Determining Masses and Spins of New Particles (with missing energy)

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KEK seminar
18 September 2009
Outline

• Mass determination
  ■ $M_{T2}$ variable
  ■ Jet contamination
  ■ Solving decay chains
  ■ ‘Inclusive’ observables

• Spin determination
  ■ Decay chains
  ■ Dileptons
  ■ Three-body decays
  ■ Cross sections
Mass determination with $M_{T2}$
\( M_{T2} \) variable

- \( pp \to YYX, Y \to aN, Y \to bN \)
- \( a, b \) visible, \( N \) invisible
- Transverse mass:

\[
m_T^2(p_T^1, p_T^a; \mu_N) = \mu_N^2 + m_a^2 + 2(E_T^1E_T^a - p_T^1 \cdot p_T^a)
\]

\[
m_{T2}^2(\mu_N) \equiv \min_{p_T^1 + p_T^2 = p_T} \left[ \max\{m_T^2(p_T^1, p_T^a; \mu_N), m_T^2(p_T^2, p_T^b; \mu_N)\} \right]
\]

\[
\leq m_Y^2 \text{ when } \mu_N = m_N
\]
CDF top mass from $M_{T2}$

CDF note 9679

$mT2$ Mass 0tag

$mT2$ Mass 1tag

- 0.2 fb$^{-1}$ $\Rightarrow m_t = 168.0 \pm 5.6/-5.0$ GeV (prelim.)
**Top mass from \(M_{T2}\) at LHC**

Cho, Choi, Kim & Park, 0804.2185

\[
\begin{array}{|c|c|}
\hline
\chi^2 / \text{ndf} & 21.33 / 14 \\
\hline
p_0 & 171.1 \pm 1.1 \\
p_1 & 4.998 \pm 0.731 \\
p_2 & 558.5 \pm 55.4 \\
p_3 & 142.9 \pm 1.5 \\
\hline
\end{array}
\]

- **Input mass 170.9 GeV; PYTHIA+PGS; b-tagging 50%**
- **10 fb\(^{-1}\) @ LHC (14 TeV) \(\Rightarrow m_t = 171.1 \pm 1.1\) GeV**
Initial-state QCD radiation

- Irreducible source of “jet contamination”

  → Misidentification of processes
  → Combinatorial ambiguities
Jet contamination

- Fully leptonic $t\bar{t}$: 2 jets (+2 leptons + MET)
- Matched = top decay parton within $\Delta R=0.5$ and $\Delta E/E=0.3$
- Generated with MC@NLO (no underlying event)

Half of events have an extra jet
$E_T$ ordering of jets

$\bullet P(1 \text{ or both leading jets unmatched}) > 50\%$
Reducing jet contamination

- Idea: demand more jets, select lowest $M_{T2}$
  As long as one is correct, this cannot raise edge

Alwall, Hiramatsu, Nojiri & Shimizu, 0905.1201

- $7 \text{ fb}^{-1}$ MC@NLO, no b-tagging
- $>50\%$ events have extra jets
- Hardest 2 jets (red) $\Rightarrow$
  ISR contaminates edge
- Smallest $M_{T2}$ from 3 hardest
  (blue) $\Rightarrow$ less contamination
Solving decay chains

- Measure visible momenta $1\ldots n$, $1'\ldots n'$ and missing $p_T$
- 6 unknown momentum components per event
- $n+n'+2$ on-mass-shell constraints per event
- $N_m$ unknown masses $\rightarrow$ we need $N_{ev}(n+n'-4) \geq N_m$ to solve for masses

- Identical chains: $n=n'$, $N_m = n+1$ $\rightarrow$ need $N_{ev} = 2$ for $n=3,4$
- Non-identical ($N=N'$): $N_m = n+n'+1$ $\rightarrow$ need $N_{ev} = 6$ for $n+n'=5$
Solving pairs of events

- Two identical chains

- SPS 1a masses

<table>
<thead>
<tr>
<th>$\tilde{\chi}_1^0$</th>
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</table>

Chen, Gunion, Han, McElrath 0905.1344
Fitting decay chains

- Assume a mass hypothesis: if \( n+n' > 4 \) then each event is over-constrained.
- E.g. if \( n, n'=3 \), can solve for \( p_N, p_{N'} \).

\[ \xi^2 = (p_N^2 - M_N^2)^2 + (p_{N'}^2 - M_{N'}^2)^2 \]

- Measure goodness of fit by \( \xi^2 \).

N.B. \( p_N^2 - M_N^2 = p_Z^2 - M_Z^2 = p_Y^2 - M_Y^2 = \ldots \)

Best-fit points for 100 samples of 25 events (all combinations)

- Effects of jet contamination and background under study.
Global Inclusive Observables
Inclusive observables

• How can jets from hard subprocess be distinguished from ISR jets?

• In principle, there is no way! So let’s look at “global inclusive” observables

• Consider e.g. the total invariant mass $M$ visible in the detector:

$$M = \sqrt{E^2 - P^2_z - E_T^2}$$

or (Konar, Kong & Matchev, 0812.1042)

$$\hat{s}^{1/2}_{\text{min}}(M_{\text{inv}}) = \sqrt{M^2 + E_T^2} + \sqrt{M_{\text{inv}}^2 + E_T^2}$$
Inclusive observables: MC results

\[ s_{\text{min}}^{1/2}(M_{\text{inv}}) = \sqrt{M^2 + E_T^2} + \sqrt{M_{\text{inv}}^2 + E_T^2} \]

\[ M = \sqrt{E^2 - P_z^2 - E_T^2} \]

\[ H_T = E_T + E_T \]

Konar, Kong, Matchev, 0812.1042
ISR effects on inclusive observables

\[ \frac{d\sigma}{dM^2} = \int \frac{d\bar{x}_1}{x_1} \frac{d\bar{x}_2}{x_2} dx_1 dx_2 f(\bar{x}_1, Q_c) f(\bar{x}_2, Q_c) K \left( \frac{x_1}{\bar{x}_1}; Q_c, Q \right) K \left( \frac{x_2}{\bar{x}_2}; Q_c, Q \right) \hat{\sigma}(x_1 x_2 S) \delta(M^2 - \bar{x}_1 \bar{x}_2 S) \]

- **ISR at** \( \theta > \theta_c \sim \exp(-\eta_{\text{max}}) \) **enters detector**
- **Hard scale** \( Q^2 \sim \hat{s} = x_1 x_2 S \) **but** \( M^2 = \bar{x}_1 \bar{x}_2 S \)
- **PDFs sampled at** \( Q_c \sim \theta_c Q \)

A Papaefstathiou & BW, 0903.2013
ISR Effects: MC Results

\[ \hat{S}^{1/2}_{\text{min}}(M_{\text{inv}}) = \sqrt{M^2 + E_T^2} + \sqrt{M_{\text{inv}}^2 + \bar{E}_T^2} \]

\[ M = \sqrt{E^2 - P_z^2 - \bar{E}_T^2} \quad \quad H_T = E_T + \bar{E}_T \]

---

**fHERWIG6.510**

\[ \eta_{\text{max}} = 5 \]

\[ \text{evolution} \{ \text{---, ---, ---} \} \]

\[ \text{d} \sigma / \text{d} M \text{ (pb/GeV)} \]

\[ M (\text{GeV}) \]

---

Mass & Spin Determination 18

KEK 18/09/2009
Dependence on $\eta_{\text{max}}$

- $E, M, \hat{S}_{\text{min}}$ strongly dependent; $\mathcal{E}_T, E_T, H_T$ not
Conclusions on Masses

- $M_{T^2}$ will be an important observable
  - New ideas on reducing ISR jet contamination

- Decay chains: solving vs fitting
  - Which is more robust w.r.t. ISR & background?

- Global inclusive observables
  - Only transverse observables are robust
  - Scale information from others?
Spin Determination with ...

- Sequential decay chains
- Dileptons
- Three-body decays
- Cross sections

See also: review by Wang & Yavin, 0802.2726
Decay chains
“Classic” decay chain again

- Two distinct helicity structures, with different spin correlations:
  - Process 1: \( \{q, l_{\text{near}}, l_{\text{far}}\} = \{q_L, l^-_L, l^+_L\} \) or \( \{\bar{q}_L, l^+_L, l^-_L\} \) or \( \{q_L, l^+_R, l^-_R\} \) or \( \{\bar{q}_L, l^-_R, l^+_R\} \);
  - Process 2: \( \{q, l_{\text{near}}, l_{\text{far}}\} = \{q_L, l^+_L, l^-_L\} \) or \( \{\bar{q}_L, l^-_L, l^+_L\} \) or \( \{q_L, l^-_R, l^+_R\} \) or \( \{\bar{q}_L, l^+_R, l^-_R\} \).

Smillie, Webber, hep-ph/0507170
Datta, Kong, Matchev hep-ph/0509246
Angular variables

\[ \tilde{\chi}_0^2 / Z^* \]
\[ \tilde{\chi}_1 / \gamma^* \]
\[ \theta^* \text{ defined in } \tilde{\chi}_2 / Z^* \text{ rest frame} \]
\[ \theta, \phi \text{ defined in } \tilde{l} / l^* \text{ rest frame} \]
**Invariant masses**

- $ql^{\text{near}}$: \[ \frac{m_{ql}}{\left(m_{ql}\right)_{\text{max}}} = \sin\left(\frac{\theta^*}{2}\right) \]

- $ll^{\text{near \ far}}$: \[ \frac{m_{ll}}{\left(m_{ll}\right)_{\text{max}}} = \sin\left(\frac{\theta}{2}\right) \]

- $ql^{\text{far}}$: \[ \frac{m_{ql}}{\left(m_{ql}\right)_{\text{max}}} = \frac{1}{2} \left[ (1 - y)(1 - \cos \theta^* \cos \theta) + \frac{1}{2} \right] \]

  \[ + (1 - y)(\cos \theta^* - \cos \theta) - 2 \sqrt{y} \sin \theta^* \sin \theta \cos \phi \]

where \[ x = \frac{m_{Z^*}^2}{m_q^2}, \ y = \frac{m_{l^*}^2}{m_{Z^*}^2}, \ z = \frac{m_{\gamma^*}^2}{m_{l^*}^2} \]
Helicity dependence

- Process 1 (SUSY)
  \[ q_L \quad \tilde{q} \quad \tilde{\chi}_2^0 \quad \tilde{l}^+ \quad l^-_L \]

- Process 1 (UED, transverse Z*: \( P_T/P_L = 2x \))
  \[ q_L \quad q^* \quad Z^* \quad l^* \quad l^-_L \]

- Both prefer high \((ql^-)_{near}\) invariant mass
UED and SUSY mass spectra

● UED models tend to have quasi-degenerate spectra

<table>
<thead>
<tr>
<th>γ*</th>
<th>Z*</th>
<th>qL*</th>
<th>lR*</th>
<th>lL*</th>
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<tbody>
<tr>
<td>501</td>
<td>536</td>
<td>598</td>
<td>505</td>
<td>515</td>
</tr>
</tbody>
</table>

Table 1: UED masses in GeV, for $R^{-1} = 500\text{GeV}$, $\Lambda R = 20$, $m_h = 120\text{GeV}$, $\overline{m}_h^2 = 0$ and vanishing boundary terms at cut-off scale $\Lambda$.

● SUSY spectra typically more hierarchical

<table>
<thead>
<tr>
<th>$\tilde{\chi}_1^0$</th>
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<th>$\tilde{u}_L$</th>
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<td>96</td>
<td>177</td>
<td>537</td>
<td>143</td>
<td>202</td>
</tr>
</tbody>
</table>

Table 2: SUSY masses in GeV, for SPS point 1a.

($M_n \sim n/R$ broken by boundary terms and loops, with low cutoff)
ql^{near} mass distribution

UED masses

SPS 1a masses

UED and SUSY not distinguishable for UED masses
$q_l^{\text{far}}$ mass distribution

Correlation weak but slightly enhances UED-SUSY difference
Jet + lepton mass distribution

UED masses

- UED spins
- MSSM spins
- Phase space

$\hat{m} = m_{jl}/(m_{jl})_{\text{max}}$

SPS 1a masses

- UED spins
- MSSM spins
- Phase space

$\hat{m} = m_{jl}/(m_{jl})_{\text{max}}$

Not resolvable for UED masses, maybe for SUSY masses

Charge asymmetry due to quark vs antiquark excess
Production cross sections (pb)

<table>
<thead>
<tr>
<th>Masses</th>
<th>Model</th>
<th>$\sigma_{\text{all}}$</th>
<th>$\sigma_{q^*}$</th>
<th>$\sigma_{\bar{q}^*}$</th>
<th>$f_q$</th>
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<tr>
<td>UED</td>
<td>UED</td>
<td>253</td>
<td>163</td>
<td>84</td>
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<td>18</td>
<td>9</td>
<td>0.65</td>
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<tr>
<td>SPS 1a</td>
<td>UED</td>
<td>433</td>
<td>224</td>
<td>80</td>
<td>0.74</td>
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<tr>
<td>SPS 1a</td>
<td>SUSY</td>
<td>55</td>
<td>26</td>
<td>11</td>
<td>0.70</td>
</tr>
</tbody>
</table>

$\sigma_{\text{UED}} \gg \sigma_{\text{SUSY}}$ for same masses (100 pb = 1/sec)

$q^*/\bar{q}^* \sim 2 \Rightarrow$ charge asymmetry
Charge asymmetry

\[ A = \frac{(j^+_l) - (j^-_l)}{(j^+_l) + (j^-_l)} \]

UED masses

SPS 1a masses

Similar form, different magnitude

Not detectable for UED masses
Charge asymmetry at detector level

A Barr, hep-ph/0405052

- Same decay chain: \( \tilde{q}_L \rightarrow \tilde{\chi}^0_2 q_L \rightarrow \tilde{\ell}_R^\pm \ell^\mp q_L \)
- Different MSSM point (now excluded)
- Compared with no spin (i.e. phase space) only
- More careful study of background and detector effects
- Points are for 500 fb\(^{-1}\)
- Used HERWIG

See also: Goto, Kawagoe, Nojiri, hep-ph/0406317
Gluino spin correlations

- Lowest mass dijet \sim (12)

- Medium mass dijet \sim (23)

Krämer, Popenda, Spira, Zerwas, 0902.3795
Production/Decay Spin Correlations in Herwig

- Example: top quark pairs in e+e- annihilation:

Full spin correlations included, by factorized, step-by-step algorithm

\[ |M|^2 = \rho_{\text{prod}}^{\lambda_c \lambda'_c \lambda_d \lambda'_d} D_c^{\lambda_c \lambda'_c} D_d^{\lambda_d \lambda'_d} \]

\[ \rho_{\text{prod}}^{\lambda_c \lambda'_c \lambda_d \lambda'_d} = M_{ab\to cd}^{\lambda_c \lambda_d} M_{ab\to cd}^{\lambda'_c \lambda'_d}, \]

\[ D_c^{\lambda_c \lambda'_c} = M_{c \text{ decay}}^{\lambda_c} M_{c \text{ decay}}^{\lambda'_c}, \]

Richardson, hep-ph/0110108
Top spin correlations in Herwig

Lepton-beam correlation

Top-beam correlation

- SM, SUSY & UED in Herwig++

Hw++ manual: Bähr et al., 0803.0883
Dileptons
Dileptons in “classic” chain

\[ \frac{dP_{UED}}{d\hat{m}_{ll}} = \frac{4\hat{m}_{ll}}{(2 + y)(1 + 2z)} \left[ y + 4z + (2 - y)(1 - 2z)\hat{m}_{ll}^2 \right] \]

- \( y = \frac{m_{l*}^2}{m_{Z*}^2} \) and \( z = \frac{m_{\gamma*}^2}{m_{l*}^2} \)

- UED: \( y = 0.92 \) \( z = 0.95 \)

- SPS Ia: \( y = 0.65 \) \( z = 0.45 \)

→ Sensitivity greatest at small \( y \) and \( z \)
Dilepton mass distribution

\[ \frac{dP}{dm} \]

UED spins, UED masses
UED spins, SPS 1a masses
MSSM spins

\[ \hat{m} = \frac{m_{ll}}{(m_{ll})_{\text{max}}} \]

No sensitivity for these masses!
Dilepton mass distribution (2)

\[ y = \frac{m_l^2}{m_{Z^*}^2} = 0.65, \quad z = \frac{m_{\gamma^*}^2}{m_l^2} = 0.95 - 0.05 \]

\[ \hat{m} = \frac{m_{ll}}{(m_{ll})_{\text{max}}} \]

Independent of masses and spins at \( \hat{m} = 1/\sqrt{2} \) (\( \theta = \pi/2 \))
All possible spin assignments

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{D} & \textbf{C} & \textbf{B} & \textbf{A} \\
\hline
Scalar & Fermion & Scalar & Fermion \\
Fermion & Vector & Fermion & Vector \\
Fermion & Scalar & Fermion & Scalar \\
Fermion & Vector & Fermion & Scalar \\
Scalar & Fermion & Vector & Fermion \\
\hline
\end{tabular}
\end{center}

\{ SUSY \} not distinguishable

... but some others are.

Athanasiou, Lester, Smillie, Webber, hep-ph/0605286
All possible assignments (2)

Allowing arbitrary mixtures of L and R couplings:

<table>
<thead>
<tr>
<th>Processes $P_1$</th>
<th>Processes $P_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>${q_L, \ell_L^R, \ell_L^{R+}}$</td>
<td>${q_L, \ell_L^R, \ell_L^{R+}}$</td>
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<tr>
<td>$f_{\ell L}</td>
<td>f_{\ell L}^2</td>
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Burns, Kong, Matchev, Park, 0808.2472

Dilepton invariant mass-squared
Dislepton production

- $q\bar{q} \rightarrow Z^0/\gamma \rightarrow \tilde{\ell}^+\tilde{\ell}^- \rightarrow \tilde{\chi}_1^0\ell^+ \tilde{\chi}_1^0\ell^-$

- Distribution of $\cos \theta_{ll}^* \equiv \tanh(\Delta \eta_{\ell^+\ell^-}/2)$ is correlated with $Z^0/\gamma$ decay angle $\theta^*$

![Graphs showing distribution of $\cos \theta_{ll}^*$ for SUSY and UED](graph.png)

A Barr, hep-ph/0511115

(neglects KKlepton polarisation)
Dislepton production (2)

- Outer error bars: after SUSY & SM background subtraction
- Significance strongly dependent on mass spectrum
Disleptons at CLIC

Detector level

Battaglia, Datta, DeRoeck, Kong, Matchev, hep-ph/0502041, 0507084

UED: Bhattacharya, Dey, Kundu, Raychaudhuri, hep-ph/0502031

Mass & Spin Determination
Azimuthal correlations in $e^+e^-$

$$\phi = \phi_F = 2\pi - \phi_T$$

Buckley, Choi, Mawatari, Murayama, 0811.3030
Spin Correlations in HERWIG

\[ e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow \tilde{l}_R^+ \tilde{l}^- \tilde{\chi}_1^0 \rightarrow l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]

Unpolarised

\[ e^- e^+ \]

\[ e_L^- e_R^+ \]

\[ e_R^- e_L^+ \]

Gigg, Richardson, hep-ph/0703199
Three-body decays
Three-body gluino decays

Three-body gluino decays

Csaki, Heinonen, Perelstein, 0707.0014

Kullback-Leibler measure:

\[ N \sim \log R / KL(T, S) \]

\[ KL(T, S) = \int m \log \left( \frac{p(m|T)}{p(m|S)} \right) p(m|T) \, dm \]
$p p \rightarrow Y (1) + \bar{Y} (2) \rightarrow V (p_1) \chi (k_1) + V (p_2) \chi (k_2)$, $Y \rightarrow q (p_q) \bar{q} (p_{\bar{q}}) \chi (k)$.

$M_{T2} (p_i, m_\chi) \equiv \min_{k_{1T} + k_{2T} = p_{T\text{miss}}} \left[ \max \{ M_T^{(1)}, M_T^{(2)} \} \right]$ assign 4-momenta

$m_{\chi,Y} = m_{\chi,Y}^{\text{true}}$

$L = \infty$

$m_\chi = 0$, $m_Y = M_{T2}^{\text{max}} (m_\chi = 0)$

$L = 300 \text{ fb}^{-1}$

Cho, Choi, Kim, Park, 0810.4853
Cross sections
Cross sections imply spins

Higher spins mean higher cross sections (for given masses)

Datta, Kane, Toharia hep-ph/0510204
Cross sections imply spins (2)

- Can match cross section and one distribution by adjusting masses
- Cannot match several cross sections or distributions ...

Kane, Petrov, Shao, Wang, 0805.1397
**Cross sections imply spins (3)**

- Can vary masses to fit cross section and one distribution
- E.g. match jet counts $\rightarrow H_T$ doesn’t match $\rightarrow$ ambiguity resolved
Conclusions on Spins

- Sequential decay chains
  - Possibilities -- but difficult for degenerate masses
  - Gluino spin -- some ideas, just starting

- Dileptons
  - SUSY vs UED difficult at LHC -- other cases possible

- Three-body decays
  - $M_{T2}$ assistance looks useful here (and elsewhere?)

- Cross sections
  - Should be included

- Full simulations (and data) needed!