Brief Introduction to Missing Transverse Energy Reconstruction at LHC

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Non-interacting particle production in hadron collisions

Neutrinos
Most often decay products from W bosons – also some Z decays

BSM particles (SUSY and exotics)
End products in SUSY decay chains
Long-lived particles decaying outside signal (time) window

Detection and measurement
Only indirectly by implying conservation
Full momentum or energy conservation in parton collisions not experimentally accessible – no access to effective collision energy due to massive energy losses along beam pipes

Need to use transverse momentum conservation in hard interaction
Expect transverse momentum of all observable final state products to cancel if no non-interacting particle is produced in hard interaction
Residual non-zero transverse momentum can indicate production of these particles

$W \rightarrow \ell \nu, \ell = e^\pm, \mu^\pm, \nu = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$

$Z \rightarrow \tau^+ \tau^-,$

\[
\begin{align*}
\text{with each } \tau^+ \rightarrow & \left\{ \\
& e^\pm + \nu_e + \nu_\tau \\
& \mu^\pm + \nu_\mu + \nu_\tau \\
& \pi^\pm + (0...3) \times \pi^0 + \nu_\tau \\
& \pi^0 + \pi^+ + \pi^- + \pi^0 + \nu_\tau
\end{align*}
\]

$\sim 18\%$

$\sim 18\%$

$\sim 48\%$

$\sim 16\%$

SM "search modes":

\( H \rightarrow WW \rightarrow \ell \nu \ell \nu \)

\( H \rightarrow \tau \tau \)

\( H \rightarrow ZZ' \rightarrow \nu_\ell \bar{\nu}_\ell \nu_\ell \bar{\nu}_\ell \) (invisible Higgs)
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effective center-of-mass energy in hadron collisions:
\[ \hat{s} = x_1 x_2 s \]

with \( x_1, x_2 \) the momentum fractions carried by the colliding partons (Bjorken-\( x \))

\( x_1, x_2 \) can only be reconstructed in perfect 2 → 2 processes (theoretically):
\[ x_{1,2} = \frac{E_T}{\sqrt{s}} (e^{\pm n_1} + e^{\mp n_2}) \]

requires good reconstruction of scalar \( E_T \) from hard scattering only (no underlying event, pile-up, etc. → experimentally very challenging!)

note: \( s = 4E_{beam}^2 \) and \( x_1 = x_2 = 1 \) \( \Rightarrow \hat{s} = s \) in \( e^+ e^- \) colliders \( \Rightarrow \) total energy constraint for each interaction!
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transverse momentum conservation:
\[
\sum_{\text{obs. particles}} \vec{p}_T + \sum_{\text{jets}} \vec{p}_T + \vec{p}_{T,\text{non-interacting}} = 0
\]

\[ \Rightarrow \vec{p}_{T,\text{non-interacting}} = - \sum_{\text{obs. particles}} \vec{p}_T - \sum_{\text{jets}} \vec{p}_T \]

missing transverse energy \( (p_{\text{non-interacting}} \gg m_{\text{non-interacting}}) \):

\[ \mathcal{E}_T = E_{T,\text{miss}} = \left| \vec{p}_{T,\text{non-interacting}} \right| \]

observable scalar transverse energy sum:

\[ E_{T,\text{sum}} = \sum_{\text{obs. particles}} E_{T,\text{particles}} + \sum_{\text{jets}} E_{T,\text{jets}} \]

\[ \approx \sum_{\text{obs. particles}} |\vec{p}_{T,\text{particles}}| + \sum_{\text{jets}} |\vec{p}_{T,\text{jets}}| \propto Q^2 - \mathcal{E}^2_T \]
Experimental Aspects

Missing ET (MET) subject to detector effects

Need fullest possible coverage
Principal contribution from calorimeter signals

Subjected to limited acceptance and coverage
Lack of signals from low energetic particles (magnetic field, dead materials)
Low quality of small signals
Limited coverage in pseudo-rapidity
Threshold for physics object reconstruction

Subjected to all systematic uncertainties
Physics object reconstruction – electrons, taus, muons, jets
Signals outside of physics objects

Combines fluctuations from very different resolution functions
Identified particles
Reconstructed jets
Non-negligible signals outside of physics objects

Some cancellations observed
Small signal sources often symmetric in azimuth – underlying event, pile-up
Partially cancels systematic errors on MET but still contributes to fluctuations

<table>
<thead>
<tr>
<th>Process</th>
<th>Experimental Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qq \rightarrow W \rightarrow \ell \nu$</td>
<td>$e, \mu + E_T^{miss}$ (&quot;W+0 jets&quot;)</td>
</tr>
<tr>
<td>$qq \rightarrow Wg \rightarrow \ell \nu g$</td>
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Topology dependence
MET reconstruction quality depends on generated event topology
E.g., MET contribution different for “truly” no jet versus “no jet reconstructed”

Observable topology represents filtered and modified true event topology
MET cannot reconstruct a particular non-interacting particle
Best case Met follows distribution of non-interacting particle kinematics
**MET reconstruction requires un-ambiguous event**

Typically all calorimeter signals used for reconstruction of all physics objects

E.g., same clusters can be used for particles and jets

**Need to establish ambiguity resolution**

Decide use of common signals in different physics objects

Can be done using geometrical distance or based on common signal use

Needs priority for choice of surviving object

**Prioritization of reconstructed physics objects in calorimeter**

Identified electrons and photons – highest reconstruction quality (1)

Other identified particles (e.g., taus) – reduced reconstruction quality (2)

Jets – lowest reconstruction quality for physics objects (3)

All signals outside physics objects – low quality due to missing truth level calibration (4)

**Muon contribution**

Typically measured with muon spectrometer, not calorimeter – complementary signals and MET contribution
Detector Signal Contributions To MET

**Hard signal in calorimeters**

- Fully reconstructed & calibrated particles and jets
- Not always from hard interaction!

**Hard signal in muon spectrometer**

- Fully reconstructed & calibrated muons
- May generate isolated or embedded soft calorimeter signals
- Care needed to avoid double counting

**Soft signals in calorimeters**

- Signals not used in reconstructed physics objects
- I.e., below reconstruction threshold(s)
- Needs to be included in MET to reduce scale biases and improve resolution
- Can also reduce topology dependence!

**Need to avoid double counting**

- Common object use strategy in ATLAS
  - Find smallest available calorimeter signal base for physics objects (cells or cell clusters)
- Check for exclusive bases
  - Same signal can only be used in one physics object
- Veto MET contribution from already used signals
  - Track with selected base
- Priority of association is defined by reconstruction uncertainties
  - Electrons (highest quality) → photons → muons* → taus → jets (lowest quality)
MET is determined by hard signals in event
- Reconstructed particles and jets above threshold
- All objects on well defined energy scale, e.g. best reconstruction for individual object type

Really no freedom to change scales for any of these objects
- Little calibration to be done for MET
- Note that detector inefficiencies are corrected for physics objects

Some freedom for soft MET contribution...
- Signals not used in physics objects often lack corresponding context to constrain calibration
  - ATLAS has developed a low bias “local” calibration for the calorimeters based on signal shapes inside calorimeters
  - Some degree of freedom here – e.g., exploit dependence on reconstructed topology
    - But contribution is small and mostly balanced in Et anyway – source here often UE/pile-up!

...and overall acceptance limitations
- Detector “loses” particles in non-instrumented areas or due to magnetic field in inner cavity
  - Same remarks as above, very small and likely balanced signals
- Event topology dependent adjustments to MET are imaginable to recover these losses
  - Understand “fake” MET

I prefer “validation” rather than “calibration”
- Discrepancies in MET need to be isolated for systematic control
Z Mass Constraint

**MET scale can be checked with physics**

- Look for one hadronic and one leptonic tau from Z decays
- Can be triggered nicely with lepton + MET requirement
- Use collinear approximation to reconstruct invariant mass
  - Massless taus
  - Neutrinos assumed to be collinear to observable tau decay products

**Check dependence of invariant mass on MET scale variations**

- Expect correlation!

\[ m_{\tau\tau} = \sqrt{2 \left( E_{\text{had}} + E_{\nu_1} \right) \left( E_{\ell} + E_{\nu_2} \right) \left( 1 - \cos \theta_{\text{had,}\ell} \right)} \]

Determined from two reconstructed MET components and directions of detectable decay products; uses collinear decay assumption (non-trivial!)
What is that?

**MET contribution from response variations**
- Cracks, azimuthal response variations...
- Never/slowly changing
- Particle dependent

**MET contribution from mis-calibration**
- E.g., QCD di-jet with one jet under-calibrated
- Relative effect generates MET pointing to this jet

**Dangerous source of MET**
- Disturbs many final states in a different way
  - Can fake new physics

**Suppression strategies**

**Track jets**
- Reconstructed track bundle points to missing calorimeter jet

**Energy sharing between calorimeters**
- Suppresses contributions not from the event vertex, e.g. cosmics

**Event topology analysis**
- Study MET as function of direction of hardest jet
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Fluctuation of MET around expected value

MET resolution in each component as function of scalar Et sum for various final states

Systematically evaluated with MC in ATLAS

No direct experimental access

Minimum bias has MET expectation value 0 – resolution study possible with limited reach/precision?

Limited reach in scalar Et!

Concern is pile-up effect on scalar Et

\[ \sigma_{E_T} = \frac{1}{\sqrt{2}} \sqrt{\left\langle (E_{T,x} - E_{T,x}^{\text{nonInt}})^2 \right\rangle + \left\langle (E_{T,y} - E_{T,y}^{\text{nonInt}})^2 \right\rangle} \]

Minimum bias events \((E_{T,x}^{\text{nonInt}}, E_{T,y}^{\text{nonInt}}) = (0,0)\):

\[ \sigma_{E_T} = \frac{1}{\sqrt{2}} \sqrt{\left\langle E_{T,x}^2 \right\rangle + \left\langle E_{T,y}^2 \right\rangle} \]
Experimental access

Use bi-sector signal projections in Z decays
Longitudinal projection sensitive to scale
  Calibration of hadronic recoil
Perpendicular projection sensitive to angular resolution

Neutrinofication

Assume hadronic recoil to be very similar in Z and W
One lepton in Z decay can be “neutrinofied” (call its Et missing!)
Access to MET resolution
MET scale

- Folds hadronic scale with acceptance
  - Note: no jets needed!
- Experimental tool to validate calibration of "unused" calorimeter signal
  - Hard objects can be removed from recoil
  - One possible degree of freedom in MET "calibration"
- Relevance for other final states to be evaluated
  - Otherwise purely experimental handle!

MET resolution

- Can be measured along perpendicular and longitudinal axis
- Resolution scale is scalar $E_t$ sum of hadronic calorimeter signal
  - Biased by UE and pile-up (MC needed here)
- Qualitatively follows calorimeter energy resolution
Missing ET is a complex experimental quantity

Sensitive to precision and resolution of hard object reconstruction
  MET is calibrated by everything
Easily affected by detector problems and inefficiencies
  Careful analysis of full event topology
  Signal shapes in physics and detector

Known unknown (1): effect of underlying event

Some correlation with hard scattering
Insignificant contribution??
  To be confirmed early with di-jets

Known unknown (2): effect of pile-up

Level of activity not so clear
  Minimum bias first and urgent experimental task
Expectation is cancellation on average (at least)
  Detector signal thresholds/acceptance potentially introduce asymmetries
  Need to know the “real” detector
Considerable contribution to MET fluctuations
  Severe limitation in sensitivity for discovery