Hard QCD Results with Jets and Photons at the Tevatron

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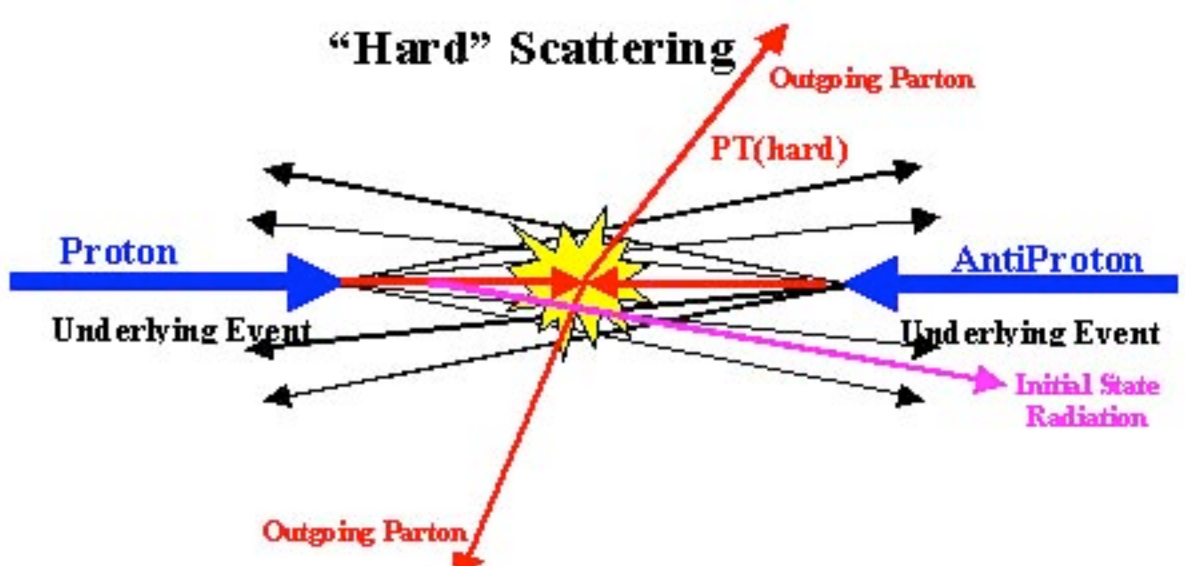
Introduction

- Mature QCD studies at the Tevatron benefit physics program at the LHC
  - Challenging measurements, sensitive to (N)NLO effects as well as non-perturbative physics
  - Mature experiments have had time to think about running conditions and detector effects and how to mitigate effects of systematic uncertainties
- Almost any new physics involves QCD
  - Parton Distribution Functions (PDFs) for background and signal processes
  - QCD often a (hugely) dominant background to new physics
    - e.g. diphotons for Higgs discovery, jet substructure for boosted Higgs, etc.
- Better understanding of QCD means improved sensitivity to new physics



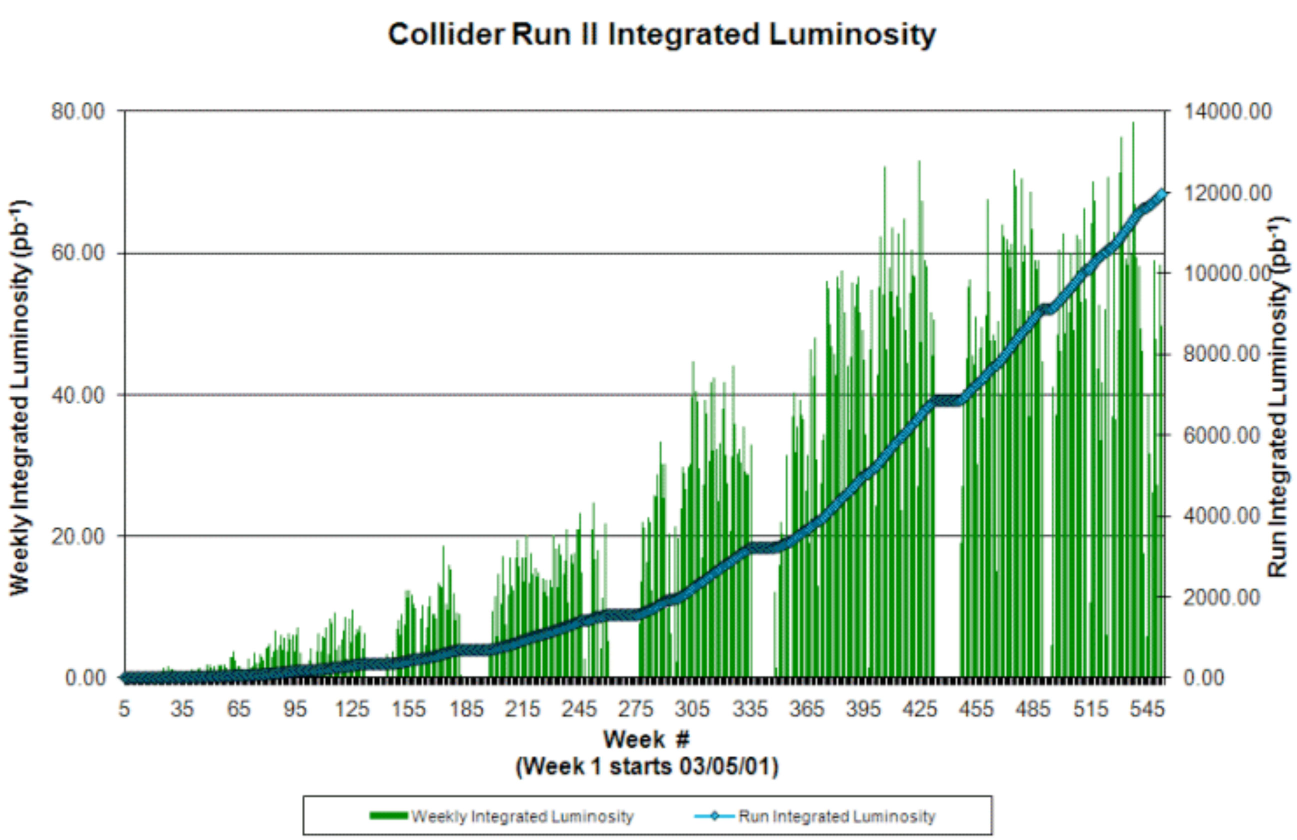
Outline

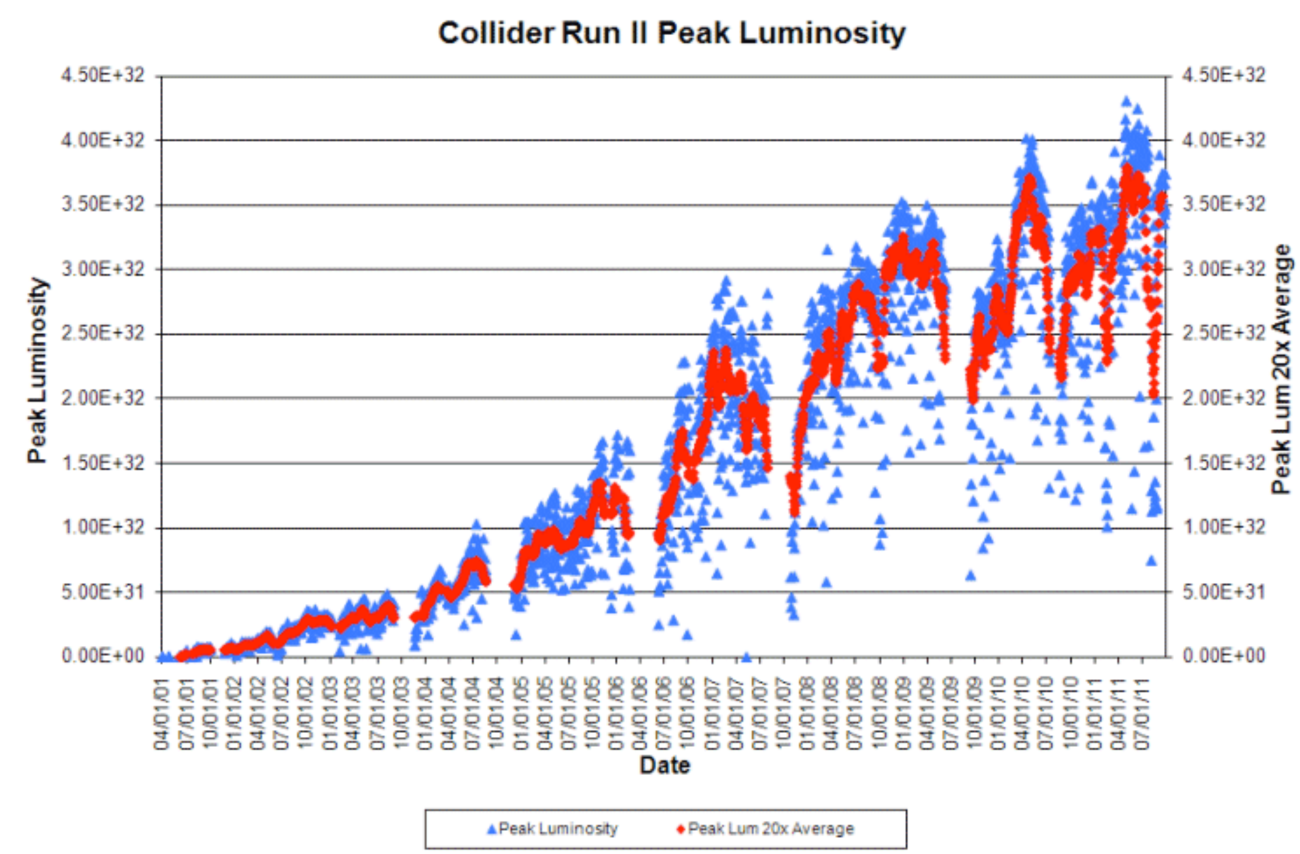
- Introduction to the Tevatron
- Measurements
  - Diphoton Production (CDF/D0)
  - Exclusive Diphoton Production (CDF)
  - Multijet Production (D0)
  - Jet Substructure (CDF)
- Conclusions

The Tevatron

p-pbar Collisions at $\sqrt{s}$=1.96 TeV

Tevatron Performance

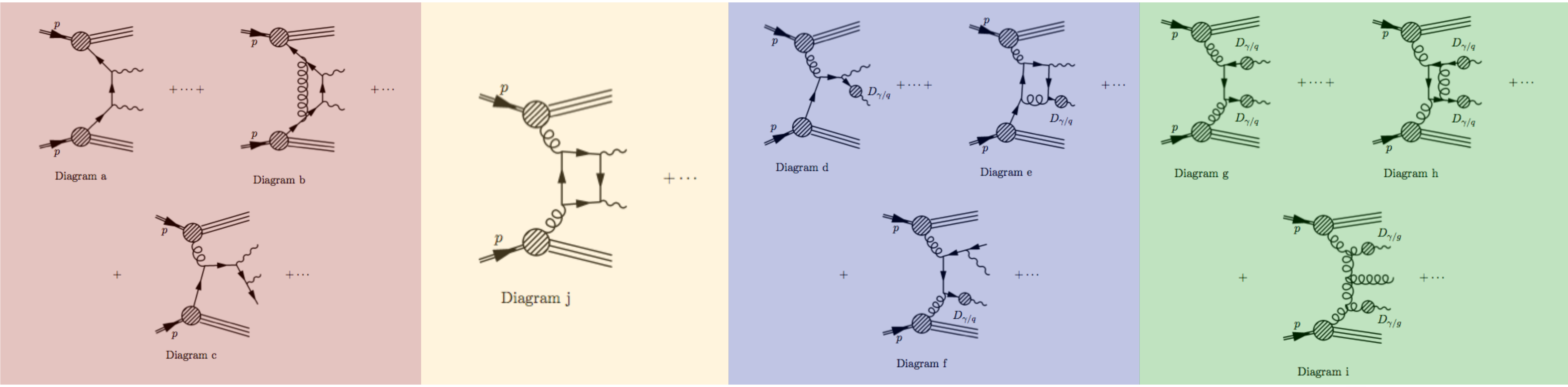




- Run II ended September 30th, 2011
  - Delivered 12 fb^{-1}
  - Peak $4.3\times10^{32}\ cm^{-2}s^{-1}$
- By comparison, Run I delivered 120 pb^{-1}

Diphoton Production

- Dominant background for many new physics processes
  - low mass Higgs, graviton production in ADD/RS models, gauge-mediated SUSY, etc.
- Canonical channel for testing perturbative QCD
- SM diphoton production is sum of many contributions
  - Born, Box, and single- and double-fragmentation
  - dominated by quark annihilation (Born) process
  - major contribution from gluon fusion (Box) process at low Q^2
  - Contribution from fragmentation suppressed by requiring isolated photons

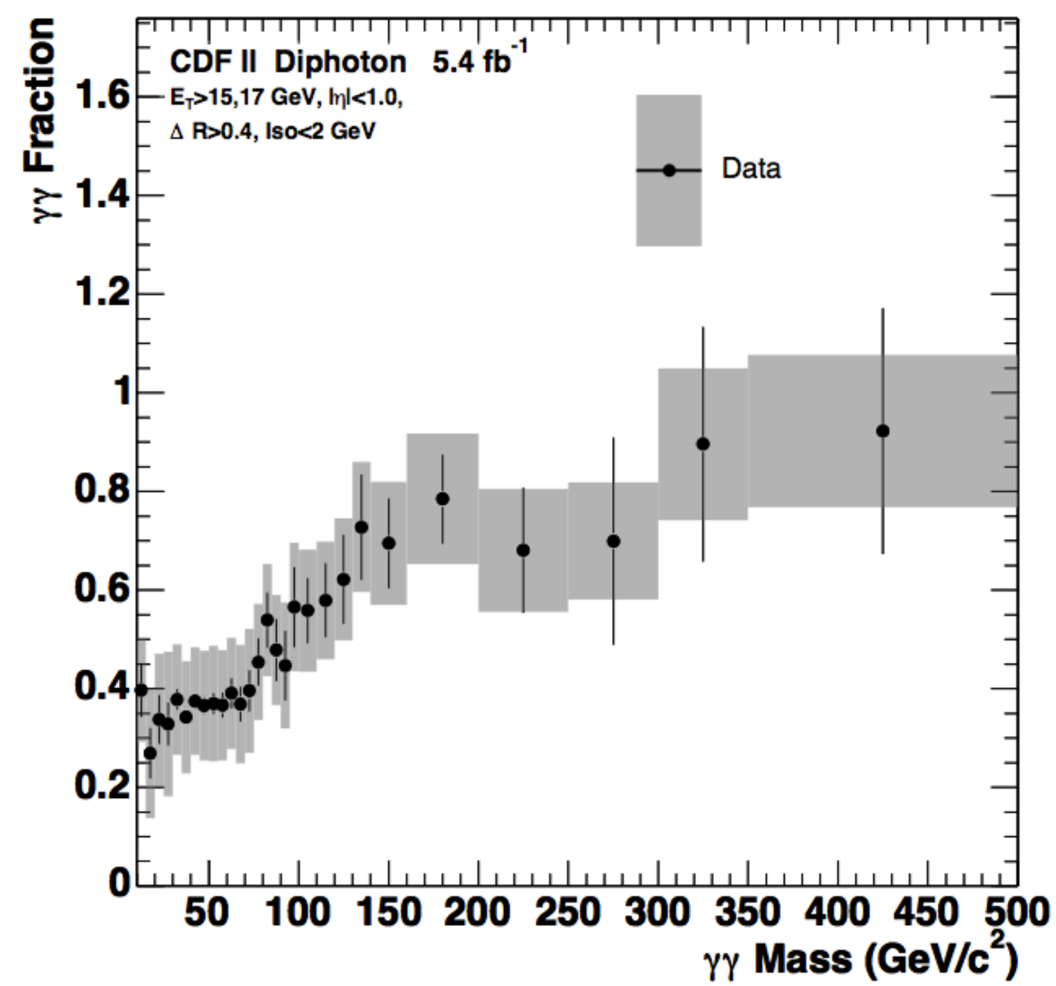


Diphoton Event Selection and Background Subtraction

PRL 107, 102003 (2011); PRD 84, 052006 (2011)

- Select two photons with
  - asymmetric energy selection: E_T>17 GeV and E_T>15 GeV
  - showers consistent with photon: CES χ^2<20
  - fiducality to the central EM calorimeter: -1<y<1
  - isolation: calorimeter E_T<2 GeV in a cone of ΔR<0.4

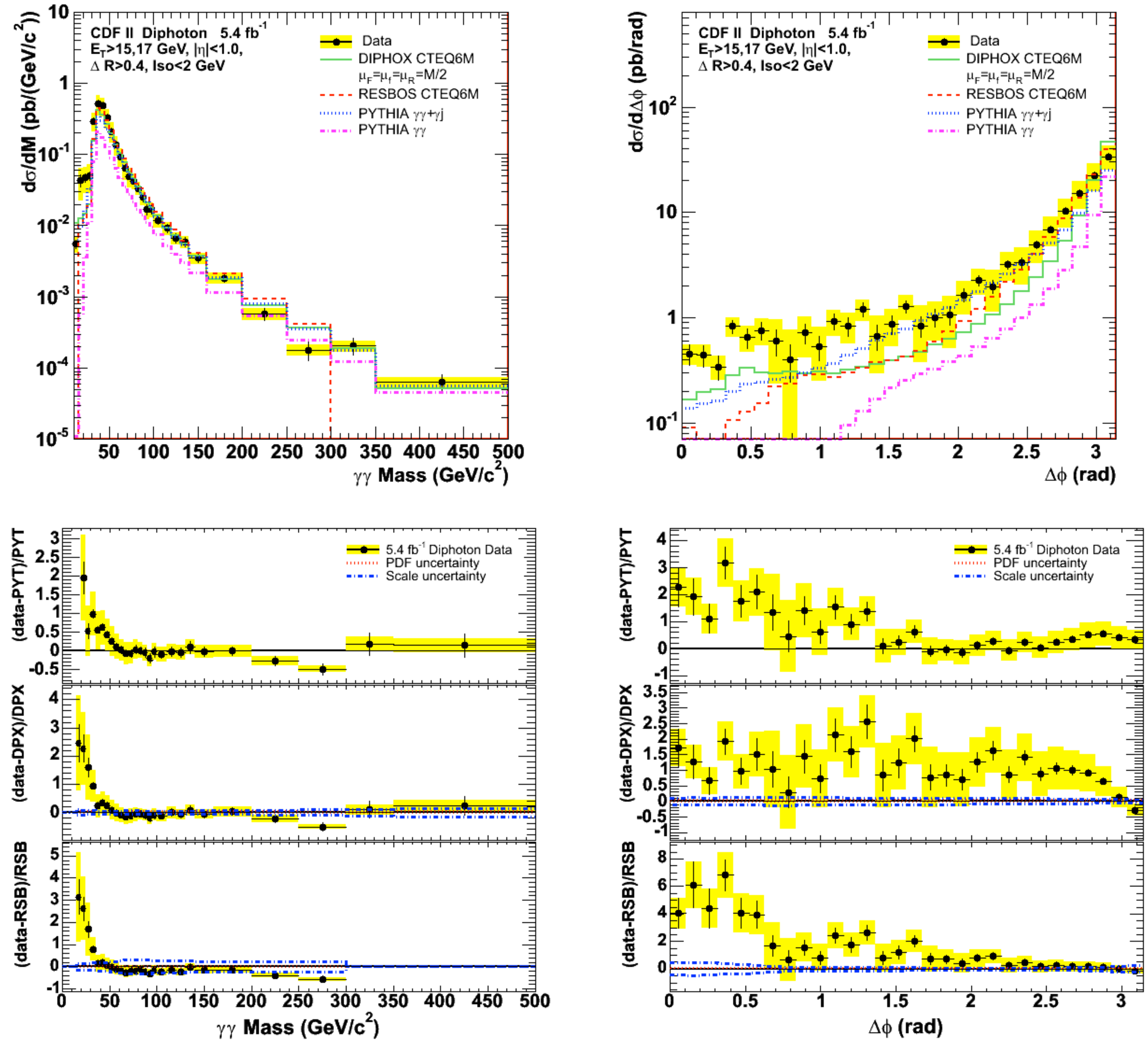
- Use track isolation to statistically subtract backgrounds from π^0's/EM jets
  - Less sensitive than calorimeter isolation to effects of pileup, multiple interactions, energy resolution effects (at low E_T)
    - Compare data/MC efficiency difference with complementary cones
  - Systematic uncertainty on fraction of events due to diphotons: 15-20%



Diphoton Results

PRL 107, 102003 (2011); PRD 84, 052006 (2011)

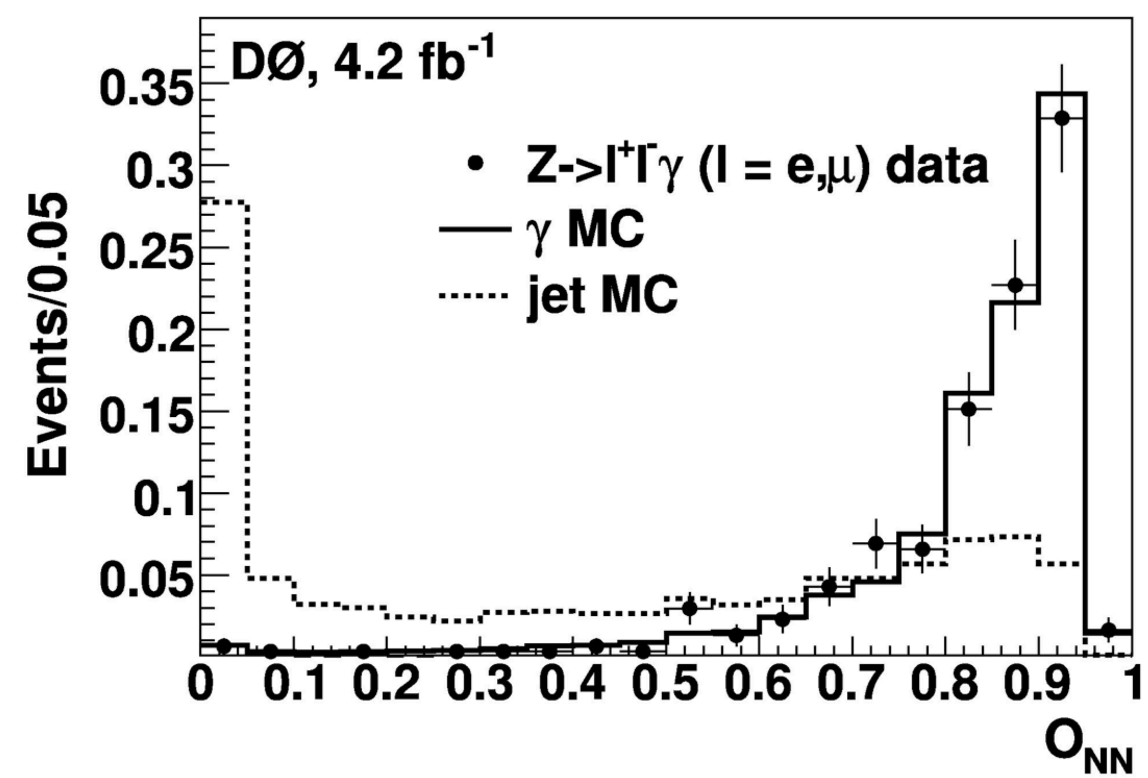
- Compare against various simulations
  - Pythia: Both LO ME+PS and LO γγ+γj w/ QED ISR/FSR
  - RESBOS: collinear initial-state gluons resummed to NNLL
  - DIPHOX: NLO (LO box diagram)
- Generally good agreement except for low $M_{\gamma\gamma}$ and small $\Delta\phi$
- Uncertainty dominated by uncertainty on background subtraction

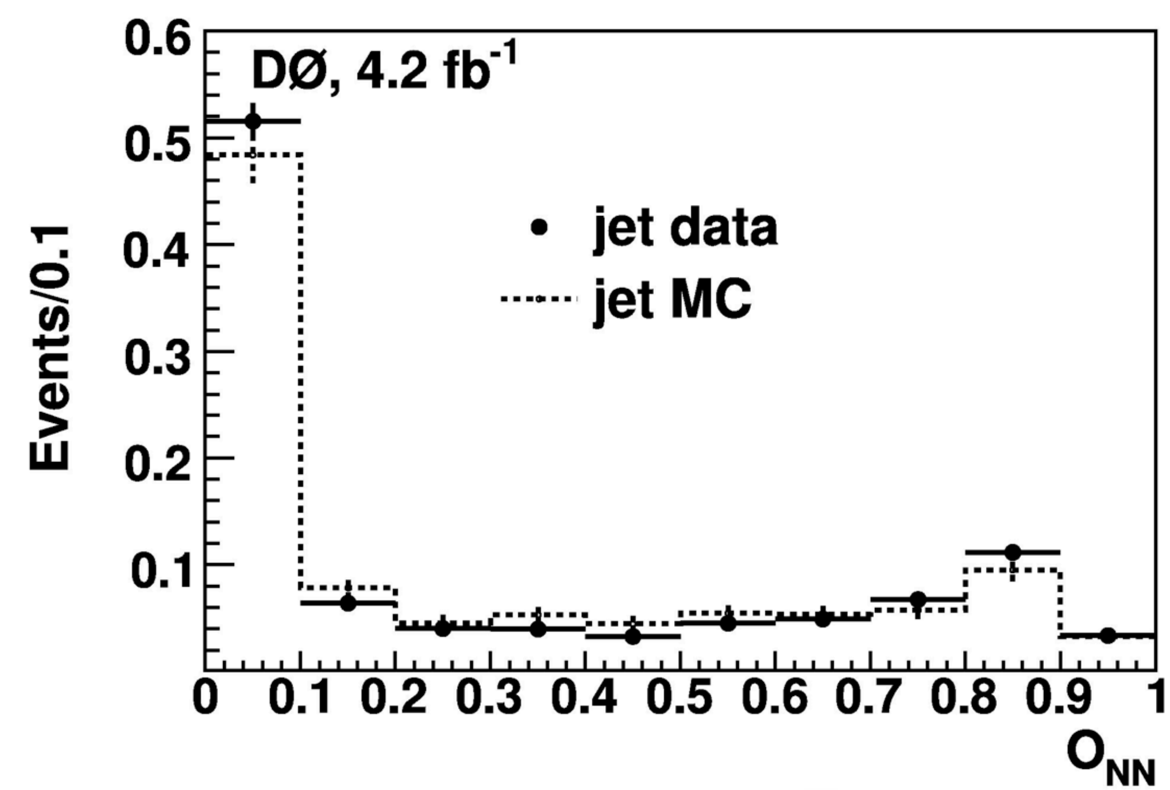


Diphoton Event Selection and Background Subtraction

- Select two photons with
  - asymmetric energy selection: $E_T>21$ GeV and $E_T>20$ GeV
  - shower shape consistent with photon
  - central photons: $|\eta|<0.9$
  - isolation: calorimeter E_T in cone $\Delta R<0.4$ is <10% of photon E_T
- Use neural network to separate direct photons from π^0's/EM jets
  - trained on tracker and calorimeter isolation and preshower information
  - $O_{NN}>0.3$ (97% efficient for photons, 40% efficiency for π^0's)

PLB 690, 108 (2010)

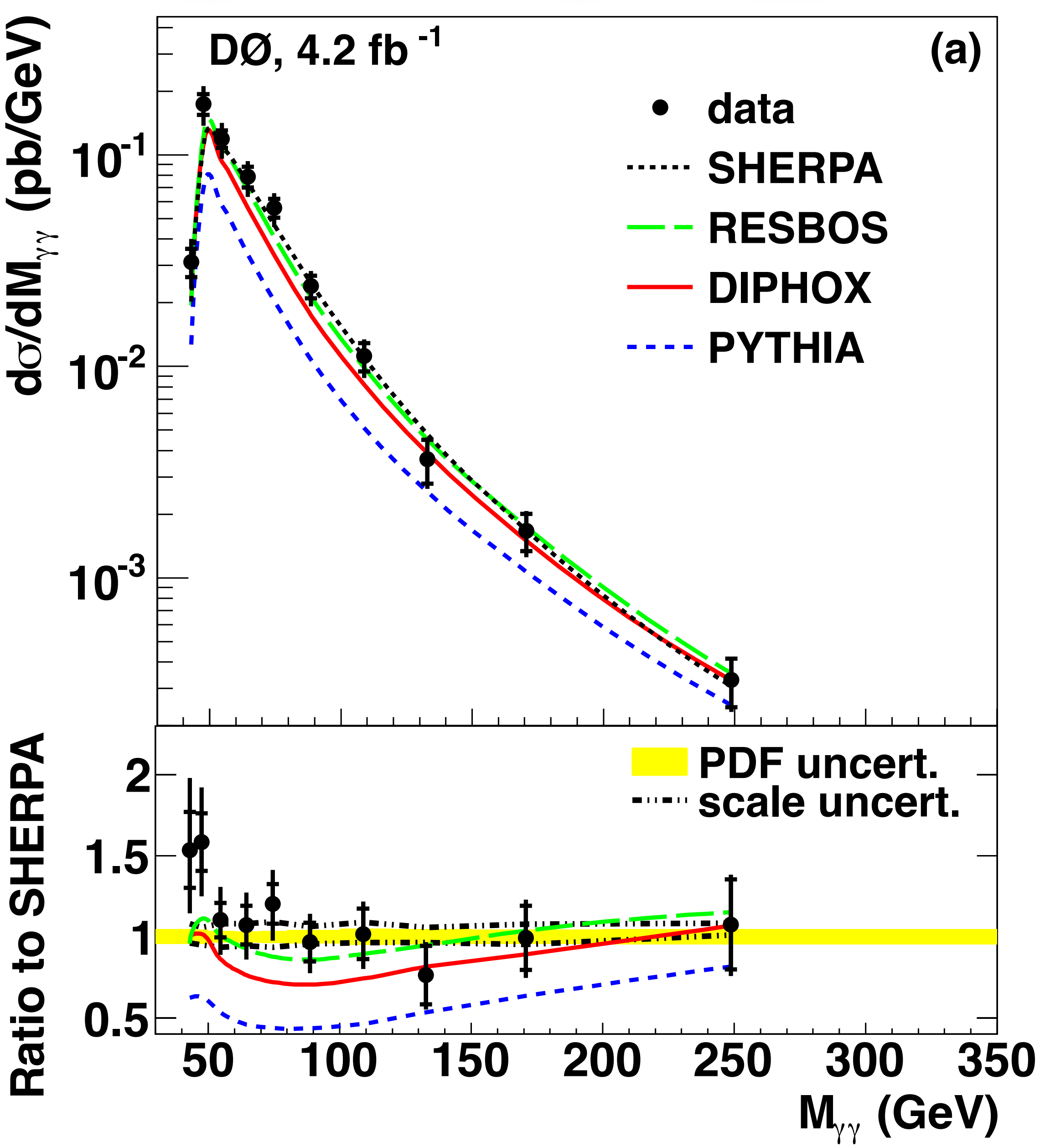


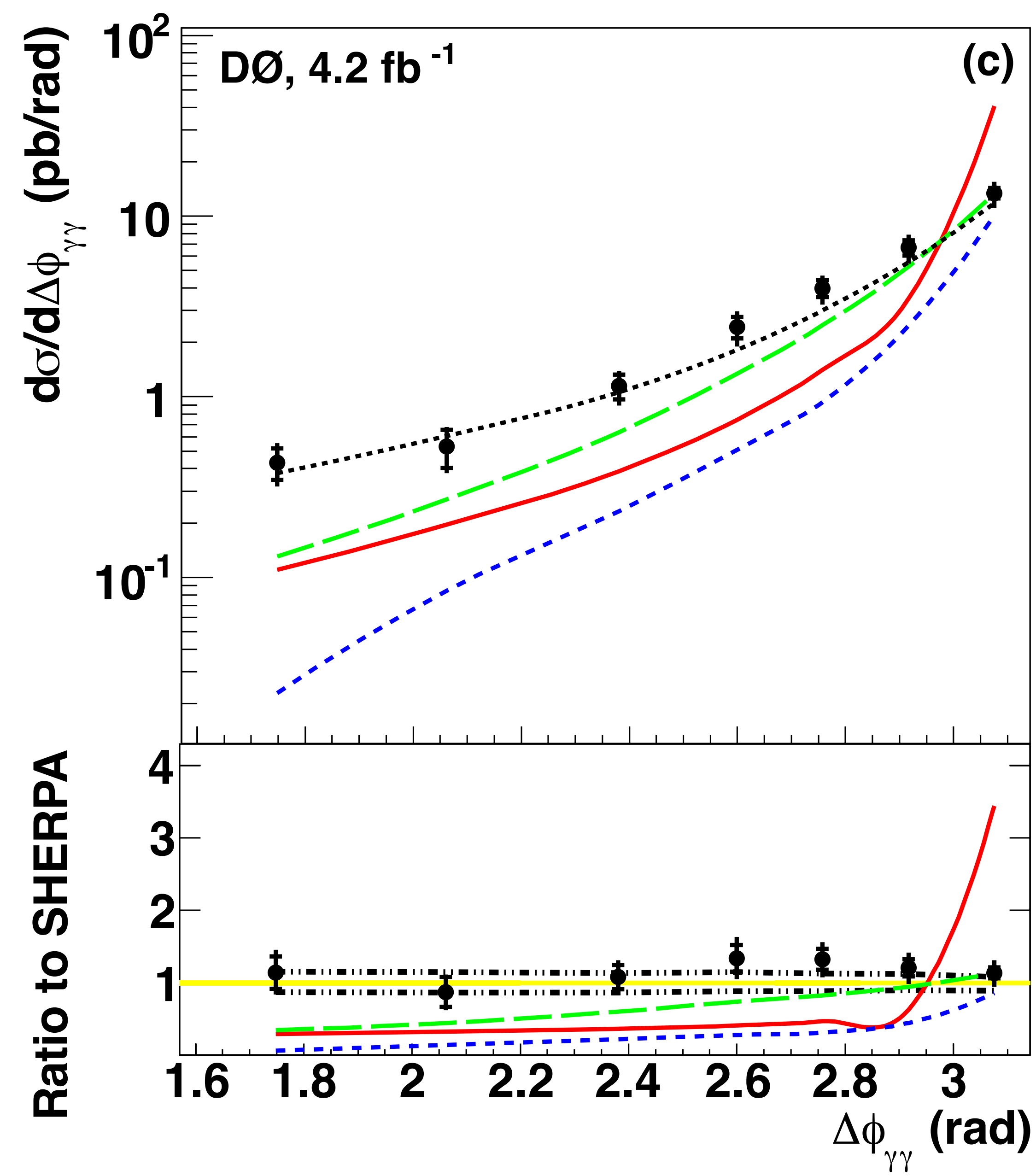


Diphoton Results

PLB 690, 108 (2010)

- Includes additional comparison with Sherpa
  - Pythia is only LO γγ

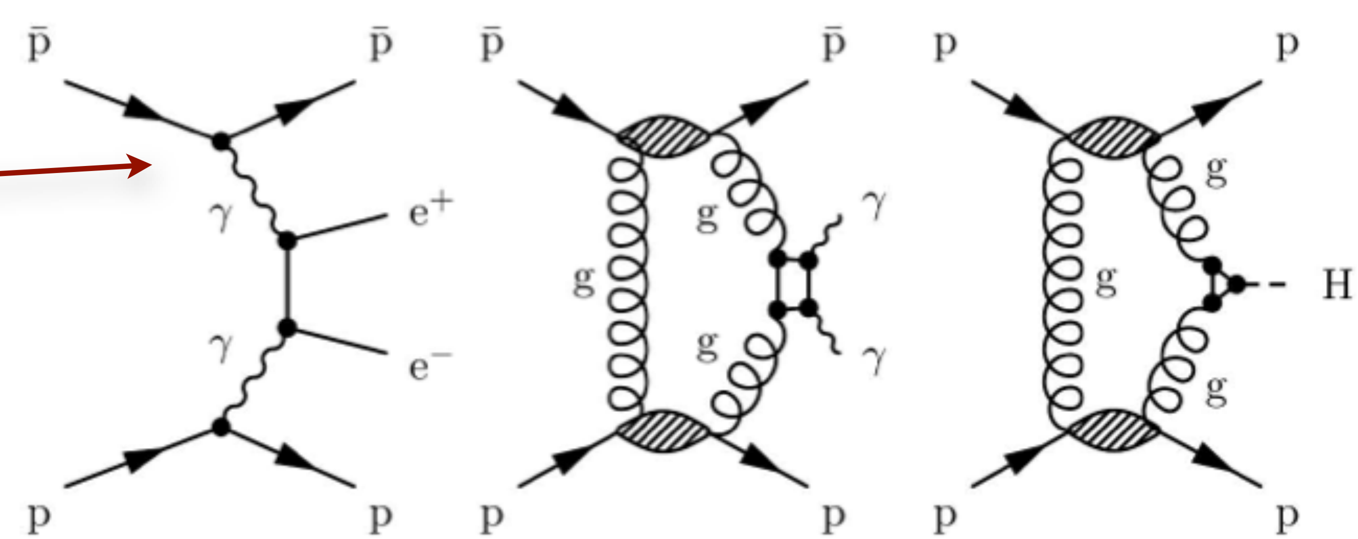




Exclusive Diphotons

CDF10524

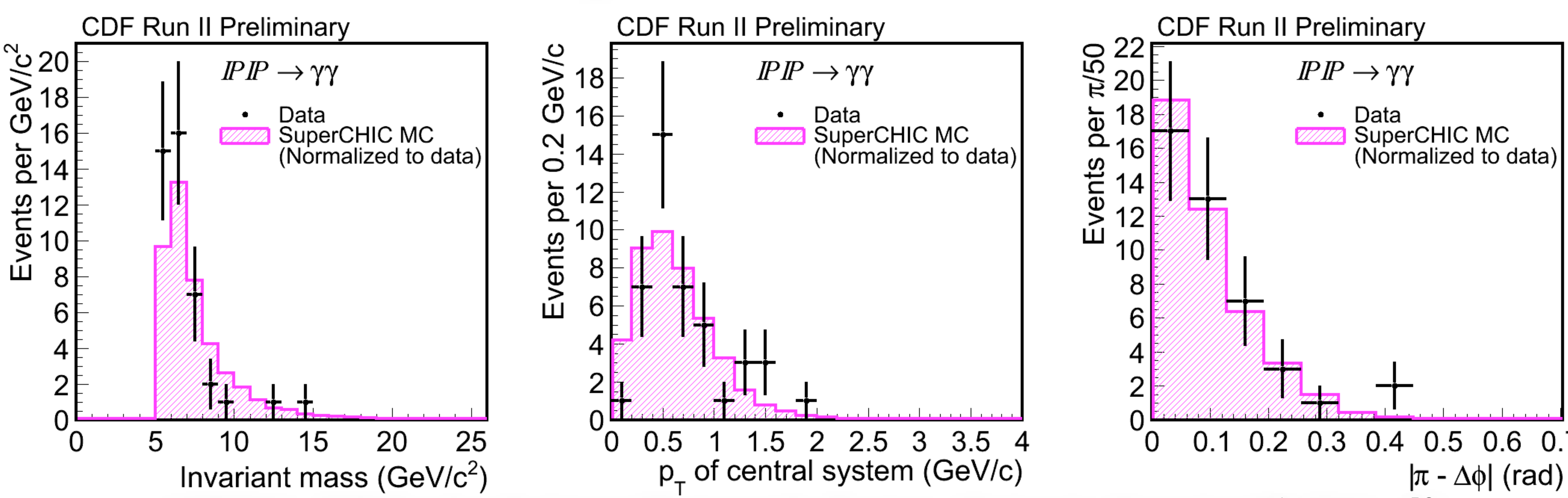
- Also possible to produce two "*exclusive*" photons through double pomeron exchange
  - $p\bar{p} \rightarrow p + \gamma\gamma + \bar{p}$ ('+' implies rapidity gap)
  - protons scatter diffractively (p_T<1 GeV)
  - proceeds through gluon fusion; second gluon exchange ensures color cancellation
- Process suppressed (σ~0.7 pb) with large uncertainty (factor of 3)
  - sensitive to unintegrated gluon PDFs & non-perturbative effects
  - Sudakov suppression & rapidity gap survival factor
  - protons cannot disassociate
  - use QED production of exclusive dielectrons as a control channel



Exclusive Diphoton Selection and Background Suppression

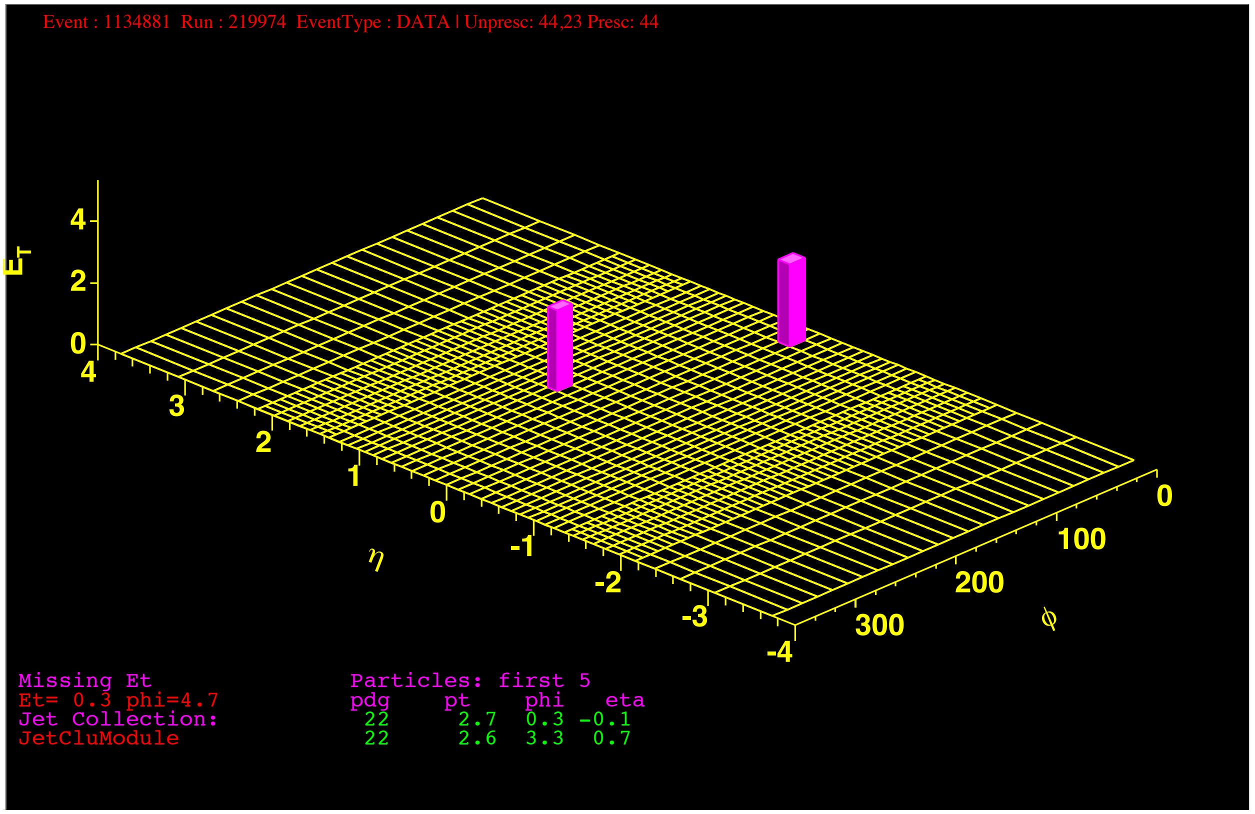
CDF10524

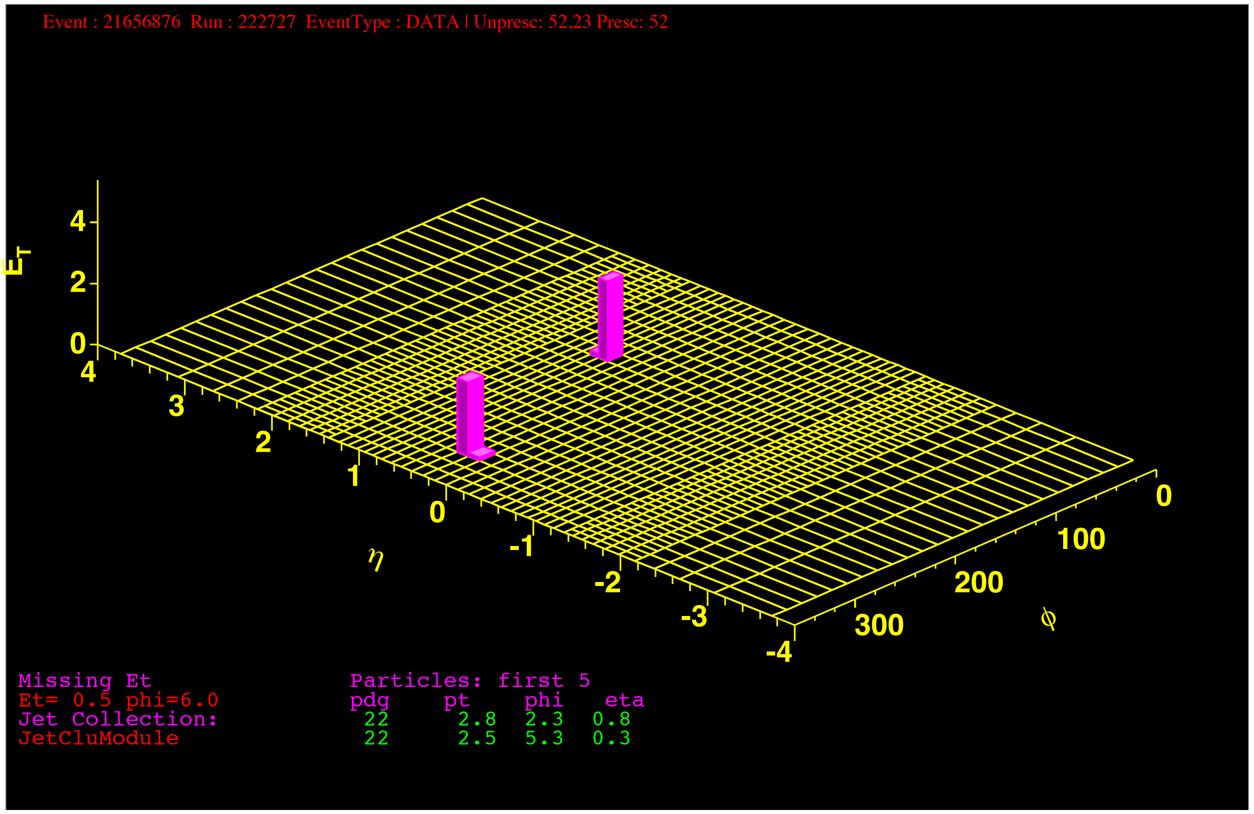
- Require two well-reconstructed, central photons with E_T>2.5 GeV
- No other activity in the detector
  - Including calorimeters (|η|<3.6), miniplug (3.6<|η|<5.2), beam shower counters (5.4<|η|<7.4), and gas Cherenkov detectors (3.7<|η|<4.7)
  - effective luminosity (0 pileup events) is 70±4 pb^{-1}; ~7% efficiency
- Processes other than gg→γγ contribute to final state
  - Irreducible qq→γγ (<5%) and γγ→γγ (<1%)
  - Reducible $\pi^0\pi^0$ and ηη backgrounds shown to be small
    - π^0 fake possible only if γ ranges out or falls in un-instrumented region

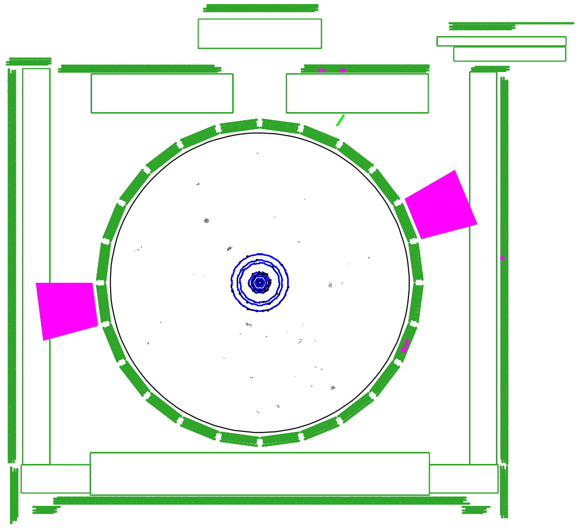


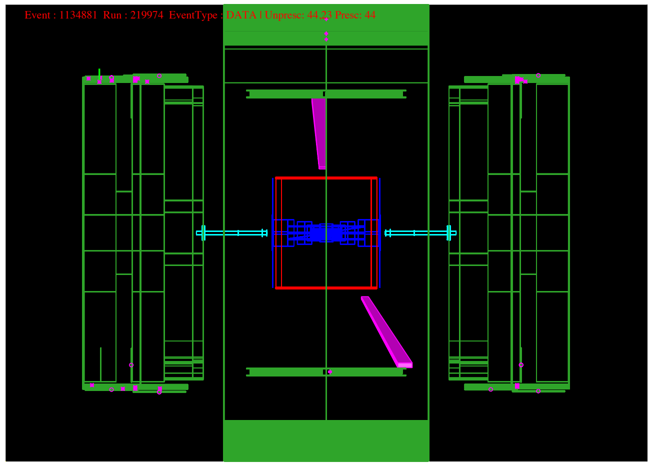
Exclusive Diphoton Events

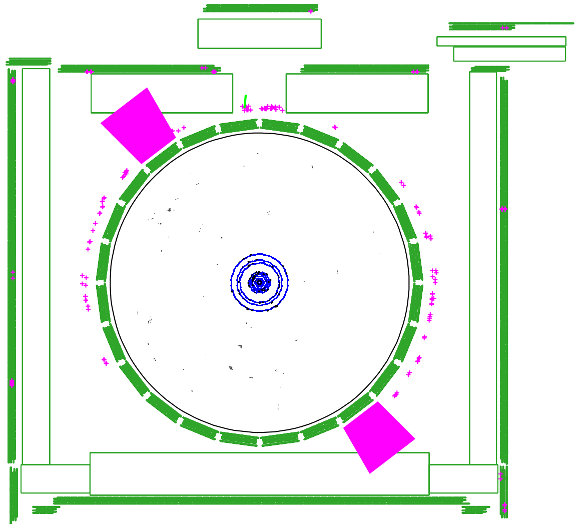
CDF10524

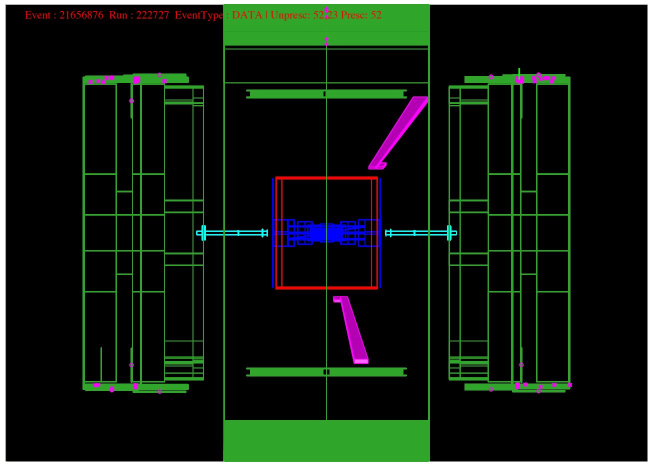












Exclusive Diphoton Cross Section

CDF10524

- Other measurements of exclusive production at CDF
  - jets
  - charmonium
- These measurements distinguish between a wide variety of phenomenological predictions
  - which for exclusive Higgs were varying by a factor of 100

$$\sigma^{|\eta|<1, E_T(\gamma)>2.5\mathrm{GeV}}_{e^+e^-,\mathrm{exclusive}} = 2.88 \pm 0.59(stat) \pm 0.62(syst)\ \mathrm{pb}$$

QED prediction: (3.25±0.7) pb

$$\sigma^{|\eta|<1, E_T(\gamma)>2.5\mathrm{GeV}}_{\gamma\gamma,\mathrm{excl}} = 2.48 \pm 0.42(stat) \pm 0.41(syst)\ \mathrm{pb}$$

- Exclusive diphoton results agree nicely with KMR (Khoze, Martin, Ryskin) model

Dijet Cross Section (D0)

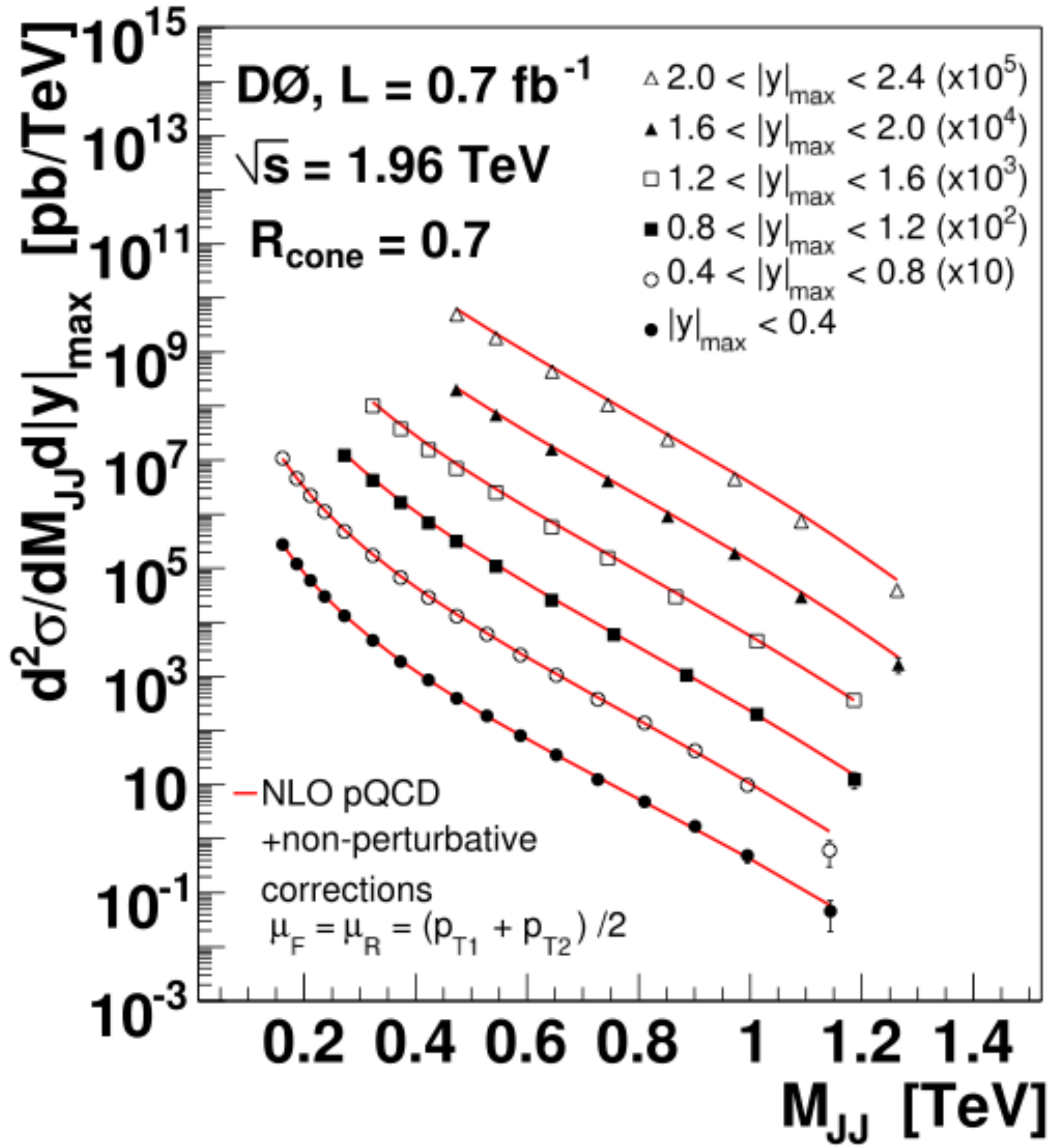
PLB 693, 531 (2010)

- The dijet cross section is a test of perturbative QCD
    - constrains PDFs
        - notably large-x gluon distribution function
    - Sensitive to new physics
        - low mass, electroweakly produced dijet resonances not readily accessible at the LHC
- Selection
    - both jets required to have pT>40 GeV
    - midpoint 0.7 cone algorithm used
    - differential xs measured in bins of $|y|_{max}=max(|y_1|,|y_2|)$
    - corrected for instrumental effects and presented at particle level

Dijet Cross Section (D0)

- Measure double-differential cross section
  - Compare with NLOJET++
    - Using MSTW2008NLO PDFs (this is the same data used to derive the PDFs)
  - Uncertainty dominated by jet-energy scale uncertainty
  - Experimental uncertainties similar in size to both PDF and scale uncertainties

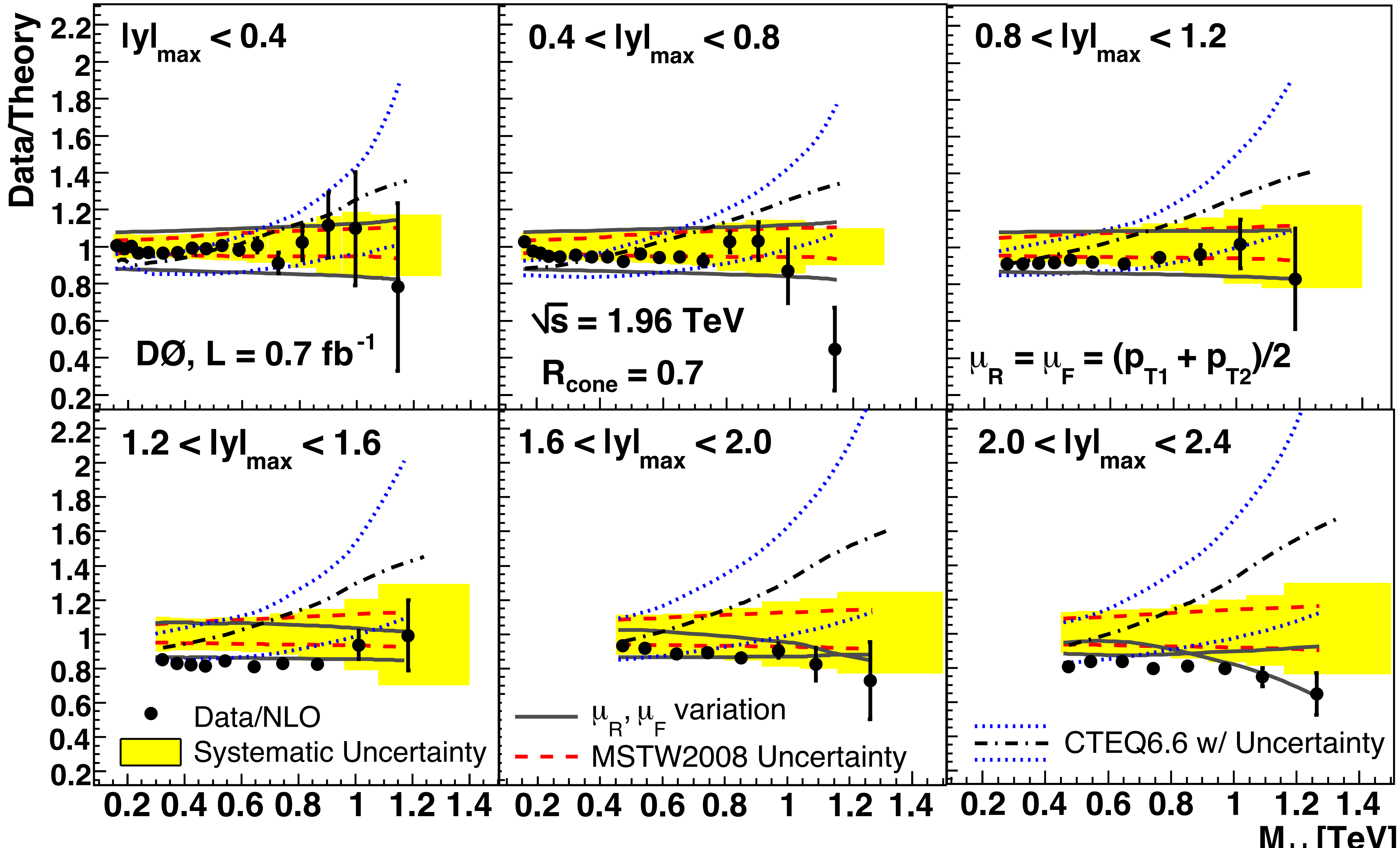
PLB 693, 531 (2010)



Dijet Cross Section (D0)

PLB 693, 531 (2010)

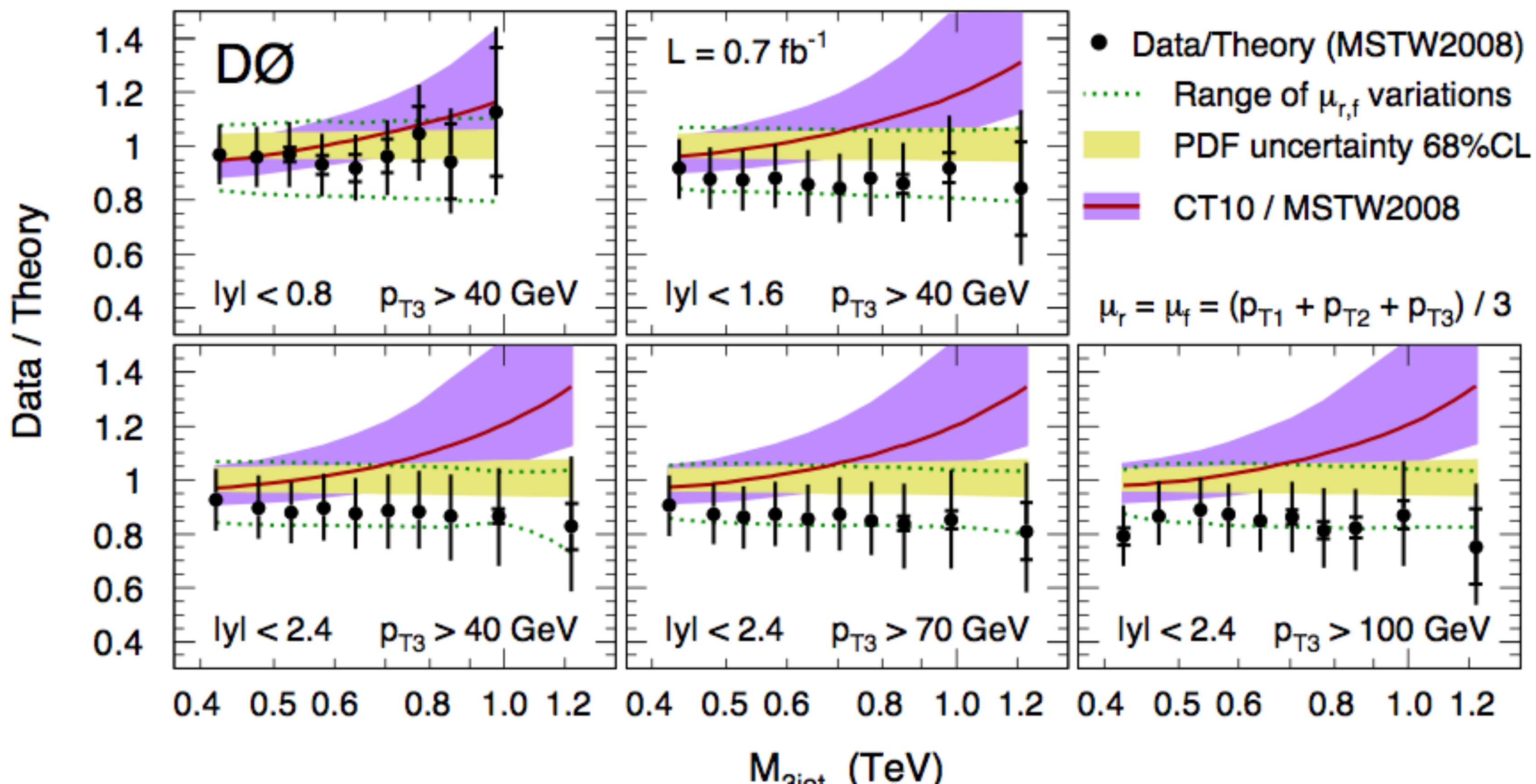
- decent agreement with CTEQ6.6 PDFs at large |y|
  - CT10 PDFs have been updated with this data, as well
- fully correlated 6.1% luminosity not shown



Multijet Production (D0)

PLB 704, 434 (2011)

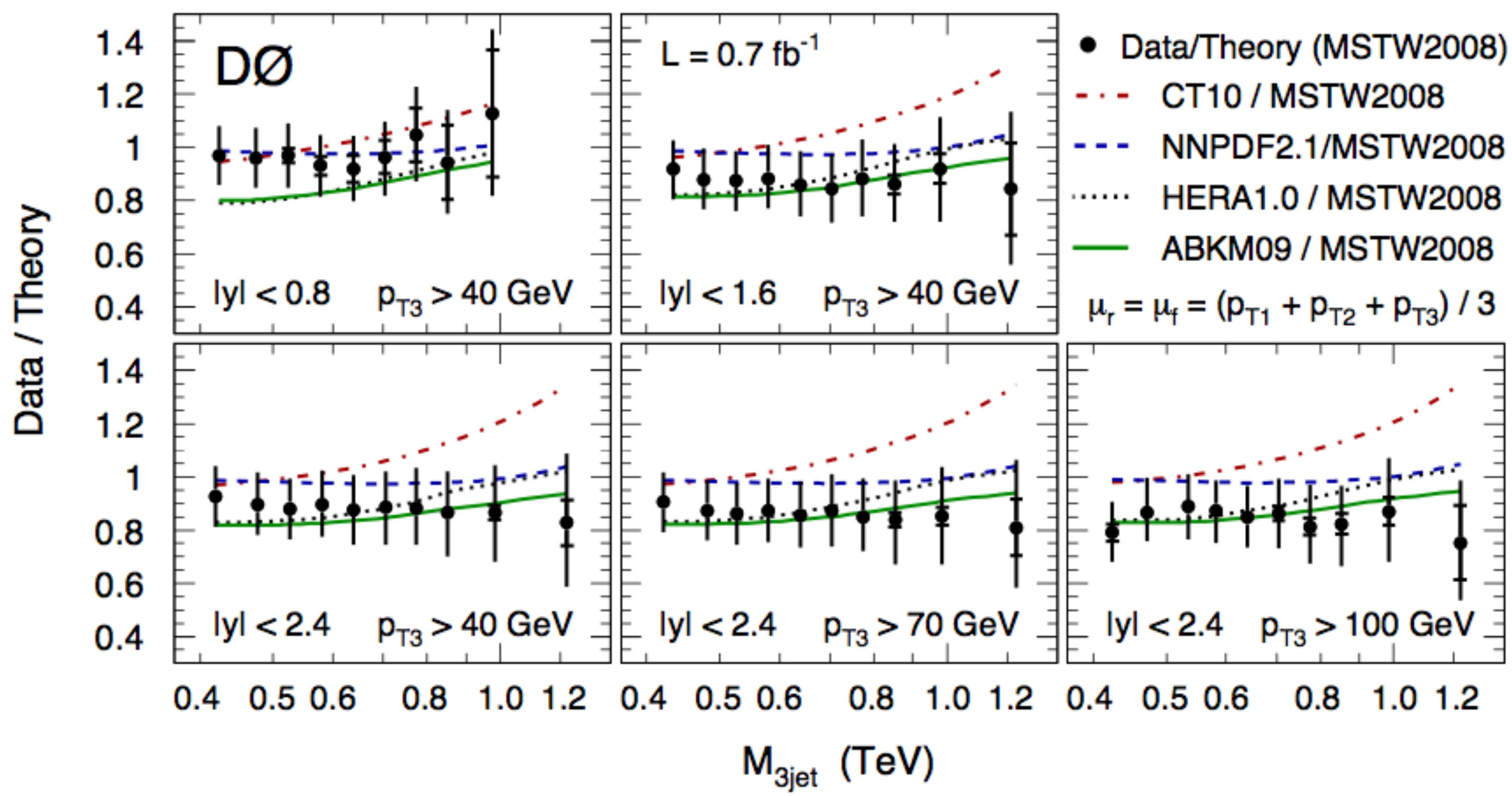
- Measure three-jet differential cross section
  - test of pQCD at higher order in α_s
  - Require p_{T1}>150 GeV and p_{T3}>40 GeV and well-separated jets (R_{ij}>1.4)
    - no requirement on p_{T2} except ordering
  - midpoint 0.7 jet clustering algorithm



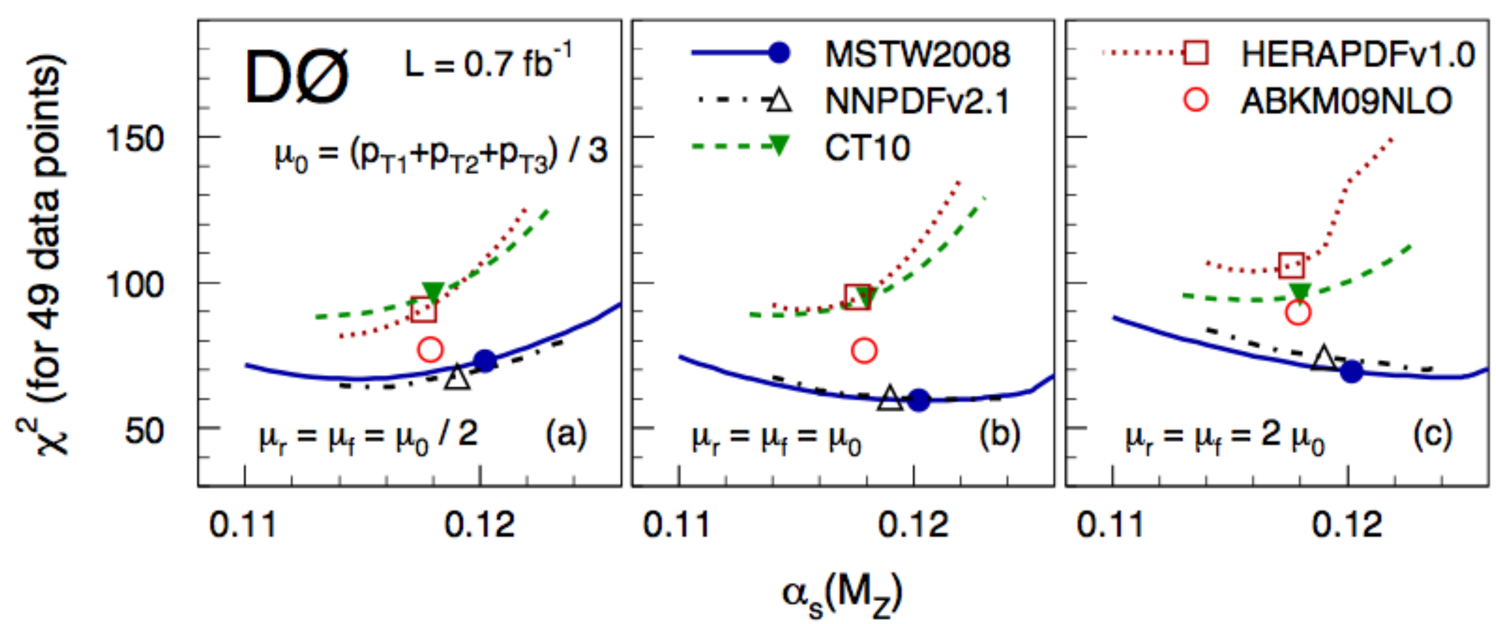
Multijet Production (D0)

- Overall good agreement with a variety of different PDF sets
  - MSTW and NNPDF fare best

PLB 704, 434 (2011)



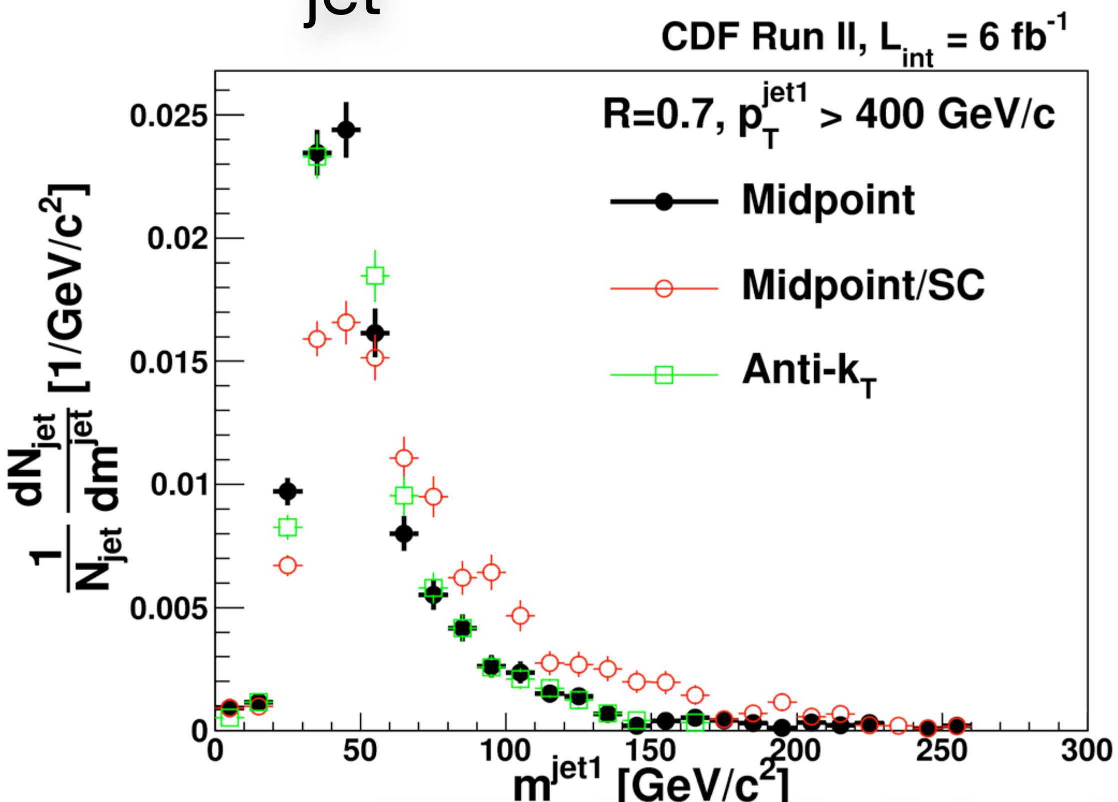
- Also provide goodness-of-fit as a function of α_s



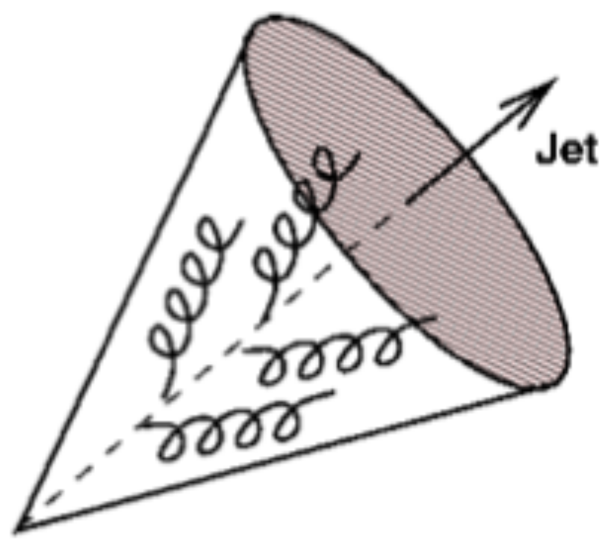
Jet Substructure

arXiv:1106.5952

- Considerable LHC program to search for new physics with boosted objects
  - Z' to boosted tops, W/Z+boosted Higgs, GMSB+boosted Higgs, etc.
  - Initial feasibility studies performed on simulation only
    - Important to test QCD directly with data
- Selected events with on central jet with p_T>400 GeV
  - Reject events where the jet recoils against MET or another massive jet



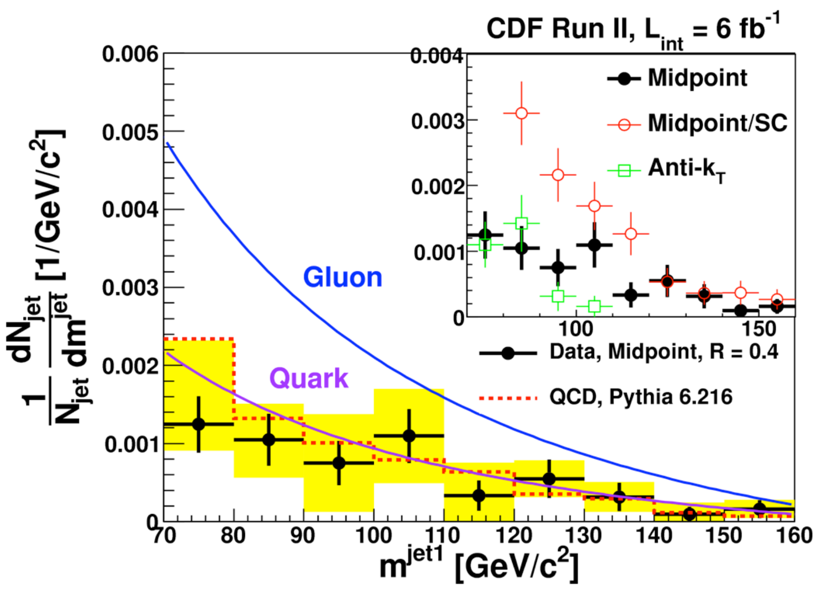
- Subtract expected pileup/UE contribution to the mass with complementary cones method

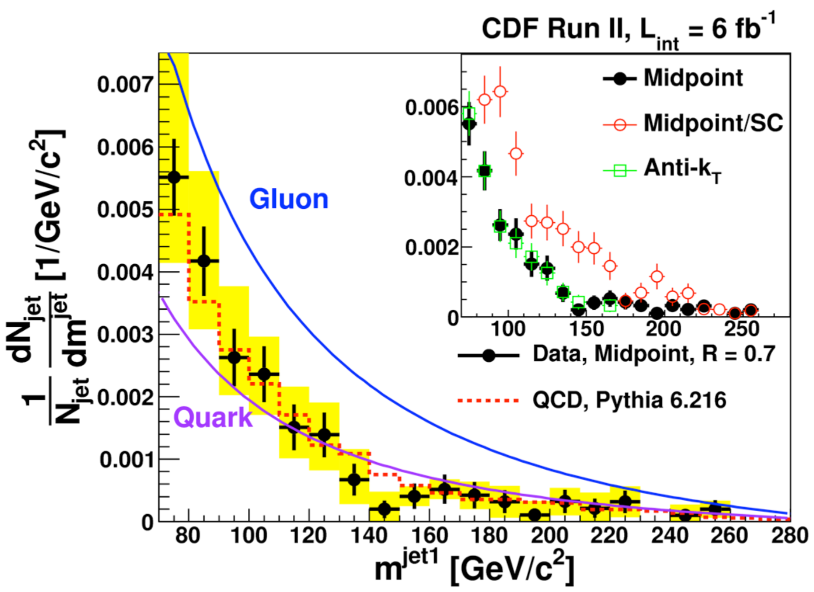


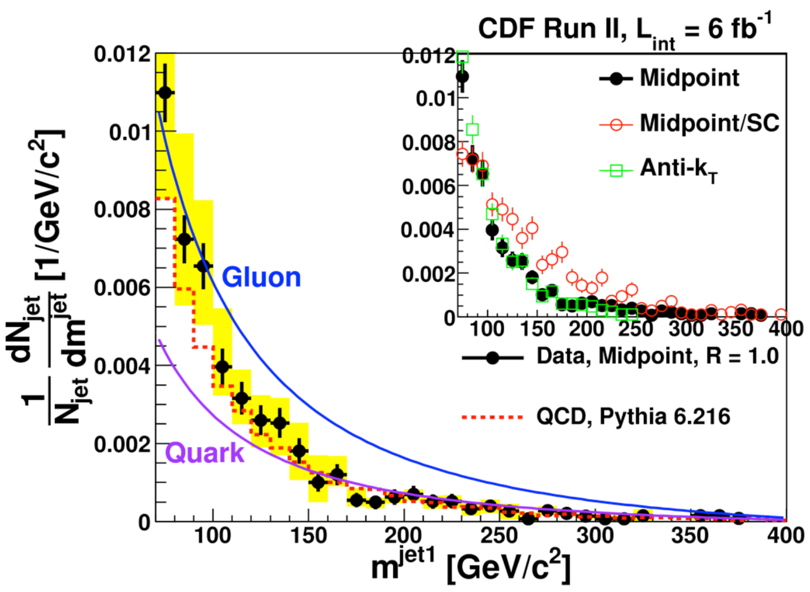
Jet Substructure

arXiv:1106.5952

- Compare differential jet cross section as a function of jet mass for different algorithms and cone sizes
  - In leading-log approximation, a jet typically acquires a large mass due to a single hard gluon emission





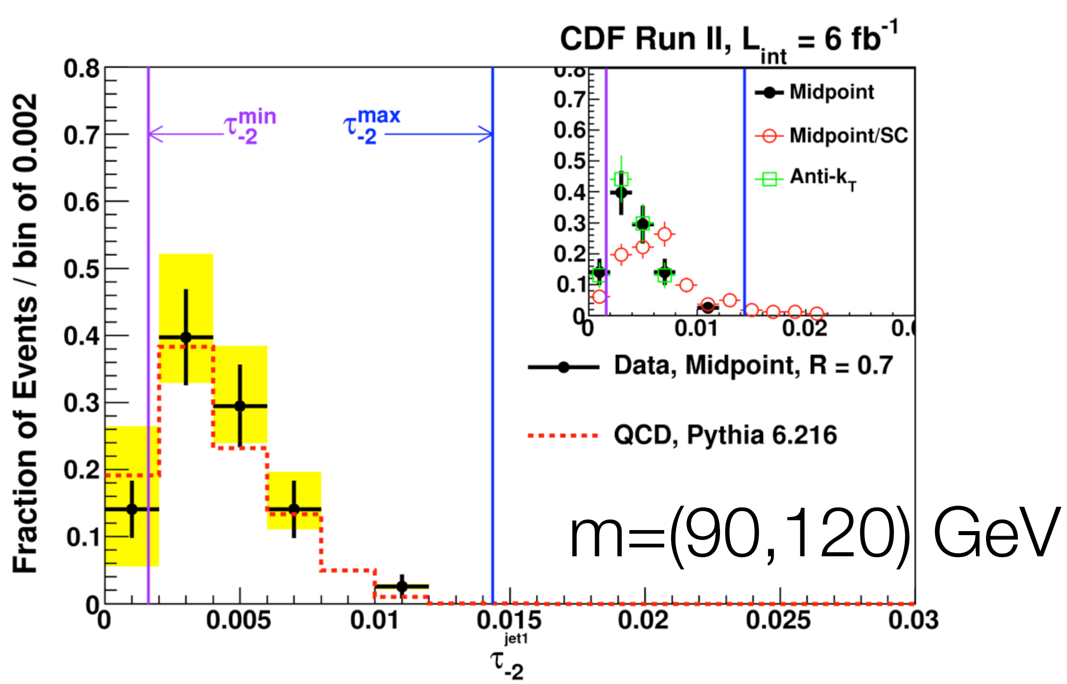


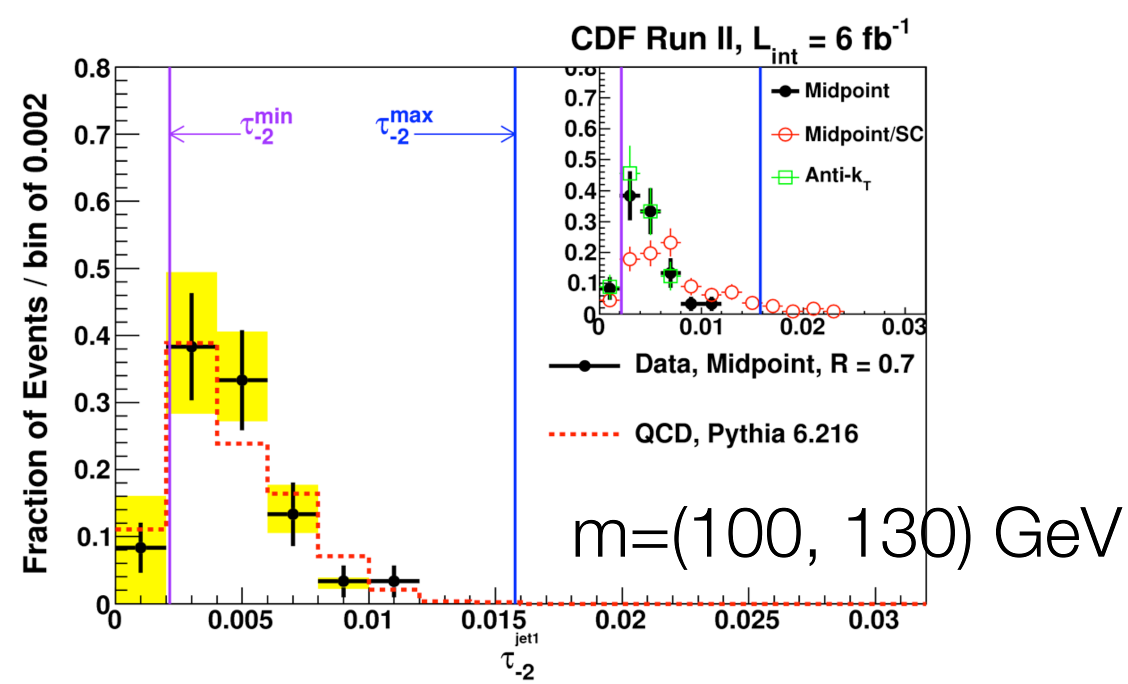
Jet Substructure

arXiv:1106.5952

- Angularity is defined by
  - $$\tau_a(R, p_T) = \frac{1}{m_J} \sum_{i \in jet} \omega_i \sin^a \theta_i \left[1 - \cos\theta_i\right]^{1-a} \sim \frac{2^{a-1}}{m_J} \sum_{i \in jet} \omega_i \theta_i^{2-a}$$
    tower energy
  - sum is over all jet constitutents (i.e. towers)
- pQCD predicts angularities of high mass jets to have sharp kinematic edges, with min and max given by:

$$\tau_{-2}^{\min} \approx \left(\frac{2p_{\mathrm{T}}}{m_{\mathrm{jet}}}\right)^{-3} \qquad \tau_{-2}^{\max} \approx \frac{m_{\mathrm{jet}}}{p_{\mathrm{T}}} \frac{R^2}{8}$$



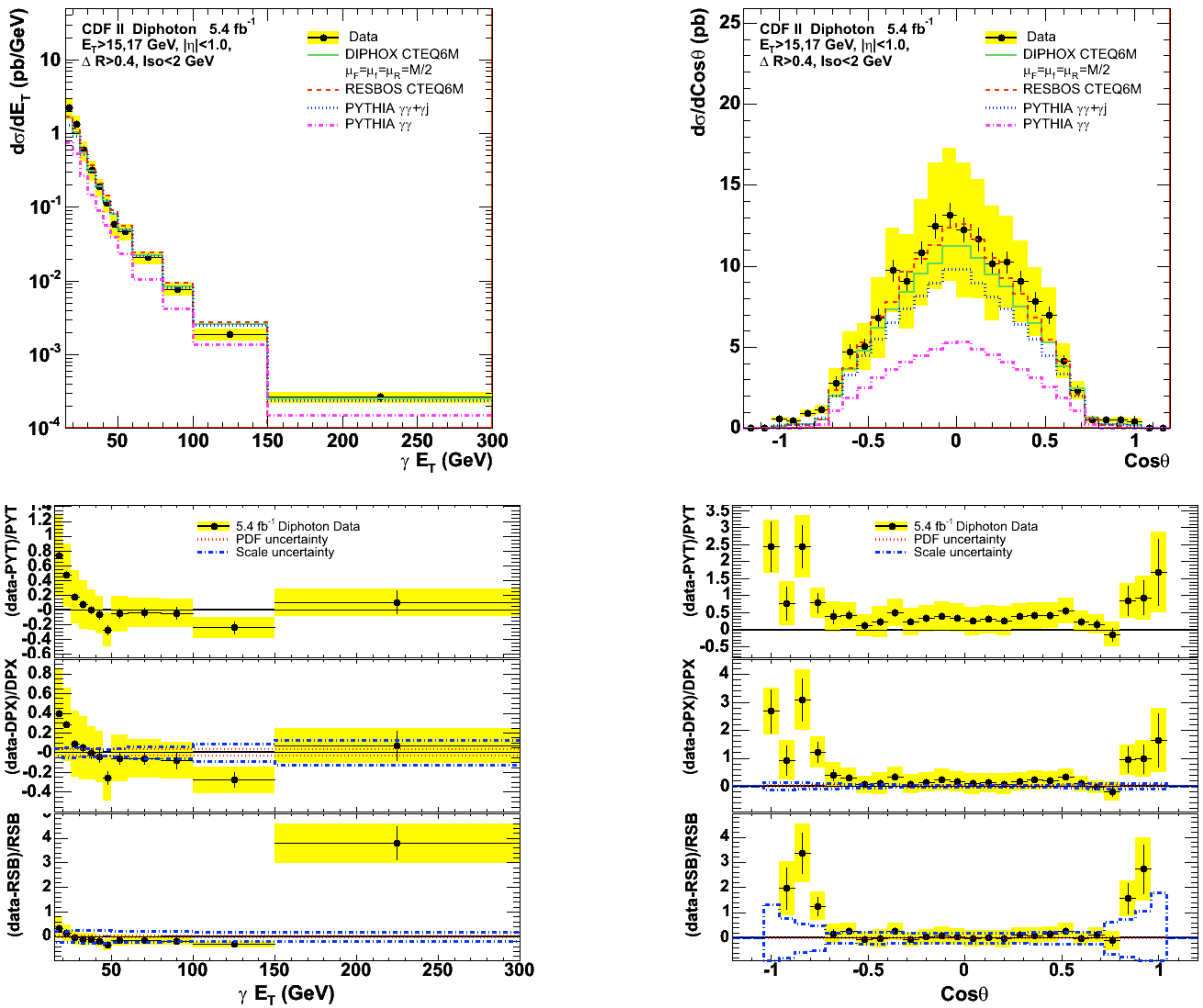


Summary

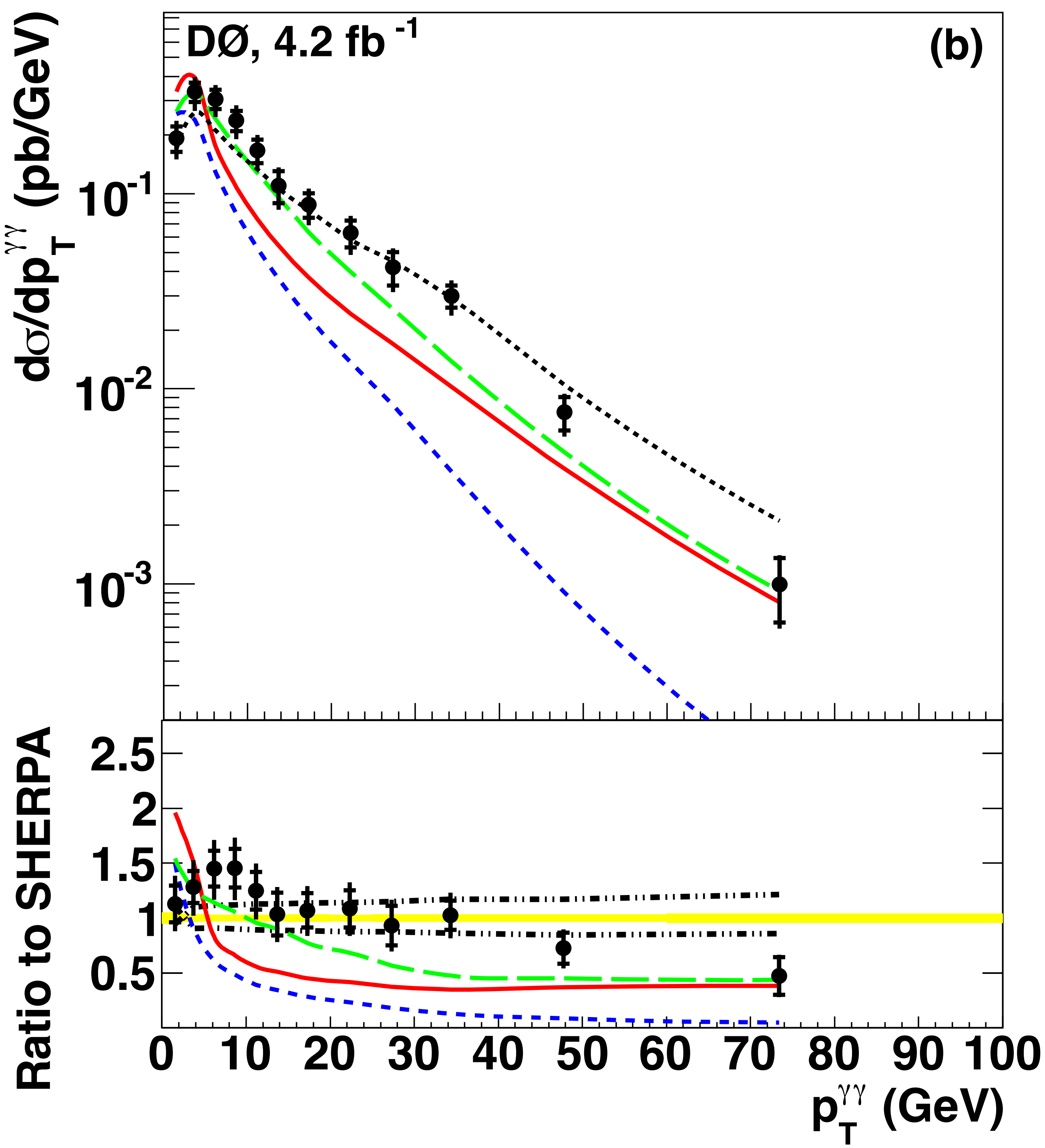
- Diphoton differential cross sections disagree with NLO calculations at low $M_{\gamma\gamma}$ and small $\Delta\phi$
  - indication of the importance of NNLO terms and better treatment of fragmentation
  - see arXiv:1110.2375 for NNLO treatment
- First observation of exclusive diphoton production consistent with expectation
  - Exclusive Higgs production at the LHC may be possible
- Nice agreement of dijet and three-jet mass cross sections with pQCD and MSTW PDFs
- Jet substructure at the Tevatron sees good overall agreement with prediction
  - First measurement of its kind (“jetography”)

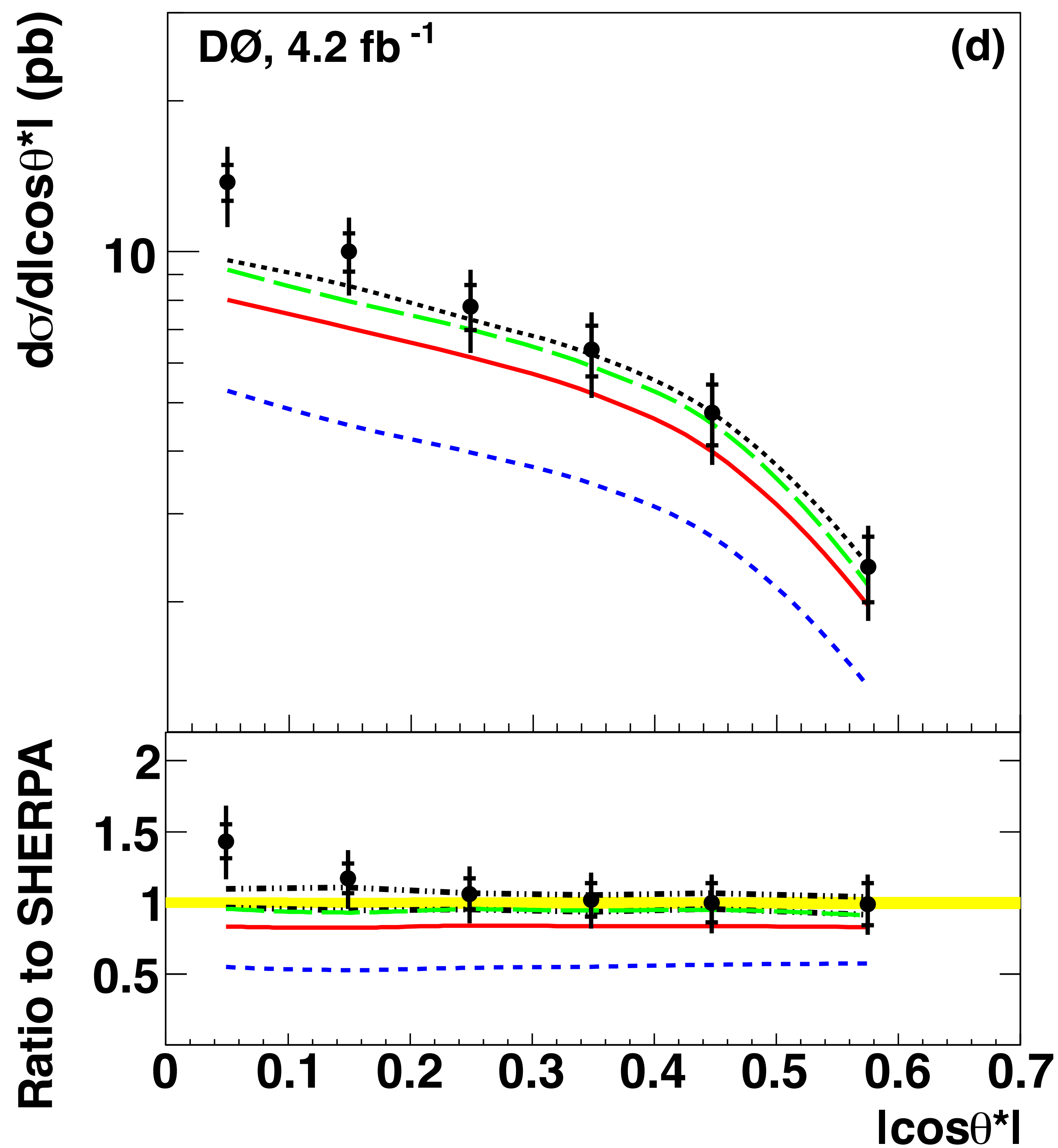
Backup Slides

Diphotons (CDF)

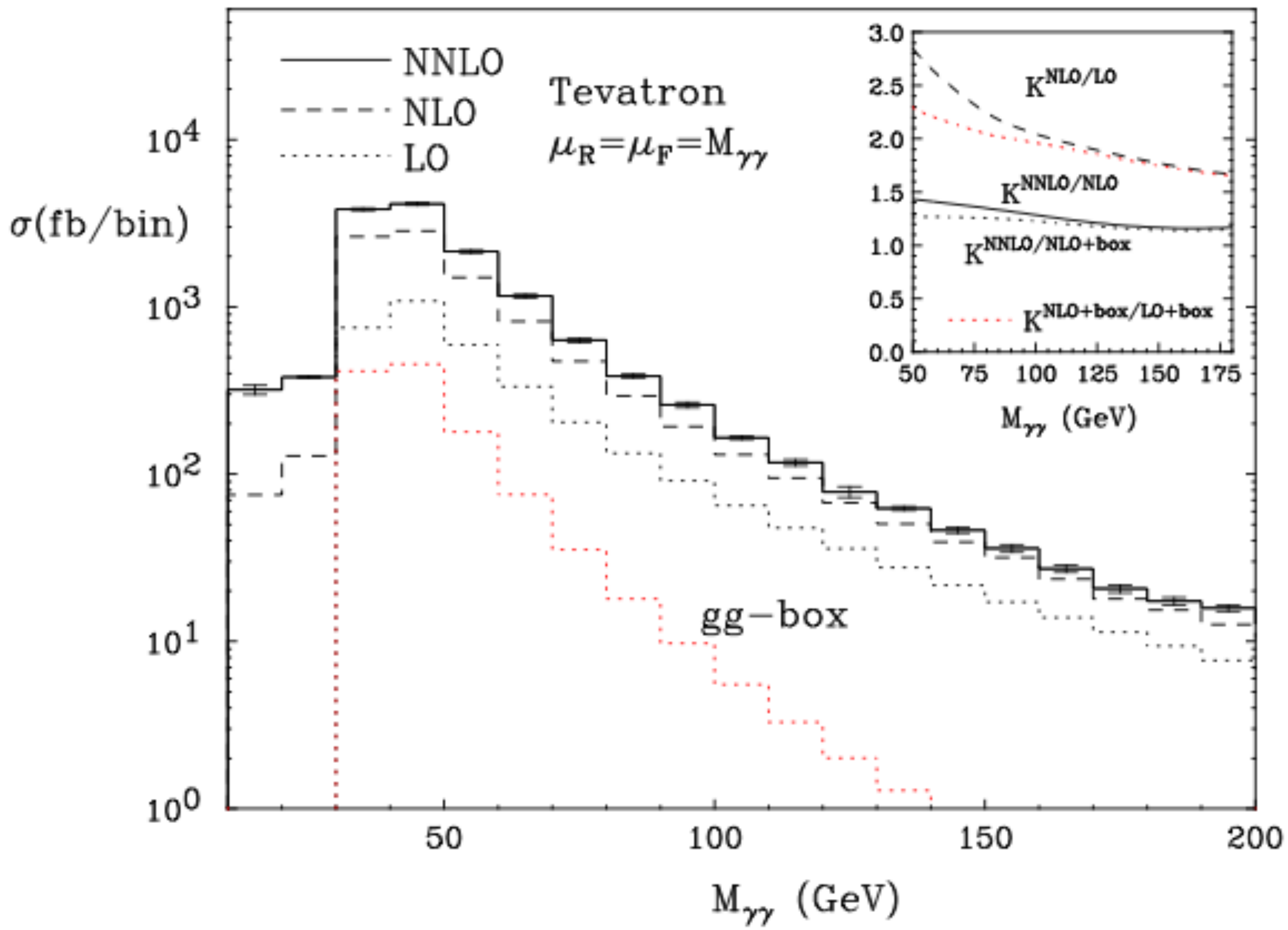


Diphotons (D0)





NNLO Diphotons at the Tevatron



arXiv:1110.2375

Exclusive Diphoton Yield

Exclusive $\gamma\gamma$	Value
Events	43
$\mathcal{L}_{\mathrm{int}}$	1.11 ± 0.07 fb^{-1}
Photon efficiency	0.40±0.02 (stat)±0.03 (syst)
Exclusive efficiency	0.0680±0.004 (syst)
Conversion acceptance	0.57±0.06 (syst)
$\pi^0\pi^0$ background (events)	0.0, <16% (95% C.L.)
Dissociation B/G (events)	0.14 ±0.14 (syst)
Exclusive e^+e^-	
Events	34
Electron efficiency	0.33±0.01(stat)±0.02 (syst)
Radiative acceptance	0.42±0.08 (syst)
Dissociation B/G (events)	3.8±0.4 (stat)±0.9 (syst)