

High E_T jet physics at the Tevatron

Thomas Nunnemann

Ludwig-Maximilians-University, Munich

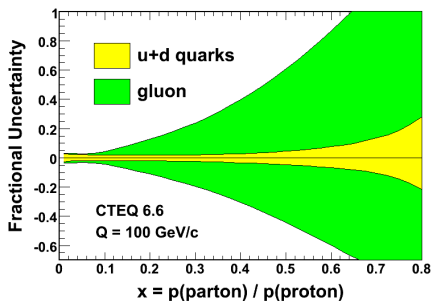
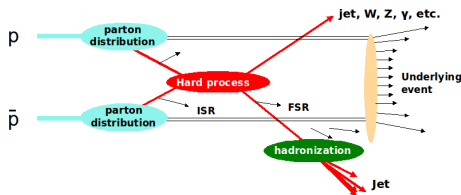
PIC 2010

Karlsruhe, 2.9.2010



High E_T jet production at hadron colliders

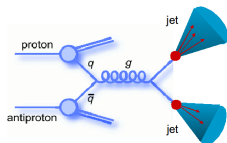
- test perturbative QCD
- constrain structure of the proton
 - parton distribution functions (PDFs)
 - gluon (← incl. jets)
 - heavy flavor (← $W/Z/\gamma^* + \text{HF}$)
- measure important backgrounds to searches for Higgs, Supersymmetry, and other new physics
 - processes with large jet multiplicities only calc. to LO → large uncert.
 - provide data to constrain models, to tune event generators to be used at Tevatron and LHC
 - especially important: $W/Z + \text{jets}$
- search for new phenomena in signatures with jets (e.g. resonances)



Outline

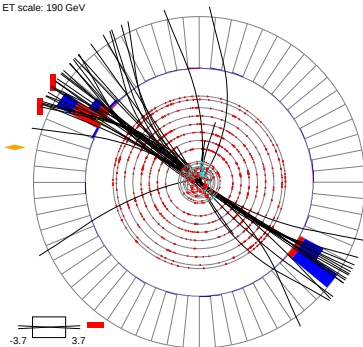
- ▶ jet reconstruction and energy scale calibration
- ▶ measurements of jet production
 - ▶ inclusive jets, dijets, trijets
 - ▶ α_s and PDF extraction
 - ▶ searches for physics beyond the standard model
- ▶ measurements of $W/Z/\gamma^* + \text{jet production}$
 - ▶ jets of any flavor
 - ▶ b and c quark jets

Jet reconstruction

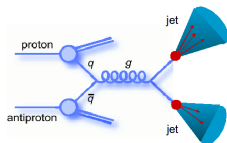


Run 162592 Event 5490755 Fri Oct 25 11:57:39 2002

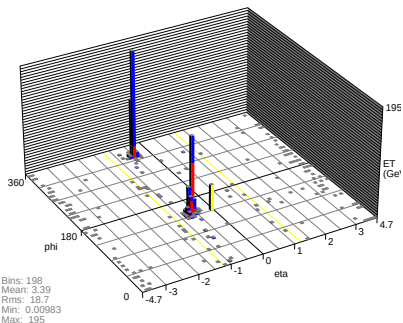
ET scale: 190 GeV



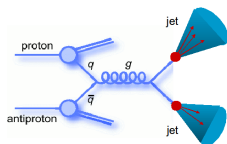
Jet reconstruction



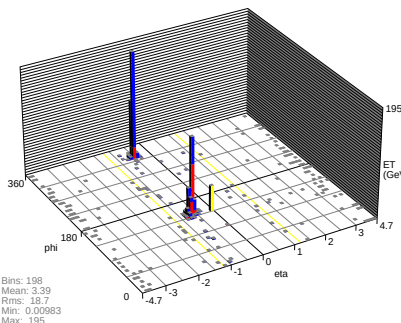
Run 162592 Event 5490755 Thu Oct 24 13:54:25 2002



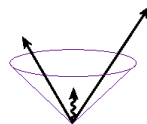
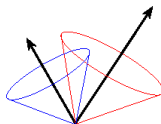
Jet reconstruction



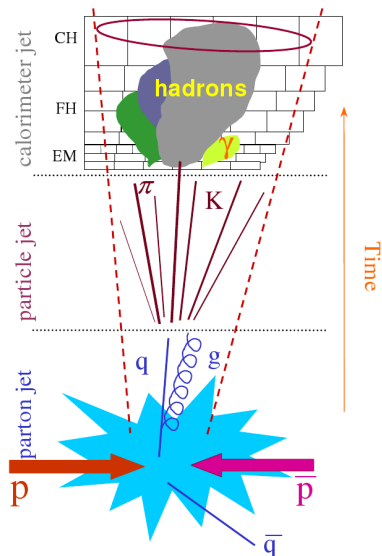
Run 162592 Event 5490755 Thu Oct 24 13:54:25 2002



- ▶ standard jet reconstruction algorithm at Run II: seeded, iterative, **midpoint cone algorithm**
 - ▶ use particles (calorimeter tower) as seeds
 - ▶ add particles within cone using 4-vectors (E -scheme)
 - ▶ iterate until stable
 - ▶ use mid-points between jets as additional seeds
 - improved infrared stability
 - ▶ split/merge jets with overlapping cones



Jet production and measurements



- ▶ unfold measurements to the hadron (particle) level
 - ▶ need jet energy scale calibration and energy resolution



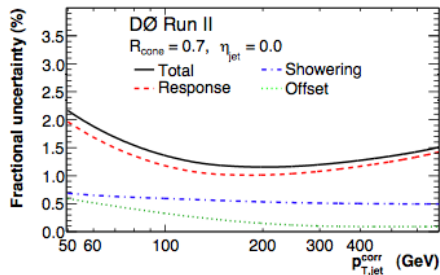
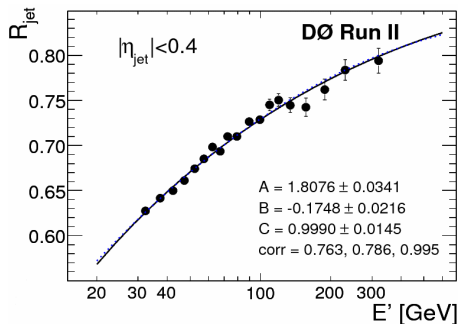
data-theory comparison at hadron (particle) level



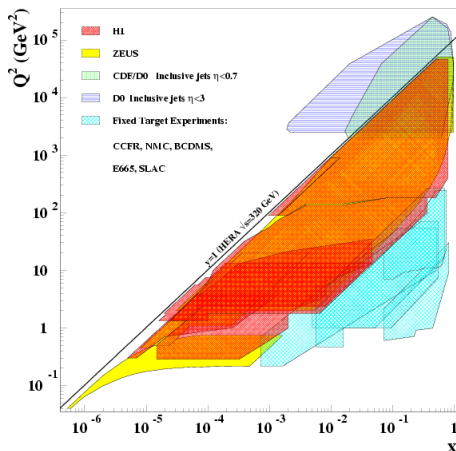
- ▶ correct parton-level theory for non-perturbative effects
 - ▶ fragmentation/hadronization, underlying event

Jet energy scale (JES) calibration

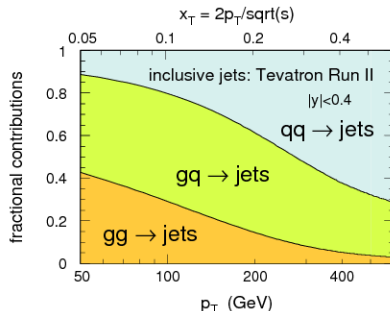
- ▶ $E_{\text{particle}} = \frac{E_{\text{cal}} - O}{R \cdot S}$
 - ▶ E_{cal} : measured energy (calorimeter, at EM scale)
 - ▶ O : offset energy: noise from electronics, uranium, pileup, multiple collisions
 - ▶ R : calorimeter response: determined from E_T -balance in γ +jet events
 - ▶ S : showering correction: net flow of energy in and out of cone
- ▶ **DO**: JES uncertainties as low as 1.2% for central jets with $p_T \sim 100$ GeV
 - ← 7 years of work!



Inclusive jet production



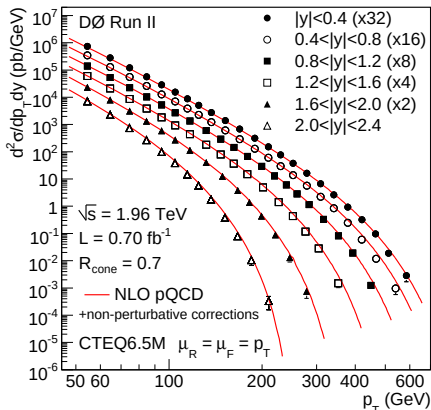
- kinematic reach in (x, Q^2) compared to HERA and fixed target exp.: sensitive to PDFs at large momentum fractions x and scales Q^2
- sensitive to gluon content of the proton



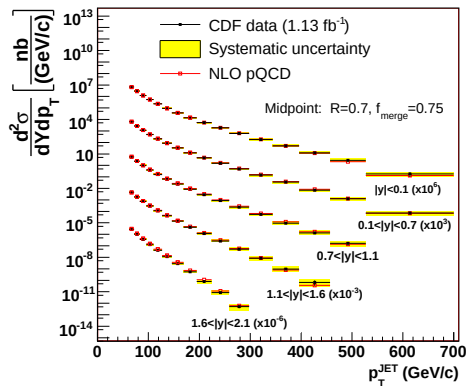


Inclusive jet p_T cross sections

- ▶ measurements of $\frac{d^2\sigma}{dp_T dy}$: tests of pQCD over 8 decades
- ▶ sensitive to new physics at high $p_T(\text{jet})$
 - ▶ benefits from increased Run II energy ($\sqrt{s} = 1.8 \rightarrow 1.96 \text{ TeV}$), e.g. cross section $\times 5$ at $p_T(\text{jet}) = 600 \text{ GeV}$



Phys. Rev. Lett. 101, 062001 (2008)



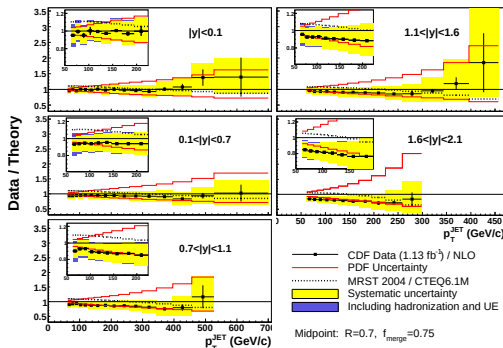
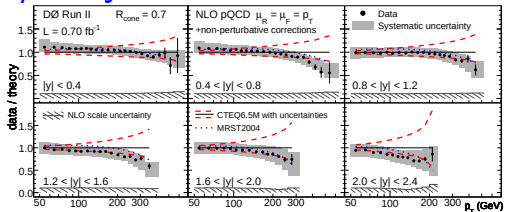
Phys. Rev. D 78, 052006 (2008)



Inclusive jet p_T : data/theory, uncertainties

- both measurements are in agreement with NLO pQCD
 - both data sets favor smaller gluon densities
- exp. systematics (dominated by JES uncertainty) < theory uncert. (mostly PDF)
 - thanks to precise JES
- PDF sensitivity:

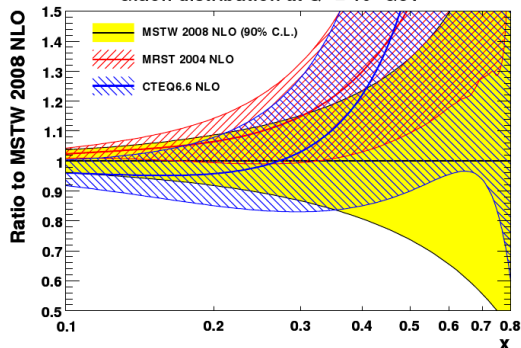
$$x \propto 2p_T/\sqrt{s}$$
- see also: inclusive jets with k_T , CDF, Phys. Rev. D, 75, 092006 15(2007)



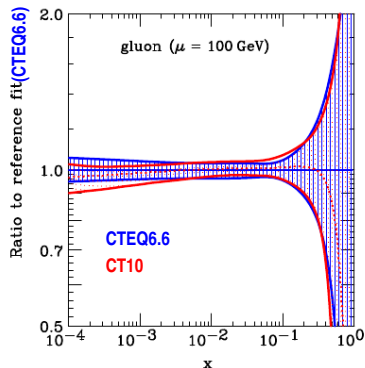
PDF influence of Tevatron data

- ▶ MSTW2008 and CT10 (also CT09) PDF fits include Tevatron Run II inclusive jets
 - ▶ Run II data lead to softer high- x gluons and provide more precise constraints
 - ▶ no visible reduction in PDF uncertainty due to new fit procedures
 - ▶ Run II data more consistent with DIS measurements than Run I

Gluon distribution at $Q^2 = 10^4 \text{ GeV}^2$



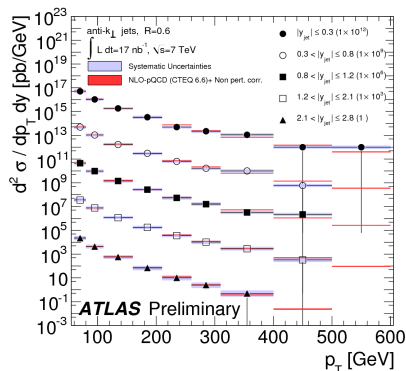
MSTW2008: Eur.Phys.J.C63:189-285,2009



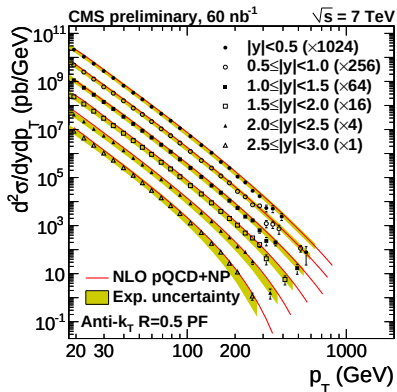
CT10: arXiv:1007.2241

First LHC results

- ▶ inclusive jet cross sections based on first ATLAS and CMS data
- ▶ see Wednesday's talks by Nadia Pastrone and Brian Peterson and poster session
- ▶ both ATLAS and CMS use anti- k_T jets (default algorithm)



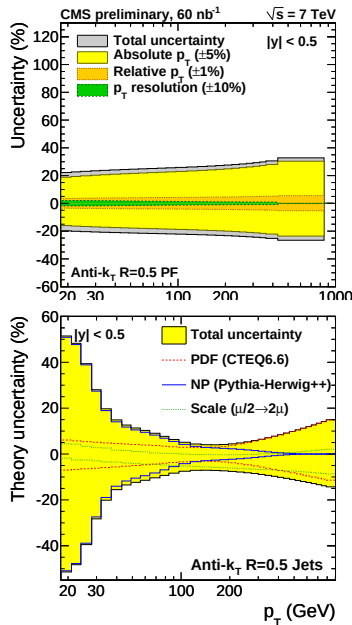
ATLAS-CONF-2010-050



CMS-PAS-QCD-10-011

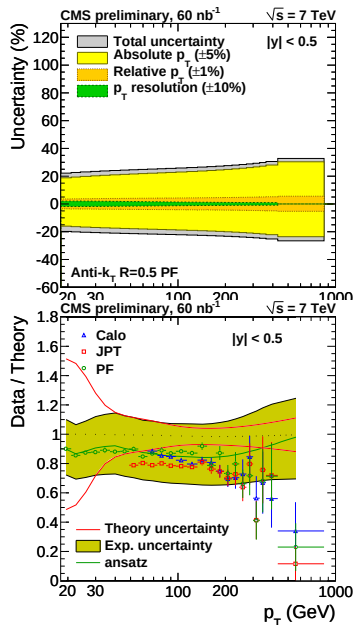
LHC: PDF sensitivity

- ▶ jet energy scale uncertainty largely dominates exp. systematics
 - ▶ conservative estimates: ATLAS: 7%, CMS (particle flow): 5%
 - ▶ expect significant improvements soon, but remember long process at Tevatron
- ▶ theory: NLO pQCD, uncert. dominated by
 - ▶ low p_T : non-perturbative corrections
 - ▶ high p_T : PDF uncertainty
- ▶ for central rapidities, cross section for fixed $x_T = 2p_T/\sqrt{s} \propto x$: $\sigma(\text{LHC}) \ll \sigma(\text{Tevatron})$
 - ▶ Tevatron will still be more sensitive to high- x gluon for several years.



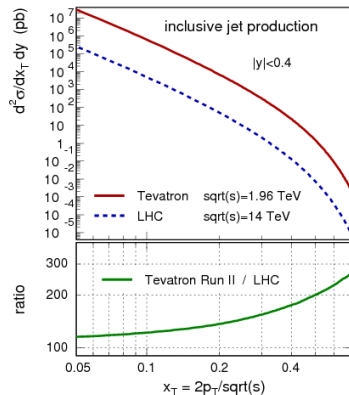
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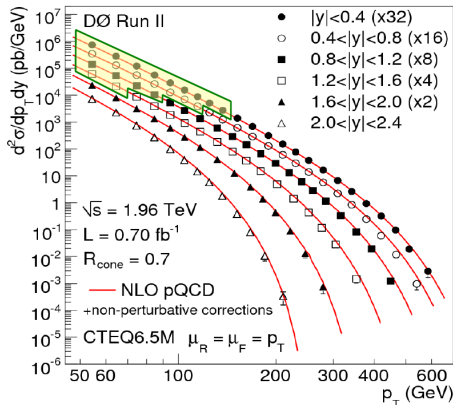
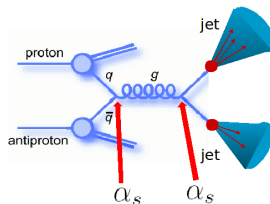
α_s from inclusive jets

- inclusive jet cross section directly related to α_s measurement:

$$\sigma_{\text{theory}}(\alpha_s) = \sigma_{\text{pert}}(\alpha_s) \cdot c_{\text{nonpert}}$$

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

- c_n : NLO pQCD + 2-loop corr.
- $f_{1,2}(\alpha_s)$: MSTW2008NNLO α_s dependent fits:
 $\alpha_s(M_Z) = 0.110 - 0.130$
- keep only 22 (of 110) data points in kinematic region where PDF fit is not dominated by Tevatron:
 $x_{\text{max}} \lesssim 0.25$





α_s from inclusive jets

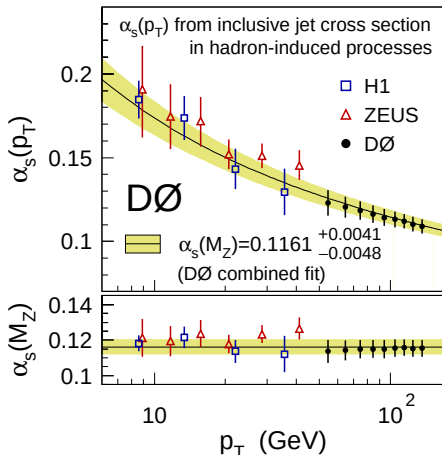
- ▶ measurement of running α_s at highest p_T (together with CDF Run I)
- ▶ most precise determination of α_s from hadron collider

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

▶ uncertainties:

- ▶ experimental: $+0.0034$
 -0.0033
- ▶ theory: $+0.0023$
 -0.0035

($\mu_{r/f}$ variation, non-perturbative corrections, PDF)

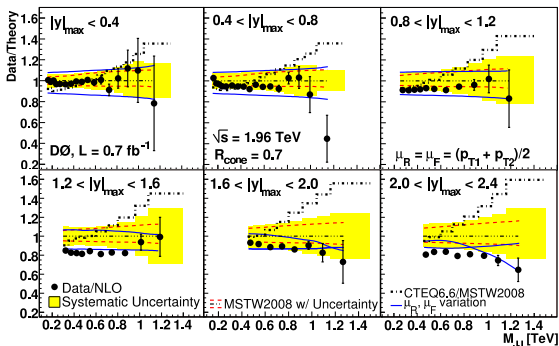
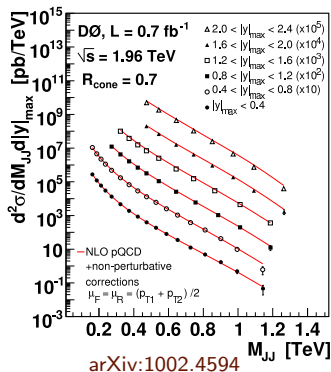


Phys. Rev. D 80, 111107 (2009)



Dijet mass cross section

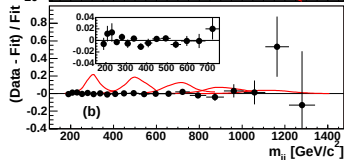
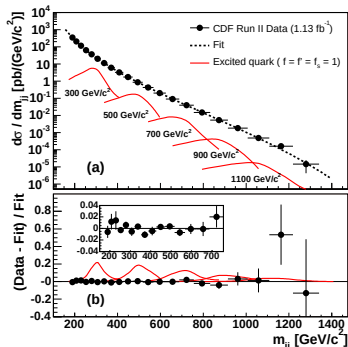
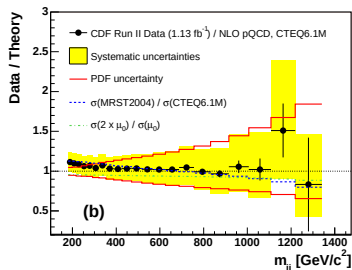
- ▶ measurement of $\frac{d^2\sigma}{dM_{JJ}d|y|_{\max}}$ in 6 rapidity bins up to $M_{JJ} \sim 1.3$ TeV
 M_{JJ} : dijet mass, $|y|_{\max} = \max(|y_1|, |y_2|)$, $p_{T1,2} > 40$ GeV
- ▶ central rapidities: data well described by pQCD
- ▶ forward region: data below prediction
 - ▶ reminder: MSTW2008 includes Run II incl. jets
 - ▶ discrepancy w.r.t. CTEQ6.6 even larger





Dijet mass: searches for resonances

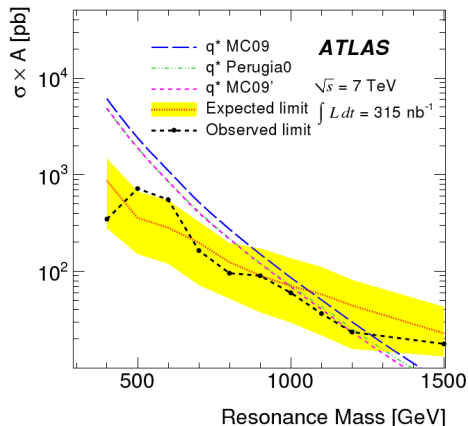
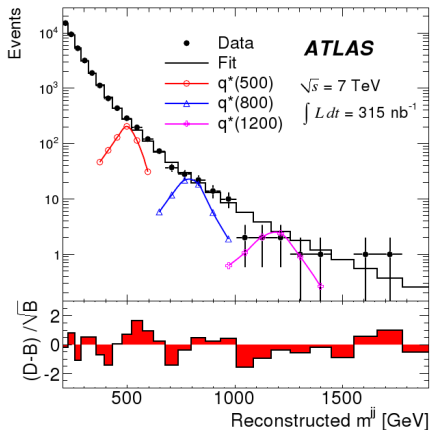
- ▶ dijet mass distribution for jet rapidities $|y| < 1$
- ▶ sensitive to new particles decaying into dijets: q^* , W' , Z' , ρ_T , axigluon, Randall-Sundrum-graviton, etc.
 - ▶ mostly produced more centrally
- ▶ search for narrow mass resonance as signal of physics beyond the Standard Model (BSM), lower mass bounds, e.g.:
 - ▶ $M(q^*) > 870 \text{ GeV}$
 - ▶ $M(\text{axigluon}) > 1.25 \text{ TeV}$



Phys. Rev. D 79, 112002 (2009)

LHC takes over...

- ▶ with just 0.0003 fb^{-1} LHC exceeds Tevatron sensitivity
 - ▶ $M(q^*) > 1.26 \text{ TeV}$
- ▶ see Wednesday's talk by Brian Peterson



arXiv:1008.2461



Dijet angular distribution

► measurement of

$1/\sigma_{\text{dijet}} \cdot d\sigma/d\chi_{\text{dijet}}$ in bins of M_{jj}

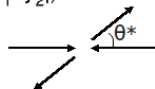
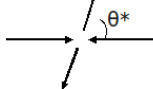
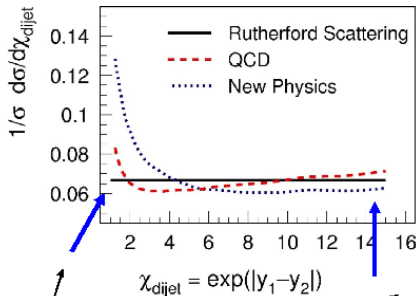
- $\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$
- massless $2 \rightarrow 2$ scattering:

$$\chi_{\text{dijet}} = \frac{(1 + \cos \theta^*)}{(1 - \cos \theta^*)}$$
- BSM: excess at large M_{jj} and small χ_{dijet}

► consistent with NLO QCD

► limits on BSM mass scales:

- quark compositeness: $\sim 2.9 \text{ TeV}$
- large extra dimensions (ADD (GRW) and TeV^{-1}): $\sim 1.6 \text{ TeV}$





Dijet angular distribution

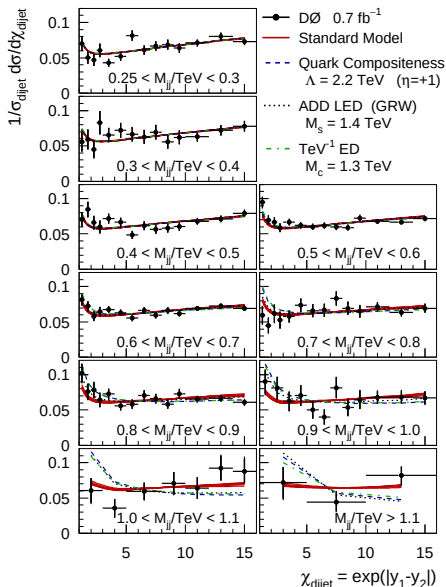
- measurement of

$$1/\sigma_{\text{dijet}} \cdot d\sigma/d\chi_{\text{dijet}} \text{ in bins of } M_{jj}$$

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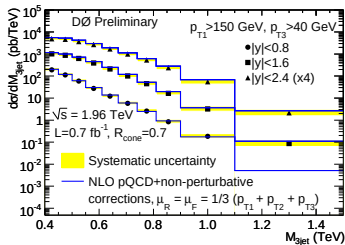


Phys. Rev. Lett. 103, 191803 (2009)

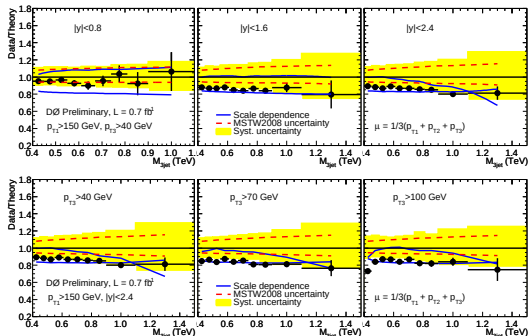


Three jet mass

- 3-jet mass distribution $d\sigma/dM_{3\text{jet}}$ with $p_{T1} > 150 \text{ GeV}$, $p_{T3} > 40 \text{ GeV}$, reaching $M_{3\text{jet}} > 1.1 \text{ TeV}$
- compared to NLO pQCD with MSTW2008 PDF
 - reasonable description, but again: data prefer lower bound on theory prediction



DØ Note 6043-CONF (2010)



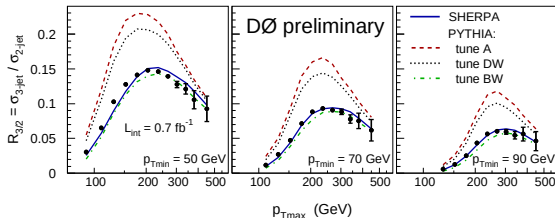


$R_{3/2}$: ratio of inclusive 3-jet to 2-jet production

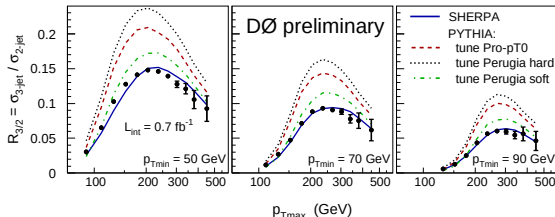
- test of QCD, less dependent on PDFs, probes α_s
- well described by SHERPA v1.1.3
- CKKW matching of matrix elements and parton shower
- here: MEs up to 4 partons
- PYTHIA: large dependence on tunes, generally too many 3-jets (except for BW)
- both for Q^2 and p_T ordered parton shower
- tune BW cannot describe e.g. dijet azimuthal decorrelation

→ hampers α_s extraction

PYTHIA: Q^2 -ordered shower



PYTHIA: p_T -ordered shower

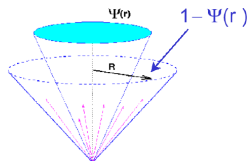


D0 Note 6032-CONF (2010)

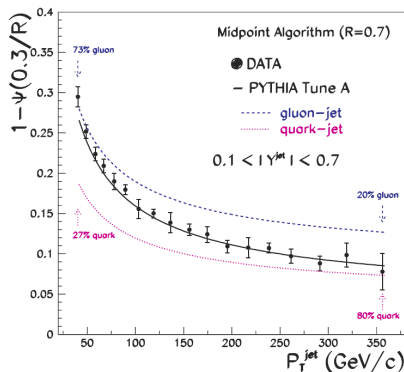
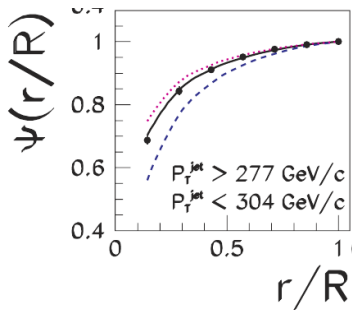


Jet shape measurements

- ▶ jet shape is dictated by multi-gluon emission from primary outgoing parton
 - ▶ plus contributions from initial state radiation and underlying event
- ▶ allows to distinguish quark/gluon jets
- ▶ sensitive to generator tunes



$$\Psi(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{P_T(0, r)}{P_T^{\text{jet}}(0, R)}$$

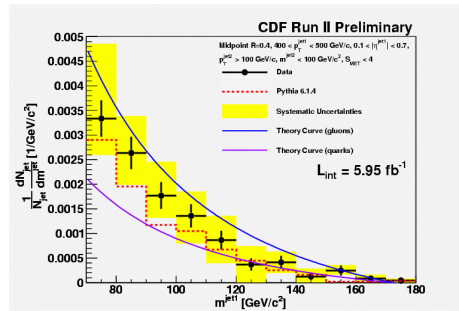
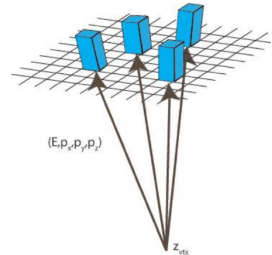


Phys. Rev. D 71, 112002 (2005)



Substructure of high E_T jets

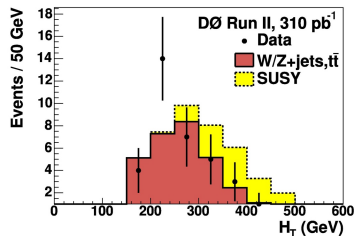
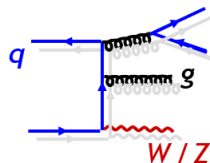
- ▶ massive boosted jets comprise important background for high- p_T top, Higgs and various BSM searches
- ▶ standard E -scheme for mass calculation: vector sum over (E, p_x, p_y, p_z) of towers (with $m = 0$) in jets
- ▶ data in agreement with PYTHIA prediction
- ▶ data between quark and gluon prediction (80% quarks from jet shapes)
- ▶ also other jet shapes measured: angularity, planar flow



CDF/PUB/JET/PUBLIC/10199 (2010)

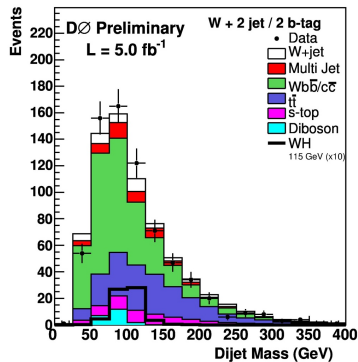
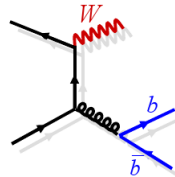
W/Z + jets production

- ▶ W/Z + jets: critical background at Tevatron and LHC for top, Higgs, Supersymmetry, many BSM scenarios
 - ▶ in particular: $W/Z + b\bar{b}$
 - correct modelling essential
 - ▶ Matrix-Element calculations (ME) for each parton multiplicity
 - ▶ works well for large angles and p_T
 - ▶ NLO calculations available up to 3 jets
 - ▶ parton showers (PS, PYTHIA, HERWIG)
 - ▶ successive radiation $q \rightarrow qg$ etc.
 - ▶ works well for small angles and p_T
- matching of LO-MEs (up to 6 partons) and PS in ALPGEN, SHERPA event generators
- validation with data essential



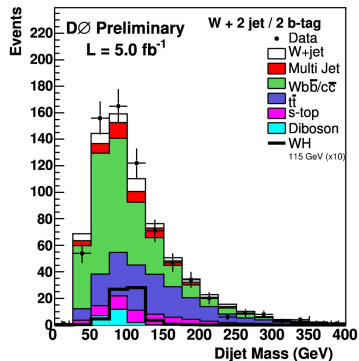
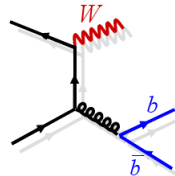
$W/Z + \text{jets}$ production

- ▶ $W/Z + \text{jets}$: critical background at Tevatron and LHC for top, Higgs, Supersymmetry, many BSM scenarios
 - ▶ in particular: $W/Z + b\bar{b}$
→ correct modelling essential
 - ▶ Matrix-Element calculations (ME) for each parton multiplicity
 - ▶ works well for large angles and p_T
 - ▶ NLO calculations available up to 3 jets
 - ▶ parton showers (PS, PYTHIA, HERWIG)
 - ▶ successive radiation $q \rightarrow qg$ etc.
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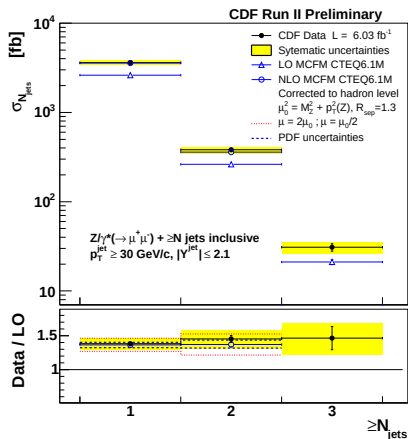




$Z/\gamma^*(\rightarrow \mu^+\mu^-) + \text{jets production}$

incl. jet multiplicity

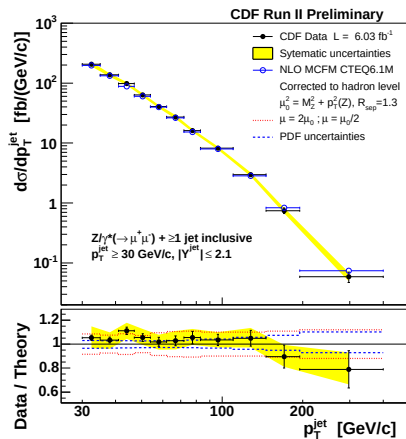
incl. jet p_T distr. for ≥ 1 jet



CDF note 10216

⇒ good agreement with NLO pQCD (MCFM)

► scale uncertainties: 10-15%

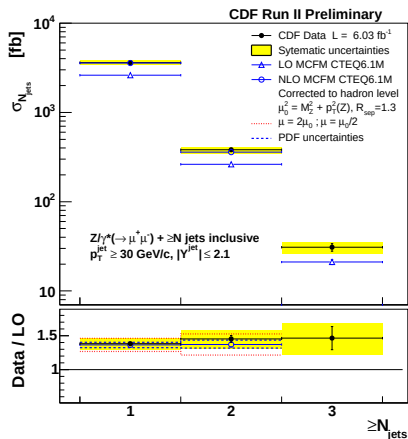




$Z/\gamma^*(\rightarrow \mu^+\mu^-) + \text{jets production}$

incl. jet multiplicity

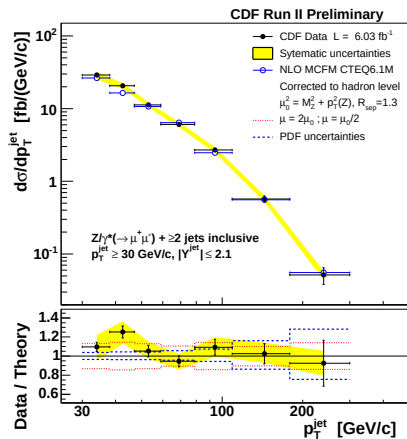
incl. jet p_T distr. for ≥ 2 jet



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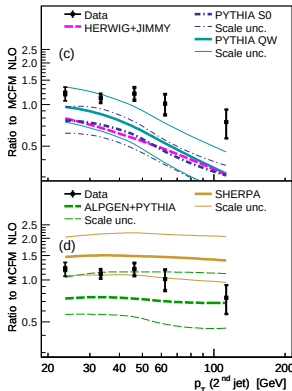
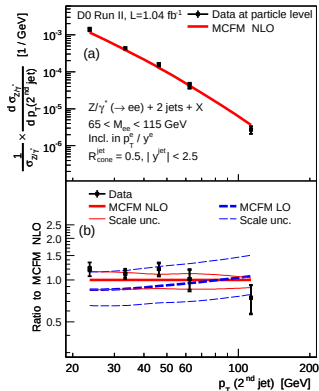




$Z/\gamma^*(\rightarrow e^+e^-) + \text{jets: jet } p_T \text{ spectra}$

- ▶ $1/\sigma_{Z/\gamma^*} \cdot d\sigma_{Z/\gamma^*}/dp_T(\text{jet}_i)$ in events with $\geq i$ jets, $i = 1, 2, 3$

e.g. ≥ 2 jets, $p_T(2^{\text{nd}} \text{ jet})$, ratios to NLO QCD



parton shower
generators

ME+PS
generators

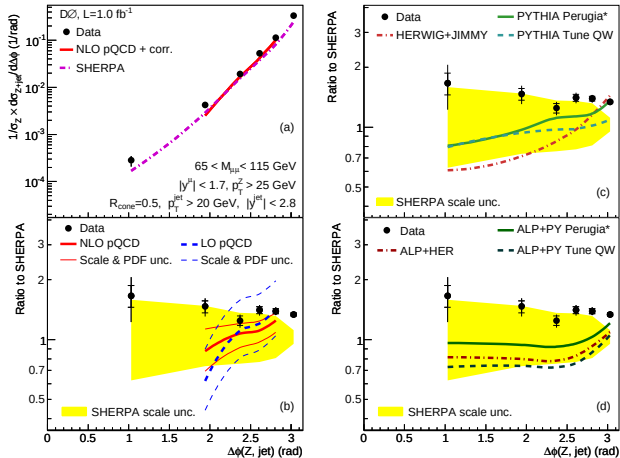
PLB 678, 45 (2009)

- ▶ shape of p_T distribution well described by ME+PS generators, but large scale uncertainties ($\leftarrow$ LO MEs)
- ▶ parton shower generators predict too soft spectrum



$Z/\gamma^*(\rightarrow \mu^+\mu^-) + \text{jets: angular observables}$

- observables
 - $\Delta\phi(Z, \text{jet}_1)$, shown $\Rightarrow$
 - $\Delta y(Z, \text{jet}_1)$
 - $\frac{1}{2}(y_Z + y_{\text{jet}_1})$
- further constrains kinematics
- avoids systematics of jet energy scale
- fixed-order pQCD predictions not valid for small $\Delta\phi$



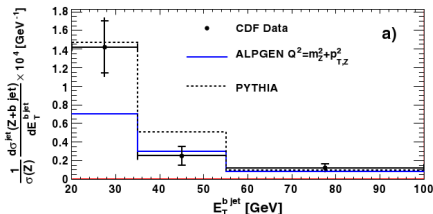
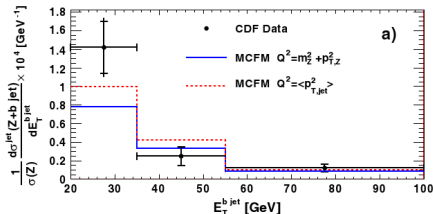
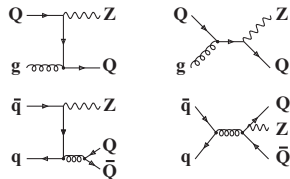
Phys. Lett. B 682, 370 (2010)

- shape of angular observables well described by SHERPA, but large scale uncertainties



Z + b jet

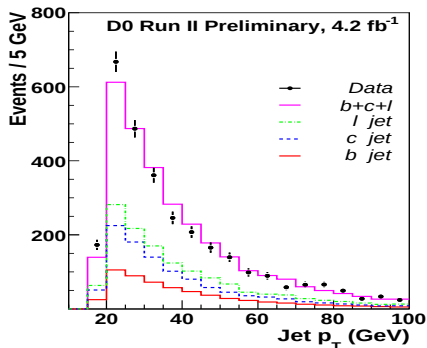
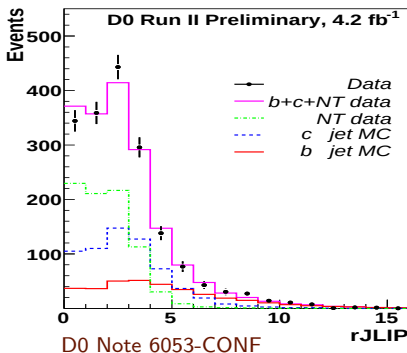
- probes b -quark PDF and fragmentation
- $Z + b$ and $Z + b\bar{b}$
 - $b\bar{b}$ from gluon splitting can collapse in one jet
- measurements require ≥ 1 b -jet
- for jets with $E_T > 20 \text{ GeV}$, $|\eta| < 1.5$
 - $\frac{\sigma(Z+b)}{\sigma(Z+\text{jet})} = (2.08 \pm 0.33 \pm 0.34)\%$
 - MCFM (NLO, not complete for $Z + (b\bar{b})_{1\text{jet}}$): 1.8 – 2.2%
 - large difference between ALPGEN/PYTHIA
 - different scales
 - only $g \rightarrow b\bar{b}/b$ -PDF



Phys.Rev.D79, 052008 (2009), $L=2 \text{ fb}^{-1}$



Z + b jet



- ▶ jet flavor fractions determined from fit to jet lifetime probability tag
 - ▶ templates: b , c : ALPGEN+PYTHIA, light q , g : negative tag data
- ▶ jet p_T distribution well described
- ▶ for jets with $p_T > 20$ GeV, $|\eta| < 1$
 - ▶ $\frac{\sigma(Z+b)}{\sigma(Z+jet)} = (1.76 \pm 0.24(\text{stat}) \pm 0.23(\text{syst}))\%$
 - ▶ consistent with NLO QCD



W + b jet

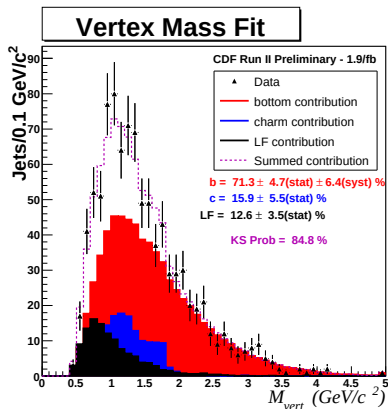
- b-jet fraction determined from fit to vertex-mass distribution

M_{vert}

- measurement of

$$\sigma(W + b) \times \mathcal{B}(W \rightarrow \ell \nu)$$

- with $p_T^\ell > 20 \text{ GeV}$, $|\eta^\ell| < 1.1$,
 $p_T^\nu > 25 \text{ GeV}$,
 $E_T^{b\text{-jet}} > 20 \text{ GeV}$, $|\eta|^{b\text{-jet}} < 2$
- $(2.74 \pm 0.27 \pm 0.42) \text{ pb}$
- NLO QCD: $1.22 \pm 0.14 \text{ pb}$
 (Campbell, Febres Cordero, Reina)
 $\sim 3\sigma$ smaller
- ALPGEN+PYTHIA: 0.78 pb



Phys. Rev. Lett. 104, 131801 (2010)



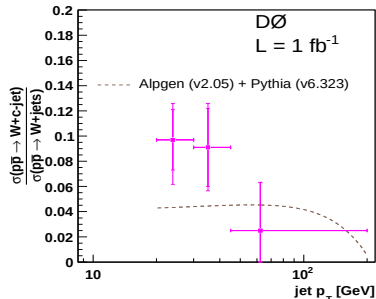
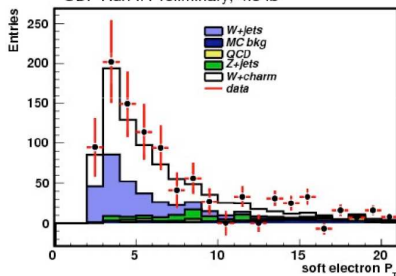
$W + c$ jet

- ▶ $s + g$ fusion: $\sim 90\%$ contribution
- probes g and s PDFs at high Q^2
- ▶ c-jet identified by soft lepton
- ▶ CDF, 4.3 fb^{-1}
 - ▶ c-jet: $p_T > 12 \text{ GeV}$, $|\eta| < 1.5$
 - ▶ $\sigma(W + c) \times \mathcal{B}(W \rightarrow \ell\nu) =$
 $(33.7 \pm 11.4(\text{stat}) \pm 4.7(\text{syst})) \text{ pb}$
 - ▶ NLO: $17.8 \pm 1.7 \text{ pb}$
- ▶ D0, 1 fb^{-1}
 - ▶ jet: $p_T > 20 \text{ GeV}$, $|\eta| < 2$
 - ▶ $\frac{\sigma(W+c)}{\sigma(W+\text{jet})} =$
 $(7.4 \pm 1.9(\text{stat})^{+1.2}_{-1.4}(\text{syst}))\%$
 - ▶ ALPGEN+PYTHIA: 4.4%

⇒ reasonable agreement

CDF note 10089

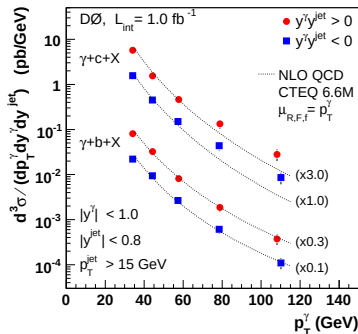
CDF Run II Preliminary, 4.3 fb^{-1}



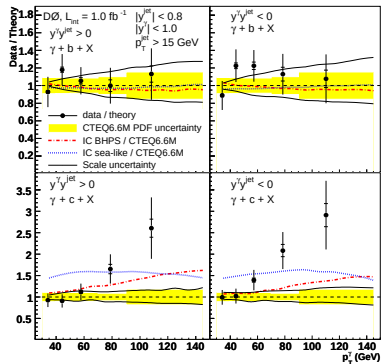
Phys. Lett. B 666, 23 (2008)



$\gamma + b/c$ jet



Phys. Rev. Lett. 102, 192002 (2009)



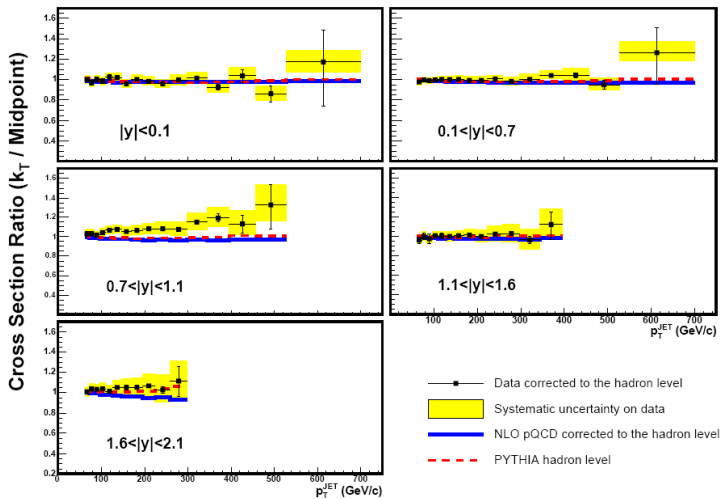
- again: sensitivity to heavy flavor and gluon content of proton
- $p_T^{\text{jet}} > 15 \text{ GeV}$, $30 \text{ GeV} < p_T^\gamma < 150 \text{ GeV}$
- $\gamma + b$: agreement over full p_T^γ range
- $\gamma + c$: NLO QCD underestimates rate at large p_T^γ , some improvement for PDF sets with inclusive charm
- CDF: $\gamma + b$ in agreement with NLO QCD, Phys. Rev. D81, 052006 (2010)

Conclusions

- ▶ understanding of high E_T jet and $W/Z + \text{jet}$ production significantly advanced over the last years
- ▶ inclusive jet cross section
 - ▶ high precision due to precise jet energy scale calibration
 - precision measurement of running α_s
 - stringent constraints on gluons at high x
- ▶ multijets
 - ▶ agreement with NLO QCD, but data prefer lower bound on theory
- ▶ dijet mass and angular distribution
 - ▶ best limits on quark compositeness, extra dimensions, etc.
- ▶ $Z/W/\gamma + \text{jets}(s)$
 - ▶ test pQCD, help generator modeling/tuning
 - ▶ crucial for SUSY and Higgs searches (in particular for b -jets)
 - ▶ $W + b, \gamma + c$: some tension with theory
- ▶ Tevatron expects 12 fb^{-1} until 2011 (and prospects beyond)
 - ▶ extend measurements to higher p_T , M_{jj} and multiplicities



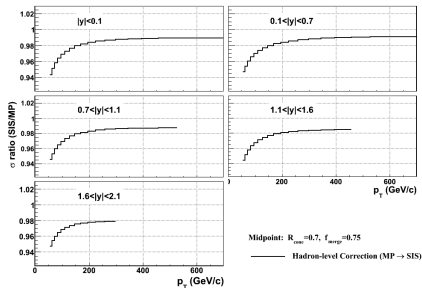
Inclusive jets: k_T vs. midpoint cone



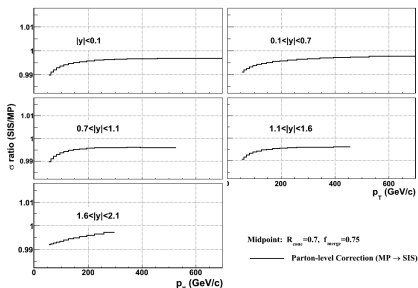


Inclusive jets: SIS cone vs. midpoint cone

hadron level



parton level



$\Rightarrow$ effect on data/pQCD comparison $< 1\%$

