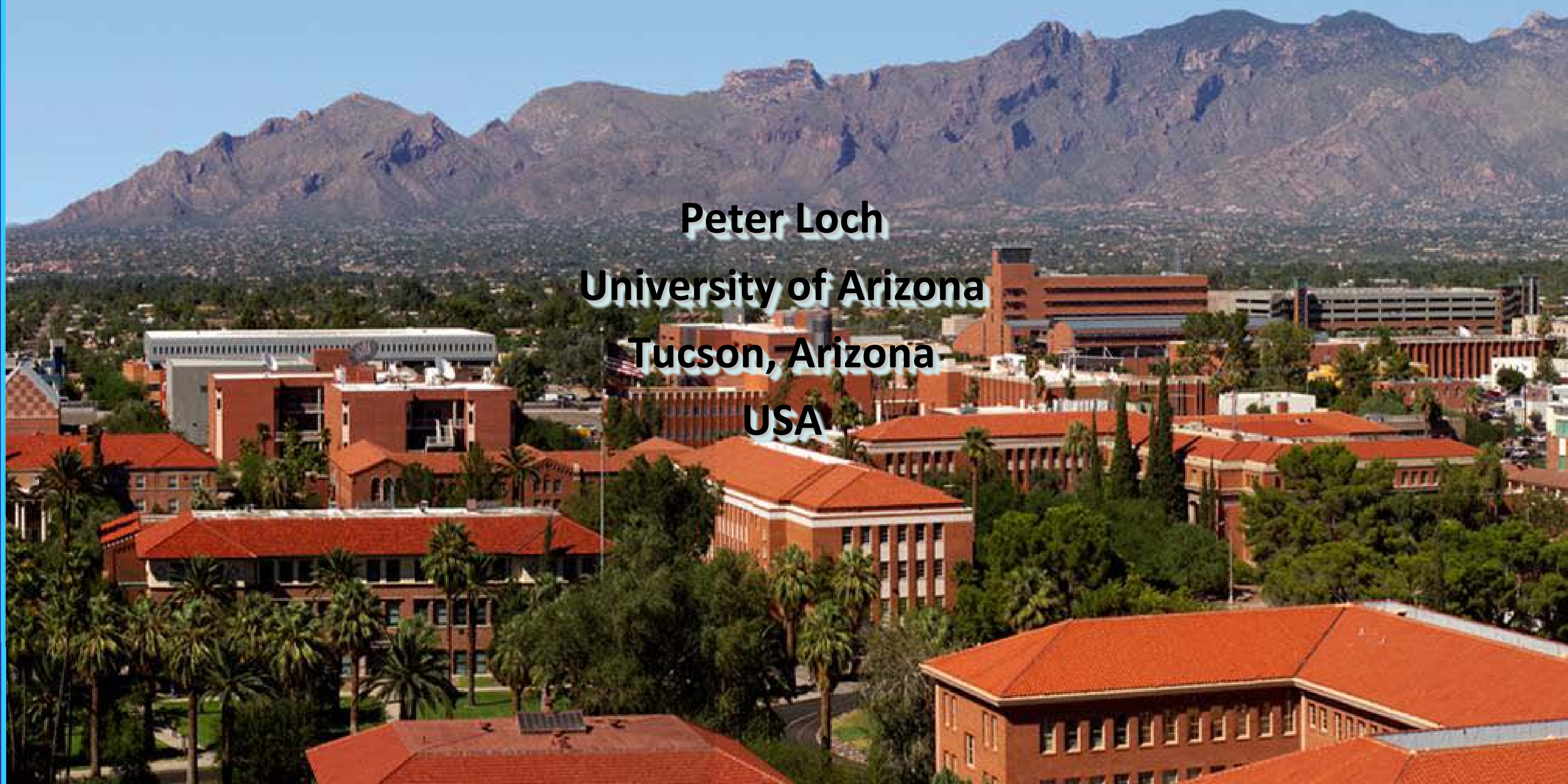
Brief Introduction to Missing Transverse Energy Reconstruction at LHC



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Missing Transverse Energy

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April 22, 2010

Non-interacting particle production in hadron collisions

- Neutrinos
  - Most often decay products from W bosons – also some Z decays
- BSM particles (SUSY and exoctics)
  - 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

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

$$Z \to \tau^{\pm}\tau^{\mp},$$

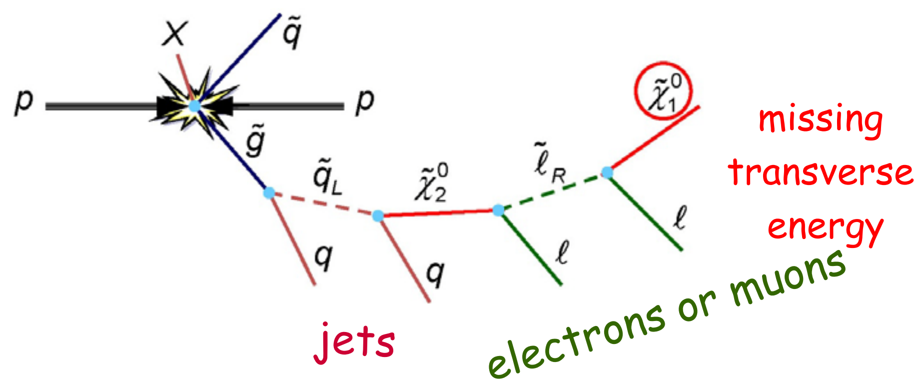
$$\text{with each } \tau^{\pm} \to \begin{cases} e^{\pm} + \nu_e + \nu_\tau & \sim 18\% \\ \mu^{\pm} + \nu_\mu + \nu_\tau & \sim 18\% \\ \pi^{\pm} + (0\ldots3)\times\pi^0 + \nu_\tau & \sim 48\% \\ \pi^{\pm} + \pi^{\mp} + \pi^{\pm} + \pi^0 + \nu_\tau & \sim 16\% \end{cases}$$

SM "search modes":

$$H \to WW \to \ell\nu\ell\nu$$

$$H \to \tau\tau$$

$$H \to ZZ' \to \nu_\ell\bar{\nu}_\ell\nu_{\ell'}\bar{\nu}_{\ell'} \text{ (invisible Higgs)}$$



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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 $2 \rightarrow 2$ processes (theoretically):

$$x_{1,2} = \frac{E_T}{\sqrt{s}}\left(e^{\pm\eta_1} + e^{\mp\eta_2}\right)$$

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

[note: $s = 4E_{\mathrm{beam}}^2$ 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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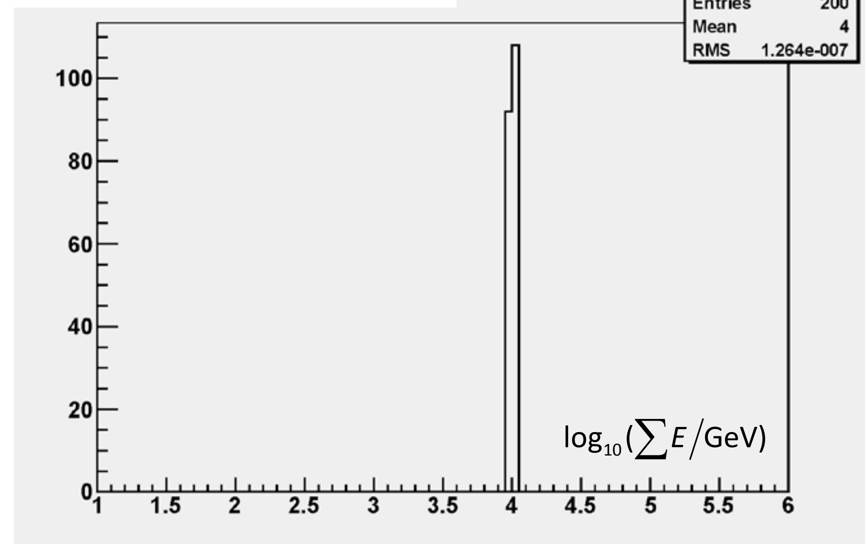
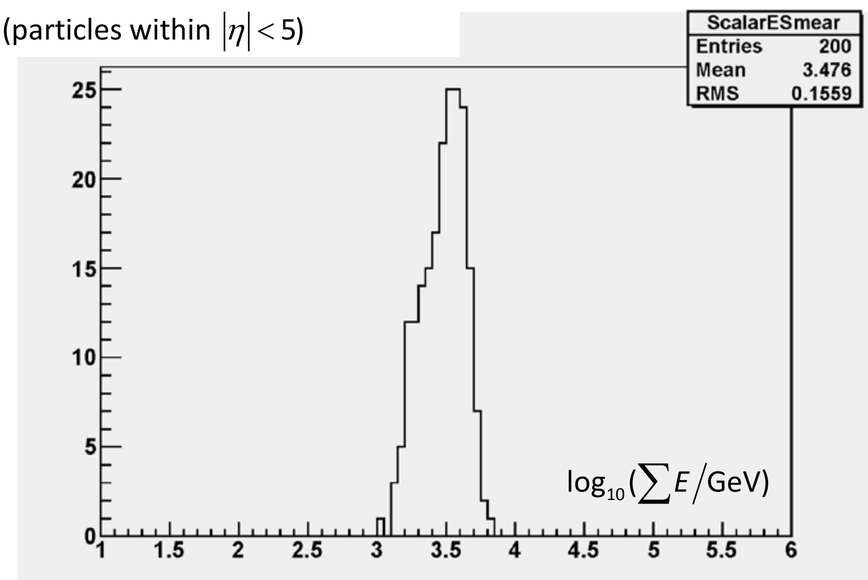
Pythia QCD 2 $\rightarrow$ 2 total energy sum



Pythia QCD 2 $\rightarrow$ 2 total energy sum
(particles within $|\eta| < 5$)



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transverse momentum conservation:

$$\sum_{\substack{\text{observable}\\\text{particles}}} \vec{p}_{\mathrm{T}} + \sum_{\text{jets}} \vec{p}_{\mathrm{T}} + \vec{p}_{\mathrm{T,non\text{-}interacting}} = 0$$

$$\Rightarrow \vec{p}_{\mathrm{T,non\text{-}interacting}} = -\sum_{\substack{\text{observable}\\\text{particles}}} \vec{p}_{\mathrm{T}} - \sum_{\text{jets}} \vec{p}_{\mathrm{T}}$$

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

$$\not{E}_{\mathrm{T}} = E_{\mathrm{T}}^{\text{miss}} = \left|\vec{p}_{\mathrm{T,non\text{-}interacting}}\right|$$

observable scalar transverse energy sum:

$$E_{\mathrm{T}}^{\text{sum}} = \sum_{\substack{\text{observable}\\\text{particles}}} E_{\mathrm{T,particles}} + \sum_{\text{jets}} E_{\mathrm{T,jets}}$$

$$\approx \sum_{\substack{\text{observable}\\\text{particles}}} \left|\vec{p}_{\mathrm{T,particles}}\right| + \sum_{\text{jets}} \left|\vec{p}_{\mathrm{T,jets}}\right| \propto Q^2 - \not{E}_{\mathrm{T}}^2$$

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

Process	Experimental Signature	
$qq \to W \to \ell\nu$	$e,\mu + E_T^{miss}$	("W+0 jets")
$qq \to Wg \to \ell\nu g$	$e,\mu + E_T^{miss}$	("W+0 jets")
	$e,\mu + E_T^{miss} + j$	("W+1 jets")
$qq \to Wqq \to \ell\nu qq$	$e,\mu + E_T^{miss}$	("W+0 jets")
	$e,\mu + E_T^{miss} + j$	("W+1 jets")
	$e,\mu + E_T^{miss} + 2j$	("W+2 jets")
$qq \to Wqqg \to \ell\nu qqg$	$e,\mu + E_T^{miss}$	("W+0 jets")
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	$e,\mu + E_T^{miss} + 2j$	("W+2 jets")
	$e,\mu + E_T^{miss} + 3j$	("W+3 jets")

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

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Additional Experimental Considerations

MET reconstruction requires un-ambiguous event

- Typically all calorimeter signals usedfor 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

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Detector Signal Contributions To MET

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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)

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MET Calibration?

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- **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!

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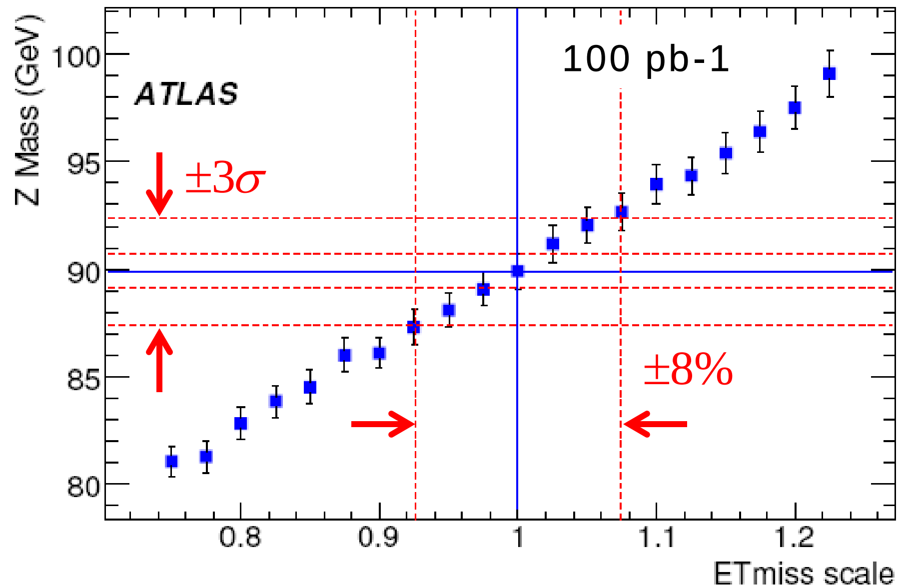

$$m_{\tau\tau} = \sqrt{2\underbrace{\left(E_{had} + E_{\nu_1}\right)}_{\text{hadronic } \tau \text{ decay}}\underbrace{\left(E_{\ell} + E_{\nu_2}\right)}_{\text{leptonic } \tau \text{ decay}}\underbrace{\left(1-\cos\theta_{had,\ell}\right)}_{\sphericalangle \text{ hadronic, leptonic}}}$$

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

Fake Missing ET

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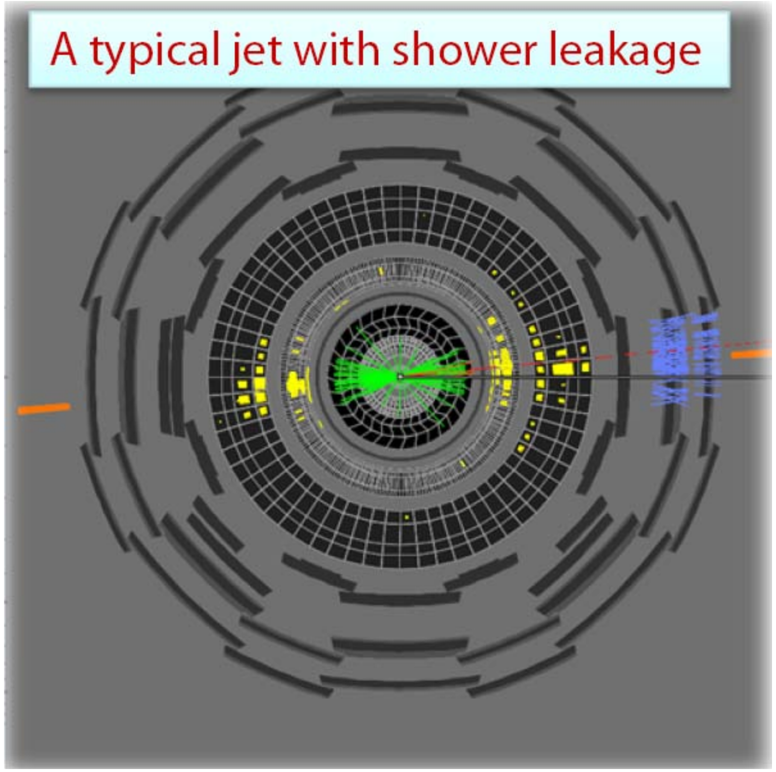
What is that?

- 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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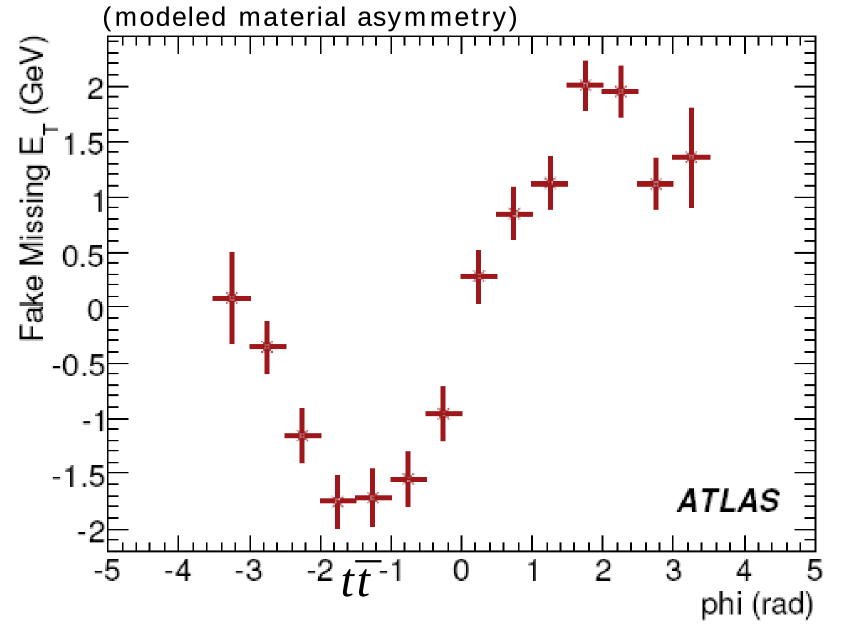

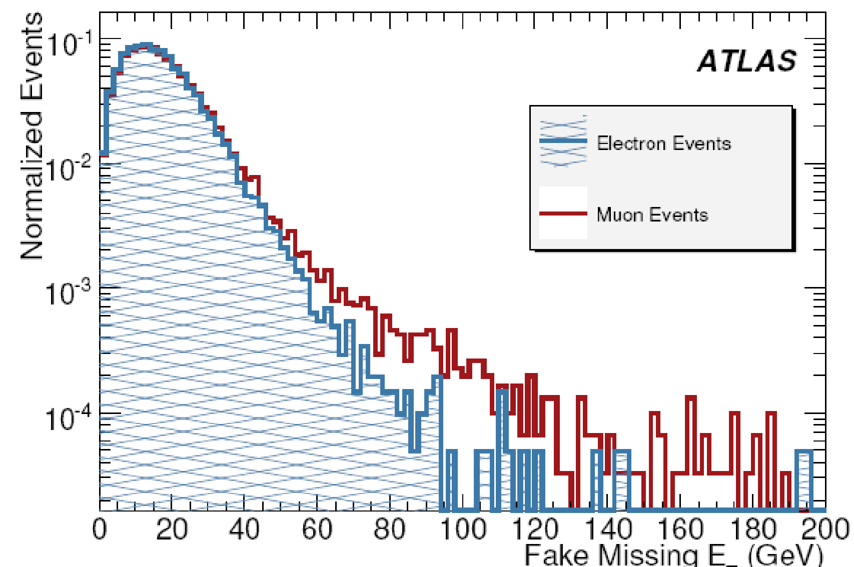

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MET Resolution From MC

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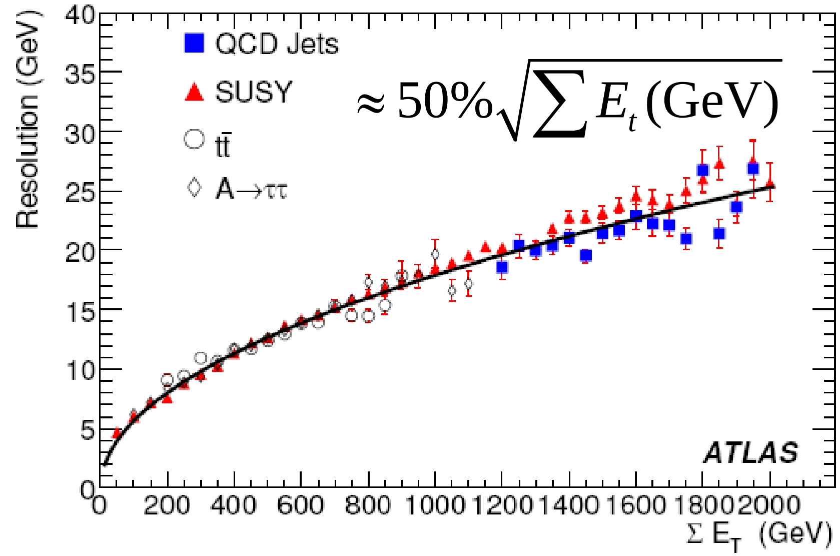
Fluctuation of MET around expected value

- 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



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$$\sigma_{\not{E}_T} = \frac{1}{\sqrt{2}}\sqrt{\left\langle\left(E_{T,x} - E_{T,x}^{\mathrm{nonInt}}\right)^2\right\rangle + \left\langle\left(E_{T,y} - E_{T,y}^{\mathrm{nonInt}}\right)^2\right\rangle}$$

Minimum bias events $\left(E_{T,x}^{\mathrm{nonInt}}, E_{T,y}^{\mathrm{nonInt}}\right) = (0,0)$:

$$\sigma_{\not{E}_T} = \frac{1}{\sqrt{2}}\sqrt{\left\langle E_{T,x}^2\right\rangle + \left\langle E_{T,y}^2\right\rangle}$$

MET Scale & Resolution

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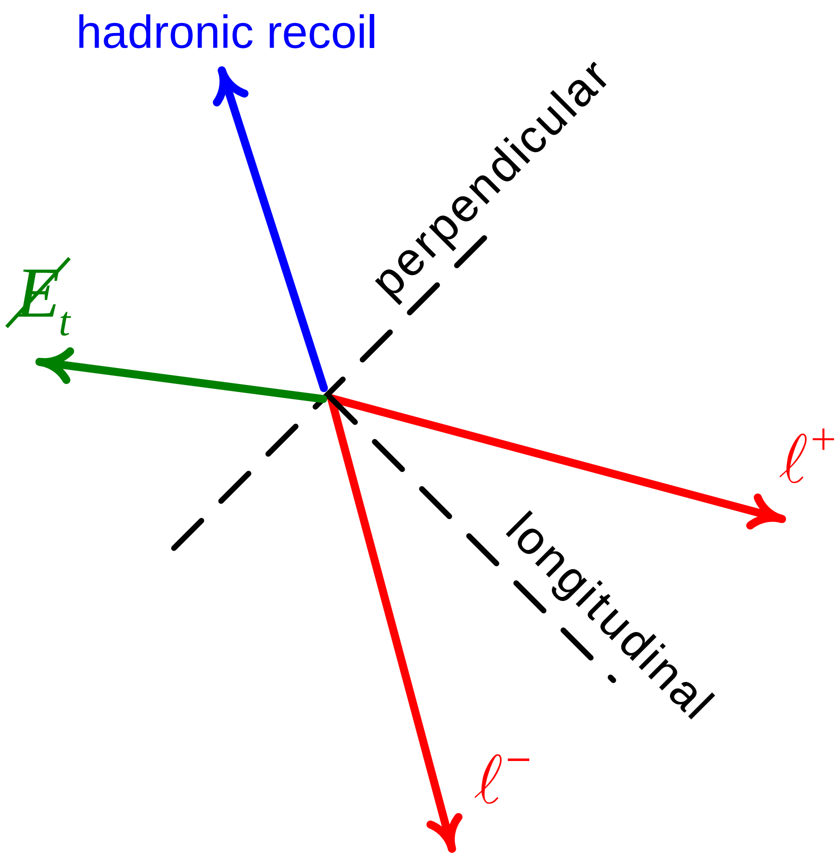
Experimental access

- 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



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MET Scale & Resolution

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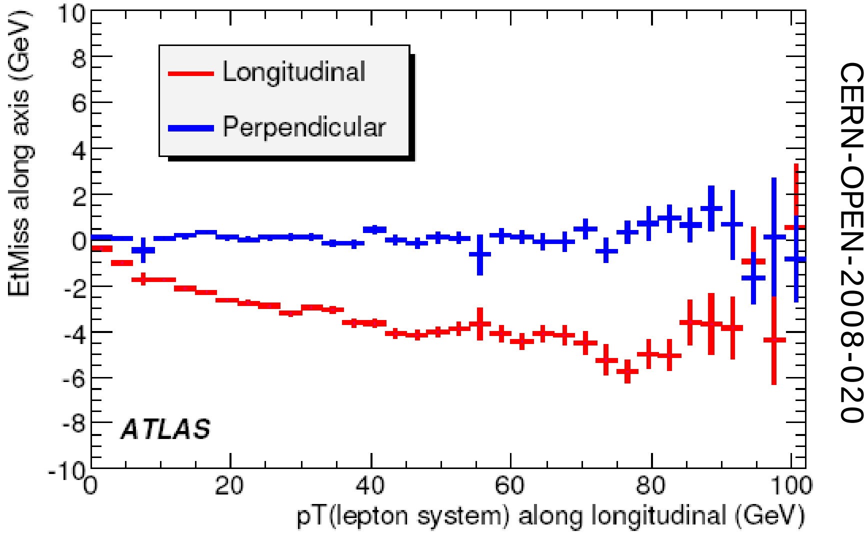
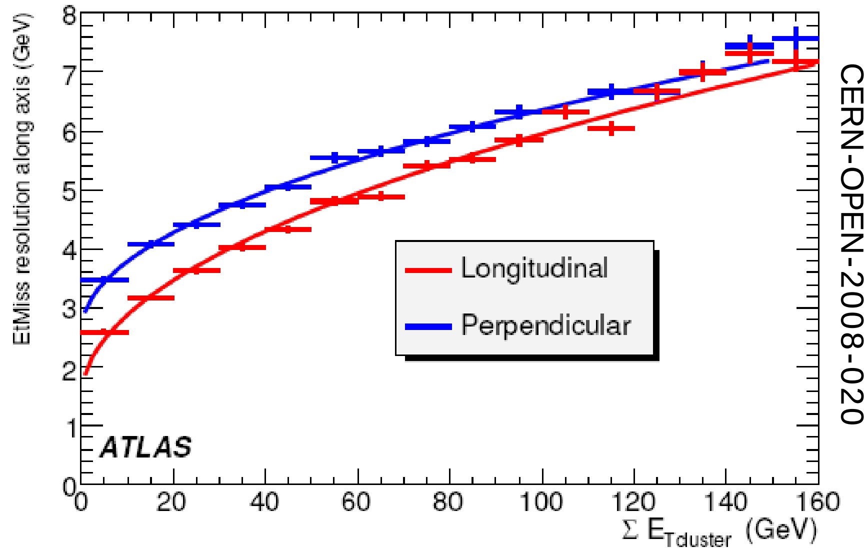
MET scale

- 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 Et sum of hadronic calorimeter signal
  - Biased by UE and pile-up (MC needed here)
- Qualitatively follows calorimeter energy resolution





Closing Remarks

- **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