High Multiplicity Searches Using Jet Masses

Eder Izaguirre

Perimeter Institute for Theoretical Physics

w/Anson Hook, Mariangela Lisanti and Jay Wacker

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Natural SUSY spectrum

Moderately light gluinos
Light Stops
Light Higgsinos

$\tilde{g}$
$\tilde{t}$
$\tilde{\chi}^0$

$M$

800 GeV
400 GeV
200 GeV
Final signature
Rich final state
Rich final state

Not trivial to disentangle from background
Rich final state

Not trivial to disentangle from background

High Multiplicity Backgrounds

No NLO

Tree-level is state of the art

Data Driven Extrapolation: $N \rightarrow N + 1$
Rich final state

Not trivial to disentangle from background

High Multiplicity Backgrounds
  No NLO
  Tree-level is state of the art
  Data Driven Extrapolation: $N \rightarrow N + 1$

Various final states (+ b-tagging)

$4W : (8j, 0\ell) \rightarrow (0j, 4\ell)$
Rich final state

Not trivial to disentangle from background

High Multiplicity Backgrounds

No NLO

Tree-level is state of the art

Data Driven Extrapolation: $N \rightarrow N + 1$

Various final states (+ b-tagging)

$4W : (8j, 0\ell) \rightarrow (0j, 4\ell)$

Partons can be accidentally grouped together

A variety of final state jet multiplicities

Isolated Jet $P_T$ is Reduced

Easily fall beneath $\sim 50$ GeV
Other examples from SUSY
2 Step Cascade Decay
\[ \tilde{g} \rightarrow \tilde{W} \rightarrow \tilde{H} \rightarrow \tilde{B} \]
“Standard” SUSY searches

anti-$k_T$ R = 0.4 to 0.6 jets (aka “thin” jets)

Lots of room for isolated jets

Good at separating high multiplicity from low multiplicity

Instead cluster events into “fat” jets

e.g. anti-$k_T$ R = 1.2

Only enough room for 4 to 6 jets
Aren’t we losing the special feature of the event?
Typical QCD background

13 Jet

3 Jet
Need to distinguish

Signal

Background
Jet mass

Large Jet Mass

\[ x \equiv \frac{m_j}{p_T} \sim 1 \]

Small Jet Mass

\[ x \equiv \frac{m_j}{p_T} \sim \alpha_s^{\frac{1}{2}} R \]
Detour: Are jet masses correlated?
Each jet mass is approximately independent for QCD and V+jets

Consider $x = m_j/p_T$ of leading two jets

$$H(x_1, x_2) = \frac{\int h(x_1, x_2) dx_1 dx_2}{\int h(x_1, x_2) dx_1 \int h(x_1, x_2) dx_2},$$

QCD: $2 < \Delta R_{j_1 j_2} < 3.5$

Z$^0$+nj with Pythia 6.4

~5% correlations

Slightly positive correlation
QCD jets only have small correlations

Data driven background predictions possible

\[ P_3(x_1, x_2, x_3) \simeq P_1(x_1)P_1(x_2)P_1(x_3) \]

Measure in one sample and extrapolate
Introduce one new variable

Sum of Jet Masses

\[ M_J = \sum_{n=1}^{N_J} m_{j_n} \]

QCD jets have most of their mass generated by the parton shower

Top events have their mass capped near 2 m_{top}
**M_J as a replacement for H_T**

\[
H_T = \sum_{n=1}^{N_J} E_{T,j_n}
\]

\[
H_T = \sum_{i=1}^{n_J} \left( p_{T,i}^2 + m_{j_i}^2 \right)^{\frac{1}{2}}
\]

\[
m_j = \kappa p_T R
\]

\[
\propto \sum_{i=1}^{n_J} \sqrt{\langle m_{j_i}^2 \rangle \left( (\kappa R)^{-2} + 1 \right)} \approx M_J \frac{\sqrt{1 + (\kappa R)^2}}{\kappa R}
\]

**Signal**  \[\langle m_{j_i}^2 \rangle \propto p_{T,i}^2 R^2\]  
**Background** \[\langle m_{j_i}^2 \rangle \propto \alpha_s p_{T,i}^2 R^2\]

Signal typically has higher M_J for fixed H_T

Never does worse
Treating top as a signal

Real signal even steeper

$M_J$ (GeV)

$H_T$ (GeV)
One benchmark model

\[ M \]

\[ \tilde{g} \]

800 GeV

\[ \tilde{\chi}^0 \]

100 GeV

\[ t\bar{t} \]

4 Top
missing energy, and consider each class separately in the following subsections. We search for these two classes will differ in whether a moderate missing energy requirement is necessary. We study two classes of signals, both arising from radiative processes; in this case, the corrections to Eq. 3 involve a sum over masses, this anti-correlation is not significant, and does not contribute large corrections to Eq. 3. The jet masses for the QCD and gluino in the stealth SUSY topology is shown in green. LSP, are shown in black and purple, respectively. A 500 GeV 800 GeV gluino in the multi-top topology and a 600 GeV gluino in the 2-step cascade decay topology, both with a massless association with (up to) two jets.

As examples of signals with suppressed missing energy, we consider a pair-produced gluinos which include SM backgrounds, which include parton shower/matrix element matching scheme. The events are then showered and hadronized in Pythia 6.4. The single-top and vector boson-pair production are subdominant and are thus not shown in the distributions in this paper, though they are included in the limit calculations.
FIG. 4: (Left) $H_T$ distributions and (Right) $M_J$ distributions, after requiring four or more fat jets and $\slashed{E}_T > 150$ GeV. Signal and background as in Fig. 3.

Next-to-leading-order (NLO) corrections affect the normalization of both signal and background distributions. The largest corrections are to the inclusive production cross section and can be absorbed into $K$-factors. The leading order cross sections of the signal are normalized to the NLO cross sections calculated in Prospino 2.1 [48].

For the remainder of this article, the leading fat jet is required to have $p_T^{j1} > 120$ GeV and the sub-leading fat jets have $p_T > 50$ GeV. Fig. 3 shows the missing energy distributions for benchmark multi-top and cascade decay topologies with massless LSPs after requiring $N_j \geq 4$. Both these signals have events with missing energy above $\sim 100$ GeV, but not enough to effectively separate them from background.

Figure 4 shows the $H_T$ and $M_J$ distributions for these two benchmarks after a moderate missing energy cut of $150$ GeV. It is clear that the $M_J$ variable provides a far better discriminant against background than $H_T$, as expected from our discussion in the previous section.

By requiring several widely separated jets, QCD must produce these jets through an intrinsically $2 \rightarrow 4$ process, as opposed to producing additional jets through the parton shower of a hard dijet event. Requiring three or four fat jets plus a mild missing energy cut succeeds in keeping QCD under control. Electroweak vector bosons plus jets are subdominant backgrounds at low missing energy and are further reduced by the multiplicity requirement, especially at large jet mass.

The dominant background comes from $t\bar{t}$ production, though the jet multiplicity and missing energy requirements help to keep it under control. To pass these requirements, several of the jets must be grouped together to get sufficiently large jet mass and it is unusual to have two or more massive fat jets in top decays. As discussed in Sect. II, the jet masses from top quarks are more signal-like, in that they arise primarily from overlapping partons in the top decay. Therefore, the total jet mass $M_J$ is not as suppressed as that for QCD. However, the top quark events give rise to $M_J < \sim 2m_t$, especially when at least one of the tops is forced to decay semileptonically by the missing energy requirement. Therefore, a $M_J > \sim 400$ GeV is typically sufficient in removing the majority of the top background.

Figure 5 shows the expected 2σ sensitivity to the multi-top and two-step cascade signals for a massless LSP, using 1.34 fb$^1$ of integrated luminosity. The expected limits from optimal signal regions in $H_T$ are compared against the sensitivity of a $M_J$ search region. A 20% systematic uncertainty on the backgrounds is assumed and is added in quadrature with the statistical error. The cuts that define each signal region are presented in Tab. I.
Gain at high $M_J$

After cut of $E_T > 150$ GeV
**Final search region**

Compare to standard search regions

<table>
<thead>
<tr>
<th>Search</th>
<th>(N_j)</th>
<th>(R)</th>
<th>Leptons</th>
<th>(N_b)</th>
<th>(\sqrt{E_T})</th>
<th>(M_J)</th>
<th>(H_T)</th>
<th>(M_J)</th>
</tr>
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<tbody>
<tr>
<td>ATLAS</td>
<td>6-8(^+)</td>
<td>0.4</td>
<td>0</td>
<td>0(^+)</td>
<td>3.5</td>
<td>(\sqrt{H_T})</td>
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<td>(\emptyset)</td>
</tr>
<tr>
<td>(H_T)+SSDL-top</td>
<td>3(^+)</td>
<td>1.2</td>
<td>SSDL</td>
<td>1(^+)</td>
<td>(\emptyset)</td>
<td>300</td>
<td>(\emptyset)</td>
<td></td>
</tr>
<tr>
<td>(H_T)-top</td>
<td>4(^+)</td>
<td>1.2</td>
<td>0(^+)</td>
<td>1(^+)</td>
<td>250</td>
<td>800</td>
<td>(\emptyset)</td>
<td></td>
</tr>
<tr>
<td>(H_T)-cascade</td>
<td>4(^+)</td>
<td>1.2</td>
<td>0(^+)</td>
<td>0(^+)</td>
<td>150</td>
<td>1000</td>
<td>(\emptyset)</td>
<td>450</td>
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<tr>
<td>(M_J) search</td>
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<td>1.2</td>
<td>0(^+)</td>
<td>0(^+)</td>
<td>150</td>
<td>(\emptyset)</td>
<td>450</td>
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</tbody>
</table>

**Maximally Inclusive**

No b-tags, no lepton vetos, low MET
4-top signal estimated sensitivity at 7 TeV
Conclusions

Jet mass a potentially useful tool in disentangling high multiplicity signals

These signals may not necessarily be boosted

But busy final state means accidental merging of partons within jets

Can extend substructure techniques to place constraints on these signals