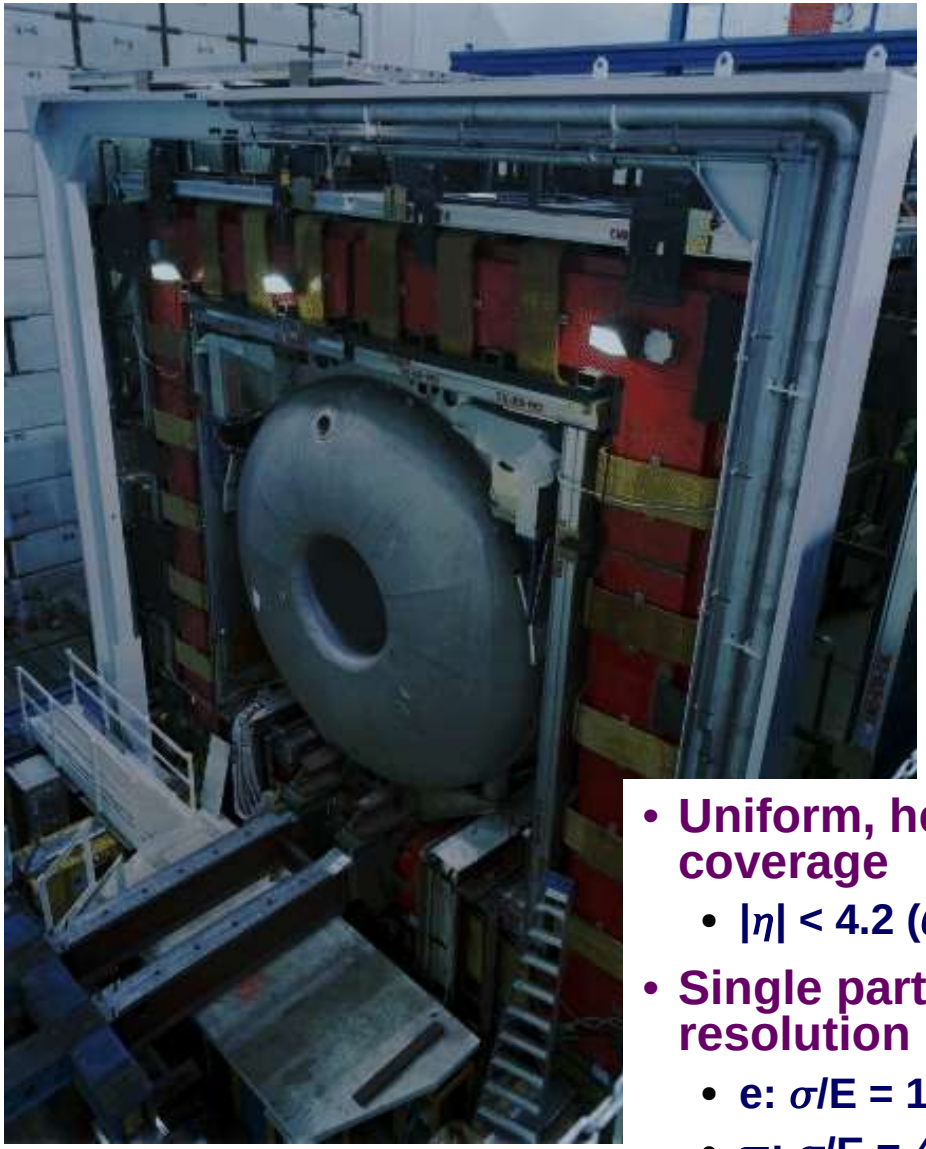
Inclusive jet cross section measurement at DØ

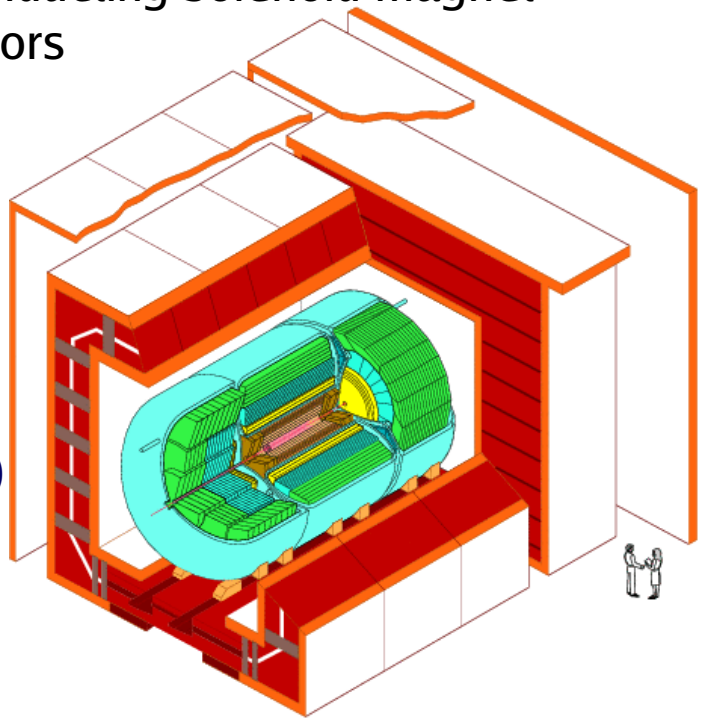
Mikko Voutilainen
University of Nebraska-Lincoln
Helsinki Institute of Physics

The DØ experiment



- The DØ experiment is based at Fermilab, complementary to the CDF experiment
- Large general purpose detector with
  - Liquid argon-uranium calorimeter (electromagnetic and hadronic)
  - Silicon microstrip and scintillating fiber trackers
  - 2 T superconducting solenoid magnet
  - Muon detectors

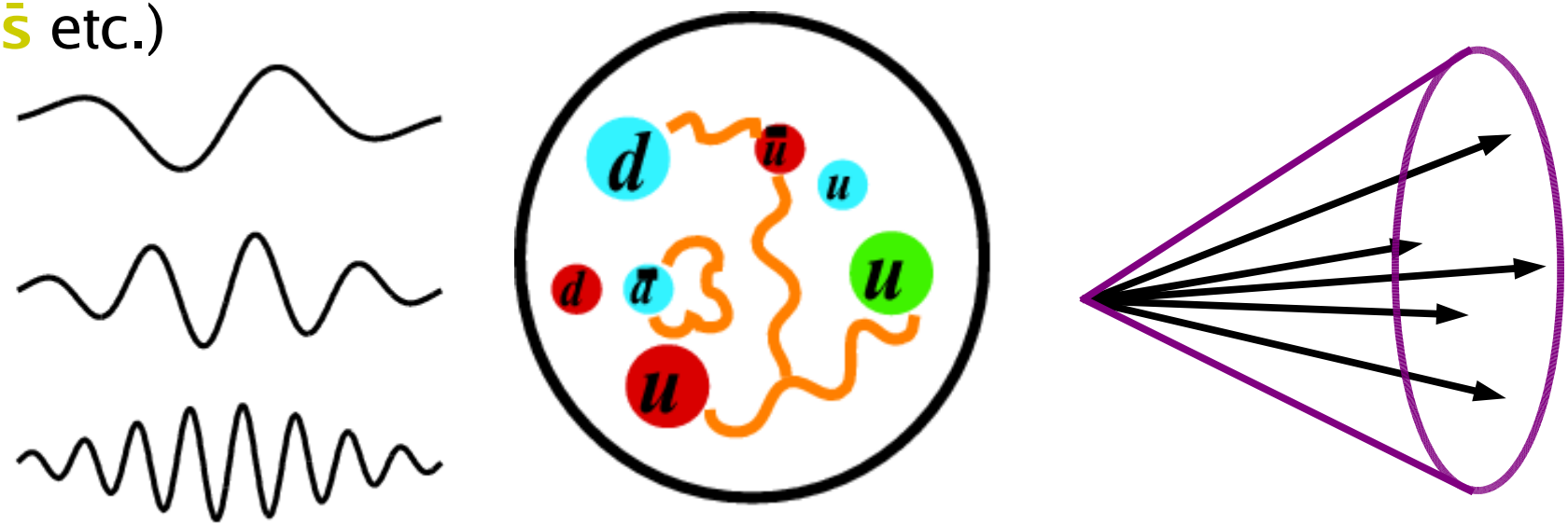
- **Uniform, hermetic with full coverage**
  - **$|\eta| < 4.2$ ($\theta \approx 2^o$), $\lambda_{int} \sim 7.2$ (total)**
- **Single particle energy resolution**
  - **e: $\sigma/E = 15\% / \sqrt{E} \oplus 0.3\%$**
  - **π: $\sigma/E = 45\% / \sqrt{E} \oplus 4\%$**



DØ Detector

Proton structure

- Proton consist of three valence quarks, up-up-down (**uud**) and antiproton of three antiquarks (**ūūđ**) bound together by a sea of gluons (**g**) and virtual quark-antiquark pairs (**uū**, **dđ**, **s$\bar{s}$** etc.)

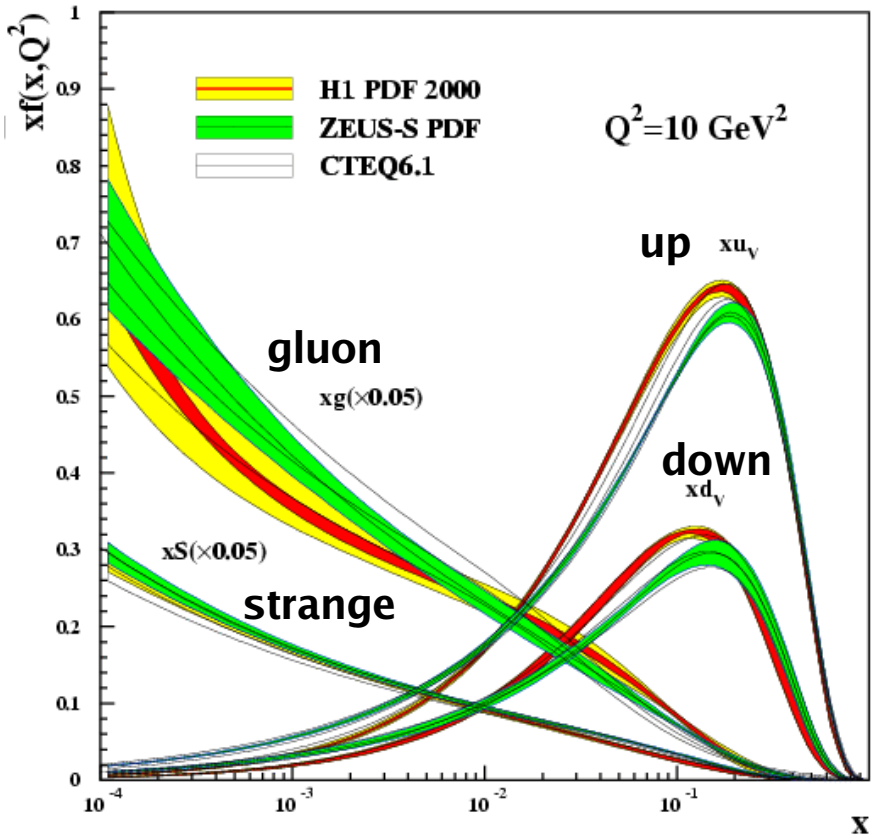


- Higher energies resolve finer detail, and Tevatron's energies are currently the highest available
- Different final states give access to different aspects; inclusive jets look at the big picture

Proton structure

- What can we learn by measuring jets?
  - Distribution of constituents in protons and antiprotons; These constituents are called partons, and their distributions are called parton distribution functions (PDFs)
  - The nature of the basic interaction between quarks and gluons
  - New physics like quark substructure?

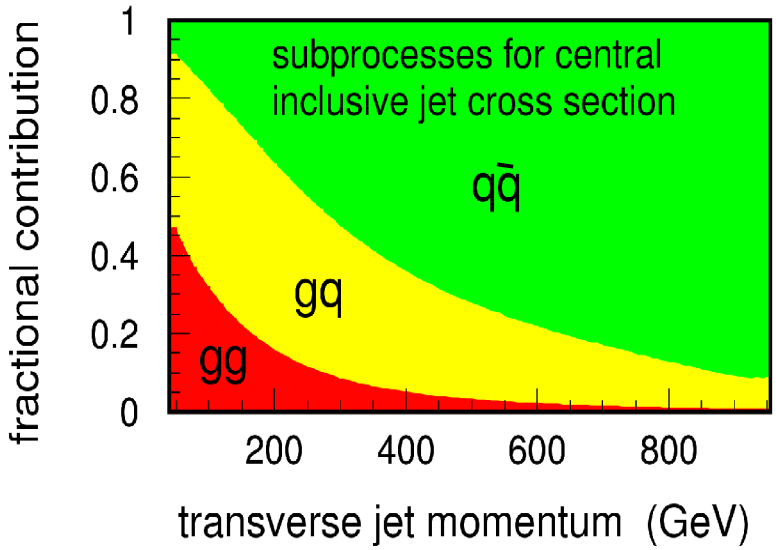
Proton parton distribution functions

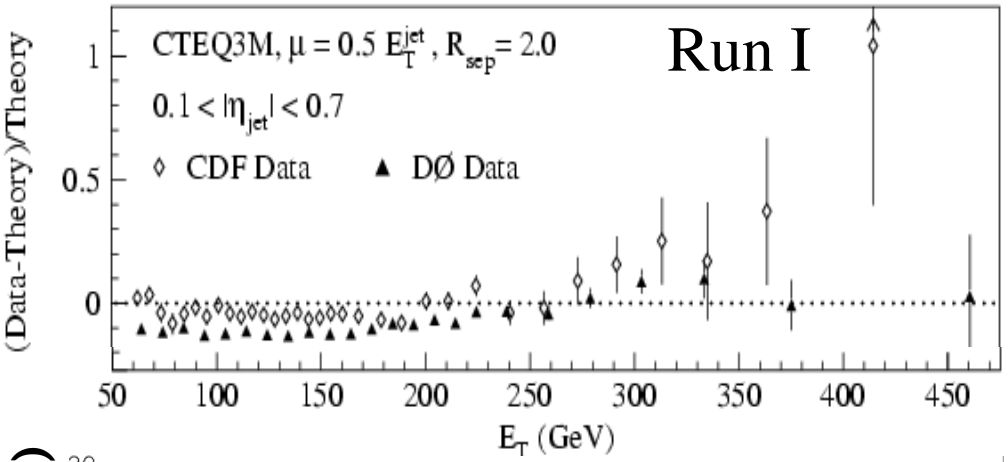


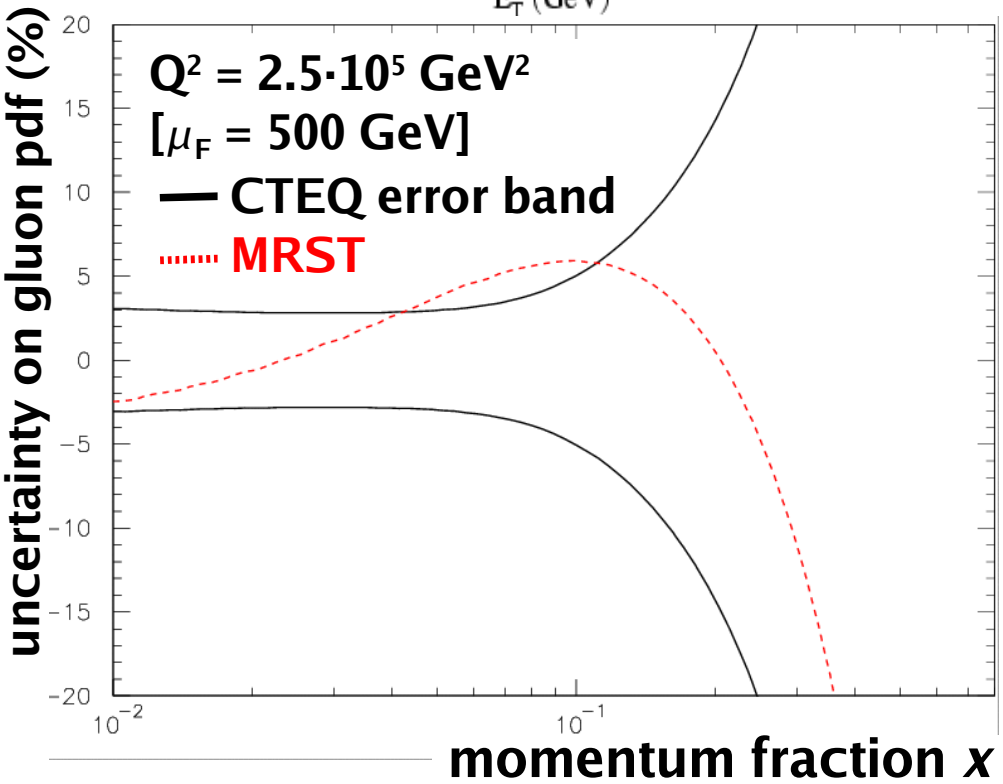
x: momentum fraction carried by individual parton
f(x,Q²): probability of finding parton with momentum fraction x in interval dx

Motivation for the measurement

- This remains an interesting topic and calls for an improved measurement in Run II
- Current integrated luminosity of 1 fb^{-1} already ten times that of Run I (~100 pb^{-1}), and 4-8 fb^{-1}expected until end of Run II
- The increased center-of-mass energy of 1960 GeV compared to 1800 GeV in Run I gives another factor of 3 at 600 GeV
- Constraining gluon PDFs within reach

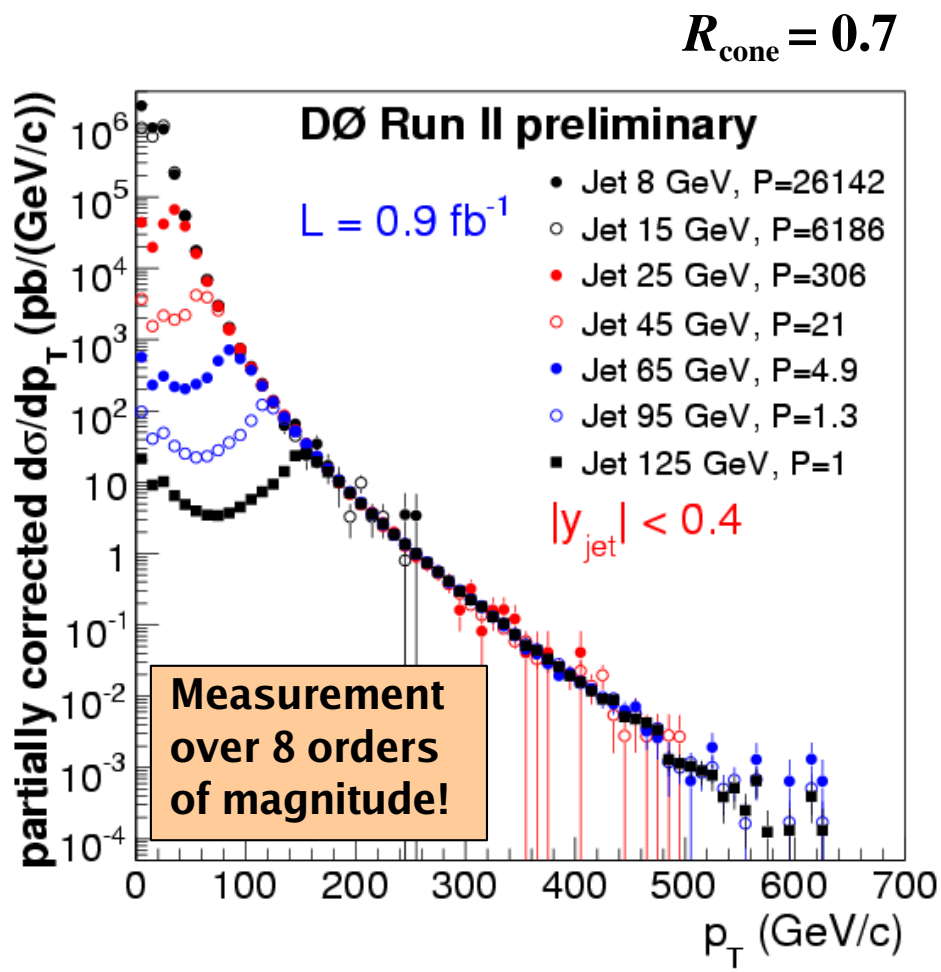






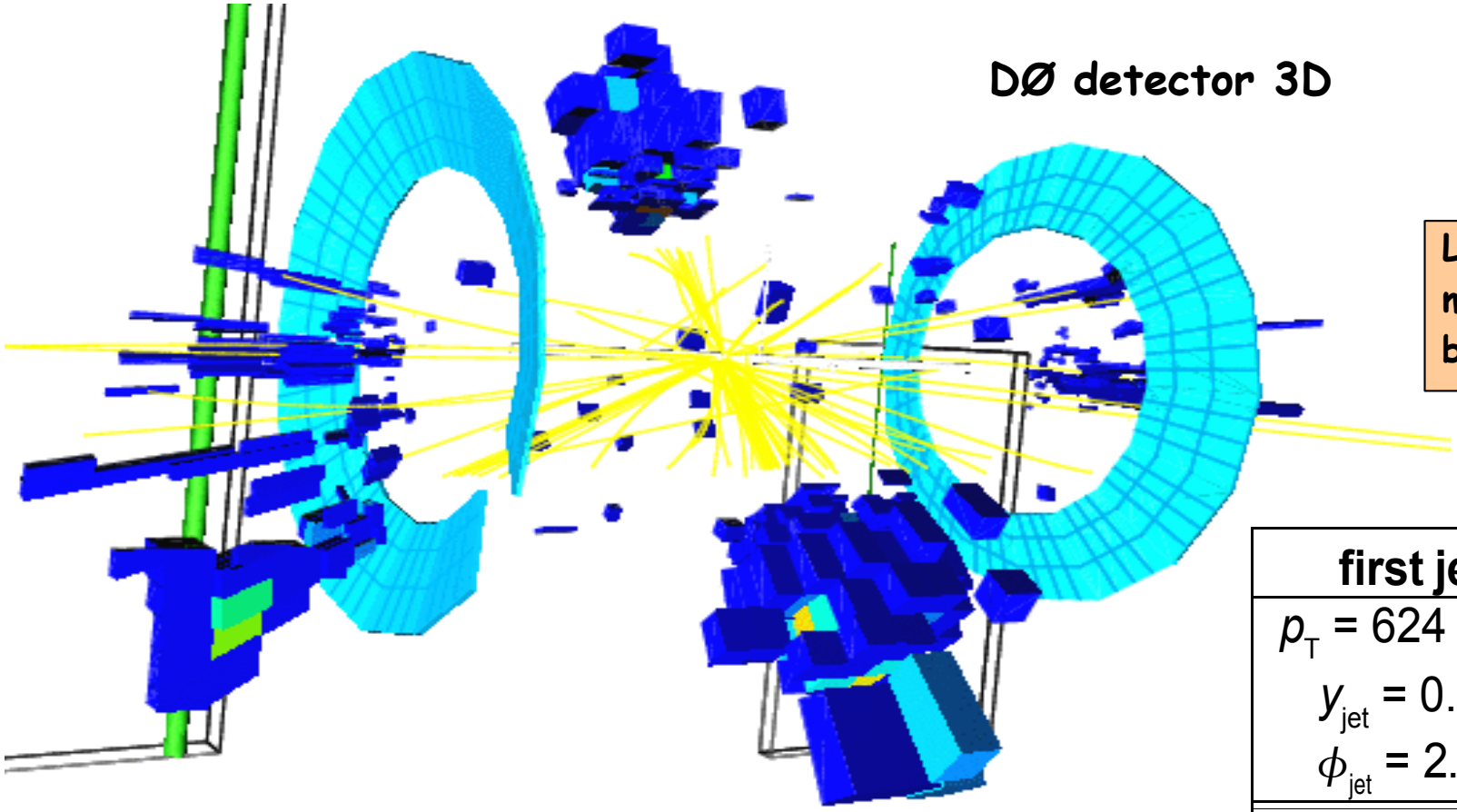
What is so great about this

- The inclusive jet cross section measurement spans an impressive eight orders of magnitude
- ...and reaches the highest energies ever created in the lab
- The full measurement is a collage of seven different triggers
- Pure data measurement, no theoretical models involved
- Open to new physics at high energy



Highest p_T jet

- 3D view of the event that contains the jet with the highest transverse momentum in the sample
- Jets are reconstructed offline with an iterative cone algorithm (R=0.7)



Leading jet has 64% of momentum available in beam proton

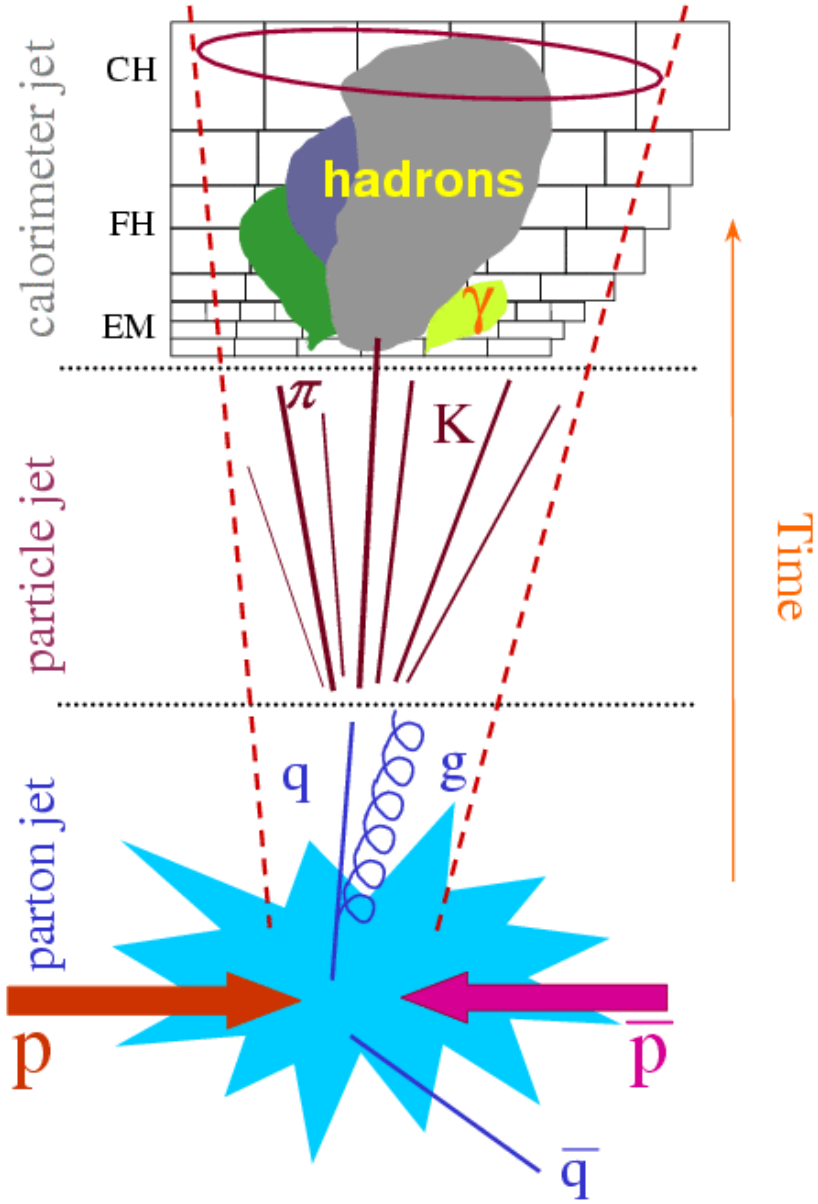
first jet	second jet
p_T = 624 GeV y_{jet} = 0.14 ϕ_{jet} = 2.10	p_T = 594 GeV y_{jet} = -0.17 ϕ_{jet} = 5.27
M_{jj} = 1.22 TeV	

Jet Energy Scale
the difficult part

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

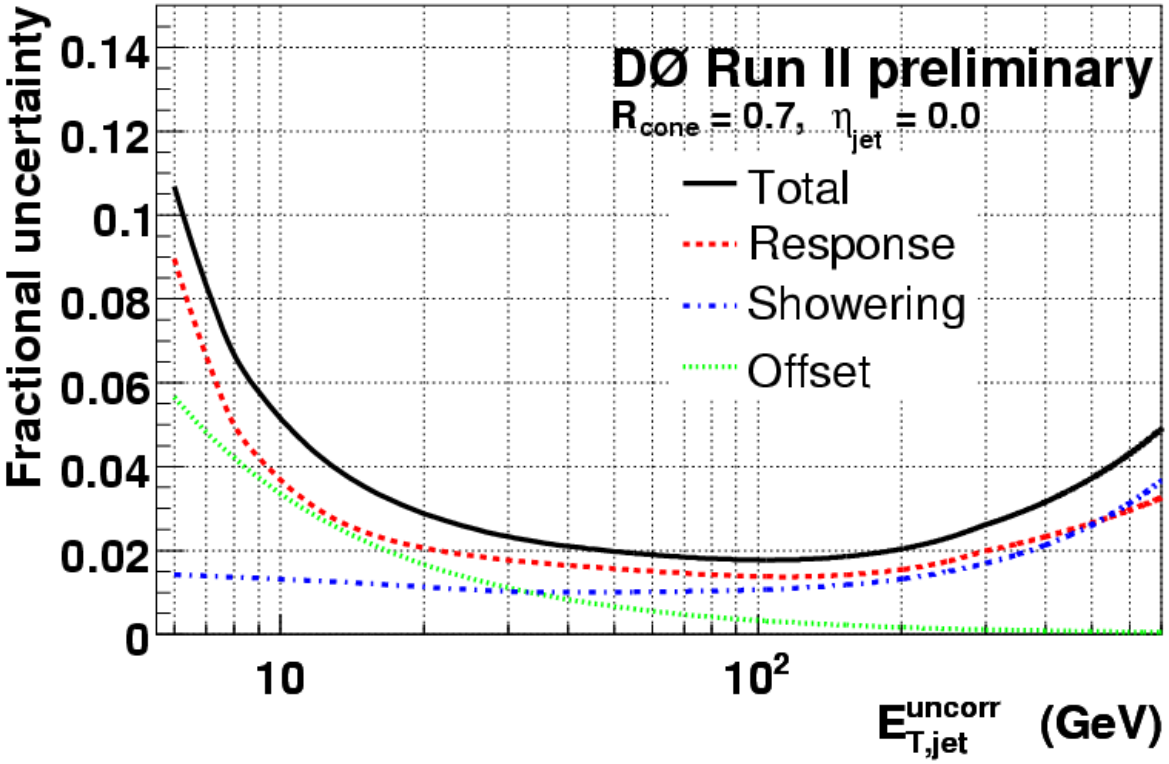
$$E_{ptcl} = \frac{E_{cal} - Offset}{R \cdot S}$$

- Offset from energy density in zero bias and minimum bias events (noise + pile-up + multiple interactions)
- EM energy scale is calibrated using $Z \rightarrow e^+e^-$ events
- Jet energy scale is set using γ+jets events
- JES η-dependence is derived combining γ+jets and dijet events for higher statistics and greater reach in energy
- Showering measured from energy density around jet, subtracting physics out-of-cone



Jet Energy Scale
the difficult part

- Current Jet Energy Scale derived for a subsample (~15%) of the full dataset
- JES improved by a factor of two at medium p_T compared to early Run II
- Further improvements with new methods and full statistics coming soon in final Run IIa jet energy scale *(to be described in Nucl. Inst. Methods)*



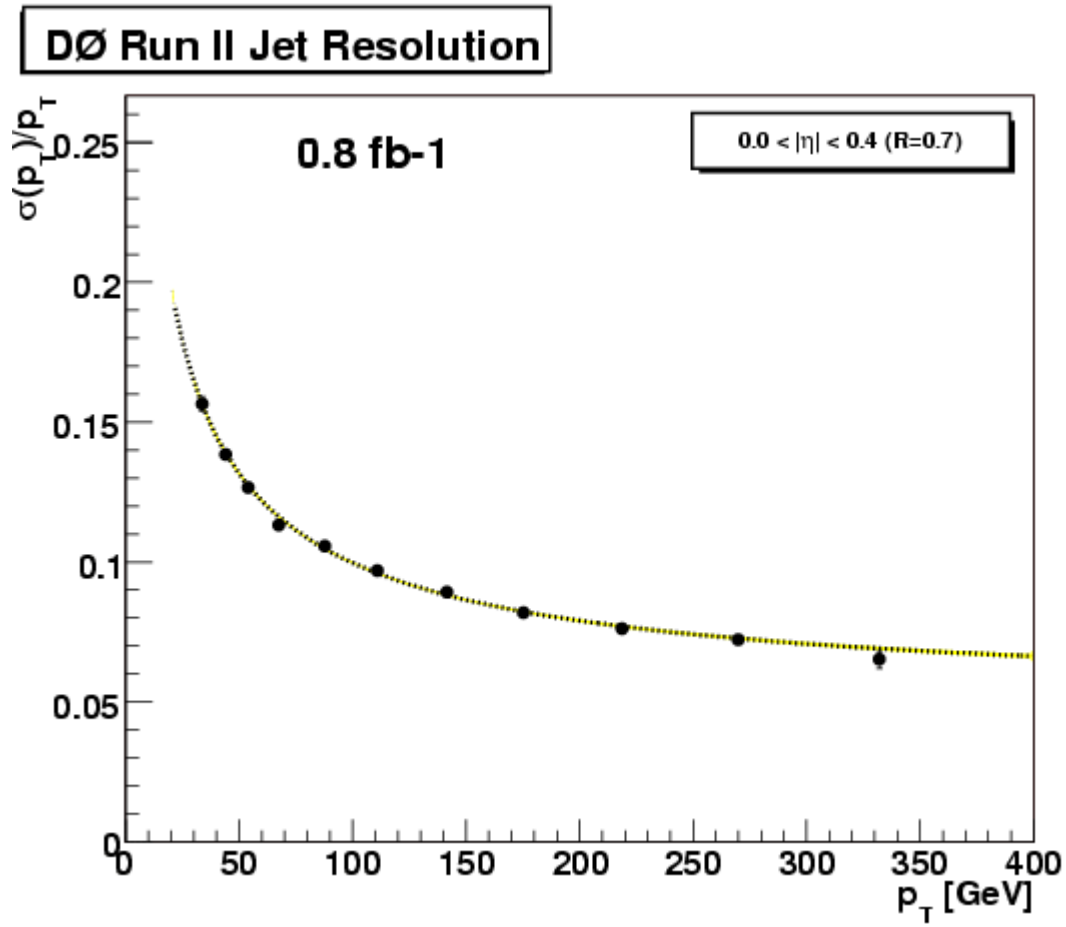
Jet p_T resolution
a little easier part

- Jet p_T resolution was measured directly on data using dijets
- Basic variable dijet asymmetry *A*, which is corrected for soft radiation (third jet below reconstruction threshold) and particle level imbalance

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

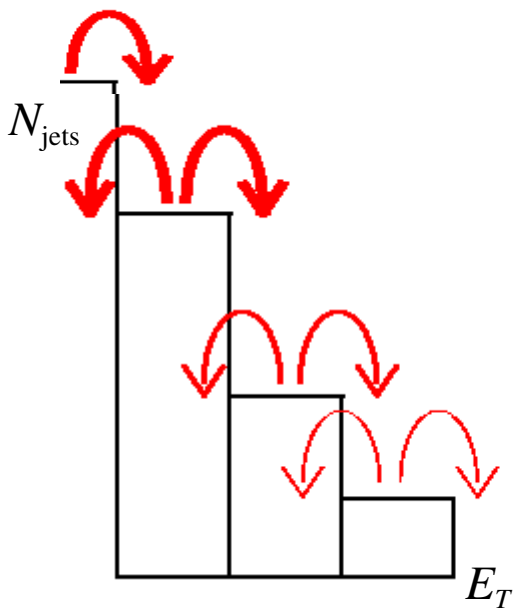
$$\frac{\sigma_{p_T}}{p_T} = \sqrt{2}\,A$$

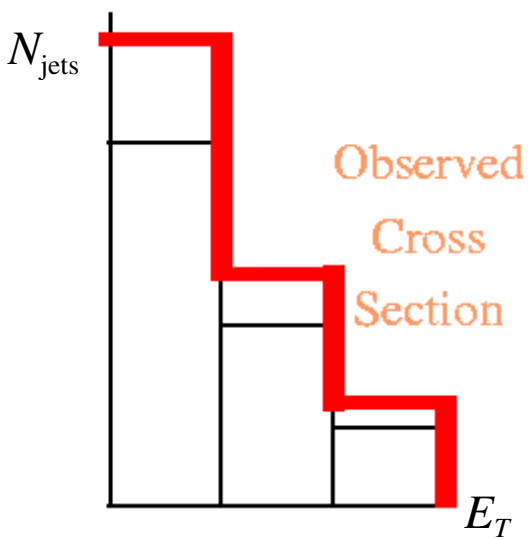
- Recent hadronic layer calibration improved resolution



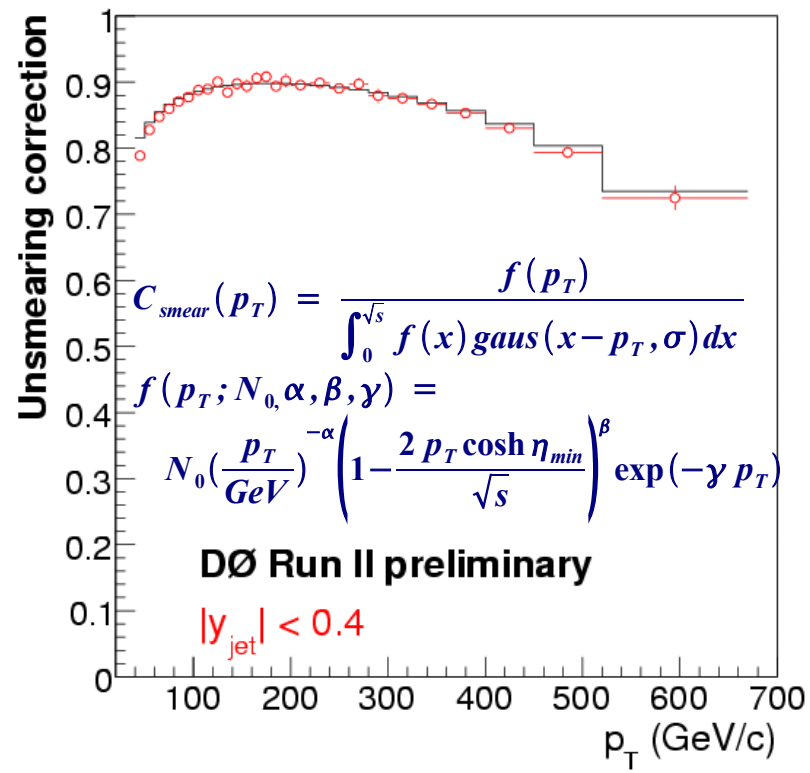
Unsmearing correction

- Cross section ansatz with four free parameters is smeared with Gaussian resolutions from data and the resulting smeared ansatz is fit to data
- Ratios of the original to the smeared ansatz functions are used to correct the data
- Result was checked using weighted and smeared Pythia Monte Carlo



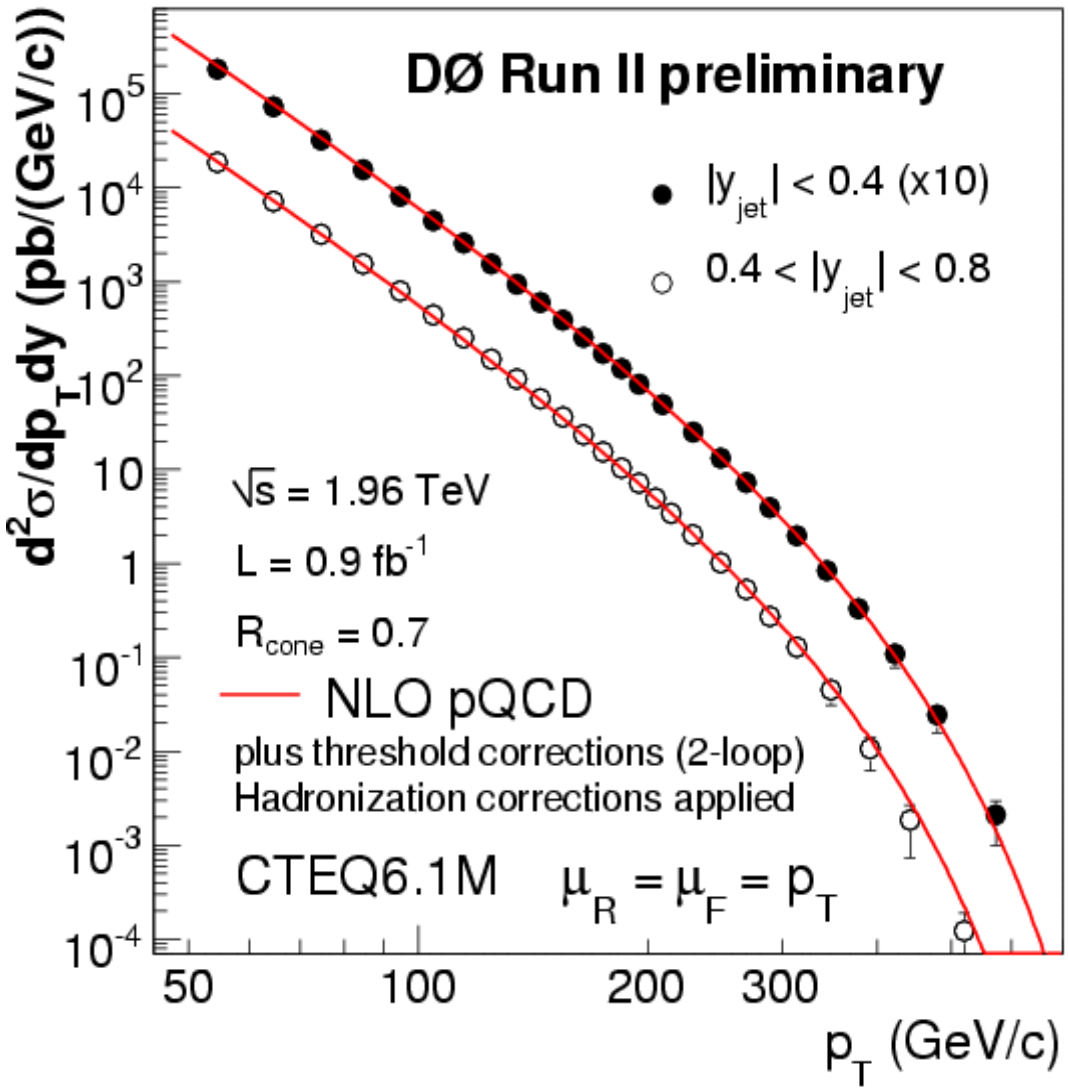


John Krane



Results

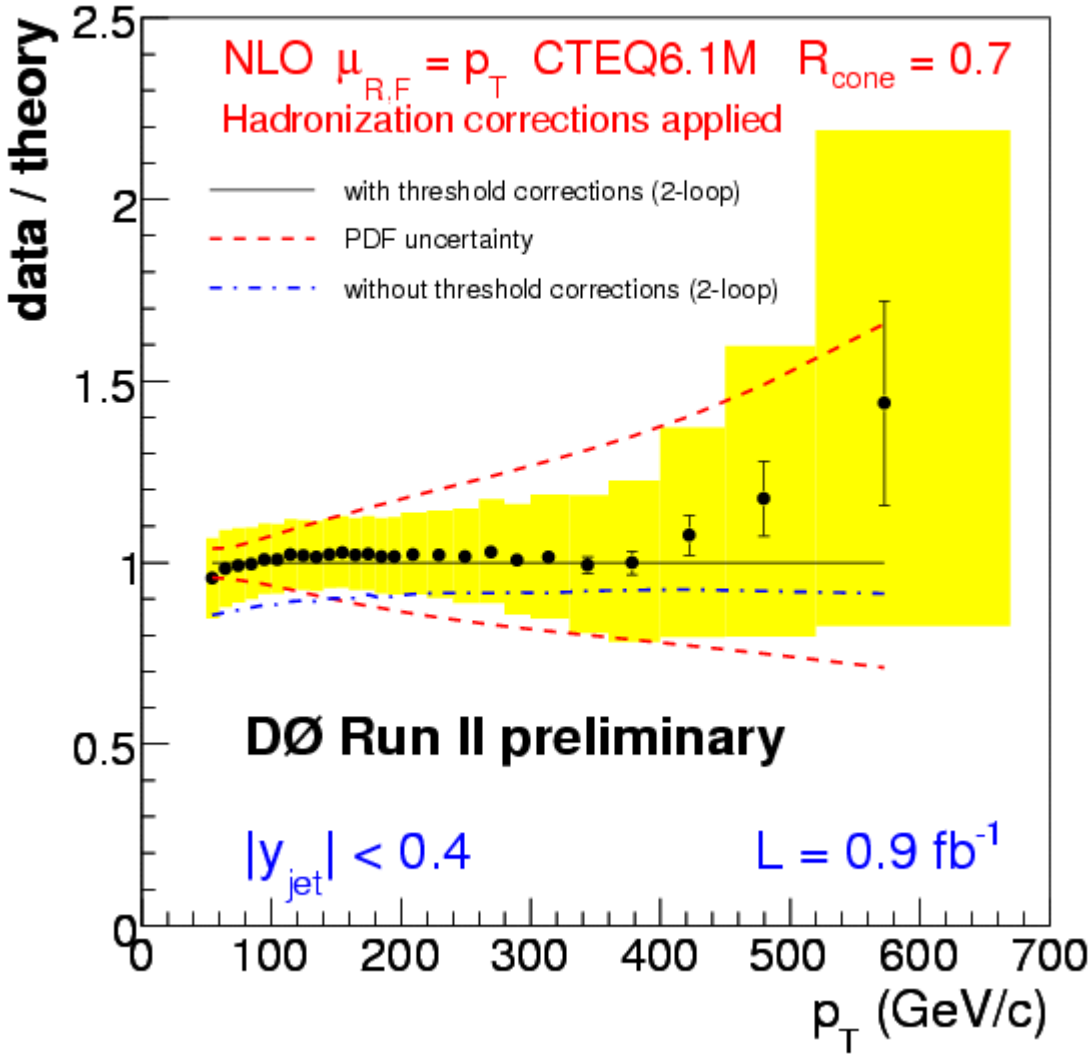
- Data compared to next-to-leading order (NLO) theory with threshold corrections and CTEQ6.1M PDF set*
- Good agreement with theory over a wide p_T range



** NLO predictions computed using fastNLO based on NLOJet++ (Z. Nagy, Phys. Rev. Lett. 88, 122003, 2002) with the CTEQ6.1M parametrisation, and the NLO threshold corrections computed using threshold resummation techniques (Kidonakis, Owens, Phys. Rev. D63, 054019, 2001)*

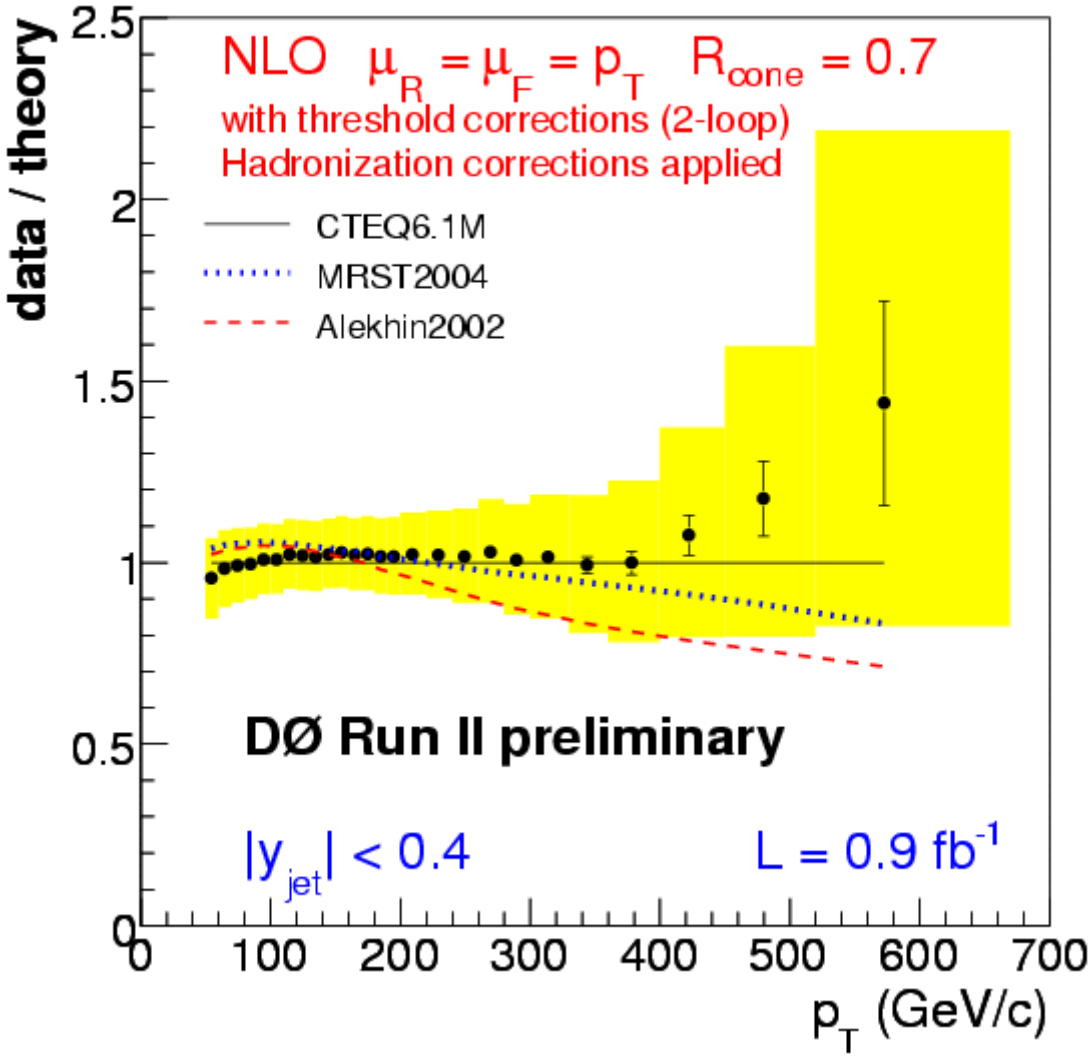
Sensitivity to gluon PDFs

- The red band corresponds to the envelope of up and down variations of the 20 parameters in the CTEQ6.1M PDF fit
- Blue line shows the next-to-leading order (NLO) cross section calculation without threshold corrections
- Measurement sensitive to gluon PDFs



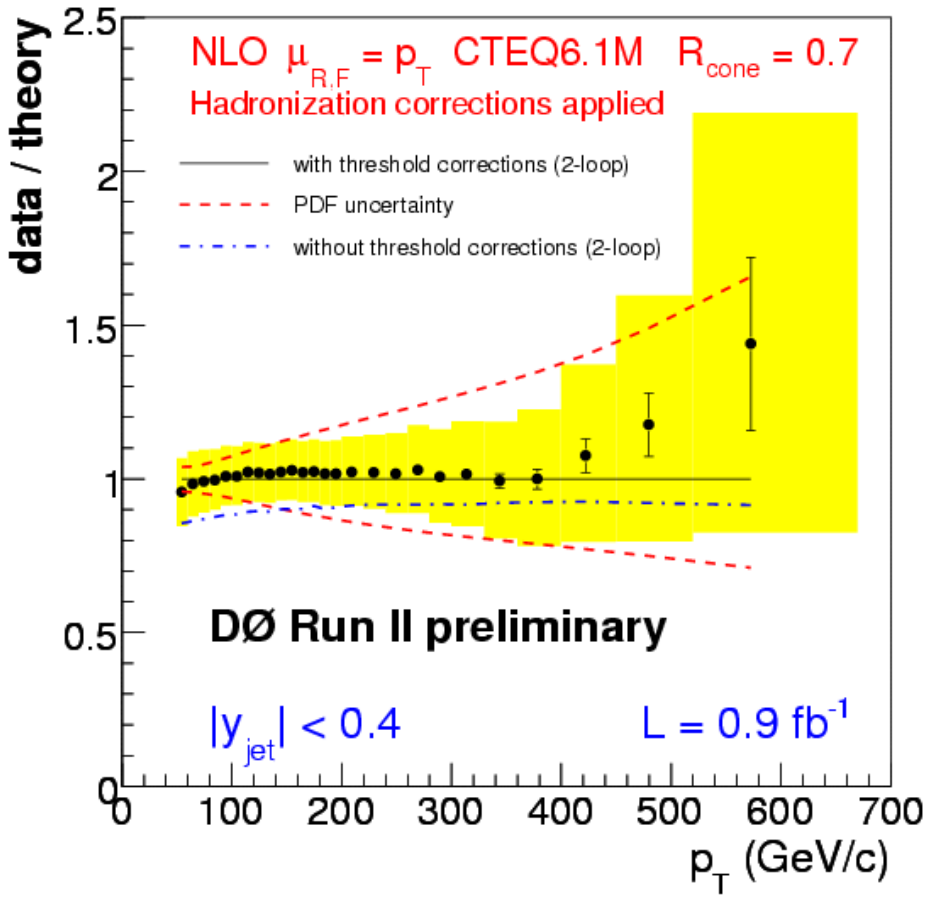
Sensitivity to PDF sets

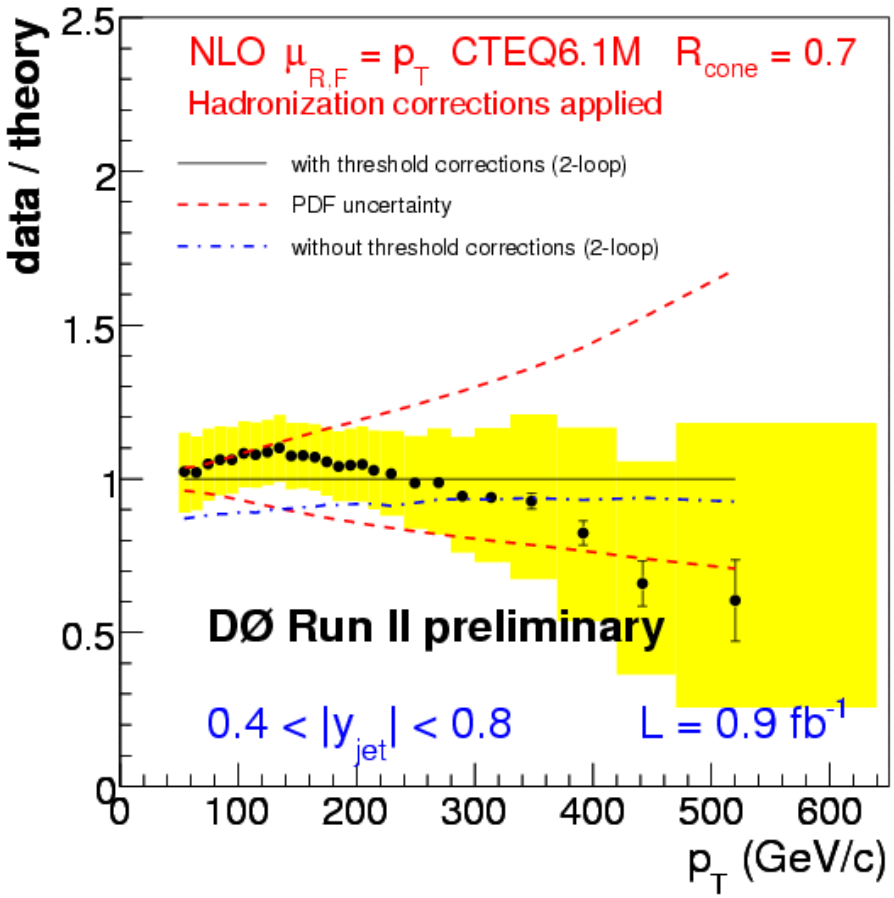
- Different PDF parametrizations are available for NLO calculations: CTEQ, MRST, Alekhin
- Different sets fairly consistent
- To discriminate between PDF sets, p_T and rapidity uncertainty correlations are needed. These will be available for the final jet energy scale



Results

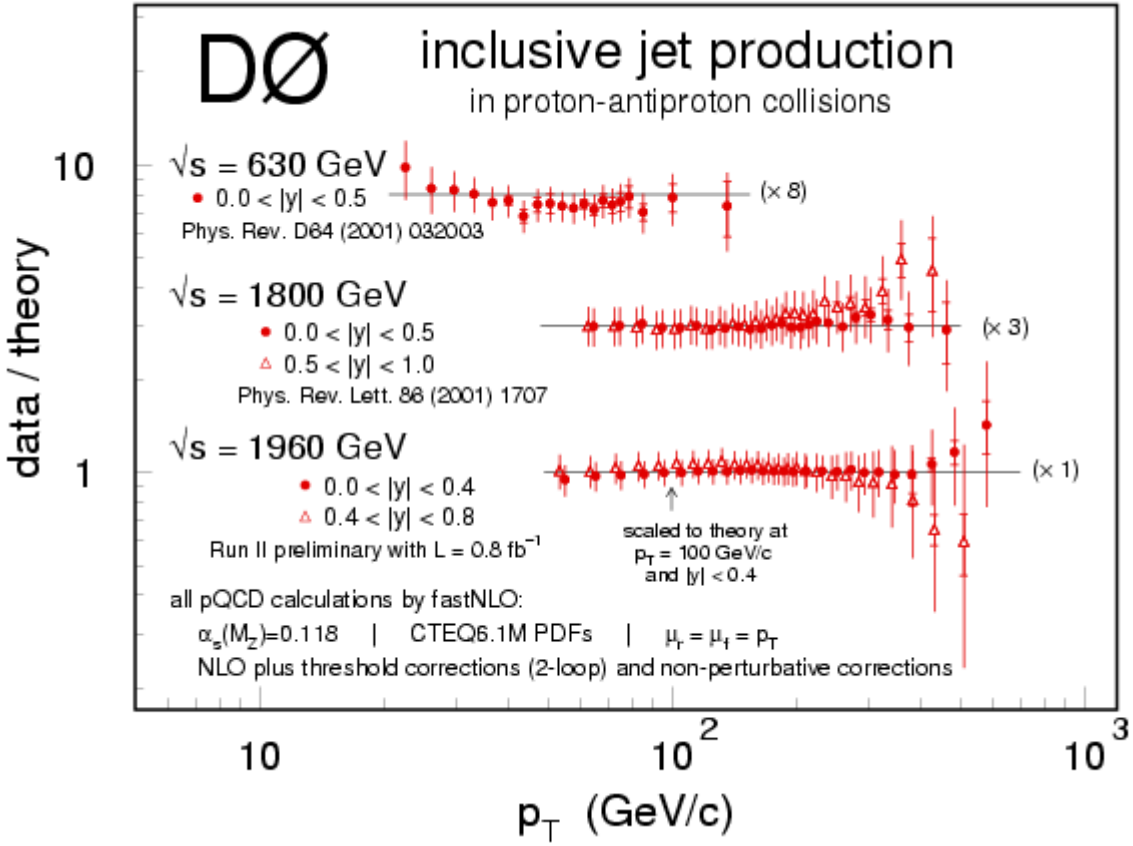
- The sensitivity to constrain PDF's is already there
- Further reductions in uncertainties, extension to rapidities up to |y|<2.4 and correlated errors underway





Summary

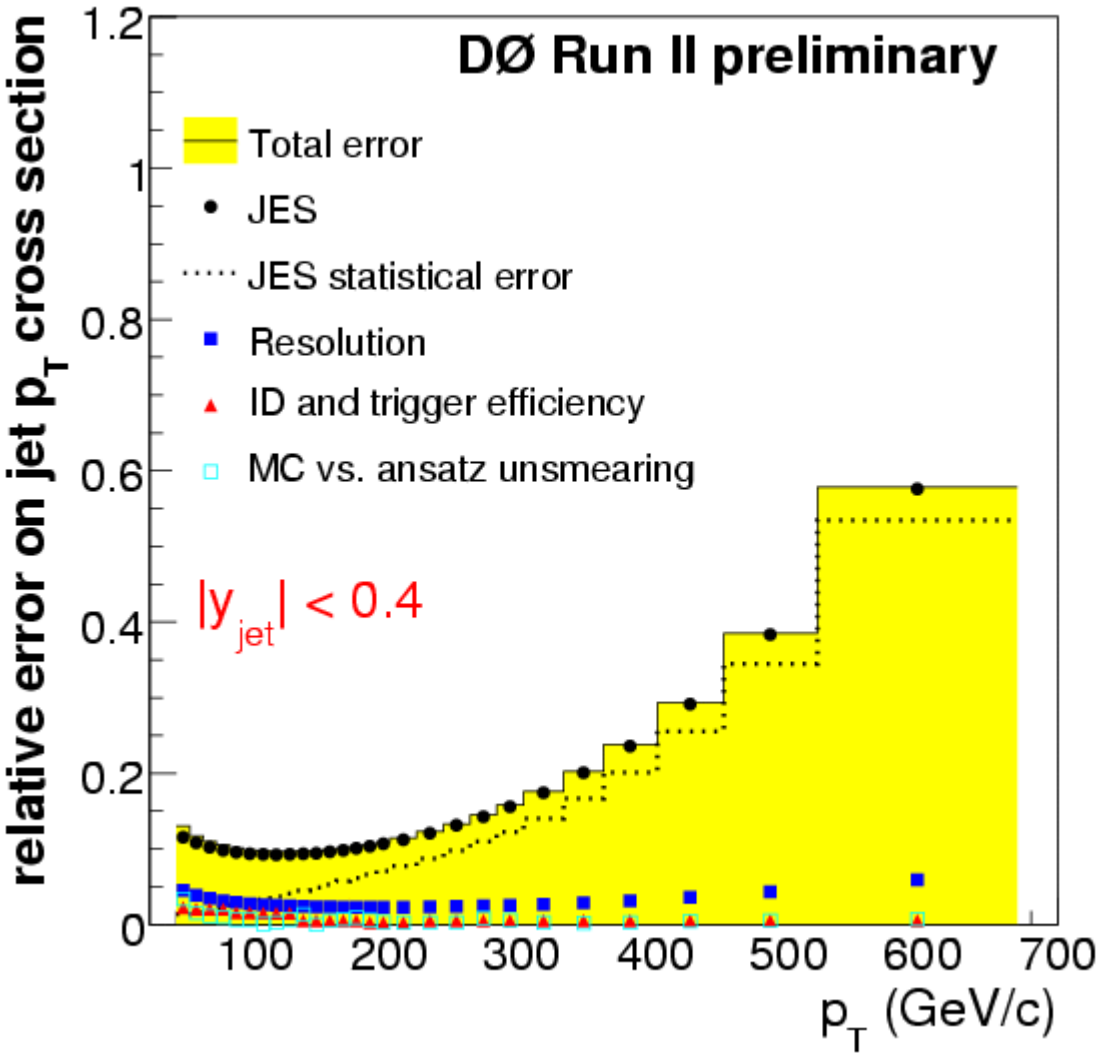
- Factor of two improvement in DØ Run II JES at medium p_T since beginning of Run II
- Uncertainties are approaching the same level as in DØ Run I
- Sensitivity to gluon PDFs is there
- Final JES and extending the measurement from two to six rapidity ranges coming soon



Back-up slides

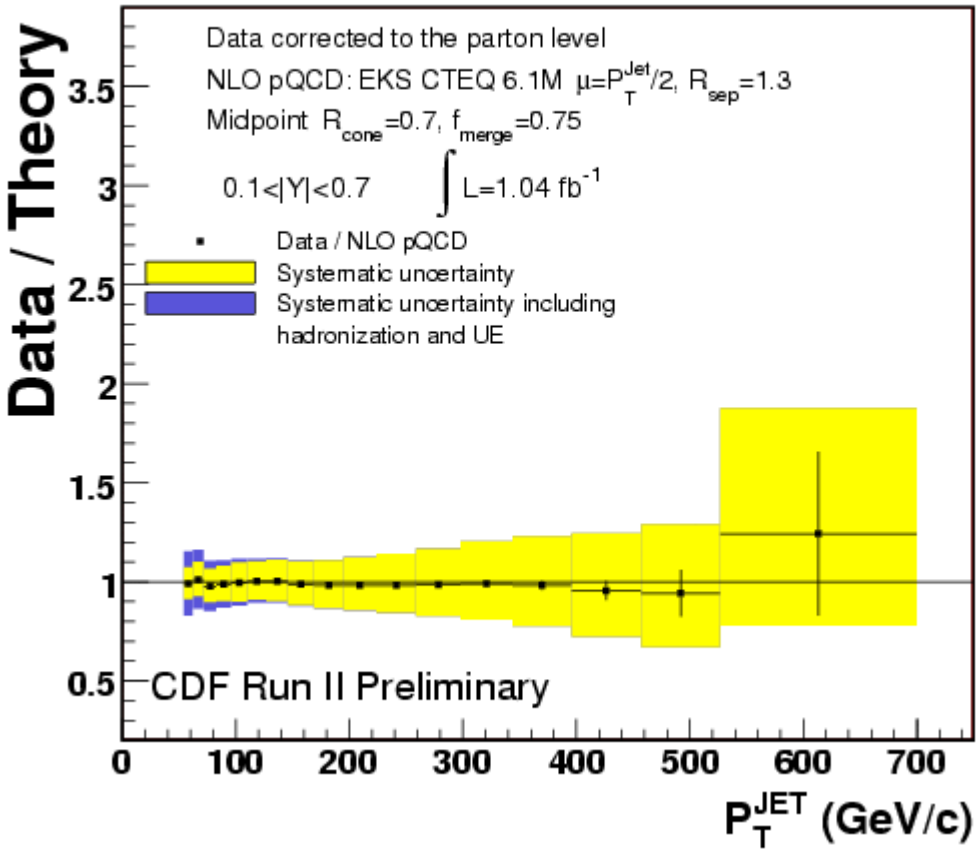
Experimental uncertainties

- Experimental uncertainty predominantly from JES
- Some contribution from resolution also
- Low p_T uncertainty is close to Run I uncertainty: 8% (RunI) vs 10% (RunII) at 100 GeV in $|y| < 0.5 / 0.4$
- High p_T still leaves room for improvement: RunI last bin 30%, RunII last bin 60%
- JES statistical error dominant at high p_T, which will improve with full statistics



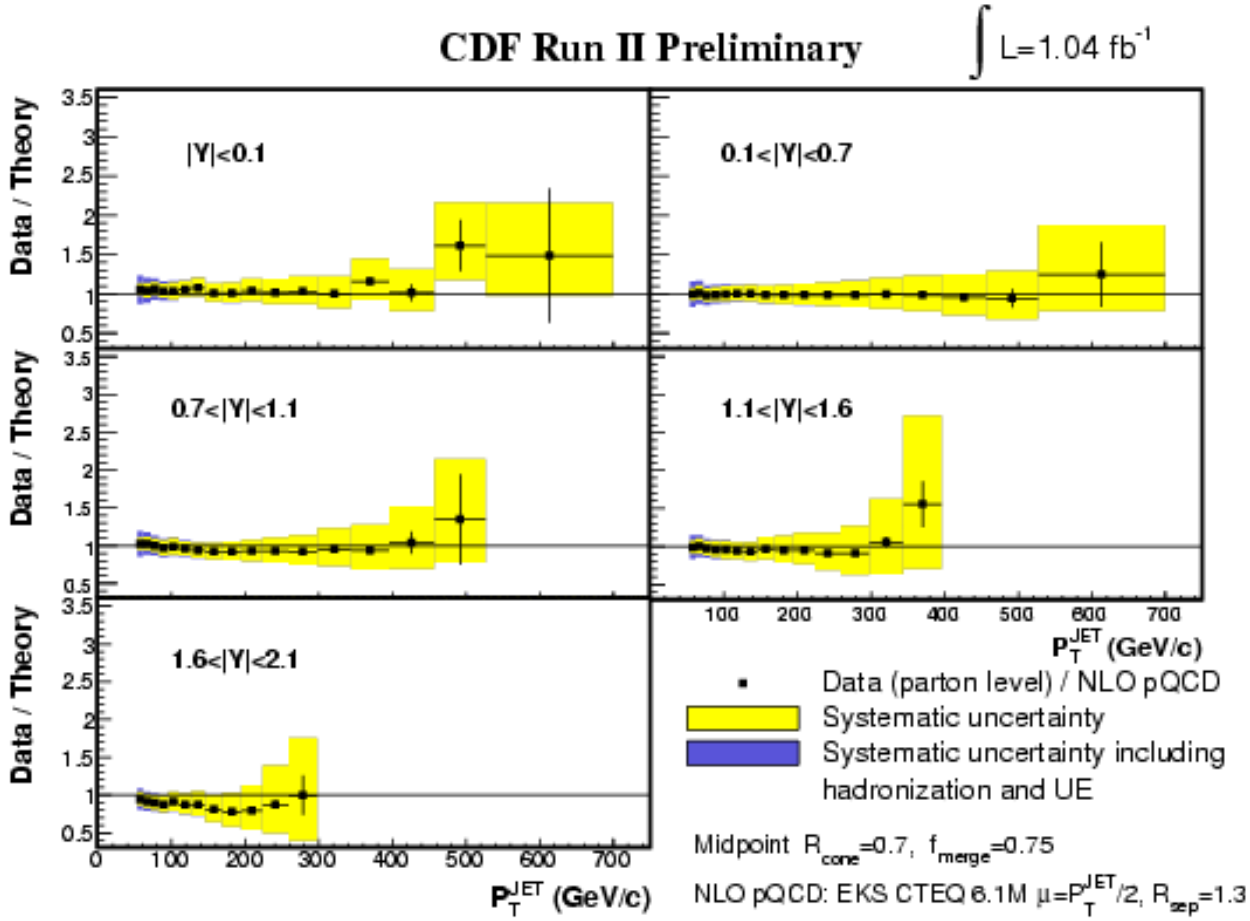
CDF results

- CDF results comparable to DZero results
- DZero corrects to particle level, CDF to parton level



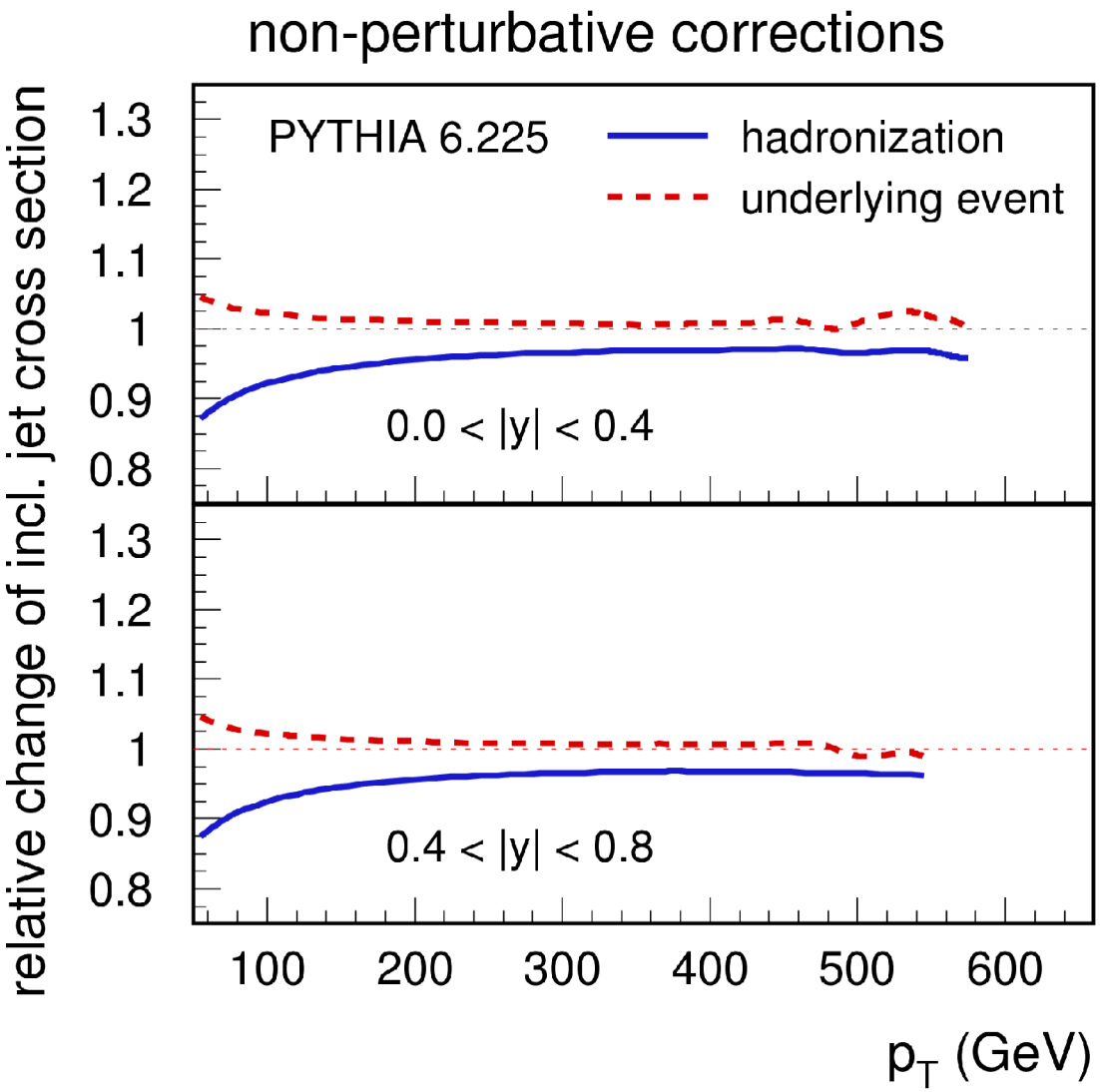
CDF results

- CDF measurements in several rapidity bins
- DZero also plans to extend measurement in rapidity



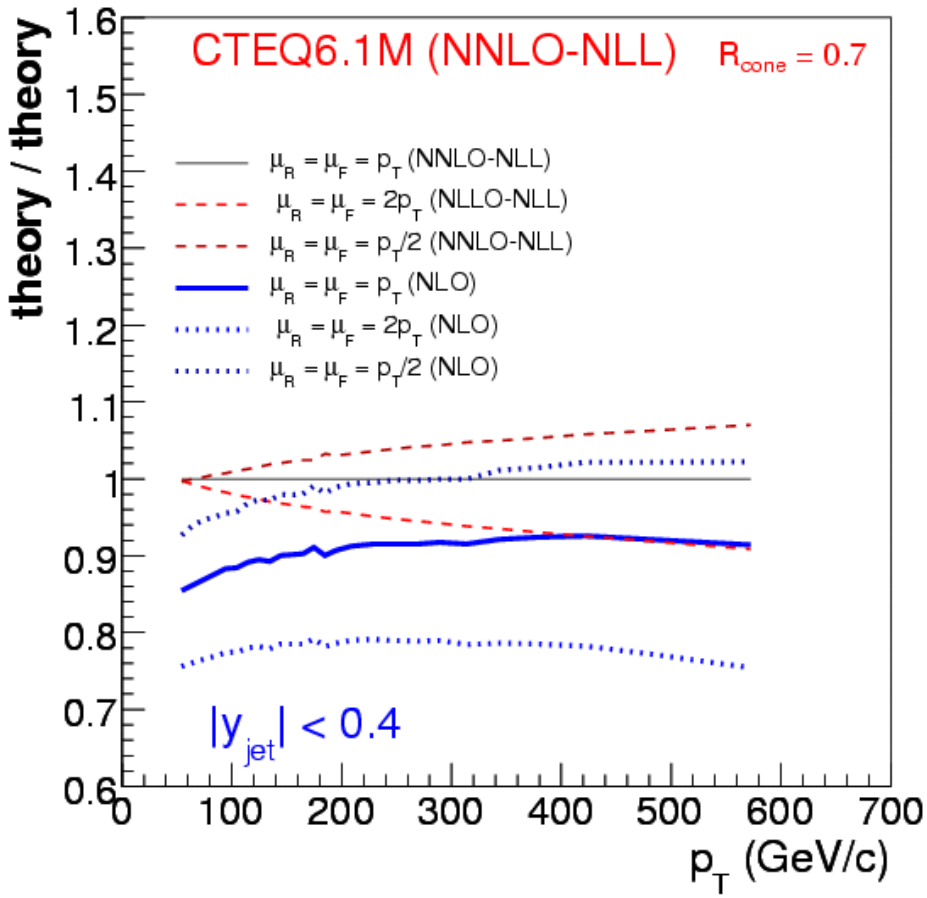
Non-perturbative corrections

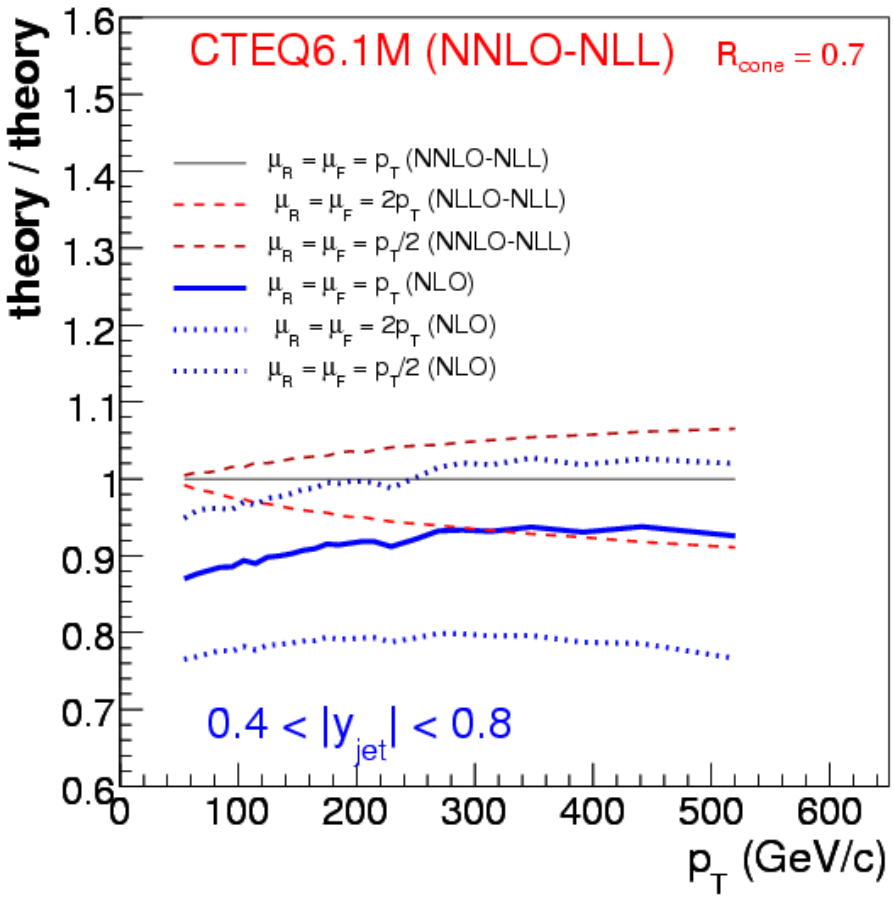
- The underlying event is already corrected by the Jet Energy Scale
- The NLO and NNLO-NLL predictions have been corrected for hadronization effects using Pythia



Theory updates

- Updated NNLO-NLL has 12% higher prediction than NLO at p_T = 100 GeV
- Scale uncertainty significantly smaller at low p_T



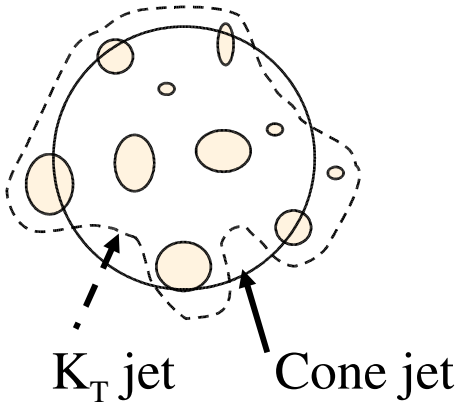


The "Run II Cone Algorithm"

"particle" = {experiment: calorimeter towers / MC: stable particles / pQCD: partons}

three parameters: $R_{cone} = 0.7$, $p_{Tmin} = 6$ GeV, overlap fraction $f = 50\%$

- Use all particles as **seeds**
  - make cone of radius $\Delta R = \sqrt{(\Delta y^2 + \Delta \phi^2)} < R_{cone}$ around seed direction
  - proto jet: add particles within cone in the "E-scheme" (adding four-vectors)
  - iterate until stable solution is found with: cone-axis = jet-axis
- Use all **midpoints** between pairs of jets as **additional seeds** ⇒ infrared safety!!!
  - (repeat procedure as described above)

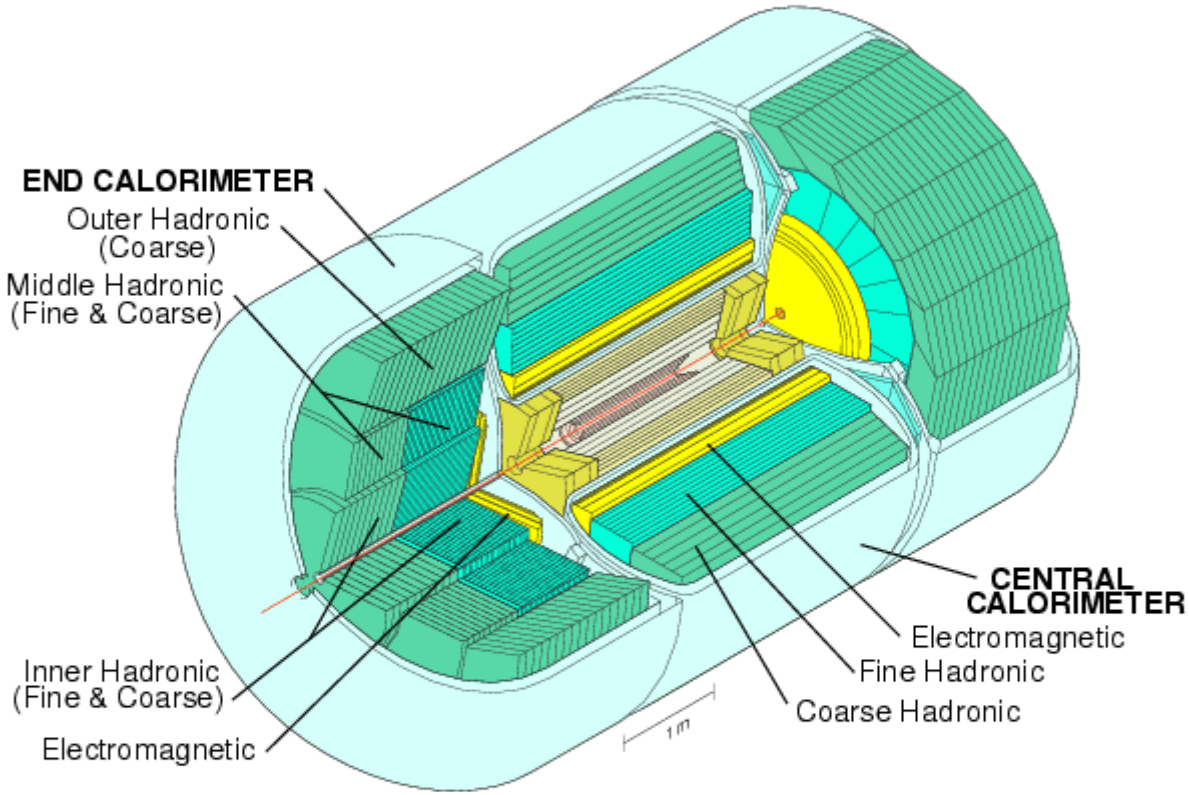


- Take all solutions from the first two steps:
  - remove identical solutions
  - remove proto-jets with $p_{Tjet} < p_{Tmin}$
- Look for jets with **overlapping cones**:
  - merge jets, if more than a fraction f of p_{Tjet} is contained in the overlap region
  - otherwise split jets: assign the particles in the overlap region to the nearest jet

  (→ and recompute jet-axes)

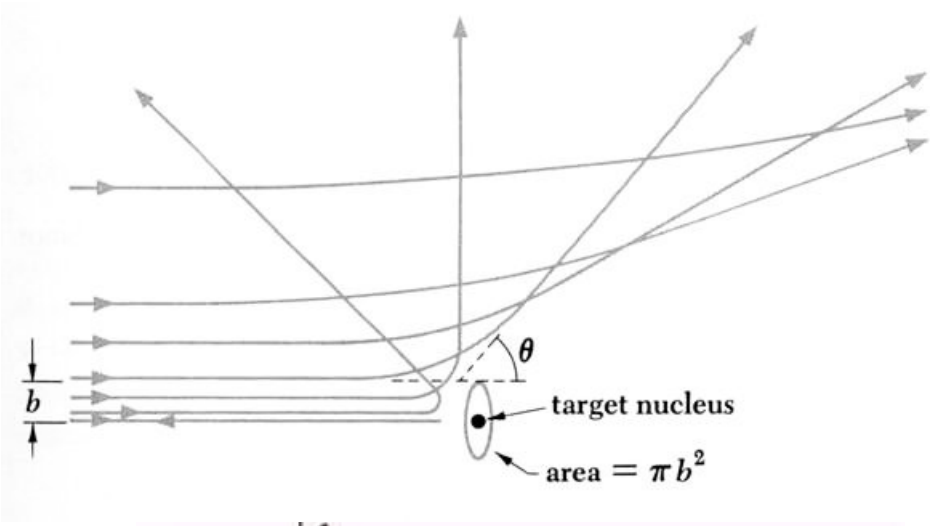
DZero

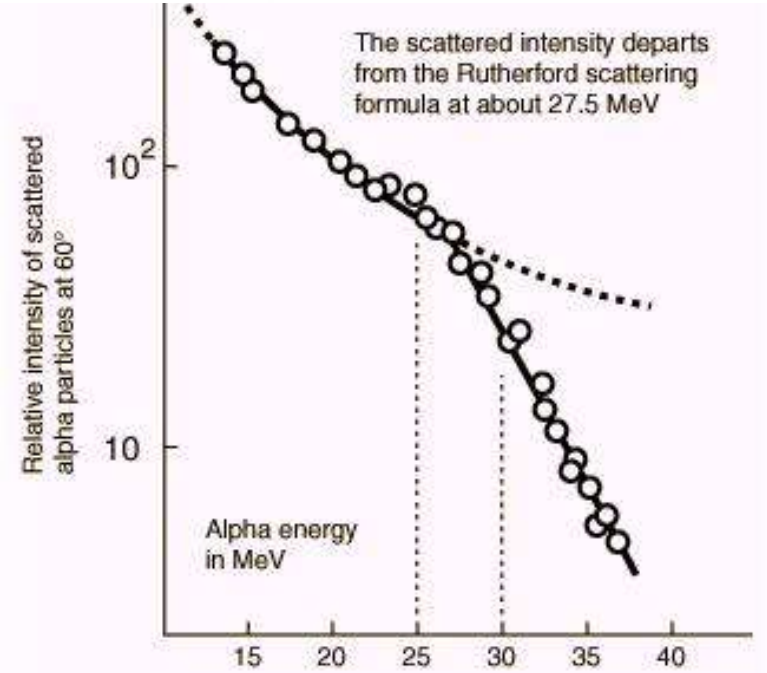
- Liquid argon - Uranium calorimeter with good jet energy resolution

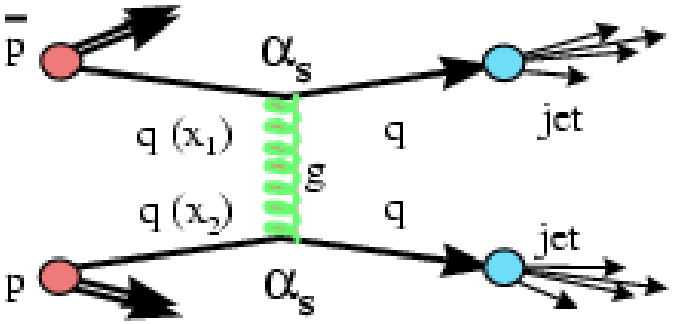


A short history of scattering

- Rutherford shoots alpha particles to gold foil and finds atomic nucleus
- Higher energy probes start to break heavier nuclei
- Very high energy probes find parton substructure of the nuclei (quarks, gluons, virtual particles)
- Modern day deep inelastic scattering experiments probe the parton structure of the proton in detail and look for the unexpected

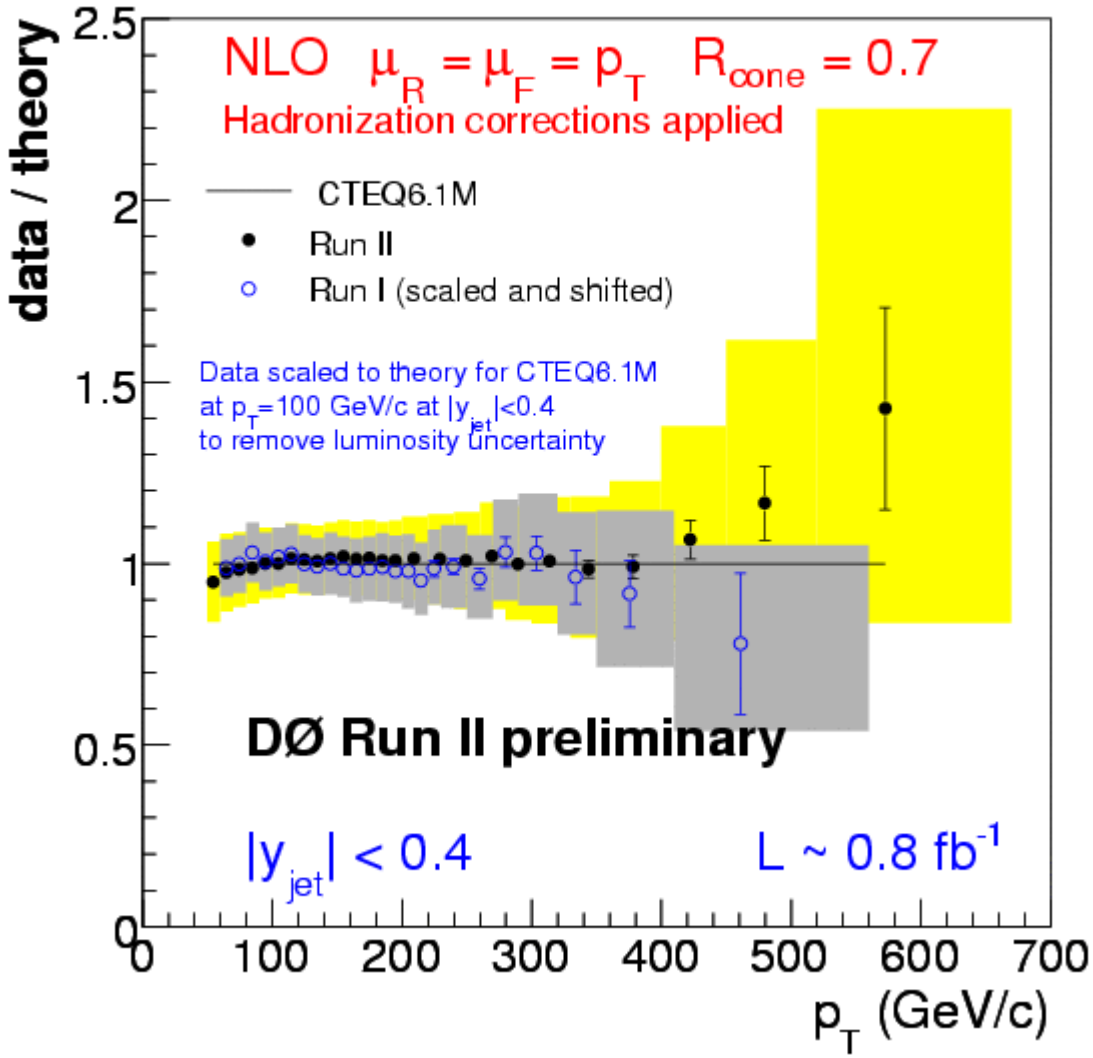






Comparison to Run I

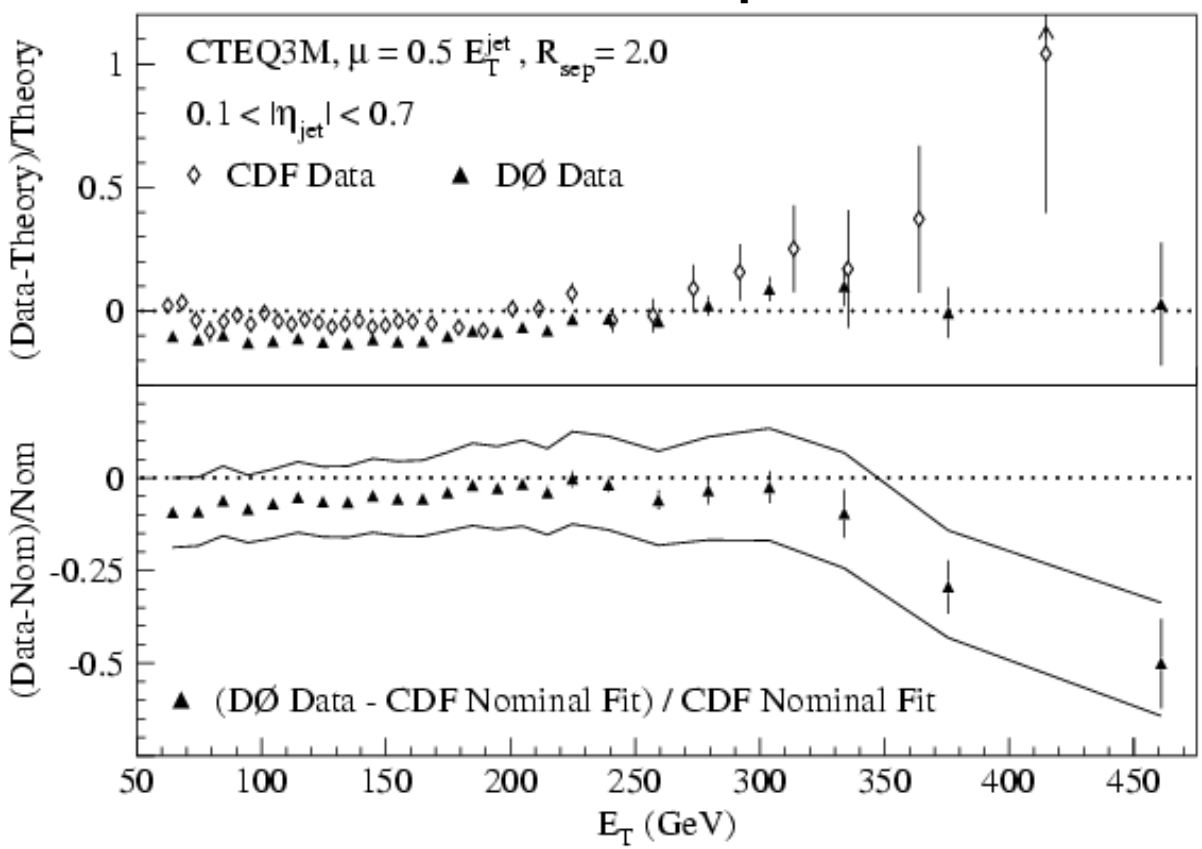
- Uncertainties are approaching the same level as in Run I
- Smaller statistical uncertainty
- Higher reach in p_T



One of the More Exciting Stories

- The inclusive jet cross section measurement caused quite some excitement in Run I when CDF saw interesting features at high E_T

CDF to DØ comparison



- Both measurements were later shown to be explainable by increased gluon PDFs, renormalization scale in theory and cone algorithm; all within the allowed parameter range of QCD