

NNLO QCD calculations at future colliders

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IFIC

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Outline

-  Introduction
-  Isolation criteria (IC)
-  IC comparison ($\gamma\gamma$ NLO)
-  Les Houches accord (“tight” isolation accord)
-  ATLAS and CMS results
-  q_T Resummation $\gamma\gamma$ (ATLAS)
-  Summary

Introduction

 $pp(\bar{p}) \rightarrow F$ / $F: \{\gamma + \text{jet}, \gamma\gamma, \gamma\gamma + \text{jet}, \gamma\gamma + (n) \text{ jets}, V\gamma, W\gamma\gamma, \dots\}$

 $\sigma = \alpha_s^a \sigma^{\text{LO}} + \alpha_s^{a+1} \sigma^{\text{NLO}} + \alpha_s^{a+2} \sigma^{\text{NNLO}} + \dots$ / $a = 0, 1, 2, \dots$

Why processes with photons in the final state are important?

 Clean experimental signature

 These are channels that we can use to check the validity of perturbative Quantum Chromodynamics (pQCD)



Soft gluon logarithmic resummation techniques

 Irreducible backgrounds for Higgs Boson searches and studies

 Backgrounds for BSM searches

 PDFs extractions

 Test of self-couplings ($V\gamma$) as predicted by the non-Abelian $SU(2)_L \times U(1)_Y$ (SM)

 S/B discrimination improvements

 Anomalous couplings

Why processes with photons in the final state are important?

$\{\gamma + \text{jet}, \gamma\gamma, \gamma\gamma + \text{jet}, \gamma\gamma + (n) \text{ jets}, V\gamma, W\gamma\gamma, \dots\}$



This talk is devoted to the study of parton level (FO) integrators and the comparison of their results with the LHC data



In particular $\longrightarrow \gamma\gamma$



What can we learn from these final states regarding the future colliders?

+) Isolation:

Marco Delmastro private communication (2015)

*) Comparison smooth-standard cone

*) Size of the cone $R = \{0.7; 0.4; 0.2; 0.1\}$

$\rightarrow$ **New requirements at Run II LHC**. A game between pile-up and how the cross section is sensitive to $\text{Log}(R)$

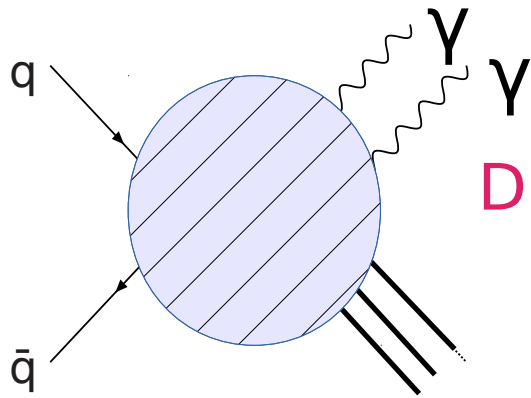
+) Origin of the discrepancies Theory/Data

*) Isolation, EW corrections, missing higher order QCD correction terms. The NNLO will be enough to describe the Data in the next years?

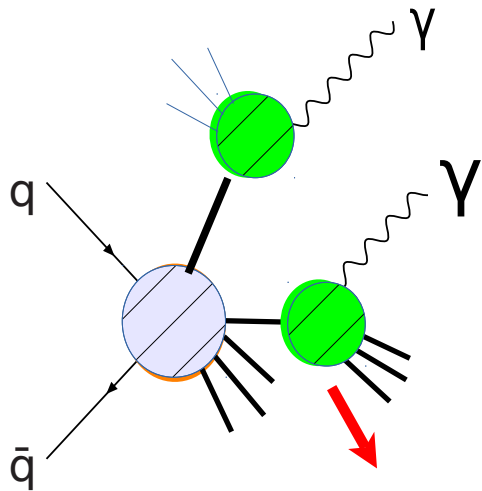
All these processes are connected by the presence of at least one-photon in the final state. Therefore all of them have a common feature: their origin arises in the photon production mechanisms

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



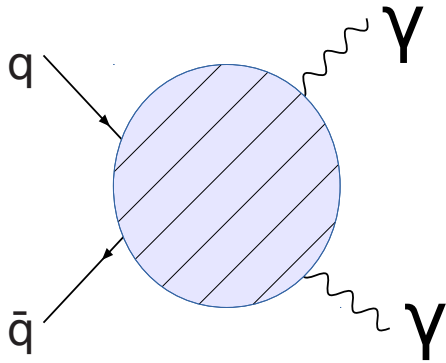
Fragmentation component: photon is produced from non-perturbative fragmentation of a hard parton (analogously to a hadron)

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

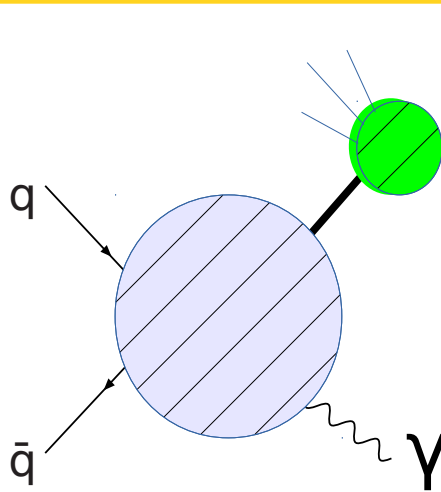
Fragmentation function:
to be fitted from data

Photon production

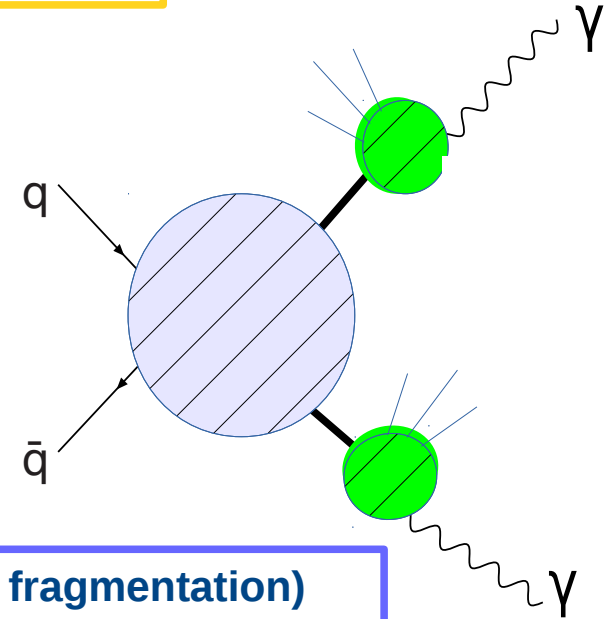
Two mechanisms for photon production



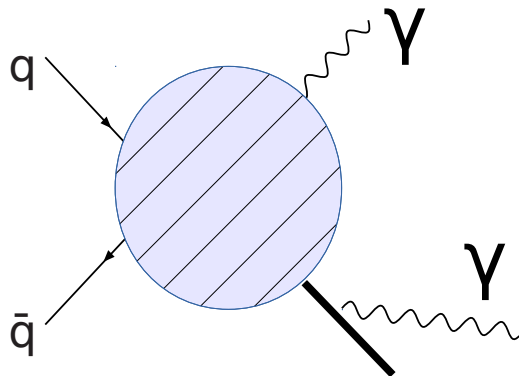
Direct (point-like)



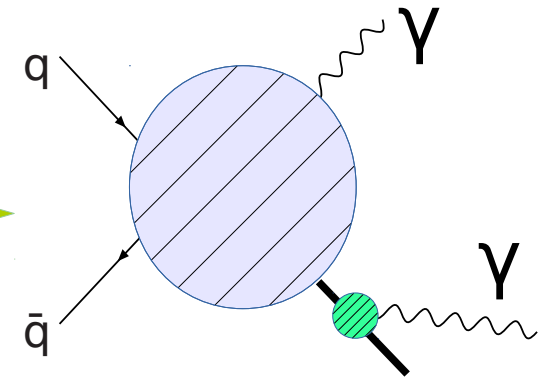
Direct and double resolved (collinear fragmentation)



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



Collinear divergence



Cancelled by fragmentation

Photon production

Experimentally photons must be isolated

Isolation reduces fragmentation component

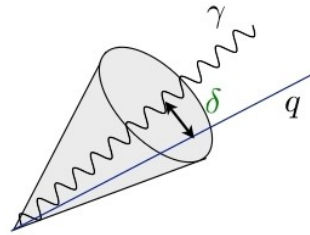
Large Corrections

Isolation criteria



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

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



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



Smooth (Frixione) S. Frixione (1998)

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

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



Democratic Glover, Morgan(1994). Gehrmann-De Ridder, Gehrmann, Glover (1997)

final state particles are clustered into jets, treating photons and hadrons equally.

The obtained object is called a photon or a photon jet, if the energy fraction $Z = E_\gamma / (E_\gamma + E_{had})$ of an observed photon inside the jet is larger than an experimentally defined value Z_{cut} .

Photon production

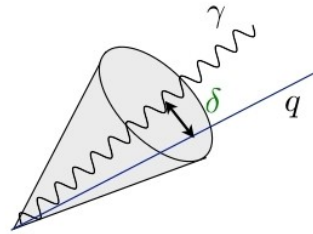
Experimentally photons must be isolated

Isolation reduces fragmentation component

Large Corrections

Experimentalist may choose:

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



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

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

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



no quark-photon collinear divergences

no fragmentation component (only direct)

direct well defined by itself

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

Available theoretical (FO) tools for $\gamma\gamma$ production

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

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

gamma2MC Zvi Bern, Lance Dixon, and Carl Schmidt

Full NLO (direct only) + Box, + partial correction to Box contribution (N^3LO)

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

Full NLO for direct, but only LO for fragmentation + partial correction to Box contribution (N^3LO)

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

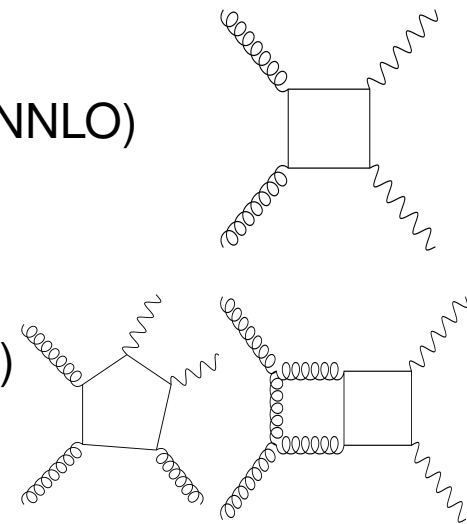
NLL q_T resummation for direct (with regulator for collinear singularities)

2 γ NNLO Catani, LC, de Florian, Ferrera, Grazzini

Full NNLO for direct + partial correction to Box contribution (N^3LO)

2 γ Res LC, Coradeschi, de Florian

Incorporates the q_T resummation at NNLL+NNLO



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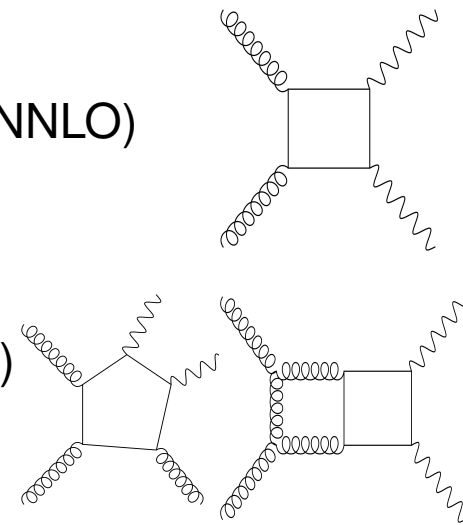
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Incorporates the q_T resummation at NNLL+NNLO



The user can use these codes to predict the q_T ($\gamma\gamma$ + jet) spectrum, but at one perturbative order less than the total Xsection

Available theoretical (FO) tools for:

$\gamma\gamma + (n < 4) \text{ jet}$

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); S. Badger, A. Guffanti, V. Yundin (2013)

$\gamma + \text{jet}$

JetPHOX Aurenche, Catani, Fontannaz, Binoth, Guillet, Pilon, Werlen

Full NLO for direct and fragmentation

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

Full NLO for direct, but only LO for fragmentation

$V\gamma \text{ production}$

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

Full NLO for direct, but only LO for fragmentation

NNLO Grazzini, Kallweit, Rathlev, Torre

Full NNLO for direct

$\gamma\gamma\gamma, W\gamma\gamma, \gamma\gamma\gamma\gamma, Z\gamma\gamma, \dots \text{ production}$

MCFM Ellis, Campbell, C. Williams , T. Dennen

Full NLO for direct, but only LO for fragmentation

Available theoretical (FO) tools for:

$\gamma + (n < 4)$ jet
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Full NLO for direct, but only LO for fragmentation

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Full NLO for direct, but only LO for fragmentation

NNLO Grazzini, Kallweit, Rathlev, Torre

Full NNLO for direct

$\gamma\gamma\gamma, W\gamma\gamma, \gamma\gamma\gamma\gamma, Z\gamma\gamma, \dots$ production

MCFM Ellis, Campbell, C. Williams , T. Dennen

Full NLO for direct, but only LO for fragmentation

**The list is not
exhaustive!!!!**

VBFNLO

Full NLO for direct

JG. Bozzi, F. Campanario, M. Rauch, H. Rzehak, D. Zeppenfeld

Available theoretical (FO) tools for:

{ γ +jet , $\gamma\gamma$, $\gamma\gamma$ + jet , $\gamma\gamma$ + (n) jets , $V\gamma$, $W\gamma\gamma$,.... }

NNLO

+) Only direct $\rightarrow$ smooth cone

NLO

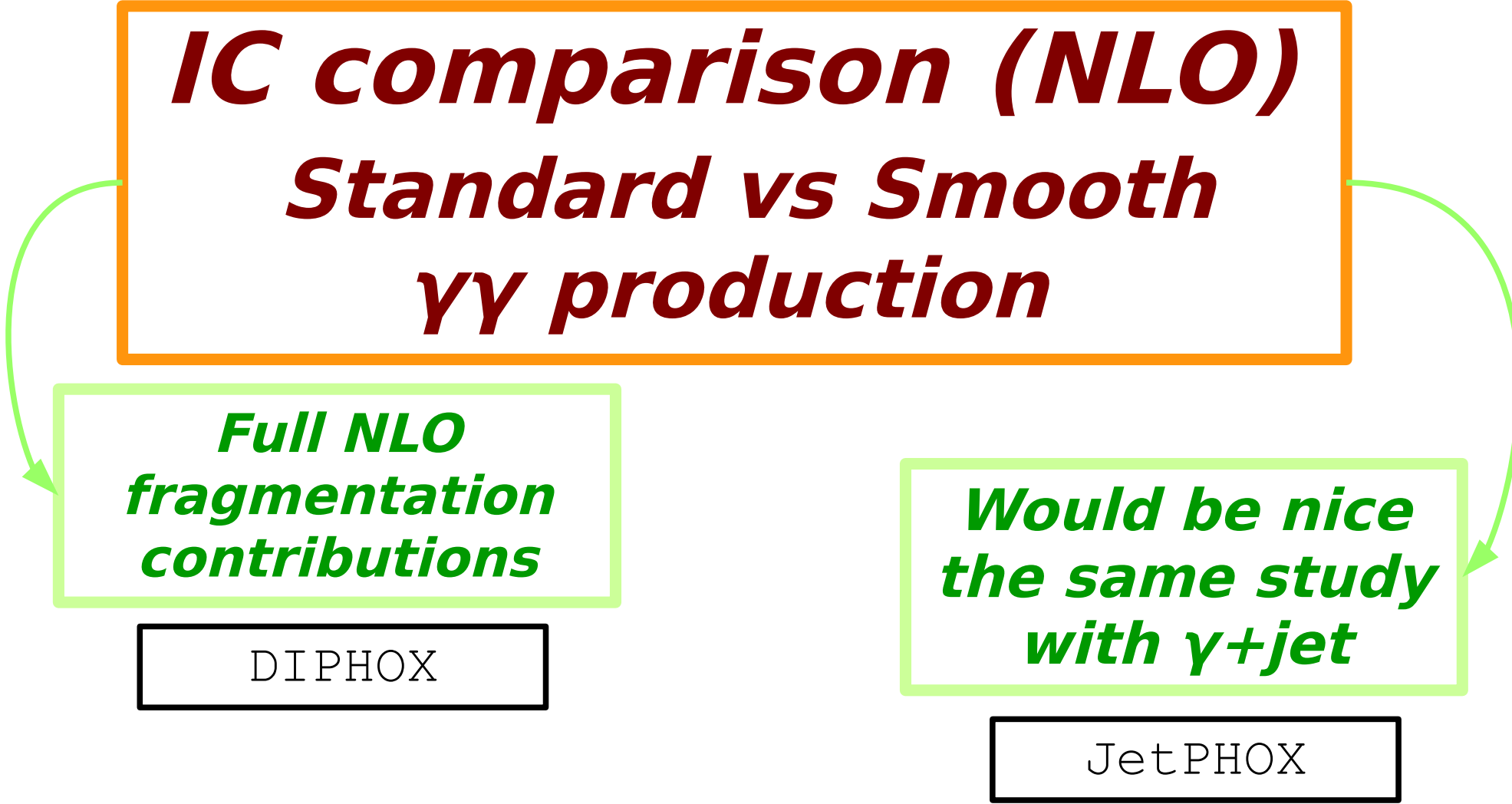
+) Only direct $\rightarrow$ smooth cone

+) Direct + Fragmentation

IC comparison (NLO)
Standard vs Smooth
 $\gamma\gamma$ production

IC comparison (NLO)

Standard vs Smooth $\gamma\gamma$ production



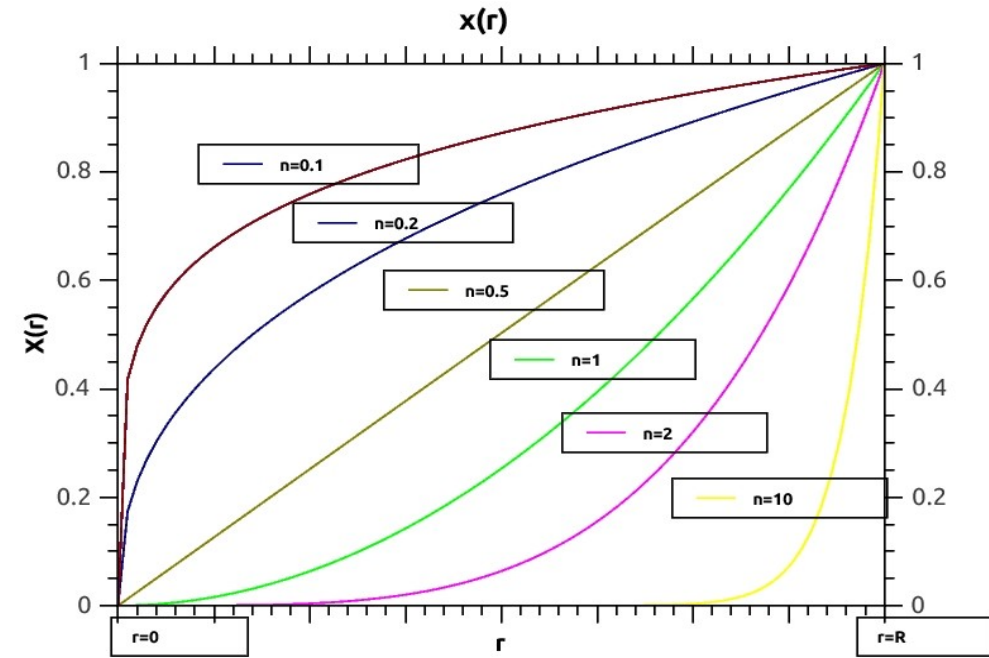
***Full NLO
fragmentation
contributions***

DIPHOX

***Would be nice
the same study
with γ +jet***

JetPHOX

IC comparison ($\gamma\gamma$ at NLO)



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

Standard

$$E_T^{had}(\delta) \leq E_{T_{max}}^{had}$$

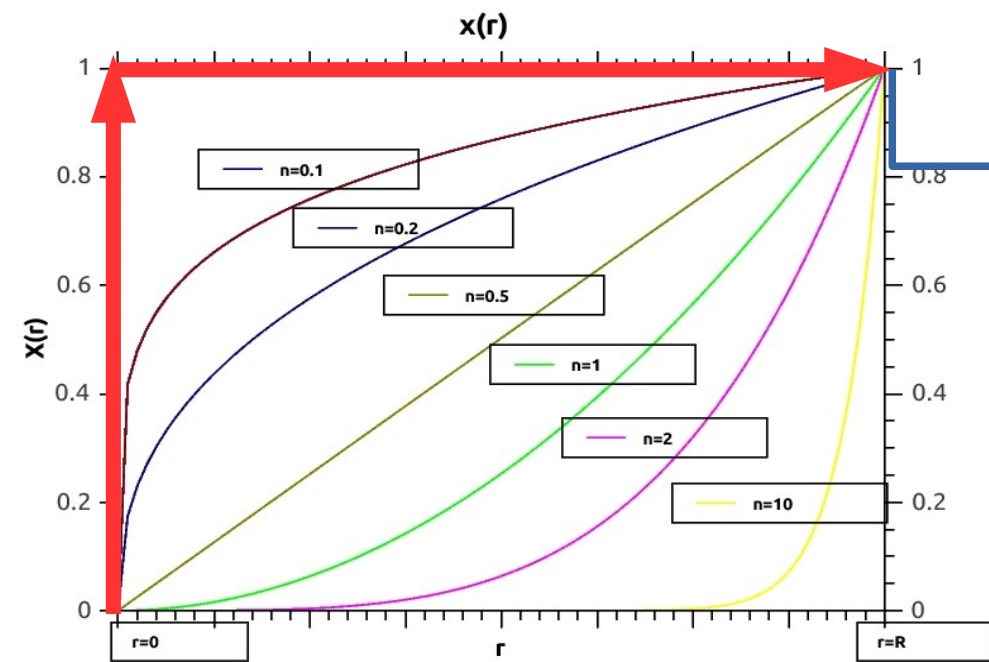
Smooth

$$E_T^{had}(\delta) \leq E_{T_{max}}^{had} \chi(\delta)$$

No quark-photon collinear divergences

No fragmentation contribution (only direct)

Direct contribution well defined



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Standard

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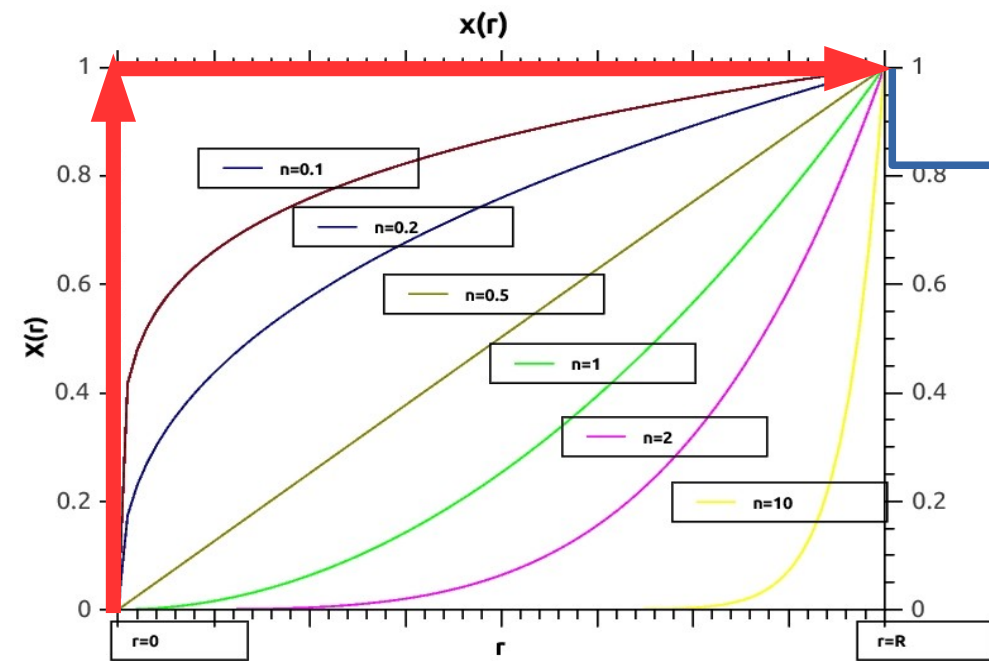
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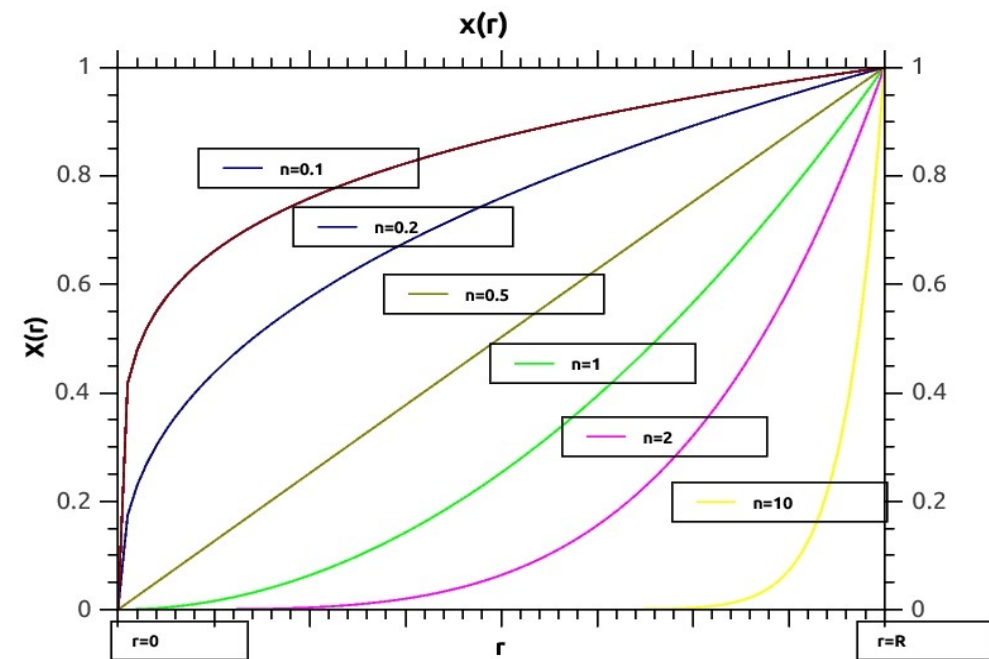
No fragmentation contribution (only direct)

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)



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

Standard

$$E_T^{had}(\delta) \leq E_{Tmax}^{had}$$

Smooth

$$E_T^{had}(\delta) \leq E_{Tmax}^{had} \chi(\delta)$$

No quark-photon collinear divergences

No fragmentation contribution (only direct)

Direct contribution well defined

In real life... how much are different?

NLO comparison

(Standard vs. Smooth)

Ro=0.4 n=1

DIPHOX → (Direct + Fragmentation)[NLO]

E_{Tmax}^{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%

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

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

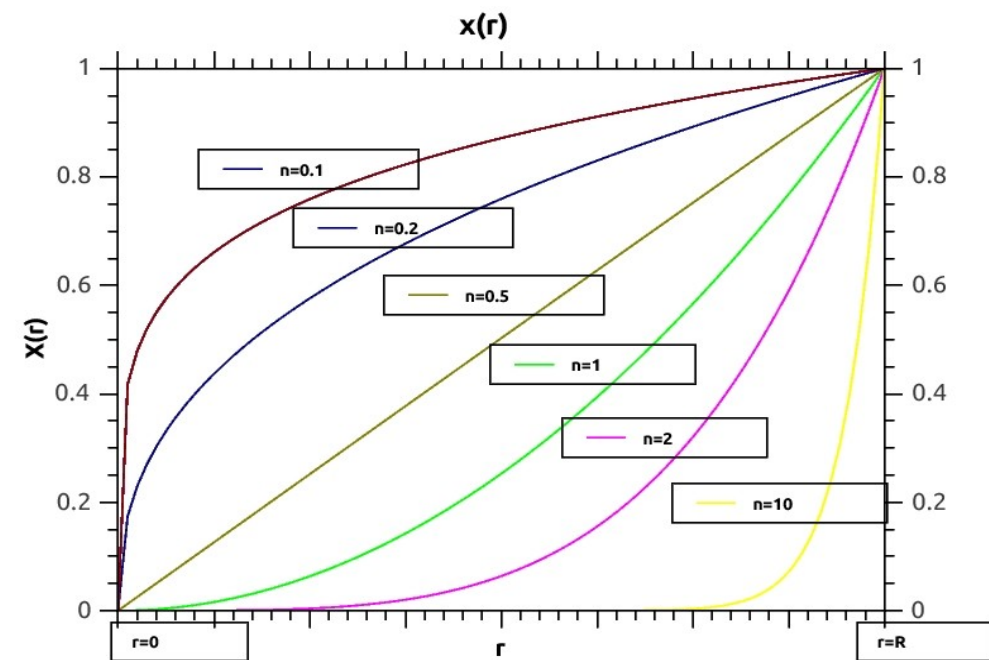
2yNNLO

S. Catani, LC, D. de Florian, G. Ferrera, and M. Grazzini (2011)

NNLL+ NNLO

2yRes

LC, Coradeschi, de Florian (2015)



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

Standard

$$E_T^{had}(\delta) \leq E_{Tmax}^{had}$$

Smooth

$$E_T^{had}(\delta) \leq E_{Tmax}^{had} \chi(\delta)$$

No quark-photon collinear divergences

No fragmentation contribution (only direct)

Direct contribution well defined

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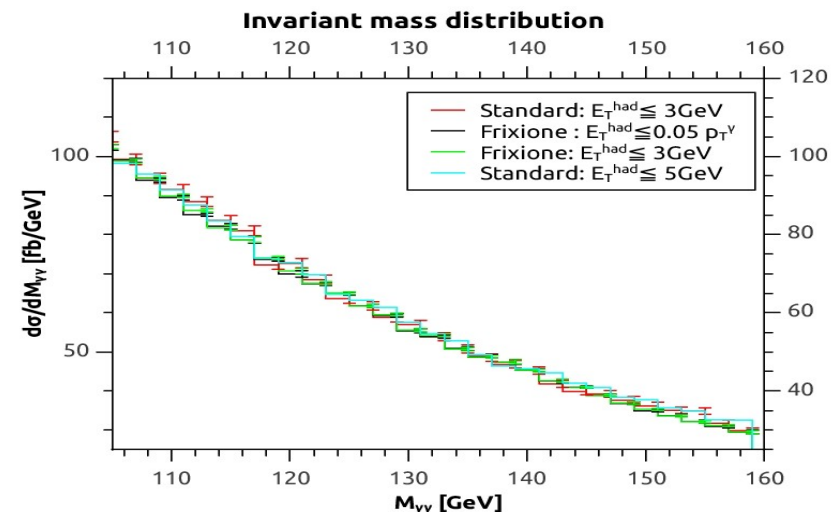
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$$\left(\frac{\delta(\delta)}{\delta(\delta)} \right)^n \leq 1$$

$$d(\delta) \leq E_{Tmax}^{had}$$

$$l(\delta) \leq E_{Tmax}^{had} \chi(\delta)$$

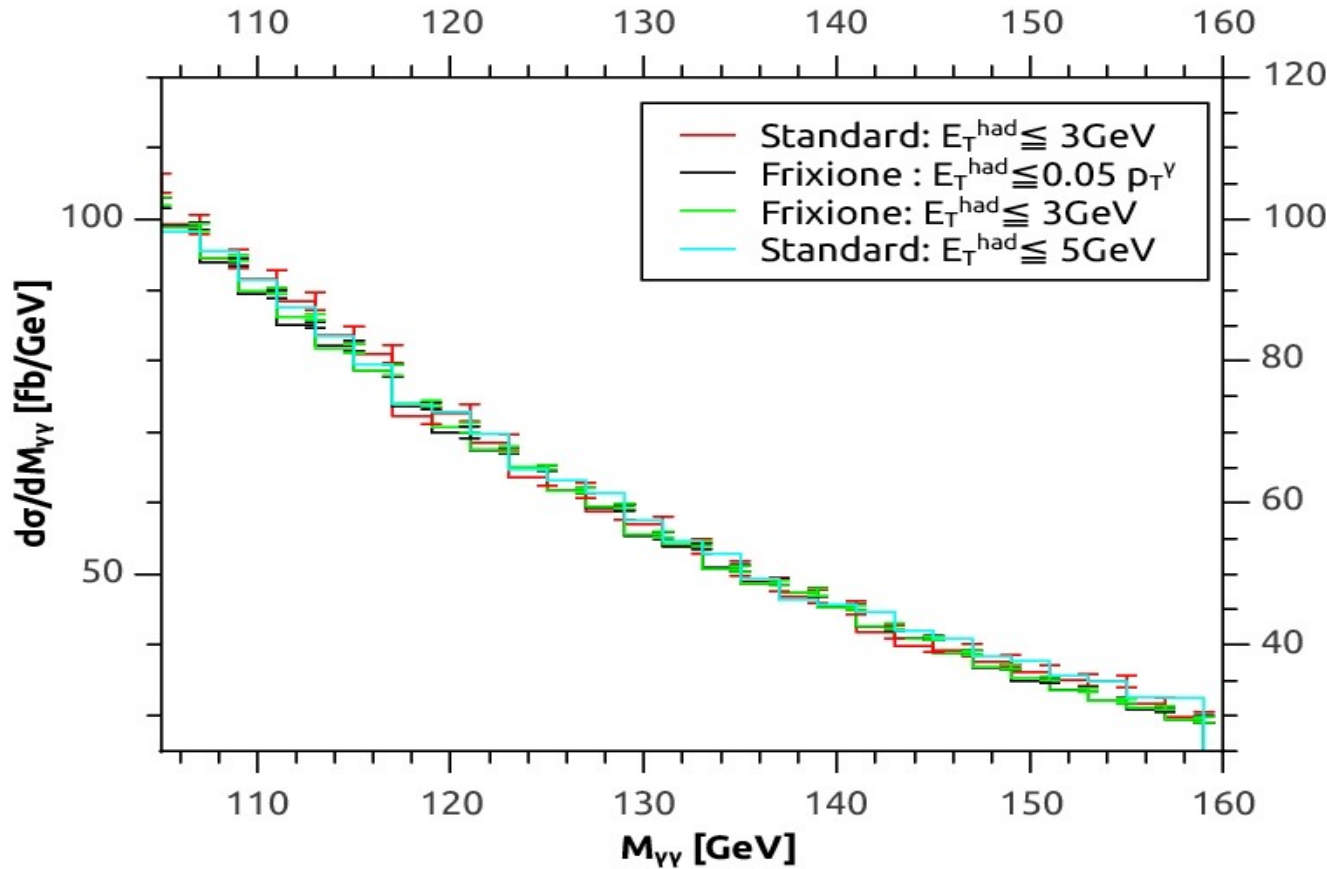
Linear divergences

Contribution (only direct)

well defined

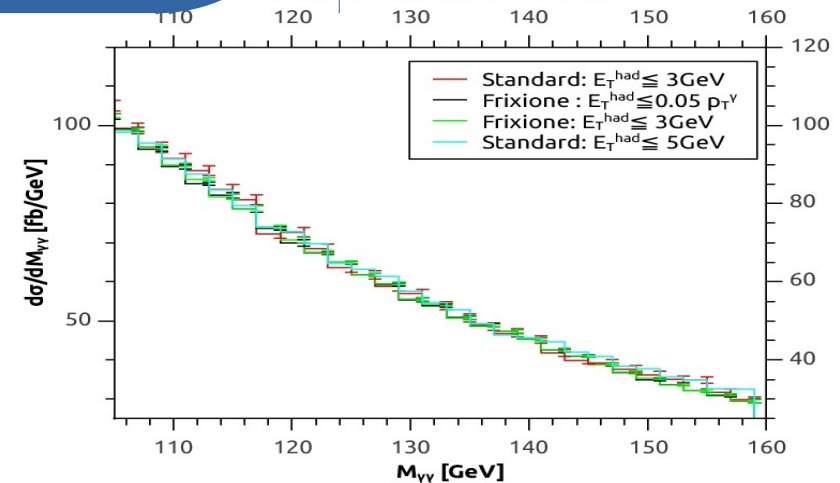
Direct + Fragmentation

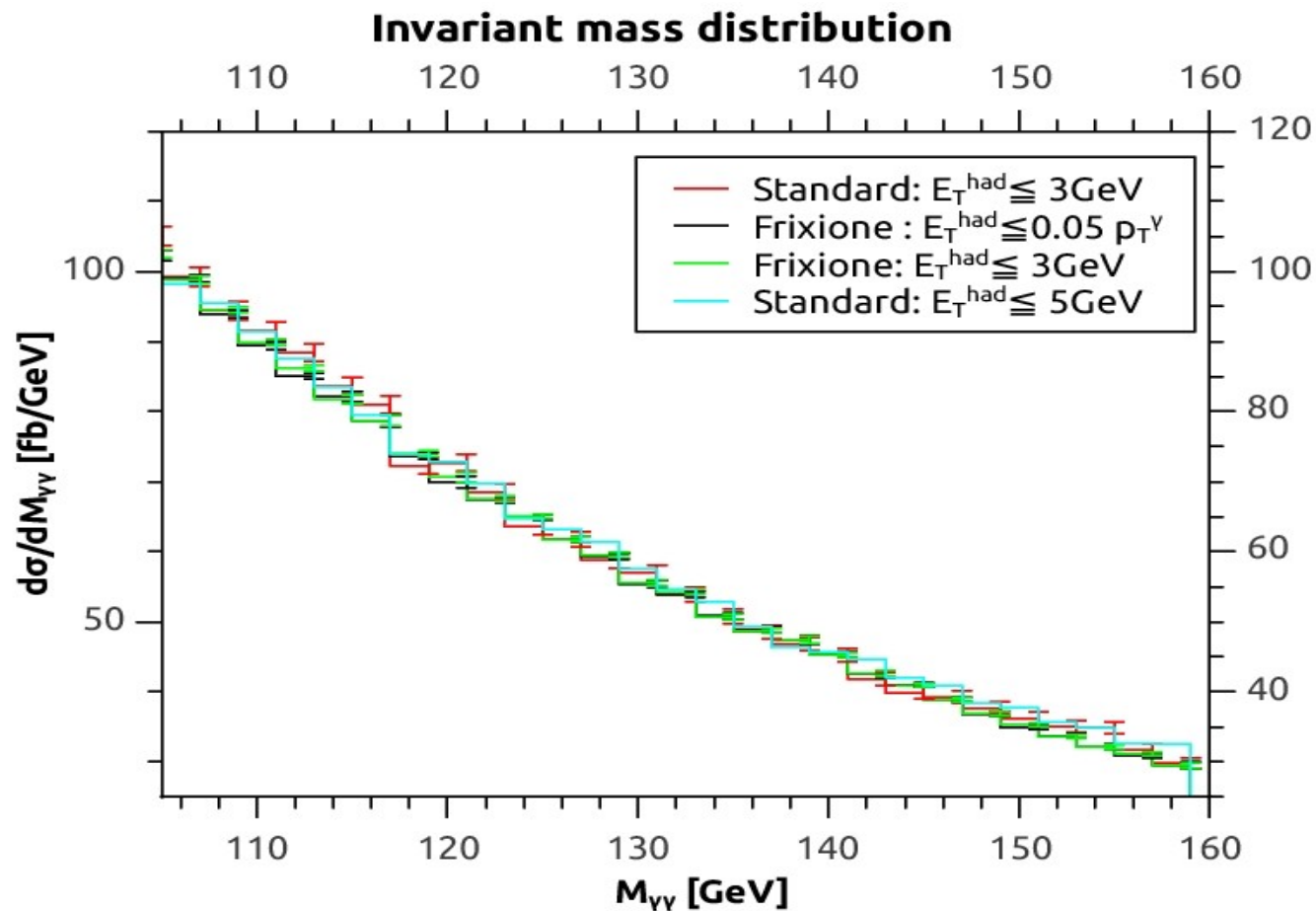
Invariant mass distribution



E_{Tmax}^{had}	standard/smooth
2 GeV	< 1%
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5 GeV	3%
0.05 p_T	< 1%
0.5 p_T	11%

Invariant mass distribution





$$\left(\frac{\chi(\delta)}{\chi(0)} \right)^n \leq 1$$

$$d(\delta) \leq E_{Tmax}^{had}$$

$$d(\delta) \leq E_{Tmax}^{had} \chi(\delta)$$

Linear divergences

Contribution (only direct)

well defined

But the effects of the fragmentation could appear strongly in kinematical regions far away from the back-to-back configuration.....

Isolation criteria comparison

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

For the next slides: [For all the cases we use the same set of isolation parameters]

$X_{\text{section}} [\text{NLO}] = \text{Direct} [\text{NLO}] + \text{Frag} [\text{NLO}]$ (Isolation Criterion: Standard, Democratic, Frixione, etc.)

$X_{\text{section}} [\text{NLO}] = \text{Direct} [\text{NLO}] + \text{Frag} [\text{NLO}]$ (Isolation Criterion: Frixione)

$X_{\text{section}} [\text{NLO}] = \text{Direct} [\text{NLO}] + \text{Frag} [\text{LO}]$ (Isolation Criterion: Standard, Democratic, Frixione, etc.)

The calculation of fragmentation contributions is very difficult:

We can find calculations in which the fragmentation component is considered at one perturbative level less than the direct component.

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

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

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

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

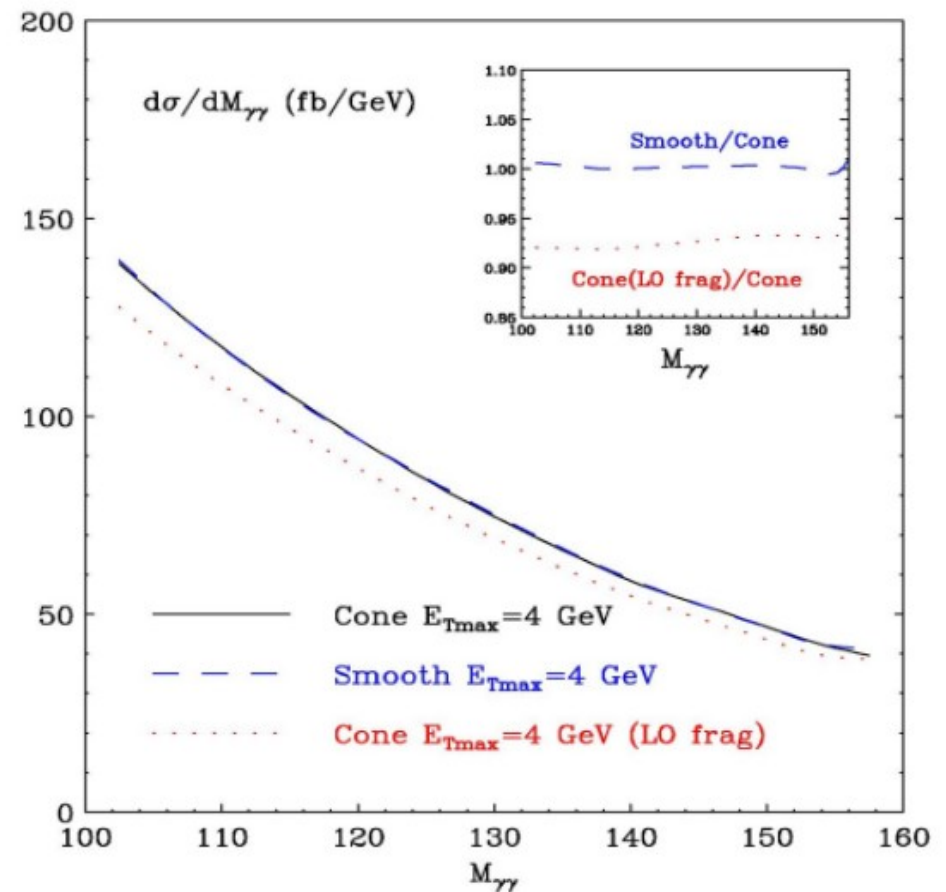
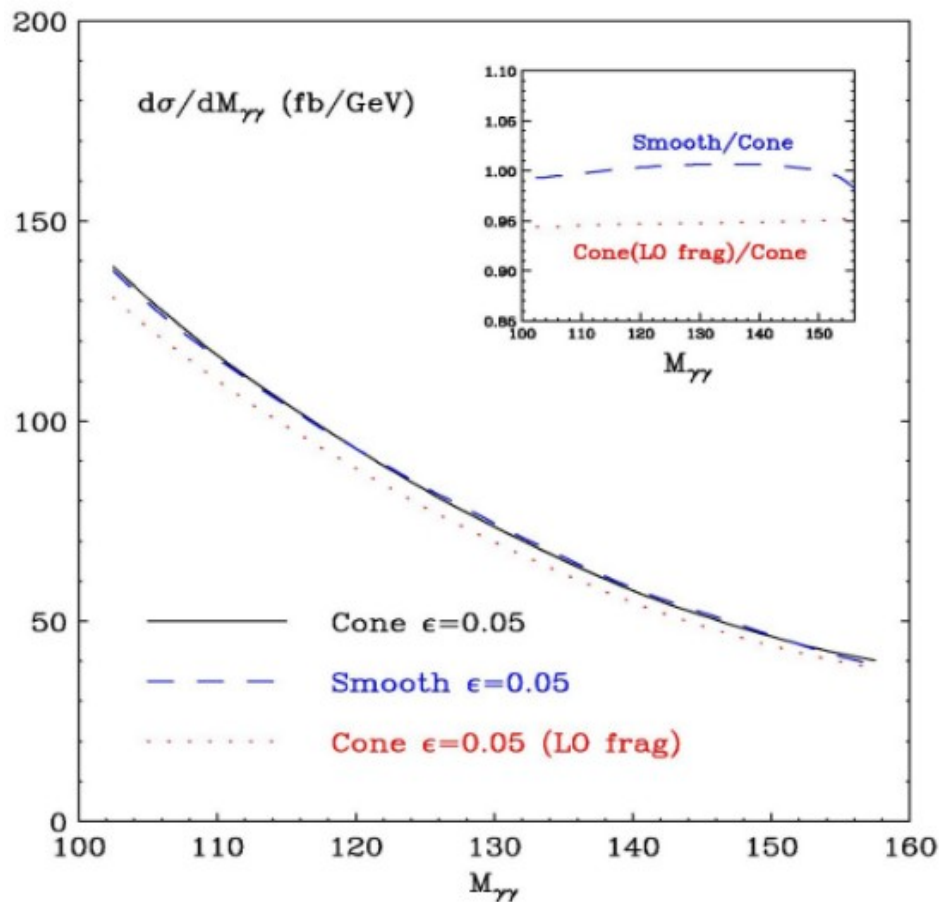
$$R_{\gamma\gamma} \geq 0.45$$

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

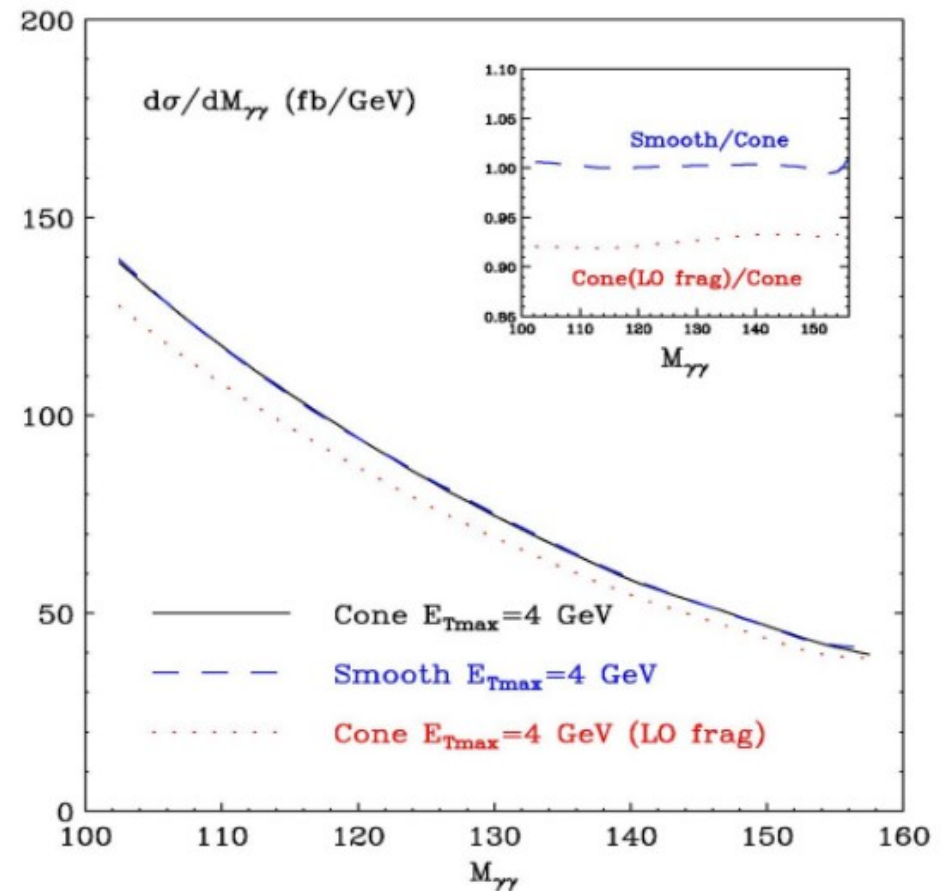
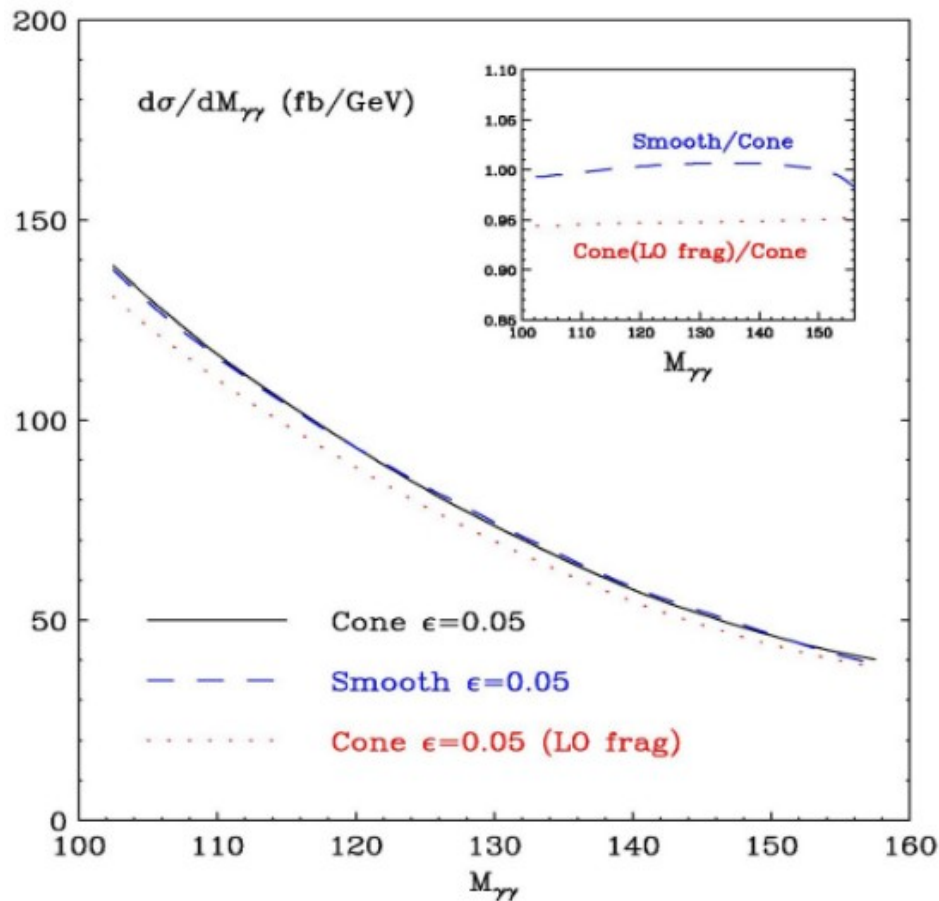
full NLO Cone (DIPHOX) vs Cone with LO fragmentation vs NLO Smooth

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

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



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



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

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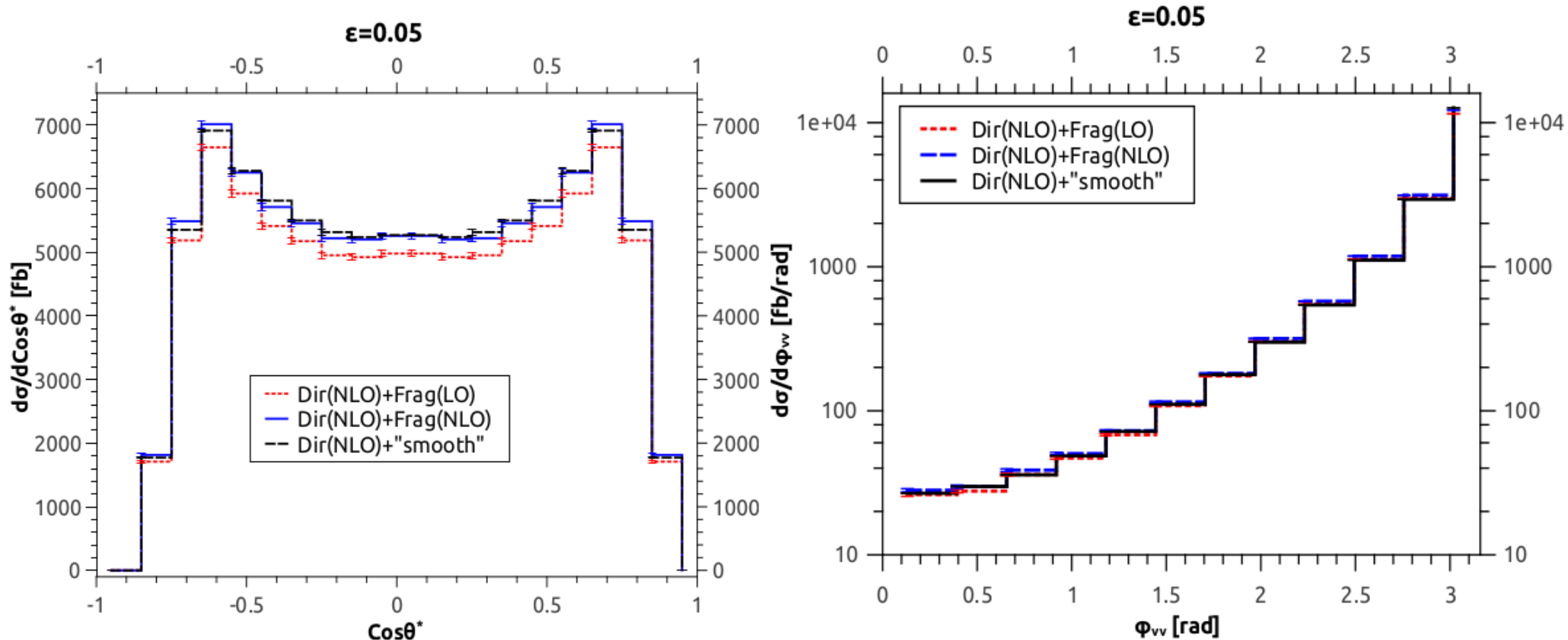
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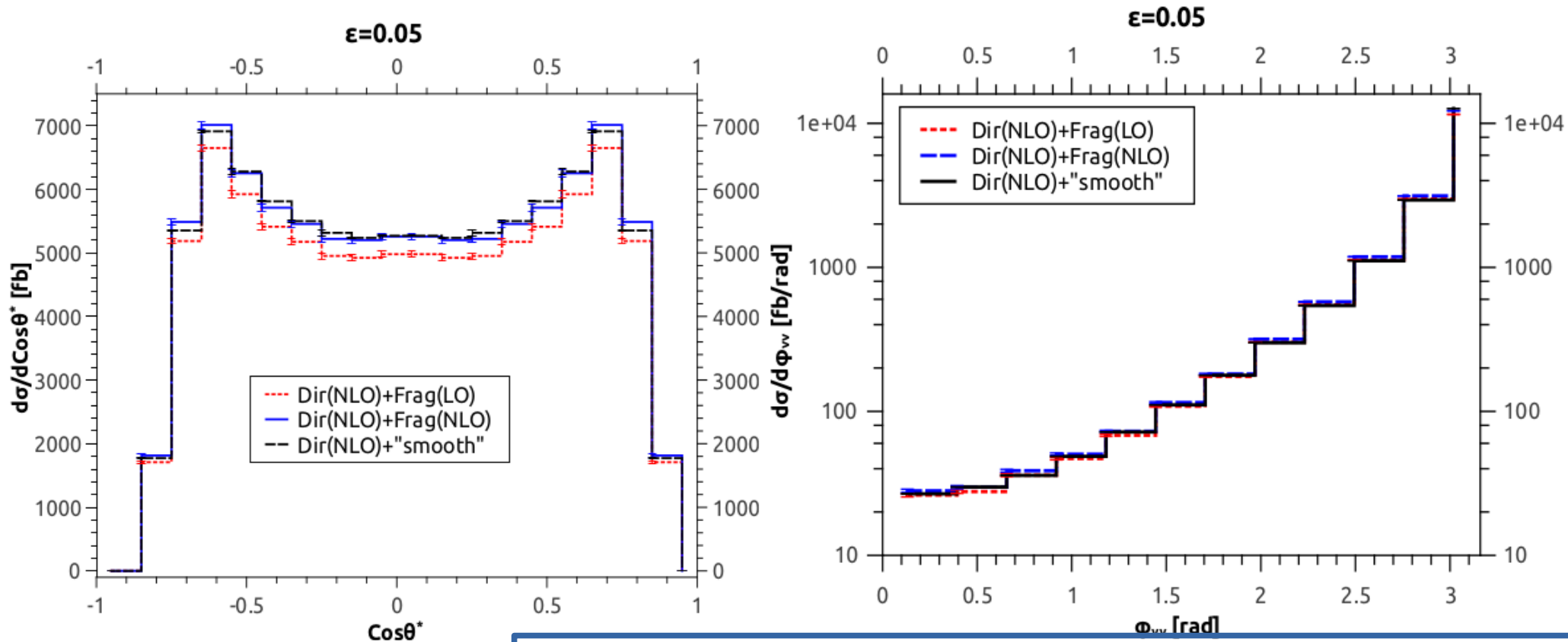
$$E_{T \text{ max}}^{\text{had}} = 4 \text{ GeV}$$



Same Features for all distributions

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

Cone + LO fragmentation component worse than 5%

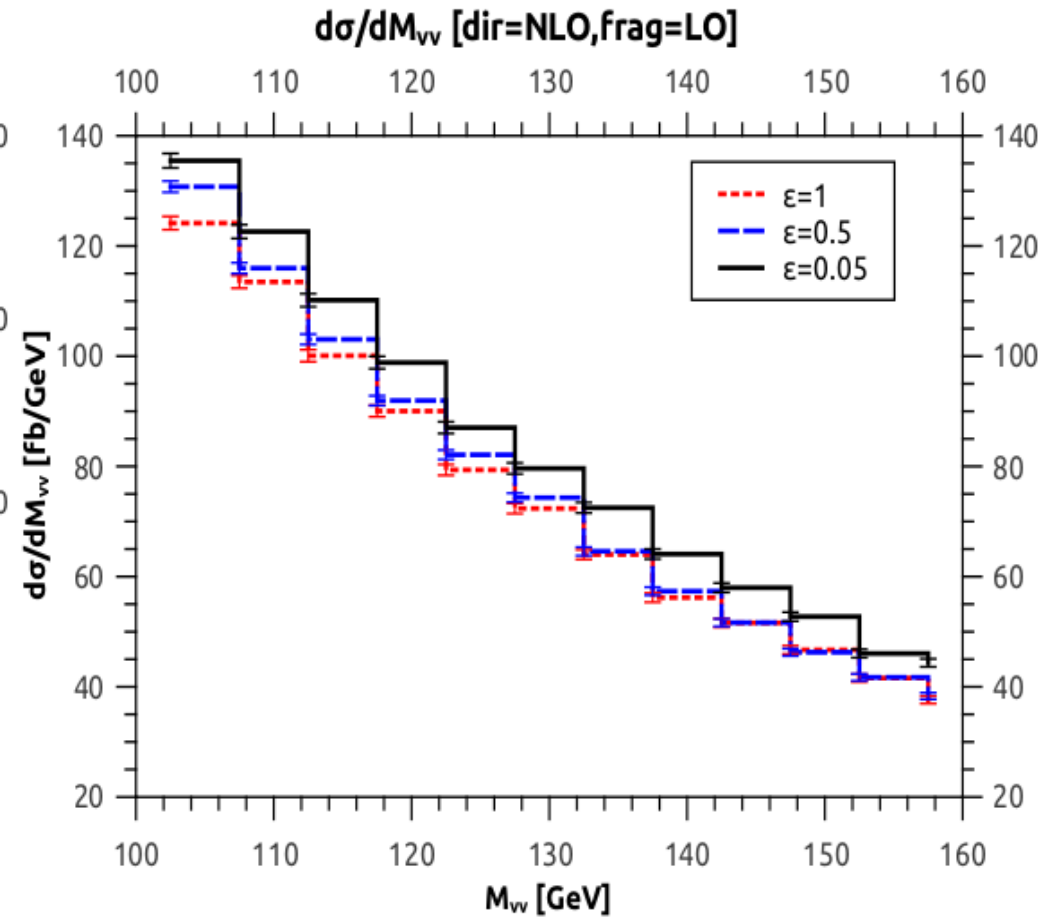
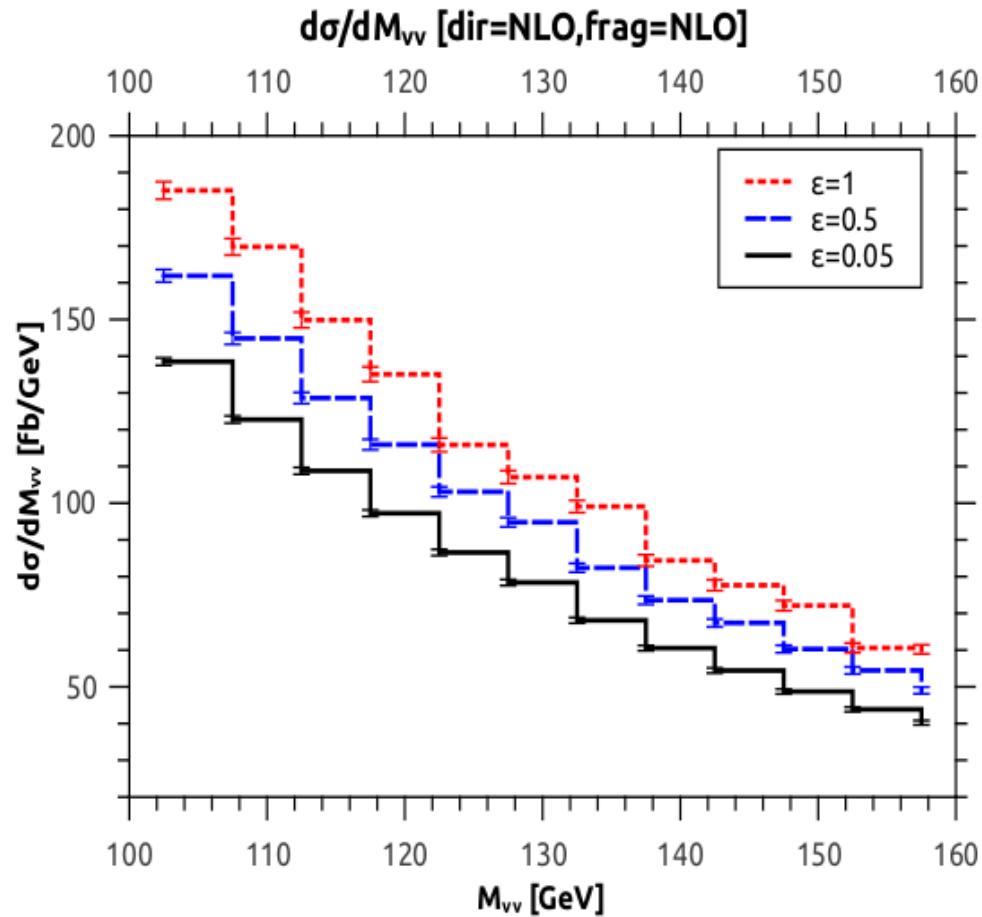


L.C , D. de Florian 2013

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

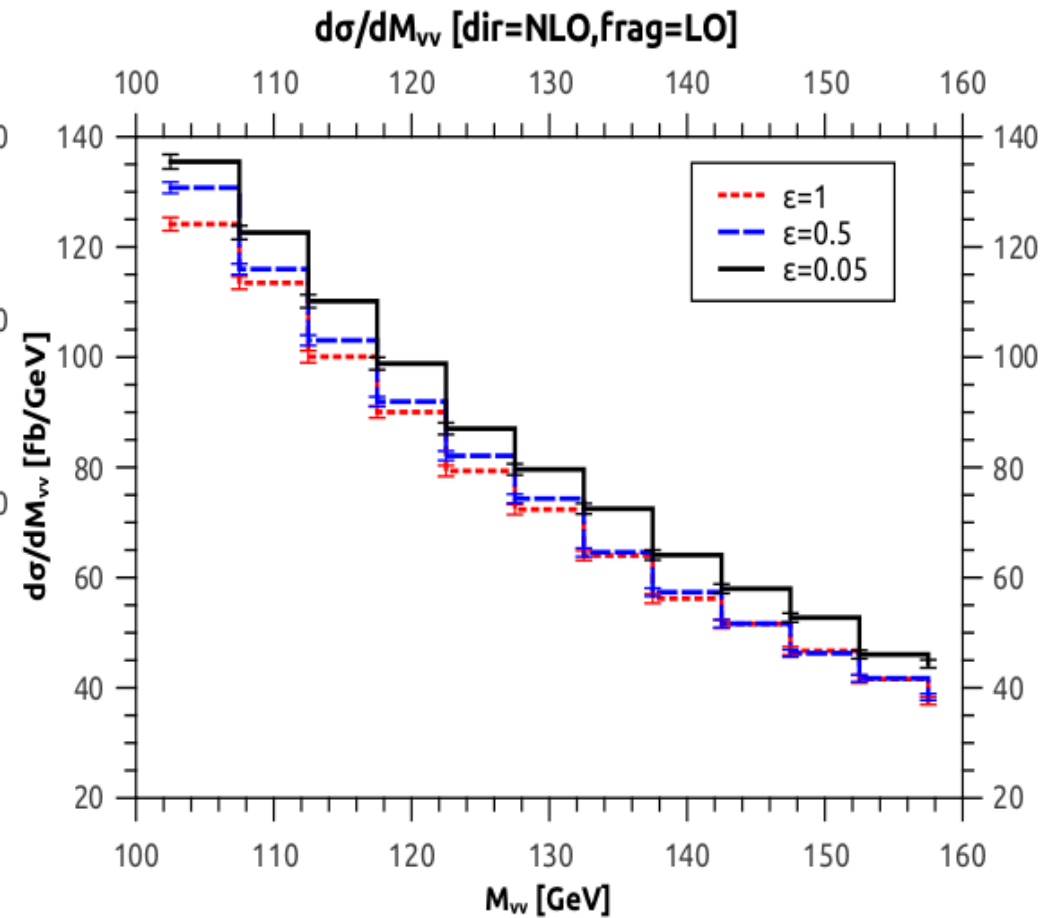
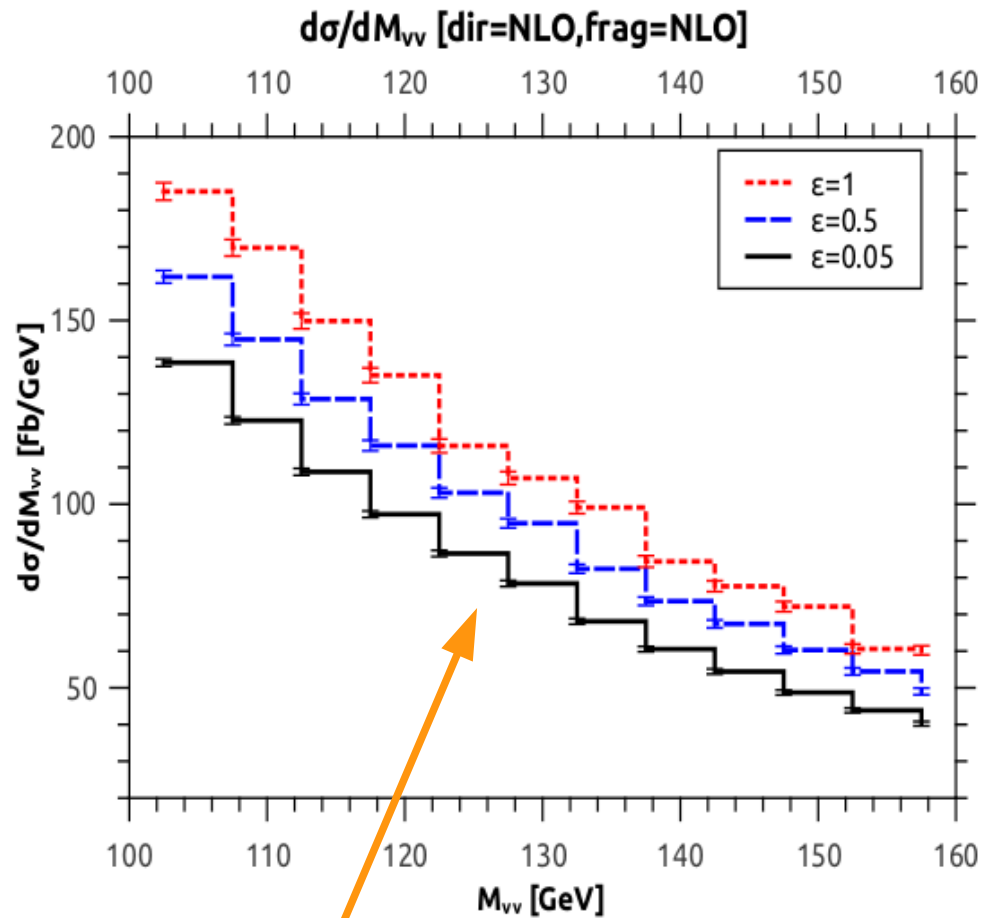
In some cases, using LO fragmentation component can make things look very strange...

Standard cone isolation $\rightarrow$ DIPHOX



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

Standard cone isolation $\rightarrow$ DIPHOX



Right behaviour!!

Les Houches accord 2013

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

“LH tight photon isolation accord”

- EXP: use (tight) Cone isolation solid and well understood
- TH: use smooth cone with same R and $E_{T\max}$ accurate, better than using cone with LO fragmentation
Estimate TH isolation uncertainties using different profiles in smooth cone

While the definition of “tight enough” might slightly depend on the particular observable (that can always be checked by a lowest order calculation), our analysis shows that at the LHC isolation parameters as $E_T^{max} \leq 5 \text{ GeV}$ (or $\epsilon < 0.1$), $R \sim 0.4$ and $R_{\gamma\gamma} \sim 0.4$ are safe enough to proceed.

This procedure would allow to extend available NLO calculations to one order higher (NNLO) for a number of observables, since the direct component is always much simpler to evaluate than the fragmentation part, which identically vanishes under the smooth cone isolation.

Les Houches accord 2013

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

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- TH: use smooth cone with same R and $E_{T\max}$ accurate, better than using cone with LO fragmentation
Estimate TH isolation uncertainties using different profiles in smooth cone

While the definition of “tight enough” might slightly depend on the particular observable (that can always be checked by a lowest order calculation), our analysis shows that at the LHC isolation parameters $E_T^{\max} \leq 5$ GeV (or $\epsilon < 0.1$), $R \sim 0.4$ and $R_{\gamma\gamma} \sim 0.4$ are safe enough to proceed.

This procedure would allow to extend available NLO calculations to one order higher (NNLO) for a number of observables, since the direct component is always much simpler to evaluate than the fragmentation part, which identically vanishes under the smooth cone isolation.

Les Houches accord 2013

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

“LH tight photon isolation accord”

- EXP: use (tight) Cone isolation solid and well understood
- TH: use smooth cone with same R and $E_{T\max}$ accurate, better than using cone with LO fragmentation
Estimate TH isolation uncertainties using different profiles in smooth cone

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:

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

$\gamma\gamma + 2\text{Jets}$ [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)

$\gamma\gamma + (\text{up to}) 3\text{Jets}$ [NLO] S. Badger, A. Guffanti, V. Yundin (2013)

Les Houches accord 2013



Generalization to other processes containing
photons in the final state



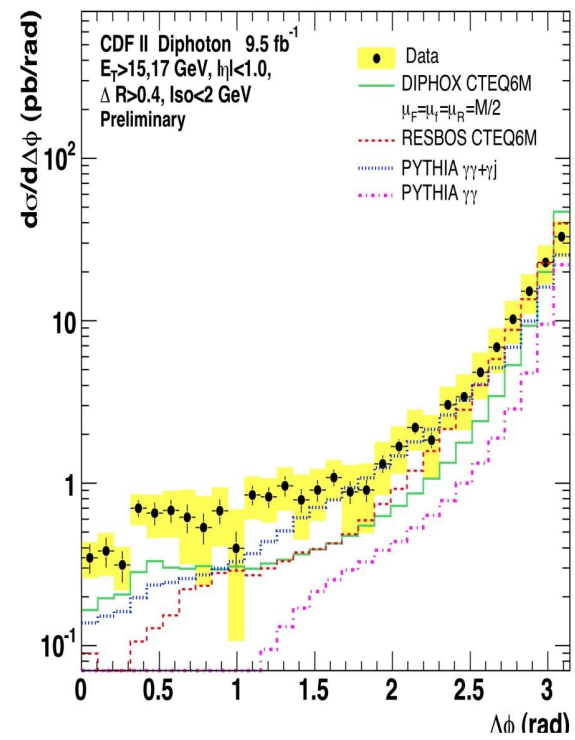
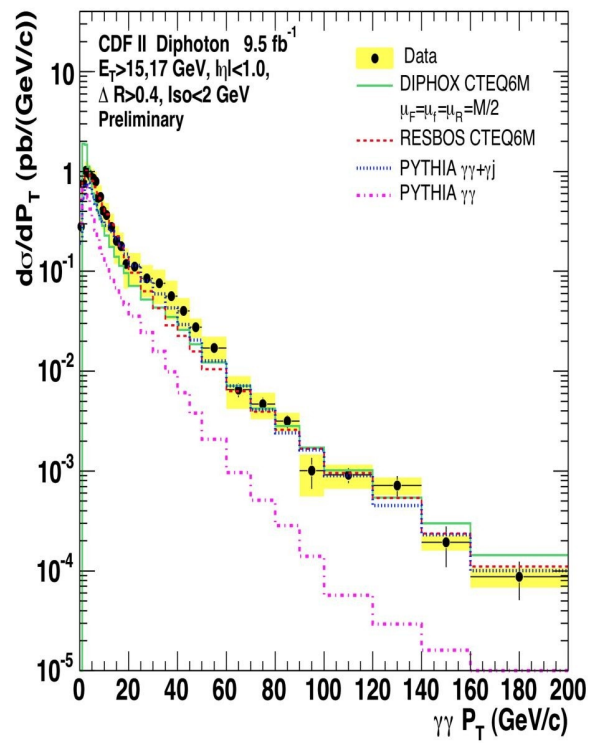
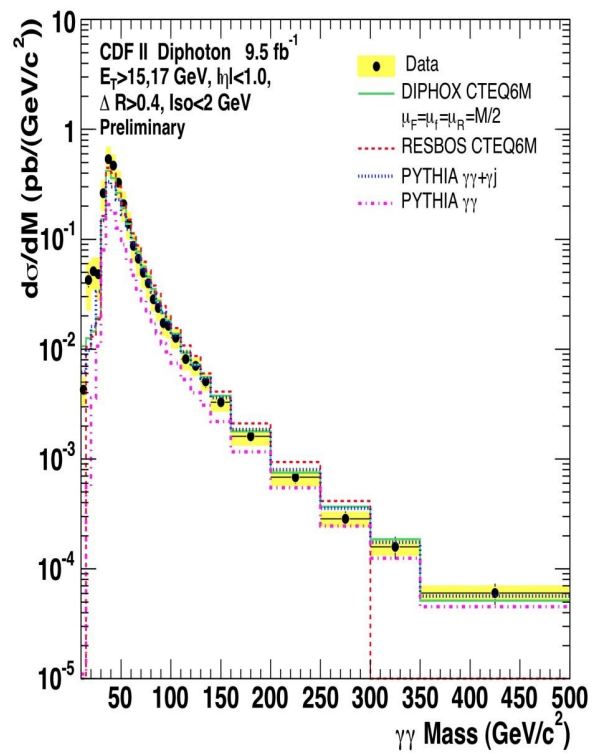
Les Houches accord 2015

What we saw:

-  ***Photon production mechanisms***
-  ***How could appear the discrepancies related to the isolation prescription***
-  ***A set of isolation parameters in order to proceed safely to the comparison T/D***

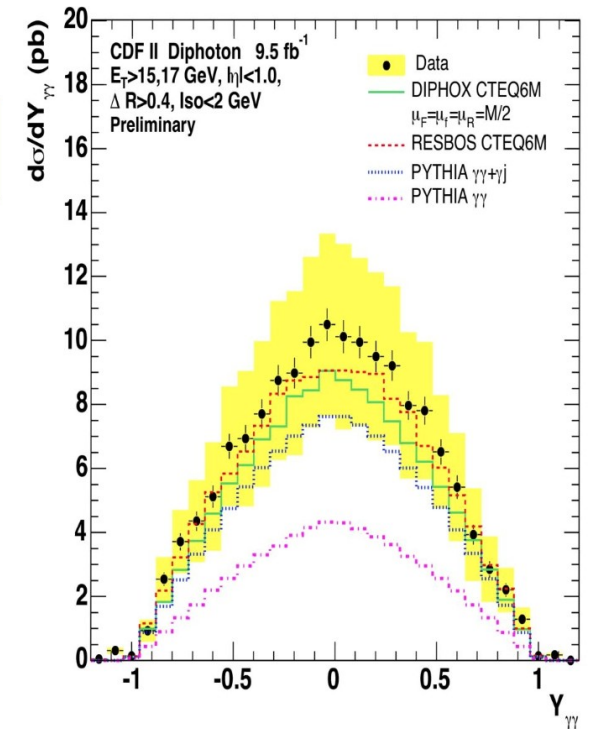
Results and comparison with data

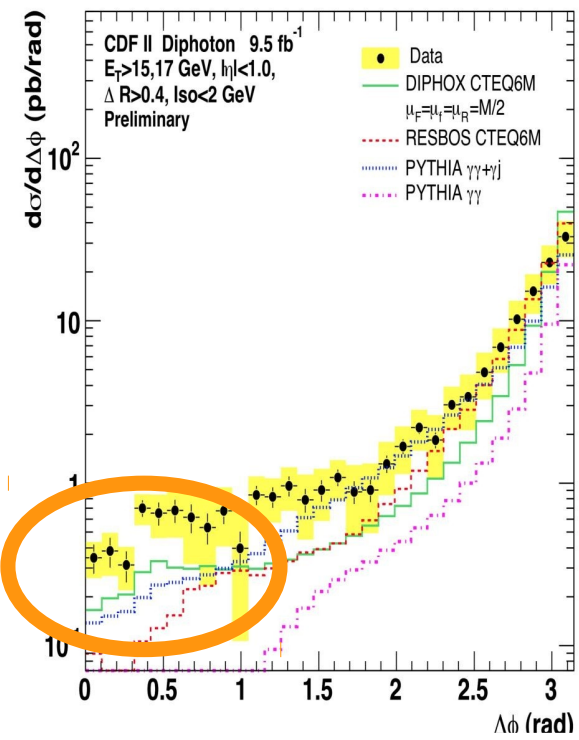
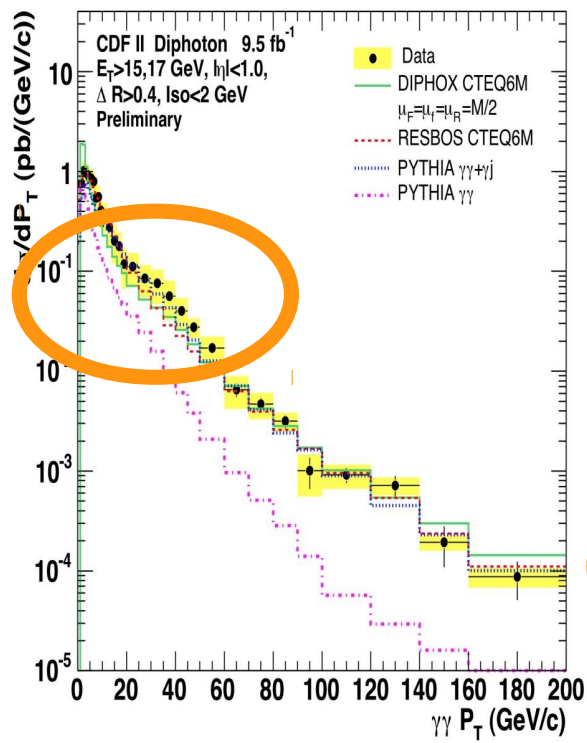
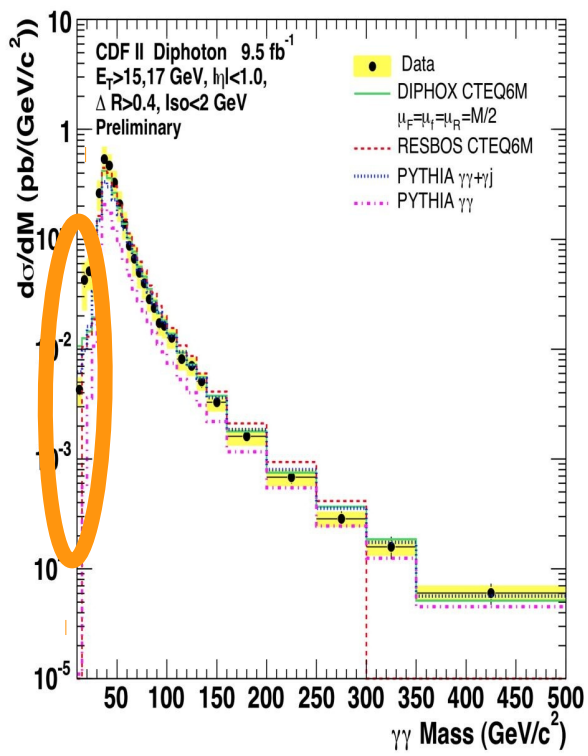
First part: Discrepancies due to missing H.O correction terms



Differential cross sections: CDF

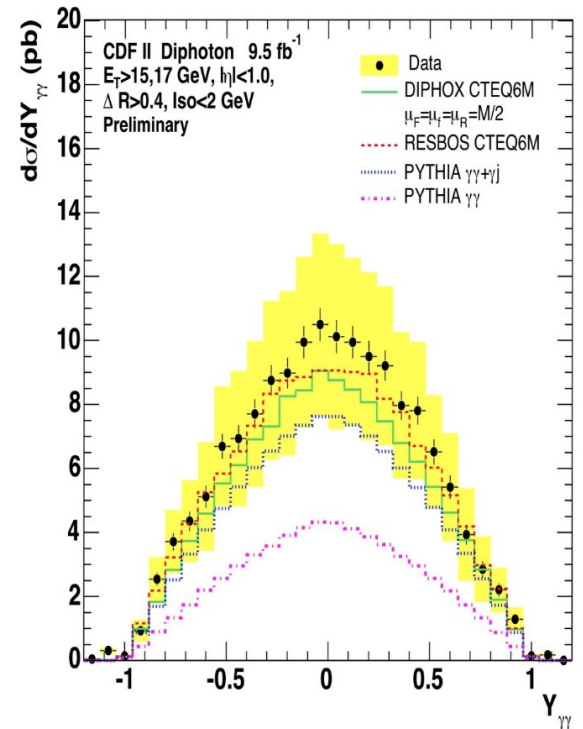
Phys.Rev. D84 (2011) 052006





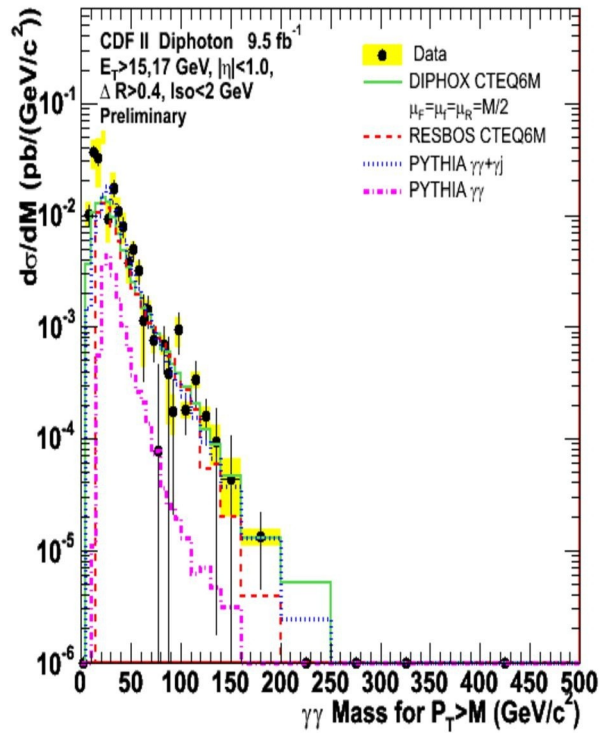
Differential cross sections: CDF

Phys.Rev. D84 (2011) 052006



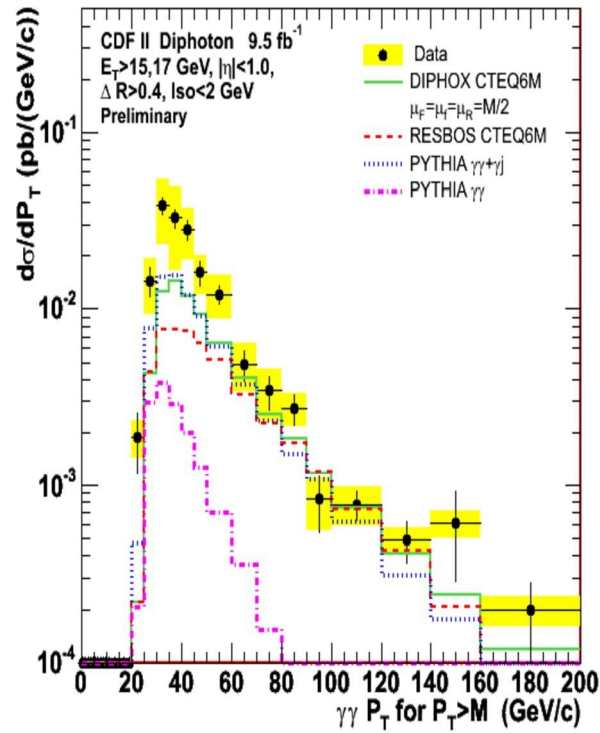
Differential cross sections for $P_T(\gamma\gamma) > M_{\gamma\gamma}$: CDF

Phys.Rev. D84 (2011) 052006

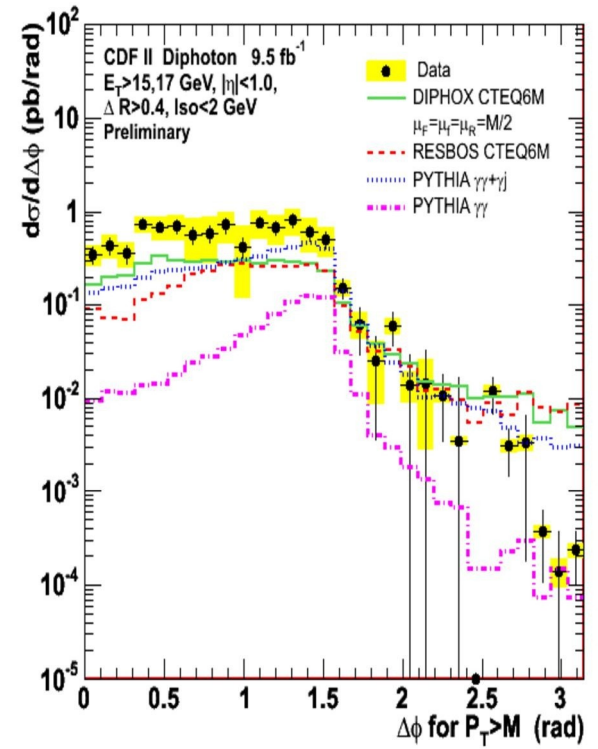


- Low statistics
- Excess of data over theory for $M_{\gamma\gamma} < 30$ GeV/c²

Costas Vellidis, Paris
 Photon workshop (2012)



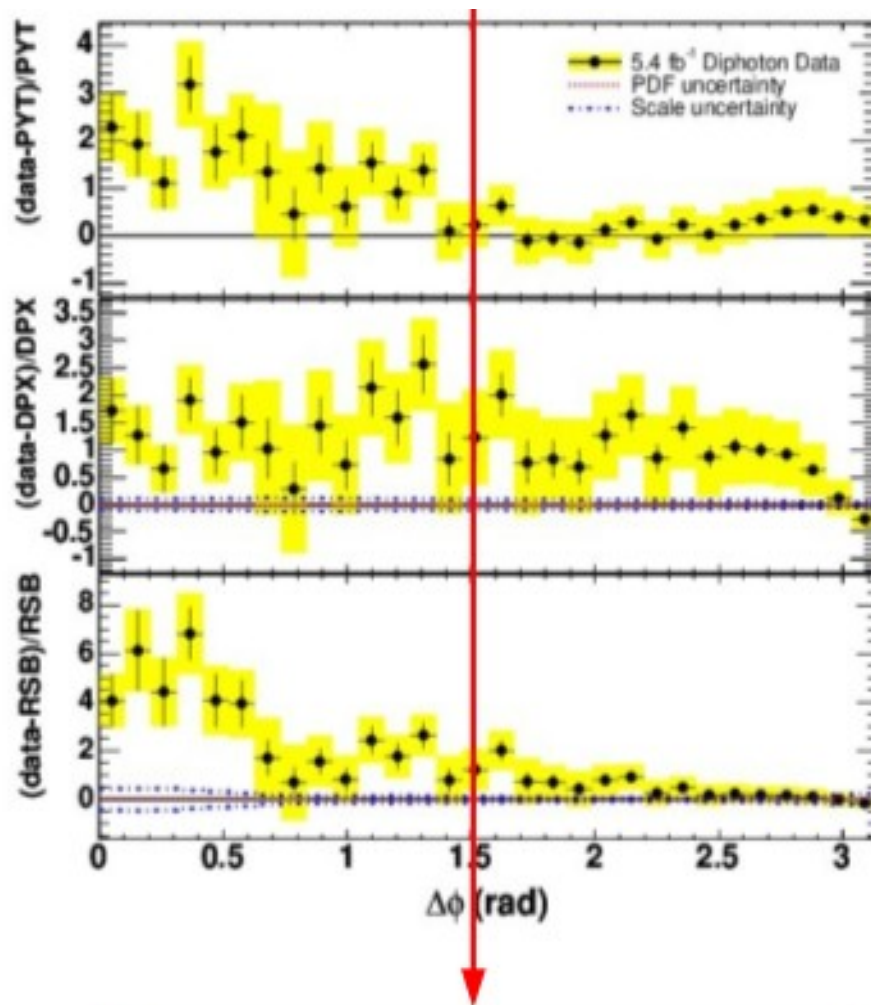
- Low statistics
- No events below $P_T(\gamma\gamma) = 20$ GeV/c
- Excess of data over theory for $P_T(\gamma\gamma) = 20 - 50$ GeV/c (the "Guillet shoulder")



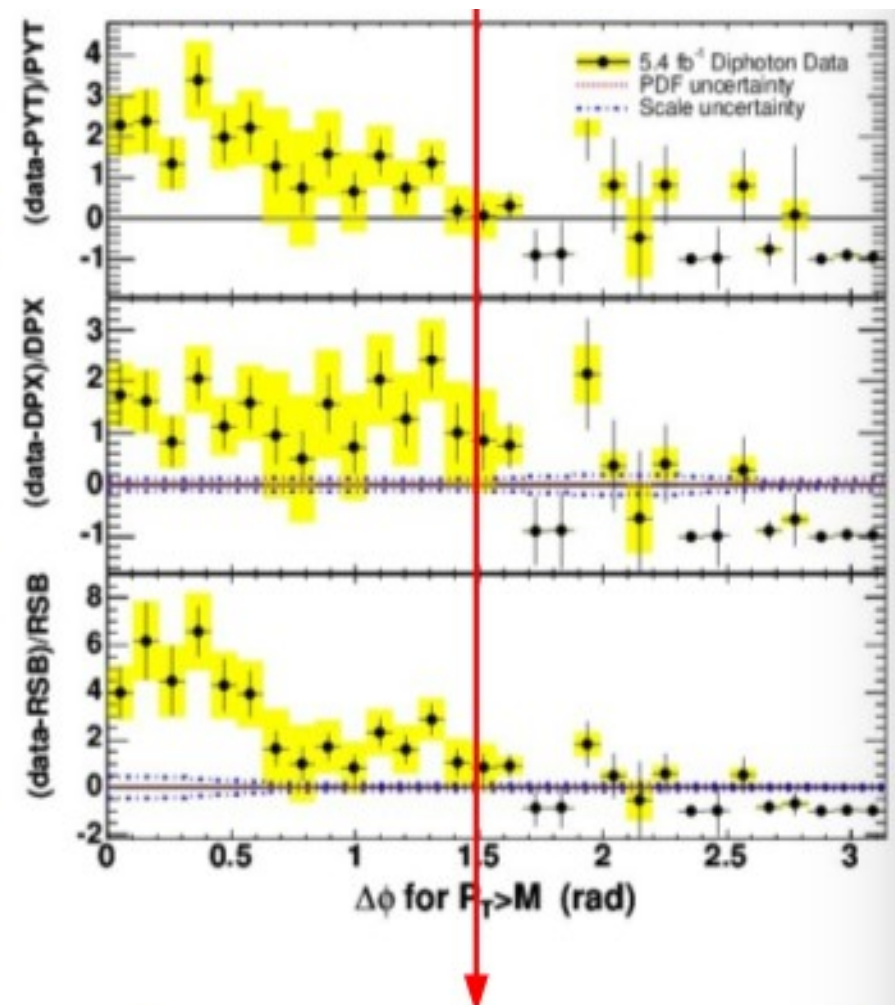
- Low statistics
- Data spectrum harder than predicted for $\Delta\phi < 1.5$ rad
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma} > 1.5$ rad

$P_T(\gamma\gamma) > M_{\gamma\gamma} \rightarrow$ Kills born-like contributions

$P_t(\gamma\gamma) > M_{\gamma\gamma} \rightarrow$ Kills born-like contributions

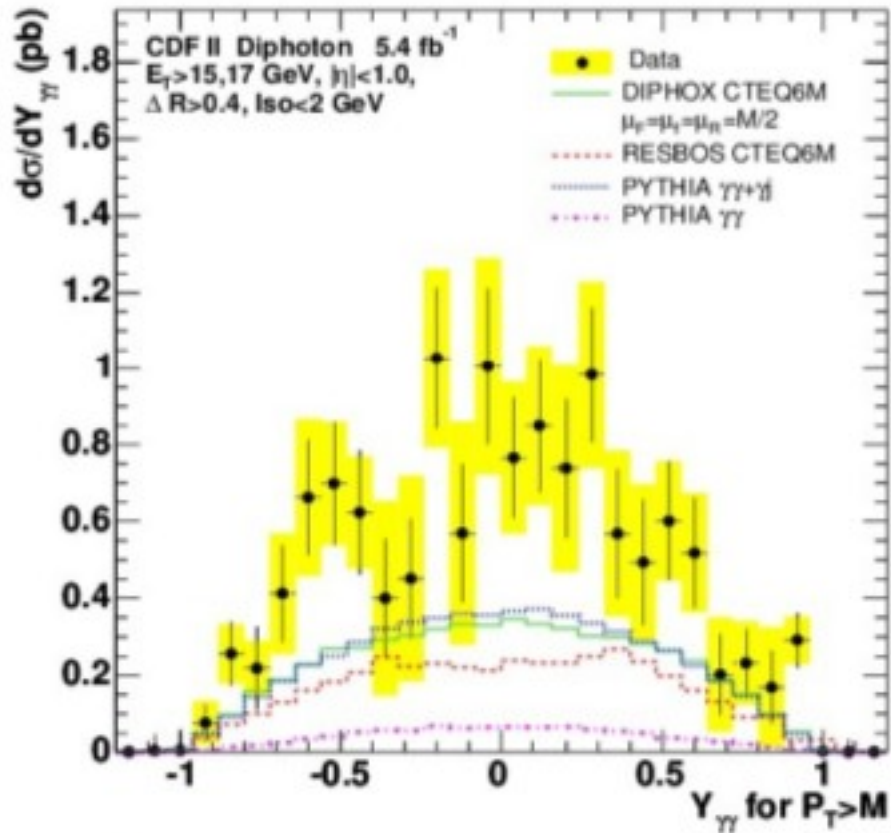


Full Xsection (NLO)

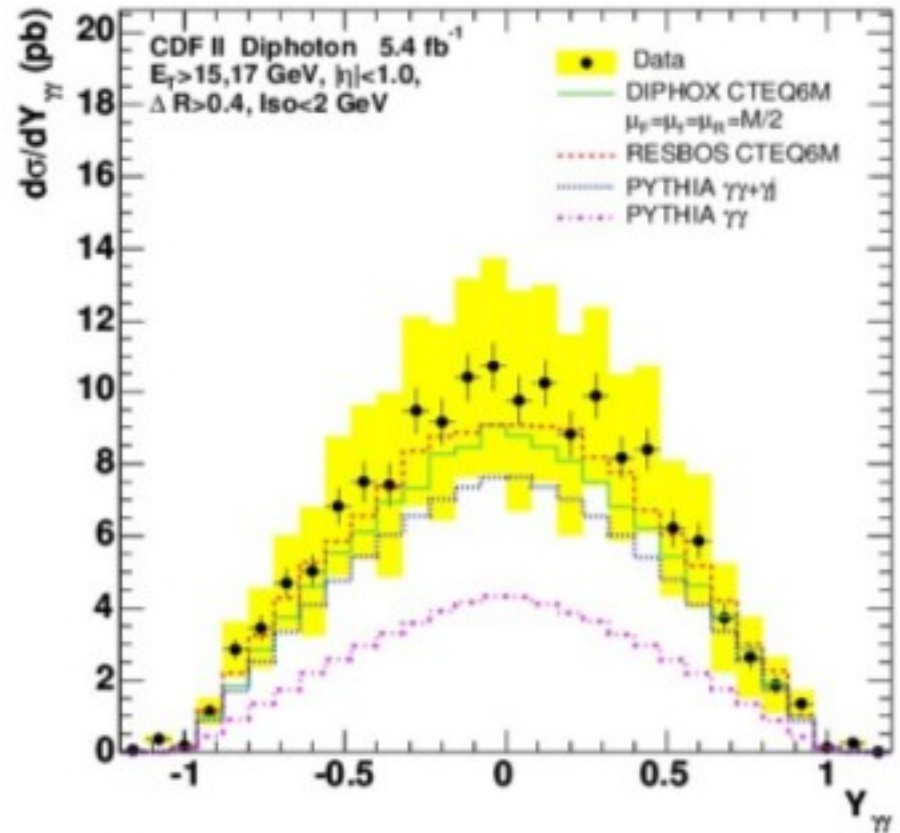


Only real corrections (NLO)

$P_t(\gamma\gamma) > M_{\gamma\gamma} \rightarrow$ Kills born-like contributions



Only real corrections (NLO)

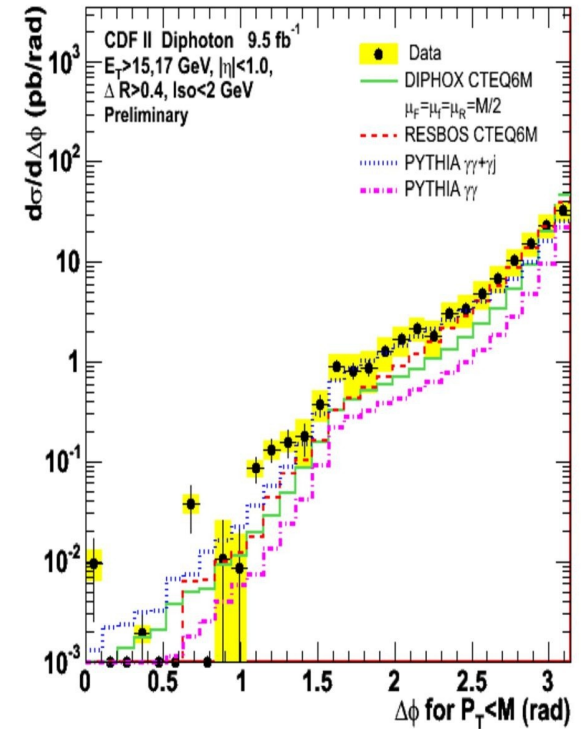
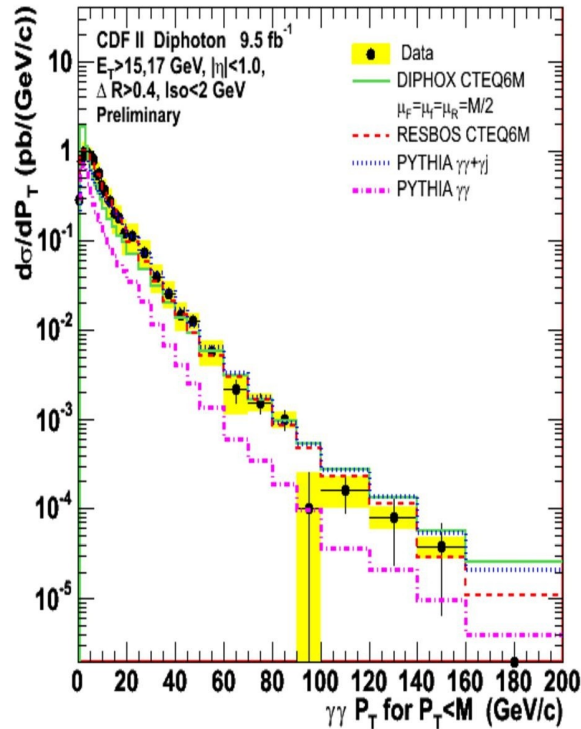
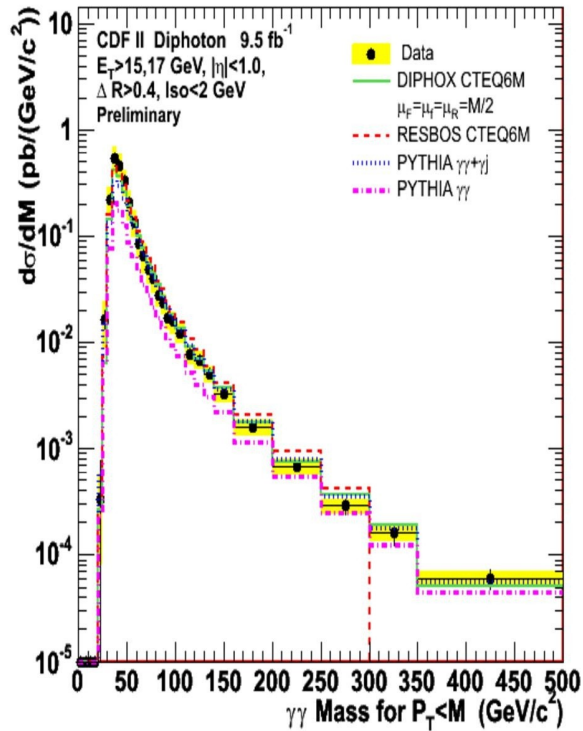


Full Xsection (NLO)

$P_t(\gamma\gamma) > M_{\gamma\gamma} \rightarrow \text{NLO} \sim \text{"LO"}$

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

Phys.Rev. D84 (2011) 052006



- Good agreement between data and theory
- No events for $M_{\gamma\gamma} < 30$ GeV/c²

Costas Vellidis, Paris
Photon workshop (2012)

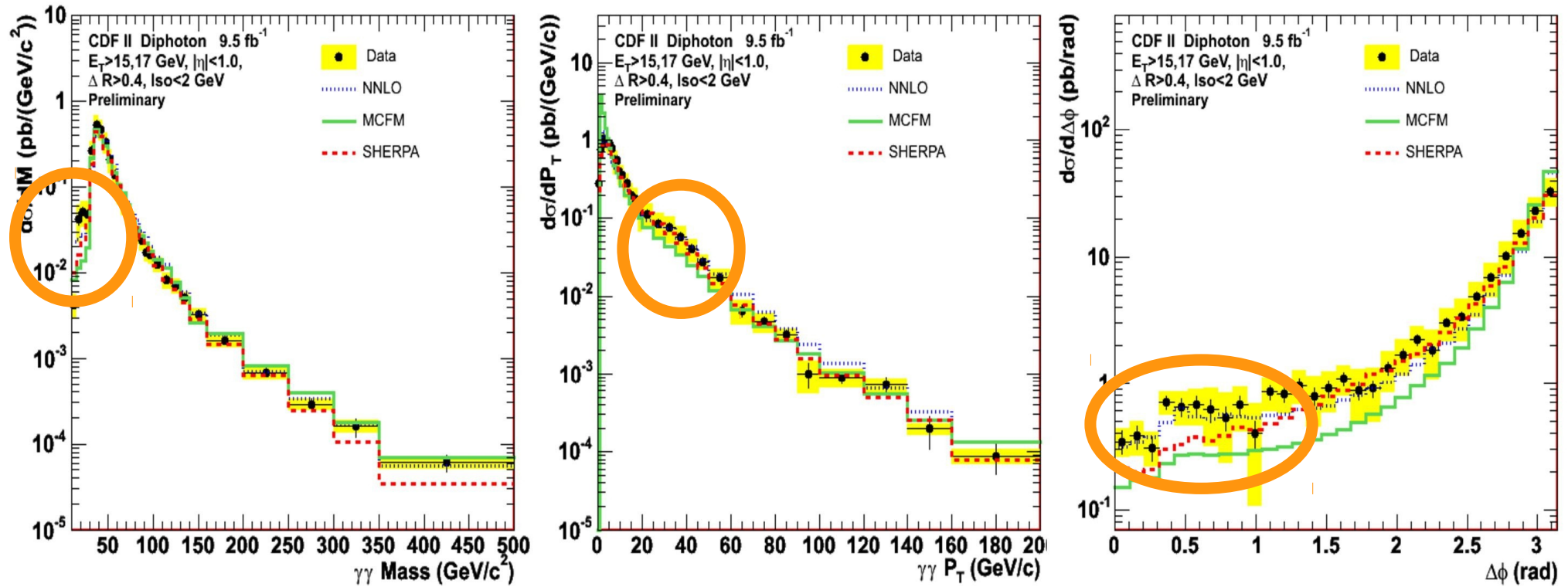
- Good agreement between data and theory
- No excess of data over theory for $P_T(\gamma\gamma) = 20 - 50$ GeV/c (the “Guillet shoulder”)

- Good agreement between data and theory
- Spectrum suppressed for $\Delta\phi_{\gamma\gamma} < 1.5$ rad

$P_T(\gamma\gamma) < M_{\gamma\gamma} \rightarrow$ Kills real radiation
“Only survive” the born-like contributions

Differential cross sections

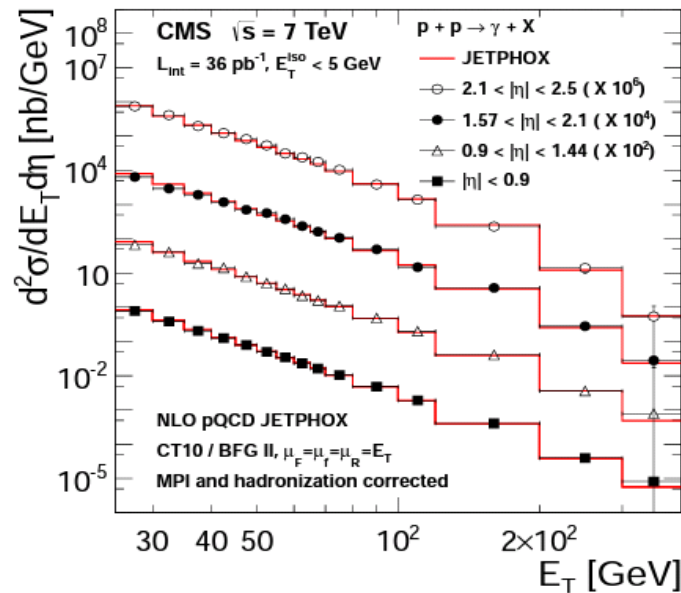
Phys.Rev.Lett. 110 (2013) 10, 101801



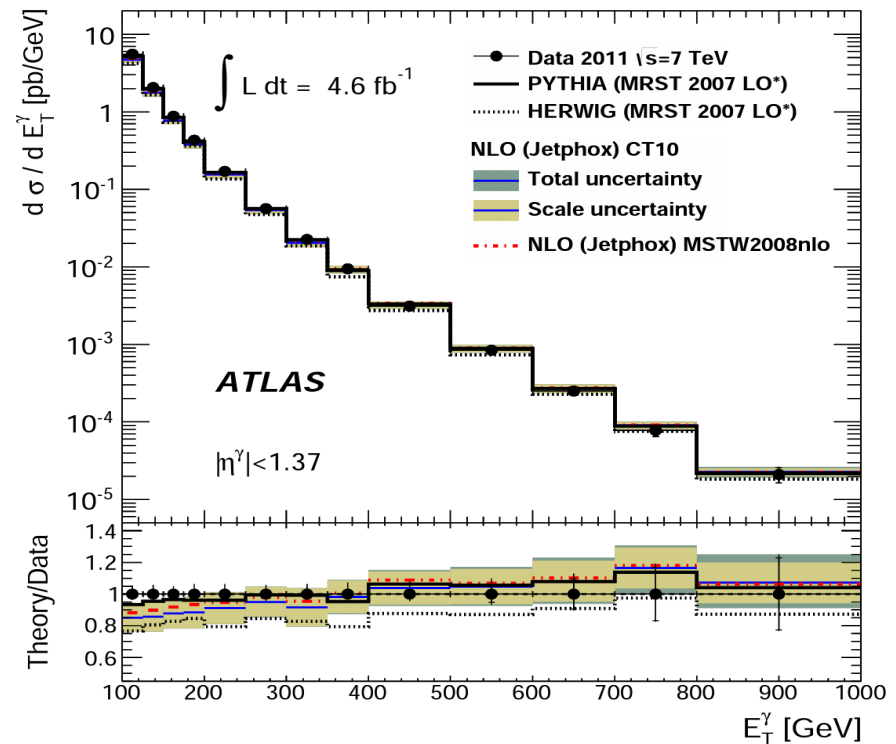
Good agreement between the NNLO distributions and the data

Results and comparison with data (LHC)

$\gamma + jet \rightarrow$ *ATLAS and CMS*



Results in good agreement with data



Phys.Rev. D89 (2014) 052004

At low ET the data tends to be higher than the NLO predictions

At low ET the predictions tend to be higher than the measured cross section

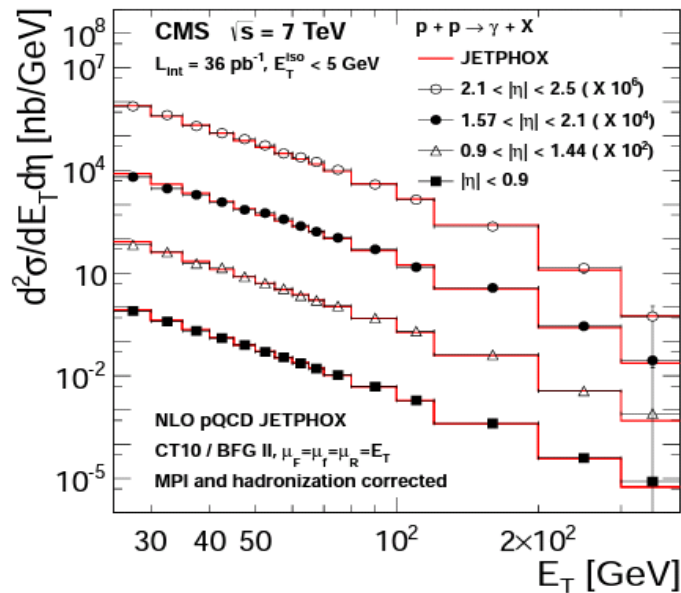
In some kinematic regimes the Xsection is sensible at PDFs variations

The Xsection has the potential to provide additional constraints on the proton PDFs

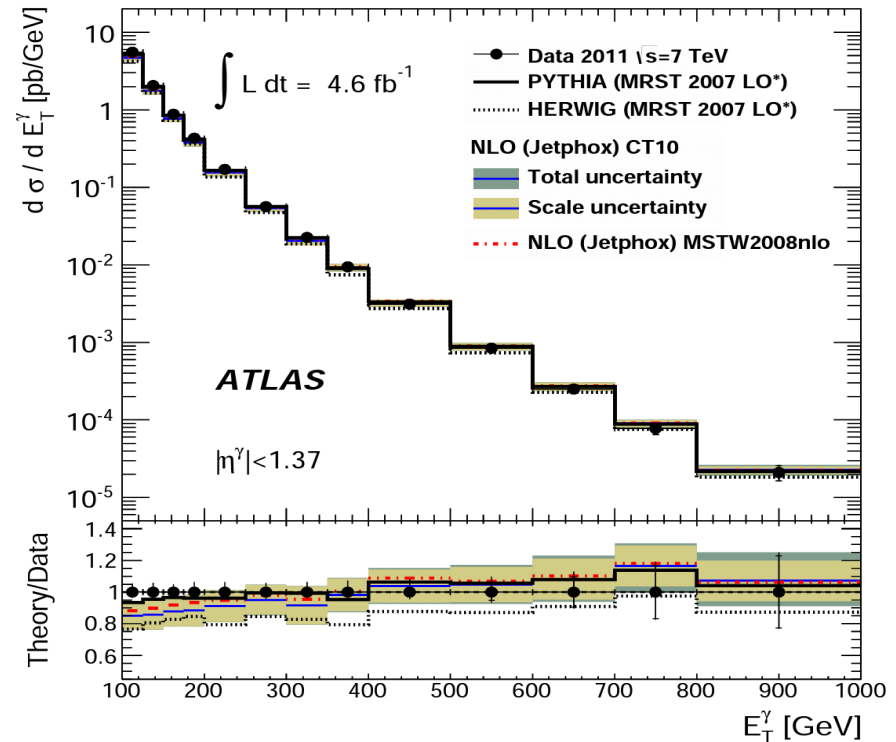
Phys.Rev. D84 (2011) 052011

Phys.Rev.Lett. 106 (2011)
 082001

$\gamma + jet \rightarrow$ ATLAS and CMS



Results in good agreement with data



Phys.Rev. D89 (2014) 052004

At low E_T the data tends to be higher than the NLO predictions

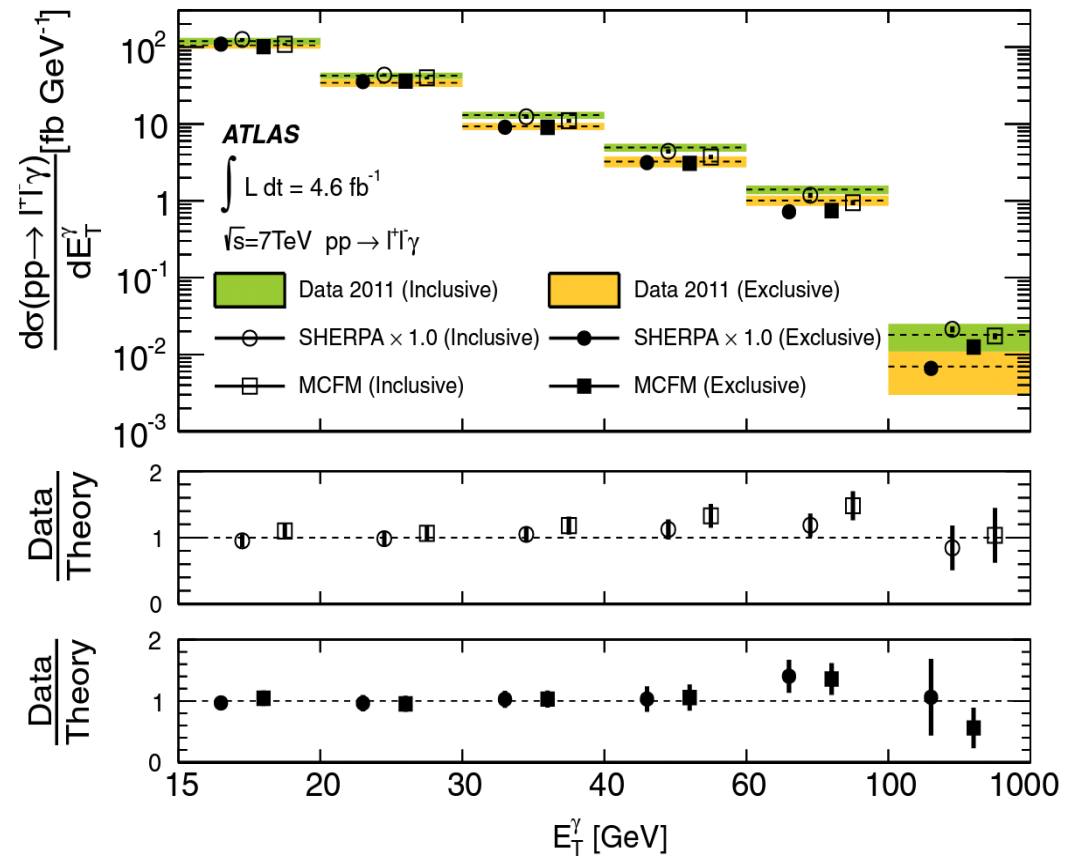
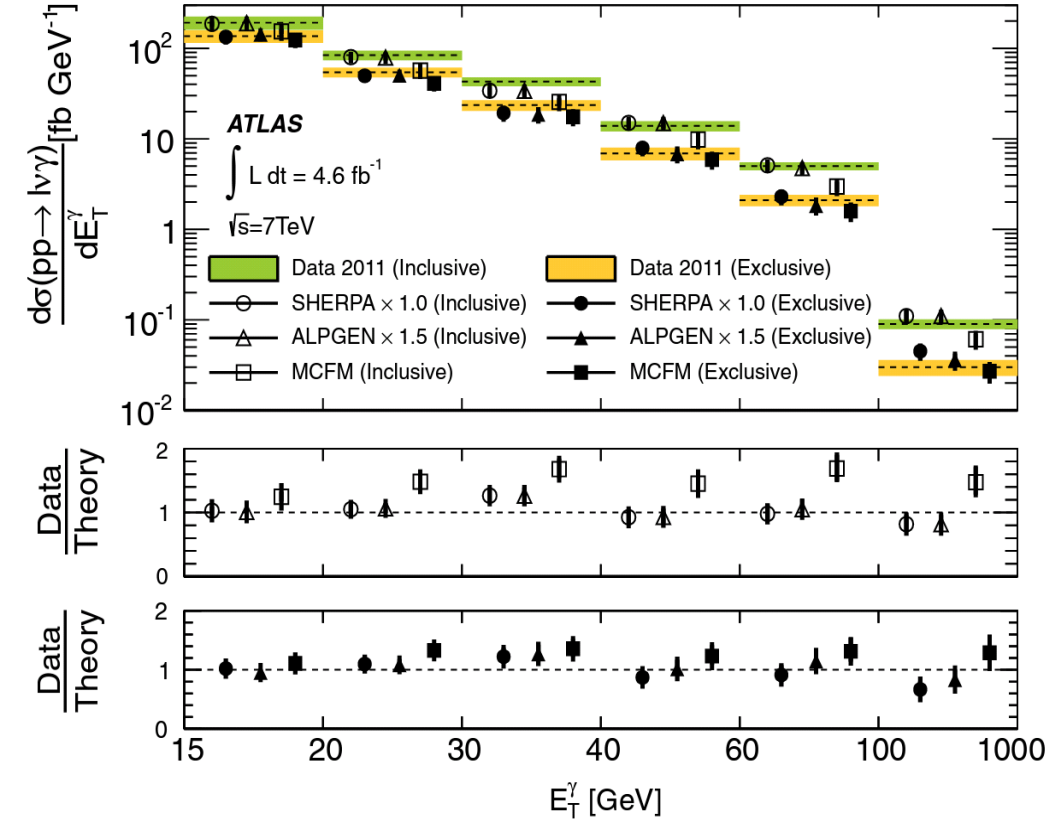
At low E_T the predictions tend to be higher than the measured cross section

In some kinematic regimes the Xsection is sensible at PDFs variations

The Xsection has the potential to provide additional constraints on the proton PDFs

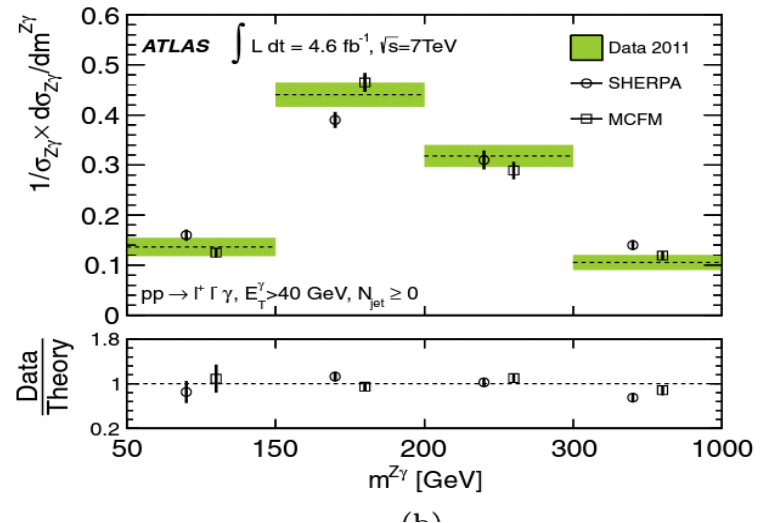
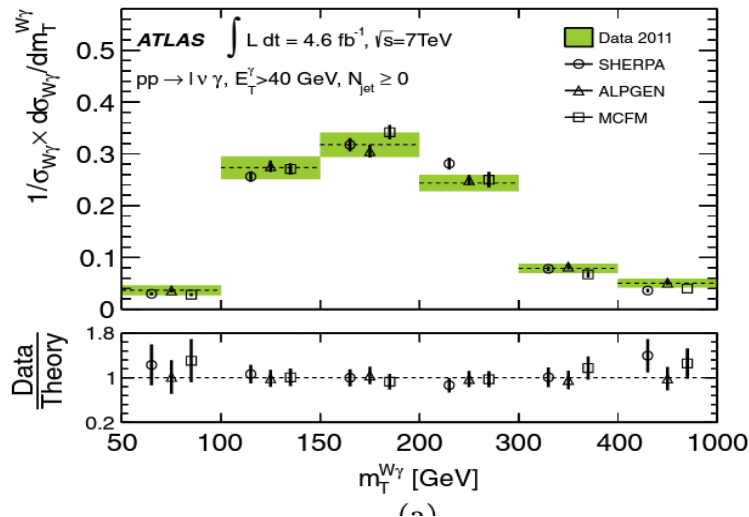
ATLAS and CMS use different values for E_{Tmax}
 $E_{Tmax}(\text{ATLAS}) > E_{Tmax}(\text{CMS})$

$V\gamma$ production

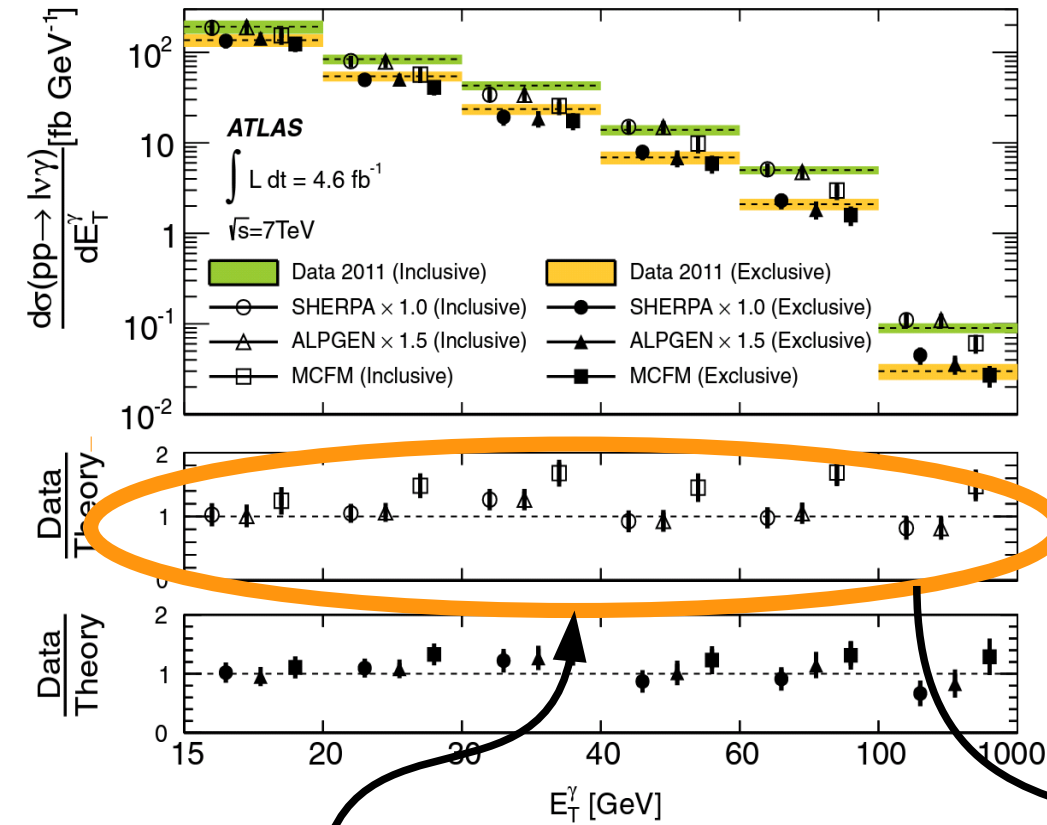


Phys.Rev. D87 (2013) 112003

**Results in
good
agreement
with data**

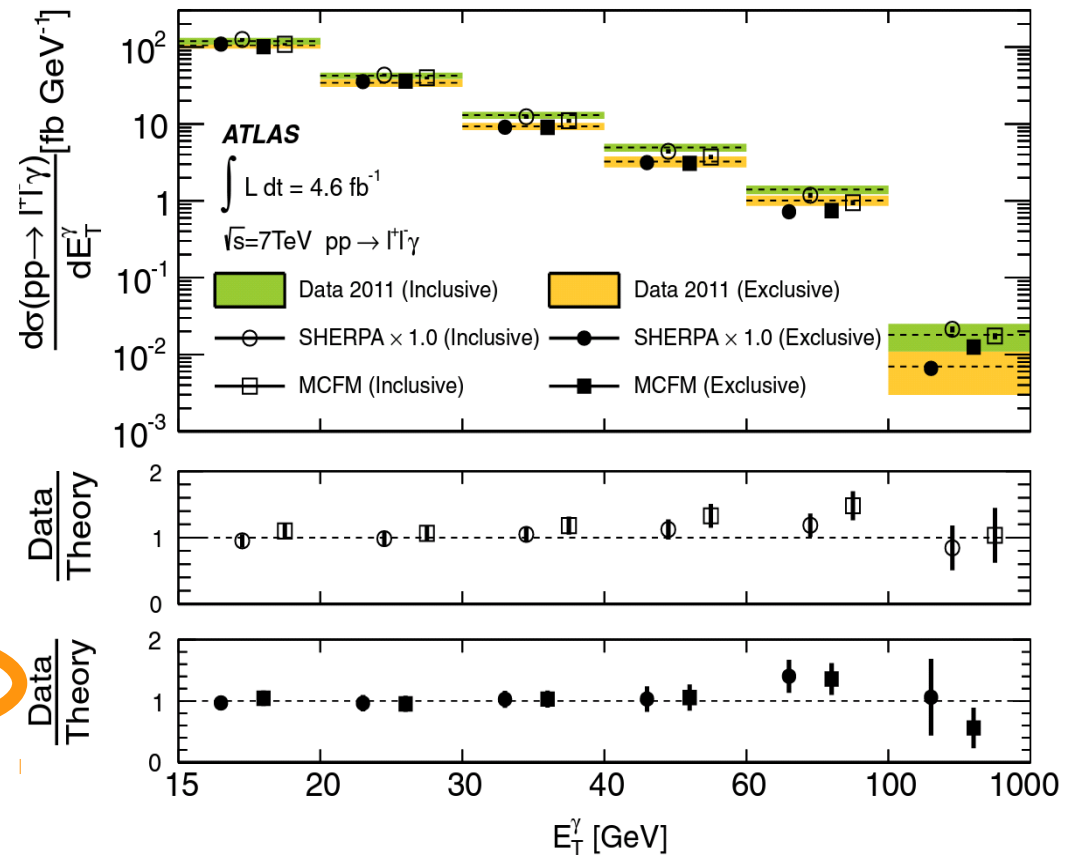


$V\gamma$ production



NLO predictions do not include multiple q/g emissions

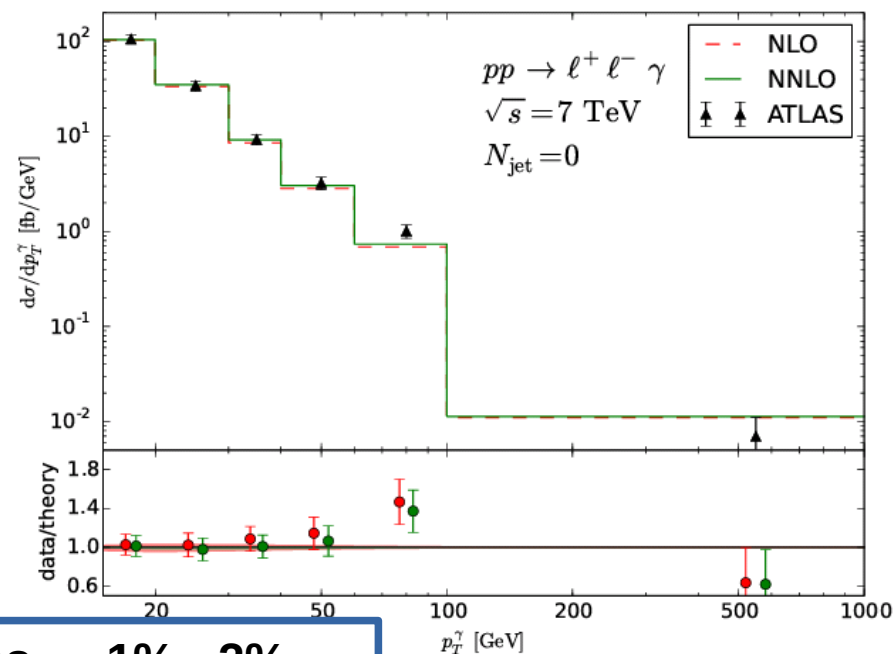
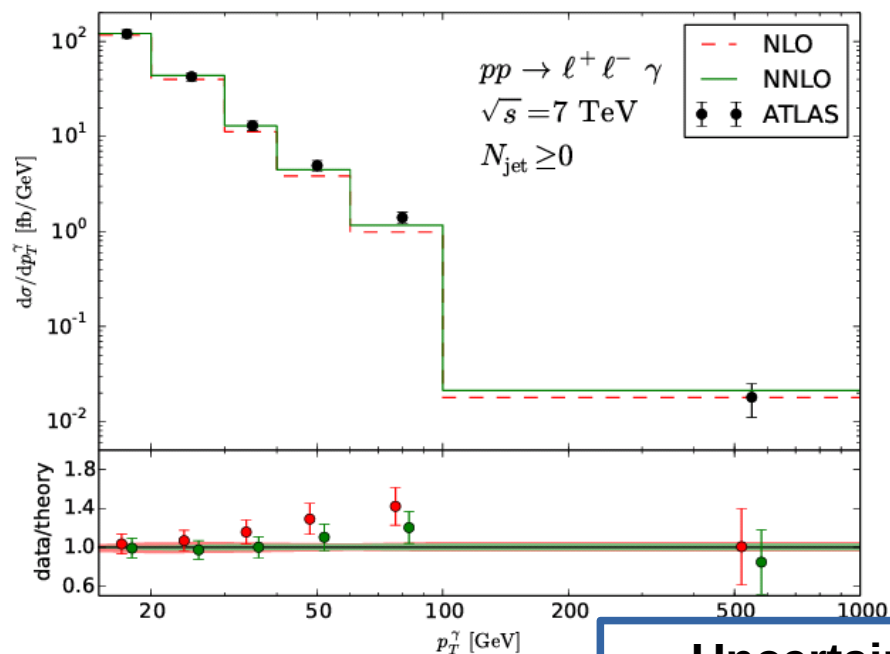
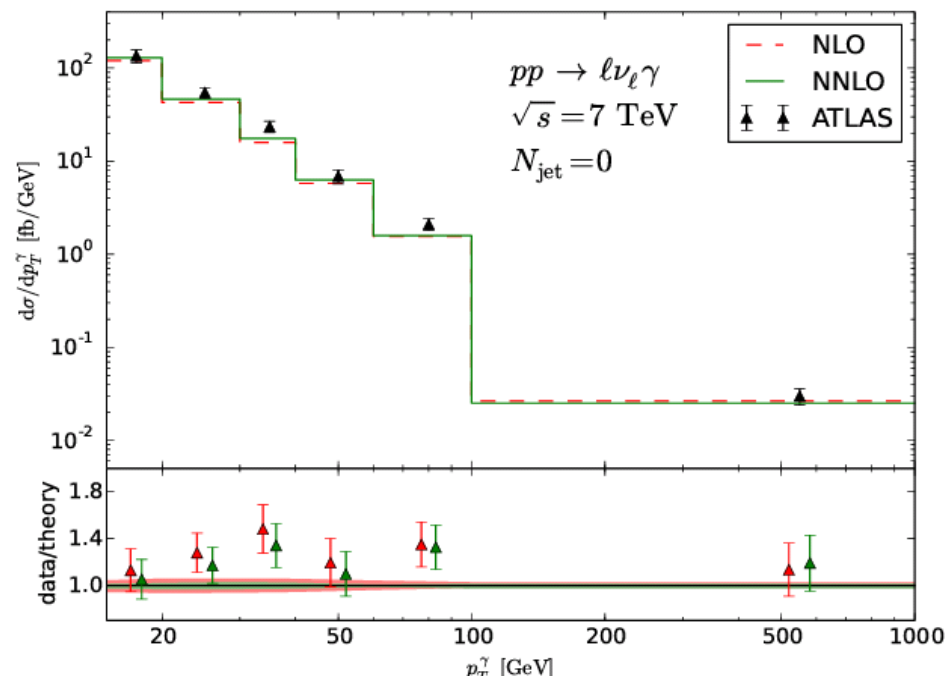
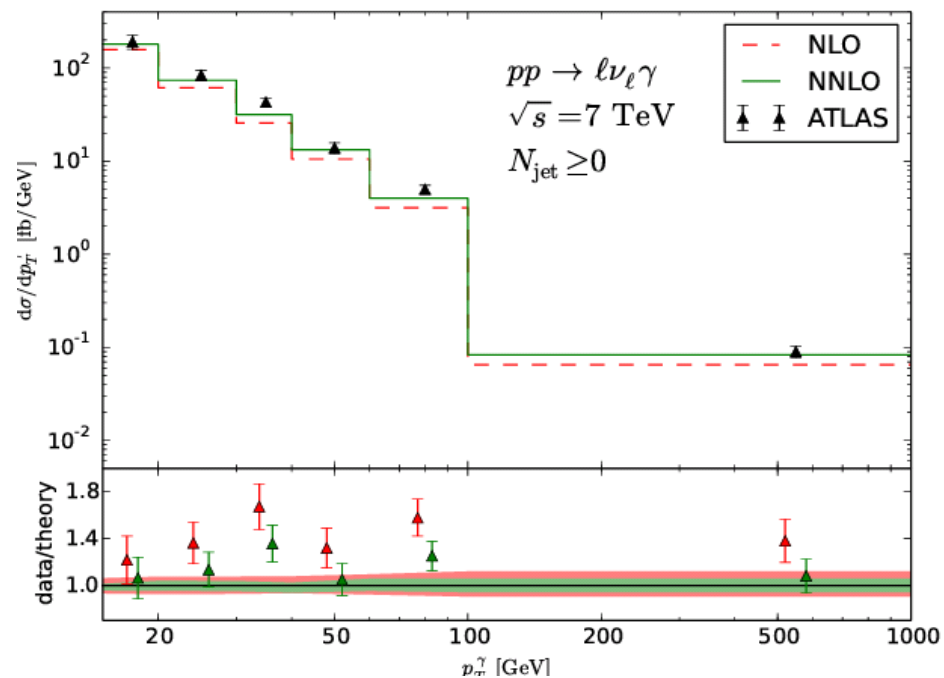
This constitutes a motivation to go at NNLO in which we have up to 2-jets in the final state



Phys.Rev. D87 (2013) 112003

$V\gamma$ production NNLO

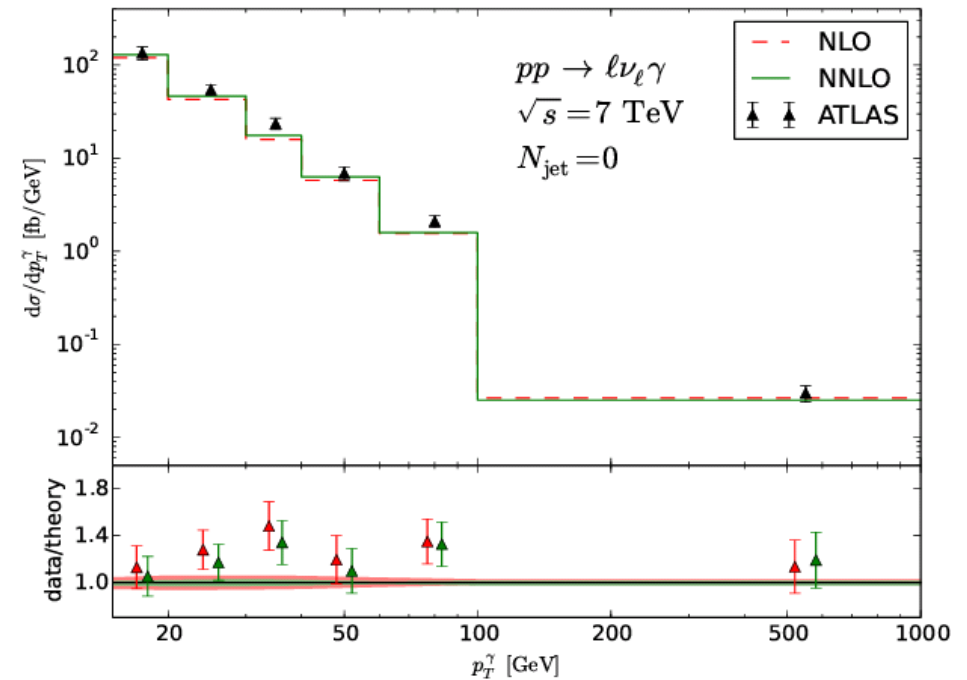
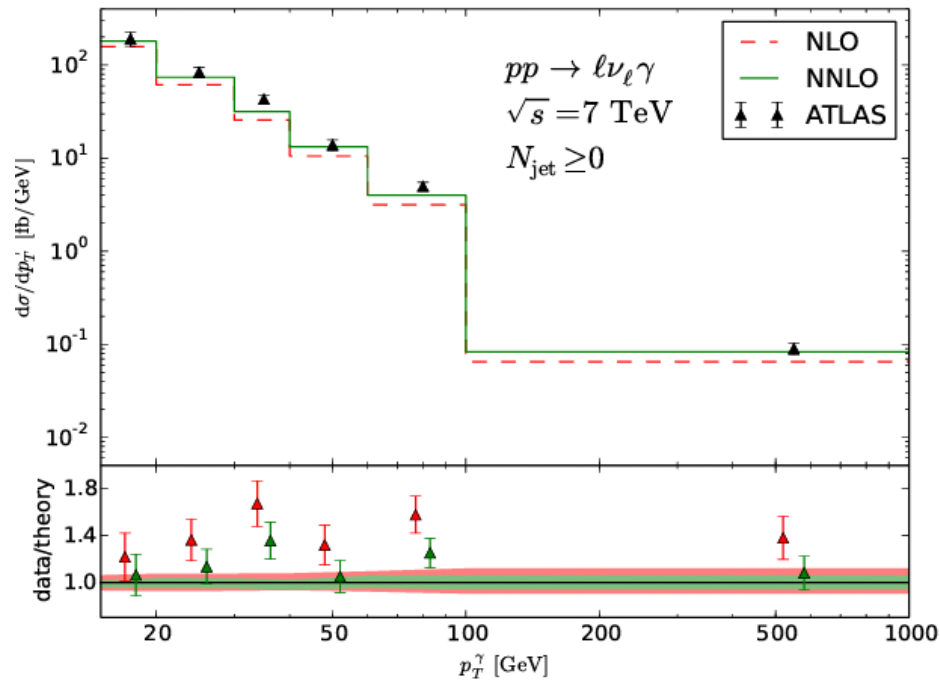
Grazzini, Kallweit, Rathlev, Torre



Uncertainties → 1% - 2%

$V\gamma$ production NNLO

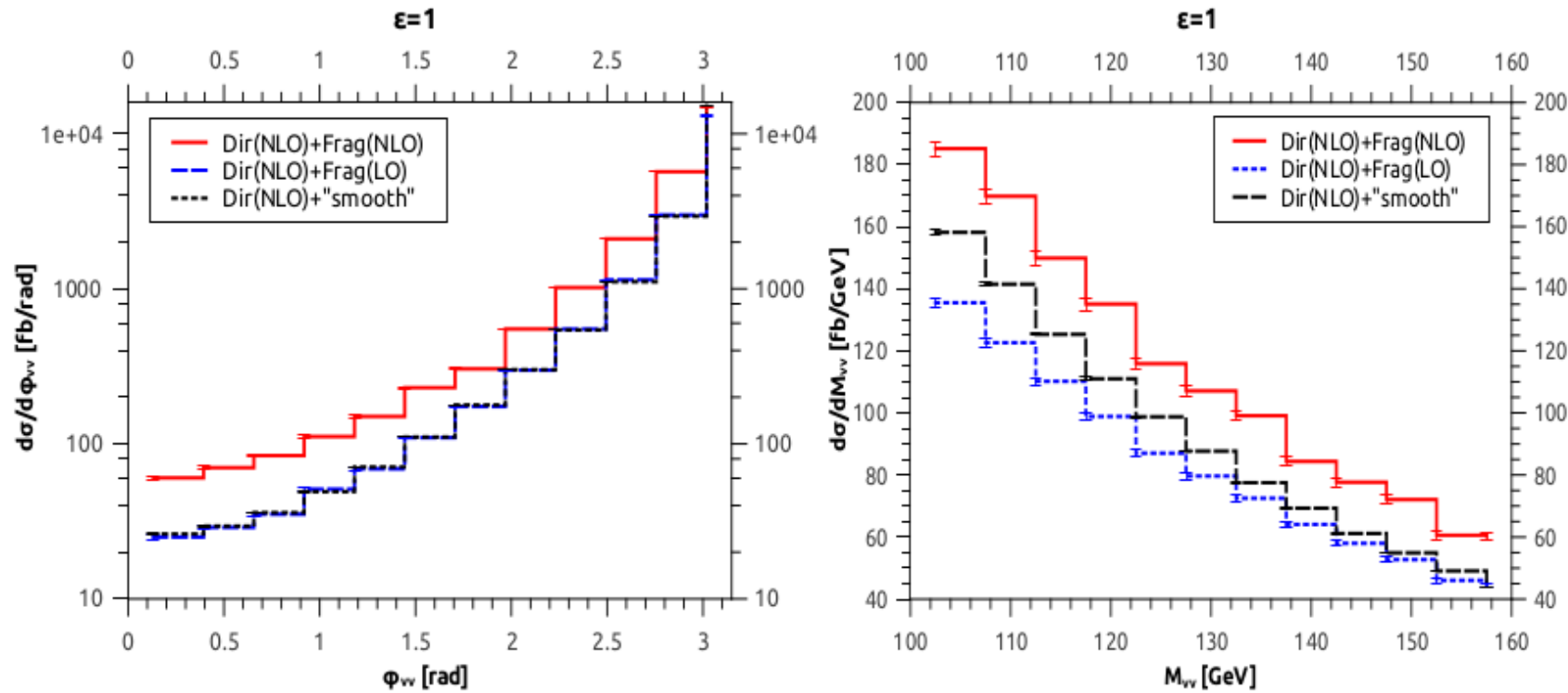
Grazzini, Kallweit, Rathlev, Torre



In the exclusive case, the excess of the measured fiducial cross sections over the theoretical prediction is reduced from 1.6σ to 1.2σ when going from NLO to NNLO

In the inclusive case, the excess of the data over the theoretical prediction is reduced from 2σ to below 1σ when going from NLO to NNLO

What we learnt from $\gamma\gamma$



Fragmentation could be very relevant!!!!

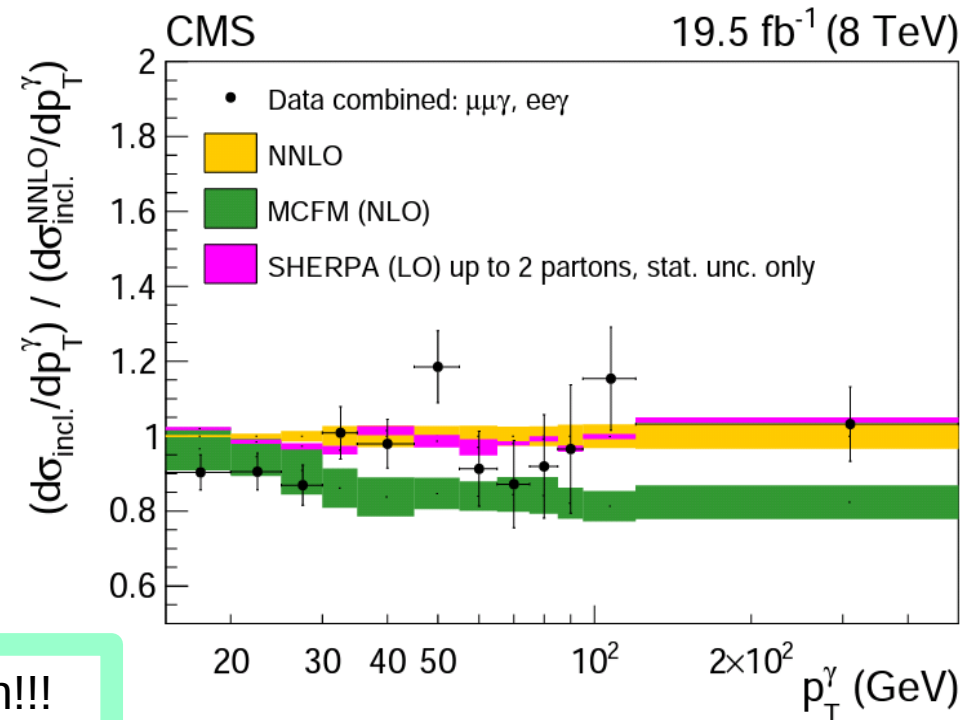
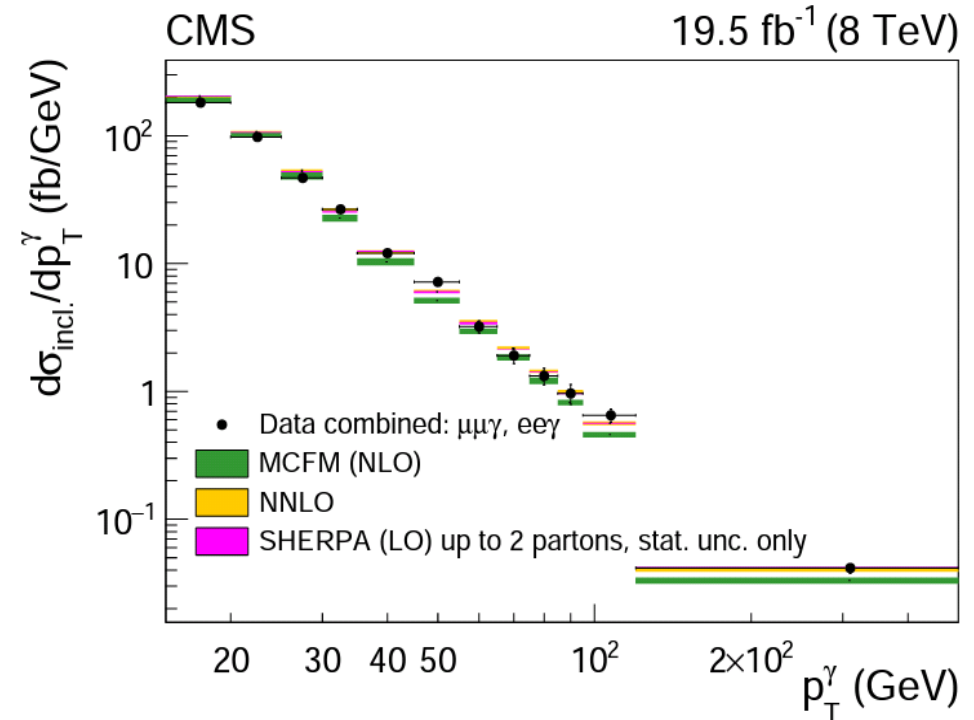
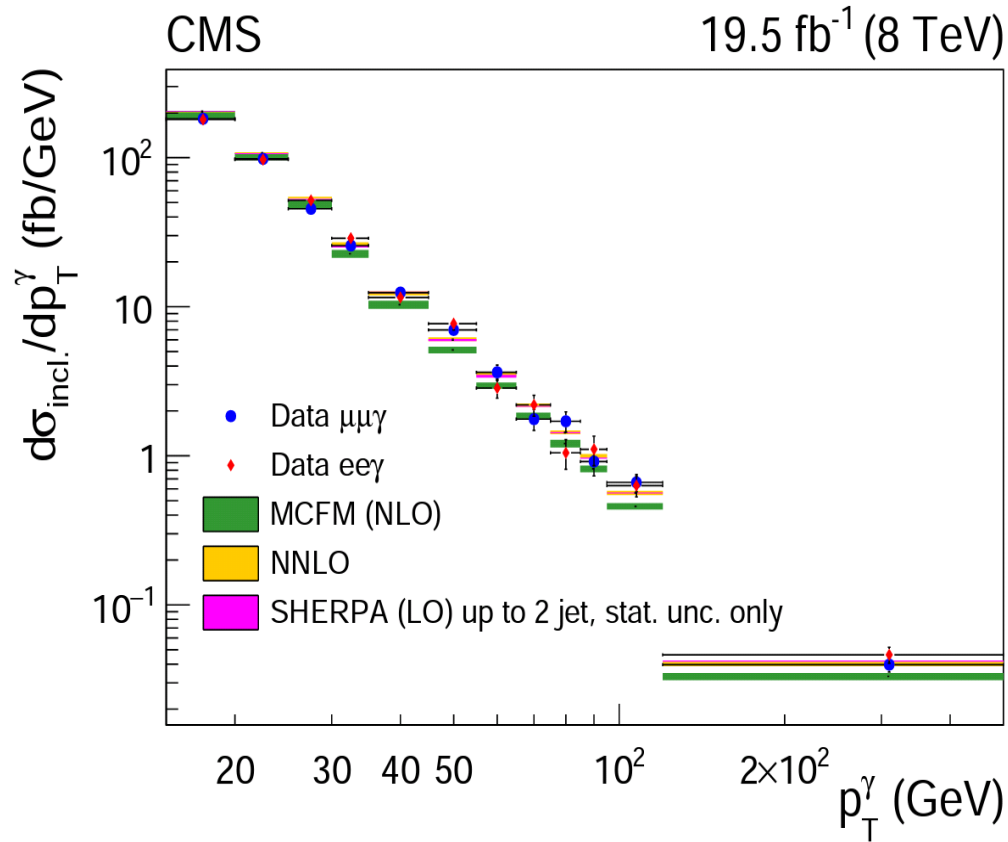
$$E_T \text{ max} \sim 20 \text{ GeV}$$

$V\gamma$ ATLAS

$$E_T < \epsilon_\gamma p_T^\gamma, \quad \epsilon_\gamma = 0.5$$

$Z\gamma$ production

JHEP04 (2015) 164

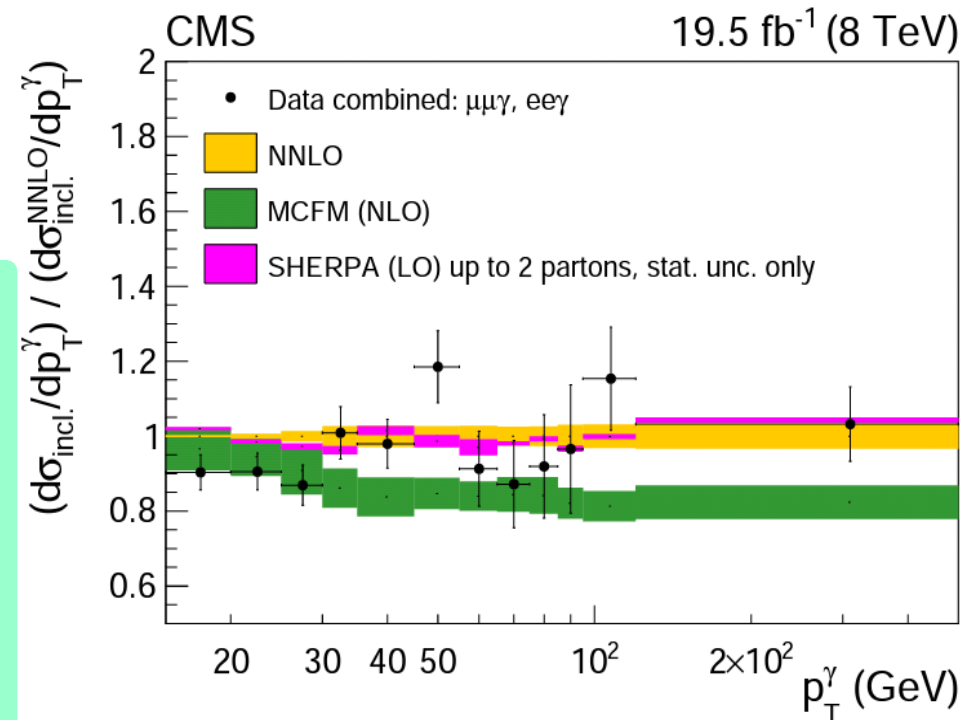
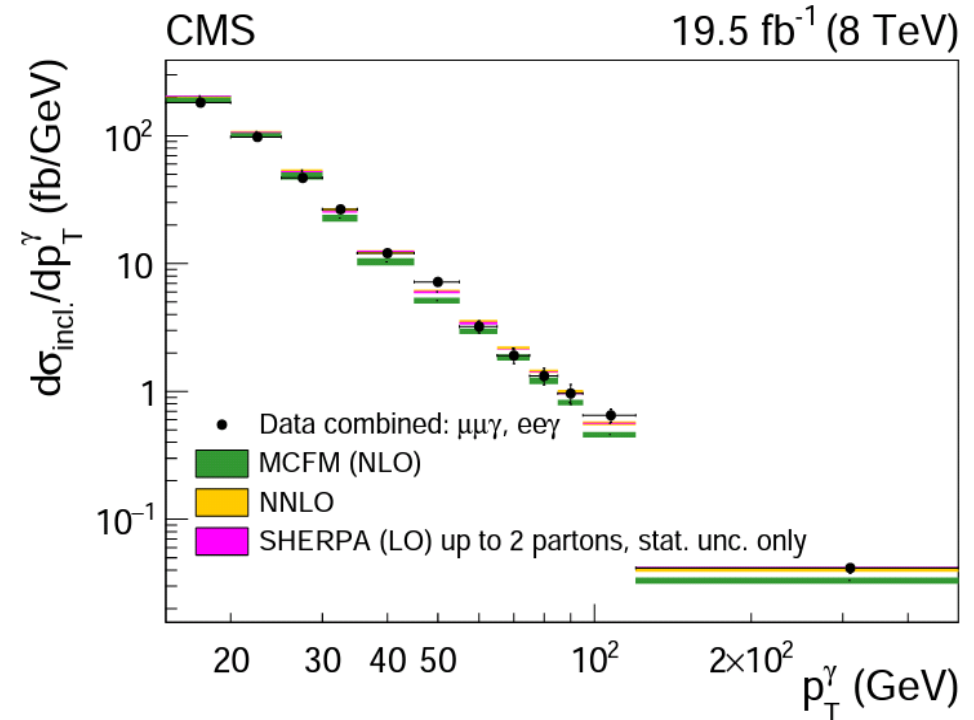
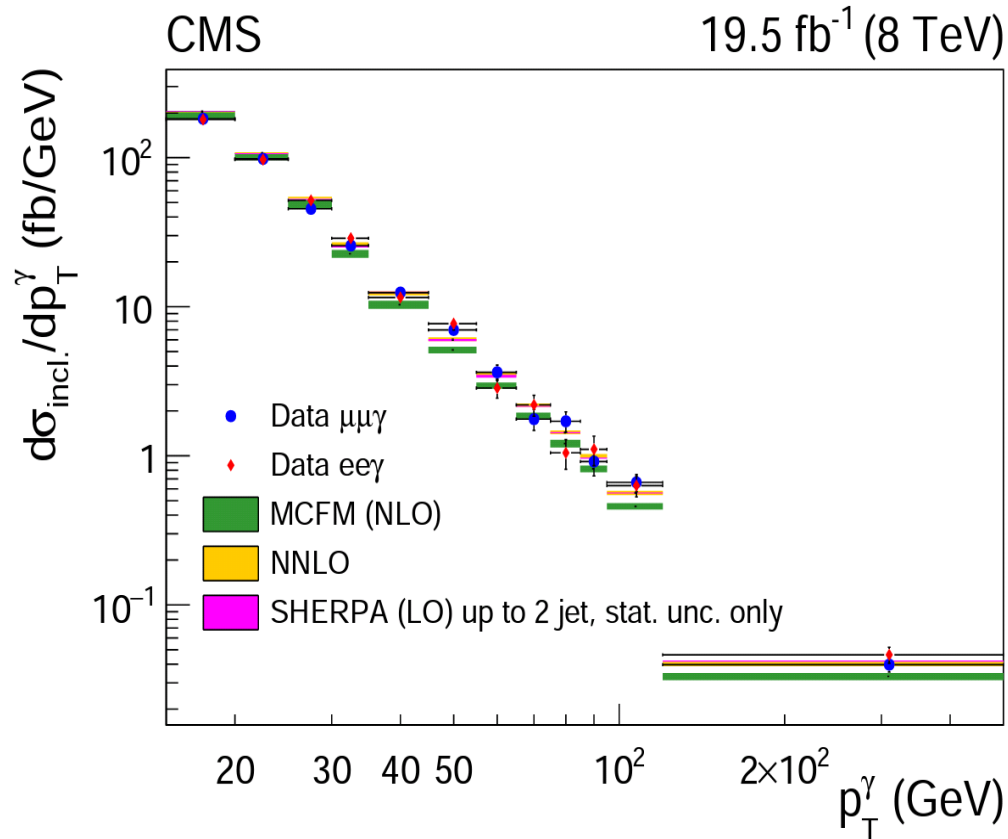


$I_{\text{gen}} < 5 \text{ GeV}$

to exclude photons to jet fragmentation!!!

$Z\gamma$ production

JHEP04 (2015) 164



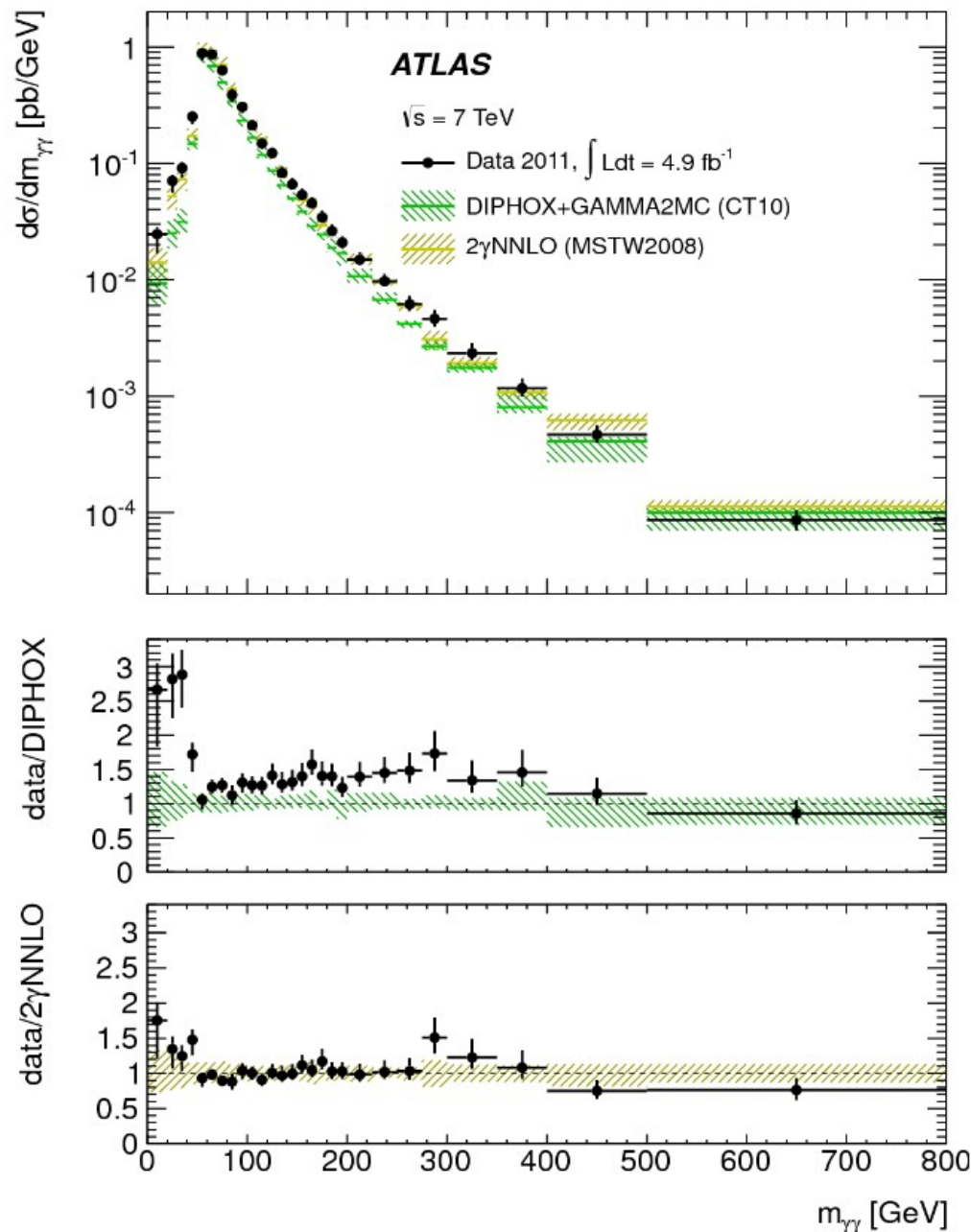
- +) Are important the EW contributions?
- +) The isolation issues are under control?
- +) If the last two items are under control : can we repeat the study of CDF in order to identify the origin of the discrepancies? (missing higher order correction terms → Real radiation)

ATLAS results $\gamma\gamma$

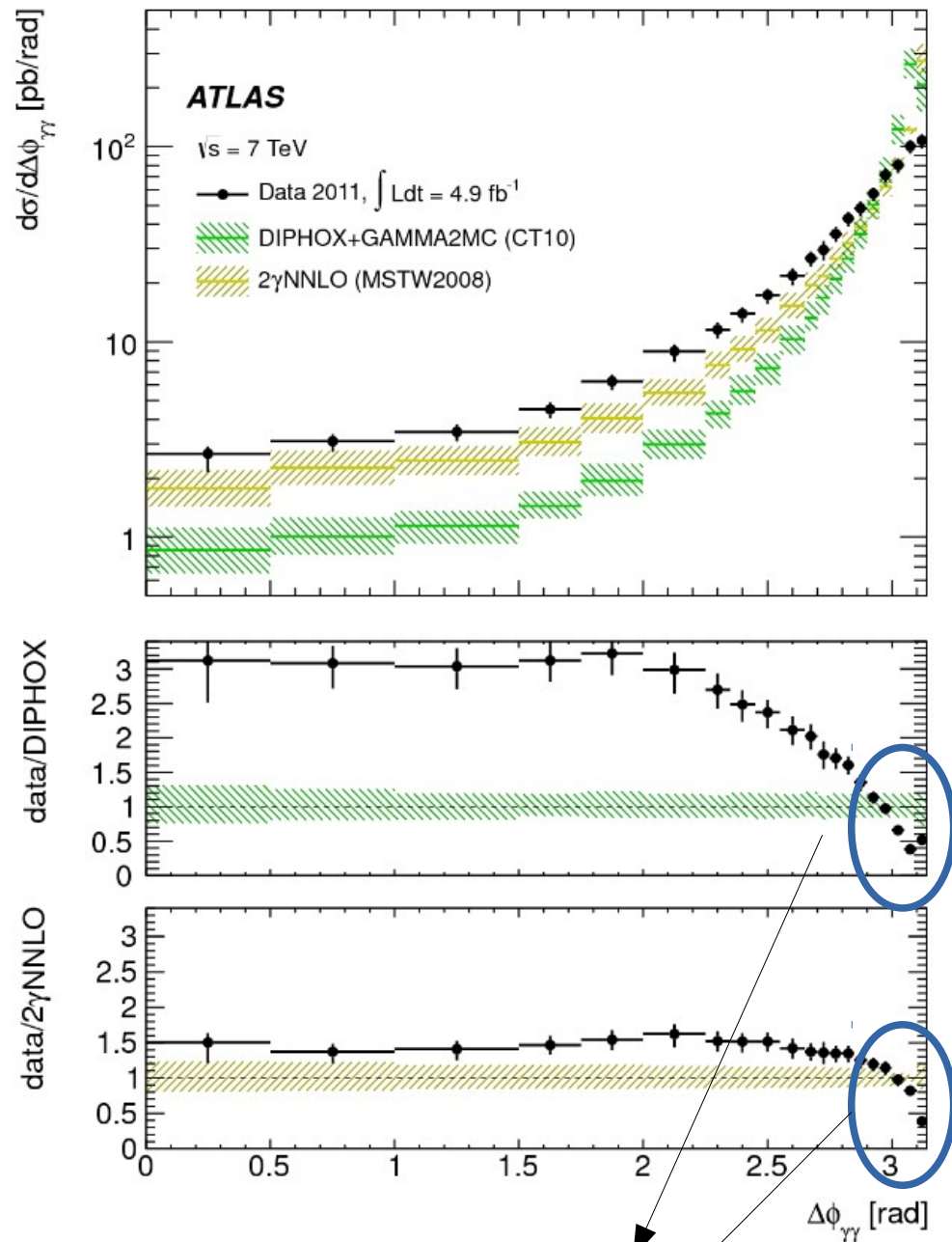
$$\begin{aligned} p_T^{\text{harder}} &\geq 25 \text{ GeV}, \quad p_T^{\text{softer}} \geq 22 \text{ GeV}, \\ |y_\gamma| &< 1.37 \quad \vee \quad 1.52 < |y_\gamma| \leq 2.37, \\ E_{T \text{ max}} &= 4 \text{ GeV}, \quad n = 1, \quad R = 0.4, \\ R_{\gamma\gamma} &= 0.4 \end{aligned}$$

ATLAS results $\gamma\gamma$

arXiv:1211.1913 [hep-ex].

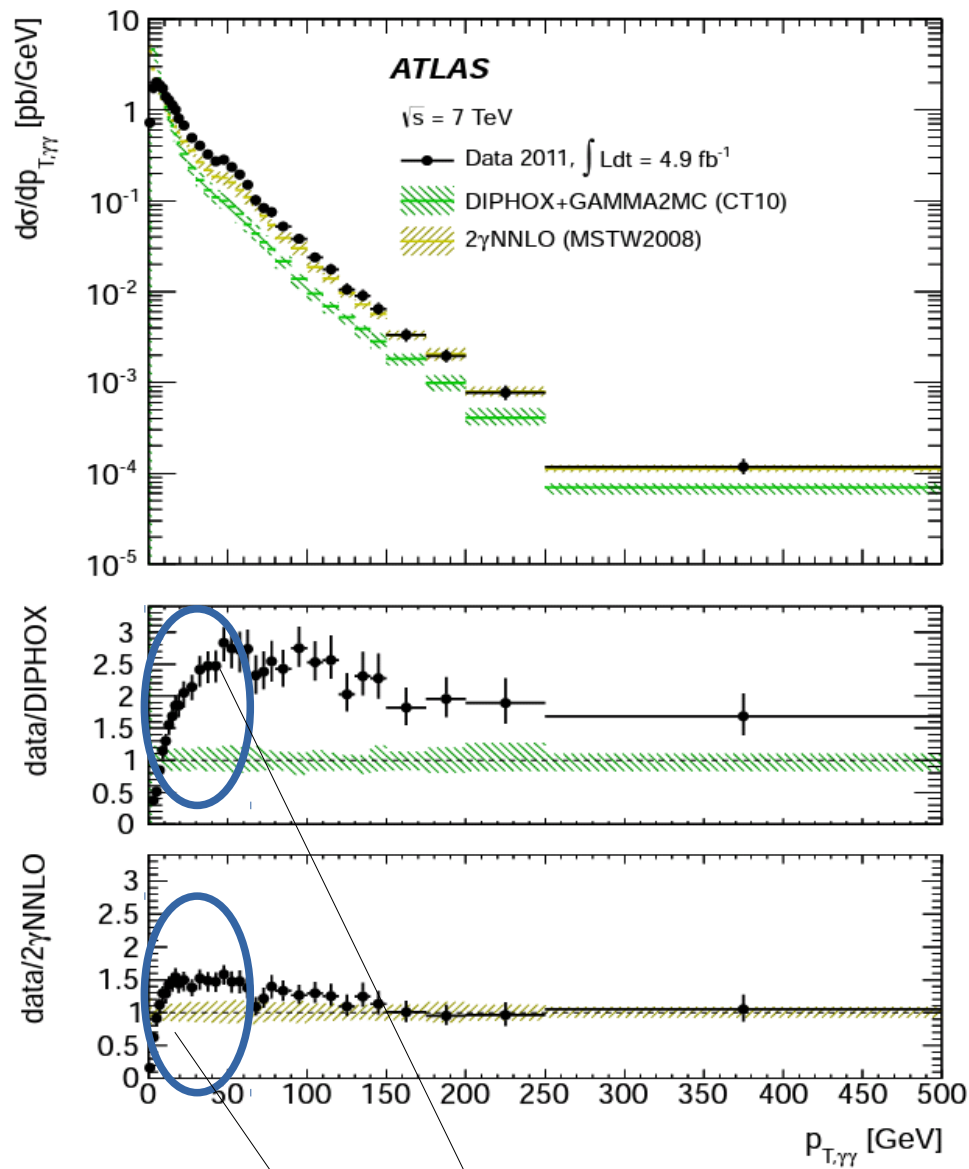


Uncertainties $\rightarrow$ 6% - 8%

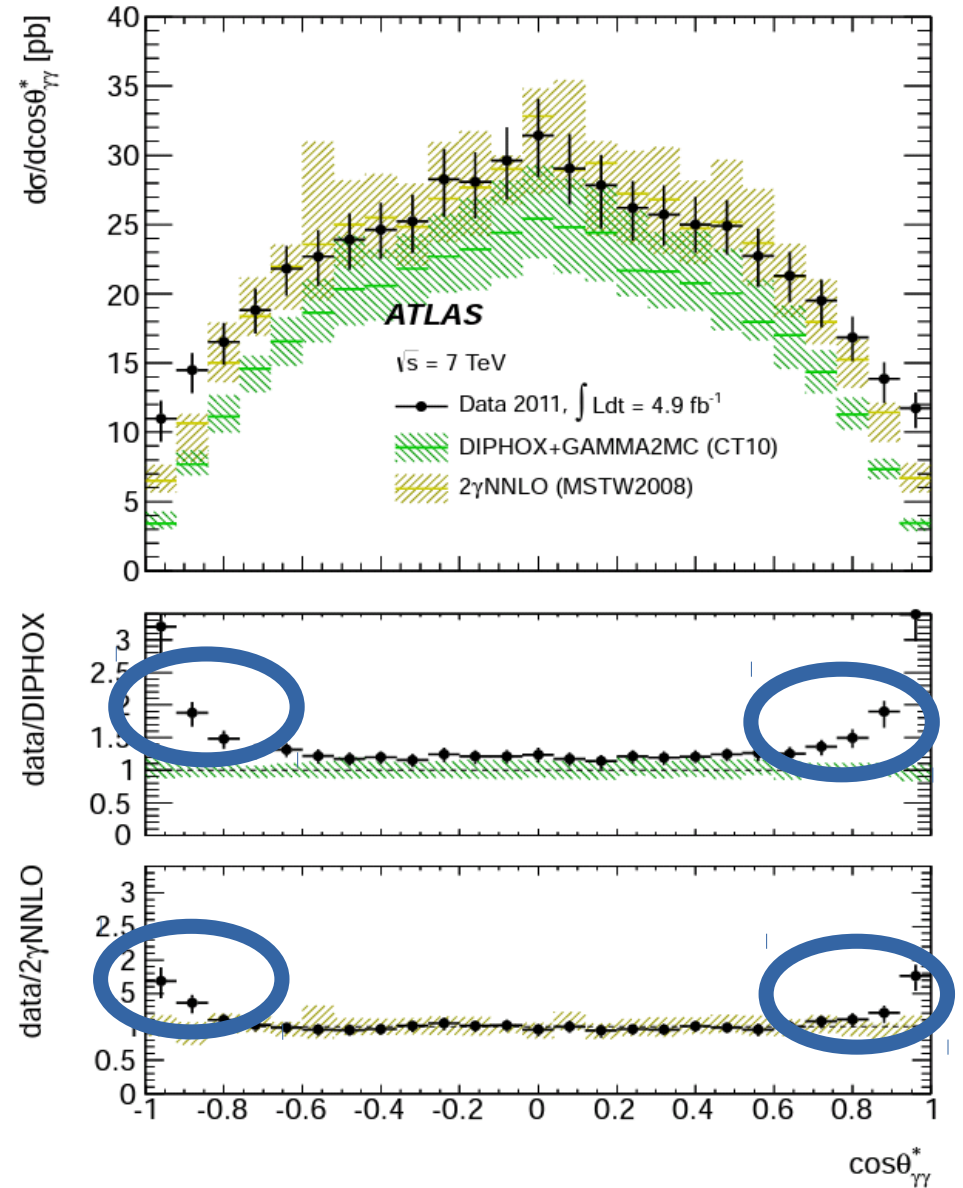


Fixed order tools

ATLAS results $\gamma\gamma$



Fixed order tools



Uncertainties $\rightarrow$ 6% - 8% due to the opening of the gg channel which is “effectively” LO at NNLO

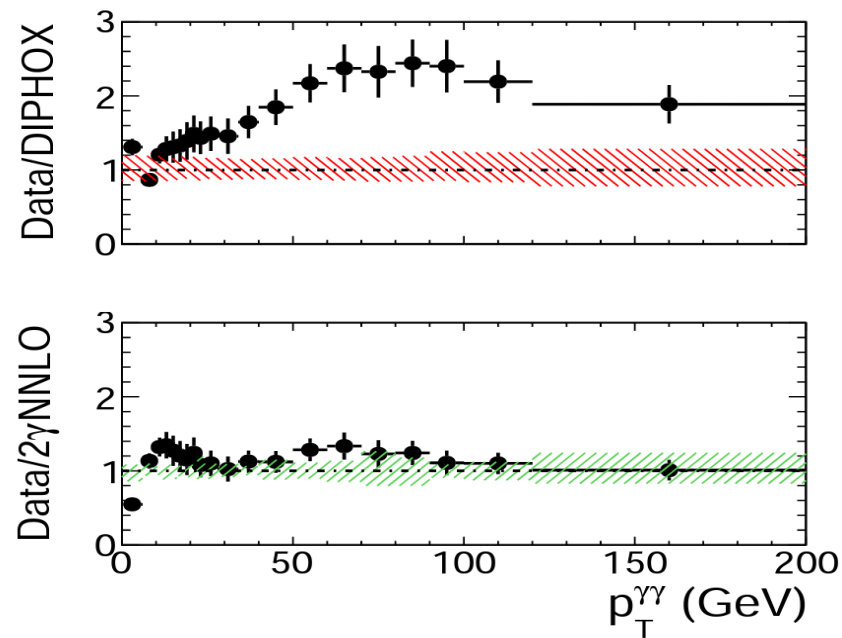
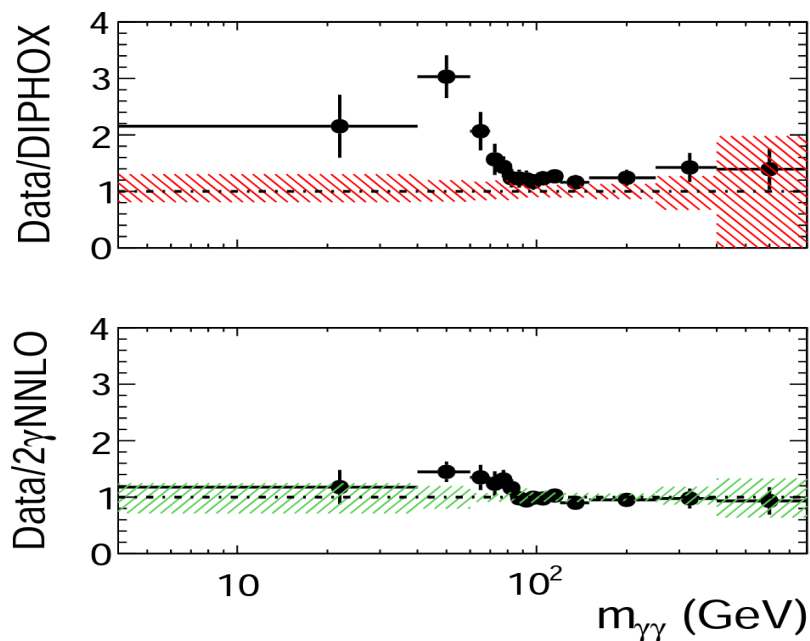
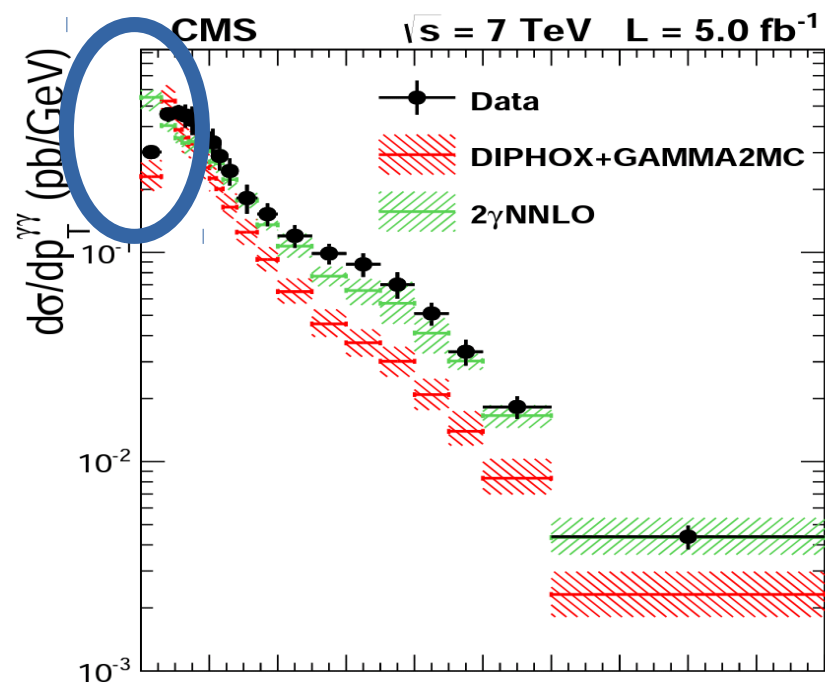
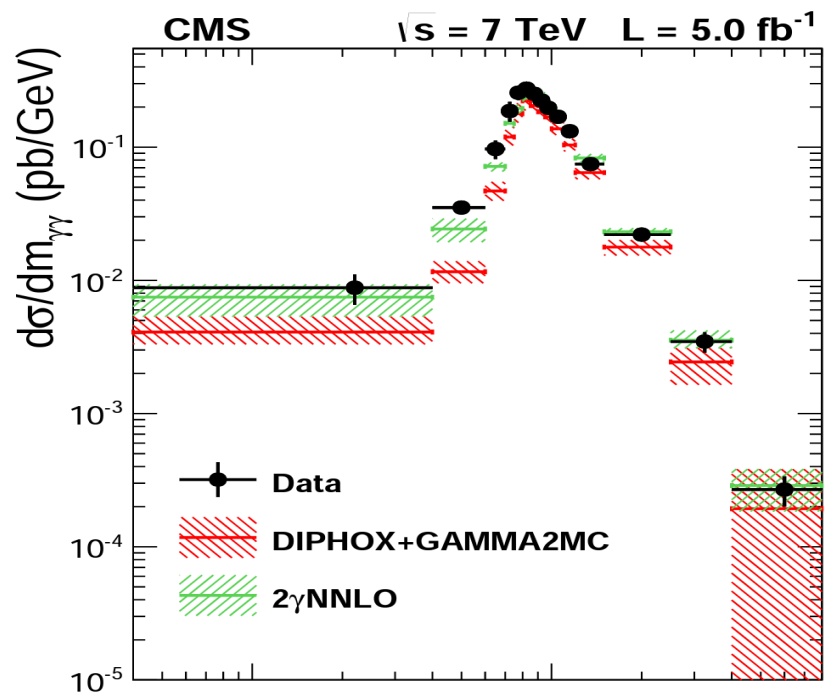
CMS results $\gamma\gamma$

arXiv:1405.7225

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

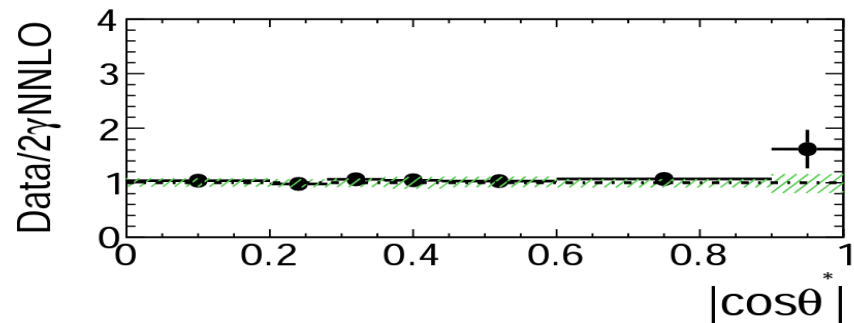
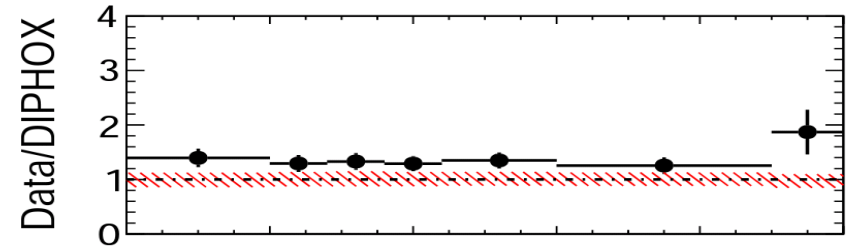
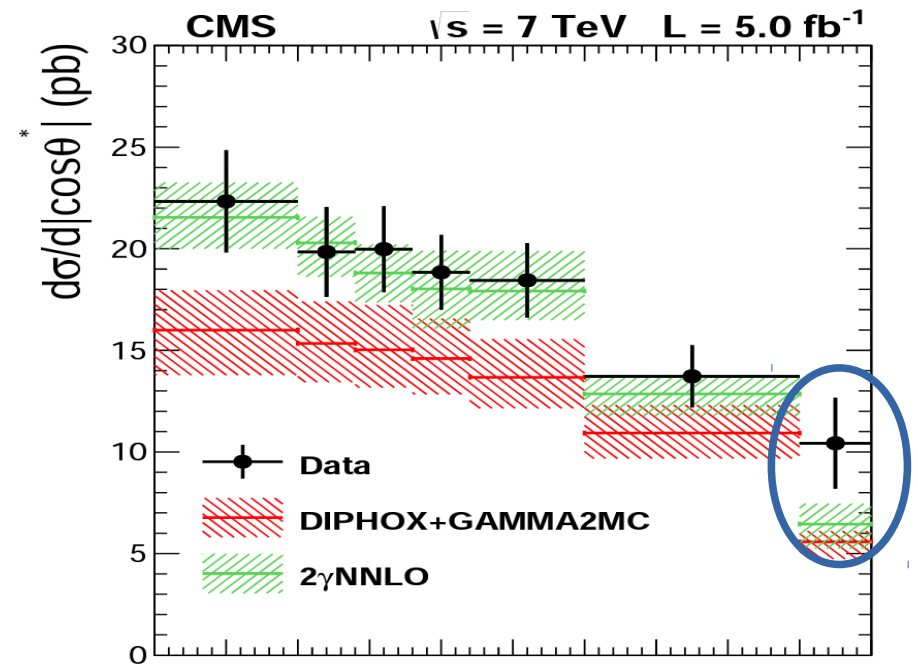
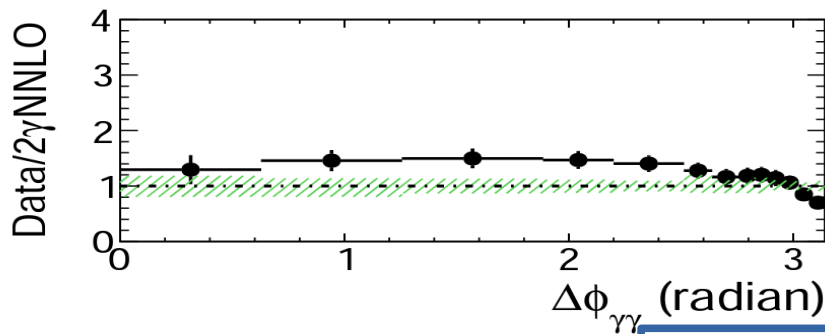
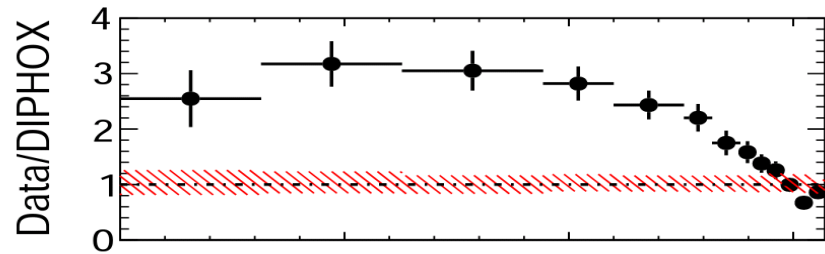
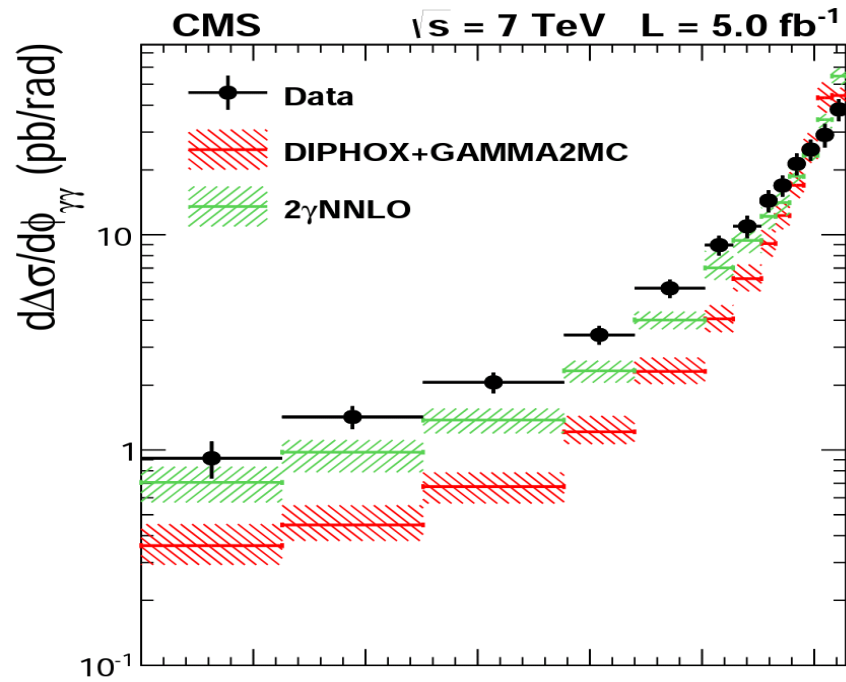
CMS results $\gamma\gamma$

arXiv:1405.7225



CMS results $\gamma\gamma$

arXiv:1405.7225

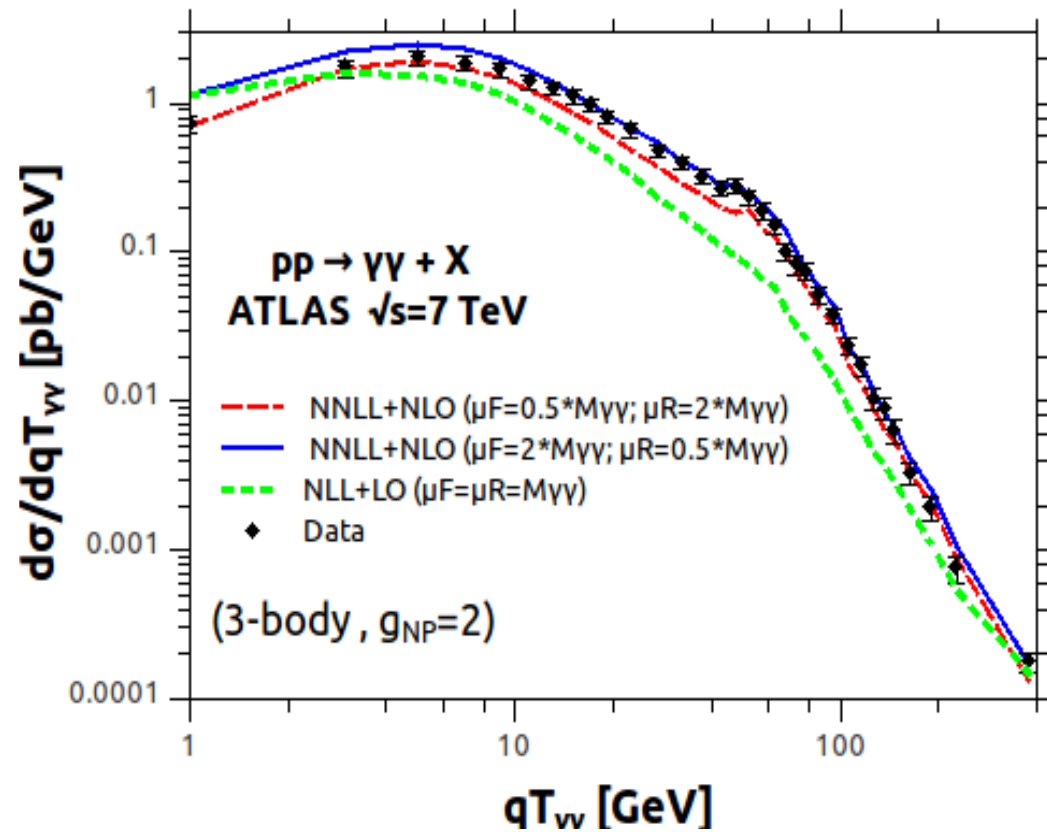
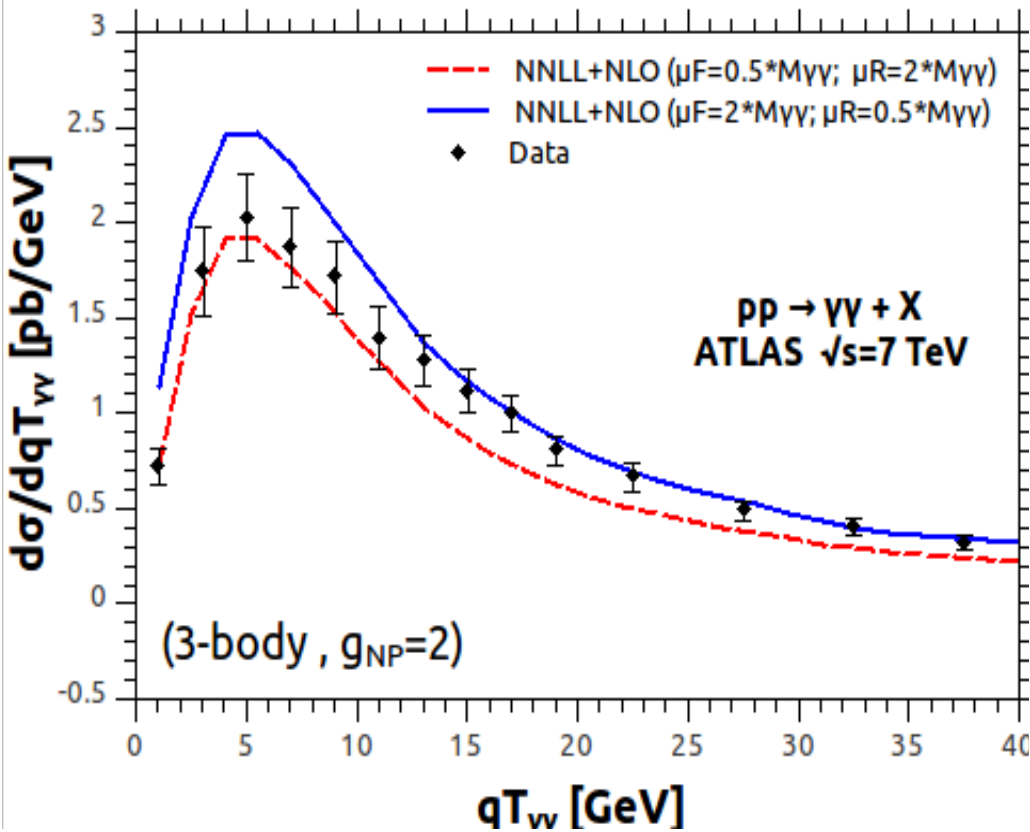


Uncertainties $\rightarrow$ 6% - 8%

Resummation → ATLAS $\gamma\gamma$

LC, Coradeschi, de Florian

First results!



$$S_{NP}^a = \exp(-C_a g_{NP} b^2)$$

$a = F$ for $q\bar{q}$ and $a = A$ for gg

$C_F = (N_c^2 - 1)/(2N_c)$ and $C_A = N_c$

$$p_T^{\text{harder}} \geq 25 \text{ GeV}, \quad p_T^{\text{softer}} \geq 22 \text{ GeV},$$

$$|y_\gamma| < 1.37 \quad \vee \quad 1.52 < |y_\gamma| \leq 2.37,$$

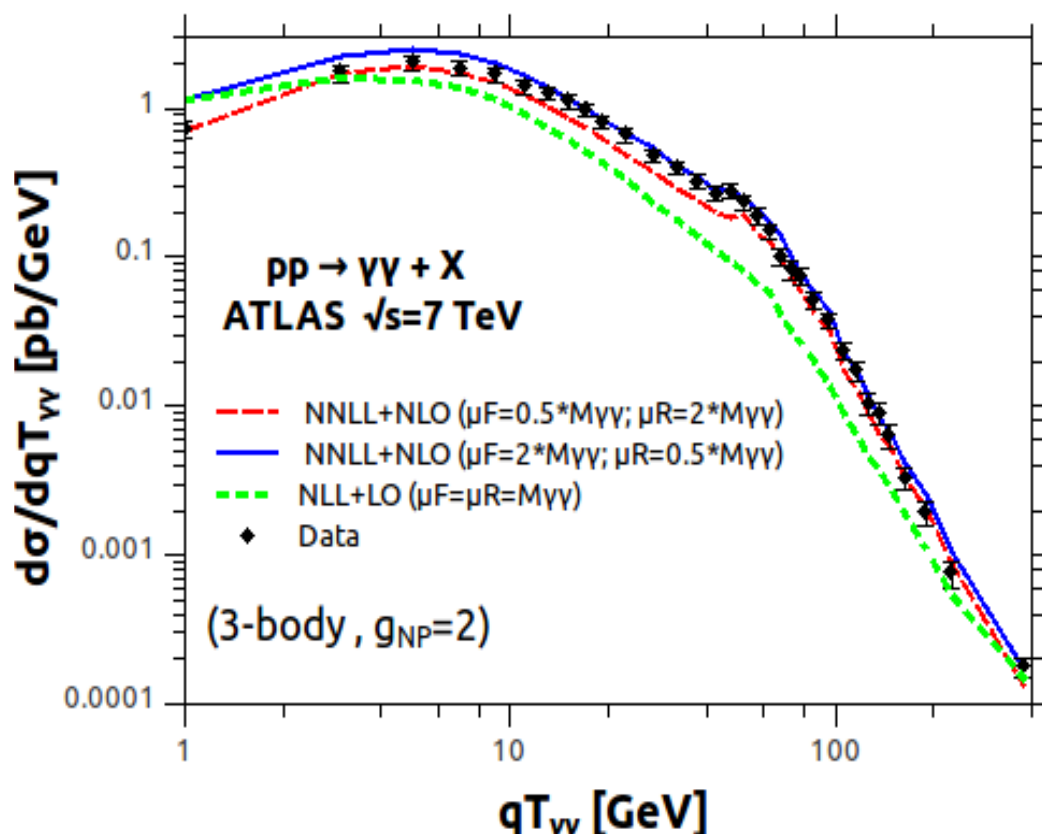
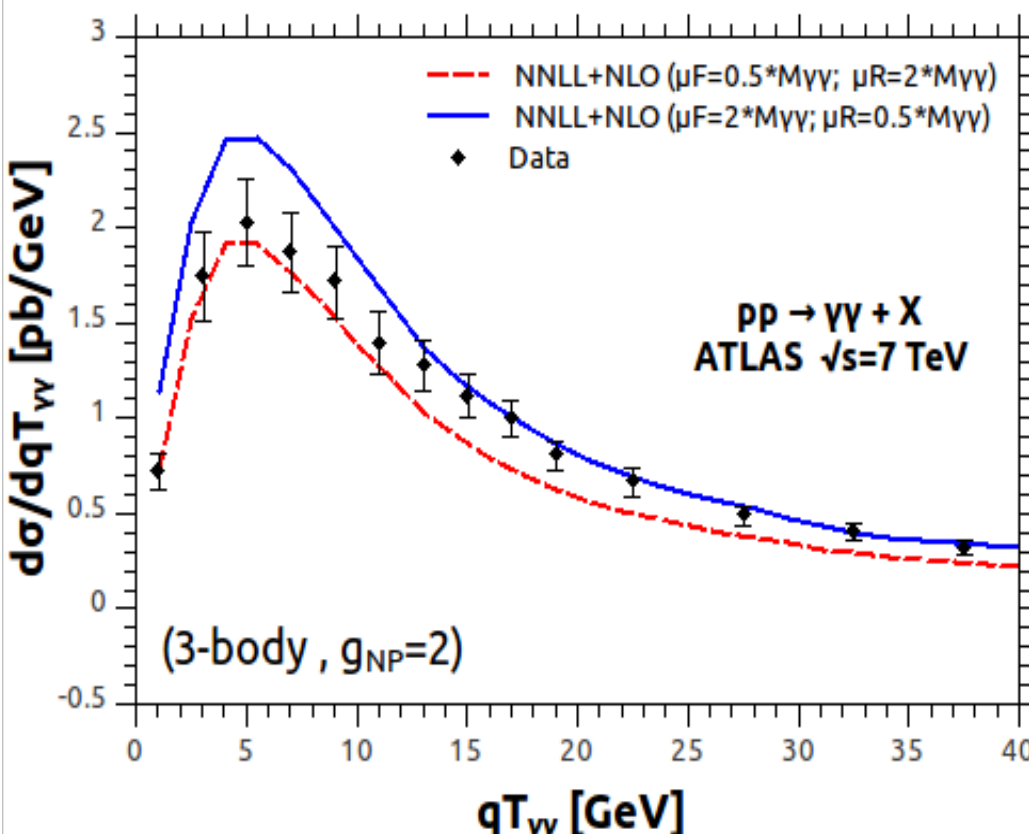
$$E_{T \text{ max}} = 4 \text{ GeV}, \quad n = 1, \quad R = 0.4,$$

$$R_{\gamma\gamma} = 0.4$$

Resummation → ATLAS $\gamma\gamma$

LC, Coradeschi, de Florian

First results!



qT resummation “spreads” the uncertainties of the gg channel over the whole qT range

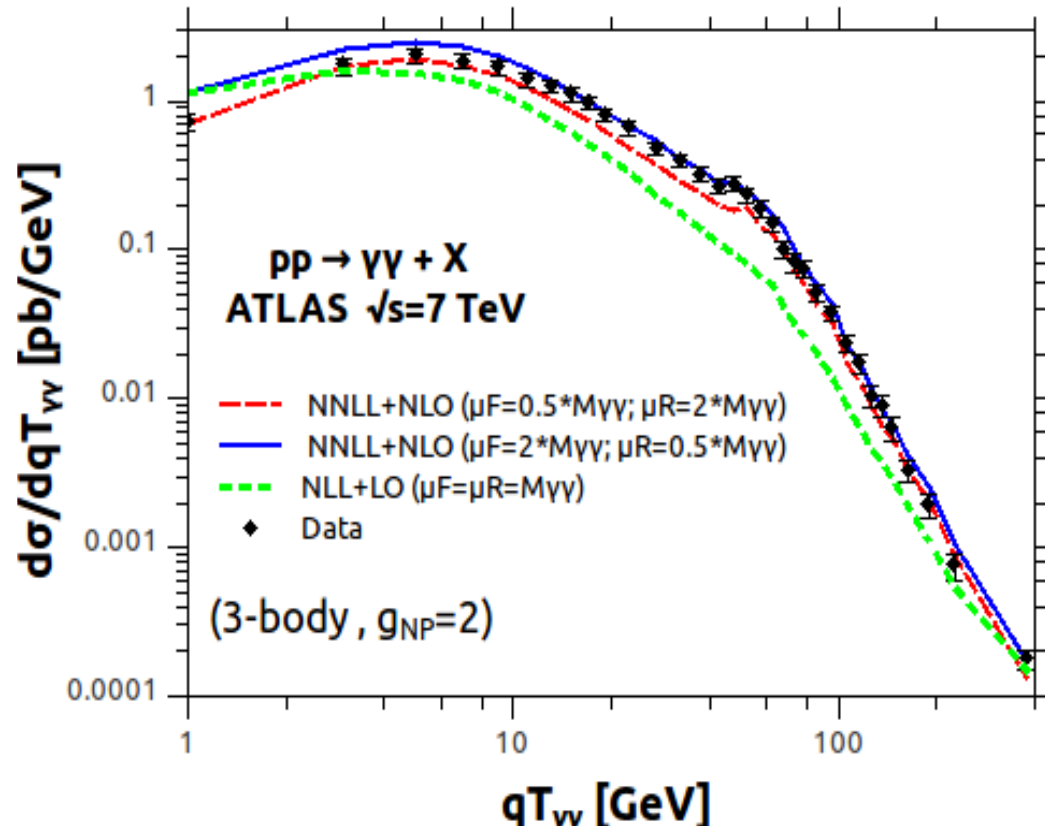
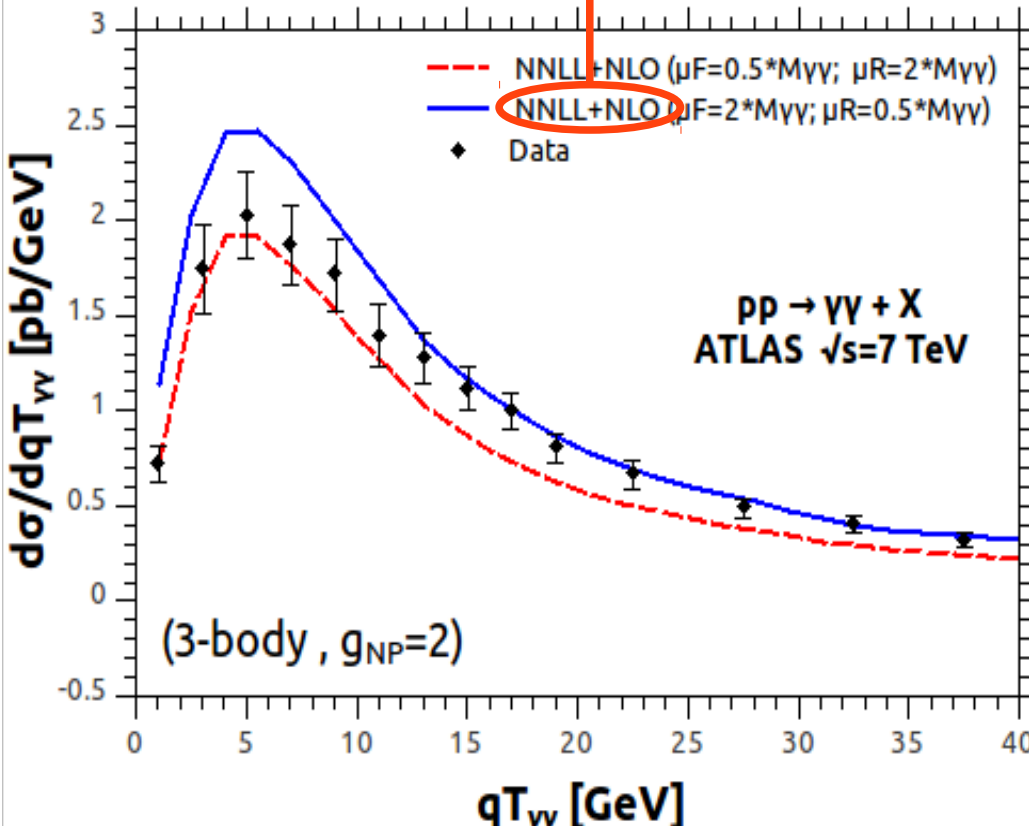
$$\begin{aligned}
 & p_T^{\text{harder}} \geq 25 \text{ GeV}, \quad p_T^{\text{softer}} \geq 22 \text{ GeV}, \\
 & |y_\gamma| < 1.37 \quad \vee \quad 1.52 < |y_\gamma| \leq 2.37, \\
 & E_{T \text{ max}} = 4 \text{ GeV}, \quad n = 1, \quad R = 0.4, \\
 & R_{\gamma\gamma} = 0.4
 \end{aligned}$$

Resummation → ATLAS $\gamma\gamma$

LC, Coradeschi, de Florian

+) NLO here means: $\gamma\gamma$ + jet at NLO

+) $\gamma\gamma$ + jet at NLO is a part of $\gamma\gamma$ production at NNLO



$$S_{NP}^a = \exp(-C_a g_{NP} b^2)$$

$a = F$ for $q\bar{q}$ and $a = A$ for gg

$$C_F = (N_c^2 - 1)/(2N_c) \text{ and } C_A = N_c$$

$$p_T^{\text{harder}} \geq 25 \text{ GeV}, \quad p_T^{\text{softer}} \geq 22 \text{ GeV},$$

$$|y_\gamma| < 1.37 \quad \vee \quad 1.52 < |y_\gamma| \leq 2.37,$$

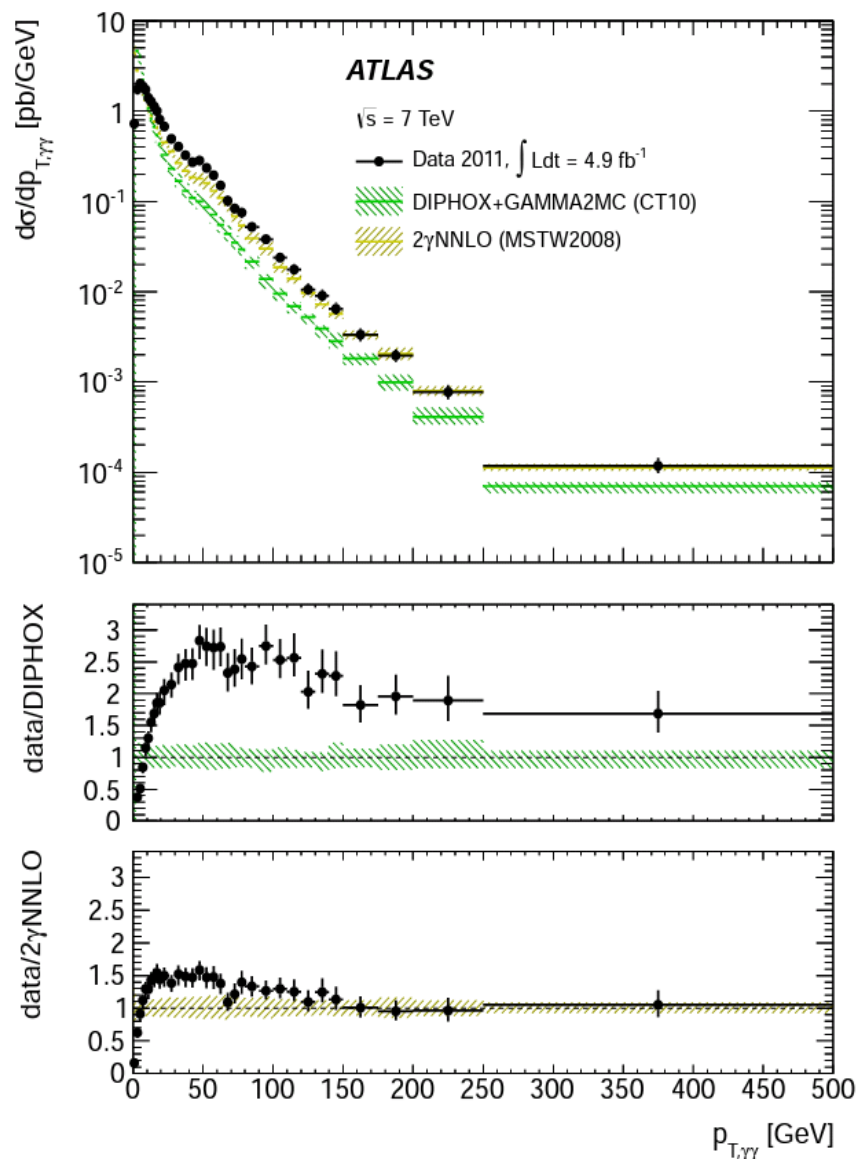
$$E_{T \text{ max}} = 4 \text{ GeV}, \quad n = 1, \quad R = 0.4,$$

$$R_{\gamma\gamma} = 0.4$$

Resummation $\rightarrow$ ATLAS $\gamma\gamma$

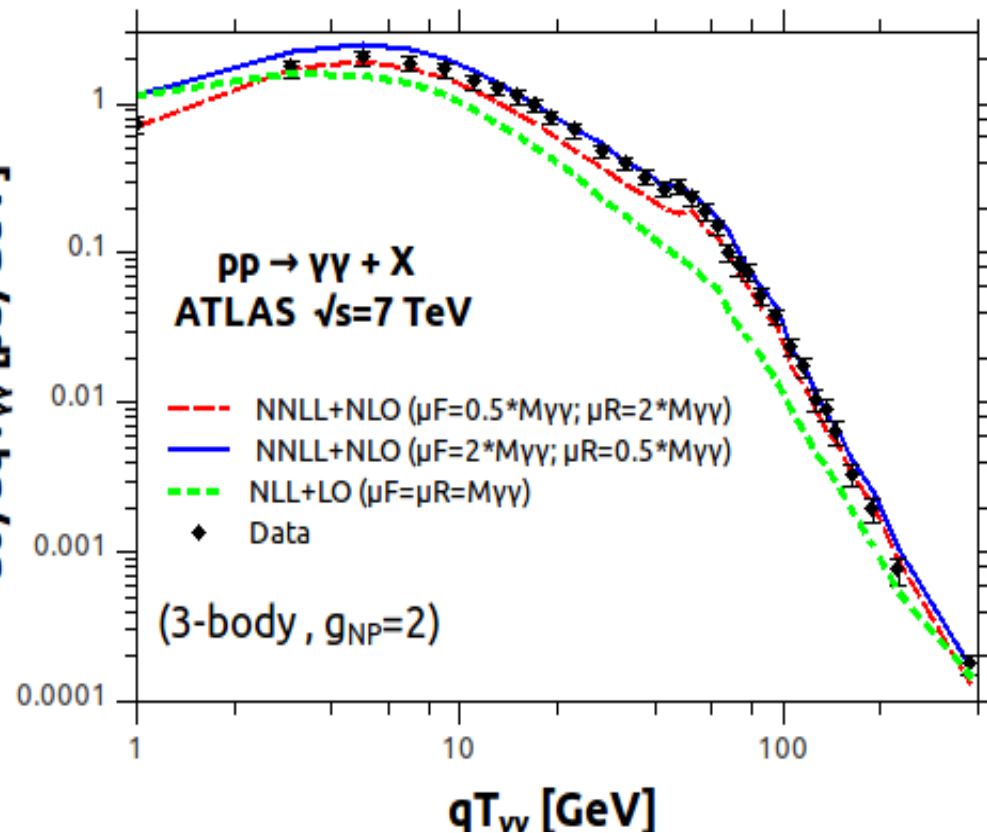
LC, Coradeschi, de Florian

Fixed order



q_T resummation “spreads” the uncertainties of the gg channel over the whole q_T range

$d\sigma/dq_{T_w}$ [pb/GeV]

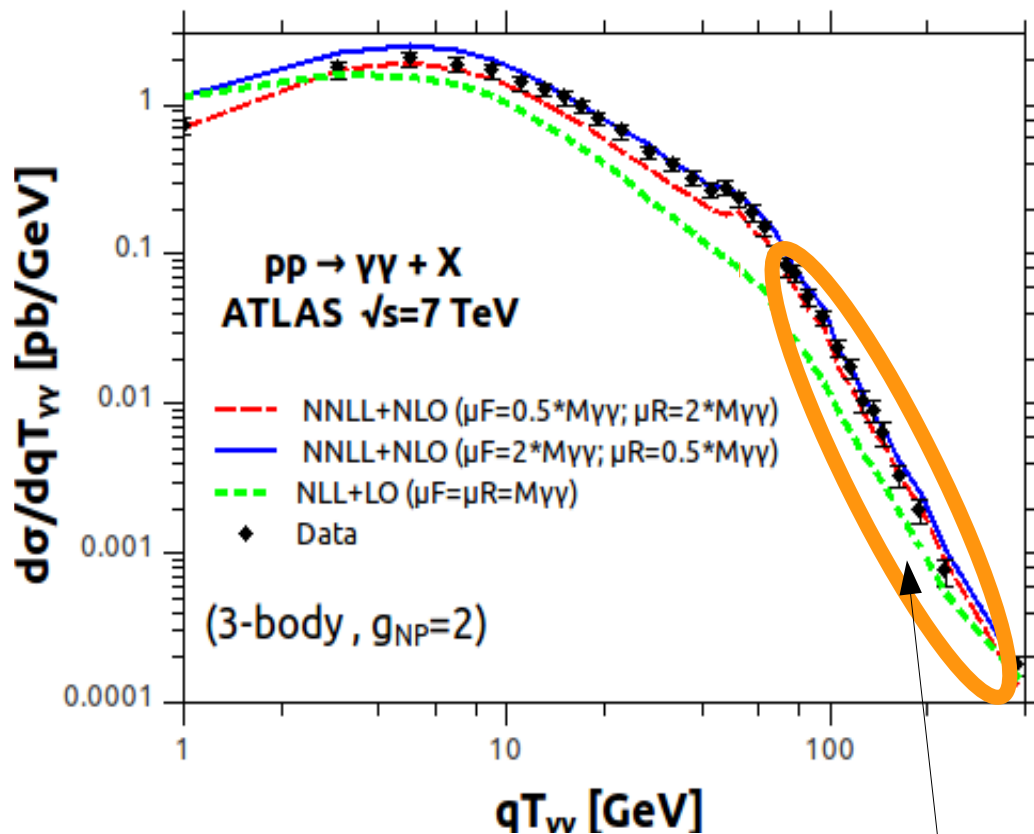
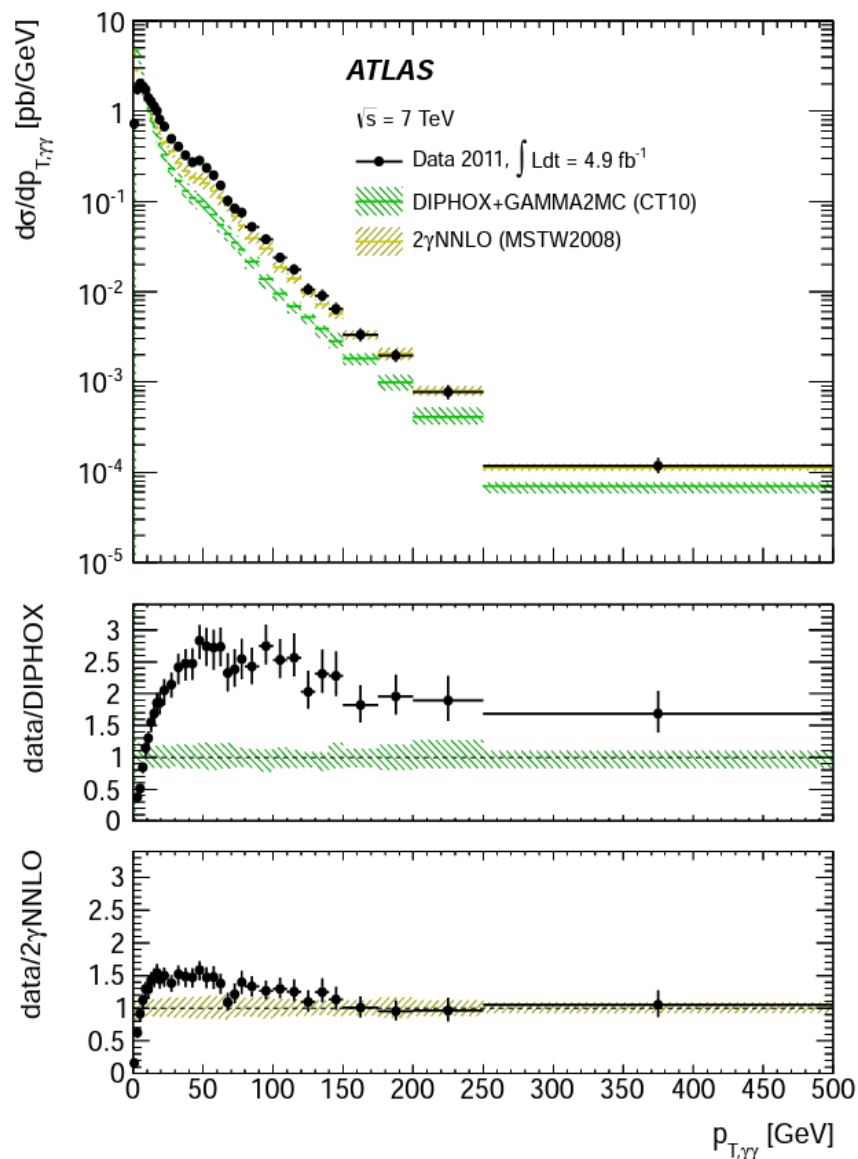


With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small q_T region, with the spectrum going to zero.

Resummation → ATLAS $\gamma\gamma$

LC, Coradeschi, de Florian

Fixed order



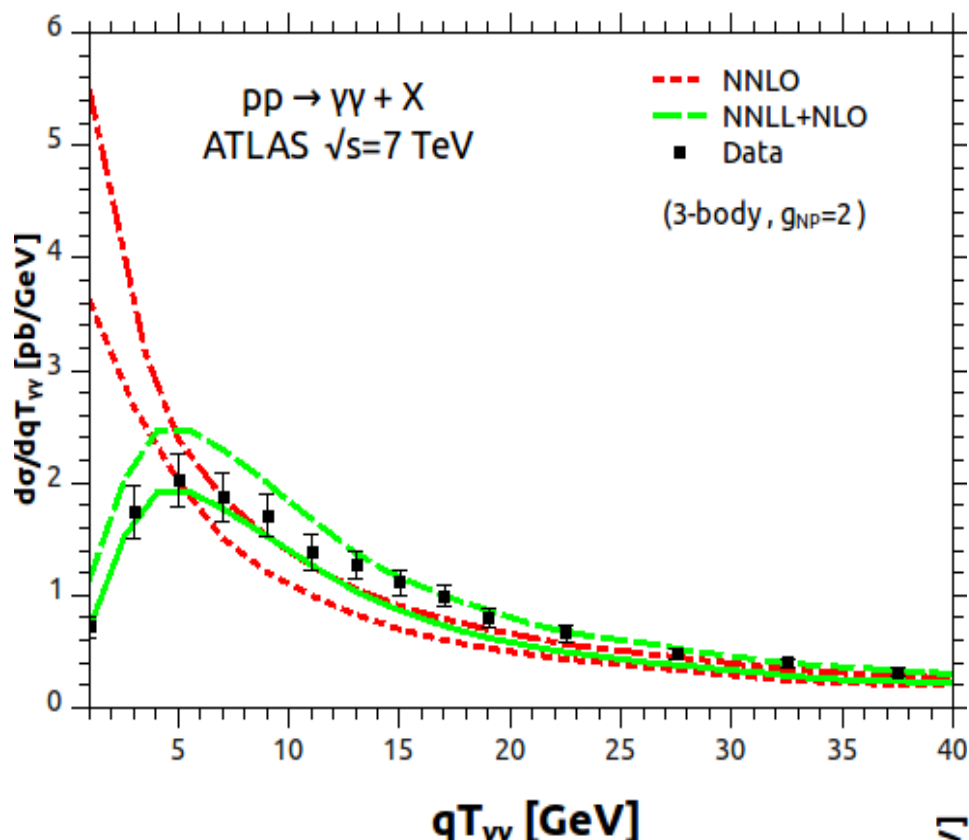
The size of the bands is proportional to the luminosity of the PDF of the gluon

q_T resummation “spreads” the uncertainties of the gg channel over the whole q_T range

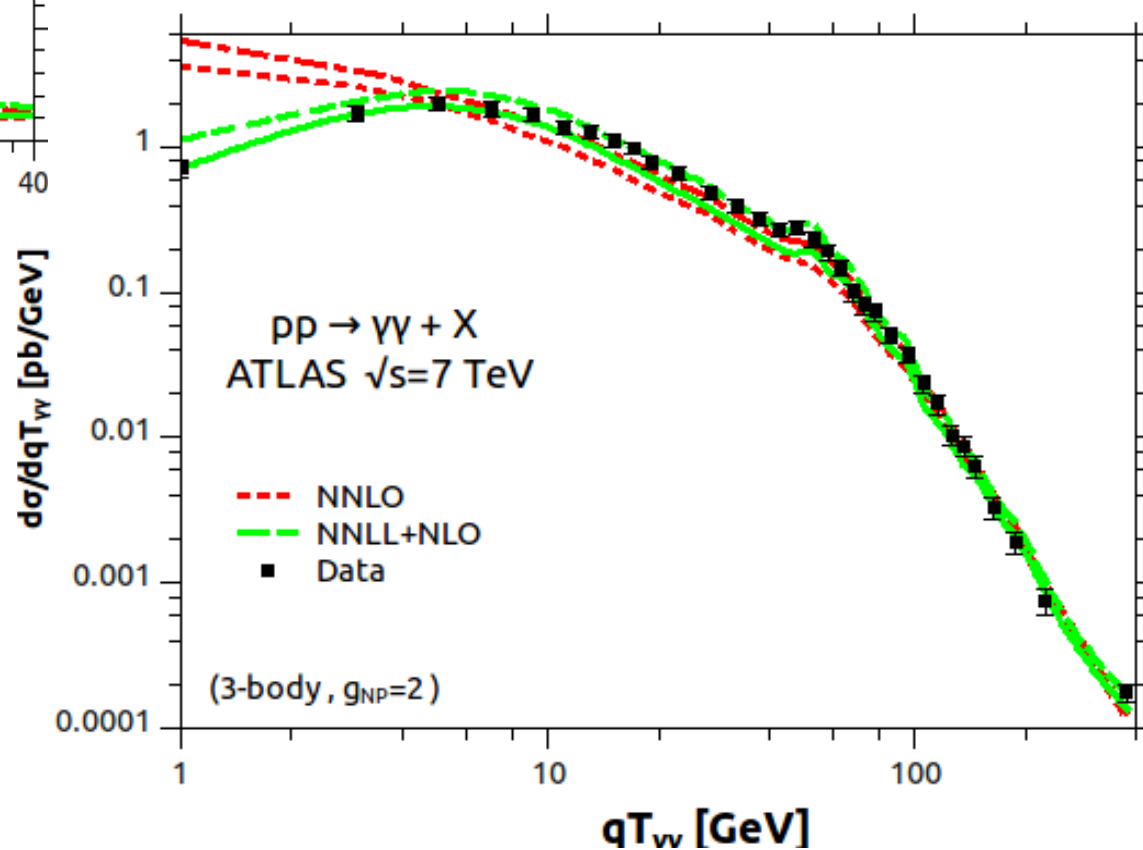
Resummation $\rightarrow$ ATLAS $\gamma\gamma$

LC, Coradeschi, de Florian

Good agreement
between theory
and experiment
over the whole
 qT range.



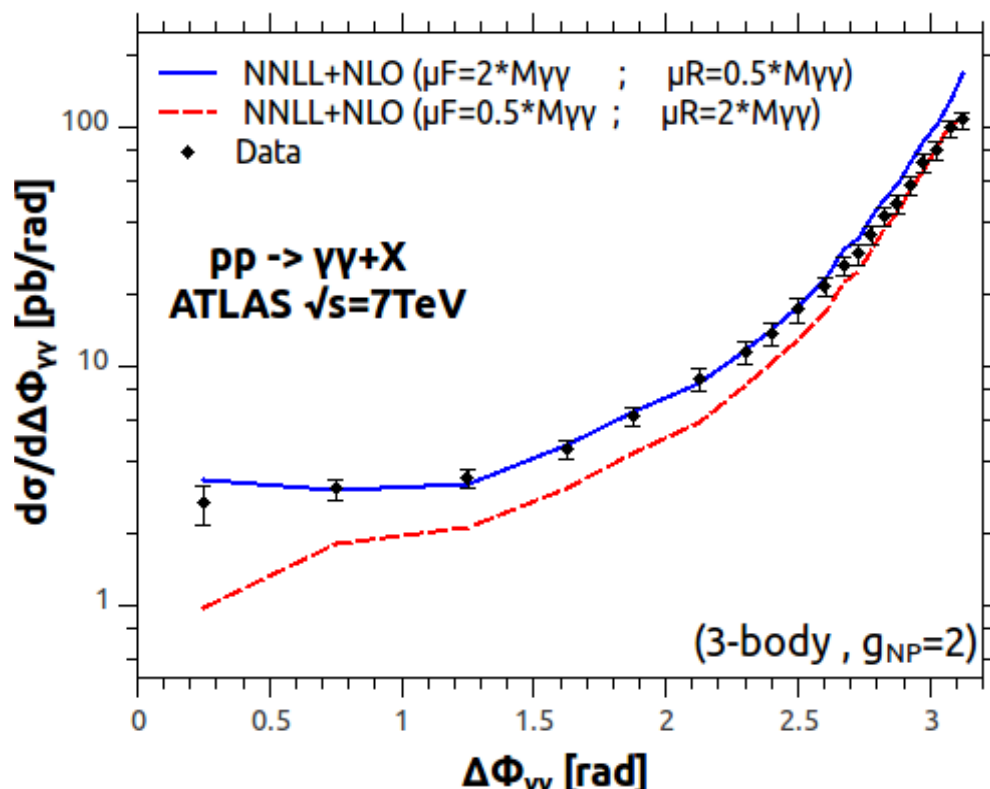
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.



Resummation → ATLAS $\gamma\gamma$

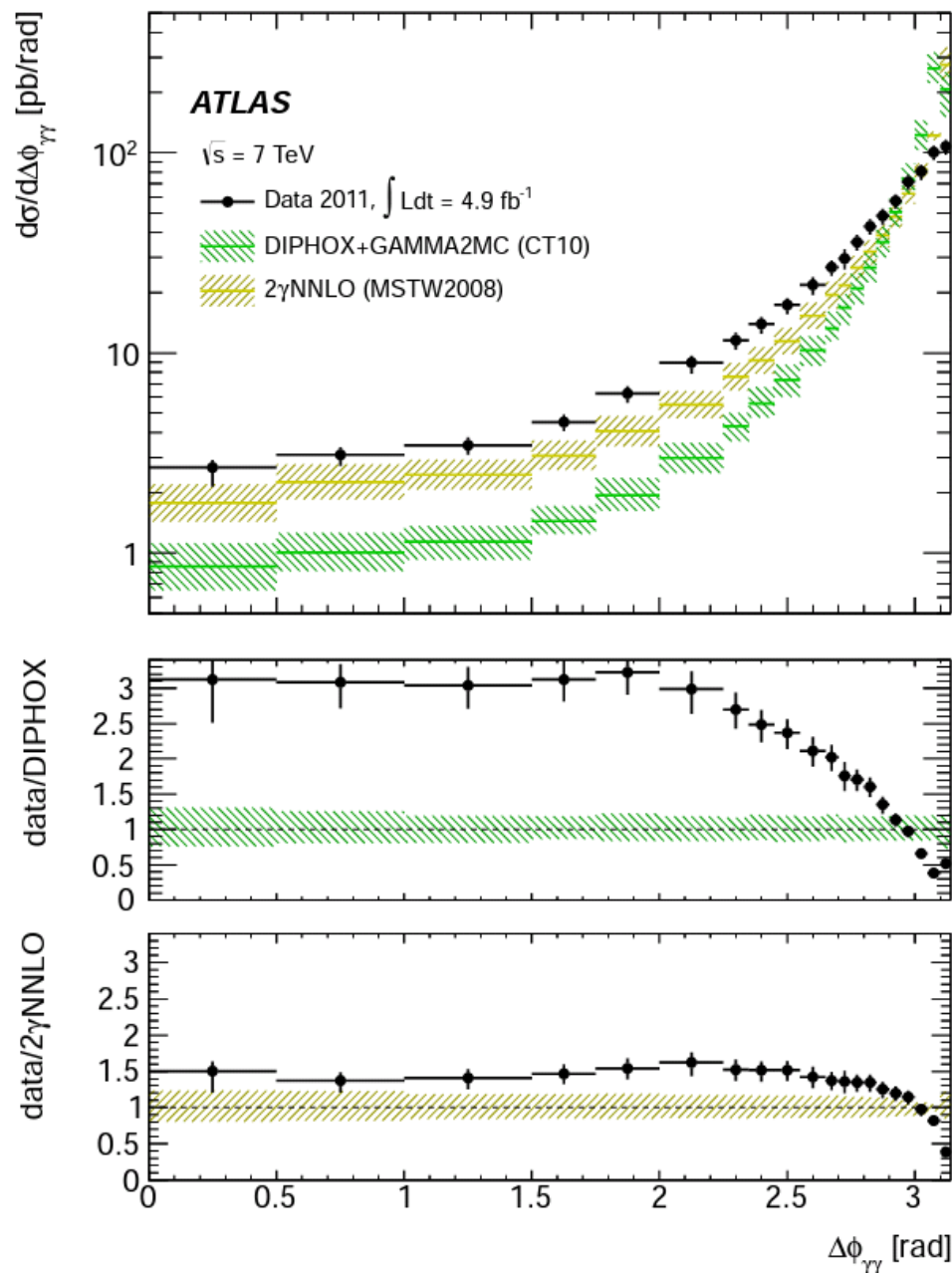
LC, Coradeschi, de Florian

First results!



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

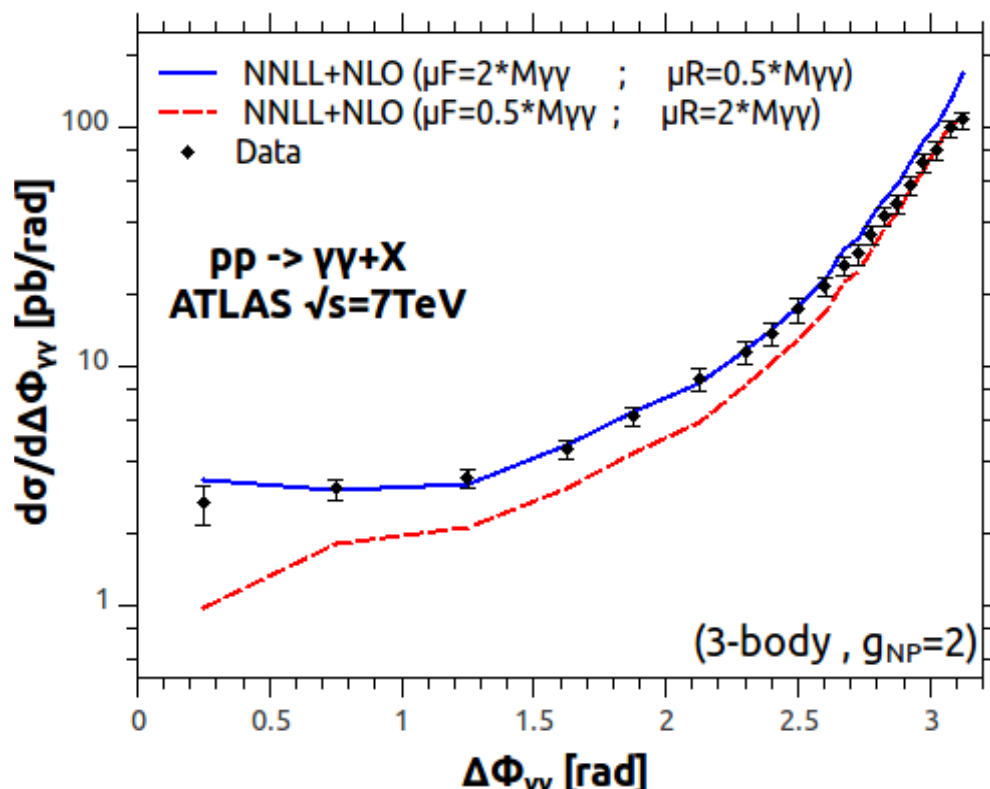
Uncertainties → 6% - 8%



Resummation → ATLAS $\gamma\gamma$

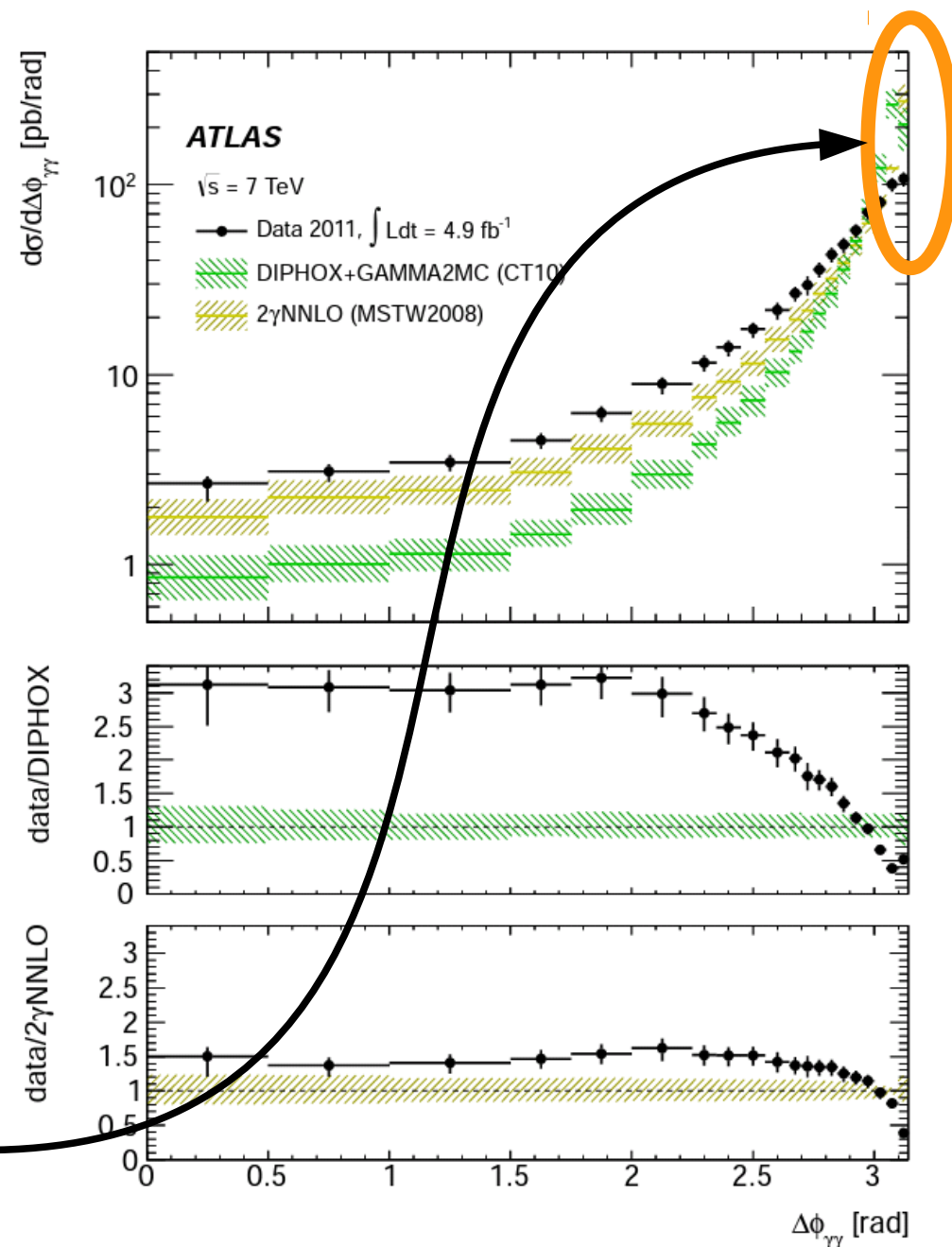
LC, Coradeschi, de Florian

First results!

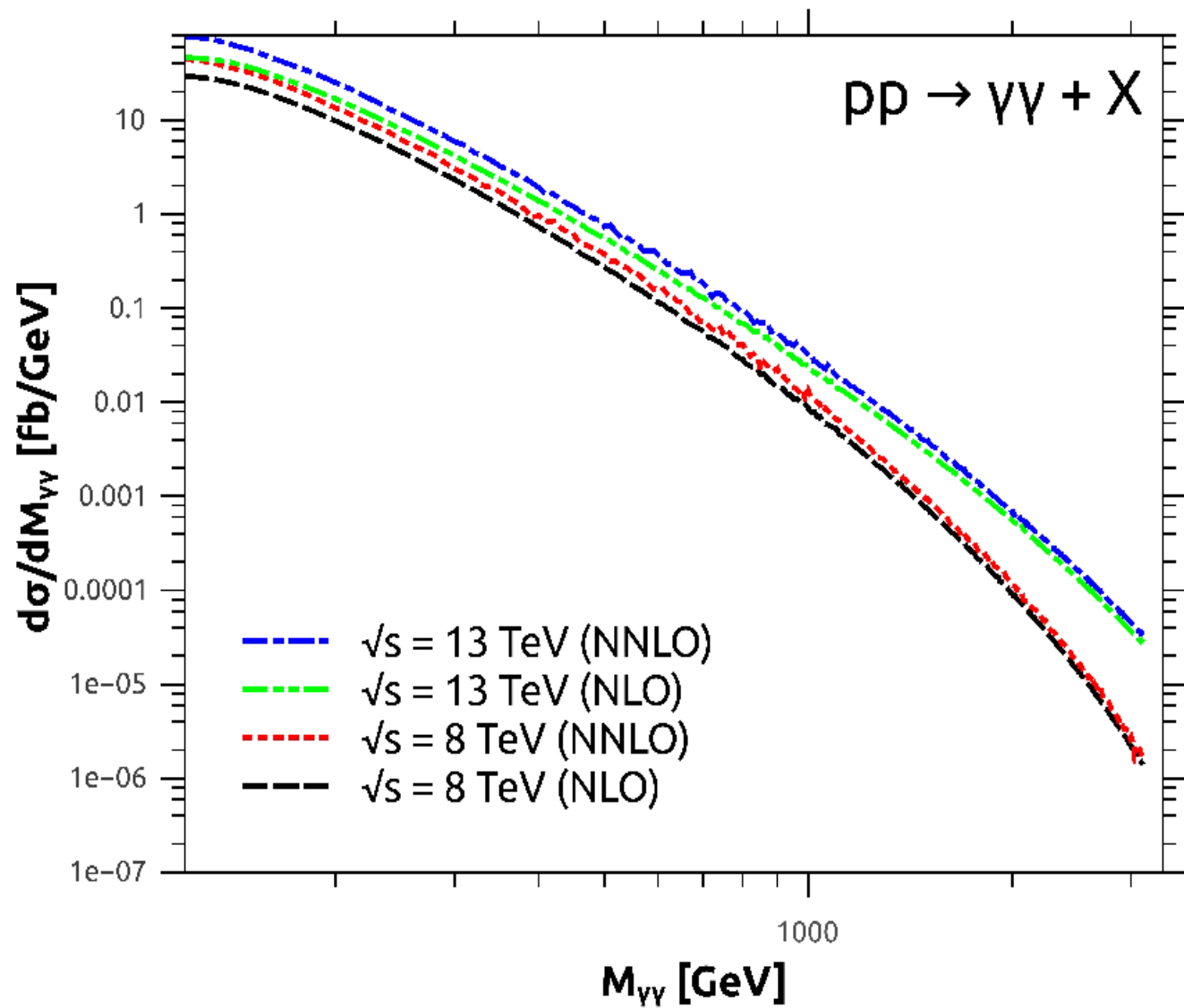


Uncertainties → 6% - 8% due to the opening of the gg channel which is “effectively” LO at NNLO

qT resummation “spreads” the uncertainties of the gg channel over the whole $\Delta\phi$ range



LHC Run II $\rightarrow$ 13 TeV

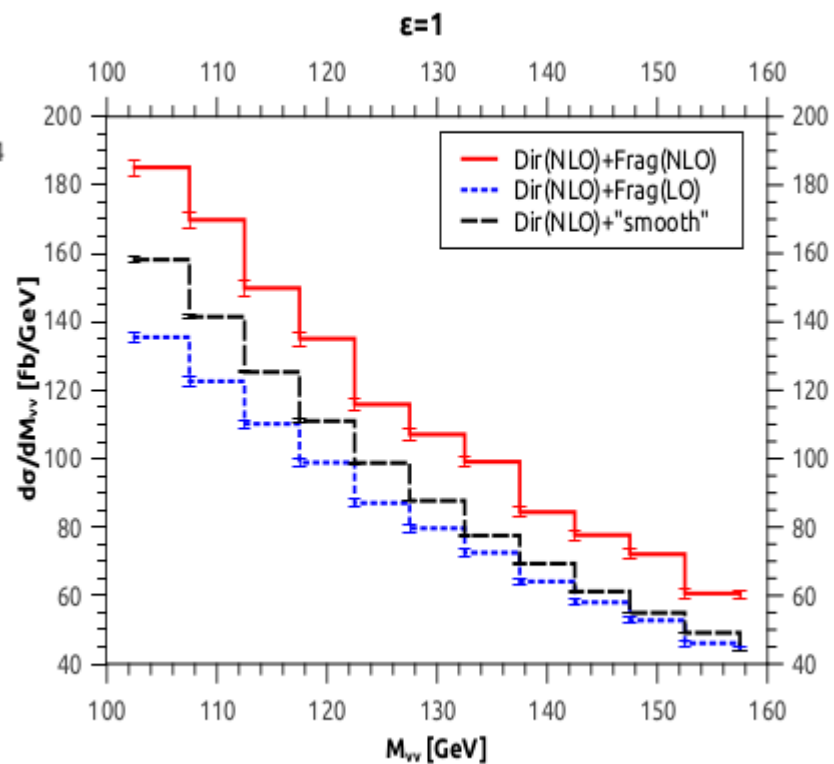
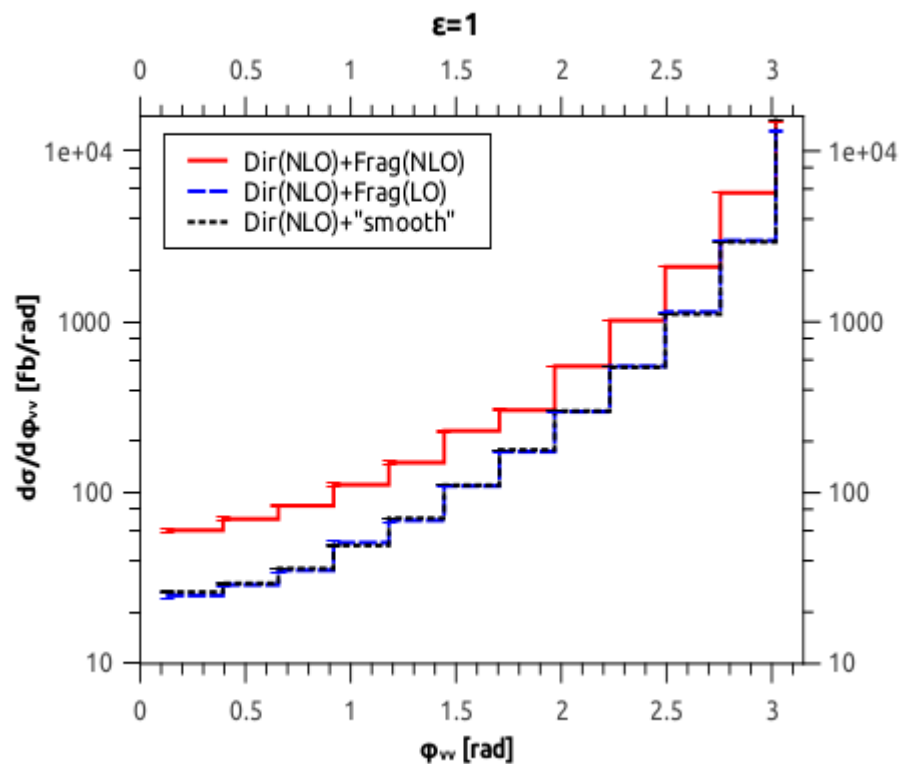


Summary

-  Cross section with “smooth” isolation is a lower bound for cross section with standard isolation.
-  Other calculations use the “smooth” isolation to reach the highest level of accuracy: $V\gamma$ production, $\gamma\gamma + (n)$ Jets, etc.
-  We have to be aware, that inconsistent results could appear, if we use the fragmentation component at one perturbative level less than the direct component.
-  Pragmatic accord (LH 2013): it is far better accepting a few % error arising from the isolation, than neglecting those huge QCD effects towards some, “more pure implementation” of the isolation prescription.
-  Good agreement between theory and data for γ +jet production
-  Good agreement between theory and data for $V\gamma$ production with a few exceptions
-  First results of diphoton production at NNLL+NNLO show an improved agreement (respect NNLO) with the LHC data over the whole q_T range.

Thank you!!!

Backup slides



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

Standard cone isolation → DIPHOX

CMS [7 TeV]

	Code	$\sum E_T^{had} \leq$	$\sigma_{total}^{NLO}(\text{fb})$	$\sigma_{dir}^{NLO}(\text{fb})$	$\sigma_{onef}^{NLO}(\text{fb})$	$\sigma_{twof}^{NLO}(\text{fb})$	Isolation
a	DIPHOX	2 GeV	3746	3504	239	2.6	Standard
b	DIPHOX	3 GeV	3776	3396	374	6	Standard
c	DIPHOX	4 GeV	3796	3296	488	12	Standard
d	DIPHOX	5 GeV	3825	3201	607	17	Standard
e	DIPHOX	$0.05 p_T^\gamma$	3770	3446	320	4	Standard
f	DIPHOX	$0.5 p_T^\gamma$	4474	2144	2104	226	Standard
g	DIPHOX	<i>incl</i>	6584	1186	3930	1468	none
h	$2\gamma\text{NNLO}$	$0.05 p_T^\gamma \chi(r)$	3768	3768	0	0	Smooth
i	$2\gamma\text{NNLO}$	$0.5 p_T^\gamma \chi(r)$	4074	4074	0	0	Smooth
j	$2\gamma\text{NNLO}$	2 GeV $\chi(r)$	3743	3743	0	0	Smooth
k	$2\gamma\text{NNLO}$	3 GeV $\chi(r)$	3776	3776	0	0	Smooth
l	$2\gamma\text{NNLO}$	4 GeV $\chi(r)$	3795	3795	0	0	Smooth
m	$2\gamma\text{NNLO}$	5 GeV $\chi(r)$	3814	3814	0	0	Smooth

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

Standard cone isolation → DIPHOX

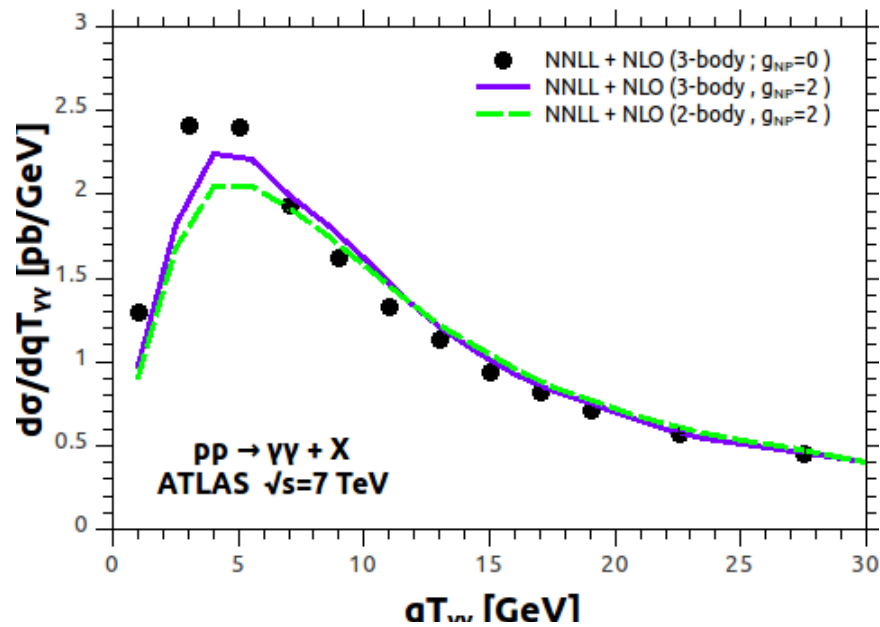
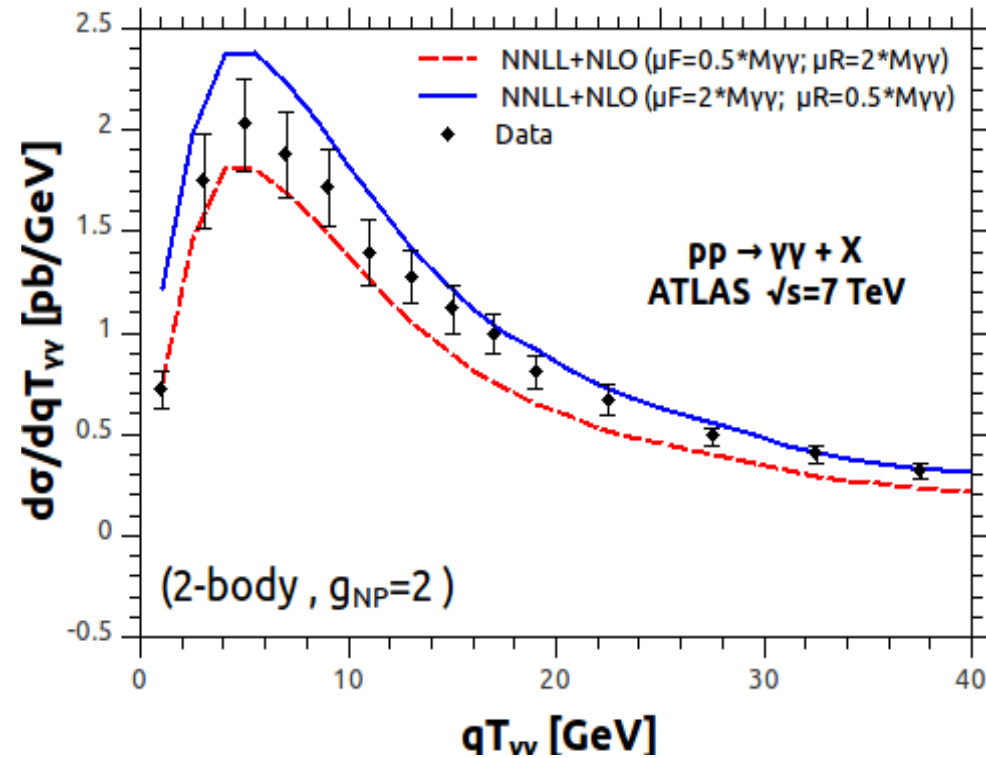
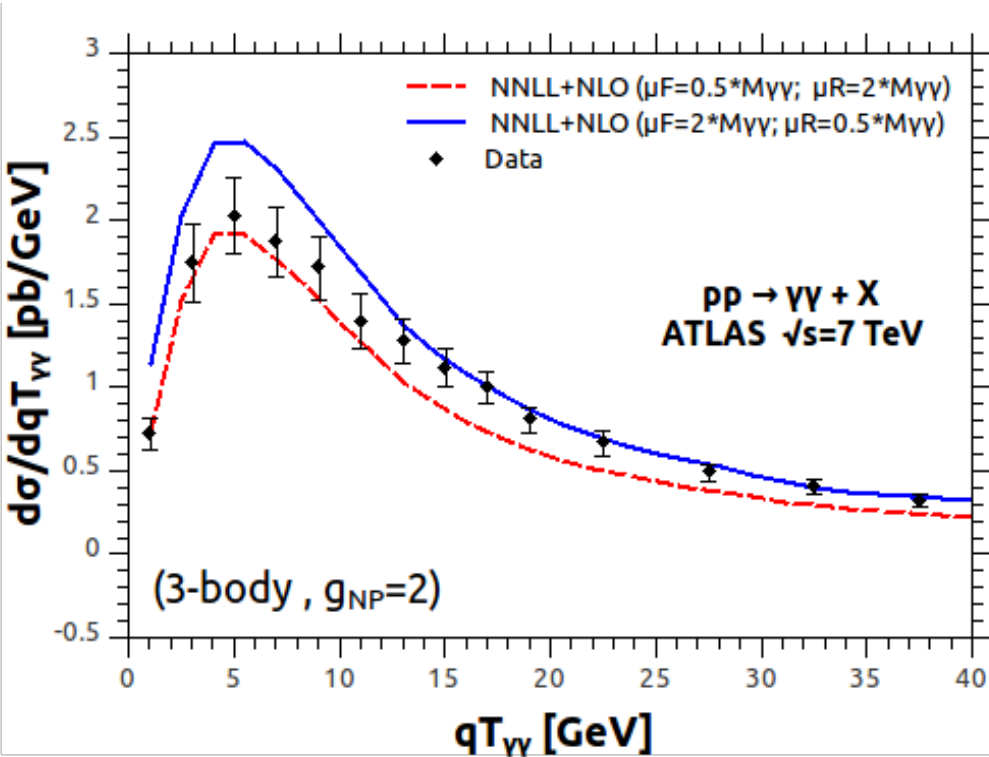
CMS [7 TeV]

	Code	$\sum E_T^{had} \leq$	$\sigma_{total}^{NLO}(\text{fb})$	$\sigma_{dir}^{NLO}(\text{fb})$	$\sigma_{frag}^{NLO}(\text{fb})$	$\sigma_{frag}^{NLO}(\text{fb})$	Isolation
a	DIPHOX	2 GeV	3746	3504	239	2.6	Standard
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m	$2\gamma\text{NNLO}$	5 GeV $\chi(r)$	3814	3814	0	0	Smooth

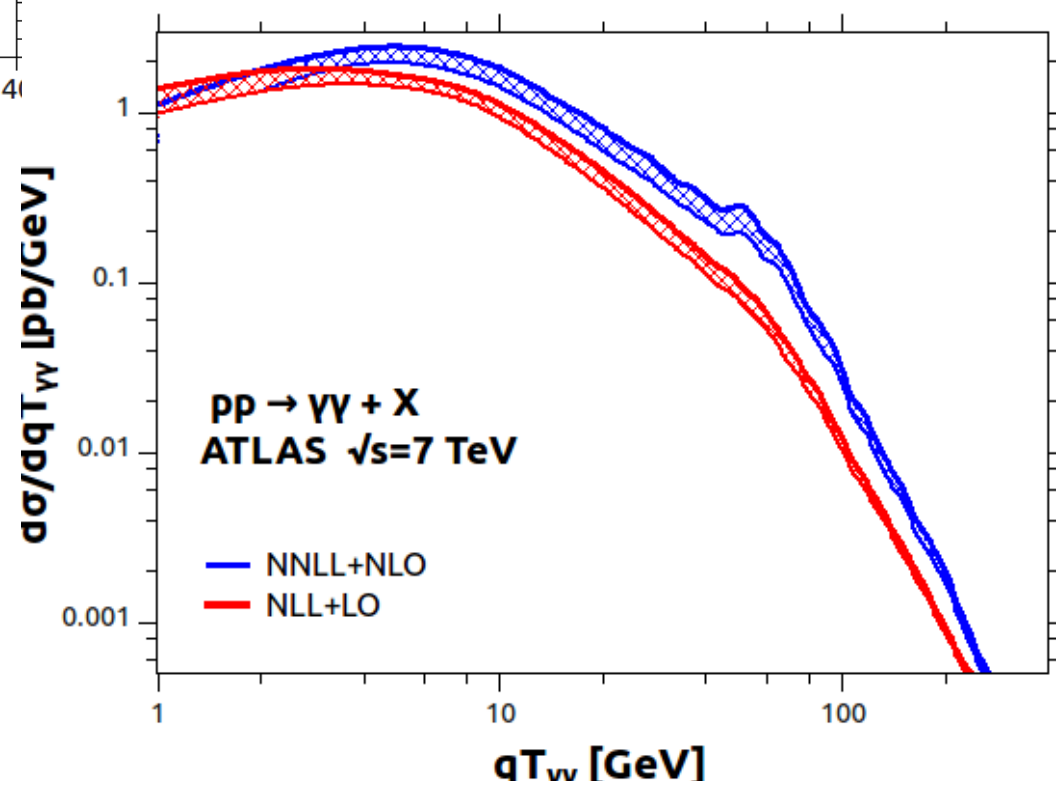
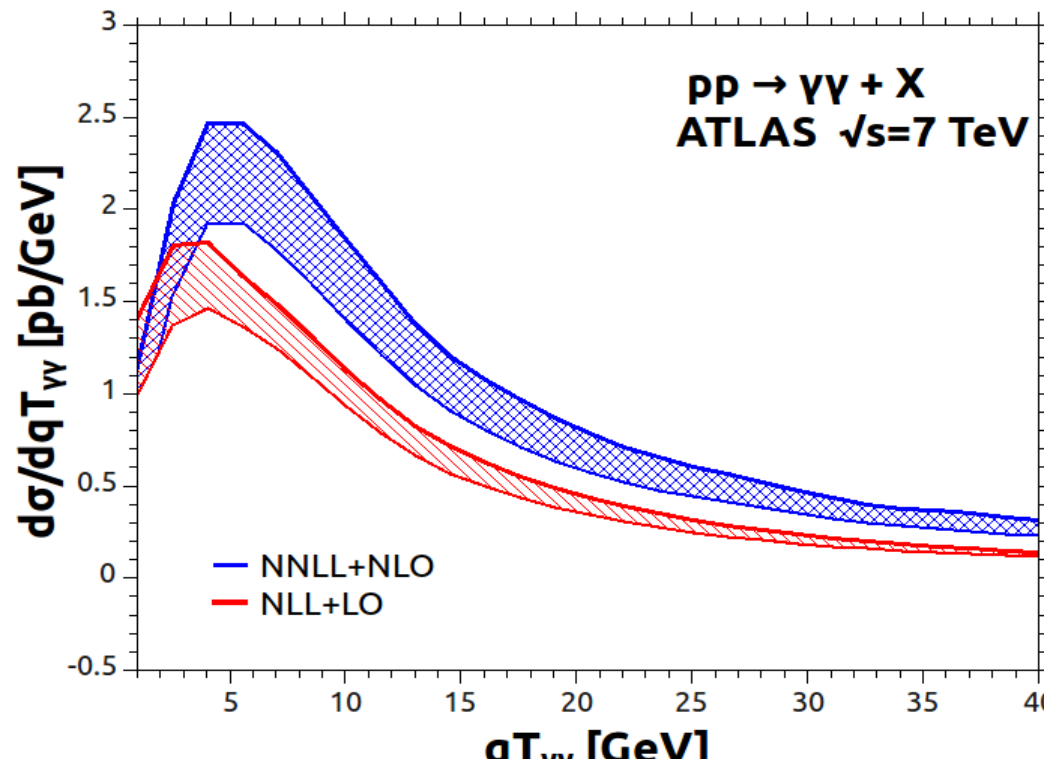
Tighter criteria

Direct component increasing

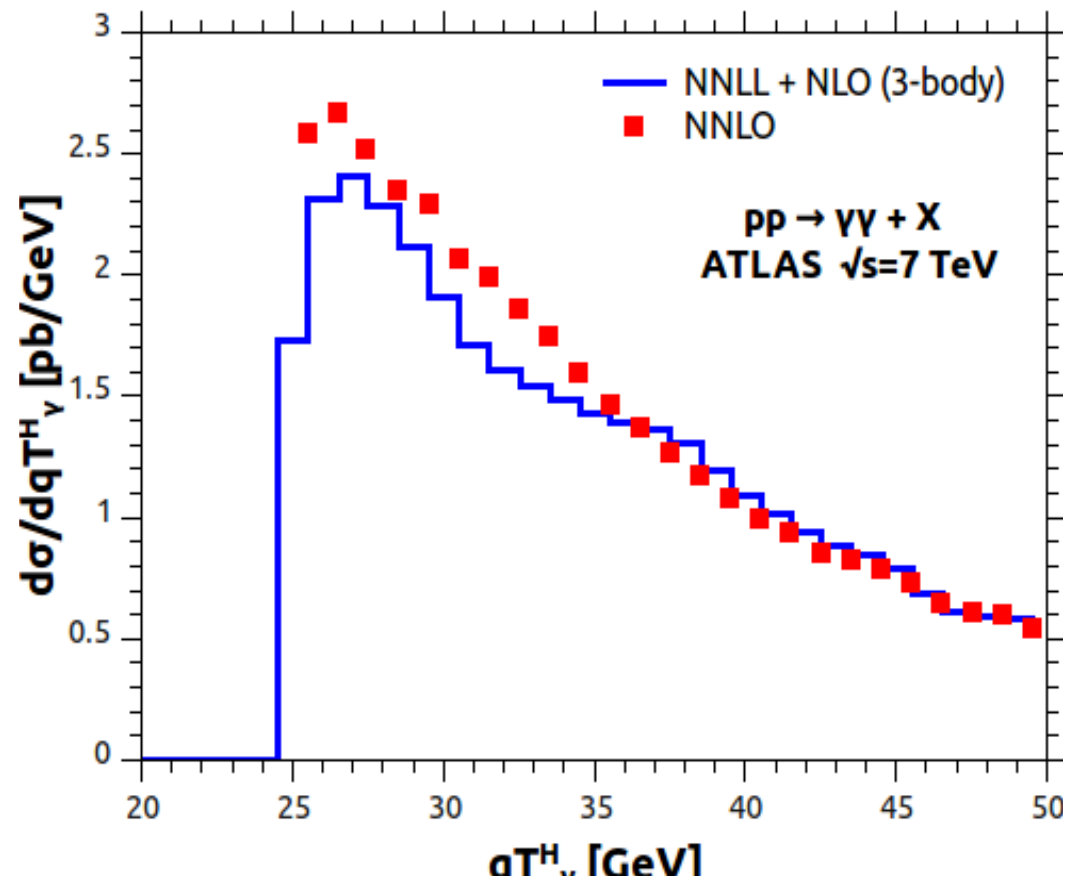
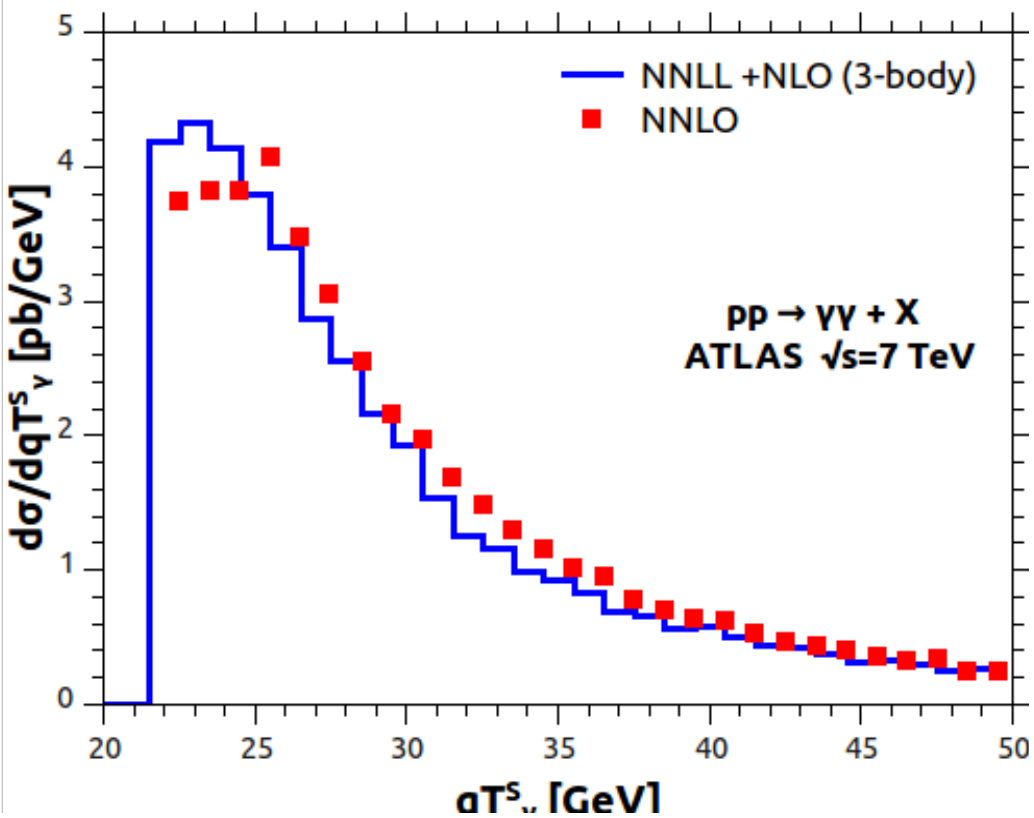
Resummation



Resummation

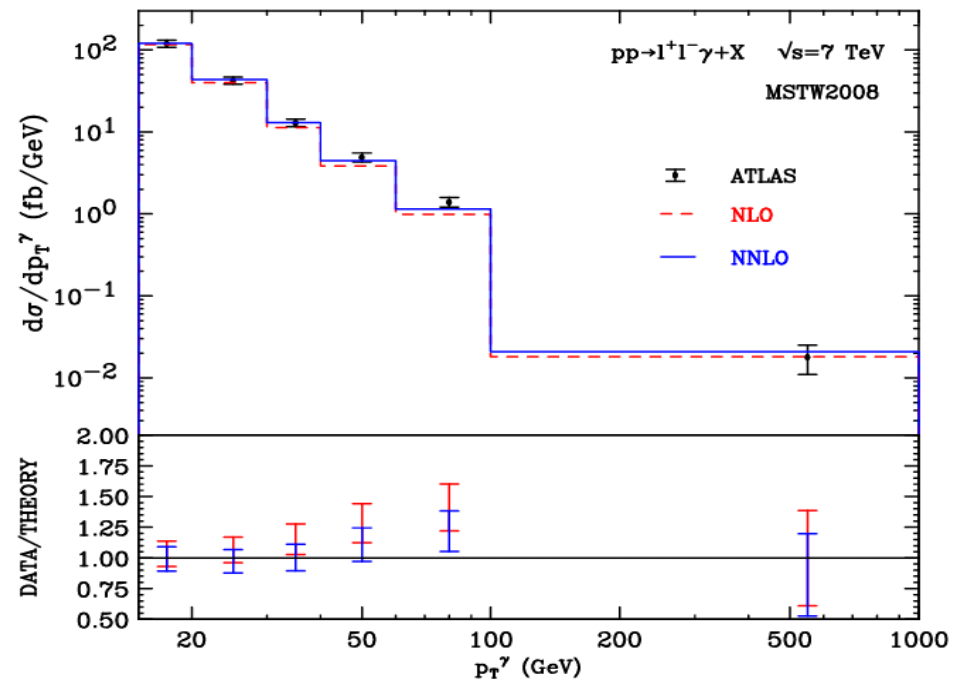
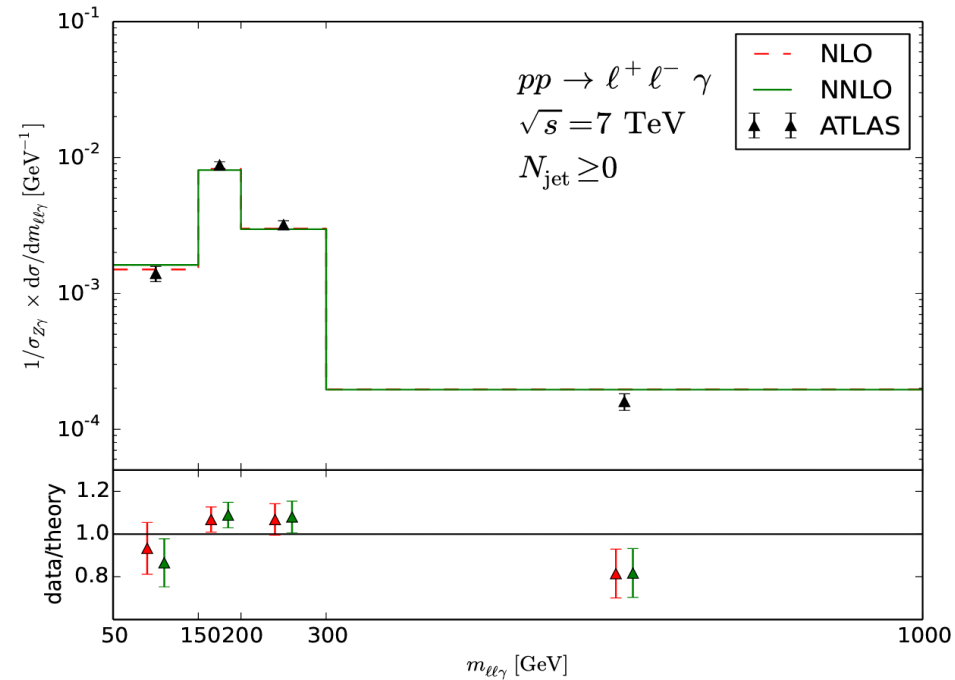
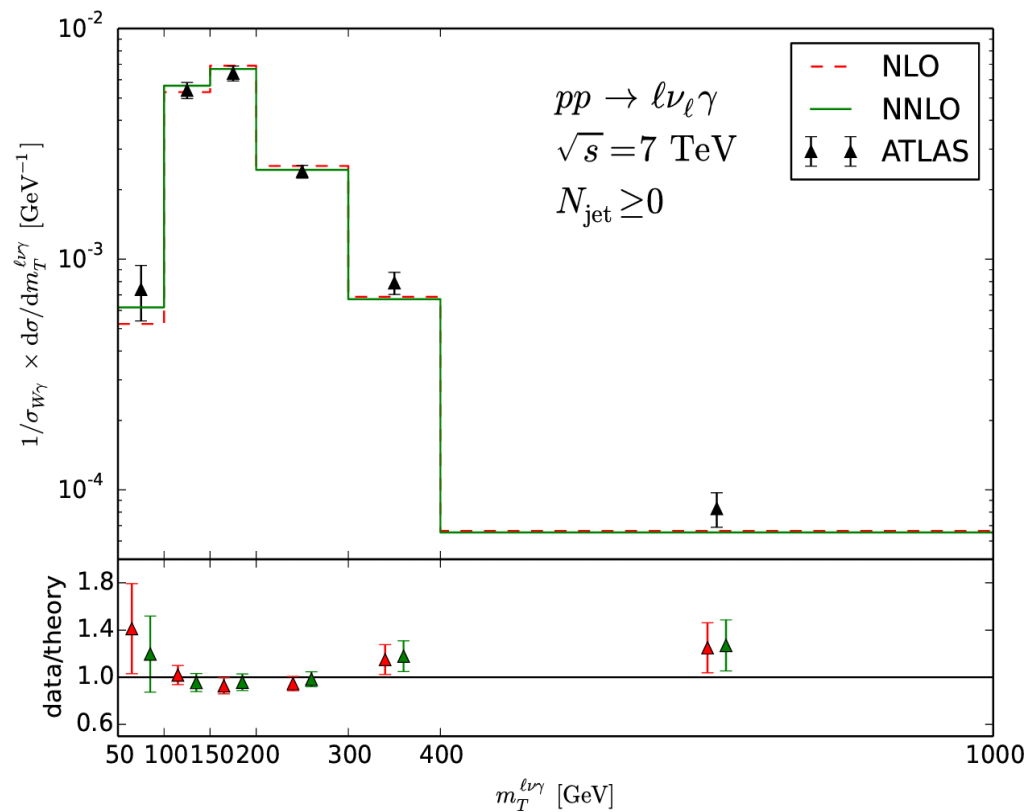


Resummation



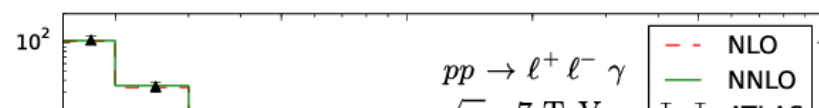
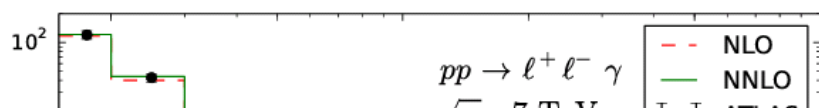
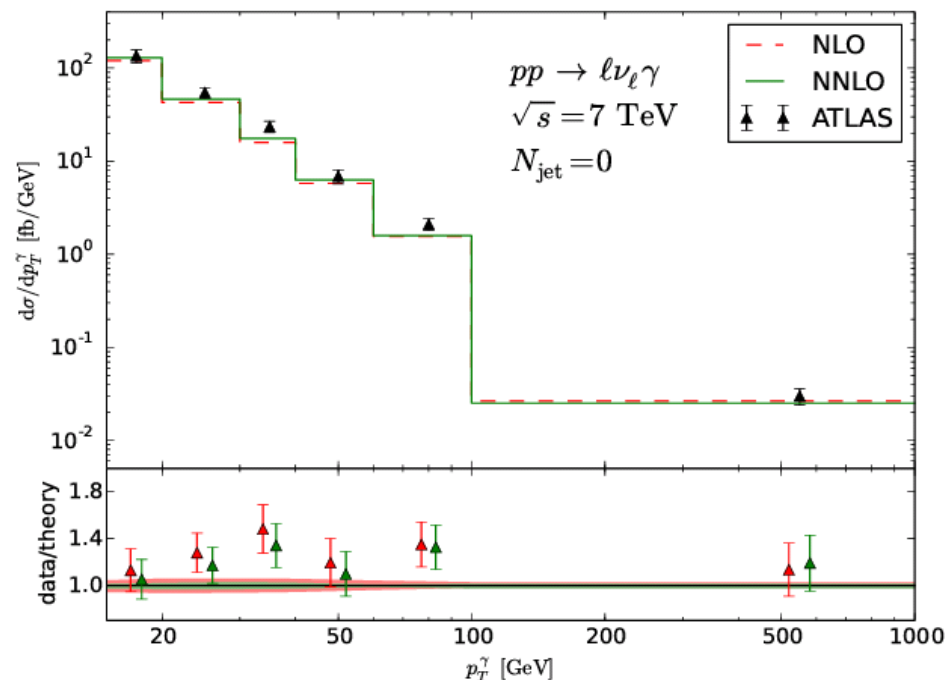
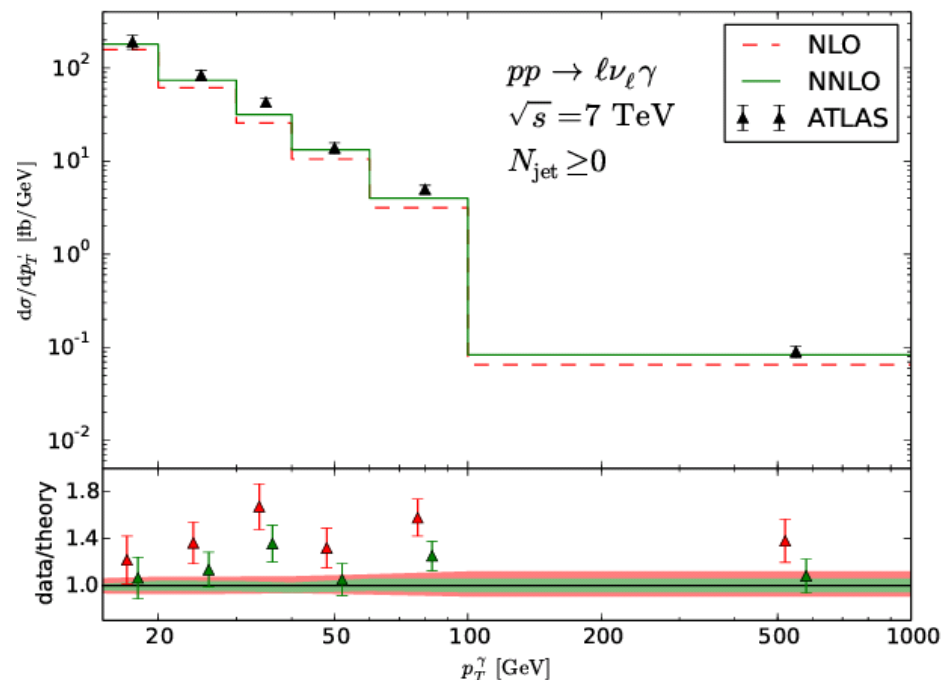
$V\gamma$ production NNLO

Grazzini, Kallweit, Rathlev, Torre

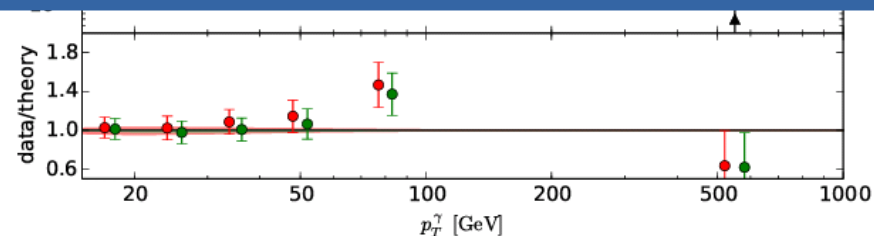
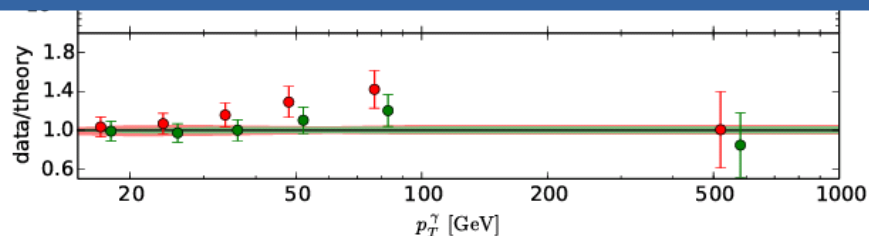


Vy production NNLO

Grazzini, Kallweit, Rathlev, Torre



It is clear that the $W\gamma$ process features much larger radiative effects with respect to the $Z\gamma$ processes. This should be contrasted to what happens in the case of inclusive W and Z boson production, where QCD radiative corrections are essentially identical. It is thus the emission of the additional photon that breaks the similarity between the charged current and the neutral current processes.



$V\gamma$ production NNLO

Grazzini, Kallweit, Rathlev, Torre

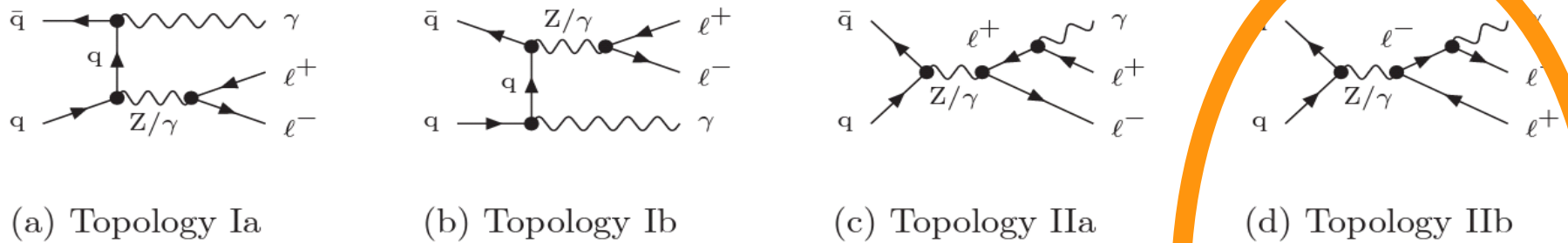


Figure 1: Feynman diagrams contributing to $Z\gamma$ production at Born level.

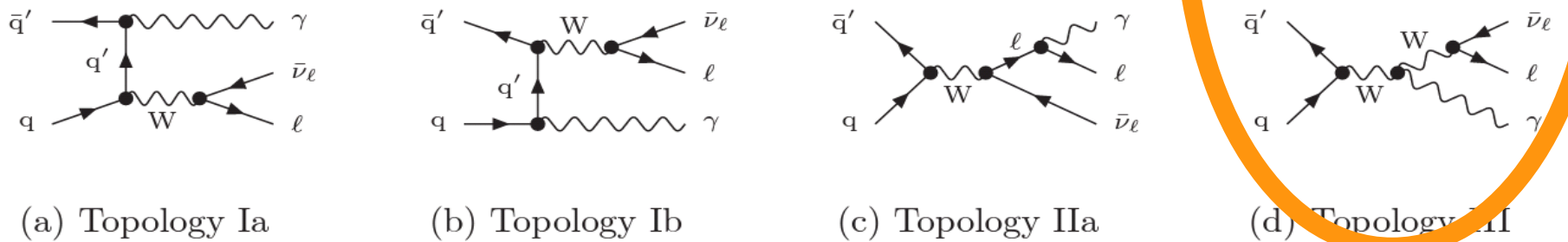


Figure 2: Feynman diagrams contributing to $W\gamma$ production at Born level.

It is clear that the $W\gamma$ process features much larger radiative effects with respect to the $Z\gamma$ processes. This should be contrasted to what happens in the case of inclusive W and Z boson production, where QCD radiative corrections are essentially identical. It is thus the emission of the additional photon that breaks the similarity between the charged current and the neutral current processes.

Outline

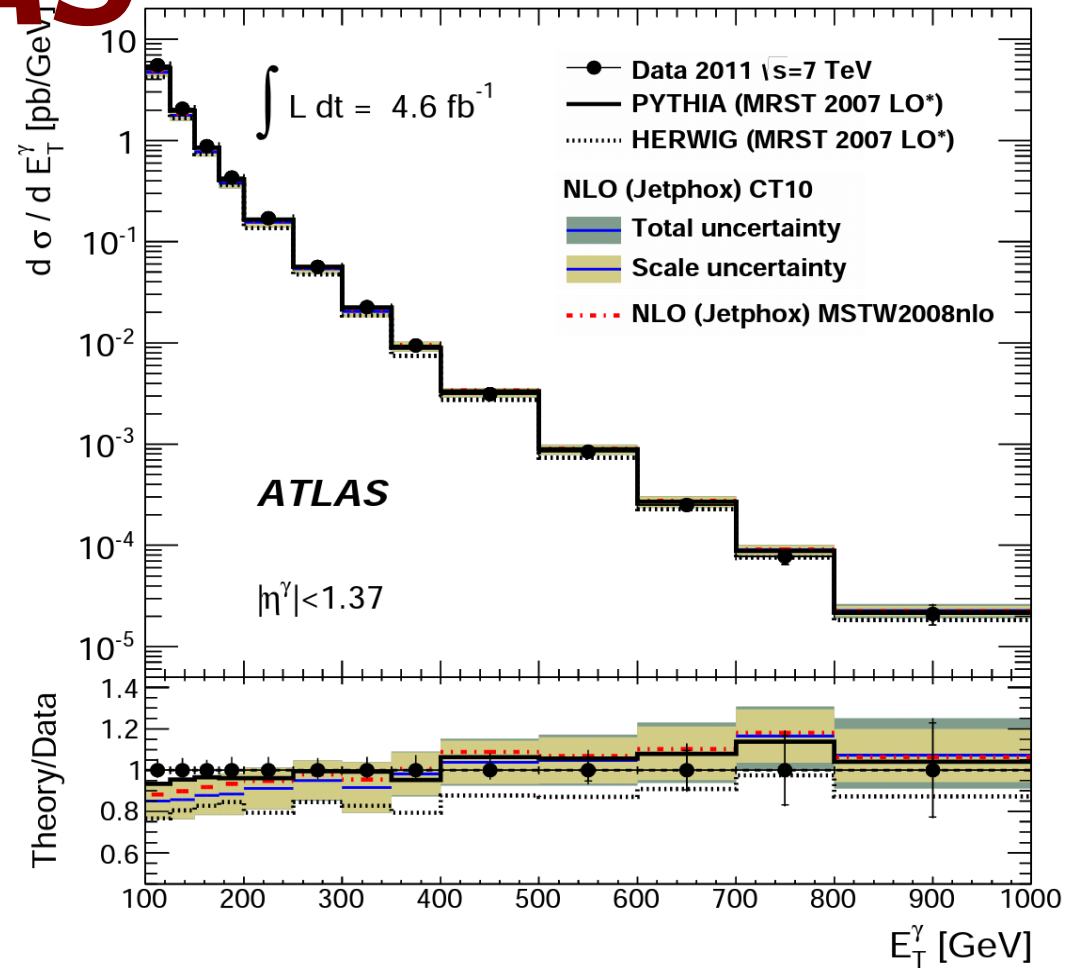
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 - 📌 Isolation criteria (IC)
 - 📌 Available FO tools
 - 📌 IC comparison ($\gamma\gamma$ NLO)
 - 📌 Les Houches accord (“tight” isolation accord)
 - 📌 ATLAS and CMS results
 - 📌 q_T Resummation $\gamma\gamma$ (ATLAS)
 - 📌 Summary
-
- ```
graph LR; Intro[Introduction] --> Motivation[Motivation]; IC[Isolation criteria (IC)] --> Production[Production mechanisms];
```

# $\gamma + \text{jet}$ ATLAS

Phys.Rev. D89 (2014) 052004

Results in good agreement with data

The data are also compared to MC predictions that include only direct photons from  $qg \rightarrow q\gamma$  and  $qq \rightarrow g\gamma$  processes calculated at LO QCD. These MC generators predict a cross section at low  $E_T^\gamma$  that is 20% lower than the data which includes all the higher-order fragmentation processes. This difference is reduced at high  $E_T^\gamma$ , where the contribution from photons originating from fragmentation becomes small. This shows that the higher order fragmentation processes contribute significantly to the shape of the predicted  $E_T^\gamma$  cross section.



In some kinematic regimes the Xsection is sensible at PDFs variations

The kinematic regions in which appear the discrepancies allow us to discriminate real radiation from fragmentation?

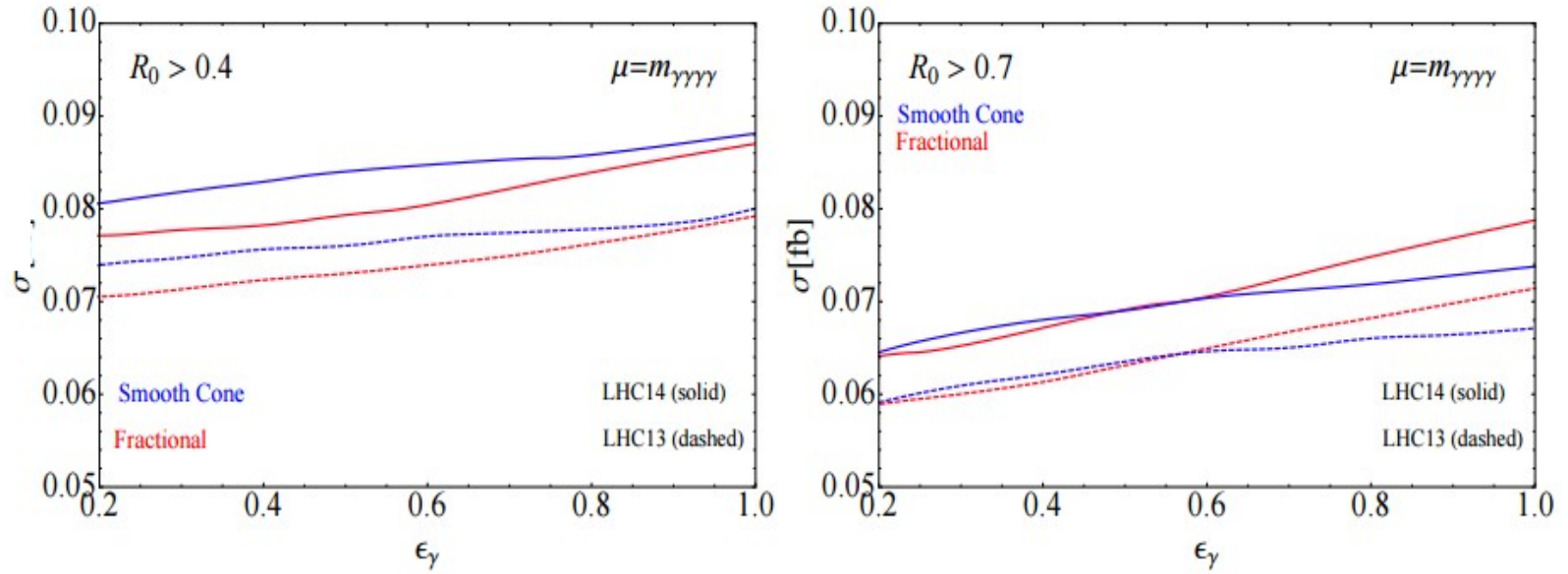


Figure 4: Dependence of the NLO cross section for different isolation criteria at 13 and 14 TeV. The plot on the left hand side corresponds to a cone size of  $R_0 > 0.4$ , whilst the plot on the right illustrates the dependence for the larger cone size choice of  $R_0 > 0.7$ .

| $\sqrt{s}$ [TeV] | Cuts                                                                    | LO [fb] | NLO [fb] | $K$ -factor |
|------------------|-------------------------------------------------------------------------|---------|----------|-------------|
| 33               | $p_T^\gamma > 20$ GeV                                                   | 0.081   | 0.21     | 2.64        |
|                  | $p_T^{\gamma_1} > 50, p_T^{\gamma_2} > 40, p_T^{\gamma_{3,4}} > 20$ GeV | 0.060   | 0.16     | 2.56        |
| 100              | $p_T^\gamma > 20$ GeV                                                   | 0.25    | 0.73     | 2.96        |
|                  | $p_T^{\gamma_1} > 50, p_T^{\gamma_2} > 40, p_T^{\gamma_{3,4}} > 20$ GeV | 0.19    | 0.53     | 2.81        |

Table I: Cross sections at LO and NLO at  $\sqrt{s}$  center of mass energies that may correspond to those of future machines. Cuts are those described in the previous section, apart from the  $p_T$  requirements, which are displayed in the table.

| $\sqrt{s}$ | photon cut            | LO [fb]              | NLO [fb]              | $K$ -factor |
|------------|-----------------------|----------------------|-----------------------|-------------|
| 7 TeV      | $p_T^\gamma > 30$ GeV | $3.36^{+1\%}_{-2\%}$ | $7.49^{+6\%}_{-4\%}$  | 2.23        |
|            | $p_T^\gamma > 50$ GeV | $0.64^{+2\%}_{-1\%}$ | $1.30^{+6\%}_{-5\%}$  | 2.03        |
| 8 TeV      | $p_T^\gamma > 30$ GeV | $3.89^{+2\%}_{-3\%}$ | $8.87^{+5\%}_{-5\%}$  | 2.28        |
|            | $p_T^\gamma > 50$ GeV | $0.77^{+1\%}_{-1\%}$ | $1.60^{+6\%}_{-4\%}$  | 2.08        |
| 13 TeV     | $p_T^\gamma > 30$ GeV | $6.42^{+4\%}_{-5\%}$ | $15.87^{+4\%}_{-3\%}$ | 2.47        |
|            | $p_T^\gamma > 50$ GeV | $1.38^{+1\%}_{-1\%}$ | $3.13^{+5\%}_{-4\%}$  | 2.27        |
| 14 TeV     | $p_T^\gamma > 30$ GeV | $6.91^{+5\%}_{-6\%}$ | $17.28^{+4\%}_{-3\%}$ | 2.50        |
|            | $p_T^\gamma > 50$ GeV | $1.50^{+1\%}_{-2\%}$ | $3.44^{+5\%}_{-4\%}$  | 2.29        |

TABLE II: Summary of LHC triphoton cross sections at various LHC operating energies, with two choices of photon  $p_T$  threshold.

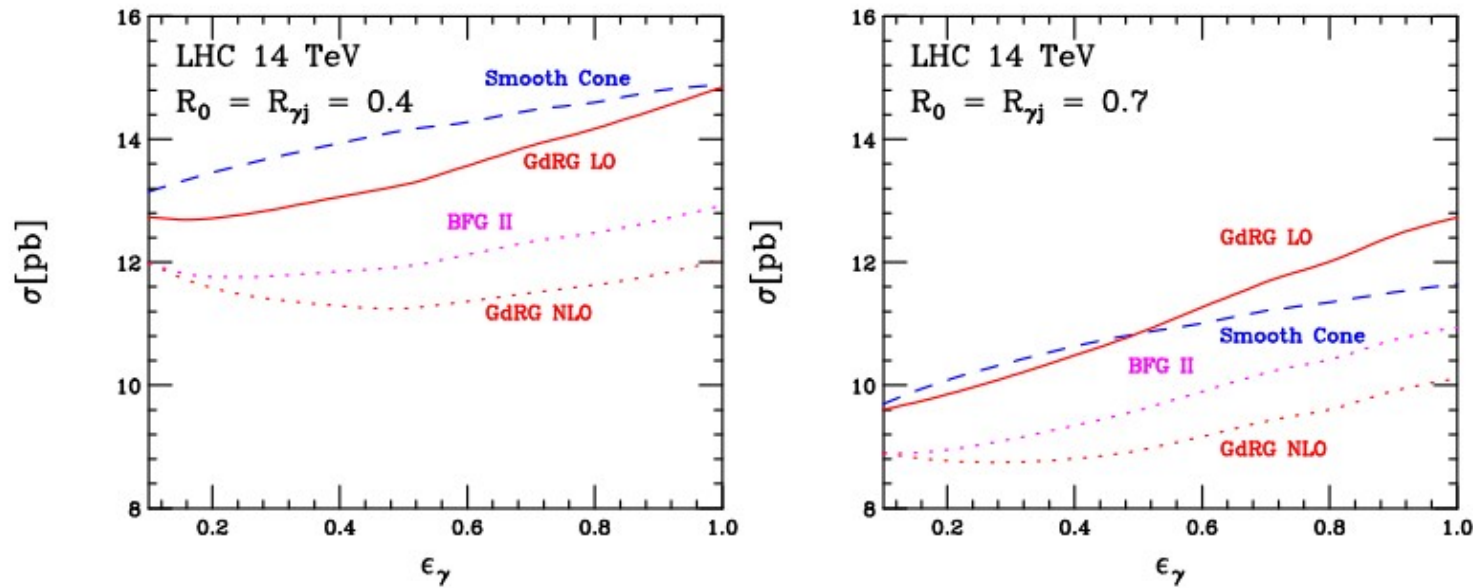


FIG. 3: Dependence of the NLO  $\gamma\gamma$ +jet cross section on the parameter that controls the amount of hadronic energy inside the isolation cone,  $\epsilon_\gamma$ . Results are shown for the fractional and smooth cone isolation procedures, using an isolation cone of size  $R_0 = 0.4$  (left) and  $R_0 = 0.7$  (right).