High E_T jet physics at the Tevatron

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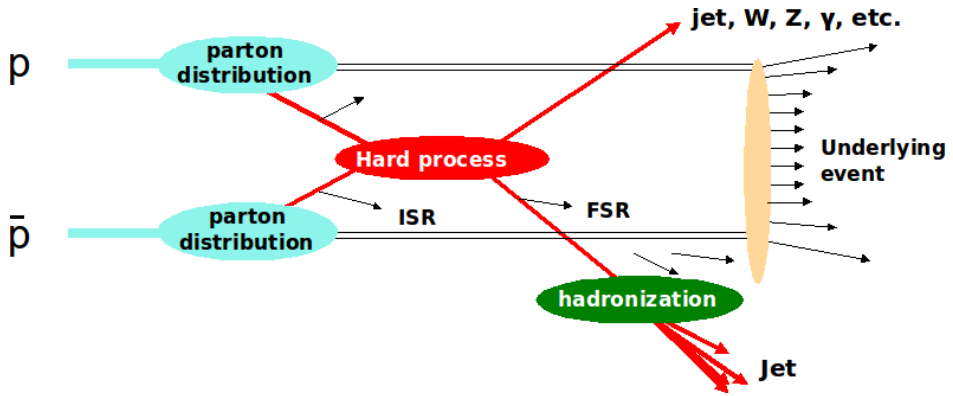
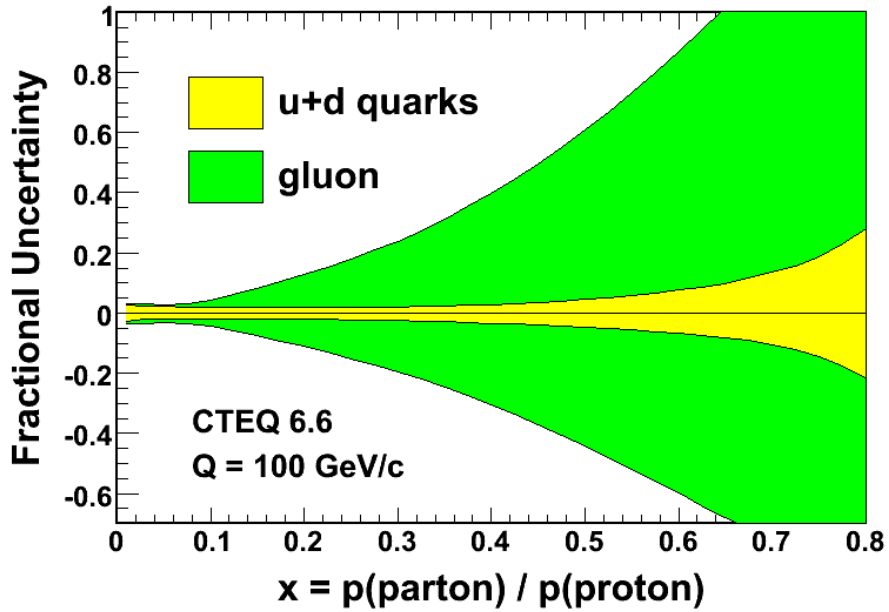
High E_T jet production at hadron colliders

- test perturbative QCD
- constrain structure of the proton

  $\rightarrow$ parton distribution functions (PDFs)
  gluon ($\leftarrow$ incl. jets)
  heavy flavor ($\leftarrow$ $W/Z/\gamma^*$+HF)

- measure important backgrounds to searches for Higgs, Supersymmetry, and other new physics
  - processes with large jet multiplicities only calc. to LO $\rightarrow$ large uncert.
  - provide data to constrain models, to tune event generators to be used at Tevatron and LHC
  - especially important: W/Z+jets
- search for new phenomena in signatures with jets (e.g. resonances)

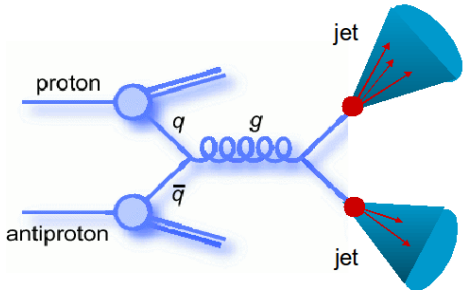




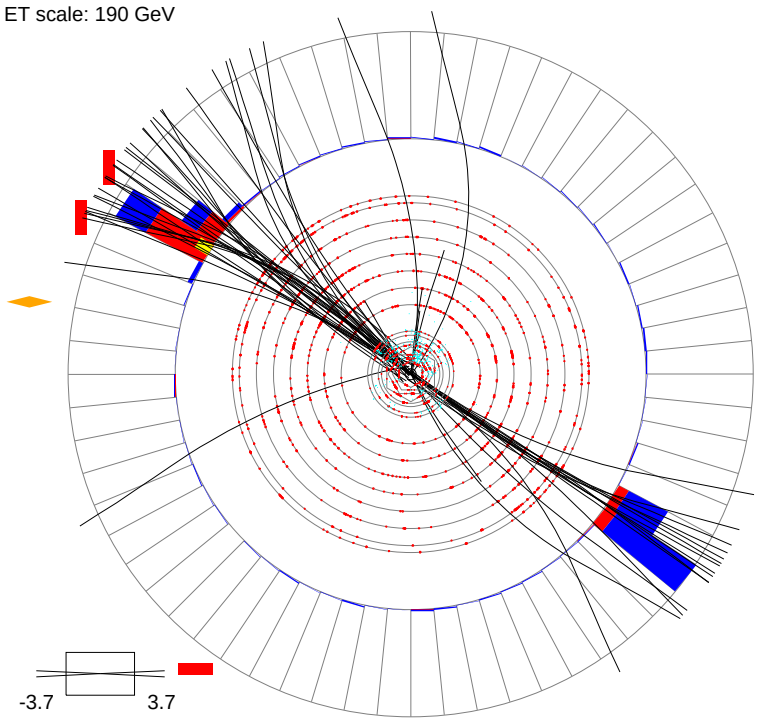
Outline

- 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 $W/Z/\gamma^* +$ jet production
  - jets of any flavor
  - b and c quark jets

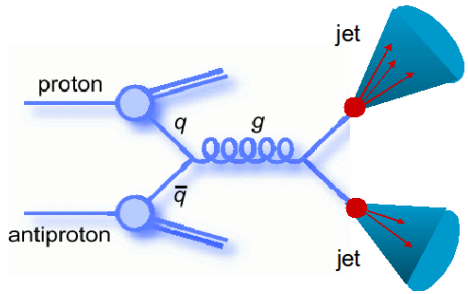
Jet reconstruction



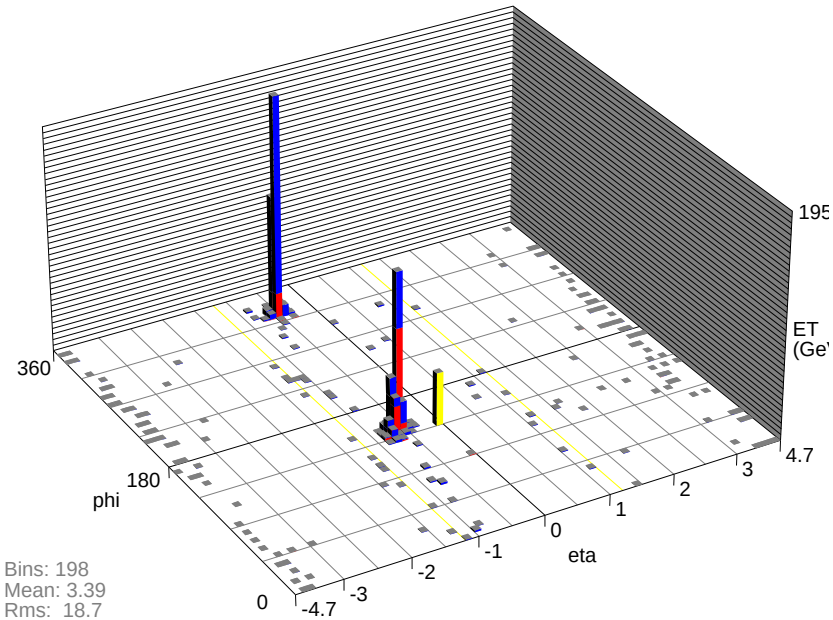
Run 162592 Event 5490755 Fri Oct 25 11:57:39 2002



Jet reconstruction

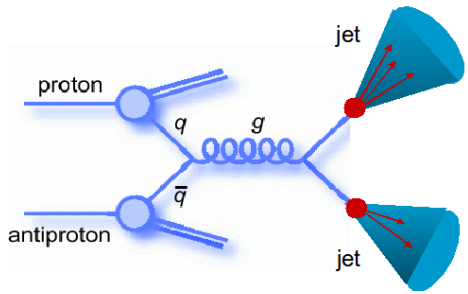


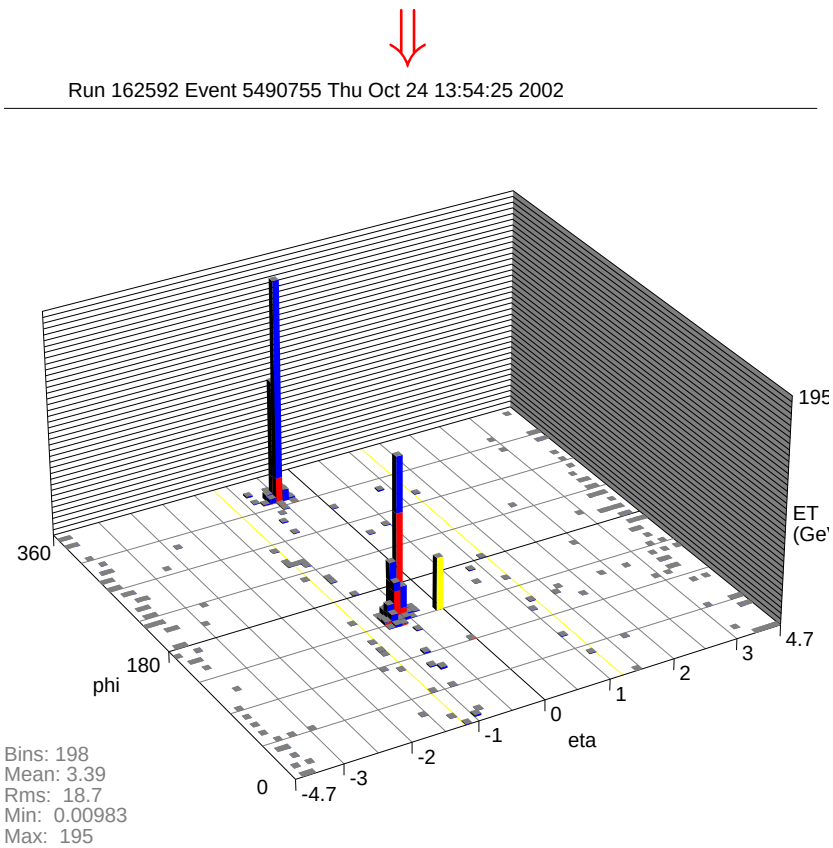
Run 162592 Event 5490755 Thu Oct 24 13:54:25 2002



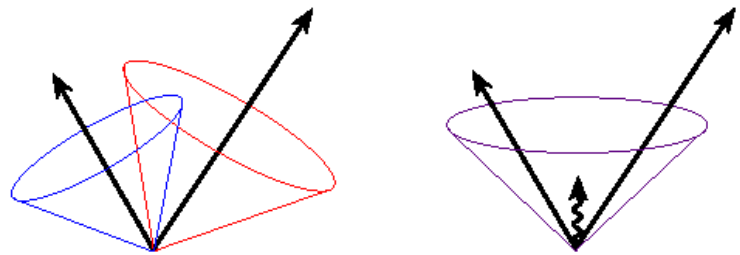
Bins: 198
Mean: 3.39
Rms: 18.7
Min: 0.00983
Max: 195

Jet reconstruction

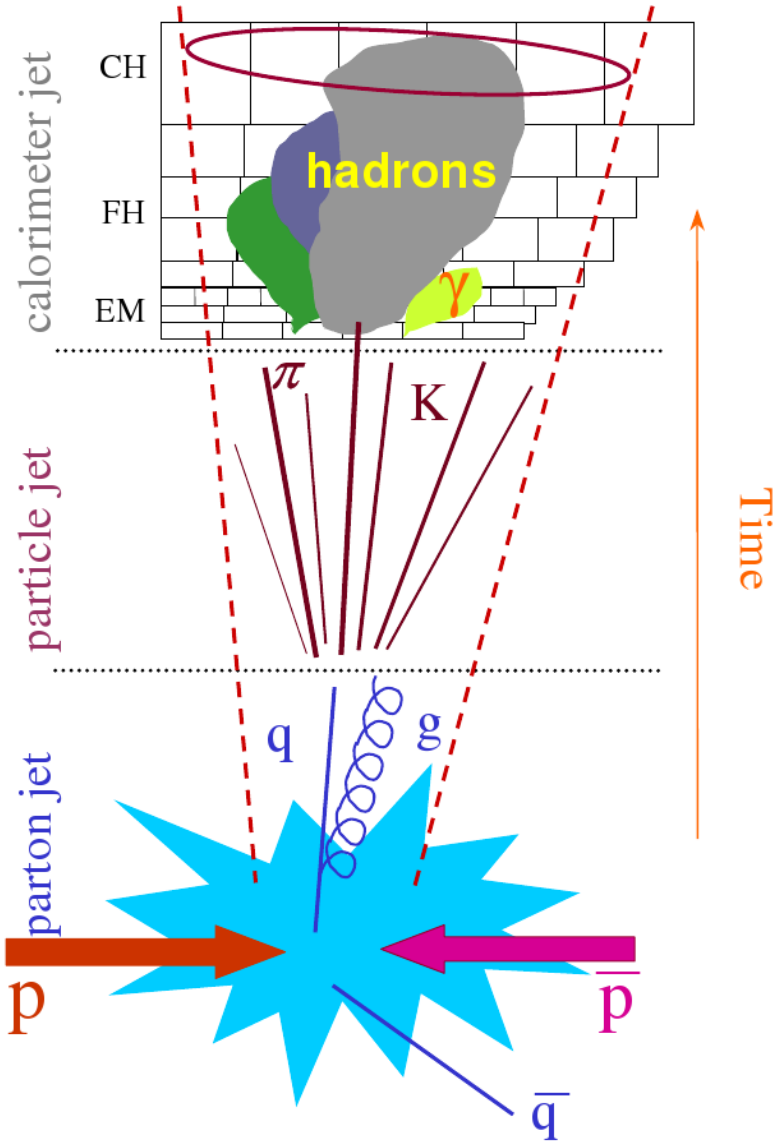




- standard jet reconstruction algorithm at Run II: seeded, iterative, midpoint cone algorithm
  - use particles (calorimeter tower) as seeds
  - add particles within cone using 4-vectors (E-scheme)
  - iterate until stable
  - use mid-points between jets as additional seeds
    $\rightarrow$ improved 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

$\Downarrow$

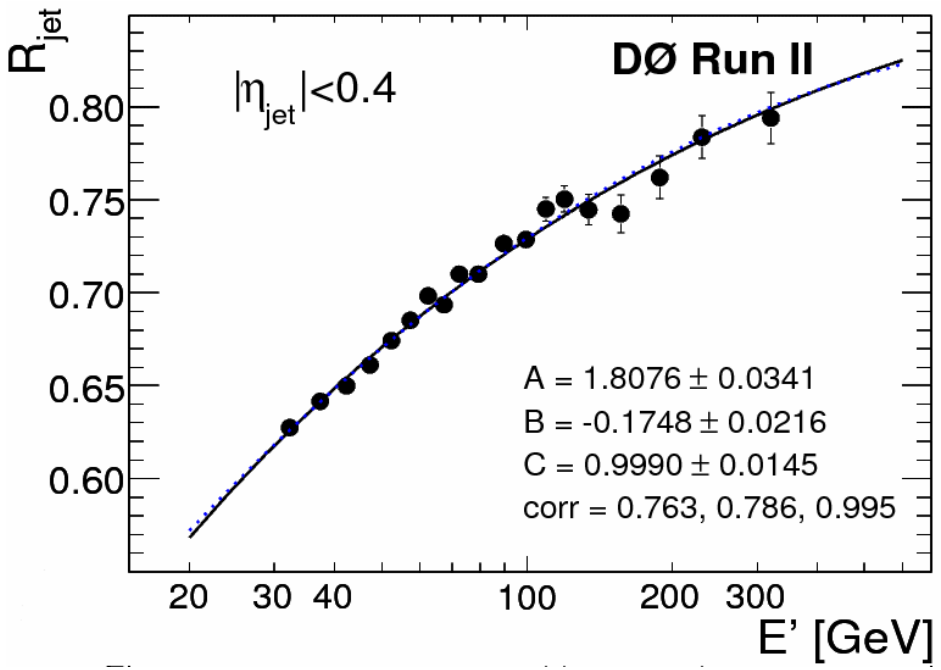
data-theory comparison at hadron (particle) level

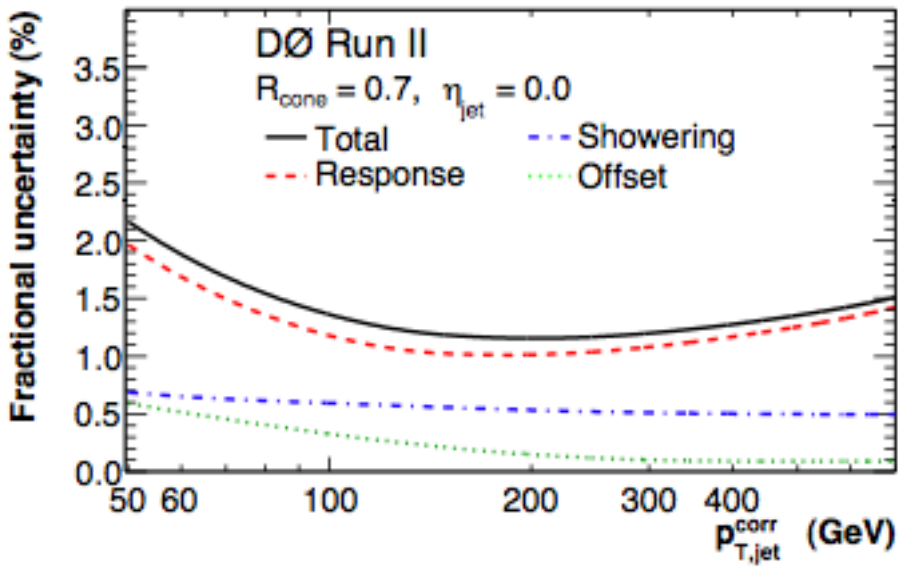
$\Uparrow$

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

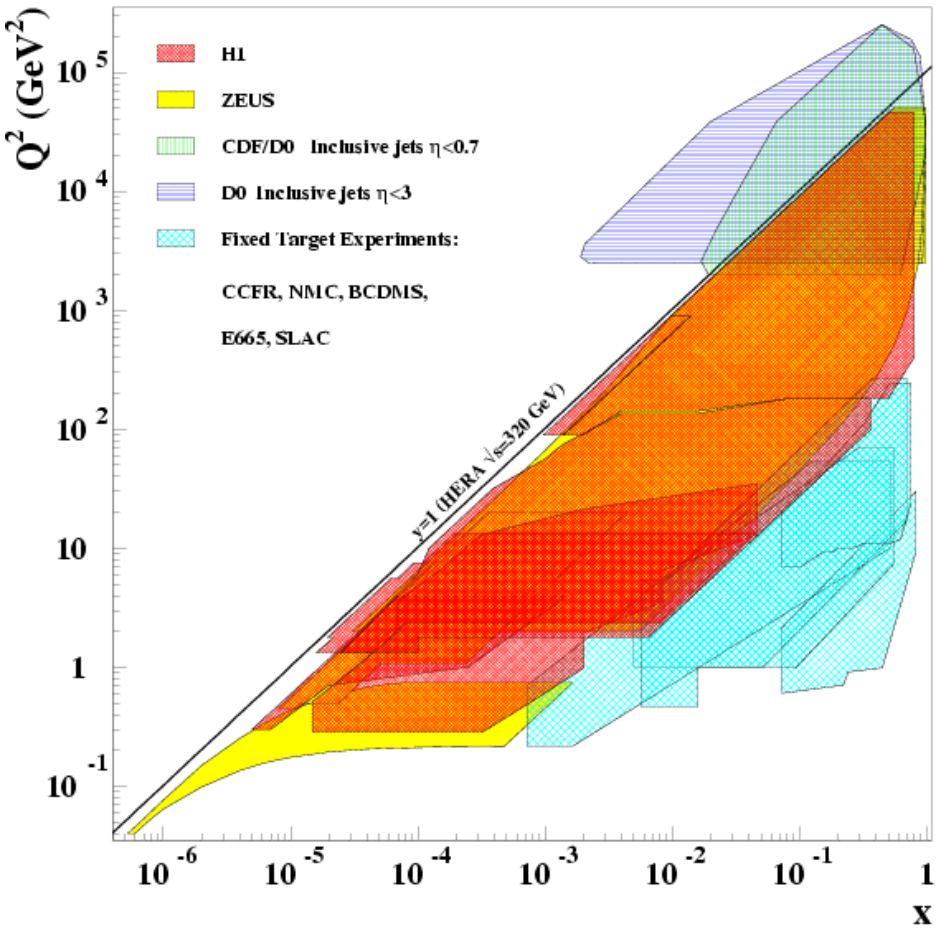
Jet energy scale (JES) calibration

- $E_{\text{particle}} = \frac{E_{\text{cal}} - O}{R \cdot S}$
  - E_{cal}: measured enery (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 $p_T \sim 100\,\text{GeV}$
  ← 7 years of work!

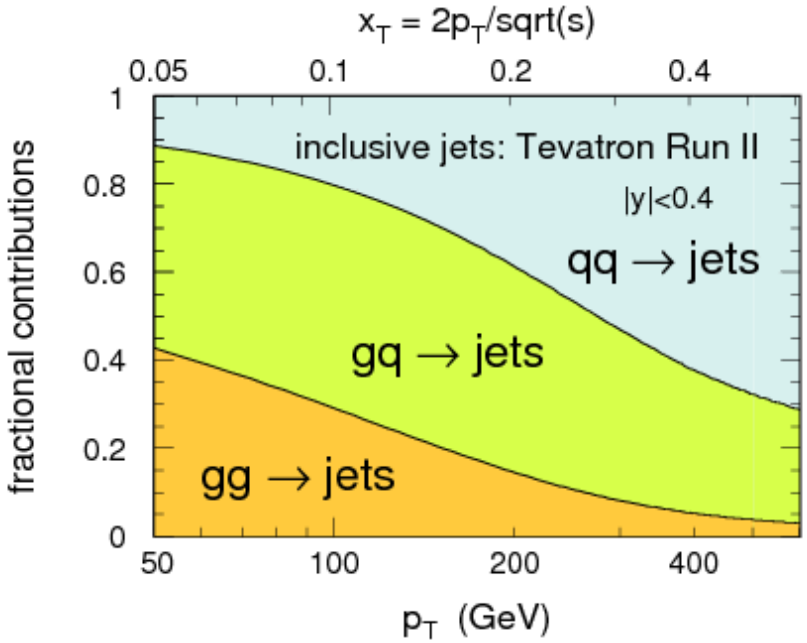




Inclusive jet production

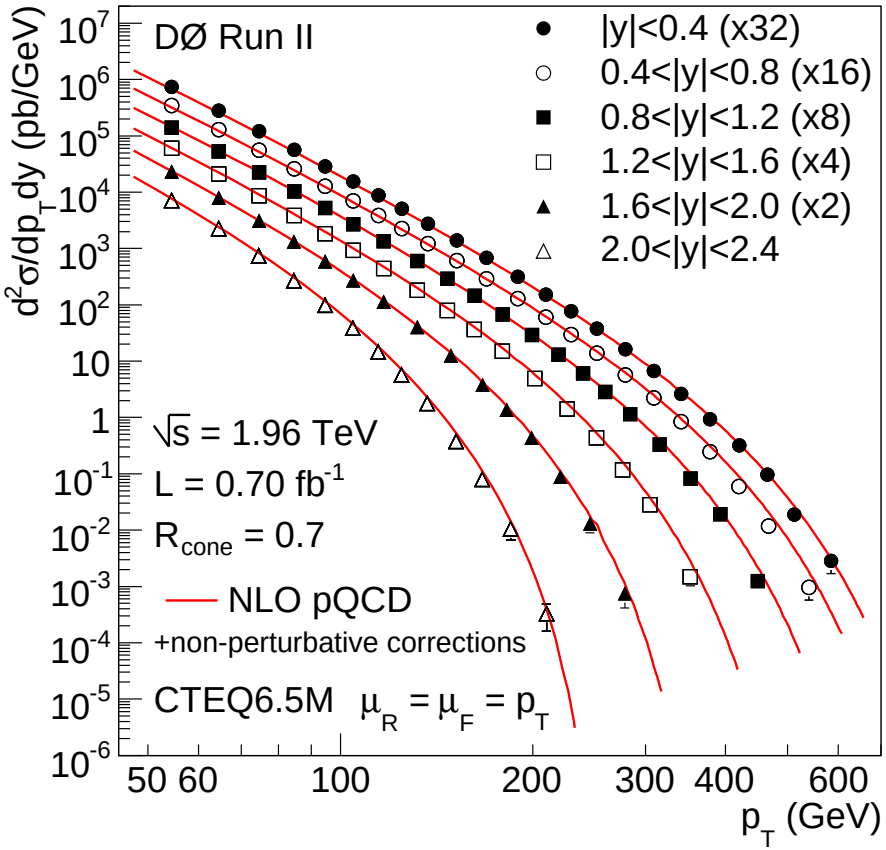


- kinematic reach in (x, Q^2) compared to HERA and fixed target exp.: sensitive to PDFs at large momentum fractions x and scales Q^2
- sensitive to gluon content of the proton

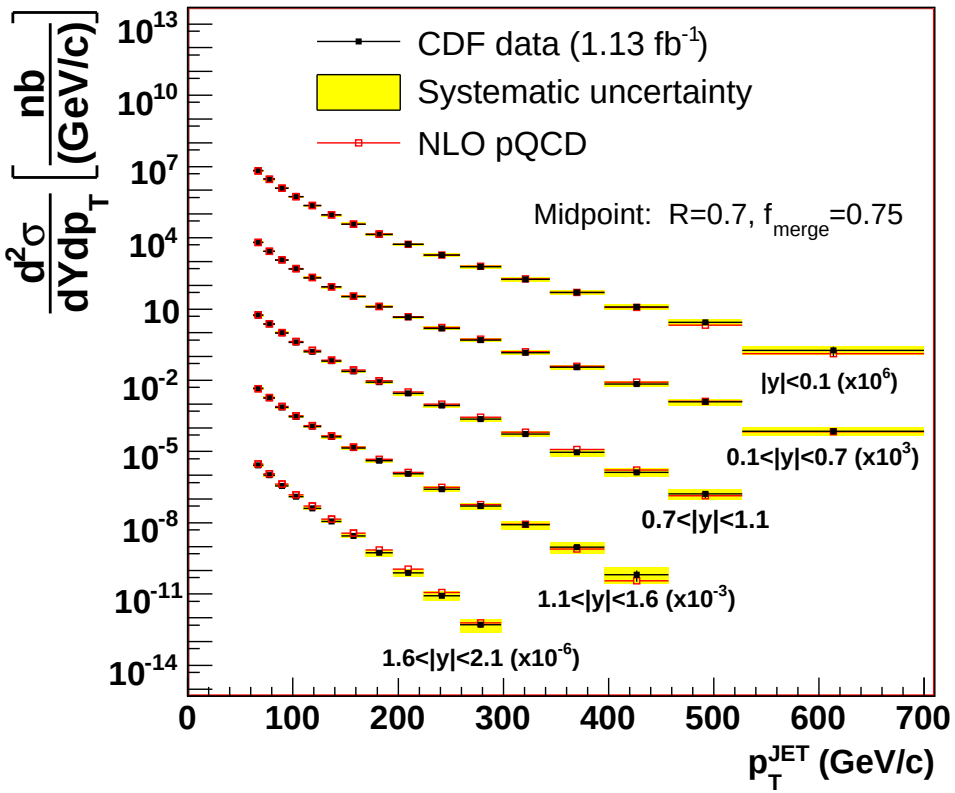


Inclusive jet p_T cross sections

- 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 ($\sqrt{s} = 1.8 \rightarrow 1.96\ TeV$), e.g. cross section $\times 5$ at $p_T(\text{jet}) = 600\,\text{GeV}$



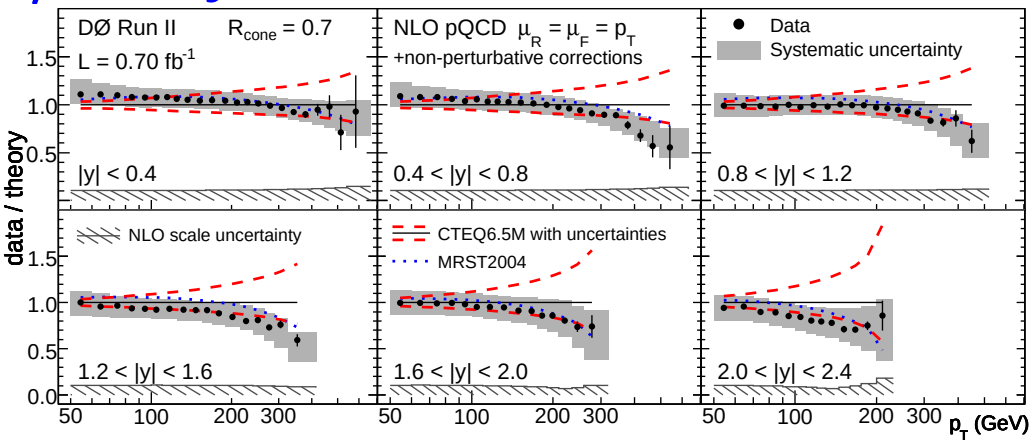
Phys. Rev. Lett. 101, 062001 (2008)

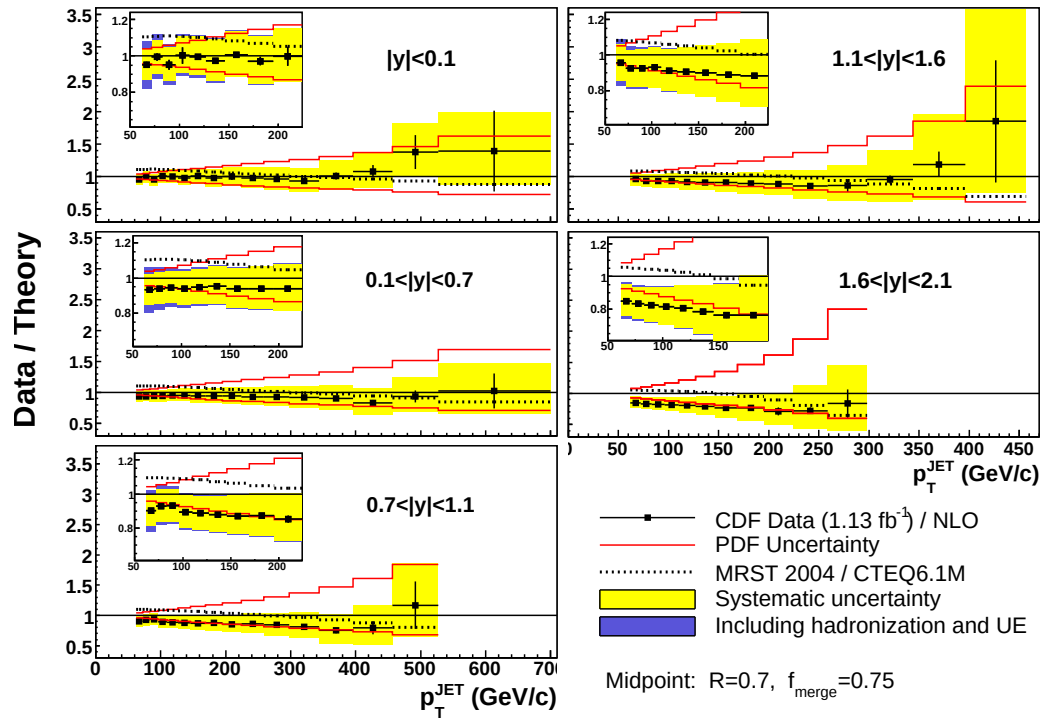


Phys. Rev. D 78, 052006 (2008)

Inclusive jet p_T: data/theory, uncertainties

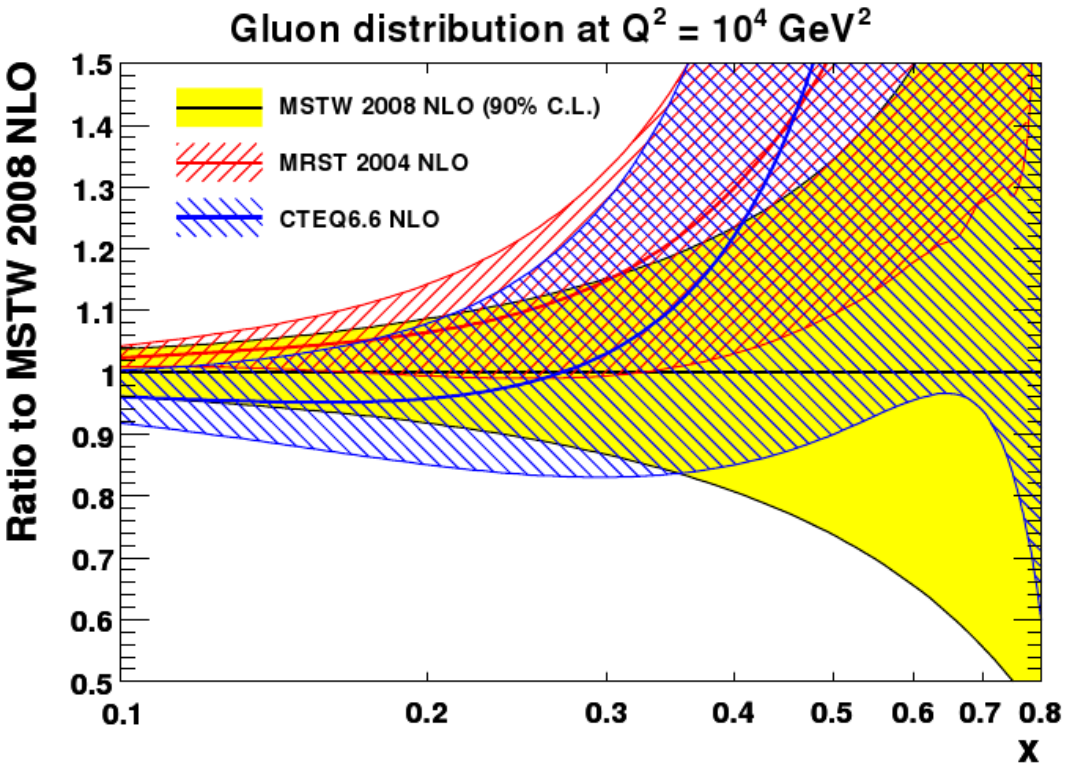
- both measurements are in agreement with NLO pQCD
  - both data sets favor smaller gluon densities
- exp. systematics (dominated by JES uncertainty) < theory uncert. (mostly PDF)
  - thanks to precise JES
- PDF sensitivity: $x \propto 2p_T/\sqrt{s}$
- see also: inclusive jets with k_T, CDF, Phys. Rev. D, 75, 092006 15(2007)



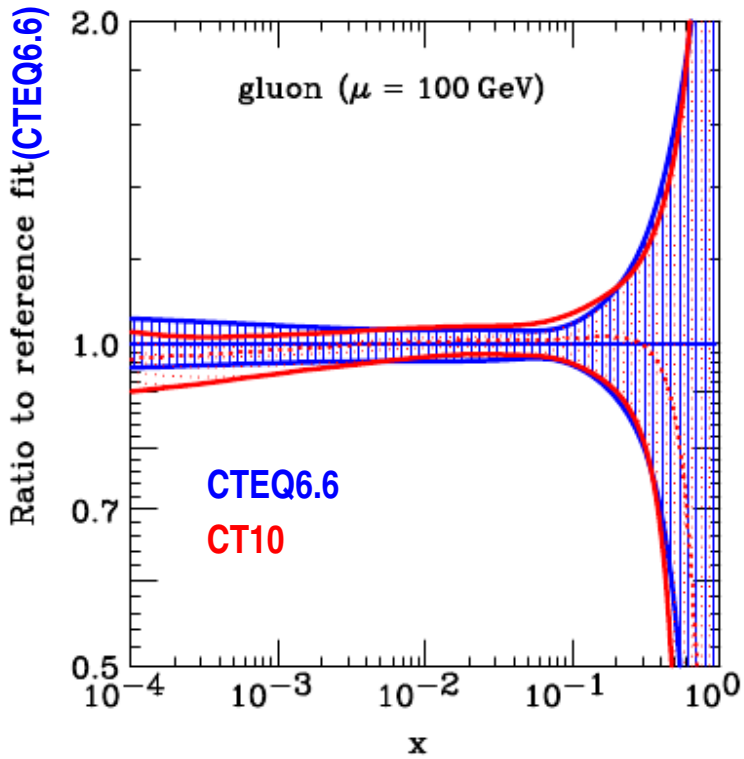


PDF influence of Tevatron data

- 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



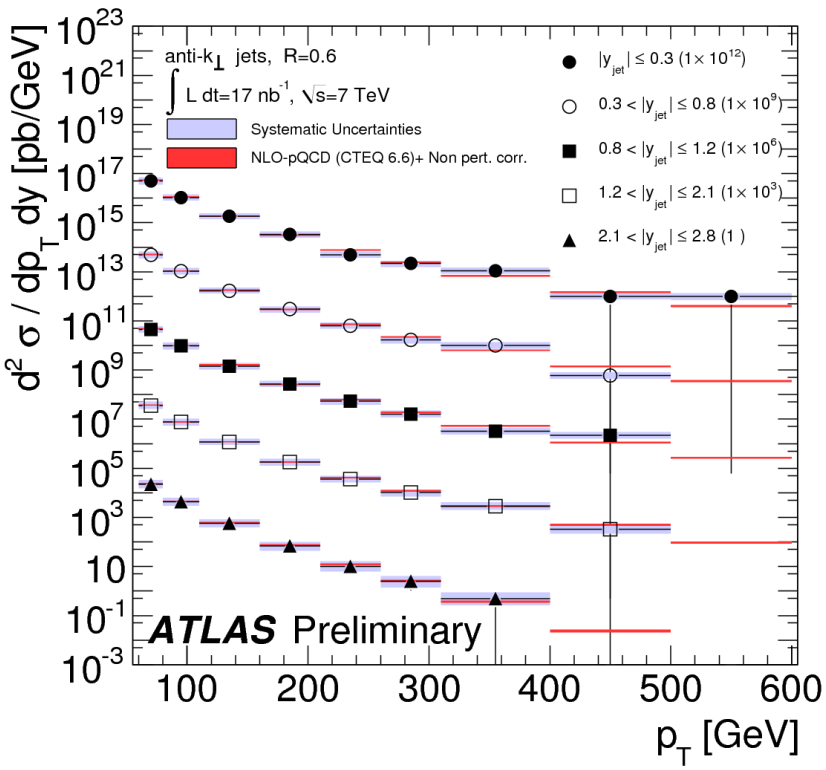
MSTW2008: Eur.Phys.J.C63:189-285,2009



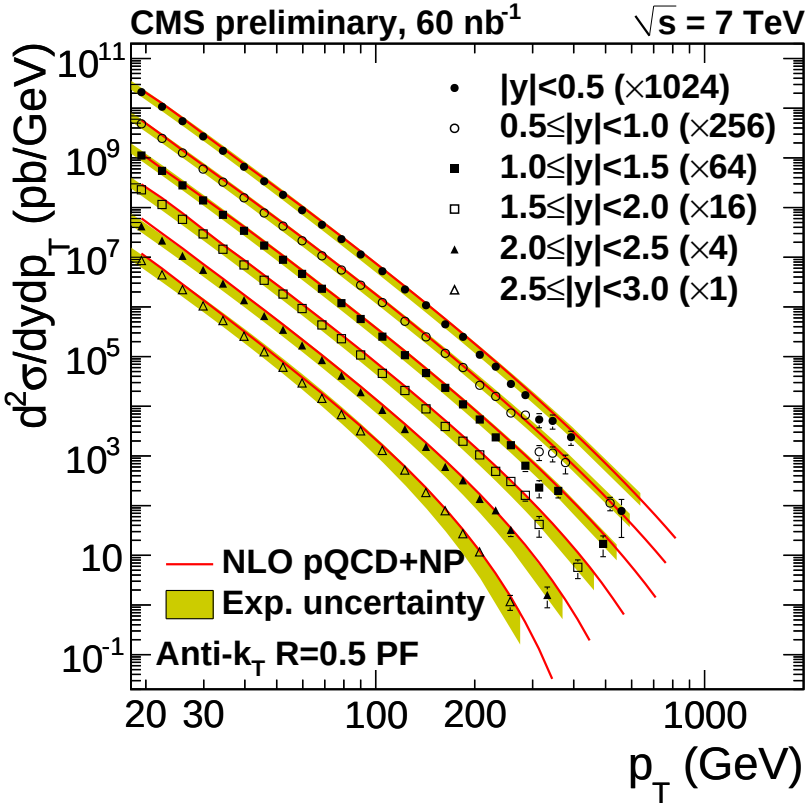
CT10: arXiv:1007.2241

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)



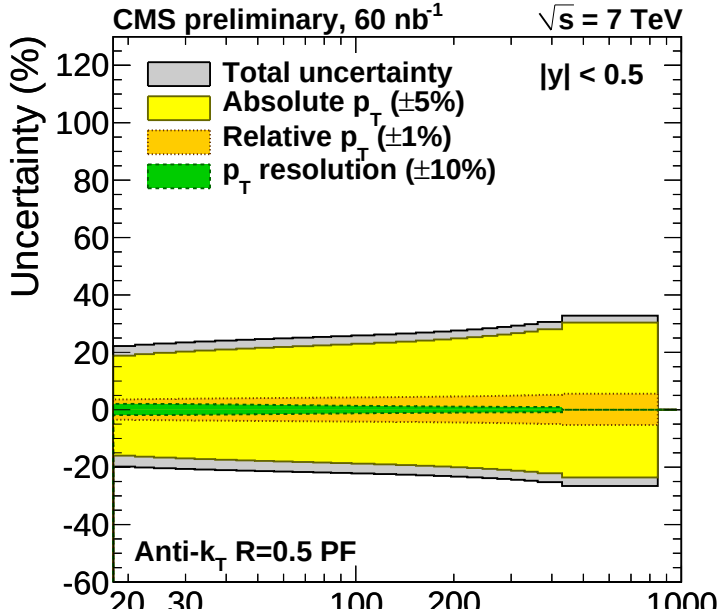
ATLAS-CONF-2010-050

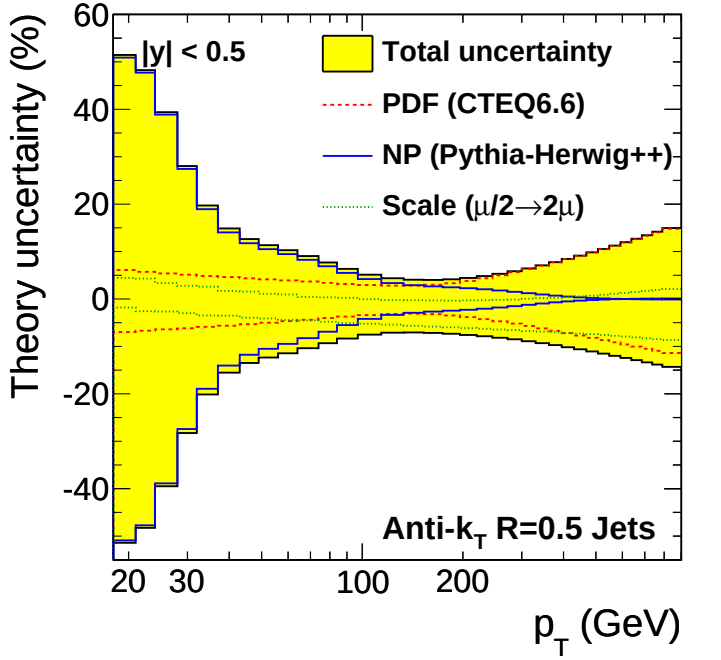


CMS-PAS-QCD-10-011

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 $x_T = 2p_T/\sqrt{s} \propto x$: $\sigma(\mathrm{LHC}) \ll \sigma(\mathrm{Tevatron})$
  - Tevatron will still be more sensitive to high-x gluon for several years.





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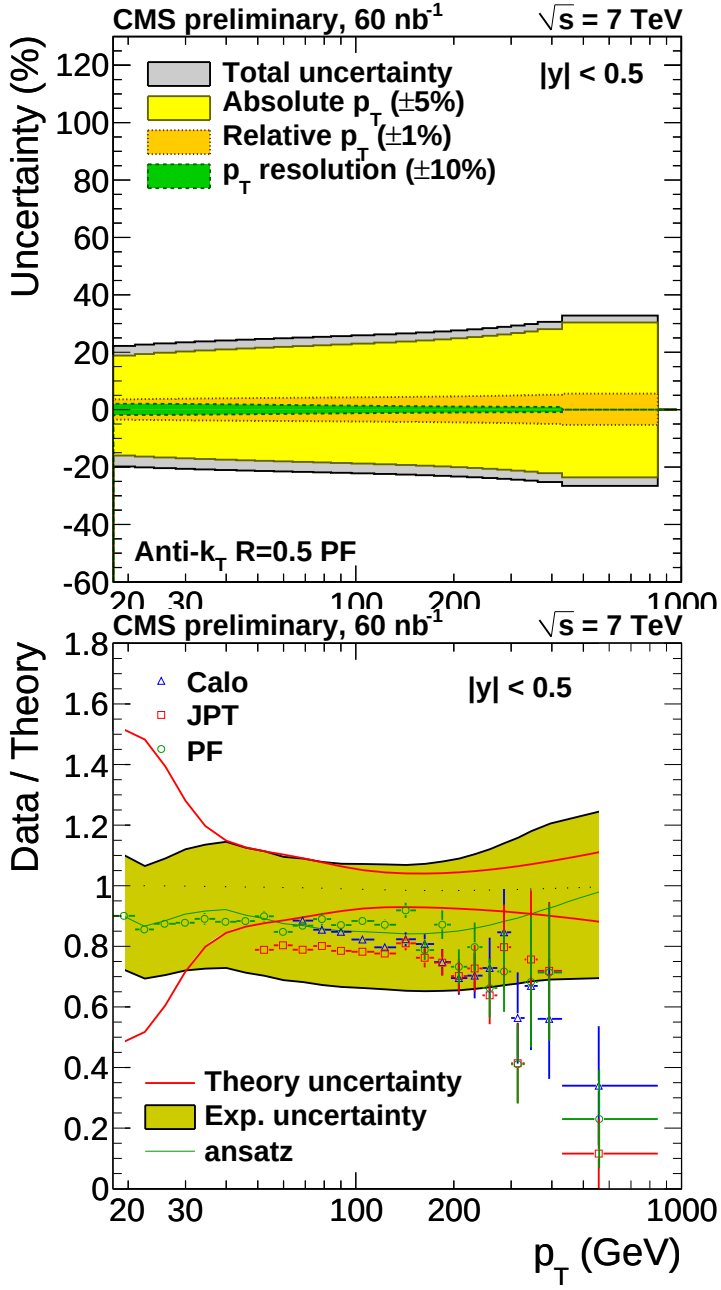

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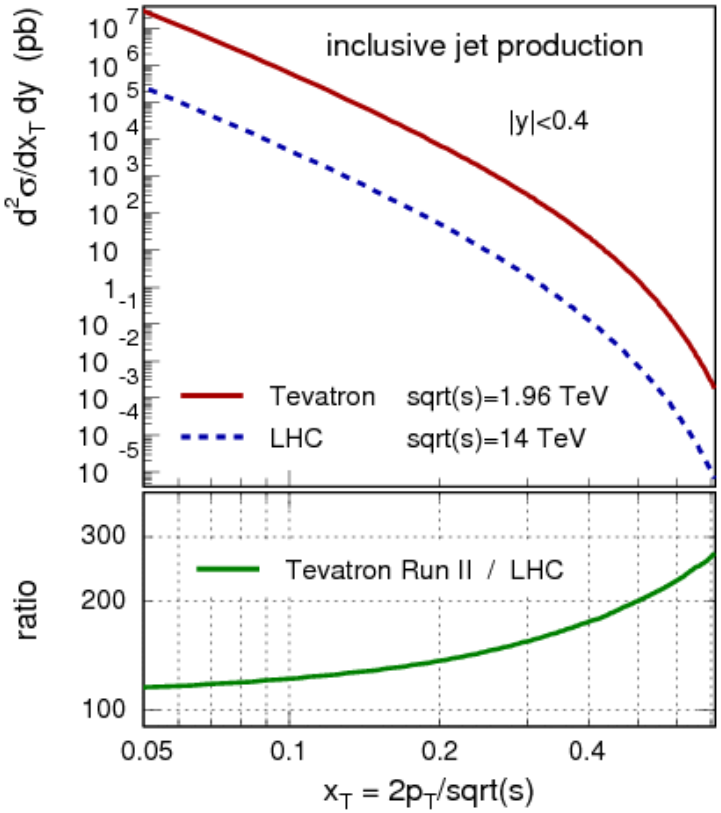
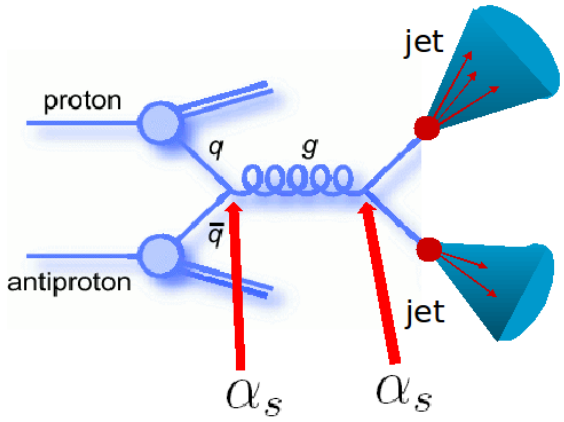
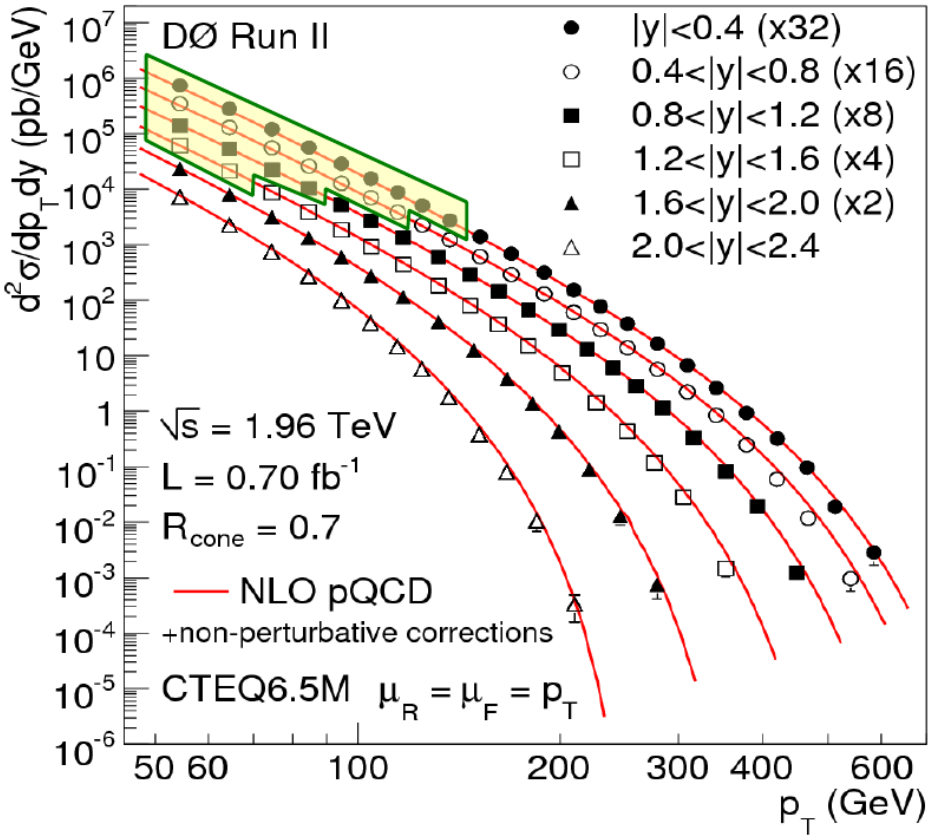


α_s from inclusive jets



- 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:
  $x_{\text{max}} \lesssim 0.25$

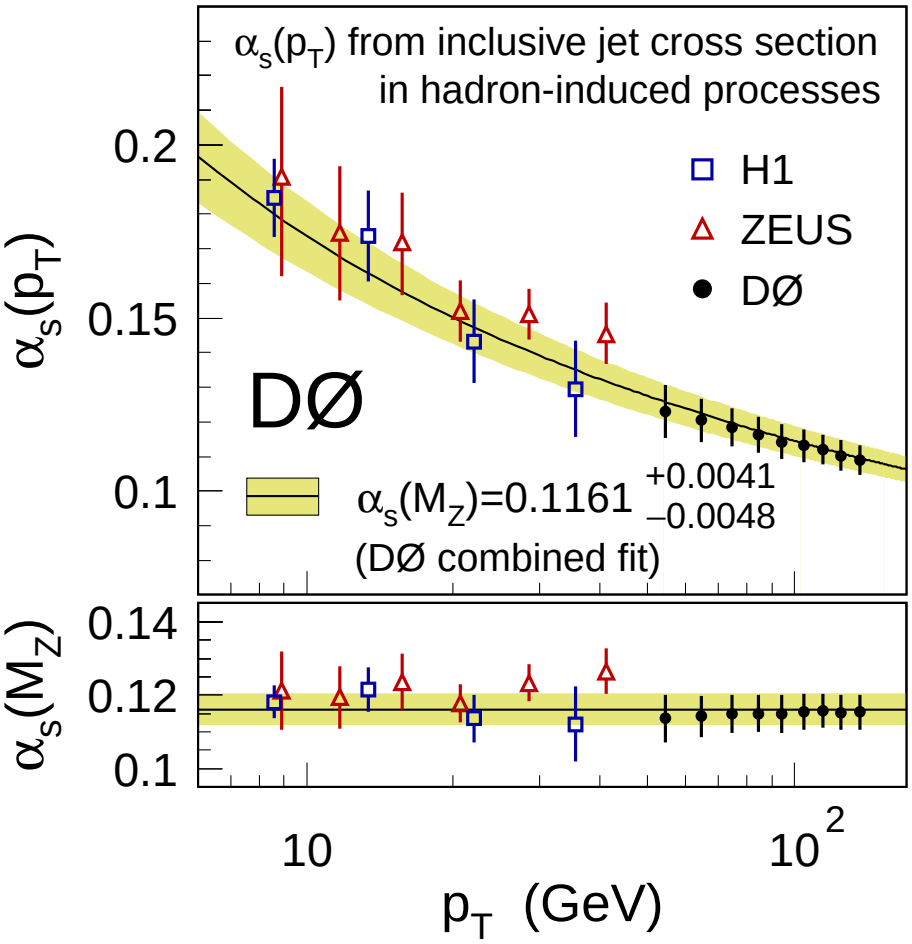


α_s from inclusive jets

- 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)

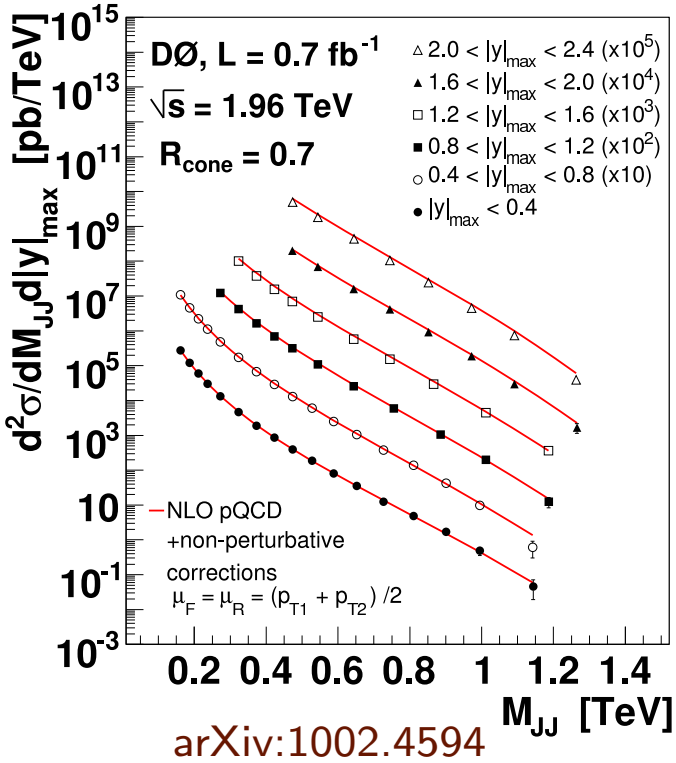


Phys. Rev. D 80, 111107 (2009)

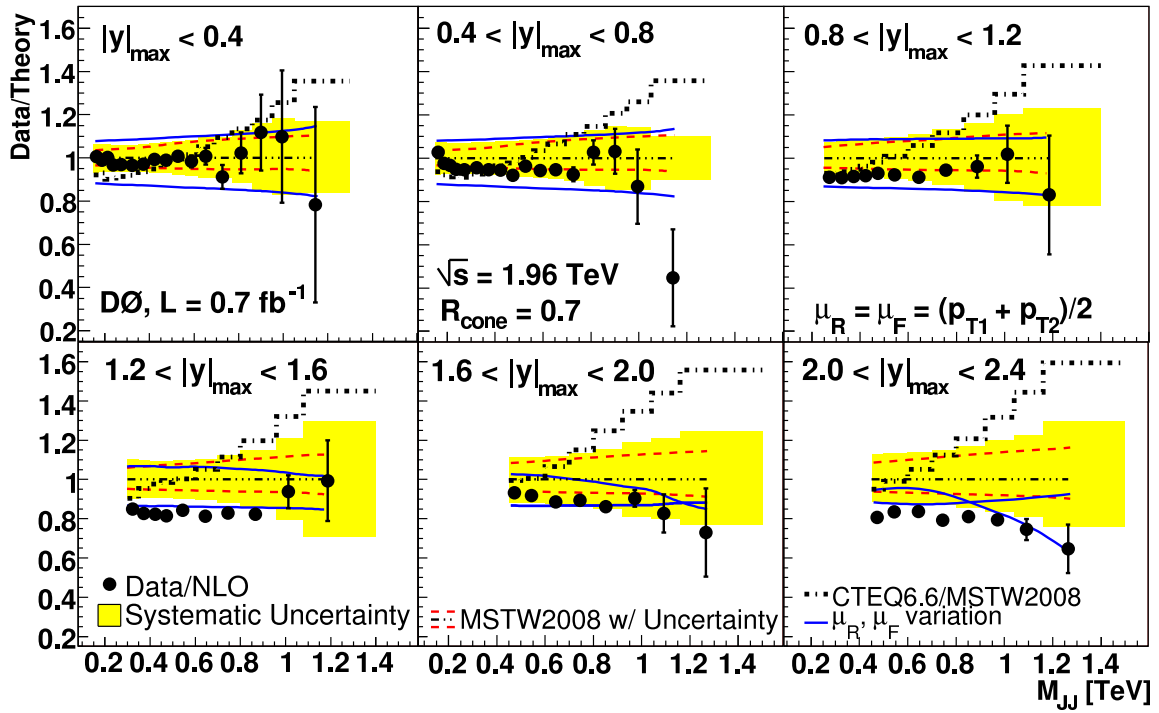
Dijet mass cross section

- measurement of $\frac{\mathrm{d}^2\sigma}{\mathrm{d}M_{JJ}\mathrm{d}|y|_{\max}}$ in 6 rapidity bins up to $M_{JJ} \sim 1.3\,\mathrm{TeV}$

  M_{JJ}: dijet mass, $|y|_{\max} = \max(|y_1|, |y_2|)$, $p_{T1,2} > 40\,\mathrm{GeV}$
- 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

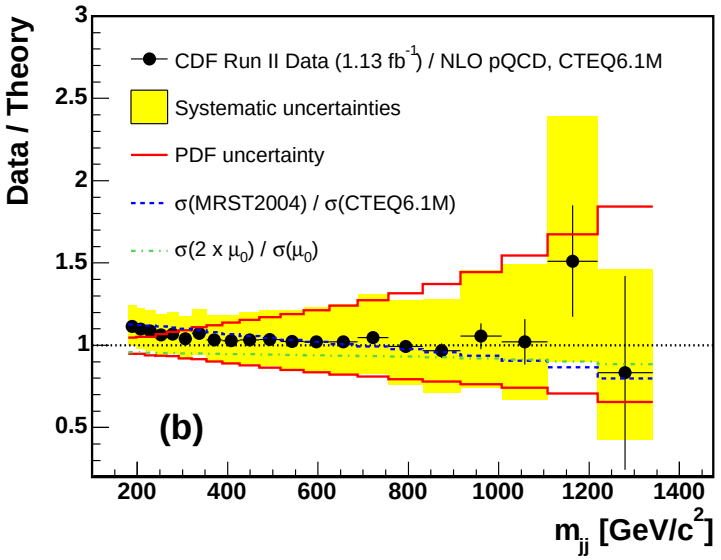


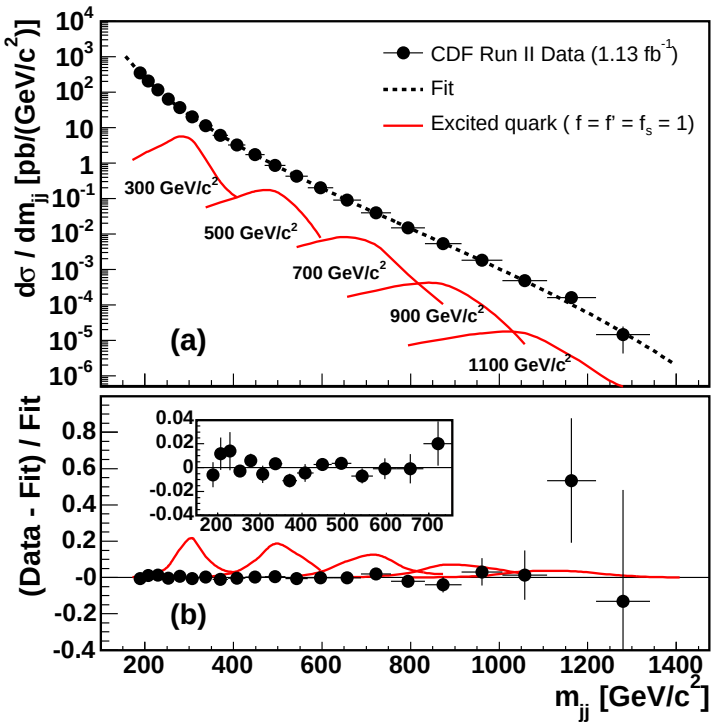
arXiv:1002.4594



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.:
  - $M(q^*) > 870\,\mathrm{GeV}$
  - $M(\mathrm{axigluon}) > 1.25\,\mathrm{TeV}$

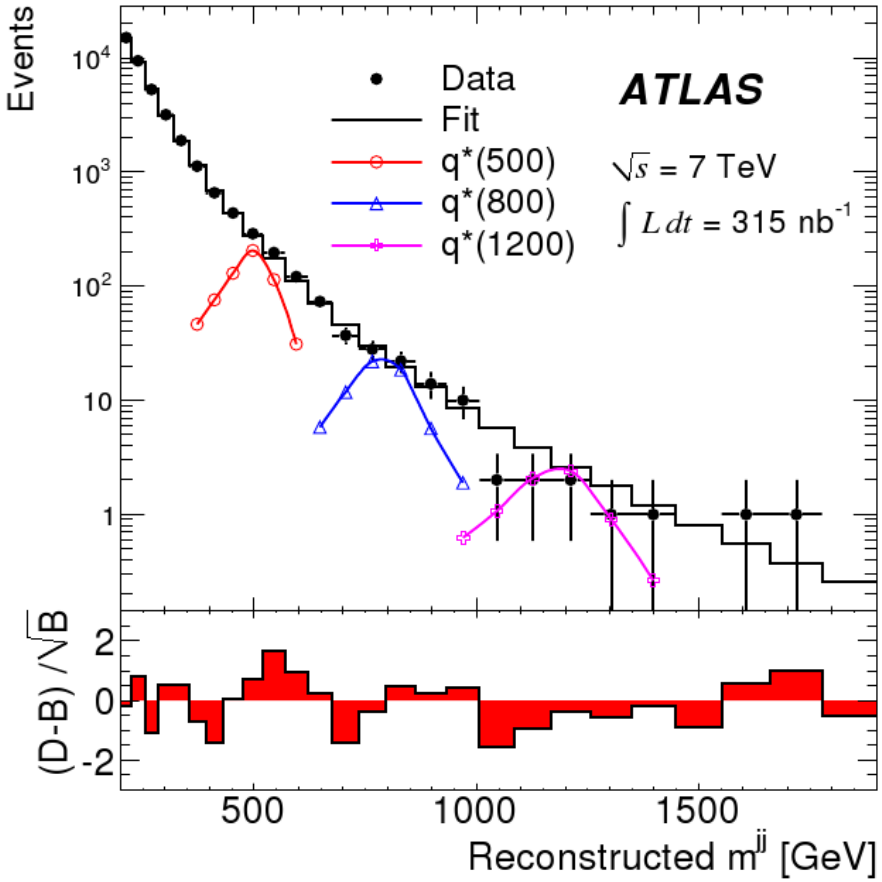


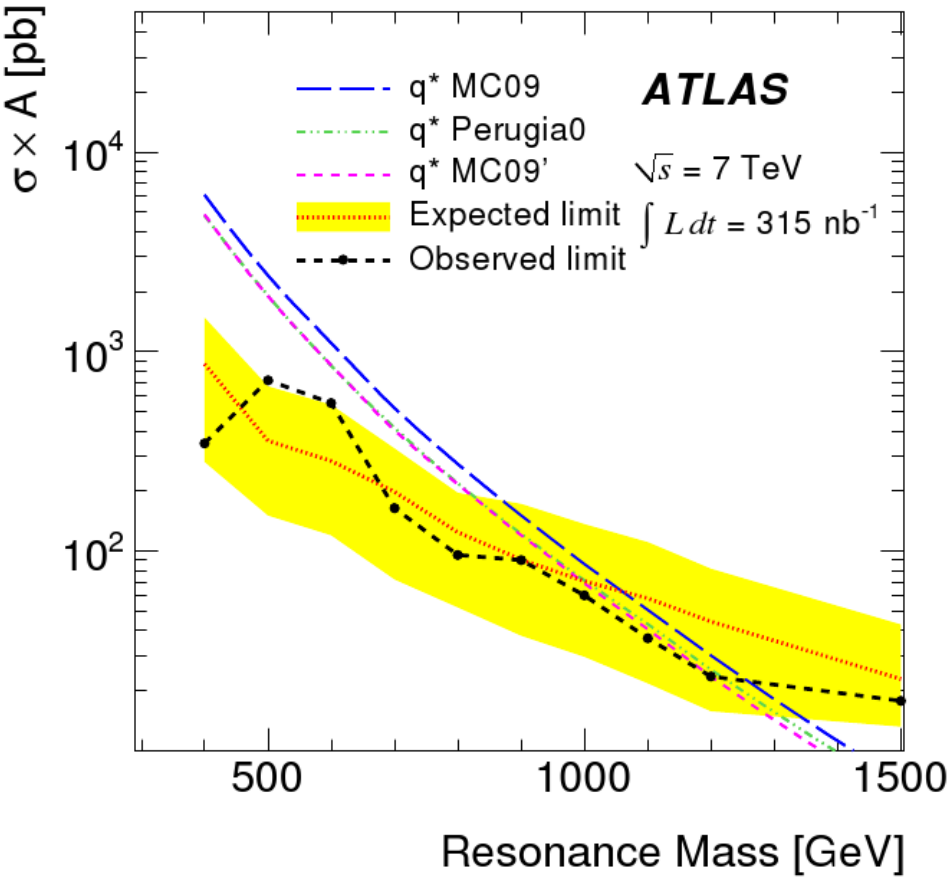


Phys. Rev. D 79, 112002 (2009)

LHC takes over...

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





arXiv:1008.2461

Dijet angular distribution

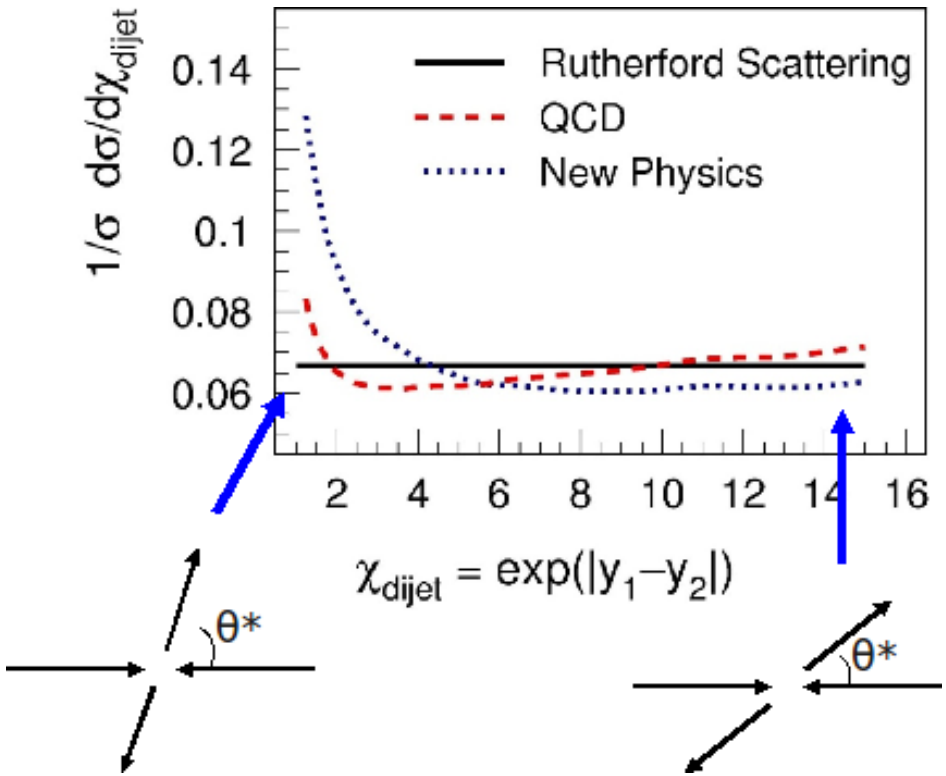
- measurement of

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

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

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

- consistent with NLO QCD
- limits on BSM mass scales:
  - quark compositeness: $\sim$2.9 TeV
  - large extra dimensions (ADD (GRW) and TeV^{-1}): $\sim$1.6 TeV



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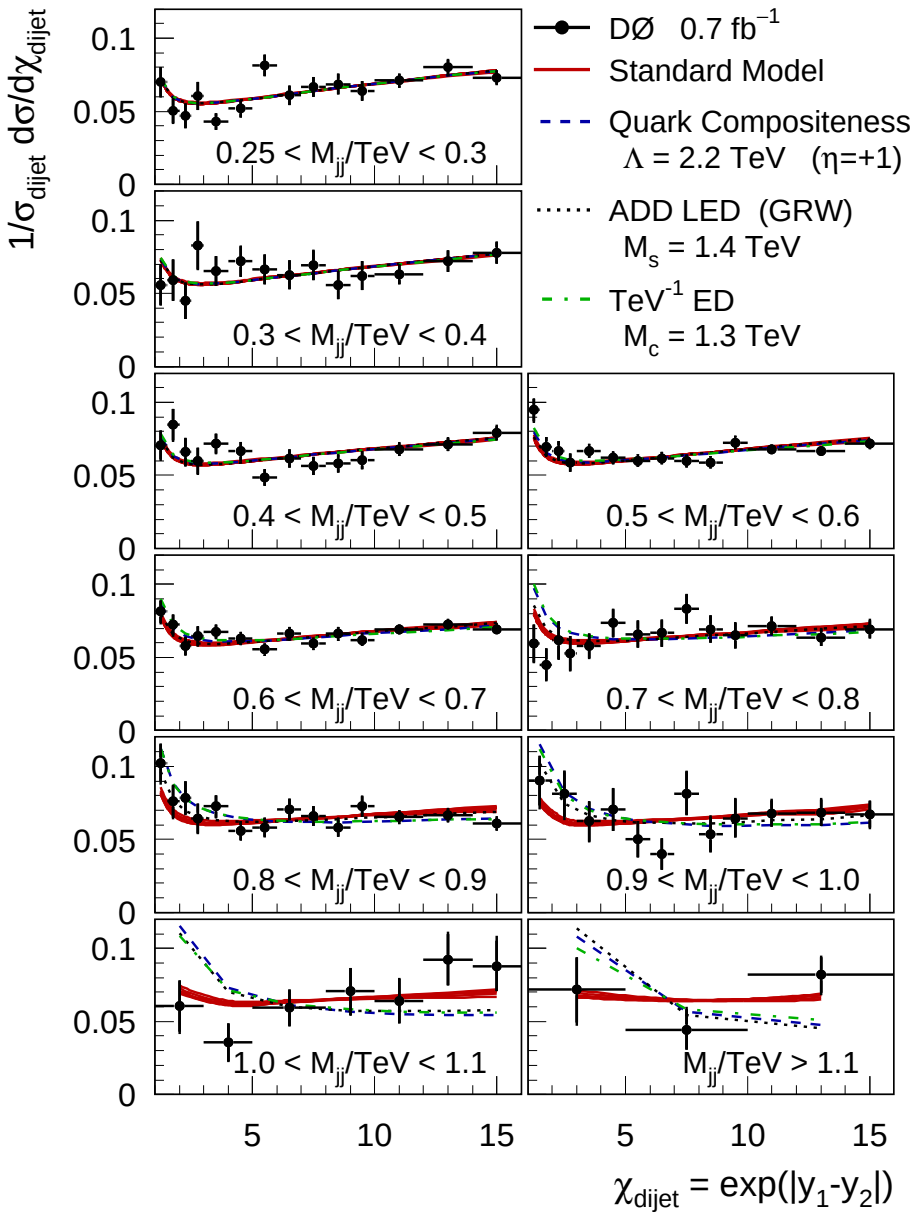
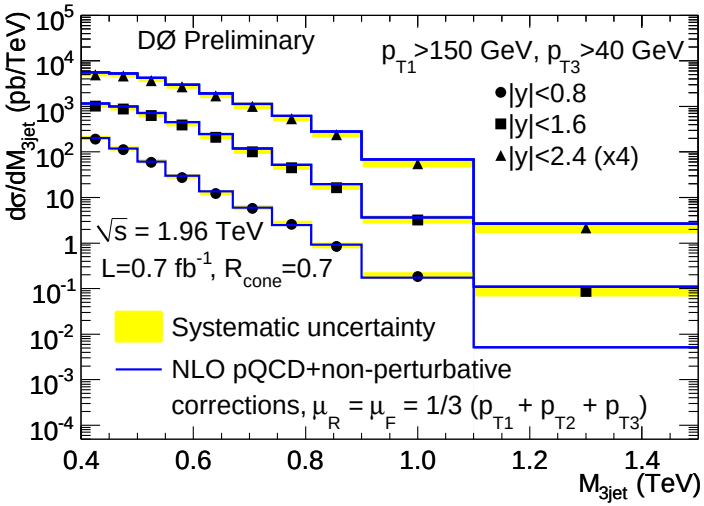


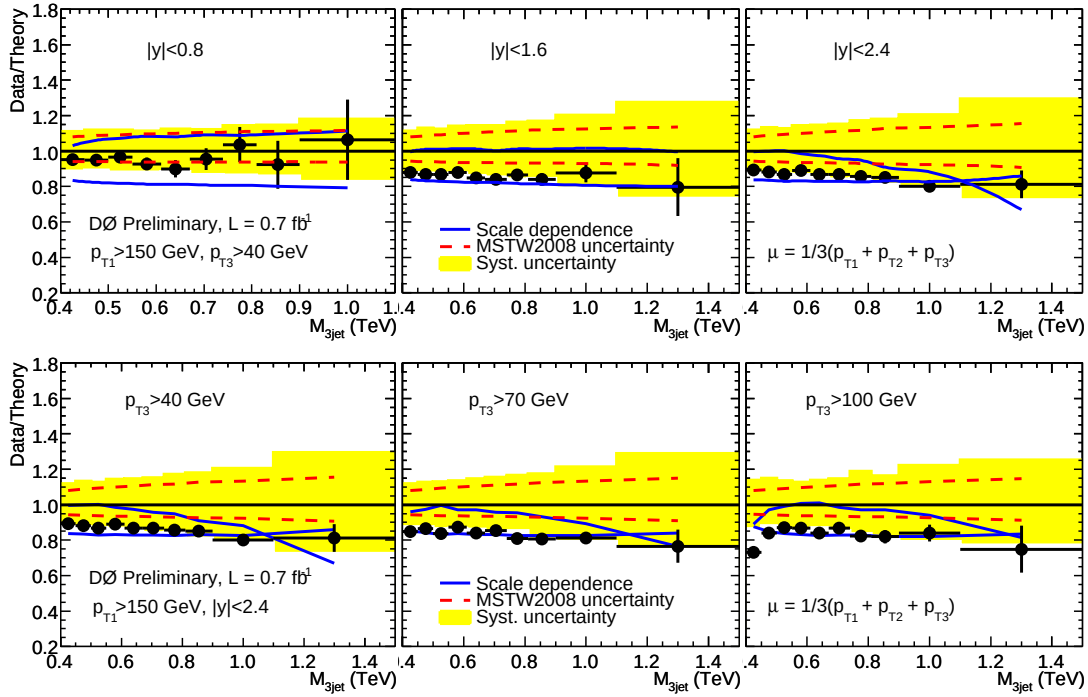
Phys. Rev. Lett. 103, 191803 (2009)

Three jet mass

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



D0 Note 6043-CONF (2010)

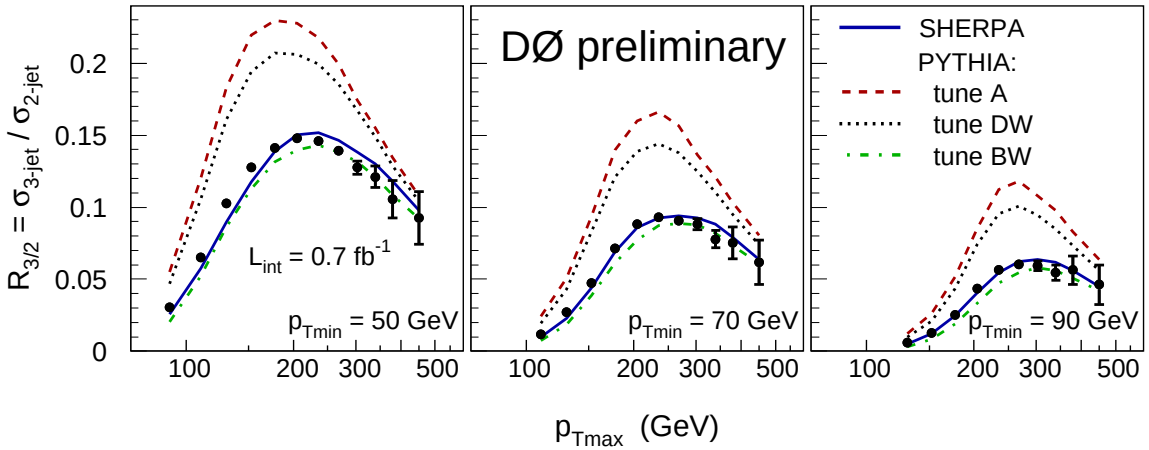


$R_{3/2}$: ratio of inclusive 3-jet to 2-jet production

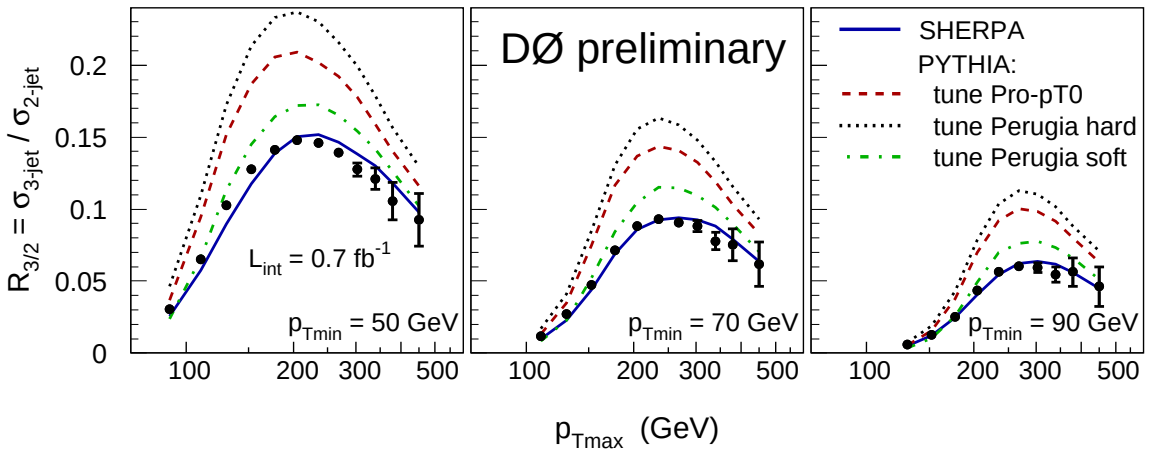
- test of QCD, less dependent on PDFs, probes α_s
- well described by SHERPA v1.1.3
  - CKKW matching of matrix elements and parton shower
  - here: MEs up to 4 partons
- PYTHIA: large dependence on tunes, generally too many 3-jets (except for BW)
  - both for Q^2 and p_T ordered parton shower
  - tune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

$\rightarrow$ hampers α_s extraction

PYTHIA: Q^2-ordered shower



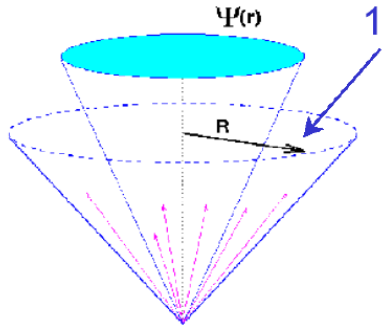
PYTHIA: p_T-ordered shower



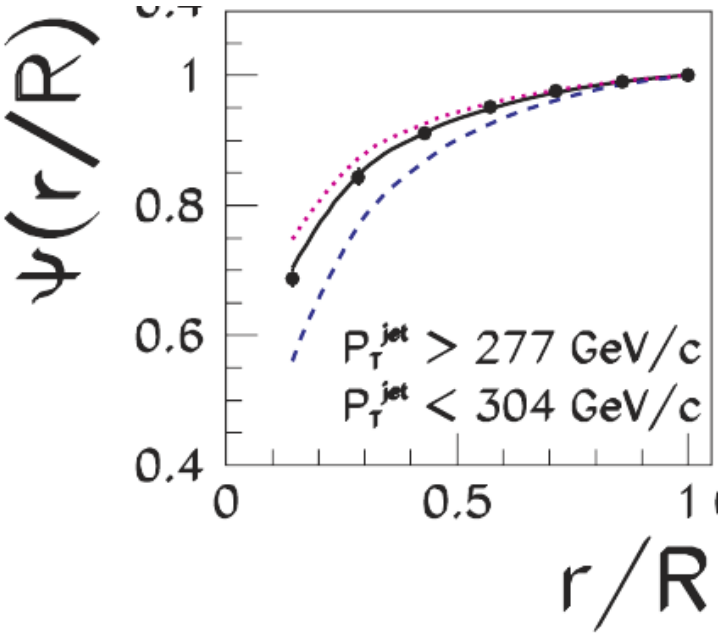
D0 Note 6032-CONF (2010)

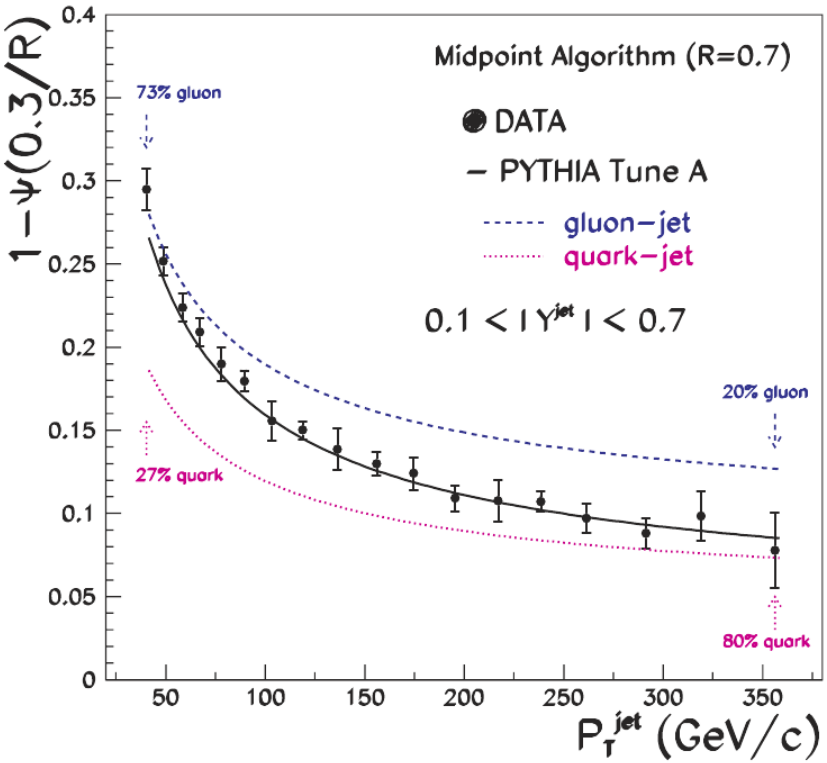
Jet shape measurements

- 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



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

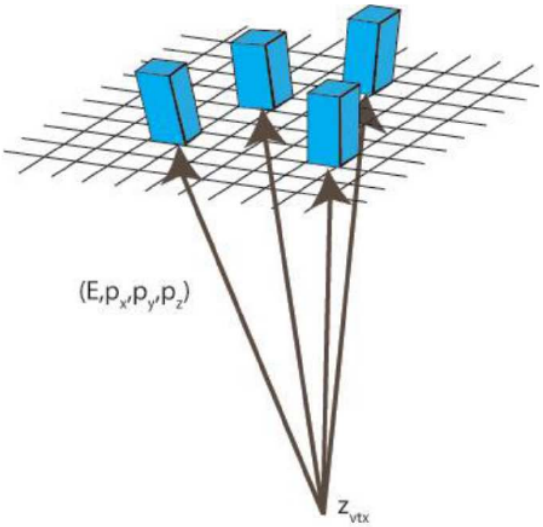


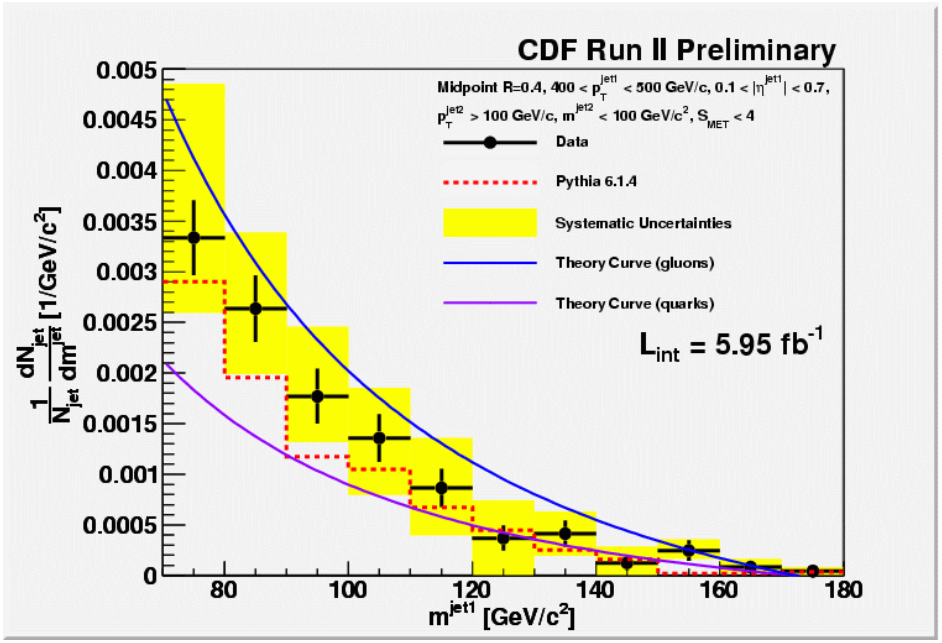


Phys. Rev. D 71, 112002 (2005)

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)

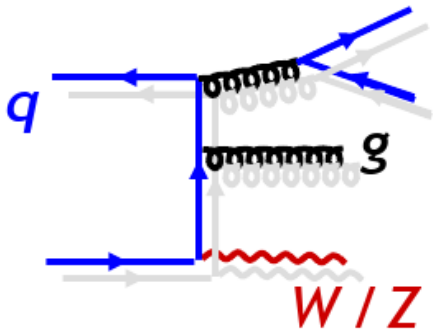
W/Z + jets production

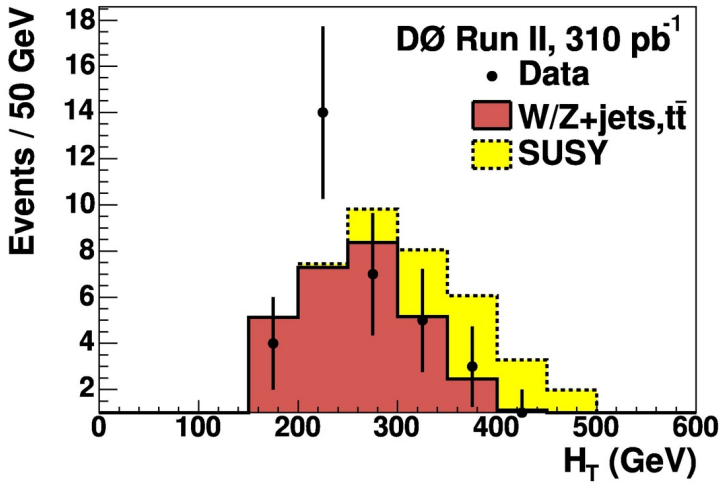
- W/Z + jets: critical background at Tevatron and LHC for top, Higgs, Supersymmetry, many BSM scenarios
  - in particular: $W/Z + b\bar{b}$

  → 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 $q \to qg$ 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





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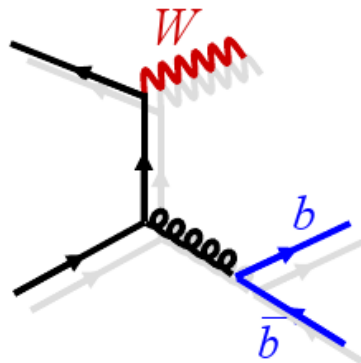

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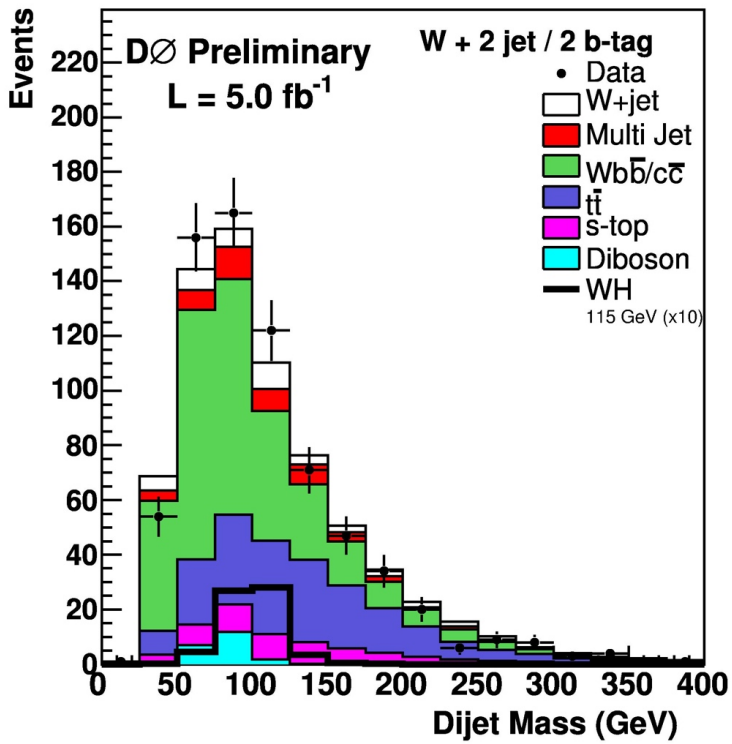

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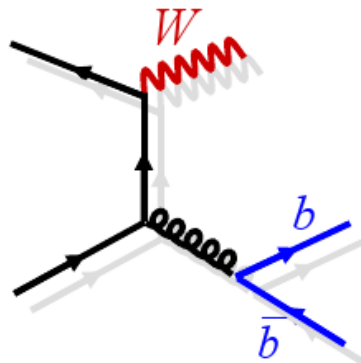

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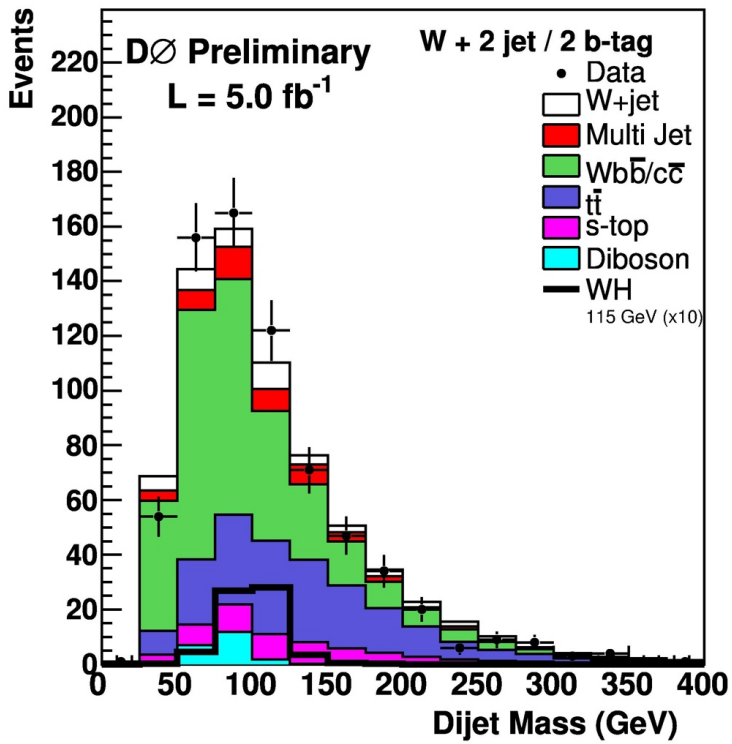
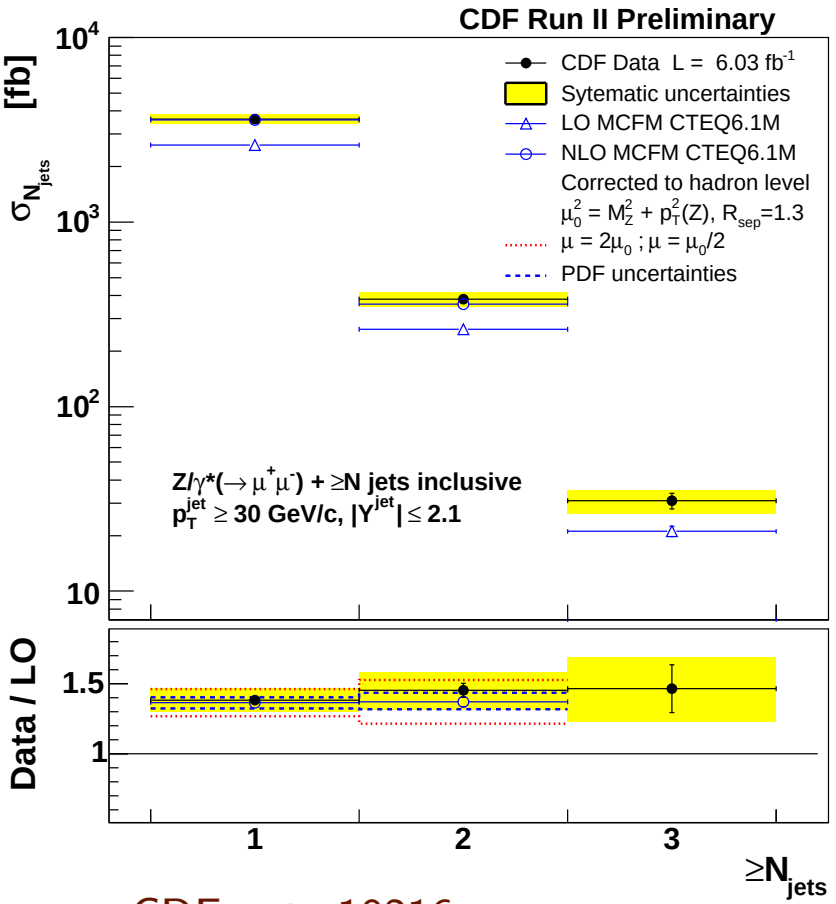


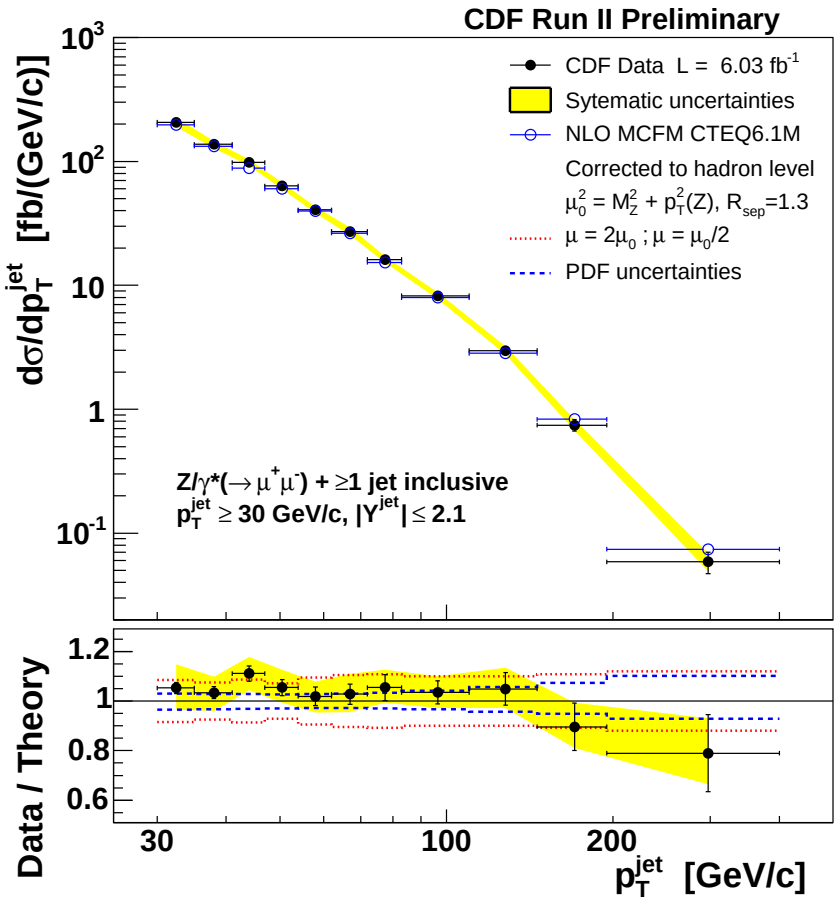
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$ + jets production

incl. jet multiplicity



CDF note 10216

incl. jet p_T distr. for ≥ 1 jet

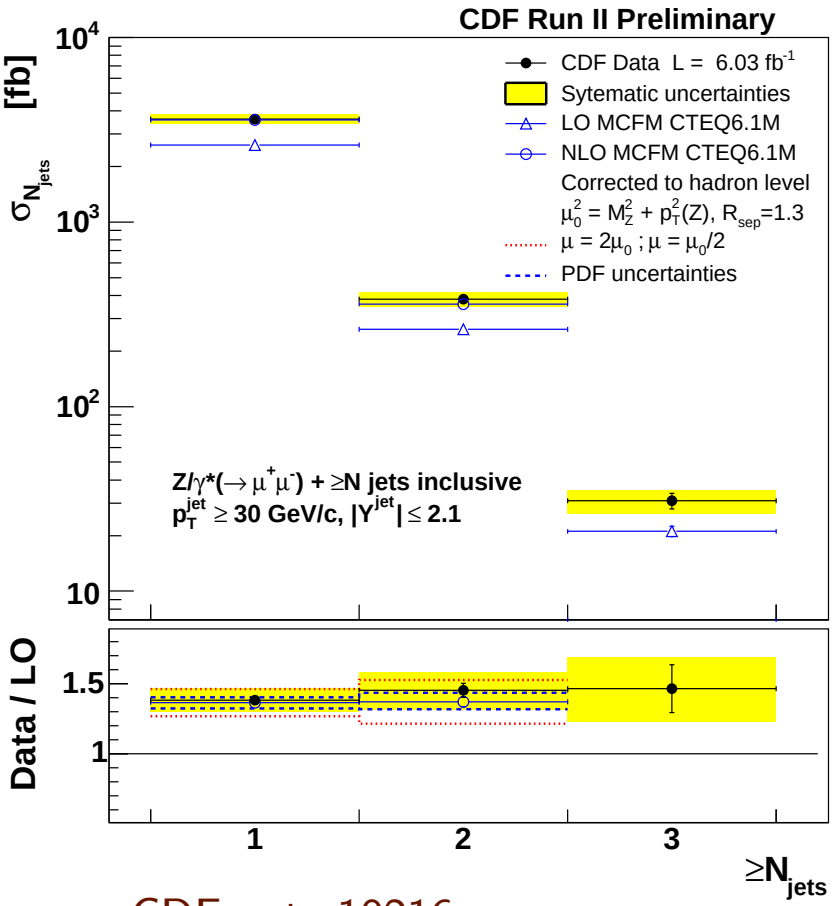


$\Rightarrow$ good agreement with NLO pQCD (MCFM)

- scale uncertainties: 10-15%

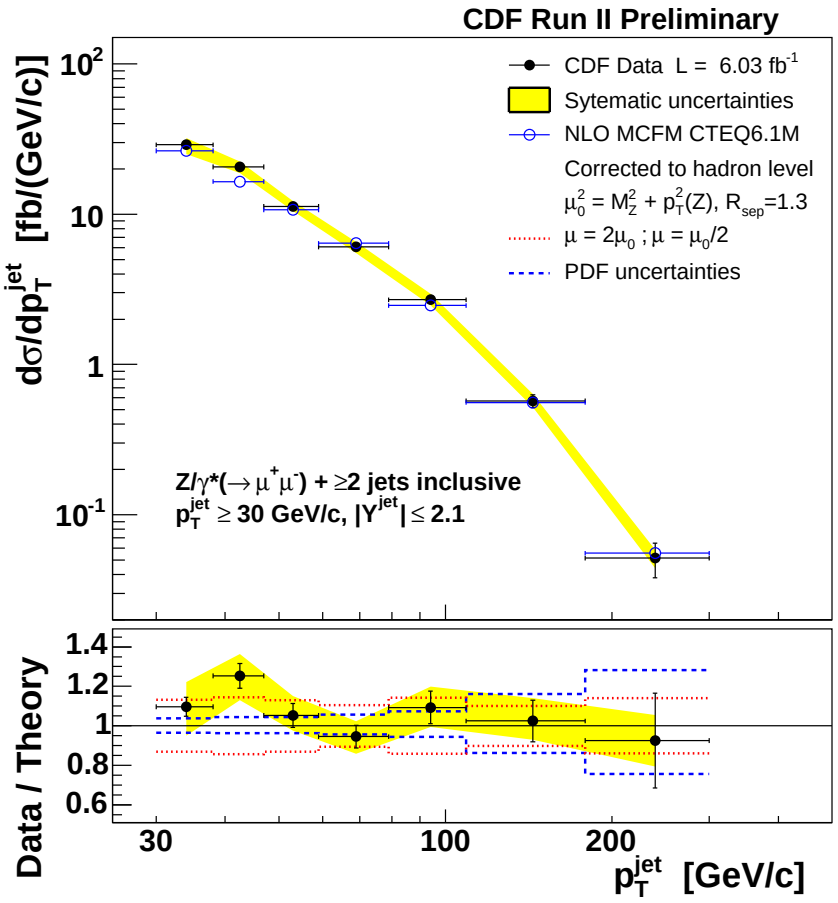
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$ + jets production

incl. jet multiplicity



CDF note 10216

incl. jet p_T distr. for ≥ 2 jet



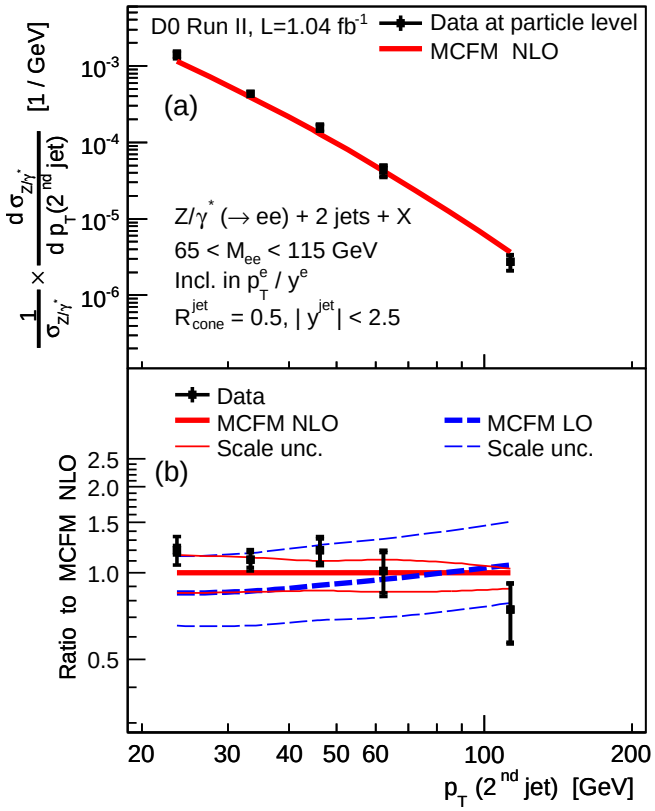
⇒ good agreement with NLO pQCD (MCFM)

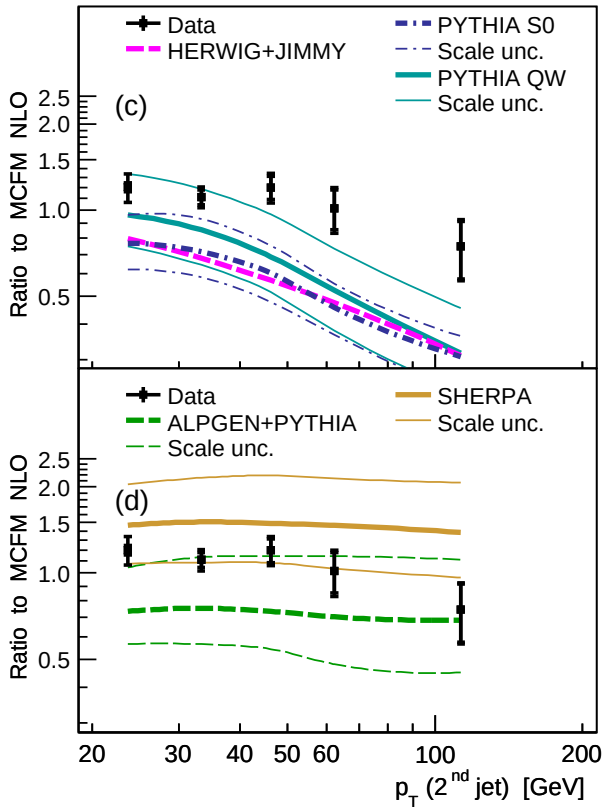
- scale uncertainties: 10-15%

$Z/\gamma^*(\to e^+e^-)$ + jets: jet p_T spectra

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

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





parton shower generators

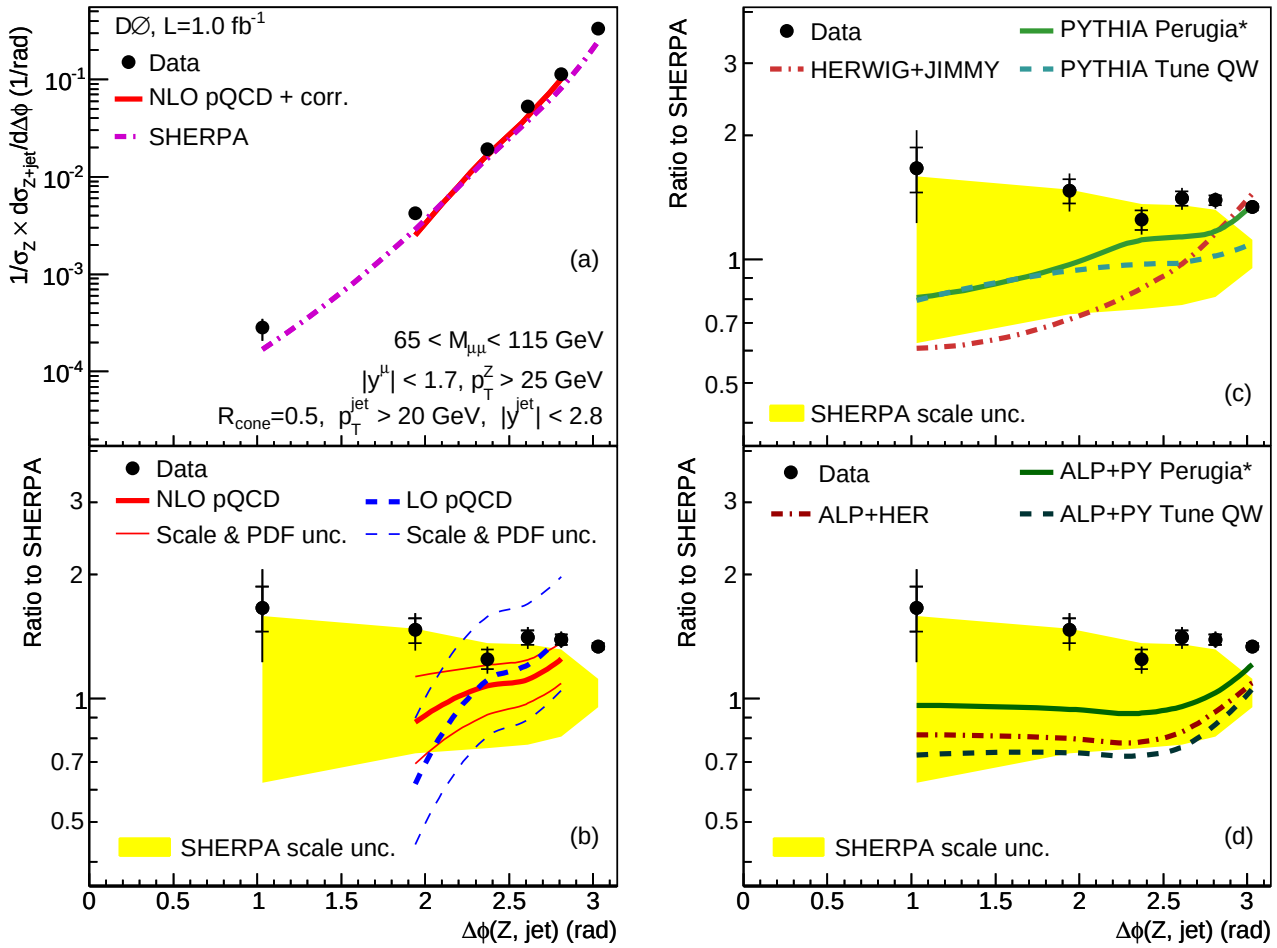
ME+PS generators

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

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

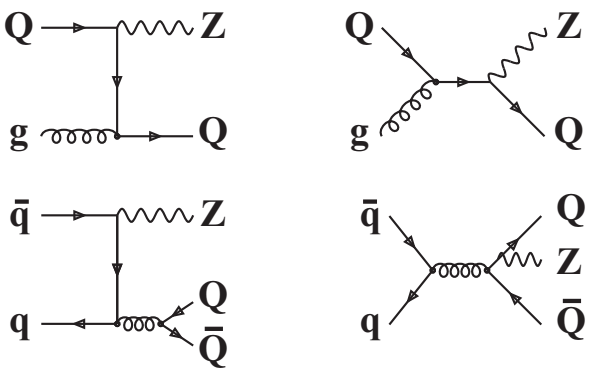
- observables
  - $\Delta\phi(Z, \mathrm{jet}_1)$, shown $\Rightarrow$
  - $\Delta y(Z, \mathrm{jet}_1)$
  - $\frac{1}{2}(y_Z + y_{\mathrm{jet}_1})$
- further constrains kinematics
- avoids systematics of jet energy scale
- fixed-order pQCD predictions not valid for small $\Delta\phi$



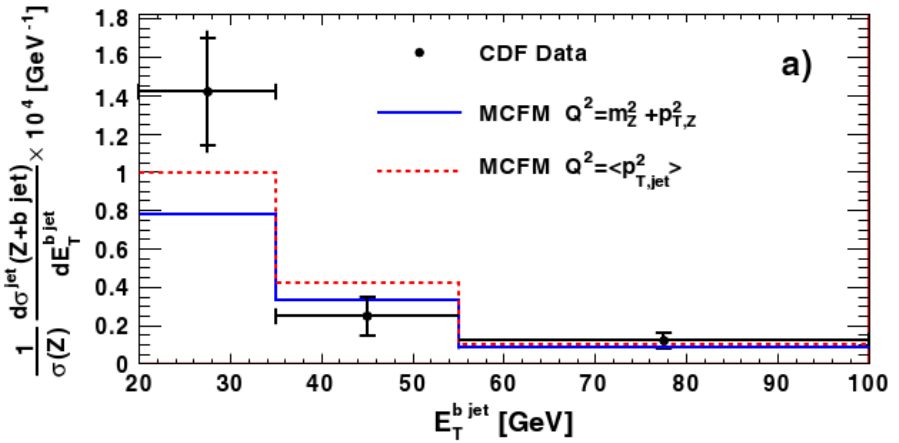
Phys. Lett. B 682, 370 (2010)

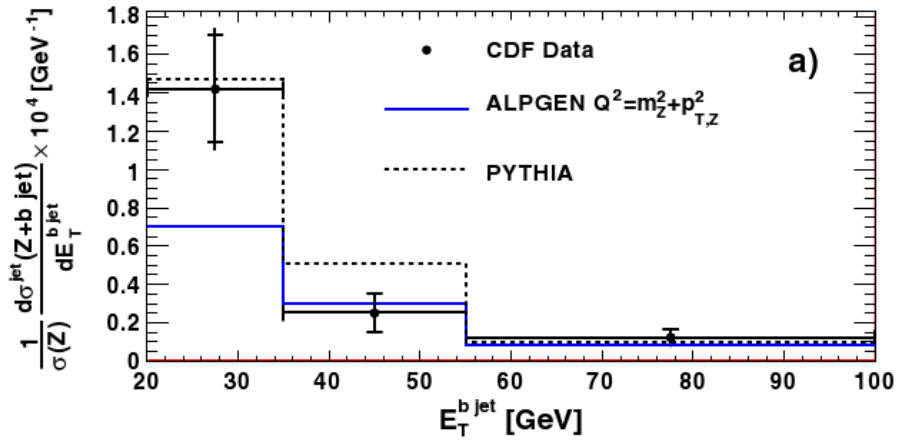
- shape of angular observables well described by SHERPA, but large scale uncertainties

$Z + b$ jet



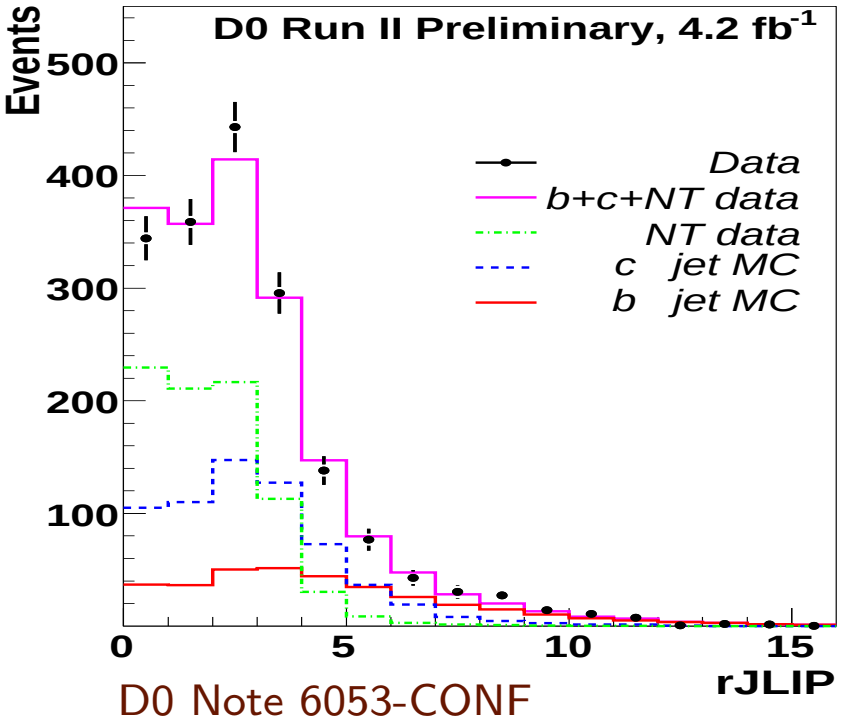
- probes b-quark PDF and fragmentation
- $Z + b$ and $Z + b\bar{b}$
  - $b\bar{b}$ from gluon splitting can collapse in one jet
- measurements require ≥ 1 b-jet
- for jets with $E_T > 20\,\mathrm{GeV}$, $|\eta| < 1.5$
  - $\frac{\sigma(Z+b)}{\sigma(Z+\mathrm{jet})} = (2.08 \pm 0.33 \pm 0.34)\%$
  - MCFM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



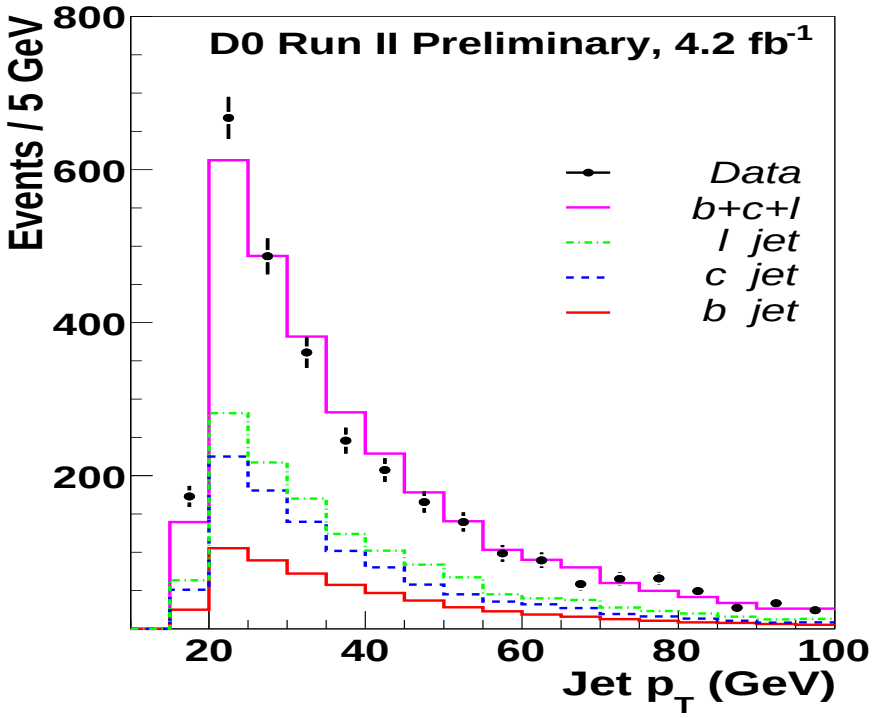


Phys.Rev.D79, 052008 (2009), L=2 fb^{-1}

$Z + b$ jet



D0 Note 6053-CONF



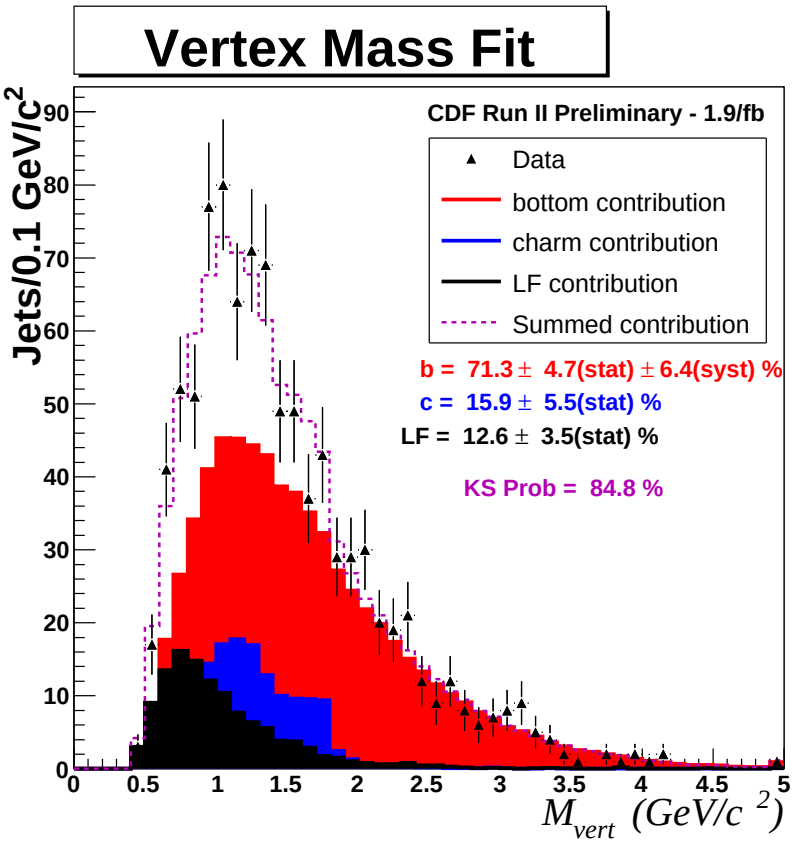
- jet flavor fractions determined from fit to jet lifetime probability tag
  - templates: b, c: ALPGEN+PYTHIA, light q, g: negative tag data
- jet p_T distribution well described
- for jets with $p_T > 20\,\mathrm{GeV}$, $|\eta| < 1$
  - $\frac{\sigma(Z+b)}{\sigma(Z+\mathrm{jet})} = (1.76 \pm 0.24(\mathrm{stat})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

$W + b$ jet

- b-jet fraction determined from fit to vertex-mass distribution M_{vert}
- measurement of

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

  - 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: $0.78\,\text{pb}$



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

$W + c$ jet

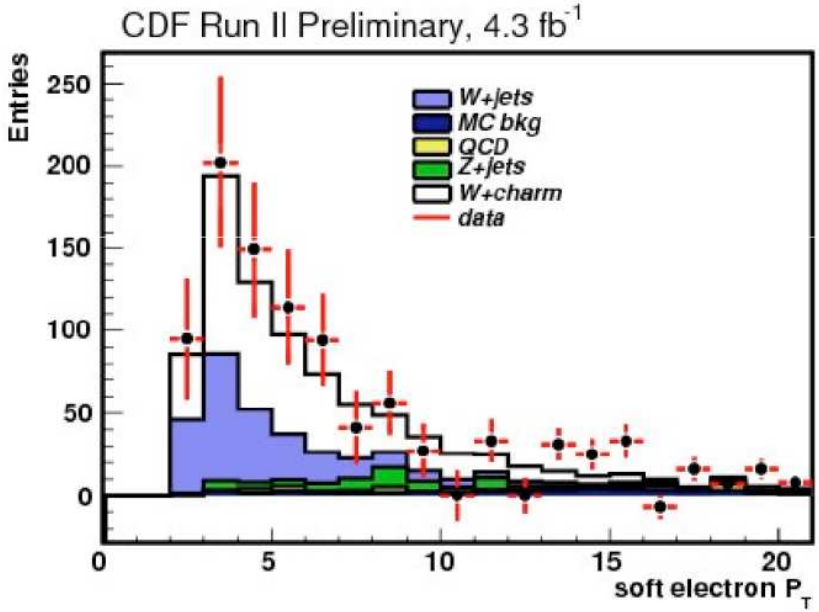
- $s + g$ fusion: $\sim 90\%$ contribution

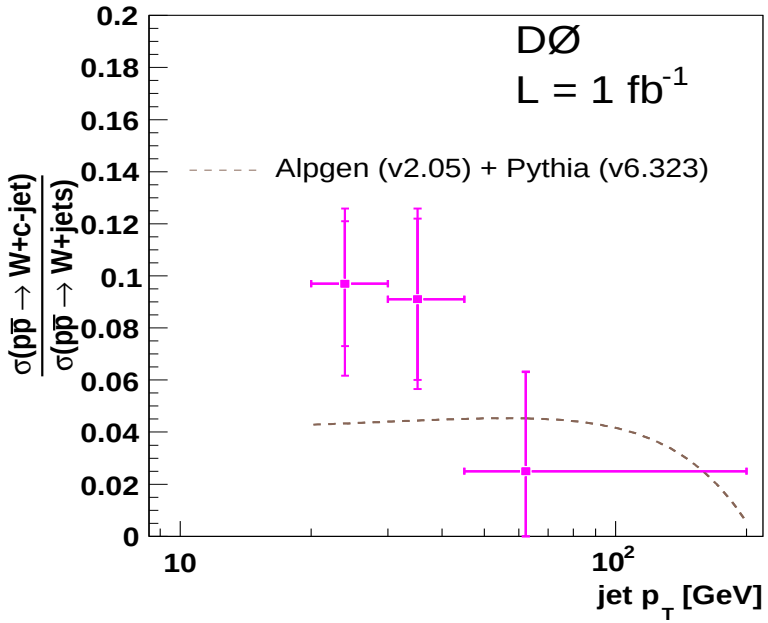
$\rightarrow$ probes g and s PDFs at high Q^2

- c-jet identified by soft lepton
- CDF, $4.3\,\text{fb}^{-1}$
  - c-jet: $p_T > 12\,\text{GeV}$, $|\eta| < 1.5$
  - $\sigma(W + c) \times \mathcal{B}(W \to \ell\nu) =$ $(33.7 \pm 11.4(\text{stat}) \pm 4.7(\text{syst}))\,\text{pb}$
  - NLO: $17.8 \pm 1.7\,\text{pb}$
- D0, $1\,\text{fb}^{-1}$
  - 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%

$\Rightarrow$ reasonable agreement

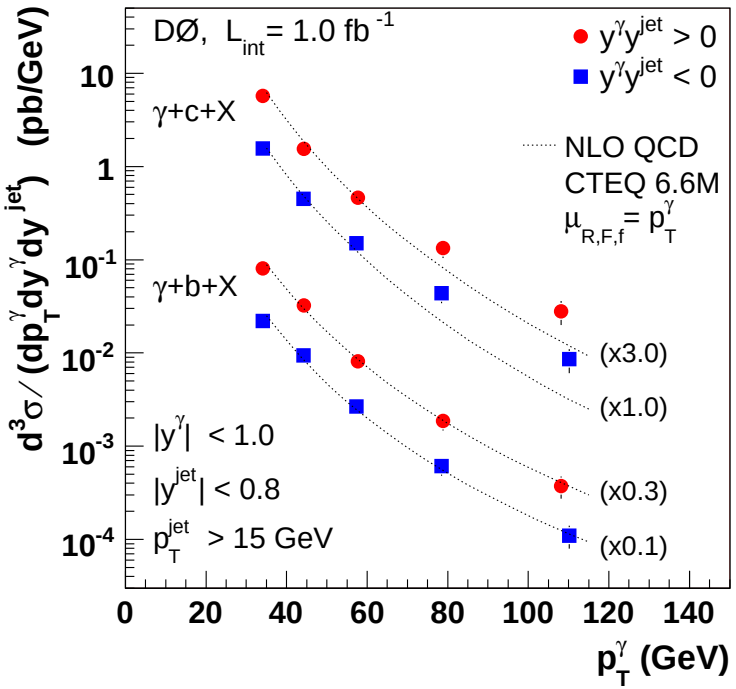
CDF note 10089



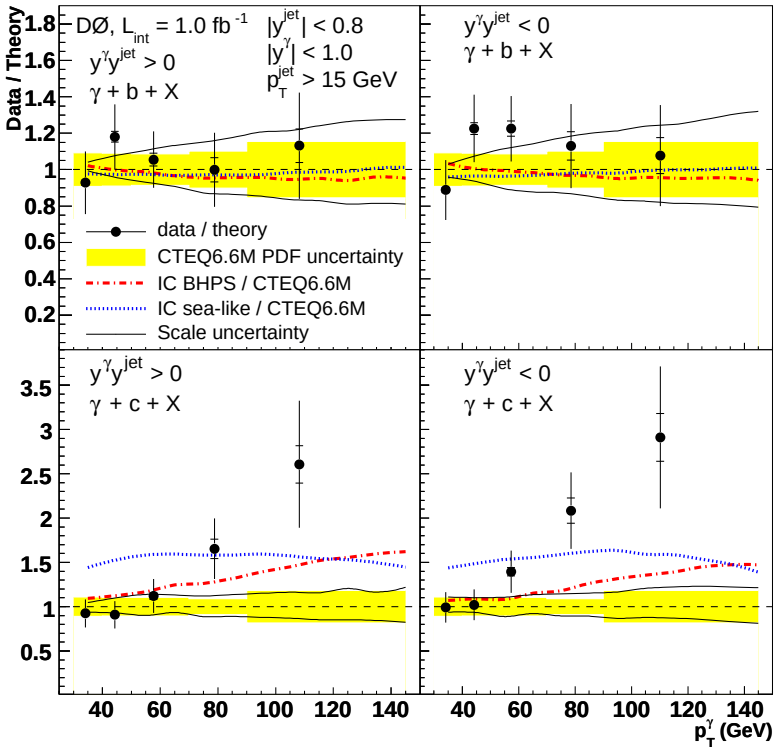


Phys. Lett. B 666, 23 (2008)

$\gamma + b/c$ jet



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



- again: sensitivity to heavy flavor and gluon content of proton
- $p_T^{jet} > 15\,\mathrm{GeV}$, $30\,\mathrm{GeV} < p_T^\gamma < 150\,\mathrm{GeV}$
- $\gamma + b$: 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)

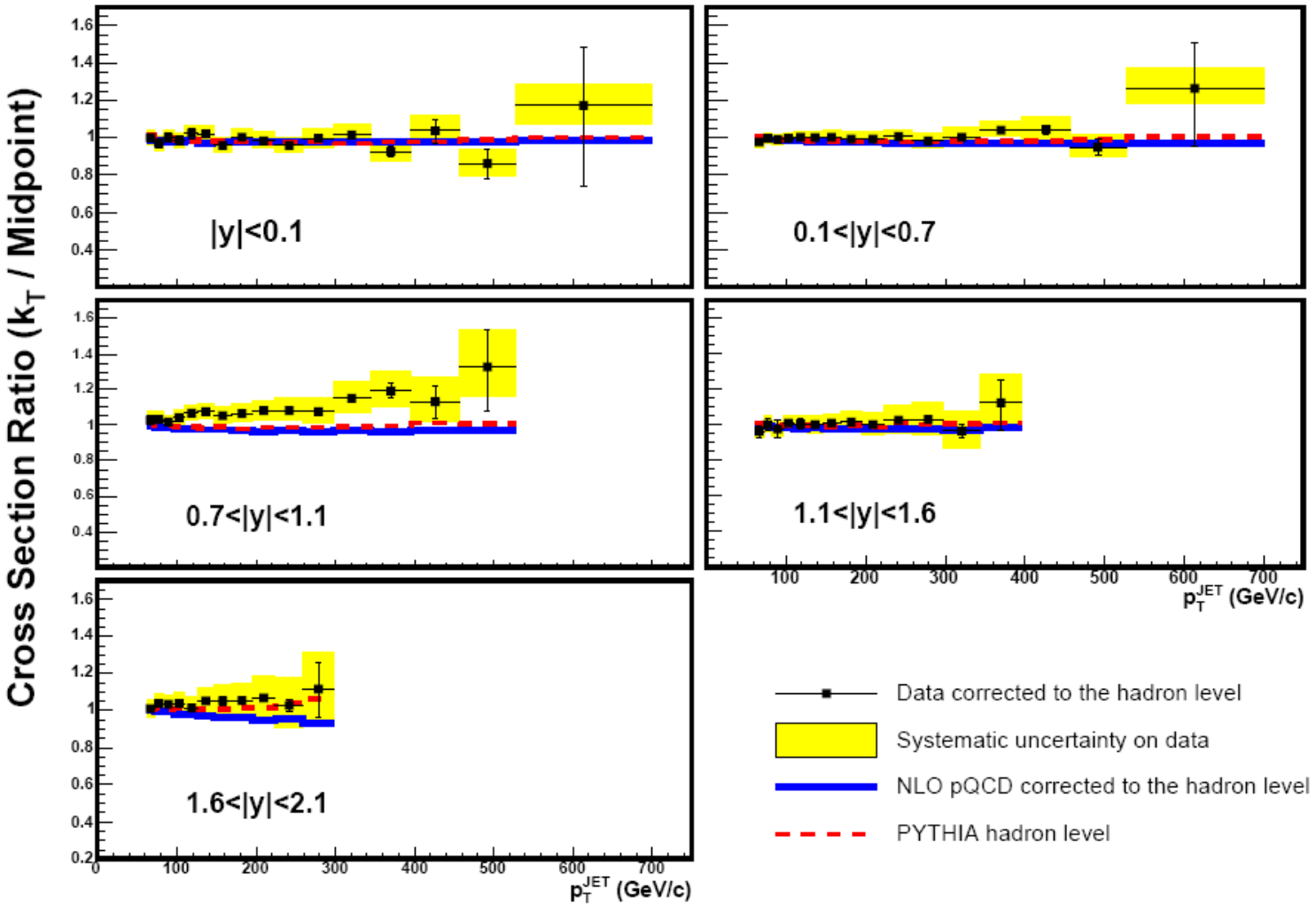
Conclusions

- understanding of high E_T jet and W/Z+jet production significantly advanced over the last years
- inclusive jet cross section
  - high precision due to precise jet energy scale calibration

  $\longrightarrow$ precision measurement of running α_s

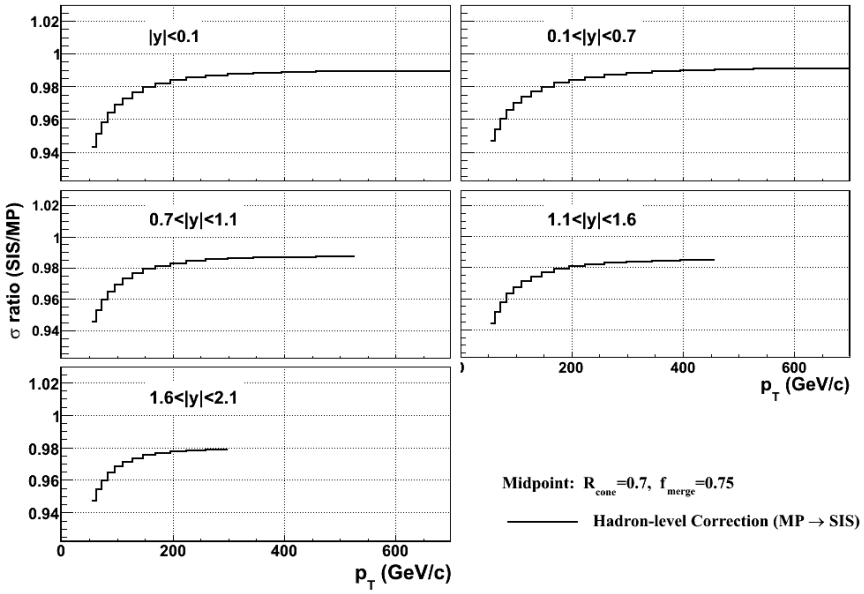
  $\longrightarrow$ stringent constraints on gluons at high x
- multijets
  - agreement with NLO QCD, but data prefer lower bound on theory
- dijet mass and angular distribution
  - best limits on quark compositeness, extra dimensions, etc.
- $Z/W/\gamma$ + jets(s)
  - test pQCD, help generator modeling/tuning
  - crucial for SUSY and Higgs searches (in particular for b-jets)
  - $W + b$, $\gamma + c$: some tension with theory
- Tevatron expects $12\,\text{fb}^{-1}$ until 2011 (and prospects beyond)
  - extend measurements to higher p_T, M_{jj} and multiplicities

Inclusive jets: k_T vs. midpoint cone

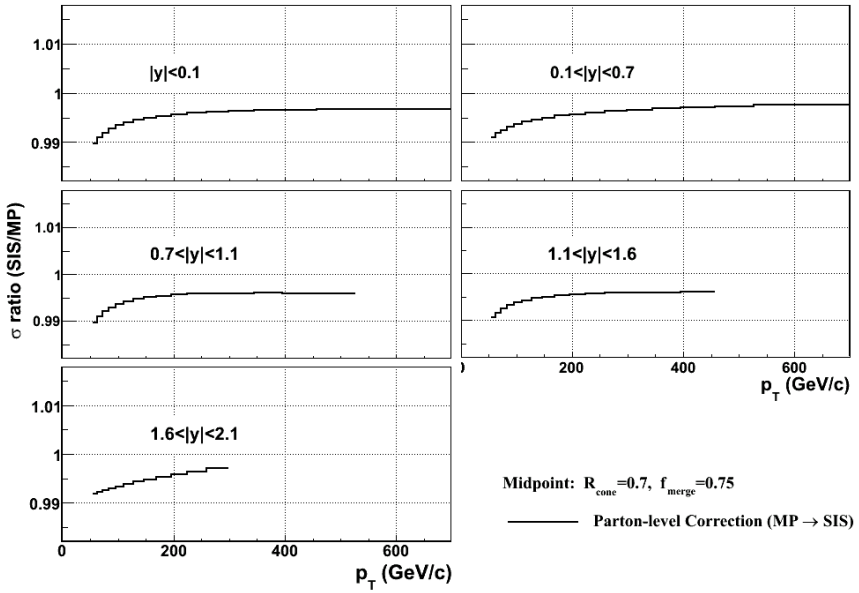


Inclusive jets: SIS cone vs. midpoint cone

hadron level



parton level



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