Diphoton production at the LHC

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Outline

- **Why diphoton production is important?**
- **Isolation criteria**
- **Numerical code for γγ production → 2γNNLO**
- **NNLO results @ LHC**
- **NNLO results @ LHC [CMS → 750 GeV excess]**
- **Outlook**

Why diphoton production is important?

- **γγ** → very clean final state
- **γ do not interact strongly with other final-state particles** → Prompt photons represent ideal probes to test SM
- **γγ channel** → have played a crucial role in the recent discovery at the LHC of a **Higgs boson**
- **γγ measurements** → important in many new physics scenarios: extra dimensions, supersymmetry, etc.
- **γγ invariant mass measurements** → Recently the LHC have shown an **excess of events with invariant mass of about 750 GeV** → that may indicate the presence of resonances over the diphoton SM background

CMS-PAS-EXO-15-004 CMS-PAS-EXO-16-018

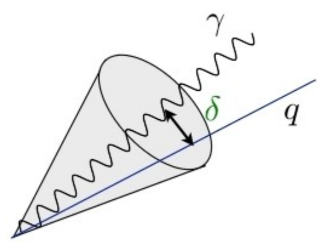
ATLAS-CONF-2015-081

Isolation criteria

- **Experimentally photons must be isolated**
- **Isolation reduces fragmentation component** — Large corrections

- **Standard (cone)** Baer, Ohnemus, Owens (1990)
Aurenche, Baier, Fontannaz (1990)

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



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

- **Smooth (Frixione)** S. Frixione (1998)

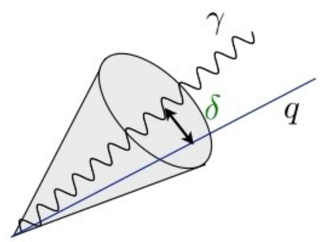
$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

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

Isolation criteria

- **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.

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

Smooth cone Isolation

Soft emission allowed arbitrarily close to the photon

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

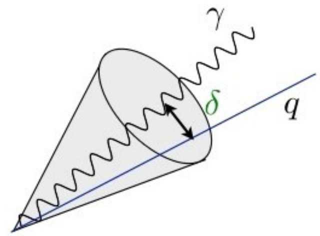
$$\sum_{\delta<R_0} E_T^{had} \leq E_T^{max} \chi(\delta)$$

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

Isolation criteria

Experimentalist may choose:

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



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

- **The smooth cone isolation criterion is more restrictive than the standard one**
- $$\sigma_{Frix}\{R, E_{T\ max}\} \leq \sigma_{Stand}\{R, E_{T\ max}\}$$

(both theoretically and experimentally)

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

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Les Houches accord 2013

[Les Houches 2013: Physics at TeV Colliders: Standard Model Working Group Report]

"LH tight isolation accord"

- Exp: use (tight) cone isolation → Solid and well understood
- TH: use smooth cone with same R and E_{Tmax} → Accurate, better than using cone with LO fragmentation → Estimate TH isolation uncertainties using different profiles in smooth cone

Les Houches accord 2013

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Considering that NNLO corrections are of the order of 50% for diphoton cross sections and a few 100% for some distributions in extreme kinematical configurations, it is far better accepting a few % error arising from the isolation (less than the size of the expected NNNLO corrections and within any estimate of TH uncertainties!) than neglecting those huge QCD effects towards some "more pure implementation" of the isolation prescription.

Recently, some calculations use the smooth cone isolation criteria to arrive at the highest level of accuracy:

Vγ production [NNLO] M. Grazzini, S. Kallweit, D. Rathlev, A. Torre (2013), (2015)

γγ + 2Jets [NLO] T. Gehrmann , N. Greiner , G. Heinrich (2013) ;Z. Bern, L.J. Dixon, F. Febres Cordero, S. Hoeche, H. Ita, D.A. Kosower, N. A. Lo Presti, D. Maitre (2013)

γγ + (up to) 3Jets [NLO] S. Badger, A. Guffanti, V. Yundin (2013)

2γNNLO

Catani, LC, de Florian, Ferrera, Grazzini (2011)

- **Our numerical code is based on the qT subtraction formalism**

  Catani, Grazzini (2007)

- **The NLO corrections to the Box contribution (formally N^3LO) are not included in the following analysis** Bern, Dixon, Schmidt (2002)
- **Our results agree with the recent implementation of the qT subtraction formalism in the numerical code MATRIX, for diphoton production** Grazzini, Kallweit, Rathlev, Wiesemann
- **2γNNLO was used by the CDF, D0, ATLAS and CMS collaborations in their analyses**
- **Our resummed results are implemented in the numerical code 2γRes** LC, Coradeschi, de Florian (2015)

NNLO results @ LHC

ATLAS results → γγ

ArXiv:1211.1913

$$p_T^{\text{harder}} \geq 25 \text{ GeV}, \;\; p_T^{\text{softer}} \geq 22 \text{ GeV},$$
$$|y_\gamma| < 1.37 \;\vee\; 1.52 < |y_\gamma| \leq 2.37,$$
$$E_{T\ max} = 4 \text{ GeV}, \quad n = 1, \quad R = 0.4,$$
$$R_{\gamma\gamma} = 0.4$$

ATLAS results → γγ

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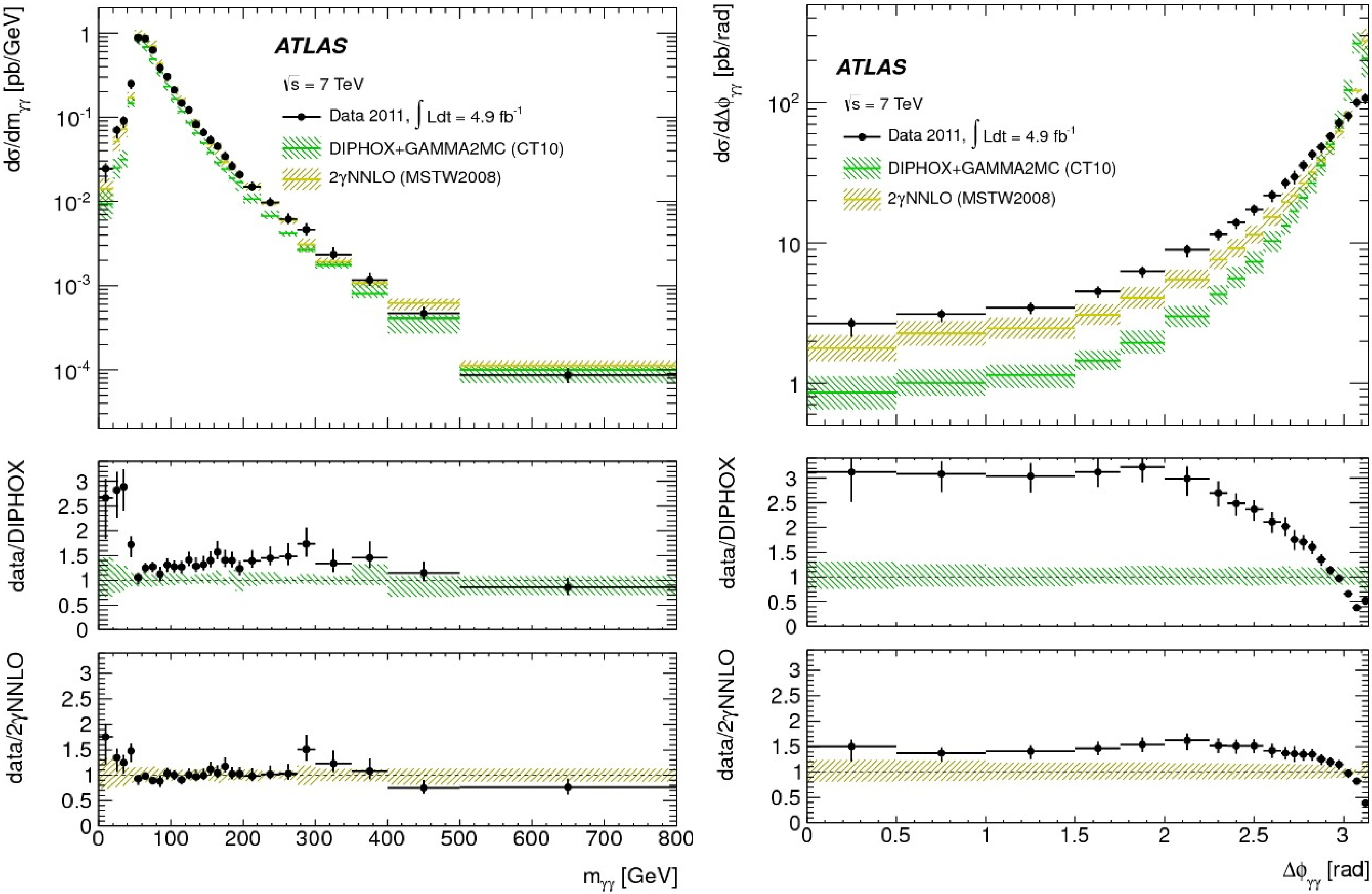

ATLAS results → γγ

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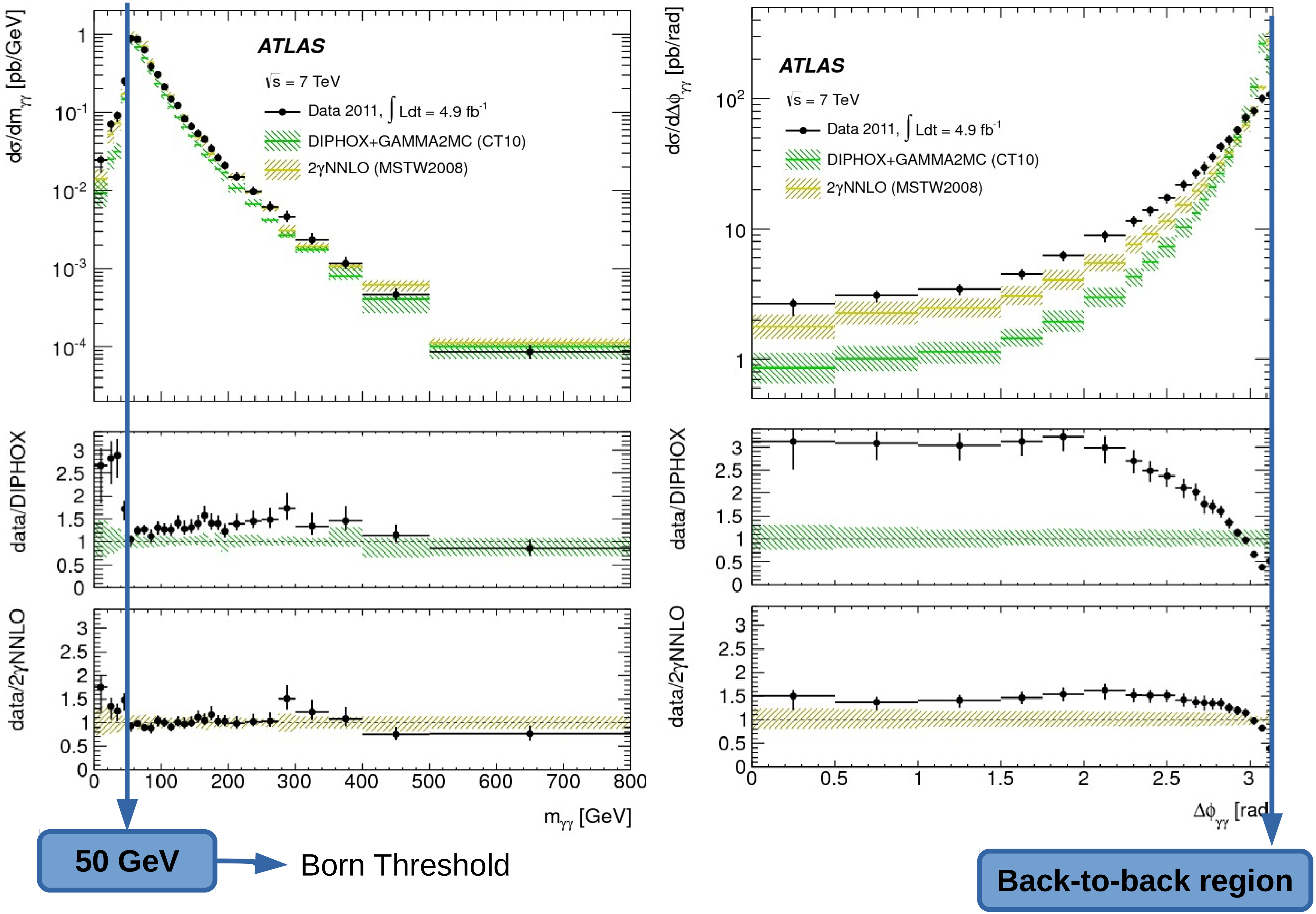

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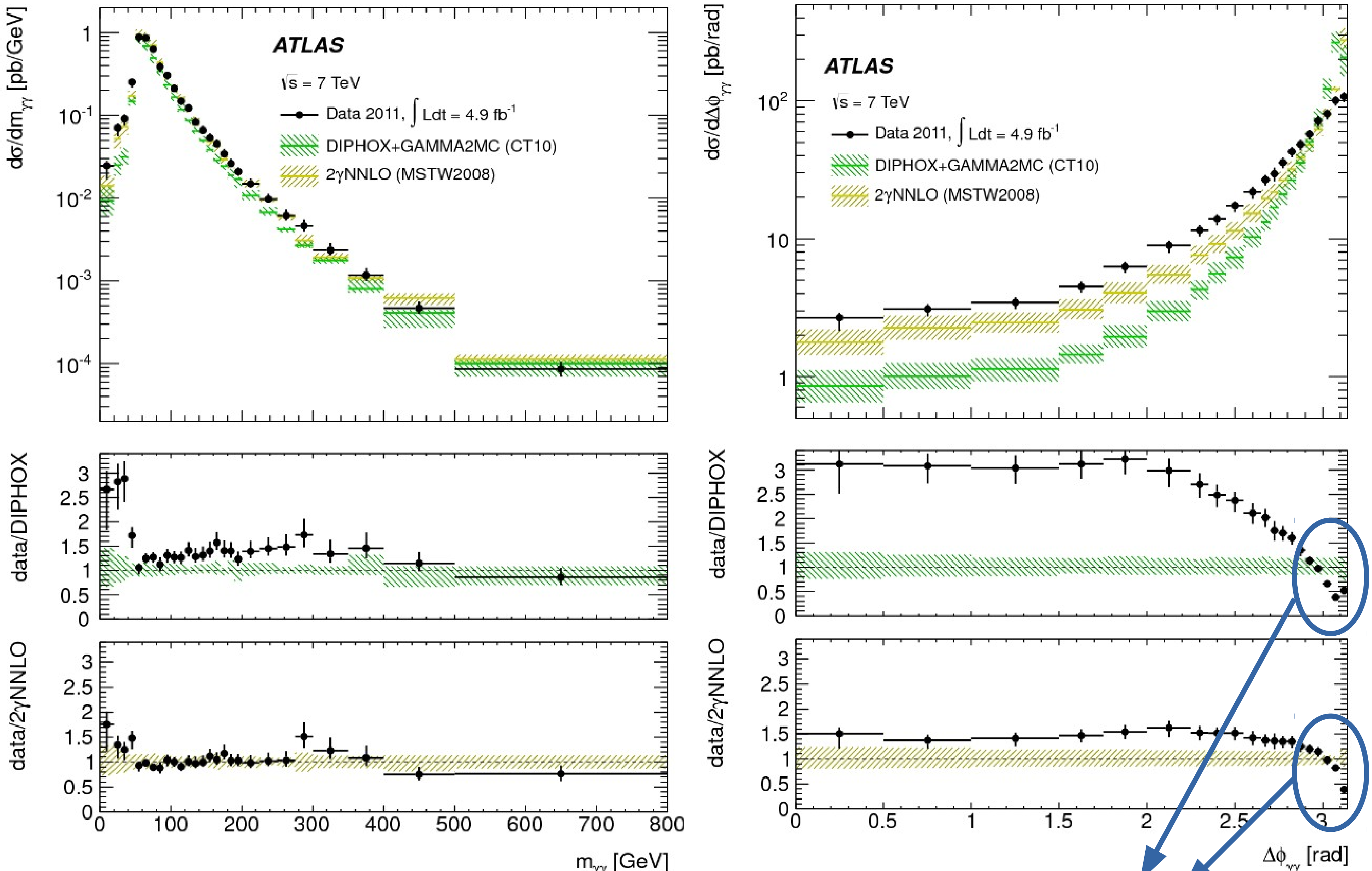
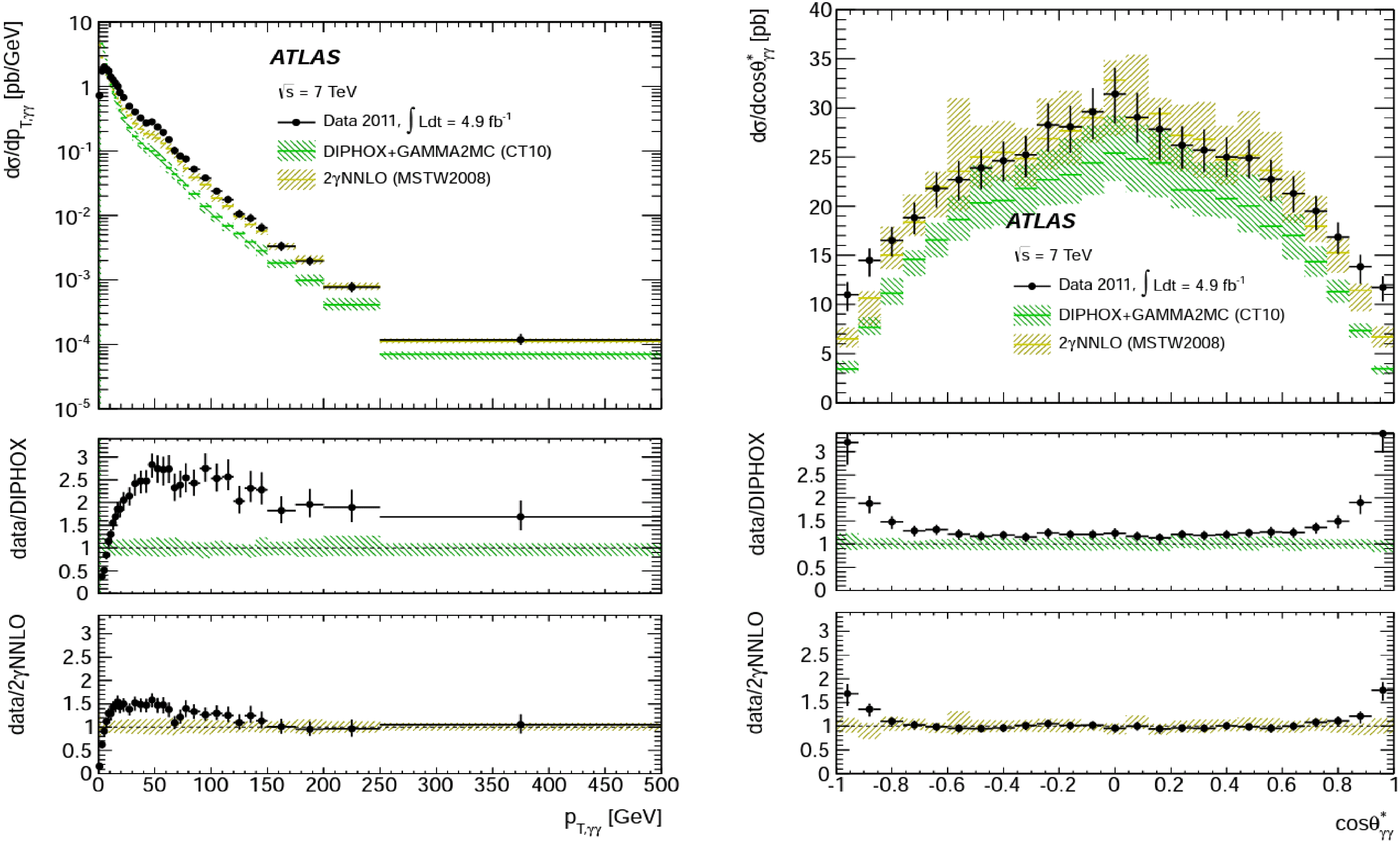


Uncertainties → 6% - 8%

Fixed order tools

ATLAS results → γγ

ArXiv:1211.1913



ATLAS results → γγ

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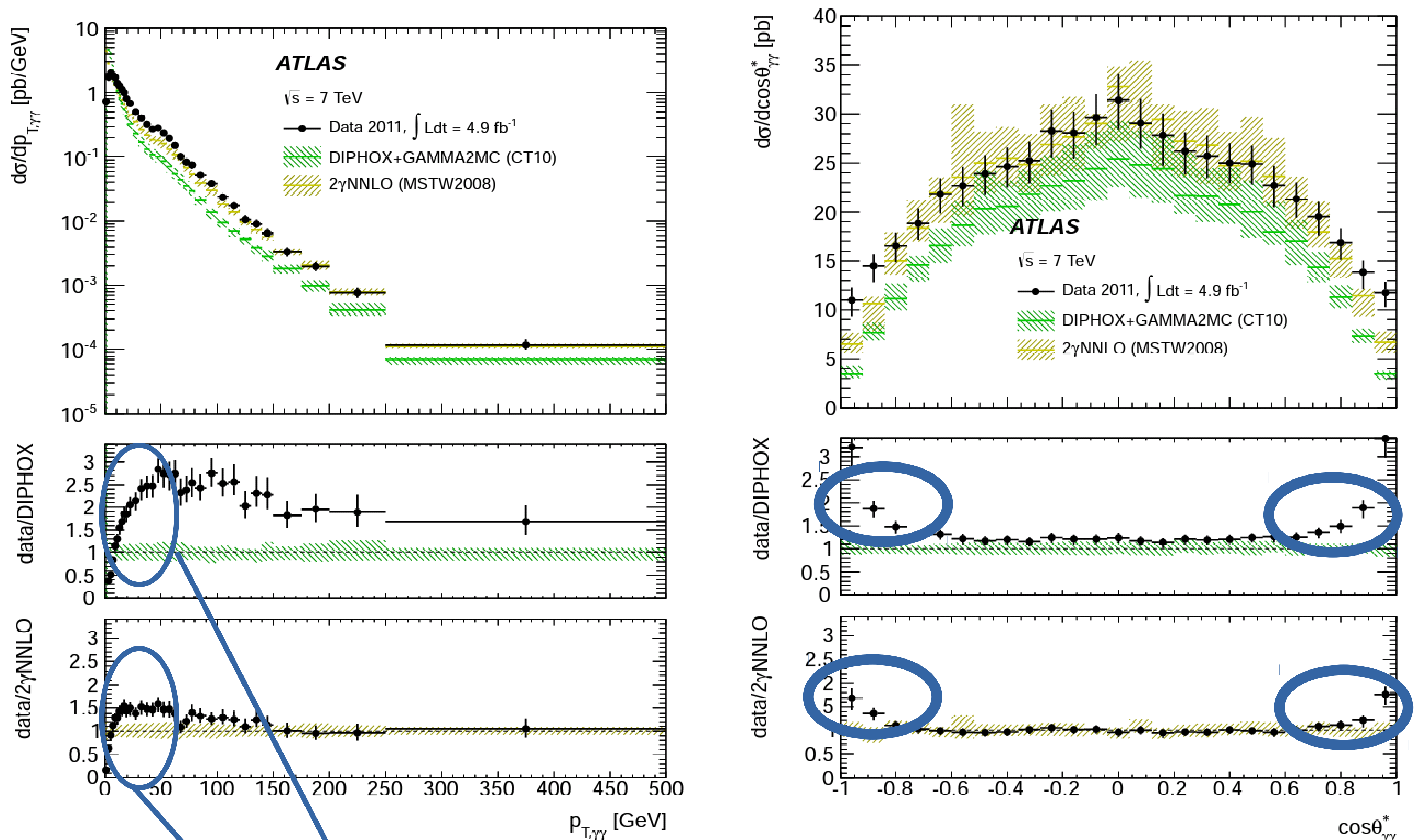
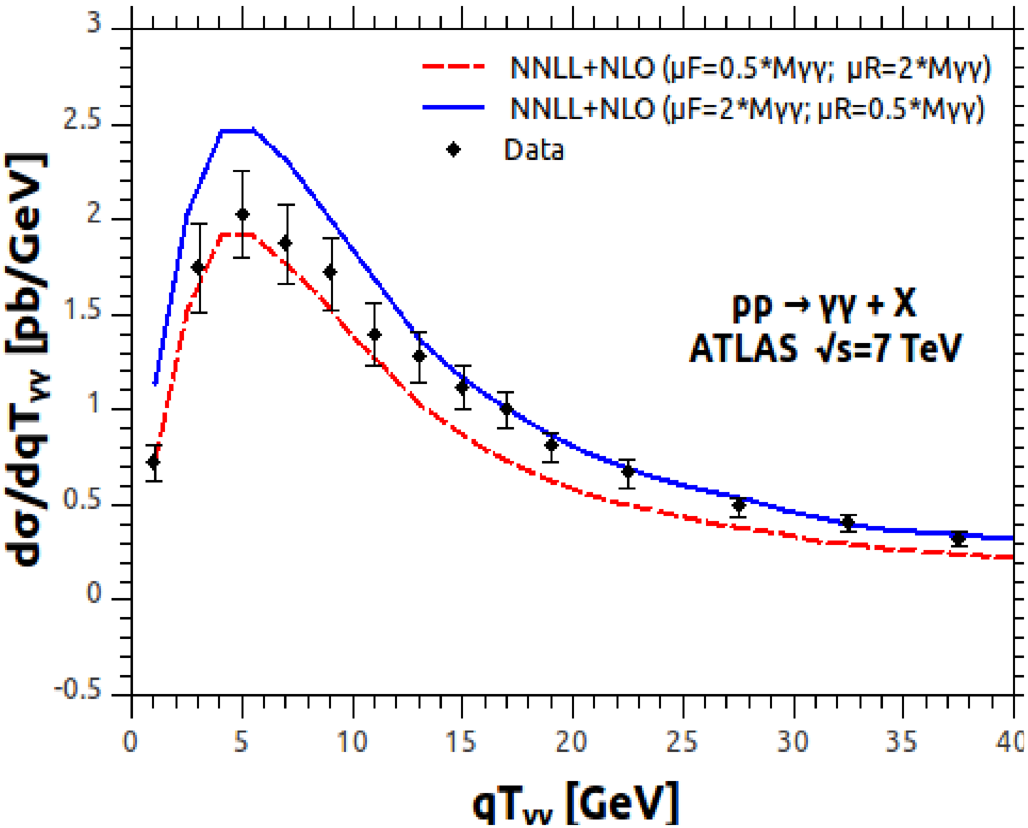


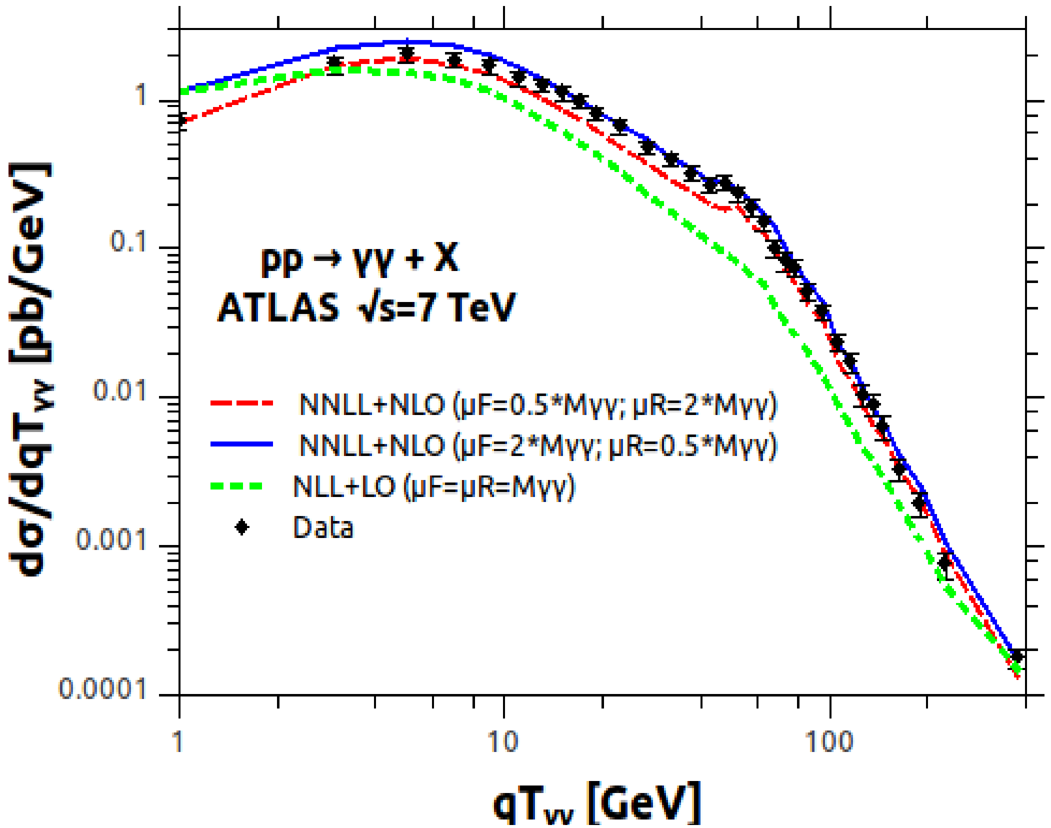
Fixed order tools

Uncertainties → 6% - 8% due to the opening of the gg channel which is "effectively" LO at NNLO

Resummation → ATLAS γγ

LC, Coradeschi, de Florian (2015)

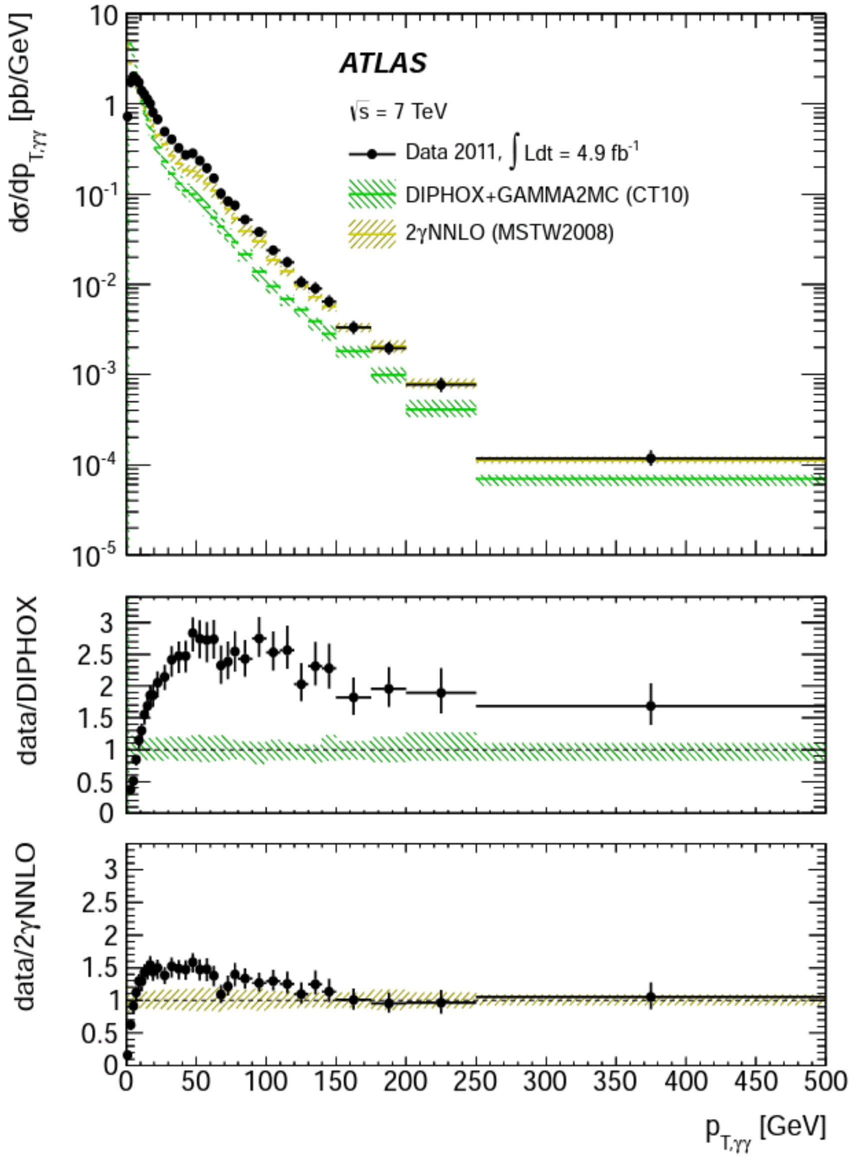




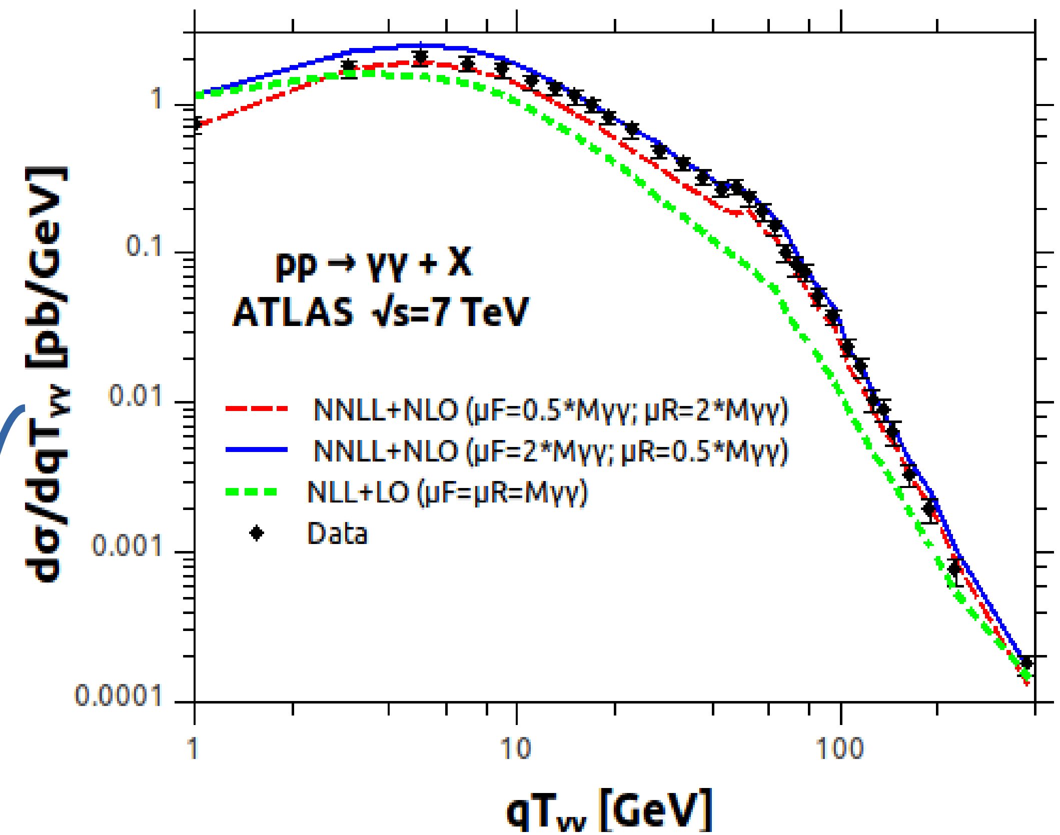
qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

Resummation → ATLAS γγ

Fixed order



LC, Coradeschi, de Florian (2015)

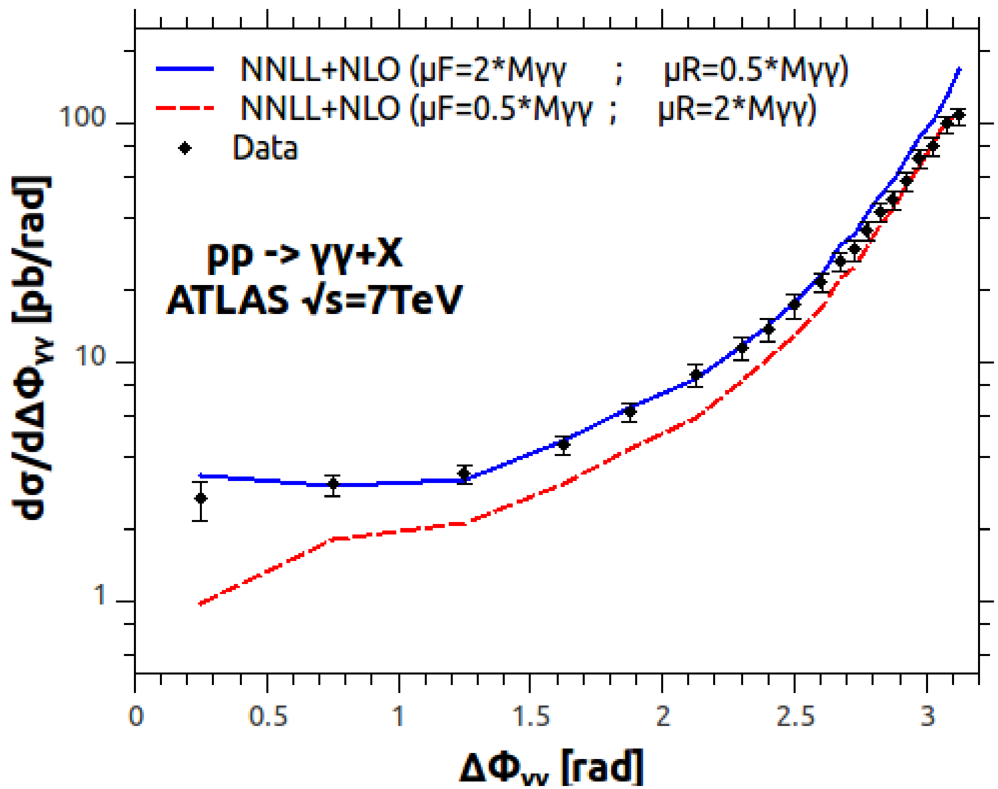


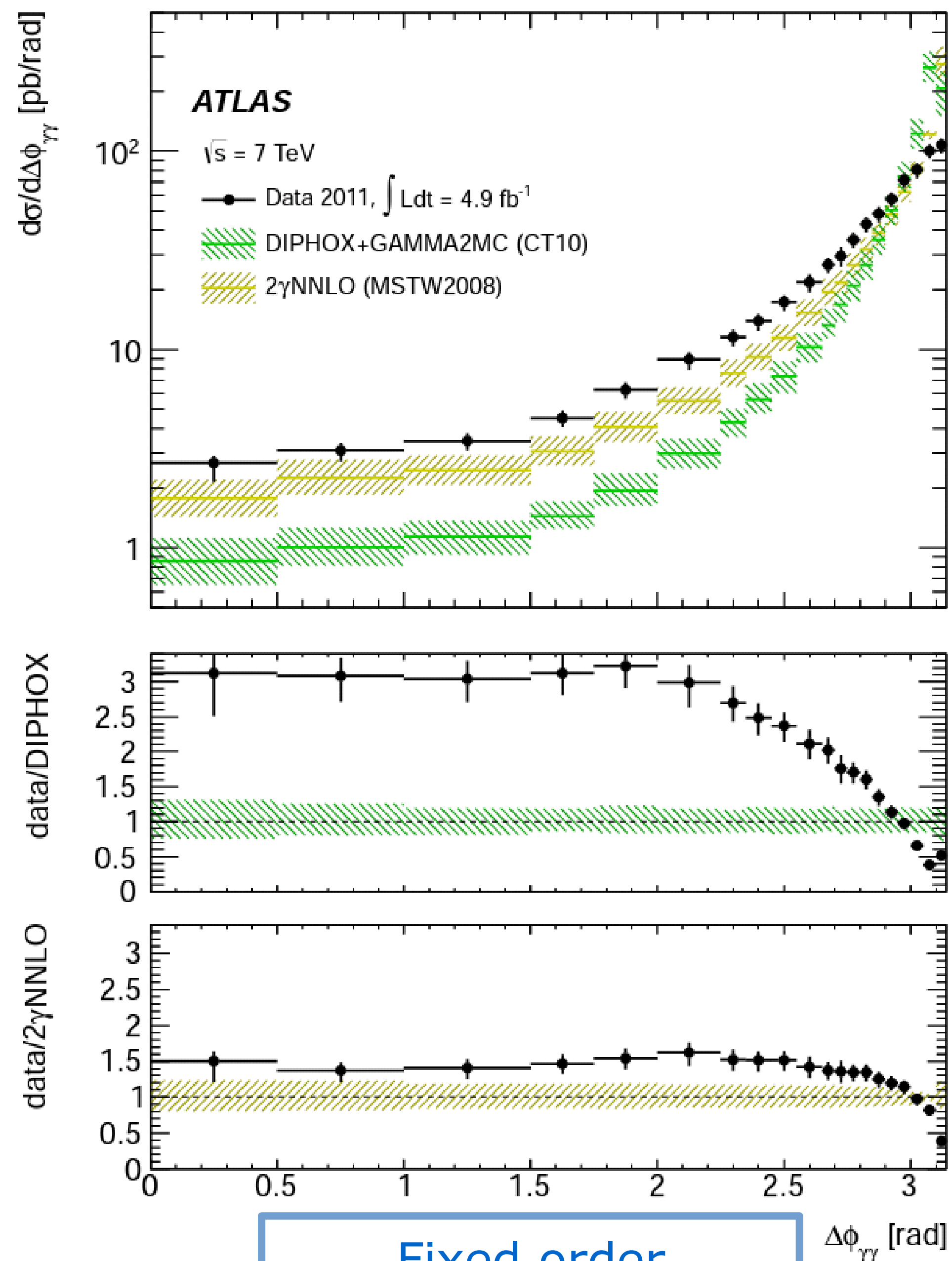
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.

qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

Resummation → ATLAS γγ

LC, Coradeschi, de Florian (2015)





The same set-up also allows the calculation of more exclusive observable distributions

Fixed order

CMS results → γγ

ArXiv:1405.7225

$$p_T^{\text{harder}} \geq 40\ \text{GeV}, \quad p_T^{\text{softer}} \geq 25\ \text{GeV},$$
$$|y_\gamma| < 1.44 \ \vee \ 1.57 < |y_\gamma| \leq 2.5,$$
$$E_{T\ max} = 5\ \text{GeV}, \quad n = 0.05, \quad R = 0.4,$$
$$R_{\gamma\gamma} = 0.45$$

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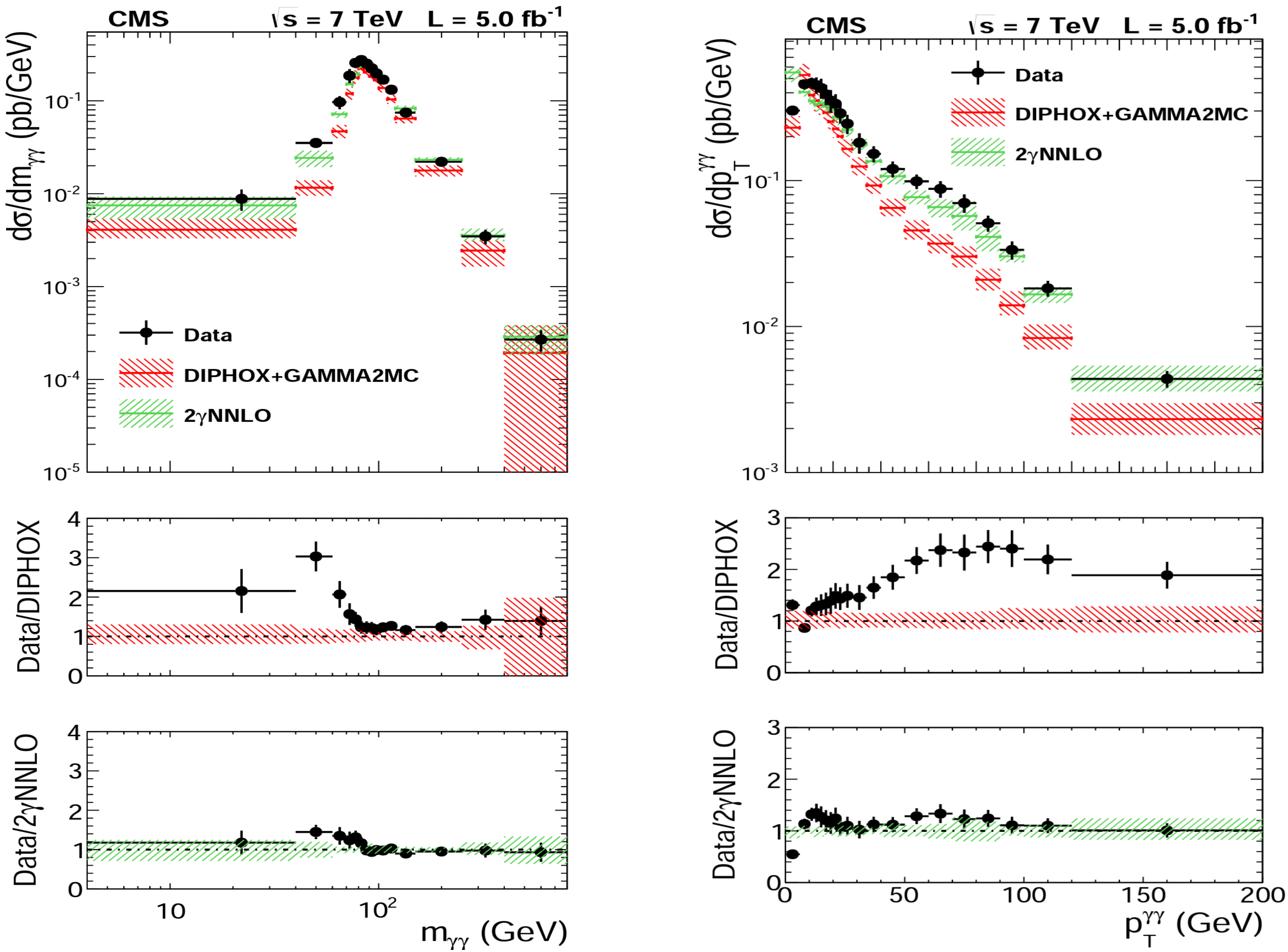

CMS results → γγ

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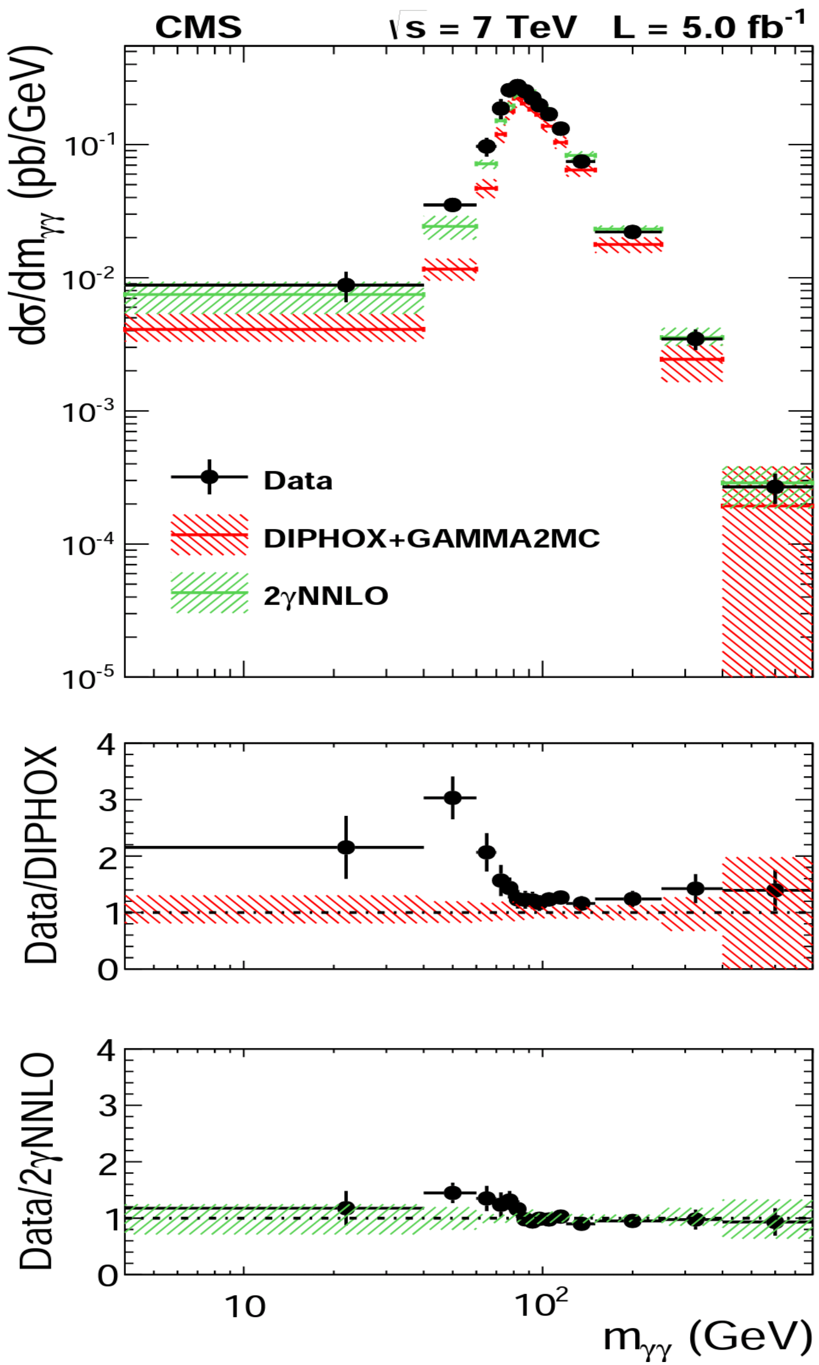

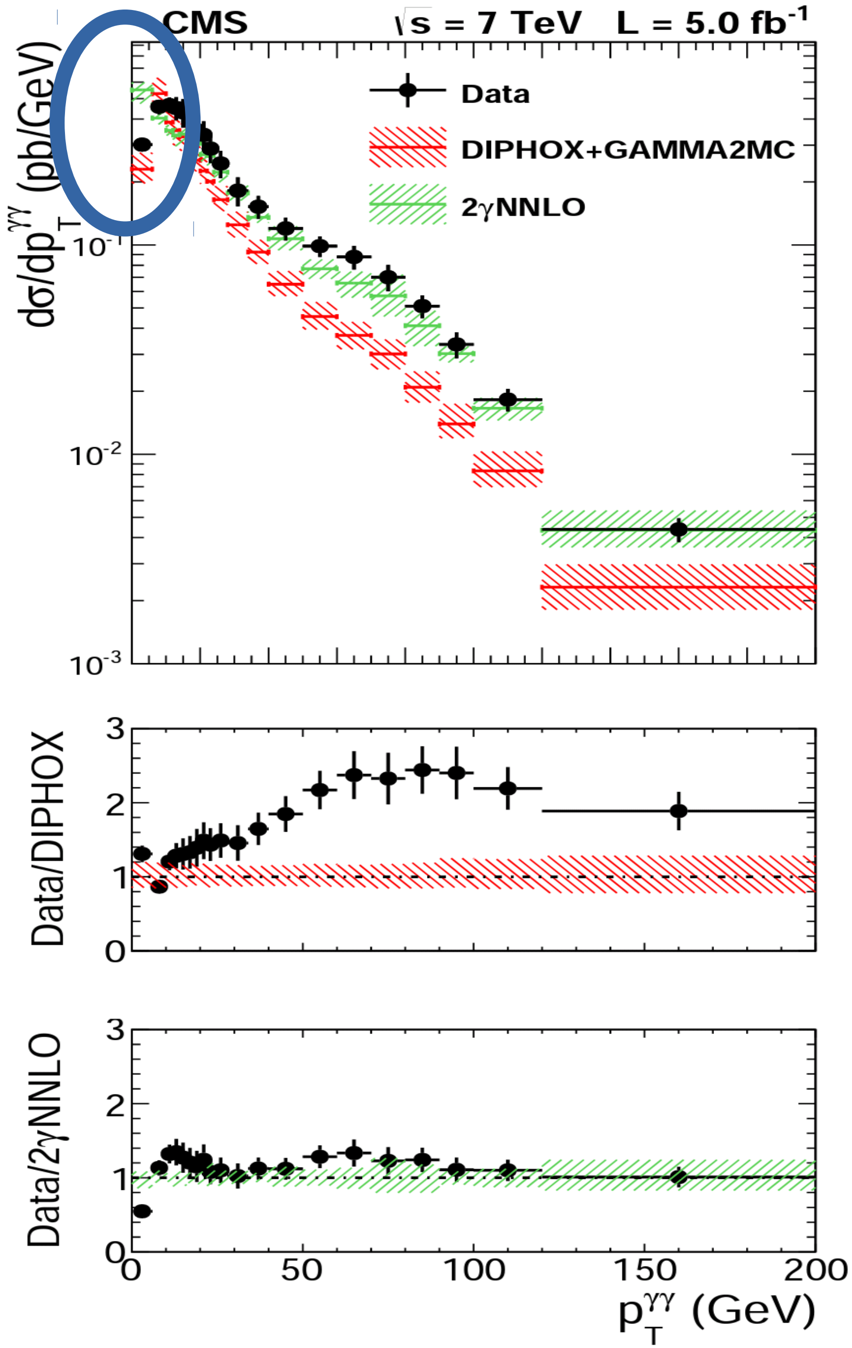

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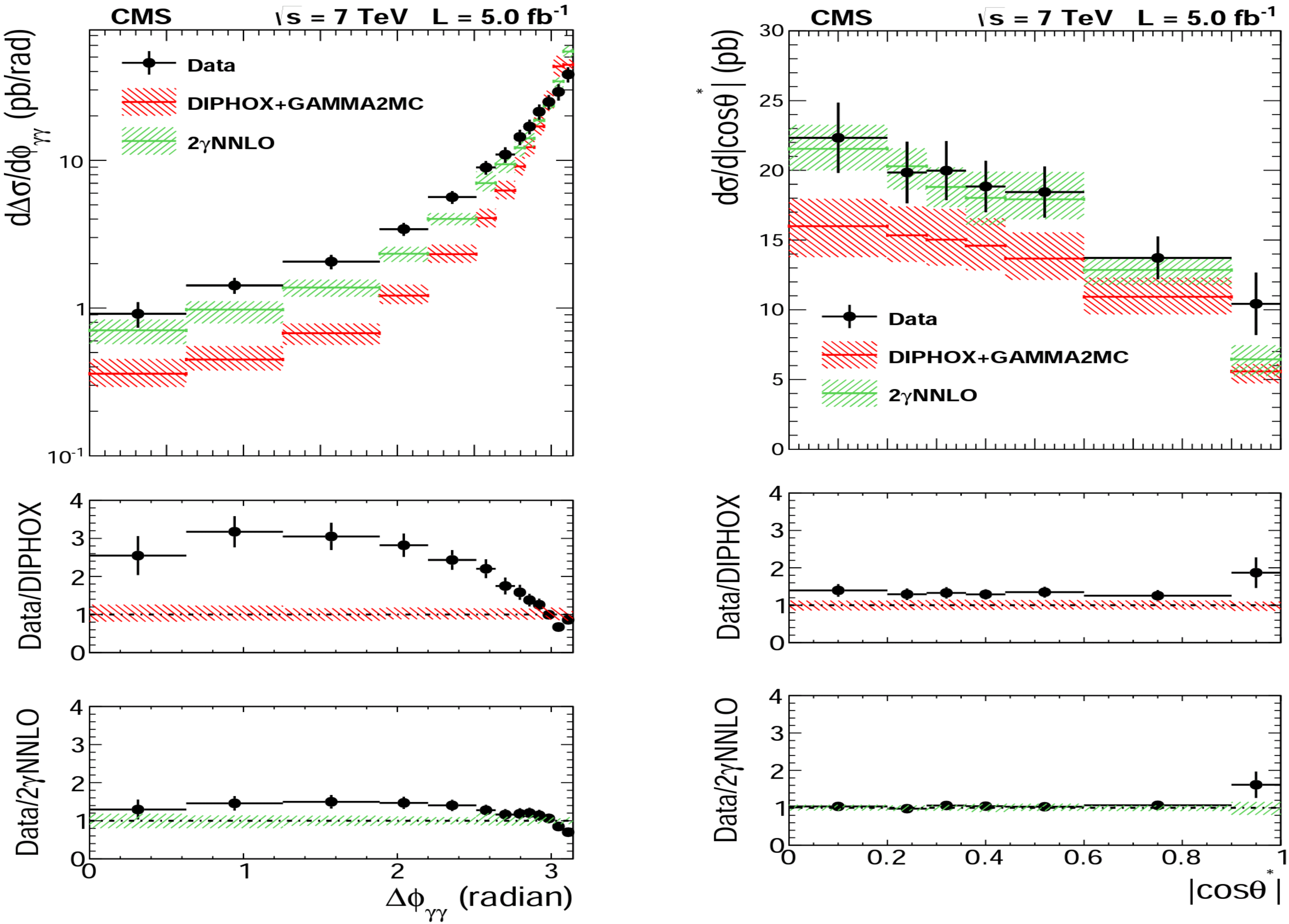

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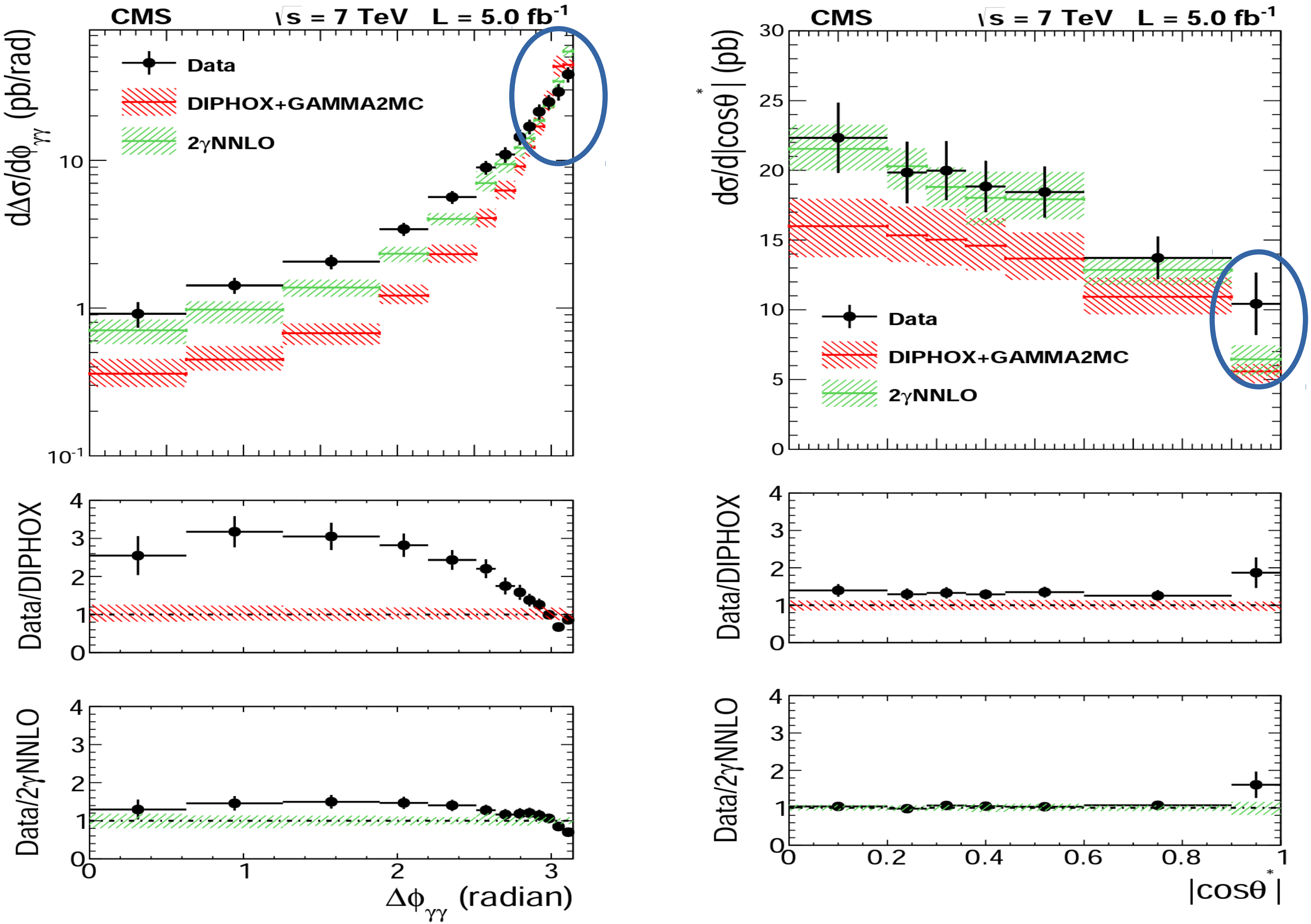
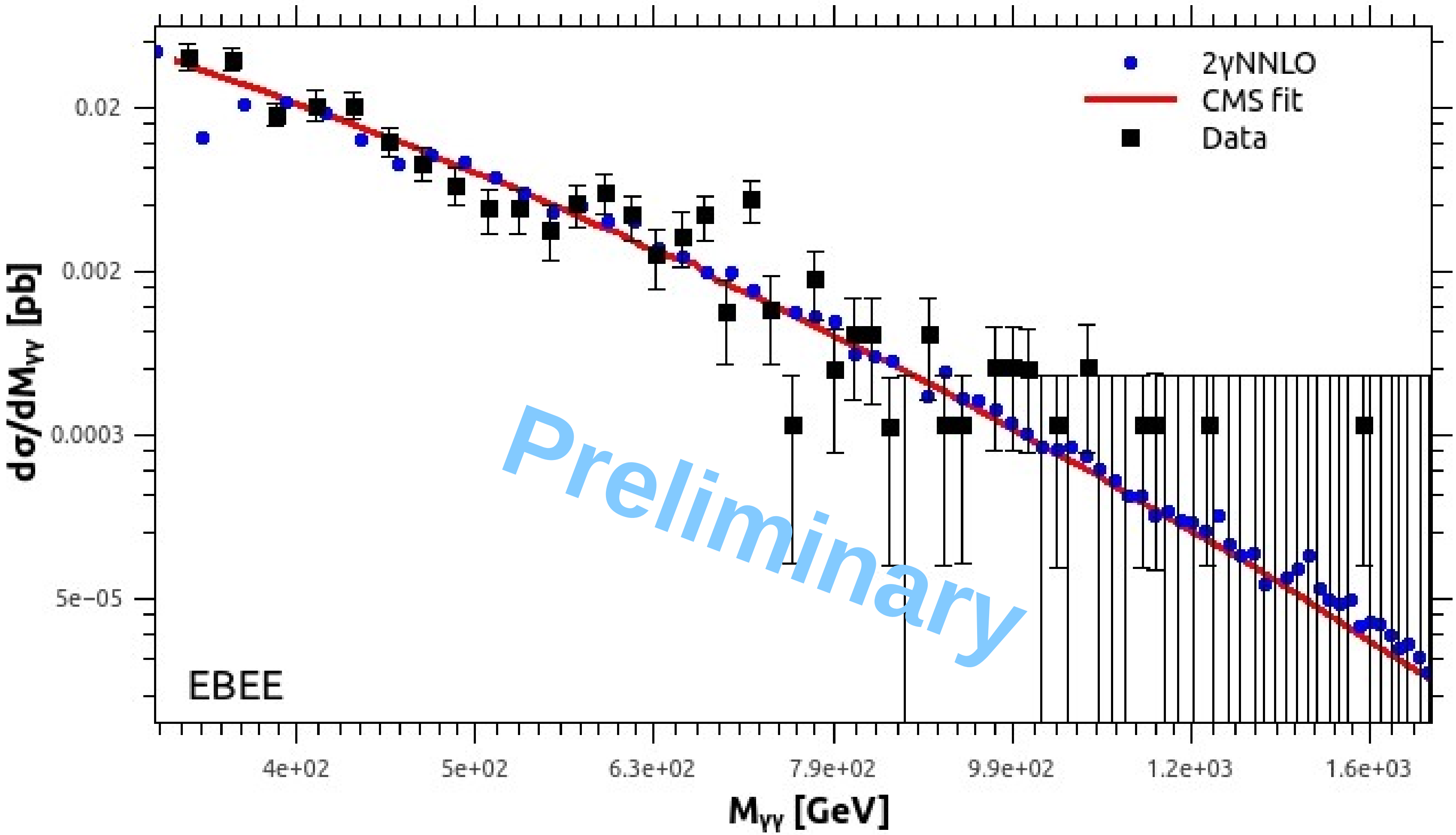


CMS results → γγ (750 GeV excess)

CMS-PAS-EXO-15-004

LC, Gehrmann, Greiner, Heinrich



"EBEE": One photon in the ECAL barrel and the other in the ECAL endcap
$|\eta^{\gamma}|<1.44$ and $|\eta^{\gamma}|>1.57$ [$M^{\gamma\gamma}>320$ GeV]

$\sqrt{s}=13$ TeV ; Etmax = 5 GeV ; R=0.3 ; $|\eta^{\gamma}|<2.5$; $pT^{\gamma}>75$ GeV

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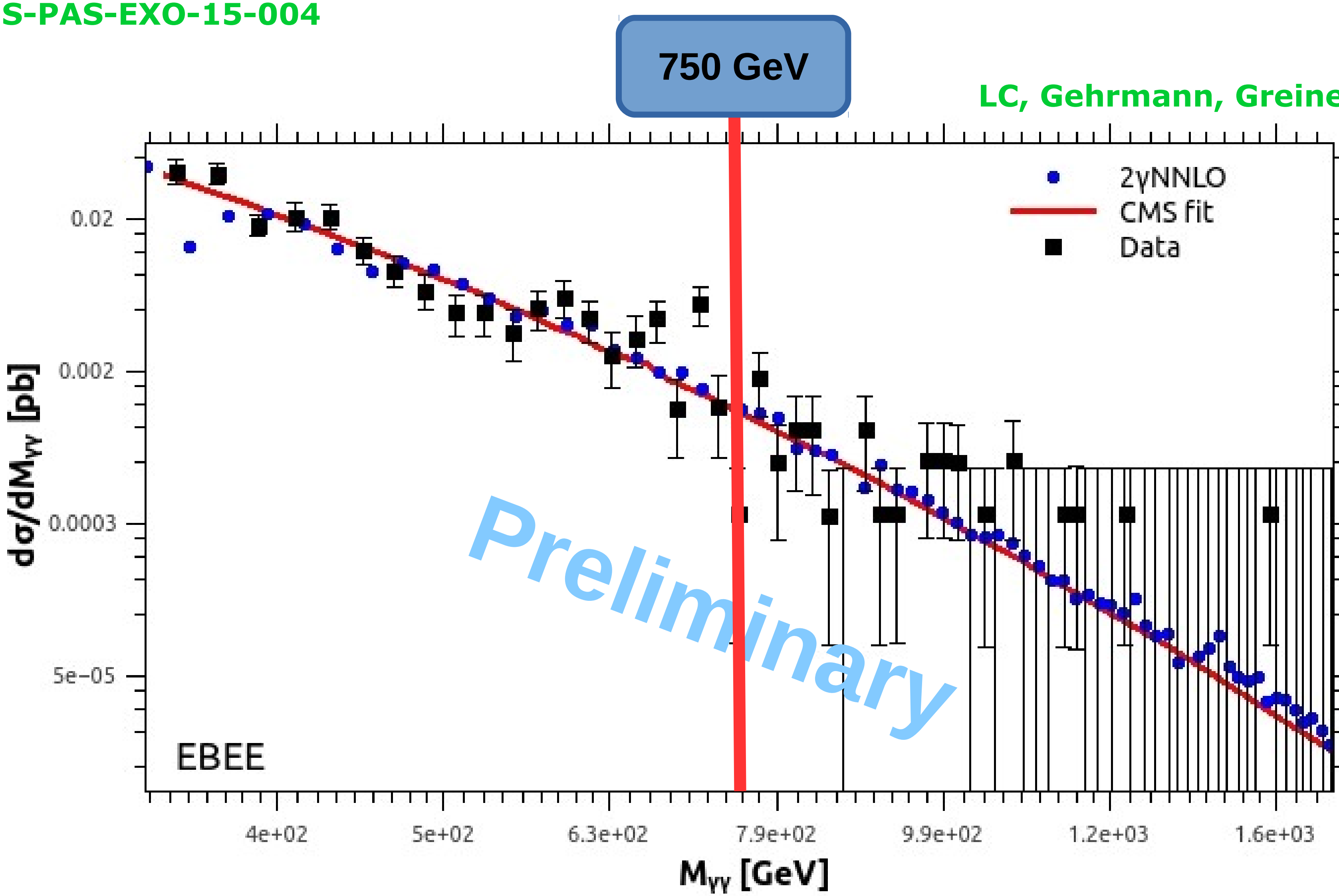

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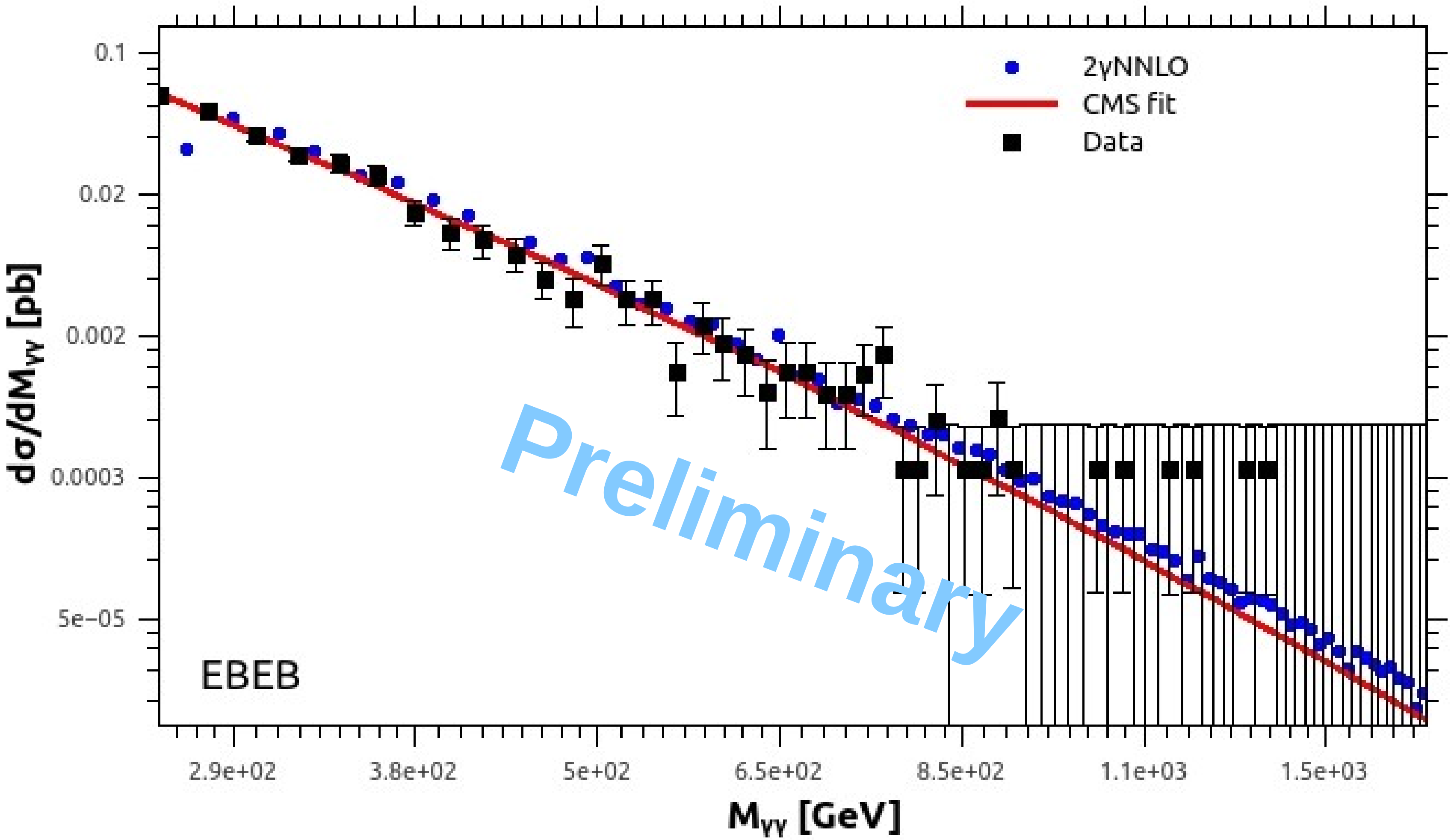

"EBEB": Both photons in the ECAL barrel → $|\eta^{\gamma}|<1.44$ [$M^{\gamma\gamma}>230$ GeV]

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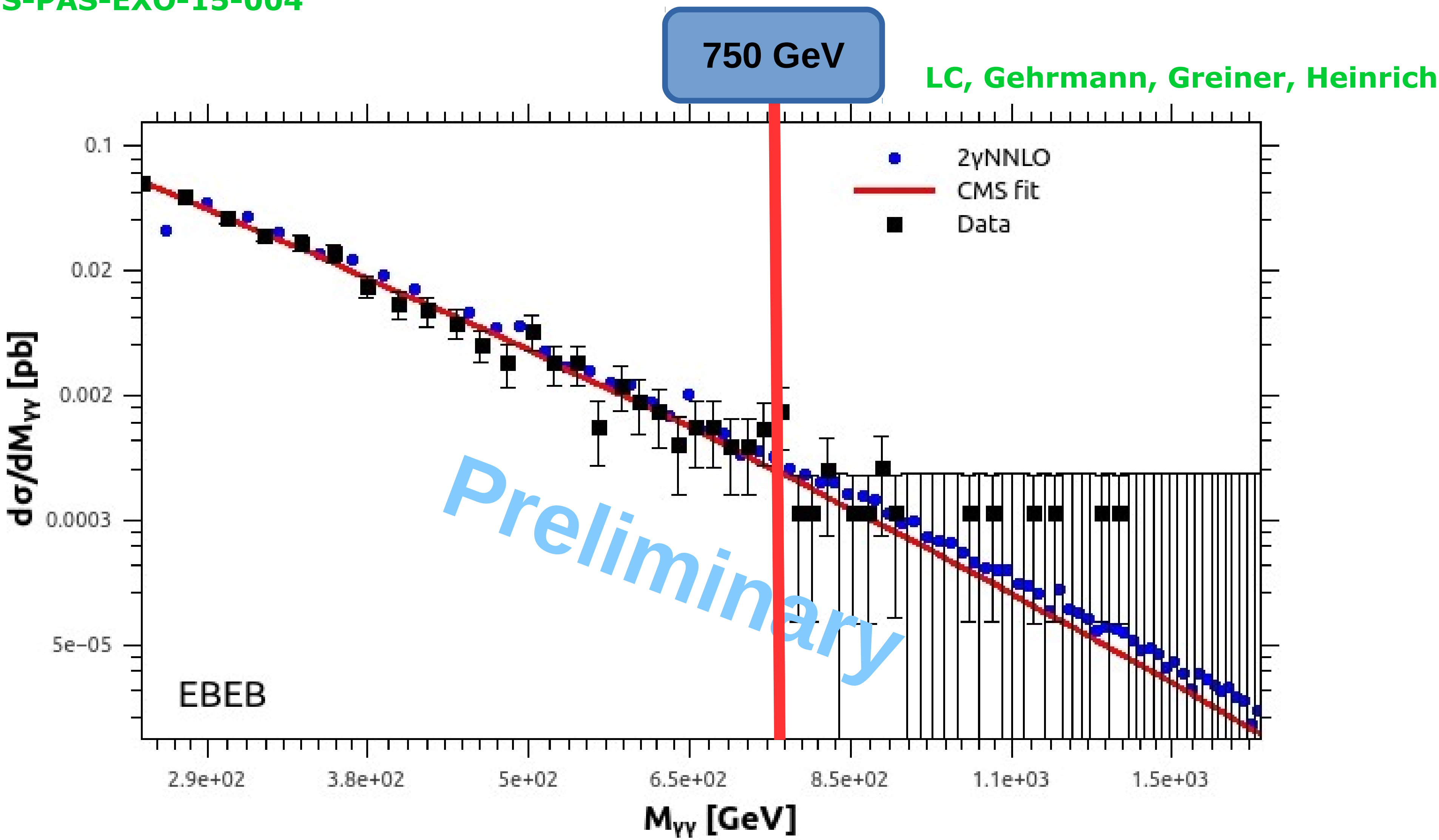

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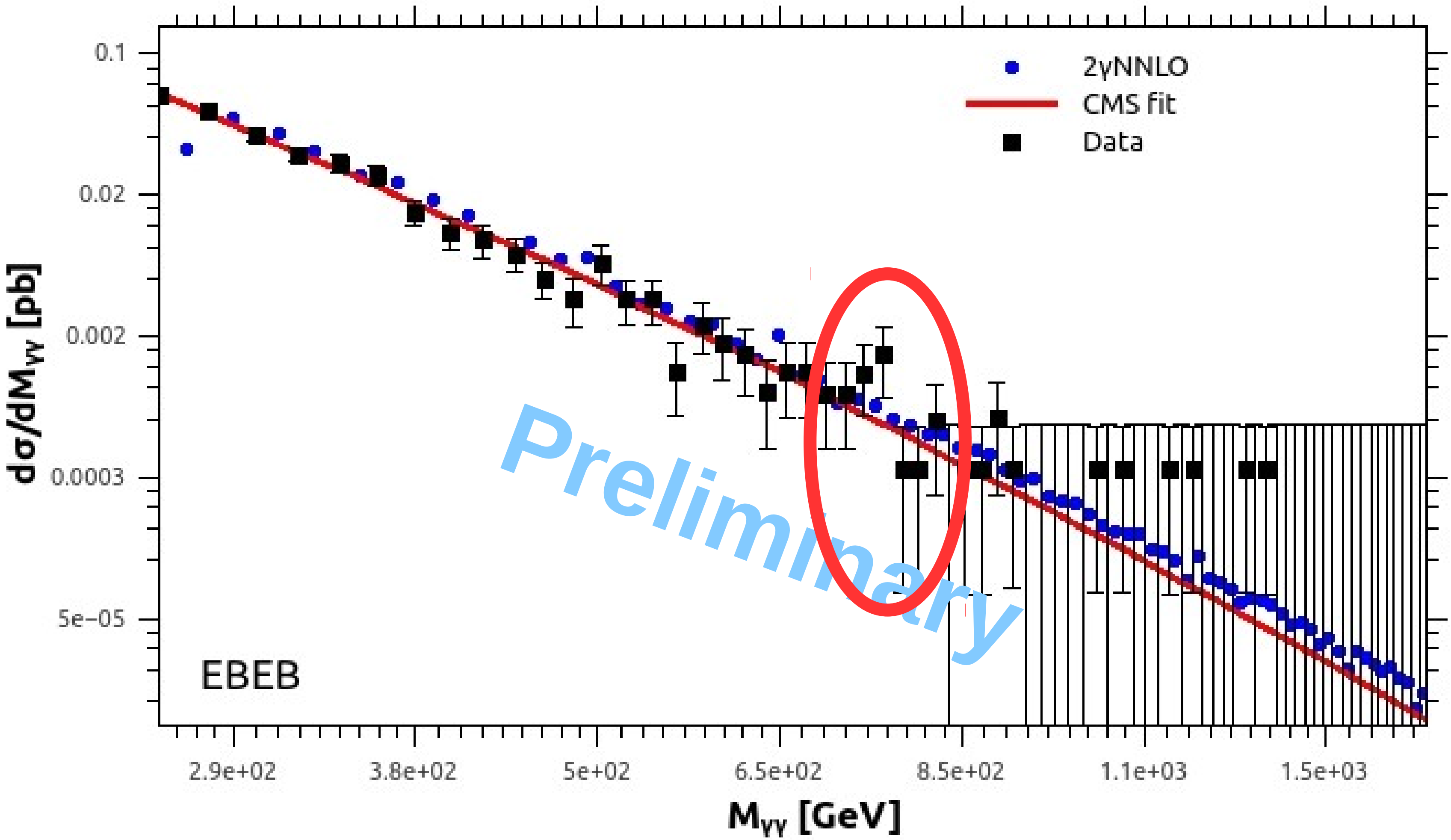

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Outlook

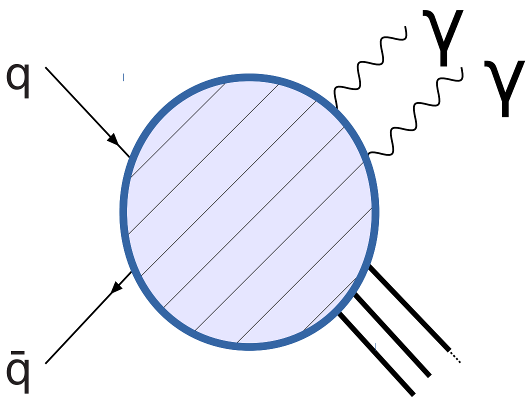
- **NNLO corrections are substancial for diphoton kinematical configurations of interest at high-energy hadron colliders**
- **The analyses performed by the ATLAS and CMS collaborations show good agreement between the NNLO description of γγ and data**
- **Transverse momentum resummation is important in order to recover the theoretical predictivity in kinematical regions $q_T \to 0$**
- **The NNLO results used in the recent CMS analysis of the diphoton invariant mass (which shows an excess of events with $M_{\gamma\gamma} \sim 750$ GeV) agree with the CMS fit function**

Thanks!!!

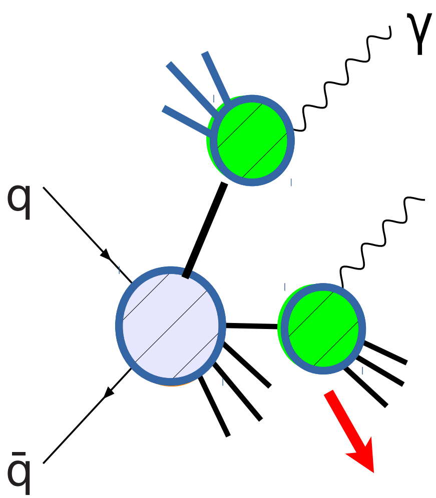
Backup Slides

Photon production

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



Direct component: photon is directly produced through the hard interaction



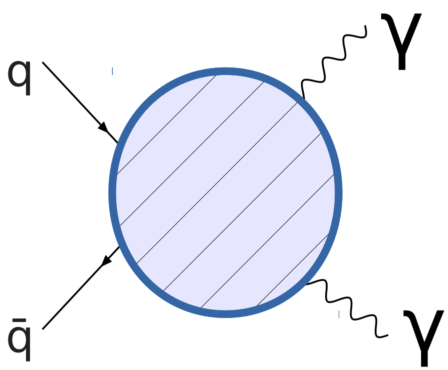
Fragmentation component: photon is produced from non-perturbative fragmentation of a hard parton (analogously to a hadron)

Fragmentation function: to be fitted from data

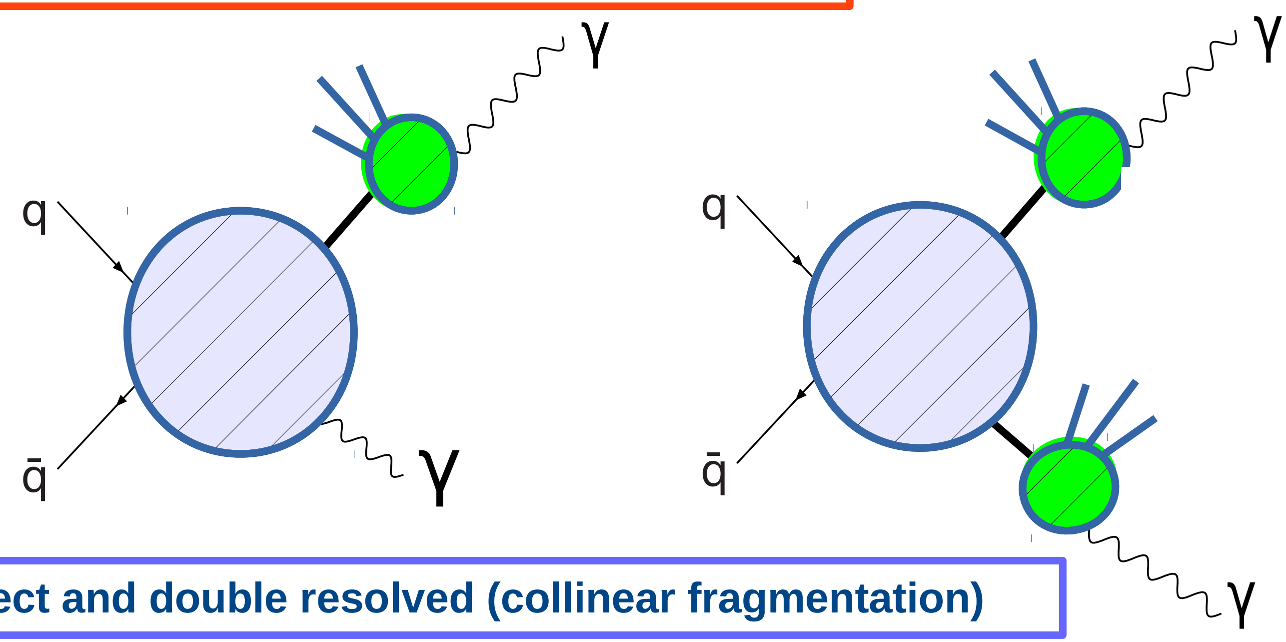
Calculations of cross sections with photons have additional singularities in the presence of QCD radiation. (i.e. When we go beyond LO)

Photon production

Two mechanisms for photon production

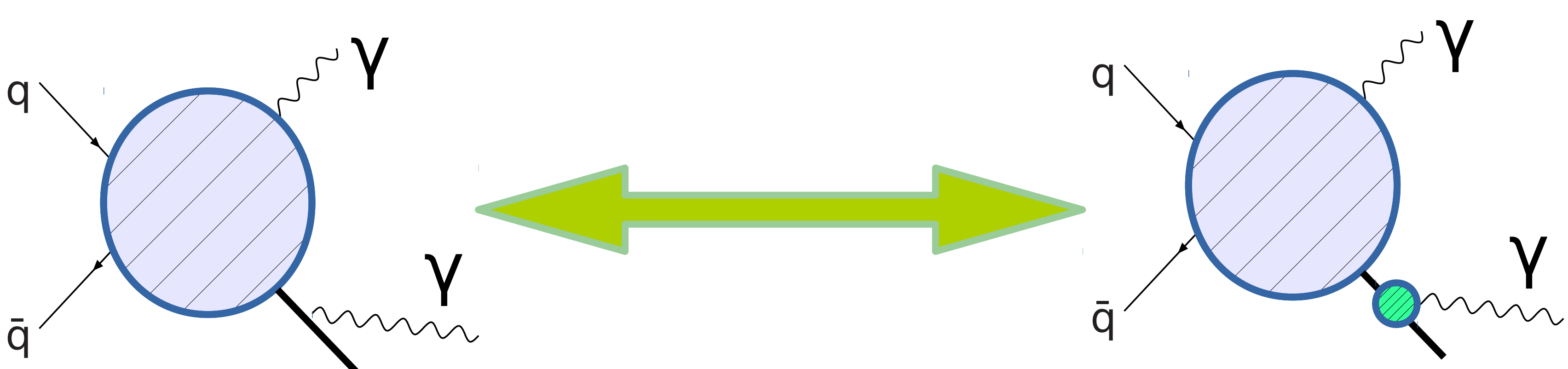


Direct (point-like)



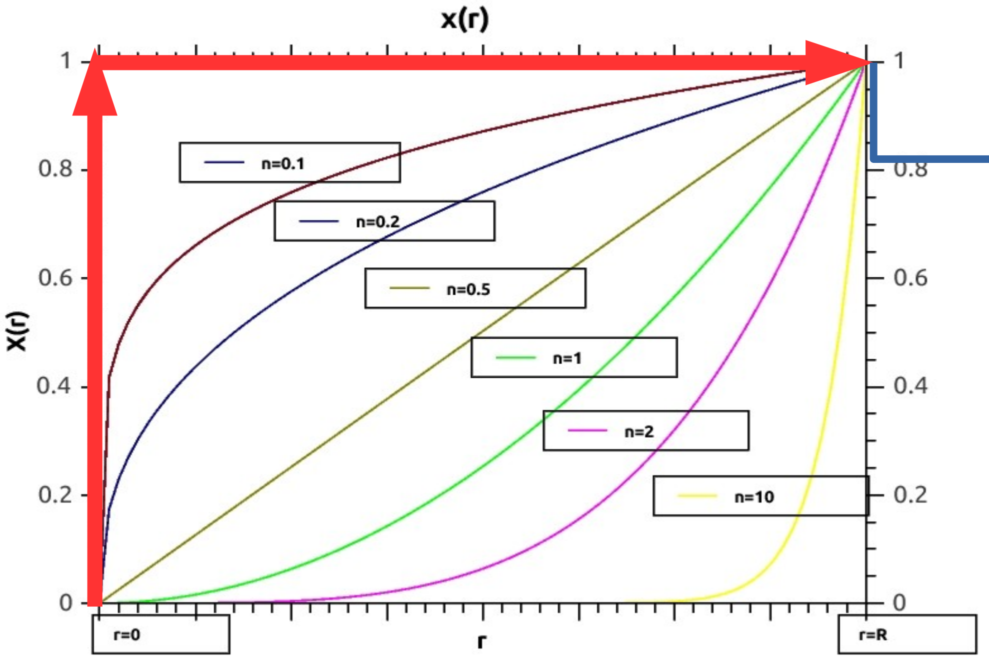
Direct and double resolved (collinear fragmentation)

In general the separation between them is not-physical (beyond LO)



Collinear divergence

Cancelled by fragmentation



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

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

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

- **No quark-photon collinear divergences**
- **No fragmentation contribution (only direct)**
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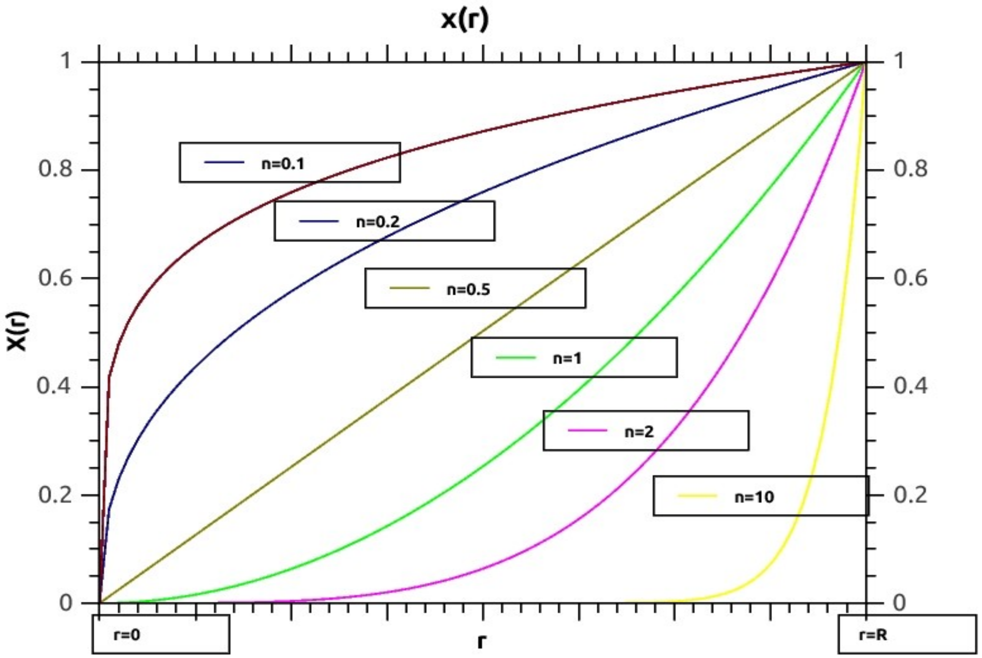
- **The smooth cone isolation criterion is more restrictive than the standard one**
- $\sigma_{Frix}\{R, E_{T\ max}\} \leq \sigma_{Stand}\{R, E_{T\ max}\}$

(both theoretically and experimentally)



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In real life... how much are different?

NLO comparison (Standard vs. Smooth) Ro=0.4 n=1

DIPHOX → (Direct + Fragmentation)[NLO]

T. Binoth, J. Guillet, E. Pilon, and M. Werlen (1999)

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

NLO:
- **MCFM** J. M. Campbell, R. K. Ellis, and C. Williams (2011)
- **gamma2MC** Bern, Dixon and Schmidt (2011)
- **Resbos** Balazs, Berger, Nadolsky, C.P Yuan (2007)

NNLO:
- **2γNNLO** S. Catani, LC, D. de Florian, G. Ferrera, and M. Grazzini (2011)

NNLL+ NNLO:
- **2γRes** LC, Coradeschi, de Florian (2015)

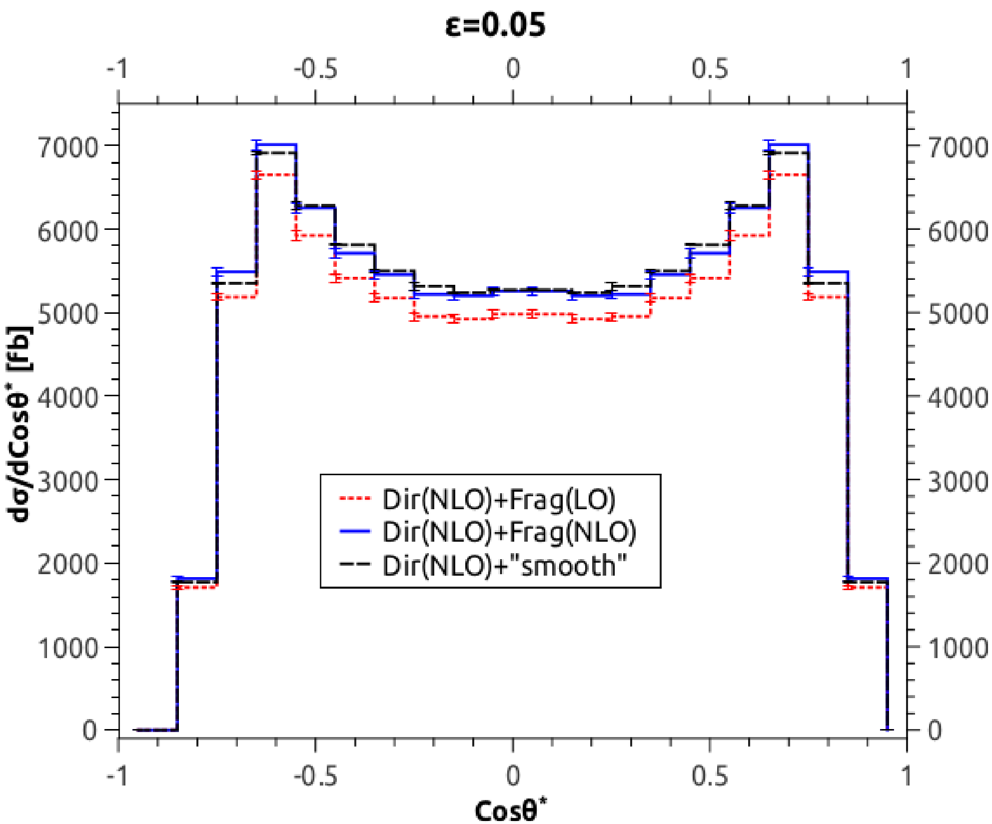
Diphoton production $\sqrt{s} = 8\,\text{TeV}$ CTEQ6M $\mu_F = \mu_R = M_{\gamma\gamma}$

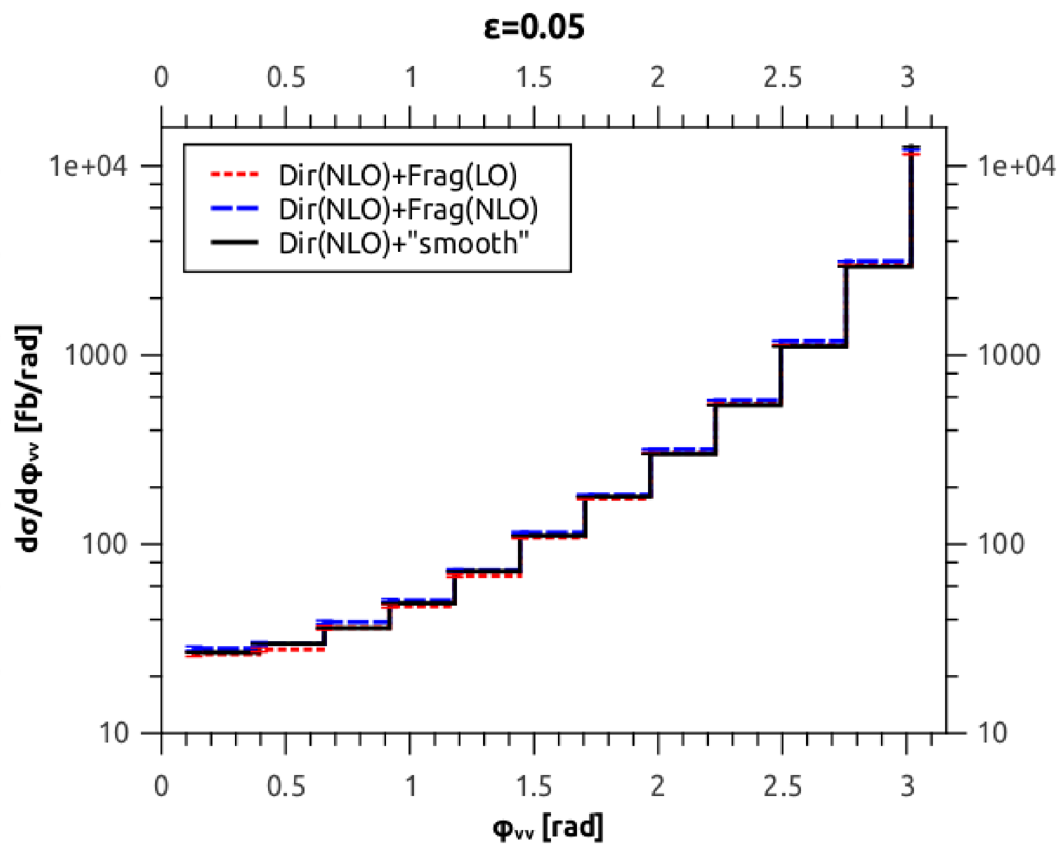
$$p_T^{\gamma\,hard} \geq 40\,\text{GeV} \qquad p_T^{\gamma\,soft} \geq 30\,\text{GeV} \qquad 100\,\text{GeV} \leq M_{\gamma\gamma} \leq 160\,\text{GeV} \qquad |\eta^{\gamma}| \leq 2.5 \qquad R_{\gamma\gamma} \geq 0.45$$

full NLO Cone (DIPHOX) vs Cone with LO fragmentation vs NLO Smooth

$E_{T\,max}^{had} = \epsilon\, p_T^{\gamma}$ $\epsilon = 0.05$

$E_{T\,max}^{had} = 4\,\text{GeV}$



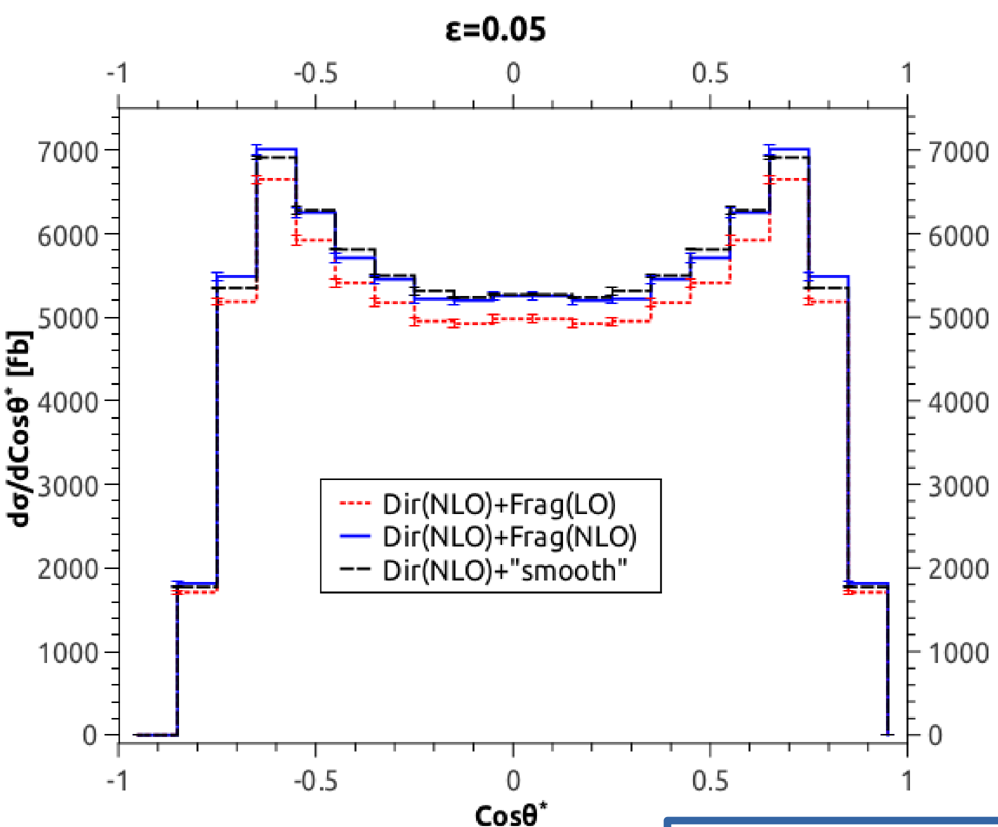


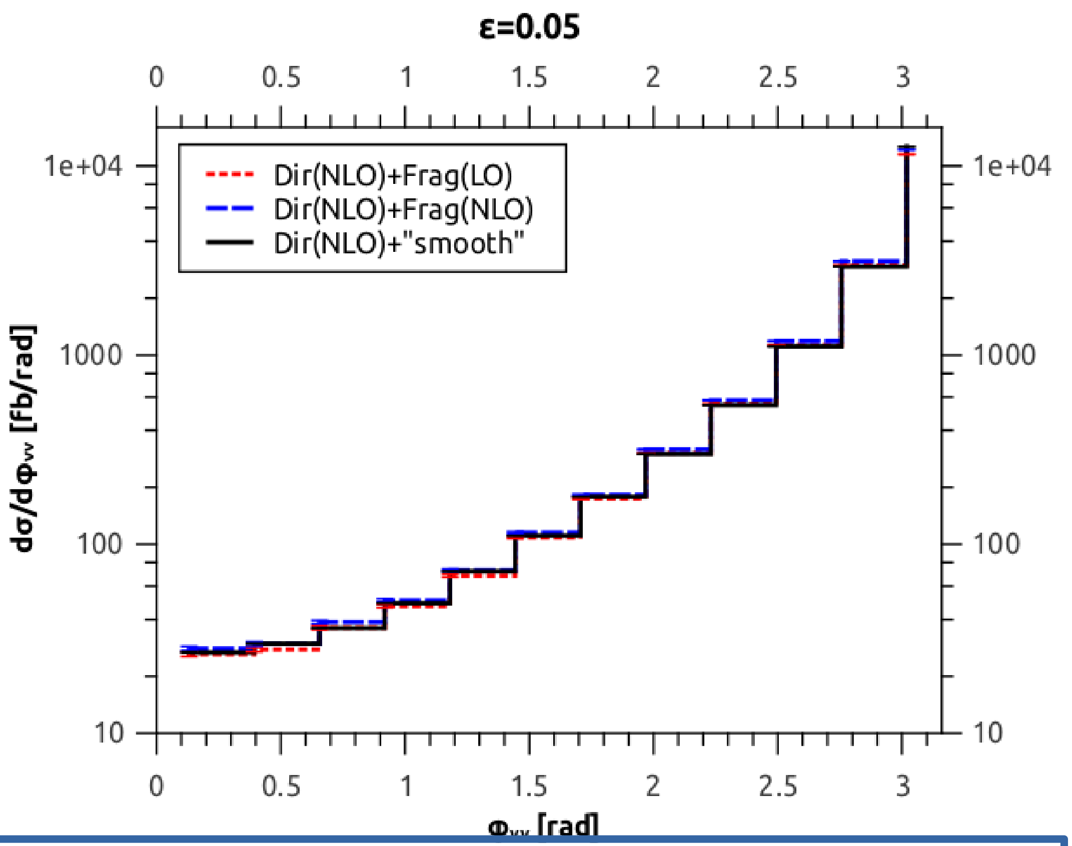
L.C , D. de Florian 2013

Same Features for all distributions

Smooth cone @NLO ~ Cone @ NLO 1-2 %

Cone + LO fragmentation component worse than 5%



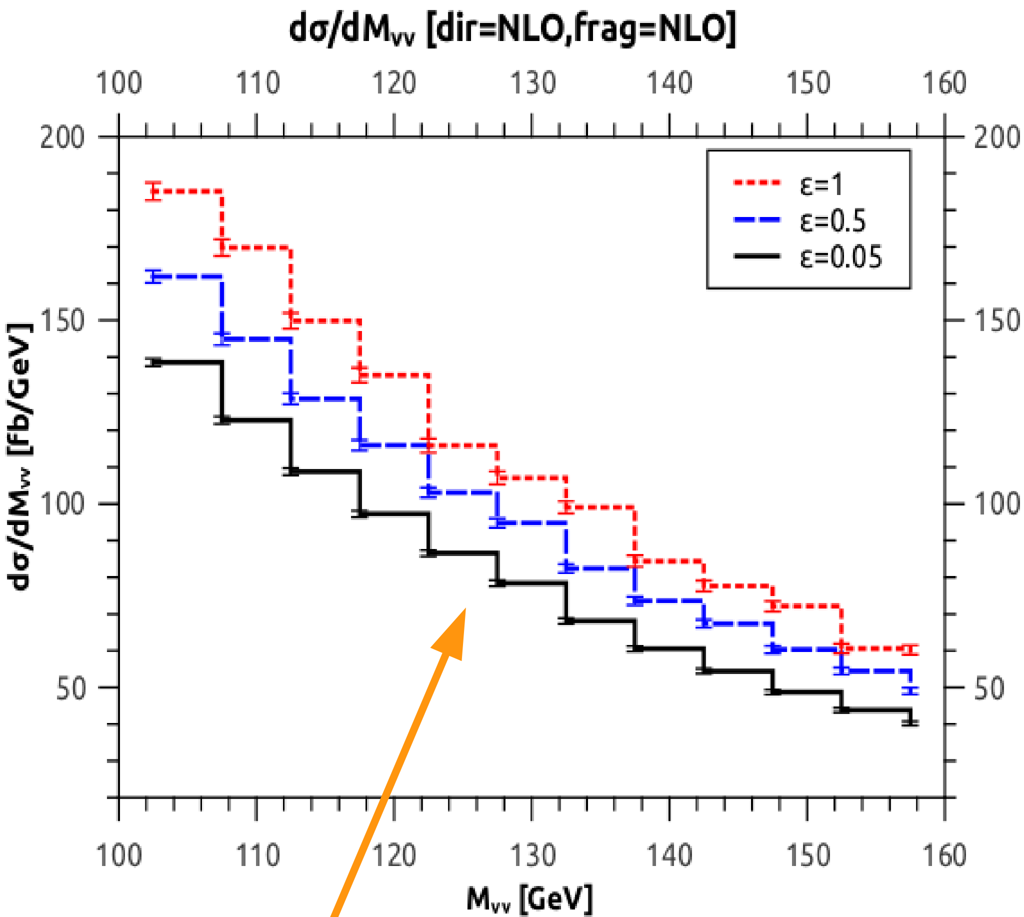


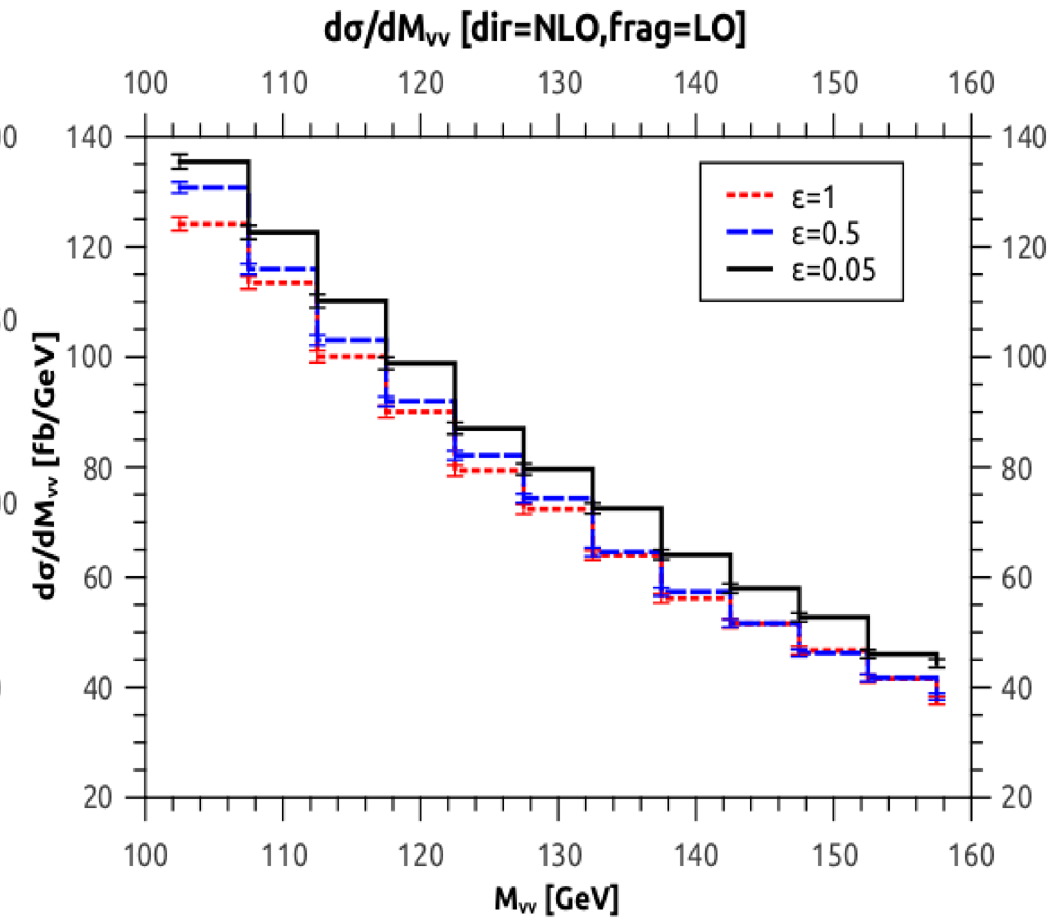
L.C , D. de Florian 2013

Be carefull to make conclusions here
It is not true that the smooth approach gives a larger Xsection
See the Full NLO result with Fragmentation

In some cases, using LO fragmentation component can make things look very strange...

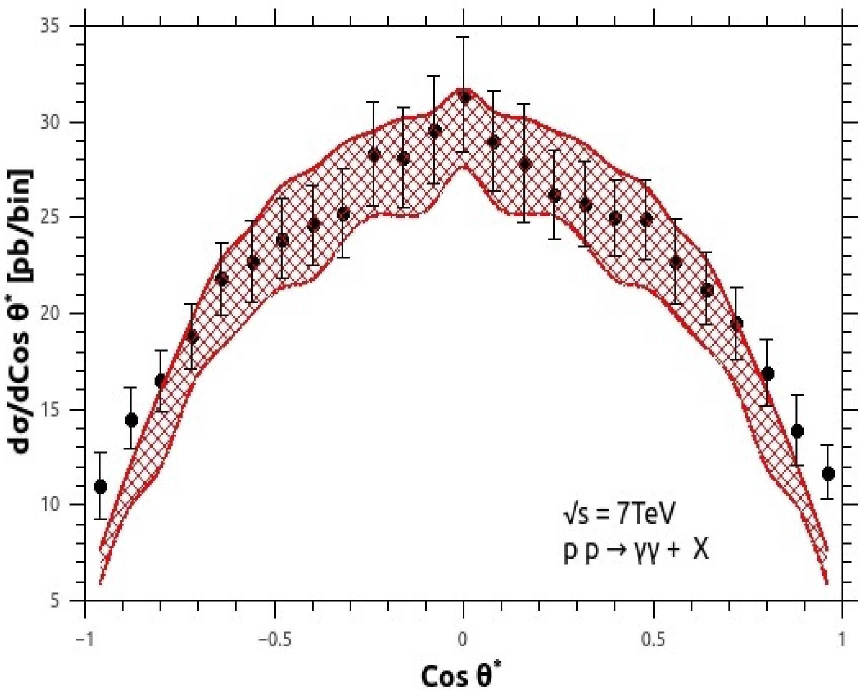
Standard cone isolation → DIPHOX



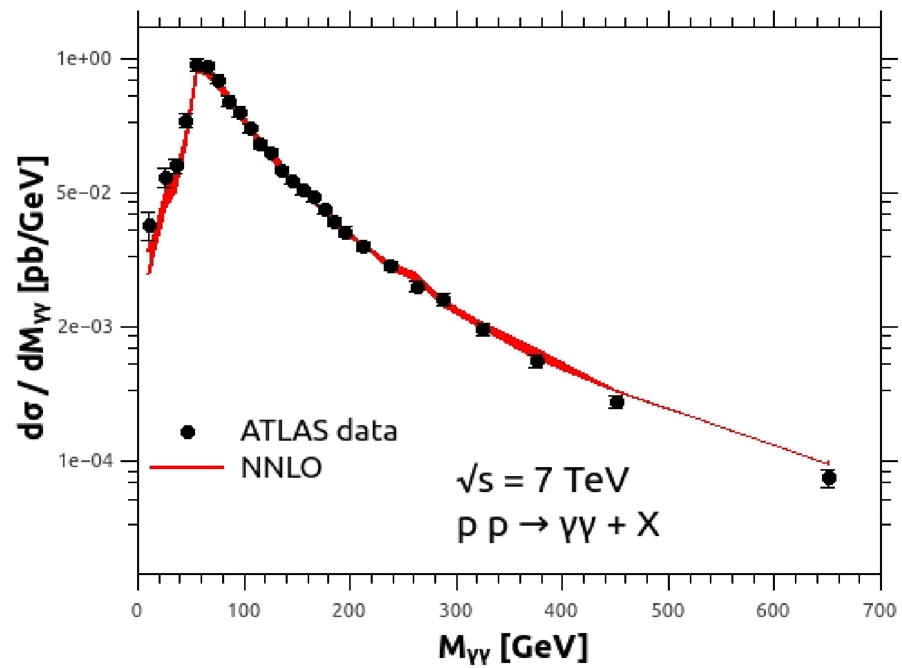


Right behaviour!!

L.C , D. de Florian 2013

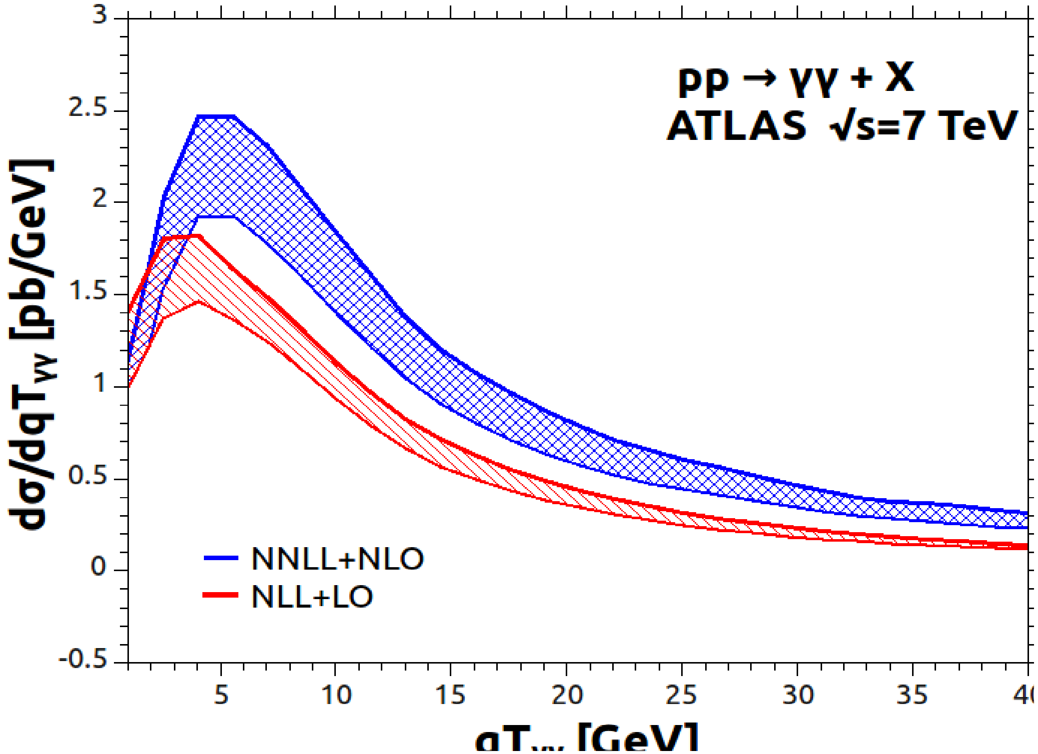


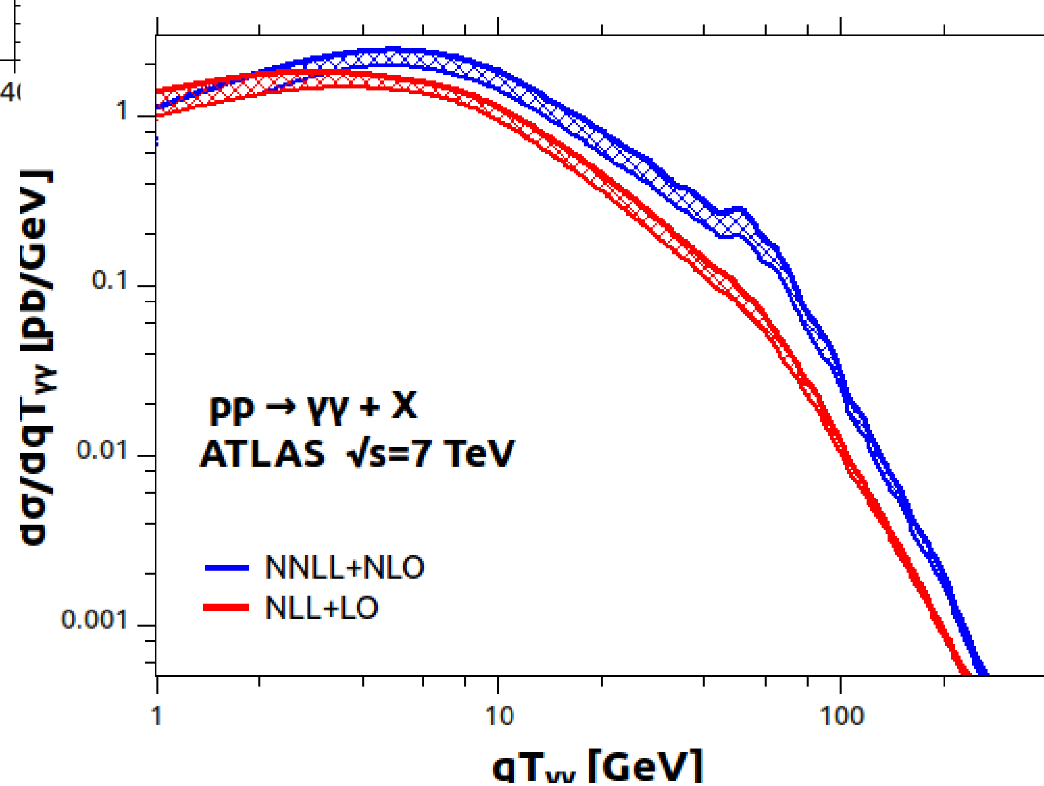
dσ/dCos θ* [pb/bin]
Cos θ*
√s = 7TeV
p p → γγ + X
35
30
25
20
15
10
5
−1
−0.5
0
0.5
1



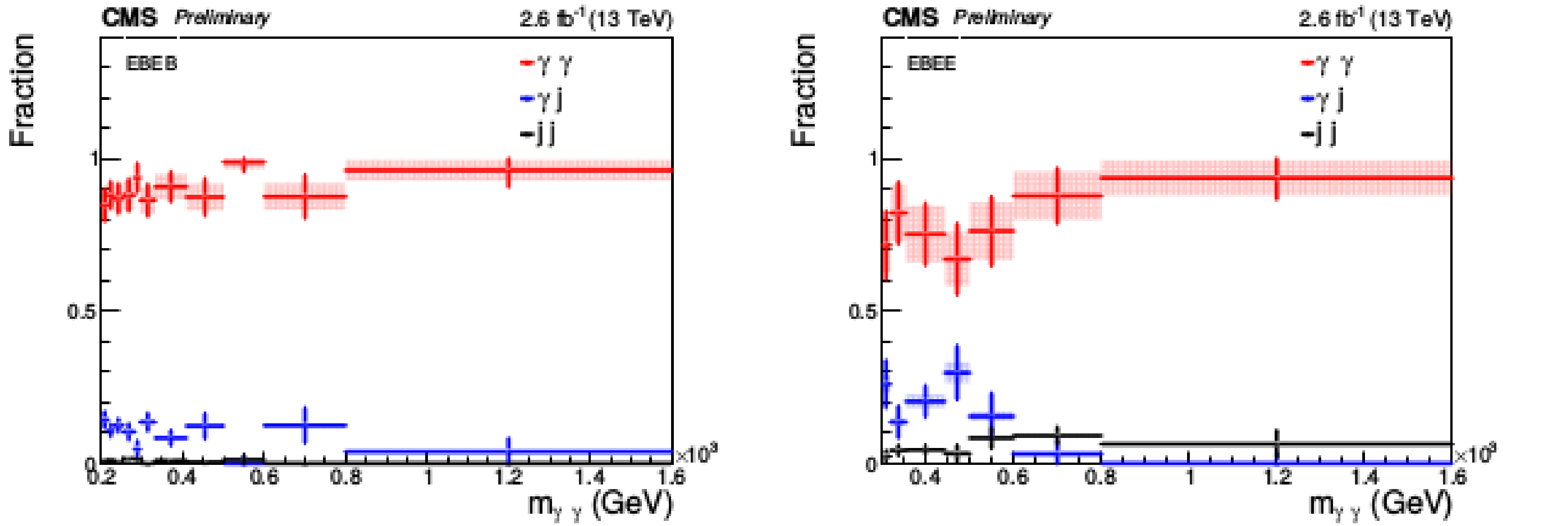
dσ / dMγγ [pb/GeV]
Mγγ [GeV]
ATLAS data
NNLO
√s = 7 TeV
p p → γγ + X
1e+00
5e−02
2e−03
1e−04
0
100
200
300
400
500
600
700

Resummation → ATLAS γγ

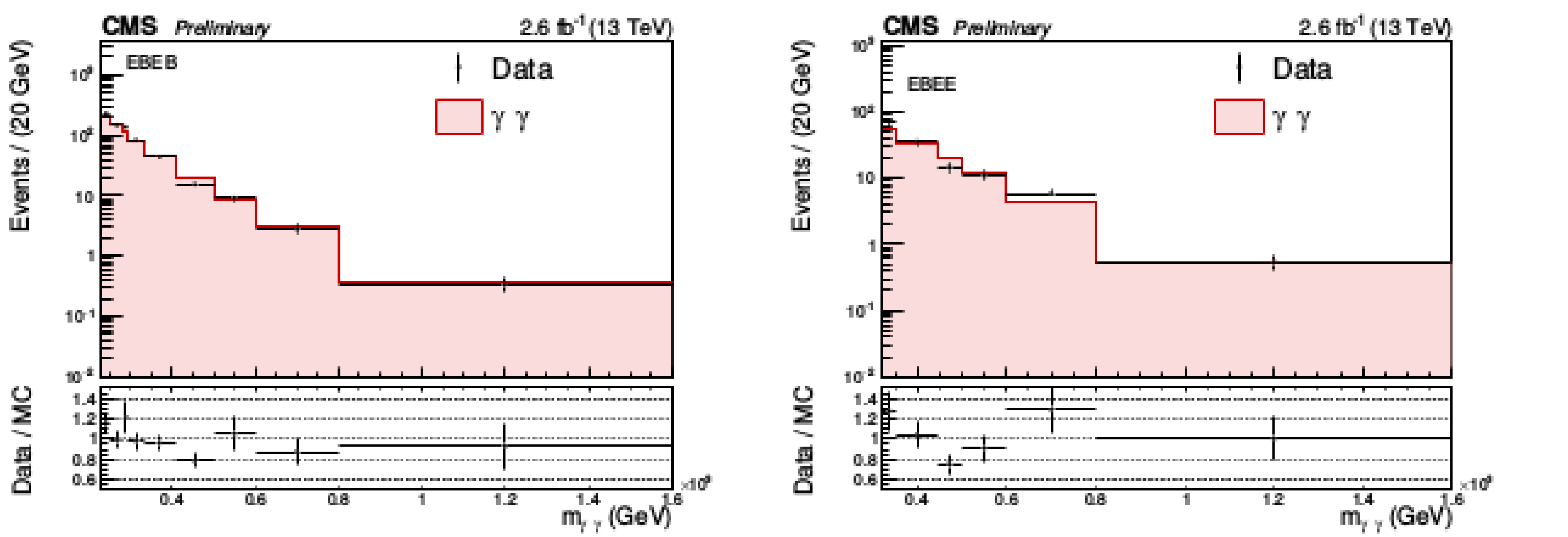




CMS-PAS-EXO-15-004



Measured composition of the background for the EBEB (left) and EBEE (right) categories.



Comparison between the measured and the predicted invariant mass spectrum of the non resonant $\gamma\gamma$ background for the EBEB (left) and EBEE (right) categories.