Progress in parton-level SM xsection calculations and comparison with data

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Outline

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

Outline

- Introduction → Motivation; Production mechanisms
- Isolation criteria (IC)
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- IC comparison (γγ NLO)
- Les Houches accord (“tight” isolation accord)
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- qT Resummation γγ (ATLAS)
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Why processes with photons in the final state are important?

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

- **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?

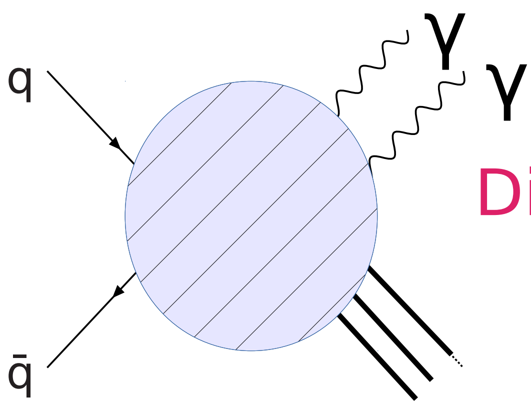
{γ+jet , γγ , γγ+ jet , γγ + (n) jets , Vγ , Wγγ }

- **This talk is devoted to the study of parton level (FO) integrators and the comparison of their results with the LHC data**
- **In the case of FO tools for γγ + (n<4) jets production and the comparison of their results with the LHC data→ Simon**
- **In the case of Event Generators (PS) and the comparison of their results with the LHC data → Frank**
- **The connection of all these processes with BSM searches → Abdelhak**
- **The connection of some of these processes with PDFs extractions → Stefano**

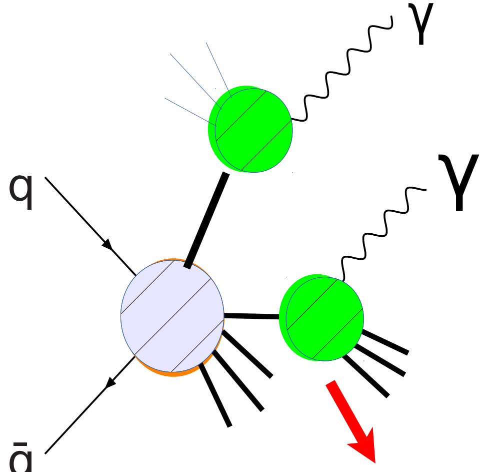
All these processes are connected by the presence of at least one-photon in the final state. Therefore all of them have a common feature: their origin arises in the photon production mechanisms

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



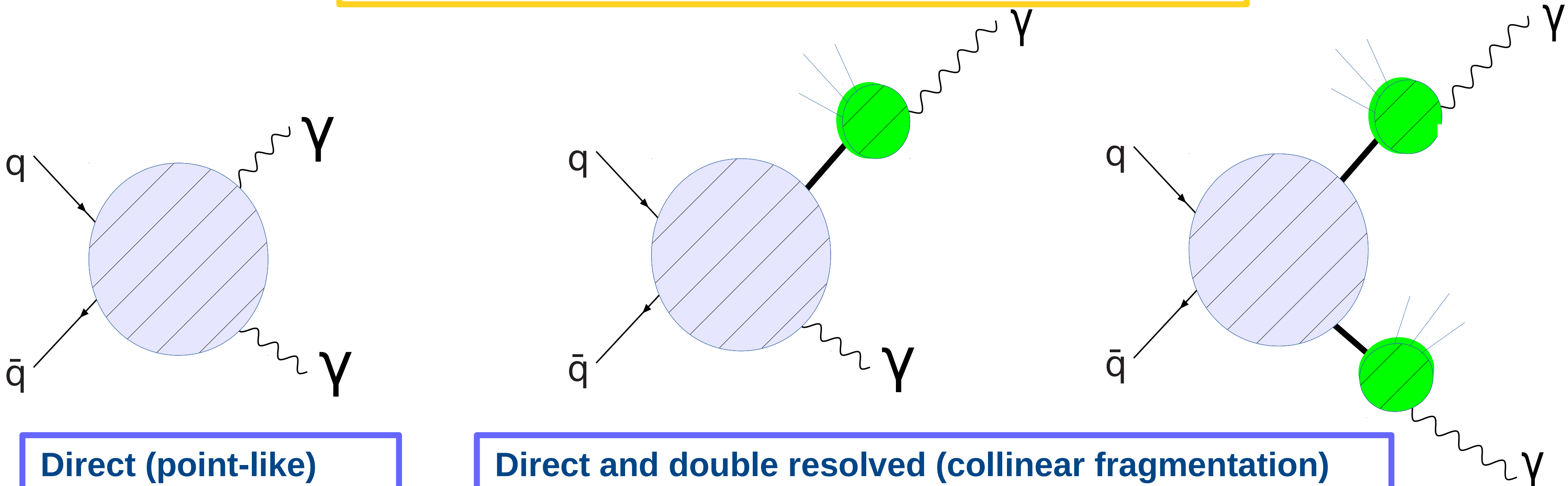
Fragmentation component: photon is produced from non-perturbative fragmentation of a hard parton (analogously to a hadron)

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

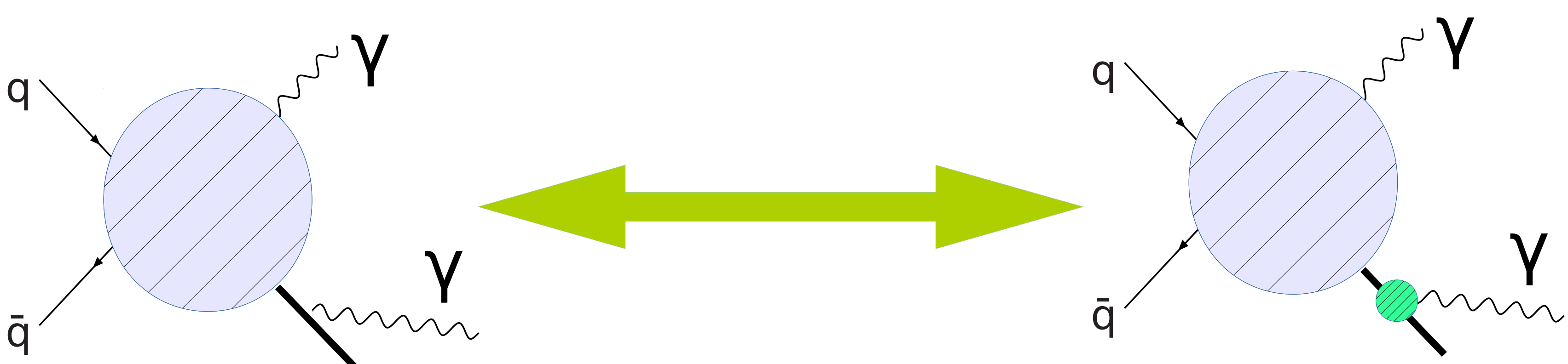
Two mechanisms for photon production



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

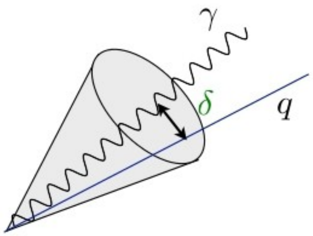
Photon production

- Experimentally photons must be isolated
- Isolation reduces fragmentation component → Large Corrections

Isolation criteria

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

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



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

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

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

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

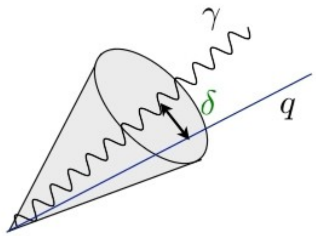
- **Democratic** Glover, Morgan(1994). Gehrmann-De Ridder, Gehrmann, Glover (1997)

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 = Eγ/(Eγ + Ehad)** of an observed photon inside the jet is larger than an experimentally defined value **Zcut**.

Photon production

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

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



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

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

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

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

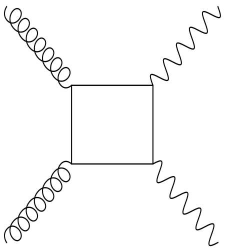
$$\sum_{\delta<R_0} E_T^{had} \leq E_T^{max}\chi(\delta)$$

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

Available theoretical (FO) tools for γγ production

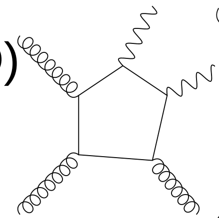
DIPHOX T. Binoth, J.Ph. Guillet, E. Pilon and M. Werlen

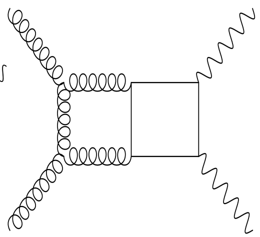
Full NLO for direct and fragmentation + Box contribution (one piece of NNLO)



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)

2γNNLO Catani, LC, de Florian, Ferrera, Grazzini

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

2γRes LC, Coradeschi, de Florian

Incorporates the qT resummation at NNLL+NNLO

Available theoretical (FO) tools for γγ production

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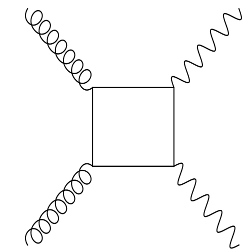

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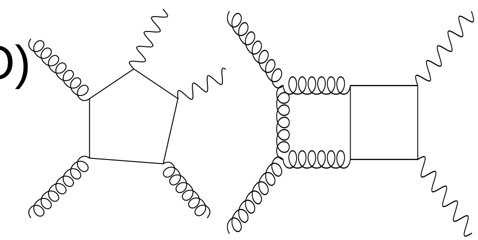

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NLL q_T resummation for direct (with regulator for collinear singularities)

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

2γNNLO

Catani, LC, de Florian, Ferrera, Grazzini

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

2γRes

LC, Coradeschi, de Florian

Incorporates the qT resummation at NNLL+NNLO

Available theoretical (FO) tools for:

γγ + (n<4) jets → Simon talk

γ + 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

Vγ 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

γγγ, Wγγ, γγγγ, Zγγ, ... production

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

Full NLO for direct, but only LO for fragmentation

Available theoretical (FO) tools for:

$\gamma\gamma$ + (n<4) jets → Simon talk

γ + jet

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Full NLO for direct and fragmentation

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NNLO Grazzini, Kallweit, Rathlev, Torre

Full NNLO for direct

$\gamma\gamma\gamma$, W$\gamma\gamma$, $\gamma\gamma\gamma\gamma$, Z$\gamma\gamma$, ... production

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

Full NLO for direct, but only LO for fragmentation

→ First Evidence March ATLAS 2015

Available theoretical (FO) tools for:

γγ + (n<4) jets → Simon talk

γ + jet

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Full NLO for direct and fragmentation

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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

IC comparison (NLO)

Standard vs Smooth

$\gamma\gamma$ production

IC comparison (NLO)

Standard vs Smooth

γγ production

Full NLO fragmentation contributions

DIPHOX

IC comparison (NLO)

Standard vs Smooth

γγ production

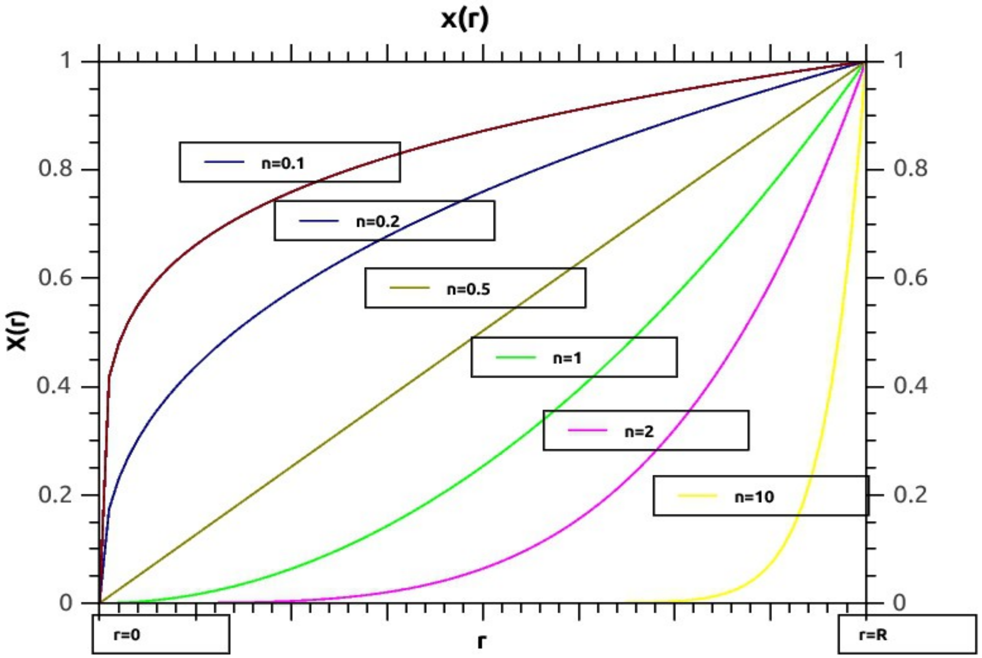
Full NLO fragmentation contributions

DIPHOX

Would be nice the same study with γ+jet

JetPHOX

IC comparison (γγ at NLO)

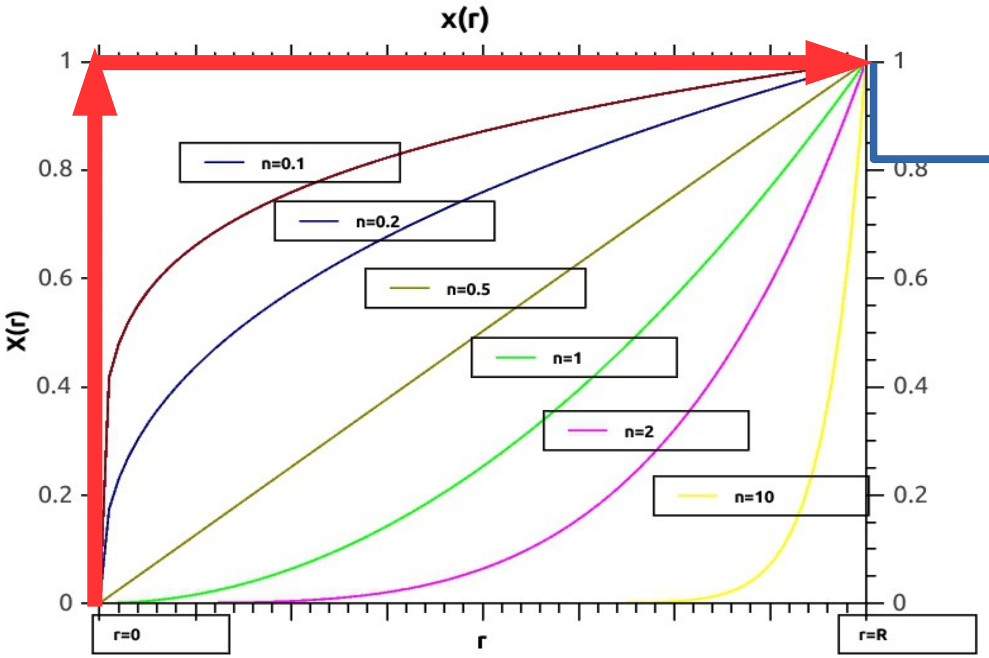


$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

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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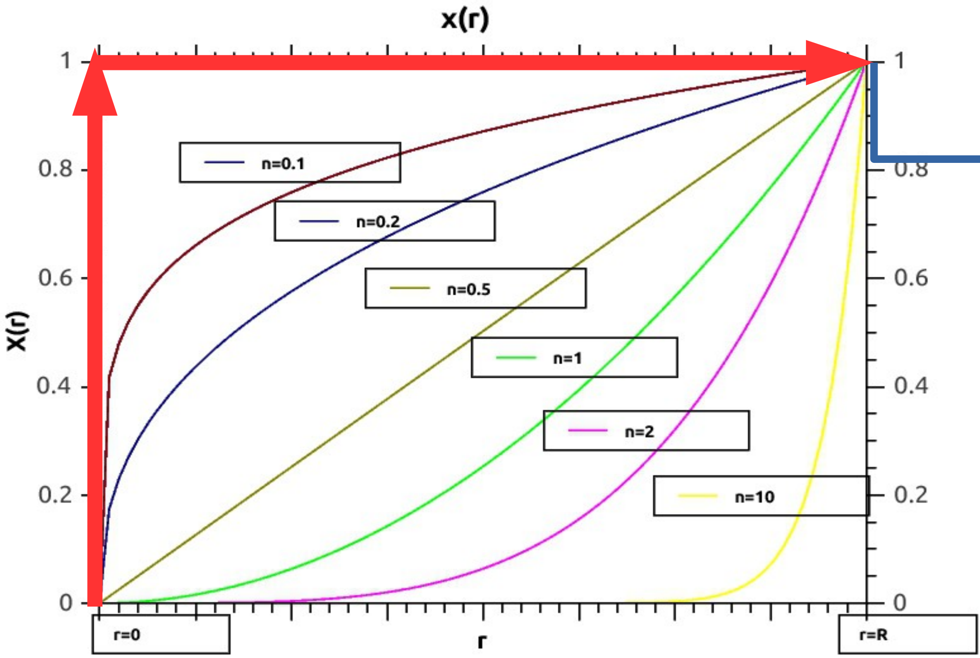

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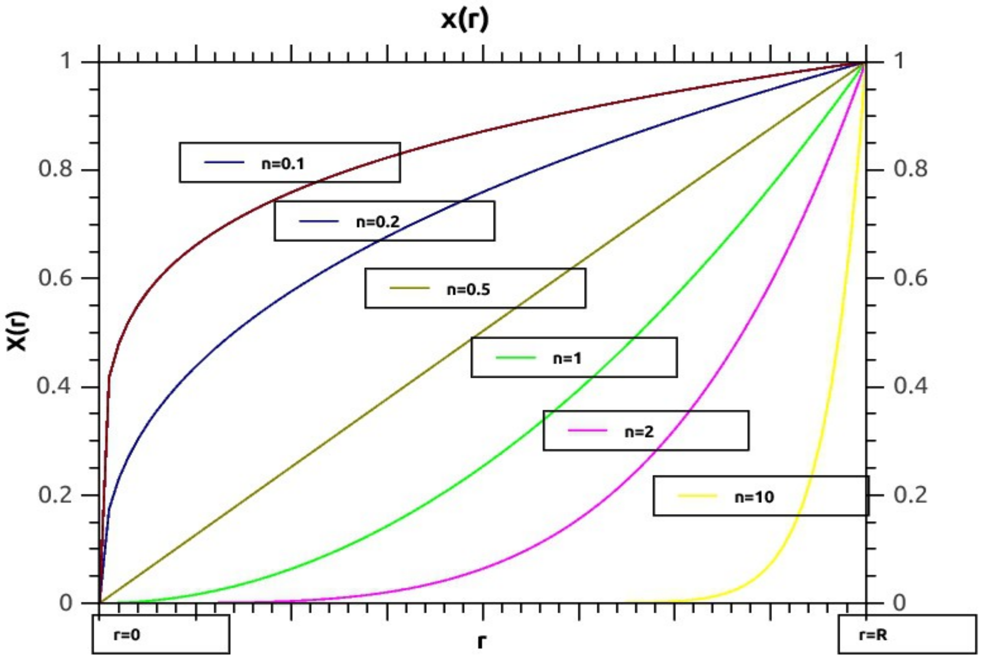
- **The smooth cone isolation criterion is more restrictive than the standard one**
- $$\sigma_{Frix}\{R, E_{T\ max}\} \leq \sigma_{Stand}\{R, E_{T\ max}\}$$

(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]

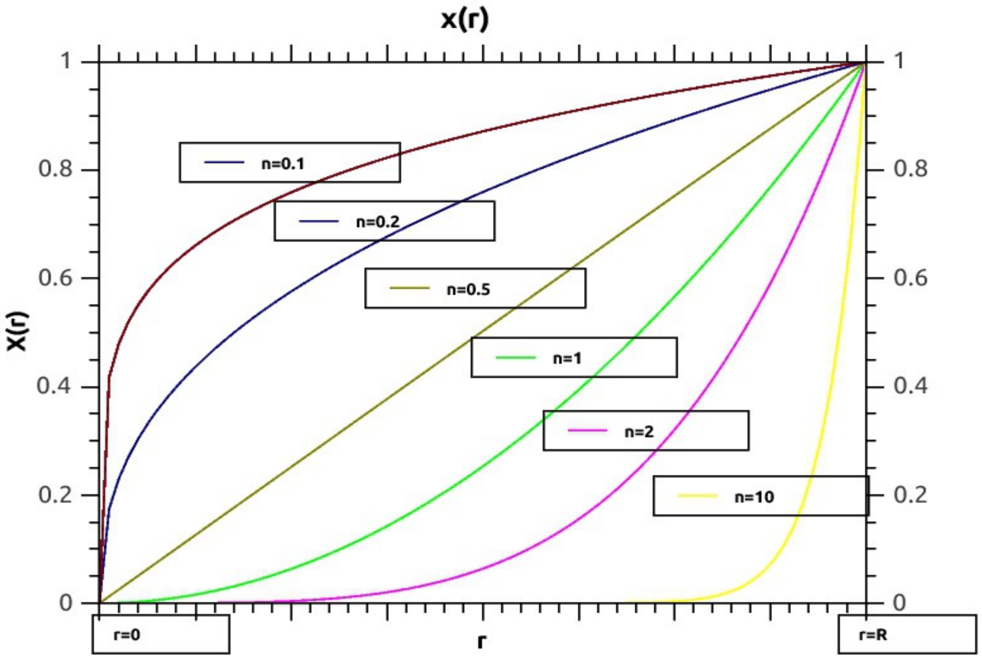
T. Binoth, J. Guillet, E. Pilon, and M. Werlen (1999)

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



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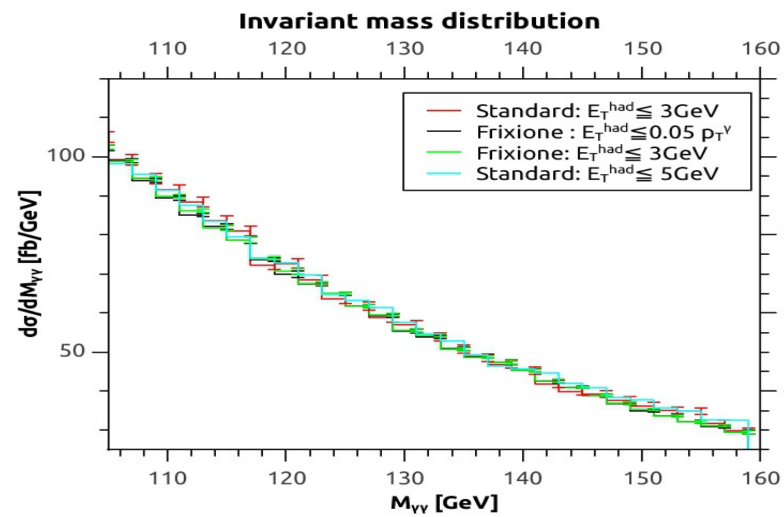

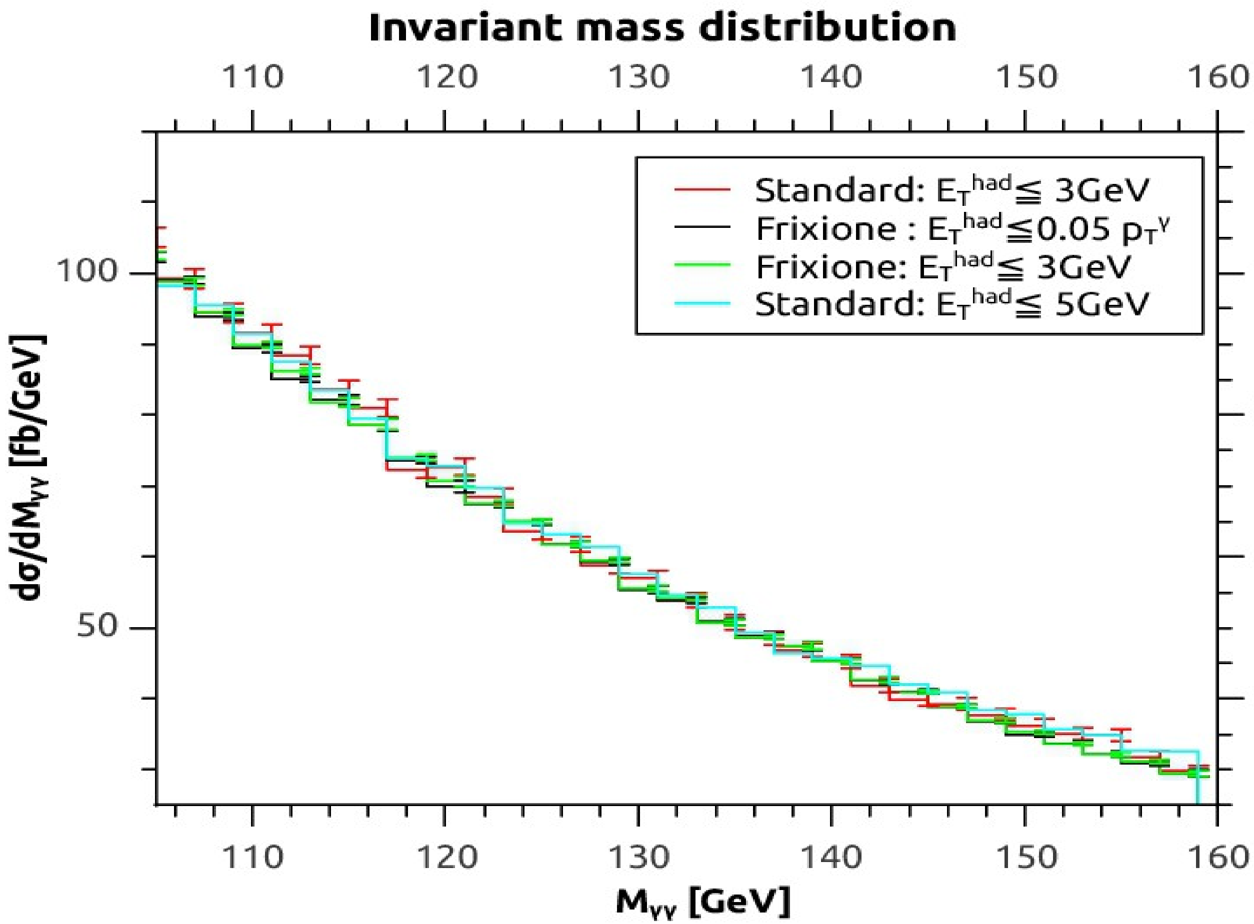

$$\ldots(\delta)) \Big)^n \leq 1$$

$$\ldots^d(\delta) \leq E_{T\,max}^{had}$$

$$\ldots^d(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$$

llinear divergences

ntribution (only direct)

well defined

ect + Fragmentation

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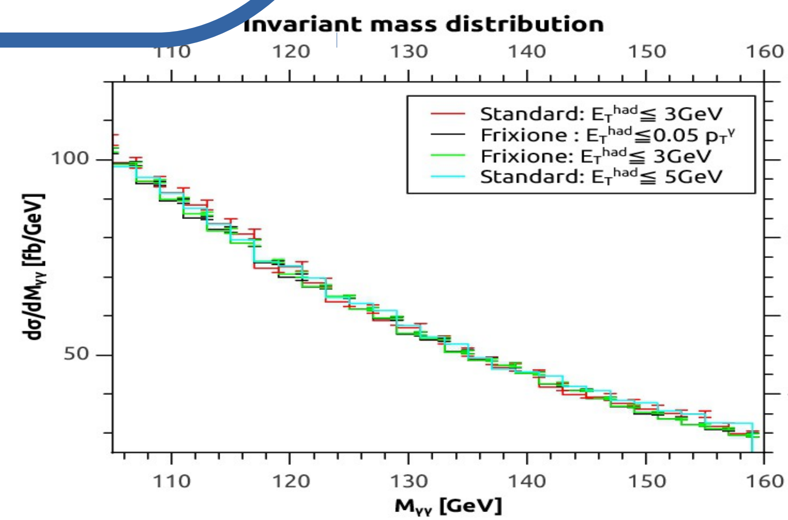

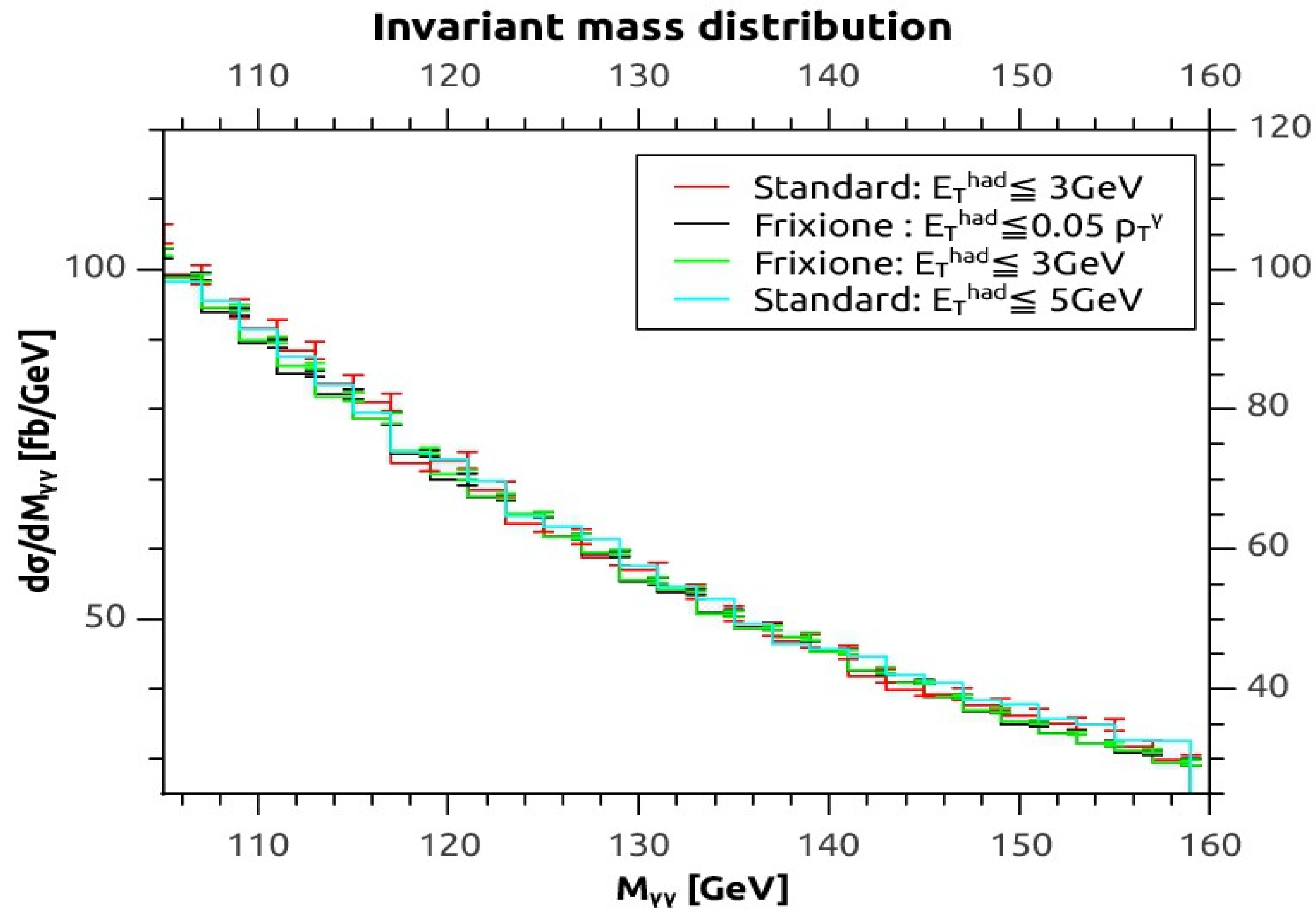

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$$\ldots^d(\delta) \leq E_{T\,max}^{had}$$

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llinear divergences

ntribution (only direct)

well defined

But the effects of the fragmentantion 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]**

Xsection [NLO] = **Direct [NLO] + Frag [NLO]** (Isolation Criterion: Standard, Democratic, Frixione, etc.)

Xsection [NLO] = Direct [NLO] ~~+ Frag [NLO]~~ (Isolation Criterion: Frixione)

Xsection [NLO] = Direct [NLO] + **Frag [LO]** (Isolation Criterion: Standard, Democratic, Frixione, etc.)

The calculation of fragmentation contributions is very difficult:

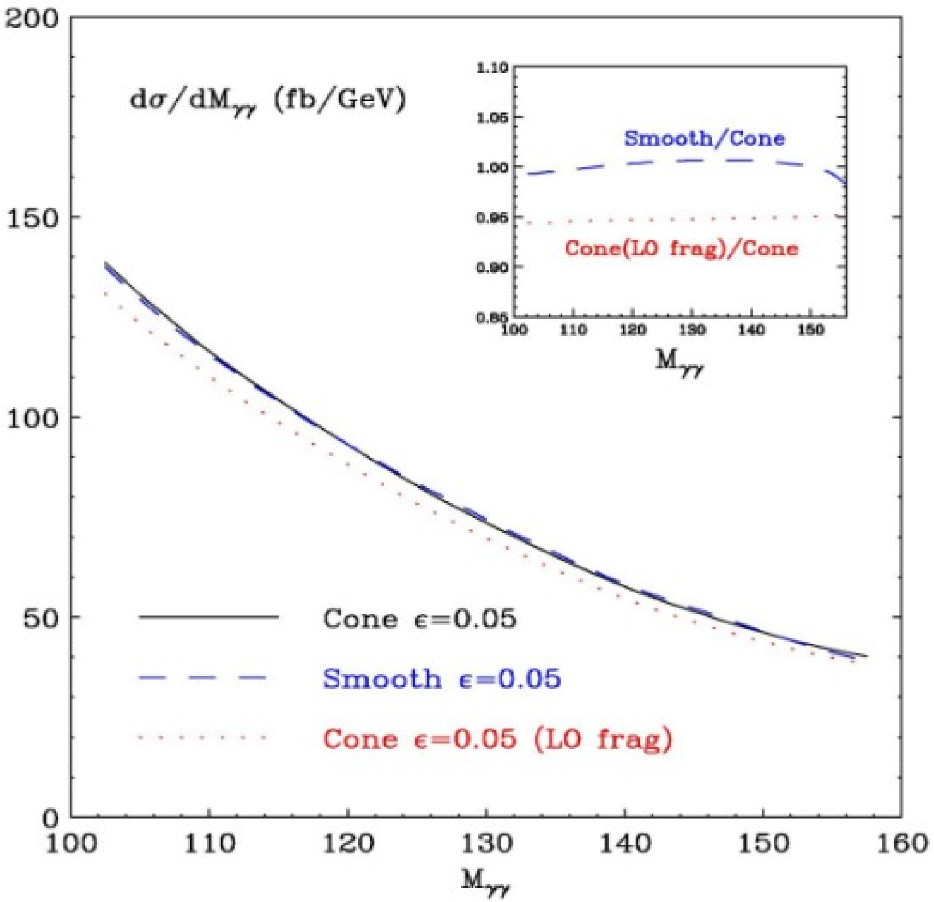
We can find calculations in which the fragmentation component is considered at one perturbative level less than the direct component.

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

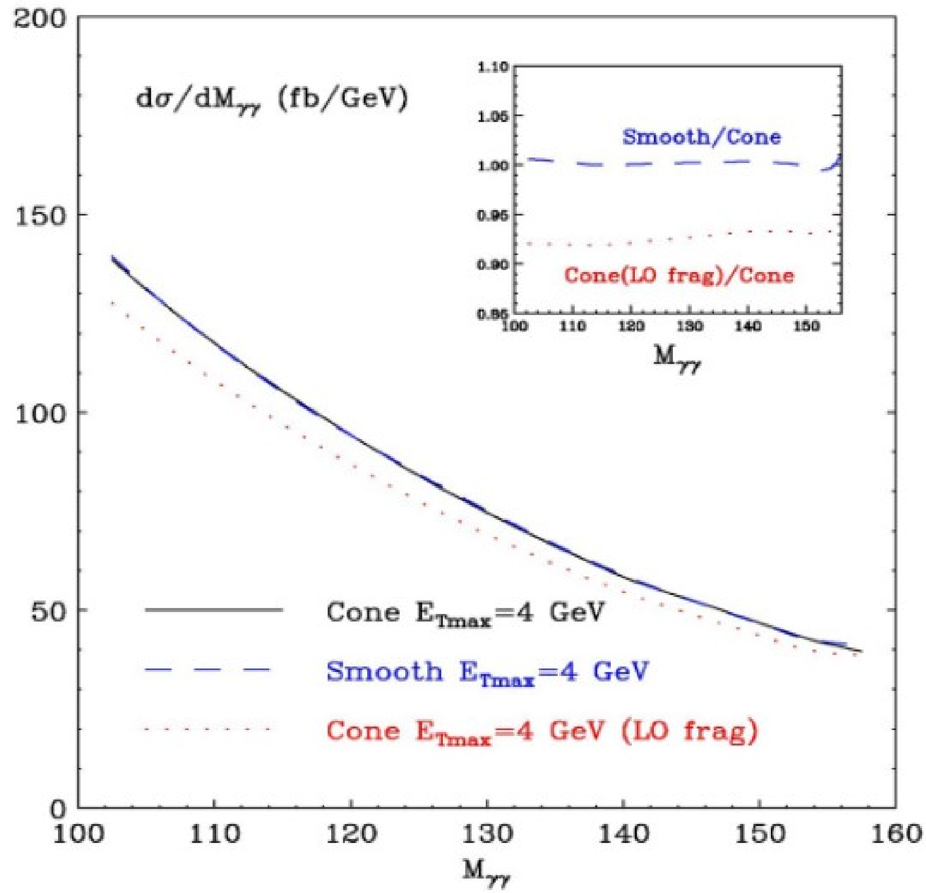
$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$ $p_T^{\gamma\,soft} \geq 30\,\mathrm{GeV}$ $100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$ $|\eta^\gamma| \leq 2.5$ $R_{\gamma\gamma} \geq 0.45$

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

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

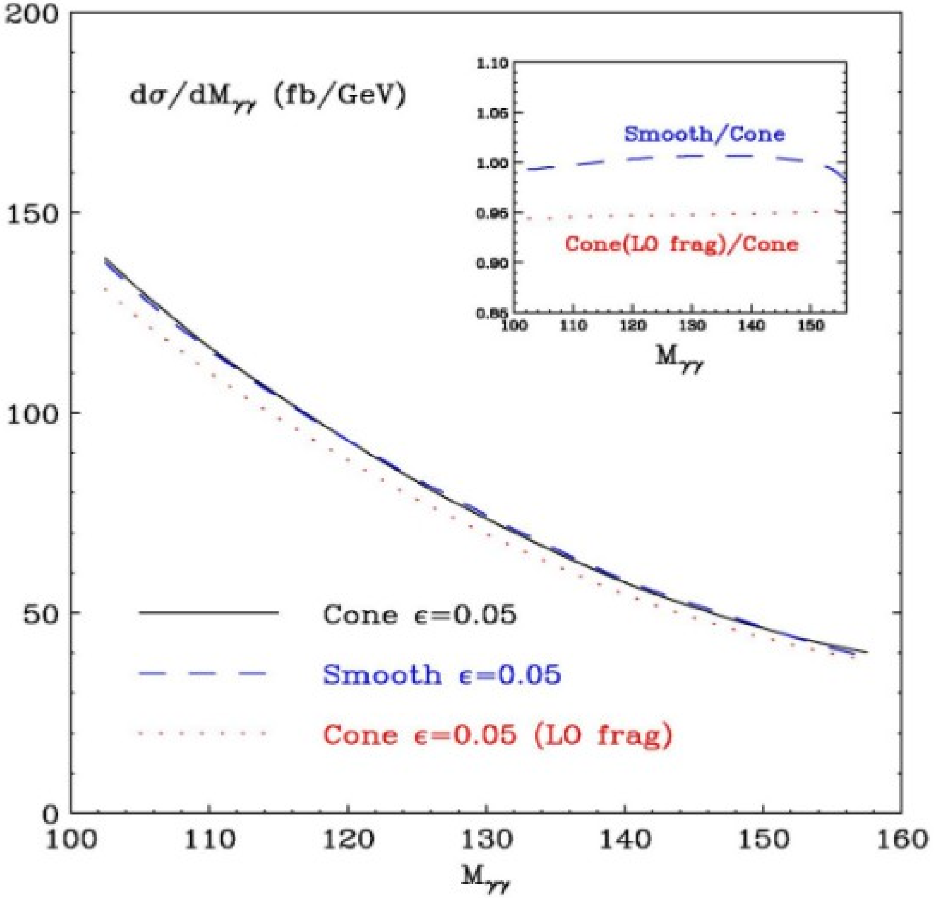


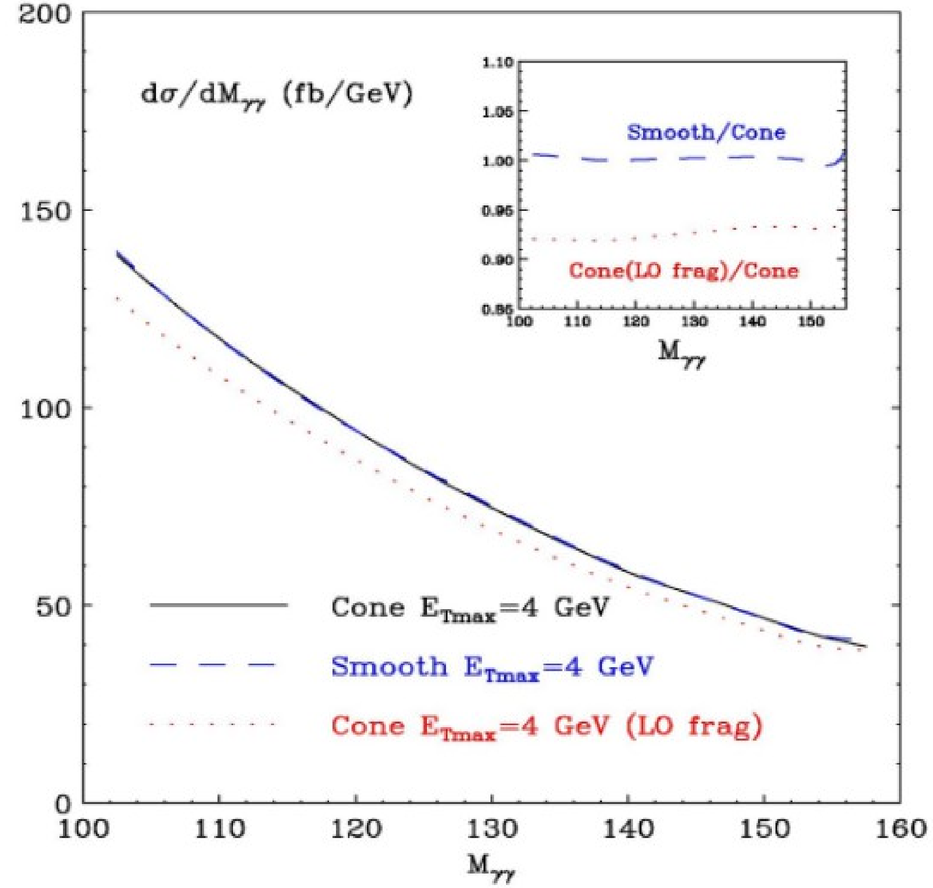
$E_{T\,max}^{had} = 4\,\mathrm{GeV}$



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





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

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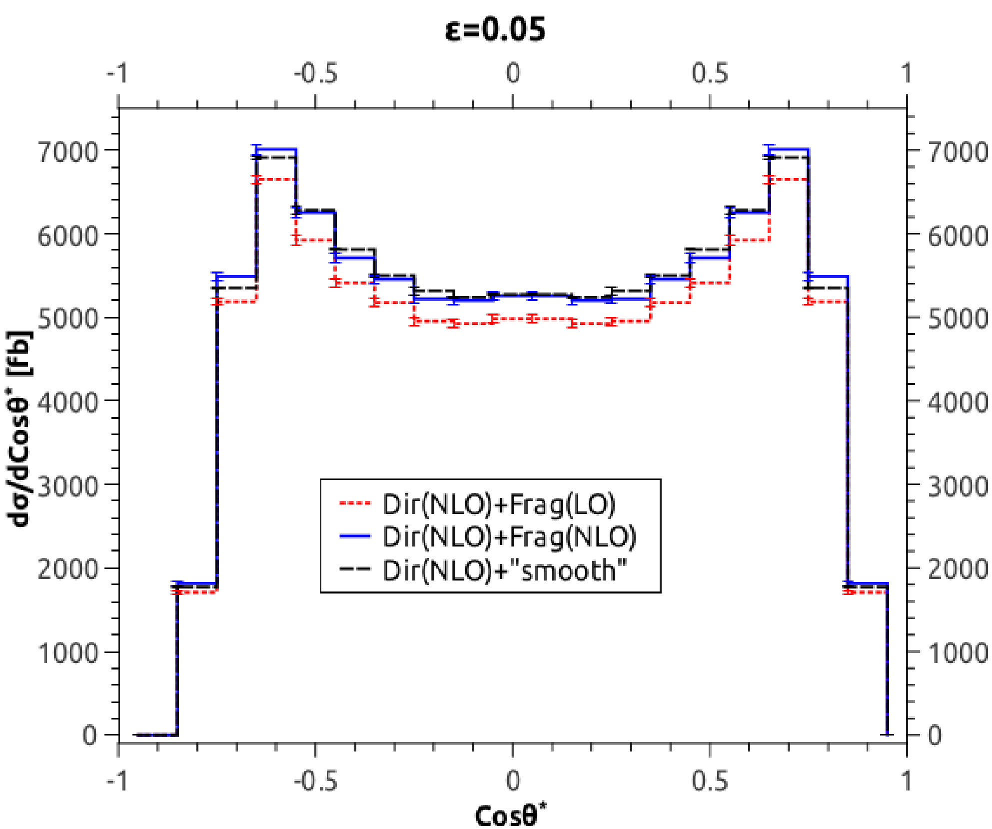
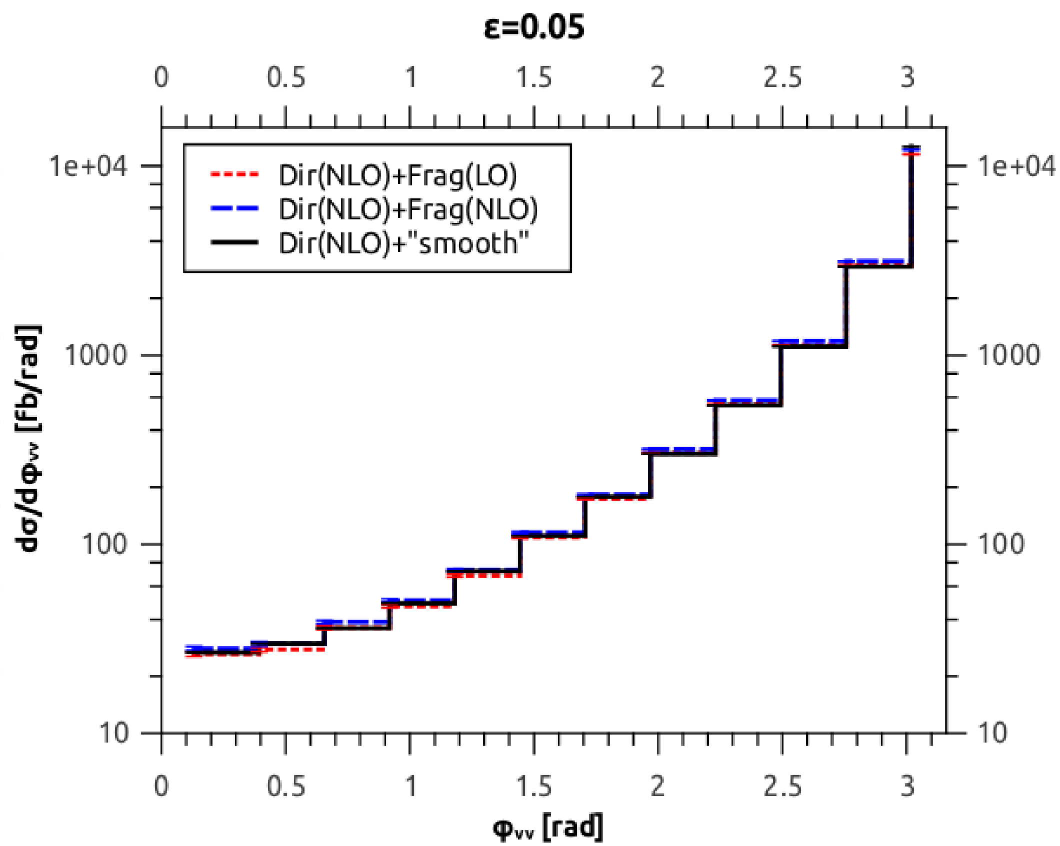


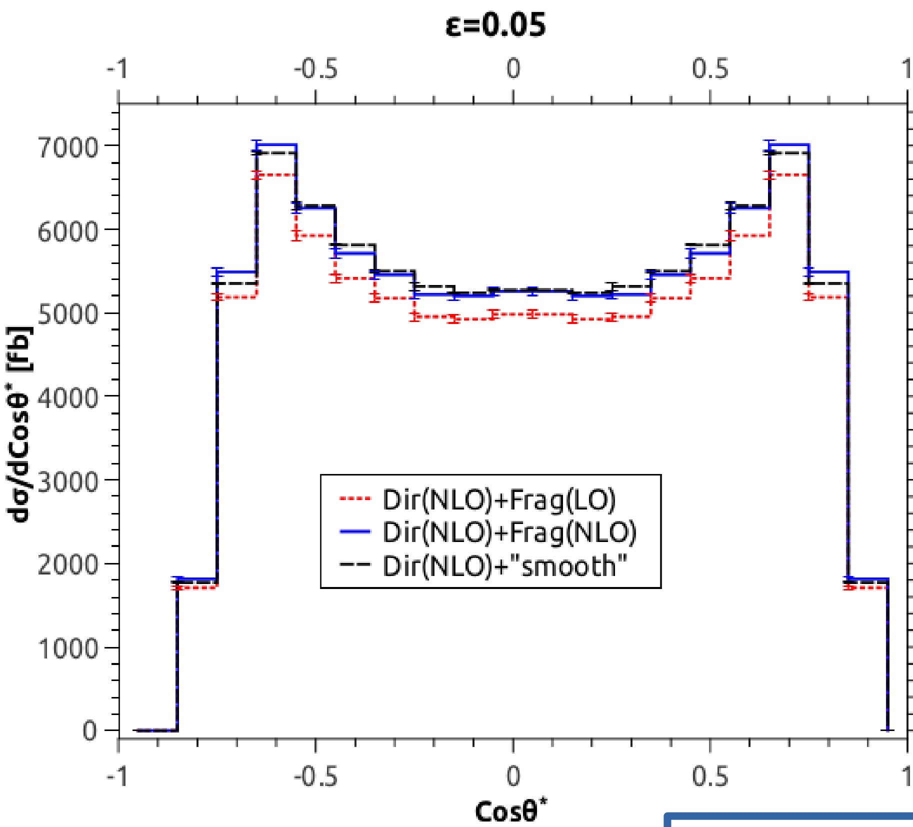


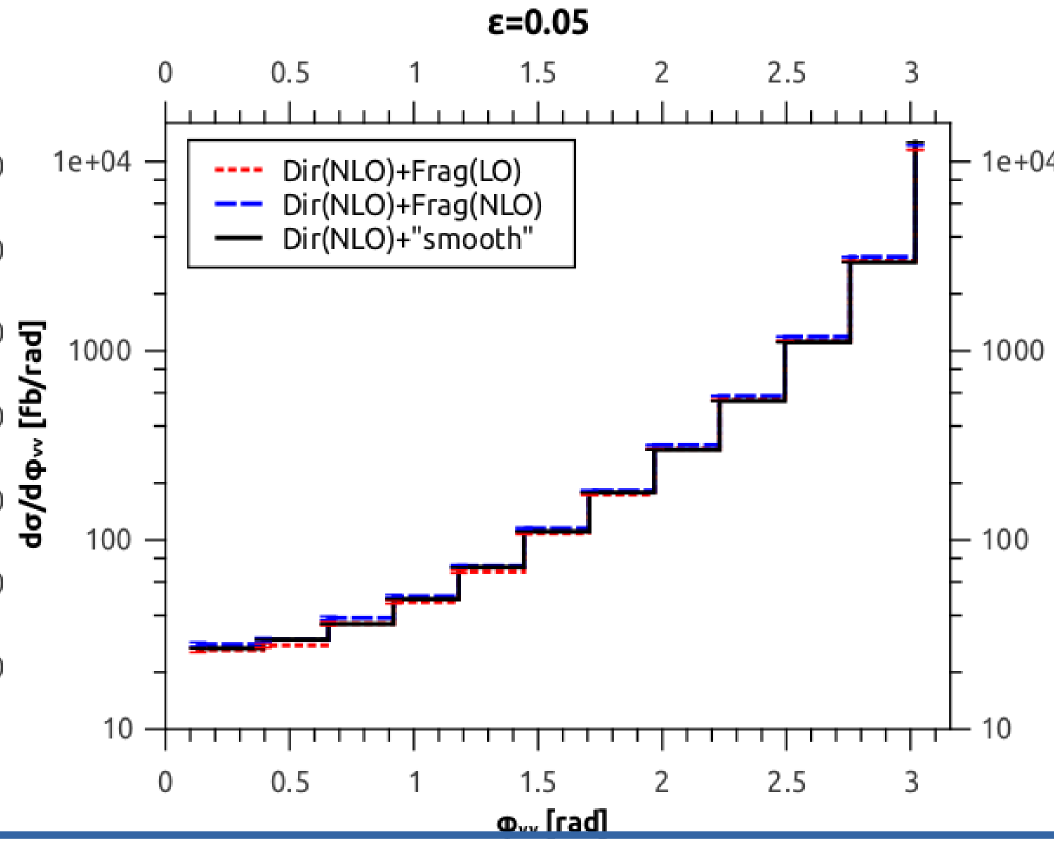
L.C , D. de Florian 2013

Same Features for all distributions

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

Cone + LO fragmentation component worse than 5%



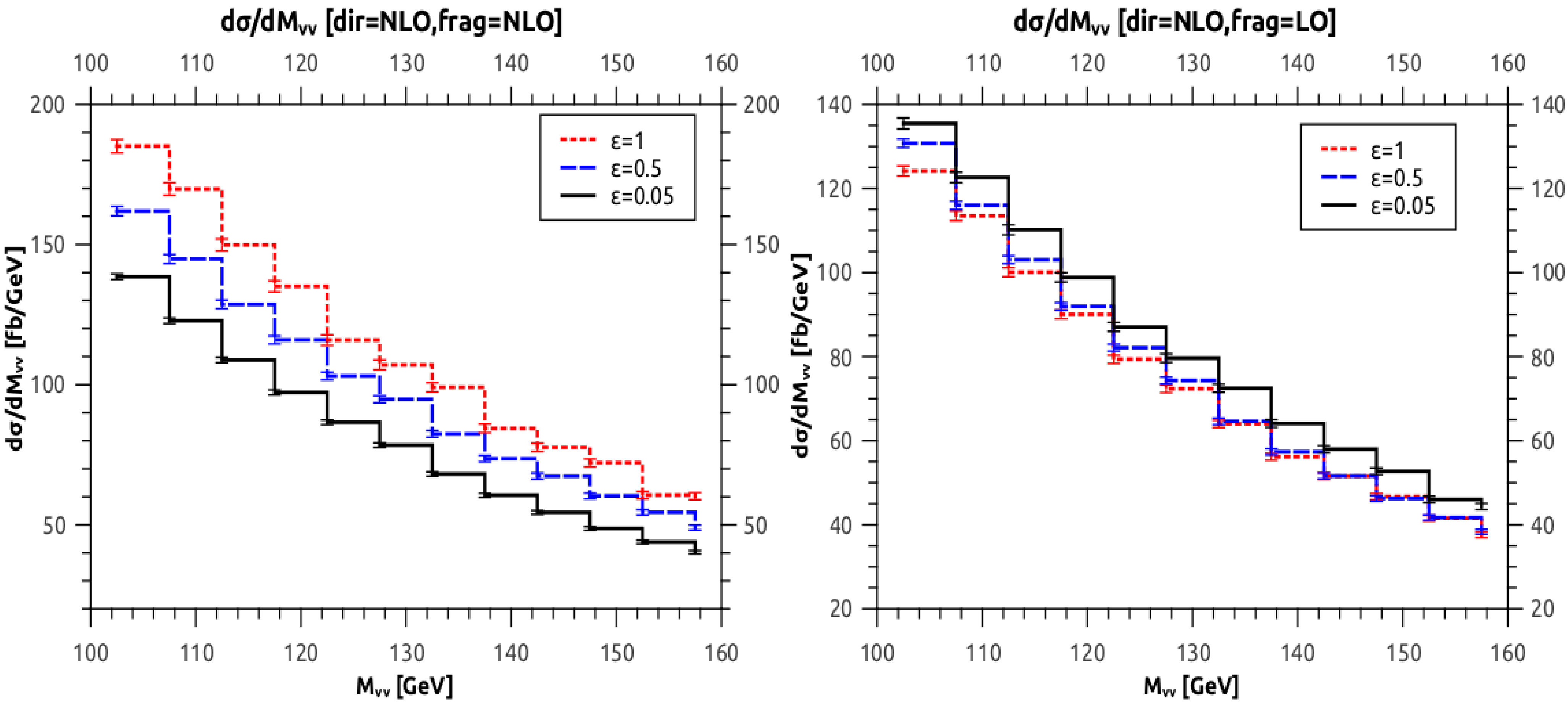


L.C , D. de Florian 2013

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



L.C , D. de Florian 2013

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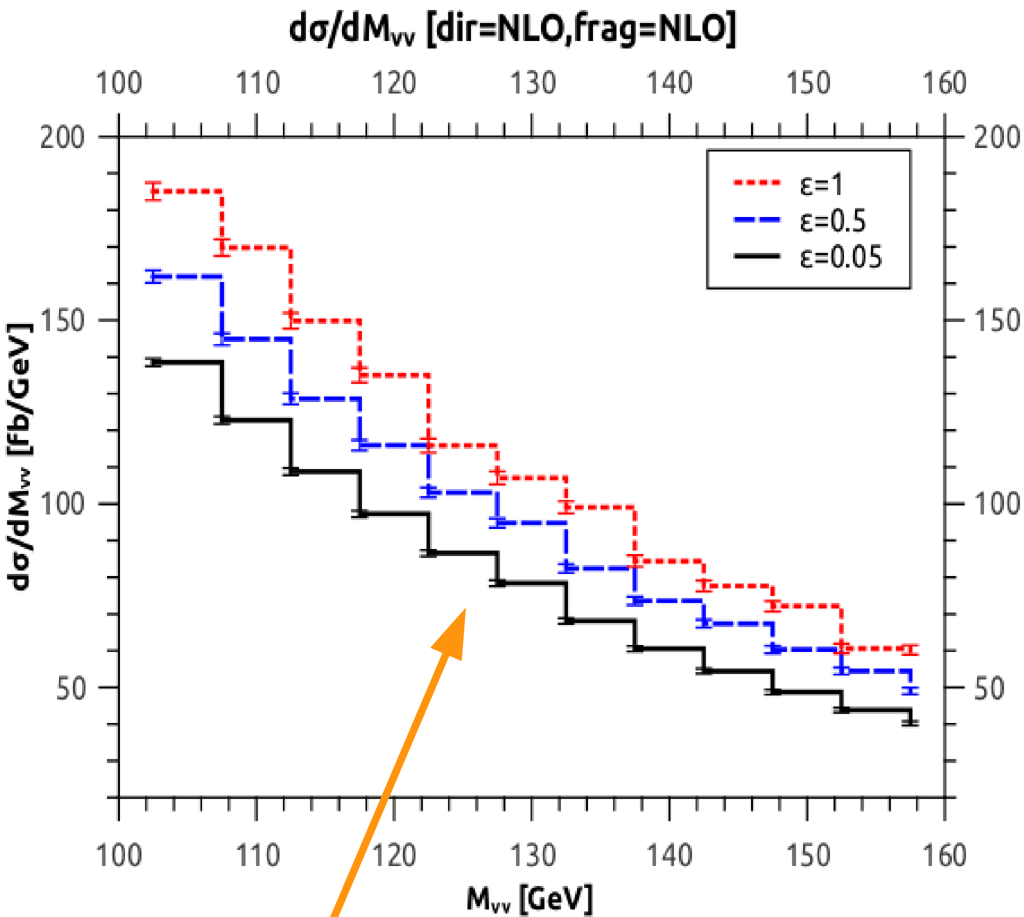

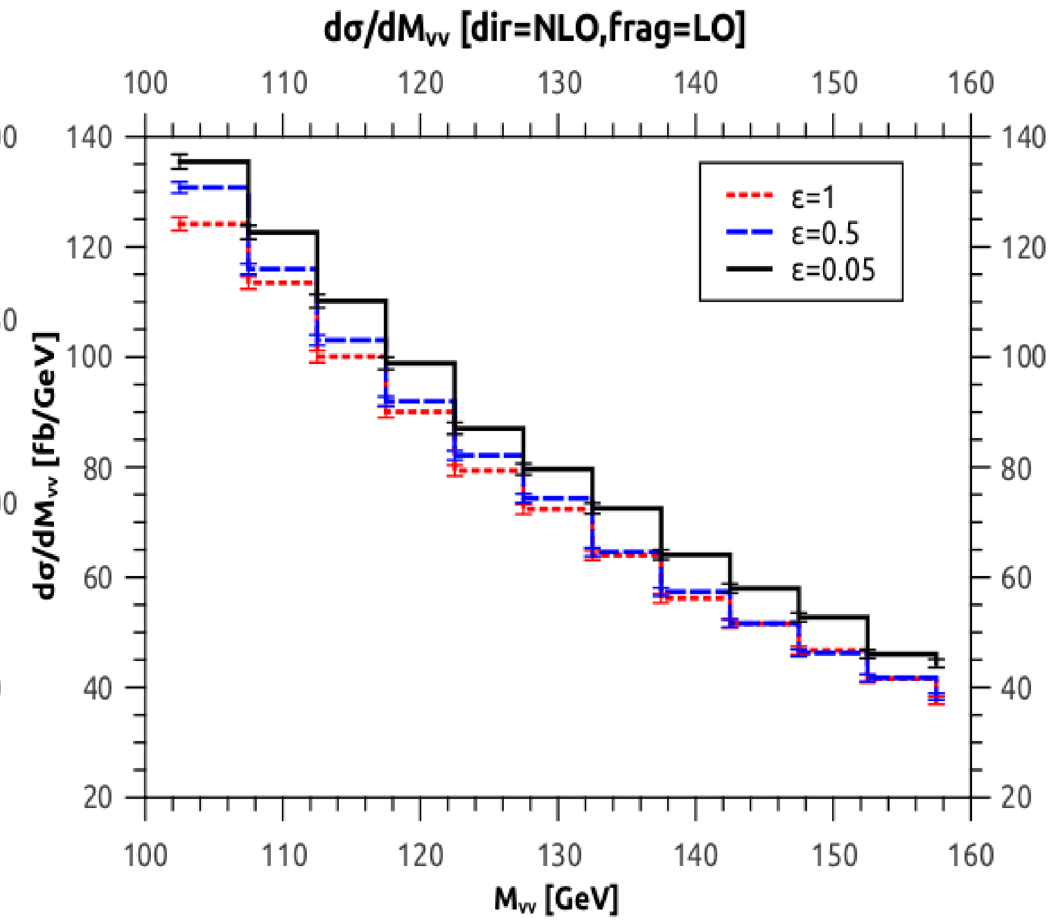

Right behaviour!!

L.C , D. de Florian 2013

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 $E_T^{max} \leq 5$ GeV (or $\epsilon < 0.1$), $R \sim 0.4$ and $R_{\gamma\gamma} \sim 0.4$ are safe enough to proceeed.

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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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:

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

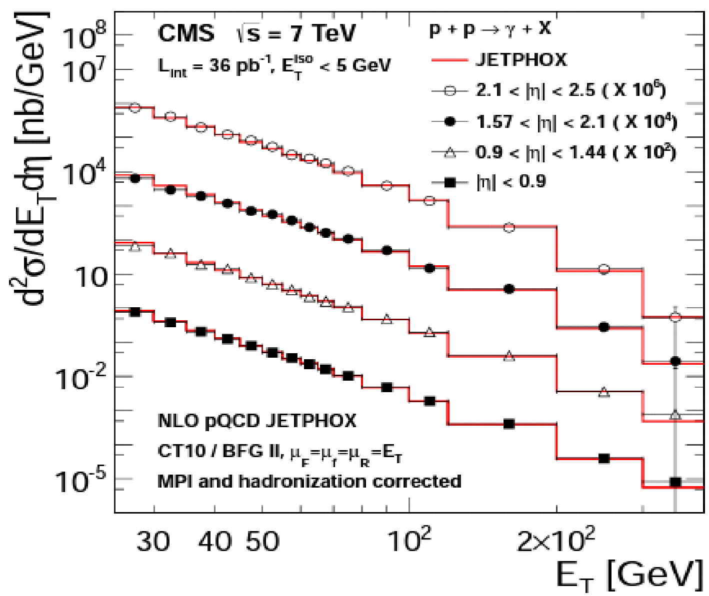
γγ + 2Jets [NLO] — T. Gehrmann , N. Greiner , G. Heinrich (2013) ;Z. Bern, L.J. Dixon, F. Febres Cordero, S. Hoeche, H. Ita, D.A. Kosower, N. A. Lo Presti, D. Maitre (2013)

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

Results and comparison with data

γ + jet CMS

Phys.Rev. D84 (2011) 052011
Phys.Rev.Lett. 106 (2011) 082001

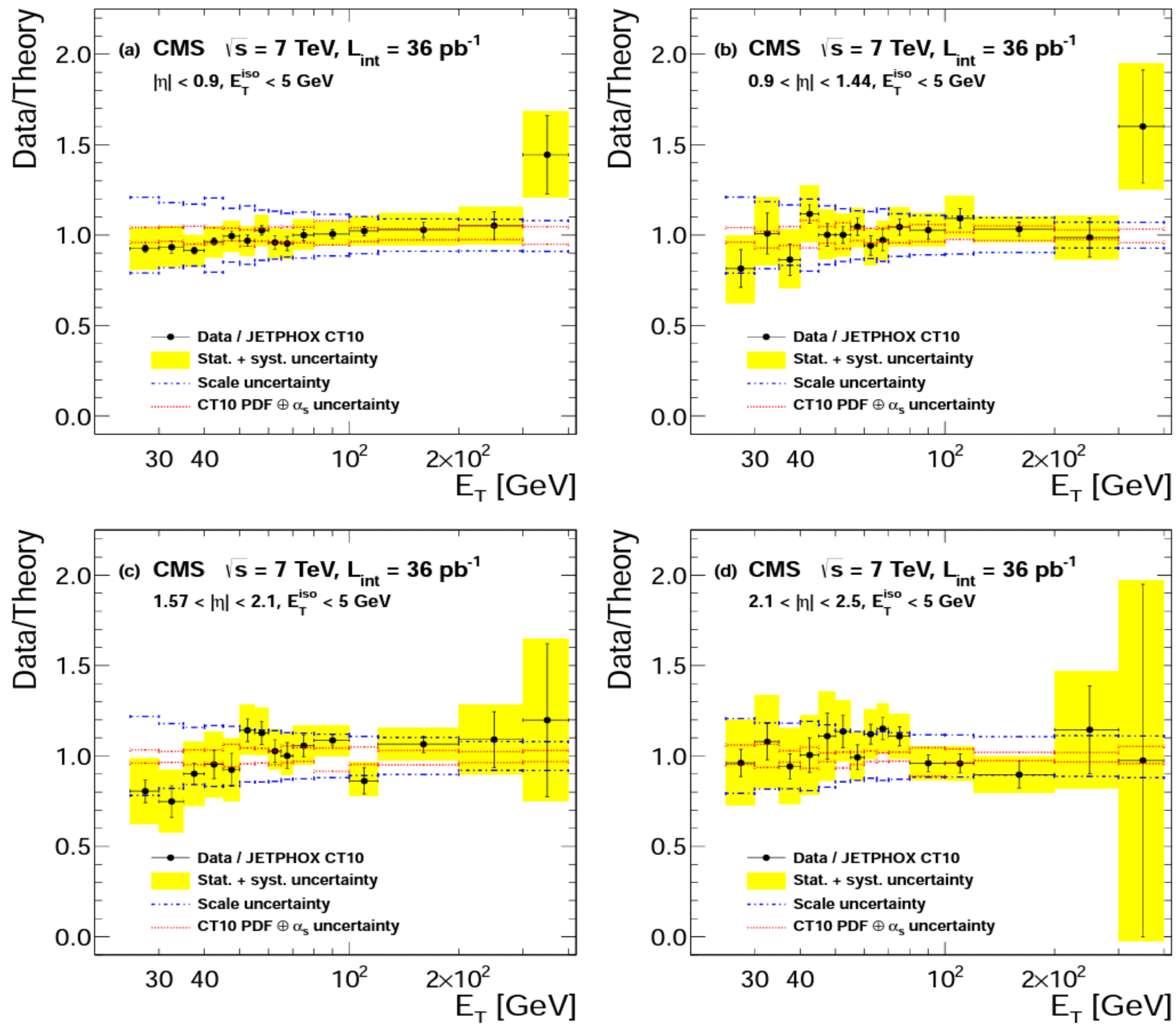


At low ET the predictions tend to be higher than the measured cross section

In some kinematic regimes the Xsection is sensible at PDFs variations

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

Results in good agreement with data

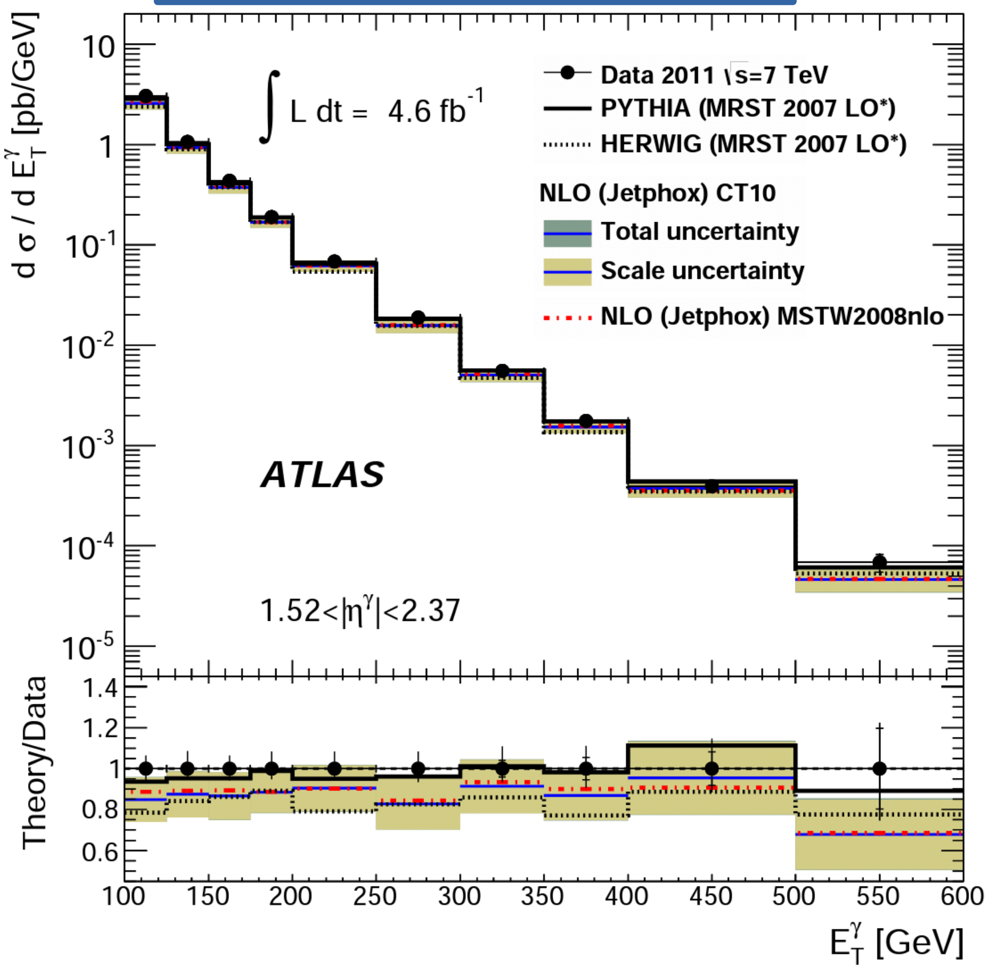


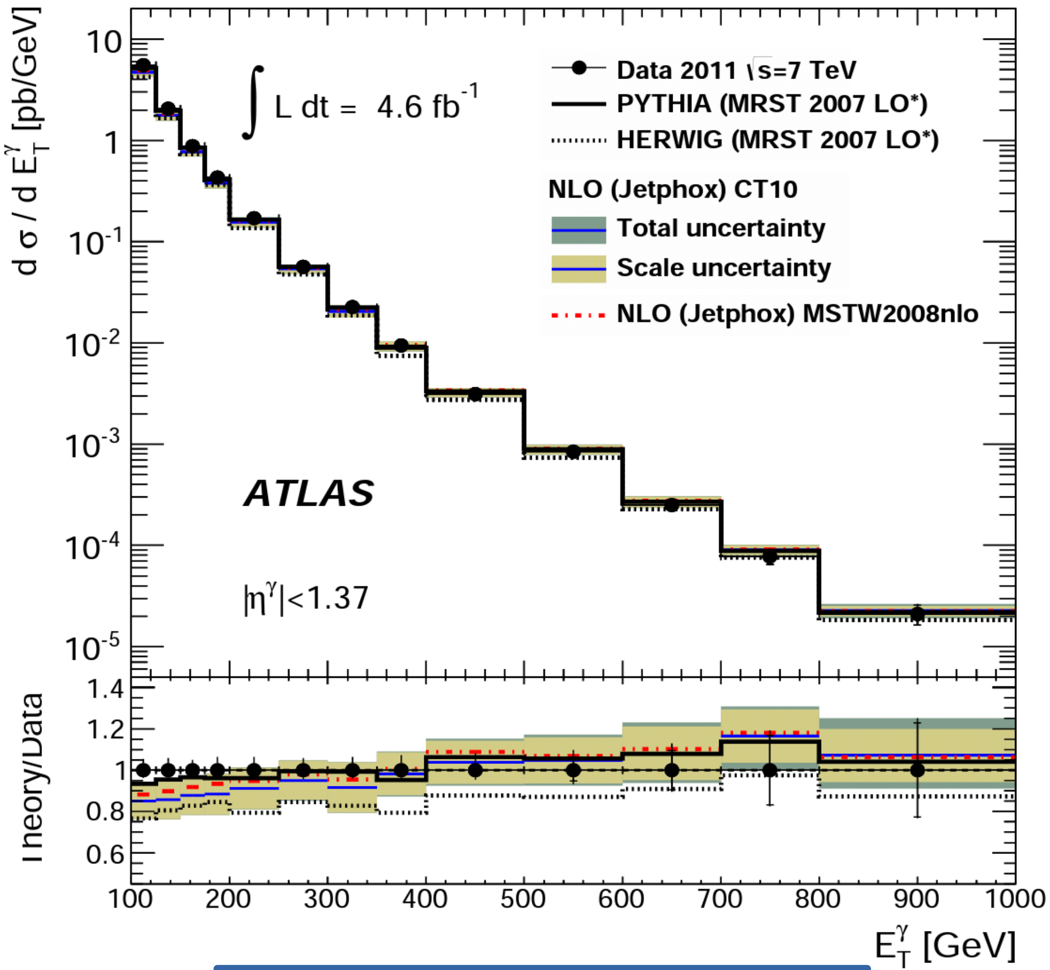
γ + jet ATLAS

Phys.Rev. D89 (2014) 052004

Results in good agreement with data

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





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Phys.Rev. D89 (2014) 052004

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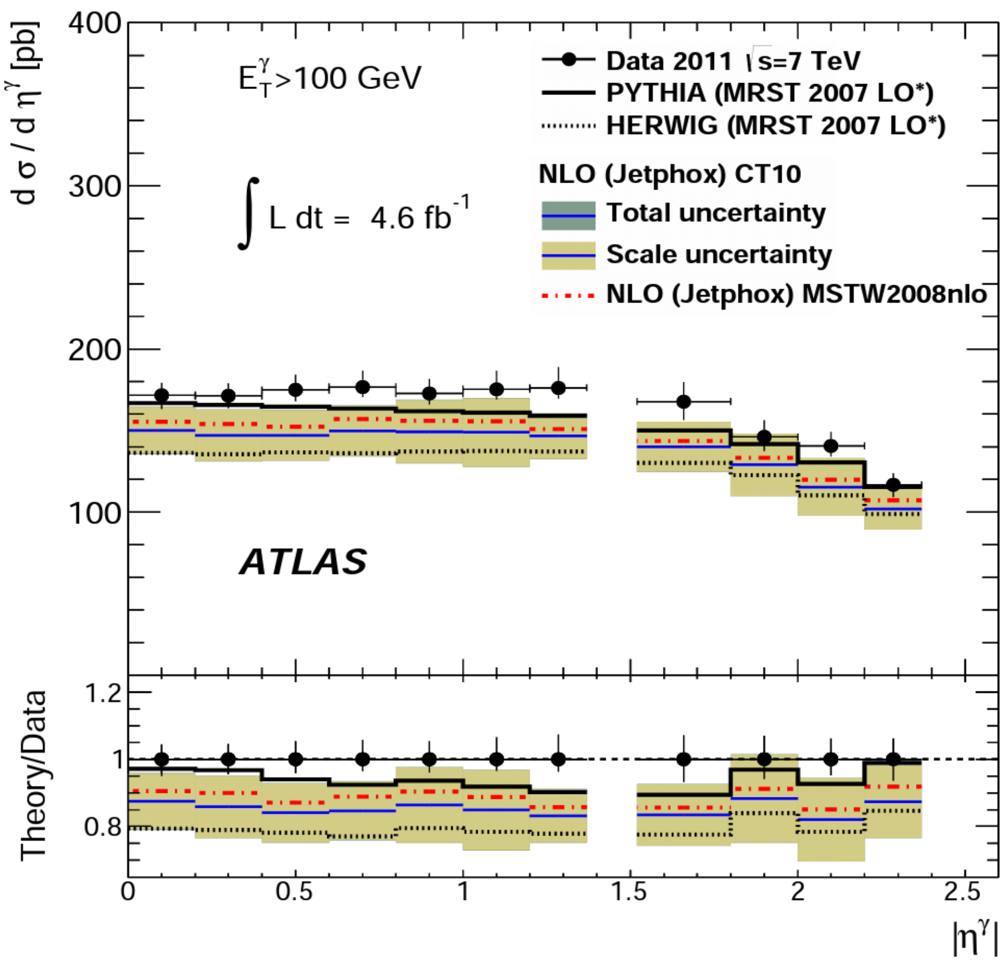
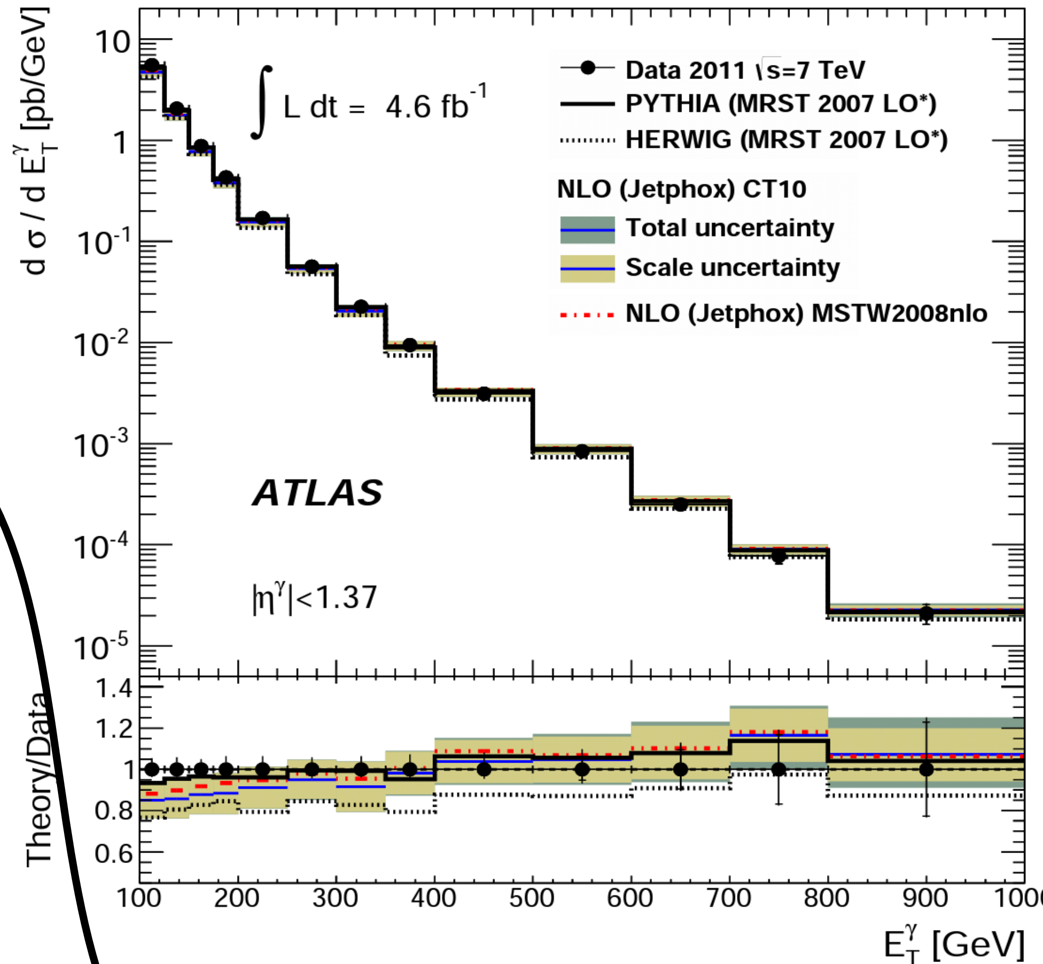




The opposite case for CMS

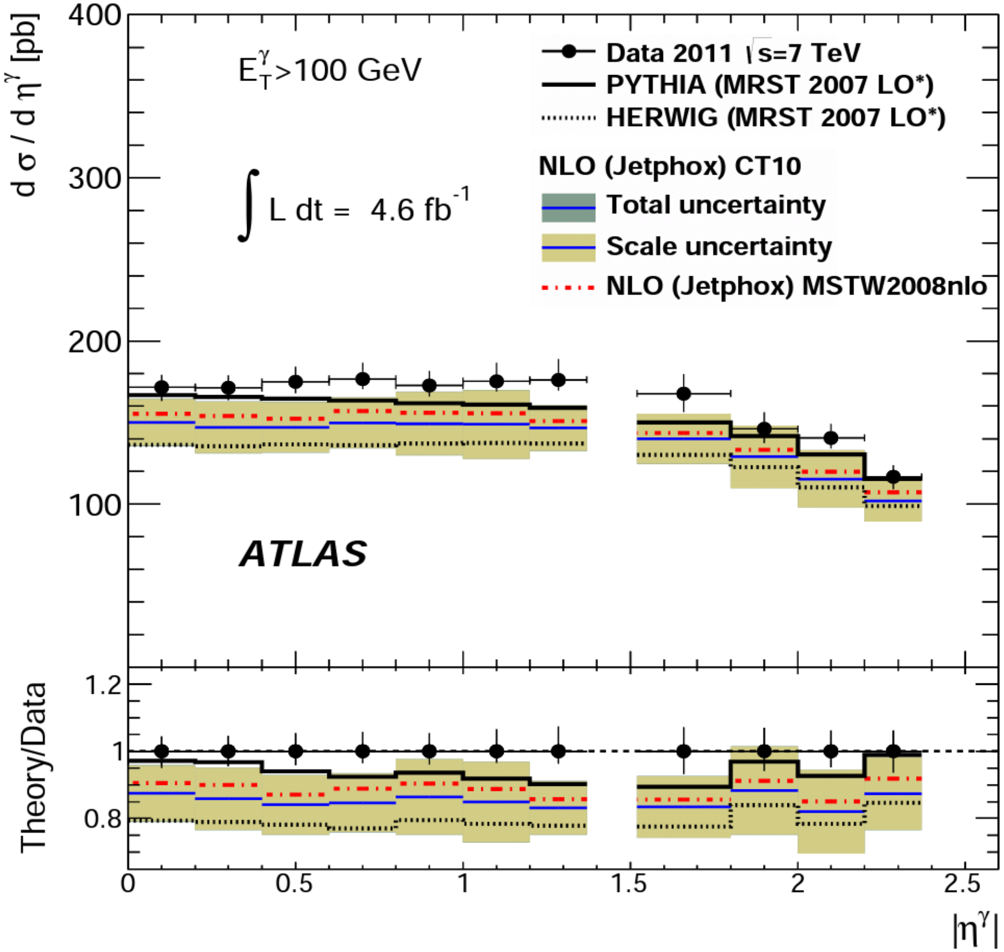
ATLAS and CMS use different values for Etmax

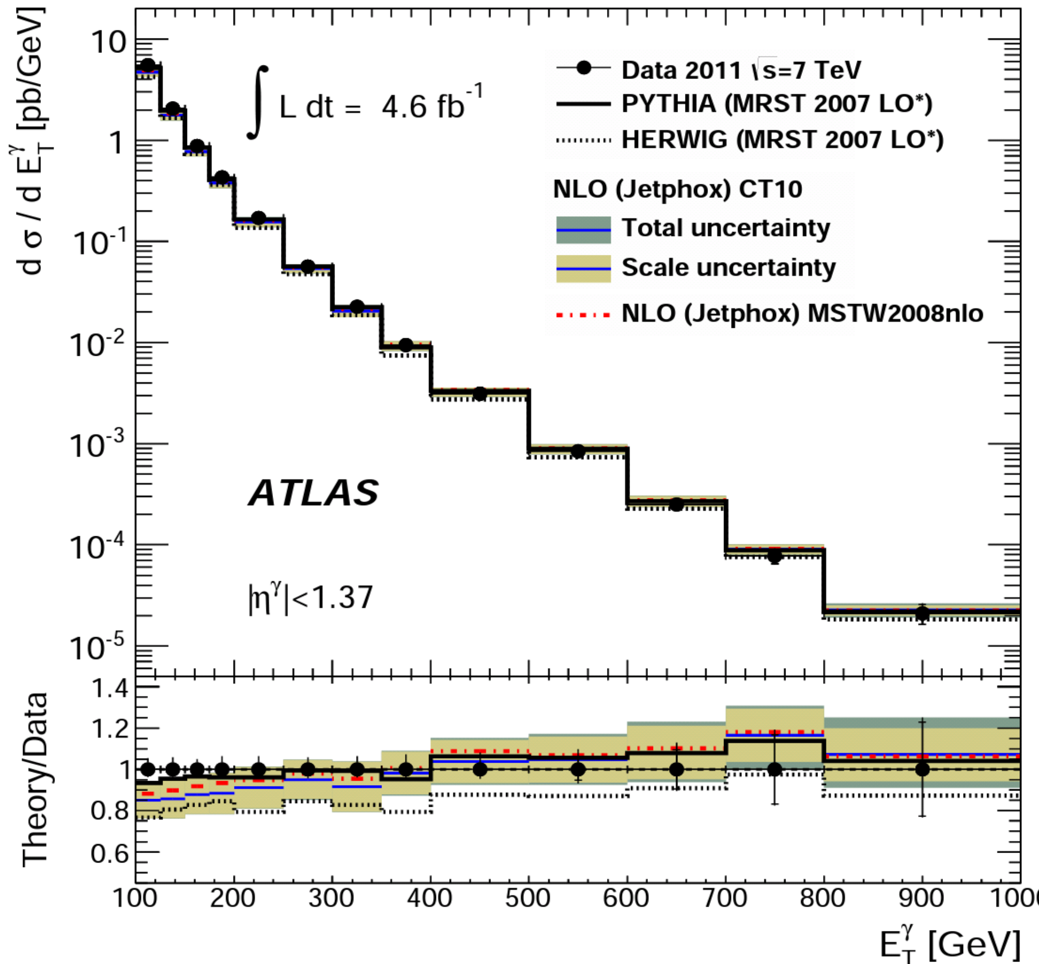
ETmax(ATLAS)>ETmax(CMS)

γ + jet ATLAS

Phys.Rev. D89 (2014) 052004

Results in good agreement with data



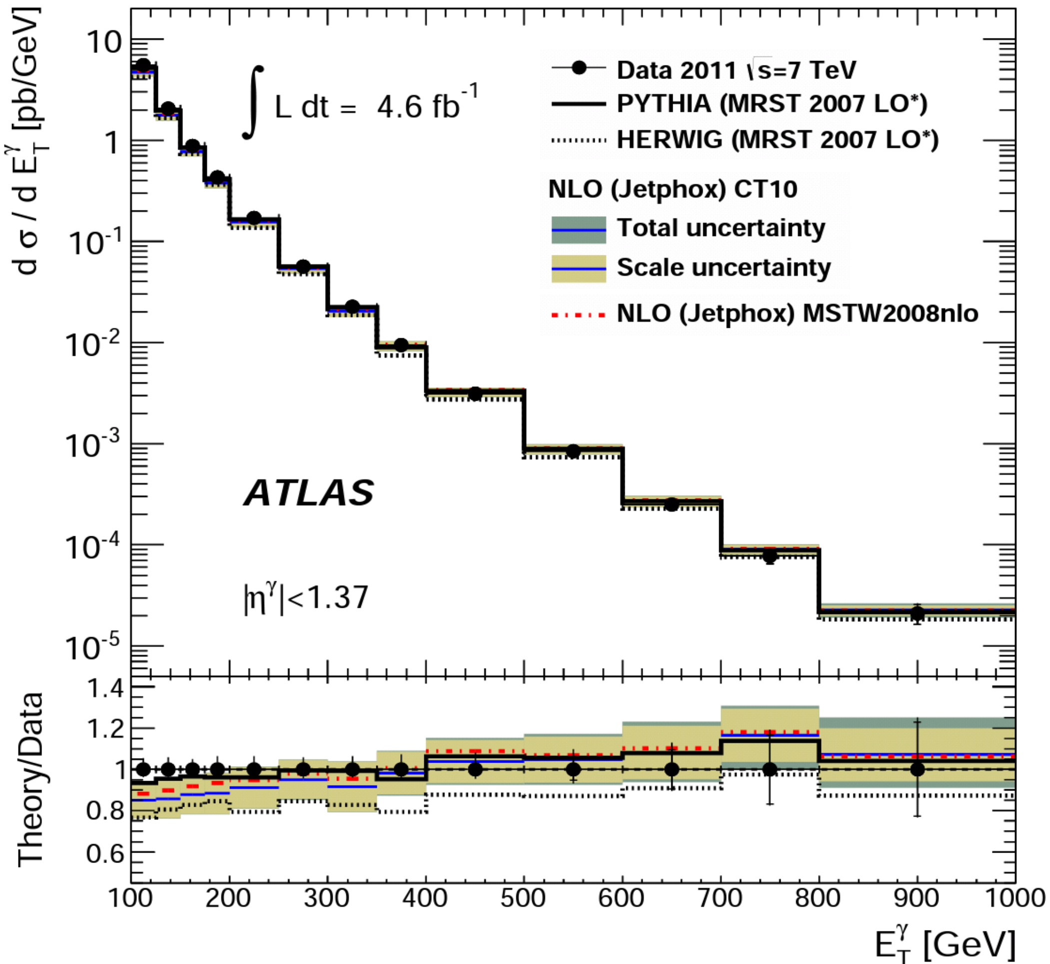


In some kinematic regimes the Xsection is sensible at PDFs variations

γ + jet ATLAS

Phys.Rev. D89 (2014) 052004

Results in good agreement with data

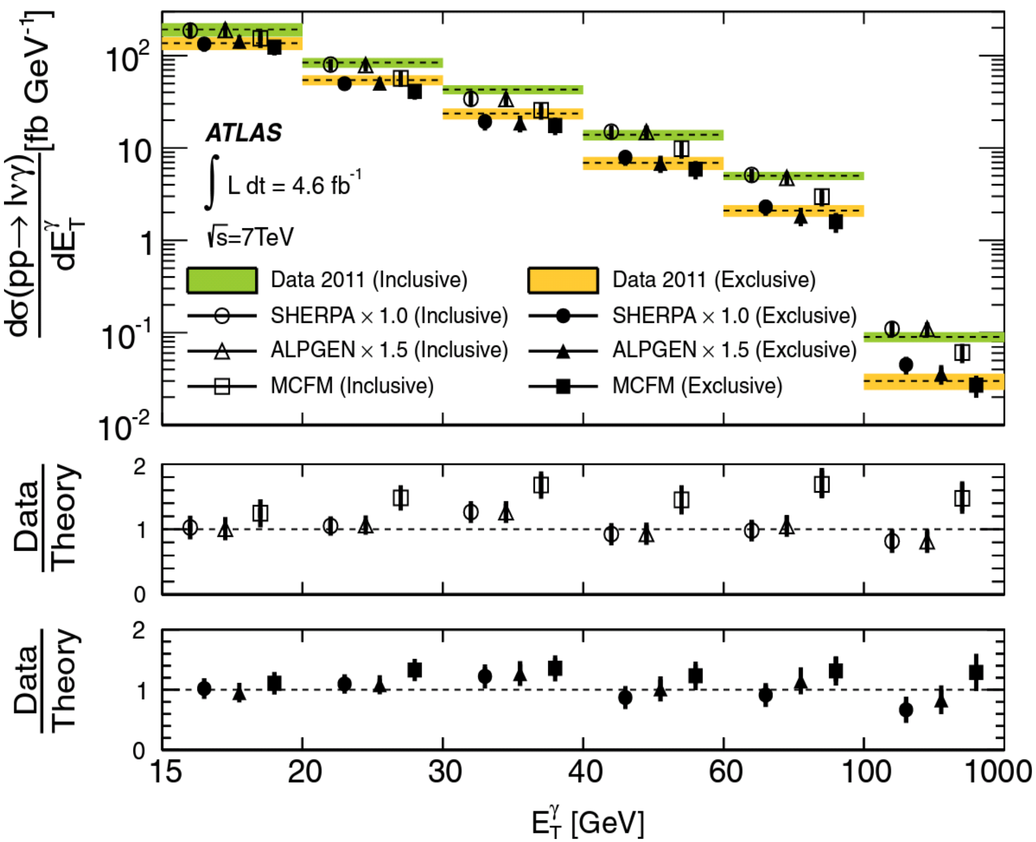


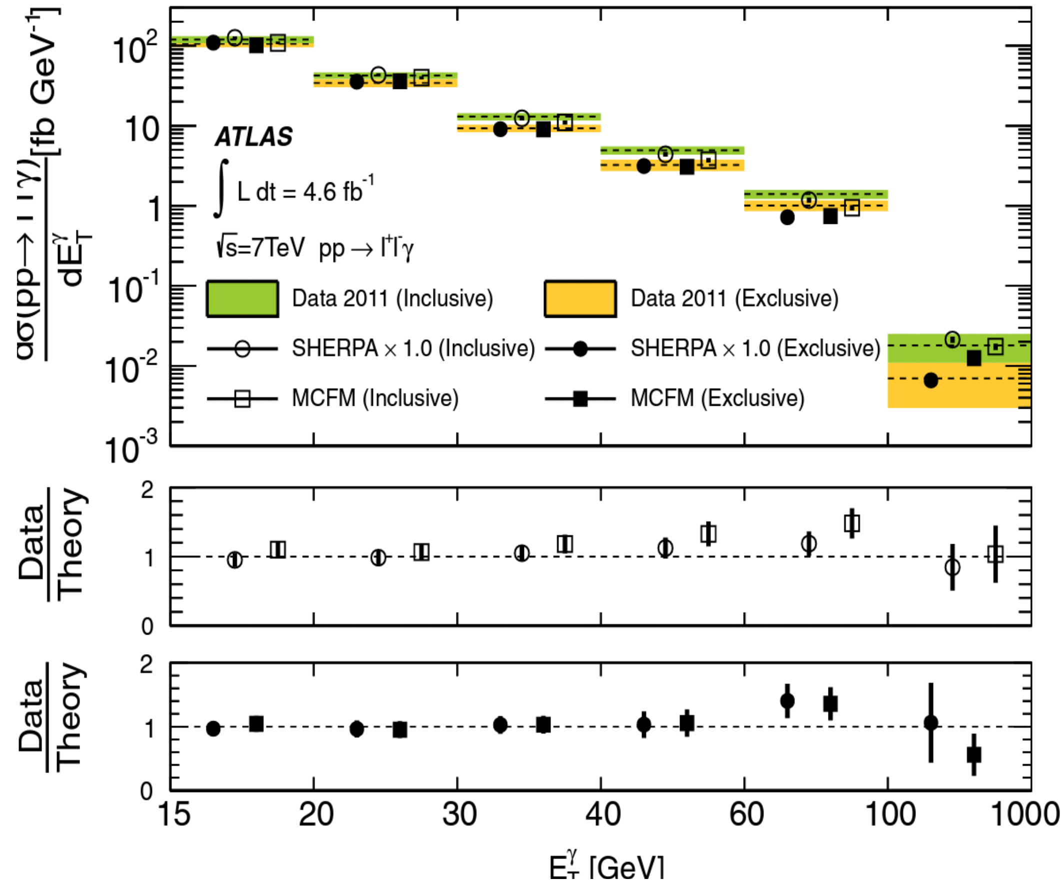
The data are also compared to MC predictions that include only direct photons from qg → qγ and qq → gγ processes calculated at LO QCD.These MC generators predict a cross section at low EγT that is 20% lower than the data which includes all the higher-order fragmentation processes. This difference is reduced at high EγT, where the contribution from photons originating from fragmentation becomes small. This shows that the higher order fragmentation processes contribute significatly to the shape of the predicted EγT 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?

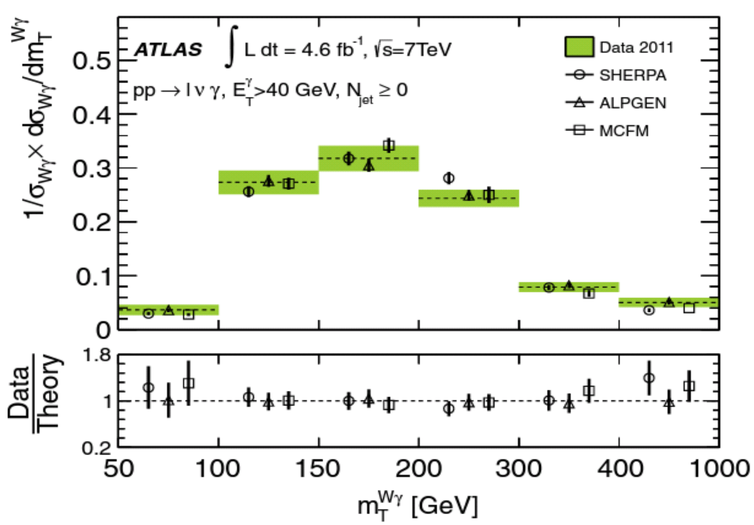
Vγ production

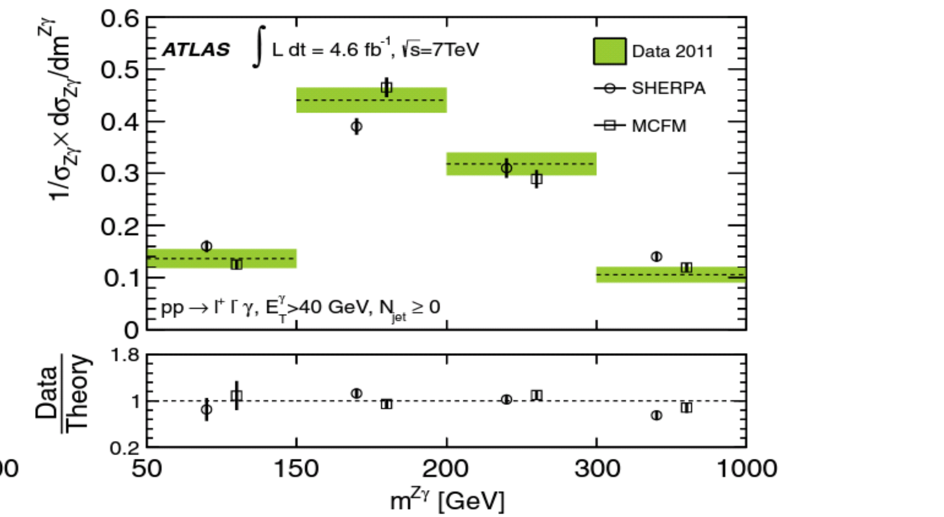




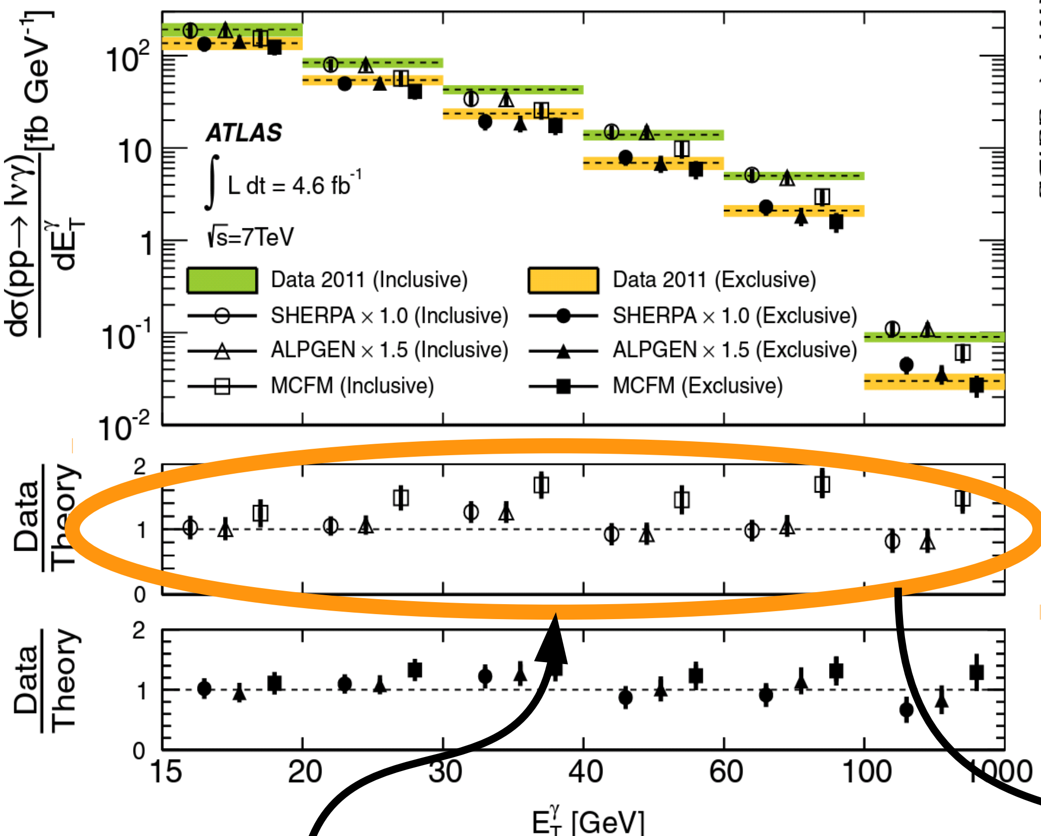
Phys.Rev. D87 (2013) 112003

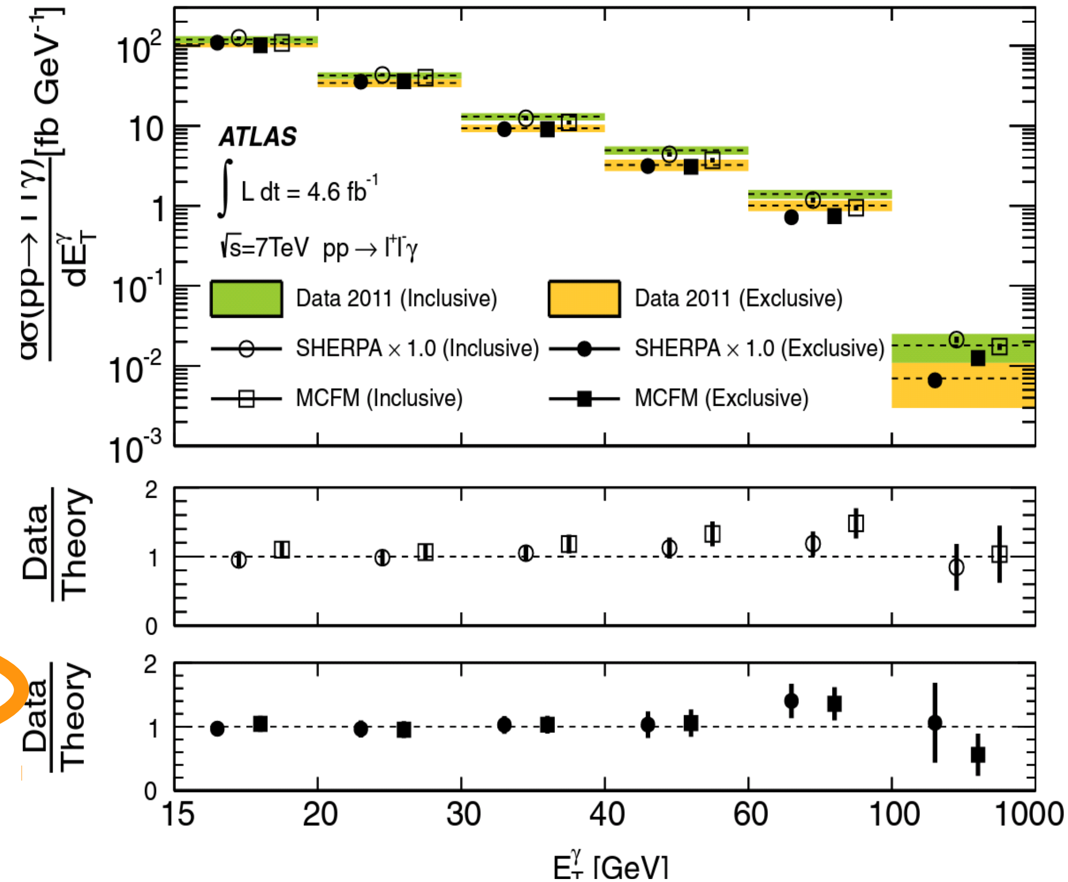
Results in good agreement with data





Vγ production





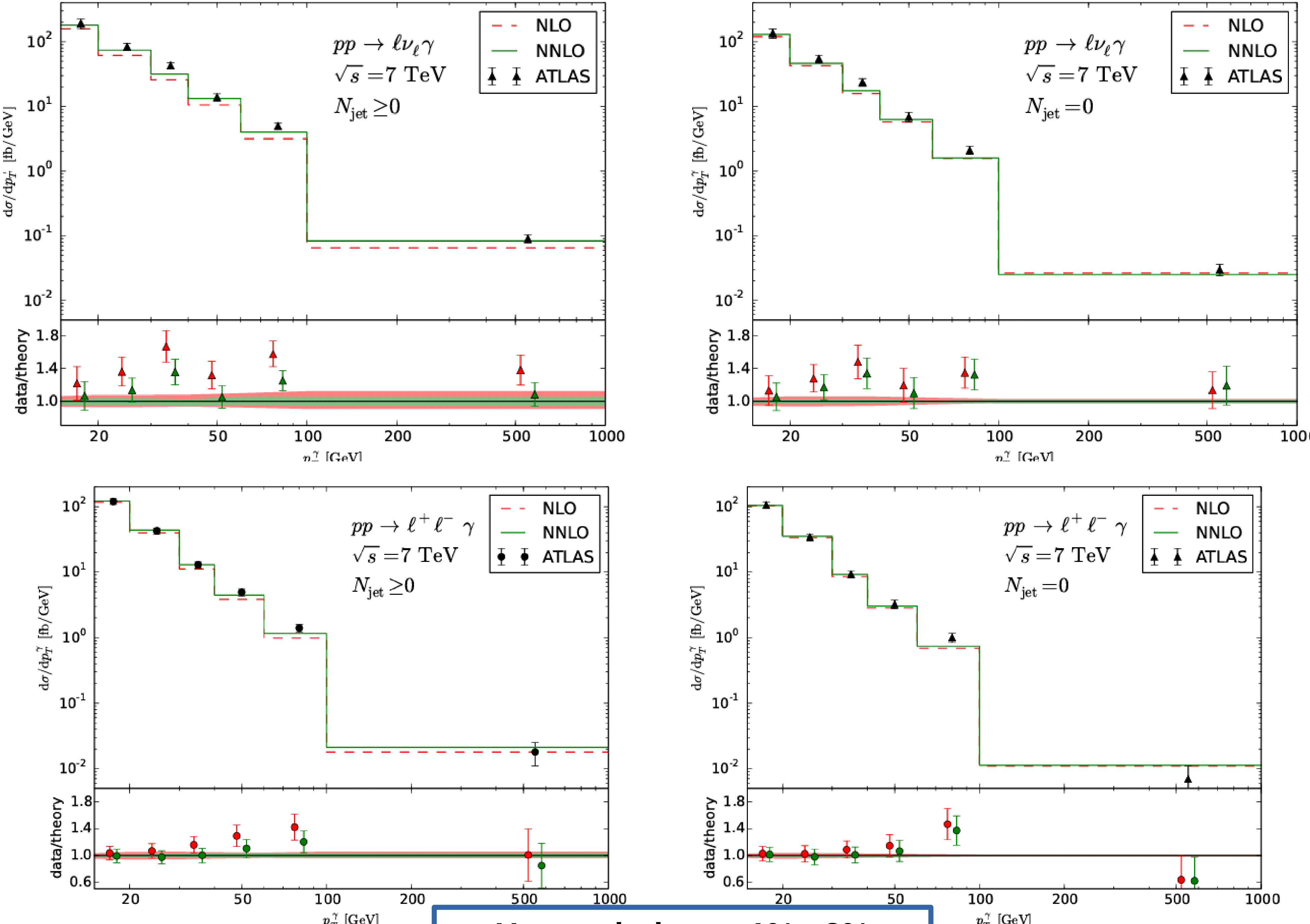
Phys.Rev. D87 (2013) 112003

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

Vγ production NNLO

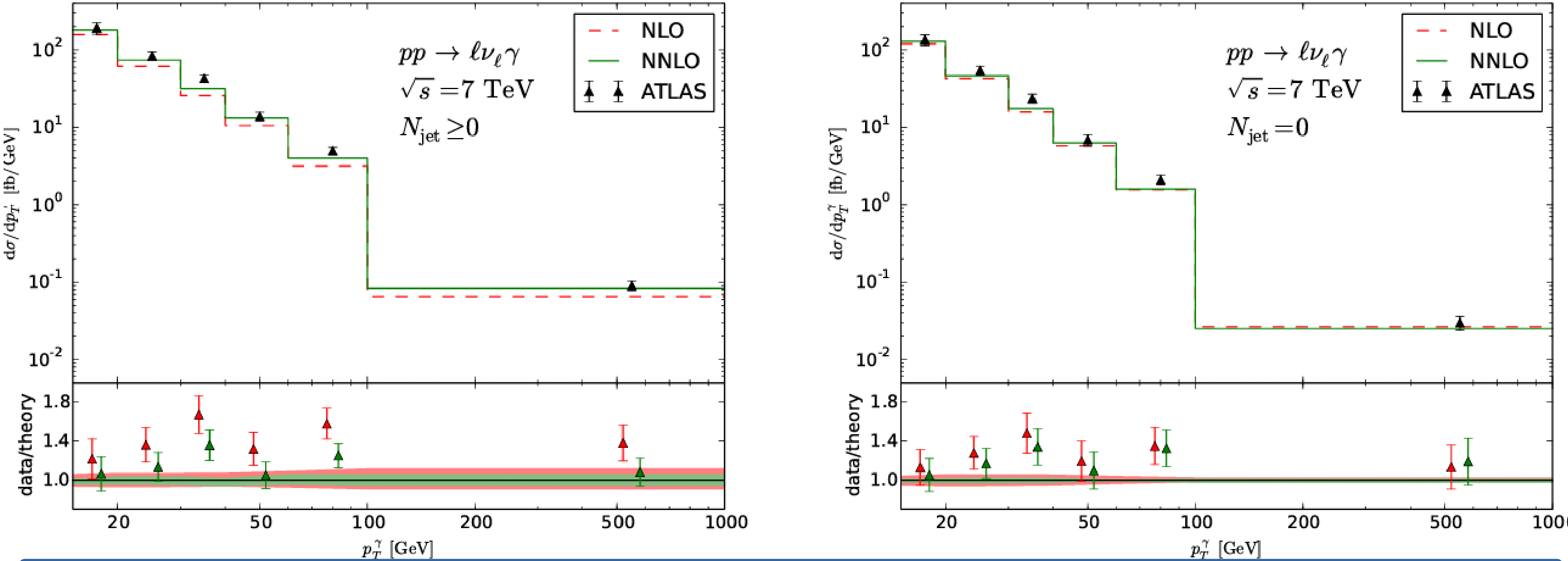
Grazzini, Kallweit, Rathlev, Torre



Uncertainties → 1% - 2%

Vγ production NNLO

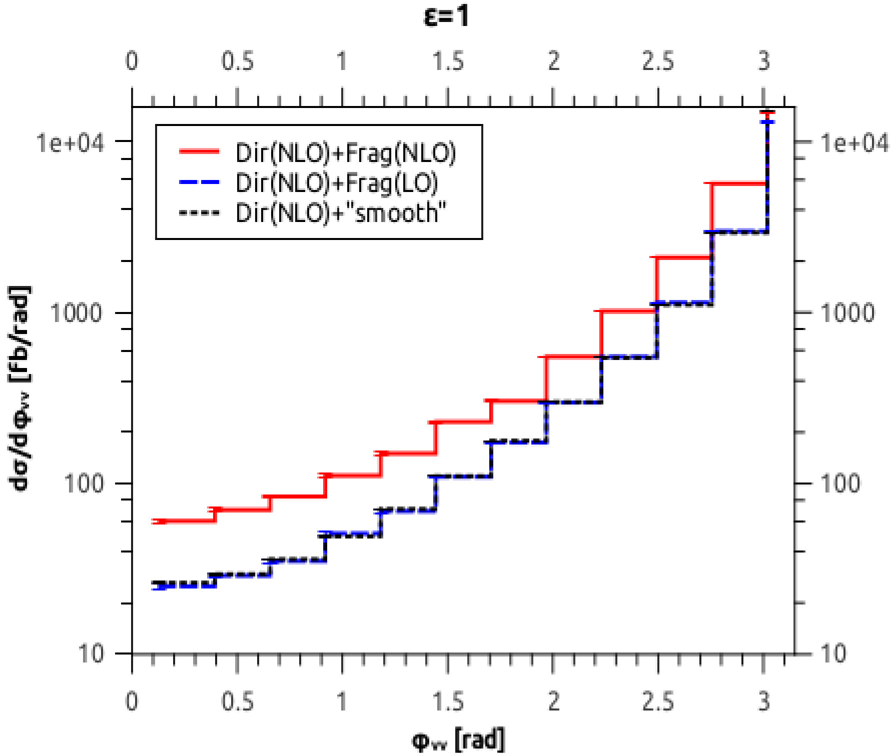
Grazzini, Kallweit, Rathlev, Torre

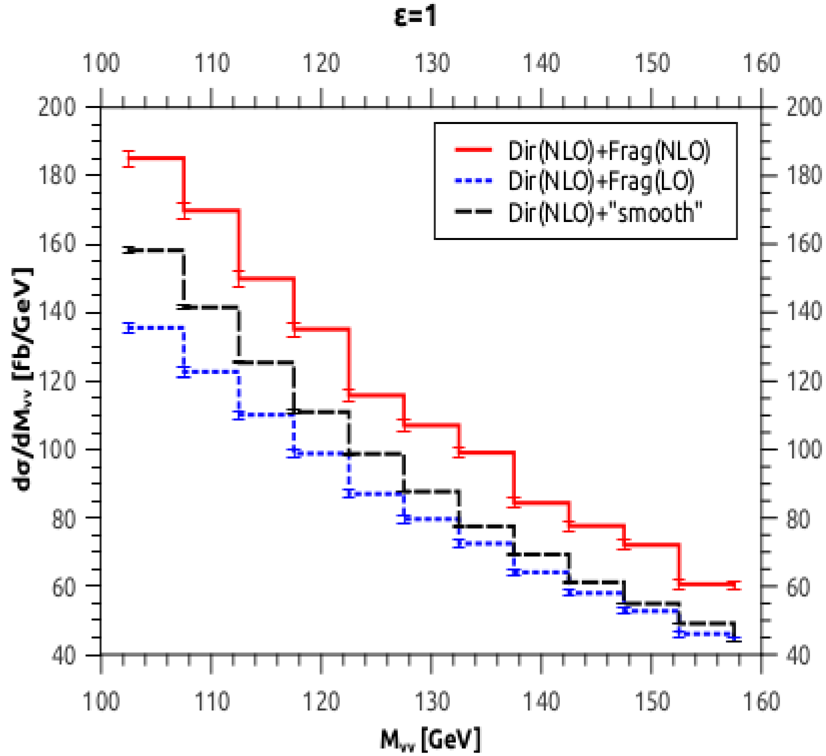


In the exclusive case, the excess of the measured fiducial cross sections over the theoretical prediction is reduced from 1.6σ to 1.2σ when going from NLO to NNLO

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 γγ





Fragmentation could be very relevant!!!!

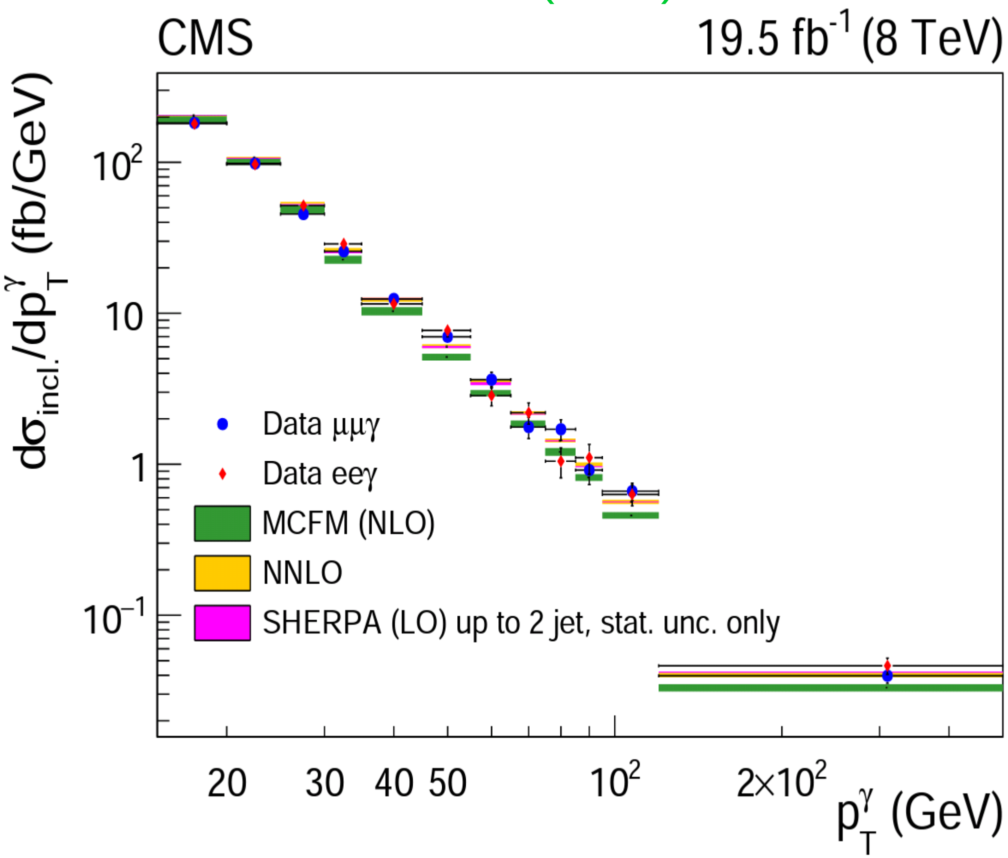
$$E_{T\ max} \sim 20\ \mathrm{GeV}$$

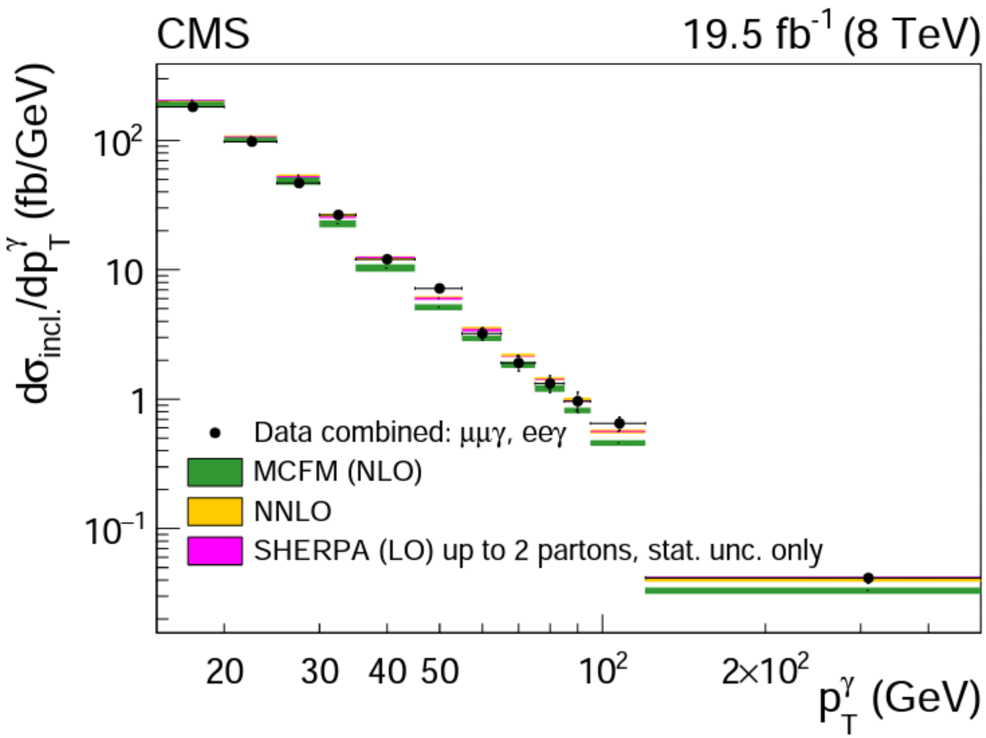
Vγ ATLAS

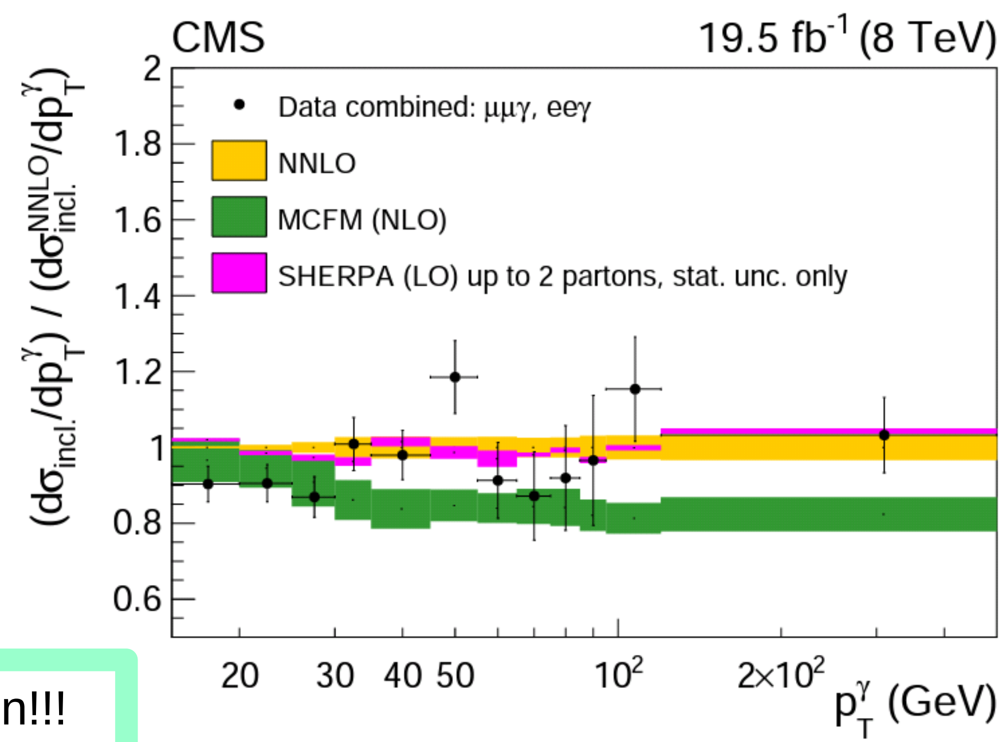
$$E_T < \epsilon_\gamma\, p_T^\gamma \quad , \qquad \epsilon_\gamma = 0.5$$

Zγ production

JHEP04 (2015) 164







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

to exclude photons to jet fragmentation!!!

ATLAS results γγ

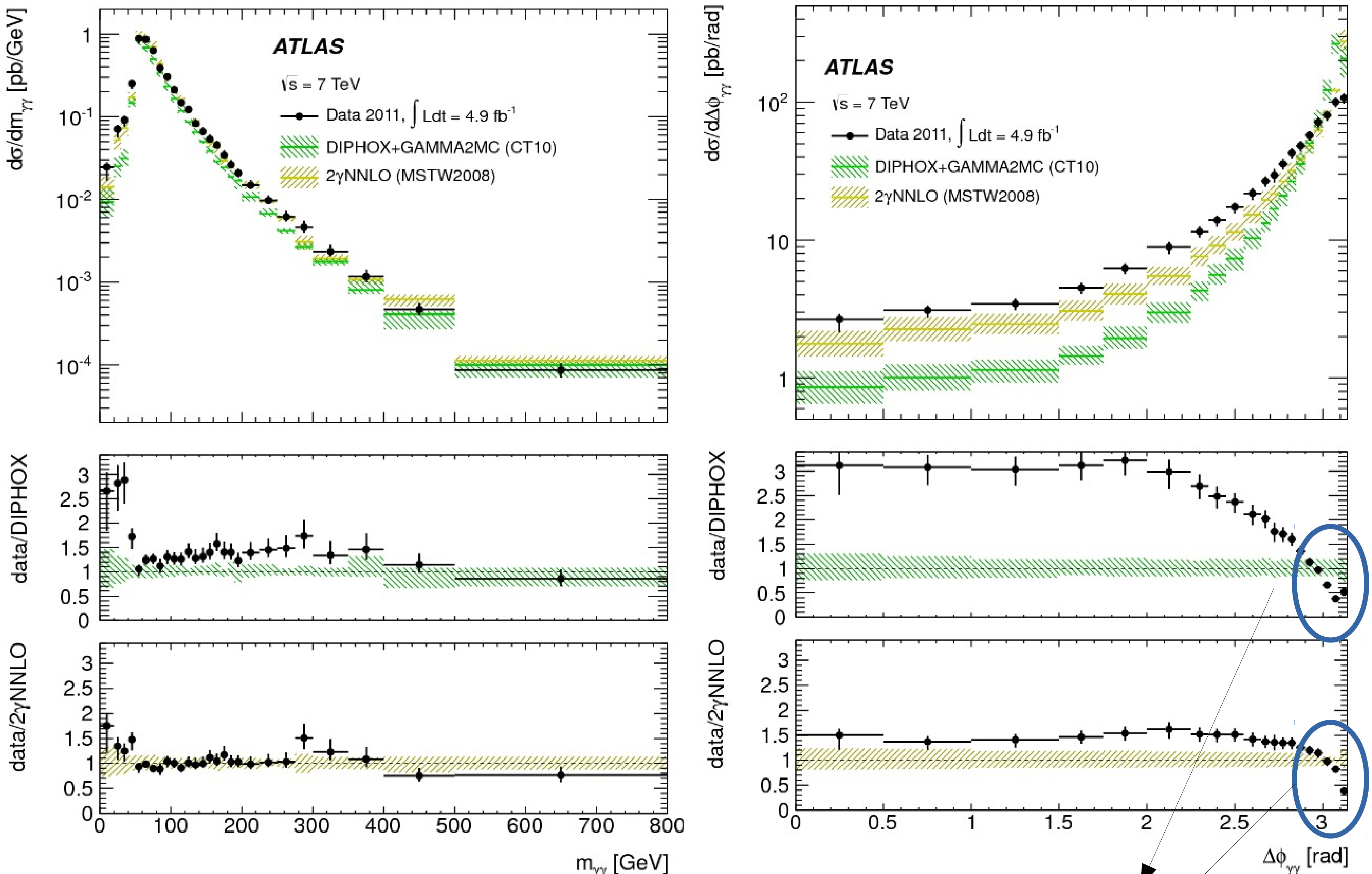
$$p_T^{\text{harder}} \geq 25 \text{ GeV}, \;\; p_T^{\text{softer}} \geq 22 \text{ GeV},$$
$$|y_\gamma| < 1.37 \;\; \vee \;\; 1.52 < |y_\gamma| \leq 2.37,$$
$$E_{T\ max} = 4 \text{ GeV}, \quad n = 1, \quad R = 0.4,$$
$$R_{\gamma\gamma} = 0.4$$

For the discussion

1 Which is the algorithm (or value) used to correct all the FO tools? In order to include the non—perturbative corrections due to PS and/or UE within the isolation cone

ATLAS results γγ

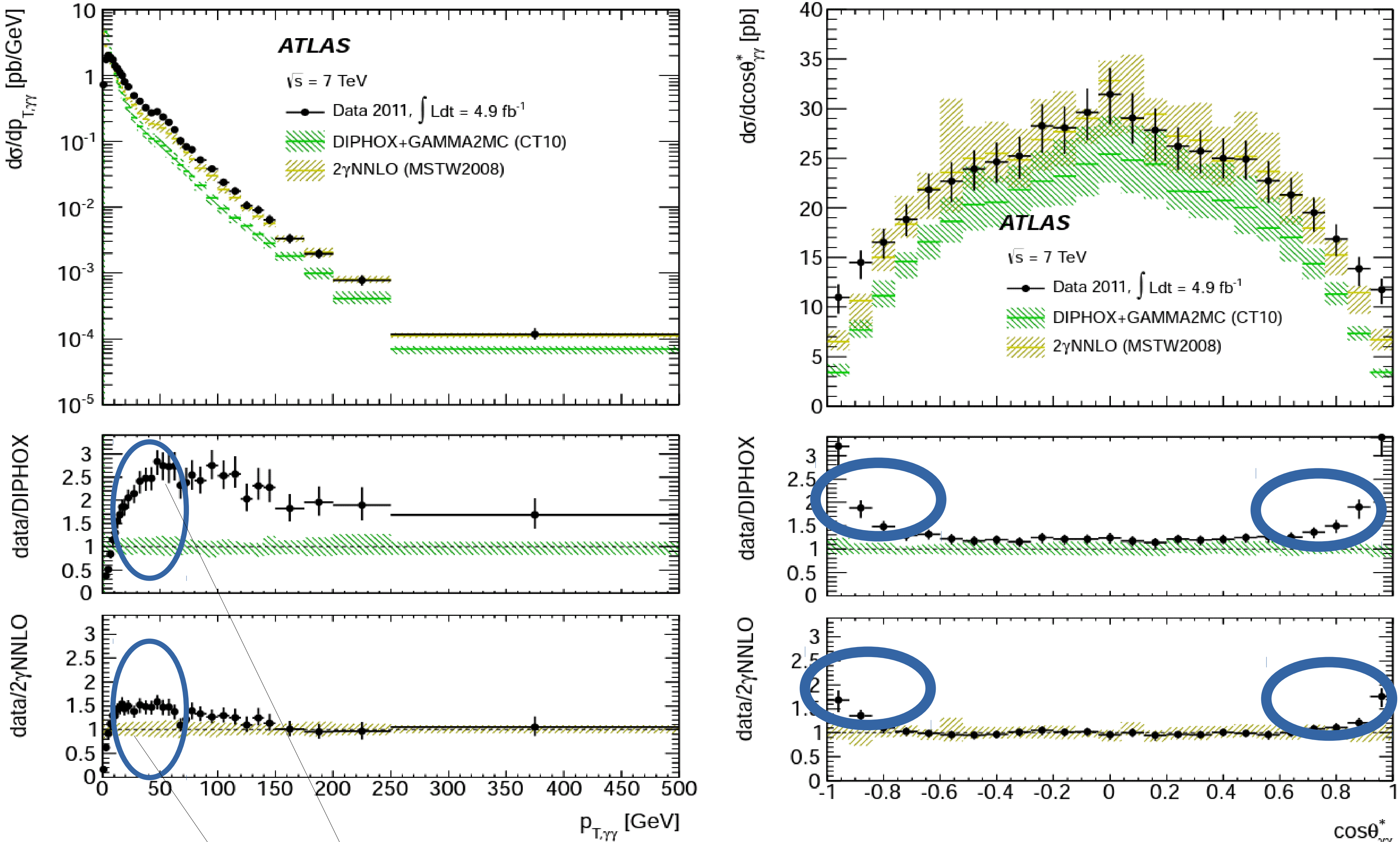
arXiv:1211.1913 [hep-ex].



Uncertainties → 6% - 8%

Fixed order tools

ATLAS results γγ



Fixed order tools

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

CMS results γγ

arXiv:1405.7225

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

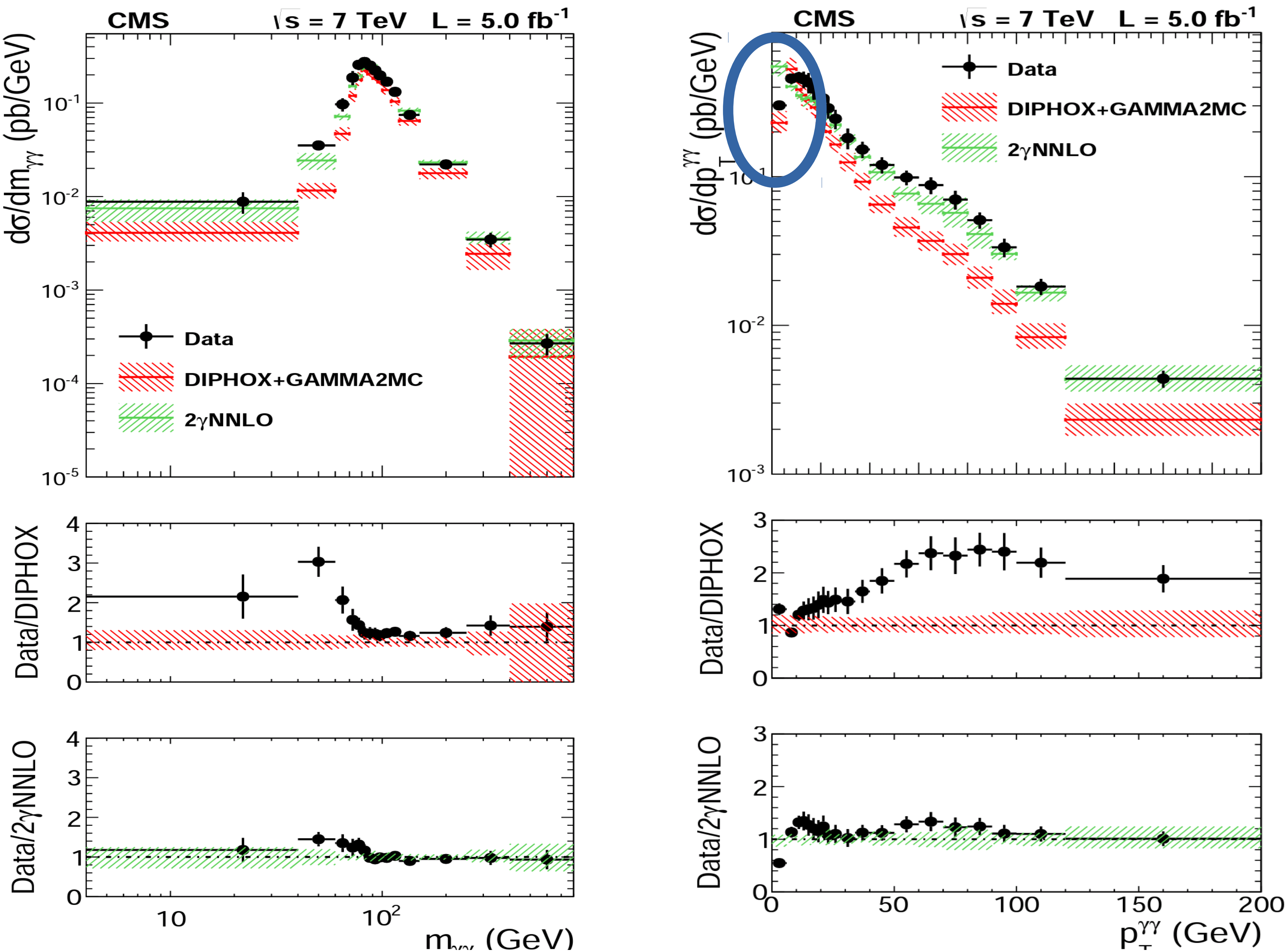
For the discussion

1 (n=0.05) The NLO with DIPHOX is the same than NLO with smooth cone?

2 Which is the algorithm (or value) used to correct all the FO tools?
In order to include the non—perturbative corrections due to PS
and/or UE within the isolation cone

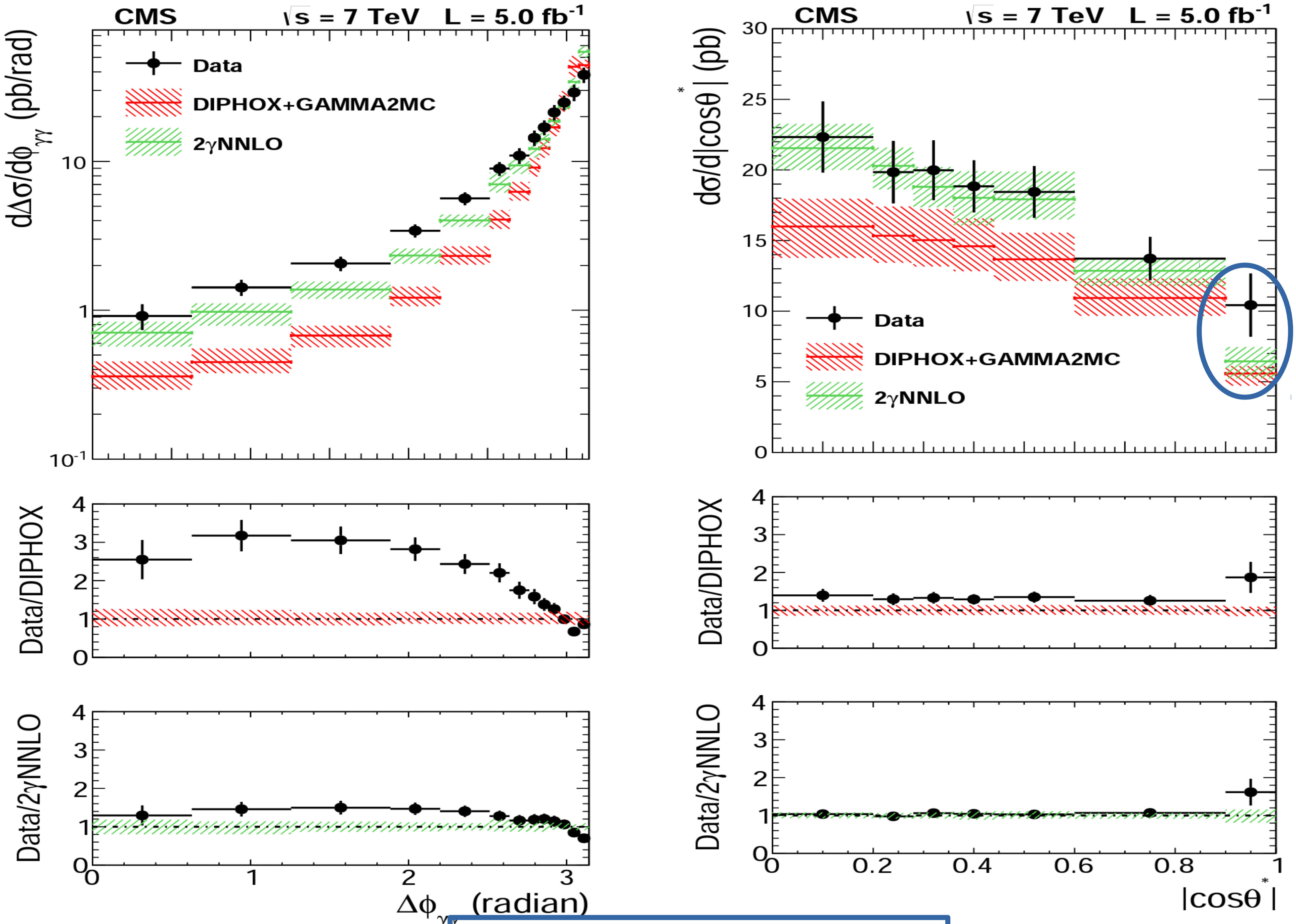
CMS results γγ

arXiv:1405.7225



CMS results γγ

arXiv:1405.7225

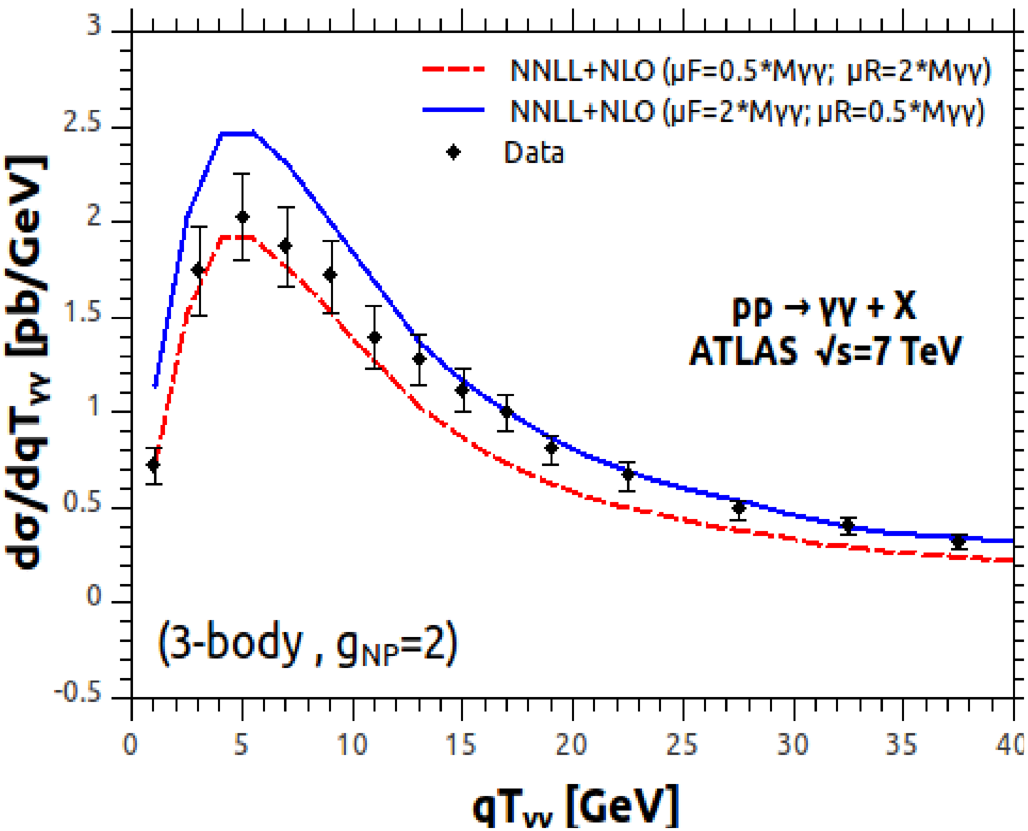


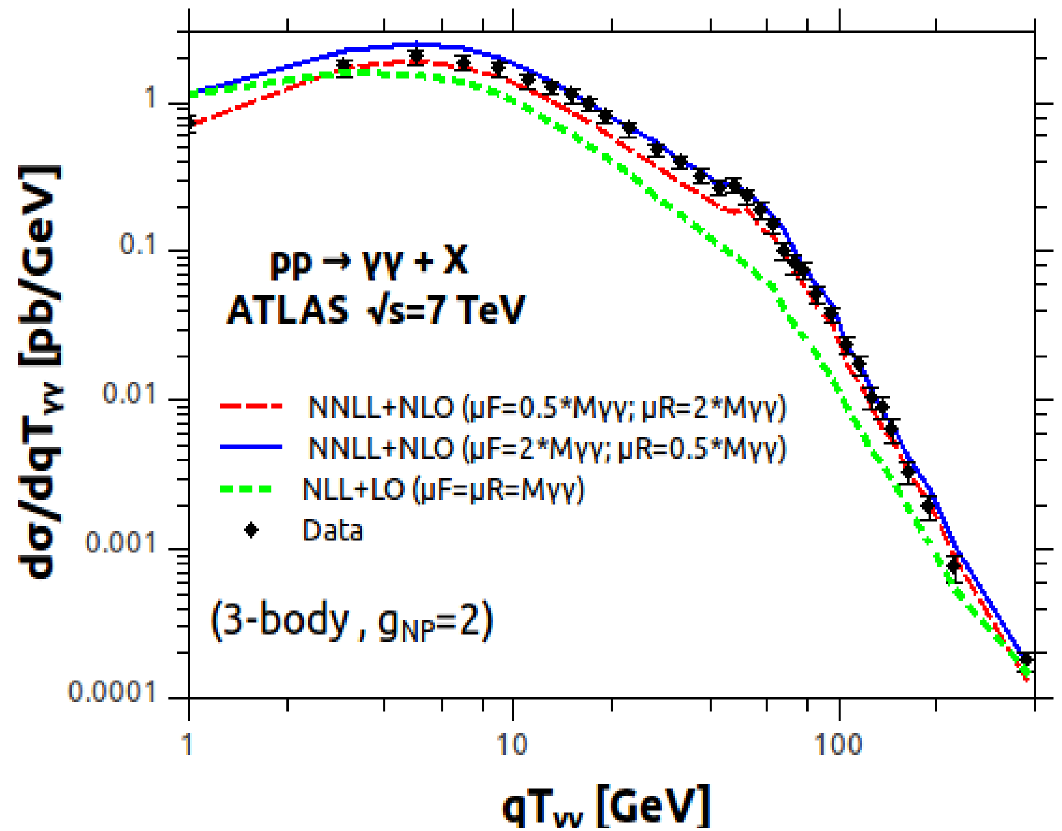
Uncertainties → 6% - 8%

Resummation → ATLAS γγ

LC, Coradeschi, de Florian

First results!





$$S^a_{NP} = \exp(-C_a\, g_{NP}\, b^2)$$

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

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

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

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

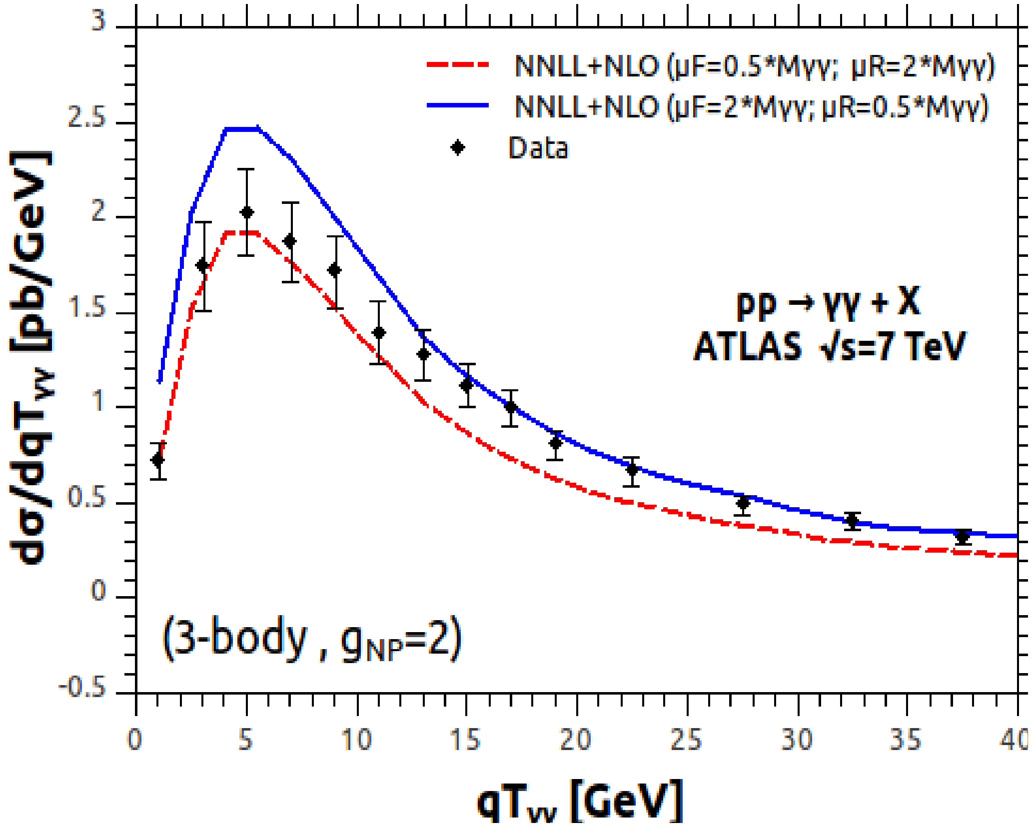
$E_{T\ max} = 4$ GeV, $n = 1$, $R = 0.4$,

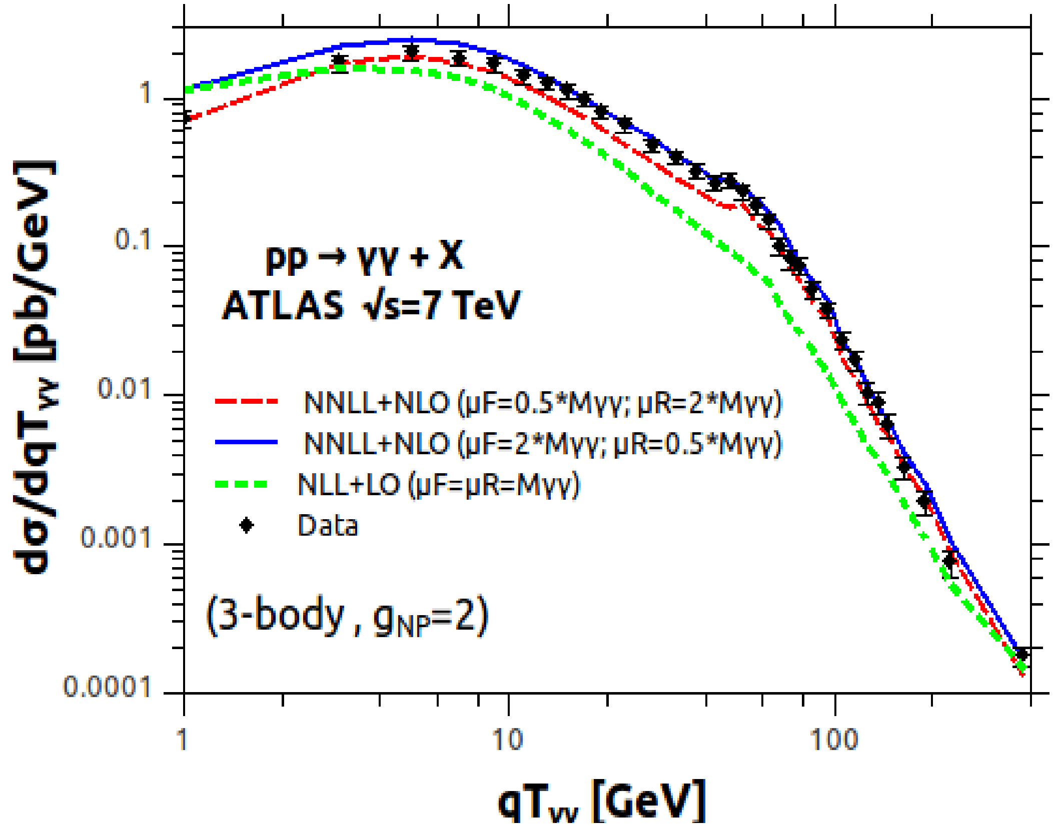
$R_{\gamma\gamma} = 0.4$

Resummation → ATLAS γγ

LC, Coradeschi, de Florian

First results!





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

$$p_T^{\text{harder}} \geq 25 \text{ GeV}, \quad p_T^{\text{softer}} \geq 22 \text{ GeV},$$
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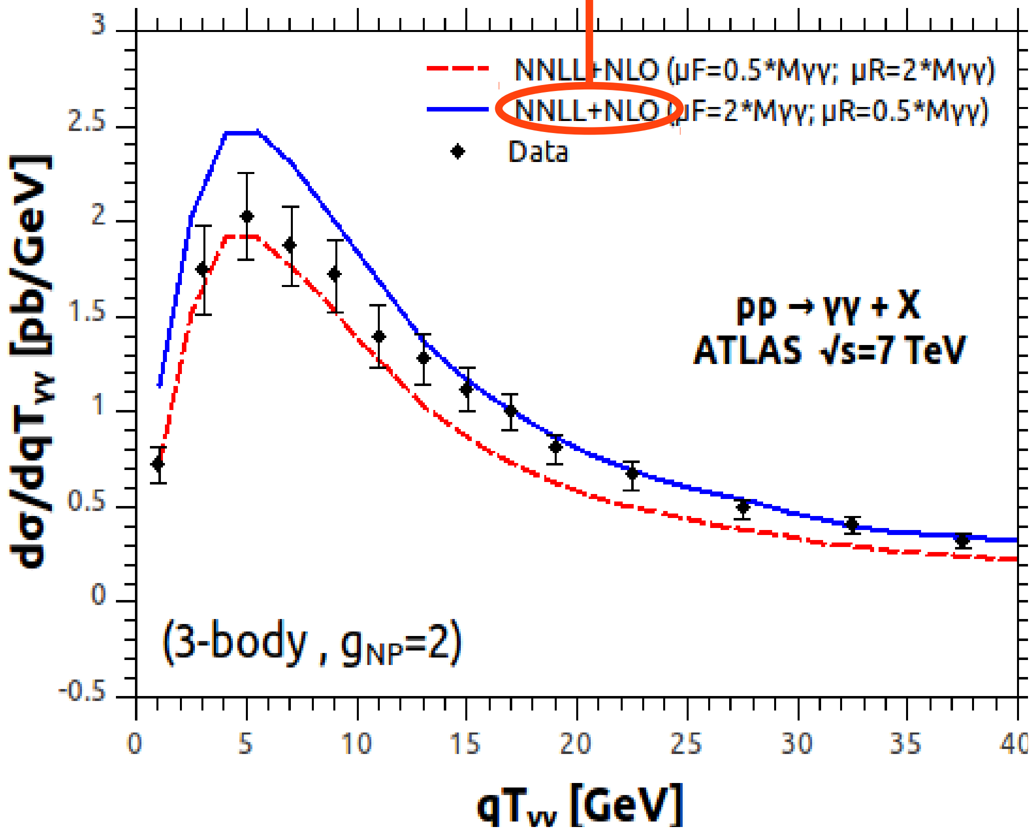
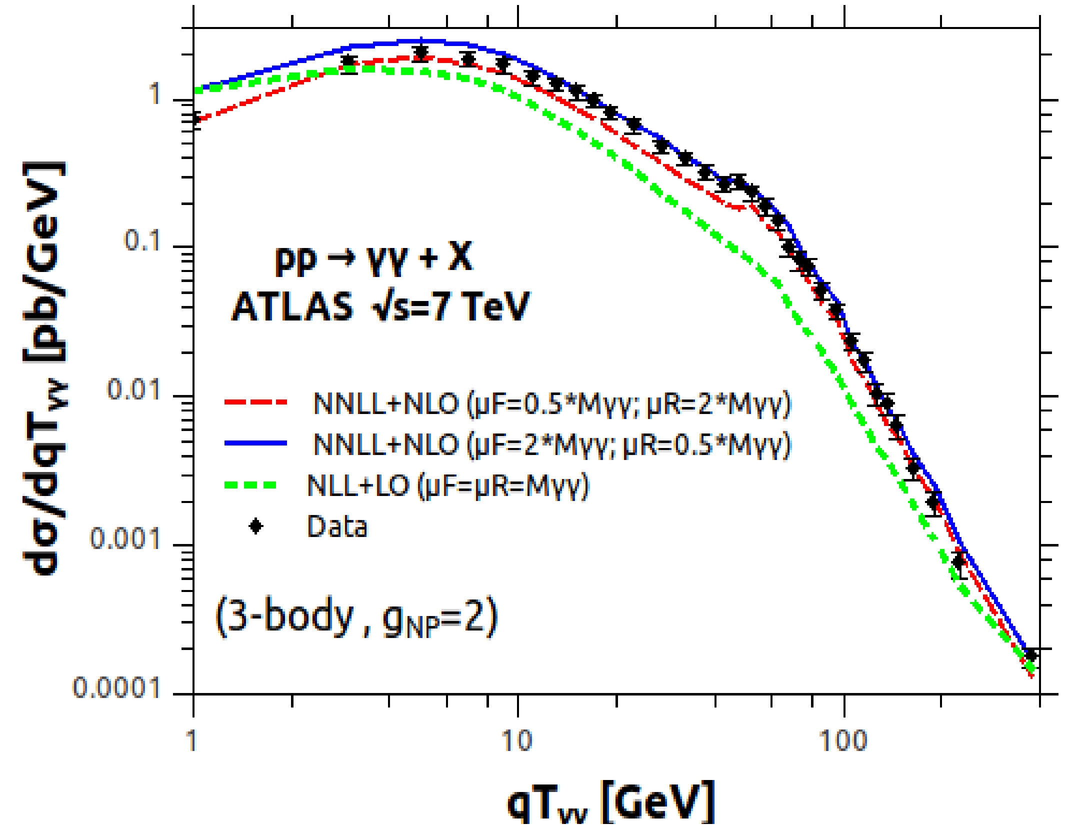
$$R_{\gamma\gamma} = 0.4$$

Resummation → ATLAS γγ

LC, Coradeschi, de Florian

+) NLO here means: γγ + jet at NLO
+) γγ + jet at NLO is a part of γγ production at NNLO





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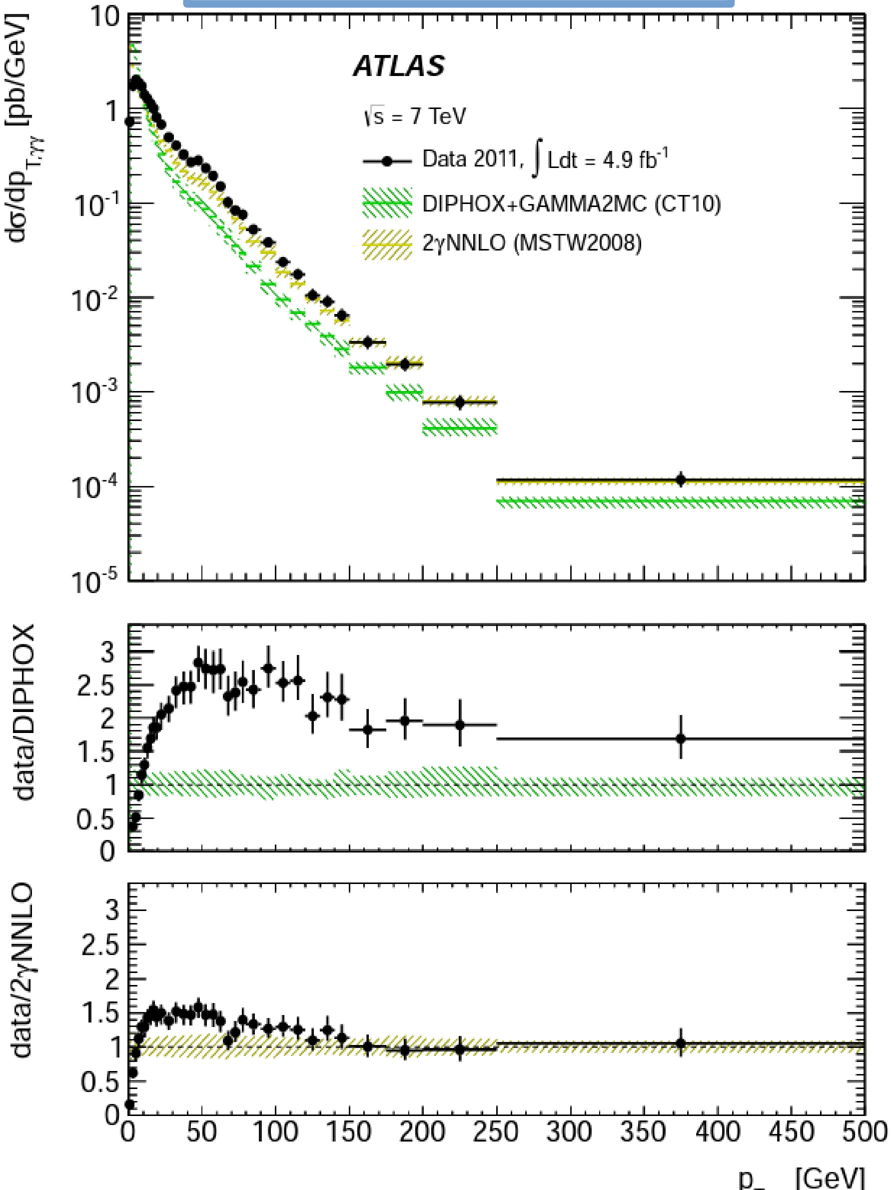
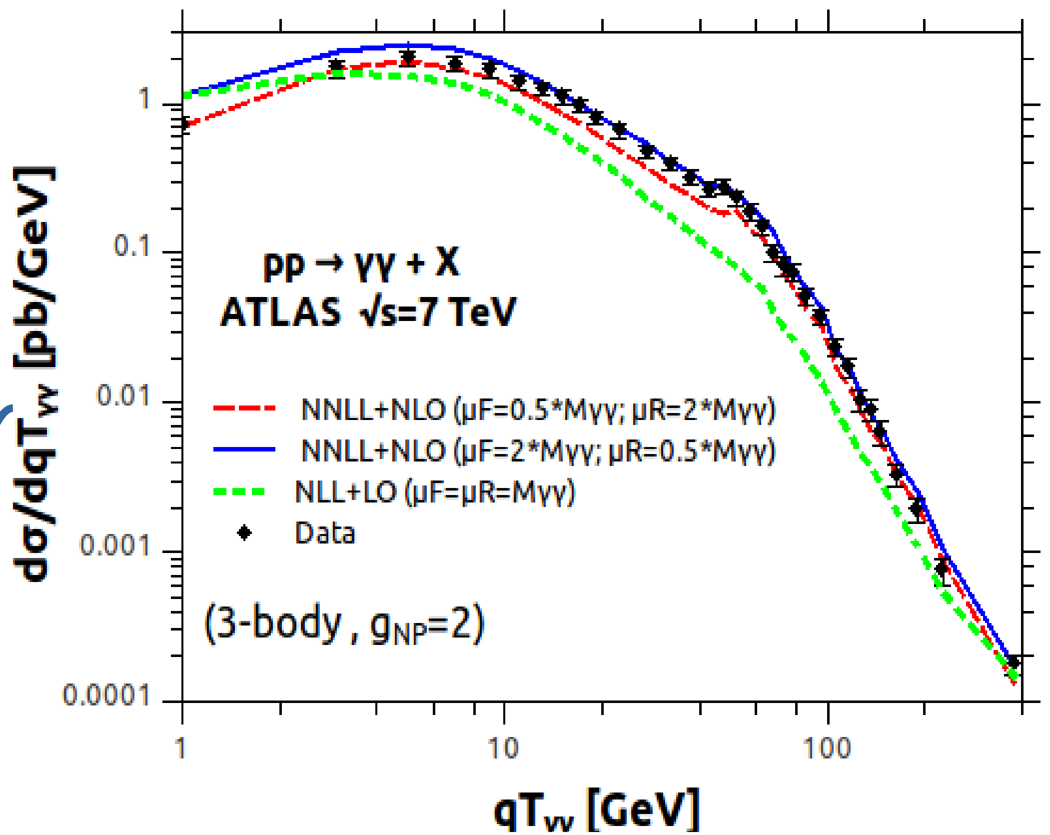
$R_{\gamma\gamma} = 0.4$

Resummation → ATLAS

LC, Coradeschi, de Florian

Fixed order





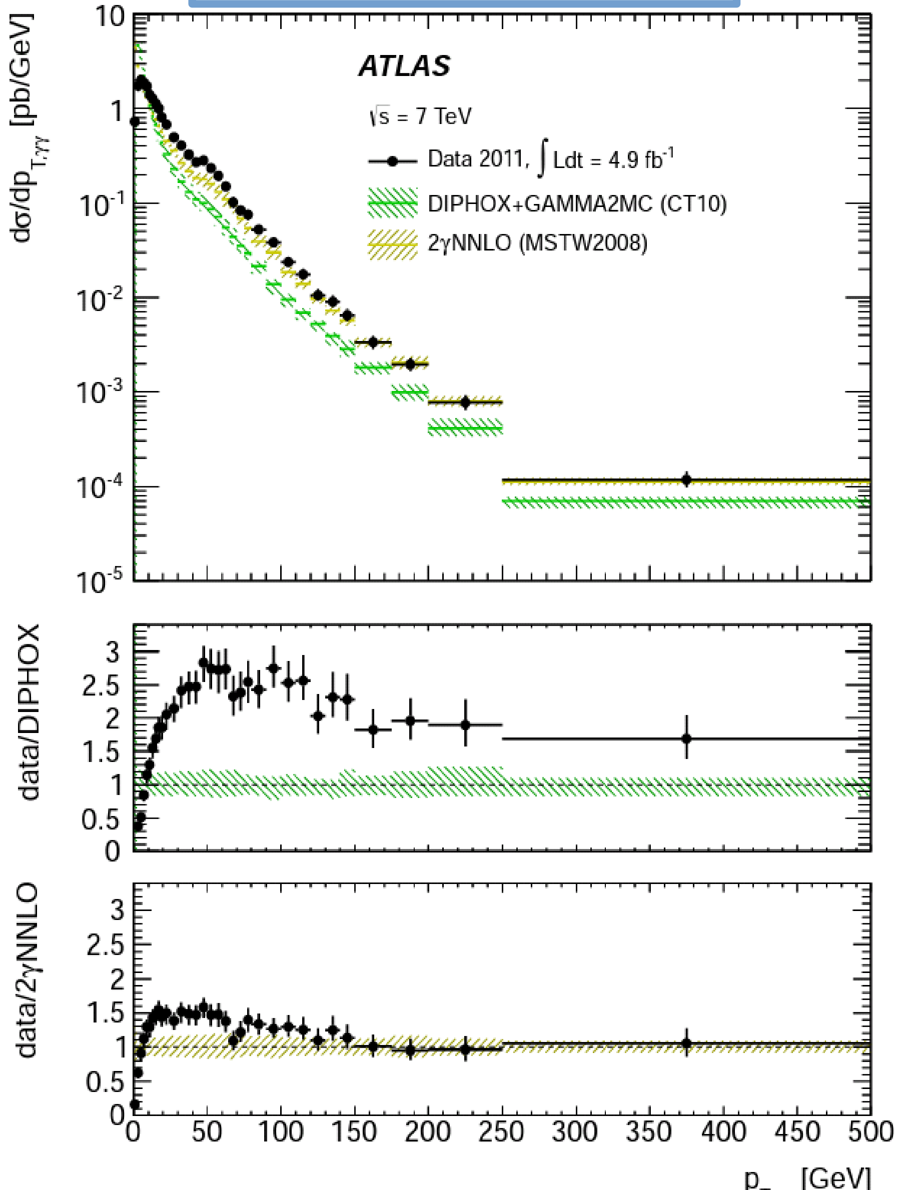
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.

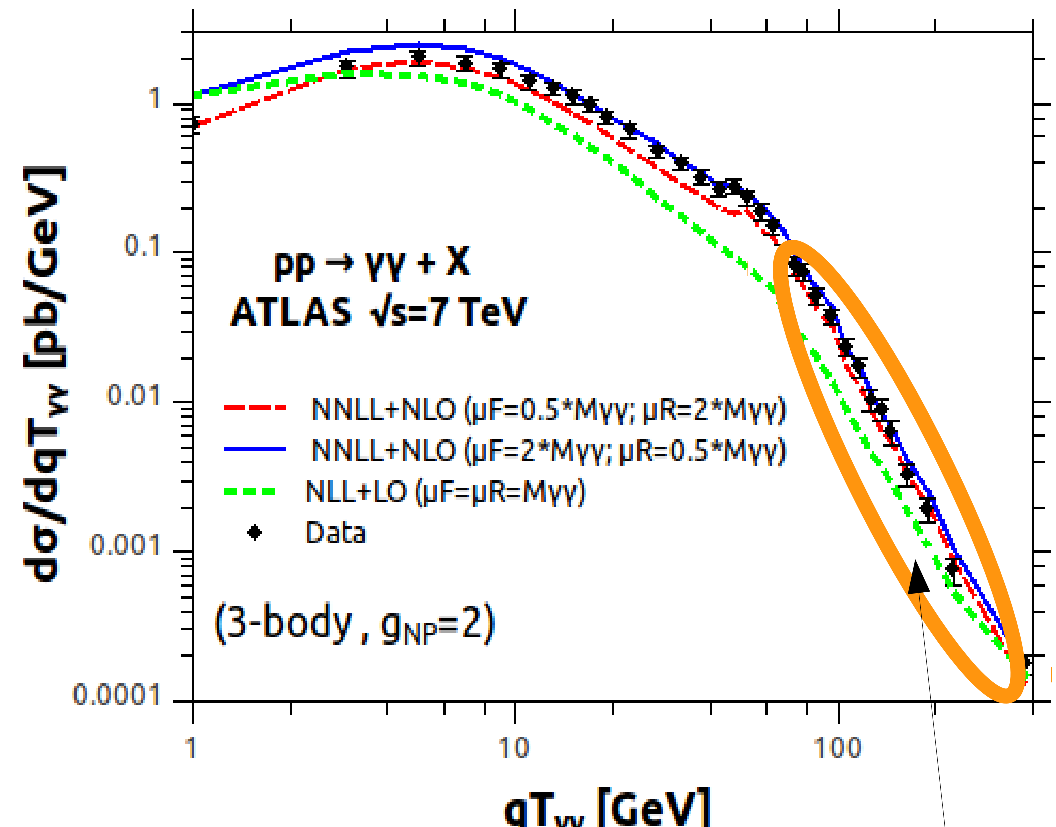
qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

Resummation → ATLAS

LC, Coradeschi, de Florian

Fixed order



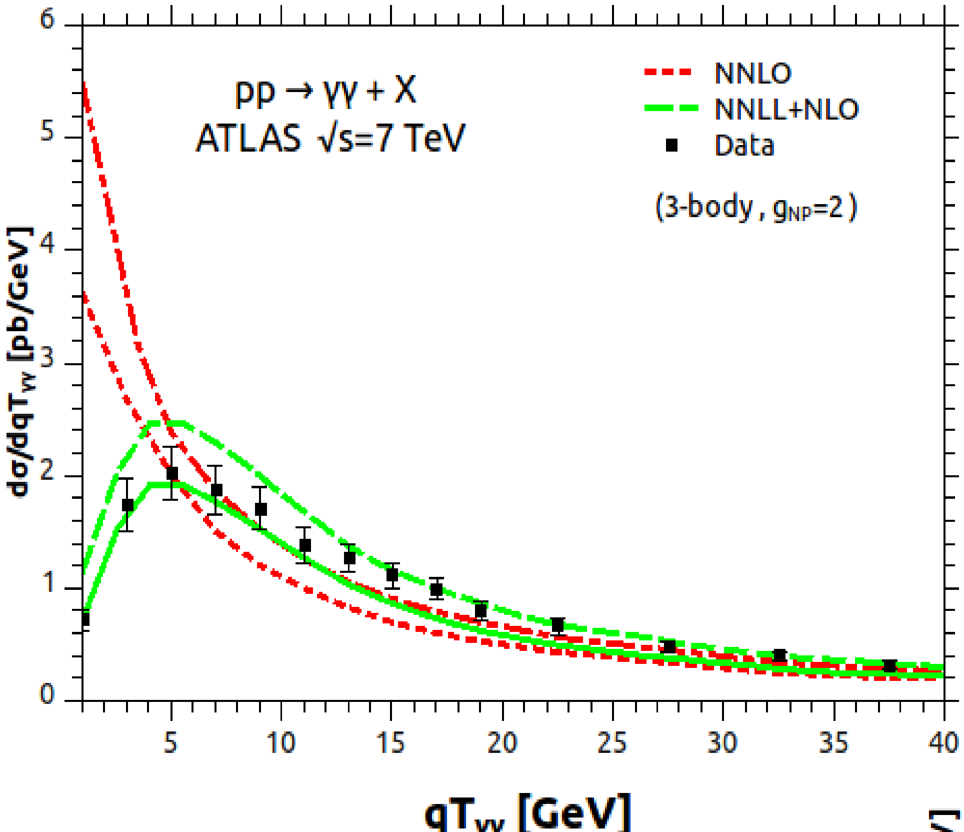


The size of the bands is proportional to the luminosity of the PDF of the gluon

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

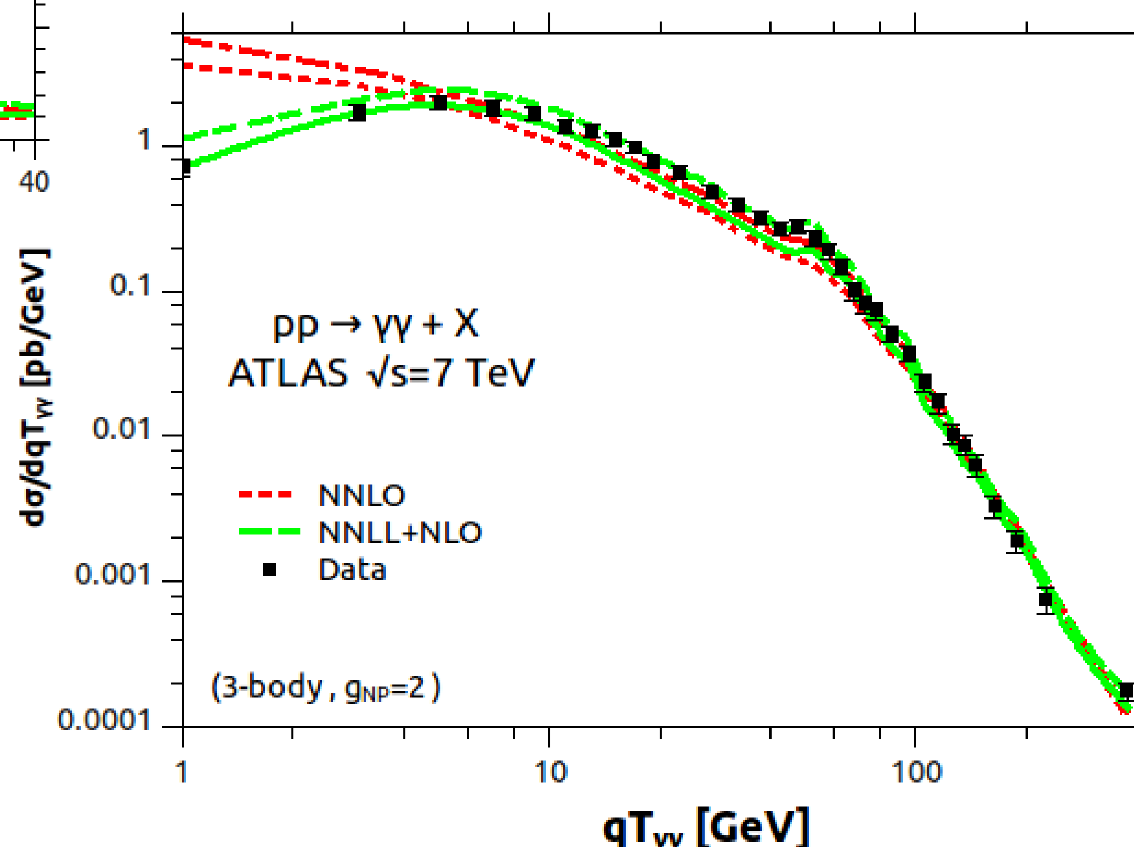
Resummation → ATLAS γγ

LC, Coradeschi, de Florian



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

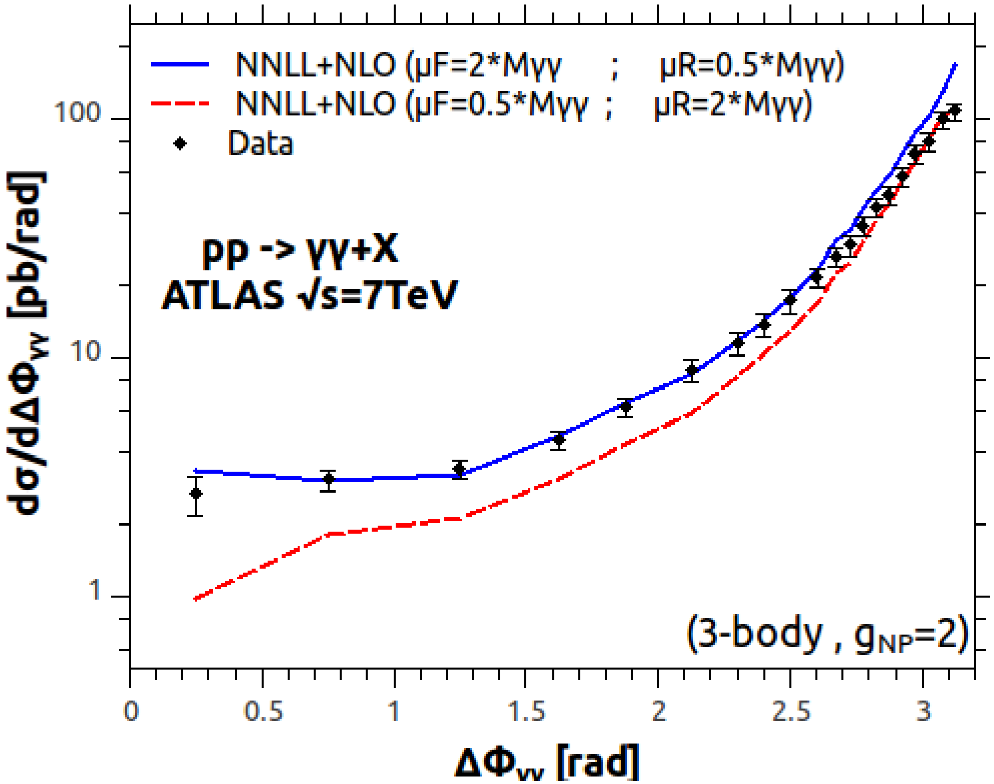
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.

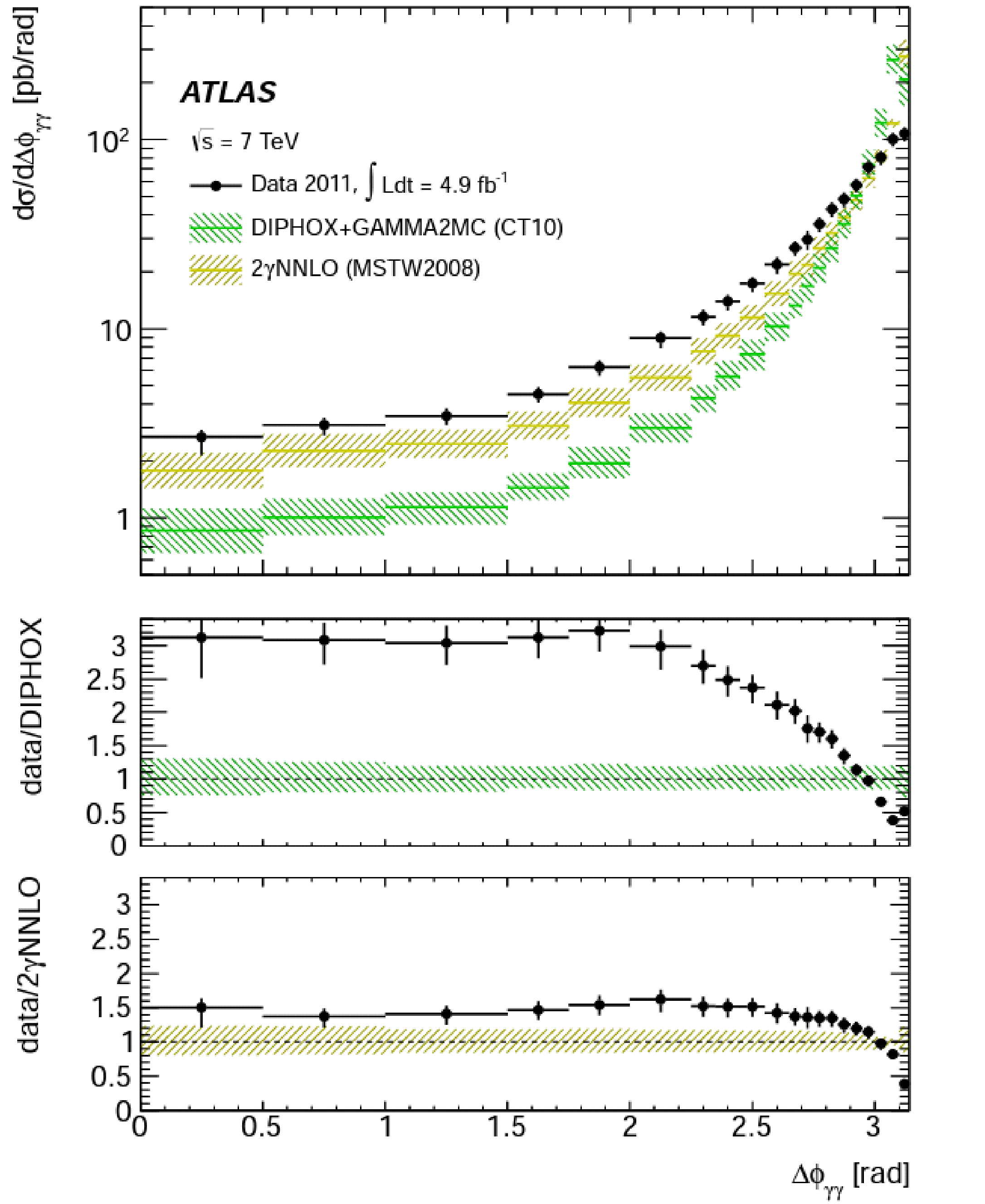


Resummation → ATLAS γγ

LC, Coradeschi, de Florian

First results!





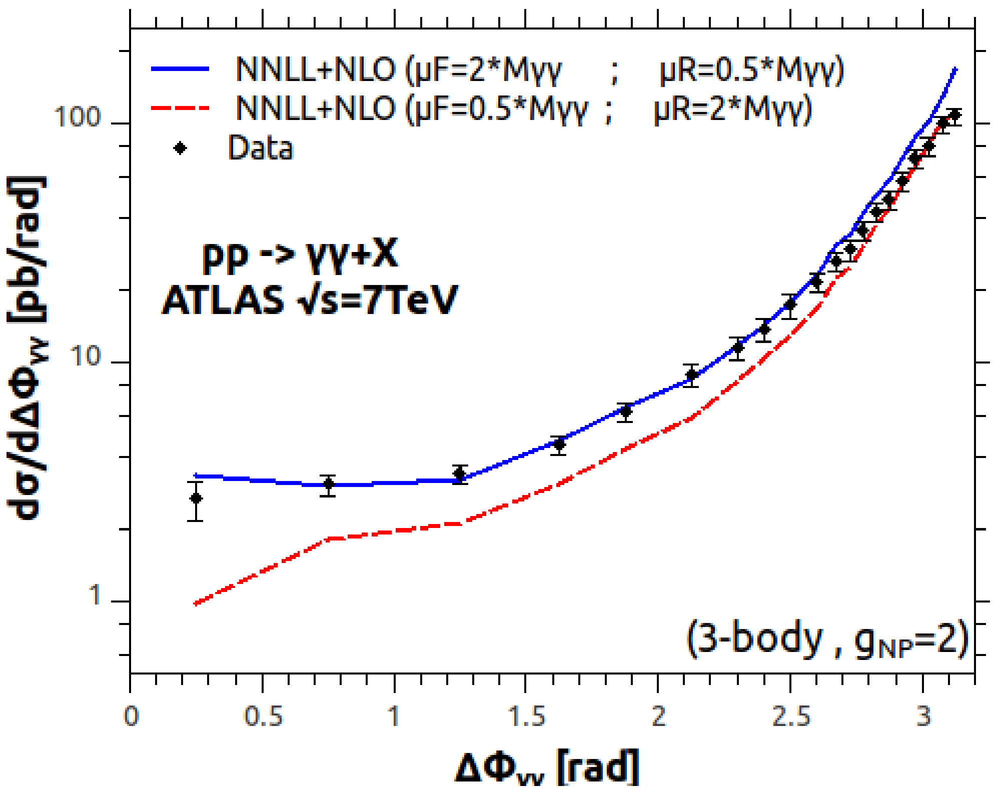
The same set-up also allows the calculation of more exclusive observable distributions

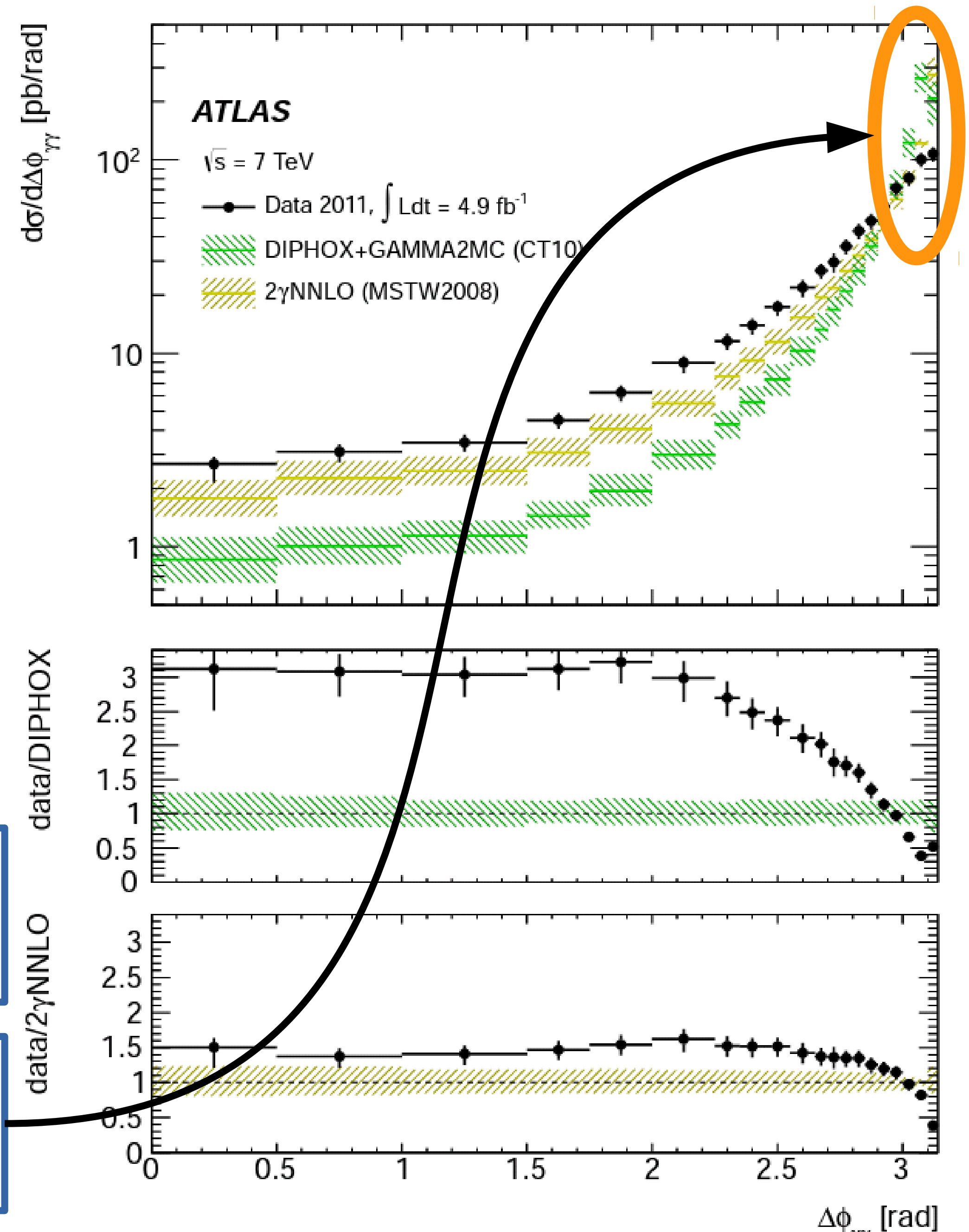
Uncertainties → 6% - 8%

Resummation → ATLAS γγ

LC, Coradeschi, de Florian

First results!





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

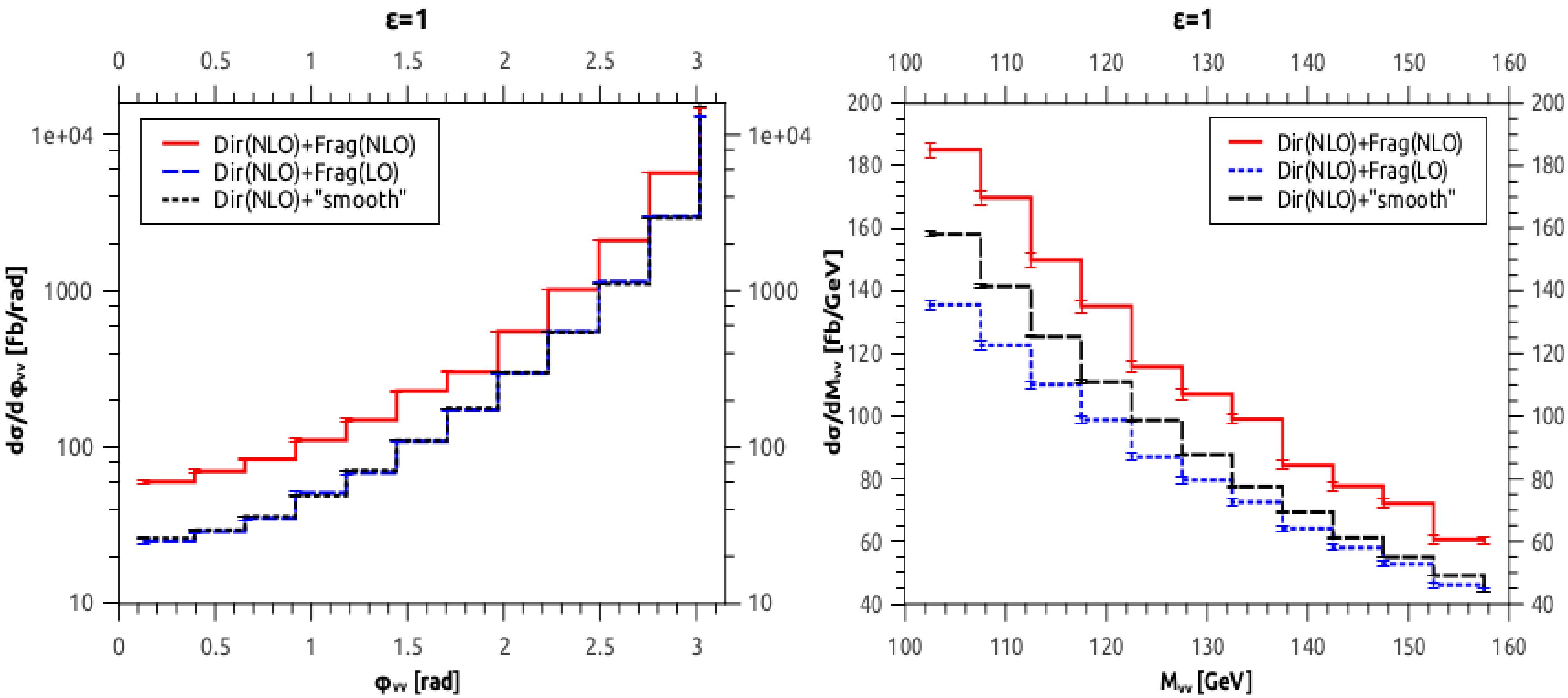
qT resummation "spreads" the uncertainties of the gg channel over the whole Δφ range

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: Vγ production, γγ + (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 Vγ 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 qT range.

Thank you!!!

Backup slides



ε=1
Dir(NLO)+Frag(NLO)
Dir(NLO)+Frag(LO)
Dir(NLO)+"smooth"
dσ/dφγγ [Fb/rad]
φγγ [rad]
ε=1
Dir(NLO)+Frag(NLO)
Dir(NLO)+Frag(LO)
Dir(NLO)+"smooth"
dσ/dMγγ [Fb/GeV]
Mγγ [GeV]

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

Standard cone isolation → DIPHOX

CMS [7 TeV]

	Code	$\sum E_T^{had} \leq$	σ^{NLO}_{total}(fb)	σ^{NLO}_{dir}(fb)	σ^{NLO}_{onef}(fb)	σ^{NLO}_{twof}(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	*incl*	6584	1186	3930	1468	none
h	2γNNLO	$0.05\ p_T^\gamma\ \chi(r)$	3768	3768	0	0	Smooth
i	2γNNLO	$0.5\ p_T^\gamma\ \chi(r)$	4074	4074	0	0	Smooth
j	2γNNLO	2 GeV $\chi(r)$	3743	3743	0	0	Smooth
k	2γNNLO	3 GeV $\chi(r)$	3776	3776	0	0	Smooth
l	2γNNLO	4 GeV $\chi(r)$	3795	3795	0	0	Smooth
m	2γNNLO	5 GeV $\chi(r)$	3814	3814	0	0	Smooth

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

Standard cone isolation → DIPHOX

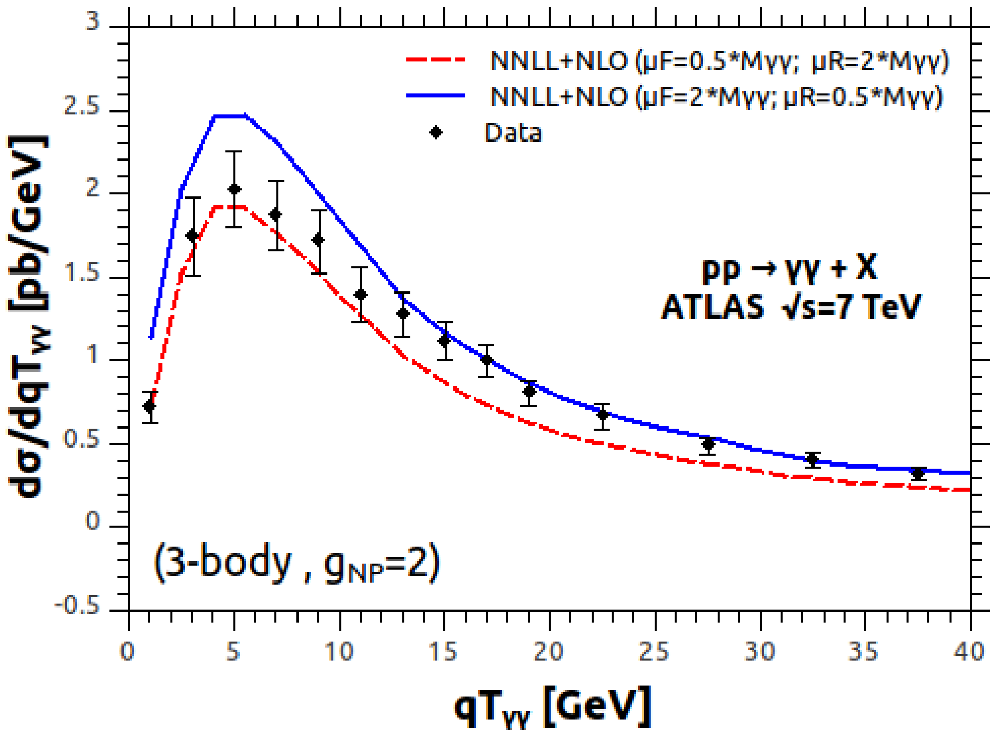
CMS [7 TeV]

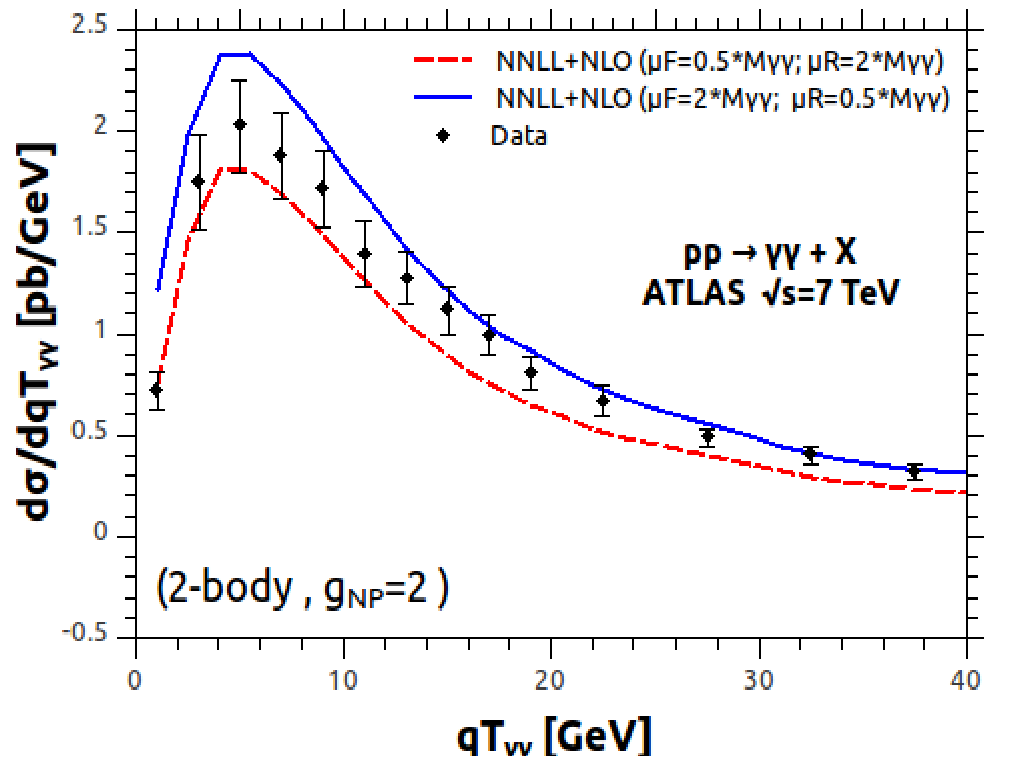
	Code	$\sum E_T^{had} \leq$	σ_{total}^{NLO}(fb)	σ_{dir}^{NLO}(fb)	$\sigma_{one f}^{NLO}$(fb)	$\sigma_{two f}^{NLO}$(fb)	Isolation
a	DIPHOX	2 GeV	3746	3504	239	2.6	Standard
b	DIPHOX	3 GeV	3776	3396	374	6	Standard
c	DIPHOX	4 GeV	3796	3296	488	12	Standard
d	DIPHOX	5 GeV	3825	3201	607	17	Standard
e	DIPHOX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

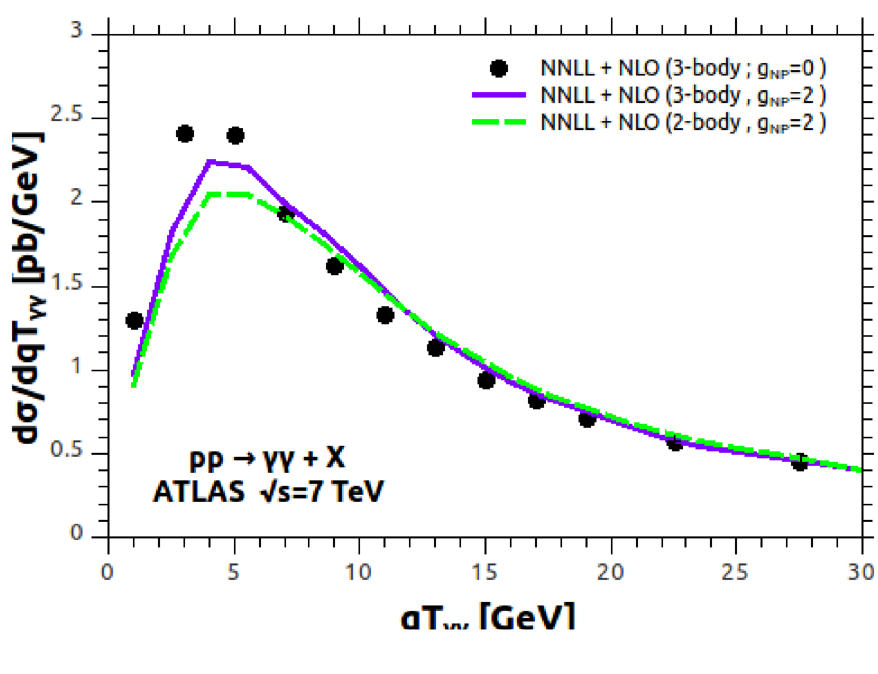
Tighter criteria

Direct component increasing

Resummation







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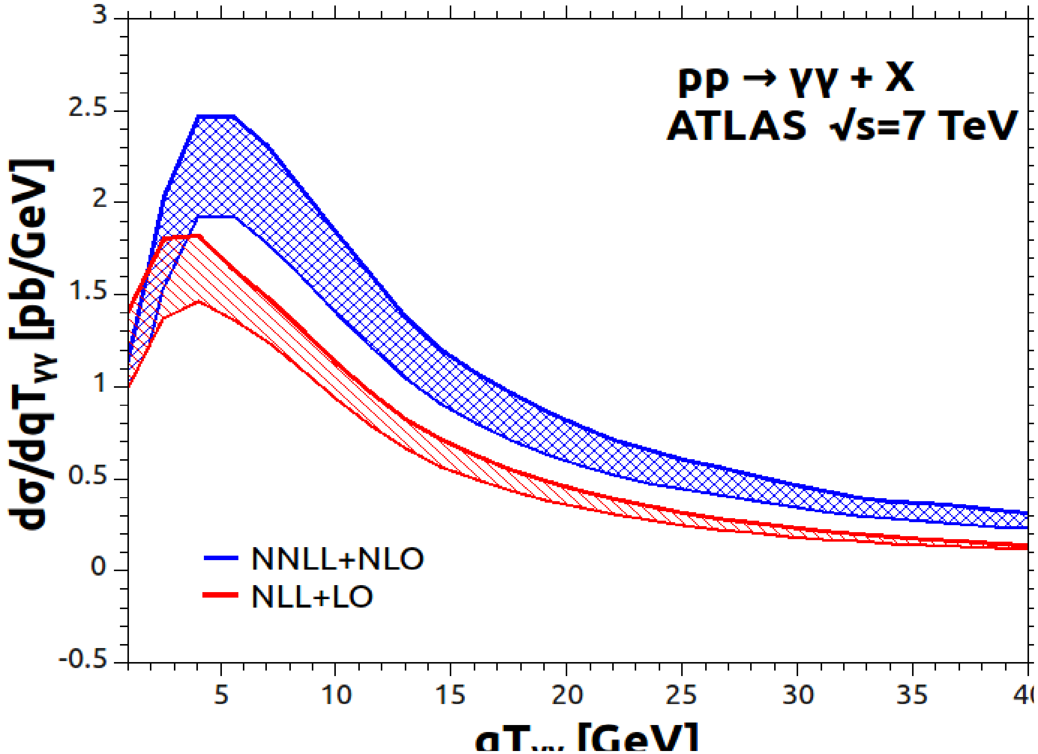
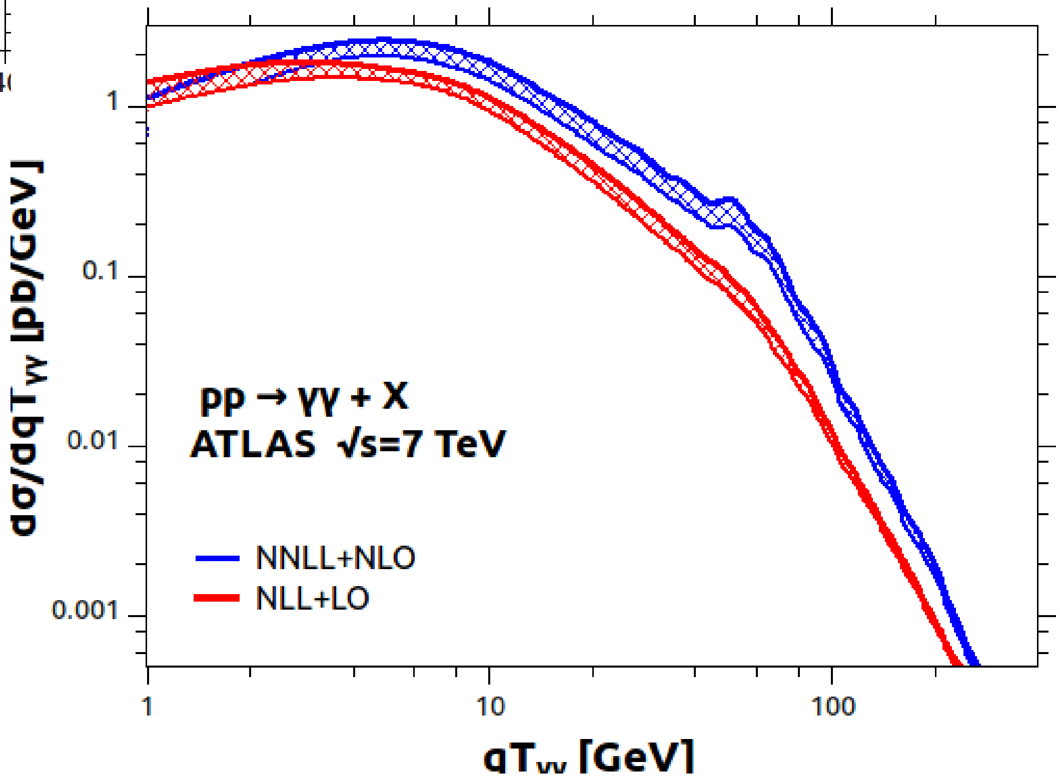
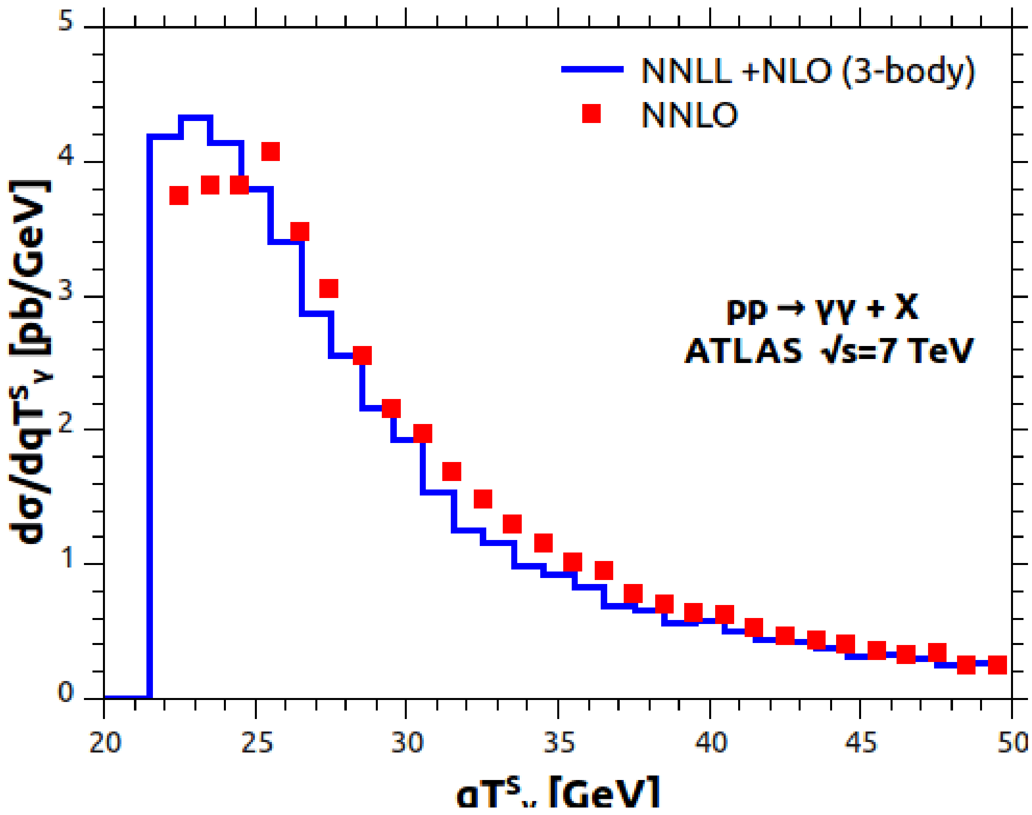
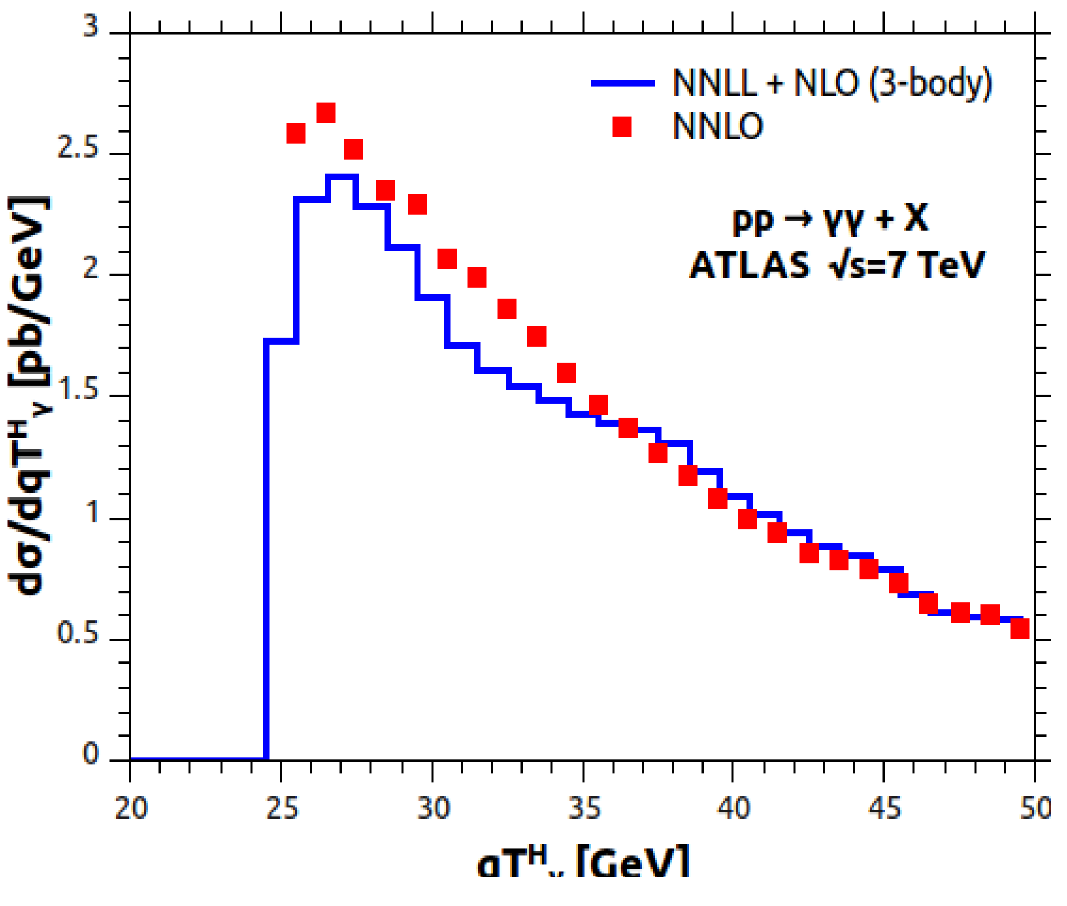




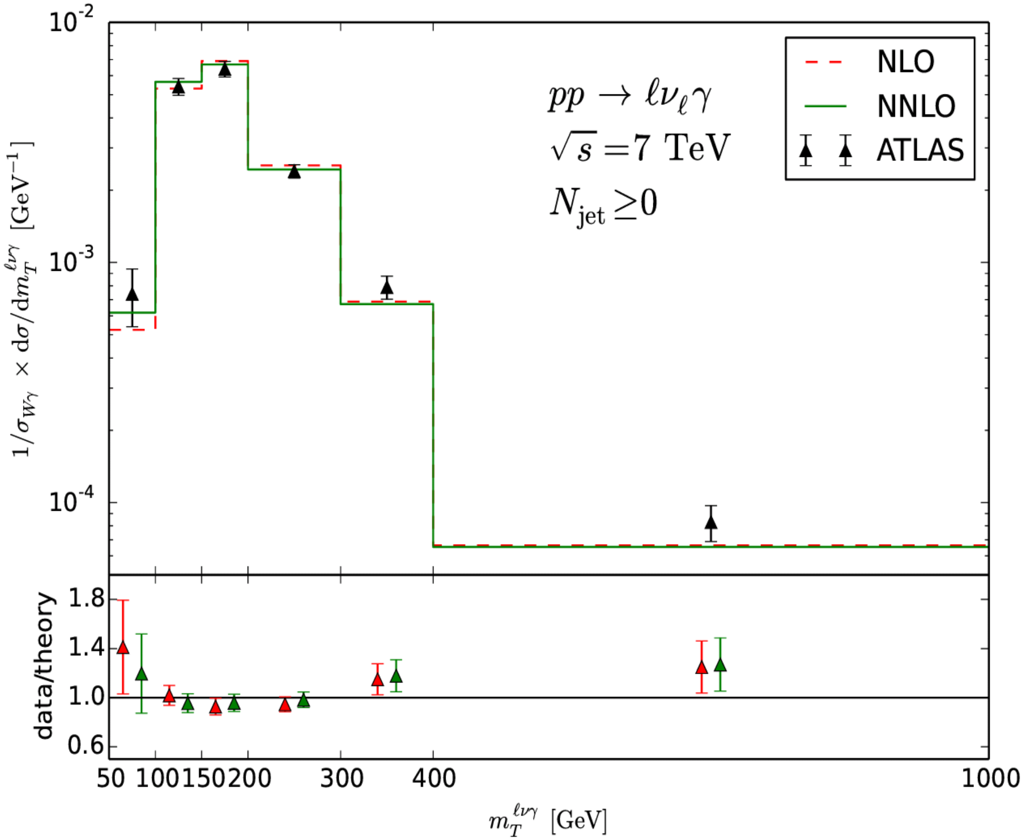
Resummation

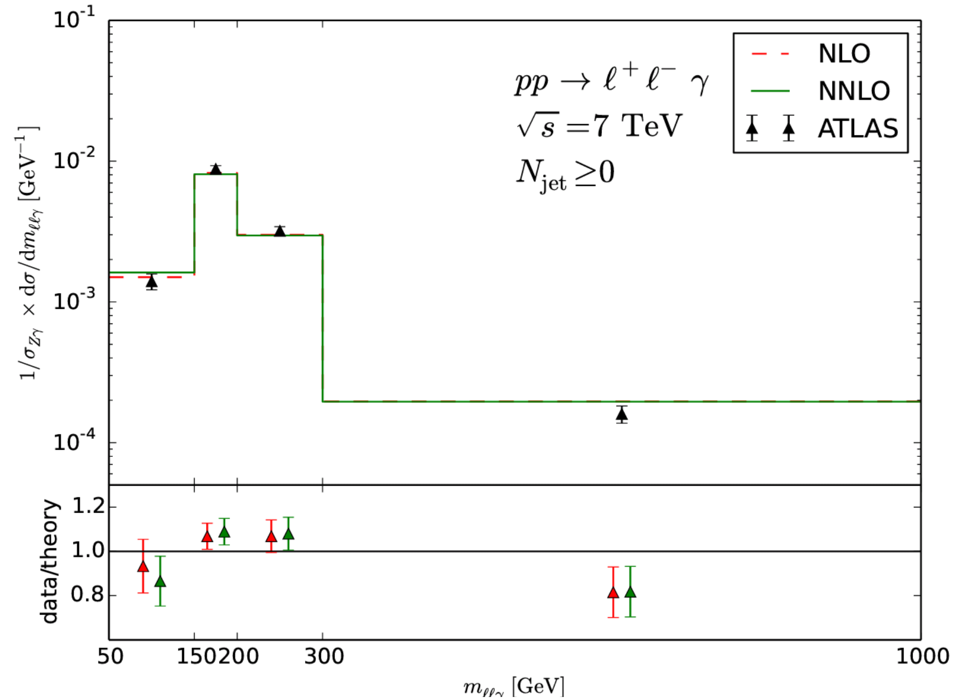


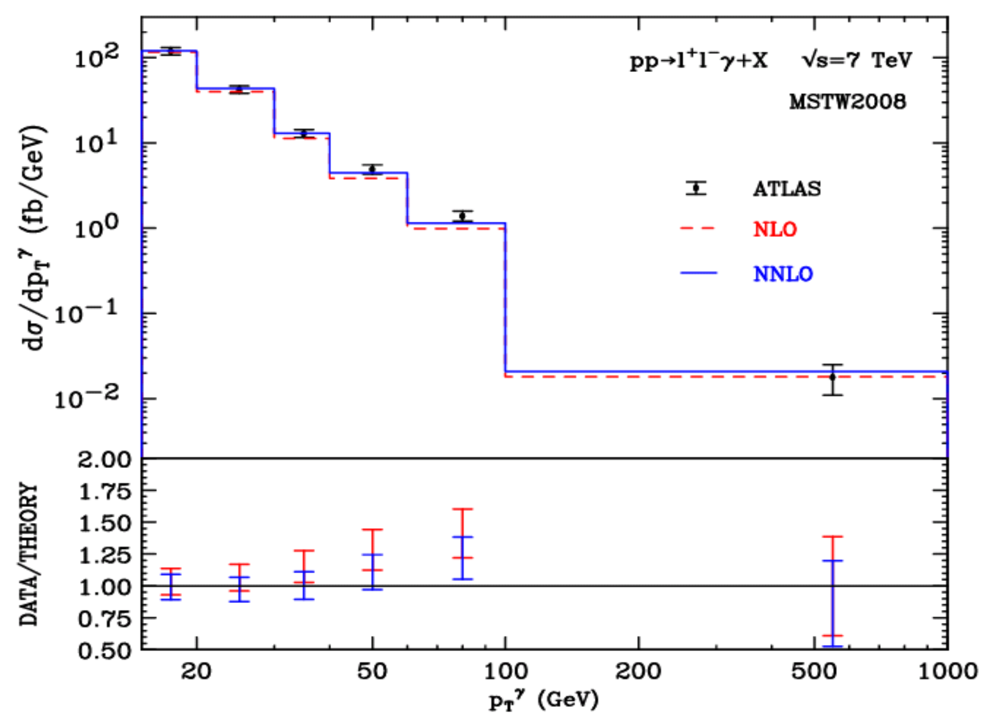


Vγ production NNLO

Grazzini, Kallweit, Rathlev, Torre

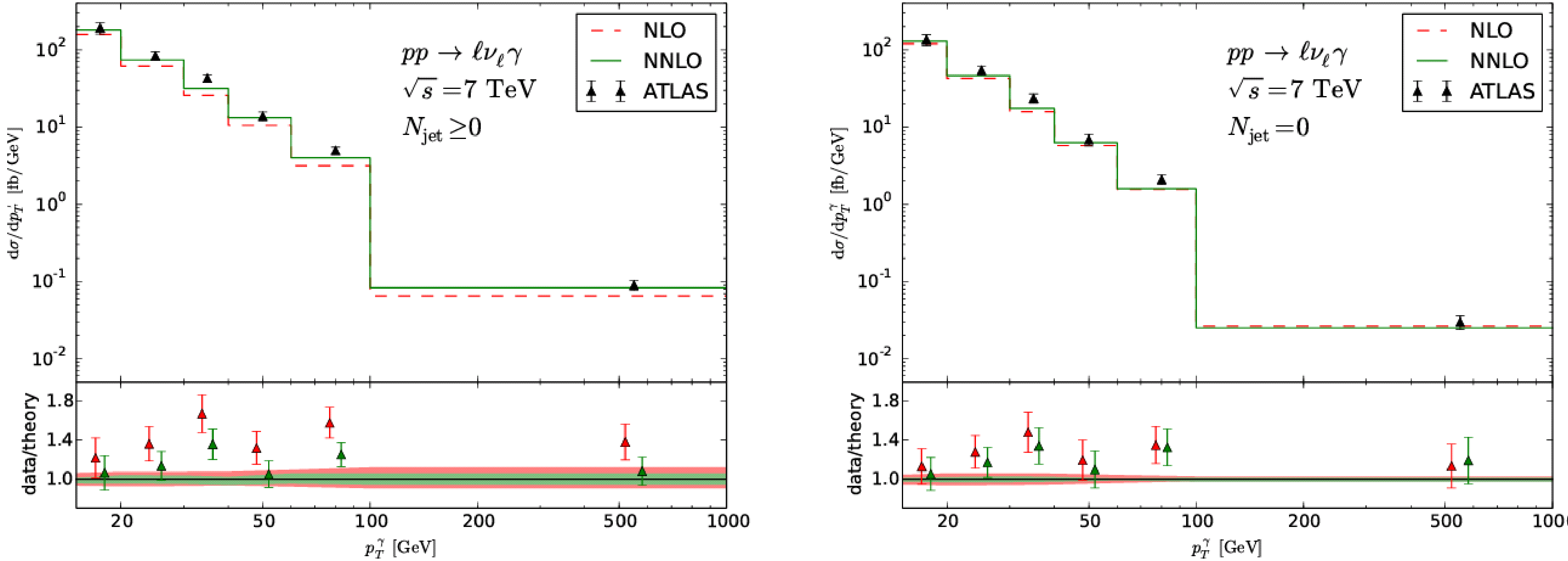




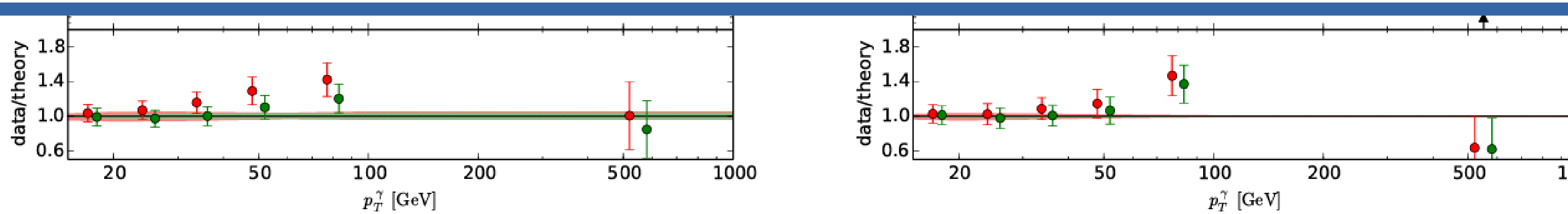


Vγ production NNLO

Grazzini, Kallweit, Rathlev, Torre

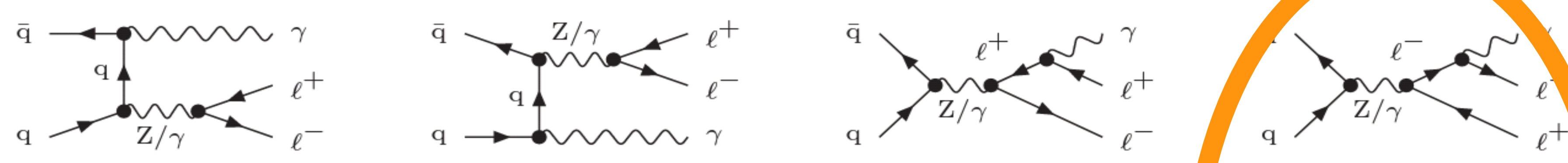


It is clear that the Wγ process features much larger radiative effects with respect to the Zγ processes. This should be contrasted to what happens in the case of inclusive W and Z boson production, where QCD radiative corrections are essentially identical. It is thus the emission of the additional photon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



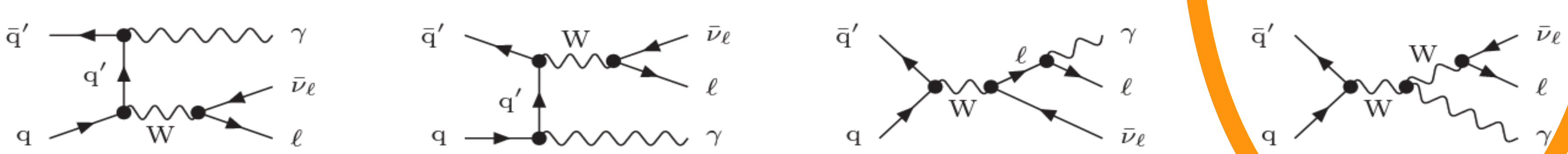
Vγ production NNLO

Grazzini, Kallweit, Rathlev, Torre



(a) Topology Ia (b) Topology Ib (c) Topology IIa (d) Topology IIb

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



(a) Topology Ia (b) Topology Ib (c) Topology IIa (d) Topology III

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

It is clear that the Wγ process features much larger radiative effects with respect to the Zγ 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.