Detection of $W \rightarrow jj$ in Jets + MET Final State using New Data-Driven Technique

Bi-Event Subtraction Technique

Why? How? Where?

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Develop technique(s)

a) To extract key final states;
b) To measure SUSY masses in a minimal framework;
c) To determine model parameters;
d) To extract \( \Omega \) (amount of the dark matter) at the LHC; \( \Omega_{\text{SUSY}} \equiv \Omega_{\text{DM}} \)
e) To expand to non-minimal scenarios;
f) To expand to non-SUSY scenarios (e.g., UED);

and carry out at ATLAS and CMS!
PPC Projects at A Glance

http://faculty.physics.tamu.edu/kamon/research/TEVpheno/
http://faculty.physics.tamu.edu/kamon/research/ILCpheno/
http://faculty.physics.tamu.edu/kamon/research/LHCpheno/


“Supersymmetry Parameter Analysis: SPA Convention and Project”

We test “mSUGRA” cases first, followed by a “non-universal SUGRA” case.
BEST Part 1 : Why?

Our studies have been based on mSUGRA. ①

However, when we extend it to non-minimal scenarios, we see a case where W's become a key to reconstruct the SUSY masses. ②

We want to reconstruct $W \rightarrow jj$ in all hadronic mode of SUSY events ...
Non-Universal SUGRA

Dutta, Kamon, Kolev, Krislock, Oh

mSUGRA:
Unified masses at the GUT scale
Parameters: $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$, $\text{sign}(\mu)$

(*) Good enough to confirm that the dark matter is the SUSY weakly interacting neutral particle.

nuSUGRA:
Unified masses at the GUT scale, except Higgs
Parameters: $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$, $\mu(m_H)$

(*) small $\mu$ makes neutralino Higgs-like $\rightarrow$ annihilation cross section is large enough to have right amount of dark matter today.

[Q] Is a cosmological measurement possible for non-minimal case?
Non-Universal SUGRA

Is a cosmological measurement possible?

1) Start with over-abundance region in SSC-like mSUGRA (e.g., $m_{1/2} = 500$, $m_0 = 360$, $m_{Hu} = 360$)

2) Reduce Higgs coupling parameter, $\mu$, by increasing $m_{Hu}$ (e.g., $m_{1/2} = 500$, $m_0 = 360$, $m_{Hu} = 732$)
   → Extra contributions to $\Omega h^2$
   → More annihilation (less abundance)
   → Normal values of $\Omega h^2$

3) Find smoking gun signals

4) Technique to calculate $\Omega h^2$
W(s) in MET + Jets


$\tilde{q}_L \rightarrow q' \tilde{\chi}_1^\pm \rightarrow W^\pm$

$\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm \rightarrow W^\pm$

$\tilde{\chi}_2^\pm \rightarrow W^\pm$

$\tilde{\chi}_2^0 \rightarrow \tau$

$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0$

$m_{1/2} = 500, m_0 = 360, \tan\beta = 40, m_{\text{top}} = 175$

$m_{\tilde{H}_u} = 732, m_{\tilde{H}_d} = 732$

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$M(jj)$ Distribution

$E_T^{\text{miss}} > 180$ GeV;
$N(J) \geq 2$ with $E_T > 200$ GeV;
$E_T^{\text{miss}} + E_T^{J1} + E_T^{J2} > 600$ GeV

$N(j_i) \geq 2$ with $p_T > 20$ GeV

Counts / 5 GeV

A clear peak at the W mass, but can we see the BG shape?
# Data-Driven $M(jj)$ Extraction

<table>
<thead>
<tr>
<th>Event</th>
<th>Jets</th>
<th>$M(jj)$</th>
<th>$M(jj)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a, 1b, 1c</td>
<td>$M(2a, 1a), M(2a, 1b), M(2a, 1c)$, $M(2b, 1a), M(2b, 1b), M(2b, 1c)$</td>
<td>$M(2a, 2b)$</td>
</tr>
<tr>
<td>2</td>
<td>2a, 2b</td>
<td>$M(3a, 2a), M(3a, 2b)$, $M(3b, 2a), M(3b, 2b)$, $M(3c, 2a), M(3c, 2b)$, $M(3d, 2a), M(3d, 2b)$</td>
<td>$M(3a, 3b), M(3a, 3c), M(3a, 3d)$, $M(3b, 3c), M(3b, 3d), M(3c, 3d)$</td>
</tr>
<tr>
<td>3</td>
<td>3a, 3b, 3c, 3d</td>
<td>For each $j_i$ in Event $X$, $M(j_i, j_k)$ is calculated with $j_k$ in Event $X-1$</td>
<td></td>
</tr>
</tbody>
</table>

For each $j_i$ in Event $X$, $M(j_i, j_k)$ is calculated with $j_k$ in Event $X-1$. $M(jj) > nnn$ GeV for normalization.
For each $j_i$ in Event $X$, $M(j_i, j_k)$ is calculated with $j_k$ in Event $X-1$. The method seems to be reasonable for SUSY...
Start with “JW”

\[ E_T^{\text{miss}} > 180 \text{ GeV}; \]
\[ N(J) \geq 2 \text{ with } E_T > 200 \text{ GeV}; \]
\[ E_T^{\text{miss}} + E_T^{J1} + E_T^{J2} > 600 \text{ GeV} \]

\[ N(j) \geq 2 \text{ with } p_T > 30 \text{ GeV} \]
\[ N(b) \geq 0 \text{ with } p_T > 30 \text{ GeV} \]
\[ N(\tau) = 0 \text{ with } p_T > 20 \text{ GeV} \]

Jet Mix to extract W’s

Note there might be \( b \)-jets and/or \( \tau \)-jets in event, but not counted as “\( J \)” nor “\( j \)”.

\[ \tilde{q}_L \rightarrow q' \rightarrow W^\pm \]
\[ \tilde{\chi}_1^\pm \rightarrow W^\pm \]
\[ \tilde{\chi}_1^0 \rightarrow W^\pm \]

\[ \text{Ture} = 714 \text{ GeV} \left( \chi_1^{+/-} \right) \]

\[ \tilde{q}_L \rightarrow q' \rightarrow W^\pm \]
\[ \tilde{\chi}_1^0 \rightarrow W^\pm \]
\[ \tilde{\chi}_1^\pm \rightarrow W^\pm \]
\[ \tilde{\chi}_1^0 \rightarrow W^\pm \]

\[ \text{Ture} = 739 \text{ GeV} \left( \chi_4^0 \right) \]

\[ \text{500-360-732} \]

[Vetoing events with any \( \tau \)'s with \( p_T > 20 \text{ GeV} \)]

\[ \text{Endpoint} = 774 \text{ GeV} \]

\[ \text{Ture} = 739 \text{ GeV} \left( \chi_4^0 \right) \]
Part 1: Summary

We are pretty happy to be able to reconstruct the squark mass through $W\rightarrow jj$ in all hadronic mode of SUSY events ...

Can we validate with data?
BEST Part 2: Validation - How?

TTbar events!
ATLAS and CMS reconstruct the top quark mass using kinematical constrains specific to TTbar events.

1) $\chi^2$
2) $M3$

$$pp \rightarrow t\bar{t} + j \rightarrow (W^+b) \ (W^-\bar{b}) + j \rightarrow jj \rightarrow l^−\nu$$
N(isolated lepton) = 1
N(jets) ≥ 4 \[N(b\text{-jets}) ≥ 0\]
No MET cut

Table 1: Event yields and relative contribution of the different processes after the final selection step for an integrated luminosity of 35.9 ± 1.4 pb\(^{-1}\). The uncertainties account for the finite statistics of the simulation samples and for the uncertainty on the luminosity but not for cross-section uncertainties. The \(\bar{t}t\) and single top samples were generated using \(m_t = 172.5\) GeV.

<table>
<thead>
<tr>
<th>Data</th>
<th>Total expected</th>
<th>(\bar{t}t)</th>
<th>Single-Top</th>
<th>W \rightarrow l\nu</th>
<th>Z/\gamma* \rightarrow l^+l^-</th>
<th>QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Events</td>
<td></td>
<td>Single-Top</td>
<td>W \rightarrow l\nu</td>
<td>Z/\gamma* \rightarrow l^+l^-</td>
<td>QCD</td>
</tr>
<tr>
<td></td>
<td>Fraction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Events</td>
<td>396</td>
<td>358 ± 37</td>
<td>209 ± 33</td>
<td>12 ± 1</td>
<td>116 ± 9</td>
<td>12 ± 1</td>
</tr>
<tr>
<td>Fraction</td>
<td>-</td>
<td>100%</td>
<td>59%</td>
<td>3%</td>
<td>32%</td>
<td>3%</td>
</tr>
<tr>
<td>Events</td>
<td>392</td>
<td>345 ± 32</td>
<td>169 ± 27</td>
<td>9.5 ± 0.6</td>
<td>99 ± 7</td>
<td>16 ± 1</td>
</tr>
<tr>
<td>Fraction</td>
<td>-</td>
<td>100%</td>
<td>50%</td>
<td>3%</td>
<td>28%</td>
<td>4%</td>
</tr>
</tbody>
</table>

\(N(\text{top}) \sim 378\) events \rightarrow 11 events / pb\(^{-1}\)

\(N_S / \sqrt{N_S + N_B} = 13\) (for e & \(\mu\))

assumed for each of the jet-parton associations [12].

To select events in the muon+jets channel, we require exactly one isolated muon \((p_T > 20\) GeV, \(|\eta| < 2.1\)) and at least four PF jets \((p_T > 30\) GeV, \(|\eta| < 2.4\)). For the electron+jets channel, we require exactly one isolated electron \((p_T > 30\) GeV, \(|\eta| < 2.5\)). The jet requirements are the same as for the muon+jets channel.
Figure 2: The top quark mass before (top) and after (middle) the kinematic fit, and the estimated uncertainty on the fitted top mass (bottom), for the jet assignment that yields the lowest $\chi^2$ in the electron+jets (left) and muon+jets (right) channel. In addition to the reference event selection, we require at least one solution with $\chi^2 < 10$. The simulation is normalized to the number of events in data. The QCD contribution is modeled using events from data. Statistical uncertainties on the model prediction, while not always negligible, are not shown.

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N(isolated lepton) = 1
N(jets) ≥ 4 [N(b-jets) = 2]
No MET cut

Fig. 2

N(top) = 78 (e+µ)

M(top) and M(W) using M3 and M2

\[ M_3 = M_{jjb} \left( \max\{p_T(jj)\} \right) \]
\[ M_2 = M_{jj}(M_3) \]

Figure 4: M3 (top left), M2 (top right) and ΔM32 (bottom) distributions for the muon+jets channel in data compared to the MC predictions, using the central sample with \( m_t = 172.5 \) GeV and JES = 1.
Very powerful.

However, those kinematical constraints would NOT be available for general searches

A new technique?
Detection of $W \rightarrow jj$

**Bi-Event Subtraction Technique**


\[ pp \rightarrow t \bar{t} + j \rightarrow (W^+ b) \ (W^- \bar{b}) + j \]

\[ pp \rightarrow W + jjjjj \]

\[ \rightarrow l^- \nu \]

**BEST: “jet” mixing**

from two different events

(TTbar, TTbar), (TTbar, W), (W, W)

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In summary (phase space)

\#\mu(p_T > 30.0\text{GeV}) = 1
\#\text{jet}(p_T > 30.0\text{GeV}) \geq 3
\#b\text{-tag jet}(p_T > 30.0\text{GeV}) \geq 1
\Delta R(\text{jet1, jet2}) > 0.4
TTbar in MadGraph (I)

MC Closure Test

Work in Progress for discussion

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TTbar in MadGraph (II)

N(isolated muon, pT > 20) ≥ 1
N(jets, pT >30) ≥ 3 [N(b-jets, pT>30) ≥ 1]
MET > 20
ΔR(two jets)>0.4

3,701,947 events

\[ \frac{M(jj)_{\text{same}}}{M(jj)_{\text{bi}}} \]

a) Hadronization ... simulated by Pythia6 as well as the underlying events with the tune Z2.
b) Pile-up events ... simulated comparable to the current LHC run
c) CMS detector response ... simulated by a GEANT4 based program.
BEST Part 3: Where?

We are analyzing the CMS data and seeking any advice.

Applications?
Improvements?
Next Step?
Potential Applications

- **Jet Energy Correction:**
  - possibilities of calibrating the jet energy scale from the W mass peak

- **The top quark measurements:**
  - BEST might offer independent measurements of the top quark mass and the production cross section

- **Investigation of Mjj in W jets (CDF dijet anomaly):**
  - BEST might provide independent and purely data-driven combinatorial background model

- **SUSY Searches:**
  - SUSY cascade decay chains often end with LSPs, which carry away fractions of the mass.
  - BEST can reconstruct portion of the mass peak with the endpoint around the mass difference between the produced SUSY particle and LSP
Future BEST in SUSY

$\mathbf{m_{jj}}$

Counts / 50 GeV

Counts / 50 GeV
Phase Space Matching

Proposed

A

B rotated

Then "Mix"?

\[ \phi \] rotation

Choice of Phase Space:

\[ p_T, \eta, \phi, \text{MET}, N_j, H_T \ldots \]
BEST seems to be a powerful tool to reconstruct $W\rightarrow jj$ in all hadronic mode of SUSY events ... 

Can we generalize?