NNLO QCD results for diphoton production at the LHC and the Tevatron

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MARIE CURIE ACTIONS

Outline

- Introduction
- Available theoretical tools (NLO)
- q_T subtraction method (NNLO)
- Diphoton production with **2γNNLO**
- Summary

In collaboration with S. Catani, D. de Florian, G. Ferrera and M. Grazzini

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- Introduction
  - Why is diphoton production important?
  - Photon production mechanisms and isolation
- Available theoretical tools (NLO)
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- Available theoretical tools (NLO)
  - Comparison theory vs. data
  - Some discrepancies (theory ↔ data)
- q_T subtraction method (NNLO)
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  - Features of the code
  - Results
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  - Features of the code
  - Results →
    - Diphoton production
    - Higgs boson searches
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Why is diphoton production important?

- It is a channel that we can use to check the validity of perturbative Quantum Chromodynamics (pQCD)
  - Collinear factorization approach
  - K_T factorization approach
  - Soft gluon logarithmic resummation techniques

- It constitutes an irreducible background for new physics searches
  - Universal Extra Dimensions
  - Randall-Sundrum ED
  - Supersymmetry
  - New heavy resonances

- **Irreducible background**
  - **In studies and searches for a low mass Higgs boson decaying into photon pairs**

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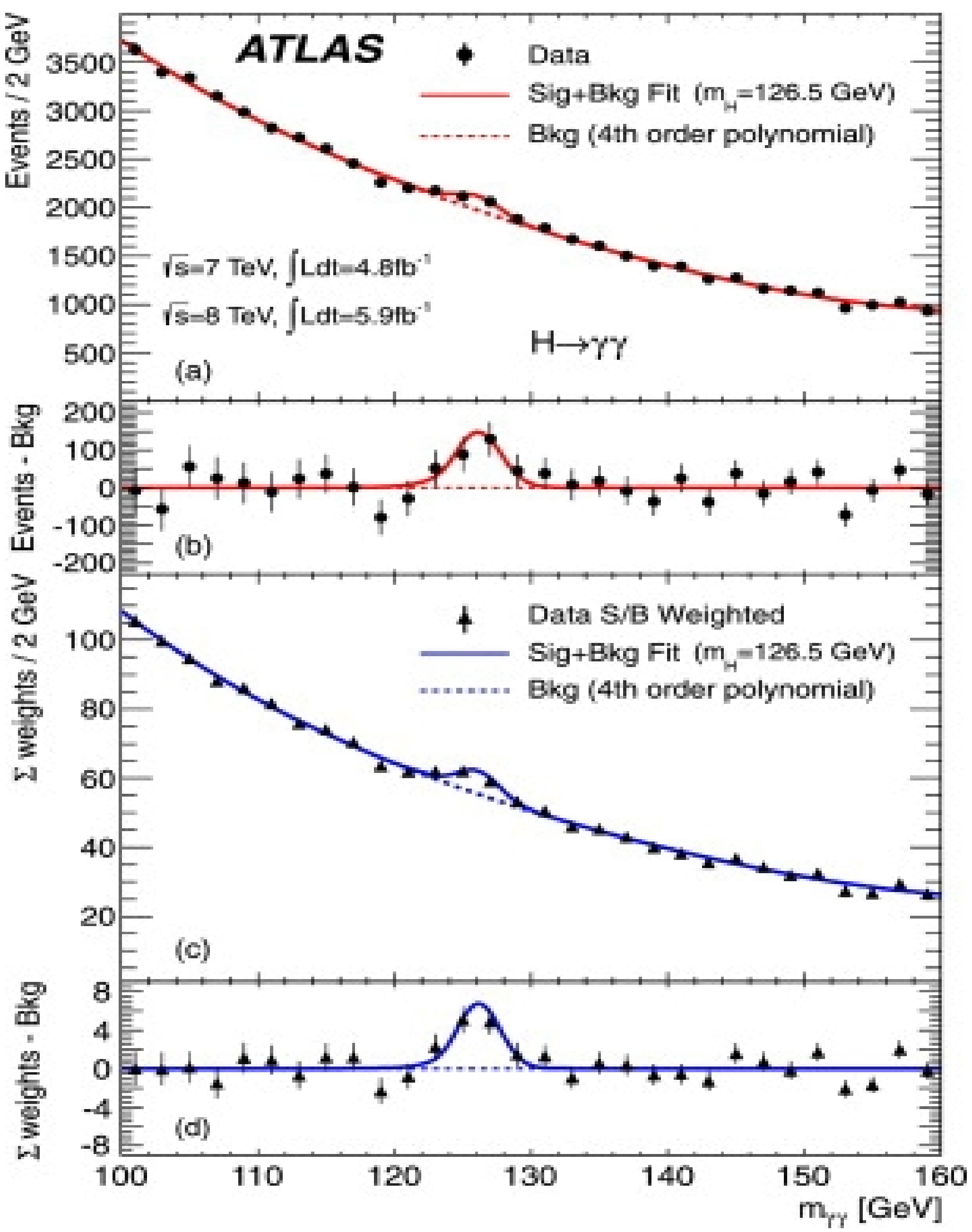
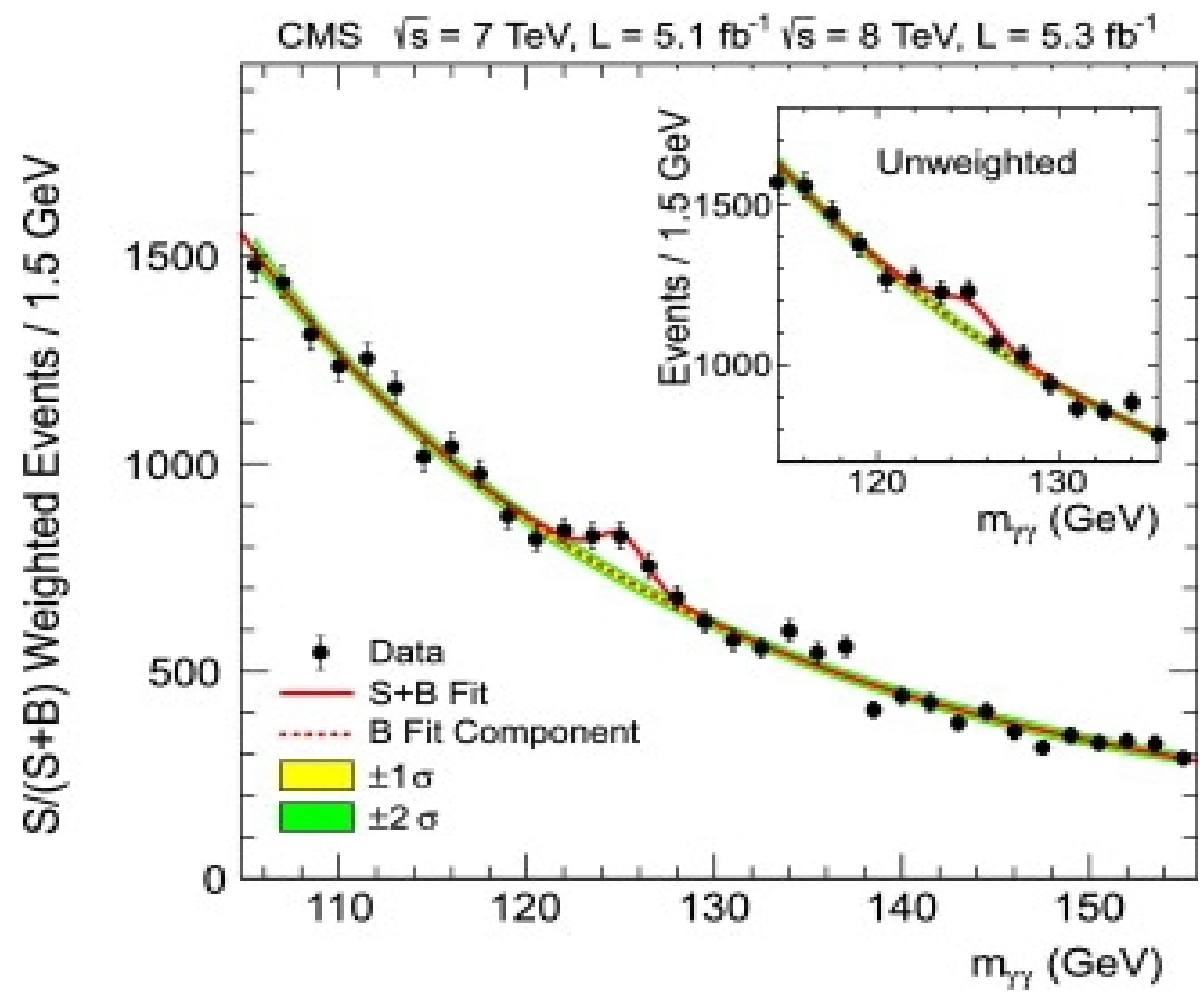
- **Irreducible background**
  - **In studies and searches for a low mass Higgs boson decaying into photon pairs**

The search for the SM Higgs boson

All these motivations are strengthened by the spectacular observation of a new neutral boson (M~125 GeV)

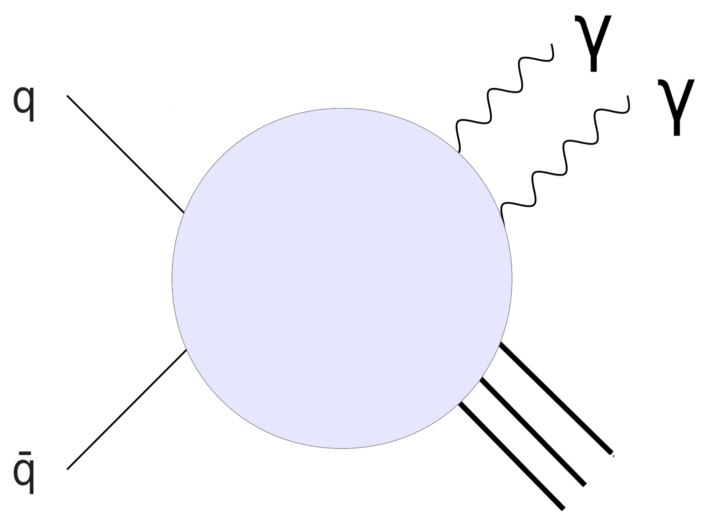




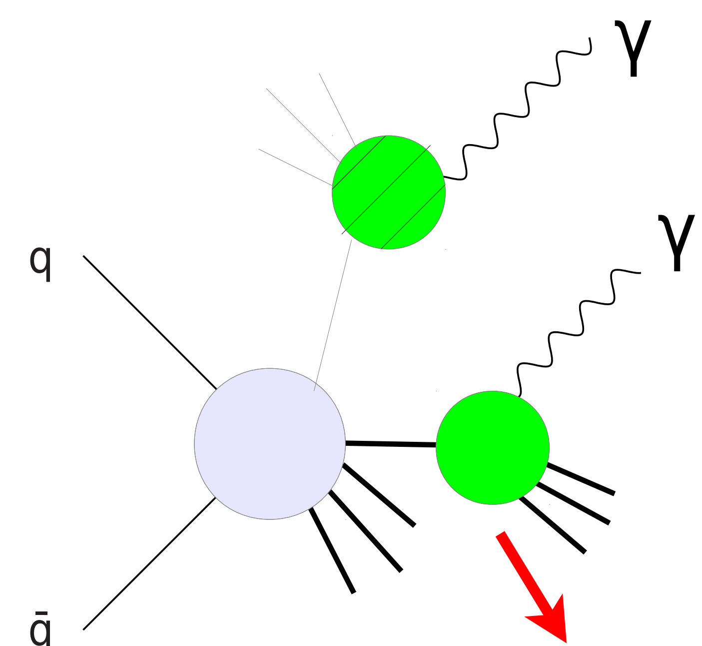
Phys.Lett. B716 (2012) 1-29 (ATLAS)
Phys.Lett. B716 (2012) 30-61 (CMS)

Photon production

When dealing with the production of photons we have to consider two production mechanisms:



Direct component: photon directly produced through the hard interaction



Fragmentation function: to be fitted from data

Fragmentation component: photon produced from non-perturbative fragmentation of a hard parton (analogously to a hadron)

Single and double resolved (collinear fragmentation)

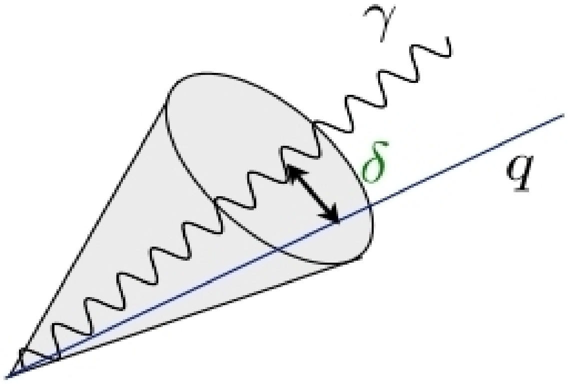
Calculations of cross sections with photons have additional singularities in the presence of QCD radiation. (i.e. When we go beyond LO)

When quark and photon are collinear → singular propagator

Photon production

- Experimentally photons must be isolated
- Isolation reduces fragmentation component → Large Corrections
- Experimentalist may choose:

$$\sum_{\delta<R_0} E_T^{had} \leq \varepsilon_\gamma p_T^\gamma$$



$$\sum_{\delta<R_0} E_T^{had} \leq E_T^{max}$$

Using conventional isolation, only the sum of the direct and fragmentation contributions is meaningful.

Photon production

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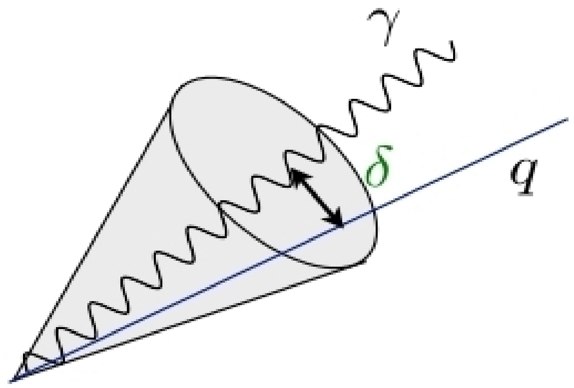


$$\sum_{\delta<R_0} E_T^{had} \leq E_T^{max}$$

Using conventional isolation, only the sum of the direct and fragmentation contributions is meaningful.

But there is a way to isolate and make the direct cross section physical (Infrared safe)

Smooth cone Isolation

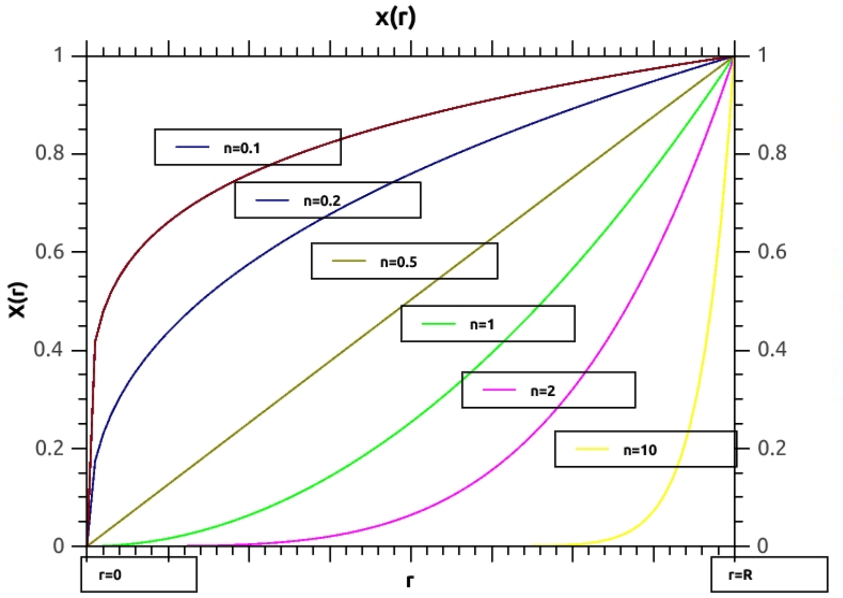
S. Frixione, Phys.Lett. B429 (1998) 369–374,

Soft emission allowed arbitrarily close to the photon

$$\chi(\delta) = \epsilon_\gamma E_T^\gamma \left(\frac{1-\cos(\delta)}{1-\cos(R_0)} \right)^n$$

$E_T^{had}(\delta) \leq \chi(\delta)$ such that $\lim_{\delta\to 0} \chi(\delta) = 0$

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- direct well defined by itself



Standard Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}$

Smooth Photon Isolation $E_T^{had}(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$

S.Frixione

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct contribution well defined

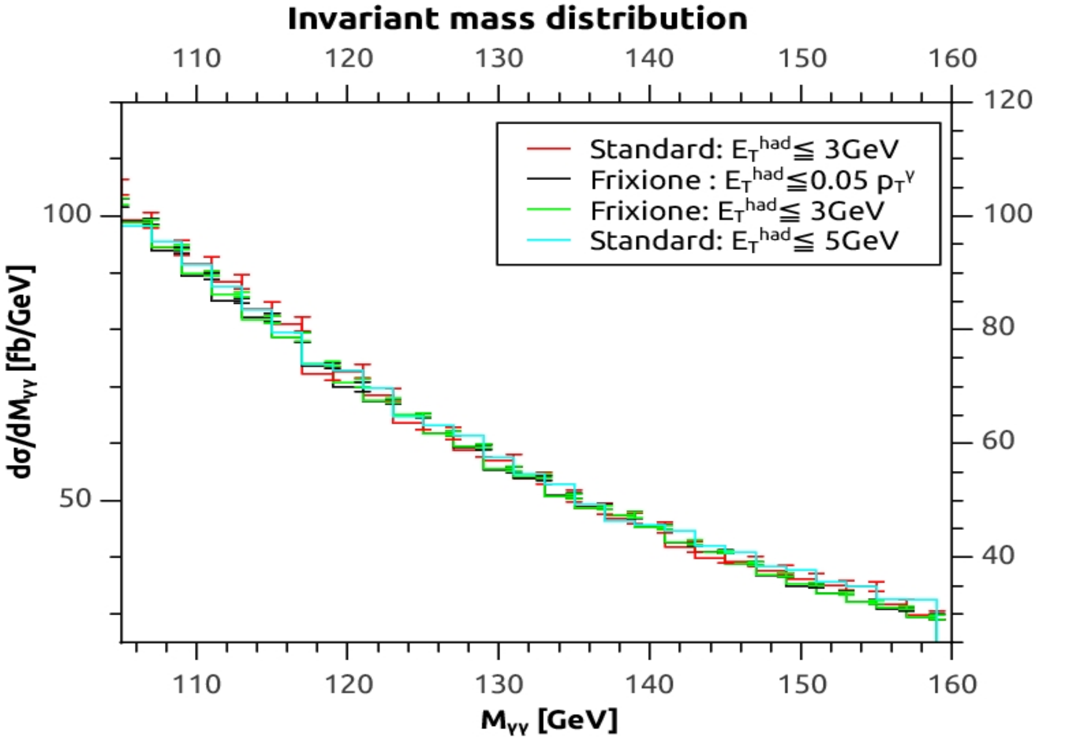
More restrictive than usual cone : lower limit on cross section (close for small R)

In real (TH)life... how much different? NLO comparison $R_0 = 0.4 \quad n = 1$

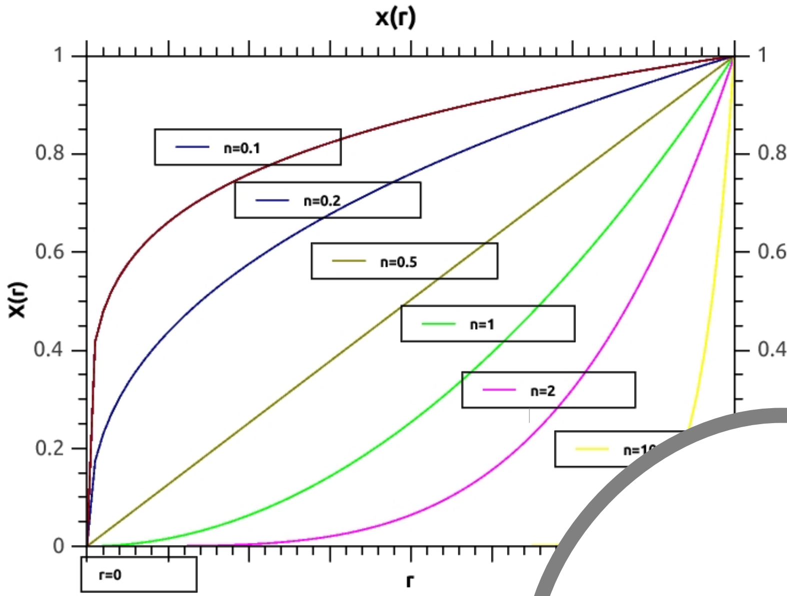
CMS Higgs cuts at 7 TeV

$E_{T\,max}^{had}$	standard/smooth
2 GeV	< 1%
3 GeV	< 1%
4 GeV	1%
5 GeV	3%
0.05 p_T	< 1%
0.5 p_T	11%

Standard: direct+fragmentation (Diphox)



if isolation tight enough, hardly any difference between standard and smooth cone



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S.Frixione

$\chi(\delta) = \Big(\frac{1\ -}{1\ -}$

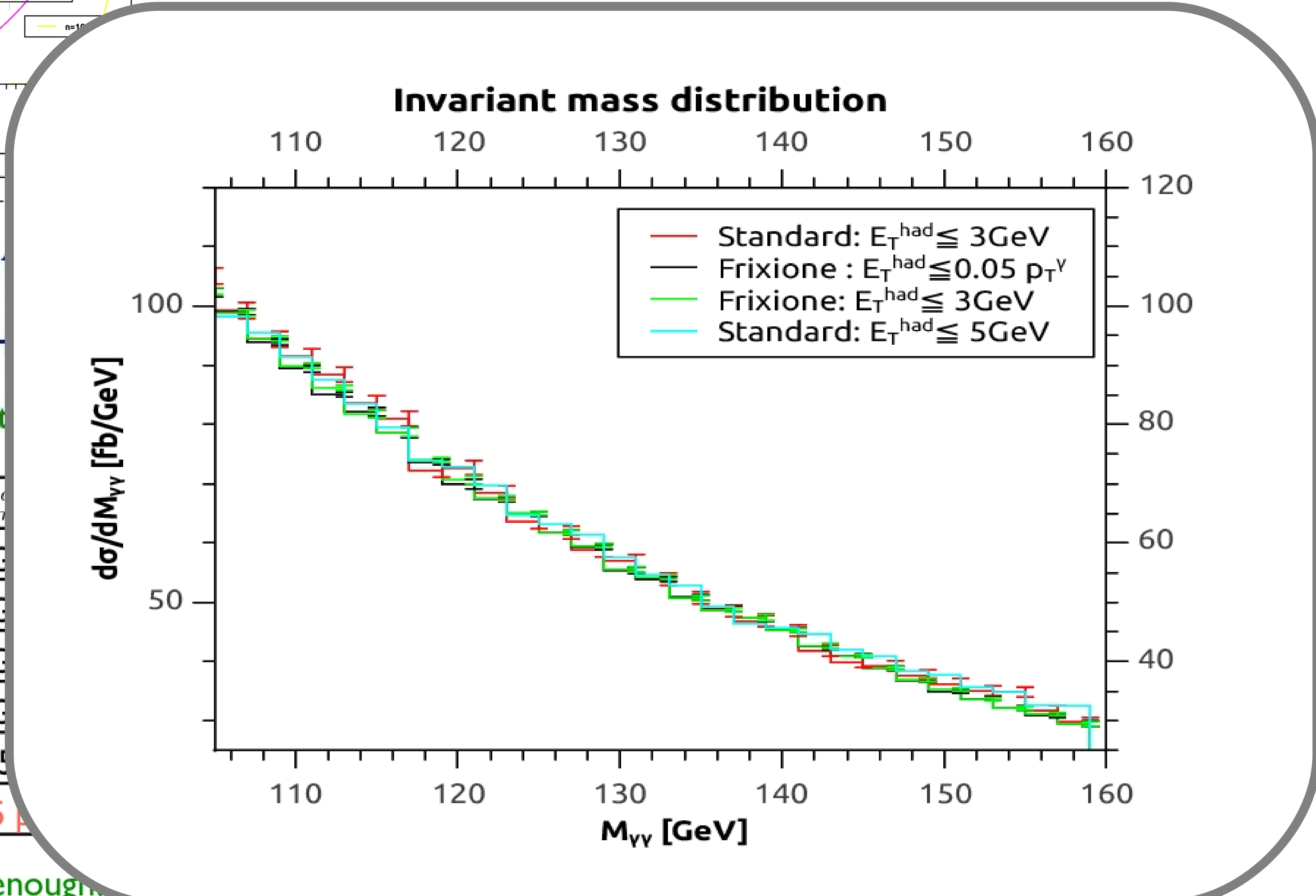
More restric

In real (TH

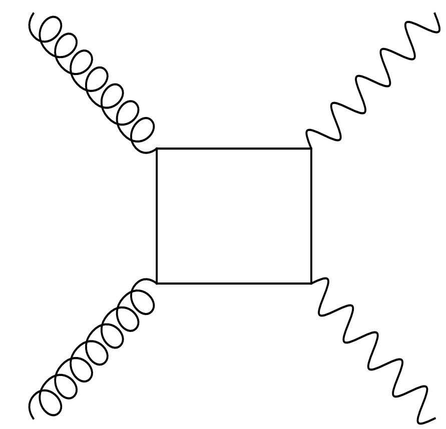
CMS Higgs cut

$E_{T\,m}^{had}$
2 G
3 G
4 G
5 G
0.05
0.5 p

if isolation tight enough,



Available theoretical tools



DIPHOX Full NLO for direct and fragmentation

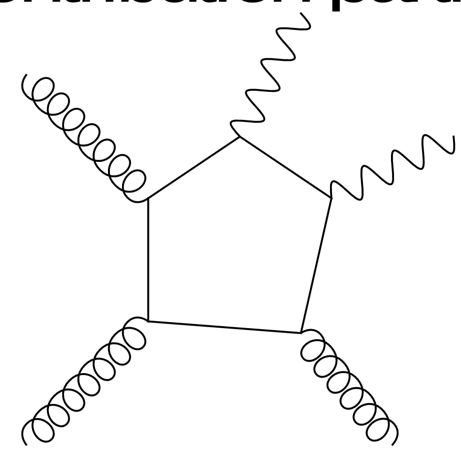
+ Box contribution (one piece of NNLO)

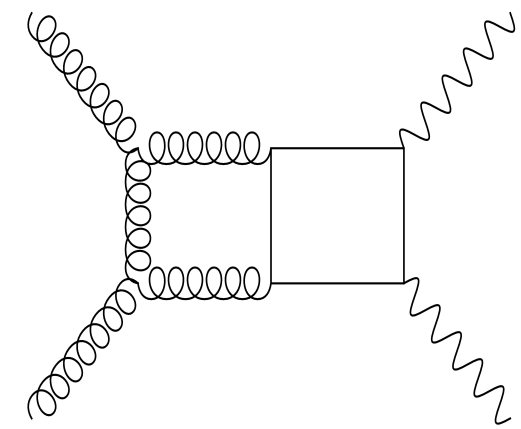
T. Binoth, J.Ph. Guillet, E. Pilon and M. Werlen

gamma2MC Full NLO (direct only) + Box

+ correction to Box contribution partial N^3LO term

Zvi Bern, Lance Dixon, and Carl Schmidt





MCFM Full NLO for direct, but only LO for fragmentation

+ correction to Box contribution partial N^3LO term

John M. Campbell, R.Keith Ellis, Ciaran Williams

Resbos NLL q_T resummation for direct (with regulator for collinear singularities)

+ correction to Box contribution partial N^3LO term

C. Balázs, E. L. Berger, P. Nadolsky, and C.-P. Yuan

+ MC generators : Herwig, Pythia, SHERPA

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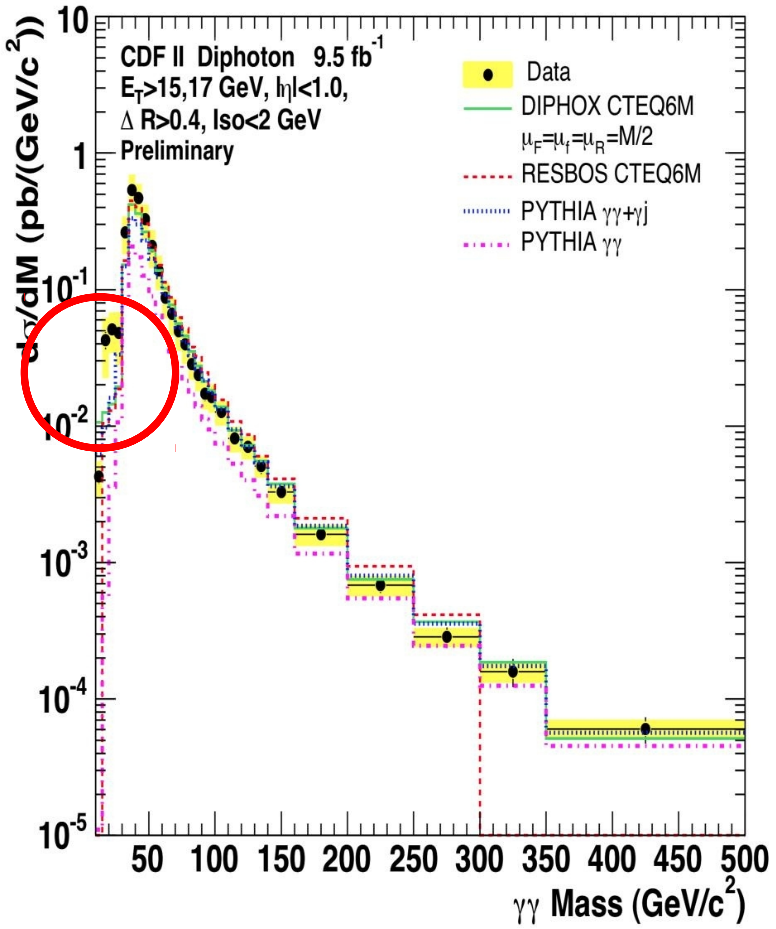
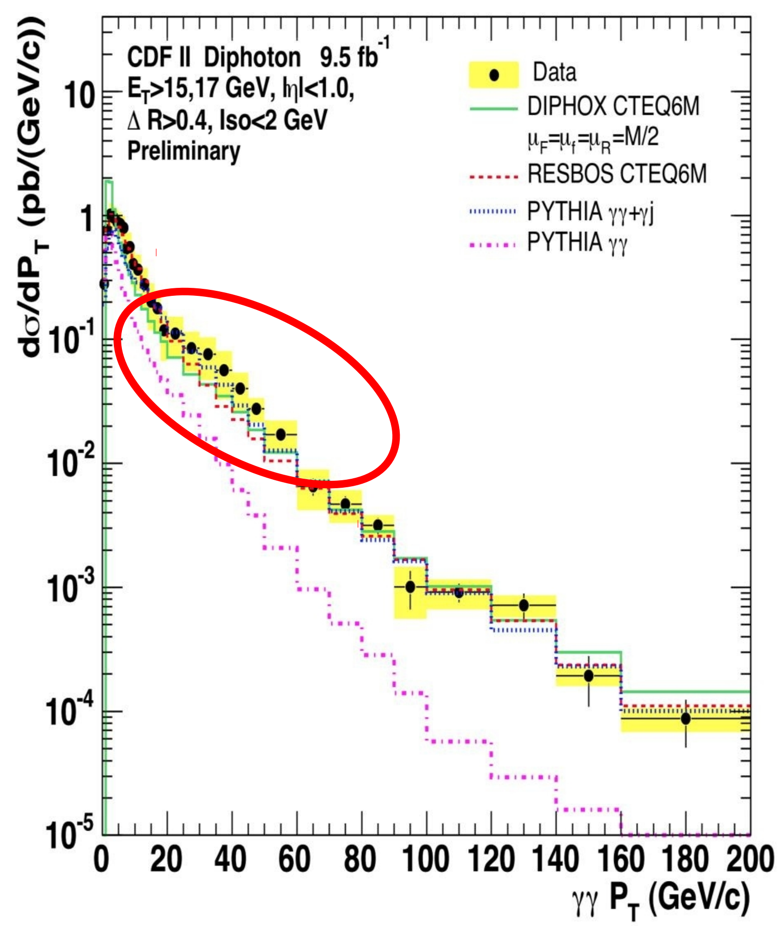
Results tipically in good agreement with data, but some differences observed:

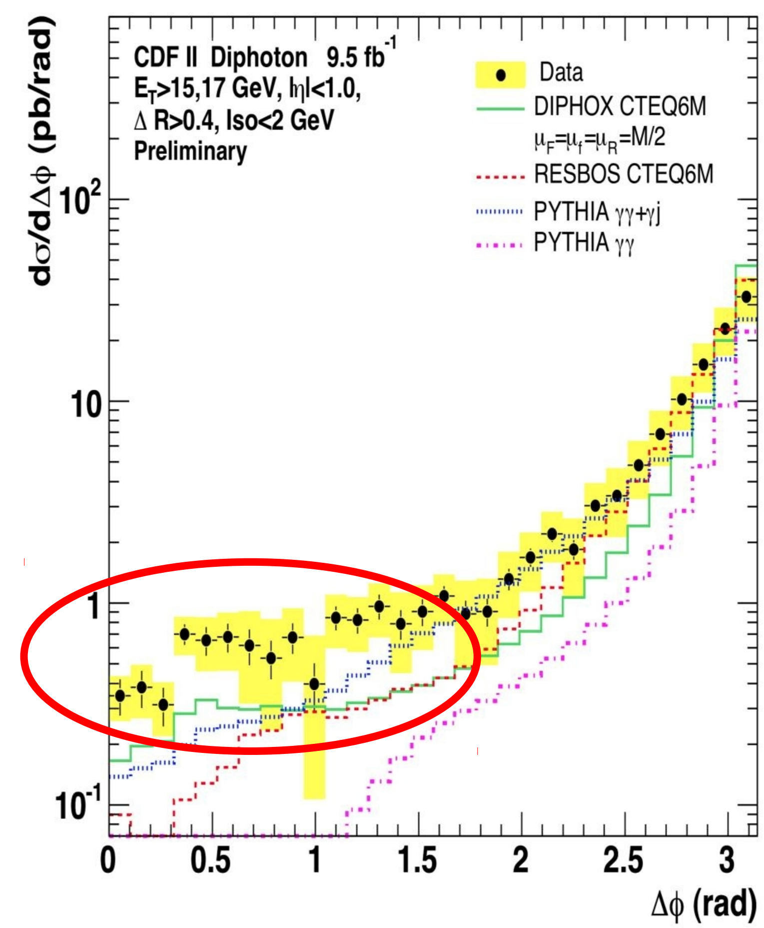
- **Azimuth separation for diphoton production**
- **Low mass region of the invariant mass distribution**

It is desireable to count on a NNLO description of the phenomenology of diphoton production

Differential cross sections: CDF







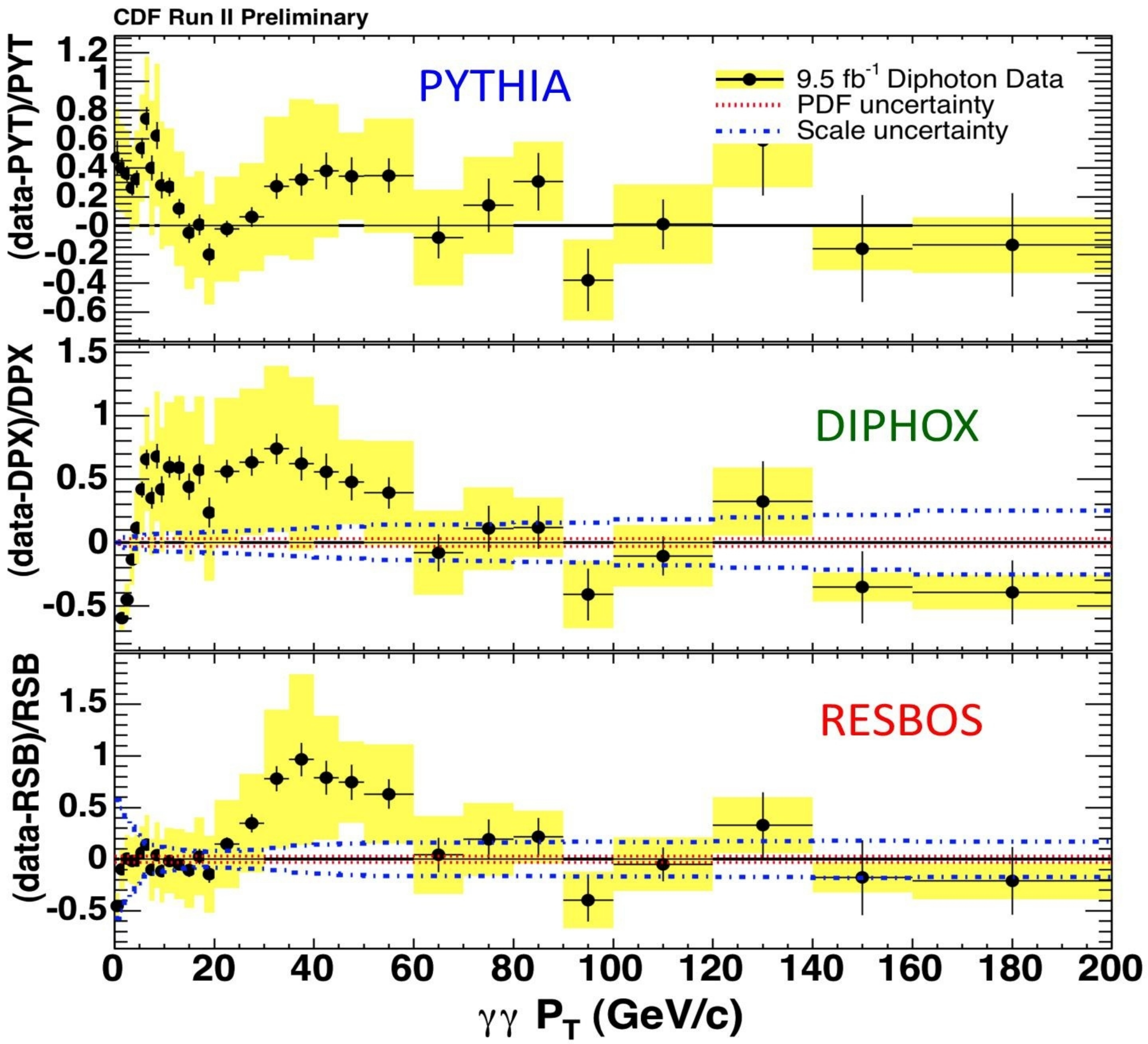
- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2

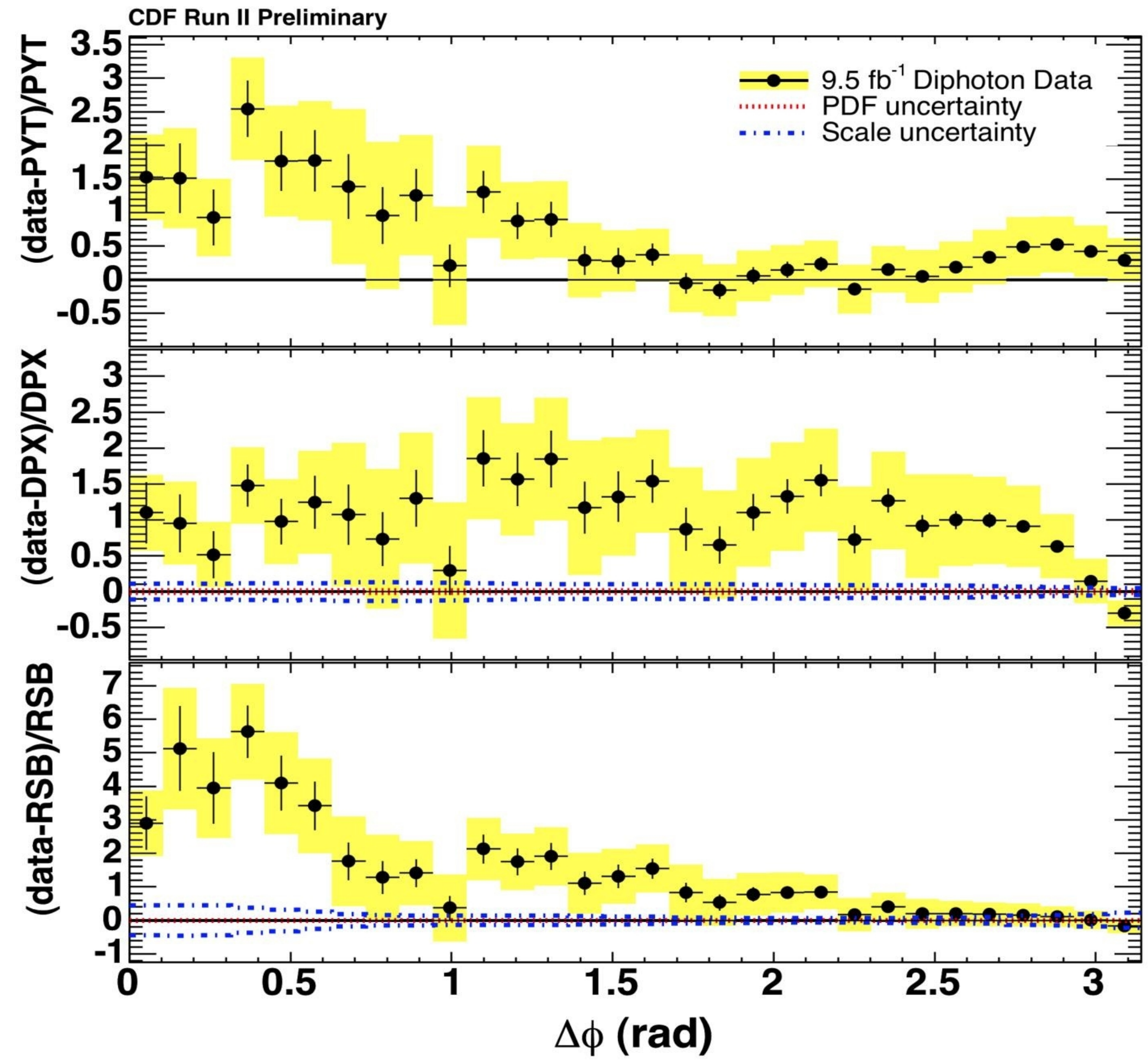
- Resummation important
- Fragmentation causes excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the “Guillet shoulder”)

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

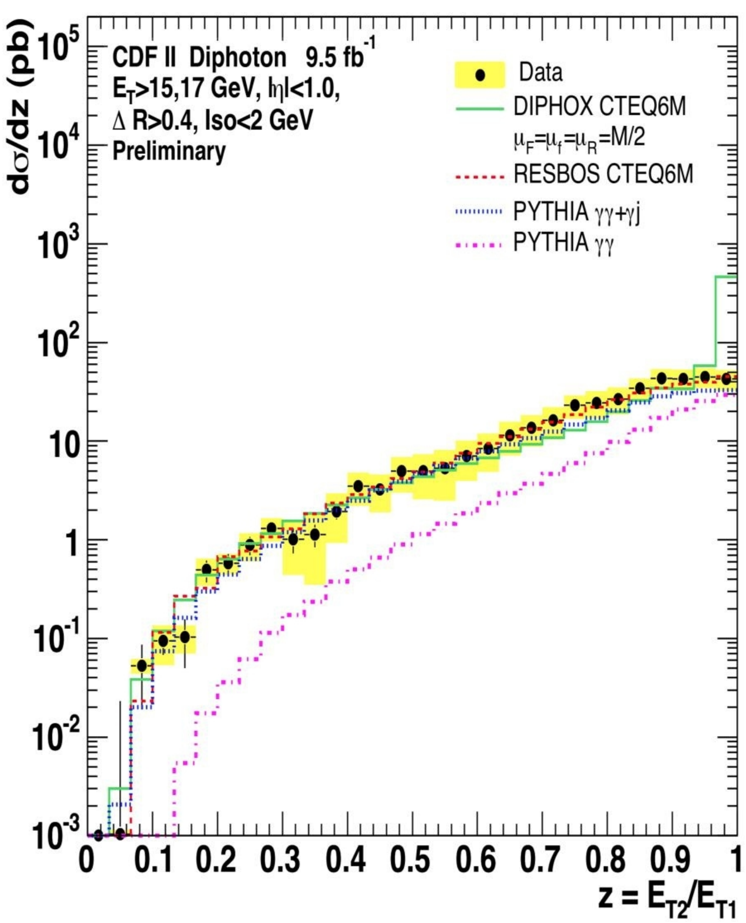
Data-to-theory cross section ratios: CDF

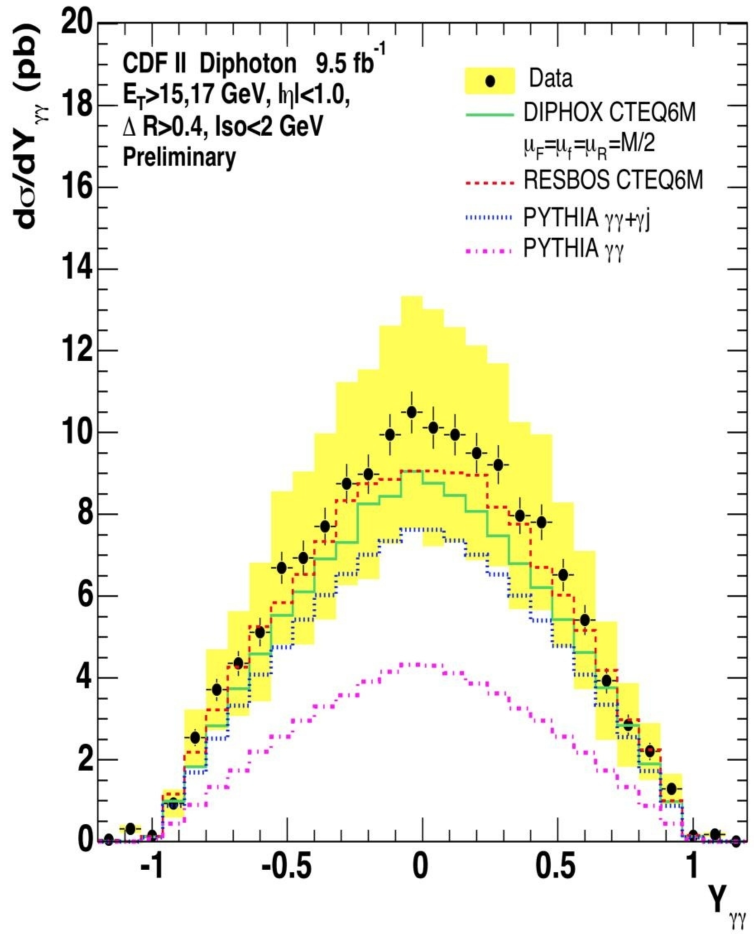
NB: Vertical axis scales are not the same

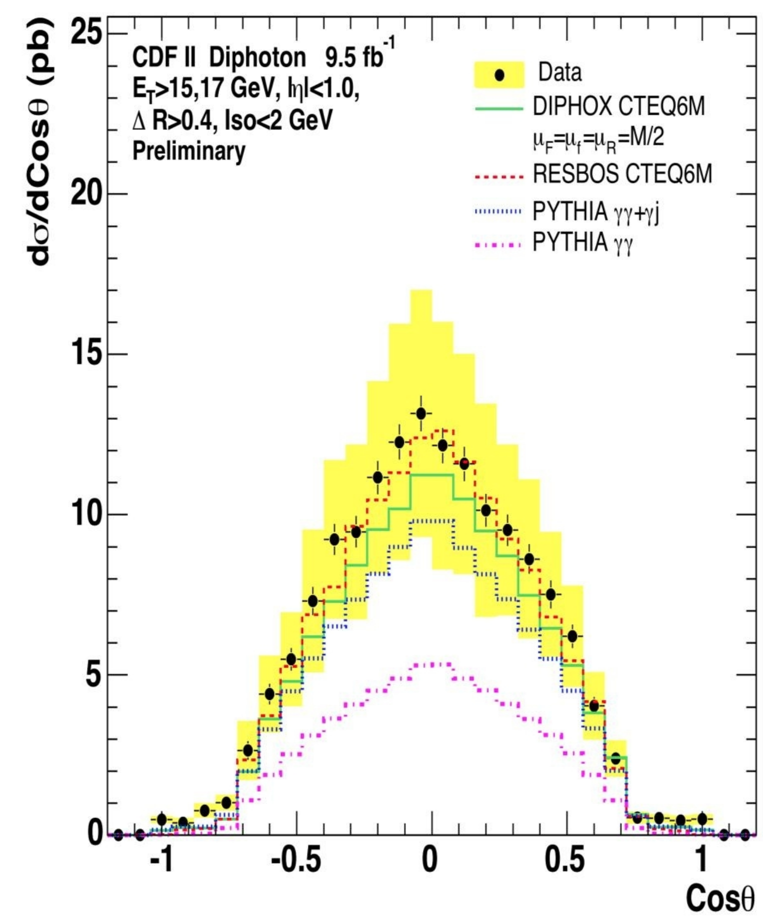




Differential cross sections: CDF







- Good agreement between data and 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 $|\cos\theta|\rightarrow 1$

Data-to-theory cross section ratios: CDF

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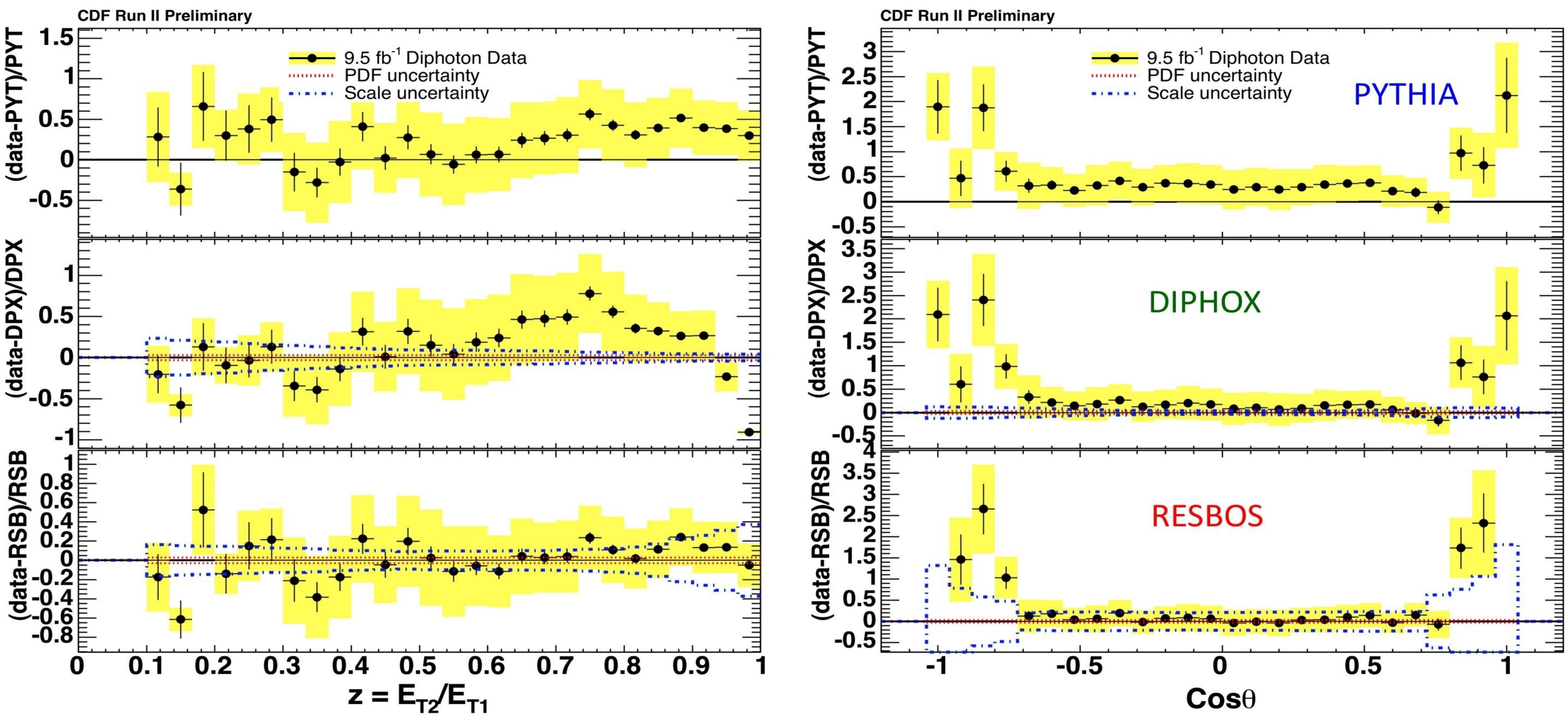
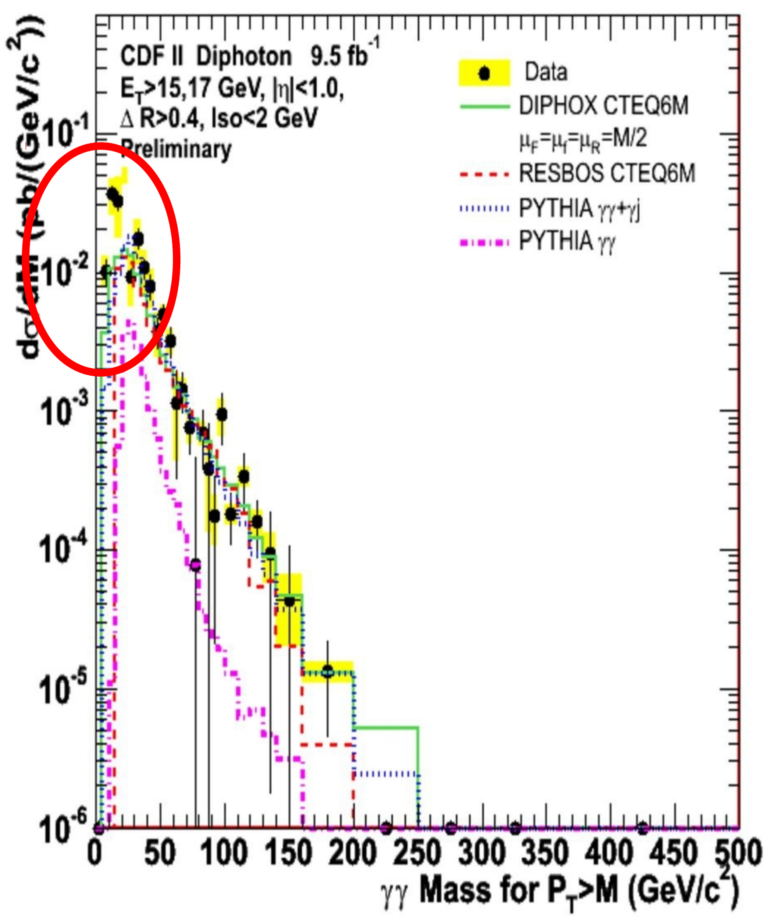
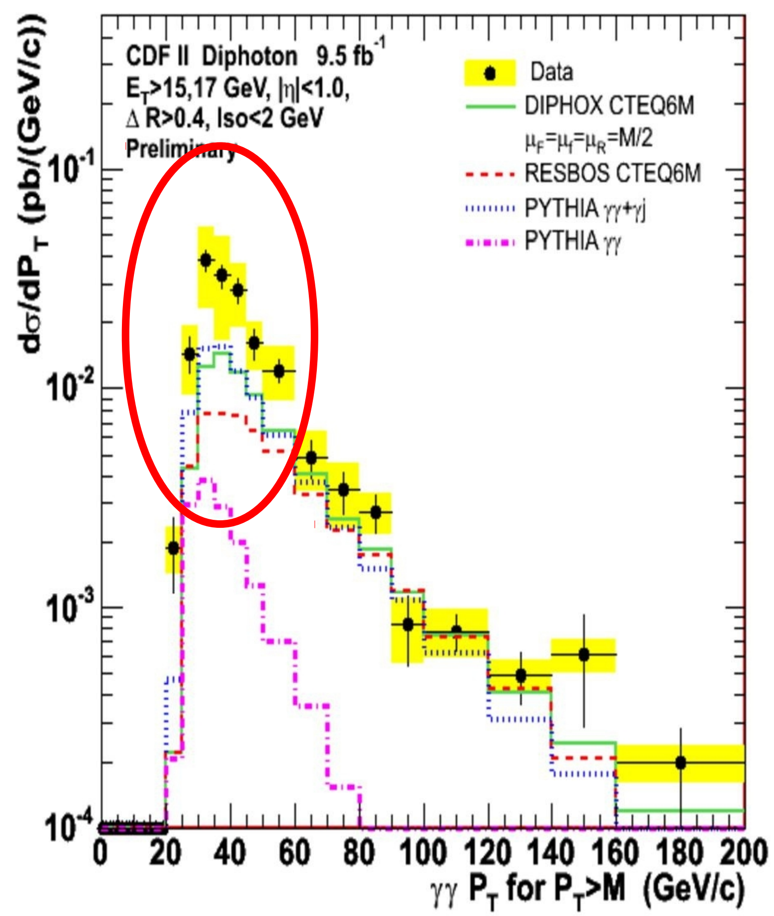
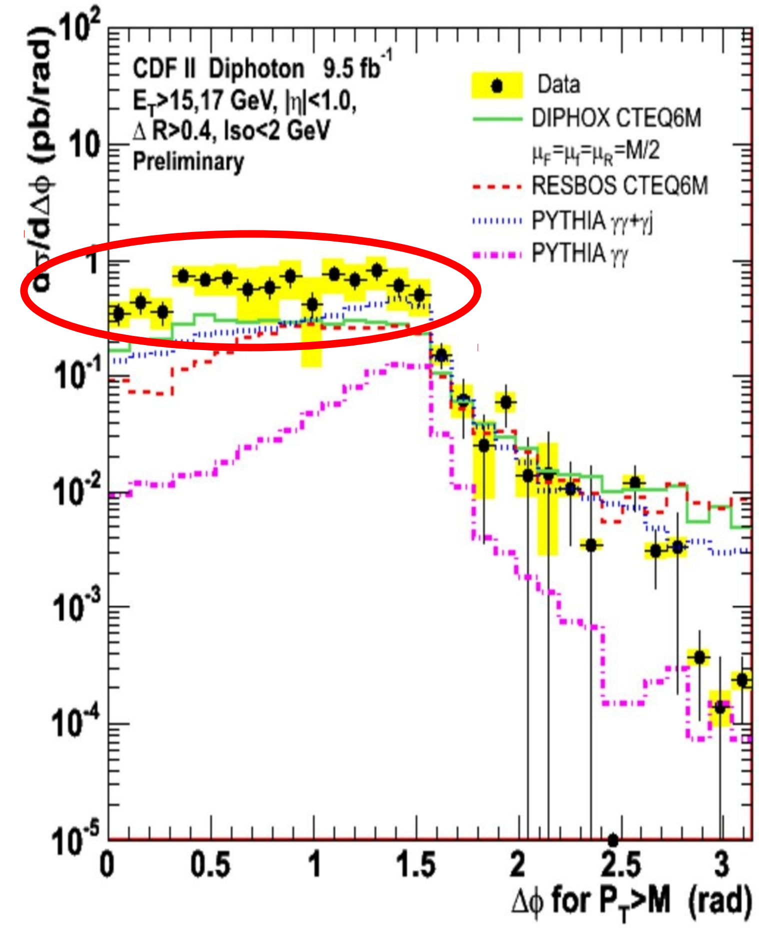


Differential cross sections for $P_T(\gamma\gamma)>M_{\gamma\gamma}$: CDF







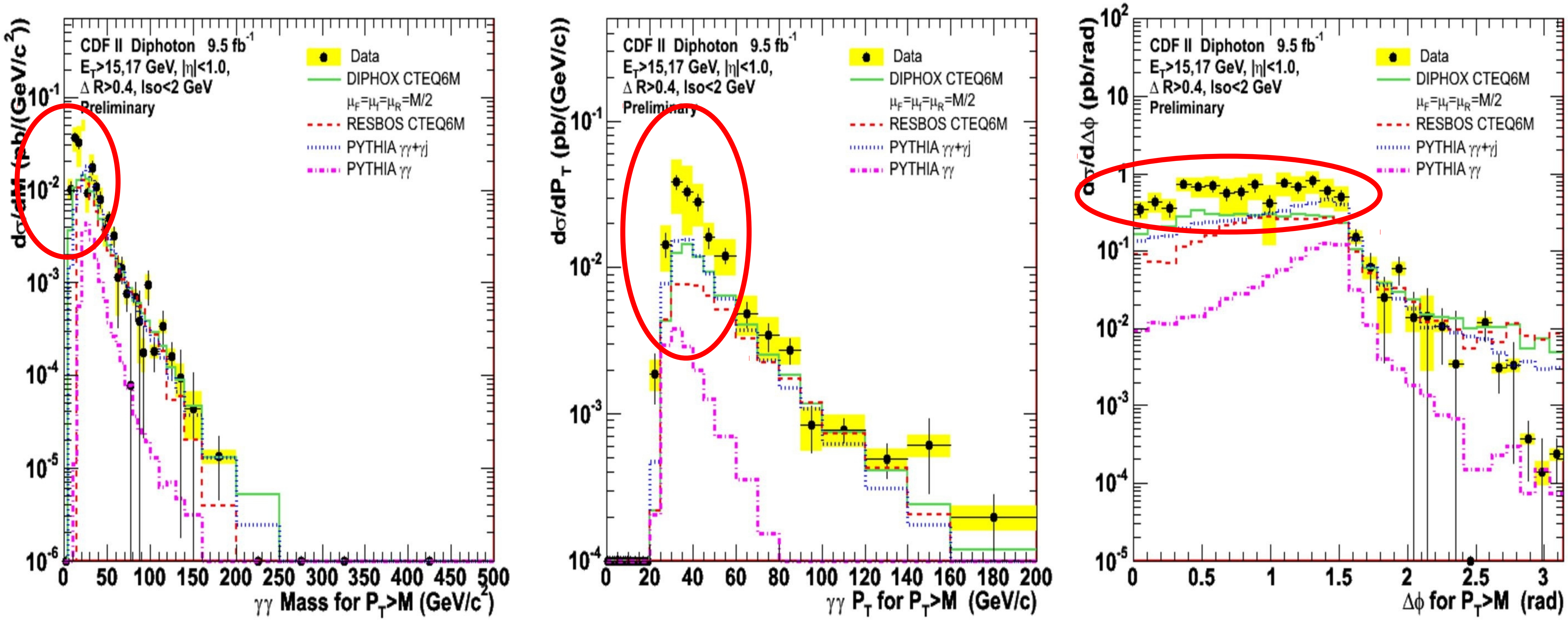
- Low statistics
- Excess of data over theory for $M_{\gamma\gamma}<30$ GeV/c^2

- Low statistics
- No events below $P_T(\gamma\gamma)$ = 20 GeV/c
- Excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the "Guillet shoulder")

- Low statistics
- Data spectrum harder than predicted for $\Delta\phi<1.5$ rad
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma}>1.5$ rad

Kills Born-like contributions

Differential cross sections for $P_T(\gamma\gamma)>M_{\gamma\gamma}$: CDF



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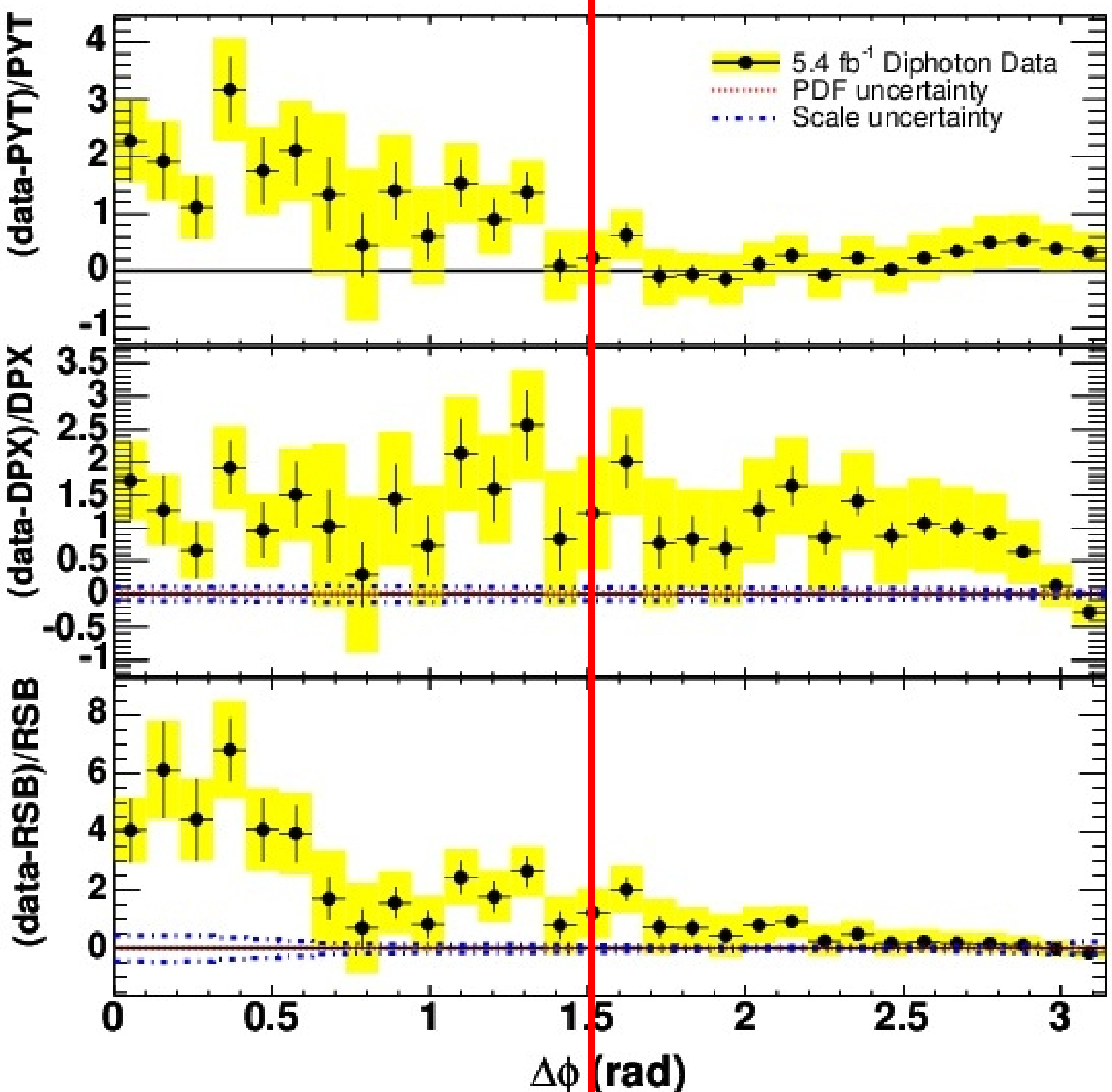

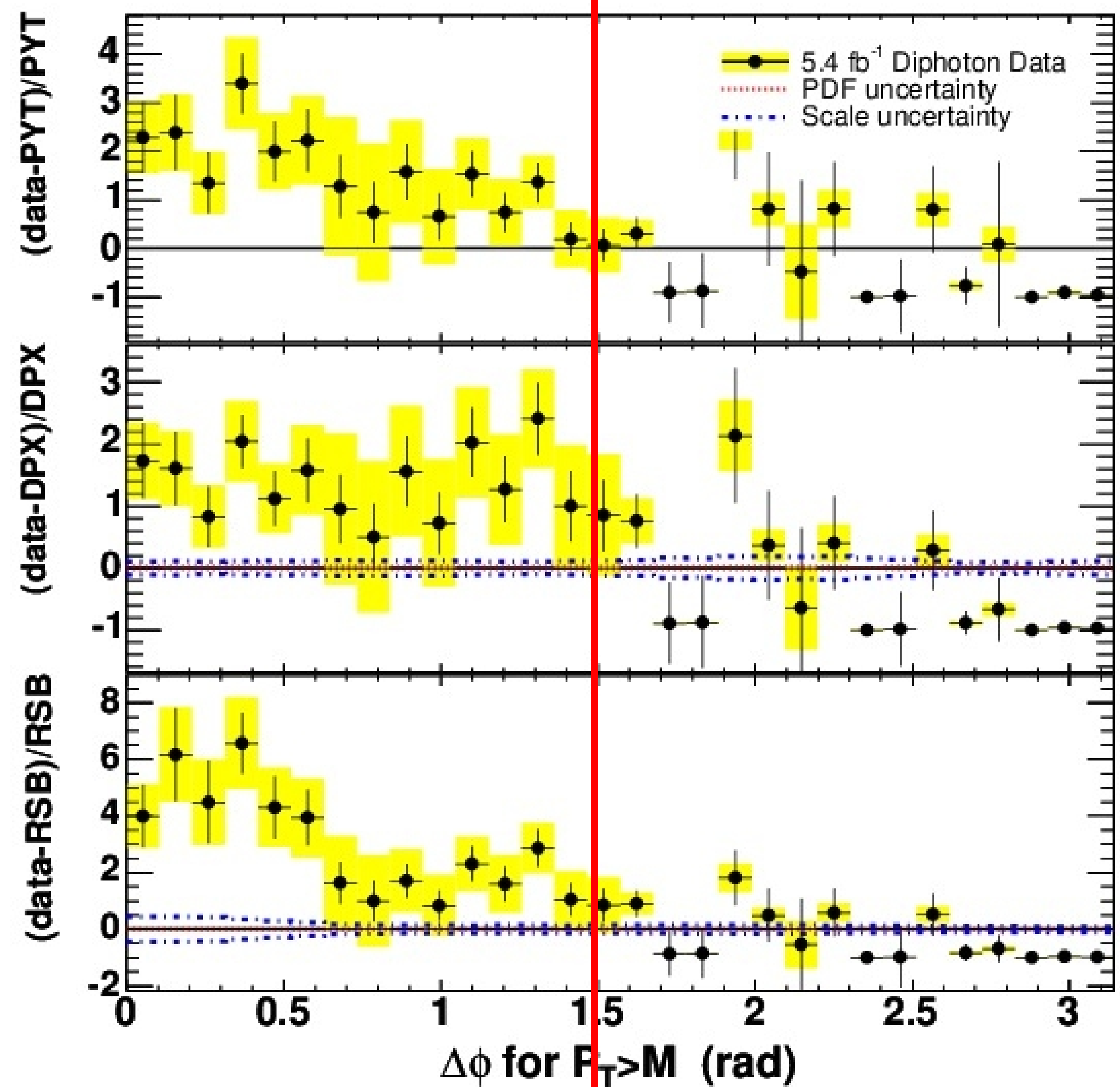

Full Xsection (NLO)

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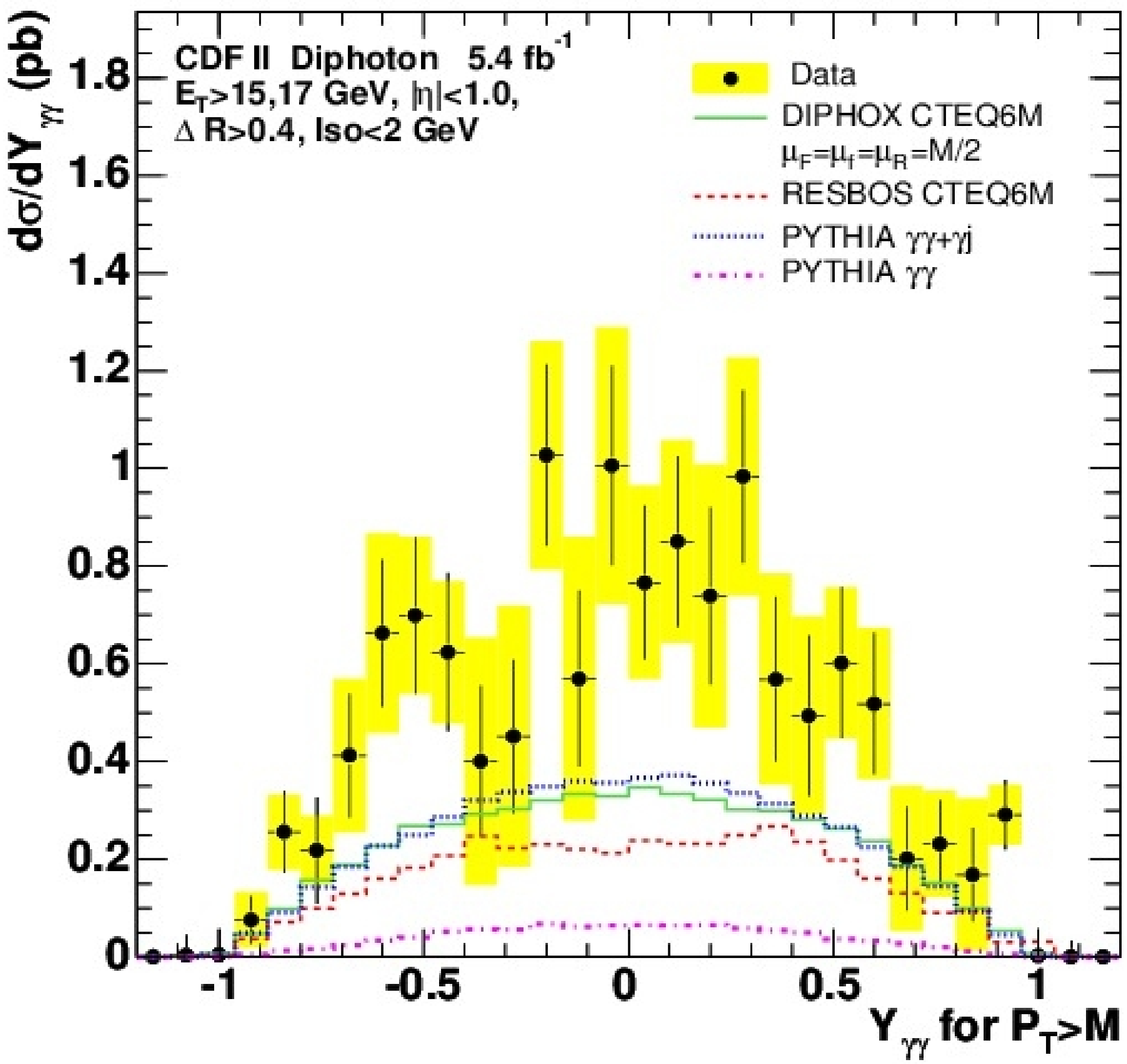
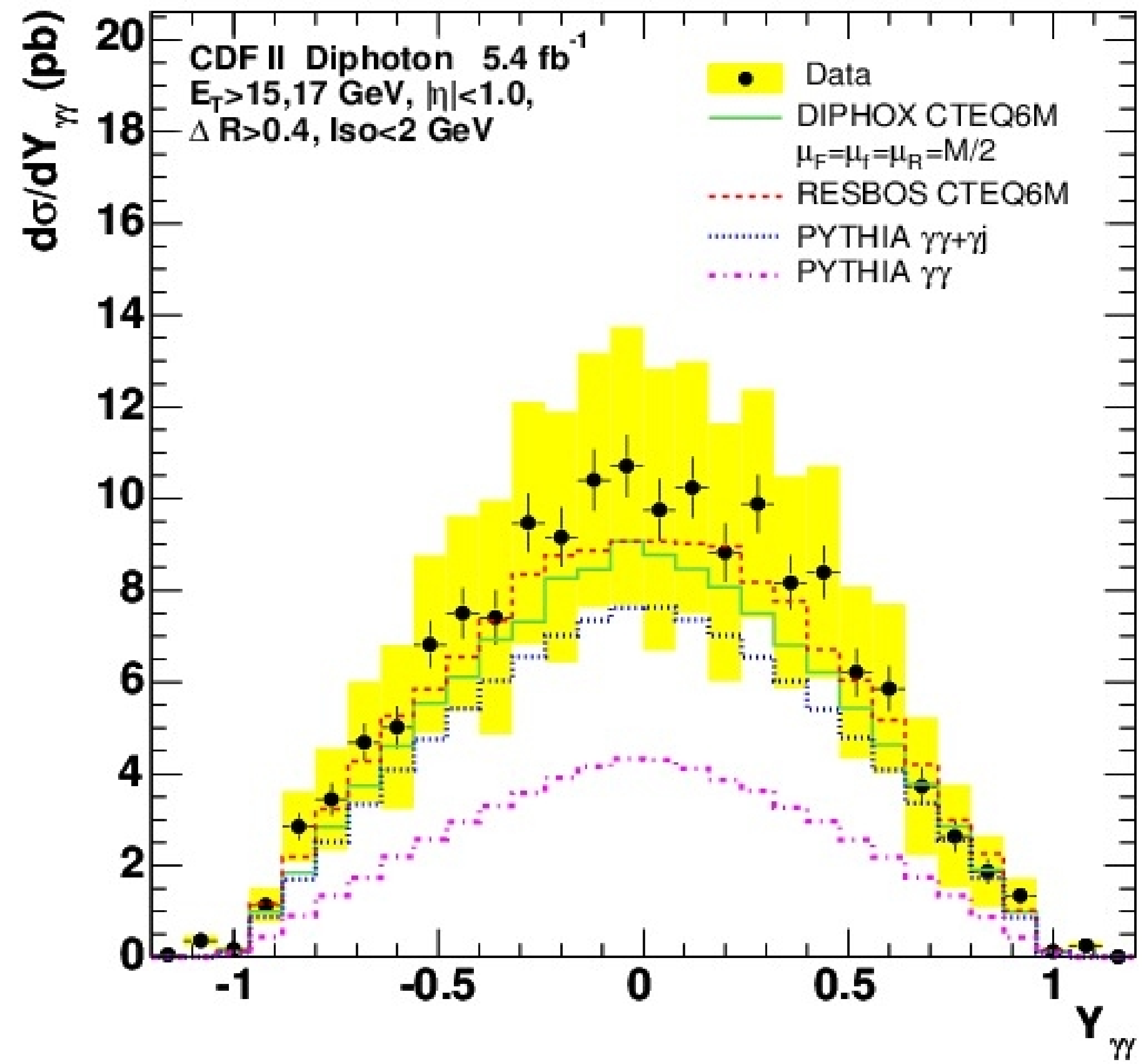


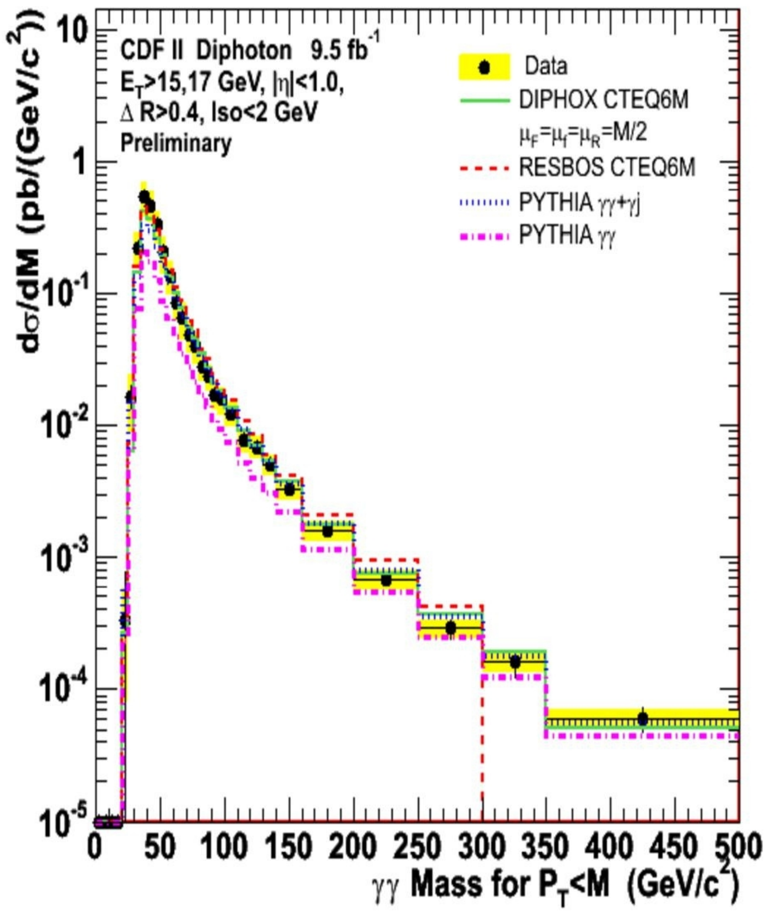


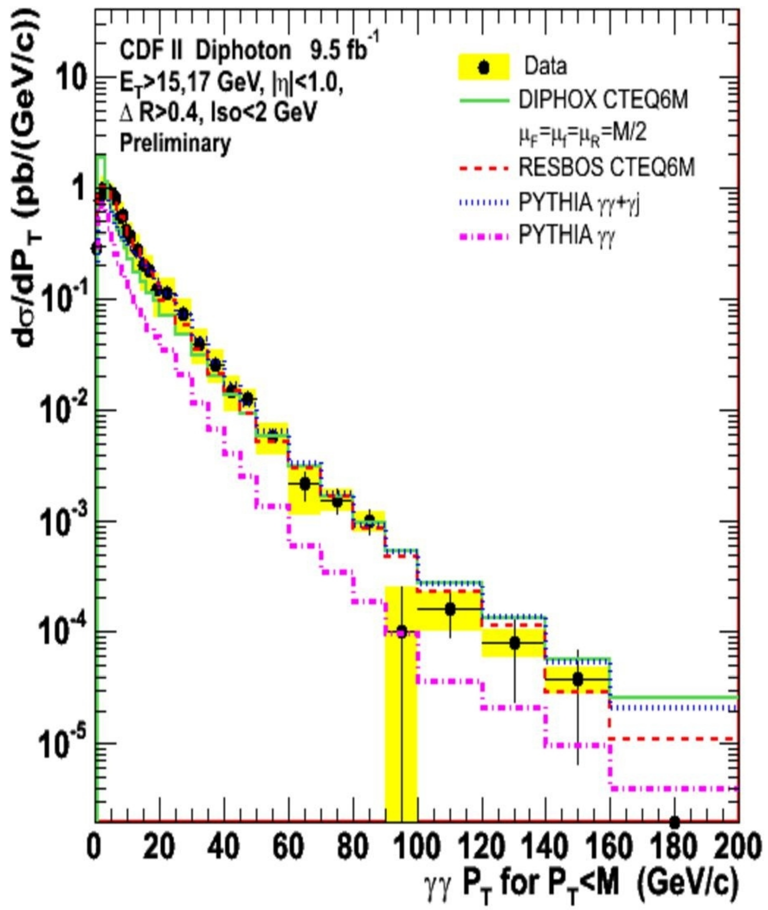
Only real corrections (NLO)

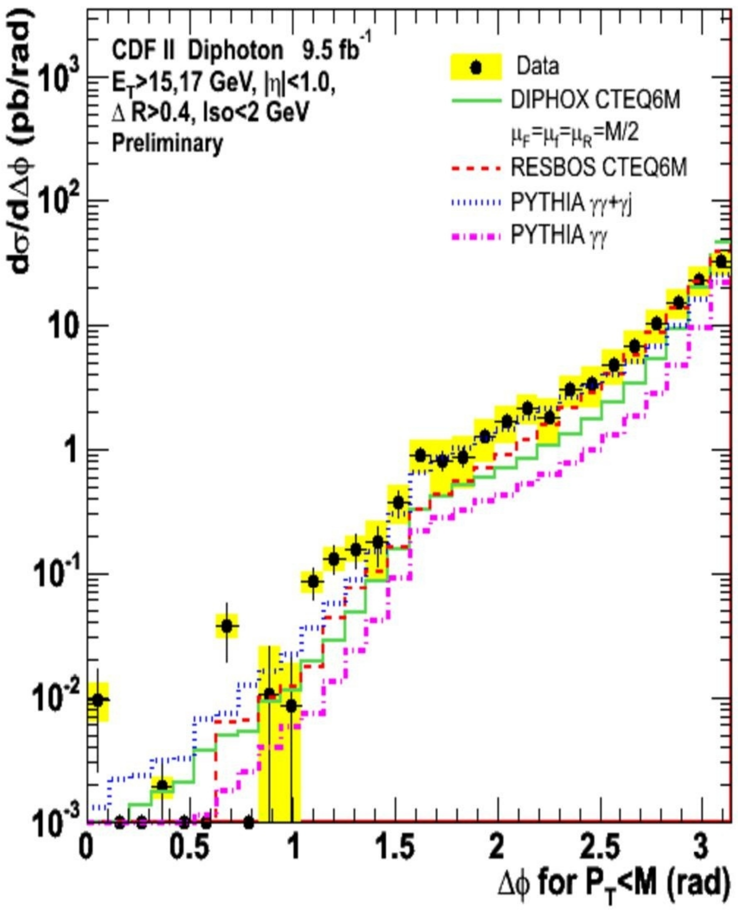
Full Xsection (NLO)

$$q_T^{\gamma\gamma} > M_{\gamma\gamma} \;\rightarrow\; \text{NLO} = \text{“LO”}$$

Differential cross sections for $P_T(\gamma\gamma)<M_{\gamma\gamma}$: CDF







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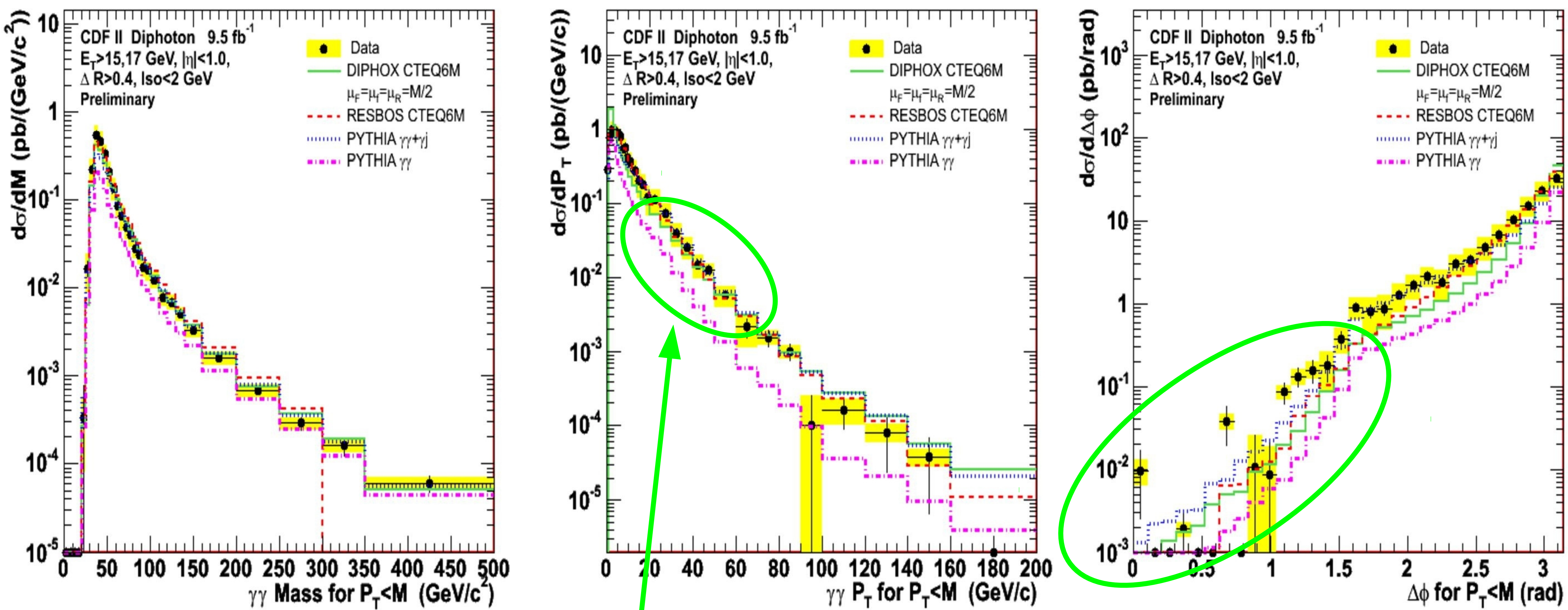
Real radiation suppressed (NLO)

Differential cross sections for $P_T(\gamma\gamma)<M_{\gamma\gamma}$: CDF



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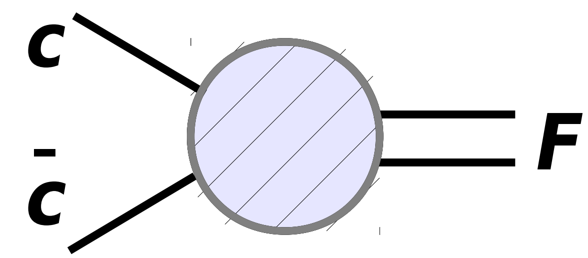
q_T subtraction method

S. Catani, M. Grazzini (2007)

Let us consider a specific, though important class of processes: the production of colourless high-mass systems ***F*** in hadron collisions

(***F*** may consist of lepton pairs, vector bosons, Higgs bosons......)

At LO it starts with $c\bar{c} \to F$



Strategy: start from NLO calculation of ***F+jet(s)*** and observe that as soon as the transverse momentum of the ***F***, $q_T \neq 0$, on can write:

$$d\sigma^{F}_{(N)NLO}|_{q_T\neq 0} = d\sigma^{F+\text{jets}}_{(N)LO}$$

Define a counterterm to deal with singular behaviour at $q_T \to 0$

But.....

the singular behaviour of $d\sigma^{F+\text{jets}}_{(N)LO}$ is well known from the resummation program of large logarithmic contributions at small transverse momenta

G. Parisi, R. Petronzio (1979)
J. Collins, D.E. Soper, G. Sterman (1985)
S. Catani, D. de Florian, M.Grazzini (2000)

q_T subtraction method

S. Catani, M. Grazzini (2007)

choose $$d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$$

where $$\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots.$$

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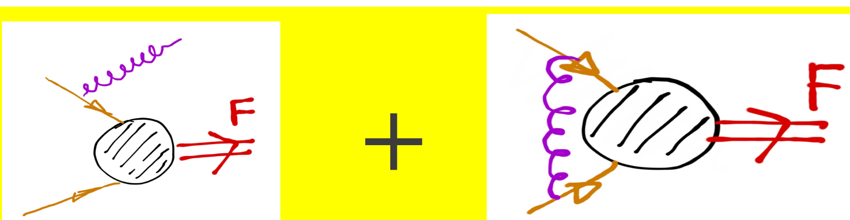

...ation of the counterterm at (N)LO and

... to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

[Real + Virtual]$_{\text{Contributions}}$

$$+ \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots.$$

q_T subtraction method

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where
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$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right)\mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2\mathcal{H}^{F(2)} + \ldots\ldots$$

σ^F_{LO} (Born)

q_T subtraction method

S. Catani, M. Grazzini (2007)

choose
$$d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$$

where
$$\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO}\right]$$

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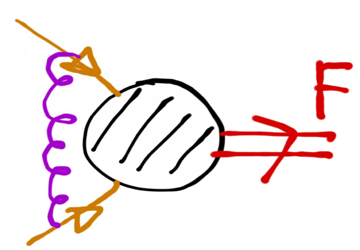
Finite (NLO)



q_T subtraction method

S. Catani, M. Grazzini (2007)

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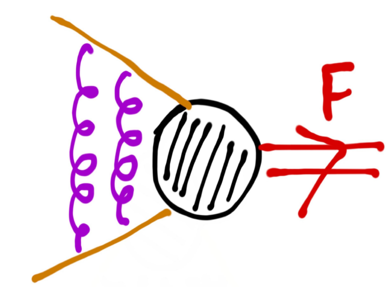

Finite (NNLO)

◉ The Normalization H

Expand to the fixed order in α_s

$$\mathcal{H}^F = 1 + \frac{\alpha_S}{\pi}\,\mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots \qquad \sim \delta(q_T^2)$$

LO NLO NNLO

Normalization of $\sigma_{tot}^{(N)NLO}$ → computational effort comparable to $\sigma_{tot}^{(N)NLO}$

$$p_T^2 \ll Q^2 \qquad \int_0^{p_T^2} dq_T^2 \, \frac{d\sigma^F}{dq_T^2} \equiv \sigma_{LO}^F \, R^F(p_T/Q)$$

The coefficients appear in the constant term

$$R^{F(1)} = l_0^2\, \Sigma^{F(1;2)} + l_0\, \Sigma^{F(1;1)} + \mathcal{H}^{F(1)} + \mathcal{O}(p_T^2/Q^2)$$

$$l_0 = \ln \frac{Q^2}{p_T^2}$$

$$R^{F(2)} = l_0^4\, \Sigma^{F(2;4)} + l_0^3\, \Sigma^{F(2;3)} + l_0^2\, \Sigma^{F(2;2)}$$
$$+ l_0\, (\Sigma^{F(2;1)} - 16\zeta_3 \Sigma^{F(2;4)}) + \mathcal{H}^{F(2)} - 4\zeta_3 \Sigma^{F(2;3)} + \mathcal{O}(p_T^2/Q^2)$$

Very hard to reach that accuracy... but...

$$\int_0^{p_T^2} dq_T^2 \, \frac{d\sigma^F}{dq_T^2} \equiv \sigma_{tot}^{(N)NLO} - \int_{p_T^2}^{\infty} dq_T^2 \, \frac{d\sigma^{F+jet(N)LO}}{dq_T^2}$$

Inclusive

(analytic) distribution

Integral can be carried out in 4-dimensions

known for Drell-Yan and Higgs!

Method used to obtain $\mathcal{H}^{F(2)}$ for Higgs and Drell-Yan

$$\int_0^{p_T^2} dq_T^2 \frac{d\sigma^F}{dq_T^2} \equiv \sigma_{tot}^{(N)NLO} - \int_{p_T^2}^{\infty} dq_T^2 \frac{d\sigma^{F+jet(N)LO}}{dq_T^2}$$

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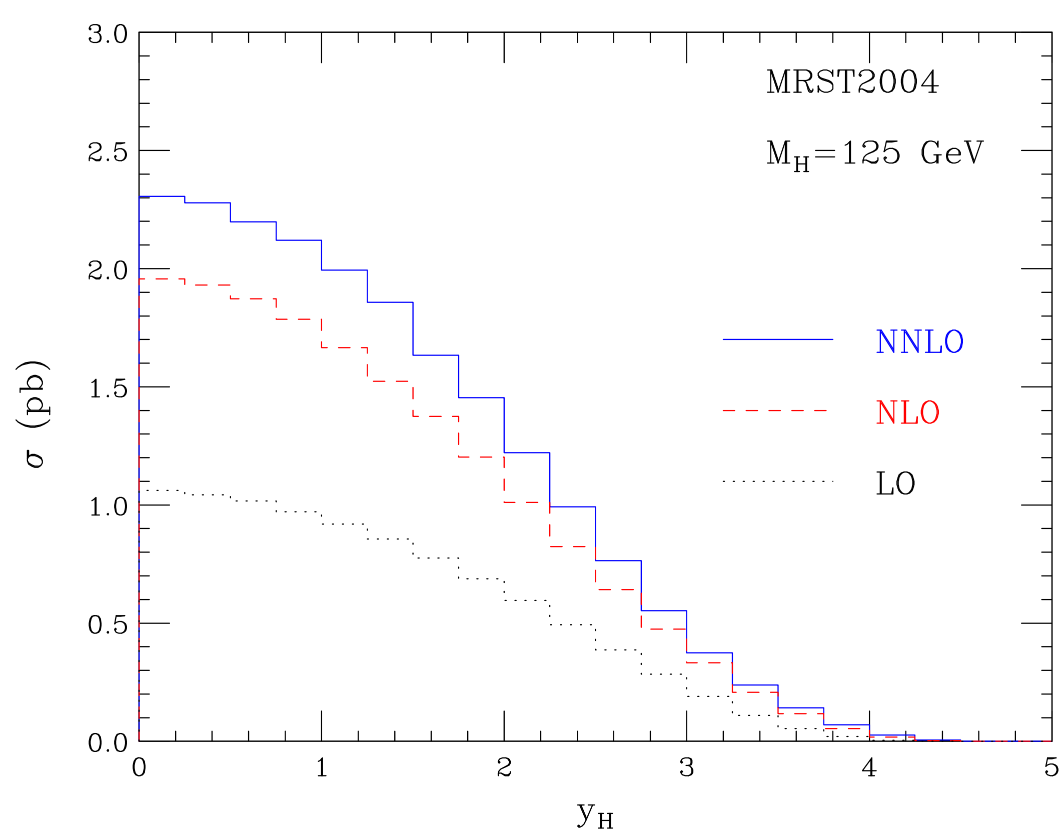
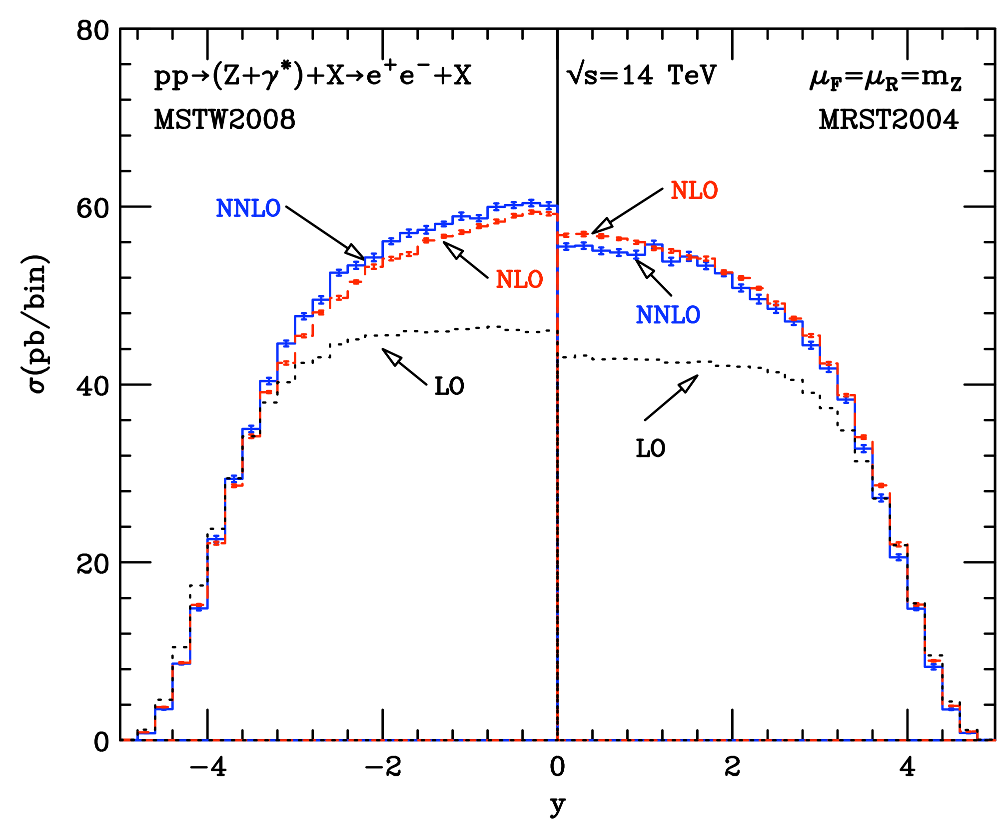
Method used to obtain $\mathcal{H}^{F(2)}$ for Higgs and Drell-Yan

HNNLO S.Catani, M.Grazzini

DYNNLO S.Catani, L.Cieri, DdeF, G.Ferrera, M.Grazzini





Up to now, Inclusive and analytical Momentum Distribution needed for Exclusive

q_T subtraction method

S. Catani, M. Grazzini (2007)

- Why we used a "subtraction" method for $H^{F(2)}$?
  - We didn't know the "internal" estructure of $H^{F(2)}$

Before 2γNNLO

q_T subtraction method

S. Catani, M. Grazzini (2007)

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    Before 2γNNLO

  - We dind't know how to relate $H^{F(2)}$ and the finite component of the two-loops virtual matrix elements.

    Before 2γNNLO

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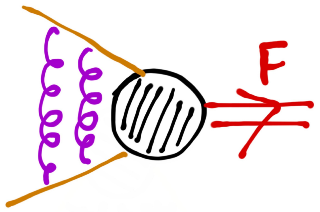
S. Catani, M. Grazzini (2007)

- Why we used a “subtraction” method for $H^{F(2)}$?
  - We didn't know the “internal” estructure of $H^{F(2)}$ — Before 2γNNLO
  - We dind't know how to relate $H^{F(2)}$ and the finite component of the two-loops virtual matrix elements. — Before 2γNNLO
  - The generalization of the precedent method implies to find the universal terms contained in $H^{F(2)}$

$$H^{F(2)} = H^{F(2)}_{\text{Universal}} + \text{Finite}^{(2X0)}$$



q_T subtraction method

S. Catani, M. Grazzini (2007)

For a generic $pp \to F + X$ process:

- At NLO we need a LO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{LO}$ and $\mathcal{H}^{F(1)}$
  - the counterterm $d\sigma^{CT}_{LO}$ requires the resummation coefficients $A^{(1)}, B^{(1)}$ and the one loop anomalous dimensions
  - the general form of $\mathcal{H}^{F(1)}$ is known

D. de Florian, M. Grazzini (2000)
G. Bozzi, S. Catani, D. de Florian, M.Grazzini (2005)

- At NNLO we need a NLO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{NLO}$ and $\mathcal{H}^{F(2)}$
  - the counterterm $d\sigma^{CT}_{NLO}$ depends also on the resummation coefficients $A^{(2)}, B^{(2)}$ and on the two loop anomalous dimensions
  - we have computed $\mathcal{H}^{F(2)}$ for Higgs and vector boson production!
  - generalized to any process with final state colorless system ***F***

S. Catani, M. Grazzini (2007)
S. Catani, L. C, G.Ferrera, D. de Florian, M. Grazzini (2009)
S. Catani, L. C, G.Ferrera, D. de Florian, M. Grazzini (2011)

q_T subtraction method

S. Catani, M. Grazzini (2007)

For a generic $pp \to F + X$ process:

This is enough to compute NNLO corrections for *any* process in this class provided that F+jet is known up to NLO and the two loop amplitude for $c\bar{c} \to F$ is known

- At NNLO we need a NLO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{NLO}$ and $\mathcal{H}^{F(2)}$
  - the counterterm $d\sigma^{CT}_{NLO}$ depends also on the resummation coefficients $A^{(2)}, B^{(2)}$ and on the two loop anomalous dimensions
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In our case

DiPhoton production at NNLO

Two-loop amplitudes available C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans

Di-photon + jet at NLO computed V.Del Duca, F.Maltoni, Z.Nagy, Z.Trocsanyi

implemented in NLOJet++

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implemented in NLOJet++

Fully exclusive NNLO code for $pp \to F$

2γNNLO

First exclusive NNLO in pp collisions with two final state particles

S.Catani, L.Cieri, D.de Florian, G.Ferrera, M.Grazzini (2011)

Diphoton production with 2γNNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

- Based on the q_T subtraction formalism

S. Catani, M. Grazzini

- Fully exclusive NNLO description(direct contribution) for $pp(\bar{p}) \rightarrow \gamma\gamma$
- No fragmentation contribution

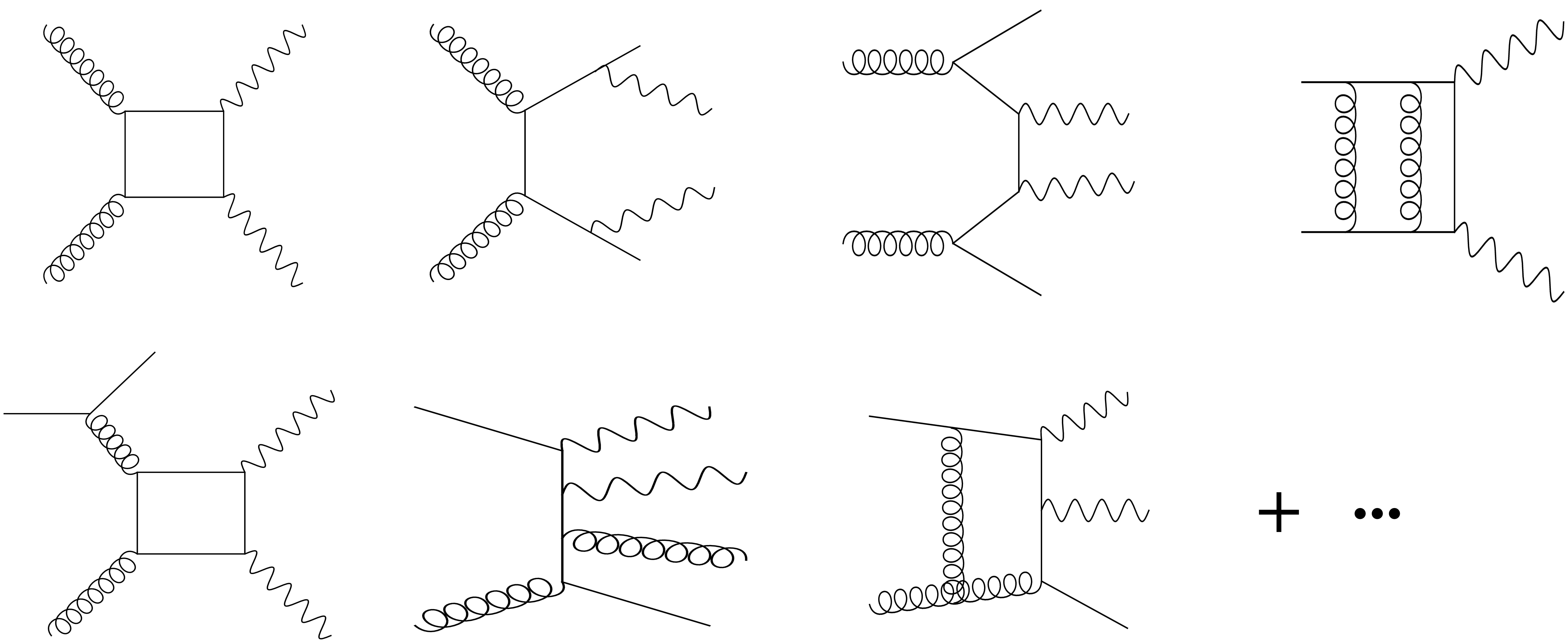
Frixione Isolation

- Also corrections to Box contribution, partial N^3LO terms available

Zvi Bern, Lance Dixon, and Carl Schmidt

(Available, but not present in the following analysis)

Full NNLO means full control of the $\mathcal{O}\left(\alpha_s^2\right)$ diagrams:



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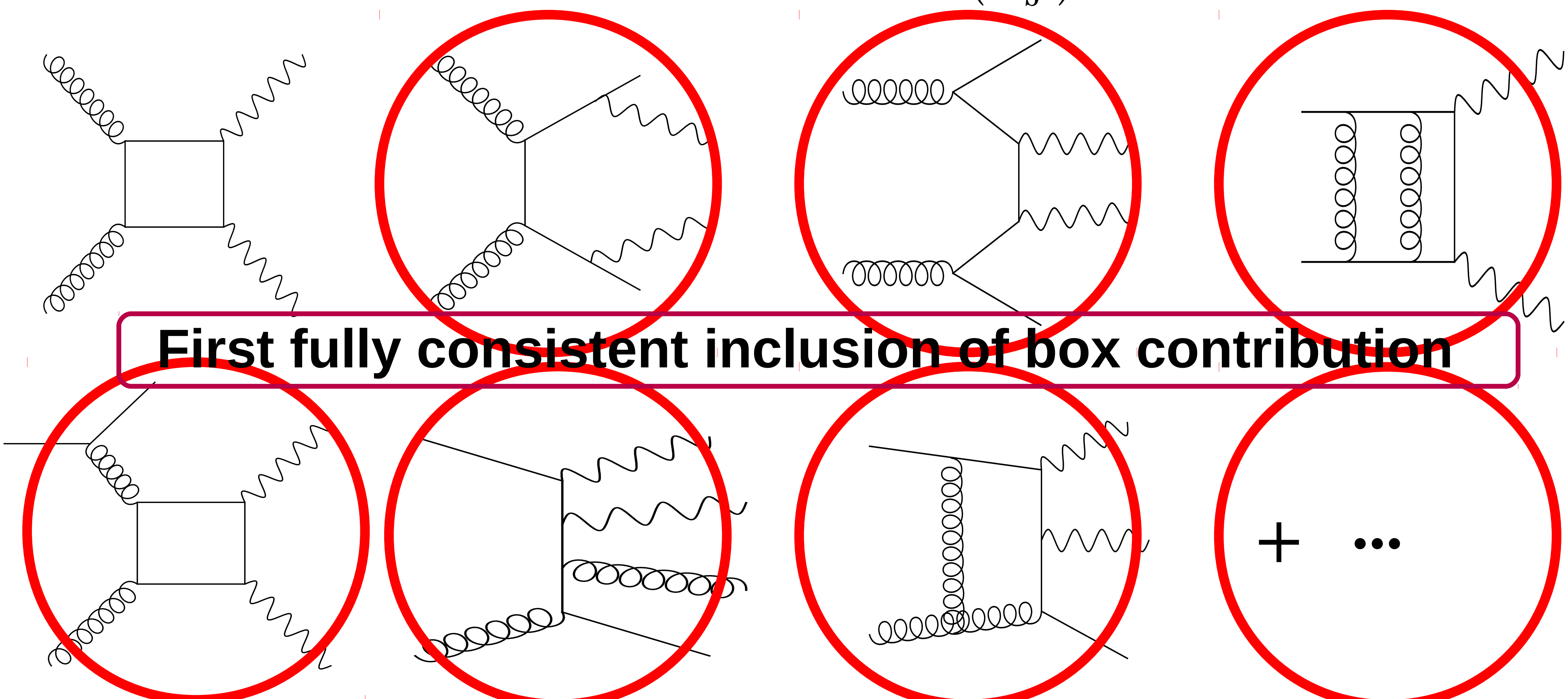
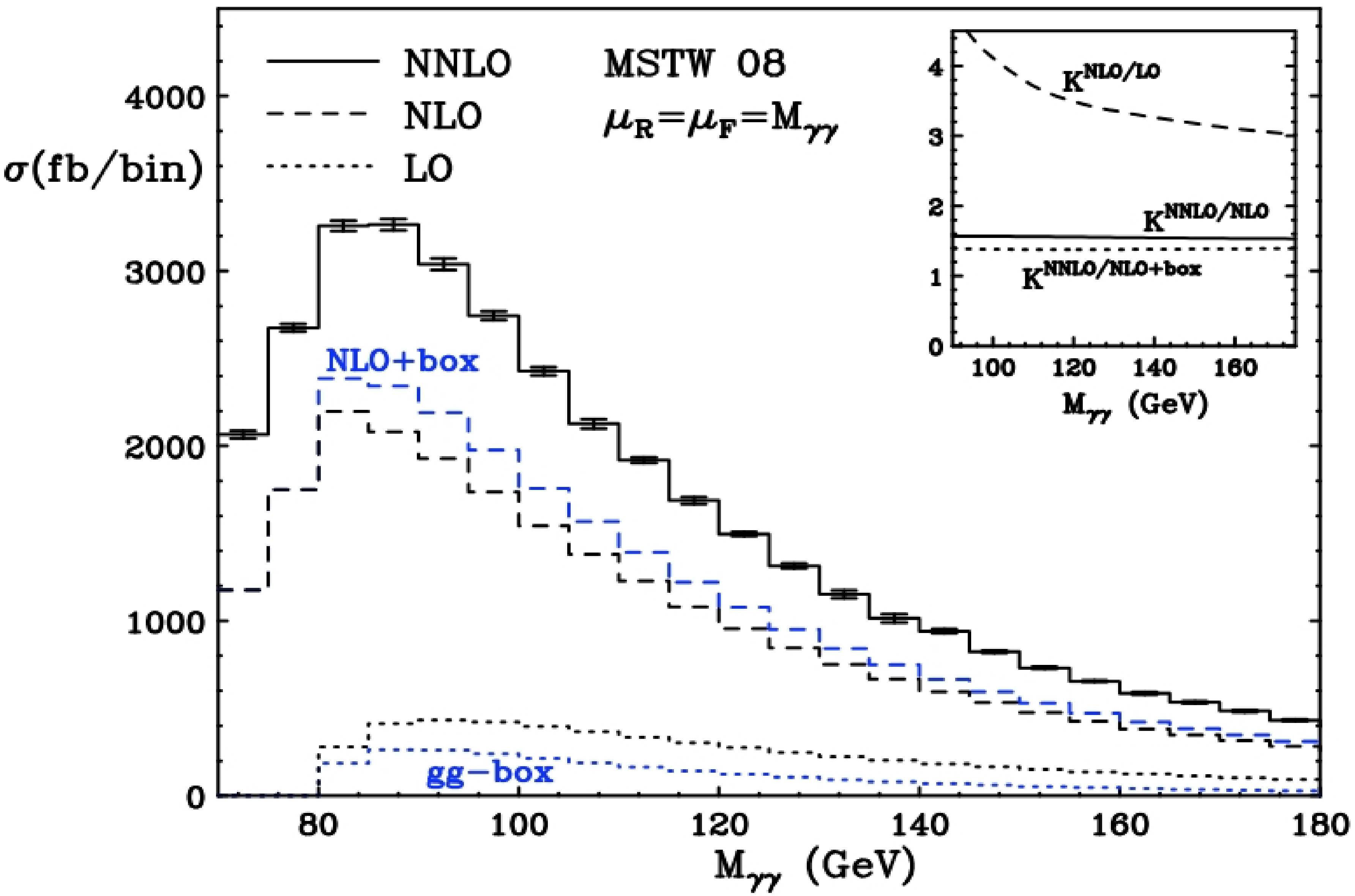


Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

First results using 2γNNLO



$\sqrt{S} = 14\,\mathrm{TeV}$

$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$

$p_T^{\gamma\, soft} \geq 25\,\mathrm{GeV}$

$|\eta^\gamma| \leq 2.5$

$20\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 250\,\mathrm{GeV}$

$\mu_R = \mu_F = M_{\gamma\gamma}$

NNLO effect about +50 % in the peak region

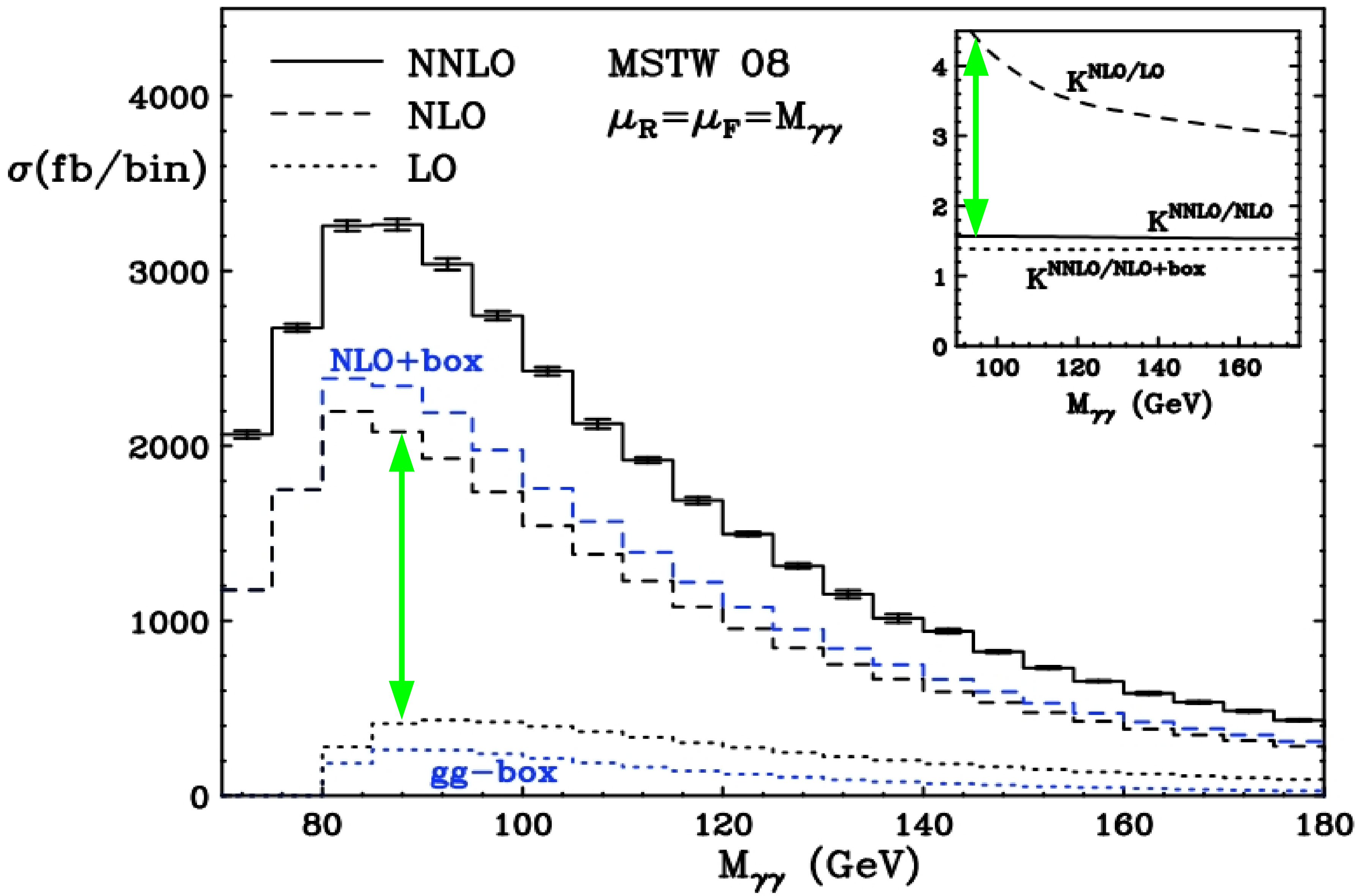
Box only ~22% of NNLO correction

Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

First results using $2\gamma\mathrm{NNLO}$



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$|\eta^\gamma| \leq 2.5$

$20\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 250\,\mathrm{GeV}$

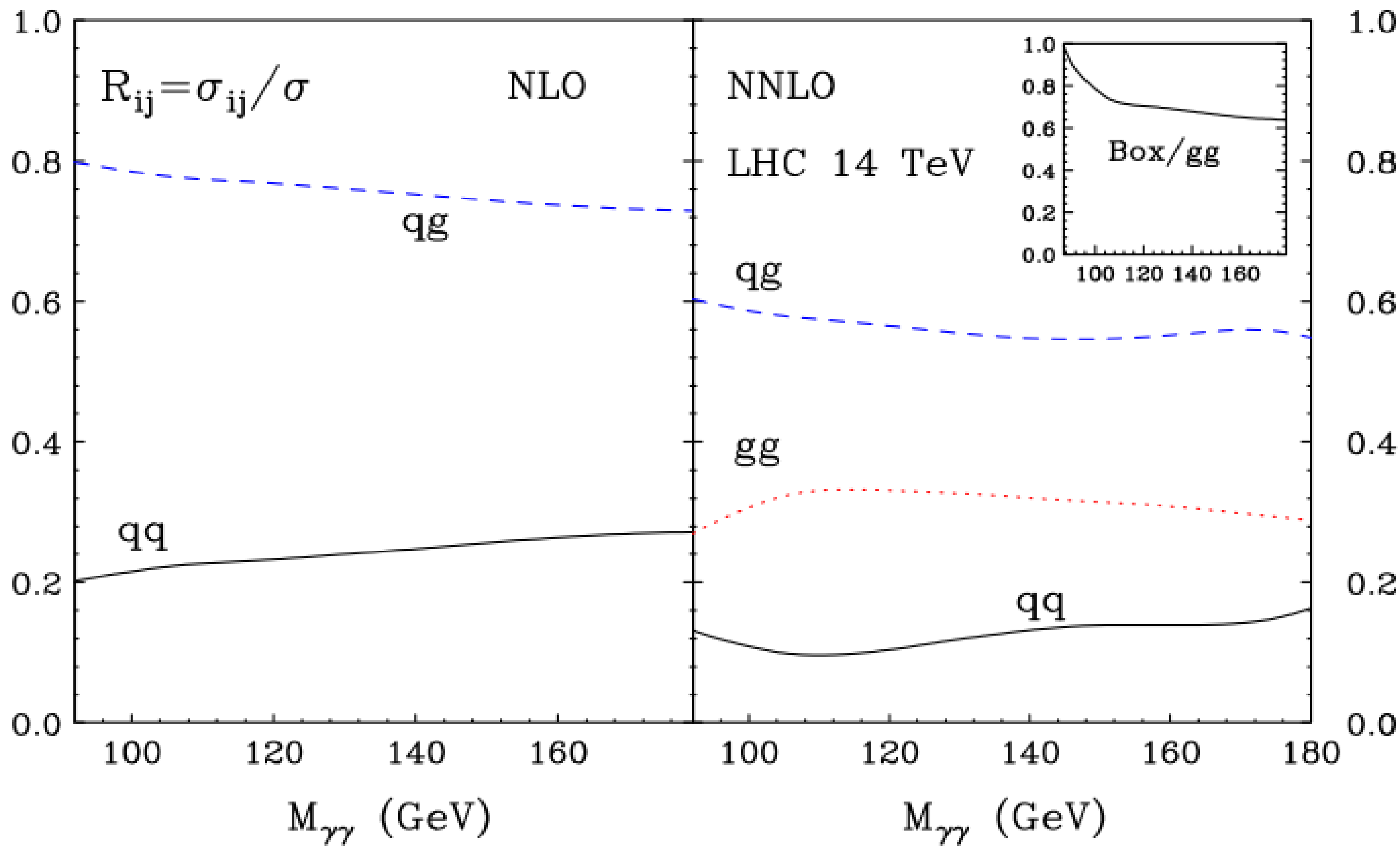
$\mu_R = \mu_F = M_{\gamma\gamma}$

$$\frac{\sigma^{NNLO}}{\sigma^{NLO+Box}} \sim 1.35$$

$$\frac{\sigma^{NNLO}}{\sigma^{NLO}} \sim 1.55$$

Huge corrections 1 : new channels

Channels @ 14 TeV



Box only ~22% of NNLO correction

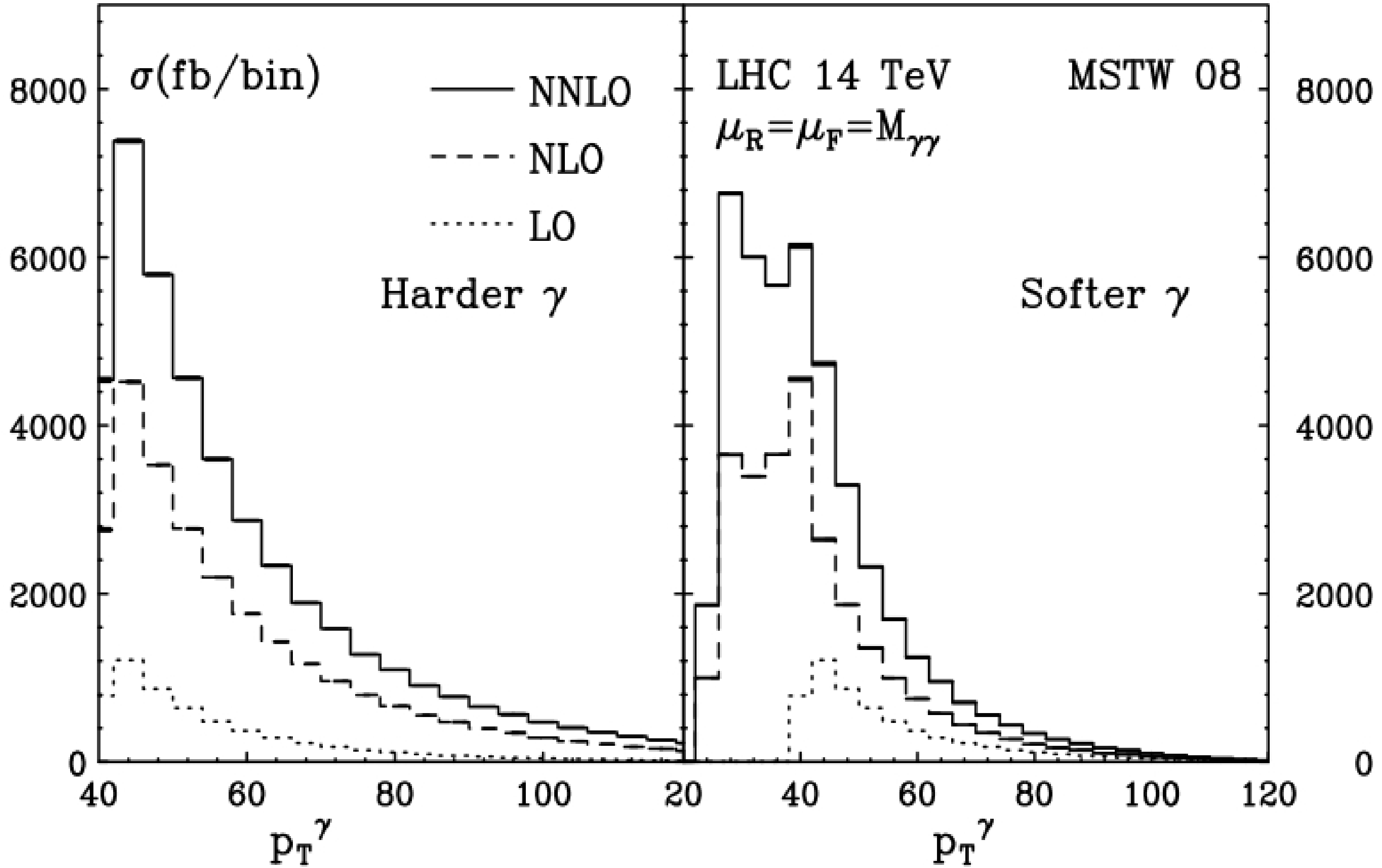
Main contribution from qg channel
(corrections to NLO dominant channel)

Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

p_T of harder and softer photon



The requirement $p^{\gamma}_{T1} \geq 40$ GeV implies that at LO also the softer photon must have $p^{\gamma}_{T} \geq 40$ GeV

Diphoton production at NNLO

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First exclusive NNLO with two final state particles

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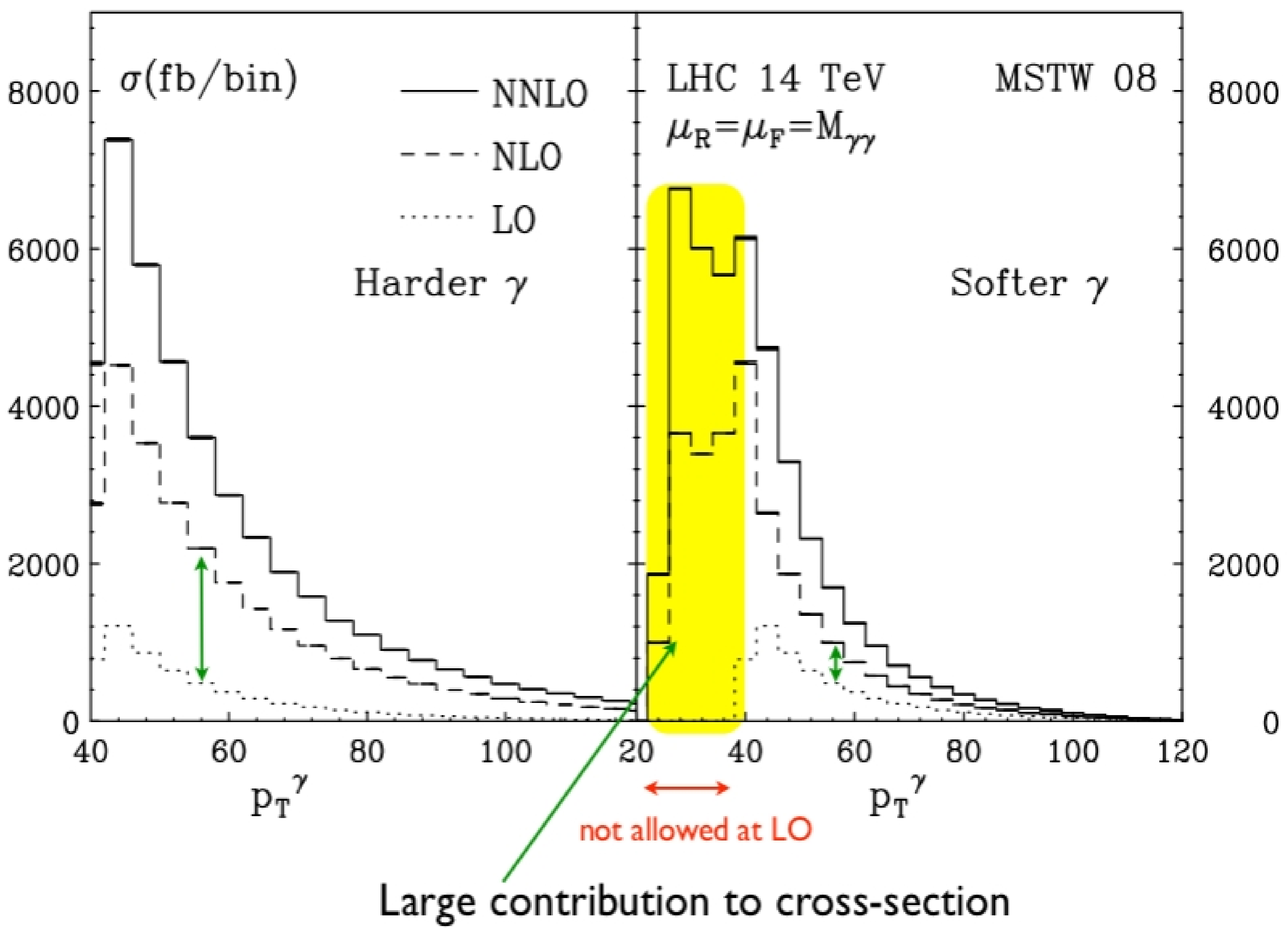


The requirement $p^{\gamma}_{T1} \geq 40$ GeV implies that at LO also the softer photon must have $p^{\gamma}_{T} \geq 40$ GeV

- Substantial contribution from radiation in the region 25 GeV < pT < 40 GeV
- Unphysical peak in $\mathbf{p}^{\gamma}_{T2}$ at $\mathbf{p}^{\gamma}_{T}$ =40 GeV

S. Catani, M. Fontannaz, J.P. Guillet, E. Pilon. JHEP 0205 (2002) 028

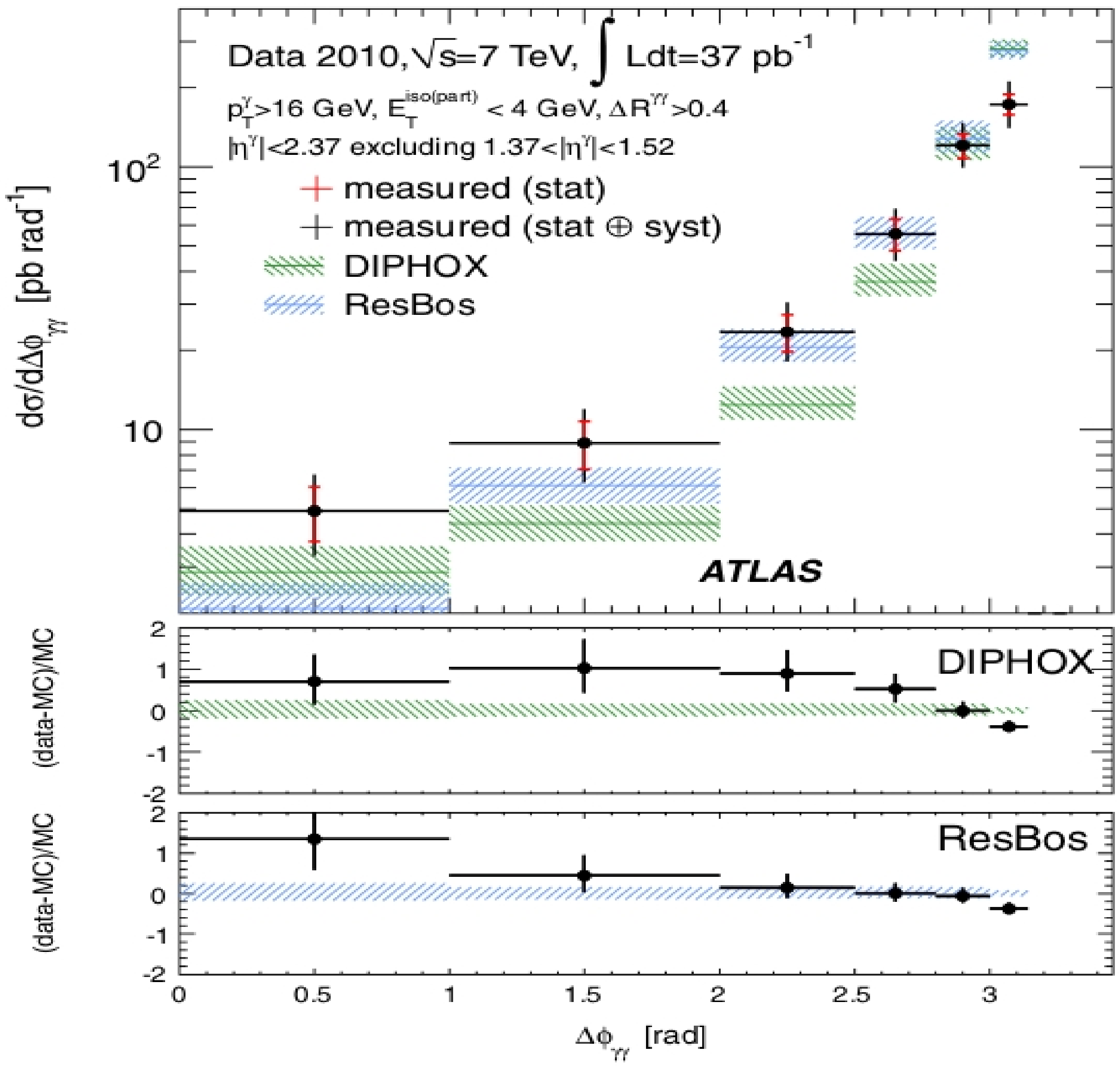
Catani, Webber. JHEP 9710 (1997) 005

Diphoton production at NNLO

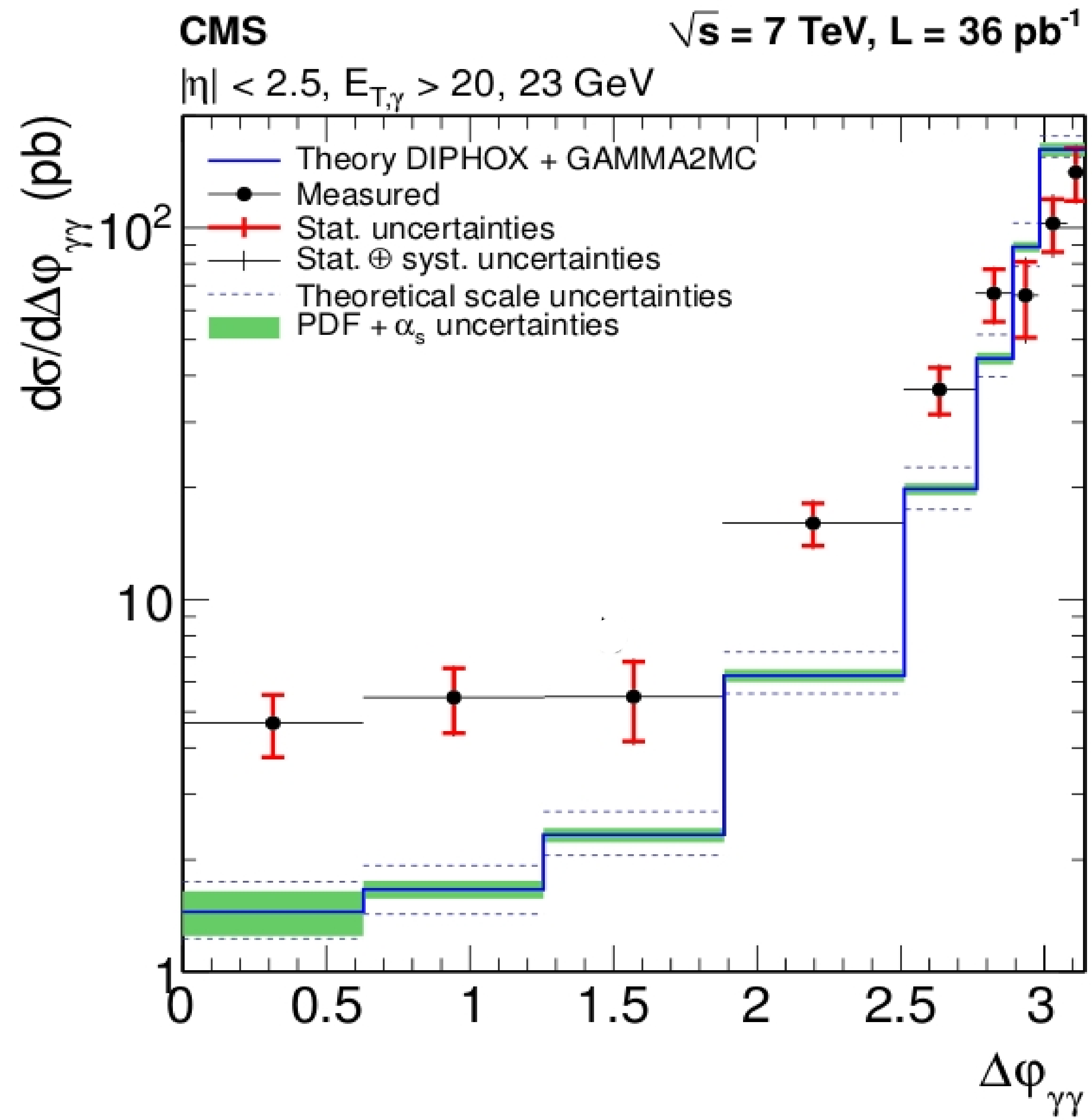
S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data



PRD 85, 012003 (2012)



JHEP 01(2012)133

Same discrepancies found by CDF: Phys.Rev.Lett.107:102003,2011.

Diphoton production at NNLO

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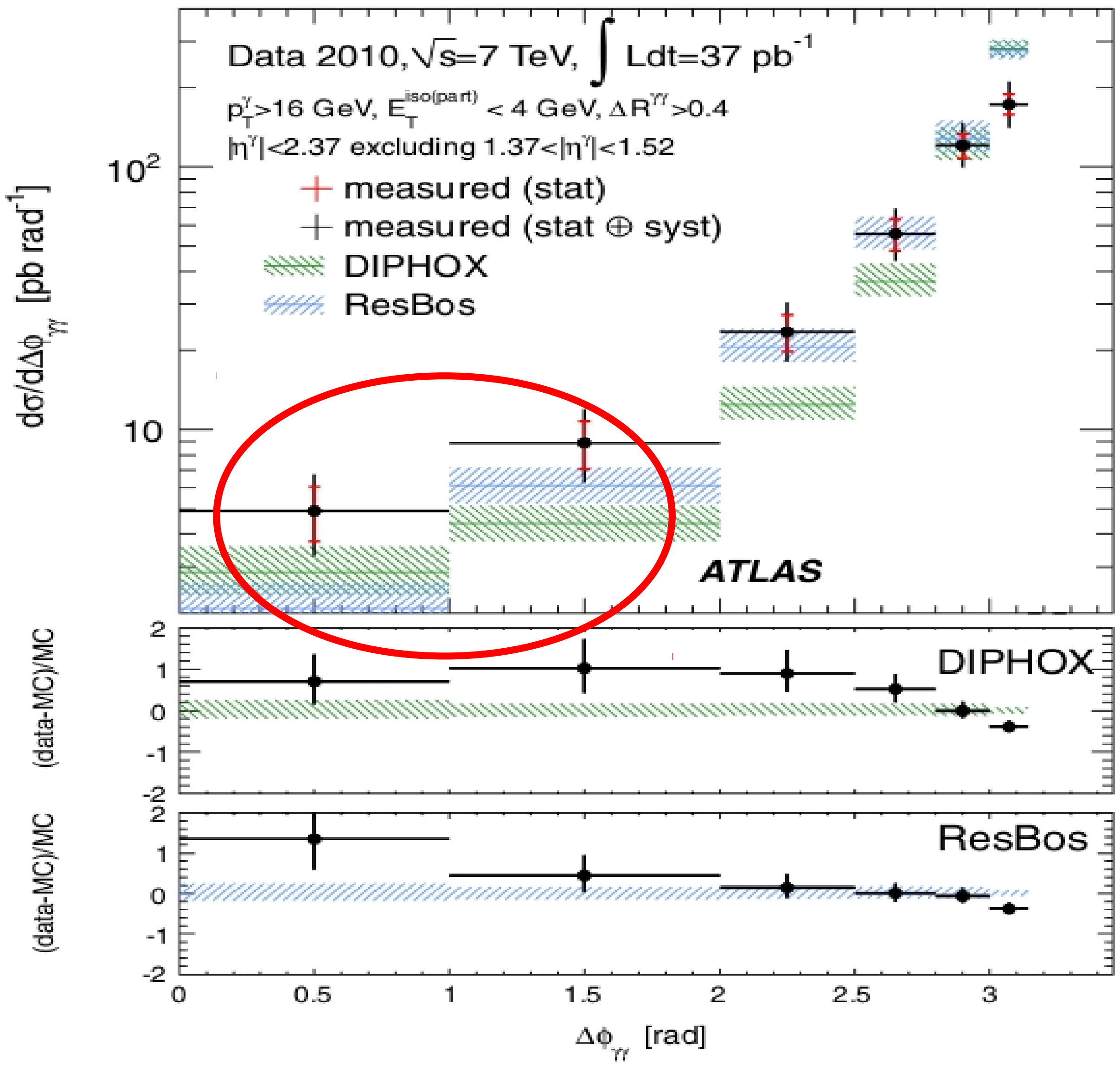

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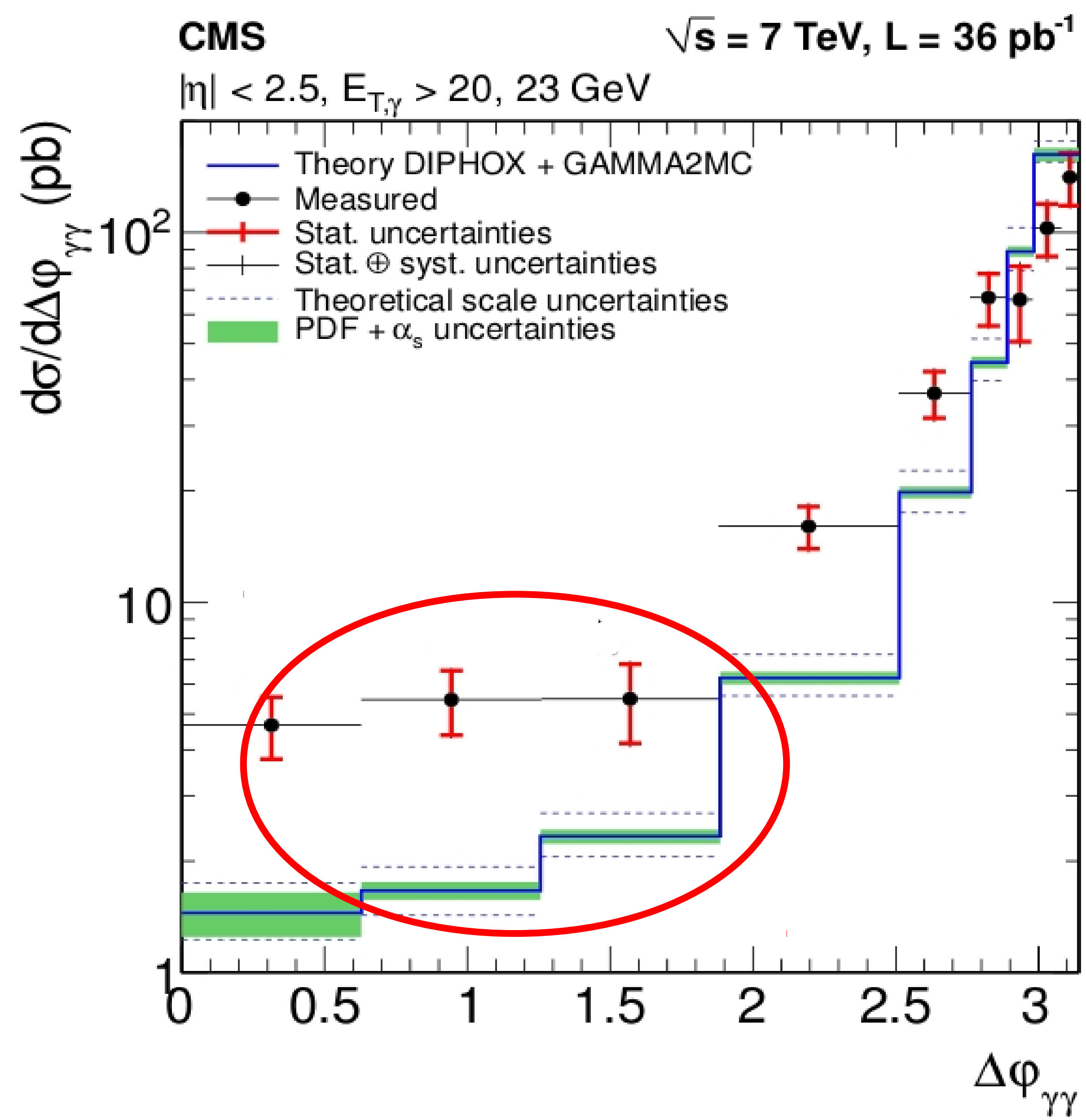

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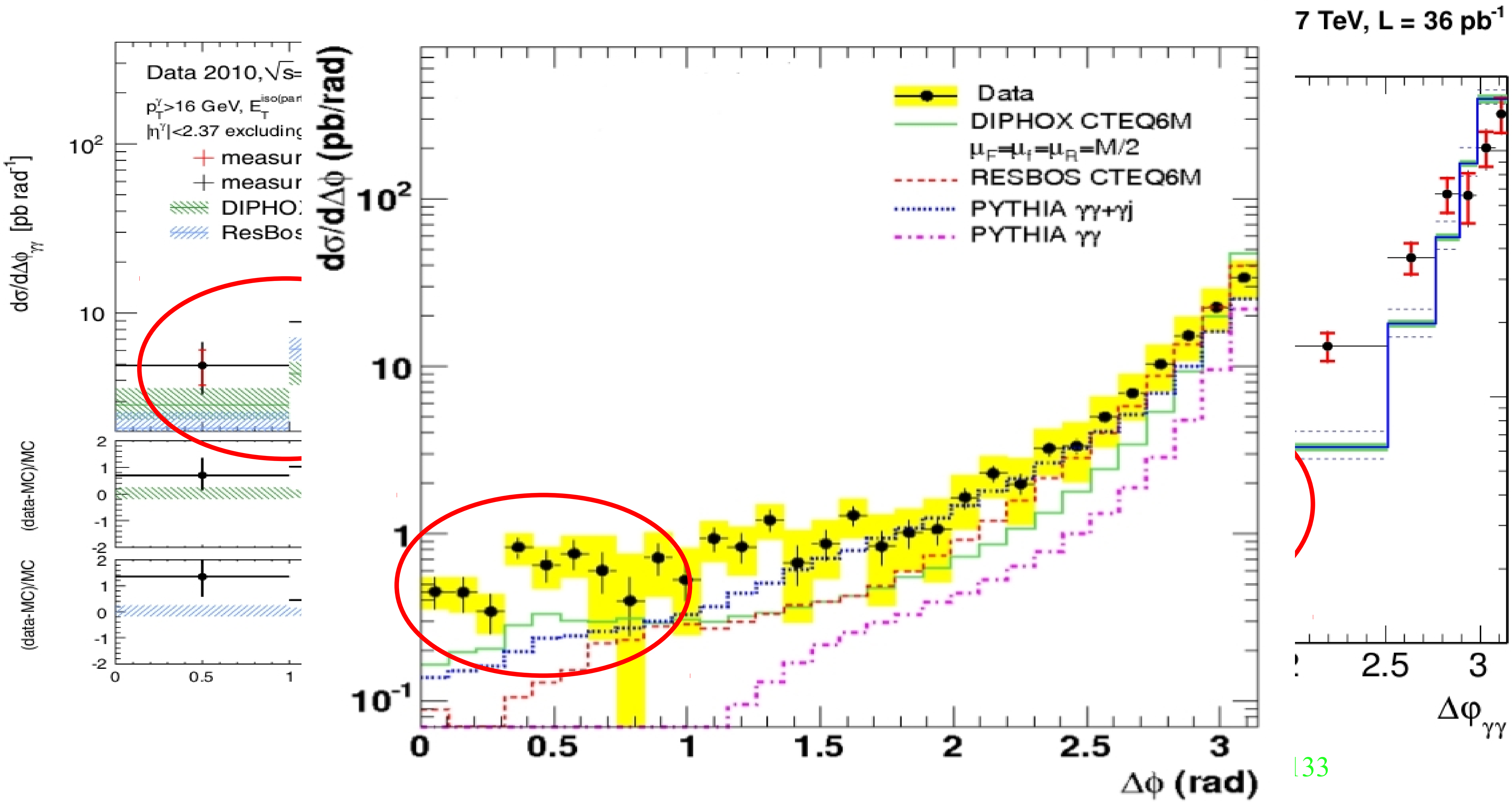

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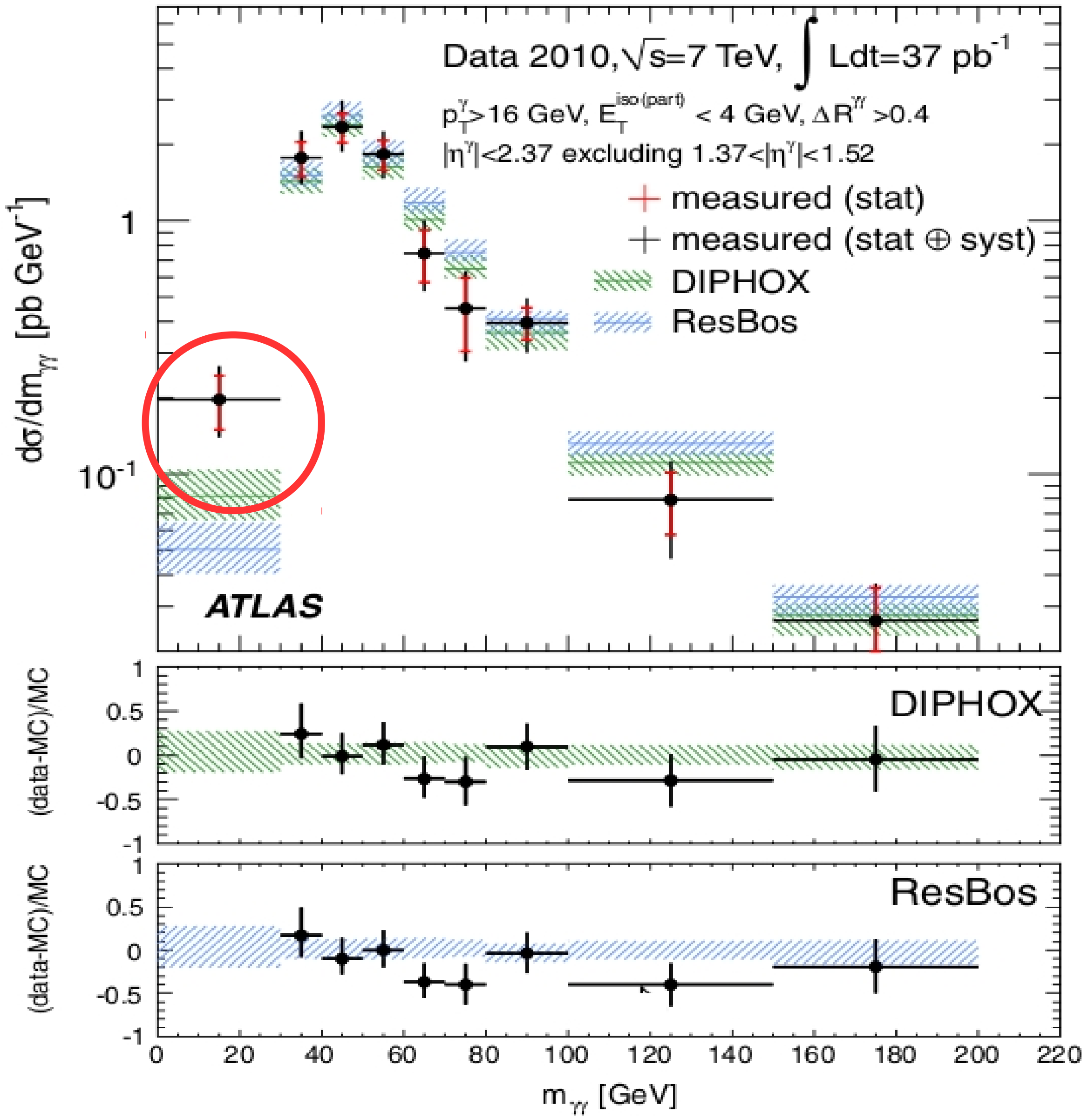

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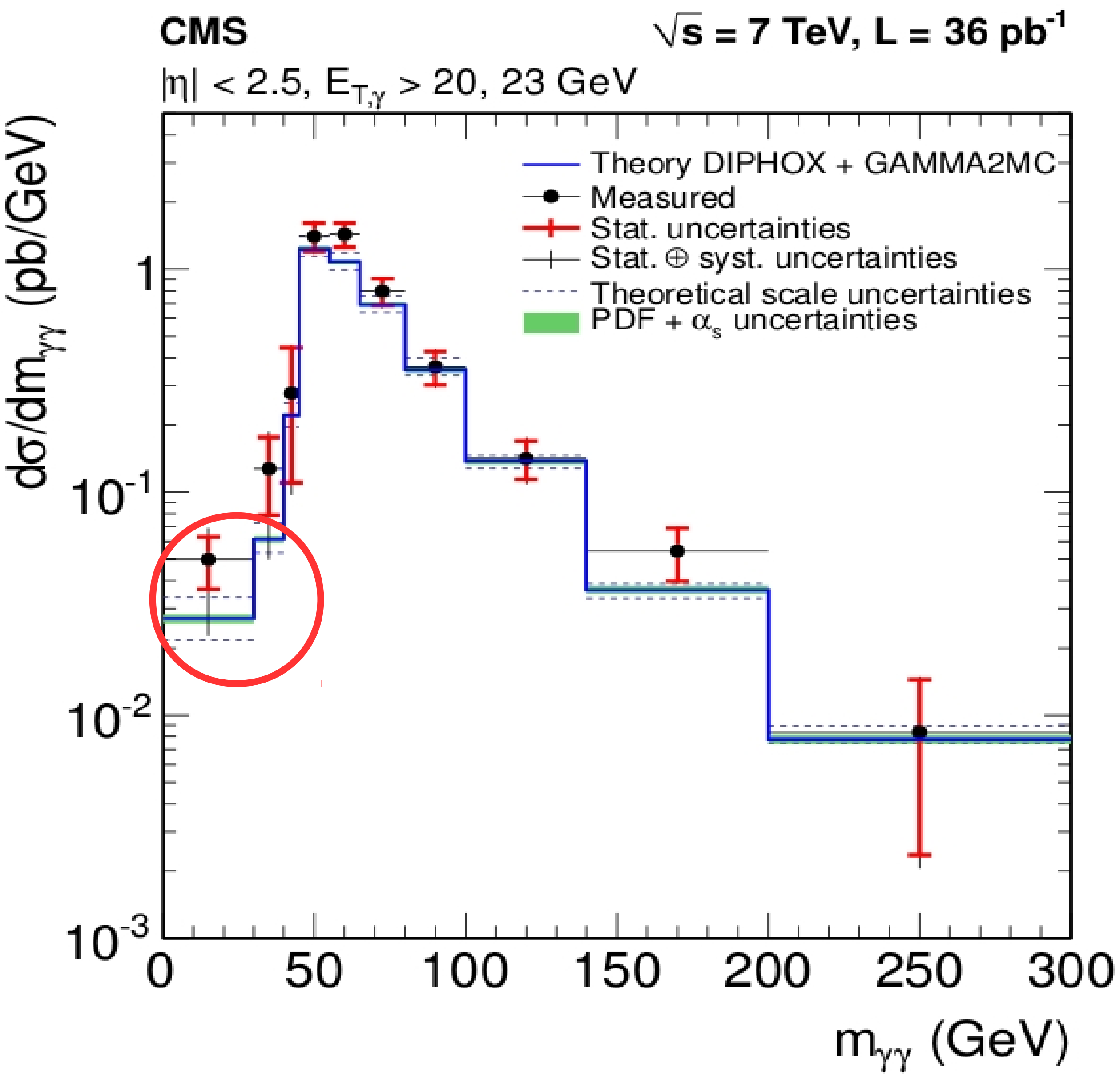

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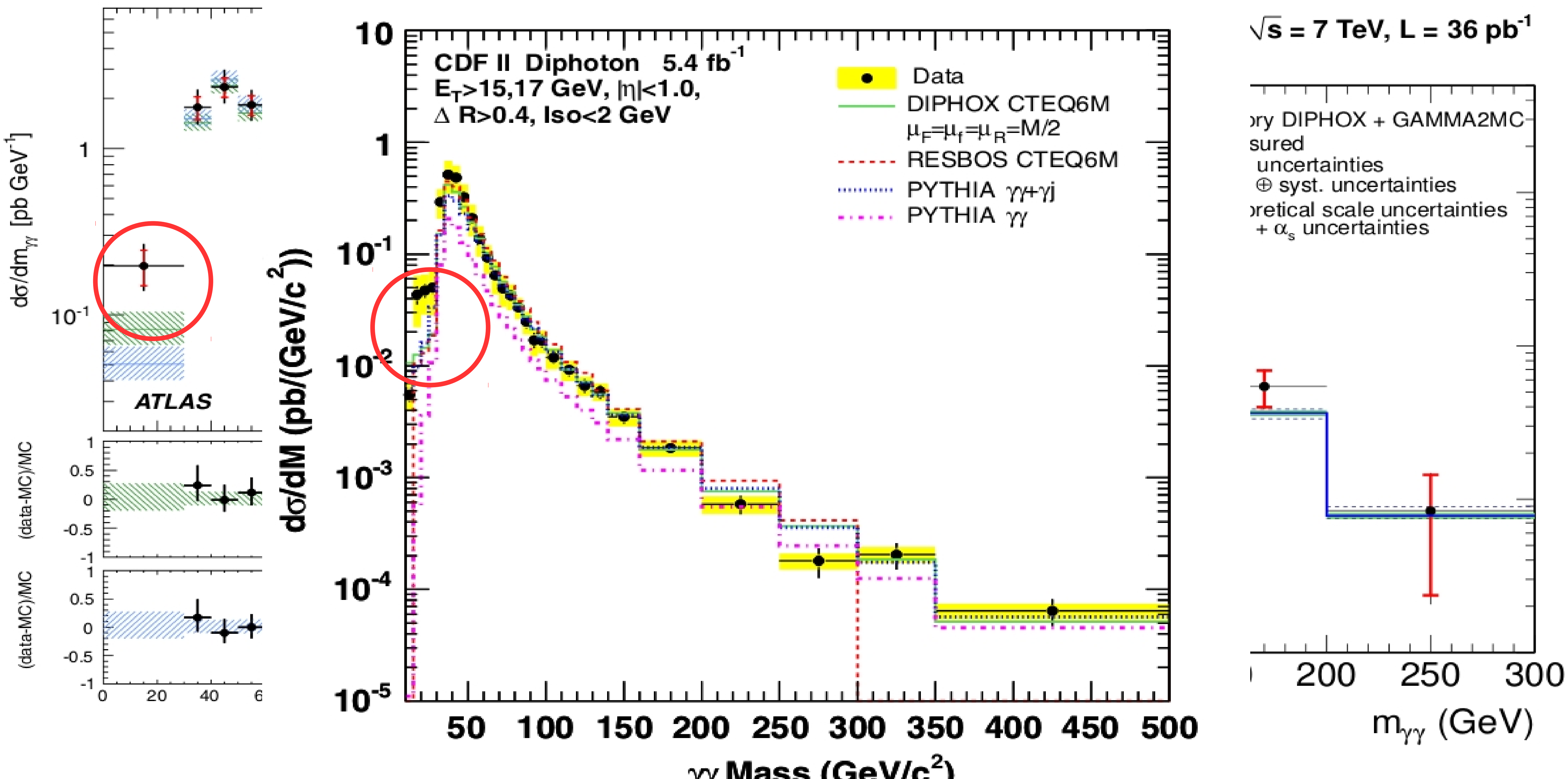

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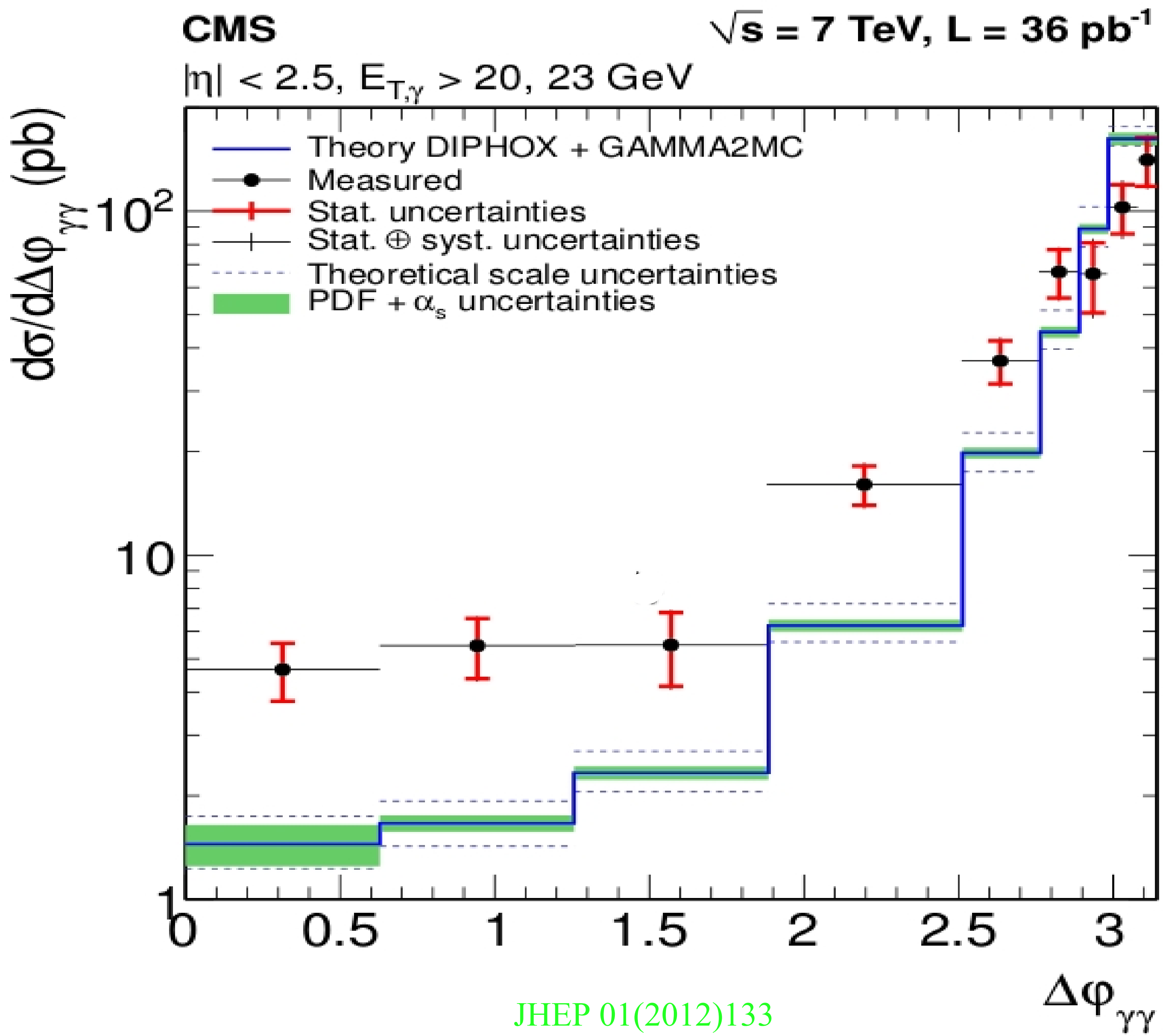
Diphoton production at NNLO

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data at low Δφ



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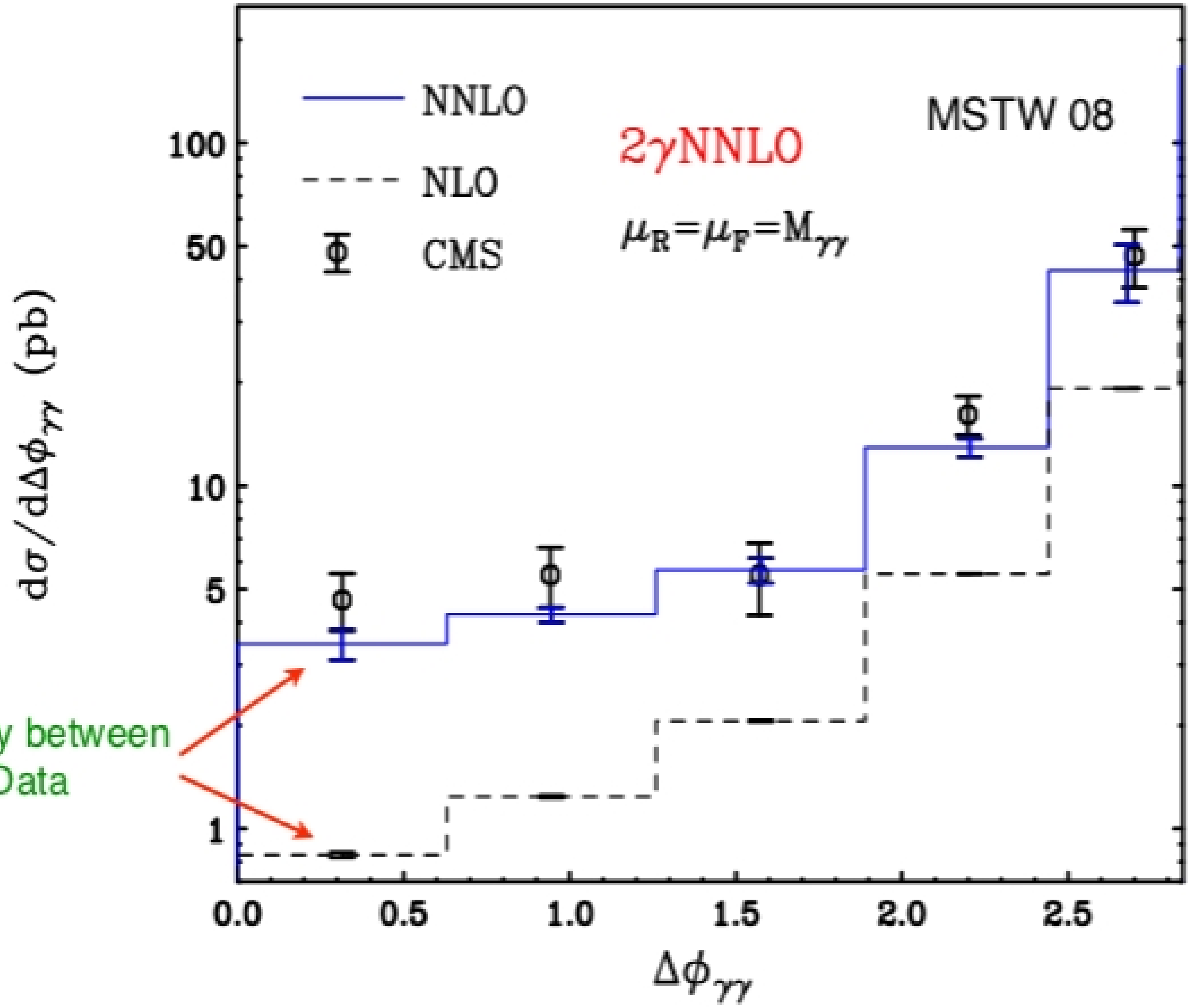
Diphoton production at NNLO

Preliminary results

S.Catani, D. de Florian, G.Ferrera, M.Grazzini, LC

NNLO Corrections much larger in some kinematical regions
NLO effectively lowest order

"away from back-to-back configuration"



large discrepancy between NLO and Data

$\sqrt{S} = 7$ TeV

CMS diphoton cuts

$p_T^{\gamma\, hard} \geq 23$ GeV

$p_T^{\gamma\, soft} \geq 20$ GeV

$|\eta^\gamma| \leq 2.5$

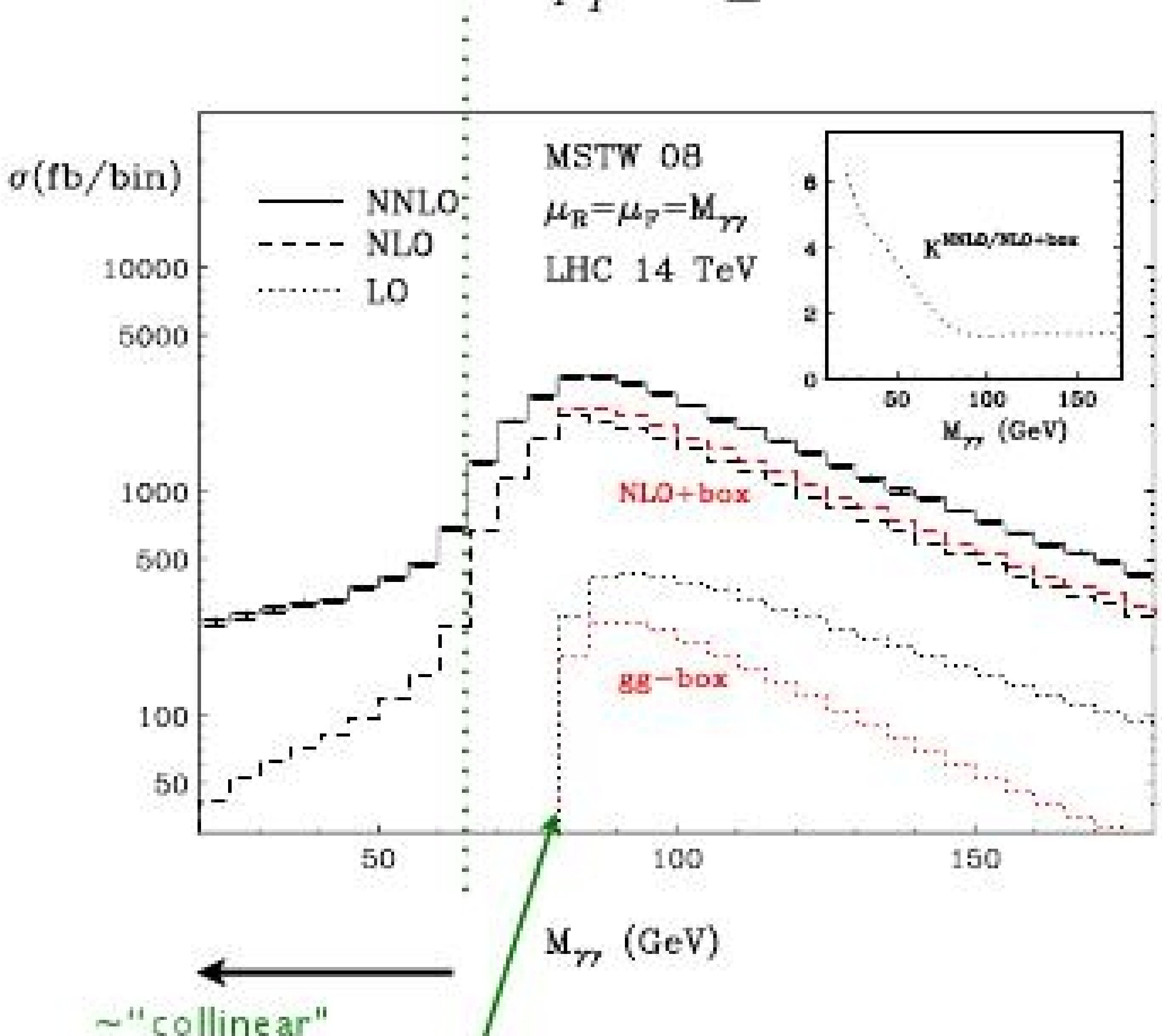
$R_{\gamma\gamma} > 0.45$

smooth cone isolation

NNLO corrections essential to understand the background

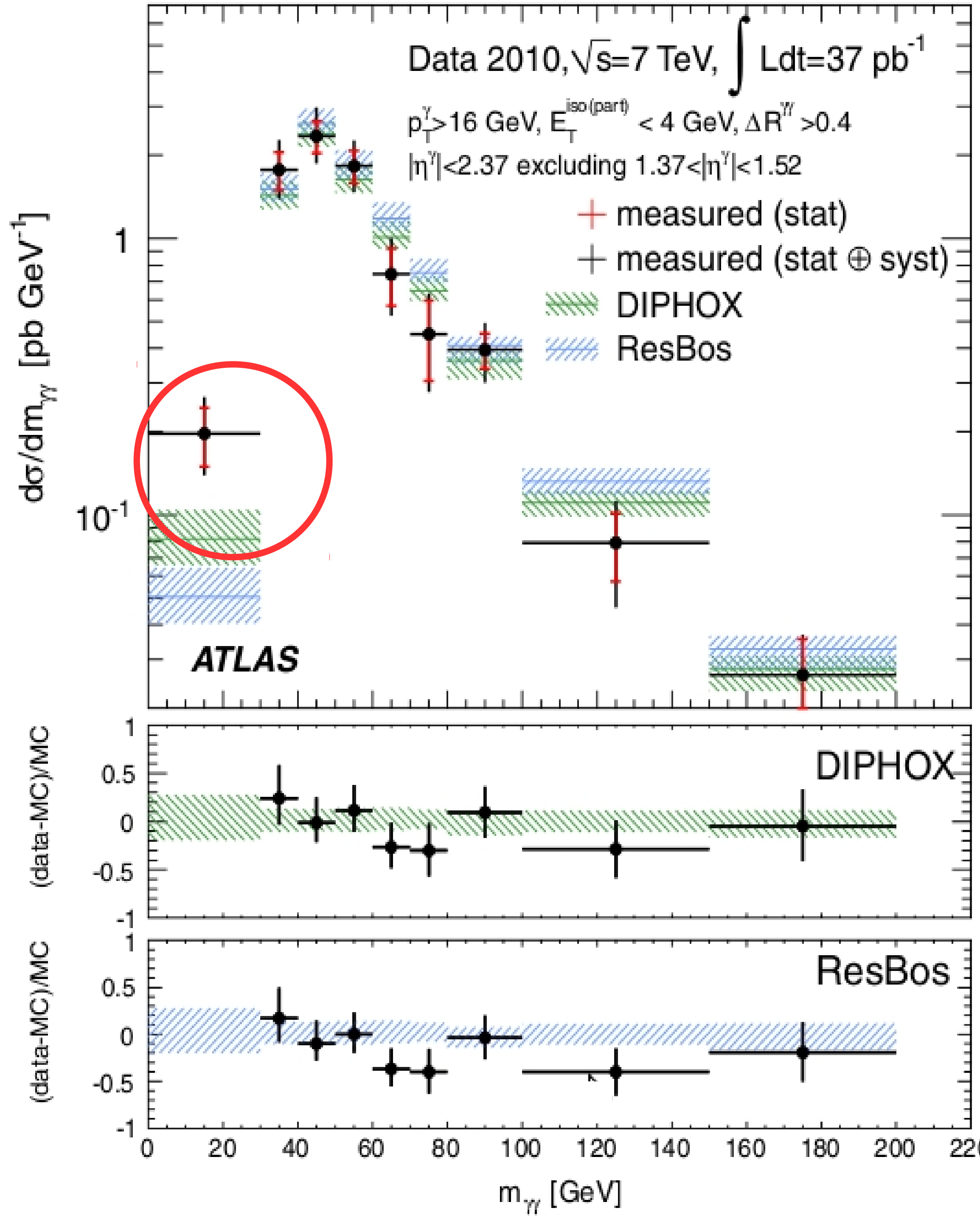
invariant mass below the LO threshold

$\sqrt{S} = 14\,\mathrm{TeV}$ $\quad p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$ $\quad p_T^{\gamma\, soft} \geq 25\,\mathrm{GeV}$



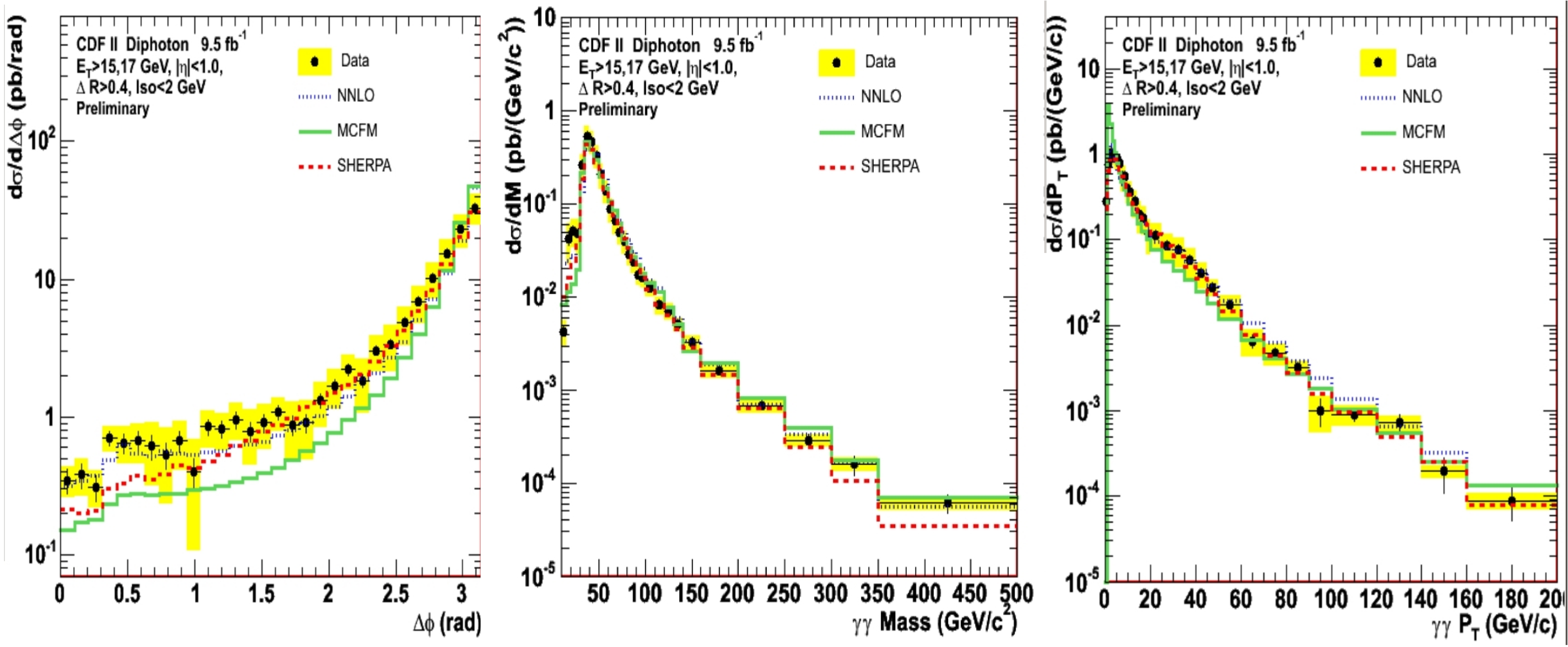
LO threshold at 80 GeV

"No back-to-back"



This discrepancy can be related to the discrepancy observed in the $\Delta\varphi$ distribution.

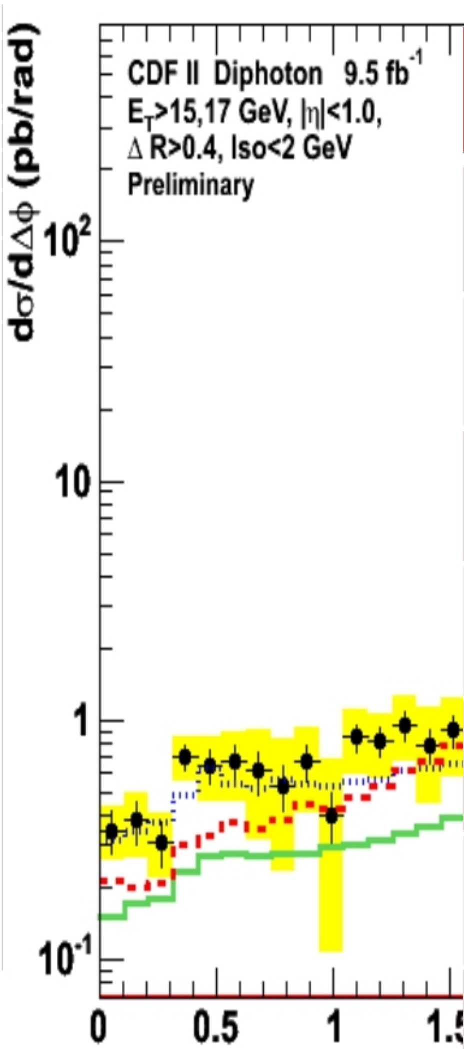
Preliminary comparison CDF 9.5 fb^{-1} results



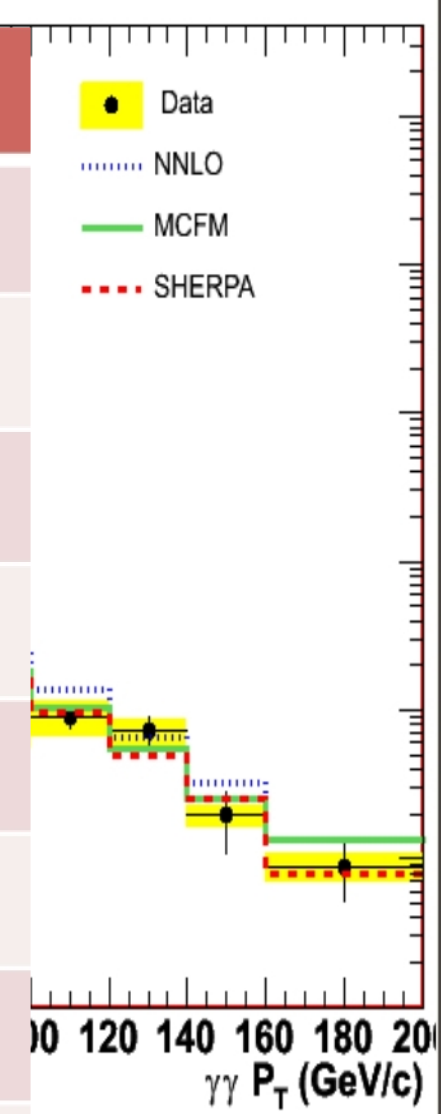
$P^{\gamma}_{T\ harder} \geq 17GeV$ $P^{\gamma}_{T\ softer} \geq 15GeV$ Isolation(Parameters): R=0.4 ; $E_{t\ max}$ = 2 GeV

$|\eta| \leq 1$ $R_{\gamma\gamma} \geq 0.4$

Preliminary comparison CDF 9.5 fb^{-1} results



	Total cross section (pb)
Data (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	11.8 + 1.7 – 0.6

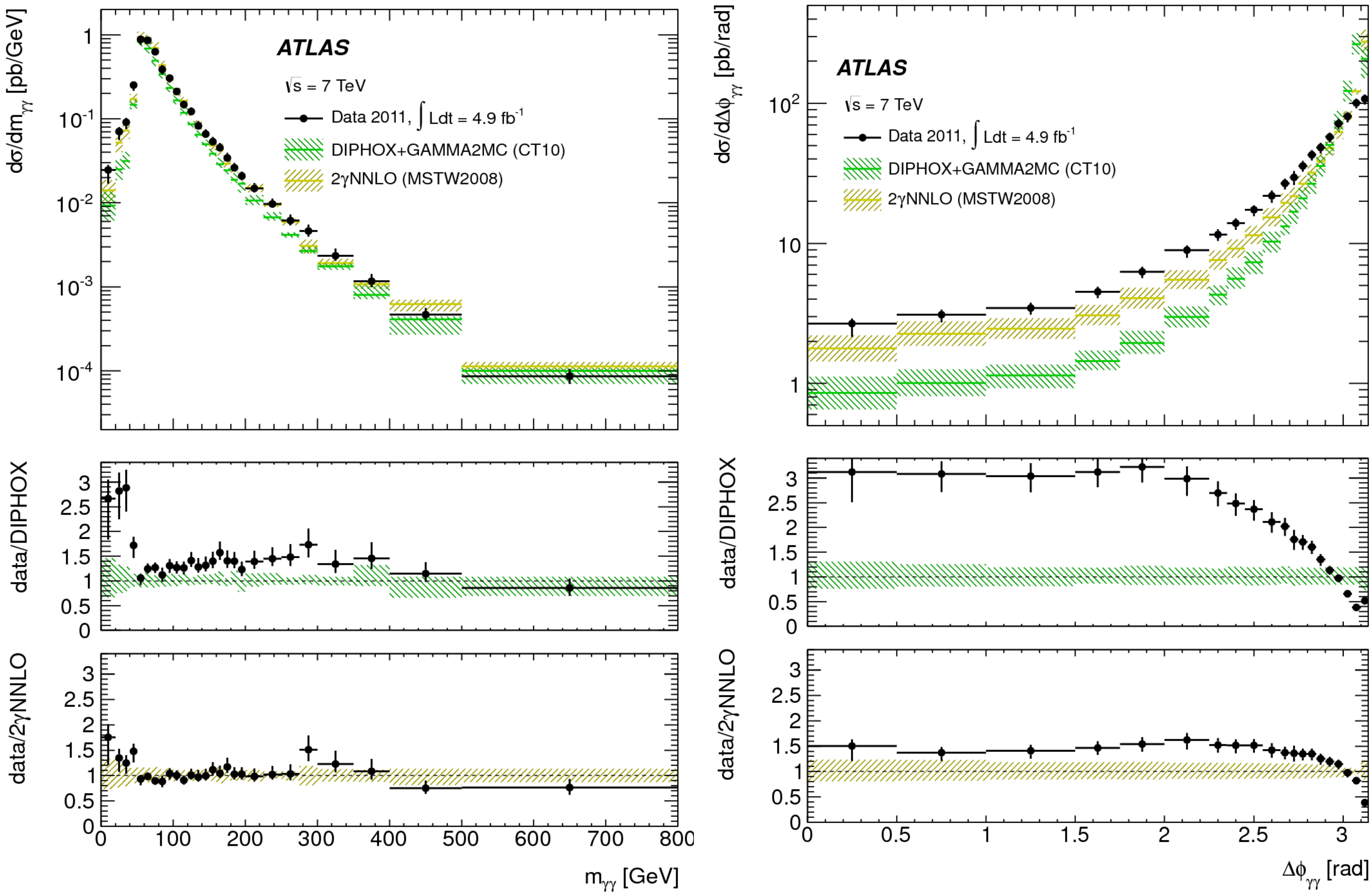


$P^{\gamma}_{T\ harder} \geq 17GeV$ $P^{\gamma}_{T\ softer} \geq 15GeV$ Isolation(Parameters): R=0.4 ; $E_{t\ max}$ = 2 GeV

$|\eta| \leq 1$ $R_{\gamma\gamma} \geq 0.4$

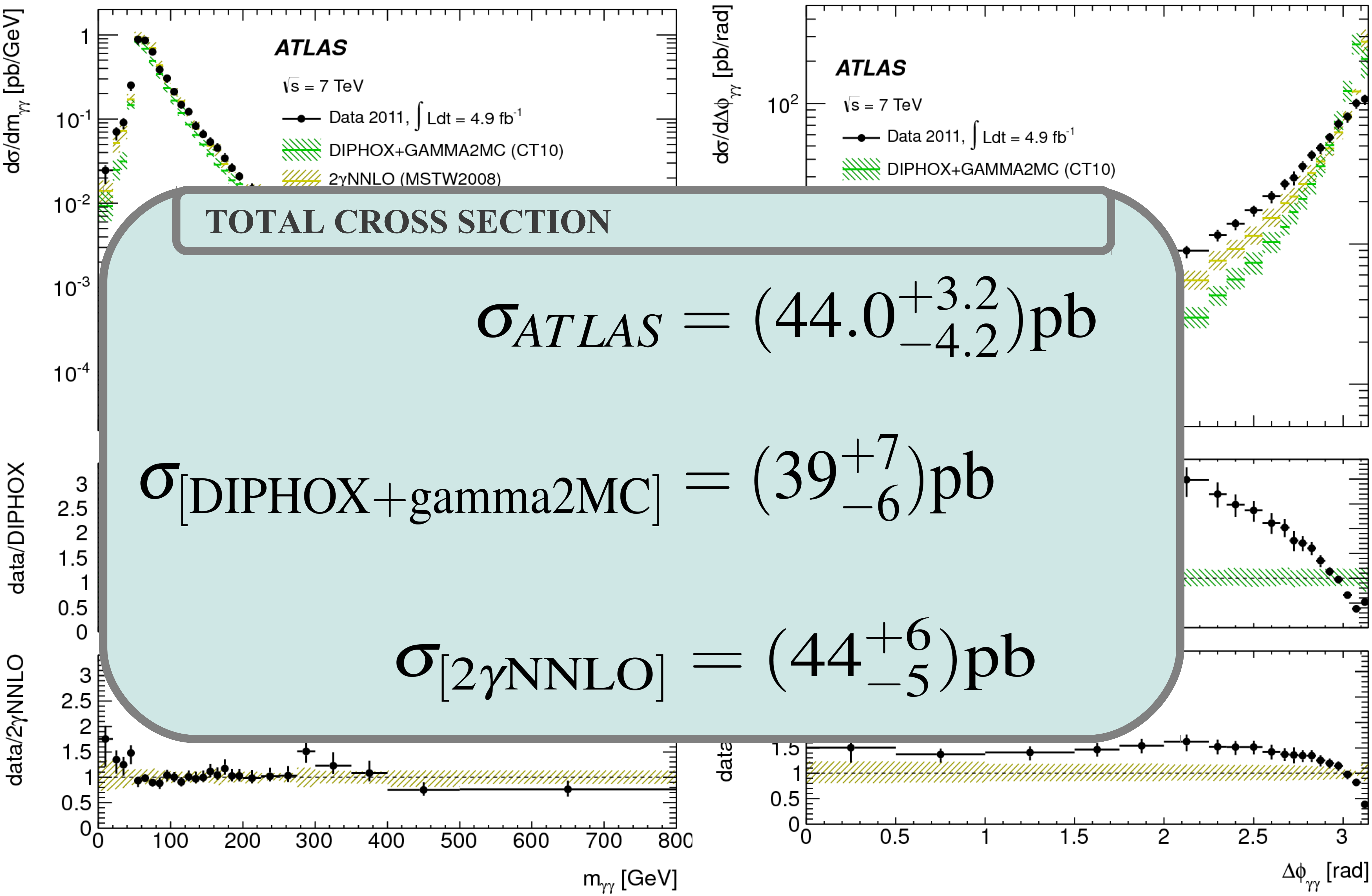
ATLAS results

arXiv:1211.1913 [hep-ex].



ATLAS results

arXiv:1211.1913 [hep-ex].



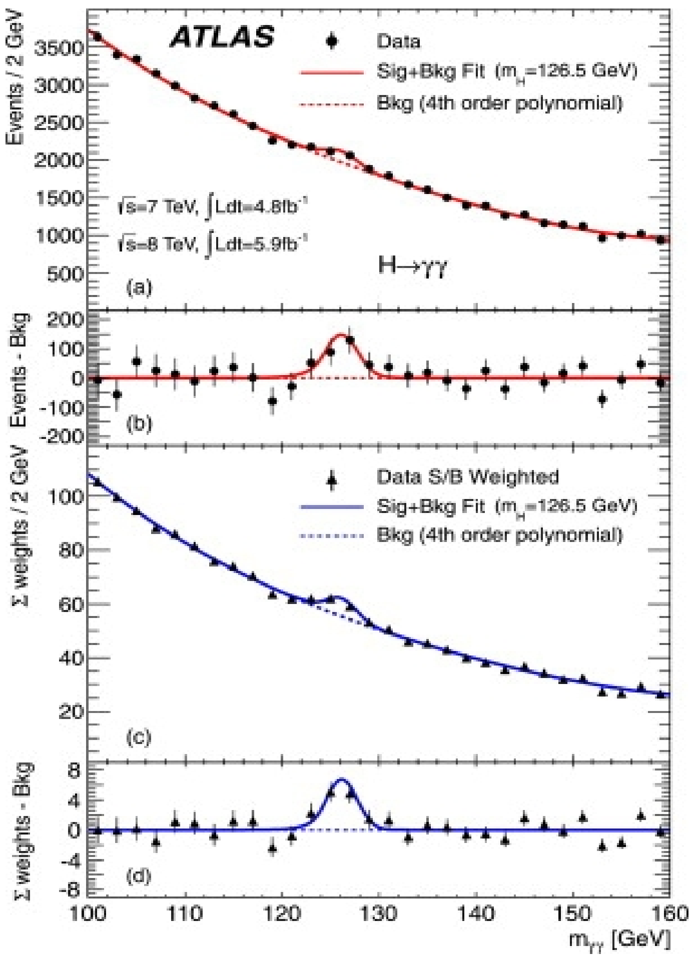
TOTAL CROSS SECTION

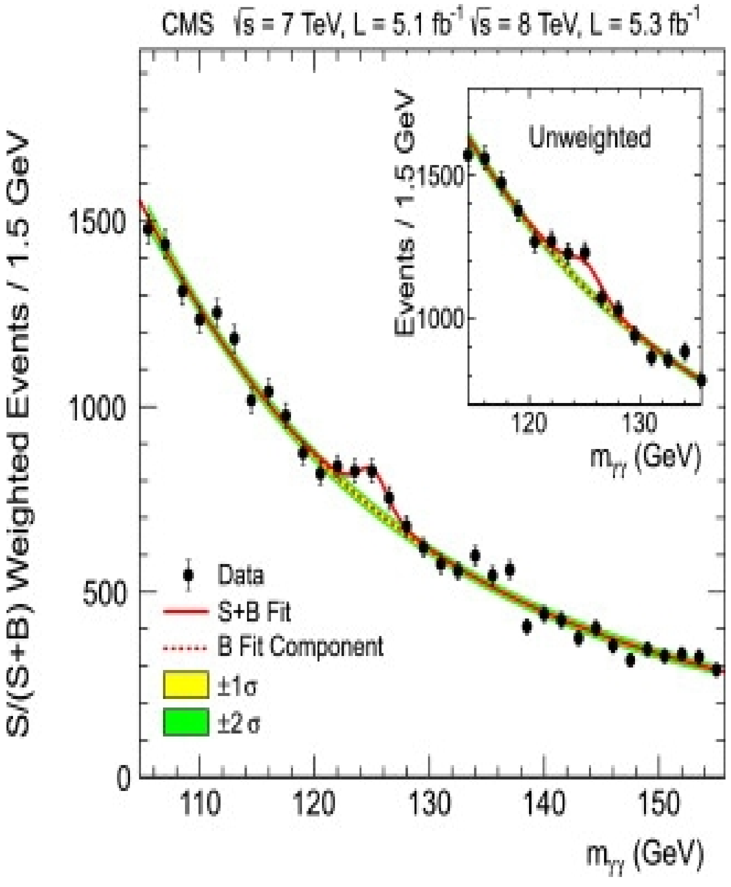
$$\sigma_{ATLAS} = (44.0^{+3.2}_{-4.2})\mathrm{pb}$$

$$\sigma_{[\mathrm{DIPHOX+gamma2MC}]} = (39^{+7}_{-6})\mathrm{pb}$$

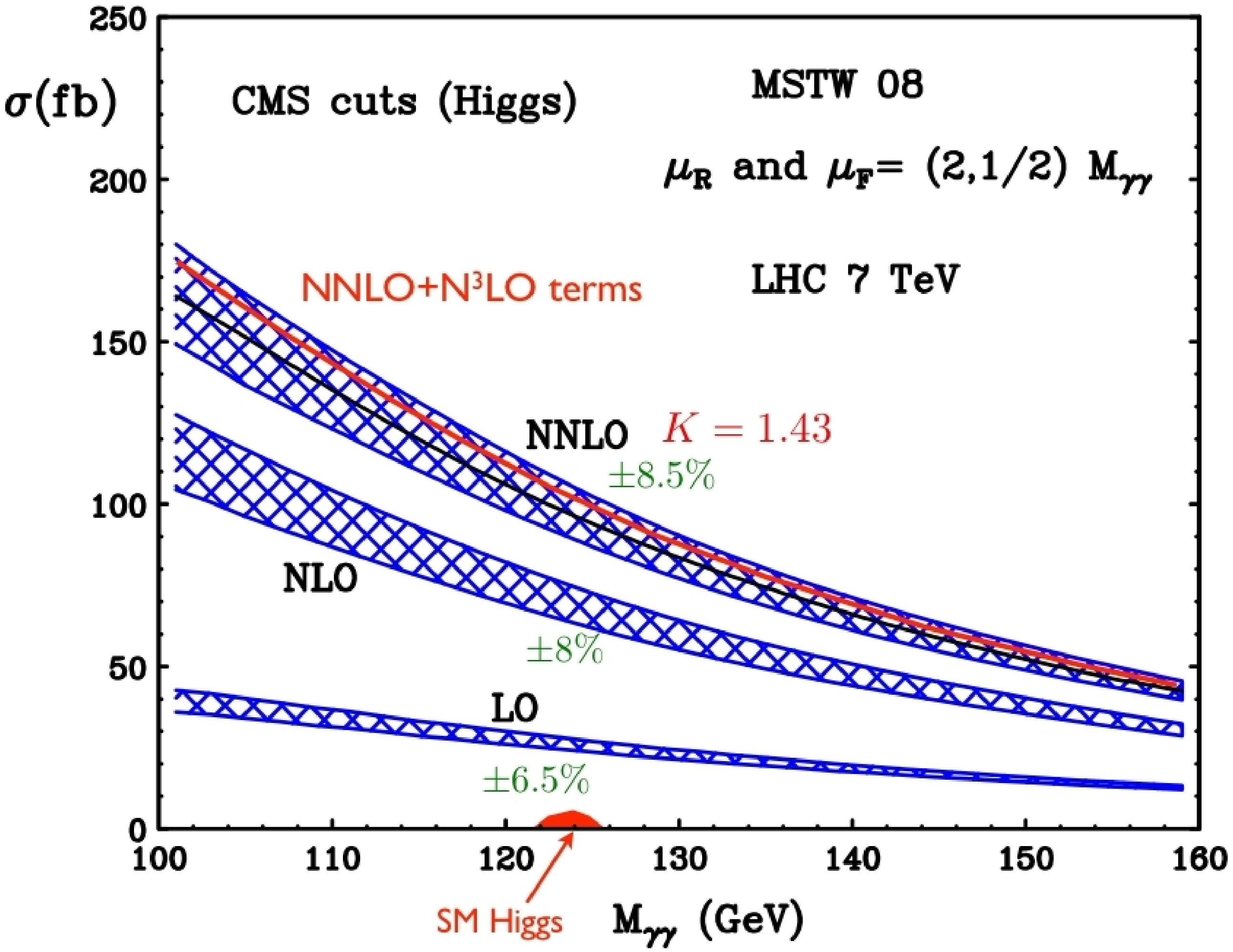
$$\sigma_{[2\gamma\mathrm{NNLO}]} = (44^{+6}_{-5})\mathrm{pb}$$

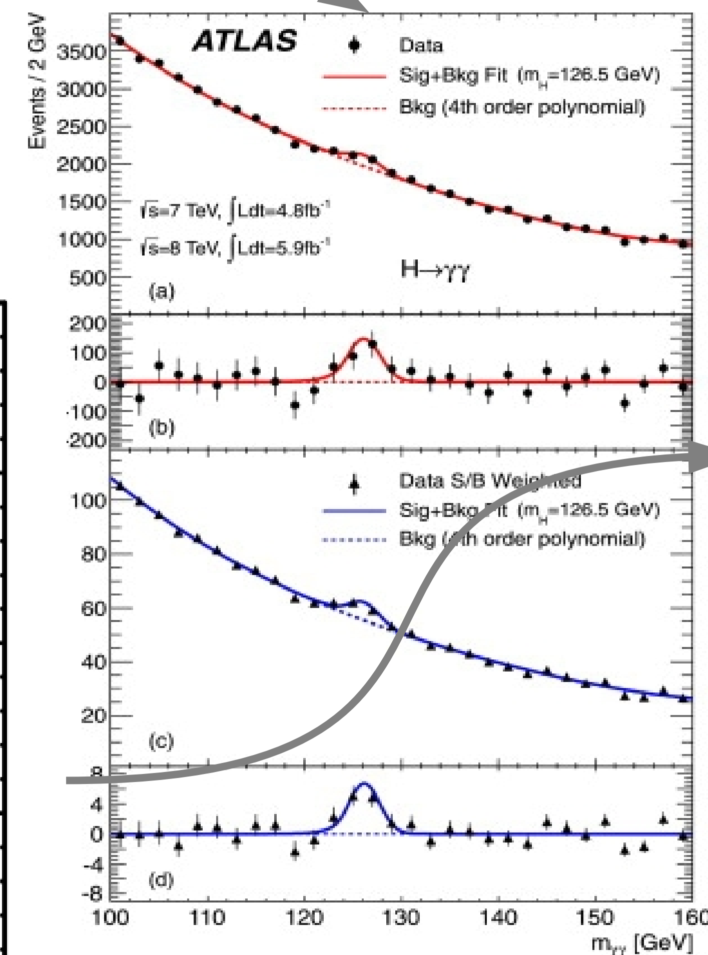
Higgs boson searches

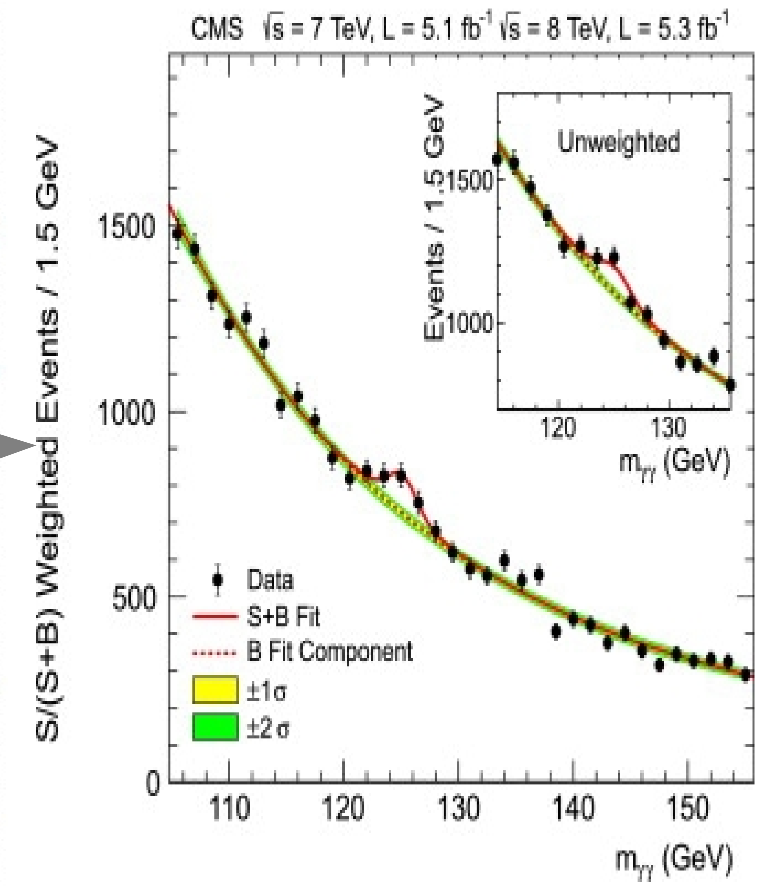




Higgs boson searches







$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$

$p_T^{\gamma\, soft} \geq 30\,\mathrm{GeV}$

$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$

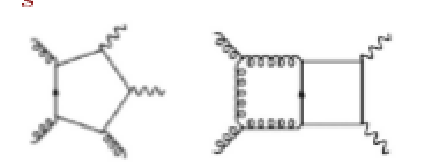
$|\eta^\gamma| \leq 2.5$

excluding $1.4442 \leq |\eta^\gamma| \leq 1.566$

$\epsilon = 0.05$

- Scale does not represent TH uncertainties at LO and NLO → new channels
- All channels open at NNLO → estimate of TH uncertainties

α_s^3 Bern, Dixon, Schmidt (2002)



Some N³LO terms known to contribute ~5%

Summary

- Cross section with "smooth" isolation, is a lower bound for cross section with standard isolation.

- Sizeable NNLO corrections to the γγ mass distribution in kinematical regions related to Higgs boson searches

  40-55% effect over NLO

- NNLO very large away from back-to-back configuration (effectively NLO)

  needed to understand LHC data

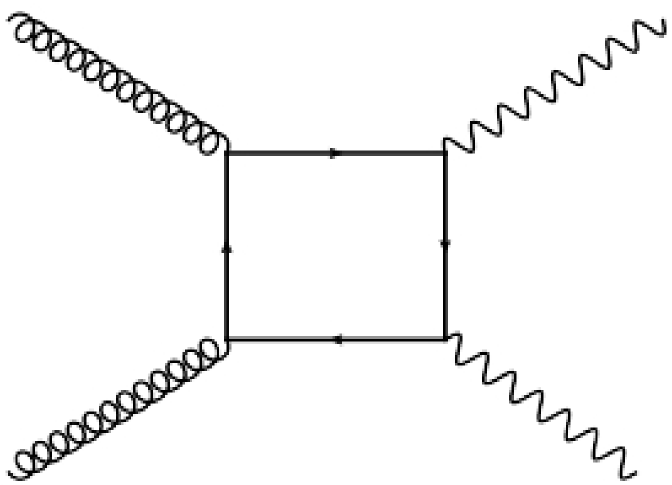
- At NNLO starts to reliably predict values of cross sections in all kinematical regions (with very few exceptions; e.g $p_{T\gamma\gamma} \to 0$)

Backup Slides

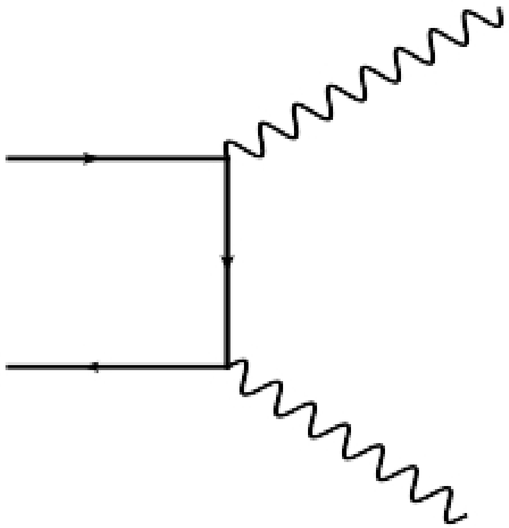
Why do we need NNLO corrections?

NNLO QCD corrections in diphoton production

$\gamma\gamma$ production → some NNLO terms known to be as large as Born!



$O(\alpha_s^2)$ but gg Luminosity



$O(\alpha_s^0)$ but $q\bar{q}$ Luminosity

- Box contribution already included in NLO calculation

DIPHOX: T.Binoth, J.P.Guillet, E.Pilon, M.Werlen

Why do we need NNLO corrections?

NNLO QCD corrections in diphoton production

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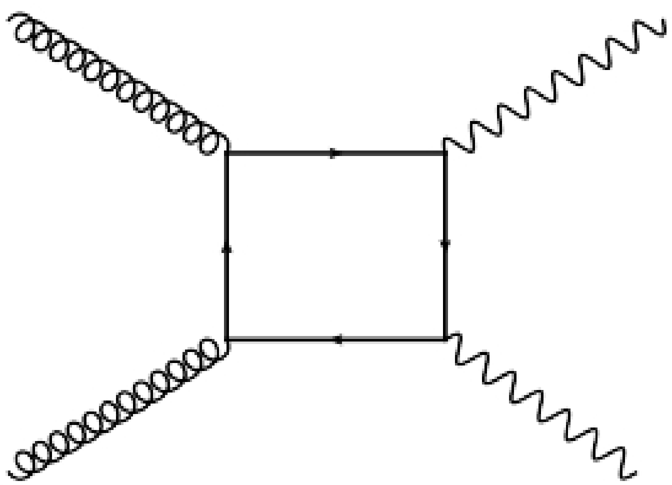
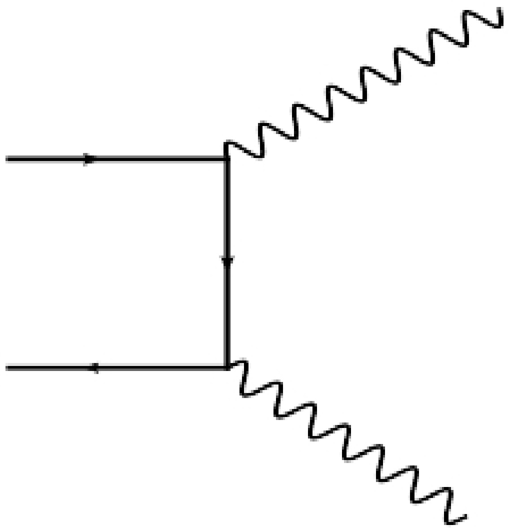


$O(\alpha_s^2)$ but gg Luminosity



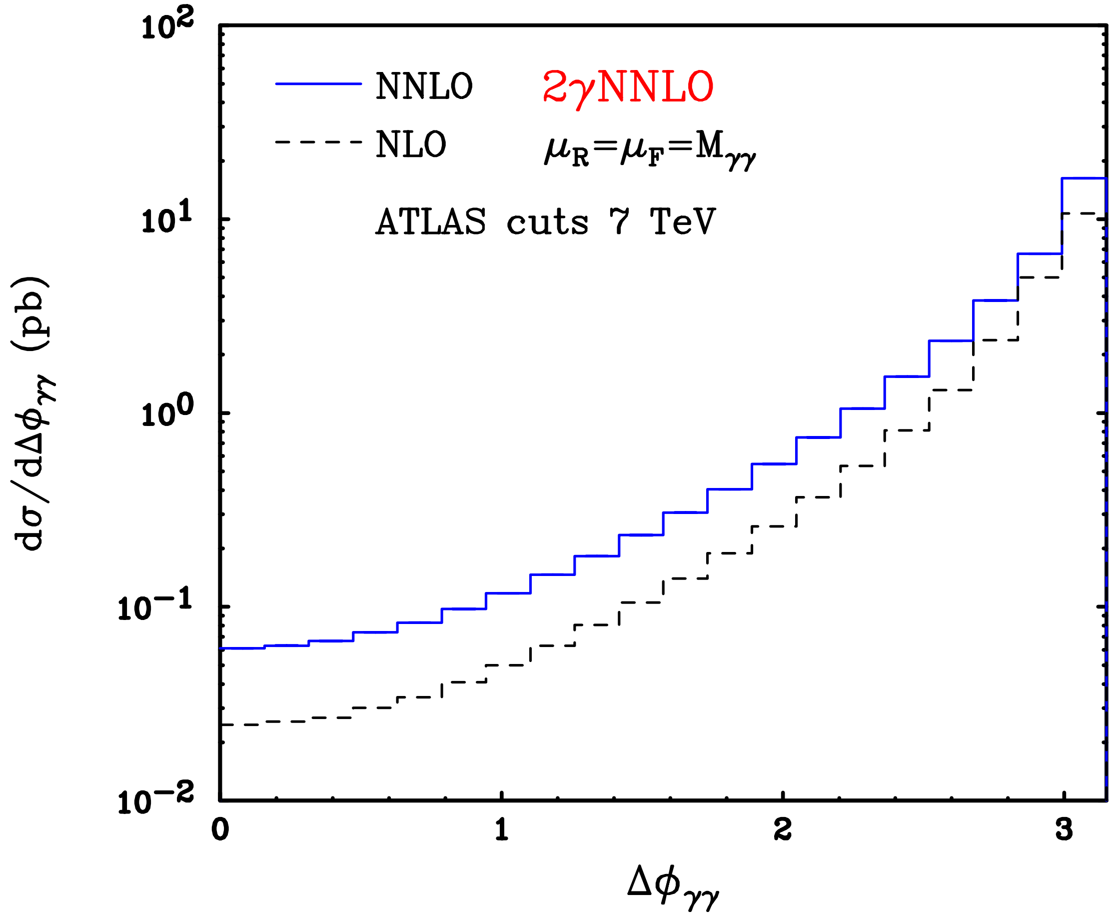
$O(\alpha_s^0)$ but $q\bar{q}$ Luminosity

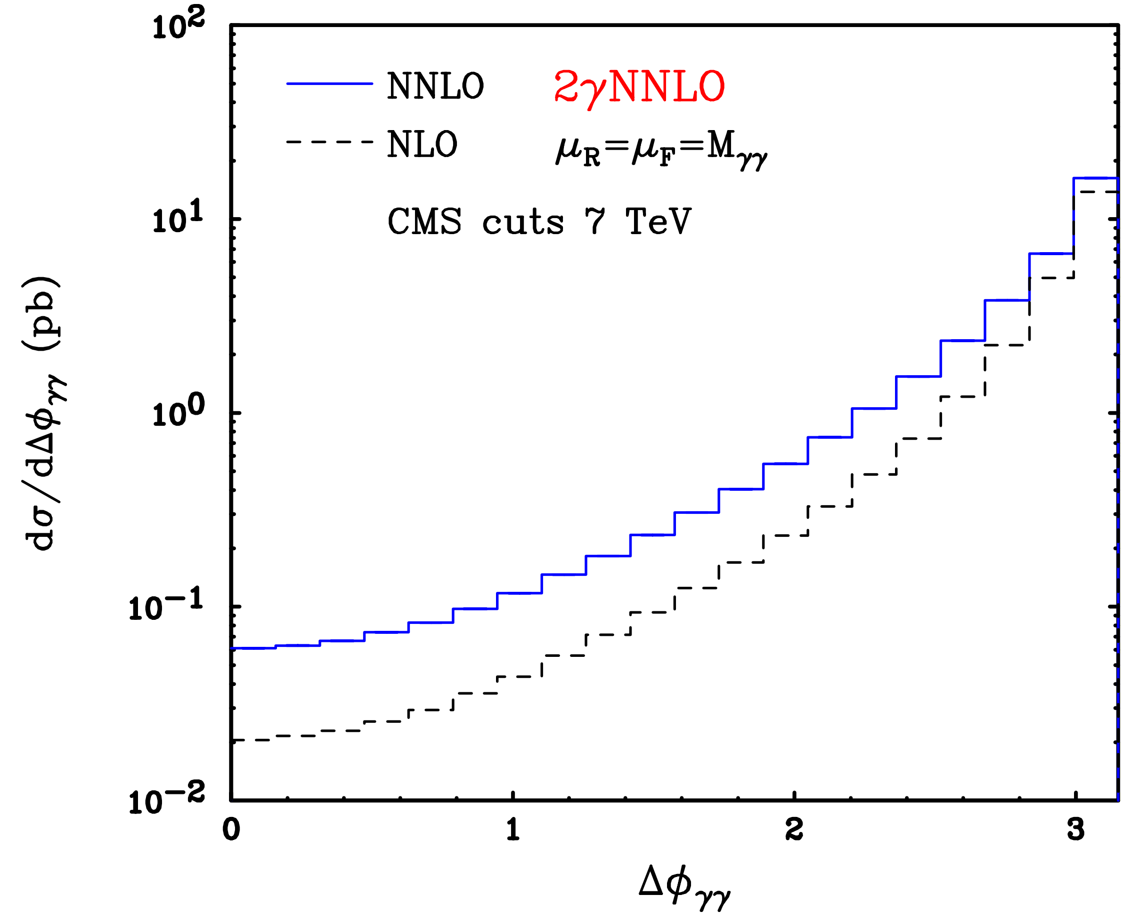
- Box contribution already included in NLO calculation

DIPHOX: T.Binoth, J.P.Guillet, E.Pilon, M.Werlen

- Full NNLO control of Di-photon production is desired (main light Higgs bkg)

With Higgs search cuts at 7 TeV





ATLAS cuts:

$$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$$
$$p_T^{\gamma\,soft} \geq 25\,\mathrm{GeV}$$
$$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$$
$$|\eta^\gamma| \leq 2.37$$
excluding $1.37 \leq |\eta^\gamma| \leq 1.52$
$$\epsilon = 0.05$$

CMS cuts:

$$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$$
$$p_T^{\gamma\,soft} \geq 30\,\mathrm{GeV}$$
$$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$$
$$|\eta^\gamma| \leq 2.5$$
excluding $1.4442 \leq |\eta^\gamma| \leq 1.566$
$$\epsilon = 0.05$$

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 ($z<1$)

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

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

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)