Jet results from the Tevatron

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On behalf of D0 and CDF Collaborations

Standard Model Benchmarks at the Tevatron and the LHC
Workshop, Fermilab, November 19, 2010

Outline

- Motivations
- Inclusive jet cross sections
- Alpha_s measurement
- Dijet mass and sensitivity to new physics
- Dijet angular distributions
- Three-jet mass
- Mass of high pT jets

Motivations for the jet measurements

- Test of pQCD, PDF constrains

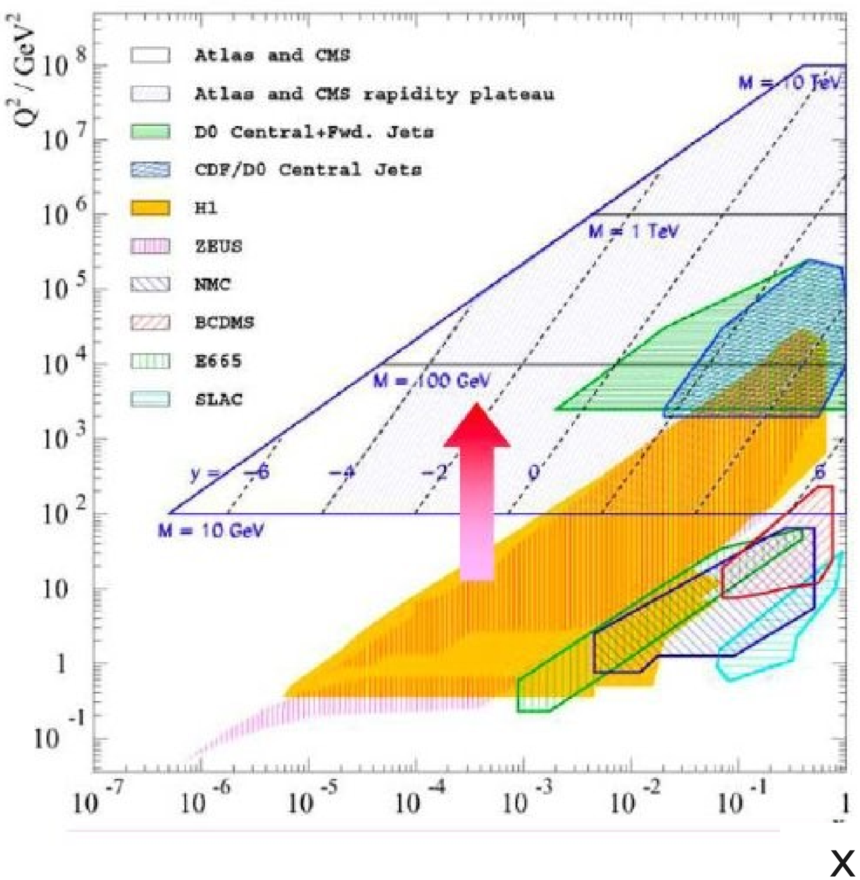
– x-Q^2 regions accessible at the fixed target, DIS, Tevatron and LHC are complementary to each other

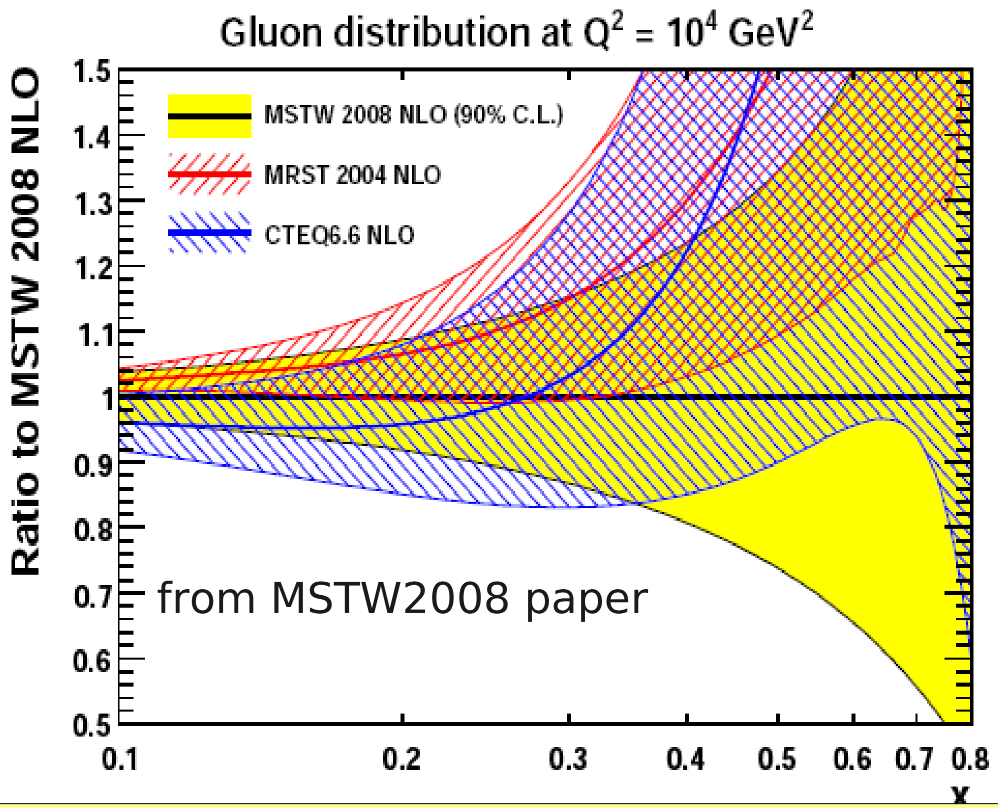
– only Tevatron incl. jet data provide significant constrain on gluon PDF at high x and high Q^2

- New phenomena searches:

– searches for new phenomena are limited without proper understanding QCD background

– direct search with jet final states



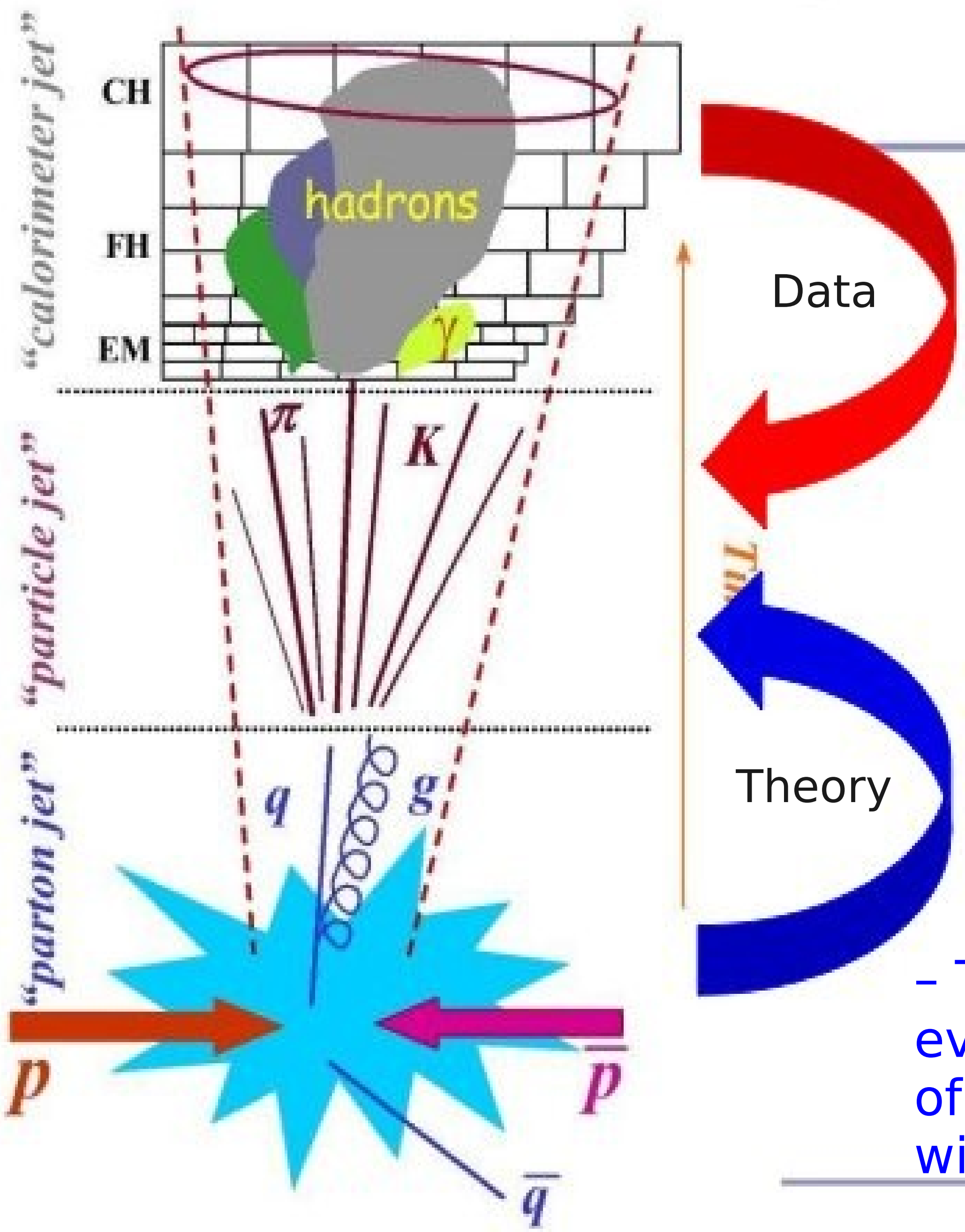


–CTEQ6.6 does not use Tevatron Run II jet data, while MSTW does

– MSTW2008 and CTEQ6.6 results are in agreement for x<0.3

=> Tevatron jets mostly affect PDF at x>0.3

Corrections to particle level



In Run II jet results, in most cases:

– data are corrected to particle level

– particle level measurements are compared to NLO theory

– NLO theory is corrected to particle level using parton shower MC

$$C_{had} = \frac{\text{observable (particle level)}}{\text{observable (parton level)}}$$

– There is also correction (C_{ue}) for the underlying events (MPI). Usually we run Pythia with a couple of Tunes, Herwig+Jimmy and correct predictions with MPI to that without.

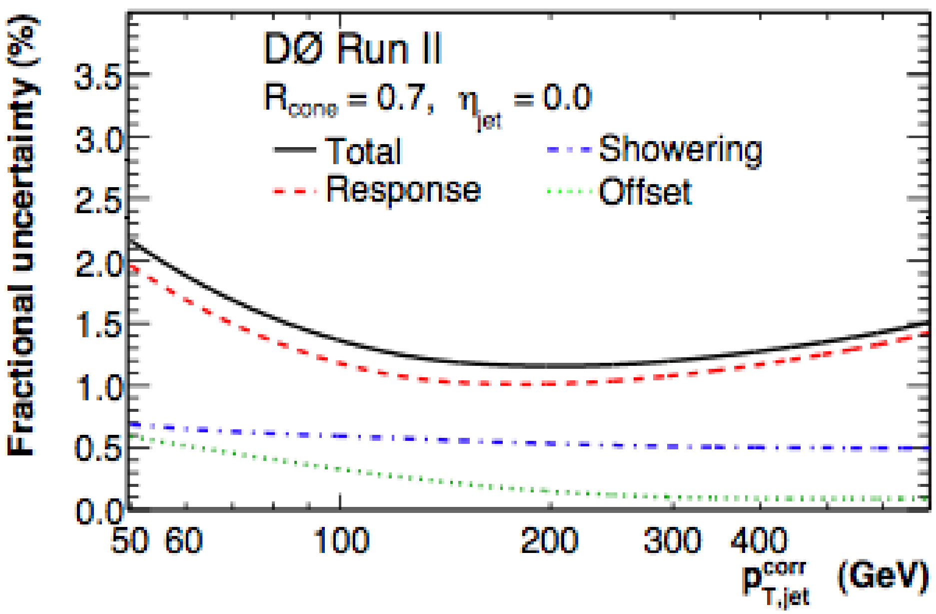
Jet energy scale calibration

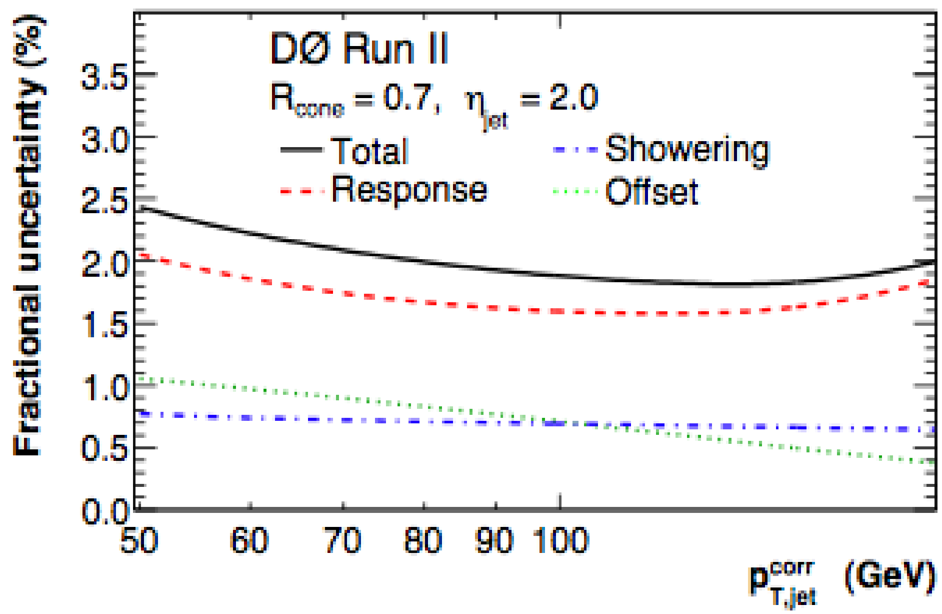
- We do not “see” partons or particles in calorimeter, only ADC counts
- ADC counts --> cell energies
- Run jet cone algorithm (see Backup) with
  $\Delta R = \sqrt{(\Delta y^2 + \Delta \Phi^2)} < R_{cone}$

Jet's E are corrected to the particle level using the Jet Energy Scale (JES) setting procedure :

- Calibrate using γ+jets (dijets and Z+jets)
- JES includes: Energy Offset (energy not from the main hard scattering process); Detector Response, Out-of-Cone showering; Resolution
- Responses in the calorimeter for quark and gluon jets are different: additional corrections are applied to convert γ+jet → dijet JES.

Energy scale uncertainty: 1-2.5% (a lot of hard work of many people)!



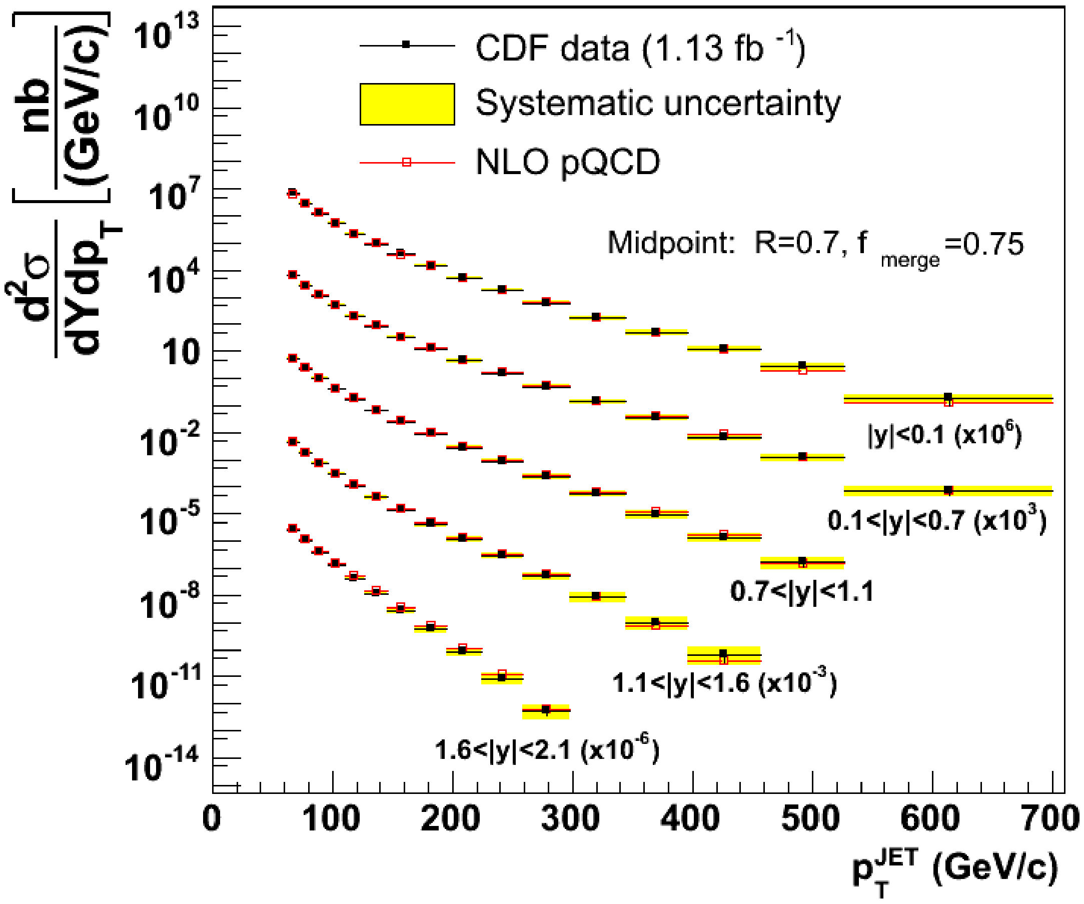


Inclusive jet production (CDF)

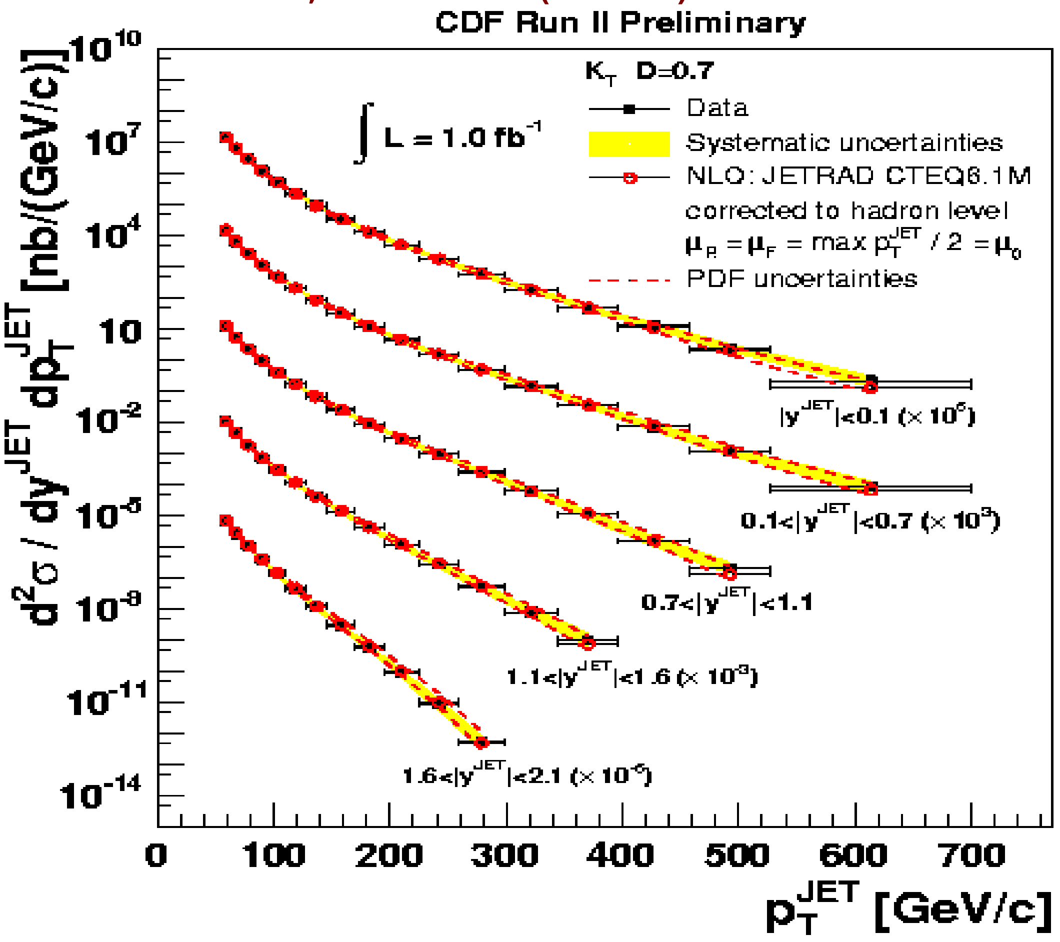
Inclusive jet measurements test pQCD over 8 orders of magnitude in 5 rapidity regions up to jet pT ~600 GeV.

- CDF measured inclusive jet cross section with Midpoint cone algorithm (R=0.7) and kT (D=0.4, 0.7, 1.0) algorithm.
- Data/Theory consistent for the cone and kT (for all D parameters) algorithms
  => they both can be successfully used at hadron colliders.

PRD78, 052006 (2008)



PRD75, 092006 (2007)



Inclusive jet production (D0)

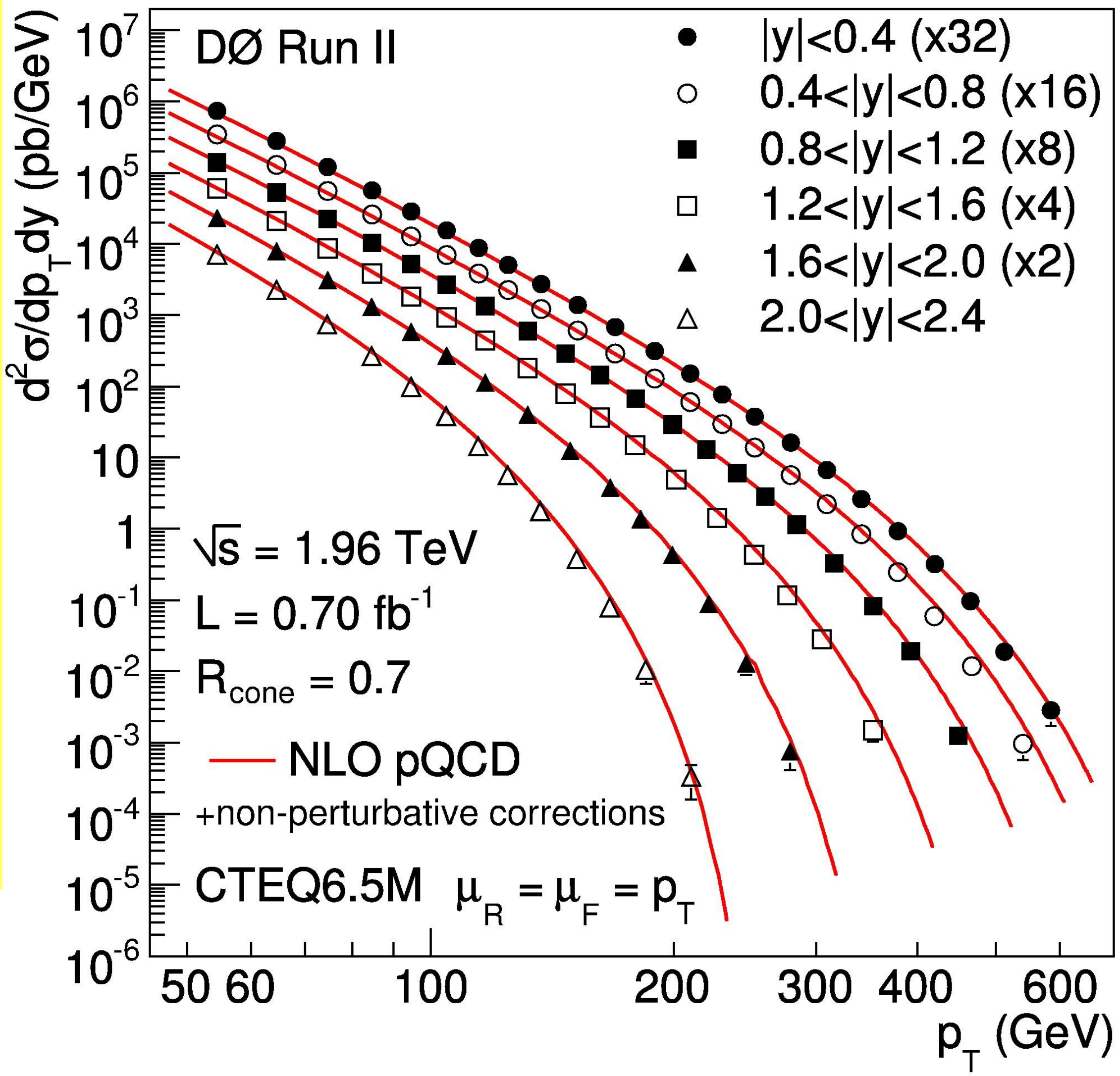
PRL 101, 062001 (2008)

D0 also measured inclusive jet cross section using Midpoint algorithm in 6 rapidity regions.

Dominant systematic uncertainty is from JES:
Steeply falling spectrum:
=> Even small JES uncertainty leads to large uncertainties on cross section

Typical JES uncertainty:
2-3% in CDF, 1-2% in D0

Total uncertainty on the cross sections:
15-50% in CDF, 15-30% in D0

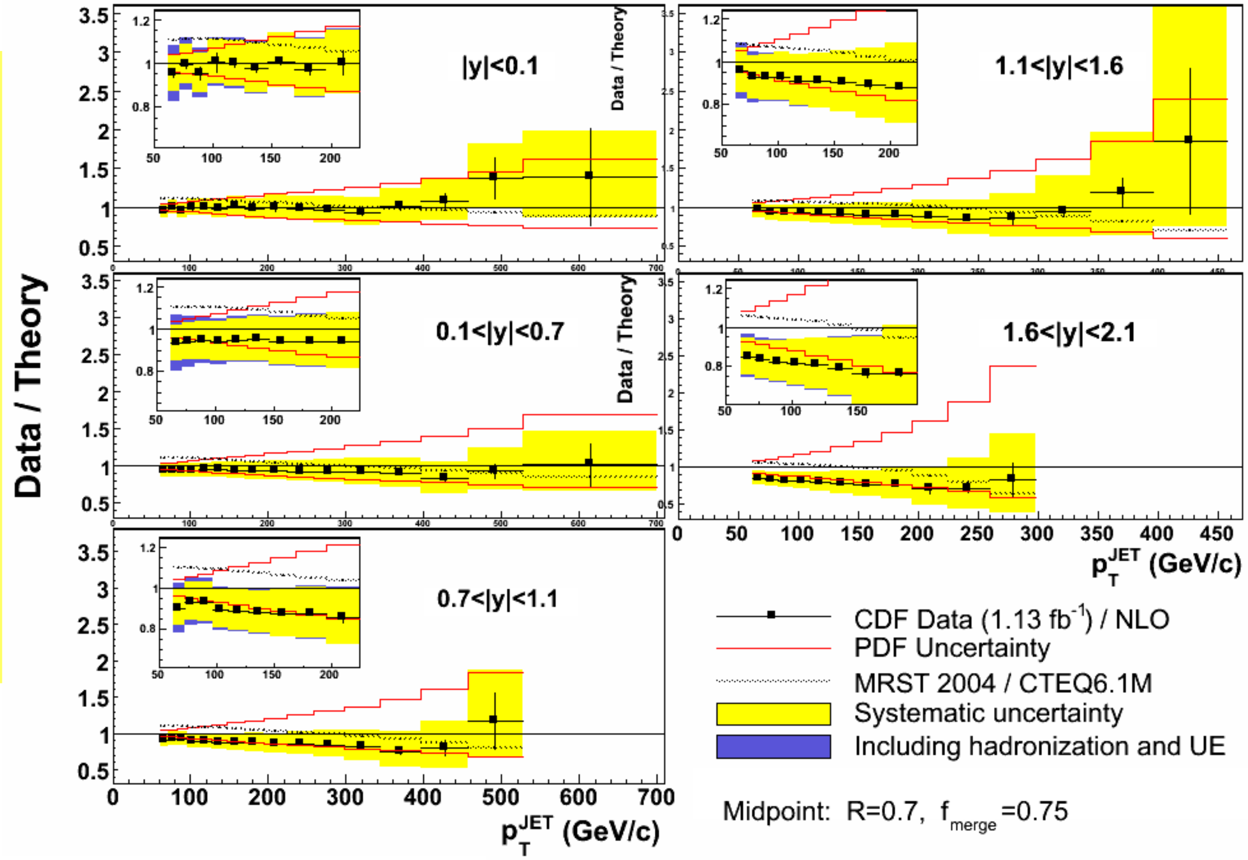


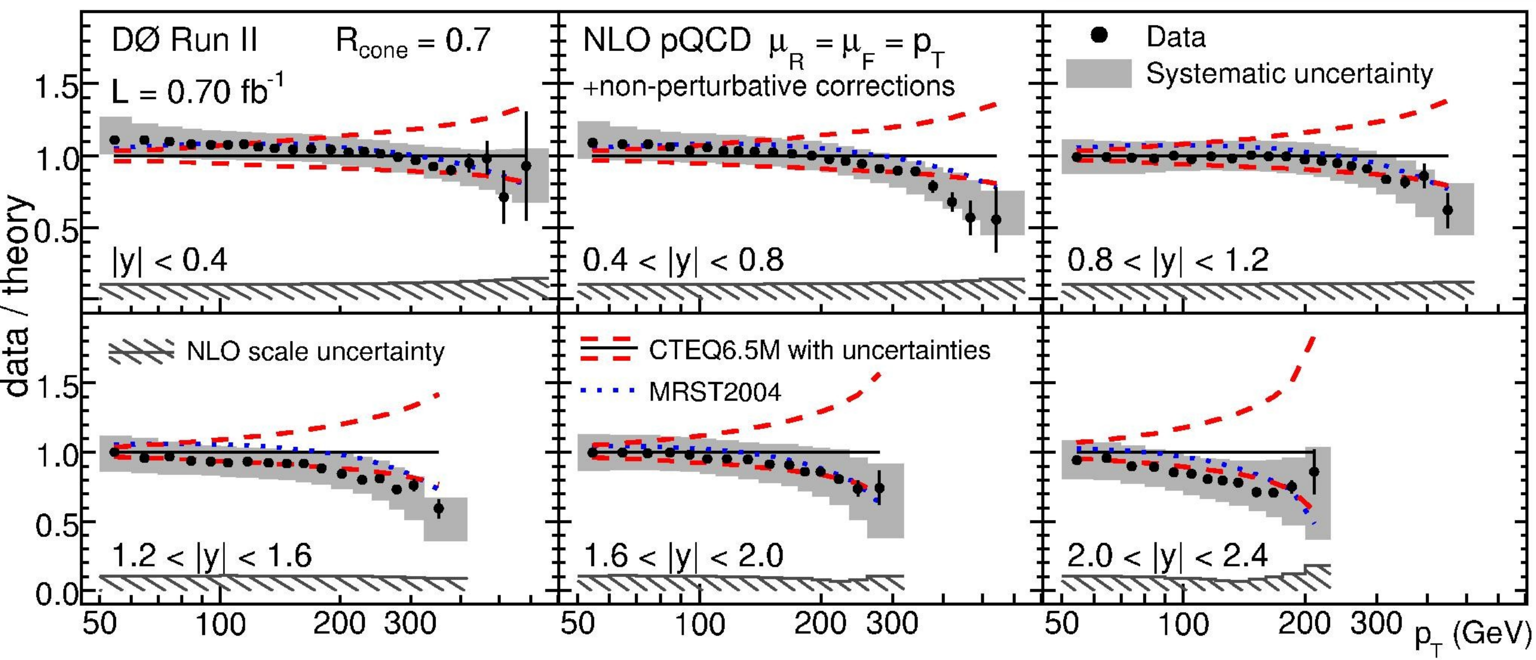
Inclusive jet production: Data/Theory

CDF and D0 measurements are in agreement with QCD NLO predictions.

However, data favor more lower bound of the theoretical (CTEQ6.5M PDF) predictions, with smaller gluon content at high x.

Experimental uncertainties at high pT are lower than theoretical (largely PDF ones): => constrain PDF





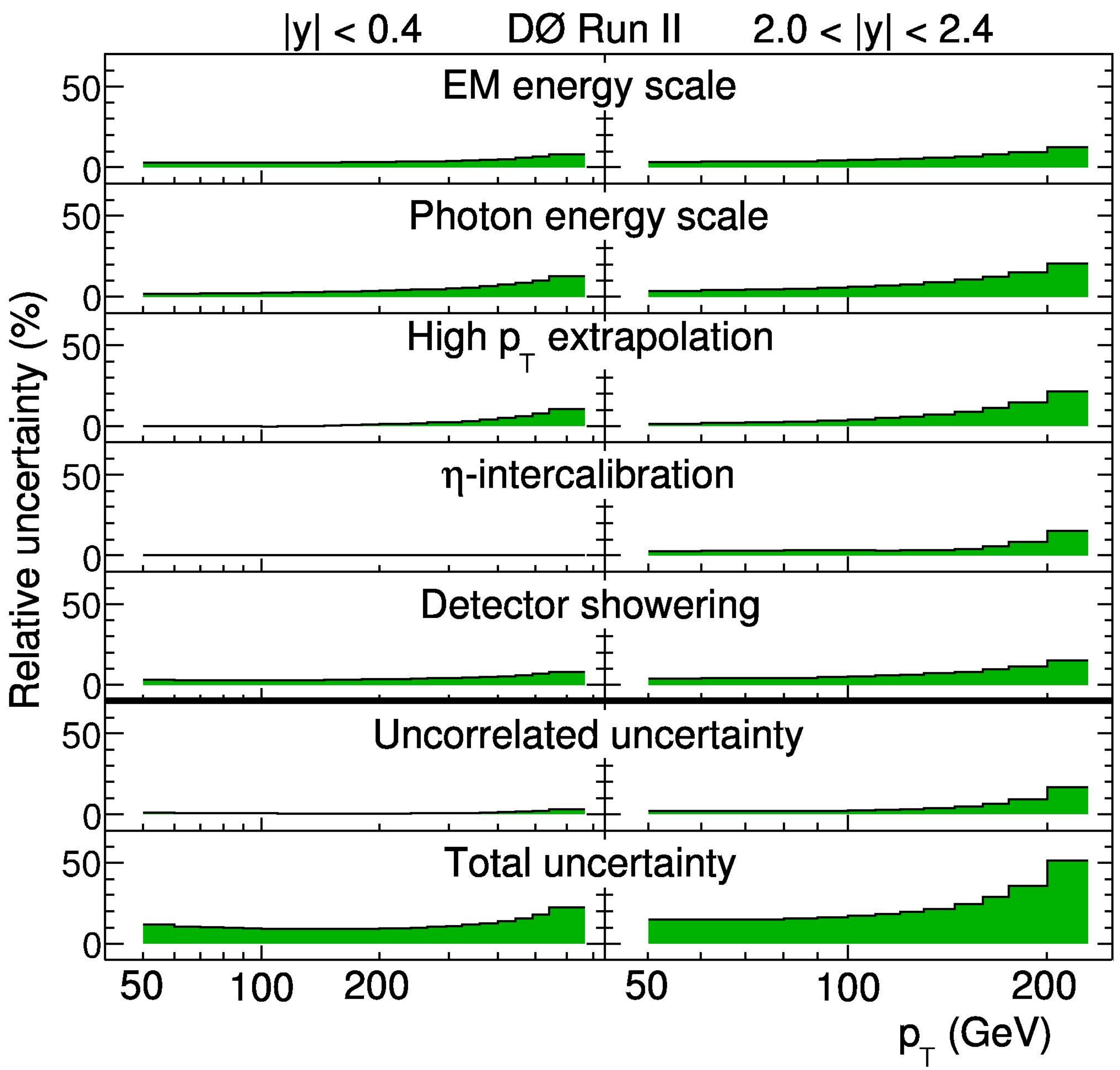
MSTW 2008 uses CDF kT and D0 cone results.

Leads to modified central values (esp. at x>0.3) and reduced PDF uncertainties.

D0 results are most precise measurement to date.

Inclusive jet production (D0): correlations study

- All systematic uncertainties in data compose 24 main groups
- Possibility to constrain PDF further using the provided correlation matrices
- Detailed paper on the measurement to be submitted soon to PRD



Main sources of systematic uncertainties

Measurement of α_s from inclusive jets (D0)

PRD 80, 111107 (2009)

- Cross section formula:

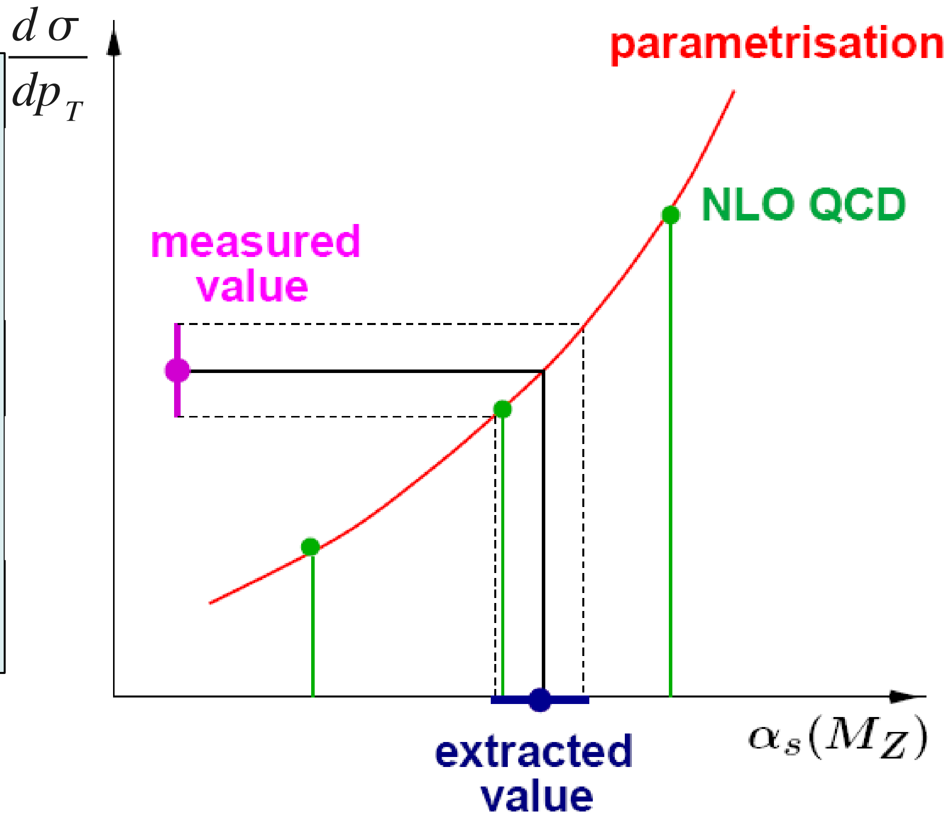
$$\sigma_{\text{theory}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n \right) \otimes f_1 \otimes f_2$$

- c_n: perturbative coefficients (→ pQCD matrix elements)
- f_1, f_2: PDFs of colliding $p, \bar{p}$

Determine α_s from data:

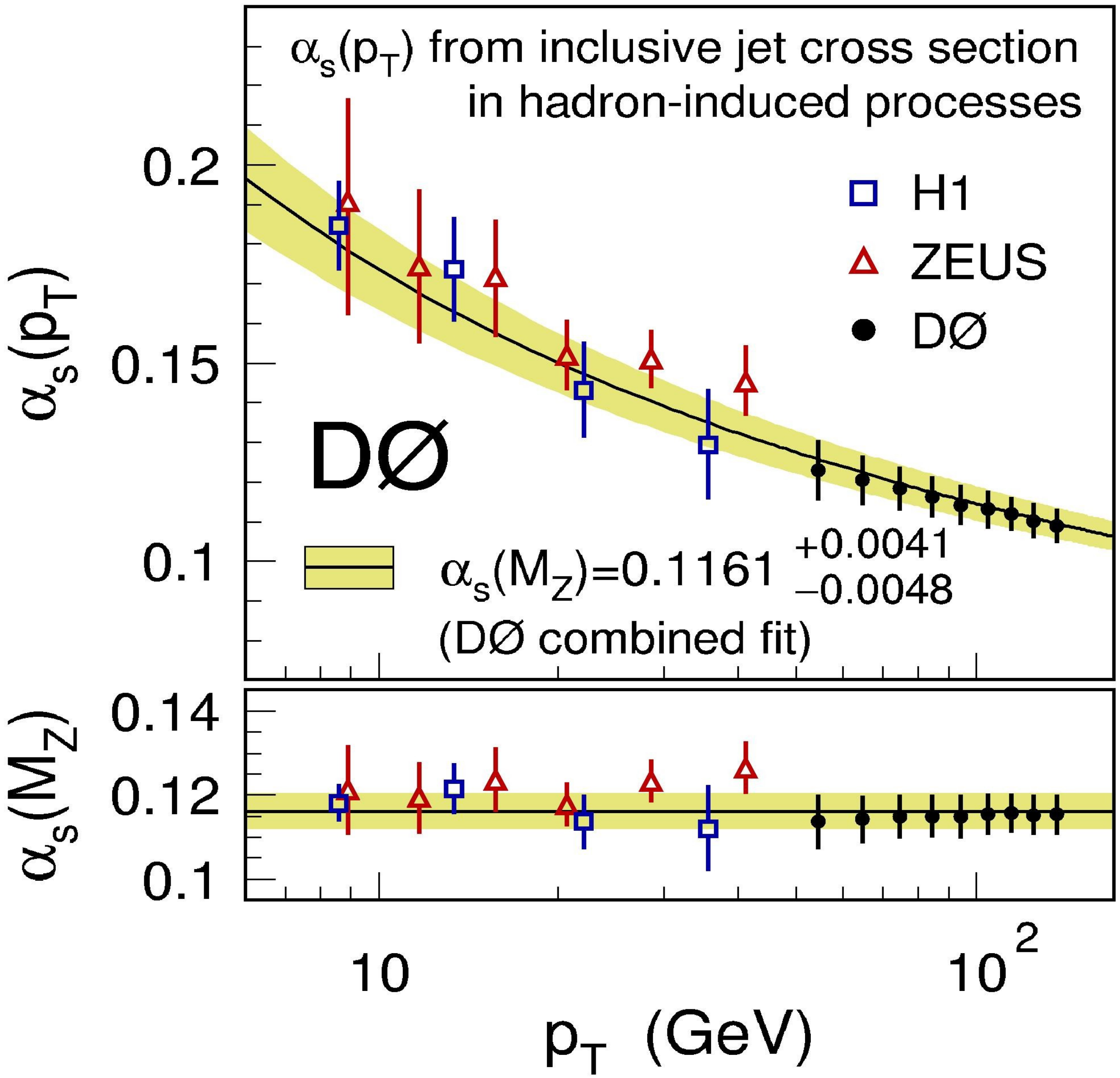
- Vary α_s until σ_{theory} agrees with σ_{exper}
- ...for each single bin →
- i.e. fit of theory to data (p. 29 in backup) using 21 NNLO PDF sets from MSTW2008

  with α_s within 0.107-0.127 in 0.001 steps
- (5 NLO CTEQ6.6M sets are also considered)
- Only 22 points of 110 are used (with x<0.2)



Running of α_s(pT)

- Combine points in different |y| regions at same pT
  → Produce 9 α_s(pT) points from selected 22 data points



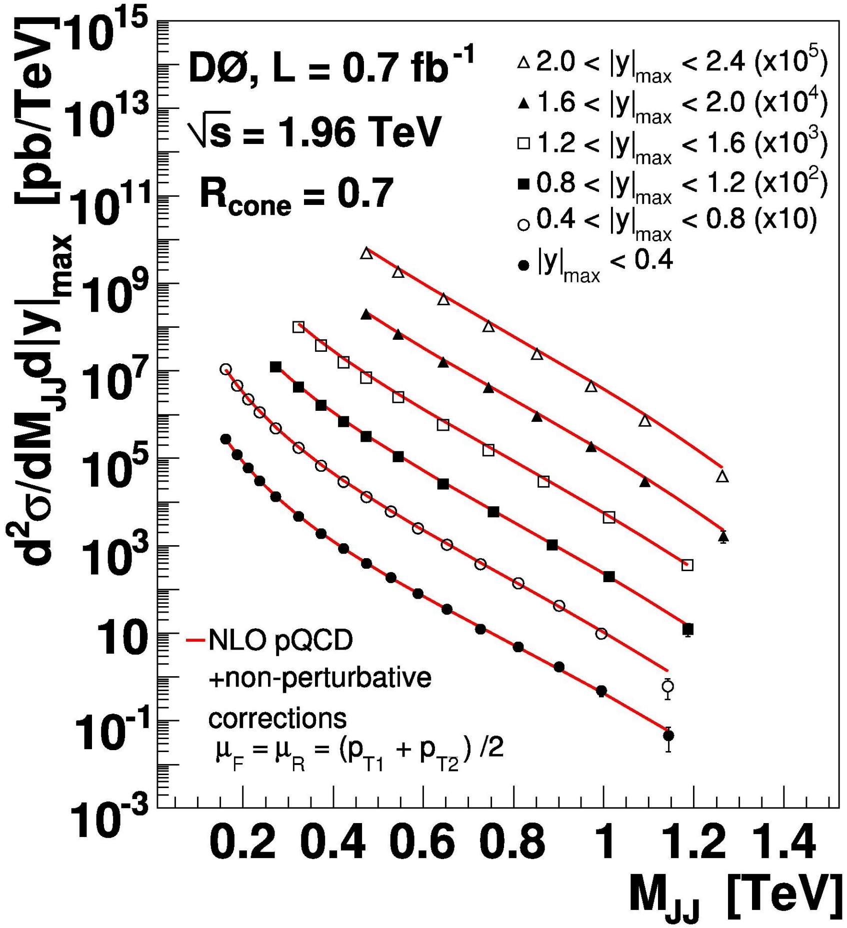
theory:NLO+2-loop threshold corrections

Compare to HERA results from H1 and ZEUS
→ consistency
→ our results extend pT reach of HERA results to pT range of 50-145 GeV
→ About same precision as HERA jets (0.1189 ±0.0032)
→ The only Run II result on α_s
→ Strong improvement as compared with Run I

PRD 80, 111107 (2009)

Dijet mass cross section measurement (D0)

PLB 693, 531 (2010)

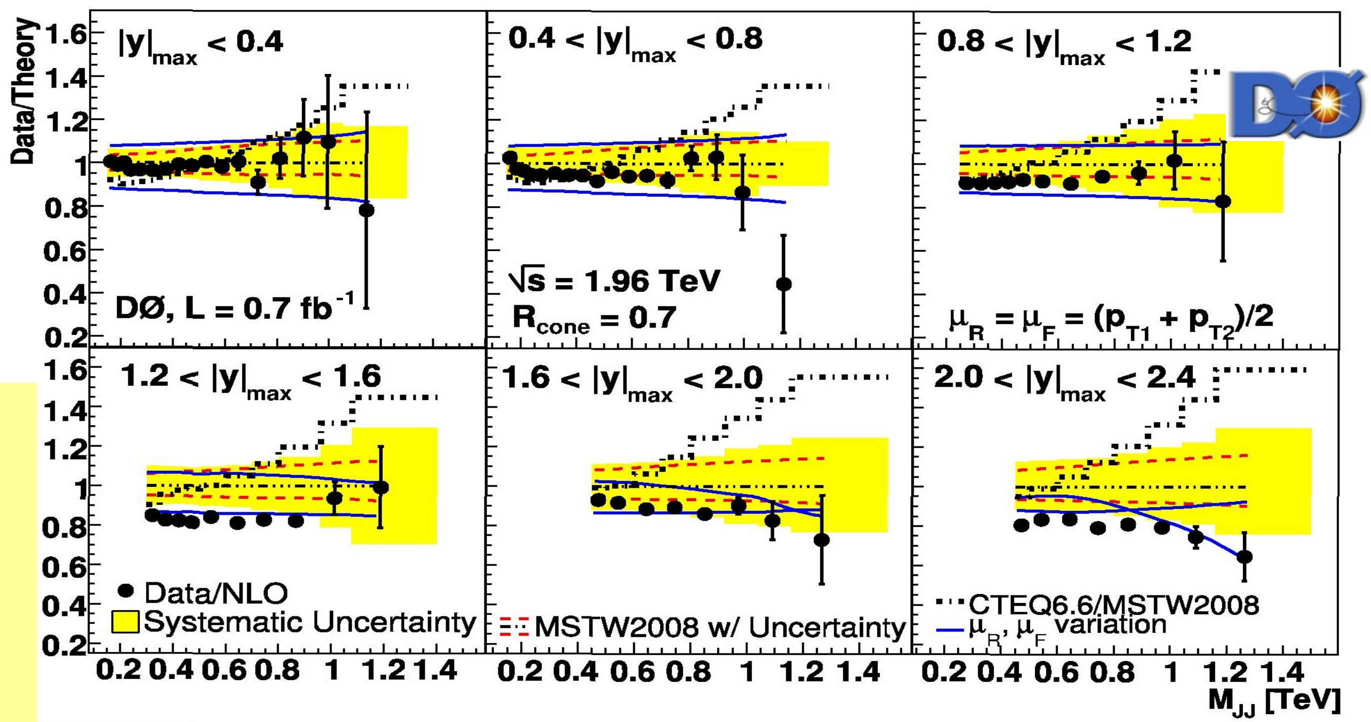


Measurement of dijet mass in six rapidity bins, $|y|_{max} = \max(|y_1|, |y_2|)$

Non-perturbative corrections (-10%, 23%)

Comparison to NLO pQCD with MSTW2008 and

CTEQ6.6M NLO PDFs, $\mu_F = \mu_R = (pT_1 + pT_2)/2$

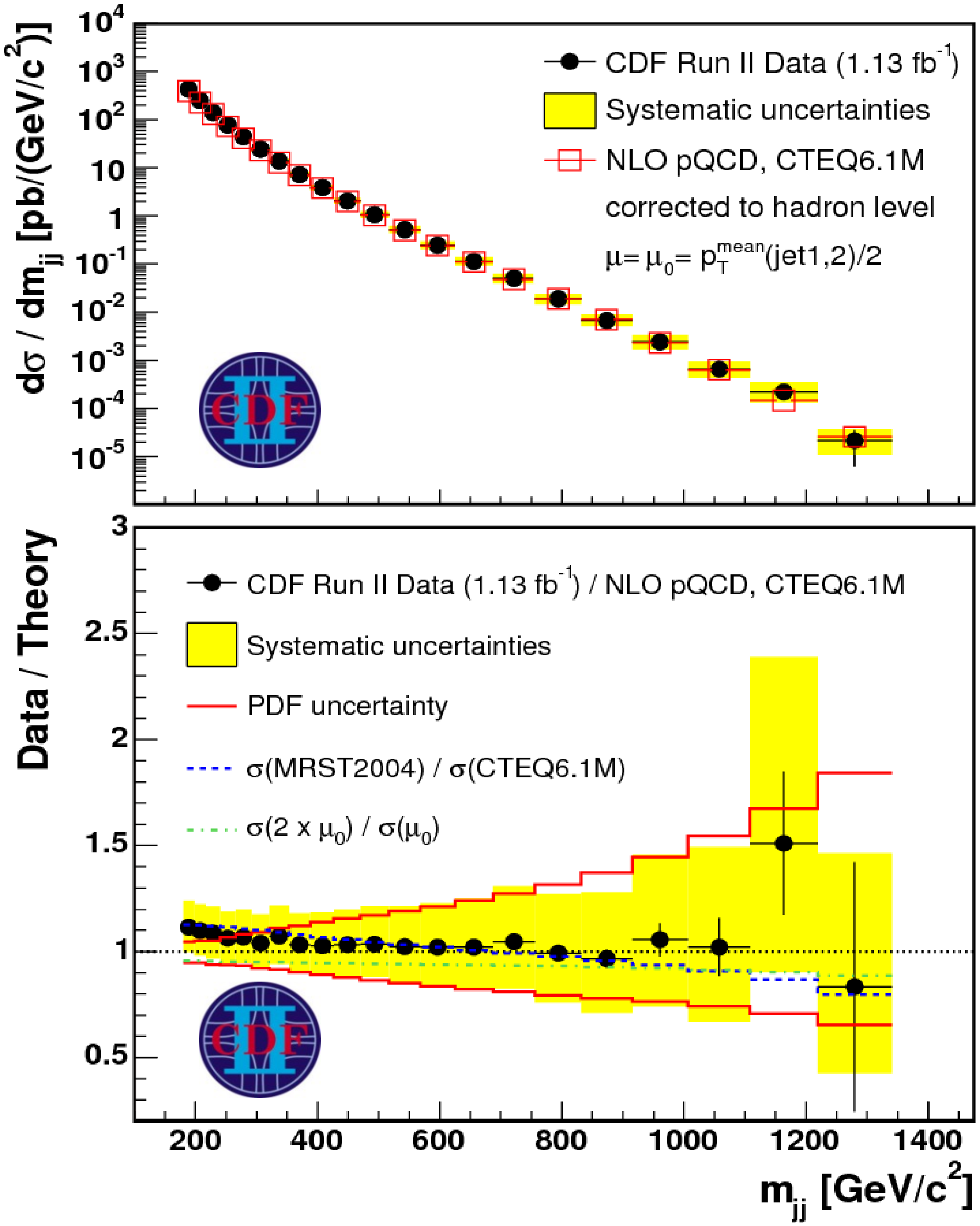


– 40—60% difference between PDFs (MSTW2008/CTEQ6.6) at high masses

– Data/QCD in good agreement in central region
– Data lower than central pQCD prediction at higher rapidities

Dijet mass cross section measurement (CDF)

PRD 79, 112002 (2009)



Study dijet events in |y|<1.0

(uses same dataset as the inclusive jets)

=>New physics expected to be produced more centrally & expect better S/B in central region

Total uncertainty: $^{+13}_{-12}$% at low m_{jj}

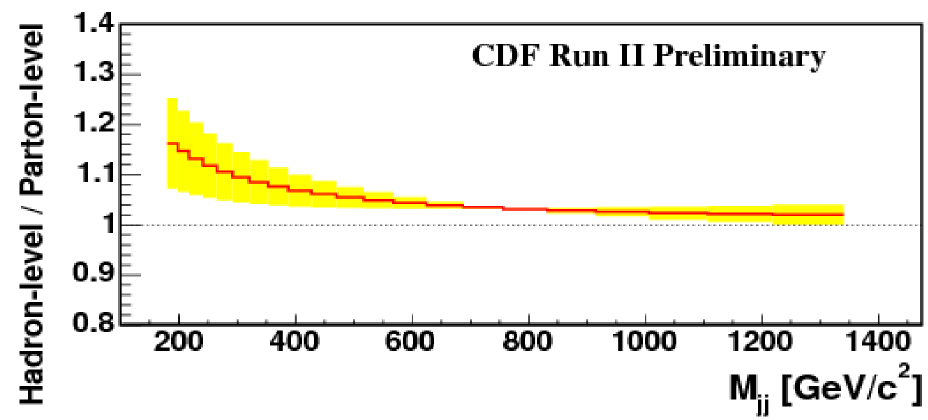
$^{+76}_{-49}$% at high m_{jj}

NLO pQCD fits to data: χ^2/ndf = 21/21

(syst. uncertainties and non-perturbative corrections all independent; fully correlated over m_{jj})

PARTON-TO-HADRON LEVEL CORRECTION

Pythia (TuneA) central value; Herwig PS taken as uncertainty

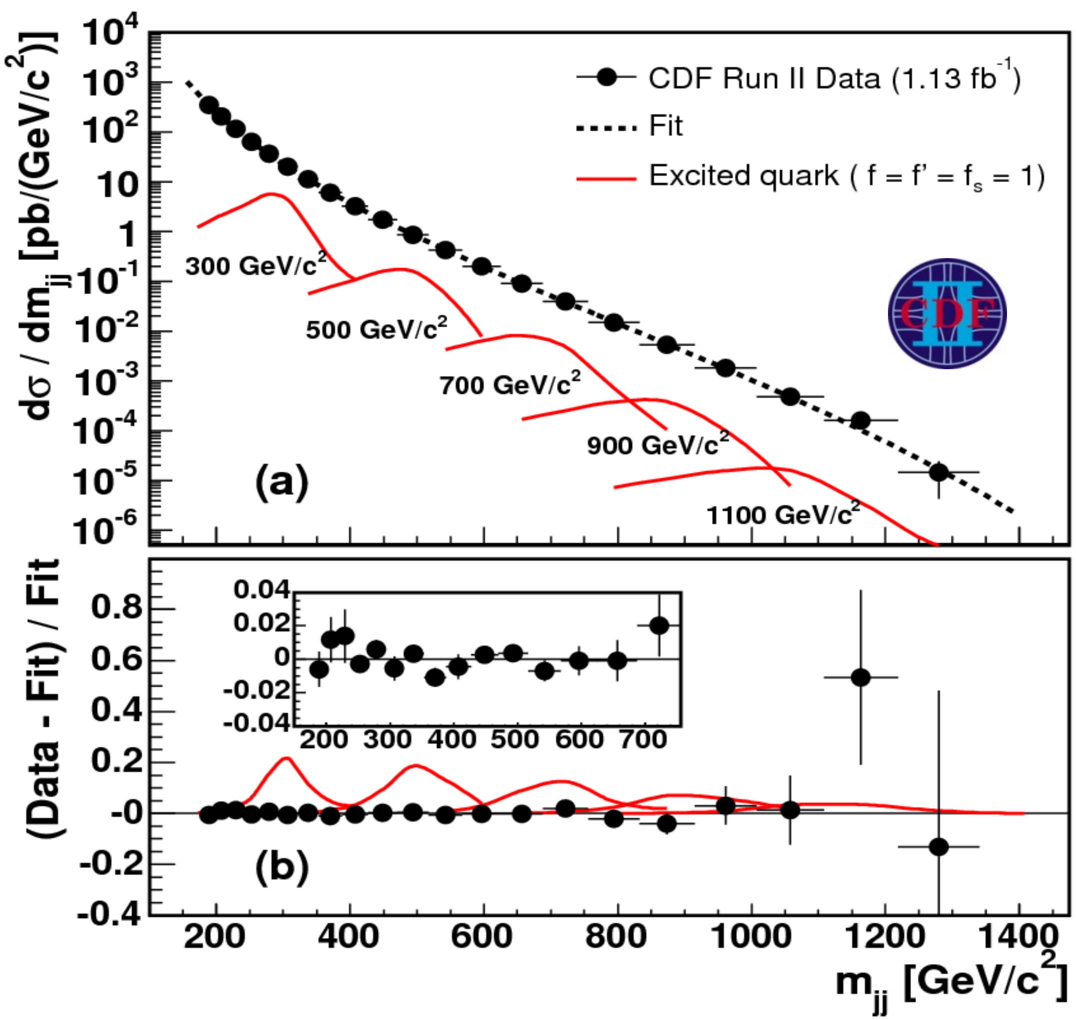


Dijet mass: searches for new physics (CDF)

PRD 79, 112002 (2009)

Dijet mass tests pQCD but also sensitive to presence of new physics via dijet resonances
=> Use uncorrected jet data to maximise sensitivity to resonances

No significant evidence for resonant structure has been observed, so set limits

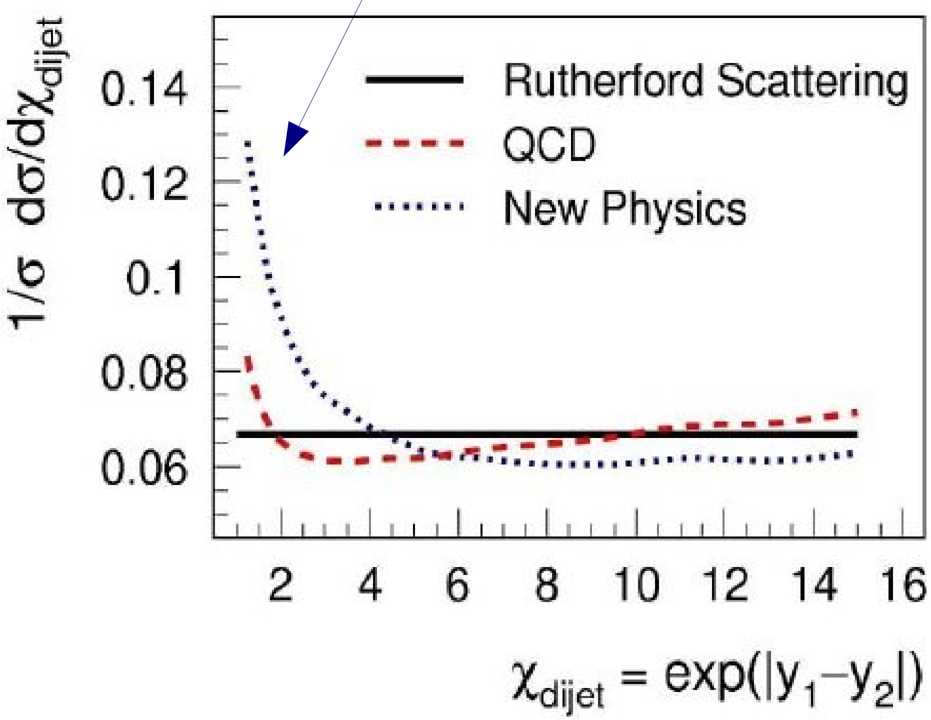


Observed mass exclusion range	Model description
260-870 GeV/c²	Excited quark → qg (f=f'=f_s=1)
260-1100 GeV/c²	ρ_{T8} techni-rho
260-1250 GeV/c²	Axigluon/coloron
290-630 GeV/c²	E_6 diquark
280-840 GeV/c²	W' (SM couplings)
320-740 GeV/c²	Z' (SM couplings)

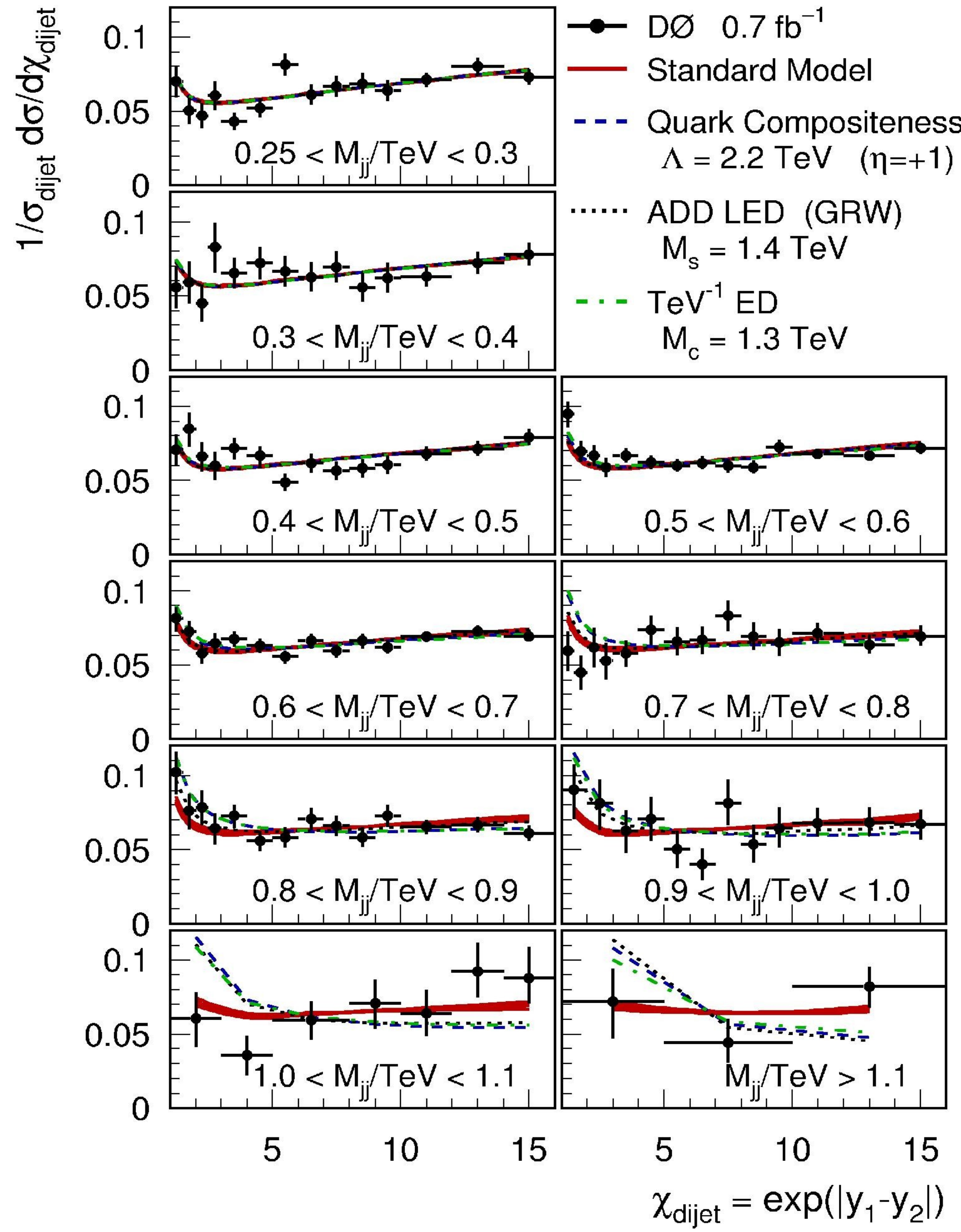
Angular distributions: dijet χ (D0)

- Measure $\chi = \exp(|y_1 - y_2|)$ in 10 regions of dijet mass with M_{jj}>250 GeV (last bin: >1.1TeV)
- Good agreement with NLO pQCD(MSTW2008)
- Data are used to set limits on the models of
  Quark compositeness: ~ 3 TeV,
  TeV-1 extra dim. : ~1.6 TeV
  ADD extra dim. :~1.3-1.9 TeV (dep. on Ned)

Large excess at small △y is expected in QC and ED models

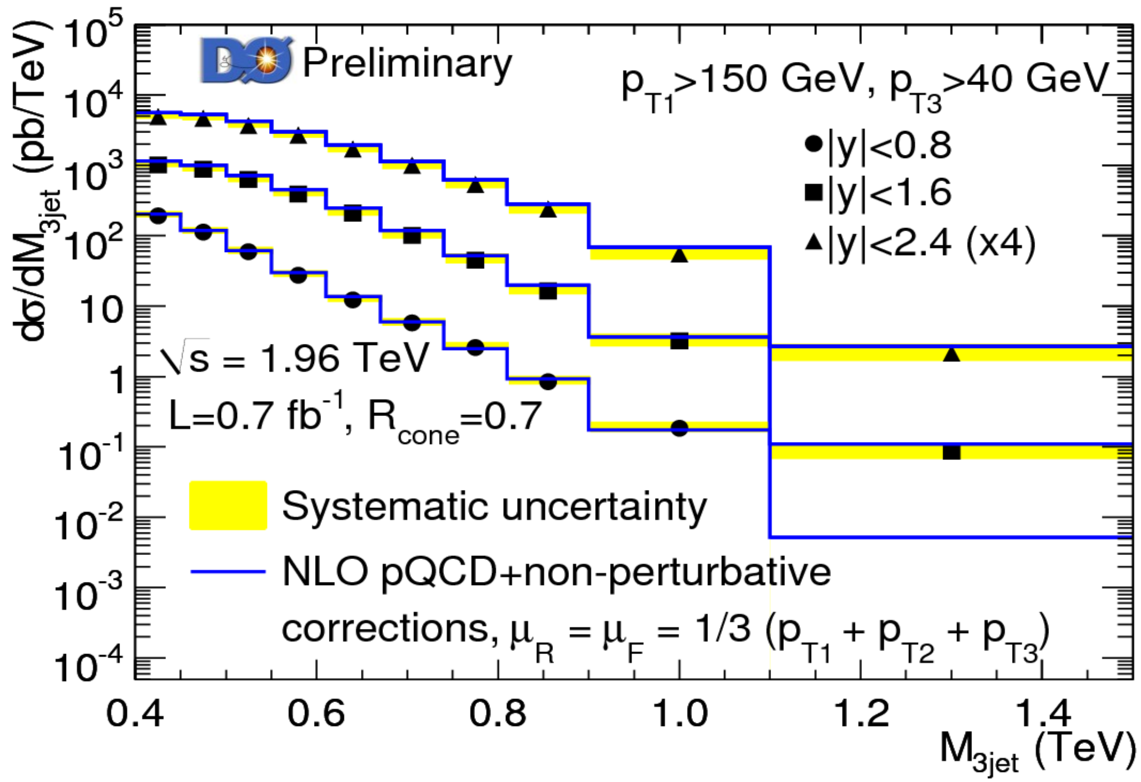


PRL 103, 191803 (2009)



Three jet mass cross section (D0)

Preliminary

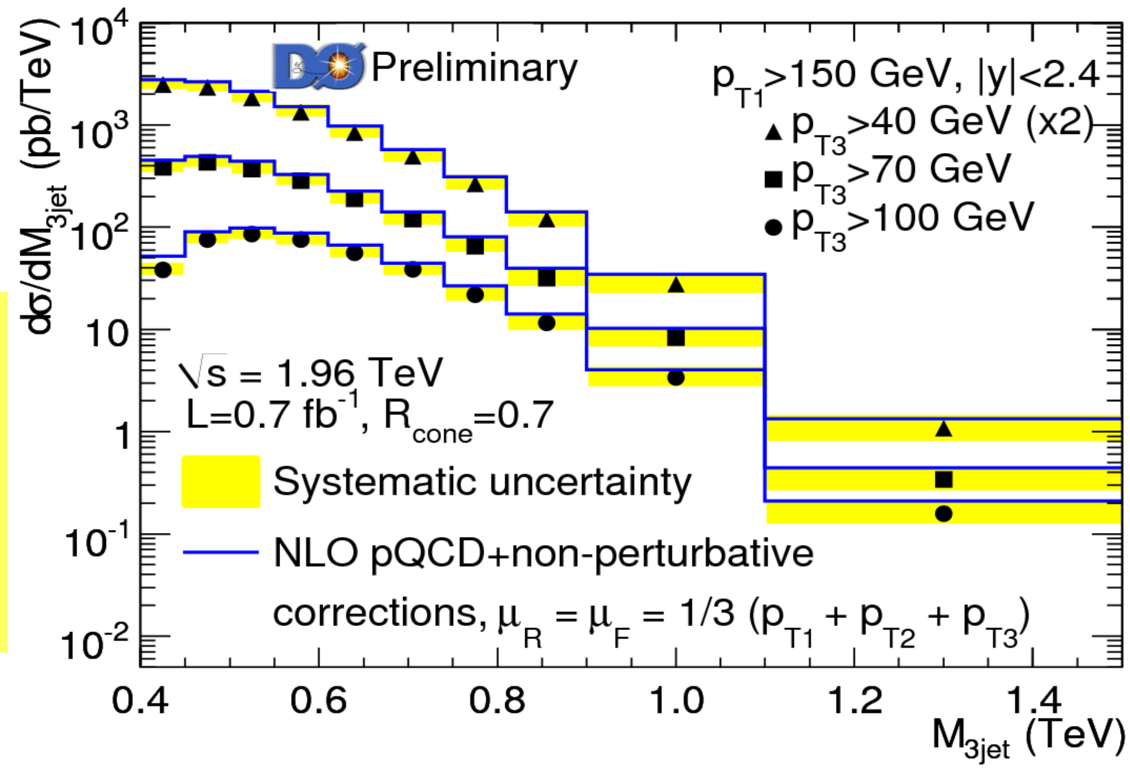


Differential measurements of 3-jet mass:
p_T^{lead}>150 GeV, p_T^{3rd} >40 GeV; ΔR_{jj}>1.4

– Studies Invariant masses > 1 TeV !

– Measurement is done in 3 rapidity and pT Intervals of 3rd jet.

– Three-jet calculation available @NLO
Used NLOJET++ 4.1.2 with MSTW2008
Default scale mu = 1/3(pT1+pT2+pT3)



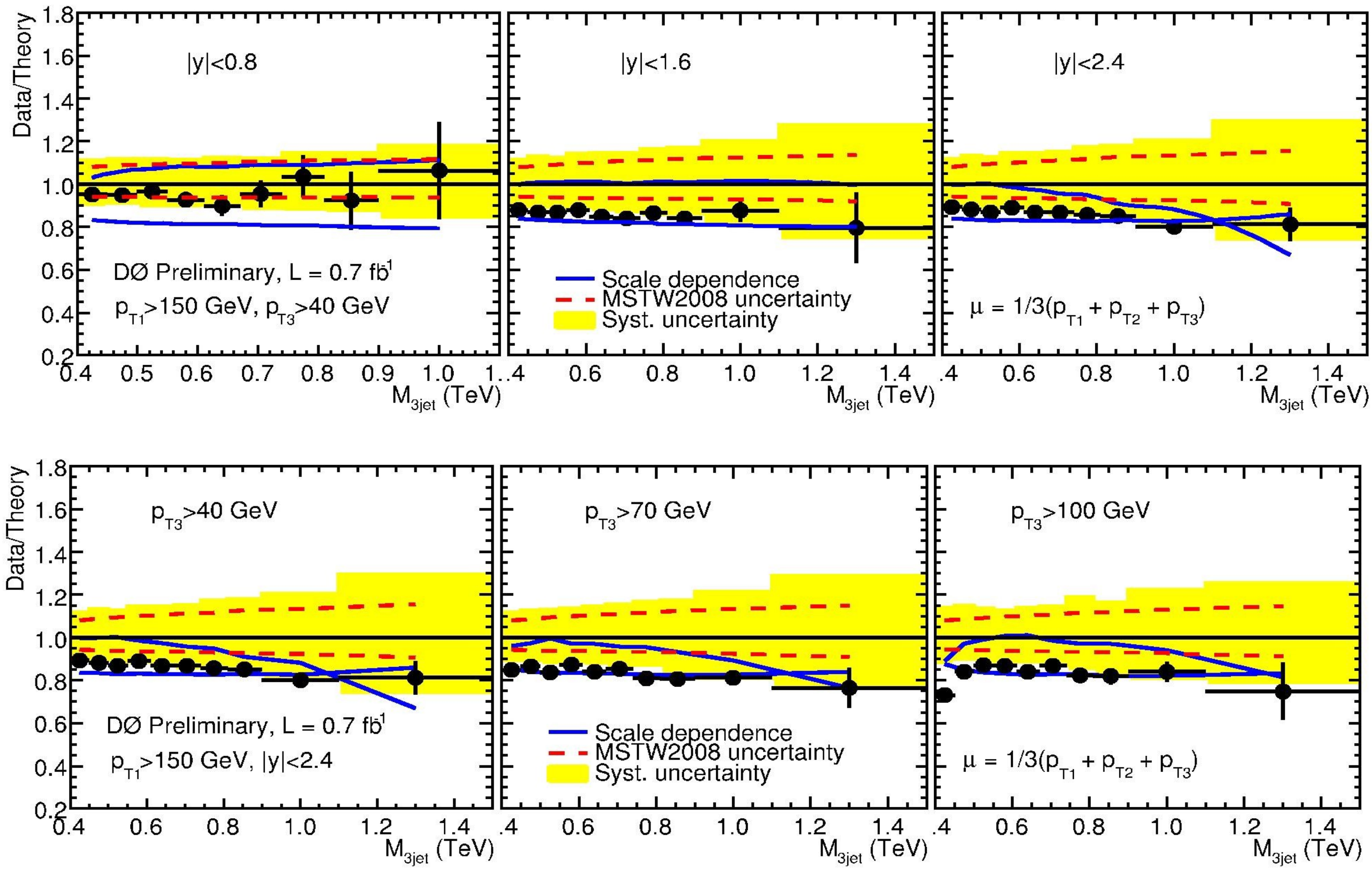
– NLO non-perturbative corr.: -3%,+6%

– Total systematic uncertainty: 20-30%
(dominated by JES, p_T resolution and lumin.)

Three jet mass cross section (D0)

Differential in rapidity

Differential in jet p_T



– Reasonable agreement seen between data and NLO
(scale uncertainty: variation of the default scale by a factor 2)
– More 3-jet variables can be studied in future with this dataset.

Ratio of 3 to 2 jet production cross sections (D0)

Preliminary

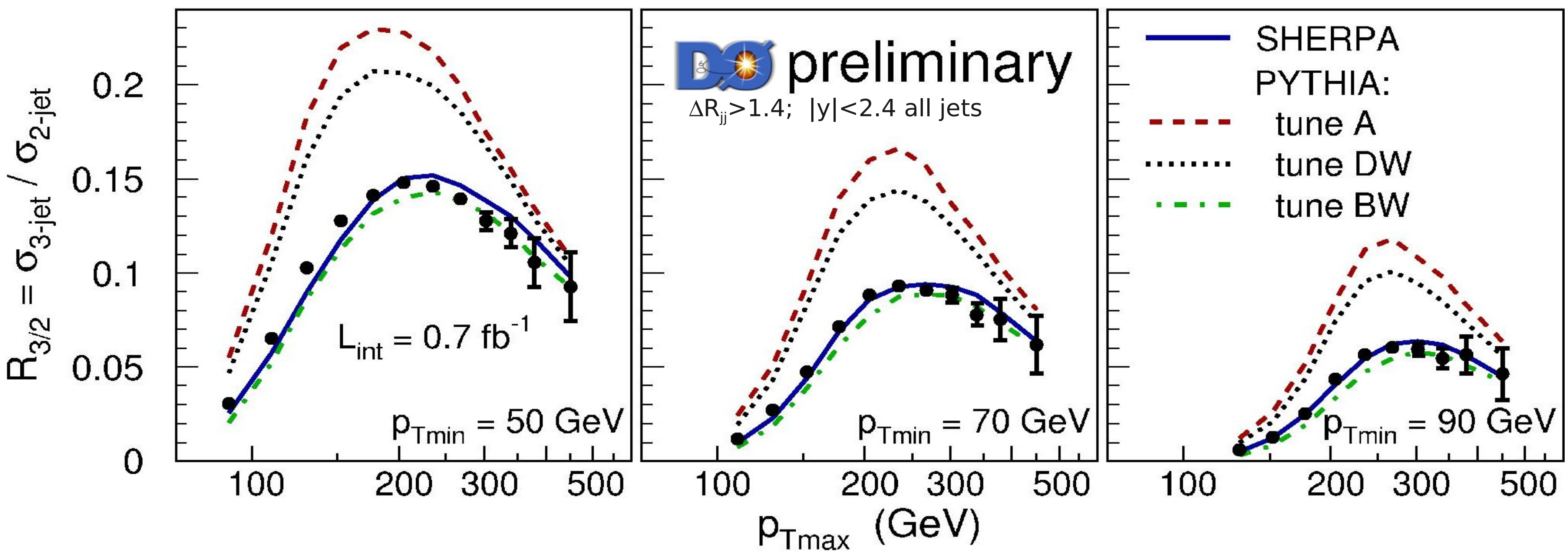
– First measurement of ratios of multijet cross-sections at Tevatron
– Test of QCD almost independent of PDFs
– Many experimental uncertainties also cancel in the ratio $R_{3/2}$.

– Measure as a function of two momentum $R_{3/2}(p_{Tmax}, p_{Tmin}) = P(3^{rd}\text{ jet} \mid 2\text{ jets})$:

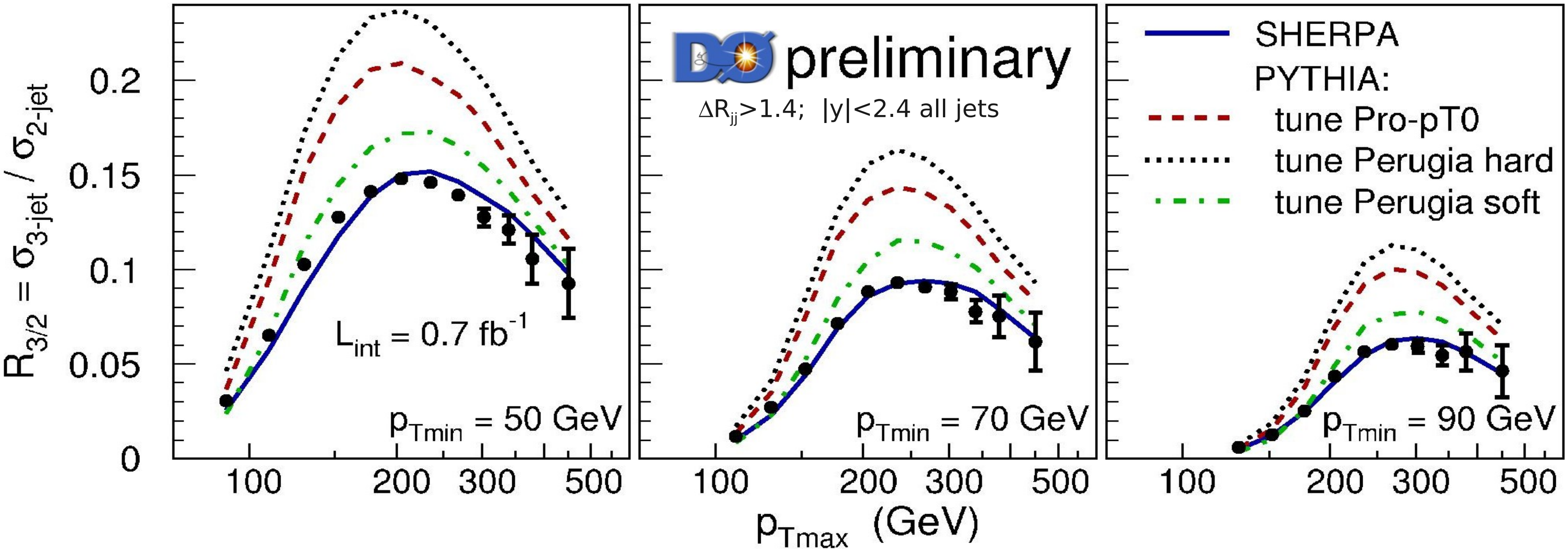
p_{Tmax} – leading jet p_T (common between 2- and 3-jet productions)

p_{Tmin} – scale at which other 1-2 jets resolved

→ Probes running of α_s in Tevatron energy regime up to p_T of 500 GeV



Ratio of 3 to 2 jet production cross sections (D0)



– Experimental corrections small everywhere: (-10%,+20%)
Dominated by systematics below pT_{max} 250—300 GeV :
JES 3—5%, model-dependent corrections 2—6%, pT-resolution 1.5%

– Excellent agreement to Sherpa 1.1.3 (MSTW2008 LO)
– Pythia tune QW, re-weighted to describe the dijet χ data (slide 15), does not describe the $R_{3/2}$ data; tension with the azimuthal decorrelation results [PRL 94, 221801 (2005)]: Tune DW does not work here, while BW works.

– Future studies: NLO pQCD comparisons (coming); extract α_s(pT)

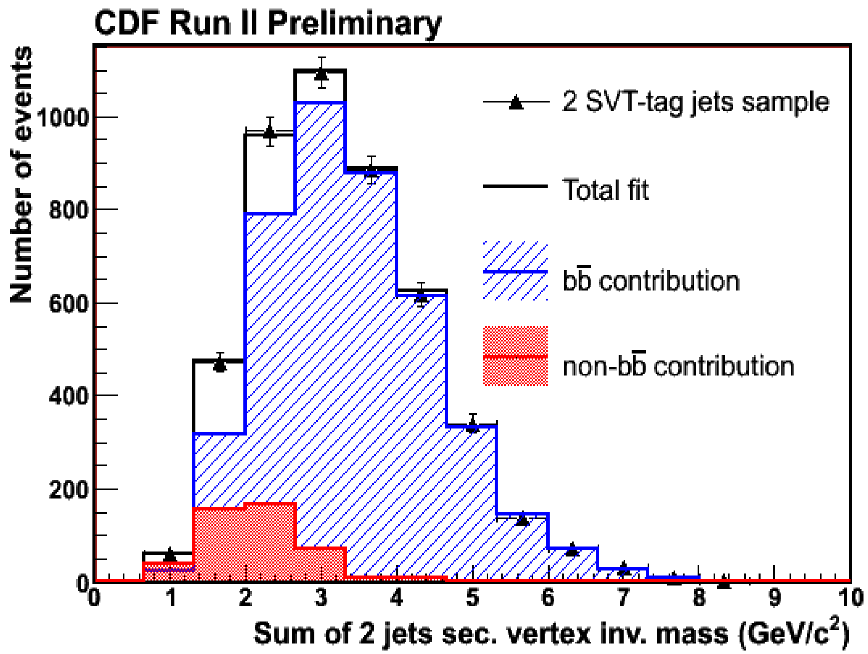
b-bbar Dijet Production (CDF)

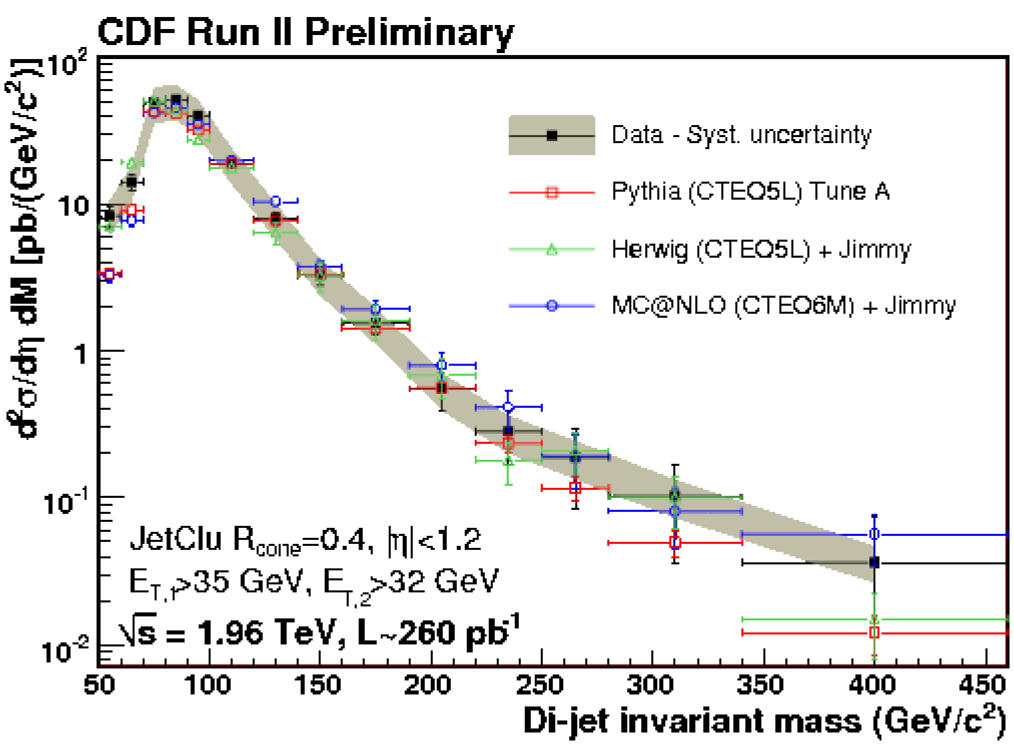
- Preliminary cross section results with L = 260 pb-1
- jet pT>35 and 32 GeV, |eta|<1.2
- The purity of b-bbar events is calculated using SVT track mass; purities in the mass/$\triangle\Phi$ bins are 75-90%
- Comparison with Pythia (tune A), Herwig+Jimmy and MC@NLO+Jimmy:

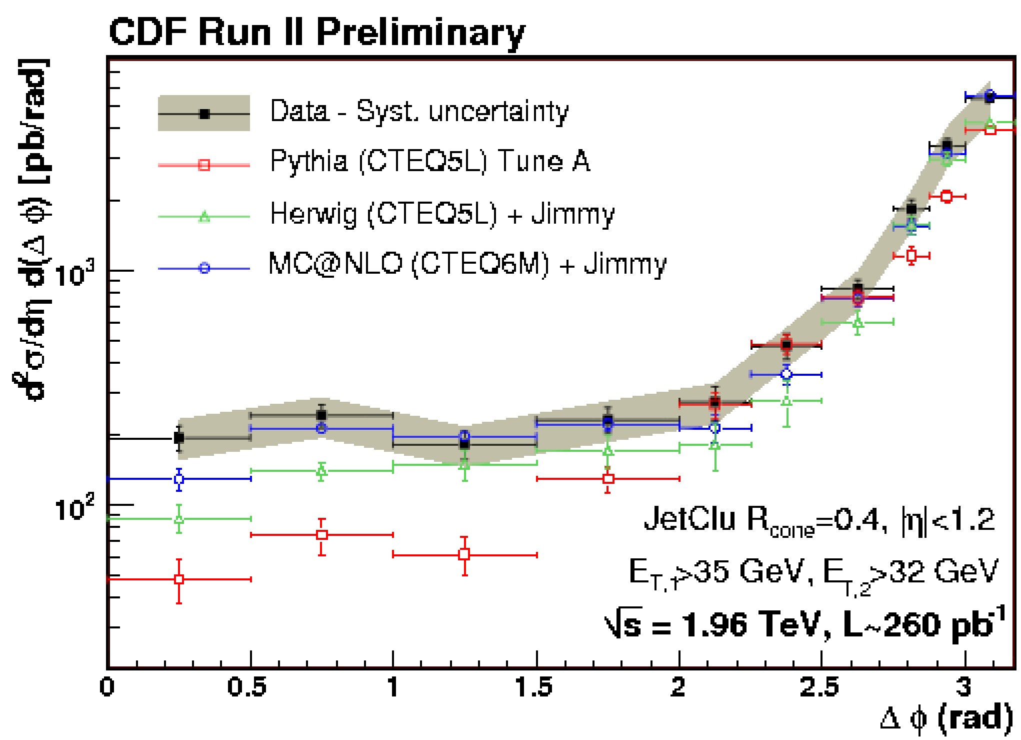
Data: σ = 5664 ± 168(stat) ± 1270 (syst) pb
Pythia: σ = 5136 ± 52(stat)
Herwig: σ = 5296 ± 98(stat)
MC@NLO: σ = 5421 ± 105(stat)

- Tested: lead.jet pT, dijet mass, $\triangle\Phi$; good agreement
- Discrepancy with MC gen. predictions at small $\triangle\Phi$.

Preliminary



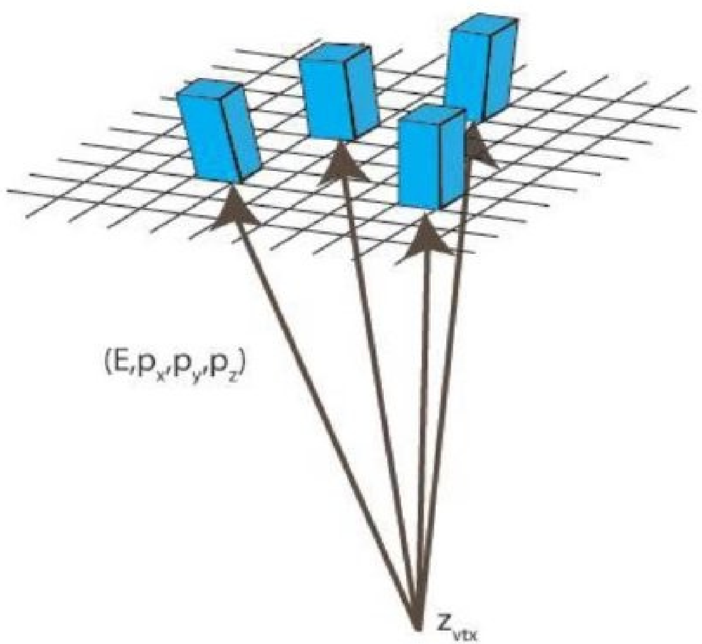




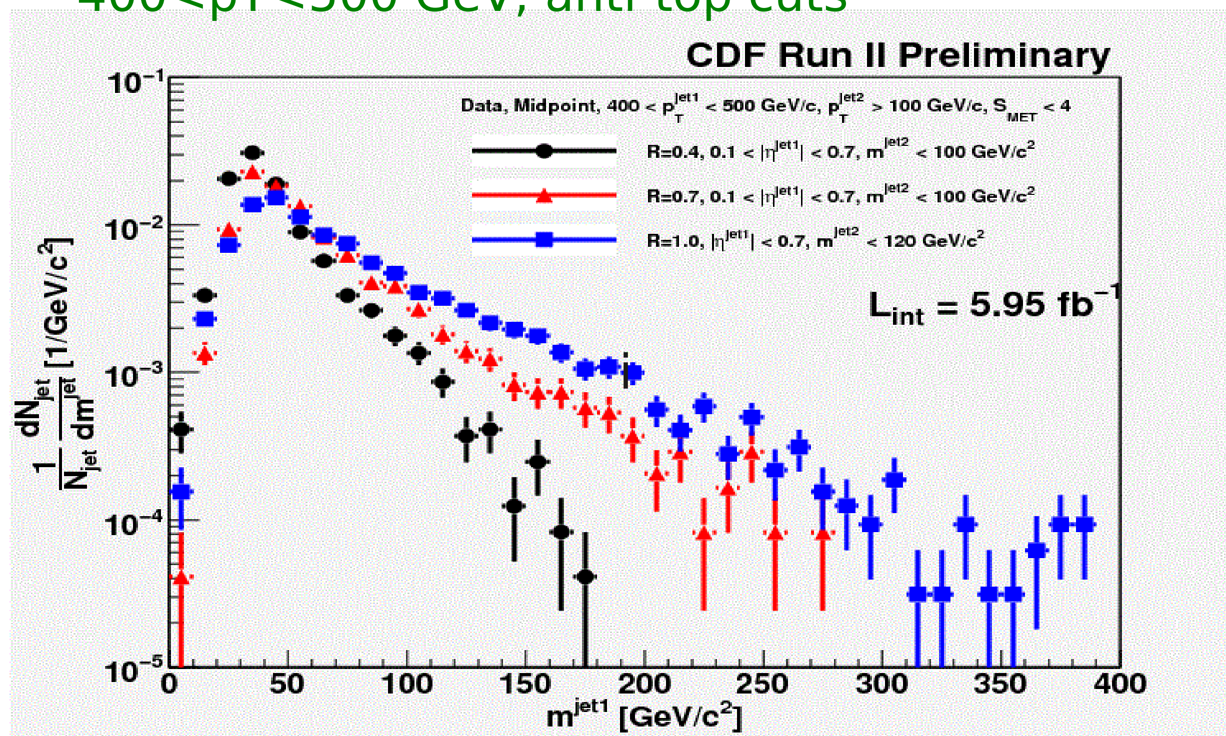
Structures of high pT jets (CDF)

Preliminary, July 2010

- Motivation: (a) test of QCD, tuning parton showering mechanism
  (b) such jets are significant background to new physics searches with a heavy resonance decay (Higgs, neutralinos, high pT top-quarks)
  => See also Steve Ellis' talk yesterday at LPC on the related topic.
- Mass is calculated using standard E-scheme: 4-vector sum over towers in a jet, which gives (E,px,py,pz)
- Angularity and planar flow variables study the jet substructure; quite robust against soft radiation, less dependent on the jet algorithm used.
- Selections: ≥1 jet with pT>400 GeV, 0.1<|y|<0.7: 3136 (3621) events, jet R=0.4(0.7)
  anti-top: m_jet2<100 GeV and S_met < 4 and pT_jet2>100 GeV



400<pT<500 GeV, anti-top cuts

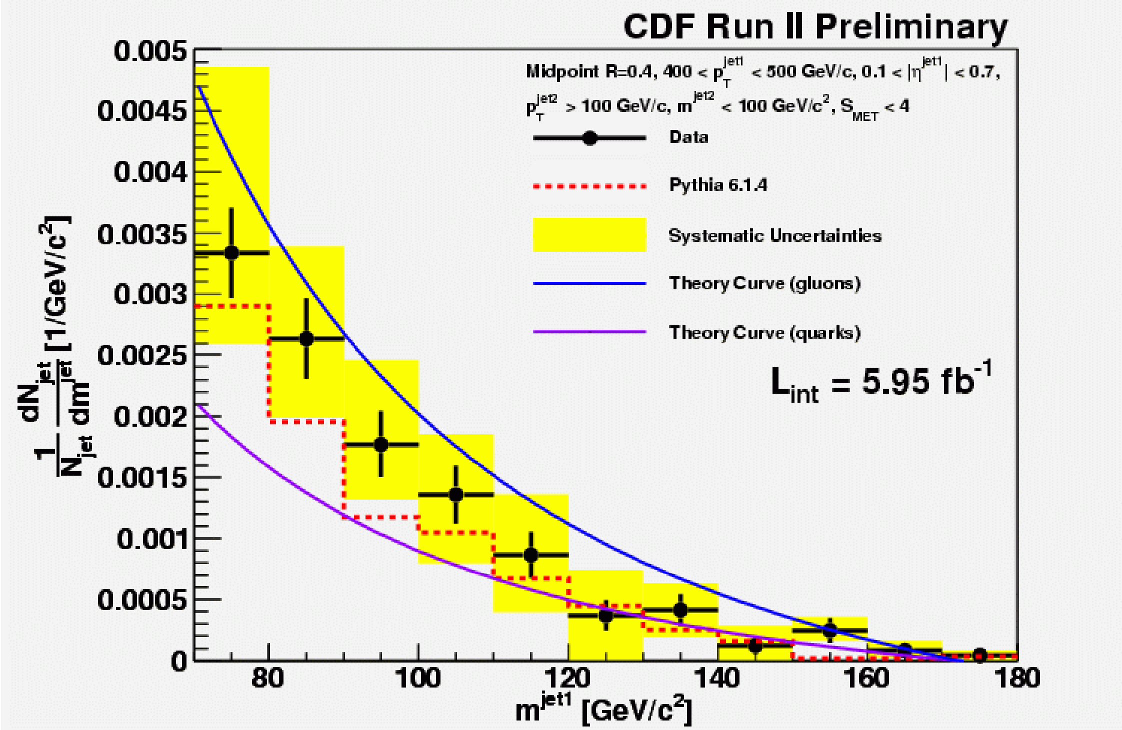


Mass of high pT jets: comparison with theory (CDF)

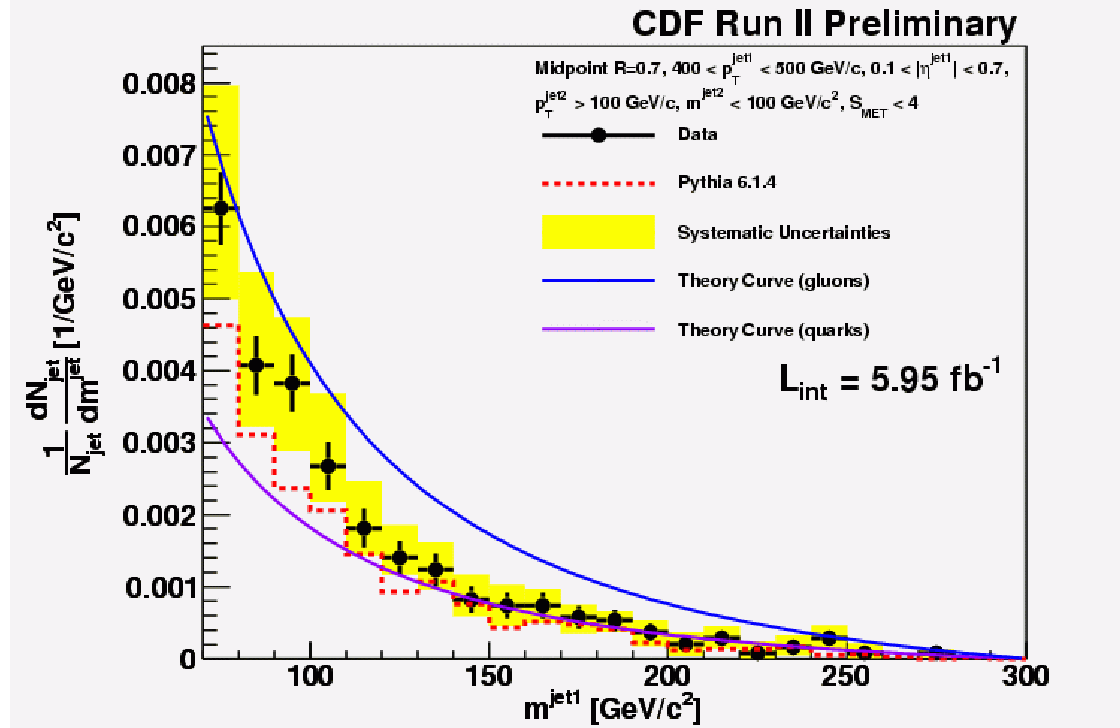
– Good agreement between data and LLA QCD and Pythia predictions over jet mass range 70-250 GeV and for both jet cones, R=0.4 and 0.7.

– Data interpolate between QCD predictions for quark and gluon jets; about 80% of jets are caused by quark fragmentation.
(Please see more on the theory in 0807.0234, 0810.0934)

R = 0.4



R = 0.7



Angularity and planar flow (CDF)

– Angularity: sum over calorimeter towers:

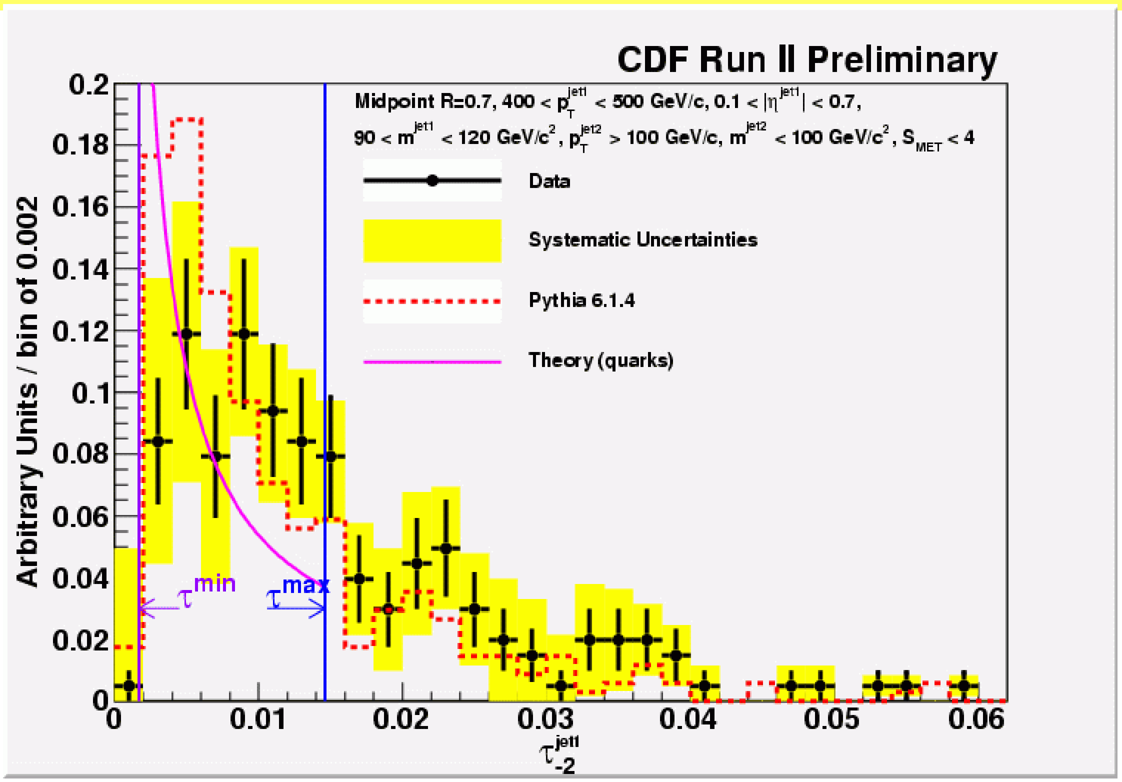
$$\tau_a(R, p_T) = \frac{1}{m_J} \sum_{i \in jet} \omega_i \sin^a \theta_i \left[1 - \cos\theta_i\right]^{1-a} \sim \frac{2^{a-1}}{m_J} \sum_{i \in jet} \omega_i \theta_i^{2-a}$$

where w_i is energy of a jet tower (particle)

– It is sensitive to the degree of symmetry in the energy deposition inside a jet: can distinguish jet originating from regular QCD production of light quarks and gluons from boosted heavy particle decay.

– Data show fewer jets at lower angularity, i.e. prefer more 'spherical' jets.

– Jet planar flow (see slide 31 for definition) was also studied: at high jet masses (140-200) data prefer more aplanar configuration than QCD prediction.



Summary

- A few last Tevatron jet results are presented: current level of understanding jet ID, systematics and jet energy scale leads in many cases to experimental uncertainties similar or lower than theory uncertainties.

- Inclusive jet cross-sections: precision measurement due to well-calibrated JES, extended to higher rapidities and transverse momenta up to 600 GeV
  - results are used to limit high x gluon PDF
  - extracted $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$
  - detailed studies of the effect of different jet algorithms: can be important for LHC

- Dijet measurements of (dijet mass and angular): good agreement with pQCD, limits on quark compositeness, extra dimensions and other models

- Three-jet mass: reasonable agreement with NLO QCD

- Ratio of 3-to-2 jet cross-sections: good agreement with Sherpa and Pythia tune BW (the 'best' tune is not consistent with other D0 dijet angular measurements)

- Di-b-jet production: good agreement in pT, mass, but some discrepancy with the considered MC predictions at small $\triangle\Phi$.

- Mass of high pT jets: data show more aplanar and spherical jets than QCD predicts.

BACK-UP SLIDES

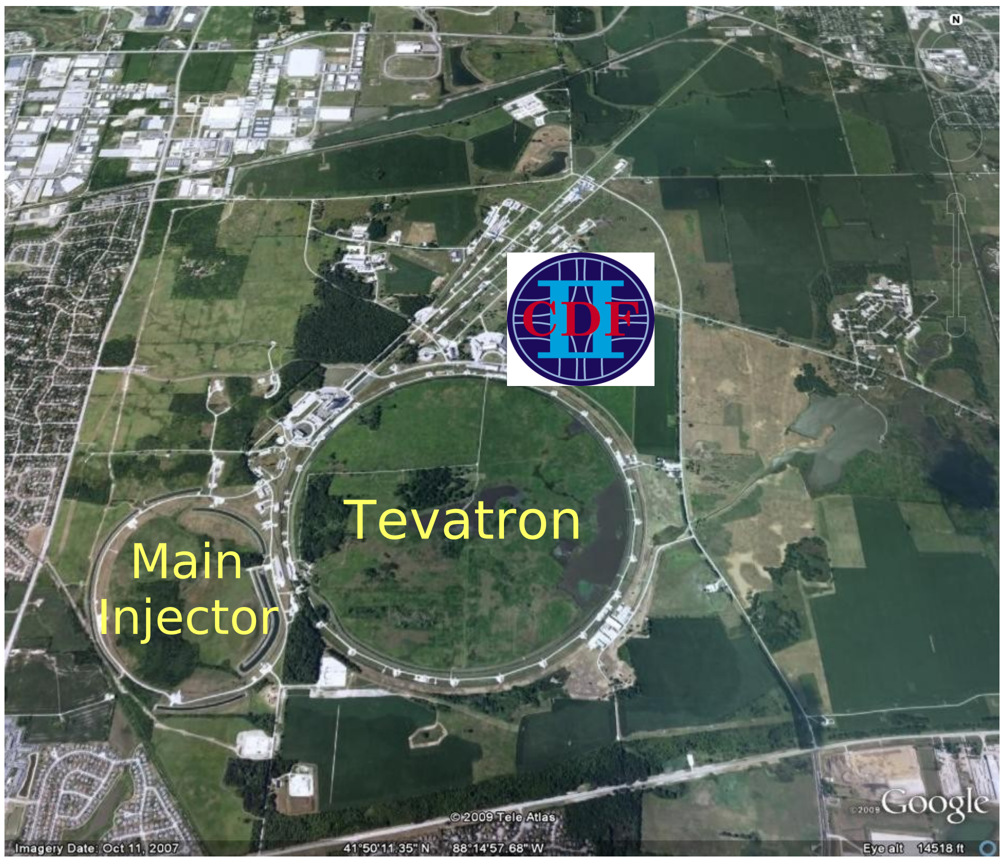
Fermilab Tevatron Run II

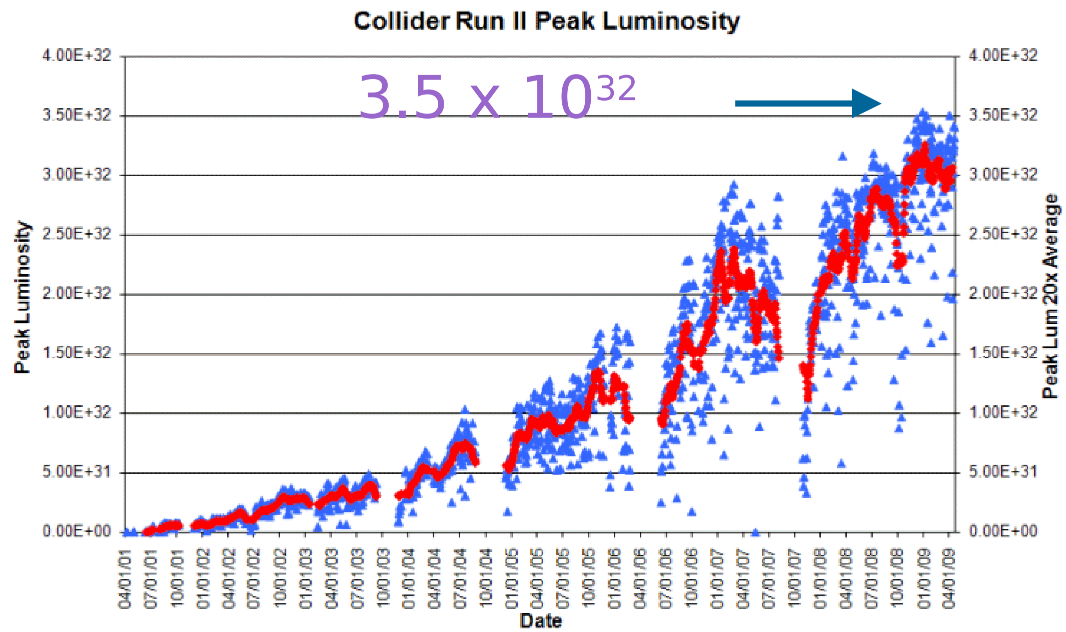
$\sqrt{s}$ = 1.96 TeV

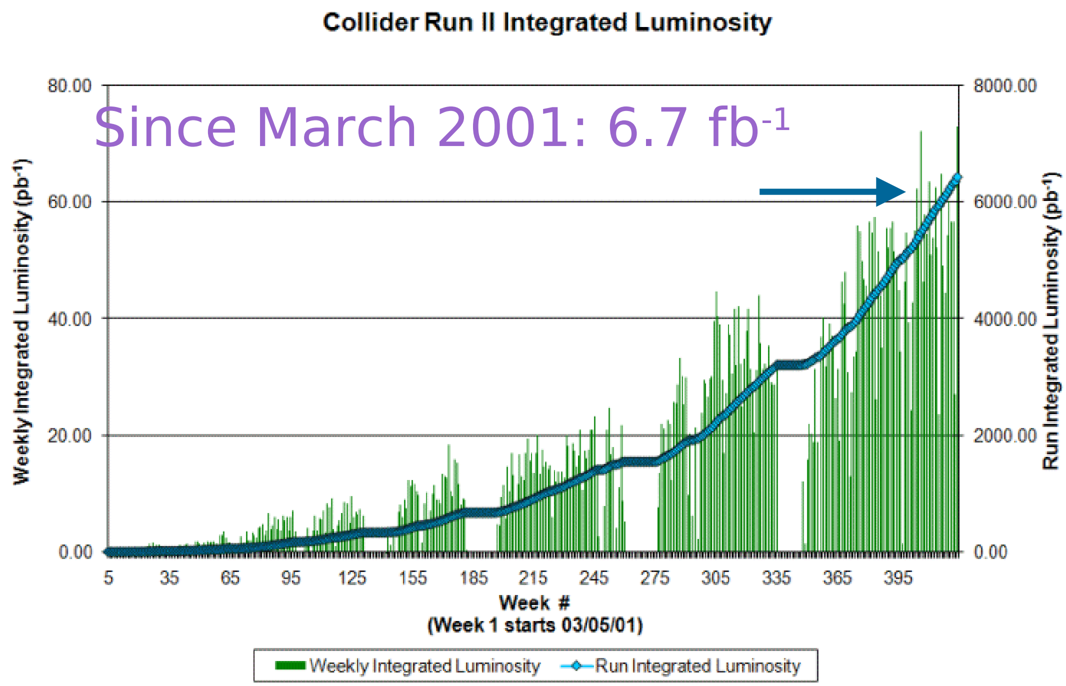
Peak Luminosity: 3.5×10^{32} $cm^{-2}s^{-1}$

About 6.7 fb^{-1} delivered

Experiments typically collect data with 80-90% efficiency







D0 RunII Midpoint Jet Cone Algorithm

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

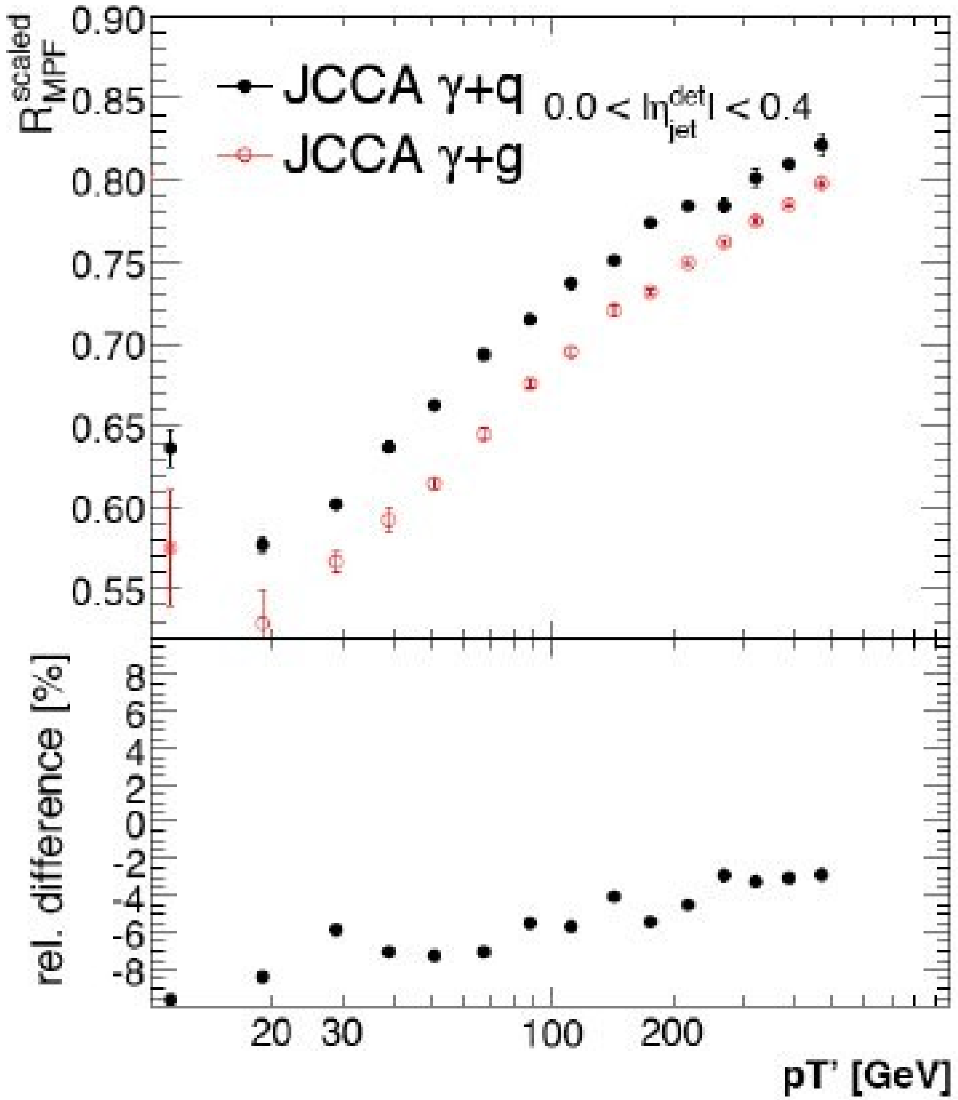
three parameters: $R_{\text{cone}} = 0.7$, $p_{T\,\text{min}} = 8$ GeV, overlap fraction $f = 50\%$

- Use all particles as **seeds**
  — make cone of radius $\Delta R = \sqrt{(\Delta y^2 + \Delta\phi^2)} < R_{\text{cone}}$ 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** $\Longrightarrow$ infrared safety!!!
  — (repeat procedure as described above)

- Take all solutions from the first two steps:
  — remove identical solutions
  — remove proto-jets with $p_{T\,\text{jet}} < p_{T\,\text{min}}$
- Look for jets with **overlapping cones**:
  — merge jets, if more than a fraction f of $p_{T\,\text{jet}}$ is contained in the overlap region
  — otherwise split jets: assign the particles in the overlap region to the nearest jet
  ($\rightarrow$ and recompute jet-axes)

Difference between quark and gluon responses

Responses in the calorimeter for quark and gluon jets are different
=> Different corrections are need depending on final state
(dijet events are dominated by the gluon jets, ttbar ones are quark dominated, etc)



JCCA – midpoint cone R=0.7

Fit Method [→ backup]

- Minimize chi2 (used in many PDF fits, dijet angular PRL)

$$\chi^2(\xi,\vec{\epsilon},\vec{\alpha}) = \sum_i \frac{\left[d_i - t_i(\xi,\vec{\alpha})\left(1+\sum_j \delta_{ij}(\epsilon_j)\right)\right]^2}{\sigma^2_{i,\mathrm{stat.}} + \sigma^2_{i,\mathrm{uncorr.}}} + \sum_j \epsilon_j^2 + \sum_k \alpha_k^2$$

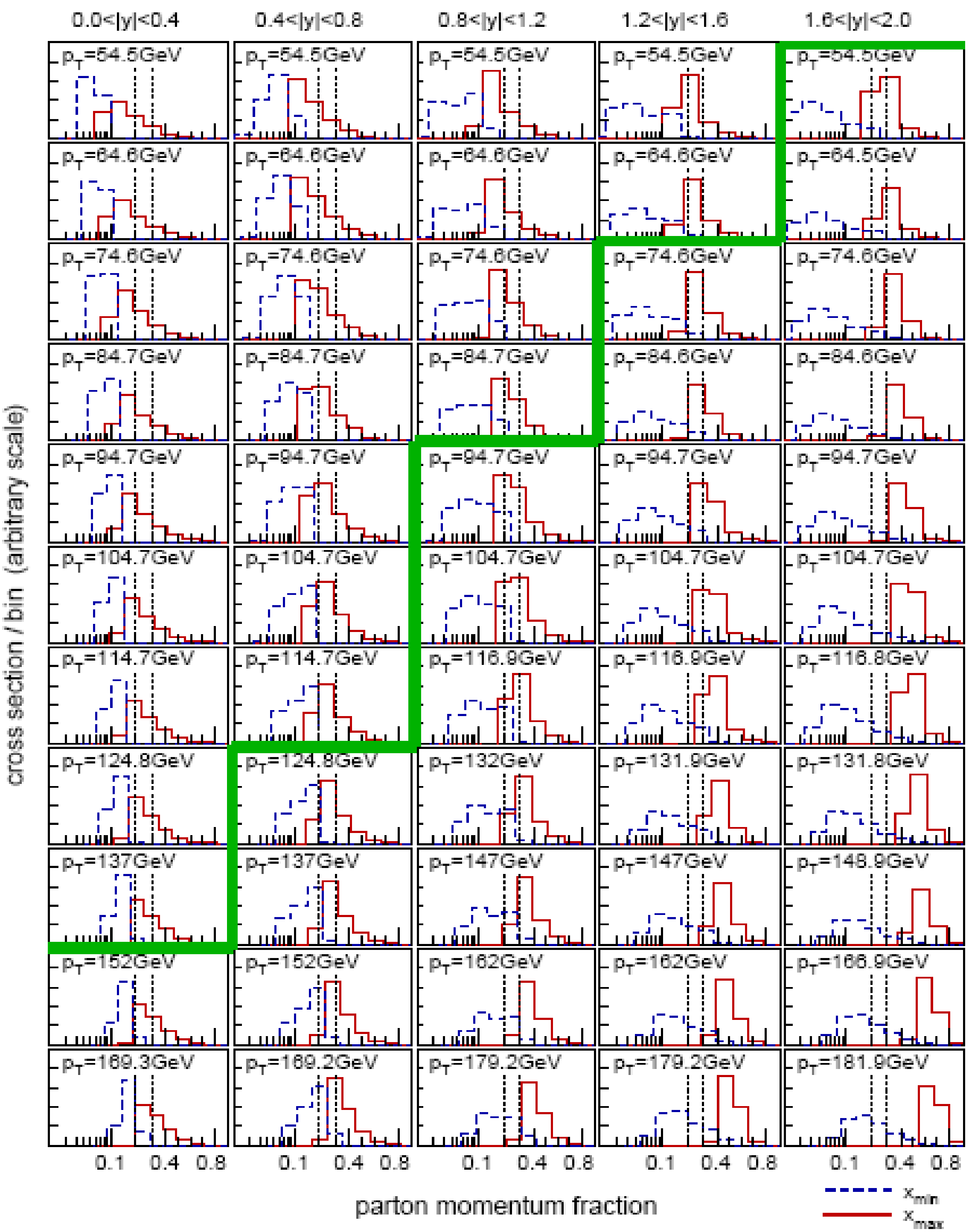
→ 23 experimental correlated sources of uncertainty
→ non-perturbative corrections uncertainties
→ PDF uncertainties

Separate treatment for **renormalization and factorization scales** (convention from LEP, HERA):

- perform fits for fixed scale
- repeat for scale factors 2.0, 0.5
- quote differences as 'scale uncertainty'

→ does not assume Gaussian distributed scale uncertainties

x-min / x-max distributions



Every analysis bin is one plot

Each plot: x-min & x-max distributions

x-min/max = min/max (x1, x2)

- What is the x-value for a given incl. jet data point @(pT, |y|) ?

→ Construct 'test-variable' (treat as if other jet was at y=0):

$$x\text{-test} = xT[\ \exp(|y|) + 1\ ] / 2$$

- Cut on test-variable x-test < 0.15

→22 data points remain

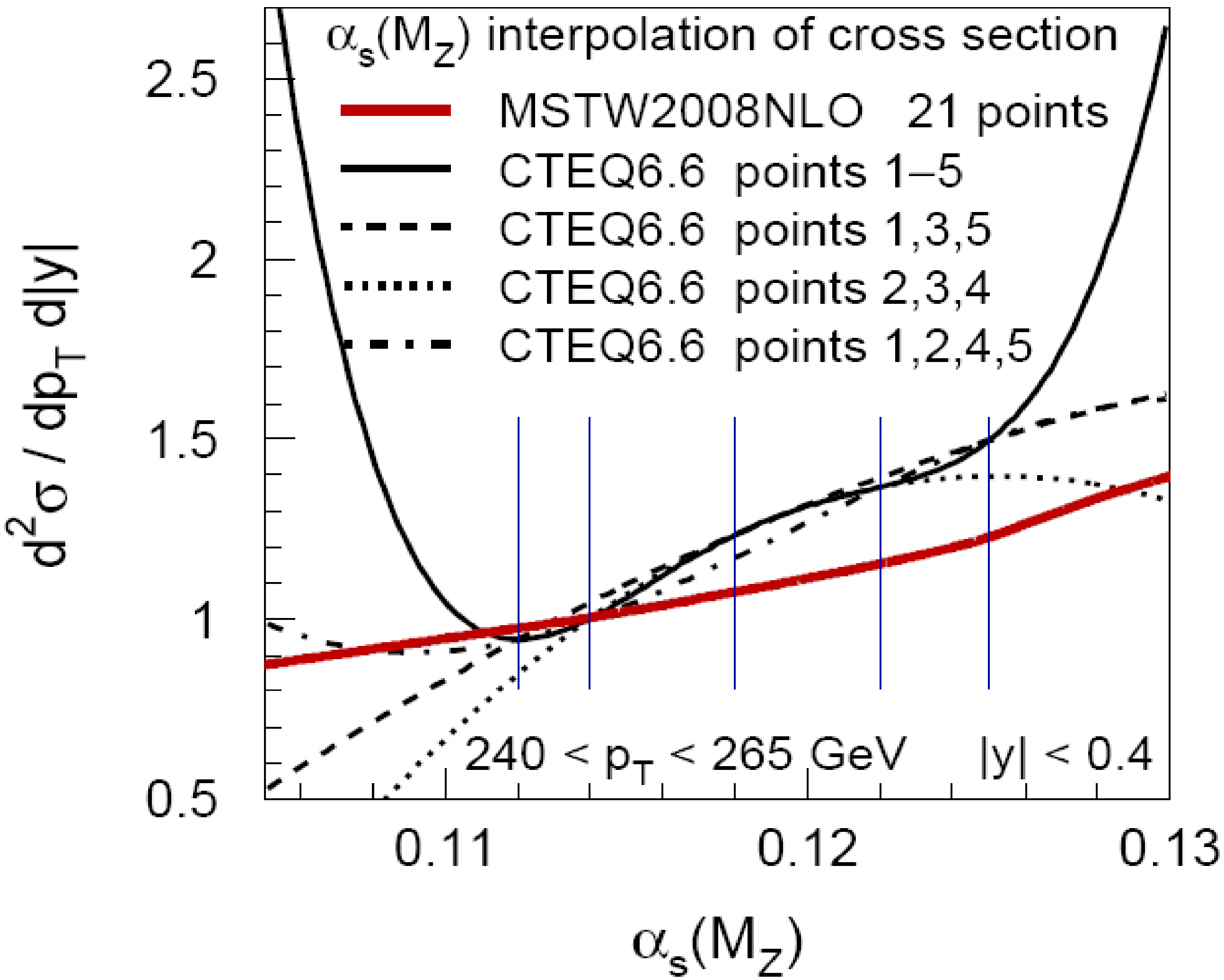
→ It corresponds to data points with x-max peaking at x-max<0.2

→The data points have small contributions from x>0.2-0.3

← Only data points above green line are used

alphas dependence of PDFs

Compare cross section interpolations for MSTW2008 and CTEQ6.6



For MSTW2008:
nice & smooth interpolation

CTEQ6.6:
Significant differences between different interpolations.
No obvious preference
(maybe points 1,3,5 because of monotonic behavior – but can't be justified)

→ Can not justify to use CTEQ6.6
→ But MSTW2008 is o.k. → provide NNLO

Angularity and planar flow (CDF)

– Planar flow is another jet substructure variable:

$$I_w^{kl} = \frac{1}{m_J} \sum_i w_i \frac{p_{i,k}}{w_i} \frac{p_{i,l}}{w_i} \qquad Pf = 4\frac{\det(I_w)}{\mathrm{tr}(I_w)^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$$

where w_i is energy of a jet tower (particle), p_i,k is a k-th component of transverse momentum relative to the jet momentum axis; λ_1,2 is eigenvalue of the matrix I_w.

– ***Pf*** should vanish for linear shapes and close to unity for isotropic depositions of energy.

– At high jet masses (140-200 is considered) data prefer more aplanar configuration than QCD prediction (anti-top cuts are applied).