NON-CONVENTIONAL OBJECTS FOR COLLIDER PHENOMENOLOGY: JET-LIKE OBJECTS AND THEIR APPLICATIONS

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Charting the Unknown: interpreting LHC data from the energy frontier
What we wanted to see

• “Famous” Golden channel (multi-leptons) in SUSY

• Not so many channels to provide MANY “prompt” leptons in SM
What bothers us

- “Non-prompt” (or fake) leptons from heavy flavor
- Di-lepton $t\bar{t}$ channels (one fake from B-jet)
Conservative identification

- The basic objects:
  1. Muon
  2. electron / photon
  3. Jet
  4. Heavy flavor jet, Tau-lepton

- Require tight isolation criteria to remove “fake” objects

Di-lepton $t\bar{t}$
Clustering “energy deposits”

- Collect energy deposits to capture particles from the initial parton
- Supercluster ECALs to capture energies from showers

**Generalized** concept of “jet (clustering)” have been used!
A Jet of jets

- Capture jets (quarks) from energetic [(highly) boosted] Top / W / Z / H

\[ \Delta R \approx \frac{2M(V/t/H)}{P_T(V/t/H)} \]

\[ \ell \]
\[ \nu \]
\[ W \]
\[ H \]

M. Seymour (1994)


\[ pp \rightarrow V/H, (H \rightarrow b\bar{b}) \]
\[ \Delta R \approx \frac{2M(V/t/H)}{P_T(V/t/H)} \]

- D. Kaplan, K. Rehermann, M. D. Schwartz, B. Tweedie (2008)
- MANY !

No combinatorics  
V.S.  
Rejecting QCD BKG
Scaling down

• When a “light” particle decays,

\[ \Delta R \sim \frac{2M}{P_T} \]

Clustering relevant objects
Isolating from QCD junks

Nima, N. Weiner (2008)

“Lepton-Jet”

1. Clustering relevant objects
2. Isolating from QCD junks
Scaling down

• Fake photon

\[ \gamma_{\text{fake}} \rightarrow \gamma \rightarrow A^0 \rightarrow h^0 \rightarrow A^0 \rightarrow \gamma \rightarrow \gamma_{\text{fake}} \]


• Separating photon-jet, photon and QCD-jet


• Photon-jet got huge love-call from theorists recently :)

Extend clustering object

• Jet like objects from an **OFF-SHELL** particle.

• A lepton-jet from OFF-SHELL Z ($Z^*$)

• A fat-jet from OFF-SHELL Squark ($\tilde{q}^*$)
Degenerated Higgsinos

- In SUSY, EWSB

\[
\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} \approx -\mu^2 - m_{H_u}^2
\]

\[
\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx \frac{m_W^2}{M_2} + \frac{m_W^2 \tan^2 \theta_W}{M_1}
\]

C. Han, D. Kim, S. Munir, MP (2015)
• Reduce a requirement for ISR PT.

• Once we tag a “particle”, we can impose more cuts.
• “R = 0.3 is a conventional isolation cut”

Major BKG:

- **$V + \gamma^* + jets$:** A large $E_T$ results from the $W \rightarrow \ell\nu$ decay or the $Z \rightarrow \nu\nu$ decay and the two collinear muons originate from the virtual photon, $\gamma^*$. To reduce this background, we require $m_{\mu\bar{\mu}} > 1.0\text{ GeV}$ and $\Delta R_{\mu\bar{\mu}} > 0.1$.

- **$\tau\bar{\tau} + jets$:** Each tau decays into a muon and a pair of neutrinos. Due to the large boost in the leading jet, these muons become highly collimated. The neutrinos produced

- **$Vbb + jets$ and $Zb + jets$:** This background mimics our signal when the $b$-quarks decay into pairs of muons via double semileptonic decays. However, it is suppressed by $2 \times 10^{-5}$
• Basic kinematic cuts to reduce Backgrounds

• Using a ratio of MET over PT(muon-jet). This represents a momentum flow of signals where most of energy goes into MET.

• The endpoint behavior of (transverse) mass variables are sensitive to the number of invisible particles. For signals \( n=2 \), while BKG \( n=1 \).
• For HL LHC (3000 inverse fb) of 14TeV collision,

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$W\gamma^*j$</th>
<th>$Z\gamma^*j$</th>
<th>$j\tau\tau$</th>
<th>Total BKG</th>
<th>BP1</th>
<th>BP2</th>
<th>BP3</th>
<th>$(fb)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-jet</td>
<td>8.057</td>
<td>8.82</td>
<td>6.674</td>
<td>23.0</td>
<td>0.052</td>
<td>0.072</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td>Basic $\mu_{col}$</td>
<td>0.753</td>
<td>1.05</td>
<td>0.314</td>
<td>2.1</td>
<td>0.041</td>
<td>0.042</td>
<td>0.028</td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi(\mu_{col}, E_T)$</td>
<td>0.288</td>
<td>0.324</td>
<td>0.035</td>
<td>0.65</td>
<td>0.028</td>
<td>0.030</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>$m_{\mu_{col}}$</td>
<td>0.106</td>
<td>0.118</td>
<td>0.024</td>
<td>0.248</td>
<td>0.017</td>
<td>0.023</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>$M_T &amp; \frac{E_T}{p_T(\mu_{col})}$</td>
<td>0.037</td>
<td>0.044</td>
<td>0.011</td>
<td>0.092</td>
<td>0.013</td>
<td>0.016</td>
<td>0.010</td>
<td></td>
</tr>
</tbody>
</table>

$S/B$                              | 0.14 | 0.17 | 0.11 |

$S/\sqrt{B} (\sigma)$             | 2.4  | 2.9  | 1.85 |

• di-muon backgrounds from $J/\Psi$
Color Octet - Color Singlet (Gluino - bino)

- When a colored particle is NLSP and \( \Delta m \ll m_{\tilde{g}} \)
  the hadron colliders (LHC) may produce the colored particle, but the decaying products would be too soft to tag

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A. Simone, G. Giudice, A. Strumia (2014)

Too soft jets...

- Tagging ISR jets + MET
  - signals from SUSY decay become **soft**
  - PT of ISR gets **harder** with the mass scale of SUSY
  - Major BKG will be Z(to neutrinos)+jets

- Possibility to discriminate ISR jet (initially gluon) v. s. quark jets (in Z+jets)

• Need to tag “Signals” from SUSY decay to understand properties of SUSY particles (masses, spin and coupling structure)
• Use a “Fat (Merged)”- Jet

\[ \Delta R = \frac{2M_{FJ}}{P_{T(FJ)}} \gg 1 \]

to enhance PT of jets

but maybe we need to have too large size?
Shaping a phase-space

\[ \Delta R \approx \frac{2M_{FJ}}{P_T(FJ)} \]

- If we require a transverse momentum of fat-jet as \( \mathcal{O}(m_{FJ}) \),

\[
P_{qq'} = \left[ \frac{m_g^2 + m_{\tilde{\chi}}^2}{3} \left( 2 - \sqrt{1 + \frac{12m_g^2m_{\tilde{\chi}}^2}{(m_g^2 + m_{\tilde{\chi}}^2)^2}} \right) \right]^{1/2}
\]

\[ \Delta m \ll m_g \frac{\Delta m}{\sqrt{2}} \]
Shaping a phase-space

- If we require a transverse momentum of fat-jet as $O(m_{FJ})$

$$\Delta R \approx \frac{2M_{FJ}}{P_{T(FJ)}}$$

$$\Delta R \approx \frac{2M_{FJ}}{P_{T(FJ)}} \approx 2 \frac{\Delta m}{\sqrt{2}} \frac{1}{\Delta m} \approx 1.4$$
A price to use Fat-jet

- Contaminations from soft QCD can be removed by jet-grooming methods.

\[ \sqrt{< M_J^2 >_{\text{NLO}}} \approx 0.2 p_J R \]

\[ < M_J > \approx 30 \text{GeV} \quad \text{with} \quad P_J = 100 \text{GeV} \]
Sorting out QCD jet by requiring a signal jet to satisfy

Symmetric condition: same as BDRS Higgs tagger

1. \( \frac{m_{j_1}}{m_{FJ}} < \mu = 0.67 \)

2. \( \left( \frac{\min(p_{T,j_1}^2, p_{T,j_2}^2)}{m_j^2} \right) \Delta R_{(j_1,j_2)}^2 > y_{\text{cut}} = 0.09 \)
Jet substructure

• MDT helps to reconstruct Jet-mass. But, QCD always wins with cross-sections…

• Need to have another handle

\[ \rho = \frac{m_{FJ}^2}{p_{TFJ}^2 R^2} \simeq z(1 - z) \frac{R_{qq'}^2}{R^2} \simeq 0.2 \]

q-initiated jet:

\[ \frac{\rho}{\sigma} \frac{d\sigma}{d\rho} = \frac{\alpha_s C_F}{\pi} \left[ \Theta(\rho - y_{cut}) \ln \frac{1}{\rho} + \Theta(y_{cut} - \rho) \ln \frac{1}{y_{cut}} - \frac{3}{4} \right] \]

<table>
<thead>
<tr>
<th>BP</th>
<th>cuts</th>
<th>Signal ((\epsilon_{tag}))</th>
<th>Z + j ((\epsilon_{fake}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_{\chi_1^0} = 600</td>
<td>10 &lt; m_{FJ} &lt; 40</td>
<td>0.75</td>
<td>0.55</td>
</tr>
<tr>
<td>Δm = 40</td>
<td>Additional (\rho &gt; 0.1) cut</td>
<td>0.40</td>
<td>0.18</td>
</tr>
<tr>
<td>BP2</td>
<td>40 &lt; m_{FJ} &lt; 100</td>
<td>0.62</td>
<td>0.22</td>
</tr>
<tr>
<td>Δm = 100</td>
<td>Additional (\rho &gt; 0.1) cut</td>
<td>0.42</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Prescreening with Fat Jet

1. Find all the jets after C/A algorithm $p_T > \Delta m$ denoted by $j_1, j_2, \ldots, j_n$. Each jet the pass MDT and calculate the $\rho_{j_i}$.

2. Choose the jet who has the largest $\rho$, take this jet as the signal jet. $\rho > 0.1$

$$\frac{1}{4} \Delta m < m_{FJ} < \Delta m$$ for $\Delta m \geq 20 \text{GeV}$,

$$5 \text{ GeV} < m_{FJ} < 20 \text{ GeV}$$ for $\Delta m < 20 \text{ GeV}$.

ATLAS analysis

<table>
<thead>
<tr>
<th>Signal region ”2jm”</th>
<th>cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>&gt; 160</td>
</tr>
<tr>
<td>$p_T(j_1)$ [GeV]</td>
<td>&gt; 130</td>
</tr>
<tr>
<td>$p_T(j_2)$ [GeV]</td>
<td>&gt; 60</td>
</tr>
<tr>
<td>$\Delta \phi(j_{1,2,(3)}, E_T^{\text{miss}})_{\text{min}}$</td>
<td>&gt; 0.4</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/\sqrt{H_T}[\text{GeV}^{1/2}]$</td>
<td>&gt; 15</td>
</tr>
<tr>
<td>$m_{\text{eff}}(\text{incl.})$ [GeV]</td>
<td>&gt; 1200</td>
</tr>
</tbody>
</table>

Very degenerated spectrum of $\Delta m \lesssim 20 \text{GeV}$ is challenging due to a jet qualification issue after pile-up removal.
Pile-up issue

Need to look into PT $\sim O(100)$ GeV
Boosted object


- We assume that top-quarks \( \sim \) ON-shell when they are from a very heavy resonance.
- Boosted Top-tagger (with top-quark mass window)

- What happen if there are non-negligible portion of top-quark from a heavy resonance being OFF-SHELL?

\[
\mathcal{L} \supset \frac{c_t}{\Lambda^2} G_{\mu} (\bar{Q}_L \tilde{H} ) \gamma^\mu (\tilde{H}^\dagger Q_L) \\
\text{can induce unitarity violation}
\]

\[
t(p_1) + G_\sigma (p_2) \rightarrow W^\mu (p_3) + b(p_4)
\]

A new physics should arise before the cut-off.
Heavy Top-partner

- Spin 1 color octet G and vector-like top-partner T

\[ \mathcal{L} \ni g_s G_\mu \bar{T} \gamma^\mu T - m_T \bar{T}T - (y Q_L \tilde{H} T_R + y_t \bar{Q}_L \tilde{H} t_R + h.c.), \]

mixing \[ \left( \begin{array}{cc} t_L & \bar{T}_L \\ \bar{T}_L & T_L \end{array} \right) \left( \begin{array}{cc} y_t \frac{v}{\sqrt{2}} & y \frac{v}{\sqrt{2}} \\ 0 & m_T \end{array} \right) \left( \begin{array}{c} t_R \\ T_R \end{array} \right) \]

\[ \left( \begin{array}{c} t'_{L,R} \\ T'_{L,R} \end{array} \right) = \left( \begin{array}{cc} \cos \theta_{L,R} & \sin \theta_{L,R} \\ -\sin \theta_{L,R} & \cos \theta_{L,R} \end{array} \right) \left( \begin{array}{c} t_{L,R} \\ T_{L,R} \end{array} \right) \]

with \[ \sin \theta_L \sim \frac{y v}{\sqrt{2}m_T}, \quad \sin \theta_R \sim \frac{m_t}{m_T} \sin \theta_L \]

by integrating out a top-partner

\[ \mathcal{L} \simeq \frac{c_t}{m_T^2} G_\mu (\bar{Q}_L \tilde{H}) \gamma^\mu (\tilde{H}^\dagger Q_L) \]
Recovering Unitarity

\[ t(p_1) + G_\sigma(p_2) \rightarrow W^\mu(p_3) + b(p_4) \]

There would be a cancelation between two diagrams

\[
\mathcal{M}_1 \propto \sin^2 \theta_L \cos \theta_L \bar{u}_b \frac{v_3}{m_w} P_L \frac{1}{p_1 + p_2 - m_t} \gamma_\sigma P_L u_t \epsilon_G \propto \frac{\sin^2 \theta_L \cos \theta_L \bar{u}_b P_R}{m_w} \left( \frac{m_t}{p_1 + p_2 - m_t} + 1 \right) \gamma_\sigma P_L u_t \epsilon_G
\]

\[
\mathcal{M}_2 \propto -\sin^2 \theta_L \cos \theta_L \bar{u}_b \frac{v_3}{m_w} P_L \frac{1}{p_1 + p_2 - m_T} \gamma_\sigma P_L u_t \epsilon_G \propto -\frac{\sin^2 \theta_L \cos \theta_L \bar{u}_b P_R}{m_w} \left( \frac{m_T}{p_1 + p_2 - m_T} + 1 \right) \gamma_\sigma P_L u_t \epsilon_G
\]

\[
\mathcal{M} \propto \bar{u}_b P_R \left( \frac{m_t}{p_1 + p_2 - m_t} - \frac{m_T}{p_1 + p_2 - m_T} \right) \gamma_\sigma P_L u_t \epsilon_G
\]
Visible effects

- From G decay, there would be a trace of a heavy top-partner in the invariant mass of (b,W)

$$m_G = 2 \text{ TeV}$$
Effects on collider phenomenology

- If we consider large $G \rightarrow t\bar{t}$ branch ratio, $pp \rightarrow GG$ would be dominant over single G production
  - Four top-quark channel with 4b+ 2l

Define a measure to check the “off-shellness”

$$M_{(b,\ell)}^{(\text{max})} = \max_{i=1,2} \left( \min_{j=1,\ldots,4} \{m_{(b_j,\ell_i)}\} \right)$$

- **MC1:** $pp \rightarrow GG \rightarrow b\bar{b}b\bar{b}\ell^+ \ell^- \nu\bar{\nu}jjjj$
- **MC2:** $pp \rightarrow GG \rightarrow t\bar{t}t\bar{t}$

$m_G = 1.8\,\text{TeV}, \ m_T = 3.5\,\text{TeV}, \ y = 2.0 \ (\sin \theta_L = 0.1)$
Effects on collider phenomenology

LHC 14TeV 3ab(-1) (fb)

<table>
<thead>
<tr>
<th>Analysis cut</th>
<th>MC1</th>
<th>MC2</th>
<th>(t\bar{t}bW\bar{b}W)</th>
<th>(bW\bar{b}Wb\bar{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T$ requirements ($p_T^{\ell,j} &gt; 50$ GeV)</td>
<td>0.22</td>
<td>0.19</td>
<td>0.18</td>
<td>5.5</td>
</tr>
<tr>
<td>Heavy flavored jet tagging (one high $P_T$ top and four b-jet)</td>
<td>0.051</td>
<td>0.050</td>
<td>0.0024</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$M_{(b,\ell)}^{(\text{max})} &gt; 170$ GeV</td>
<td>0.012</td>
<td>0</td>
<td>$10^{-4}$</td>
<td>$&lt; 10^{-4}$</td>
</tr>
</tbody>
</table>

- Top tagging / faking: 0.5 / 0.01
- b tagging: 0.8

We will observe the trace of a Heavy top-partner as $\mathcal{O}(30)$
Summary

• Theorists have provided “Non-conventional” object to the collider experiments to check - Otherwise, we will miss the physics behind them.

• We propose to enlarge a concept of “Jet” to cluster off-shell particles.

• If we keep using the conventional concept (in tagging top-quark from a heavy resonance) we may miss some interesting thing!