Jets and E_T^{miss} reconstruction, calibration and performance with the ATLAS detector at LHC

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Outline

- Atlas calorimeter pile-up sensitivity
- Input signals to Jets and E_T^{miss}
- Jet reconstruction and calibration:
  - Pile-up correction:
    - Effect on Jet Energy Resolution
  - Jet Energy Scale and uncertainty
- E_T^{miss} reconstruction and calibration:
  - Pile-up correction of Soft Term:
    - Effect on E_T^{miss} Resolution
  - E_T^{miss} uncertainty

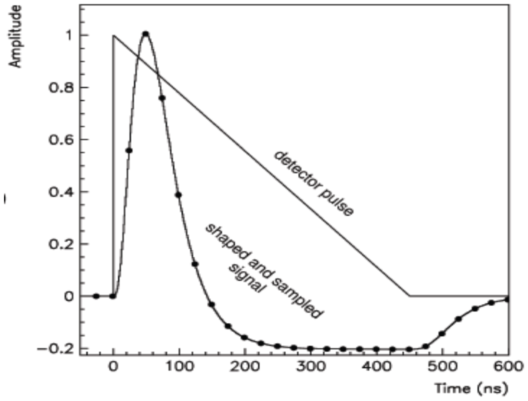
Jets and E_T^{miss} play a major role for the physics @ LHC:

- Jets:
  - Measurements of hadronic jets provide tests of strong interactions.
  - They can be backgrounds and/or signals for many New Physics searches.
  - The uncertainty on the jet calibration dominates the experimental uncertainty for many physics results.
- E_T^{miss} :
  - Measurement of E_T^{miss} is crucial for the search of Higgs boson in the decay channels $H \rightarrow WW \rightarrow l\nu l\nu$ and $H \rightarrow \tau\tau$ where a good measurement of E_T^{miss} allows for the accurate reconstruction of the Higgs boson mass.
  - Large E_T^{miss} is a key signature for searches for New Physics processes such as SUSY and extra dimensions.

Calorimeter pile-up sensitivity

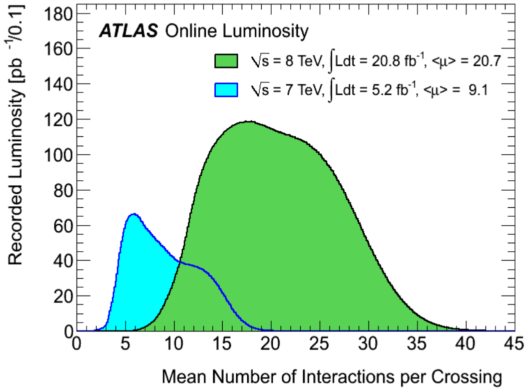
➔ Pile-up is one of the main challenges for jets and E_T^{miss} at LHC

- **In-time pile-up:** additional pp collisions in the same bunch crossing
  - Adds energy in calorimeters mainly from minimum bias interactions (MB)
  - Estimated by the number of reconstructed primary vertices (N_{PV})



- **Out-of time pile-up:** residual contributions from collisions in preceding bunch crossings
  - LAr calorimeters sensitive to bunch crossing history:
    - Long charge collection time (≅ 400 ns)
    - Bi-polar shaped signal (600 ns) with zero integral over time does not permit full pile-up cancellation:
      - optimized for 25 ns spacing (currently 50 ns)
      - large fluctuations of number of interactions from bunch crossing to bunch crossing.
  - Estimated by the average number of interactions per bunch crossing <μ> over time window >> 600 ns

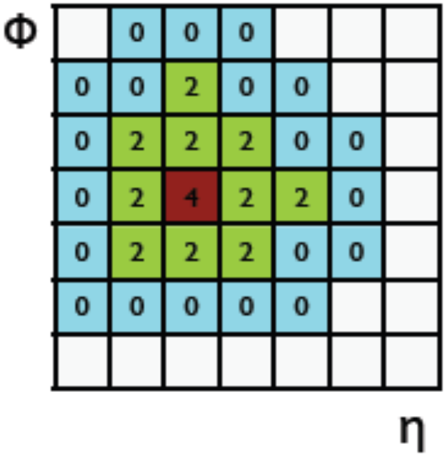
$$\langle\mu\rangle = L \times \sigma_{inel} \;/\; N_{bunch} \times f_{LHC}$$



Input signals to Jets and E_T^{miss}

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

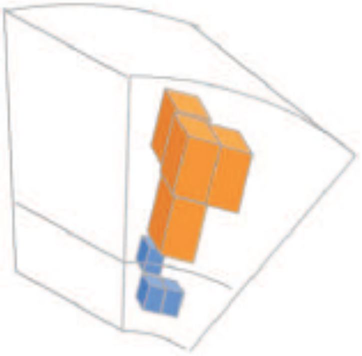
- Cluster cells in 3D via noise-driven thresholds:
  - Seed: $|E_{cell}| > 4\,\sigma_{noise}$
  - Neighbours: $|E_{cell}| > 2\,\sigma_{noise}$
  - Perimeter cells $|E_{cell}| > 0$
  - $\sigma_{noise} = \sqrt{(\sigma_{noise}^{electronic})^2 + (\sigma_{noise}^{pile\text{-}up})^2}$



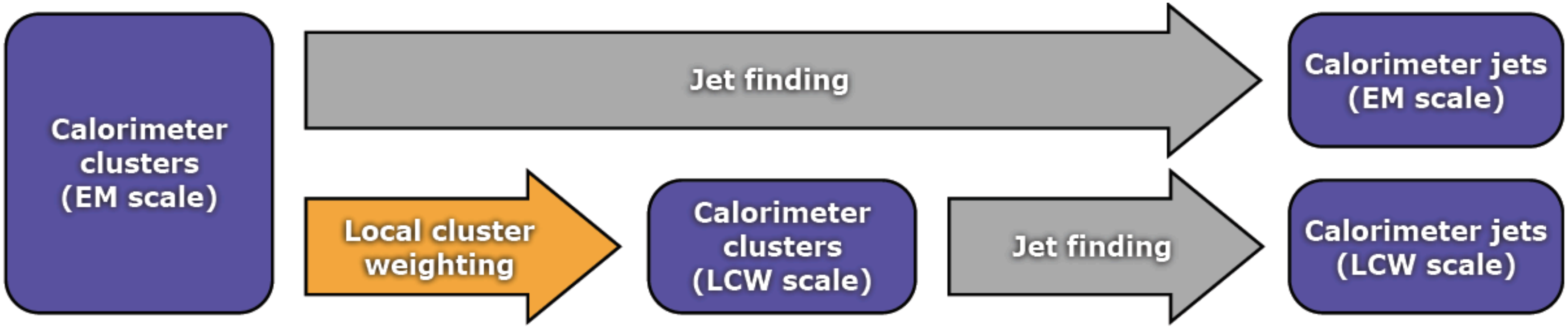
	0	0	0			
0	0	2	0	0		
0	2	2	2	0	0	
0	2	4	2	2	0	
0	2	2	2	0	0	
0	0	0	0	0		

- Calibration using the local cluster 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
- Improve correspondence between clusters and stable particles

➔ Contribution from pile-up fluctuations can survive and overlap on large signal from hard scattering process, more pile-up suppression techniques needed



Jet reconstruction and calibration



Calorimeter clusters (EM scale)

Jet finding

Calorimeter jets (EM scale)

Local cluster weighting

Calorimeter clusters (LCW scale)

Jet finding

Calorimeter jets (LCW scale)

Reconstruction of calorimeter jets:

- Reconstructed from EM or LCW calibrated topo-clusters
- Using anti-k_t algorithm with distance parameters R = 0.4 and 0.6

Calorimeter jets (EM or LCW scale)

Pile-up correction

Energy & η calibration

Residual *in situ* calibration

Calorimeter jets (EM+JES or LCW+JES scale)

Calibration of calorimeter jets:

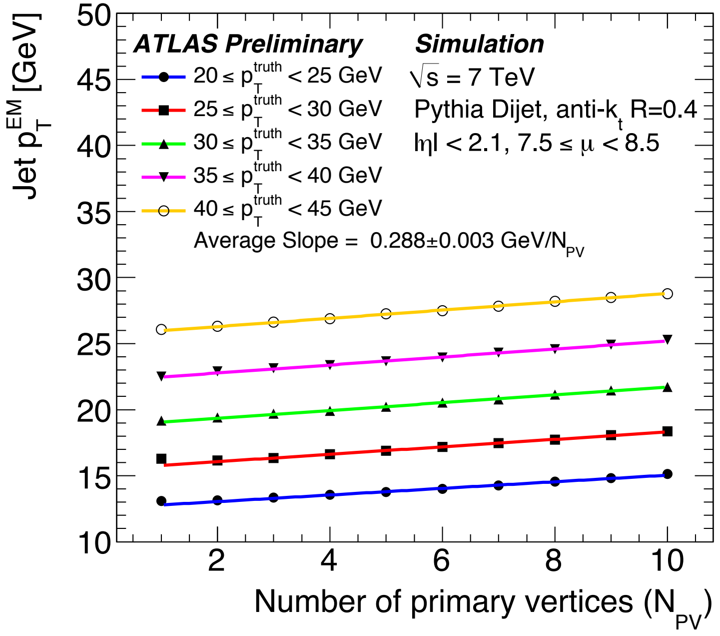
- Multi-step approach that combines “in-situ” and MC methods

Jet pile-up correction

Pile-up correction

Signal added from pile-up:

- Distorts the energy reconstructed in jets:
  - Modifies p_T, smears resolution, adds mass, shift jet axis in η, ϕ
- Jets from additional pp collisions



First method: **Offset correction**

- MC based correction derived from jet response to pile-up
- Parametrization in N_{PV} and $<\mu>$:

  $\Delta p_T = \alpha \times (N_{PV} - 1) + \beta \times <\mu>$

  α, β obtained from the fits (slopes)
- Dependent on jet type and $|\eta|$

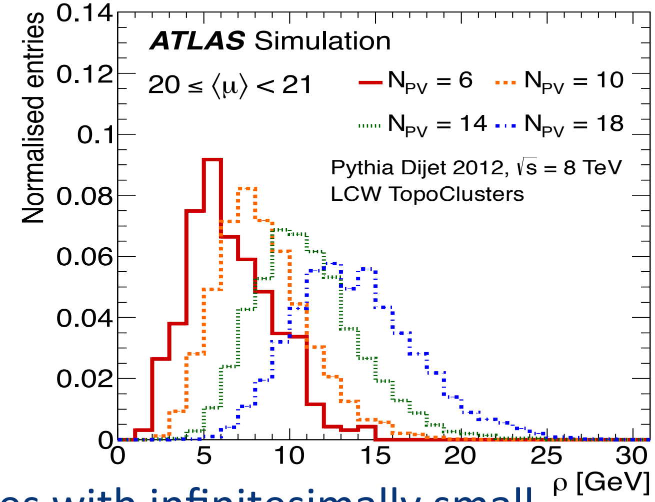
Limitations: Average correction, does not account for event fluctuations in pile-up activity.

Jet pile-up correction

Pile-up correction

Second method: **"jet area"**

More sophisticated correction based on the idea that noise (pile-up) has a lower density (ρ) than signal:



$$\rho = \text{median}\left\{ \frac{p_{T,i}^{jet}}{A_i^{jet}} \right\}$$

- ρ calculated for k_t jets with R=0.4
- A_i^{jet} = jet area calculated with FastJet active area based on ghost particles:
  - Randomly generated distribution of particles with infinitesimally small p_T added to the event and clustered with real signal in jet finding process.
  - Number of ghost particles associated to a jet is a measure of the jet area.
- Correction: $p_{T,i}^{jet\ corr} = p_{T,i}^{jet} - \rho\, A_i^{jet}$

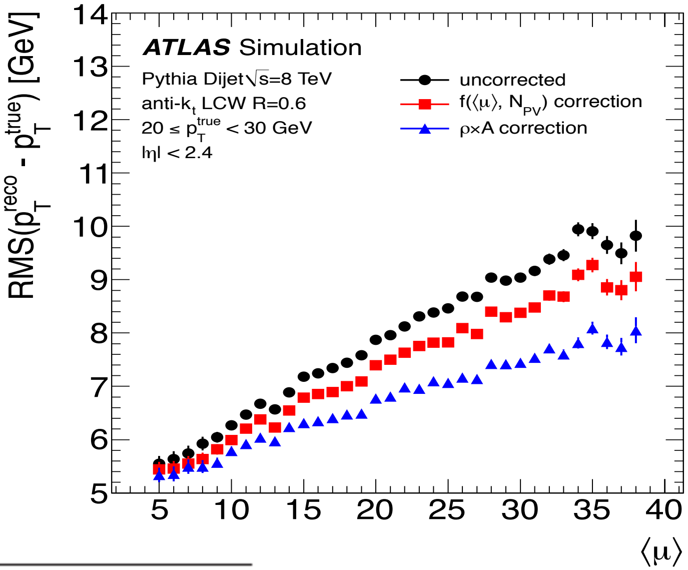
Advantages:

- Captures event-by-event fluctuations not described by N_{PV}, $<\mu>$
- Use of jet area accounts for jet by jet variations in sensitivity
- Data driven method: no dependence on pile-up modelling

Effect of pile-up correction on Jet Energy Resolution (JER)

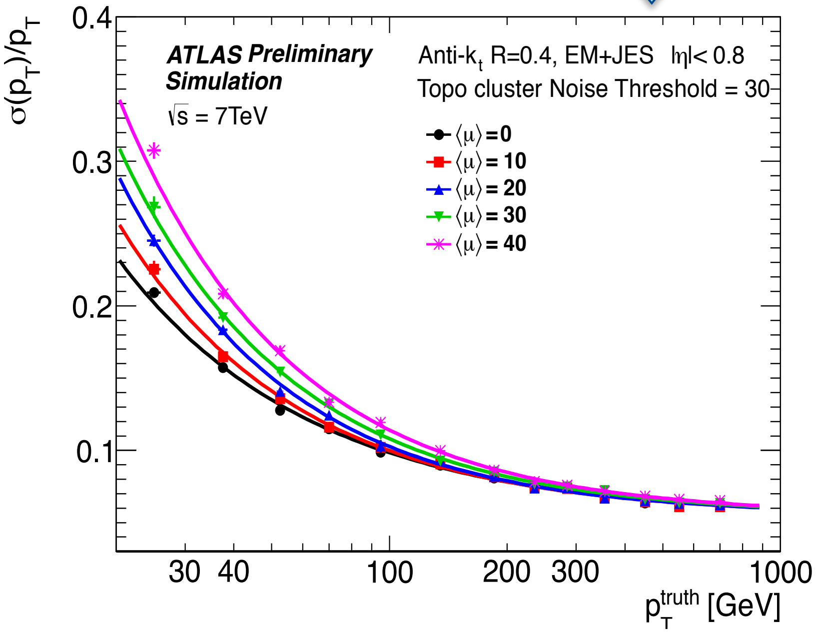
Improvements of RMS ($p_T^{reco} - p_T^{truth}$) for "jet area" over the offset correction

- still some residual dependence on $\langle\mu\rangle$

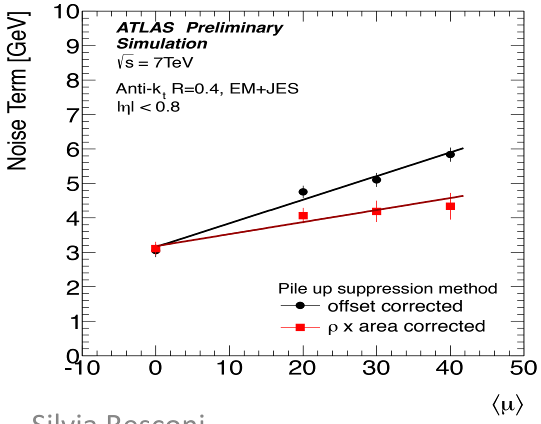


Fractional jet energy resolution vs jet p_T^{truth} degrades with increasing pile-up conditions:

- noise term increases with $\langle\mu\rangle$ and dominates at low p_T



$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{N^2}{p_T^2} + \frac{S^2}{p_T} + C^2}$$



Noise term (N) vs $\langle\mu\rangle$ obtained from the fits to the jet energy resolution.

N is reduced by applying "jet area" correction

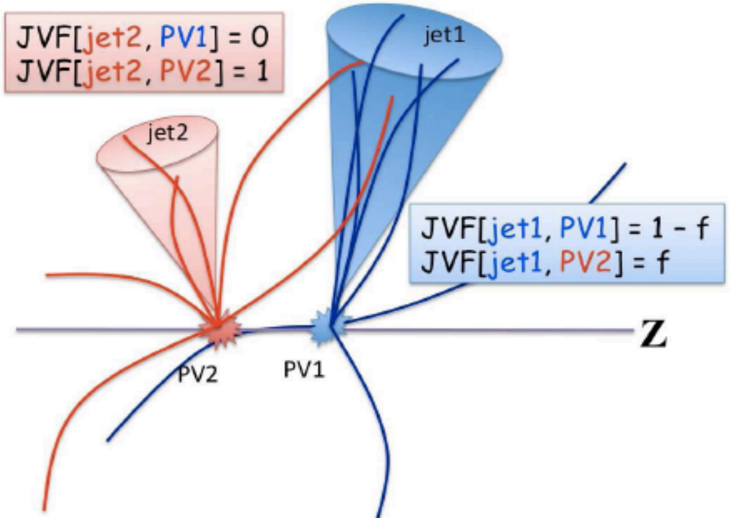
Track-based pile-up suppression

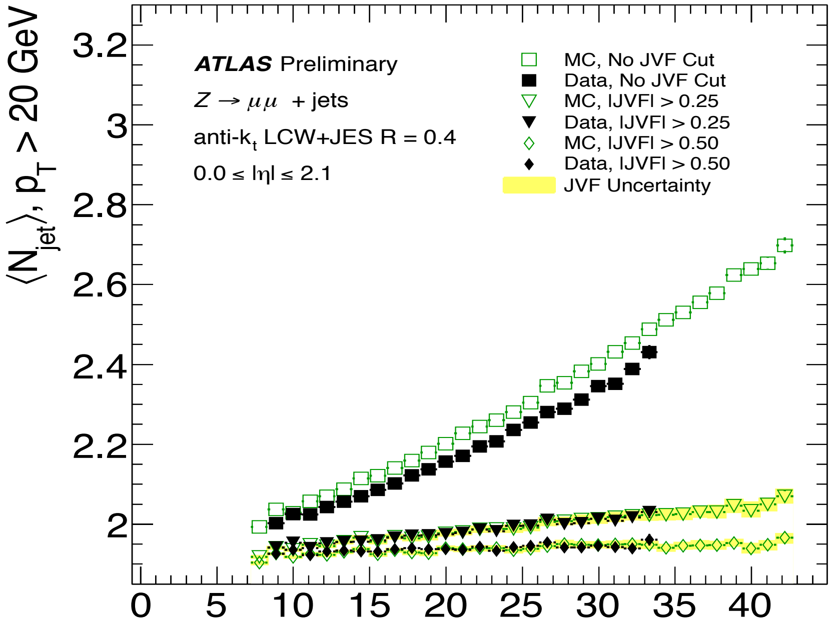
Jet Vertex Fraction (JVF):

- Track based quantity to filter pile-up jets:

  JVF = (Σ p_T track^{jet} PV / Σ p_T track^{jet})

- Probability for jets with matched tracks to come from hard-scatter vertex selected with the highest Σ_{tracks} (p_T^2)





Three different JVF regions:

- JVF=-1: no matched tracks
- JVF= 0: all matched tracks from pile-up
- 0 < JVF ≤ 1: JVF closer to 0 for jet with significant pile-up contribution

JVF cut reduces pile-up jets:

- Mean jet multiplicity in Z+jets
- improves data/MC agreement

Jet energy calibration

Energy & *η* calibration

Simple correction based on MC relating the reconstructed jet energy to the truth jet energy:

- Correction factor = $E_{jet}^{truth} / E_{jet}^{EM/LCW}$ dependent on E, |η|
- Much smaller correction for LCW-scale jets wrt EM-scale jets

Residual in situ calibration

Residual *in situ* calibration

From in situ techniques that exploit the p_T balance between the jet p_T and the p_T of a reference object:

- Correction factor = $< p_T^{jet} / p_T^{ref} >_{data} / < p_T^{jet} / p_T^{ref} >_{MC}$
- Multiple methods to cover large kinematic phase space:
  - Dijet η-intercalibration: equalize p_T^{jet} between central and forward
  - γ/Z + jet direct balance: compare p_T^{γ} or p_T^{Z} with recoiling p_T^{jet}
  - Multi jet balance: low p_T^{jet} system recoils against a high p_T^{jet} used to calibrate jets in the TeV regime.

Jet Energy Scale (JES)

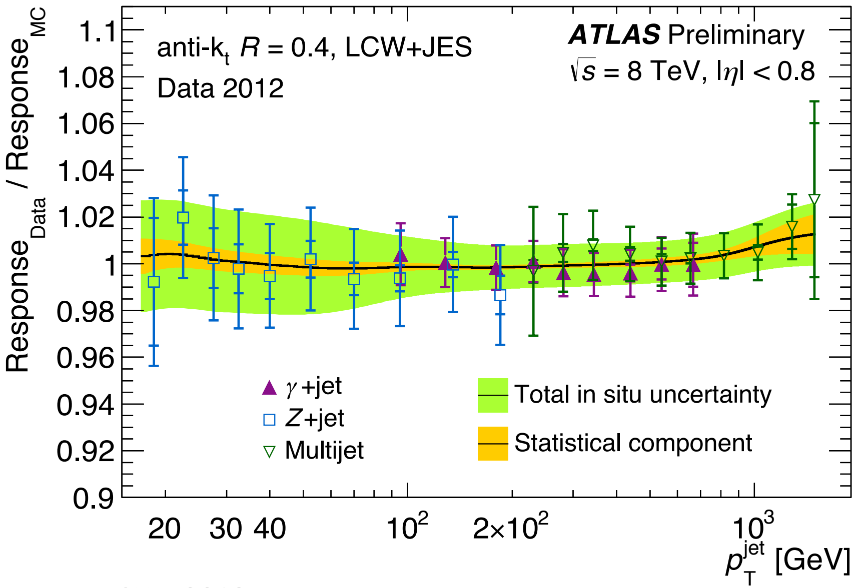
Residual *in situ* calibration

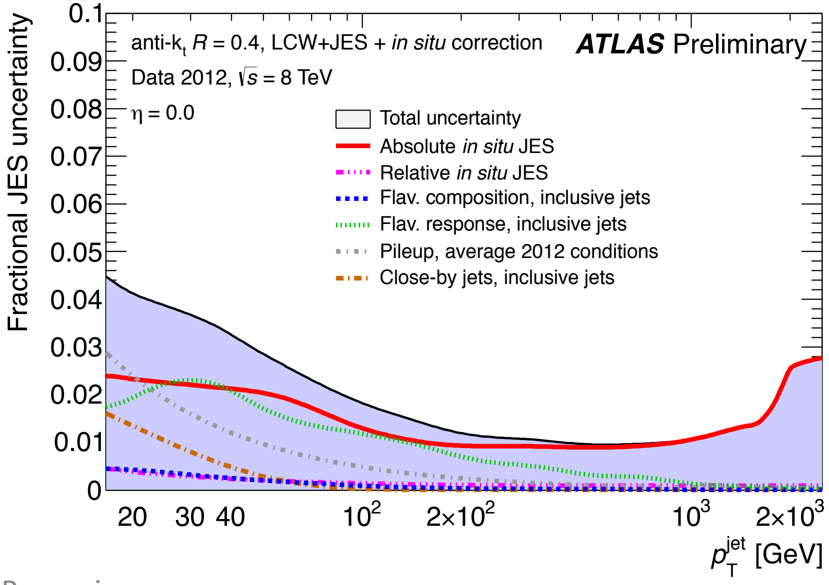
Total in situ JES correction as a function of p_T^{jet} obtained from the combined in situ techniques:

- Z+jet allows to probe the energy scale down to $p_T^{jet} \approx 17$ GeV
- γ +jet relevant for $100 \leq p_T^{jet} \leq 800$ GeV
- Multi jet balance provides results at high p_T^{jet} (1.5 TeV)

➔ The residual calibration is minimal (≈1%) with a maximum uncertainty ≈3%.

➔ Adding additional uncertainties due to pile-up, flavour response, close-by jets fractional uncertainty < 2.5 % for central jets with p_T > 100 GeV





E_T^{miss} reconstruction and calibration

Missing transverse momentum (E_T^{miss}) is a complex event quantity:

- Adding significant signals from all detectors
- Asking for momentum conservation in the transverse plane.

Reconstructed physics objects:
e, γ, τ, jets, muons

Soft energy:
topo-clusters and tracks
not associated to physics objects

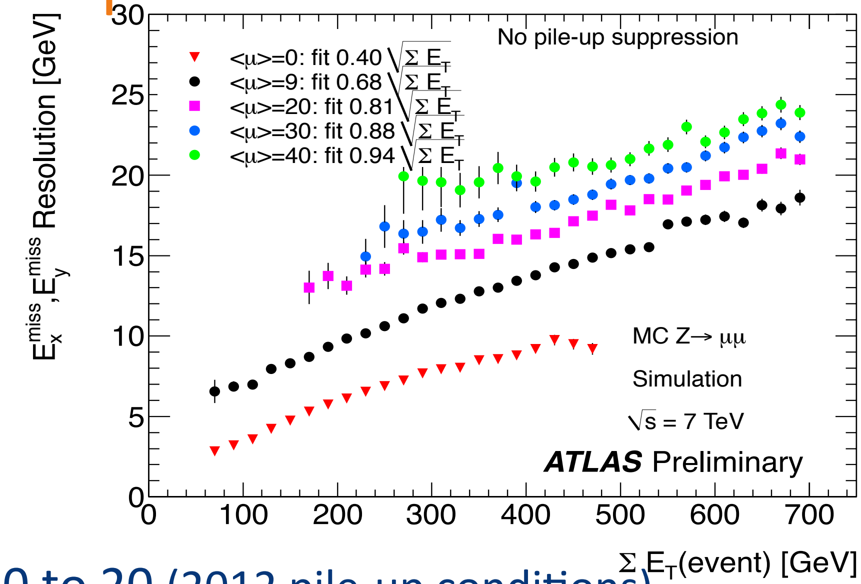
→ Decomposition into constituent topo-clusters to veto multiple contributions and avoid energy double counting

→ Keep separate contributions calculated from the negative sum of calibrated $p_{x(y)}$ of physics objects and soft energy

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

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

Effect of pile-up on E_T^{miss} Resolution



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

- largest acceptance (coverage area) of any given reconstructed quantity.

Dramatic effect on $E_{x,y}^{miss}$ resolution with increasing pile-up conditions:

- $E_{x,y}^{miss}$ resolution = $k \times \sqrt{\Sigma E_T}$
- $E_{x,y}^{miss}$ resolution doubles from $\langle\mu\rangle = 0$ to 20 (2012 pile-up conditions)
- Large impact on analyses with E_T^{miss} in final state (SUSY searches, $H \rightarrow \tau\tau$ invariant mass reconstruction)
- Jet term and Soft Term are the most affected by pile-up:
  - Jet term pileup correction with "jet area" method plus JVF cut.
  - 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 → very challenging

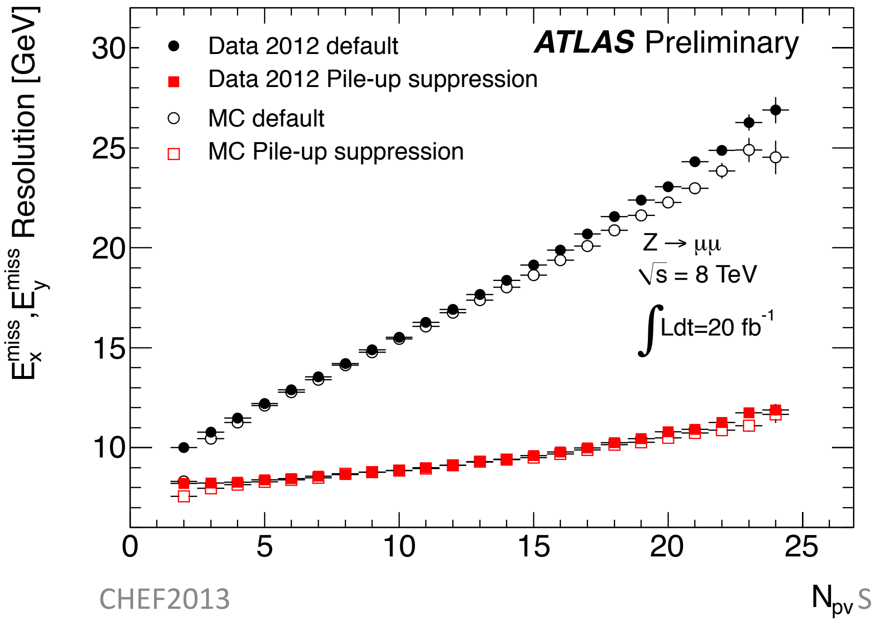
E_T^{miss} Soft Term pile-up correction

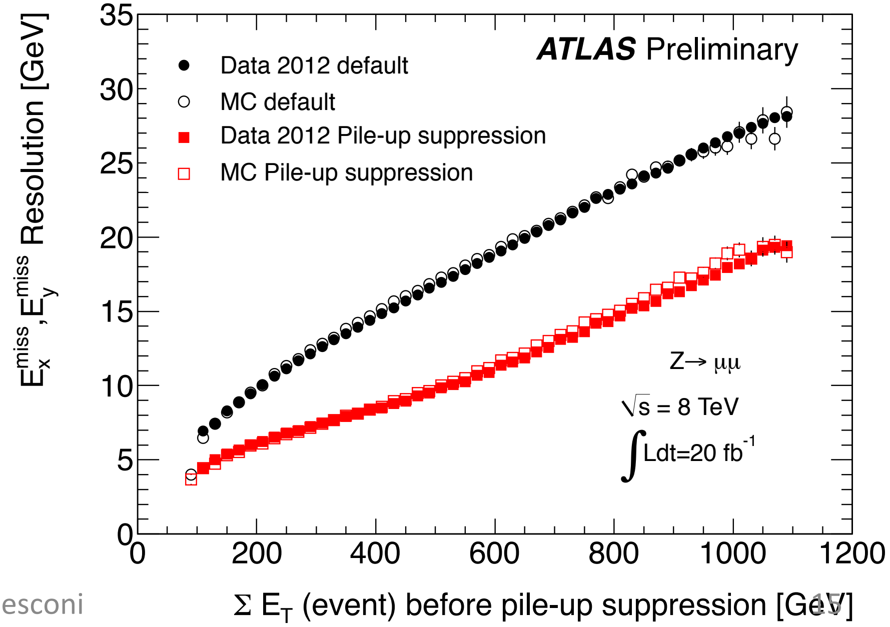
First method: **Soft Term Vertex Fraction (STVF)**

- Track based quantity to scale Soft Term:

  STVF = (Σ p_T track $^{\text{Soft Term}}$ PV / Σ p_T track $^{\text{Soft Term}}$)

- Uses tracks not associated to physics objects and matched to PV to provide a reliable estimate of pile-conditions.
- **Restore $E_{x,y}^{miss}$ resolution closer to that observed in absence of pileup**
- Limitations: calculated in limited coverage (ATLAS ID $|\eta| < 2.5$) and does not take into account neutral contributions



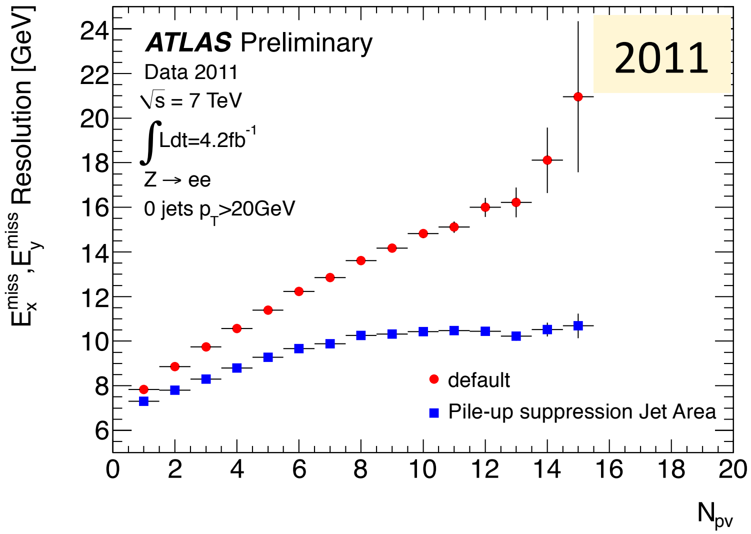


E_T^{miss} Soft Term pile-up correction

Second method: **“jet area”**

- Similar approach as the one described for jets but more challenging when applied to Soft Term.
- Procedure:
    - Reconstruct k_t jets with R=0.4 from topo-clusters and tracks of Soft Term
    - Correct each jet for pile-up applying a filter and recalculate Soft Term

$$E_{x(y)}^{\text{miss, Soft Term}} = -\sum p_{x(y),i}^{\text{jet corr}} , \quad p_{T,i}^{\text{jet corr}} = \begin{cases} p_{Ti}^{\text{jet}} - \rho A_i^{\text{jet}}, & p_{Ti}^{\text{jet}} > \rho A_i^{\text{jet}} \\ 0 & , p_{Ti}^{\text{jet}} \le \rho A_i^{\text{jet}} \end{cases}$$

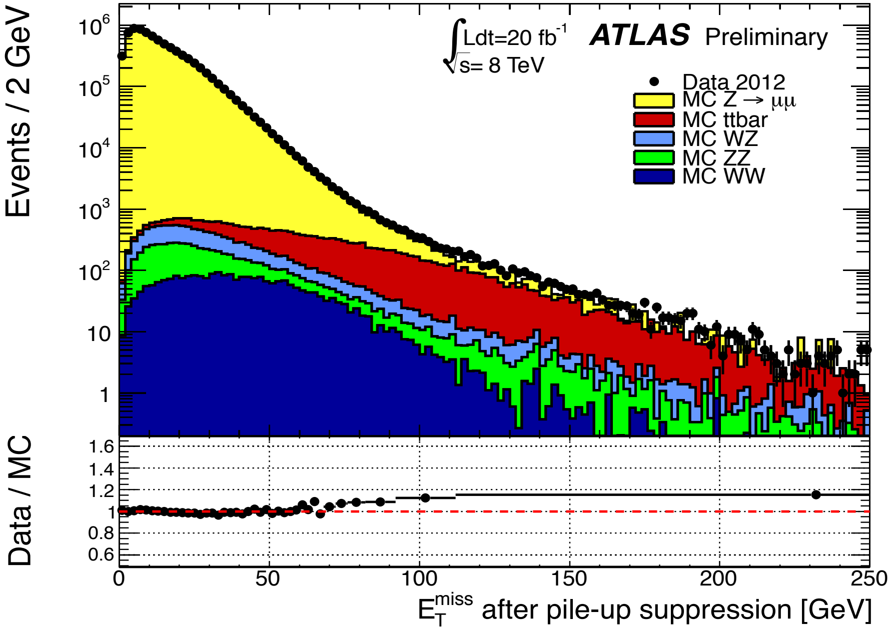


Jet area method:

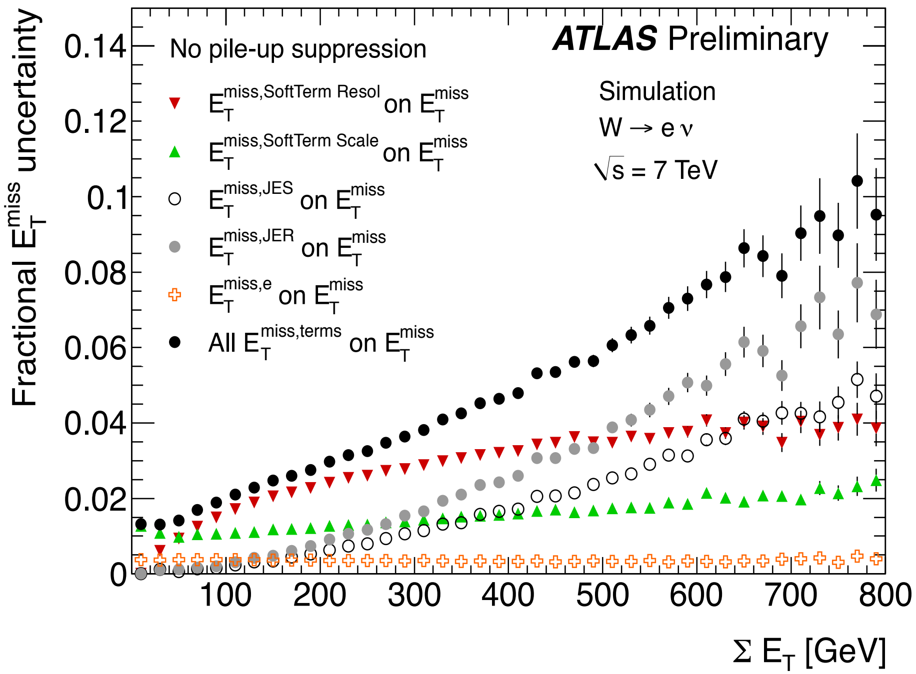
- Improves the resolution but some residual dependence on N_{PV} still present
- Can be combined with a track based filter (JVF) on k_t jets similar to what explained for jets

E_T^{miss} data/MC agreement and uncertainty

Z →μμ



W →eν



- Good E_T^{miss} data/MC agreement in Z →μμ in 2012 data (≅ 20 fb $^{-1}$)
- Total E_T^{miss} fractional uncertainty obtained combining uncertainties of all physics objects (e, γ, τ, jets, μ) used to calculate E_T^{miss} terms and the Soft Term:
  - Depends on event topology: on average 3% in W→eν (in 2011), increasing with ΣE_T

Conclusions

ATLAS has developed and commissioned several techniques to mitigate pile-up effects coherently on jets and E_T^{miss} :

- Topological clustering, intrinsically noise and pile-up suppressed.
- "Jet area" method to estimate event-by-event the p_T density from pile-up.
- Use of tracks to filter pile-up jets and scale the Soft Term:
  - Jet multiplicity and E_T^{miss} resolution closer to that observed in absence of pile-up.

A high precision obtained for JES in 2012 with in-situ techniques:

- JES uncertainty smaller than 2.5% for jets with p_T> 100 GeV

➔Dedicated optimization of all these techniques needed to face the new challenge in 2015 at very high luminosity:

  - New techniques, like jet "grooming", have been developed to reduce pile-up sensitivity in boosted topologies

Back-up

References

TopoClusters and LCW calibration:

- ATL-LARG-PUB-2009-001

Jet Area method:

- M. Cacciari, G. P. Salam, *Pileup subtraction using jet areas*, Phys.Lett.B659(2008), arXiv:0707.1378 [hep-ph]

Jet pile-up correction:

- ATLAS-CONF-2012-064
- Updated performance plots for 2012 data: *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013Pileup1*

Jet Energy Scale and its systematic uncertainty:

- ATLAS-CONF-2013-004
- Updated performance plots for 2012 data: *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013JESUncertainty*

Performance of E_T^{miss} :

- ATLAS-CONF-2012-101
- Updated performance plots for 2012 data: *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013EtMiss*

Jet substructure:

- ATLAS-CONF-2012-065, ATLAS-CONF-2012-066

Jet substructure

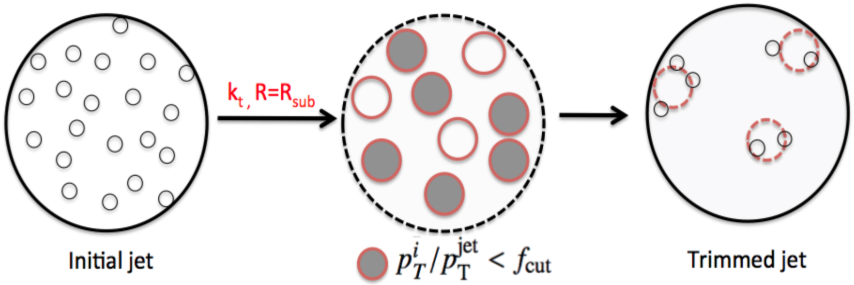
The large centre-of-mass energy of LHC enables the production of boosted heavy particles whose decay products can be reconstructed as one large radius jet.

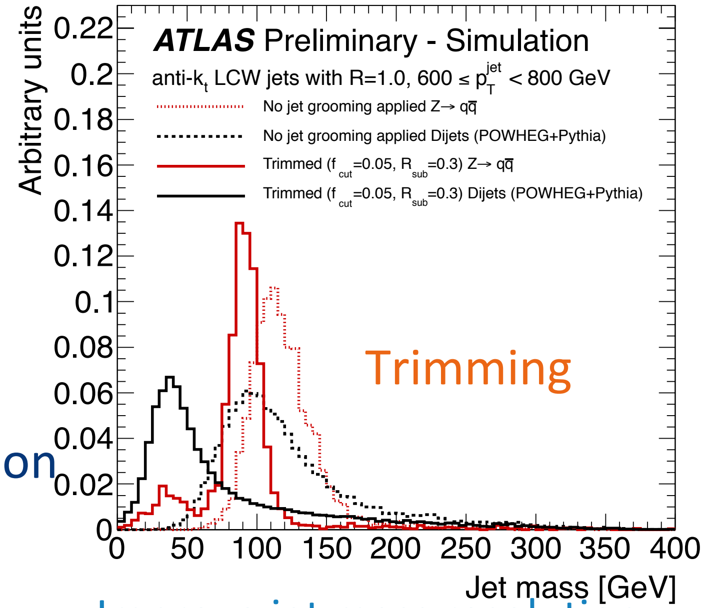
Needed new techniques: Jet "grooming"

- Emphasize hard substructure removing soft radiation
- Reduce their sensitivity to pile-up
- Three algorithms: **Trimming, pruning, filtering**

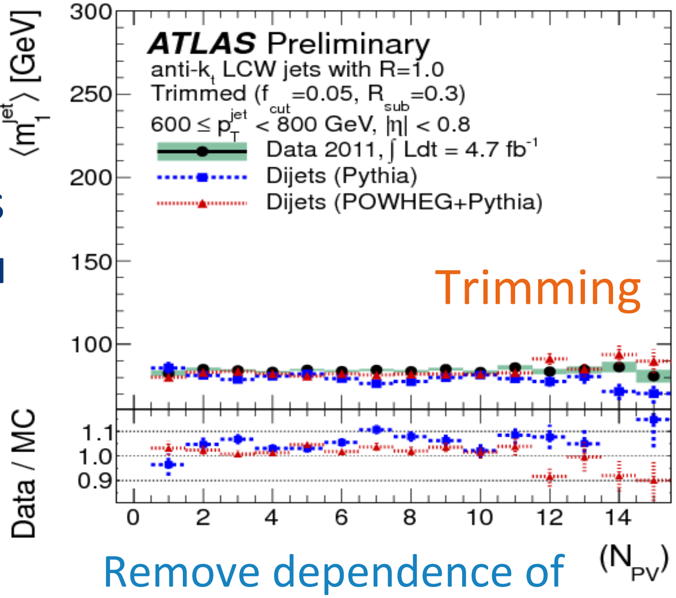
Trimming algorithm:

- Recluster k_t subjects, remove those with $p_{Ti} / p_{Tjet} < f_{cut}$ to form the trimmed jet
- MC based calibration to restore a uniform jet mass response over the full η range and validated in situ





Improve jet mass resolution for signal (Z→$q\bar{q}$)



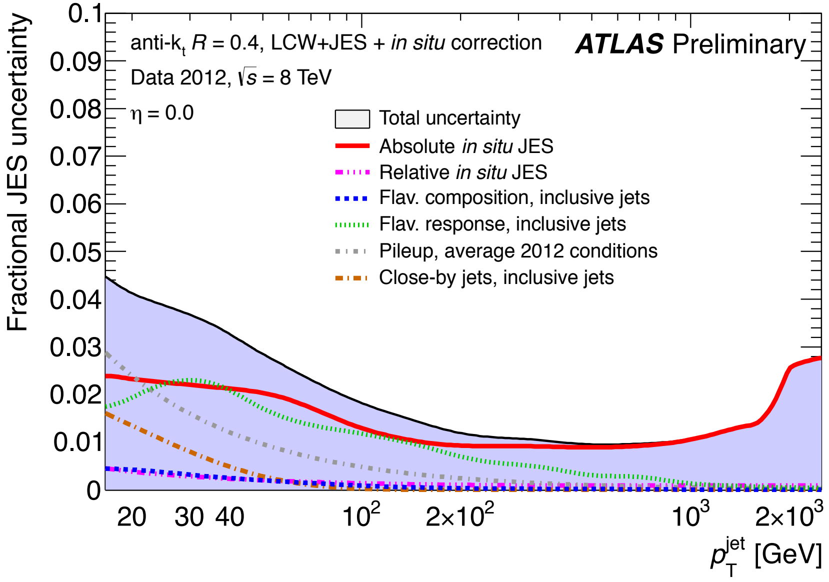
Remove dependence of Jet mass vs N_{PV}

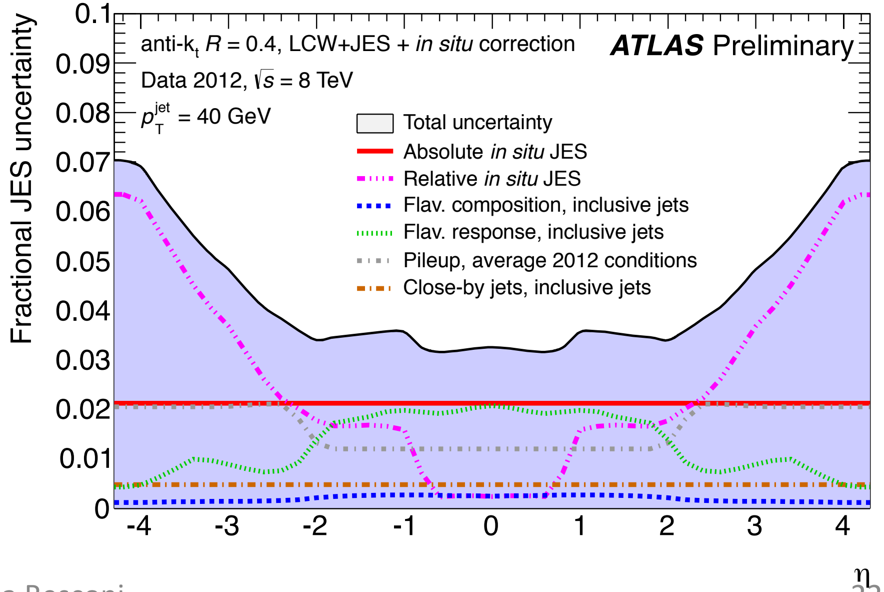
Jet Energy Scale uncertainty

Residual *in situ* calibration

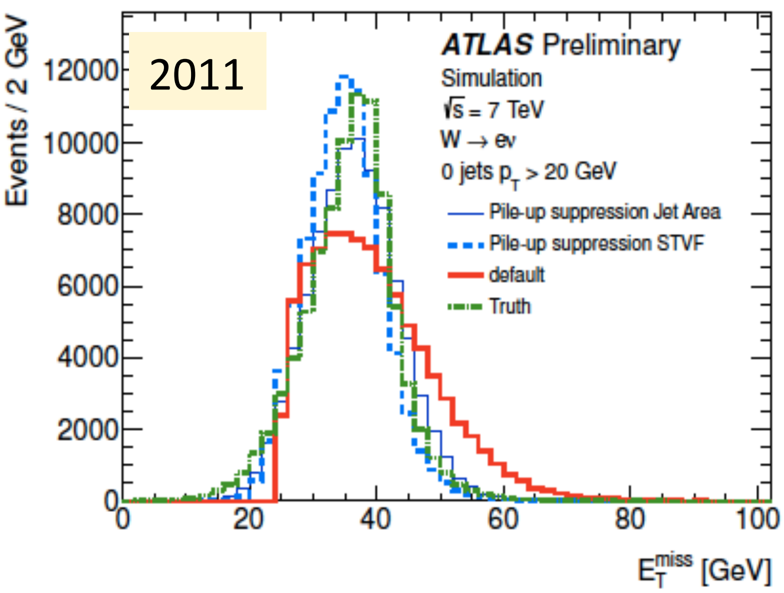
Fractional JES uncertainty as a function of p_T^{jet} and η :

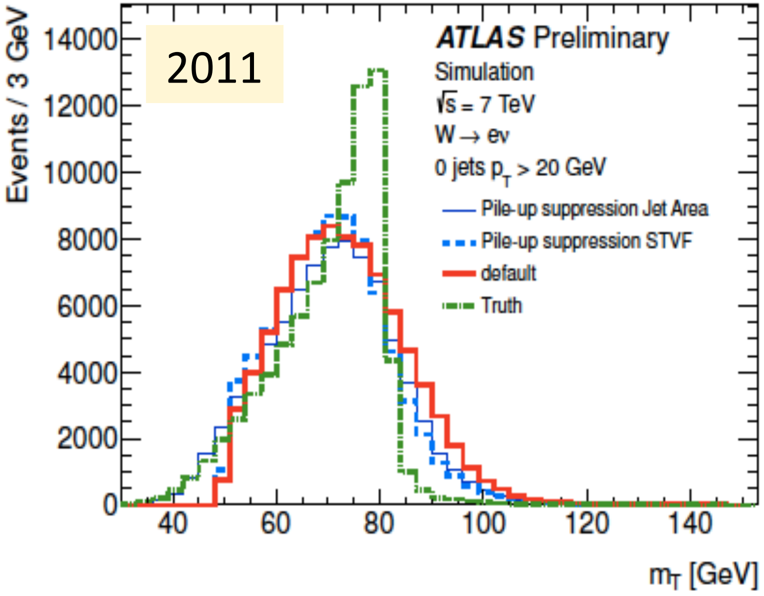
- ➔ In central region: uncertainty < 2.5 % for central jets with p_T > 100 GeV
- ➔ In forward region: uncertainty increases in the forward region up to 7% due to difference in the modelling of the parton showering between PYTHIA and HERWIG++ in the dijet η-intercalibration method.





Effect of pile-up correction on E_T^{miss} Scale





$$m_T = \sqrt{2(p_{Tlept} * E_T^{miss})(1 - \cos|\Delta\phi_{lept,}\ E_T^{miss}|)}$$

Check the effect of pileup correction for Soft Term on E_T^{miss} scale in W→eν events without jets :

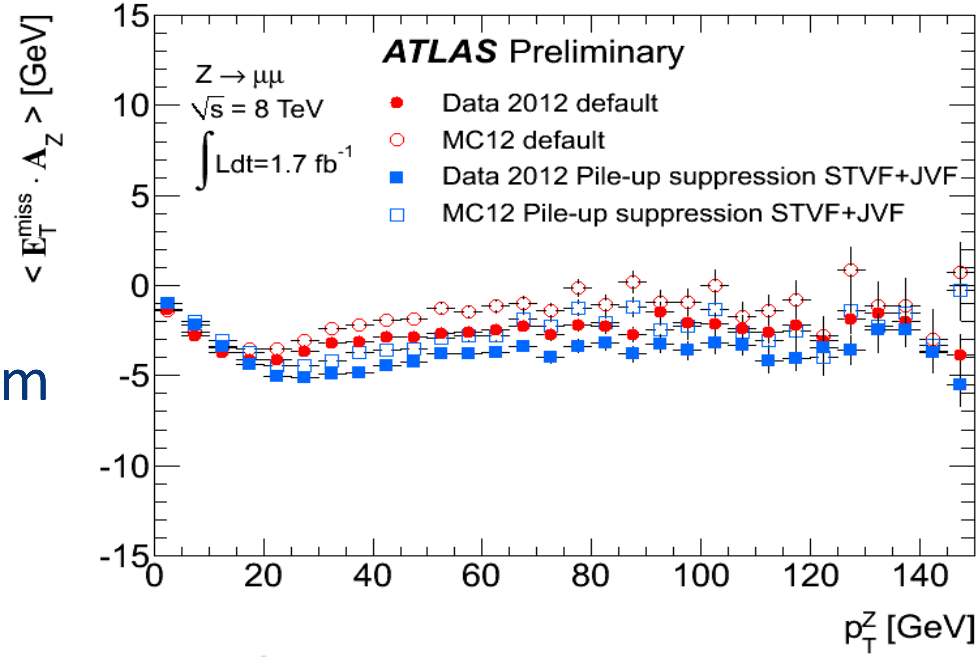
- both STVF and “jet area” methods improves the agreement of E_T^{miss} and the transverse mass with the Truth.

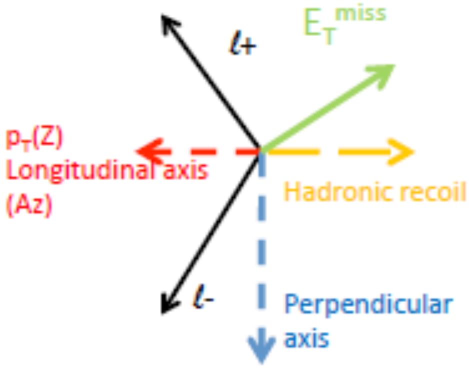
Effect of pile-up correction on E_T^{miss} Scale

E_T^{miss} scale in Z→μμ events:

Mean value of the projection of E_T^{miss} onto the longitudinal axis defined by the vectorial sum of the 2 leptons momenta:
➔sensitive to the balance between the leptons and the hadronic recoil.

➔after pileup suppression slight increase of the bias

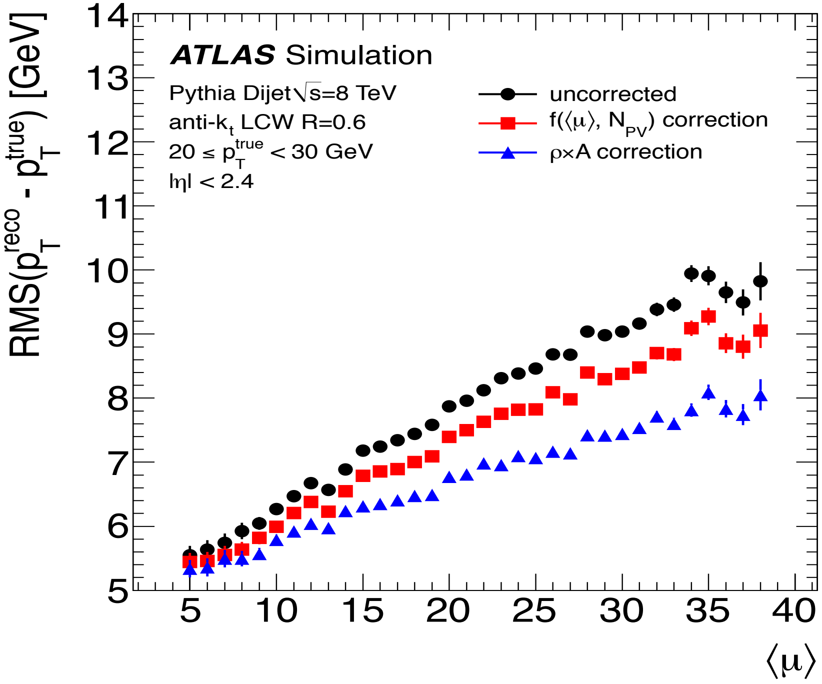


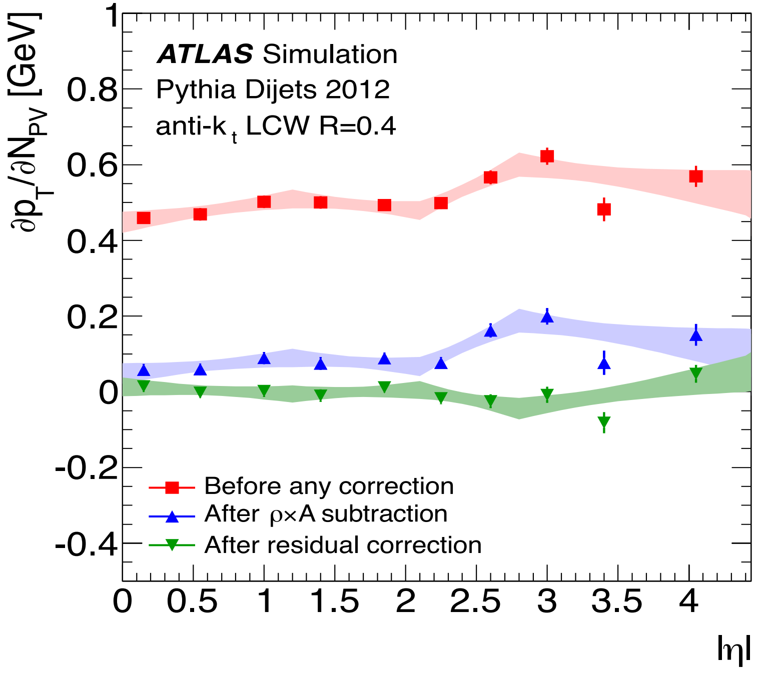


If the 2 leptons from Z perfectly balance the hadronic recoil the projection of E_T^{miss} along Z direction should be zero.

Jet pile-up correction

Pile-up correction





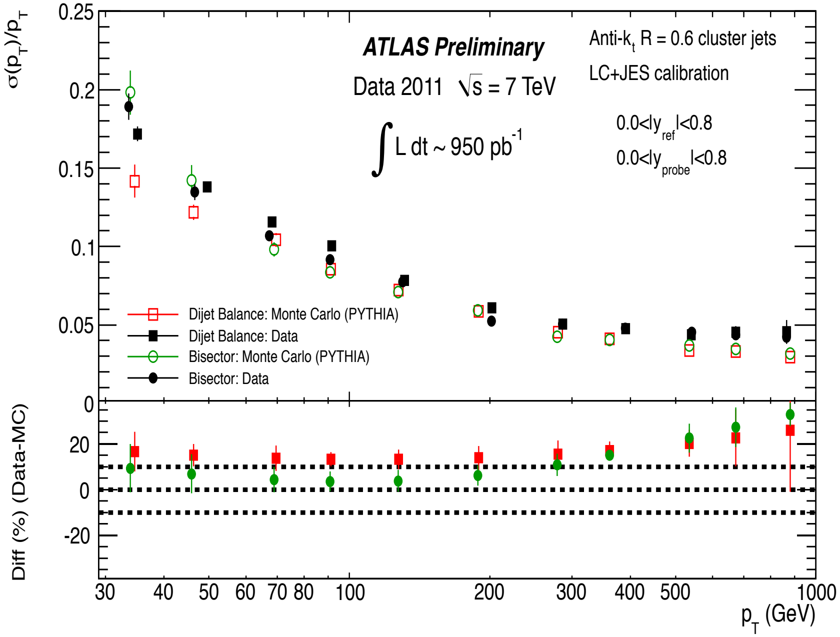
- Resolution: improvements of jet area over the offset correction
  - "Jet area" provides 10% improvement wrt offset correction
  - Still some residual dependence on <μ>.
- Scale: shown dependence of jet p_T on N_{PV} vs $|\eta|$
  - Needed a residual correction very similar to the offset correction (in particular in Forward calorimeter)

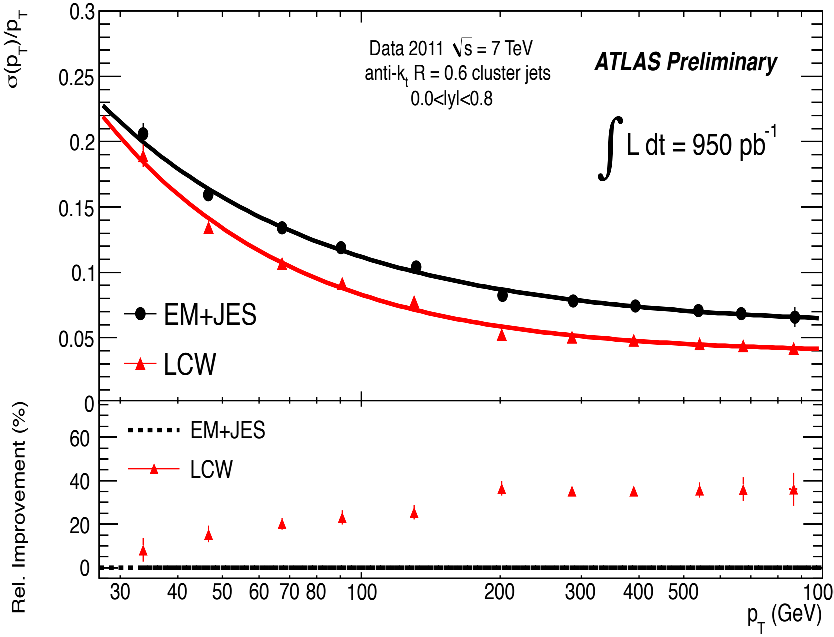
Jet energy resolution (JER)

Fractional jet energy resolution vs jet $p_{T:}$

- measured in situ using dijet balance and bisector techniques.
- Slight better data-MC agreement obtained with the bisector method

- Jets with LCW calibration provides improved resolution up to 40% at 1 TeV wrt EM+JES calibration





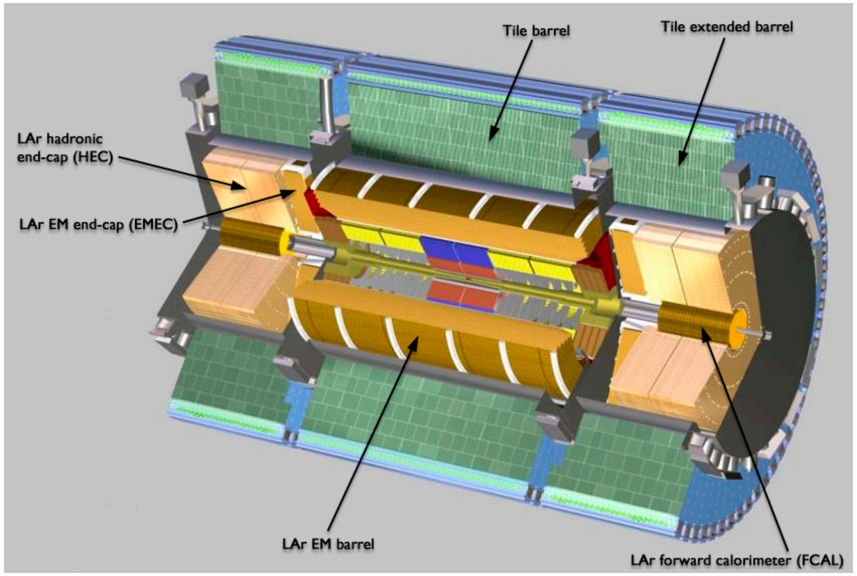
ATLAS calorimeters

Main features for jet and E_T^{miss} reconstruction and calibration:

- Heterogeneous system with fine granularity calorimeters and many transition regions:
  - "Crack" regions: $|\eta| \cong 1.4, 3.2$
- 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



ATLAS Fiducial Regions:

- Hadronic Calorimeter:

Barrel (Tile) $|\eta| < 1.7$

Endcap (LAr-Cu) $1.5 < |\eta| < 3.2$

- Electromagnetic Calorimeters:

Barrel (LAr-Pb) $|\eta| < 1.4$

Endcap (LAr-Pb) $1.375 < |\eta| < 3.2$

- Forward (LAr) : $3.2 < |\eta| < 4.9$

The Soft Term track-cluster matching algorithm

(1) Track selection

All tracks from TrackContainer

Apply quality criteria
Veto on tracks associated to high physics objects

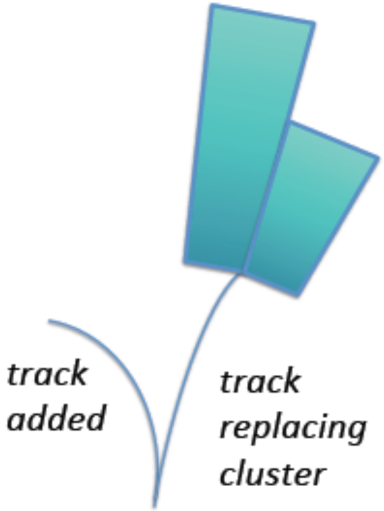
Add good tracks to E_T^{miss} calculation

(2) Cluster removal

All TopoClusters not associated to physics objects

Veto on TopoClusters associated to good tracks

Add remained 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