High Q^2 QCD Physics at the Tevatron

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Duke University
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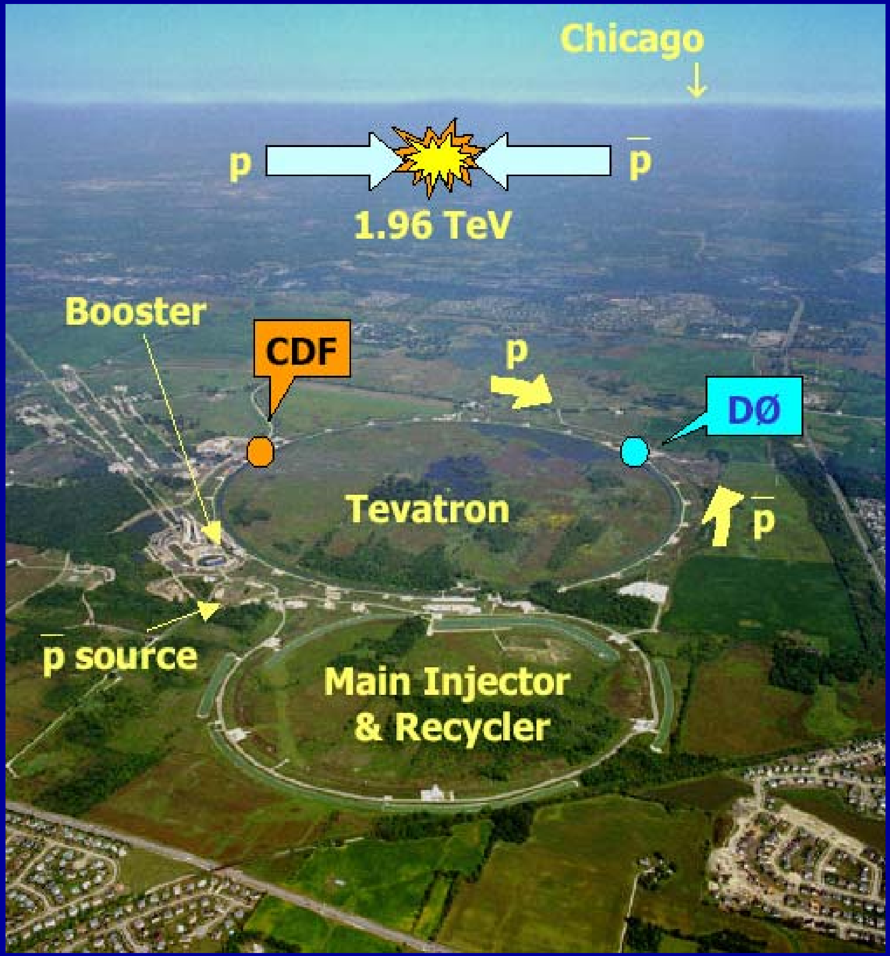
Outline

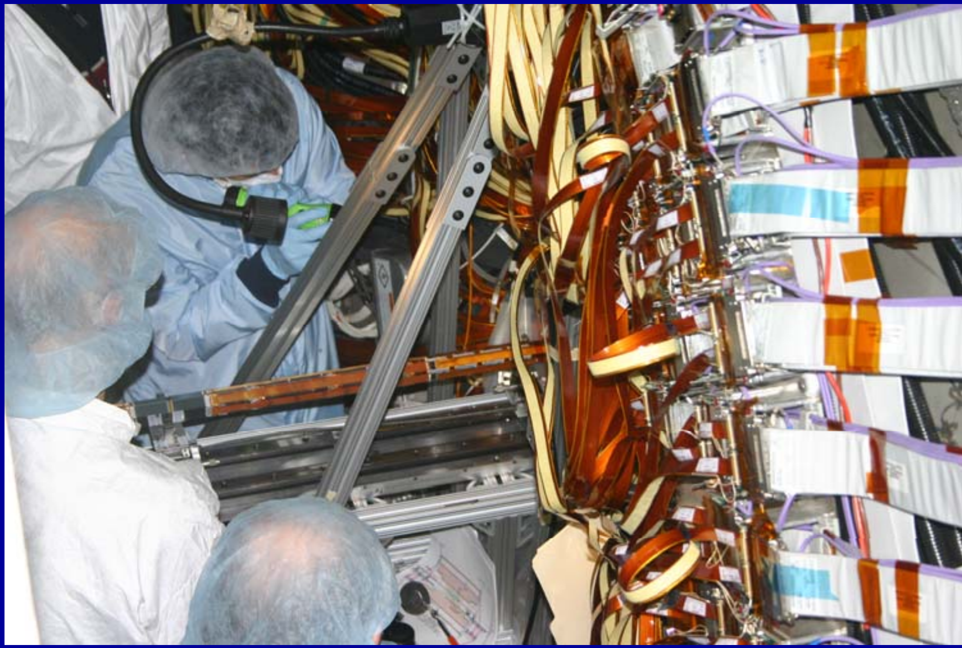
- Introduction
- Fragmentation / underlying event
- Jet production
- Photon production
- Bosons + jets
- Heavy-flavor jets
- Conclusions

The Fermilab Tevatron Collider Run II

- Proton-antiproton collisions at √s=1.96 TeV

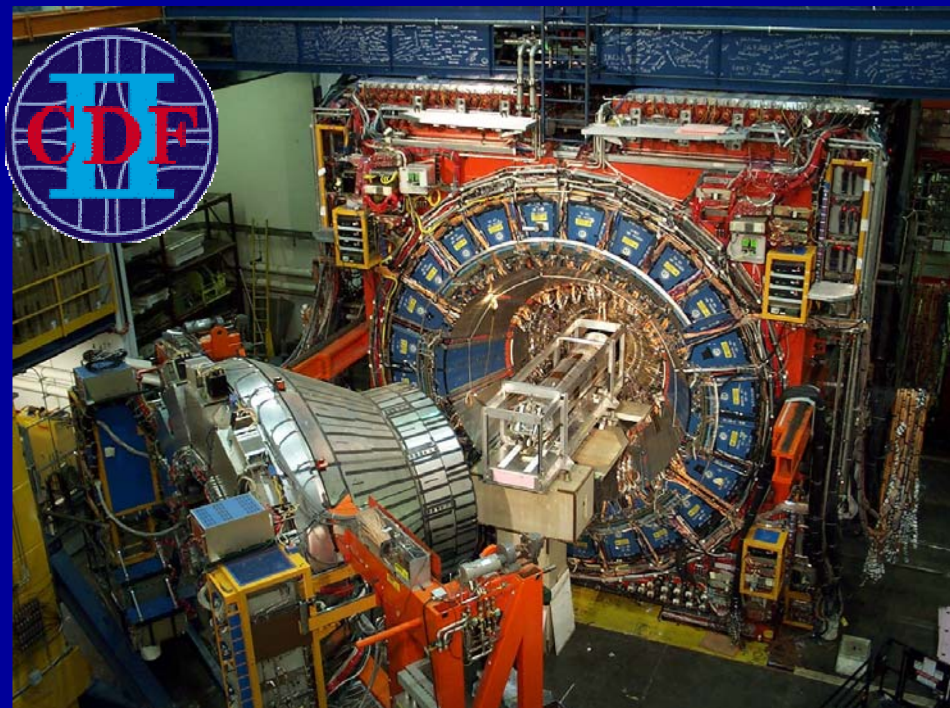


- Tevatron wrapping up 14-week shutdown during which DØ successfully installed innermost "Layer 0" silicon



- Accelerator and CDF also made improvements for delivering and collecting high luminosity data

CDF and DØ Run II detectors



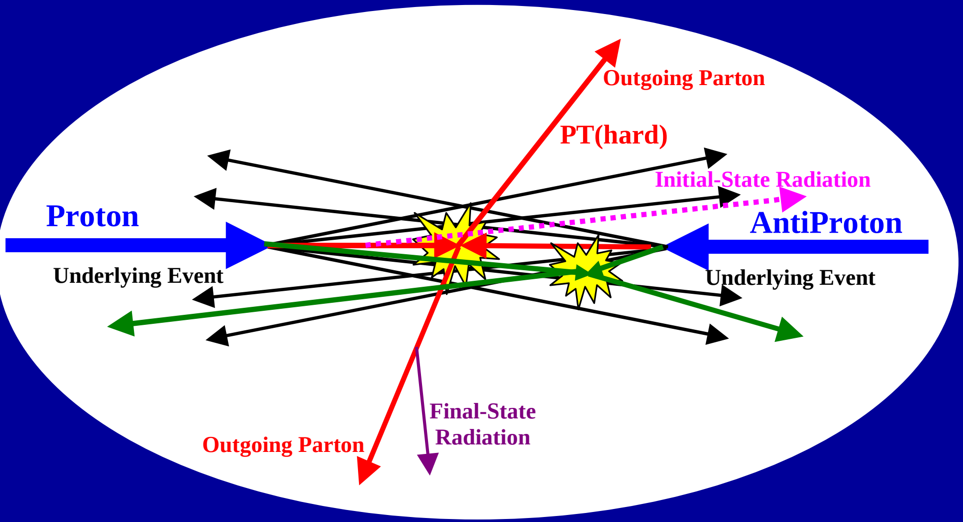
L2 trigger on displaced vertices
Excellent tracking resolution

Excellent muon ID and acceptance
Excellent tracking acceptance $|\eta| < 2\text{-}3$

Both detectors

- Silicon microvertex tracker
- Solenoid
- High rate trigger/DAQ
- Calorimeters and muons

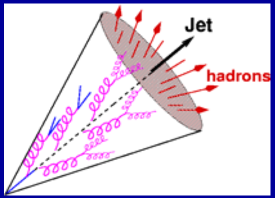
Jet physics at the Tevatron

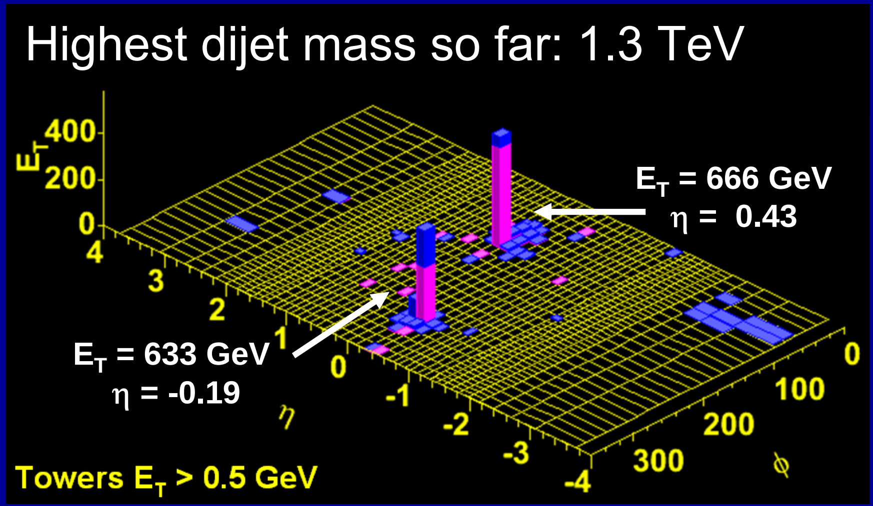


Components of a hadron-hadron collision:

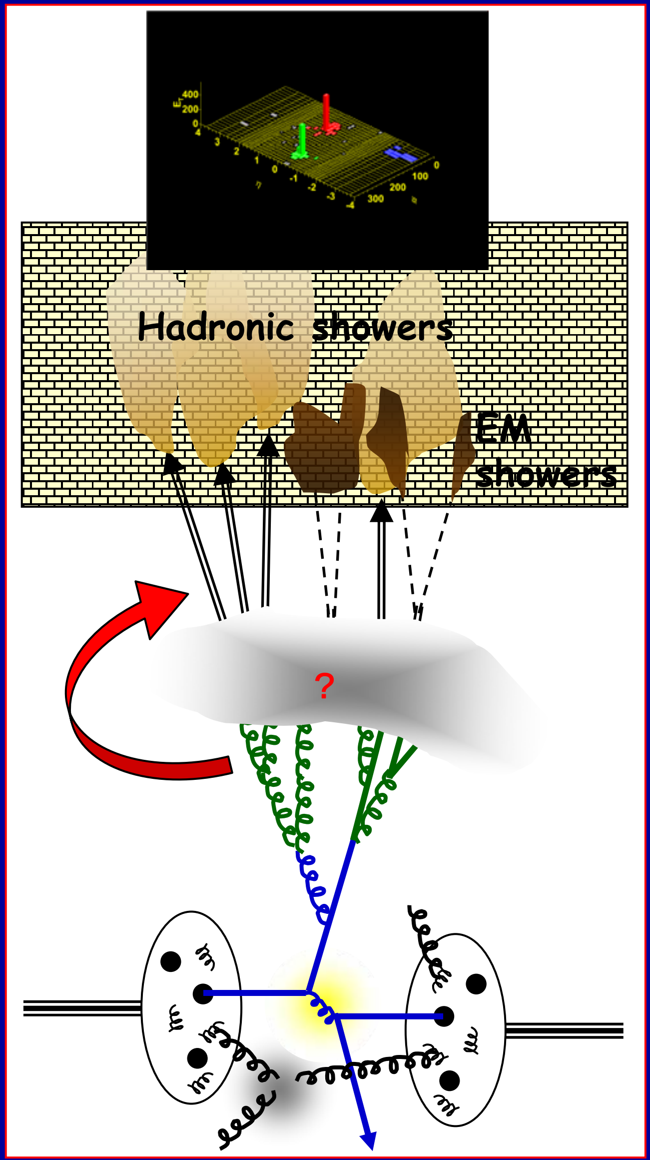
- 2→2 hard scattering
  - Described by pQCD
  - Dominated by dijet events
- Initial and final state radiation
- Underlying event
  - Hard initial and final-state radiation
  - Beam-beam remnants
  - Multiple parton interactions

- Colored partons hadronize into color-neutral hadrons
- Particles from ISR, FSR, UE, and the hard scattering are indistinguishable in the detector
- Jet clustering algorithms combine particle energies from all components of the event to form jets





Jet energy corrections



Measure calorimeter-level jets

- Correct for pile-up energy from multiple $p\bar{p}$ interactions
- Correct for jet energy scale and resolution
  - Average energy loss due to non-compensating nature of calorimeter
  - Smearing effect due to jet energy resolution

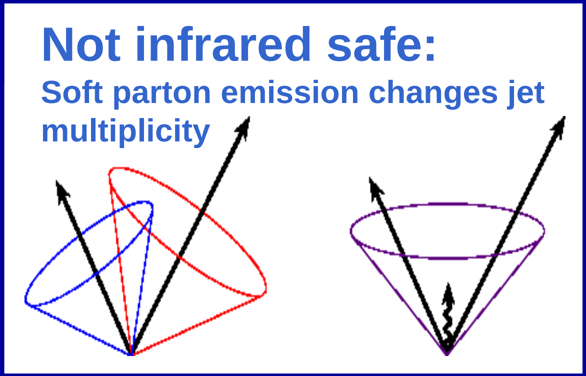
→ Hadron-level jets

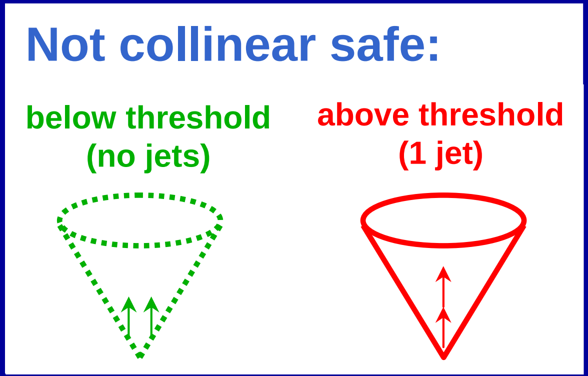
- Correct for underlying event and energy loss out-of-cone due to hadronization using Monte-Carlo models

→ Parton-level jets

Jet reconstruction – cone algorithms

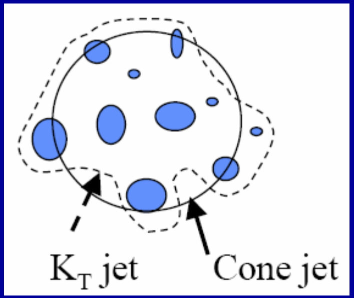
- Draw a cone of radius R around each seed (calorimeter tower above threshold) and form "proto-jet"
- Draw new cones around "proto-jets" and iterate until stable cone



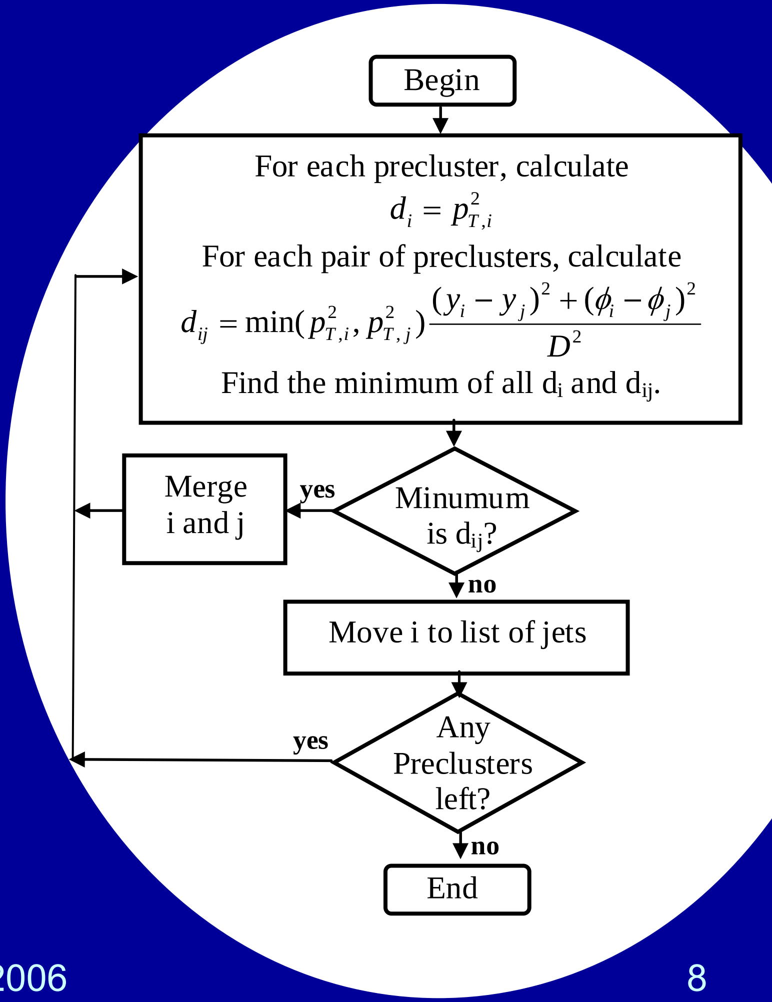


- Put seed in Midpoint ($\eta-\phi$) for each pair of proto-jets separated by less than 2R and iterate for stable jet → infrared safe
- CDF uses an initial search cone of R/2 to prevent unclustered high-E_T towers, then uses full cone radius R once a stable solution is found
- Merge jets if jet shares fraction $>f_{merge}$ of its p_T with another jet
- DØ: f_{merge}=50%
- CDF: overlapping jets more common -- better results with f_{merge}=75%
- CDF: R_{sep} parameter at parton level (NLO) to approximate split/merge

Jet reconstruction – k_T algorithm



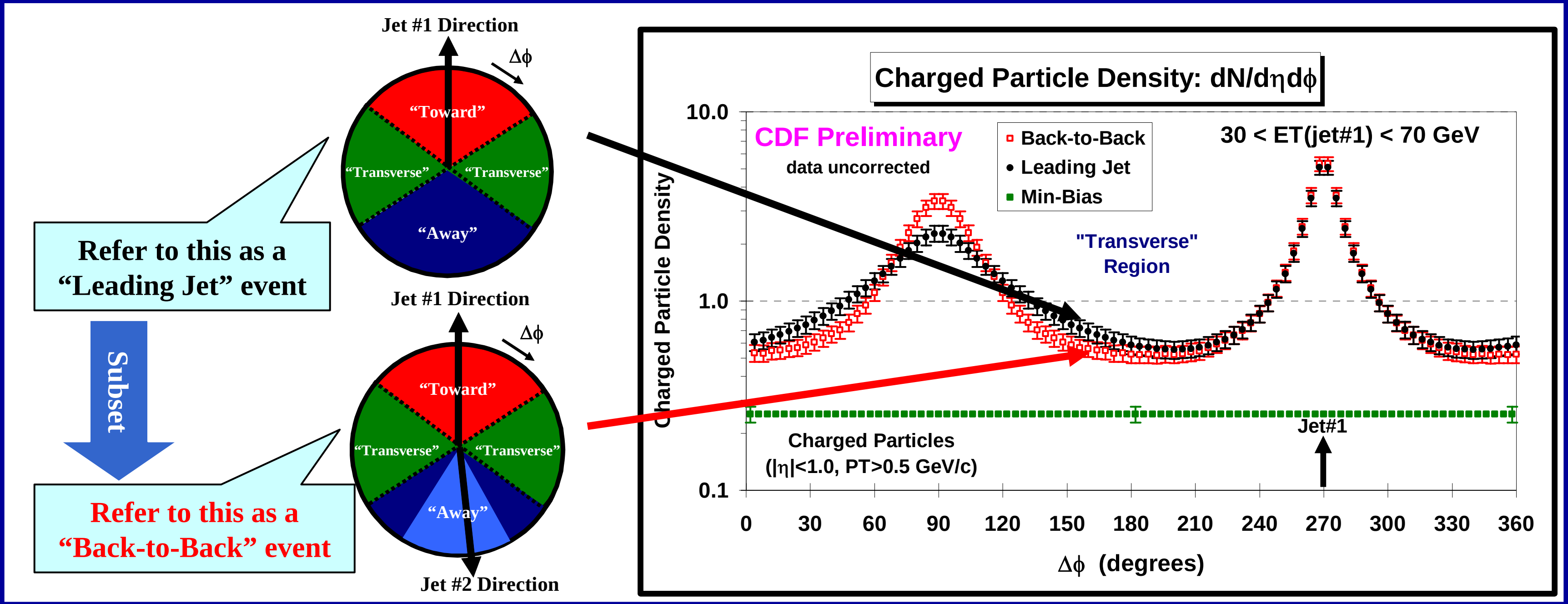
- Cluster objects according to their relative transverse momentum (k_T)
- Infrared and collinear safe at all orders of pQCD (relevant for NNLO)
- No biases from seed towers
- No splitting and merging of jets
- Every parton, particle, or tower is assigned to a “jet”
- Theoretically preferred
- Successfully used at LEP and HERA but relatively new in hadron colliders
  - More difficult environment (underlying event, multiple $p\bar{p}$ interactions)



Fragmentation and the Underlying Event

Underlying event / MC tuning (CDF)

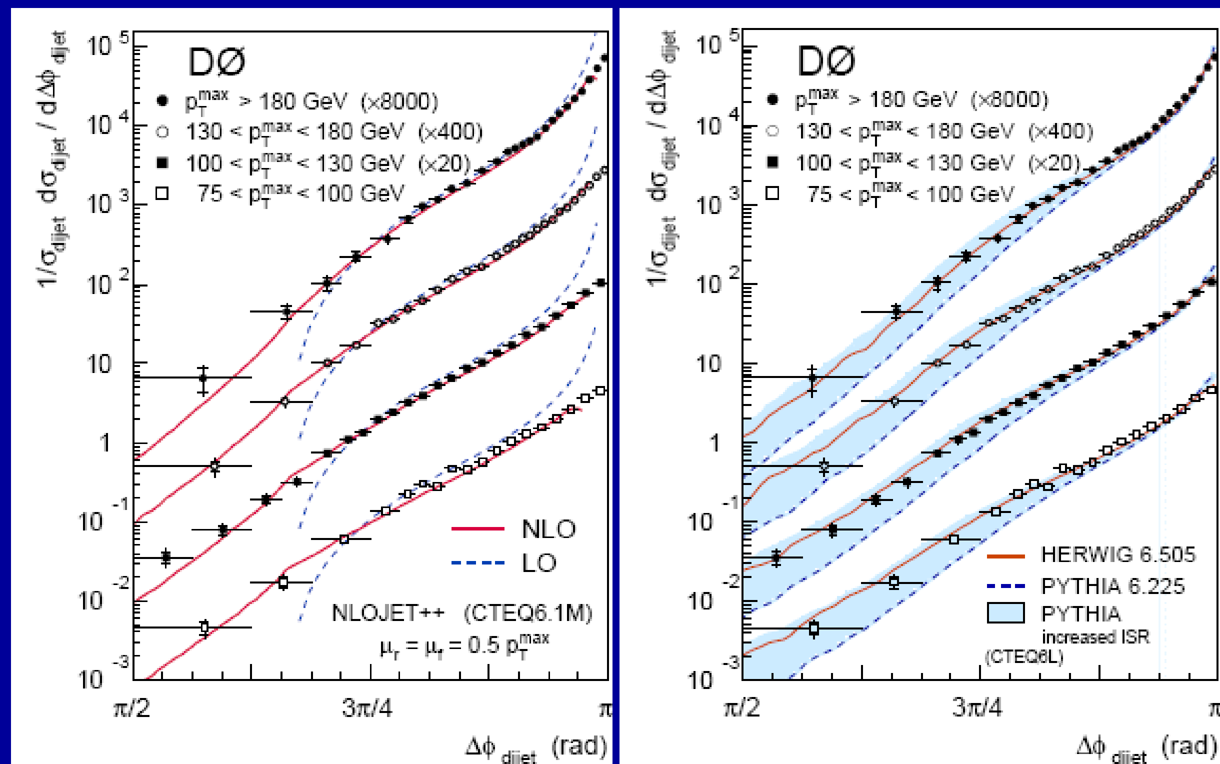
- Physics in all areas at the Tevatron rely on accurate Monte-Carlo modeling of all characteristics of the event
- Studies of the underlying event in jet events in Run I led to Pythia Tune A
- Studies are being expanded in Run II and new MC tunes are expected this summer



Dijet azimuthal decorrelations (DØ 150pb^{-1})

Phys. Rev. Lett. 94, 221801 (2005)

- Accurate description of QCD multi-parton radiation important for many precision measurements and searches for new physics
- Study depends only on the reconstruction of the $\Delta\phi$ between the two highest-p_T jets
- Less correlation at smaller p_T
- Good agreement with NLO pQCD (calculation unphysical near divergence at π)
- Good agreement with HERWIG MC
- PYTHIA agrees only when ISR increased (also in CDF Tune A)



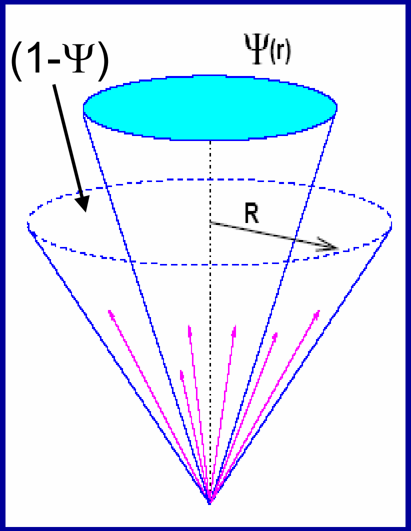
Inclusive jet shapes (CDF 170pb^{-1})

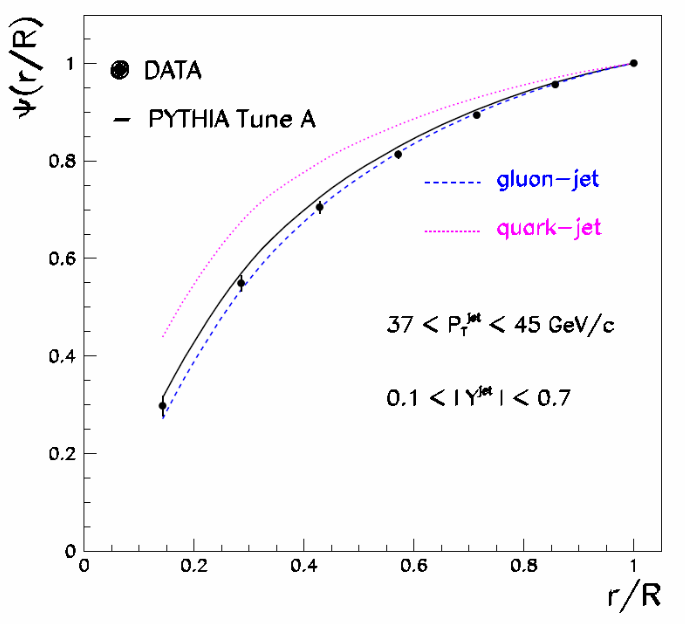
Phys. Rev. D 71, 112002 (2005)

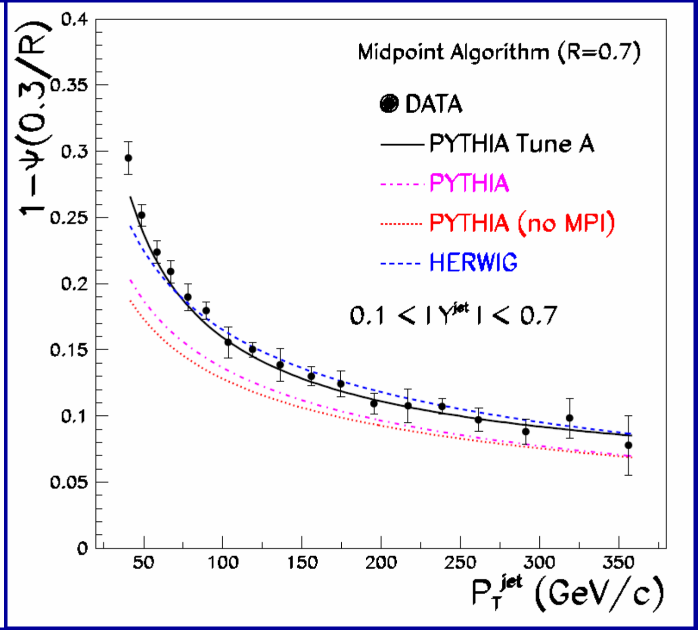
Jet shapes governed by multi-gluon emission from primary parton

- Test of parton shower models
- Sensitive to underlying event structure
- Sensitive to quark and gluon mixture in the final state
- Find excellent agreement with PYTHIA Tune A

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

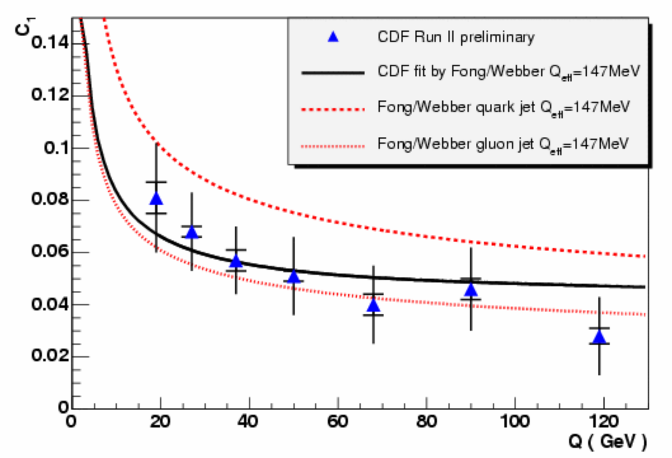


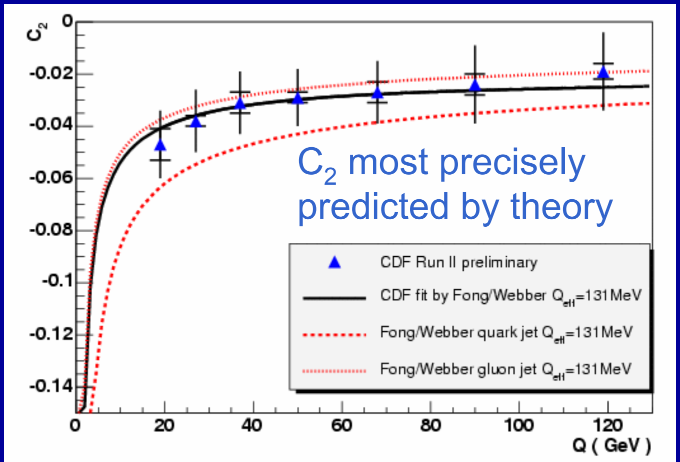




Fragmentation studies: two-particle momentum correlation in jets (CDF 385pb^{-1})

- Jet fragmentation (parton shower, hadronization):
  CDF Run I results: multiplicity, momentum distributions of particles in jets ~ same for partons/hadrons
- Ratio of 2-particle to 1-particle momentum distribution functions $R=C_0+C_1(\Delta\xi_1+\Delta\xi_2)+C_2(\Delta\xi_1-\Delta\xi_2)^2$ where $\xi=\log(E_{jet}/p_{hadron})$
- Different dijet mass ranges to study evolution with energy scale
- C_0 sensitive to definition of expansion point, disagrees in magnitude, but has same shape (~flat with Q) as prediction
- C_1, C_2 show reasonable agreement with theoretical predictions based on Next-to-Leading Log Approximation and Local Parton-Hadron Duality
- Two-particle momentum correlations survive hadronization

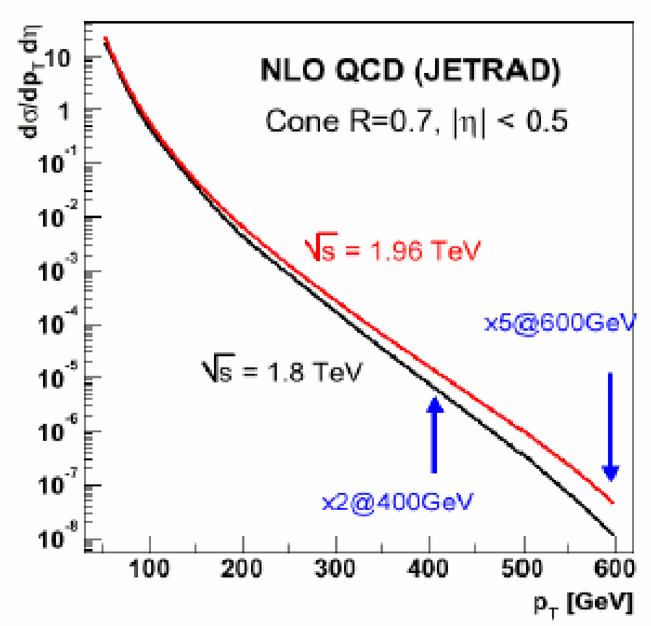


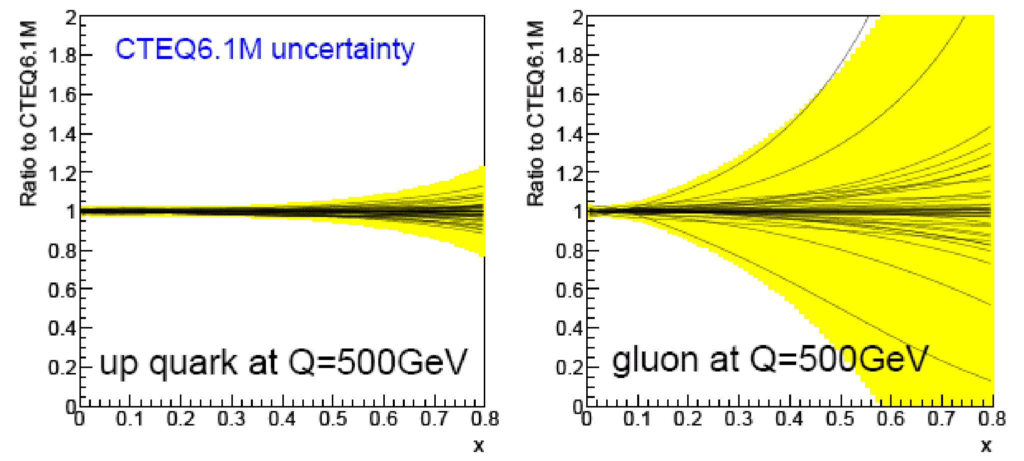


Jet production

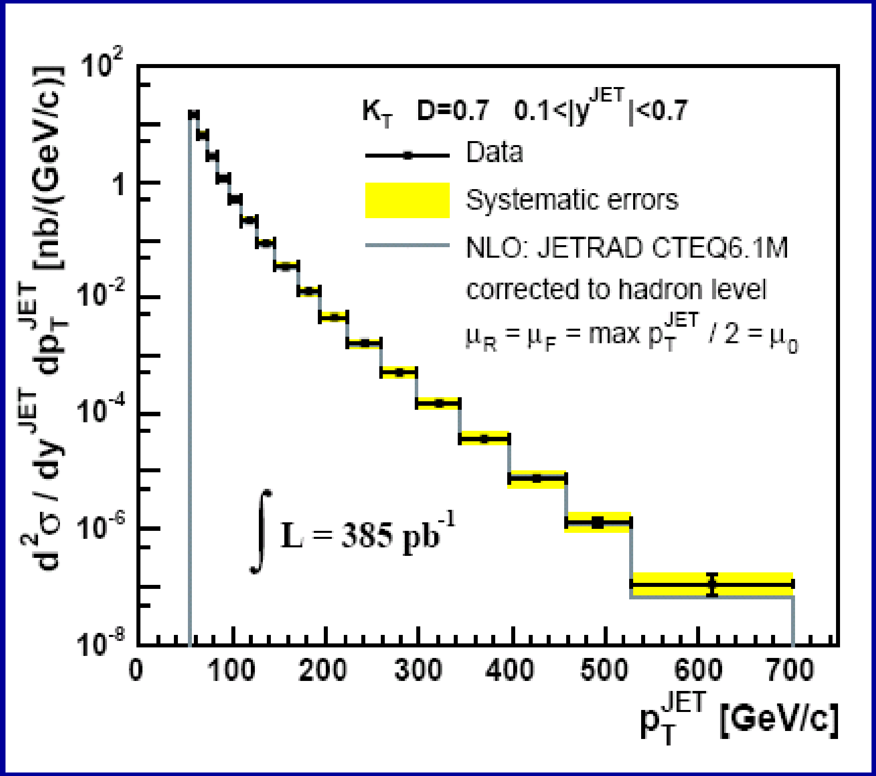
Inclusive jet cross section

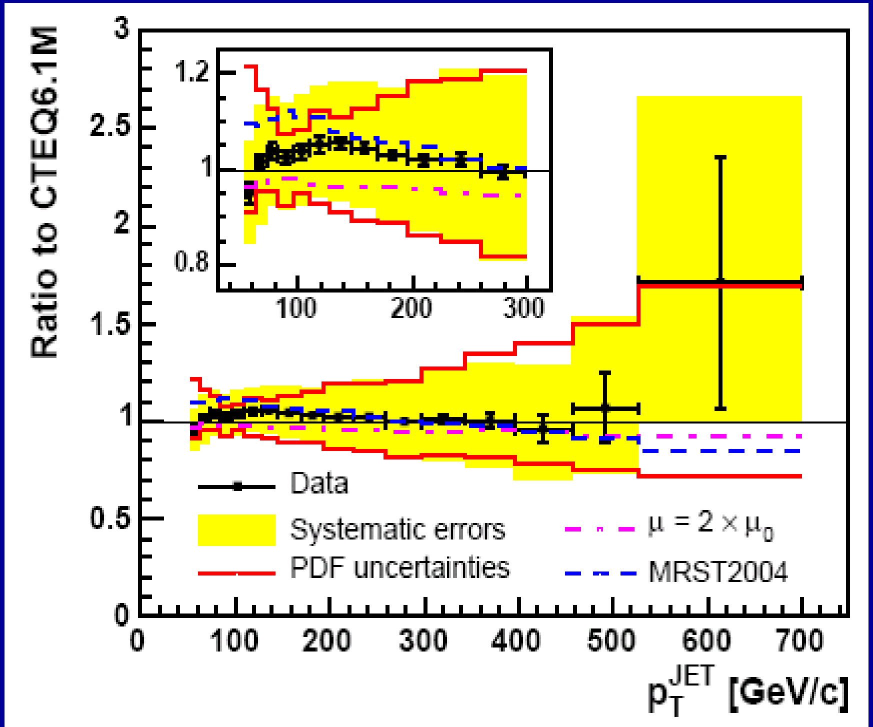
- Stringent test of pQCD over 9 orders of magnitude
- Sensitive to distances ~ 10^{-19} m
- Higher jet cross section with respect to Run I
  - Reach to higher p_T jet production
- Tail sensitive to new physics and PDFs
- Constrain gluon PDF at high-x where it is not well known

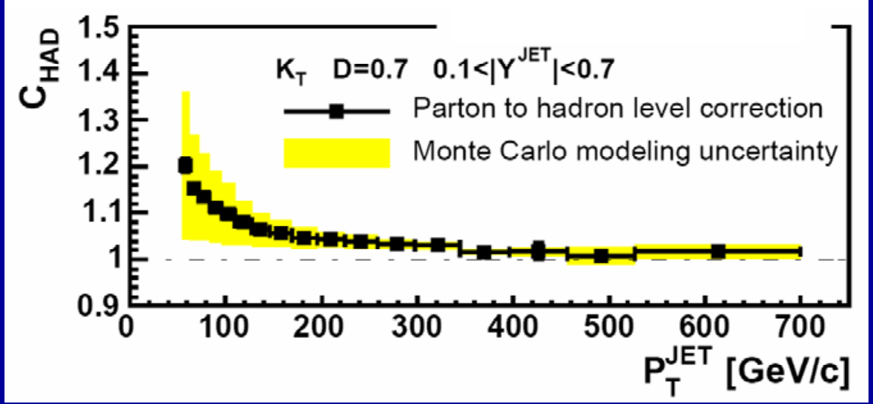




Inclusive jet cross section in the central region (CDF published 385pb^{-1}) Phys. Rev. Lett. 96, 122001 (2006)

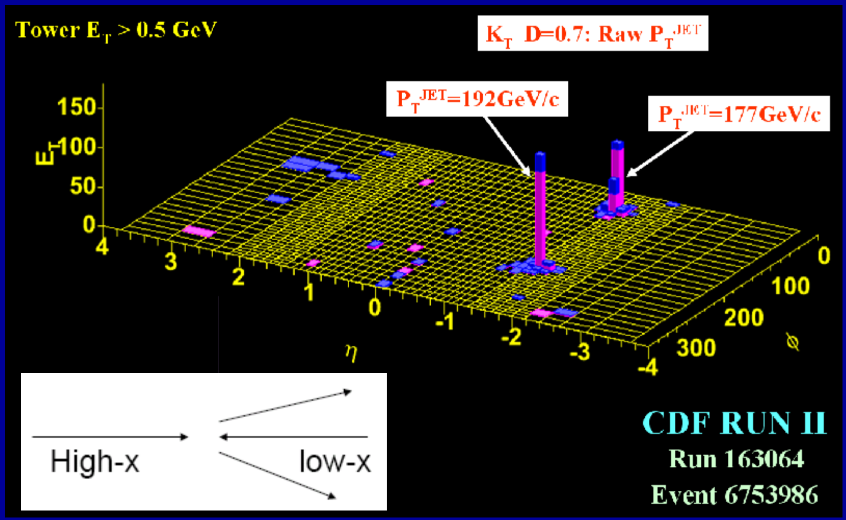


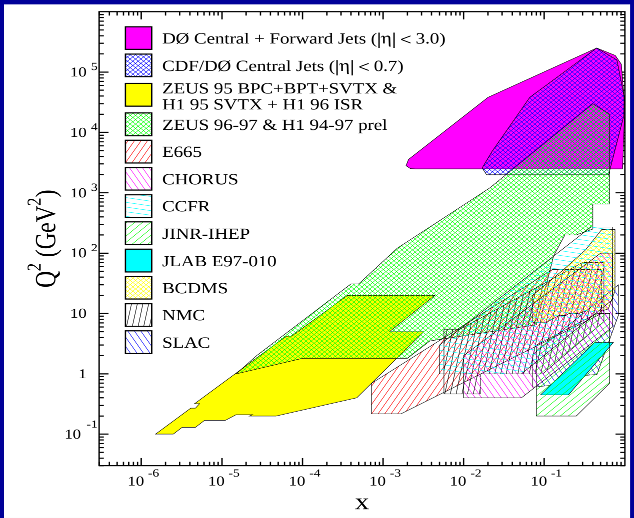




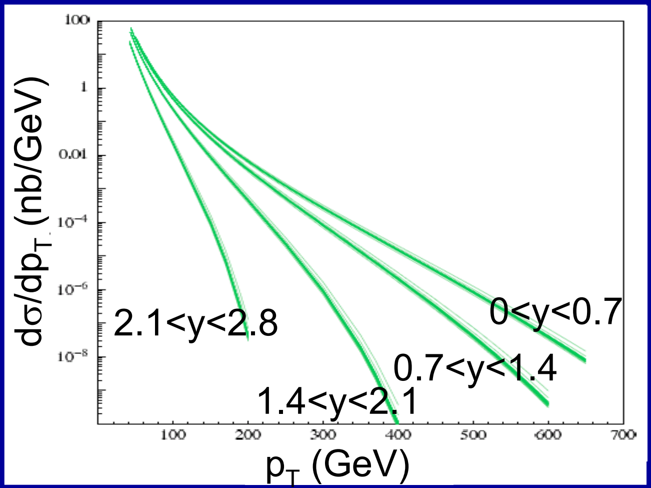
- Both k_T (shown here) and midpoint results show good agreement with NLO predictions
- k_T algorithm works fine in a hadron collider environment

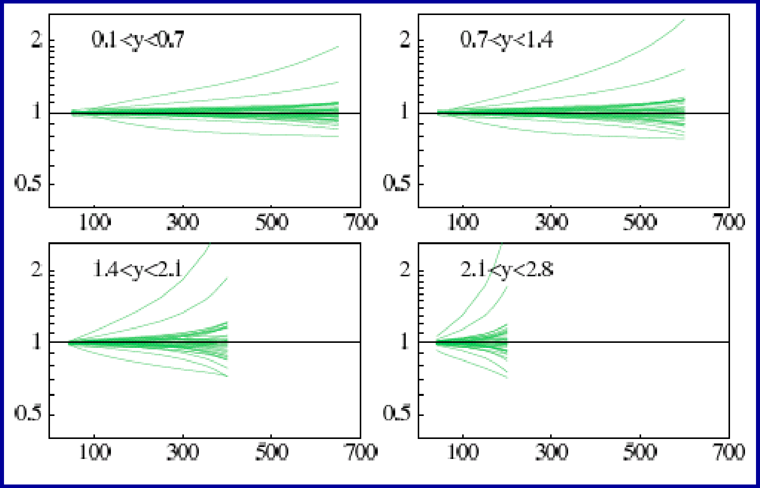
Forward jet production



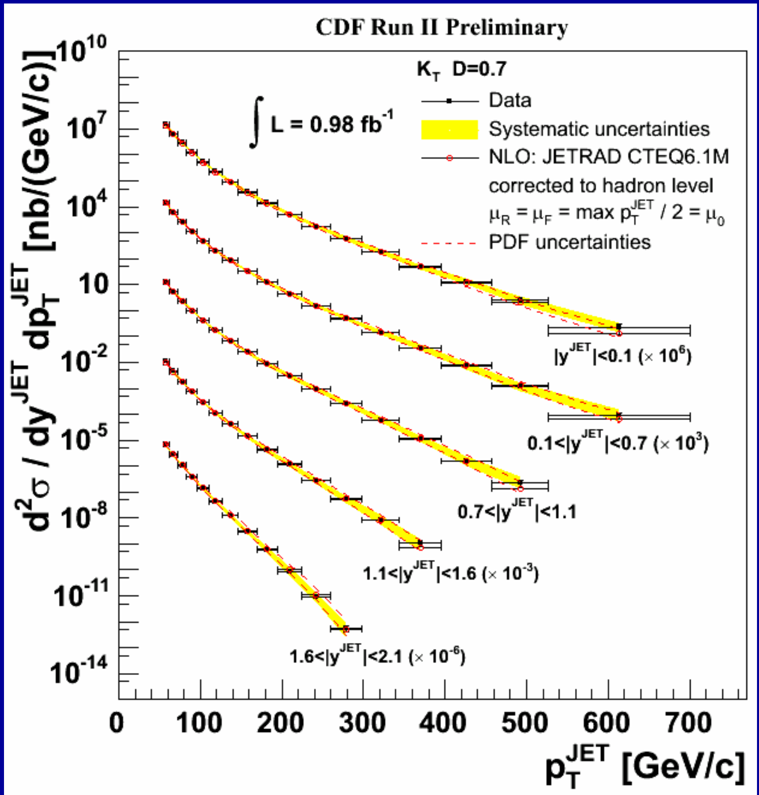


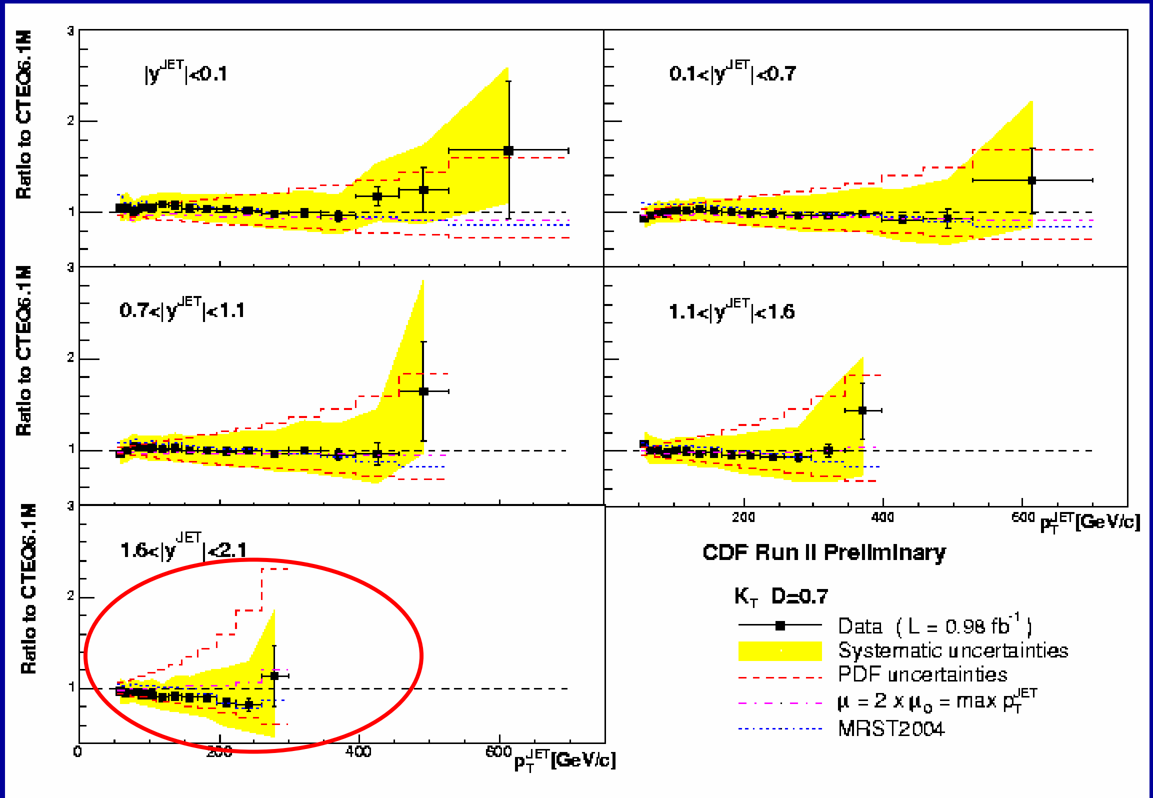
Measurements in the forward region (high-x, low-Q^2) constrain the gluon distribution (new physics expected to appear at high Q^2)





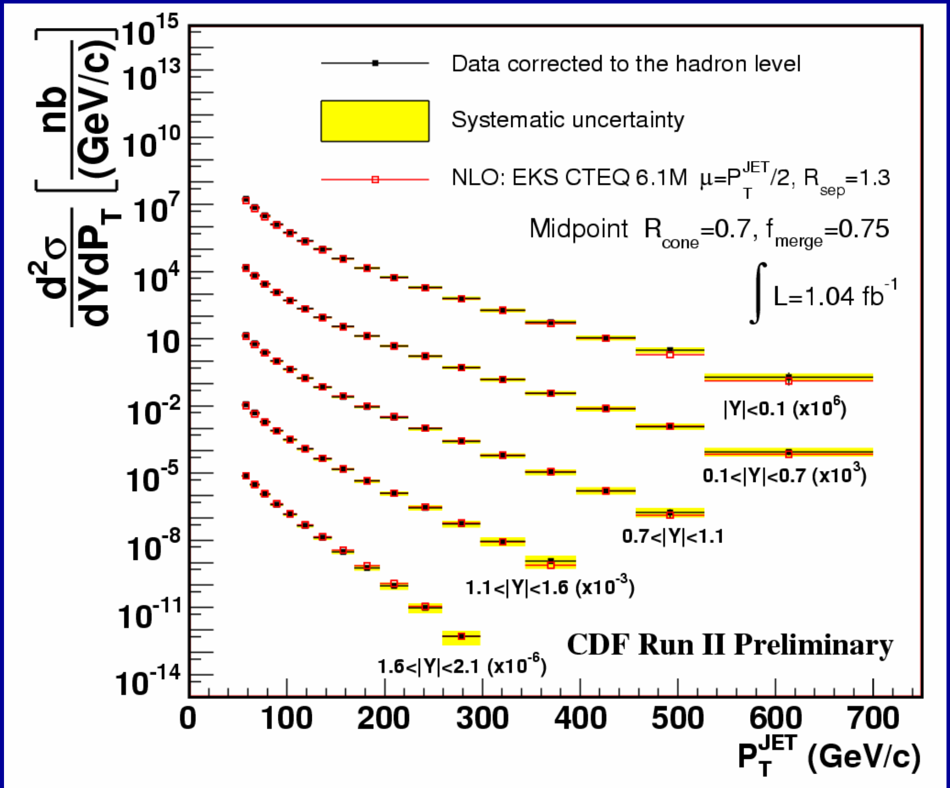
Inclusive jet cross section extended to the forward region: k_T algorithm (CDF $1fb^{-1}$)

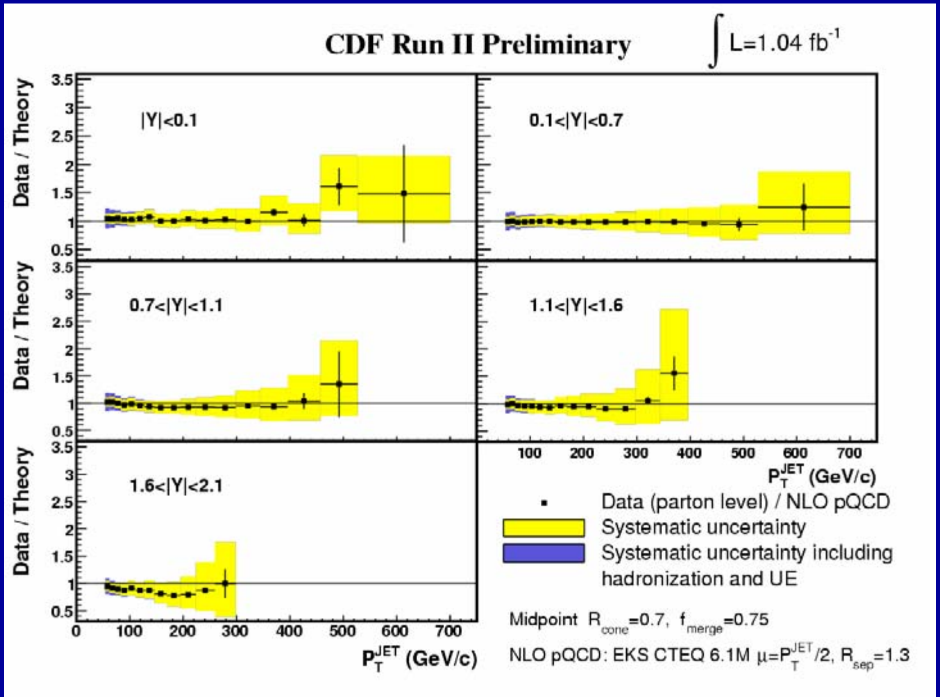




- Good agreement with NLO predictions
- Measurements in the forward region will reduce PDF uncertainties

Inclusive jet cross section extended to the forward region: Midpoint algorithm (CDF 1fb^{-1})

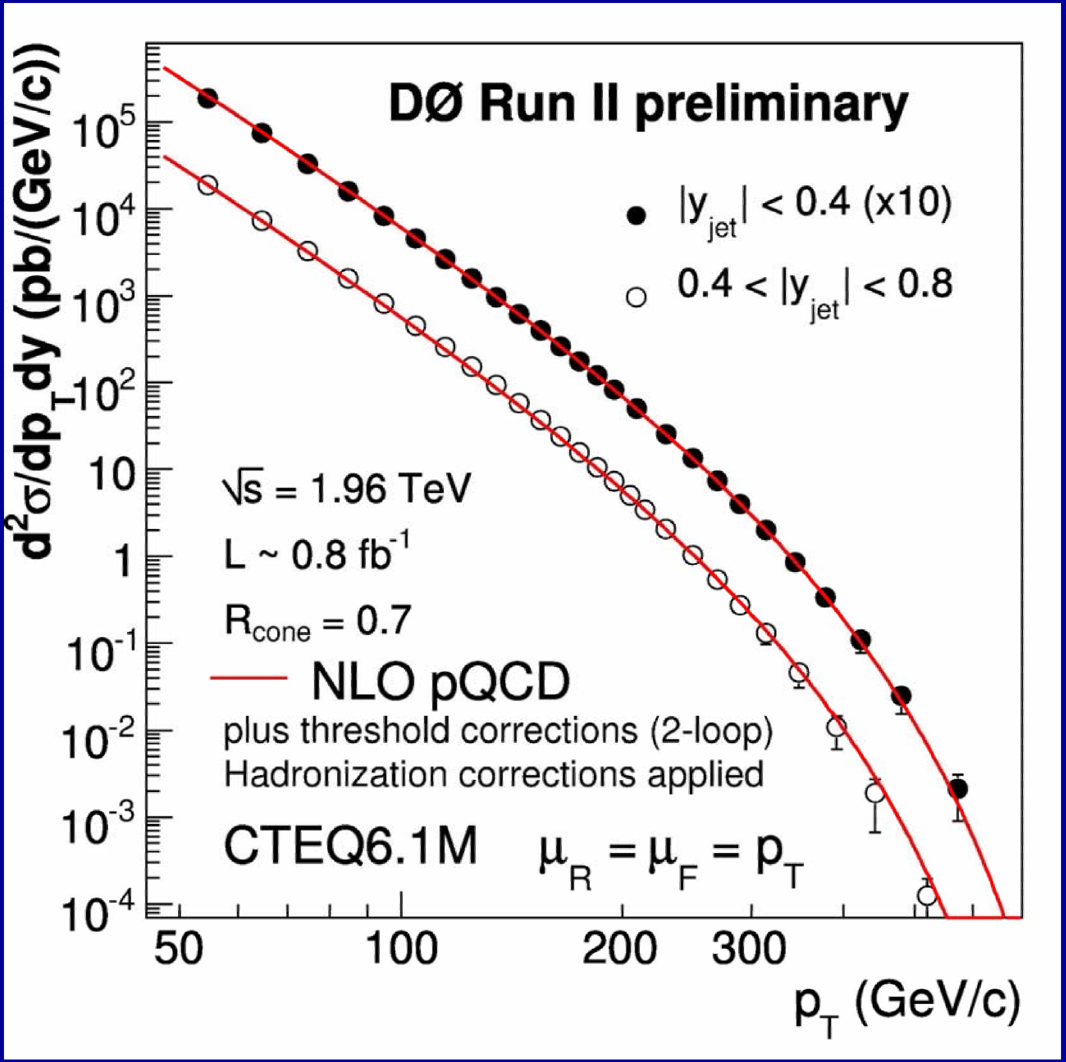




- Again we see good agreement with NLO predictions

Inclusive jet cross section (DØ 0.8fb^{-1})

- Measurement in two rapidity regions
- Data scaled to theory at p_T=100 GeV for $|y_{jet}|$<0.4 to remove luminosity uncertainties: shape shows good agreement over entire p_T range



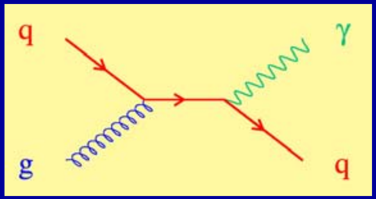
Photon production

Direct photon production

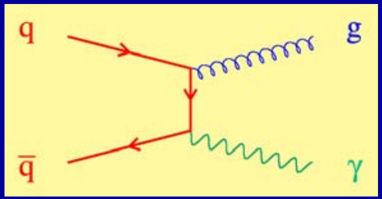
Using prompt photons one can precisely study QCD dynamics:

- Well known coupling to quarks
- Access to lower p_T
- Clean: no need to define "jets"
- Constrain gluon PDF
- Complementary to constraints from jet production (0.005<x<0.3)

Compton scattering (dominant process p_T<~120GeV)



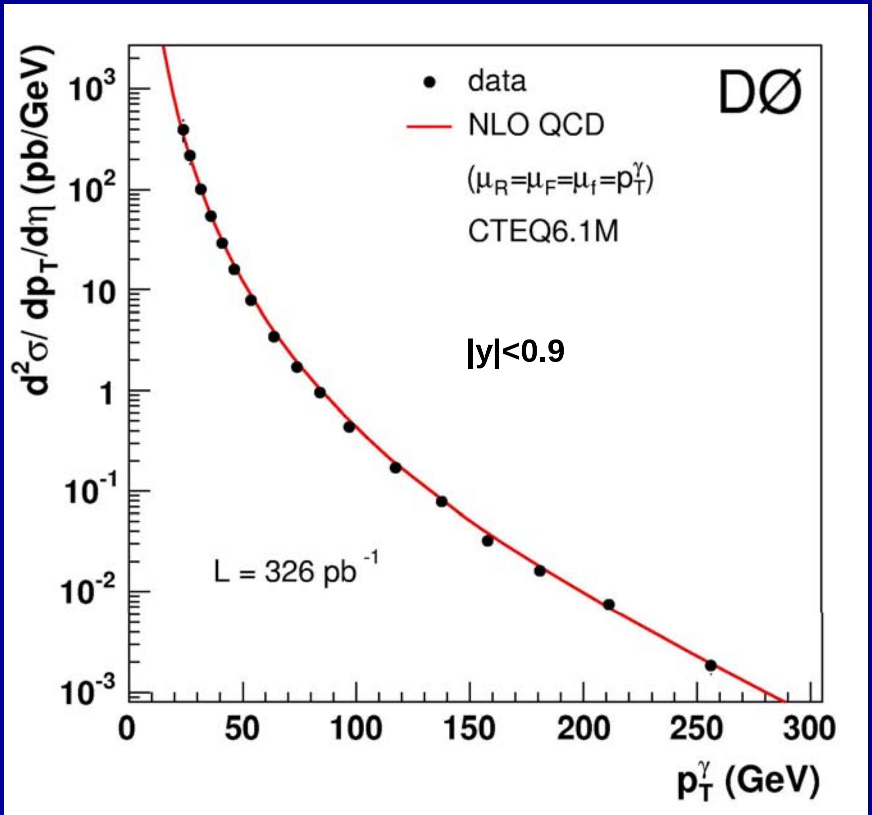
$q\bar{q}$ annihilation (dominant at higher p_T)

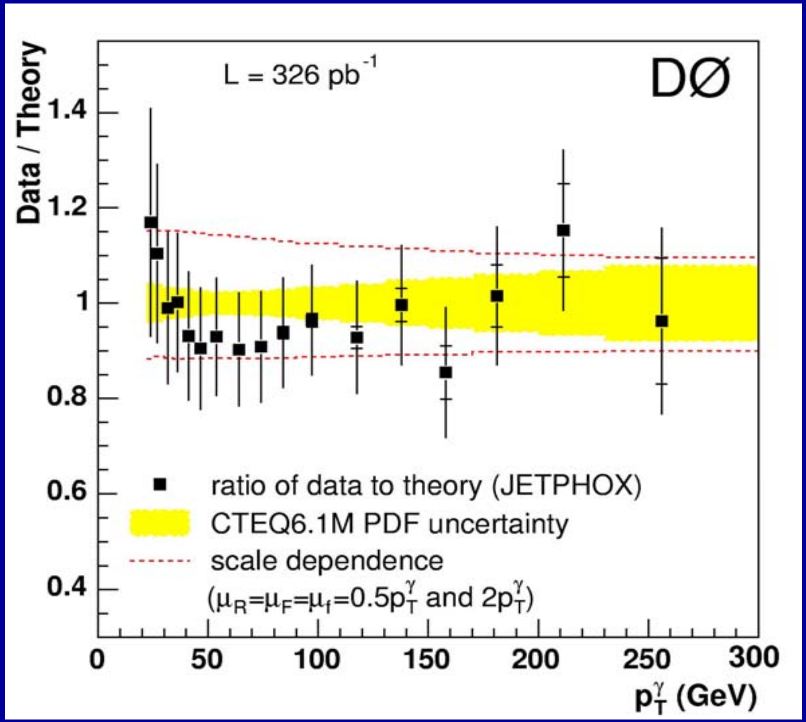


- Large background from π^0, η decays at low p_T suppressed by isolation requirement
- Isolated e from W/Z production background at high p_T
- DØ uses a neural net to further suppress background, mainly from jets with large EM fraction

Inclusive isolated γ cross section (DØ 326pb^{-1})

submitted to Phys. Lett. B





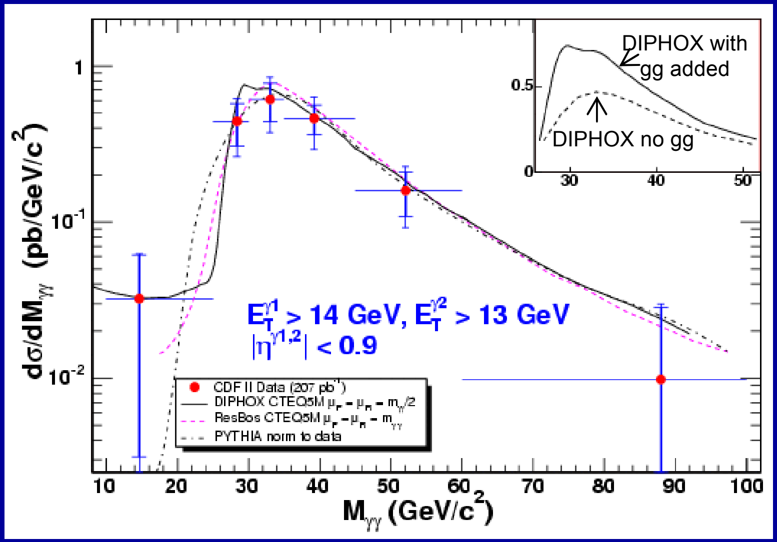
5 events above 300 GeV (highest 442 GeV)

- Good agreement with NLO pQCD
- Uncertainties ~20% dominated by photon purity
- Advances in theory prediction also needed in order to constrain gluon PDF

Prompt diphoton cross section (CDF 207pb^{-1})

Phys. Rev. Lett. 95, 022003 (2005)

- QCD background to searches for new physics with $\gamma\gamma$ signature
- Sensitive to initial state soft gluon radiation in the transverse momentum of $\gamma\gamma$ system (q_T)
- Main processes $q\bar{q}\rightarrow\gamma\gamma$, $gg\rightarrow\gamma\gamma$ (low $\gamma\gamma$ mass), also one or both γ's from fragmentation of hard parton
- Require isolation to reduce background from π^0,η
  - Also reduces photons coming from fragmentation
- Residual background removed statistically based on shower shape

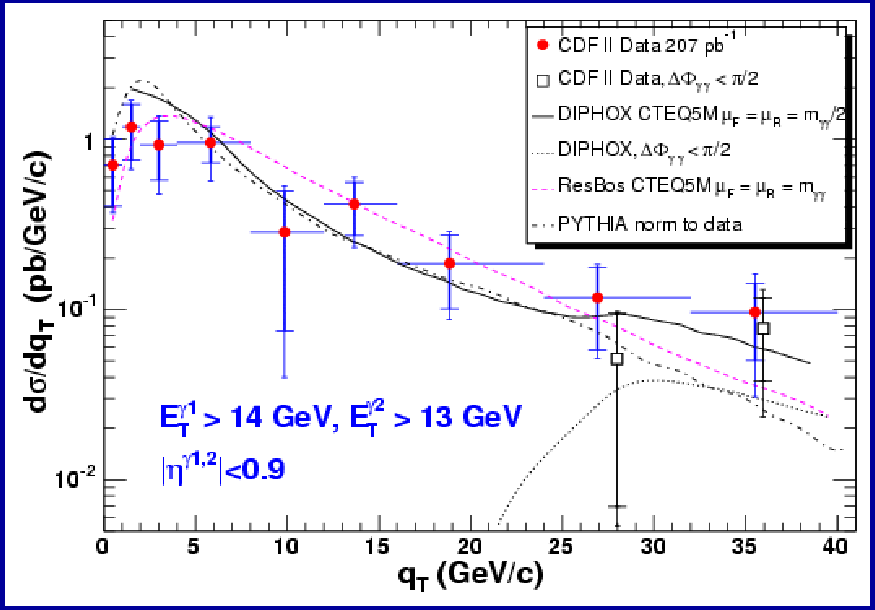


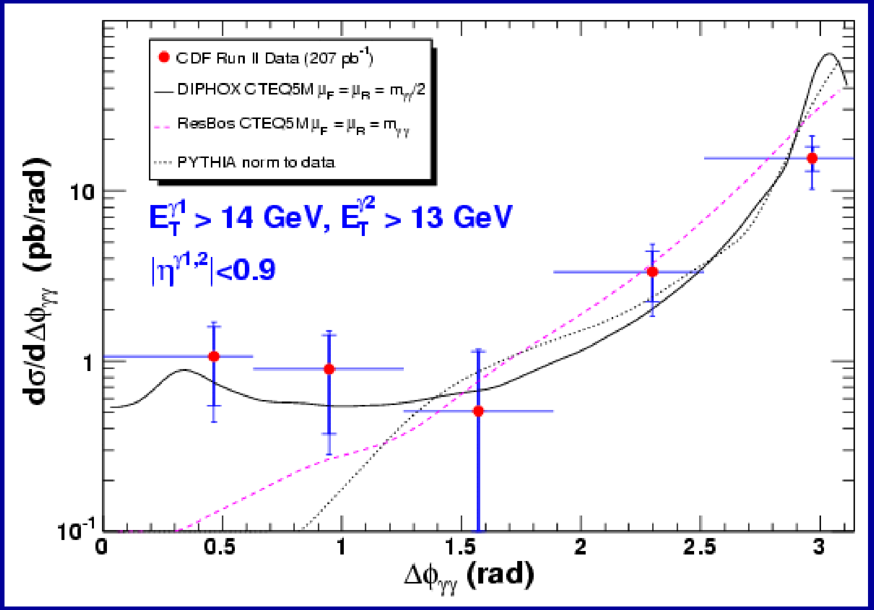
- DIPHOX
  - All processes at NLO
  - Fixed order calculation
- ResBos
  - Direct contributions at NLO; fragmentation LO
  - Initial state soft gluon resummation
- PYTHIA (scaled to data by factor 2)
  - LO + parton shower

Prompt diphoton cross section (CDF 207pb^{-1})

Phys. Rev. Lett. 95, 022003 (2005)

- DIPHOX breaks at small q_T (no soft gluon resummation)
- ResBos is OK at small q_T, but fails at small $\Delta\phi$ (importance of NLO fragmentation contribution)



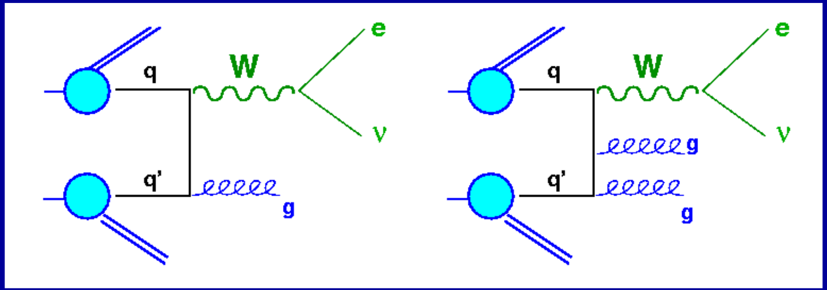


- Statistical uncertainties dominant – hope to have results with larger data sample soon

Bosons + Jets

W/Z + jets production

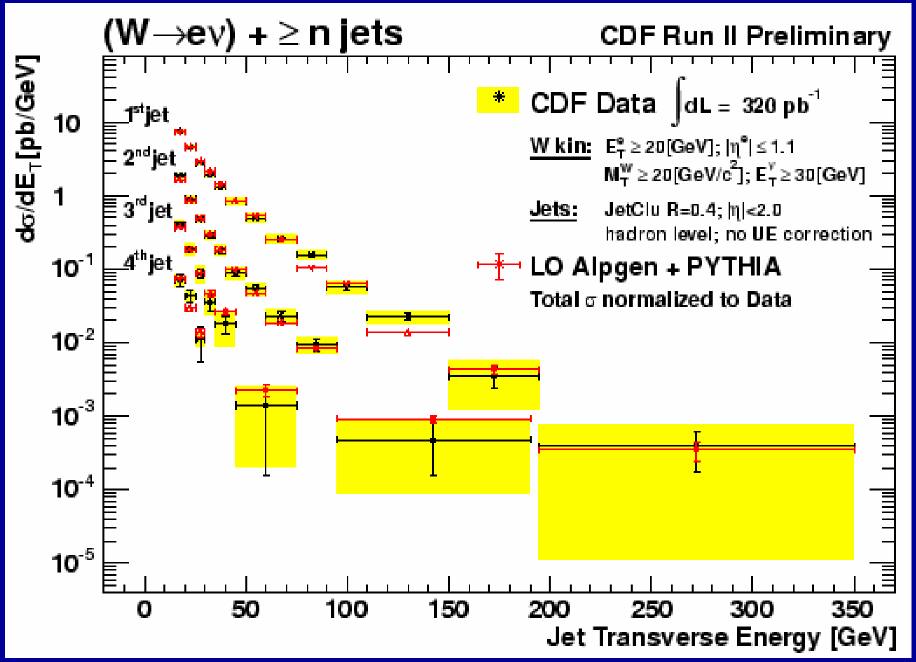
- W/Z + jets is a possible signature for production of:
  - Top pair and single top
  - Higgs boson
  - Supersymmetric particles
- QCD production of W/Z + jets is a large background for these processes

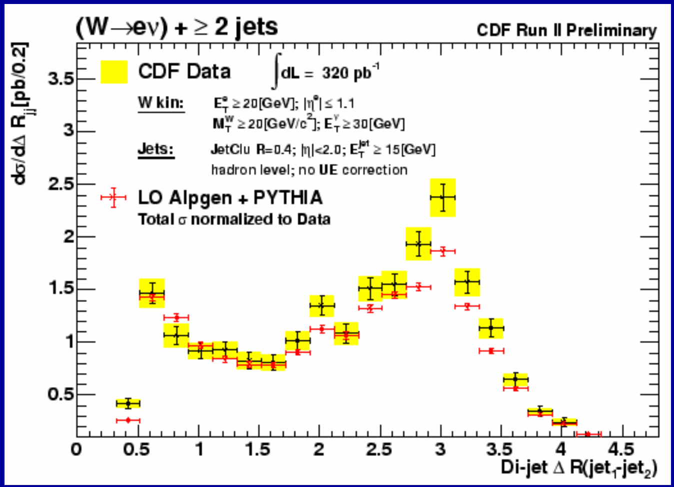


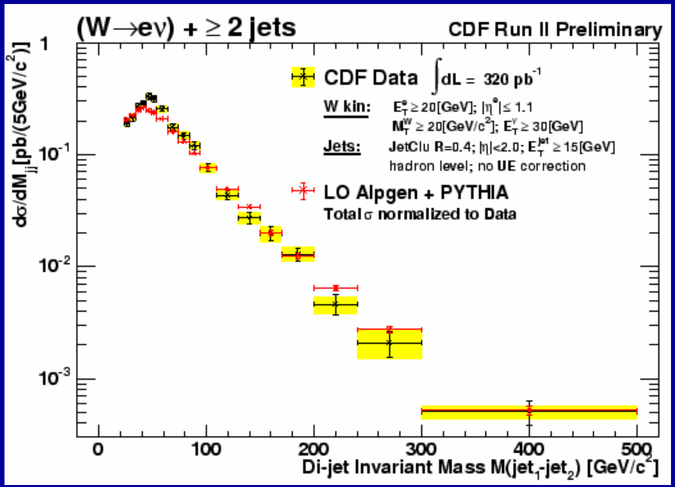
- Key sample to test LO and NLO Matrix Element + Parton Showering predictions
- Presence of W/Z ensures high Q^2
  - Test pQCD in a multijet environment

W + jets production (CDF 320pb^{-1})

- Cross sections given for a restricted W kinematic phase space in order to be model-independent
- Current comparison with LO Alpgen (v2) + PYTHIA in shape only

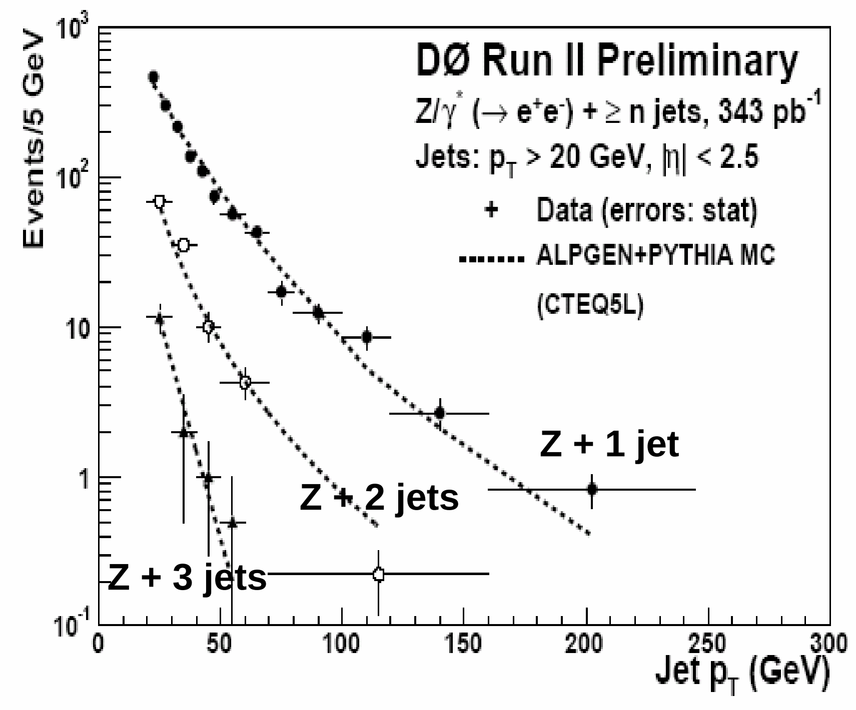


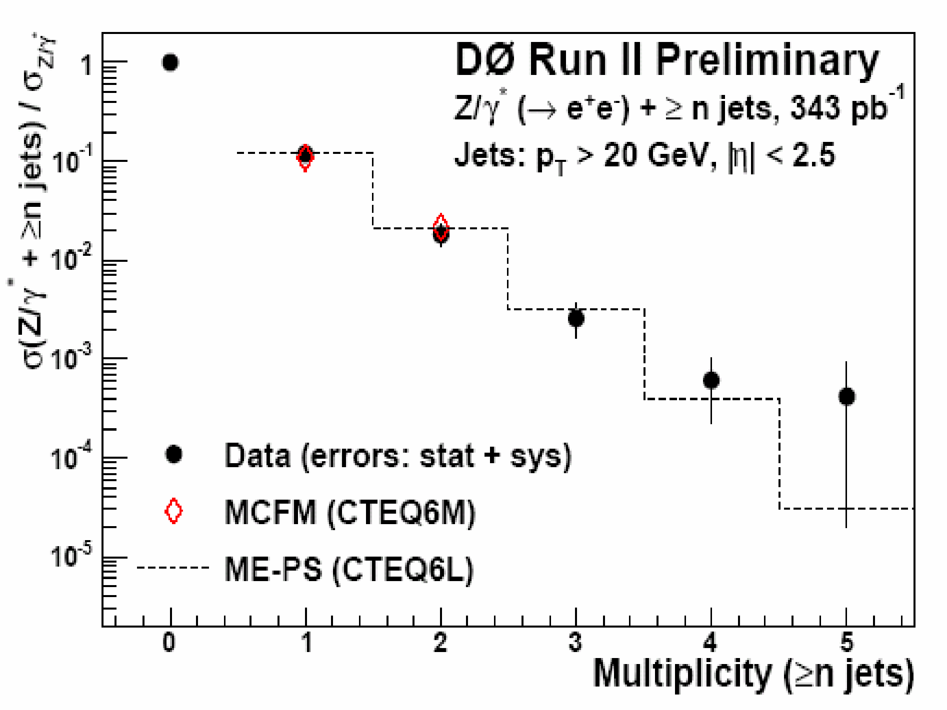




Z + jets production (DØ 343pb^{-1})

- Smaller cross section than W + jets but cleaner

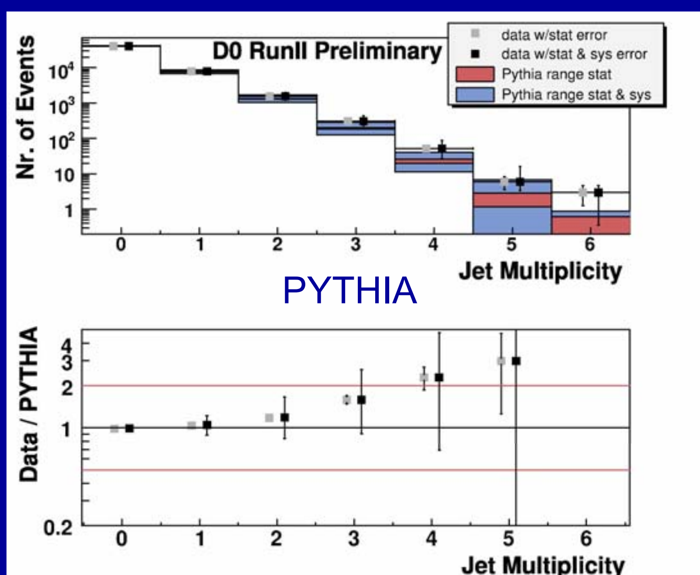


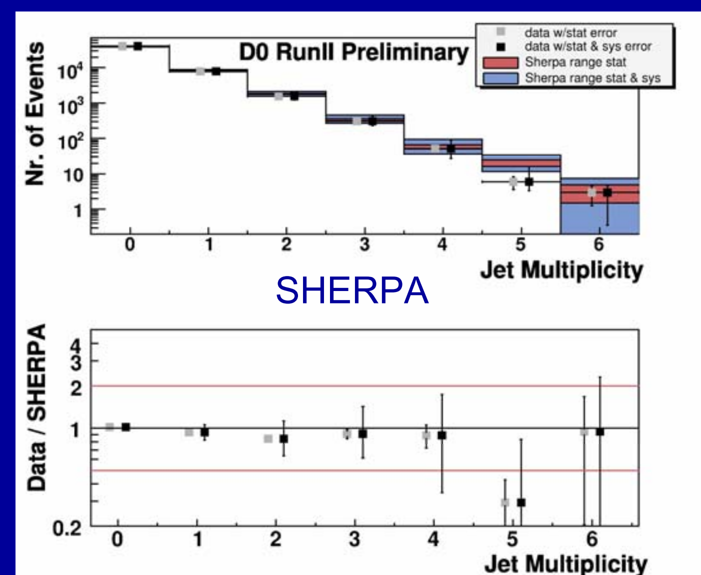


- Good agreement with
  - MCFM: NLO for Z + <=2p
  - ME + PS: MADGRAPH Z + <=3p tree level process and PYTHIA used for parton showering

Z + jets (DØ 950pb^{-1})

- Comparison to PYTHIA and Sherpa 1.0.6 (matrix element + parton shower, CKKW matching)
- PYTHIA predicts fewer hard jets than seen in data; discrepancy increases with jet multiplicity
- Sherpa agrees well for the p_T of the Z, jet multiplicities, jet p_T, and $\Delta\eta$(jet-jet) and $\Delta\phi$(jet-jet) correlations





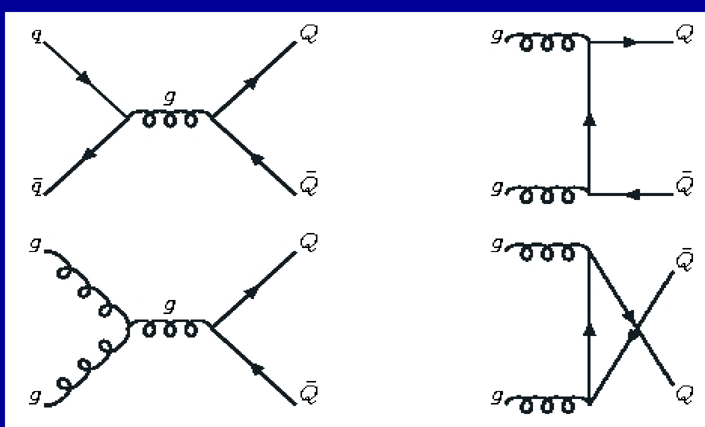
Heavy-flavor jets

b-jet production

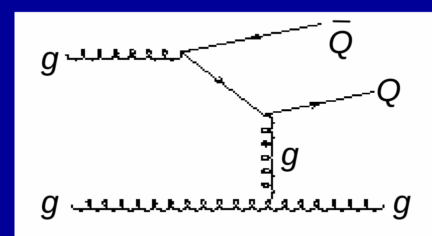
- *b*-jets include most of *b*-quark remnants
  → small dependence on fragmentation
- PDFs have evolved significantly in recent years
- Different processes (b, $b\bar{b}$, γ+b, Z+b) probe different production mechanisms

Leading Order

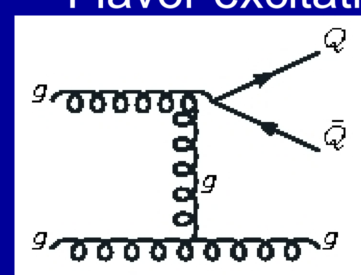
Next to Leading Order



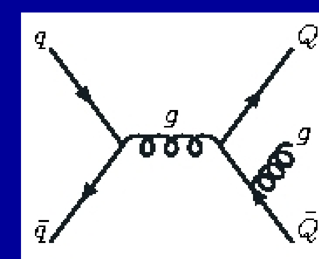
Flavor creation



Flavor excitation



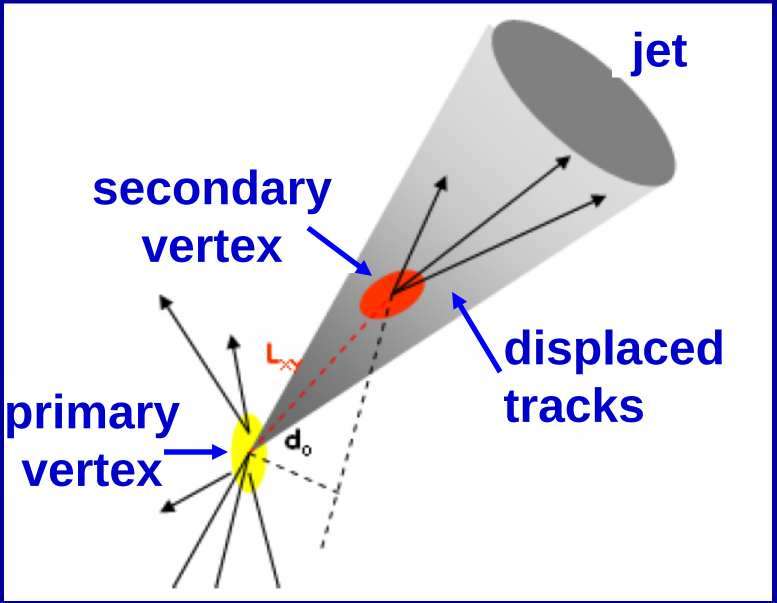
Gluon splitting

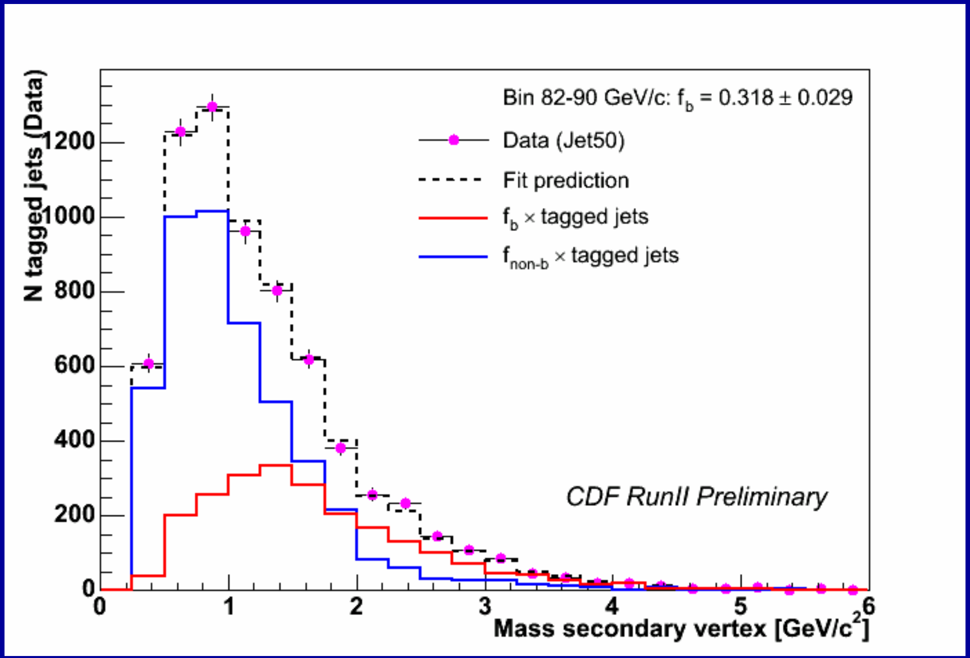


other radiative corrections...

b tagging

- Reconstruct secondary vertex from B hadron decays (*b*-tagging)

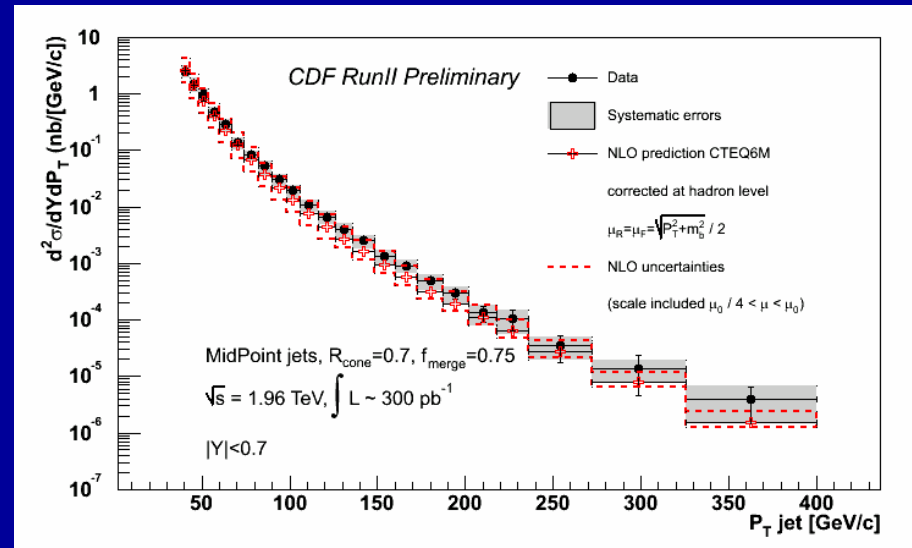


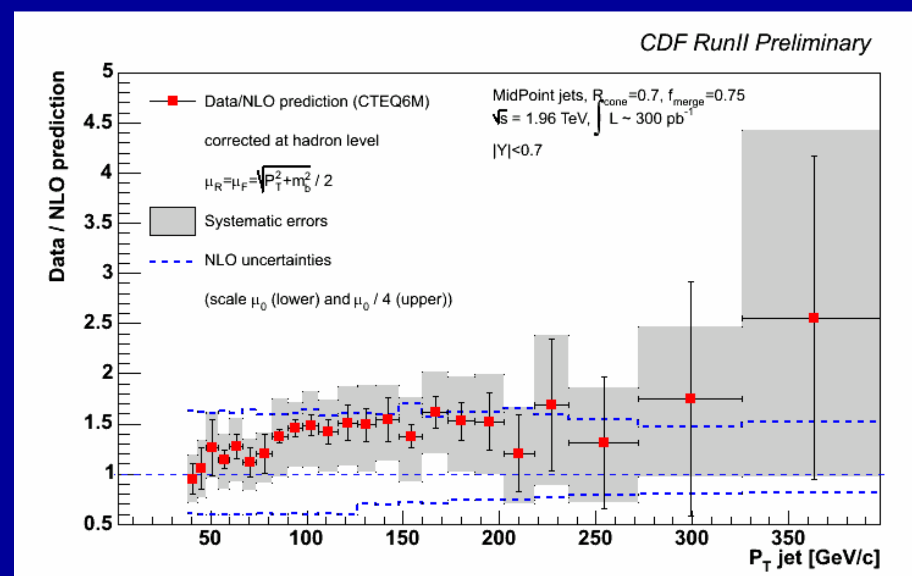


- Shape of invariant mass of tracks from secondary vertex used to extract fraction of tagged jets which are *b*-jets (CDF)

Inclusive *b*-jet cross section (CDF 300pb^{-1})

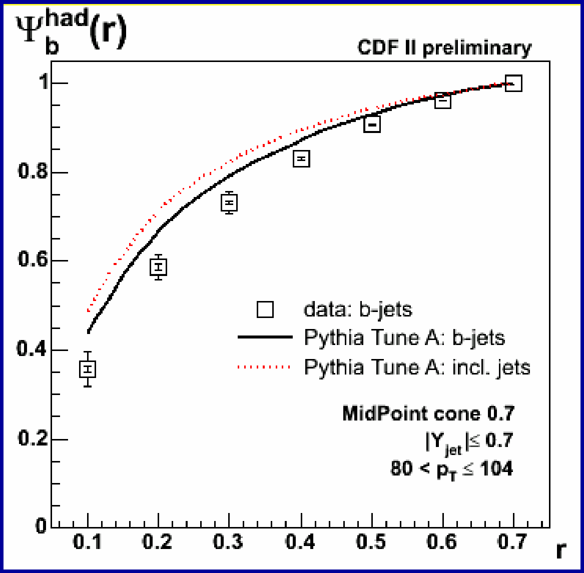
- Test of pQCD covering more than 6 orders of magnitude
- Systematic uncertainties in the jet energy scale and in the fraction of tagged jets which are true *b*-jets dominate for the data
- Main uncertainties on NLO prediction due to μ_R/μ_F scales
- Agreement with NLO pQCD within systematic uncertainties

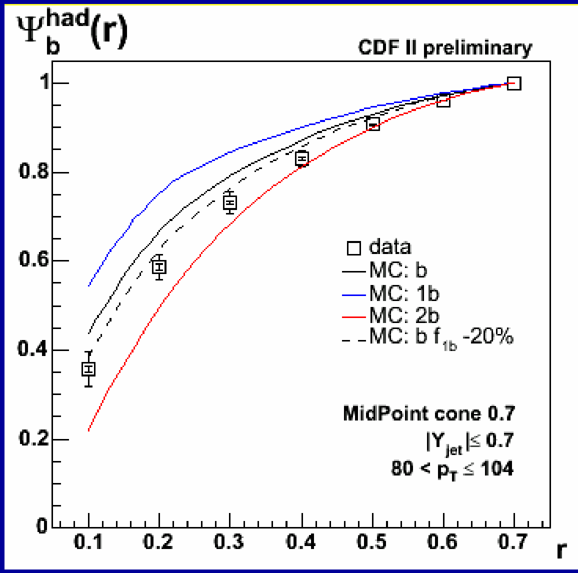


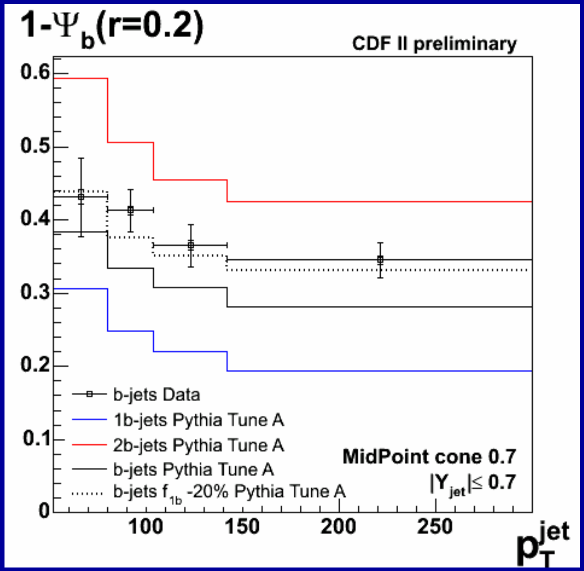


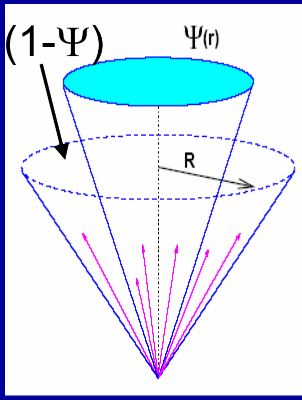
b-jet shapes (CDF 300pb^{-1})

- Energy flow in *b*-tagged jets measured in 4 p_T bins from 52-300 GeV
- PYTHIA predicts jets with *b*-quarks to be wider than inclusive jets
  - Jets with a single *b*-quark narrower, 2 *b*-quarks wider
- Measure *b*-jets to be wider than inclusive jets
- Agreement with PYTHIA is poor
  - Better if the ratio of jets with 1- to 2- *b*-quarks is decreased by 20%
- Need to compare to other MC (in progress)



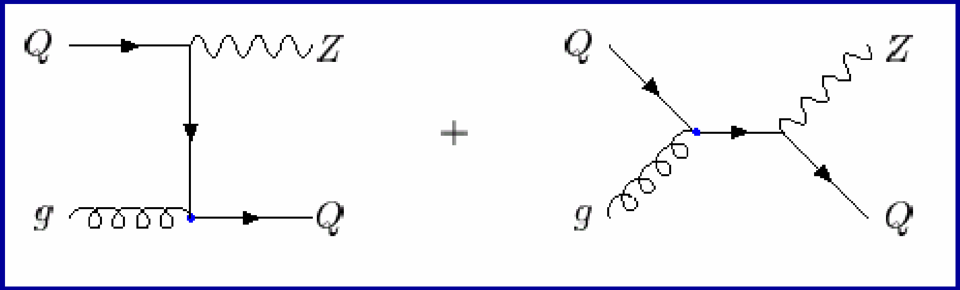






Z + *b*-jet production

- Probe *b* content of proton



- Background for searches for new physics
  e.g. Higgs ZH→$Zb\bar{b}$

Z + *b*-jet production (DØ 180pb^{-1})

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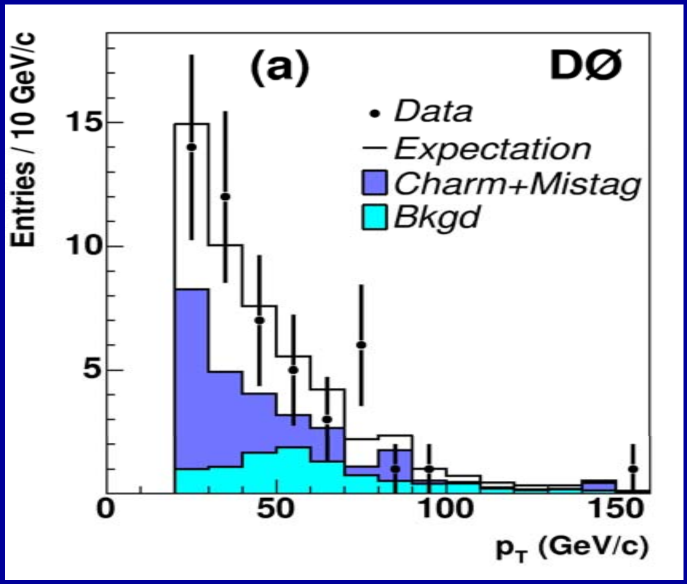
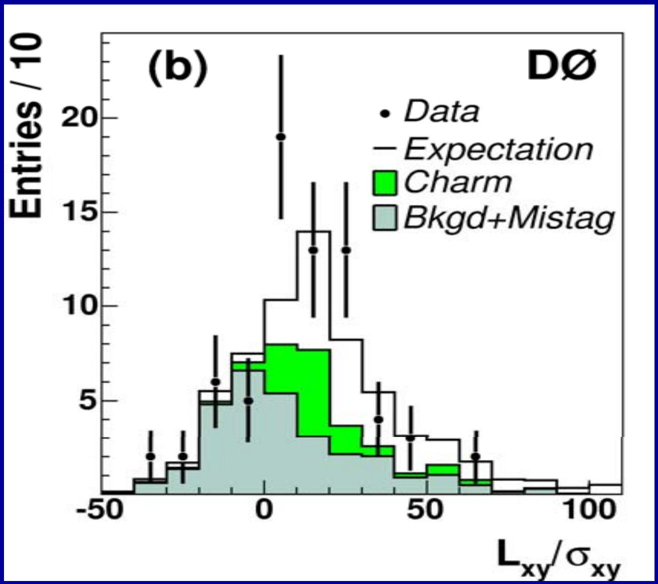
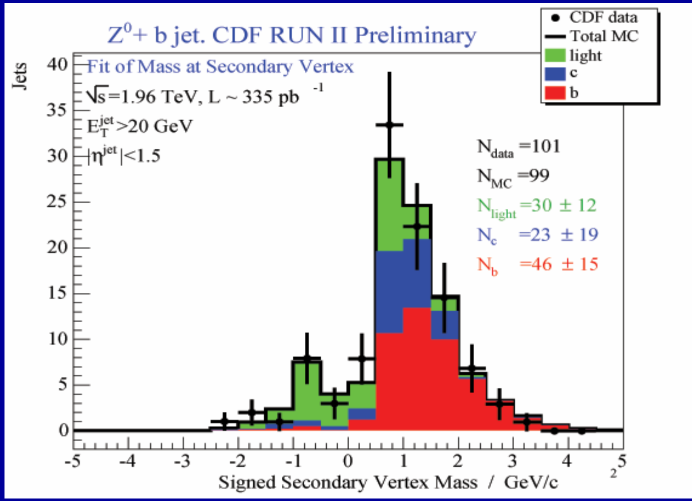
- Charm content taken from theoretical prediction of *Z+b* and Z+*c* production: $N_c=1.69N_b$ (Campbell, *et al.*)
- Cross section ratio ($p_T^{jet}>20$GeV/c, $|\eta^{jet}|<2.5$)
  $\sigma(Z^0+b\text{-jet})/\sigma(Z^0+\text{jet}) = 0.023\pm0.004(\text{stat})^{+0.002}_{-0.003}(\text{syst})$
  consistent with NLO prediction 0.018±0.004 using MCFM and CTEQ6M

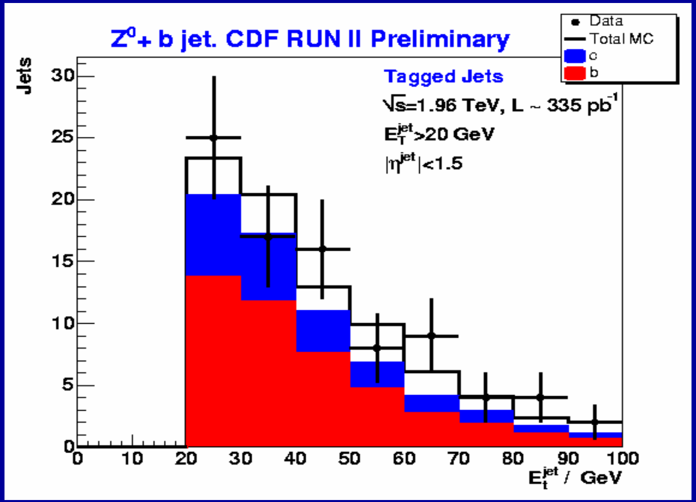




Z + *b*-jet production (CDF 335pb^{-1})

- No assumptions made on charm content – template fit based on mass of charged tracks at secondary vertex





- Cross section (p_T^{jet}>20GeV/c, $|\eta^{jet}|$<1.5)
  $\sigma(Z^0+b\ \text{jet})=0.96\pm0.32(\text{stat})\pm0.14(\text{syst})$ pb
  and ratio
  $\sigma(Z^0+b\ \text{jet})/\sigma(Z^0+\text{jet}) = 0.0237\pm0.0078(\text{stat})\pm0.0033(\text{syst})$
  consistent with NLO predictions 0.48 pb and 0.018±0.004
- Measurement still statistically limited

Conclusions

- The Tevatron has a broad program which is making a significant impact on our understanding of high Q^2 QCD
  - Jets, photons, bosons + jets, heavy-flavor jets
  - Tuning of Monte-Carlo event generators, parton showering, etc
  - Constraining the PDFs, especially gluon at high-x
  - Measuring cross sections of QCD processes which contribute large backgrounds to searches for new physics
  - Many analyses will benefit from larger datasets
    - Besides those mentioned: dijet and $b\bar{b}$ cross sections, photon + heavy-flavor production
- Stay tuned as the Tevatron continues to produce important results in high Q^2 QCD