Kathy Turner, BNL
Riken-BNL Workshop on
Hard Parton Physics in High-Energy Nuclear Collisions
March 1,1999

Hard Parton Physics at the Tevatron

$\longrightarrow$ Results from DØ

Focus on results that will be applicable to RHIC:

$\longrightarrow$ What can we learn from the Tevatron results that we may need to know for RHIC data.

My talk will be available at:
$\mathrm{http://www.rhic.bnl.gov/~kathy/star\_welcome.html}$

Results I Will Cover

- **Properties of Jets**
  - **Dijet Angular Distribution**
  - **Dijet Mass Distribution**
  - **Jet shape**
  - **Color Coherence**
    - **multi-jet events**
    - $W+$**jet events**

- **Properties of Photons**
  - **Inclusive Cross Section**
  - $\gamma+$ **jet angular distribution**
  - **Di-Photon Production**

Fermilab Tevatron Running $\longrightarrow$ DØ

$$p + \bar{p} \quad \text{at} \quad \sqrt{s} = 1.8 \text{ TeV}$$

$\Rightarrow$ 1992-1993: Run 1A, $\mathcal{L} \approx 15\ pb^{-1}$

$\Rightarrow$ 1994-1995: Run 1B, $\mathcal{L} \approx 89\ pb^{-1}$

- WWW pages where all I show can be found:
  Fermilab $\rightarrow$ DØ $\rightarrow$ Results $\rightarrow$
  - Summer 98 (papers to ICHEP)
  - Physics Groups $\rightarrow$ QCD $\rightarrow$ approved plots OR working groups

Jets at DØ

Use uranium liquid-argon sampling calorimeter to measure jet energy and position

- fine-segmentation in ϕ and η
- hermetic coverage for $|\eta| < 4$
- details of triggering and reconstruction in preceding talk in this workshop

- Dijet Angular Distribution
  PRL **80 666 (1998)**
  DØ contact person: bkabbott@lbl.gov
- **Dijet Mass Spectrum**
  submitted to PRL, hep-ex/9807014
  DØ contact person: bertram@fnal.gov
- **JETRAD, NLO QCD: Giele, Glover, Kosower**
  Nucl Phys. B403 (1993) 633.
  Contact person: giele@fnal.gov

Dijet Angular Distributions

$\rightarrow$ **Provides direct test of QCD:**

- **insensitive to parton distribution functions**
- **shape of angular dist. unaffected by boost of system**
- $gg \rightarrow gg$, $gq \rightarrow gq$, $qq \rightarrow qq$ **produce similar angular distribution**

$\rightarrow$ **Measure** $\frac{1}{N}\frac{dN}{d\chi}$ **vs.** χ **with** $\chi = e^{2|\eta^\star|}$
– $\eta^\star$ **is** η **of c.o.m. system**
- flattens out angular distribution

$\rightarrow$ $\chi \approx 20$ **corresponds to** $\cos\theta^\star = 1$

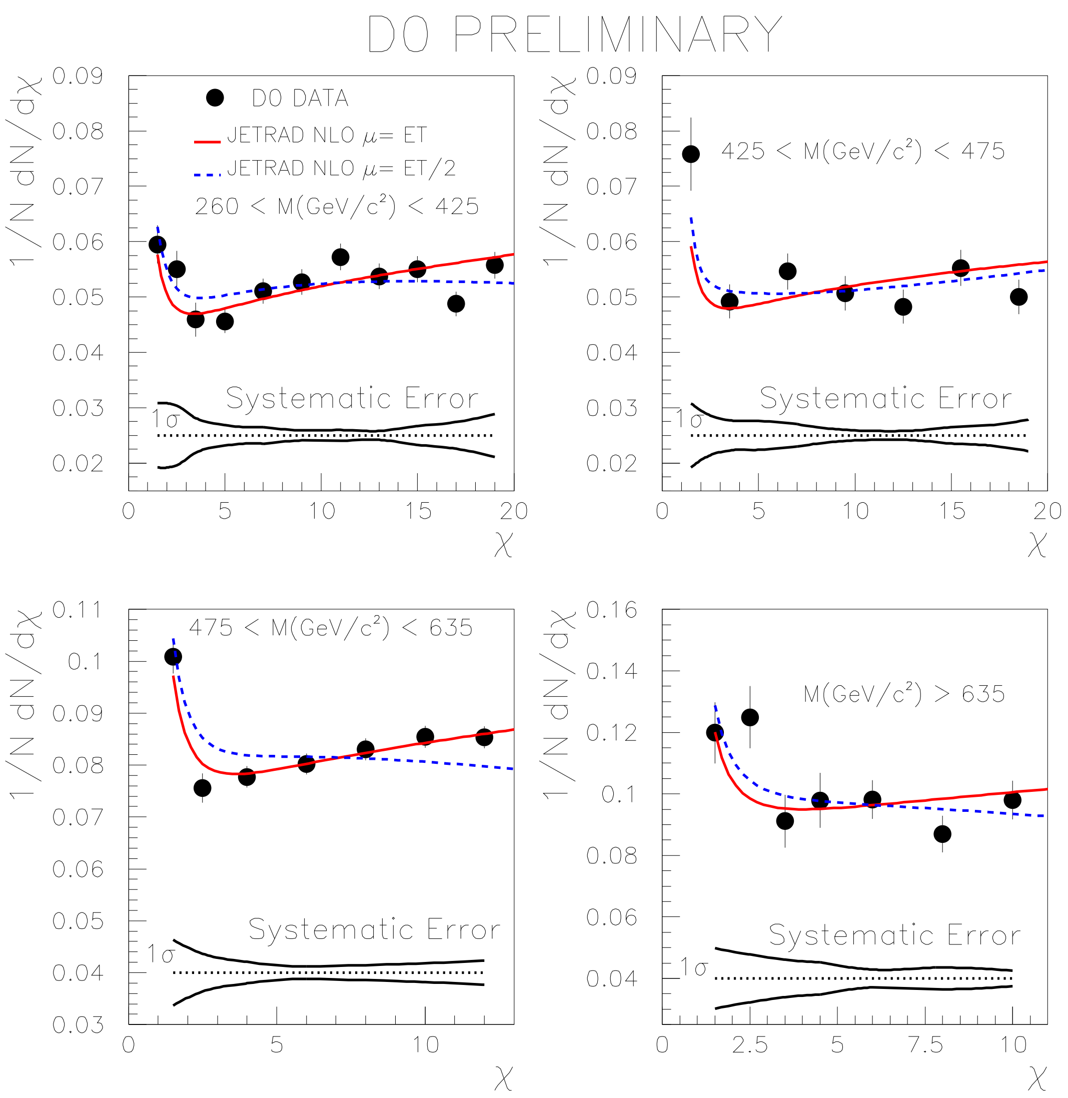
$\rightarrow$ $\frac{dN}{d\chi}$ **sensitive to contact interactions introduced by compositeness models**

$\star$ **same data sample as for jet inclusive measurement**

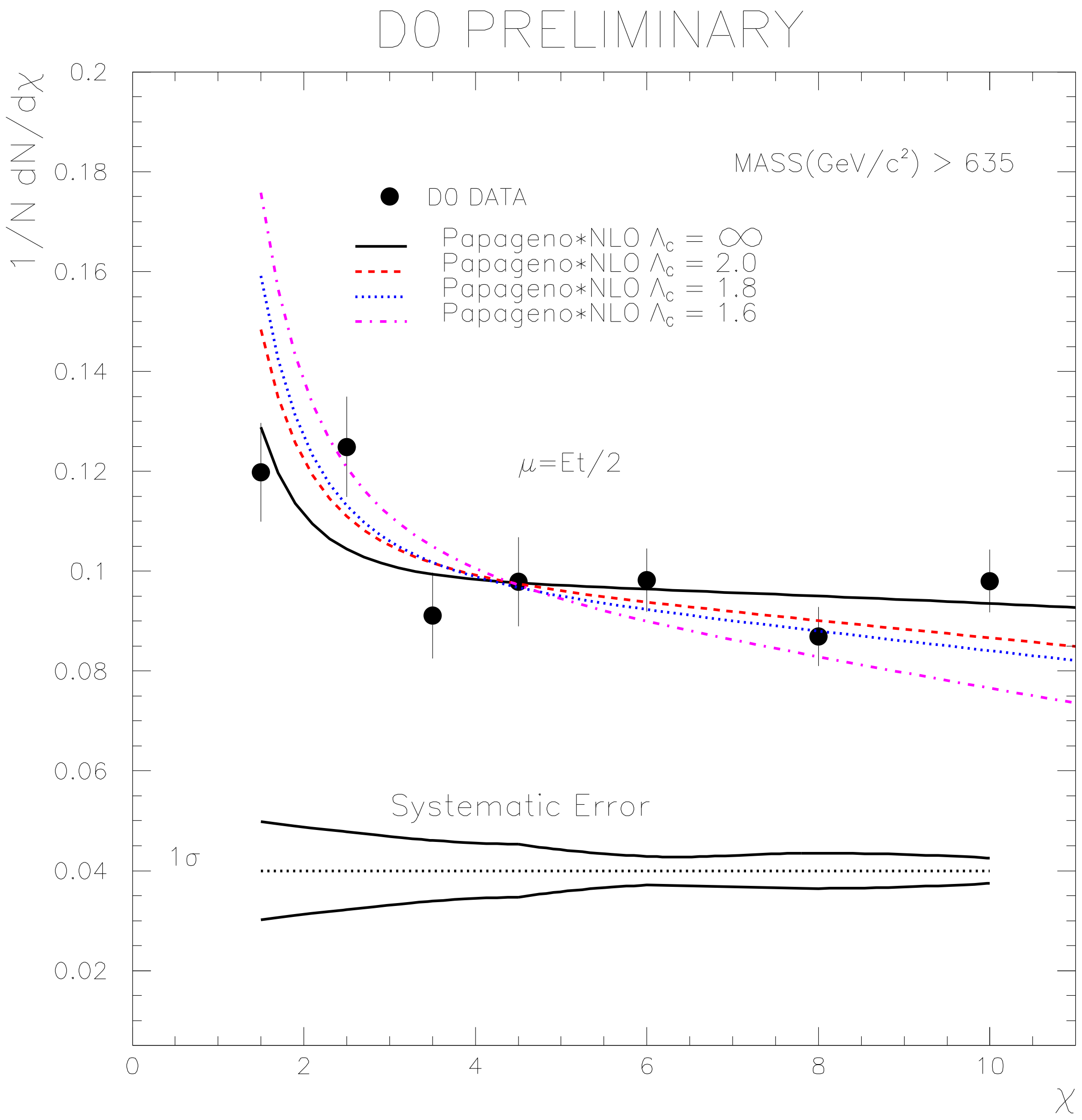
$\star$ **events with 2 or more jets selected**

$\star$ **range to** $|\eta| < 3.0$

Dijet Angular Distributions



Dijet Angular Distributions



Di-Jet Mass Spectrum

Provides:

⋆ **test of QCD**

⋆ **constraint on pdfs**

⋆ **limit on quark compositeness**

For events with at least 2 jets passing all quality criteria, calculate dijet mass, assuming jets are massless:

$$M^2 = 2E_T^1 E_T^2 [cosh(\Delta\eta) - cos(\Delta\phi)]$$

Results for:

- $M^2 > 200$ GeV at $|\eta_{jet}| < 1.0$
- ratio of spectra in 2 $|\eta|$ bins
- comparisons of pdfs
- comparisons to NLO QCD
- limits on compositeness

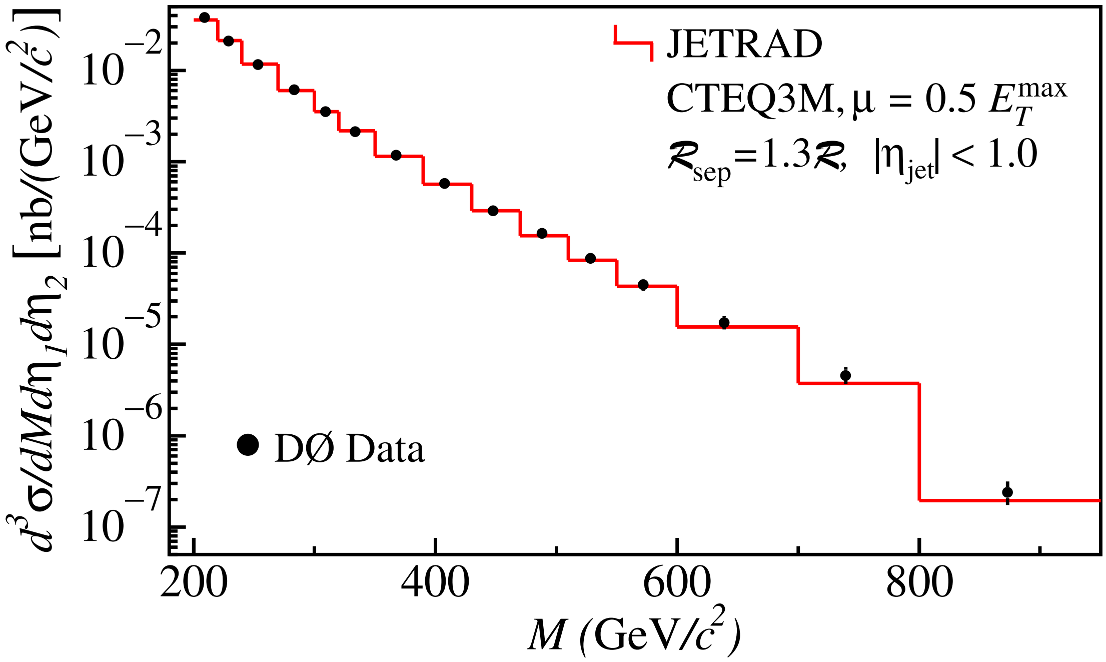
Di-Jet Mass Spectrum

Data are consistent with NLO QCD predictions

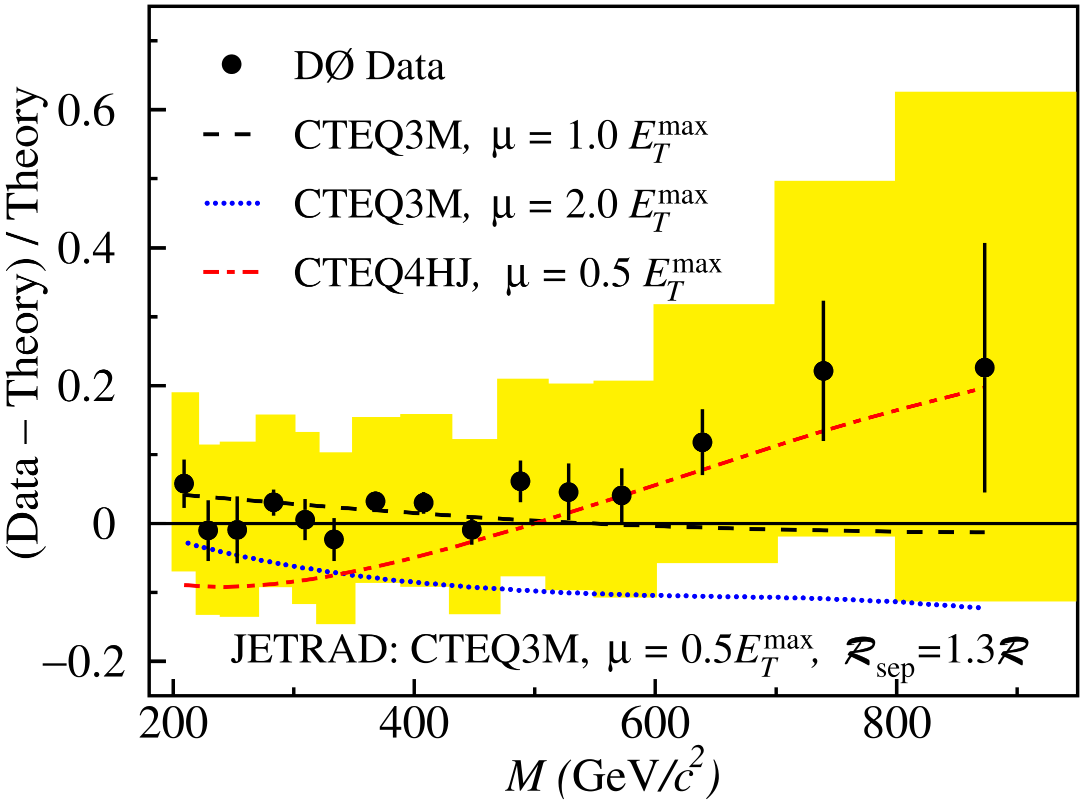
To place limits on quark compositeness:

- $\star$ **Use Pythia with and without compositeness to scale the NLO predictions.**
- $\star$ **Mass scale Λ characterizes strength of substructure binding and physical size of composite state**
- $\star$ **The 95% lower limits on mass scale are $\Lambda^+ > 2.7\,\mathrm{TeV}$ and $\Lambda^- > 2.4\,\mathrm{TeV}$**

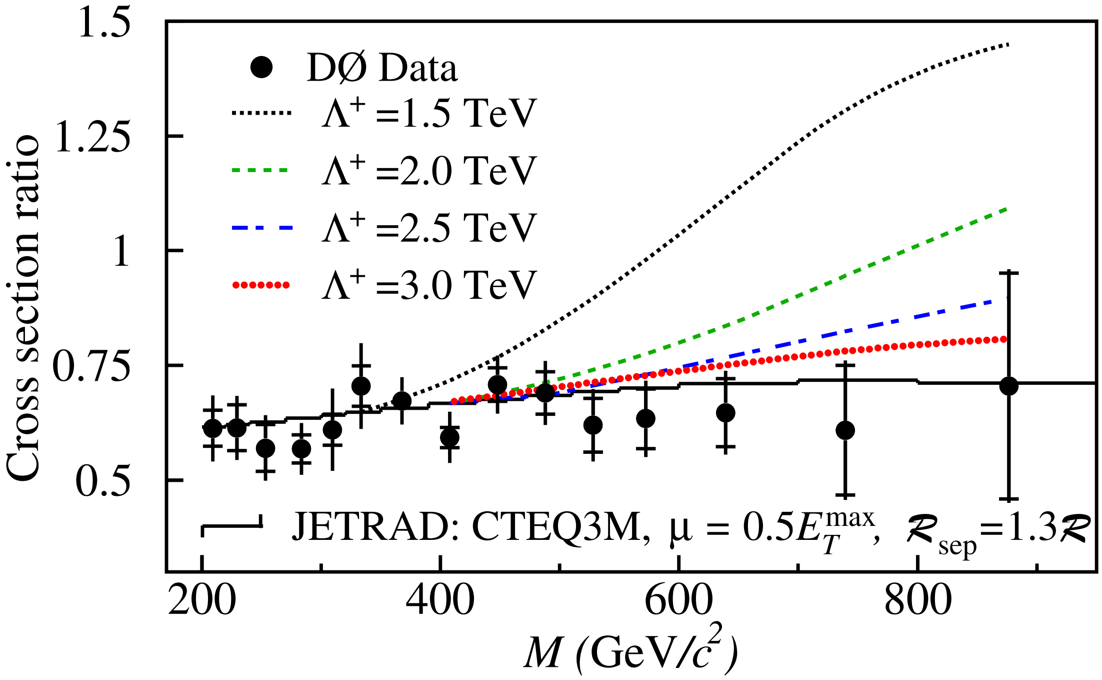
Di-jet Mass Spectrum



Di-jet Mass


DØ Data
CTEQ3M, μ = 1.0 E_T^{max}
CTEQ3M, μ = 2.0 E_T^{max}
CTEQ4HJ, μ = 0.5 E_T^{max}
JETRAD: CTEQ3M, μ = 0.5E_T^{max}, $\mathcal{R}_{sep}$=1.3$\mathcal{R}$
(Data – Theory) / Theory
0.6
0.4
0.2
0
–0.2
200
400
600
800
M (GeV/c^2)

Di-jet Mass


DØ Data
Λ^+ =1.5 TeV
Λ^+ =2.0 TeV
Λ^+ =2.5 TeV
Λ^+ =3.0 TeV
JETRAD: CTEQ3M, $\mu = 0.5E_T^{max}$, $\mathcal{R}_{sep}=1.3\mathcal{R}$
Cross section ratio
1.5
1.25
1
0.75
0.5
200
400
600
800
M (GeV/c^2)

Jet Shapes

⋆ **Jets have structure due to:**

- **Gluon radiation**
- **Fragmentation**

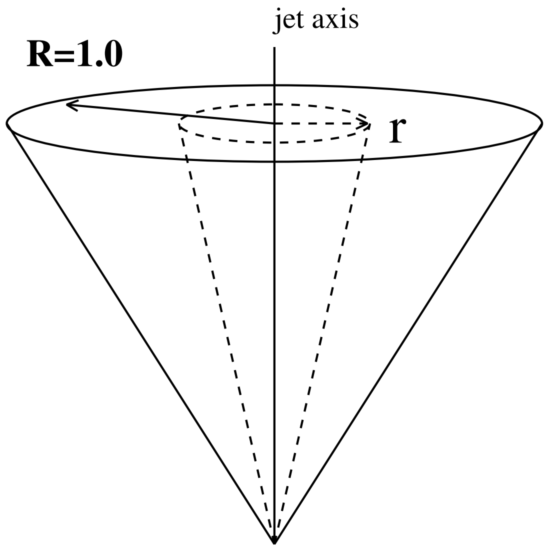
⋆ **Measure radial E_T distribution in jets**

⋆ **Compare to QCD predictions: NLO at parton level**

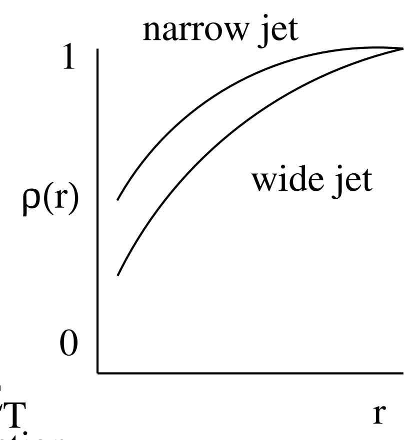
- **LO - 2 partons in final state**
  - Jets have no shape
- **NLO - 2 or 3 partons in final state**
  - First order a jet shape prediction can be made

- Jet Shape analysis - PLB **357 (1995) 500.**
- **Follow-up theory paper: hep-ph/9510420**
- **DØ contact person: kathy@bnl.gov**

Jet Shape Measurement



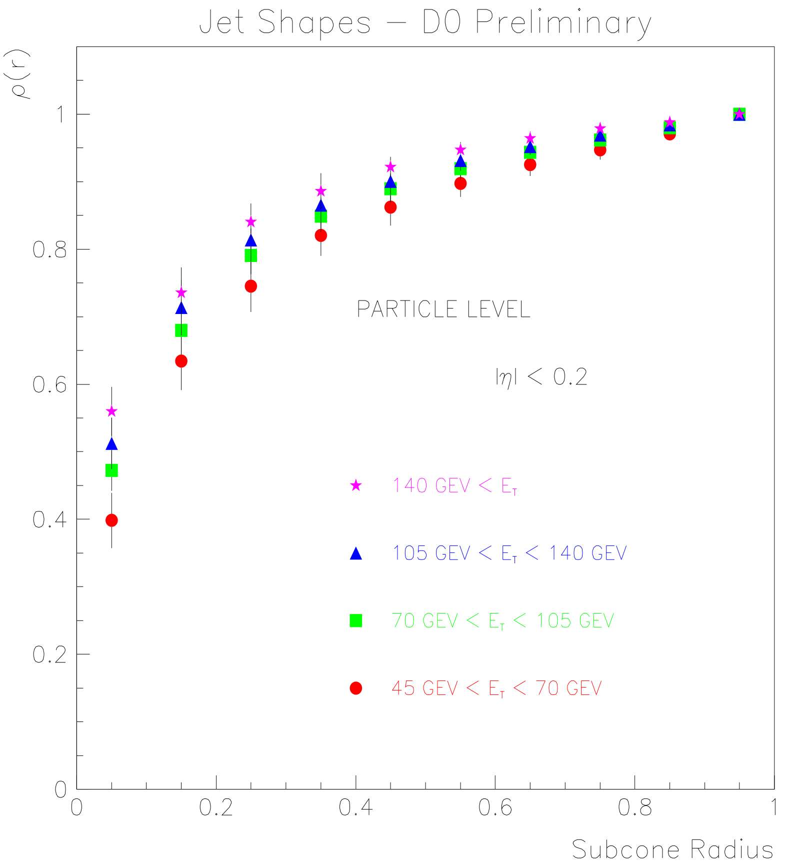
Measure E_T (P_T) flow in 10 subcones around jet axis in $\Delta r = 0.1$ increments



Calculate average integrated E_T fraction of jet energy as a function of radial distance from jet axis:

$$\rho(r) = 1/N_{jets}\left[\Sigma_{jets}\left(E_T(r)/E_T(R)\right)\right]$$

D0 Jet Shape - CENTRAL



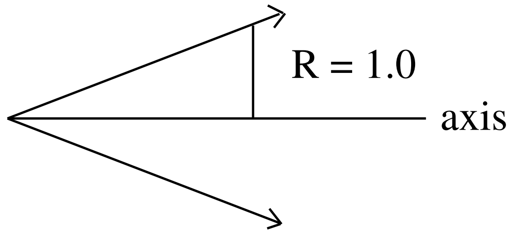
Slide 9

Clustering Algorithms used in Theoretical Predictions

- Method 1 - Ellis et al. & Giele et al.

  -- draw cone (R=1) around jet axis - the two partons are clustered if they are within the cone

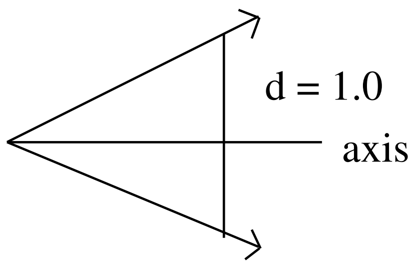
  -- Ellis: partons within distance Rsep < 1.3



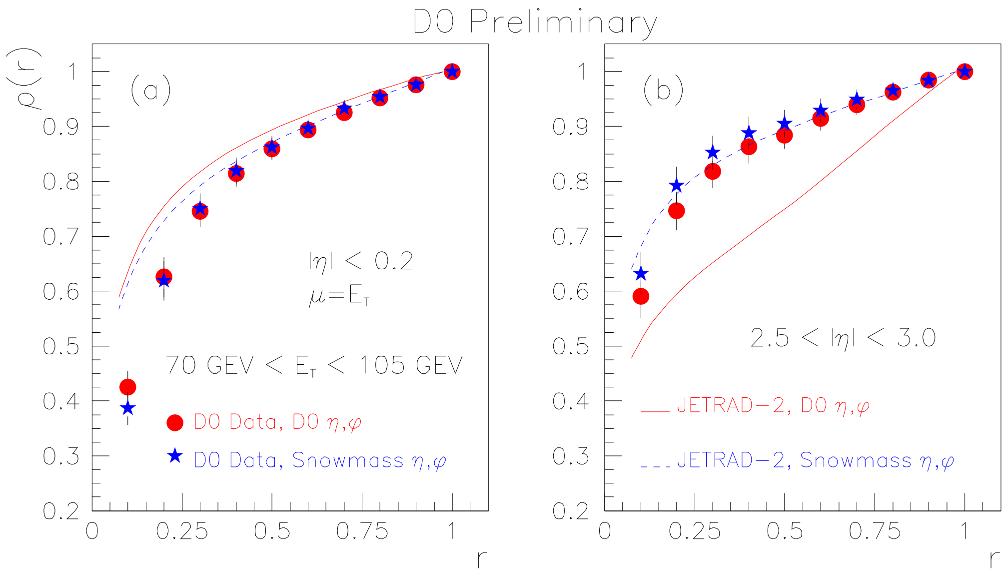
- Method 2 - JETRAD only (Giele et al.)

  -- closest to experimental definition

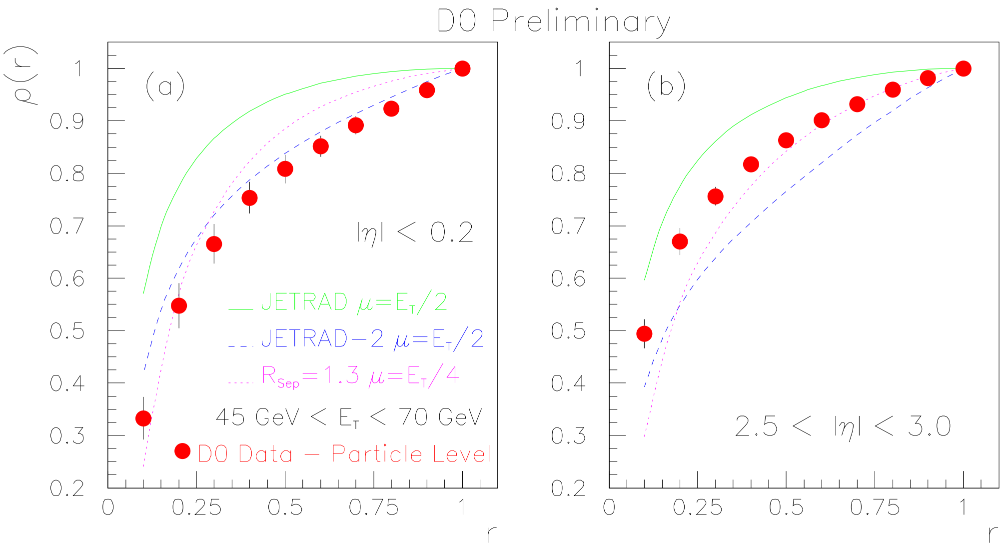
  > if the two partons are within d=1 of each other, then they are clustered into a jet



DØ Jet Shapes - published



DØ Jet Shapes - published



Jet Shapes - Conclusions

- ⋆ **Data Insensitive to jet axis definition**
- ⋆ **HERWIG is narrower than data in central and forward regions, but describes trend of data well**
- ⋆ **NLO Predictions at parton level**
  - **Sensitive to parton clustering algorithm**
  - **Sensitive to jet axis definition**
  - **Should use Snowmass for NLO comparisons**

Color Coherence

In QCD: Interference of soft gluon radiation emitted along color connected particles
$\rightarrow$ want details of hadronic final state and characteristic jet structure

$\rightarrow$ well established in e^+e^- production: suppression of soft g radiation in certain regions

$\rightarrow$ more subtle in hadron-hadron collisions:

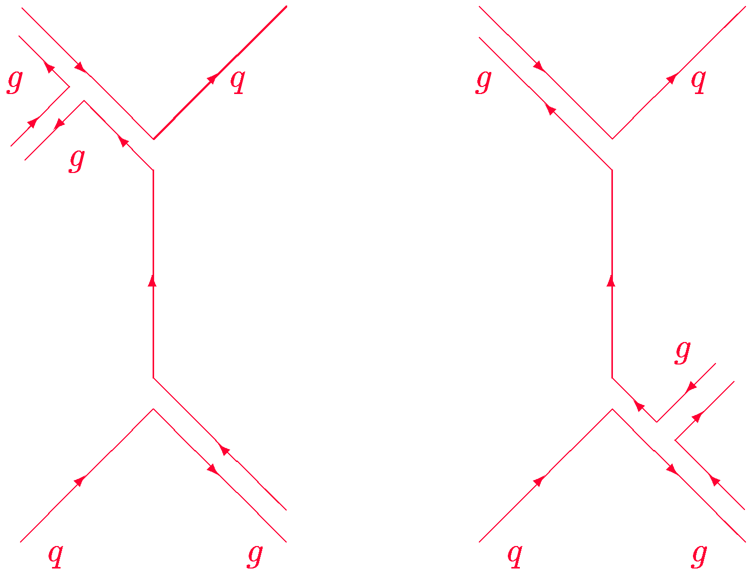
- **have interference effects in initial & final states & between initial and final states**
- **can color coherence effects survive hadronization?**
- **what is relative importance of perturbative vs. non-perturbative contributions?**

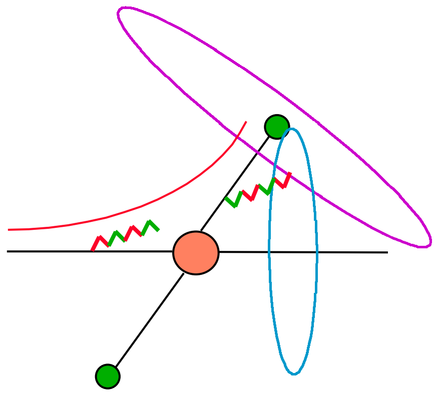
- Color Coherence Multi-jet analysis - PLB **414 (1997) 419.**
- $W+$ **jets analysis - preliminary**
- **DØ contact person: nikos@fnald0.fnal.gov**

Interjet Coherence

$p\bar{p}$ interactions:

- Colored constituents in initial *and* final state (more complicated that e^+e^-)
- Probes initial-initial, final-final and **initial-final** state color interference



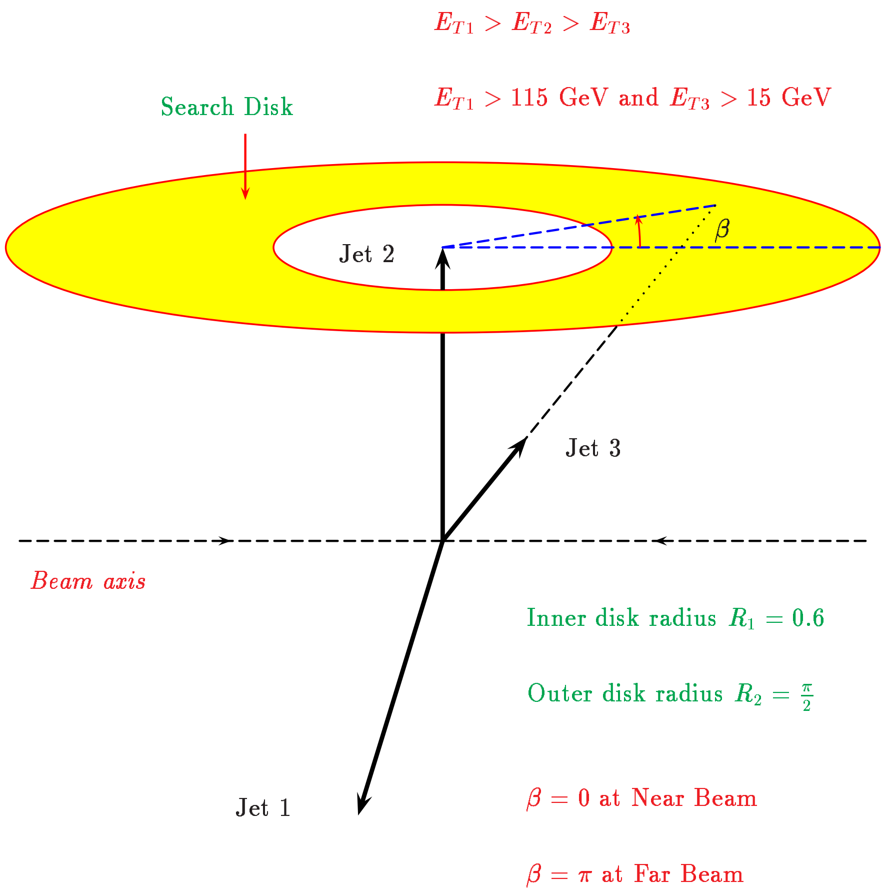


Multijets Results

$p\bar{p} \rightarrow 3\,jets + X$

- Select events with three or more jets

- Measure the angular distribution of "softer" 3rd jet around the 2nd highest E_T jet in the event



- Compare data to several event generators with different color coherence implementations

Monte Carlo Simulations

- Generate high statistics particle/parton level MC samples including detector position and energy resolution effects

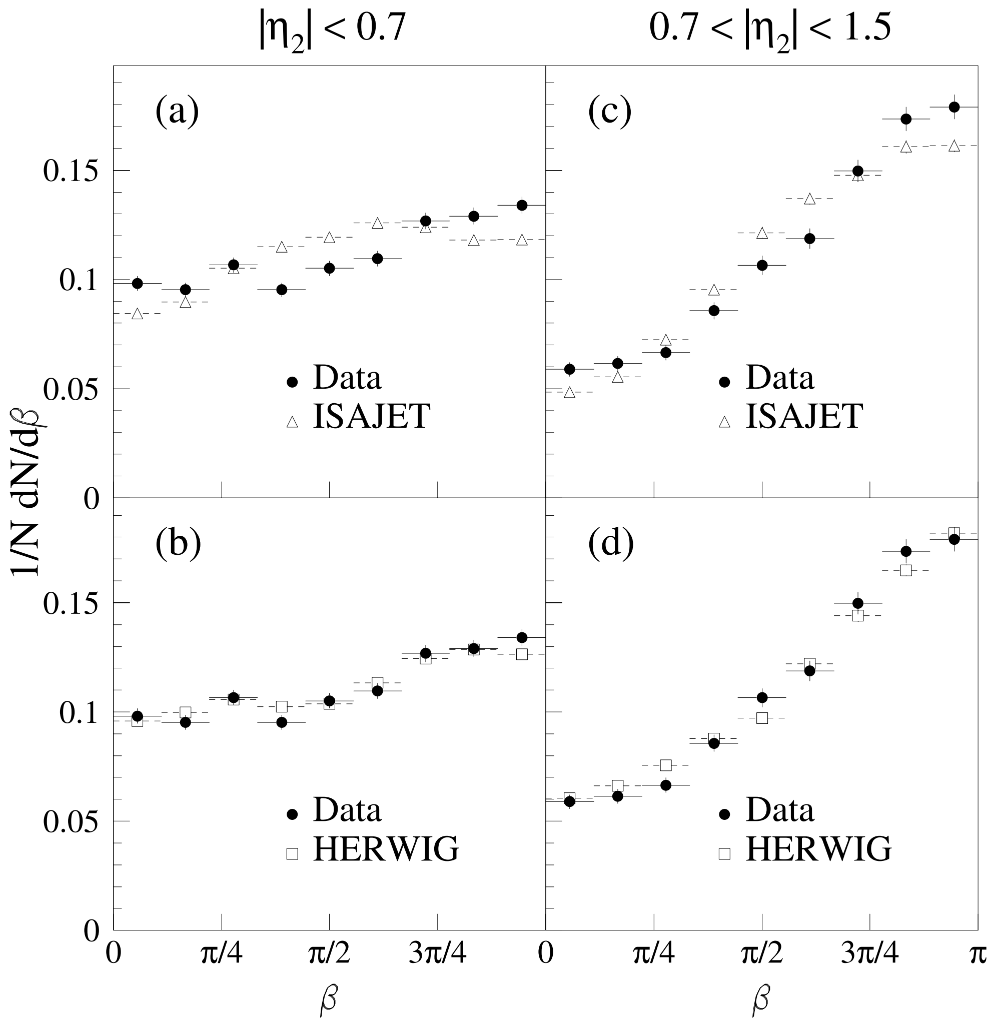
• **Shower-level event generators**:

- ISAJET v7.13
  - Does not include color coherence effects
  - Independent fragmentation
- HERWIG v5.8
  - AO approximation
  - Cluster fragmentation
- PYTHIA v5.7
  - AO approximation (no azimuthal correlations for ISR)
  - AO may be turned off
  - String or independent fragmentation

• **Parton-level pQCD calculation**:

- JETRAD v1.1
  - $O(\alpha_s^3)$ parton level, one loop $2 \rightarrow 2$, tree level $2 \rightarrow 3$ scattering amplitudes
  - No fragmentation

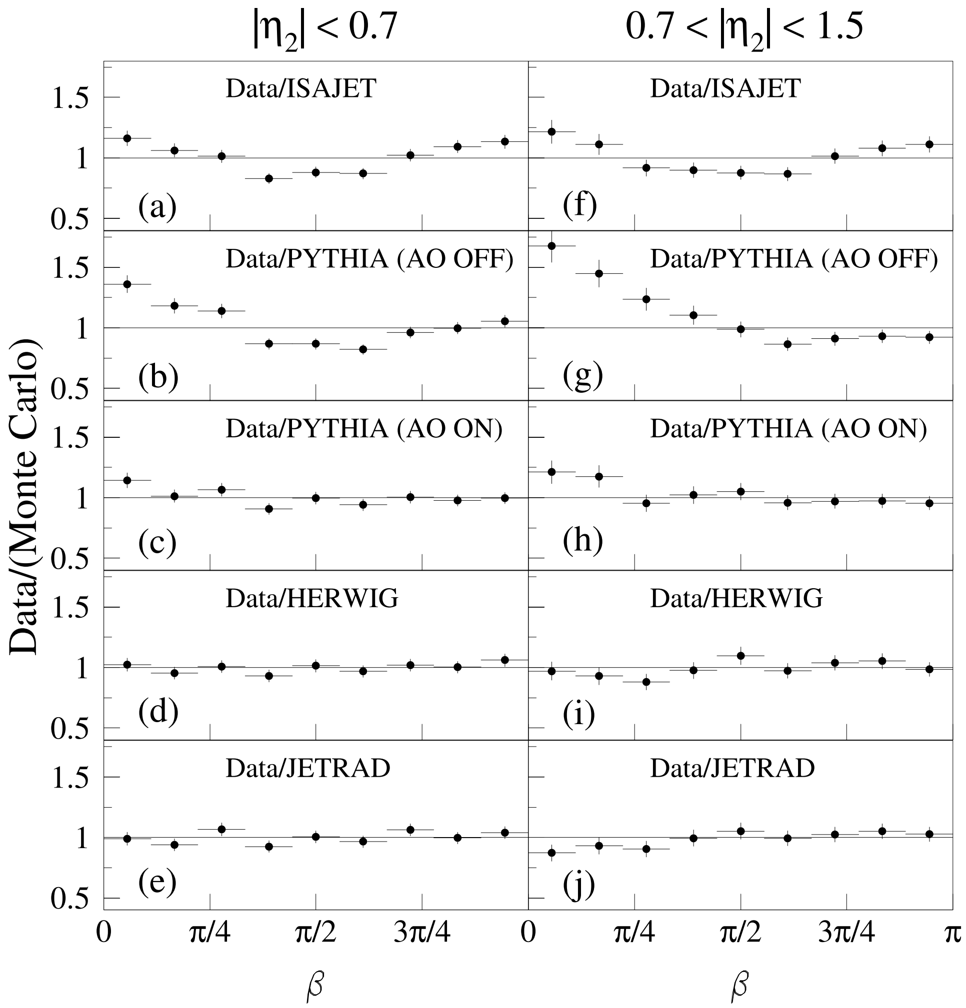
3–jet β distributions



HERWIG agrees with the data distributions

Color Coherence: Multi-Jet Analysis

3–jet Data/Monte Carlo



- HERWIG and JETRAD agree best with the data
- MC models w/o CC effects disagree with the data

Color Coherence: W+jet Events Analysis

- **around W, expect angular distribution of soft gluons to be uniform**
- **around jet, expect to have structure**

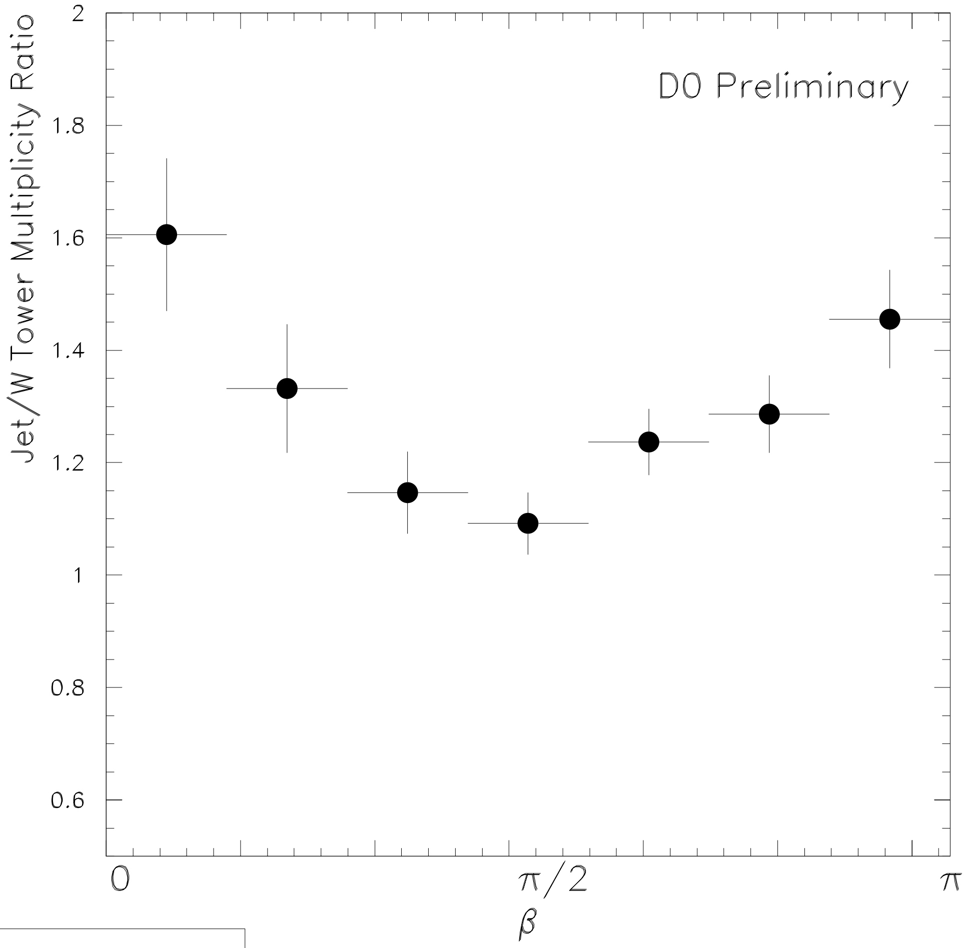
find W, select leading E_T jet in ϕ opposite W

- **measure multiplicity of calorimeter towers above $250\ \mathrm{MeV}$ in ring around jet or W from $.7 < R < 1.5$**
- **expect enhancement of multiplicity around jet in event plane vs. transverse plane (compared to W)**

Prediction by Khoze and Stirling: hep-ph/9612351
$\rightarrow$ parton cascade evolved much further than traditional QCD

W+Jet Results

D0 Preliminary



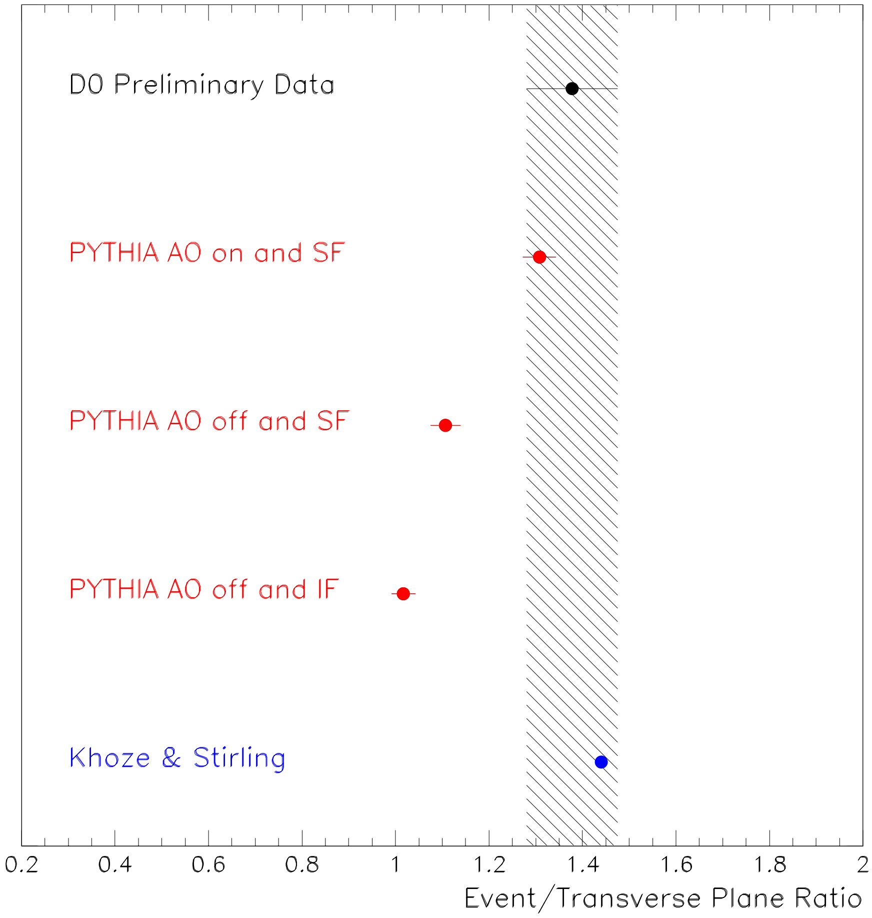
Near beam

Far beam

$N^{JET}_{TWR} / N^{W}_{TWR}$ vs. β

W+Jet Results

$$\text{Event/Transverse Plane Ratio} = \frac{\text{Jet/W } (\beta=0+\pi)}{\text{Jet/W } (\beta=\pi/2)}$$



PYTHIA w/ AO & SF ***AND*** MLLA+LPHD agree with Data

Direct Photons

$\rightarrow$ **probes for hard parton interactions w/o fragmentation effects**

$\rightarrow$ **dominant production modes are**
$q + g \rightarrow \gamma + q$ **and** $q + \bar{q} \rightarrow \gamma + g$

$\rightarrow$ **give information on:**

- **intrinsic p_T (k_T) $\rightarrow$ measure contribution from higher order corrections, especially multiple soft gluon emission**
  (di-photon)
- **gluon PDF sensitivity at low x**
  (inclusive γ spectrum)
- **matrix elements**
  (angular distribution)

$\Rightarrow$ Analysis based on Run 1A data sample (published)
- PRL 77 (1996) 5001.

$\Rightarrow$ Preliminary results based on Run 1B data
- PRL in progress

$\Rightarrow$ DØ contact person: womersley@fnal.gov

Direct Photons - Data Analysis

Basic Strategy:

Use calorimeter to measure energy AND require no matching track in chamber

- calorimeter EM towers are 0.1×0.1 in $\Delta\eta \times \Delta\phi$ (0.05×0.05 at shower max)
- calorimeter-based trigger towers 0.2×0.2 in $\Delta\eta \times \Delta\phi$
- $\frac{\sigma_E}{E} = \frac{15\%}{\sqrt{E}} \oplus .3\%$
- 20 radiation lengths
- 4 longitudinal layers
- range out to $|\eta| < 4$

Data Collection & Reconstruction:

$\Rightarrow$ L1 trigger required a trigger tower with $E_T > 2.5, 7, 10$ GeV

$\Rightarrow$ L2 trigger imposed shower shape requirements and EM cluster of cells with $E_T > 6, 14, 30$ GeV

$\Rightarrow$ Reconstruction Cuts

- shower shape
- acceptance
- fraction of energy in EM calorimeter $> 95\%$
- no track in region 0.2×0.2 around EM cluster
- isolation: $E_T < 2$ GeV in region between 0.2 to 0.4 around γ

Direct Photons - Photon Purity

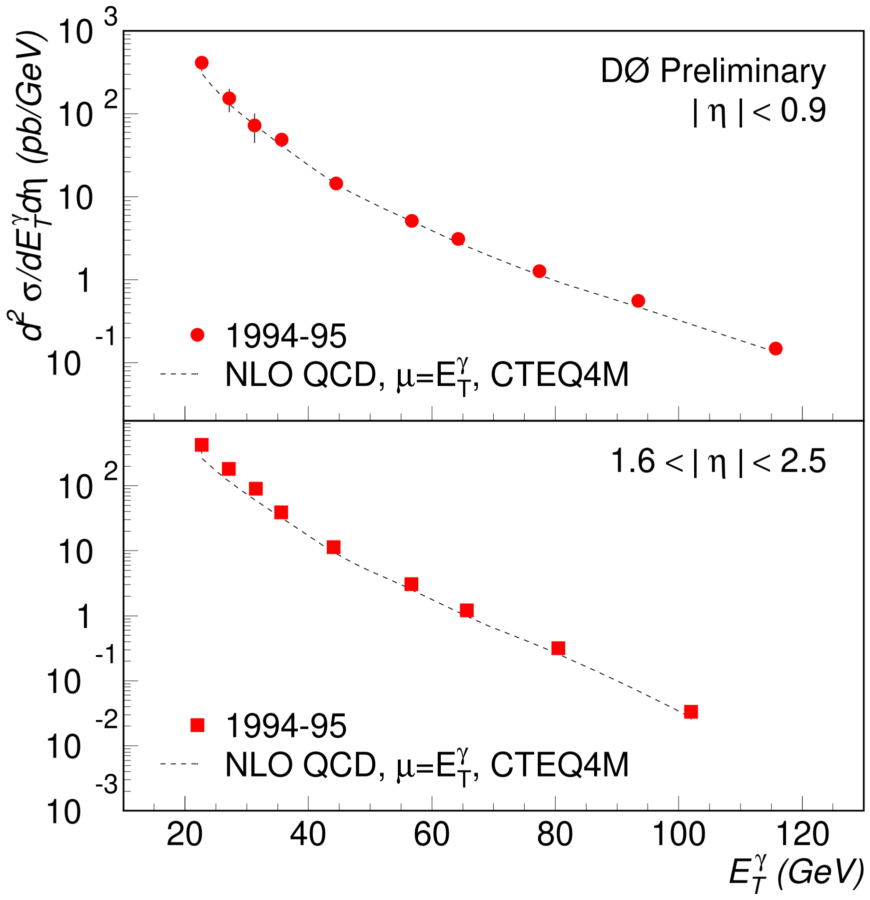
Must extract direct-γ signal out of π^0 and η background from QCD jets

- probability of a jet fluctuating to π^0 or η which carries most of the jet E_T is $\approx 10^{-3}$ ... but jet x-sect is $> 10^3$ greater so this bkgnd can be large!
- for meson $E_T > 10$ GeV, the 2 γ's coalesce
- model purity of signal using MC and the longitudinal segmentation of the calorimeter
  $\rightarrow$ differences in shower profile for direct γ and mesons

New DØ Measurement of the Direct Photon Cross Section

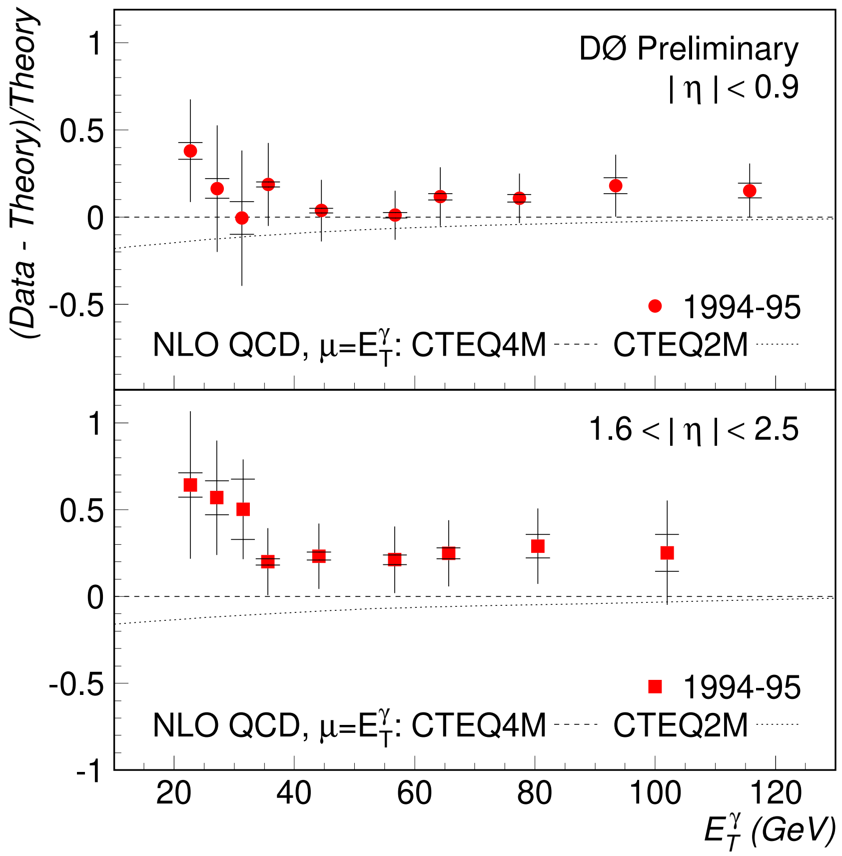
95 pb^{-1} from 1994–95 run

Isolated photon cross section $d^2\sigma/dE_T^\gamma d\eta$:



New DØ Measurement of the Direct Photon Cross Section

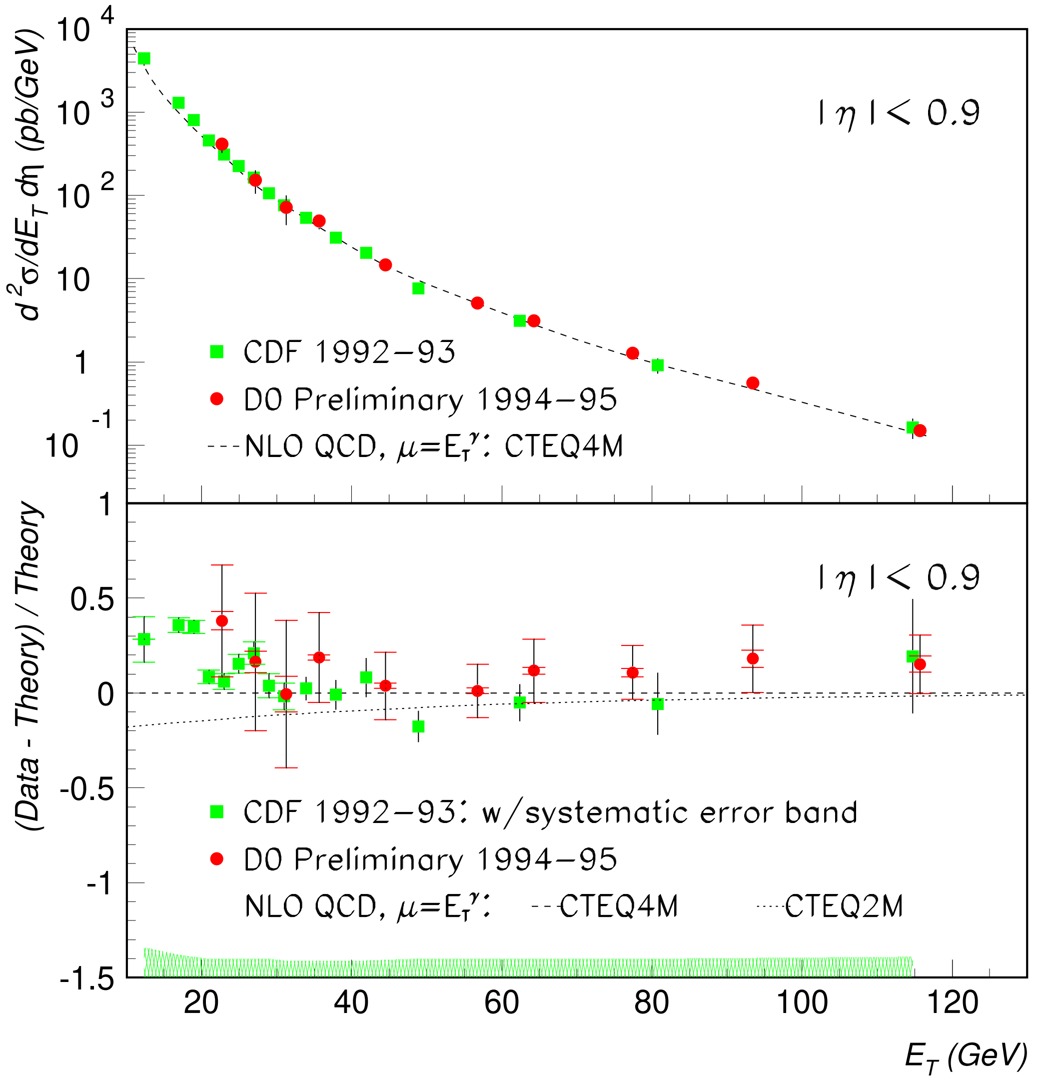
95 pb^{-1} from 1994–95 run



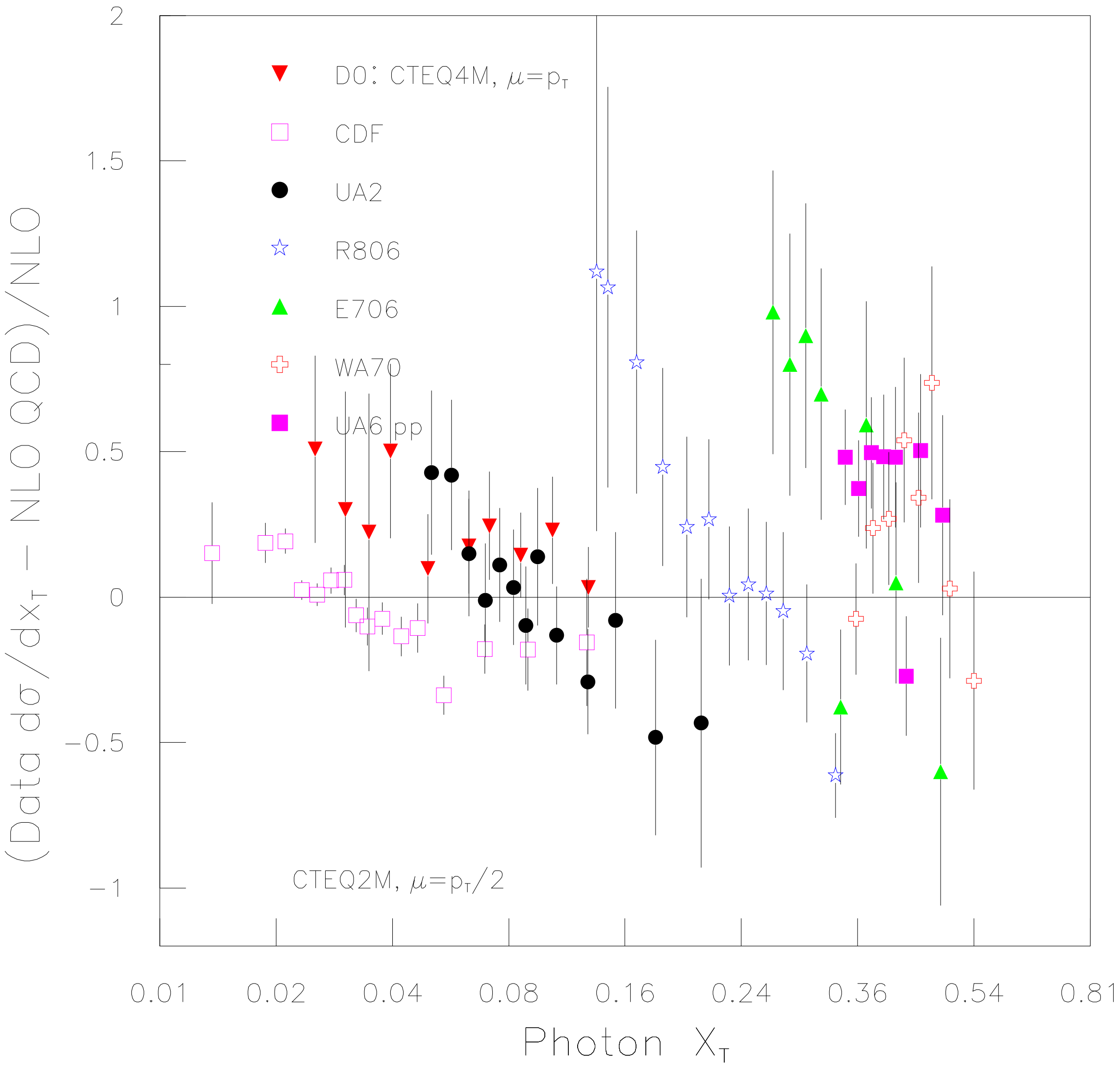
Systematic errors at 40 GeV: purity estimation = 16%, jet modeling = 9%, luminosity = 5%, efficiencies = 3%.

Data are consistent with QCD prediction (Baer, Ohnemus & Owens) over the whole range of E_T^γ.

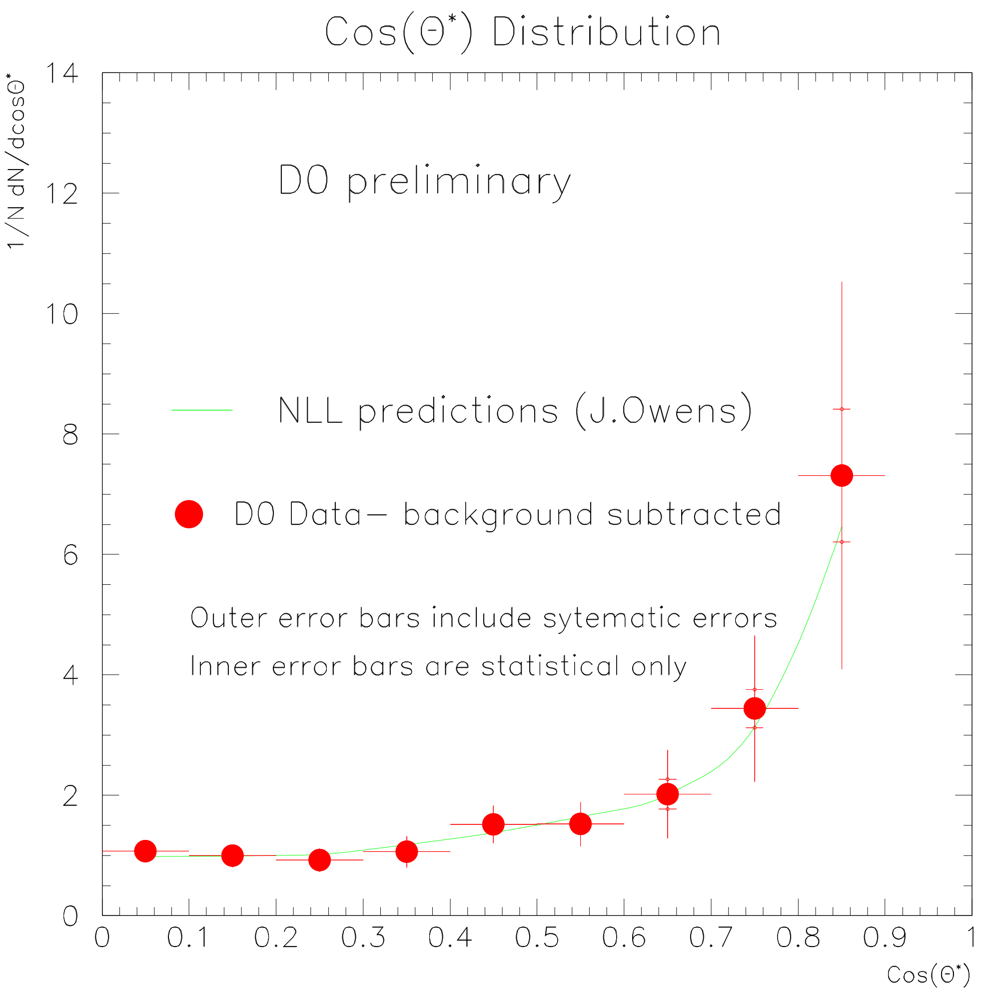
DØ and CDF Direct Photon Cross Section



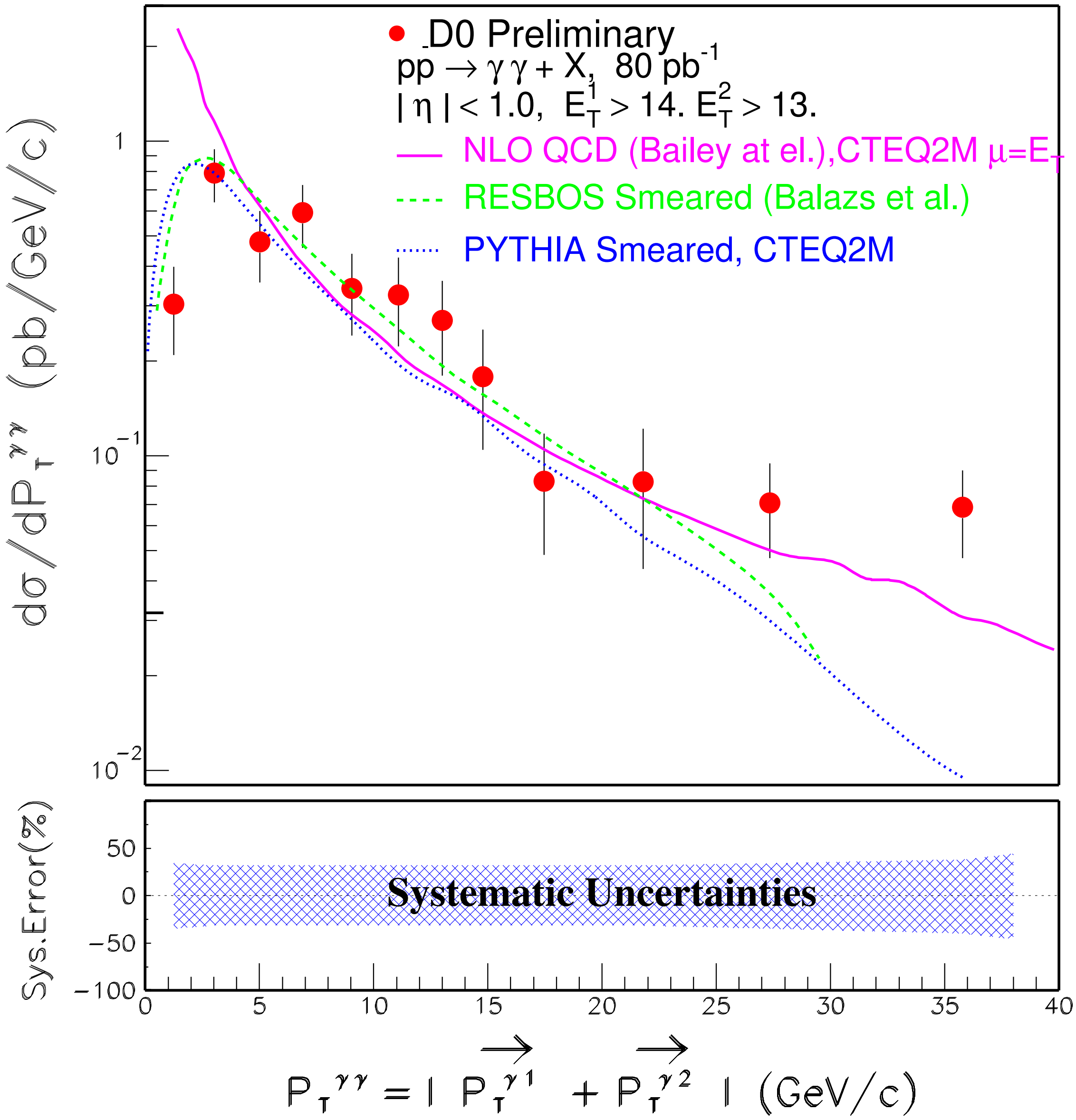
Direct Photon Cross Section



Photon + Jet Angular Distribution



Di-Photon p_T Spectrum



Direct Photons - Conclusions

- **Inclusive Spectrum**
  Consistent with NLO QCD ... but all data shows trend away from predictions - especially at low p_T where data is above prediction
  $\rightarrow$ effect of k_T (soft gluons)? OR
  $\rightarrow$ modification of fragmentation required?
  $\star$ Still unanswered question!!
  (NLO Predictions from PRD42 (1990)61)
- **γ-Jet Angular Distribution**
  Agrees with NLO (NLO Predictions from PRD42 (1990)61)
- **Di-Photon Spectrum**
  Shows deviation from NLO at low p_T. Predictions which add in multiple gluon emission (Pythia or resummed QCD calc.) are consistent with data
  (NLO: PRD46(1992)2018, Resbos: hep-ph/9704258)

Summary

Lots of Other Data Analyses!

- **Multi-jet correlations (published)**
- **Jets with k_T algorithm (prelim)**
- **triple differential cross section (prelim)**
- **Jet Multiplicities (prelim)**
- **Diffractive production (published + other results pending)**
- **Cross Section vs. Jet cone size**
- **Cross Section vs. η**

Just check out the WWW pages!

Look forward to exciting data here at RHIC! $\rightarrow$ Hope these Tevatron results can help us.