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Challenge of Measuring Missing Energy

Richard TEUSCHER
CERN
Switzerland

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Missing Transverse Energy: The Challenge

1. Introduction
2. Measuring E_T^{miss}
3. Challenges
4. Commissioning
5. Outlook

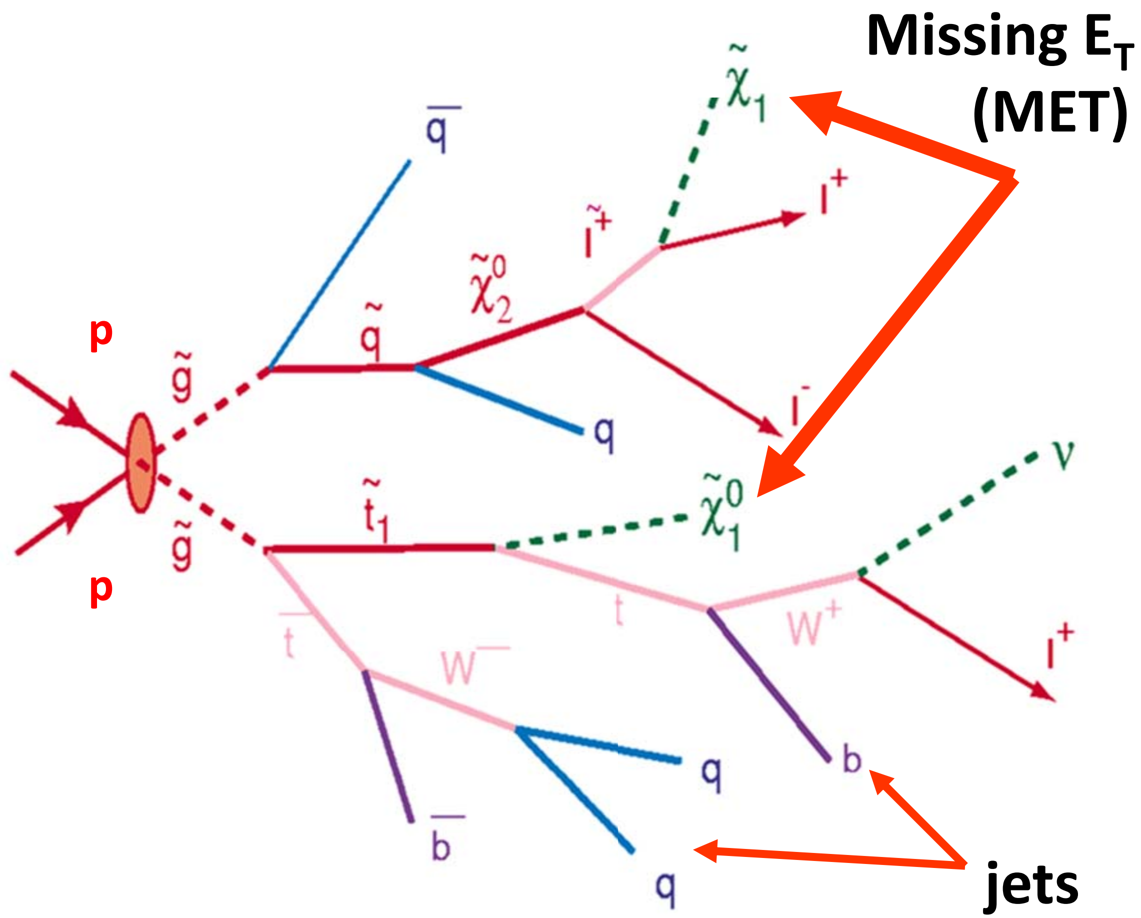
Richard Teuscher
IPP / University of Toronto

On Behalf of the ATLAS Collaboration

Introduction

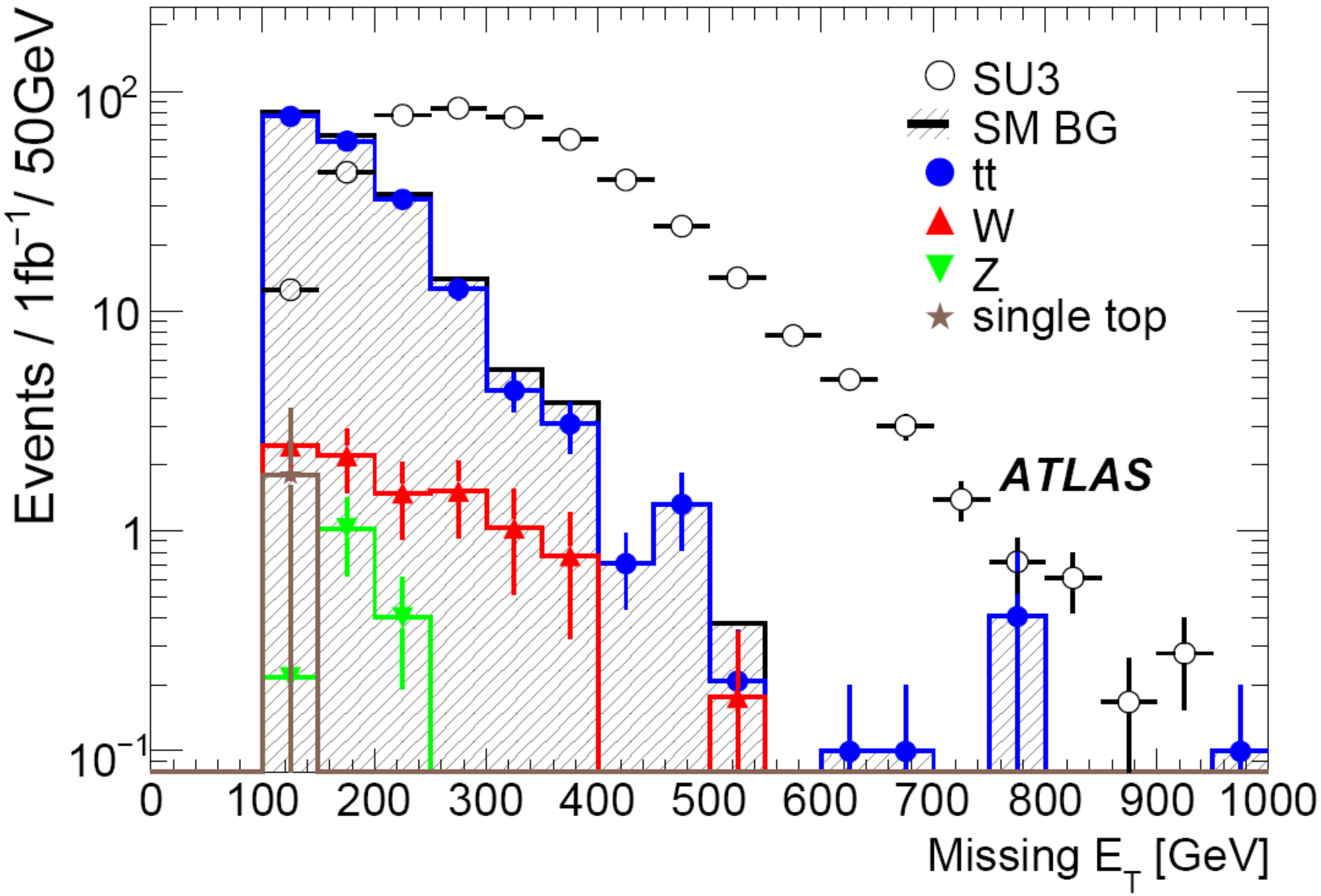
Motivation: New Physics Discovery (e.g. R-Parity conserving SUSY)

- R-Parity conserving SUSY search channels:
  - Large Missing Transverse Energy (E_T^{miss})
  - Large jet multiplicity;
  - Large E_T^{sum}.



$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow cascade\ decay$$

Example of E_T^{miss} in SUSY vs Standard Model (SM)



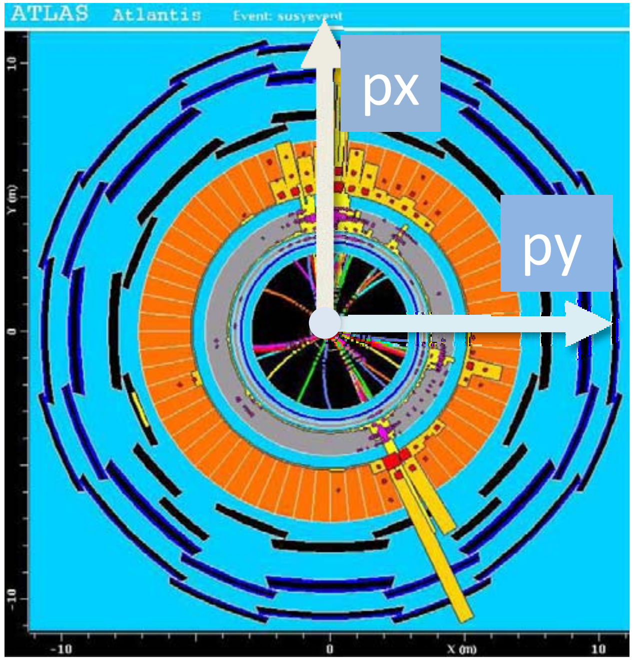
Cuts:

1-lepton (e,μ) with p_T>20 GeV

4 jets p_T>50 GeV

1 jet p_T>100 GeV

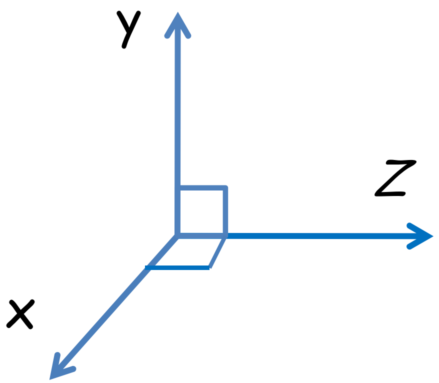
Sphericity S_T>0.2

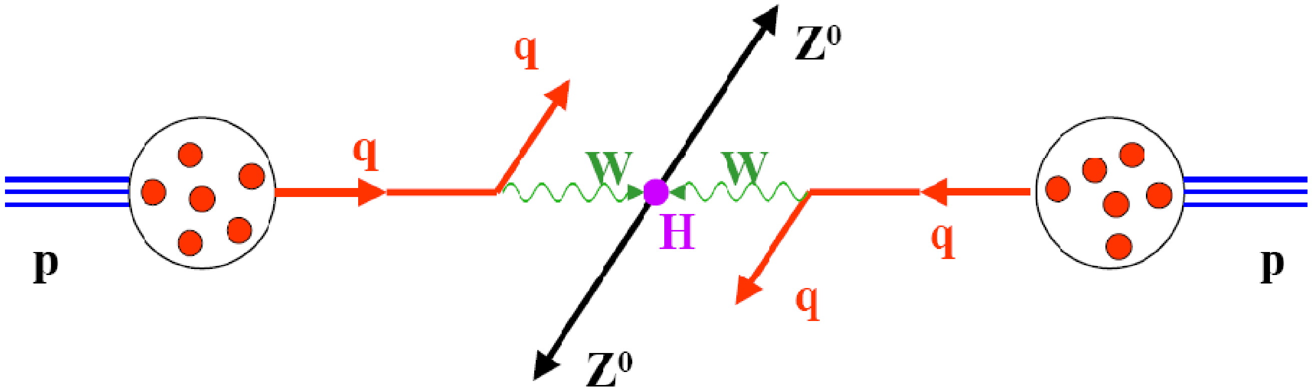


$$E_T^{miss} = \sqrt{\left(\sum E_x\right)^2 + \left(\sum E_y\right)^2}$$

Sum over (e.g. calorimeter cells)

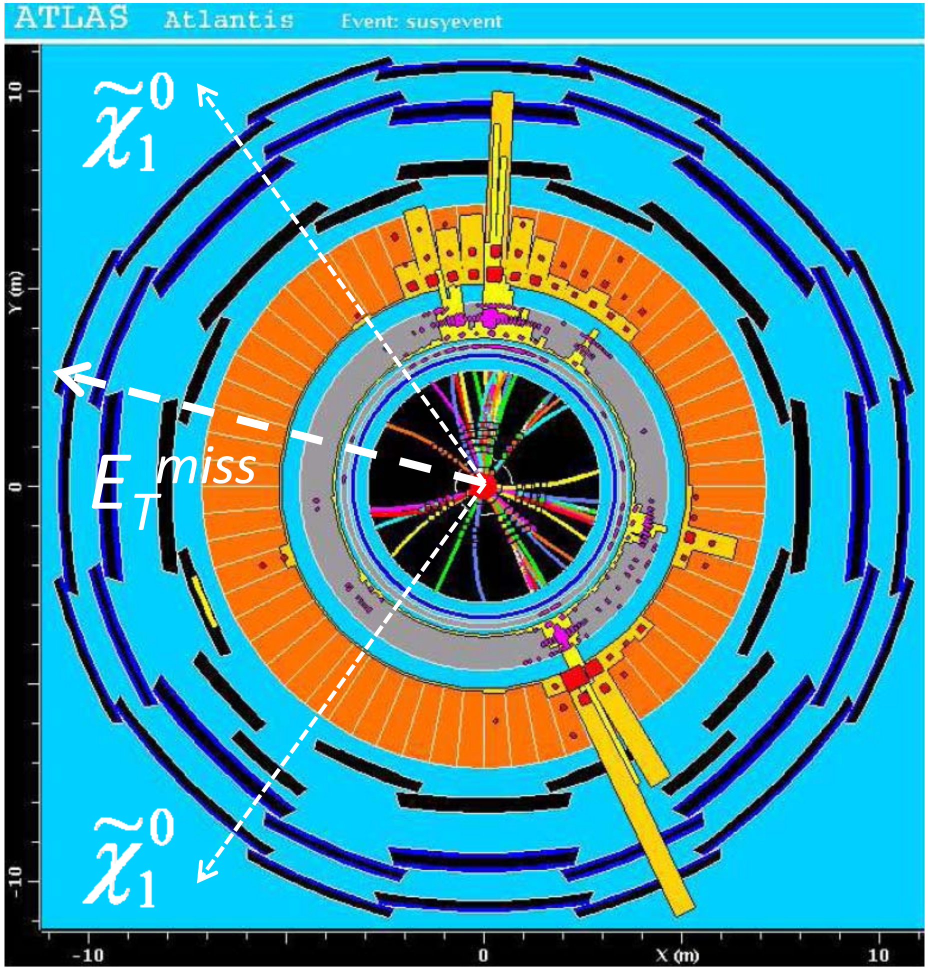
Why E_T? In proton-proton collisions, Ez is not balanced (proton parton densities) so only look at (x,y) components. These should average to 0 for events with no intrinsic E_T^{miss}.



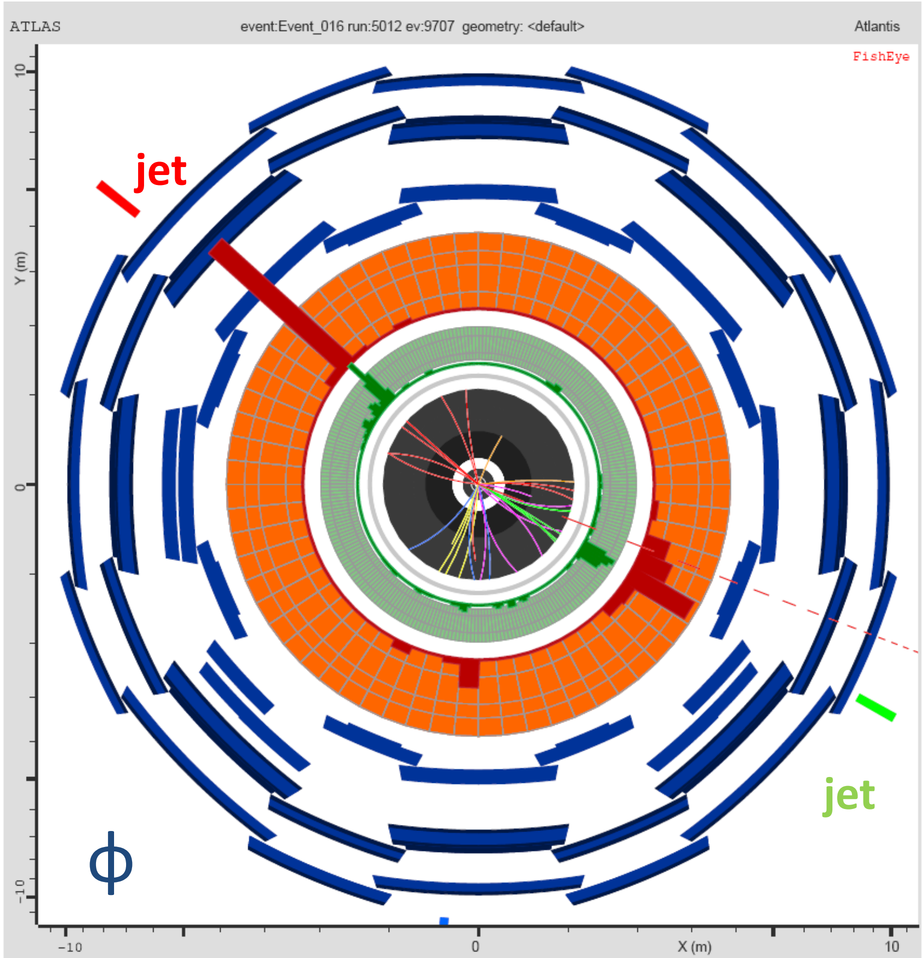


Example Topologies: SUSY vs QCD

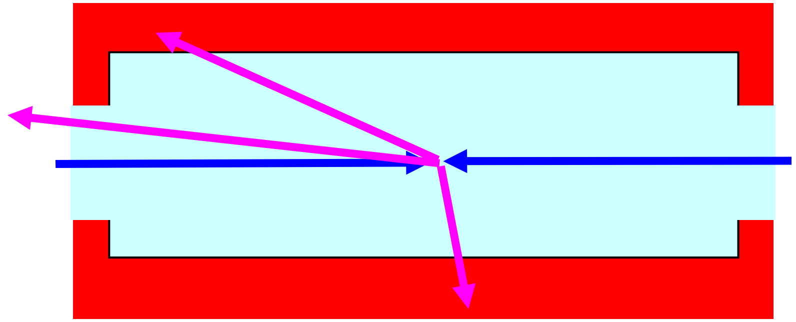
SUSY: $E_T^{miss} > 100$ GeV



QCD: jets, low E_T^{miss}



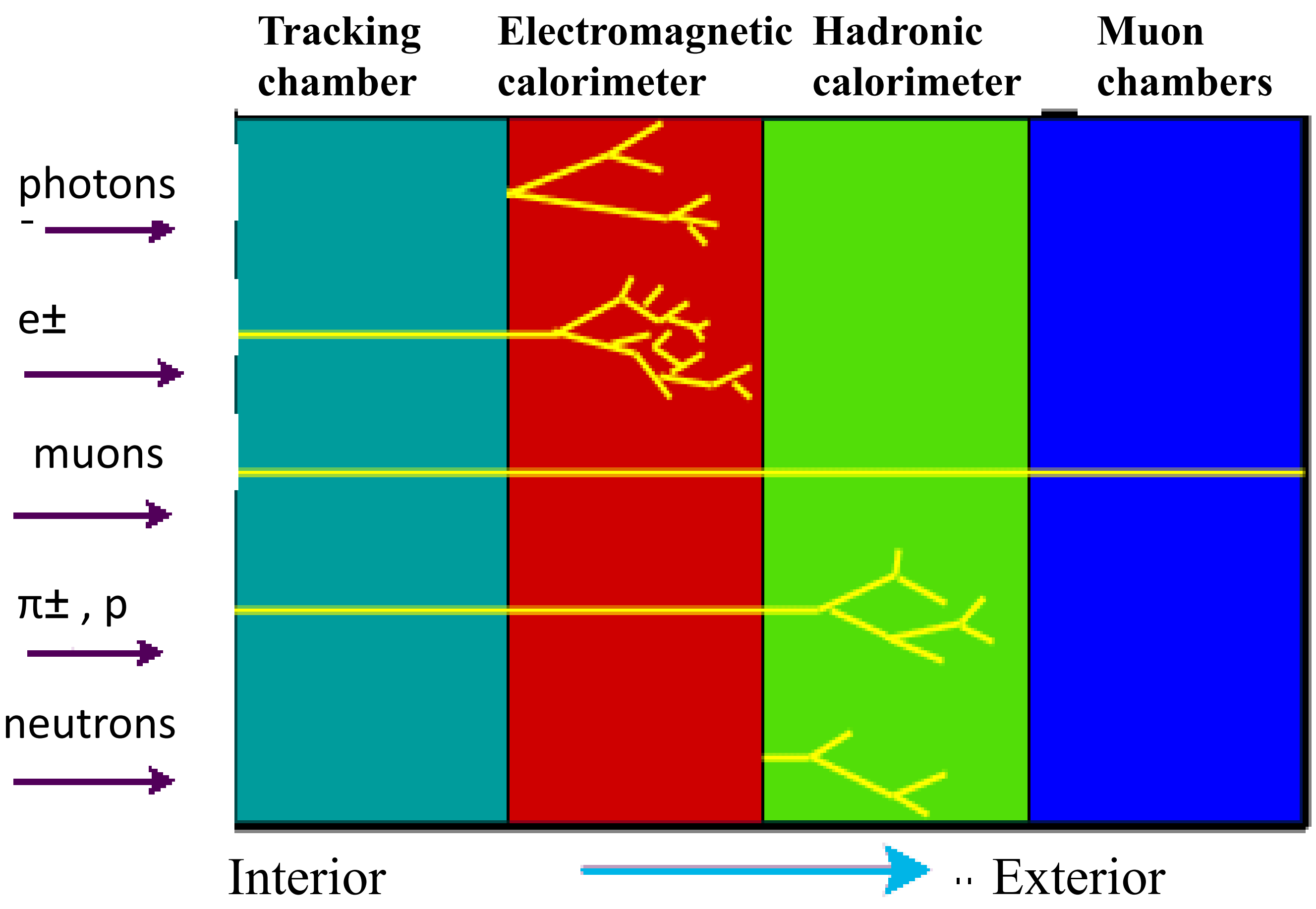
Measuring E_T^{miss}



- Measuring E_T^{miss} is hard
  - Energy sum of all objects in event
    - Jets, electrons, muons, taus, …
  - Detectors not perfect
    - Holes for detector along beamline
    - Holes and cracks for cables and services
- Many sources of “fake” E_T^{miss}
  - Mis-measured jets, fluctuations, resolution, etc.
  - Electronics noise
  - Dead / un-instrumented regions of detector
  - Punch-through
  - Physics (minimum bias, jets) overlap with other backgrounds
    - Cosmic ray muons undergoing hard bremsstrahlung
    - Beam-halo, other machine background
- Events with real E_T^{miss} (Leptonic decays (ν))

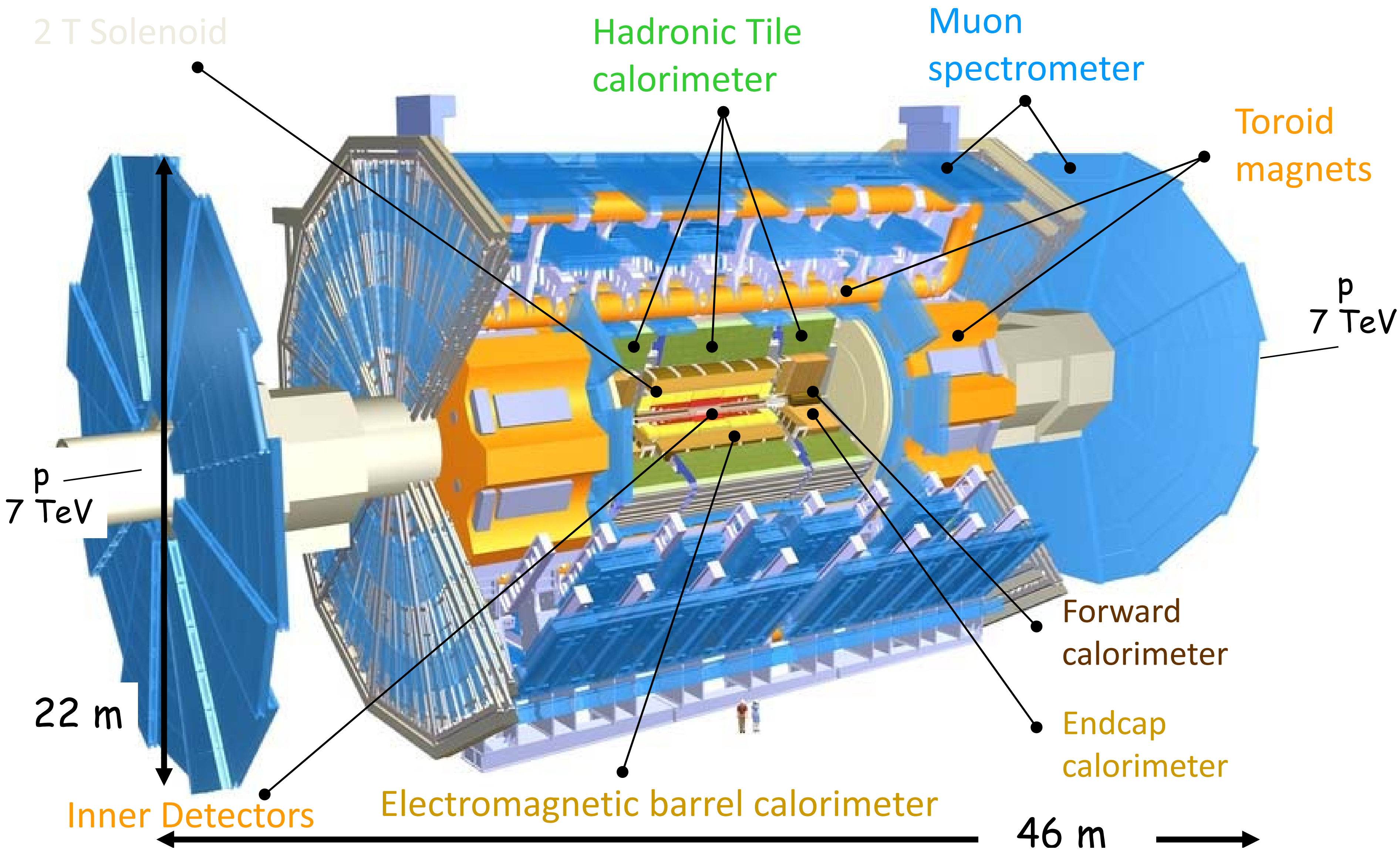
Measuring E_T^{miss} with the ATLAS Detector

Basic Detector Components



“Hadros” = Greek for “strong”

ATLAS (A Toroidal LHC ApparatuS)

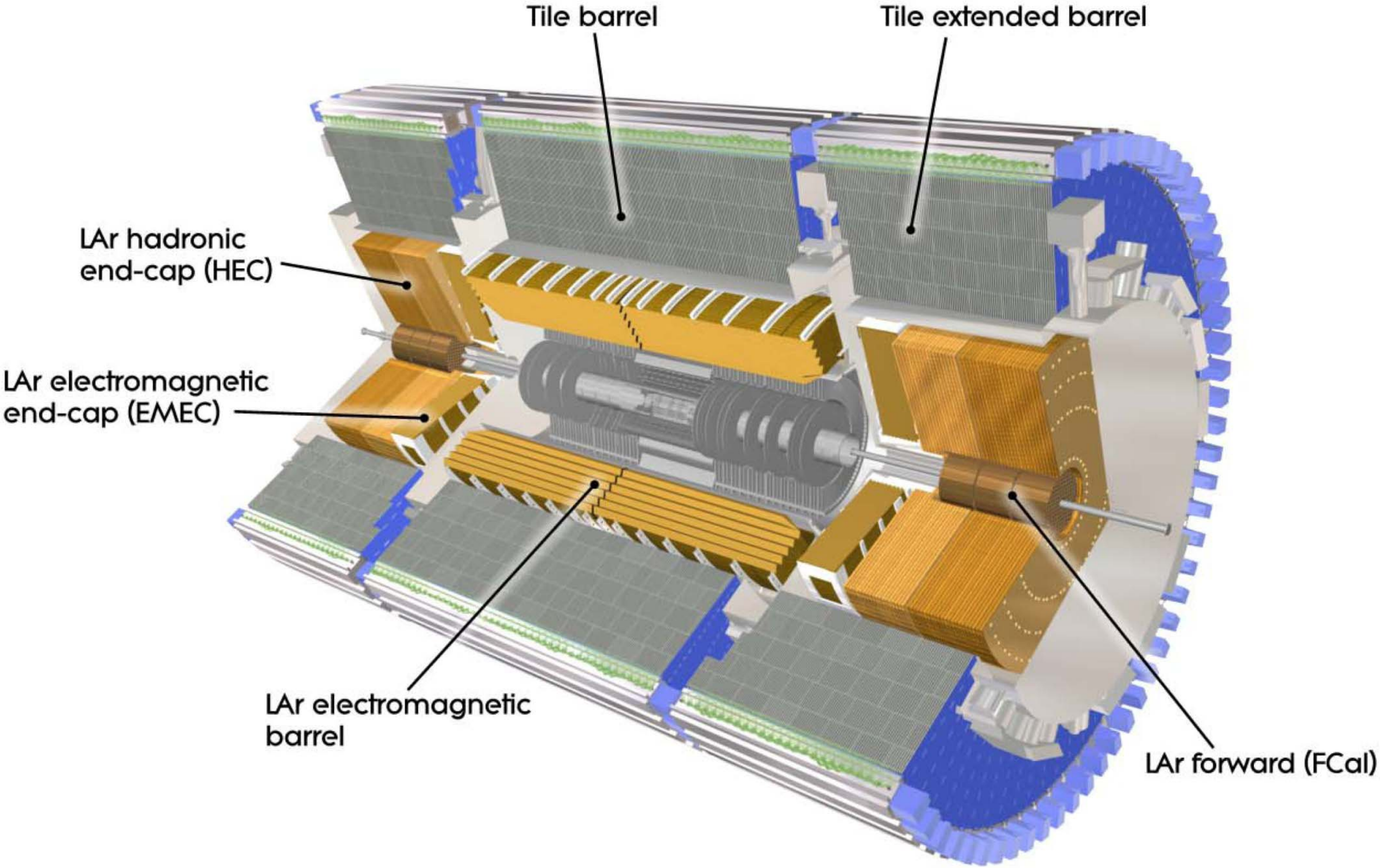


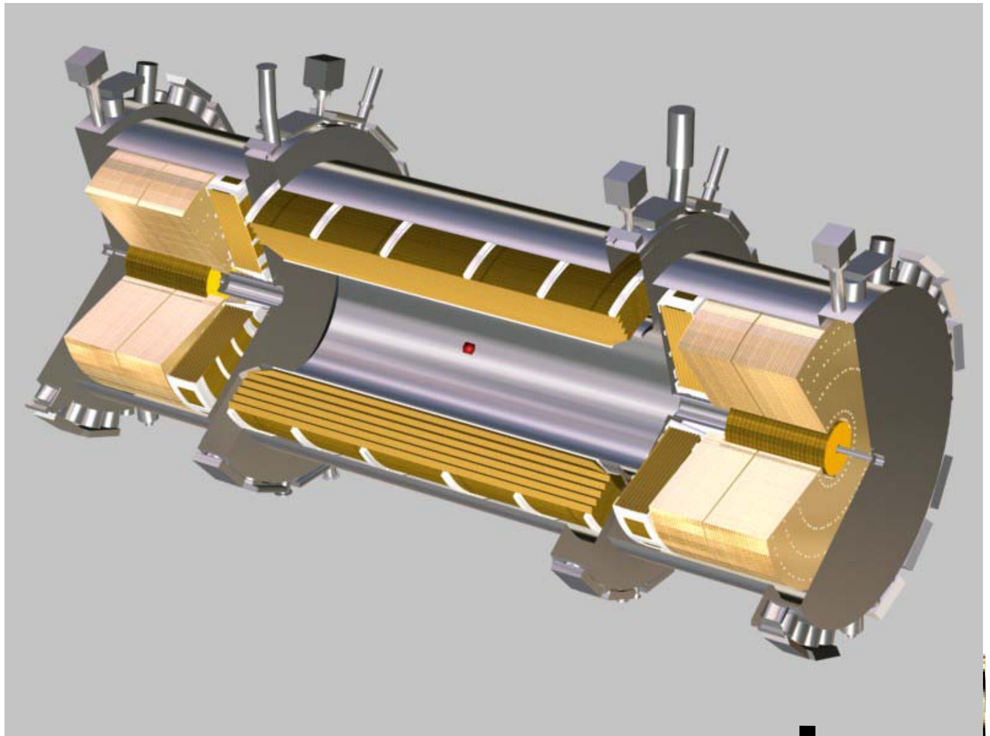
Total mass ~ 7000 tonnes, as much steel as the Eiffel tower
100 million readout channels (100 Megapixel camera), over 3000 km cables

ATLAS Design Characteristics

- High resolution and acceptance for electrons and photons
  - High granularity LAr calorimeter with longitudinal sampling
  - Transition Radiation Tracker (TRT) detector.
  - Good two-photon separation (important for Higgs→2 photons).
- Hermetic calorimeters (full coverage) for high resolution measurements of missing ET and E(jet).
  - Down to $\eta = 5$, $where\ \eta = -\log\{\tan(\theta/2)\}$
- High resolution and high acceptance MUON measurements, by measuring momentum
  - Air-Core Toroid (to avoid large energy loss)
- Good vertex resolution (with 3 layers of pixel)
  - Detection of secondary vertices, even in a high background environment
  - important for b and Tau tagging, in various searches for various Higgs production modes
- Electronics readout at 40 MHz LHC bunch crossing rate

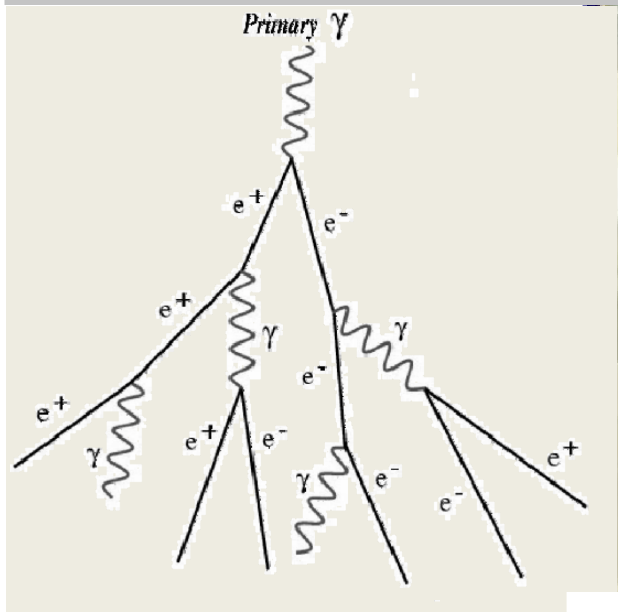
ATLAS Calorimetry

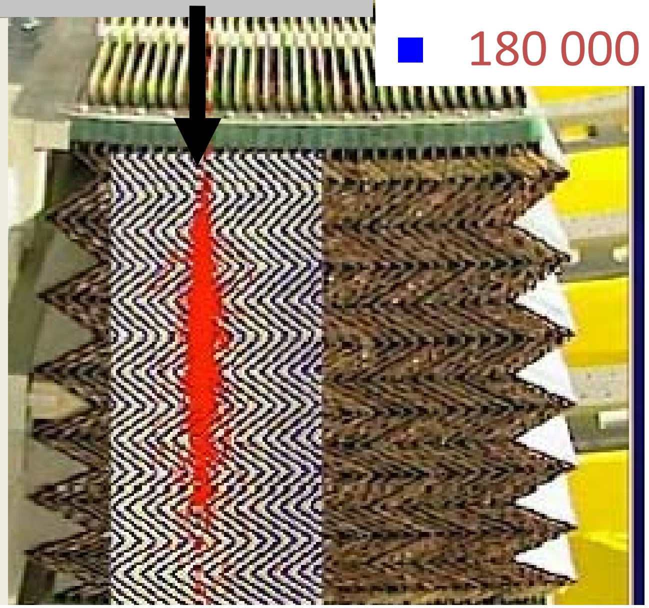




Liquid Argon EM Calorimeter

- Electron / photon identification
- Lead absorber initiates shower
- Particles ionize liquid Argon,
- High Voltage between plates cause ions and electrons to drift
- Collected charge is proportional to energy of incident particle
- 180 000 readout channels
  - Dead channels < 0.5%





$|\eta| < 3:$

$\sigma(E)/E$

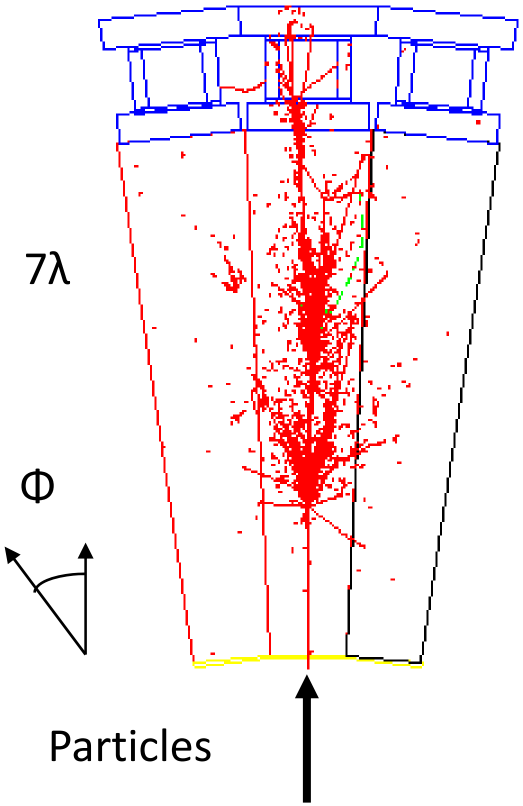
$\sim 10\%/\sqrt{E} \oplus 0.7\% \oplus 0.2/E$

'accordion' geometry

> 22 X_0

Hadronic Tile Calorimeter (TileCal)

Measure light produced by charged particles in plastic scintillator.



PMT

WLS fiber

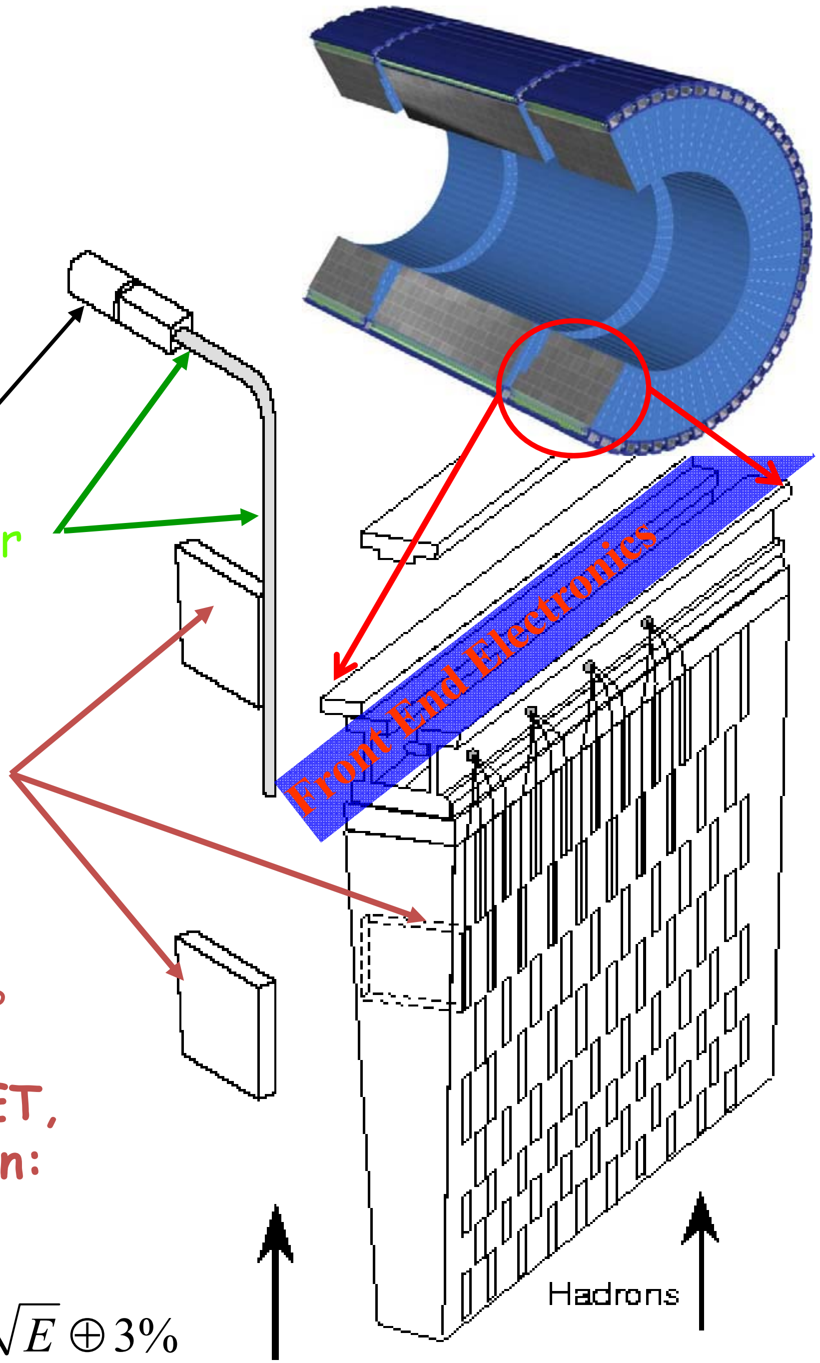
Plastic scintillator inside steel absorber structure

10 000 channels
Dead channels < 1%

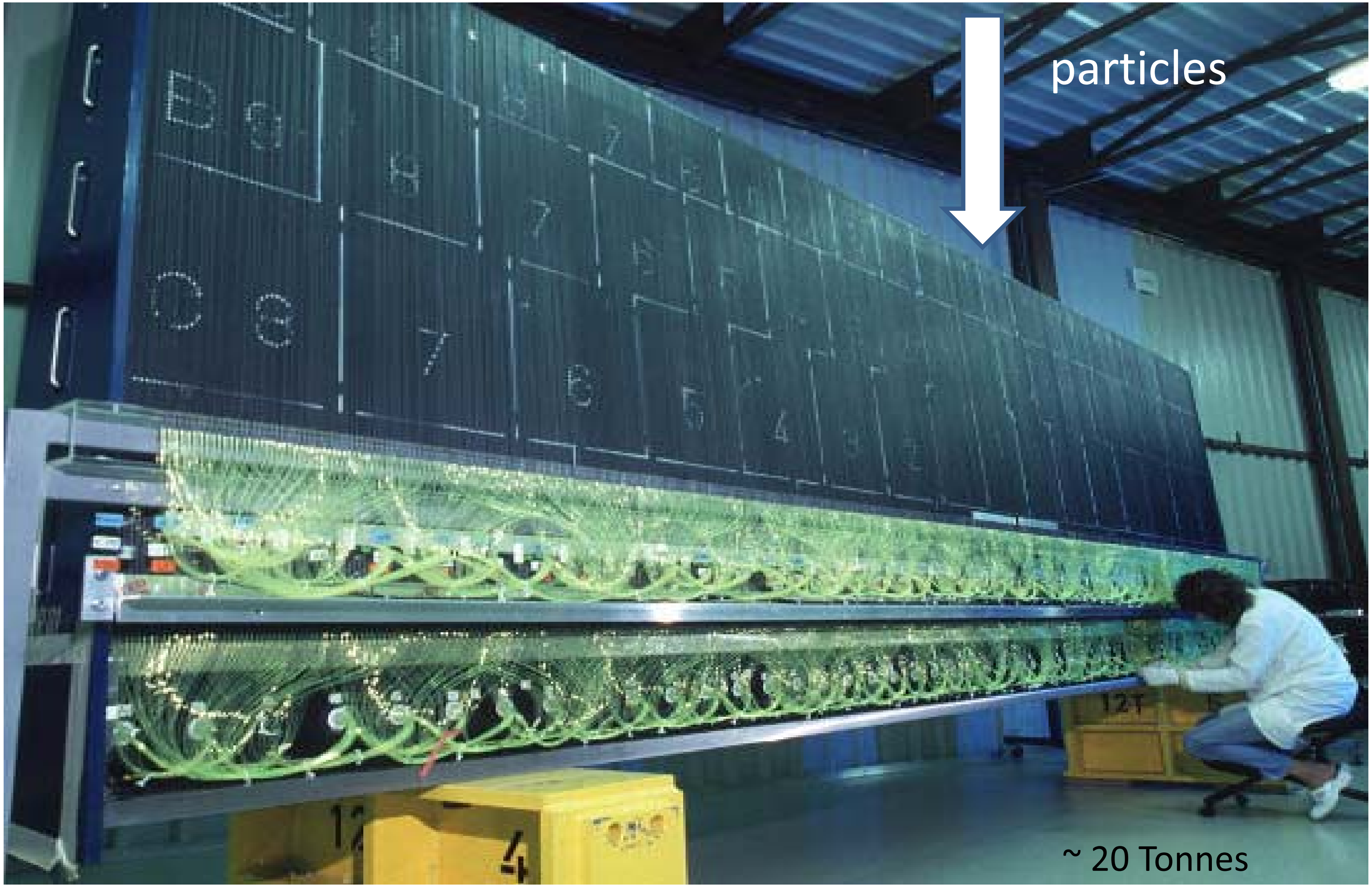
Jets and Missing ET, Combined resolution:

$|\eta| < 3: \ central$

$$\sigma(E)/E \sim 50\%/\sqrt{E} \oplus 3\%$$

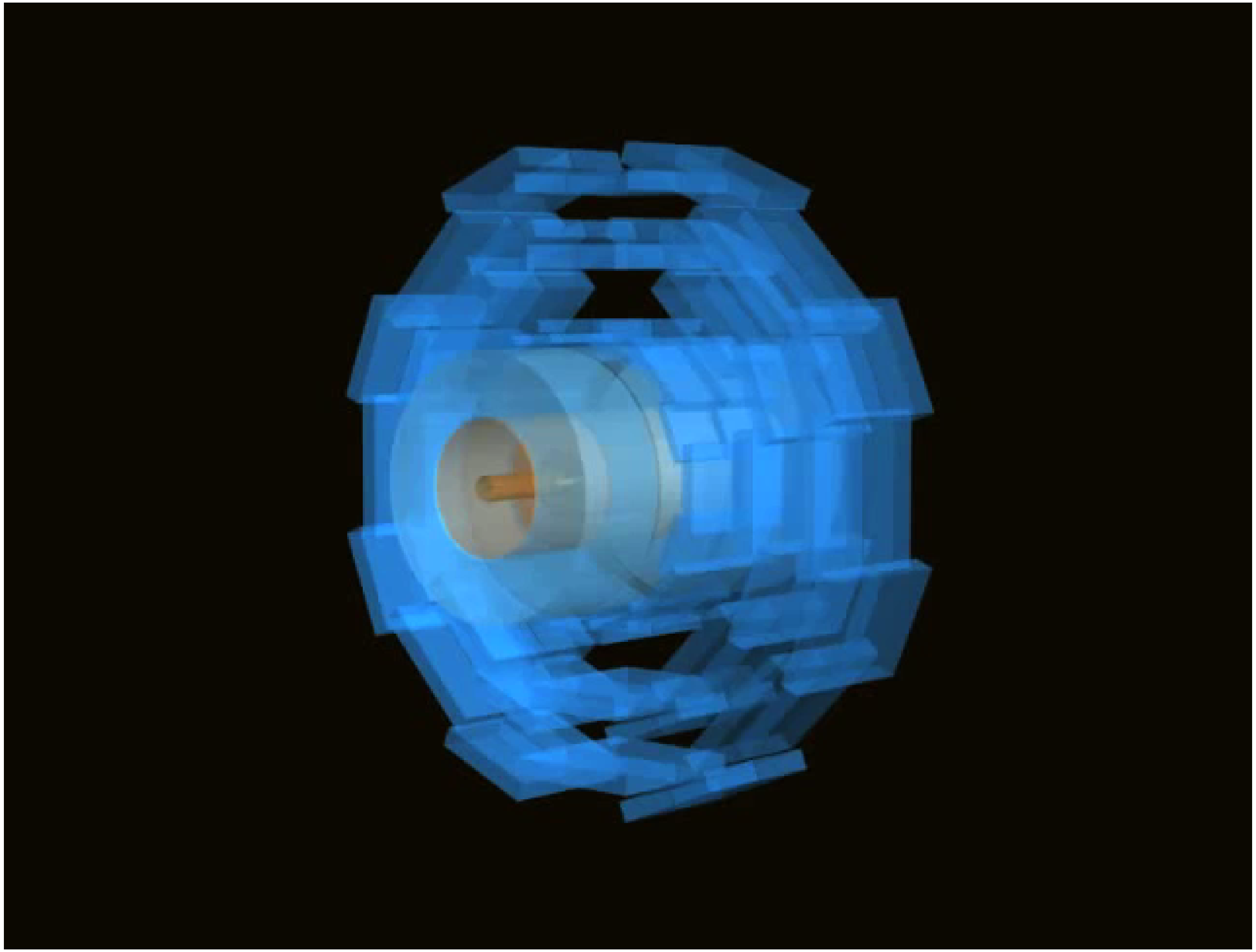


One TileCal Barrel Module

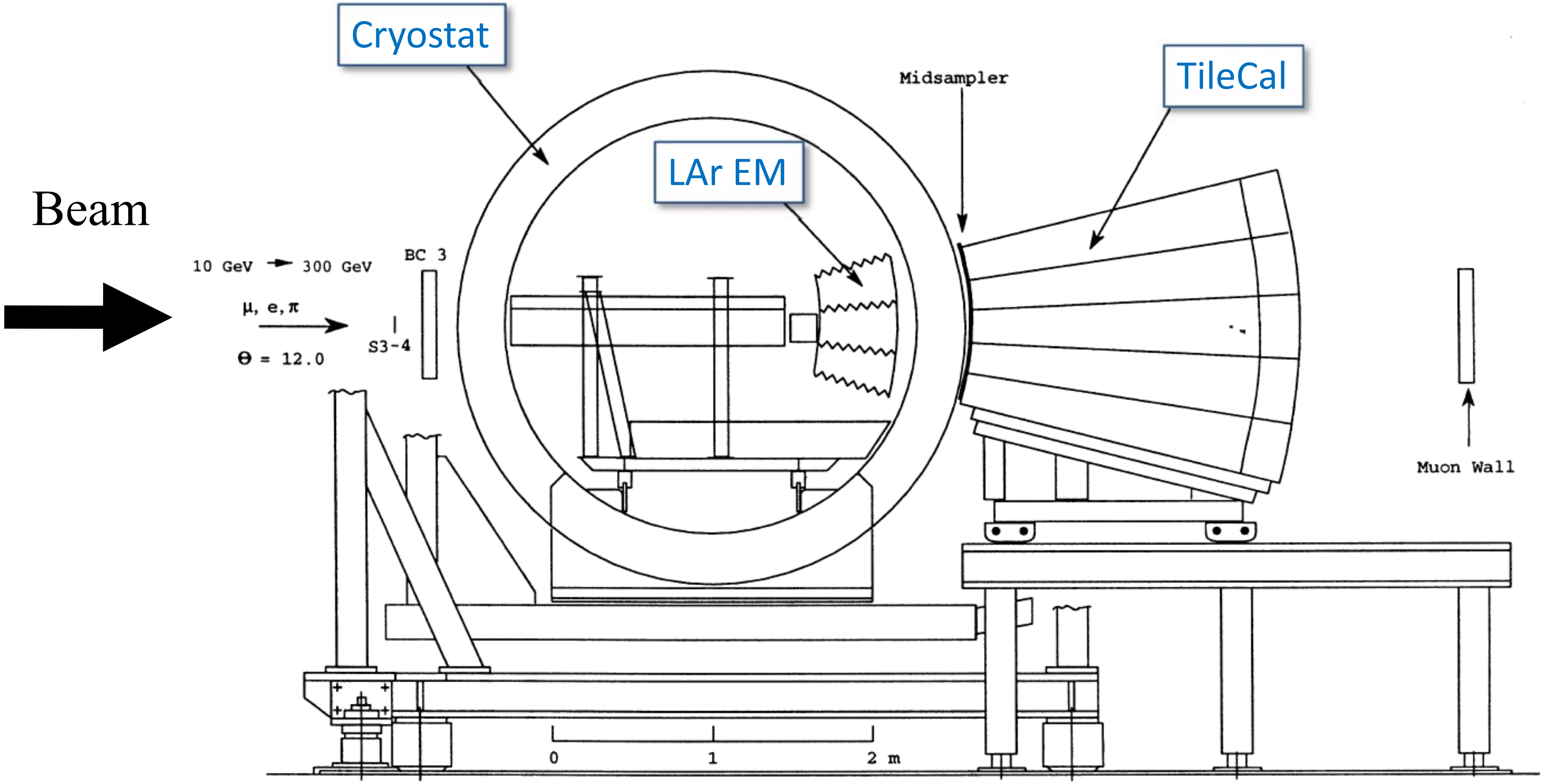


3 Longitudinal samples: 1.8 + 4 +1.4 λ

Video of Particle Interactions in ATLAS



Combined Calorimeter Performance: Barrel Calorimeter Testbeam

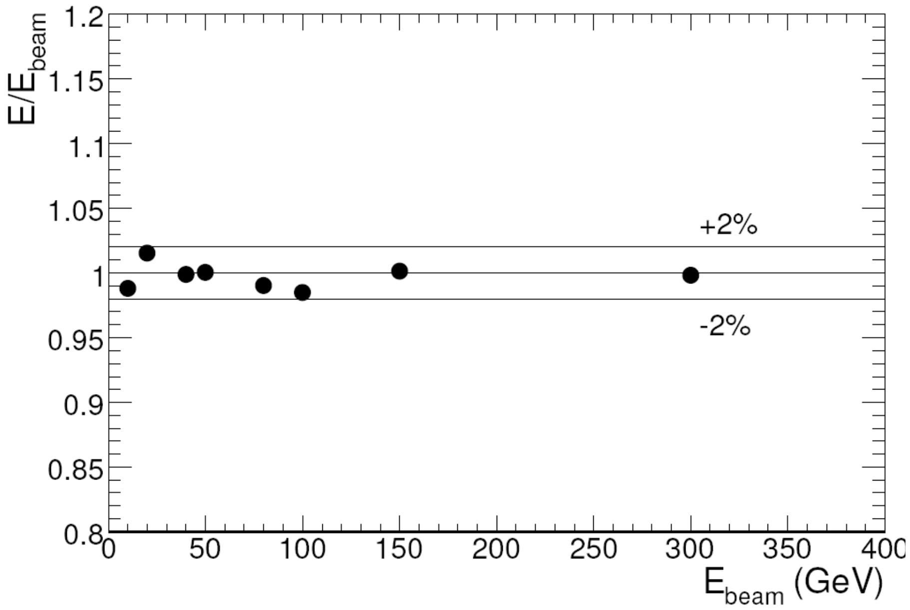


Calibrate with particle beams of known energy up to 300 GeV.

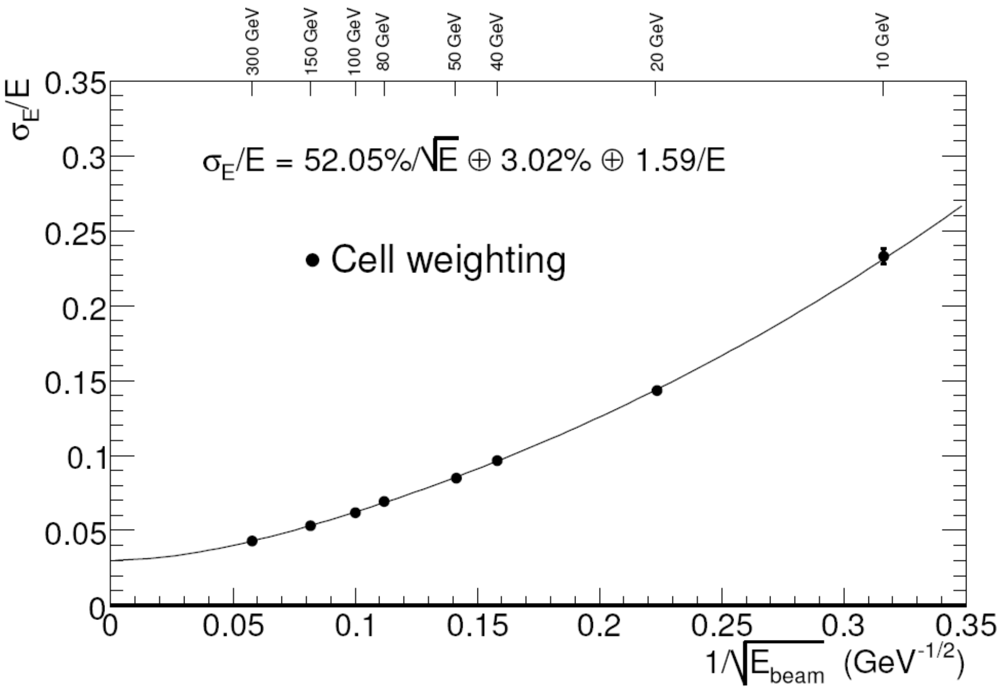
Nuclear Instruments and Methods in Physics Research A 449 (2000) 461–477

Combined Calorimeter Performance

Linearity

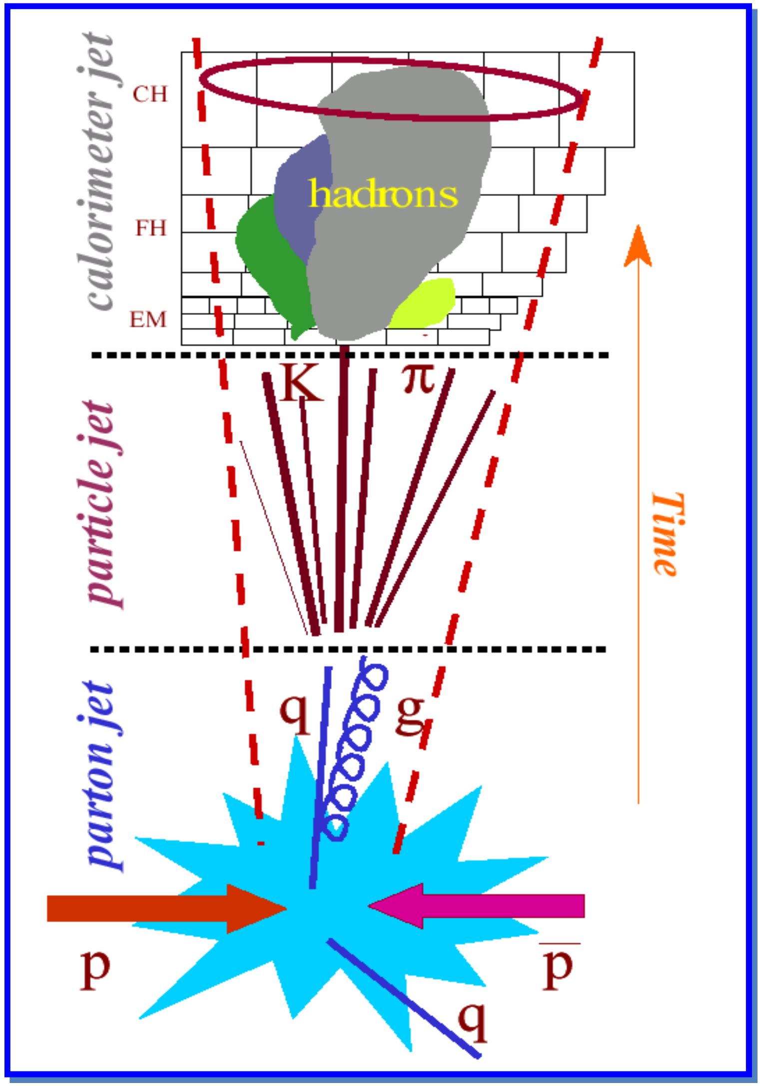


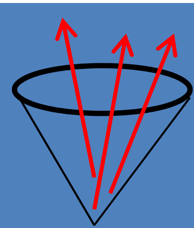
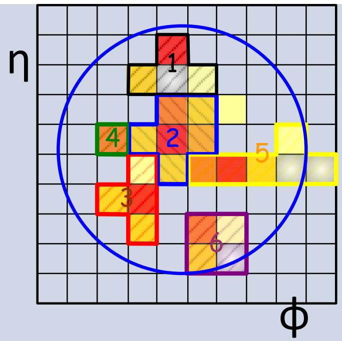
Resolution



Stochastic term: 52% (sampling fluctuations), dominant @ mid E
constant term 3% (non-uniformities, inter-calibration), dominant @ high E
noise term 1.6% (electronics), dominant @ low E

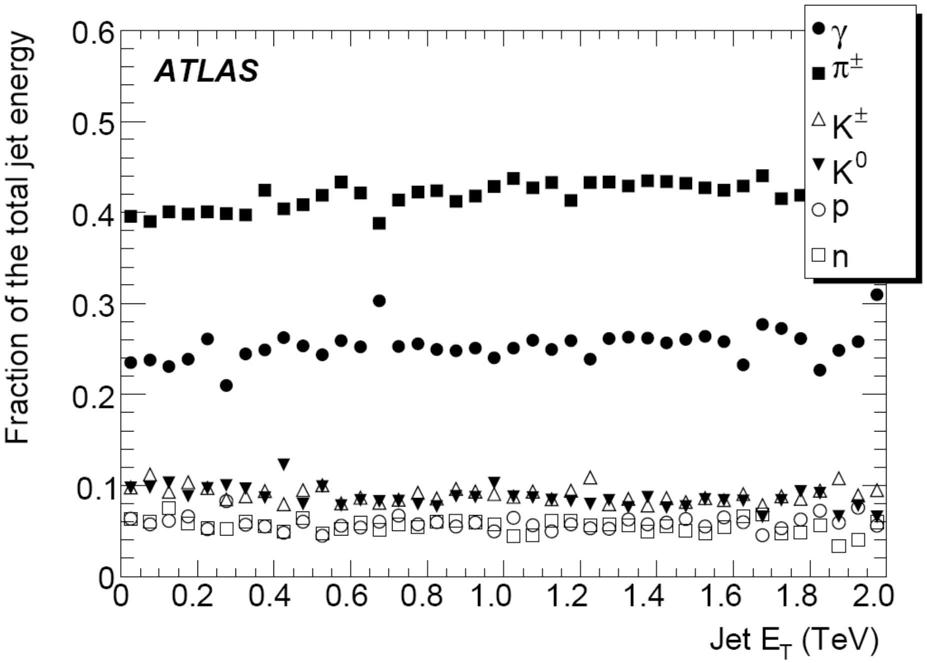
Reminder: Jets



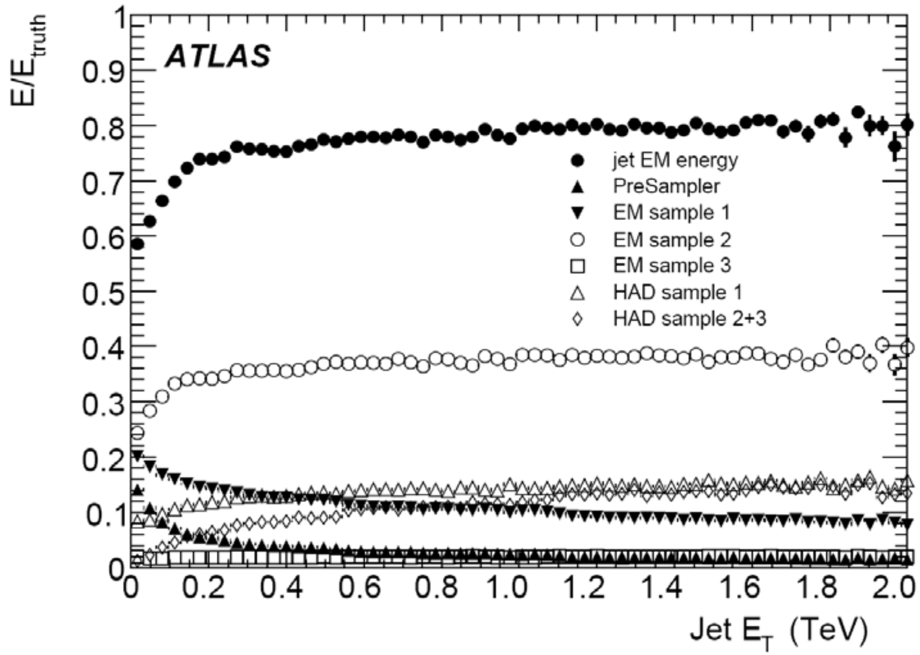
Cone jets	 Radius $R = (\Delta\eta^2+\Delta\phi^2)^{1/2}$	Maximizes energy inside a cone of (η,ϕ) (R=0.4 for SUSY)
Cluster		Clusters nearest neighbours (3D clustering in ATLAS)

Both cone-jets and cluster-jets used in ATLAS (other algorithms also studied).

Jet: Composition and Energy Deposits LAr/TileCal



Jet energy carried by particle types
e.g. 40% $\pi^{\pm}$, 25% γ



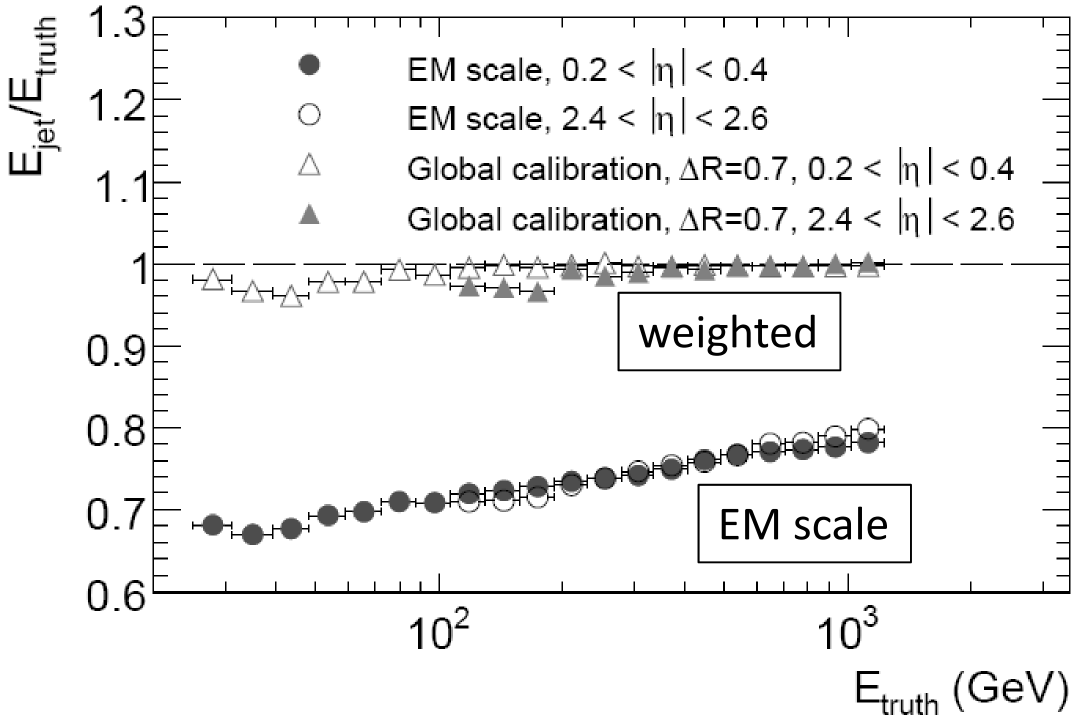
60-80% of true jet energy in LAr EM calorimeter, for $|\eta| < 0.7$ central region

Calorimeter Calibration

- LAr and TileCal non-compensating calorimeters (e/h ≠ 1)
- Must apply a calibration scheme
- Example: cell weighting (CDHS, H1)
- Electromagnetic showers: high energy density, no weighting
- Hadronic showers: lower energy density, weight to scale up energy

$$E_{jet} = \sum_{cells} E_i \times w_i(\rho_i)$$

$$\rho_i = E_i / V_i$$

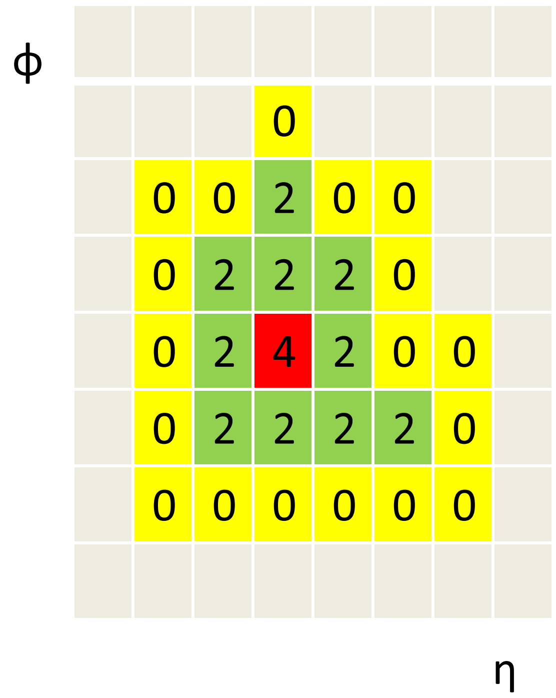


Jet response before and after cell weighting

Details of Calculating E_T^{miss}

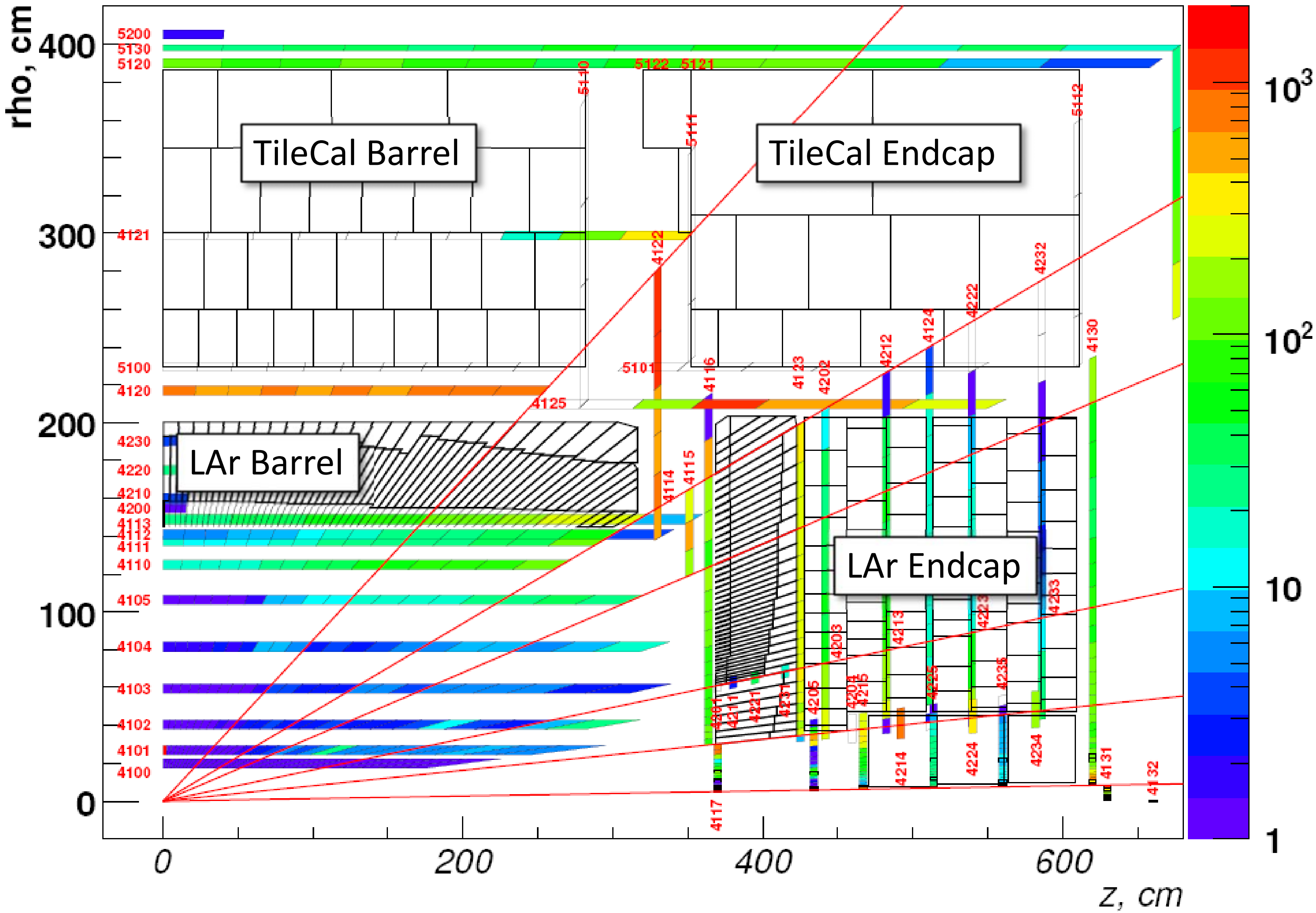
Calculating E_T^{miss}

- Calorimeter electronics noise suppression, two methods in ATLAS
  - Cell-based: sum all cells above 2σ noise
  - Cluster based: 3-dimensional clusters for cells above noise threshold (4σ seed, 2σ neighbours, 0 σ surrounding cells)

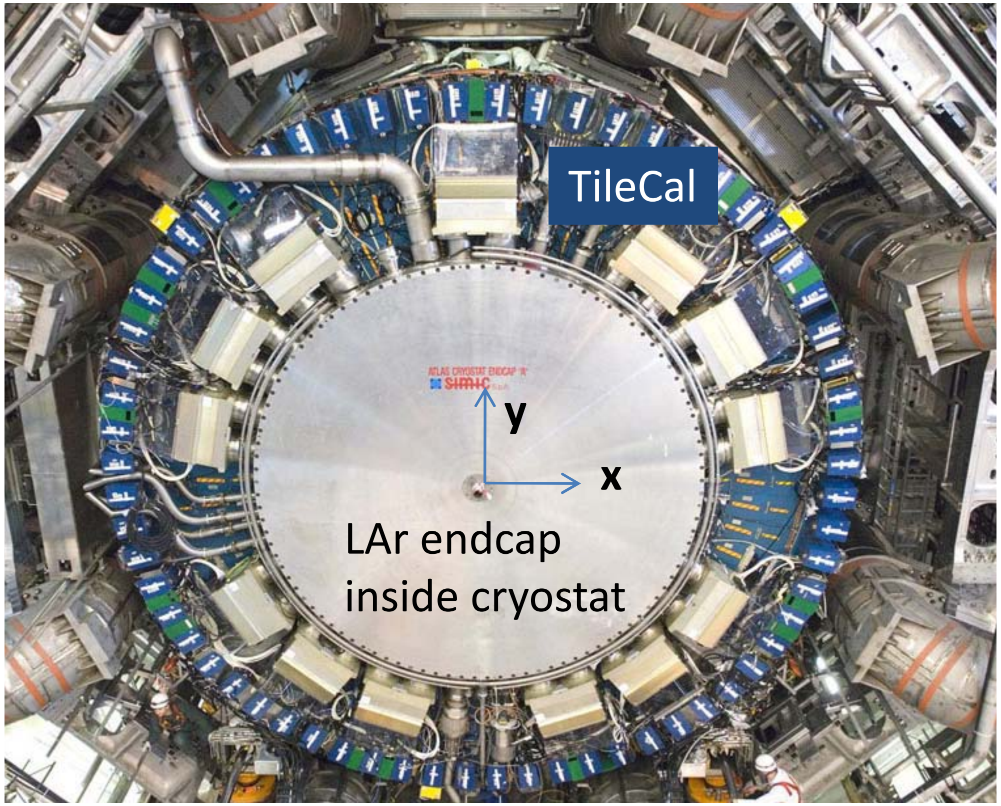


- Resulting E_T^{miss} is summed either from all cells above noise or all cells from 'Topoclusters'

Calorimeter Cells



Cryostat correction



- Hadronic showers can lose energy in cryostat between LAr & TileCal
  - Thickness of LAr barrel electromagnetic calorimeter and TileCal is about 0.5 interaction lengths
- Apply correction:

$$E_{jet}^{cryo} = w^{cryo}\sqrt{E_{EM3} \times E_{HAD}}$$

All reconstructed jets are summed in the event to form the (x,y) components of energy lost in the cryostat.

EEM3 = jet energies in 3rd layer of EM calorimeter

EHAD = energy in first layer of hadronic calorimeter

w^{cryo} = a calibration weight factor (typically 0.5)

Overall cryostat correction can be ~ 5% for jets above 500 GeV.

Refined E_T^{miss}

- Final step is the refinement of calibrated cells associated with each high p_T object
- Use calibrated cells from
  - electrons
  - photons
  - τ
  - Jets
  - Muons
  - Unused cells in topoclusters

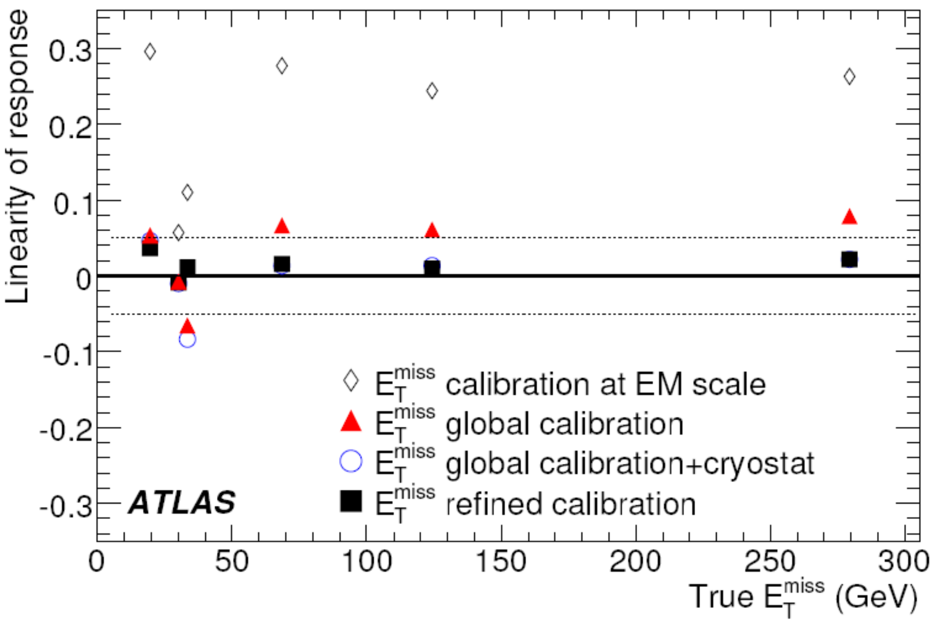
$$E_{x,y}^{ref} = -\left(E_{x,y}^{\gamma/e} + E_{x,y}^{\tau} + E_{x,y}^{(b)\,jet} + E_{x,y}^{muon} + E_{x,y}^{out}\right)$$

- Including refined calorimeter term:

$$E_{x,y}^{Final} = E_{x,y}^{ref} + E_{x,y}^{Cryo} + E_{x,y}^{Muon}$$

E_T^{miss} Performance

Linearity



Linearity tested with Monte Carlo (MC) simulations with true average E_T^{miss}:

20 GeV: Z→ττ

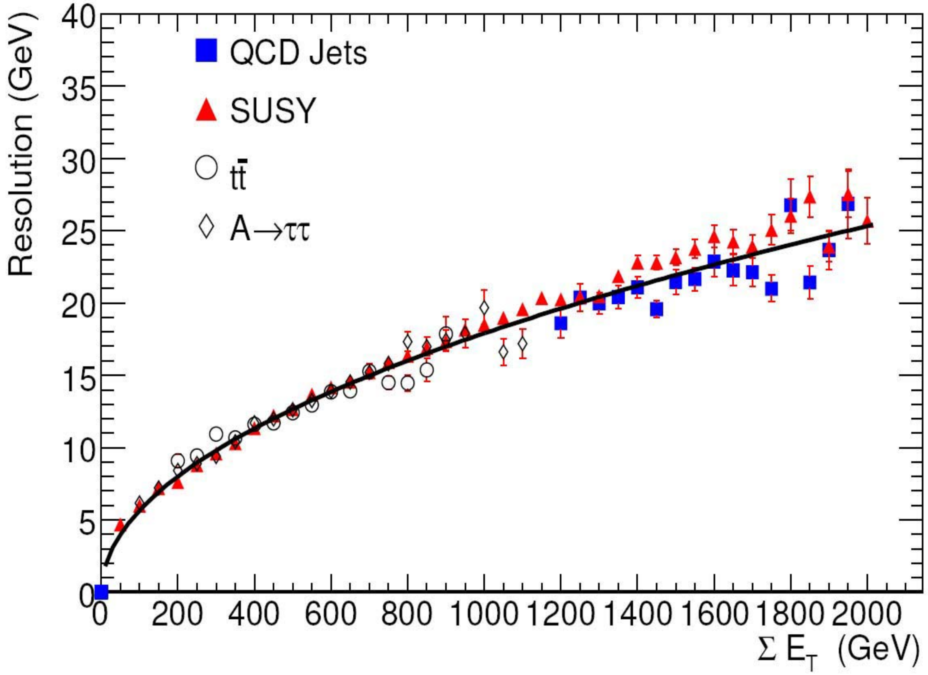
35 GeV: W → eν, μν

68 GeV: tt → semi-leptonic

124 GeV: A → ττ

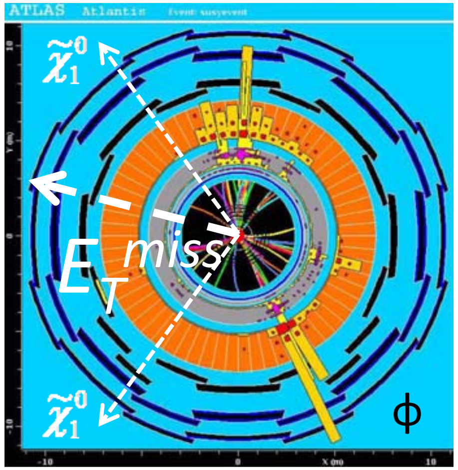
280 GeV: SUSY (1 TeV)

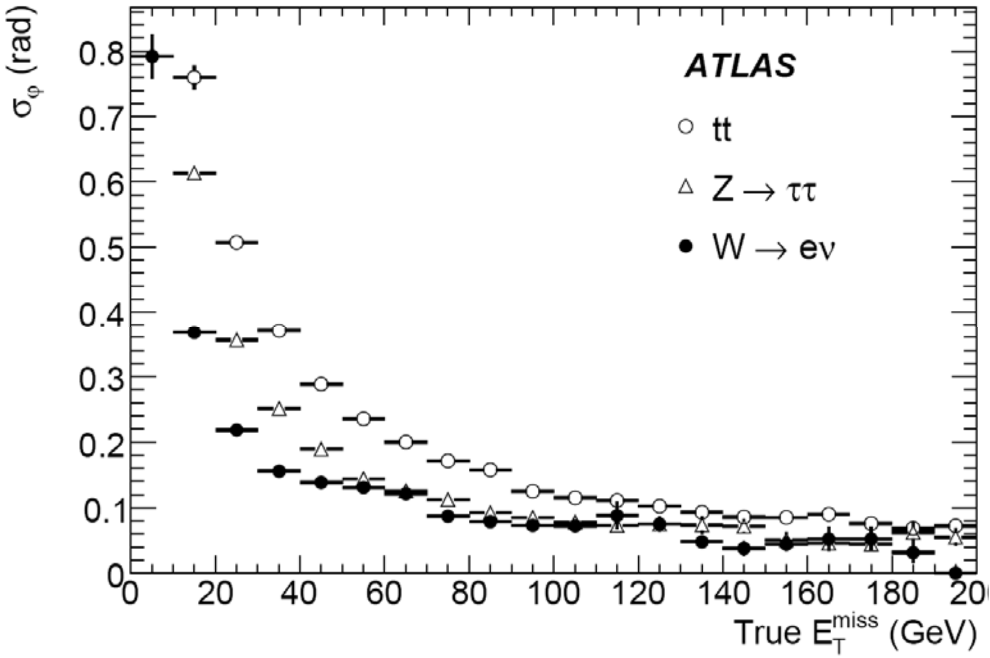
Resolution:

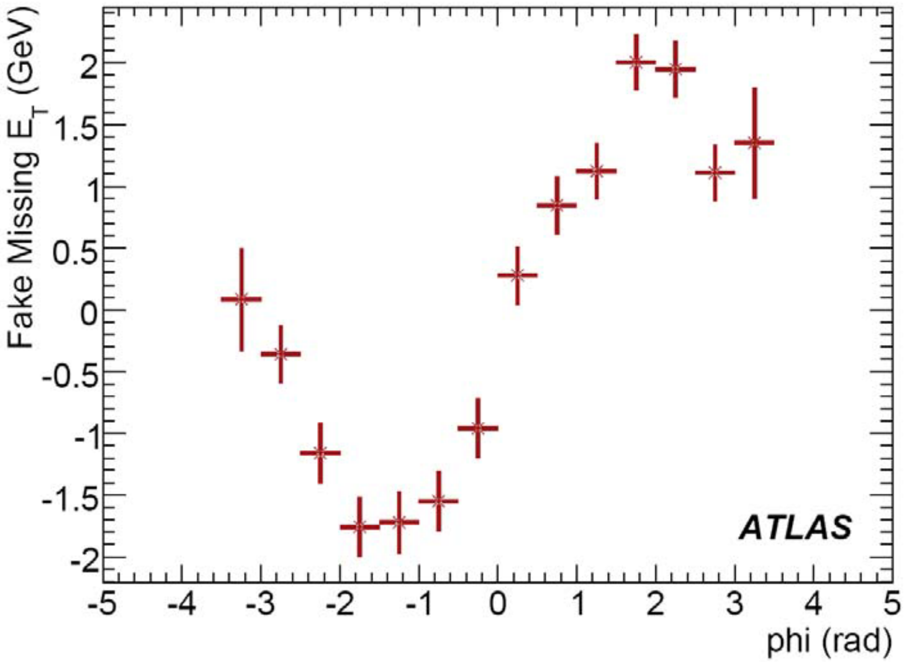


$$\sigma = 0.57 \Big/ \sqrt{\sum E_T}$$

Resolution on $\phi(E_T^{miss})$







Accuracy of the measurement of the E_T^{miss} vector in ϕ as a function of true E_T^{miss} .

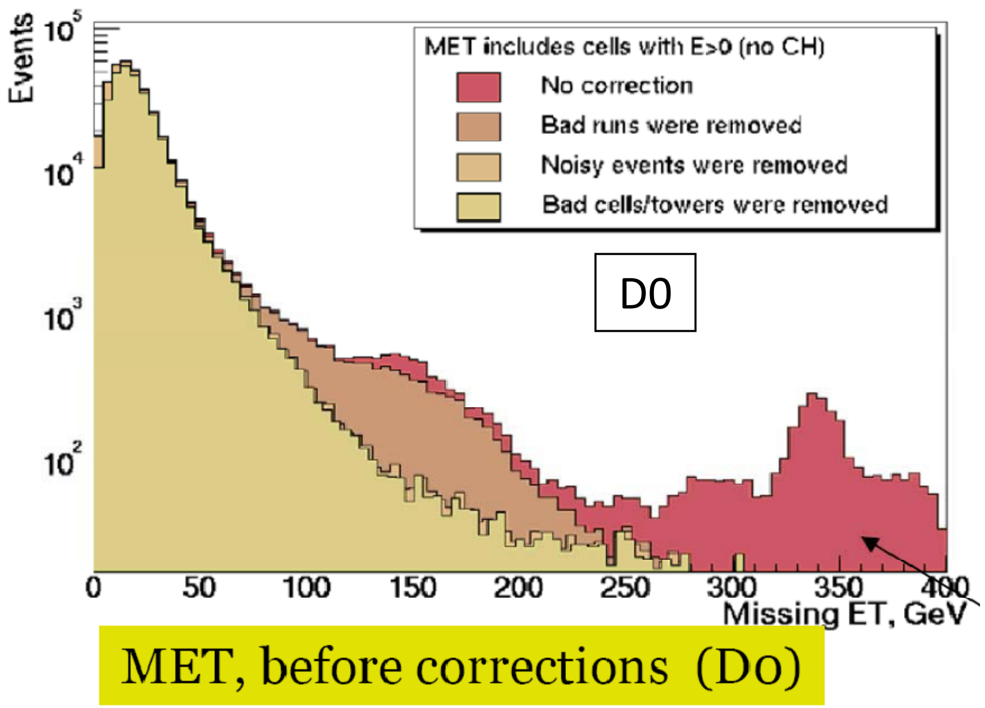
Extra dead material can introduce a modulation in ϕ (E_T^{miss}).

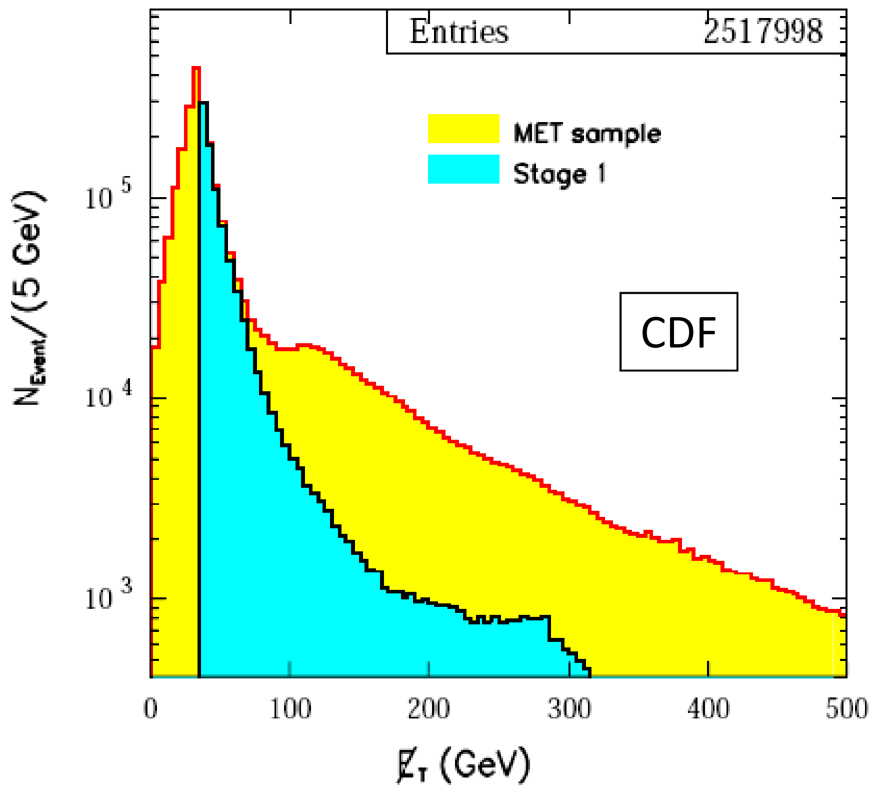
Challenges to Measuring E_T^{miss}

‘Fake’ E_T^{miss}

- Mismeasurements
  - Muons
  - Jets
- Dead material
- Shower Leakage
- Noise (coherent)
- Backgrounds
  - Cosmic rays
  - Beam halo, beam gas

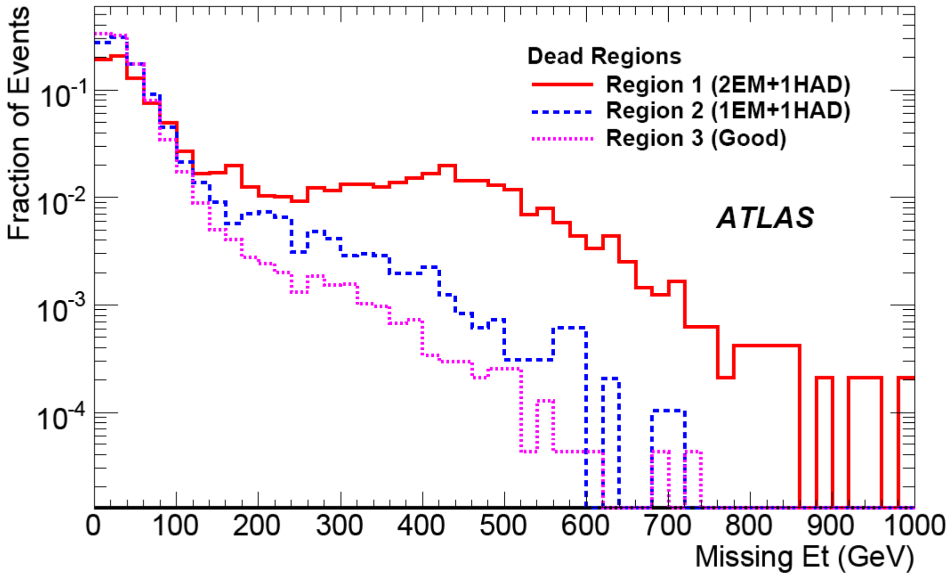
E_T^{miss} From Previous Experiments

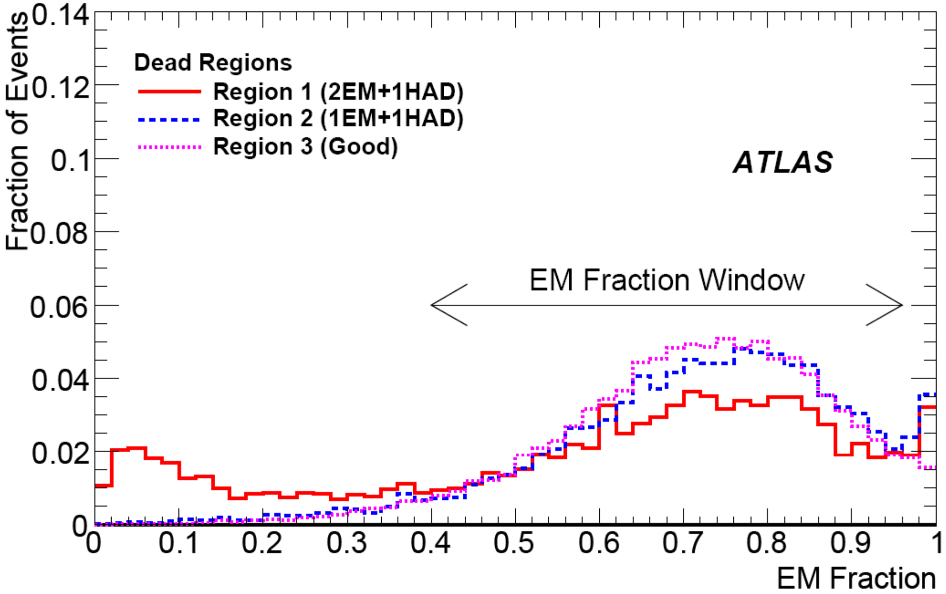




E_T^{miss} from Tevatron experiments before cleaning cuts

Fake E_T^{miss} :Dead Detector Regions



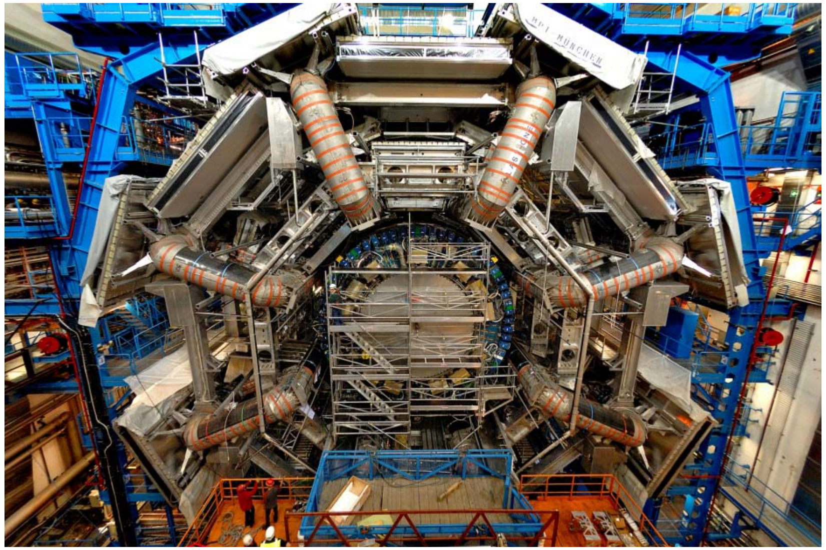


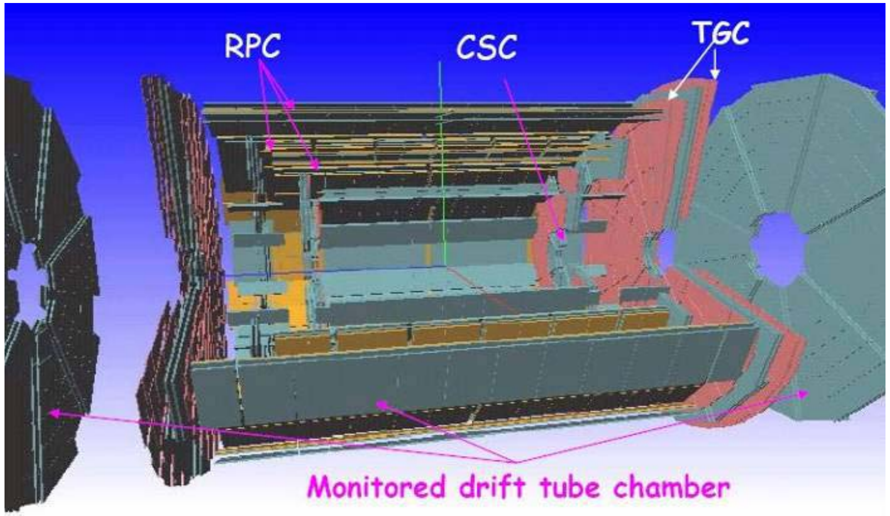
- No detector is perfect:
  - High voltage trips, low voltage power supplies (LVPS), front-end electronics readout, …
- Simulate dead regions in Monte Carlo samples, study effect on E_T^{miss}
  - Here LAr readout failures simulated (2/58 LVPS ~ 3.4% channels)
    - Successively kill 1 LVPS EM barrel, 1 LVPS barrel + hadronic endcap
- Recover by removing events with jets having low electromagnetic fraction

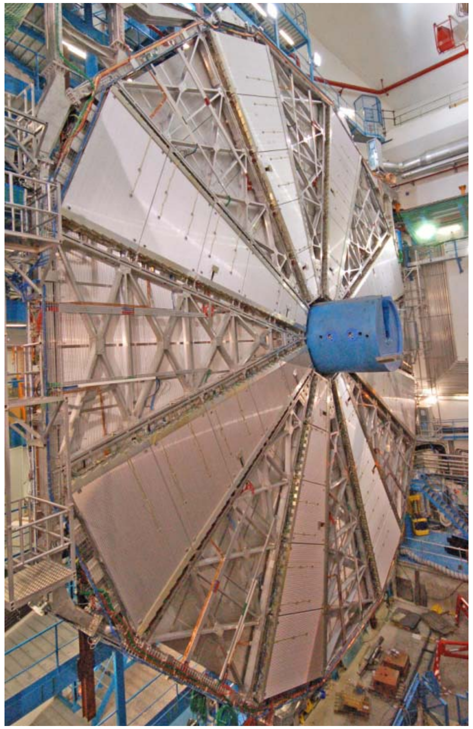
Muon Term

- Typically muons will be minimum ionizing particles and thus deposit only a small amount of their energy (few GeV) in the calorimeters
- Must correct for their momentum measured in the muon spectrometer
  - Otherwise this could generate 'fake' E_T^{miss}

ATLAS MUON Spectrometer fully installed and operational

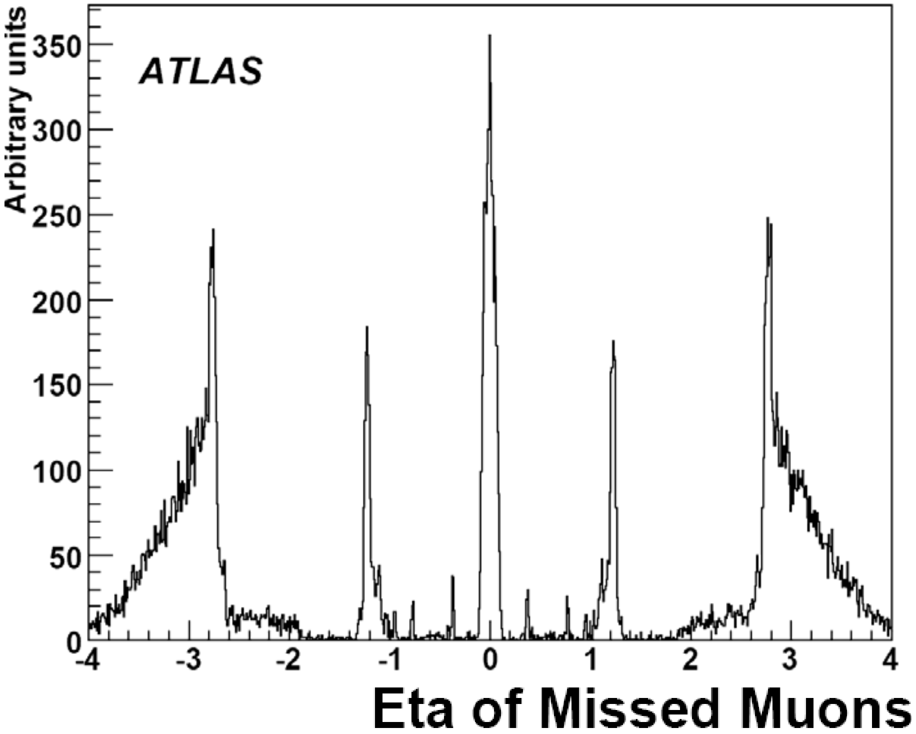


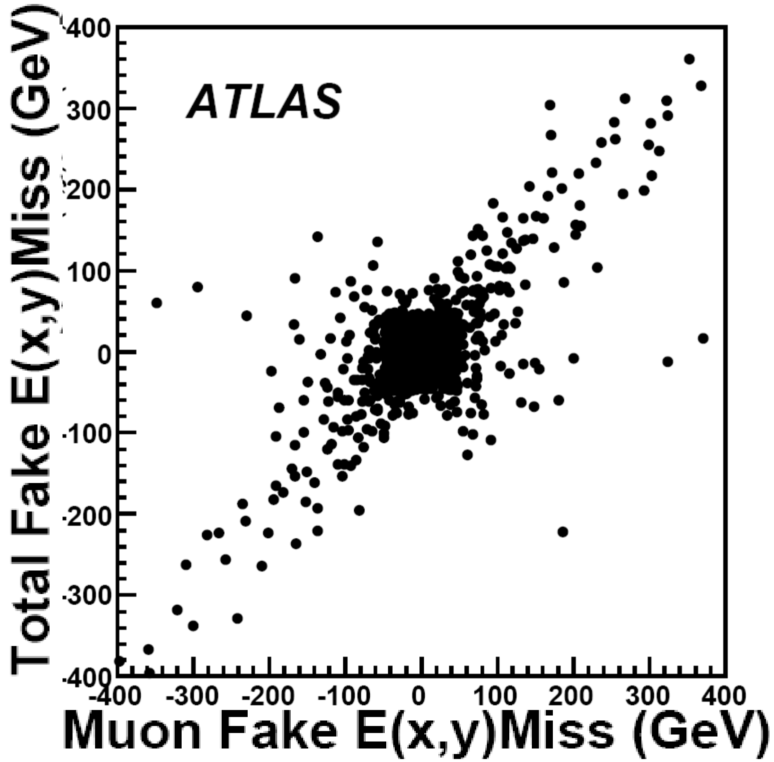




- 1.5 10E6 channels, all operational
- Resolution 10% at p_T= 1 TeV
- Identify resonances, provide muon trigger

Fake E_T^{miss} from Muons





η of true muons missed in reconstruction of Z→μμ MC sample.

η =0: Holes in muon spectrometer for cables, services to inner detector & calorimeter.

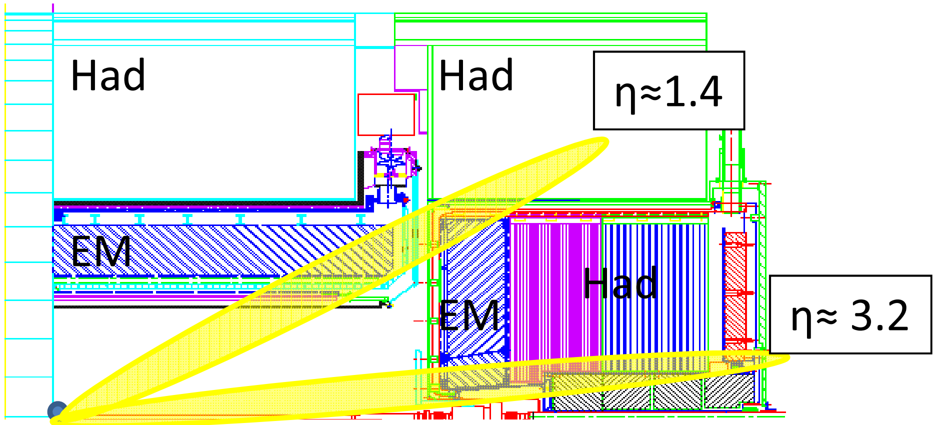
| η|>2.7: no muon coverage

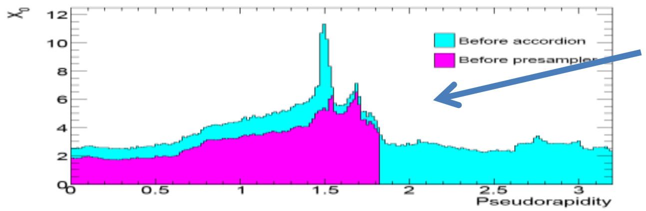
Fake $\mathbf{E_T^{miss}}$ from mis-reconstructed muons

$$\not{E}_{x,y}^{Fake} = \not{E}_{x,y} - \not{E}_{x,y}^{True}$$

$$\not{E}_{x,y}^{FakeMuon} = \not{E}_{x,y}^{Muon} - \not{E}_{x,y}^{MuonTrue}$$

Fake E_T^{miss} : QCD Jets

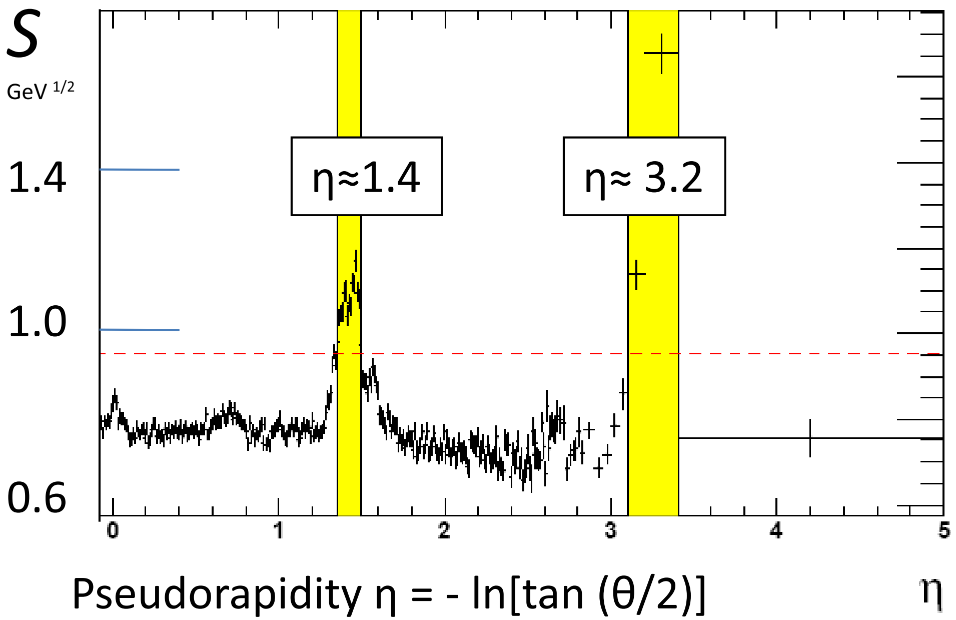




Material in front of EM calorimeter

ATLAS Fiducial Regions:

- Hadronic Calorimeters
  - TileCal: |η| < 1.7
  - Endcap: 1.5 < |η| < 3.2
  - Forward: 3.2 < |η| < 4.9
- Electromagnetic Calorimeters
  - Barrel: |η| < 1.4
  - Endcap: 1.375 < |η| < 3.2
- Total ~ 0.02 % to 0.2% dead cells
- "Crack" regions: η≈1.4, 3.2

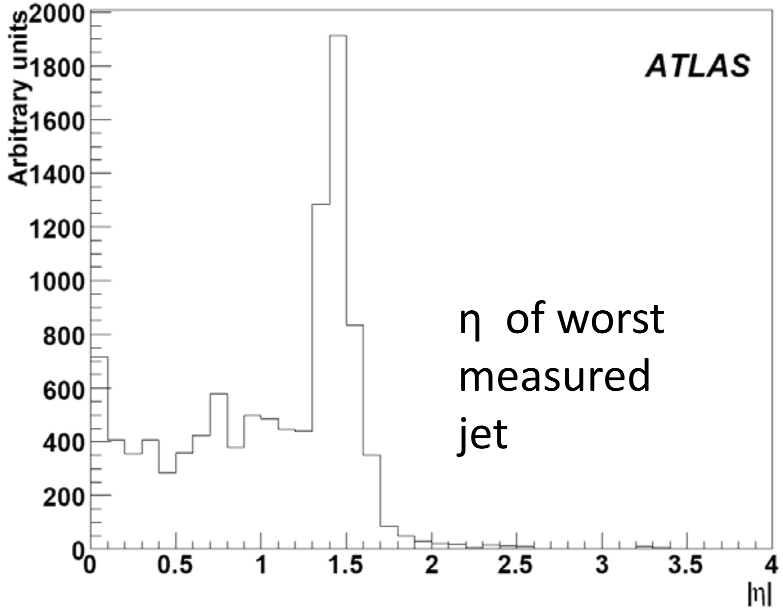


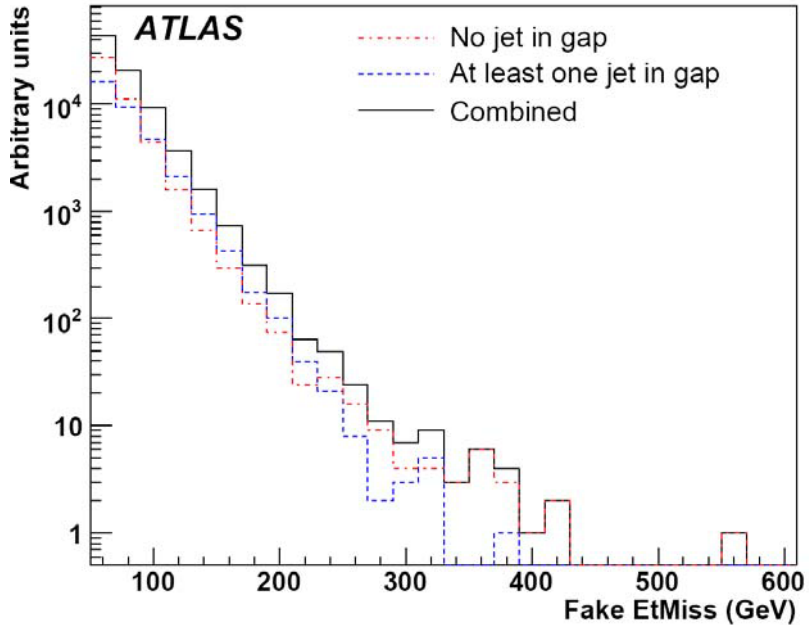
QCD jets can fake MET when falling in poorly-instrumented regions (yellow). Probe fiducial regions with simulated QCD dijet sample:

$$S = E_T^{miss} \Big/ \sqrt{\sum E_T}$$

Cleaning cuts:
Reject QCD events with a jet having S > 0.95 and P_T(Jet) > 40 GeV.

Fake E_T^{miss} : Calorimeter Leakage





Leakage of jets entering 'crack' region η=1.4
Detect via ratio of energy in outermost layers

$$E_{Tile2} / E_{Total} > 0.05$$

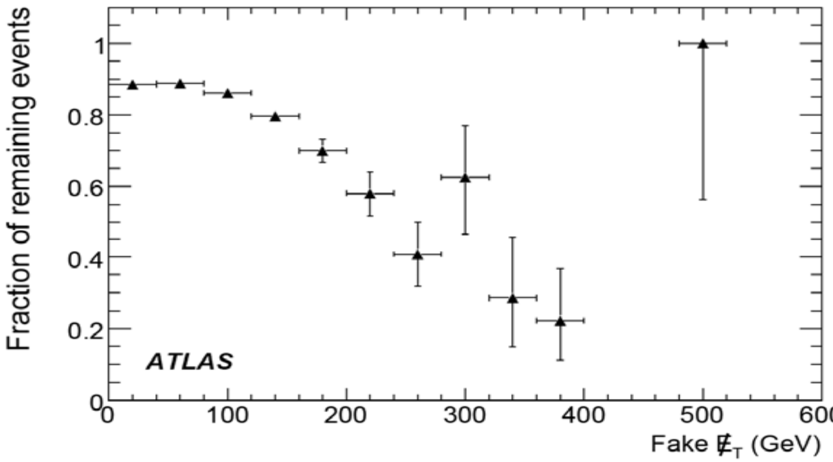
$$E_{Tile0,1} / E_{Total} > 0.7$$

$$E_{Cryo} / E_{Total} > 0.2$$

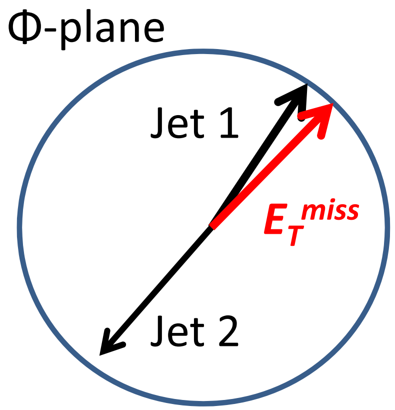
$$E_{Gap} / E_{Total} > 0.2$$

$$E_{HEC2} / E_{Total} > 0.5$$

Fraction of fake E_T^{miss} remaining after these cuts

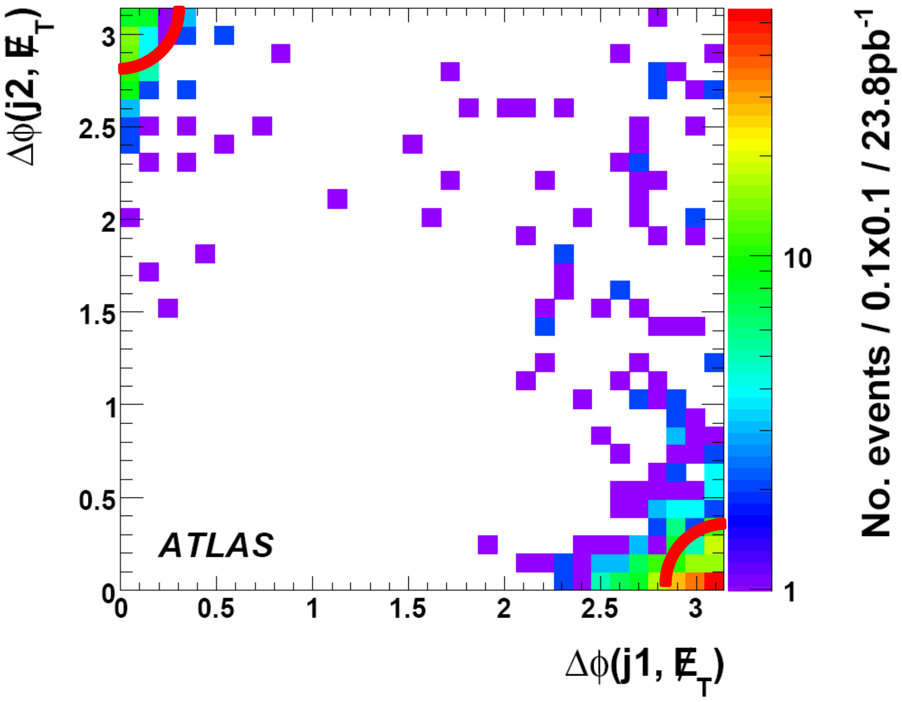


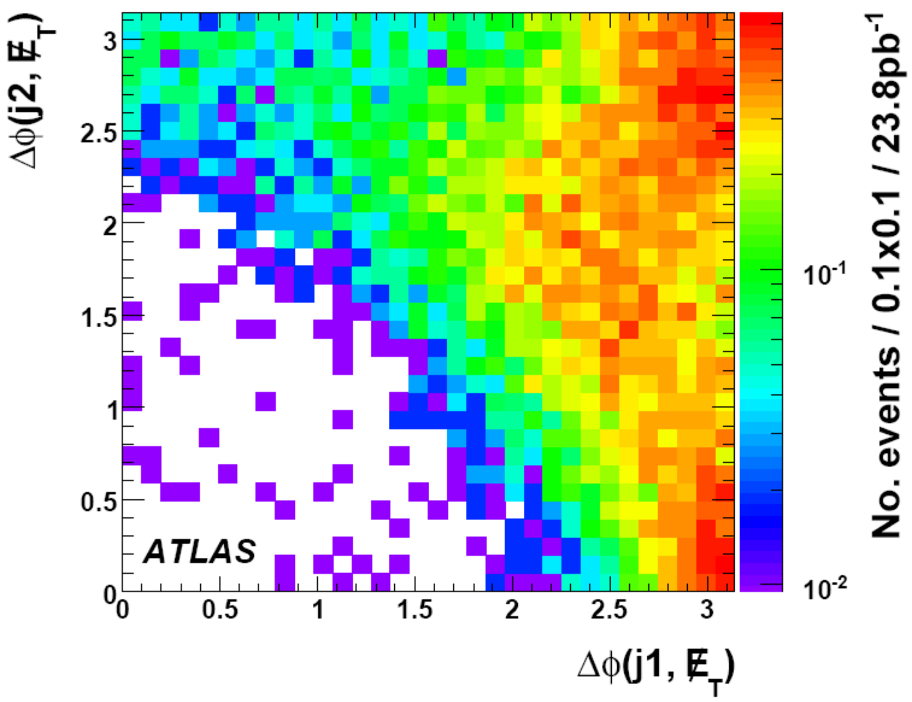
Cleaning: Jet-MET ϕ Correlations



- Reject events in which E_T^{miss} is closely associated with one of the leading jets in the ϕ plane. (standard @ Tevatron)

Distributions for events with $E_T^{miss} > 100$ GeV:

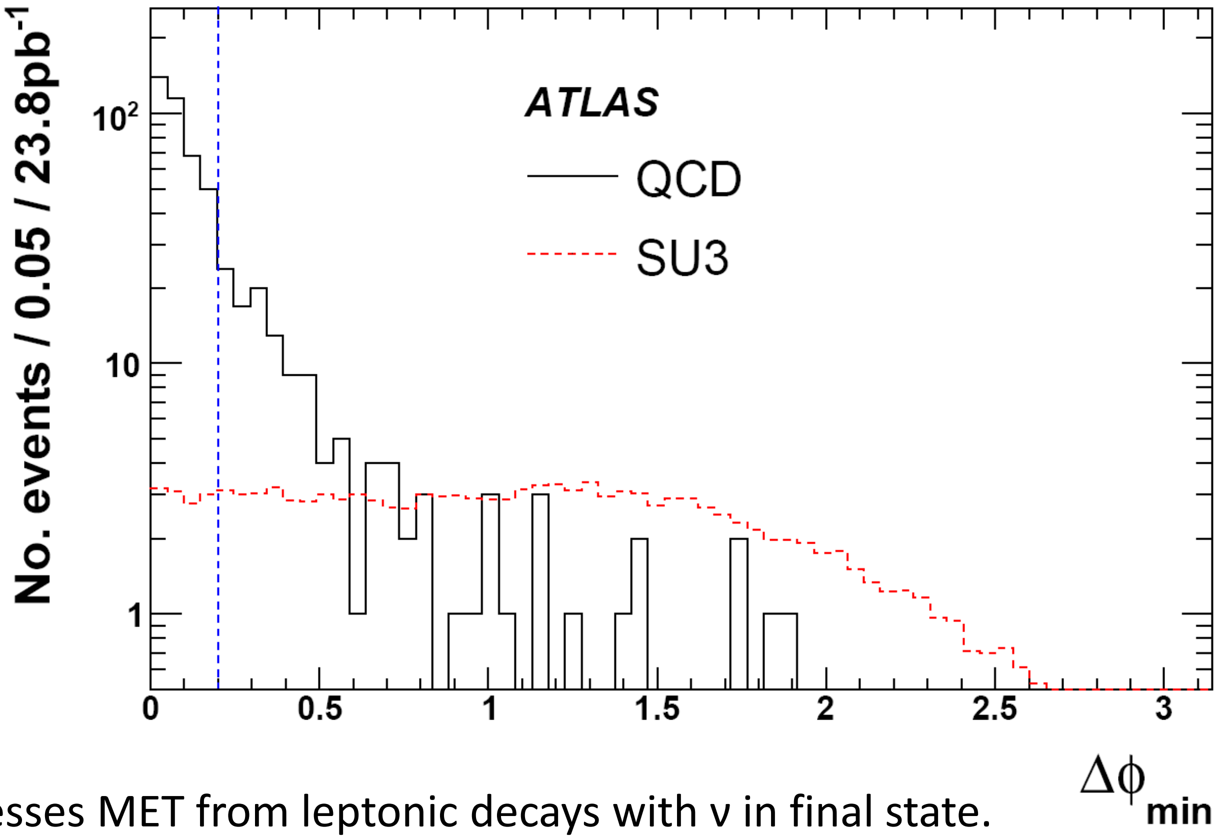




Jet-MET ϕ Correlations (cont)

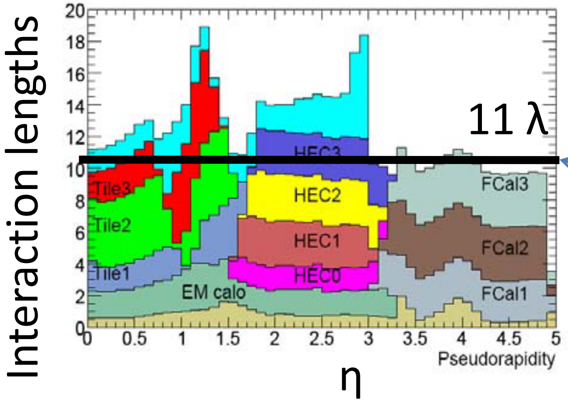
Generalize for leading 3 jets: $\Delta\phi_{\min} = \min[\Delta\phi(j_1 E_T^{miss}), \Delta\phi(j_2 E_T^{miss}), \Delta\phi(j_3 E_T^{miss})]$

Reject events with: $\Delta\phi_{\min} < 0.2$

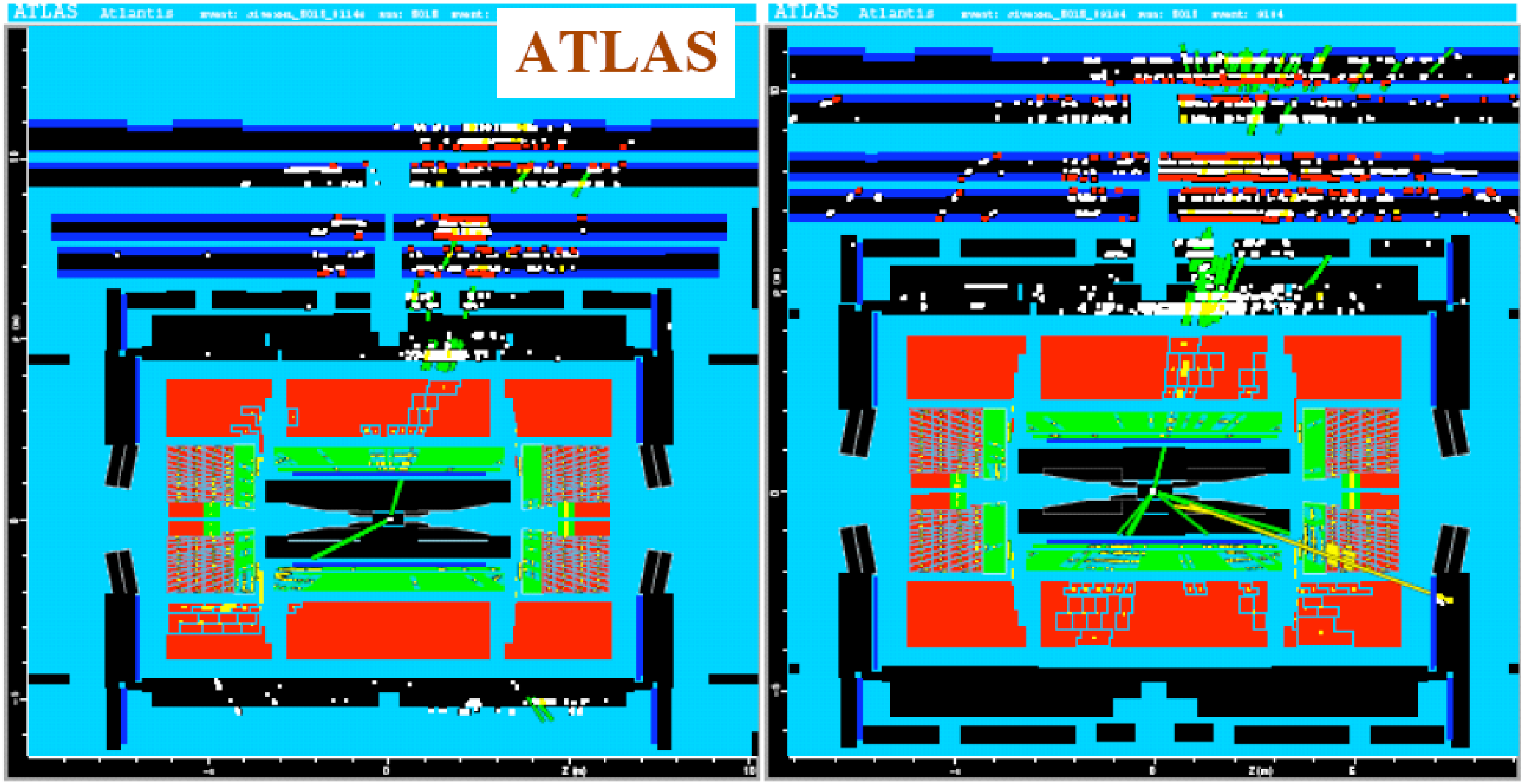


Also suppresses MET from leptonic decays with ν in final state.

Other Effects: Jet Punch Through

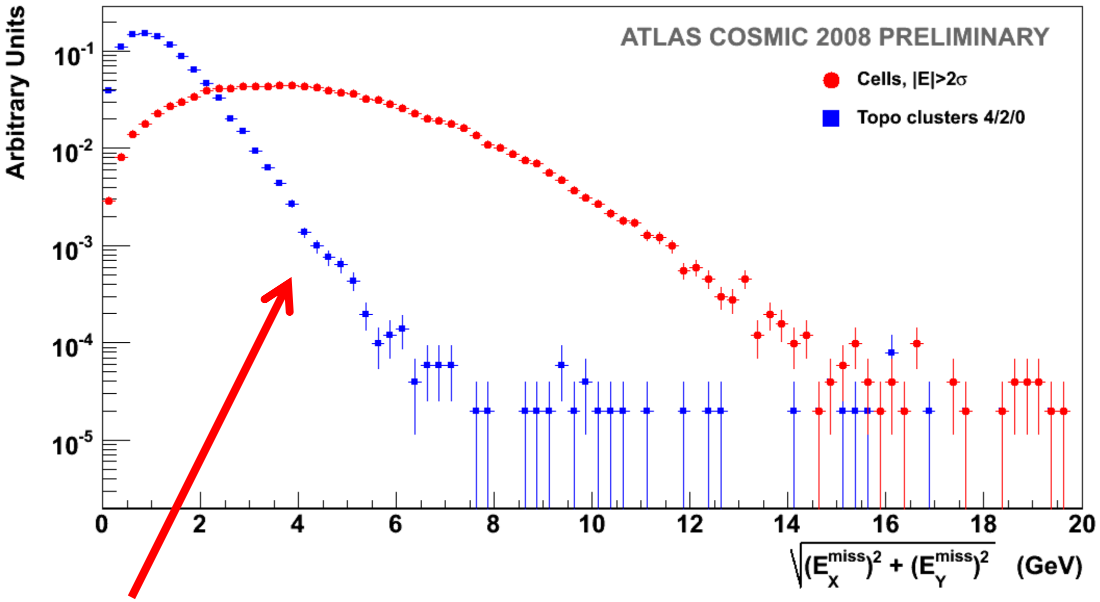


Active detector ~ 11 λ (interaction lengths) over full coverage. For 100 pb^{-1}, can still expect a few events with jet punch-through (detected as excess of activity in muon chambers). Can also compare E_T^{miss} from calorimeter vs tracking.

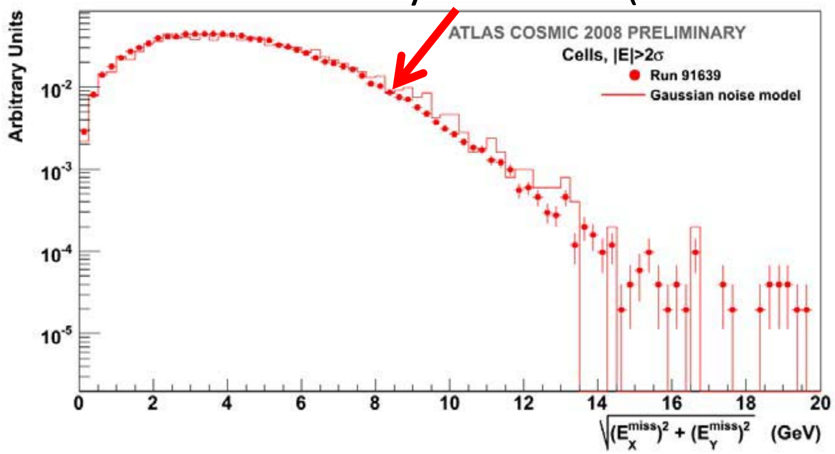


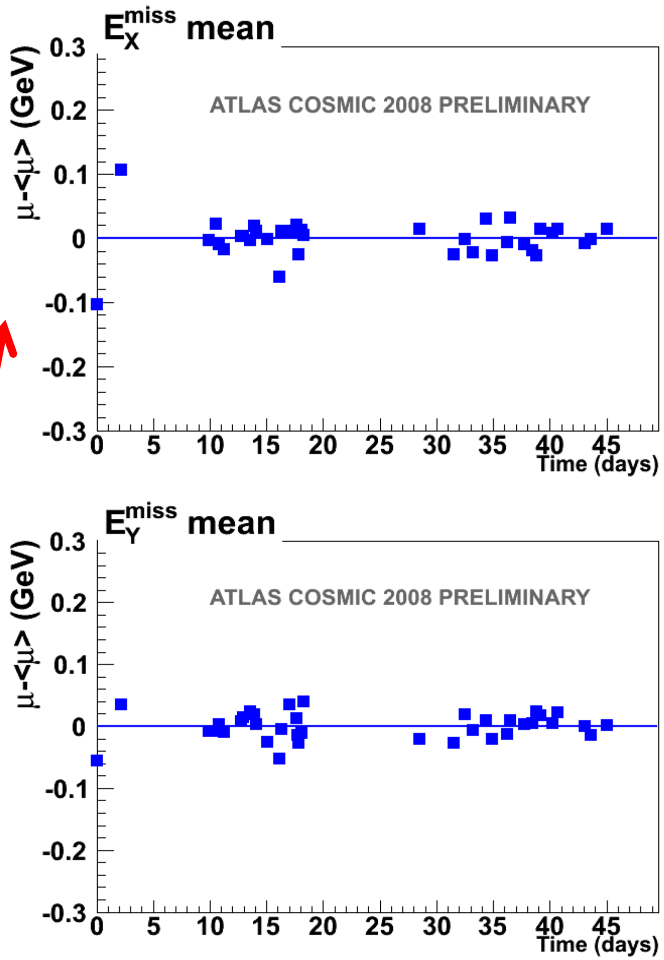
Commissioning E_T^{miss} with Cosmic Rays

Final Measured Calorimeter Noise: Random Triggers

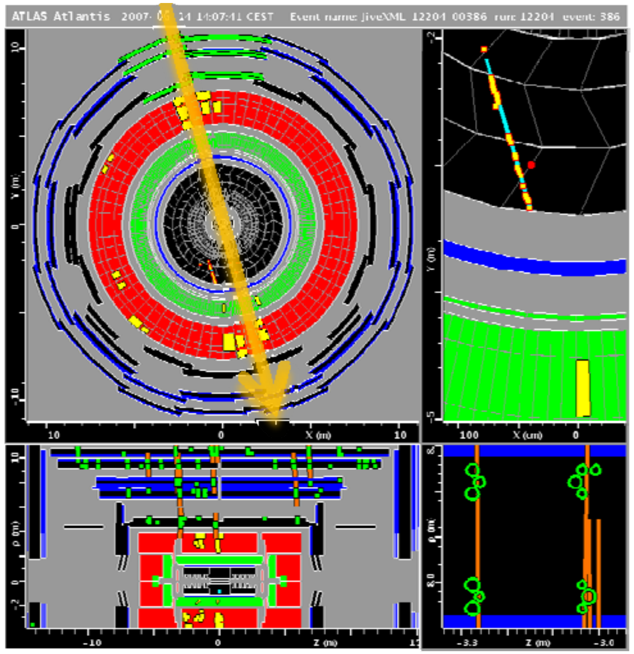


- Noise measured from random events, suppressed by clusters vs cells.
- Well-modelled by Gaussian (tails from PS, now fixed)





- E_T^{miss} (x,y) components stable over time (45 days)

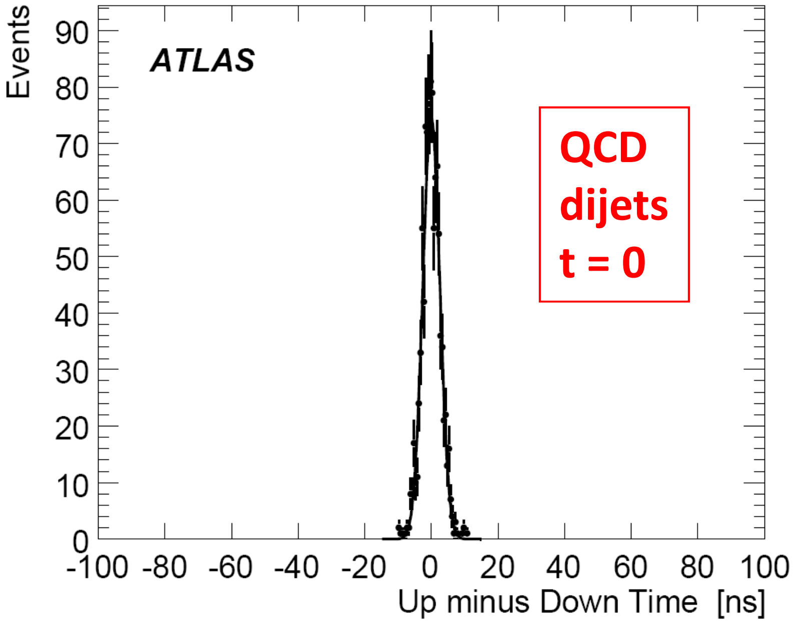


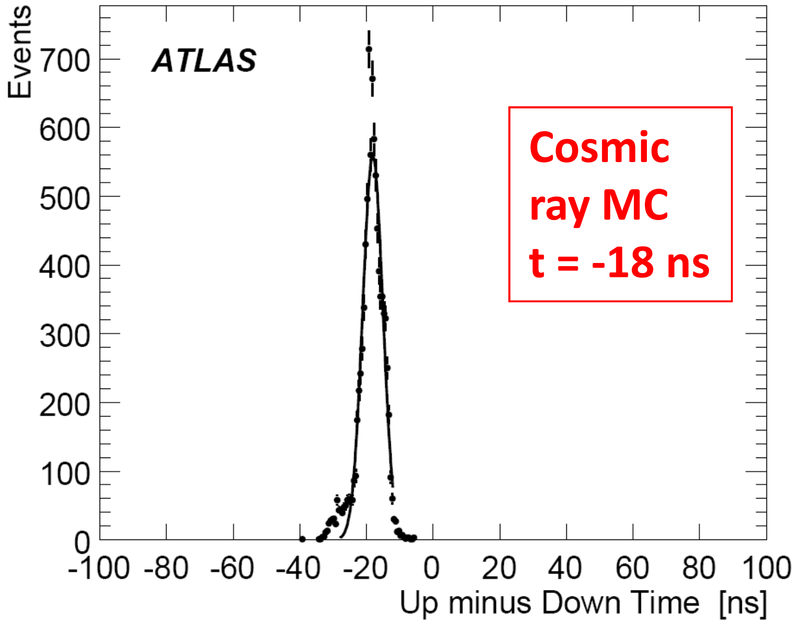
Cosmic Ray Backgrounds

- Cosmic rays, triggered by themselves or overlapping with QCD jets / minbias, can generate fake E_T^{miss}
- Exploit precision calorimeter timing ~ 1 ns
- Transit time ~ 18 ns from top to bottom of calorimeter:

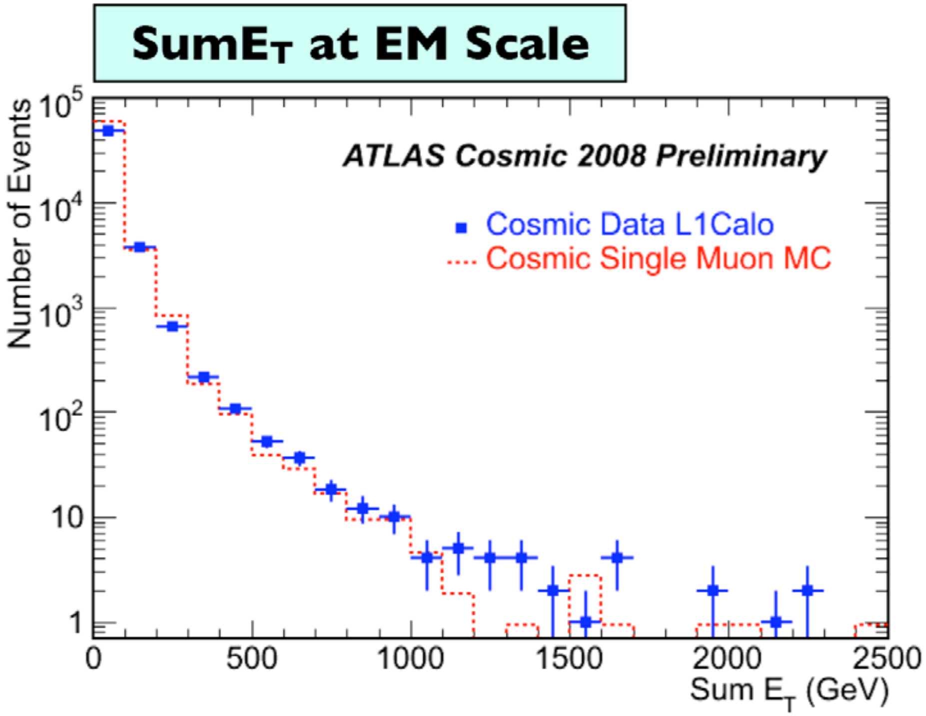
$$t_{\mathrm{up(down)}} = \sum_i (E_i^{\mathrm{up(down)}} \times t_i) / \sum_i E_i^{\mathrm{up(down)}}$$

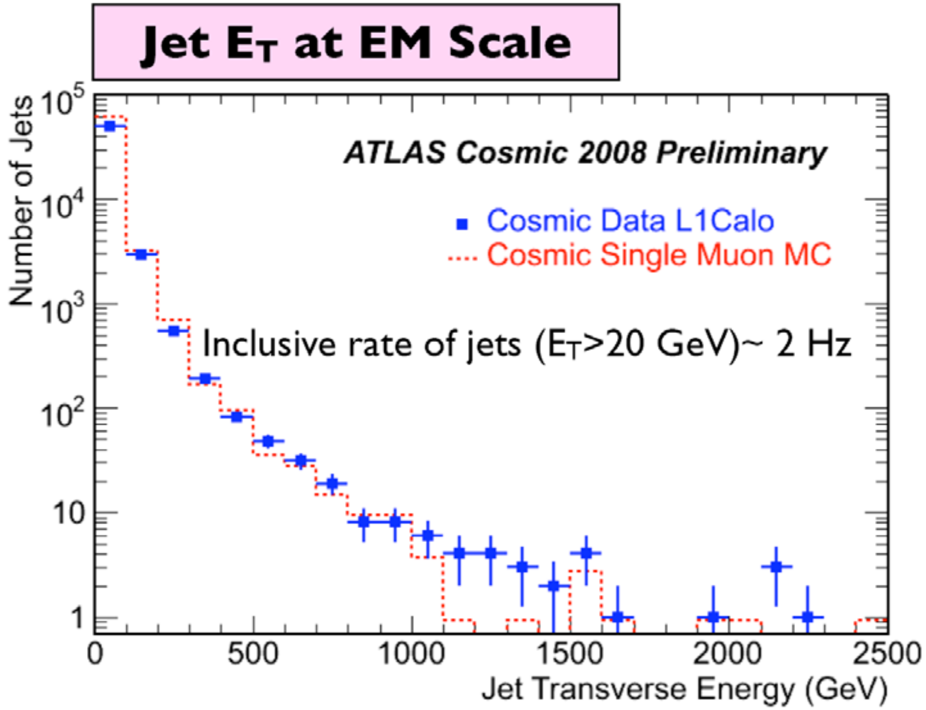
- t = 0 for particles from pp collisions
- (Also absolute cell times to remove isolated deposits)





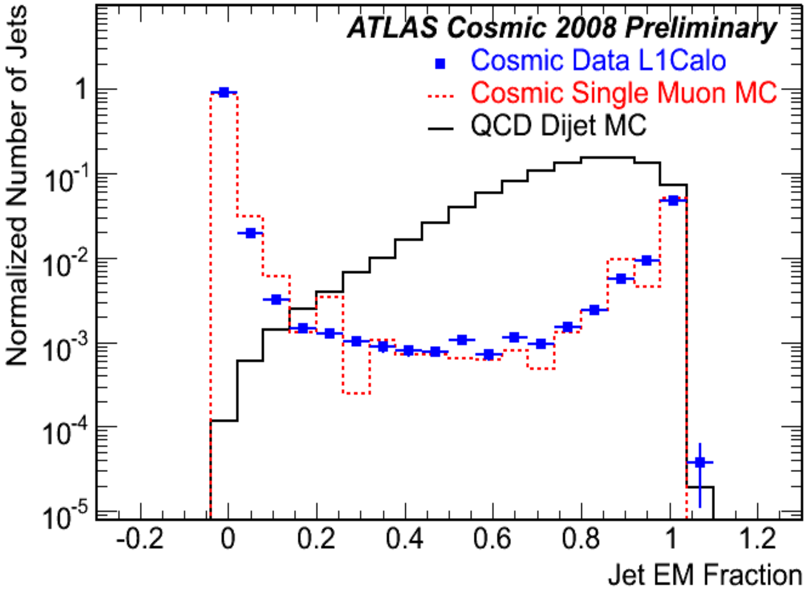
Fake E_T^{miss} :cosmic rays

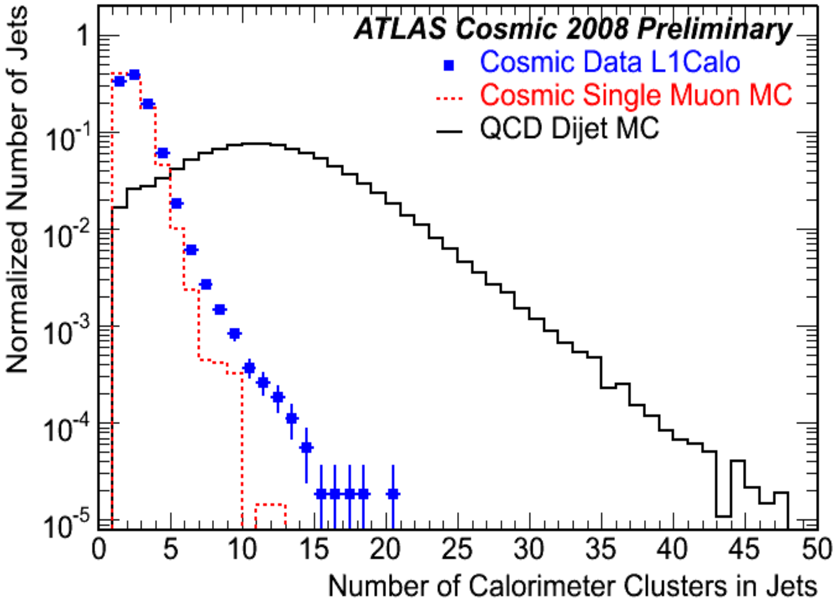




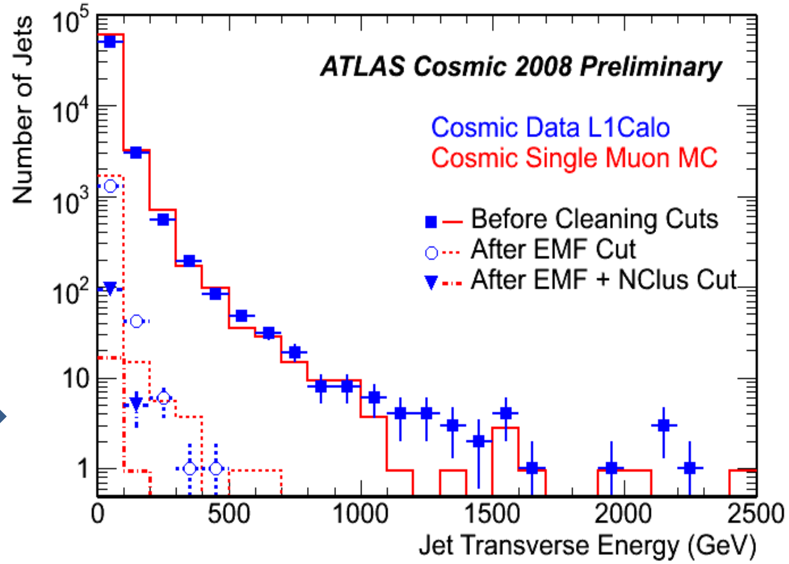
- High-energy cosmic ray muons undergoing hard bremsstrahlung can generate fake E_T^{miss}
- Discrepancy in tails due to MC statistics and from cosmic ray air showers (not modelled in MC)

Cleaning Cuts

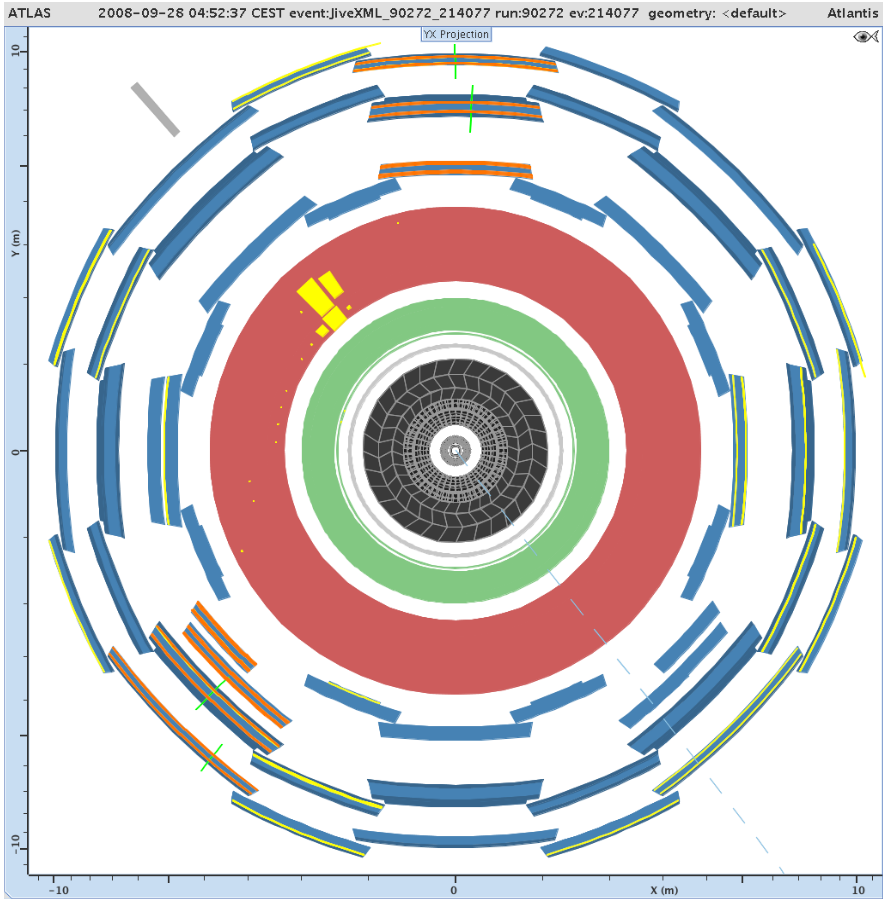


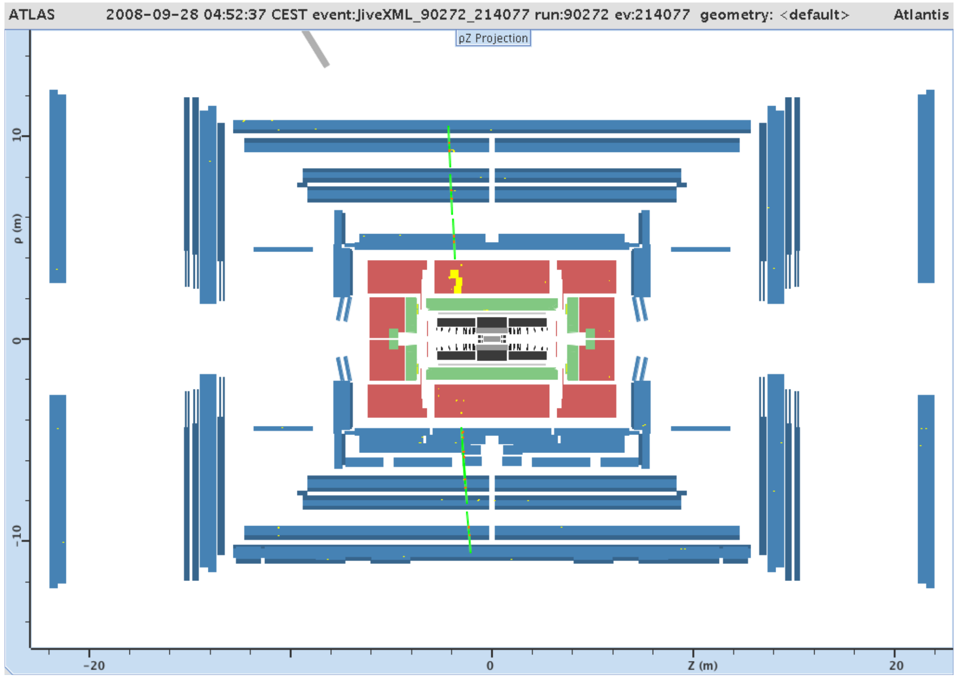


- Jet EM fraction (F_{EM})
  - Typically 0 or 1 for muons undergoing bremstrahlung in (TileCal or LAr)
- Number of clusters (N_{clus})
  - Fewer clusters in cosmics
- Also tracking (not shown)
- Resulting rejection
  - $0.2 < F_{EM} < 0.97$
  - $N_{clus} >= 7$



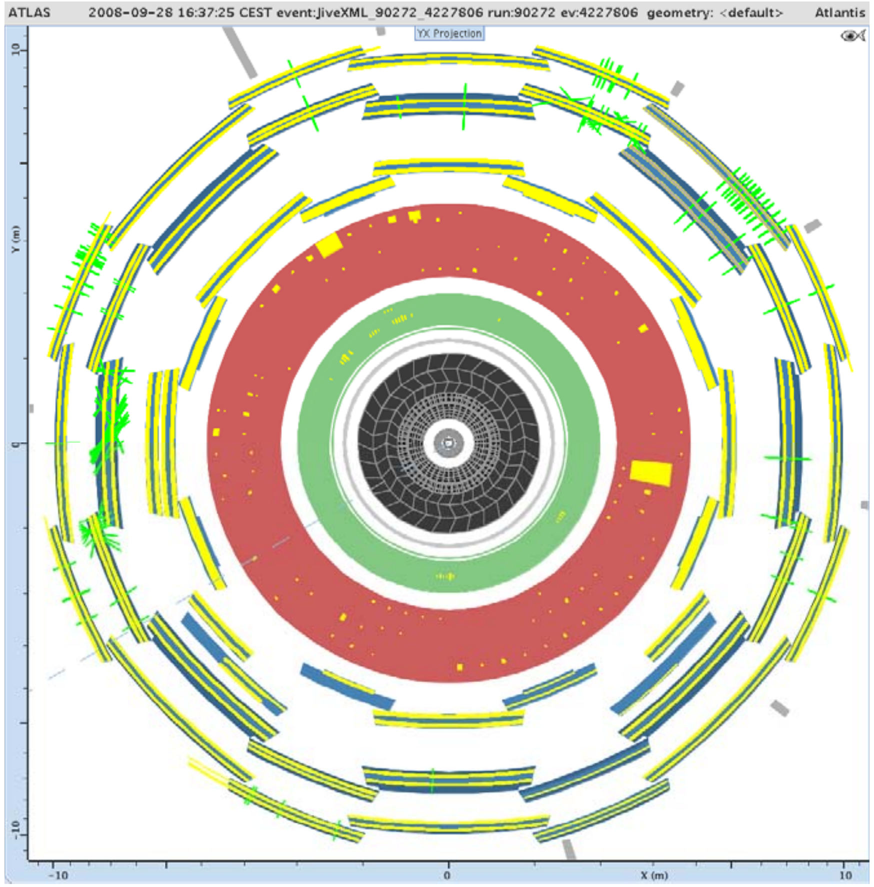
TeV event from single cosmic ray muon

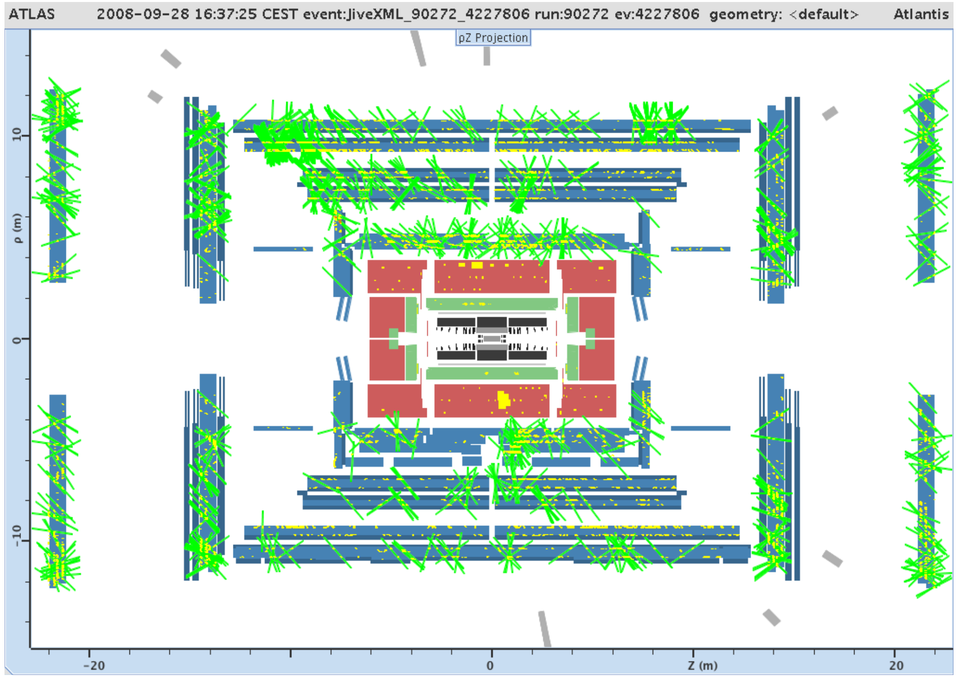




- Green: muon segments
- Yellow: TileCal Cell
- Gray: jets
- Blue: missing ET

TeV event from cosmic ray air shower



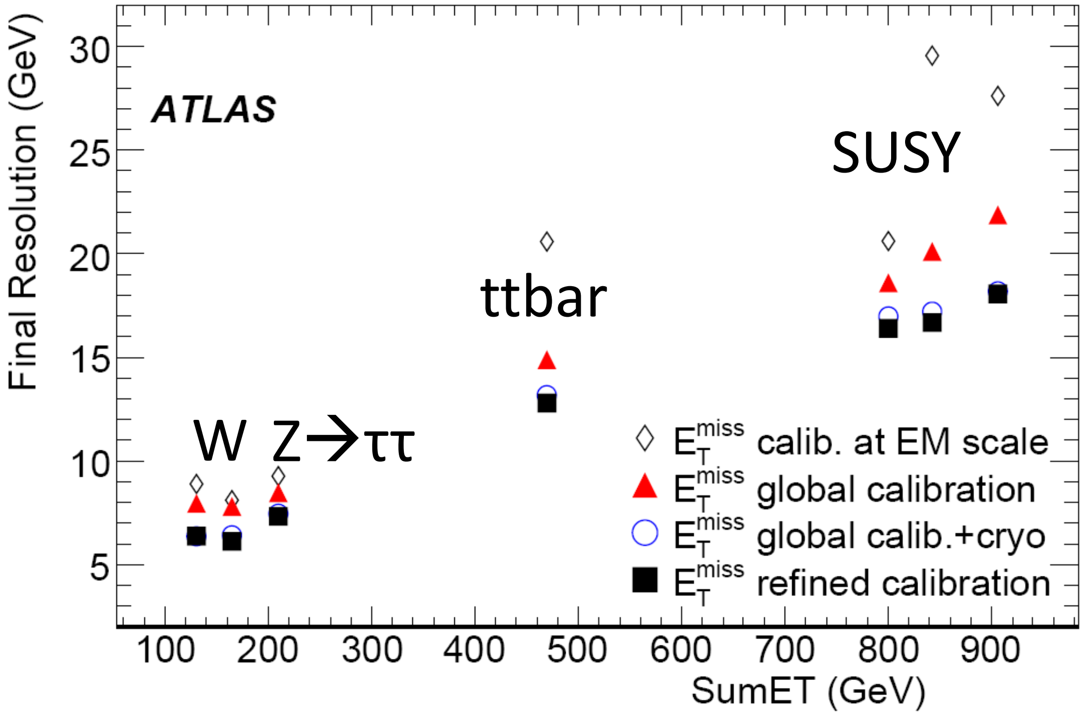


- Green: muon segments
- Yellow: TileCal Cell
- Gray: jets
- Blue: missing ET

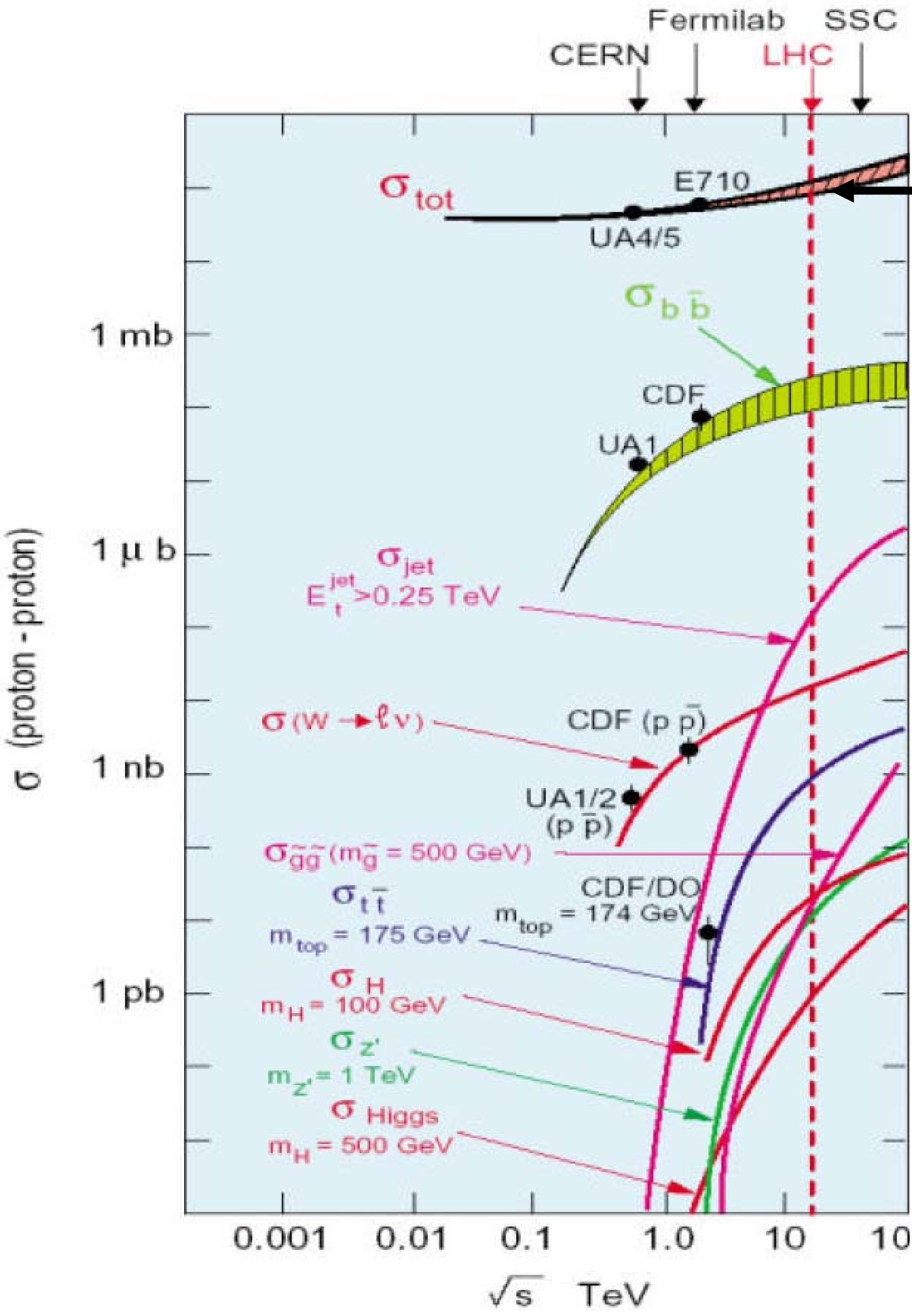
Commissioning E_T^{miss} with First Collisions

E_T^{miss} Resolution in Early Data

- First master detector effects
  - Dead channels
  - Noisy channels
- Start to apply refined calibration
  - Electrons, photons, τ, Jets, Muons, Unused cells
- Validate with
  - Samples with no E_T^{miss} (minimum bias)
  - Samples with E_T^{miss} (W,Z)



First Data: Minimum Bias



Total event rate:

$R = L \times \sigma_{inelastic}$ (pp)

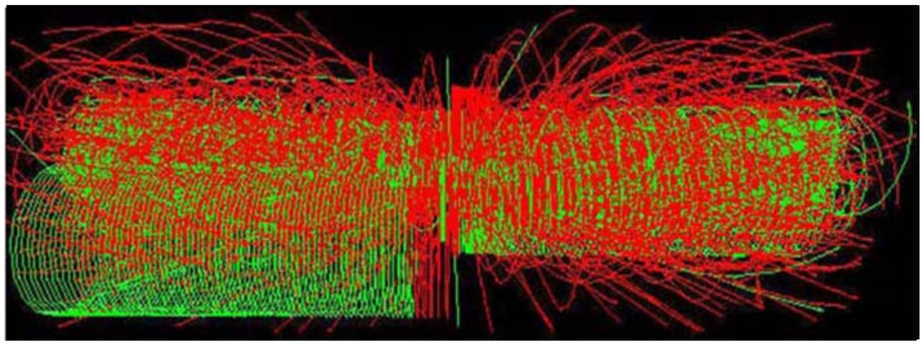
$\approx 10^{30}\ cm^{-2}\ s^{-1} \times 70$ mb (L_0)

$\approx$ 70 kHz (700 MHz @ L_{nom} 10^{34})

10^{34} : ~ 25 inelastic "minimum bias" low-p_T events produced on average in each bunch crossing of 25 ns → pile-up

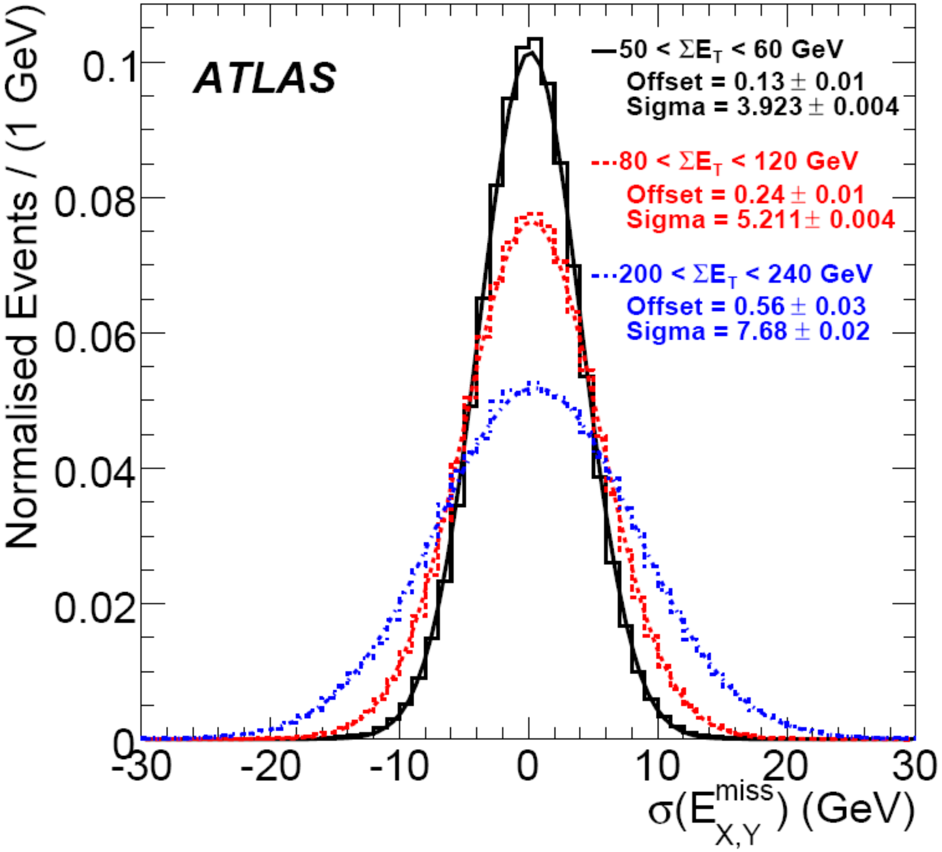
e.g. "Golden" Higgs channel:

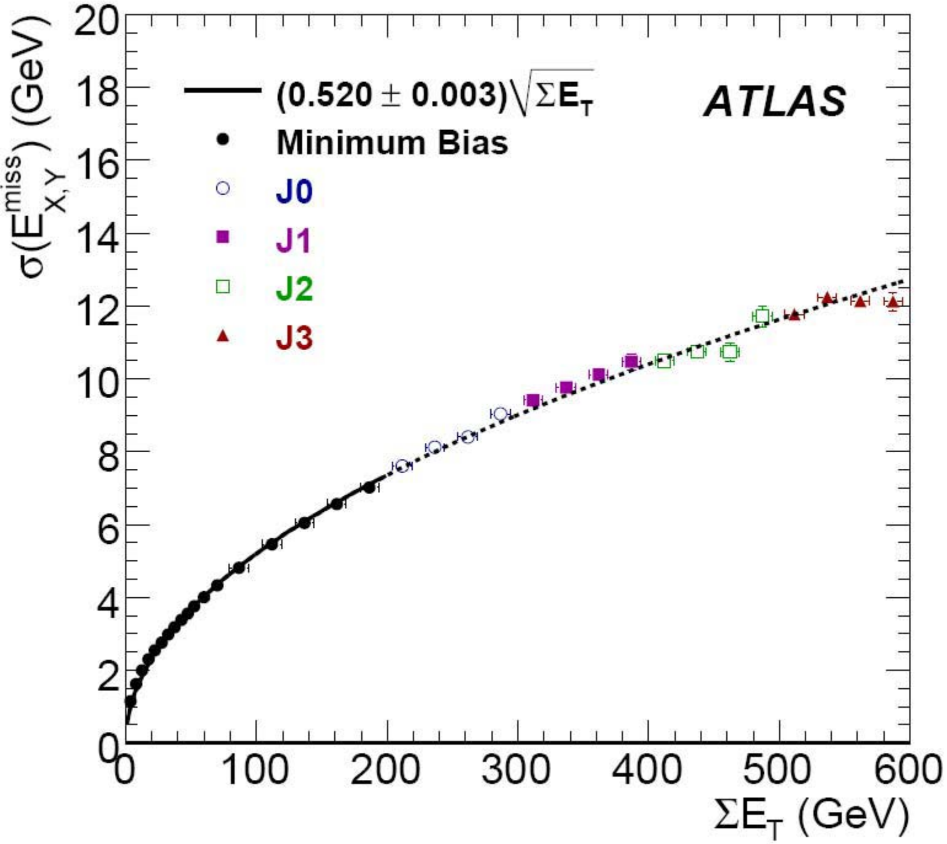
$$H \rightarrow ZZ \rightarrow 4\mu$$



Reconstructed tracks p_T>25 GeV

Minimum Bias and E_T^{miss}



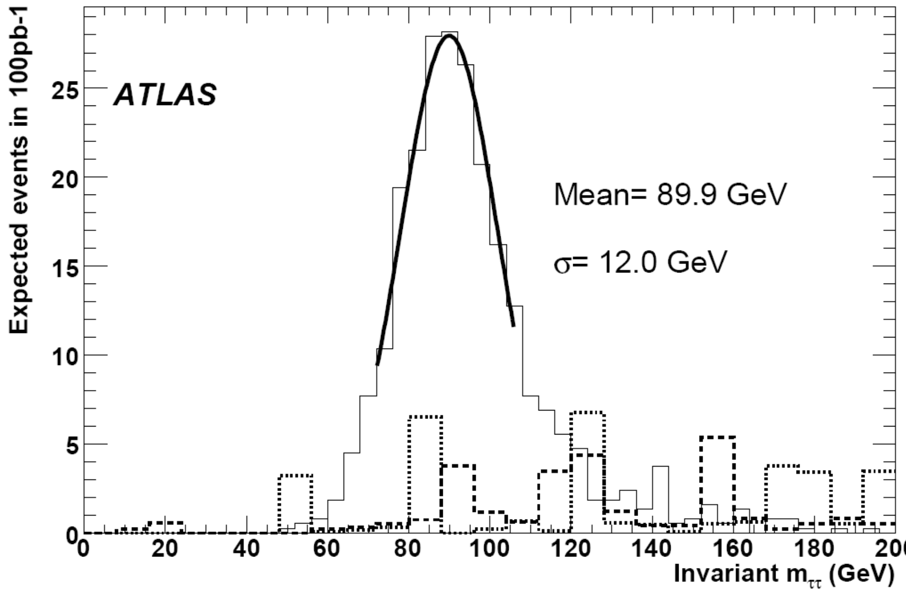


Minimum bias events have no intrinsic E_T^{miss} . Useful for measuring resolution, bias, in (x,y) components of E_T^{miss} .

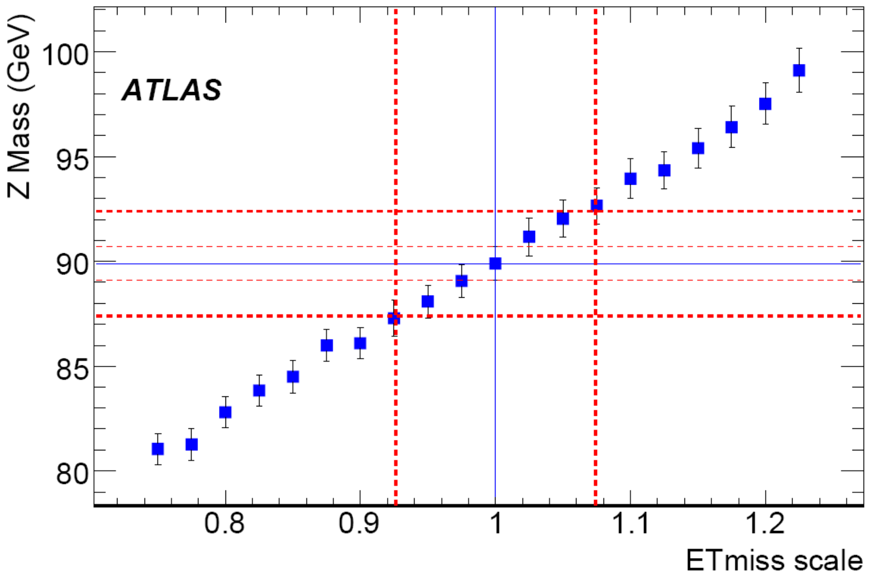
Resolution on sum E_T from minimum bias (up to 200 GeV) and di-jets in early data.

Towards 100 pb^{-1}

- Search for $Z \rightarrow \tau\tau$
  - τ leptonic + τ hadronic decay
  - trigger on lepton + E_t^{miss}
- Use collinear approximation to reconstruct m_Z
  - Massless τ's & ν's collinear to observed τ decay products



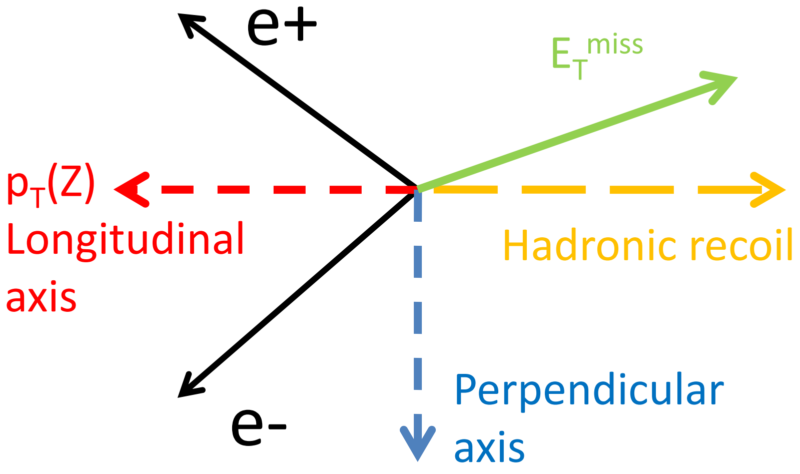
$$m_{\tau\tau} = \sqrt{2\left(E_{had} + E_{\nu 1}\right)\left(E_{\ell} + E_{\nu 2}\right)\left(1 - \cos\theta\right)}$$

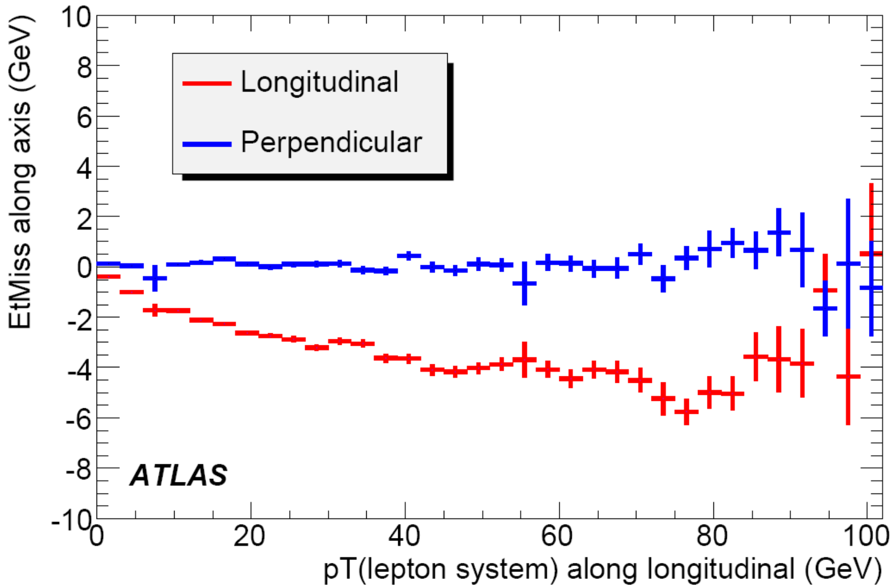


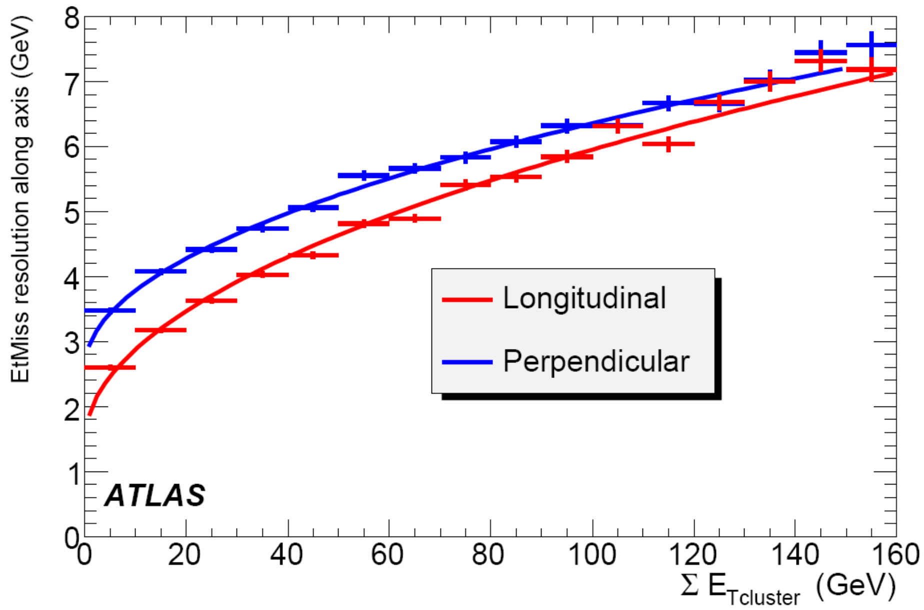
Reconstructed Z mass as a function of E_T^{miss} scale.

Towards 100 pb^{-1}
Z→ee,μμ

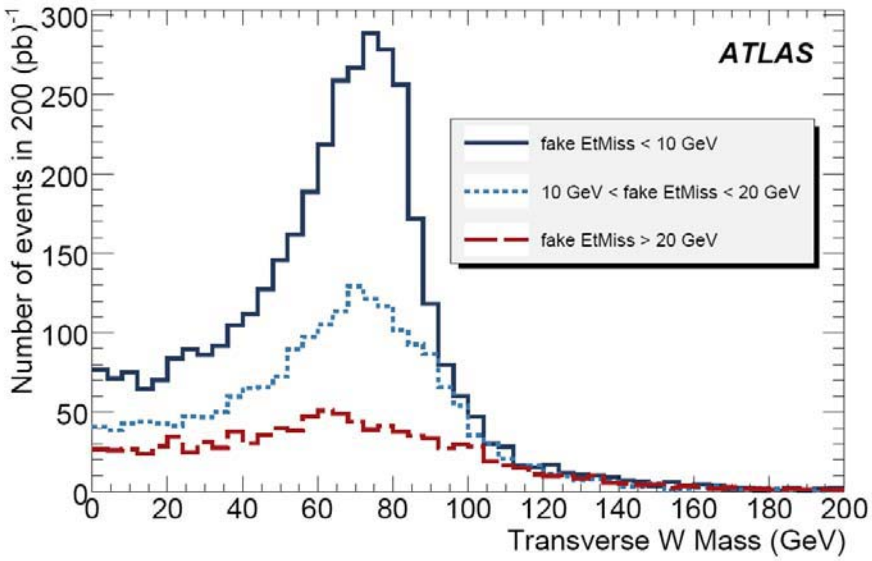
- P_T of leptons from Z decay should be balanced by hadronic recoil
- Project E_T^{miss} along axes perpendicular and parallel to Z

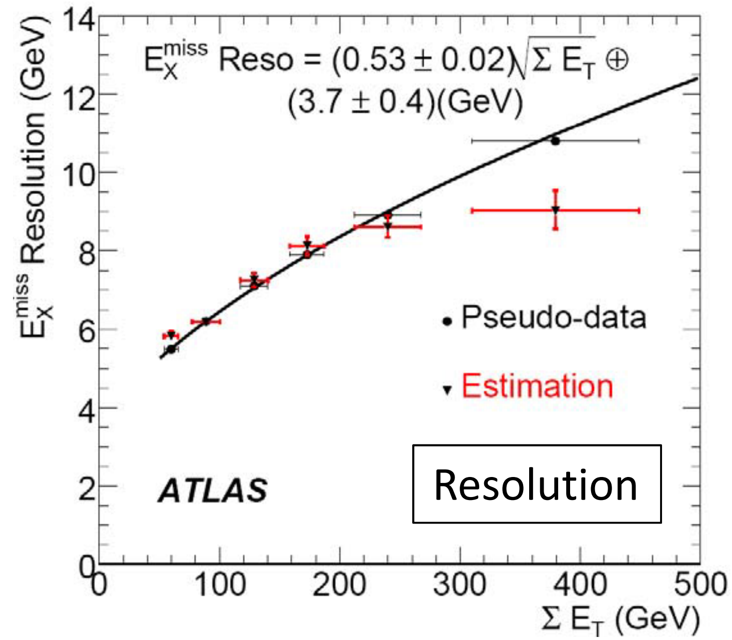


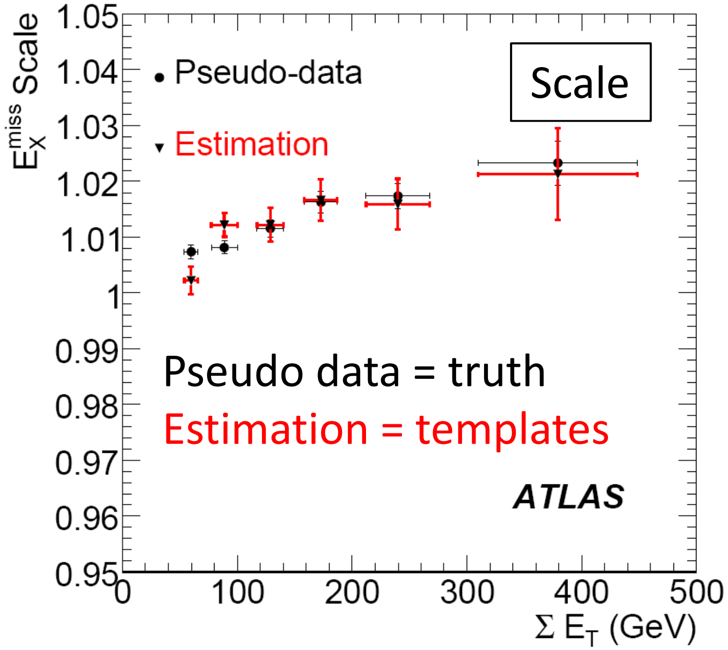




Transverse W mass



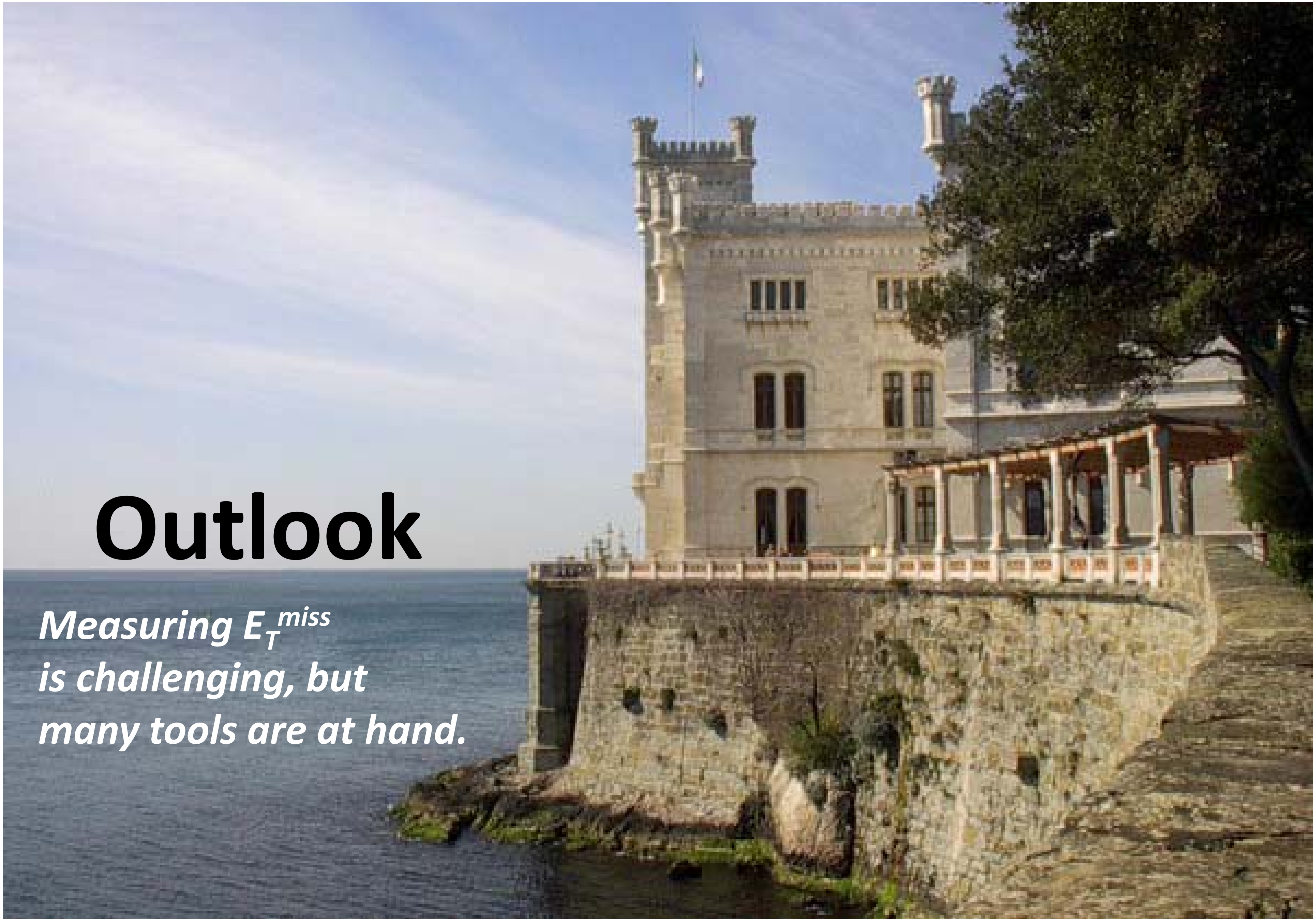




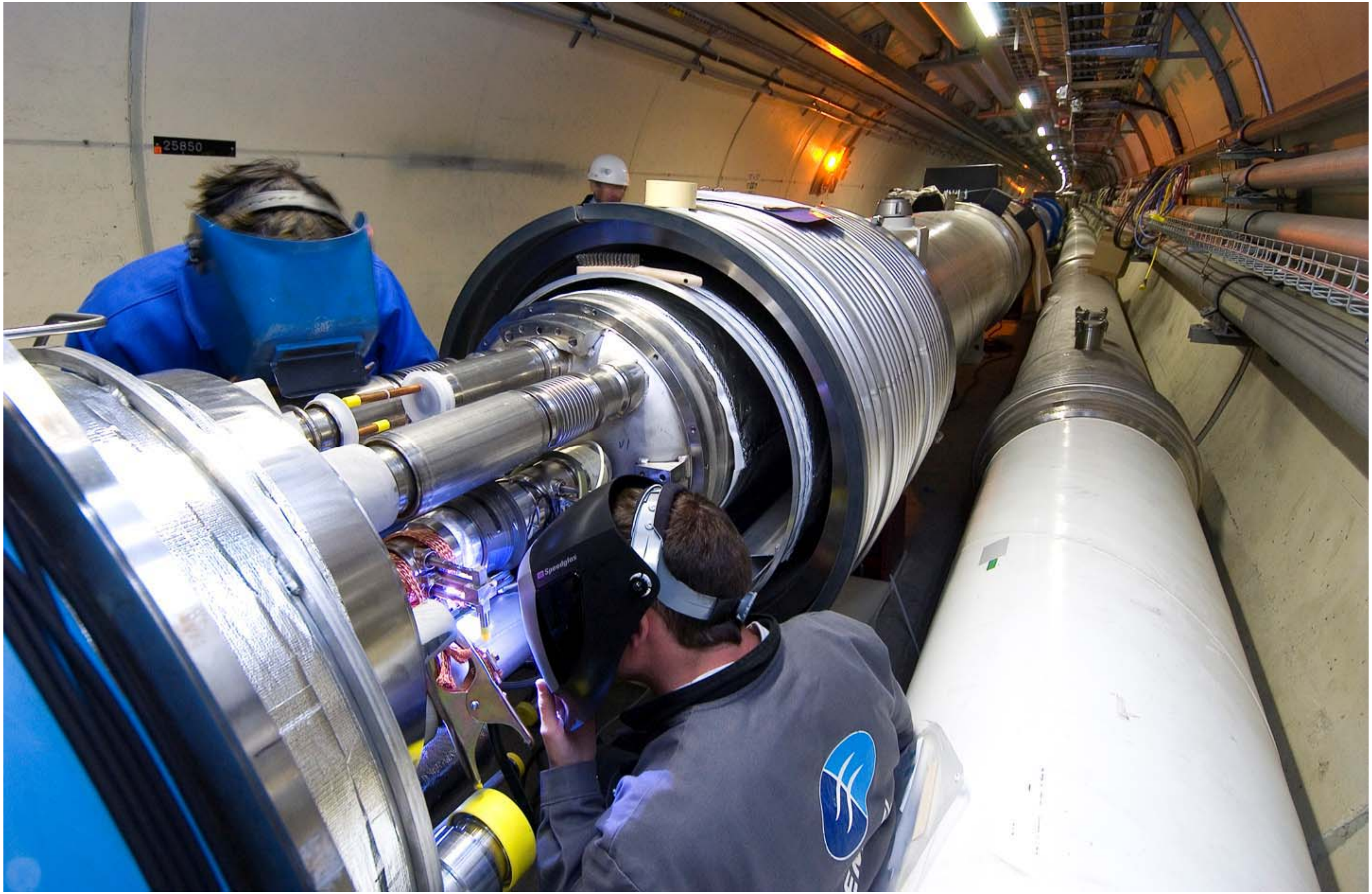
- Transverse mass of W boson sensitive to both E_T^{miss} resolution and scale.
- Fit m_T^W with template distributions for different (resolution, scale)
- Example for W→μν

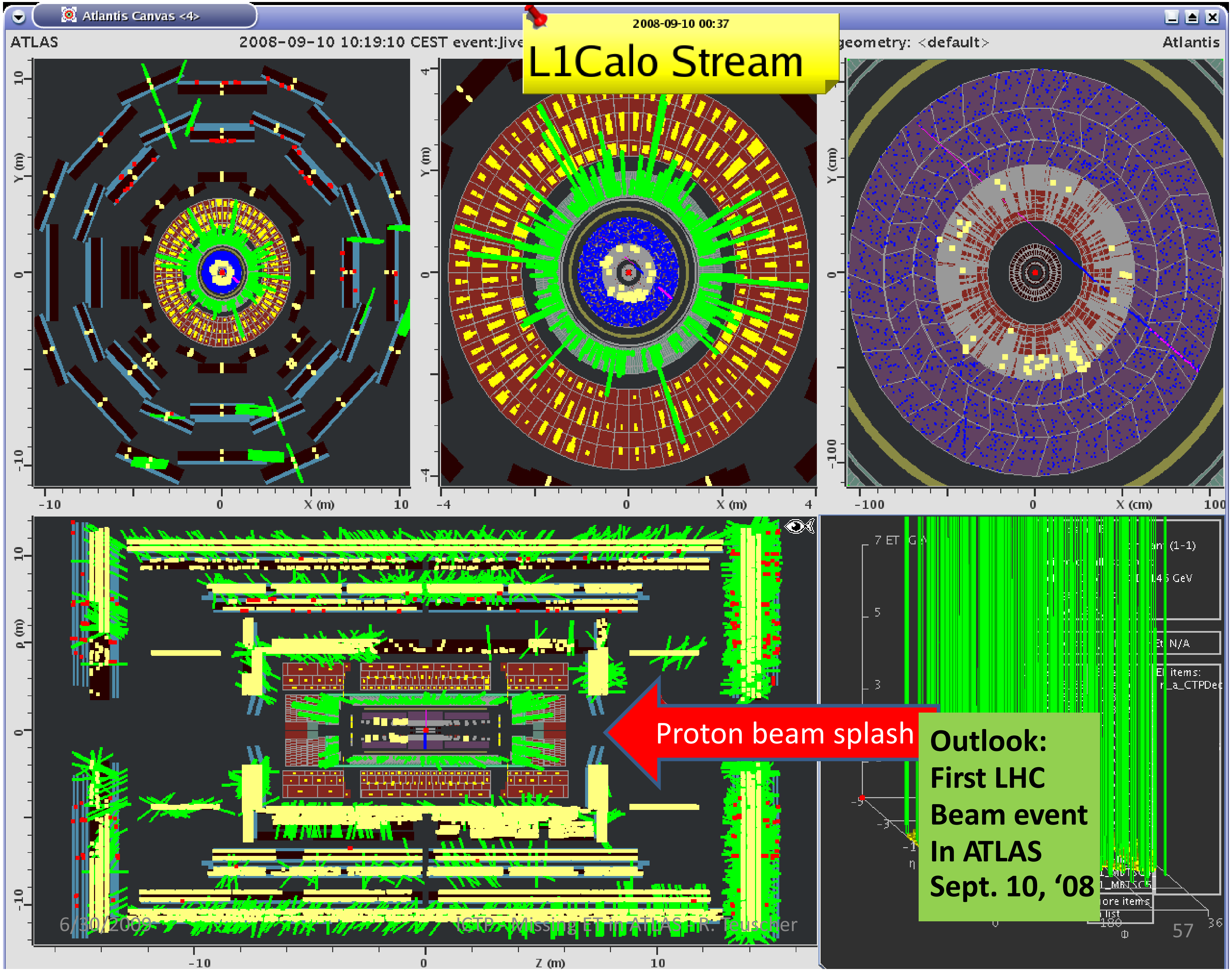
Outlook

Measuring E_T^{miss} is challenging, but many tools are at hand.



LHC: Restart in Fall, Long Winter Run

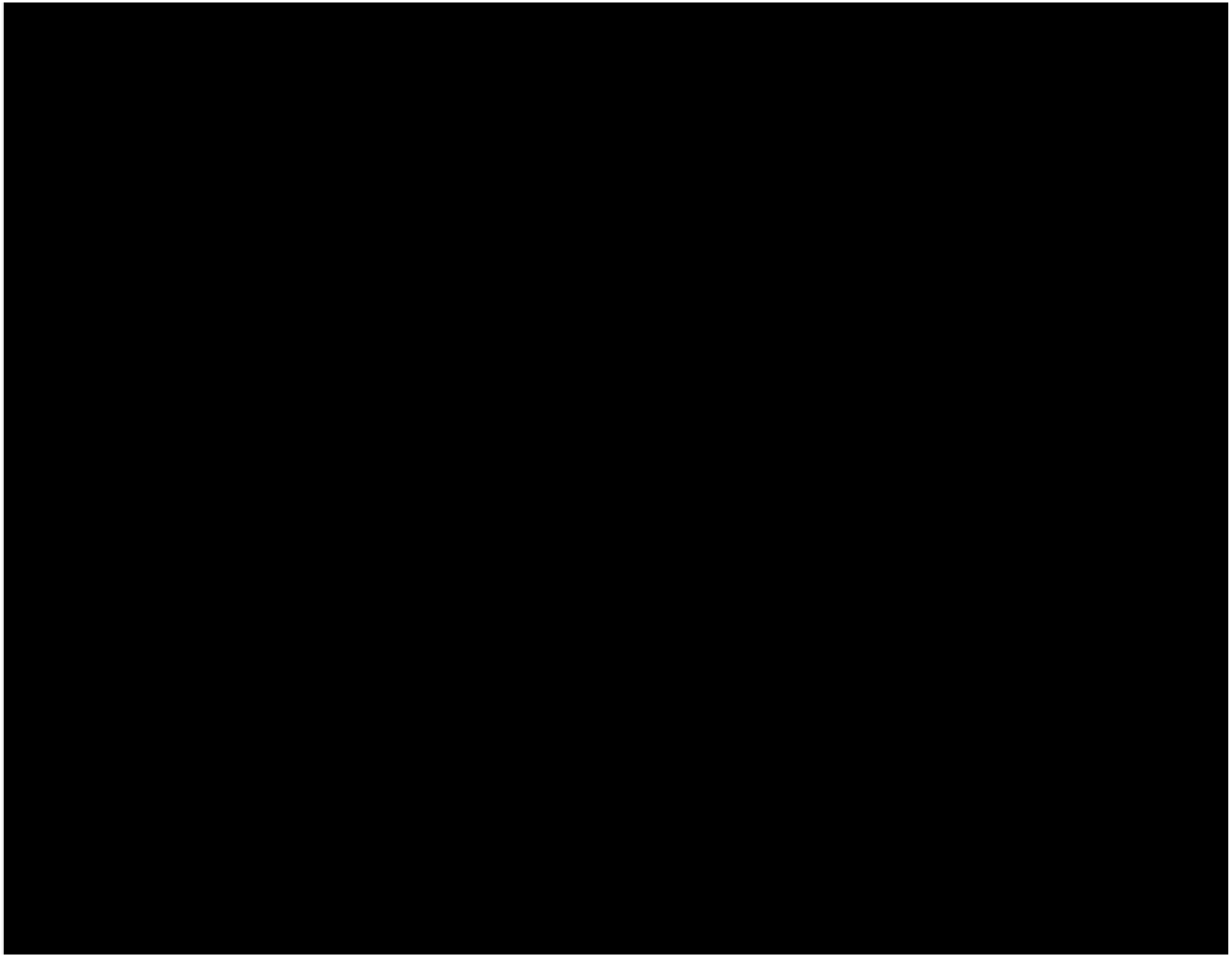




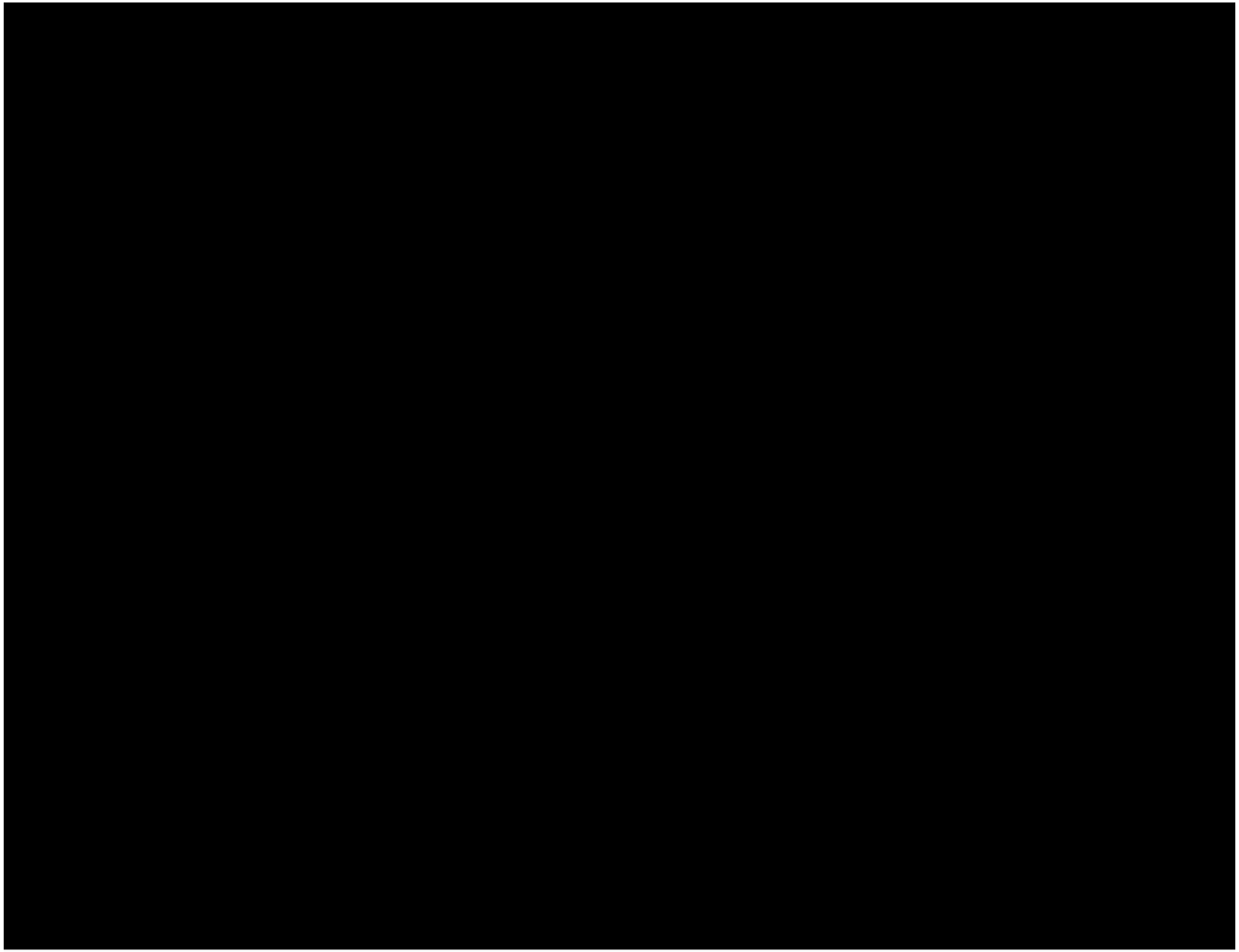
Atlantis Canvas <4>
ATLAS
2008-09-10 10:19:10 CEST event:Jive
geometry: <default>
Atlantis
2008-09-10 00:37
L1Calo Stream
Proton beam splash
Outlook:
First LHC
Beam event
In ATLAS
Sept. 10, '08

Backup

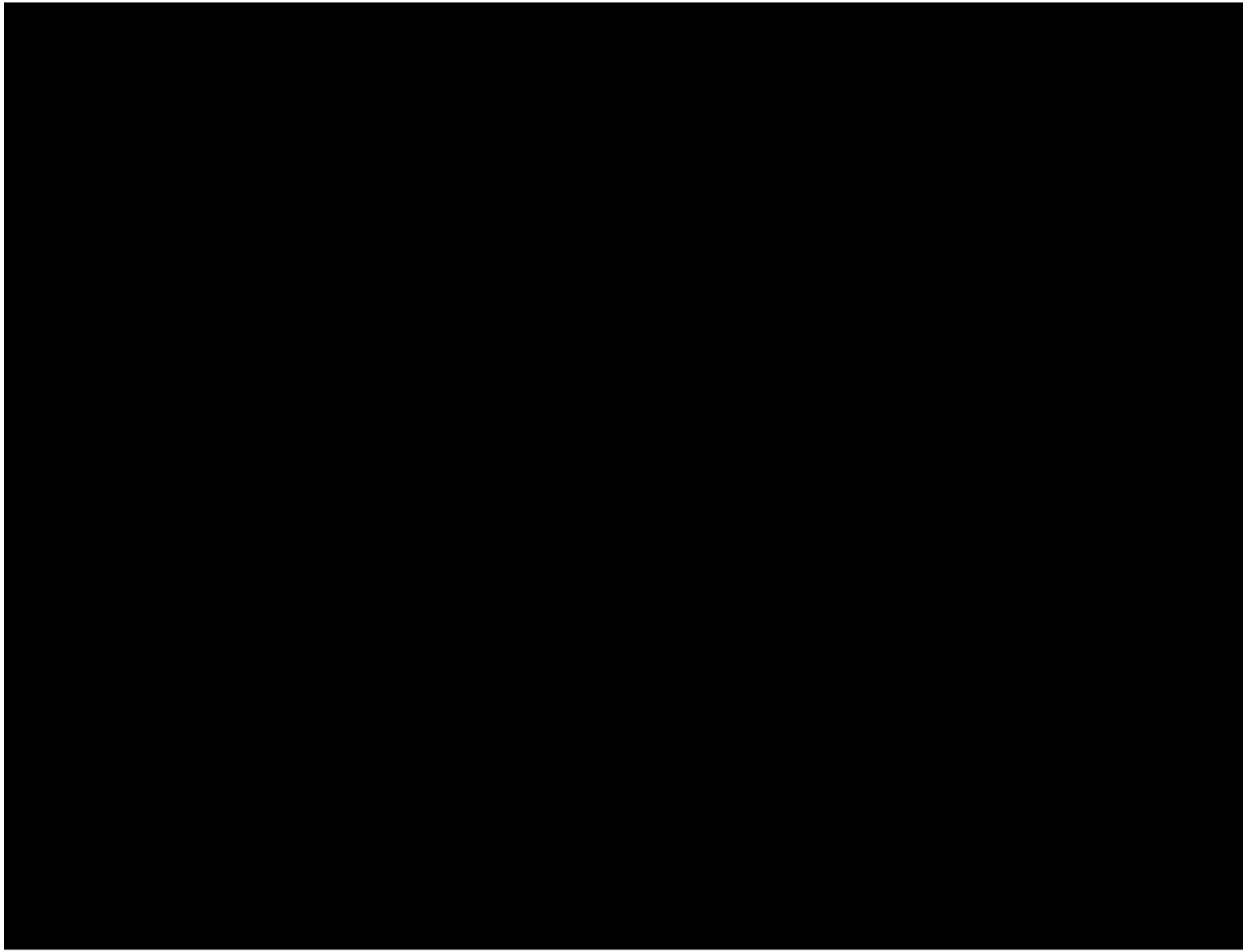
Video of Particle Interactions in ATLAS LAr Calorimeter



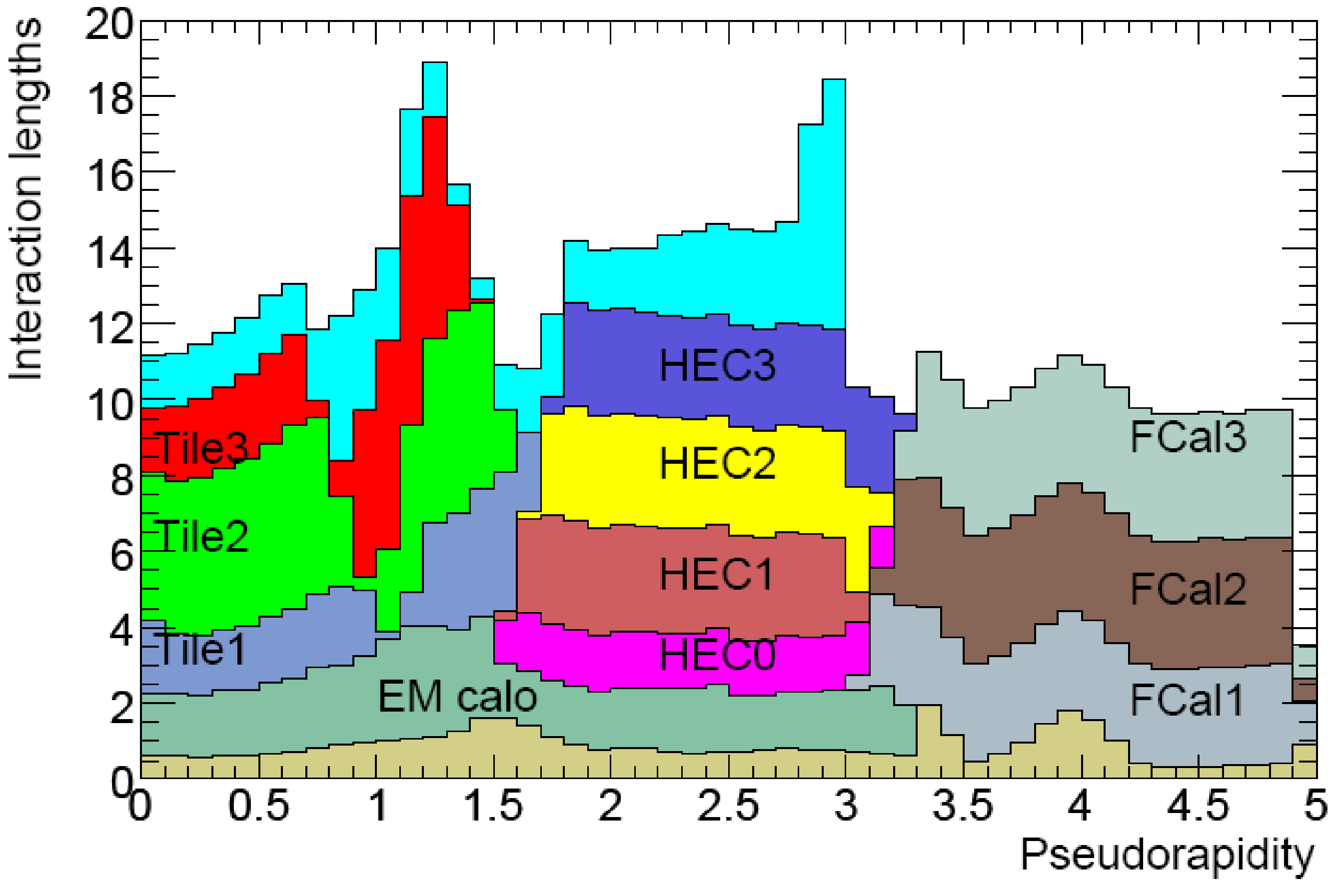
Video of Particle Interactions in ATLAS TileCal



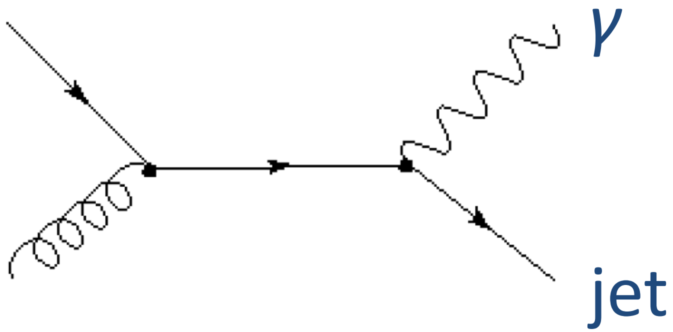
Video of Particle Interactions in ATLAS Muon Spectrometer



ATLAS Calorimetry



Calorimeter Gaussian Response Function from Data



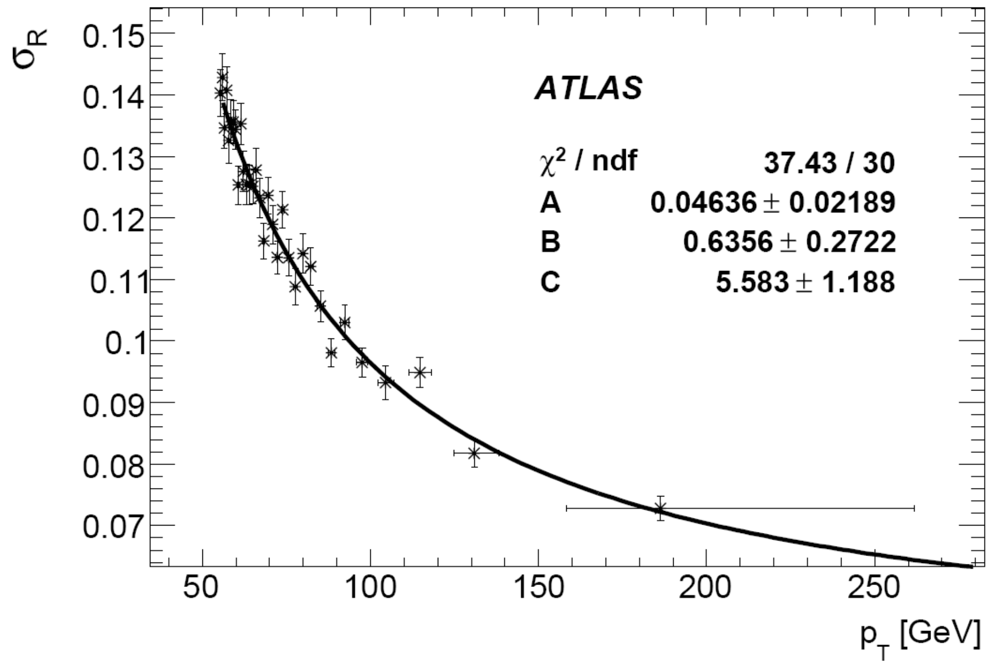
- "E_T^{miss} projection method": use transverse momentum conservation in γ + jet events to calculate Gaussian response of calorimeters to jets:

$$R_1 = 1 + \frac{\vec{p}_T^{\,miss} \cdot \vec{p}_T^{\,\gamma}}{|\vec{p}_T^{\,\gamma}|^2}$$

where R_1 is measured in bins of p_T^γ

- Then parameterize Gaussian response:

$$\sigma_R = A + \frac{B}{\sqrt{p_T}} + \frac{C}{p_T}$$

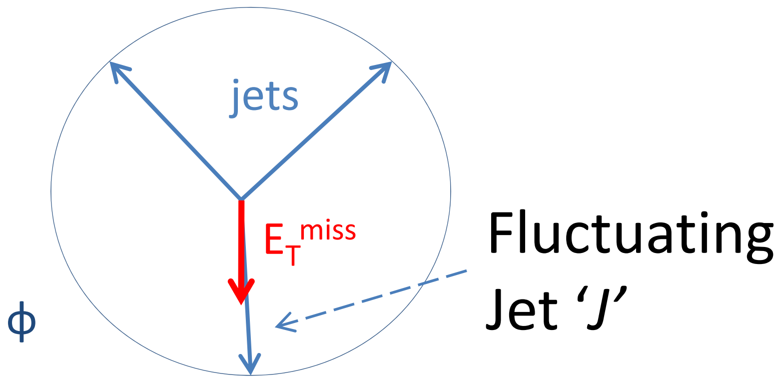


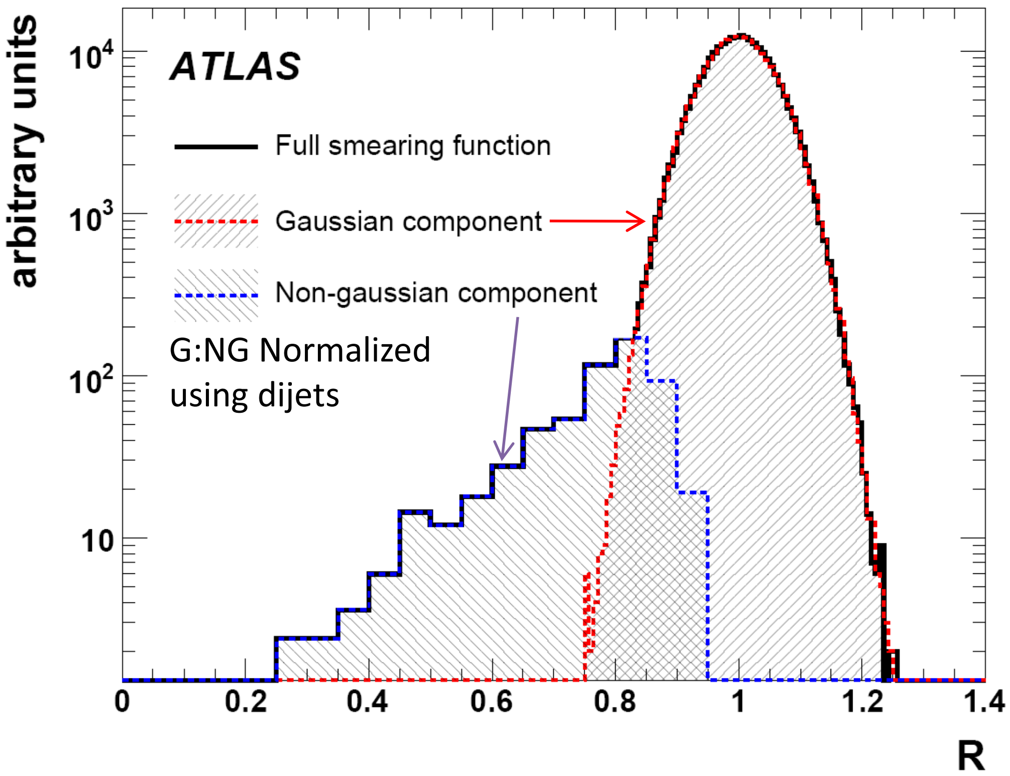
Full Gaussian + Non-Gaussian Response Function

- Use events in which E_T^{miss} vector can be associated in ϕ to a single jet '*J*' to measure non-Gaussian response of calorimeters:

$$R_2 = \frac{\vec{p}_T(J) \cdot \vec{p}_T(J, true)}{|\vec{p}_T(J, true)|^2}$$

$$\vec{p}_T(J, true) \approx \vec{p}_T(J) + \vec{p}_T^{miss}$$

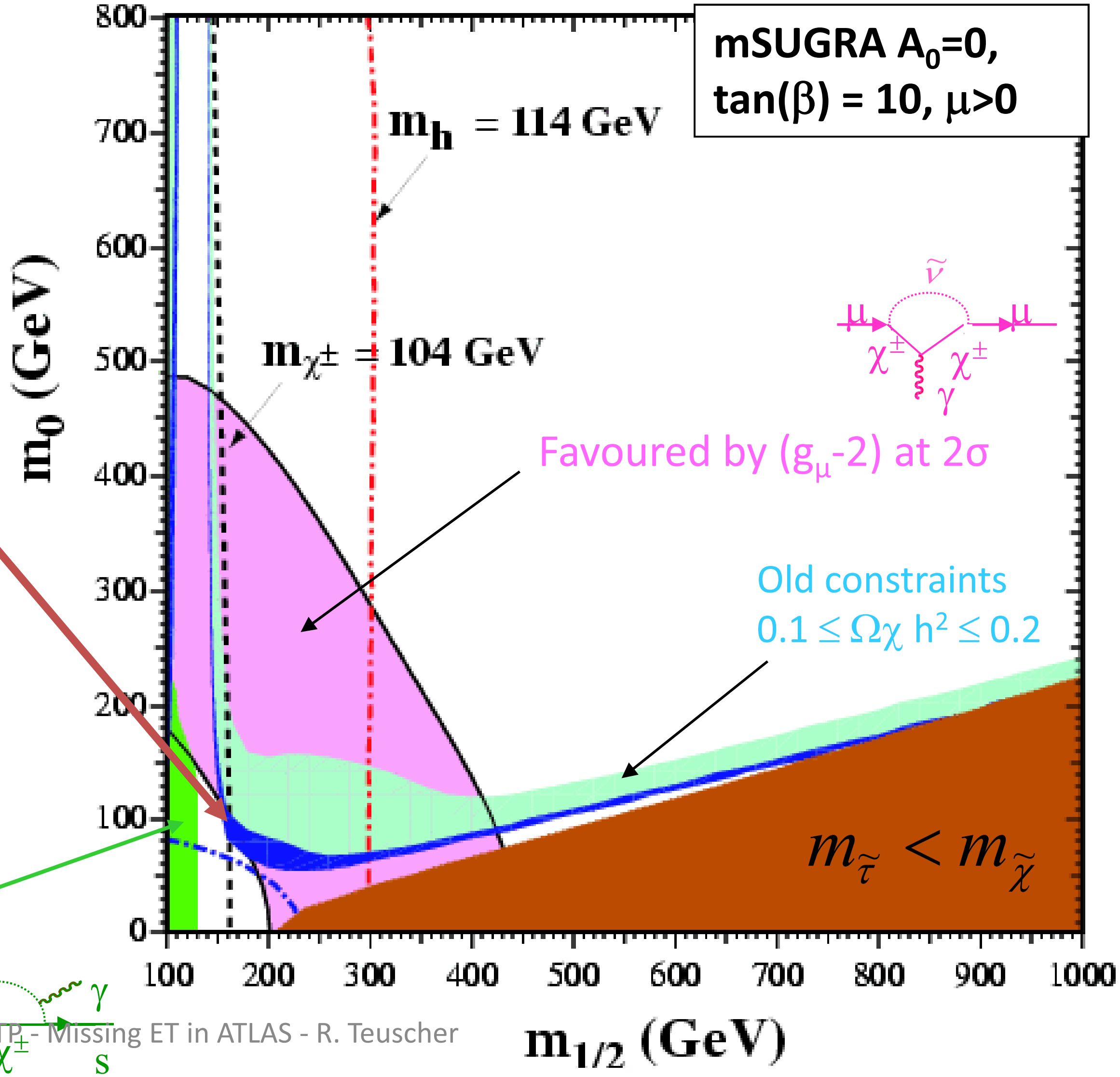




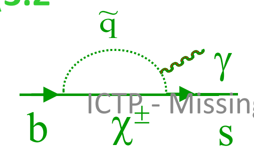
Constraints on SUSY

- SUSY is strongly constrained by cosmology – WMAP
  - New allowed region $0.094 \leq \Omega\chi\ h^2 \leq 0.129$
  - $\Omega\chi\ h^2 \sim m\chi\ n\chi$ (relic density) implies lighter neutralino
- Can we find SUSY?

Ellis et al. hep-ph/0303043



Region Disfavoured by BR ($b \to s\gamma$) = (3.2 ± 0.5) • 10^{-4} (CLEO, BELLE)



J. Wenninger
CERN, June 2009

LHC Luminosity targets

- The presently installed collimation system limits the total intensity to ≈10-20% of the nominal intensity.

- Possible performance for the 2009/2010 run (5 TeV/beam):

	No. bunches/ beam	Protons/ bunch	% of nominal intensity	Peak L (cm^{-2} s^{-1})
	43	5×10^{10}	0.7	$6.9\text{x}10^{30}$
	156	5×10^{10}	2.4	$5.0\text{x}10^{31}$
	156	1×10^{11}	4.8	$2.0\text{x}10^{32}$
	720 (50 ns)	5×10^{10}	11.1	$1.2\text{x}10^{32}$
DESIGN	2808	1.15×10^{11}	100	$1.0\text{x}10^{34}$

Int. luminosity target of 200-300 pb-1 is achievable with ~40% availability.

- One month Pb ion run foreseen end 2010.

Ion setup should be 'straight forward' as little difference wrt protons.

References

- ATLAS Collaboration (G. Aad *et al*), Expected Performance of the ATLAS Experiment, arXiv:0901.0512, CERN-OPEN-2008-020 (January 2009).
- ATLAS Collaboration (G. Aad *et al*), The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3: S08003 (2008).
- Public ATLAS Jet/MET results with cosmic ray data: https://twiki.cern.ch/twiki/bin/view/Atlas/ApprovedCosmicPlotsJetEtMiss