Expected Uncertainties on the Jet Cross Section Measurement in ATLAS

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Jet Measurements – Truth Definition

- Typically the aim is to test parton level predictions (measure the partons originating the jets)
- The parton level result is “masked” at different levels:
  - theoretical level (everything which leads to the final state particles: ISR/FSR, hadronization, multiple parton-parton interactions, multiple proton-proton interactions)
  - experimental level (detector inefficiencies, non-linearities, resolution)
- The measurement goes through two different steps:
  - Remove the effect of the detector, i.e., measure at best the final state particles: this is a common step of all the possible analysis done with jets
  - Correct the final state objects to get back the parton level
  - The truth jets (particle jets) are those obtained running the same reconstruction algorithm used in the detector on the final state MC particles.

What enters where

- While discussing about Jet Energy Scale we should keep in mind this picture

longitudinal energy leakage

detector signal inefficiencies (dead channels, HV…)

(pile-up noise from (off-time) bunch crossings)

electronic noise

calo signal definition (clustering, noise suppression ,…)

dead material losses (front, cracks, transitions…)

detector response characteristics (e/h ≠ 1)

jet reconstruction algorithm efficiency

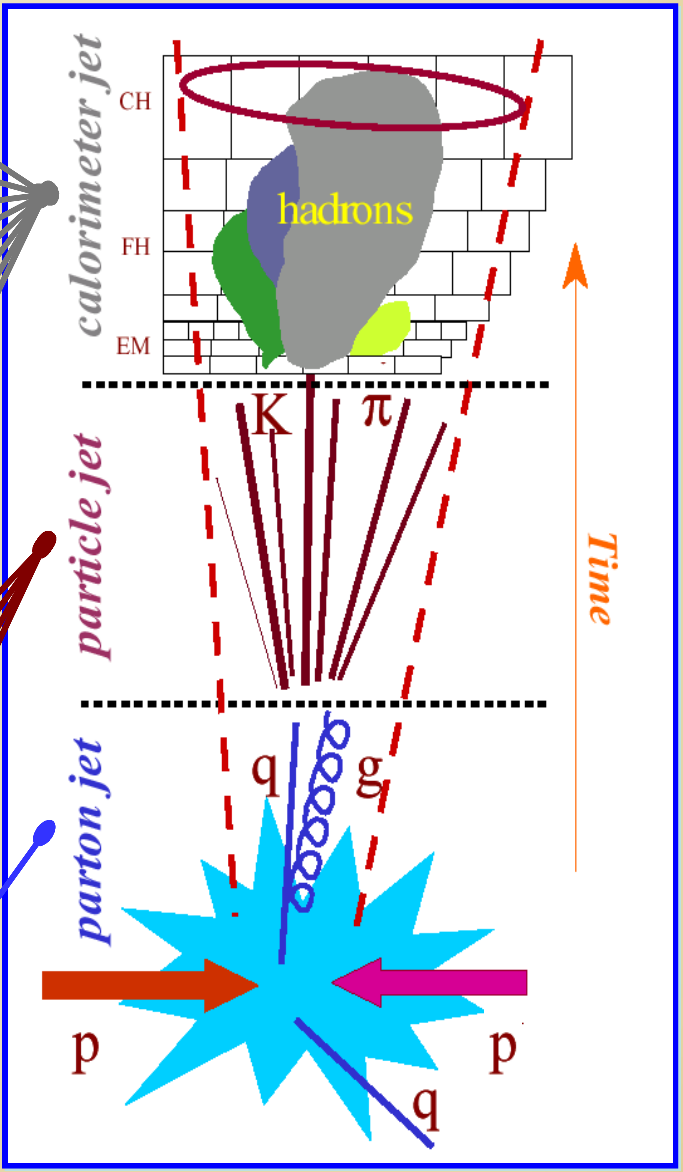
jet reconstruction algorithm efficiency

(added tracks from in-time (same trigger) pile-up event)

added tracks from underlying event

lost soft tracks due to magnetic field

physics reaction of interest (parton level)

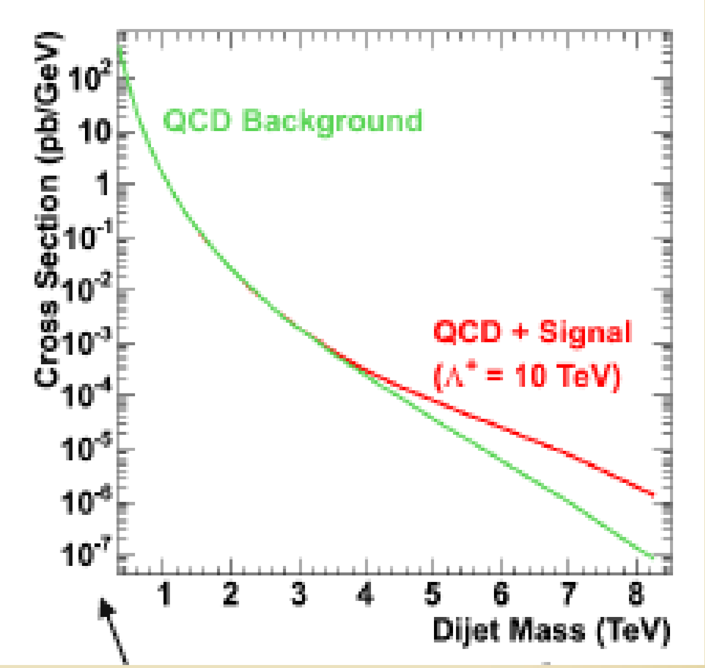


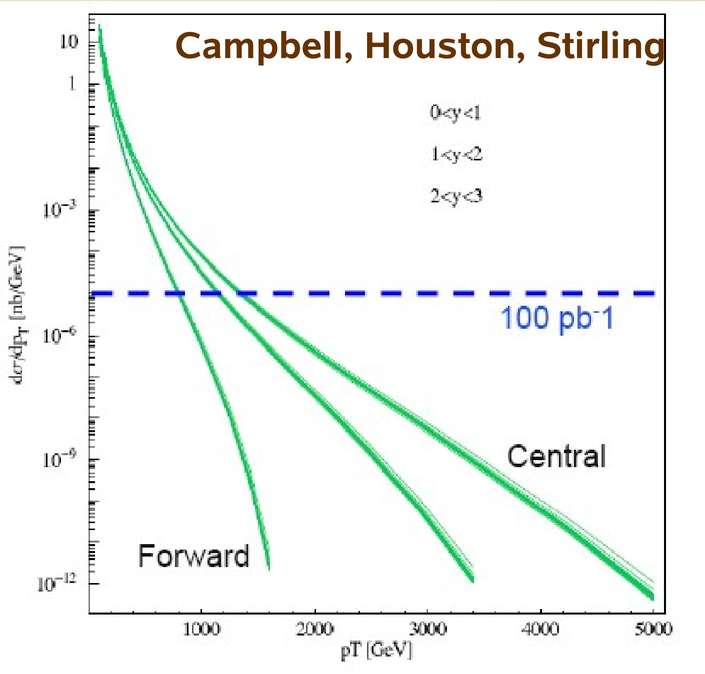
Introduction - Disclaimer

- Most of the material I am showing is "work in progress":
  - Documented in ATLAS-COM-PHYS-2008-62 – P.Francavilla, C.Roda
  - Documented in ATLAS-COM-PHYS-2007-014 – T. LeCompte
  - Documented in an ATLAS TWiKi page (public)
- Part of the material is (or will become soon) public in the ATLAS CSC notes.
- Long list people contributing

Inclusive Jet Cross Section

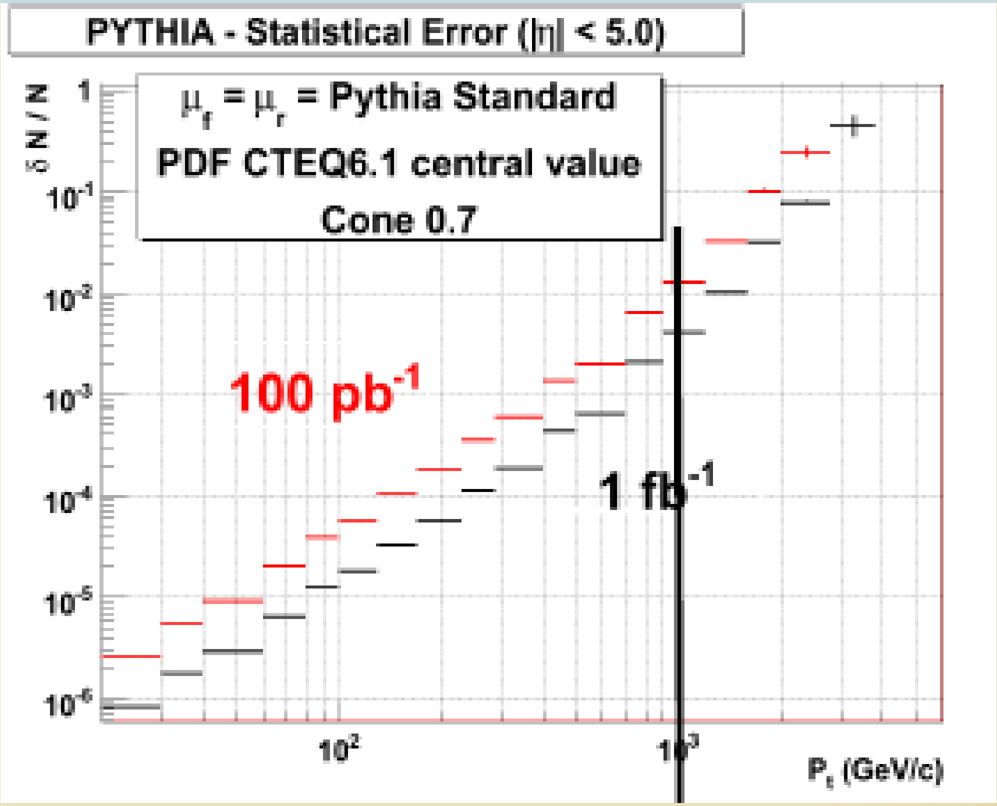
- Physics motivations:
  - interesting per-se
  - Background for <u>all</u> the physics channels
  - Possible signals from physics BSM
- Uncertainties in the theoretical prediction:
  - Renormalization and factorization scale
  - PDF
- Experimental issues:
  - Understanding of the X axis:
    - *Jet Scale and resolution*
    - *Underlying event – pileup*
  - Understanding the Y axis (jet counting):
    - *Jet reconstruction efficiencies*
    - *Jet trigger efficiencies*
    - *Luminosity*





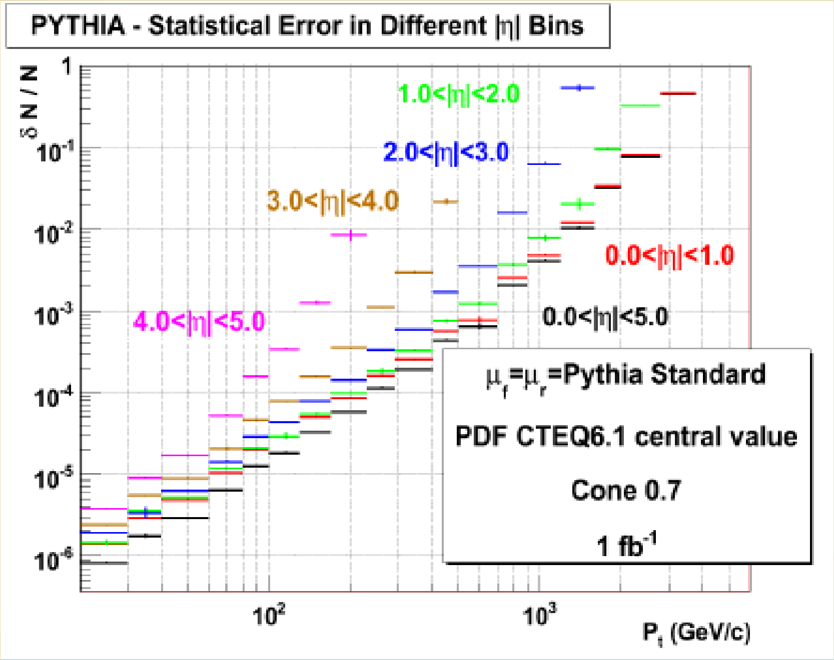
Inclusive Jet Cross Section (2)

- Up to what scale can we probe with the first data?
  - The statistical error at 1 TeV is 1.2% with 100 pb^{-1}, 0.4% with 1 fb^{-1}
  - This is much lower than other errors



ATLAS MC preliminary

With 1 fb^{-1} we can measure up to ~2.5 TeV (statistical error ~ theoretical error)

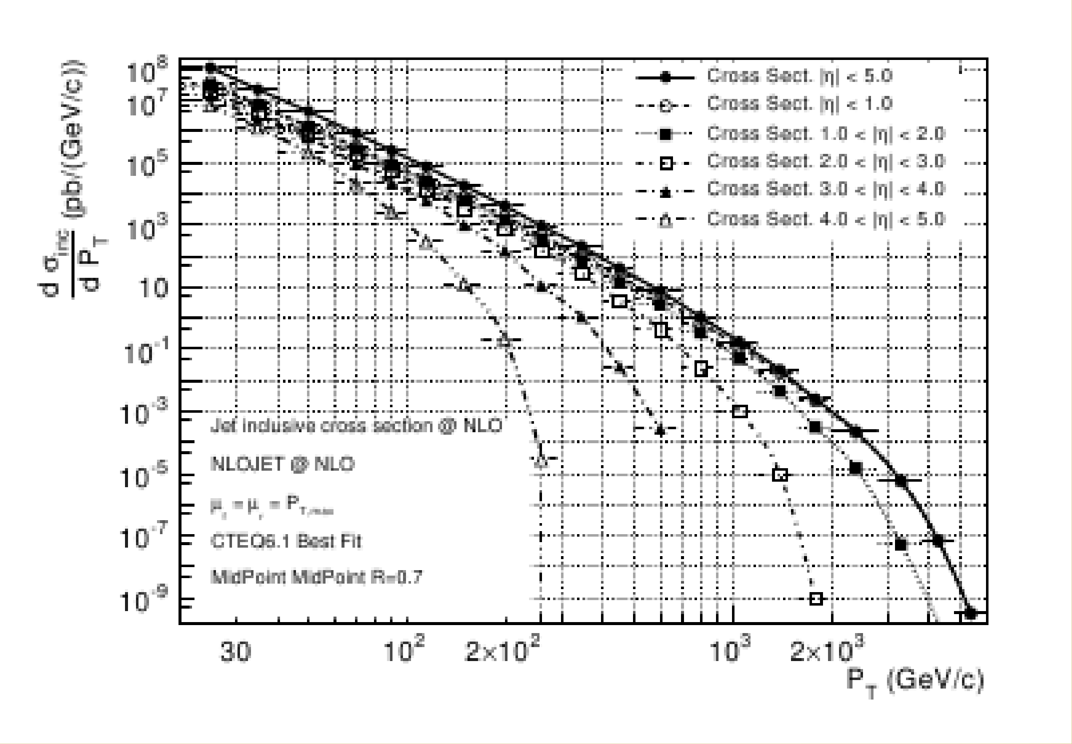


ATLAS MC preliminary

Theoretical Uncertainties

- Two main theoretical uncertainties considered so far:
  - Neglected higher orders (renormalization and factorization scales)
  - PDF uncertainties
- Cross sections evaluated using NLOJET++ (Nucl. Phys. B269 (1986) 445-484) and Pythia:
  - NLOJET can provide the LO and NLO estimate:
    - *With consistent choices, Pythia and NLOJET give the same result at LO*
    - *NLOJET allows only parton level studies*
  - NLO cross section with CTEQ6.1, $\mu_f = \mu_r = P_{tmax}$ has been chosen as reference

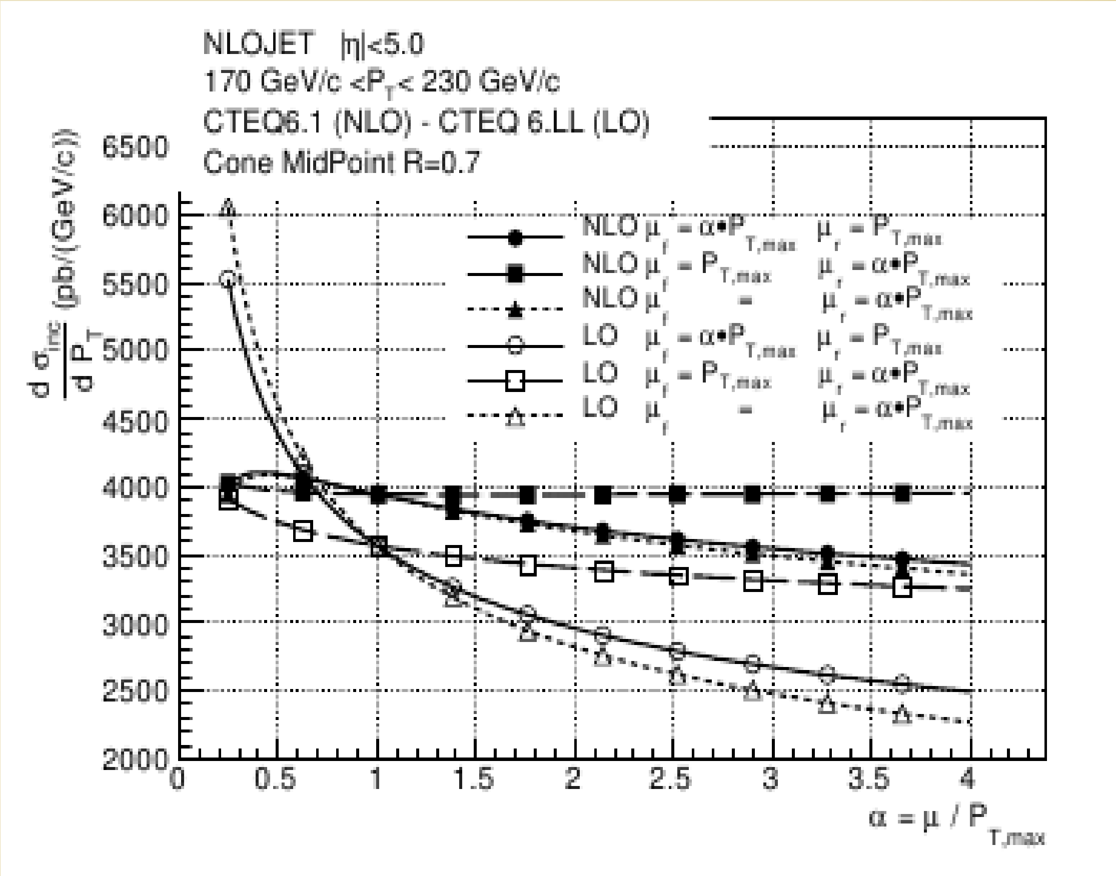
ATLAS MC preliminary



Theoretical Uncertainties (2)

- Sensitivity of the cross section to the choice of μ_f and μ_r.
  - Define $\mu_f, \mu_r = \alpha P_{Tmax}$, with $0.25 < \alpha < 4$.
  - Let μ_f, μ_r vary separately and together
  - Compute the ratio $\sigma(\mu_f, \mu_r)/\sigma(\mu_f = P_{tmax}, \mu_r = P_{Tmax})$
    - Only jets with 170 GeV < P_T < 230 GeV are considered in this plot
    - The LO is sensitive in particular to μ_r. $\sigma(\mu_r = 0.25P_{tmax}) \sim 2\,\sigma(\mu_r = 4P_{tmax})$
    - Limited sensitivity of the NLO

ATLAS MC preliminary

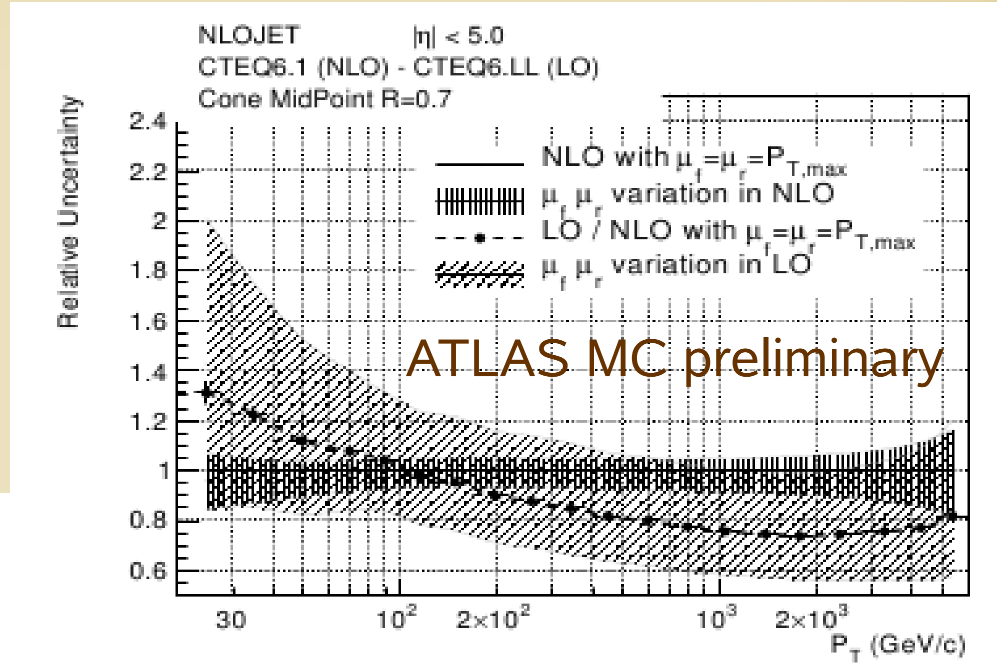


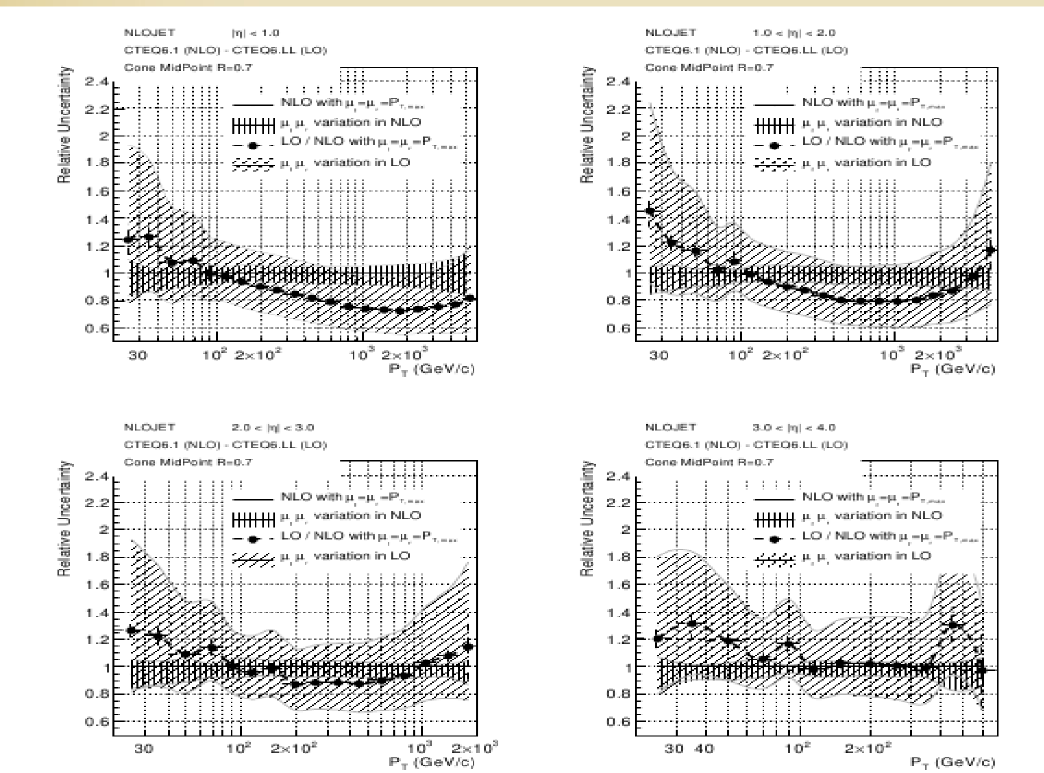
Theoretical Uncertainties (3)

- Bands obtained as max and min of the ratio

$$\frac{\sigma(\mu_r = x\,P_{Tmax}, \mu_f = y\,P_{Tmax})}{\sigma(\mu_r = P_{Tmax}, \mu_f = P_{Tmax})}$$

x,y = 0.5,1,2



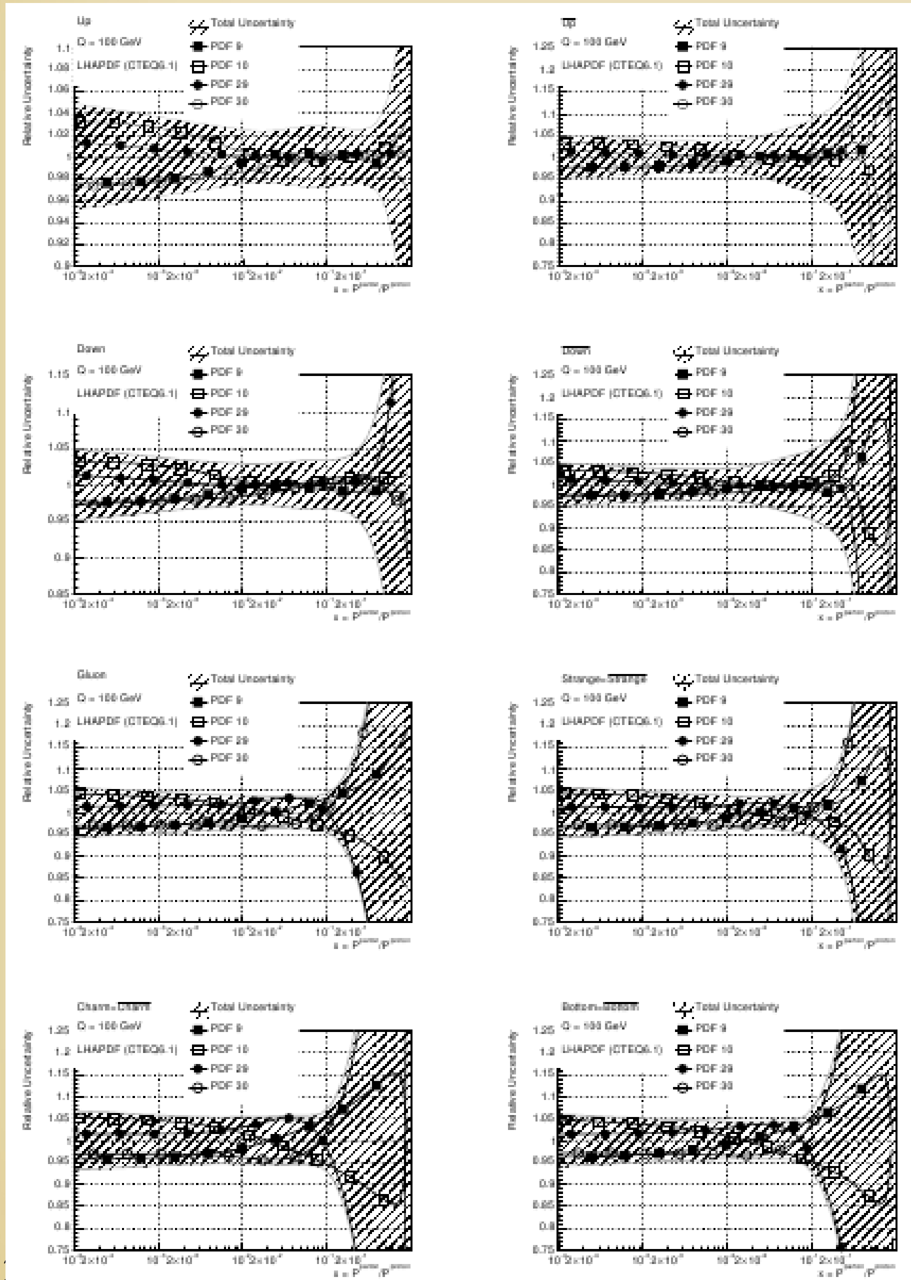


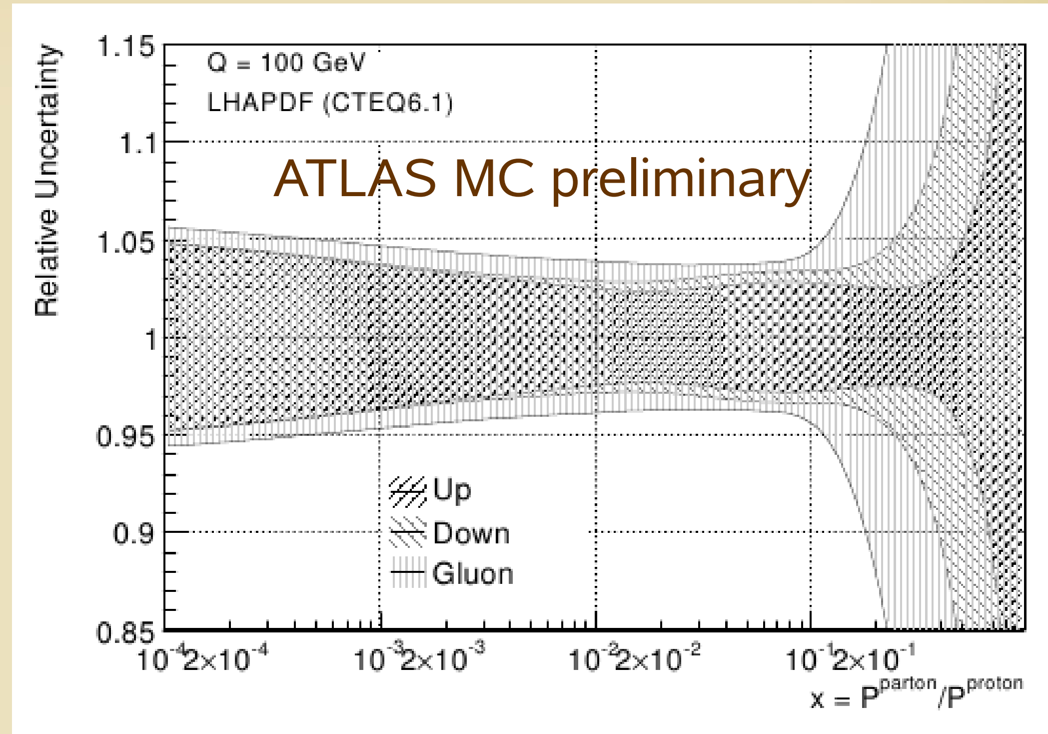
- The uncertainty is almost independent of P_T above 200 GeV. The numbers are:
  - 7% for the NLO
  - 22% for the LO

ATLAS MC preliminary

Theoretical Uncertainties (4)

ATLAS MC preliminary



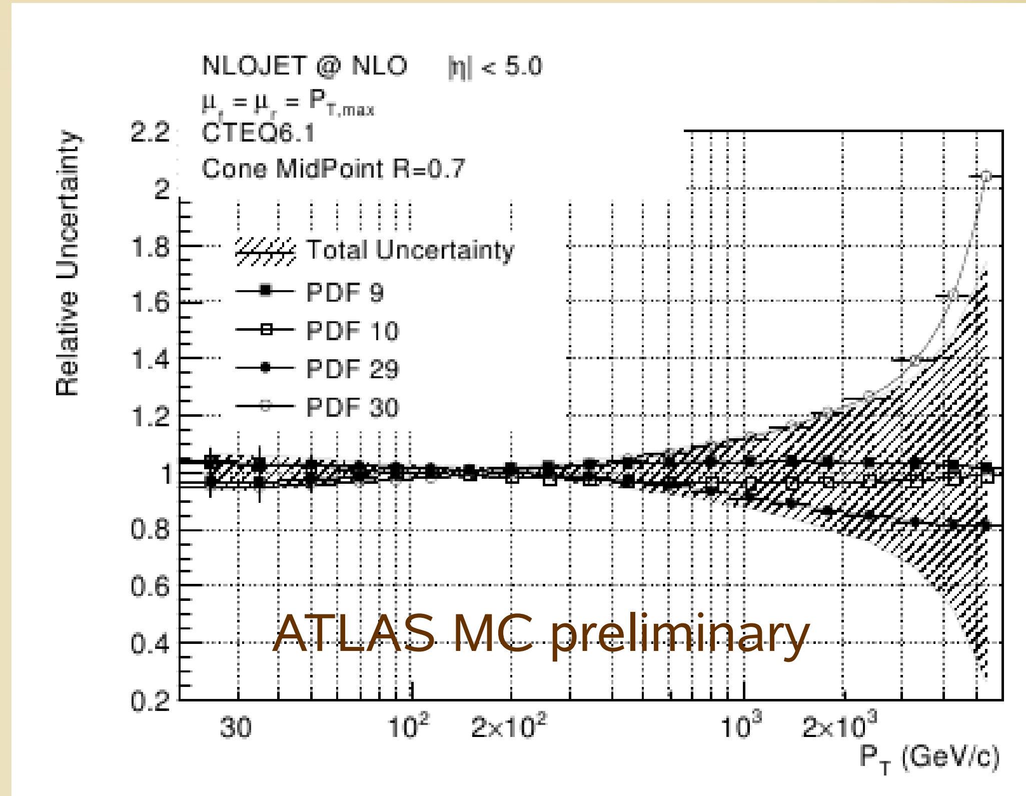


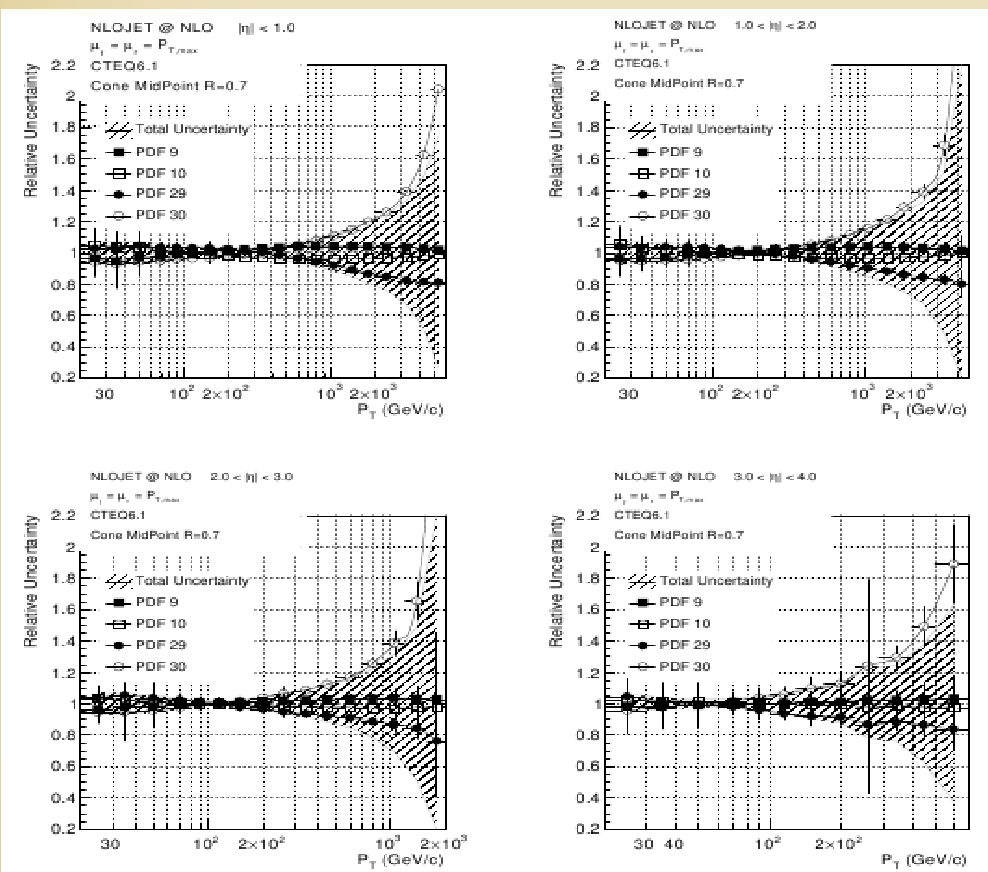
- Uncertainty due to the PDF (LHAPDF CTEQ6.1 used):
  - Uncertainty is dominated by the gluon PDF.
    - *Low x -> PDF sets 9 and 10*
    - *High x -> PDF sets 29 and 30*

Theoretical Uncertainties (5)

- The uncertainty of the PDFs propagates in an uncertainty of the cross section

$$\Delta\sigma=\frac{1}{2}\sqrt{\sum_i\left(\sigma\left(f_i^{max}\right)-\sigma\left(f_i^{min}\right)\right)^2}$$





- The error is 2% at 200 GeV and 1 TeV at 13%

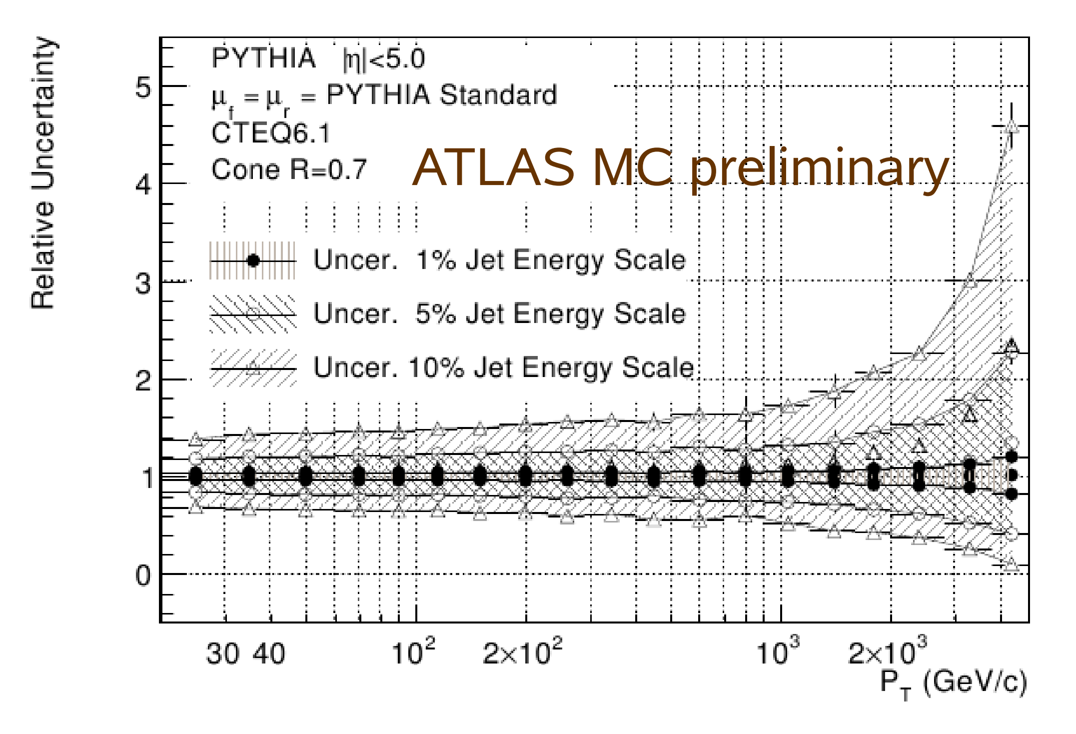
ATLAS MC preliminary

Experimental uncertainties

- Several different ingredients enter in the jet cross section measurement at particle level
- Discussed in the following:
  - Jet energy scale and jet resolution
  - Jet trigger efficiencies
  - Jet reconstruction efficiencies
- Not discussed:
  - Luminosity
  - Corrections to apply to the particle level measurement
- The general approach: try to get an estimate of the uncertainties associated with the early data:
  - As much as possible data drive approach to the measurement

Inclusive Jet Cross Section

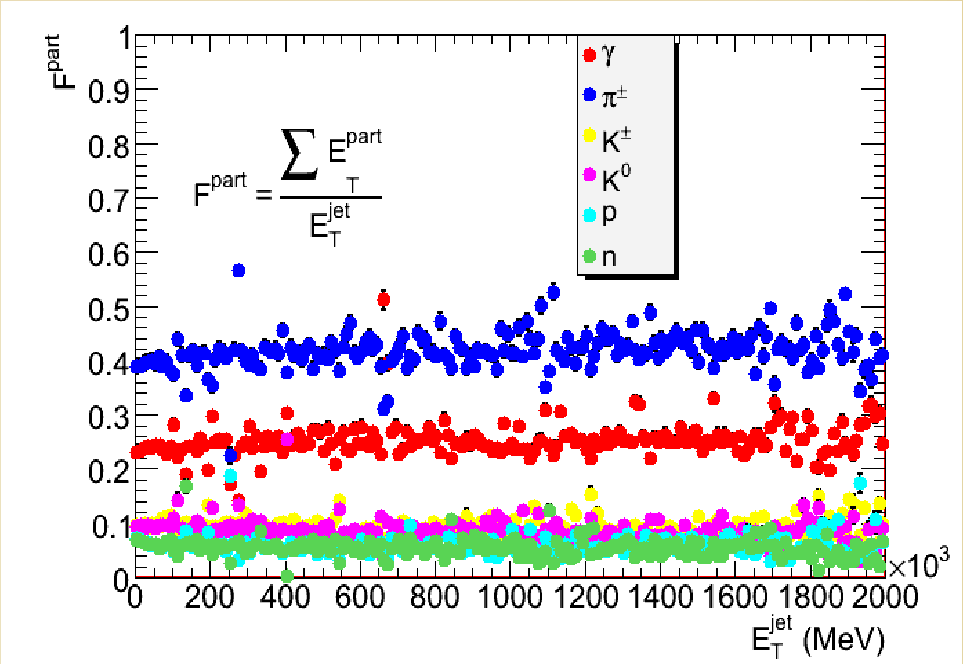
- Study on the role of the jet scale uncertainty:
  - The ATLAS fast simulation has been used to estimate the error on the cross section due to the jet scale.
  - The response of the ATLAS fast simulation jets is manually shifted by
    - *1% (ATLAS TDR claim)*
    - *5% (Optimistic initial ATLAS jet scale)*
    - *10% (Pessimistic initial ATLAS jet scale)*

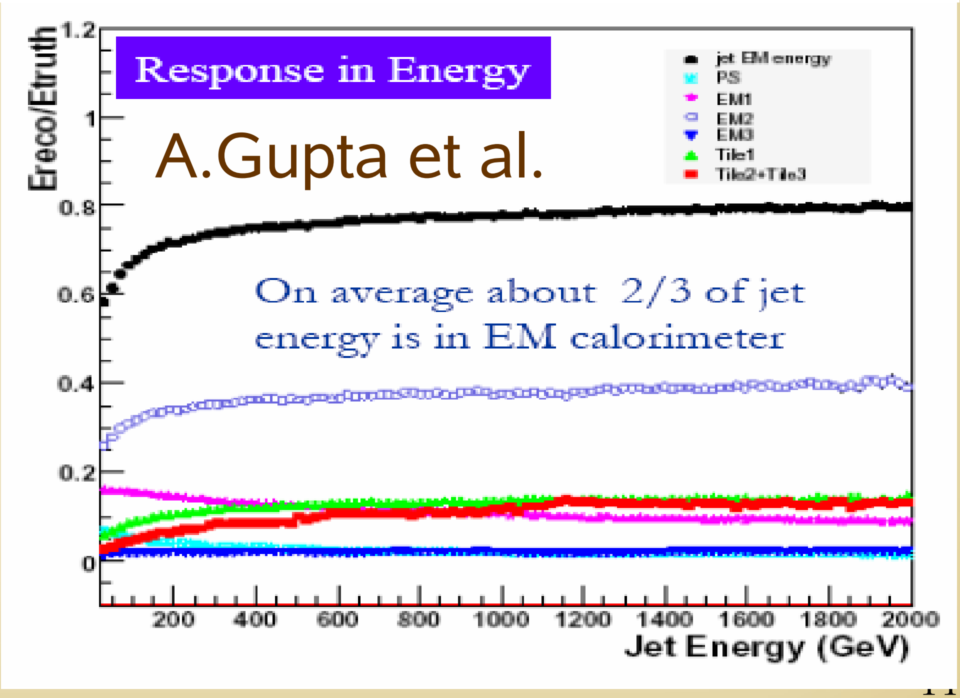


- 10% error on the jet scale → 60% error on the cross section @ 1 TeV
- 5% error on the jet scale → 30% error on the jet scale @ 1 TeV

Jet Energy Measurement

- 25% of the jet energy is carried by photons
- 75% of the energy is hadronic – energy dependent EM fraction in the shower
- The ATLAS calorimeters are non-compensating:
  - The response to EM and HAD energy is different
  - The measured jet energy is non-linear with the true jet energy
- The detector has holes and dead material:
  - ~10% of the energy is lost





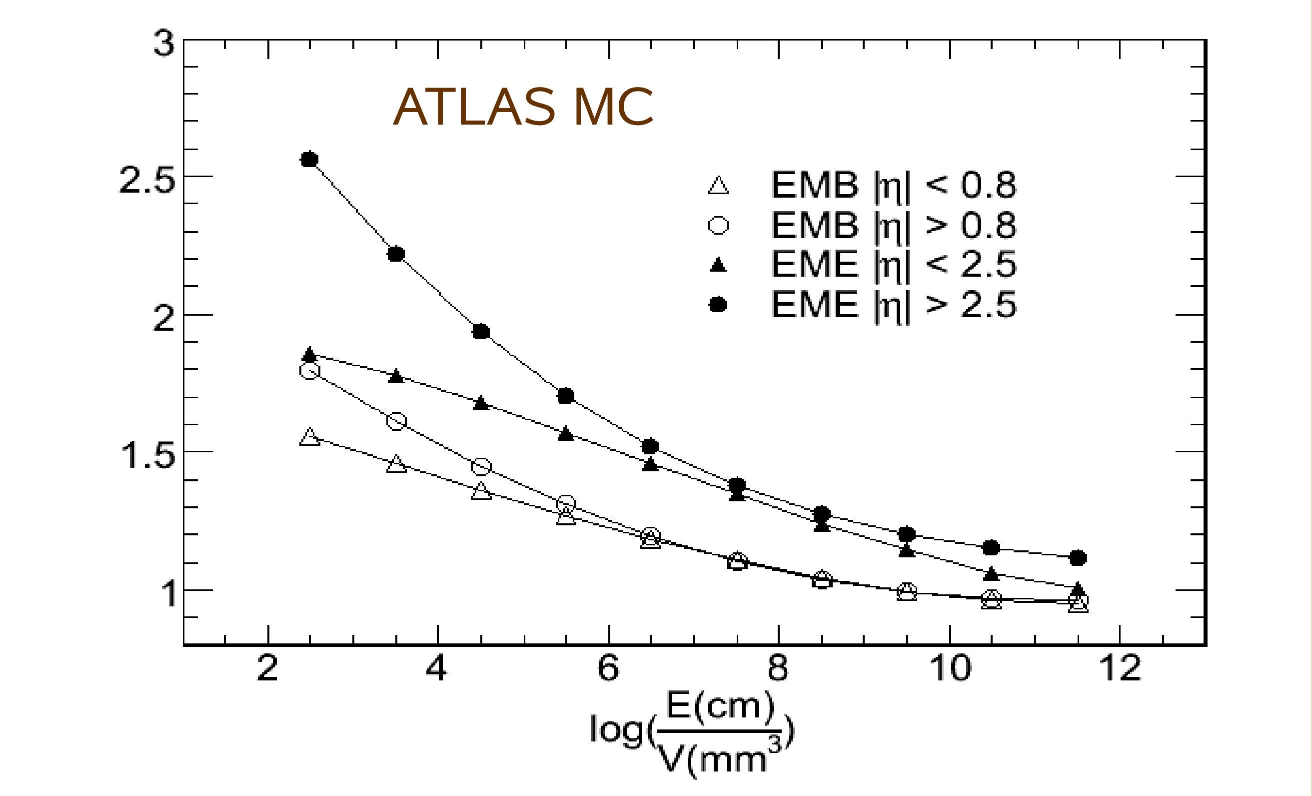
Jet Energy Measurement (2)

- An event by event correction for the dead material energy loss and fluctuations in the em fraction of the hadronic shower gives an improved jet resolution
- In ATLAS we studied the possibility to correct using:
  - Longitudinal shower development (weights associated to the longitudinal calorimeter samplings)
  - Energy density in the cells (cell level weights depending on the energy density)
  - Cluster level corrections using both the above (local hadron calibration)
- All these quantities are sensitive to the electromagnetic/hadronic fraction of a shower.
- The corrections are usually MC based.

H1 jet corrections

- The total energy is computed as follows: $E_{rec}^{jet} = \sum_{i=cells} w_i(\frac{E_i}{V_i}) E_i$
- The weights depend on the cell energy density (and pseudorapidity, through a rough binning)

$$w_i(\frac{E_i}{V_i}) = \sum_{j=0}^{3} a_j \log \frac{E_i}{V_i}$$

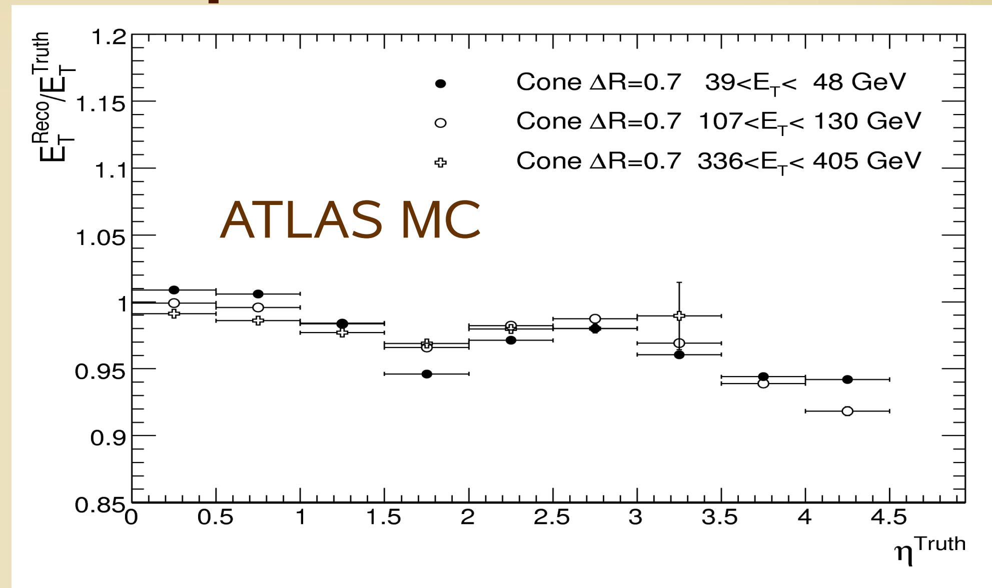


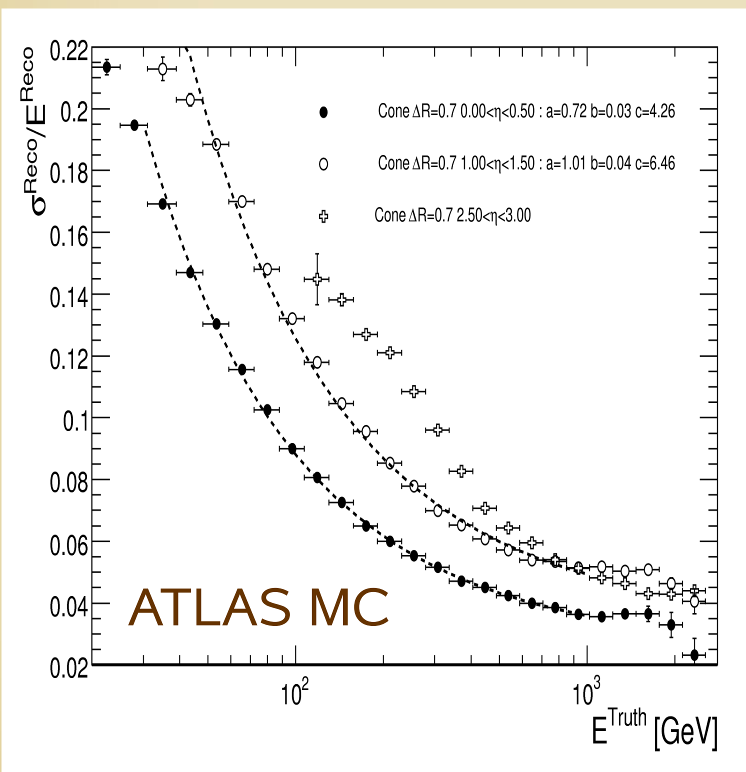
The weights enhance the response of low energy density cells (Had energy).

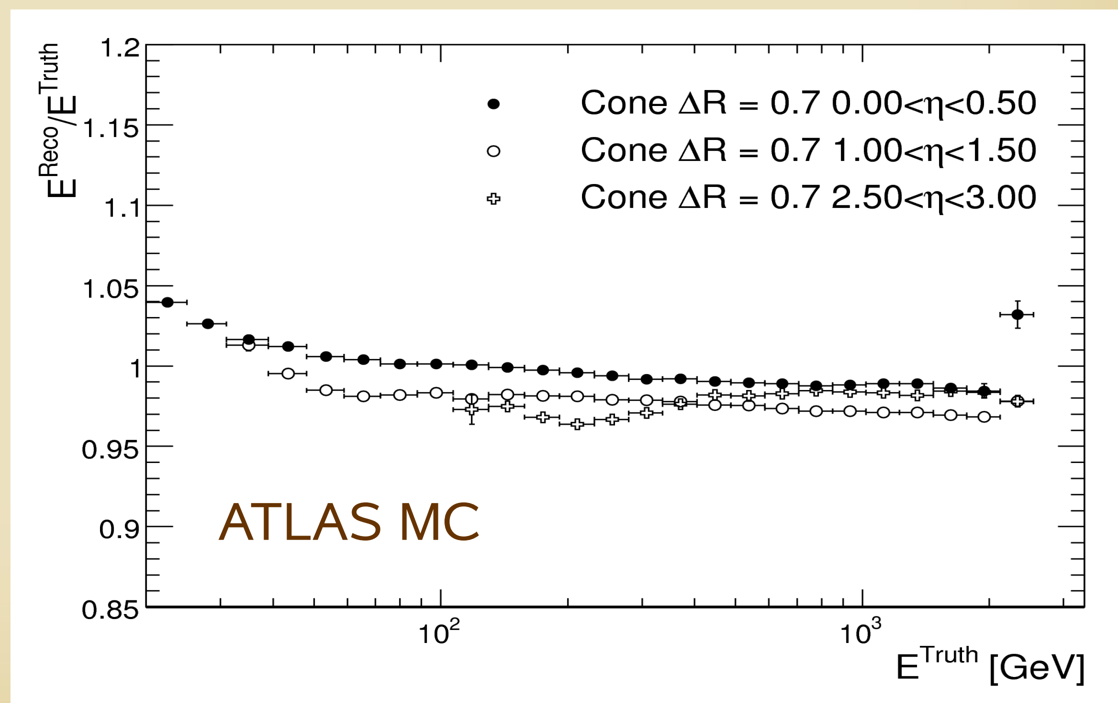
High density is associated with EM deposits: the weights go to 1

Some examples

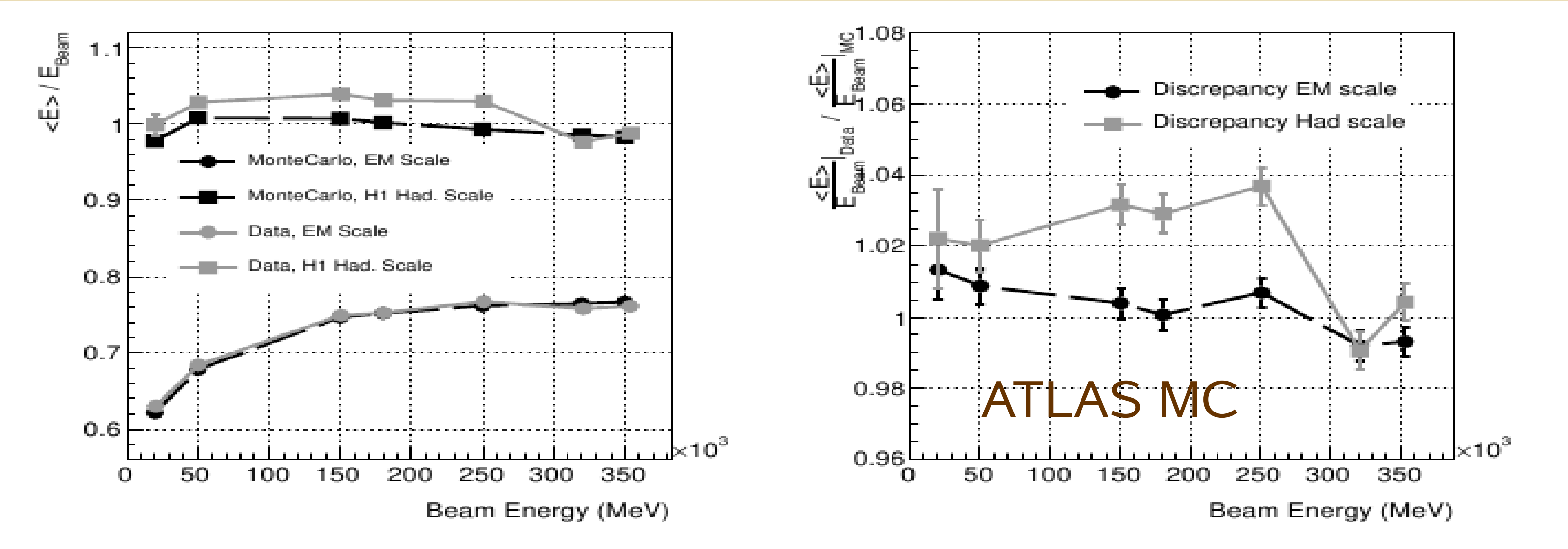
- SU3 sample plots
- SU3 is very different from what has been used to find the calibration constants







Combined Test Beam data



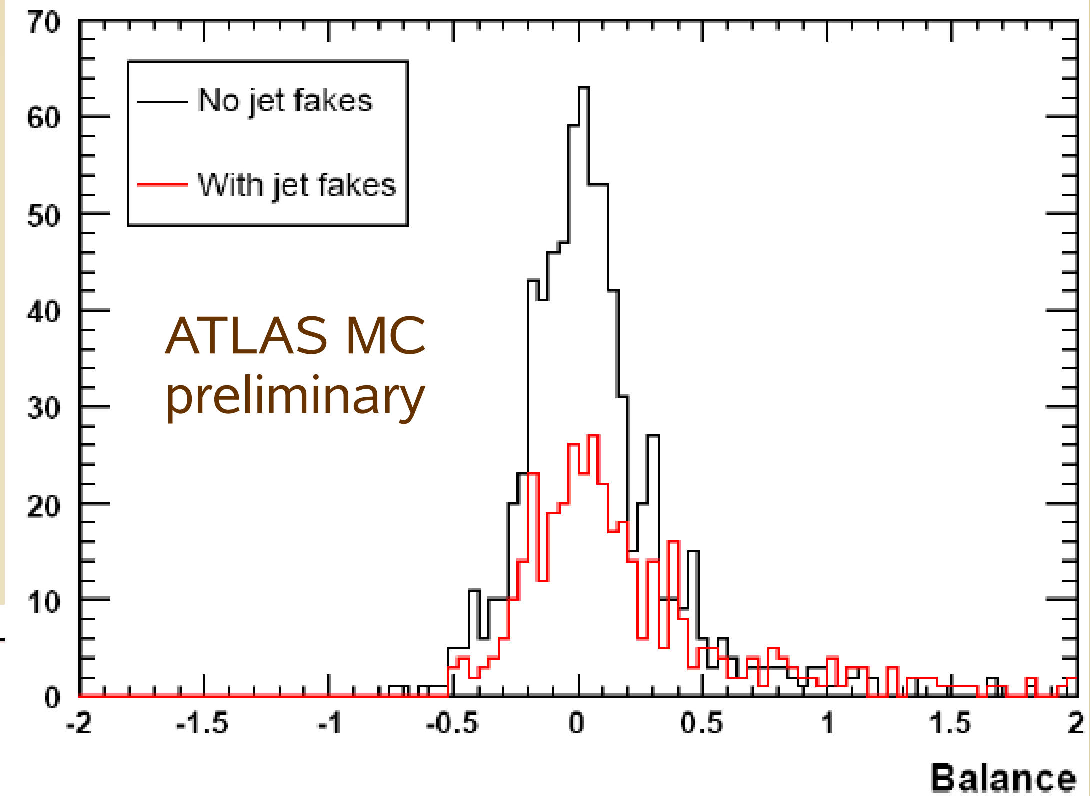
- Estimate the scale bias at day 1 directly from the test beam data:
  - Make use of CTB2004 pion
  - Apply the jet corrections (computed for jets in the ATLAS setup) to the real pions
  - Agreement MC/DATA (before corrections) good:
    - *Maximum disagreement ~1-2%*
  - After the corrections:
    - *Maximum disagreement ~4%*

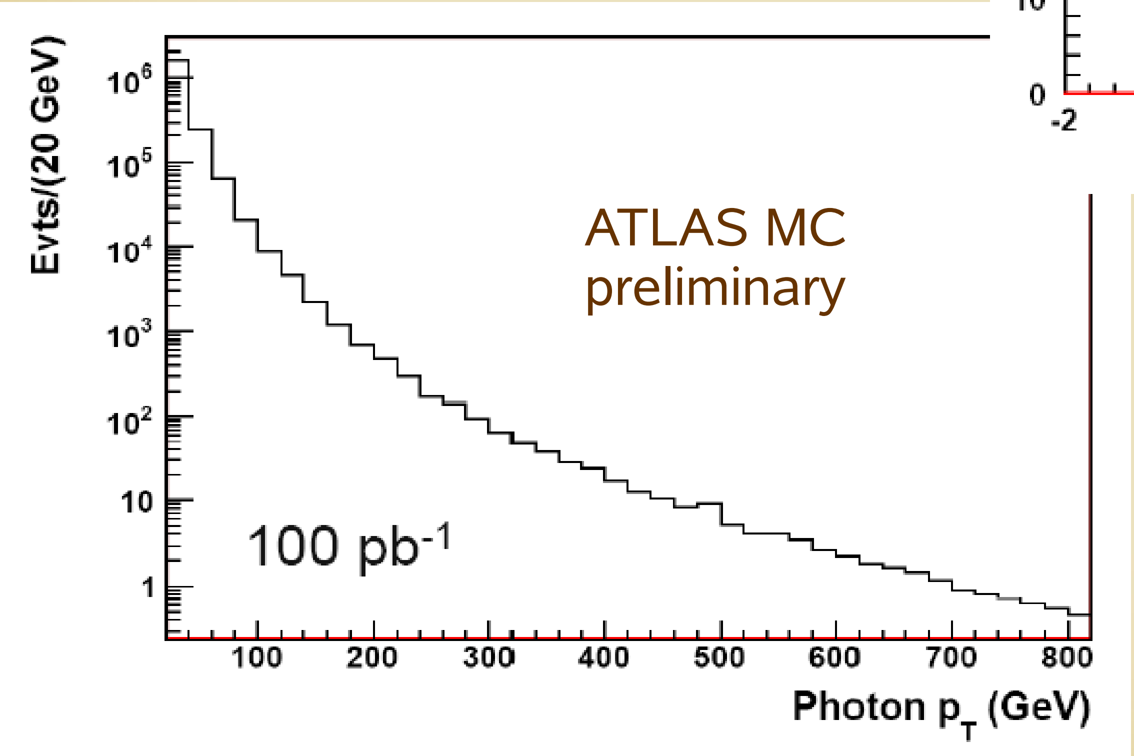
Comments on the Jet Scale

- Corrections to fix the jet scale are in place:
  - Performance tested in a variety of different geometries, physics channels, jet fragmentation, showering model, Combined Test Beam data. .
  - Each of the above introduces uncertainties of the order of few percent (rarely larger than 5%)
  - It looks plausible to achieve ~5% jet scale using the best G4 physics list (QGSP_BERT) with accurate as-built geometry.

In situ verification of the jet scale

- Check the energy scale with γ+jet
- The balance looks good, but:
  - Large background from DiJet





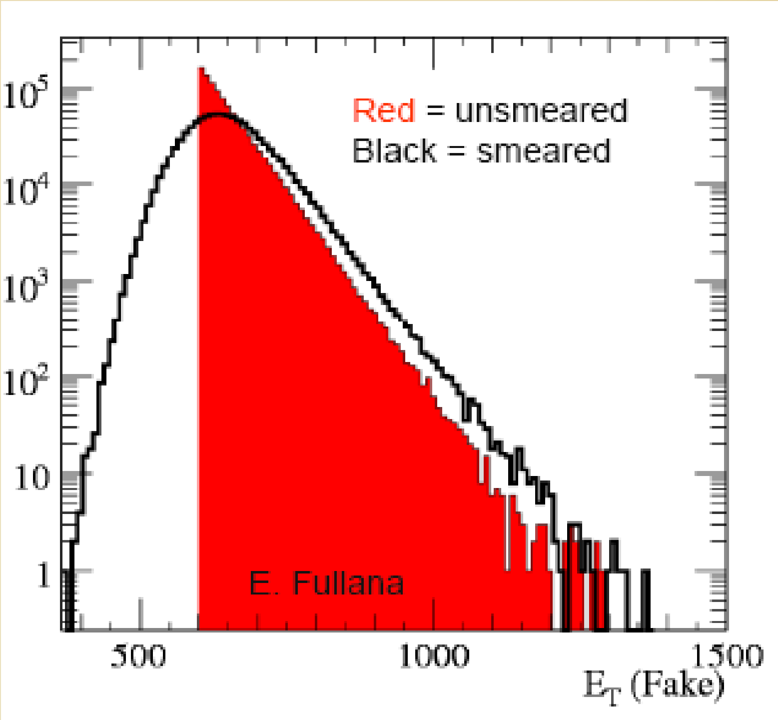
- 100 pb^{-1}: γ+jet can probe up to few hundreds GeV:
  - We need a way to get up to the TeV scale

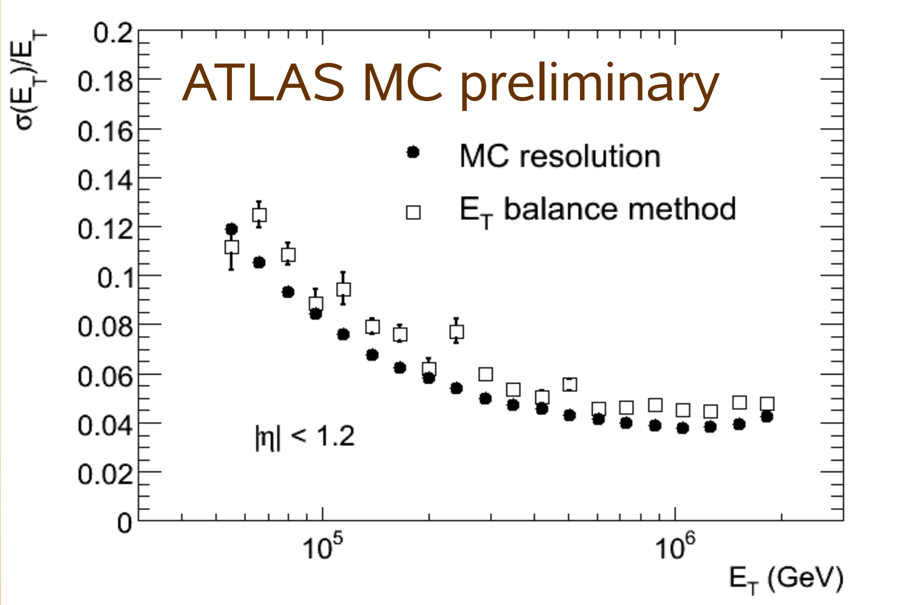
Jet Resolution

- Experimental resolution + a steeply falling P_T spectrum → bias in the energy measurement
- Correcting for this requires the knowledge of the jet resolution.
- The di-jet balance method :
  - Define the unbalance in the transverse plane between the leading jets as

$$A = \frac{(E_{T1} - E_{T2})}{(E_{T1} + E_{T2})}$$

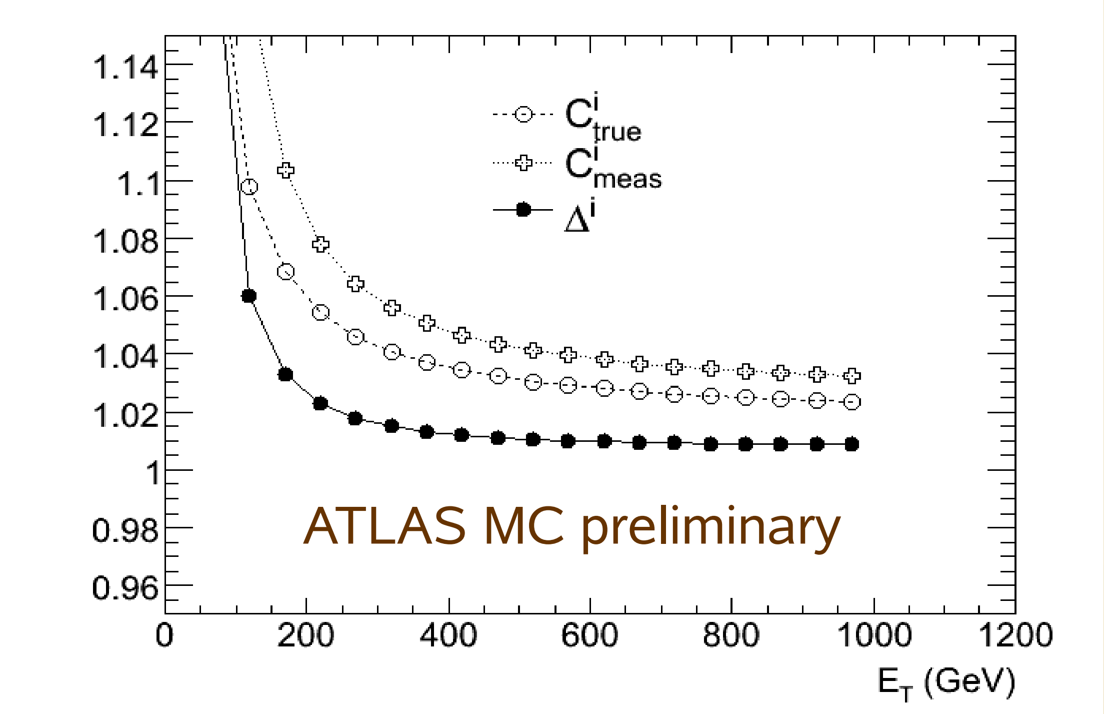
It can be shown that $\sigma(E_T)/E_T = \sqrt{2}\,\sigma_A$ if $\langle E_{T1}\rangle = \langle E_{T2}\rangle$ and $\sigma(E_{T1}) = \sigma(E_{T2})$, which means balanced jets with uniform resolution





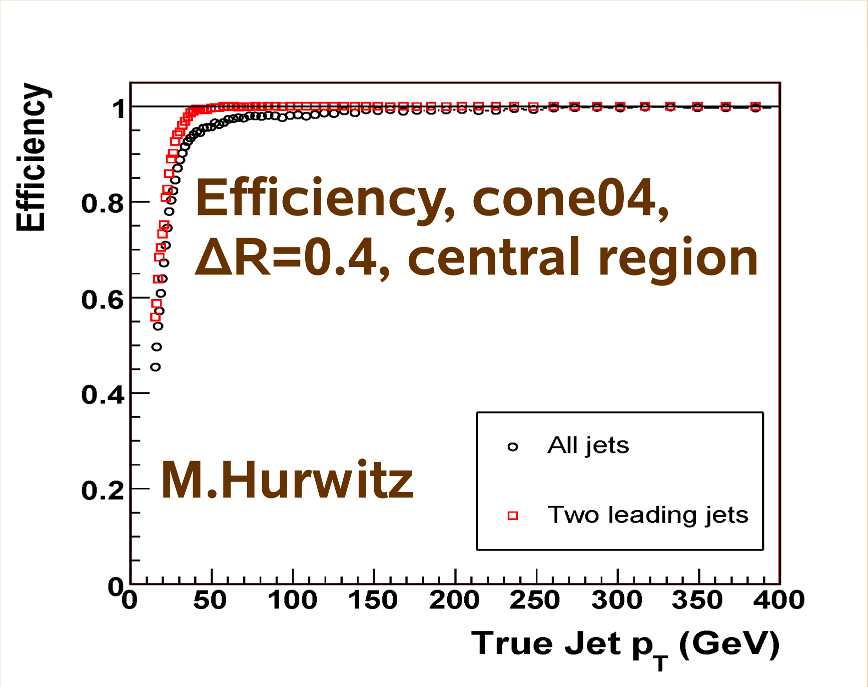
Jet Resolution (2)

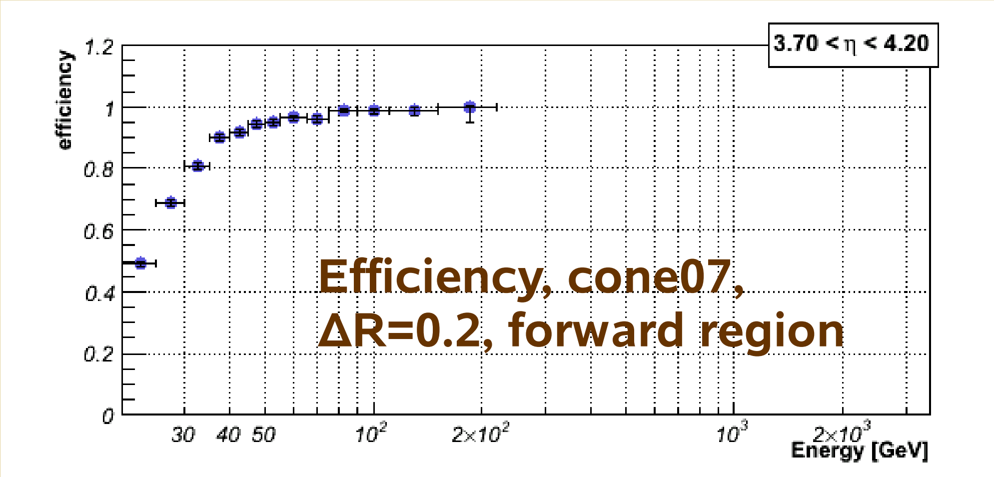
- The "true" corrections to the cross section are of the order of 5% at 200 GeV, 3% at 1 TeV
- The "measured" corrections are ~ 8% at 200 GeV, 4% at 1 TeV
- The introduced bias is ~5% at 100 GeV, ~2% at 200 GeV and it decreases with E_T

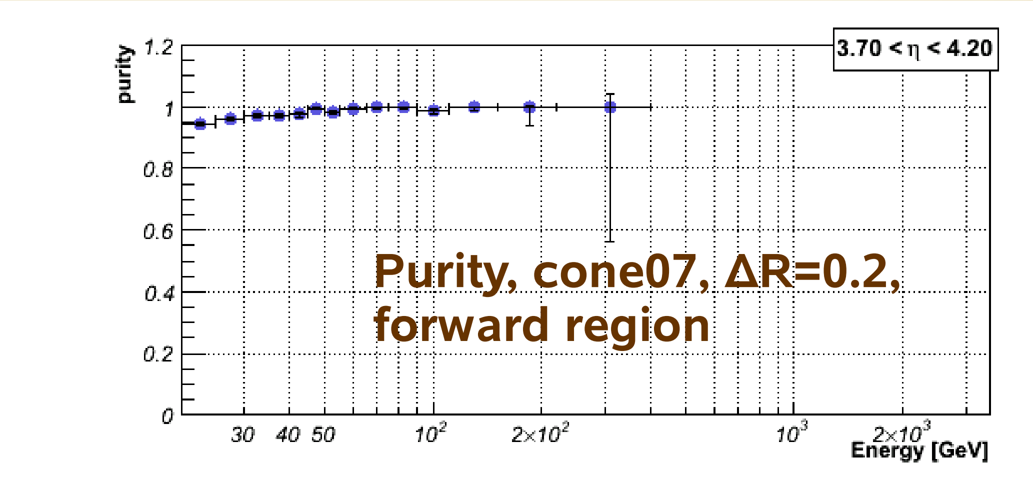


Jet Reconstruction Efficiencies

- Reconstruction efficiency:
  - Define a ΔR_{match} (choice based on the angular resolution)
  - Match reconstructed jets with truth jets if $\Delta R < \Delta R_{match}$
  - The efficiency is the number of matched reco jets/number of truth jets
  - The purity is the number of matched reco jets/number of reco jets
- Both numbers depend on ΔR_{match}



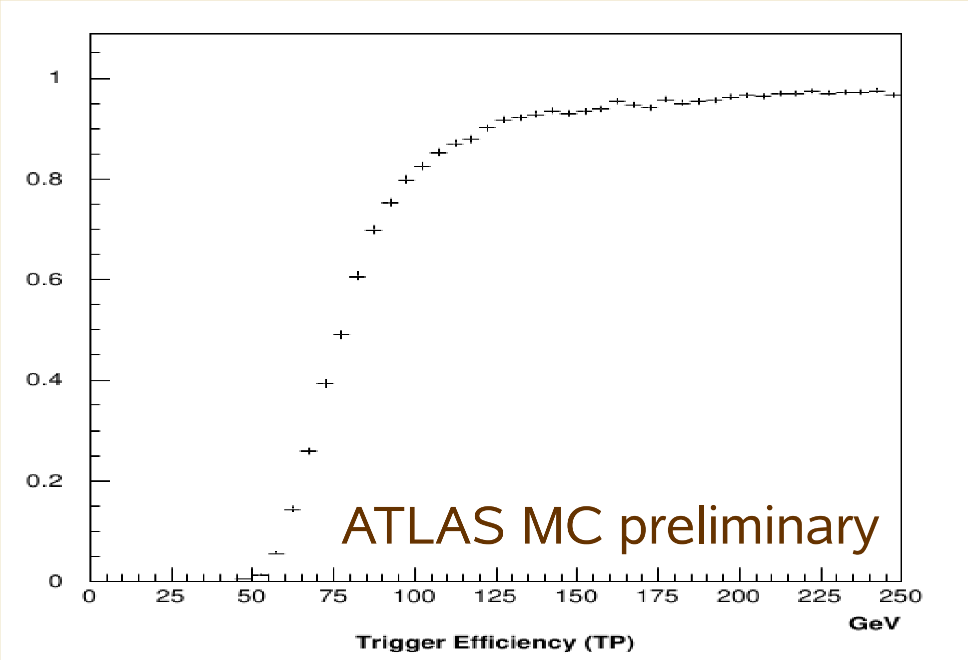


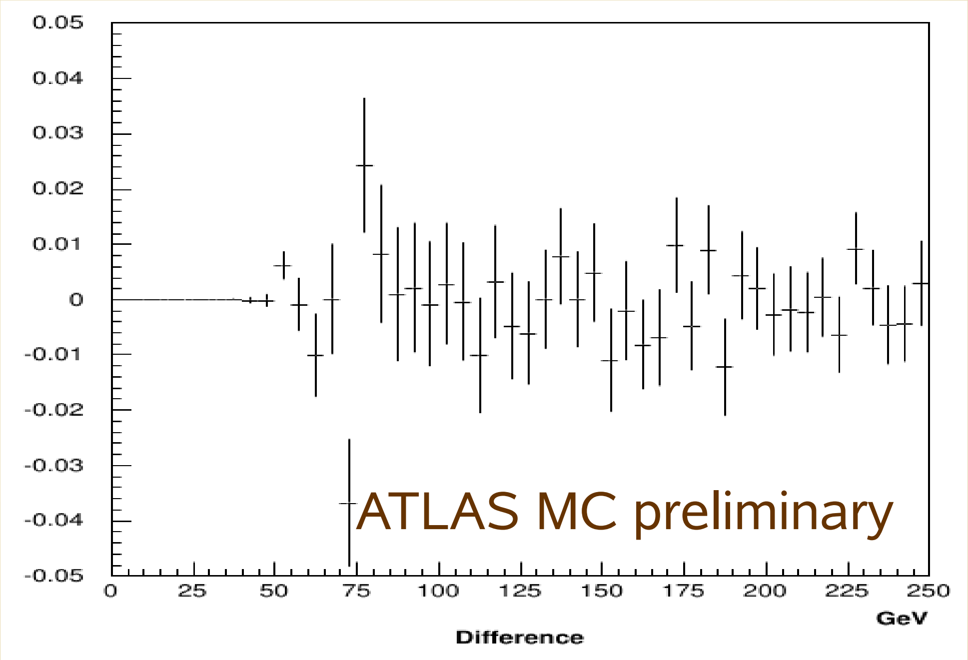


V.Giangiobbe & K.Lohwasser

Trigger efficiencies

- Data drive approach to understand trigger efficiencies.
- Two possible approaches:
  - Start with MB trigger and understand the efficiency of the lowest jet trigger. Iterate
  - Tag and probe:
    - *The jet that triggered is the tag*
    - *The other jets in the event are the probe*
    - *Efficiency curves obtained matching the probes to the ROIs*





Summarizing....

- The dominant error is by far the one on JES:
  - should not be true anymore if the nominal 1% is reached
- Largest theoretical error comes from the PDF uncertainty
- Statistical error, jet resolution, small compared to the JES

Error	200 GeV/c	1 TeV/c
Jet Energy Scale (10%)	43%	57%
Jet Energy Scale(5%)	21%	29%
Neglected higher orders (LO)	22%	21%
Parton distribution functions	2%	13%
Neglected higher orders (NLO)	6%	7%
Jet Energy Scale(1%)	5%	5%
Jet Energy Resolution (20%)	6%	4%
Jet Energy Resolution (10%)	3%	2%
Statistical error (100 pb^{-1})	0.018%	1.2%

What is missing

- The analysis aims to measure the jet cross section at particle level:
  - particle/parton level corrections not studied much:
    - *UE correction from MC after its tuning? Event by event subtraction using the energy density? Early subtraction a la D0*
    - *Hadronization corrections not in place*
- At “experimental” level:
  - Uncertainty on the luminosity not estimated
  - Assuming a working detector. Dead cells not in the game (current status ~0.1% dead cells in Lar EM, ~0.8% in Tile (HAD)
  - Statistics available in 2008 basically an unknown (small) number
  - No studies done at 10 TeV

Conclusions

- Jet performance well understood (on simulated events):
  - Good performance in terms of reconstruction efficiencies, jet linearity and resolution
  - Strategies are in place to estimate them from the data
- Inclusive jet cross section measurement:
  - We hope to measure up to E_T~ 1 TeV with the first 100 pb^{-1}
  - The most relevant experimental uncertainty comes from the jet energy scale:
    - *It will be controlled with γ+jets up to ~300 GeV (with 100 pb^{-1})*
    - *Scale variations changing material, shower model, physics sample are maximum 5%*
    - *A direct estimation with real CTB data gives 5% error*
- Wating for the data

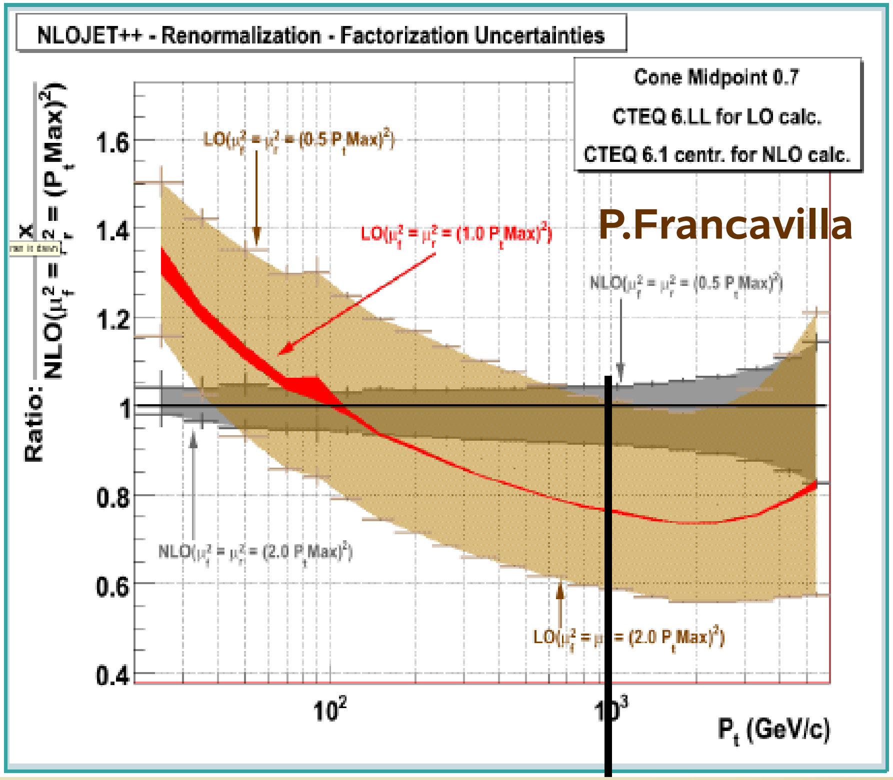
BACKUP

Jet Measurements – Truth Definition (2)

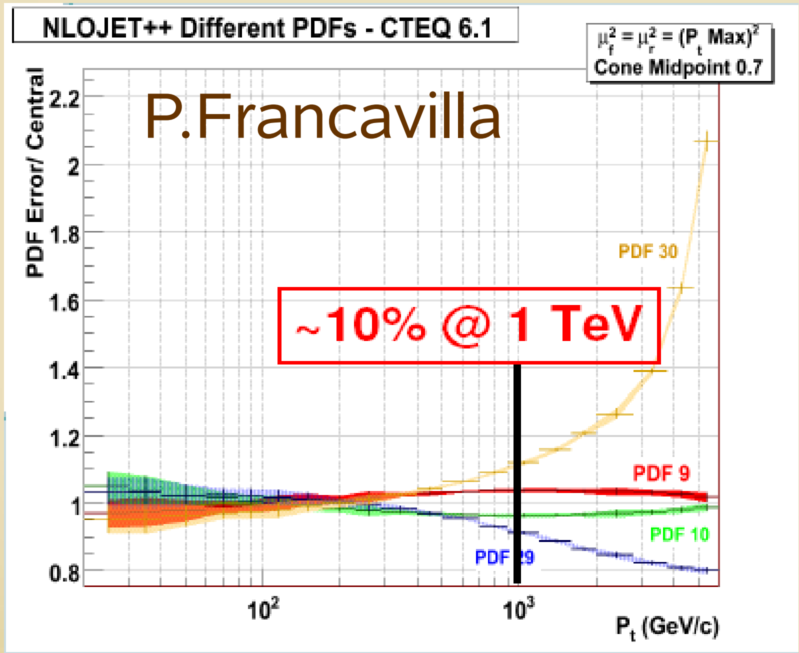
- The aim: the reconstructed final state is close to that reconstructed from the final state particles (truth):
  - The truth jets (particle jets) are those obtained running the same reconstruction algorithm used in the detector on the final state MC particles.
- Two issues play a role:
  - Jet reconstruction algorithms (how one does cluster particles/calorimeter clusters to get jets)
  - Jet calibration
- What ATLAS uses for the jet reconstruction:
  - Cone algorithm with and without midpoints – about to import the SIS cone algorithm from the FastJet (G.Salam et al.)
  - K_T different ΔR parameters

Inclusive Jet Cross Section (2)

- There are quite large uncertainties in the theoretical prediction. The main sources are:
  - Renormalization and factorization scales
  - PDF uncertainties (evaluated using the LHAPDF)
    - *At high energy the high x gluon PDF gives the largest uncertainty*



1 TeV uncertainty:
- 30% LO
- 7 % NLO



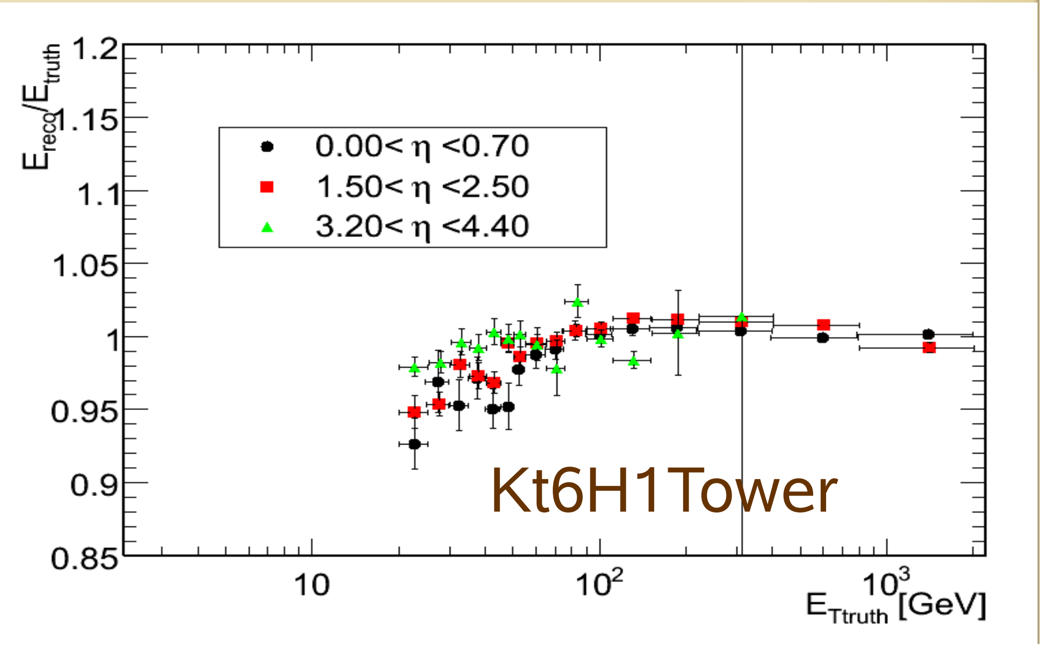
	1 TeV	200 GeV
Ren/Fact	7%	5%
PDF	10%	<5%

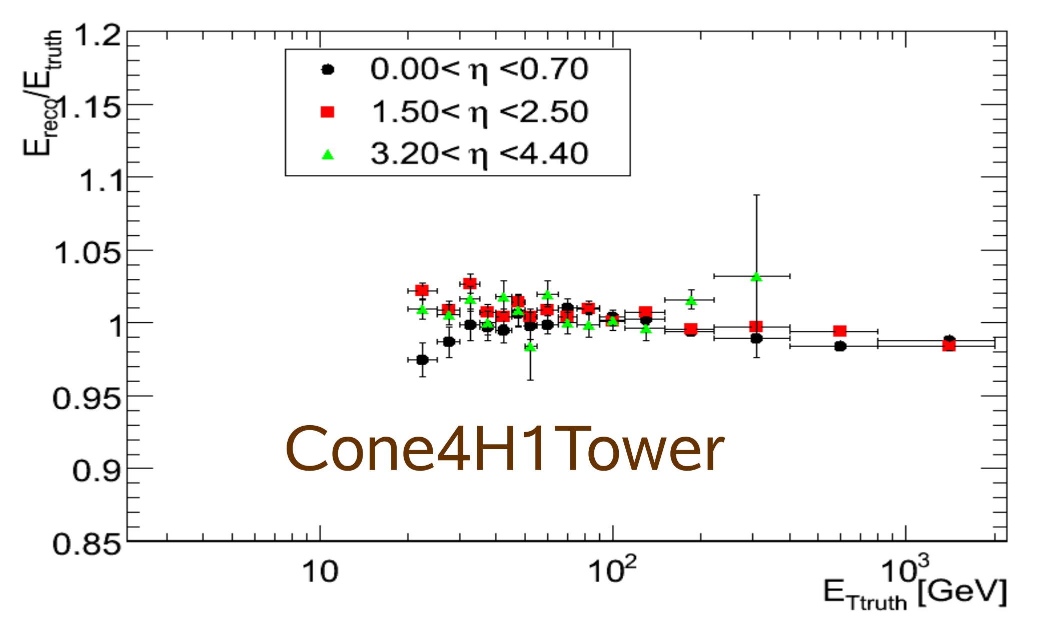
H1 jet corrections

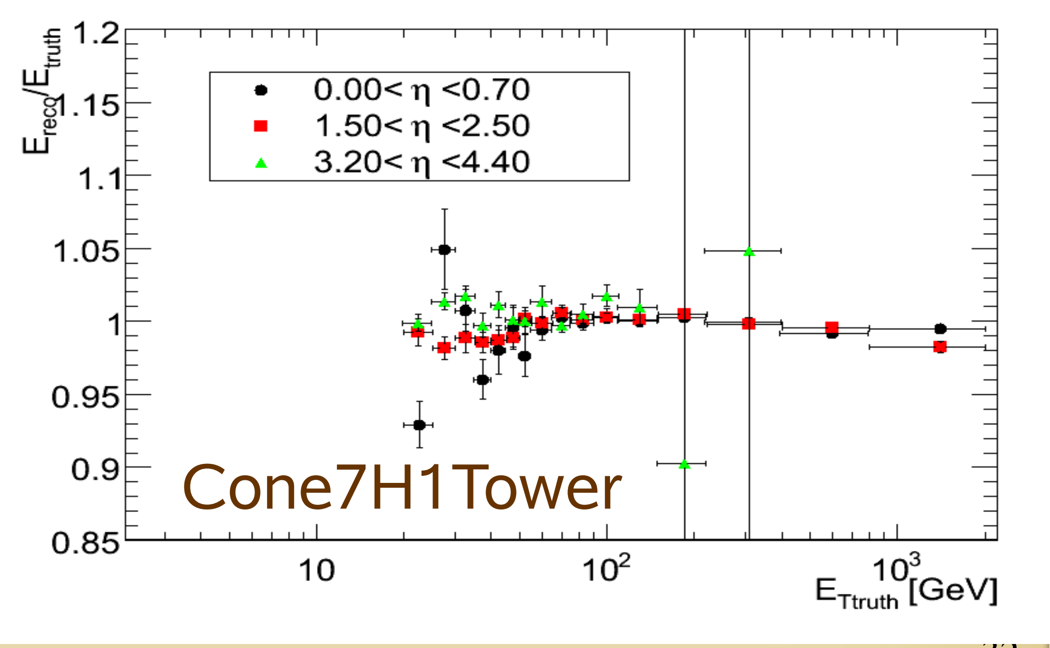
- The weights w_i are the same for all the reco algos, all inputs.
  - They are the same still hard coded for EtMiss reconstruction
- Crack and Gap regions not taken into account in the weight computing. For each reco algo and input clusters, a scale factor is computed:
  - Intended to correct for non-linearities caused by the gap and the crack
  - It corrects also for residual reconstruction algorithm dependent effects

Jet Linearity in FastCaloSim

- Linearity close to 1 in a large range of jet E_T, in different pseudorapidity regions
- Some 5% deviation observed for Kt6 at low E_T
- Kt4 and TopoJets not done yet

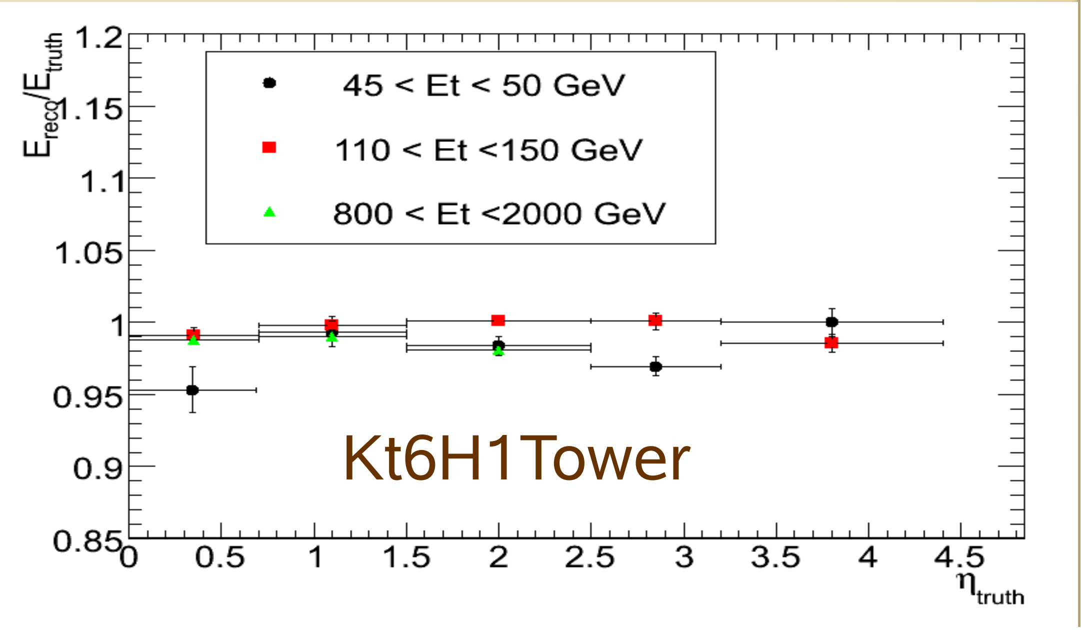


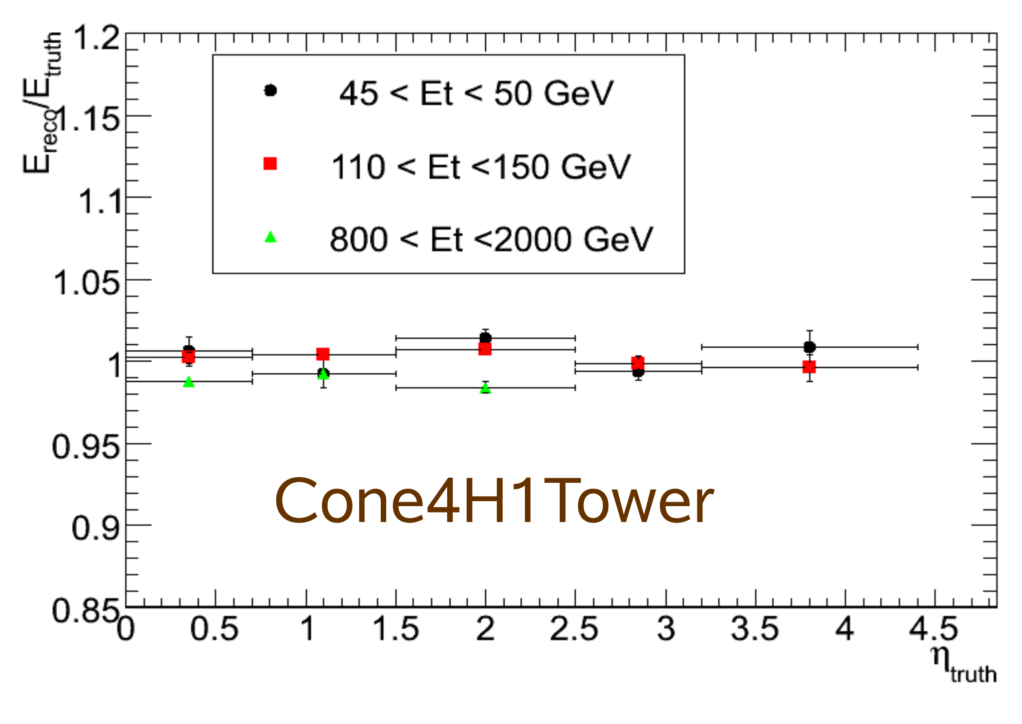


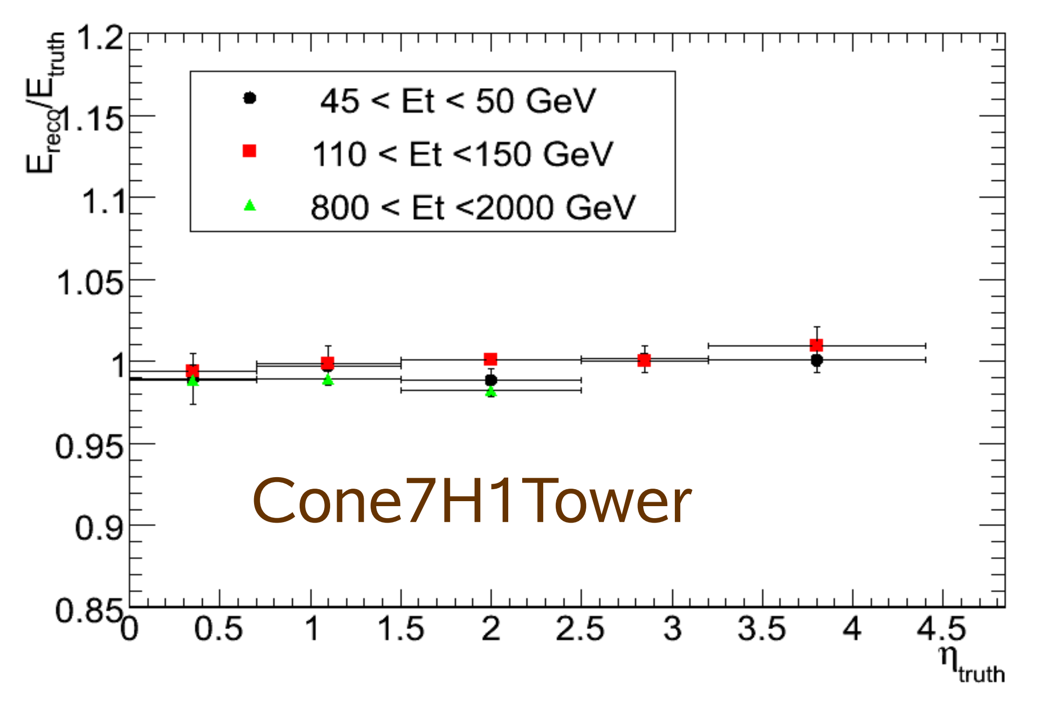


Uniformity over Pseudorapidity

- Uniformity also very good on all the pseudorapidity range
- Again some 5% deviation for Kt6 at low energy in the central region

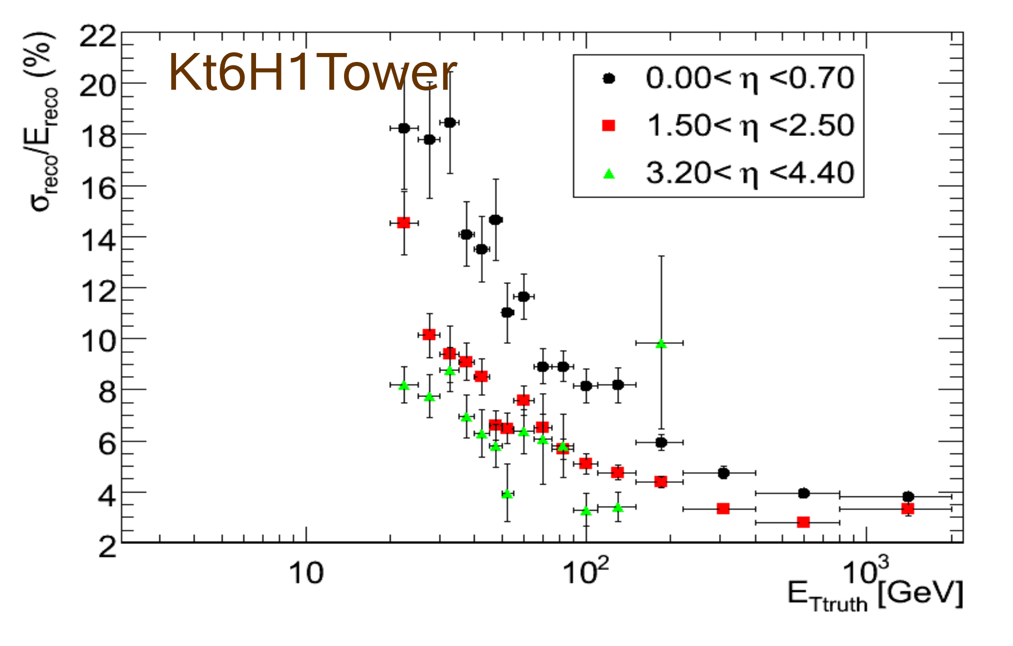


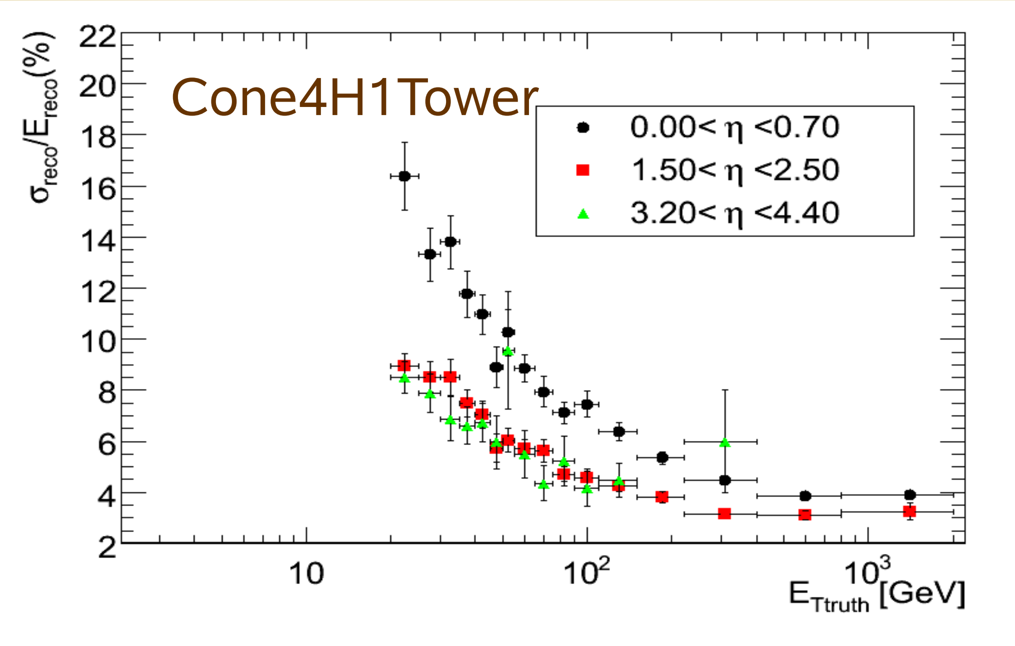


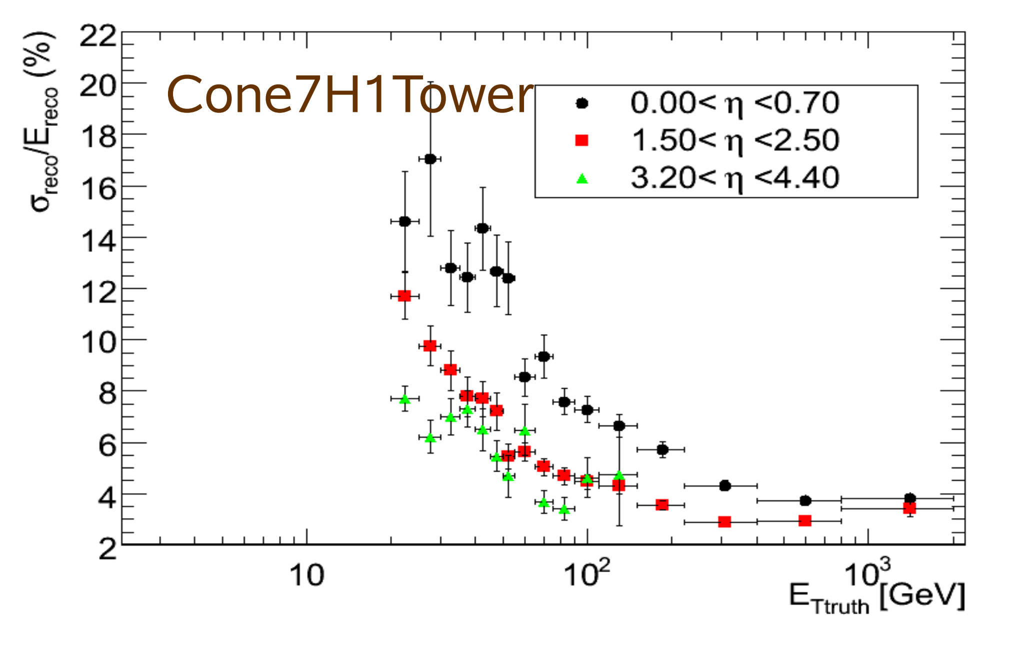


Resolution

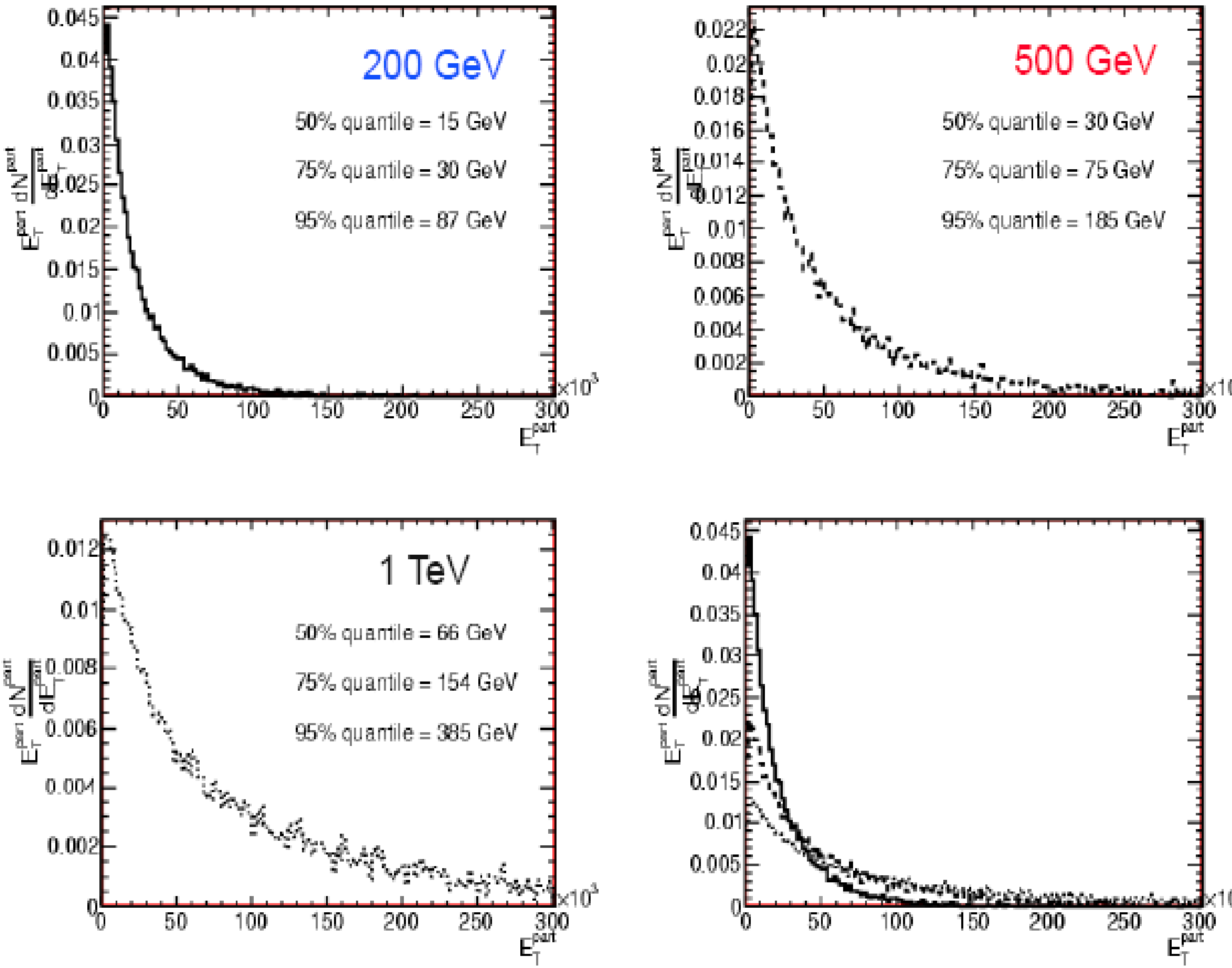
- The plot is $\sigma(E_{rec})/E_{rec}$ Vs E_T (need to be fixed in JetPerformance)
- Resolution is a little bit worse in K_T (known)







Jet Constituents



I. Viverelli

Getting to TeV-scale jets

- Photon-jet balancing tests the JES to 200-250 GeV in early running.
- A 500 GeV jet has only ~20% of its energy in particles not probed by γ-jet balancing at 250 GeV. That number increases to ~50% at 1 TeV.
- We need a multi-stage process
  - Balance low multiplicity jets (a few high p_T particles) with inclusive jets of the same energy (200 GeV)
  - Balance γ's against jets at 200 GeV.
  - Infer what the extrapolation uncertainty to 1 TeV is. (Looks to be around 15% or 20% of the energy is not directly verified to be calibrated)
  - We hope to test this process by looking at 100 GeV jets, and checking with 200 GeV jets (where we have data)

Reconstruction Algorithms

SEEDED CONE ALGORITHM

- Seed: E_T > 1 GeV in ATLAS
- Cone size → ATLAS: ΔR=0.7-0.4
- Compute the centroid, iterate until a stable axis is found
- Split & Merge: 50% of the more energetic jets
- The resulting final jet has a (quite) precise geometrical shape

K_T ALGORITHM

For each cluster pair ij:

- compute d=

$$d = \begin{cases} d_{ii} = k_{T,i}^2 \\ d_{ij} = \min(k_{T,i}^2, k_{T,j}^2)\dfrac{\Delta R_{ij}^2}{D^2} \end{cases}$$

- If $d_{min} = d_{ii}$ the jet is found
- If $d_{min} = d_{ij}$ then cluster i and j together
- Iterate
- The jet shape is not defined
- No split and merging applied

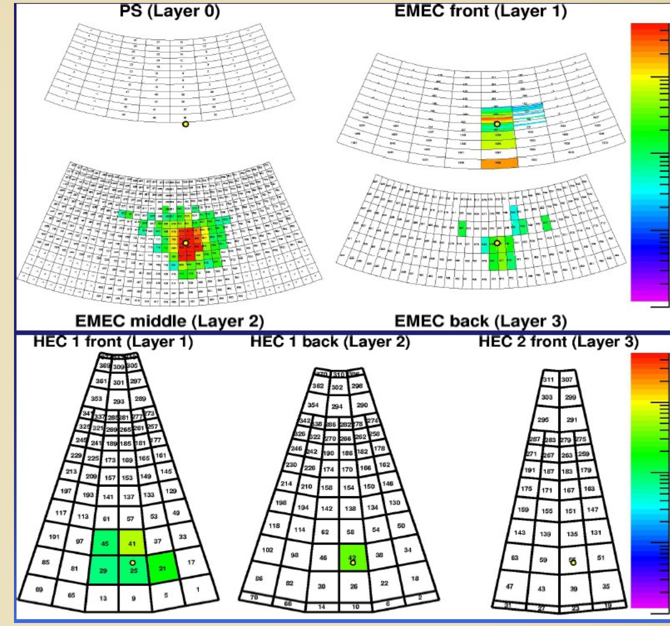
D = 0.6, 0.4

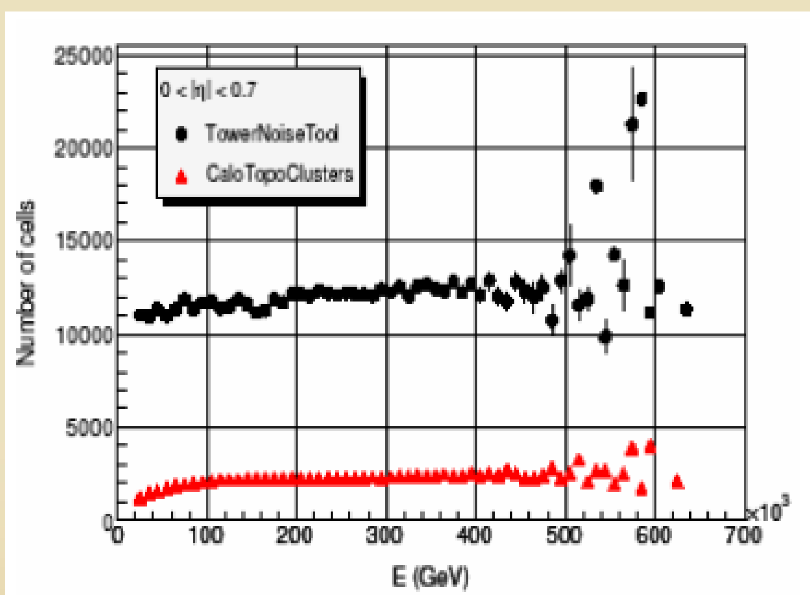
The most used reconstruction algorithm in ATLAS is the seeded cone with ΔR = 0.4

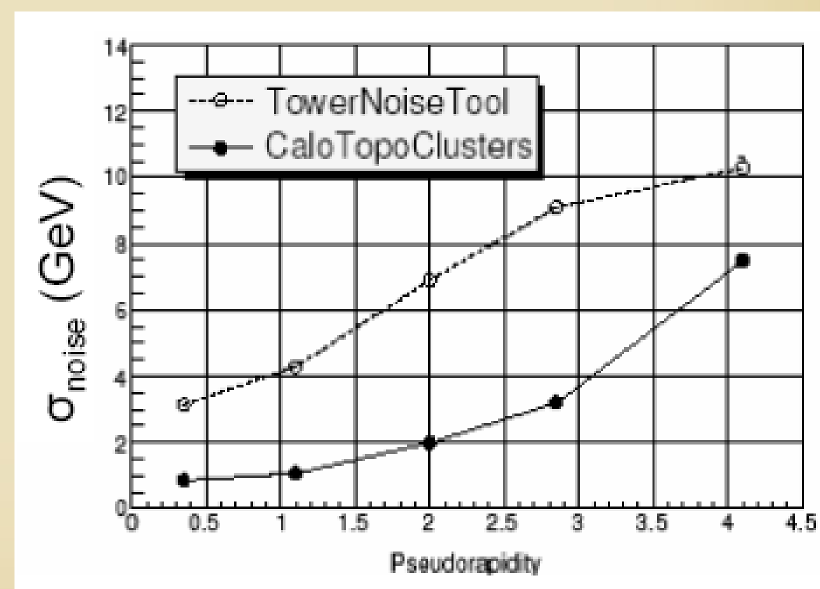
$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$

Reconstruction Algorithms Inputs

- Two preclustering algorithm:
  - Calorimeter towers ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$): no noise suppression (unbiased), finer granularity
  - Topological clusters: no fixed size, sophisticated noise treatment
- Higher noise level in tower jets (as a consequence of the higher number of cells)

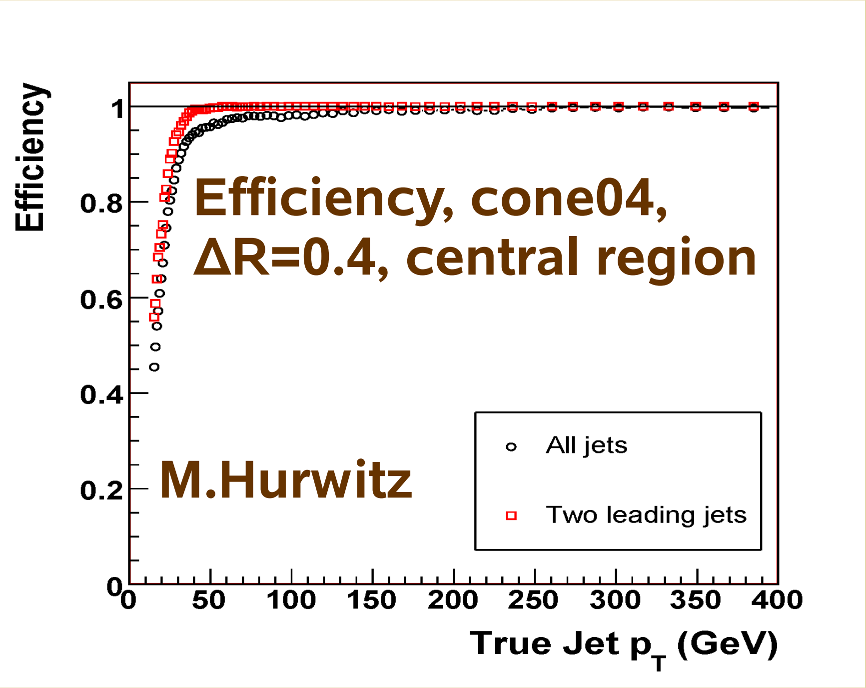




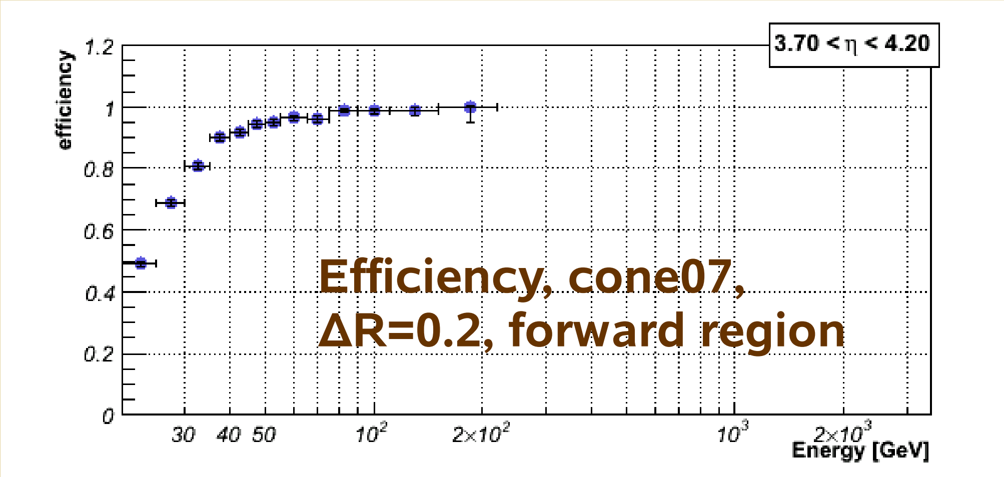


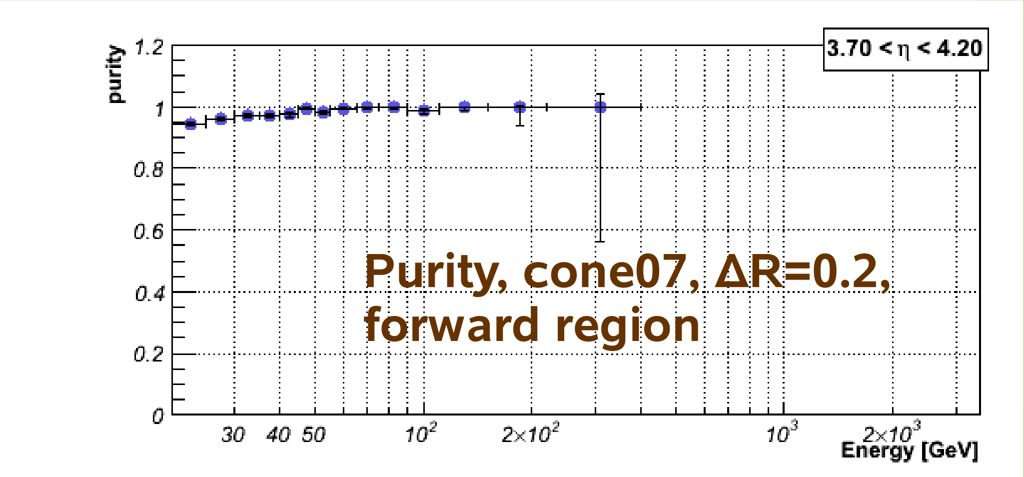
Jet Reconstruction Efficiencies

- Reconstruction efficiency:
  - Define a ΔR_{match} (choice based on the angular resolution)
  - Match reconstructed jets with truth jets if $\Delta R < \Delta R_{match}$
  - The efficiency is the number of matched reco jets/number of truth jets
  - The purity is the number of matched reco jets/number of reco jets



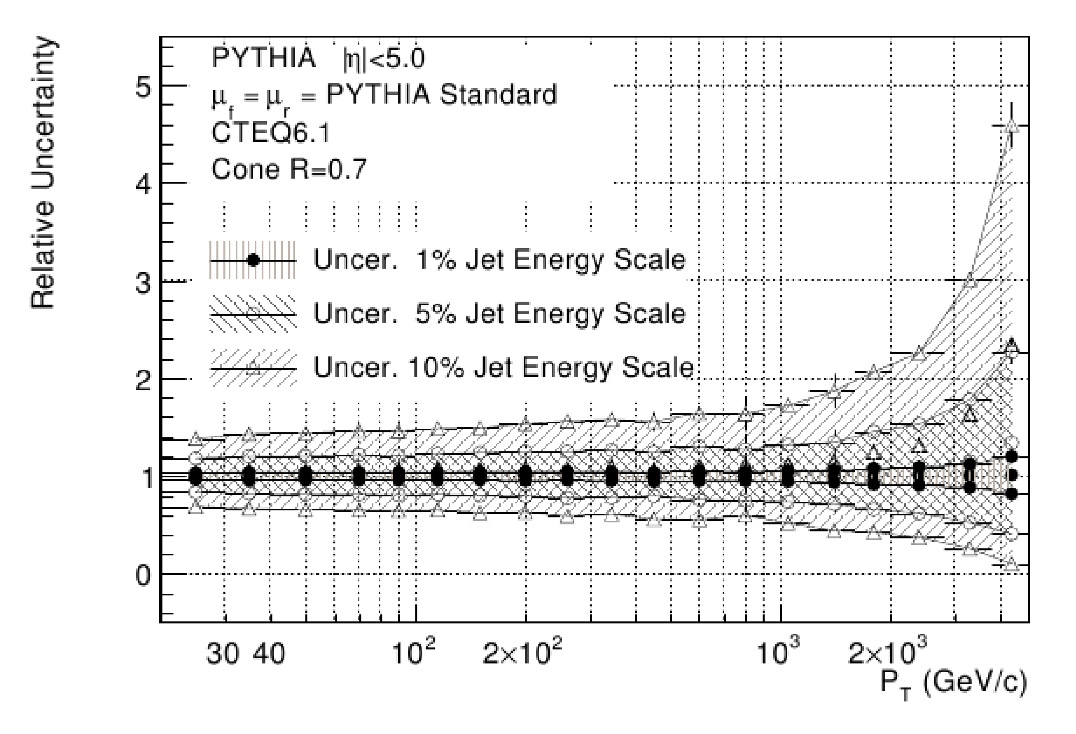
- Both numbers depend on ΔR_{match}

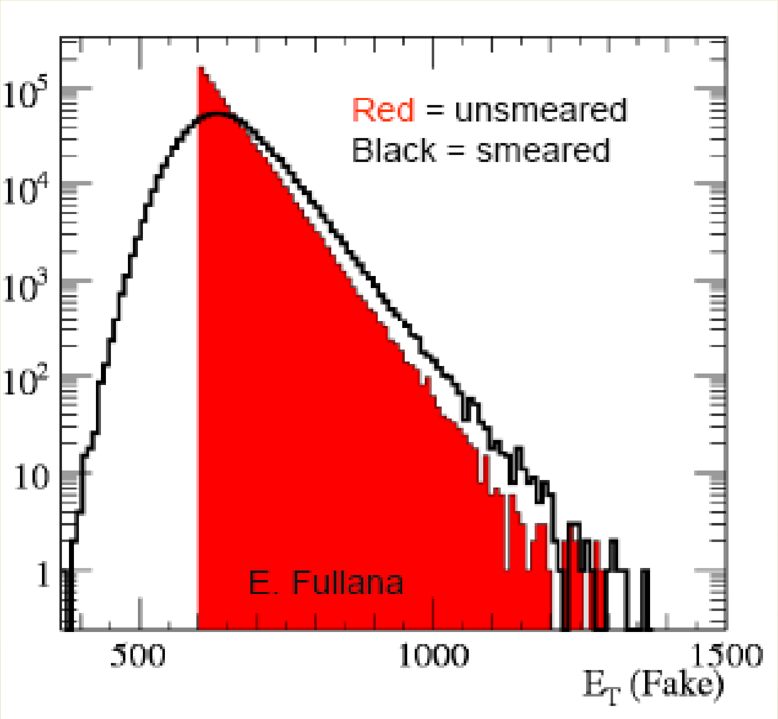




Inclusive Jet Cross Section (3)

- The uncertainty on the jet energy scale is the dominant experimental uncertainty:
  - 10% error on the energy at 1 TeV means 50% error on the cross section





- Experimental resolution + a steeply falling P_T spectrum → bias in the energy measurement