QCD at the Tevatron: The Production of Jets & Photons plus Jets

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for the

CDF and DØ Collaborations

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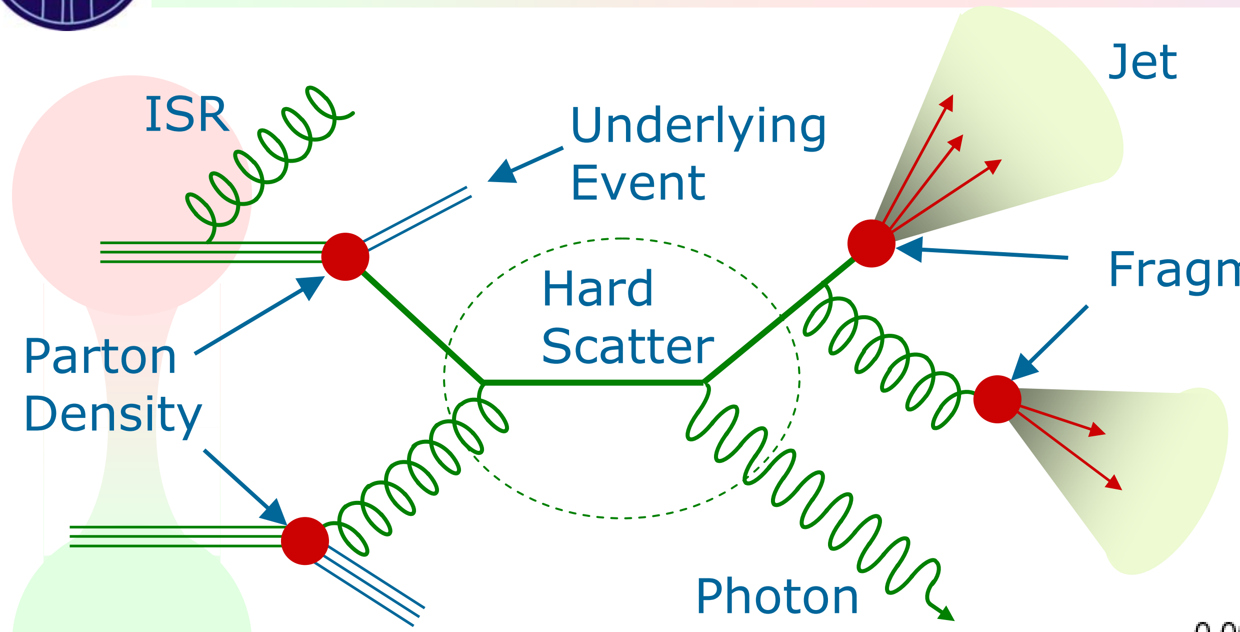
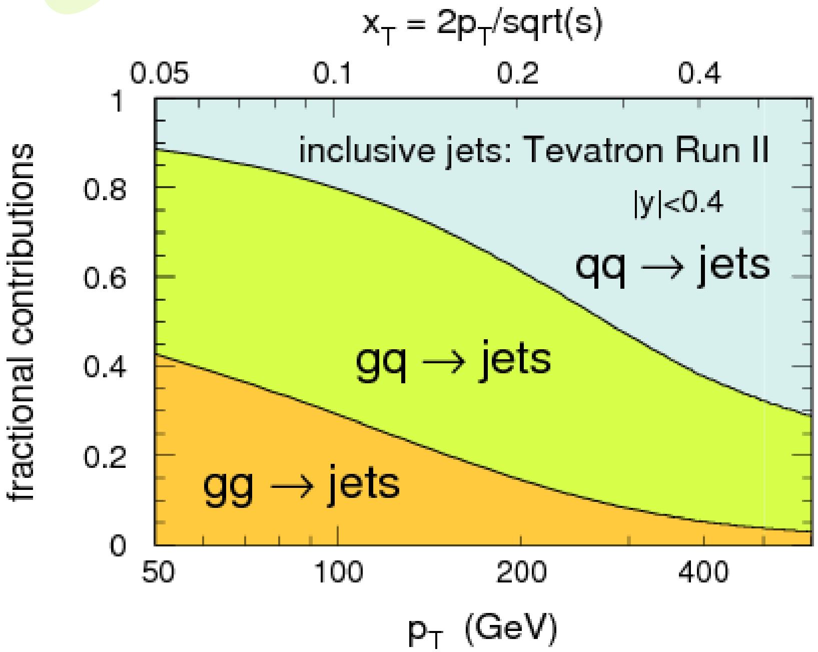
Outline

- Introduction to
  - QCD physics
  - The Tevatron and Detectors
  - Jet measurement issues
- Results
  - Jets
  - Photons plus jets

QCD Scattering Processes



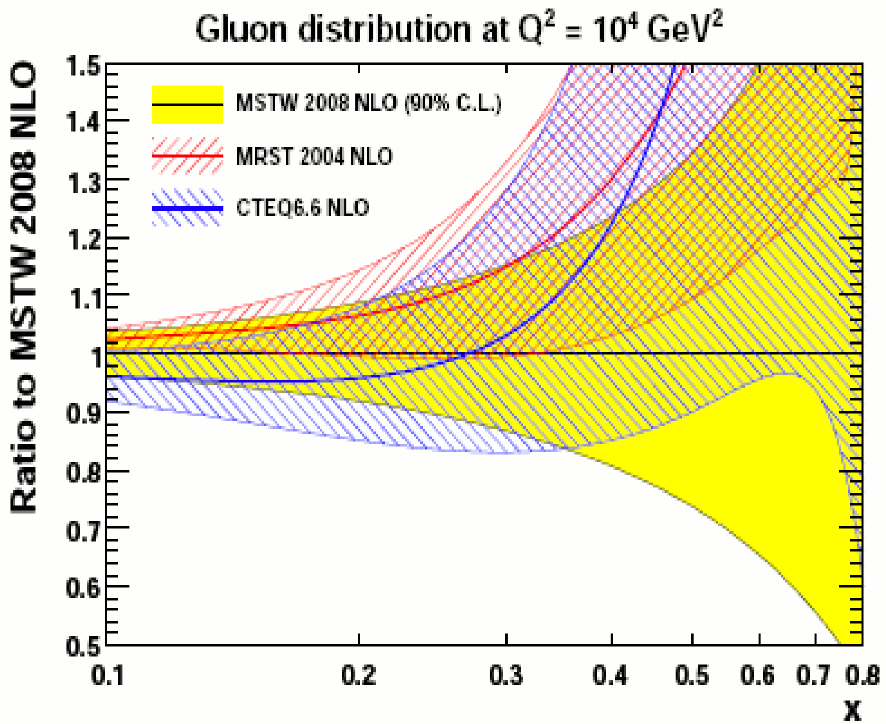
- Jets of particles originate from hard collisions between quarks and gluons
- Quark and gluon density described by Parton Distribution Functions (PDFs)
- Proton remnants form underlying event



Why Look at Jet Physics?

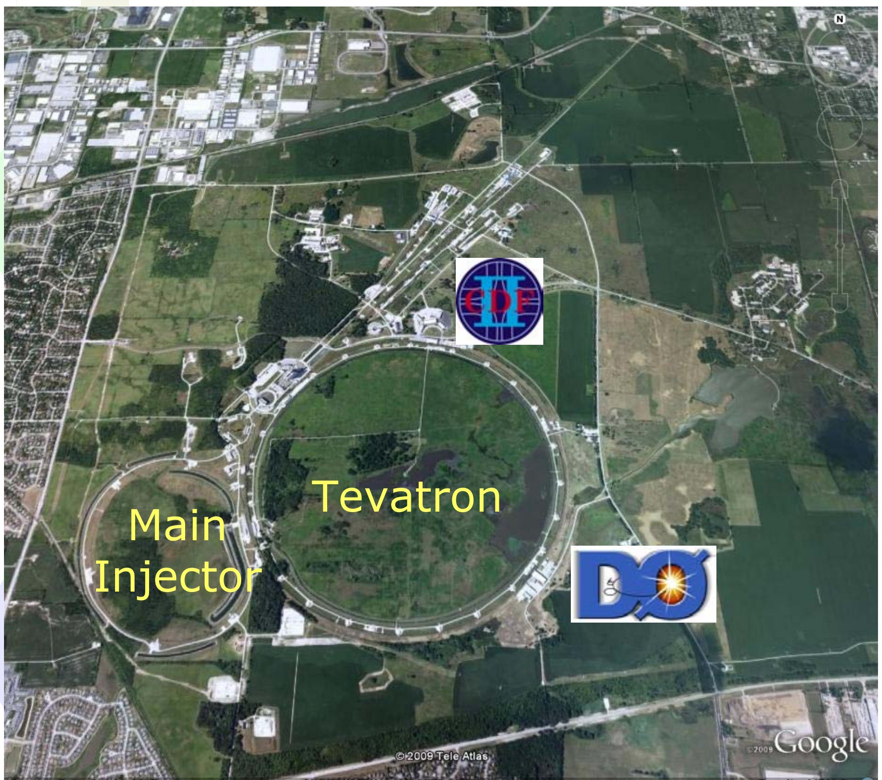
Measurements of large p_T processes with jet final states:

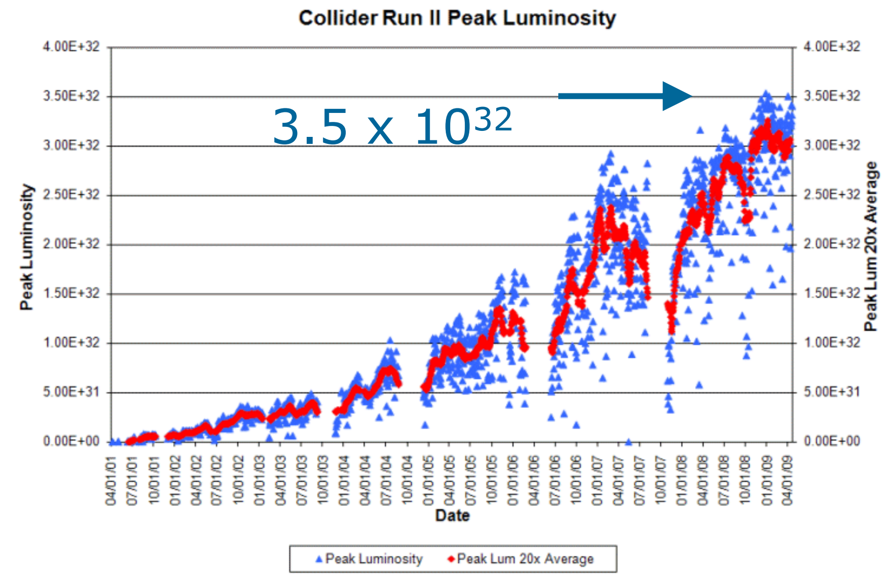
- Are the dominant process at hadron colliders
- Allow precision tests of pQCD
- Constrain PDFs, fragmentation, and α_s
  - Crucial to understand as background to other processes
- Are sensitive to new physics including quark substructure and heavy particles

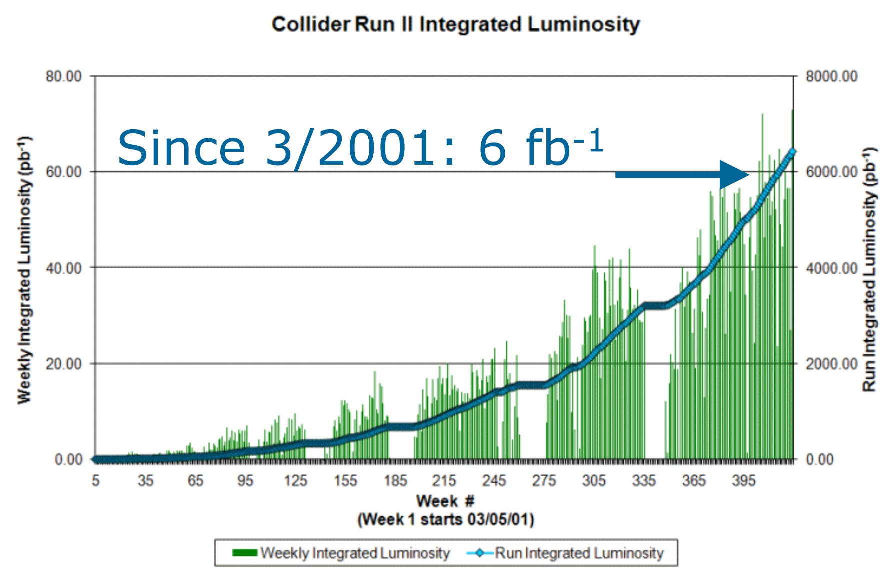


The Tevatron

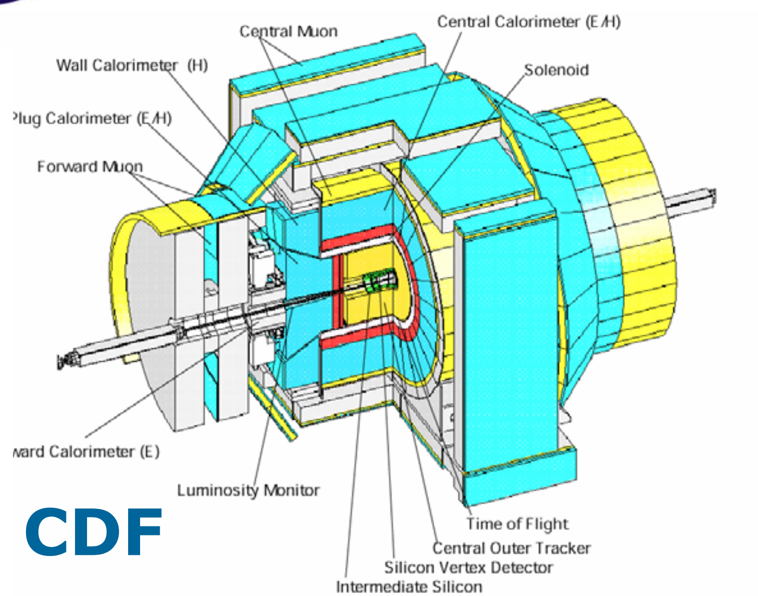
- $\sqrt{s}$ = 1.96 TeV
- Peak Luminosity: 3.5×10^{32} $cm^{-2}s^{-1}$
- Over 6 fb^{-1} delivered
- Experiments typically collect data with 80-90% efficiency





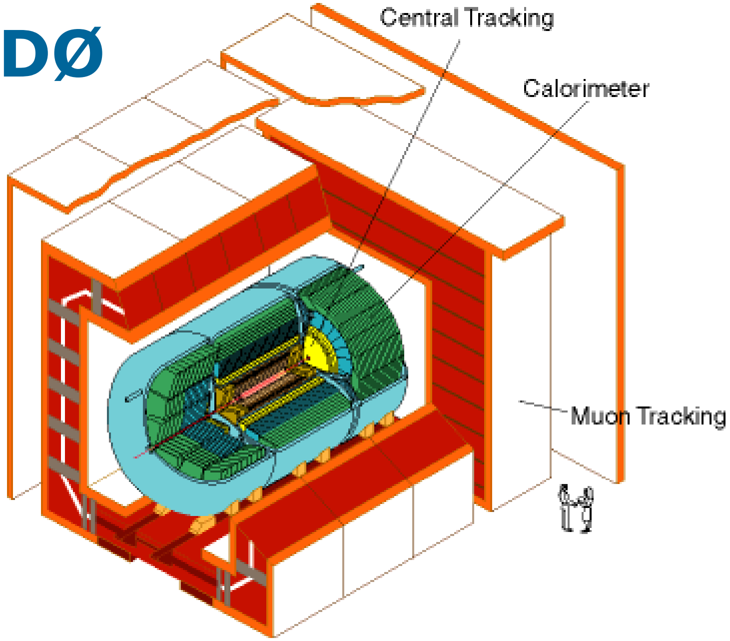


The Detectors

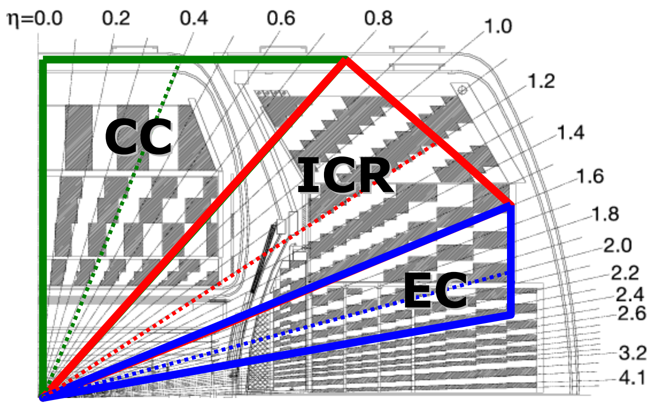


CDF

DØ



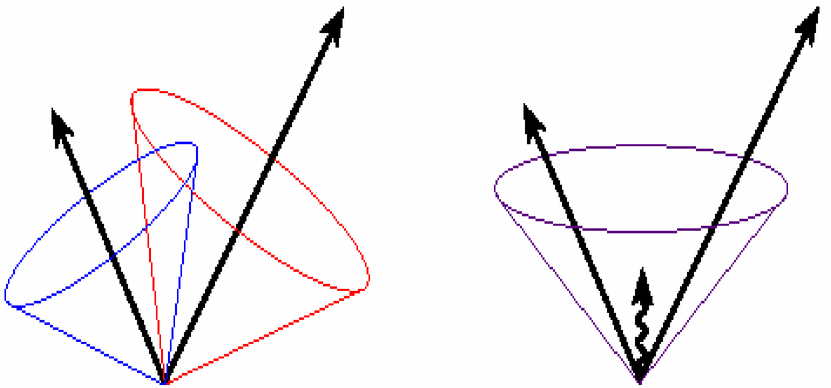
- Common features
  - Magnetic trackers with silicon vertexing
  - electromagnetic and hadronic calorimeters
  - muon systems
- Distinctive features
  - CDF has better track momentum resolution and displaced track triggers at Level 1
  - DØ has finer calorimeter segmentation and a muon system extending farther forward.



DØ calorimeter and pseudorapidity segmentation

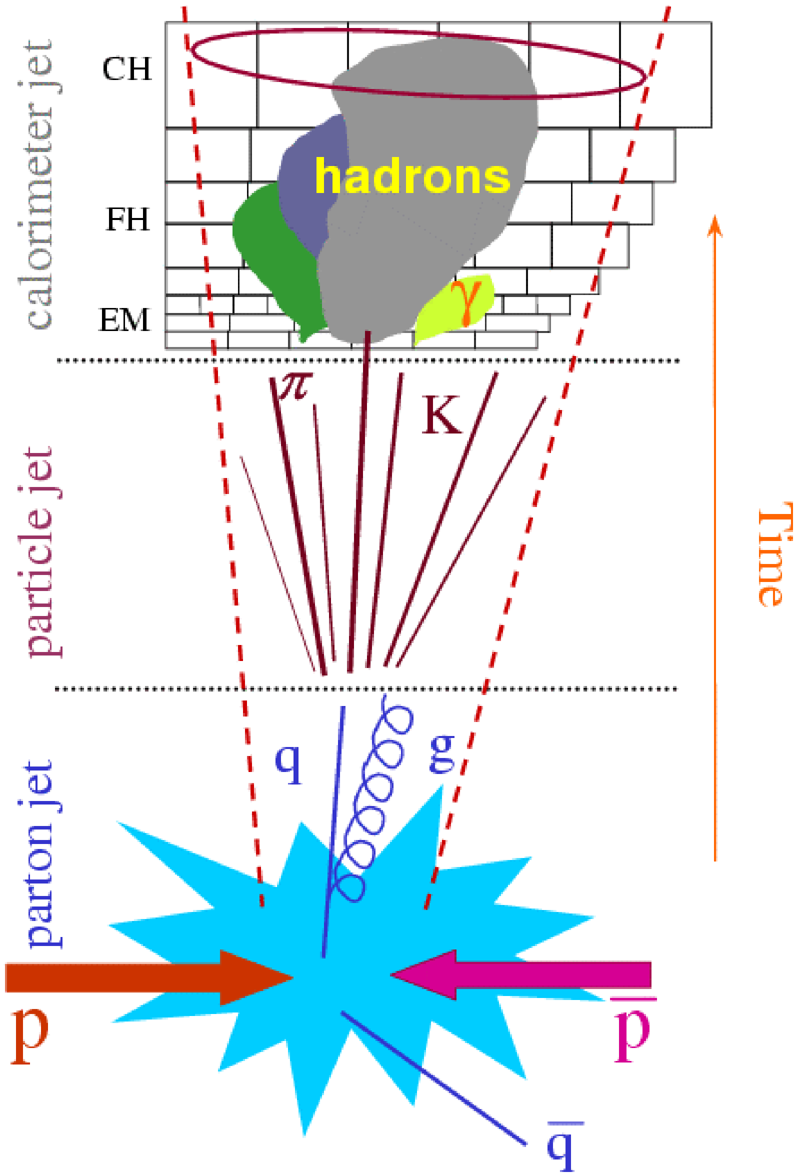
Defining Jets

- Run II cone algorithm:
  - Start with seed
  - Add particles with energy in a cone around seed:
    - $\Delta R = \sqrt{(\Delta\eta^2+\Delta\Phi^2)} < R_{cone}$
  - Merge jets if overlap
    - Some differences in DØ and CDF merging, etc.
- Other methods (such as the k_T algorithm) can also be used but not are not used in any of the analysis described today



Jets, Particles, and Partons

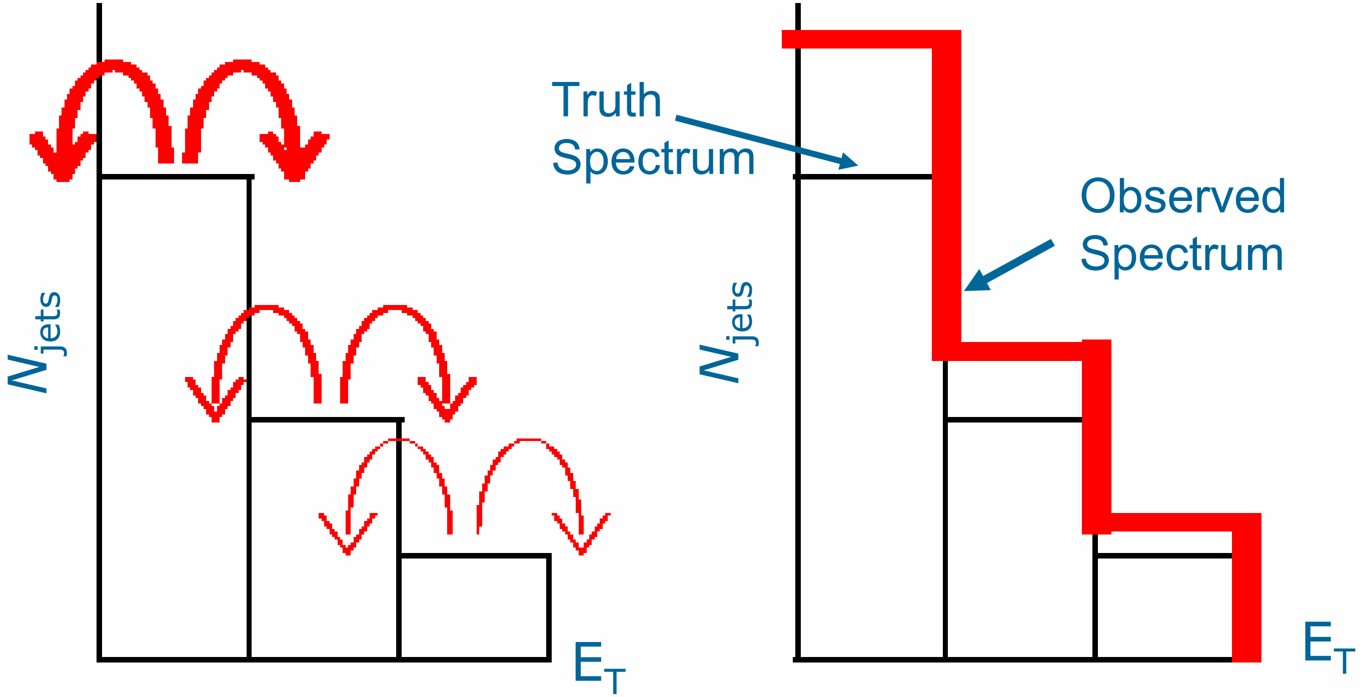
- We do not see partons or particles
- Calorimeter ADC counts are corrected to the particle level using the Jet Energy Scale (JES)
- Calibrate using *Z*+jets, *γ*+jets, dijets
- JES can include
  - Energy Offset (energy not from the hard scattering process)
  - Detector Response
  - Out-of-Cone showering
  - Resolution
- Energy scale uncertainties typically are the largest systematic errors in jet measurements.
- Correction to parton level requires fragmentation model



Resolution and Unsmearing

Many measured distributions are steeply falling

- Due to finite resolution of the detector, higher bins are preferentially populated
- Unsmearing (unfolding) corrects for this effect
- Different unsmearing methods are used

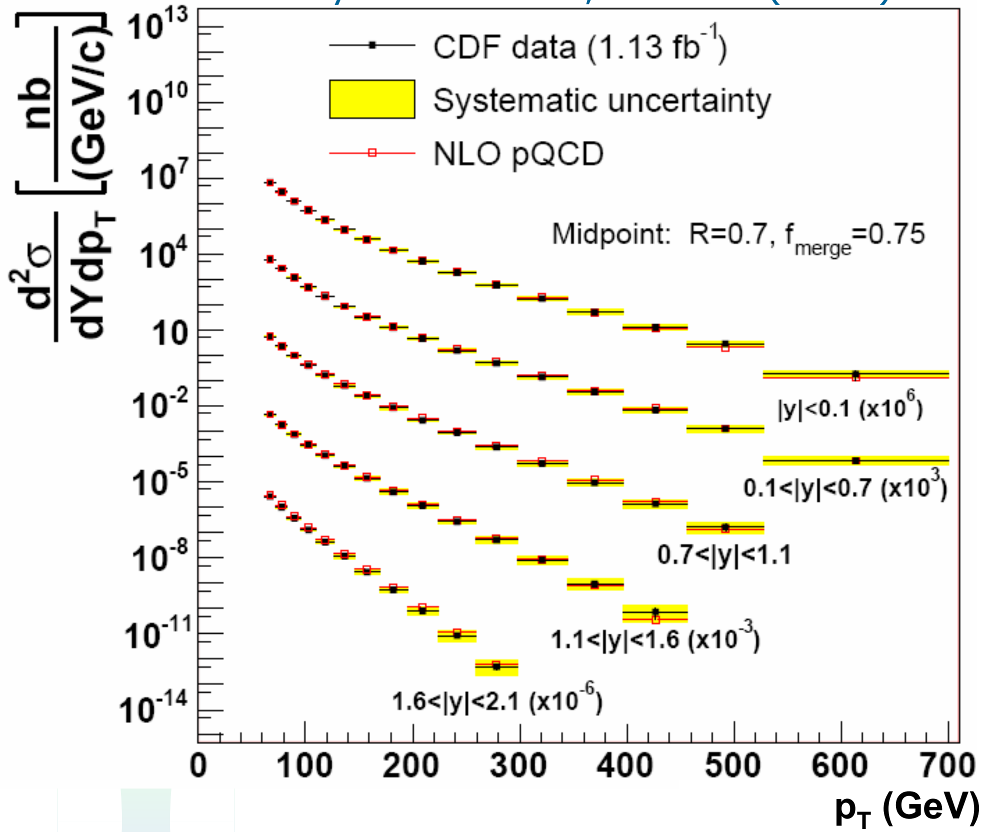


Analyses to Discuss

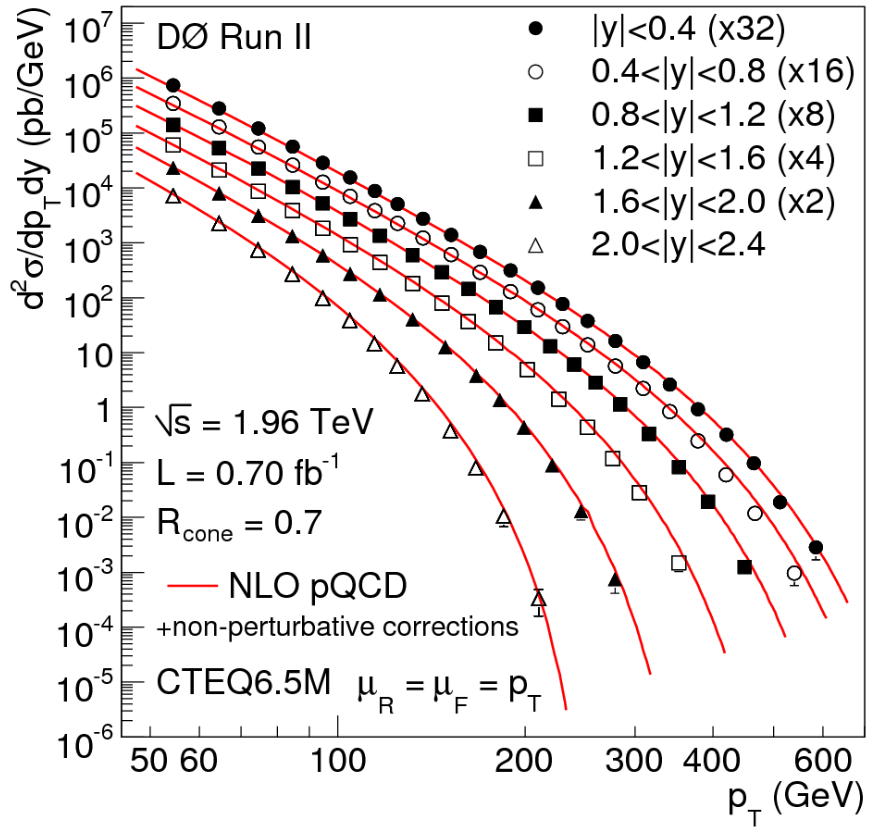
- Production of Jets
  - Inclusive Jet Production Cross Section
  - Dijet Mass Production Cross Section
  - Dijet Angles
- Production of Photons Plus Jets
  - Inclusive Photon Production Cross Section
  - Photon plus Jets Production Cross Section
  - Production of Photons plus Heavy Flavors
  - Double Parton Scattering

Inclusive Jet Production

Phys. Rev. D 78, 052006 (2008)



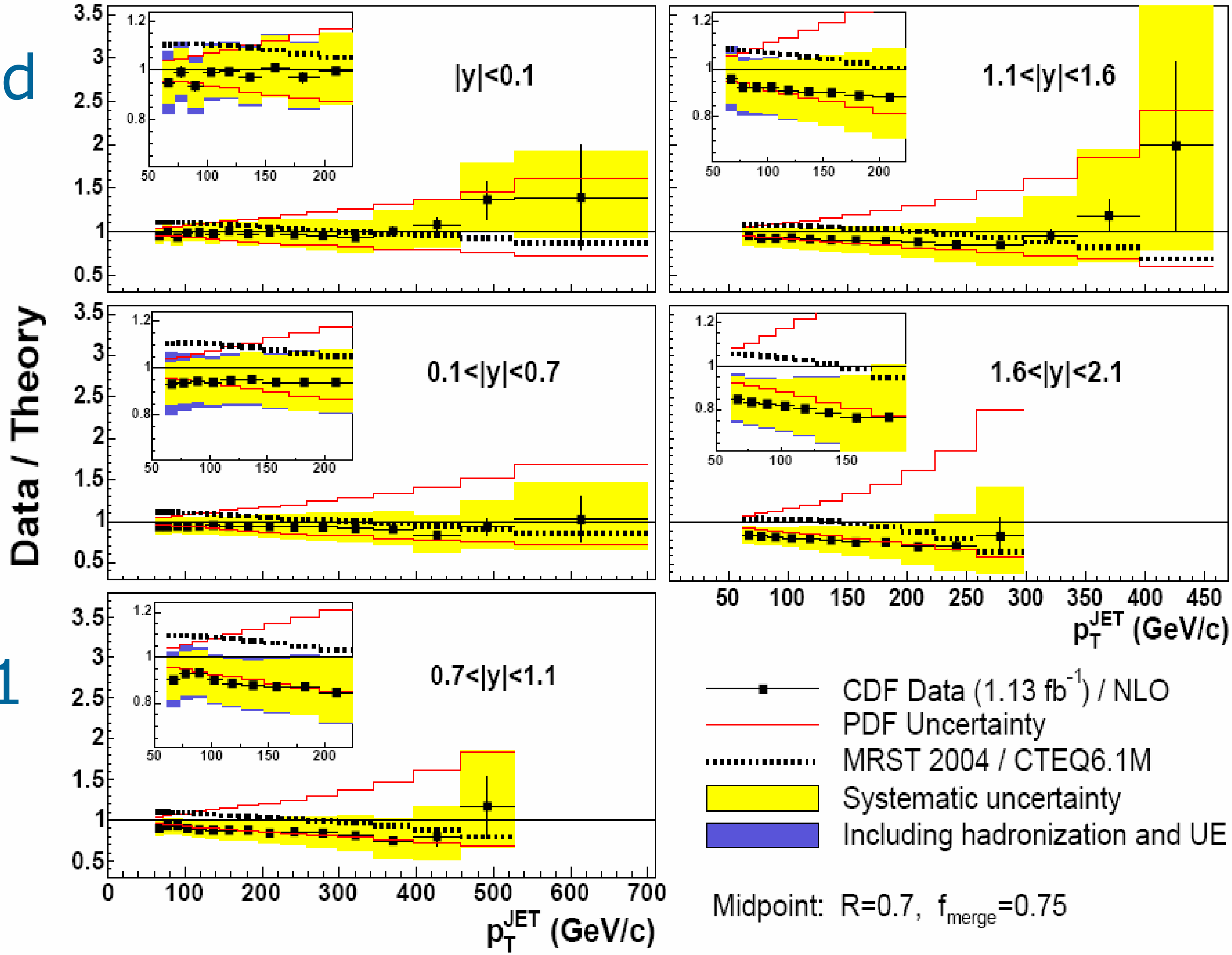
PRL 101, 062001 (2008)



- Large amount of data
- Measurement over large rapidity region up to high p_T

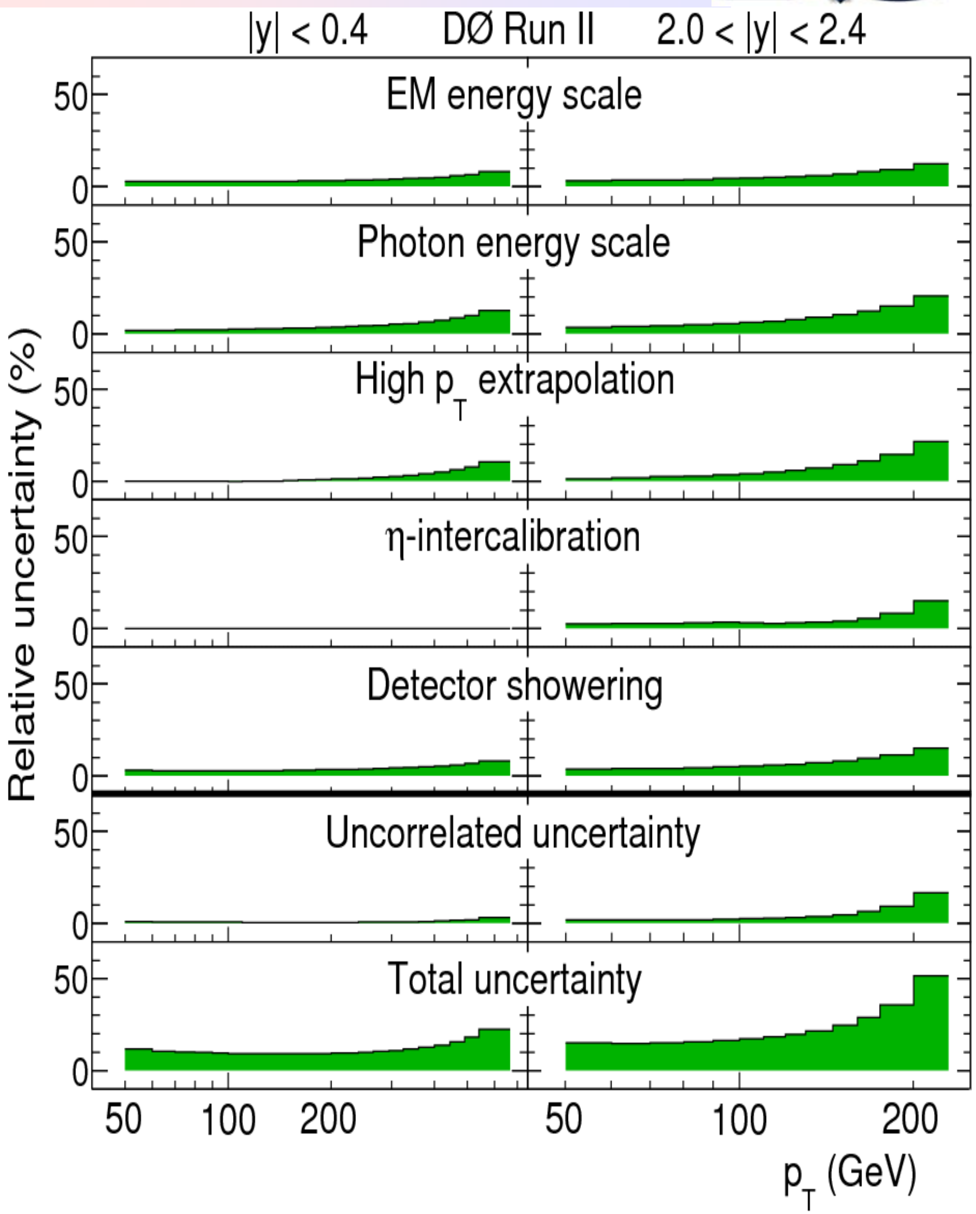
CDF Data/Theory

- Data and theory agree
- Data favors the lower edge of CTEQ6.1 at high p_T

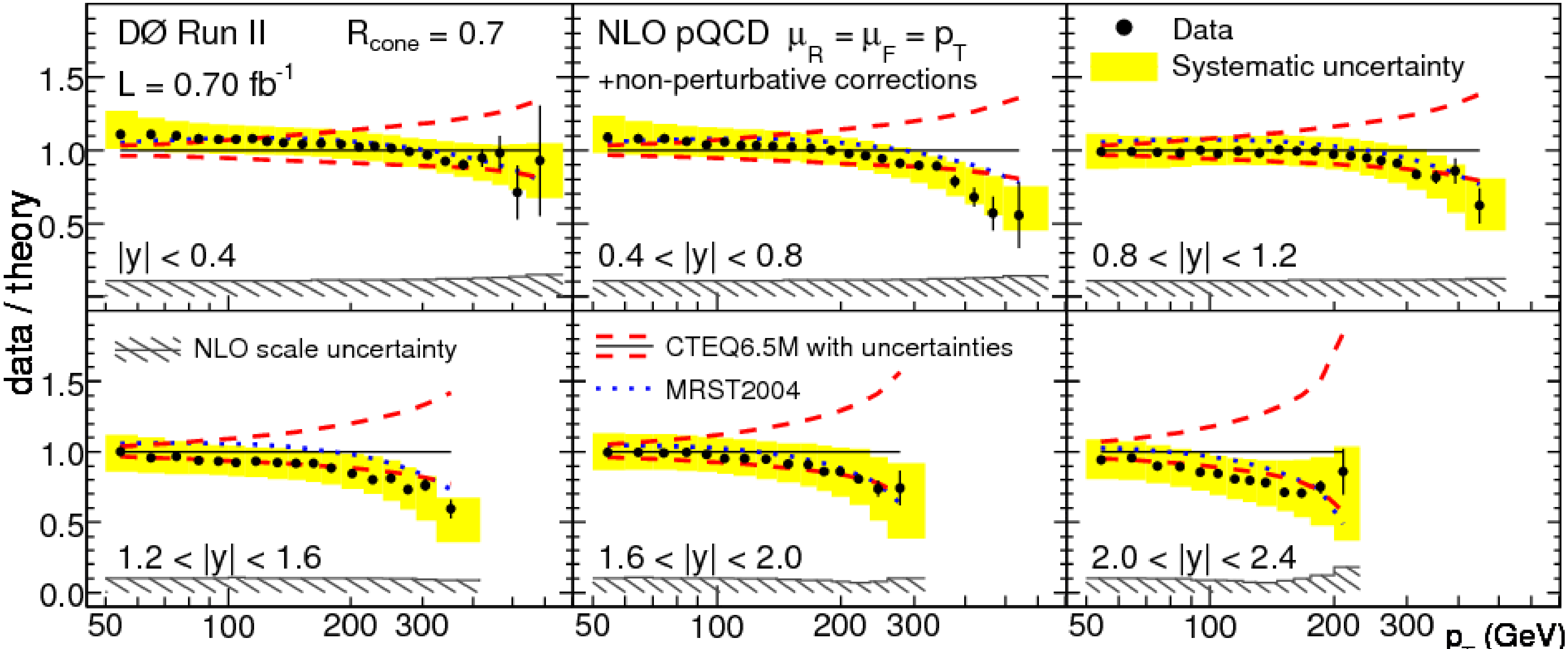


Uncertainty & Correlations

- Leading sources of uncertainty are from JES
  - The DØ uncertainties are improved by up to a factor of two in the central region since 2006
- Uncertainties that are 100% correlated can only change measurement normalization
  - Only 5 highest out of 23 correlated uncertainties are shown.

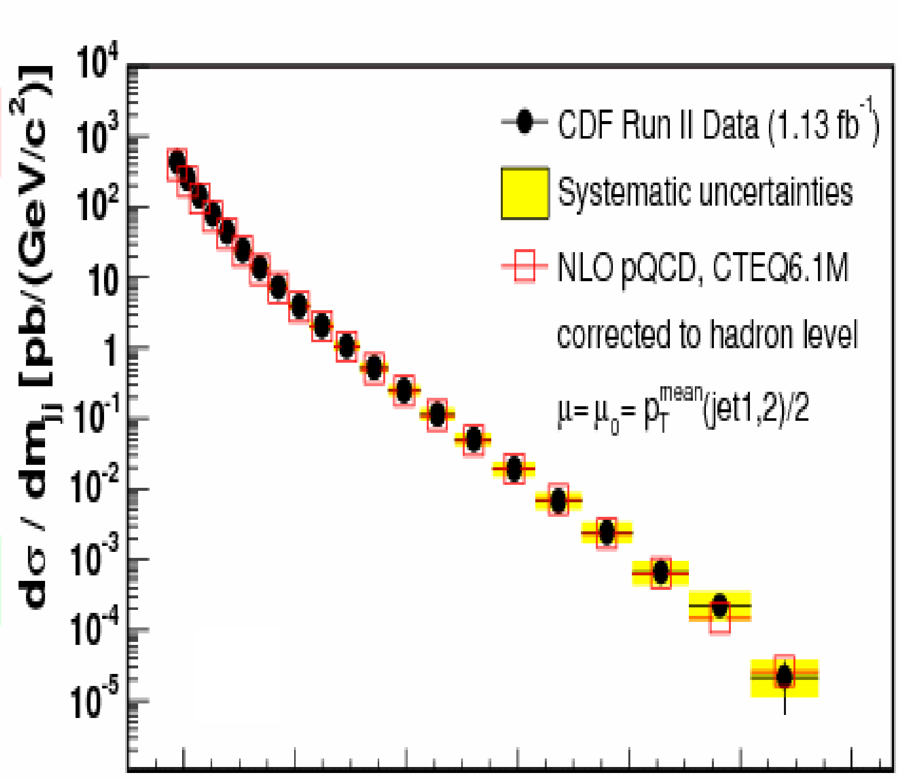


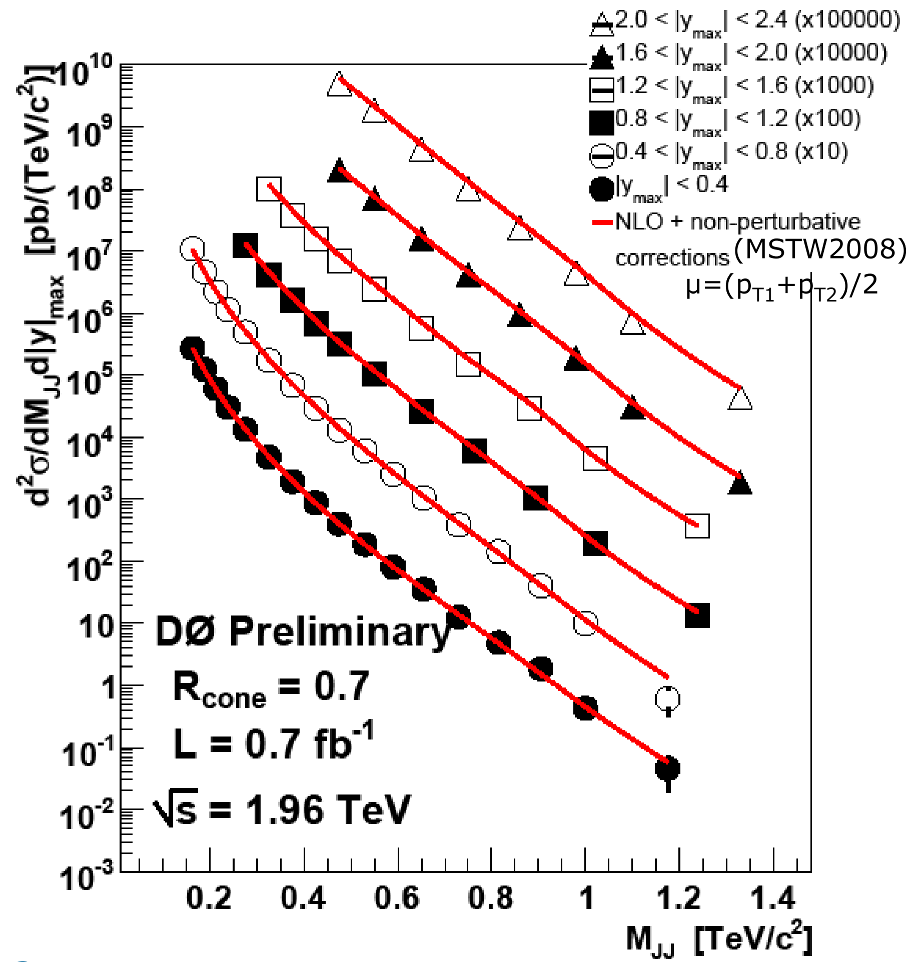
DØ Data/Theory



- CDF/DØ are consistent & well-described by NLO pQCD
- Experimental uncertainties are less than PDF uncertainties
  - CTEQ6.5 reduced PDF uncertainties by about a factor of 2 compared to CTEQ6.1

Dijet Mass Cross Section

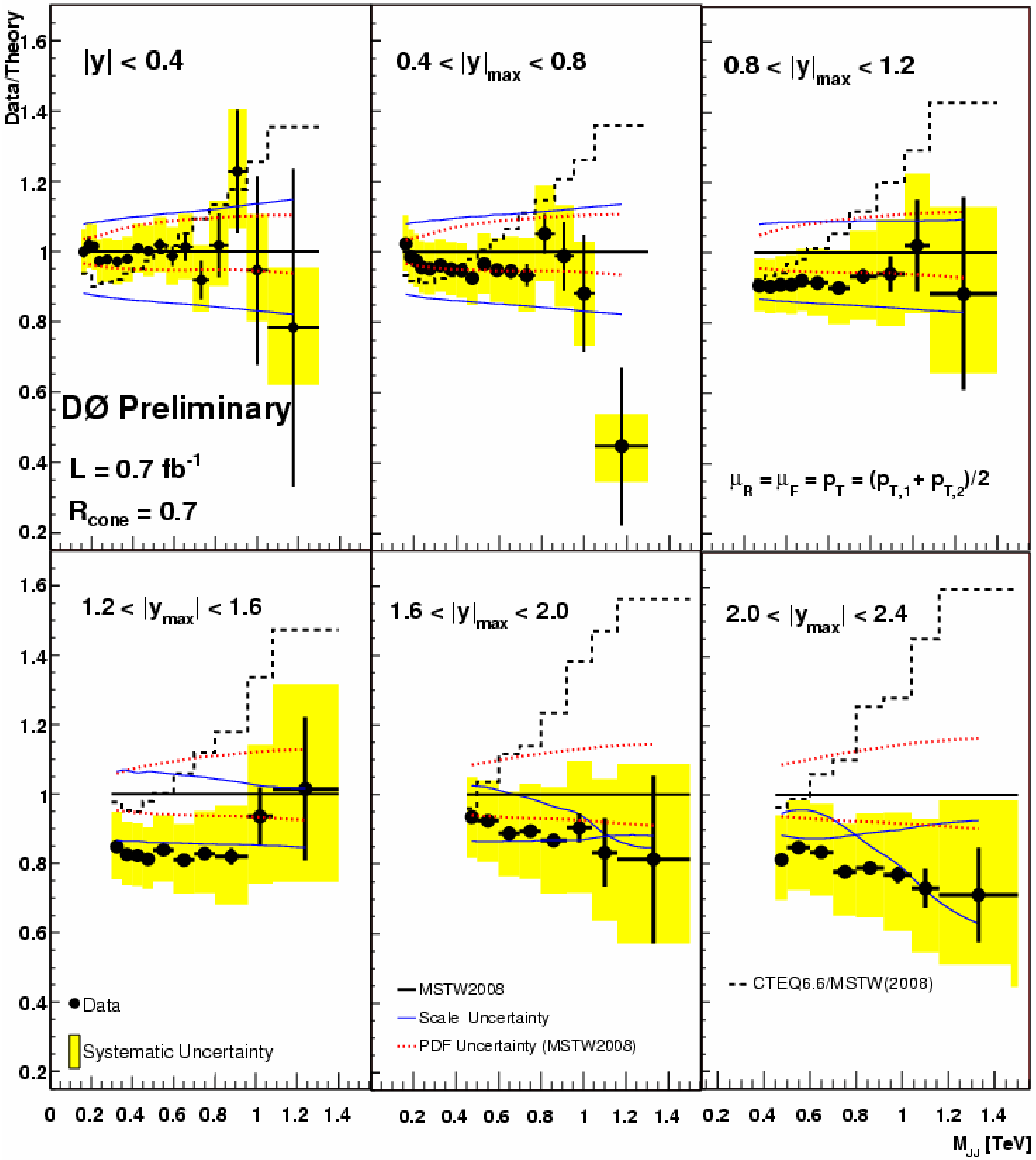




- $E_{jet} = \Sigma E_i$, $\mathbf{p}_{jet} = \Sigma \mathbf{p}_i$
- $M_{jj}^2 = (E_{j1}+E_{j2})^2 - (\mathbf{p}_{j1}+\mathbf{p}_{j2})^2$
- Additional sensitivity to heavy particle resonances

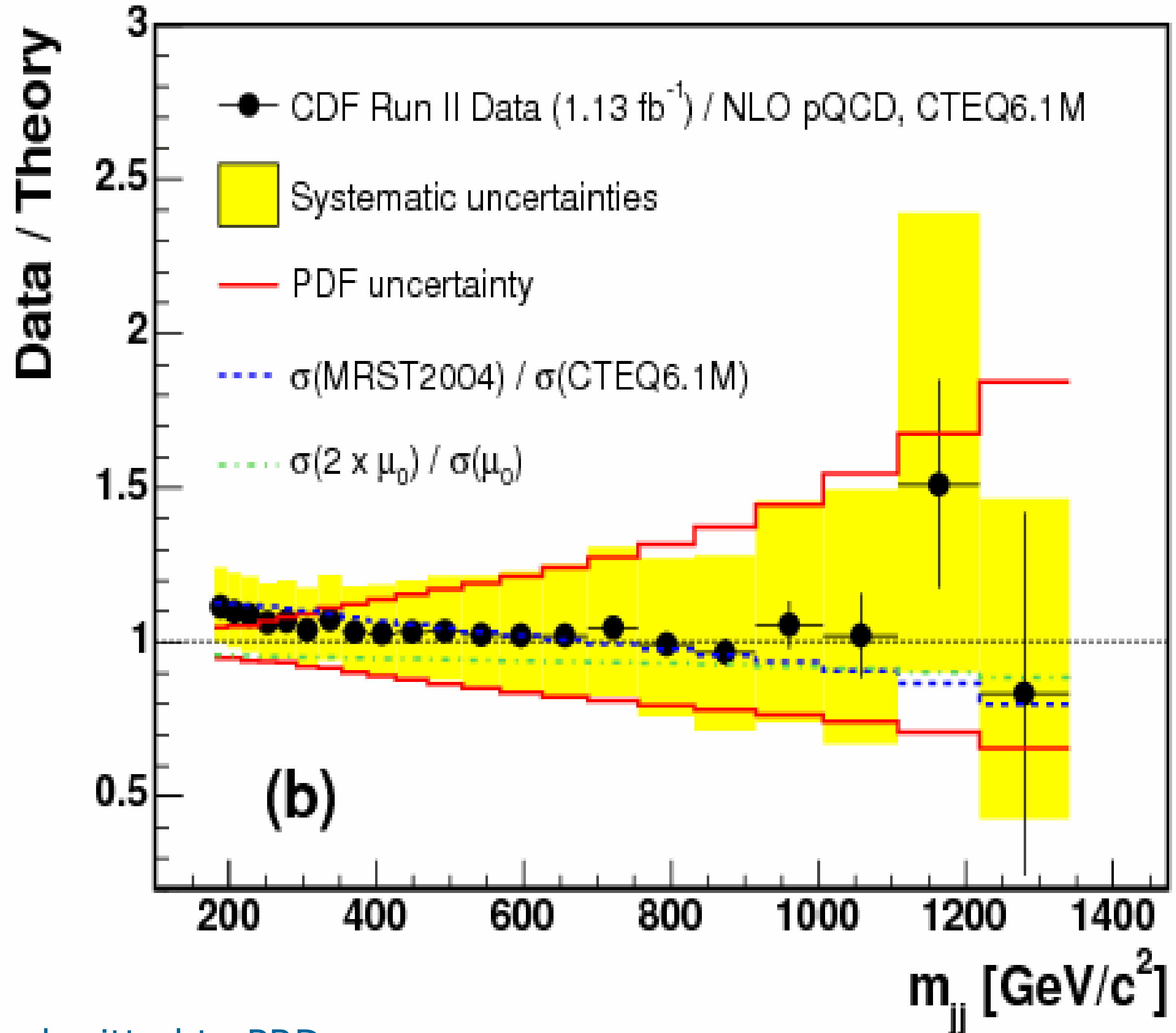
DØ Dijet Data/Theory

- Data agrees with MSTW2008 within pdf and scale uncertainties
- Central region is compatible with CTEQ6.6 but not forward regions



CDF Dijet Data/Theory

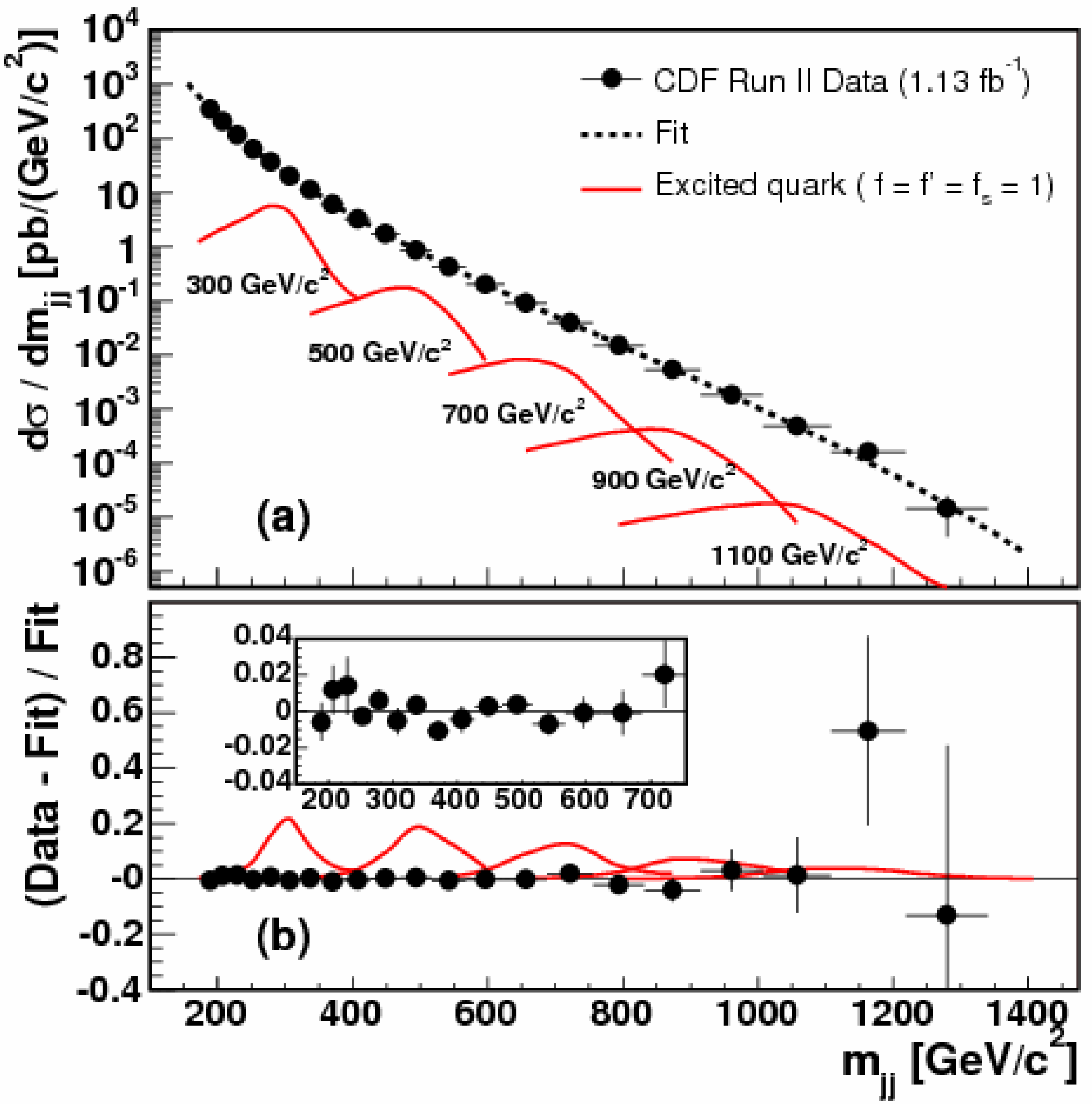
- Data in good agreement with NLO prediction (CTEQ6.1M)



arXiv:0812.4036 [hep-ex], submitted to PRD

CDF Dijet Resonance Search

- Select jets with $|\eta|<1.0$
- Use midpoint cone algorithm with $R=0.7$
- Select M_{jj} > 180 GeV
  - M_{jj} up to 1.3 TeV!
- Fit spectrum with parameterized model shape
  - Described by NLO pQCD
  - No indications for resonances
  - Set limits using Bayesian approach

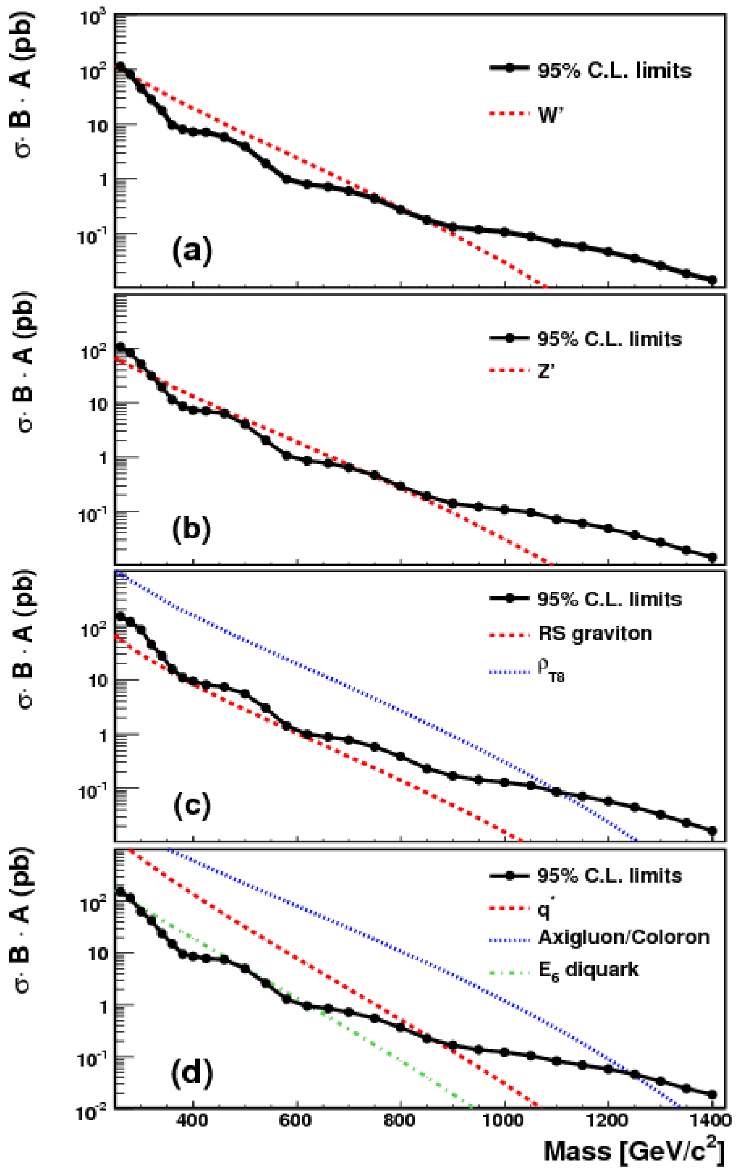


Limits from CDF Dijet Mass

Exclusion (GeV)	Model
280−840	*W′* (SM couplings)
320−740	*Z′* (SM coupling)
260−870	Excited quark (SM couplings)
260−1100	Color-octet techni-rho
260−1250	Axigluon & flavor-universal color
290−630	E_6 diquark

Most Stringent limits except for *W′* and *Z′*

No exclusion for RS Graviton



Dijet Angular Distribution

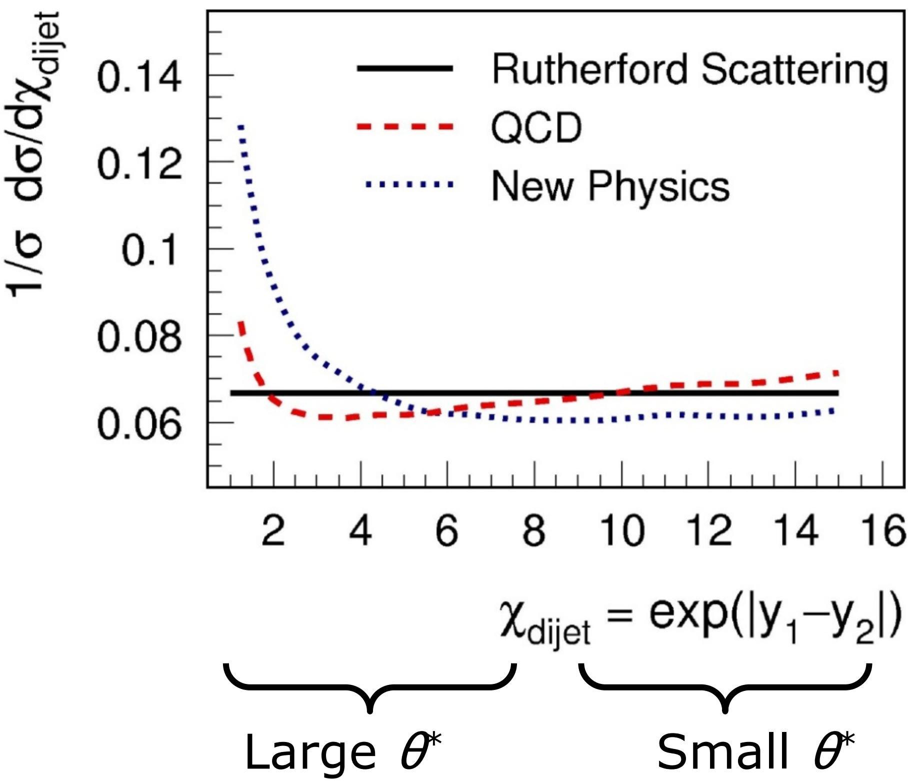
Search for new physics using $\chi_{dijet} = \exp(|y_1 - y_2|)$

- At LO, related to parton CM scattering angle, θ^*:

  $\chi_{dijet} = \{(1+\cos\theta^*)/(1-\cos\theta^*)\}$
- Enhanced at low χ_{dijet} for many new physics models
  - Quark compositeness
  - Large extra dimensions
  - TeV^{-1} extra dimensions
- Examine normalized distribution

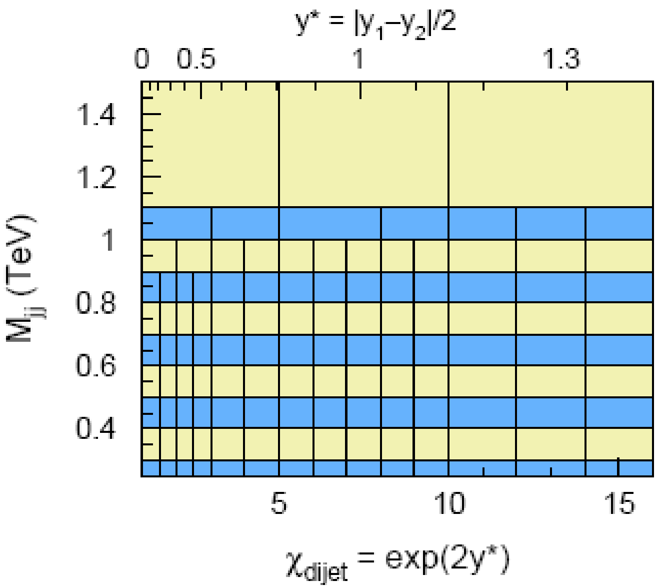
  $$(1/\sigma)(d\sigma/d\chi_{dijet})$$

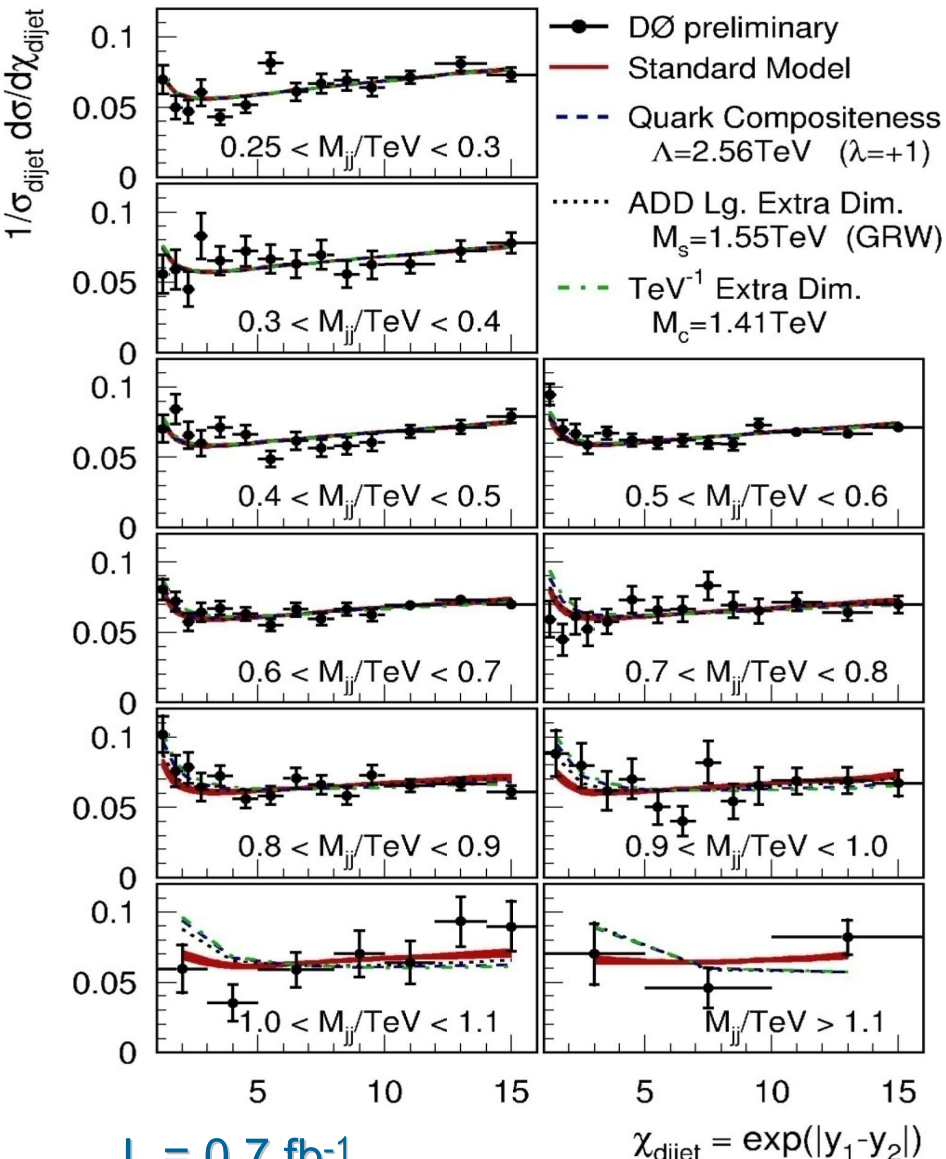
  to reduce experimental and theoretical uncertainties



Dijet Angular Distribution

- Correct distributions to particle level
- Analyze data in ranges of dijet invariant mass
- Measures angular distributions of a scattering process above 1 TeV
- Good agreement w/QCD, set limits on new physics models





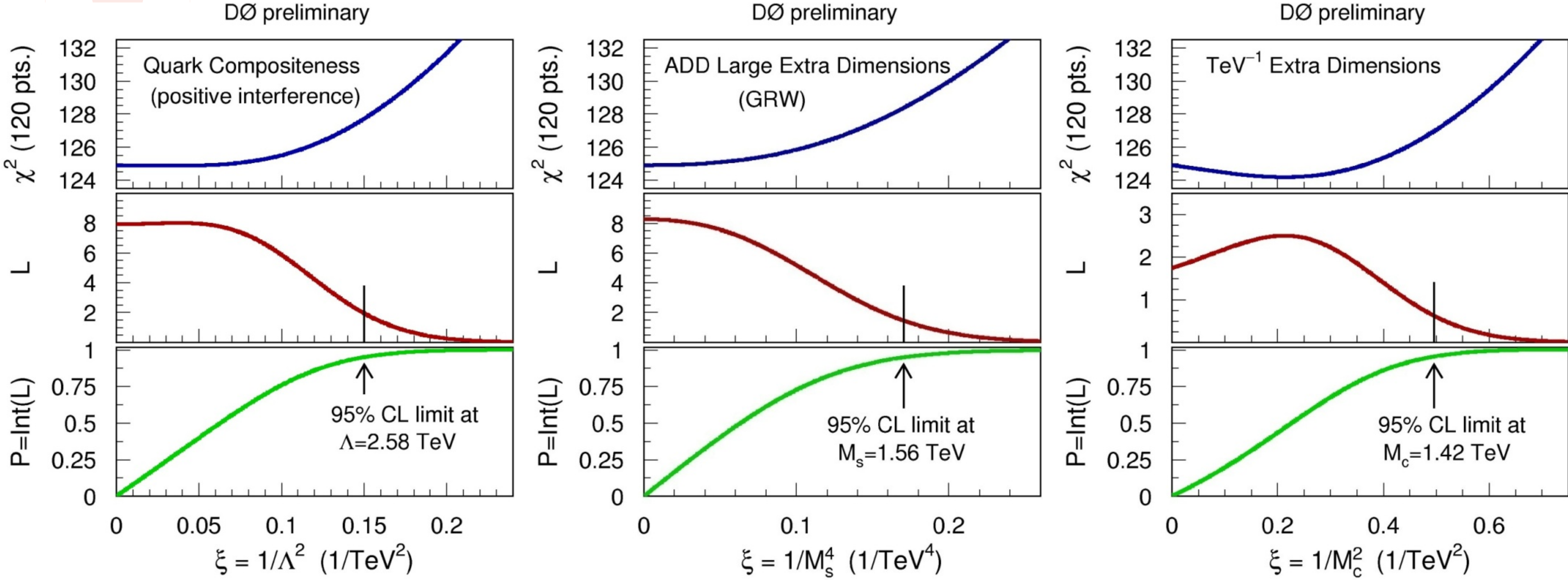
$L = 0.7\ fb^{-1}$

Limits from DØ Dijet Angles

Quark Compositeness: Λ=2.58 TeV

A.D.D. LEDs: M_S=1.56 TeV

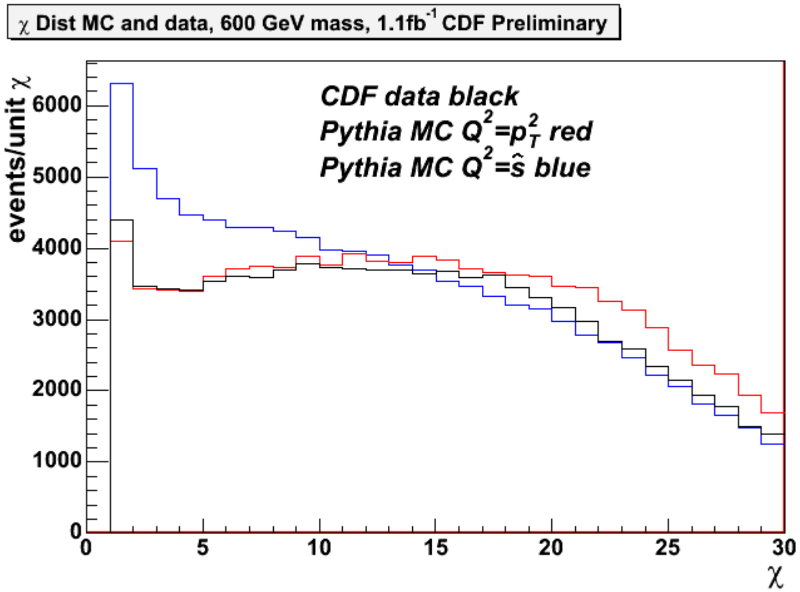
TeV^{-1} Extra Dims.: M_C=1.42 TeV

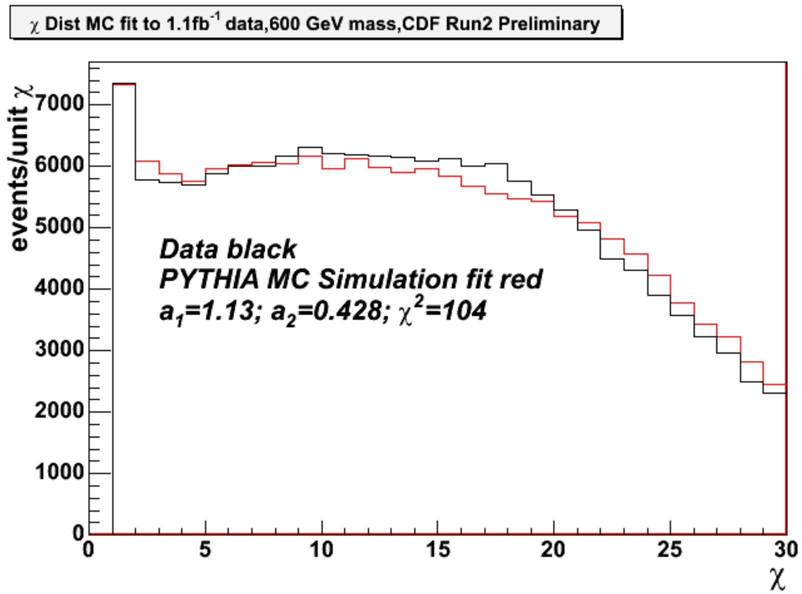


Bayesian limits shown

CDF Angle Distribution

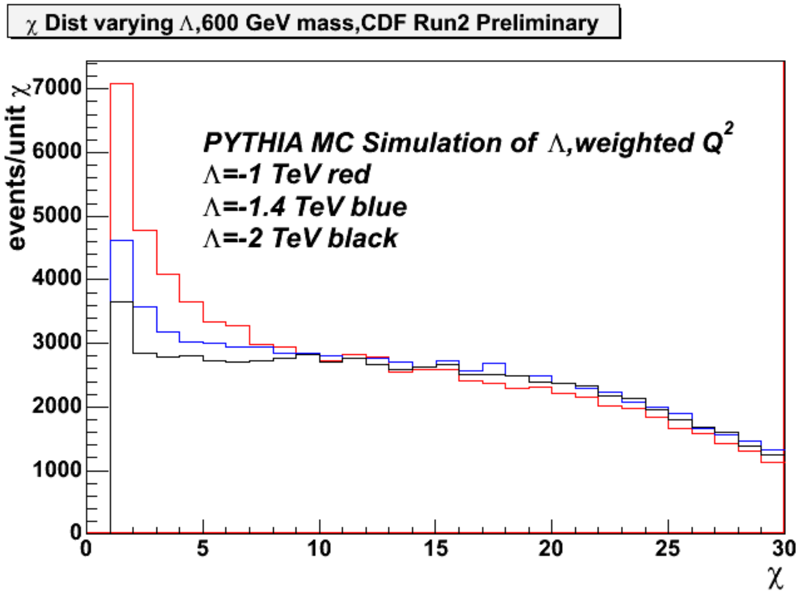
- Analysis done in four bins of M_{jj}
  - 550-650 GeV
  - 650-750 GeV
  - 750-850 GeV
  - 850-950 GeV
- Analysis uses $\chi = \exp(|\eta_1 - \eta_2|)$
- Fit fractions of $Q^2 = p_T^2$ and $Q^2 = \hat{s}$

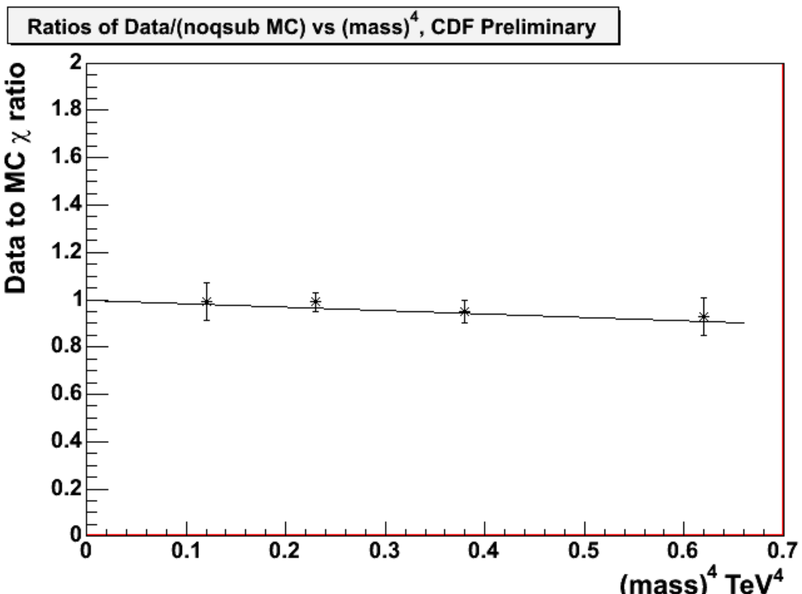




Limits from CDF Angles

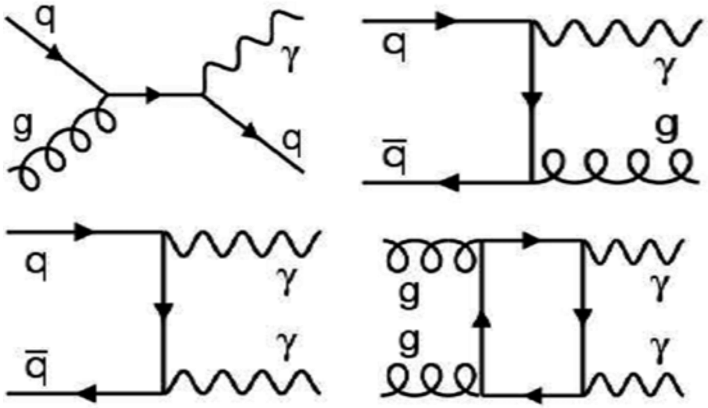
- Study effect of substructure on χ as a function of scale Λ in MC
- Compare ratio of $R(\Lambda)/R(\infty)$ where $R(\Lambda) = (1<\chi<10)/(15<\chi<25)$ in MC and data
  - $R(\infty)$ means no substructure
- Set limit using Cousins-Feldman method
  - $\Lambda > 2.4$ TeV @ 95% CL



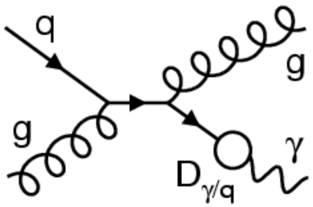


Photon Production & Detection

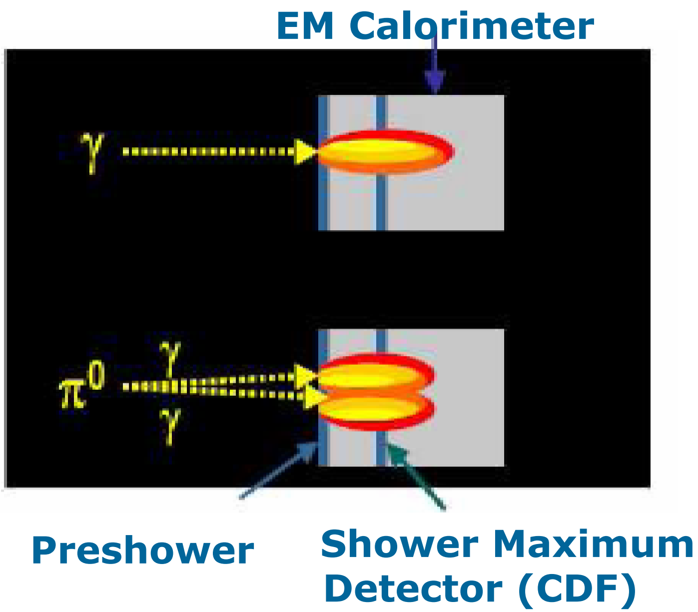
- Direct photons come unaltered from the hard scattering
  - Allows probe of hard scattering dynamics with fewer soft QCD effects
  - Probes gluon PDFs
- Background from neutral mesons and EM object in jets.
  - Use isolated photons
  - Purity of sample must be determined



plus some fragmentation effects

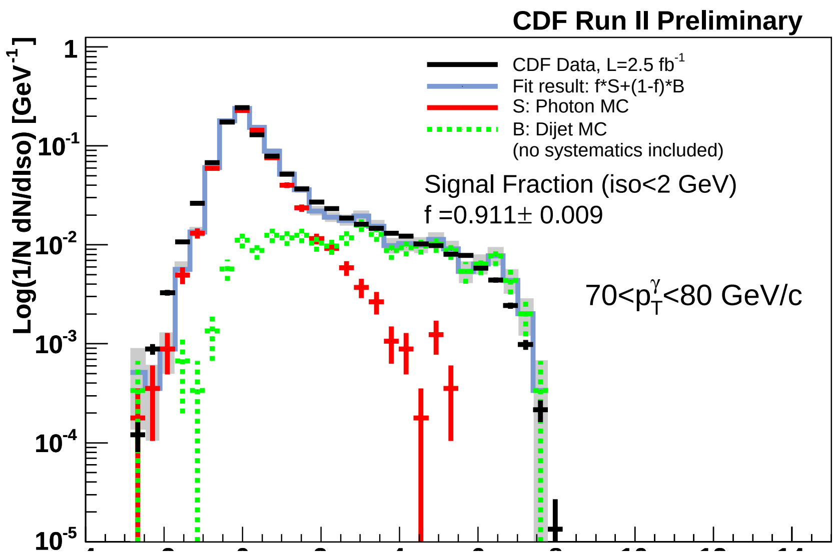


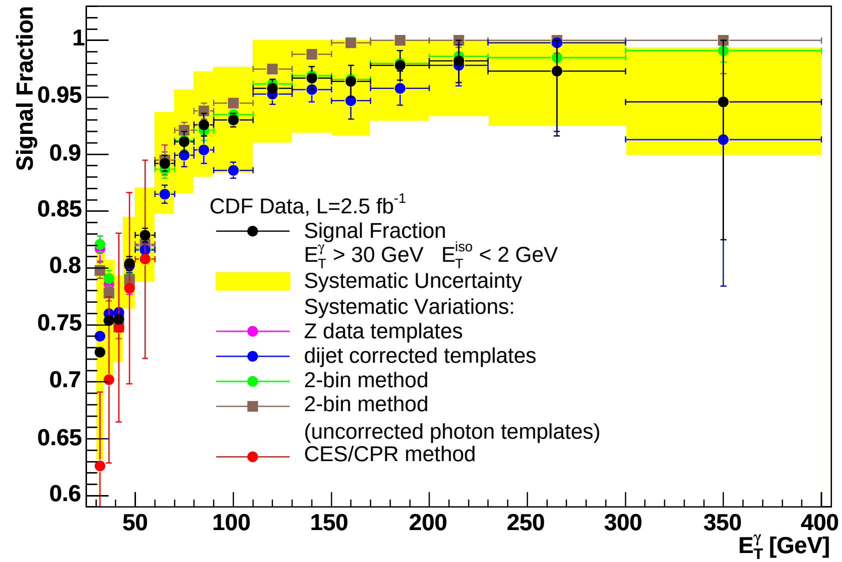
ElectroMagnetic Shower Detection



CDF Photon Purity

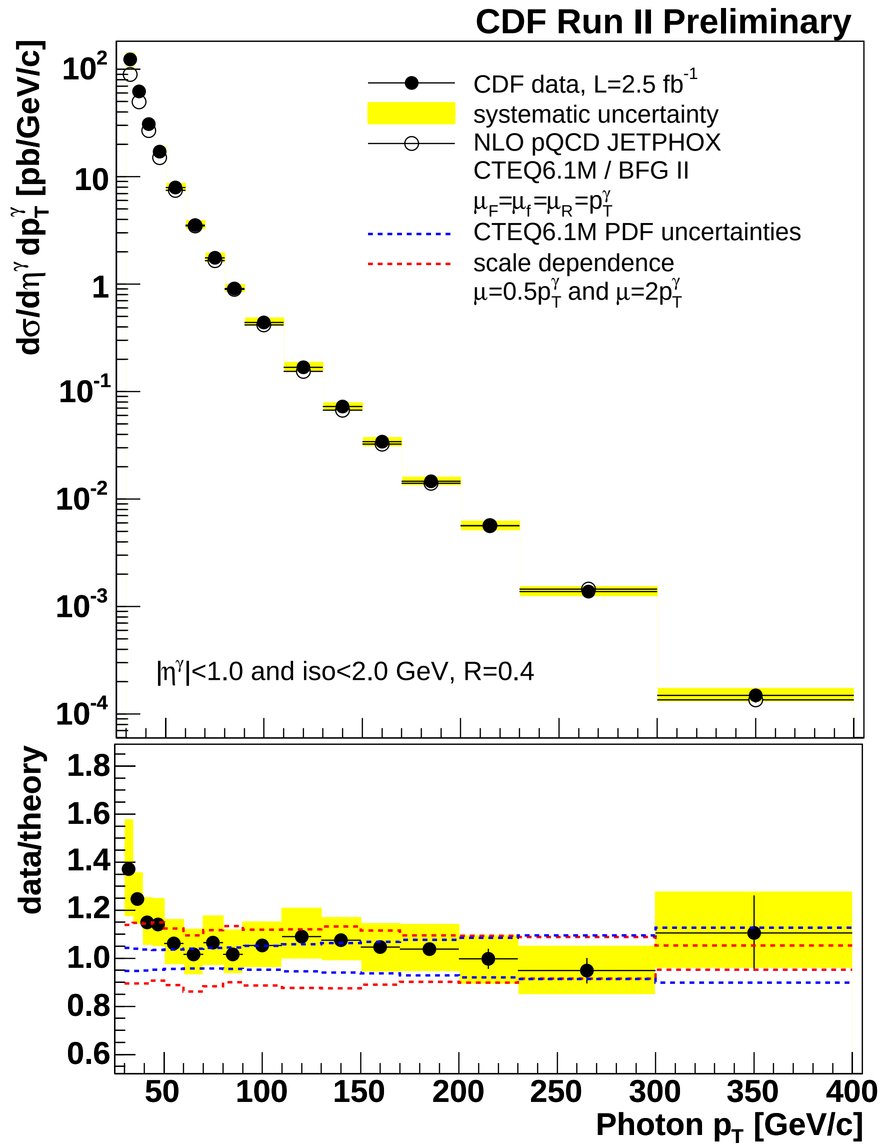
- CDF has new measurement of the inclusive isolated photon production cross section using 2.5 fb^{-1}!
- Use MC to create templates for photon and background isolation.
  - Done in bins of p_T
- Fit data to combination to determine photon signal fraction
  - Use other methods to determine systematic uncertainty





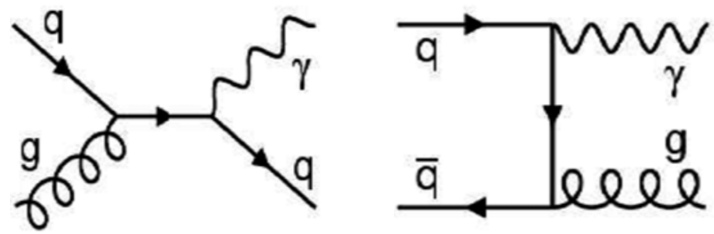
CDF Direct Photon Results

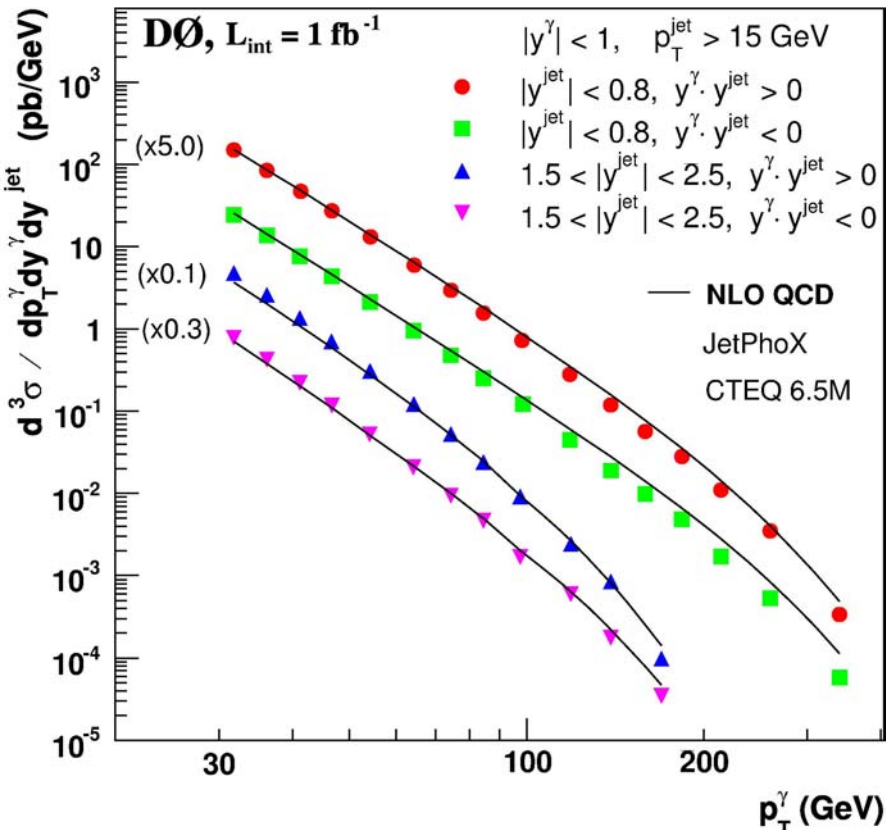
- Data/theory agree except at low p_T
  - Low p_T has historically been an area of disagreement.
  - Measurement to p_T = 400 GeV



Photon plus Jet Production

- Investigate source(s) for data/theory disagreement
  - measure differential distributions
  - tag photon and jet
  - reconstruct full event kinematics
- measure in 4 regions of y_γ, y_{jet}
  - photon: central ($|\eta|<1$)
  - jet: central / forward
  - same side / opposite side
- Dominant production at low p_T^γ (< 120 GeV) is through Compton scattering: $qg \rightarrow q+g$
  - Probe PDF's in the range $0.007<x<0.8$ and $p_T^\gamma = 900<Q^2<1.6\times10^5$ GeV^2

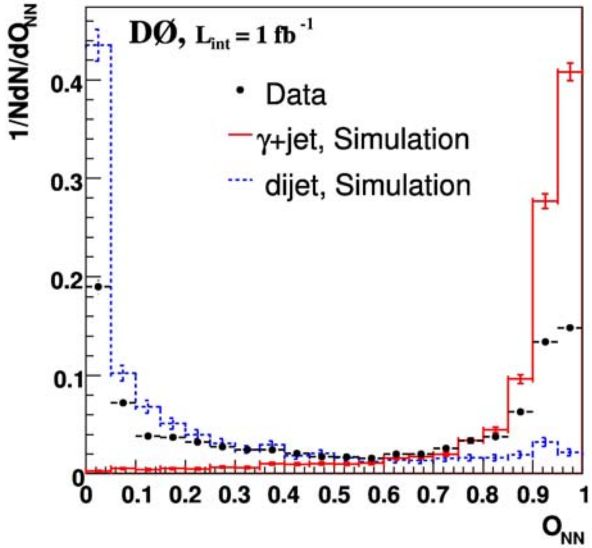


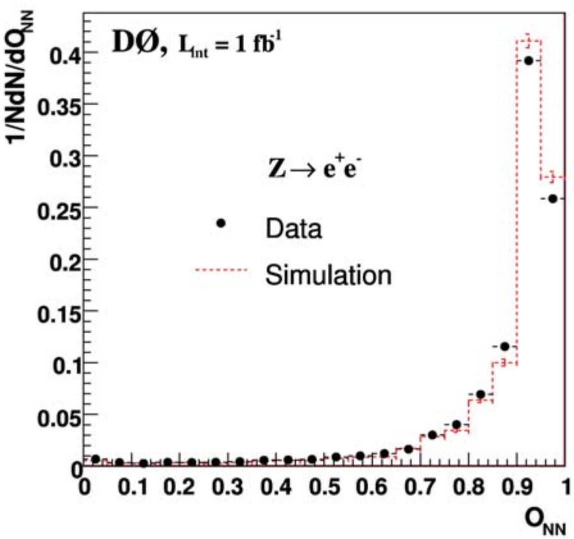


Phys.Lett.B666, 2008

DØ Photon Purity

Neural net is used to determine photon purity





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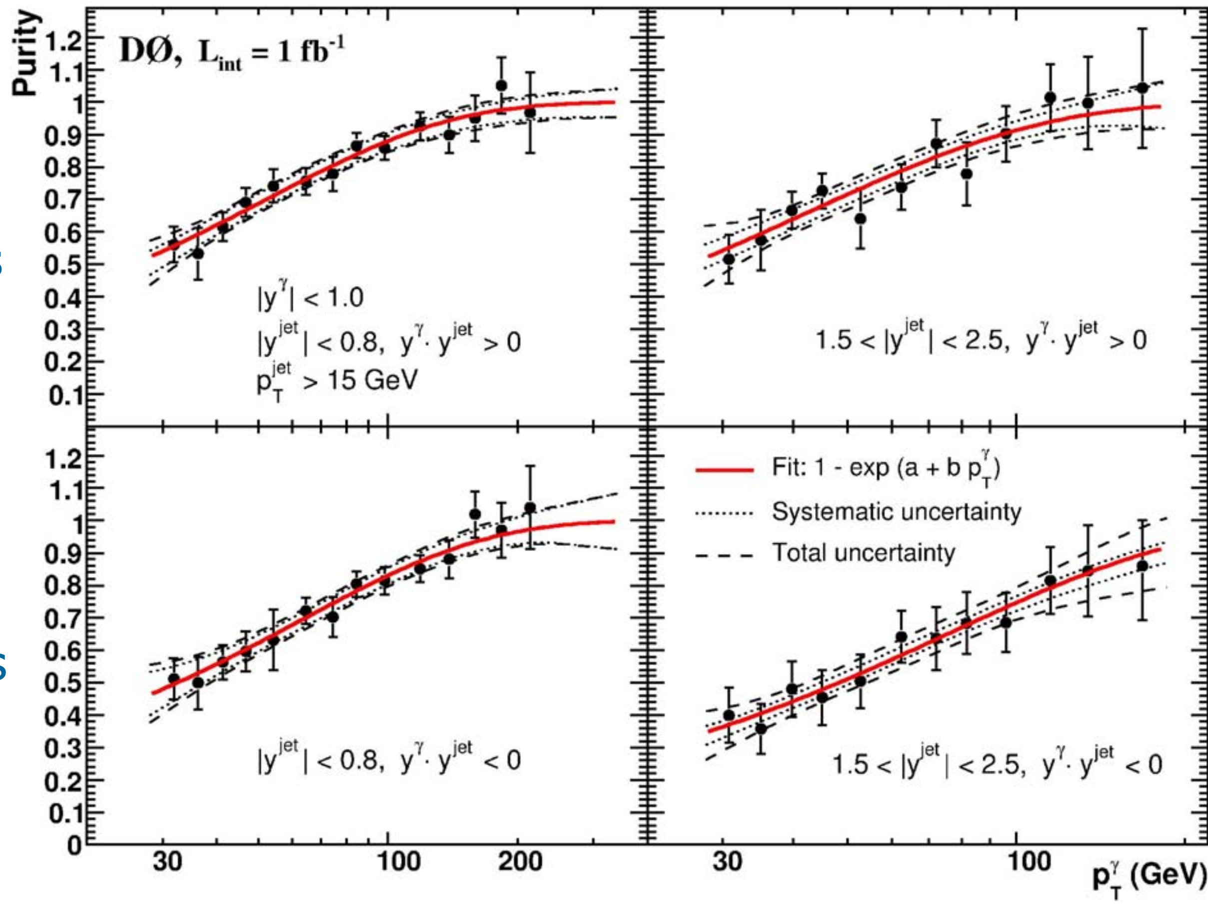
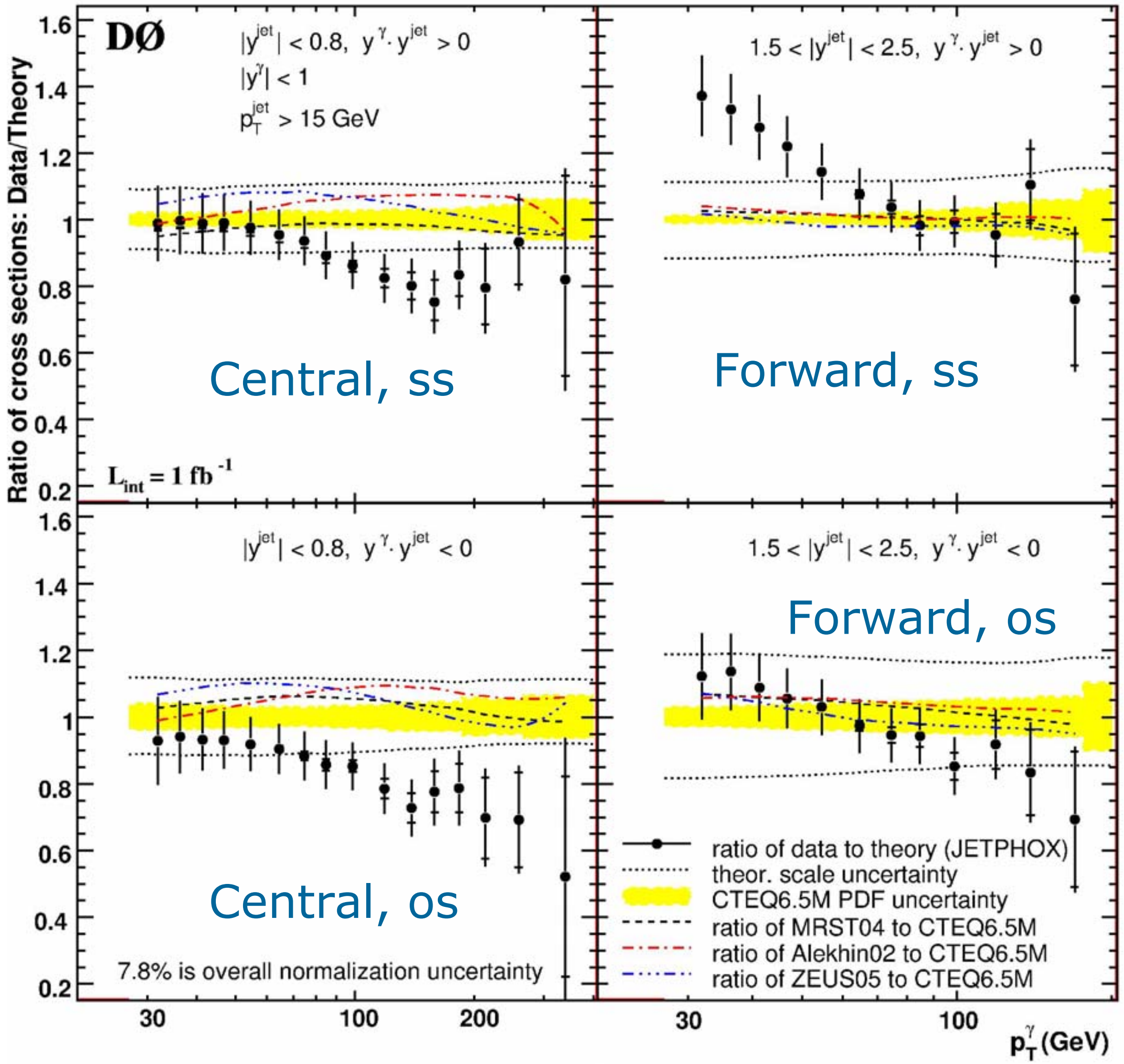


central forward

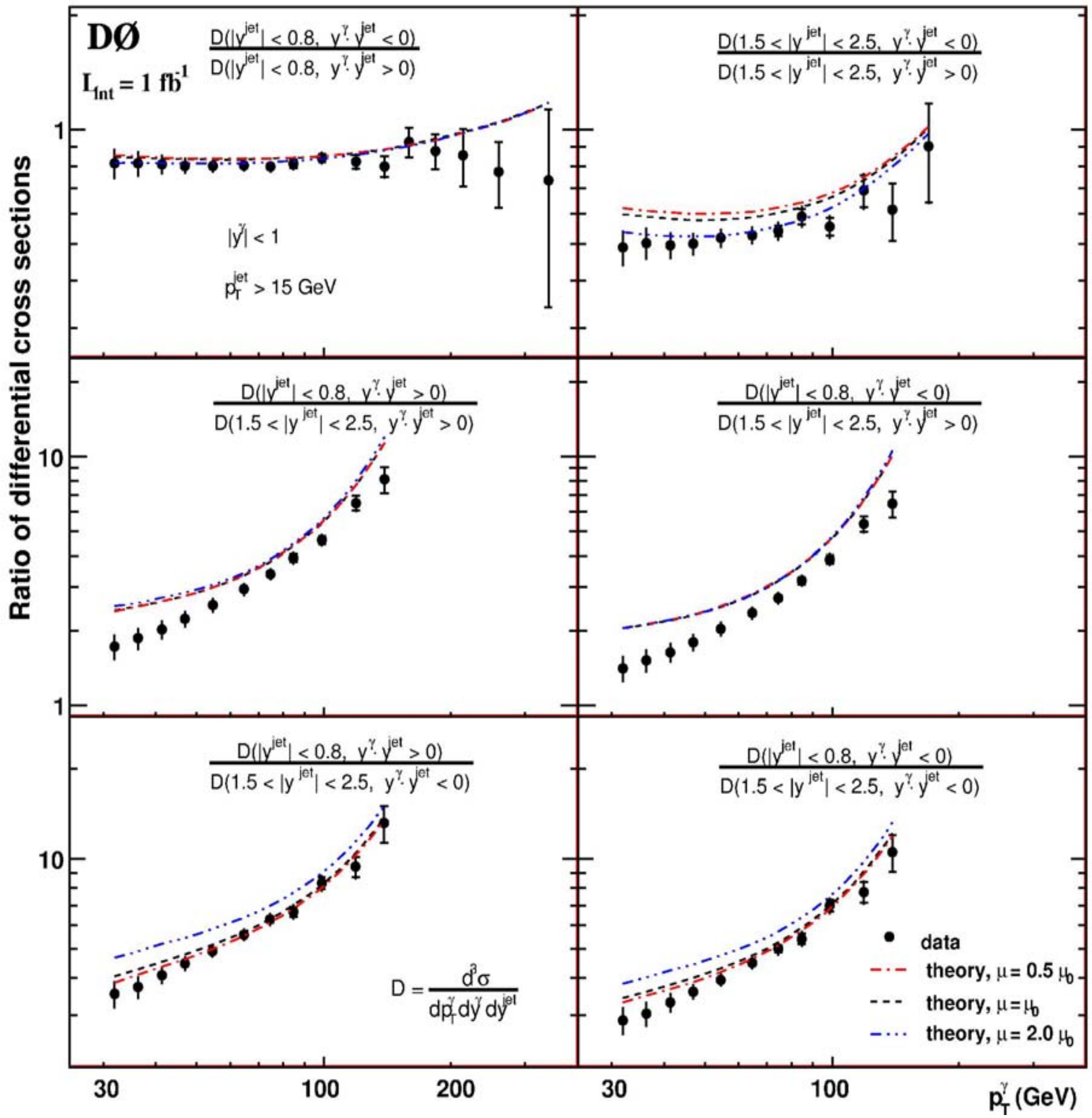
DØ Photon plus Jets Results

All shapes cannot be easily accommodated by any single theory



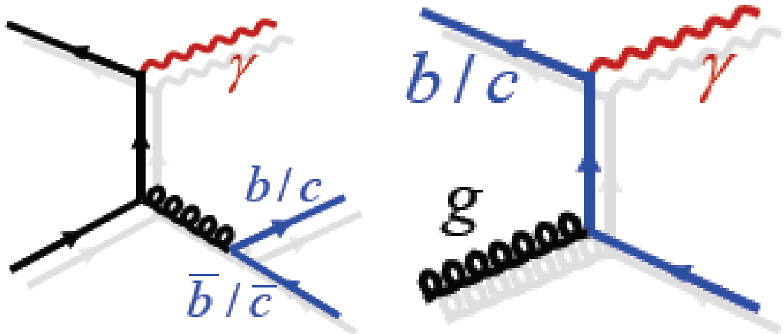
DØ Ratio of Regions

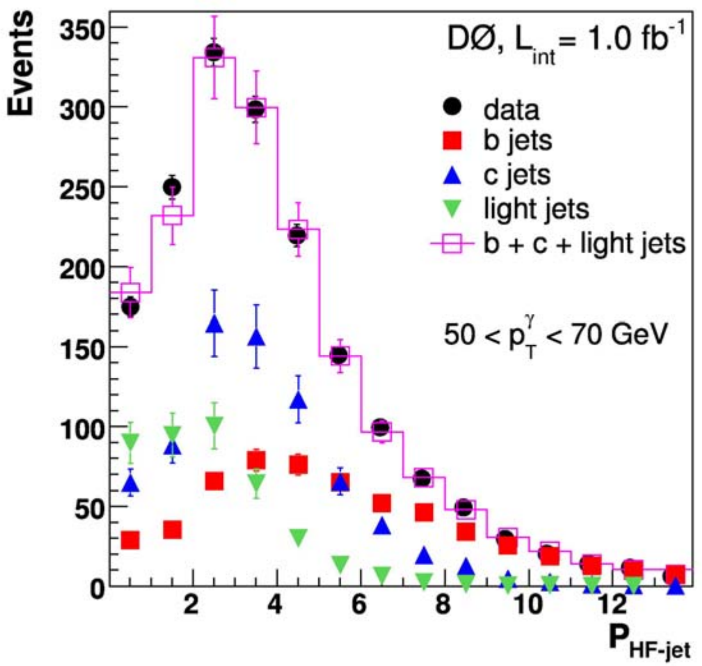
- Most errors cancel in ratios between regions (3-9% across most p_T^{γ} range)
- Data & Theory agree qualitatively
- A quantitative difference is observed in the central/forward ratios
- Need improved and consistent theoretical description for γ+ jet



DØ Photon plus HF (b/c) Jets

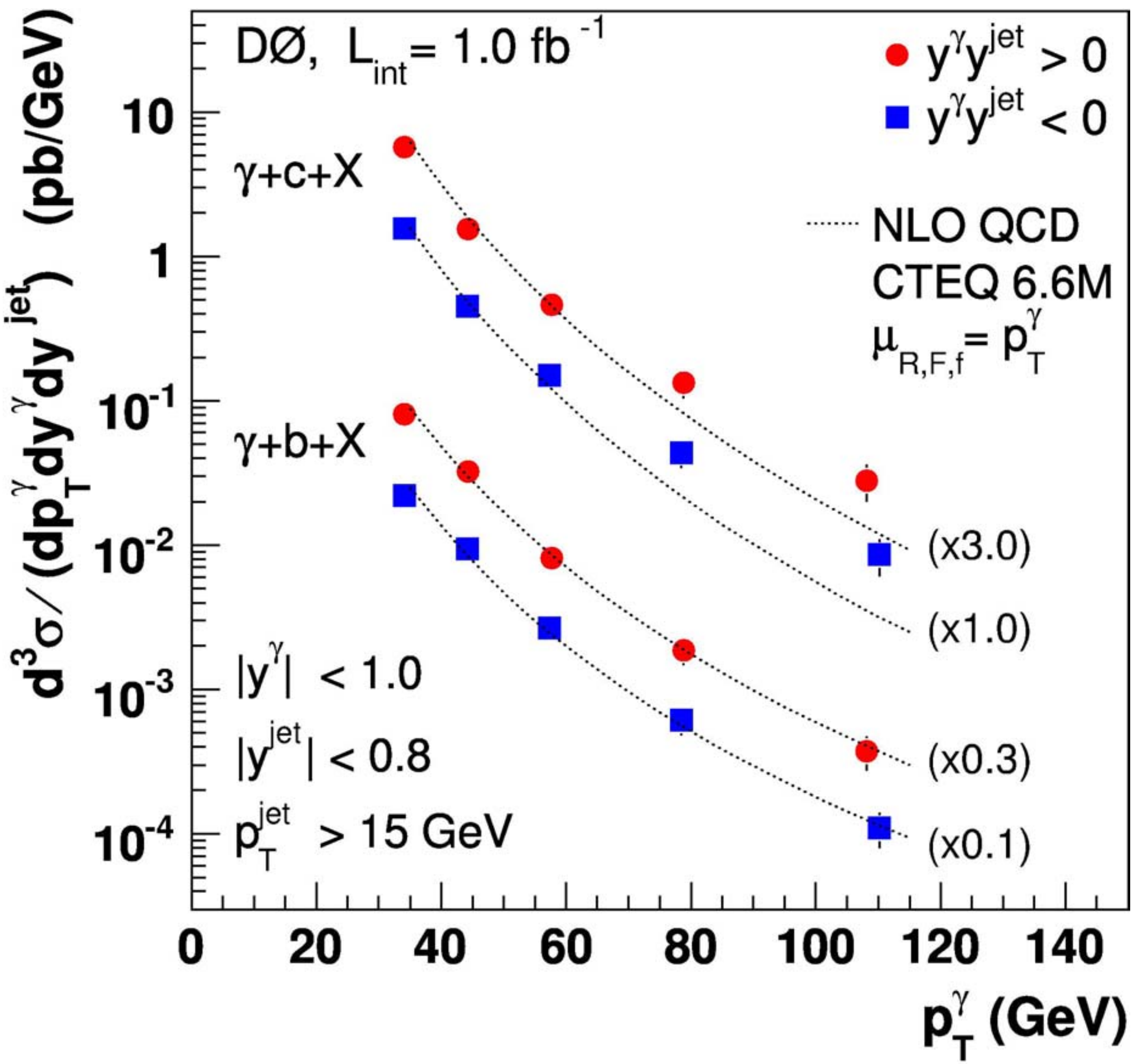
- Measure triple differential cross section: $d^3\sigma/(dp_T\, dy_\gamma\, dy_{jet})$
  - Jet and γ in central region
  - $y_\gamma y_{jet} > 0$
  - $y_\gamma y_{jet} < 0$
- Use MC template to determine particle fractions





arXiv:0901.0739 [hep-ex], submitted to PLB

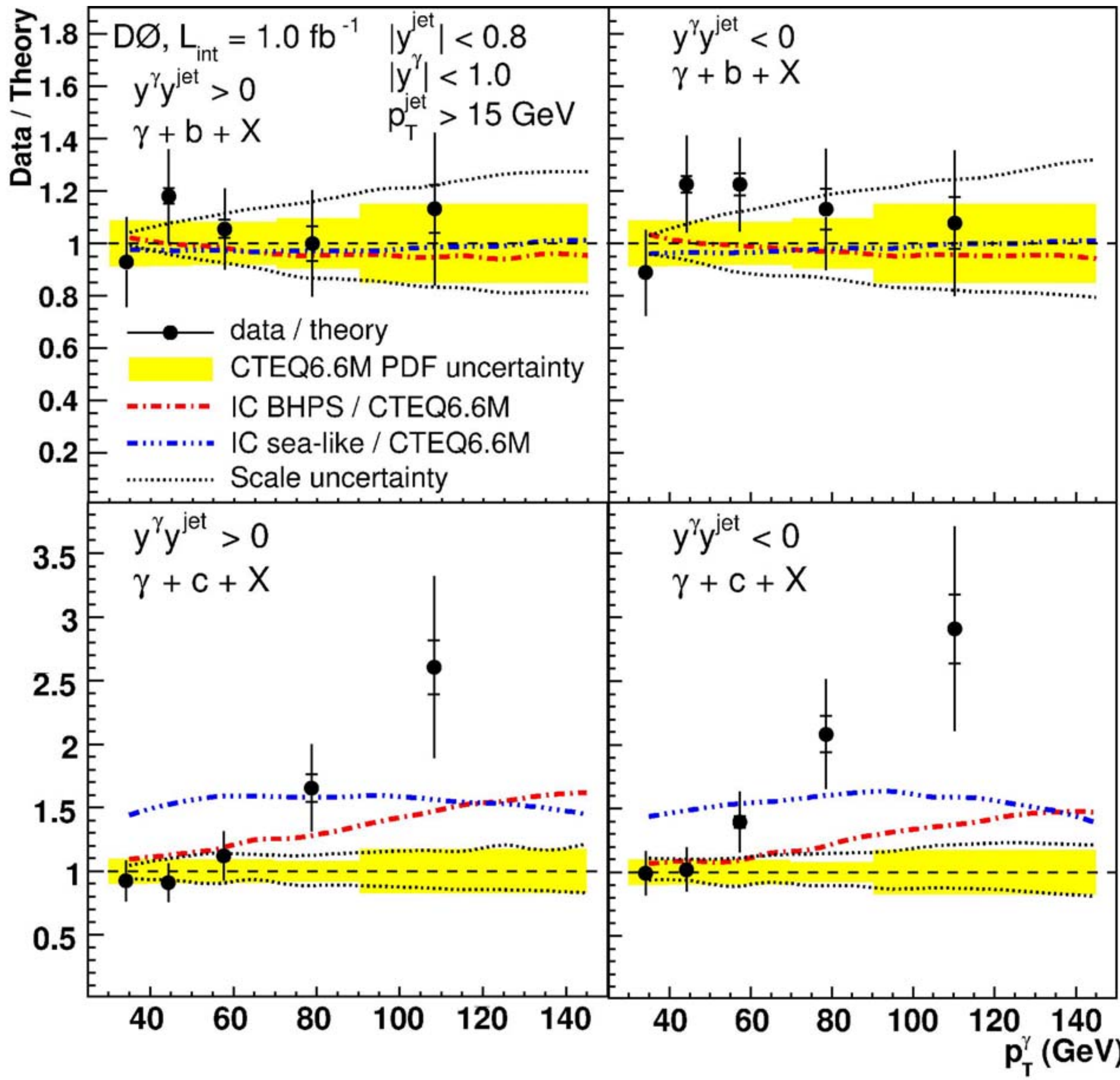
DØ Photon plus HF Results



Photon plus HF Data/Theory

Theory describes data for b jets but not for c jets.

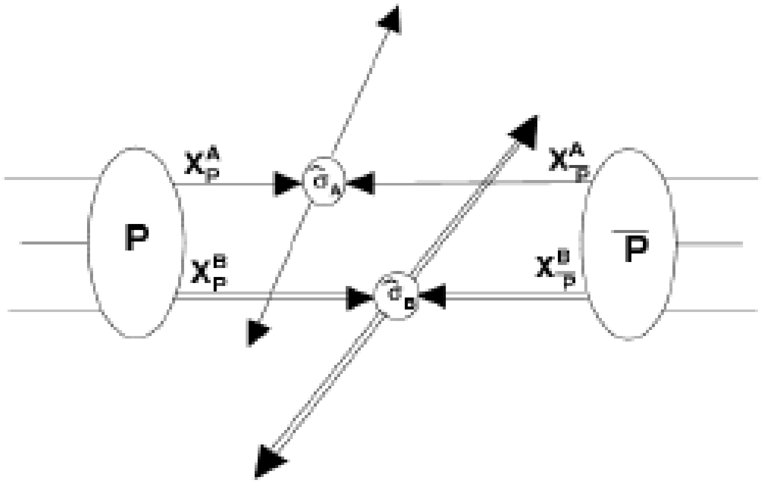
- Disagreement increases with higher p_T^γ
- Maybe too little intrinsic charm in proton, or not enough charm in gluon splitting from annihilation process.



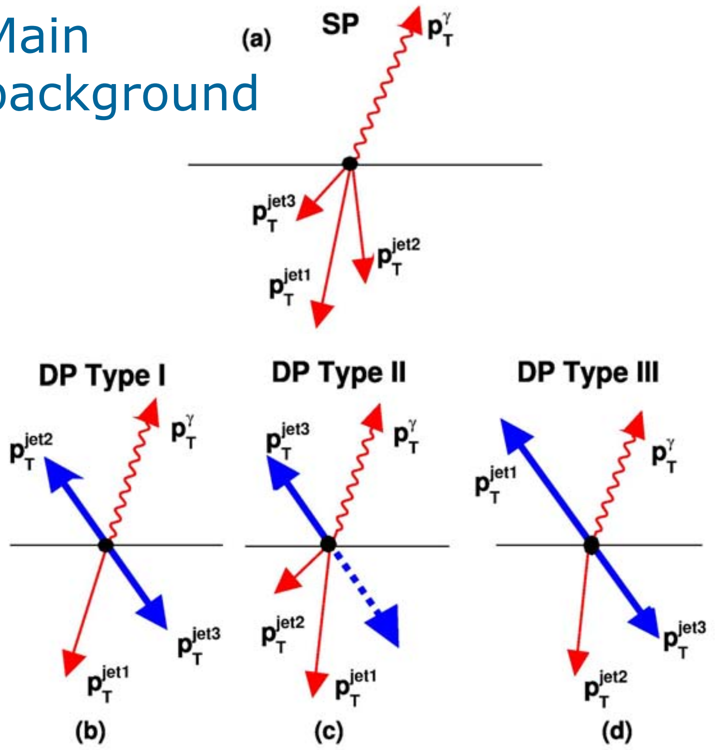
DØ Double Parton using 3 Jet+γ

- Study reactions in which two partons in a single proton interact
  - May impact PDFs
  - Help understand multiple interactions and high luminosity

$$\sigma_{DP} = \sigma_{\gamma j}\ \sigma_{jj}/\sigma_{eff}$$



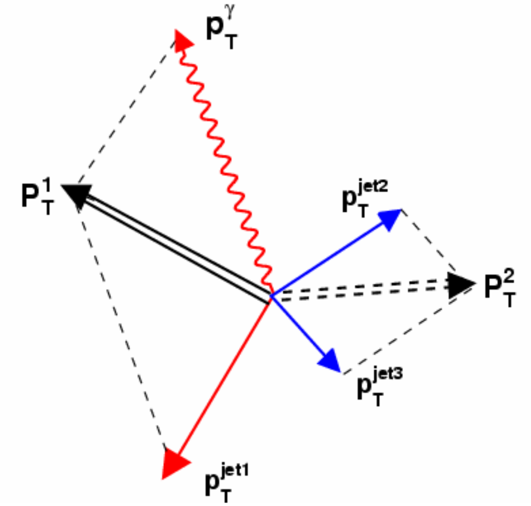
Main background

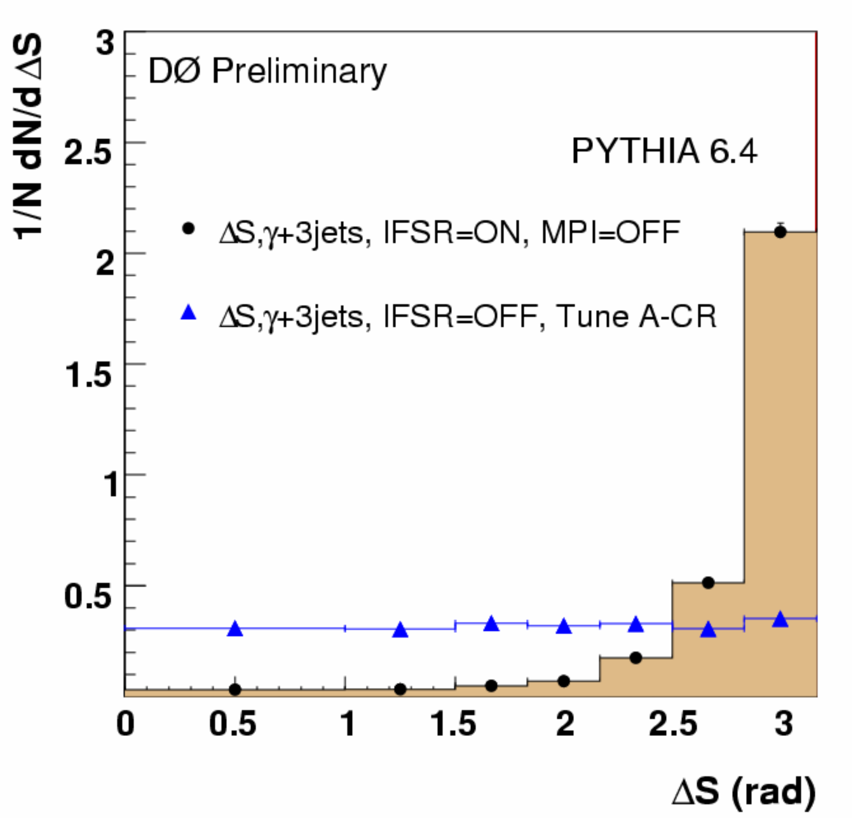


signal

Double Parton Signal Variables

Calculated for the pair that gives the minimum value of *S*.





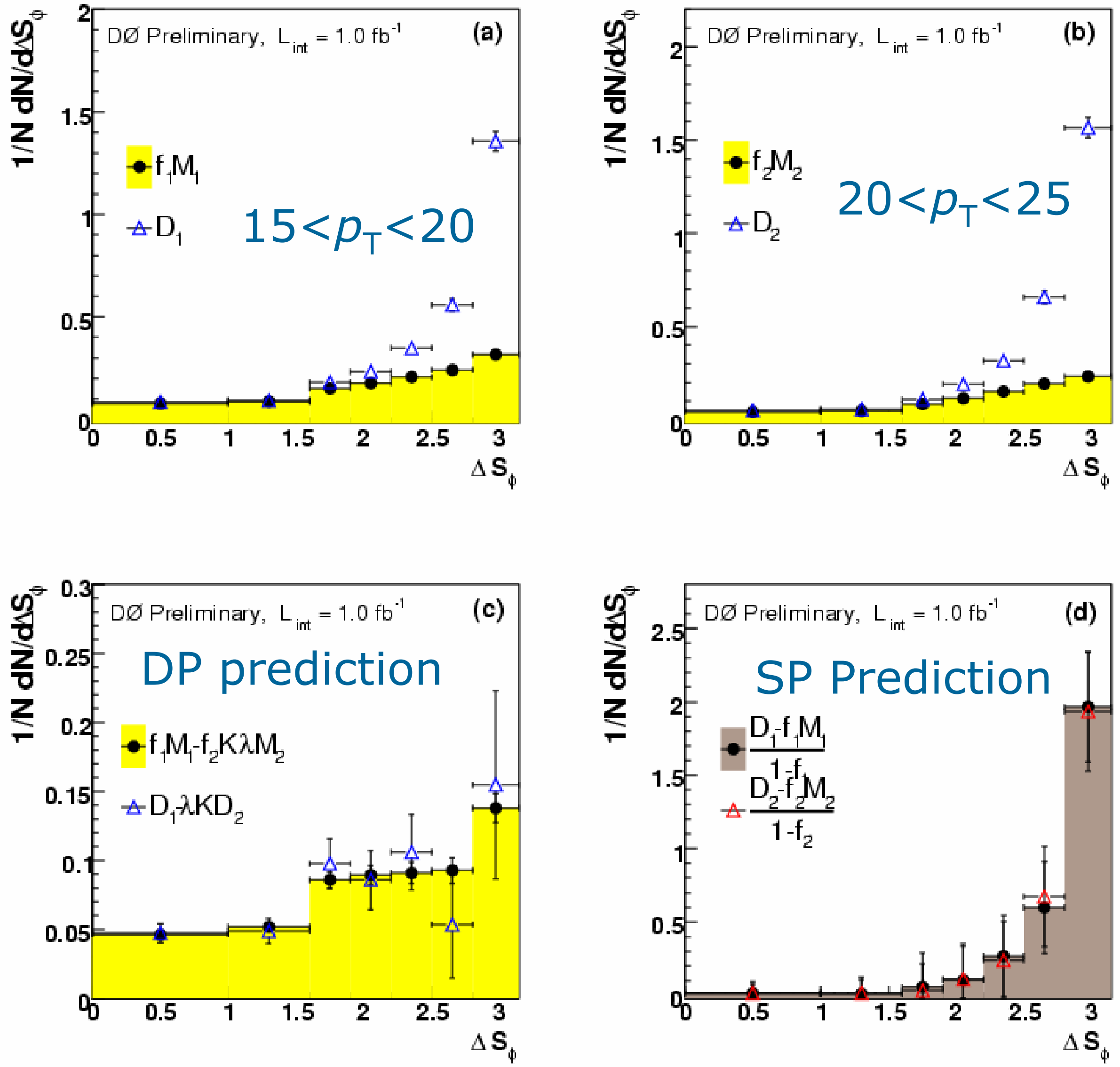
$$S_\phi = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2+\left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$$

$$S_{pT} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{P}_T(\gamma,i)|}{\delta P_T(\gamma,i)}\right)^2+\left(\frac{|\vec{P}_T(j,k)|}{\delta P_T(j,k)}\right)^2}$$

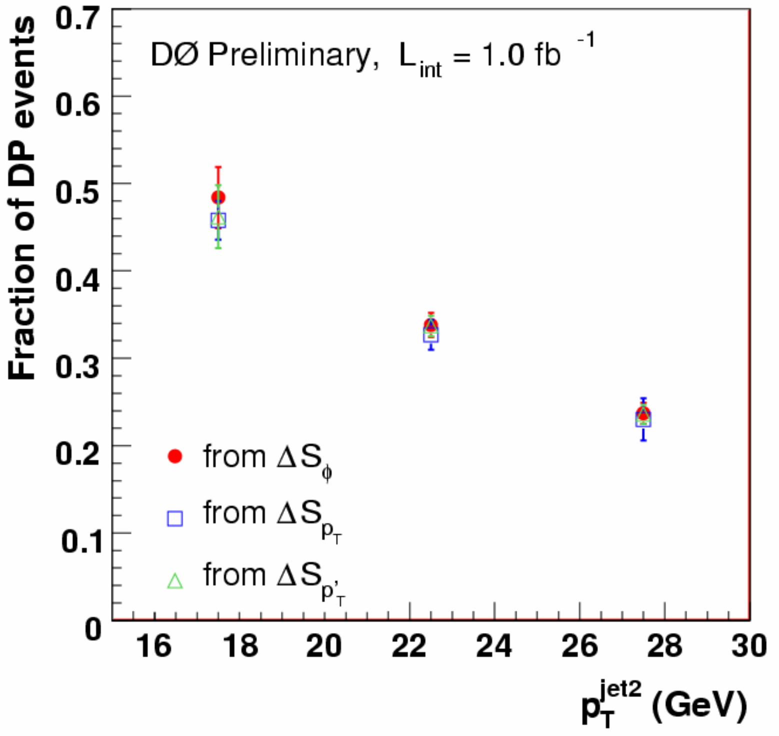
$$\Delta S = \Delta\phi\left(\mathrm{p}_T^{\gamma,jet_i},\ \mathrm{p}_T^{jet_j,jet_k}\right)$$

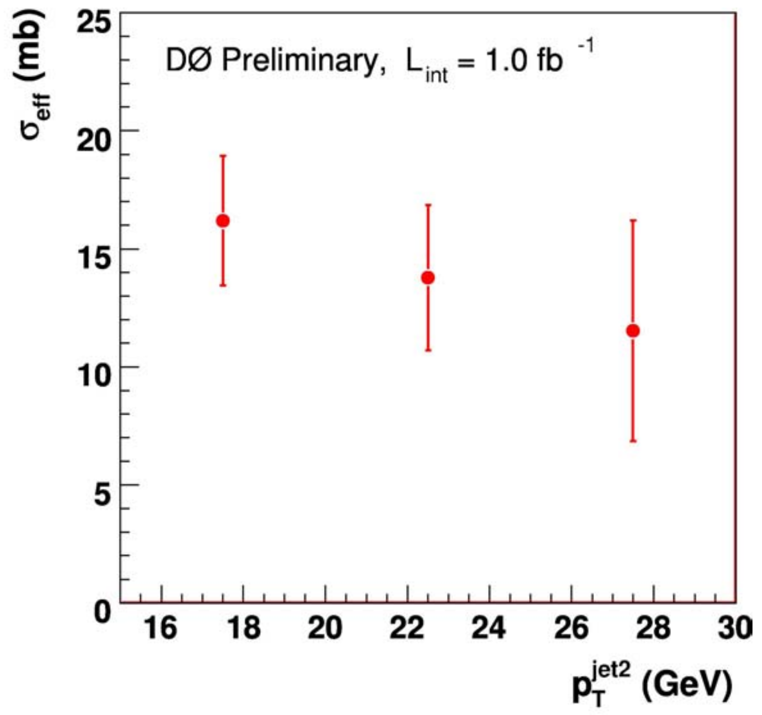
Double Parton Measurement

- The measurement is done in 3 bins depending on the p_T of the 2nd jet:
  - 15-20 GeV
  - 20-25 GeV
  - 25-30 GeV
- Lower p_T should have higher fraction of DP events



DØ Double Parton Results





- The measured DP fraction drops from 0.47±0.04 at $15<p_{T2}<20$ GeV to 0.23±0.03 at $25<p_{T2}<30$ GeV
- Effective cross section is approximately the same and averages to σ_{eff} = 15.1±1.9 mb
- Good agreement with previous measurements by CDF

Conclusions

- The Tevatron is operating at $\sqrt{s}$ = 1.96 TeV with very high luminosity
- QCD measurements using Jets and Photons are probing higher energy scales than ever before
- Current PDFs model most processes quite well
- Still some improvement needed in PDFs at very highest *x*
- No evidence from QCD measurements of any physics beyond the standard model
- QCD will continue to be a rich field of study and extremely important in the LHC era