European Physical Society Conference, July 20–27, 2011

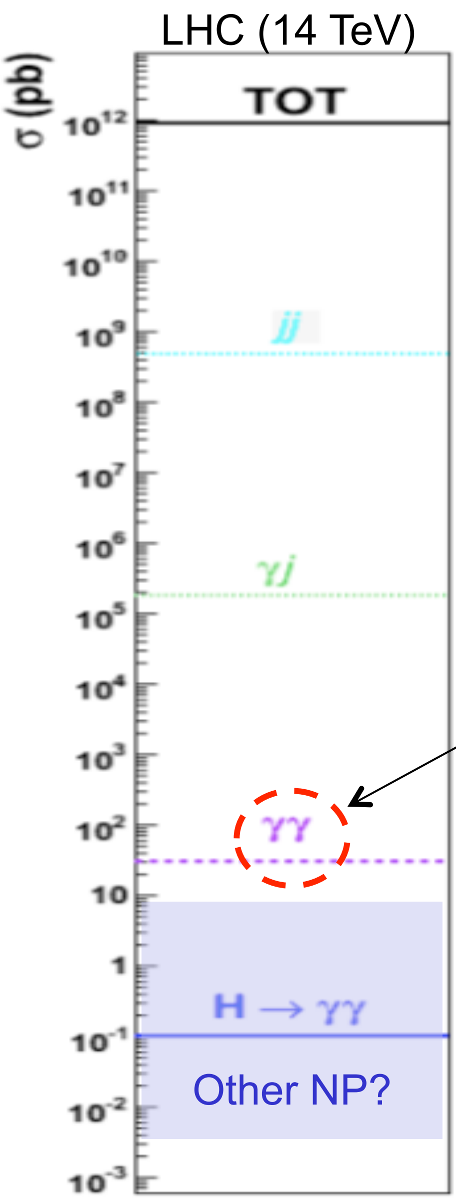
Measurement of the Cross section for Prompt Isolated Diphoton Production in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.96 TeV

Costas Vellidis

FNAL

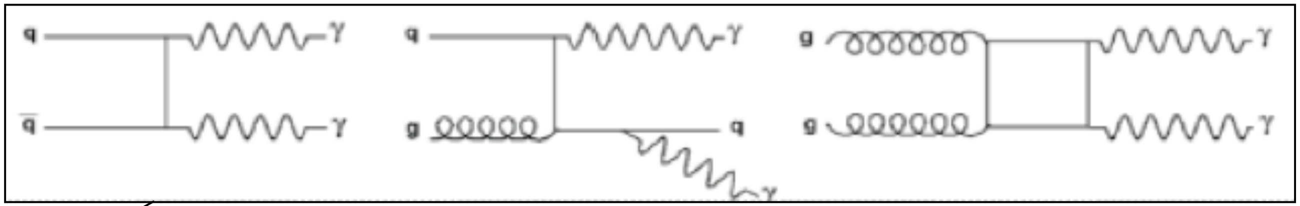
On behalf of the CDF Collaboration

Prompt diphoton production at hadron colliders



- Prompt photons = photons produced directly in perturbative scattering or via parton fragmentation (as opposed to non-perturbative photon production in meson decays).

- Main source of prompt diphoton production at hadron colliders via QCD interactions.



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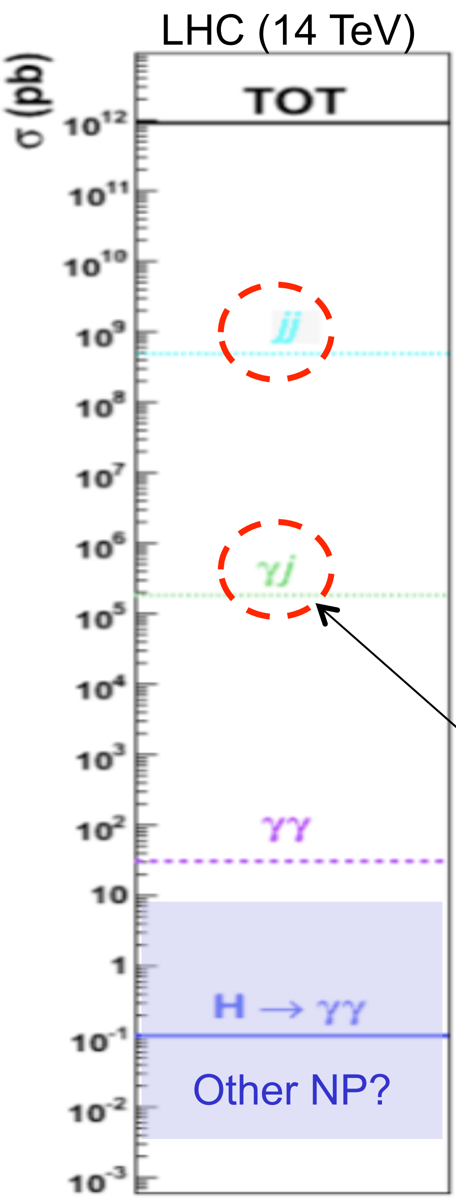

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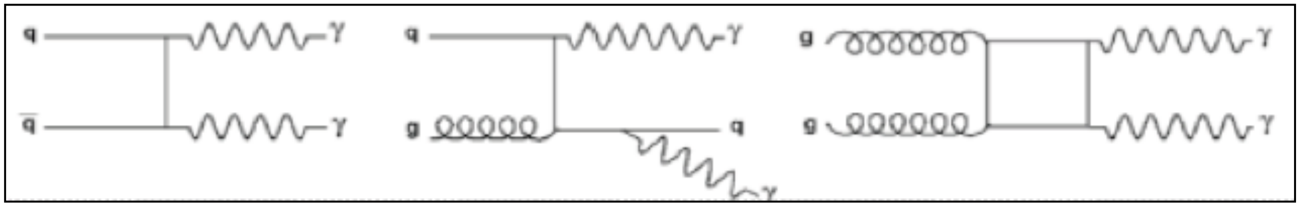
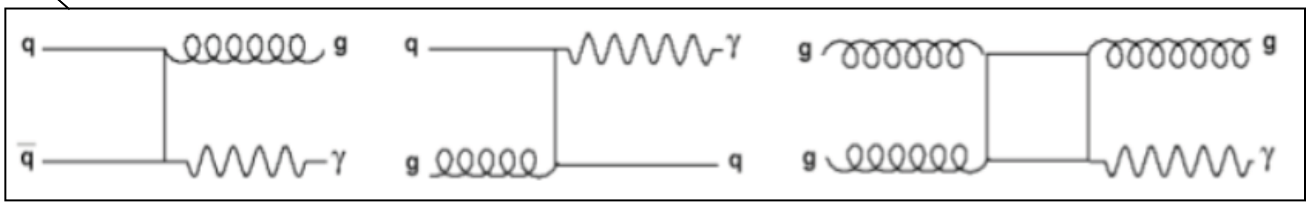


- Main background: γ+jet and dijet, with one or two jets misidentified as photons ➔ reducible background.



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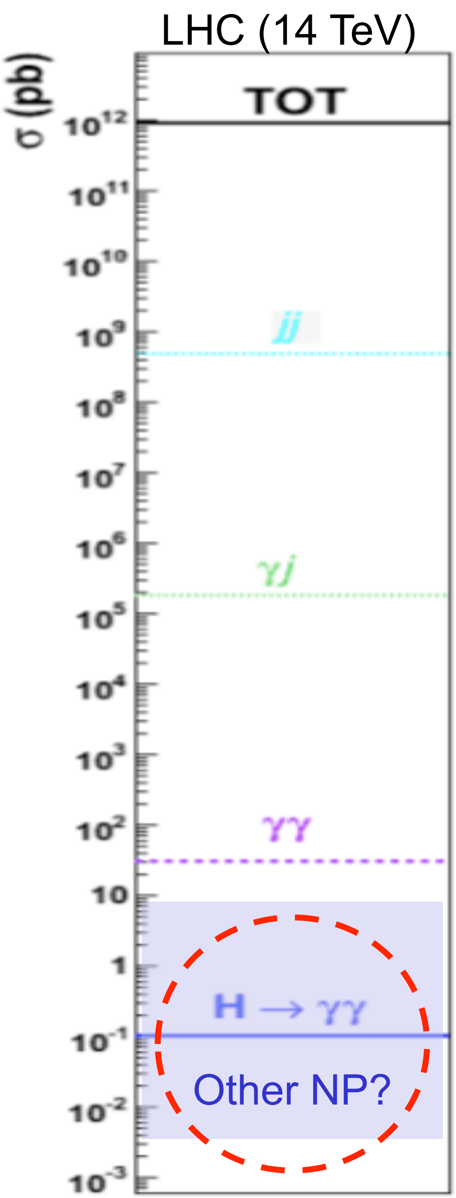
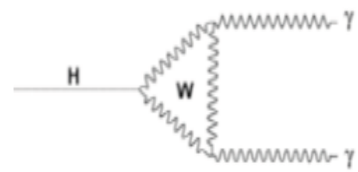
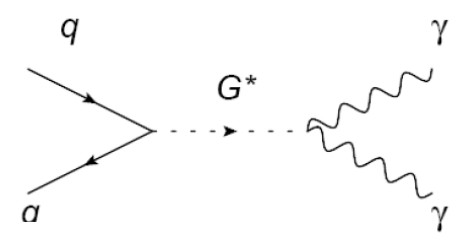


- Prompt photons = photons produced directly in perturbative scattering or via parton fragmentation (as opposed to non-perturbative photon production in meson decays).

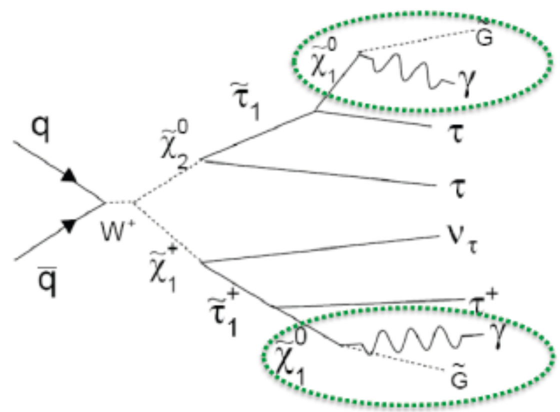
- At much smaller rate, prompt diphotons may originate from more exotic (and exciting!) production mechanisms:
  - Higgs decay



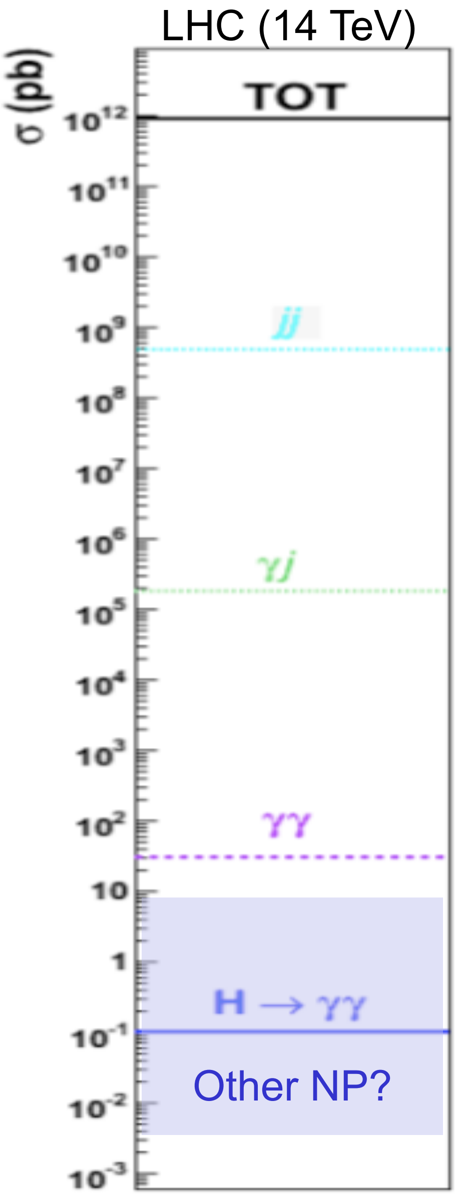
  - Extra dimensions



  - SUSY
  - …



Prompt diphoton production at hadron colliders



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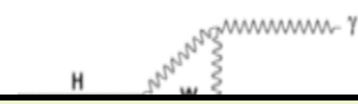
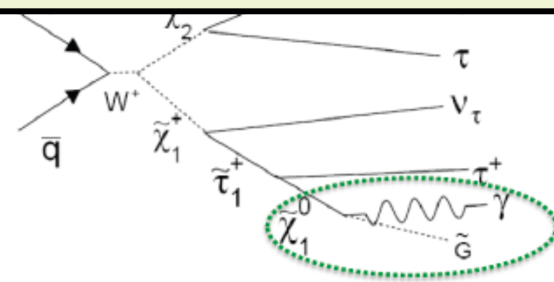


Precise measurements of QCD γγ production should put us on solid footing to search for new physics:

- Validate/improve theoretical predictions for irreducible (QCD γγ) background.
- Develop/demonstrate good control over reducible backgrounds.

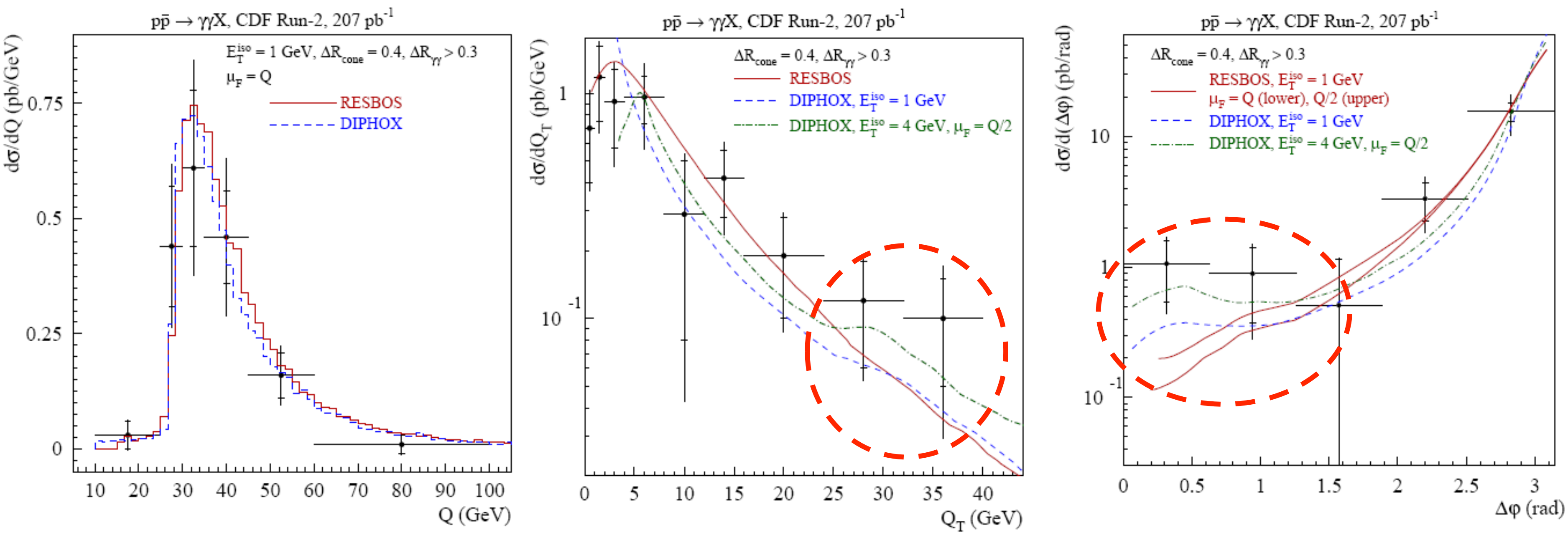
  - SUSY
  - …



Previous Tevatron measurements

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

PRD 76, 013009 (2007)

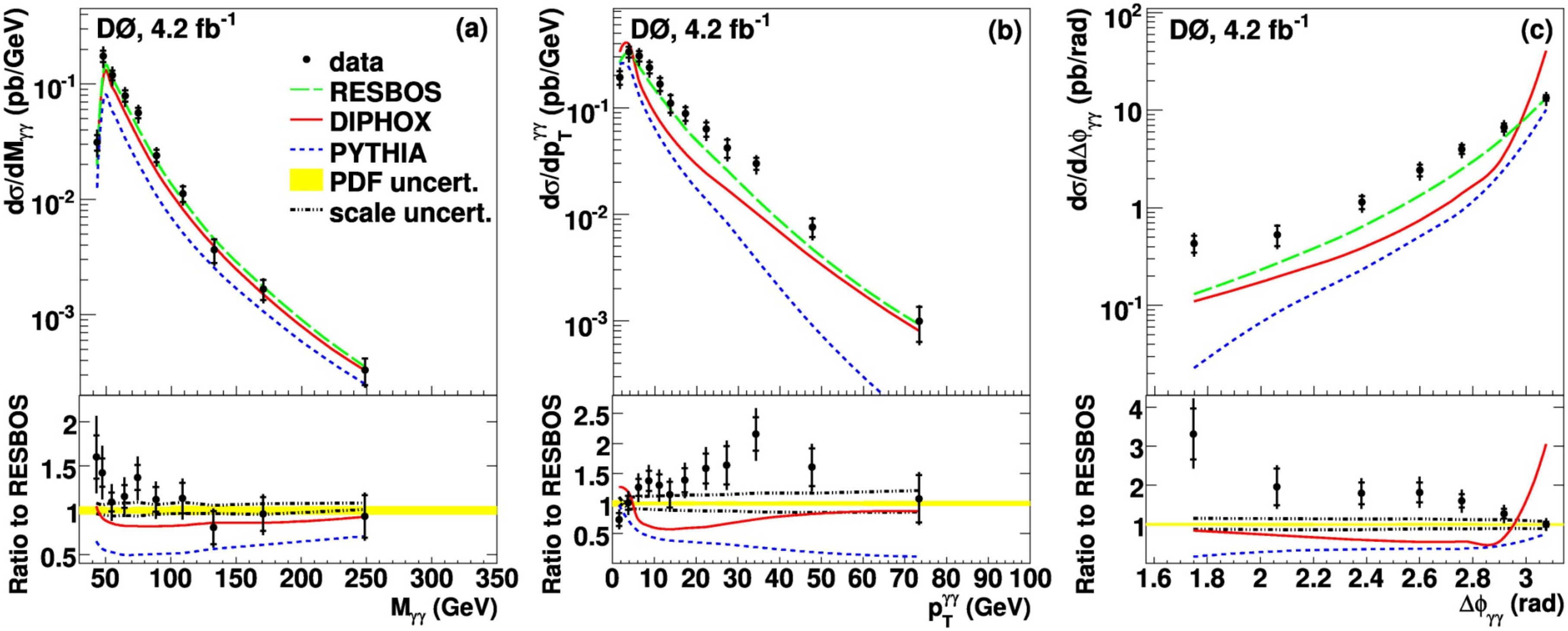


- $p_T(\gamma\gamma)$>25 GeV region in data dominated by events with $p_T(\gamma\gamma)$>$M(\gamma\gamma)$ and $\Delta\phi(\gamma,\gamma)<\pi/2$ ➔ potentially large fragmentation contributions.
- Large sensitivity of theoretical prediction on isolation requirement.

Here the Pythia prediction uses only matrix element based production of photons

Previous Tevatron measurements

- 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.

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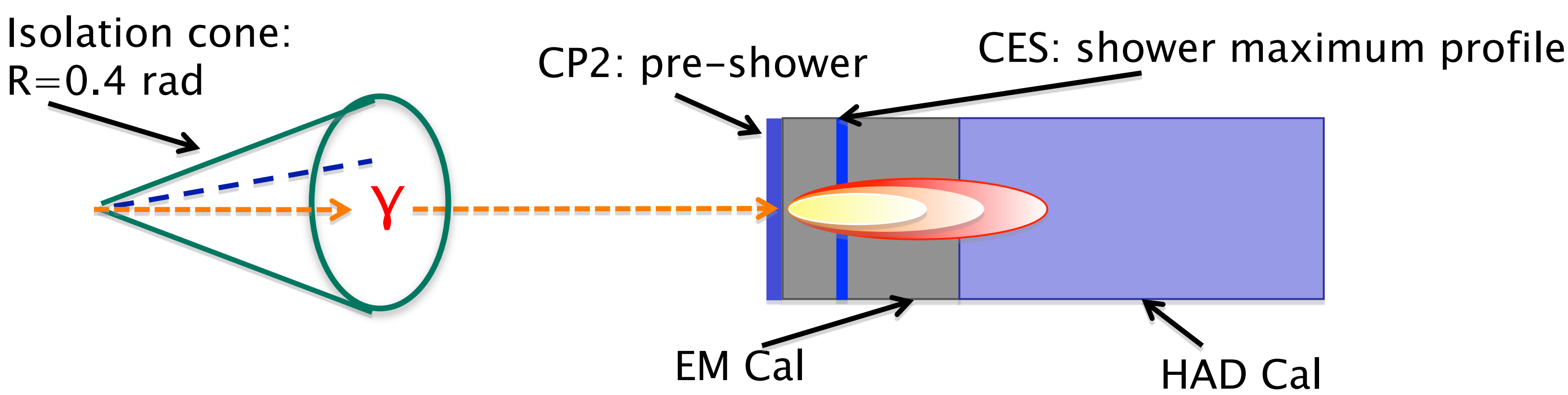
Photon identification and event selection

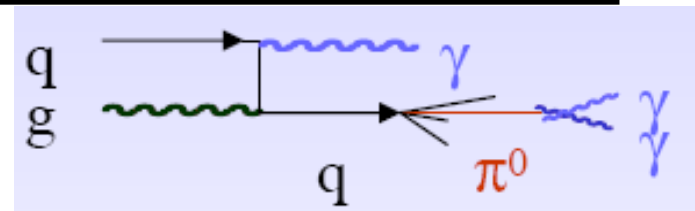


- Photons are selected offline from EM clusters, reconstructed within a cone of radius R=0.4 in the $\eta-\phi$ plane, and requiring:
  - Fiducial to the central calorimeter: $|\eta|<1.1$
  - $E_T \geq 17$ GeV (1st γ in the event), 15 GeV (2nd γ) ← Avoids divergence in NLO calculation
  - Isolated in the calorimeter: $I_{cal} = E_{tot}(R=0.4) - E_{EM}(R=0.4) \leq 2$ GeV
  - (The two criteria above) Imply that $\Delta R(\gamma,\gamma) \geq 0.4$
  - 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: $\chi^2_{CES} \leq 20$
  - E_T of 2nd CES cluster ≤ 2.4 GeV $+ 0.01 \times E_T$

Background

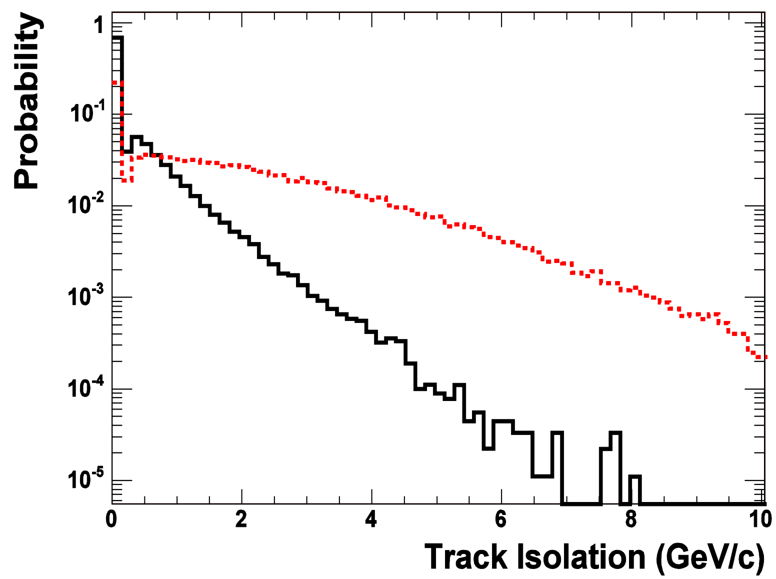
$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta}$$

Jets misidentified as photons: dijet and γ+jet



- Fluctuations in jet fragmentation to leading π^0 or η^0 meson ($\pi^0,\eta^0 \rightarrow \gamma\gamma$)
- Normalization and shape estimated from MC using **track isolation**: $I_{trk} = \sum_{tracks\ in\ R<0.4}^{|z_{vtx}-z_{trk}|<5cm} p_T^{trk}$
- Sensitive only to underlying event and jet fragmentation (for fake γ), immune to multiple interactions (due to z-cut) and calorimeter leakage
- Good resolution in low-E_T region, where background is most important
- Uses charged particles only

Substantially different shape of signal and background I_{trk} distributions can be used to characterize true and fake γ



Background estimation: 4×4 matrix method

- Use the track isolation cut for each photon to compute a per-event weight under the different hypotheses (γγ, γ+jet and dijet):

$$\begin{pmatrix} w_{jj} \\ w_{j\gamma} \\ w_{\gamma j} \\ w_{\gamma\gamma} \end{pmatrix} = E^{-1} \times \begin{pmatrix} w_{ff} \\ w_{fp} \\ w_{pf} \\ w_{pp} \end{pmatrix}$$

Both photons fail
Leading fail, trailing passes
Leading passes, trailing fails
Both photons pass

$$E = \begin{pmatrix} (1-\epsilon_{j1})(1-\epsilon_{j2}) & (1-\epsilon_{j1})(1-\epsilon_{\gamma2}) & (1-\epsilon_{\gamma1})(1-\epsilon_{j2}) & (1-\epsilon_{\gamma1})(1-\epsilon_{\gamma2}) \\ (1-\epsilon_{j1})\epsilon_{j2} & (1-\epsilon_{j1})\epsilon_{\gamma2} & (1-\epsilon_{\gamma1})\epsilon_{j2} & (1-\epsilon_{\gamma1})\epsilon_{\gamma2} \\ \epsilon_{j1}(1-\epsilon_{j2}) & \epsilon_{j1}(1-\epsilon_{\gamma2}) & \epsilon_{\gamma1}(1-\epsilon_{j2}) & \epsilon_{\gamma1}(1-\epsilon_{\gamma2}) \\ \epsilon_{j1}\epsilon_{j2} & \epsilon_{j1}\epsilon_{\gamma2} & \epsilon_{\gamma1}\epsilon_{j2} & \epsilon_{\gamma1}\epsilon_{\gamma2} \end{pmatrix}$$

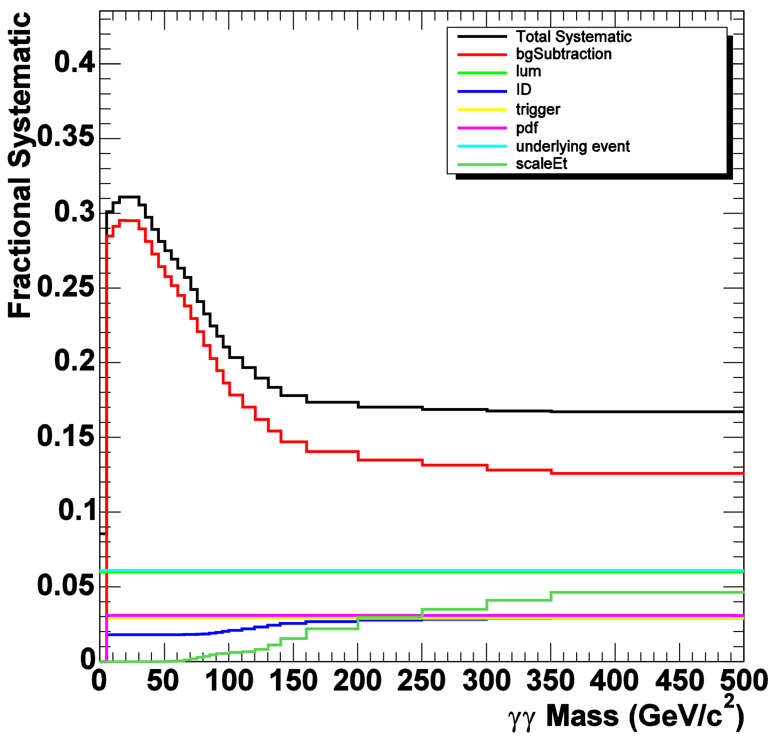
- For instance, if leading passes/trailing fails, the event weight is:

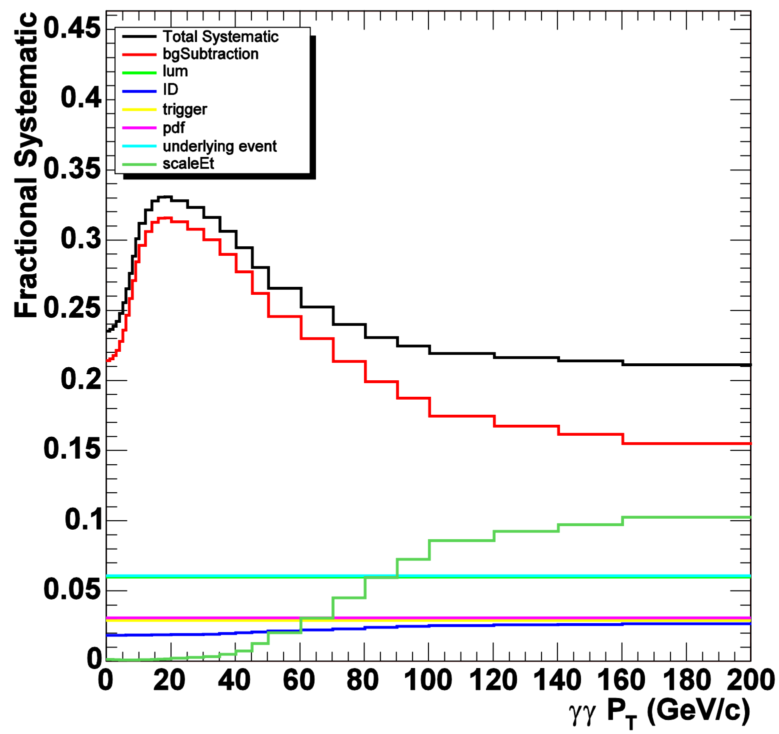
$$\begin{pmatrix} w_{ff} \\ w_{fp} \\ w_{pf} \\ w_{pp} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

- Estimated number of prompt diphoton events bin-by-bin is given by the sum of γγ weights:

$$N_{\gamma\gamma} = \sum_{i=1}^{N_{data}} w_{\gamma\gamma}^{i}$$

Experimental systematic uncertainties





- Total systematic uncertainty ~15-30%, smoothly varying with the kinematic variables considered
- Main source is background subtraction, followed by overall normalization (efficiencies: 7%; integrated luminosity: 6%; UE correction: 6%)

Theoretical predictions

- **DIPHOX**: Fixed-order NLO calculation including non-perturbatve fragmentations (T. Binoth *et al*., Phys. Rev. D **63**,114016 (2001))

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

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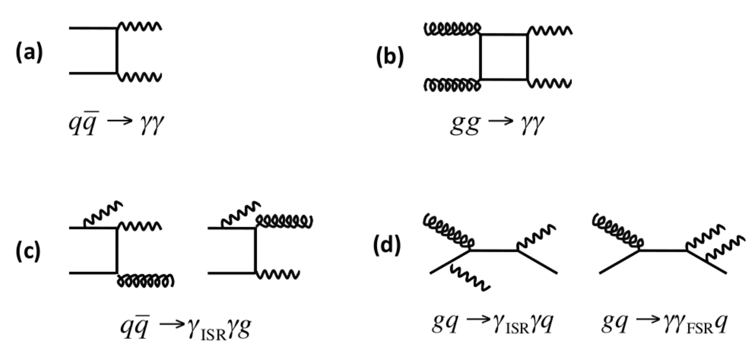
  Two separate calculations, one involving (a – b) only ("PYTHIA γγ") and one involving (a – d) ("PYTHIA γγ+γj"), are compared with the data



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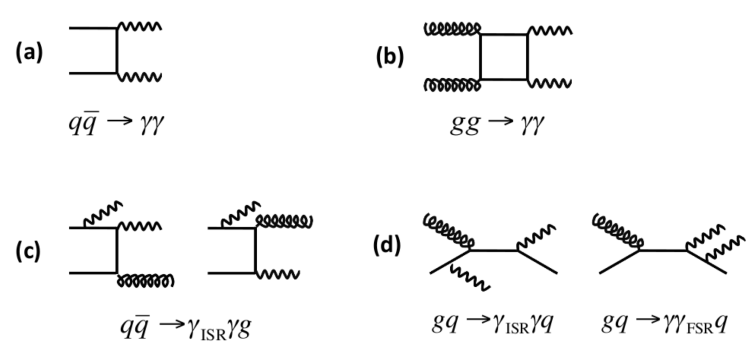

- NLO theoretical uncertainties:
  - PDFs: 3-6%; use 44 eigenvectors from CTE6.1M
  - Renormalization/factorization/fragmentation scales: ~10-20% depending on the observable; all scales simultaneously varied by ×2 up and down

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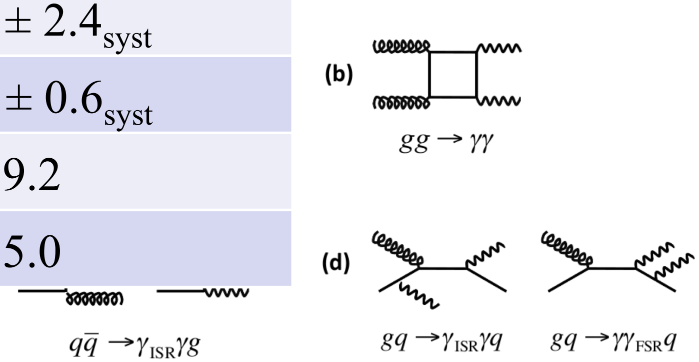
	Total cross section (pb)
Data	$12.5 \pm 0.2_{stat} \pm 3.7_{syst}$
RESBOS	$11.3 \pm 2.4_{syst}$
DIPHOX	$10.6 \pm 0.6_{syst}$
PYTHIA γγ+γj	9.2
PYTHIA γγ	5.0



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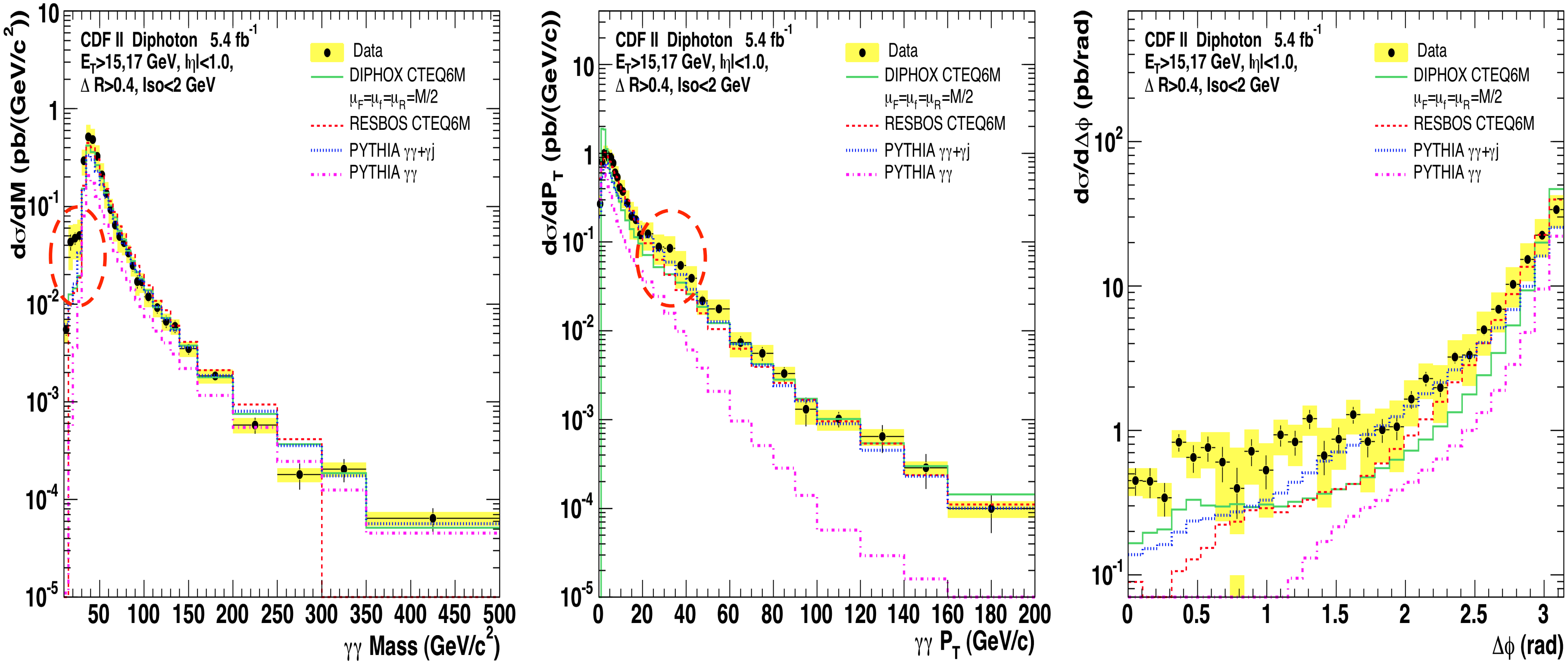
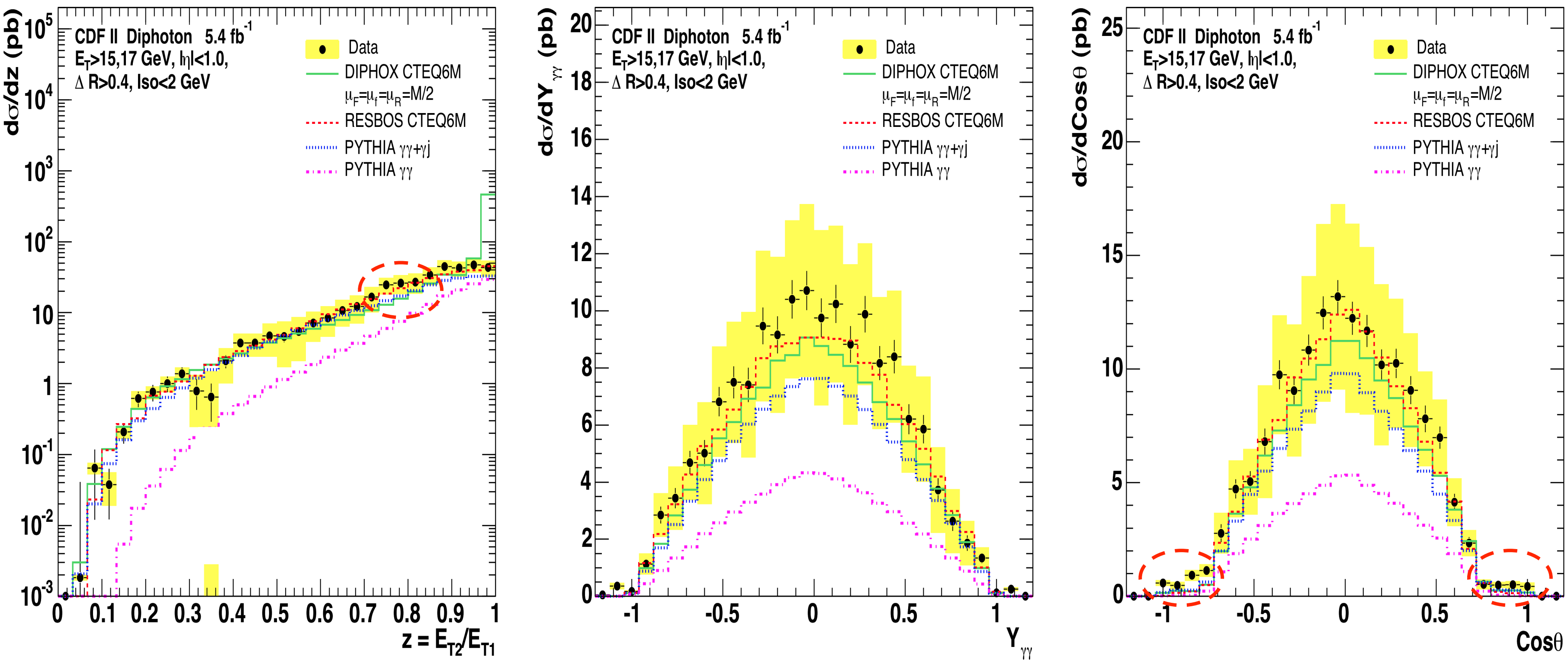
Differential cross sections



- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2
- Resummation important for $p_T(\gamma\gamma)$ > 20 GeV/c
- Fragmentations cause excess of data over theory for $p_T(\gamma\gamma)$ = 20 – 50 GeV/c
- Resummation important for $\Delta\phi_{\gamma\gamma}$ > 2.2 rad
- Data spectrum harder than predicted

Differential cross sections

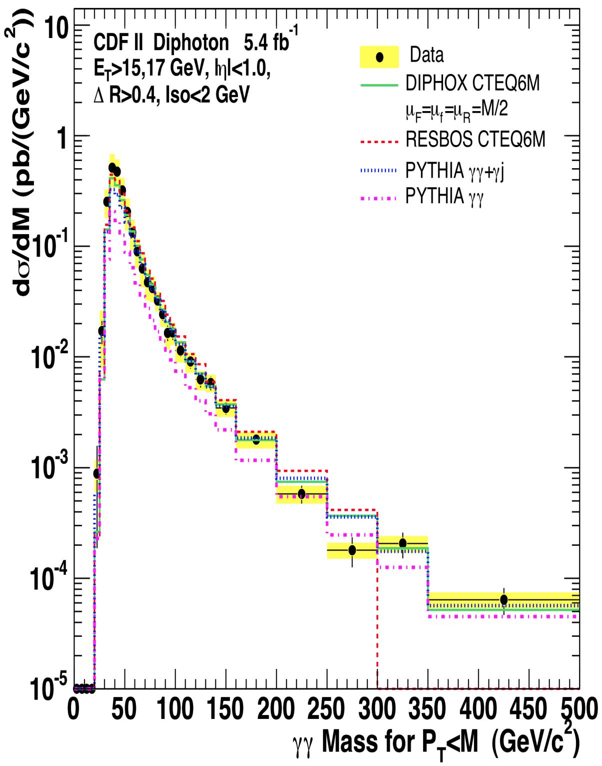


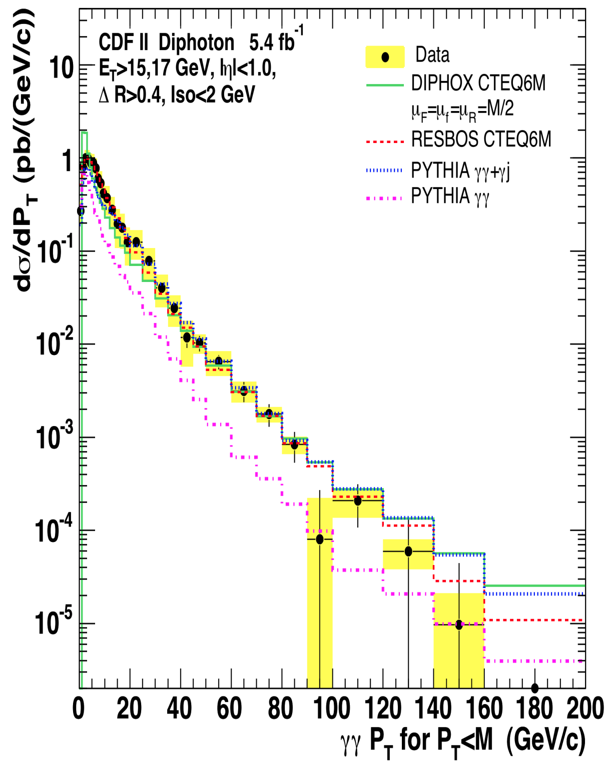
- Good agreement between data and RESBOS
- Good agreement between data and DIPHOX, except for 0.7<z<0.8

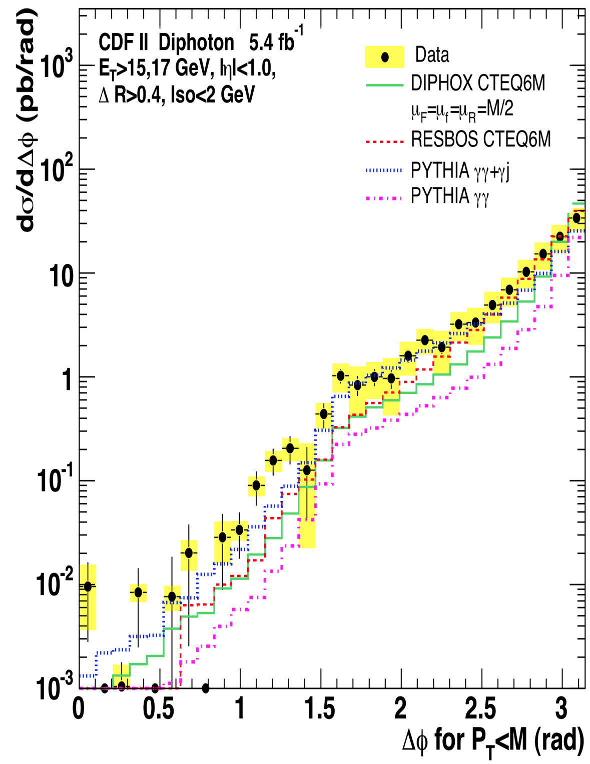
- Good agreement between data and theory

- Observable sensitive to PDFs
- Good agreement between data and theory, except for $|\cos\theta^*| \rightarrow 1$

Differential cross sections for $p_T(\gamma\gamma)<M(\gamma\gamma)$

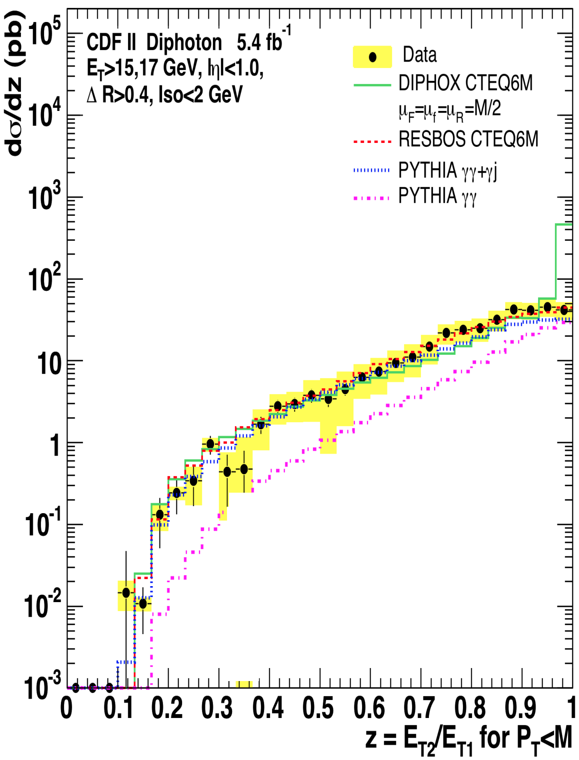


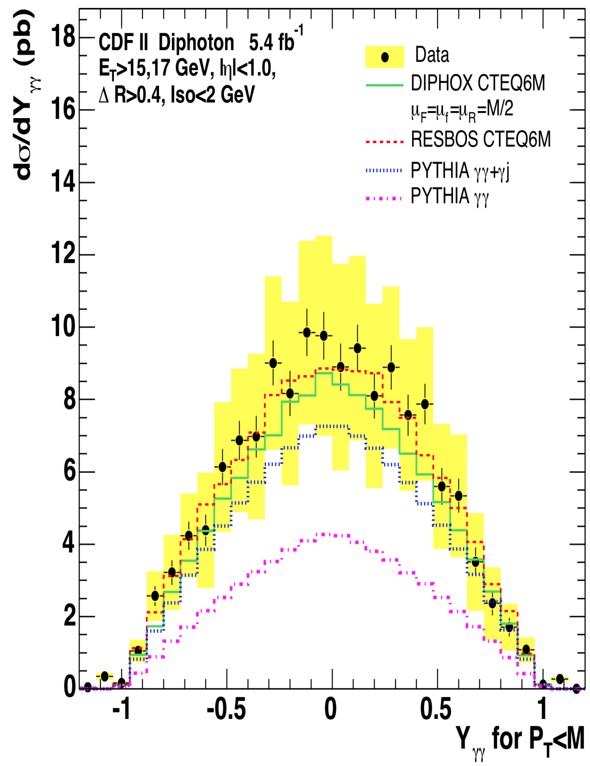


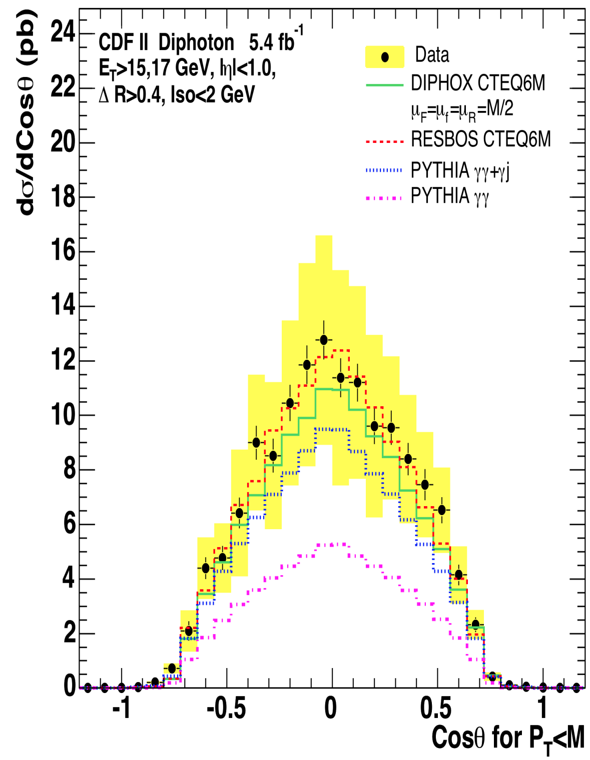


- Good agreement between data and theory
- "Shoulder" in data for $p_T(\gamma\gamma)$ = 20 – 50 GeV/c signifcantly reduced
- Discrepancies between data and theory for $\Delta\phi_{\gamma\gamma}$ < 1.7 rad reduced

Differential cross sections for $p_T(\gamma\gamma)<M(\gamma\gamma)$







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

- Good agreement between data and theory

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Summary and conclusions

- Reported measurements of differential cross sections for direct diphoton production at $\sqrt{s}$=1.96 TeV using 5.4 fb^{-1}.

$$\frac{d\sigma}{dM_{\gamma\gamma}} \quad \frac{d\sigma}{dp_T^{\gamma\gamma}} \quad \frac{d\sigma}{d\Delta\phi_{\gamma\gamma}} \quad \frac{d\sigma}{dz} \quad \frac{d\sigma}{dy_{\gamma\gamma}} \quad \frac{d\sigma}{d\cos\theta^*}$$

- Measurements are compared to state-of-art theoretical predictions such as **DIPHOX**, **RESBOS**, and **PYTHIA**. Overall agreement between data and theory, within known limitations, is 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 kinematic regions [$M(\gamma\gamma)$ <60 GeV/c^2, 20 GeV/c < $p_T(\gamma\gamma)$ < 50 GeV/c, $\Delta\phi_{\gamma\gamma}$<1 rad].

- Data-to-theory comparisons show best agreement for $p_T(\gamma\gamma) < M(\gamma\gamma)$, where theoretical uncertainties are smaller and predictions are less sensitive to the isolation requirement.

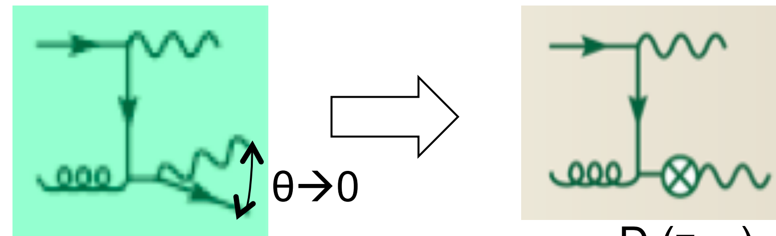
- Parton-shower **PYTHIA** Monte Carlo, which in previous analyses limited to matrix-element-based simulations was found to fail reproducing the data, now provides a description of the data competitive with full NLO calculations by including ISR and FSR photons

- A PRL (arXiv:1106.5123) and a PRD (arXiv:1106.5131) have been submitted

Backup slides

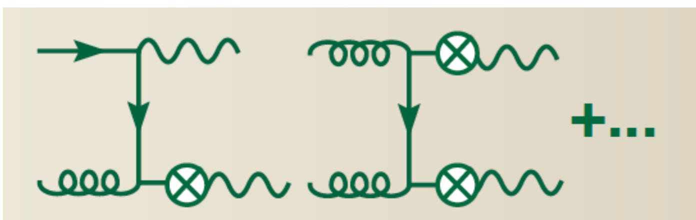
Fragmentation contributions

- Collinear singularity in final state photon radiation off a parton can be handled e.g. via fragmentation functions.

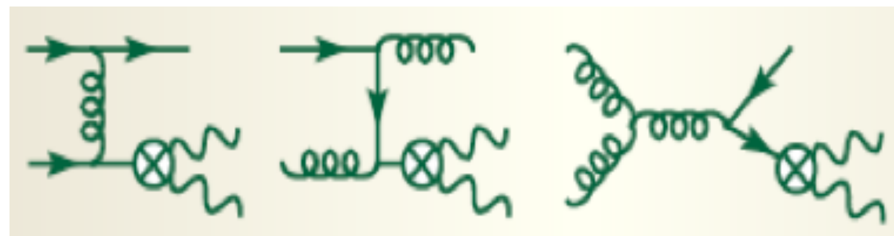


$D_\gamma(z,\mu_f)$

Single-photon fragmentation



Double-photon fragmentation



Low-mass/small-angle diphoton pairs

Not included in any theoretical prediction!

- Fragmentation contributions can be suppressed via:
  - experimental photon isolation requirements (can only be approximated in theory)
  - $p_T(\gamma\gamma) < M(\gamma\gamma)$

$$E_T^{iso} = \sum_{\substack{\text{partons or hadrons} \\ \text{within } R<0.4}} E_T - E_{T\gamma}$$

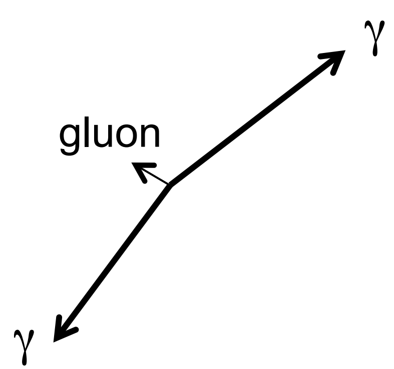
Resummation of initial state gluons

- At fixed $M(\gamma\gamma)$, the differential cross section as a function of $p_T(\gamma\gamma)$ at $O(\alpha_s)$ given by:

$$\frac{d\sigma}{dp_{T\gamma\gamma}^2} = \sigma_0 \frac{\alpha_s}{\pi} \frac{1}{p_{T\gamma\gamma}^2} \left[a_1 \ln\left(\frac{M_{\gamma\gamma}^2}{p_{T\gamma\gamma}^2} \right) + a_0 \right]$$

Fixed-order calculation less reliable for $p_T(\gamma\gamma) \ll M(\gamma\gamma)$ and diverges as $p_T(\gamma\gamma) \to 0$.

[Also when $\Delta\phi(\gamma,\gamma) \to \pi$.]



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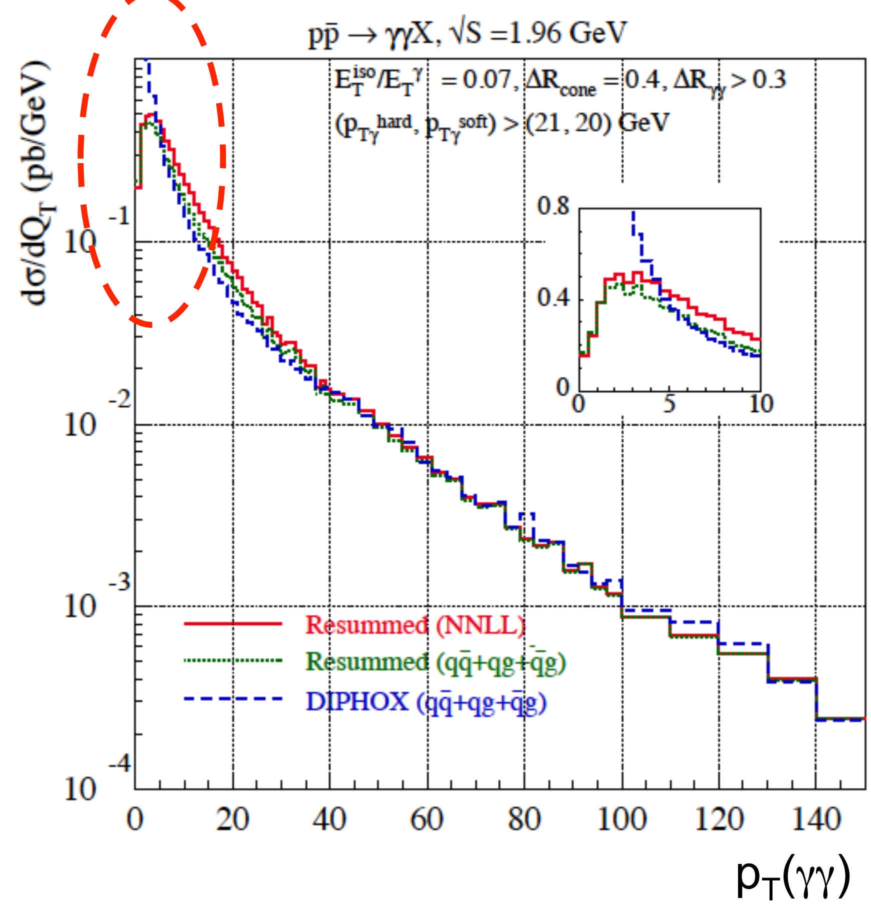

Resummation of initial state gluons

- At fixed M(γγ), the differential cross section as a function of $p_T(\gamma\gamma)$ is given by:

$$\frac{d\sigma}{dp^2_{T\gamma\gamma}} = \sigma_0 \frac{\alpha_s}{\pi} \frac{1}{p^2_{T\gamma\gamma}} \left[a_1 \ln\left(\frac{M^2_{\gamma\gamma}}{p^2_{T\gamma\gamma}} \right) + a_0 \right]$$

Fixed-order calculation less reliable for $p_T(\gamma\gamma) \ll M(\gamma\gamma)$ and diverges as $p_T(\gamma\gamma) \rightarrow 0$.

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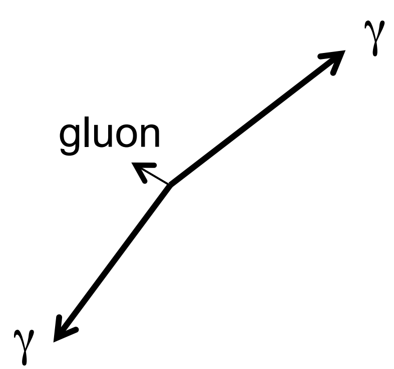

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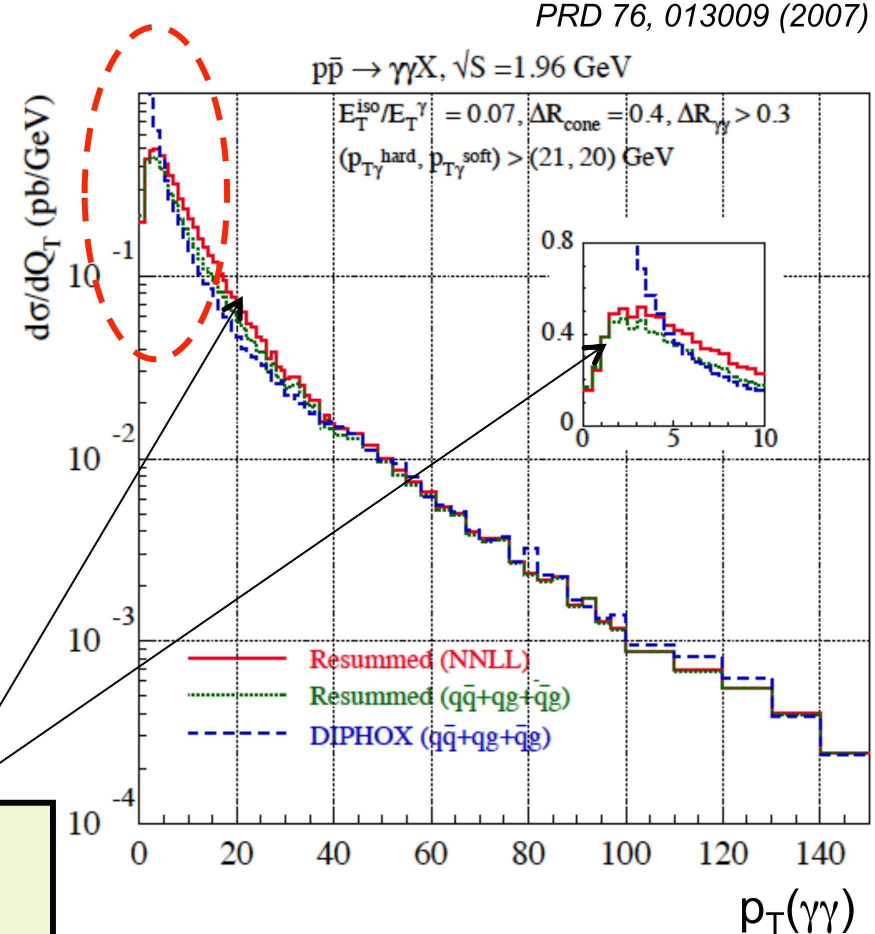


Physical description of the $p_T(\gamma\gamma)$ and $\Delta\phi(\gamma,\gamma)$ distributions requires all-order resummation of soft and collinear logarithms.

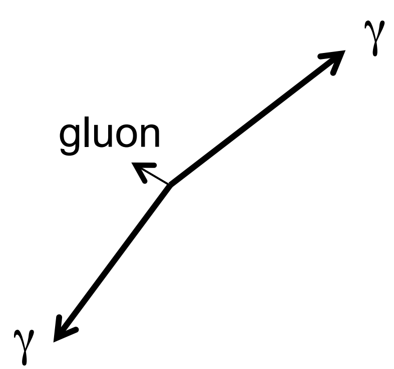
Resummation of initial state gluons

- At fixed M(γγ), the differential cross section as a function of $p_T(\gamma\gamma)$ is given by:

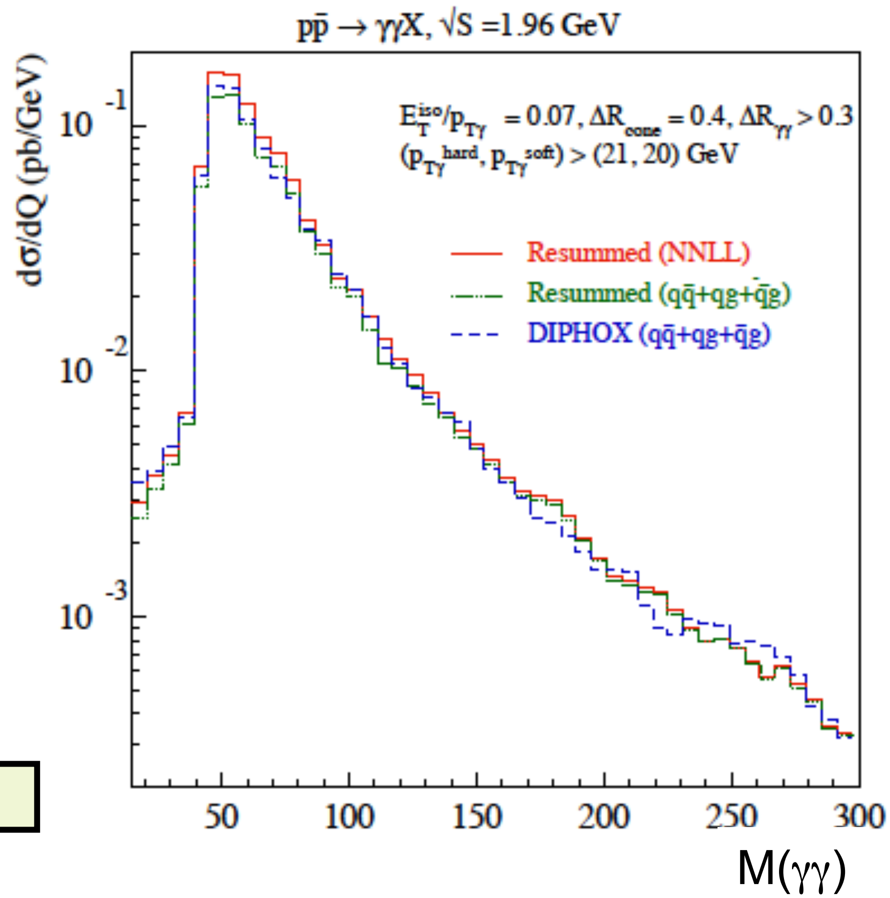
$$\frac{d\sigma}{dp_{T\gamma\gamma}^2} = \sigma_0 \frac{\alpha_s}{\pi} \frac{1}{p_{T\gamma\gamma}^2}\left[a_1 \ln\left(\frac{M_{\gamma\gamma}^2}{p_{T\gamma\gamma}^2}\right) + a_0\right]$$

Fixed-order calculation less reliable for $p_T(\gamma\gamma) \ll M(\gamma\gamma)$ and diverges as $p_T(\gamma\gamma) \to 0$.

[Also when $\Delta\phi(\gamma,\gamma) \to \pi$.]

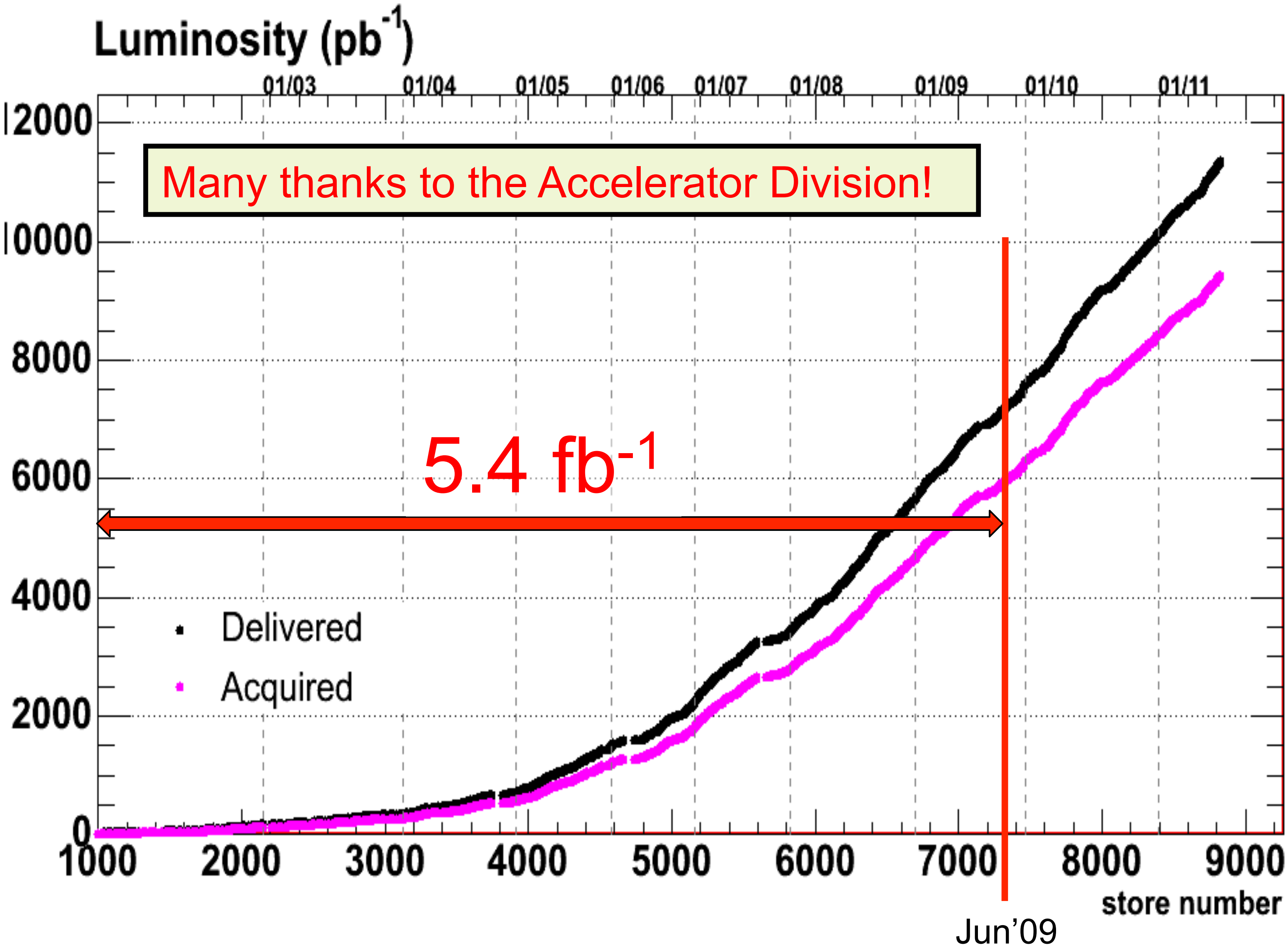


PRD 76, 013009 (2007)



Only small effect on M(γγ) from resummation

Data set



x27 more luminosity than previous CDF publication!

Triggers

Diphoton-12

- **L1:**
  - EM $E_T \geq 8$ GeV
  - $E_{HAD}/E_{EM} \leq 0.125$
  - $N_{cluster} = 2$
- **L2:**
  - EM $E_T \geq 10$ GeV
  - $E_{HAD}/E_{EM} \leq 0.125$
  - $N_{cluster} = 2$
  - Isolation ≤ 3 GeV or IsoFraction ≤ 0.15
- **L3:**
  - EM $E_T \geq 12$ GeV
  - $E_{HAD}/E_{EM} \leq 0.055 + 0.00045 \times E_{tot}/\text{GeV}$
  - $N_{cluster} = 2$
  - Isolation ≤ 2 GeV or IsoFraction ≤ 0.1
  - Shower profile: $\chi^2_{CES} \leq 20$

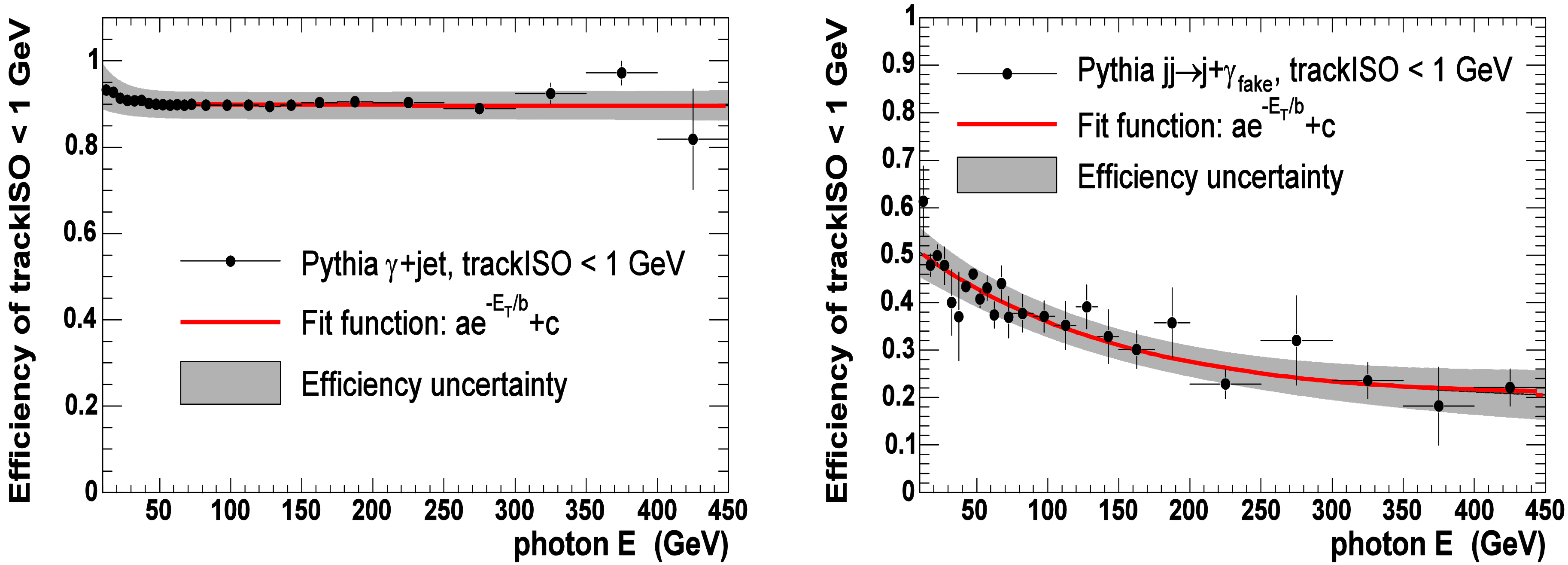
"OR"

Diphoton-18 Same as diphoton-12 except:

- **L2:**
  - EM $E_T \geq 16$ GeV
  - No isolation
- **L3:**
  - EM $E_T \geq 18$ GeV
  - No isolation

Trigger efficiency after offline event selection: 100% for $E_T \geq 15$ GeV

Photon characterization using track isolation



For a single γ, a weight can be defined to characterize it as signal or background:

$$w = \frac{\varepsilon - \varepsilon_b}{\varepsilon_s - \varepsilon_b}$$

➔ ε = 1 (0) if I_{trk} < (≥) 1 GeV/c

➔ ε_s = signal efficiency for I_{trk} < 1 GeV/c

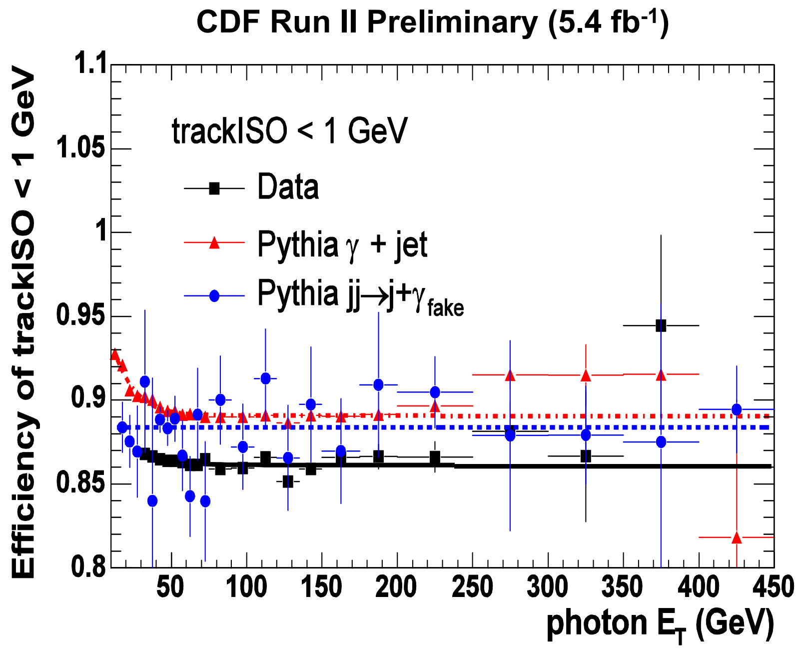
➔ ε_b = background efficiency for I_{trk} < 1 GeV/c

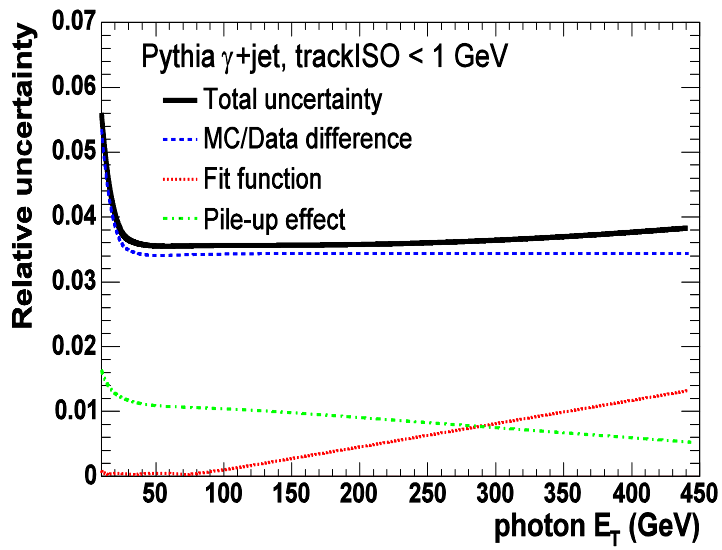
} Both modeled by $ae^{-E_T/b} + c$

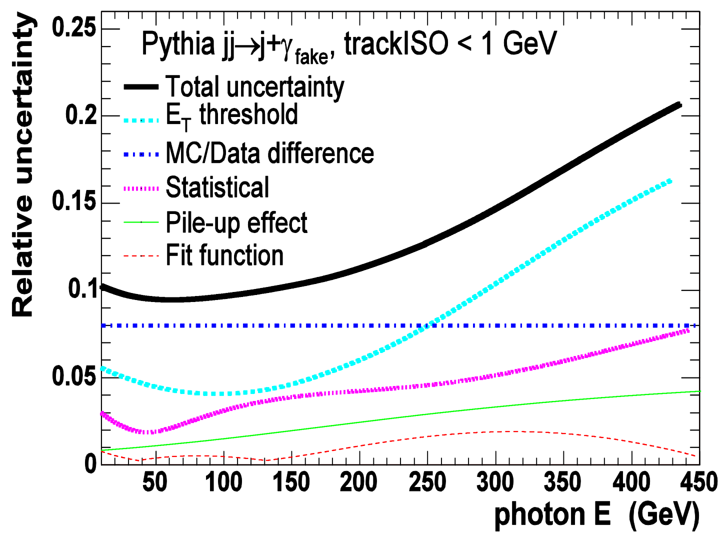
Cut chosen at I_{trk} = 1 GeV/c, where $\varepsilon_s - \varepsilon_b$ = max, to optimize resolution

Background estimation: 4×4 matrix method

- Relative uncertainties for photon and jet track ISO efficiencies estimated as a function of E_T using MC.
- Compared data and MC in complementary cones (same θ, $\phi\pm\pi/2$ with true photon cones, assumed to collect same amount of underlying event):







➔ Data and MC consistent to within 3%.

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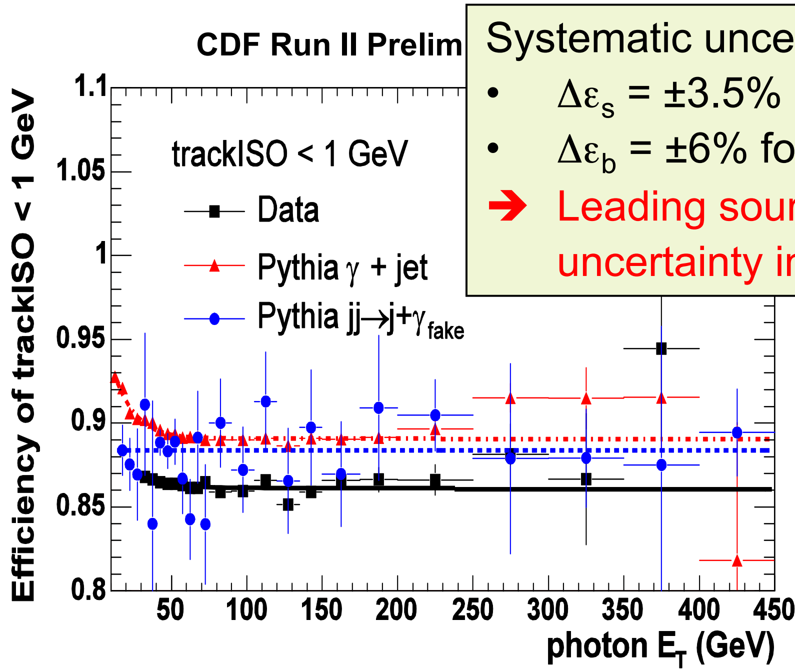
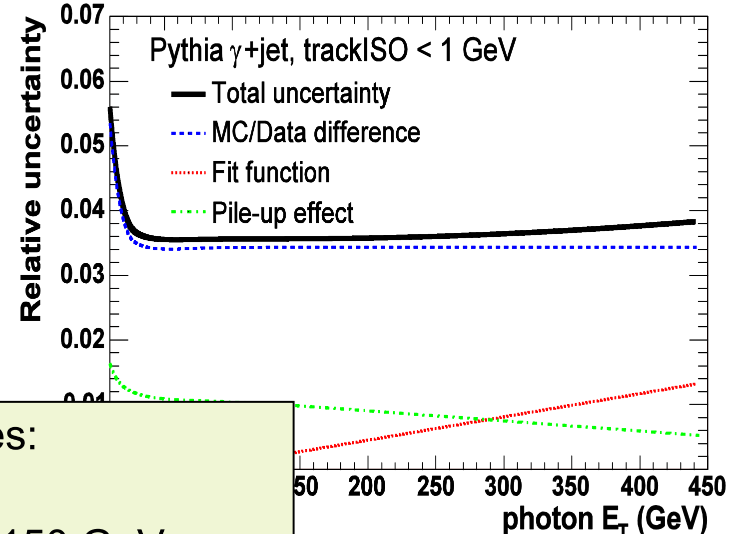
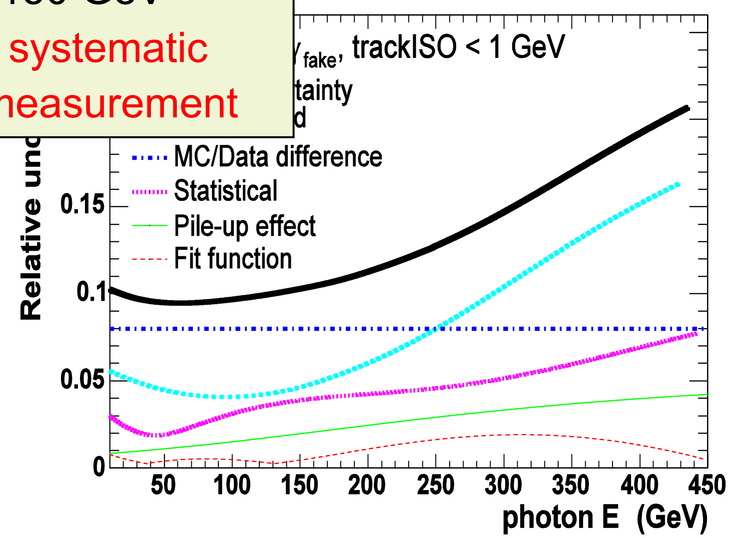




Systematic uncertainties:

- $\Delta\varepsilon_s = \pm 3.5\%$
- $\Delta\varepsilon_b = \pm 6\%$ for $E_T < 150$ GeV

➔ Leading sources of systematic uncertainty in this measurement



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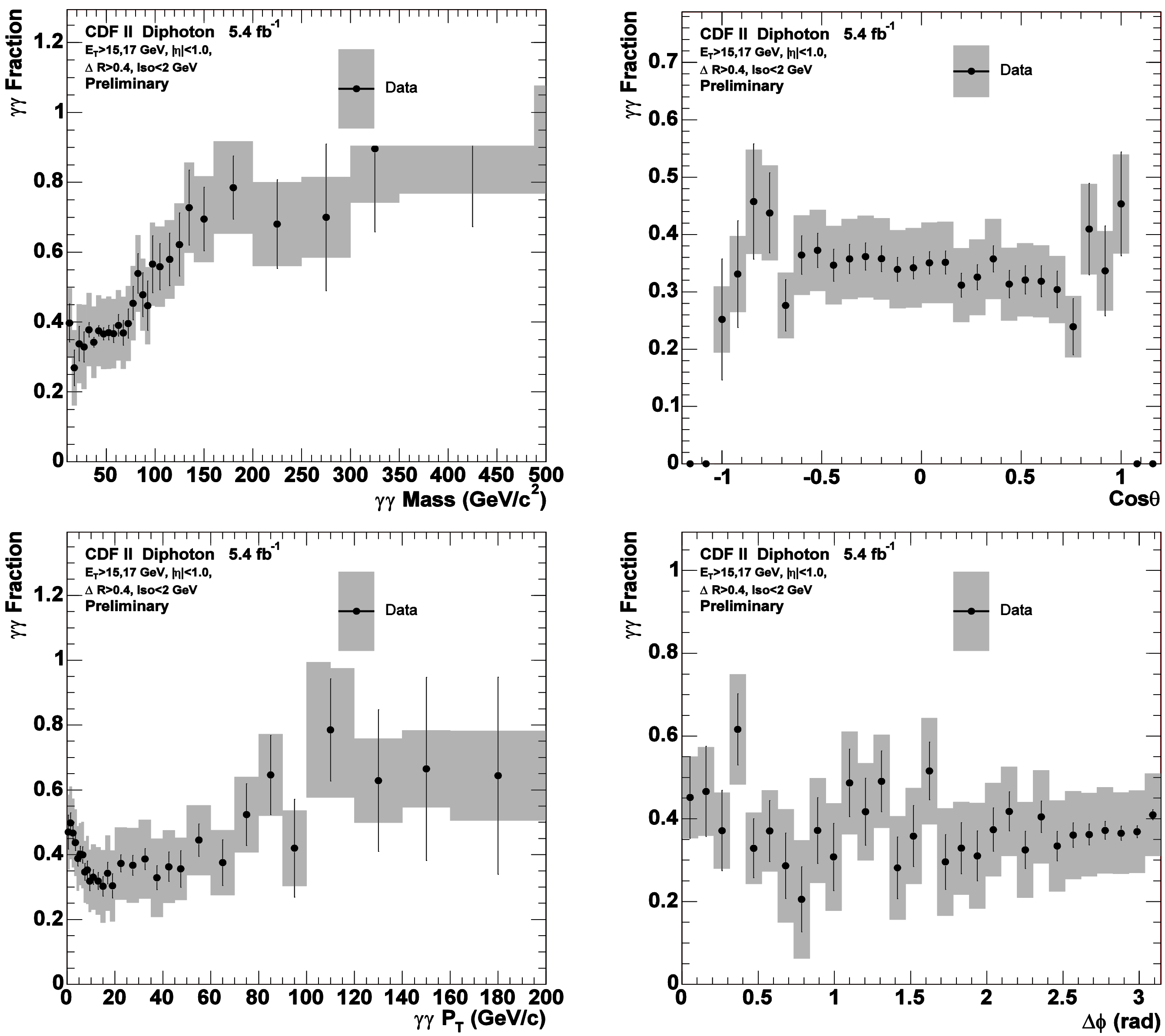
Signal fraction

$$Signal\ fraction = \frac{N_{\gamma\gamma}}{N_{data}}$$



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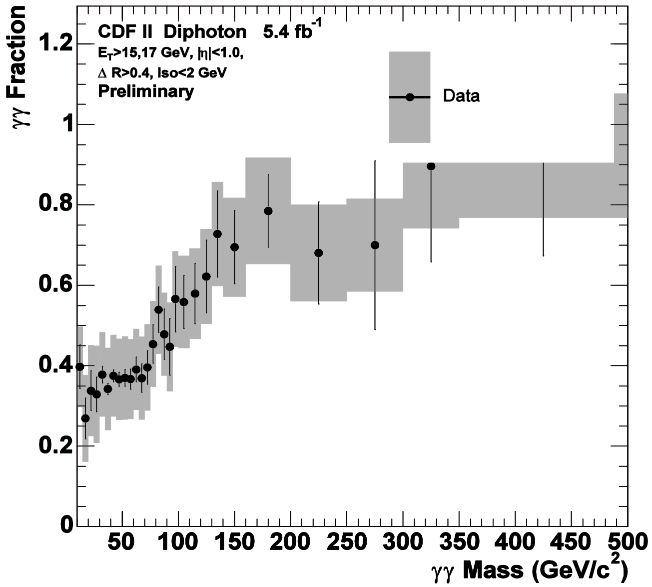
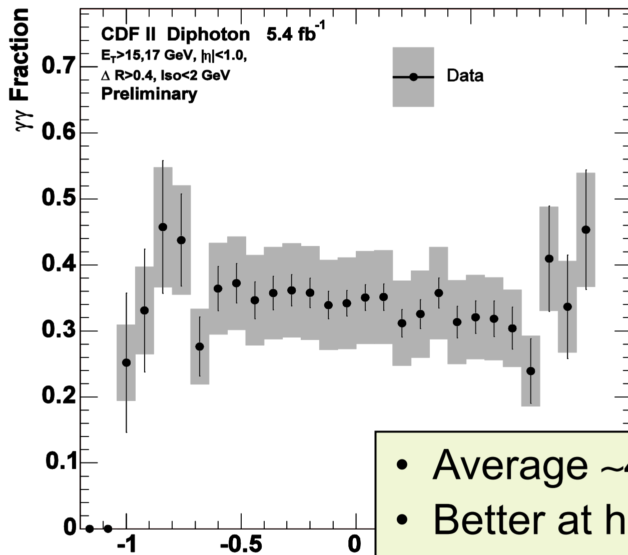
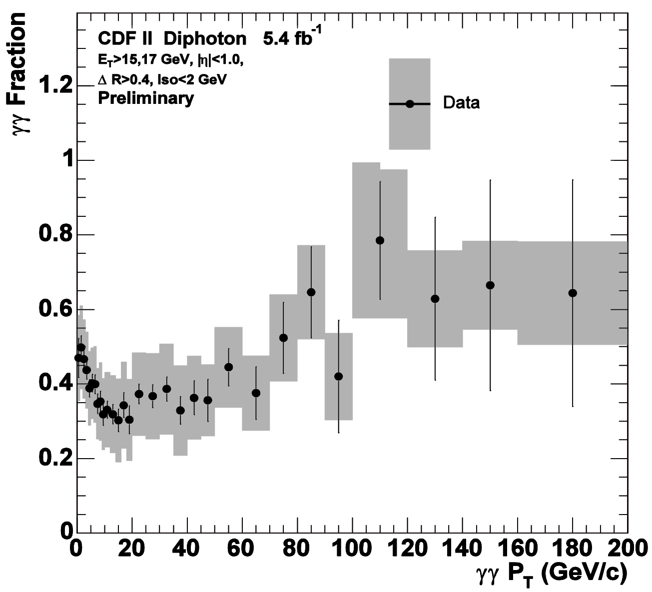
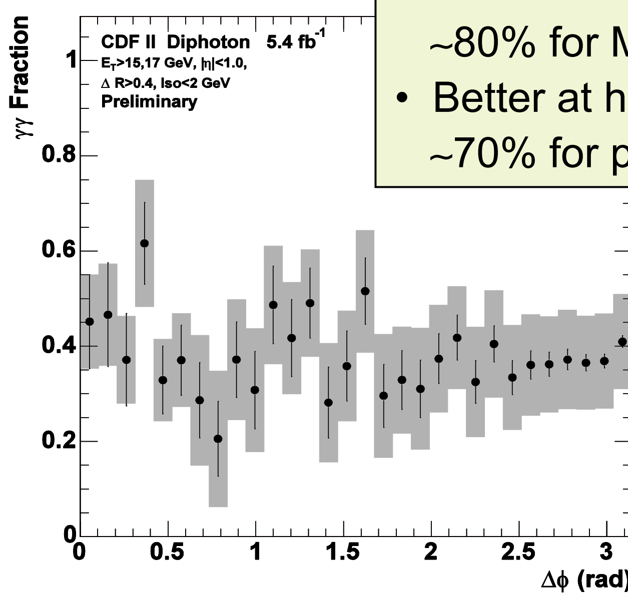








- Average ~40%
- Better at high mass:
  60-80% for M(γγ) ~80-150 GeV/c^2
  ~80% for M(γγ)>150 GeV/c^2
- Better at high $p_T(\gamma\gamma)$:
  ~70% for $p_T(\gamma\gamma)$ >100 GeV/c

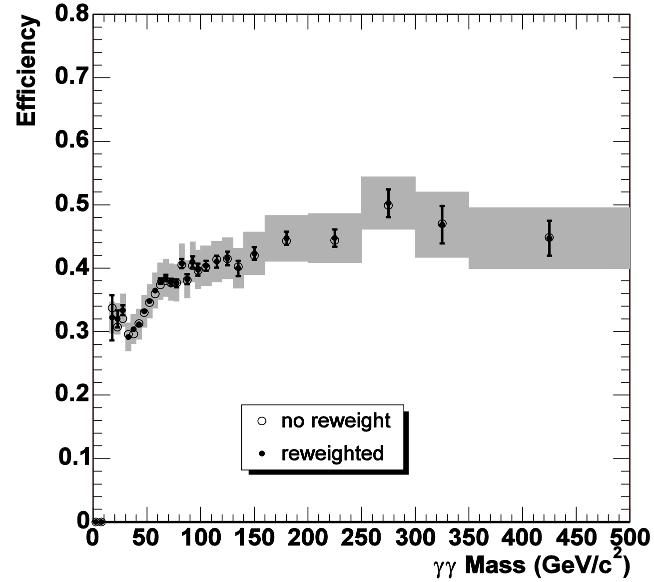
Acceptance × efficiency

$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta}$$

- Defined as:

$$\frac{\textit{Number of events with two reconstructed EM clusters passing all cuts}}{\textit{Number of events with two generator-level photons passing kinematic and isolation cuts}}$$

- Estimated using detector- and trigger-simulated and reconstructed PYTHIA events reweighted to match the data



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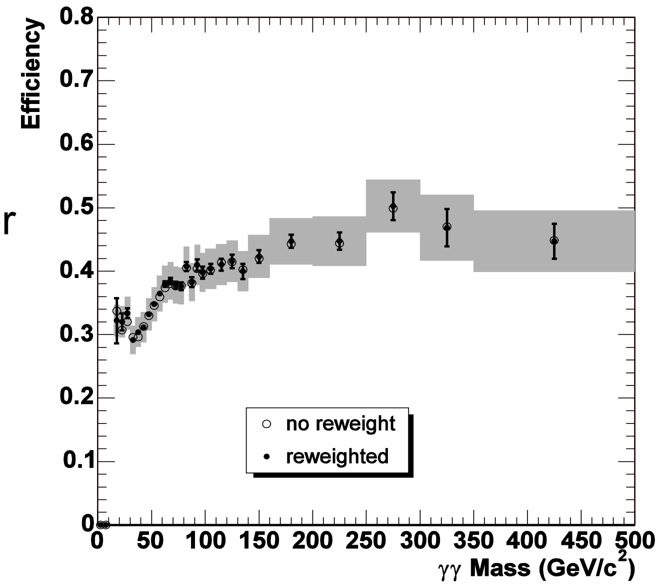
- RESBOS and DIPHOX do not include non-perturbative effects: underlying event and hadronization
  ➔ lower efficiency of the isolation cut relative to PYTHIA

  (PYTHIA events are removed from the isolated denominator of the efficiency due to the underlying event)

- Correction estimated by convoluting PYTHIA UE isolation energy with DIPHOX energy in the isolation cone
  ➔ constant per event factor of 0.88 applied to the data



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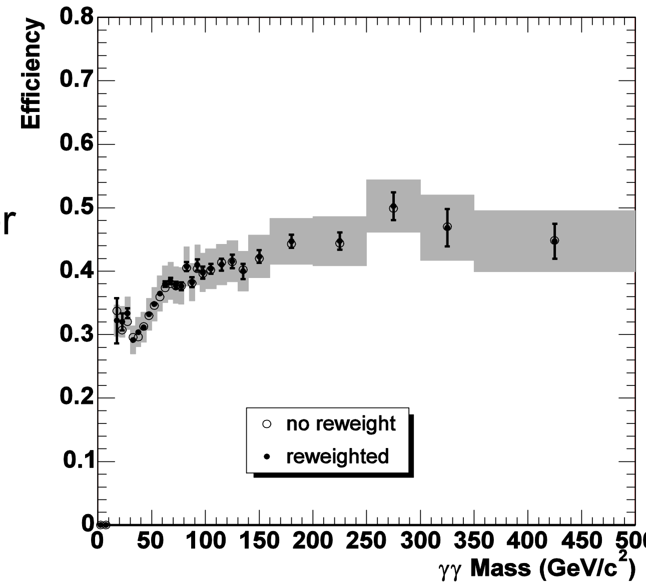

Uncertainties in the efficiency estimation:

- 3% from material uncertainty
- 1.5% from the EM energy scale
- 3% from trigger efficiency uncertainty
- 6% (3% per photon) from UE correction

Average efficiency ~40%
Total systematic uncertainty: ~7-15%
Comparable statistical uncertainty

Corrections and tests

- EM energy scale set by tuning the reconstructed $Z^0 \rightarrow e^+e^-$ mass to the world average by Gaussian fitting in the window M_{ee} = 86-96 GeV/c^2

  ➔ correction applied as a function of time before event selection to account for a few events below the energy threshold which the correction pushes above threshold

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- Measurement of the $Z^0 \rightarrow e^+e^-$ cross section tests the cross section measurement procedures:

  ➔ Trigger efficiency
  ➔ Ability of MC to predict event selection efficiency
  ➔ Efficiency corrections
  ➔ Luminosity

  "Photon-like" e^+e^- selection applied with special requirements:
  ➔ Two tracks allowed in cluster
  ➔ Leading p_T^{trk} cut applied on the 2nd track in cluster
  ➔ Track isolation corrected subtracting leading p_T^{trk}
  ➔ $0.8 \leq E/p \leq 1.2$ cut applied to eliminate hard radiation

Measured/published ratio in the window M_{ee} = 65-115 GeV/c^2: 1.007±0.01 with 5% RMS over time

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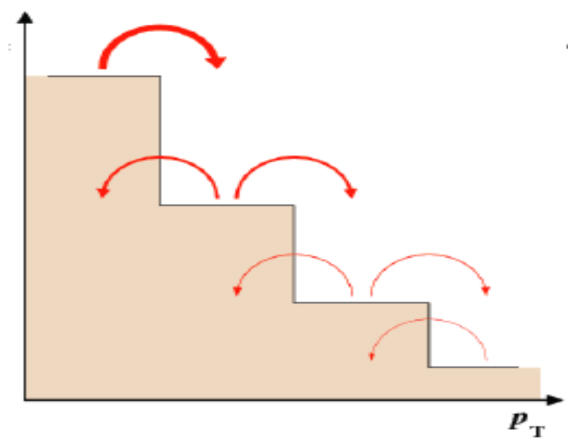
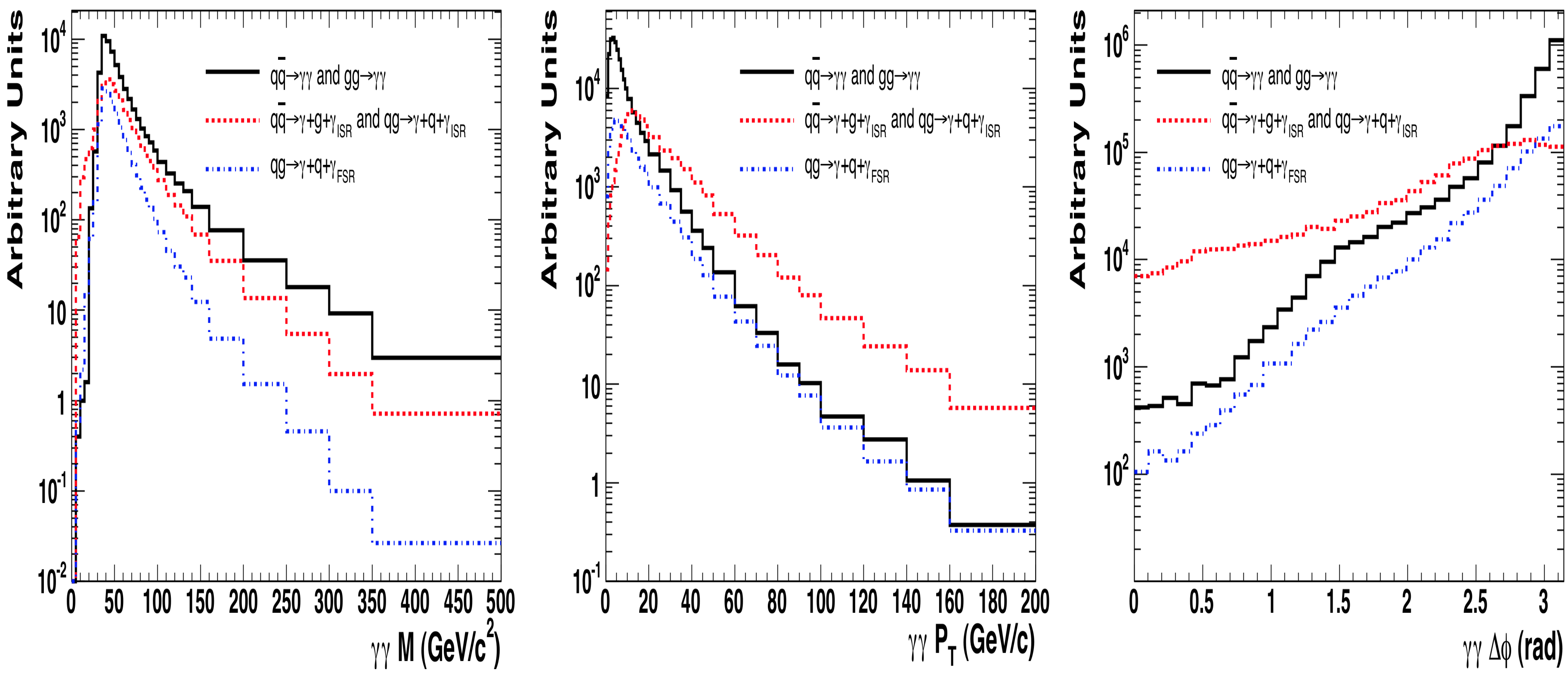


- Experimental effects (photon energy resolution, misvertexing) lead to event migration

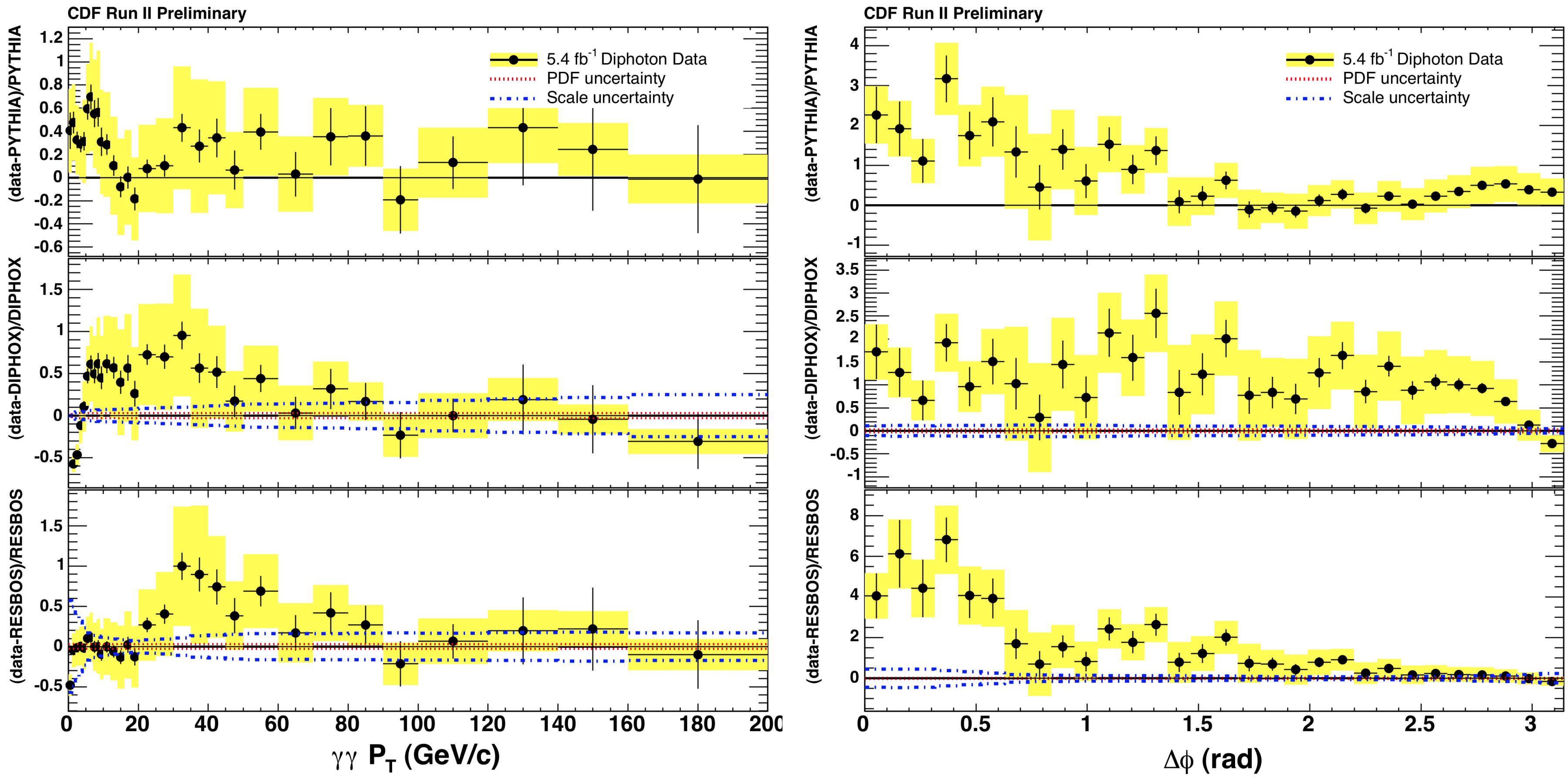
  Purity (bin i) = N(gen bin i AND reco bin i)/N(reco bin i)

  ➔ The acceptance correction also accounts for this

Matrix element and radiation contributions in Pythia



Data-to-theory cross section ratios



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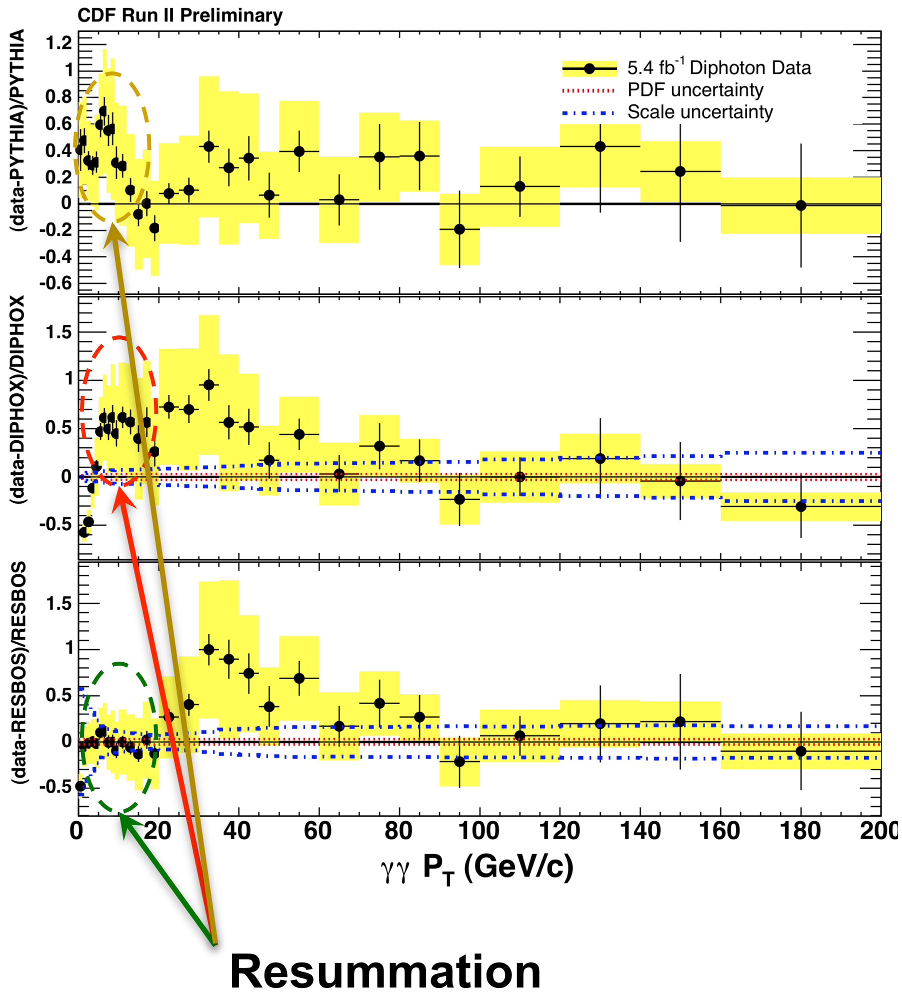

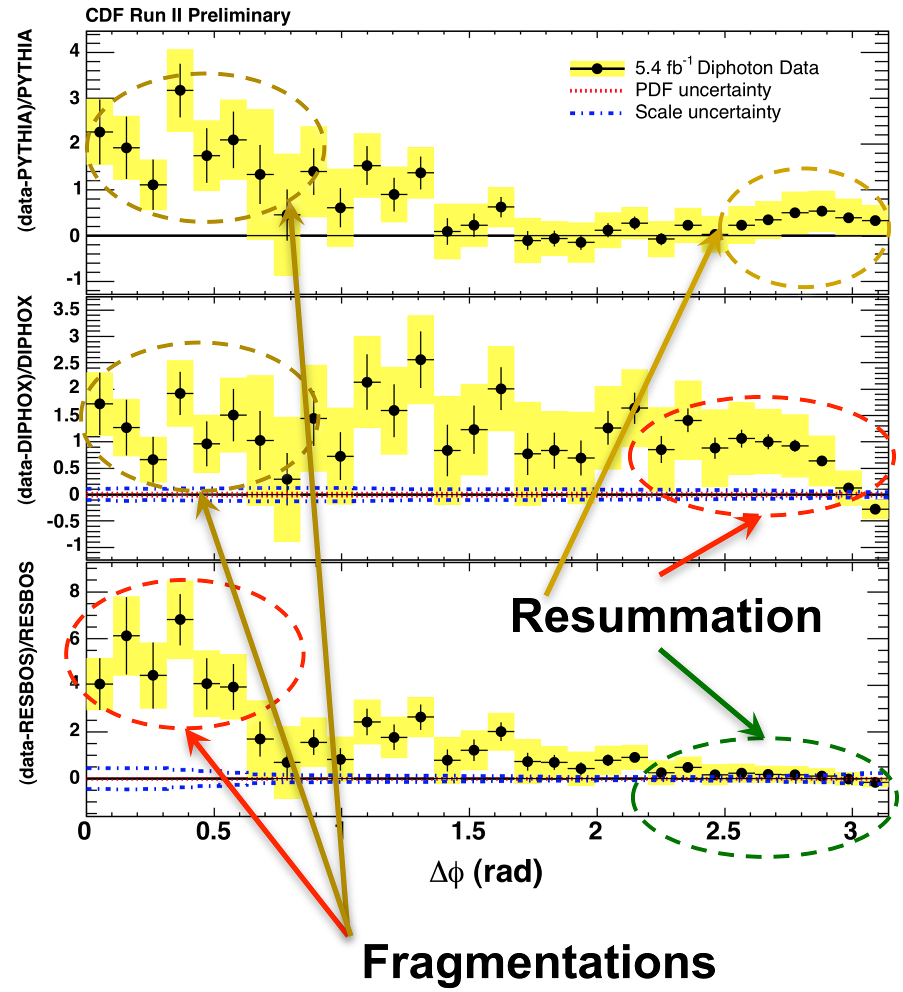

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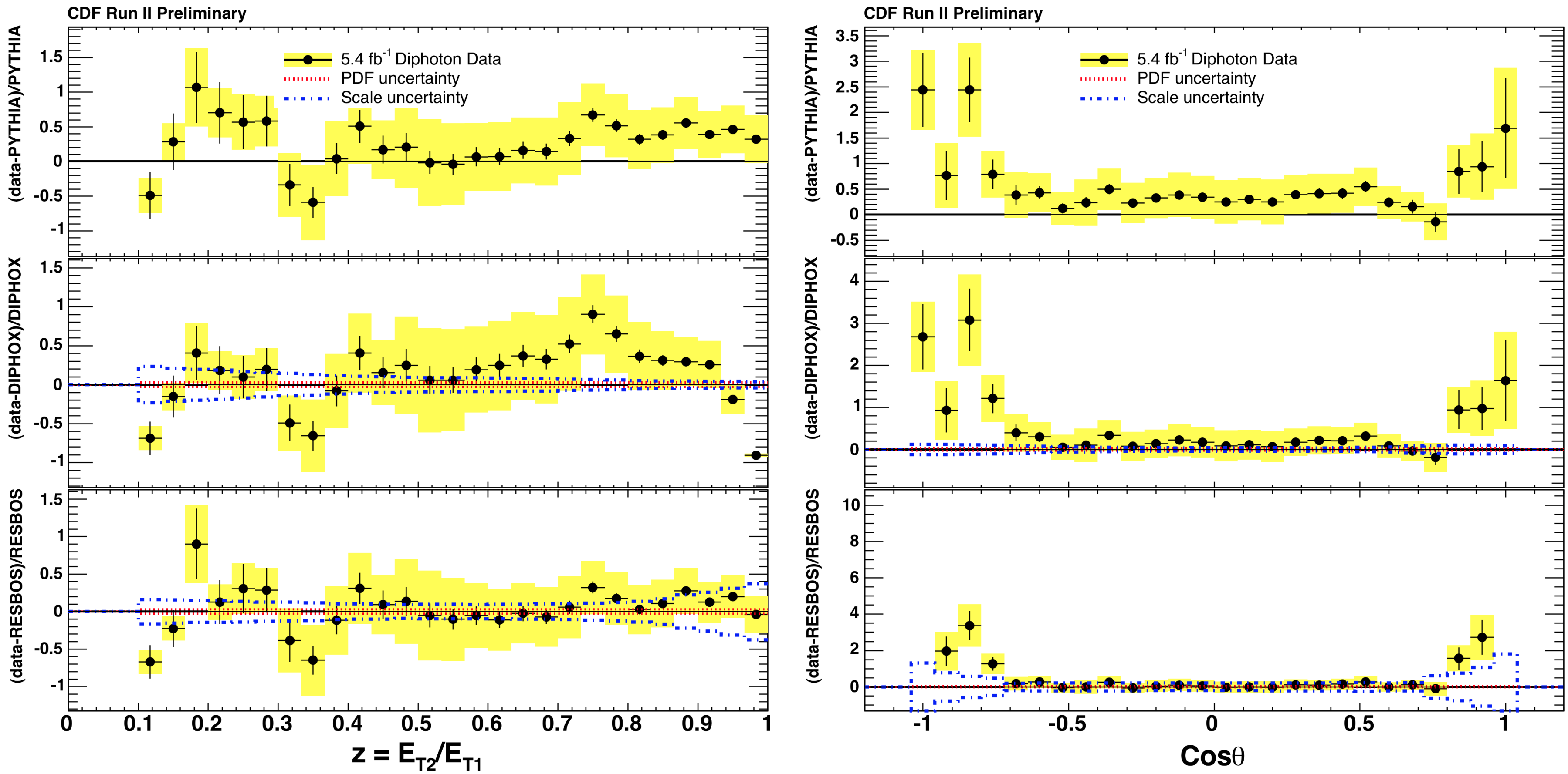

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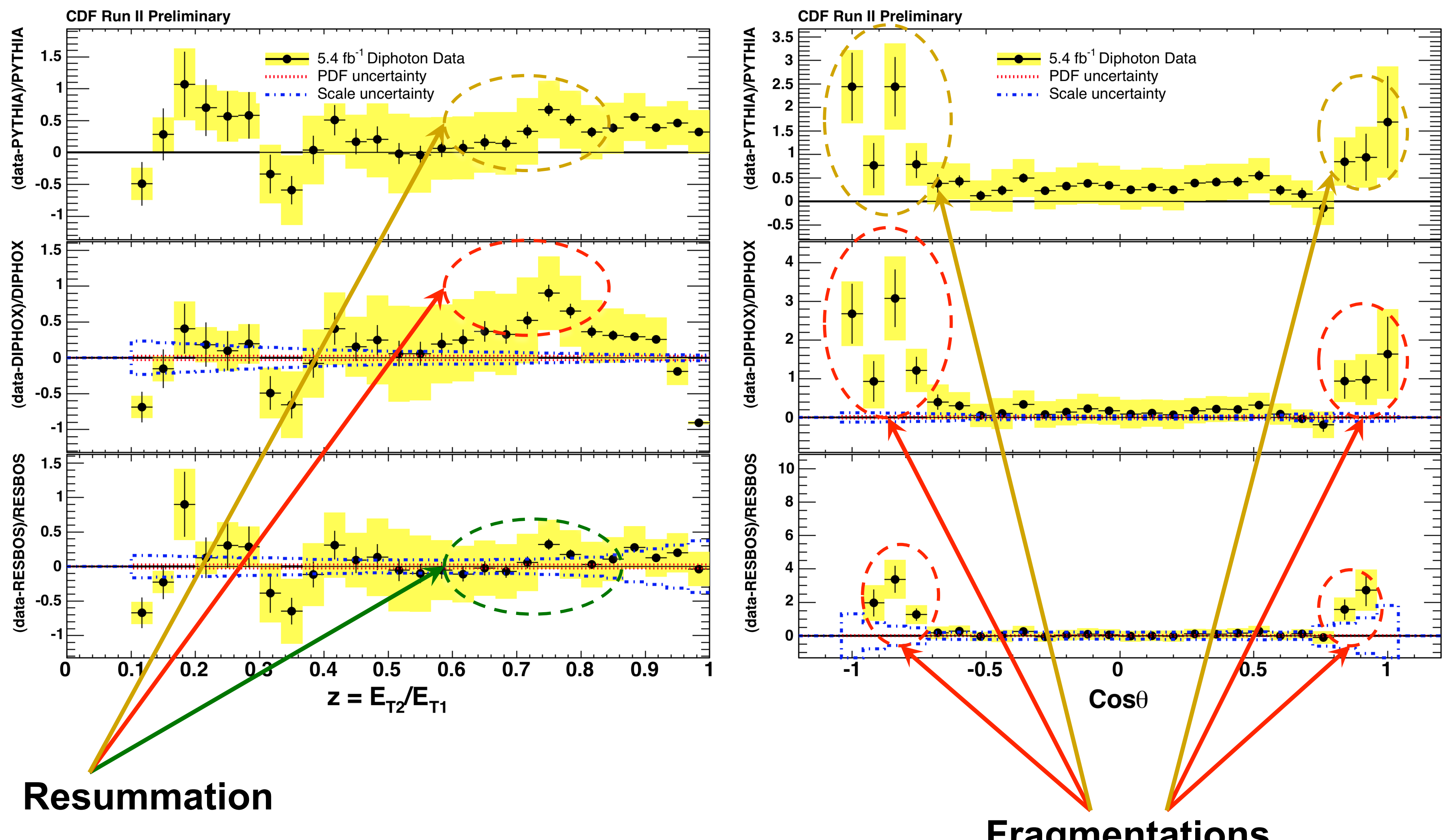
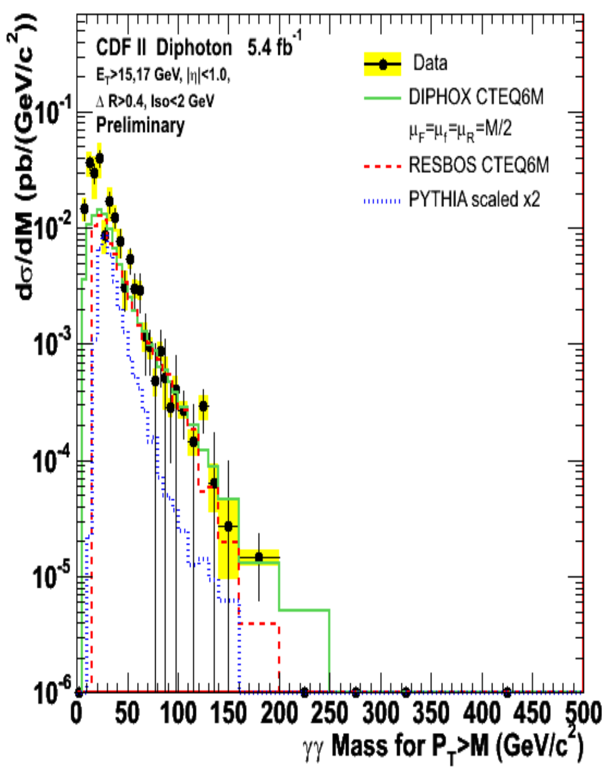
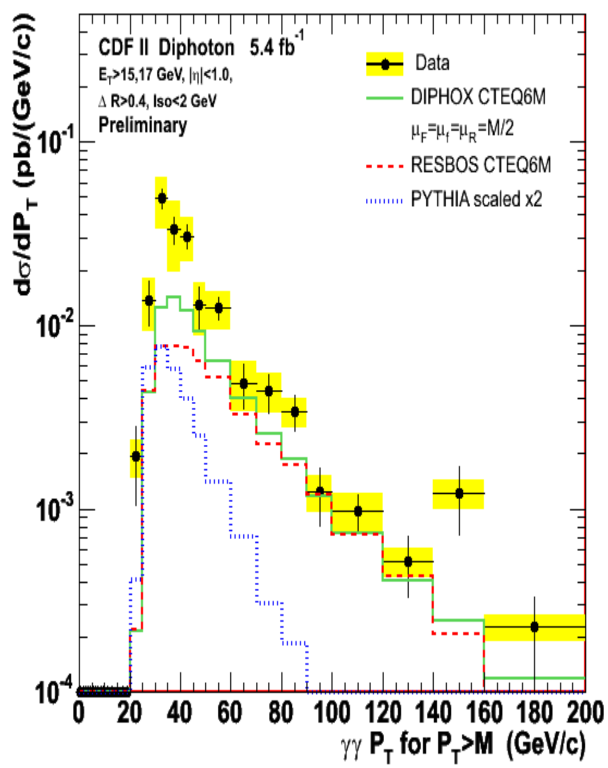
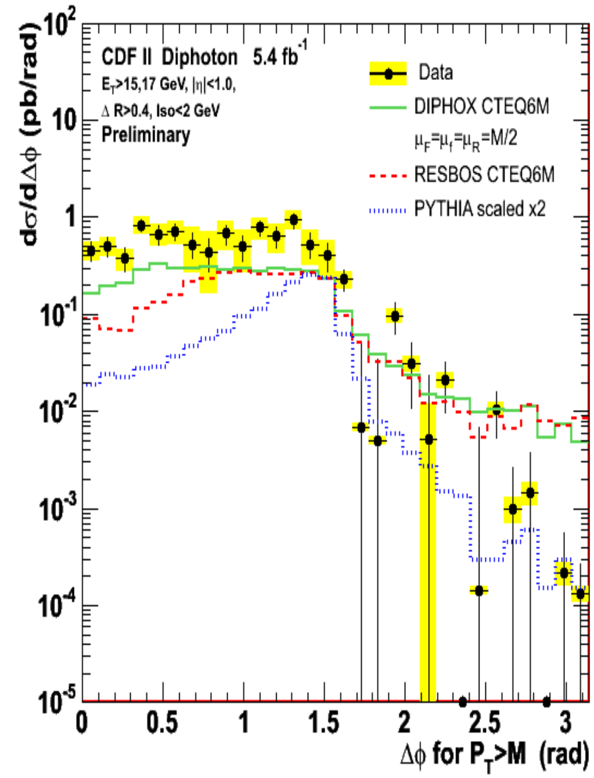


Differential cross sections for $p_T(\gamma\gamma) > M(\gamma\gamma)$

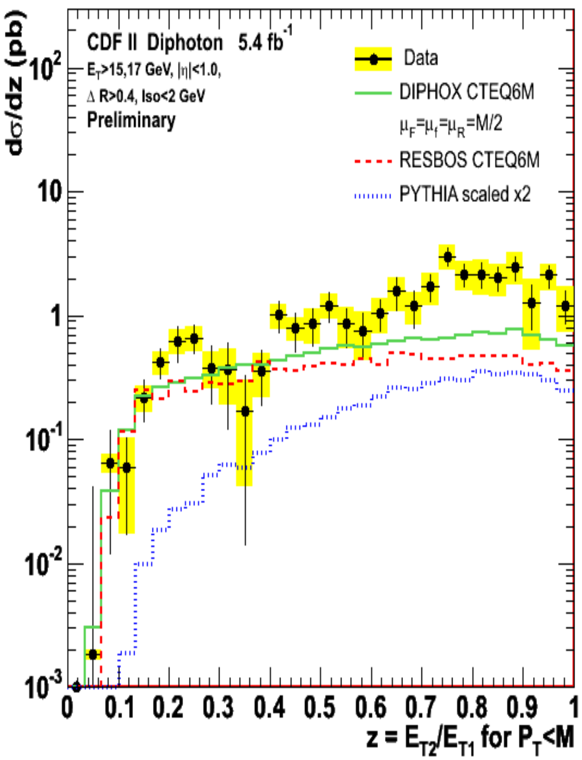






- Theory underestimates the data at the peak $M_{\gamma\gamma} \sim 30$ GeV/c^2
- Theory underestimates the data for $p_T(\gamma\gamma) < 90$ GeV/c
- Theory underestimates the data for $\Delta\phi_{\gamma\gamma} < 1.7$ rad

Differential cross sections for $p_T(\gamma\gamma)>M(\gamma\gamma)$



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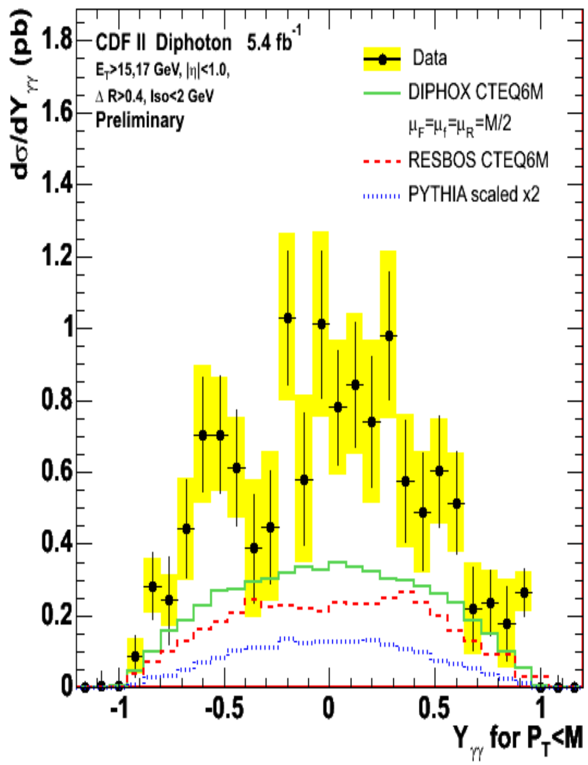

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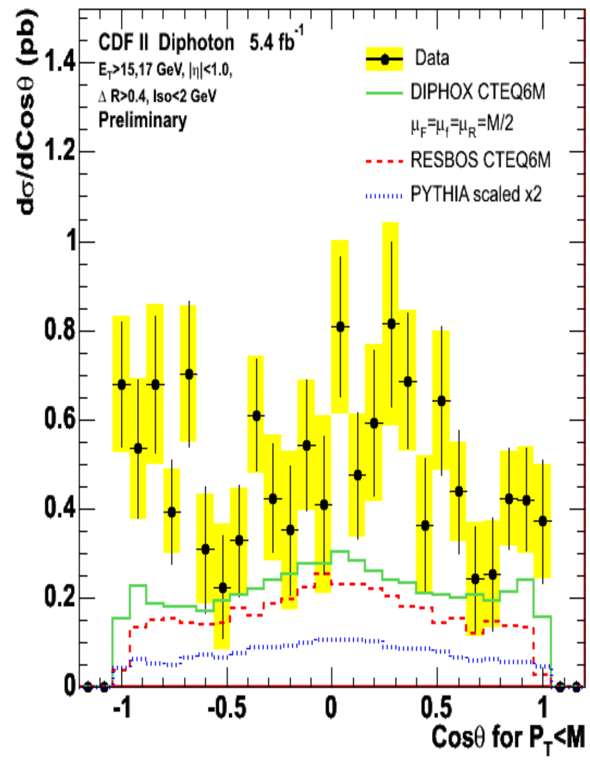

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