A key variable: 
Missing Transverse Momentum - 
reconstruction, pile-up and its significance 

SUSY2019, Corpus Christi, 20 - 24 May 2019

Xuanhong Lou
Deutsches Elektronen-Synchrotron

For the ATLAS collaboration
Introduction

What is missing transverse momentum (MET)

- MET - total transverse momentum of the invisible particles

\[ E_{T}^{\text{miss}} = \sum_{\text{invisible particles}} \vec{p}_{T,i} = - \sum_{\text{visible particles}} \vec{p}_{T,i} \]

- Two sources of MET
  - Real MET:
    weakly interacting particles
  - Fake MET:
    particle out of detector acceptance
    mis-measured objects
    additional interaction (pile-up)

- MET performance is very important for many ATLAS analyses!
  - Improved resolution, better distinction between real and fake MET, etc.
Introduction

Resolution of MET

- Negative vector sum of calibrated objects (hard term) plus soft term

\[ E_T^{\text{miss}} = - \left( \sum_{i \in \text{muons}} p_T^i + \sum_{i \in \text{electrons}} p_T^i + \sum_{i \in \text{photons}} p_T^i + \sum_{i \in \text{hadronic } \tau} p_T^i + \sum_{i \in \text{jets}} p_T^i + \sum_{i \in \text{Soft Term}} p_T^i \right) \]

- Resolution of MET
  - RMS extracted from the combined distribution of $E_{x}^{\text{miss}}$ and $E_{y}^{\text{miss}}$
  - Dependent on the resolution of input objects

Blue: only uses tracker information
Green: uses tracker-based soft term
Black: uses calorimeter-based soft term
**Introduction**

**MET performance in the ATLAS experiments (2017 - 2018)**

**Reconstruction input**
- Hard term including calorimeter jets
- Tracker-based soft term (TST)

**Jet selection**
- Central jets ($|\eta| < 2.4$):
  - pass Jet Vertex Tagger requirement
  - transverse momentum ($p_T$) > 20 GeV
- Forward jets ($|\eta| > 2.4$):
  - transverse momentum ($p_T$) > 30 GeV

$<\mu>$ - average number of interaction
- Higher $<\mu>$ indicates higher pile-up

**Jet Vertex Tagger (JVT)**
- A multivariate approach to reject pile-up objects via jet-vertex association

---

**Graph**

**ATLAS Preliminary**

Z $\rightarrow \mu\mu$ Topology
Track Soft Terms (TST)
EM + JES Jets
Tight $E^{miss}_T$

- Data 17, 33 fb$^{-1}$
- Data 18, 6.5 fb$^{-1}$

---

**JETM-2018-004**
Towards higher precision

Particle Flow (PFlow) reconstruction

- Particle Flow (PFlow) MET
  - Combine the optimal resolution of tracker and calorimeter information
  - Higher accuracy of the charged-hadron measurement
  - Retaining the calorimeter measurements of neutral-particle energies

---

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 140 fb$^{-1}$

**Z → ee Selection**

![Graph showing data and theoretical predictions for Z → ee selection.]

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 36 fb$^{-1}$

Loose $E_T^{\text{miss}}$

$Z \rightarrow \text{ee}$

![Graph showing $E_T^{\text{miss}}$ RMS resolution vs. average number of interactions $\langle \mu \rangle$.]
Towards higher precision

- PFlow MET is nice, but what about the forward region?
  - Inclusion of forwards jets is crucial to MET reconstruction
    - more precise MET computation under low pile-up condition
    - more pronounced pile-up dependence

- Forward jet selection (pile-up rejection)
  - Simple $p_T$ cut: $p_T > 30$ GeV
  - Forward Jet Vertex Tagger (fJVT)

---

**ATLAS Simulation**

Powheg+Pythia8 $Z \rightarrow \mu\mu$

\(\sqrt{s} = 13\) TeV

Anti-$k_T$, EM+JES R=0.4

$E_T > 20$ GeV

**FTAG**

Forward jets included in $E_T^{\text{miss}}$

Forward jets not included in $E_T^{\text{miss}}$

---

MET significance

Object-based MET significance

- Evaluation of MET significance
  - Is the reconstructed MET consistent with the zero MET hypothesis, when taking the resolution of all input objects into account?
  - High MET significance means:
    MET cannot be explained from momentum resolution effects indicate the presence of true invisible particle

- Object-based MET significance
  - Compared to the traditional event-based MET significance, object-based MET significance considers the expected resolutions for all objects entering MET computation and their angular correlation
  - Momentum resolution on $p_T$ scale and direction, pile-up mitigation and soft term...

\[ S = \frac{E_{\text{miss}}}{\sigma(E_{\text{miss}})} \]
Performance of MET significance dependent on event topology

- $ZZ \rightarrow ee\nu\nu$ vs. $Z \rightarrow ee$, pre-selected with MET > 50 GeV and $|m_Z - m_{ee}| < 15$ GeV

Jet Veto

ATLAS
Simulation Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, 36 \text{ fb}^{-1} \]

ee-channel
$|m_Z - m_{ee}| < 15$ GeV
$E_T^{\text{miss}} > 50$ GeV,
 MET significance

**Application of object-based MET significance in SUSY: sbottom multi-b**

- Search for bottom-squark pair production in final states containing Higgs bosons, b-jets and missing transverse momentum
  - Multiple b-jets + no lepton + MET (from neutralinos)
  - Three kinematic topologies - SRA, SRB and **SRC**

**SRC Target**

- In SRC the $\Delta R$-based Higgs reconstruction is ineffective due to low b-jet multiplicity
- Object-based MET significance becomes the best discriminating variable in SRC

Small mass splitting between $\tilde{b}_0$ and $\tilde{\chi}_2^0$, $m(\tilde{\chi}_1^0) = 60$ GeV

Soft b-jets from $\tilde{b}_0$ and Higgs, lower b-jet multiplicity required in the final state

Discriminating variable: **object-based MET significance**
MET significance

Application of object-based MET significance in SUSY: sbottom multi-b

Integrated expected significance for scalar signal, \(m(\tilde{b}_0, \tilde{\chi}_i^0, \tilde{\chi}_j^0) = (1100, 1095, 60) \text{ GeV}\)
All standard model backgrounds and total uncertainty taken into consideration

Aside from sbottom multi-b, another recent SUSY search also uses object-based MET significance as one of the discriminating variables: **EW 2LoJ**

Search for electroweak production of charginos and sleptons decaying in final states with two leptons and missing transverse momentum

Xuanhong Lou | A key variable: Missing Transverse Momentum - reconstruction, pile-up and its significance | 22 May 2019 | Page 10
Summary

- **Missing transverse momentum (MET)**
  - Used in many ATLAS analyses
  - *Distinguish between real and fake MET*

- **Efforts are made to improve MET performance**
  - Usage of **Particle Flow jets**
  - **Forward jet selections**

- **Object-based MET significance**
  - Considers *the resolution of all objects*
  - Better discriminating power wrt. the traditional approach
  - Used in several SUSY searches, e.g. **sbottom multi-b**

**Thanks for your attention!**
Reconstruction performance of MET is evaluated using data collected by the ATLAS detector in 2017 and 2018

- Hard term including calorimeter jets + tracker-based soft term
- Pile-up (PU) suppression

  - Central jets ($|\eta| < 2.4$): pass Jet Vertex Tagger, $p_T > 20$ GeV
  - Forward jets ($|\eta| > 2.4$): $p_T > 30$ GeV
Towards higher precision

Particle Flow (PFlow) reconstruction

4 steps of the PFlow algorithm

1. Match each track to one topo-cluster
2. Add neighbouring topo-clusters if higher energy deposit is expected in the calorimeter (calculation based on tracker information)
3. Subtract the expected energy cell-by-cell from the matched topo-cluster until the expected energy is reached
4. Clean the remnants if it’s fluctuation

---


---

Xuanhong Lou  |  A key variable: Missing Transverse Momentum - reconstruction, pile-up and its significance  |  22 May 2019  |  Page 14
**Towards higher precision**

**Particle Flow (PFlow) reconstruction**

---

**Performance of PFlow jet**

- Better energy resolution at low $p_T$ region due to track matching
- Fake jet ratio significantly lowered at central region - *forward region outside of tracker acceptance*
- PU energy removed from the topo-cluster if matched with a PU track - *effective PU suppression*

---

**Performance of PFlow MET**

- Better resolution of MET due to track matching
- Great PU mitigation at central region - *no JVT available for EMTopo jets with $p_T > 60$ GeV*
- MET tail mainly due to muon mis-measurement and mis-identified jets

---

ATLAS Preliminary

$\sqrt{s} = 13$ TeV

2.4 fb$^{-1}$, zero-bias data

Anti-$k_T$, $R = 0.4$

$|\eta_{	ext{def}}| < 0.7$, $\langle \mu \rangle = 37.8$

---

ATLAS Simulation Preliminary

$\sqrt{s} = 13$ TeV

$36$ fb$^{-1}$

$Z \rightarrow \mu\mu$, 0 jets with $|\eta| > 2.4$

---

**ATLAS-CONF-2018-023**

---

**JETM-2019-01**

---

**JETM-2017-006**
Towards higher precision

Forward Jet Vertex Tagger

1. For each vertex \( i \), compute \( p_T^{\text{miss}, i} \) with QCD pile-up tracks;

2. Check if there is a forward jet balancing the \( p_T^{\text{miss}, i} \);

3. If so, remove this forward jet.

A candidate \( Z \rightarrow \mu\mu \) event containing two QCD pile-up jets

Red: tracks from the primary vertex

Yellow: tracks from the muons

Green: tracks from the pile-up vertex with highest \( \Sigma p_T^2 \)

Towards higher precision

Different MET working points

- MET working points based on different forward jet selections
  - Loose working point
    retaining hard-scatter jets in the forward region, good resolution at low PU
  - Tight working point
    much better resolution at high PU wrt. loose working point, worse at low PU
  - fJVT working point
    improved resolution at high PU wrt. loose working point
    optimal for analyses where hard-scatter forward jets are expected, e.g. VBF process

| Working Point | Central jets ($|\eta| < 2.5$) | Forward jets ($|\eta| > 2.5$) |
|---------------|-----------------------------|-----------------------------|
| Loose         | $p_T > 20$ GeV              | $p_T > 20$ GeV              |
|               | pass JVT when $p_T < 60$ GeV|                             |
| Tight         | $p_T > 20$ GeV              | $p_T > 30$ GeV              |
|               | pass JVT when $p_T < 60$ GeV|                             |
| fJVT          | $p_T > 20$ GeV              | $p_T > 20$ GeV              |
|               | pass JVT when $p_T < 60$ GeV| pass fJVT when $p_T < 50$ GeV|
MET significance

Event-based and object-based MET significance

Event-based MET significance
- Event-based quantity, neglecting the physics nature of different objects
- Only consider the scale of $p_T$, no angular correlation taken into account

$$S = \frac{E_T^{miss}}{\sqrt{\sum E_T}}$$

Object-based MET significance
- Based on the expected resolutions for all objects entering MET computation
- Momentum resolution on $p_T$ scale and direction, PU mitigation and soft term

$$S = \frac{|E_T^{miss}|}{\sqrt{\sigma^2_L (1 - \rho^2_{LT})}}$$
Performance of MET significance dependent on event topology

- \( ZZ \rightarrow ee\nu\nu \) vs. \( Z \rightarrow ee \), pre-selected with \( |m_Z - m_{ee}| < 15 \text{ GeV} \)

**ATLAS**

Simulation Preliminary

\( \sqrt{s} = 13 \text{ TeV}, 36 \text{ fb}^{-1} \)

ee-channel

\( |m_Z - m_{ee}| < 15 \text{ GeV} \)

\( E_T^{\text{miss}} > 50 \text{ GeV} \)
Application of object-based MET significance in SUSY: sbottom multi-b

- Search for bottom-squark pair production in final states containing Higgs bosons, b-jets and missing transverse momentum
  - Multiple b-jets + no lepton + MET (from neutralinos)
  - Three kinematic topologies - SRA, SRB and SRC

Discriminating variable:
- Effective mass
- Object-based MET significance

High mass splitting between $\tilde{b}_0$ and $\tilde{\chi}_2^0$
- All b-jets have relatively high $p_T$, Higgs tagging possible

Small mass splitting between $\tilde{b}_0$ and $\tilde{\chi}_2^0$, $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV
- Very soft b-jets from $\tilde{b}_0$ decay, Higgs tagging possible

Small mass splitting between $\tilde{b}_0$ and $\tilde{\chi}_2^0$, $m(\tilde{\chi}_1^0) = 60$ GeV
- Soft b-jets from $\tilde{b}_0$ and Higgs, lower b-jet multiplicity required in the final state
Application of object-based MET significance in SUSY: sbottom multi-b

4 non-overlapping subsets of SRC binned in object-based MET sig.
Major bkg constrained in a bkg-only fit in CRs
Exclusion limit: \( \sim 1.4 \text{ TeV} \) sbottom mass