

Results on inclusive jets and jet properties



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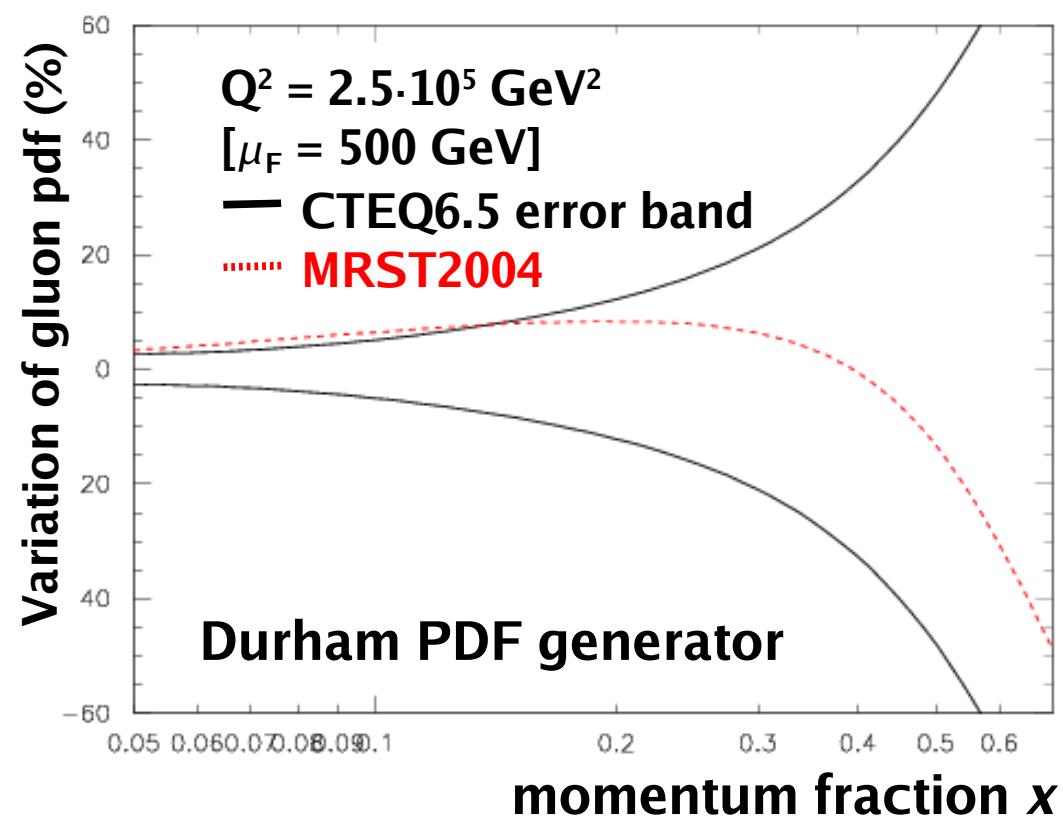
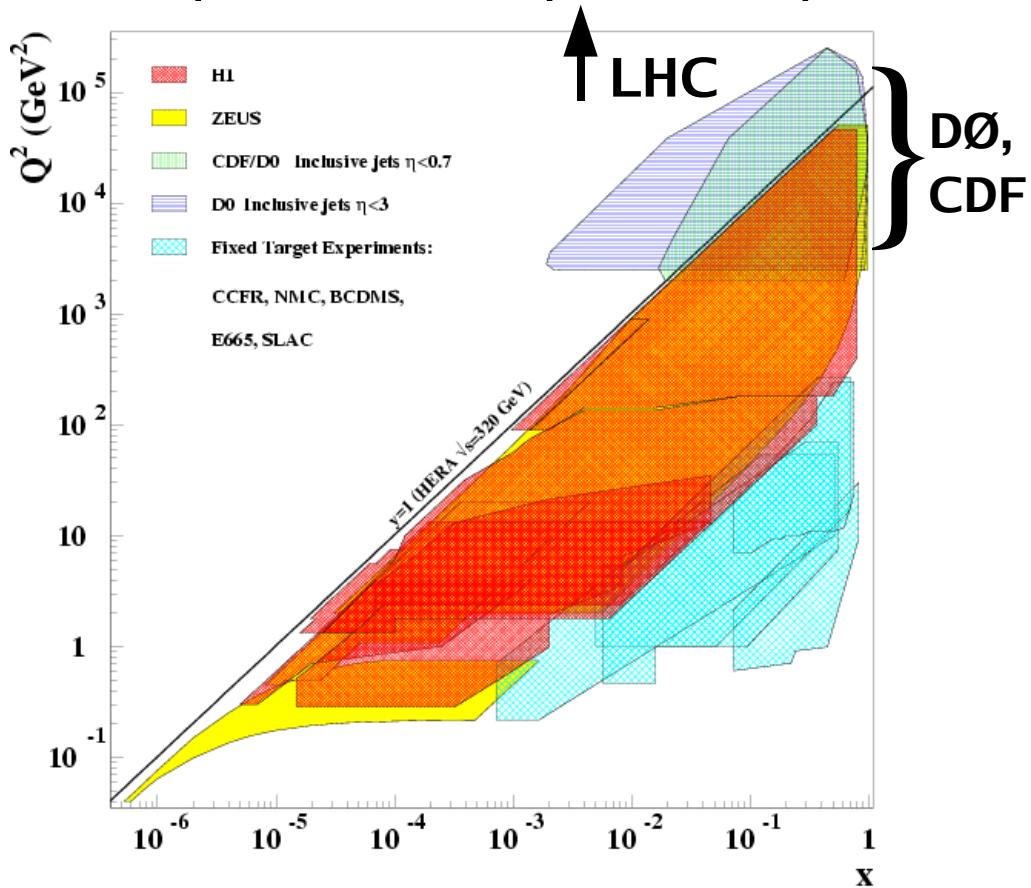
*for the
DØ collaboration*



DIS2008, 7–11 April, University College London

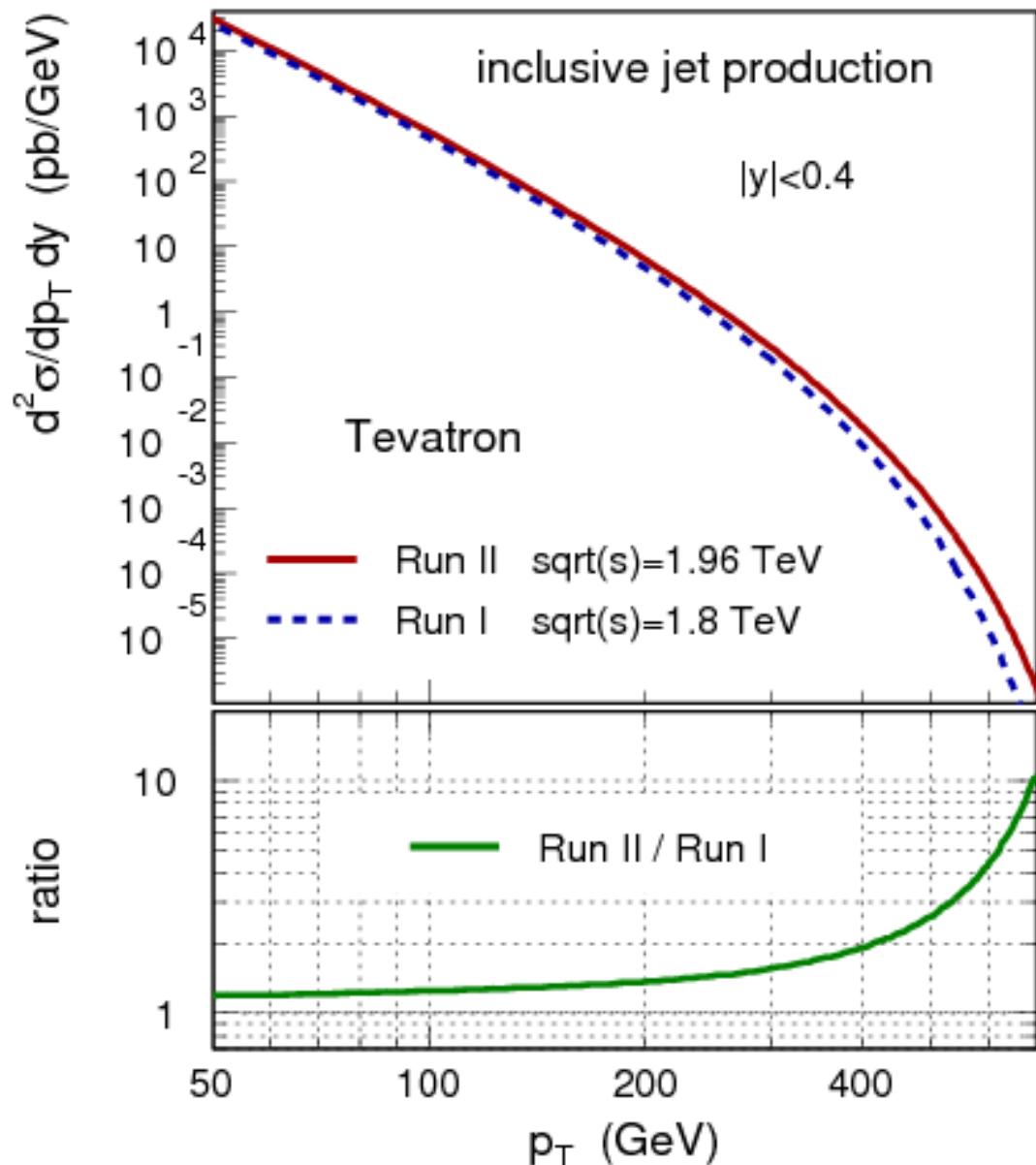
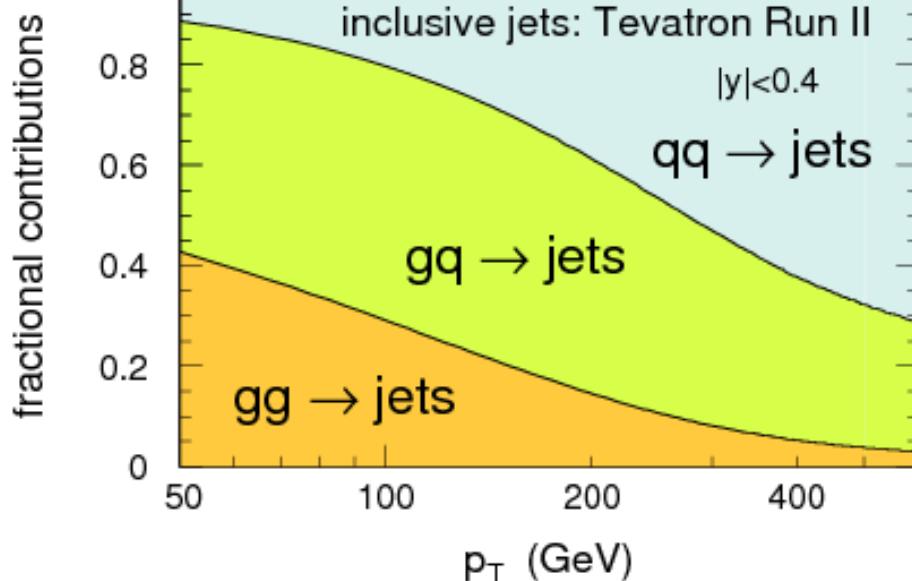
Motivation

- Inclusive jets at DØ can chart PDFs in the high energy, high- x domain
- Gluon PDF at high x has large uncertainty \Rightarrow LHC New Physics searches
- Wide rapidity coverage allows for simultaneous sensitivity to PDFs (all rapidities) and quark compositeness (central)



Data set

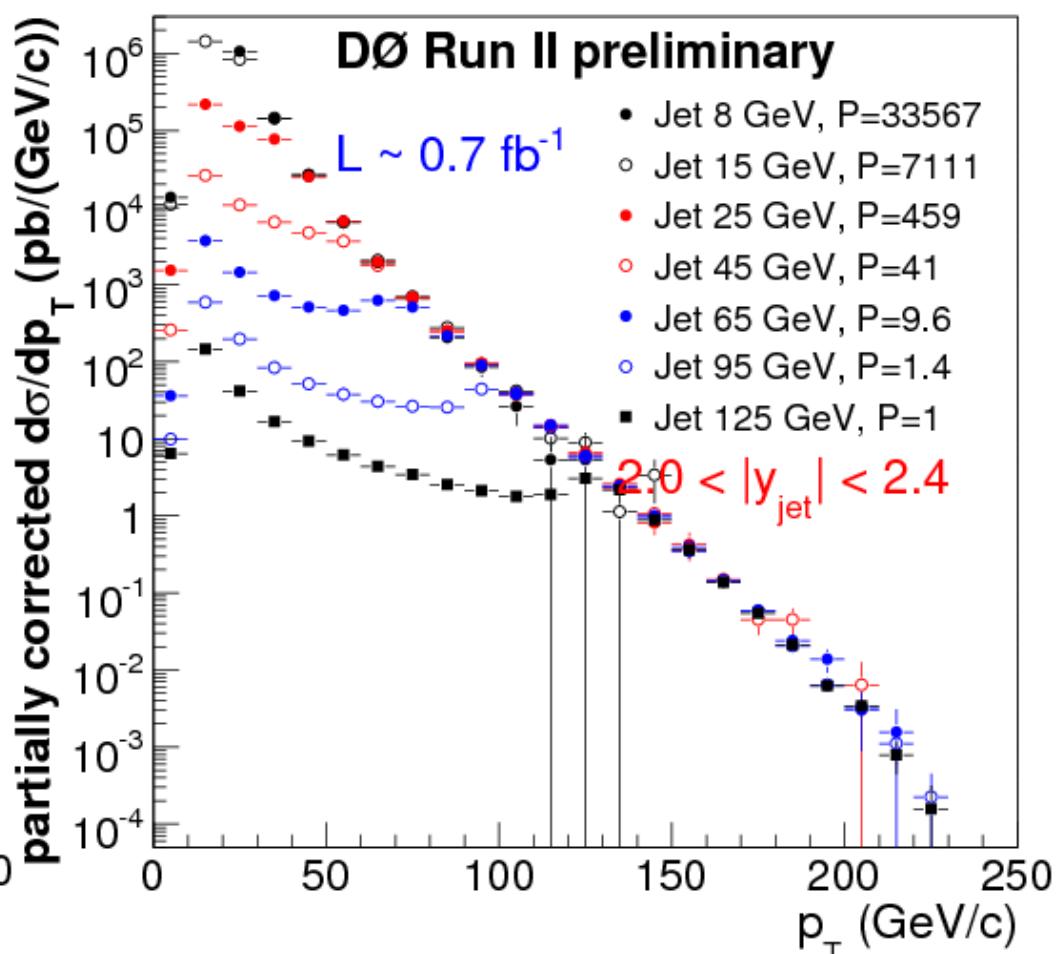
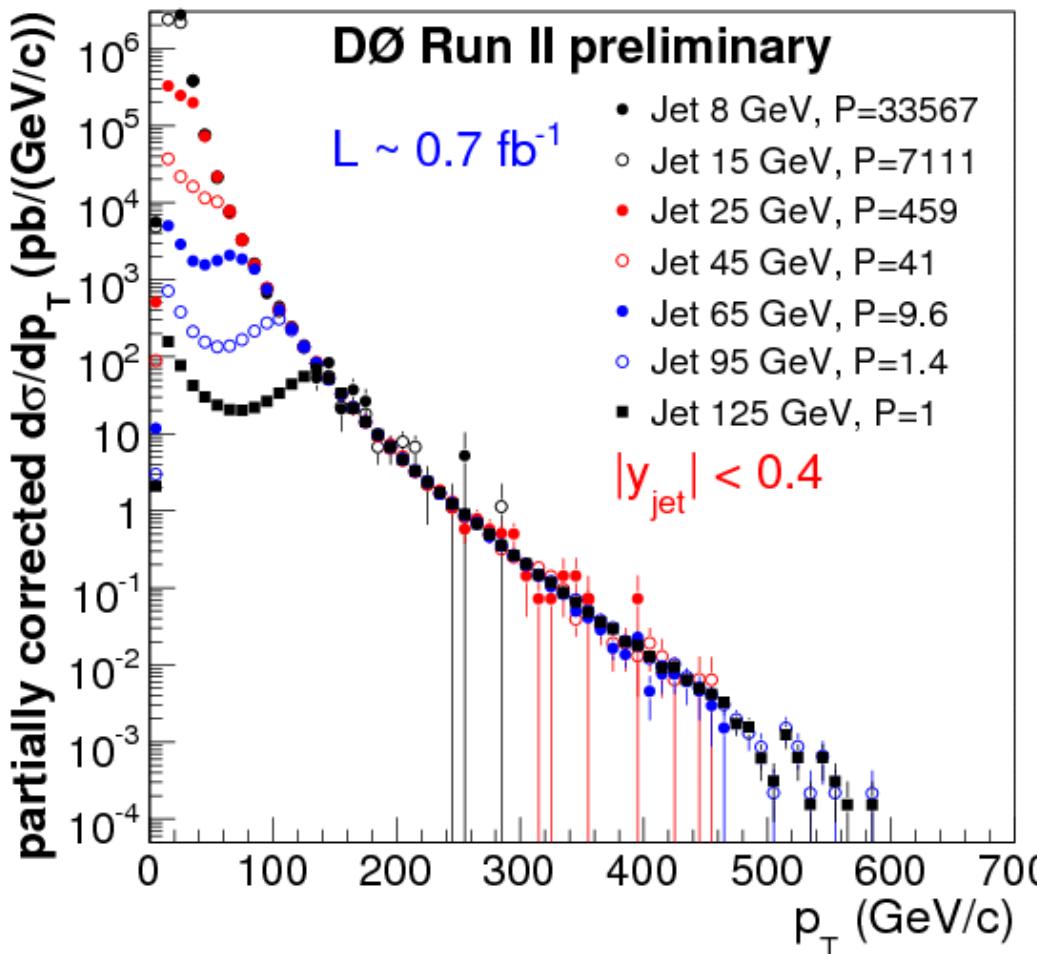
- Data were collected 2004—2005 with the upgraded DØ detector in Run II of the Fermilab Tevatron
- Data selection was based on run quality, event properties and jet quality criteria
- Integrated luminosity 0.70 fb⁻¹





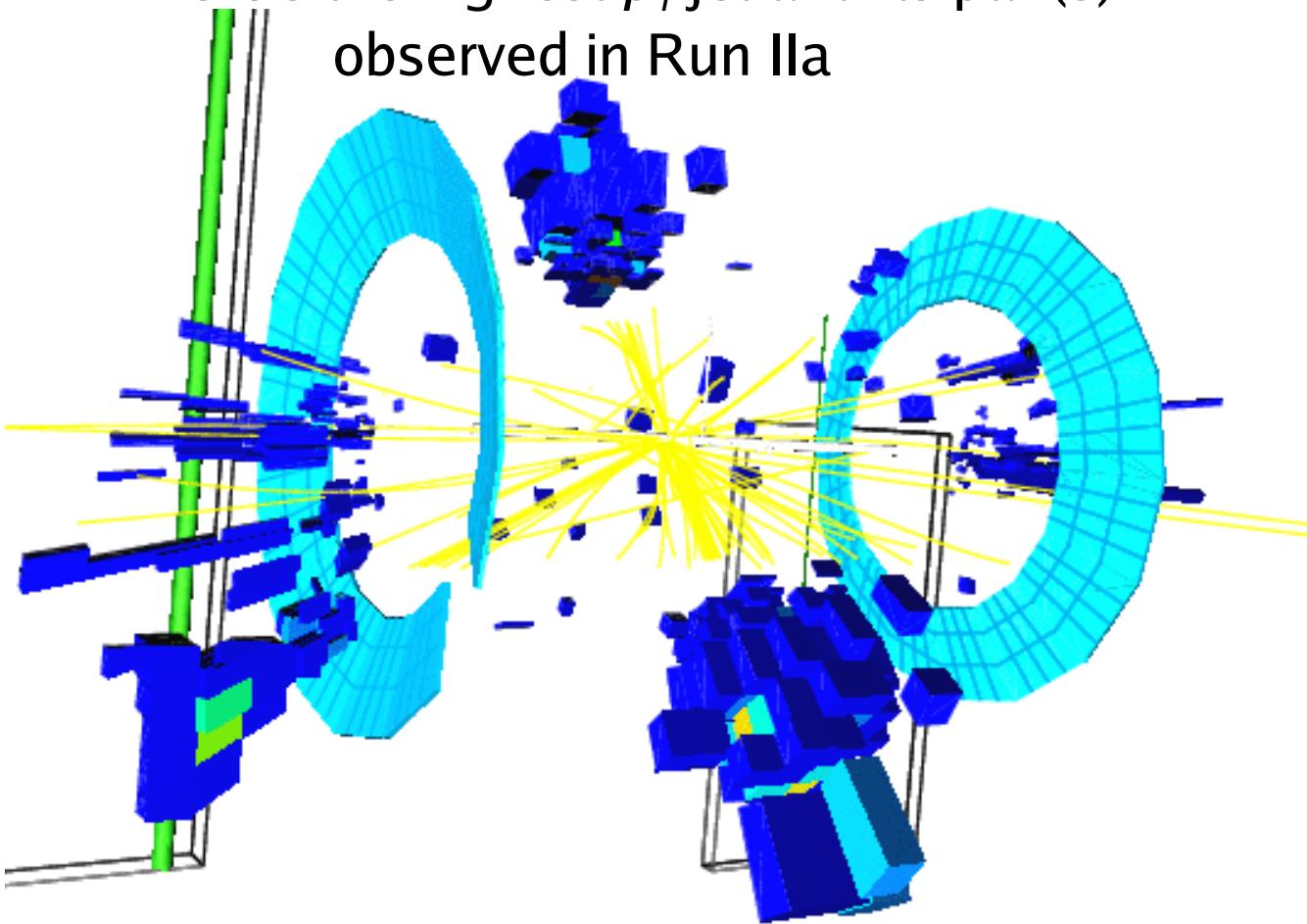
Triggers

- Triggers fire on single jets above p_T threshold
- The measurement spans eight orders of magnitude in six rapidity regions
- Full p_T spectrum combined from seven different triggers

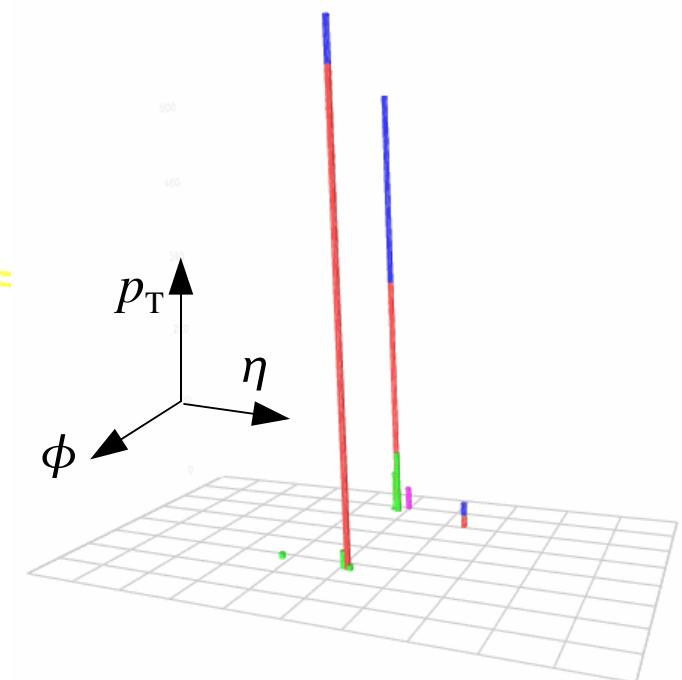


High p_T jets

- The interesting part of the measurement is observing the highest p_T jets ever produced in a collider
- Here's the highest p_T jet and its pair(s) observed in Run IIa



first jet	second jet
$p_T = 624 \text{ GeV}$	$p_T = 594 \text{ GeV}$
$y_{\text{jet}} = 0.14$	$y_{\text{jet}} = -0.17$
$\phi_{\text{jet}} = 2.10$	$\phi_{\text{jet}} = 5.27$
$M_{jj} = 1.22 \text{ TeV} !$	

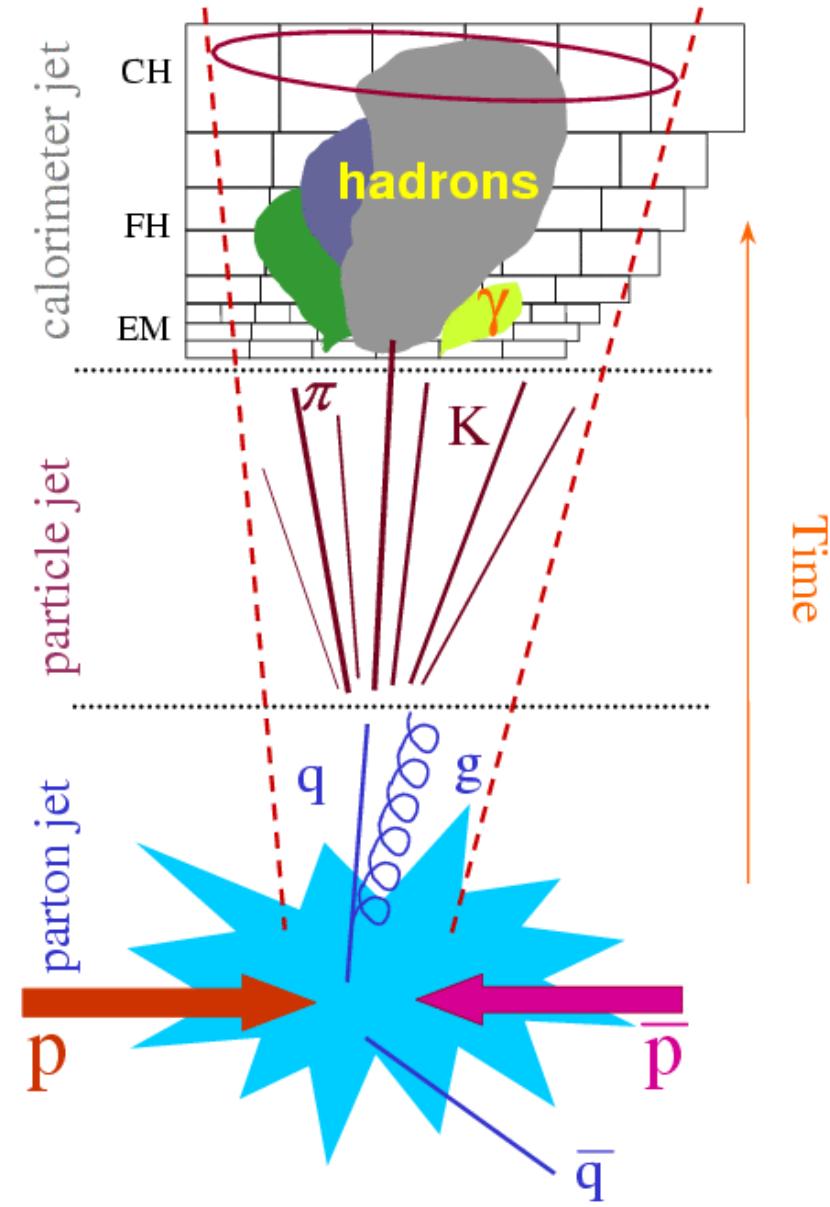


Jet energy scale

- Jet Energy Scale returns the measured calorimeter jet **energy** to the **particle level**

$$E_{ptcl} = \frac{E_{cal} - \text{Offset}}{(F_\eta \cdot R) \cdot S} \cdot k_{bias}$$

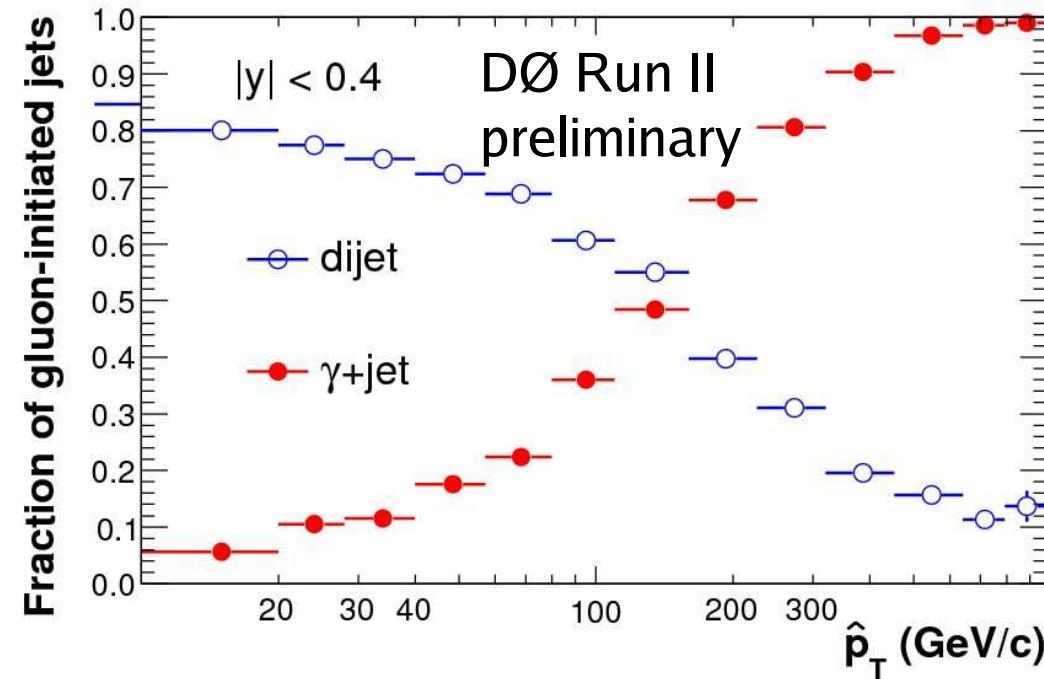
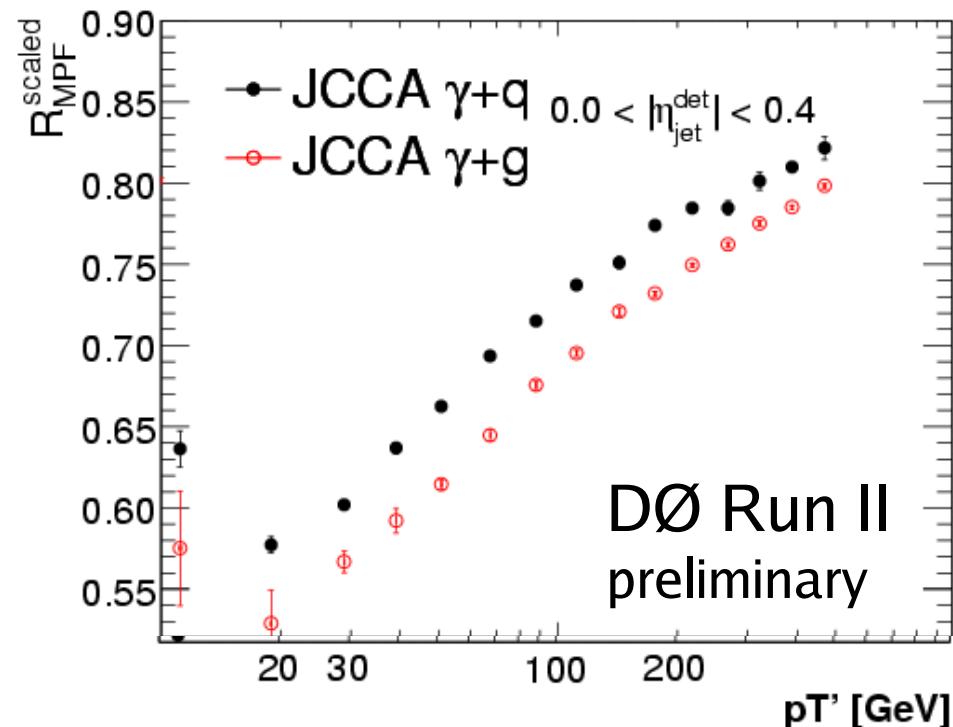
- Offset is energy not associated to the hard scatter: noise, pile-up, **multiple interactions**
- Response is the fraction of particle jet energy deposited in the calorimeter by the particles
- Detector showering accounts for **energy flow** in and out of the calorimeter jet due to detector effects (finite calorimeter tower and hadron shower size, magnetic field)
- Method biases corrected using tuned MC





JES sample dependence

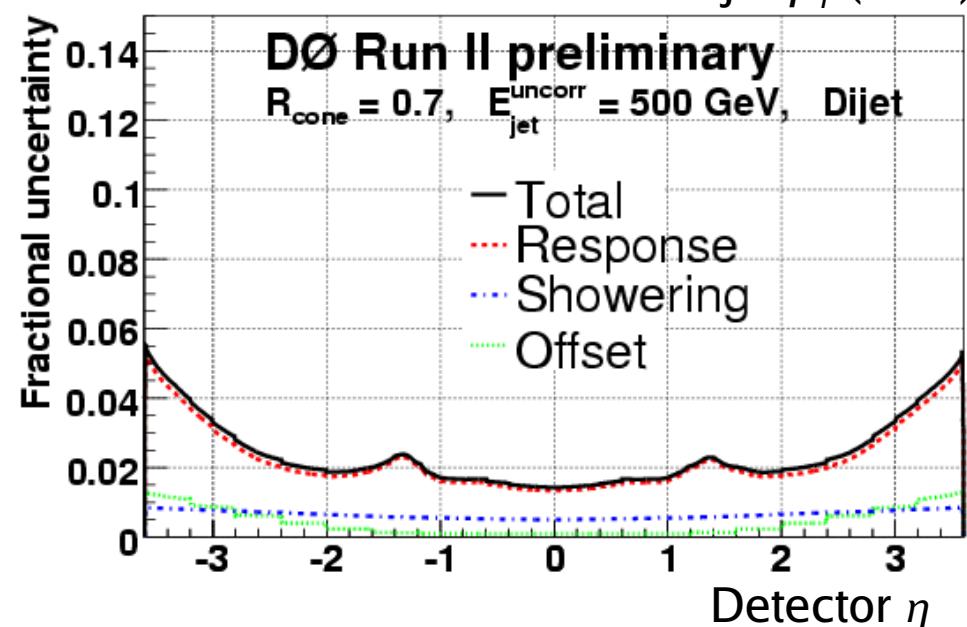
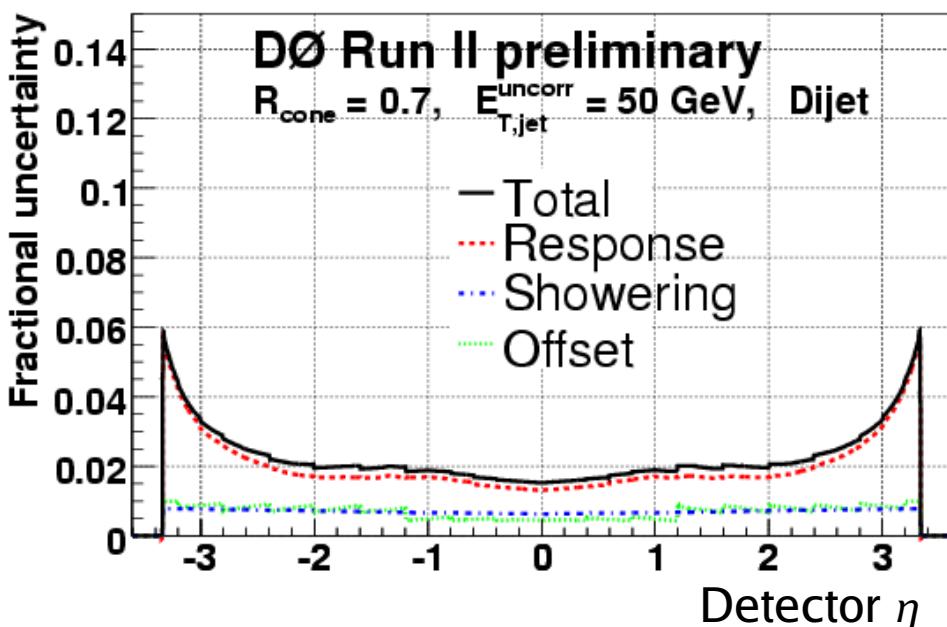
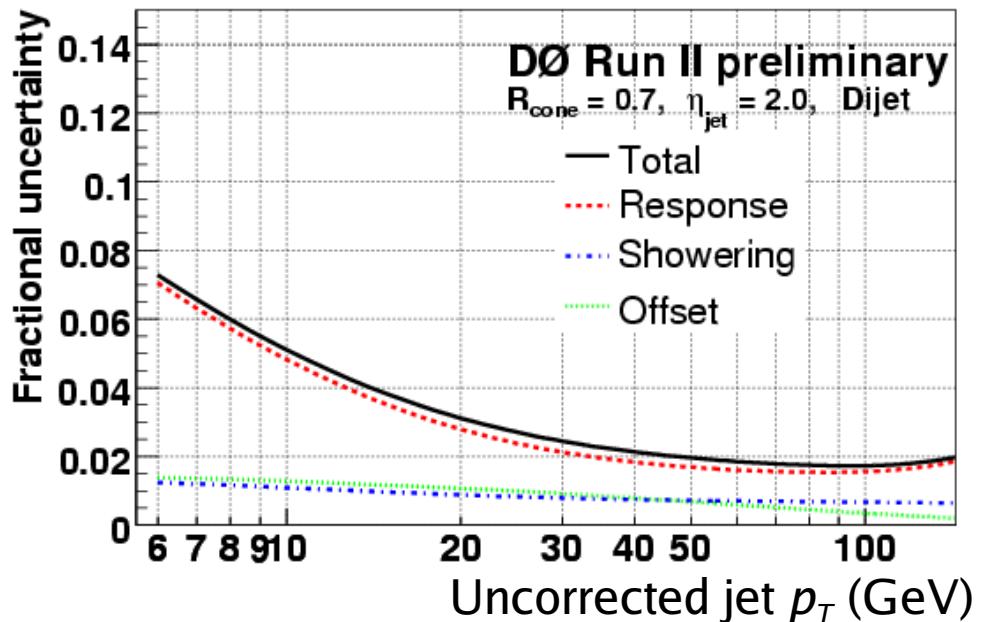
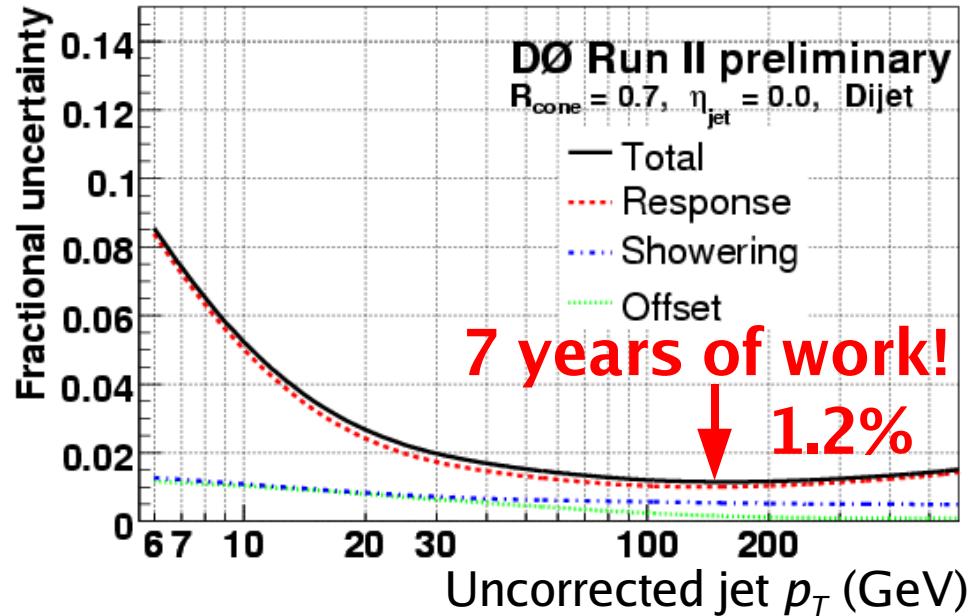
- Final Run IIa JES precise enough that cannot hide **quark and gluon jet response differences** and the **difference between E and p_T**
- The γ +jet and dijet samples have completely different jet composition

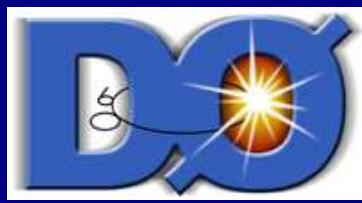


- Knowledge of single pion response is essential to predict the quark and gluon response differences
- Single pion response tuned to γ +jet data
- Forward difference larger, but calibration w.r.t. central calorimeter directly from data



Dijet JES uncertainty





Jet p_T resolution

- Jet p_T resolution is measured directly on **dijet data** using p_T asymmetry A
- Asymmetry is corrected for soft radiation (third jet below reco threshold), particle level imbalance and effects from (small) non-Gaussian tails

Raw asymmetry

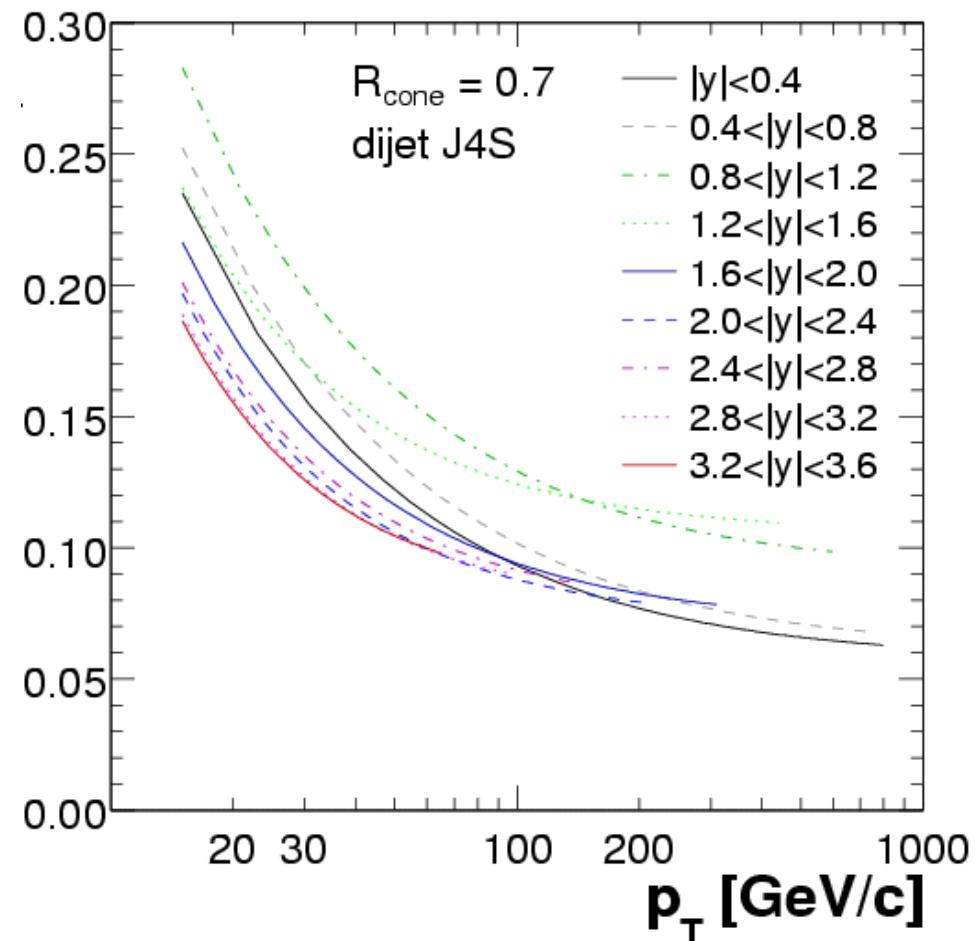
$$A = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

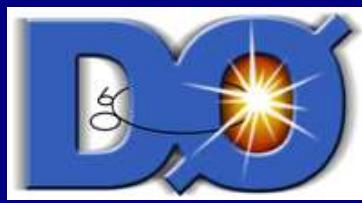
Raw resolution

$$\rightarrow \frac{\sigma_{p_T}}{p_T} = \sqrt{2 \cdot RMS(A)}$$

Finally parametrized by

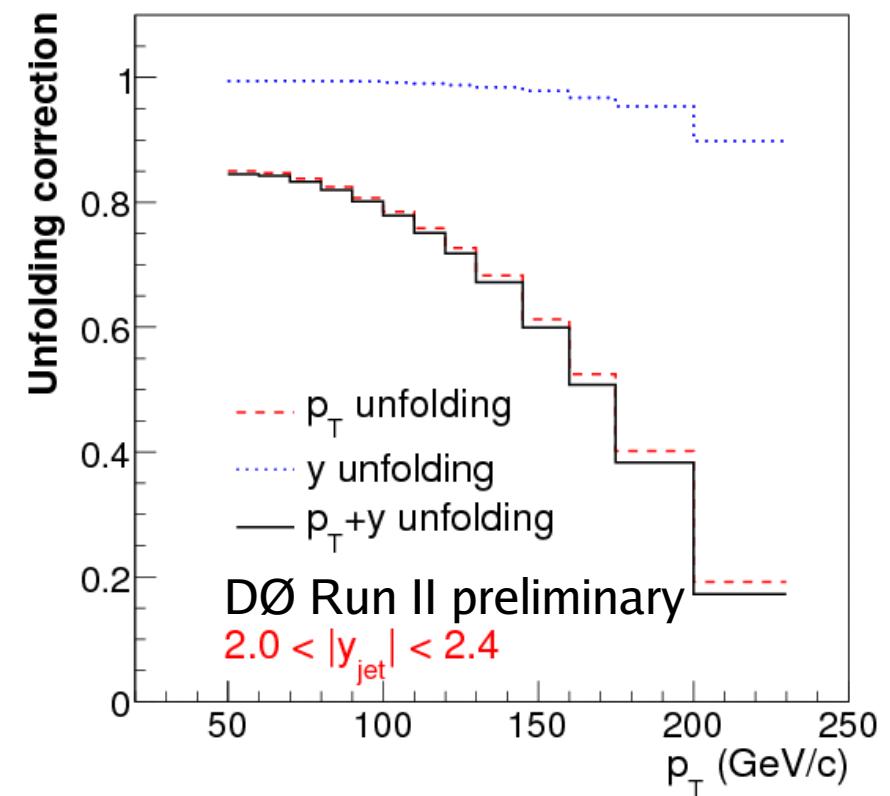
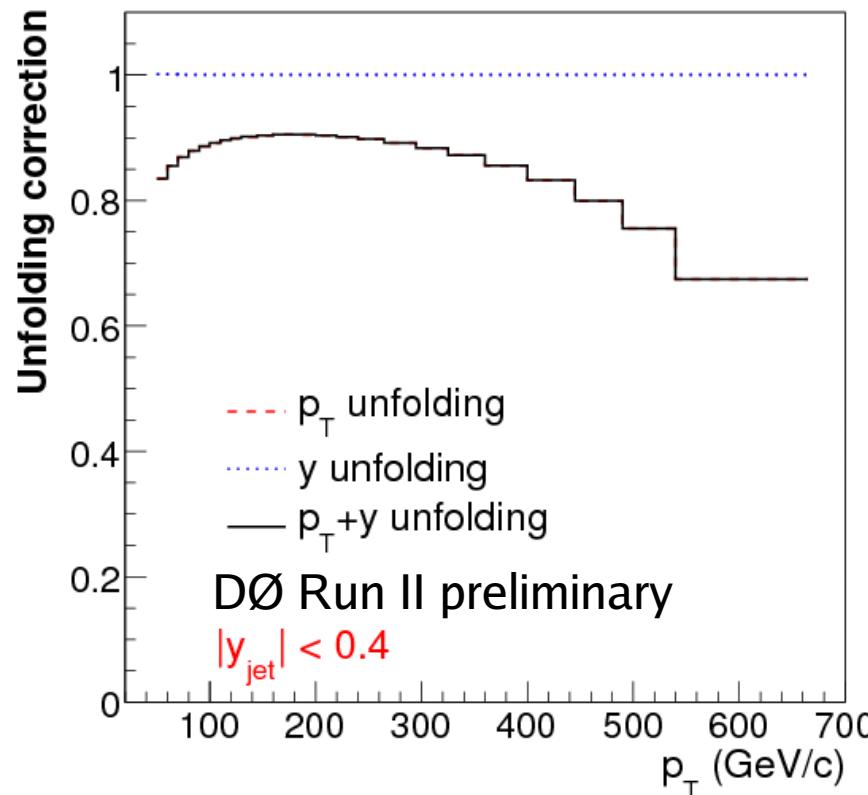
$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{N^2}{p_T^2} + \frac{S^2}{p_T} + C^2}$$





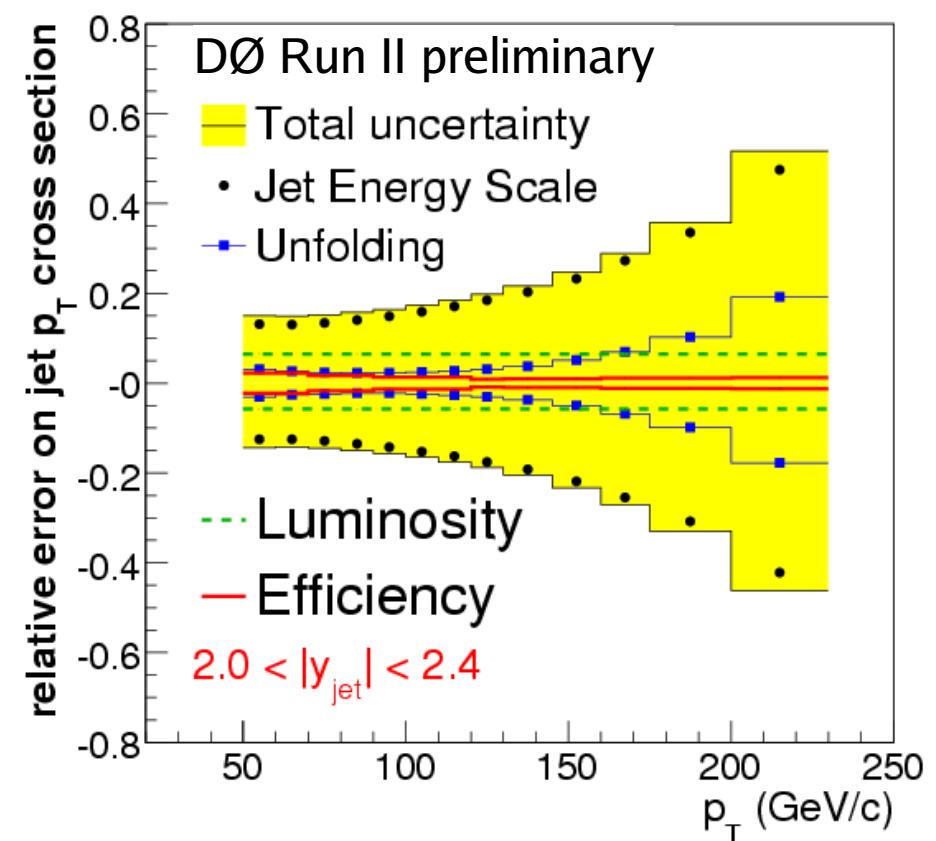
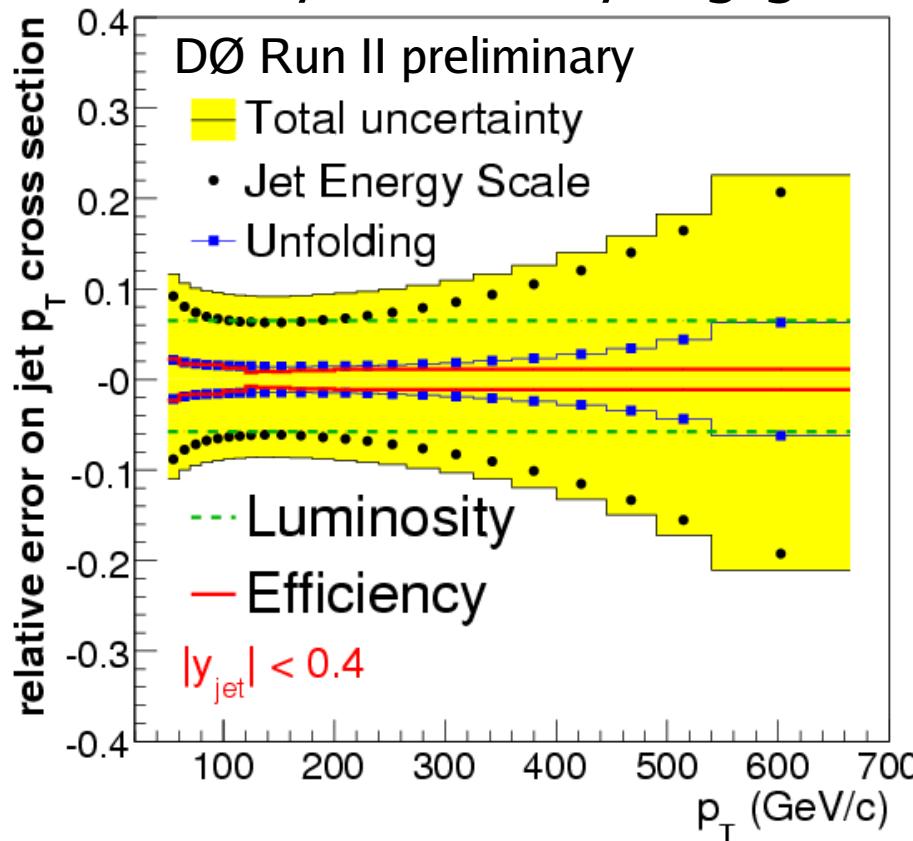
Jet p_T unfolding

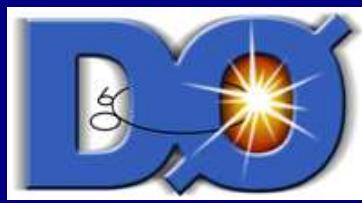
- Observed cross section is higher than true because more events migrate from high (and low) $p_{T,\text{ptcl}}$ into a given bin of measured p_T than migrate out of the bin due to jet p_T resolution \Rightarrow net increase
- Model the true cross section (ansatz method) and smear it (\Rightarrow resolution!) to obtain the observed cross section and then iteratively fit this to data



Components of uncertainty

- Total uncertainty is dominated by the (much improved!) JES
- Unfolding ($\approx p_T$ resolution) uncertainty much smaller than JES
- Luminosity is a significant uncertainty at low p_T in CC
- Efficiency uncertainty negligible

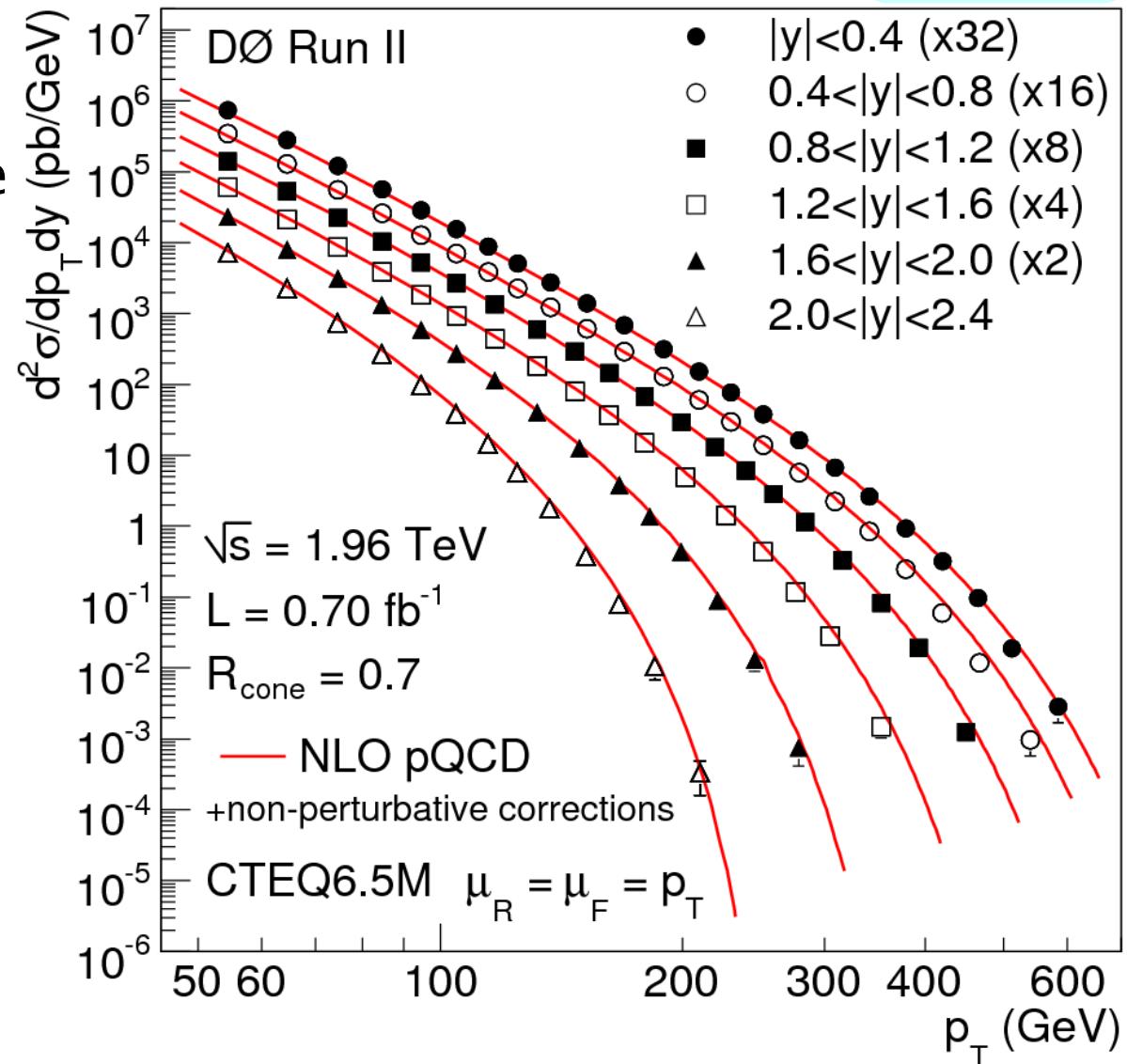




Final results

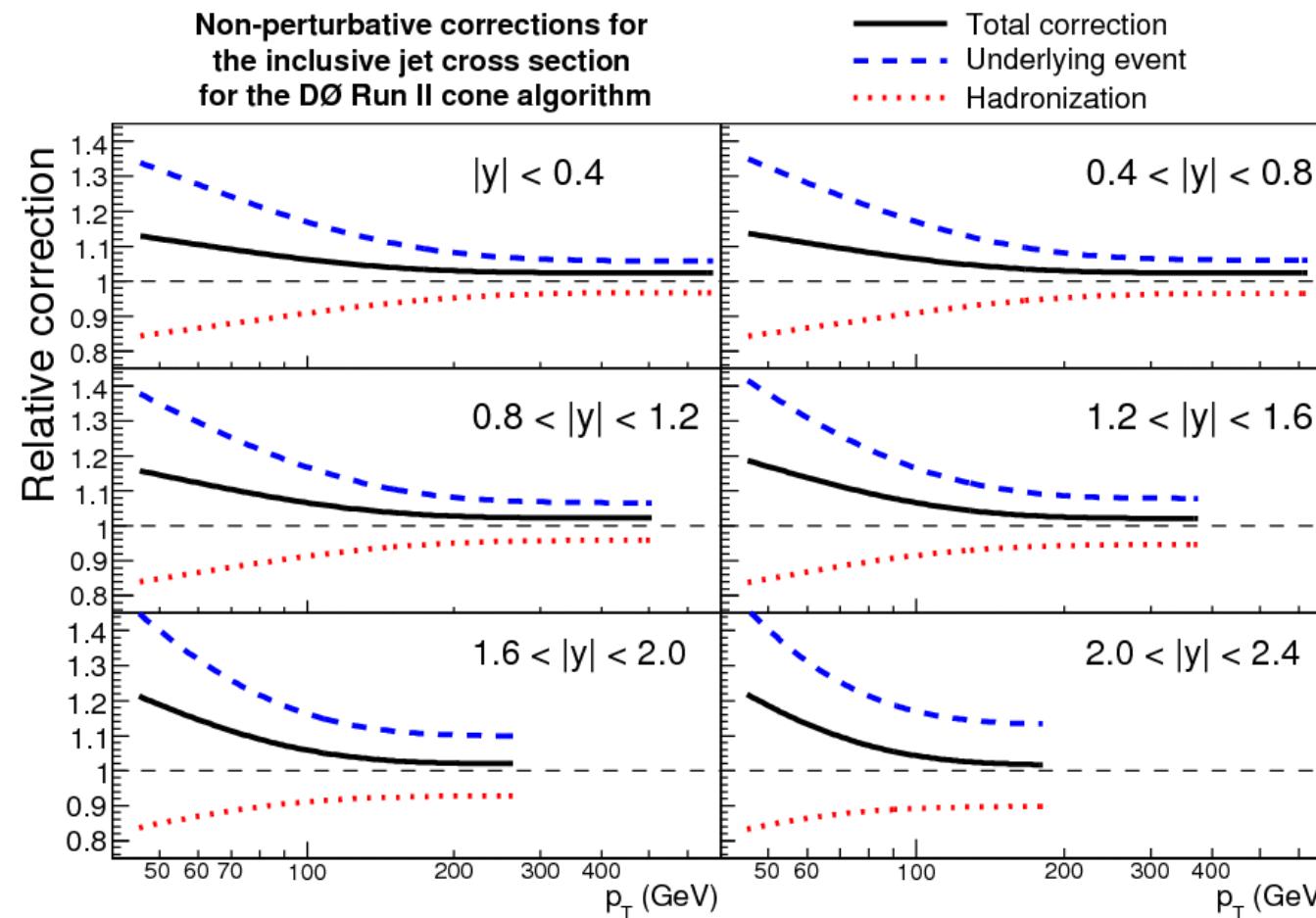
- Largest data set from Run II with the widest rapidity coverage ($|y|<2.4$) and smallest uncertainties to date
- Uncertainties competitive with (better than) Run I and CDF
- Jet spectrum presented at **particle level** with **midpoint cone** ($R_{\text{cone}} = 0.7$)
- Compared to next-to-leading order (NLO) theory with CTEQ6.5M PDFs and non-perturbative corrections from Pythia

PRL plot



Non-perturbative corrections

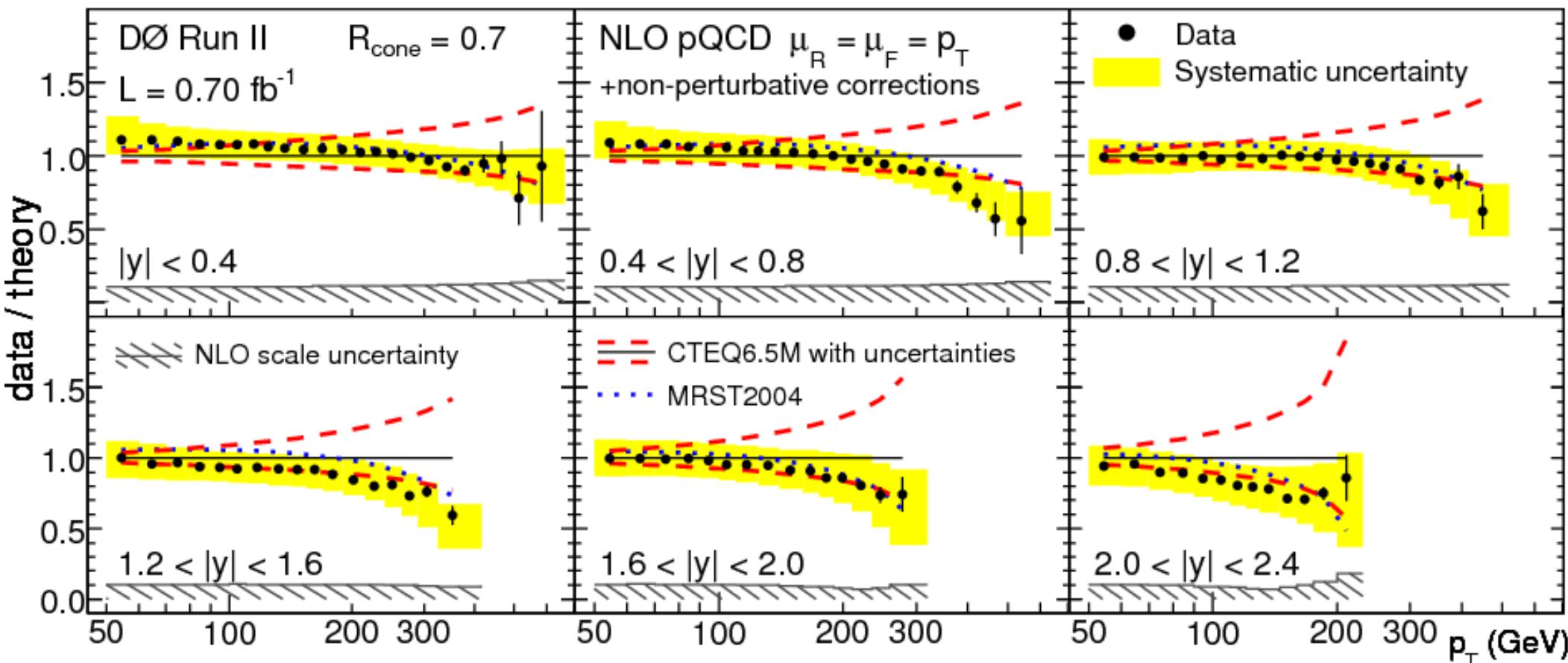
- Hadronization and underlying event are soft QCD effects and cannot be calculated with perturbation theory
- Pythia tune A used to calculate the non-perturbative corrections to theory



Final results vs. theory

- Good agreement between data and theory at all rapidities; MRST2004 PDFs and the lower end of CTEQ6.5 PDF uncertainty favored
- Scale uncertainty in next-to-leading order (NLO) theory comparable to experimental uncertainty at low p_T

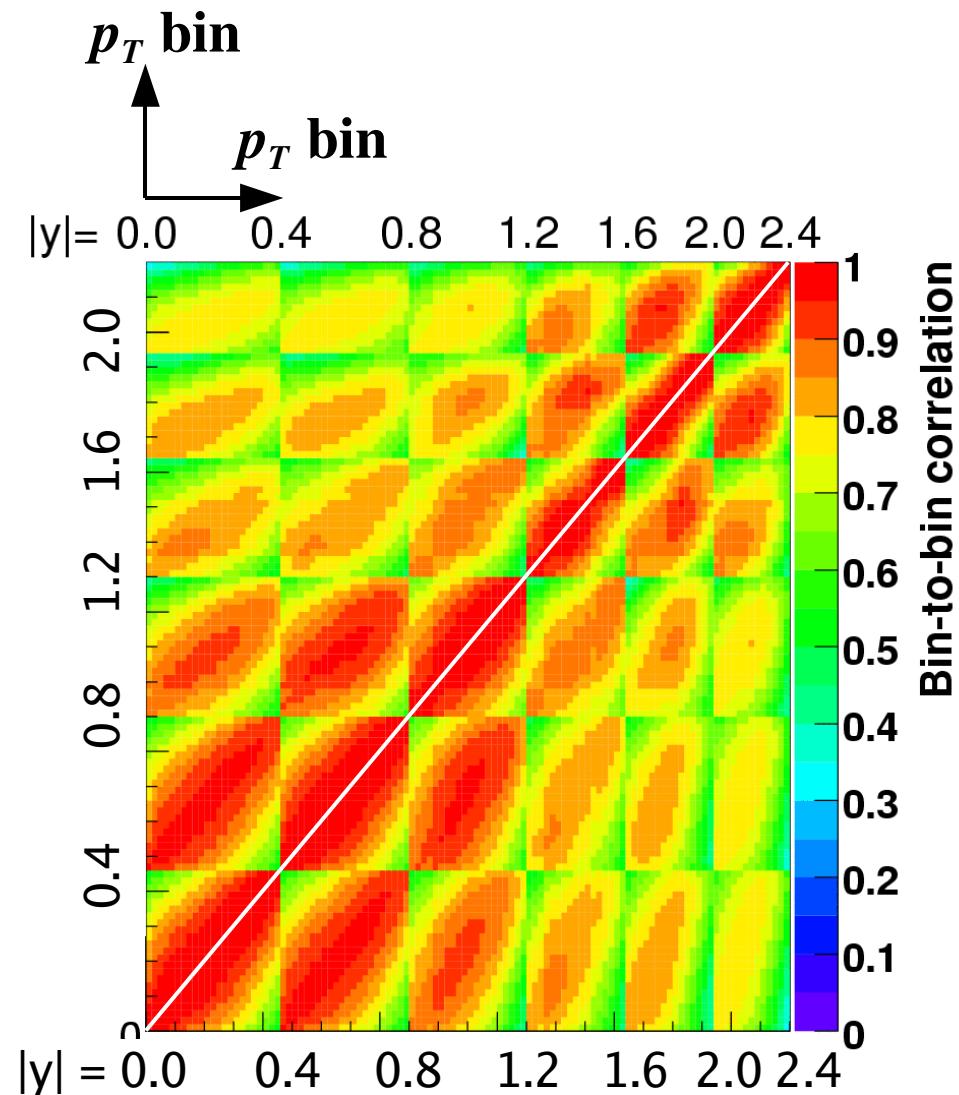
PRL plot





Uncertainty correlations

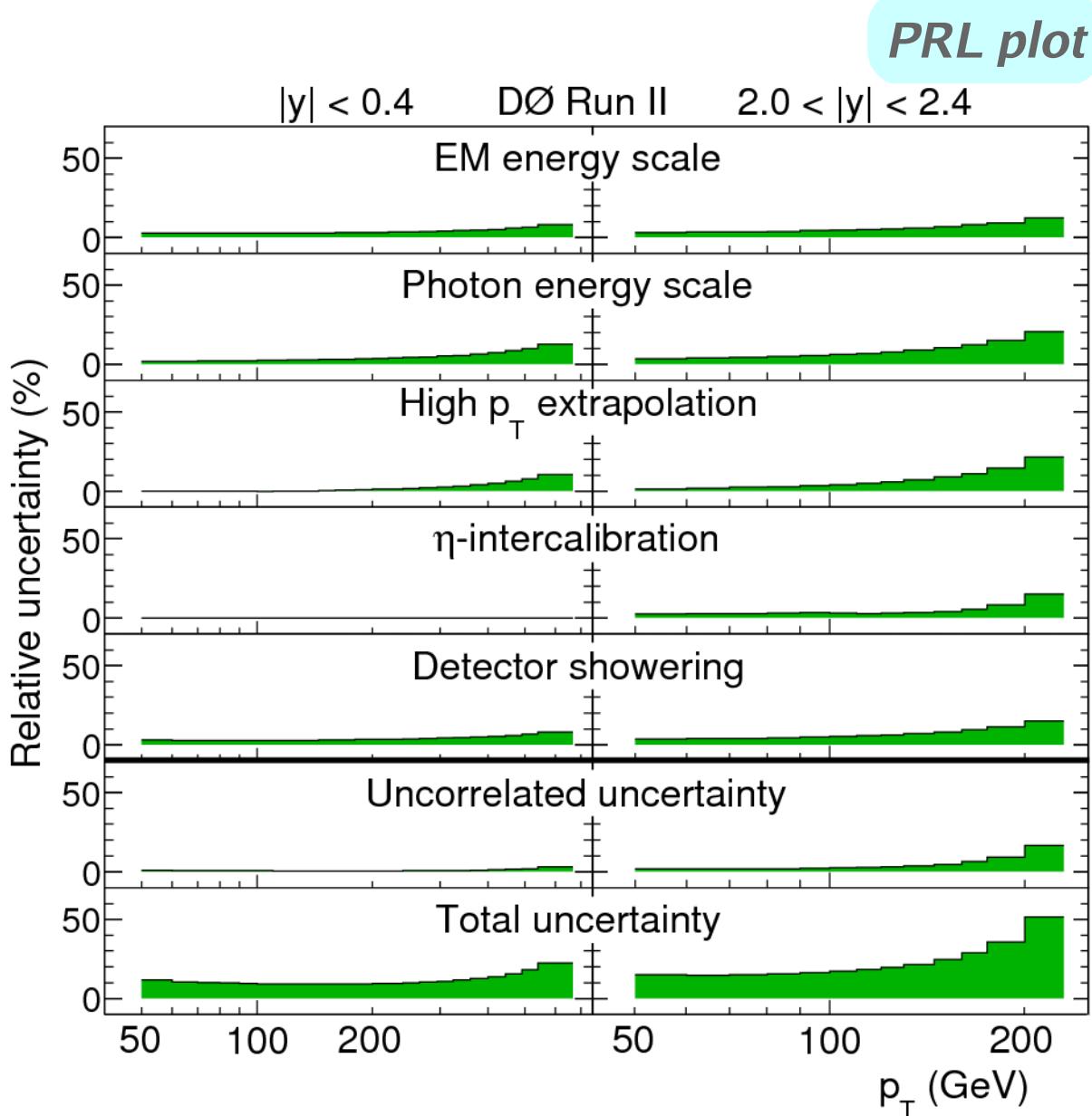
- The uncertainty correlations are provided in the format CTEQ uses: set of independent variations (sources) describing how points move together
- Average bin-to-bin correlation of about **80% with RMS of 10%**
- Using the correlation information in the global PDF fit should **further reduce the effective uncertainty** in the measurement

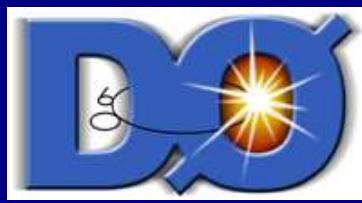




Uncertainty correlations

- Leading sources are from JES:
 - **EM energy scale** ($Z \rightarrow e^+e^-$ calibration)
 - **Photon energy scale** (MC description of e/γ response, material budget)
 - **High p_T extrapolation** (fragmentation in Pythia/Herwig, PDFs)
 - **Rapidity decorrelation** (uncertainty in η -dependence)
 - **Detector showering** (goodness of template fits)
- Only five highest out of 23 correlated systematics shown

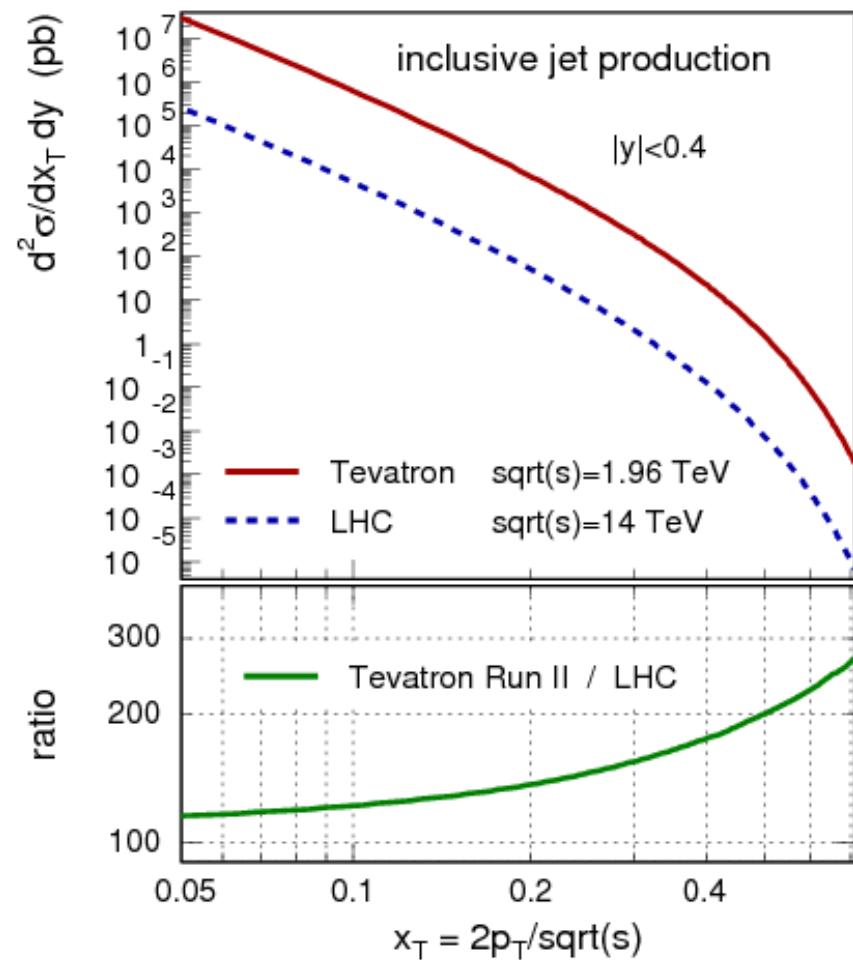


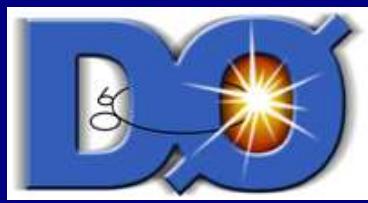


Conclusions

- Inclusive jet cross section measurement with the smallest uncertainties to date in range $p_T = 50\text{--}600 \text{ GeV}$ with wide rapidity coverage (six bins in $|y|<2.4$)
- Good agreement with NLO pQCD calculations, with reduced high- x gluon favored compared to CTEQ6.5M
- Uncertainty correlations studied in detail and correlations found to be high; 23+1 sources provided for global PDF fits
- In the future, LHC needs $\sim 200 \text{ fb}^{-1}$ for similar high- x PDF sensitivity
⇒ leading result for years
- LHC will also need 1% level JES systematics, which took us 7 years

Submitted to Phys.Rev.Lett.
[arXiv:0802.2400](https://arxiv.org/abs/0802.2400)



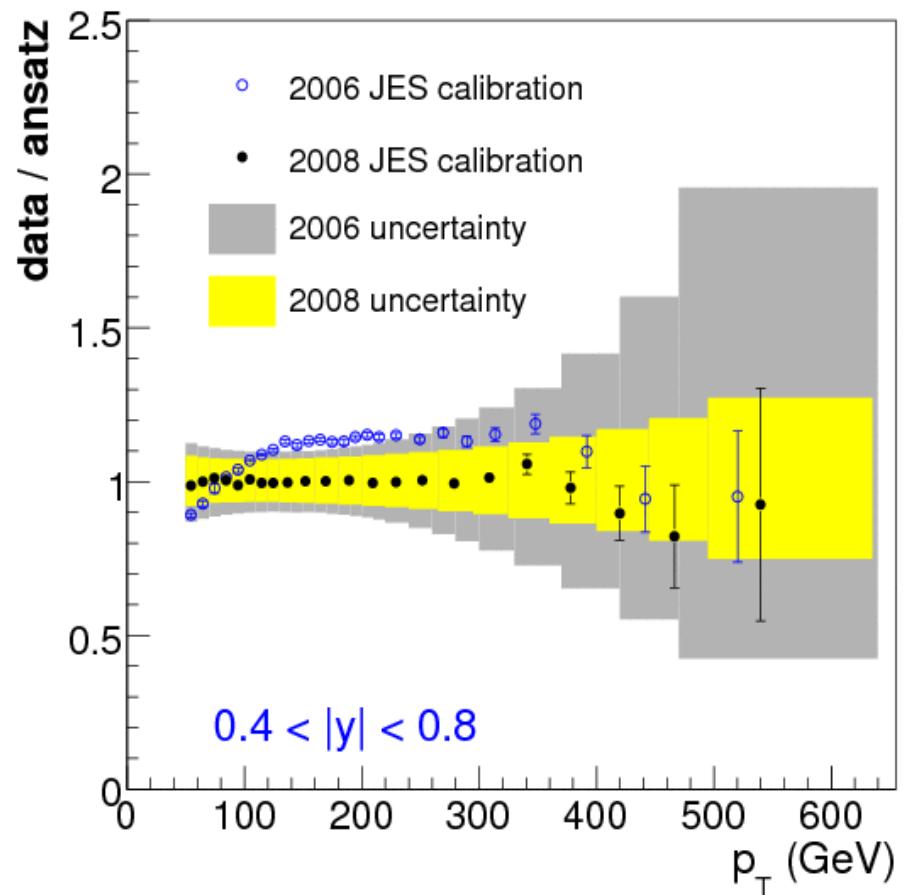
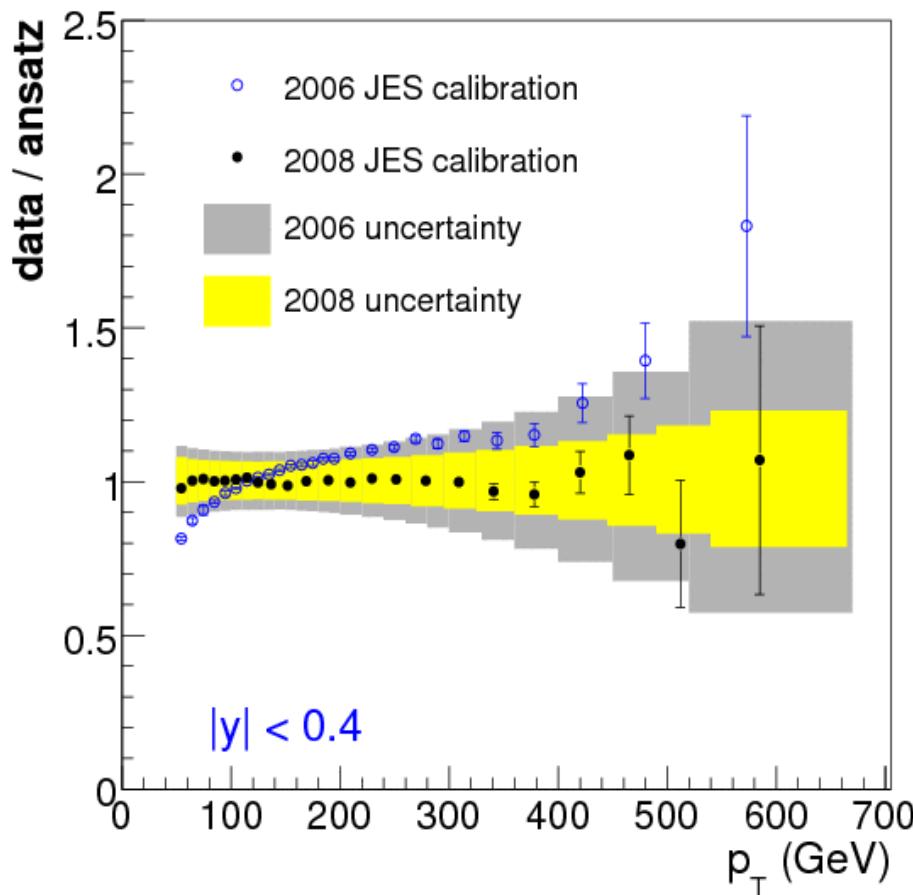


Back-up slides



Improvement since 2006

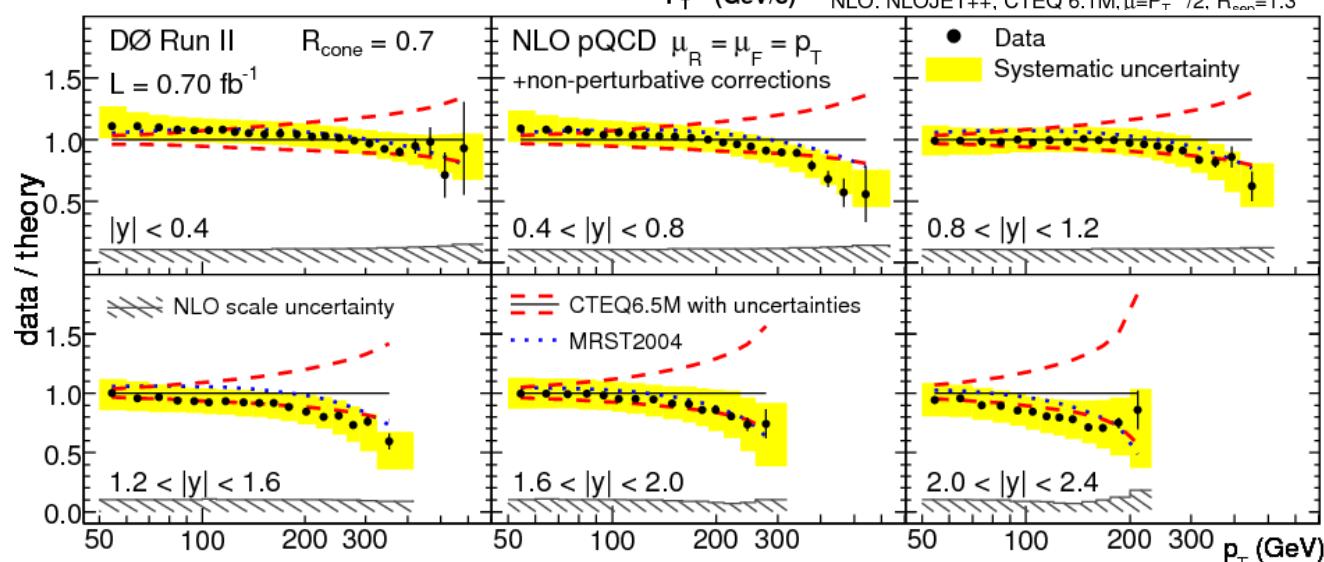
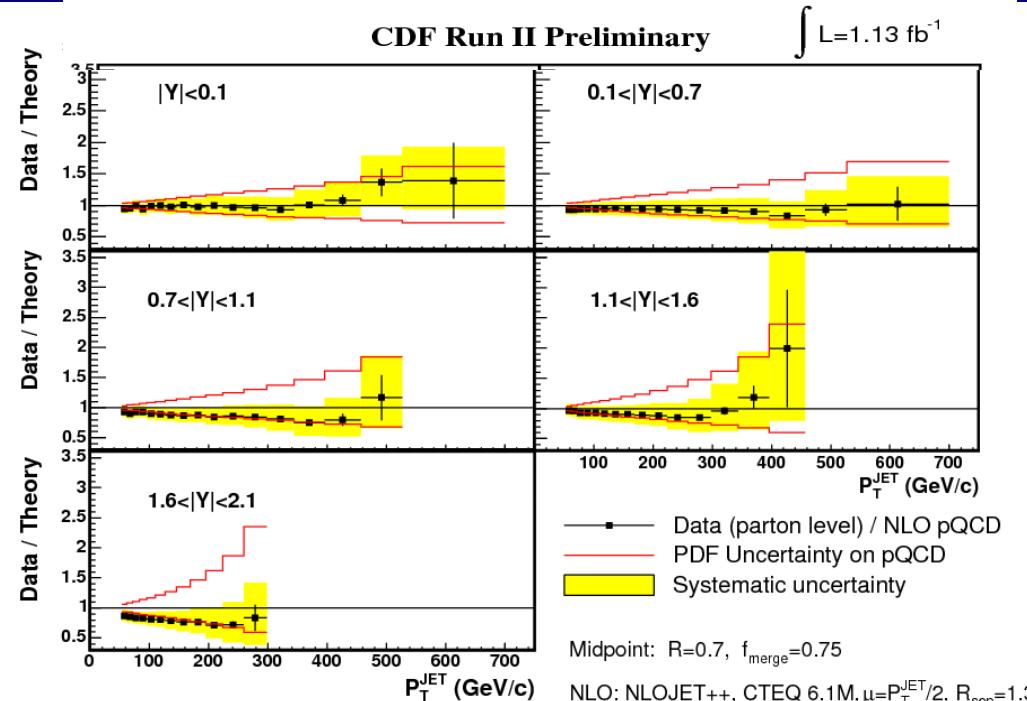
- The uncertainties have improved by up to factor two and more in the central region since preliminary JES (2006)
- Forward regions not published before, but improvement over factor ten





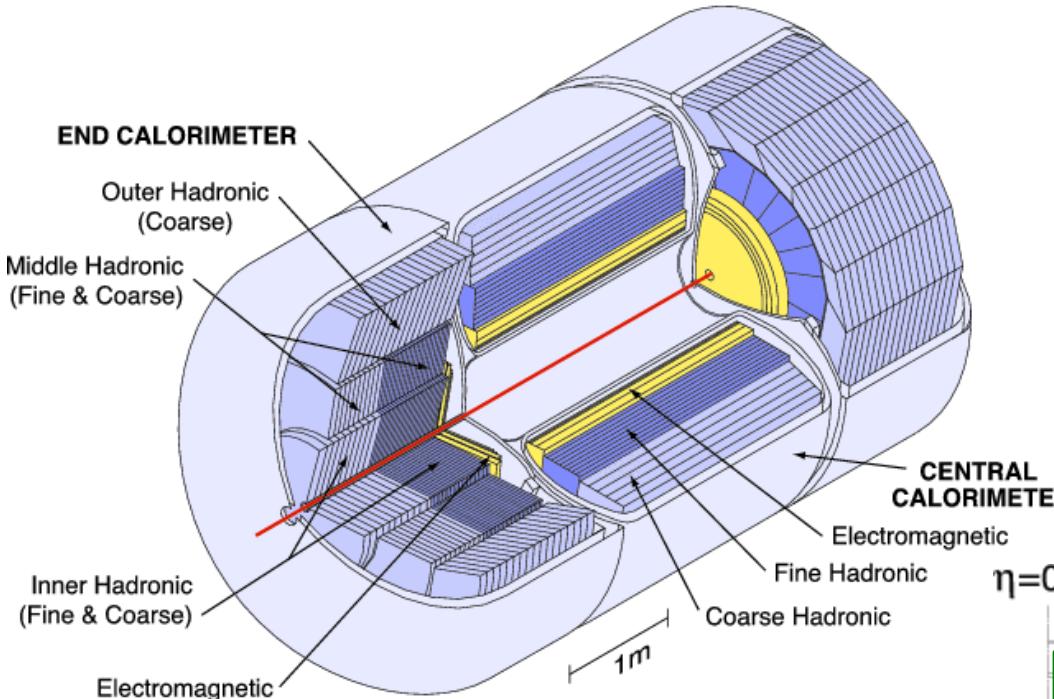
DØ and CDF comparison

- The DØ and CDF data are compatible within uncertainties
- Note that the CTEQ6.1 PDF band in the CDF plot is twice as wide as the CTEQ6.5 PDF band in the DØ plot
- Central values of the theory slightly different



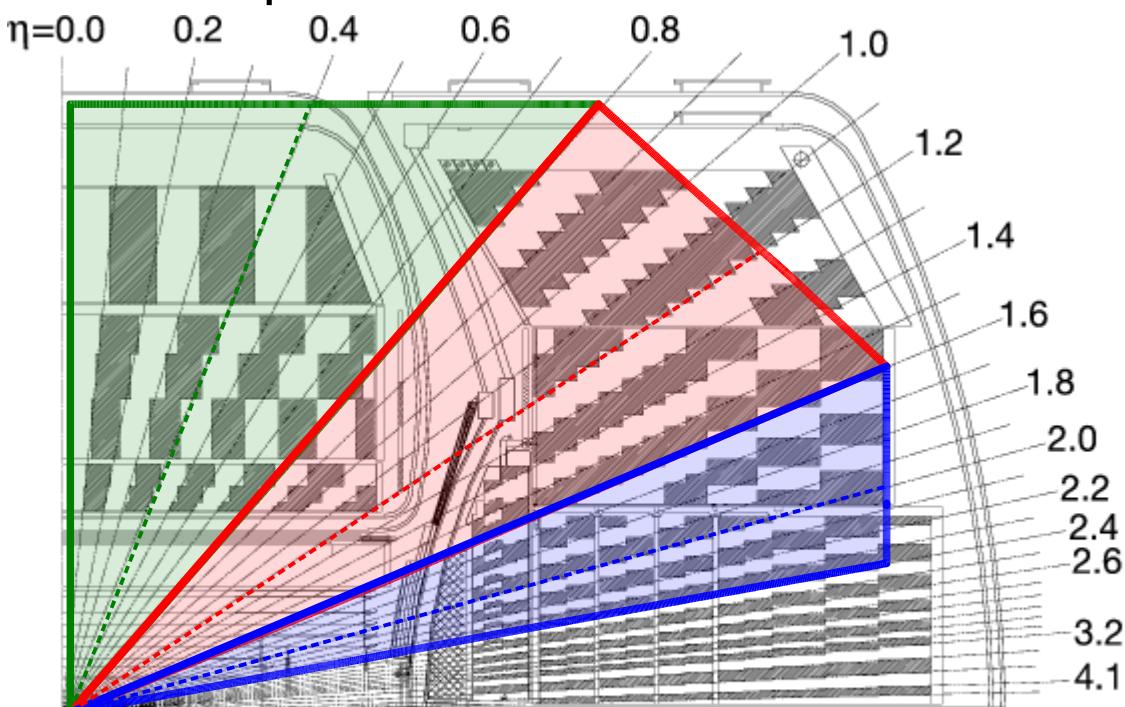


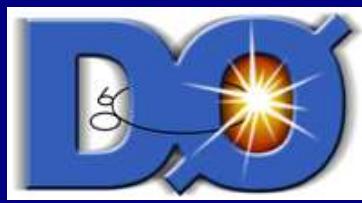
DØ calorimeter



- Calorimeter structure divides the measurement in three regions:
 - **Central calorimeter** (easiest)
 - **Intercryostat region** (challenging)
 - **End caps** (fine segmentation)

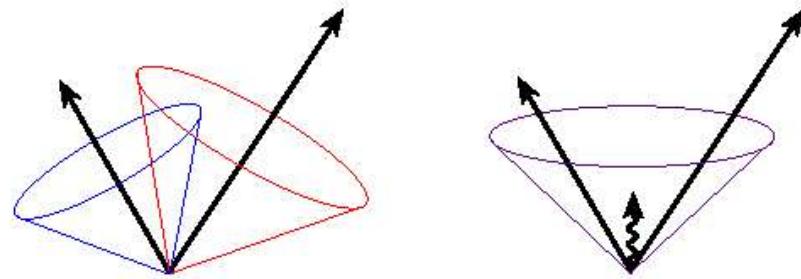
- Calorimeter is the most important detector for jet measurements
- Liquid-Argon/Uranium calorimeter:
 - Stable response, good resolution
 - Partially compensating ($e/\pi \sim 1$)
- Gaps covered with scintillator tiles





Jet algorithm

- Detailed comparison to theory needs a precise definition of jet algorithm
- This measurement uses Run II Midpoint Cone with $R_{\text{cone}} = 0.7$



Run I Legacy Cone:

Draw a cone of fixed size in $\eta-\phi$ space around a seed

Compute jet axis from E_T -weighted mean and jet E_T from $\sum E_T$'s

Draw a new cone around the new jet axis and recalculate axis and new E_T

Iterate until stable

Algorithm is sensitive to soft radiation

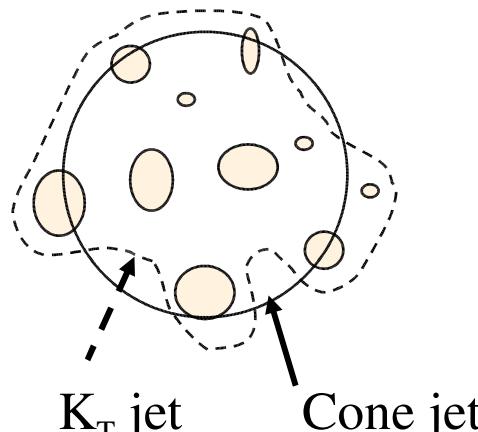
Run II Midpoint Cone:

Use 4-vectors instead of E_T

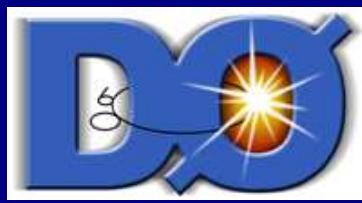
Add additional midpoint seeds between pairs of close jets

Split/merge after stable protojets found
Improved infrared safety at NLO

(DØ Run II/CDF MIDPOINT)



We characterize jets in terms of p_T and y



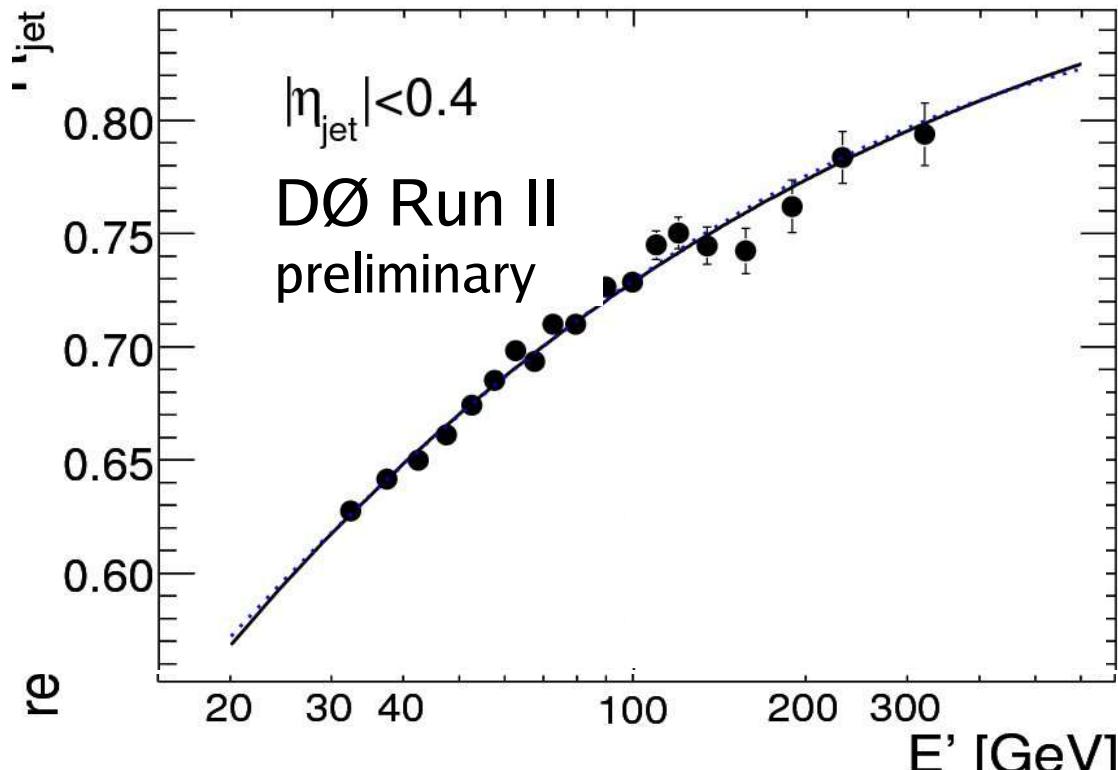
JES: Response

Response calibration performed in three steps:

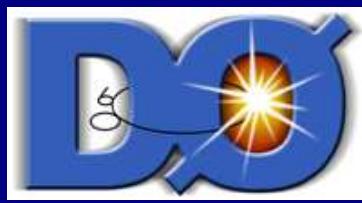
Photon energy scale is calibrated using $Z \rightarrow e^+e^-$ and tuned MC for e/γ energy scale difference

Response in CC is calibrated with $\gamma + \text{jet}$ events (R_{cc})

Equalization of calorimeter with dijet ($\gamma + \text{jet}$) events where one jet (photon) central (F_η)

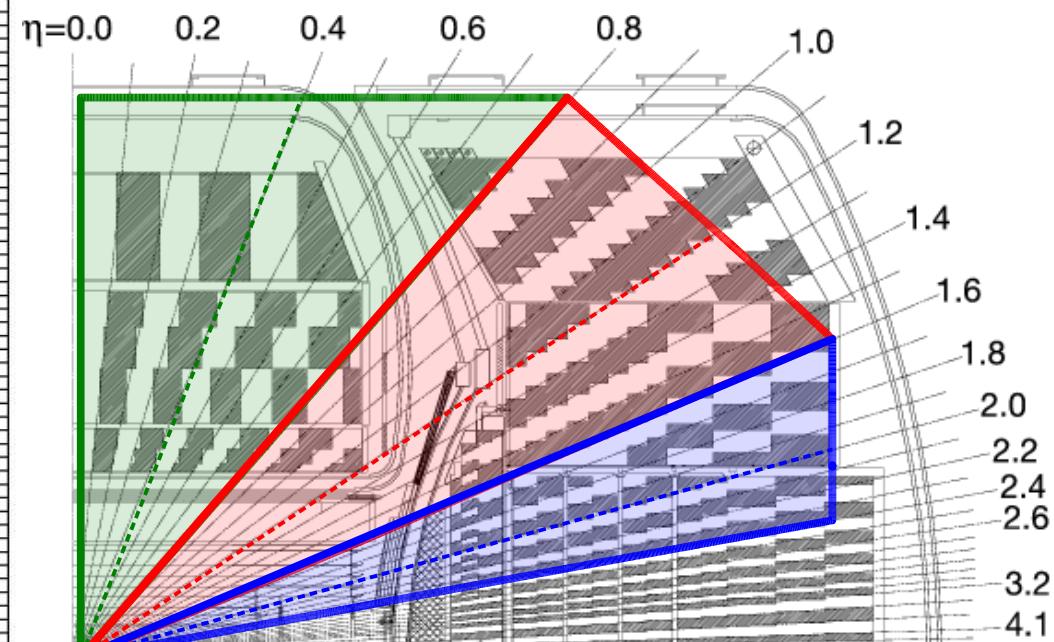
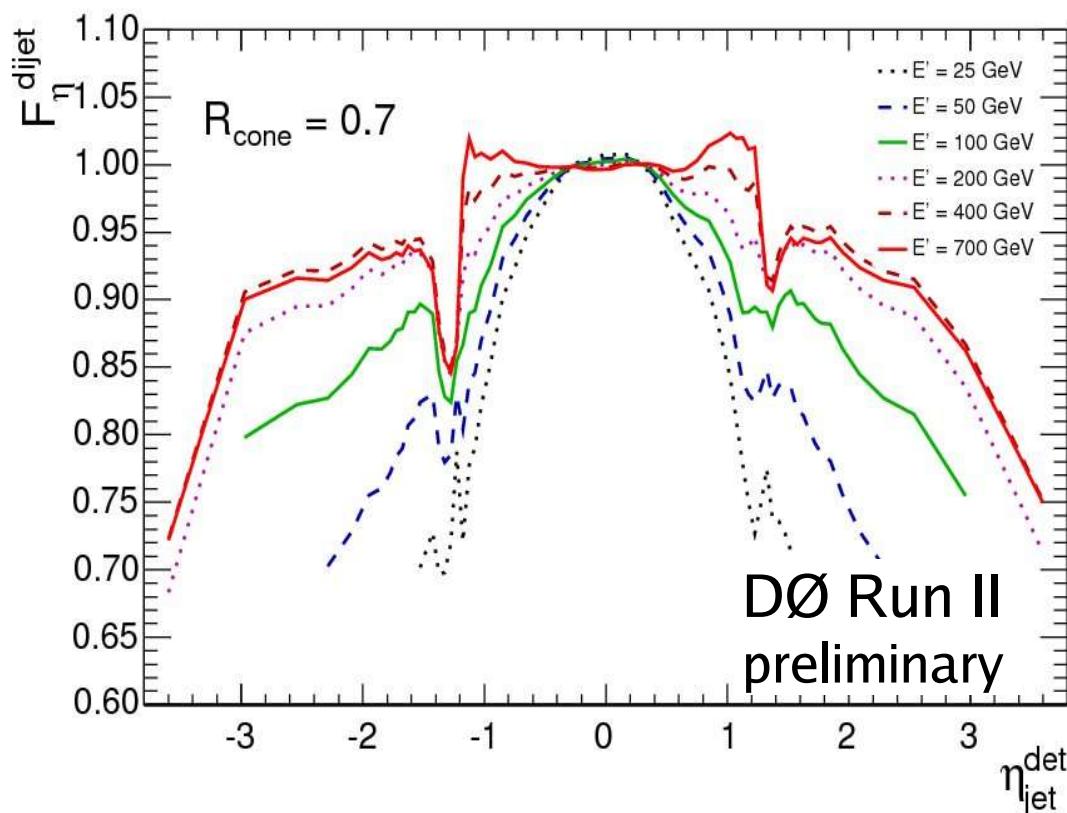


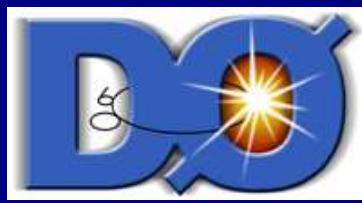
- Hadronic showers (pions) deposit less energy than electrons/photons $\Rightarrow R_{\text{jet}} < 1$
- At each “step” of showering, 1/3 of hadronic shower goes to $\pi^0 \rightarrow \gamma\gamma$ and continues to shower electromagnetically
- At higher energy more “steps” so $R_{\text{jet}} \rightarrow 1$ roughly as powerlaw $R = 1 - a p_T^{-m}$



JES: η -dependence

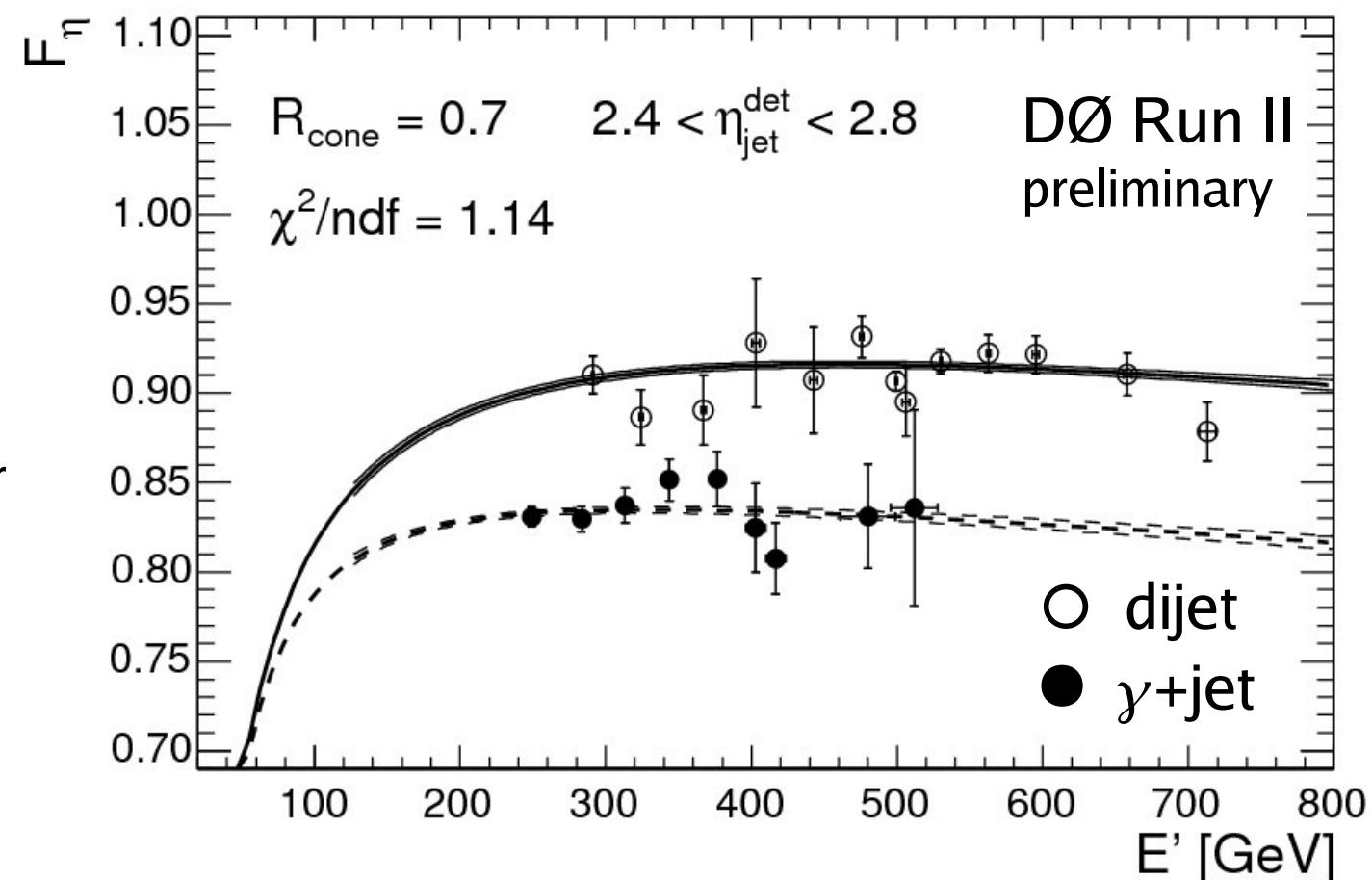
- Response depends on calorimeter region (**central**, **intercryostat**, **end cap**)
- Low residual energy dependence at high E
- Simultaneous fit to dijet and γ +jet samples taking into account sample differences

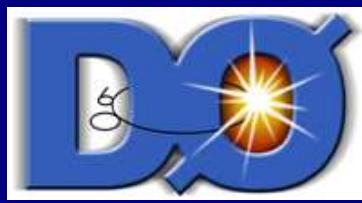




Eta-intercalibration

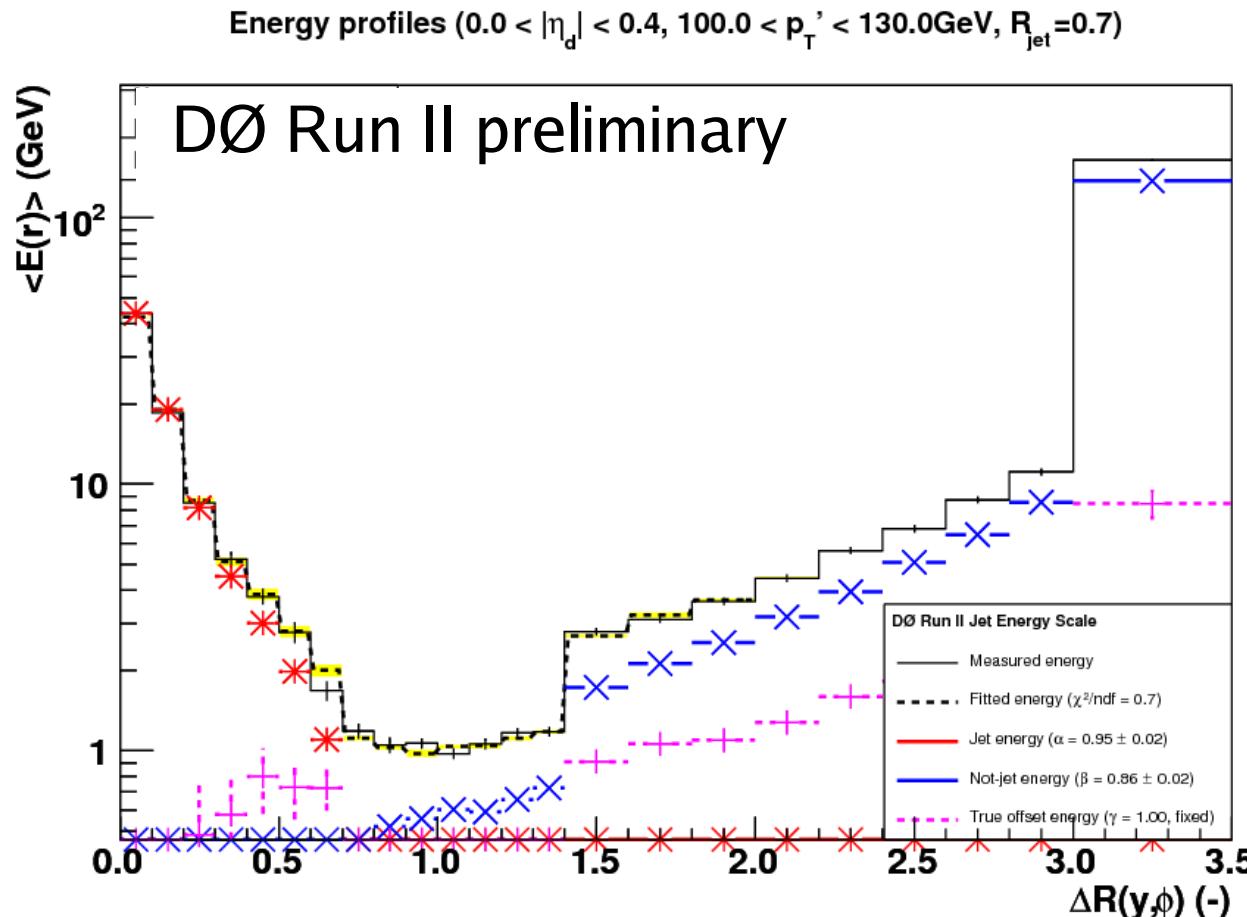
- Response η -dependence calibrated with respect to central jets and photons
- Dijets increase statistics at high p_T in the forward region compared to γ +jets
- Simultaneous fit to dijet and γ +jet samples taking into account sample differences
- Resolution bias for central jet in dijets explicitly corrected for and calibrated using central jet pairs





JES: Showering

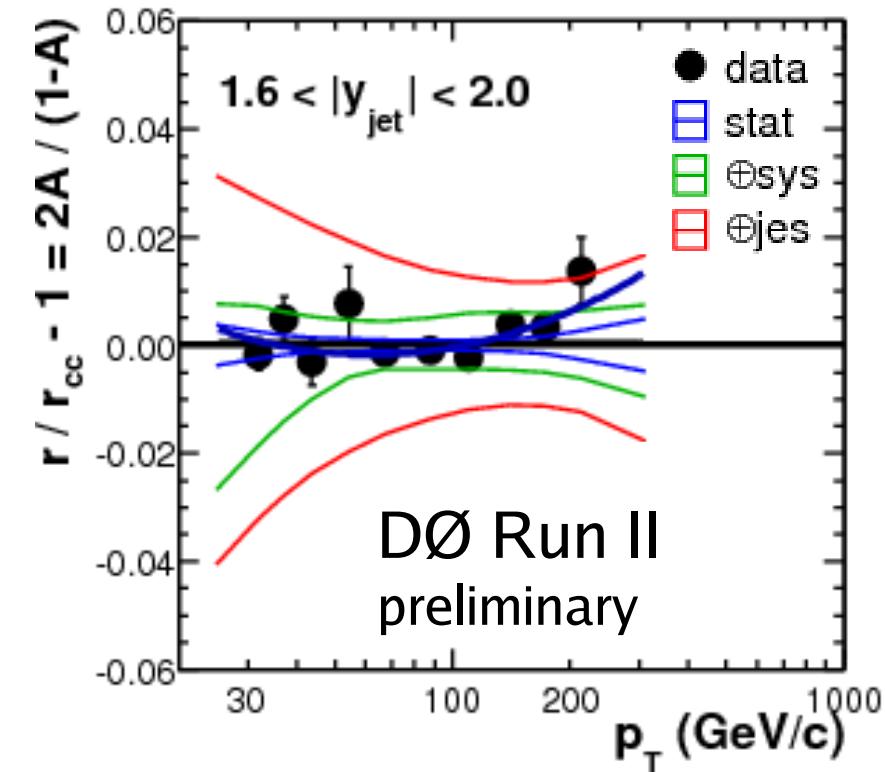
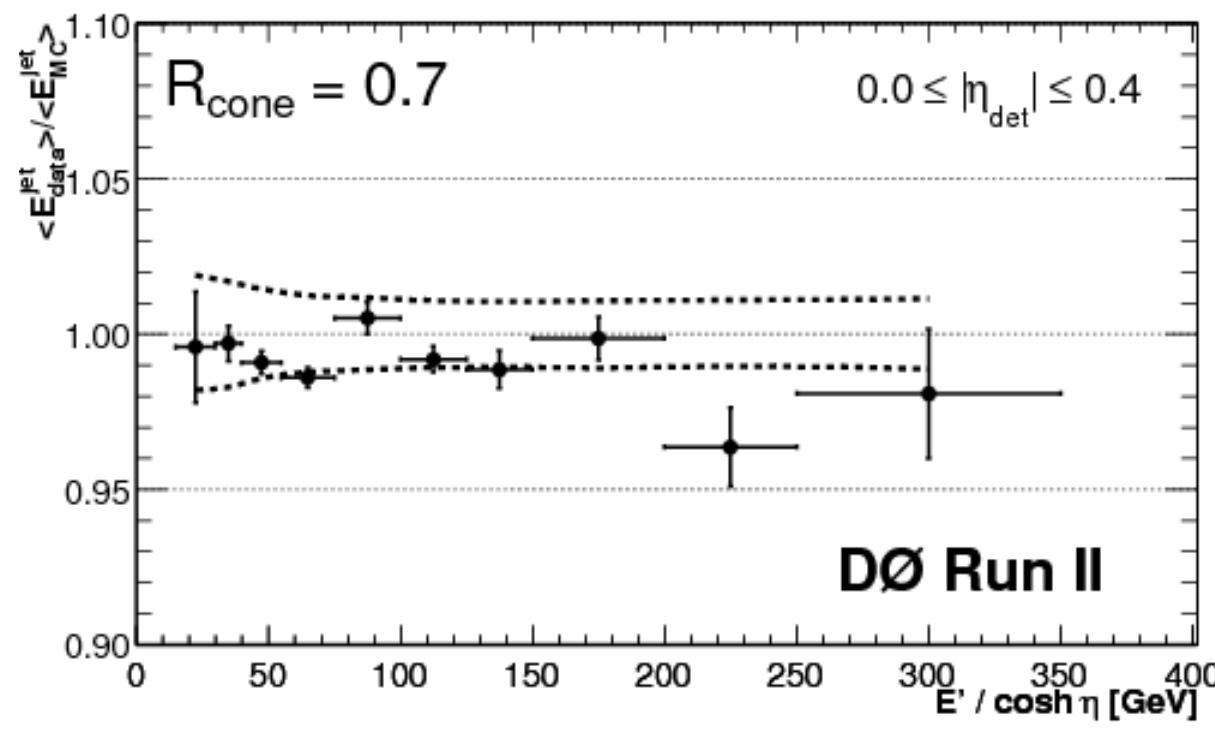
- Showering energy profiles fitted in γ +jet data
- Good agreement between tuned MC and data-based method
- Typical correction $\sim 1\%$ in CC, up to 5% in EC





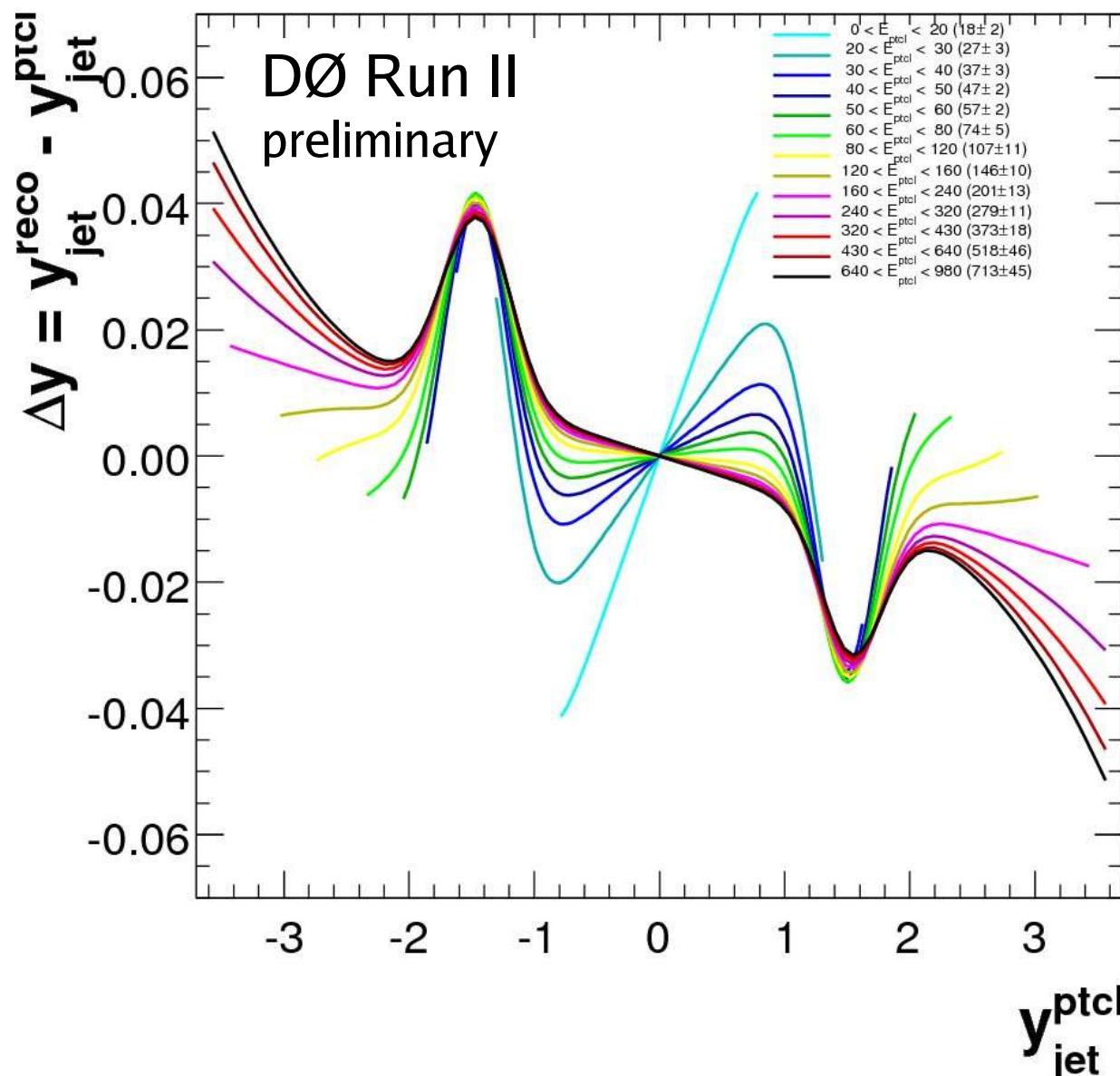
JES: Closure tests

- γ +jet closure tests consistency of JES corrections for absolute scale in CC
- Dijet closure tests the consistency of forward JES relative to CC
- Closure calculated from dijet asymmetry $A = (p_{T,fwd} - p_{T,cc}) / (p_{T,fwd} + p_{T,cc})$
- Explicit correction for residual resolution bias

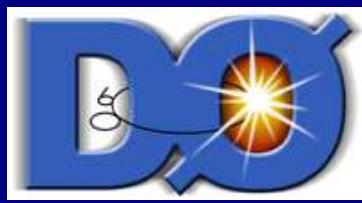




JES: Rapidity bias

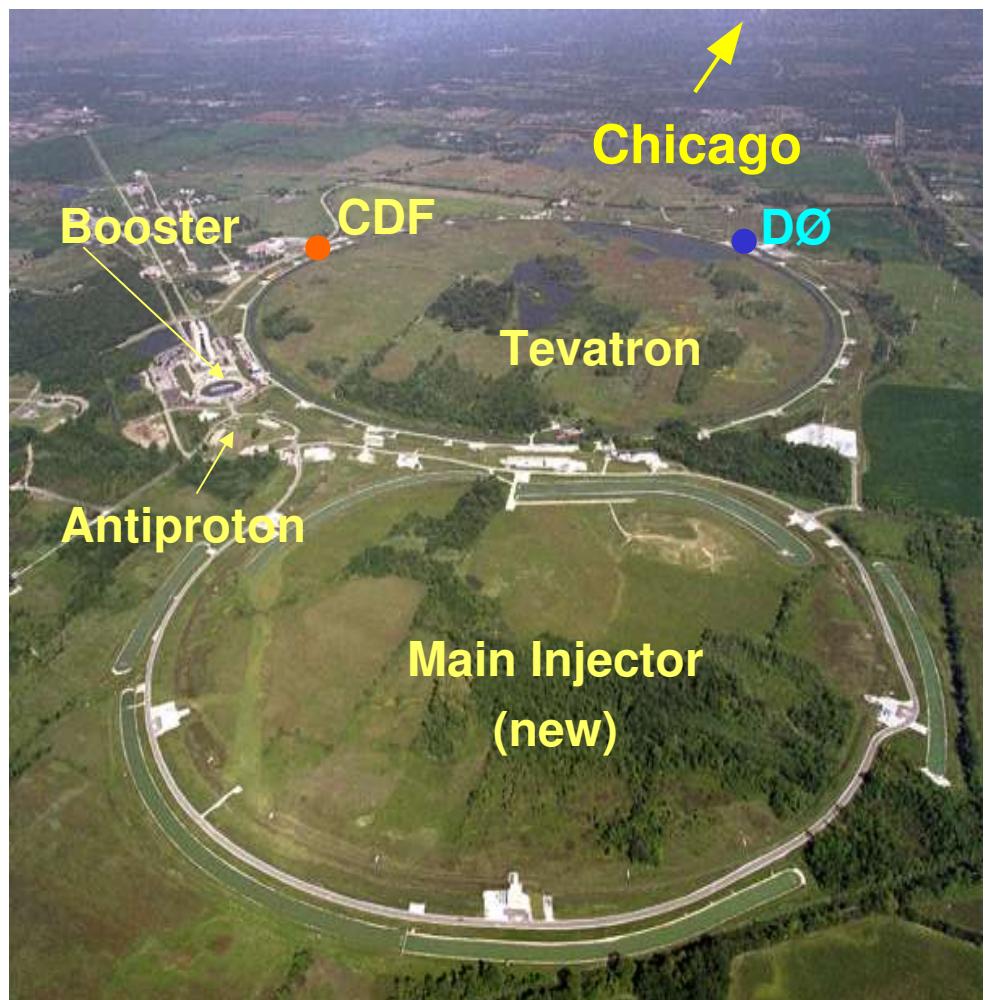
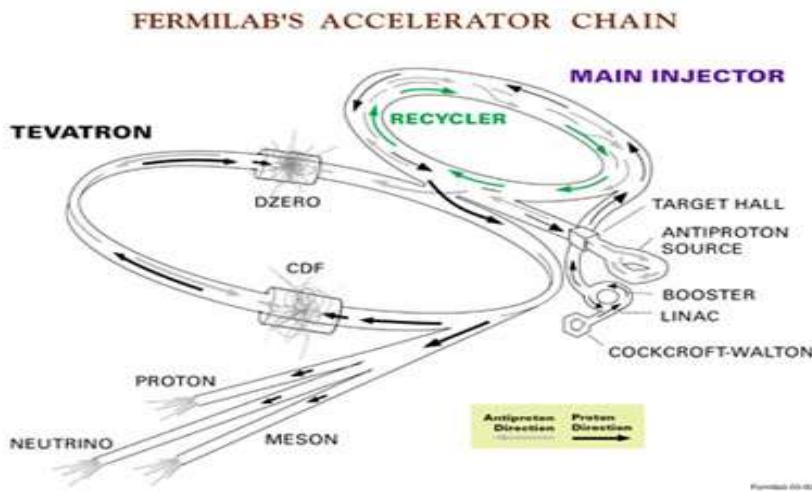


- Small detail: correction to p_T is much more important
- Jets are biased in rapidity on average toward the center of the calorimeter
- At most (in ICR), bias little less than half a cell width

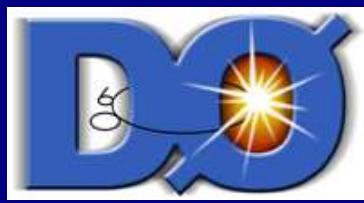


Fermilab Tevatron Collider

- Proton-antiproton collisions at a center-of-mass energy of 1.96 TeV at the world's premier (still) hadron collider, the Fermilab Tevatron Collider
- Fermilab is located in Batavia, Illinois, about 50 km west of Chicago



- Tevatron ring is around 6 km (2π) in circumference
- Two big detectors, CDF and DØ



DØ experiment

- Three main systems:
 - Tracker (silicon and scintillating fibre)
 - Calorimeter (IAr/U, some scintillator)
 - Muon chambers and scintillators
- First two used in this measurement

