Measurements with Prompt Isolated Photons at the Tevatron using the full Data Set

Costas Vellidis

Photon Physics Workshop, March 30, 2012
University of Paris

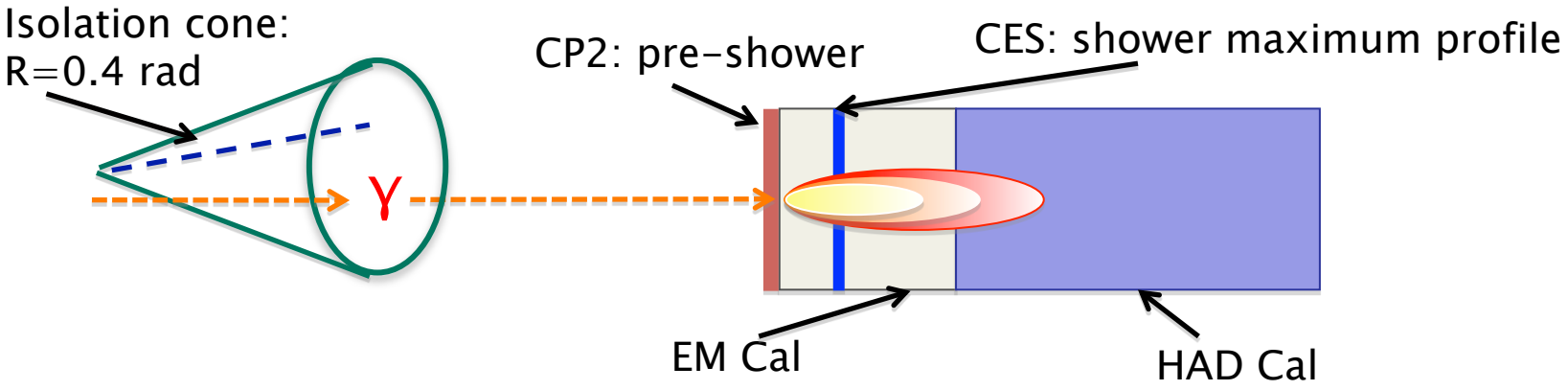
Prompt photon production in hadron colliders

- **Prompt photons** = emitted from quarks in hard scattering processes, as opposed to coming from neutral hadron decays (reducible background in cross section measurements)

- The cleanest probe of QCD – elementary particles, can be measured with **high precision** in modern calorimeters

- Probe for searching **new phenomena** – γγ is signature of possible heavy resonance decays

Photon identification and event selection at CDF



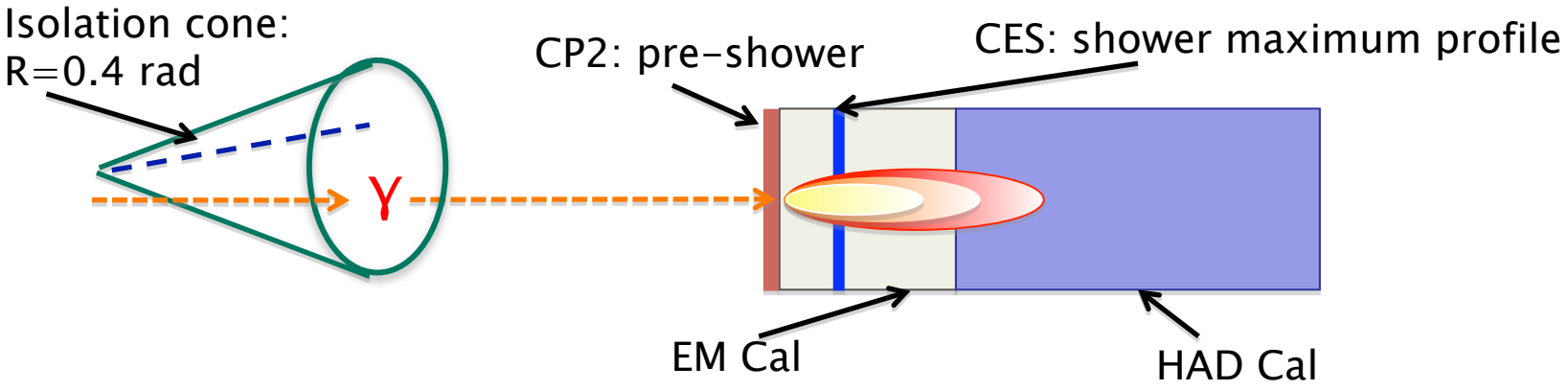
- Used dedicated diphoton triggers with optimized efficiency
- Photons were selected offline from EM clusters, reconstructed in a cone of radius R=0.4 in the $\eta-\phi$ plane, and requiring:
  - Fiducial to the central calorimeter: $|\eta|<1.1$
  - $E_T \geq 17,15$ GeV ($\gamma\gamma$ events), 30 GeV (γ+b/c events)
  - Isolated in the calorimeter: $I_{cal} = E_{tot}(R=0.4) - E_{EM}(R=0.4) \leq 2$ GeV

  } Imply that $\Delta R(\gamma,\gamma)$ or $\Delta R(\gamma,j) \geq 0.4$

  - Low HAD fraction: $E_{HAD}/E_{EM} \leq 0.055 + 0.00045 \times E_{tot}/\text{GeV}$
  - At most one track in cluster with $p_T^{trk} \leq 1$ GeV/c + $0.005 \times E_T^{\gamma}/c$
  - Shower profile consistent with predefined patterns: $\chi^2_{CES} \leq 20$
  - Only one high energy CES cluster: E_T of 2nd CES cluster ≤ 2.4 GeV + $0.01 \times E_T$

Optimized in a NN for the γ+H.F measurements

Photon identification and event selection at CDF



Main difference in D0 photon identification is the fractional instead of absolute isolation:

$$(E_{tot}^{R=0.4} - E_{em}^{R=0.2}) / E_{em}^{R=0.2} < 0.07$$

- Fiducial to the central calorimeter: $|\eta|<1.1$
- $E_T \geq 17,15$ GeV ($\gamma\gamma$ events), 30 GeV (γ+b/c events)
- Isolated in the calorimeter: $I_{cal} = E_{tot}(R=0.4) - E_{EM}(R=0.4) \leq 2$ GeV

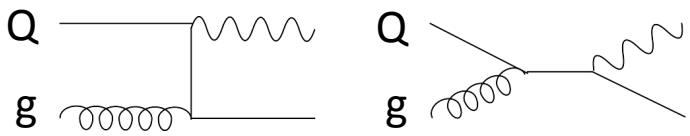
} Imply that $\Delta R(\gamma,\gamma)$ or $\Delta R(\gamma,j) \geq 0.4$

- Low HAD fraction: $E_{HAD}/E_{EM} \leq 0.055 + 0.00045 \times E_{tot}/\text{GeV}$
- At most one track in cluster with $p_T^{trk} \leq 1$ GeV/c + $0.005 \times E_T^{\gamma}/c$
- Shower profile consistent with predefined patterns: $\chi^2_{CES} \leq 20$
- Only one high energy CES cluster: E_T of 2nd CES cluster ≤ 2.4 GeV + $0.01 \times E_T$

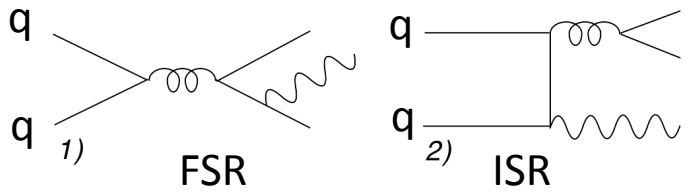
Optimized in a NN for the γ+H.F measurements

γ+b/c production

- **Probe heavy flavor content in hadrons**
- **LO contribution**: Compton scattering – dominant at low photon p_T
- **NLO contribution**: Annihilation + brems – dominant at high photon p_T



Compton scattering ~ $\alpha\alpha_s$



annihilation ~ $\alpha\alpha_s^2$

Theoretical predictions

- NLO $O(\alpha\alpha_s^2)$ matrix element + $O(\alpha_s^3)$ fragmentations (Stavreva & Owens, arXiv: 0901.3791v1)
- Pythia LO γ+Q matrix element + parton shower calculation
- Sherpa LO γ+Q+≤2partons matrix element + parton shower calculation (**D0 only**)
- k_T factorization model (Lipatov & Zotov, JETP Lett. 87:1, 2008; **D0 only**)
- Kinematic cuts (**D0**):
  - Generated photon: $|y|<1$, $1.5<|y|<2.5$, $30<p_T<250$ GeV/c
  - b or c quark: $|y|<1.5$, $p_T>15$ GeV/c
  - ΔR between photon and the leading b or c quark > 0.4
- Kinematic cuts (**CDF**):
  - Generated photon: $|y|<1$, $30<p_T<300$ GeV/c
  - b or c quark: $|y|<1.5$, $p_T>20$ GeV/c
  - ΔR between photon and the leading b or c quark > 0.4

Theoretical predictions

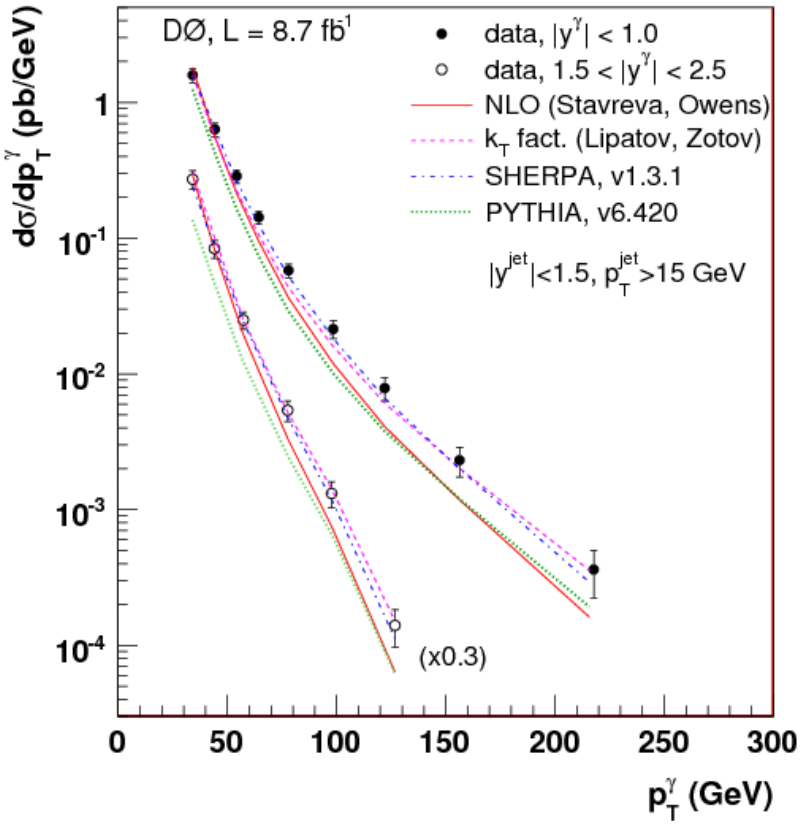
- NLO $O(\alpha\alpha_s^2)$ matrix element + $O(\alpha_s^3)$ fragmentations (Stavreva & Owens, arXiv: 0901.3791v1)
- Pythia LO γ+Q matrix element + parton shower calculation
- Sherpa LO γ+Q+<3partons matrix element + parton shower calculation (**D0 only**)
- k_T
- Ki
  -
  -
  -

	Total γ+b cross section (pb)	Total γ+c cross section (pb)
CDF	$19.7 \pm 0.7_{stat}\ (+\ 5.0 - 4.2)_{syst}$	$132.2 \pm 4.6_{stat}\ (+\ 13.2 - 19.2)_{syst}$
PYTHIA	17.0	101.4
PYTHIA (×2 g➔h.f.)	19.5	106.0
NLO	27.3 + 2.3 − 1.5	152.6 + 12.2 − 9.6

- Kinematic cuts (**CDF**):
  - Generated photon: $|y|<1,\ 30<p_T<300$ GeV/c
  - b or c quark: $|y|<1.5,\ p_T>20$ GeV/c
  - ΔR between photon and the leading b or c quark > 0.4

Comparisons – γ+b: D0

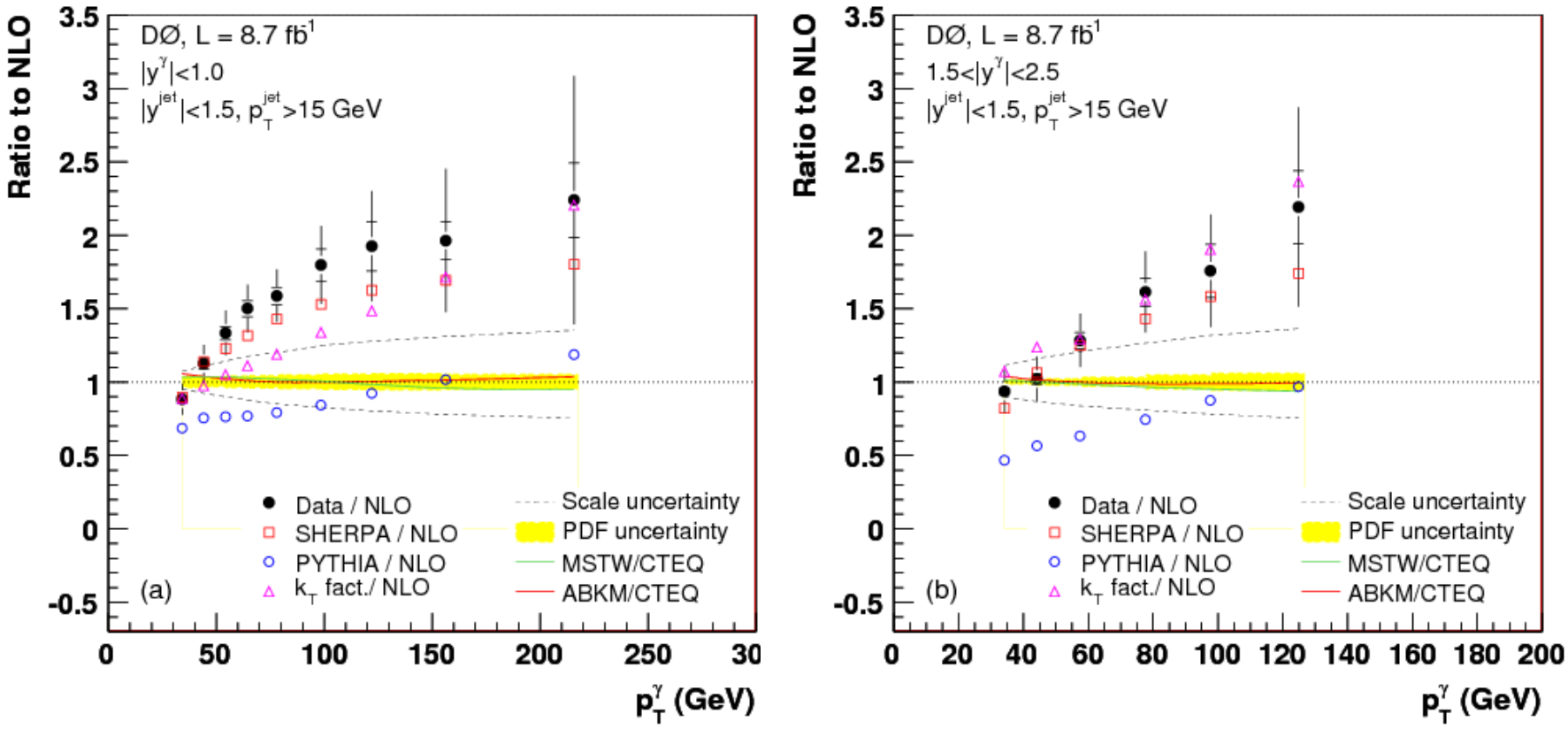
arXiv:1203.5865 (submitted to PLB)



- NLO and Pythia differ from the data by up to a factor of 2
- Sherpa and k_T model are in good agreement with the data
- Little sensitivity to the PDF choice between MSTW and ABKM

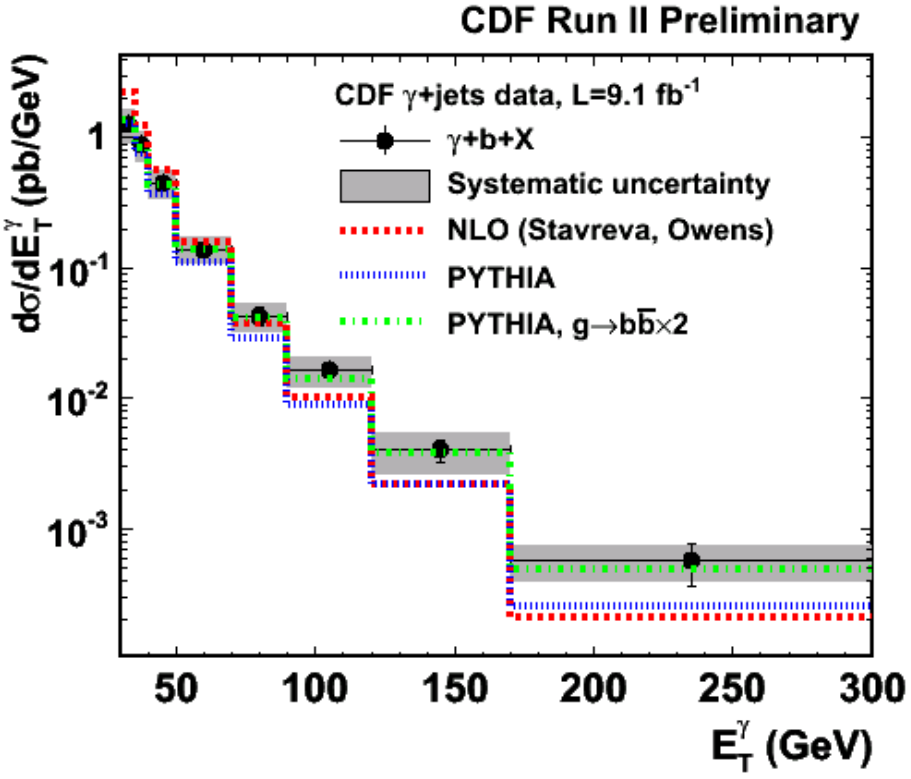
Comparisons – γ+b: D0

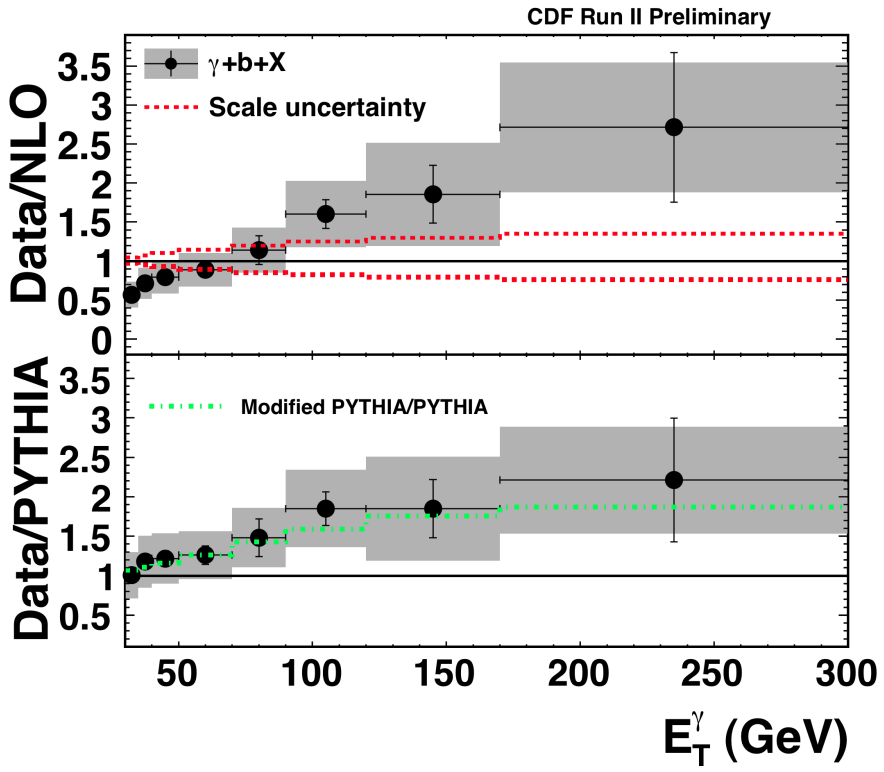
arXiv:1203.5865 (submitted to PLB)



- NLO and Pythia differ from the data by up to a factor of 2
- Sherpa and k_T model are in good agreement with the data
- Little sensitivity to the PDF choice between MSTW and ABKM

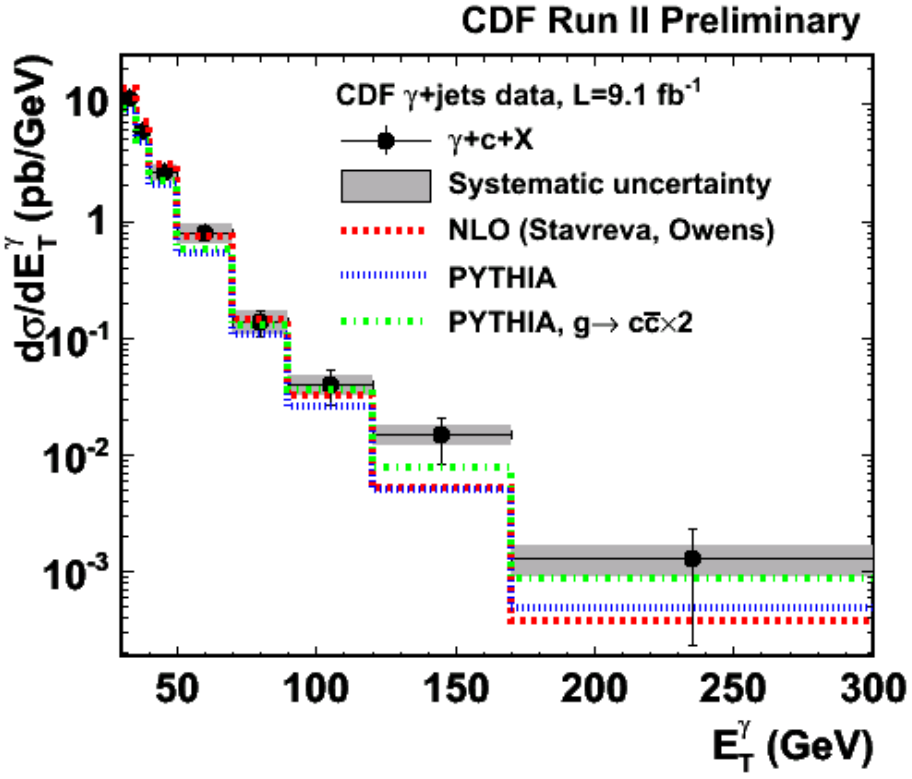
Comparisons – γ+b: CDF

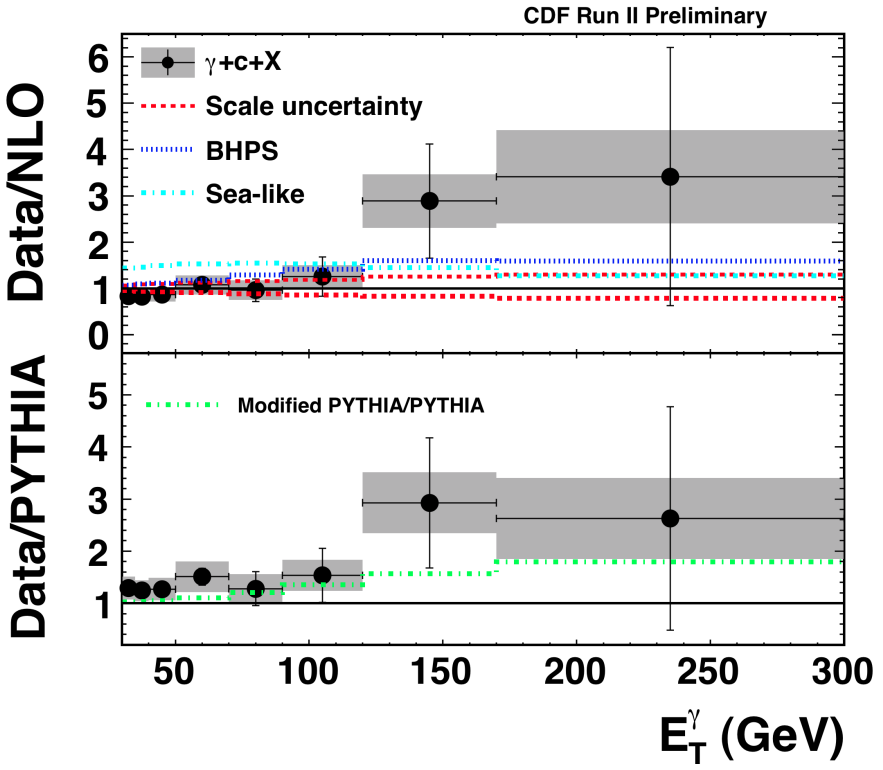




- A factor of 2-3 difference between data and default calculations at high p_T (agreement with D0)
- NLO and default Pythia agree with each other at high p_T
- Pythia with increased gluon splitting to heavy quarks agrees better with data

Comparisons – γ+c: CDF



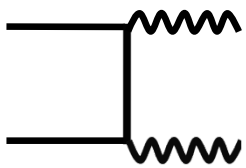


- Comparisons look similar
- NLO predictions with two intrinsic c-quark models:
  - BHPS: increase the cross section by 40% over the entire pt range
  - Sea-like: keep low-p_T cross section unchanged but increase high-p_T cross section by ≤ 60%
- No intrinsic b-quark model is available at this moment

γγ production

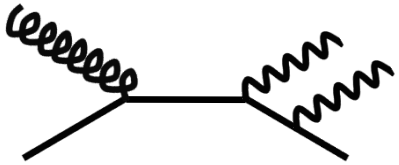
Hard QCD ("direct" γγ production):

Better control on these processes [σ ~ O(10 pb) at the Tevatron]



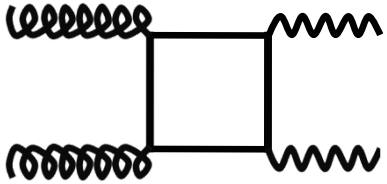
$q\bar{q} \rightarrow \gamma\gamma$

Born: Dominant at the Tevatron



$gq \rightarrow \gamma\gamma q$

Brems: Suppressed by the isolation requirement

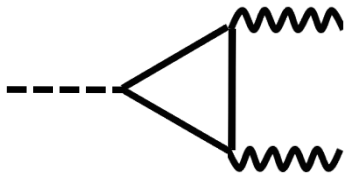


$gg \rightarrow \gamma\gamma$

"Box": Dominant at the LHC

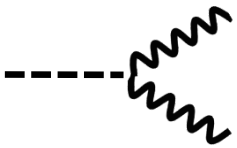
Possible heavy resonance decays:

➔ More sensitive searches for such processes [σ × BR ~ O(1 fb) at the Tevatron]



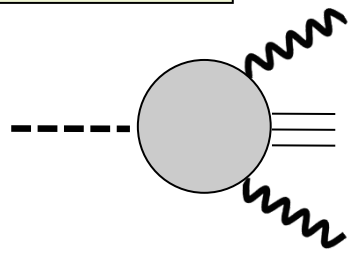
$H \rightarrow \gamma\gamma$

Low-mass Higgs boson (most sensitive channel at LHC for m_H<125 GeV/c^2)



$G^* \rightarrow \gamma\gamma$

Extra dimensions



$W \rightarrow \gamma\gamma + X$

SUSY

Theoretical predictions

- **PYTHIA** LO parton-shower calculation
  [T. Sjöstrand *et al.*, Comp. Phys. Comm. **135**, 238 (2001)]

- **SHERPA** LO parton-shower calculation with improved matching between hard and soft physics [T. Gleisberg *et al.*, JHEP **02**, 007 (2009)]

- **MCFM**: Fixed-order NLO calculation including non-perturbative fragmentation at LO [J. M. Campbell *et al.*, Phys. Rev. D **60**,113006 (1999)]

- **DIPHOX**: Fixed-order NLO calculation including non-perturbative fragmentation at NLO [T. Binoth *et al.*, Phys. Rev. D **63**,114016 (2001)]

- **RESBOS**: Low-P_T analytically resummed calculation matched to high-P_T NLO
  [T. Balazs *et al.*, Phys. Rev. D **76**, 013008 (2007)]

- **NNLO** calculation with q_T subtraction (PRELIMINARY)
  [L. Cieri *et al.*, http://arxiv.org/abs/1110.2375 (2011)]

Theoretical predictions

- **PYTHIA** LO parton-shower calculation
  [T. Sjöstrand *et al.*, Comp. Phys. Comm. **135**, 238 (2001)]

- **SHERPA** LO part… n hard and soft physics

- **MCFM**: Fixed-or… ntation at LO [J. M. Cam…

- **DIPHOX**: Fixed-c… entation at NLO [T. Binoth…

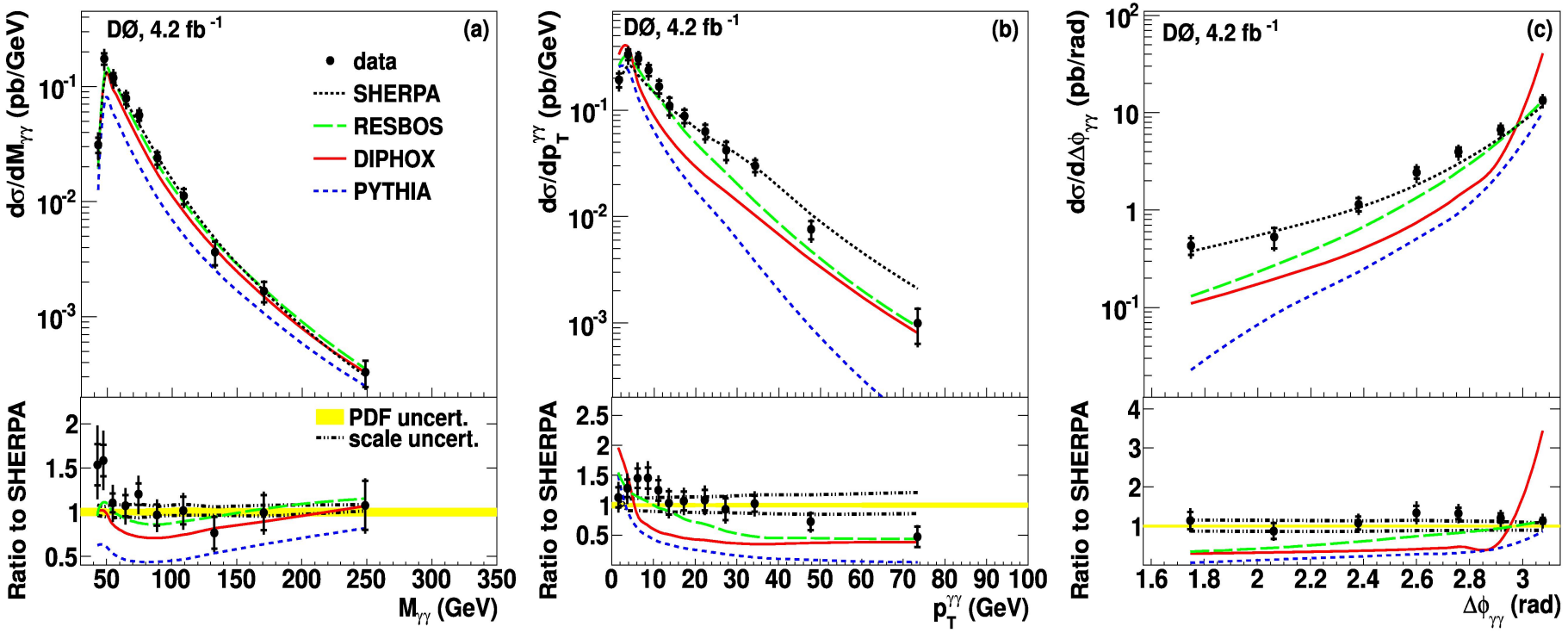
- **RESBOS**: Low-P_T… NLO [T. Balazs *et al.*,…

	Total cross section (pb)
CDF	$12.3 \pm 0.2_{stat} \pm 3.5_{syst}$
RESBOS	11.3 ± 2.4
DIPHOX	10.6 ± 0.6
MCFM	11.6 ± 0.3
SHERPA	10.9
PYTHIA γγ+γj	9.2
PYTHIA γγ	5.0
NNLO	12.2 ± 1.2

- **NNLO** calculation with q_T subtraction (PRELIMINARY)
  [L. Cieri *et al.*, http://arxiv.org/abs/1110.2375 (2011)]

Differential cross sections and data-to-theory ratios: D0

- D0 publication in Run II with 4.2 fb^{-1} *PLB 690, 108 (2010)*
- $p_{T1(2)}$>21(20) GeV/c, $|\eta_{1,2}|$<1, $\Delta R(\gamma,\gamma)$>0.4, $(E_{tot}^{R=0.4} - E_{em}^{R=0.2})/ E_{em}^{R=0.2}$<0.1, **$P_T(\gamma\gamma)$<M($\gamma\gamma$)**

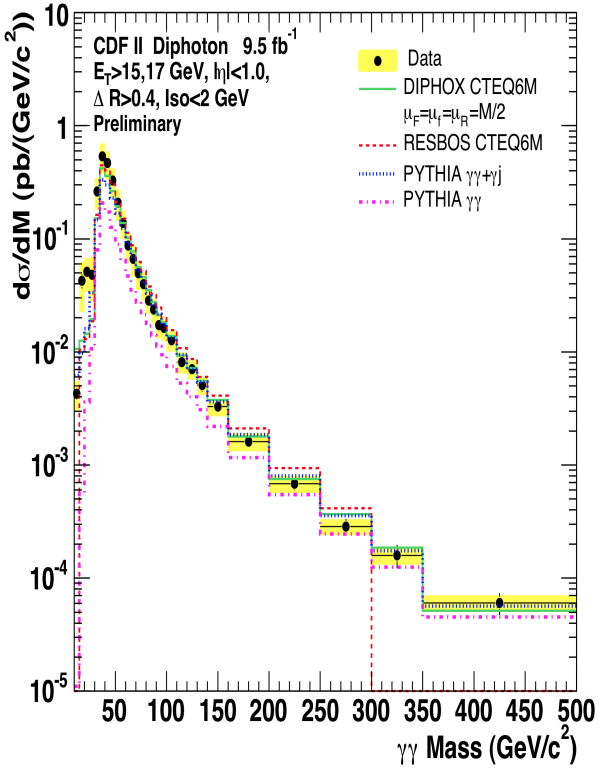


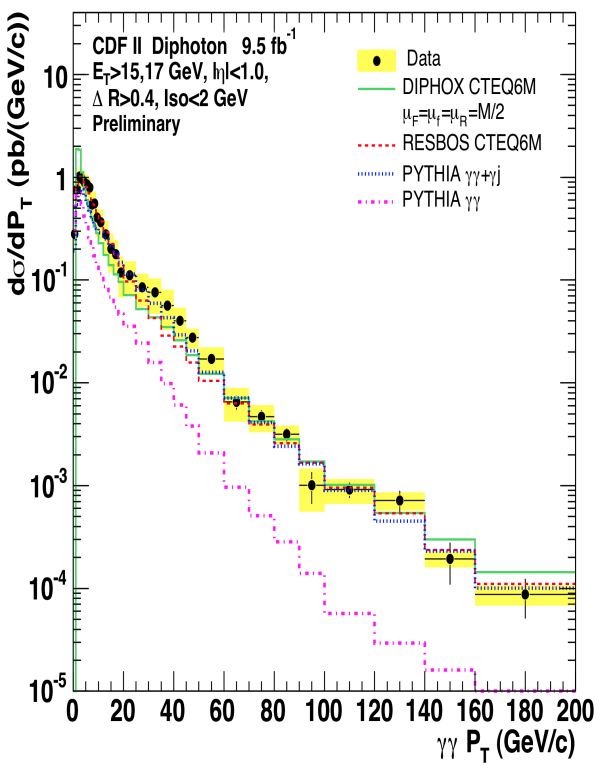
- Good agreement between data and RESBOS for $M_{\gamma\gamma}$>50 GeV/c^2
- Need for a resummed calculation
- Data spectrum harder than predicted
- Observable nearly insensitive to experimental effects
- Supports conclusion from $P_T(\gamma\gamma)$ measurement

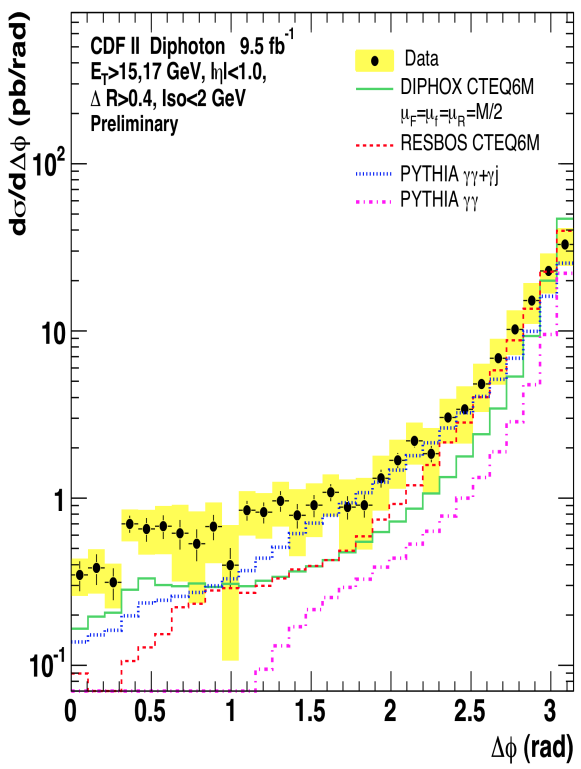
(*) Overall normalization uncertainty (7.3%) not included in data error bars.

Here the PYTHIA prediction uses only matrix element based production of photon pairs

Differential cross sections: CDF







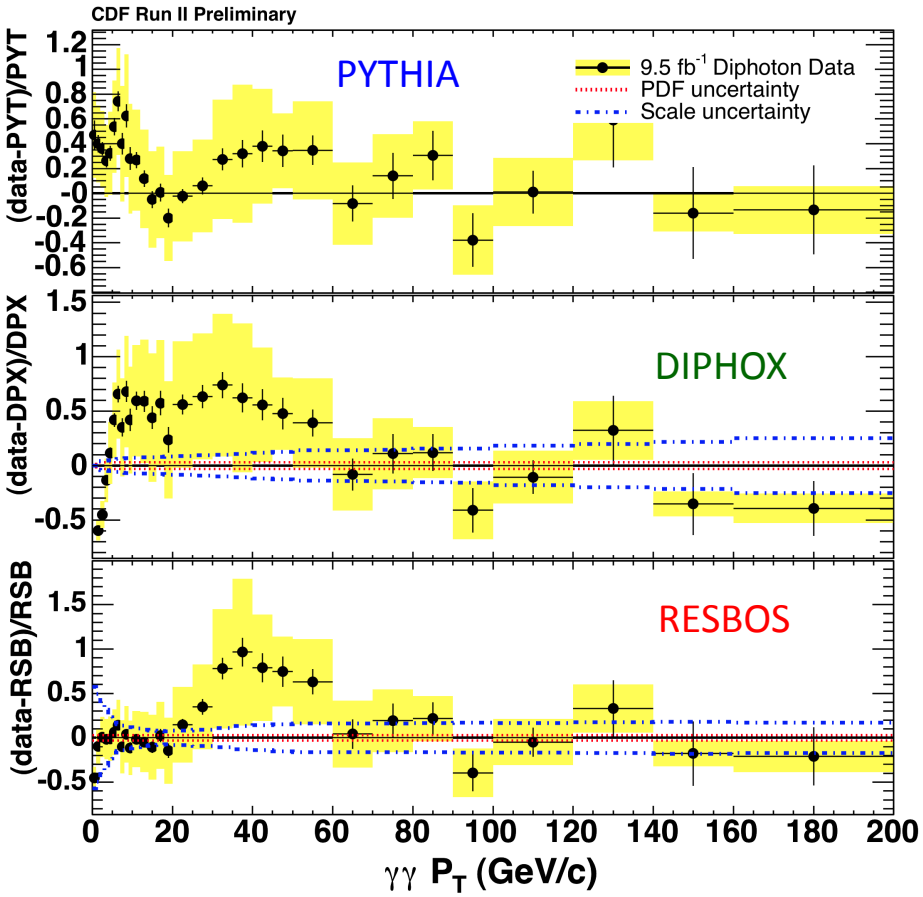
- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2

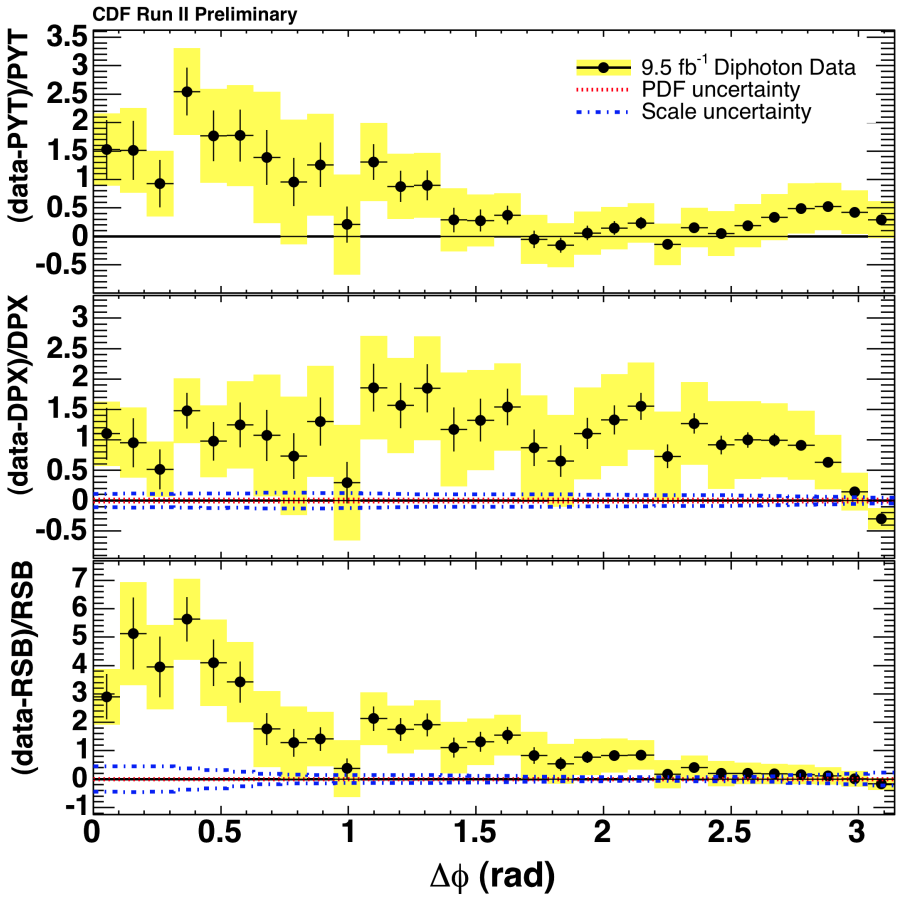
- Resummation important for $P_T(\gamma\gamma)$ > 20 GeV/c
- Fragmentation causes excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the "Guillet shoulder")

- Resummation important for $\Delta\phi_{\gamma\gamma}$ > 2.2 rad
- Data spectrum harder than predicted

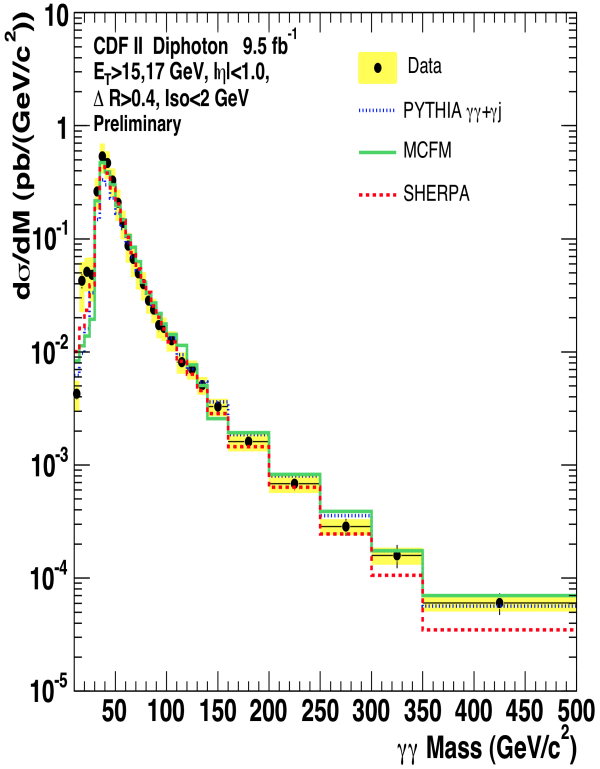
Data-to-theory cross section ratios: CDF

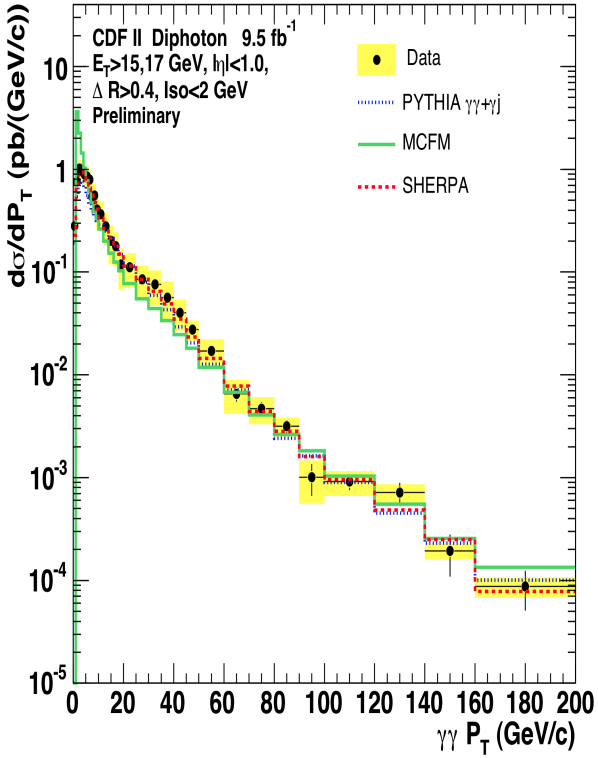
NB: Vertical axis scales are not the same

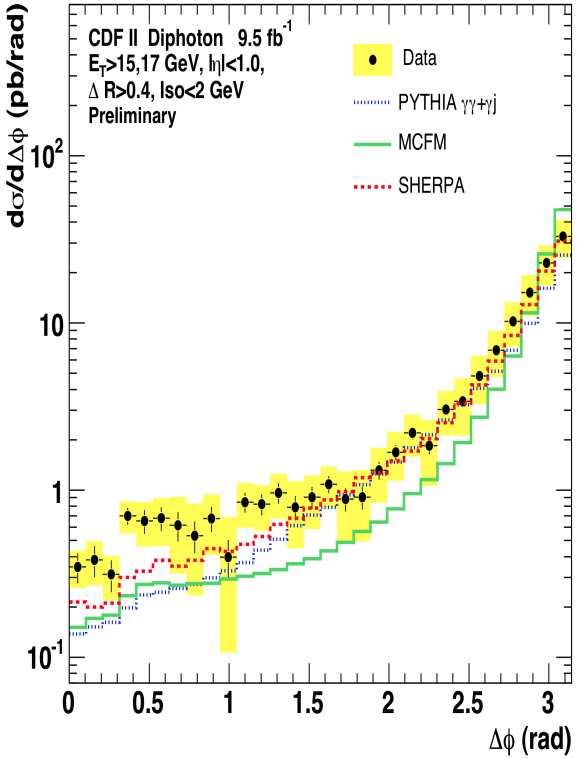




Differential cross sections: CDF



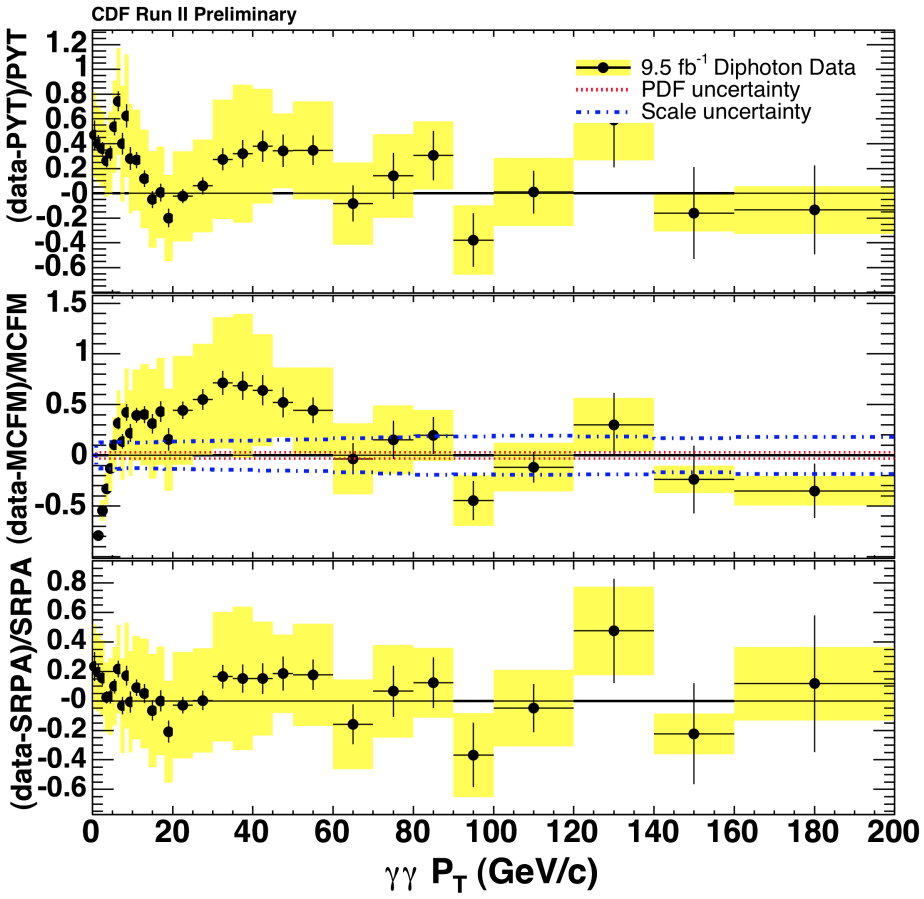


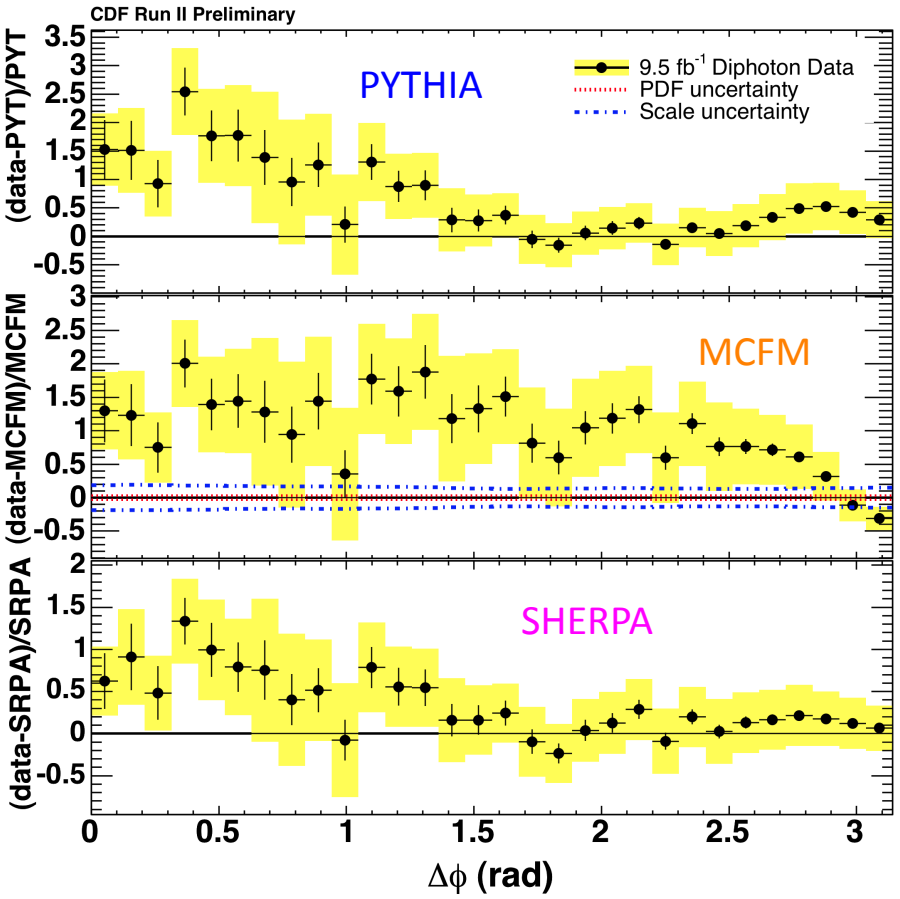


- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2
- SHERPA describes the "shoulder" of the data at $P_T(\gamma\gamma)$ = 20 – 50 GeV/c
- SHERPA lies closest to the data for $\Delta\phi_{\gamma\gamma}$ < 1.7 rad

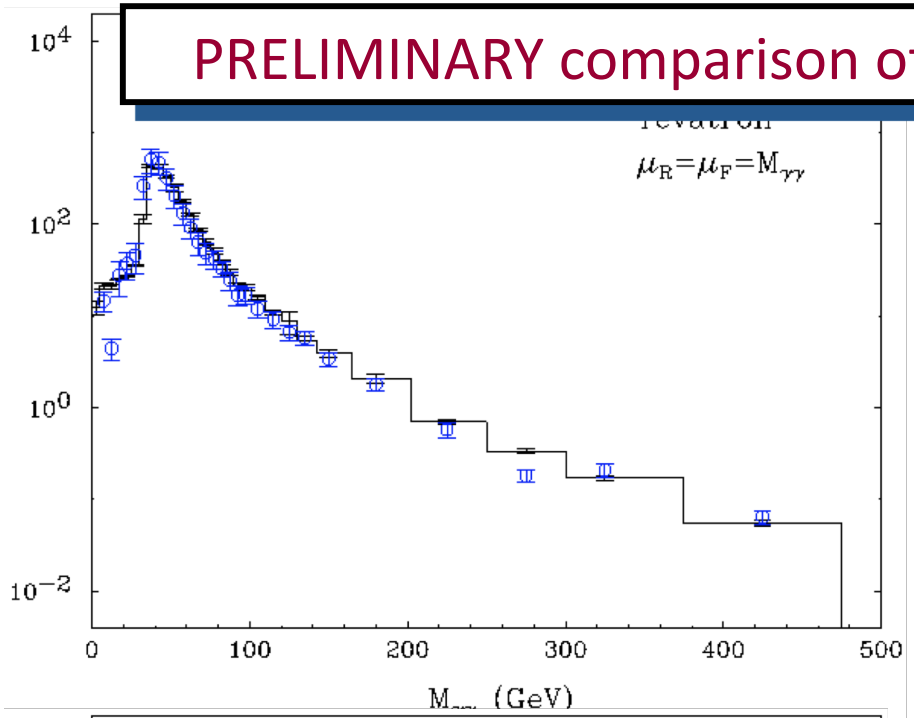
Data-to-theory cross section ratios: CDF

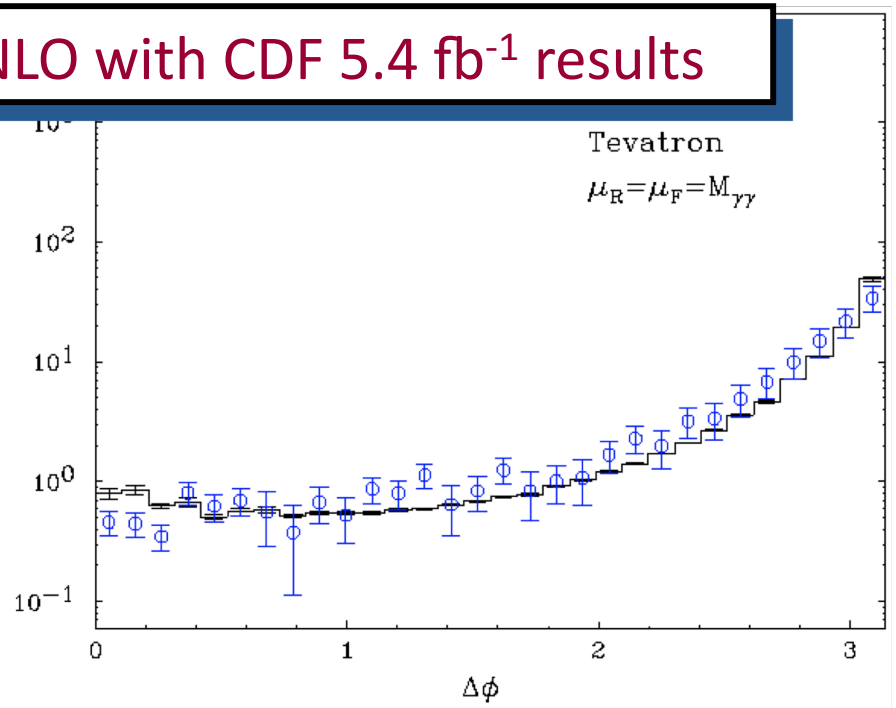
NB: Vertical axis scales are not the same

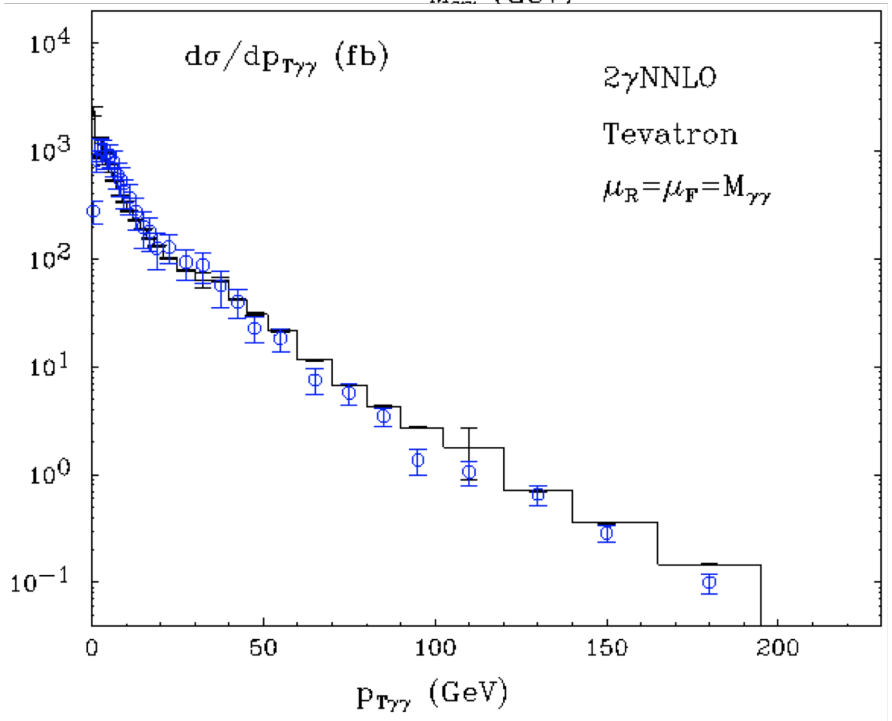


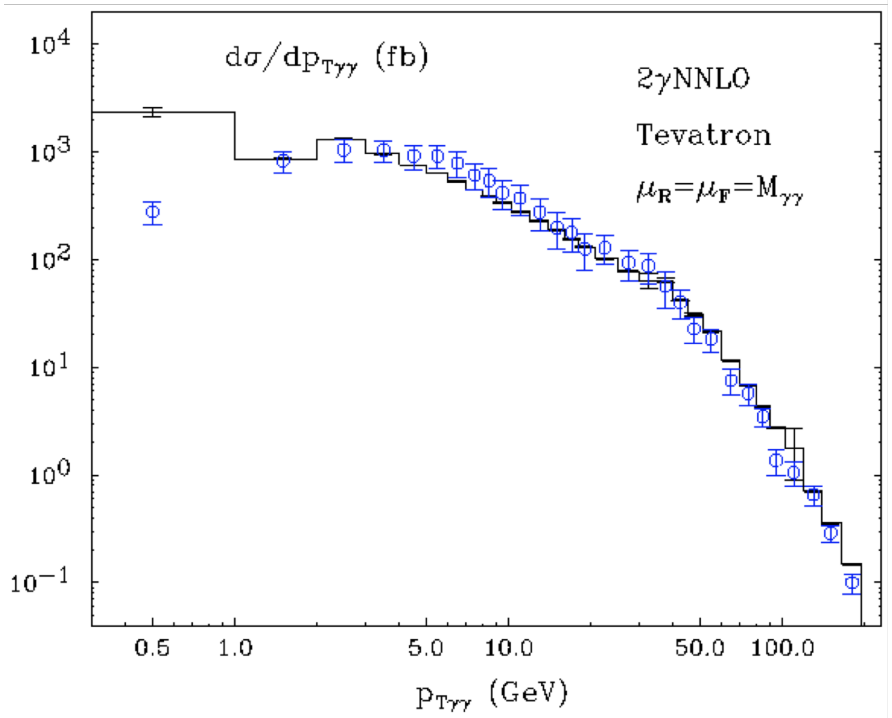


PRELIMINARY comparison of NNLO with CDF 5.4 fb^{-1} results









Summary and conclusions

- High precision γ+b/c and γγ cross sections are measured by both CDF and D0; the CDF measurements are using full dataset.
- The CDF γ+b/c data are compared with PYTHIA and NLO calculations; discrepancies are observed but PYTHIA agrees with the data when the gluon splitting to heavy flavor is increased by 2.
- The D0 γ+b data are compared with PYTHIA, NLO, k_T-factorization and SHERPA calculations; only the k_T-factorization and SHERPA calculations describe the data.
- The CDF γγ data are compared with parton shower, fixed-order and analytically resummed NLO, as well as NNLO calculations.
- The SHERPA calculation, in the overall, provides good description of the γγ data, but still is somewhat low in regions sensitive to fragmentation (very low mass, very low $\Delta\phi$ and large $|\cos\theta|$).
- The RESBOS calculation provides good description of the γγ data at low P_T, where resummation is important, but fails in regions sensitive to fragmentation.
- Impressive agreement is observed between the PRELIMINARY NNLO calculation and the CDF 5.4 fb^{-1} data

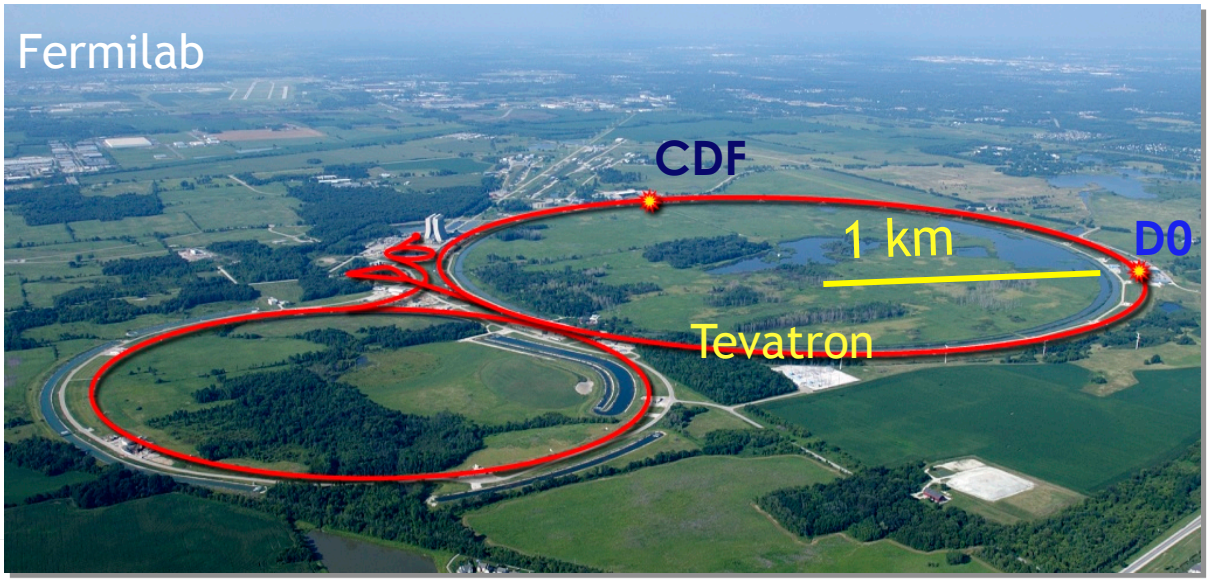
Backup slides

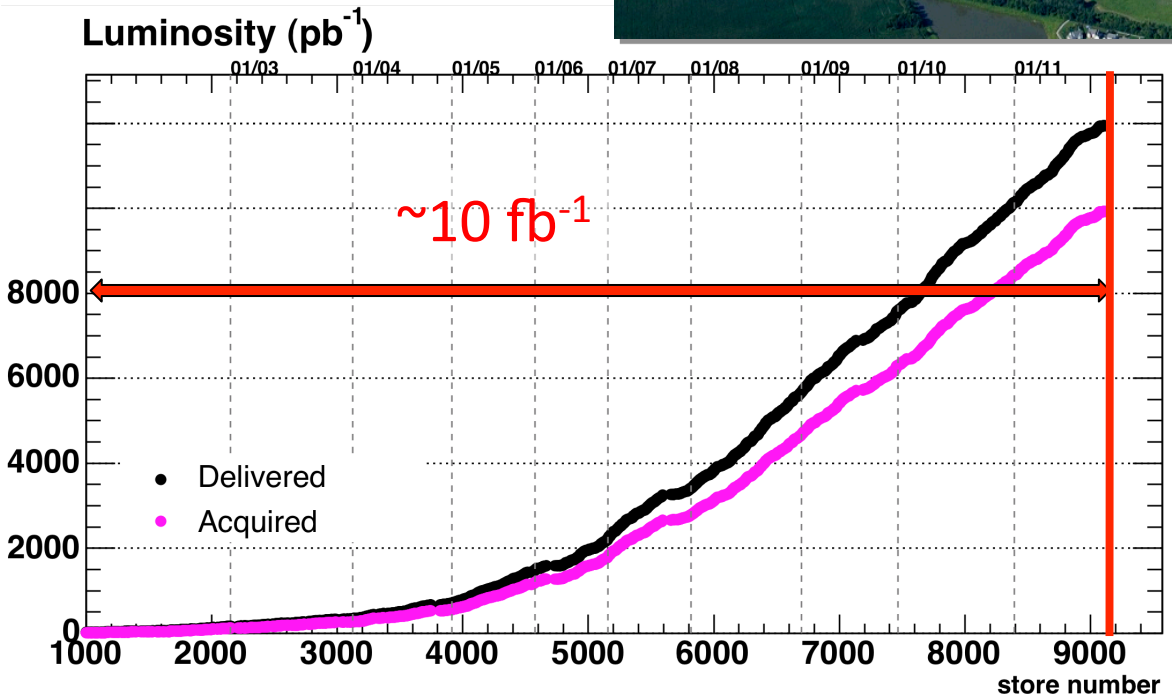
Fermilab Tevatron

Operated through 09/30/2011

Delivered ~12 fb^{-1}

Up to ~10 fb^{-1} recorded by each experiment

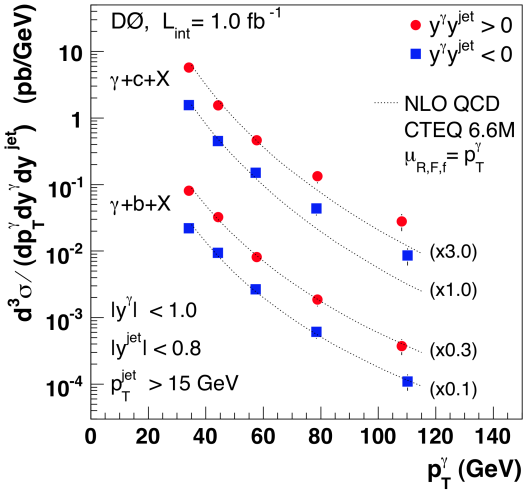




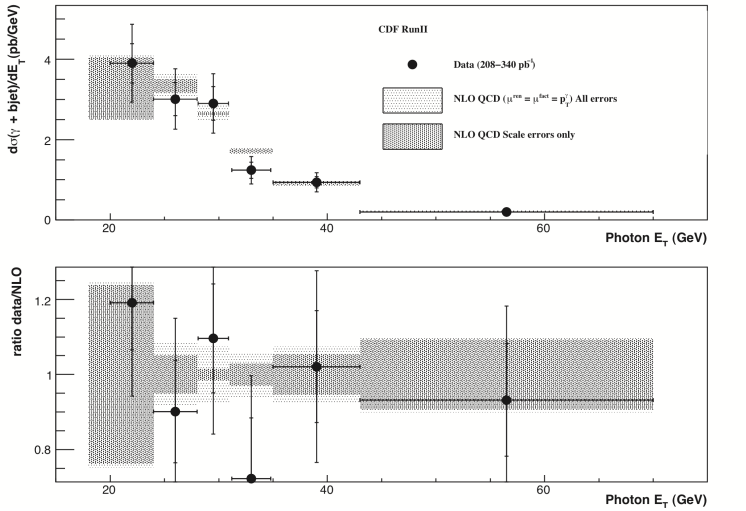
Many thanks to the Accelerator Division!

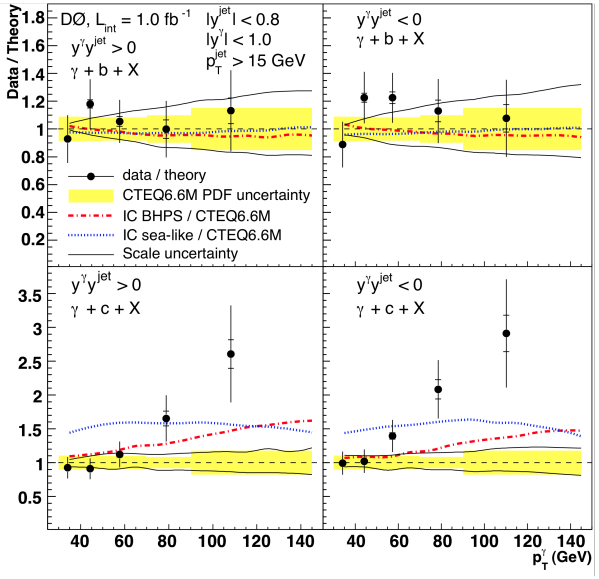
Previous results from the Tevatron

D0: PRL 102, 192002 (2009) - 1 fb^{-1}



CDF: PRD 81, 052006 (2010) - 340 pb^{-1}

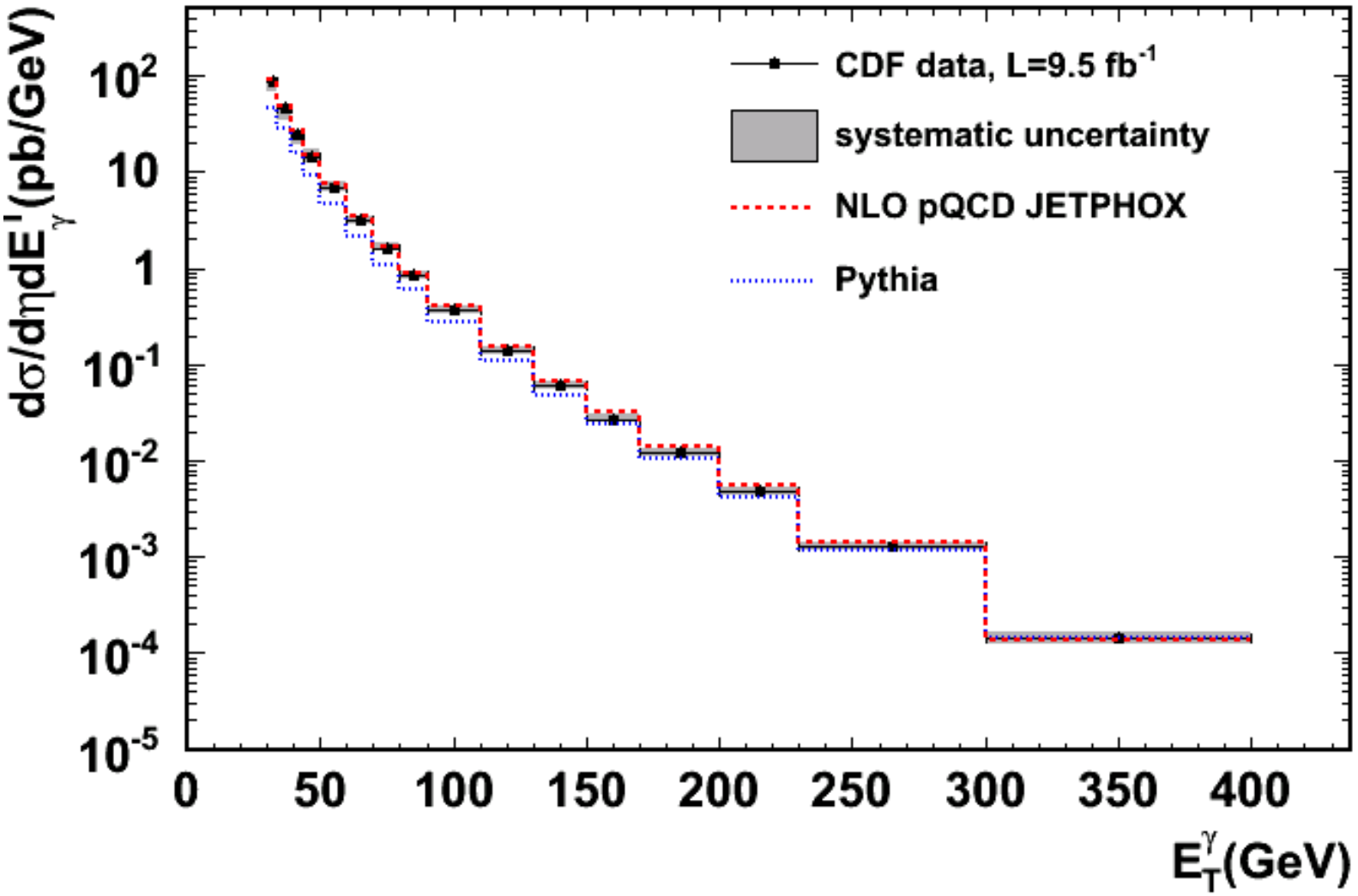




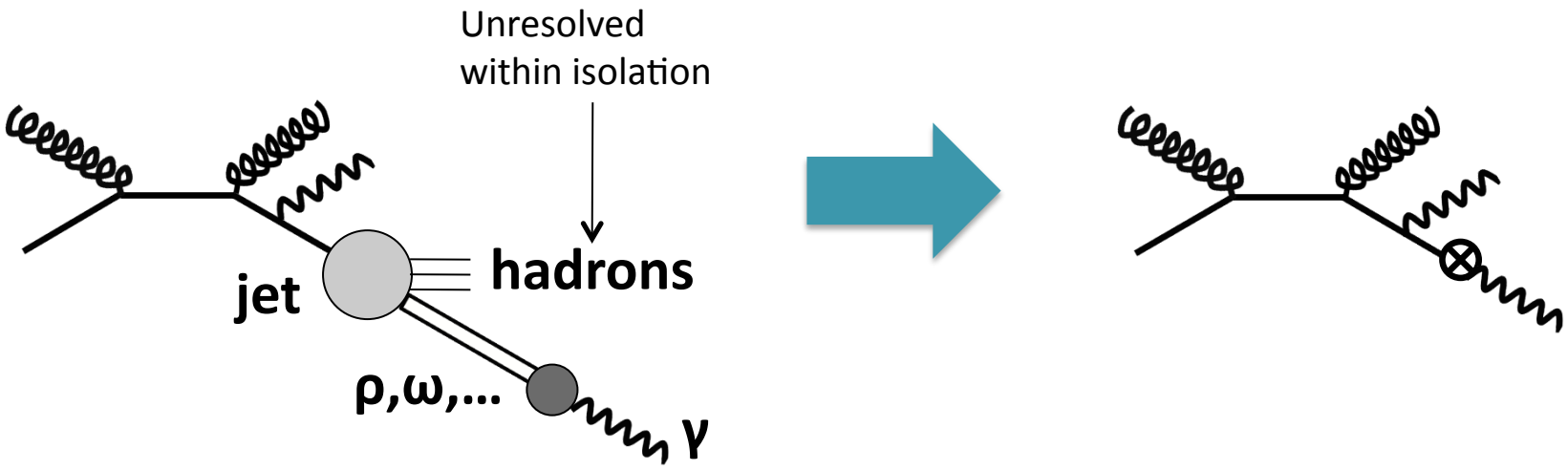
← Good agreement for γ+b

← Large discrepancy for γ+c

The inclusive photon spectrum: CDF



Aspects of the theory: Fragmentation

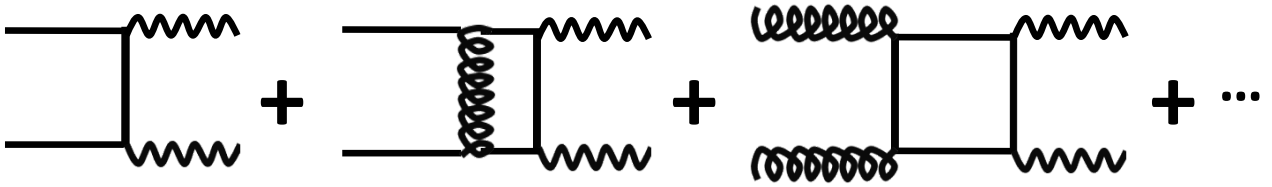


- The pQCD cross section is divergent when q and γ are collinear ➔ Non-perturbative feature of the theory, handled with phenomenological "fragmentation functions" derived e.g. from the VMD model [L. Bourhis *et al.*, Eur. Phys. J. C **2**, 529 (1998)].

- Fragmentation contributions can be suppressed by
  - $P_T(\gamma\gamma) < M(\gamma\gamma)$
  - experimental photon isolation requirements $\longrightarrow E_{\mathrm{T}}^{\mathrm{iso}} = \sum_{\substack{\text{partons or hadrons} \\ \text{within } R<0.4}} E_{\mathrm{T}} - E_{\mathrm{T}\gamma}$

Aspects of the theory: Resummation

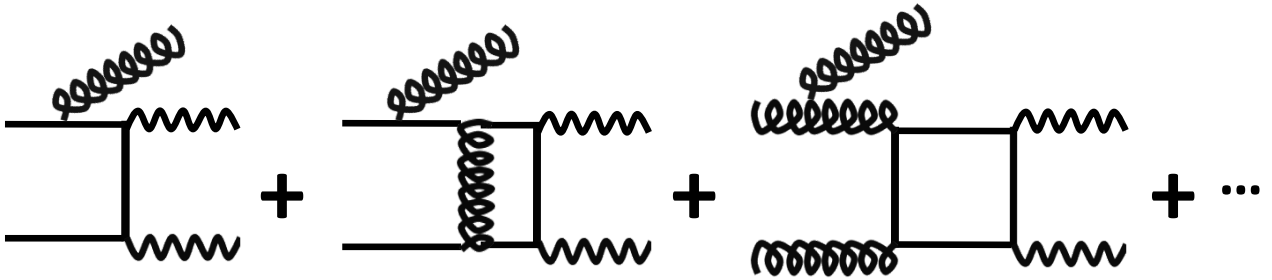
The cross section for



contains singular terms at $P_T(\gamma\gamma) \to 0$ and M(γγ) ≠ 0 of the form

$$\frac{\alpha_s^n}{P_T^2(\gamma\gamma)} \ln^m \frac{M^2(\gamma\gamma)}{P_T^2(\gamma\gamma)} \quad \text{or} \quad -\alpha_s^n \delta\left(\vec{P}_T(\gamma\gamma)\right) \qquad n = 1,\ldots\infty \qquad m = 0,\ldots,2n-1$$

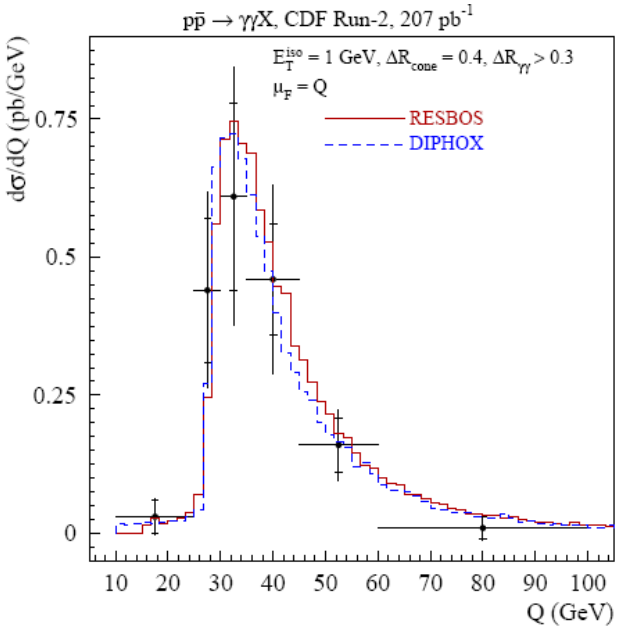
Need to add
soft gluon emission:

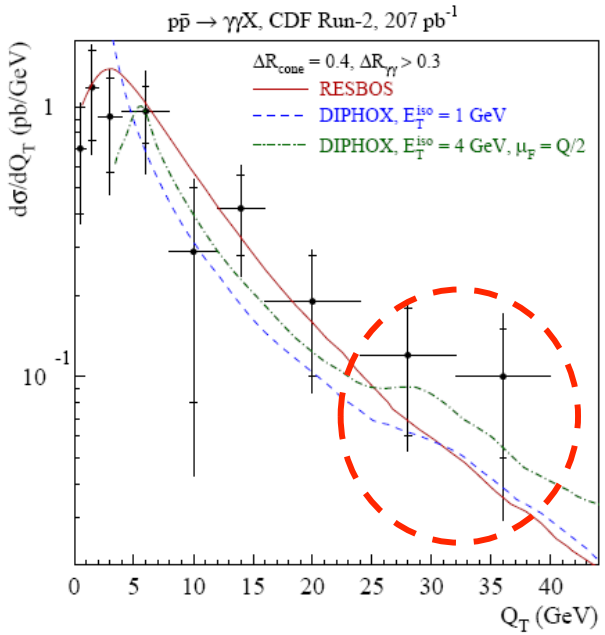


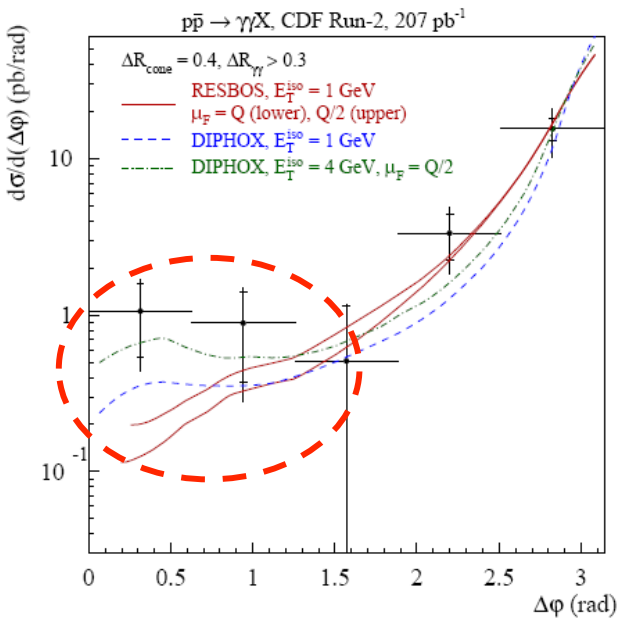
- Two ways of doing this:
  - Approach the $P_T(\gamma\gamma) \to 0$ limit with an analytically calculated cross section derived from the sum of the singular terms for all n and m = 1,2,3 (next-to-next-to-leading log accuracy, NNLL), which is then smoothly matched to the perturbative cross section at high $P_T(\gamma\gamma)$
  - Use parton showering to add gluon radiation in a Monte Carlo simulation framework which effectively resums the cross section for all n and m = 1 (leading-log accuracy, LL)

Previous γγ measurements at the Tevatron

- CDF publication in Run II with 207 pb^{-1}. *PRL 95, 022003 (2005)* *PRD 76, 013009 (2007)*
- Event selection: $p_{T1(2)}$>14(13) GeV, $|\eta_{1,2}|$<0.9, $\Delta R(\gamma,\gamma)$>0.3, E_T^{iso}<1 GeV.







- $P_T(\gamma\gamma)$>25 GeV region in data dominated by events with $P_T(\gamma\gamma)$>M(γγ) and $\Delta\phi(\gamma,\gamma)<\pi/2$ ➔ potentially large fragmentation contributions.

Theoretical predictions

- Experimental kinematic and isolation cuts are also applied to all theoretical calculations compared with the data:
  - Central photons required: $|y| < 1.1$
  - $E_T \geq 17$ GeV (1^{st} γ in the event), 15 GeV (2^{nd} γ)
  - Isolated in the calorimeter: $I_{cal} = E_{tot}(R=0.4) - E_{EM}(R=0.4) \leq 2$ GeV

Imply that $\Delta R(\gamma,\gamma) \geq 0.4$

Applied at the parton level in DIPHOX, RESBOS, MCFM ➔ can only approximate the experimental isolation

- NLO theoretical uncertainties:
  - PDFs: 3-6%; use 44 eigenvectors from CTEQ6M
  - Renormalization/factorization/fragmentation scales: ~10-20% depending on the observable; all scales simultaneously varied by ×2 up and down

Kinematic variables

$$M = \sqrt{\left(p^{\mu}_{\gamma 1} + p^{\mu}_{\gamma 2}\right)^2}$$

$$P_{\mathrm{T}} = \left| \left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) - \left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) \cdot \hat{\mathrm{z}} \right|$$

$$\Delta\phi = \left|\phi_{\gamma 1} - \phi_{\gamma 2}\right| \bmod \pi$$

$$Y_{\gamma\gamma} = \tanh^{-1} \frac{\left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) \cdot \hat{\mathrm{z}}}{\left|\vec{p}_{\gamma 1}\right| + \left|\vec{p}_{\gamma 1}\right|}$$

$$z = \frac{p^{<}_{\mathrm{T}\gamma}}{p^{>}_{\mathrm{T}\gamma}}$$

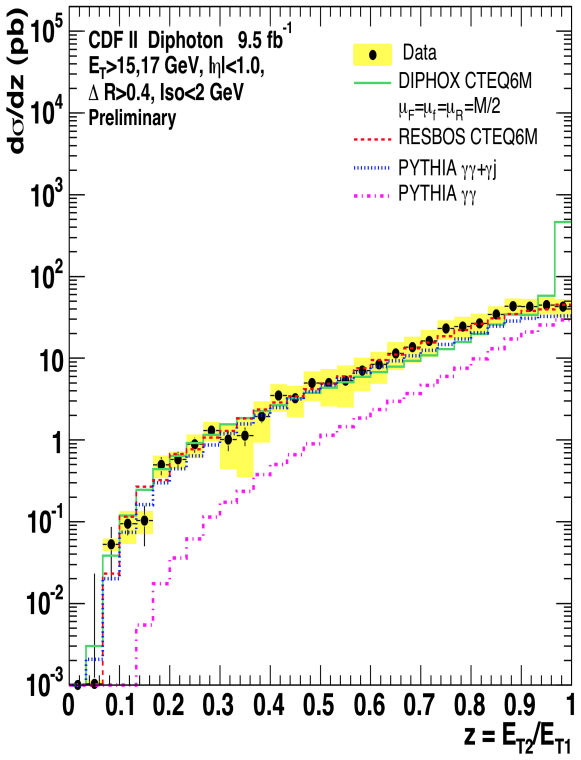
Low-p_T/high-p_T ratio of the photon pair ($z \leq 1$)

$$\cos\theta = \frac{2 p_{\mathrm{T}\gamma 1} p_{\mathrm{T}\gamma 2} \sinh\left(y_{\gamma 1} - y_{\gamma 2}\right)}{M\sqrt{M^2 + P_{\mathrm{T}}^2}}$$

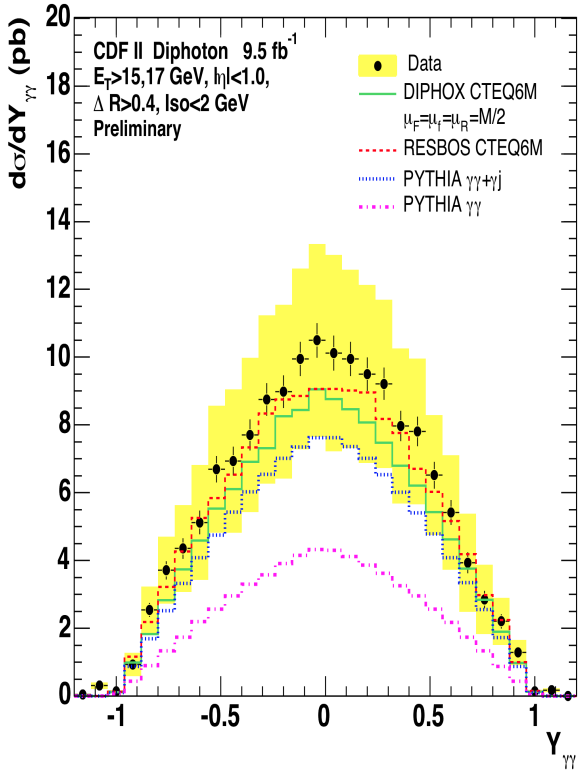
$$\begin{cases} \cos\theta \to \tanh\dfrac{y_{\gamma 1} - y_{\gamma 2}}{2} \approx 0 \quad \left(P_{\mathrm{T}} << M\right) \\ \cos^2\theta \to \dfrac{4 p_{\mathrm{T}\gamma 1} p_{\mathrm{T}\gamma 2}}{\left(p_{\mathrm{T}\gamma 1} + p_{\mathrm{T}\gamma 2}\right)^2} \approx 1 \quad \left(P_{\mathrm{T}} >> M\right) \end{cases}$$

Cosine of the leading photon polar angle in the **Collins-Soper frame** (γγ rest frame with the polar axis bisecting the angle between the colliding hadrons)

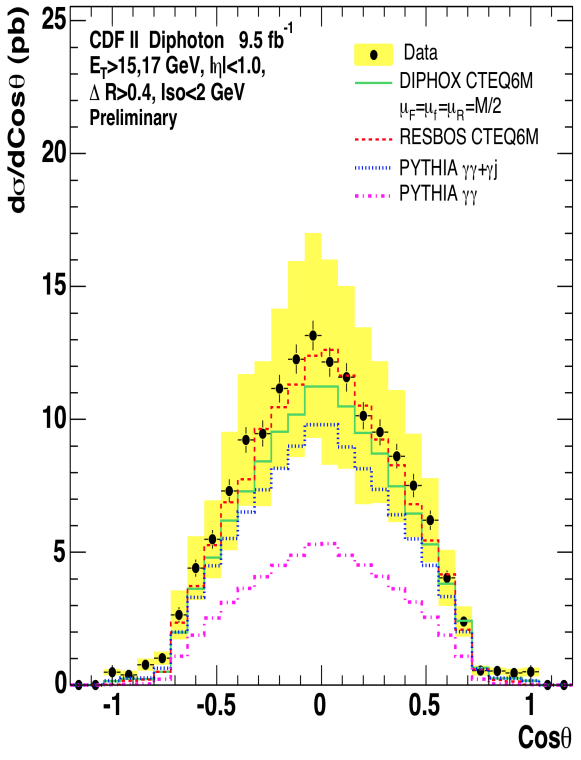
Differential cross sections: CDF



- Good agreement between data and RESBOS
- Good agreement between data and DIPHOX, except for 0.7<z<0.8



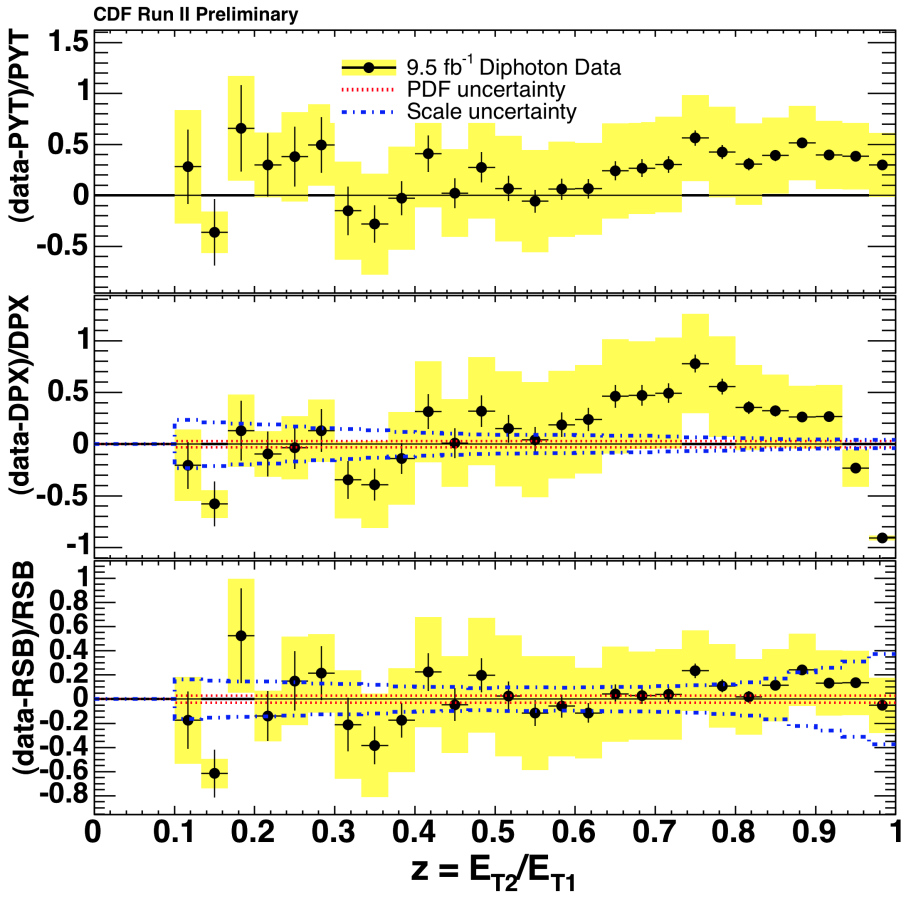
- Good agreement between data and theory

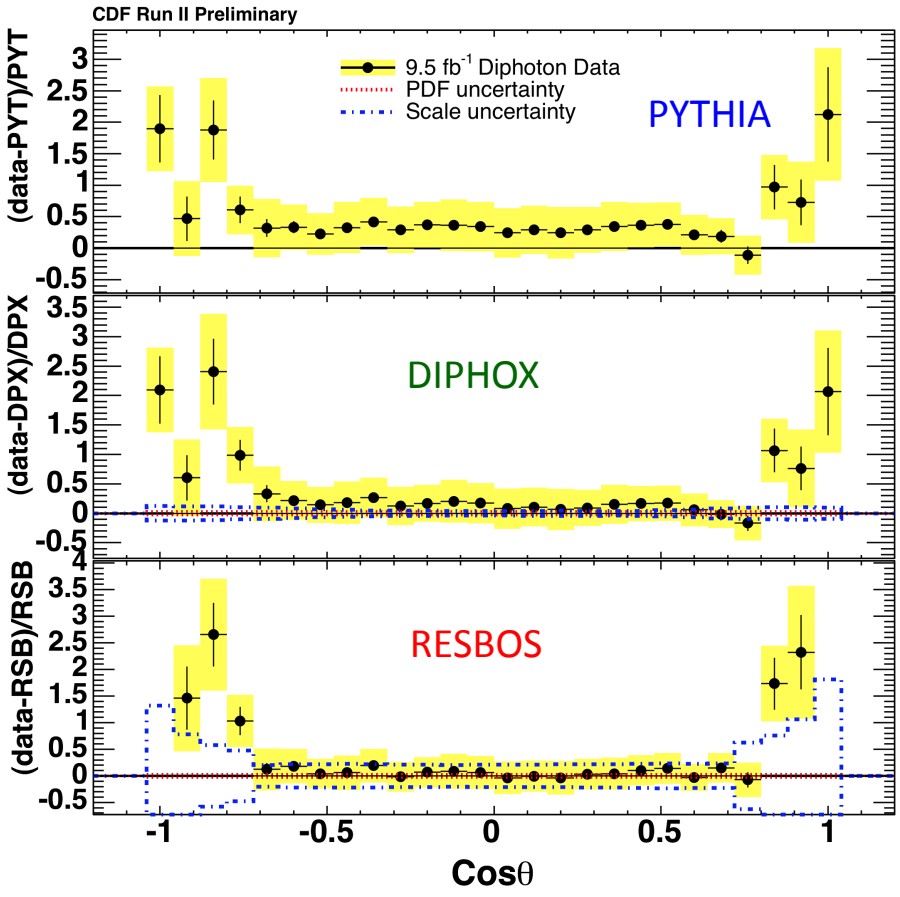


- Good agreement between data and theory, except for $|\cos\theta| \to 1$

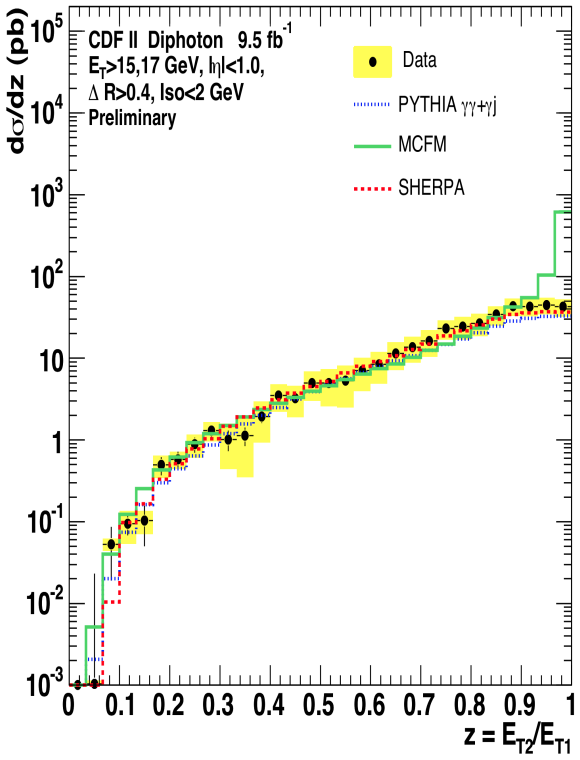
Data-to-theory cross section ratios: CDF

NB: Vertical axis scales are not the same

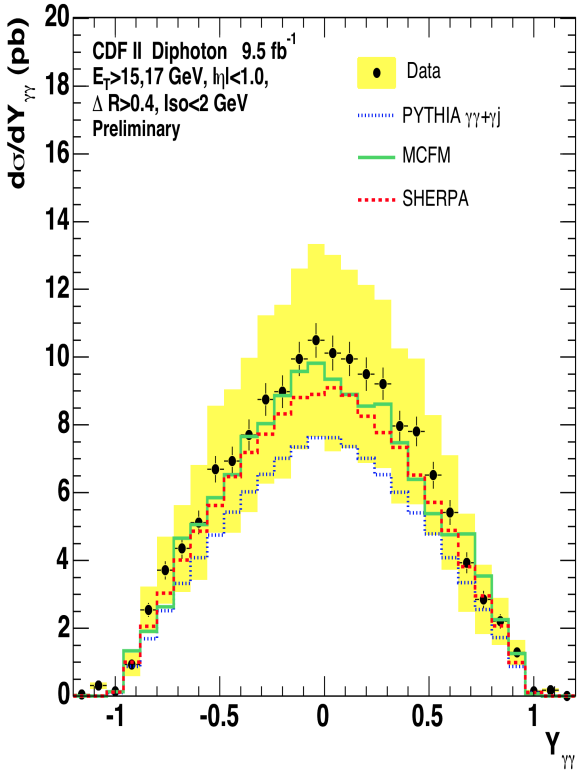




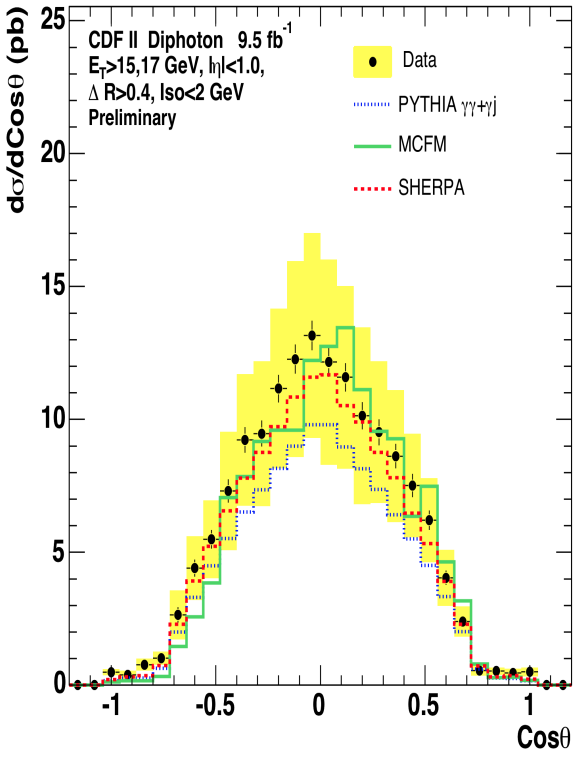
Differential cross sections: CDF



- Good agreement between data and SHERPA
- MCFM looks similar with DIPHOX, as expected



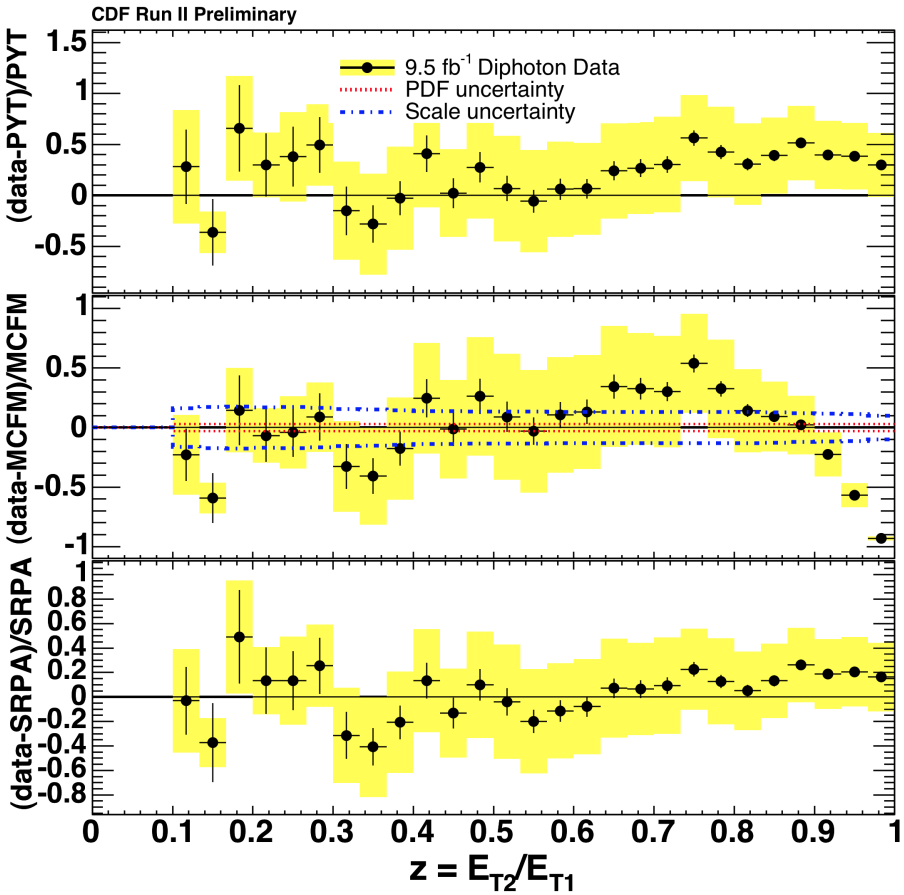
- Good agreement between data and theory

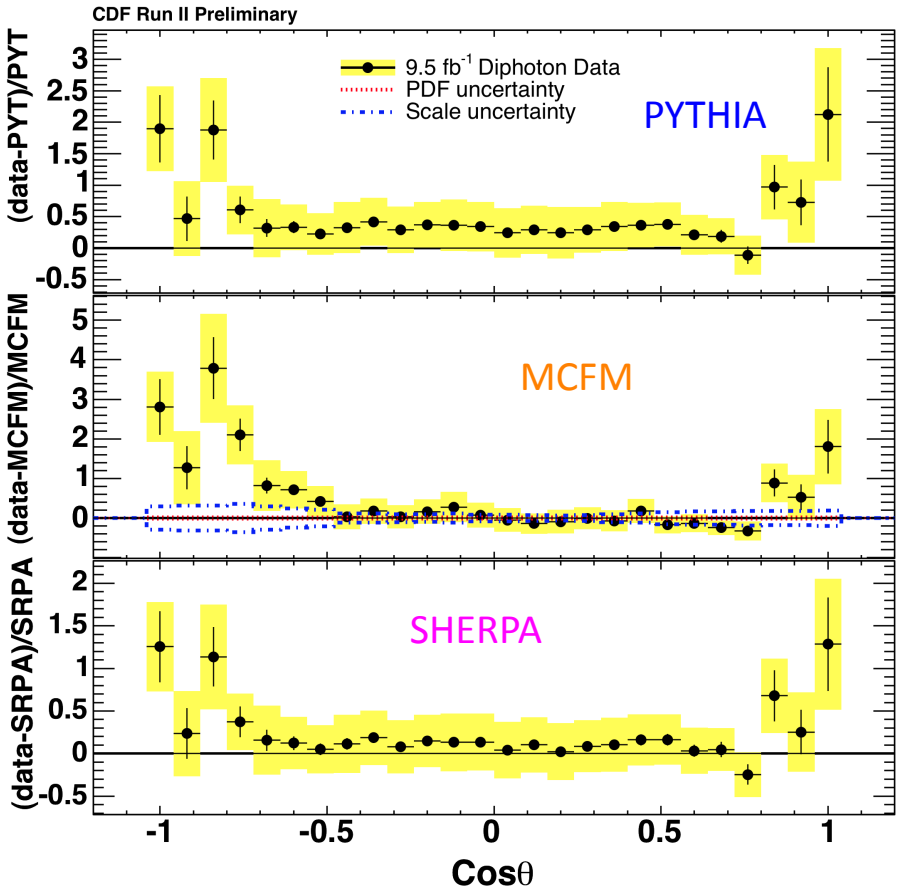


- Good agreement between data and theory, except for $|\cos\theta| \to 1$

Data-to-theory cross section ratios: CDF

NB: Vertical axis scales are not the same





Impact on searches of undiscovered particles

- The success of parton-shower Monte Carlo is important for the search of a low-mass Higgs boson and of new physics:

  - Provides a reliable background model for these searches in the framework of realistic event representation suitable for simulation of collider experiments

  - Can be used in the Higgs $\longrightarrow \gamma\gamma$ search based on a multivariate analysis that exploits the full $\gamma\gamma$ event information — all kinematic variables that can help discriminate Higgs boson decays from QCD $\gamma\gamma$ events (see arXiv:1107.4587)

  - Can also be used in searches of new physics in the mass range where data are not enough to model the QCD background by data-driven methods