Weighing WIMPS at the LHC

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BMG, 0709.2740
Barr, BMG & Lester, 0711.4008
Barr, BMG & Lester, 0902.4864
Barr, BMG & Lester, 0908.3779
Outline

- Missing energy at the LHC
- Kinematics
- Applications: SM, SUSY, LHC-DM
Missing energy at the LHC
Sources of missing energy

- Standard Model - neutrinos
- Supersymmetry?
- Thermal Relic Dark Matter?
- ...
Missing energy

Missing energy $\implies$ ignorance
- Don’t know the dynamics
- $\implies$ kinematics
- Kinematic information is lost
- Cannot reconstruct events
Missing energy

- So how do we do anything?
- How do we discover new physics?
- Think carefully about kinematics …
Janet and John...

This is Janet.

This is John.

... do kinematics
Generalities of Kinematics

- What if missing energy wasn’t missing?
- Discover new physics by plotting $\Sigma p_{\mu}^2$
- Delta function/Breit-Wigner
- Hadron collider physicists love delta functions …
Generalities of Kinematics

- Any old singularity would do
- But phase space is non-singular (modulo collinear/soft divergences)
- Missing energy \(\Rightarrow\) projection
- Projected phase space can be singular!

Kim, 0910.1149
Generalities of Kinematics

An example: 2-body decay $Y \rightarrow X + V$

- Produce $V$ at rest
- 3-momentum of $X$ satisfies
  \[
  p^2 + p_3^2 = M^2 \equiv \left( \frac{m_Y^2 - m_X^2 - m_V^2}{2m_V} \right)^2 - m_X^2
  \]
- Phase space is a 2-sphere
- $p_3$ is unobservable
- Observable phase space is a disk $p^2 \leq M^2$

BMG, Les Houches proceedings, to appear
We learn:

- That there are singularities in events with $\mathcal{E}_T$
- That there is information about masses in events with $\mathcal{E}_T$
Generalities of Kinematics

► How much information?
► Why is there information?
Specifics of Kinematics
Specifics of Kinematics

Why is there information?

- Kinematics of an event $Y \rightarrow X + V$

\[
p_X^2 = m_X^2 \\
(p_X + p_V)^2 = m_Y^2
\]

- For all $m_X, m_Y$ these have solutions with $p_X, p_Y \in \mathbb{C}$
- But momenta are real
- Energies are real and positive
- An event restricts $m_X, m_Y$
Specifics of Kinematics

Why is there information?

- Kinematics of an event \( Y \rightarrow X + V \)

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Specifics of Kinematics

Theorem: $m_Y \geq m_T(m_X)$, where

$$m_T^2(m_X) = m_V^2 + m_X^2 + 2(e_V e_X - p_V \cdot p_X)$$

$e = \sqrt{p \cdot p + m^2}$ is transverse energy

The endpoint is the singular point we saw before.
Specifics of Kinematics

What about pair production? $2Y \rightarrow 2X + 2V$

- Theorem: $m_Y \geq m_{T2}(m_X)$, where
  
  $m_{T2} = \min \max m_T$

Which really means

- Partition $\rho_T$ between two invisibles
- Compute the two $m_T$s and take the largest
- Minimize with respect to partitions
With these theorems we can go a long way ...
... If you know the mass of $X$, you can bound the mass of $Y$ (and vice versa)
Standard Model applications
The mass of the $W$-boson

$W \rightarrow l\nu$

CDF: $m_W = 80.413 \pm 0.048$ GeV

arXiv:0708.3642
The mass of the top

\[ \bar{t}t \rightarrow 2b2W \rightarrow 2b2l2\nu \]

CDF $m_{T2}$ only: $m_t = 167.9^{+5.6}_{-5.0}$ GeV

CDF note 9769

LHC $\Delta m_t \sim 1$ GeV with 10 fb$^{-1}$
The mass of the Higgs

\[ h \to WW^{(*)} \to 2l2\nu \]

- \[ m_T^{\text{approx}} = 2m_v^2 + 2(e_v \sqrt{p_i^2 + m_v^2} - p_v \cdot p_i) \]
- \[ m_T^{\text{true}} = m_v^2 + 2(e_v |p_i| - p_v \cdot p_i) \]

Barr, BMG & Lester, 0902.4864
The mass of the Higgs

\[ h \rightarrow WW^{(*)} \rightarrow 2l2\nu \]

Barr, BMG & Lester, 0902.4864
... what if you don't know the mass of $X$?
The LHC-dark matter connection
The LHC-dark matter connection

- SM applications: massless neutrinos
- Dark matter: massive LSPs
- Can we weigh WIMPs at the LHC?
Worst case scenario: DM produced in a pair of 2-body decays

- e.g. $2\tilde{q} \rightarrow 2q2\tilde{\chi}_1^0$
- All information about masses $m_{\tilde{q}}, m_{\tilde{\chi}}$ in $m_{T2}$
The LHC-dark matter connection

- With one event, get a bound from the theorem:
  \[ m_{\tilde{q}} \geq m_{T2}(m_{\tilde{\chi}}) \]
- With two events, get a better bound
- With many events, get a kink \( @ (m_{\tilde{\chi}}, m_{\tilde{q}}) \)
The LHC-dark matter connection

- Kink first seen in 3-body decay
  - Cho et al., 0709.0288
- Kink also in 2-body decays
  - BMG, 0709.2740
- $\implies$ Kink in any decay
- DM mass can be measured absolutely @ LHC.
The LHC-dark matter connection

Pair Three-body decay $2\tilde{g} \rightarrow 2q 2\bar{q} 2\tilde{\chi}_1^0$

Barr, BMG & Lester, JHEP 0208 014, 2008
The race for supersymmetry

Barr & Gwenlan, 0907.2713
How to discover SUSY at the LHC?
Typical searches are multi-cut based

- Cuts on $p_T, \rho_T, \Delta \phi, \ldots$
- Signal enriched sample
- Wastes signal events
- (What is the background contribution?)
The race for supersymmetry

The optimal search has no cuts

- Calculate $L$ for all hypotheses of $S$ and $B$
- Practically Impossible
What about a single cut?
$m_{T2}$ discriminates between $S$ and $B$:

- Signal events can have large $m_{T2}$
- Physics/detector backgrounds have small $m_{T2}$

Barr & Gwenlan, 0907.2713
The race for supersymmetry
A single $m_{T2}$ cut suffices to discover SUSY in $2j + E_T$

- 100 $\text{pb}^{-1}$ of SPS 1a @ 10 TeV
- $m_{T2} > 230 \text{GeV} \implies \frac{S}{\sqrt{S^2 + B^2}} = 15$
Summary

- Kinematic trivialities
- $\implies$ Measure the DM mass absolutely
- $\implies$ The race for SUSY
- $\implies$ The race for the top mass