Jets at LHC

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On behalf of the ATLAS collaboration

Introduction

- I will use the inclusive jet cross section as a benchmark measurement.
  - The expected dominating errors at LHC ($\sqrt{s}$ = 14 TeV, design luminosity $L_{nom} = 10^{34}$ $cm^{-2}s^{-1}$ – it will start at low luminosity $L \sim 10^{33}$, I will focus on low luminosity) are discussed.
- I will consider statistical, theoretical, experimental errors.
  - The ability of the general purpose experiments (ATLAS,CMS) to reduce the errors with the first data is reviewed.
- Conclusions.

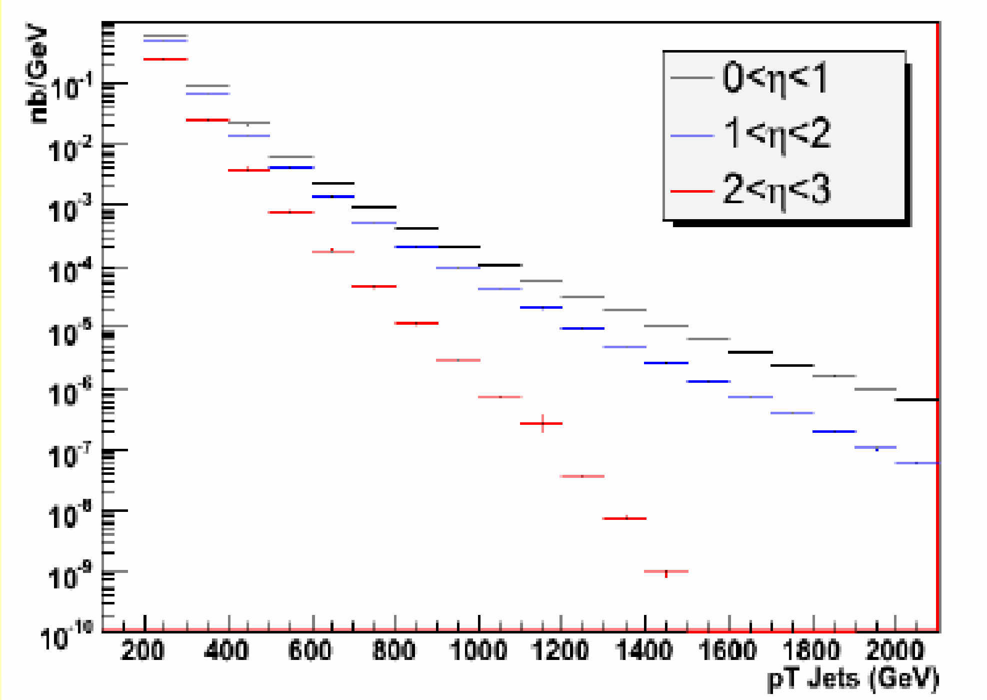
Inclusive Jet cross-section measurement

Concerning QCD, the first LHC data will be used to evaluate the systematics connected to cross section measurements.

QCD is a background for almost all the interesting physics processes.

High P_T tails in the inclusive jet cross section are sensitive to new physics.

A bad evaluation of the errors in the QCD predictions or experimental uncertainties can fake/mask new physics.



Computed using NLO jet cross section (hep-ph/0510324), CTEQ6.1, $\mu_F=\mu_R=P_T/2$, K_T algorithm (D=1)

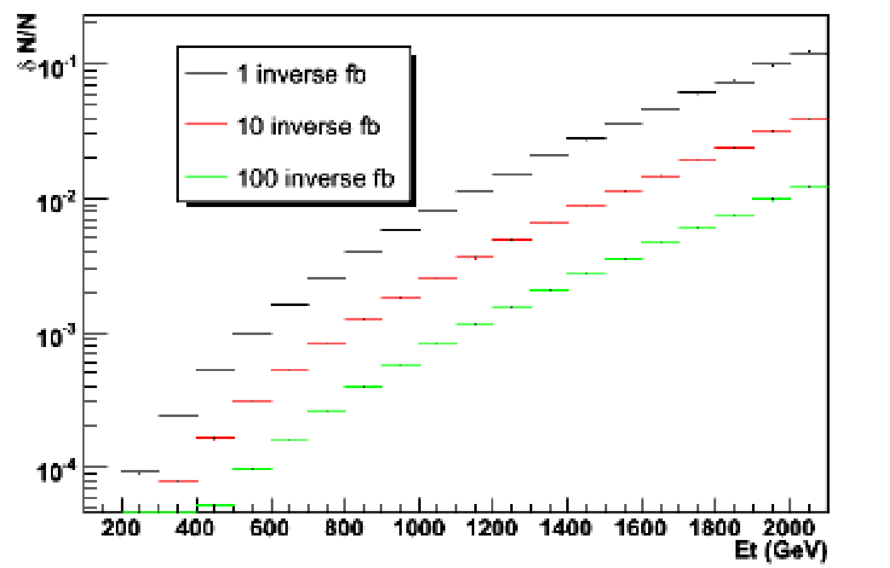
I will consider statistical, theoretical, experimental errors

Statistical Errors

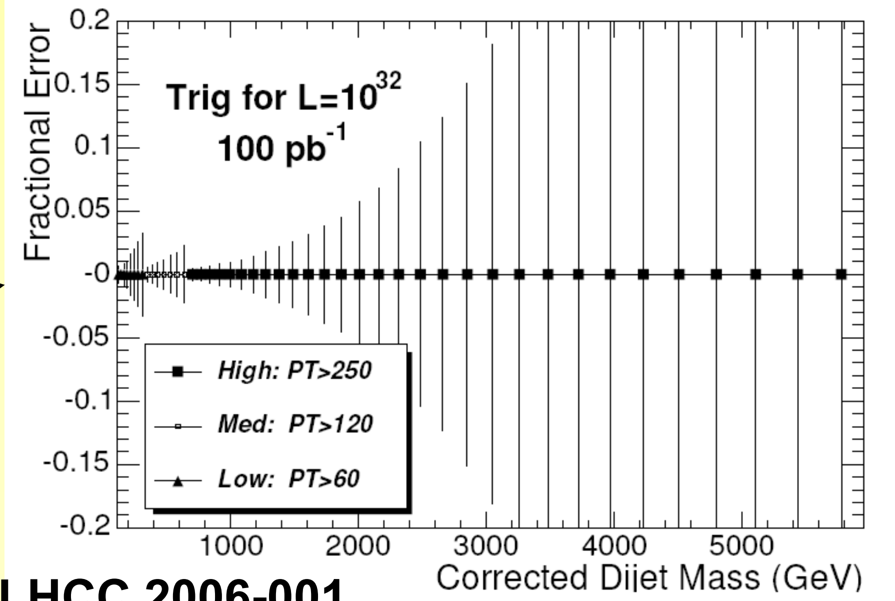
Naïve estimation of the statistical error: $\sqrt{N}/N$ as a function of E_T for different integrated luminosities.

Consider only jets in $|\eta| < 3$

For a jet P_T of ~ 1 TeV one expects 1% error for 1 fb^{-1}. In the large pseudorapidity region ($3.2 < |\eta| < 5$) the error goes up to 10%



CMS – Assuming 1 month @ 10^{32} $cm^{-2}s^{-1}$ and 40% efficiency – contributions from different triggers are taken into account. Only statistical error considered

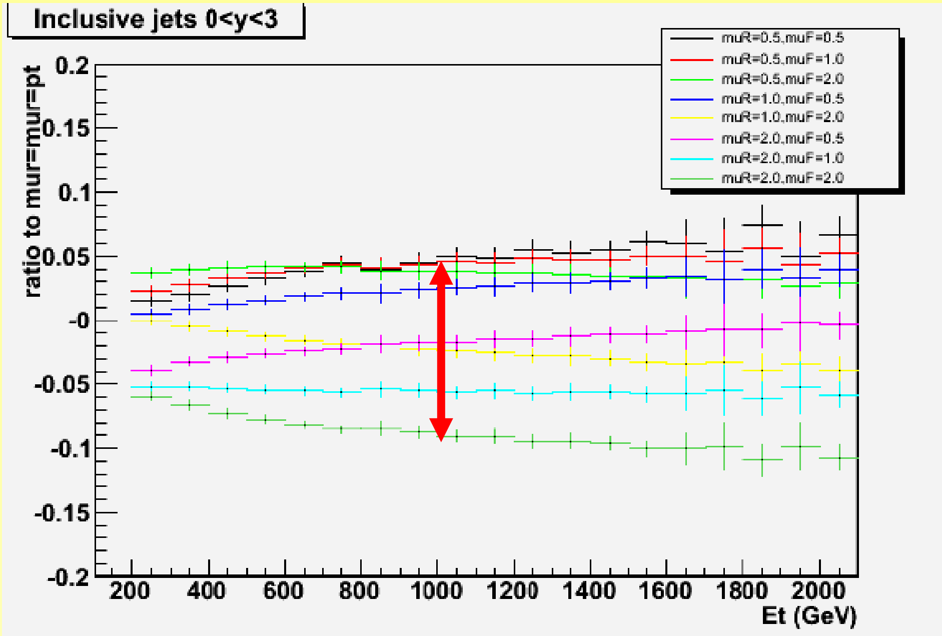


CMS TDR CERN/LHCC 2006-001

Theoretical Errors

The jet cross section is written in terms of the convolution of hard scattering process and parton momentum distributions in the proton

$$\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \hat{\sigma}_{a,b}(x_a, x_b, \mu_R)$$



Two main sources of theoretical errors (CDF):

1- Renormalization(μ_R)/Factorization(μ_F) scale uncertainties (arise from the perturbative calculation of the perturbative cross section at fixed order)

2- PDF uncertainties

Study of 1: μ_R and μ_F have been varied independently between 0.5 P_t^{max} and 2 P_t^{max} (P_t^{max} is the transverse momentum of the leading jet)

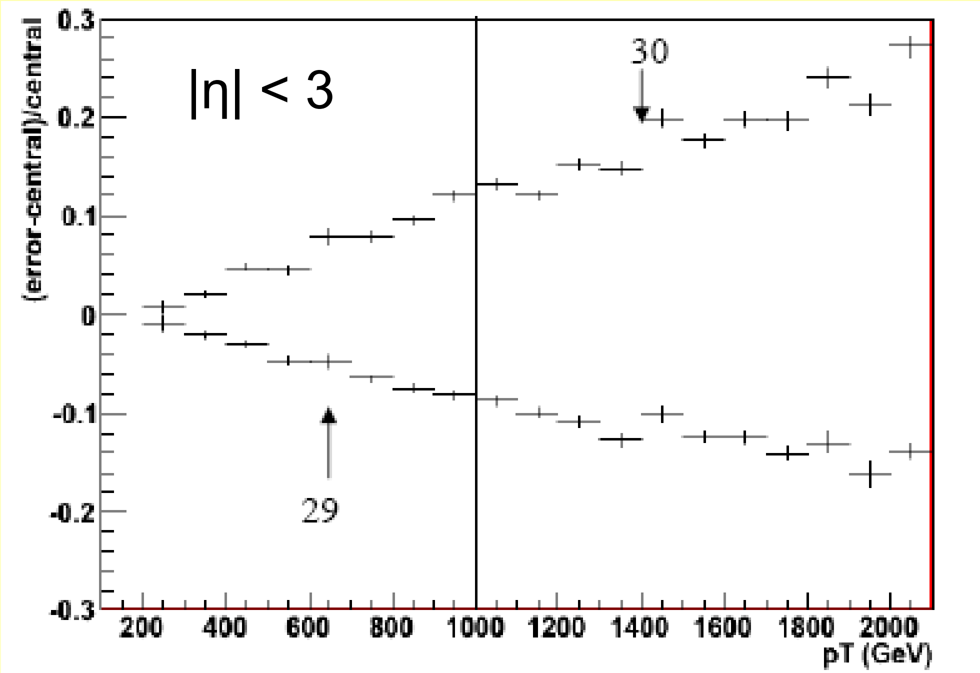
~10% uncertainty at 1 TeV

Theoretical Errors (2)

- The PDF uncertainty has been evaluated using CTEQ6, 6.1 (CDF RUN 2 not included). They come together with a number of error sets.
- Out of all the error sets, two (namely 29 and 30) are dominant in the uncertainty of the inclusive cross section in the ~TeV region. They are related to the high x gluon (relatively large uncertainty from DIS)

K_T algorithm has been used with the best fit PDF and with set 29 and 30.

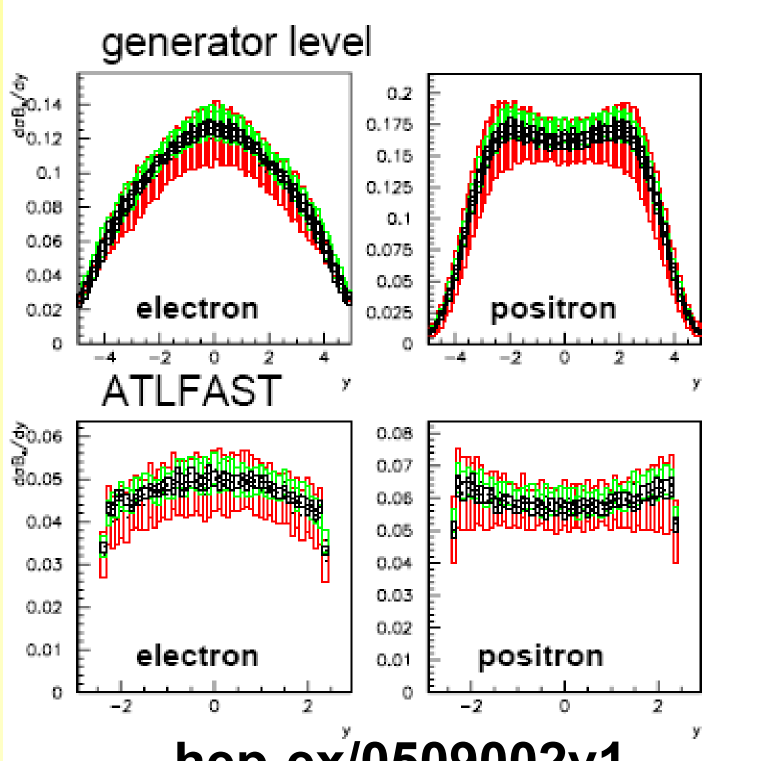
At P_T=1 TeV, the error is approximately 15%



Constraining the PDF

- W and Z production cross section is precisely predicted.
- The main theoretical uncertainty: PDF parametrization: at $Q^2 = M^2_Z$, $x \sim 10^{-2}$-10^{-4} gluon PDF is relevant.
- The lepton decay of the W is investigated: its pseudorapidity distribution is sensitive to the PDF.

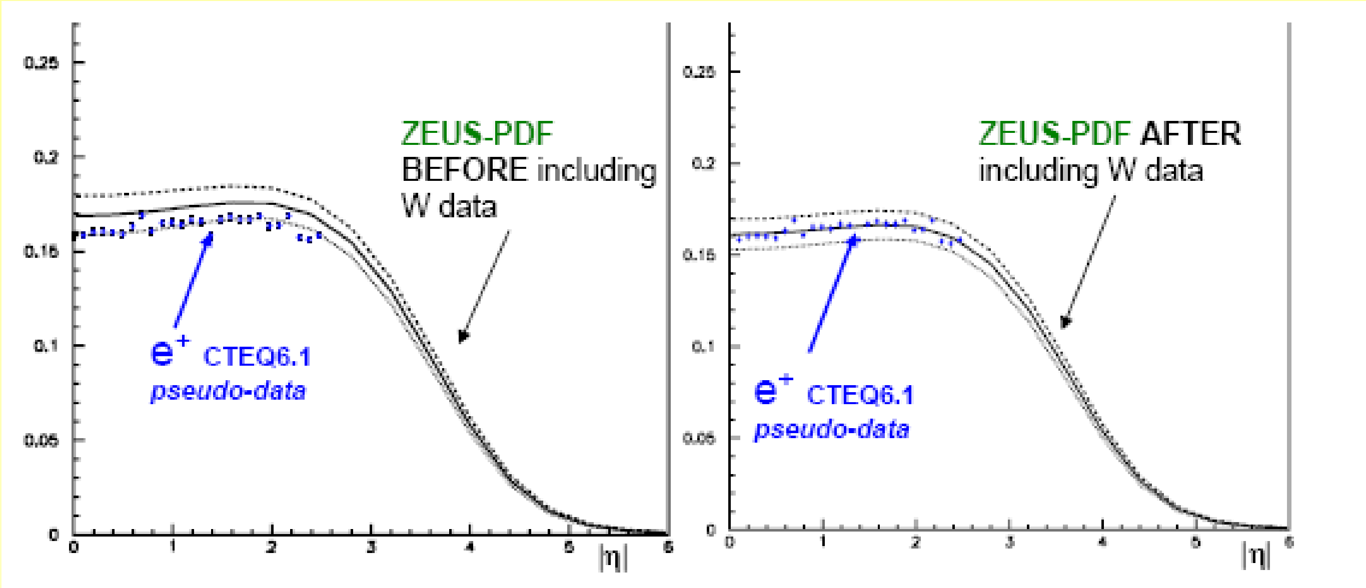
• The cross-section uncertainty at $\eta = 0$ is ±6% (ZEUS_S), ±4% (MRST01E), ± 8% (CTEQ6.1M)
•The study has been performed both at generator and at (fast simulated) detector level
•Asymmetry is almost independent from gluon uncertainties: SM benchmark
•Background and charge misidentification negligible



hep-ex/0509002v1

Constraining the PDF

1M (~200 pb^{-1}) data have been generated (CTEQ6.1) and simulated with the ATLAS fast detector simulation. Then they are corrected back for detector acceptance and included in the ZEUS PDF fit.

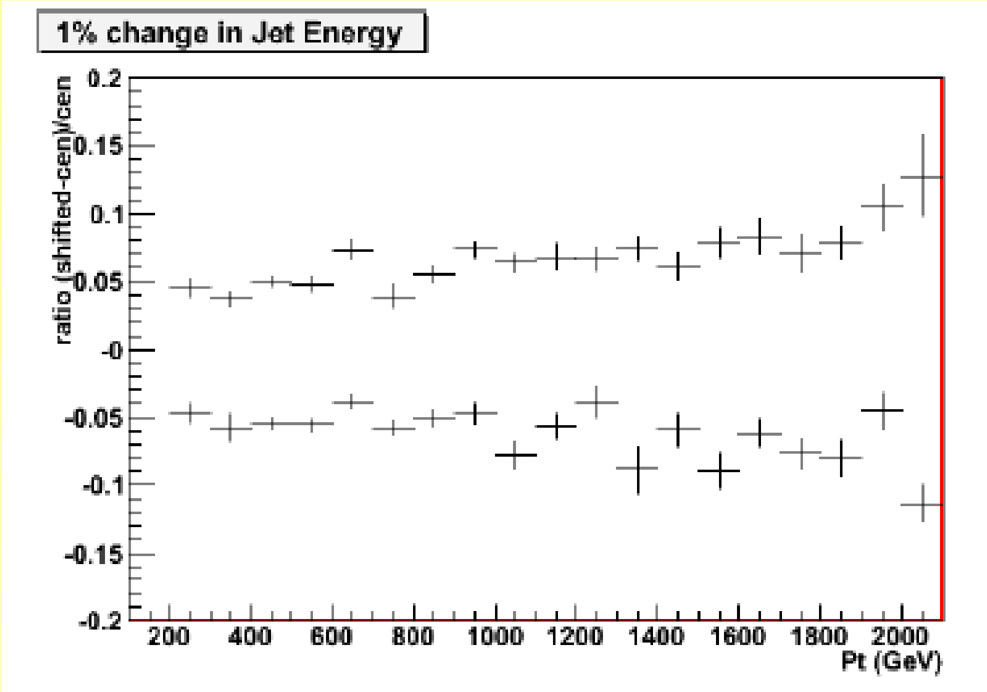


hep-ex/0509002v1

Experimental uncertainties "included" adding 4% random error on data point. Error on parameter λ ($xg(x) \sim x^{-\lambda}$) reduced by 35%

Experimental errors

- There are many possible sources of experimental errors:
  - Luminosity determination
  - Jet Energy scale
  - Jet resolution, UE subtraction, trigger efficiency
  - etc.
- Detector effects: how do we reconstruct and calibrate jets?
  - Use seeded cone and K_T
  - From the calorimeter jet to the particle jet (jet obtained running the reconstruction algorithm on the final state MC particles): use the MonteCarlo tuned on the test beam data



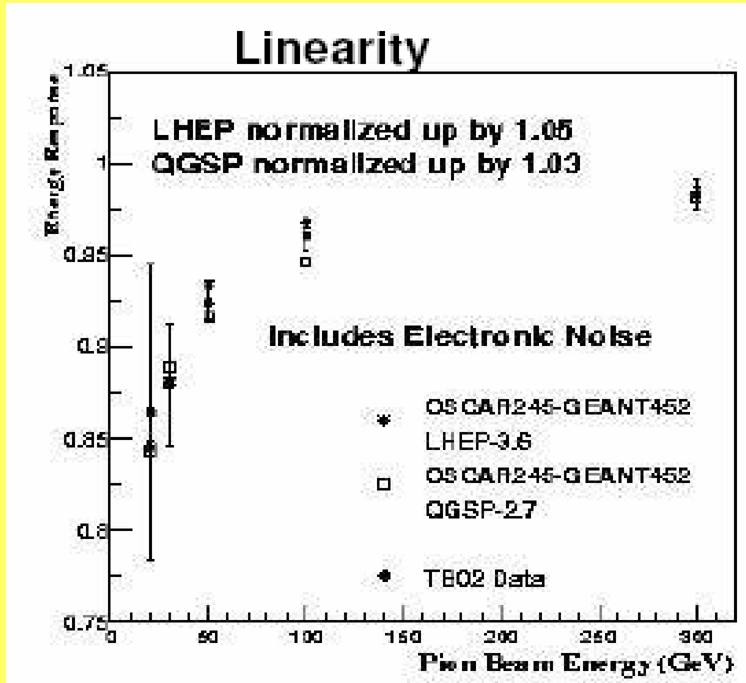
A 1% uncertainty in the jet scale gives an error of 10% on σ(jet).

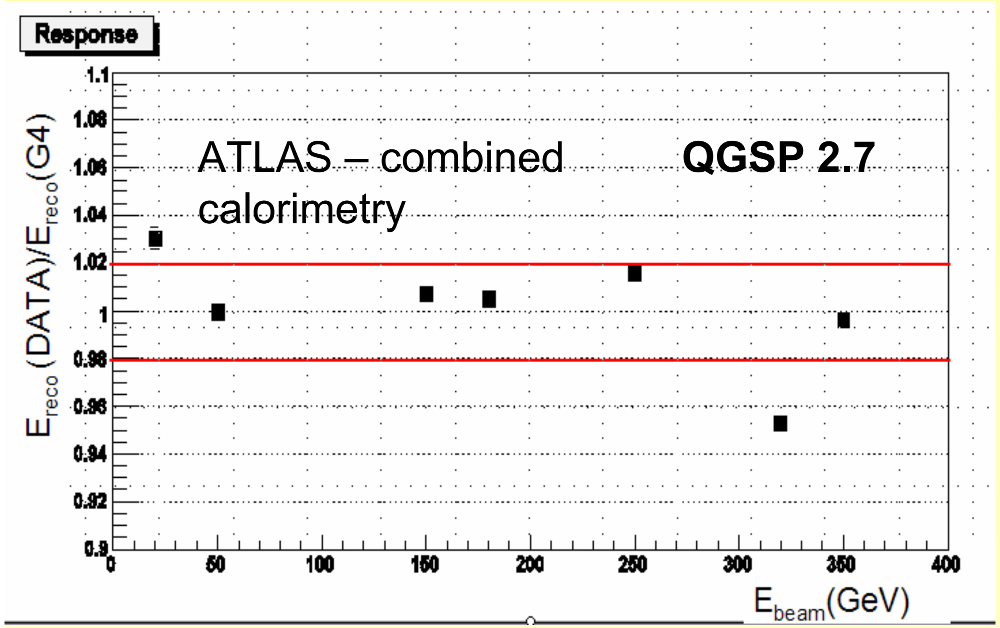
A 5% uncertainty in the jet scale gives an error of 30% on σ(jet).

Geant 4 Vs Test Beam data

A long test beam program has been done in the past years – results in the central calorimeters.

Linearity shown as a function of the beam energy





Good agreement reached between the Geant 4 detector simulation and the test beam data between 20 GeV and 350 GeV.

Analysis of low energy data ongoing

Correcting to the Particle Jet

ATLAS:

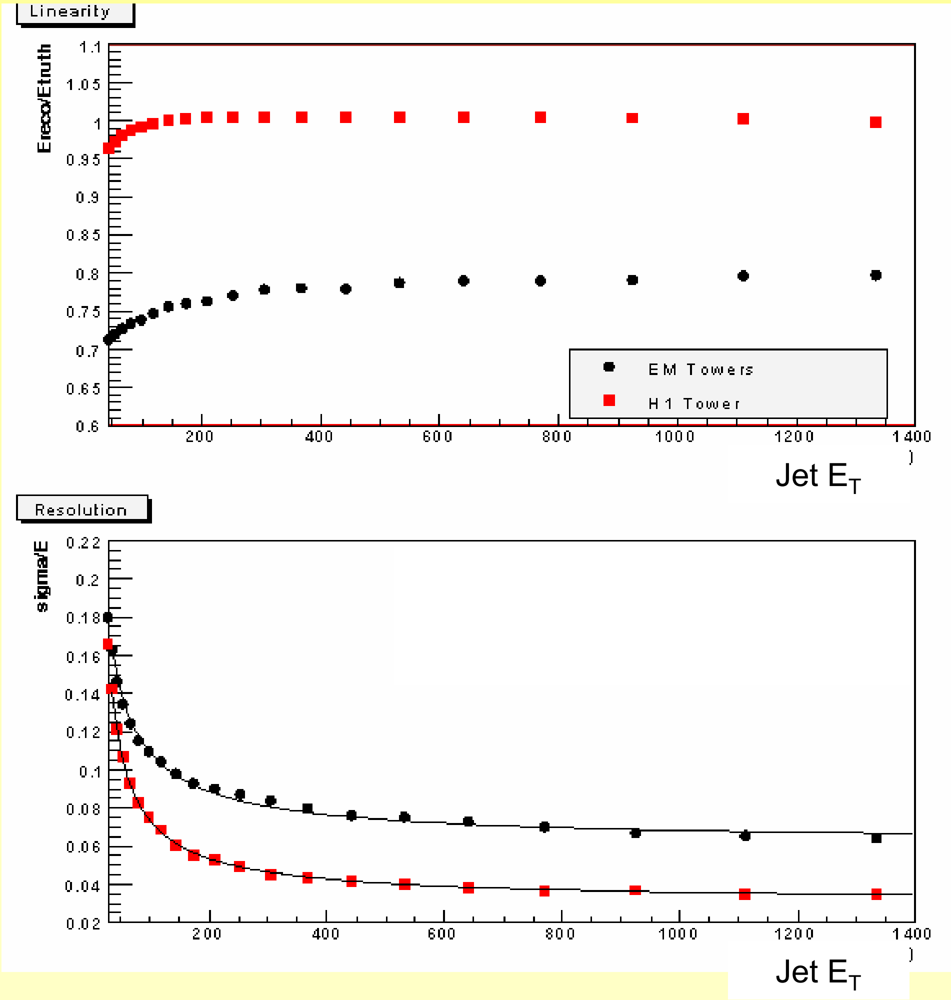
The calibrated jet energy is obtained applying (at cell level) weights that depend on the cell energy density.

$$E^{rec} = \sum_i w_i E_i$$

The weights are obtained minimizing the jet energy resolution with respect to the particle jet (i.e., reconstructed from final state particles using the same algorithm).

It allows to recover the linearity and improve the resolution

Under study: correct for detector effects at cluster level, before jet reconstruction (local calibration)

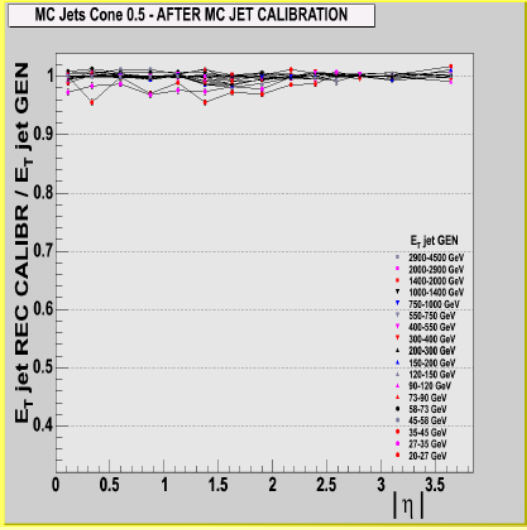


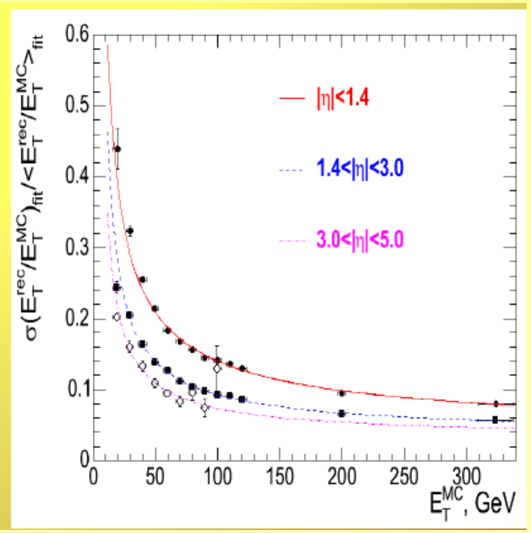
Correcting to the Particle Jet (2)

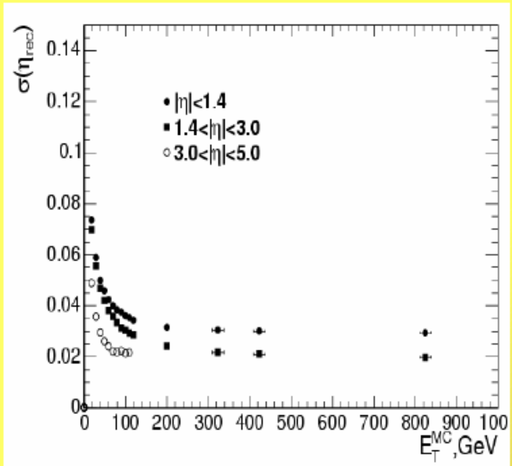
CMS:

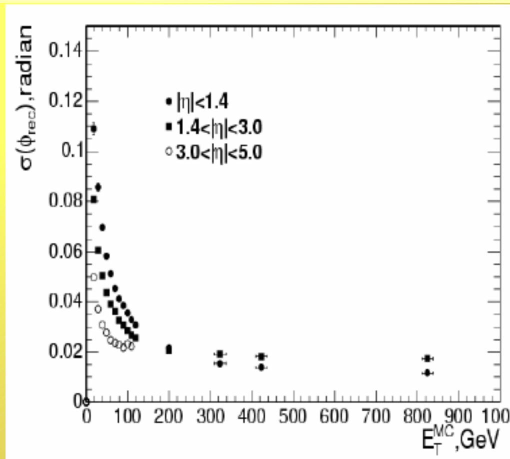
The jet energy is found multiplying E^{raw}_{jet} for a factor $R(E_T)$. The analytical form of R has been found comparing the reconstructed jet with the particle jet.

The angular resolution obtained for the iterative cone algorithm ($\Delta R = 0.5$) is below the tower granularity.









CMS NOTE 2006/036

Using the Data to Cross Check the Jet Energy

Different available processes for in-situ calibration (γ/Z+jet, W→jj (from top decay))

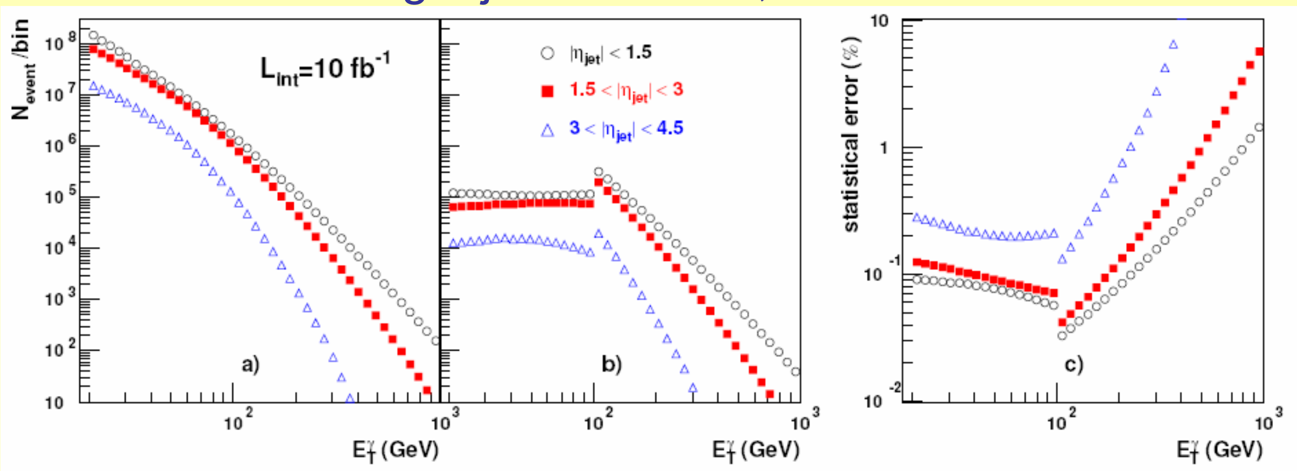
Example:CMS - make use of the P_T balance in γ+jets

Event selection: selection of events with isolated photons, no high-P_T secondary jet, photon and jet well separated in the transverse plane ($E_t^{isol} < 5$ GeV, $E_T^{jet2} < 20$ GeV, $\Delta\varphi_{\gamma,jet} > 172°$)

Trigger efficiencies included in the analysis

Statistical error small (well below 1%) after 10 fb^{-1}

The main systematics is due to non leading radiation effects, QCD backgrounds, gluon-light jet difference, etc.



CMS TDR CERN/LHCC 2006-001

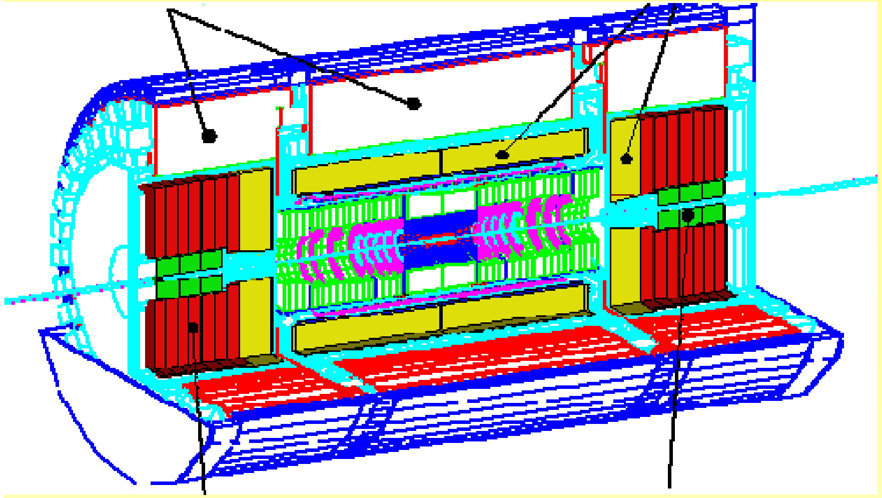
Conclusions

- The measurement of the inclusive jet cross section suffers from theoretical and experimental uncertainties
  - The main theoretical error comes from the PDF uncertainties.
- The first data can be used to constrain the PDF. The W and Z productions will be used.
  - Experimental errors not dominant if the jet scale is known at the 1-2% level.
- The careful comparison of the geant 4 simulation of the detector with real data at the test beam shows good agreement.
- Various processes (γ/Z+jet, W→jj (from top decay)) can be used to cross check the jet calibration

BACKUP

Detector / jet rec

Calorimeters in ATLAS



EM LAr + TileCal resolution (obtained at 1998 Combined TestBeam, η=0.35)

$$\frac{\sigma}{\mathrm{E}} = \left(\frac{41.9\%}{\sqrt{E}} + 1.8\%\right) \oplus \frac{1.8}{E}$$

Linearity within ±2% (10-300 GeV)

EM LAr $|\eta| < 3$:

Pb/LAr 24-26 X_0

3 longitudinal sections 1.2 λ

$\Delta\eta\times\Delta\varphi = 0.025 \times 0.025$

Central Hadronic $|\eta| < 1.7$:

Fe(82%)/scintillator(18%)

3 longitudinal sections 7.2 λ

$\Delta\eta\times\Delta\varphi = 0.1 \times 0.1$

End Cap Hadronic $1.7 < \eta < 3.2$:

Cu/LAr – **4 longitudinal sections**

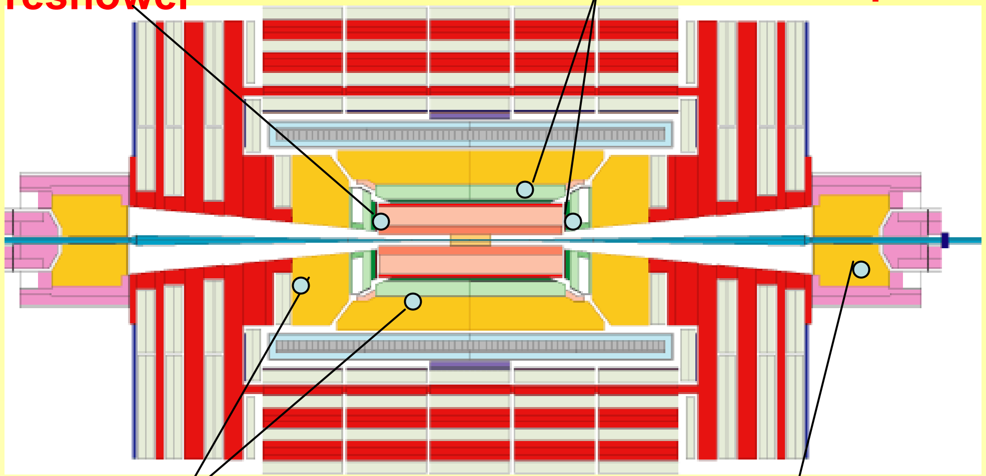
$\Delta\eta\times\Delta\varphi < 0.2 \times 0.2$

Forward calorimeter $3 < \eta < 4.9$:

EM Cu/LAr – HAD W/Lar

3 longitudinal sections

CMS Calorimeters



Single π resolution (HAD+EM obtained at combined test beam 1996)

$$\frac{\sigma}{\mathrm{E}} = \frac{101\%}{\sqrt{E}} \oplus 4\%$$ **Pions mip in Ecal**

$$\frac{\sigma}{\mathrm{E}} = \frac{127\%}{\sqrt{E}} \oplus 6.5\%$$ **Full pion sample**

EM $|\eta| < 3$:

PbWO4 cristals 24.7-25.8 X_0, 1.1 λ

1 longitudinal section+preshower (3 X_0)

$\Delta\eta\times\Delta\varphi = 0.0175 \times 0.0175$

Barrel HCal $|\eta| < 1.74$, Brass/Scintillator

2 longitudinal sections (5.9 λ) **+**

Outer Hcal (2.5 λ for $|\eta| < 1.4$)

End Cap HCAL $1.3<|\eta|<3.0$, Brass/Scintillator:

2 longitudinal sections

$\Delta\eta\times\Delta\varphi \geq 0.0875 \times 0.0875$

Forward calorimeter $3 < |\eta| < 5$:

Fe/Quartz Fibre, Cerenkov light

2 longitudinal sections (em for 16 λ,had for 9 λ)

Jet Reconstruction Algorithms

Both K_T and Cone (seeded and seedless) algorithm are being used in ATLAS.

Clusters: any object that can be used as input for the jet reconstruction algorithm (calorimetric cells/clusters, MC tracks etc.)

SEEDED CONE ALGORITHM

- Use clusters with E_T > 2 GeV as seed.
- Associate all the clusters with ΔR< 0.7 w.r.t. the seed.
- Iterate until a stable cone axis is found
- Split & Merge: merge two jets if overlapping energy is more than 50%

The jet has a precise geometric shape and dimension

K_T ALGORITHM

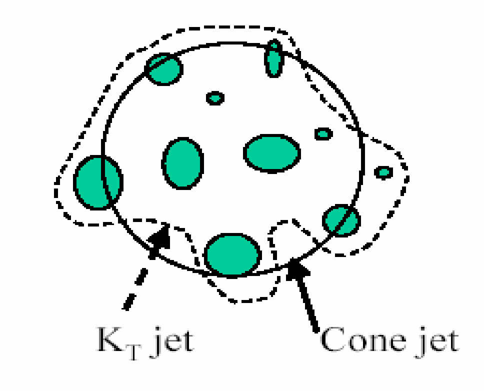
D = 1

For each cluster pair ij:

- Calculate 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} then the jet is done
- if d_{min}= d_{ij} then merge i and j

-The shape of the jet is not fixed a priori

- No overlapping jets



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

Clustering

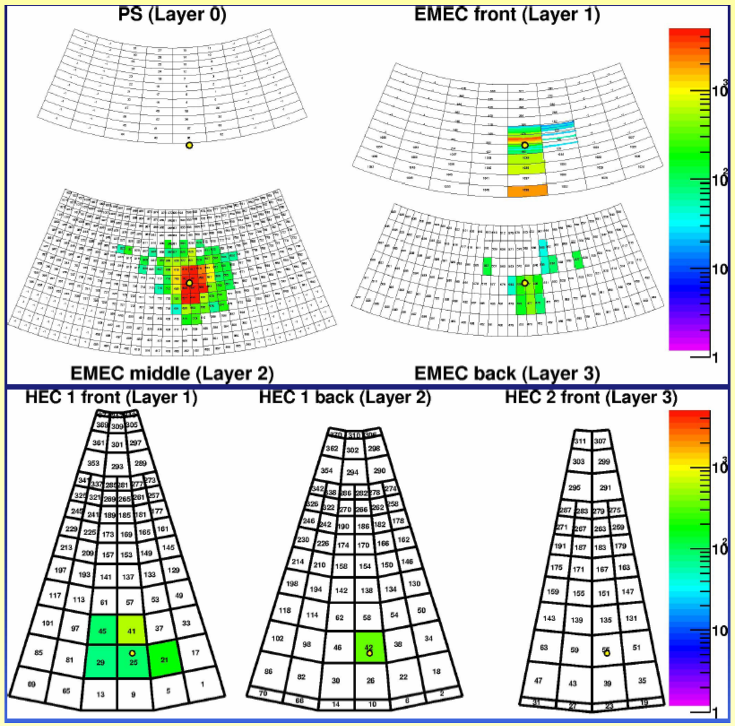
At present, cells are clusterized in two ways w.r.t. jet reconstruction:

-Consider calorimetric towers (2D)

-3D clustering accordingly to energy deposits in neighbouring cells (Topological Clusters)

TopoClusters – some details:

- Cells with $|E/\sigma_{noise}|>T_{seed}$ are used to generate a TopoCluster. The adiacent cells are checked to be associated to the cluster. Default: $T_{seed} = 4\sigma_{noise}$
- Cells with $|E/\sigma_{noise}| > T_{neigh}$ are used to expand the cluster. The adiacent cells are checked to be associated to the cluster. Default: $T_{neigh} = 2\sigma_{noise}$
- Cells with $|E/\sigma_{noise}| > T_{used}$ can be used to expand the cluster. Default T_{used}=0



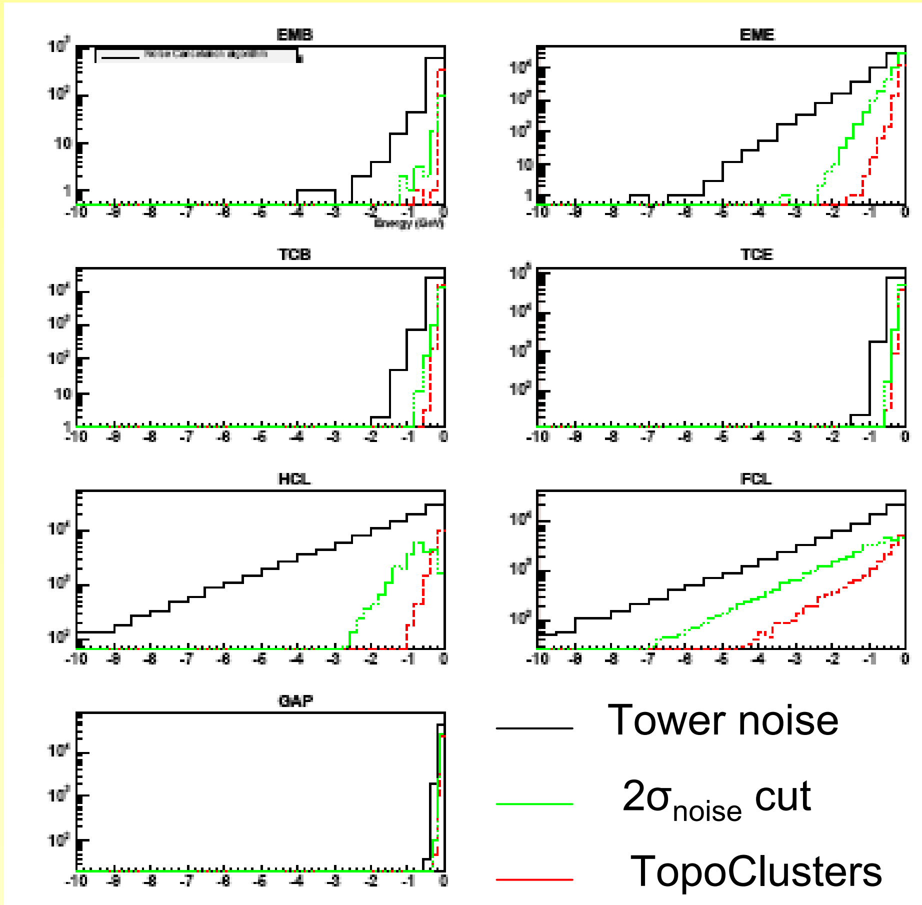
Cluster for 120 GeV pion in EMEC and HEC (2002 Test Beam data)

Noise suppression

Noise treatment is a delicate issue with respect to jet calibration. Topological Clusters are a powerful tool to suppress noise. Other algorithms are also used to suppress noise

-Negative energy cancellation at tower level: K_T algorithm cannot take negative energies in input. Sum up negative towers to the neighbours until positive energy is reached. Used if towers are used as input for the jet reconstruction algorithm

-$2\sigma_{noise}$ symmetric cut: do not consider cells with $|E| < 2\sigma_{noise}$

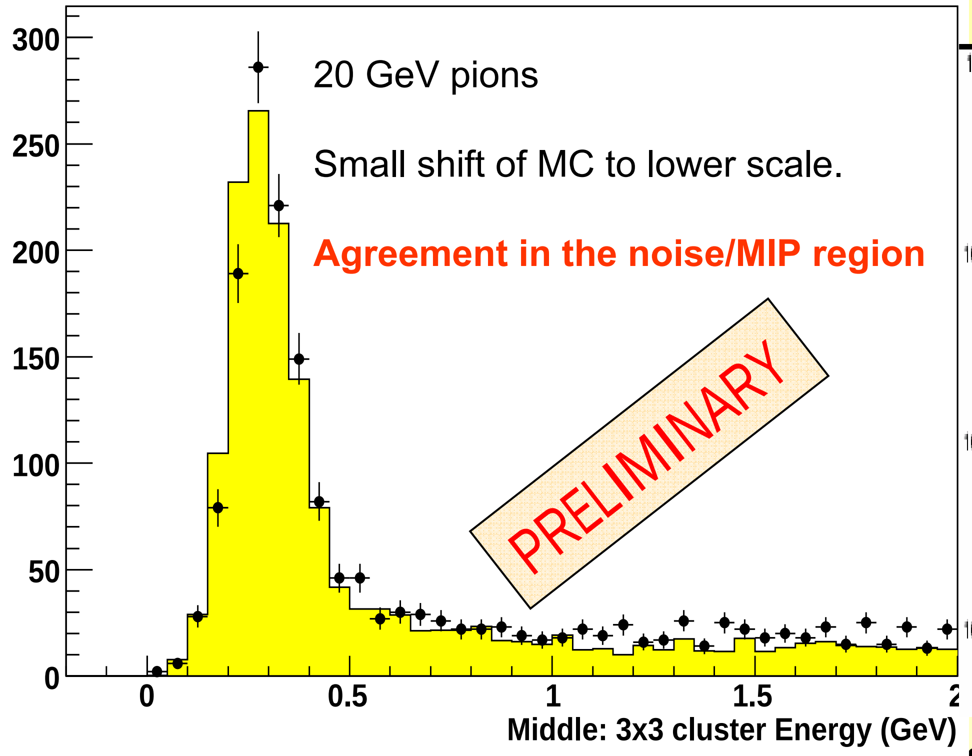


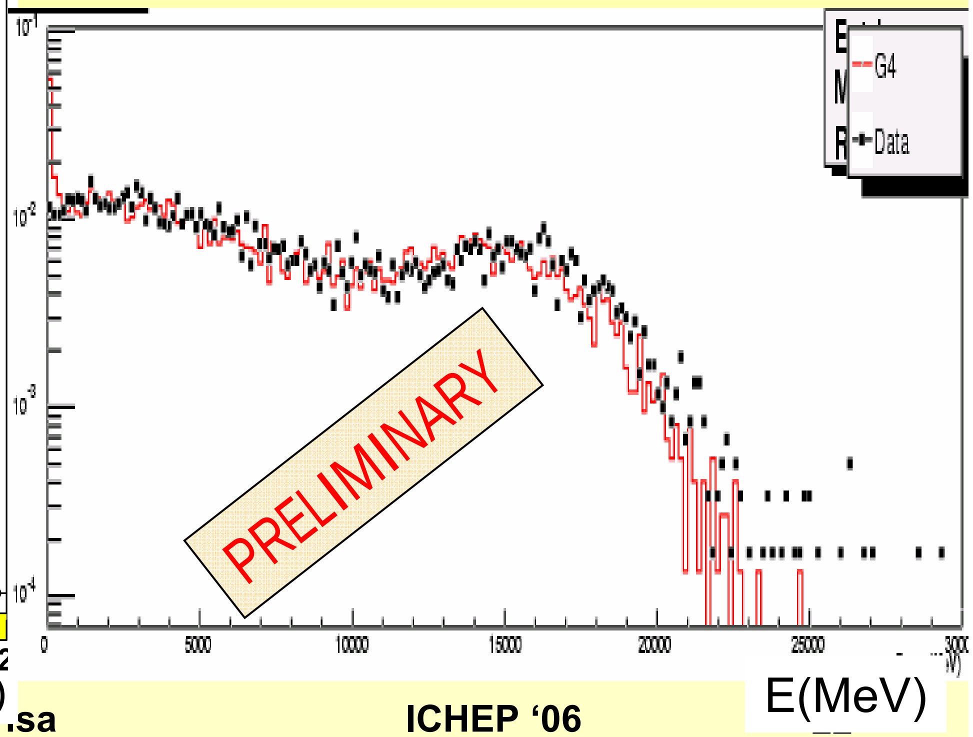
CTB 2004

Analysis of the Combined Test Beam 2004 data is ongoing. First results about the comparison G4/data

Data considered: electrons, pions. Energy considered: 20-350 GeV, at different pseudorapidities.

Comparison with low energy particles (1-9 GeV) not yet available.

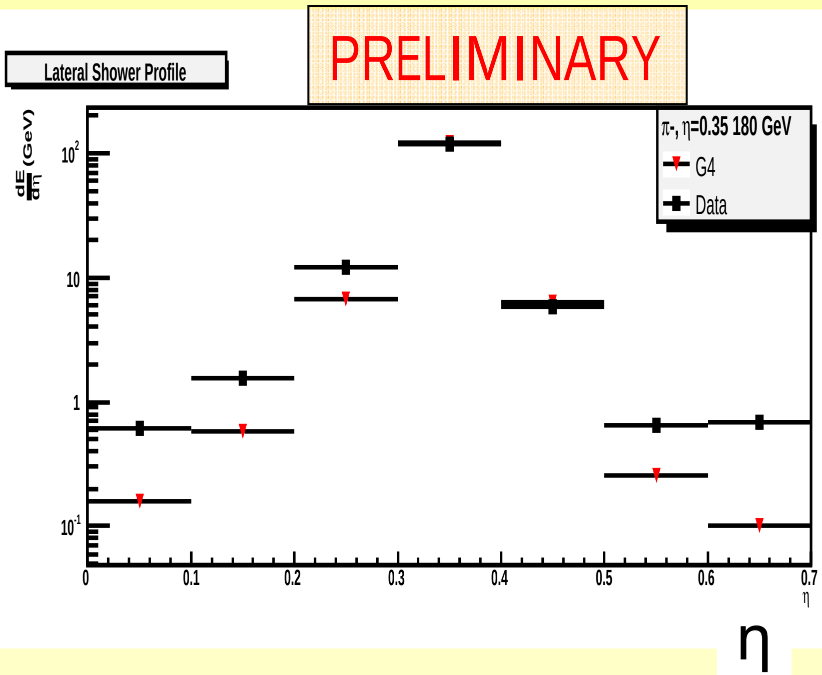


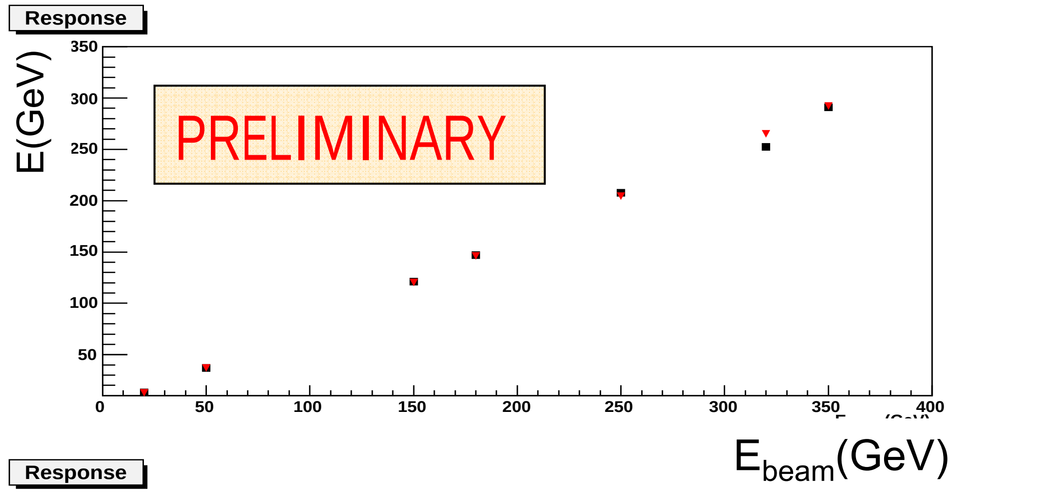


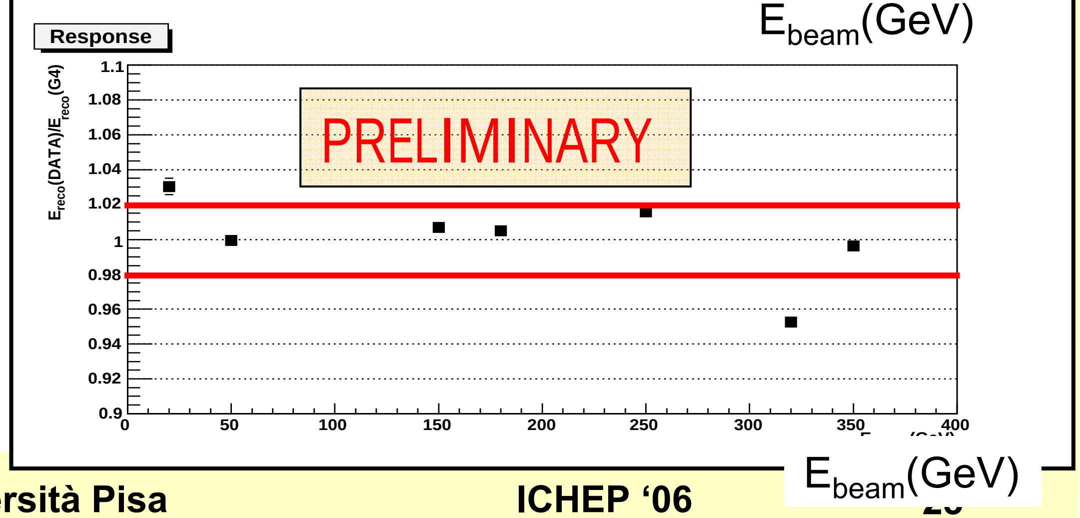
CTB2004 (2)

Overall agreement within 2% (η = 0.35). The point at 320 GeV needs better understanding.

However, preliminary results show that the shower shape has to be improved







FP Calibration Scheme

The reconstructed energy E_{rec} is calculated as :

$$E_{\mathrm{Re}c} = \sum_i w_i(E_{MC}, E_i)E_i$$

where E_i is the energy of the cell in the sample i.

The response F=<E/E_{MC}> is calculated in each η bin and a factor 1/F is applied as an additional weight

The dependence of the weights w_i on the cell energy are parametrized as:

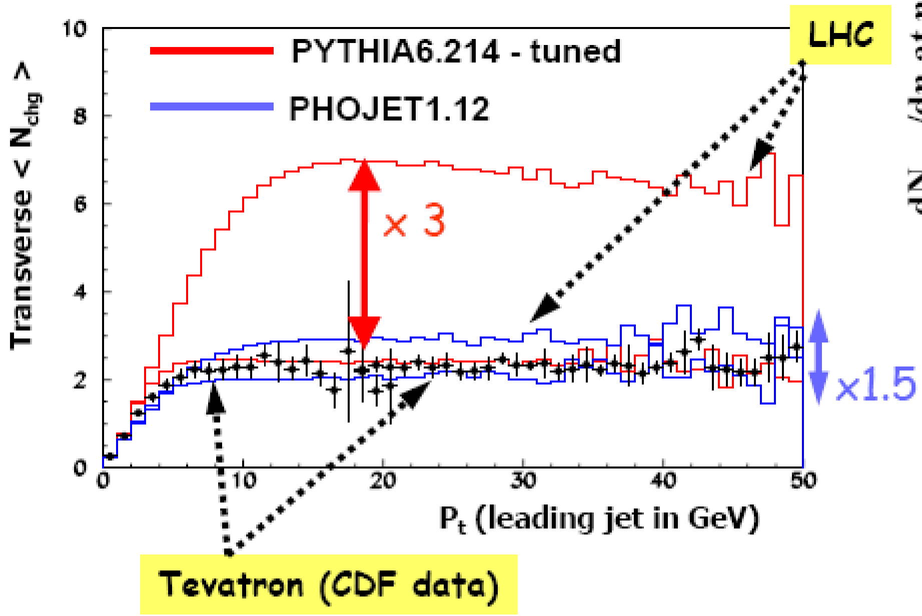
$$w_i(E_i) = a_i + \frac{b_i + \dfrac{c_i}{\alpha(E_i/Vol)}}{\alpha(E_i/Vol)^{d_i}}$$

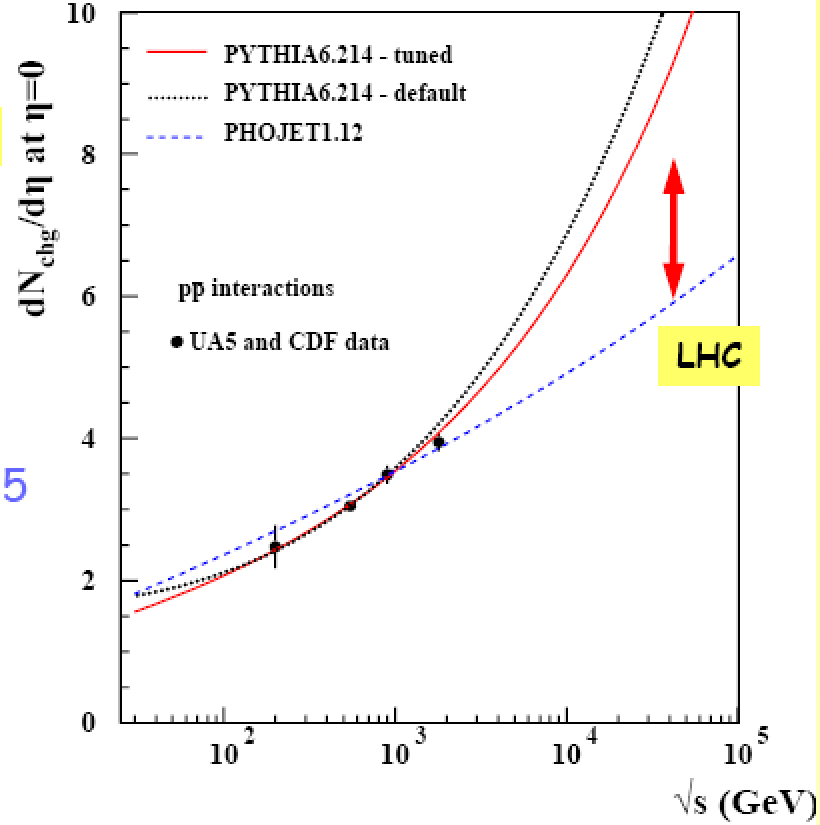
Where E_i is the cell energy in sample i and Vol is the cell volume

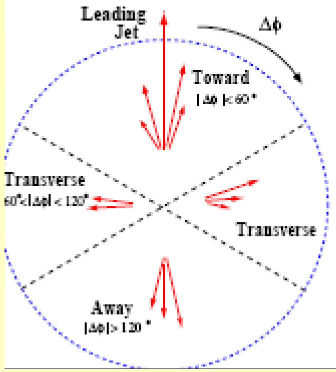
Predictions for LHC for Underlying Events

Moraes, Buttar, Dawson
(see also work of R. Field)

After comprehensive study and tuning:







Agreement with CDF data, but different predictions in region transverse to the leading jet !

MB can be easily measured at LHC
UI more difficult
Model tuning can, however, only be successful if model are more or less correct

Theo uncertainties

Separating PDFs From The Integral

- A NLO Cross-Section for DIS is normally calculated using MC by:

$$W = \sum_{m=1}^{N} w_m \left(\frac{\alpha_s(Q_m^2)}{2\pi} \right)^{p_m} q(x_m, Q_m^2)$$

For events m=1….N, (w_m is an MC weight, $q(x,Q^2)$ a PDF).

- Can instead define a weight grid in (x,Q^2), which is updated for each event m:

$$W_{i,j}^{(p)} = W_{i,j}^{(p)} + w_m$$

Where *i, j* define a discrete point in x,Q^2 space relating to the event.

- A PDF grid is also defined in x,Q^2 as $q_{i,j}$.

- Cross-Section can be reproduced by combining the PDF and weight grids *after* the Monte-Carlo run:

$$W = \sum_i \sum_j W_{i,j}^{(p)} \left(\frac{\alpha_s(Q^2)}{2\pi} \right)^{p} q_{i,j}$$

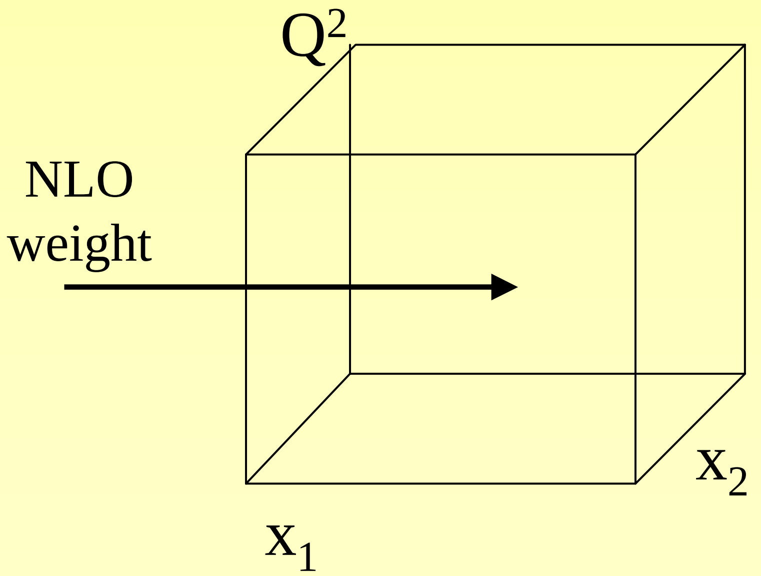
Separating PDFs From The Integral

•This method can recreate the Monte-Carlo cross-section exactly assuming grids could be made with an infinitely small spacing in (x,Q^2).

•Instead grids with a finite spacing in x,Q^2 are used and interpolation methods used between points.

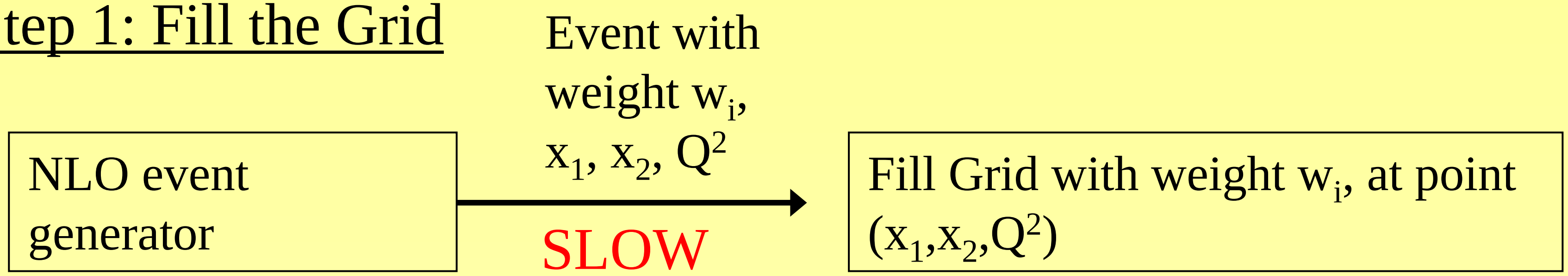
D.Graudenz, M.Hampel, A. Vogt, C Berger, D.A. Kosower, C. Adloff, S.Chekanov, M Wobisch…..

•The situation is a little more complicated in the case of hadron-hadron collisions as PDFs have to be considered for both incoming particles, hence the grid is three dimensional (x_1,x_2,Q^2).

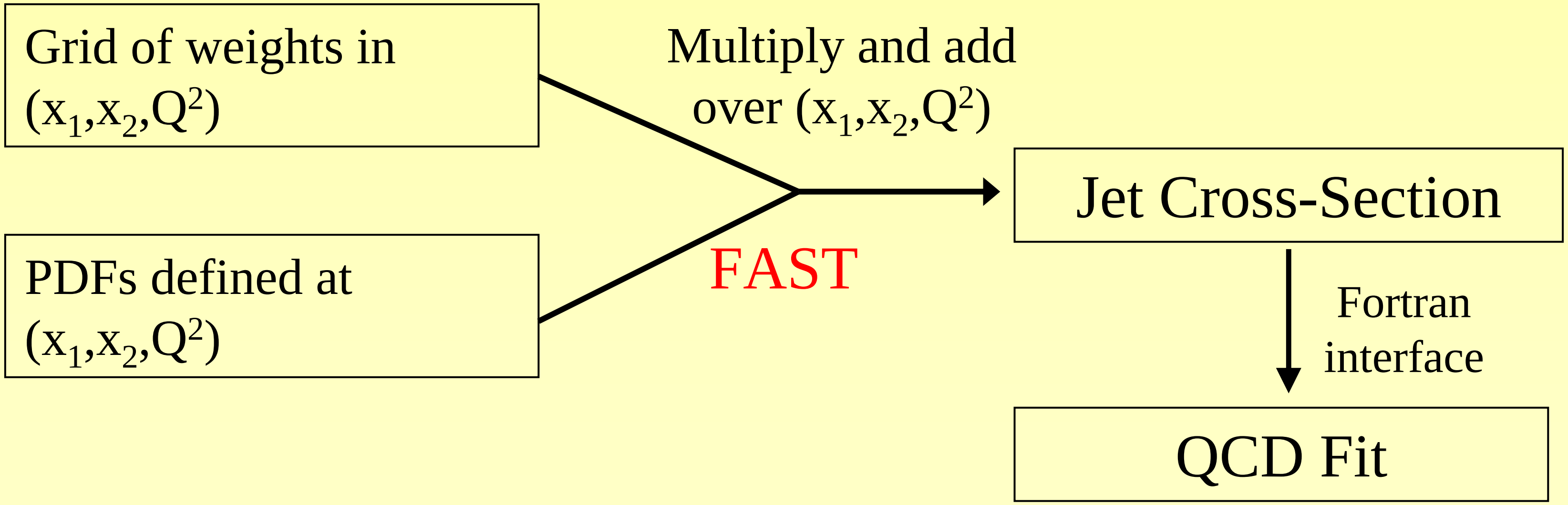


Using Integration Grids

Step 1: Fill the Grid



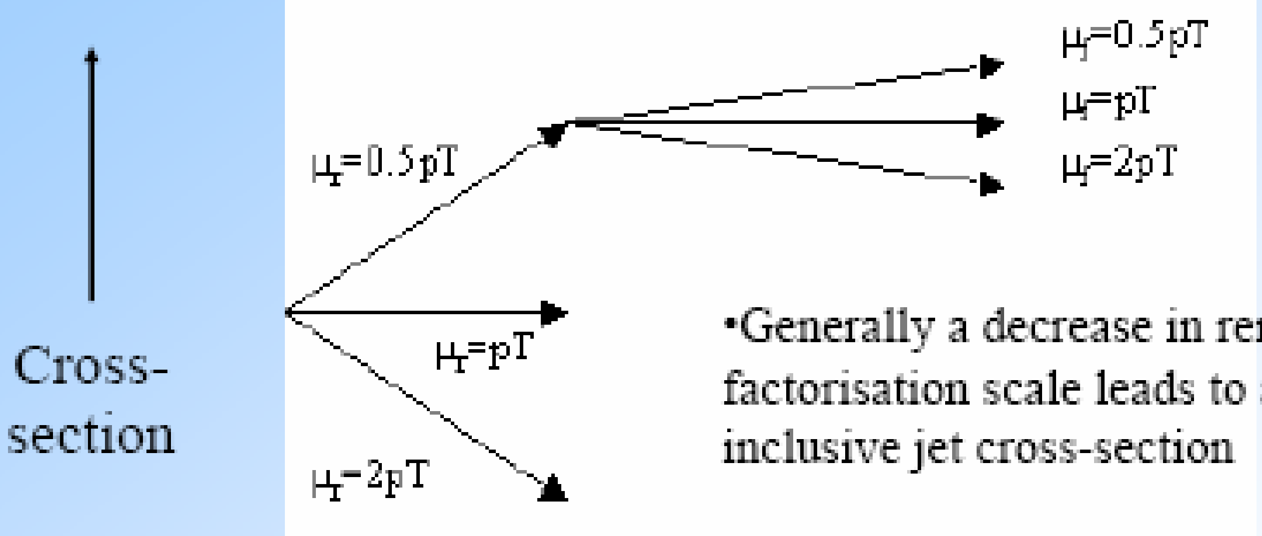
Step 2: Multiply grid by PDFs to generate Cross-Section



Renormalisation / Factorisation Scale Errors

UNIVERSITY of GLASGOW

•For NLOJET, in the region 0<y<3 (below 2TeV) the following pattern is seen:



•Generally a decrease in renormalisation and factorisation scale leads to an increase in the inclusive jet cross-section

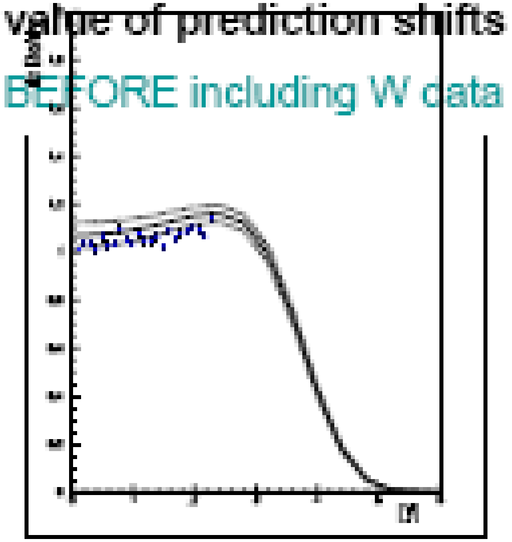
•The renormalisation scale dominates the variation in cross-section at low pT, whilst the factorisation scale dependence grows with pT.

•Scale errors lead to an uncertainty of ~ 5 to 10% on the inclusive jet cross-section for a jet pT of 1TeV.

Study of the effect of including the LHC W Rapidity distributions in global PDF fits by how much can we reduce the PDF errors with early LHC data?

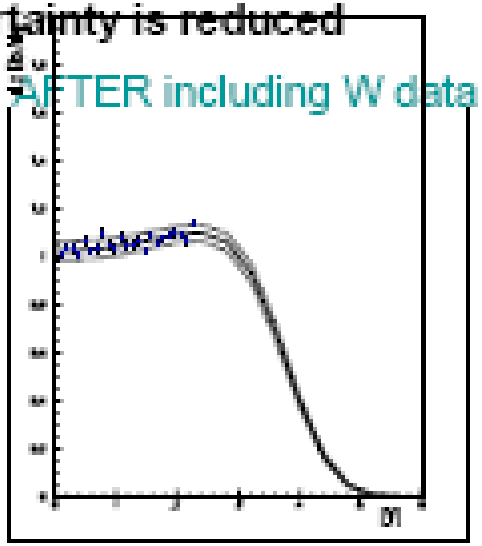
Generate data with 4% error using CTEQ6.1 PDF, pass through ATLFAST detector simulation and then include this pseudo-data in the global ZEUS PDF fit Central value of prediction shifts and uncertainty is reduced

BEFORE including W data



Lepton+ rapidity spectrum data generated with CTEQ6.1 PDF compared to predictions from ZEUS PDF

AFTER including W data



Lepton+ rapidity spectrum data generated with CTEQ6.1 PDF compared to predictions from ZEUS PDF AFTER these data are included in the fit

AMCS, A. Tricoli (Hep-ex/0509002)

Specifically the low-x gluon shape parameter λ, $xg(x) = x^{-\lambda}$, was $\lambda = -.199 \pm .046$ for the ZEUS PDF before including this pseudo-data

It becomes $\lambda = -.181 \pm .030$ after including the pseudodata

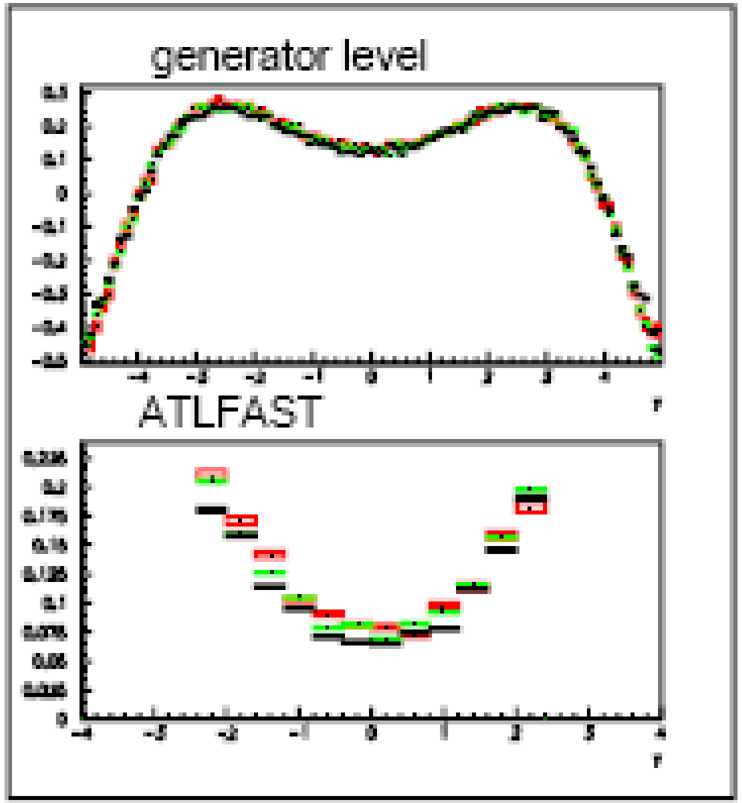
The uncertainty on the W/Z rapidity distributions is dominated by — gluon PDF dominated eigenvectors and there is cancellation in the ratios

$A_W = (W^+ - W^-)/(W^+ + W^-)$ $Z_W = Z/(W^+ + W^-)$

Remaining uncertainty comes from valence PDF related eigenvectors **Well Known? Gold plated?**

We will measure the lepton asymmetry

Within each PDF set uncertainty in the lepton asymmetry IS LESS than in the lepton rapidity spectra, e.g about 2% for the asymmetry at y=0, as opposed to about 4% for the lepton rapidity spectra themselves (using MRST2001 PDFS)



However the PDF sets differ from each other more strikingly- MRST01and CTEQ6.1 differ by about 13% at y=0!

But this is an opportunity to use ATLAS measurements to increase knowledge of the valence PDFs at x~0.005 - see AMCS February06 SM session

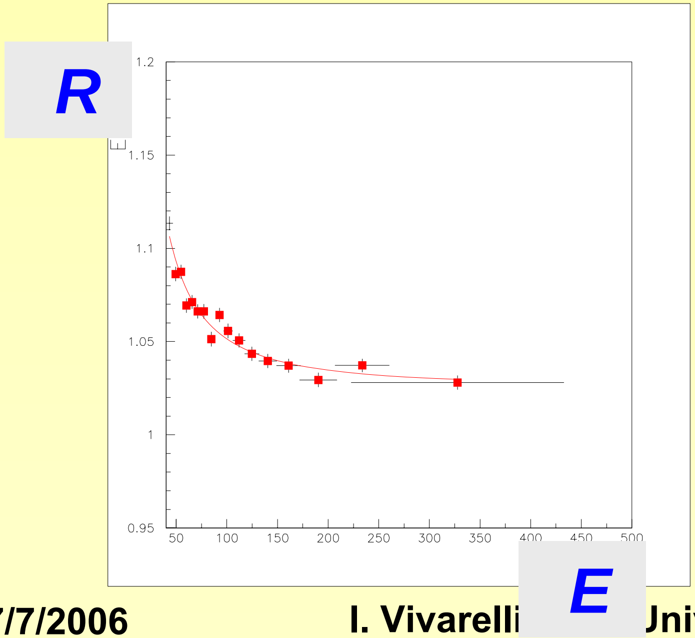
In situ calibration

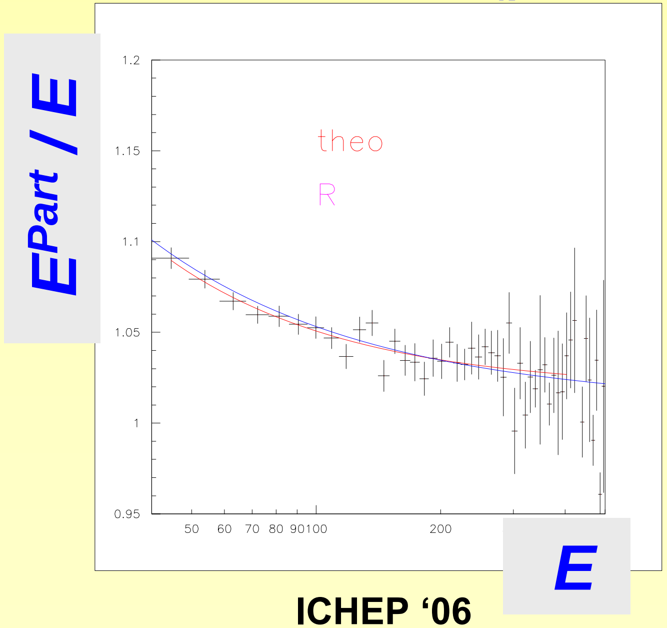
Use W→jj from top decay

Calibration constants to obtain the parton energy in the W→jj channel (where the W comes from the top decay) can be extracted:

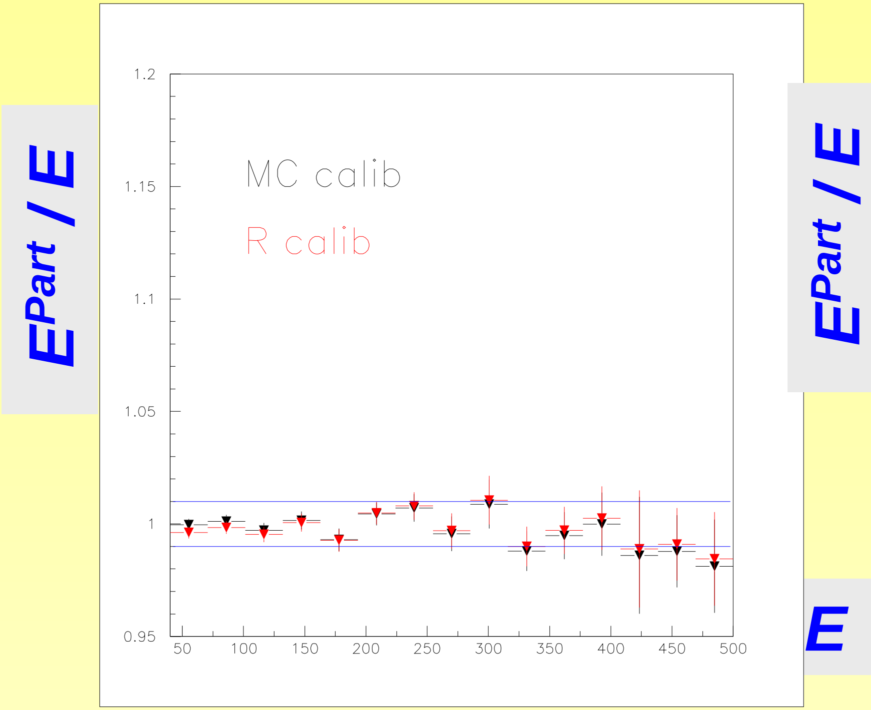
$$R \equiv M_W^{PDG} / M_W = \sqrt{\alpha_1 \alpha_2} \qquad \textit{with} \qquad \alpha_i = \frac{E_i^{part}}{E_i^{jet}}$$

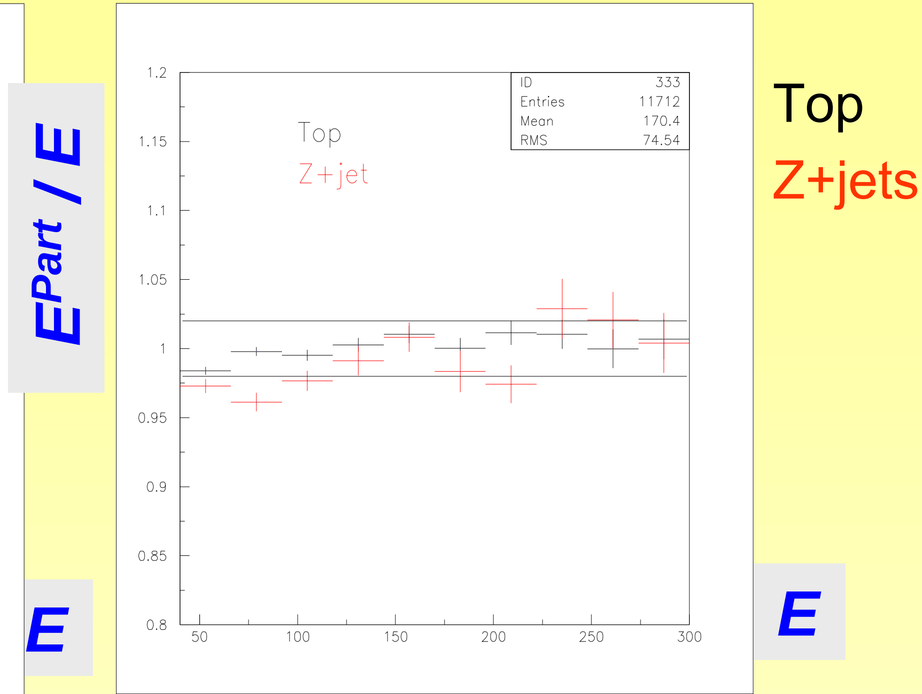
- compute R for k bins in E $\quad \alpha_k = < \alpha_{j1} \alpha_{j2} >$
- apply α_k factors on R and recompute R n times => $\alpha_k^{True} = \prod_n \alpha_k^n$



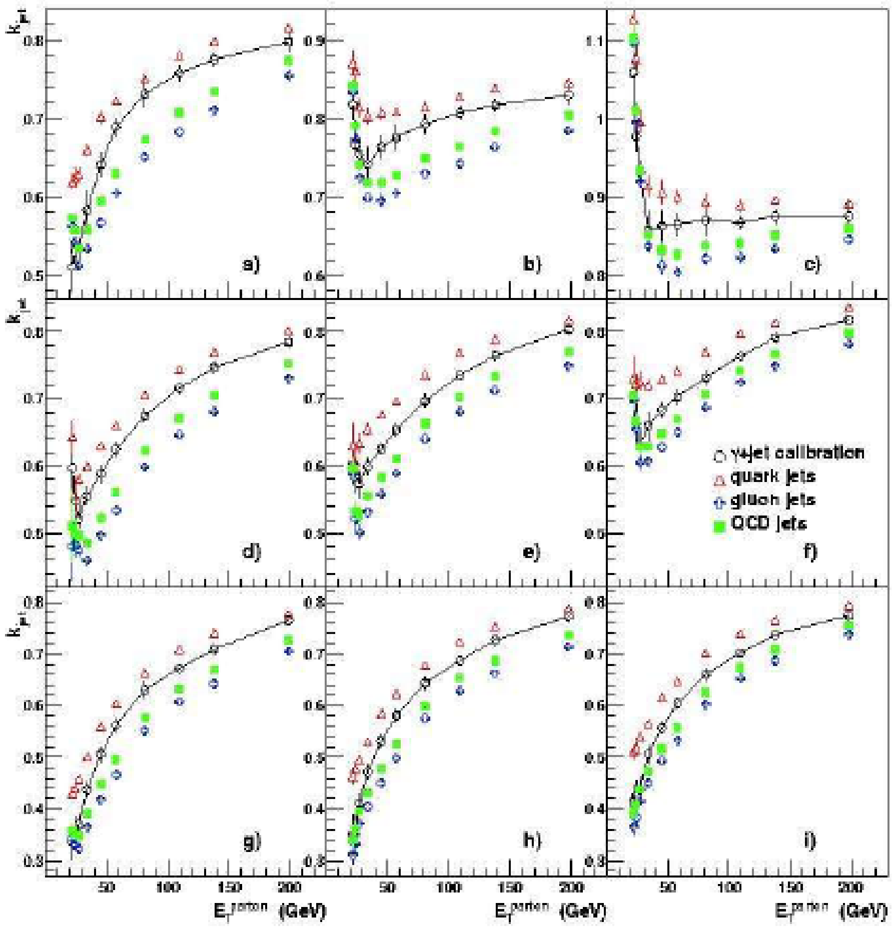


Results after recalibration





- Corrections calculated on the top sample have been used on a Z+jet sample
- Apply same cuts on jets energies
- Jets in the Z sample calibrated at 3-4% level
- Background not included in the analysis

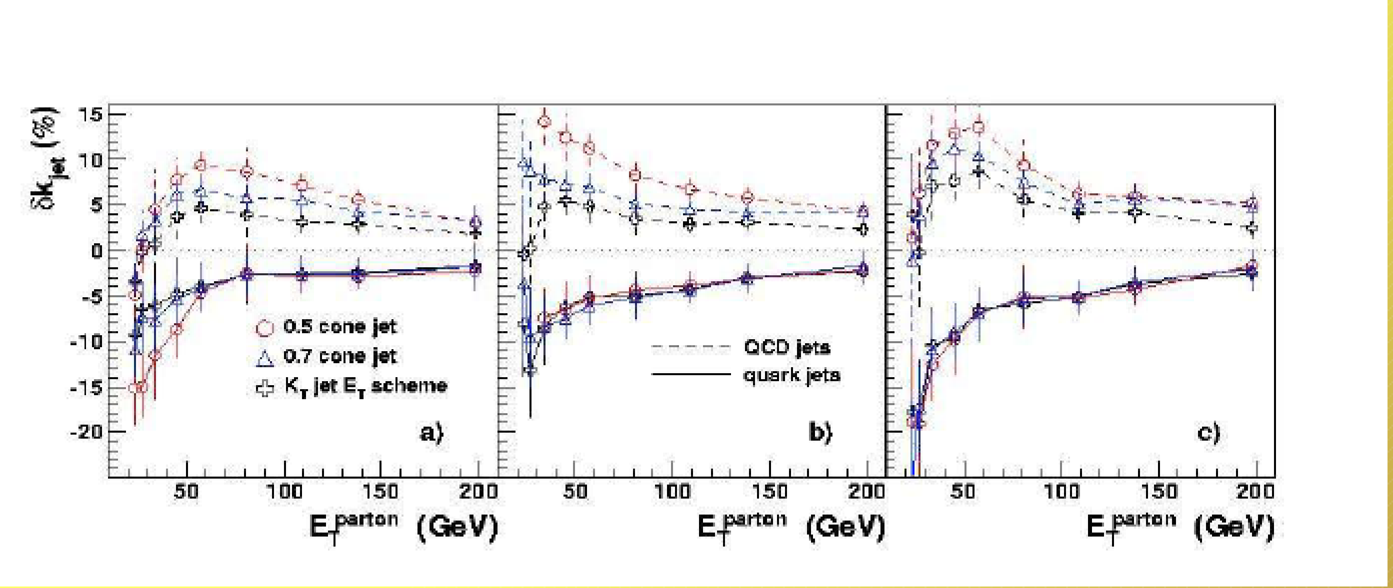


The predicted values of the calibration coefficients $k_{jet} = E_{tjet}^{reco}/E_{T\gamma}$ and the true values: $k_{jet}^{true} = E_{Tjet}^{reco}/E_{Tparton}$ for different samples (q,g,QCD)

The relative differences are on the next slide...

The relative systematic bias for the different samples: $(k_{jet} - k_{true})/k_{true}$

$k_{jet} = E_{Tjet}^{reco}/E_{T\gamma}$ $\qquad$ $k_{jet}^{true} = E_{Tjet}^{reco}/E_{Tparton}$



The main sources of systematic bias are:

- bias due to non-leading radiation effects
- background from QCD dijet events
- event selection may bias true energy scale