Diphoton production at the LHC

Based on a forthcoming paper in collaboration with: S. Catani, D. de Florian, G. Ferrera and M. Grazzini

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HP2.6 High Precision for Hard Processes 6

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Outline

- **Why diphoton production is important?**
- **Isolation criteria**
- **NNLO results @ LHC**
- **NNLO results @ LHC [CMS → 750 GeV excess]**
- **Summary**

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- **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** Phys. Lett. B 716 (2012) 1 Phys. Lett. B 716 (2012) 30
- **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

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> 20 articles (2016)

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ATLAS-CONF-2015-081

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ATLAS-CONF-2016-059 CMS-PAS-EXO-16-027

Introduction

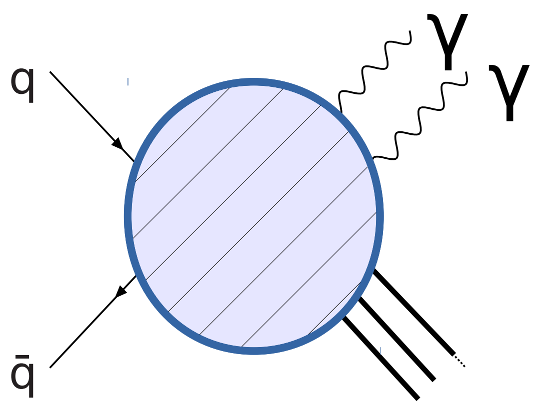
- Owing to its physics relevance, the study of diphoton production requires accurate theoretical calculations which, in particular, include QCD radiative corrections at high perturbative orders.
- $pp(\bar{p}) \rightarrow \gamma\gamma$
- $\sigma = \sigma^{LO} + \alpha^1_s\ \sigma^{NLO} + \alpha^2_s\ \sigma^{NNLO} + \ldots$
- We are interested in fixed order (f.o) theoretical (TH) tools

Fragmentation → strictly collinear

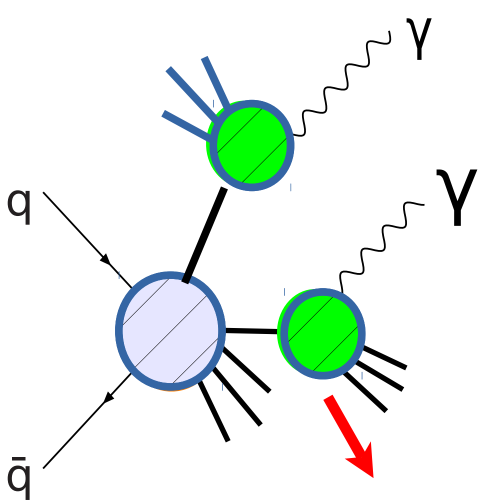
LH-2011 SM-WG

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)

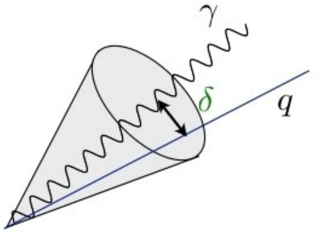
Isolation criteria

- **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)

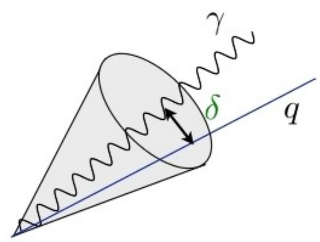
$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

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

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

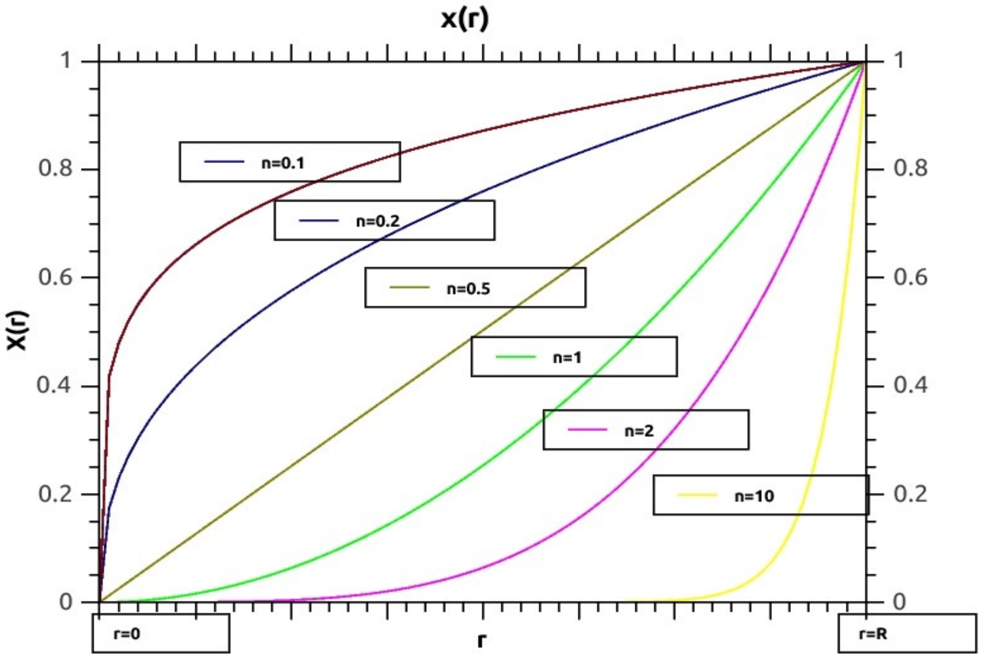
Soft emission allowed arbitrarily close to the photon

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

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

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

Isolation criteria



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

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

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- Direct contribution well defined

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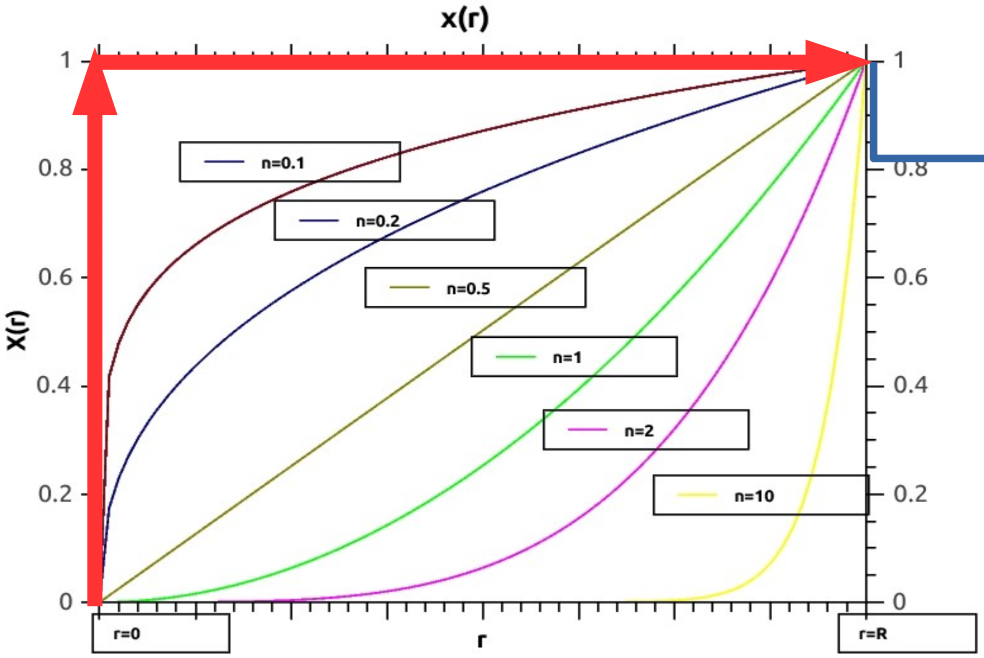

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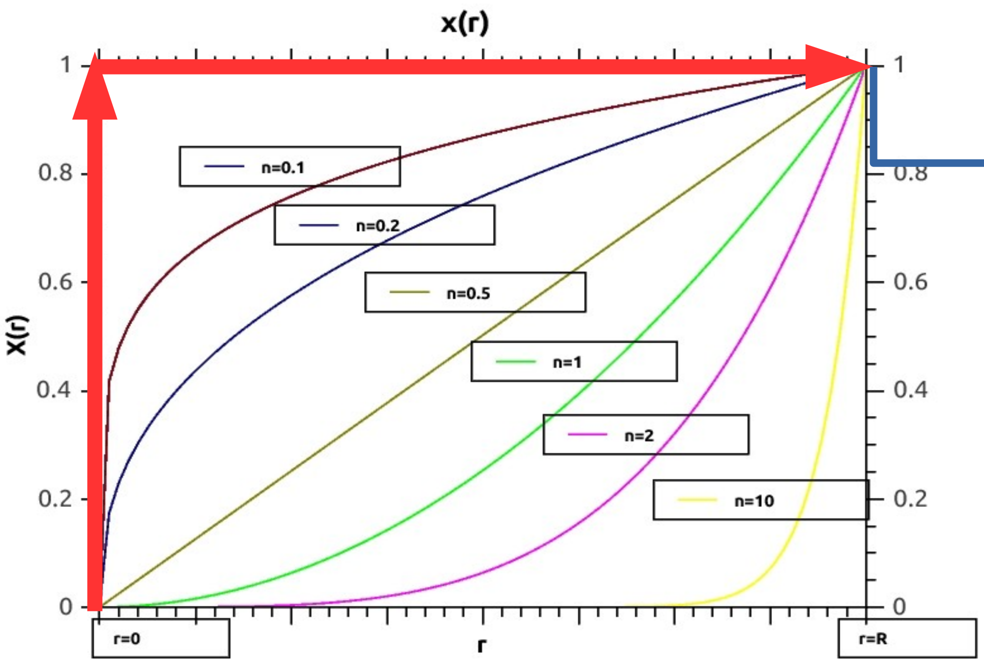

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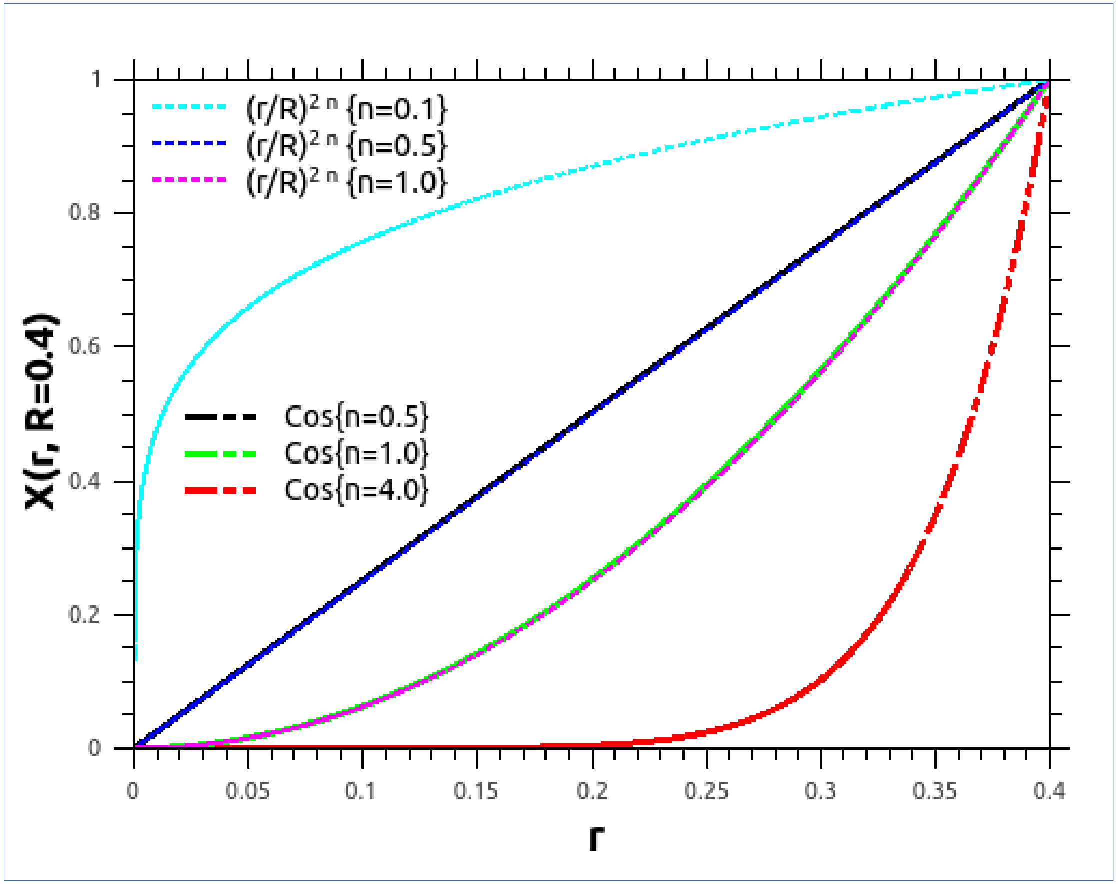
Smooth $E_T^{had}(\delta) \leq E_{T\,max}^{had}\,\chi(\delta)$

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

- 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)

Isolation criteria



$$\chi(r;R) = \left(\frac{1-\cos(r)}{1-\cos(R)}\right)^n$$

Historically the shape of this function was born for e^+e^- collisions

S. Frixione (1998)

$$\chi(r;R) = \left(\frac{r}{R}\right)^{2n}$$

$$\chi(r) \to 0 \text{ if } r \to 0$$

$$d\chi(r)/dr \to 0 \text{ if } r \to 0$$

Higgs searches cuts

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

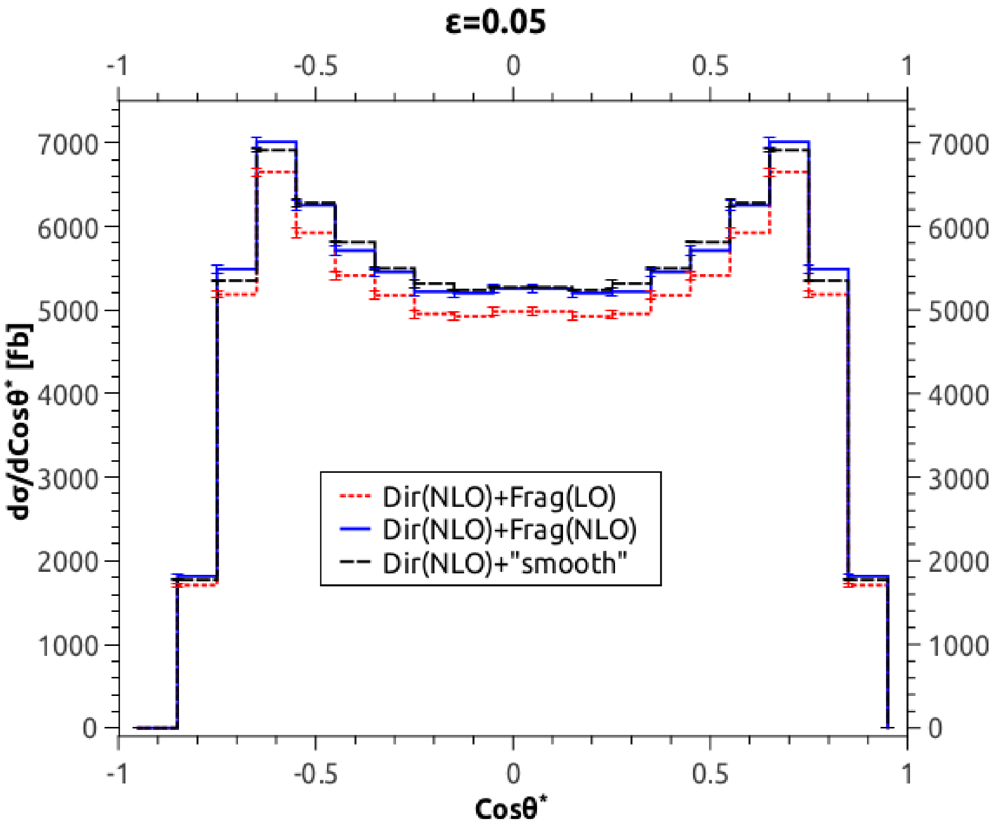
$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$

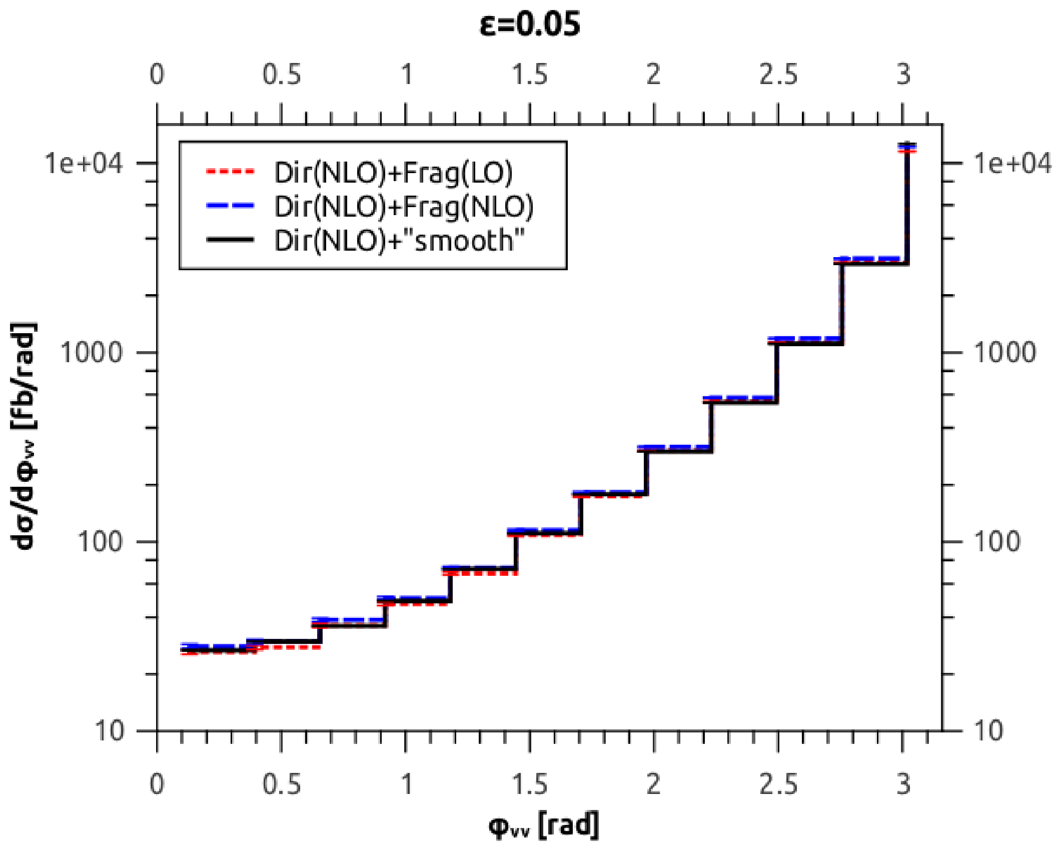
$p_T^{\gamma\,soft} \geq 30\,\mathrm{GeV}$

$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$ $|\eta^\gamma| \leq 2.5$ $R_{\gamma\gamma} \geq 0.45$

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

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





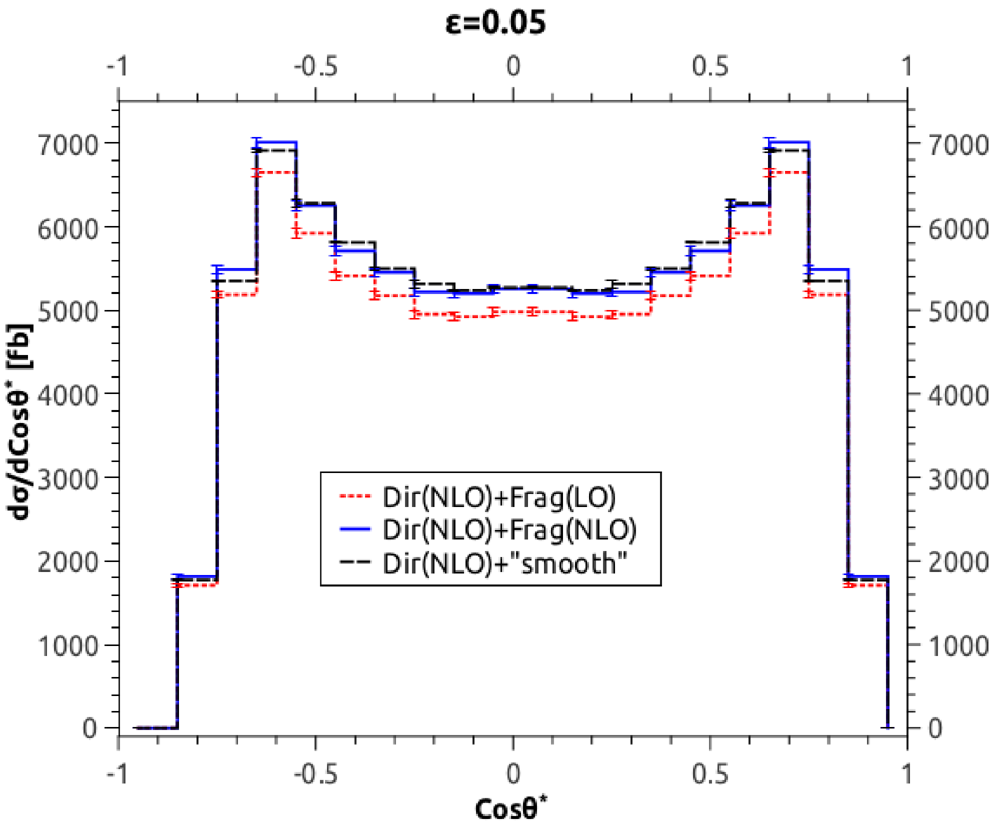
L.C , D. de Florian 2013

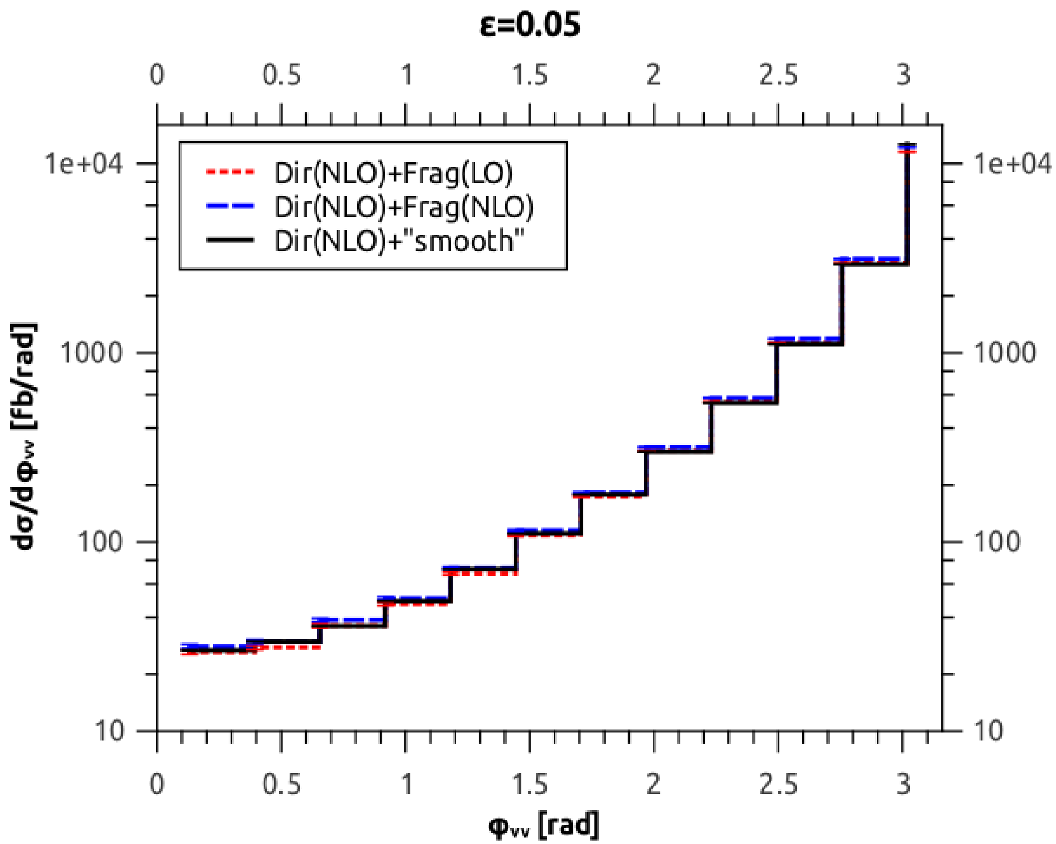
Higgs searches cuts

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

It is not true that the smooth approach gives a larger Xsection
See the Full NLO result with Fragmentation

Les Houches accord 2013

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

L.C , D. de Florian 2013

"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

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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)

ATLAS SM cuts

ArXiv:1211.1913

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

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2GeV ; 10GeV

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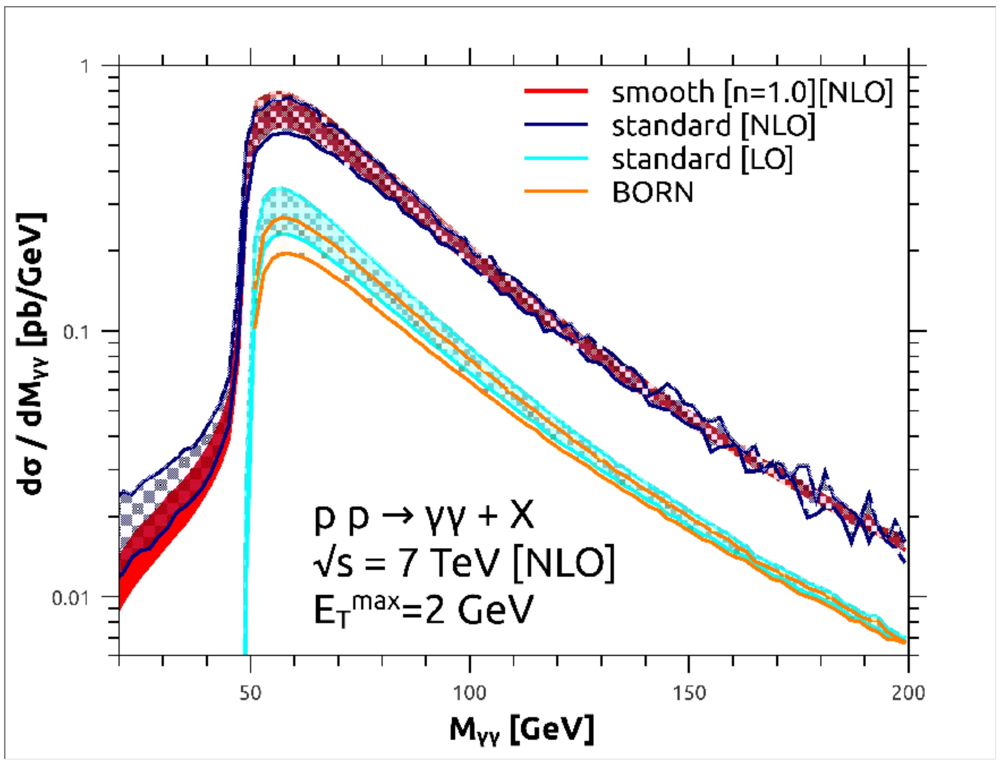
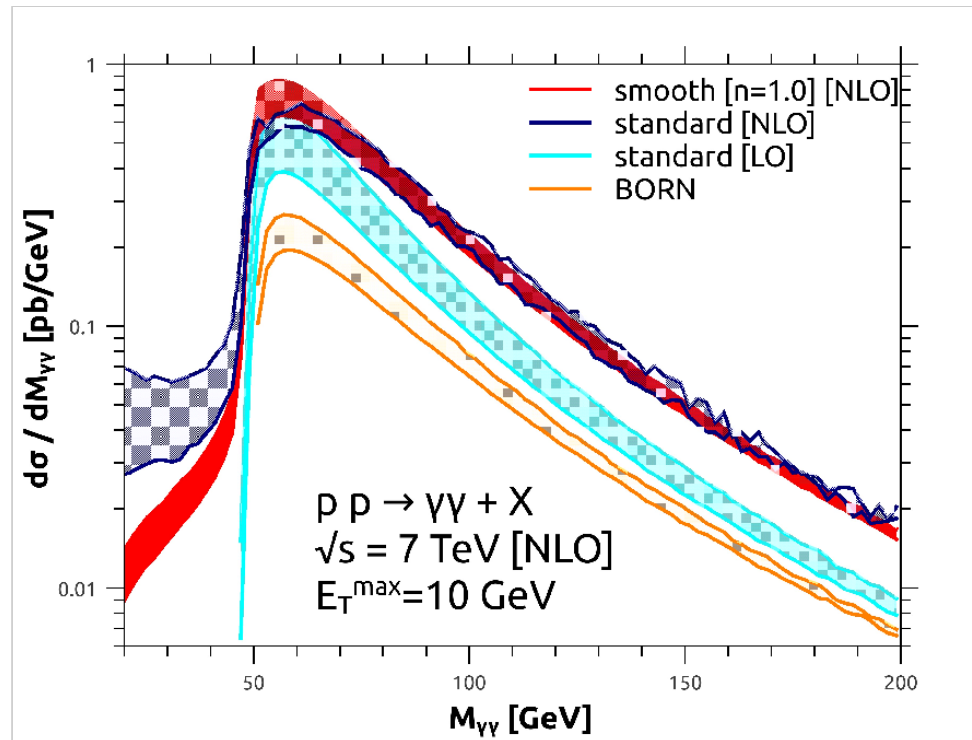
→ Tevatron

2GeV, 10GeV

LHC Run II (Marco Del Mastro P. Comm)





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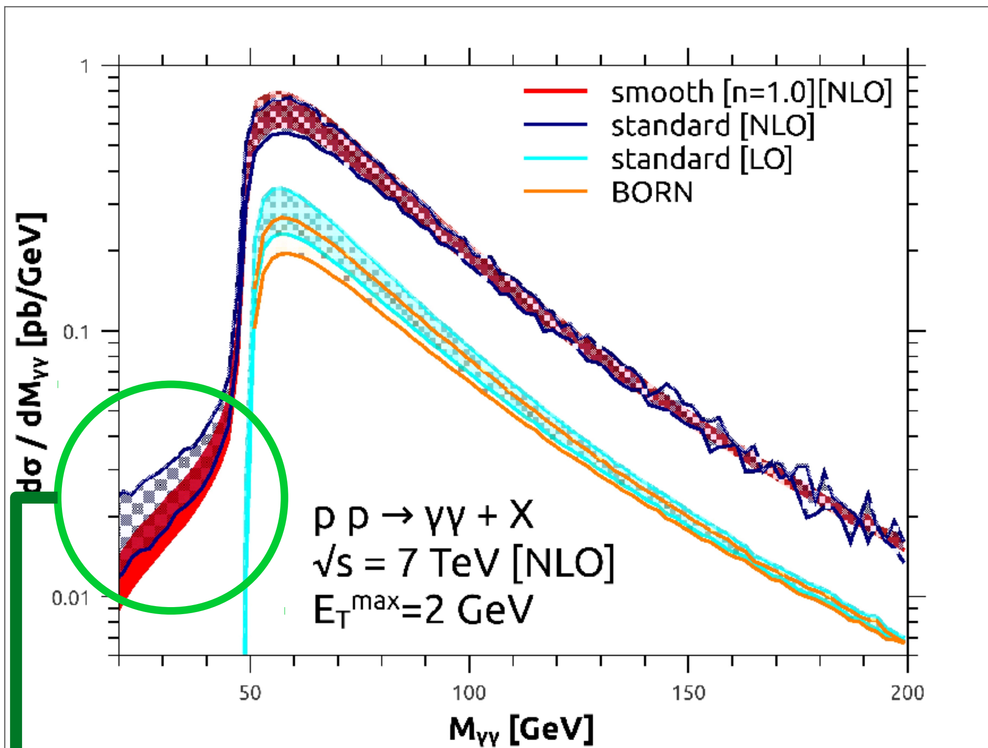

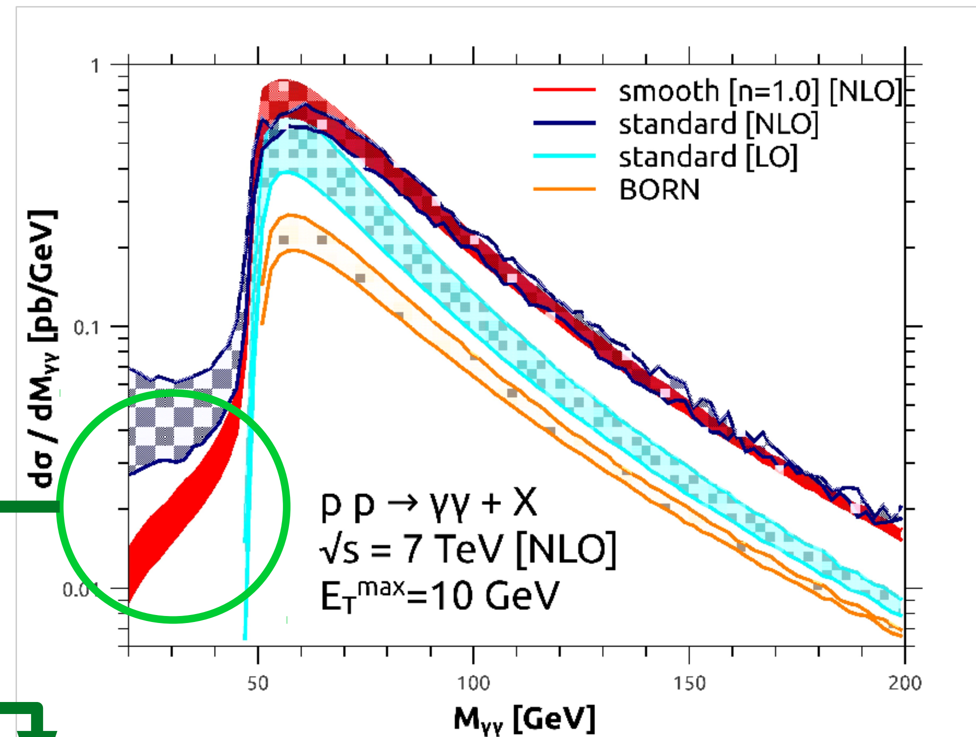

The smooth-cone result in the kinematical region far away from the back-to-back configuration is the same

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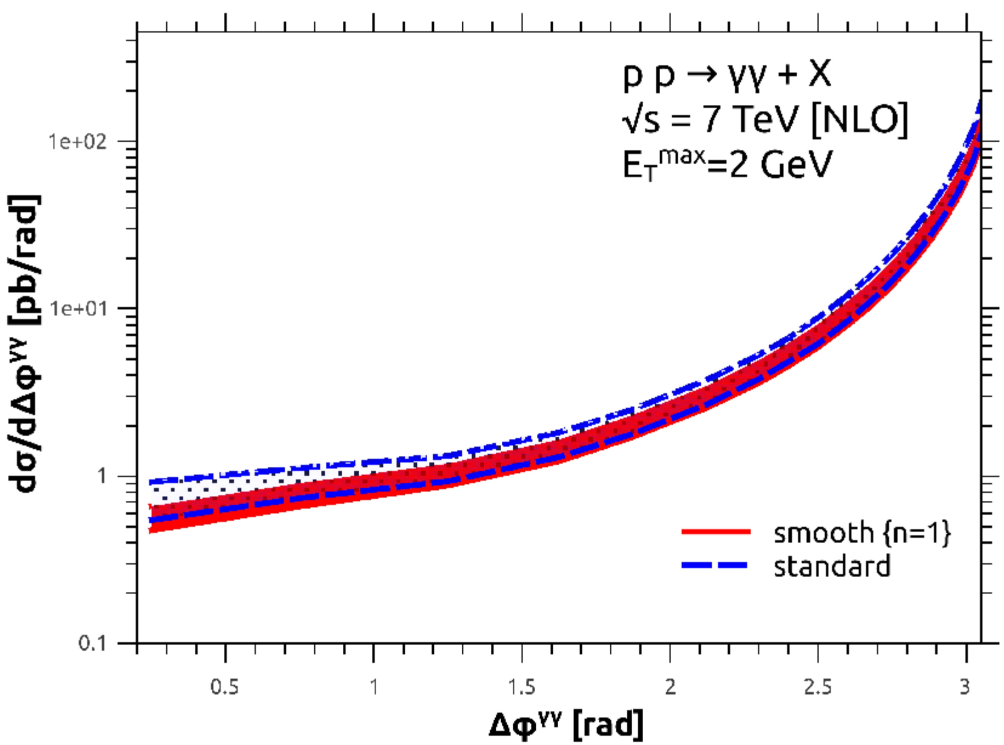

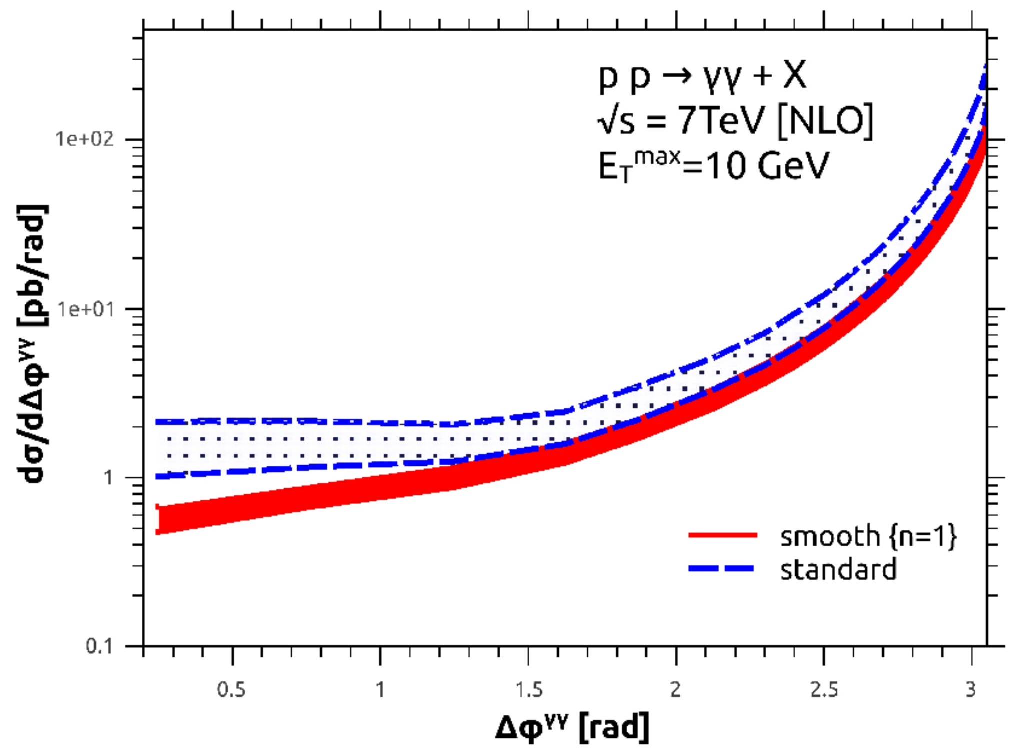

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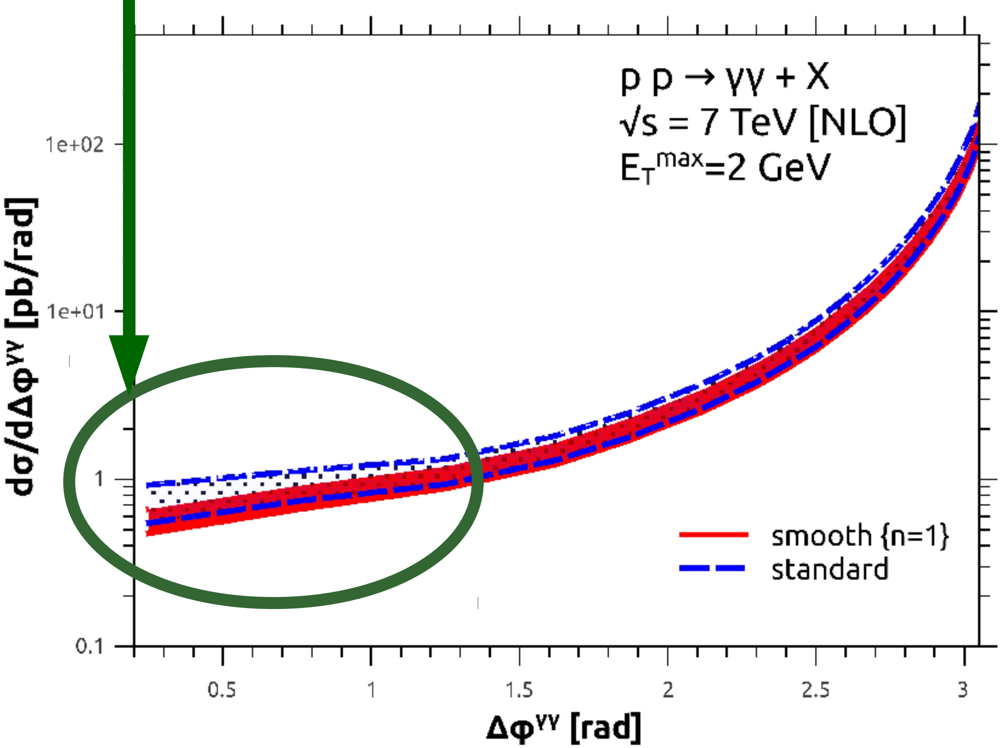
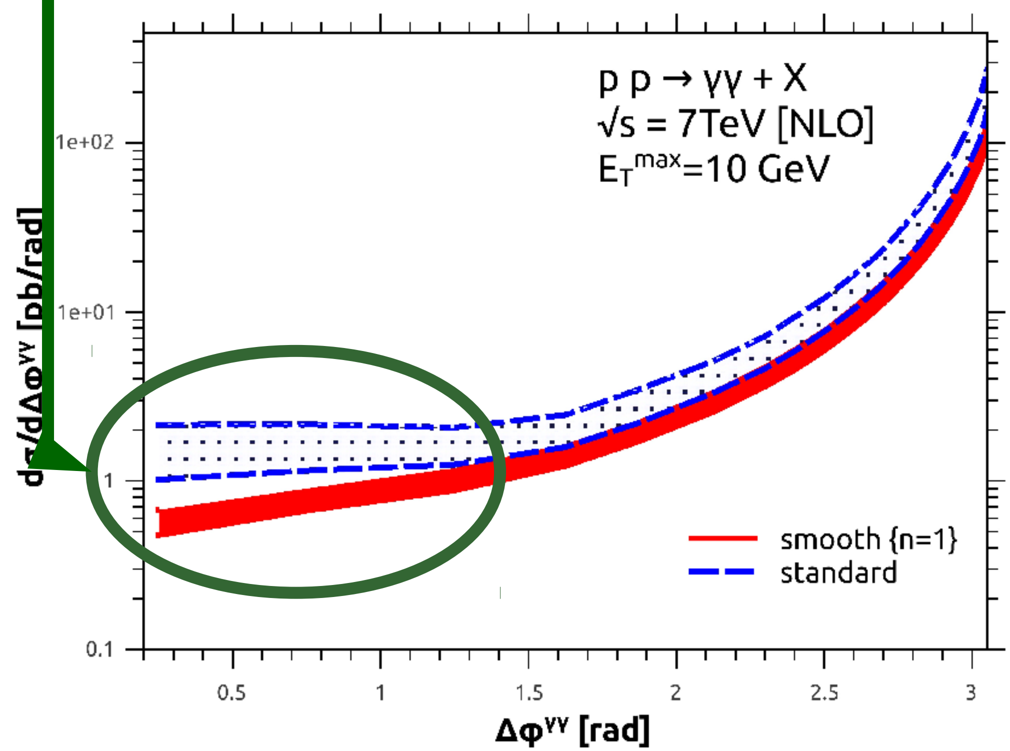
2GeV ; 10GeV

Effect of $R_{\gamma\gamma}$





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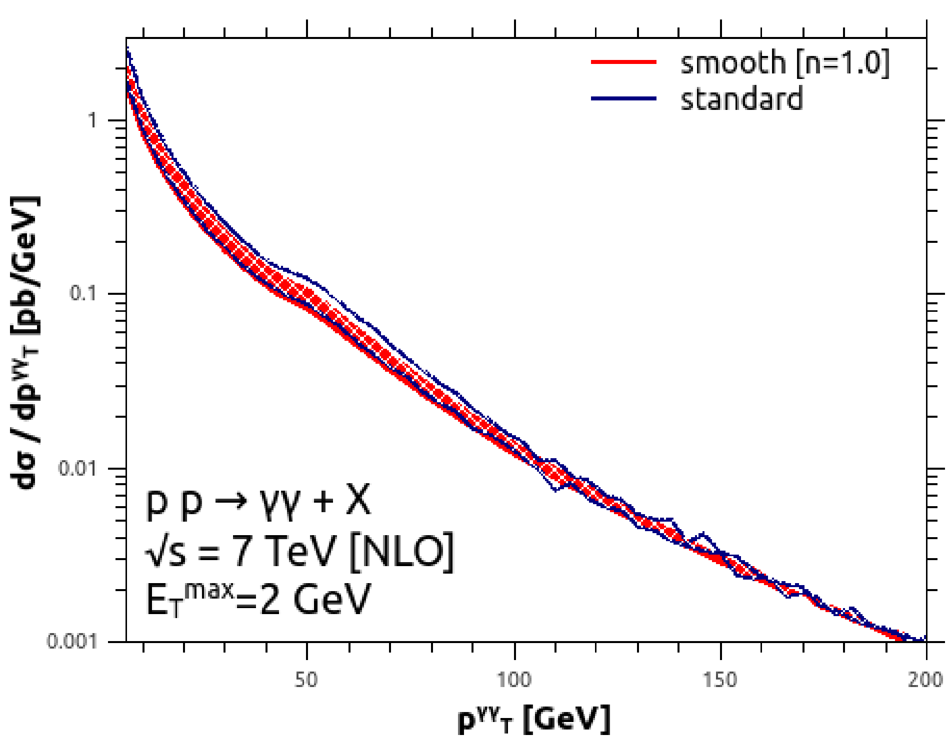
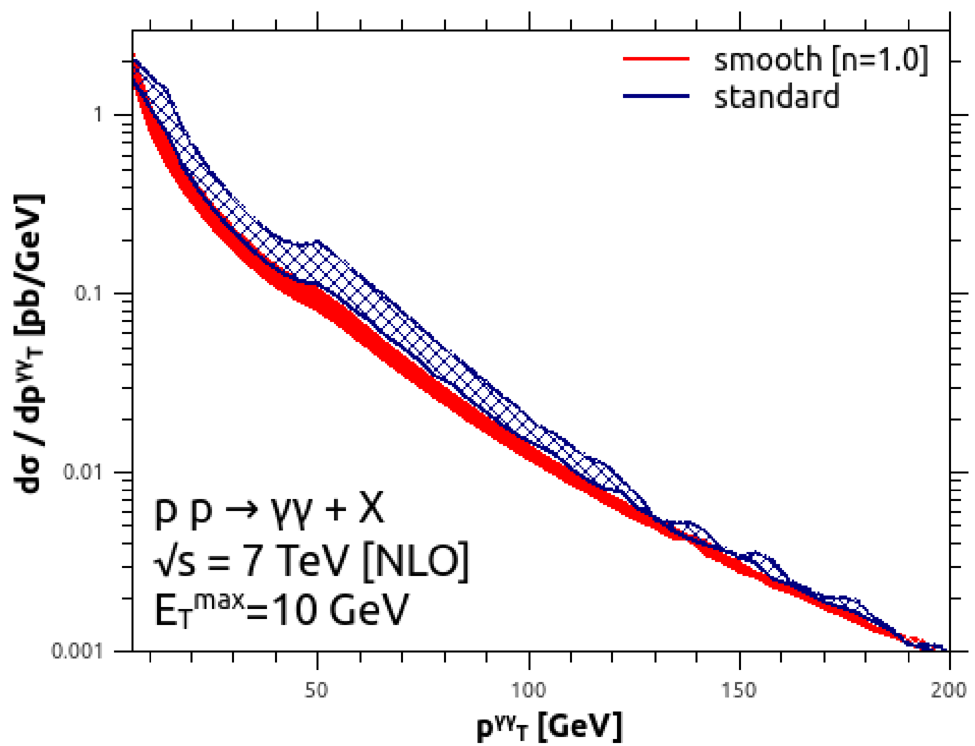
2GeV ; 10GeV





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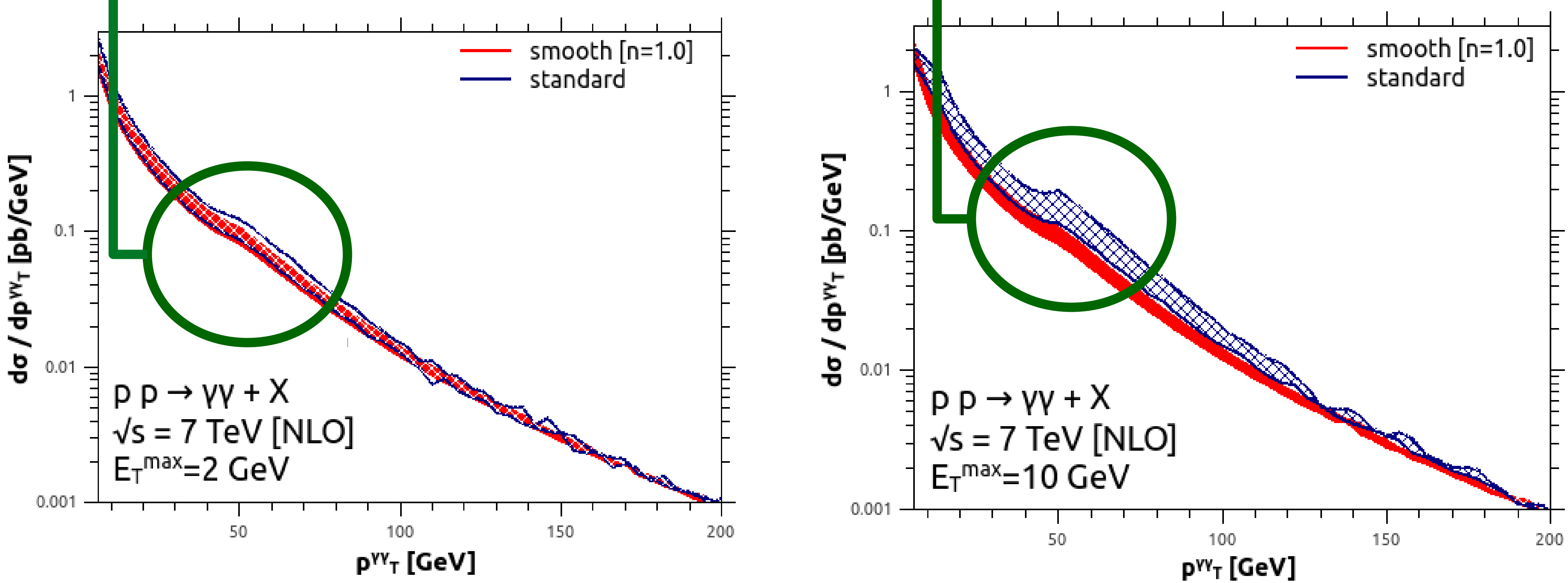
2GeV ; 10GeV

Guillet shoulder



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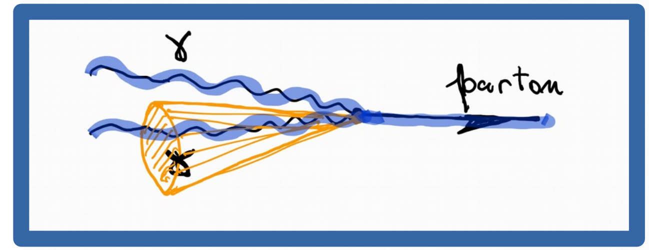

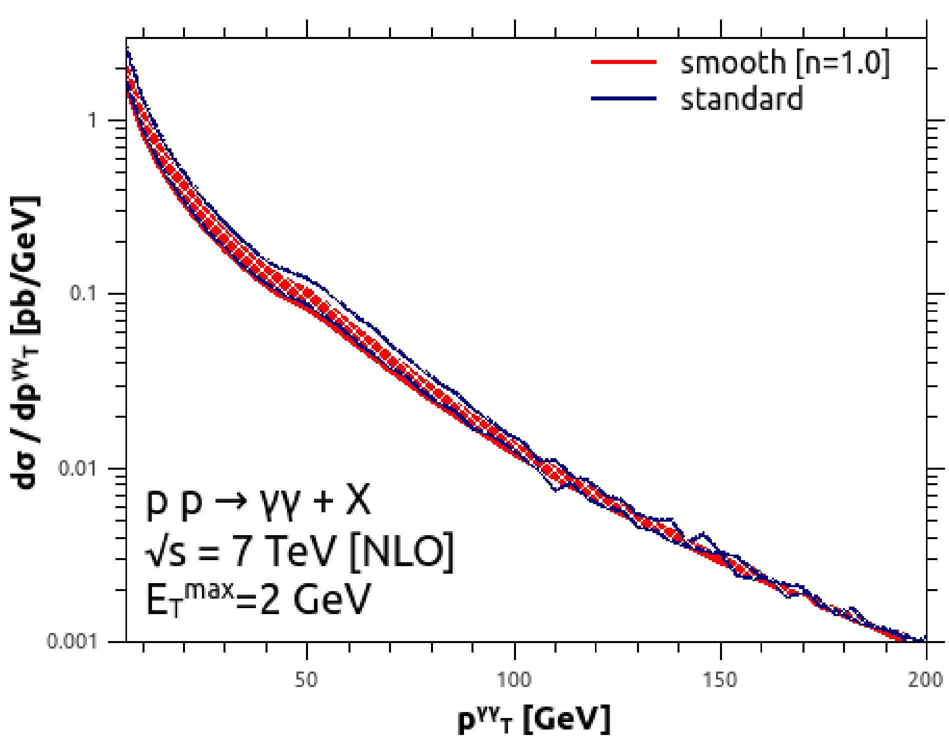

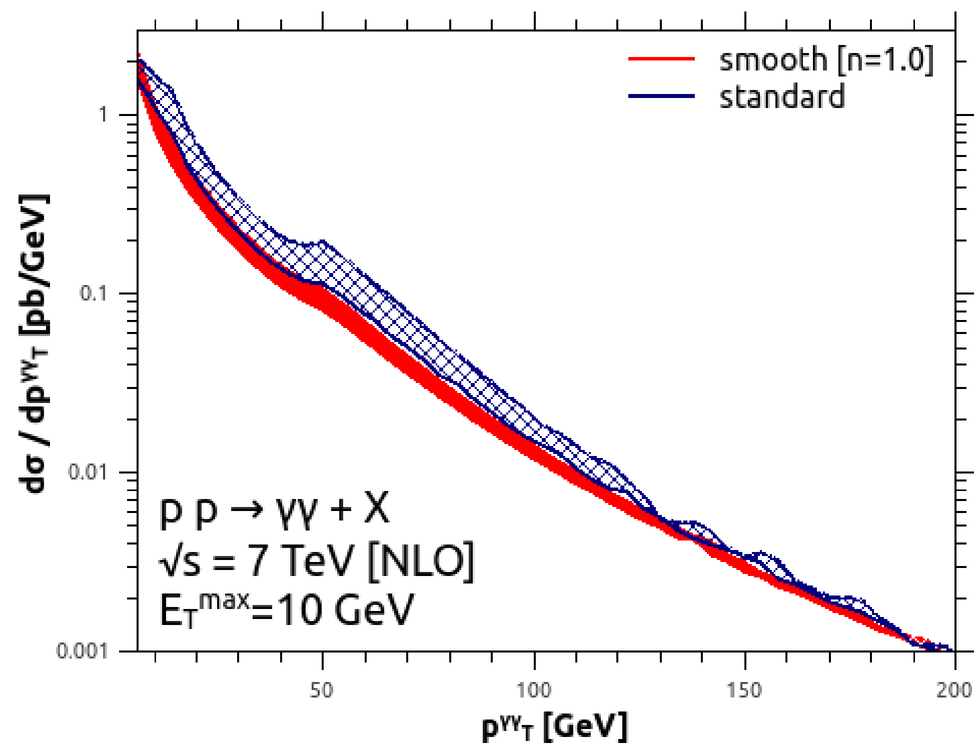

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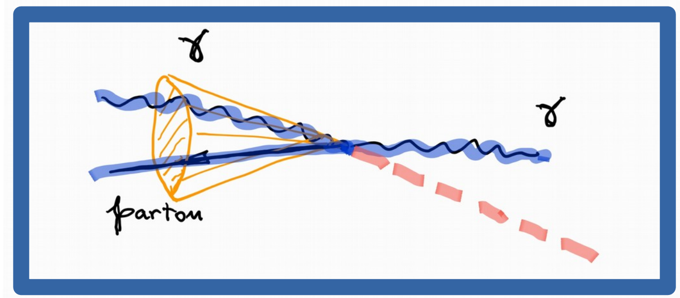

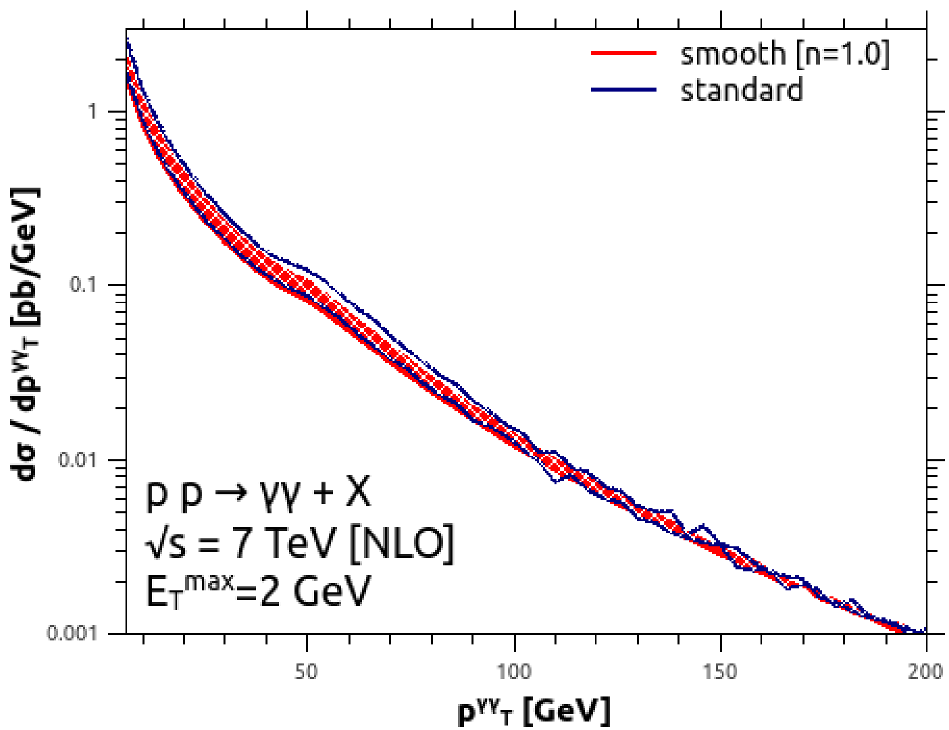

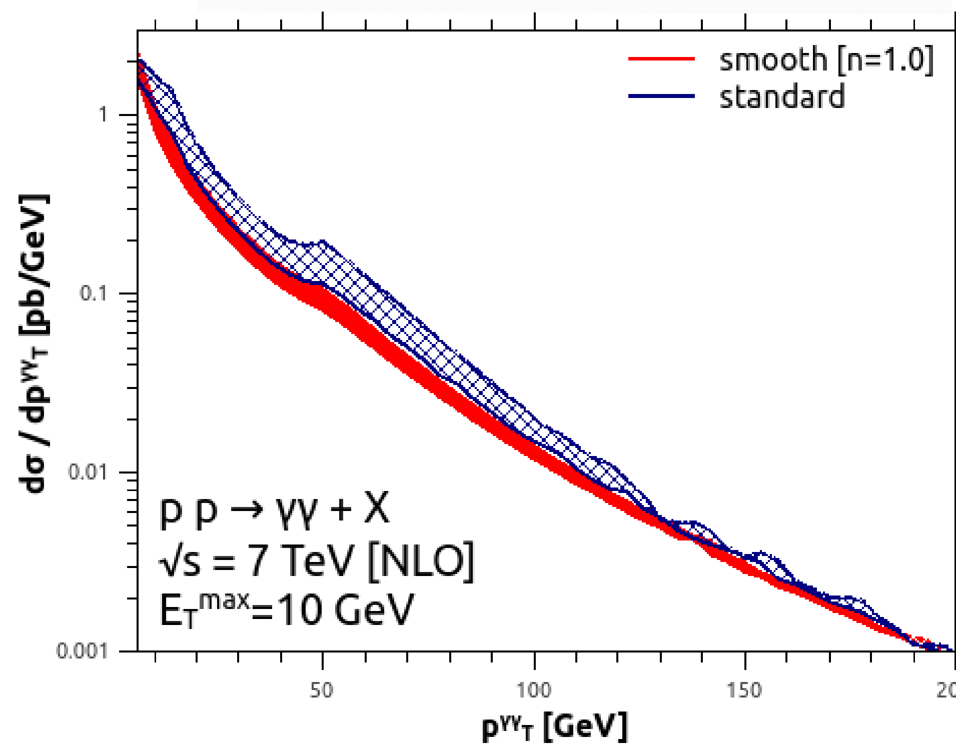

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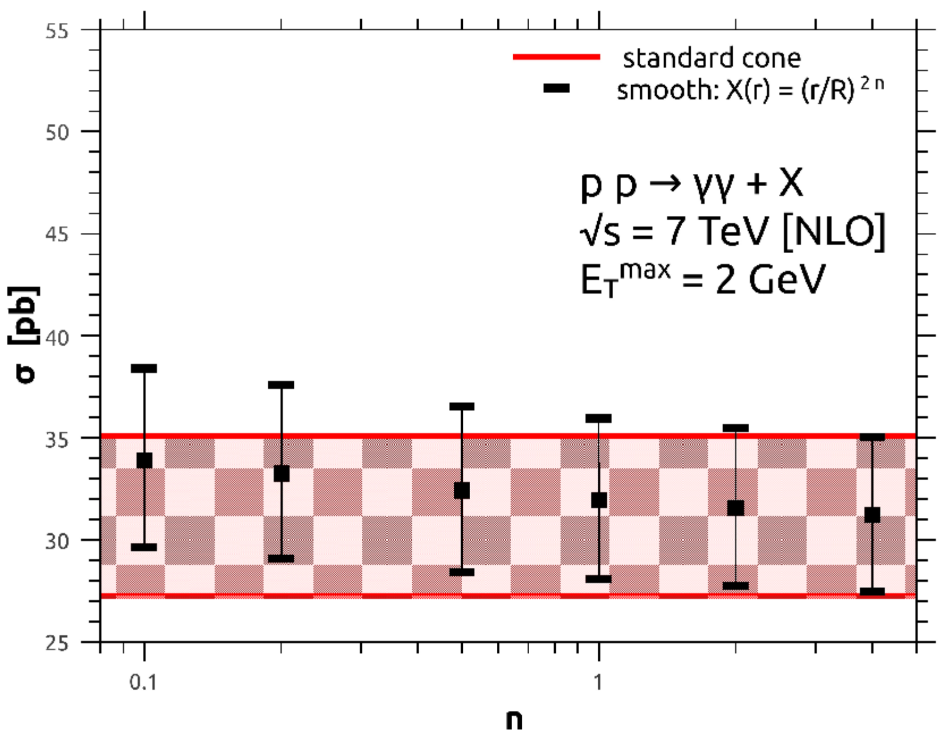

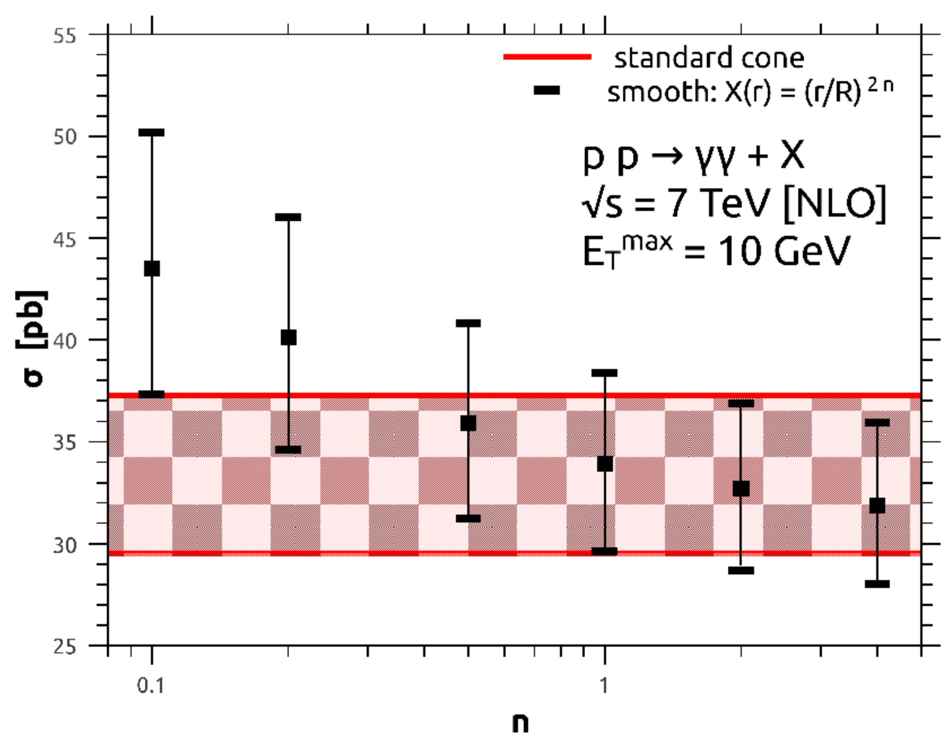

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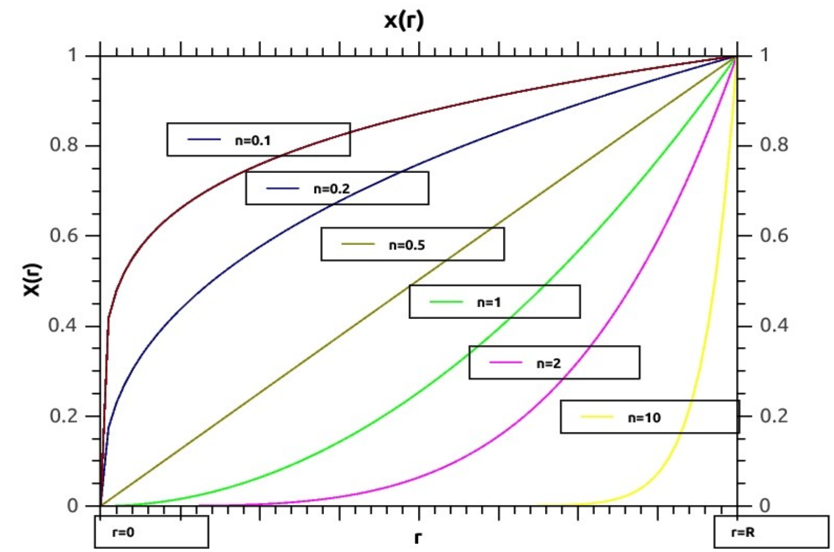

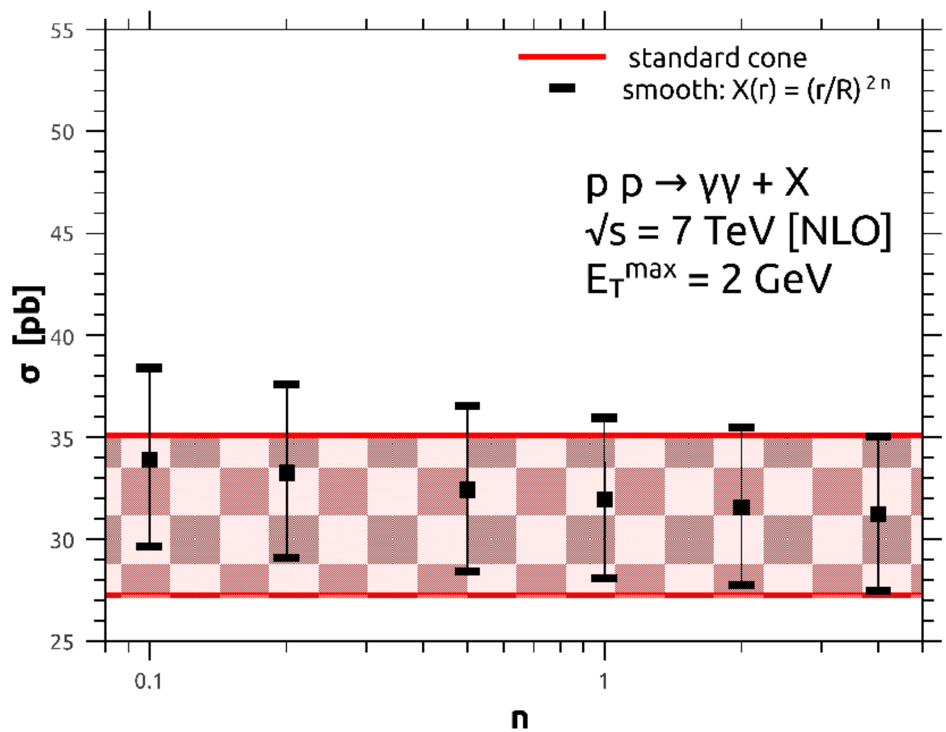

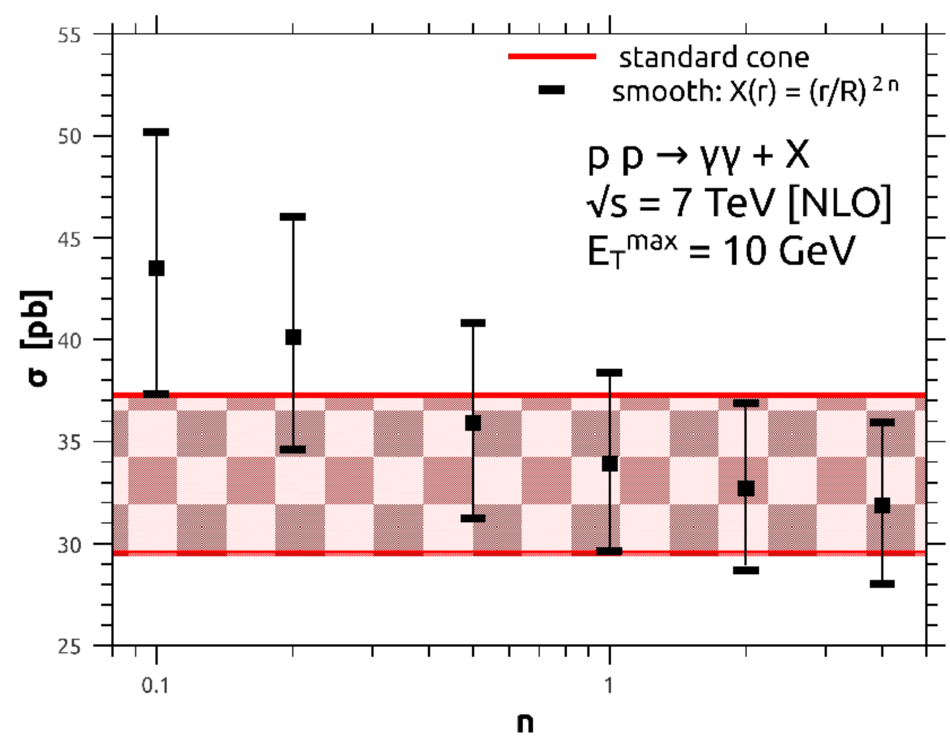

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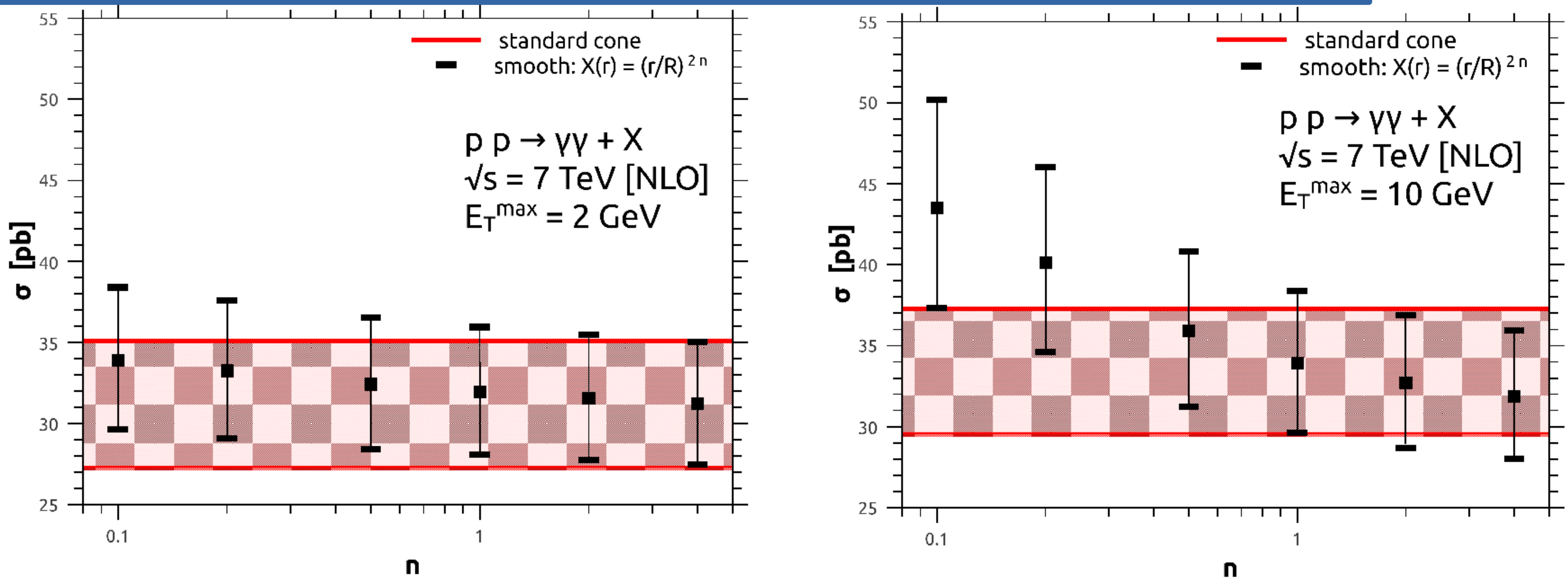
$$E_{T\ max} = \boxed{\begin{array}{c}2{\rm GeV}\ ;\\ 10{\rm GeV}\end{array}} \quad n = 1, \quad R = 0.4, \quad R_{\gamma\gamma} = 0.4$$

- **be careful! CMS case!!! n=0.05 → ArXiv:1405.7225**
  but with even more asymmetrical cuts the effect is reduced
- **The qq channel is almost constant → difference = 1.7% ($E_{T\ max}$=10GeV)**
- **The qg channel → difference = 77% ($E_{T\ max}$=10GeV)**



Summary isolation

- The LH accord is still valid for more general cuts (SM cuts). The agreement at the level of the total cross-section between the two approaches is at the percent level for wider range of $E_{T\,max}$ parameters (~15 GeV).
- For the presented X(r) functions, n=1 is the normal value (motivated by comparison with standard result)
- The smooth cone result does not present the Guillet shoulder at NLO
- Kinematical regions far away from the back-to-back configuration (with smooth cone prescription at NLO) are not sensible to the isolation parameter $E_{T\,max}$.

It is not recomended match the standard NLO total cross-section changing the values of the smooth isolation parameters ($E_{T\,max}$)
1) Due to the agreement between the two approaches
2) Beyond NLO there is no calculation with fragmentation in order to check unitarity
3) The initial motivation of reproduce fragmentation effects at NLO has no sense

Summary isolation

- The LH accord 2013 is still valid for more general cuts (SM cuts). The agreement at the level of the total cross-section between the two approaches is at the percent level for wider range of $E_{T\,max}$ parameters (< 15 GeV).
- For the presented X(r) functions, n=1 is the normal value (motivated by comparison with standard result).
- The smooth cone result does not present the Guillet shoulder at NLO.
- Kinematical regions far away from the back-to-back configuration (with smooth cone prescription at NLO) are not sensible to the isolation parameter $E_{T\,max}$.
- At large invariant mass → very low gluon luminosity → small or negligible fragmentation effects.
- Kinematical configurations of the type $p^{H\,min}_T \sim p^{S\,min}_T$ are affected by soft gluon emission near the LO threshold.
- A similar study is needed for other final states with photons → LH 2015.

NNLO results @ LHC

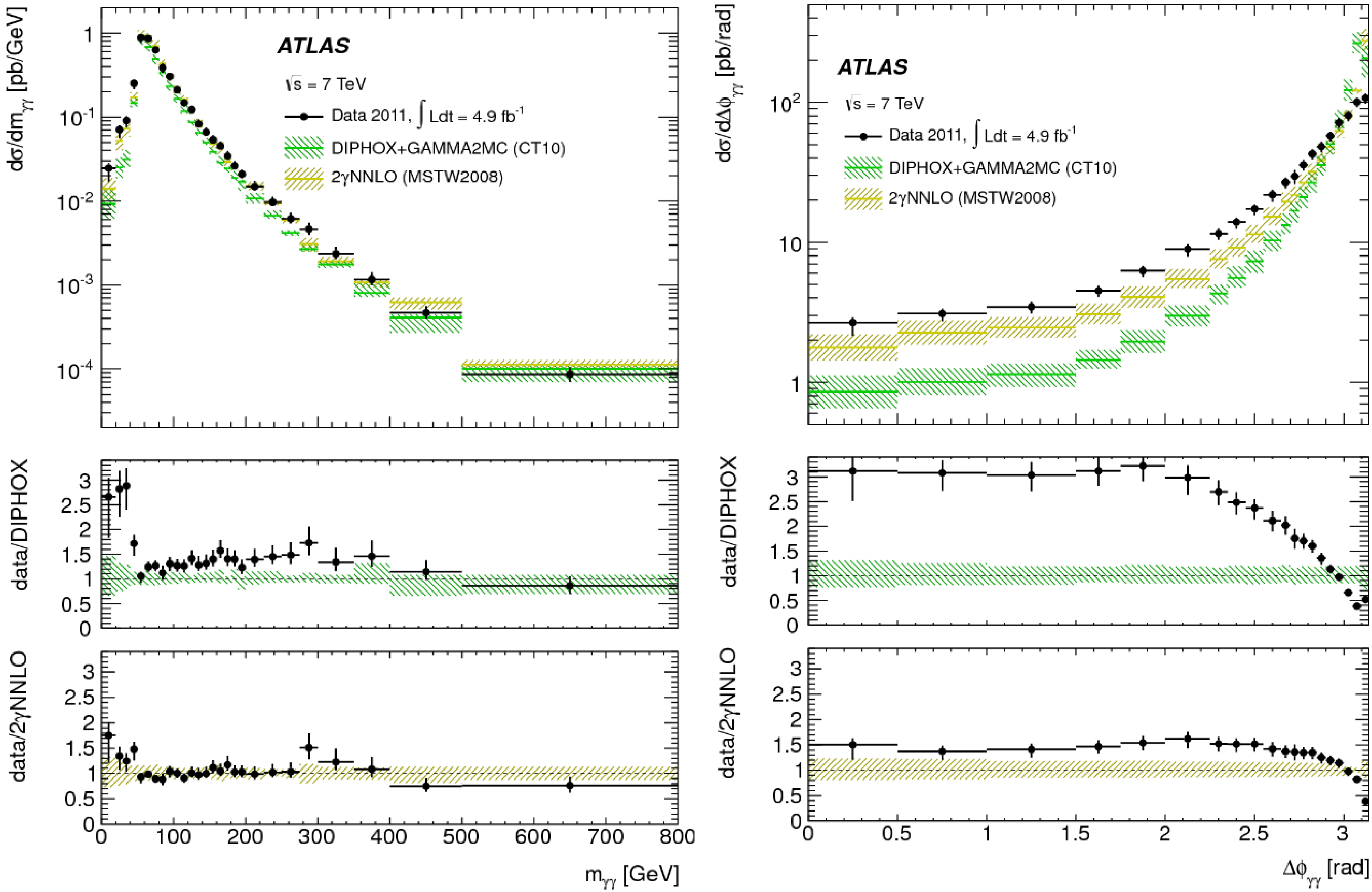
ATLAS results → γγ

ArXiv:1211.1913

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

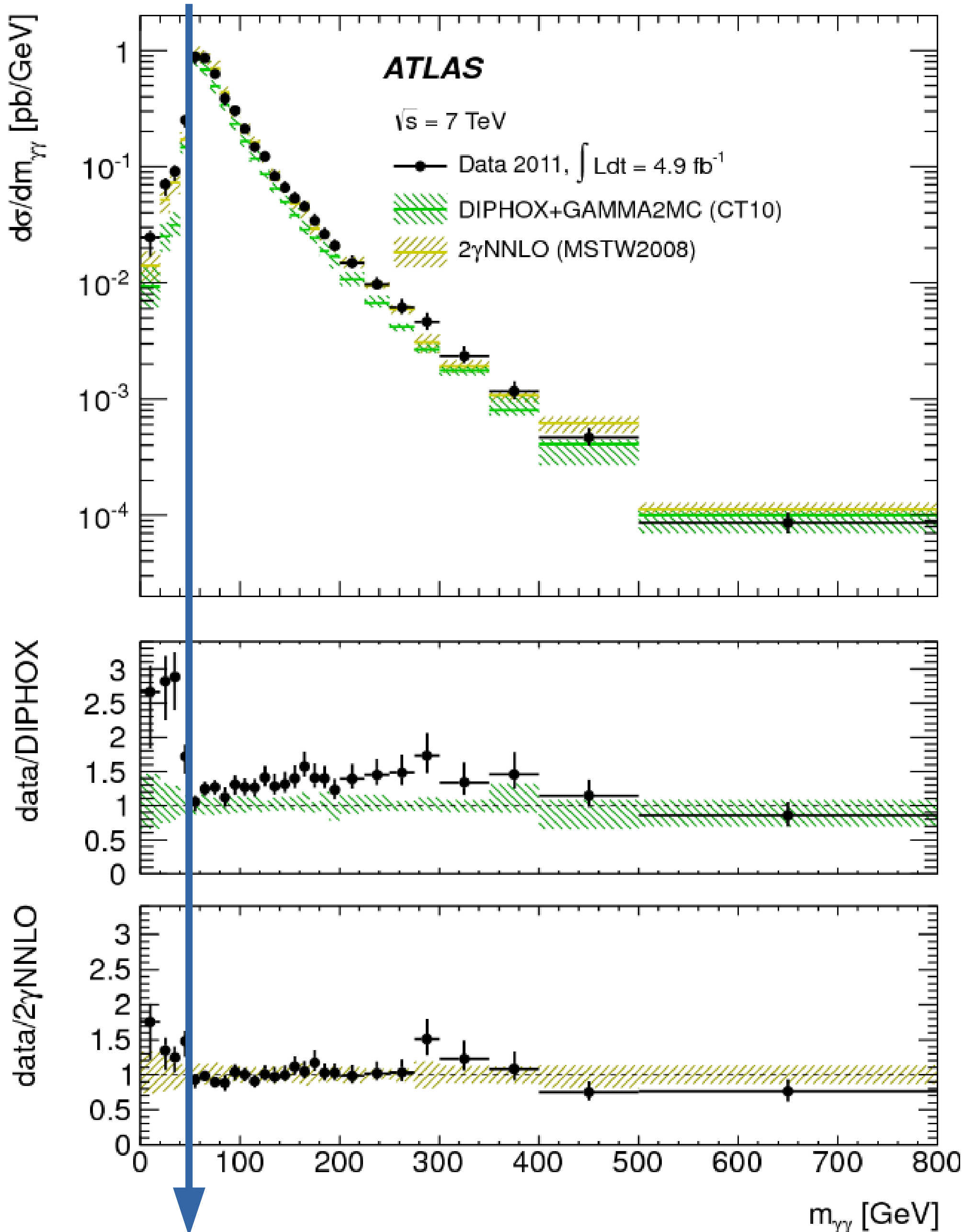
ATLAS results → γγ

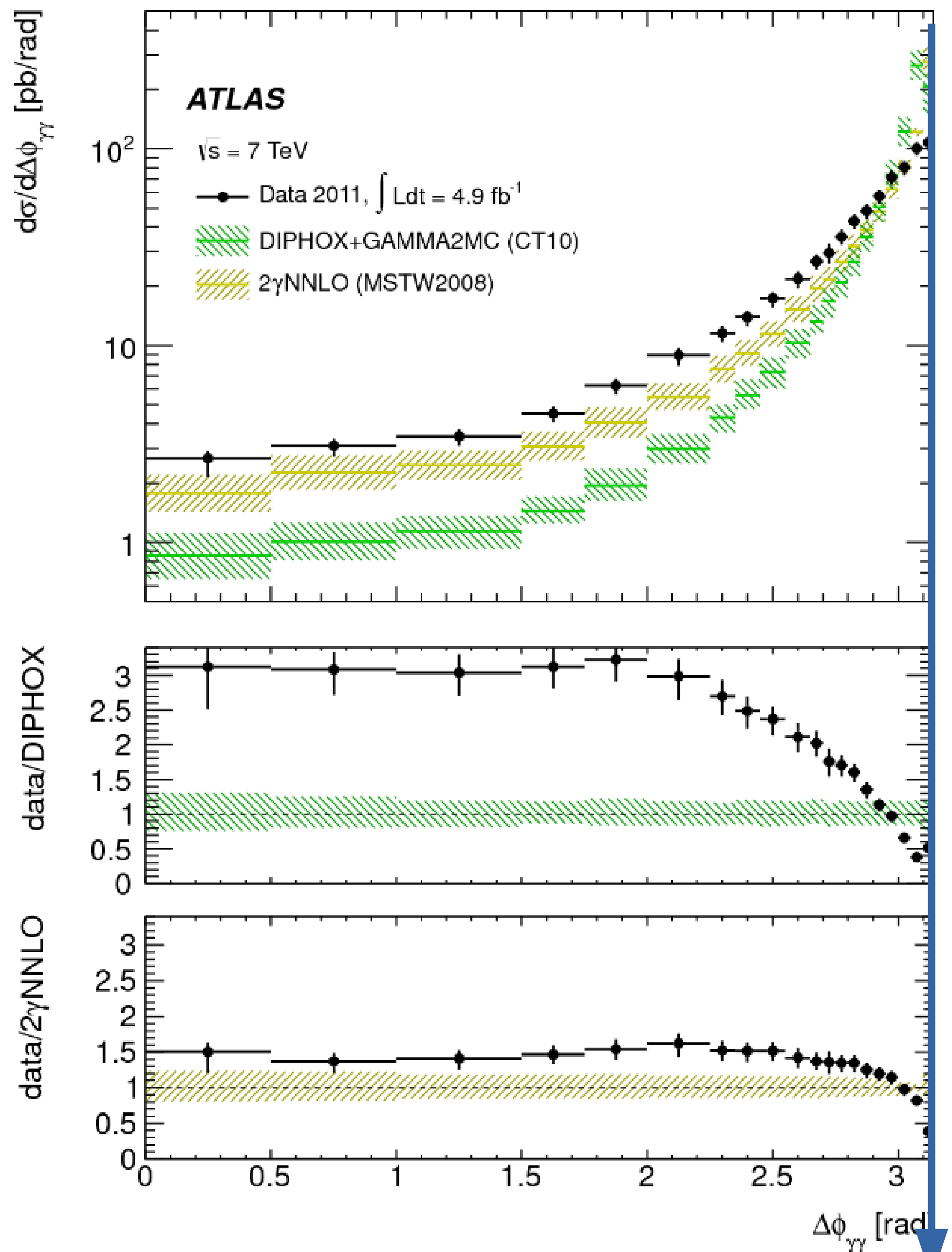
ArXiv:1211.1913



ATLAS results → γγ

ArXiv:1211.1913



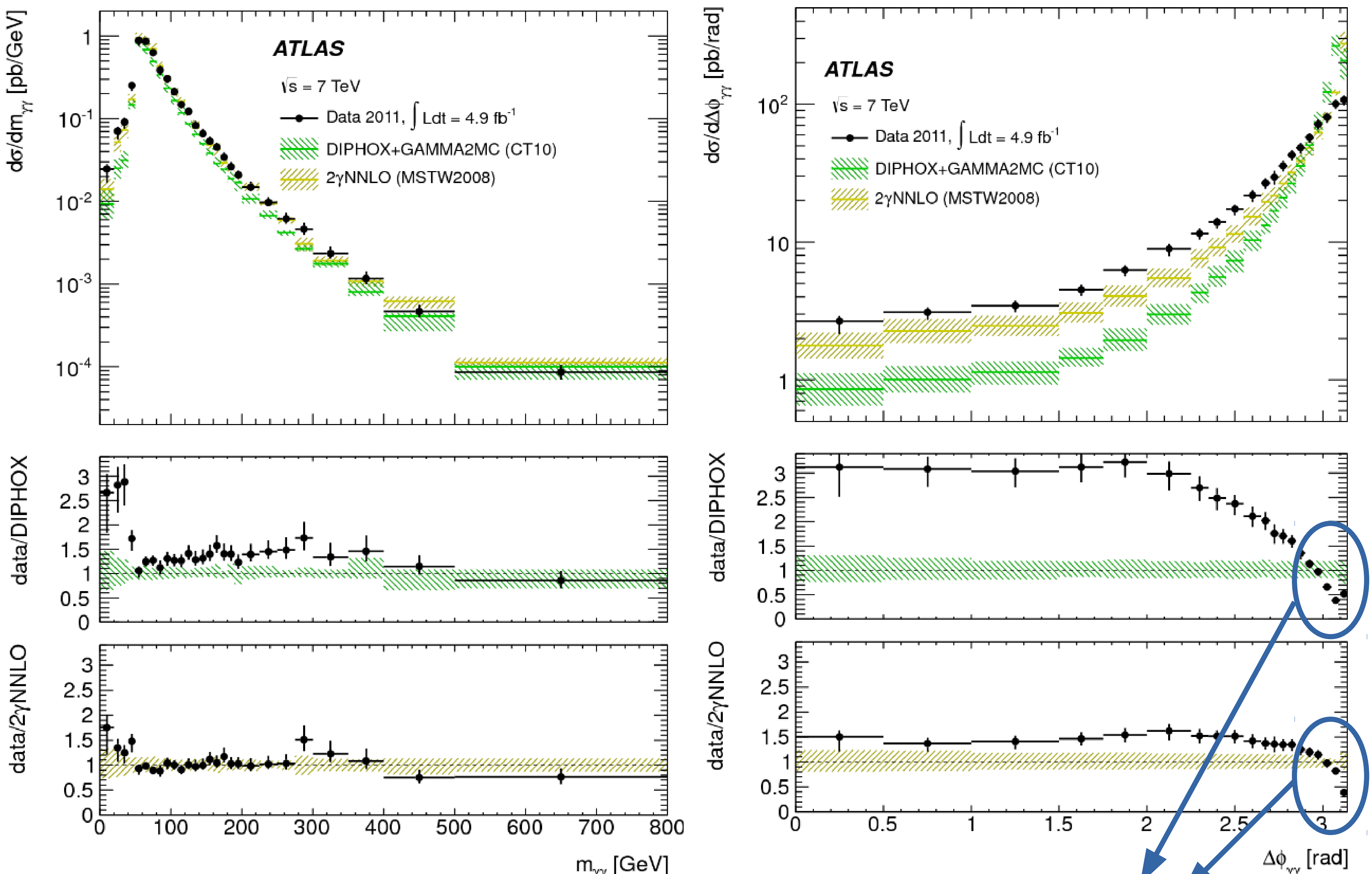


50 GeV → Born Threshold

See Francesco Talk → **Back-to-back region**

ATLAS results → γγ

ArXiv:1211.1913



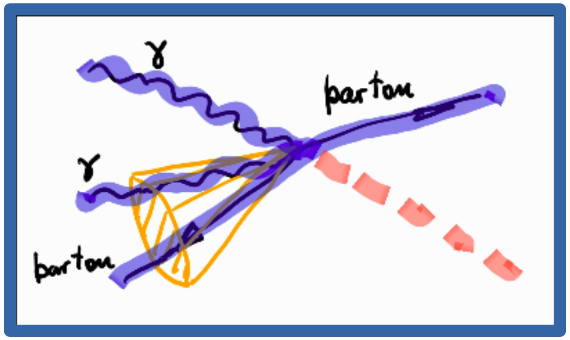
Uncertainties → 6% - 9%

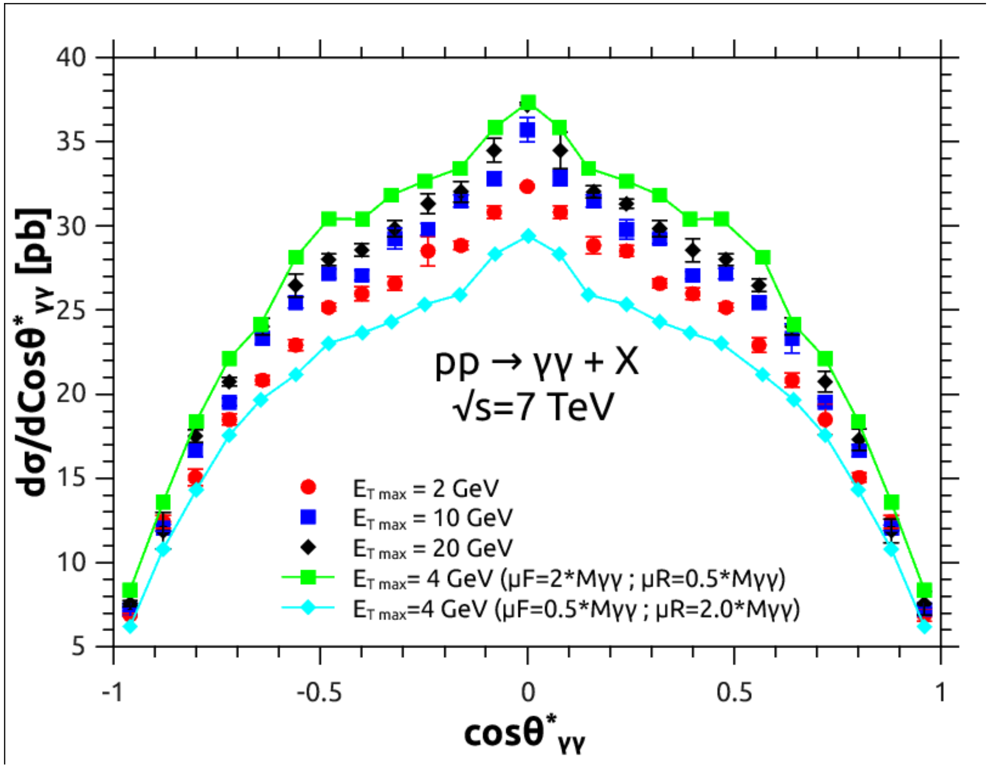
See Francesco Talk

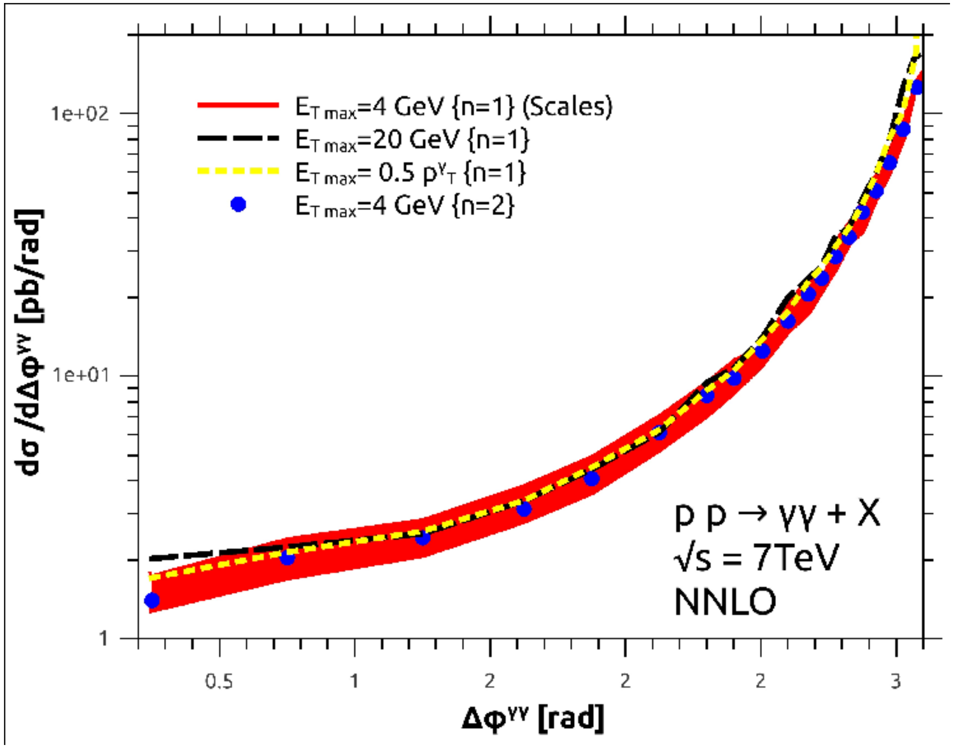
Fixed order tools

Isolation at NNLO

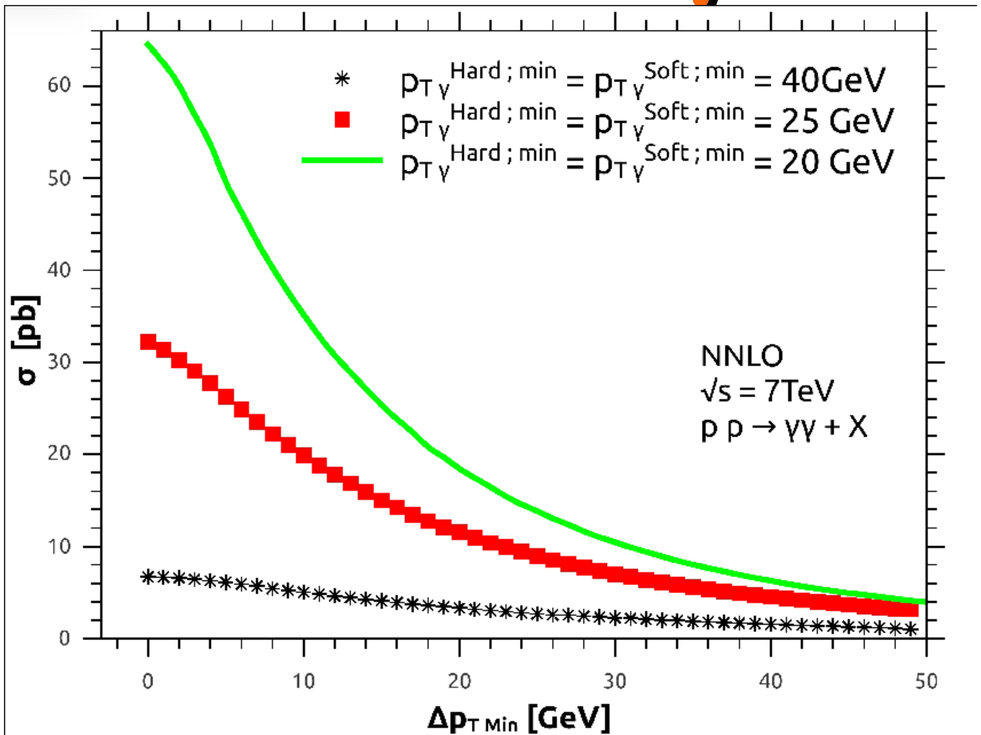
2γNNLO
Atlas cuts

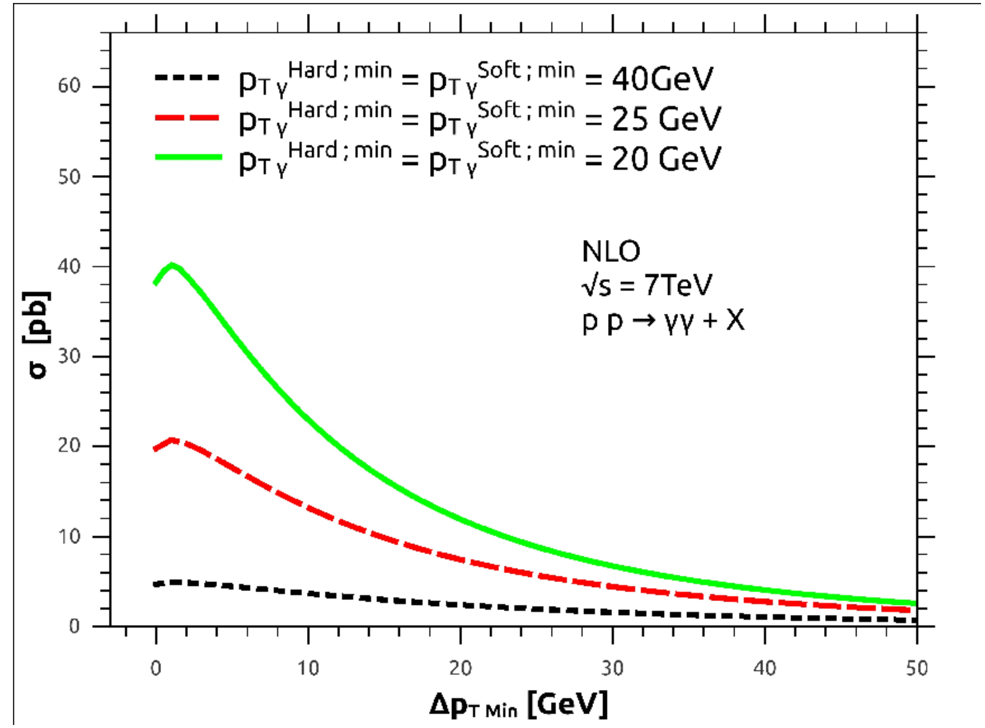


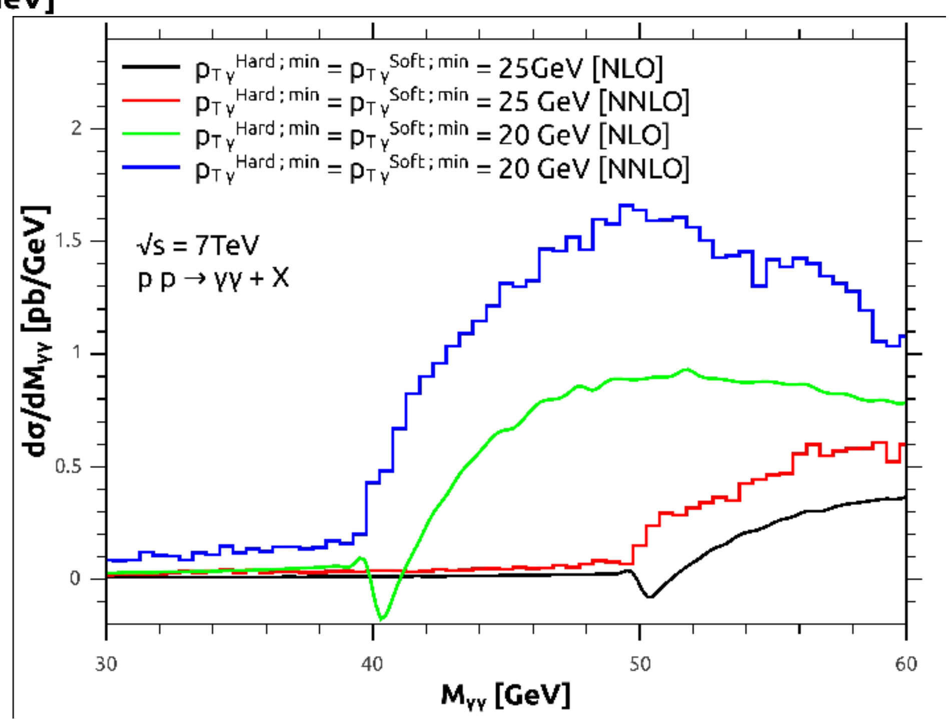




Sensitivity to symmetrical cuts







2γNNLO

CMS results → γγ

ArXiv:1405.7225

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

CMS results → γγ

ArXiv:1405.7225

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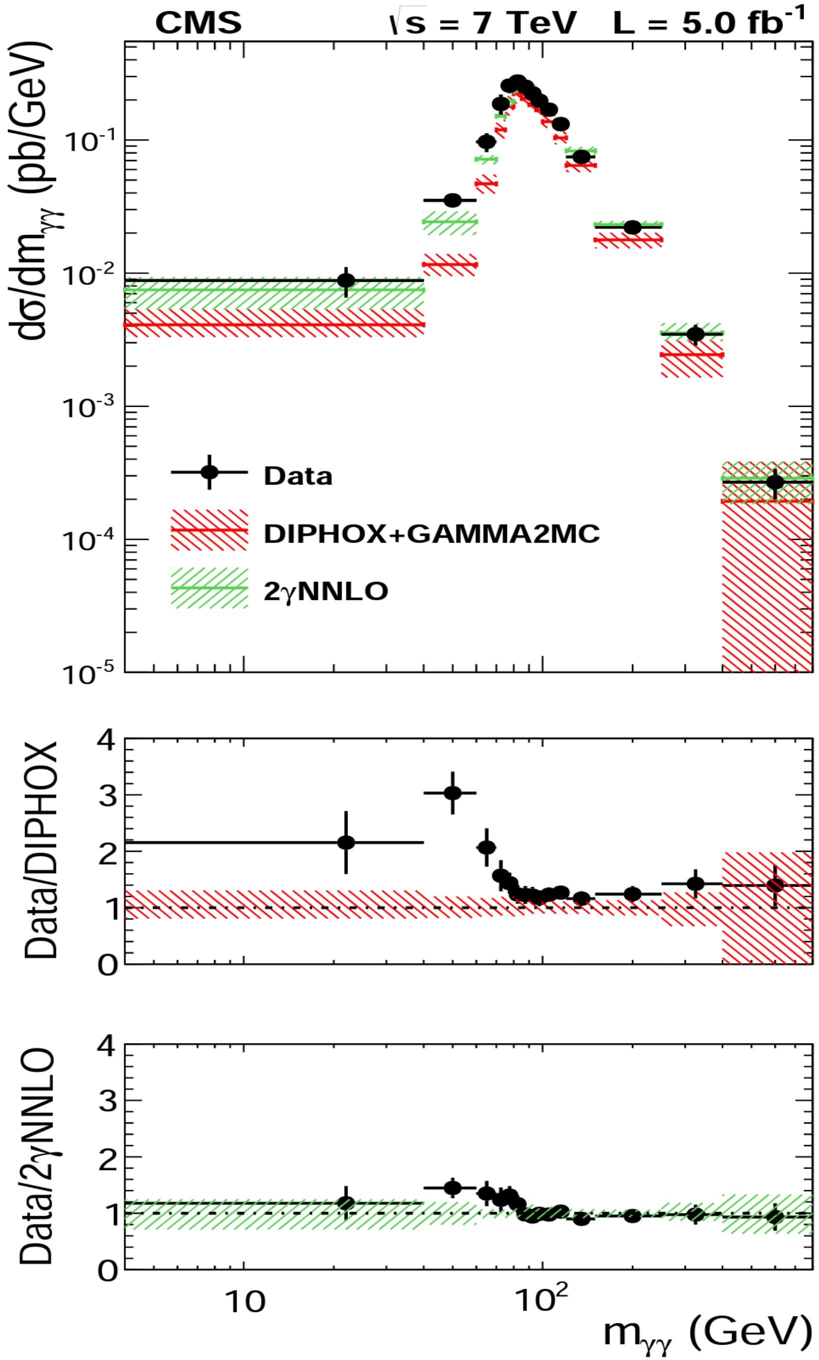
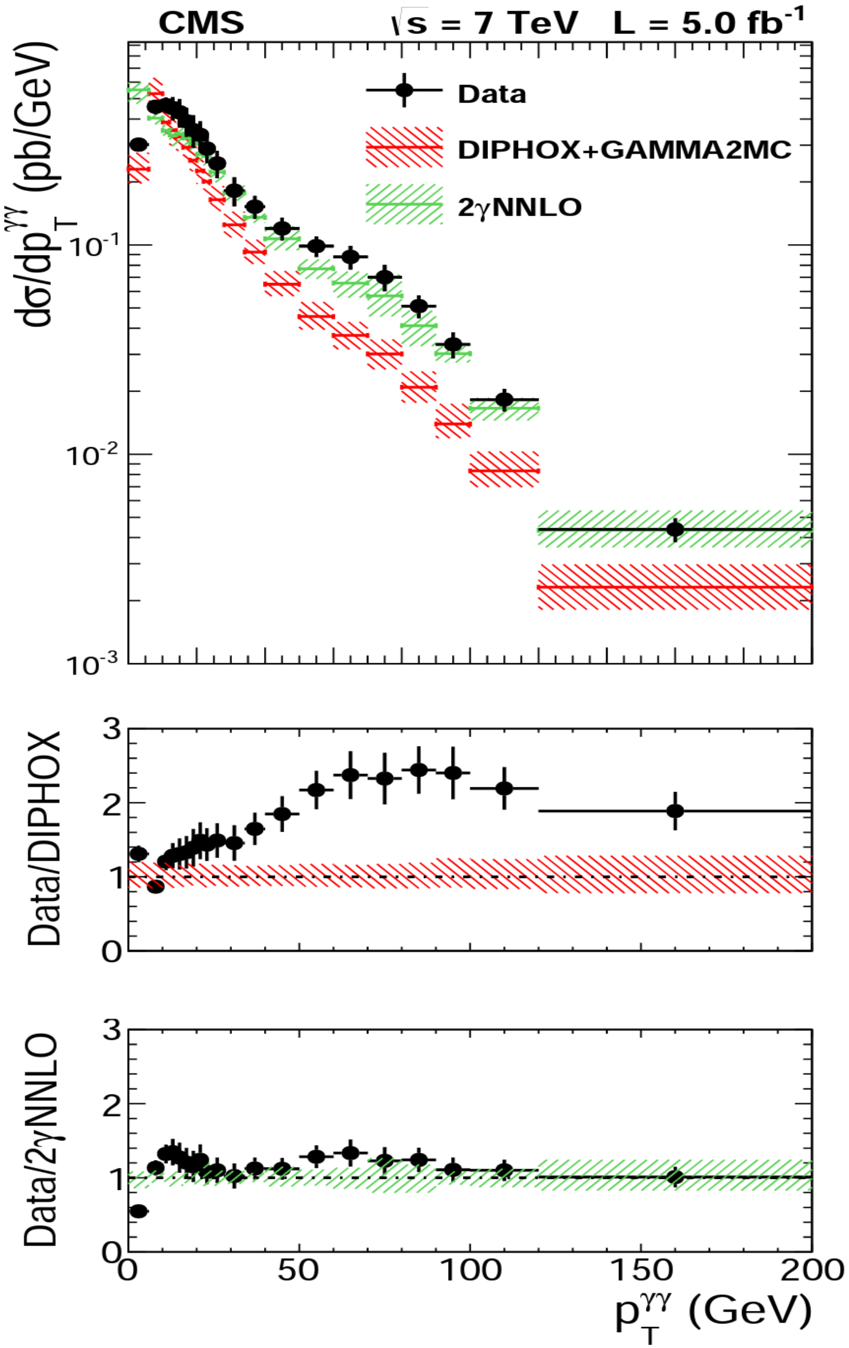
CMS results → γγ

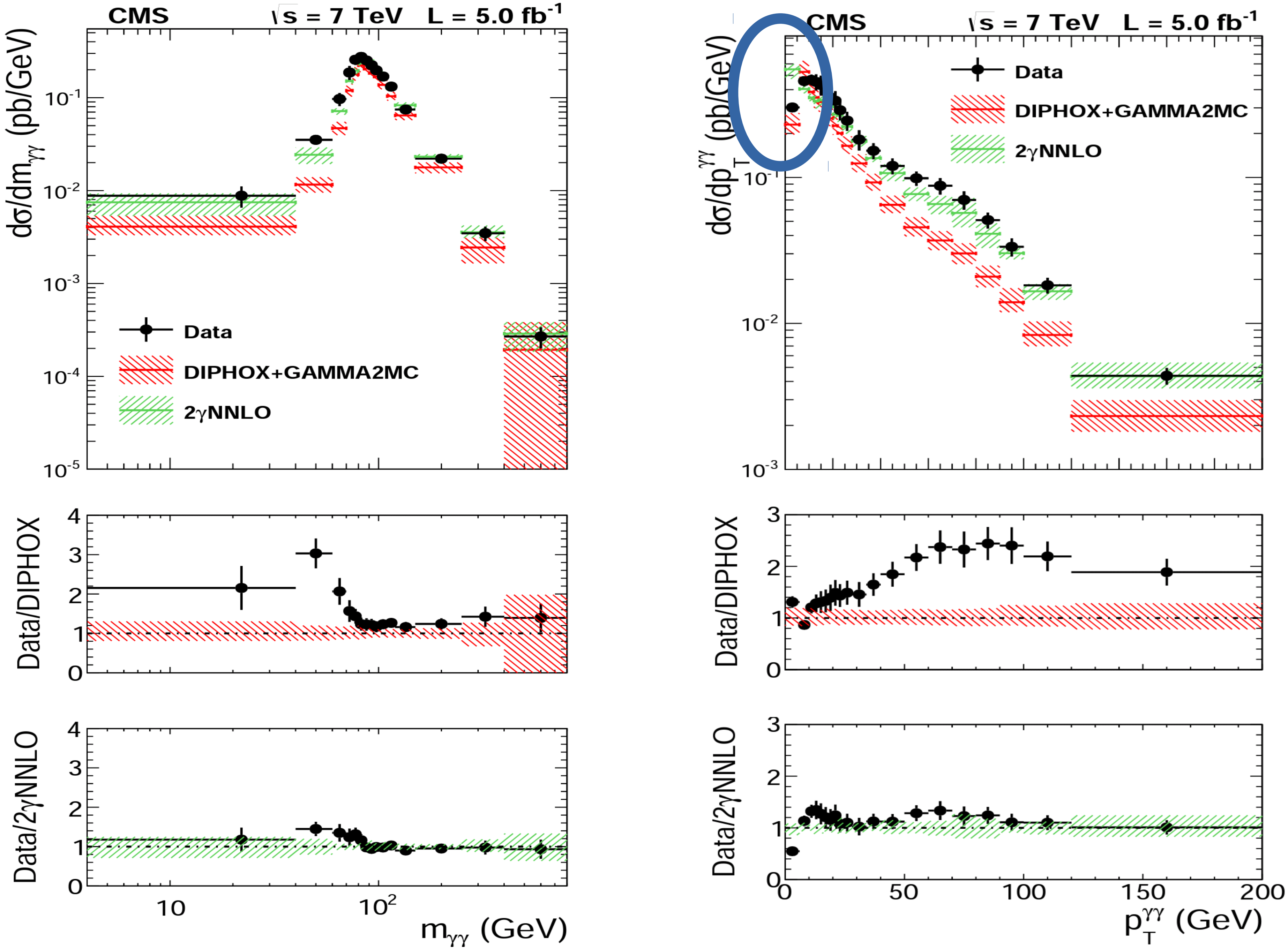
ArXiv:1405.7225





CMS results → γγ

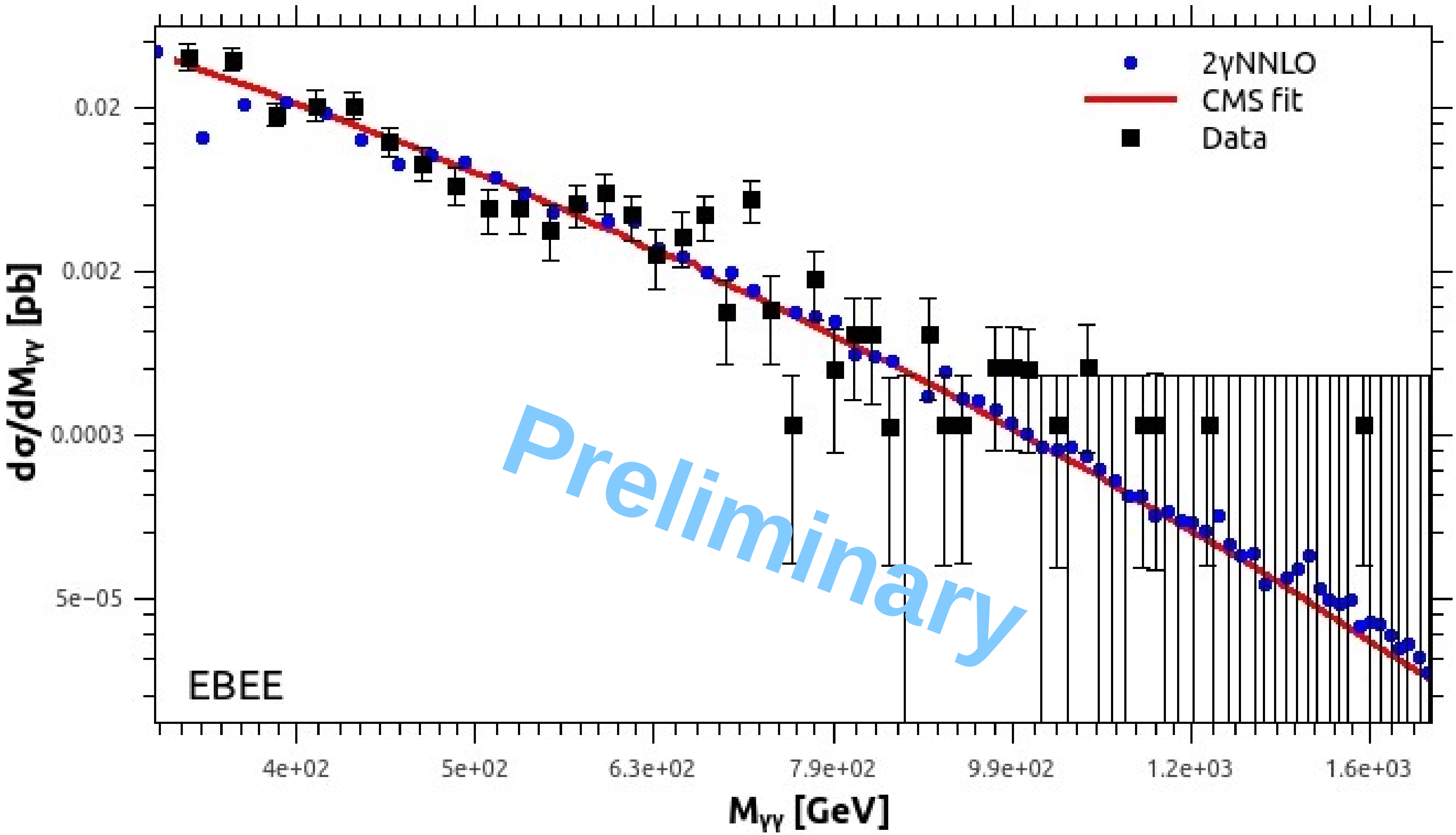
ArXiv:1405.7225



CMS results → γγ (750 GeV excess)

CMS-PAS-EXO-15-004

LC, Gehrmann, Greiner, Heinrich



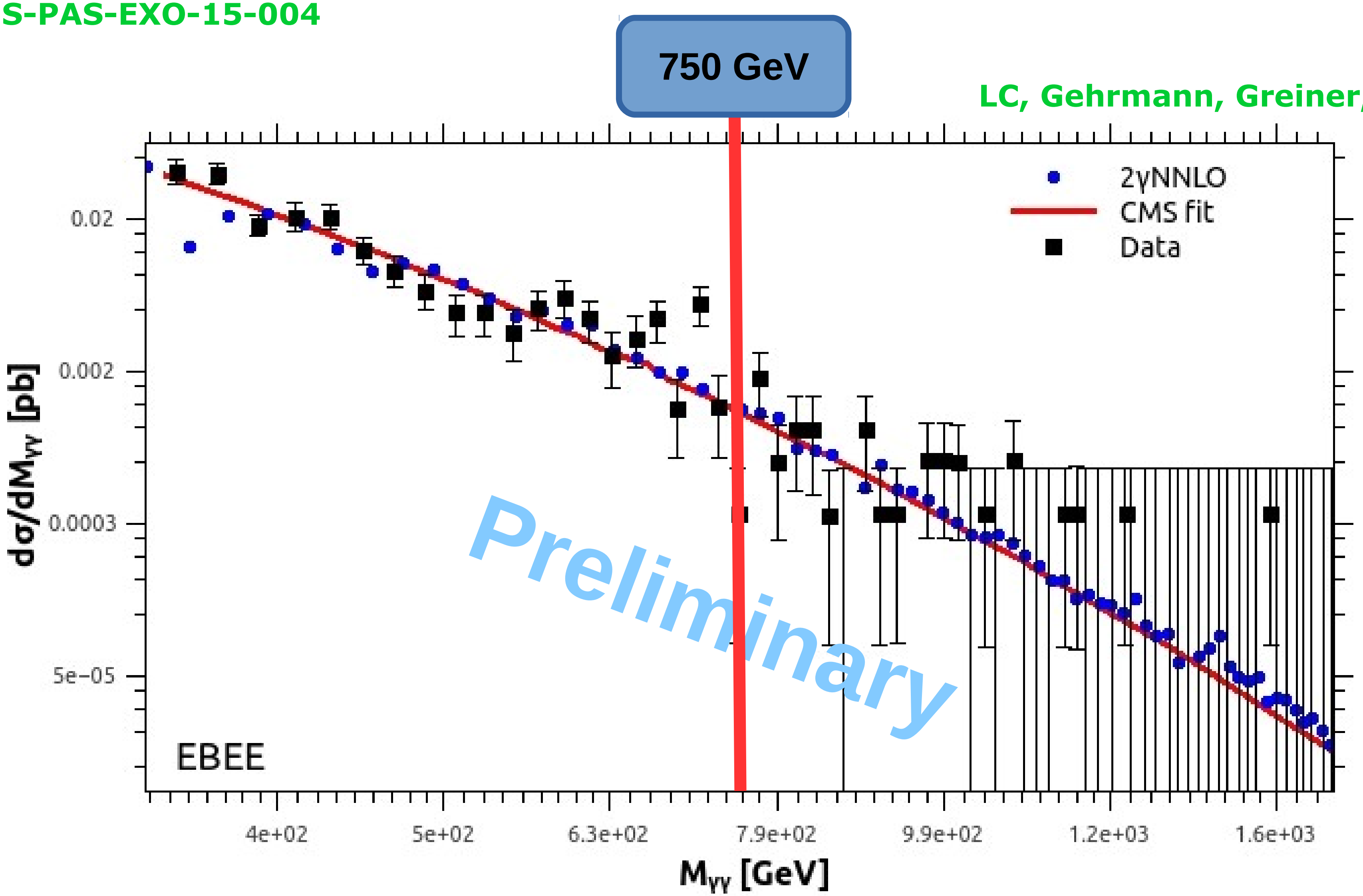
"EBEE": One photon in the ECAL barrel and the other in the ECAL endcap

$|\eta^{\gamma}|<1.44$ 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

CMS results → γγ (750 GeV excess)

CMS-PAS-EXO-15-004



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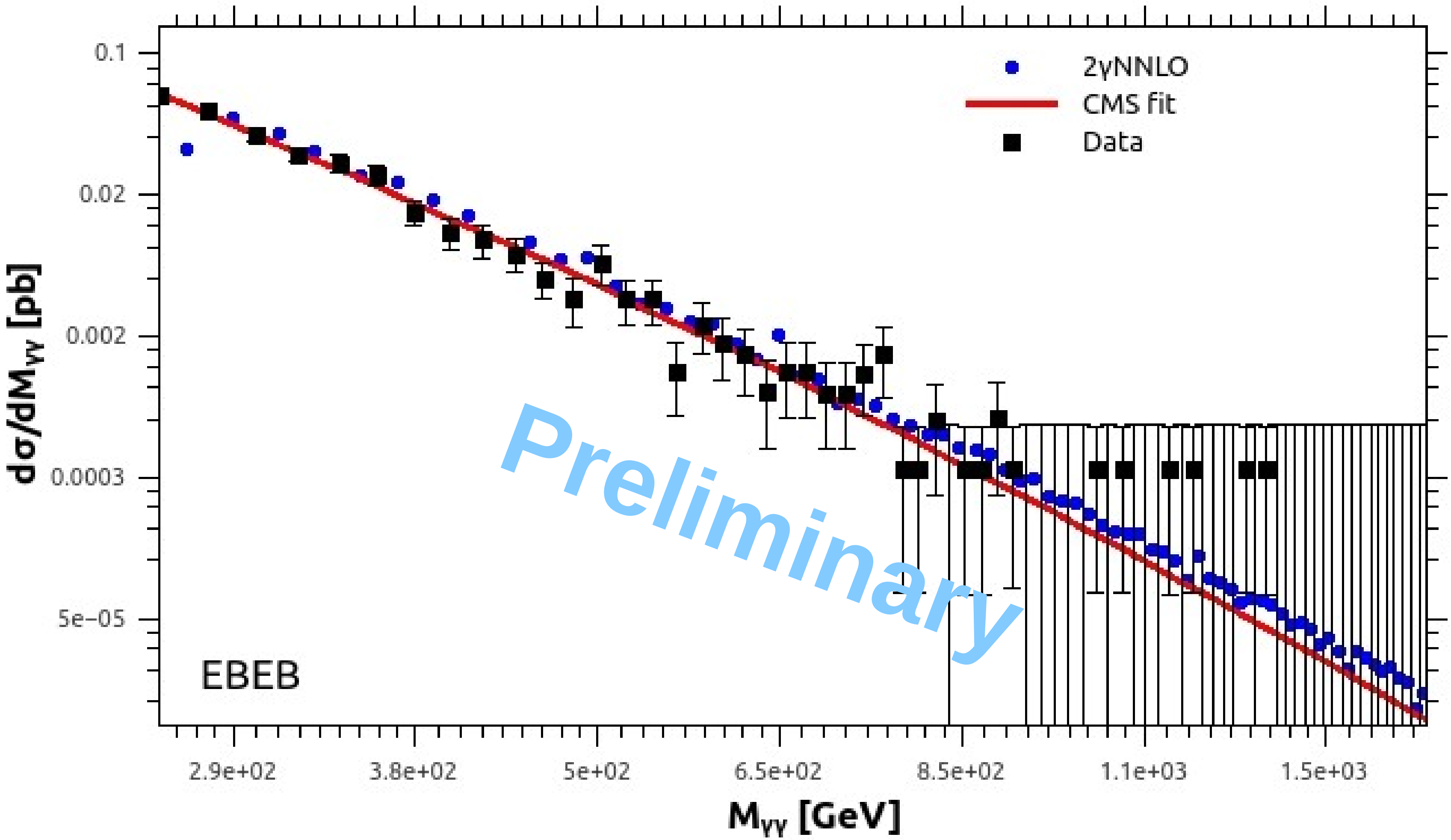
CMS results → γγ (750 GeV excess)

CMS-PAS-EXO-15-004

LC, Gehrmann, Greiner, Heinrich



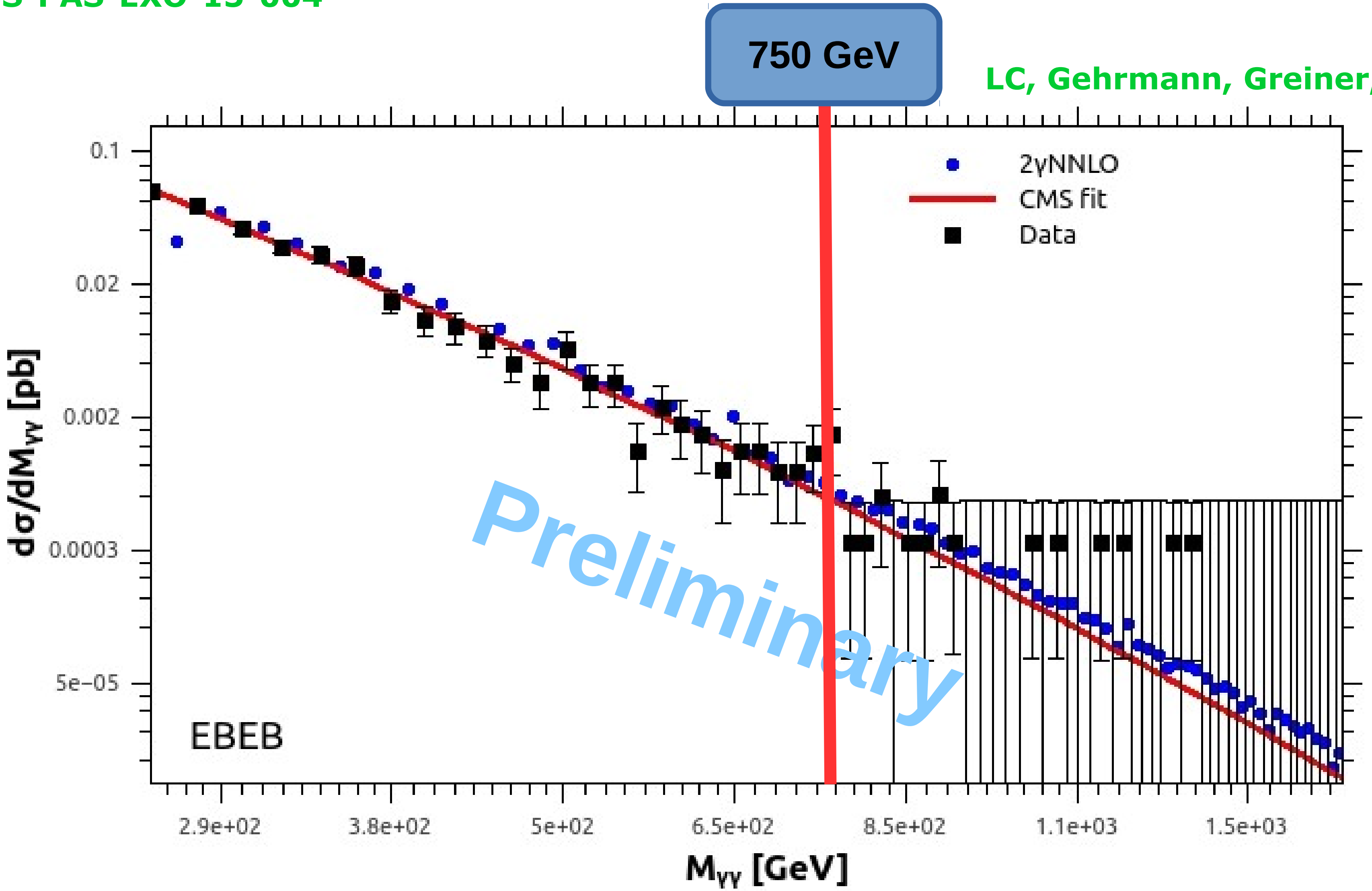
"EBEB": Both photons in the ECAL barrel → $|\eta^{\gamma}|<1.44$ [$M^{\gamma\gamma}>230$ GeV]

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

CMS results → γγ (750 GeV excess)

CMS-PAS-EXO-15-004

LC, Gehrmann, Greiner, Heinrich



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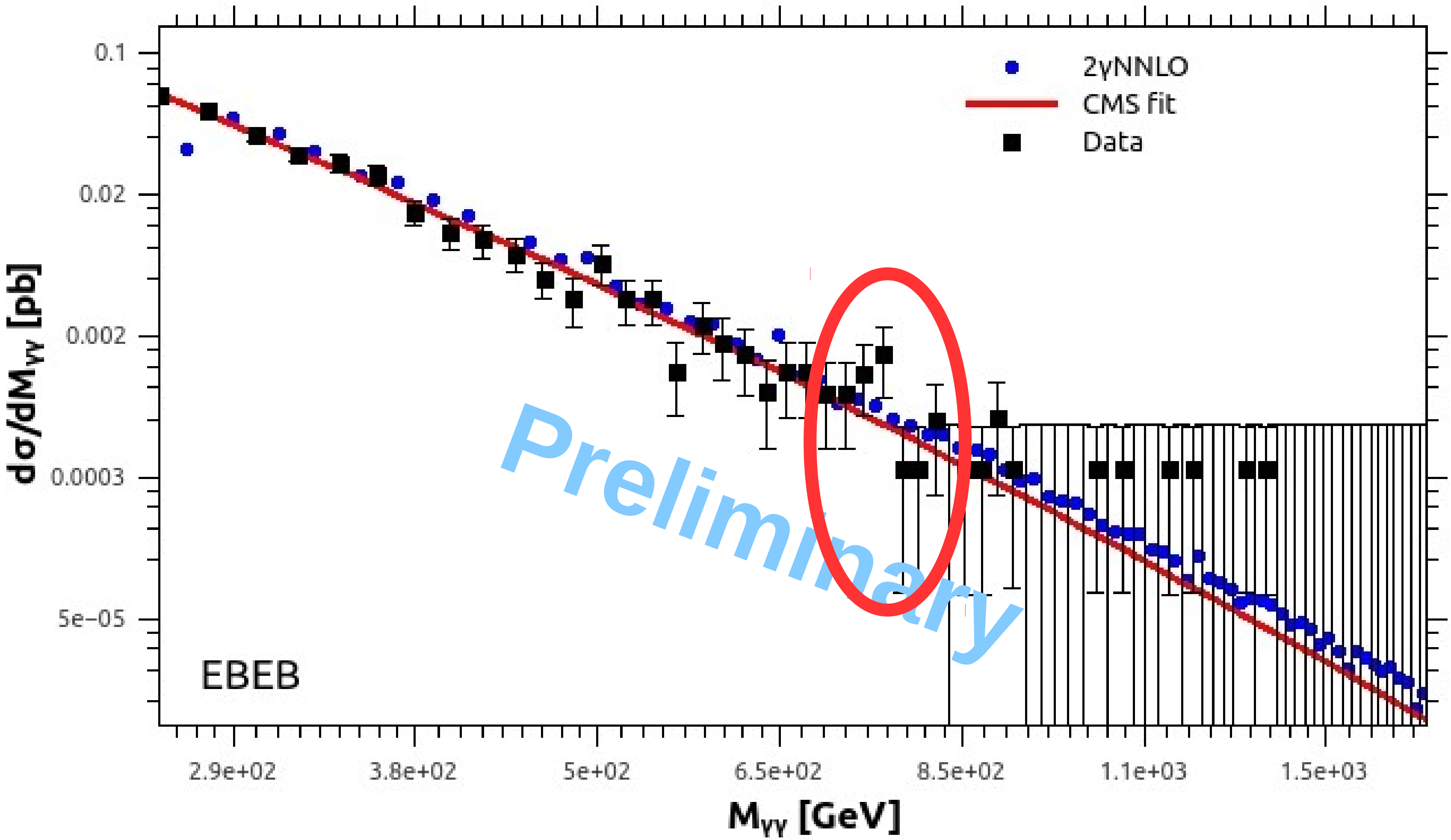
CMS-PAS-EXO-15-004

LC, Gehrmann, Greiner, Heinrich



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

Summary

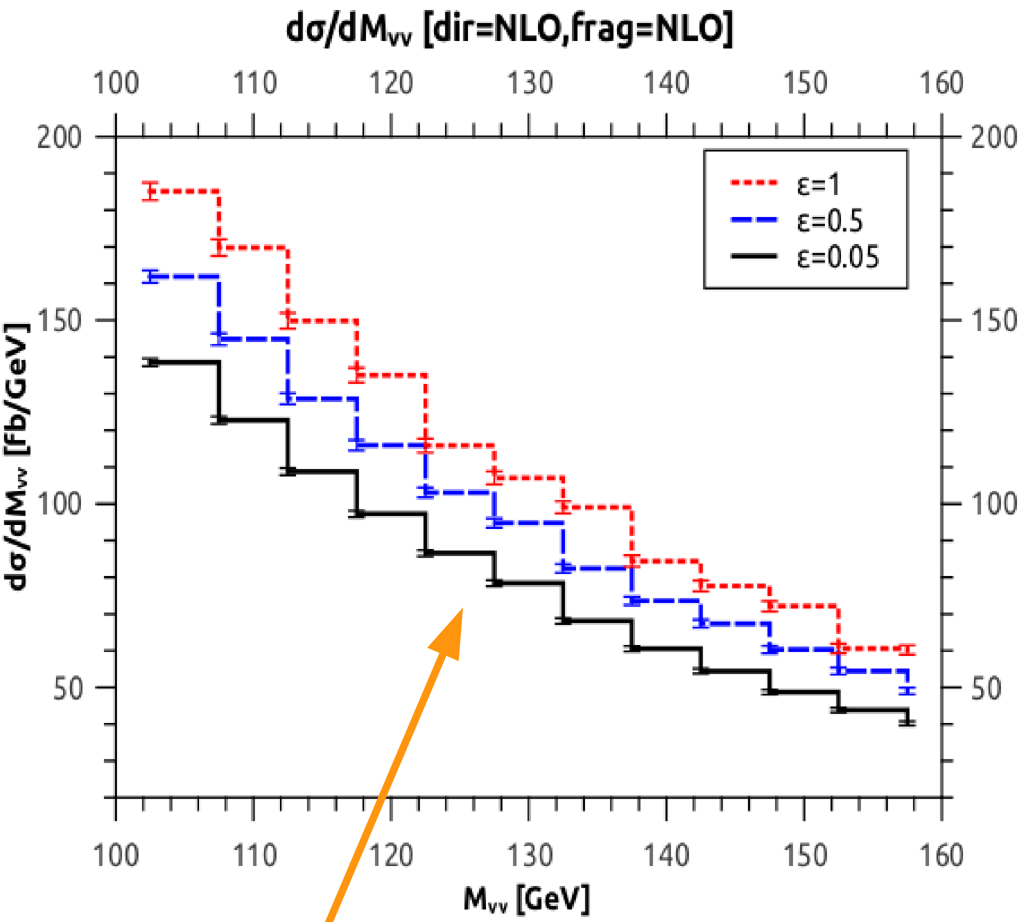
- **NNLO corrections are substancial for diphoton kinematical configurations of interest at high-energy hadron colliders**
- **The analyses performed by the ATLAS and CMS collaborations show good agreement between the NNLO description of $\gamma\gamma$ and data**
- **Transverse momentum resummation is 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**

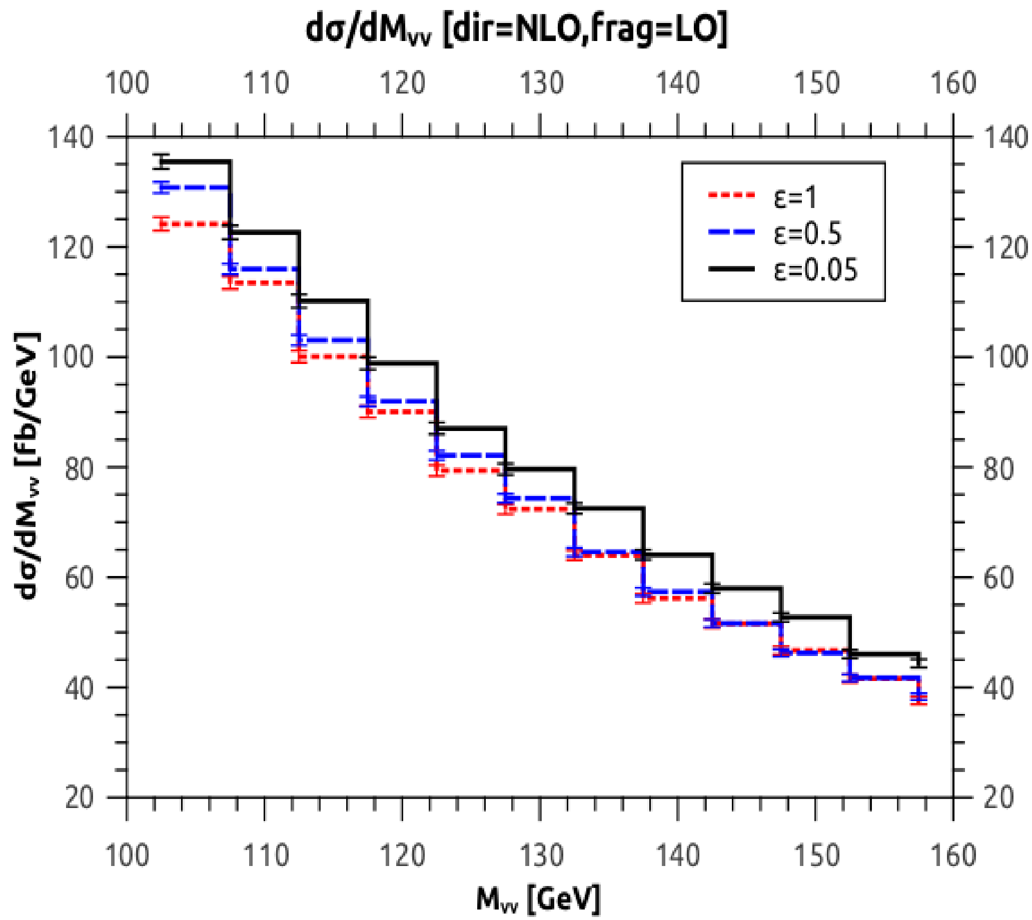
Thanks!!!

Backup Slides

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

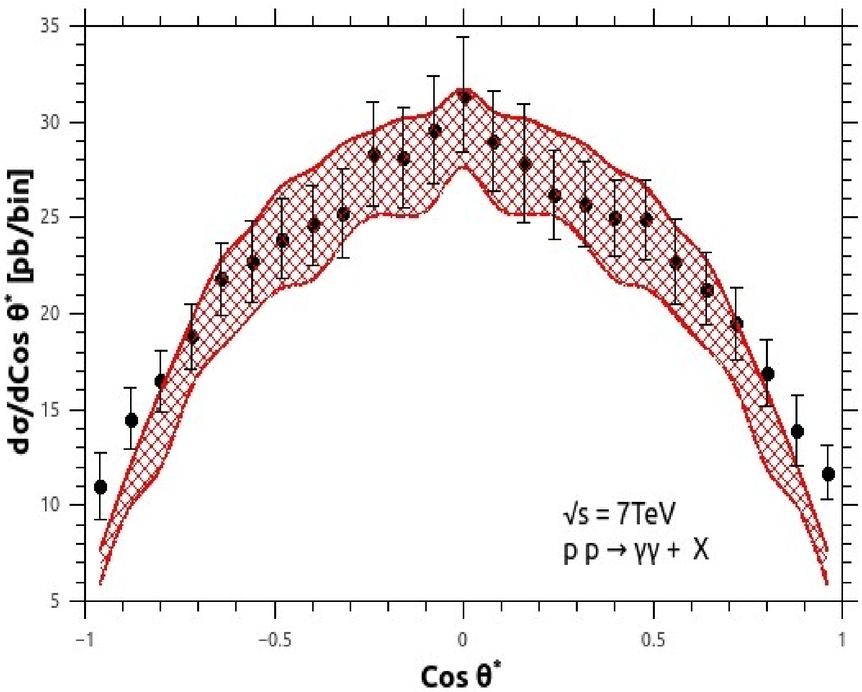
Standard cone isolation → DIPHOX



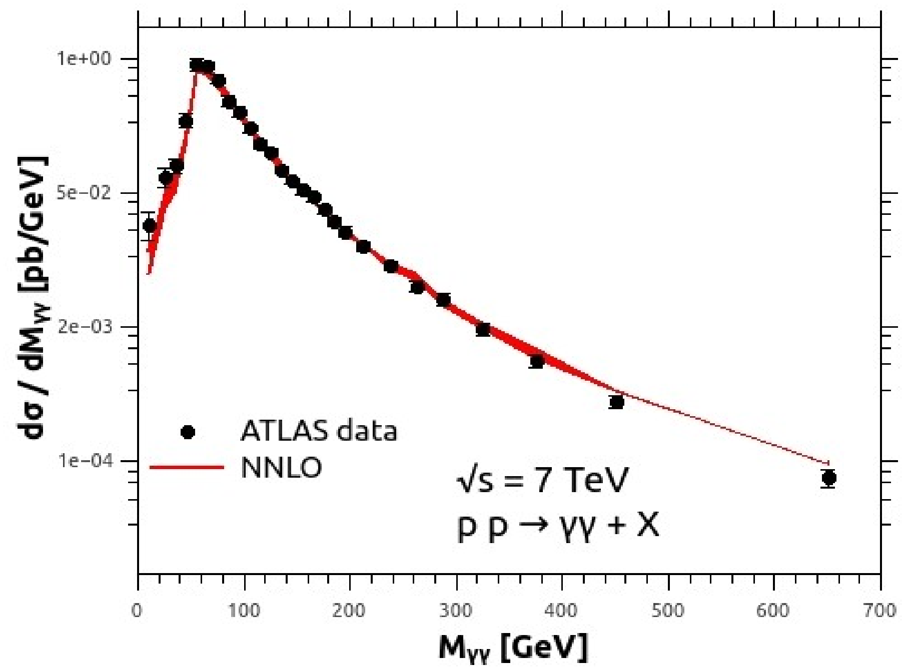


Right behaviour!!

L.C , D. de Florian 2013



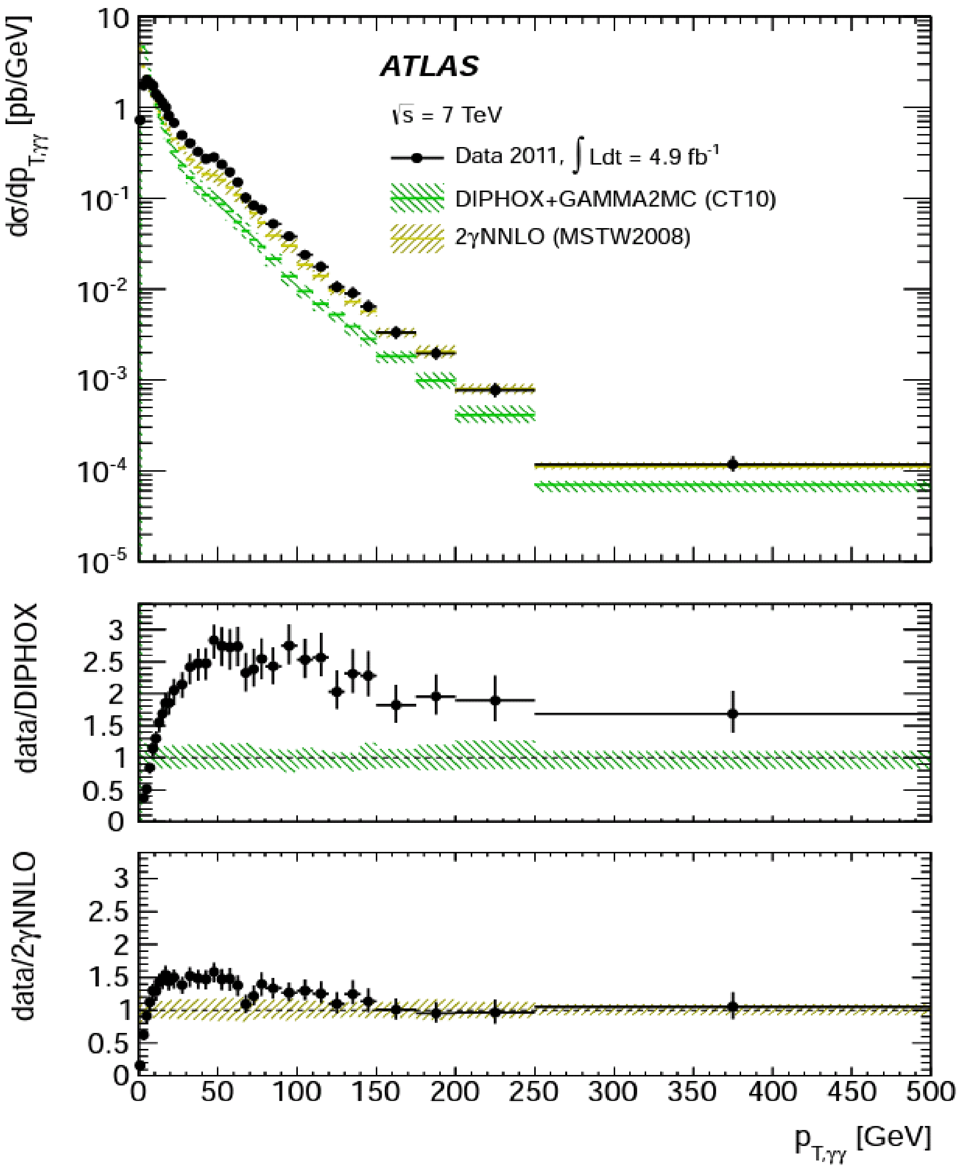
dσ/dCos θ* [pb/bin]
Cos θ*
√s = 7TeV
p p → γγ + X

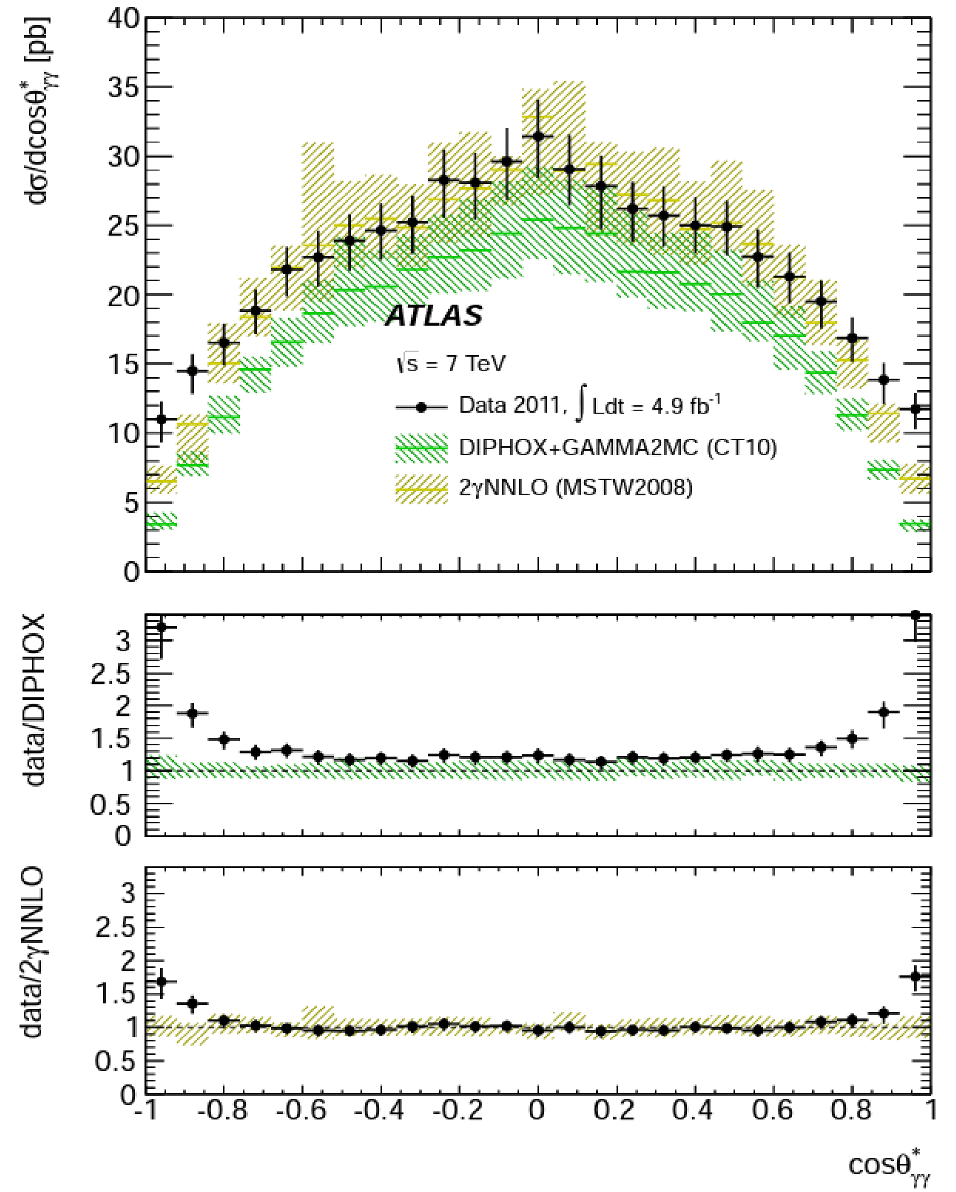


dσ / dMγγ [pb/GeV]
Mγγ [GeV]
ATLAS data
NNLO
√s = 7 TeV
p p → γγ + X

ATLAS results → γγ

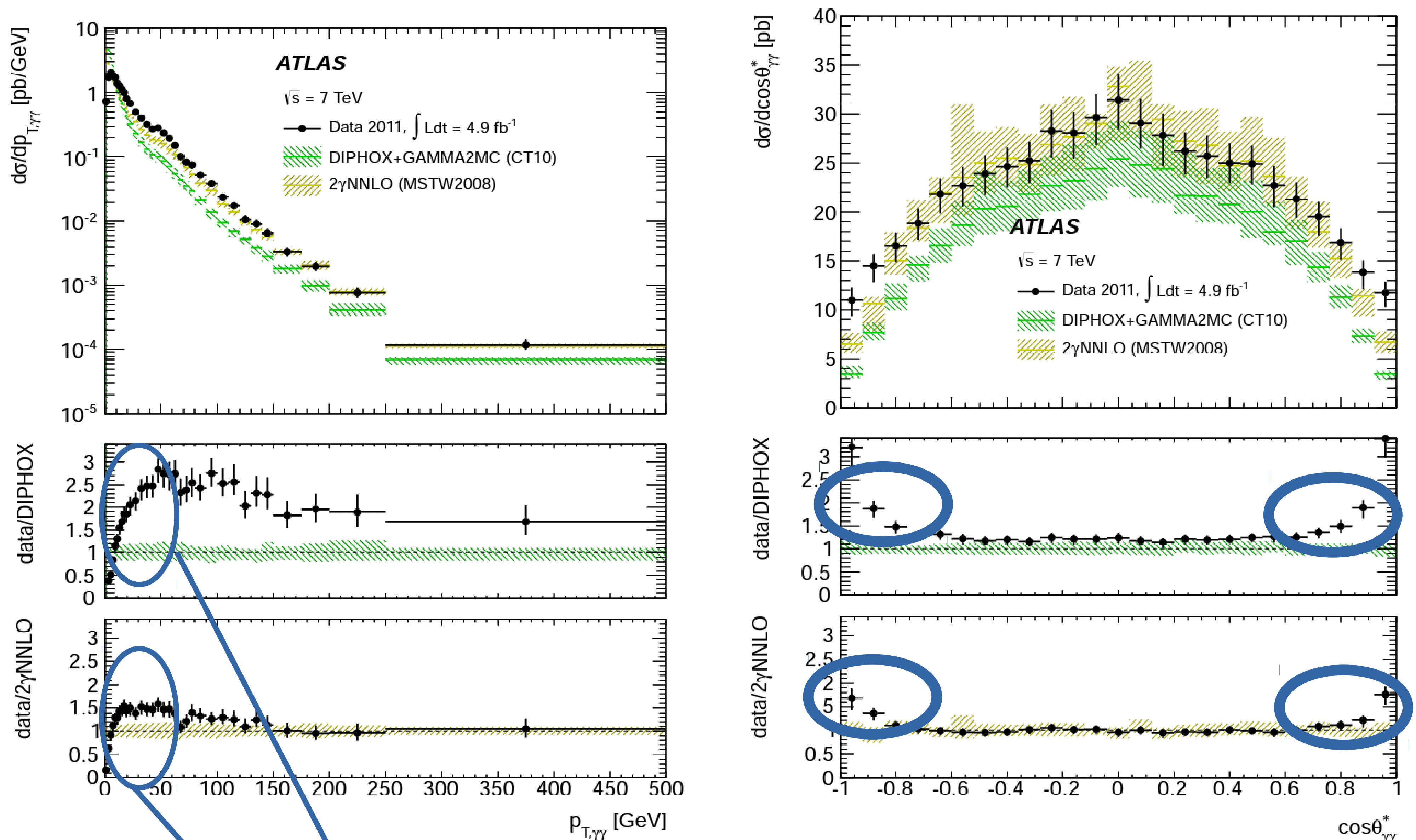
ArXiv:1211.1913





ATLAS results → γγ

ArXiv:1211.1913

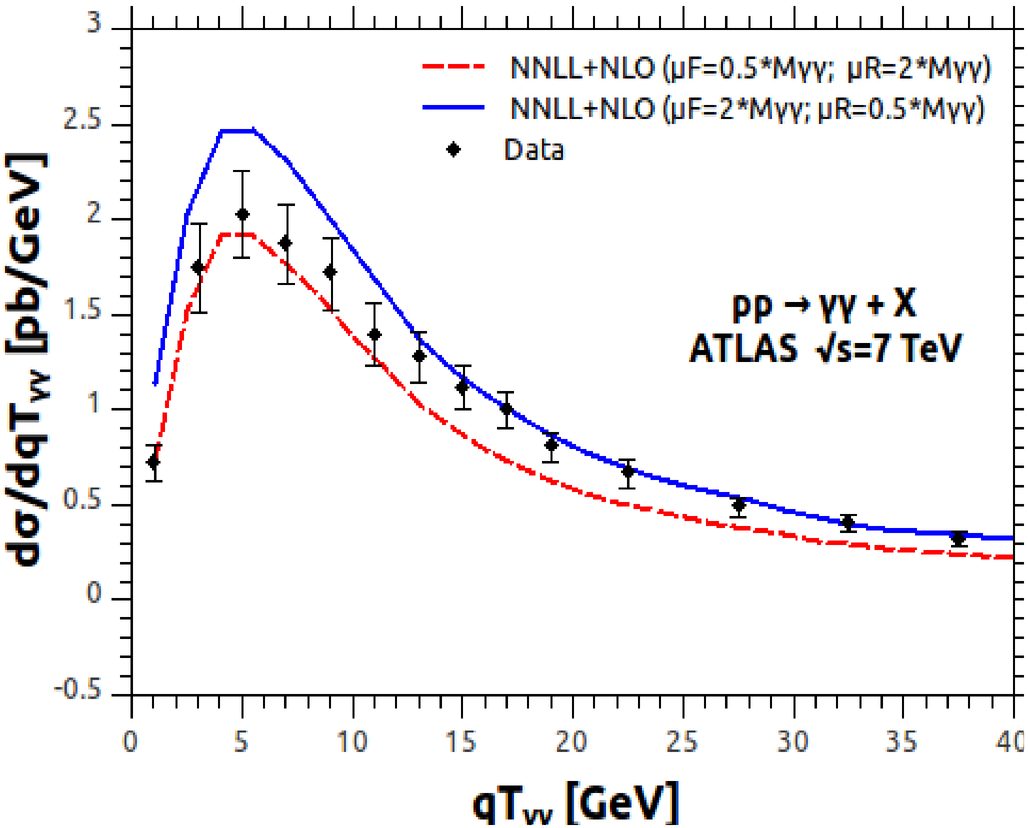


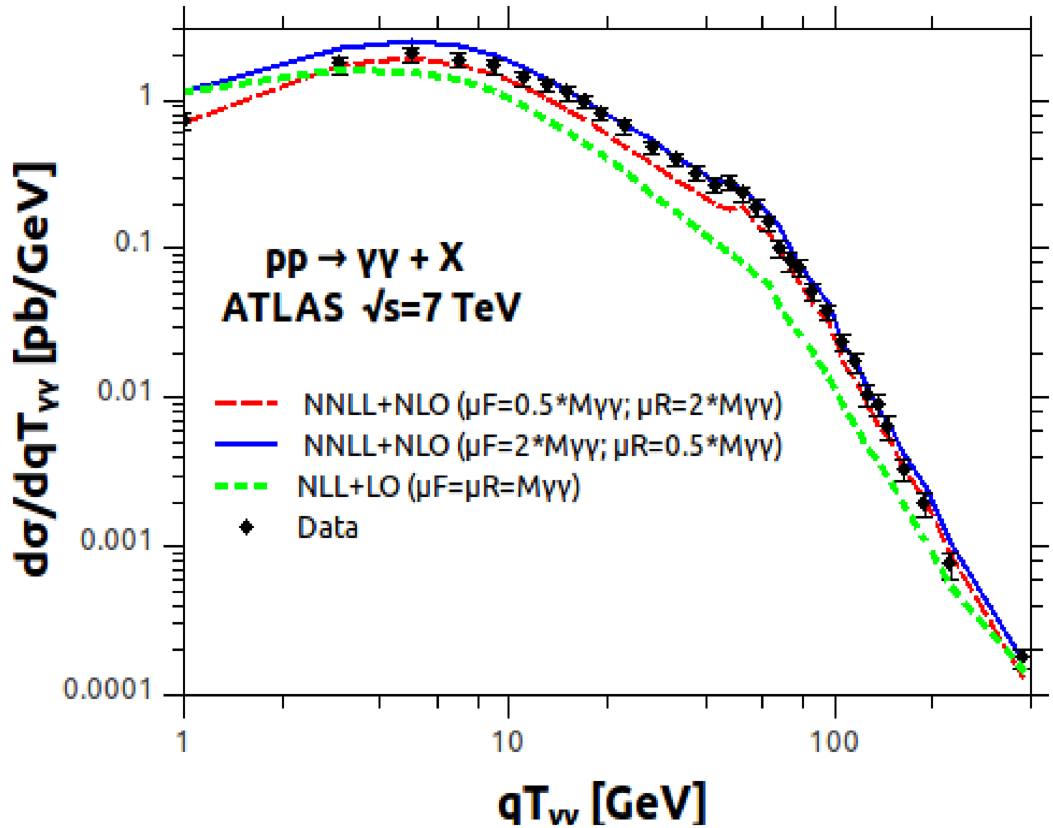
Fixed order tools

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)

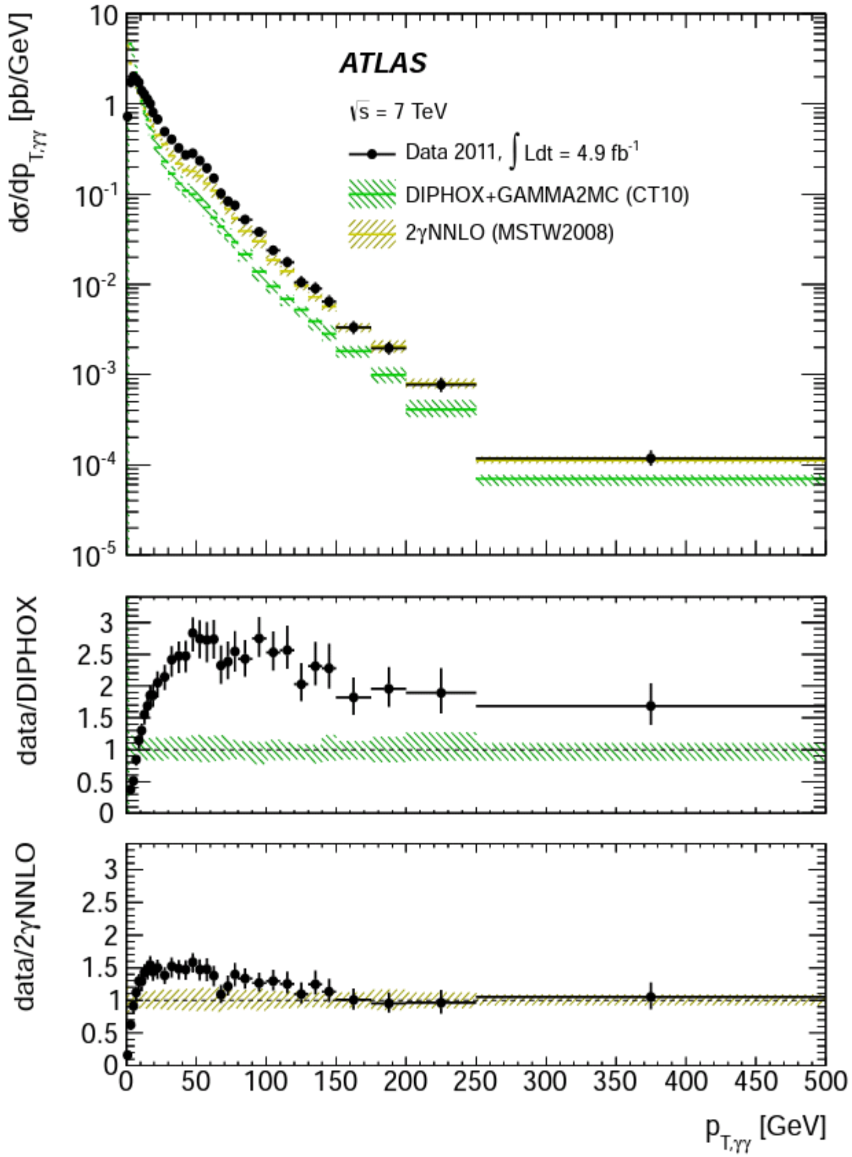




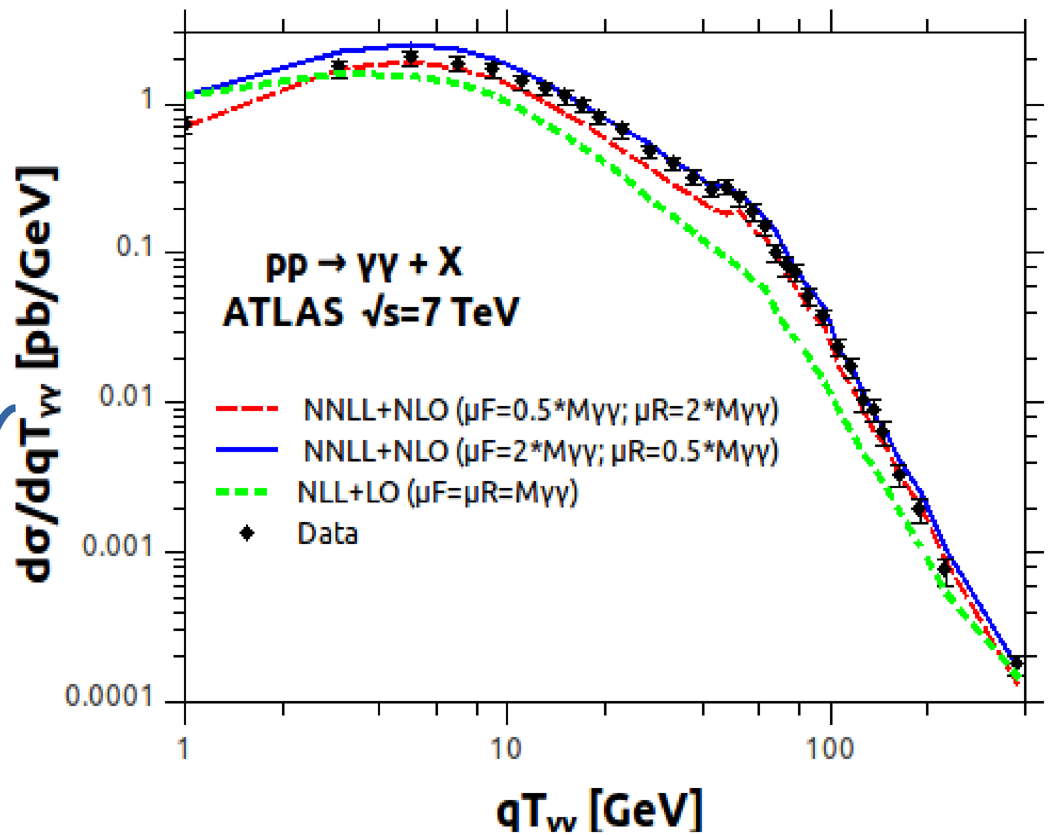
qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

Resummation → ATLAS γγ

Fixed order



LC, Coradeschi, de Florian (2015)

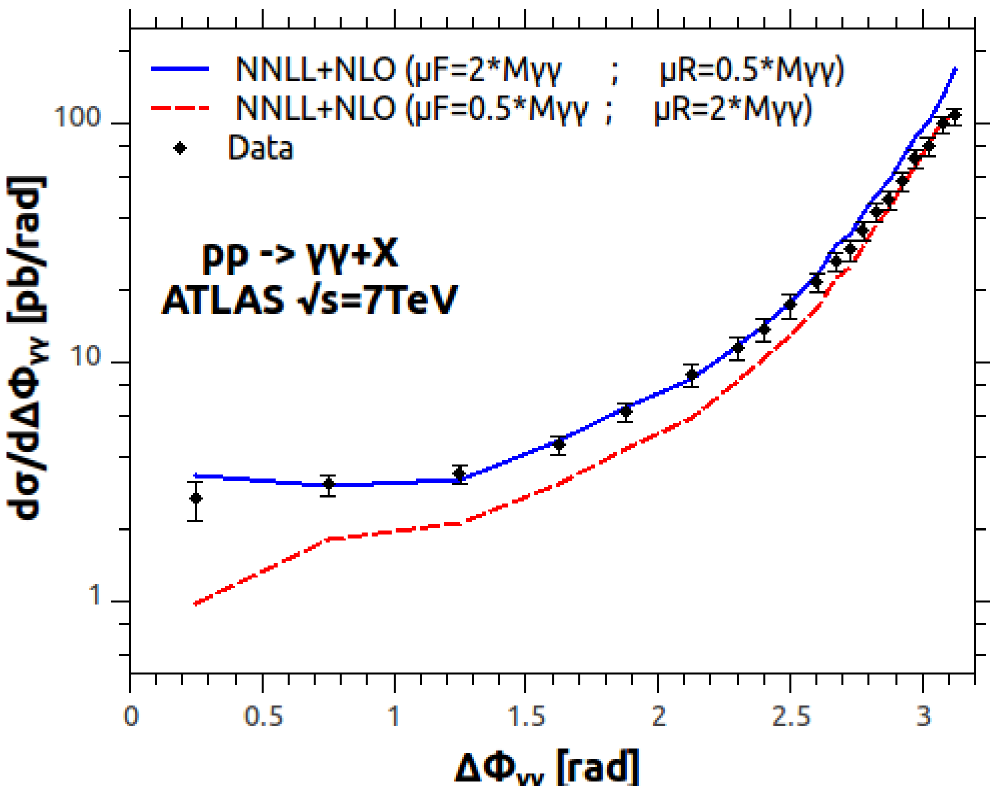


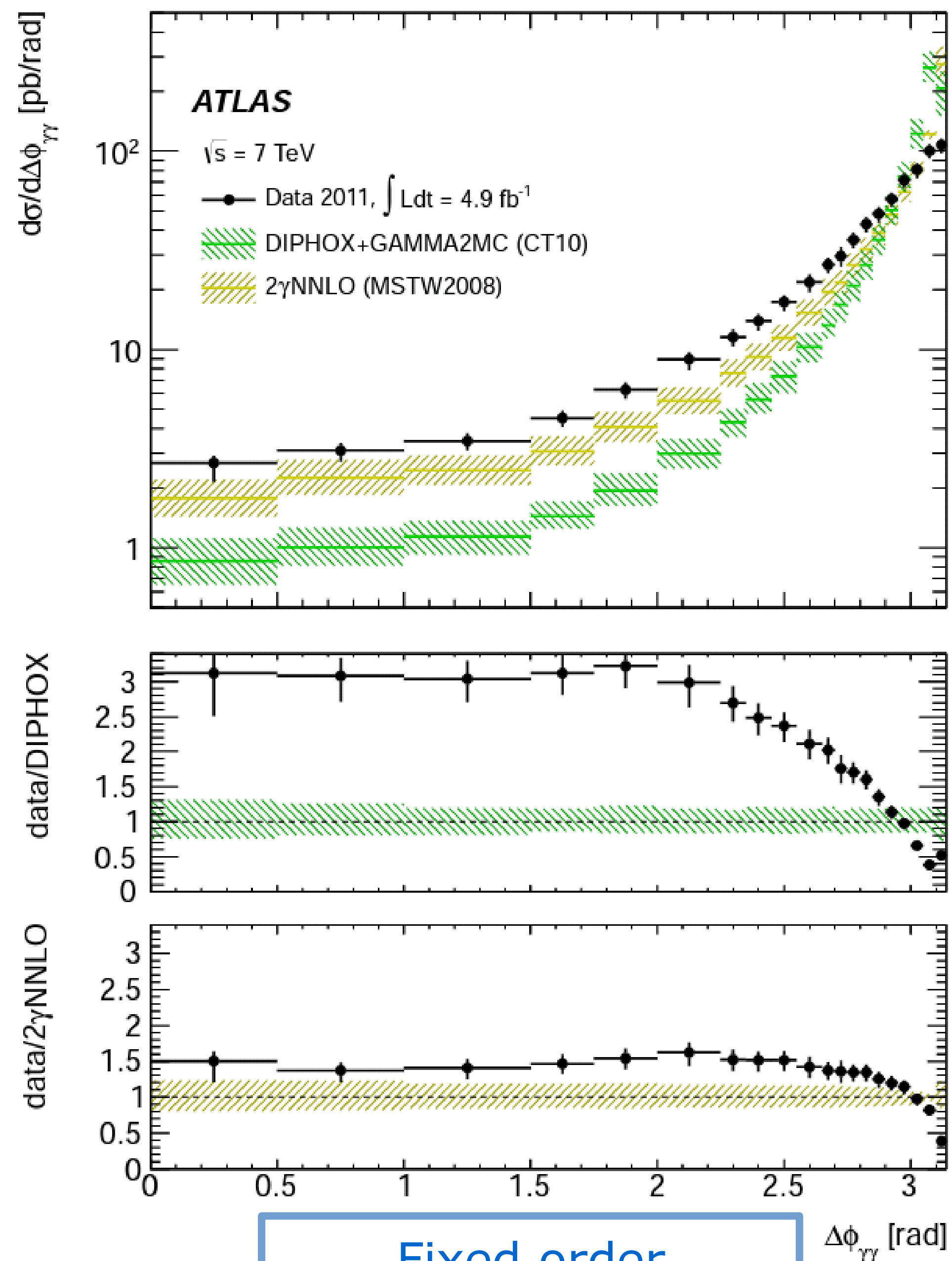
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.

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

Resummation → ATLAS γγ

LC, Coradeschi, de Florian (2015)

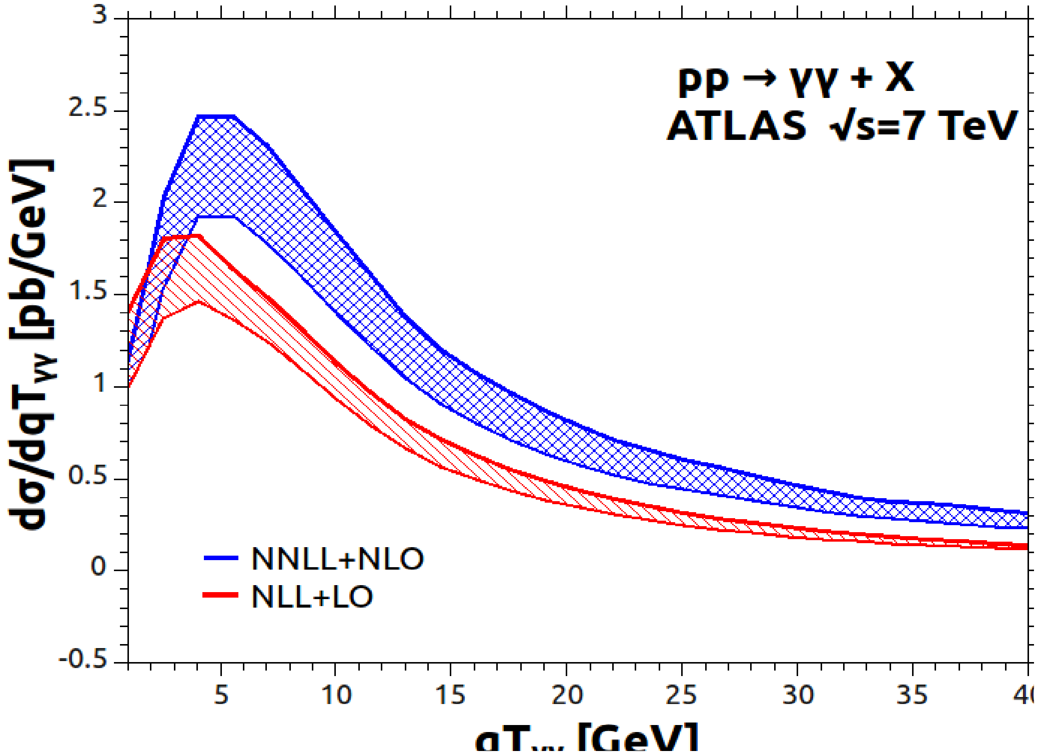


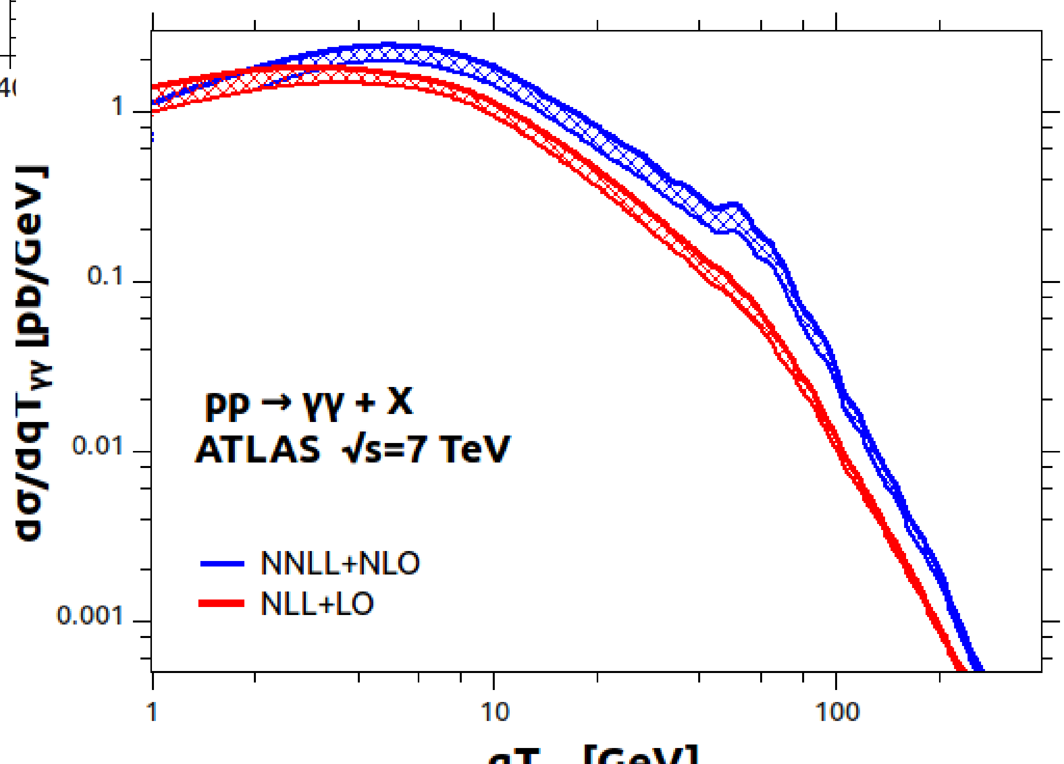


The same set-up also allows the calculation of more exclusive observable distributions

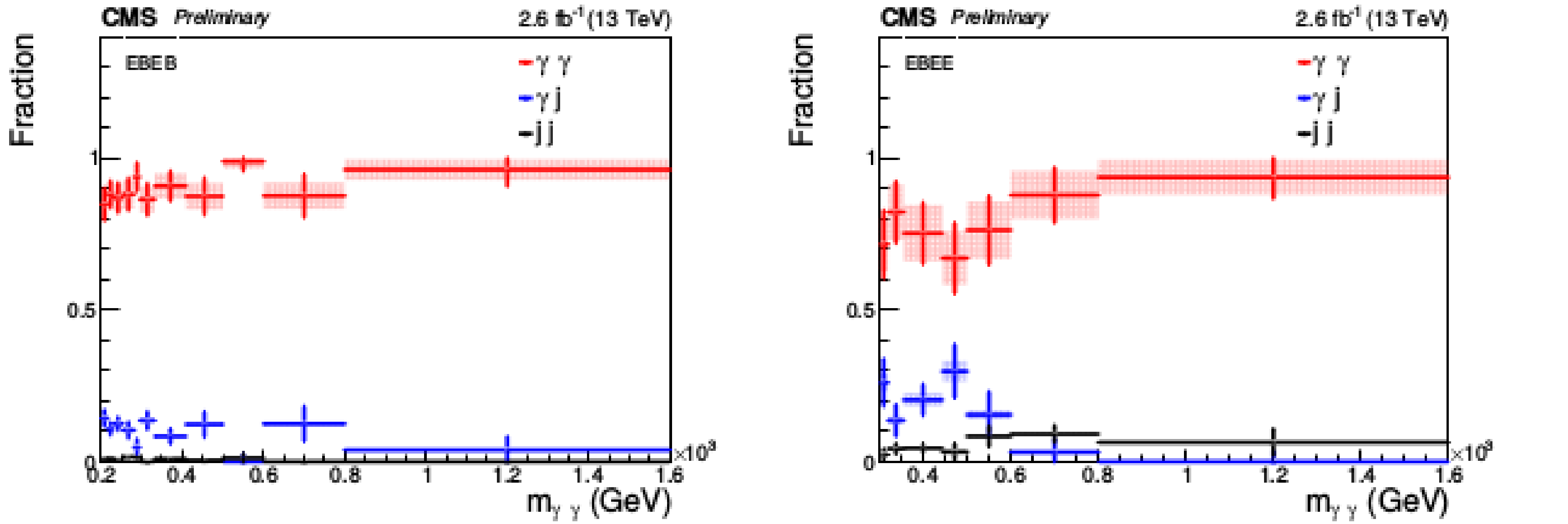
Fixed order

Resummation → ATLAS γγ

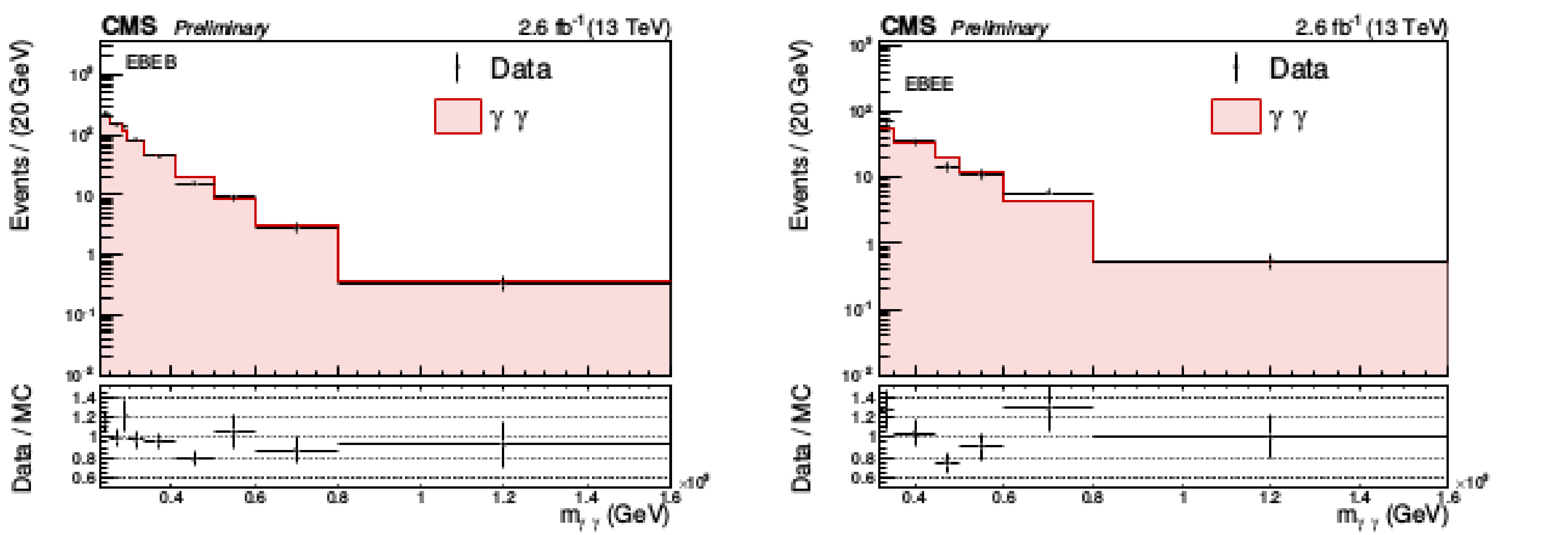




CMS-PAS-EXO-15-004



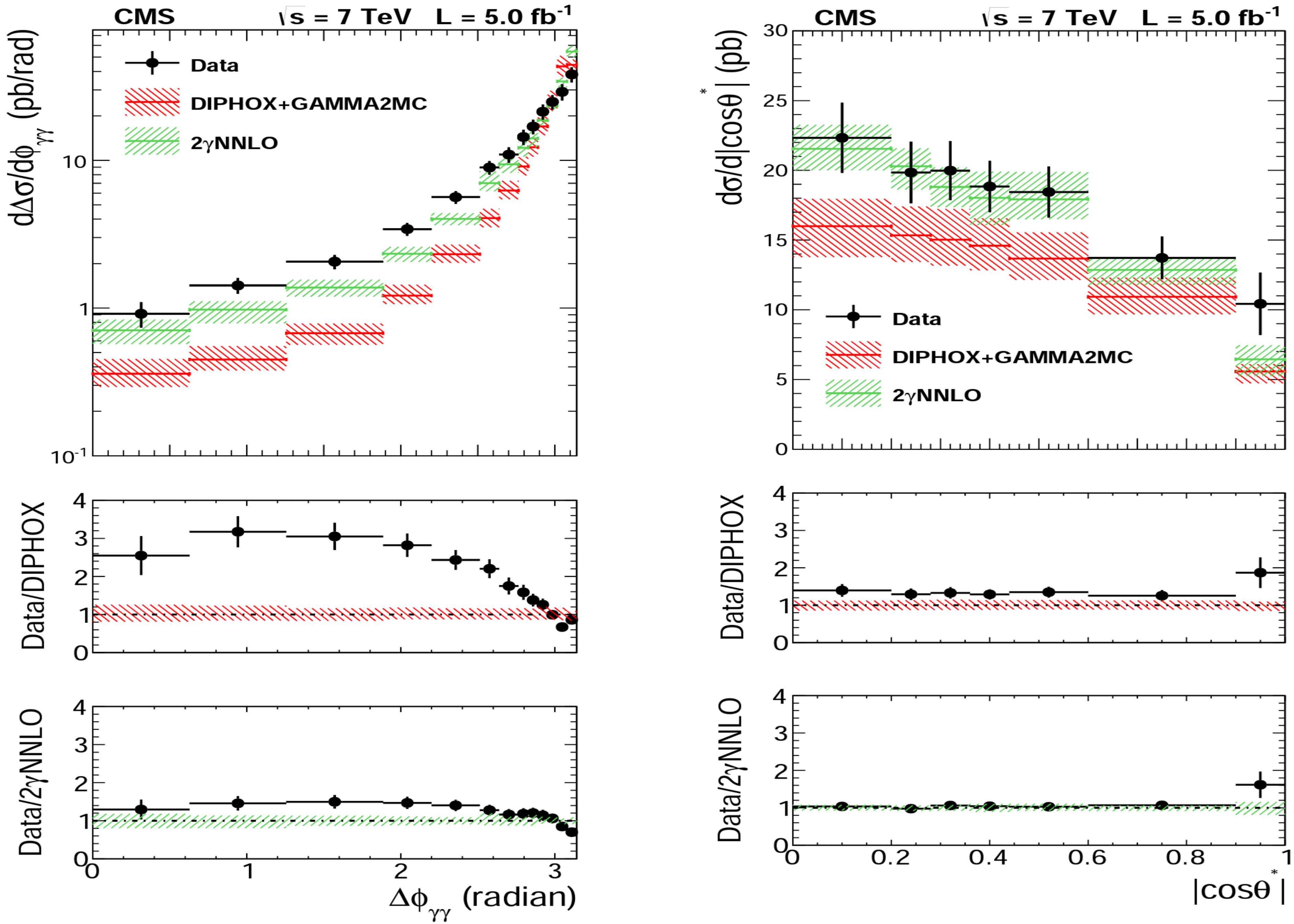
Measured composition of the background for the EBEB (left) and EBEE (right) categories.



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.

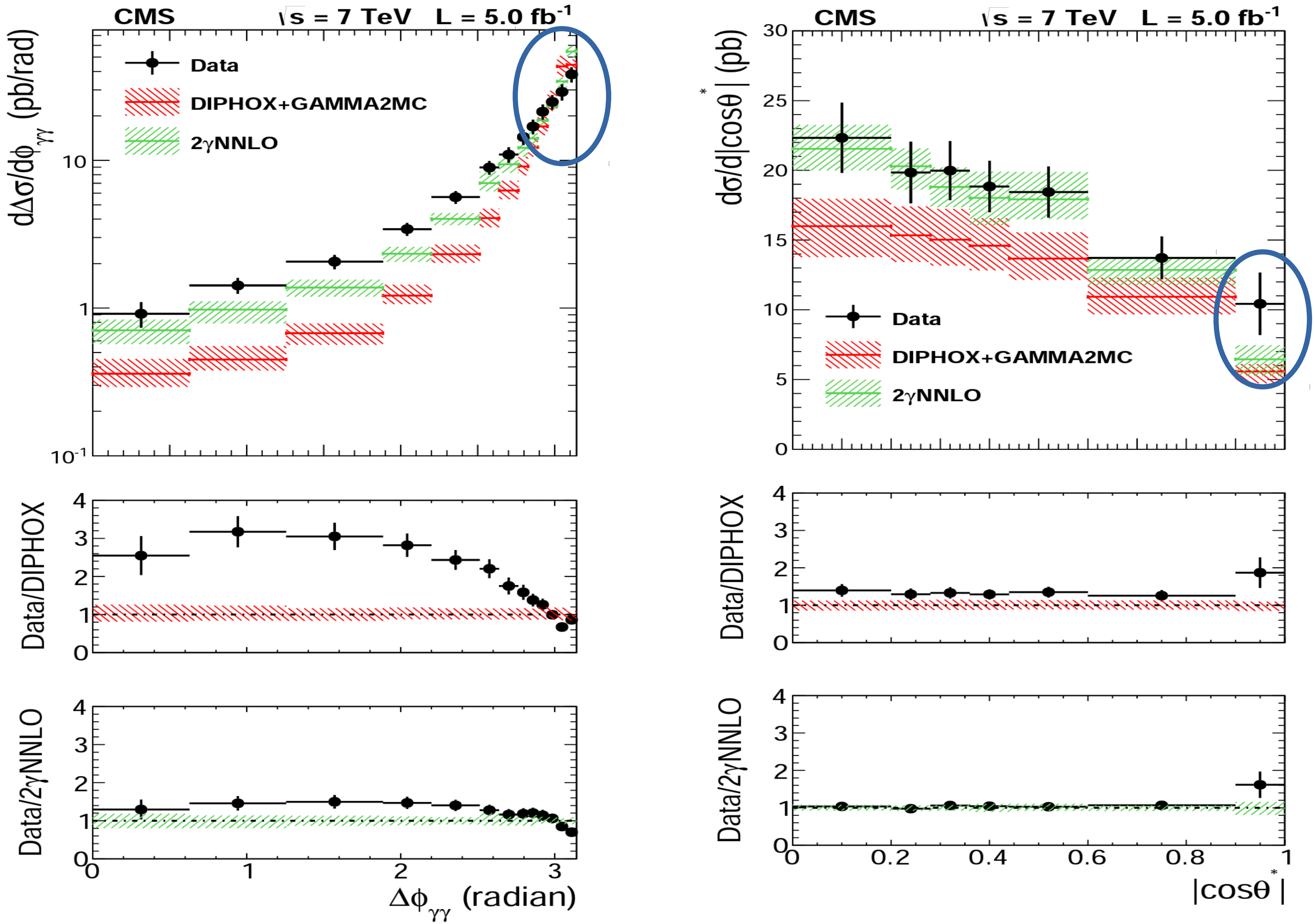
CMS results → γγ

ArXiv:1405.7225



CMS results → γγ

ArXiv:1405.7225



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

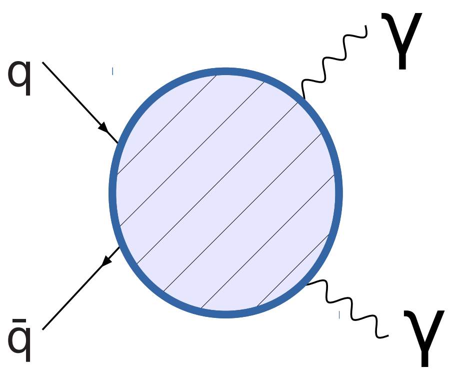
- **2γNNLO was used by the CDF, D0, ATLAS and CMS collaborations in their analyses**

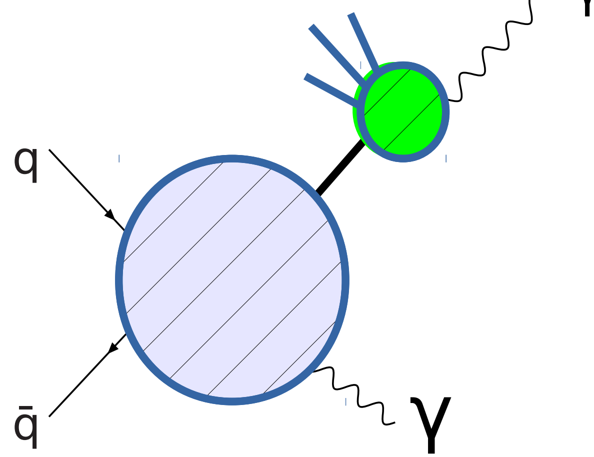
- **Our resummed results are implemented in the numerical code 2γRes**

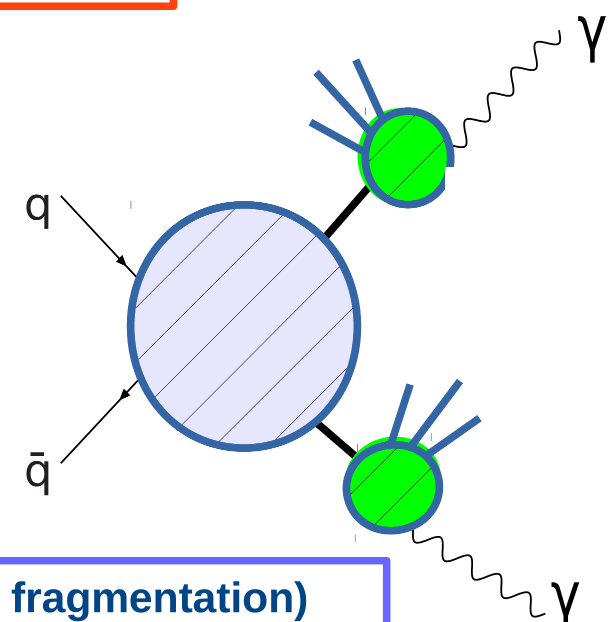
  LC, Coradeschi, de Florian (2015)

Photon production

Two mechanisms for photon production



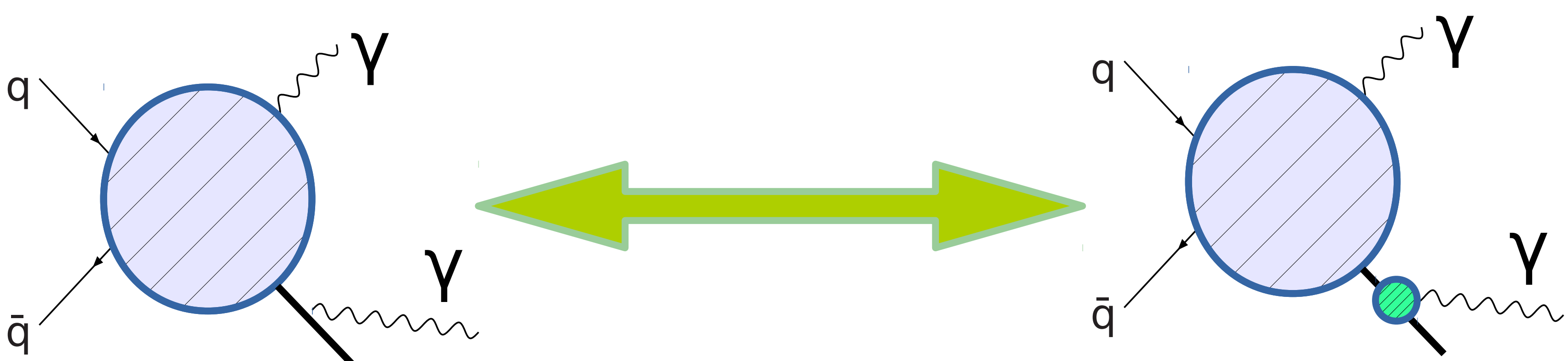




Direct (point-like)

Direct and double resolved (collinear fragmentation)

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



Collinear divergence

Cancelled by fragmentation

ATLAS SM cuts

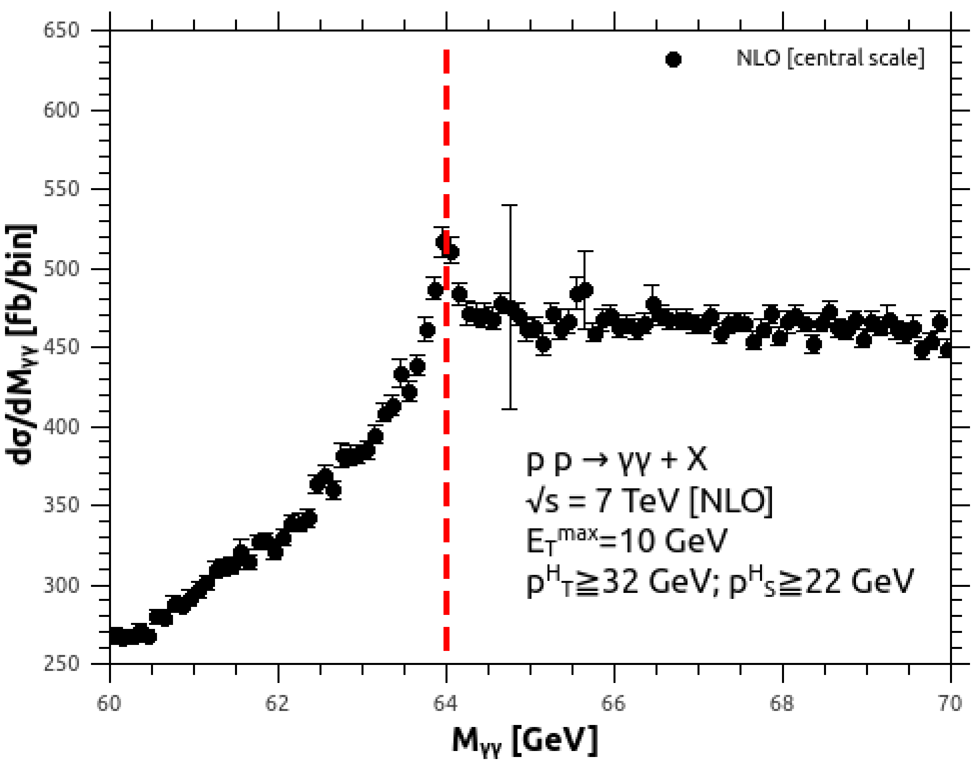
ArXiv:1211.1913

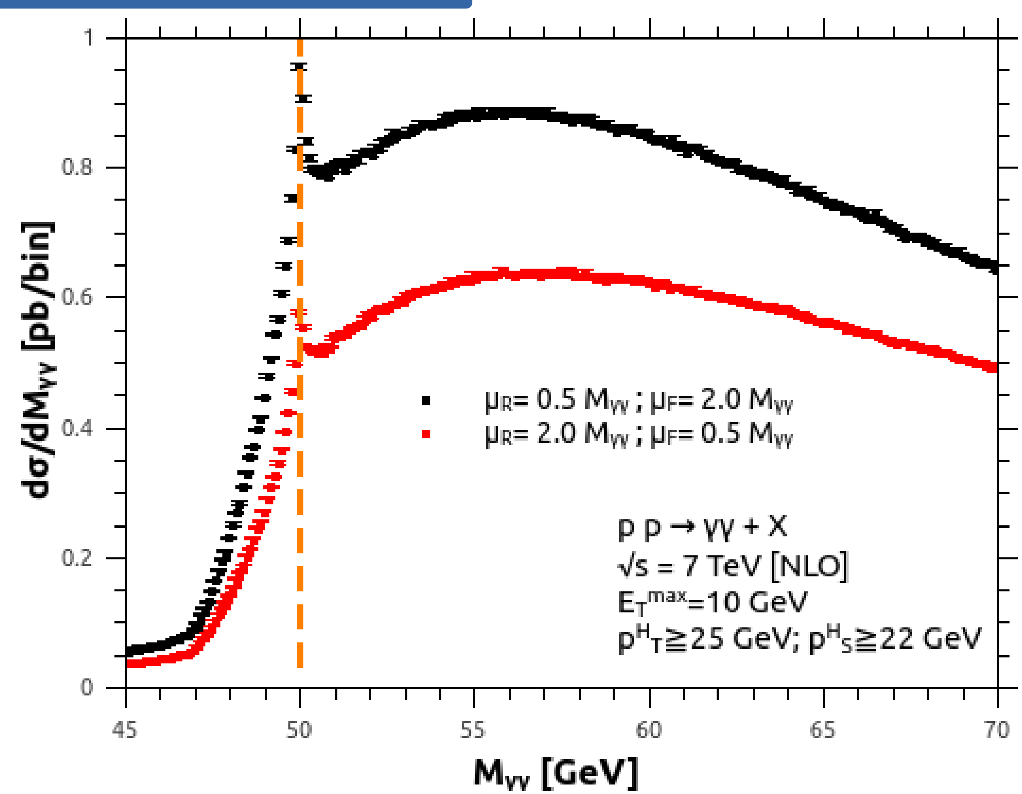
$$p_T^{\text{harder}} \geq 25 \text{ GeV}, \quad p_T^{\text{softer}} \geq 22 \text{ GeV},$$
$$|y_\gamma| \leq 2.37,$$
$$E_{T\ max} = 4 \text{ GeV}, \quad n = 1, \quad R = 0.4,$$
$$R_{\gamma\gamma} = 0.4$$

2GeV ; 10GeV

- **Reduction of 10% with more asymmetrical cuts**
- **The origin of the peak is related to the Catani-Webber effect**
- **It is not related to the subtraction formalism**

JHEP 9710 (1997) 005





ATLAS SM cuts

ArXiv:1211.1913

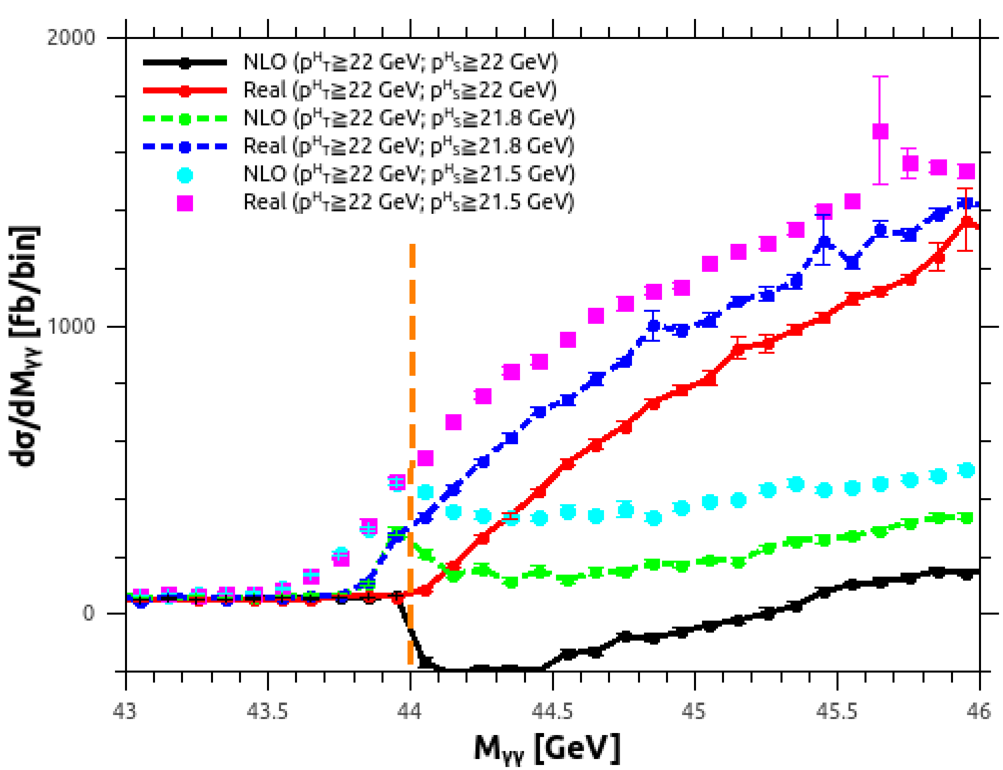
$$p_T^{\rm harder} \geq 25 \text{ GeV}, \quad p_T^{\rm softer} \geq 22 \text{ GeV},$$
$$|y_\gamma| \leq 2.37,$$
$$E_{T\ max} = 4 \text{ GeV}, \quad n = 1, \quad R = 0.4,$$
$$R_{\gamma\gamma} = 0.4$$

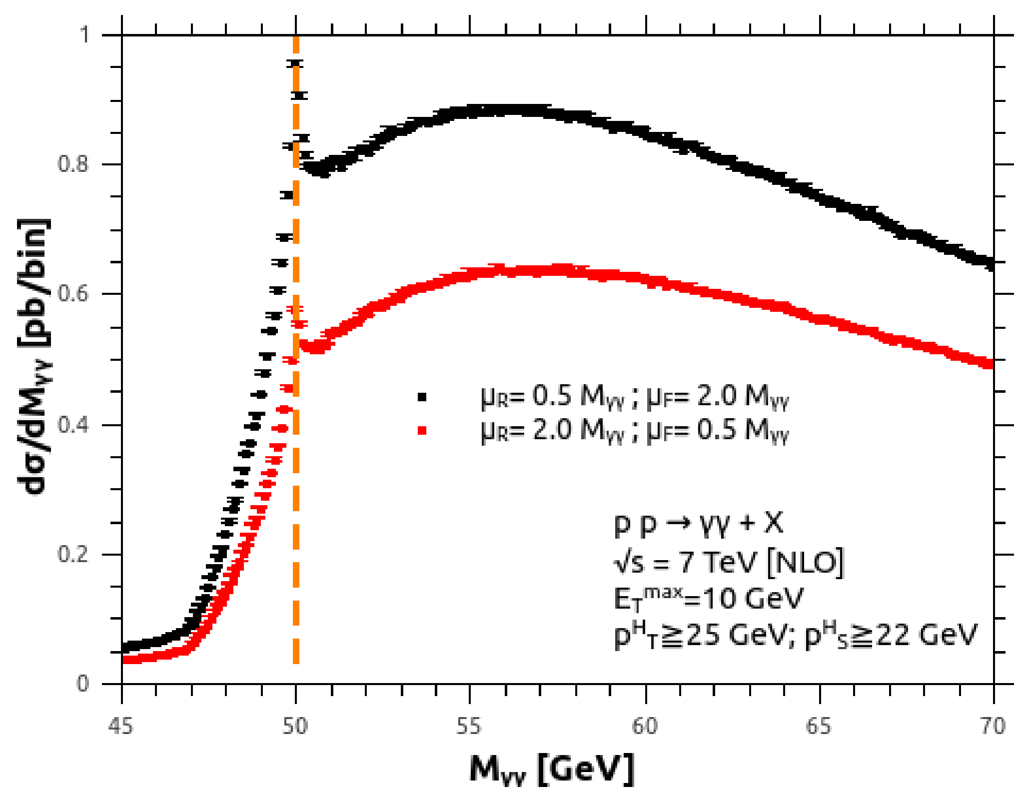
2GeV ; 10GeV

- **Plot made with qt-subtraction formalism (qtcut=0.1GeV)**
- **Symmetrical cuts related to sensitivity to soft gluon emission**

Catani-Webber (1997)

Frixione Ridolfi (1997)





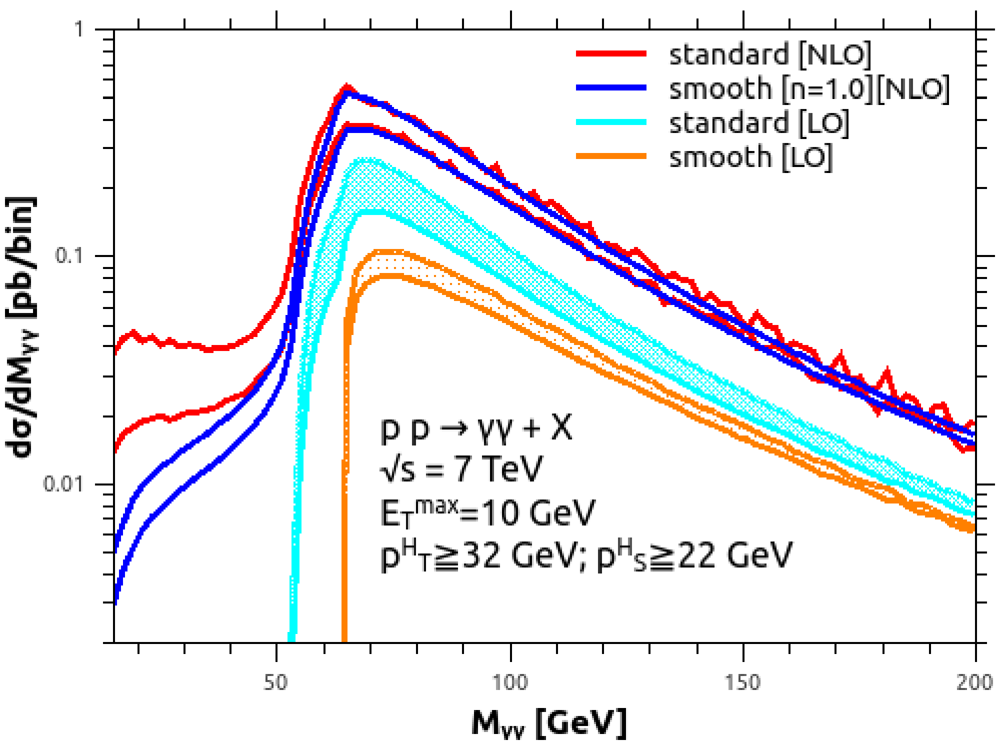
ATLAS SM cuts

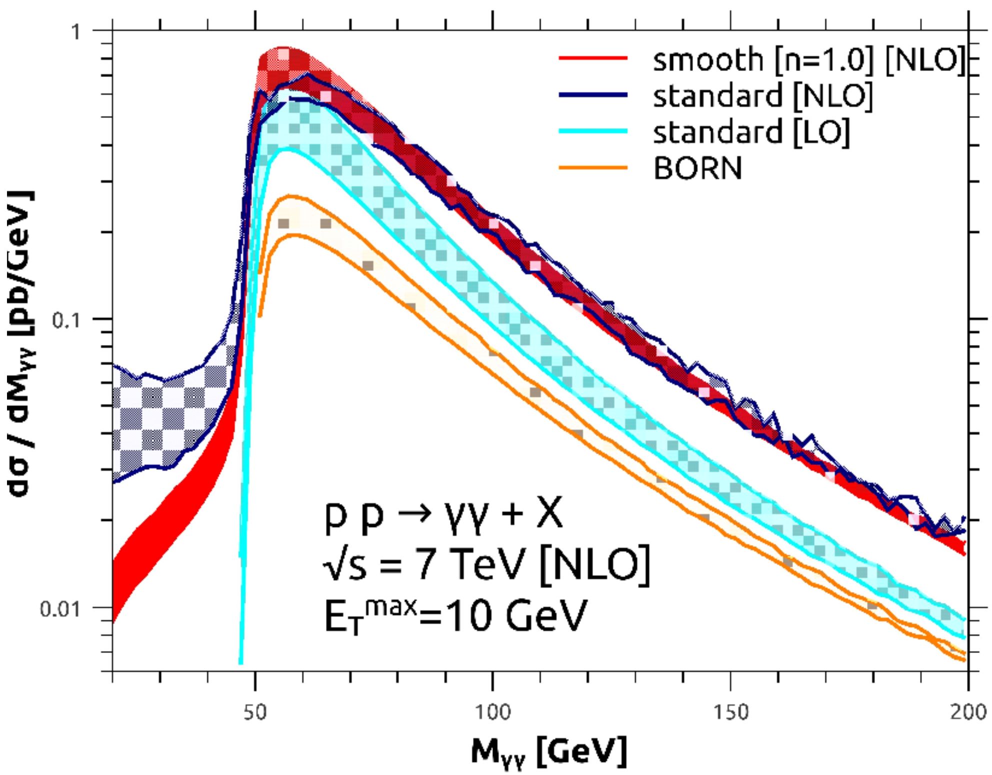
ArXiv:1211.1913

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

2GeV ; 10GeV

- More asymmetric cuts solve the problem in the peak of the invariant mass distribution
- Double game: more asymmetric cuts increment the K-factors → missing H.O correction terms could be more important





ATLAS SM cuts

ArXiv:1211.1913

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2GeV ; 10GeV