THE IMPORTANCE OF BEING TRANSVERSE

EVENT RECONSTRUCTION AND SUSY SEARCHES AT ATLAS AND THE LHC

TENG JIAN KHOO
OUTLINE

- Hadron collider physics and momentum conservation
- ATLAS event reconstruction and missing transverse momentum performance
- Transverse mass variables
- Supersymmetry searches
LHC collides protons at energy scales beyond that needed to probe proton structure.

Centre-of-mass proton collision energy $\sqrt{s} = 13$ TeV.
HADRON COLLIDER PHYSICS

- LHC collides protons at energy scales beyond that needed to probe proton structure.
- Centre-of-mass proton collision energy $\sqrt{s} = 13$ TeV.
- Effectively functions as a parton collider (gluons & quarks interact directly). Parton COM energy $\sqrt{\hat{s}} \leq 13$ TeV.
- Parton distribution functions describe energy fractions carried by colliding partons.
LATELY INSIDE THE LHC:
2 PROTONS 0.00000000000000001 SEC BEFORE THE COLLISION
Carry away remaining proton energy

Momentum fraction given by PDFs

Hard parton interaction

Beam remnant

ISR

Resonance decay

Z^0/\gamma^*

FSR
MSTW 2008 NLO PDFs (68% C.L.)

\[ Q^2 = 10 \text{ GeV}^2 \]

Valence quarks

\[ Q^2 = 10^4 \text{ GeV}^2 \]

PIECES OF ATLAS

A Toroidal LHC Apparatus
How do we spot this guy?

The dashed tracks are invisible to the detector.
INVISIBLE PARTICLES — WHAT AND WHY?

- Do not interact via electromagnetic or strong nuclear forces. Do not decay within detector.

- Standard Model: Neutrino – produced in W,Z and top decays

- Supersymmetry (SUSY) with R-parity conservation: Lightest supersymmetric particle (LSP) e.g. neutralino, gravitino

- Extra dimensional models: Kaluza-Klein graviton/photon

- Generic dark matter candidates
M.E.T.
THE EXTRA-TERRESTRIAL
THE 20TH ANNIVERSARY
MISSING TRANSVERSE MOMENTUM
— NOT ENERGY!

M.E.T.
THE EXTRA-TERRESTRIAL
THE 20TH ANNIVERSARY
MISSING TRANSVERSE MOMENTUM RECONSTRUCTION

- Parton collision rest-frame should have ~0 transverse momentum, although boost along beam-pipe unknown.
- Sum up transverse momenta of detected particles.
- Invisible particles carrying transverse momentum → apparent non-conservation.
- Susceptible to object mismeasurement/miscalibration.
8 reconstructed vertices. Mean in 2012 was \(~20\)!
A SUM OF PARTS

- Well-calibrated reconstructed particles ($e, \gamma, \mu, \tau$)
- High-pT jets
- Soft particle contributions (clusters / tracks)
A SUM OF PARTS

- Pileup causes fluctuations
- Cannot separate calo signals from different vertices
- Can distinguish pileup tracks
A SUM OF PARTS

- Pileup causes fluctuations
- Cannot separate calor signals from different vertices
- Can distinguish pileup tracks
INVISIBLE IMPROVEMENT

- Pileup robustness:
  - Inherit suppression techniques pioneered by jets – track-based discriminants, area-based subtraction, constituent subtraction
  - Require adaptation for application to soft component: calorimeter occupancy/granularity, pileup event shapes and detector-shaping, reconstruction efficiency of soft particles
PERFORMANCE

- Analyses use MET to:
  - Reconstruct event – need accurate determination of magnitude and direction: good resolution and scale.
  - Identify signals with energetic invisibles – must eliminate tails from detector effects.
  - Assess performance from $p_T$ balance in pure event sample with clean reference particle and zero intrinsic MET.
  - Chiefly focus on $Z \rightarrow \mu\mu + \text{jets}$. 
PT BALANCE

Non-zero mean indicates imbalance

Resolution components not a priori correlated.

Mean zero by symmetry

Fake MET

Hadronic recoil
Perfect balance

Soft component underestimated
Jet calibration restores scale

$\mu \mu$
$Z$

$<E_{T}^{miss}>_{Z}$

$<p_{T}^{Z}>[GeV]$

$\sqrt{s} = 8$ TeV $\int L dt = 20$ fb$^{-1}$

$Z \rightarrow \mu \mu$ Data 2012

Before pile-up suppression
Pile-up suppression STVF
Pile-up suppression Extrapolated Jet Area Filtered
Pile-up suppression Jet Area Filtered

ATLAS Preliminary

Hadronic recoil
Samples with no intrinsic MET (neutrinos)

True value is spike at 0

Width defines resolution, driven by fluctuations
2012

New challenges
New tools

2015
Core resolution improved without effect on tails
PILEUP CORRECTIONS — 2012

[Graph showing pile-up corrections with different suppression methods for Z→μμ in ATLAS Experiment, data from 2012, √s = 8 TeV.]
Soft component not negligible
Pileup-sensitivity drives resolutions
Neutral information in energetic jets critical
MASSING AROUND WITH INVISIBLES

- Standard resonant signal: invariant mass peak – requires identification of all daughter four-momenta

- MET reconstruction permits constraint on total invisible transverse momenta only:
  \[ \sum_{i \in \text{invis}} p_{x,y} = E_{\text{miss}}^{x,y} \]

  *Invisible mass and z-momentum unconstrained.*

- Partial reconstruction of *semi-invisible* decays possible given appropriate assumptions about decay chain.
ONE TO TWO

Fully visible decay

Semi-invisible decay
Want to compute something like an invariant mass.

\[ M_{\text{inv}}^2 = (P^\mu_v + P^\mu_i)^2 \]

\[ \geq \min_{p^z_i} (P^\mu_v + P^\mu_i)^2 \]

Minimise over unknown z-component

\[ = \min_{y^i} (P^\mu_v + P^\mu_i)^2 \]

Equivalent to minimising over rapidity

\[ = (p^{\alpha}_{T,v} + p^{\alpha}_{T,i})^2 = m_T^2 \]

Result: make \( y_{\text{vis}} = y_{\text{invis}} \), boost to frame where both are 0

Equivalently, ignore all longitudinal momenta.
The distribution of the transverse mass derived from the measured electron and neutrino vectors of the six electron events.
Transverse Masses — A Storm in a ‘T’-Cup

- Transverse mass $m_T$ — classically used for W discovery.

- Simplification for $\sim$massless daughters:

  \[
  m_T^2 = m_i^2 + m_v^2 + 2 \left( E_T^v E_T^i - \vec{p}_T^v \cdot \vec{p}_T^i \right)
  \approx 2 |p_T^v||p_T^i| \left( 1 - \cos(\Delta \phi_{v,i}) \right)
  \]

- Inequality: every event produces lower bound on true mass, distribution has endpoint at invariant mass.

- Can generalise to N-body decay, sum visible four-momenta, then apply transverse projection to 2+1D.

- How to generalise to N parent decays?
TWO BY TWO

Semi-invisible decay, resonant production

Semi-invisible decay, pair production
MINIMISING MORE!

- Intuitively, we probably want an $m_T$ for each of those legs. But how to partition invisible momenta?

- MET measurement constraint: $\vec{p}_T^i + \vec{q}_T^i = \vec{E}_T^{\text{miss}}$

- For any choice of $P_{\text{invis}}$, $Q_{\text{invis}}$ satisfying constraint, can define $m_T$ for corresponding parent particle.

- Assuming symmetric decay chains, $M_{\text{parent}} \geq \max(m_T^P, m_T^Q)$

- Define

$$m_{T2} = \min_{\vec{p}_T^i + \vec{q}_T^i = \vec{E}_T^{\text{miss}}} \left[ \max \left( m_T^P, m_T^Q \right) \right]$$
Table 4: Fit results from the three mass analyses with various levels of constraint. Errors are statistical (first) and systematic (second).

<table>
<thead>
<tr>
<th>Fit Quantity</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_v^2 ) (GeV^2)</td>
<td>( m_v = 0 )</td>
</tr>
<tr>
<td>( m_v^2 ) (GeV^2)</td>
<td>(-556 \pm 473 \pm 600)</td>
</tr>
<tr>
<td>( M_W ) (GeV)</td>
<td>(72 \pm 7 \pm 9)</td>
</tr>
<tr>
<td>( M_t ) (GeV)</td>
<td>(163 \pm 10 \pm 11)</td>
</tr>
</tbody>
</table>
Original motivation for MT2 definition:
Measure masses of supersymmetric particles

First step: discovery!

Strongly produced SUSY with R-parity conservation
Provides dark matter candidate – stable LSP
Large production cross-sections, low (no) lepton multiplicity
Figure 2.24: Preferred mass-like variables at each model point, having specified the \( p_T^{\text{miss}} \)-like variable to be \( M_1^R \) for the squark simplified models, \( M_{10} \) for the gluino simplified models, and \( p_T^{\text{miss}} \) for the CMSSM models, based on the preference for \( p_T^{\text{miss}} \)-like variables identified in Figure 2.21. Classes of similar variables are distinguished by colour: blue labels the single-parent mass-bound variables; green labels the two-parent mass-bound variables; and red labels the variables that are not mass bounds.
0-LEPTON SEARCHES

- Dominant backgrounds by cross-section:
  - Multijet production – eliminate with cuts on mismeasured MET
  - $W_\ell\nu+\text{jets}$, top pairs – veto leptons, control regions
  - $Z\nu\nu+\text{jets}$ – irreducible, estimate with photon and leptonic control regions
Mismeasured jets produce fake MET

Estimate response and smear well-measured events

$$R_{Z\nu\nu/\gamma} = BR_{Z\rightarrow \nu\nu} \frac{\partial \sigma_{Z\rightarrow \nu\nu}}{\partial p_T} / \frac{\partial \sigma_{\gamma}}{\partial p_T}$$
Signal-specific

More generic
ATLAS

$L^{\text{int}} = 35 \text{ pb}^{-1}, \sqrt{s} = 7 \text{ TeV}$

0 lepton combined exclusion

- Observed 95% CL limit
- Median expected limit
- Expected limit $\pm 1\sigma$

- LEP 2$\tilde{q}$
- FNAL MSUGRA/CMSSM, Run I
- D0 MSUGRA/CMSSM, Run II
- CDF MSUGRA/CMSSM, Run II

$\sigma_{\text{SUSY}} = 0.1 \text{ pb}$

$\sigma_{\text{SUSY}} = 1 \text{ pb}$

$\sigma_{\text{SUSY}} = 10 \text{ pb}$

Squark-gluino-neutralino model (massless $\tilde{\chi}_1^0$)
Thank you Mario!

But our princess is in another channel!
HOW WELL COULD WE WEIGH SUSY?

- Neutralino LSP probably massive. Observed mass will need correction for mass difference.

\[
M_{\text{corr SUSY}} = \frac{M_{\text{SUSY}}^2 - M_{\text{LSP}}^2}{M_{\text{SUSY}}} , \quad \text{where}
\]

\[
M_{\text{SUSY}} = \sum_{p \text{ in sparticles}} M_p \cdot \frac{\sigma_p}{\sigma_{\text{tot}}}
\]

2-body decay expression,
Tovey, JHEP 0804 (2008) 034

- Extend to N-body decay by assuming isotropic decay angles in a plane.

\[
M_{\text{corr SUSY}} = \frac{(N - 1)M_{\text{SUSY}} - \sqrt{M_{\text{SUSY}}^2 + (N^2 - 2N)M_{\text{LSP}}^2}}{N - 2}
\]
Figure 2: Relative deviations between the isotropic decay and 2-body decay approximations to N-body Lorentz-invariant phase space MC, corresponding to $N = 3 - 6$ in Figure 3. The cases $N = 7, 8$ are omitted to aid distinguishability of the displayed curves, but obey the same trend.
Figure 2.6: Fits to correlation plots of the peak position to the effective SUSY mass scale $M_{SUSY}^{corr}$, for a range of mass variables, in simplified models with only gluino production and decays to jets and neutralinos. The subfigures show: (a) single-parent mass bounds; (b) two-parent mass bounds, with jets partitioned into a pair of collections such that the sum of the invariant masses of the two collections is minimised; (c) two-parent mass bounds, with jets partitioned such that the value of the mass bound is minimised (i.e. using the $m_{T_{gen}}$ procedure); (d) alternative mass variables not based on the transverse bound paradigm. In the case of the Razor variables, jets are partitioned such that the sum of the invariant masses of the two collections is minimised. An arbitrary offset is applied to the points in order to distinguish different variables, as labelled on each plot.
Figure 2.7: Summary of the RMS deviations of the estimated and true values of $M_{\text{SUSY}}^{\text{corr}}$ from the linear fits versus the bias in the predictions for all variables, in simplified models with only gluino production and decays to jets and neutralinos.
(a) 1-parent  
(b) 2-parent ($M_{\text{min}}$ association)  
(c) 2-parent ($m_{T_{\text{gen}}}$ association)  
(d) Alternative mass variables

**Figure 2.4:** Fits to correlation plots of the peak position to the corrected SUSY mass scale $M'_{\text{SUSY}}$, for a range of mass variables, in simplified models with only squark production and decays to jets and neutralinos. The subfigures show: (a) single-parent mass bounds; (b) two-parent mass bounds, with jets partitioned into a pair of collections such that the sum of the invariant masses of the two collections is minimised; (c) two-parent mass bounds, with jets partitioned such that the value of the mass bound is minimised (i.e. using the $m_{T_{\text{gen}}}$ procedure); (d) alternative mass variables not based on the transverse bound paradigm. In the case of the Razor variables, jets are partitioned such that the sum of the invariant masses of the two collections is minimised. An arbitrary offset is applied to the points in order to distinguish different variables, as labelled on each plot.
Figure 2.5: Summary of the RMS deviations of the estimated and true values of $M_{\text{SUSY}}^{\text{corr}}$ from the linear fits versus the bias in the predictions for all variables, in simplified models with only squark production and decays to jets and neutralinos.
Process-dependent performance
- improve calibrations
- understand limitations

Combat pileup degradation
- refine corrections
Soft component not negligible
Pileup-sensitivity drives resolutions
Neutral information in energetic jets critical
Soft component not negligible
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Neutral information in energetic jets critical
ATLAS Preliminary
Data 2015, $\sqrt{s} = 13$ TeV
$Z \rightarrow \mu\mu$, 3.2 fb$^{-1}$
0 jets $p_T > 20$ GeV
ATLAS Preliminary

Data 2015, $\sqrt{s} = 13$ TeV

$Z \rightarrow \mu\mu$, $3.2$ fb$^{-1}$

$E_{\text{miss}}$, $E_y$

$\Sigma E_T$(event) [GeV]
**ATLAS** Preliminary

Data 2015, \( \sqrt{s} = 13 \text{ TeV} \)

\[ Z \rightarrow \mu\mu, \ 3.2 \text{ fb}^{-1} \]

0 jets \( p_T > 20 \text{ GeV} \)
**ATLAS Preliminary**

Data 2015, $\sqrt{s} = 13$ TeV

$Z \rightarrow ee$, 3.2 fb$^{-1}$

0 jets $p_T > 20$ GeV

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**Graph Details:**

- **Axes:**
  - Y-axis: $\langle E_{T}^{miss}, A_Z \rangle$ [GeV]
  - X-axis: $p_T^Z$ [GeV]

- **Data Points:**
  - Green triangles: Powheg Zee
  - Black circles: Data
Jet area

Median energy density