Missing Transverse Momentum at LHC

Donatella Cavalli
INFN Milano

CoEPP Tropical Workshop 2013

Sunday 7 July
to Friday 12 July

Cairns
Colonial Club Resort

Outline

- Missing transverse momentum (E_T^{miss}) at LHC:
  - Motivation for measuring E_T^{miss}
  - How it is defined and reconstructed

- E_T^{miss} challenge with LHC data:
  - Events cleaning
  - Pile-up

- Strategy for E_T^{miss} reconstruction and calibration:
  - Suppressing the pile-up effects

- How to study of E_T^{miss} performance:
  - Resolution
  - Scale
  - Tails

- E_T^{miss} systematic uncertainties

- Conclusions

Missing transverse momentum definition

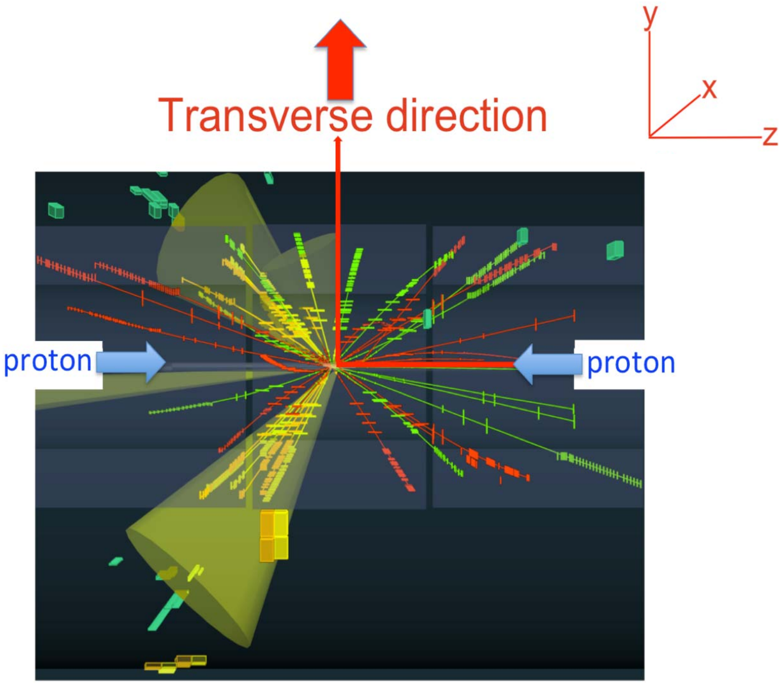
In a hadron collider event the **missing transverse momentum** (E_T^{miss}) is defined as the event momentum imbalance in the plane transverse to the beam axis, where momentum conservation is expected.
Such an imbalance may signal the presence of non detected particles, such as neutrinos and or new weakly-interacting particles

The two E_T^{miss} components, E_x^{miss} and E_y^{miss}, are calculated as the opposite sum of the momenta of all particles seen in the detector

$$\mathbf{E}^{\rm miss}_{\mathbf{x,y}} = -\sum_{\rm particles} \mathbf{p}_{\rm x,y}$$

$$\mathbf{E}^{\rm miss}_{\rm T} = \sqrt{(\mathbf{E}^{\rm miss}_{\mathbf{x}})^2 + \left(\mathbf{E}^{\rm miss}_{\mathbf{y}}\right)^2}$$

$$\sum \mathbf{E}_{\rm T} = \sum_{\rm particles} \mathbf{p}_{\rm T}$$



Motivation for measuring E_T^{miss}

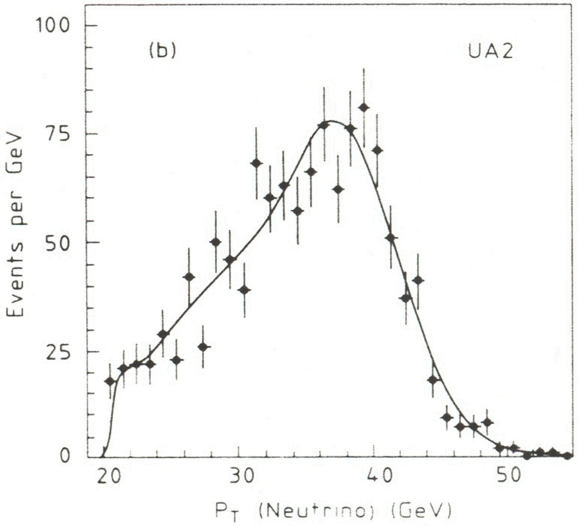
E_T^{miss} is due to non-interacting particles in detector (ν, LSP) $\Rightarrow$ **True $E_T$miss**

➔ A very good measurement of E_T^{miss}, i.e. of $p_T\nu$, is a crucial requirement for the **study of many physics measurements**

- W→lν, semi-leptonic top decays, Z→$\tau\tau$

CERN $\mathbf{p\overline{p}}$ collider 630 GeV
UA2 Collaboration
Measurement of W mass

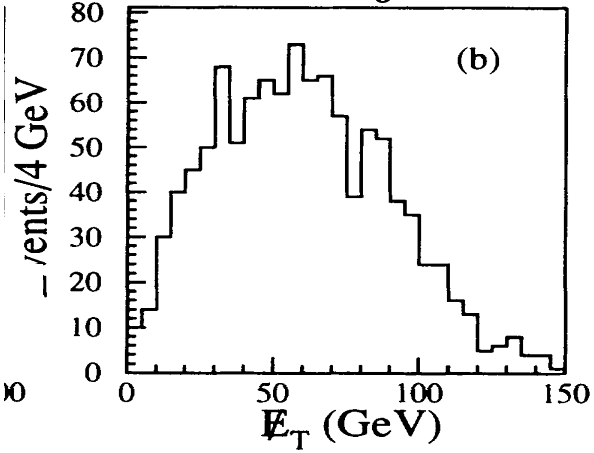
$\mathbf{W \to e\nu}$



Phys. Lett. B 241 (1990)

Tevatron $\mathbf{p\overline{p}}$ collider 1.8 TeV
CDF Collaboration
Top quark discovery

$\mathbf{t\bar{t} \to \ell\nu + jets}$



Phys. Rev. D 50 (1994)

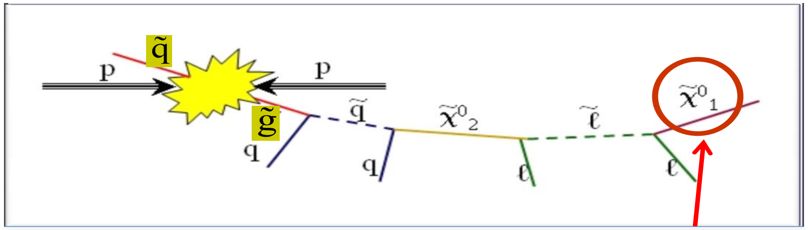
Motivation for measuring E_T^{miss}

$E_T$miss is due to non-interacting particles
in detector (ν, LSP) ⇒ **True $E_T$miss**

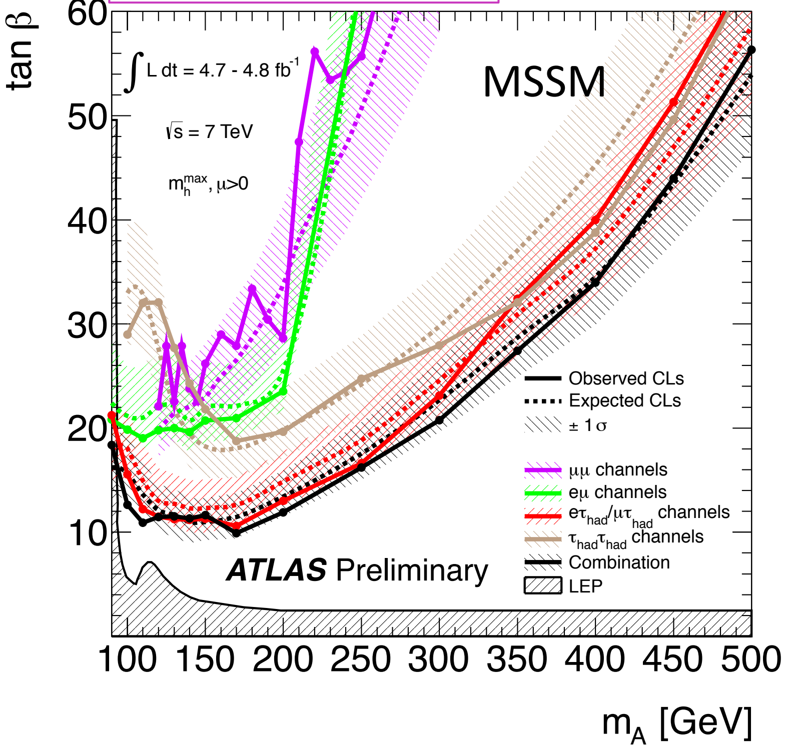
➔ E_T^{miss} plays a major role for the physics at LHC

➔ A very good E_T^{miss} measurement, i.e. of $p_T\nu$ or of p_T(lsp) is a crucial requirement for the study of many physics measurements **and for discovery physics**

- W→lν, top decays, Z→$\tau\tau$
- SM Higgs (H→$\tau\tau$, H→WW→lνlν/lν+jets)
- MSSM Higgs (A/H→$\tau\tau$, $H^\pm$→$\tau\nu$)
- Higgs to invisible decays
- SUSY → Large E_T^{miss} signature from lsp



ATLAS-CONF-2012-094



In H→$\tau\tau$ events can reconstruct the invariant $\tau\tau$ mass from the two E_T^{miss} components

E_T^{miss} reconstruction and calibration

E_T^{miss} is a complex event quantity:

- It is calculated adding all significant signals from all detectors
  - Calorimeter input signals (from charged and neutral particles)
    - used to reconstruct high p_T physics objects (e, γ, τ, jets)
    - not used in high p_T physics objects
  - Muons
  - Reconstructed tracks (from charged particles)
- Avoid double counting
- Coherent Calibration

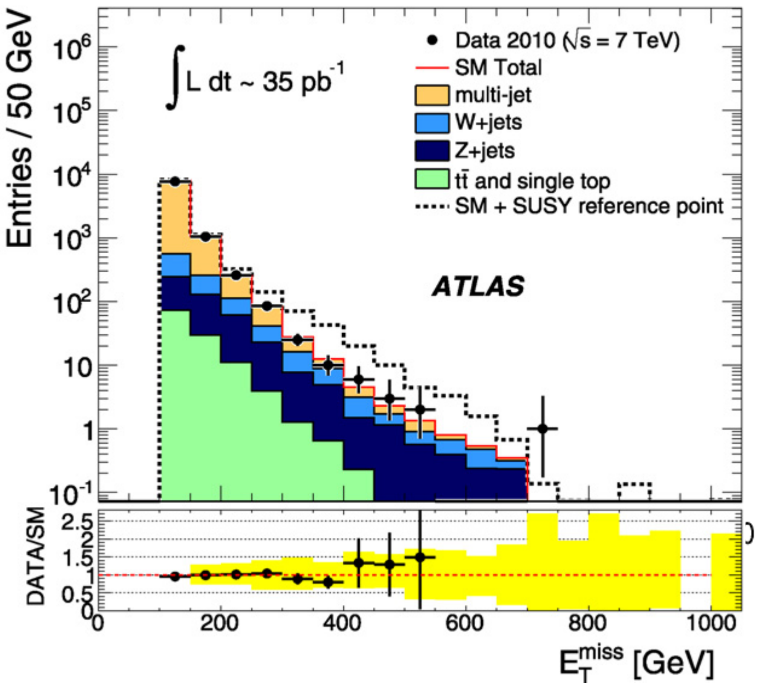
Fake E_T^{miss}

E_T^{miss} is due to non-interacting particles, BUT
E_T^{miss} can also due to:

- Problems in detector:
  - dead, hot, noisy channels
- Backgrounds:
  - cosmic rays, beam-halo, beam-gas
- Cracks/gaps in the detector, azimuthal response variations
- Energy lost in dead materials (cracks, cryostats..)
- Noise, pile-up noise
- Mis-measurements of muons, jets

⇒ **“Fake” E_T^{miss}**

Phys. Lett. B 701 (2011) 186



⇒ First require detailed understanding of instrumental E_T^{miss} sources

→ Event Cleaning

⇒ Then understand other source of “fake” E_T^{miss}

⇒ Suppress pile-up at LHC !

➔QCD with “fake” $E_T$miss are background for inclusive no-lepton SUSY events
Can fake “new physics”

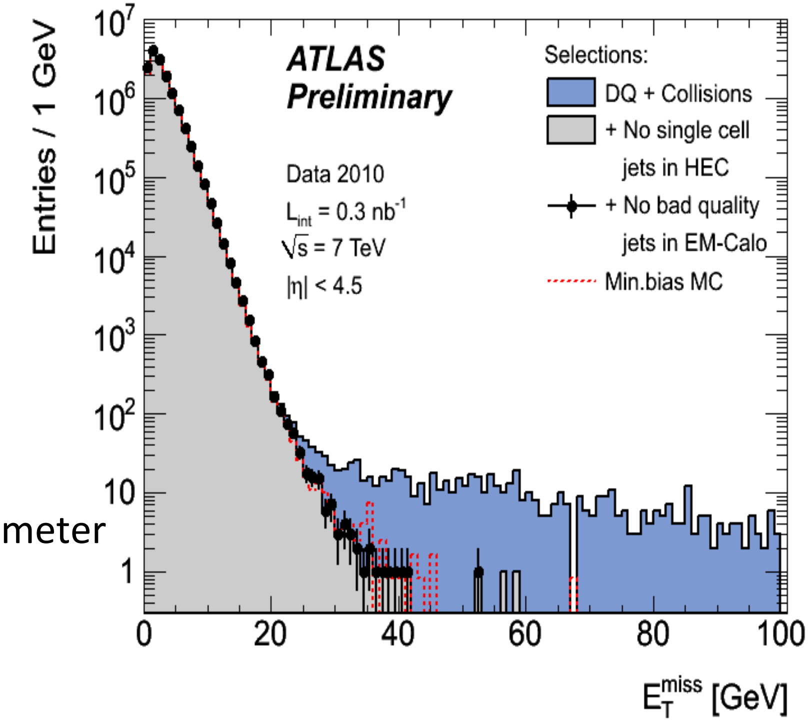
➔understanding this background is crucial for SUSY searches !

Data-quality requirements and Event cleaning

Data-quality (detector level)

- Stable proton beams, nominal magnetic field conditions.
- NO detector problems: use only data with a fully functioning calorimeter, inner detector and muon spectrometer

ATLAS-CONF-2010-038



Cleaning (event level)

Discard events with bad jets:

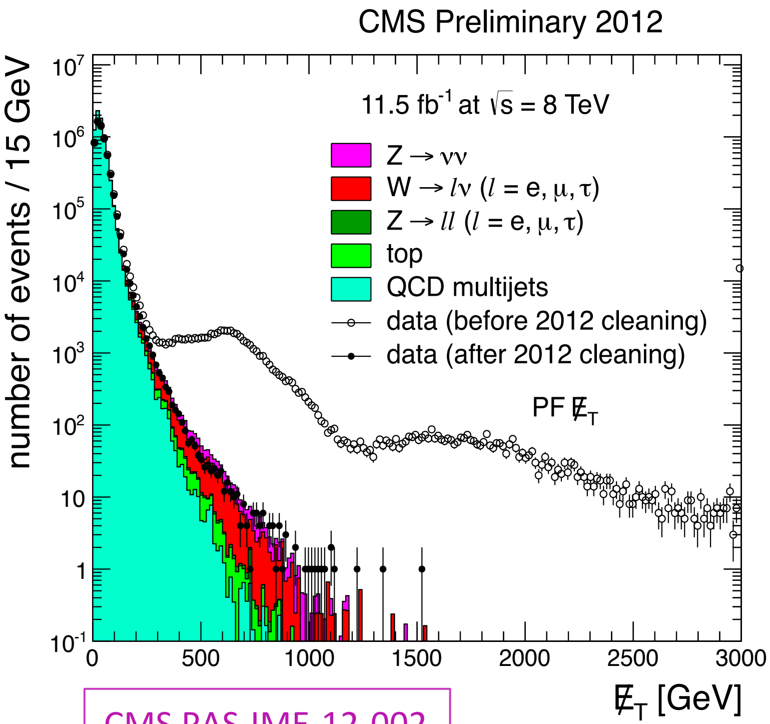
→Jets due to non-collision background

- Beam-gas events
- Beam-halo events
- Cosmic ray muons overlapping in-time with collision events

→Jets from calorimeter noise

- **Sporadic noise bursts** in the hadronic endcap calorimeter
  - few noisy calorimeter cells contribute to almost all of the jet energy.
- **Coherent noise** in the electromagnetic calorimeter.

Event cleaning



CMS PAS JME-12-002

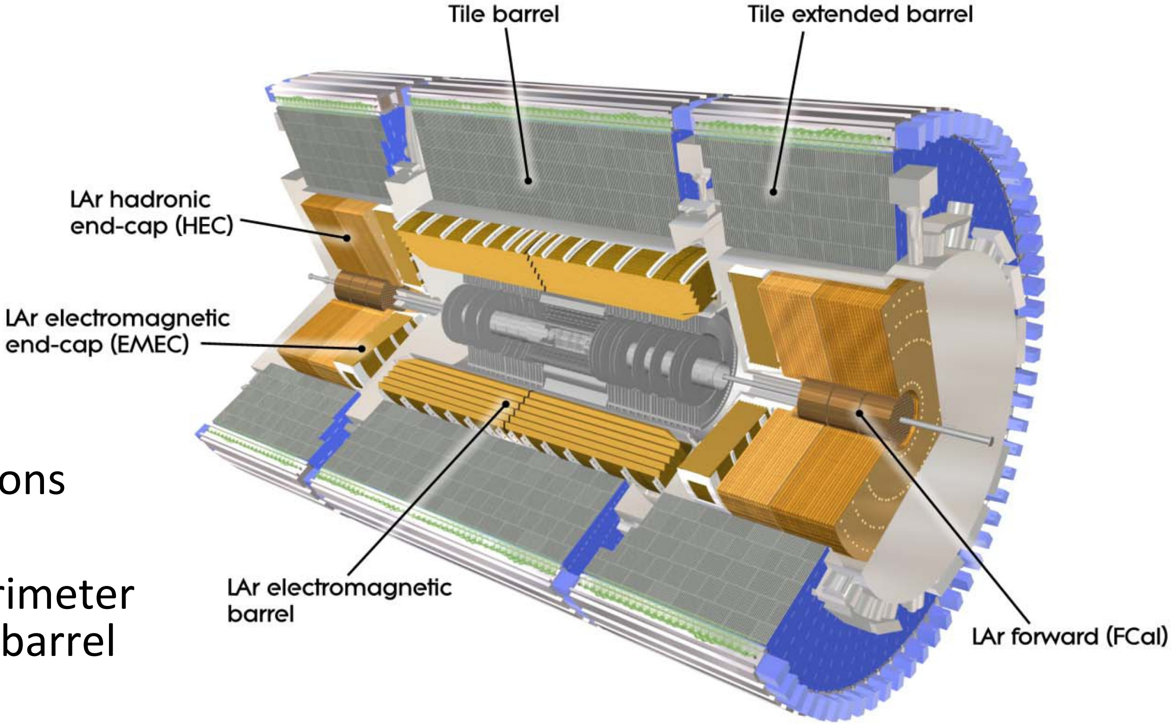
- Anomalous high E_T^{miss} events in data before 2012 cleaning mainly come from:
  - Misfires of the HCAL laser calibration system
  - Electronic noise in HCAL
  - Fake E_T^{miss} from track reconstruction

- Few remaining anomalous events are removed by applying jet identification cut
  - neutral hadron energy fraction of the jet < 0.90
  - photon energy fraction < 0.95

ATLAS calorimeters

Main features for E_T^{Miss} reconstruction and calibration:

- Noise suppression
- Non-compensating (e/h >1) :
  - Response to hadrons is lower than that to electrons and photons
  - Developed specific calibrations
- Dead material:
  - Energy loss before EM calorimeter and between EM and HAD barrel calorimeters:
    - dead material corrections
- Different technologies and many transition regions:
  - "Crack" regions: $\eta \approx 1.4, 3.2$
- Magnetic field bending



ATLAS Fiducial Regions

- Hadronic Calorimeter:
  - Barrel: $|\eta| < 1.7$
  - Endcap: $1.5 < |\eta| < 3.2$
- Electromagnetic Calorimeters
  - Barrel: $|\eta| < 1.4$
  - Endcap: $1.375 < |\eta| < 3.2$
- Forward: $3.2 < |\eta| < 4.9$

$\eta = -\log(\tan(\theta/2))$

Calorimeter input signals to E_T^{miss}

- **Hard signal in calorimeters**
  Fully reconstructed & calibrated particles and jets
  → detector inefficiencies already corrected for physics objects
  → have to avoid mis-measured objects
- **Soft signals in calorimeters**
  Signals not used in reconstructed physics objects
  → need to be included in E_T^{miss} to reduce scale biases and improve resolution
  → need to suppress noise (electronic and pile-up noise)
    - Applying symmetric or asymmetric noise cuts to cell signals can introduce a bias
    - Topological clustering applies more reasonable noise cut
  → need to be calibrated
    - low-pT particles can easily be lost due to magnetic field or because their energy does not survive noise cuts → use tracks to correct for calorimeter inefficiency
- **Need to avoid double counting**
  Same signal can only be used in one physics object
  → Veto E_T^{miss} contribution from already used signals

UA2: The neutrino transverse momentum was estimated from the transverse component of the momentum balance of the electron and of the calorimeter calibrated cells.
To avoid double counting the cells in the electron core are not used.

Fake E_T^{miss} from jets mis-measurement

Fake E_T^{miss} can be created by mis-measurement of any objects:
electrons, photons, taus, muons and hadronic jets.

In particular jet mis-measurement can be a dangerous source of fake E_T^{miss},
→ suppression strategies are needed

- Mis-measured jets in cracks → event topology analysis
- Jet leakage from the calorimeters or fluctuations in large jet energy deposits in non-instrumented regions → check energy sharing between calorimeters
- Jets mis-calibration → compare with track jets

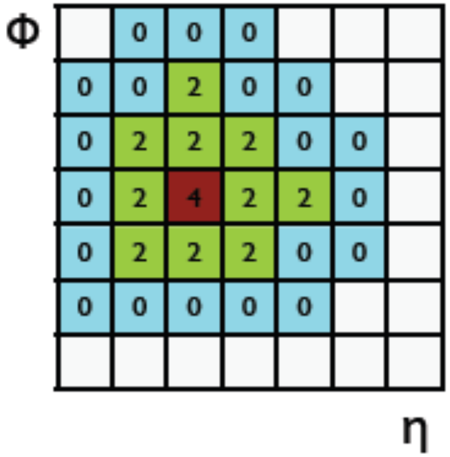
→ Generates E_T^{miss} pointing to this jet:
  - study angular correlation between E_T^{miss} and jets

→ Careful analysis of full event topology

Calorimeter noise-suppressed input signals to E_T^{miss}

Topoclusters: group of calorimeter cells topologically connected optimized for electronic noise and pile-up suppression

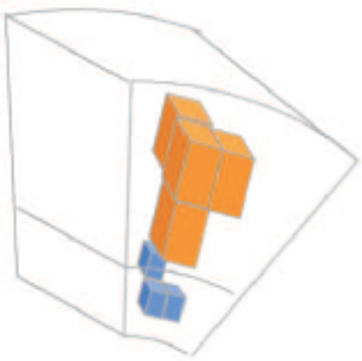
- Cluster cells in 3D via noise-driven thresholds:
  - Seed: $|E_{cell}| > 4\ \sigma_{noise}$
  - Neighbours: $|E_{cell}| > 2\ \sigma_{noise}$
  - Perimeter cells $|E_{cell}| > 0$
  - $\sigma_{noise} = \surd\,(\sigma_{noise}^{electronic})^2 + (\sigma_{noise}^{pile\text{-}up})^2$



Φ		0	0	0			
	0	0	2	0	0		
	0	2	2	2	0	0	
	0	2	4	2	2	0	
	0	2	2	2	0	0	
	0	0	0	0	0		
							η

Topoclusters calibration (Local Hadron Weighting- LCW)

- Classifications as “em-like” or “hadron-like” clusters based on cluster shape variables: energy density and depth.
- Hadronic weights, derived from pion MC simulation, applied to “hadron-like” clusters.
- Corrections for dead material and out of cluster



- No bias. Cells with very small signals can survive based on the signals in neighboring cells
- Improve correspondence between clusters and stable particles
- Intrinsically noise and pile-up suppressed, but contribution from pile-up fluctuations can survive, more pile-up suppression techniques needed

Input Muon signals to E_T^{miss}

- **Hard signal in muon spectrometer**

  Fully reconstructed & calibrated muons

  → Any muons which are not reconstructed, badly measured or fake can be a source of fake E_T^{miss}!

  - includes all muons reconstructed in muon spectrometer
    - use tracks in the region of inefficiency of muon spectrometer
  - Choose best measurement
  - Apply quality criteria to avoid bad-measured muons
  - Have to avoid fake muons:
    - Fake muons from jet punch-through

→ Muons may generate isolated or embedded soft calorimeter signals

- Care needed to avoid double counting

subtract muon energy deposited in calorimeters when the combined muon momentum (from muon spectrometer and inner detector) is used)

CDF: E_T^{miss} is defined to be the negative of the vector sum of transverse energy in calorimeter towers.
For events with muon candidates, the vector sum of the calorimeter transverse energy is corrected by vectorially subtracting the energy deposited by the muon and then adding the PT of the muon candidate as measured in the CTC.

E_T^{miss} reconstruction and calibration in ATLAS

Electrons

Photons

Taus

Jets
pT>20 Gev

Muons

Topoclusters and tracks not in objects

- → Selection of input physics objects: order is defined by reconstruction uncertainties
- → Decomposition into constituent topo-clusters to veto multiple contributions and avoid energy double counting
- → Calibration dependent on the object
- →Topoclusters+tracks not associated to physics objects form the Soft term
- → Keep separate contributions calculated from the negative sum of calibrated $p_{x(y)}$ of physics objects and soft energy

$$E_{x(y)}^{\mathrm{miss}} = E_{x(y)}^{\mathrm{miss},e} + E_{x(y)}^{\mathrm{miss},\gamma} + E_{x(y)}^{\mathrm{miss},\tau} + \boxed{E_{x(y)}^{\mathrm{miss,jets}} + E_{x(y)}^{\mathrm{miss,\ Soft\ Term}}} + E_{x(y)}^{\mathrm{miss},\ \mu}$$

$$E_T^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

$$\Sigma E_T = \Sigma E_T^{e} + \Sigma E_T^{\gamma} + \Sigma E_T^{\tau} + \Sigma E_T^{\mathrm{jets}} + \Sigma E_T^{\mathrm{Soft\ Term}} + \Sigma E_T^{\mu}$$

highly affected by pileup

Very *flexible algorithm*: different definitions and calibrations for physics objects are allowed
Coherence with Physics analysis

The ATLAS Soft Term algorithm

(1) Track selection

All reconstructed tracks

Apply quality criteria
Veto on tracks associated to high physics objects
Veto on tracks associated to TopoClusters already used

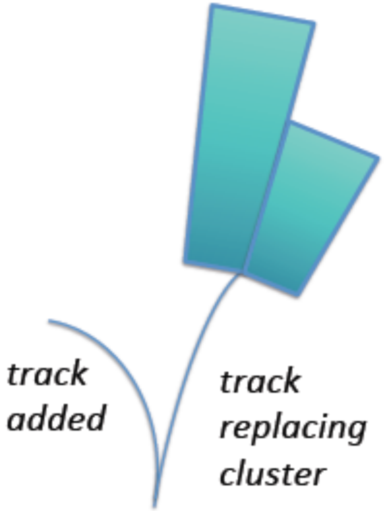
Add good tracks to E_T^{miss} calculation

(2) Cluster removal

All TopoClusters not associated to physics objects

Veto on TopoClusters associated to good tracks

Add remaining TopoClusters to E_T^{miss} calculation



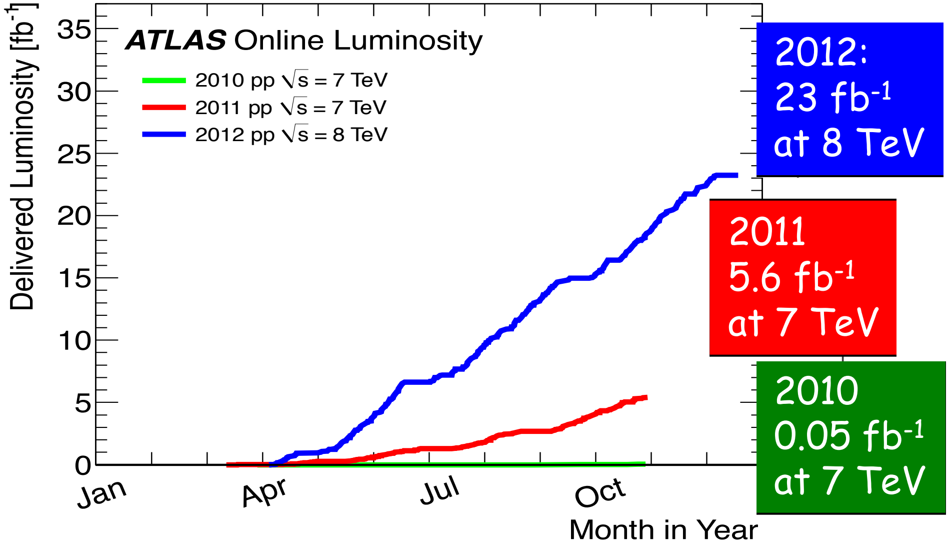
- ➔ Improve calculation of the low contribution to Soft Term
- ➔ Tracks are added to recover the contribution from low-p_T particles which do not reach the calorimeter or do not seed a TopoCluster.
- ➔ No association with PV => no pile-up suppression at this level

The pile-up

- ➔ The LHC luminosity increased from 2010 to 2012

LHC
Up to
L_{peak} $7.7 \cdot 10^{33}$ $cm^{-2} \cdot s^{-1}$
in 2012 at 8 TeV

ATLAS
~90% of delivered luminosity used in physics analyses



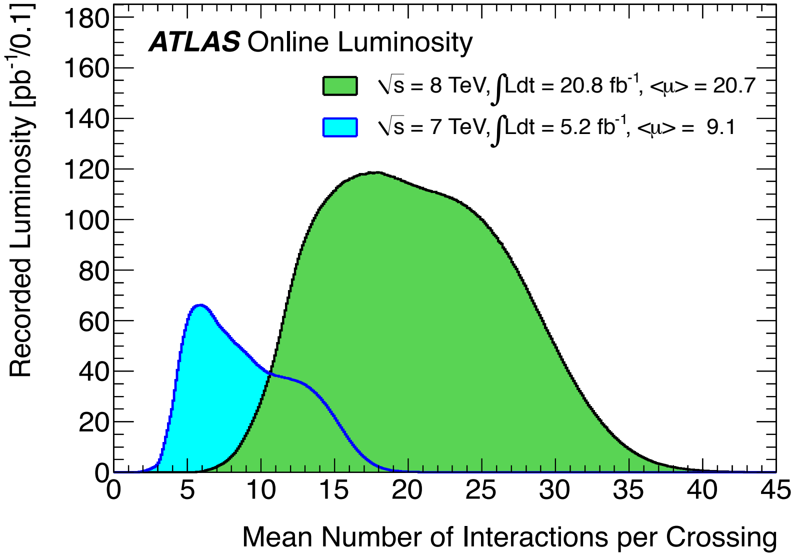
2012:
23 fb^{-1}
at 8 TeV

2011
5.6 fb^{-1}
at 7 TeV

2010
0.05 fb^{-1}
at 7 TeV

- ➔ The Pile-up, i.e. the contribution of additional pp collisions superimposed to the hard physics process, is the price to pay for this!

$$\langle\mu\rangle = L \times \sigma_{inel} \,/\, N_{bunch} \times f_{LHC}$$

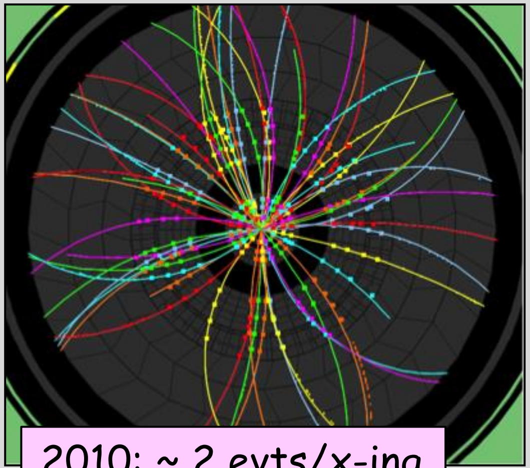


COEPP 2013

The pile-up

Pile-up is one of the main challenges for E_T^{miss} at LHC

- E_T^{miss} has the largest acceptance (coverage area) of any given reconstructed quantity.
- Considerable contribution to E_T^{miss} (and jets) fluctuations from pile-up


2010: ~ 2 evts/x-ing


2011: ~ 10 evts/x-ing


2012: ~ 20 evts/x-ing

Pile-up suppression in jets in ATLAS

Jets are corrected for pile-up using Jet Area

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \boxed{\rho A}$$

Jet Area based on the idea that noise (pile-up) has a lower p_T density (ρ) than signal:

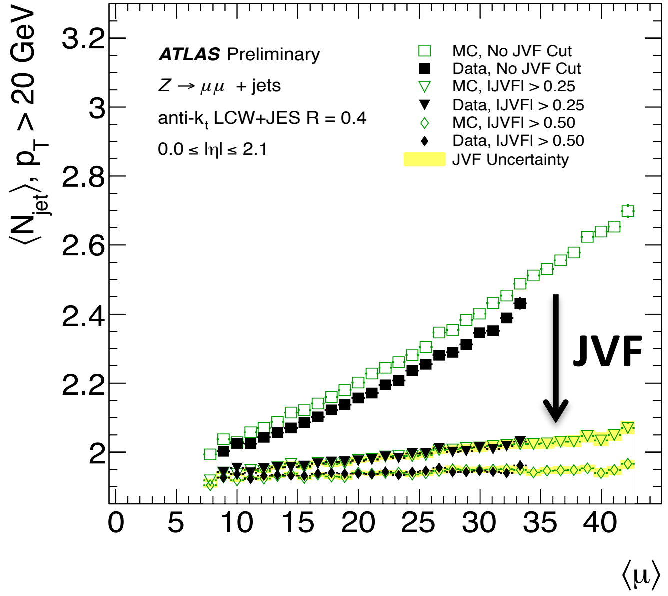
- **event p_T density ρ** is calculated from all jets (k_t jets) as median (p_T^{jet}/A^{jet})
- Each jet is then corrected subtracting ρA where **A is the jet area**

- Jet-by-jet subtraction => improves jet resolution
- Captures event-by-event fluctuations
- Data driven method: no dependence on pile-up modelling

Some pile-up jets remain after subtraction
→ Further pile-up suppression using tracks associated with the primary vertex (**Jet Vertex Fraction JVF**)

$$\mathrm{JVF} = \sum_{\mathrm{tracks_{jet},PV}} p_{\mathrm{T}} / \sum_{\mathrm{tracks_{jet}}} p_{\mathrm{T}}$$

If p_T^{jet}<50 GeV and |η|<2.4, keep jet only if |JVF|>0



Pile-up suppression in soft term in ATLAS

Soft Term is very similar to pile-up, so any correction should be based or on PV association or on exploiting the small difference between signal and pile-up

STVF is a correction based on *fraction of tracks from PV*:

$$\mathrm{STVF} = \sum_{\mathrm{tracks}_{\mathrm{SoftTerm}},\mathrm{PV}} p_{\mathrm{T}} / \sum_{\mathrm{tracks}_{\mathrm{SoftTerm}}} p_{\mathrm{T}}$$

use *tracks not matched to high-pT physics objects*

PV is the the first primary vertex (vertex with max $\Sigma p_{T\_trk}^2$)

SoftTerm scaled by the "soft term vertex fraction" STVF

- Limitations: calculated in limited coverage (ATLAS ID $|\eta| < 2.5$) and does not take into account neutral contributions

- **Jet Area** is based on the idea that noise (pileup) has a lower density (ρ) than signal
- Similar to pile-up subtraction in jets
- Here "jet" means: jet $0<p_T<20$GeV

For each event compute the pT density ρ_{ref} (estimate of event-by-event pile-up activity)
→ ***reclusterize jets*** from topoclusters and tracks from soft term with k_t algorithm

$$E_{T,jet}^{corr} = \begin{cases} 0 & E_{T,jet} \leq N\rho_{ref}A_{jet} \\ E_{T,jet} - \rho_{ref}A_{jet} & E_{T,jet} > N\rho_{ref}A_{jet} \end{cases}$$

\+ Filter jets asking for |JVF|>0.25

- captures event-by-event fluctuations
- jet-by-jet correction

p_T^{miss} reconstructed from tracks in ATLAS

Sum of pT of all **tracks from the PV** that pass the following standard criteria:

- $p_T > 500$ MeV
- at least 1 pixel hit and 6 SCT hits
- $|\eta| < 2.5$
- $|d_0| < 1.5$ mm
- $|z_0 \sin\theta| < 1.5$ mm

PV association

+

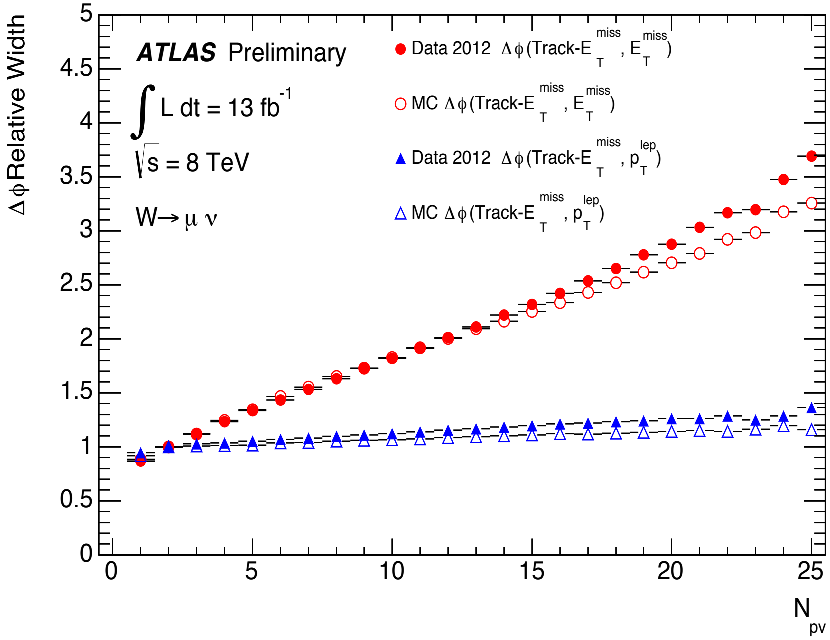
Tracks of any muons passing:

- Staco Combined
- $p_T > 6$ GeV
- $|\eta| < 2.5$

Tracks of any electrons passing:

- Medium++
- $p_T > 10$GeV
- $|\eta| < 2.47$

- Good ***stability vs pileup***
- ***Limited acceptance*** ($|\eta| < 2.5$, no neutrals) → performance degradation in events with jets



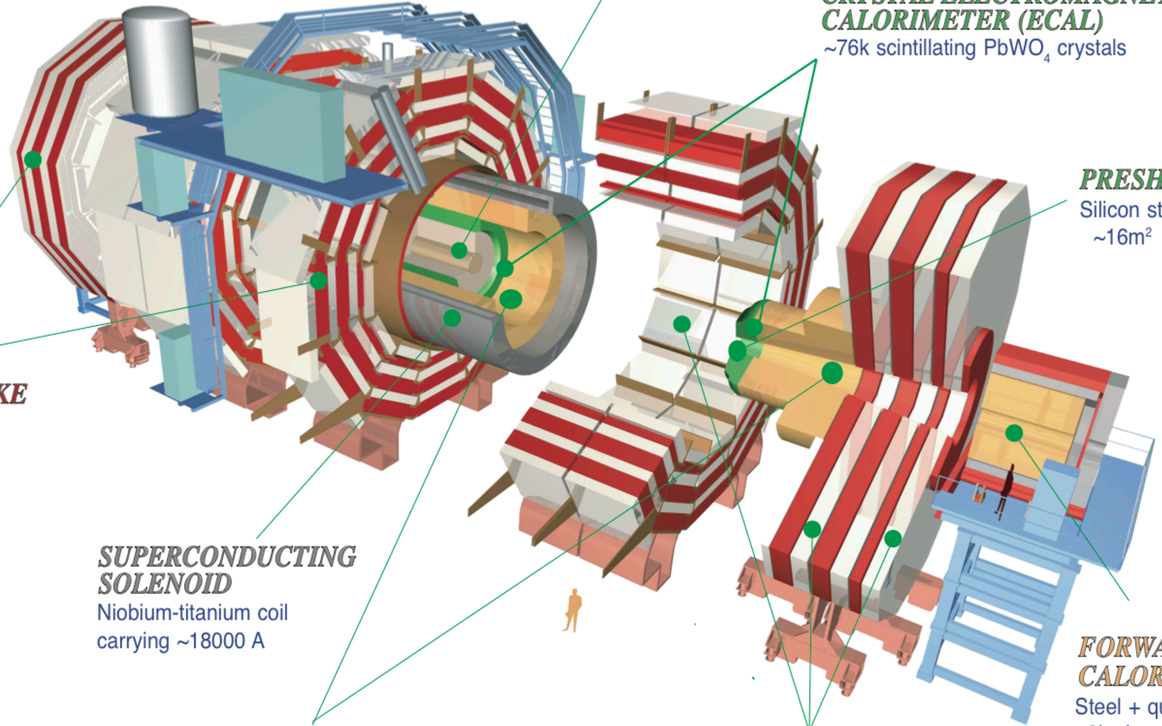
Width of $\Delta\phi(p_T^{miss}, p_T^{\mu})$ in $W \to \mu\nu$

$$p_{T_{miss}} = \sqrt{p_{x_{miss}}^2 + p_{y_{miss}}^2}$$

Compact Muon Solenoid (CMS)

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm^2)
~$1 m^2$ ~66M channels
Microstrips (80-180μm)
~$200 m^2$ ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~$16 m^2$ ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

MET reconstruction algorithms

Particle-Flow (PF) MET

$$\vec{\not{E}}_T = -\sum_{\text{pf-candidates}} \vec{p_T}$$

- ★ negative of the vector sum over all transverse momentum of PF-candidates
- ★ used in most current CMS analyses

New

No-PU PF MET

- ★ divide PF particles into: particles from hard scattering and particles from pile-up
- ★ contribution from “pile-up” particles is scaled down
- ★ re-calculate MET from two particles categories above

MVA PF MET

- ★ multivariate regression (BDT) that produces a correction for the hadronic recoil
- ★ 5 MET variables calculated from PF particles
- ★ Trainings have been done to optimize the MET resolution

The No-PU PF MET algorithm

★ **Principle:** divide PF particles into two categories

- **PF particles from hard scatter interaction (HS particles):** leptons/photons, PF particles within jets of $p_T > 30$ GeV and pass the MVA PU-jet ID, charged hadrons not clustered within jets of $p_T > 30$ GeV and associated to the HS vertex
- **PF particles from pile-up (PU particles):** charged hadrons that are neither within jets of $p_T > 30$ GeV nor associated to the HS vertex, neutral PF particles within jets of $p_T > 30$ GeV, PF particles within jets of $p_T > 30$ GeV and fail the MVA PU-jet ID

★ PF particles from pile-up are scaled down by a factor :

$$S_{\mathrm{F}} = \frac{\sum_{\text{HS-charged}} p_{\mathrm{T}}}{\sum_{\text{HS-charged}} p_{\mathrm{T}} + \sum_{\text{PU-charged}} p_{\mathrm{T}}}.$$

★ No-PU PF MET is computed from :

$$\begin{aligned} \vec{\not{E}}_{\mathrm{T}} = & -\Bigg[\sum_{\text{leptons}} \vec{p}_{\mathrm{T}} + \sum_{\text{HS-jets}} \vec{p}_{\mathrm{T}} + \sum_{\text{HS-charged}} \vec{p}_{\mathrm{T}} \\ & + S_{\mathrm{F}} \cdot \Bigg(\alpha \cdot \sum_{\text{PU-charged}} \vec{p}_{\mathrm{T}} + \beta \cdot \sum_{\text{neutrals}} \vec{p}_{\mathrm{T}} + \gamma \cdot \sum_{\text{PU-jets}} \vec{p}_{\mathrm{T}} + \delta \cdot \vec{\Delta}_{\mathrm{PU}} \Bigg) \Bigg]. \end{aligned}$$

$\alpha,\beta,\gamma,\delta$ optimized on Z → μμ to get the best MET resolution

E_T^{miss} Performance evaluation

Performance has to be studied in terms of:

- Resolution (important for mass reconstruction in decays to non detected particles)
- Scale (important for mass reconstruction and when applying threshold cuts on E_T^{miss})
- Tails (NO fake E_T^{miss})

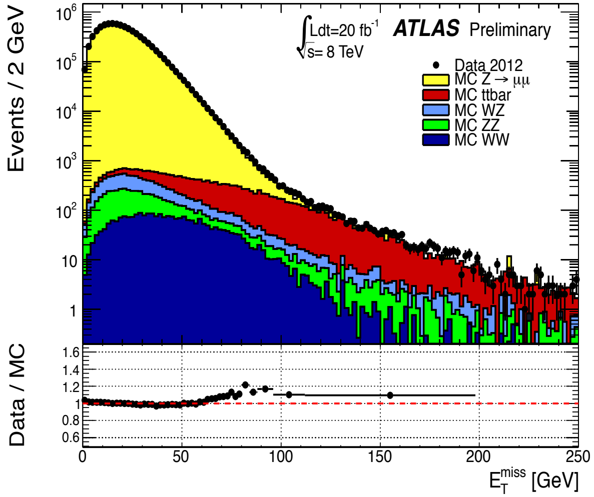
- Agreement between data and MC simulation

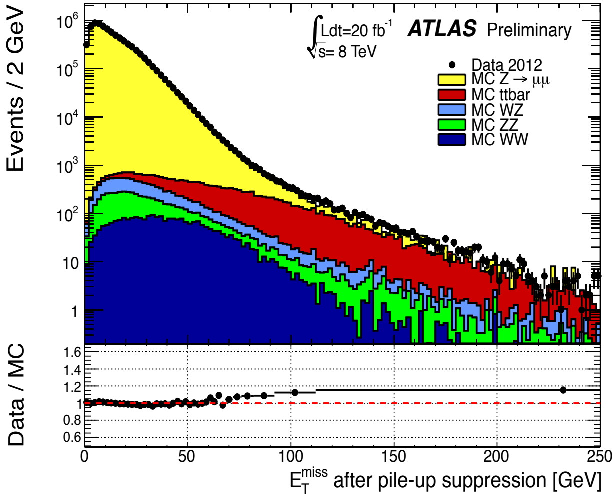
Data-MC comparison

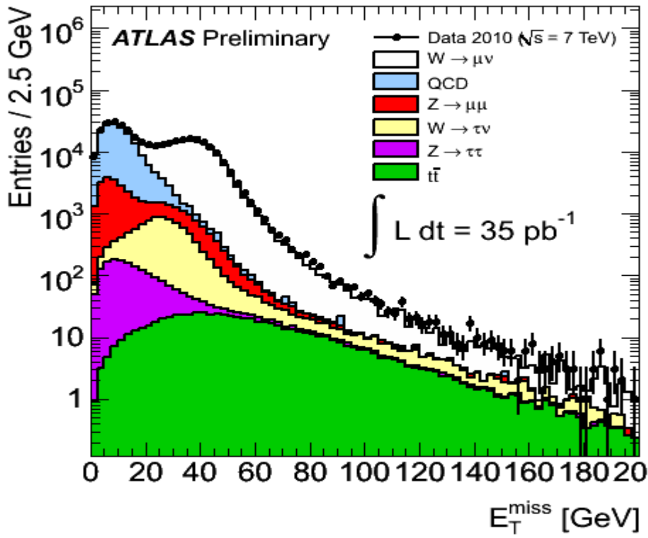
Important to understand $\mathbf{E_T^{miss}}$ both in data and simulation

- Check if the data are well described by MC simulation
- Check that there are no tails from fake $\mathbf{E_t^{miss}}$ in events where no true $\mathbf{E_T^{miss}}$ is expected

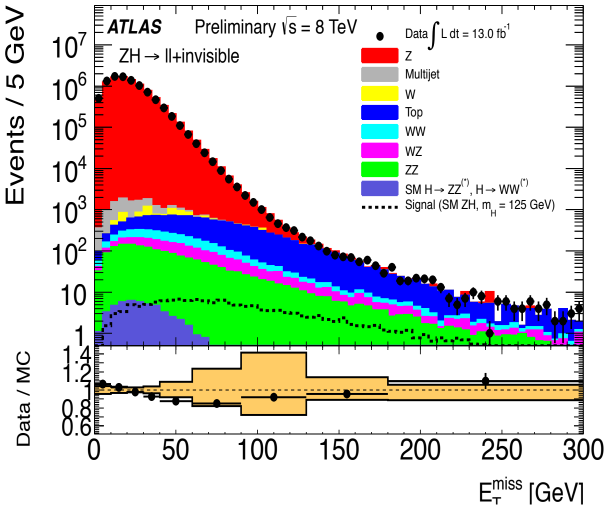
Data-MC comparison ATLAS

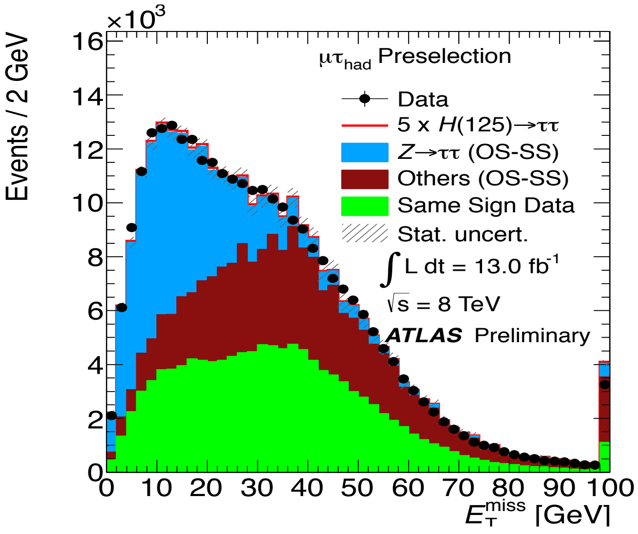


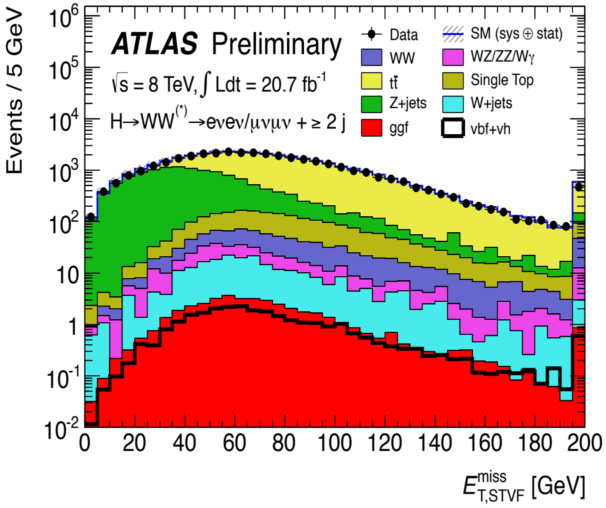




Events in tails are compatible with physics signal candidates involving real E_T^{miss}… Very few additional tails after pile-up suppression







MC simulation describes data well.

E_T^{miss} Resolution

- The E_T^{miss} measurement is obtained from what is seen in the detector, so it depends on the total transverse energy measured in the detector, mainly on the total transverse energy in calorimeters (the muon momenta are better measured)

The resolution of the two E_T^{miss} components is estimated from the width of the distributions $(E_x^{\rm miss}$ -$E_x^{\rm miss,True}$, $E_y^{\rm miss}$ -$E_y^{\rm miss,True})$

  - It is studied as a function of ΣE_T
  - The stability of the resolution vs the pile-up can be studied looking at its dependence on <μ> or on the number of reconstructed vertices Npv.

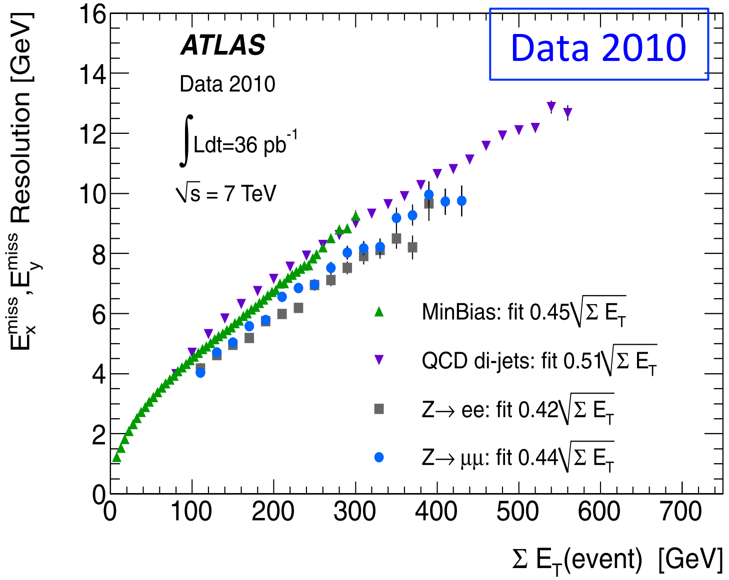
Can be studied in:

- data in events with NO true E_t^{miss}
- in events with true E_T^{miss}, the resolution can be directly studied only in MC

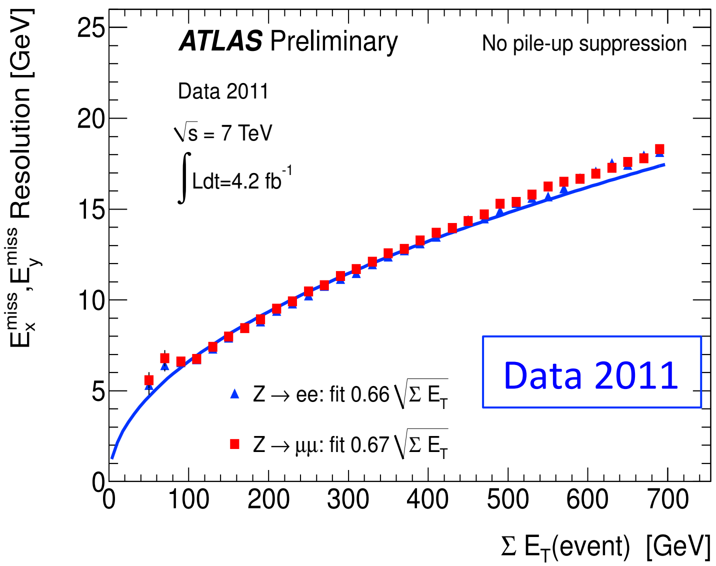
→Importance of E_T^{miss} resolution in mass reconstruction in H→ττ

Resolution vs ΣE_T in data at 7 TeV

EPJ - C 72 (2012) 1844



ATLAS-CONF-2012-101



E_T^{miss} resolution highly affected by pile-up

→ fitting with $\sigma = k \cdot \sqrt{\Sigma E_{\mathrm{T}}}.$

k ~ 0.5 Gev$^{1/2}$ in 2010, ~ 0.7 Gev$^{1/2}$ in 2011

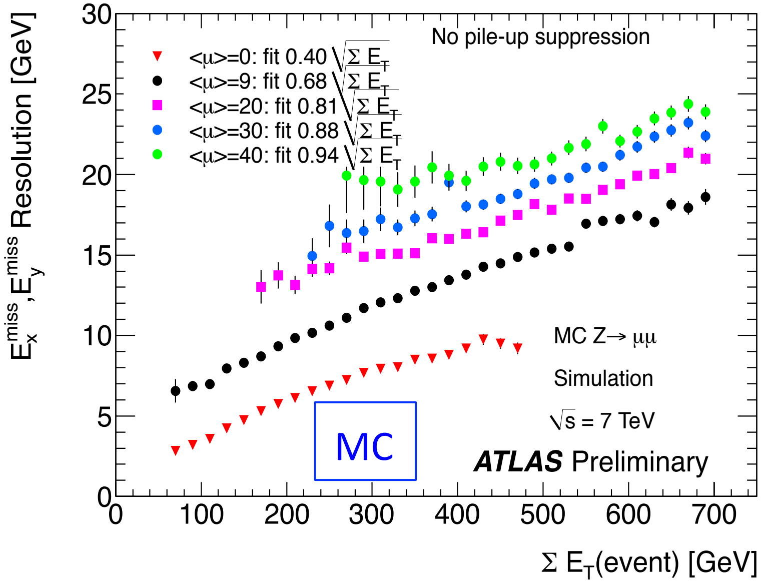
Effect of pile-up on Resolution

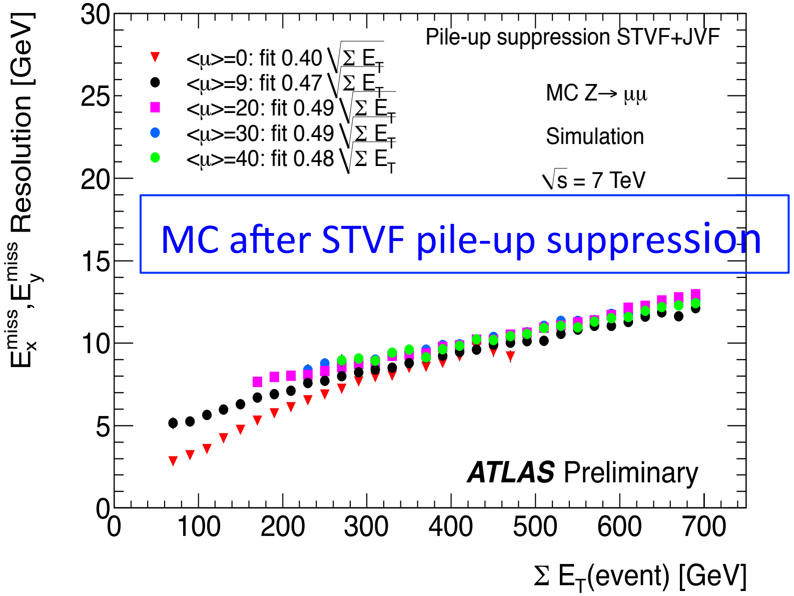
ATLAS-CONF-2012-101

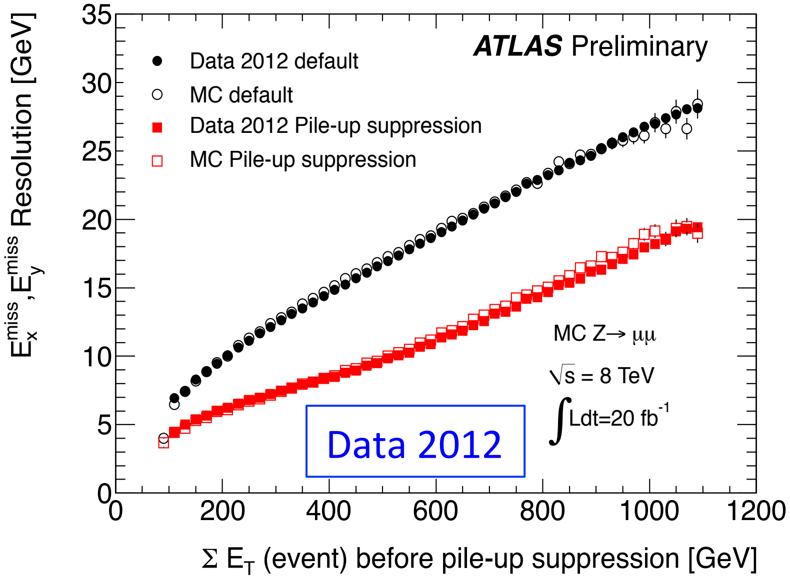
Study of resolution with increasing pile-up conditions:

- $E_{x,y}^{miss}$ resolution **doubles** from <μ> = 0 to 20 (2012 pile-up conditions)

→ $\sigma(E_x^{miss}, E_y^{miss}) = (0.4\,\mathrm{GeV}^{1/2} + 0.09\,\mathrm{GeV}^{1/2}\cdot\sqrt{\mu})\cdot\sqrt{\Sigma E_T},$



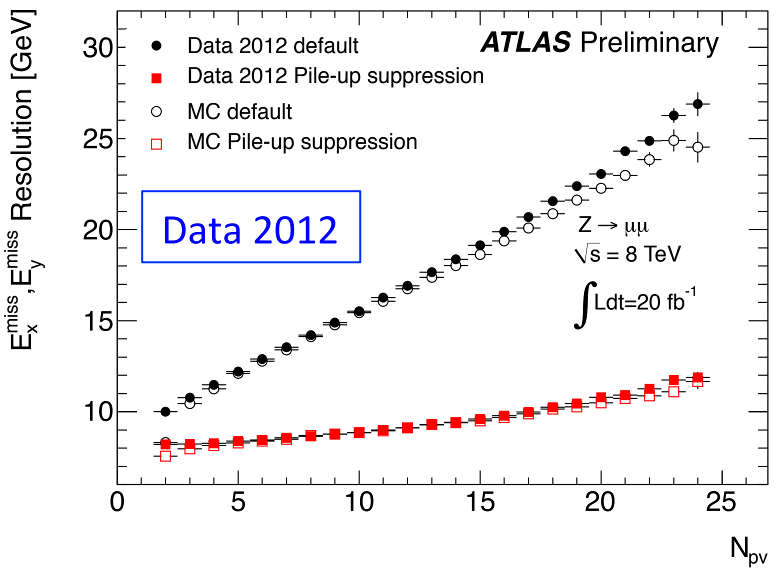




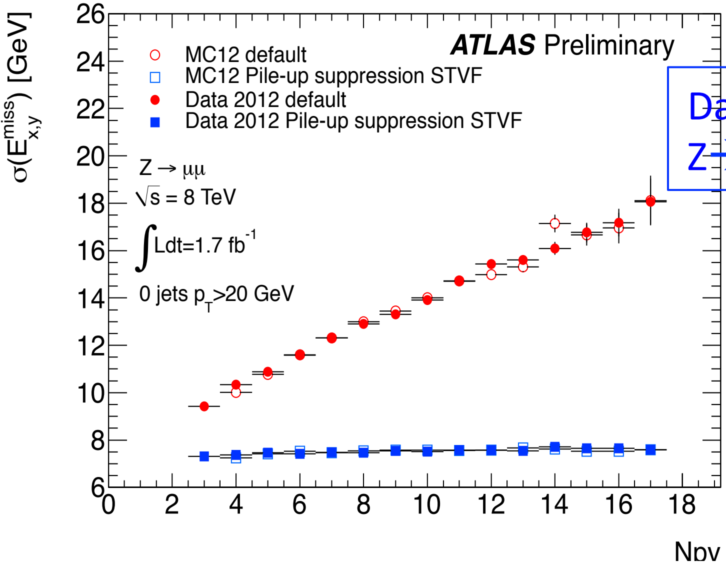
- $E_{x,y}^{miss}$ resolution closer to the resolution in after pile-up suppression with STVF

Resolution after pile-up suppression in data at 8 TeV

STVF method: Resolution less dependent on Npv



Data 2012

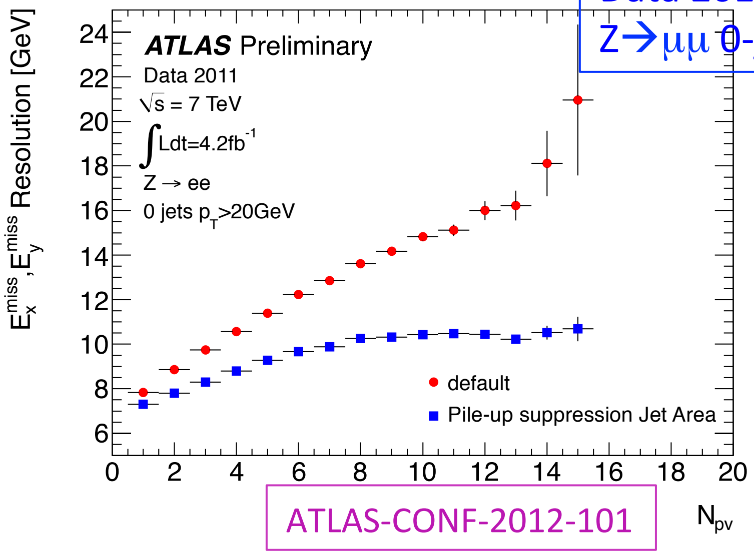


Data 2012
Z→μμ 0-jets

Jet area method:

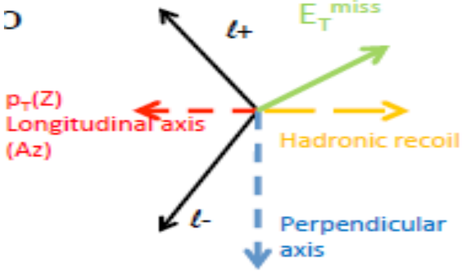
- Improves the resolution but some residual dependence on N_{PV} still present
- Some more improvement combining with a track based filter (JVF) on k_t jets

Data 2011
Z→μμ 0-jets



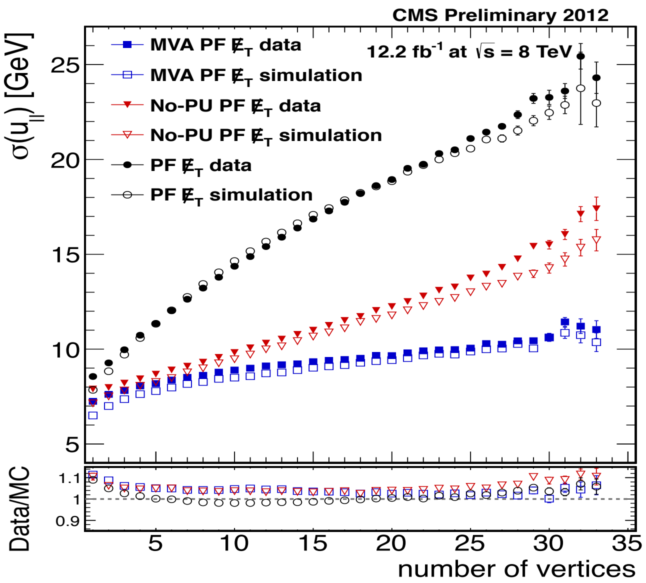
ATLAS-CONF-2012-101

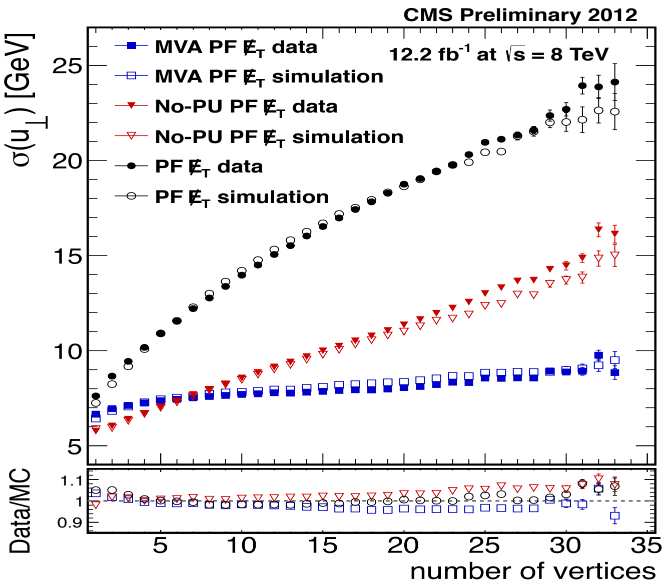
Resolution after pile-up suppression CMS



CMS shows the resolution of the hadronic recoil

Z→μμ events





CMS PAS JME-12-002

- Resolution less dependent on Npv after pile-up suppression

H→ττ mass reconstruction

The full reconstruction of the H→ττ mass

$$\mathbf{m}_{\tau\tau} = \sqrt{(\mathbf{2}(\mathbf{E}_{\tau\mathbf{had}} + \mathbf{E}_{\nu\mathbf{1}})(\mathbf{E}_{\mathbf{lep}} + \mathbf{E}_{\nu\mathbf{2}})(\mathbf{1} - \mathbf{cos}\theta)}$$

requires solving equations with more unknown than constraints.

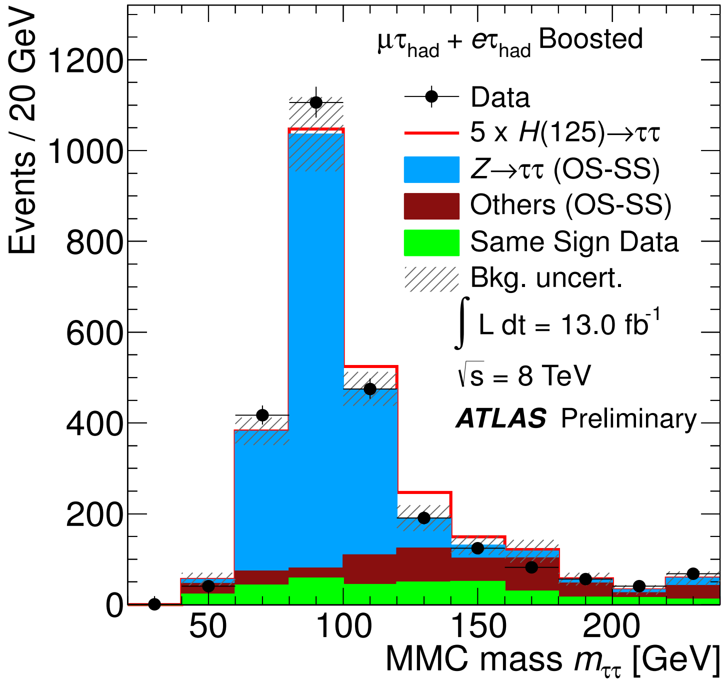
- Collinear approximation assumes that the visible and undetectable τ decay products are collinear
- Missing Mass Calculator (MMC) scans over the neutrino directions and picks the most likely value of $m_{\tau\tau}$, according to the simulated probability functions from the τ decay.

$$\not{E}_{T_x} = p_{\text{mis}_1}\sin\theta_{\text{mis}_1}\cos\phi_{\text{mis}_1} + p_{\text{mis}_2}\sin\theta_{\text{mis}_2}\cos\phi_{\text{mis}_2}$$

$$\not{E}_{T_y} = p_{\text{mis}_1}\sin\theta_{\text{mis}_1}\sin\phi_{\text{mis}_1} + p_{\text{mis}_2}\sin\theta_{\text{mis}_2}\sin\phi_{\text{mis}_2}$$

$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2p_{\text{vis}_1}p_{\text{mis}_1}\cos\Delta\theta_{vm_1}$$

$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2}p_{\text{mis}_2}\cos\Delta\theta_{vm_2}$$



A good E_T^{miss} resolution is crucial for the $m_{\tau\tau}$ reconstruction.

- E_T^{miss} after pile-up suppression gives a better invariant $m_{\tau\tau}$ reconstruction with the collinear approximation (efficiency and resolution)
- Improved MMC results with Etmiss after pile-up suppression with STVF.

ATLAS-CONF-2012-160

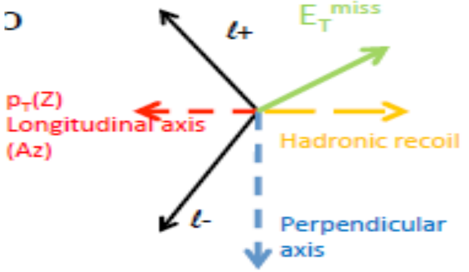
E_T^{miss} Scale

It is important to have a reconstructed E_T^{miss} as much as possible close to the the $E_T^{miss,True.}$

This can be checked:

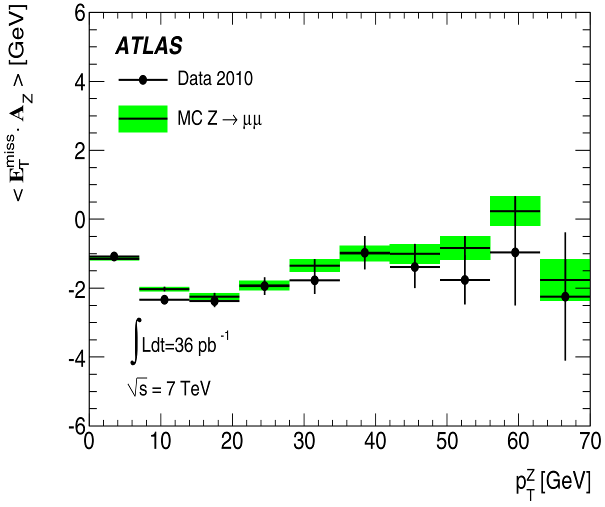
- in data Z→ll events from the projection of the E_T^{miss} along the transverse direction of the Z boson
- in events with true E_T^{miss}, the linearity $\left(E_{\mathrm{T}}^{\mathrm{miss}} - E_{\mathrm{T}}^{\mathrm{miss,True}}\right)/E_{\mathrm{T}}^{\mathrm{miss,True}}$, can be studied in MC events
- reconstructing the mass in W→lν and Z→ττ each of which contain true E_T^{miss} from unobserved neutrinos.

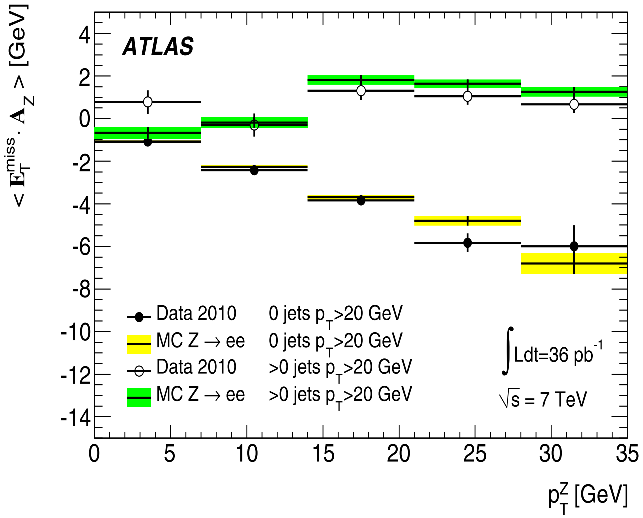
E_T^{miss} scale in Z→ll events

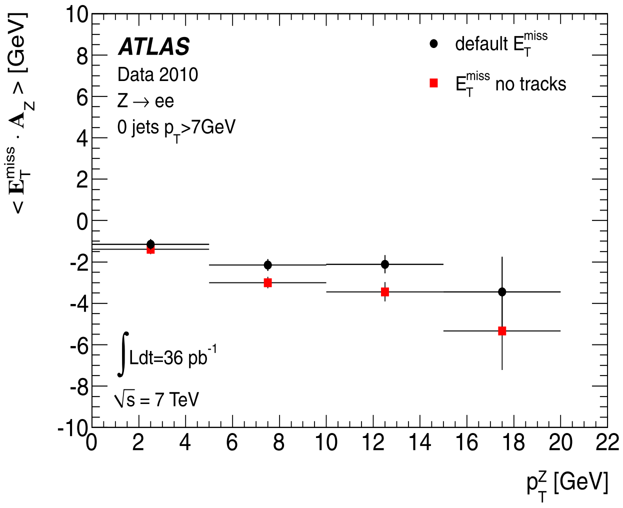


E_T^{miss} projection onto the p_T^Z

The longitudinal axis is defined by the vectorial sum of the 2 leptons momenta and it is sensitive to the balance between the muons and the hadronic recoi. If the leptons perfectly balance the hadronic recoil the projection of E_T^{miss} along the longitudinal axis (Az) should be zero → **E_T^{miss} Diagnostic plot**





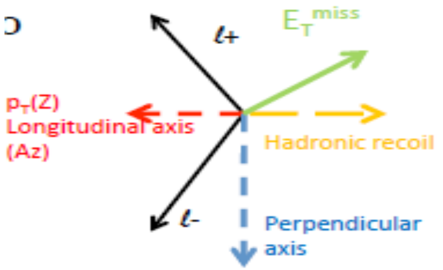


The hadronic recoil is under-estimated mainly in events with NO jets dominated by Soft Term

Adding tracks improves the hadronic recoil

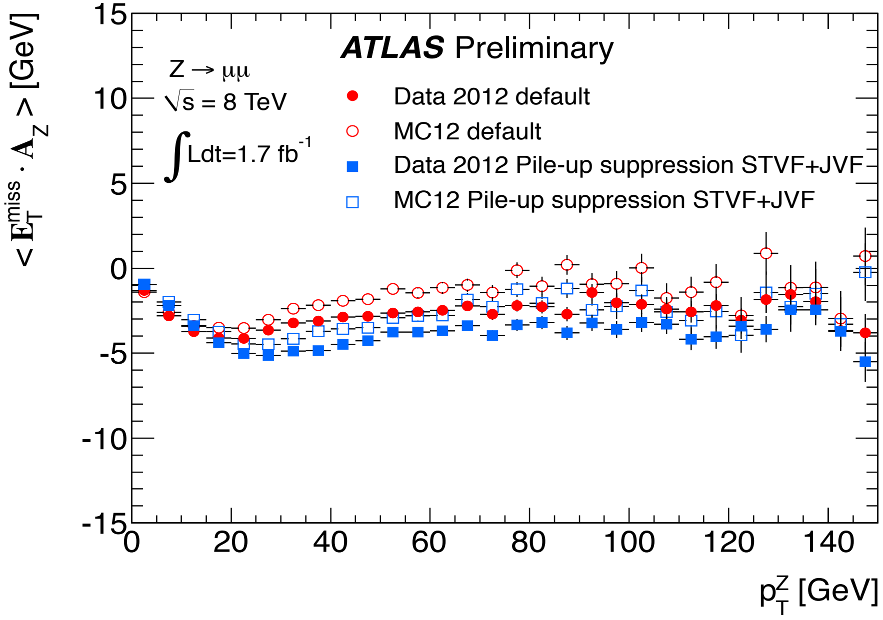
EPJ - C 72 (2012) 1844

E_T^{miss} scale: effect of pile-up



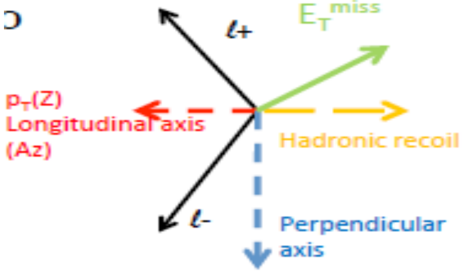
The pile-up also affect the E_t^{miss} scale:

- Some more bias is observed in the E_T^{miss} projection onto the p_T^Z (Diagnostic plot)



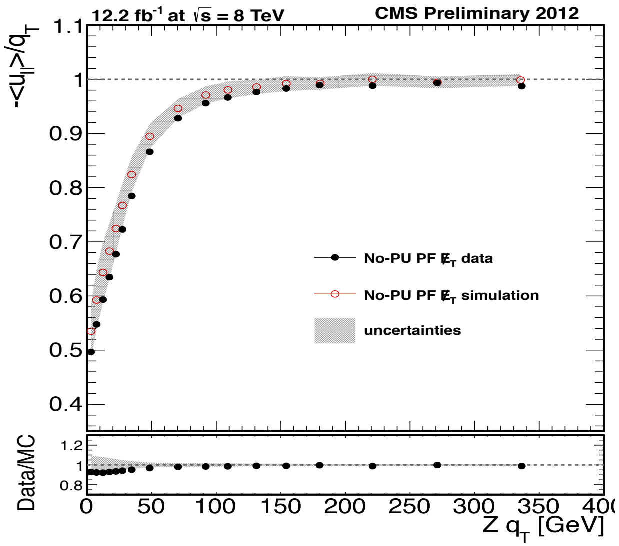
- After pile-up suppression with STVF method: the bias increases
- Smaller bias with Jet Area pile-up suppression

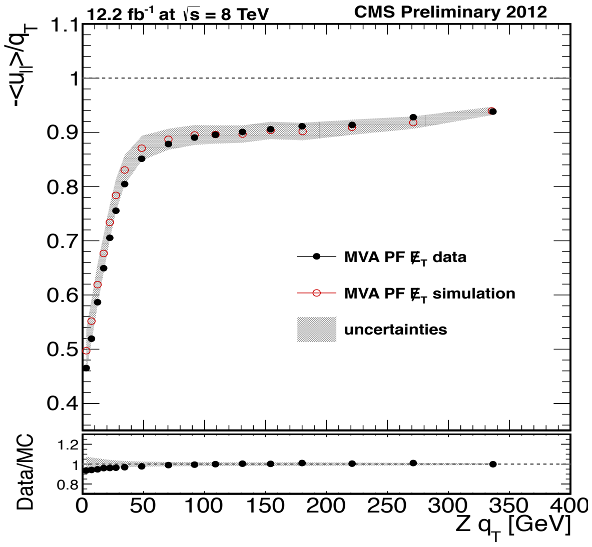
Scale after pile-up suppression CMS



CMS shows the projection of the hadronic recoil onto p_T^Z

Z→μμ events



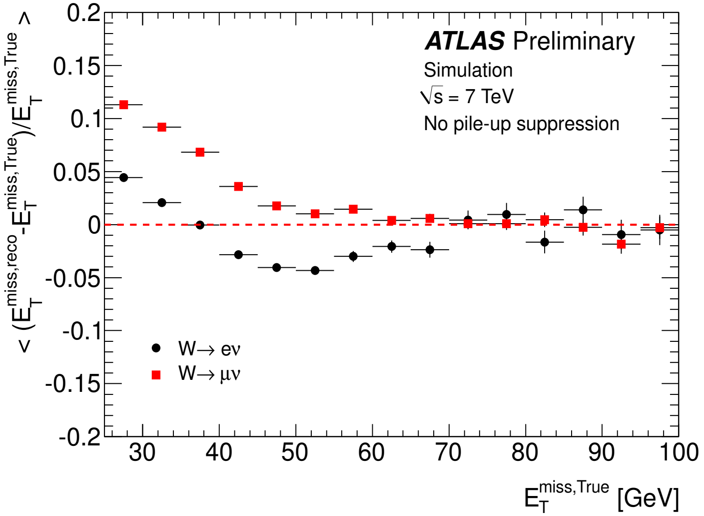


CMS PAS JME-12-002

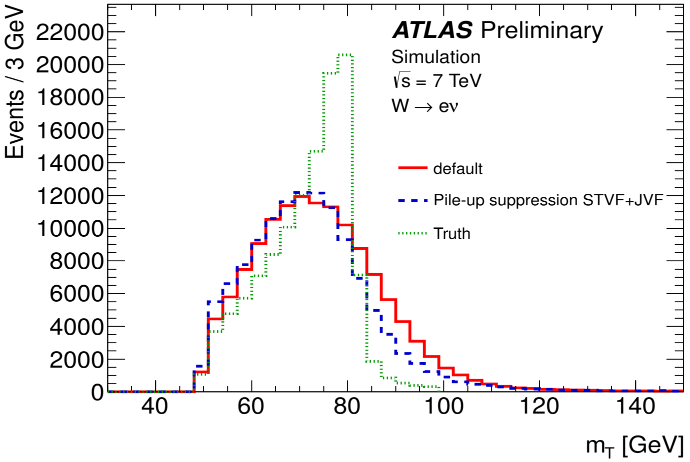
- The MVA response is around 0.9 because the BDT training for the MVA used in this study is optimized for the improved resolution rather than for the unity response.

E_T^{miss} scale: Linearity and transverse mass reconstruction in W→ln

$$(E_{\mathrm{T}}^{\mathrm{miss}} - E_{\mathrm{T}}^{\mathrm{miss,True}})/E_{\mathrm{T}}^{\mathrm{miss,True}};$$



ATLAS-CONF-2012-101



The bias at low $E_T^{miss,True}$ is due to the finite resolution of E_T^{miss}.

→ The reconstructed E_T^{miss} is positive by definition, so the relative difference is positive when the $E_T^{miss,True}$ is small.

The reconstructed $m_T = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\phi)},$ is closer to the Truth after pile-up suppression

Systematic Uncertainties

The estimation of the systematic uncertainties on the E_T^{miss} measurement is needed for physics.

Evaluation of E_T^{miss} systematic uncertainty

E_T^{miss} makes use of reconstructed objects, so its systematic uncertainty can be calculated from the uncertainty on each object and from the uncertainty on the Soft Term

The contribution of each term varies for different channels

- in Z and W events the contribution of Soft term is important.

Evaluation of systematic uncertainty on Soft Term (scale and resolution) with two methods:

- from data/MC ratio in **$Z \rightarrow \mu\mu$ events with NO jets**
  - Scale uncertainty from E_T^{miss} projection onto the p_T^Z
  - Resolution uncertainty from resolution
- from the balance between the SoftTerm and p_T^{Hard} in **$Z \rightarrow \mu\mu$ events**
  - Scale and resolution from decomposition of $E_t^{miss,SoftTerm}$ along p_T^{Hard} and its orthogonal direction

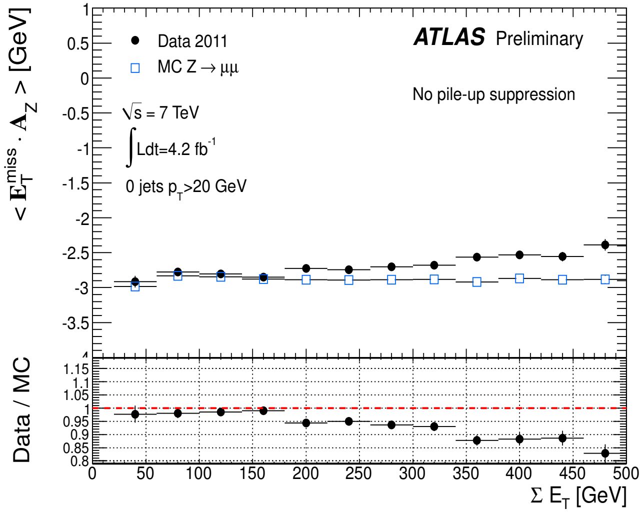
Scale uncertainty from the topocluster energy uncertainty (from e/p)

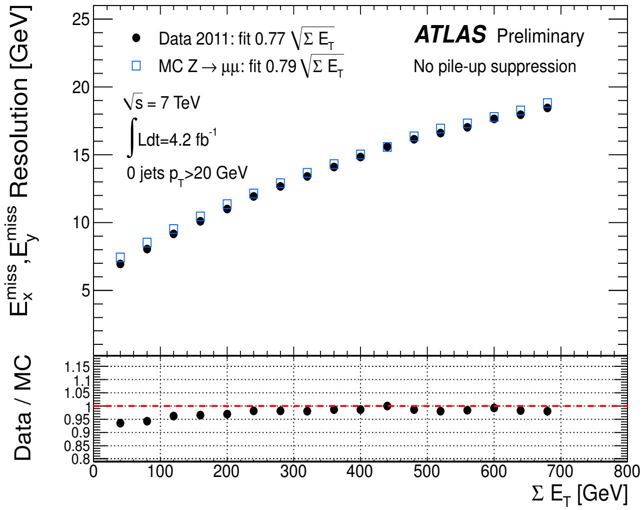
-difficult to determine clustering efficiency and scale in busy environment

-the cluster energy uncertainty in the forward region is conservatively estimated, since the uncertainty cannot be evaluated using tracks

Evaluation of E_T^{miss} systematic uncertainty

$E_t^{miss,SoftTerm}$ uncertainty from Data/MC ratio in **Z→μμ events with NO jets>20GeV**



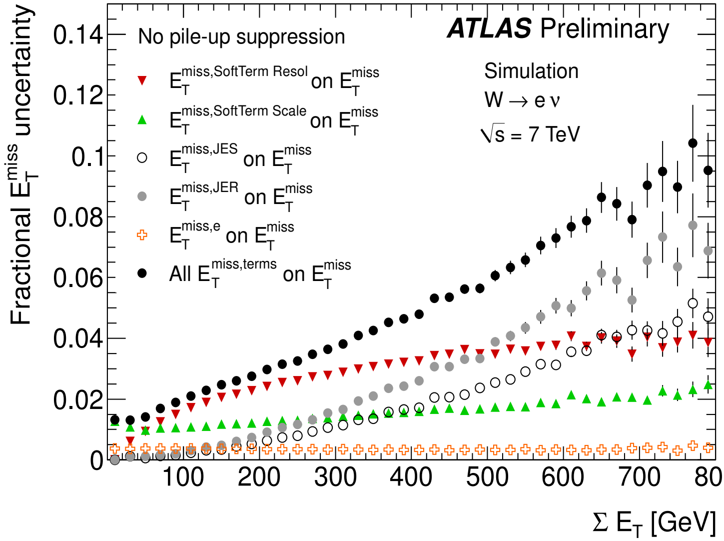


ATLAS-CONF-2012-101

- Uncertainty on scale from Data/MC ratio in Diagnostic plot (5%)
- Uncertainty on resolution from Data/MC ratio in Resolution plot (2%)

→The overall systematic uncertainty in **W→eν events** , calculated propagating the systematic uncertainties from all objects and SoftTerm and adding in quadrature is increasing with ΣE_T and around 3% in average (in 2011).

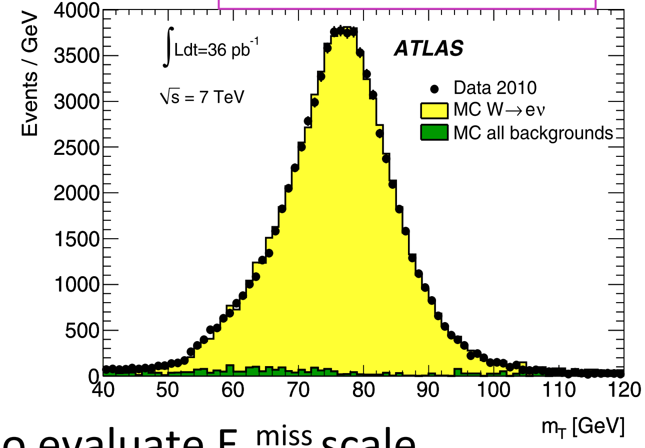
→ Systematic uncertainty is topology dependent



Evaluation of E_T^{miss} scale uncertainty in-situ

Use m_T distribution in data W→lν to evaluate scale and resolution

EPJ - C 72 (2012) 1844



→Scale/smear the m_T distribution in MC with:

$$E_T^{\text{miss,smeared}} = \alpha E_T^{\text{miss,True}} \cdot Gauss(0, k \cdot \sqrt{\Sigma E_T})$$

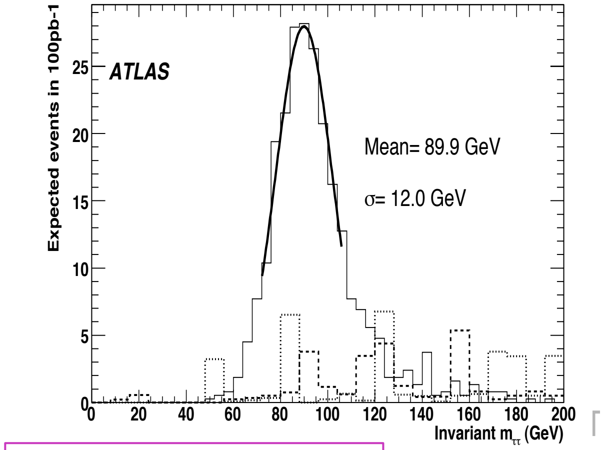
and compare with data

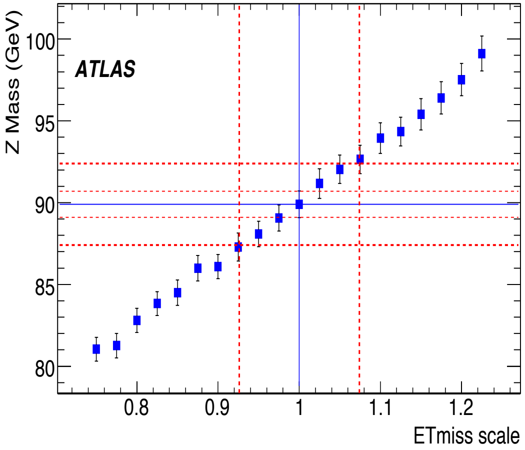
Can determine the E_T^{miss} absolute with a global uncertainty of about 2% (integrated luminosity of 36pb-1)

Use recontructed invariant mass in Z→ττ→lepton-hadron to evaluate E_T^{miss} scale

→Use collinear approximation to get $E\nu_1$ and $E\nu_2$ to reconstruct invariant mass

$$\mathbf{m}_{\tau\tau} = \sqrt{(\mathbf{2}(\mathbf{E}_{\tau\mathbf{had}} + \mathbf{E}_{\nu\mathbf{1}})(\mathbf{E}_{\mathbf{lep}} + \mathbf{E}_{\nu\mathbf{2}})(\mathbf{1} - \mathbf{cos}\theta)}$$





Check dependence of invariant mass on E_T^{miss} scale variations to get systematic uncertainty on the E_T^{miss} scale

CERN-OPEN-2008-020

Conclusions

- E_T^{miss} is an event complex quantity, calculated from signals in all detectors and is affected by detector acceptance, problems and non-collision background in the detector and by noise and pile-up
- ATLAS uses a flexible algorithm that allows to use physics objects with their proper calibration and soft energy contributions
- CMS uses a particle-flow algorithm both for high and low p_T contributions
- The pile-up conditions at increased LHC luminosity gives a deterioration in the E_T^{miss} performance
- Pile-up suppression methods are needed to mitigate pile-up mainly in jets and in the soft term to reduce the pile-up impact especially on the resolution
- A good E_T^{miss} performance in terms of resolution, scale and tails is crucial for many physics analyses
- The E_T^{miss} uncertainty is calculated from the uncertainties on the scale and the resolution of each physics object and of soft term and can also be calculated in-situ using $W \rightarrow l\nu$ and $Z \rightarrow \tau\tau$ events
- Dedicated optimisation of all these techniques needed to face the new challenge in 2015 data taking at very high luminosity.