Making the Most of MET

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1301.0345 & Phys.Rev. D

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Erice, June 2013
**Prelude**

Q: How can we discover a new particle X in incoming particles

\[
\text{whatever} + X
\]

\[
\text{whatever} + 1 + 2 + \ldots + i + \ldots
\]

Cut and count: better:

\[
\text{mass}(\sum_i p_i^\mu)
\]
## Missing Momenta

One or two invisible particles $\chi$ leaving the detector:

<table>
<thead>
<tr>
<th></th>
<th>lepton collider</th>
<th>hadron collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\chi$</td>
<td>3 unknowns: $p_\chi$</td>
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<tr>
<td></td>
<td>3 measurements: $p$</td>
<td>2 measurements: $p_T$</td>
</tr>
<tr>
<td>$2\chi$</td>
<td>6 unknowns: $p_{\chi a}, p_{\chi b}$</td>
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(assuming $m_\chi$ is known).

$2\chi$ at hadron colliders – e.g. $\mathbb{Z}_2$-symmetric dark matter at the LHC.
One Decaying Particle At A Hadron Collider: $m_T$

\[
m_W^2 = (E_l + E_\nu)^2 - (p_l + p_\nu)^2
\]
\[
= m_l^2 + m_\nu^2 + 2(E_{T,l}E_{T,\nu} \cosh(\Delta y_{l\nu}) - p_{T,l} \cdot p_{T,\nu})
\]
\[
m_T^2 \equiv (E_{T,l} + E_{T,\nu})^2 - (p_{T,l} + p_{T,\nu})^2
\]
\[
= m_l^2 + m_\nu^2 + 2(E_{T,l}E_{T,\nu} - p_{T,l} \cdot p_{T,\nu})
\]
\[
\therefore m_T \leq m_W
\]

\[
m_T^2 \equiv (E_{T,\text{vis}} + E_{T,\text{invis}})^2 - (p_{T,\text{vis}} + p_{T,\text{invis}})^2
\]
\[
\therefore m_T \leq m_X
\]

* must approximate $m_{\text{invis}} \approx 0$
Two Decaying Particles At A *Hadron* Collider: $M_{T2}$

\[
\begin{align*}
\max & \{ m_T^2(p_T,l^+, p_T,\tilde{N}_{1,a}) , \\
& m_T^2(p_T,l^-, p_T,\tilde{N}_{1,b}) \} \leq m_i^2,
\end{align*}
\]

but we don’t know the decomposition

\[
p_T = p_T,\tilde{N}_{1,a} + p_T,\tilde{N}_{1,a}
\]

\[\implies\] try all decompositions & take the most conservative:

\[
M_{T2}^2 \equiv \min_{p_1 + p_2 = p_T} \left( \max \{ m_T^2(p_T,l^+, p_1) , m_T^2(p_T,l^-, p_2) \} \right) \leq m_i^2
\]

9906349 Lester, Summers
The Massless Collinear Approximation

Aim for $\text{mass}(\sum_i p_i^\mu)$.
To constrain the kinematics we must have a prejudice about the directions of $\chi_a$ and $\chi_b$.
e.g. both are parallel to visible particles, due to boosted decays.

$\rightarrow$ unique decomposition $p_T = p_{T,\chi_a} + p_{T,\chi_b}$
$\rightarrow$ unique $p_{z,\chi_a}, p_{z,\chi_b}$
$\rightarrow$ if $\chi$ is ‘light’, set $m_\chi = 0$

In the transverse plane:
$\mathbf{p}_T$ (which is $p_{T,\chi_a} + p_{T,\chi_b}$)
Two visible particles $\parallel$ to $\chi_a$ and $\chi_b$
Other stuff

c.f. $H \rightarrow \tau\tau$ by Plehn, Rainwater, Zeppenfeld ‘99
A Pair Of Boosted Semi-invisible Decays

e.g. $2\tilde{q} \rightarrow 2q + 2\tilde{N}_1$; $\tilde{N}_1$ could decay to

- a gravitino $\tilde{G}$

1110.6444 Kats, Meade, Reece, Shih

- a pseudo-goldstino $\tilde{G}'$

1002.1967 Cheung, Nomura, Thaler,
1112.5058 Argurio et al

- a singlino $\tilde{S}$

e.g. 1202.5244 Das, Ellwanger, Teixeira

- a new photino’ $\tilde{\gamma}'$

e.g. 1206.0751 Baryakhtar, Craig, Van Tilburg
Aforementioned steps reconstruct (massless) $p_{\tilde{N}_{1,a},b}^{\mu}$.

How to pair $\tilde{N}_{1,a}, \tilde{N}_{1,b}$ with the ‘correct’ $j_a, j_b$?

**criterion $\alpha$:** $- \left( p_{\tilde{N}_{1,a}} \cdot p_{j_a} + p_{\tilde{N}_{1,b}} \cdot p_{j_b} \right)$ maximal

**criterion $\beta$:** $\left| (p_{\tilde{N}_{1,a}}^\mu + p_{j_a}^\mu)^2 - (p_{\tilde{N}_{1,b}}^\mu + p_{j_b}^\mu)^2 \right|$ minimal
Mass Reconstruction

\[ M_{\text{rec};a,b}^2 = (p_{\tilde{\nu}_{1;a,b}}^{\mu} + p_{\tilde{\nu}_{j;a,b}}^{\mu})^2 \]

\[ pp \to 2\tilde{\nu} \to 2q + 2(\tilde{\nu}_1) \to 2q + 2(\tilde{G} + \gamma) \]

Herwig++, MadGraph-PYTHIA-PGS

\[ m_{\tilde{\nu}} = 1.2 \text{ TeV} \]
\[ m_{\tilde{\nu}_1} = 100 \text{ GeV} \]
\[ m_{\tilde{G}} = 1 \text{ eV} \]
Accuracy

\[ \uparrow \text{sample of 100} \rightarrow \text{one } M \text{ value} \downarrow \]
many signal events \[ \rightarrow \text{sample of 100} \rightarrow \text{one } M \text{ value} \rightarrow P(M)dM \]
\[ \downarrow \text{sample of 100} \rightarrow \text{one } M \text{ value} \uparrow \]

\[ \therefore \text{root-mean-square}(M - M_{\text{true}}) = 5\% \ M_{\text{true}} \]
from 100 events

c.f. (with large pinch of salt!) ATLAS Technical Design Report, squark mass from kinks:
3% after one \textbf{million} signal events
Dependence On Boostedness

\[ \frac{1}{\sigma} \frac{d\sigma}{d(\Delta R)} \]

\[ \Delta R(\gamma \tilde{G}) \]

\[ \frac{1}{\sigma} \frac{d\sigma}{dM_{\text{rec}}} \]

\[ M_{\text{rec}} \text{[TeV]} \]

\[ m_{\tilde{q}} = 1.2 \text{ TeV}, \quad m_{\tilde{N}_1} = 100, 200, 400 \text{ GeV} \]
Non-degenerate Squarks; Gluinos

\[ m_{\tilde{q}} = 1.1, 1.4 \text{ TeV} \]
smaller mass,
larger mass

\[ m_{\tilde{g}} = 1.2 \text{ TeV} \]
Herwig++,
MG5–PYTHIA–PGS
Other Generalisations

- $\text{vis}_1$ = more than one particle,
- $\text{vis}_2$ = more than one particle,
- $\text{vis}_1 = \text{vis}_2$,
- $3\chi$,

see 1301.0345.
Theorists: see if your model has boosted semi-invisible decays, tell experimentalists these final states are motivated.

Experimentalists: search for resonances thusly in any clean final state – \( \text{vis}_1,2 = l, \gamma, j; \text{vis}_1,2 \neq b, t \) if unexpected bumps? PGS/HepMC output → peak-finding code at www.ippp.dur.ac.uk/~hndv85/ (or Google me)