QCD at high Q^2: new Tevatron results and LHC prospects

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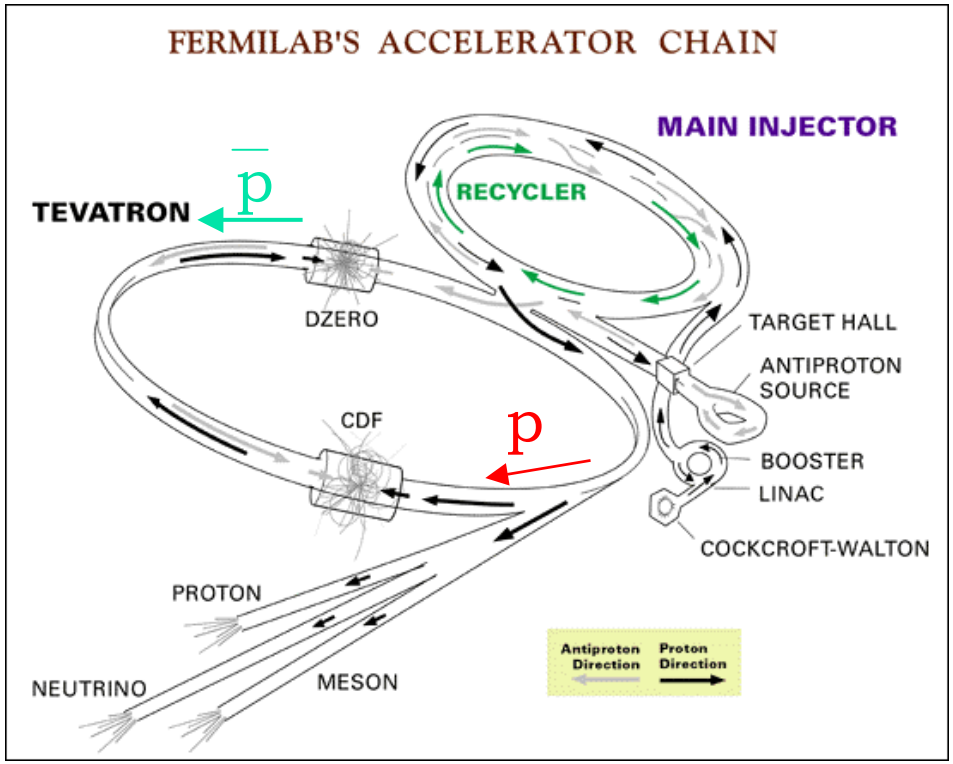
On behalf of the CDF and DØ collaborations

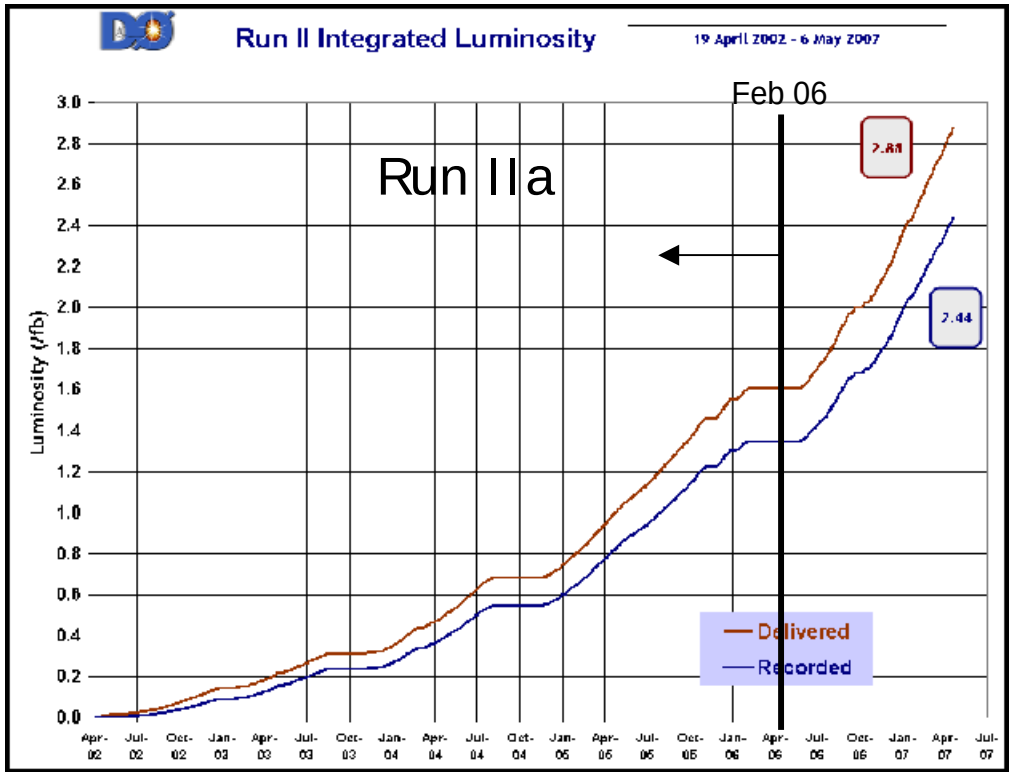
The Tevatron at Run II



- $p\bar{p}$ collider at $\sqrt{s}$ = 1.96 TeV (1.8 TeV in Run I)
- 36 x 36 bunches (6 x 6 in Run I)
- 396 ns bunch crossing interval (3500 in Run I)

- Run II started in March 2001
- Peak luminosity now close to 3E32
- Integrated luminosity delivered by the Tevatron now close to 3.0 fb^{-1}
- Projection: up to 8.0 fb-1 in 2009

Results shown here use up to 1.1 fb^{-1}

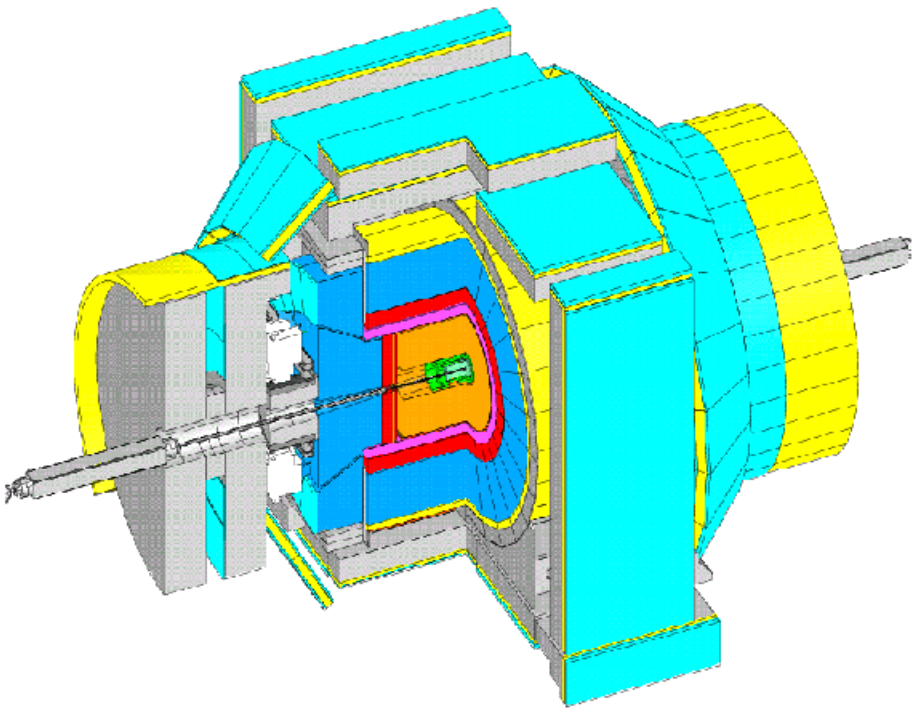


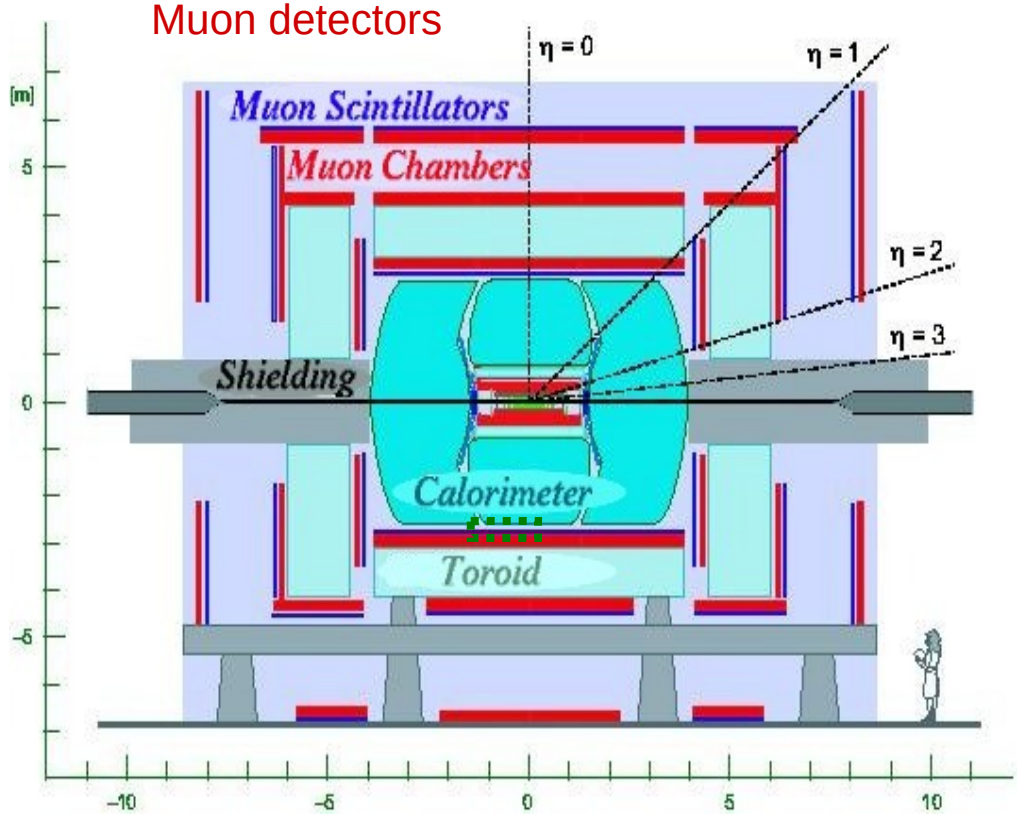
The CDF and DØ detectors at Run II

4π multi-purpose detectors: tracking, calorimeter and muon detection capabilities

Silicon tracking detectors
Central drift chambers (COT)
Solenoid Coil
EM calorimeter
Hadronic calorimeter
Muon scintillator counters
Muon drift chambers

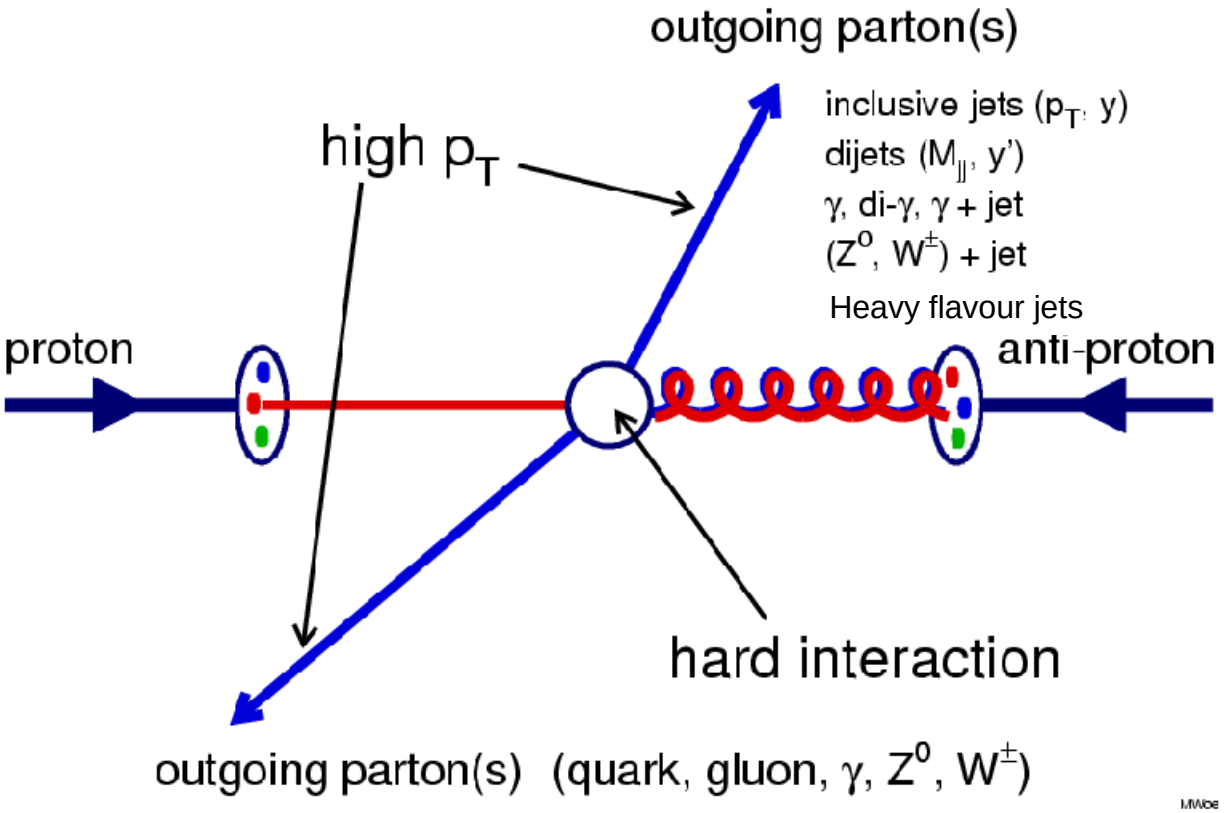
Silicon microVTX
Central Tracker (Scint Fibers)
Superconducting solenoid
Pre-shower detectors
LAr/U Calorimeter
Muon detectors

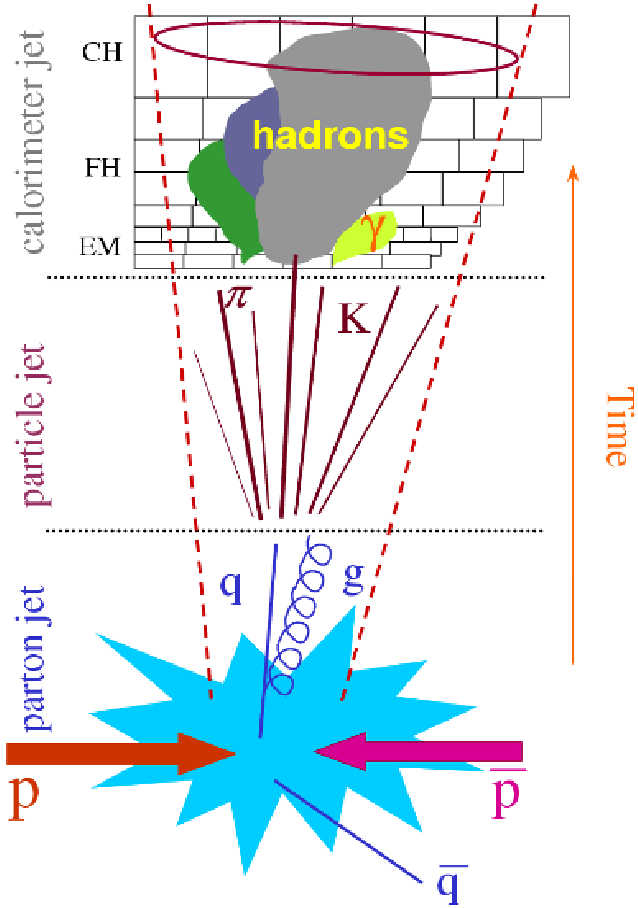




Both experiments record data with high efficiency (80-90%) and make full use of their detector capabilities

High Q^2 processes at the Tevatron





- Parton:
  Cross sections computable in perturbative QCD
  with additional input (PDF): $\sigma = \Sigma \int\int dx_i\, dx_j\, f(x_i,Q^2)\, f(x_j,Q^2)\, \sigma_{ij}$
- Parton → Particle:
  Model additional perturbative (parton showering) and non-perturbative (fragmentation and underlying event) QCD contributions in Monte Carlo
  → Event generation or hadronisation corrections
- Particle → Detector:
  Detector simulation of MC generated events
  → Direct comparison to data or measurement correction to particle level

Parton, particle and detector jets

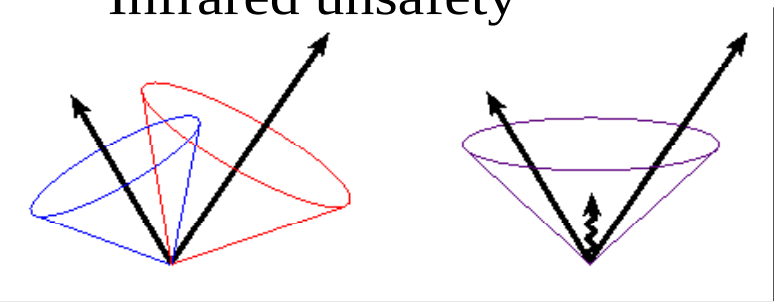
Jet algorithms

→ cluster energy depositions in calorimeter, charged tracks in tracking devices, particles in MC, or even partons in NLO calculations, into jets

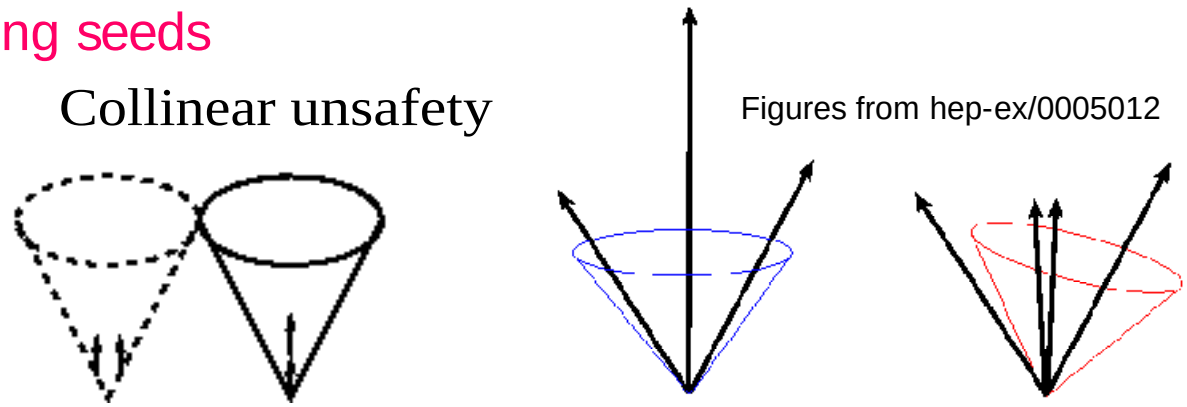
QCD ⇒ { Quark and gluon jets (identified to partons) can be compared to detector jets, if jet algorithms respect collinear and infrared safety (Sterman&Weinberg, 1977)

Problems of Cone Jet Algorithms using seeds

Infrared unsafety



Collinear unsafety



Figures from hep-ex/0005012

Solution(s)

- CDF Midpoint or D0 RunII Cone Algorithm (G.C. Blazey *et al.*, "RunII Jet Physics", hep-ex/0005012)
  - Seed-based protojet finding algorithm using also midpoints between protojets as seeds, otherwise similar to RunI
    Note: the RunII algorithm is only infrared safe up to NNLO (G.P. Salam & G. Soyez, hep-ph/0704.0292)
  - Small differences between CDF (Smaller Search Cone) and D0 (optimisation) detailed implementations of the recommended algorithm
- k_T algorithm
  - Iteratively cluster pairs of close objects until all objects are part of a jet
  - No issue with merging/splitting
  - Infrared and collinear safe to all orders by construction

High Q^2 QCD measurements

- Inclusive jet and dijet
- Inclusive photon and photon+jet
- Z+jet
- Heavy flavor jet

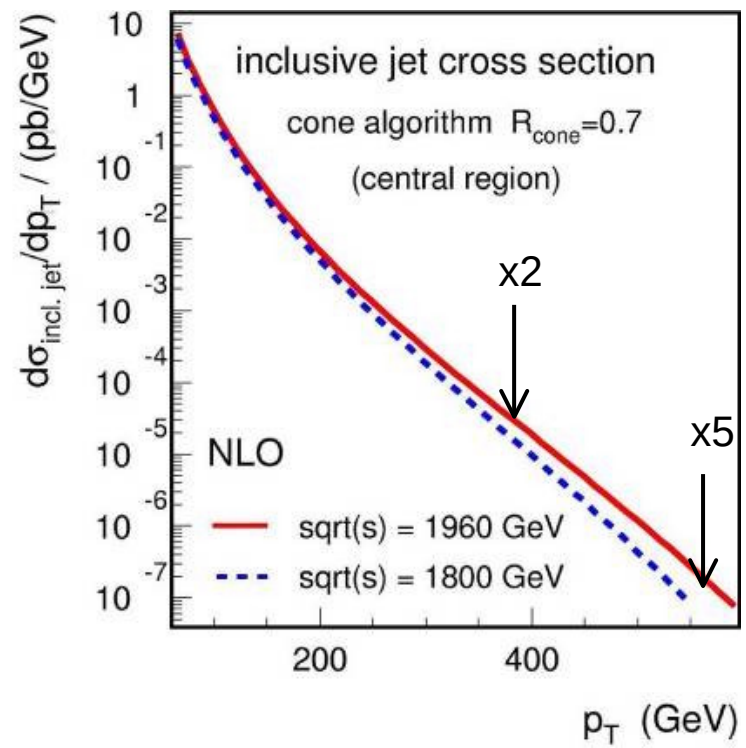
- Motivations
  - Determination of PDFs & measurement of α_S
  - Tests of higher-order perturbative QCD calculations
  - Sensitivity to new physics at highest energy (e.g. test of quark substructure)
  - Understanding of background for other analyses
  - Test of procedure for combining LO Matrix Elements (ME) parton MC with different multiplicities, after matching them with Parton Showers (PS) MC

- Experimental ingredients
  - correct jet measured energy to particle level
  - correct measured cross section to particle level according to measured resolution
  - correct parton-level pQCD predictions to particle level (scale factor to account for fragmentation and underlying event)

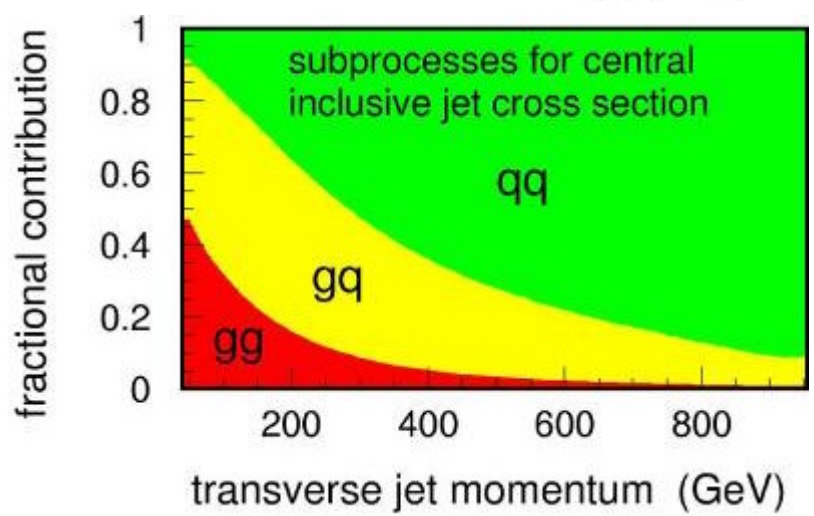
Inclusive jet

- Selection based on single jet triggers with different pT threshold to cover full range
- Count all jets in event

- cms energy 1.8 → 1.96 TeV
  Cross section X 2 (pT= 400 GeV)
  X 5 (pT= 600 GeV)
  → possible new physics at high p_T



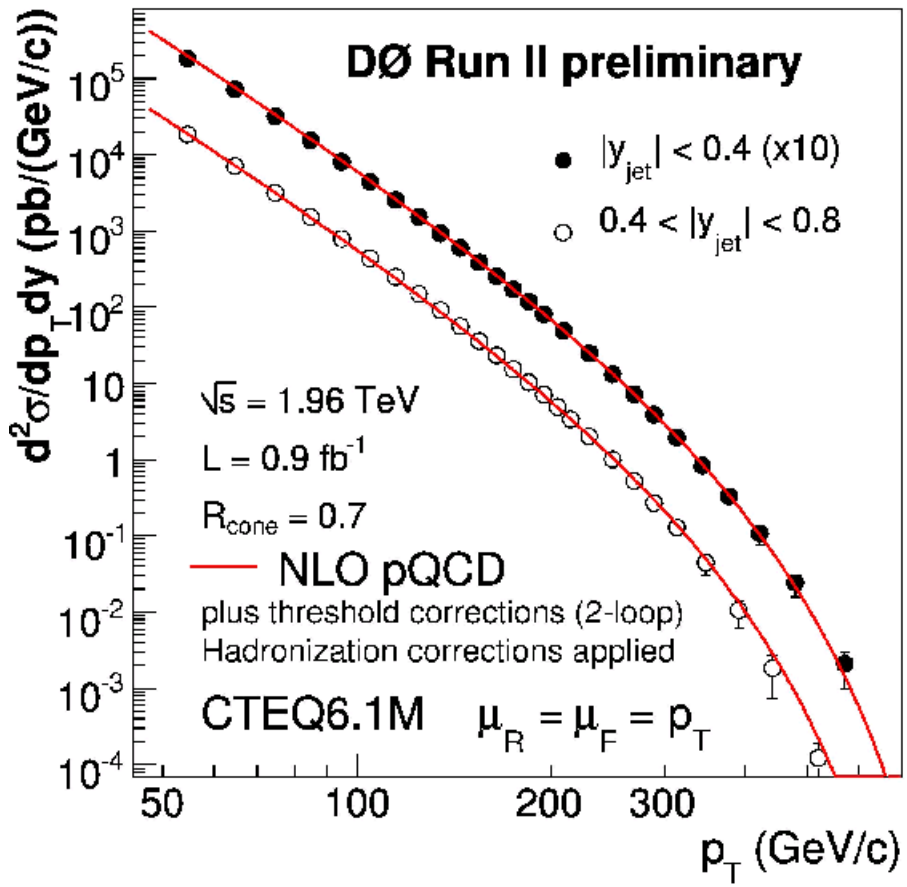
- Theory @NLO is reliable to ± 10 %
  High pT cross section dominated by qq, but qg still accounts for ~30% at 400 GeV
  → sensitivity to PDFs (high-x gluon)

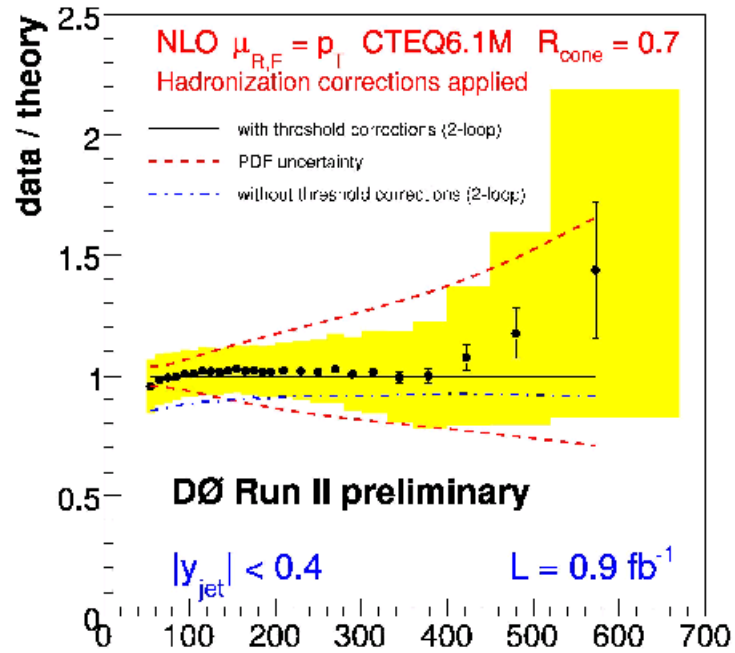


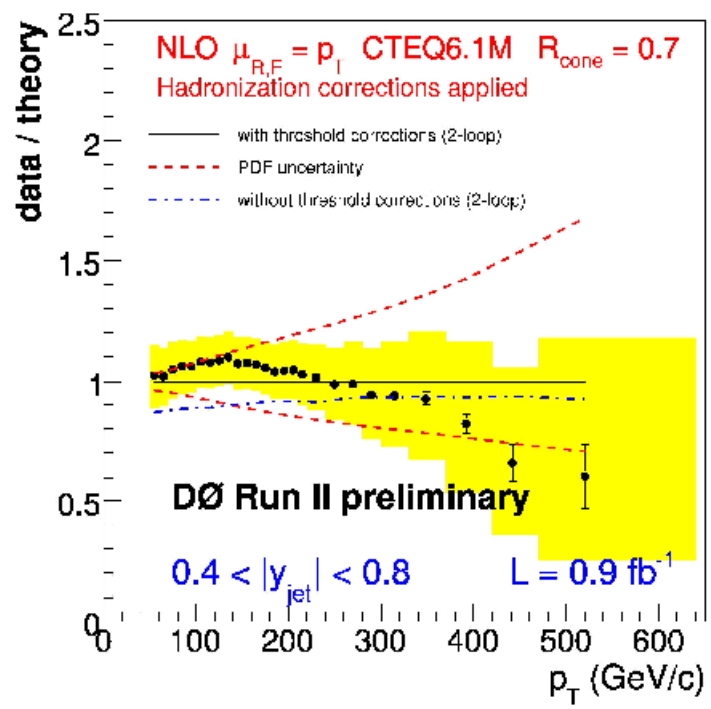
Inclusive jet cross section (D0)

- Run II Cone algorithm, R=0.7
- Cross section in two rapidity bins (0, 0.4, 0.8)
- Compare data (after unsmearing) to NLO pQCD + 2-loop corrections
  NLOJet++ (Z. Nagy, PRL 88, 122003, 2002)
  using CTEQ6.1M (Kidonakis, Owens, PRD 63, 054019, 2001)

DØ preliminary (0.9 fb^{-1})





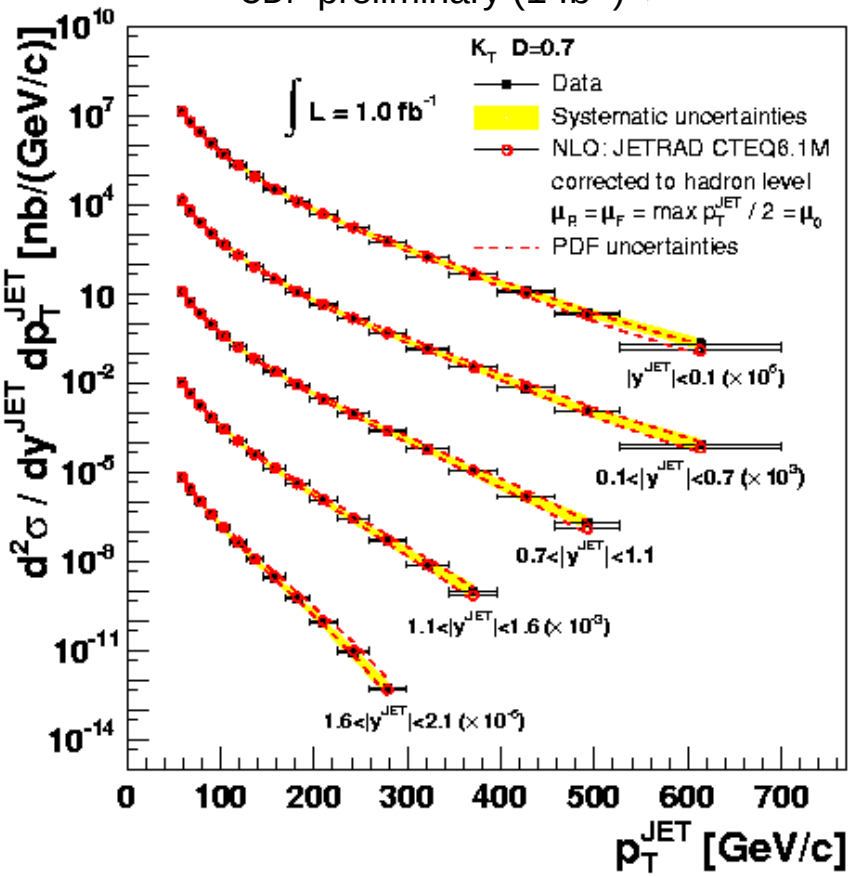


Uncertainty on data and theory comparable
→ Sensitivity to PDFs

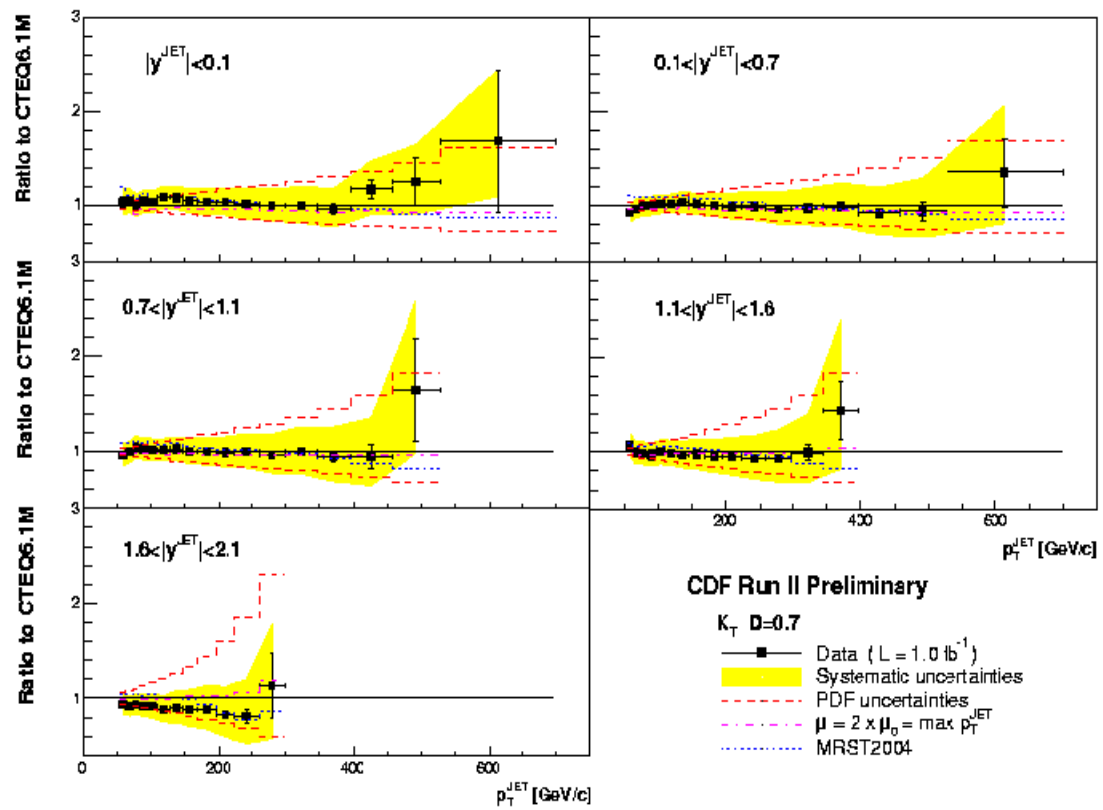
Inclusive jet cross section (CDF)

- Midpoint (R=0.7) and k_T algorithm (D=0.7)
- Cross section in 5 rapidity bins (0, 0.1, 0.7, 1.1, 1.6, 2.1)
- Compare to pQCD NLO prediction corrected for non-perturbative effects

CDF preliminary (1 fb^{-1})



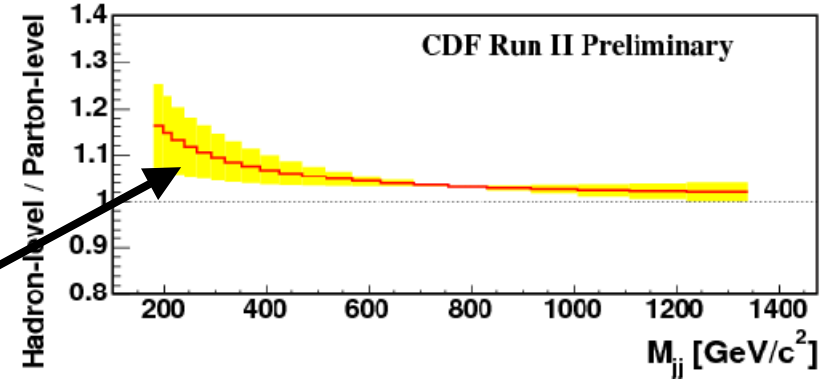
k_T

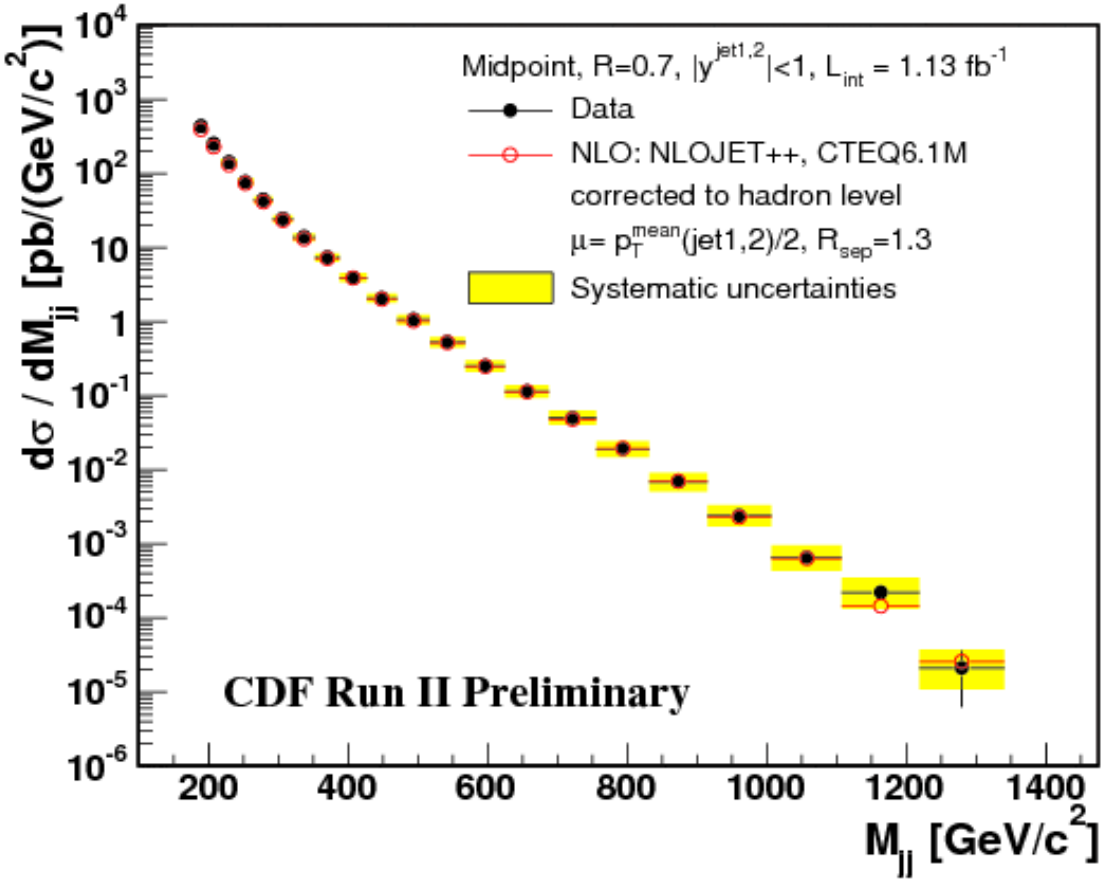


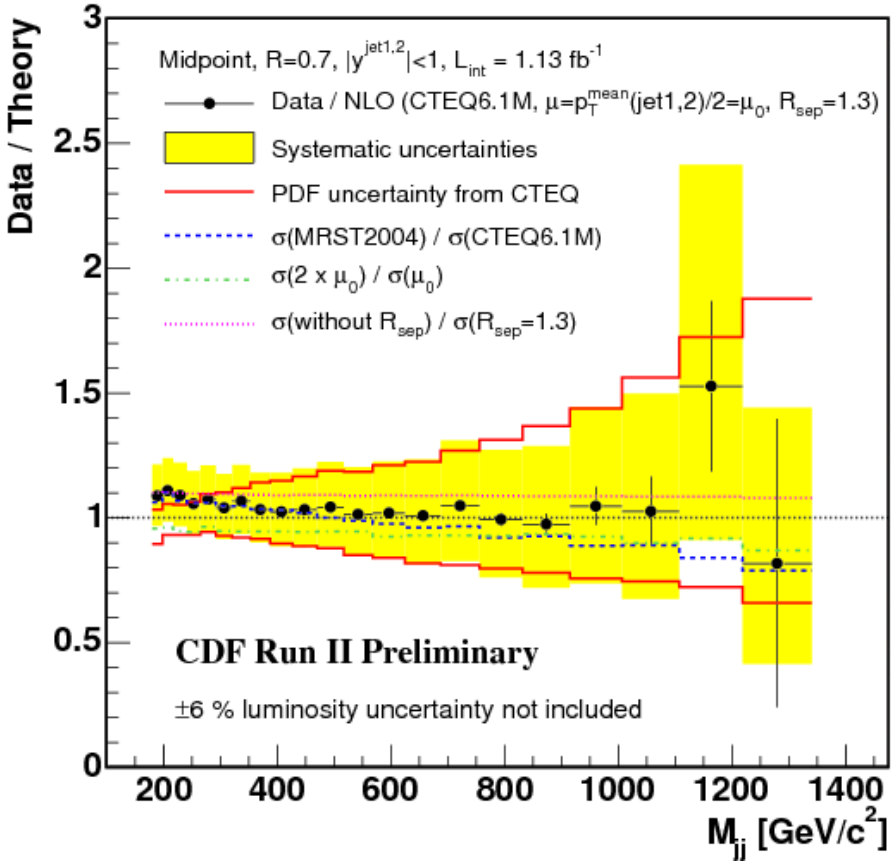
- Data well-described by NLO pQCD
- Experimental Uncertainty smaller than PDF Uncertainty
  → Measurement should contribute to reduce PDF uncertainty

Dijet mass cross section (CDF)

- Midpoint algorithm (R=0.7)
- Differential dijet mass cross section (central jets $|y_{jet}|<1$ and mass > 180 GeV)
- Result compared to NLO pQCD prediction
  example of correction to hadron level







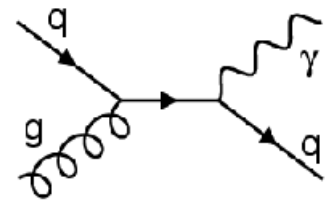
Sensitivity to compositeness (as for inclusive production) but also to dijet mass resonances (excited quark, Z′, W′,...) → new exclusion limits (soon)

Direct Photon Production

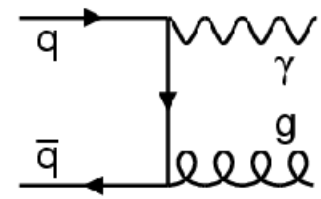
- Direct Photons come unaltered from the Hard Subprocess
  → Direct Probe of the Hard Scattering Dynamics

γ + jet

QCD Compton

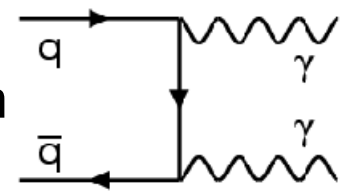


Annihilation

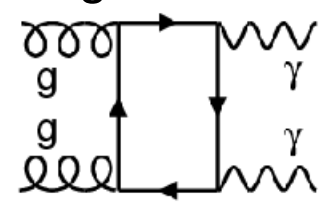


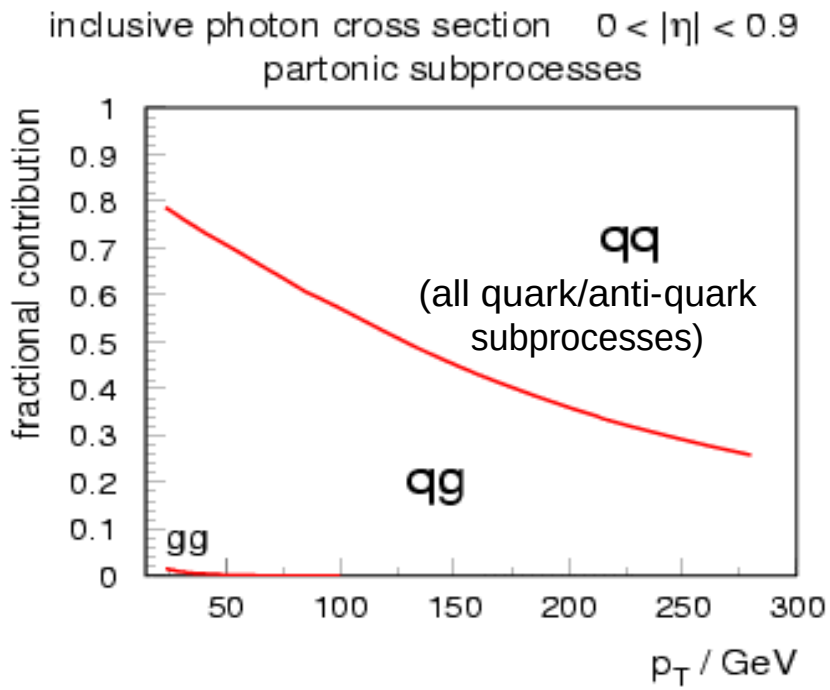
Diphoton

Annihilation



Gluon-gluon fusion



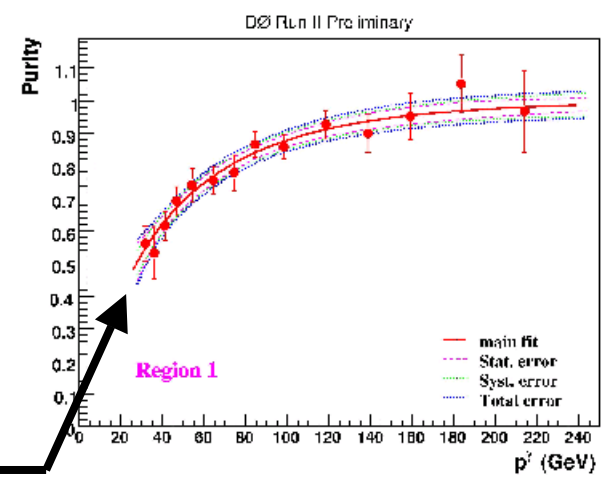


- QCD Compton expected to dominate at p_T^{γ} <120 GeV
  → cross section sensitive to gluon PDF

- $\sigma(\text{jet})/\sigma(\gamma) \approx 10^{-3}$ → challenging measurement

  main background: neutral hadrons decay to γ in jets
  → importance of isolation criteria for γ identification

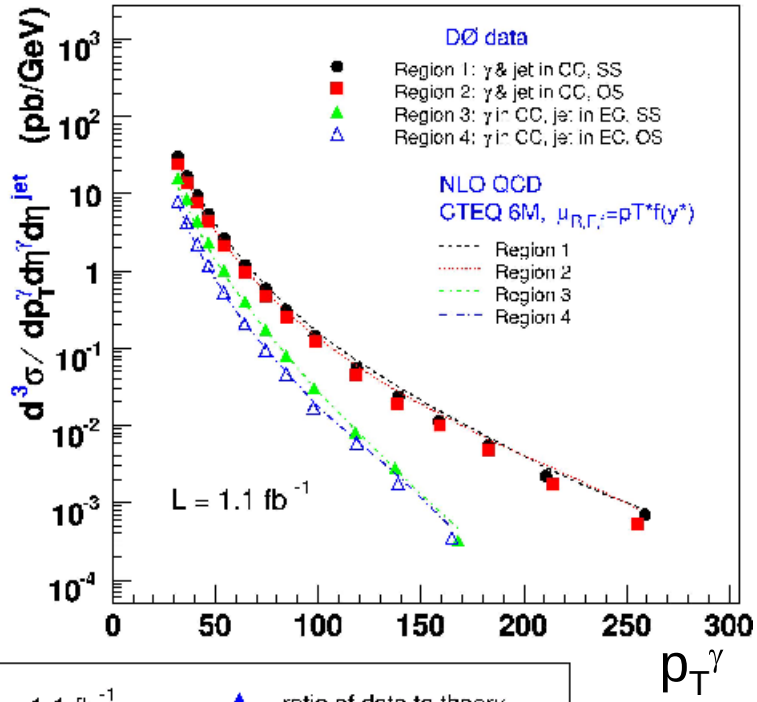
  example of photon purity in most recent D0 analysis



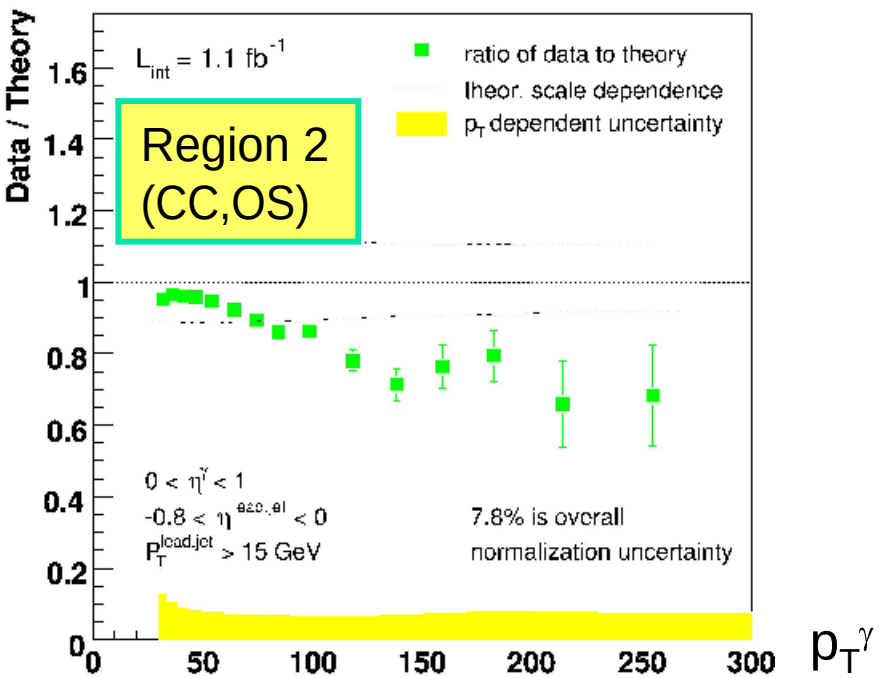
γ + jet cross section (D0)

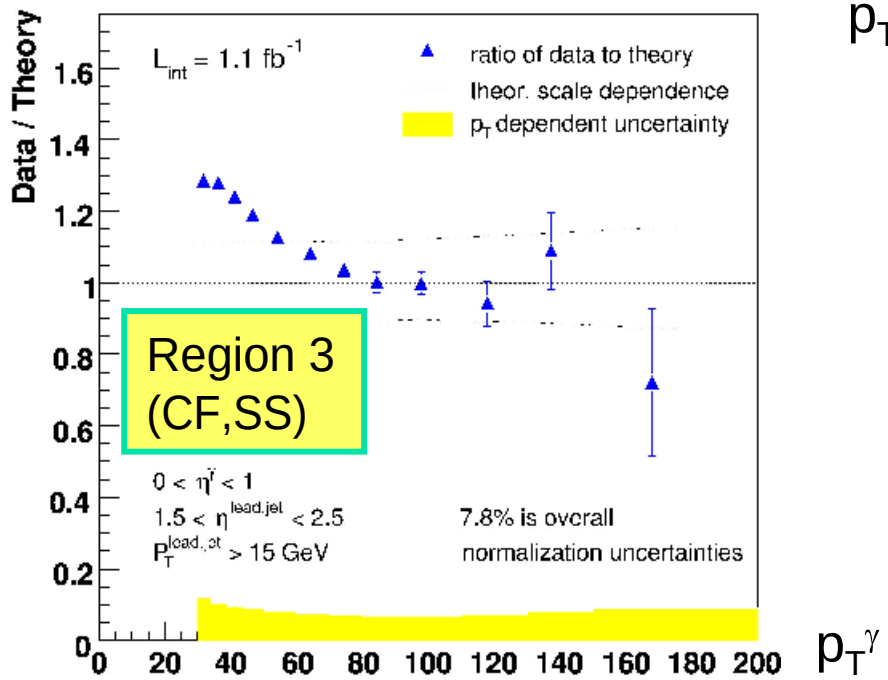
- Triple differential γ + jet cross section: $d^3\sigma / dp_T^\gamma \, d\eta^\gamma \, d\eta^{jet}$
  - Central photon (p_T^γ > 30 GeV, $|\eta^\gamma|<0.8$)
  - Leading jet (p_T^{jet} > 15 GeV) central ($|\eta^{jet}|<0.8$) or forward ($1.5<|\eta^{jet}|<2.5$)
- 4 regions { - jet central (C-C) or forward (C-F) / - η^γ & η^{jet} same (SS) or opposite sign (OS) }

  → different sensitivity to gluon PDF
- Comparison to NLO pQCD JETPHOX (CTEQ6.1M PDF)



D0 preliminary (1.1 fb^{-1})



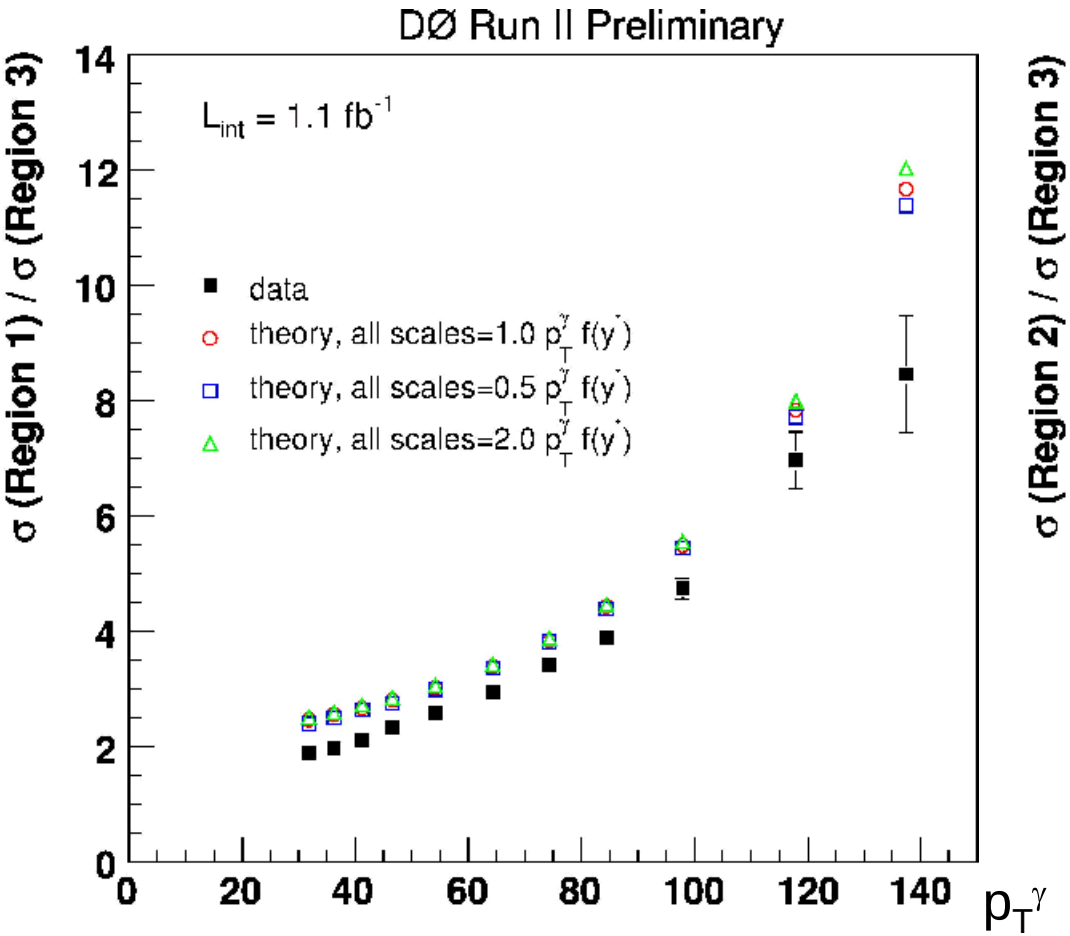


Data & theory marginally consistent (similar deviations seen before in UA2, CDF, D0)

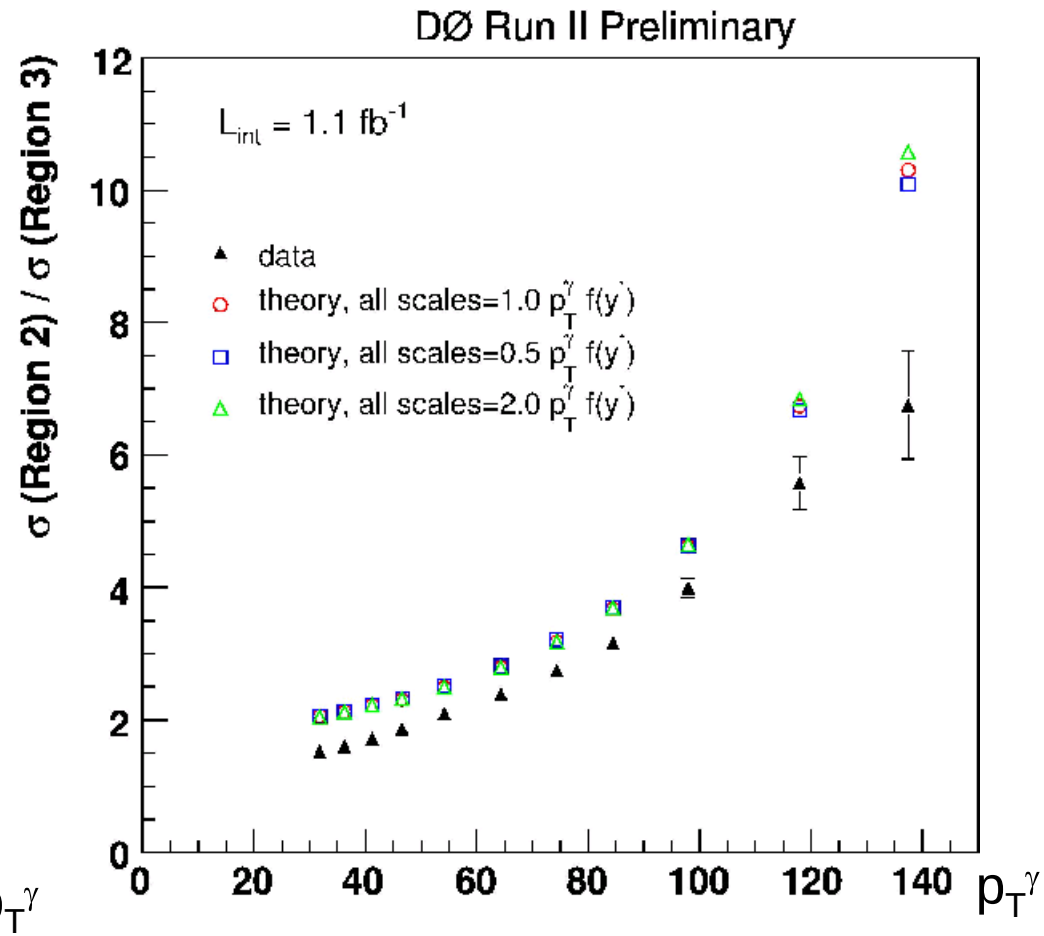
γ + jet cross section (D0)

Cross section ratios in different regions → cancellation of correlated systematics

Region 1 (CC,SS) / Region 3 (CF,SS)



Region 2 (CC,OS) / Region 3 (CF,SS)



Theory overshoots data by 20-50% over all p_T^γ range

→ Significant disagreement with theory (given uncertainties shown here)

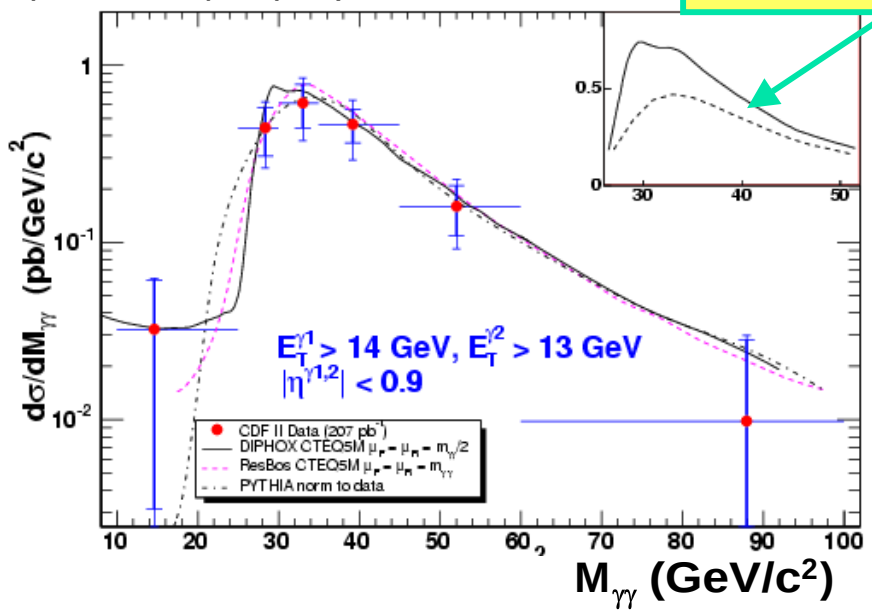
→ Experimental studies under way

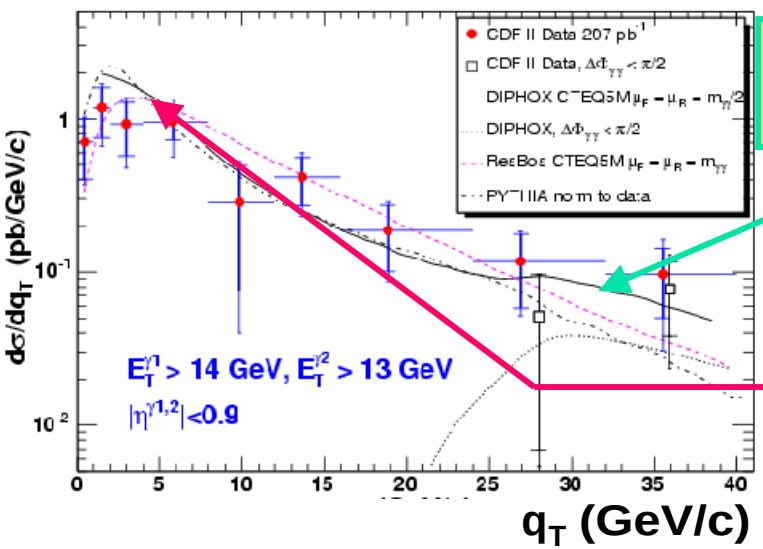
Diphoton production (CDF)

- Two central photons ($|\eta^{\gamma}|<0.9$) with p_T^{γ} > 13 & 14 GeV
- Comparison with different models
  - **DIPHOX**:
    - NLO prompt di-photons
    - NLO fragmentation (1 or 2 γ)
    - NNLO gg→$\gamma\gamma$ diagram
  - **ResBos**:
    - NLO prompt di-photons
    - LO fragmentation contribution
    - Resummed initial state gluon radiation (important for qT)
  - **PYTHIA** (scaled by factor 2)

CDF published (207pb^{-1}) PRL 95, 022003, 2005.

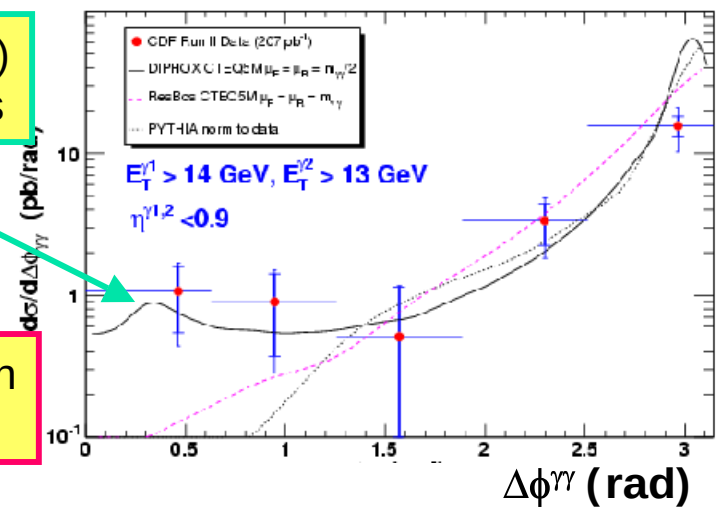
DIPHOX with & w/o NNLO gg-diagram





NLO fragmentation (DIPHOX) → high qT, low $\Delta\phi$, low mass

Resummed initial-state gluon (ResBos)→ low qT



Combined Calculation with NLO Fragmentation & Initial State Resummation needed

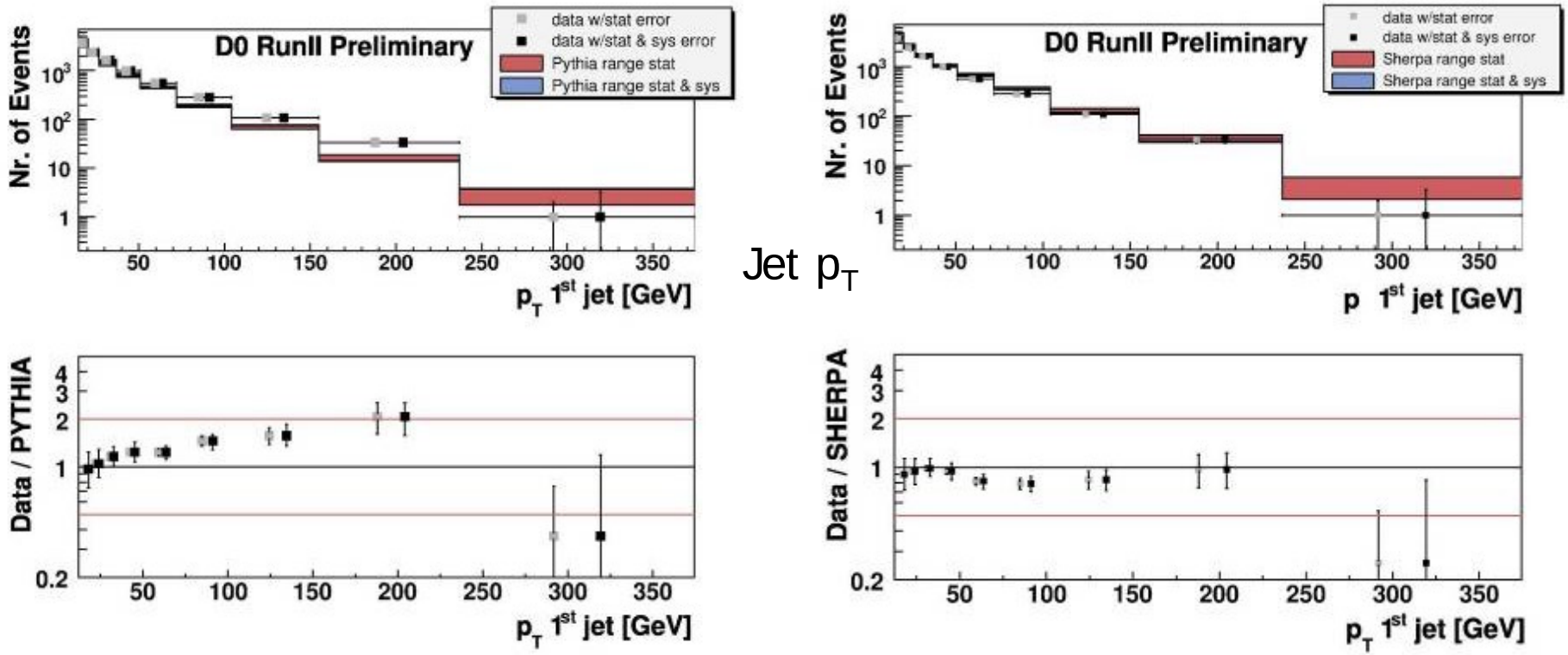
→ Important for Higgs search at LHC!

Z + ≥1 jet production (D0)

- W,Z+jets production: fundamental process to test procedure for matching LO Matrix Elements (ME) calculations with Parton Showers (PS)
- Dominant physics background at LHC for top, SUSY,...
- Z+jets Smaller Cross Section than W+Jets, but cleaner Signature

- Comparison at Detector-Level:
  Data vs. PYTHIA and SHERPA (ME up to Z+3 jets and CKKW procedure)

D0 preliminary (950 pb^{-1})



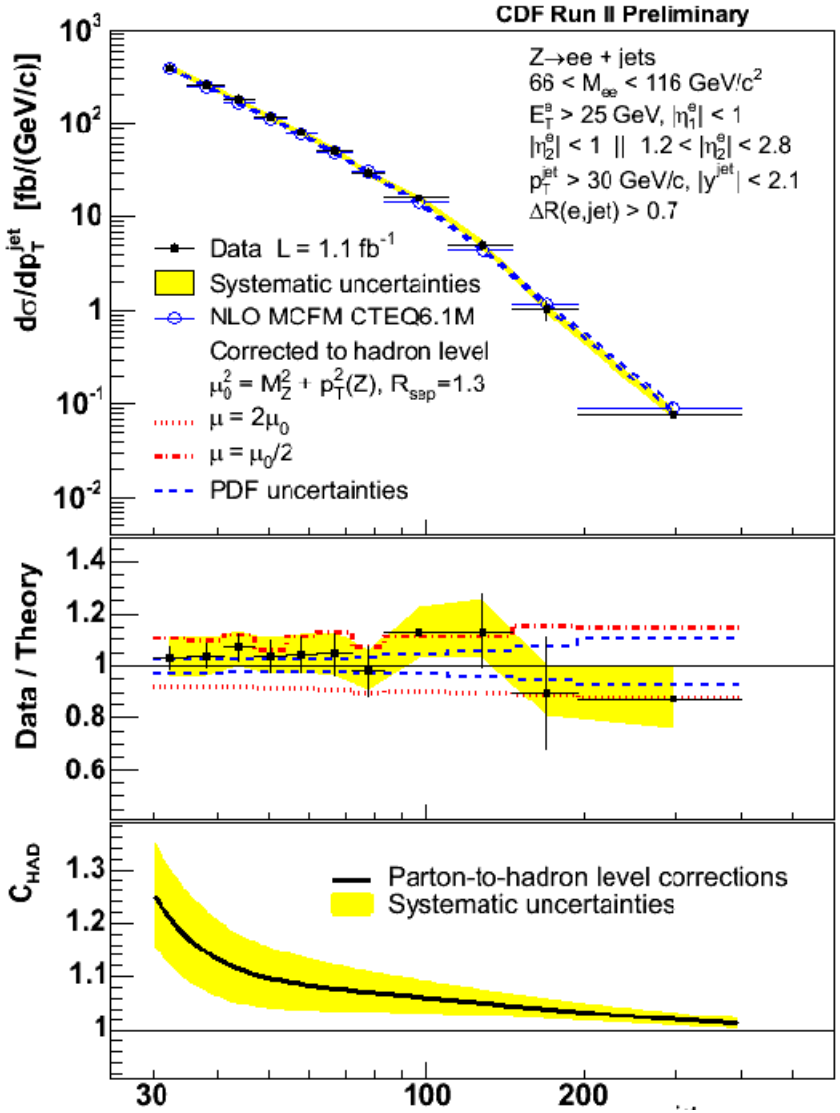
Jet p_T

→ SHERPA describes Leading Jet pT Spectrum quite well, but not PYTHIA

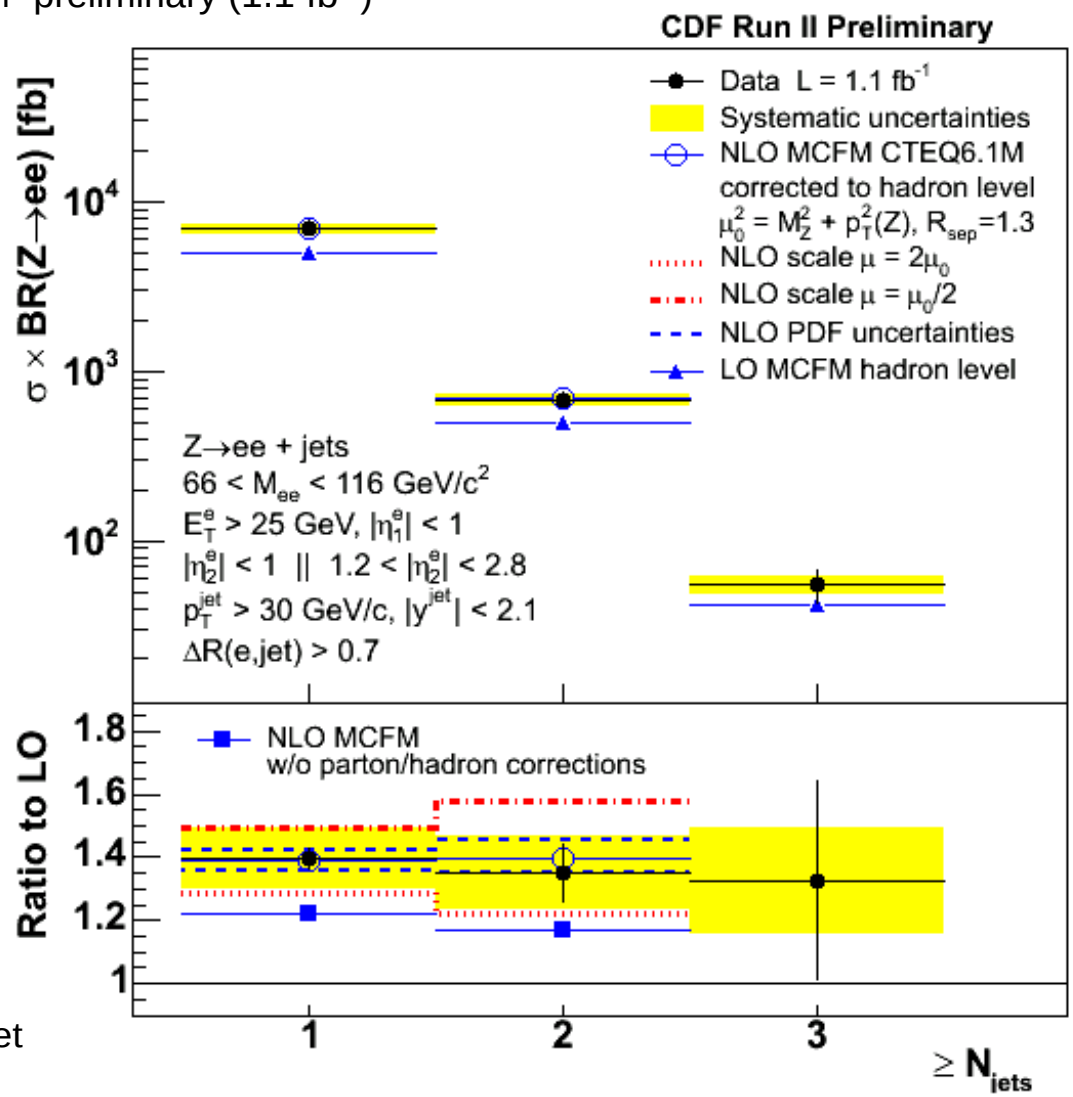
→ same is true for jet multiplicity

Z + ≥1 jet production (CDF)

- Z+≥1 jet cross section measurement, corrected to hadron level
- Comparison to NLO (for Z+2 jets, LO for Z+3 jets) calculation (MCFM)



CDF preliminary (1.1 fb^{-1})



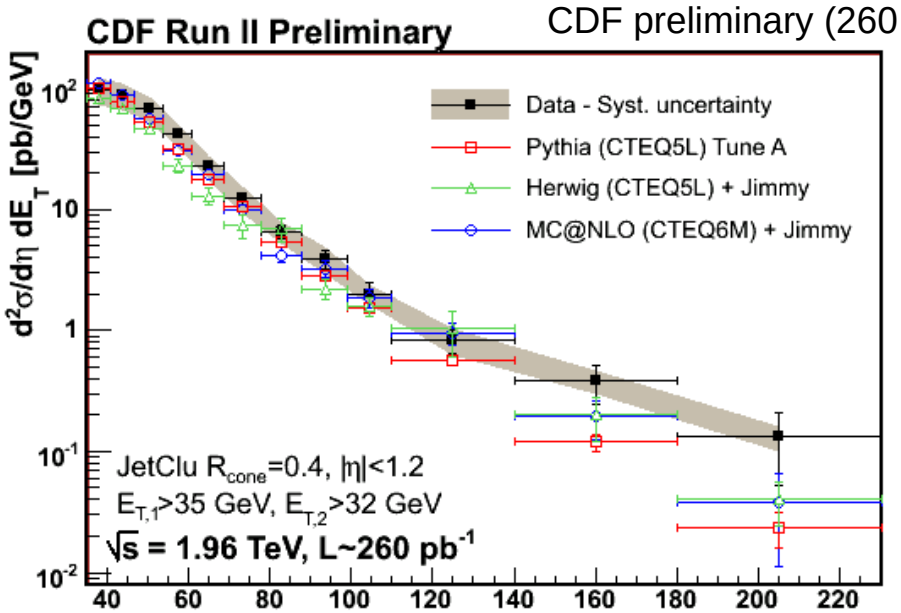
→ Good agreement between data and NLO pQCD (with hadron-level correction)

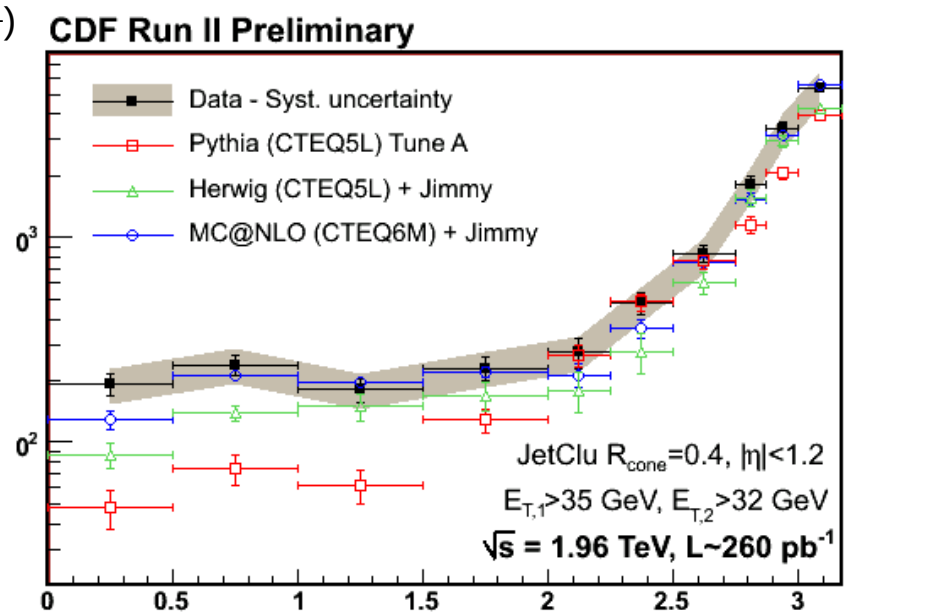
$b\bar{b}$ dijet production (CDF)

- Advantage of $b\bar{b}$ dijet compared to inclusive b :
  $\Delta\phi$(jet,jet) is sensitive to the different production mechanisms
  (flavour excitation or gluon splitting at low $\Delta\phi$, flavour creation at high $\Delta\phi$)

- b jet selection using SVT (Secondary Vertex Tagging), at trigger and offline levels
- Comparison to LO MC (Pythia Tune A and Herwig) and to NLO prediction
  (MC@NLO with CTEQ6.1M PDF + Jimmy for simulation of multiple parton interaction)

CDF preliminary (260 pb^{-1})





→ Leading jet E_T distribution is reproduced by predictions within error bars

→ MC@NLO reproduces $\Delta\phi$ within errors (low $\Delta\phi$, MC@NLO> Herwig > Pythia)

→ Simulation of Underlying Event (Jimmy) necessary to describe the data

Summary

- High Q^2 QCD studies at the Tevatron essential in RunII physics program: better understanding of QCD mechanisms benefitial to all physics analyses.
- More stringent tests of QCD calculations, new constraints on QCD unknown parameters, e.g.:
  - Proton PDFs (inclusive jet and dijet)
  - NLO calculations
  - ME-PS matching schemes (Z+jet)
  - NLO Fragmentation & Initial State Resummation (diphoton)
- QCD processes often the most important background to EW and BSM physics (and some channels also directly sensitive to new physics, e.g. excited quark in dijet mass analysis)
  → Better knowledge crucial for Tevatron, but also for LHC
- Overall very good agreement with theory, with the exception of D0 γ+jet measurement, which should trigger theory developments (if confirmed)

LHC will certainly benefit from present and forecoming results.
→ Stay tuned!

Backup slides

Run I Cone algorithm

- Based on Snowmass Algorithm: E_T -weighted recombination scheme in (η,ϕ)
- Preclustering (DØ, similar algorithm for CDF)

  Note: Tower segmentation in (η,ϕ) space: **DØ → 0.1 X 0.1, CDF → 0.11 X 0.26**
  - start from seeds (= towers with p_T >1 GeV ordered in decreasing p_T)
  - cluster (and remove) all contiguous calorimeter towers around seed in a R= 0.3 cone
- Clustering
  - start from preclusters (ordered in decreasing E_T)
  - proto-jet candidate = all particles within R_{cone} of the precluster axis in (h,f) space
    CDF: keep towers of the original precluster through all iterations (ratcheting)
  - proto-jet direction compared before/after recombination → iterate until it is stable
- Merging/Splitting (treat overlapping proto-jets)
  - $E_{T,1\cap 2} > f \,.\, \mathrm{Min}(E_{T,1}, E_{T,2})$ → Merge jets
  - $E_{T,1\cap 2} < f \,.\, \mathrm{Min}(E_{T,1}, E_{T,2})$ → Split jets = assign each particle to its closest jet
  - **DØ: f = 50 %, use only clusters with E_T > 8 GeV - CDF: f = 75 %**
- Final calculation of jet variables (modified Snowmass scheme)
  - scalar addition of **E_T (DØ)** or **E (CDF)** of particles to determine jet **E_T** or **E**
  - addition of 3-momenta of particles to determine jet direction, then (η,ϕ)
    Note: this procedure is not Lorentz invariant for boosts along beam axis
    CDF: $E_T = E \sin(\theta)$

D0 RunII Cone algorithm

- Preclustering similar to RunI except:
  - seeds = p_T ordered list of particles with p_T >500 MeV
  - precluster = all particles in a cone of r = 0.3 around seed for Cone Jets with R $\geq$ 0.5
  - precluster 4-momentum calculated using the E−scheme
- Clustering
  - seeds = p_T ordered list of preclusters with p_T > 1 GeV
    except those close to already found proto-jets: ΔR (precluster,proto-jet)< 0.5 R_{cone}
  - cone drifting until
    - cone axis coincides with jet direction
    - p_T < 0.5 Jet p_T^{min}
    - # iterations = 50 (to avoid ∞ cycles)
  - remove duplicates
  - repeat same clustering for midpoints* except
    - no condition on close proto-jet
    - no removal of duplicates

    * for pairs only, calculated using p_T−weighted mean
- Merging/splitting similar to RunI except:
  - use p_T ordered list of proto-jets (from seeds and midpoints)
  - at each merging/splitting
    - recalculate 4-momenta of merged/splitted jets
    - re-order list of merged/splitted jets

CDF Midpoint algorithm with Smaller Search Cone option

- Jets might be missed by RunII Cone Algorithm (S.D. Ellis et al., hep-ph/0111434)
  → low p_T jets
  - too close to high p_T jet to form a stable cone (cone will drift towards high p_T jet)
  - too far away from high p_T jet to be part of the high p_T jet stable cone
- Proposed solution
  - remove stability requirement of cone
  - run cone algorithm with smaller cone radius to limit cone drifting ($R_{search} = R_{cone} / \sqrt{2}$)
  - form cone jets of radius R_{cone} around proto-jets found with radius R_{search}

Remarks

- Problem of lost jets seen by CDF, not seen by DØ
  → A physics or an experimental problem?
- Proposed solution unsatisfactory w.r.t. cone jet definition

⇒ DØ prefers using RunII Cone without Smaller Search Cone

$k_\perp$ Algorithm

Description of inclusive $k_\perp$ algorithm (Ellis&Soper, PRD48, 3160, (1993))

- DØ: geometrical 2x2 preclustering, remove preclusters with E < 0
- p_T ordered list of particles → form the list of $d_i = (p_T^i)^2$
- calculate for all pairs of particles, $d_{ij} = \mathrm{Min}((p_T^i)^2, (p_T^j)^2)\ \Delta R/D$
- find the minimum of all d_i and d_{ij}
  - if it is a d_i, form a jet candidate with particle i and remove i from the list
  - if not, combine i and j according to the E-scheme
  - use combined particle i + j as a new particle in next iteration
  - need to reorder list at each iteration → computing time $\propto O(N^3)$ (N particles)
- proceed until the list of preclusters is exhausted

Remarks

- originally proposed for e^+e^- colliders, then adapted to hadron colliders
  (S. Catani et al., NPB406,187 (1993))
- universal factorisation of initial-state collinear singularities
- infrared safe: soft partons are combined first with harder partons
- collinear safe: two collinear partons are combined first in the original parton
- no issue with merging/splitting

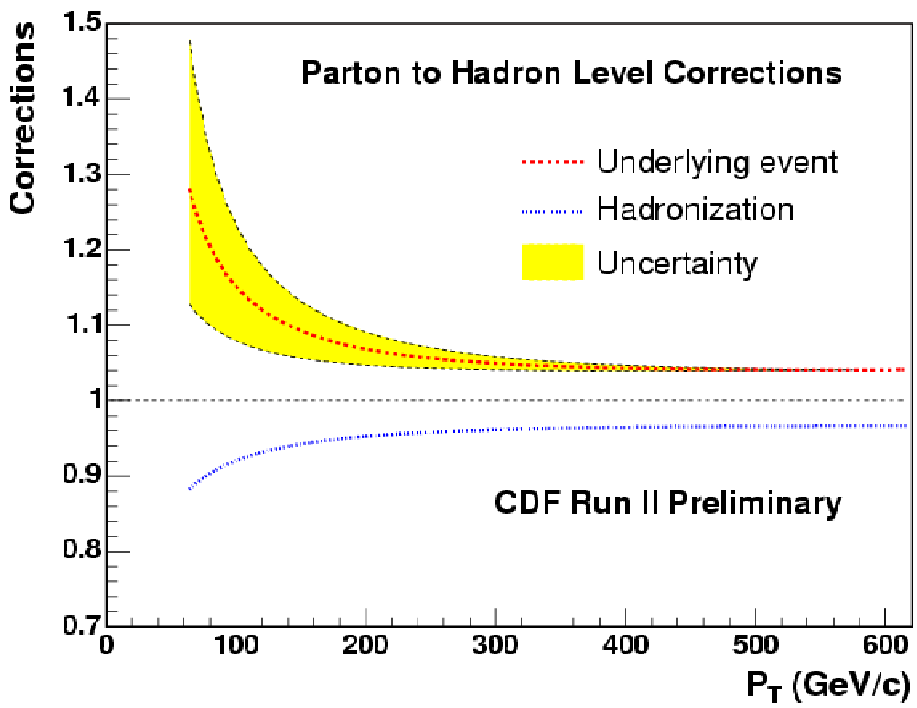
Jet Energy Scale and Unsmearing corrections (D0)

- Jet Energy Scale:
  correct jet measured energy to particle level
  $E_{particle} = (E_{cal} - \text{Offset})/(\text{Response} \times \text{Showering})$
  - Offset: energy not originating from the hard process (underlying event, pile-up, noise)
  - Showering: correction factor for the energy migration in/out of the cone due to energy deposition (detector showering only)
  - Response:
    main correction factor detector → hadron level (absolute correction fonction of E, relative correction fonction of η)

- Unsmearing: correct cross section according to measured resolution
  - Jet pT resolution measured in dijet data events
  - Use ansatz function smeared with measured resolution
  - Correct data by ratio of original to smeared ansatz function
  - Cross check with Pythia

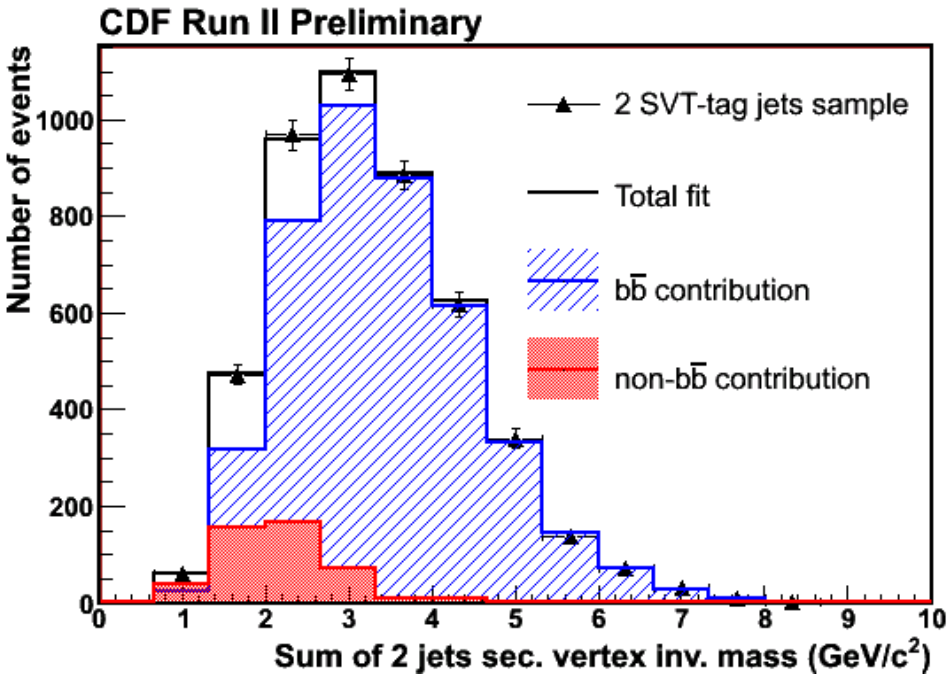
Corrections for non-perturbative QCD effects (CDF)

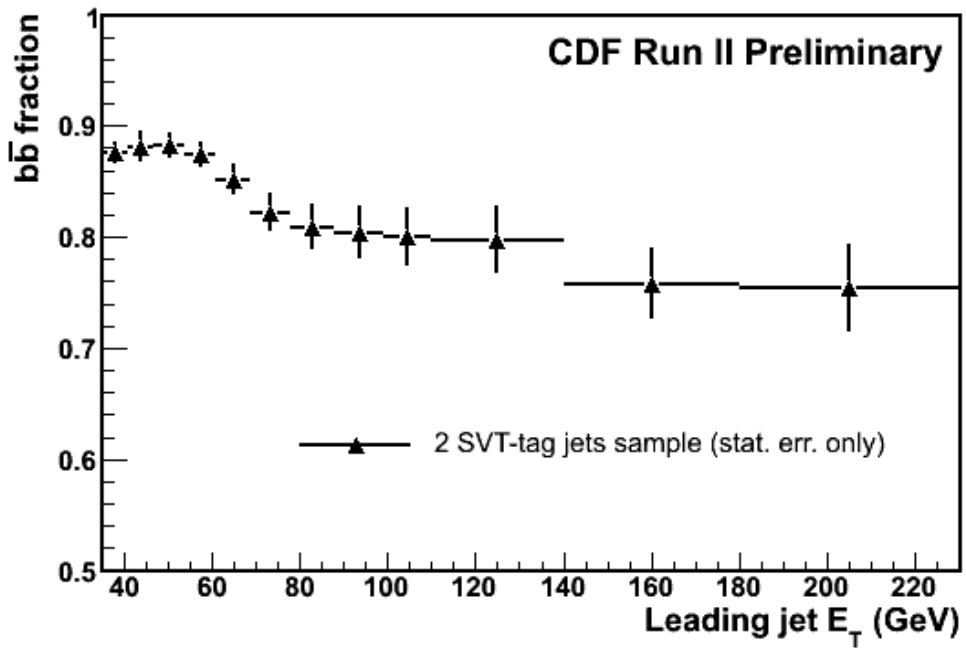
- Parton to Hadron Level (effects of non-perturbative processes) corrections studied using MC models (PYTHIA, HERWIG)
  - Hadronization
  - Underlying event (for central jet cross section)
- Corrections checked with different jet sizes (e.g. kT D=0.5 and D=1.)
  → dedicated measurements to validate MC simulation
- Correction<10 % for pT>150 GeV
  → applied to pQCD calculation (new in Run II)



bb dijet production (CDF)

- $b\bar{b}$ dijet fraction extracted from data using template fits to invariant mass of SV tracks





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