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

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Les Rencontres de Physique de la Vallée d'Aoste
March 2013

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MARIE CURIE ACTIONS

Outline

- Introduction
- Diphoton production with **2γNNLO**
- Summary

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

Outline

- Introduction
  - Why is diphoton production important?
  - Photon production mechanisms and isolation
- Diphoton production with **2γNNLO**
- Summary

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

Outline

- Introduction
- Diphoton production with **2γNNLO**
  - Features of the code
  - Results
- Summary

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

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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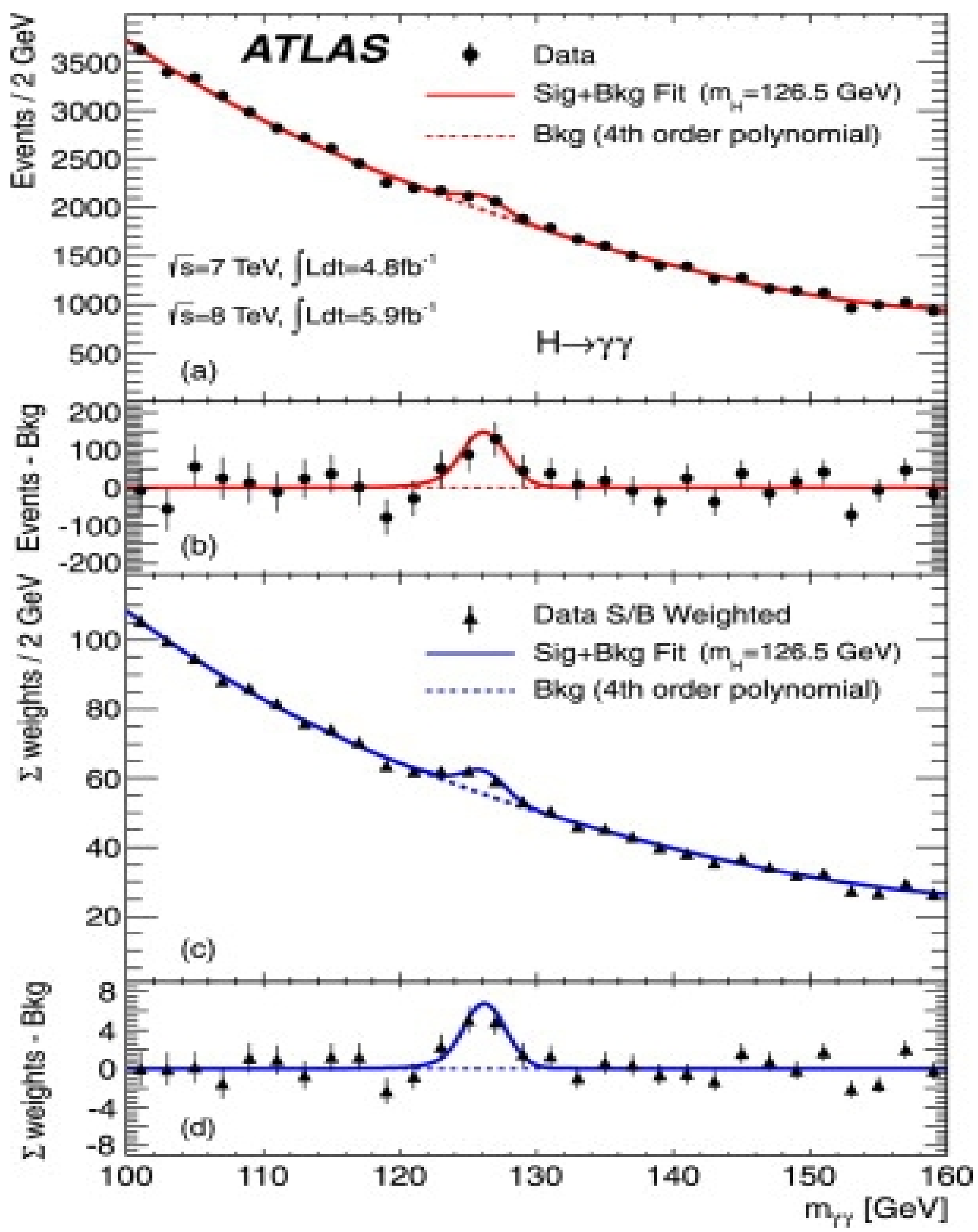
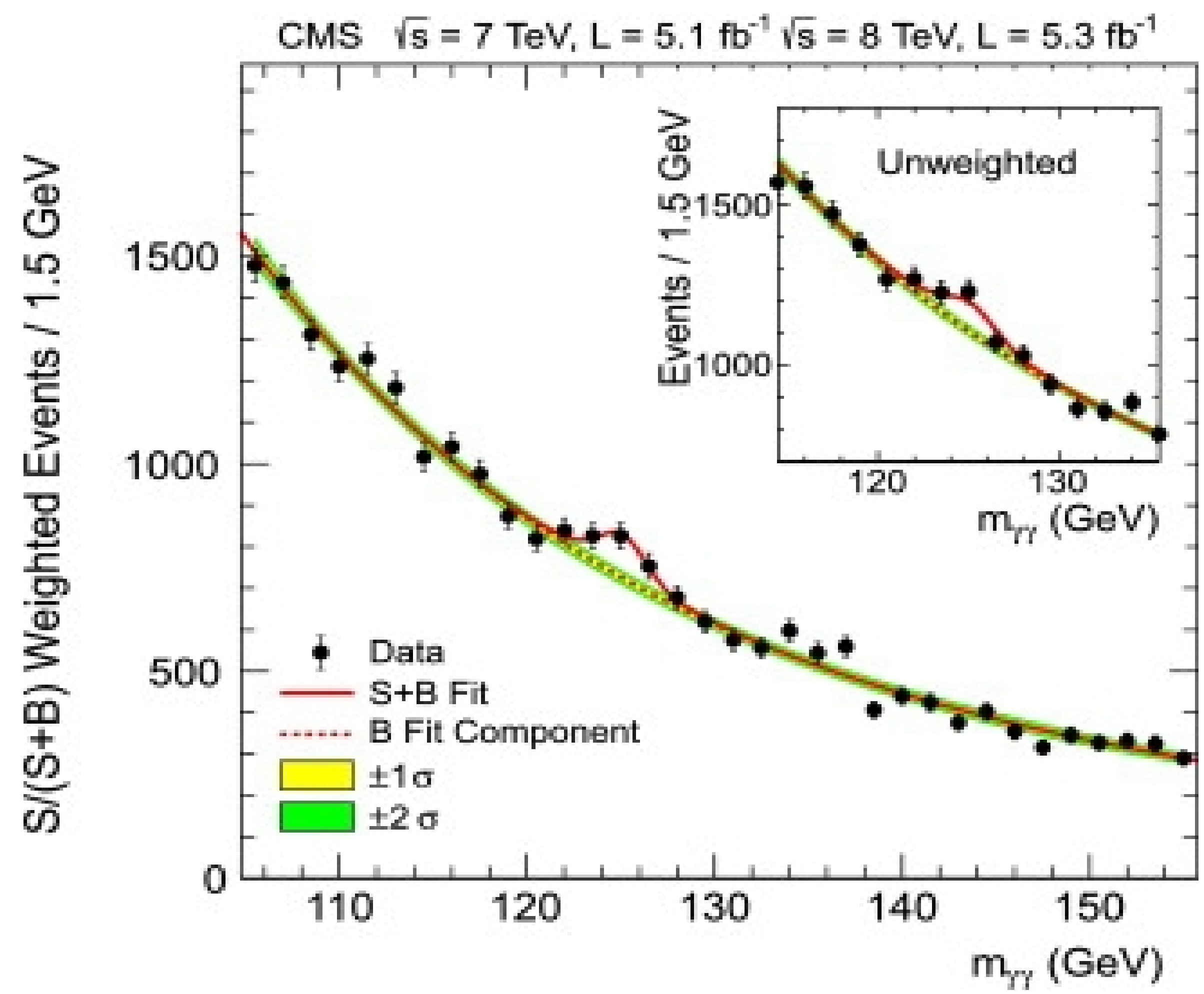
The search for the SM Higgs boson

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

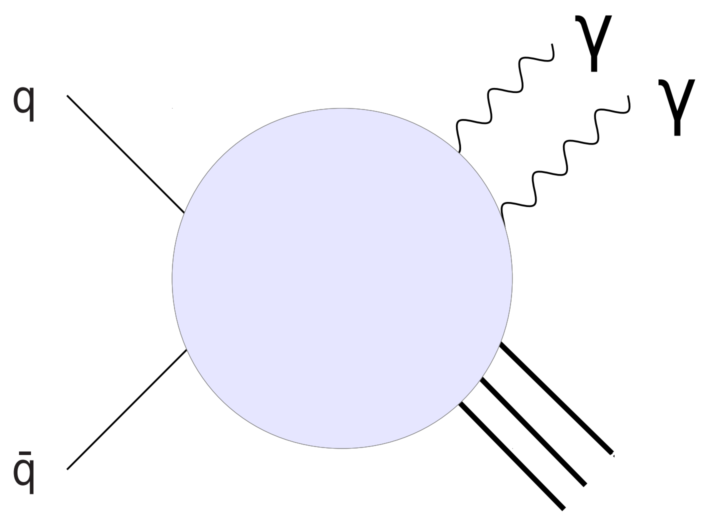




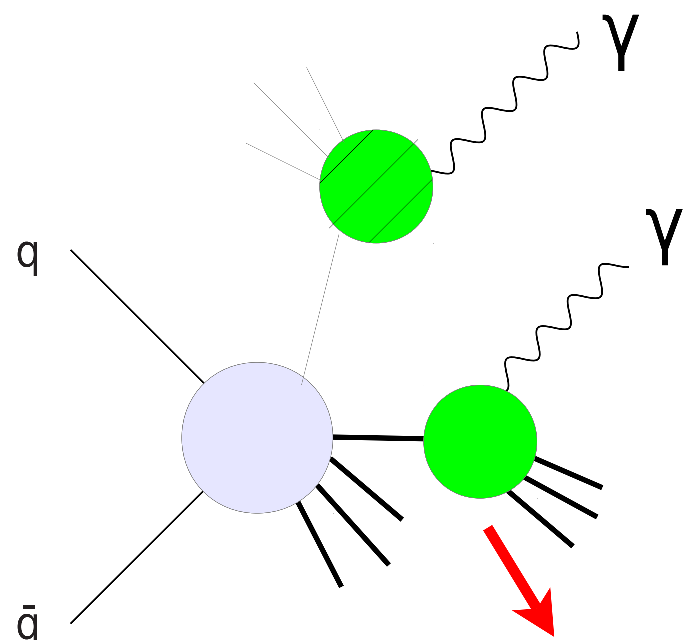
Phys.Lett. B716 (2012) 1-29 (ATLAS)
Phys.Lett. B716 (2012) 30-61 (CMS)

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)

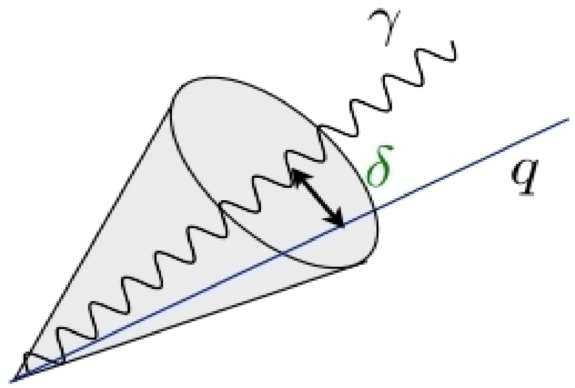
Calculations of cross sections with photons have additional singularities in the presence of QCD radiation.
(i.e. When we go beyond LO)

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.

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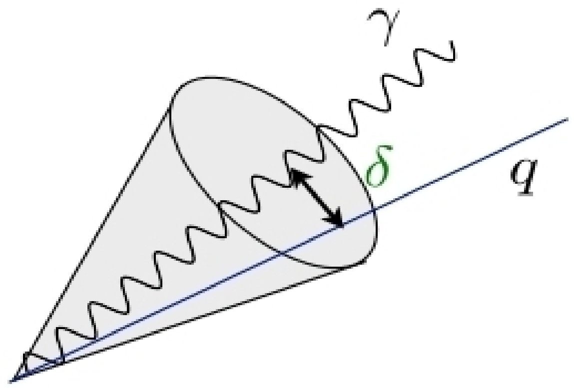


$$\sum_{\delta<R_0} E_T^{had} \leq E_T^{max}$$

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

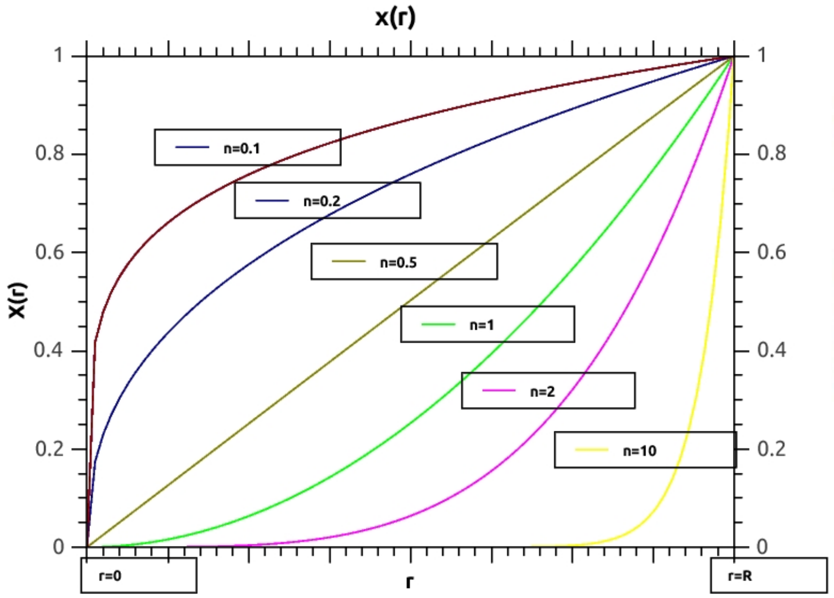
S. Frixione, Phys.Lett. B429 (1998) 369–374,

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

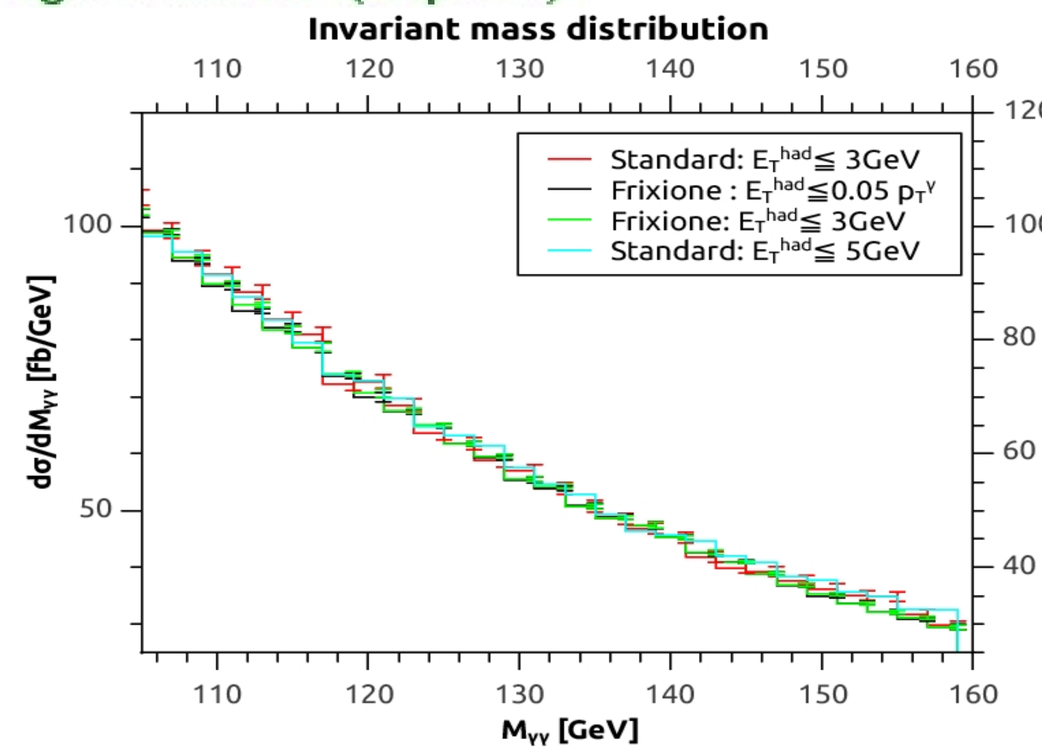
More restrictive than usual cone : lower limit on cross section (close for small R)

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

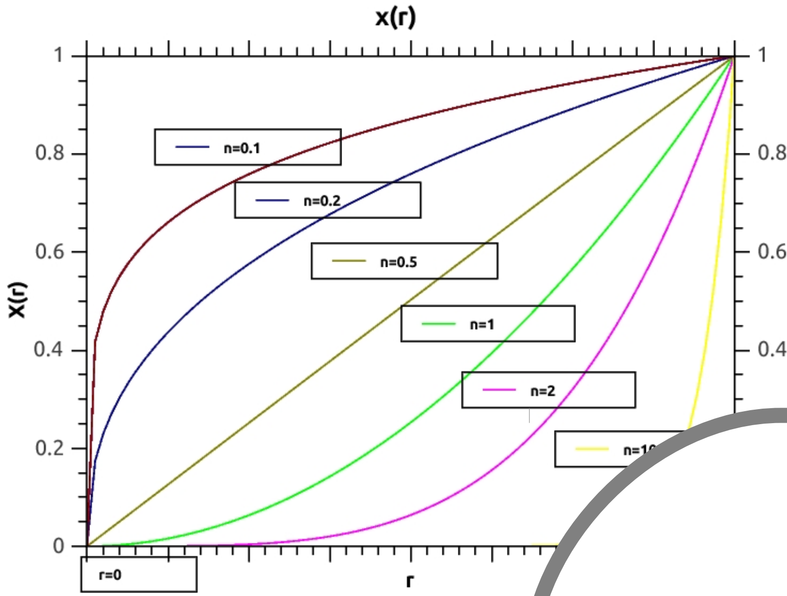
CMS Higgs cuts at 7 TeV

$E_{T\,max}^{had}$	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



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

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

S.Frixione

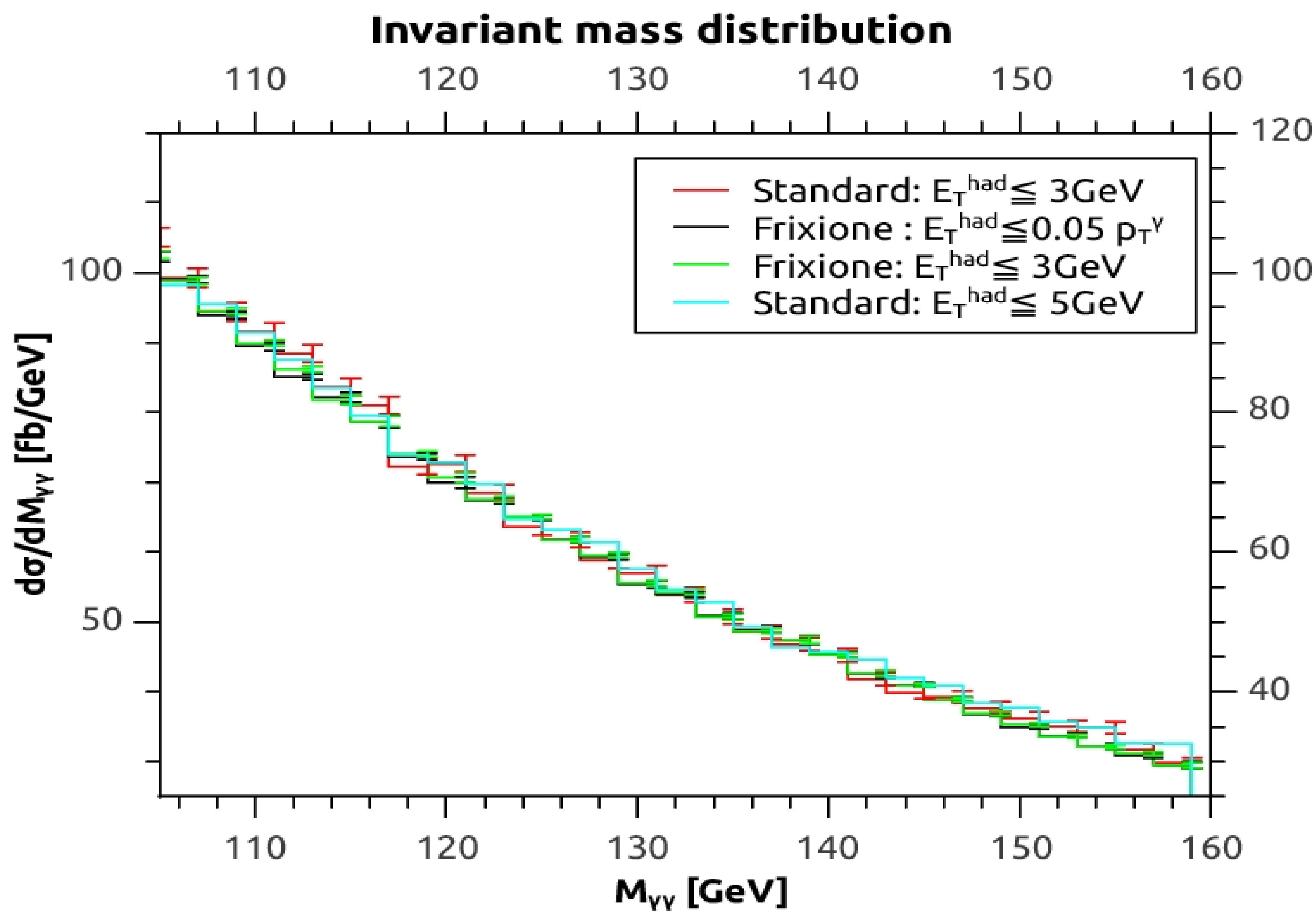
$\chi(\delta) = \left(\frac{1 -}{1 -}\right.$

More restric

In real (TH

CMS Higgs cut

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



if isolation tight enough,

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

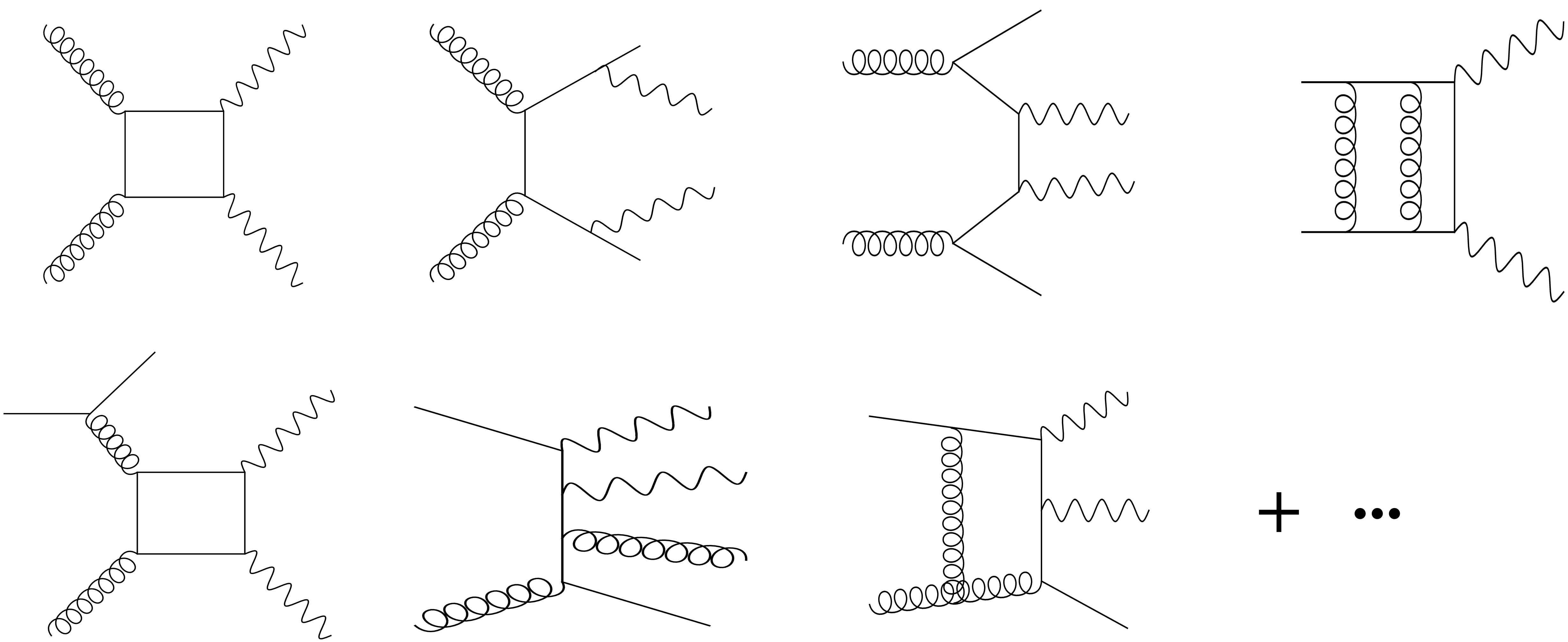
Frixione Isolation

- 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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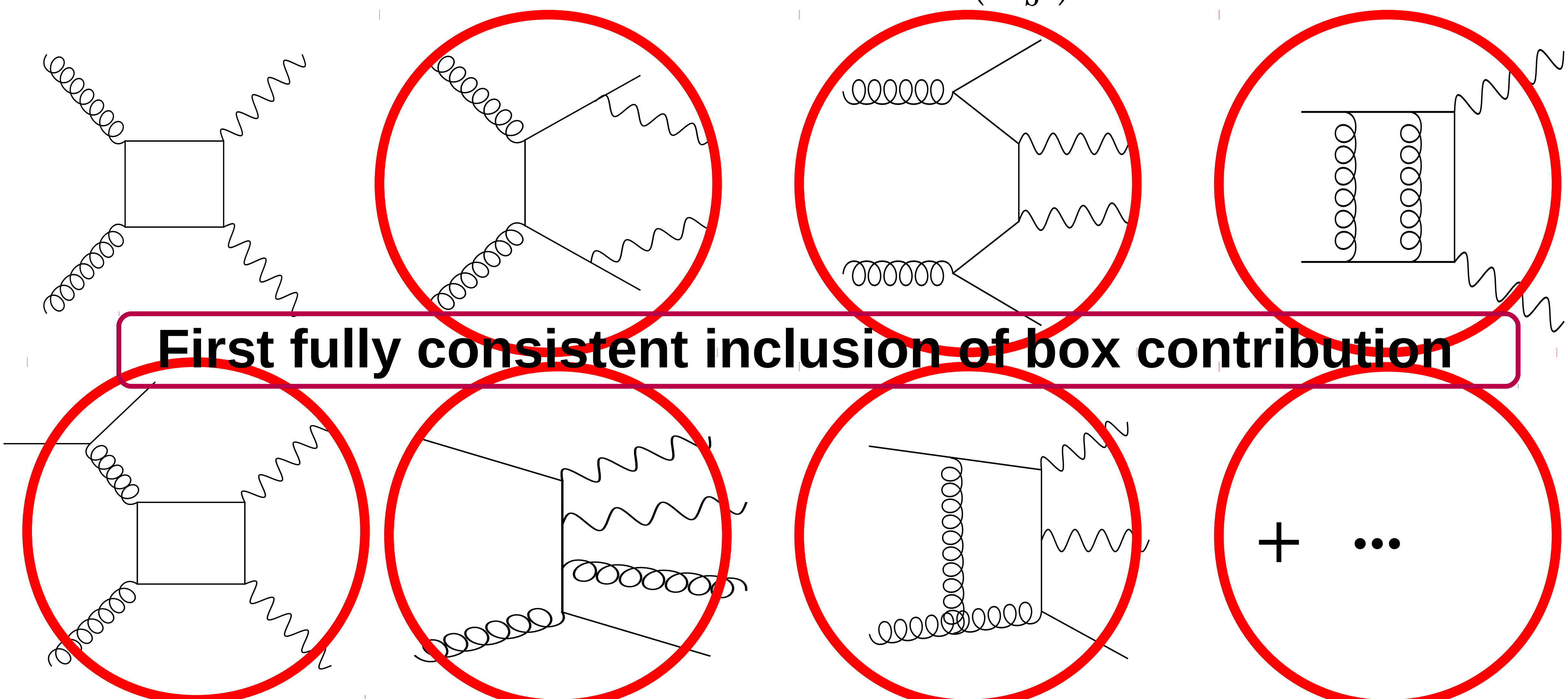


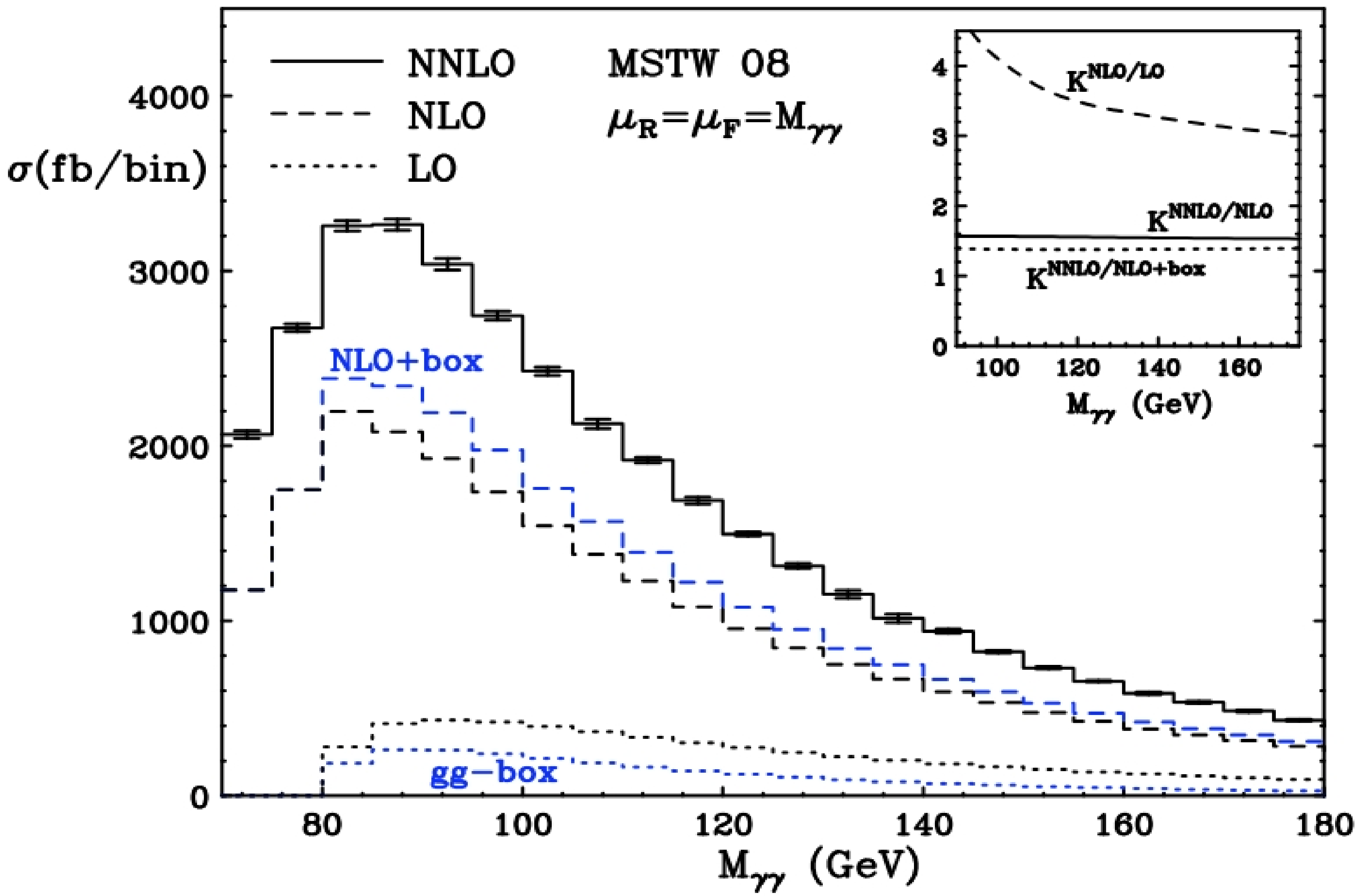
First fully consistent inclusion of box contribution

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 $2\gamma\mathrm{NNLO}$



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

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

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

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

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

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

NNLO effect about +50 % in the peak region

Box only ~22% of NNLO correction

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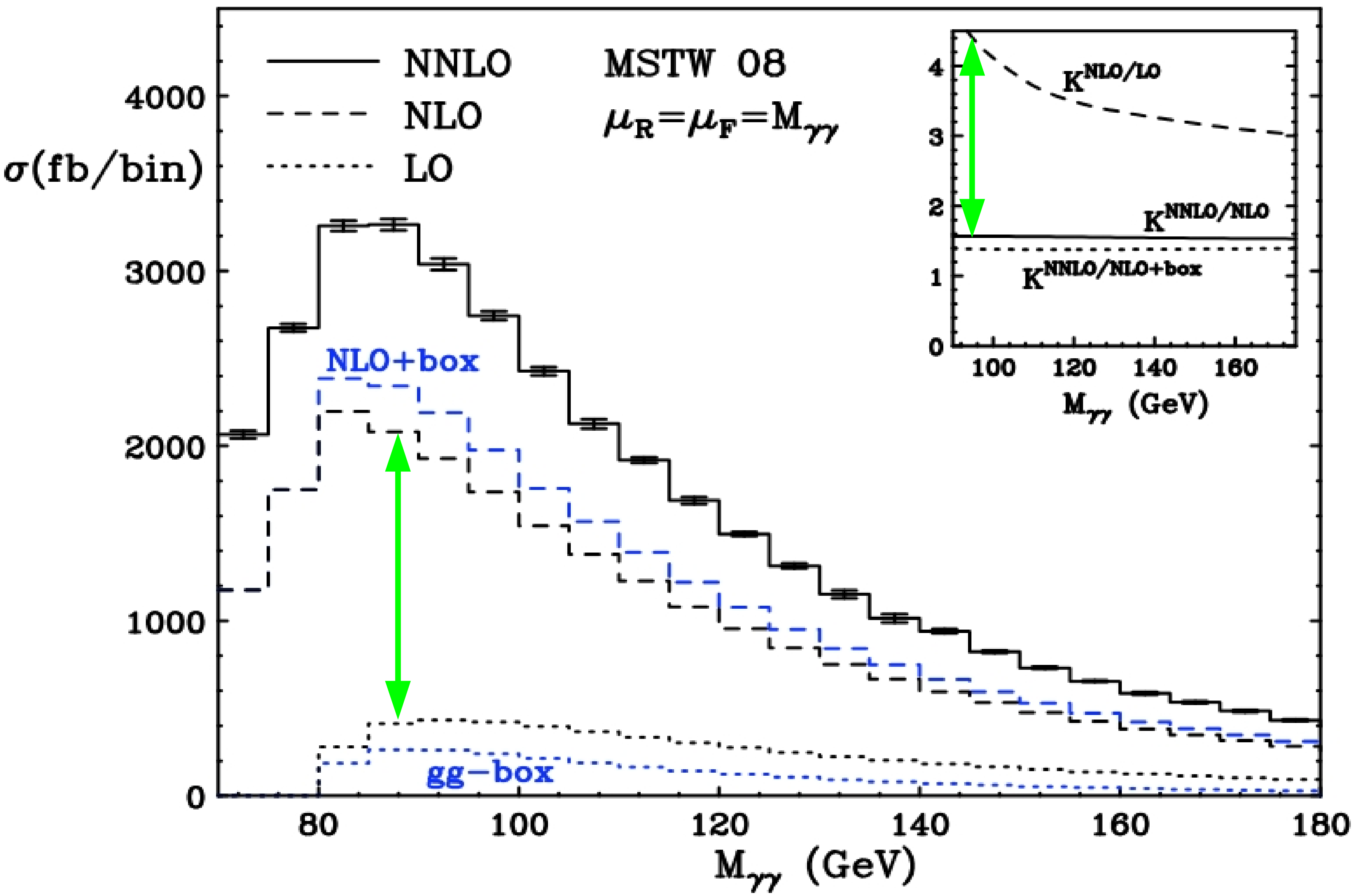

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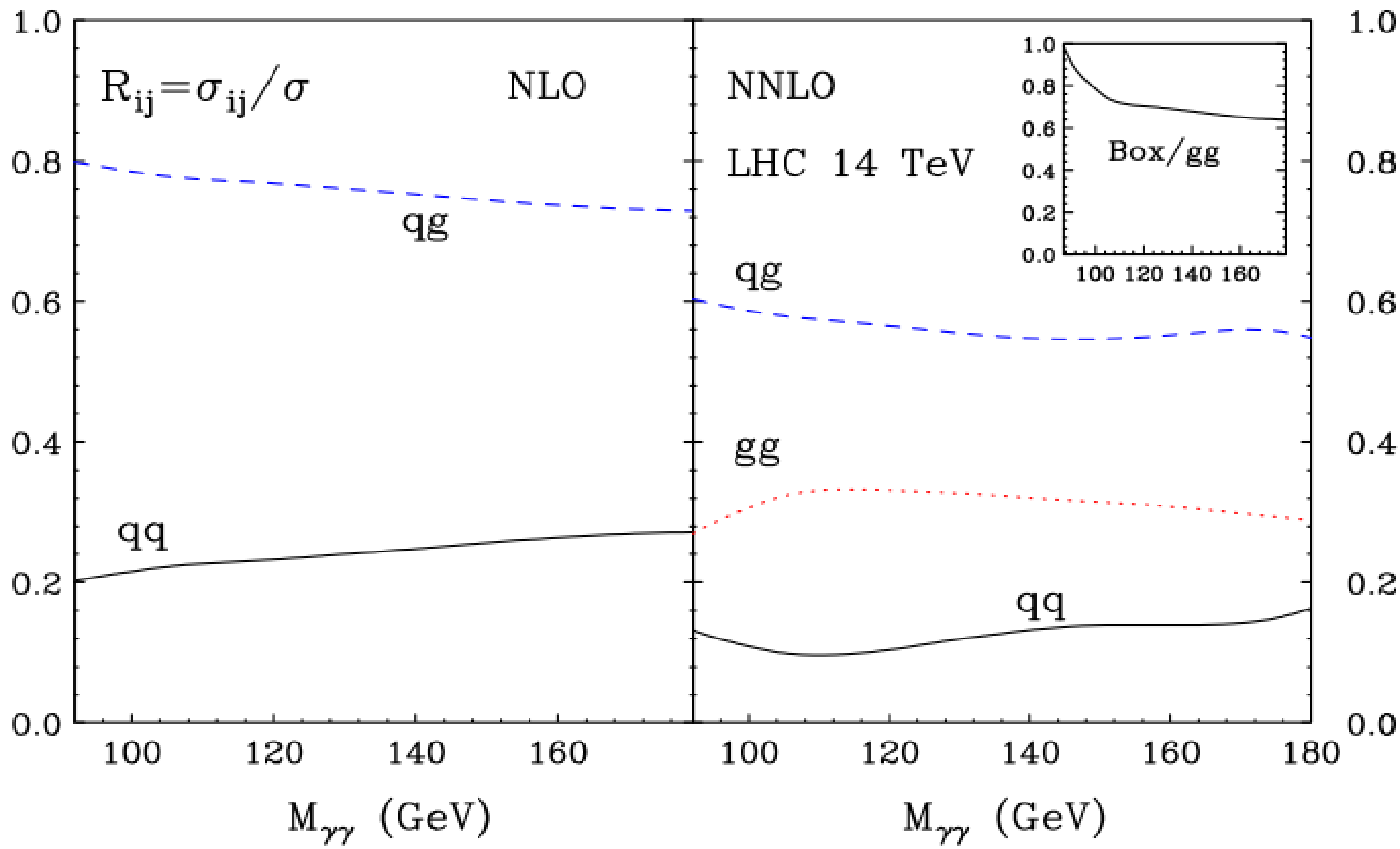
$\mu_R = \mu_F = M_{\gamma\gamma}$

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

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

Huge corrections 1 : new channels

Channels @ 14 TeV



Box only ~22% of NNLO correction

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

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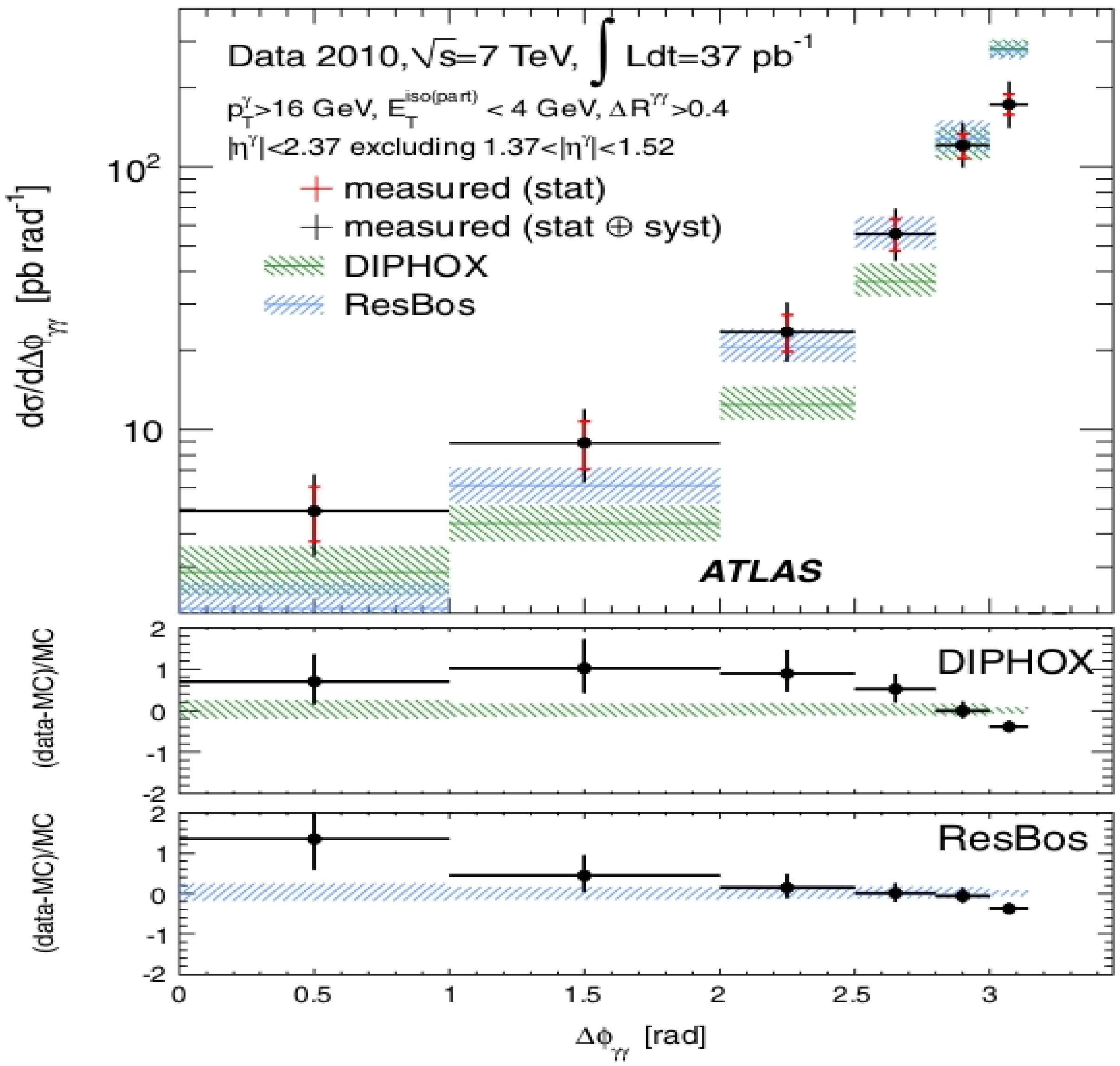
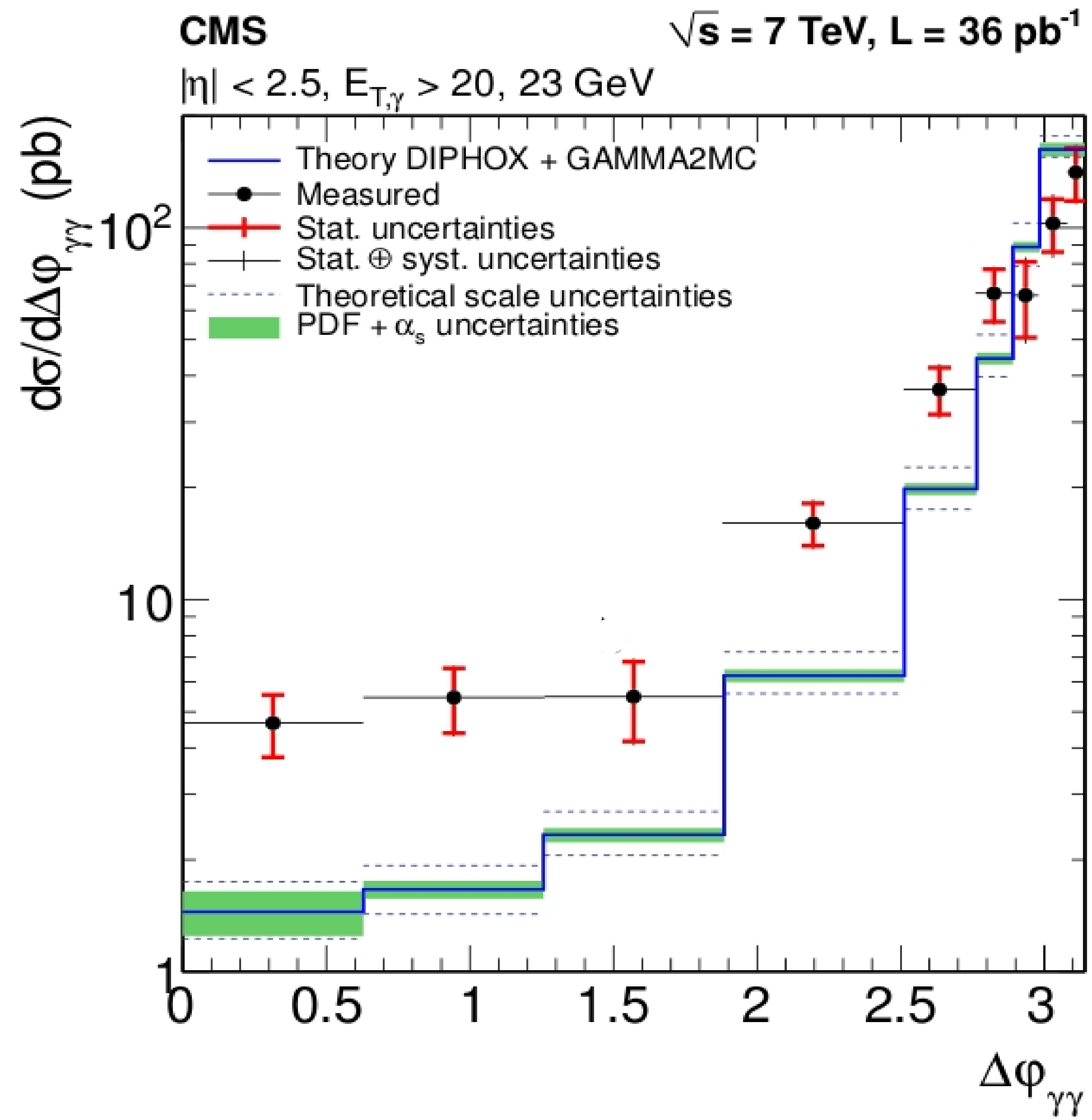
First exclusive NNLO with two final state particles

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.

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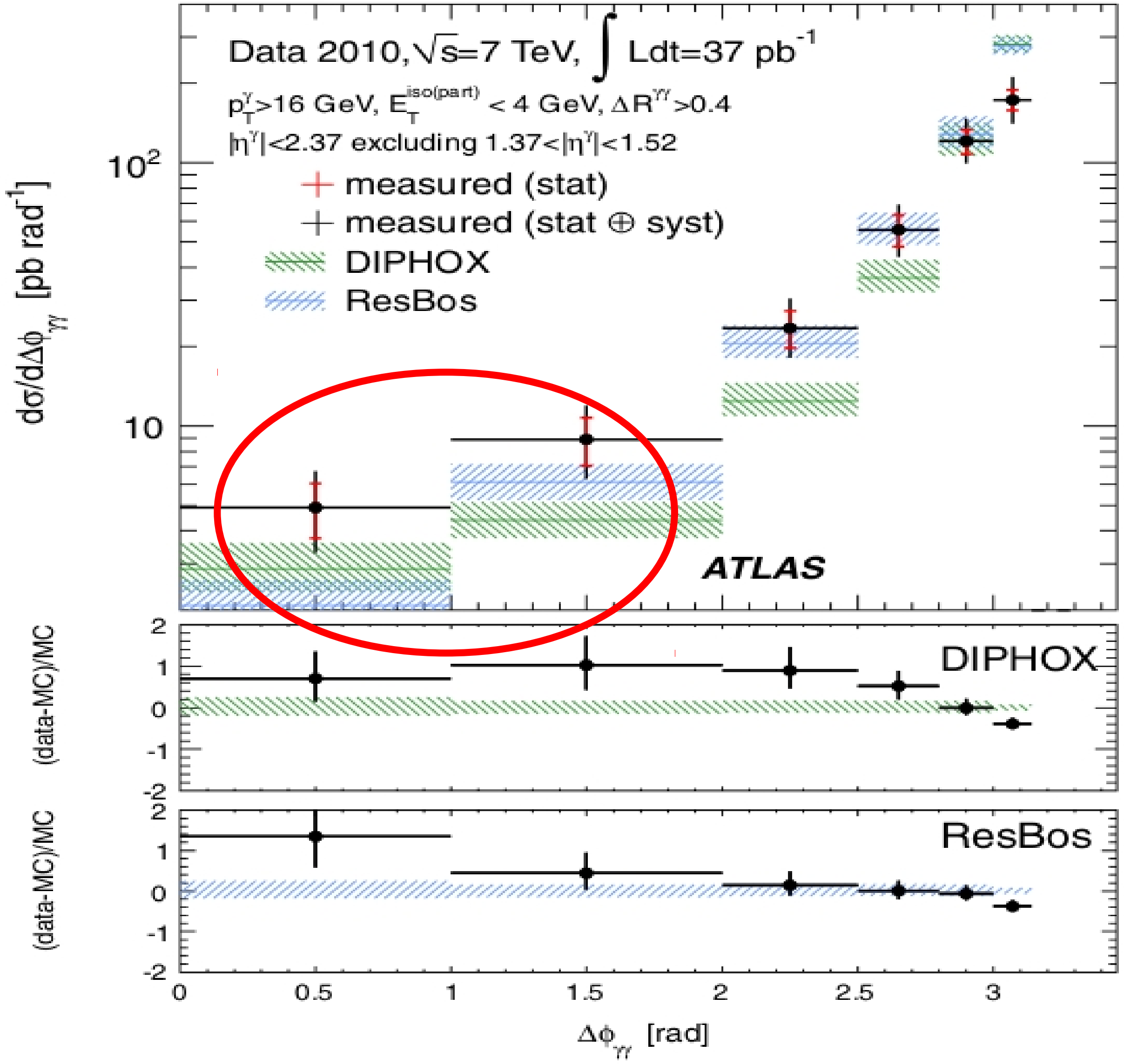

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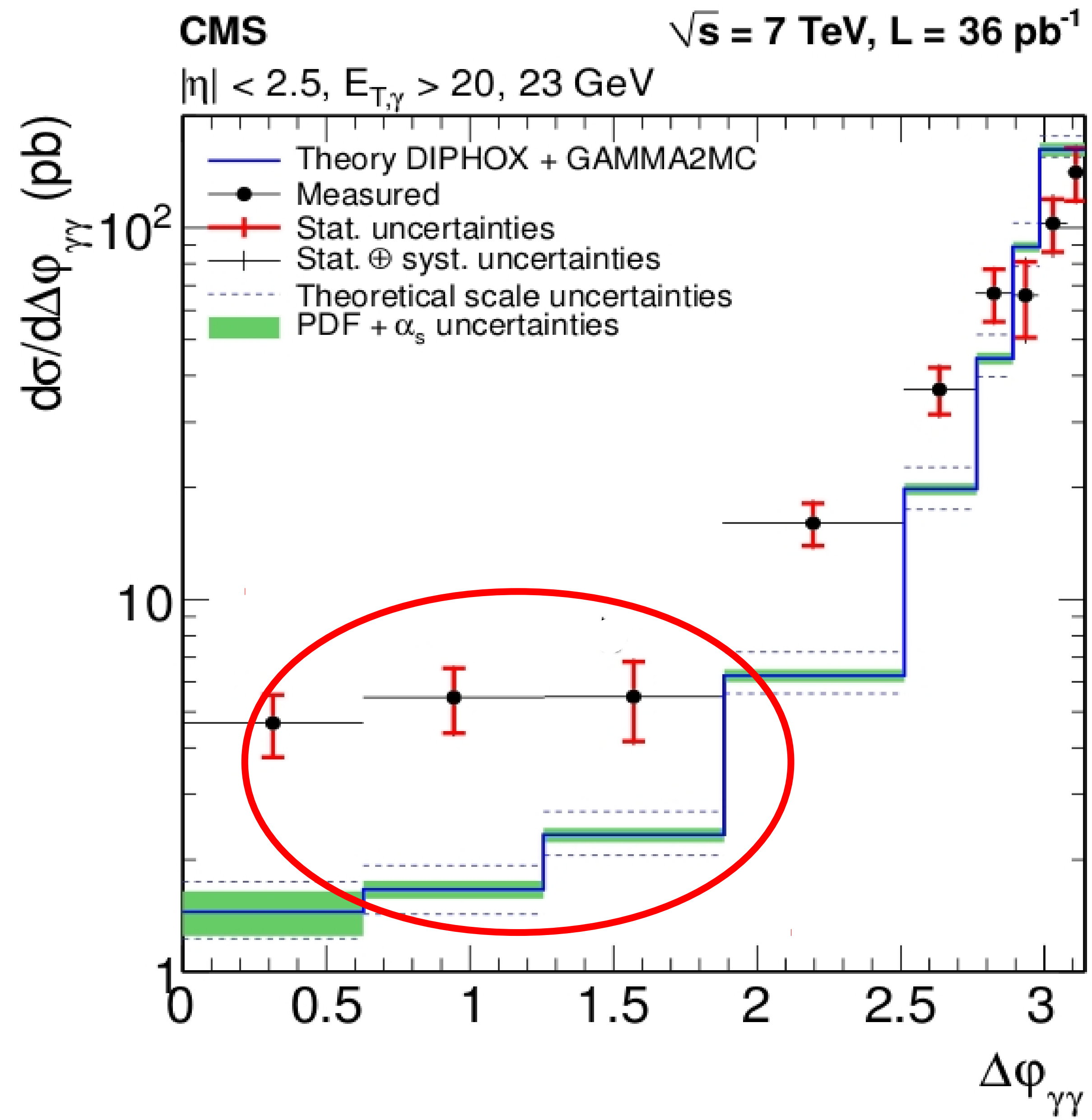

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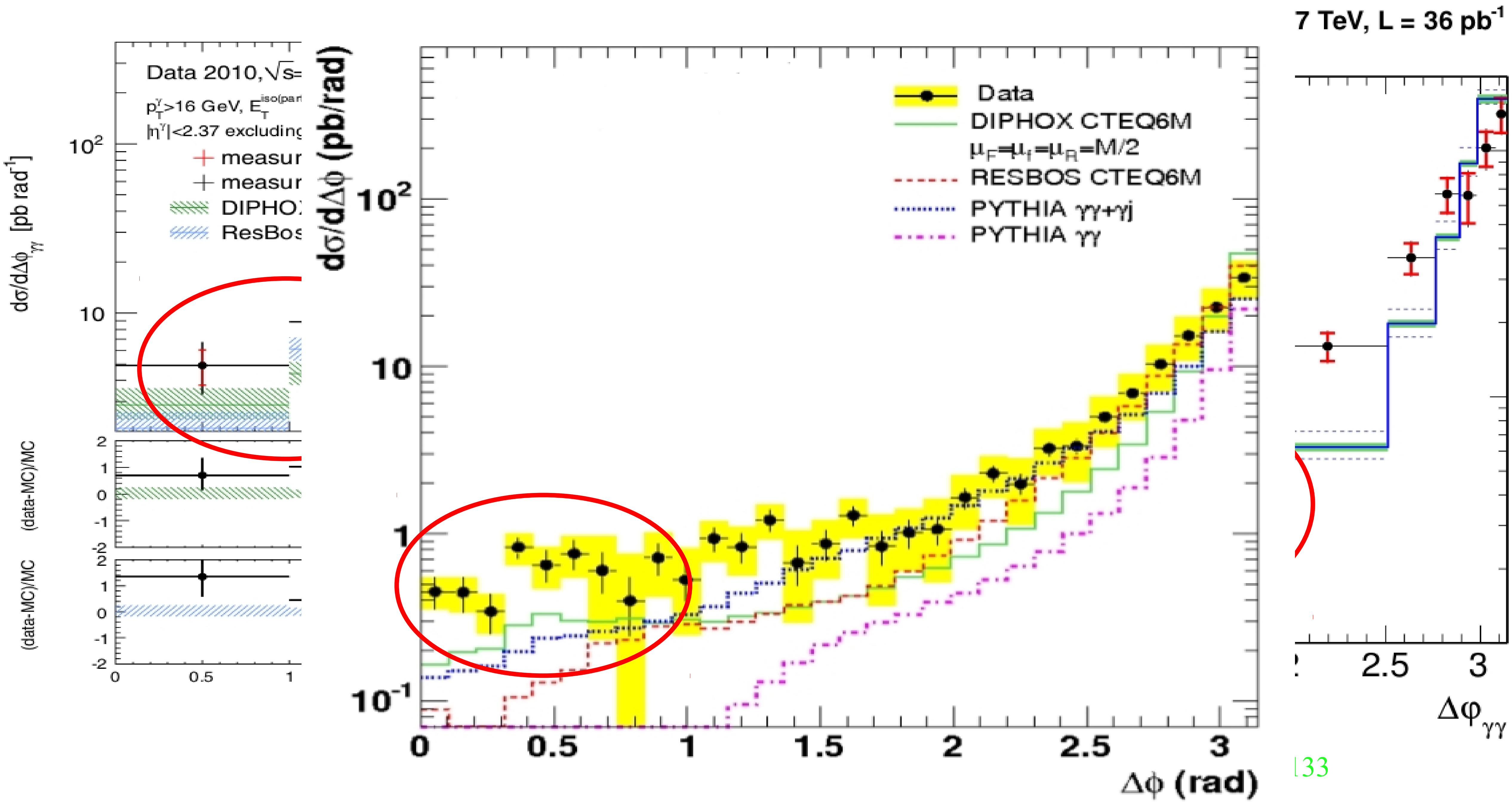

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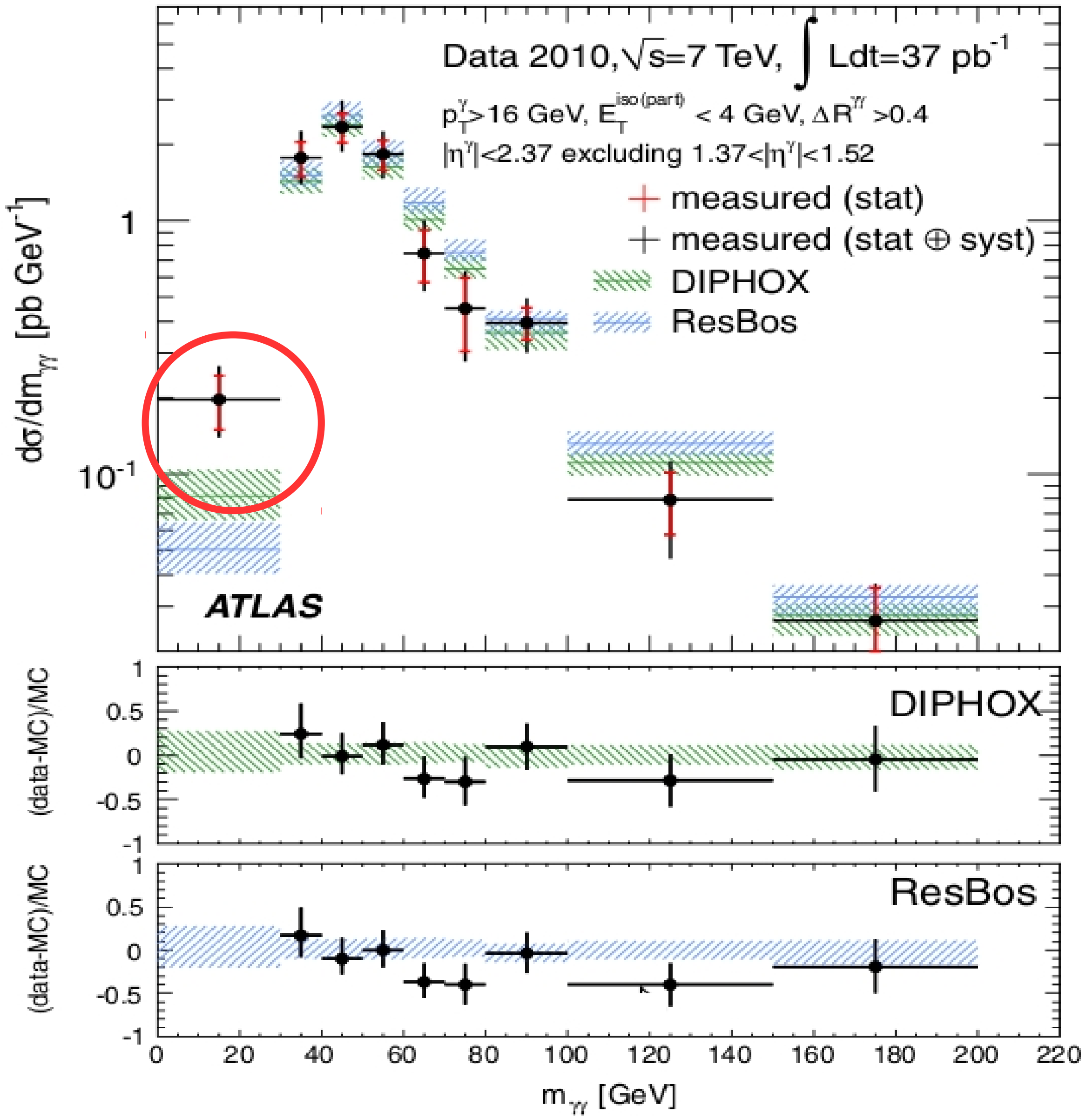

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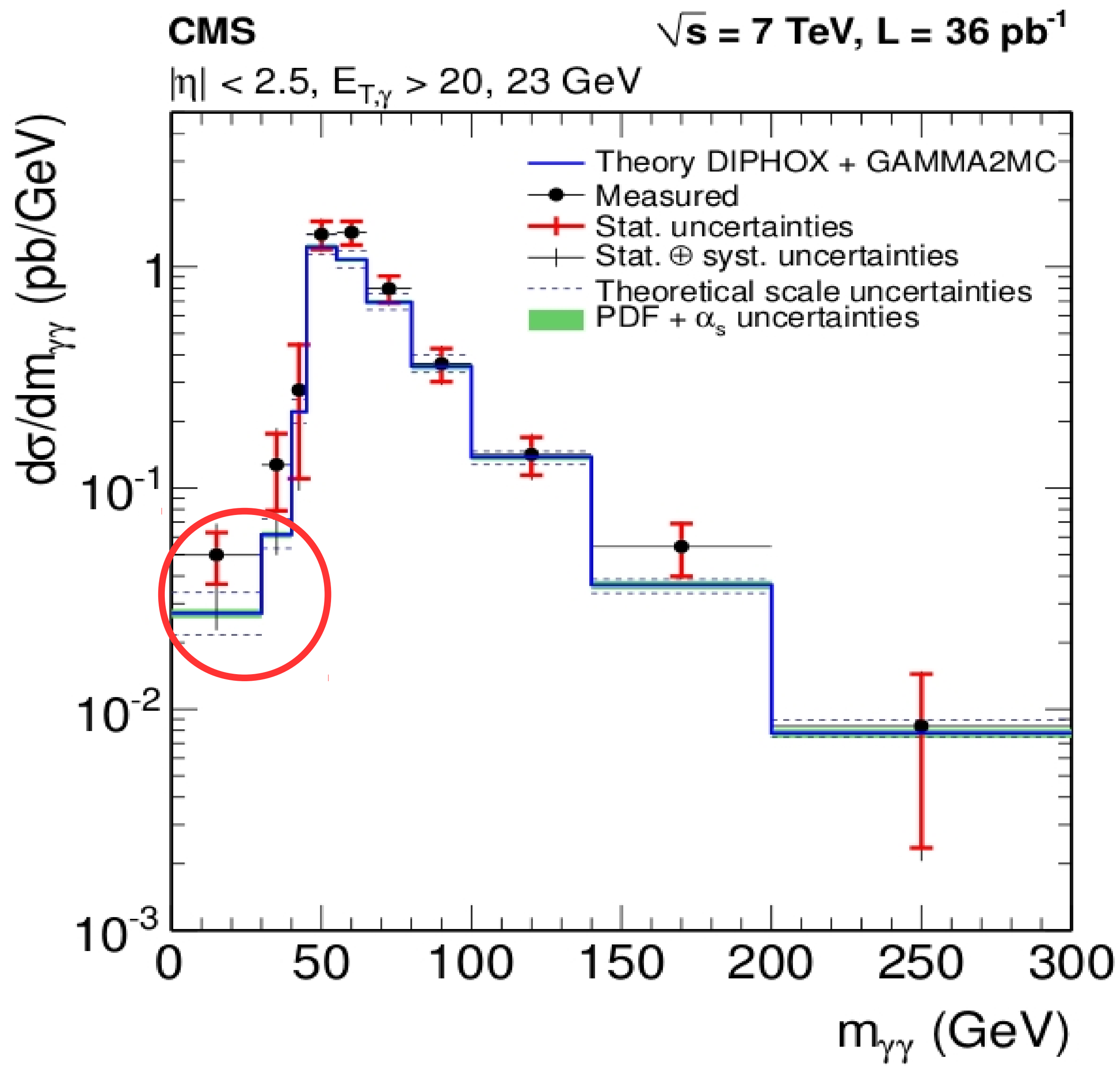

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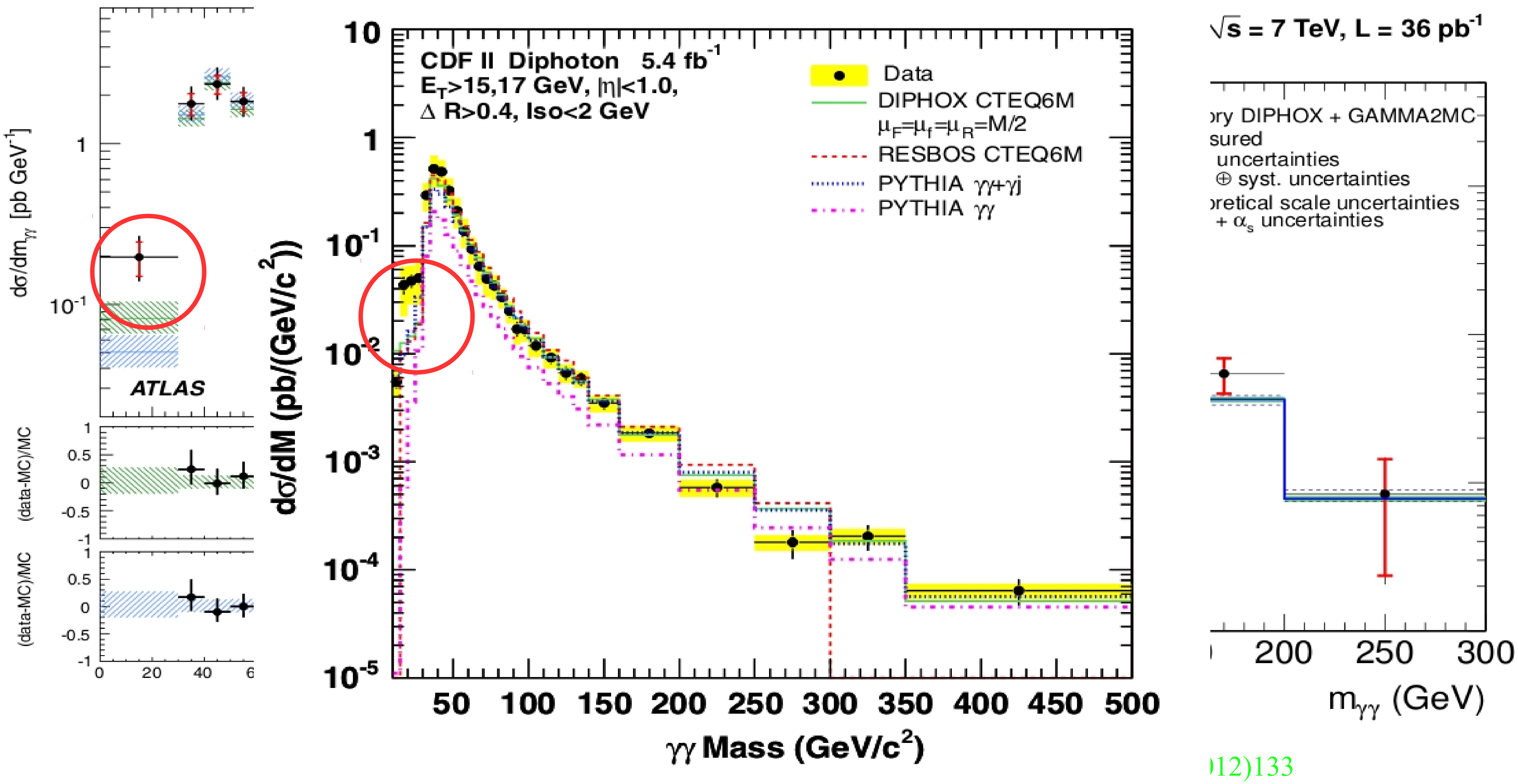

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Diphoton production at NNLO

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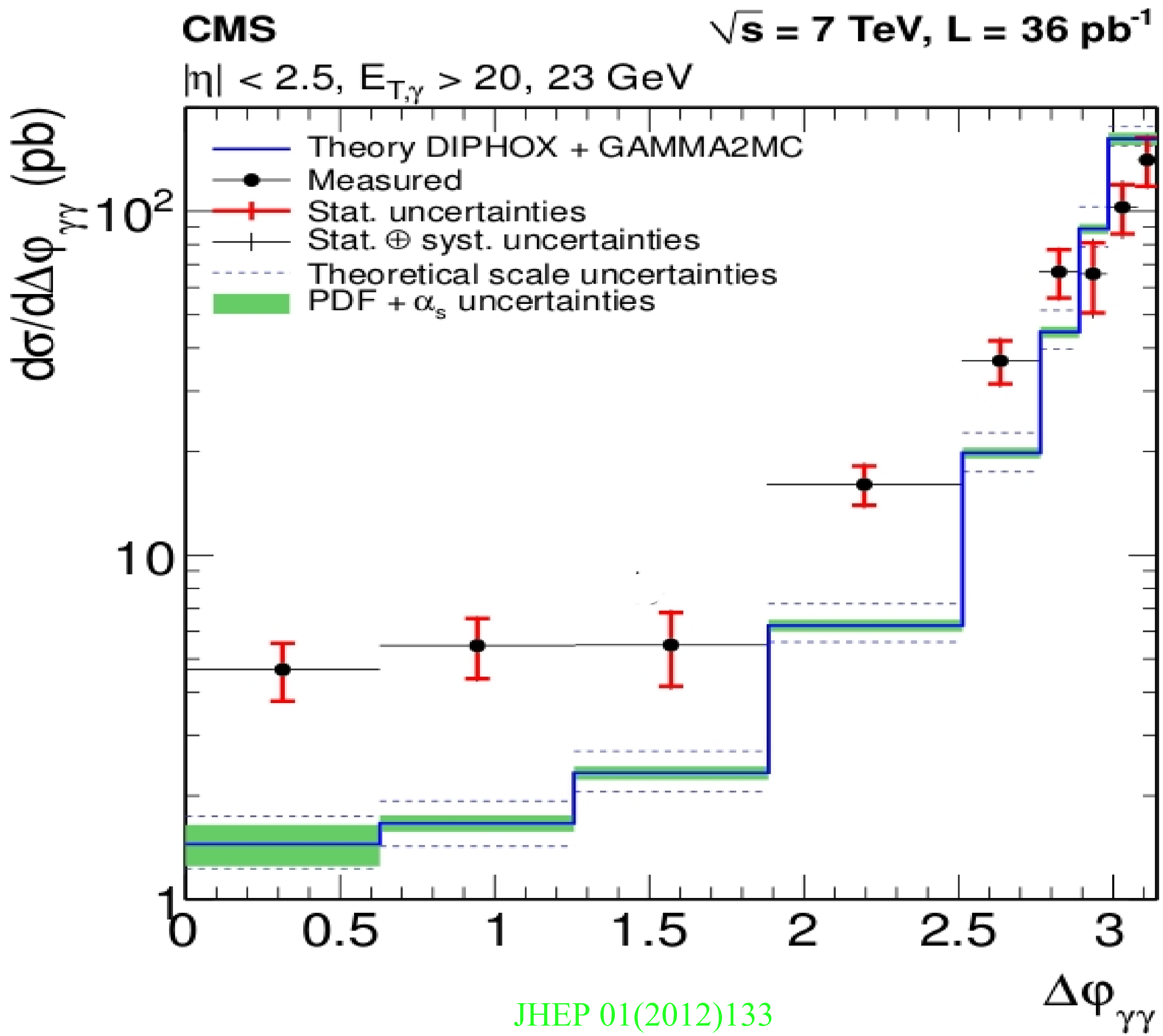
First exclusive NNLO with two final state particles

Discrepancy between NLO and experimental data at low $\Delta\varphi$



Standard Cone Isolation

JHEP 01(2012)133

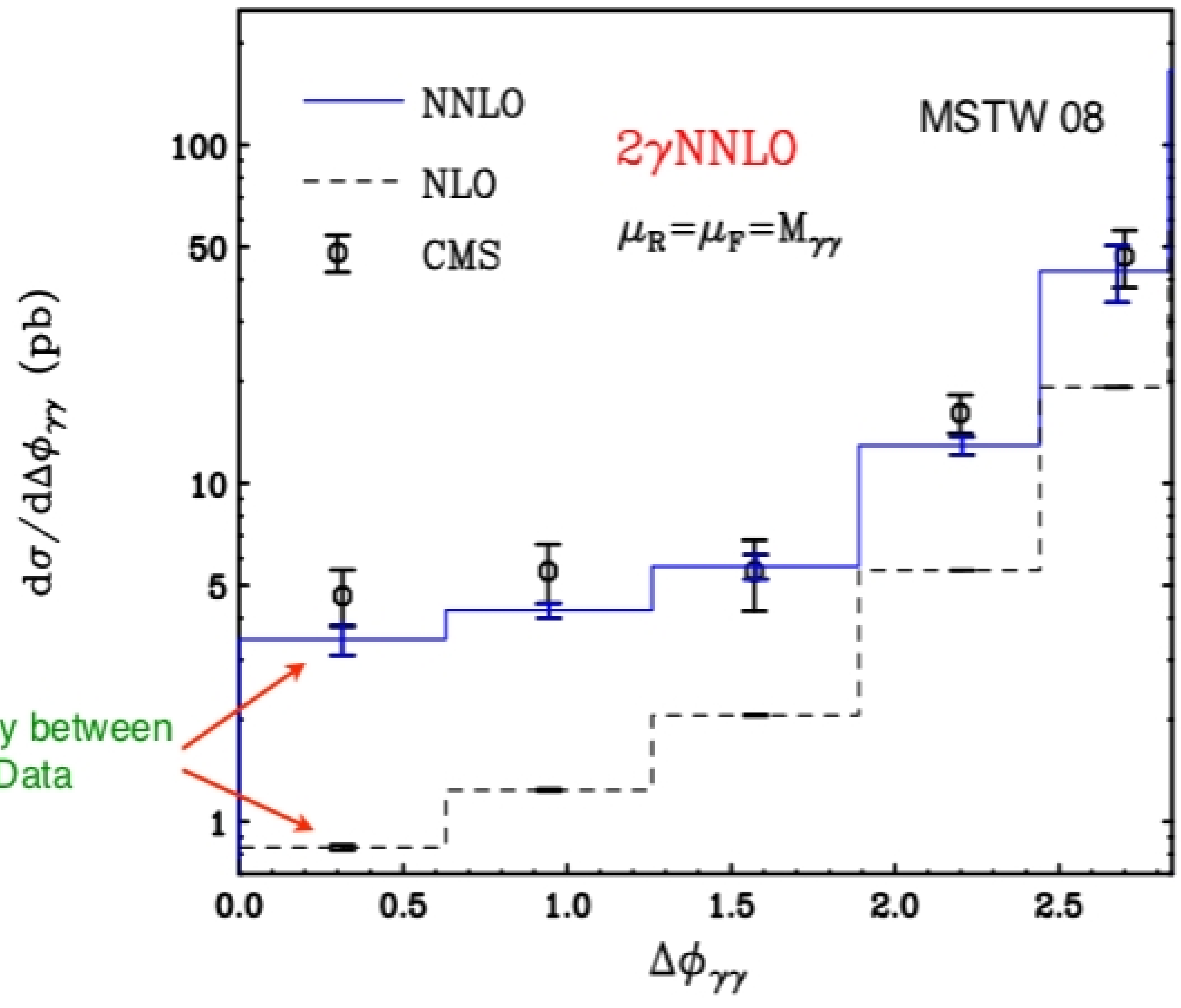
Diphoton production at NNLO

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

Preliminary results

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

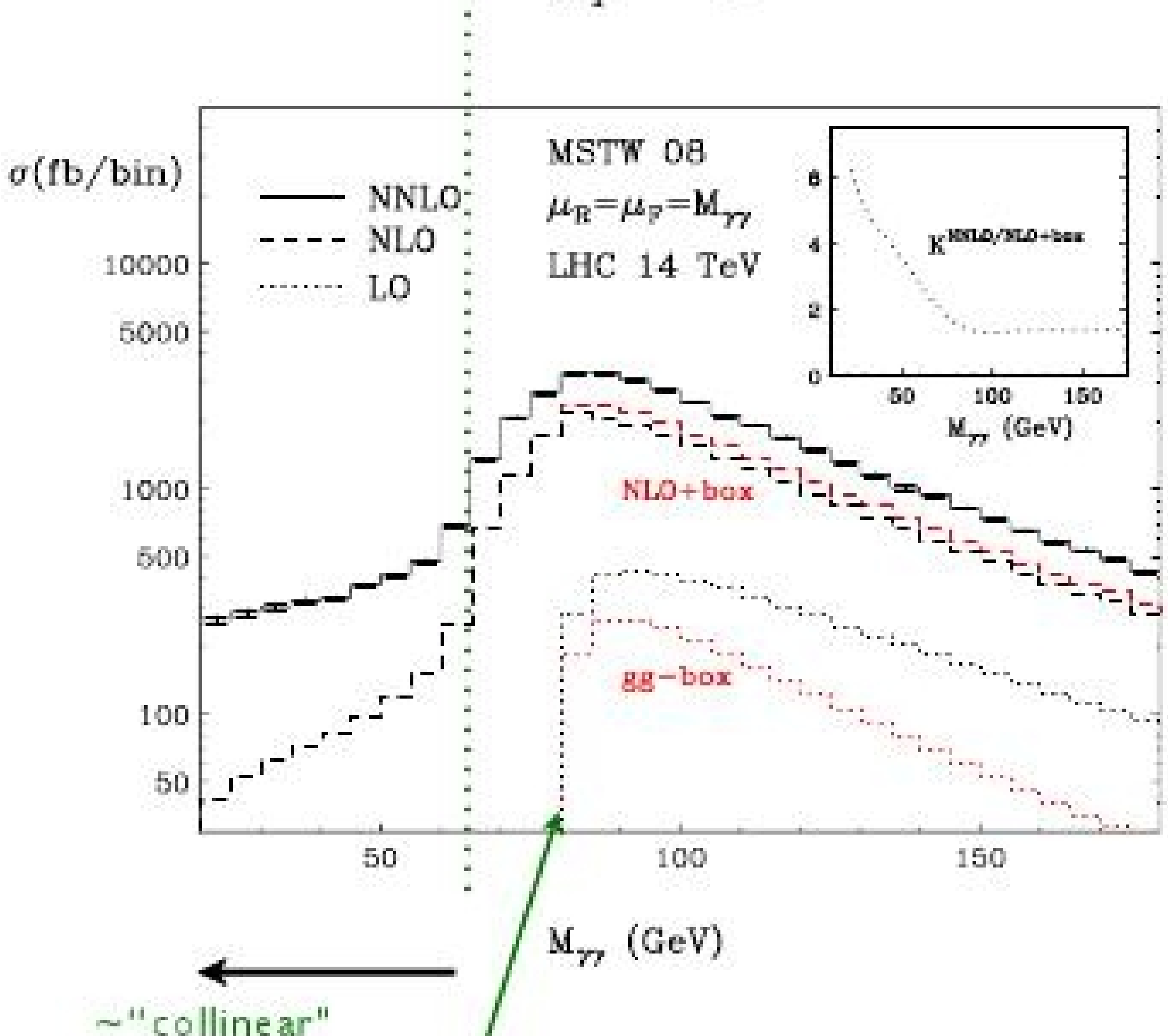
$\varepsilon=0.05$

NNLO corrections essential to understand the background invariant mass below the LO threshold

$\sqrt{S} = 14$ TeV

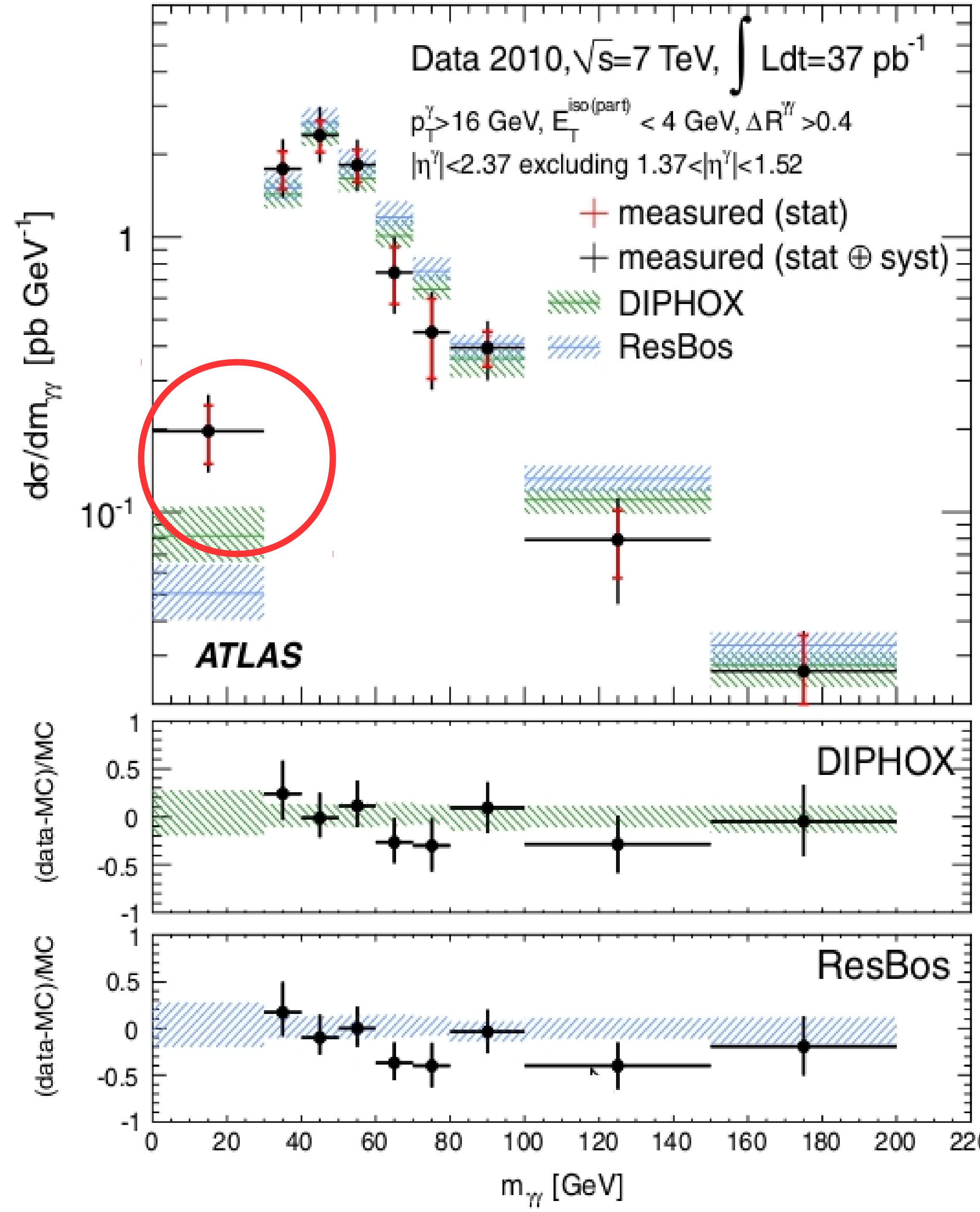
$p_T^{\gamma\, hard} \geq 40$ GeV

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



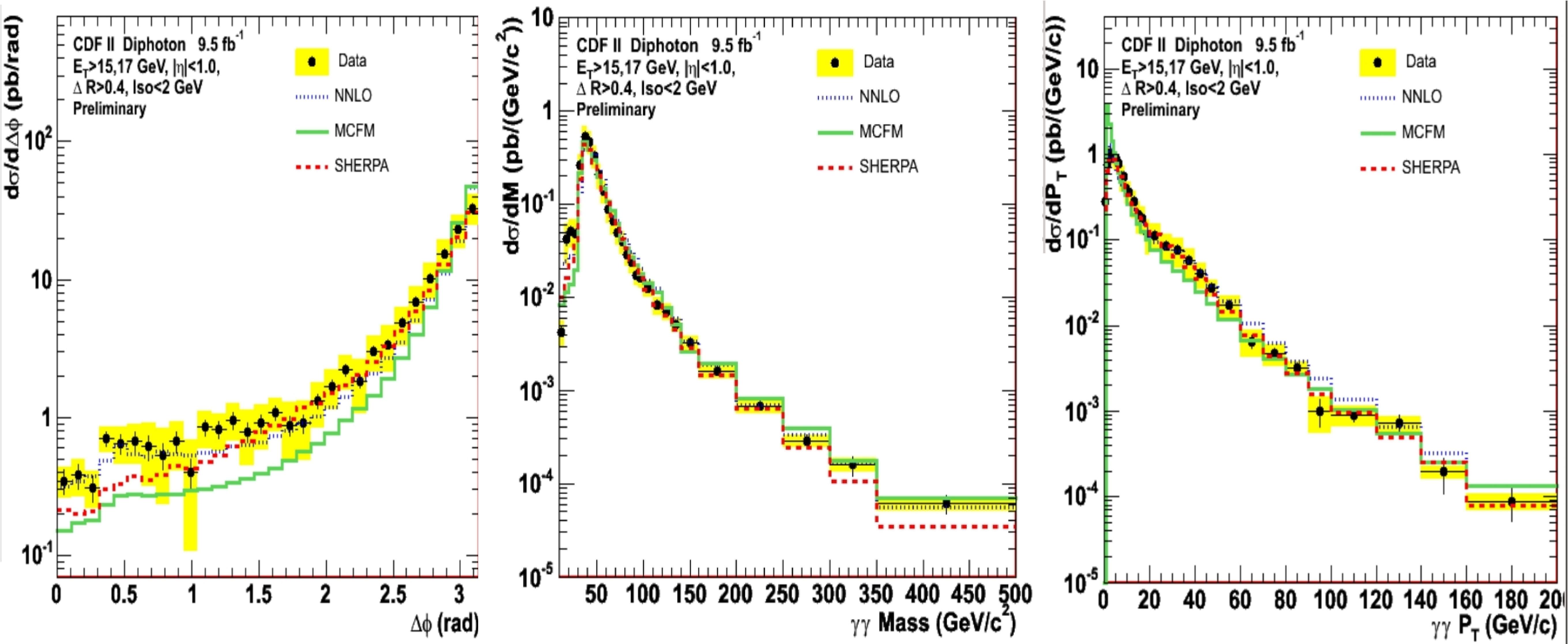
LO threshold at 80 GeV

"No back-to-back"



This discrepancy can be related to the discrepancy observed in the Δφ distribution.

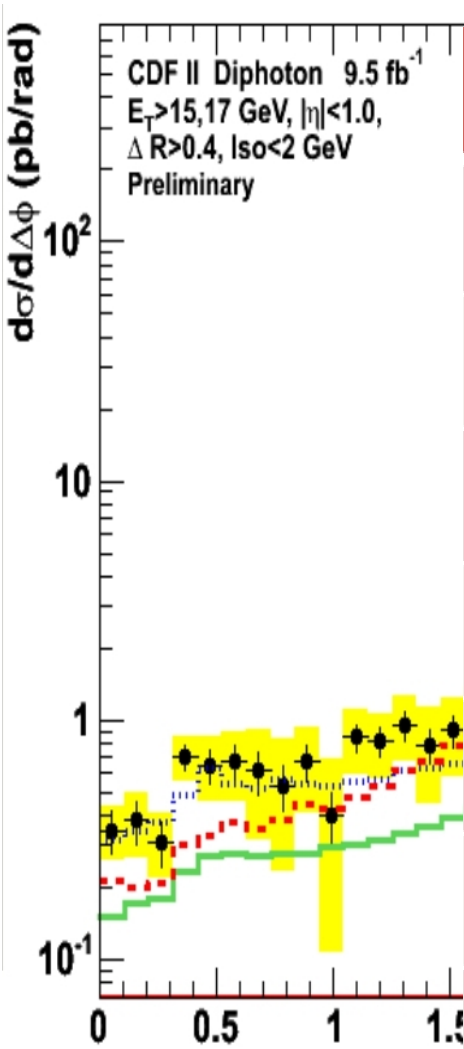
Preliminary comparison CDF 9.5 fb^{-1} results



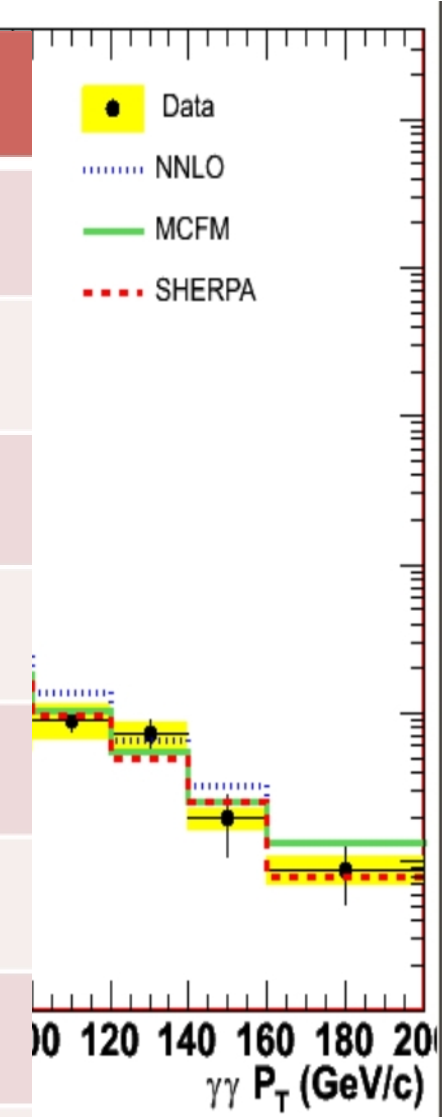
$P^{\gamma}_{T\ harder} \geq 17GeV$ $P^{\gamma}_{T\ softer} \geq 15GeV$ Isolation(Parameters): R=0.4 ; $E_{t\ max} = 2$ GeV

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

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	$11.8 + 1.7 - 0.6$



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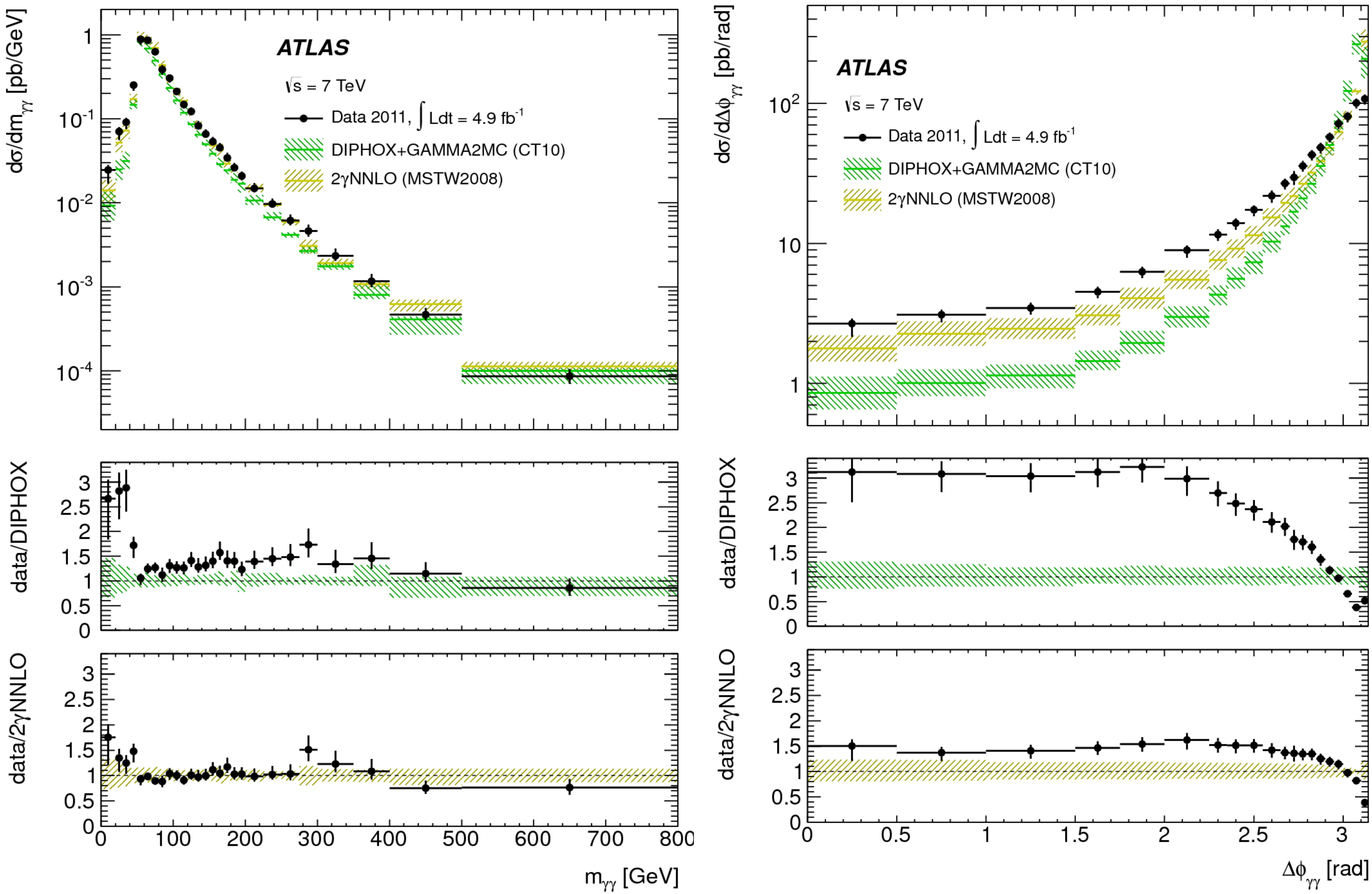
$|\eta| \leq 1$ $R_{\gamma\gamma} \geq 0.4$

ATLAS results

arXiv:1211.1913 [hep-ex].



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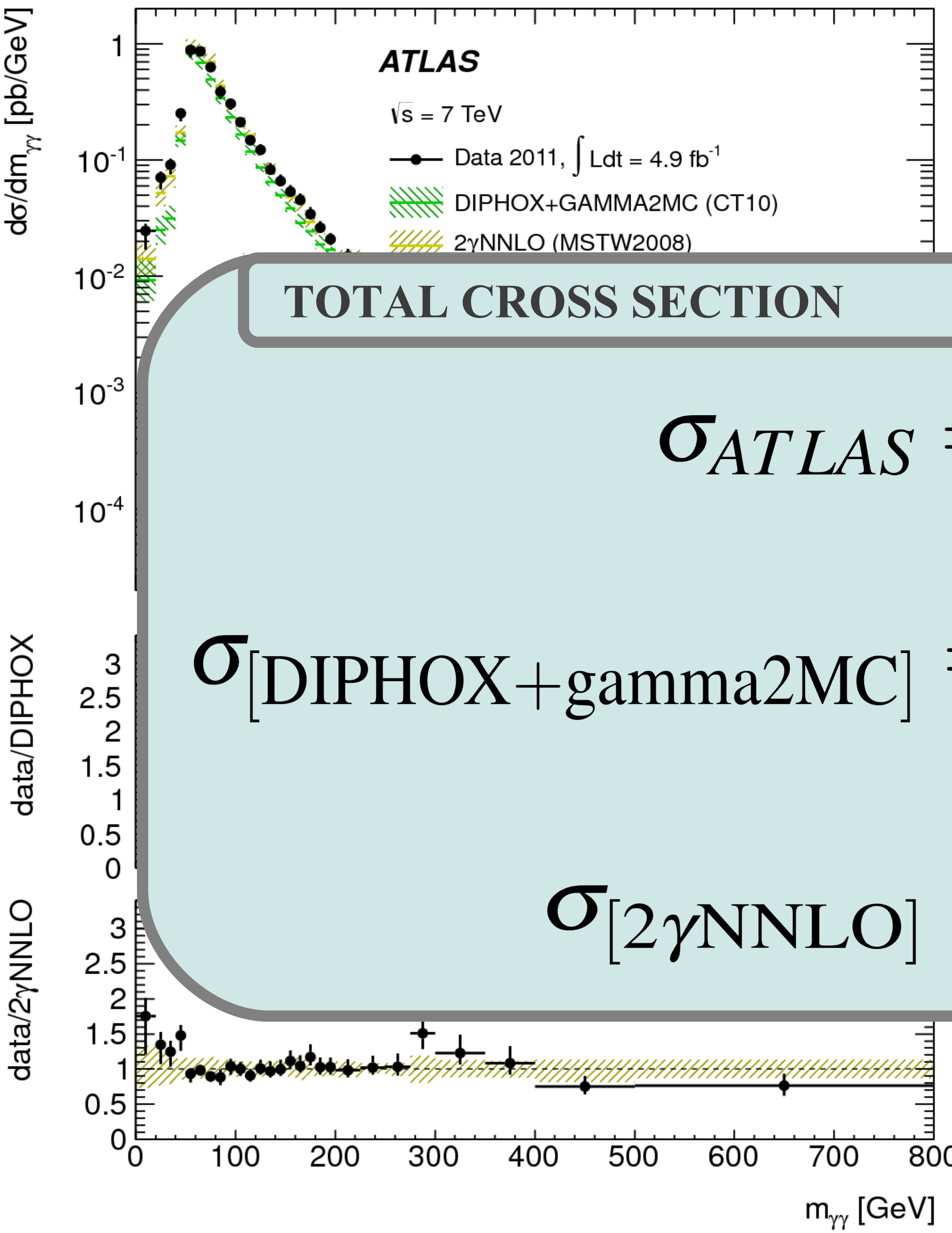
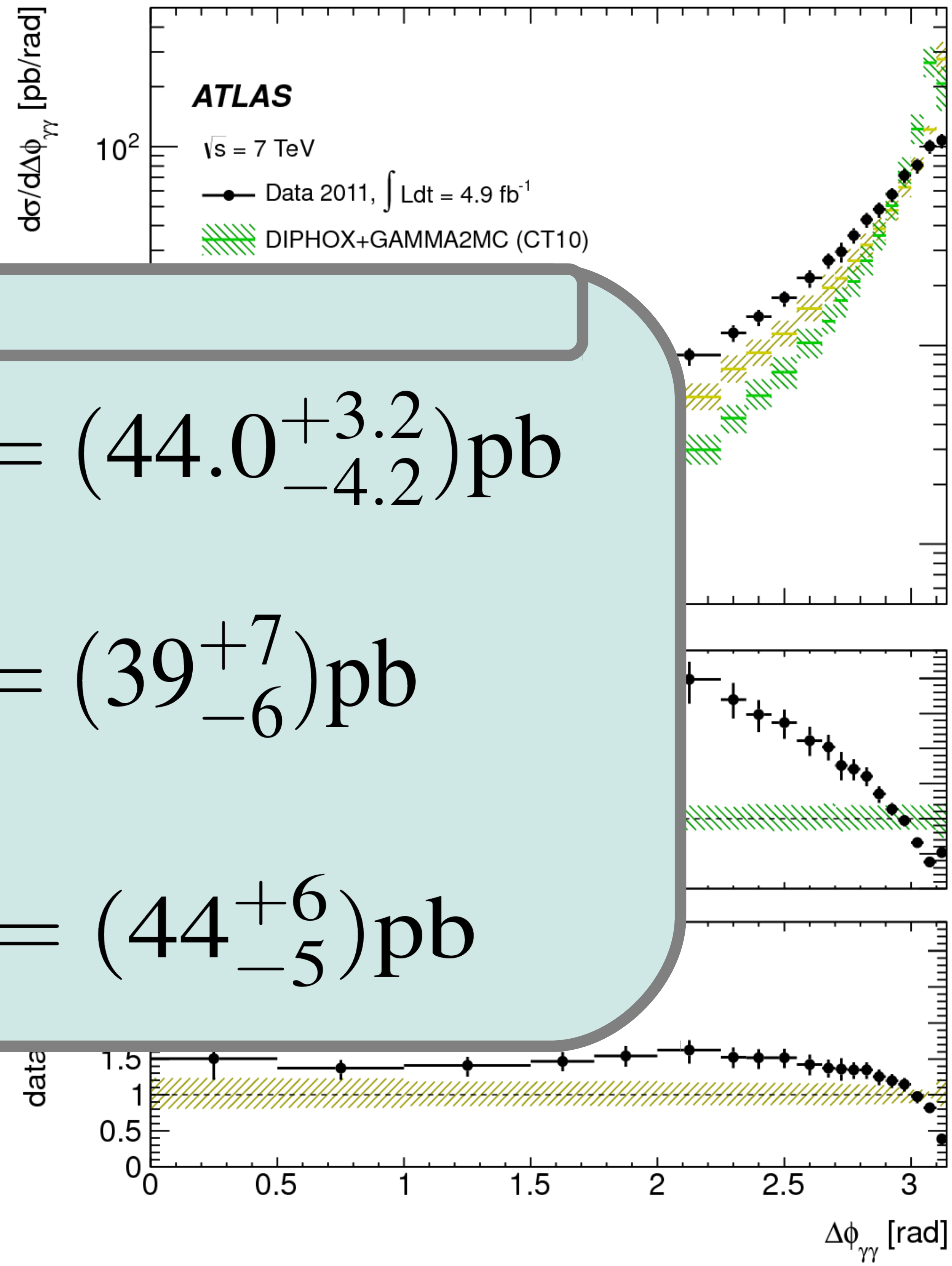




TOTAL CROSS SECTION

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

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

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

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

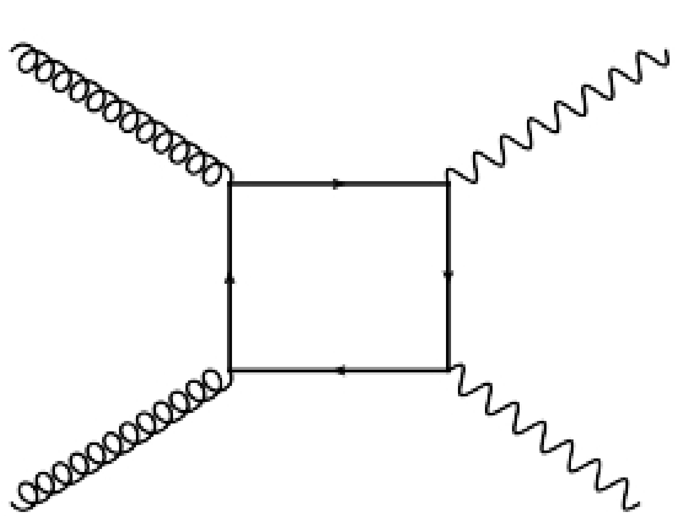
- At NNLO starts to reliably predict values of cross sections in all kinematical regions (with very few exceptions; e.g $p_{T\gamma\gamma} \to 0$)

Backup Slides

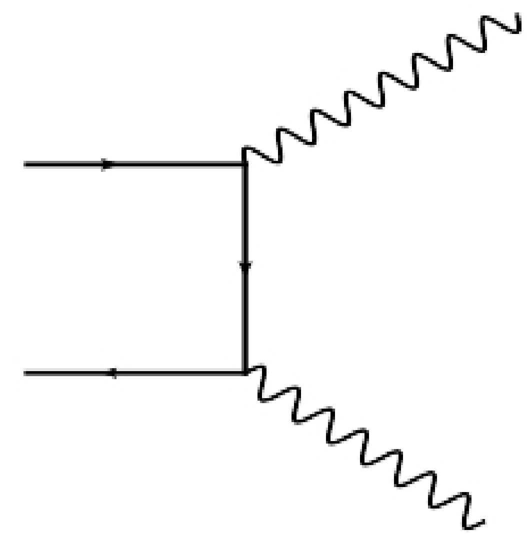
Why do we need NNLO corrections?

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

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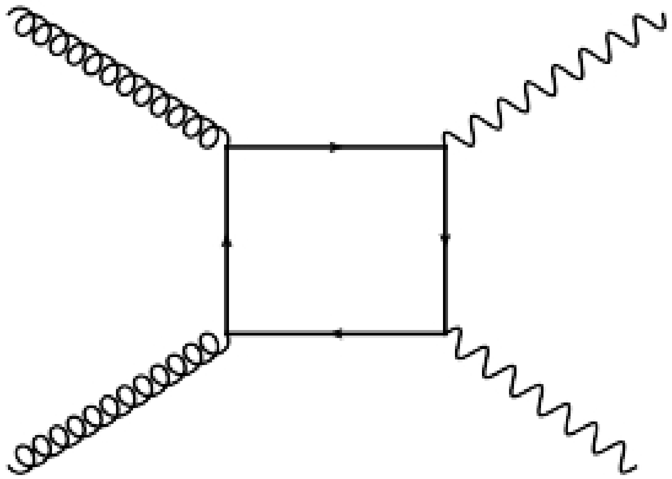

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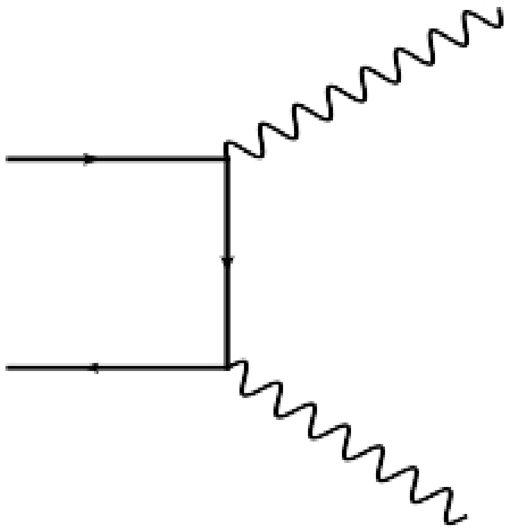

$O(\alpha_s^0)$ but $q\bar{q}$ Luminosity

- Box contribution already included in NLO calculation

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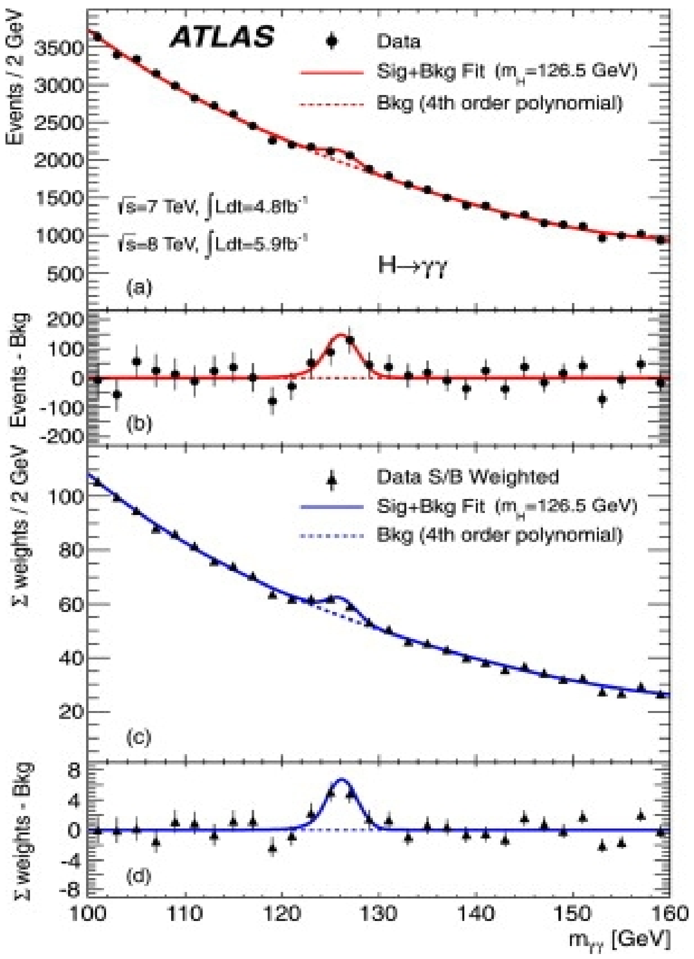
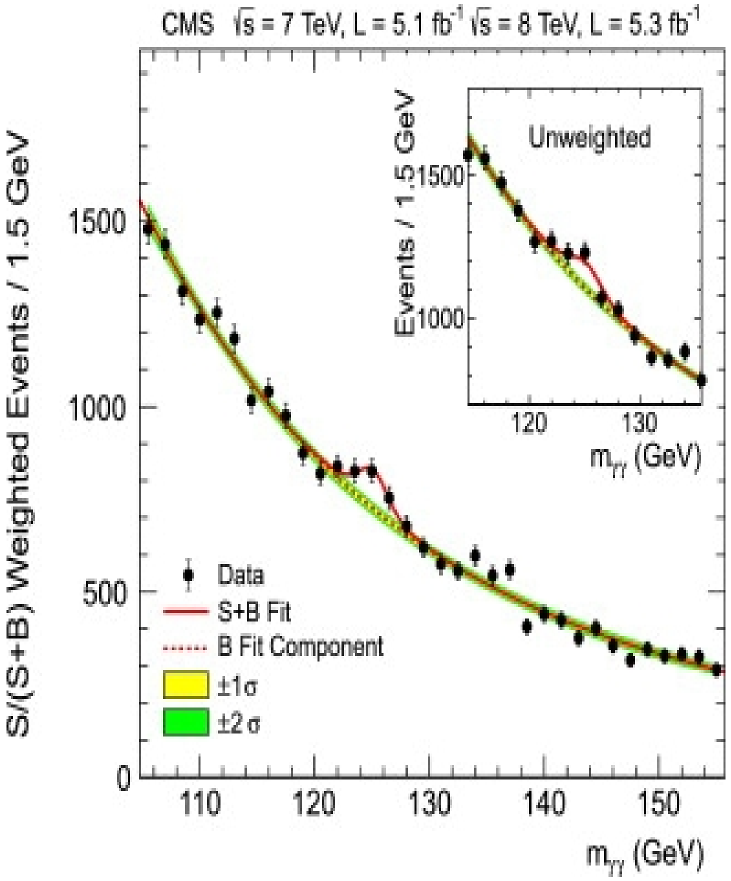
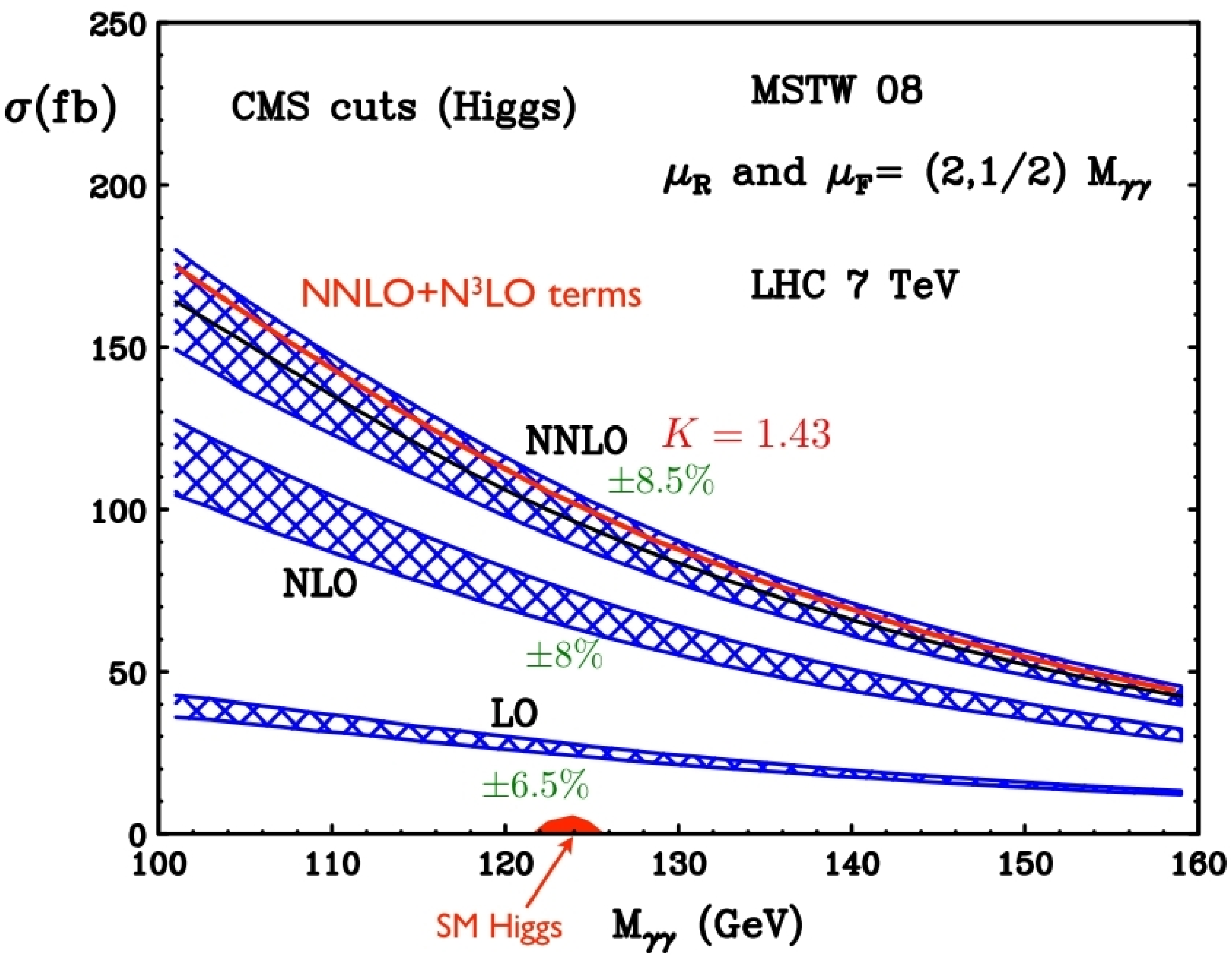
- Full NNLO control of Di-photon production is desired (main light Higgs bkg)

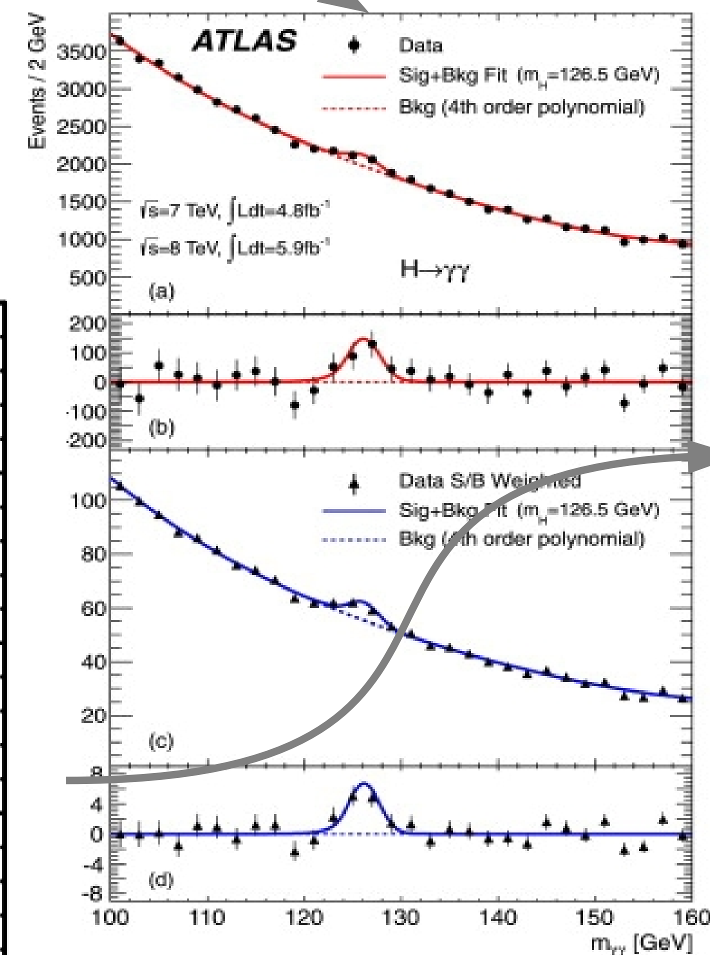
Higgs boson searches

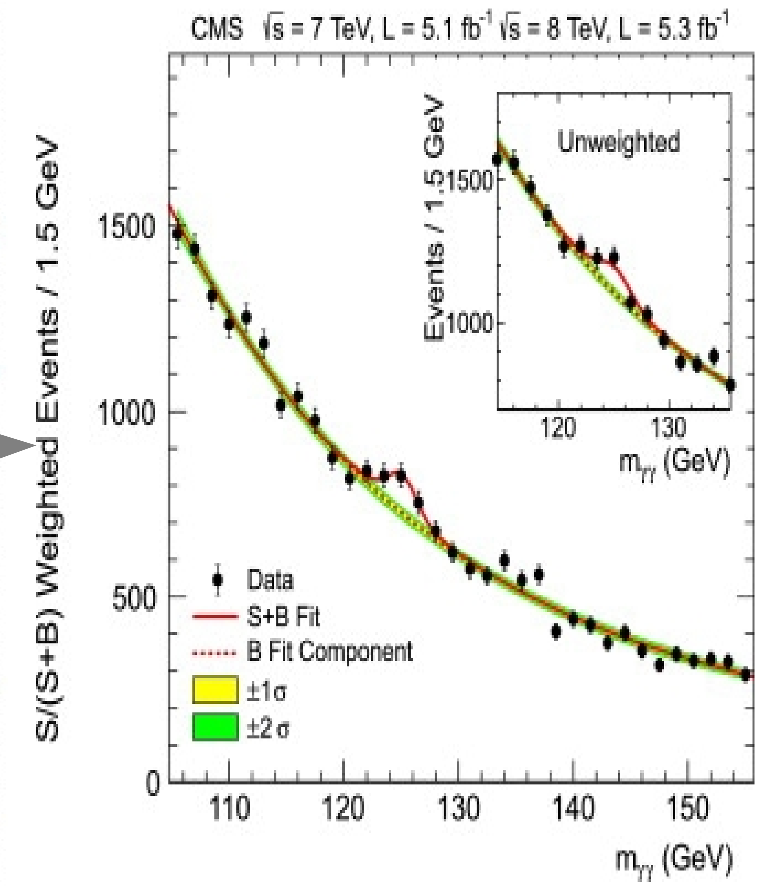




Higgs boson searches







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

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

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

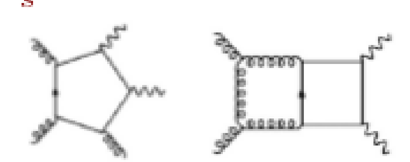
$$|\eta^\gamma| \leq 2.5$$

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%

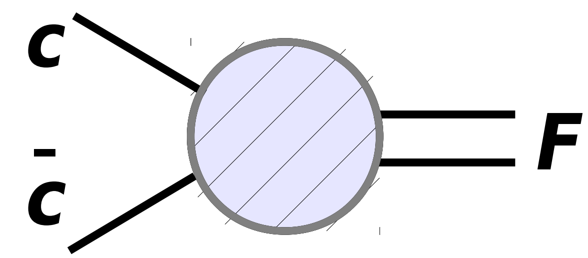
q_T subtraction method

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:

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

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

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

q_T subtraction method

S. Catani, M. Grazzini (2007)

In our case

DiPhoton production at NNLO

$\mathcal{H}^{F(2)}$

$d\sigma^{F+\mathrm{jet(s)}}$

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++

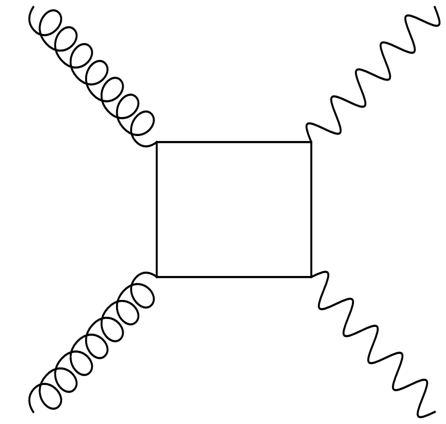
Fully exclusive NNLO code for $pp \to F$

2γNNLO

First exclusive NNLO in pp collisions with two final state particles

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

Available theoretical tools

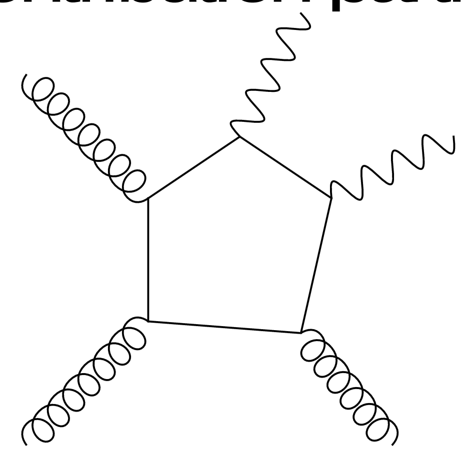


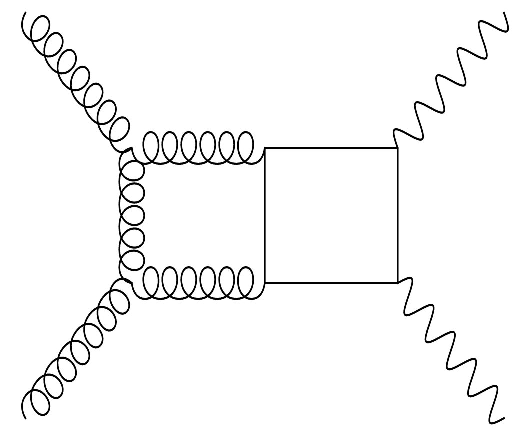
DIPHOX Full NLO for direct and fragmentation
+ Box contribution (one piece of NNLO)

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

Available theoretical tools

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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

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 ($z<1$)

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

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

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)