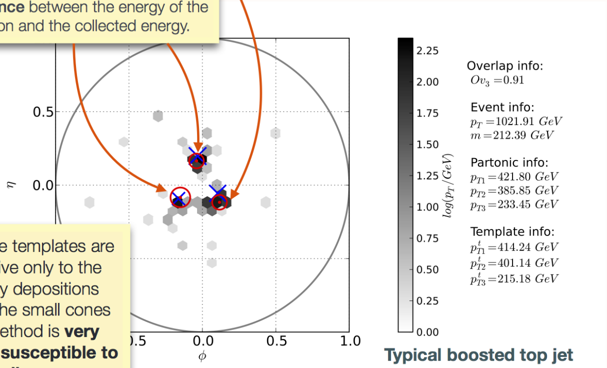
Typical boosted top jet

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

Tagging of **Boosted Objects**

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.

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



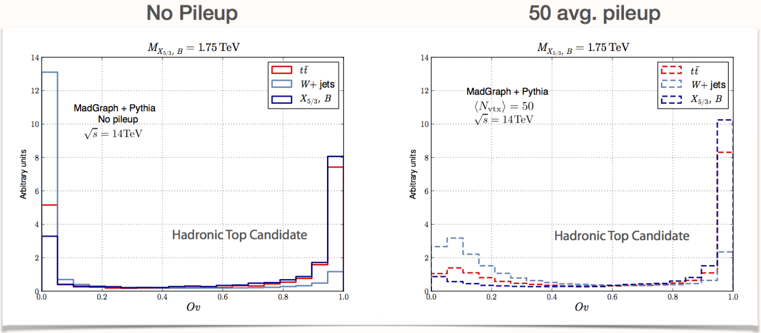
Because templates are sensitive only to the energy depositions within the small cones the method is **very weakly susceptible to pileup.**

Typical boosted top jet

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

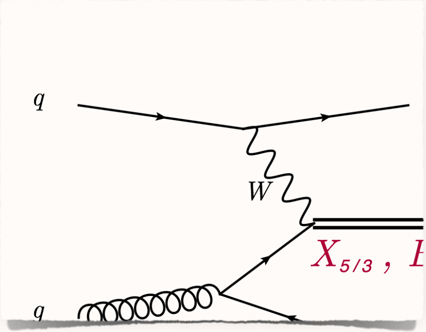
Tagging of **Boosted Objects**

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



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

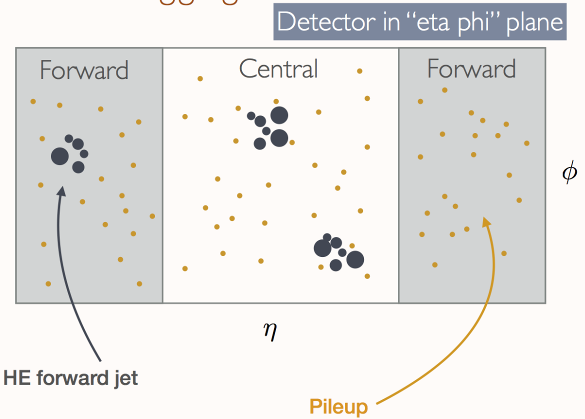
Forward Jet Tagging



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

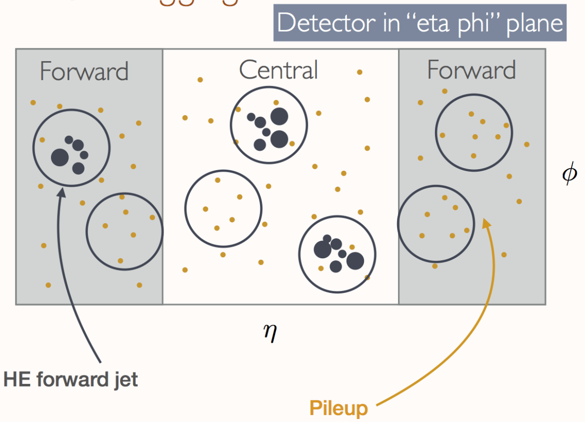
Forward Jet Tagging



Seems easy, but actually quite difficult!

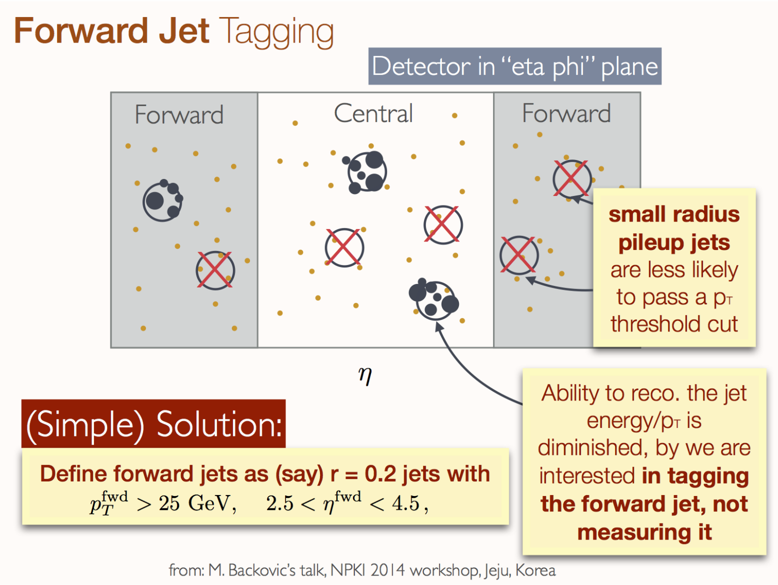
from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Forward Jet Tagging



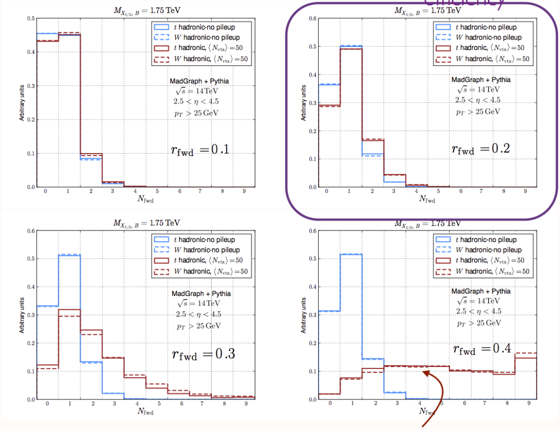
Complicated at high pileup (**fake jets appear**)

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


Forward Jet Tagging
Detector in "eta phi" plane
Forward
Central
Forward
η
small radius pileup jets are less likely to pass a pT threshold cut
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
$p_T^{\rm fwd} > 25$ GeV, $2.5 < \eta^{\rm fwd} < 4.5$,
from: M. Backovic's talk, NPKI 2014 workshop, Jeju, Korea

Forward Jet Tagging

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



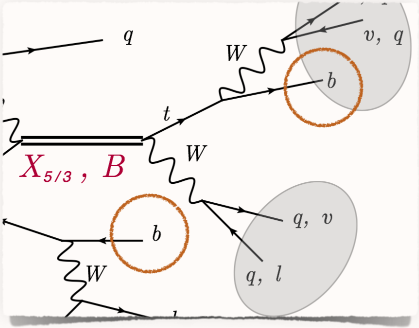
Blue - No Pileup

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



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

b-tagging Strategy

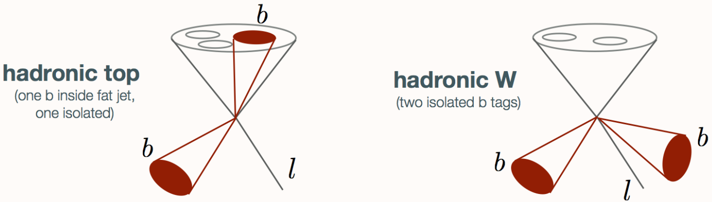
Full simulation of b-tagging requires consideration of complex detector effects (e.g. tracking info).

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.

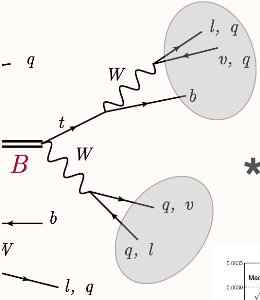
For each "**b**-tag" we use the benchmark efficiencies:

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



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

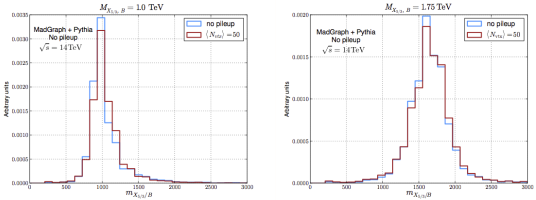
We can reconstruct the **resonance mass**



- 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