Jet and missing E_T in ATLAS

In-situ calibration strategy toward early data
(and results from cosmic-ray data)

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研究会：「ＬＨＣが切り拓く新しい物理」 April 1, 2009

Note that most of figures/numbers shown here are ***very preliminary*** or ***still in progress*** at the collaboration.

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Goal of this talk

Quickly review the in-situ calibration/validation strategy of jet and missET, and let you understand:

- ✓ What we are going to do with early data
- ✓ What are the difficulties
- ✓ We have everything in readiness for data (or not yet…)

Jet and missET appear in many signatures of interest in LHC/ATLAS

- ✓ Top physics, Higgs, SUSY…
- ✓ QCD jets are the background for most of analysis

Both objects are challenging for first data analysis:

jet: theoretically not unique…

missET: calculated from many physics objects and its performance depends on reliable corrections on them.

Outline

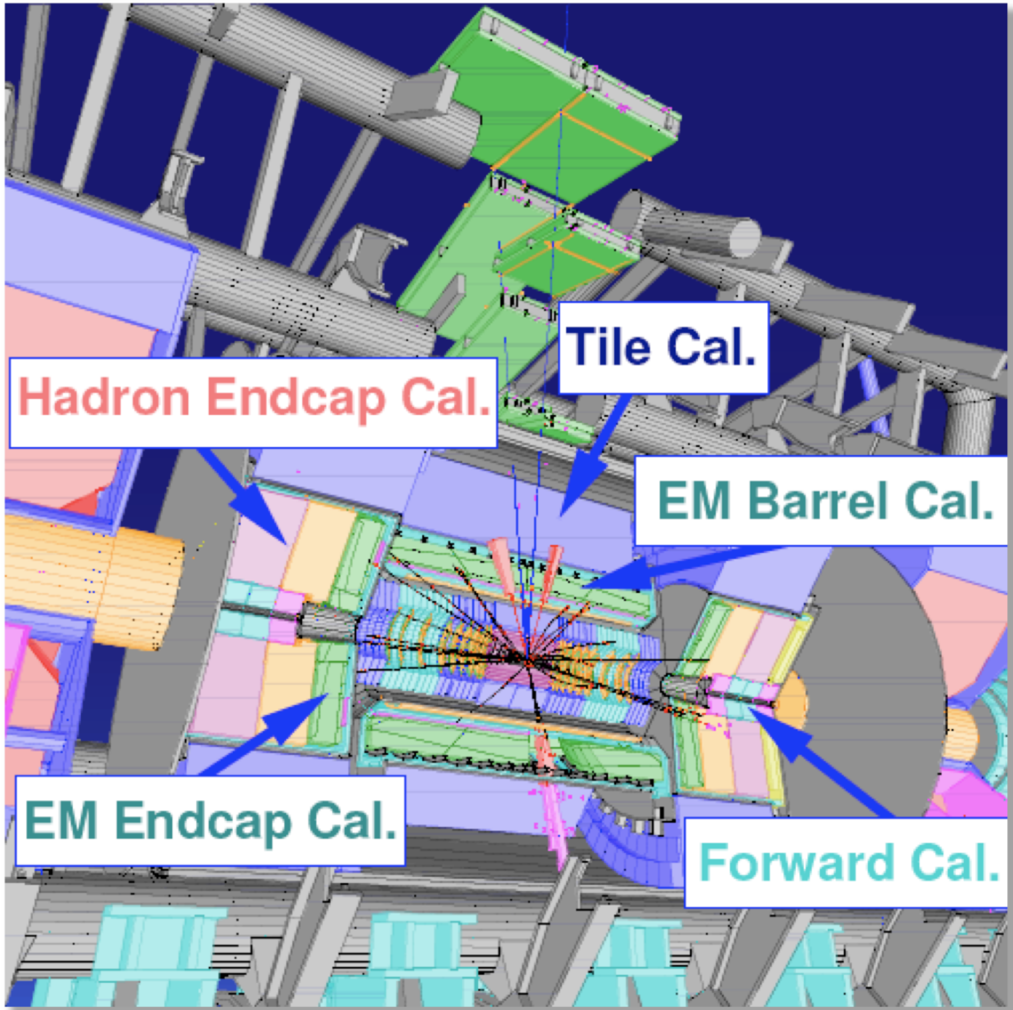
- Calorimetry in ATLAS
- Jet
  - Jet finding algorithm
  - Data-driven jet calibrations
- Missing ET
  - Reconstruction algorithm
  - In-situ determination of missET scale/resolution
- Some remarks from cosmic-ray data
- Summary

Follow-up: Calorimetry in ATLAS

EM: LAr-Pb accordion calorimeter
- $24\sim26X_0$
- $0.0025 \le \Delta\eta \le 0.05$, $0.025 \le \Delta\phi \le 0.1$
- 2-3 samplings
- Barrel (EMB): $|\eta|<1.4$
- Endcap(EMEC): $1.375<|\eta|<3.2$
- presampler: $|\eta|<1.8$

Hadron:
- Barrel(TILE): Scintillator-Fe
  - 3 longitudinal samplings
  - $|\eta|<1.7$
  - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- Endcap(HEC): LAr-Cu
  - 4 samplings,
  - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ $(1.5<|\eta|<2.5)$,
  - $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ $(2.5<|\eta|<3.2)$

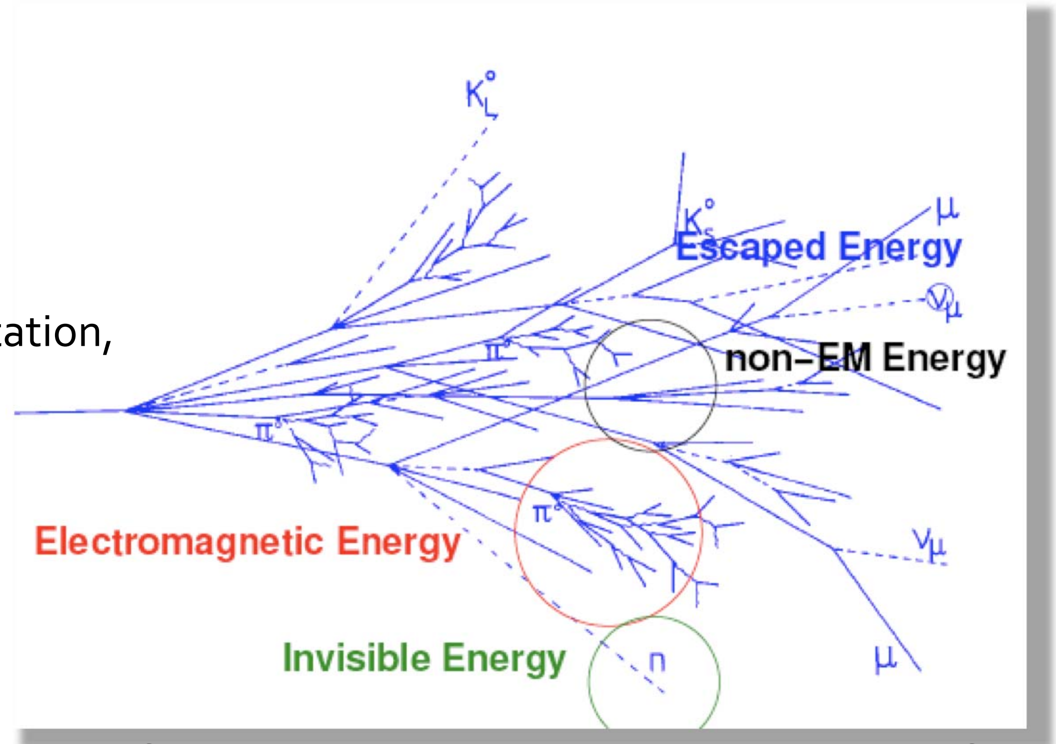
Forward(FCAL):
- $3.2<|\eta|<4.9$
- FCAL1: LAr-Cu
- FCAL2/3: LAr-W
- $\Delta\eta \times \Delta\phi \approx 0.2 \times 0.2$



Hadron Calorimetry

A hadronic shower consists of
- EM energy:
  $\pi^0 \rightarrow \gamma\gamma$, ~ O(50%)
- visible non-EM energy:
  dE/dx from $\pi^\pm, \mu^\pm, \cdots$ ~O(25%)
- invisible energy;
  breakup of nuclei and nuclear excitation,
  ~O(25%)
- escaped energy:
  ν, μ ~O(2%)

Each fraction is energy dependent
and subject to large fluctuations.



Invisible energy is the main source of the non-compensating nature of hadron calorimeters.
For the best performance, the hadronic calibration should account for the invisible and escaped energy. Also need dead-material, leakage and clusterization corrections.

General Remarks on Calorimeter Performances

Energy dependence of hadronic energy resolution of (non-compensating) calorimeter:

$\sigma/E = aE^{-1/2} \oplus b$

a: Stochastic term (governed by Poisson statistics)

b: Constant term (originate from incoherent noise, sampling fraction variations, non-uniformity of upstream material and other instrumental effects)

The first step in experiment is surelly overall hadronc energy scale correction.

But we also need to factorize the calibration and corrections dealing with hadronic shower and various instrumental effects to achieve the best performances.

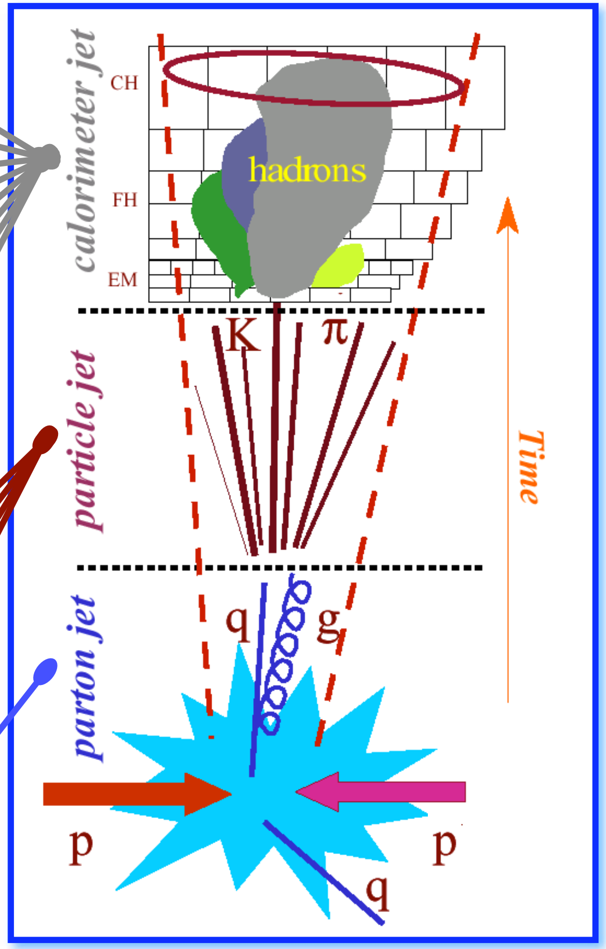
Jet

Jet Reconstruction and Calibration Overview

longitudinal energy leakage
detector signal inefficiencies (dead channels, HV...)
pile-up noise from (off-time) bunch crossings
electronic noise
calo signal definition (clustering, noise suppression ,...)
dead material losses (front, cracks, transitions...)
detector response characteristics (e/h ≠ 1)
jet reconstruction algorithm efficiency

jet reconstruction algorithm efficiency
added tracks from in-time (same trigger) pile-up event
added tracks from underlying event
lost soft tracks due to magnetic field

physics reaction of interest (parton level)

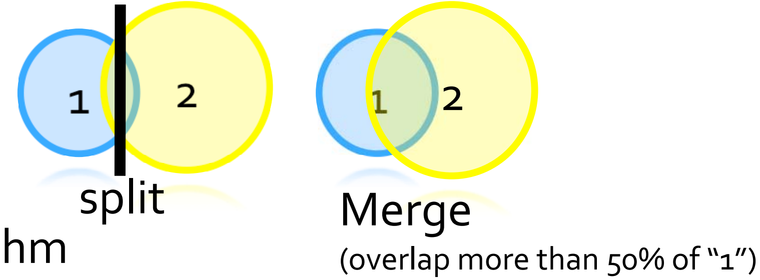


Jet Finding Algorithm

Fixed cone (R=0.4 or 0.7) with sprit & merge

Standard and widely used in ATLAS, infrared / collinear safe

1. Seed E_T threshold (typically 1GeV)
2. Collect neighbors around a seed in a given R
   - ✓ R=0.7: avoid fragmentation loss for low pT jets
   - ✓ R=0.4: separate overlapping jets (hard process, at high-luminosity)
3. Merge two jets if overlapping energy is more than 50% of the least energetic jet energy.



Alternatives:

- SISCone: Seedless Infrared-Safe Cone jet algorithm
- kt: sequential recombination with low relative p_T
- anti-kt: sequential recombination with high relative p_T
- ...

Everything is possible choice, but should be robust (at early stage) and work well under the pile-up situation (in future)

Inputs to Jet Finder

Towers (ConeTowerJet)

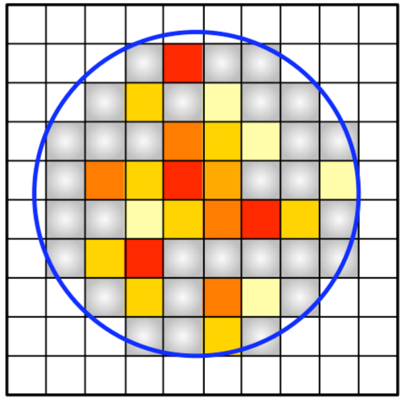
- $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- Uncalibrated EM energy
- re-summation of the towers to cancel noise
- Disadvantage: many non-signal cells are included in jets

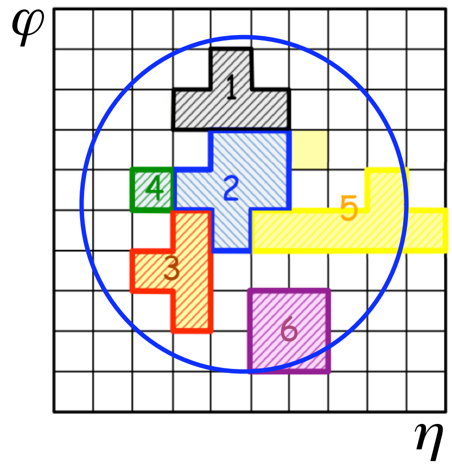
TopoCluster (ConeTopoJet)

- Topological clusterization (→next page)
- Powerful electric/pile-up noise suppression, noise level is under control.
- Allow to use “calibrated” signal as input. (local hadron calibration etc.)

Topo-Tower

- Tower made from cells of topological clusters (noise suppression)
- Gives better performance when pile-up exists?? (still under development)





Topological Clustering Illustration

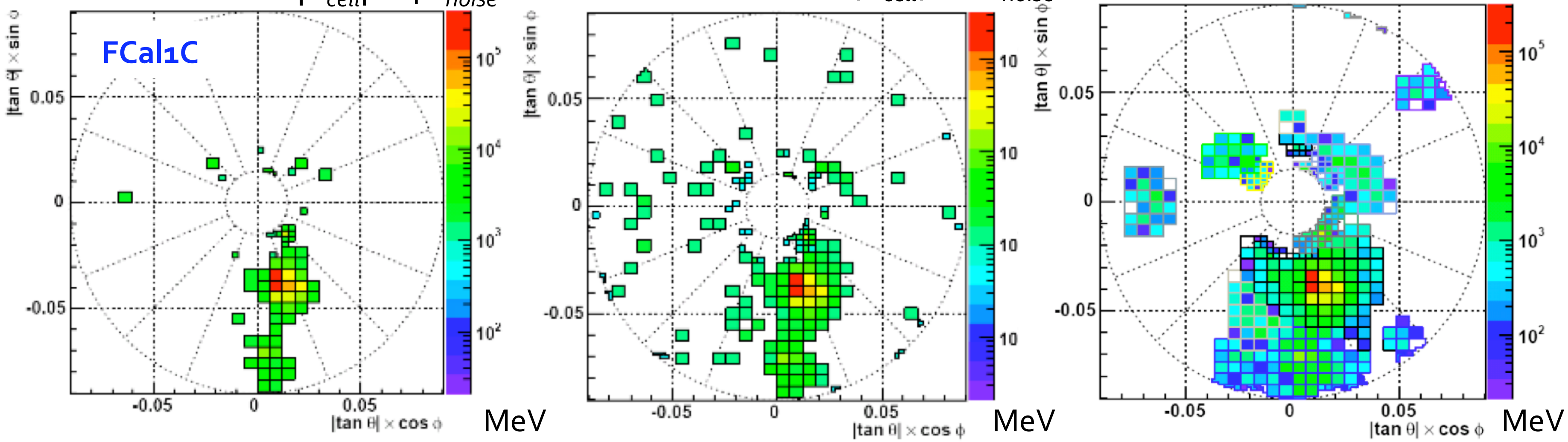
Topological clustering: 4/2/0

Hadronic cluster seeded by cell with significance |Ecell| / σ_{noise} > 4

Neighboring cells added iteratively (in 3D) if they have significance above 2. Clusters with common neighbors can be merged.

After iteration, cells along the perimeter of the cluster are added if they have a significance above 0.

Seed cells with $|E_{cell}| > 4\sigma_{noise}$ 2nd seed cells with $|E_{cell}| > 2\sigma_{noise}$



Global Hadronic Calibration

Atlas standard calibration (H1 calibration) weights are derived by QCD di-jet MC

- Pythia
- Cover the p_T range from O(10GeV) to O(1000GeV)

For each cone jet of R=0.7

- Find a matched truth particle jet (R=0.7)
- Extract all cells in the calorimeter jet
- Extract response corrections (w) for all calorimeter cells by minimizing the following χ^2

$$\chi^2 = \sum_{events} \sum_{jets} \frac{E_{jet}^{rec} - E_{jet}^{truth}}{E_{jet}^{truth}} \text{ ,where } \quad E_{jet}^{rec} = \sum_{i}^{Ncell} w_i\left(\frac{E_i^{EM}}{V_i}, \vec{x}\right) \cdot E_i^{EM}$$

Hadronic scale correction (e/h) and instrumental effect corrections are applied simultaneously. (But sometimes this make it difficult to perform the factorized approach of calibration…)

Calibration strategy for early data

Jet energy scale correction:

$p_T(\text{corr}) = [p_T - p_T^{o}(\eta, nPV, L)]$
$\times C(\eta, p_T) \times R(p_T) \times C(\text{Moments})$

p_T^{o}: offset correction (data-driven, γ +Jet, Min-bias)

$C(\eta, p_T)$: Eta-dep. correction (data-driven, di-jet)

$R(p_T)$: MC based / Data-driven (γ +Jet balance)

Jet energy scale in-situ validation:

- data/MC comparisons
- tests in Z /γ +Jet, di-jet, ttbar and min-bias events.
- (Each jet energy correction must be derived for the specific input constituent type, jet algorithm, and signal state of EM scale, H1 weighting and local hadron calibration for robustness.)

•Parton energy scale

Z/γ+jet balance
W→jj in ttbar event

•Connection with parton jet and particle jet

QCD di-jet balance

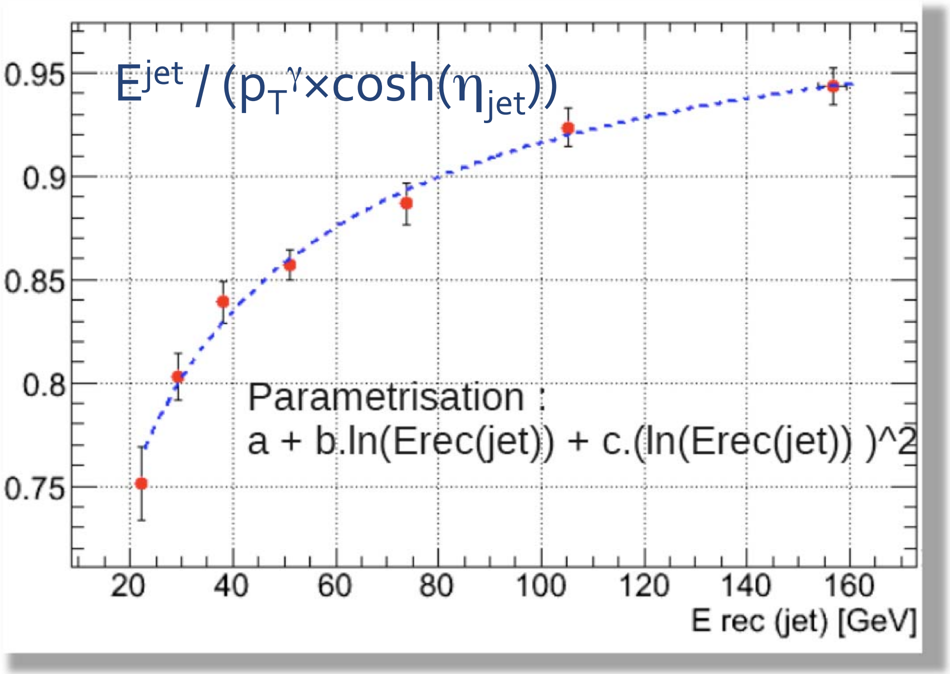
•Cover wide p_T range
•η-Intercalibration

Multi-jet balance
Track angle in jet

•Extend to higher p_T region

γ+jet p_T Balance

- ✓ Search events with one isolated γ
- ✓ γ and leading jet are back-to-back: $\Delta\phi(\gamma,\text{jet})<0.2$
- ✓ Leading jet should point to the central region of $|\eta|<1$ (small η dependence of calorimeter response)



Jet η is well-reconstructed and $p_T^{\gamma}\times\cosh(\eta_{jet})$ represents the energy of initial parton energy.

Calibration weights can be derived by:

$$p_T^{\gamma}\times\cosh(\eta_{jet}) / E_{rec}^{jet}$$

Using first data of 1pb-1, this can cover the p_T range up to 300GeV/c.
QCD background rejection needed for low-p_T jets (under study)

Z+jet p_T Balance

2 electrons + jet events with:

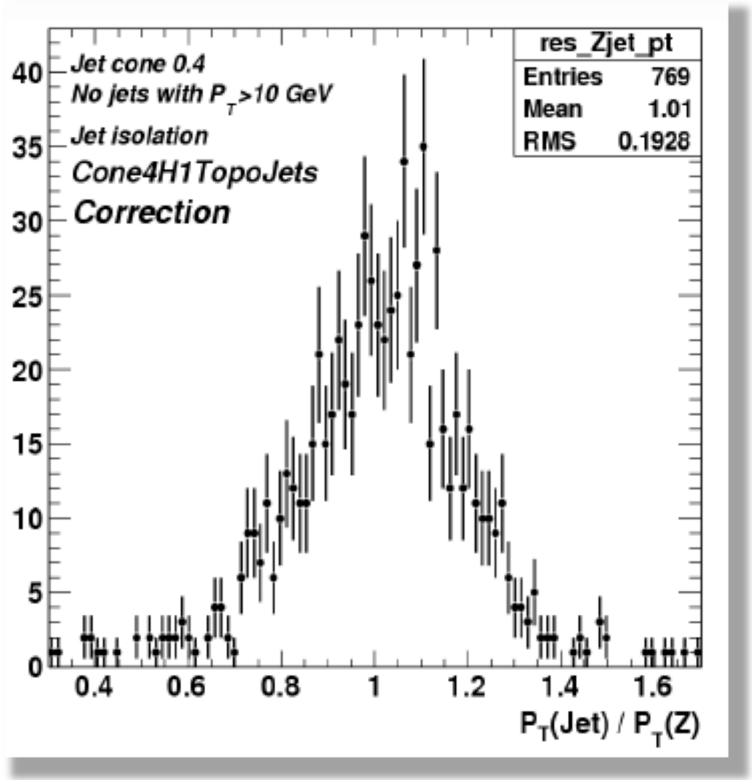
$|M_{ee}-M_Z| < 10\text{GeV}$, $p_T^Z > 50\text{GeV/c}$

p_T imbalance event rejection (originating from out-of-cone radiation):

Second leading jet $p_T < 20\text{GeV/c}$

$E_T^{jet}/E_T(R=1 \text{ cone wrt jet axis}) > 0.9$

Then calibration weights can be derived from the same way as γ+jet.



Note:

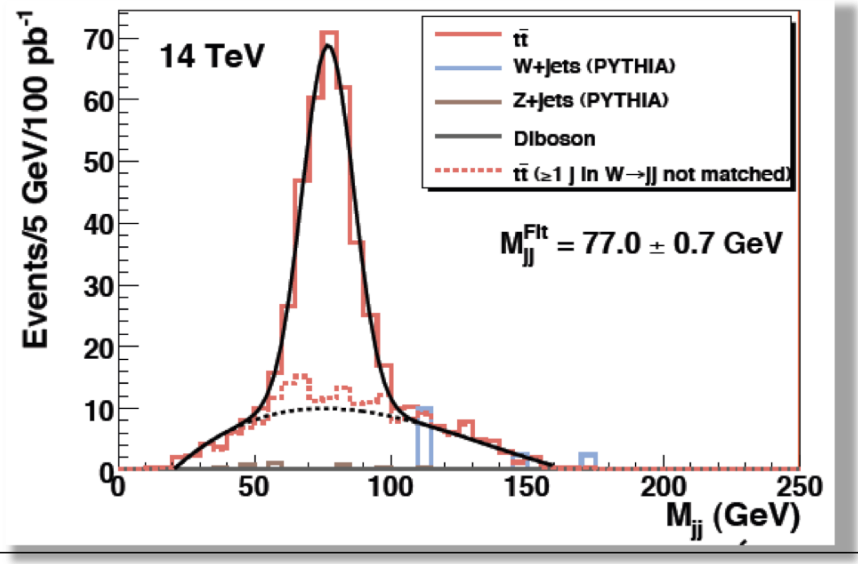
We see the truth level imbalance between Z/parton jet; This could originate from soft radiation, higher order QCD, multi-parton interaction…

We may need quote 1~2% uncertainty.

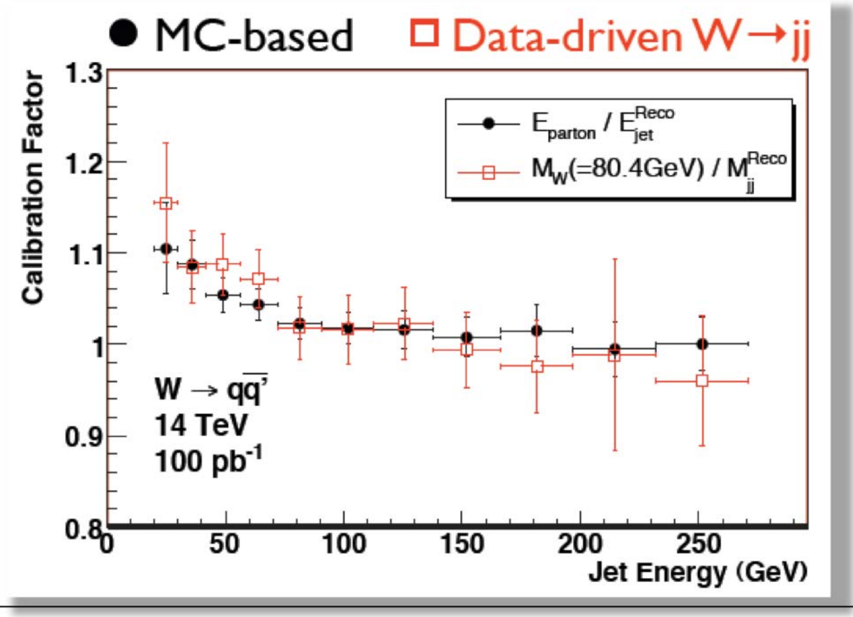
W→jj inTop Event

Preselection:
1. One electron or muon
2. missET>20GeV
3. 4 jets with pT>20GeV
   and 2 of them are b-tagged

Top candidate:
— 3 jets (1 b-jet) with m_{jjj} in 150-200 GeV
W candidate:
— 2 non b-tagged jets in top candidate



Calibration procedure:
1) Define jet energy bins.
2) For each bin, select events with one jet in the bin energy
3) Derive derive a M_W/M_{jj} weight and repeat for other energy bins
4) Apply the calibration weights to jet energies and iterate2)-3)



Di-jet p_T Balance

Higher cross section of di-jet allows us to perform $\eta(\phi)$-intercalibration.

Reference jet : central jet with $|\eta|<0.7$ and a certain p_T range
Probe jet (to be calibated): pointing outside of central region.

Asymmetry is defined as

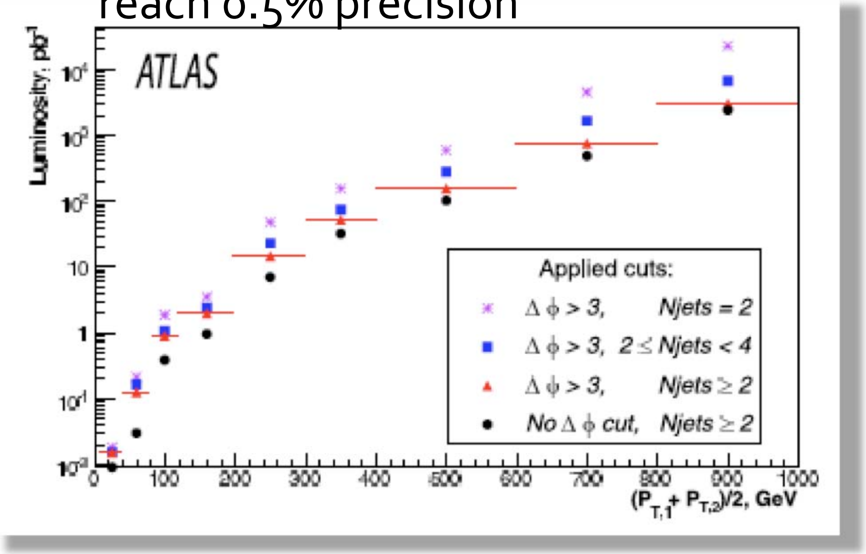
$$A = \frac{p_T^{\text{probe}} - p_T^{\text{ref}}}{(p_T^{\text{probe}} + p_T^{\text{ref}})/2}$$

Then the correction factor can be derived

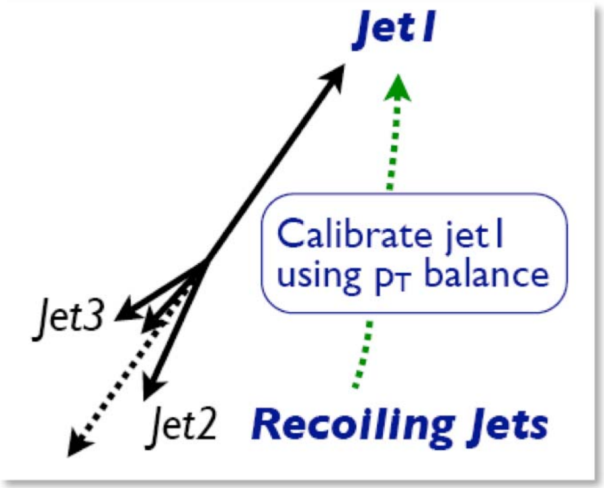
$$c = \frac{2-A}{2+A}$$

We need to apply some cuts on $\Delta\phi$ and Njet to reduce ISR/FSR effects, but can perform 0.5% level relative calibration up to ~300GeV/c using 100pb^{-1} data.

Integrated luminosity required to reach 0.5% precision



High-p_T Jet calibration



Multi-jet balance:

Select events requiring the following:

✓ ≥4 jets with pT>40 GeV

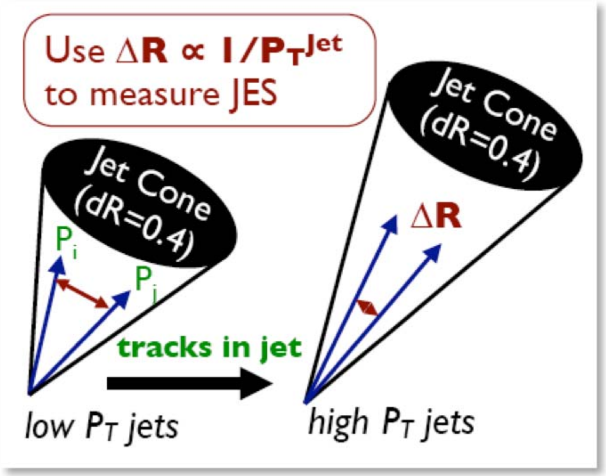
✓ Jet p_T cuts : e.g, $1000 < p_T^{Jet1} < 1140$ GeV/c, $p_T^{Jet2} < 470$ GeV /c

✓ $\Delta\varphi$(jet1, recoiling jets) > 160 deg.

Under the assumption that recoiling lower-p_T jets are well-calibrated.

Then retrieve the Jet1 scale correction from $p^{Jet1}/p^{Recoiling\ Jets}$.

Potential accuracy of <10% for ~TeV jets @1fb^{-1}



Track angle:

calculate ΔR of 2 leading-p_T tracks in the jet.

Evaluate the high p_T jet energy scale using $1/p_T^{jet}$ dependence of ΔR.

Expect ~20% accuracy for TeV jets @1fb^{-1}

(complementary to multi-jet balance method)

MissET Projection Method

In γ+jet events, missET projection R_j represents the response of jets:

$$R_j(E) = 1 + \frac{\not{E}_T \cdot \hat{n}_\gamma}{p_T^\gamma} = \frac{\sum' \overrightarrow{E}_T \cdot \hat{n}_\gamma}{p_T^\gamma}$$

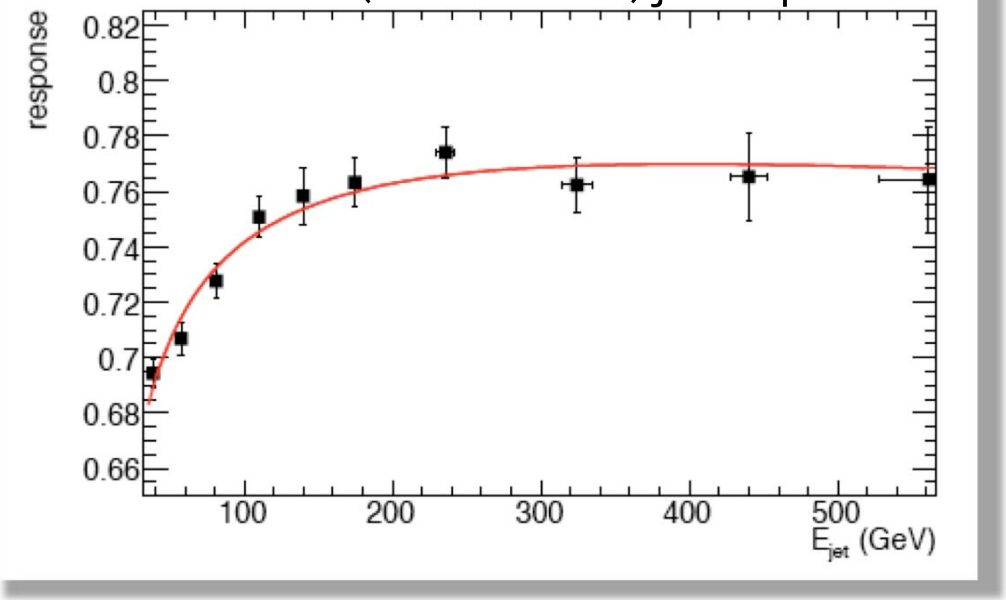
(Sum over E_T outside of γ system, and balance against γ)

Advantages:
- mostly independent of jet algorithm
- not sensitive to underlying events (ϕ symmetry)

Corrected jets are obtained by multiplying $1/R_j$:
~2% accuracy over the range of 50~900GeV

($\Delta\phi(\gamma$,jet) cut need to be introduced to reduce ISR/FSR.)

EM scale (uncalibrated) jet response



Missing ET

Reconstruction Algorithm

General approach of missET measurement:

missET is a variable representing invisible particles, thus simply calculated as imbalance energy against sum of all visible/detected particle ET.

ATLAS standard algorithm (refined calibration):

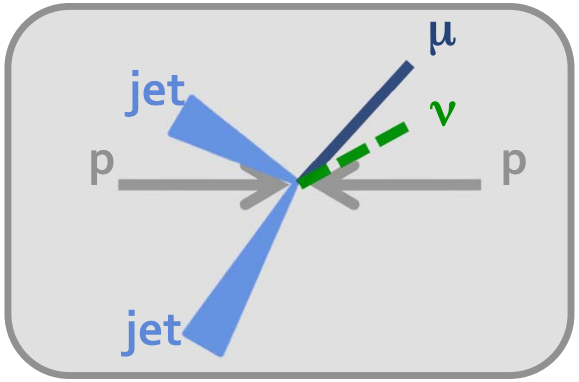
Calorimeter base calculation: large acceptance (up to |η|=5)

- Identify physics objects and decompose calorimeter signals into cells avoiding overlap.
- Simply sum over the calorimeter cell energies with their object calibration weights (w):

$$\mathrm{miss}E_{x(y)} = -\sum_{i}^{\text{objects}} \sum_{j}^{\text{cells}} w_{ij} E_{x(y)}^{j} + \sum E_{x(y)}^{\text{muon}} \qquad \mathrm{miss}E_T = \left(\mathrm{miss}E_x^2 + \mathrm{miss}E_y^2\right)^{1/2}$$

(object: e, g, t, jet, unused topo cluster)

General Description of missET Performance



missET (p_T of neutrinos) is measured as the energy imbalance with "calorimeter activities (e, γ, hadronic recoils) + muons"

- Assume hadronic energy scale is calibrated (software compensation)
- The resolutions are mainly described as the stochastic effect of visible calorimeter energy sum. (αxsumET$^{1/2}$)
- The scale shift is caused by
  - Difference between true energy sum of interacting particles ($\mathrm{sumET}_{\mathrm{truth}}$) and visible one.
  - Muons also affect the scale when undetected.
- MissEx resolution described as $\sigma(E_x^{miss}) = \alpha \cdot \Sigma E_T^{calo} \oplus \sigma(\mu \text{ inefficiency})$

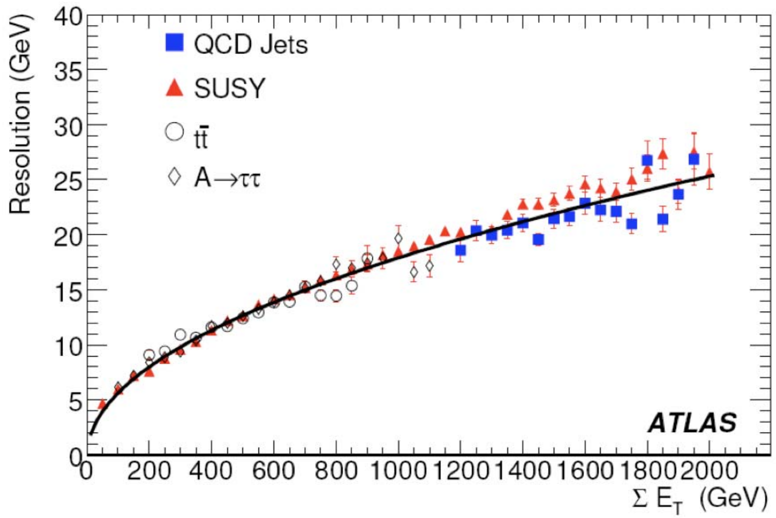
Baseline Performance

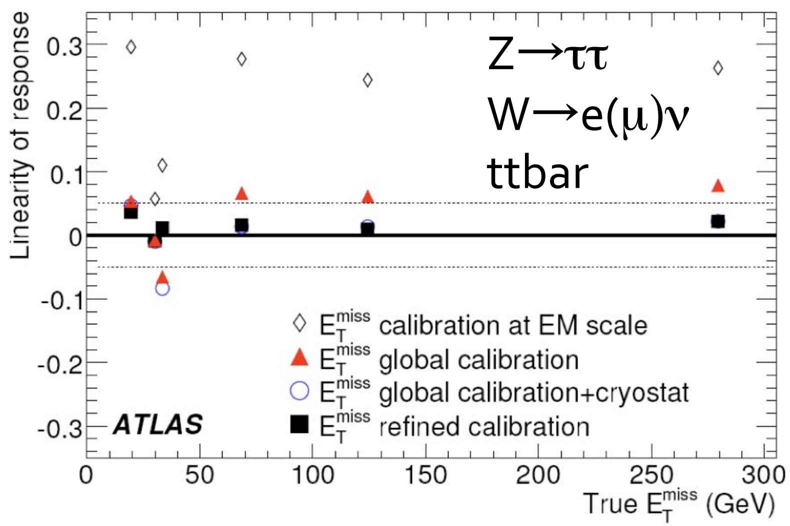
Incorporating "Refined Calibration" into missET reconstruction, we expect that <u>missEx/y resolution follows **α×sumET$^{1/2}$** over wide range of sumET</u> and <u>the scale is fairly stable against a wide range of missET and for different processes</u> (by G4 FullSim study)

.

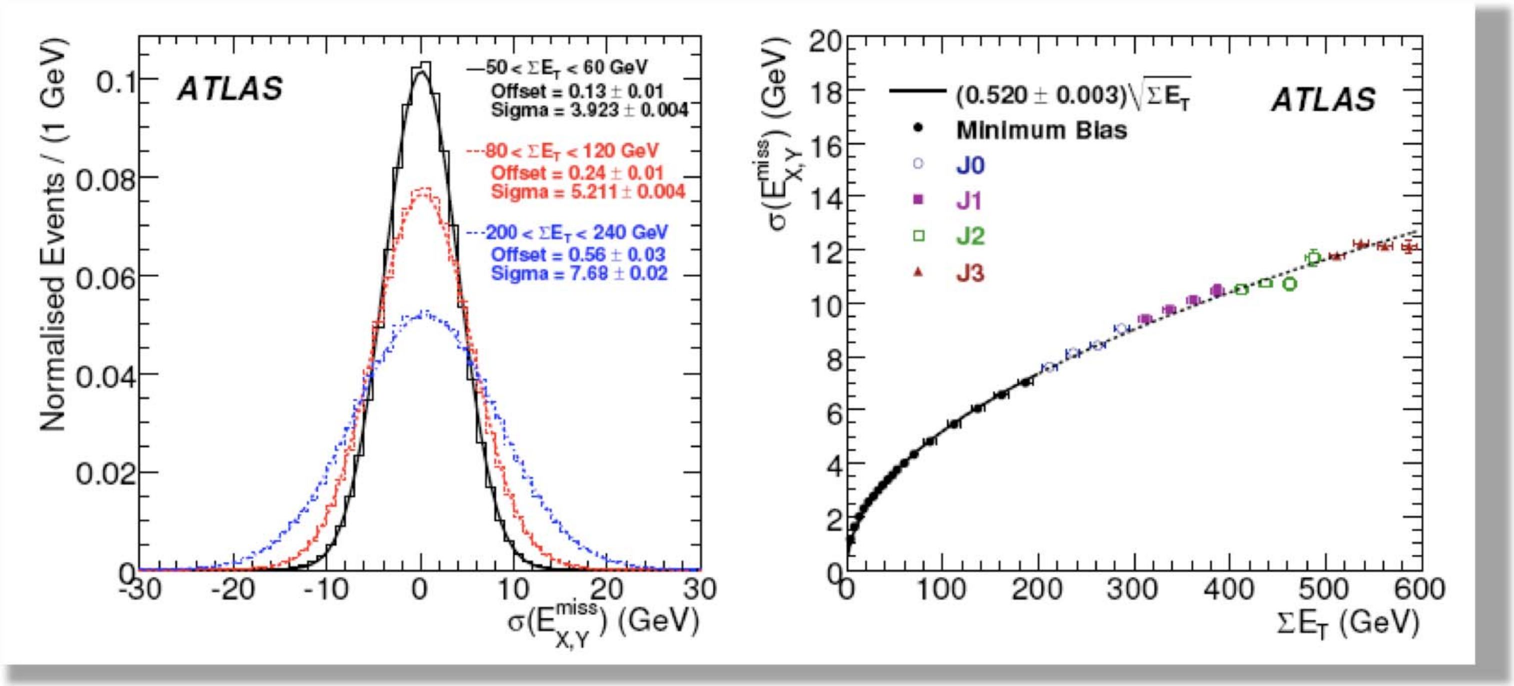
Beseline performance: $\sigma = 0.52 \times \mathrm{sumET}^{1/2}$ [GeV]

This should be confirmed using real data of various processes.





MissET in Mini-Bias Event



Mini-bias has (almost) no real missing energy, thus the spread of missEx/y/T indicate the resolution itself.

- Various measured distributions can be checked with MC expectations, covering the sumET range up to 100~200 GeV
- Should take care of beam halo, beam gas and non-collision events

W's Transverse Mass

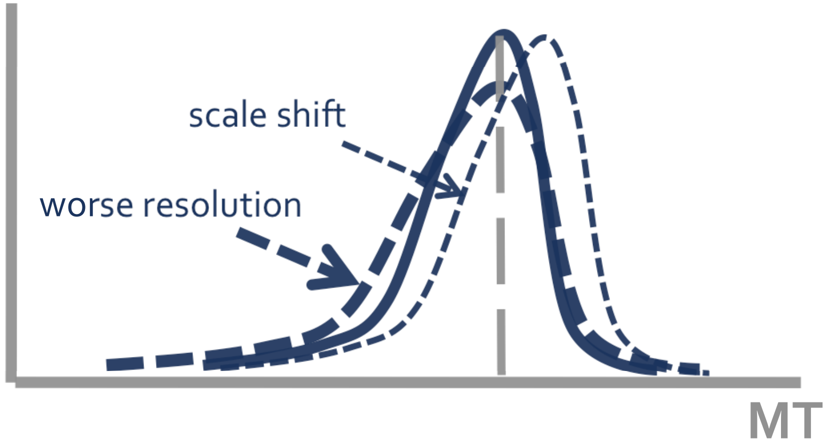
Use W→$\mu\nu$ events

- Promising performances for muon reconstruction
- Less fake rate compared to electrons.
- Enough signal yield at the early stage: σxBr~10nb (sqrt(s)=10TeV, p_T^{muon}>15GeV/c)

For W's decaying into leptons, the shape of transverse mass (MT) distribution is sensitive to missET resolution/scale:

"**spread**" ⇔ missET resolution
"**Jacobian peak**" ⇔ missET scale

Comparing with MC incorporating various resolution parameters, we can evaluate missET reconstruction performances.



$$m_T = 2p_T^l E_T^{miss}(1-\cos\Delta\phi)$$

p_T^l: transverse momentum of lepton
E_T^{miss}: transverse missing energy
$\Delta\phi$: ϕ angular difference between lepton and missET vector

W's Transverse Mass (cont.)

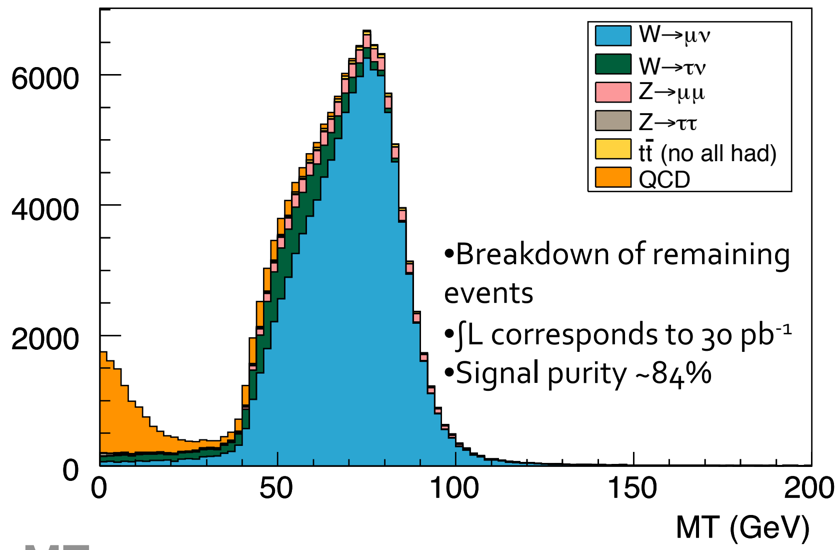
- Selection cuts
  1. Trigger: single muon (>15GeV/c)
  2. One isolated muon with p_T > 20GeV/c
  3. No tight electron above 20GeV/c
  4. MissET(RefFinal)>20GeV

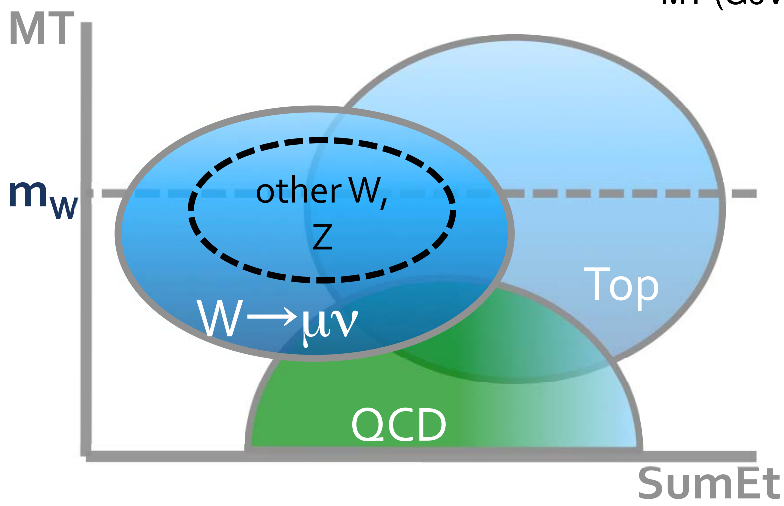
- In real data, shape of W's MT is smeared due to the contamination of backgrounds

→ Fit MC template of "MT-sumET" 2D-dist. to data with 4 free parameters (α, sumET scale β, ttbar and QCD fractions):

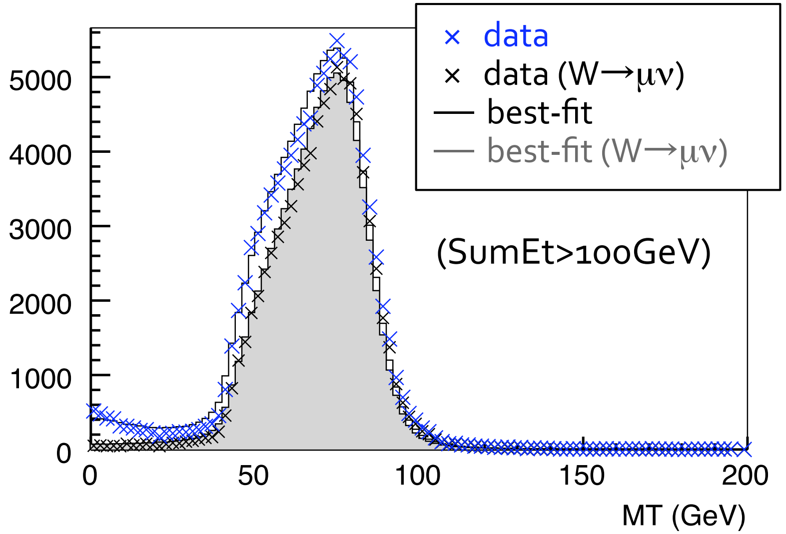
✓ W/Z background fractions are predictable (given only by branching fractions and muon ID efficiencies)

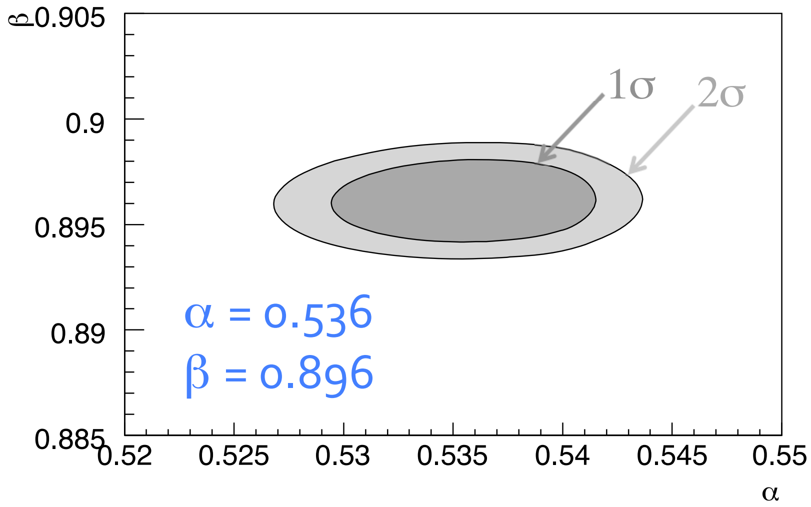
✓ sumET scale is uncertain (fragmentation, underlying event, instrumental effects…)





Result (30 pb^{-1})





- σ_{Exmiss} = 0.536× $SumEt_{rec}^{1/2} \oplus \sigma_{muon}$
  = 0.536× (0.896 × $SumEt_{truth})^{1/2} \oplus \sigma_{muon}$
  Consistent with the performances FullSim says. (α~0.52)
- Almost no correlation between α and β, as expected.
- MissEt resolution can be determined with an accuracy of <1% using a few 10 pb^{-1} data.

W in ttbar (Semi-leptoinc Decays)

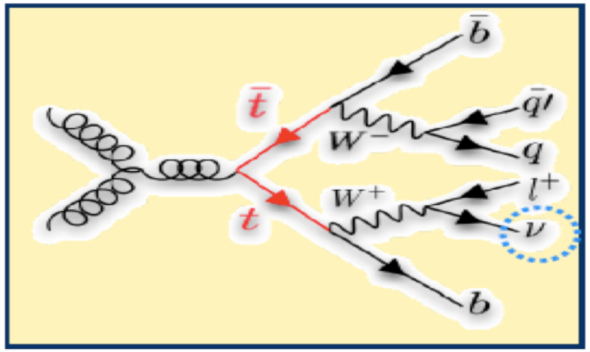
W→λν decays in ttbar can be selected with high purity by requiring multiple jets and covers the range of larger sumET (~1000GeV).

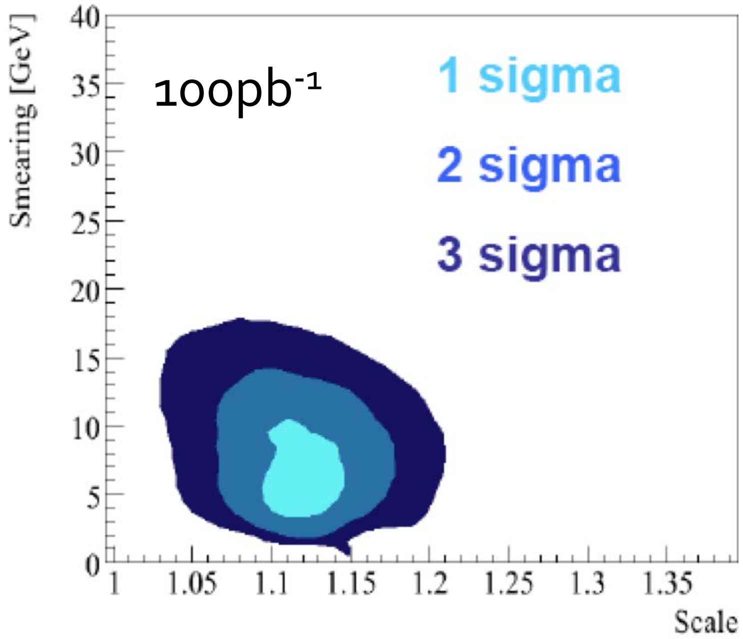
Selection:

1. > 3 jets, p_T>40 GeV
2. > 1 jet, p_T>20 GeV
3. 1 lepton (e/μ), p_T> 20 GeV
4. missET>20 GeV

Background:
Main contribution originates from W+jets, but not harmful for MT shape.

Prepare MC templates of MT by smearing missEx/y and scale, then find parameters best-matching to data (χ^2 fitting).

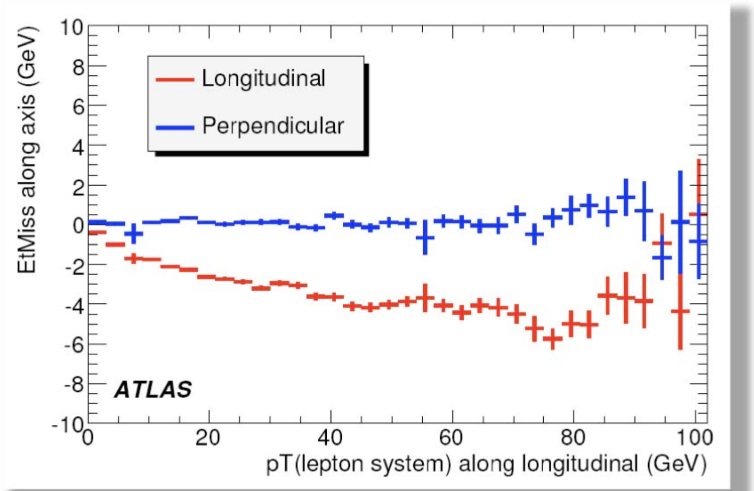




Validate MissET Scale with Z→ll

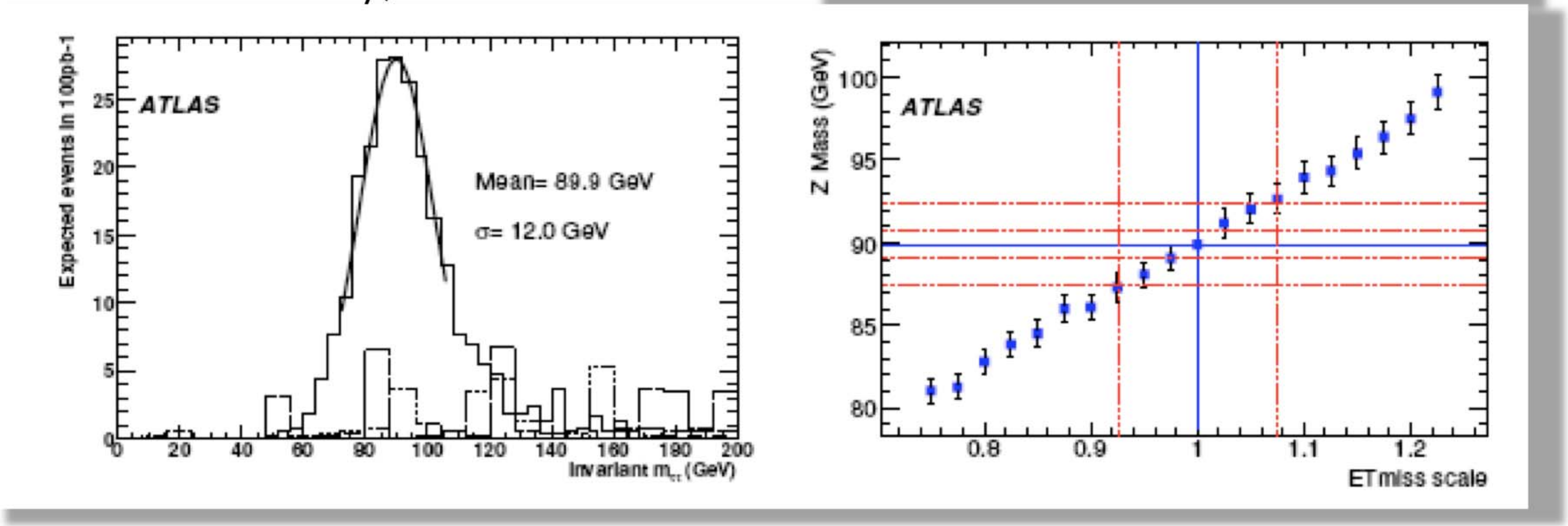
Z→ee:

Projection of missET along the Z(→ee) axis is sensitive to mis-calibration of hadronic recoils (as shown in the right figure).



Z→ττ(→lh):

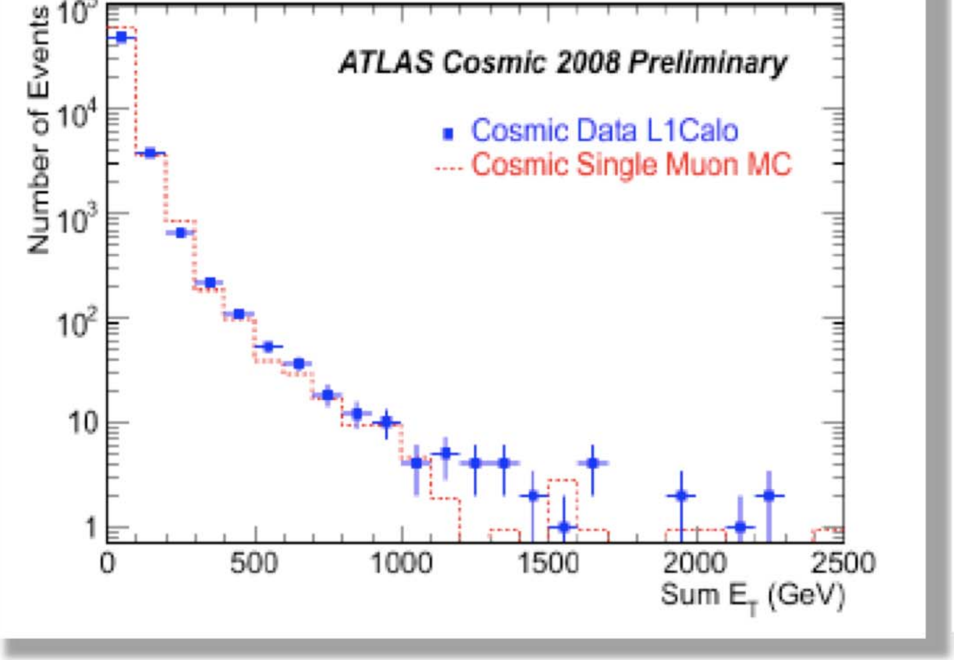
Reconstructed Z mass by collinear approximation is sensitive to missET scale (estimated with ~8% accuracy)

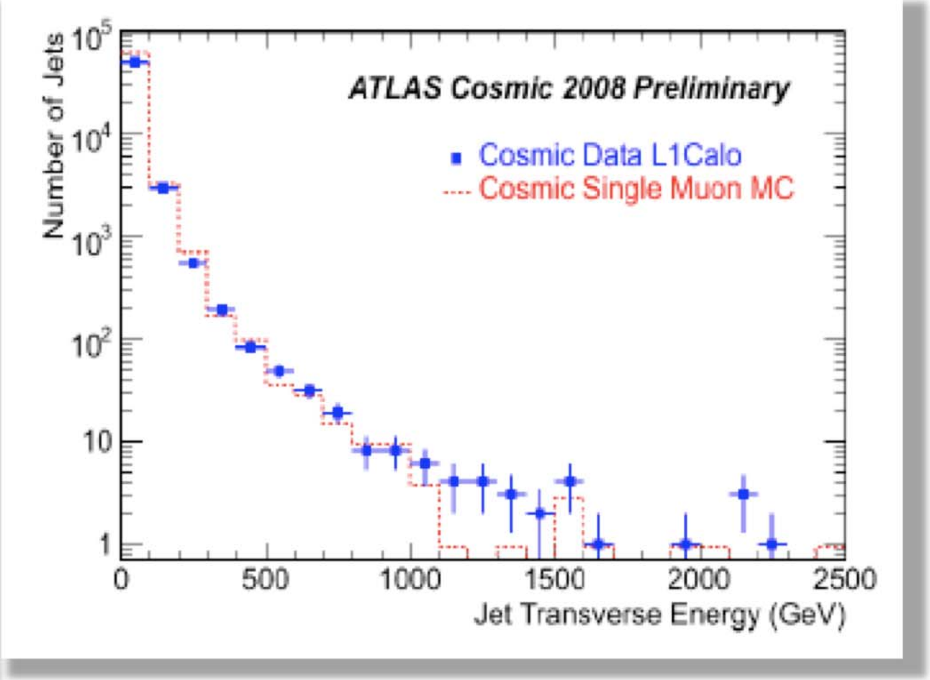


Highlights from Cosmic-ray data

A fraction of energetic cosmic-ray muons make clusters of calorimeter hits like hadronic showers by bremsstrahlung.
Our detector simulation well describes real data (sumET, jet E_T)

H.Okawa





Summary

- We don't have feeling about real collision data yet, but getting ready with in-situ jet calibration tools.
  - Lack of MC full-simulation data suffers our detailed studies for some tools (fake e/γ background from QCD jets for γ/Z-jet balances etc.); *Need real data anyway!*
  - Factorized approach of corrections may need for best performances and understanding the detector.
- Varieties of missET validation method are proposed.
  - Use many processes and cover the wide sumET range.
- Studies on robust jet finding algorithms and missET reconstruction against pile-up are also underway toward coming high-luminosity runs.

Backup

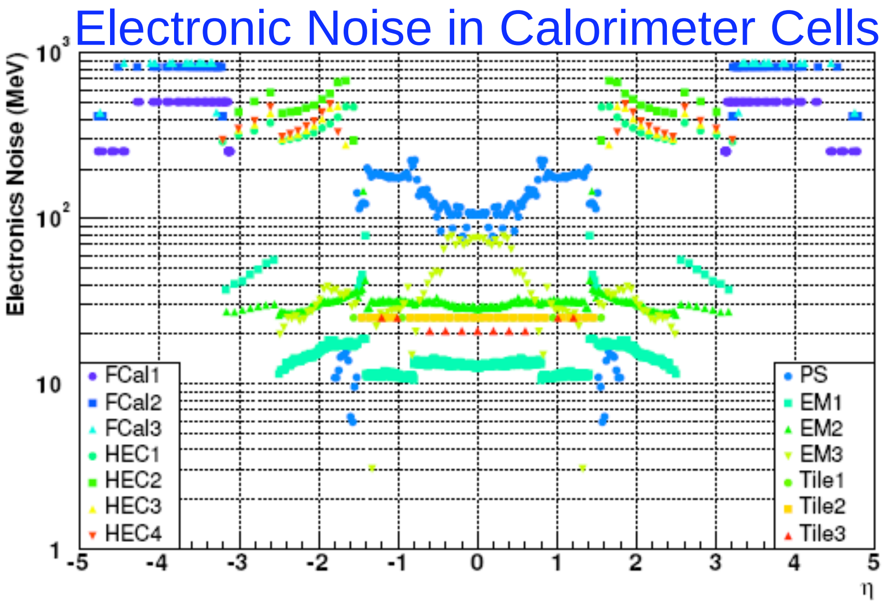
Electric/Pile-up Noise

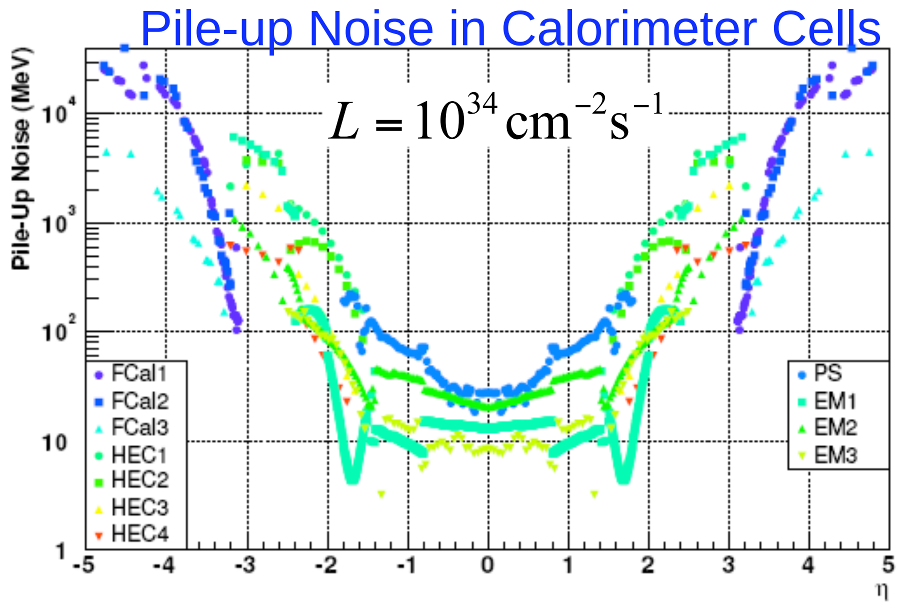
Electronic noise

- unavoidable basic fluctuation on top of each calorimeter cell signal, typically close to Gaussian (symmetric).
- ranges from ~10 MeV (in central region) to ~600MeV (forward) per cell.

Pile-up noise

- Major contributions from out-of-time signal history due to calorimeter shaping functions total of ~625 MB / triggered event affect the signal at 10^{34} $cm^{-2}s^{-1}$
- Slow charge collection (long drift time, ~ 500 ns) combined with 40MHz bunch-crossing frequency, and pp total cross section at 14 TeV
- Introduces asymmetric cell signal fluctuations from ~10 MeV (central region) up to about ~ 4GeV (RMS, in forward calorimeter) similar to coherent noise.





Local Hadron Calibration as an Alternative Approach

Local Hadron Calibration:
e/h weight and energy deposit in dead material are fully obtained by MC simulation.

Flow:
1) Use topological clusters
2) Cluster classification
--- EM, hadronic or unknown, based on EM fraction cluster shape info.
3) Hadronic scale weight
--- Derive and apply weights to cells in hadronic clusters
4) Out-of-cluster correction
--- Correction for energy deposited in calorimeter outside of cluster
5) Dead material corrections
--- Correction for energy lost in un-instrumented regions of the detector

Need to perform comparison of reconstructed variables with MC step by step, using real data.