

New Measurements with Photons at the Tevatron

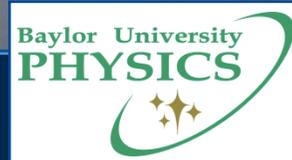
Jay R. Dittmann
Baylor University

For the CDF and DØ Collaborations



Rencontres de Moriond QCD 2012

March 15, 2012



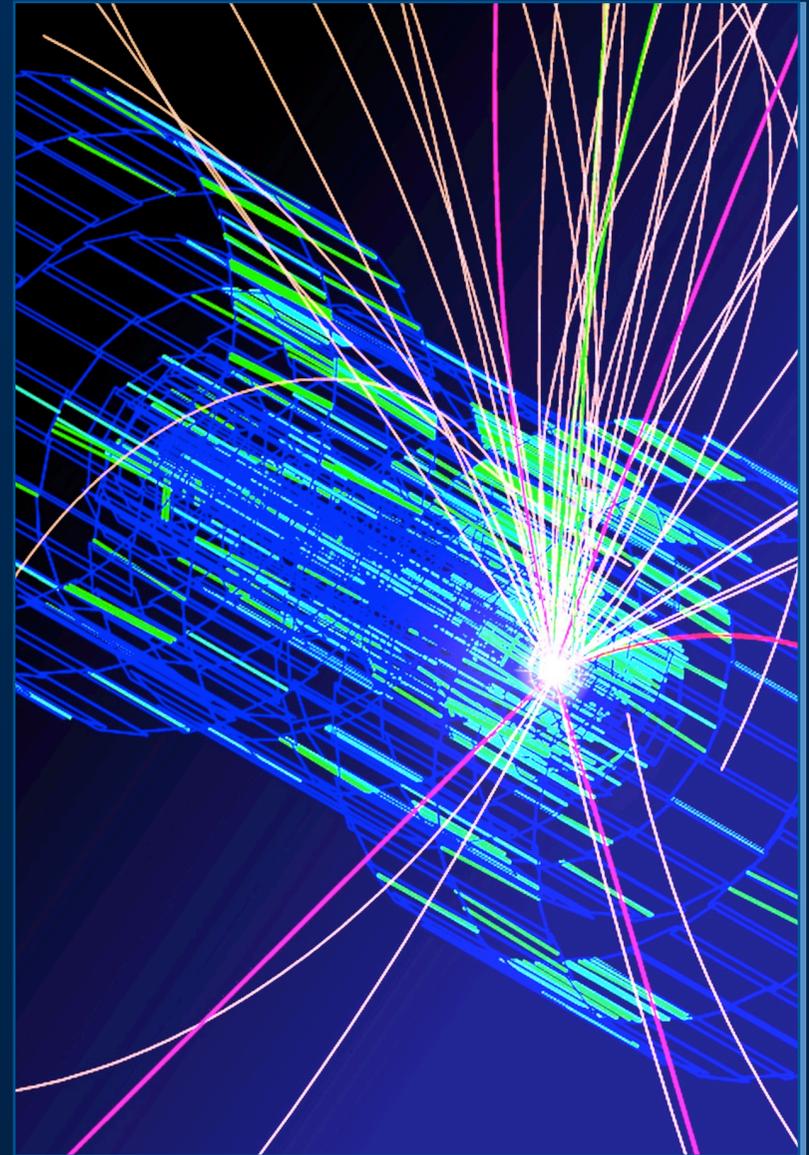
QCD at the Fermilab Tevatron

Mature QCD studies at the Tevatron will benefit physics at the LHC

- ▶ CDF and DØ are publishing results based on challenging measurements that are sensitive to N(NLO) effects and non-perturbative physics
- ▶ The CDF and DØ experiments are mature: the running environment and detector effects are well understood

Practically all new physics involves QCD!

- ▶ A superior understanding of Parton Distribution Functions (PDFs) will reduce uncertainties in a multitude of measurements
- ▶ QCD processes are a dominant background in a huge variety of measurements
- ▶ A better understanding of QCD translates to an improved sensitivity in searches for new phenomena



Outline

- Overview: The Fermilab Tevatron
- Measurements
 - ▶ Prompt Diphoton Production (CDF & DØ)
 - ▶ Angular Decorrelations in $\gamma + 2$ and 3 Jet Events (DØ)
 - ▶ Exclusive Diphoton Production (CDF)
- Summary



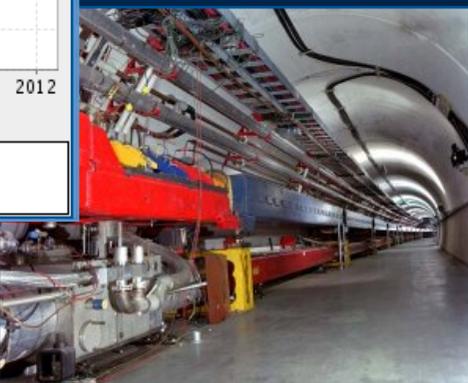
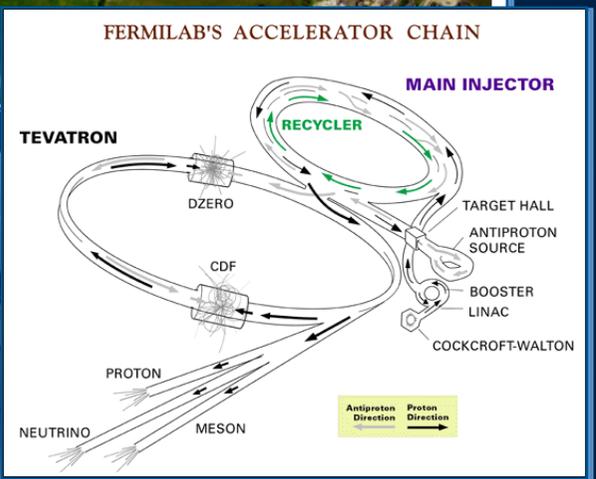
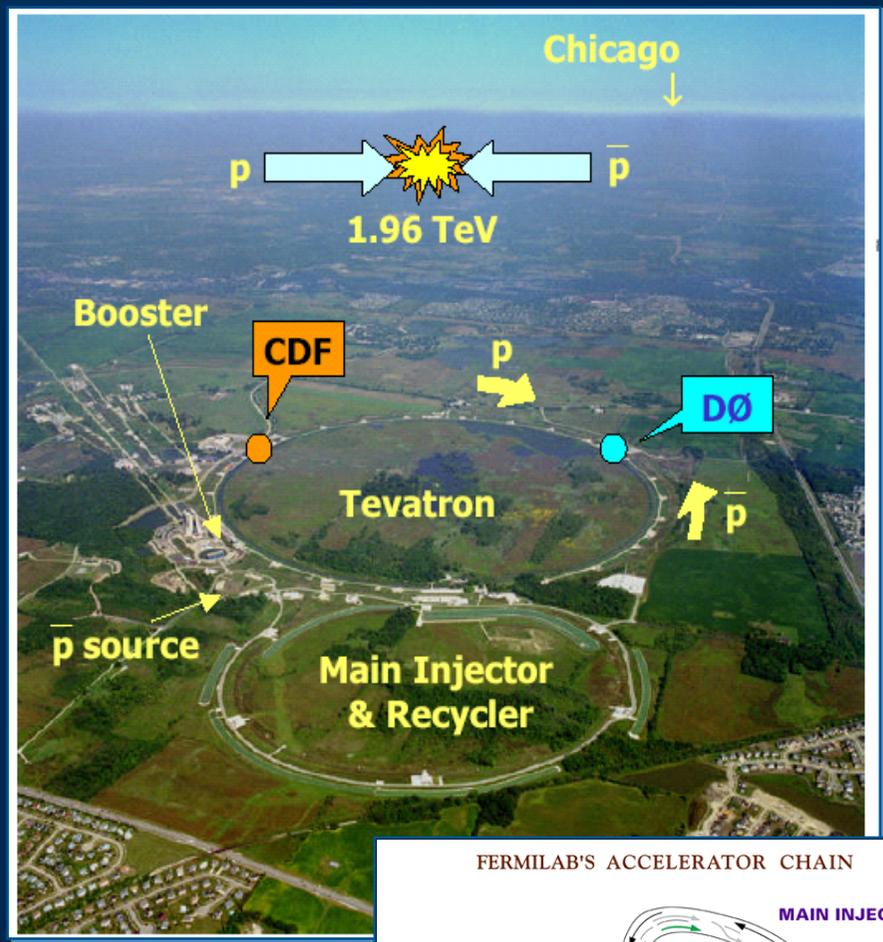
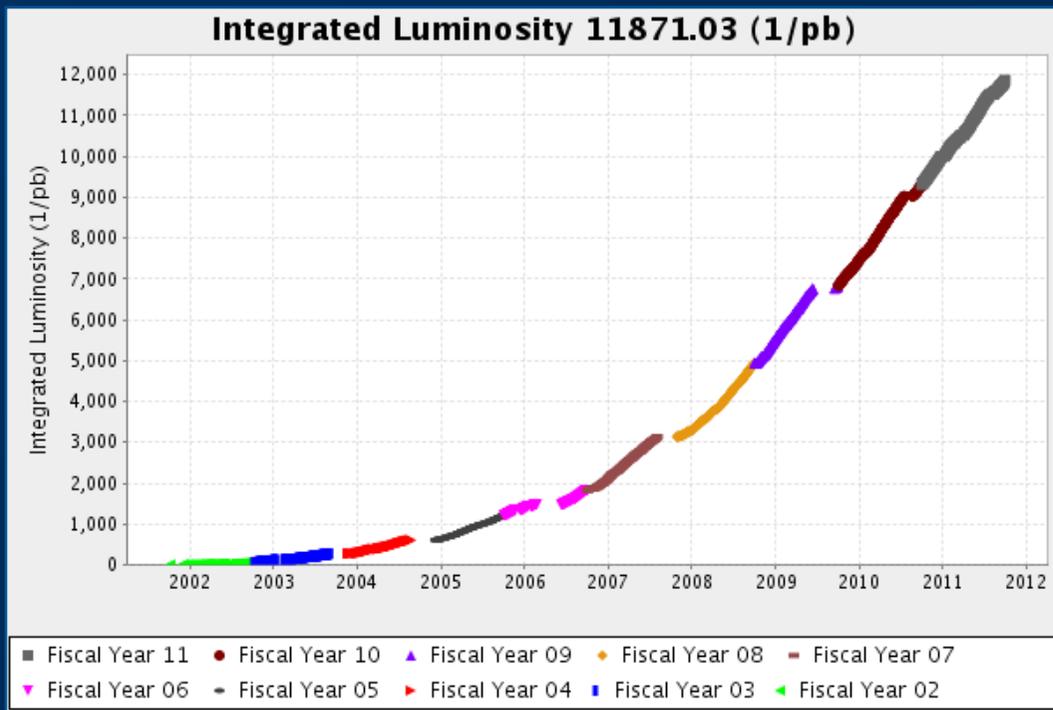
The Fermilab Tevatron

The Fermilab Tevatron

Run II at the Tevatron

- ▶ Proton-antiproton collisions at 1.96 TeV
- ▶ March 2001 – September 2011
- ▶ Peak luminosity $4.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- ▶ Delivered integrated luminosity nearly 12 fb^{-1}

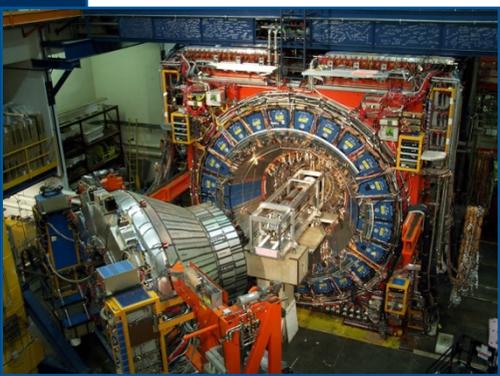
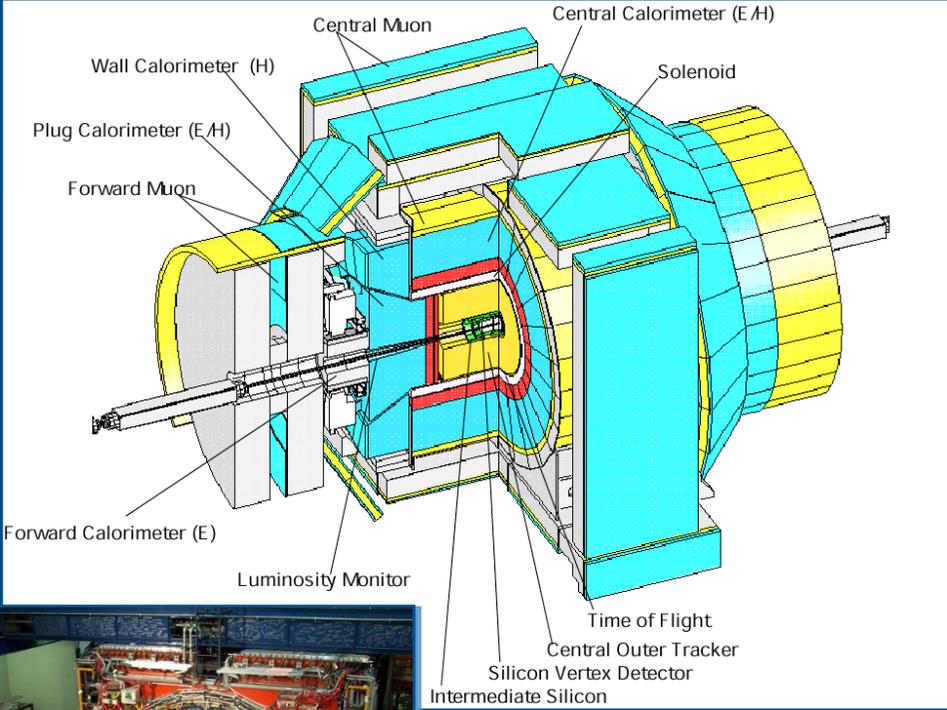
The Tevatron has operated *beautifully* in recent years.



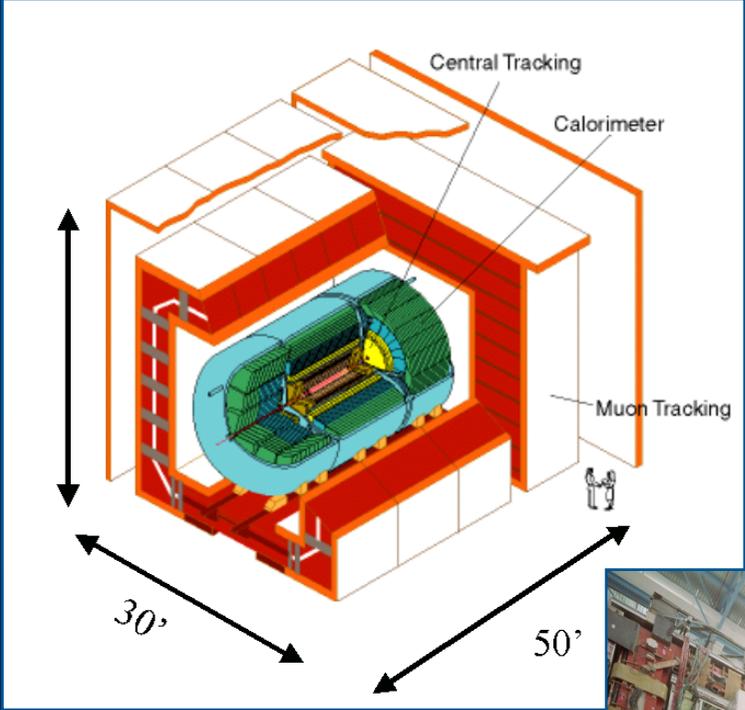
Up to about 10 fb^{-1} of data are now available for each experiment.

The CDF and DØ Experiments

The CDF Experiment



The DØ Experiment



Two Multi-Purpose Detectors:

- ▶ $e, \mu,$ and τ identification
- ▶ jet and missing energy measurement
- ▶ heavy-flavor tagging through displaced vertices and soft leptons

The data-taking efficiency for both experiments was high (> 90%)

Measurements

Prompt Diphoton Production (CDF & DØ)

Prompt Diphoton Production

Analysis: Measure the cross section for prompt isolated photon pair production

Motivation: ▶ to study photon pair production as it is a large background in many searches (low mass $H \rightarrow \gamma\gamma$, new heavy resonances, extra spatial dimensions, cascade decays of heavy new particles)

▶ to check the validity of perturbative QCD and soft gluon resummation methods

Prompt photons are produced directly from the hard scattering or fragmentation process

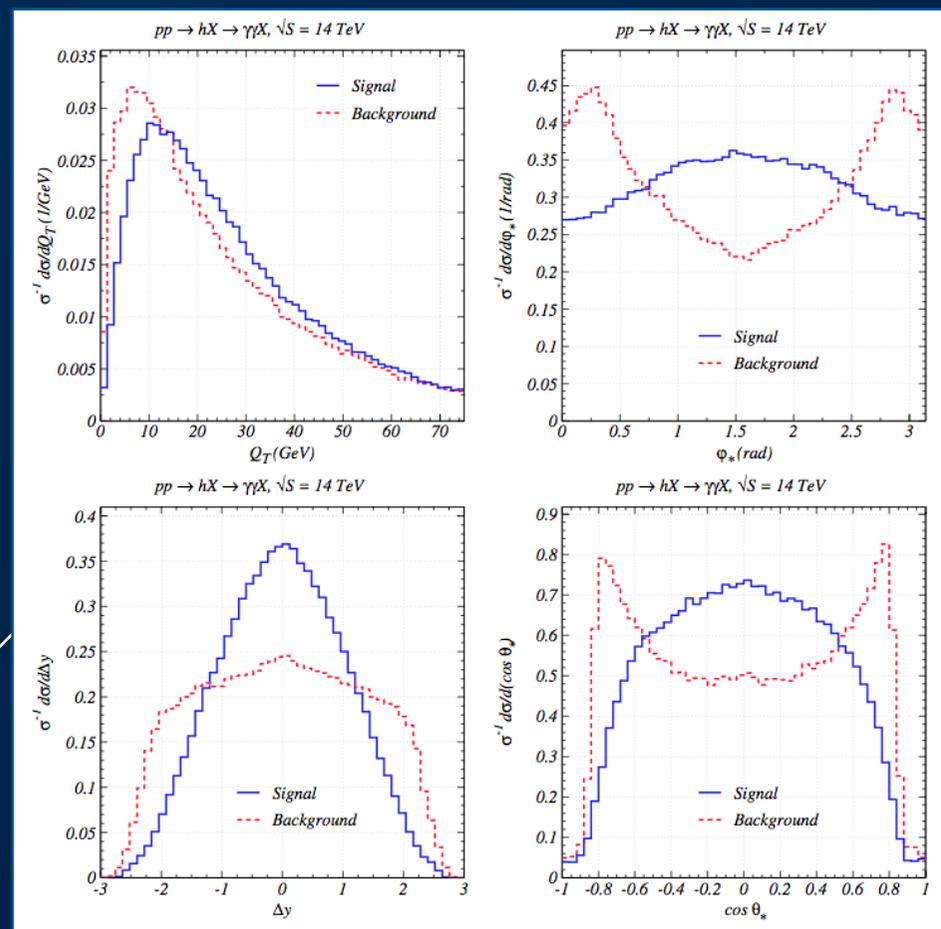
as opposed to photons from π^0 , η , or K_s^0 decay

At a much smaller rate ($< 1\%$), photon pairs may come from Higgs decay, graviton decay (extra dimensions), or neutralino decay (SUSY).

$gg \rightarrow H \rightarrow \gamma\gamma$ is the main discovery channel for SM Higgs masses up to about $130 \text{ GeV}/c^2$ at the LHC.

QCD $\gamma\gamma$ production and $H \rightarrow \gamma\gamma$ tend to be dominated by different initial states ($q\bar{q}$ vs. gg), and the resulting kinematic distributions are different.

C. Balázs *et al.*, PRD 76, 013009 (2007)



Prompt Diphoton Production (cont.)

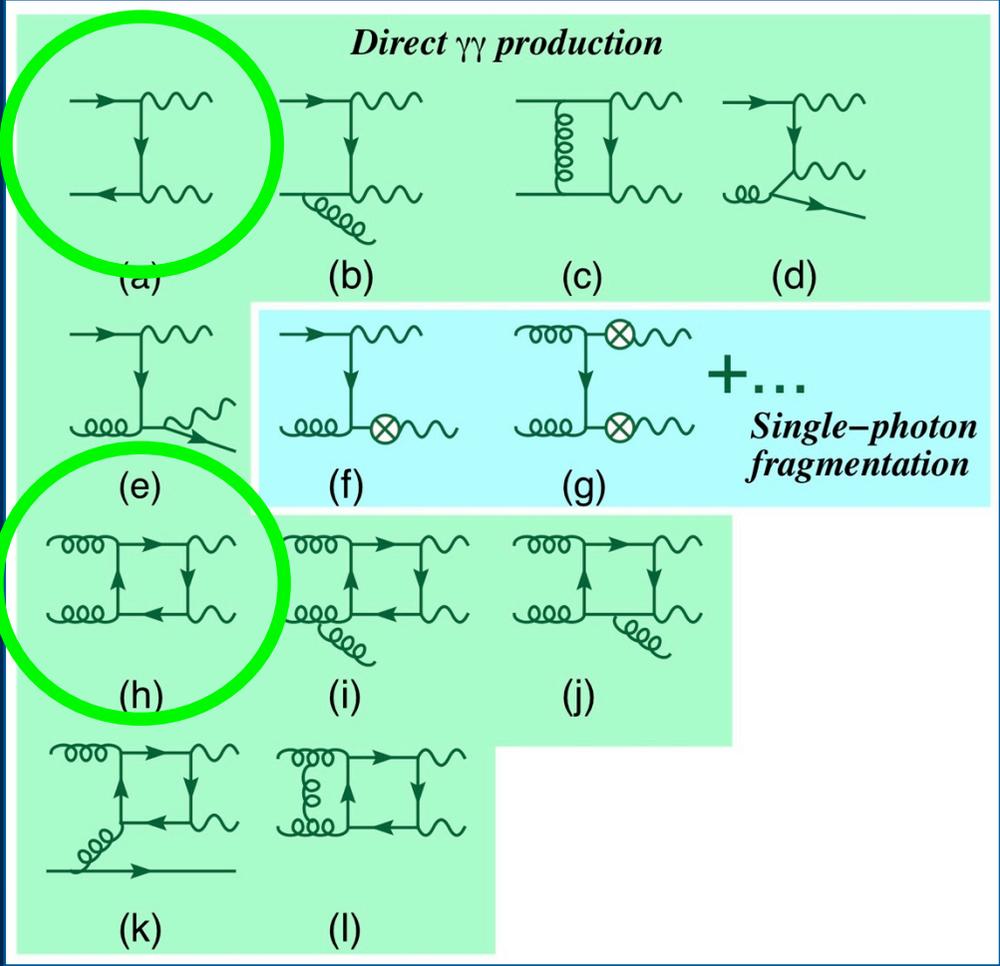
Two primary photon production mechanisms:

Direct

- ▶ At LO: $q\bar{q}$ scattering only
- ▶ At NLO: real emissions, virtual corrections (loops)
- ▶ gg scattering – $O(\alpha_s^2)$ suppression, but a large gluon PDF makes for a significant contribution at low $M(\gamma\gamma)$

Fragmentation

- ▶ Enhances the cross section in some kinematic regions (depending on the photon selection)
- ▶ Fragmentation contribution is very uncertain and can be suppressed experimentally by requiring
 - Isolated photons
 - $P_T(\gamma\gamma) < M(\gamma\gamma)$



C. Balázs *et al.*, PRD 76, 013009 (2007)

Prompt Diphoton Production (cont.)

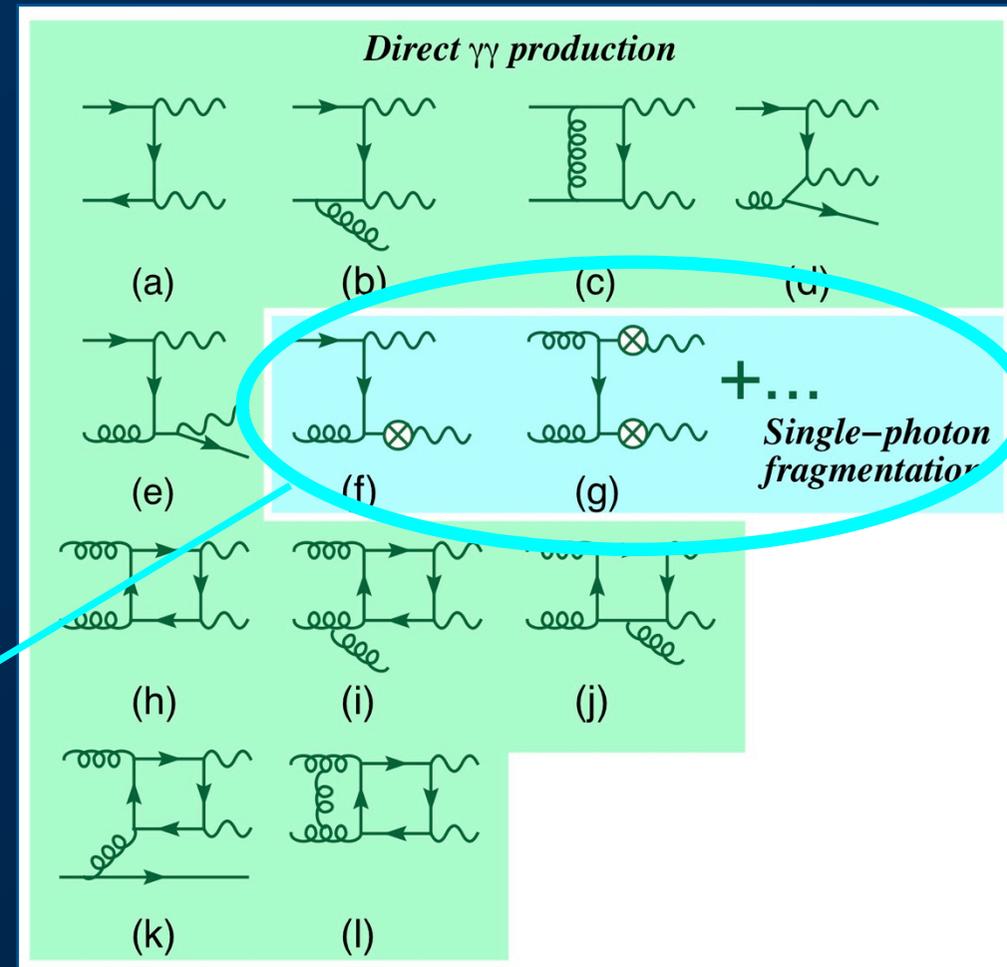
Two primary photon production mechanisms:

Direct

- ▶ At LO: $q\bar{q}$ scattering only
- ▶ At NLO: real emissions, virtual corrections (loops)
- ▶ gg scattering – $O(\alpha_s^2)$ suppression, but a large gluon PDF makes for a significant contribution at low $M(\gamma\gamma)$

Fragmentation

- ▶ Enhances the cross section in some kinematic regions (depending on the photon selection)
- ▶ Fragmentation contribution is very uncertain and can be suppressed experimentally by requiring
 - Isolated photons
 - $P_T(\gamma\gamma) < M(\gamma\gamma)$



C. Balázs *et al.*, PRD 76, 013009 (2007)

Prompt Diphoton Production (cont.)

Theoretical Predictions

PYTHIA JHEP 05, 026 (2006)

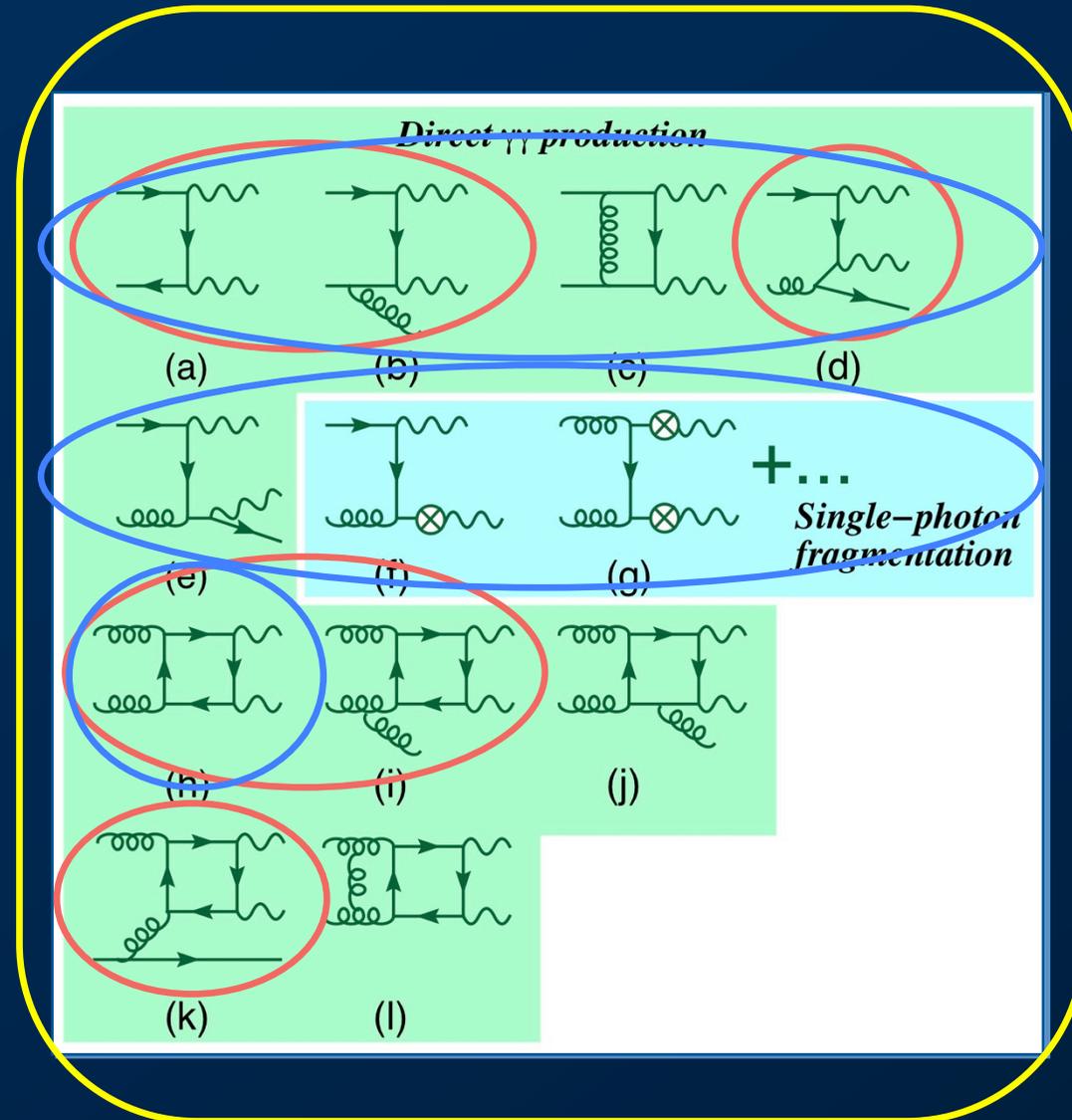
- ▶ $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ matrix elements
- ▶ All-order resummation to LL accuracy
- ▶ No fragmentation photons

DIPHOX EPJC 16, 311 (2000)

- ▶ Fixed-order NLO calculation
($gg \rightarrow \gamma\gamma$ is at LO only)
- ▶ No soft gluon resummation
- ▶ Single photon fragmentation at NLO

RESBOS PRD 76, 013009 (2007)

- ▶ NLO $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ matrix elements
- ▶ Initial soft gluon resummation at all orders to NNLL accuracy
- ▶ Single photon fragmentation included as a parameterization



C. Balázs *et al.*, PRD 76, 013009 (2007)

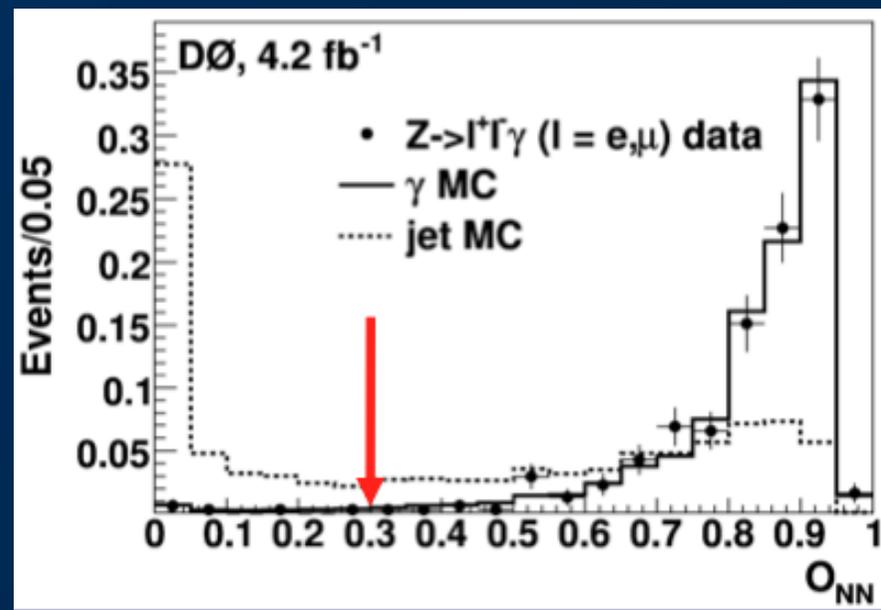
Other theoretical tools are also available ... see L. Cieri's presentation!

Prompt Diphoton Production (cont.)

Event Selection

$D\bar{D}$ (4.2 fb^{-1}) PLB 690, 108 (2010)

- ▶ Two photons, $p_T > 20$ & 21 GeV , $|\eta(\gamma)| < 0.9$
- ▶ Separated by $\Delta R(\gamma\gamma) > 0.4$
- ▶ Isolated (calorimeter and tracker)
- ▶ $P_T(\gamma\gamma) < M(\gamma\gamma)$ (suppress fragmentation)
- ▶ Photon neural net (uses calorimeter, preshower detector, and tracking)



Photon neural net output

CDF (5.36 fb^{-1}) PRL 107, 102003 (2011)
PRD 84, 052006 (2011)

- ▶ Two photons, $E_T > 15$ & 17 GeV , $|\eta(\gamma)| < 1.0$
- ▶ Separated by $\Delta R(\gamma\gamma) > 0.4$
- ▶ Isolated (calorimeter and tracker)
- ▶ With and without $P_T(\gamma\gamma) < M(\gamma\gamma)$
- ▶ Large and small $\Delta\phi(\gamma\gamma)$

Good discrimination: jets / photons
Good agreement: Data / γ MC

Typical diphoton purity $\sim 70\%$

Main backgrounds

- $\gamma + \text{jet}$ ($\sim 15\%$)
- dijet ($\sim 15\%$)
- $Z/\gamma^* \rightarrow ee$ ($\sim 2\%$)

Prompt Diphoton Production (cont.)

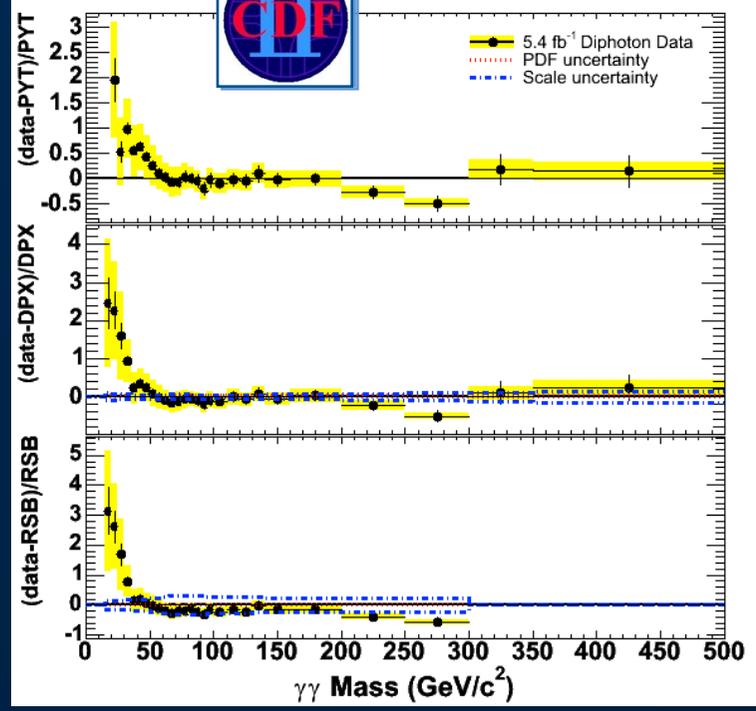
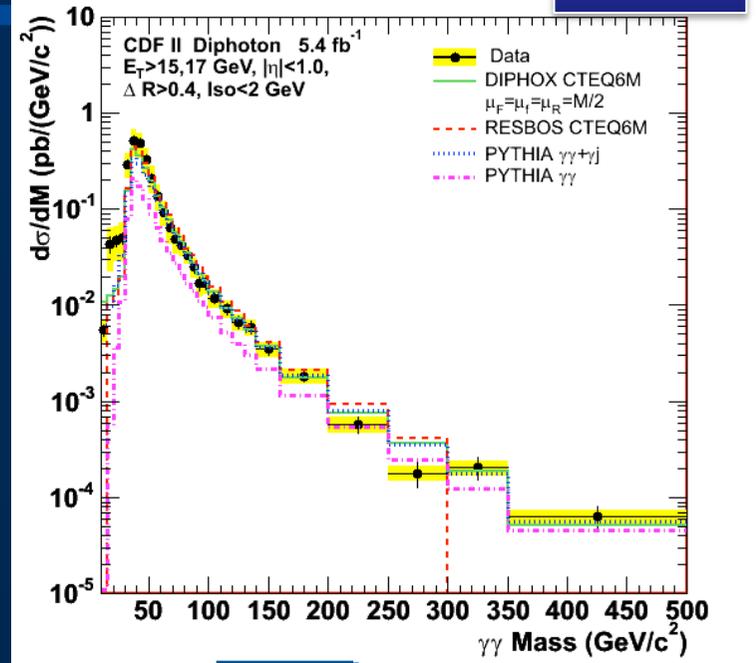
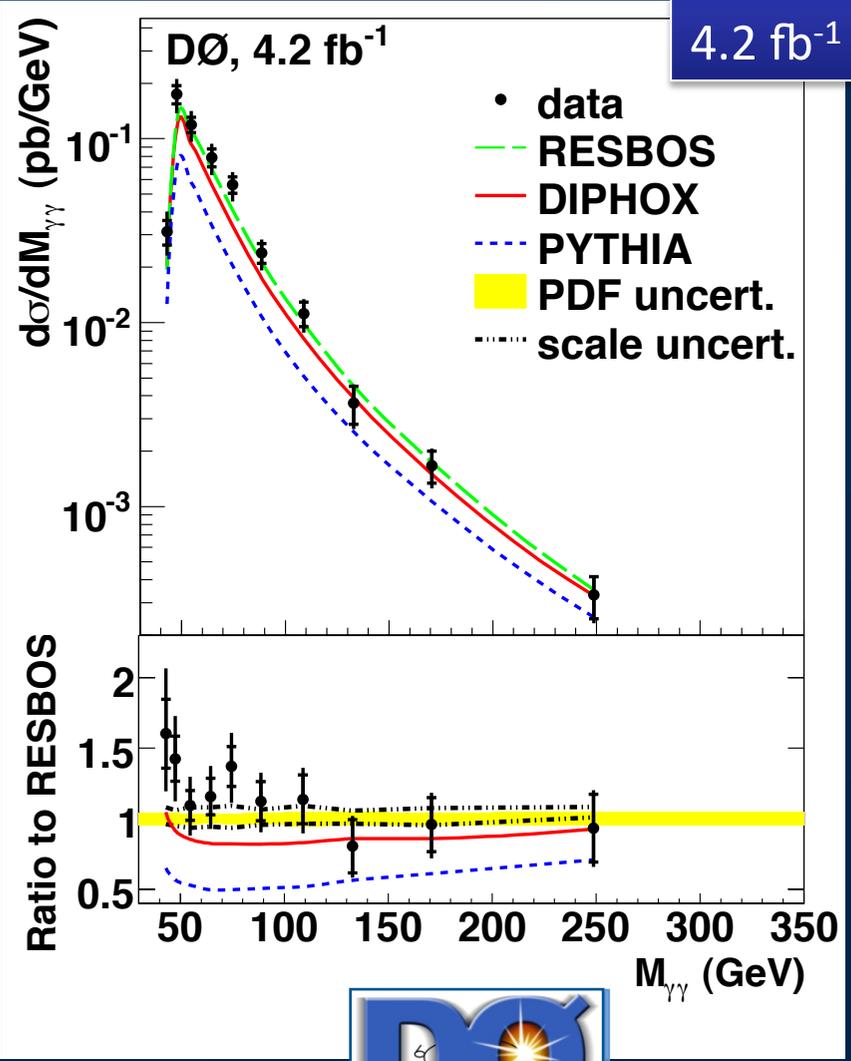
5.4 fb⁻¹

Results

$$\frac{d\sigma}{dM_{\gamma\gamma}}$$

Good agreement between data and RESBOS for $M(\gamma\gamma) > 50$ GeV

(mass region important for Higgs and new particle searches)



Including photon radiation in the initial and final states ($\gamma\gamma + \gamma j$) significantly improves the PYTHIA parton shower calculation.

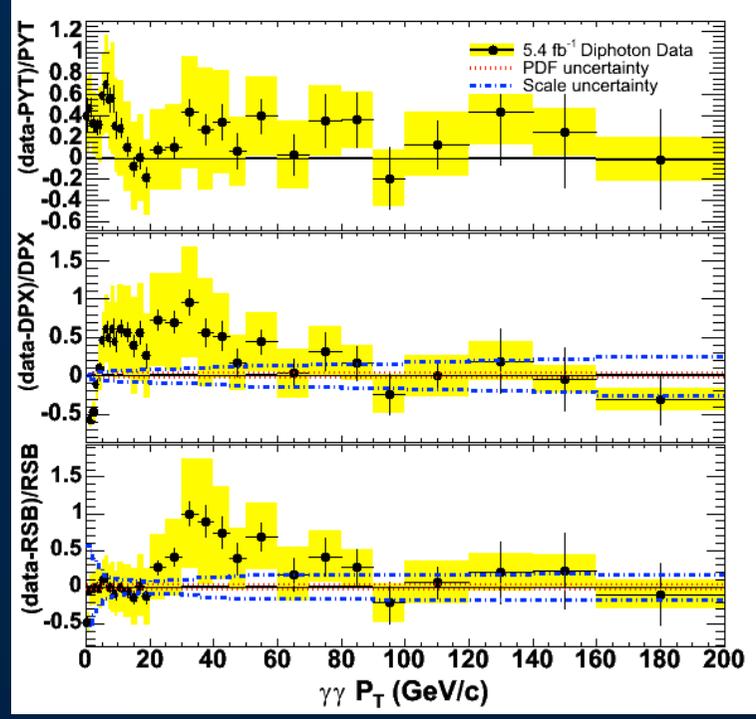
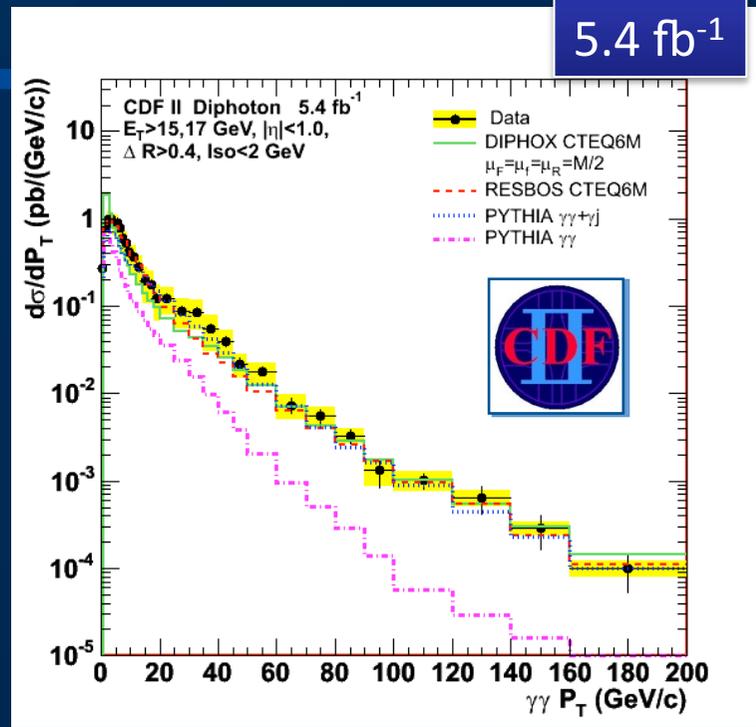
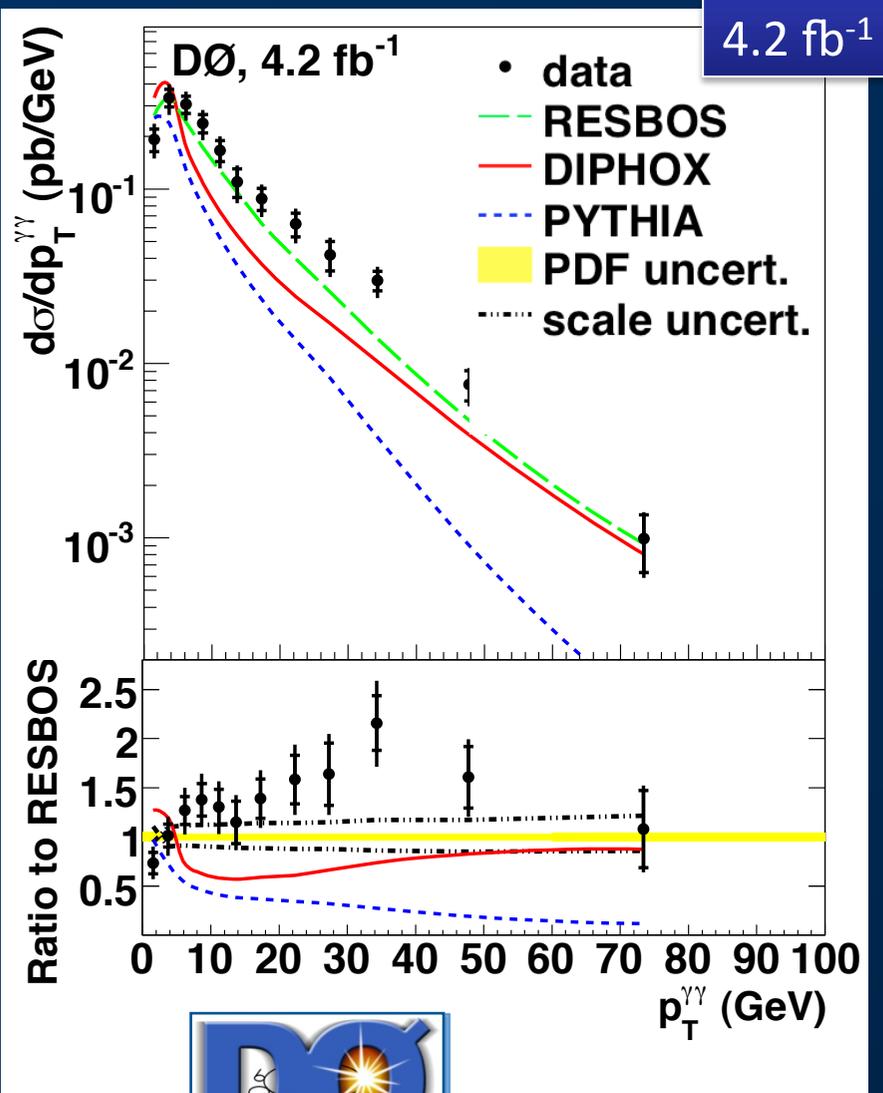
Prompt Diphoton Production (cont.)

5.4 fb⁻¹

Results

$$\frac{d\sigma}{dp_T^{\gamma\gamma}}$$

The data spectrum is harder than predicted. Need NNLO?



Discrepancy with DIPHOX and PYTHIA at small $P_T(\gamma\gamma)$ indicates that soft gluon resummation is needed.

Prompt Diphoton Production (cont.)

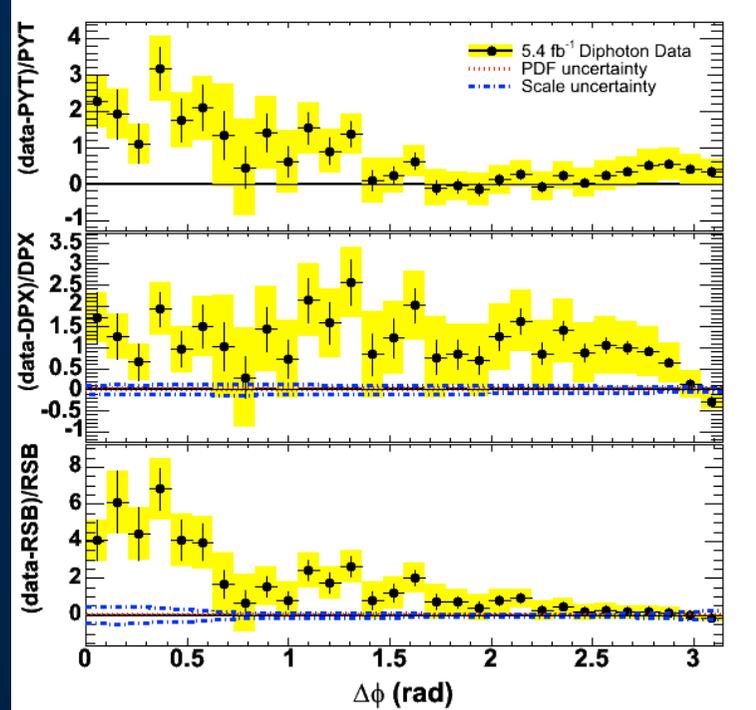
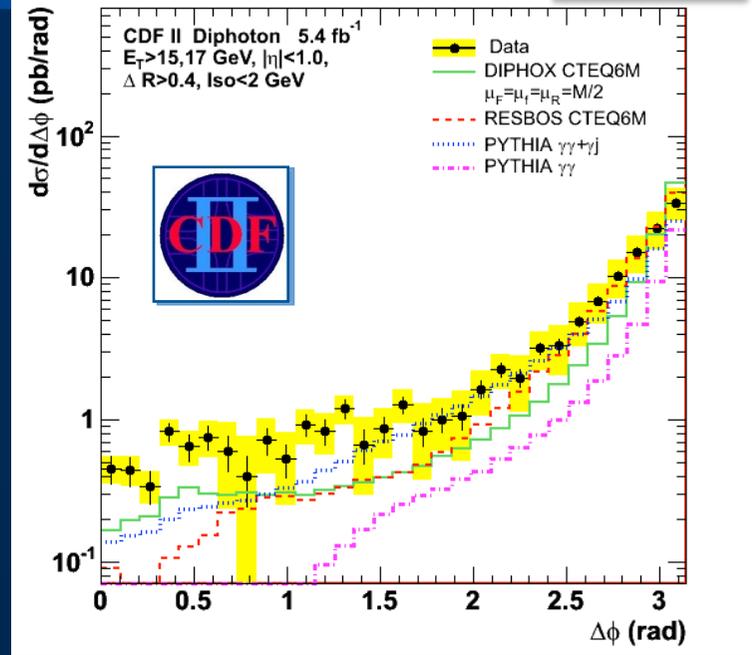
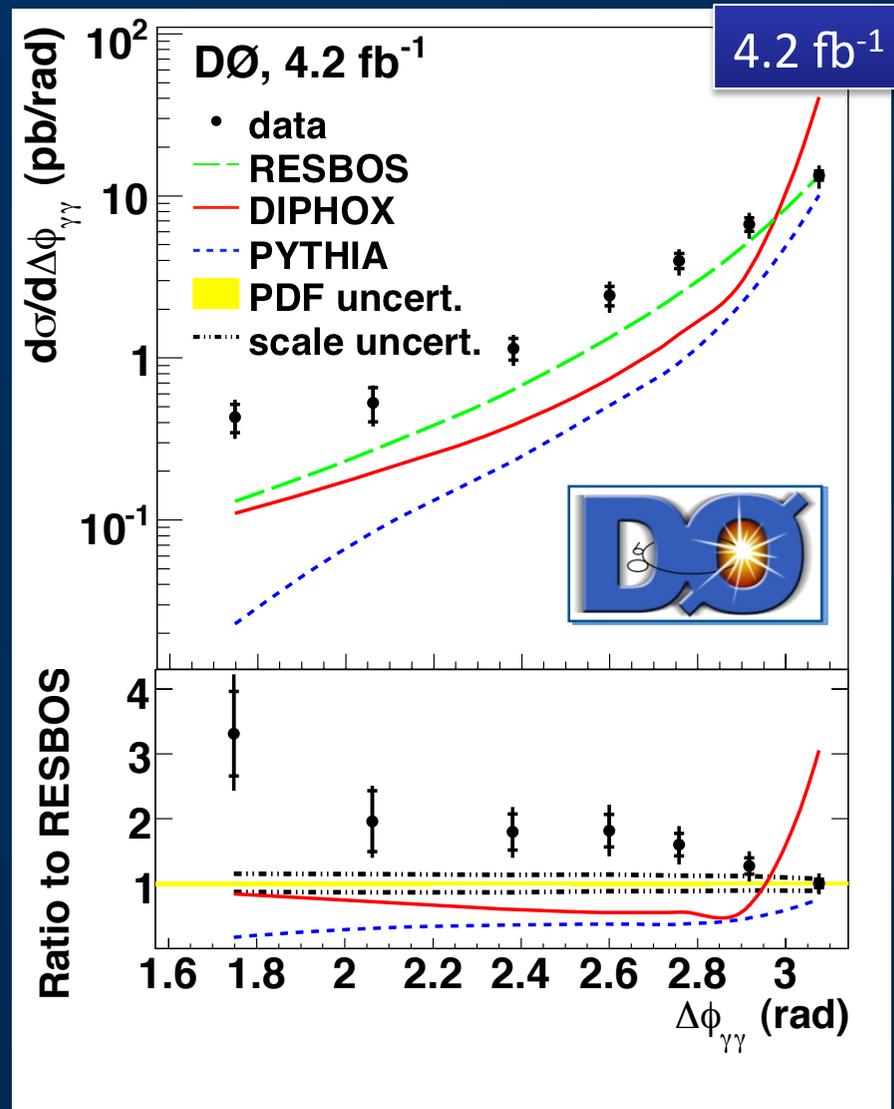
5.4 fb⁻¹

Results

$$\frac{d\sigma}{d\Delta\phi_{\gamma\gamma}}$$

Discrepancies between data and theory stand out most in this distribution.

All three predictions fail to describe the data across the whole spectrum.



For these CDF and DØ analyses, many distributions (including both single and double differential) are available!

Measurements

Angular Decorrelations in $\gamma + 2$ and 3 Jet Events (D0)



Angular Decorrelations in $\gamma + 2$ and 3 Jet Events

Analysis: Measure differential cross sections vs. azimuthal angles in $\gamma + 2$ and $\gamma + 3$ jet events.

- Motivation:**
- ▶ to better understand non-perturbative QCD and improve multiple parton interaction (MPI) models
 - ▶ to learn new and complementary information about proton substructure (spacial distribution of partons within proton, parton-parton correlations)
 - ▶ to obtain better background estimates for other analyses (rare processes, Higgs searches)

Define the following kinematic quantities:

$$\Delta\phi(\gamma + \text{jet1}, \text{jet2})$$

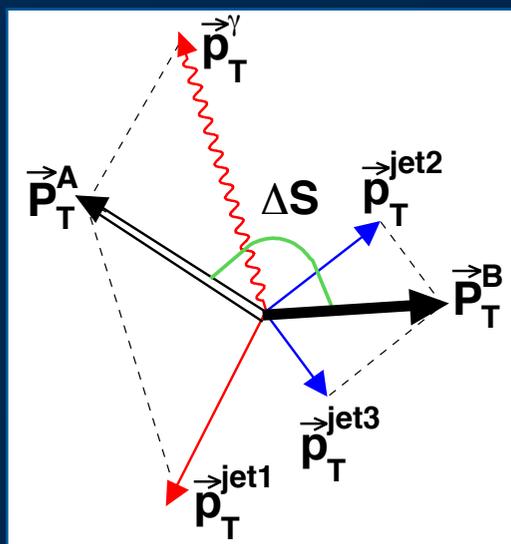
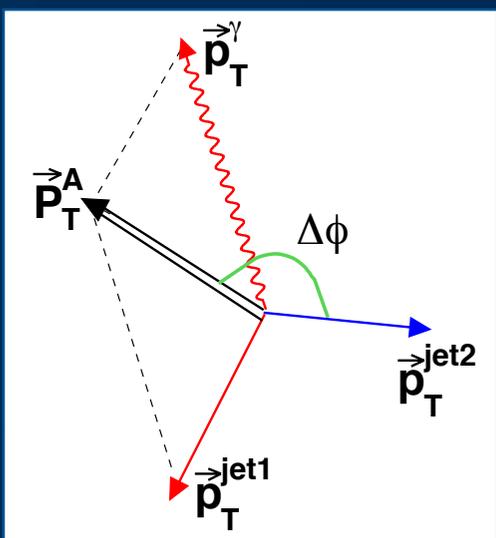
measured in 3 bins of 2nd jet p_T (15-20, 20-25, 25-30) GeV

$$\Delta S(\gamma + \text{jet1}, \text{jet2} + \text{jet3})$$

for 2nd jet p_T of 15-30 GeV

These quantities are used to distinguish between two classes of events:

- ▶ **SP** – Photon and all jets originate from the same parton-parton interaction with hard gluon bremsstrahlung in the initial or final state
- ▶ **DP** – Two independent parton-parton interactions produce the photon + jets final state.



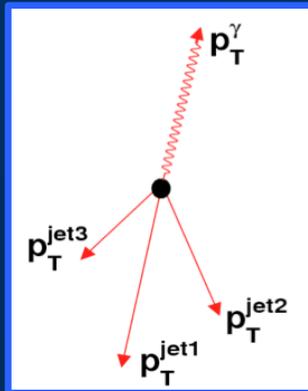
Angular Decorrelations in $\gamma + 2$ and 3 Jet Events (cont.)



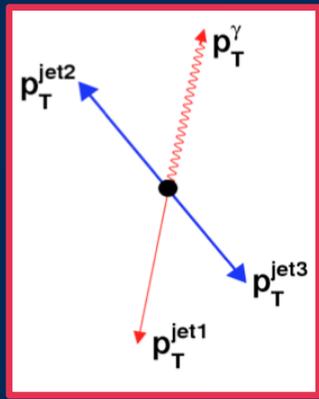
PRD 83, 052008 (2011)

1.0 fb⁻¹

- ▶ SP events yield distributions that are peaked at π



- ▶ DP events yield distributions that are flat (no correlation between the separate parton-parton interactions)



Results:

$\Delta\phi$

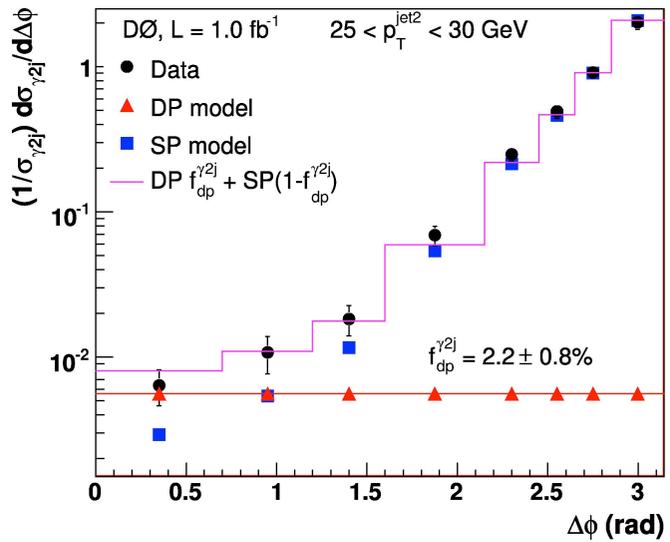
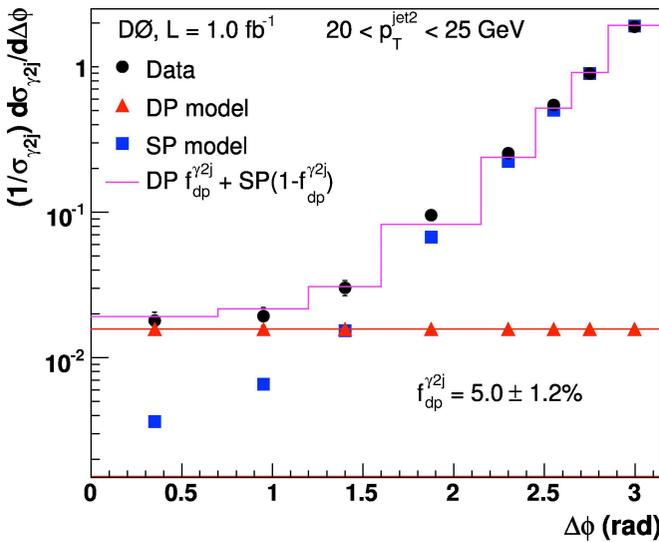
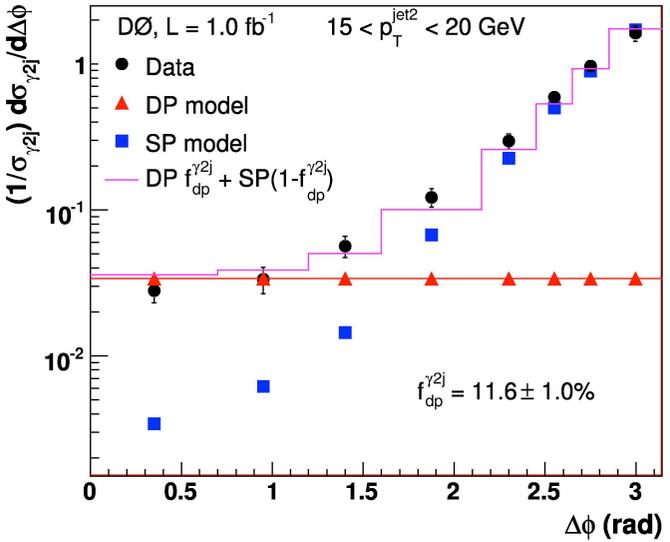
$15 < p_T^{\text{jet}2} < 20 \text{ GeV}$

$\Delta\phi$

$20 < p_T^{\text{jet}2} < 25 \text{ GeV}$

$\Delta\phi$

$25 < p_T^{\text{jet}2} < 30 \text{ GeV}$



$f_{dp}^{\gamma 2j} = 11.6 \pm 1.0\%$

$f_{dp}^{\gamma 2j} = 5.0 \pm 1.2\%$

$f_{dp}^{\gamma 2j} = 2.2 \pm 0.8\%$

- ▶ Fraction of DP events decreases for higher p_T bins

Angular Decorrelations in $\gamma + 2$ and 3 Jet Events (cont.)

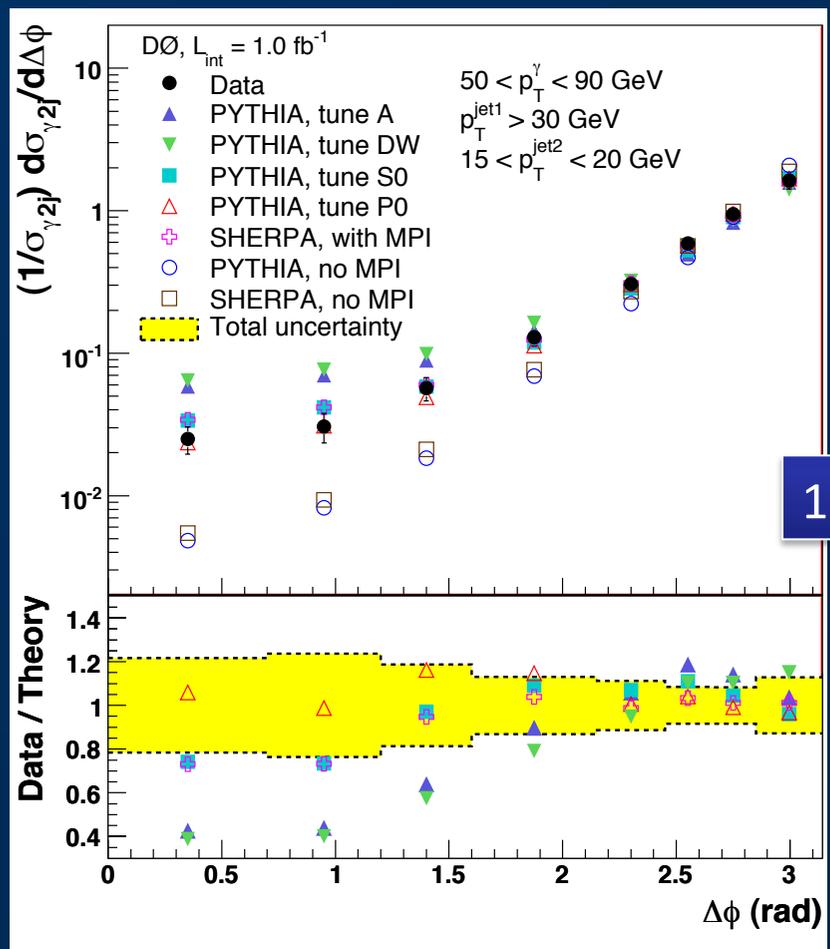


Results:

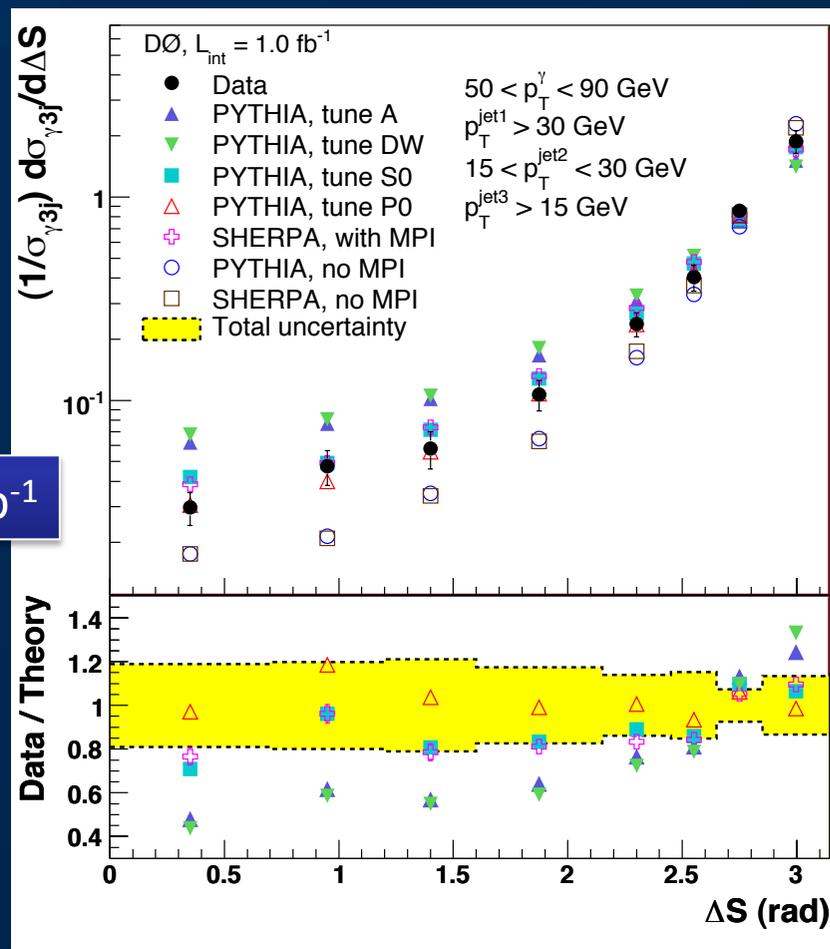
$\Delta\phi$

ΔS

PRD 83, 052008 (2011)



1.0 fb^{-1}



► Predictions of SP models alone do not provide an adequate description of the data. Additional DP models are required.



Results:

Using a χ^2 test to compare data points and theory for small angles:

1.0 fb⁻¹

TABLE VI. The results of a χ^2 test of the agreement between data points and theory predictions for the ΔS ($\gamma + 3$ jet) and the $\Delta\phi$ ($\gamma + 2$ jet) distributions for $\Delta S(\Delta\phi) \leq 2.15$ rad. Values are χ^2/ndf .

Variable	$p_T^{\text{jet}2}$ (GeV)	SP model				MPI model							
		PYTHIA	SHERPA	A	DW	S0	P0	P-nocr	P-soft	P-hard	P-6	P-X	SHERPA
ΔS	15–30	10.9	11.3	31.0	42.9	3.4	0.4	0.5	4.9	0.9	0.5	0.4	2.6
$\Delta\phi$	15–20	30.2	26.0	40.7	61.1	2.2	0.9	1.6	1.5	1.2	1.2	1.0	2.4
$\Delta\phi$	20–25	15.4	12.1	6.8	18.0	1.0	1.8	2.7	1.7	1.5	2.5	2.4	0.6
$\Delta\phi$	25–30	7.1	5.3	1.3	5.6	1.6	1.1	1.0	2.1	0.3	1.4	1.6	0.5

- ▶ The new PYTHIA MPI models with p_T -ordered showers are favored (in particular Perugia tunes P0, P-nocr, P-hard, P-6, P-X)
- ▶ The PYTHIA S0 and Sherpa with MPI tunes are favored to a lesser extent
- ▶ The PYTHIA predictions using tunes A and DW are disfavored

Measurements

Exclusive Diphoton Production (CDF)

Exclusive Diphoton Production

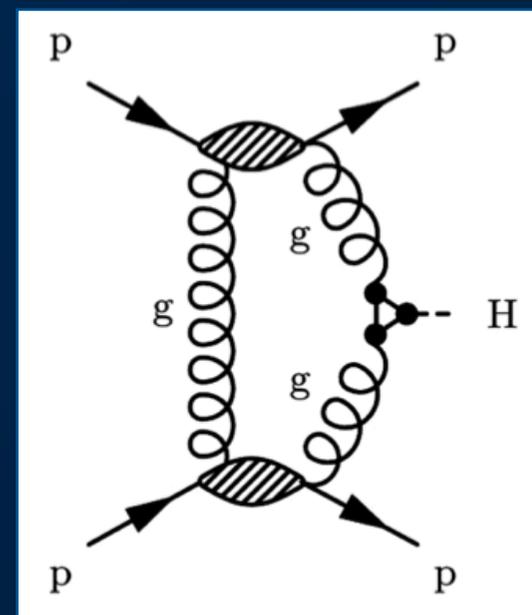
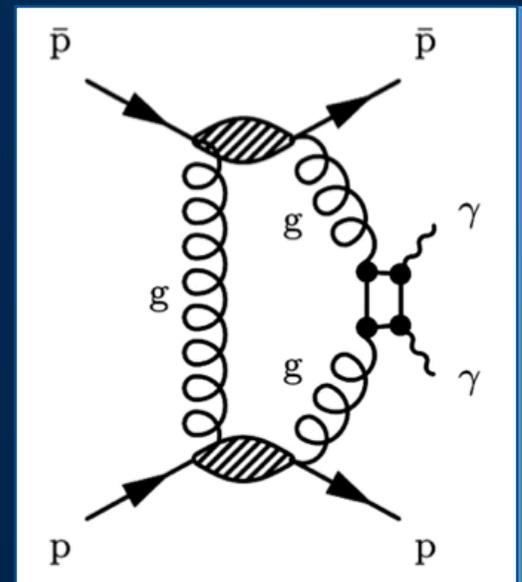
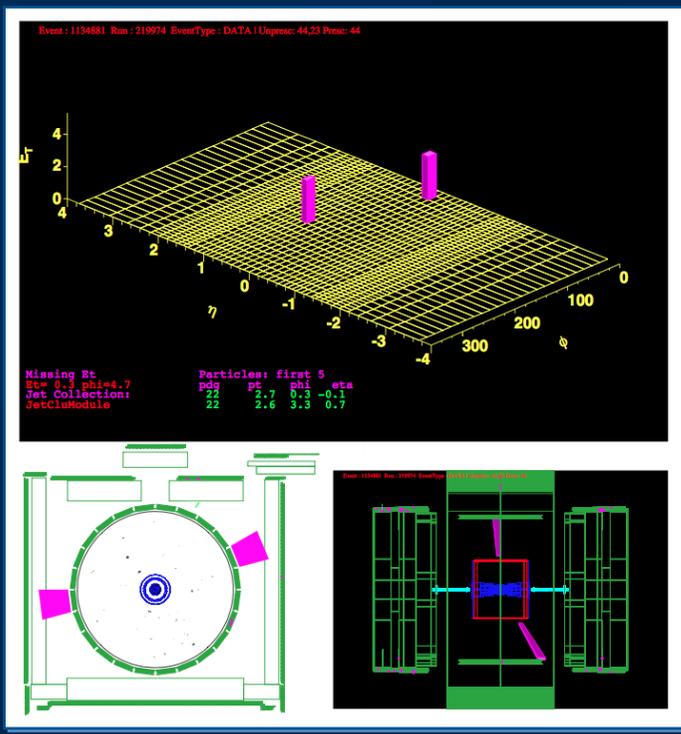
Analysis: Search for exclusive $\gamma\gamma$ production via $p\bar{p} \rightarrow p + \gamma\gamma + \bar{p}$ and compare to theoretical predictions. PRL 108, 081801 (2012)

- Motivation:**
- ▶ Intrinsically interesting as a QCD process
 - ▶ Tests the theory of exclusive Higgs boson production via $p\bar{p} \rightarrow p + H + \bar{p}$

Features:

- ▶ The proton and antiproton emerge intact with no hadrons produced
- ▶ The outgoing proton and antiproton have nearly the beam momentum ($p_T < 1 \text{ GeV}/c$), having emitted a pair of gluons in a color singlet
- ▶ Rapidity gaps are located adjacent to the proton and antiproton

Very clean $\gamma\gamma$ event signature



In Regge theory this is diffractive scattering via pomeron exchange.

Exclusive Diphoton Production (cont.)

PRL 108, 081801 (2012)

Event Selection:

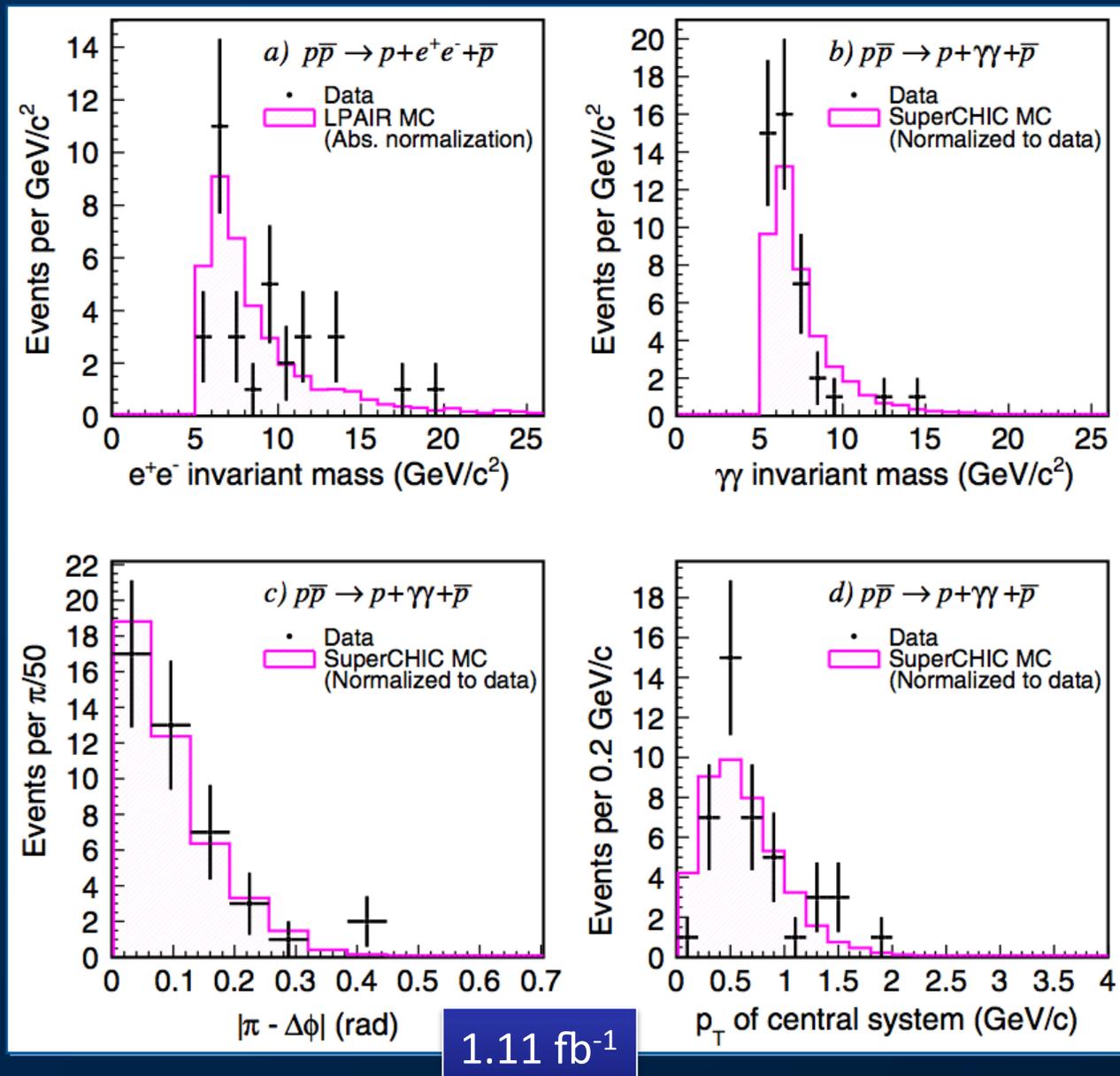
- Require two well-reconstructed, central ($|\eta| < 1.0$) photons with $E_T > 2.5$ GeV
- NO other activity in the detector

The effective luminosity (events with no pileup) is 70 ± 4 pb $^{-1}$ (~7% of data sample)

Backgrounds processes that can produce an exclusive $\gamma\gamma$ final state:

- Irreducible $q\bar{q} \rightarrow \gamma\gamma$ (<5%) and $\gamma\gamma \rightarrow \gamma\gamma$ (<1%)
- Reducible $\pi^0\pi^0$ and $\eta\eta$ shown to be small

Results:



Exclusive Diphoton Production (cont.)

Measurement of the exclusive $\gamma\gamma$ production cross section

PRL 108, 081801 (2012)

43 data events

≈ 0 for most backgrounds, tiny undetected proton dissociation

$$\sigma_{\gamma\gamma, \text{exclusive}} = \frac{N(\text{candidates}) - N(\text{background})}{\mathcal{L}_{\text{int}} \cdot \epsilon \cdot \epsilon_{\text{excl}}}$$

$$= 2.48^{+0.40}_{-0.35} (\text{stat})^{+0.40}_{-0.51} (\text{syst}) \text{ pb}$$

for $E_T(\gamma) > 2.5 \text{ GeV}$ and $|\eta(\gamma)| < 1.0$

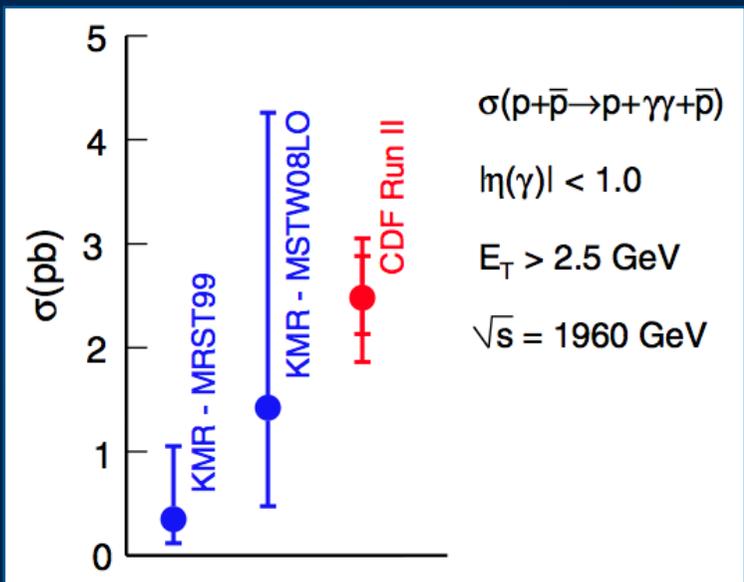
$1.11 \pm 0.07 \text{ fb}^{-1}$
Integrated luminosity

$(23 \pm 7)\%$
Photon pair efficiency x probability that the photons don't convert

$(6.8 \pm 0.4)\%$
No pileup requirement

The theoretical prediction ranges from $\sim 0.2 - 2 \text{ pb}$, and depends on:

- ▶ Low-x (unintegrated) gluon density
- ▶ $gg \rightarrow \gamma\gamma$ cross section
- ▶ Probability that neither proton dissociates (e.g. $p \rightarrow p \pi^+ \pi^-$)
- ▶ Probability that no hadrons are produced by addl. parton interactions



Good agreement w/ theory

Theory: V.A. Khoze *et al.*, EPJC 38, 475 (2005) & EPJC 14, 525 (2000); L.A. Harland-Lang *et al.*, EPJC 69, 179 (2010).

Summary

Diphoton differential cross sections disagree with NLO calculations at low $M(\gamma\gamma)$ and small $\Delta\phi$

- ▶ PYTHIA, DIPHOX, RESBOS reproduce the main features of the data, but none of them describe all features
- ▶ The importance of NNLO terms and better treatment of fragmentation is indicated
- ▶ See arXiv:1110.2375 for NNLO treatment (see Leandro Cieri's presentation!)

First observation of exclusive diphoton production consistent with expectation

- ▶ Exclusive Higgs production at the LHC may be possible

Tevatron measurements provide important feedback for MC tuning and QCD modeling.

- ▶ Many analyses show the importance of NNLO terms and of having better experimental constraints on the theories

Many more Tevatron QCD results are available:

- ▶ CDF: <http://www-cdf.fnal.gov/physics/new/qcd/QCD.html>
- ▶ D0: http://www-d0.fnal.gov/Run2Physics/qcd/D0_public_QCD.html

Acknowledgements

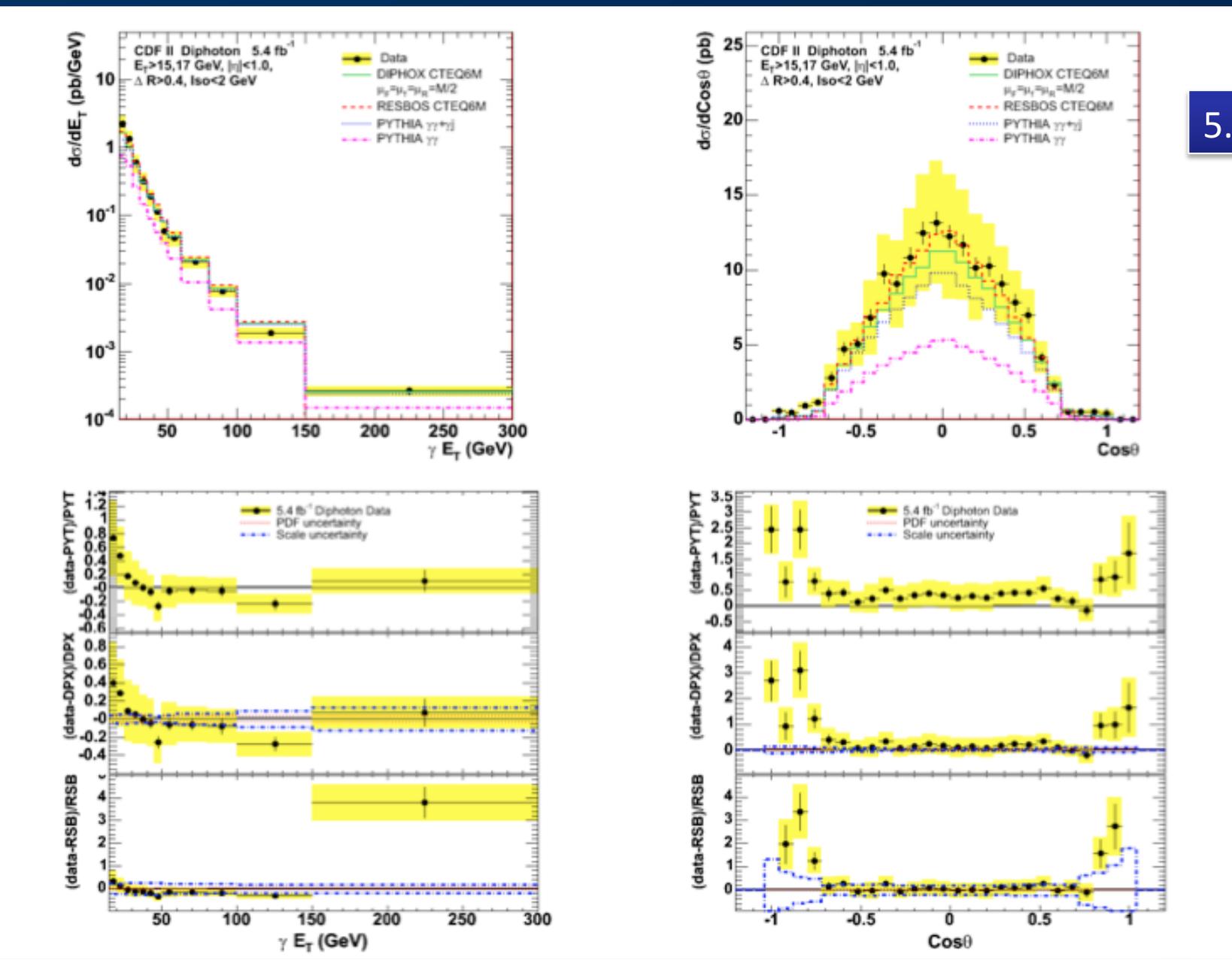
In addition to the many collaborators on CDF and DØ who performed and reviewed these analyses, and many theorists who have worked hard to prepare careful theoretical predictions, I would like to thank the following people for very helpful conversations and material for this presentation:

- ▶ Dmitry Bandurin
- ▶ Susan Blessing
- ▶ Erik Brücken
- ▶ Ray Culbertson
- ▶ John Paul Chou
- ▶ Sabine Lammers
- ▶ Anna Mazzacane
- ▶ Christina Mesropian
- ▶ Jedranka Sekaric
- ▶ Shulamit Moed Sher

Backup Slides

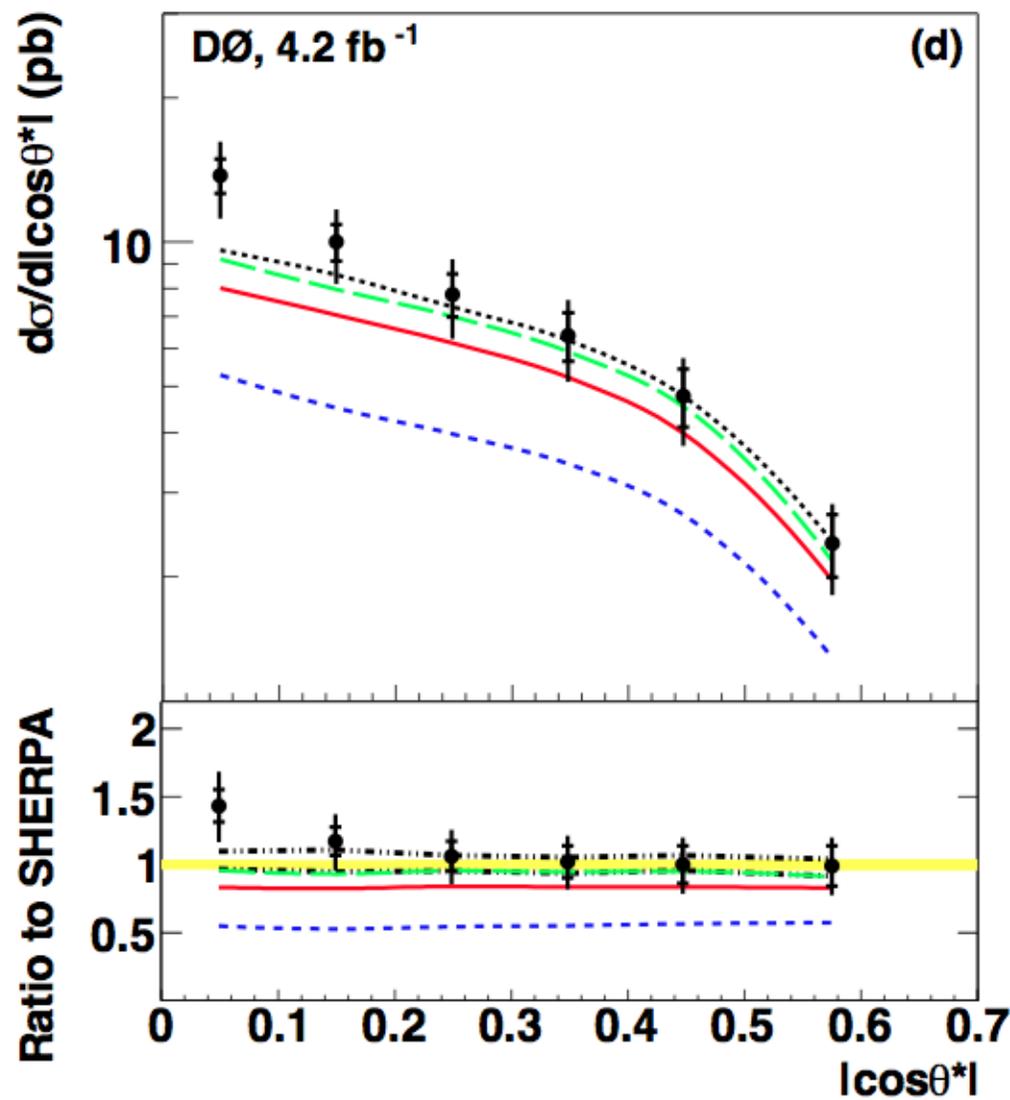
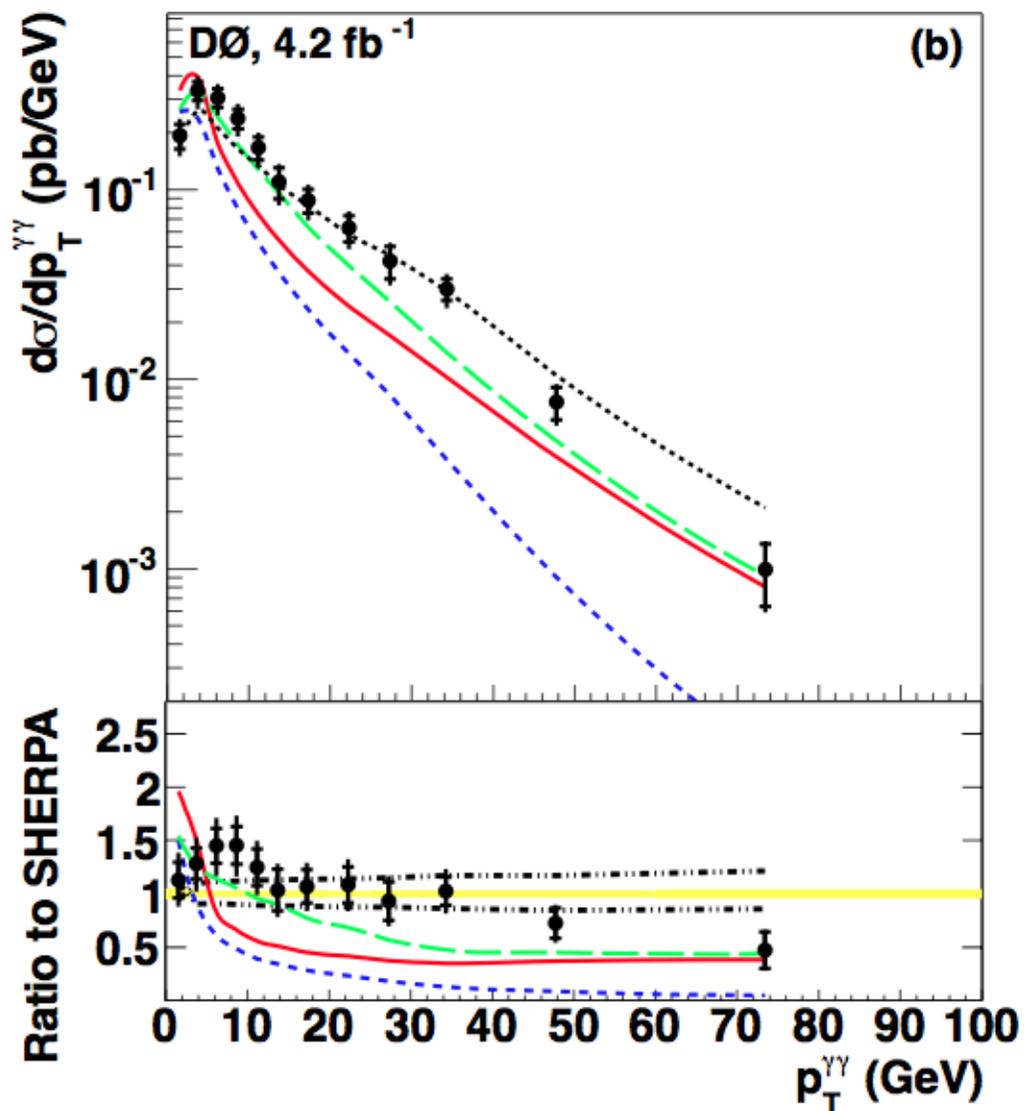
Additional CDF Results

5.4 fb⁻¹



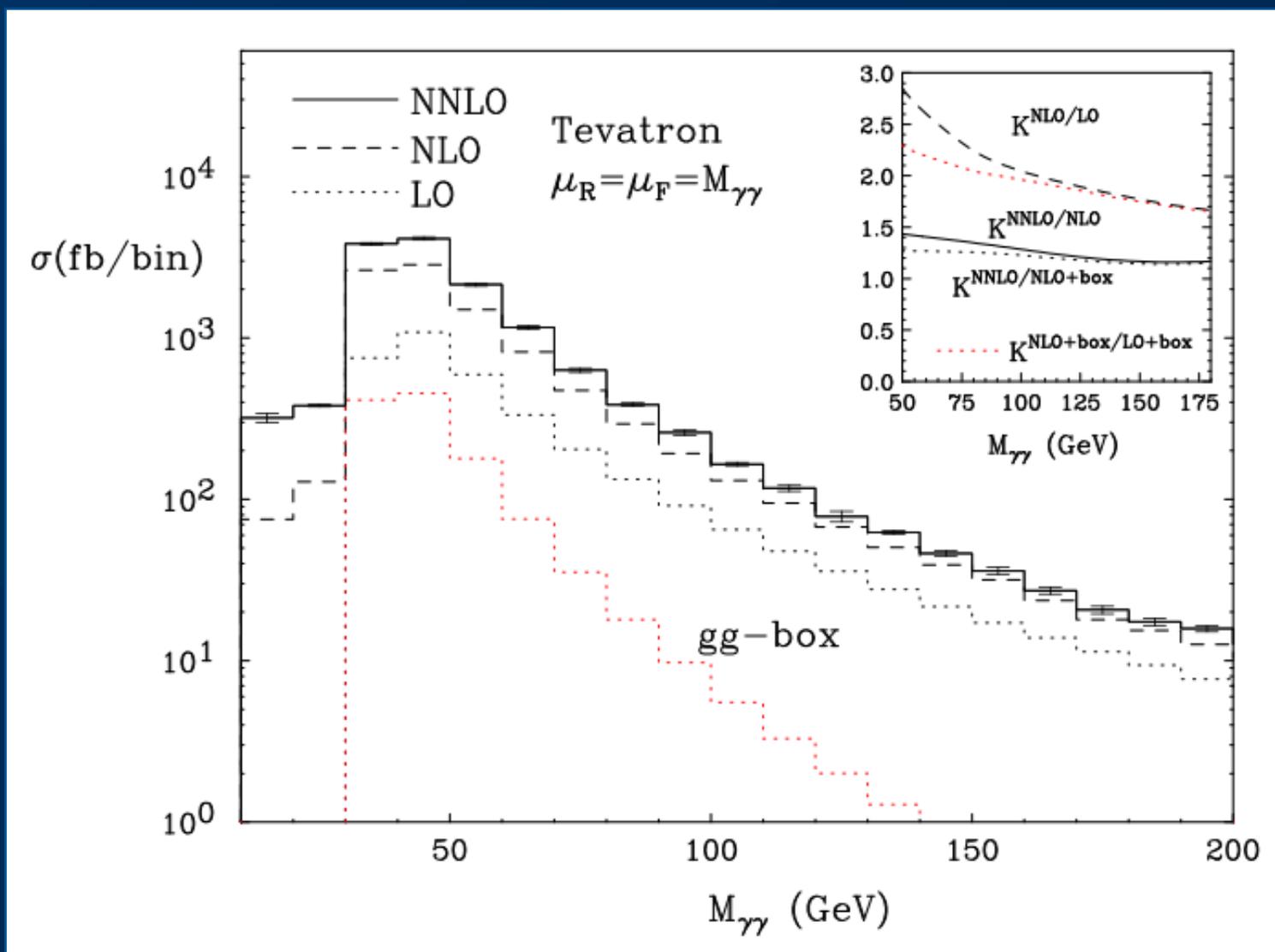


4.2 fb⁻¹



Prompt Diphoton Production (cont.)

Theory



Catani *et al.*, arXiv:1110.2375 (Oct 2011)

Angular Decorrelations in $\gamma + 2$ and 3 Jet Events (cont.)



Additional Results

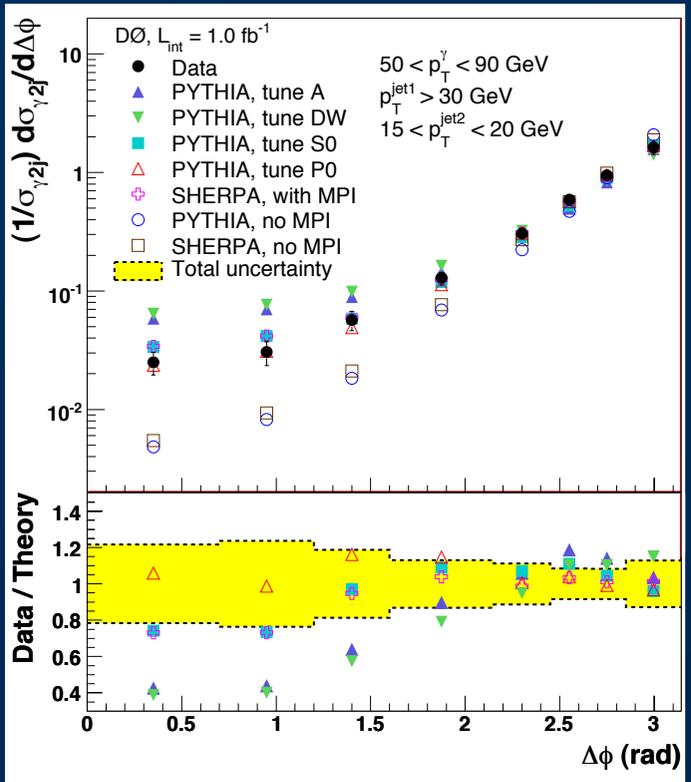
PRD 83, 052008 (2011)

1.0 fb⁻¹

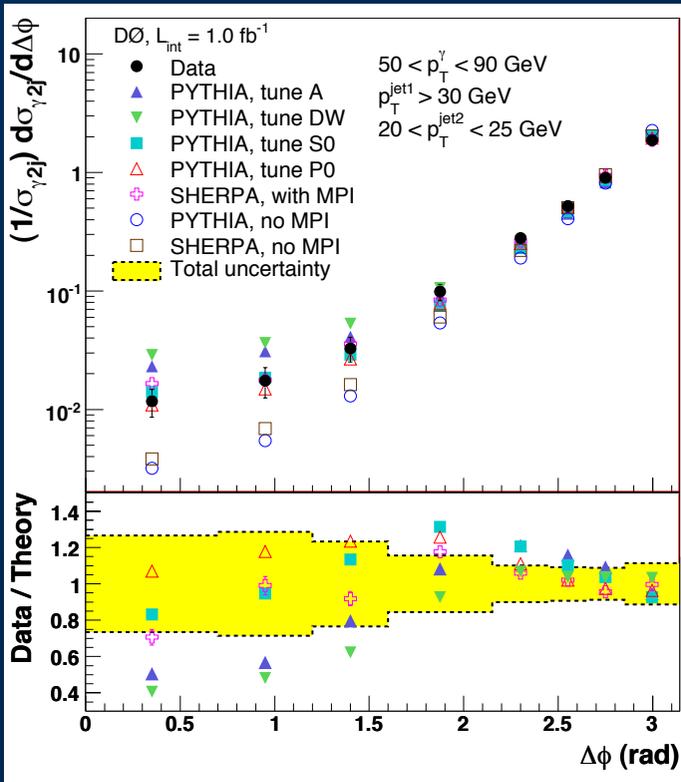
$\Delta\phi$

$\Delta\phi$

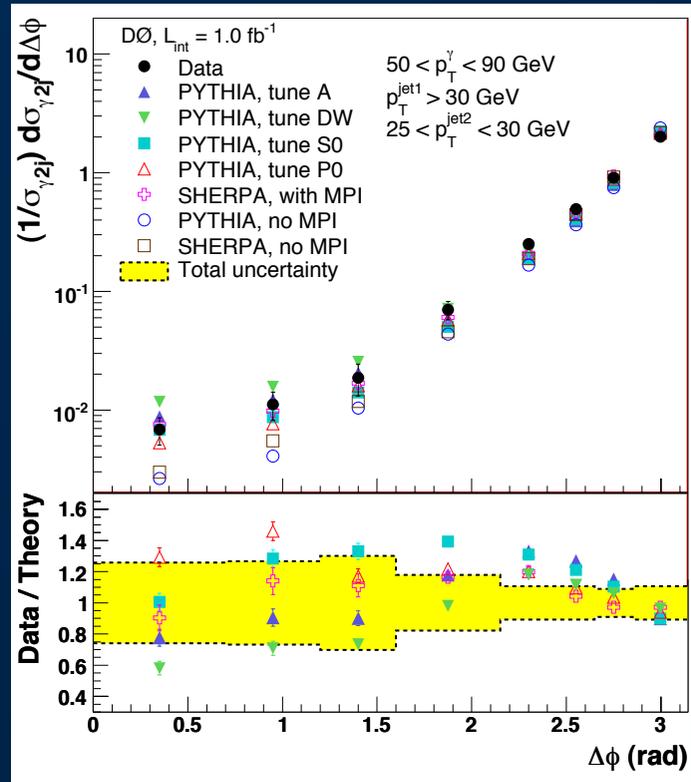
$\Delta\phi$



$15 < p_T^{\text{jet2}} < 20 \text{ GeV}$



$20 < p_T^{\text{jet2}} < 25 \text{ GeV}$



$25 < p_T^{\text{jet2}} < 30 \text{ GeV}$

Measurement of the exclusive $\gamma\gamma$ production cross section

PRL 108, 081801 (2012)

Additional Information

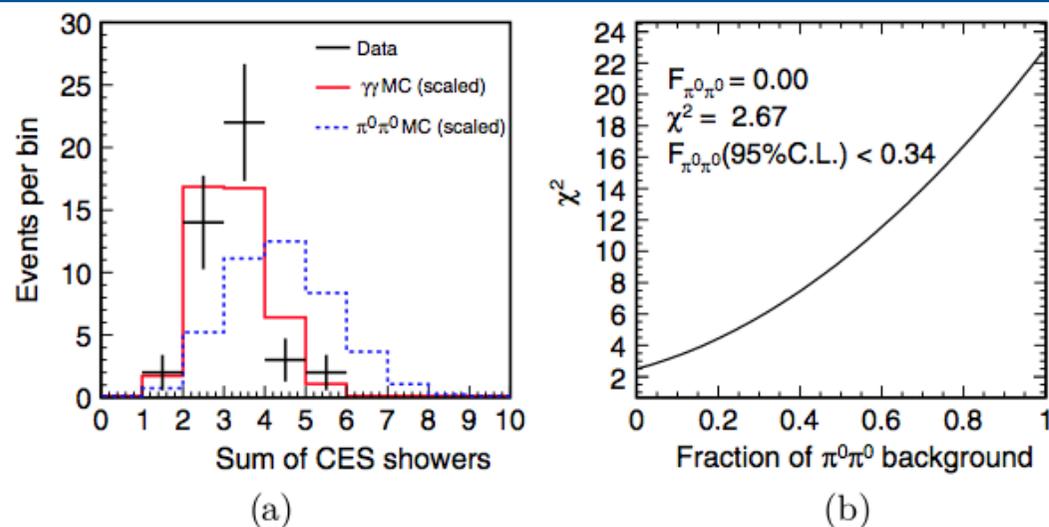


FIG. 3 (color online). Estimate of $\pi^0\pi^0$ background fraction in the candidate sample. Distribution of reconstructed CES showers per event for data compared to $\gamma\gamma$ and $\pi^0\pi^0$ Monte Carlo simulations (a). Background fraction estimate using Pearson's χ^2 test to fit the composition hypothesis to the data distribution (b).

TABLE I. Summary of parameters used for the measurement of the exclusive photon-pair cross section for $E_T(\gamma) > 2.5$ GeV and $|\eta(\gamma)| < 1.0$. Values for the e^+e^- control study are also given. Note that b/g stands for background.

Integrated luminosity \mathcal{L}_{int}	$1.11 \pm 0.07 \text{ fb}^{-1}$
Exclusive efficiency	0.068 ± 0.004 (syst)
Exclusive $\gamma\gamma$	
Events	43
Photon-pair efficiency	0.40 ± 0.02 (stat) ± 0.03 (syst)
Probability of no conversions	0.57 ± 0.06 (syst)
$\pi^0\pi^0$ b/g (events)	0.0, <15 (95% C.L.)
Dissociation b/g (events)	0.14 ± 0.14 (syst)
Exclusive e^+e^-	
Events	34
Electron-pair efficiency	0.33 ± 0.01 (stat) ± 0.02 (syst)
Probability of no radiation	0.42 ± 0.08 (syst)
Dissociation b/g (events)	3.8 ± 0.4 (stat) ± 0.9 (syst)