



Measurements of Direct Photon Production Cross Sections at the Tevatron

Costas Vellidis

(Fermilab)

on behalf of the CDF and D0 Collaborations

Workshop on Standard Model Benchmarks at the Tevatron and LHC
Fermilab, November 19, 2010

Outline

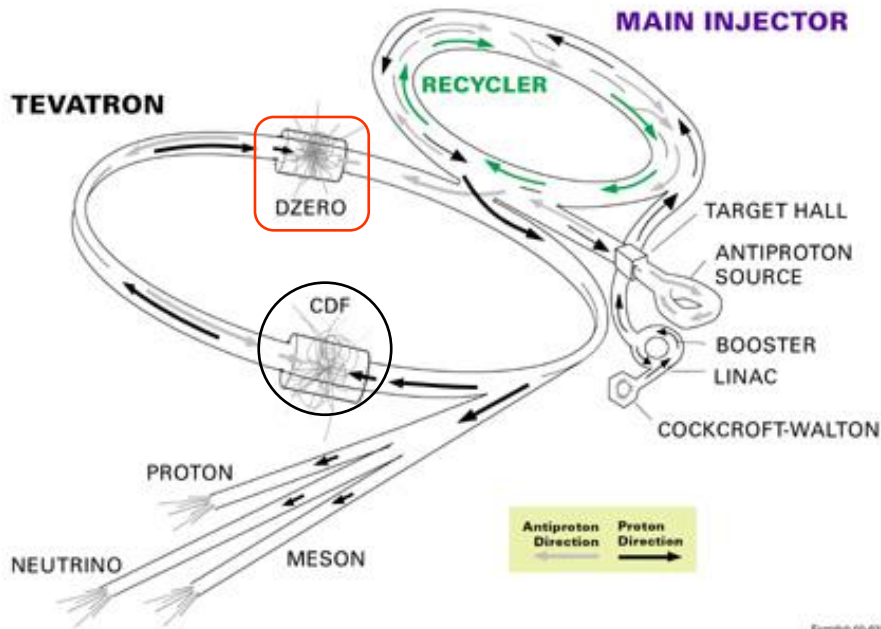
- Introduction
- Single photon production measurements
- Photon pair production measurements
- Conclusions

Introduction

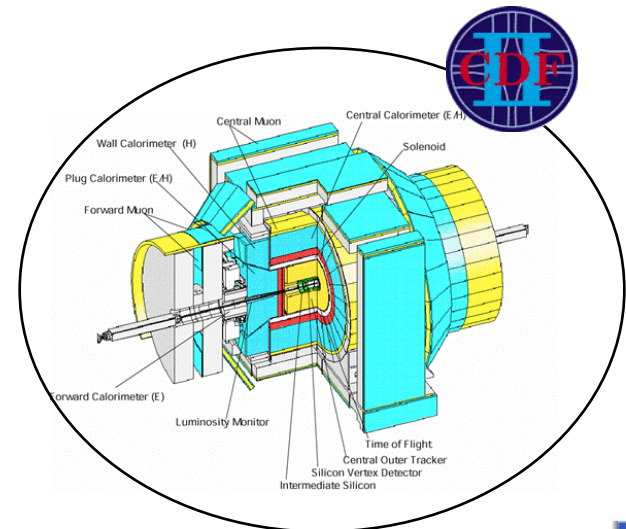
- Direct or prompt photon = not coming from neutral hadron decays (mostly π^0 and η) or from radiation in the detector material — non-prompt photons form a background which is subtracted from the data
- Photons can be measured with **high precision** in modern calorimeters
- Measurements of direct photon differential cross sections are a precision probe for understanding the dynamics of high energy hadron collisions and for searching new phenomena
- The Tevatron is an ideal place to conduct such measurements: A highly performing collider with two **well understood detectors, CDF and D0**, provide a large amount of high quality data

Experimental Environment: Fermilab Tevatron

FERMILAB'S ACCELERATOR CHAIN



- ppbar collisions at 1.96 TeV (since 2001)
- $\sim 9.5 \text{ fb}^{-1}$ delivered, $\sim 8 \text{ fb}^{-1}$ on tape for each experiment



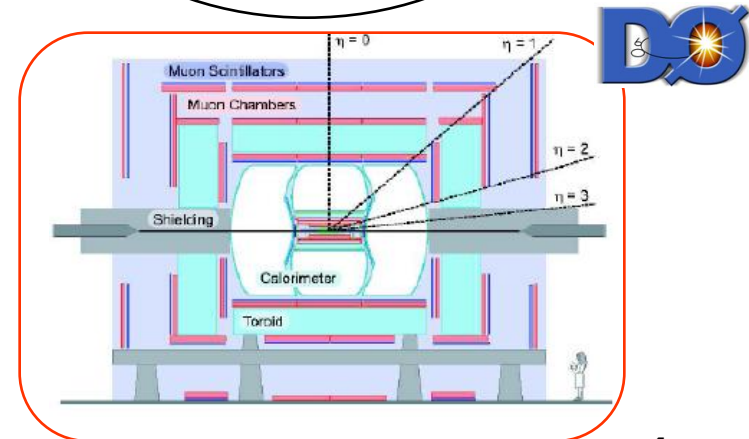
□ Central electromagnetic calorimeters

→ CDF: scintillator – lead with pre-radiation (CPR) and shower profile (CES) chambers

$$\sigma(E)/E = 13.5\% / \sqrt{E} \oplus 1.5\%$$

→ D0: liquid argon – uranium

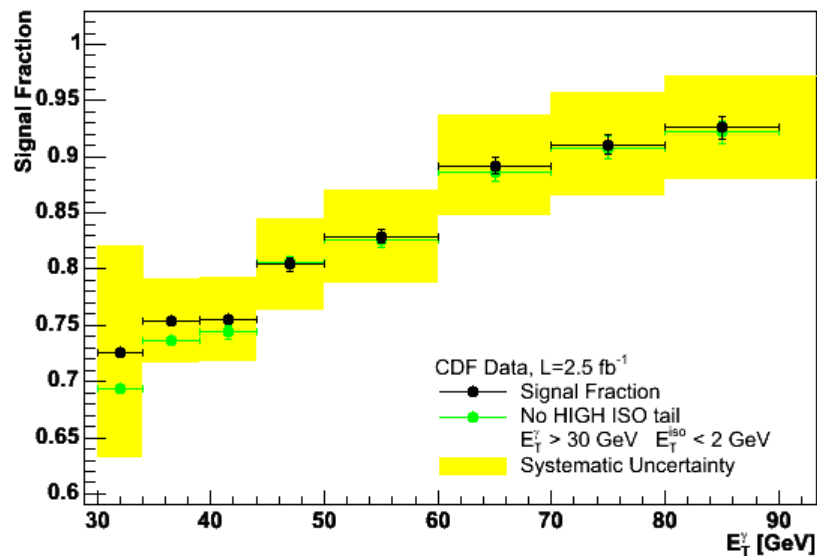
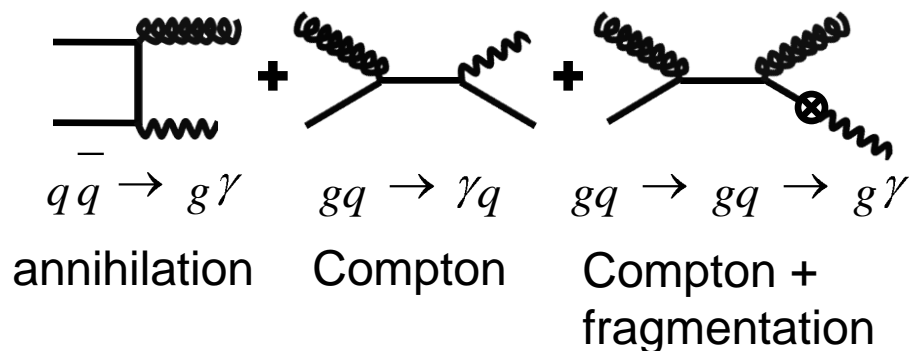
$$\sigma(E)/E = (18.0 - 20.0)\% / \sqrt{E} \oplus 2.0\%$$

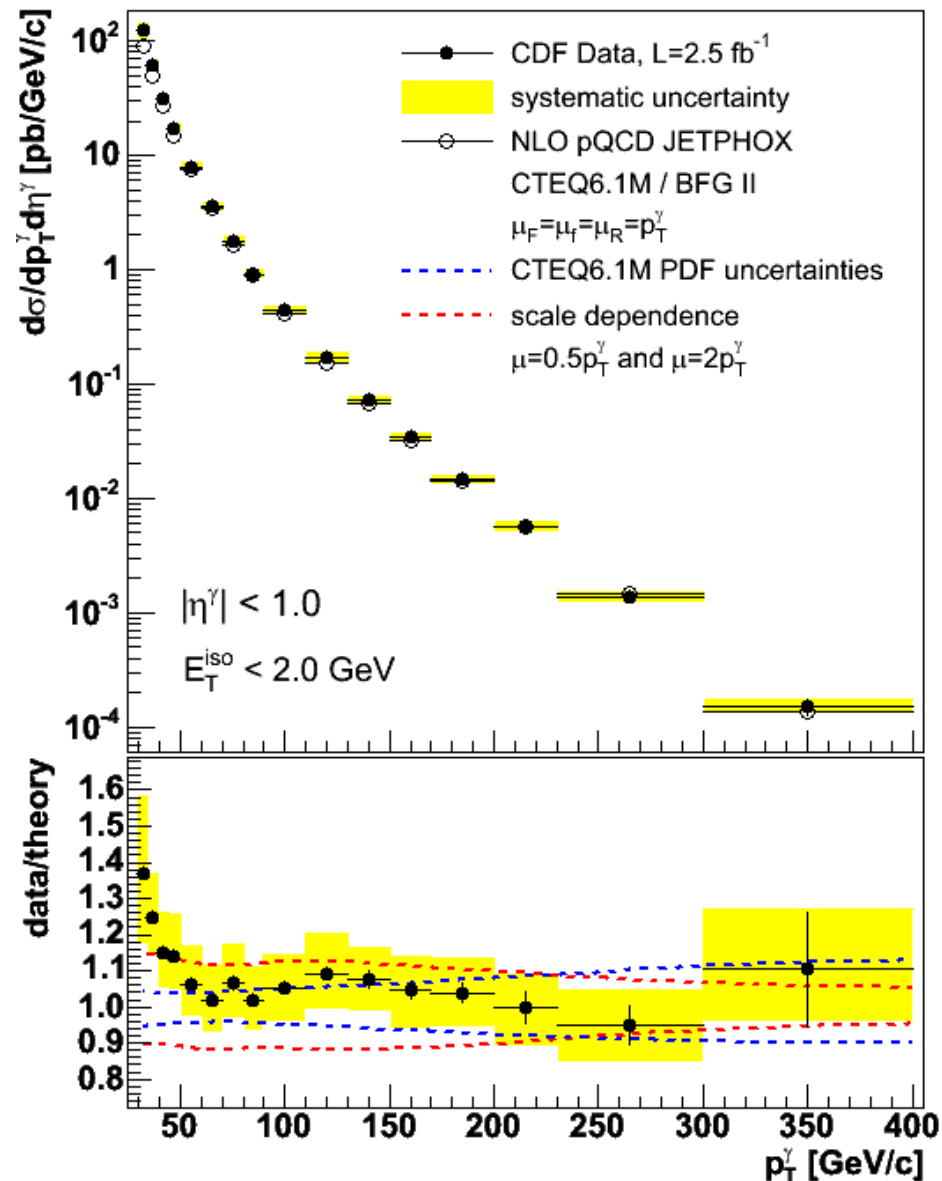


Measurement of the Inclusive Isolated Prompt Photon Cross Section using the CDF Detector

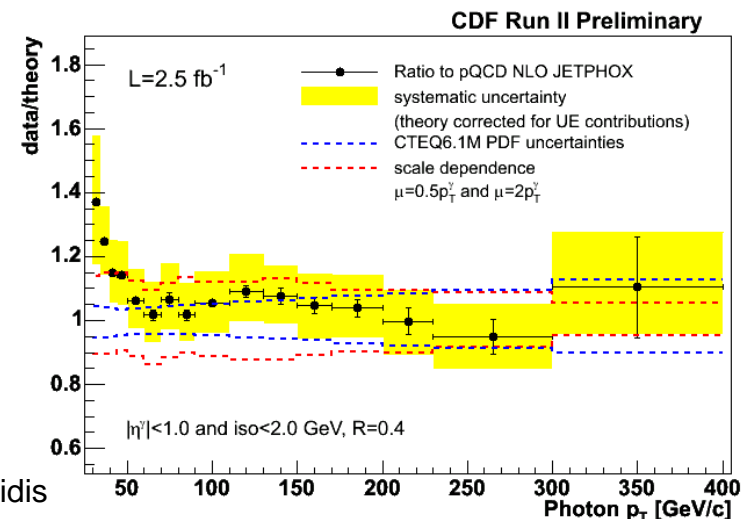
(Phys. Rev. D80: 111106, 2009 arXiv:0910.3623v2)

- Quark annihilation, Compton scattering and quark \rightarrow photon fragmentation (hard bremsstrahlung from the final state quark) dominate
- Measurement of $d\sigma/(dE_T^\gamma dy^\gamma)$ tests pQCD with potential to constrain the proton PDFs
- Isolated photons ($E_T^{R=0.4} - E_T^\gamma < 2$ GeV) with $30 \text{ GeV} < E_T^\gamma < 400 \text{ GeV}$ and $|y^\gamma| < 1$ selected from **2.5 fb⁻¹ of data**
- Background is subtracted by fitting Pythia γ +jet (for signal) and dijet (for background) templates of the **calorimeter isolation** distribution to the measured distribution in different E_T^γ bins





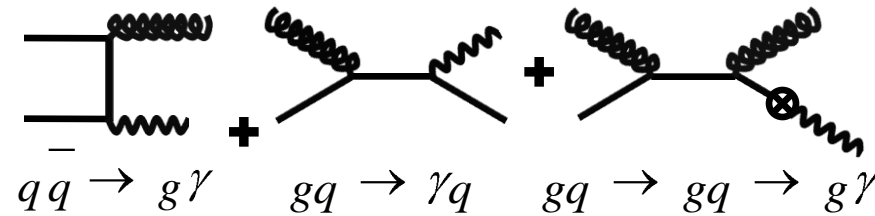
- Dominant sources of systematic uncertainty in data: **signal fraction estimate** at low E_T^γ and **energy scale** (tuned with $Z \rightarrow e^+e^-$ “photon-like” selected events) at high E_T^γ
- Data compared with NLO calculations (**Jetphox**) which include fragmentations [S. Catani *et al.*, JHEP **0205**, 028 (2002)]
- Data & theory in **fair agreement**, within uncertainties, except at low E_T^γ ($< 50 \text{ GeV}$, dominated by Compton scattering) where theory underestimates data



Measurement of the Isolated Photon Cross Section with Associated Jet using the D0 Detector

(Phys. Lett. B 666, 2435, 2008 arXiv.org:0804.1107)

- Quark annihilation, Compton scattering and quark \rightarrow photon fragmentation dominate



- Measurement of $d\sigma/(dE_T^\gamma dy^\gamma dy^{\text{jet}})$ tests pQCD with potential to constrain proton PDFs

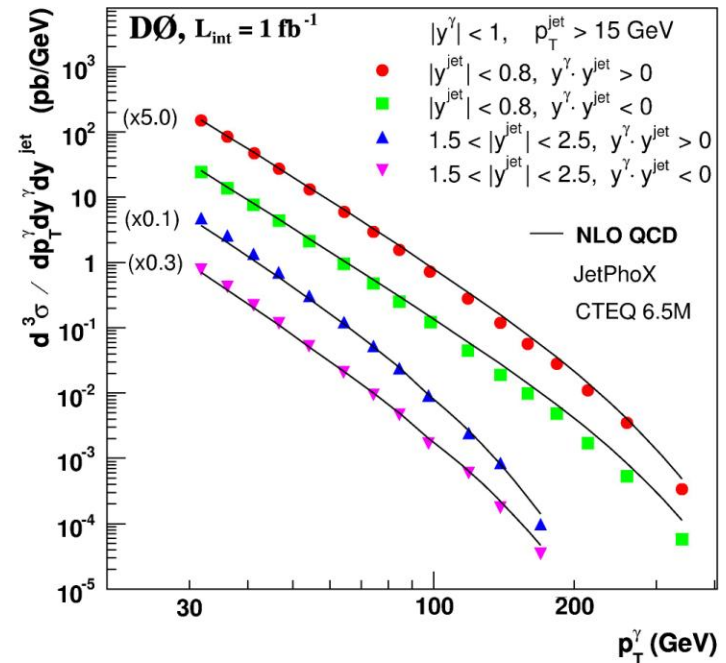
- Isolated γ 's $[(E_{\text{tot}}^{R=0.4} - E_{\text{em}}^{R=0.2})/E_{\text{em}}^{R=0.2} < 0.07)$ with $E_T^\gamma > 30$ GeV and $|y^\gamma| < 1$ selected from **1 fb⁻¹ of data**

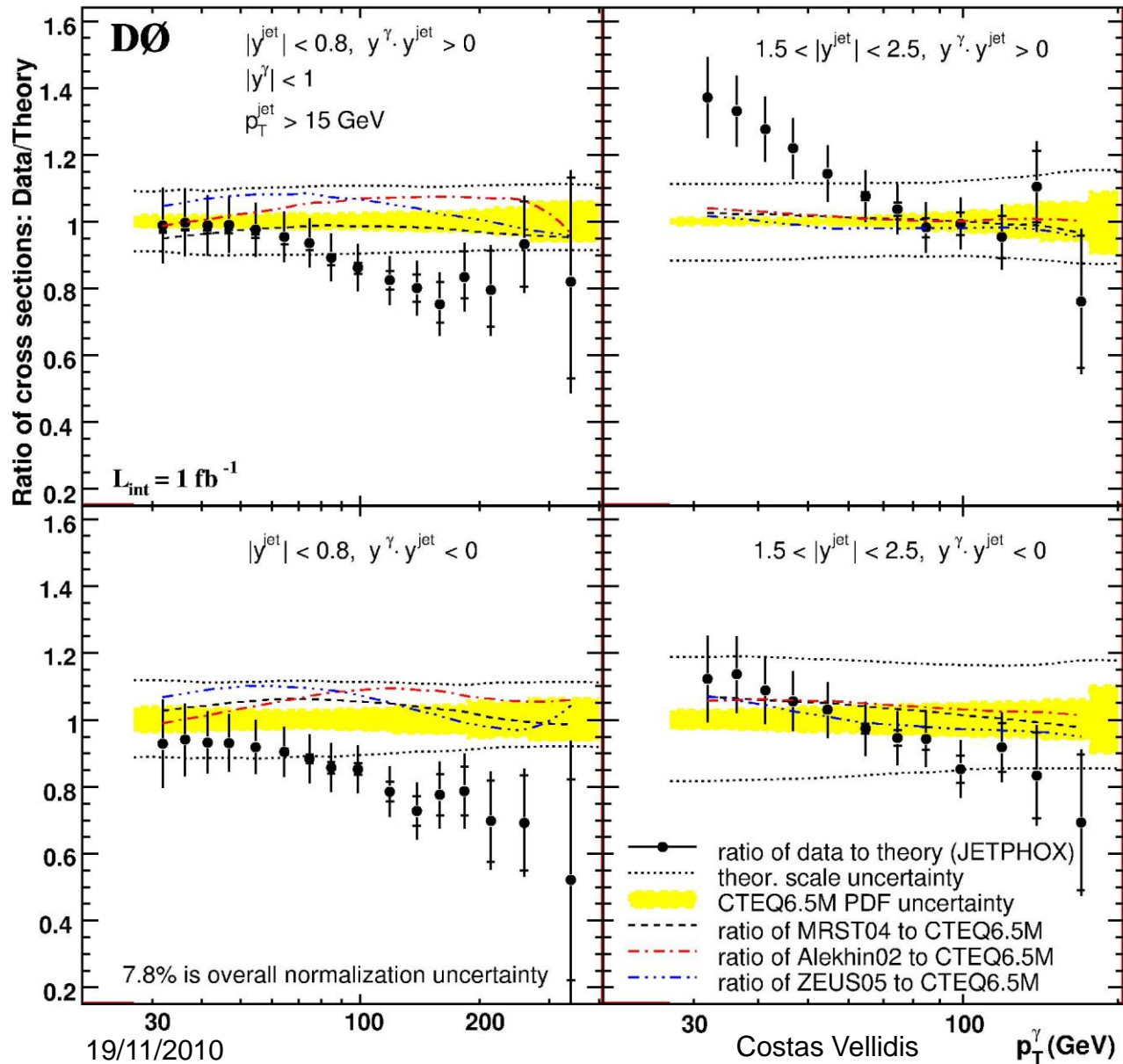
- Background photons subtracted with a NN

- **Central** ($|y^{\text{jet}}| < 0.8$) and **forward** ($1.5 < |y^{\text{jet}}| < 2.5$) jets with $E_T^{\text{jet}} > 15$ GeV selected

- Cross sections measured in 4 angular regions

$y^\gamma y^{\text{jet}} > 0$ (< 0) for central (forward jets) to separate low and high x parton scattering



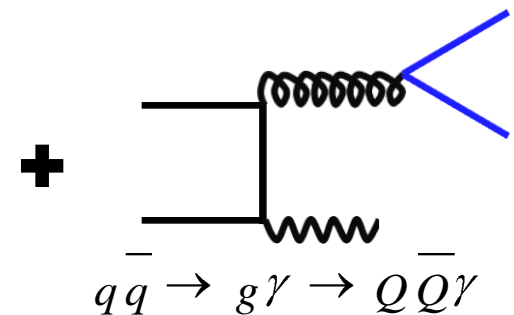
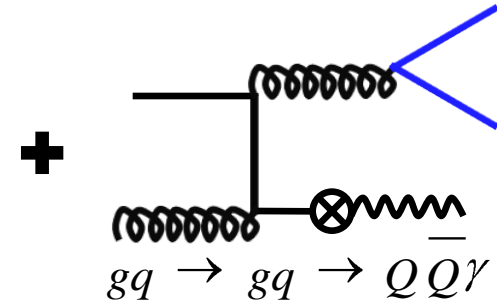
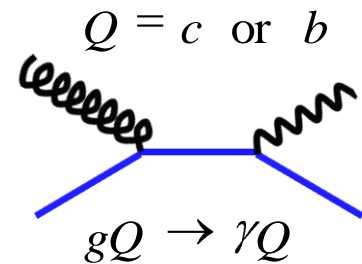


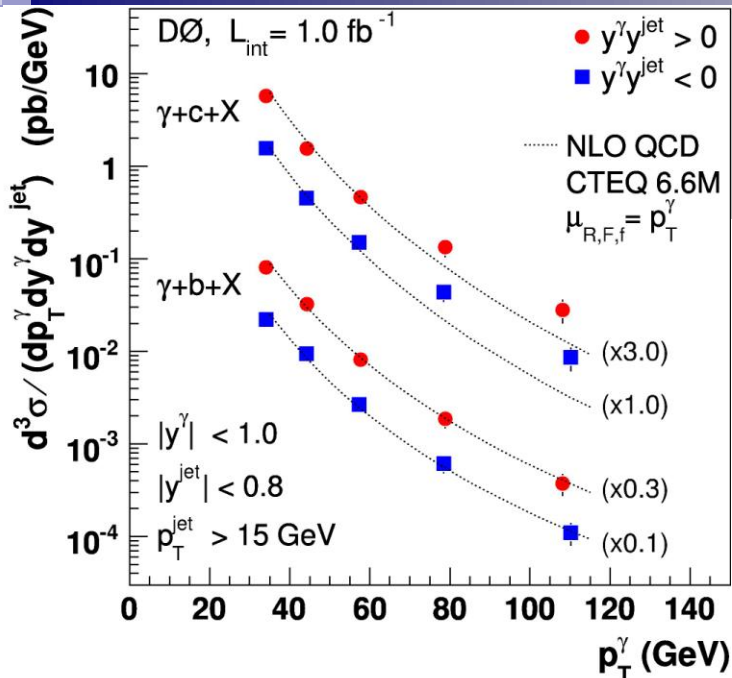
- Data compared with NLO (**Jetphox**) calculations
- Theory **does not describe the data** well enough within uncertainties

Measurement of the Photon Cross Section with Associated Heavy Flavor Jet using the D0 Detector

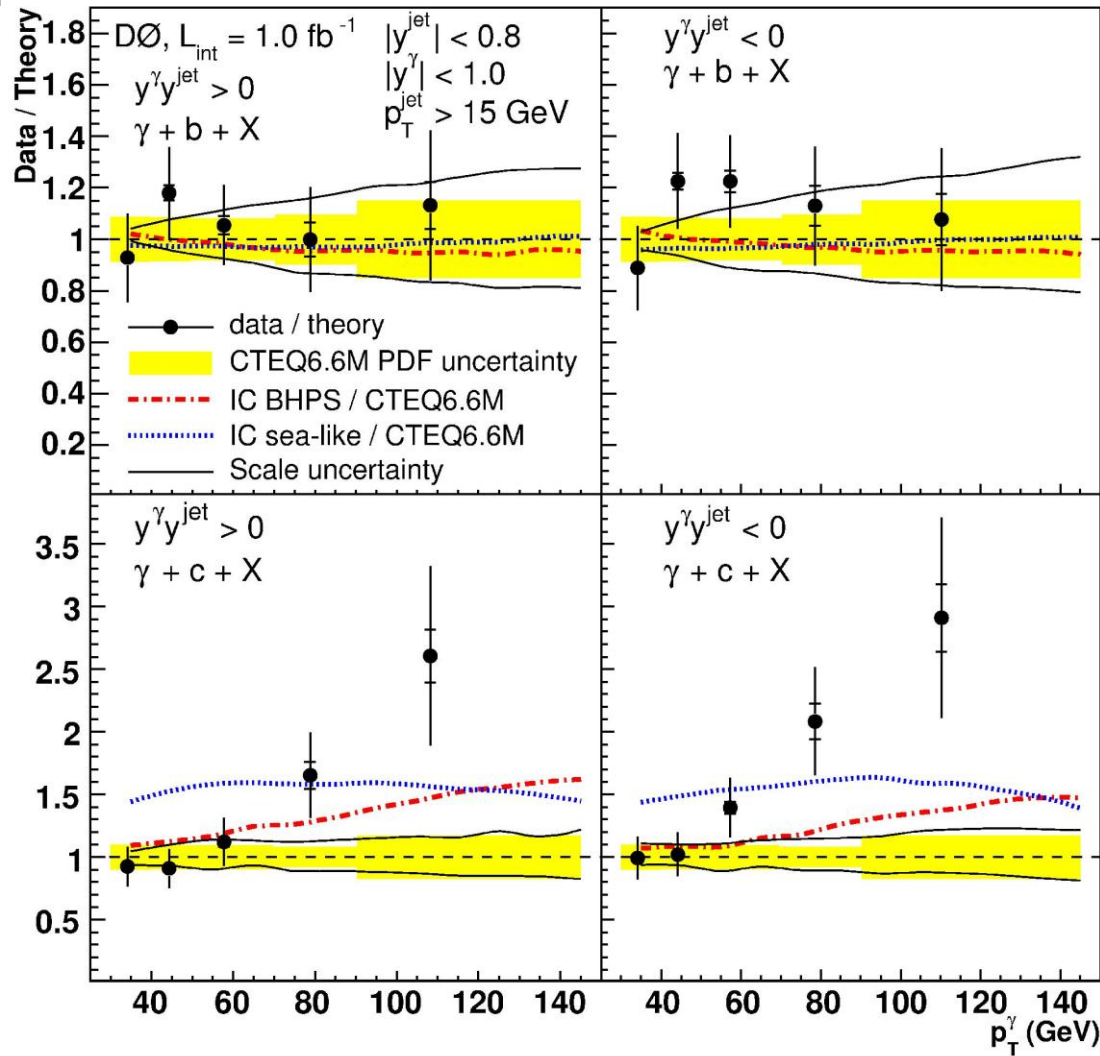
(Phys. Rev. Lett. 102, 192002, 2009 arXiv.org:0901.0739)

- Compton scattering dominates at $E_T^\gamma < 90$ (150) GeV for c (b) quarks, quark annihilation contributes too
- Measurement of $d\sigma/(dE_T^\gamma dy^\gamma dy^{\text{jet}})$ **tests the heavy flavor and gluon contents** of the proton
- Isolated γ 's [$(E_{\text{tot}}^{R=0.4} - E_{\text{em}}^{R=0.2})/E_{\text{em}}^{R=0.2} < 0.07$] with $E_T^\gamma > 30$ GeV and $|y^\gamma| < 1$ selected from **1 fb⁻¹ of data**
- Background photons subtracted with a **NN**
- Central ($|y^{\text{jet}}| < 0.8$) jets with $E_T^{\text{jet}} > 15$ GeV selected, heavy flavor tagged using a **NN** based on heavy flavor hadron life times
- γ +LF jet background subtracted by fitting **Pythia templates** compared with negative tag data





Statistical uncertainty in data 2-9%, systematic uncertainty 15-28% with main sources the γ purity at low E_T^γ and the **HF fraction** at high E_T^γ



- Data compared with NLO QCD* calculations in 2 angular regions, $y^\gamma y^{\text{jet}} > 0$ and < 0

*[arXiv:0901.3791v1 (2009) & PRD65, 094032 (2002)]

- Theory **agrees with $\gamma+b$** data but **not with $\gamma+c$** $E_T^\gamma > 70$ GeV data; adding intrinsic charm (IC) in CTEQ6.6* tends to correct the predictions

19/11/2010

*[PRD75, 054029 (2007)]

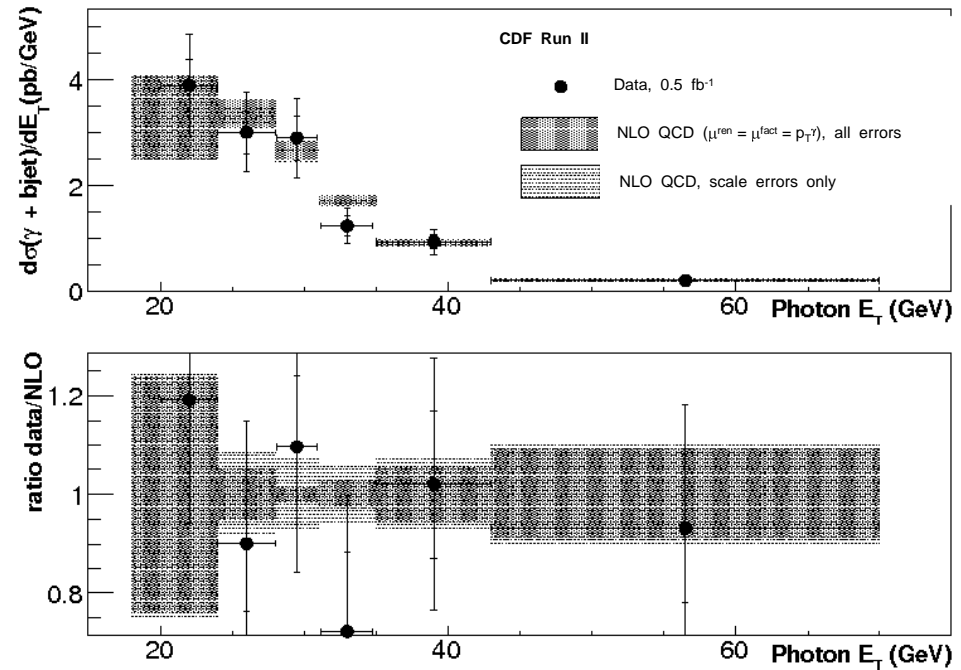
Costas Vellidis

10

Measurement of the Photon Cross Section with Associated b Flavor Jet using the CDF Detector

(Phys. Rev. D. 81, 052006, 2010 arXiv:0912.3453)

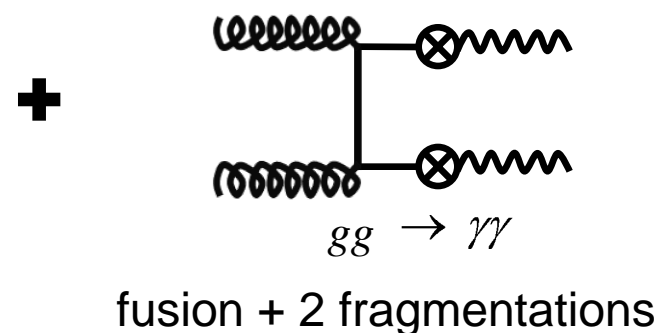
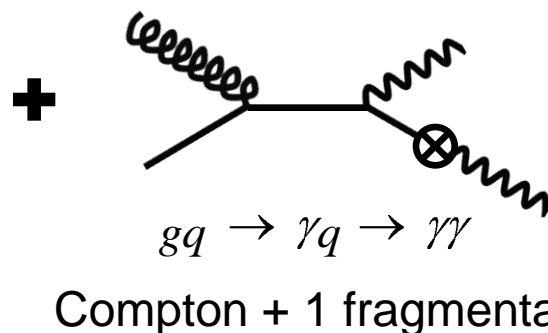
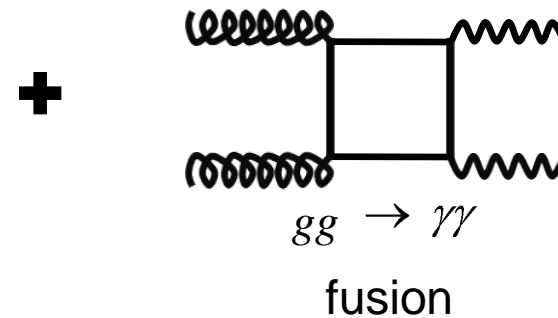
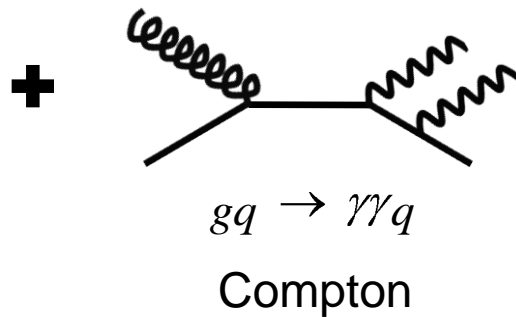
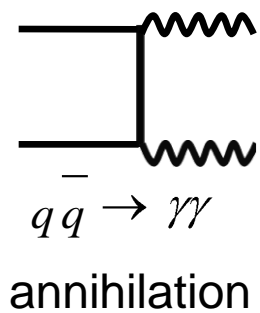
- Isolated γ 's ($\sum E_T^{R=0.4} - E_T^\gamma < 2$ GeV) with $E_T^\gamma > 20$ GeV and $|y^\gamma| < 1.1$ selected from 0.5 fb^{-1} of data
- Background photons subtracted using **CPR and CES data**
- Central ($|y^{\text{jet}}| < 1.5$) jets with $E_T^{\text{jet}} > 20$ GeV selected, b jets identified using **secondary vertex displacement**
- γ +LF jet background subtracted by fitting **Pythia** γ +HF jet and γ +LF jet **templates** to the data
- Main source of systematic uncertainty in the data ($\sim 17\%$) is the **b jet purity**



- The data are well described by NLO calculations [PRD 79, 054017 (2009)]

Direct Photon Pair Production Cross Section

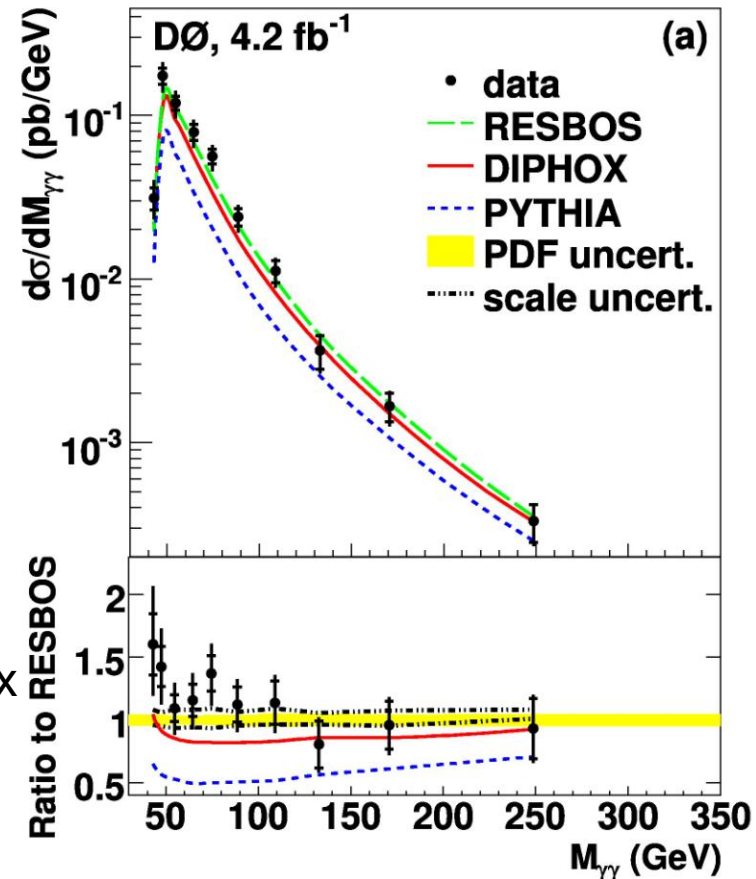
- $\gamma\gamma$ is a search channel for light mass **Higgs and new phenomena** (new heavy resonances, extra spatial dimensions, ...); direct $\gamma\gamma$ production is an irreducible background to these searches, need to be understood
- Quark annihilation, gluon fusion and Compton scattering (very small) contribute; fragmentations are also important in the gluon fusion and Compton scattering channels for high gluon luminosity
- Measuring $d\sigma/dX$ $\{X = M_{\gamma\gamma}, p_T^{\gamma\gamma}, \phi_{\gamma\gamma}, \cos\theta_* \cong \tanh[(y_{\gamma 1} - y_{\gamma 2})/2]\}$ **also tests pQCD**

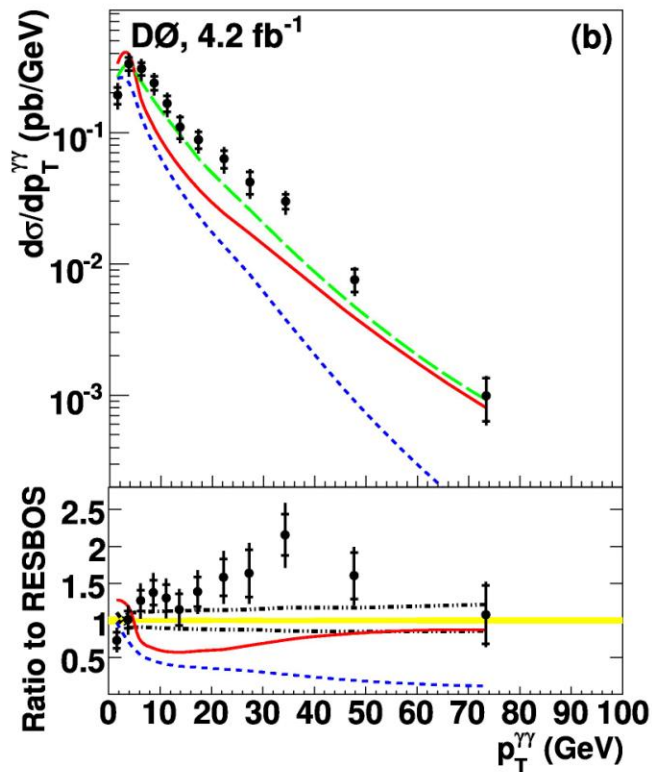


Measurement of the Direct Photon Pair Production Cross Section using the D0 Detector

(Phys. Lett. B 690, 108, 2010 arXiv.org:1002.4917)

- Isolated γ 's [$(E_{\text{tot}}^{R=0.4} - E_{\text{em}}^{R=0.2}) / E_{\text{em}}^{R=0.2} < 0.1$] with $E_{\text{T}}^{\gamma 1} > 21$ GeV, $E_{\text{T}}^{\gamma 2} > 20$ GeV and $|y^\gamma| < 1$ selected from **4.2 fb⁻¹ of data**
- Also required $\Delta R > 0.4$ and $M_{\gamma\gamma} > p_{\text{T}}^{\gamma\gamma}$ which, together with the isolation cut, eliminate most of the fragmentation contributions
- Small background from $Z \rightarrow e^+e^-$ events faking $\gamma\gamma$ subtracted using a **Pythia** $Z \rightarrow e^+e^-$ sample normalized to the NNLO $Z \rightarrow e^+e^-$ cross section
- Diphoton background subtracted with a 4x4 matrix technique using a **NN** output as the discriminant between signal and background photons
- Single- & double-differential cross sections were measured

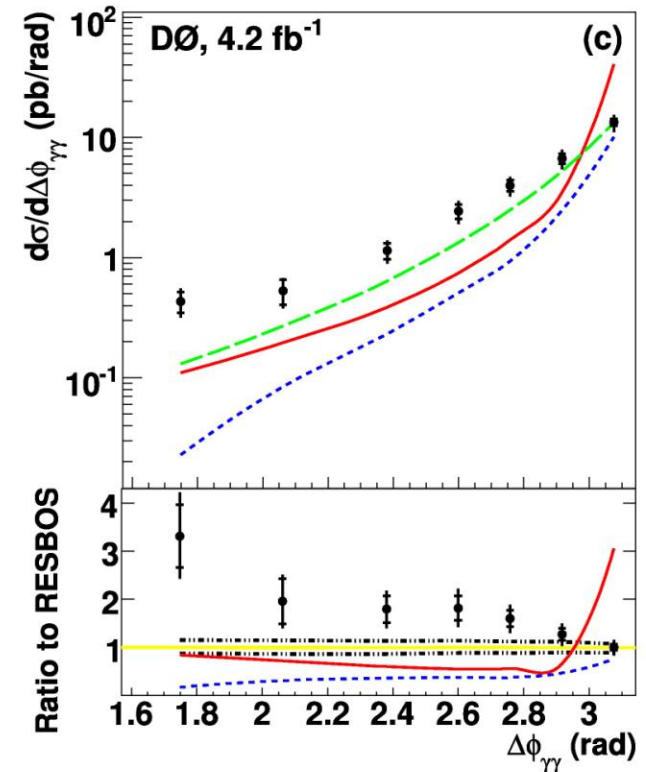




Data are compared with calculations from

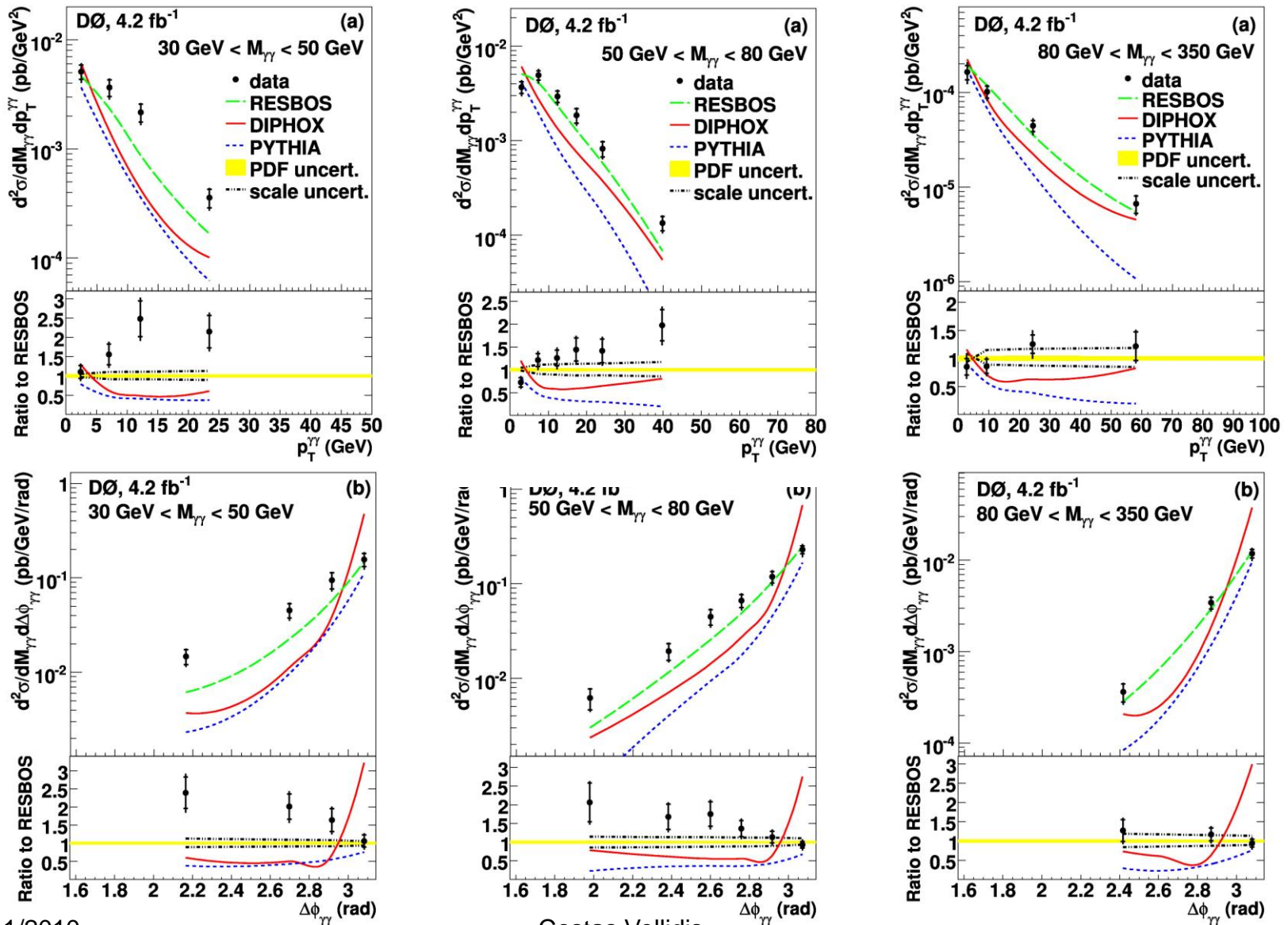
- **Pythia*** [LO + underlying event]
- **Diphox**** [NLO + fragmentations]
- **Resbos***** [NLO + soft gluon resummation]

*JHEP **0605**, 026 (2006); **Eur. Phys. J. C**16**, 311 (2000);
 ***PRD**76**, 013009 (2007)



- NLO cross sections **corrected** for multiple interactions & hadronization derived from **Pythia**
- **None of the 3 predictions describes the data** well over the full kinematic ranges
- NLO **performs well** at high $M_{\gamma\gamma}$, low $p_T^{\gamma\gamma}$, large $\Delta\phi_{\gamma\gamma}$, the range of Higgs & new physics searches
- **Sherpa*** calculations [Tree-level matrix element + parton showering] describe D0 results quite well (F. Siegert, <http://omnibus.uni-freiburg.de/~fs1015/talks/2010-05-CMS-Hgg.pdf>)

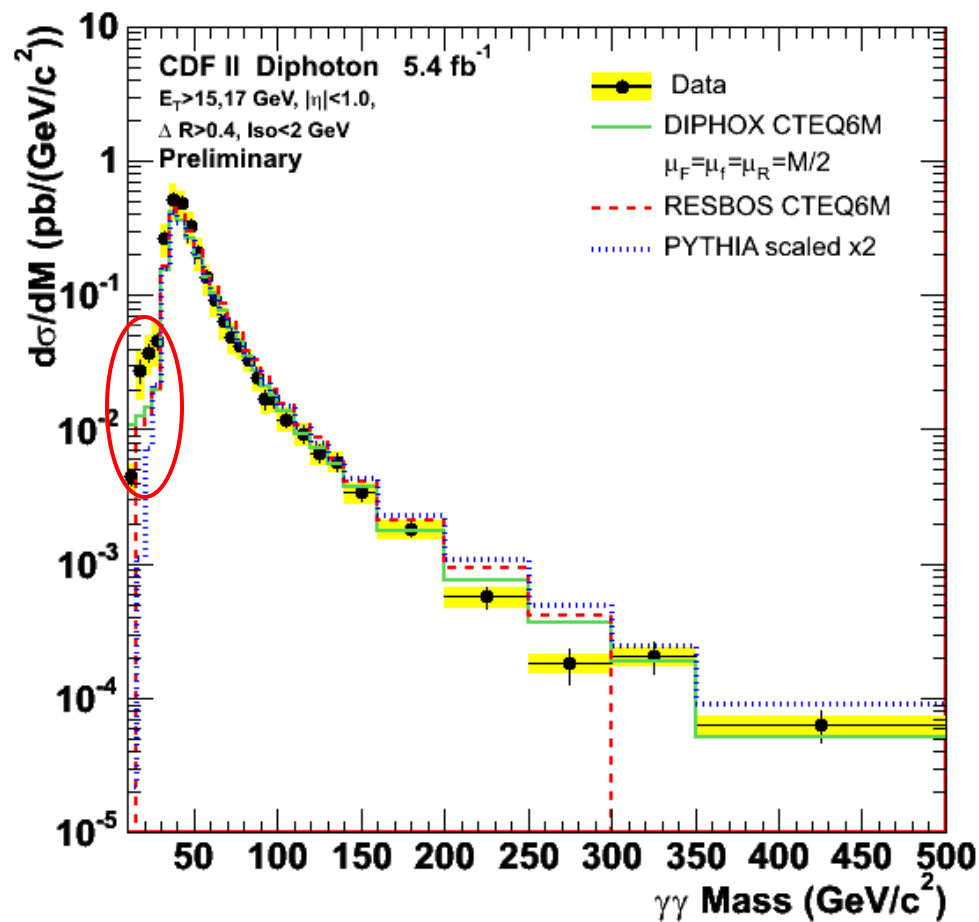
Direct Photon Pair Production Double-differential Cross Sections measured with the D0 Detector

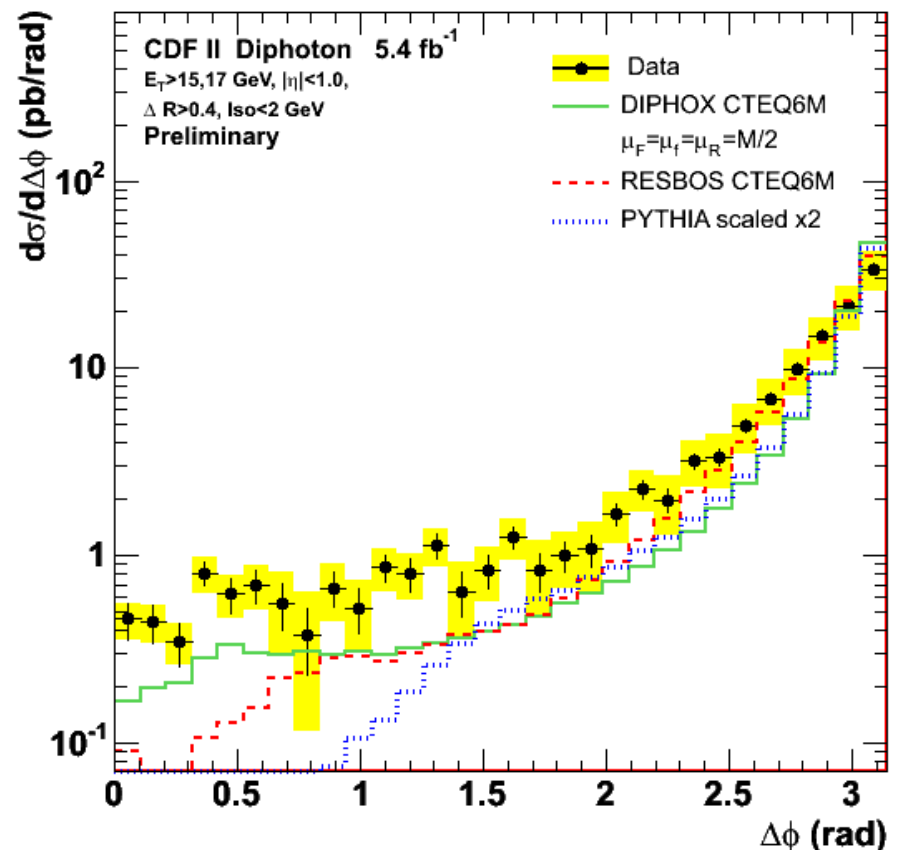
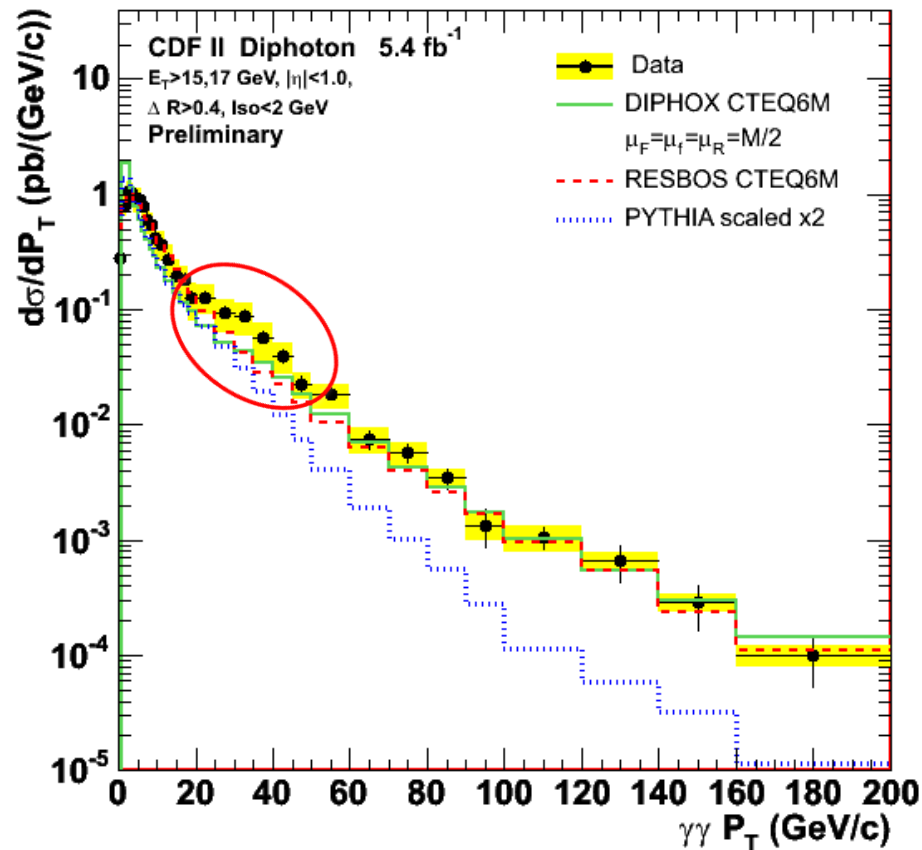


Measurement of the Direct Photon Pair Production Cross Section using the CDF Detector

(www-cdf.fnal.gov/physics/new/qcd/diphXsec_2010/public_diphoton.html)

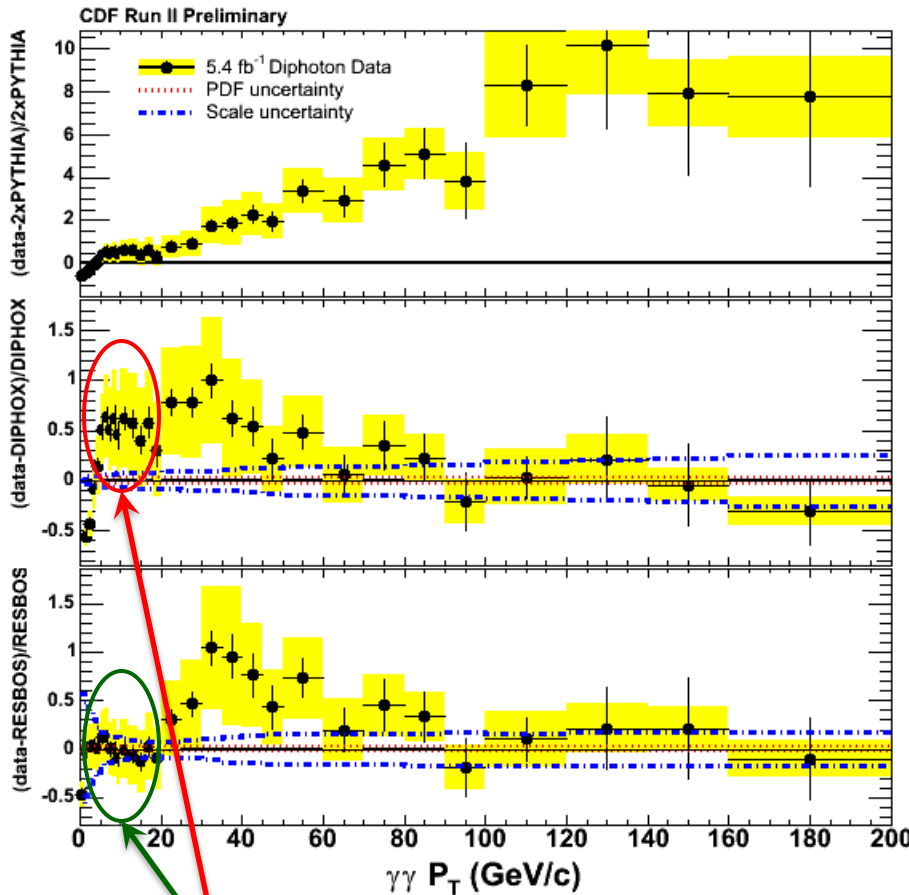
- Isolated photons ($\sum E_T^{R=0.4} - E_T^\gamma < 2 \text{ GeV}$) with $E_T^{\gamma 1} > 17 \text{ GeV}$, $E_T^{\gamma 2} > 15 \text{ GeV}$ and $|\eta^\gamma| < 1$ selected from **5.4 fb⁻¹ of data**
- Diphoton background subtracted with a 4×4 matrix technique using the **track isolation** ($\sum p_T^{R=0.4} - p_T^\gamma$) as the discriminant between signal and background photons
- Data are compared with calculations from **Pythia**, **Diphox** and **Resbos**



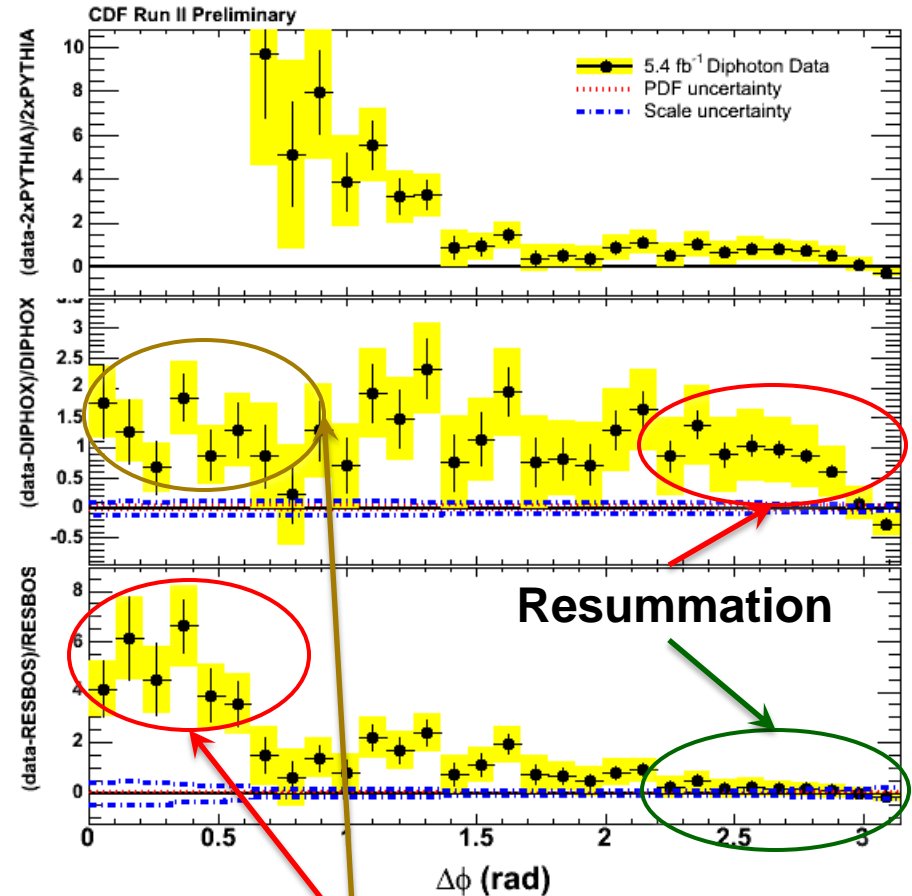


- **No model describes** the data well over the full kinematic ranges, in particular at **low** $M_{\gamma\gamma}$ (< 60 GeV/c²), moderate $p_{T\gamma\gamma}$ (20 – 50 GeV/c) and **low** $\Delta\phi_{\gamma\gamma}$ (< 1.7 rad) where fragmentations are expected to contribute significantly

Direct Photon Pair Production Differential Cross Sections measured with the CDF Detector: Ratios of Data/Theories



Resummation



Fragmentations

Conclusions

- **High precision measurements** of direct photon differential cross sections over **wide kinematic ranges** have been recently published, or will be published soon, from the Tevatron
- **Single direct photon** cross sections have been measured for
 - inclusive production
 - light flavor jet-associated production
 - heavy flavor jet-associated production

NLO pQCD calculations **do not describe well the jet-associated production**, in particular for charm flavored jets

- **Direct photon pair** cross sections have been measured
 - ❖ **Overall agreement** between data and theory, within known limitations, observed
 - ❖ **Resummation** matched with NLO pQCD calculations **works well** at low $p_T^{\gamma\gamma}$ (≤ 20 GeV/c) and large $\Delta\phi_{\gamma\gamma}$ (≥ 2.2 rad)
 - ❖ **Fragmentations** appear to be **not under good control** in sensitive regions ($M_{\gamma\gamma} \leq 60$ GeV/c², 20 GeV/c $\leq p_T^{\gamma\gamma} \leq 50$ GeV/c, $\Delta\phi_{\gamma\gamma} \leq 1.7$ rad)