Diphoton production at NNLL +NNLO at the LHC

Leandro Cieri

La Sapienza - Università di Roma

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Outline

- Introduction
- Isolation criteria (IC)
- Available FO tools
- IC comparison (γγ NLO)
- Les Houches accord ("tight" isolation accord)
- qT Resummation γγ (ATLAS)
- Summary

Outline

- Introduction → Motivation; Production mechanisms
- Isolation criteria (IC)
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Why diphoton production is important?

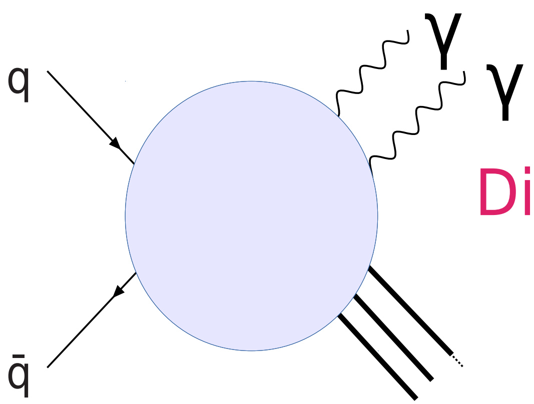
- It is a channel that we can use to check the validity of perturbative Quantum Chromodynamics (pQCD)
  - Collinear factorization approach
  - K_T factorization approach
  - Soft gluon logarithmic resummation techniques

- It constitutes an irreducible background for new physics searches
  - Universal Extra Dimensions
  - Randall-Sundrum ED
  - Supersymmetry
  - New heavy resonances

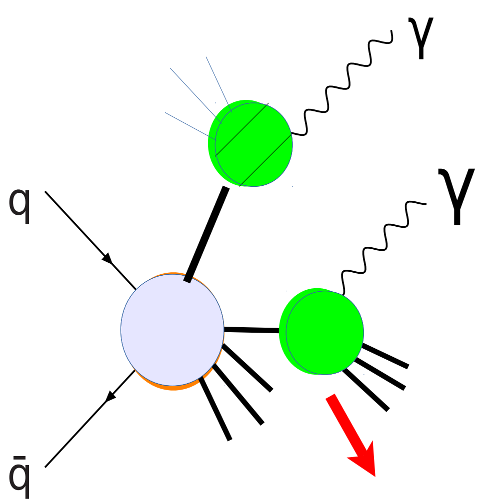
- **Irreducible background**
  - **In studies and searches for a low mass Higgs boson decaying into photon pairs**

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



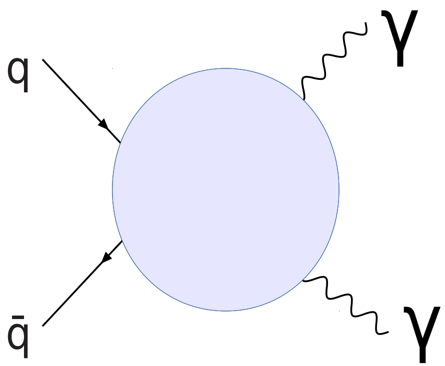
Fragmentation component: photon is produced from non-perturbative fragmentation of a hard parton (analogously to a hadron)

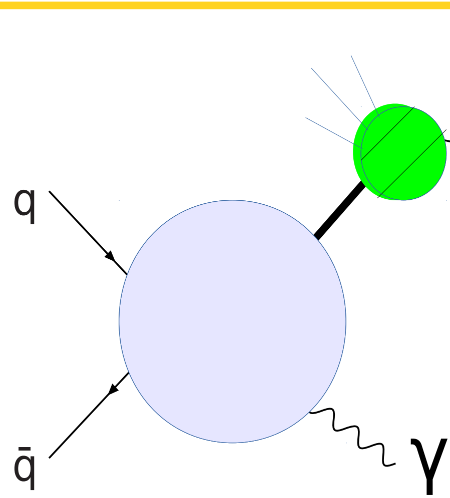
Calculations of cross sections with photons have additional singularities in the presence of QCD radiation.
(i.e. When we go beyond LO)

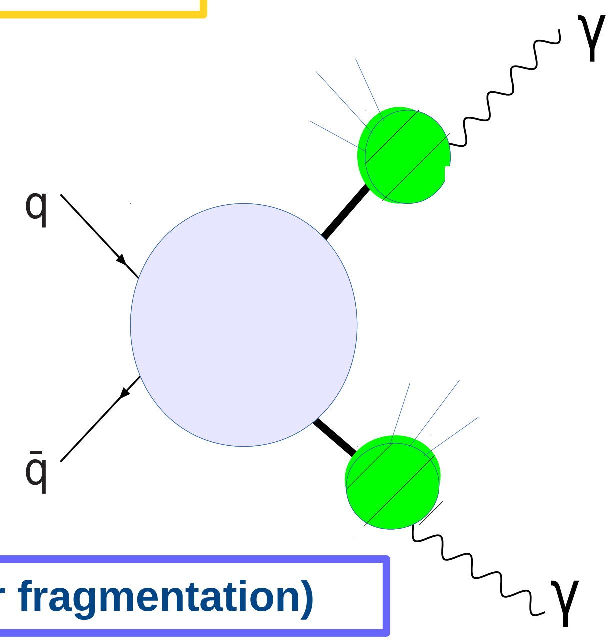
Fragmentation function:
to be fitted from data

Photon production

Two mechanisms for photon production



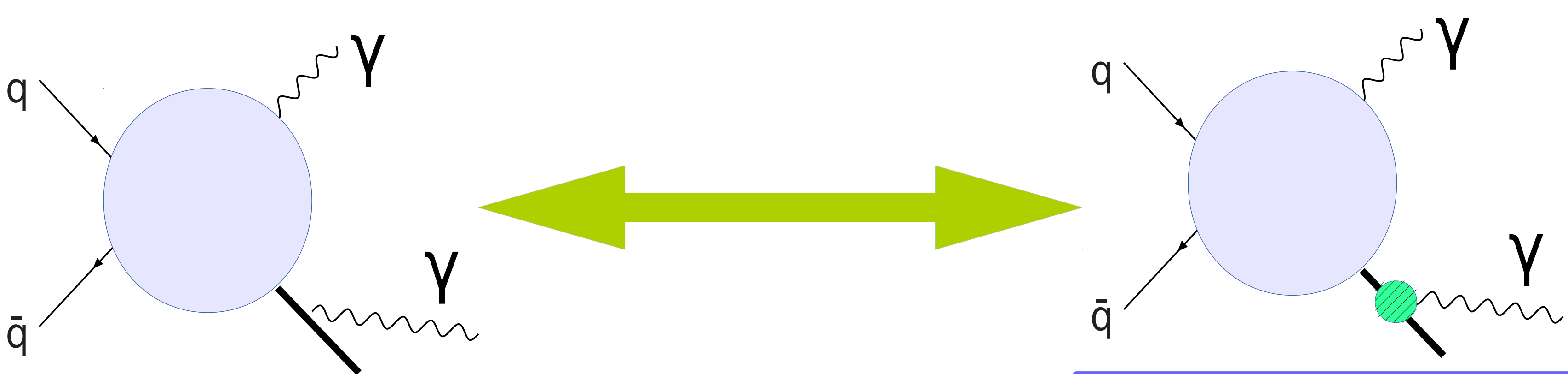




Direct (point-like)

Single and double resolved (collinear fragmentation)

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



Collinear divergence

Cancelled by fragmentation

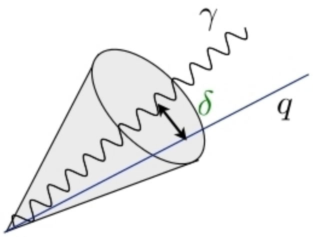
Photon production

- 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)

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

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

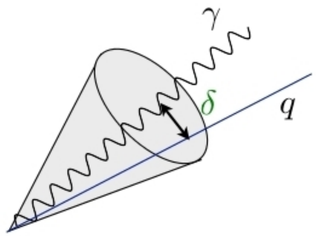
- **Democratic** Glover, Morgan(1994). Gehrmann-De Ridder, Gehrmann, Glover (1997)

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

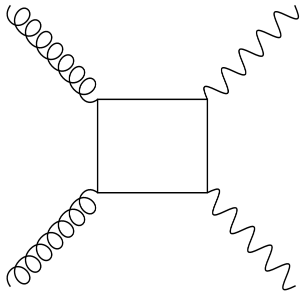
Soft emission allowed arbitrarily close to the photon

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

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

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

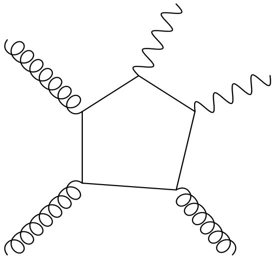
Available theoretical (FO) tools for γγ production

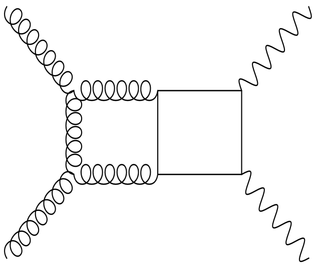


DIPHOX T. Binoth, J.Ph. Guillet, E. Pilon and M. Werlen

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

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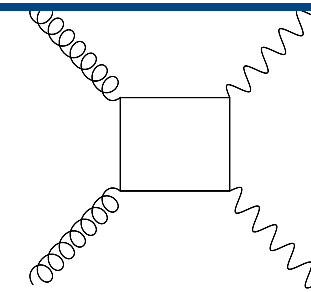

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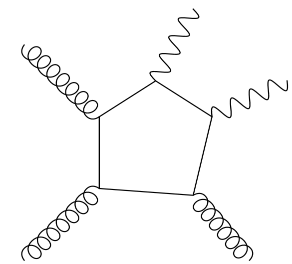

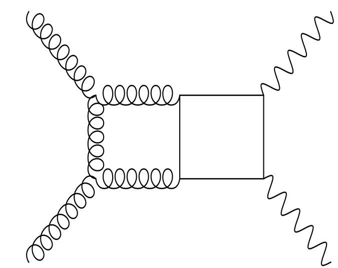

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NLL q_T resummation for direct (with regulator for collinear singularities)

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

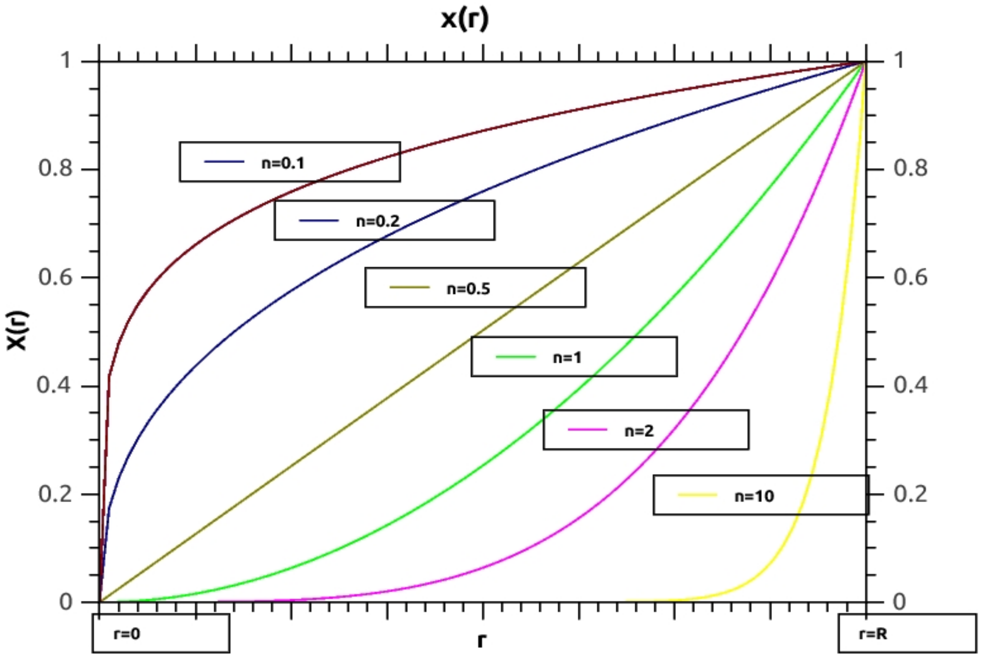
Incorporates the qT resummation at NNLL+NNLO

IC comparison (NLO)

Standard vs Smooth

$\gamma\gamma$ production

IC comparison (γγ at NLO)

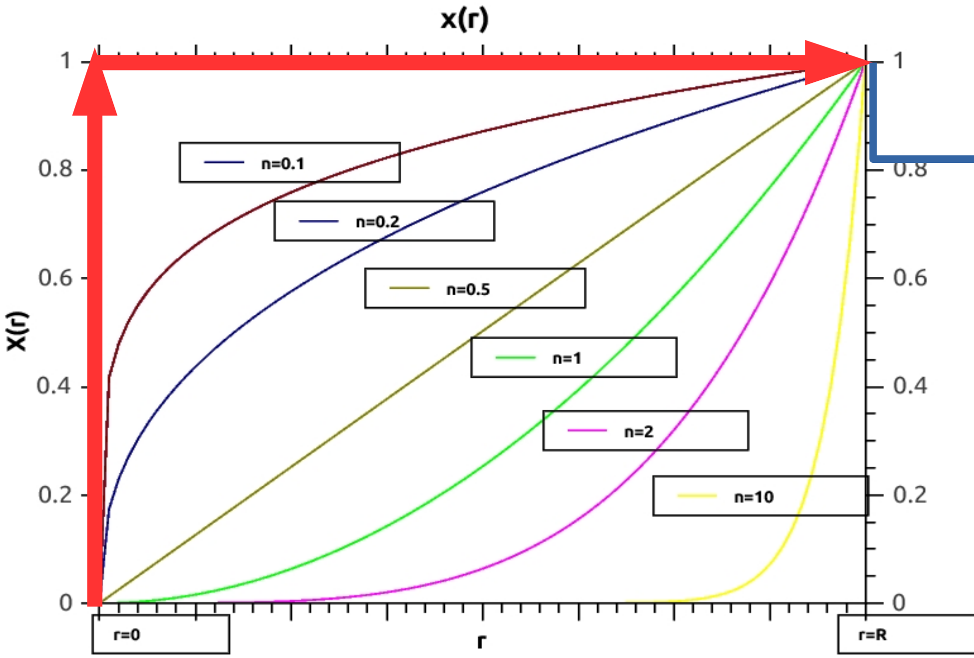


$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n \leq 1$$

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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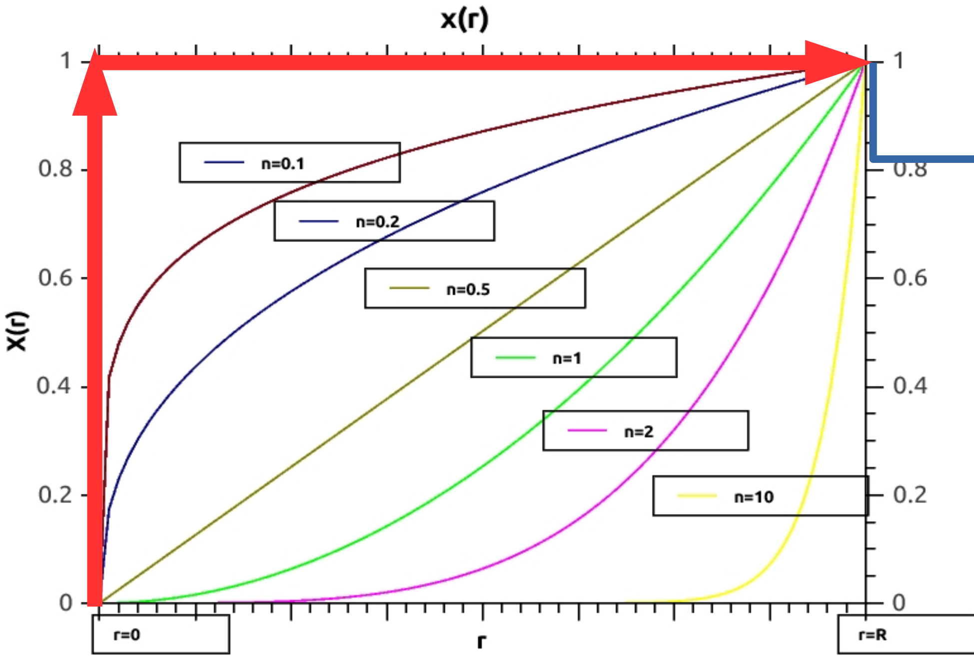

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- **No quark-photon collinear divergences**
- **No fragmentation contribution (only direct)**
- **Direct contribution well defined**

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

(both theoretically and experimentally)

Isolation criteria 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.

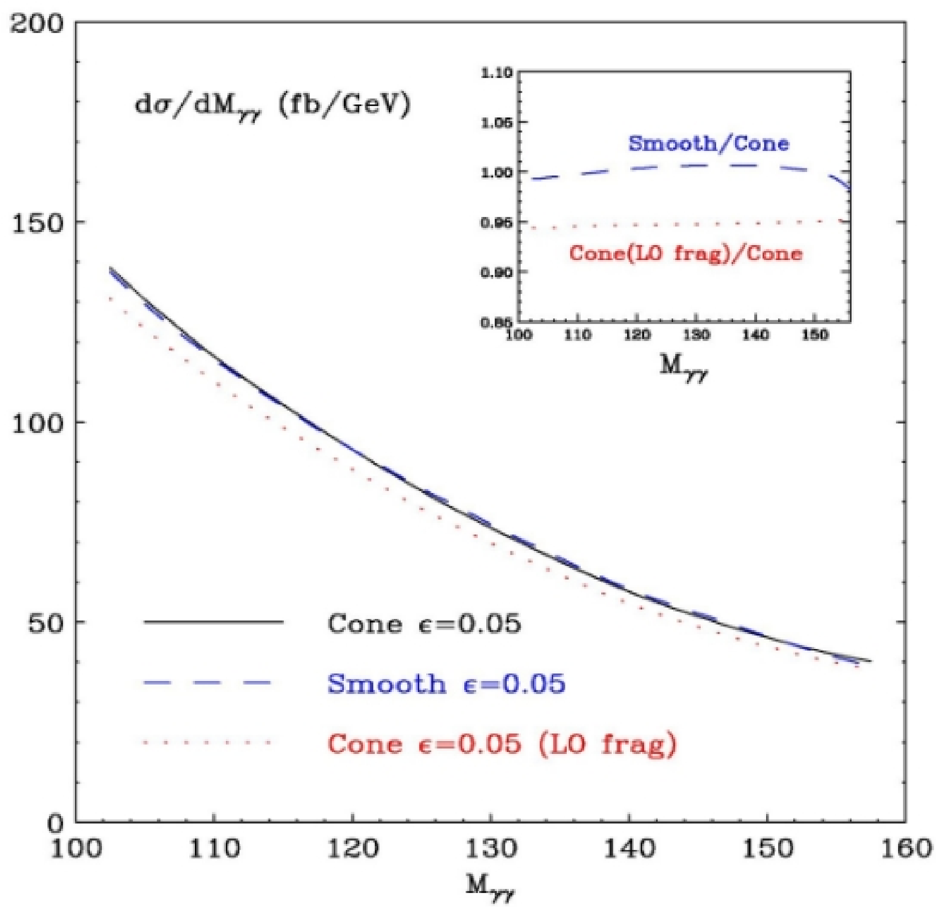
Diphoton production $\sqrt{s} = 8\,\text{TeV}$ **CTEQ6M** $\mu_F = \mu_R = M_{\gamma\gamma}$

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

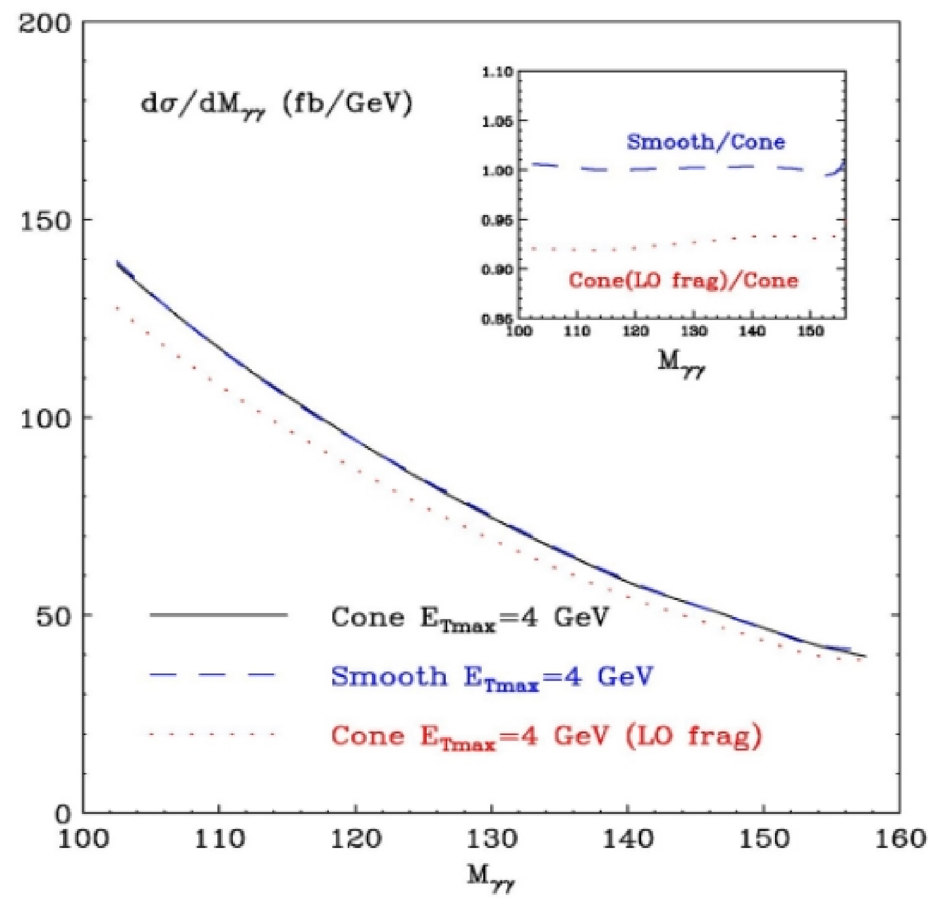
$p_T^{\gamma\,soft} \geq 30\,\text{GeV}$

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

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

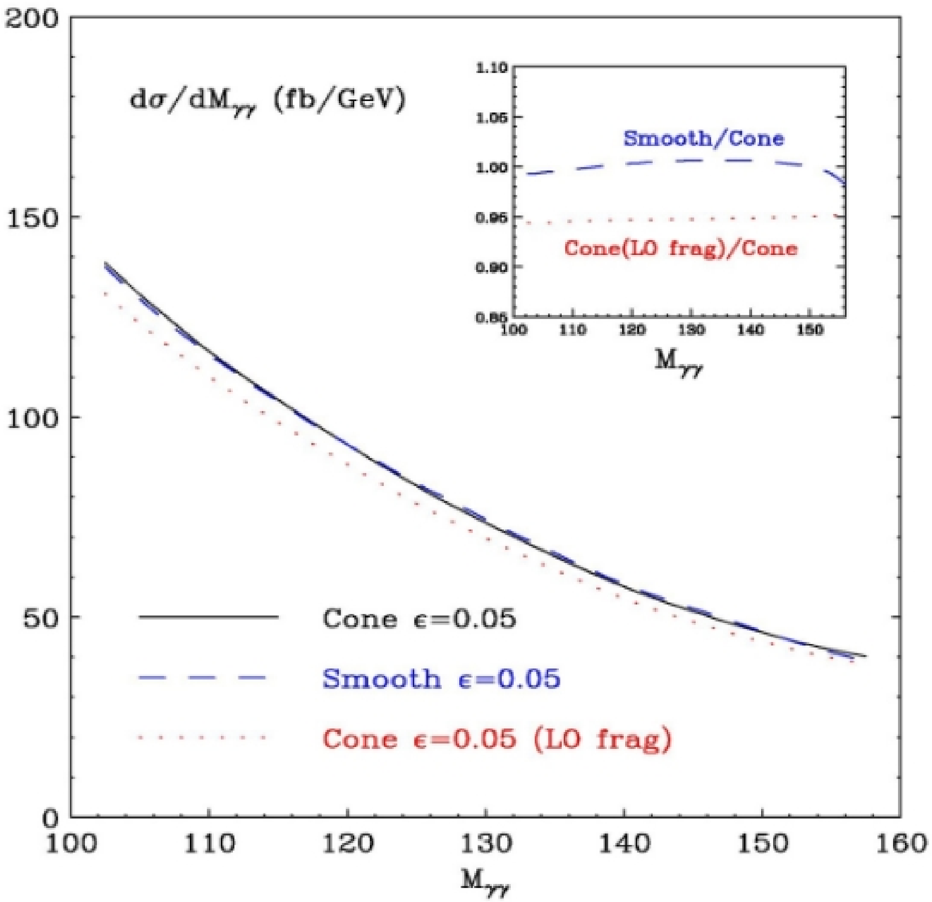


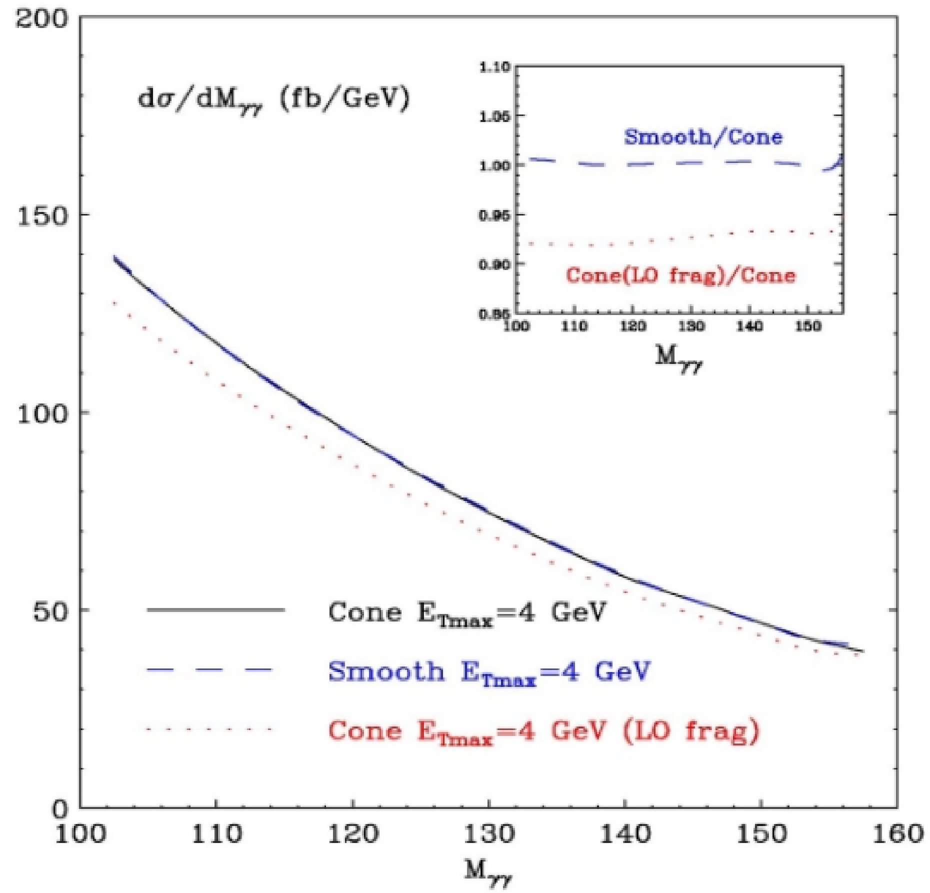
$E_{T\,max}^{had} = 4\,\text{GeV}$



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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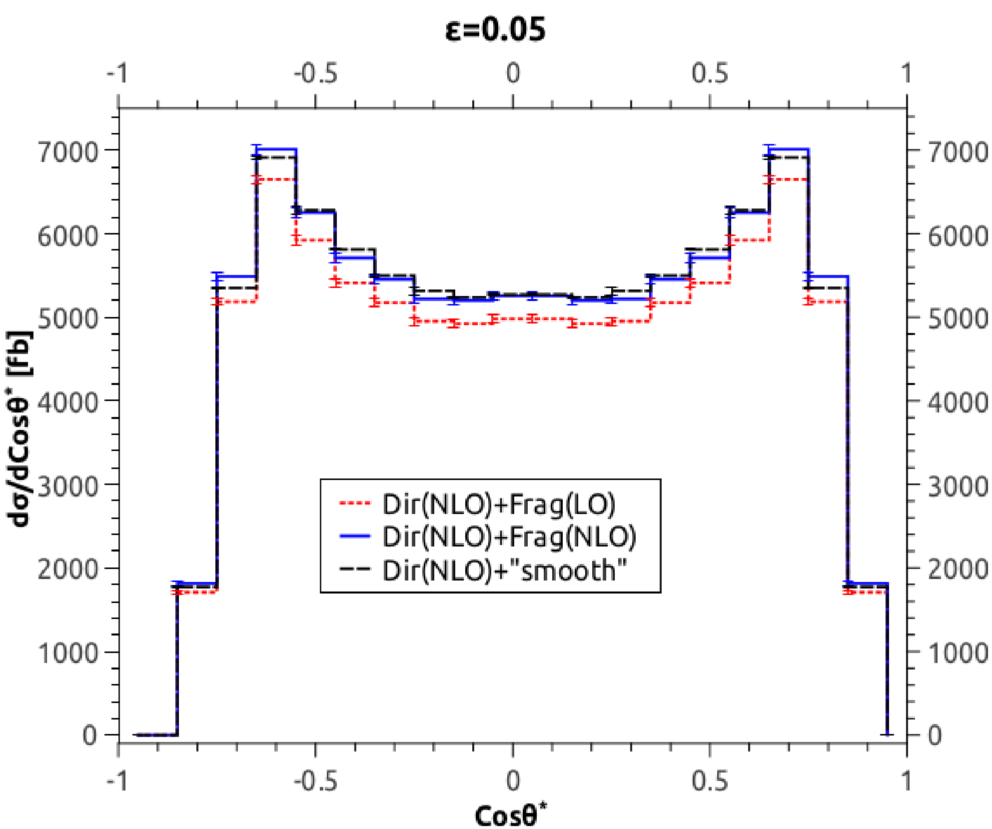
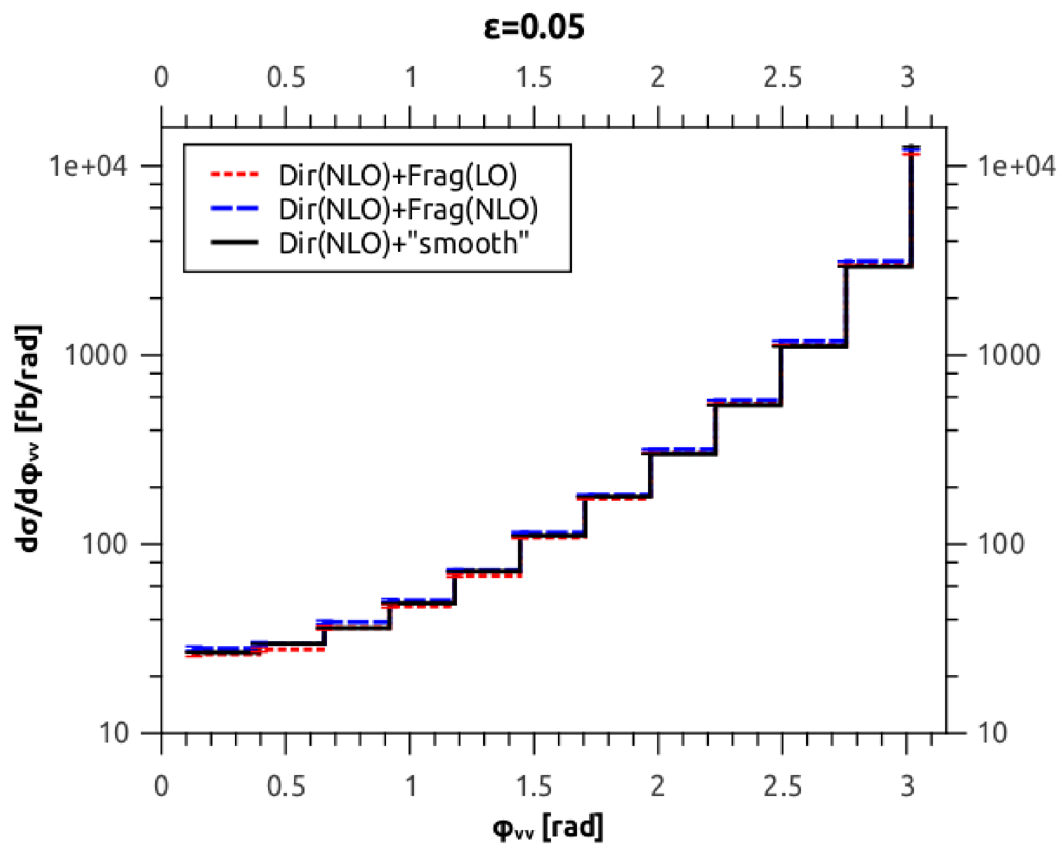
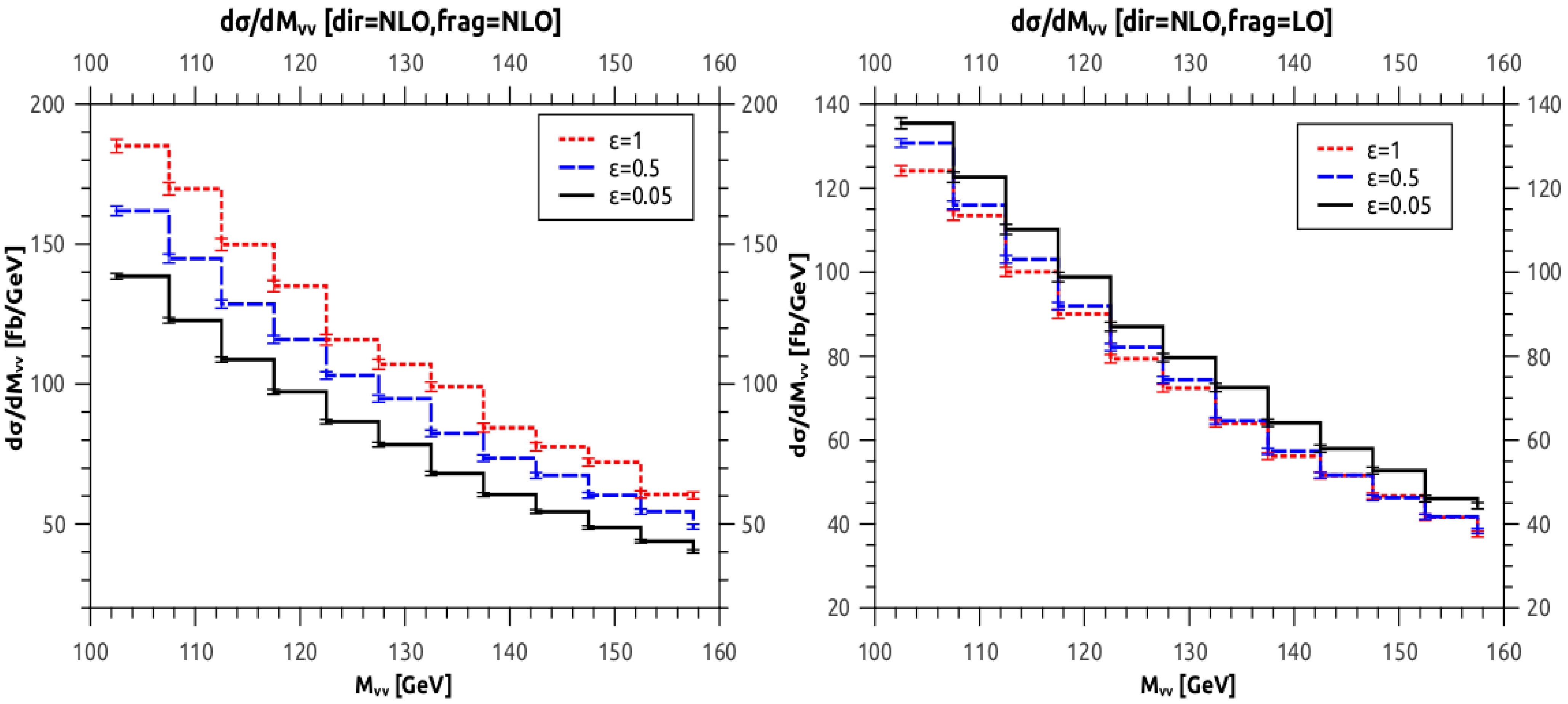




L.C , D. de Florian 2013

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

Standard cone isolation → DIPHOX



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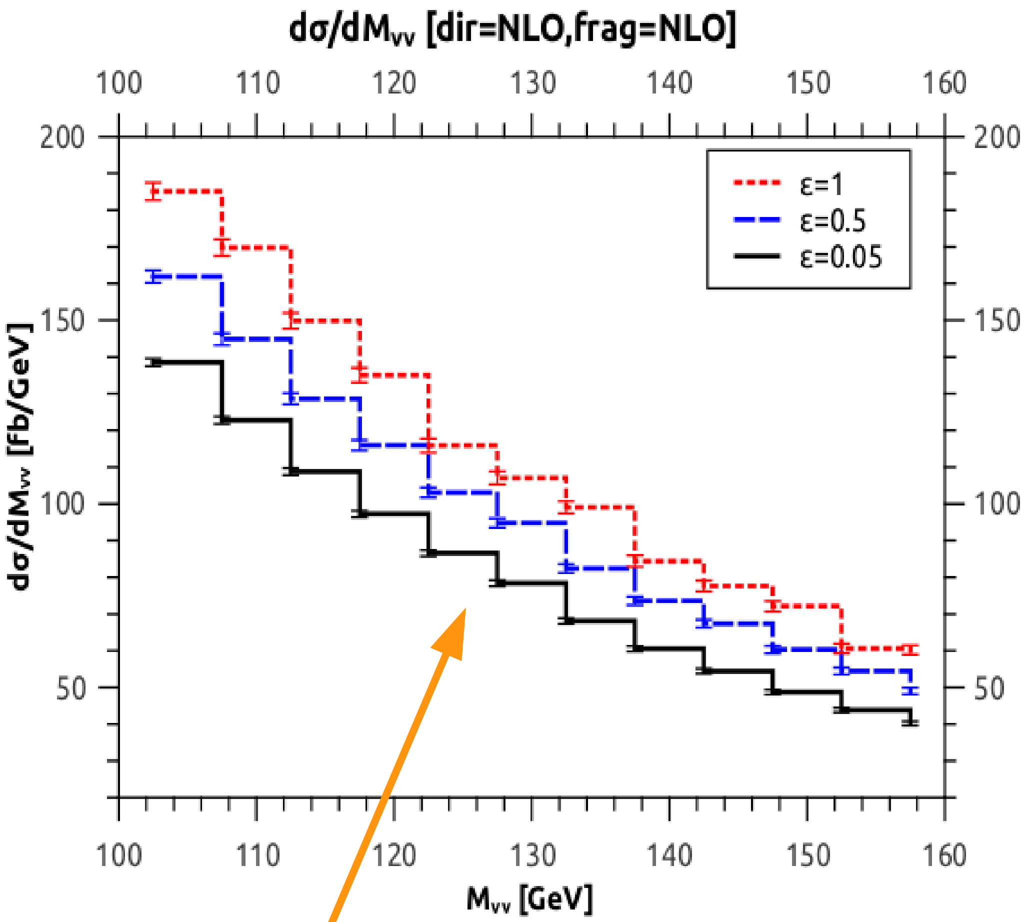

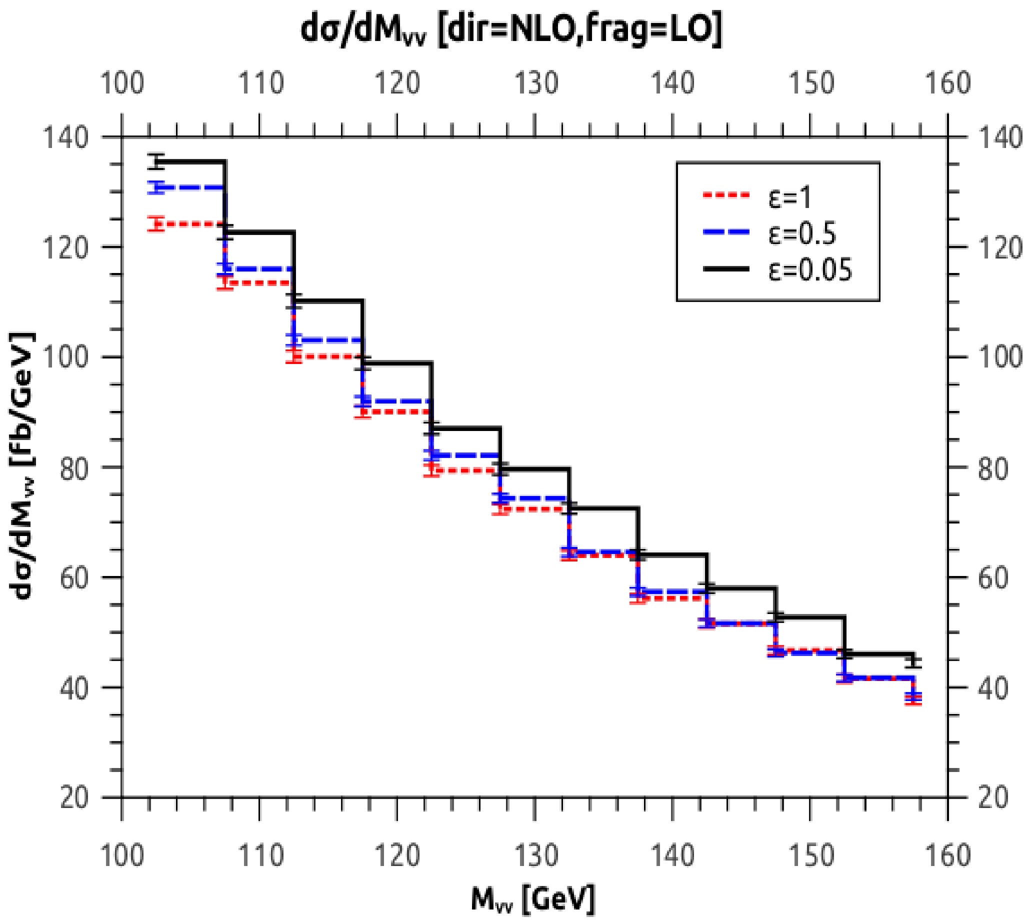

Right behaviour!!

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_{Tmax} — 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.

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

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

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

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

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

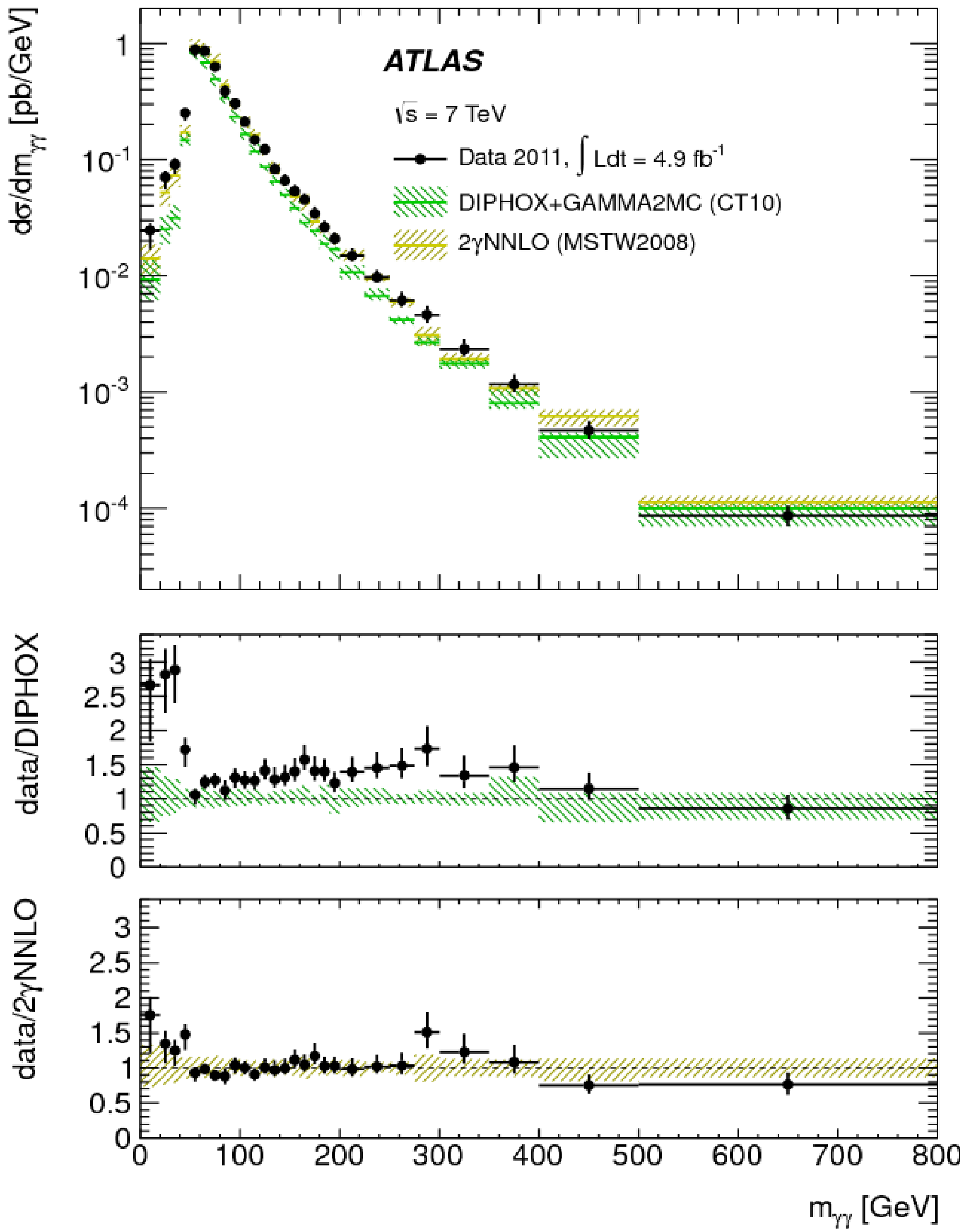
Results and comparison with data

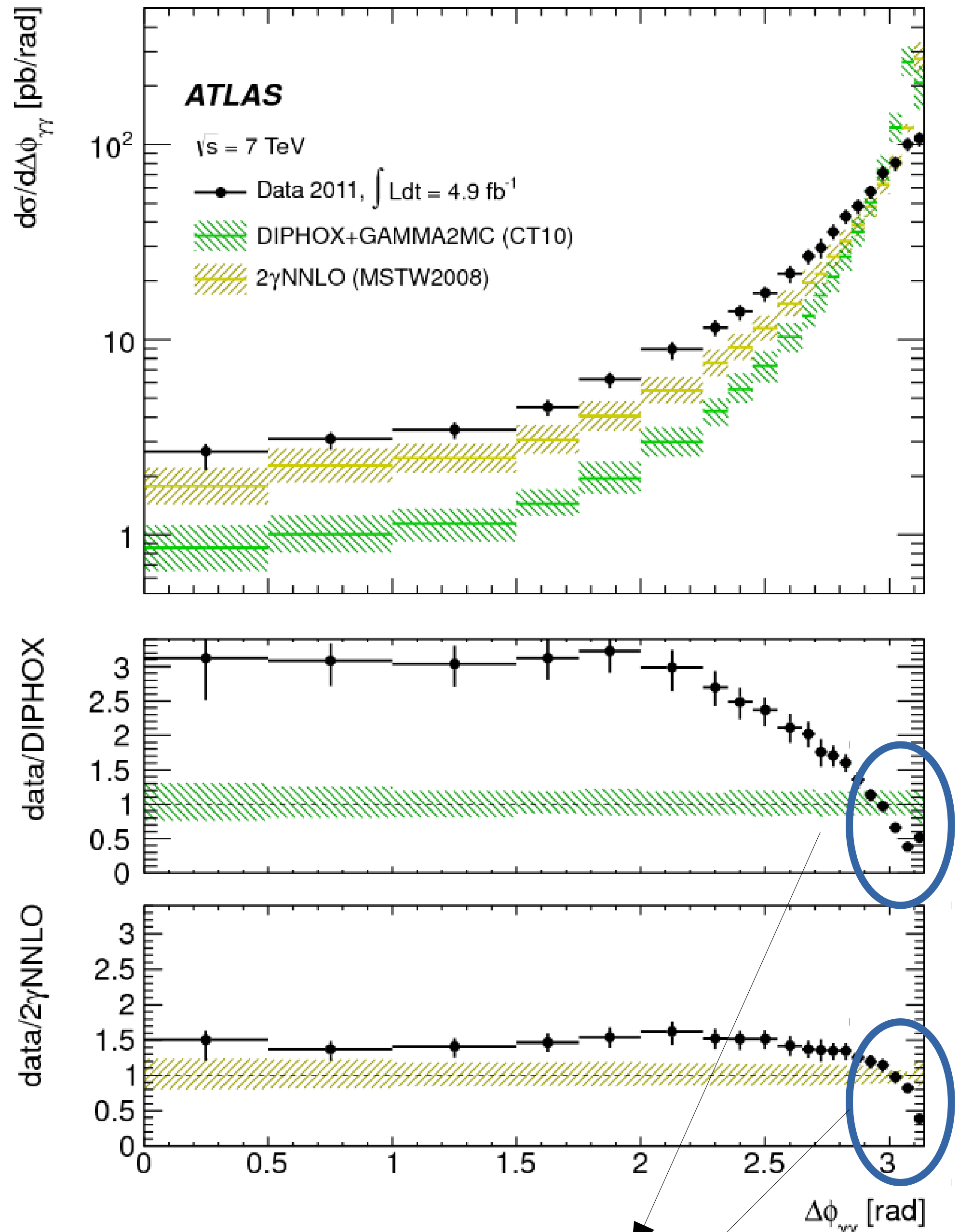
ATLAS results γγ

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

ATLAS results γγ

arXiv:1211.1913 [hep-ex].

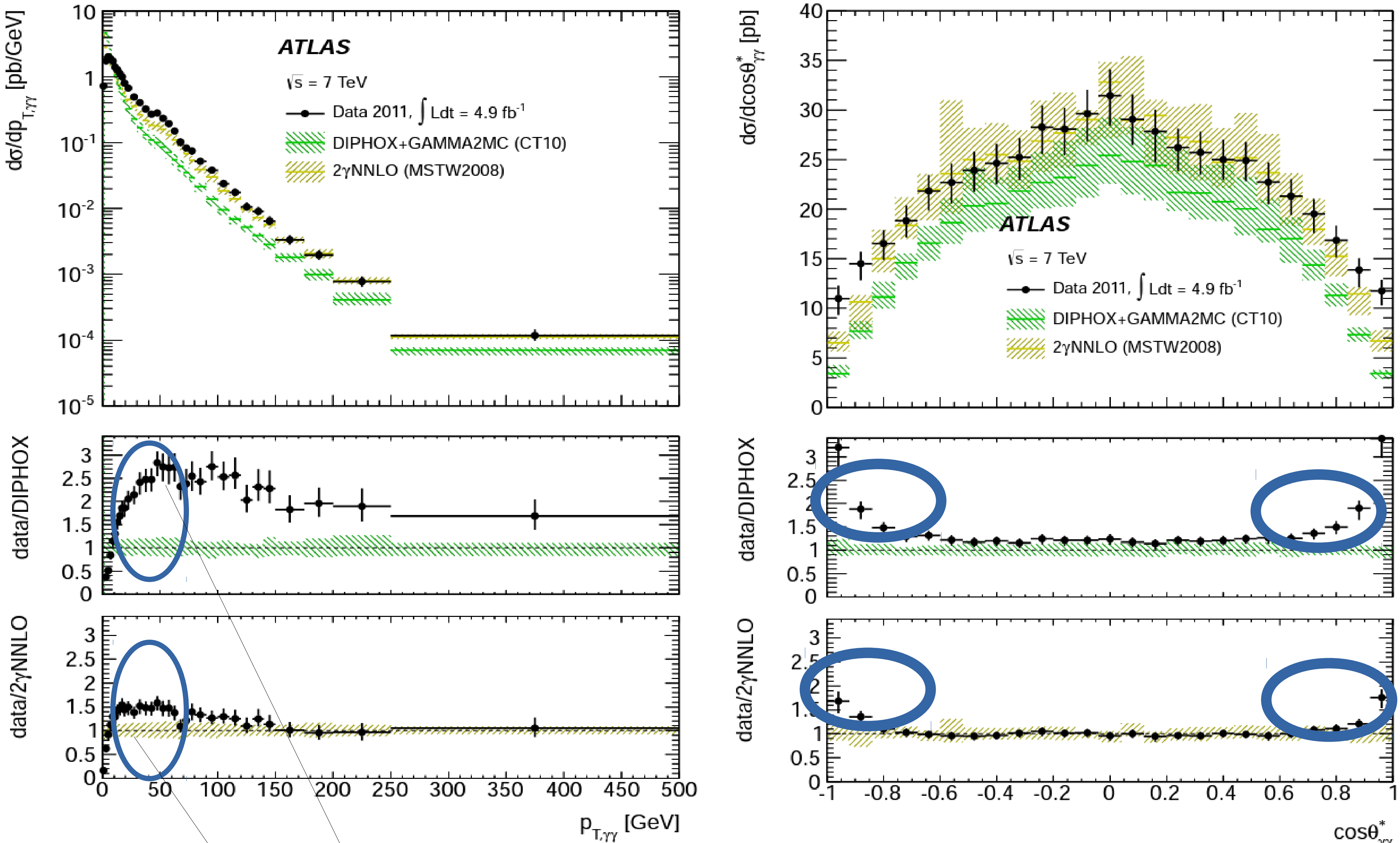




Uncertainties → 6% - 8%

Fixed order tools

ATLAS results γγ



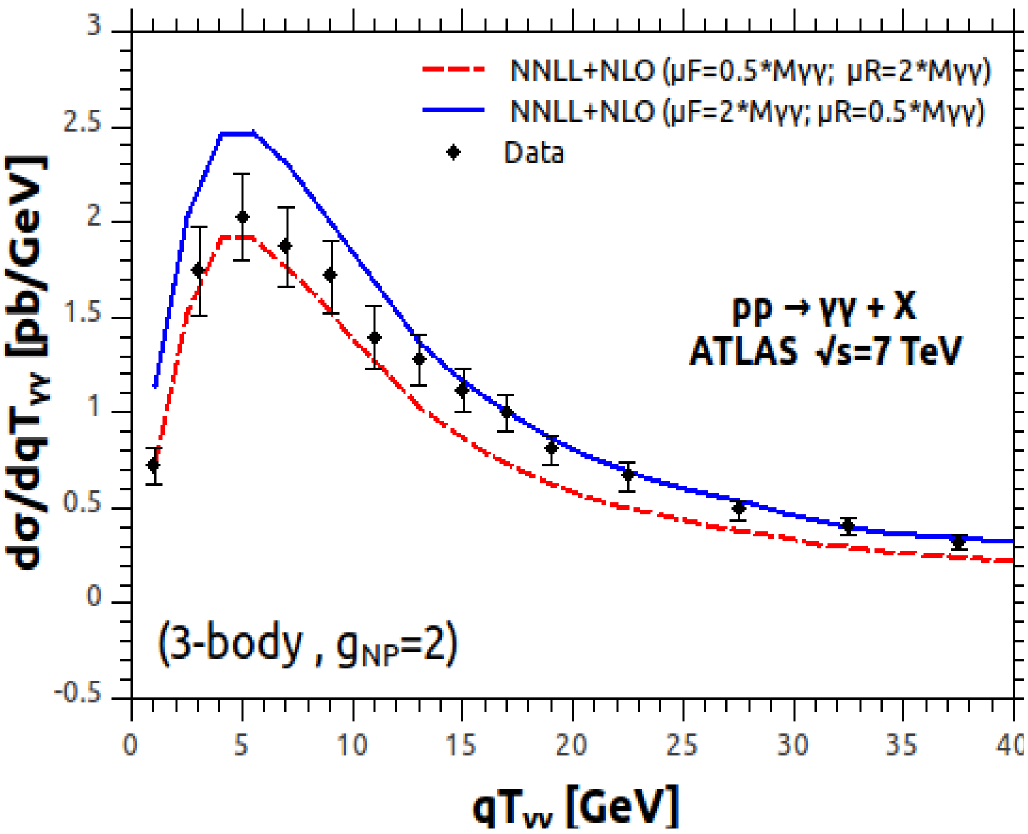
Fixed order tools

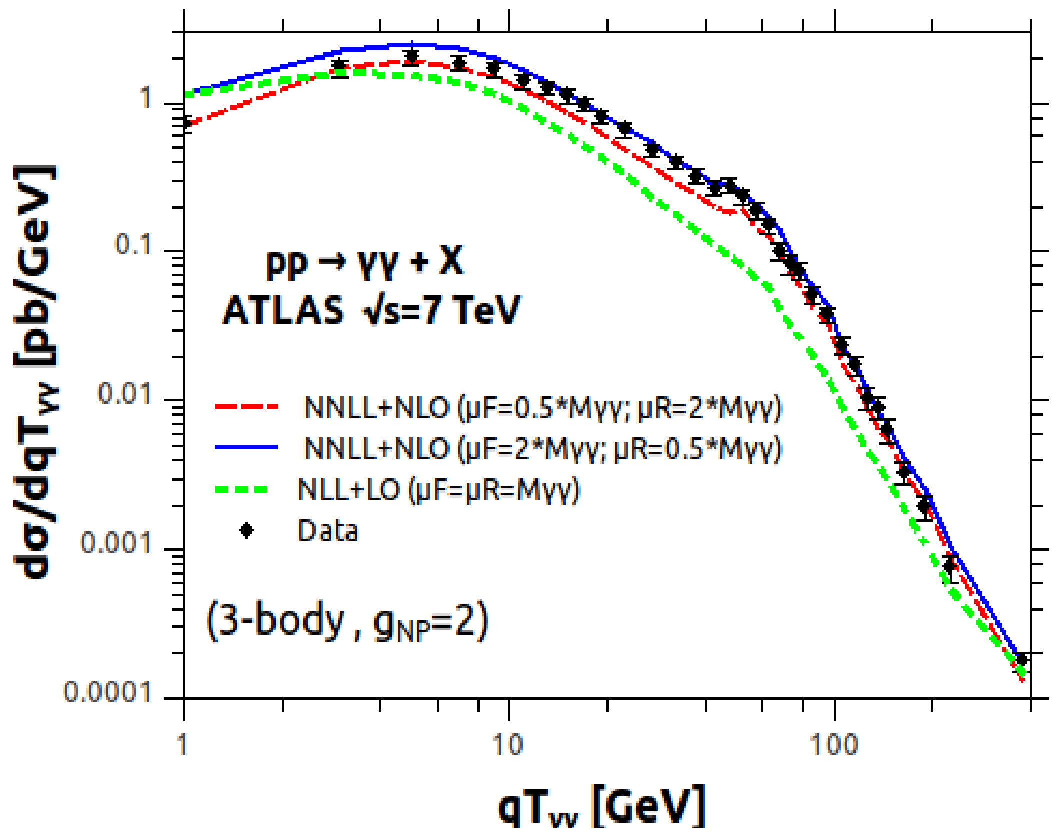
Uncertainties → 6% - 8% due to the opening of the gg channel which is “effectively” LO at NNLO

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 $C_A = N_c$

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Resummation → ATLAS γγ

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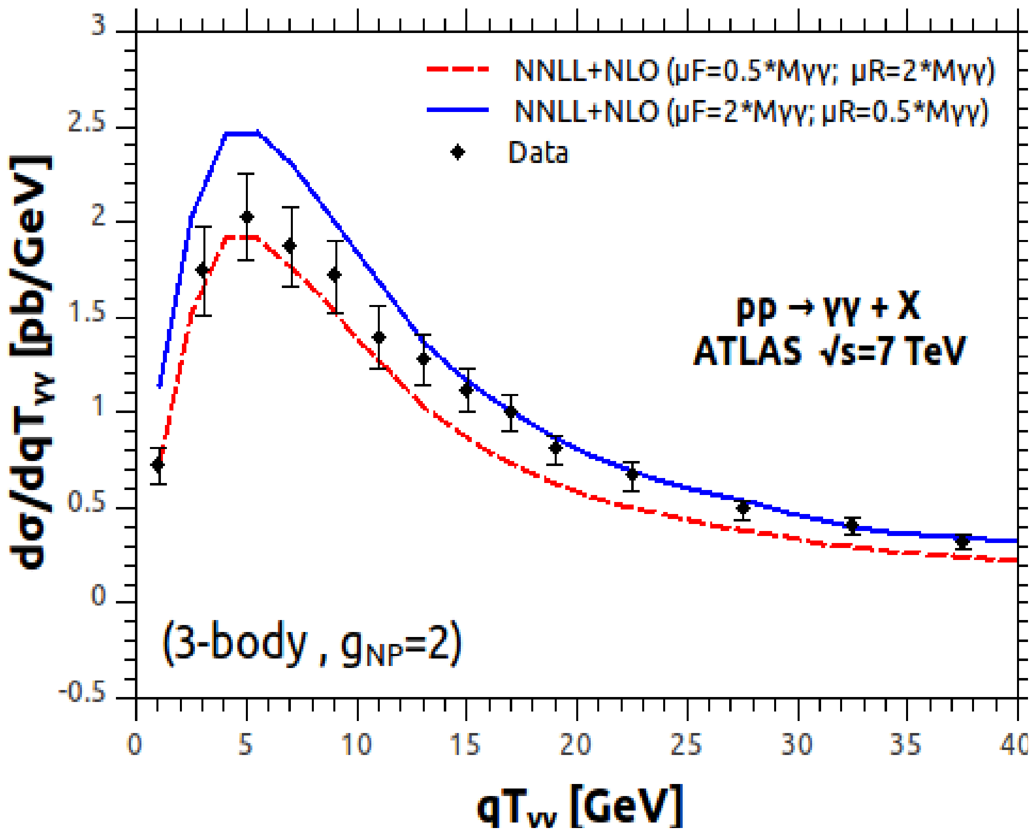

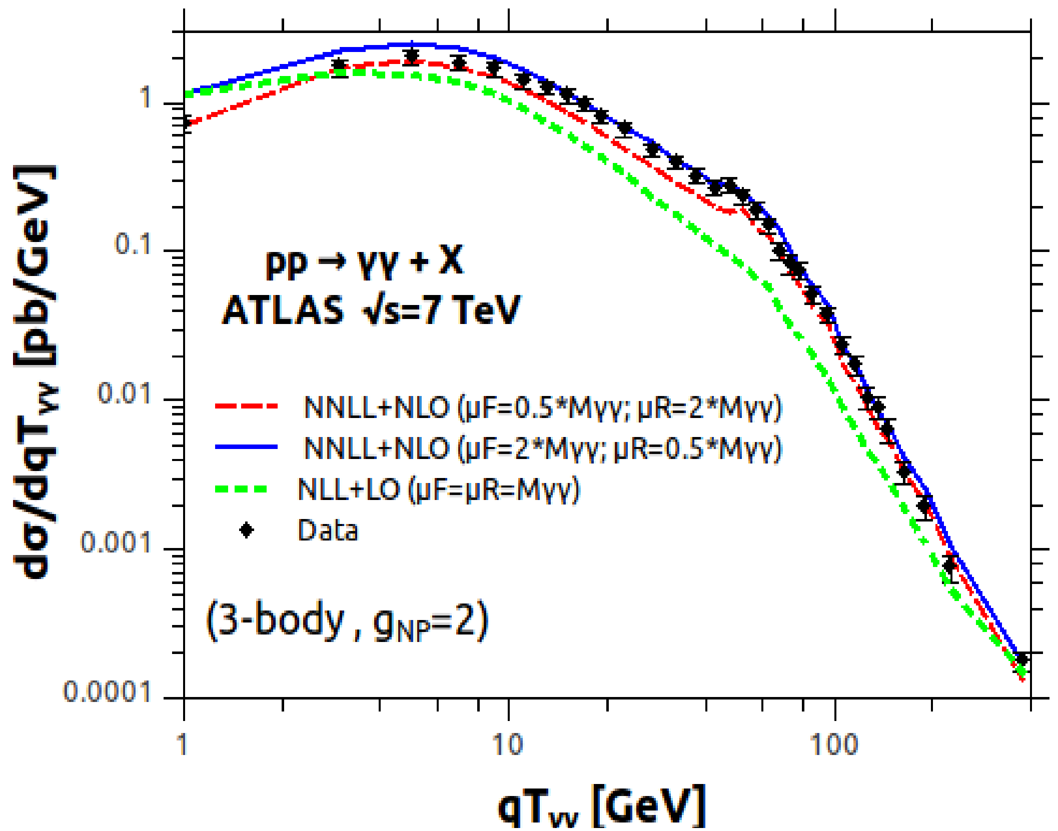

qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

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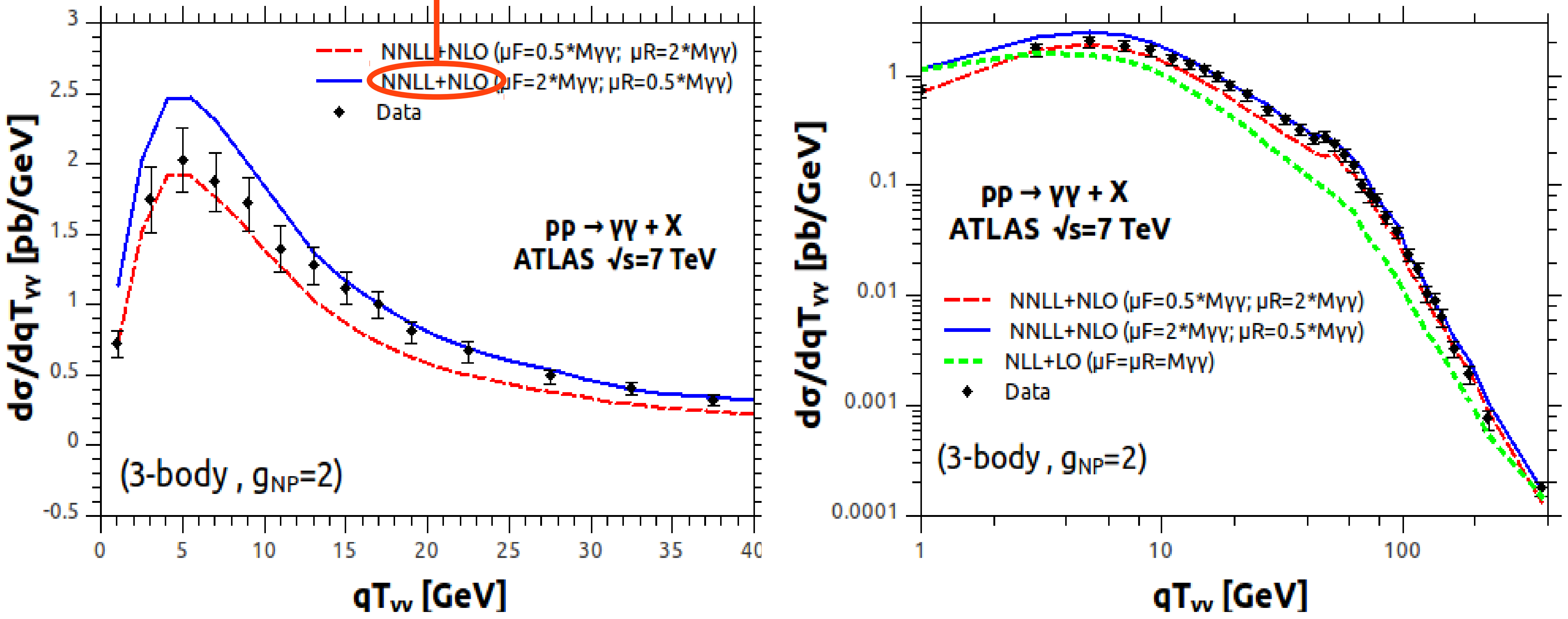
Resummation → ATLAS γγ

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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Resummation → ATLAS

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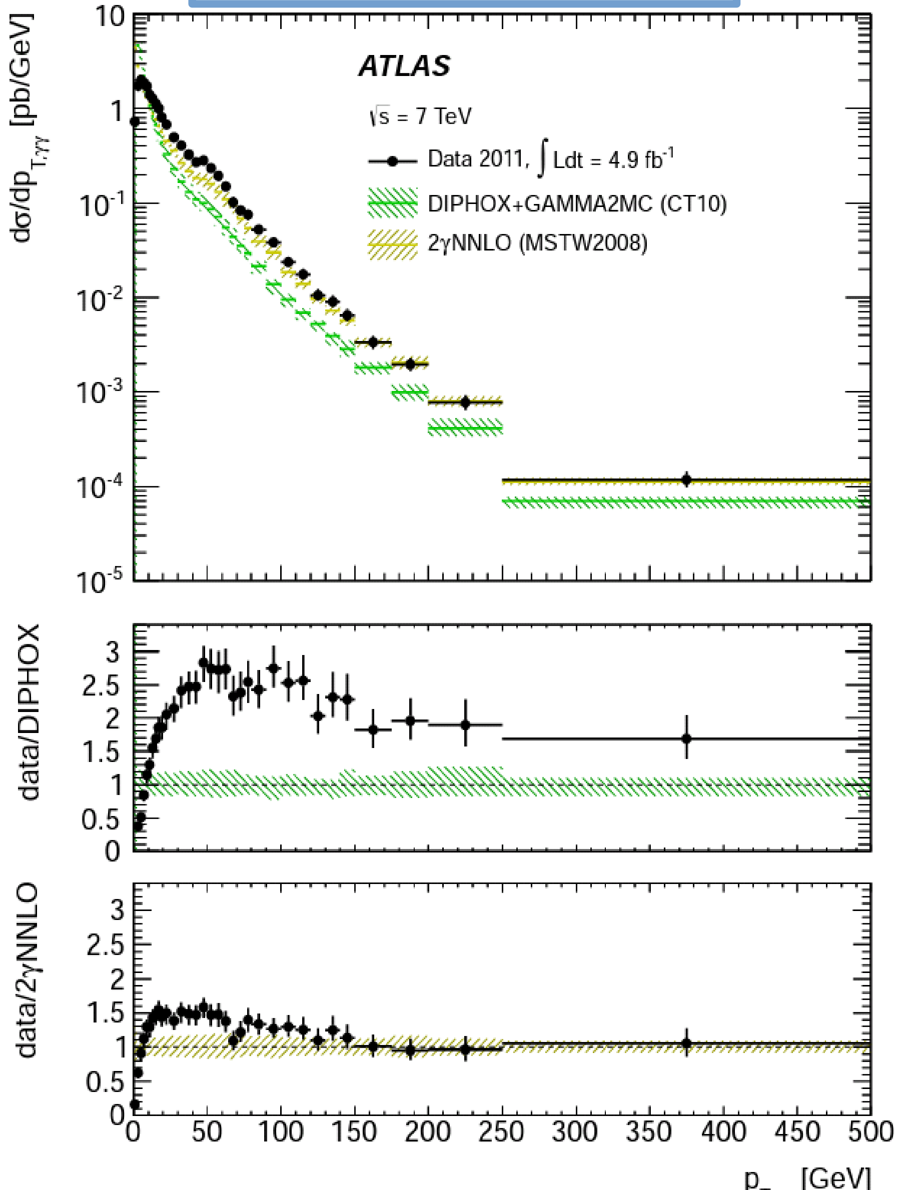
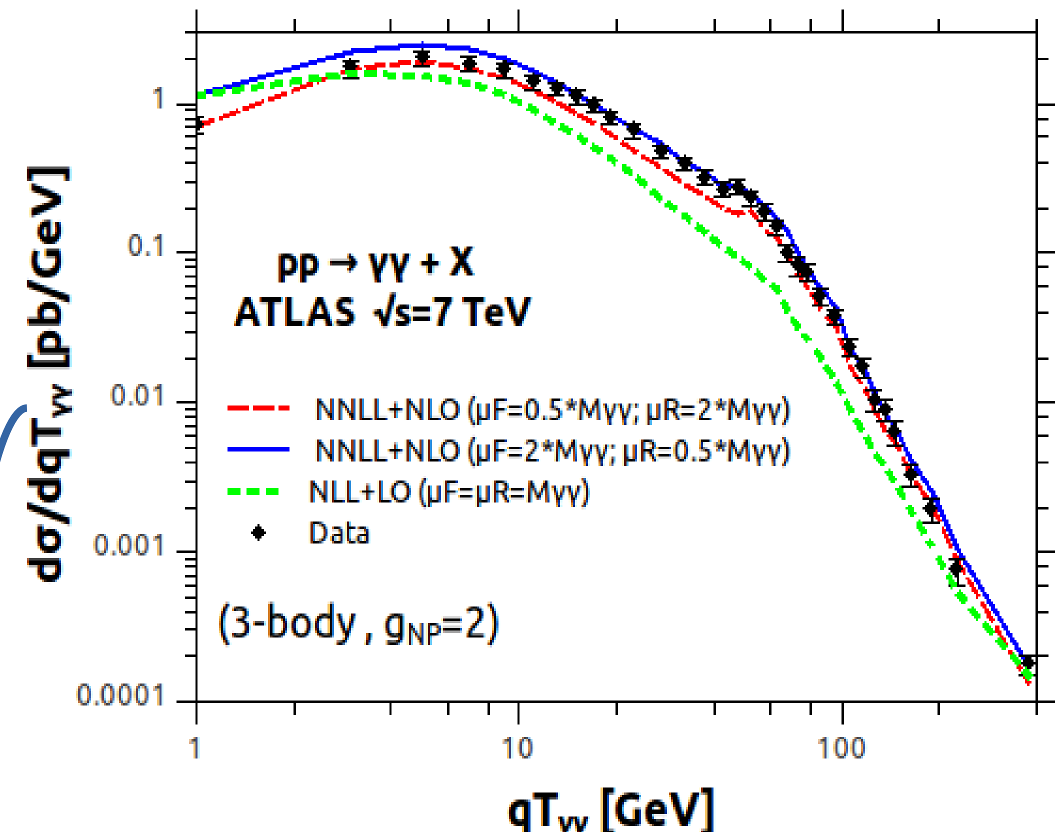
Fixed order





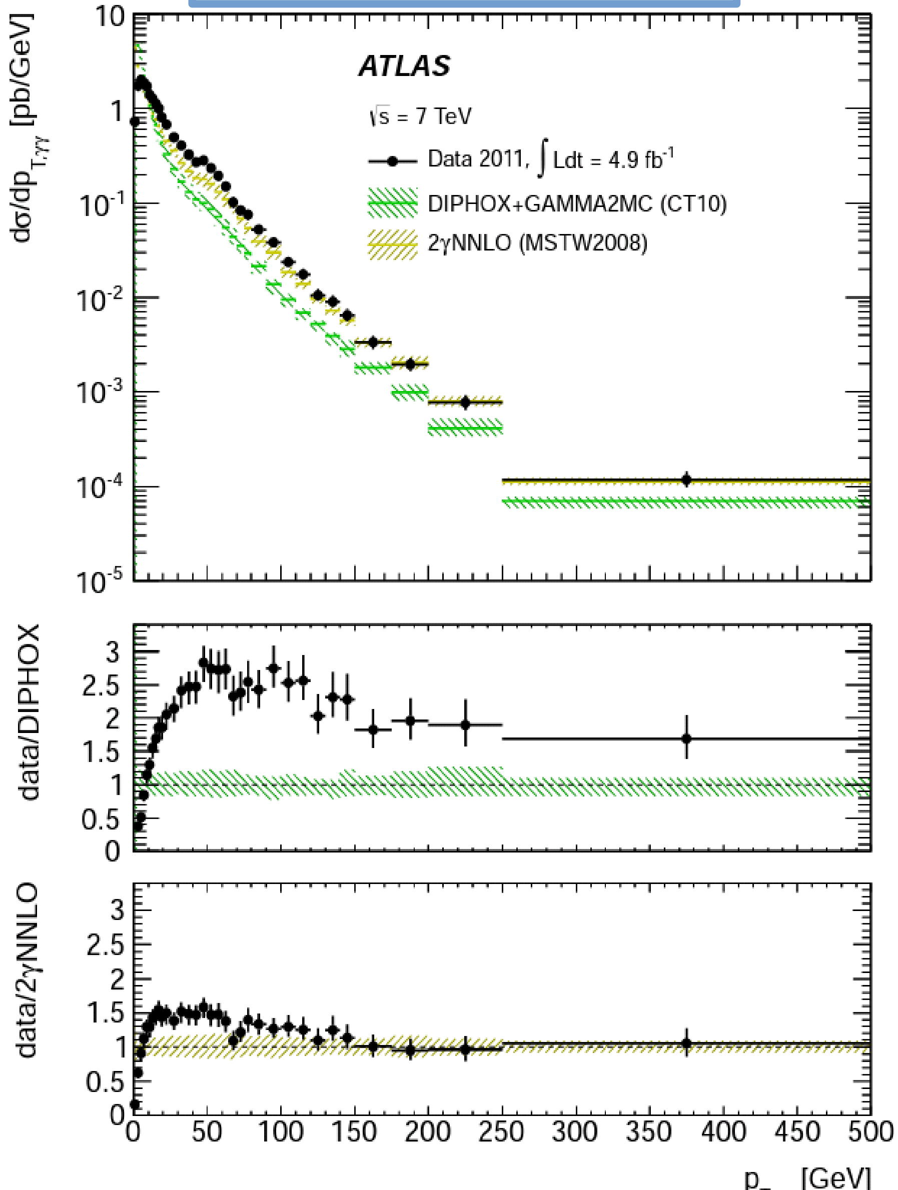
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.

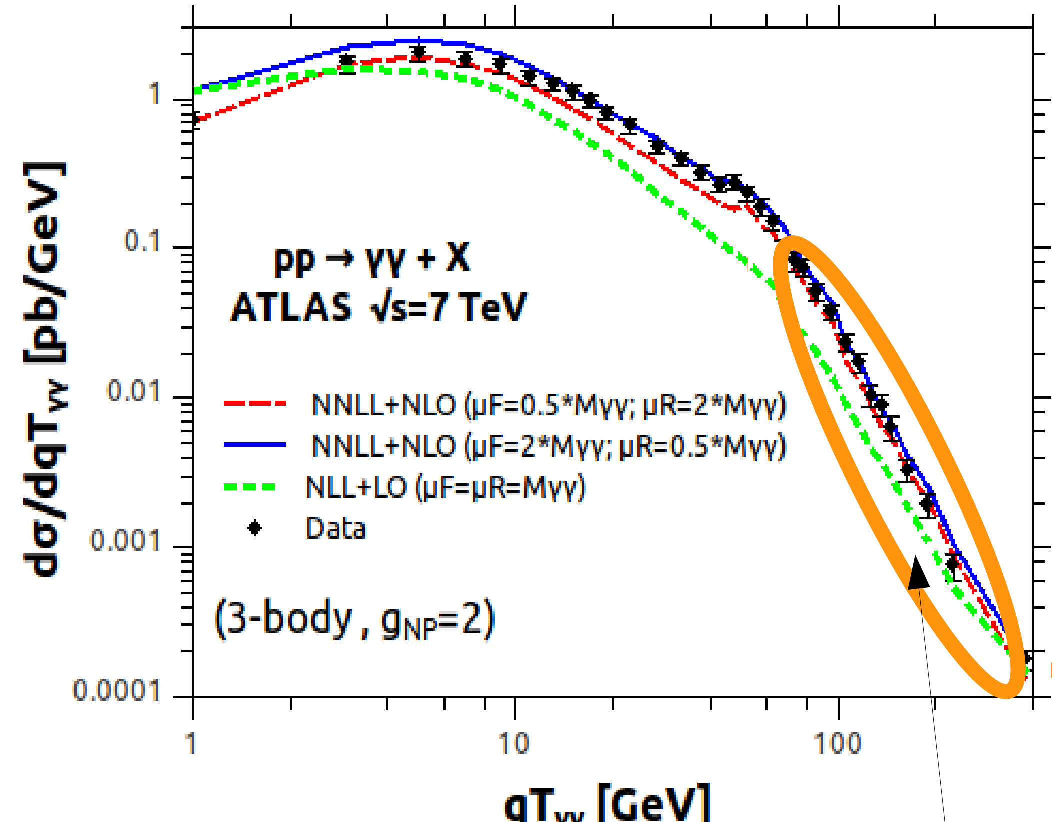
qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

Resummation → ATLAS

Fixed order

LC, Coradeschi, de Florian



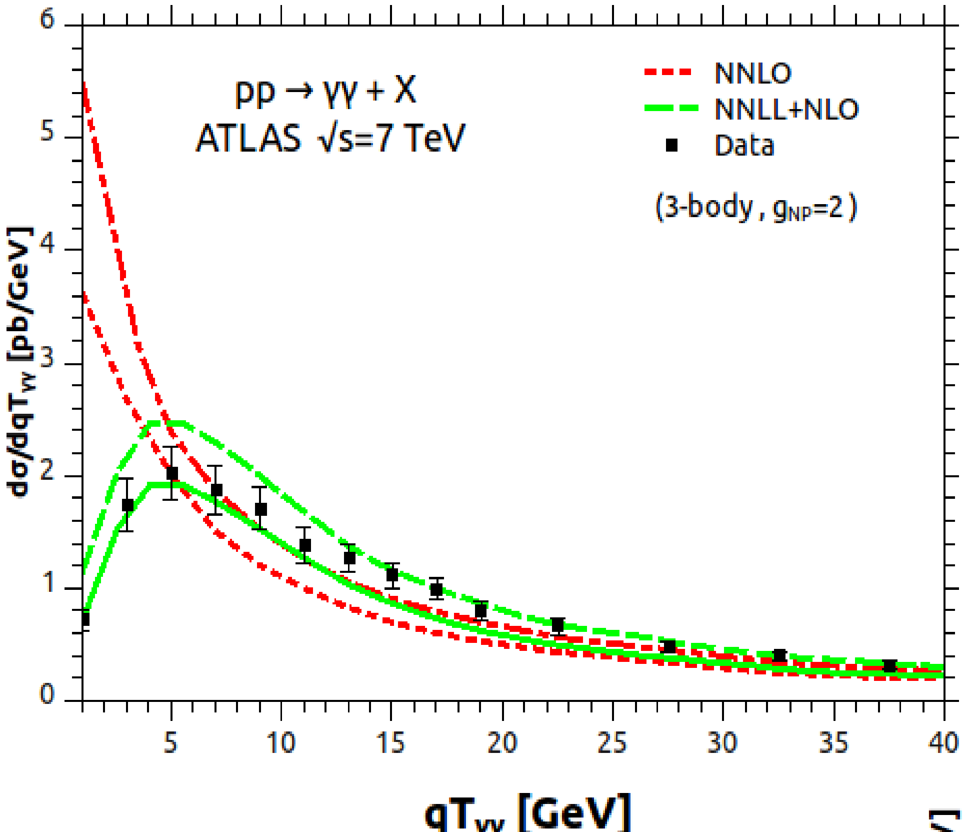


The size of the bands is proportional to the luminosity of the PDF of the gluon

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

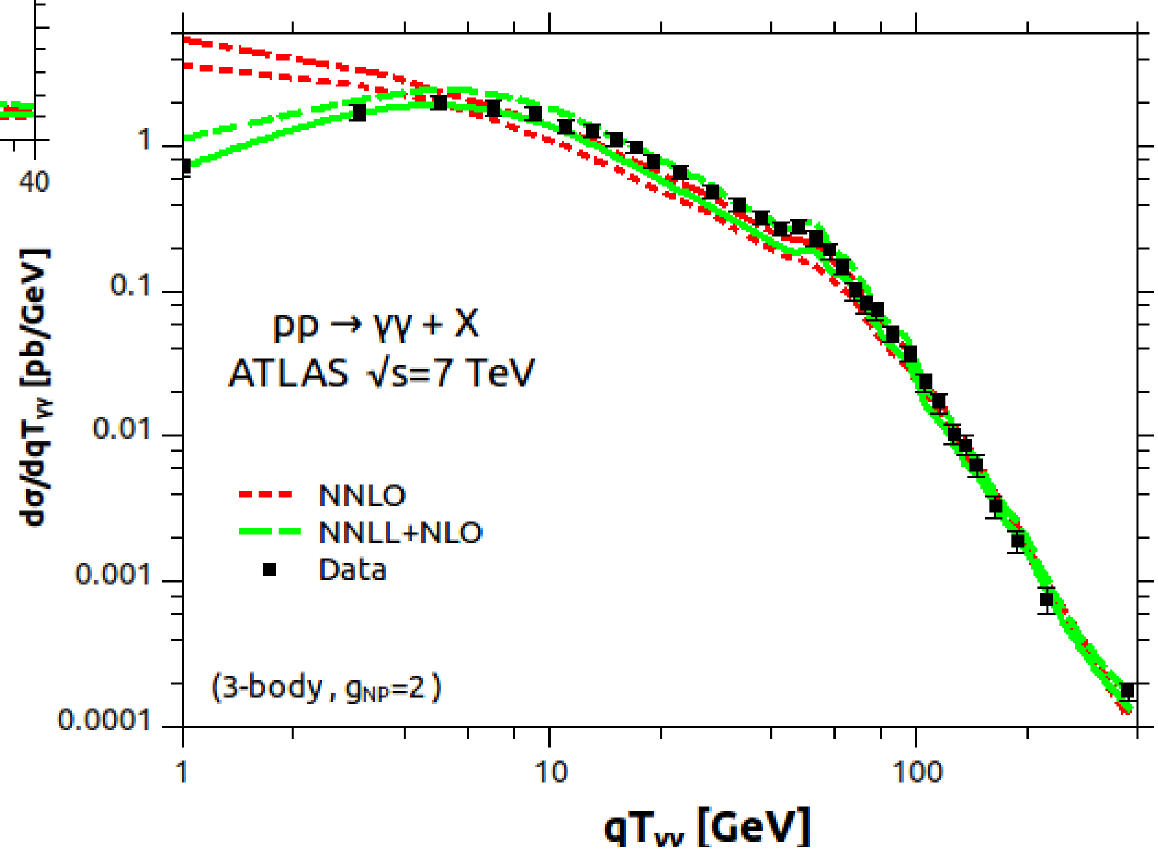
Resummation → ATLAS γγ

LC, Coradeschi, de Florian



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

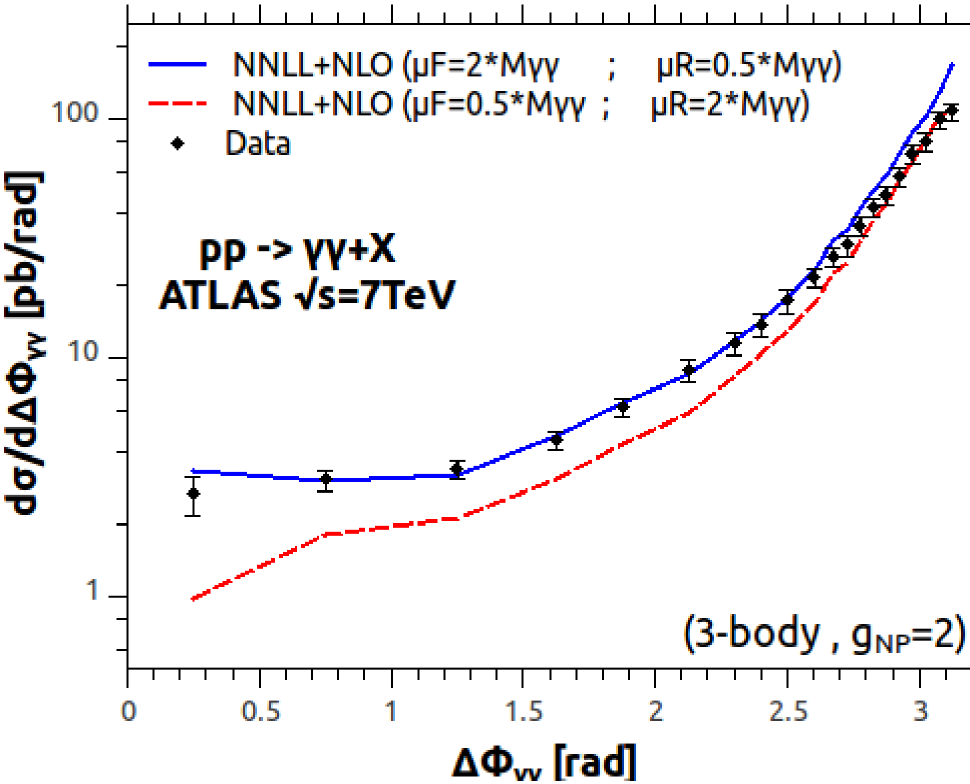
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.

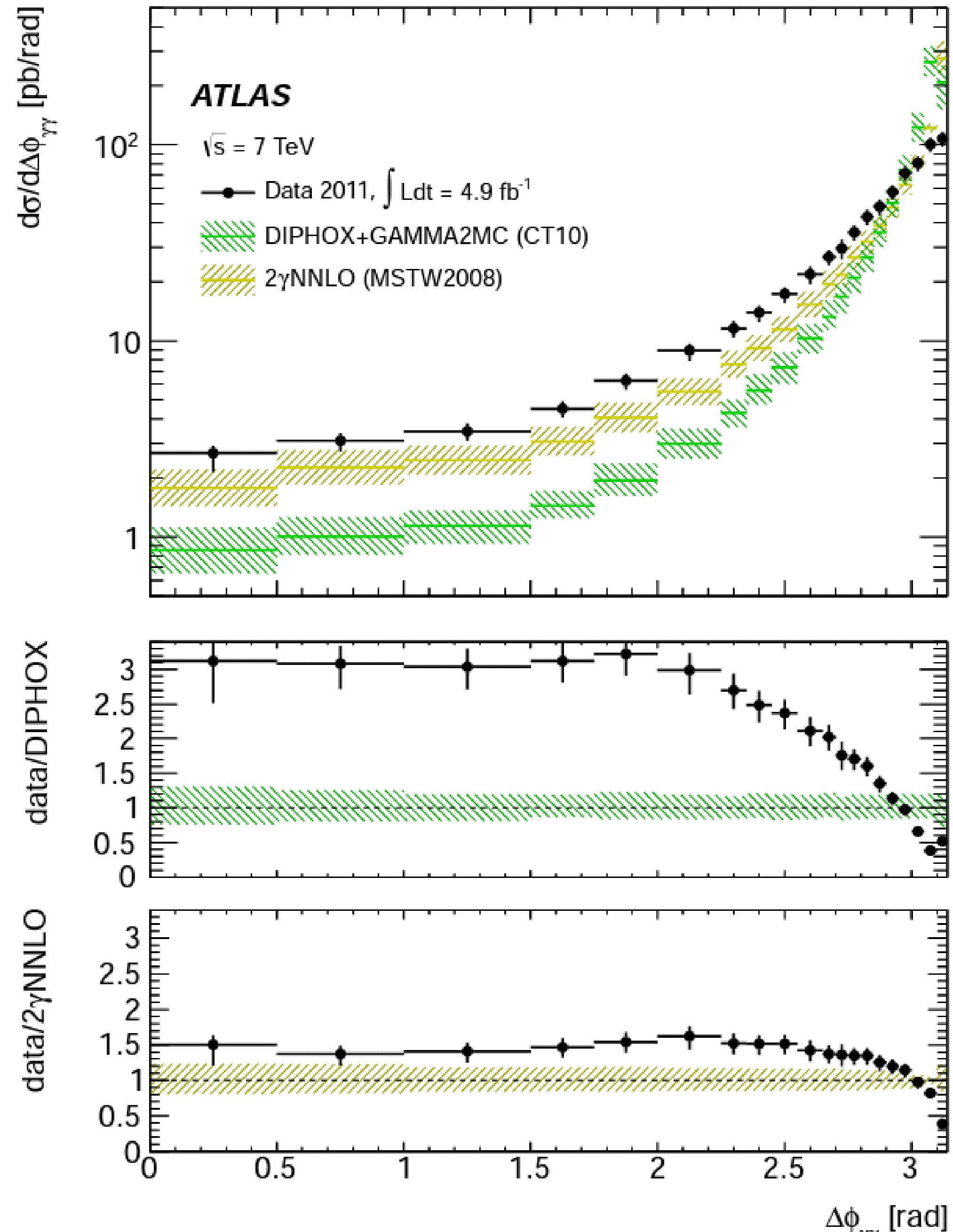


Resummation → ATLAS γγ

LC, Coradeschi, de Florian

First results!





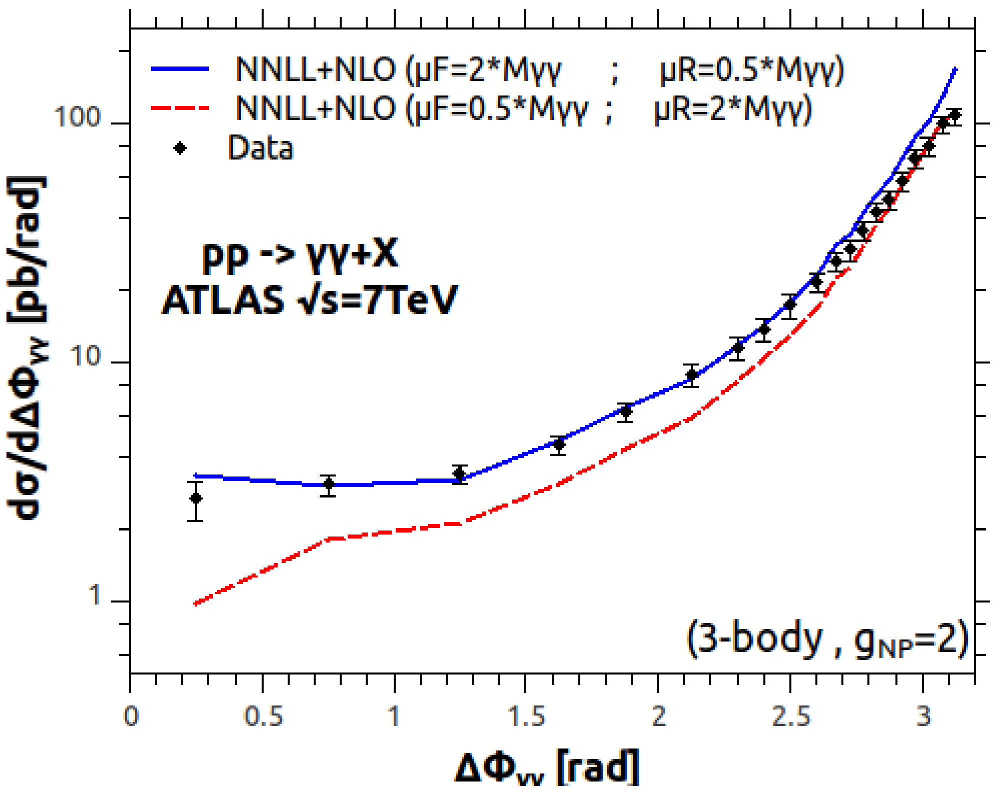
The same set-up also allows the calculation of more exclusive observable distributions

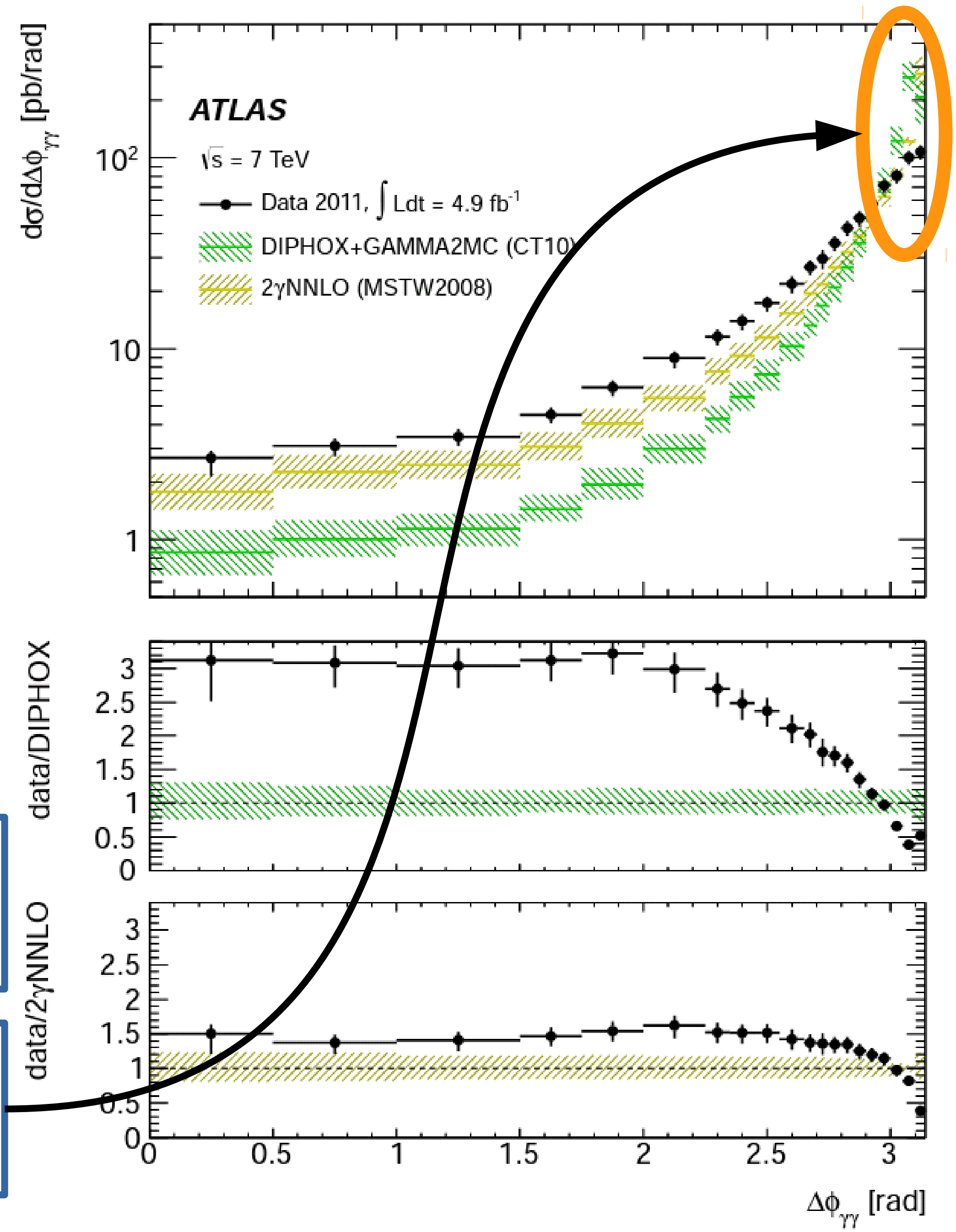
Uncertainties → 6% - 8%

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

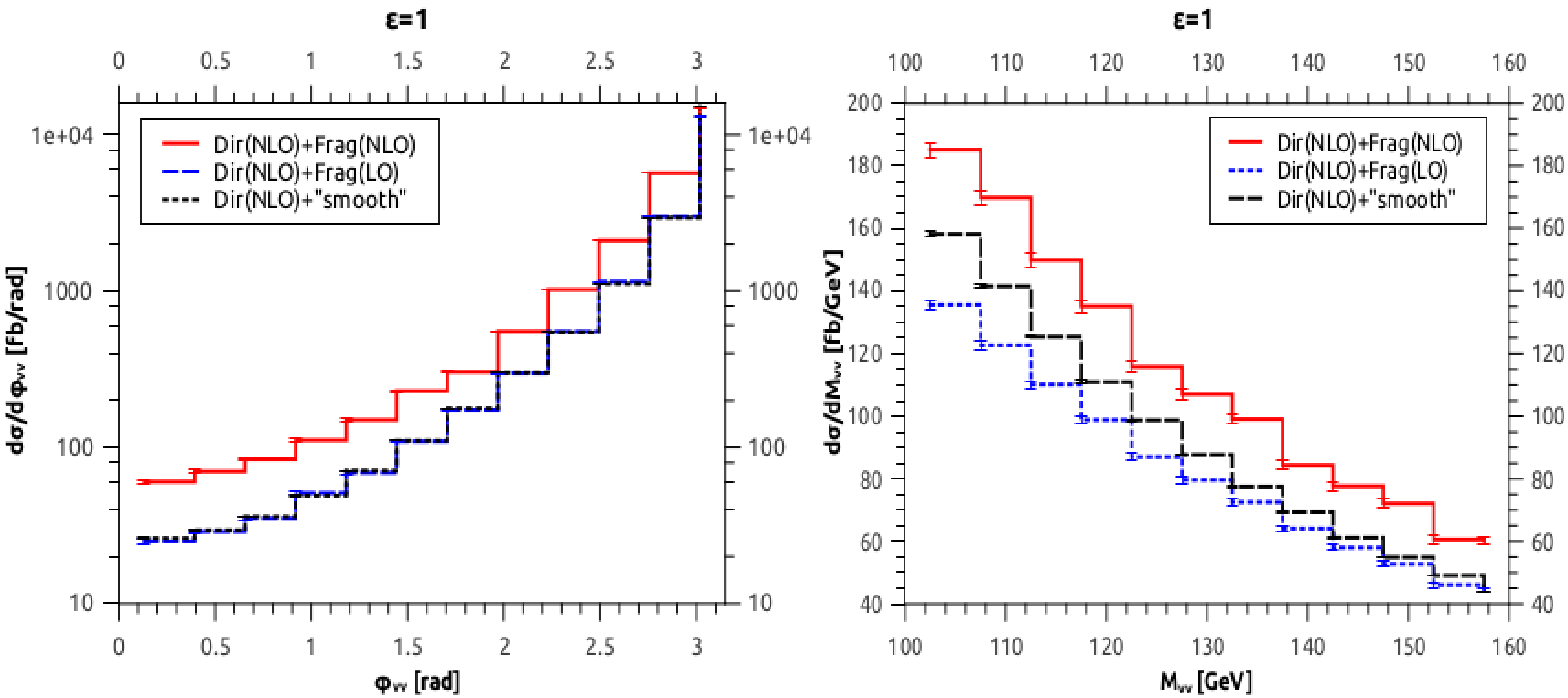
qT resummation “spreads” the uncertainties of the gg BOX over the whole Δφ range

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 2013-2015): 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 γγ 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

L.C , D. de Florian 2013

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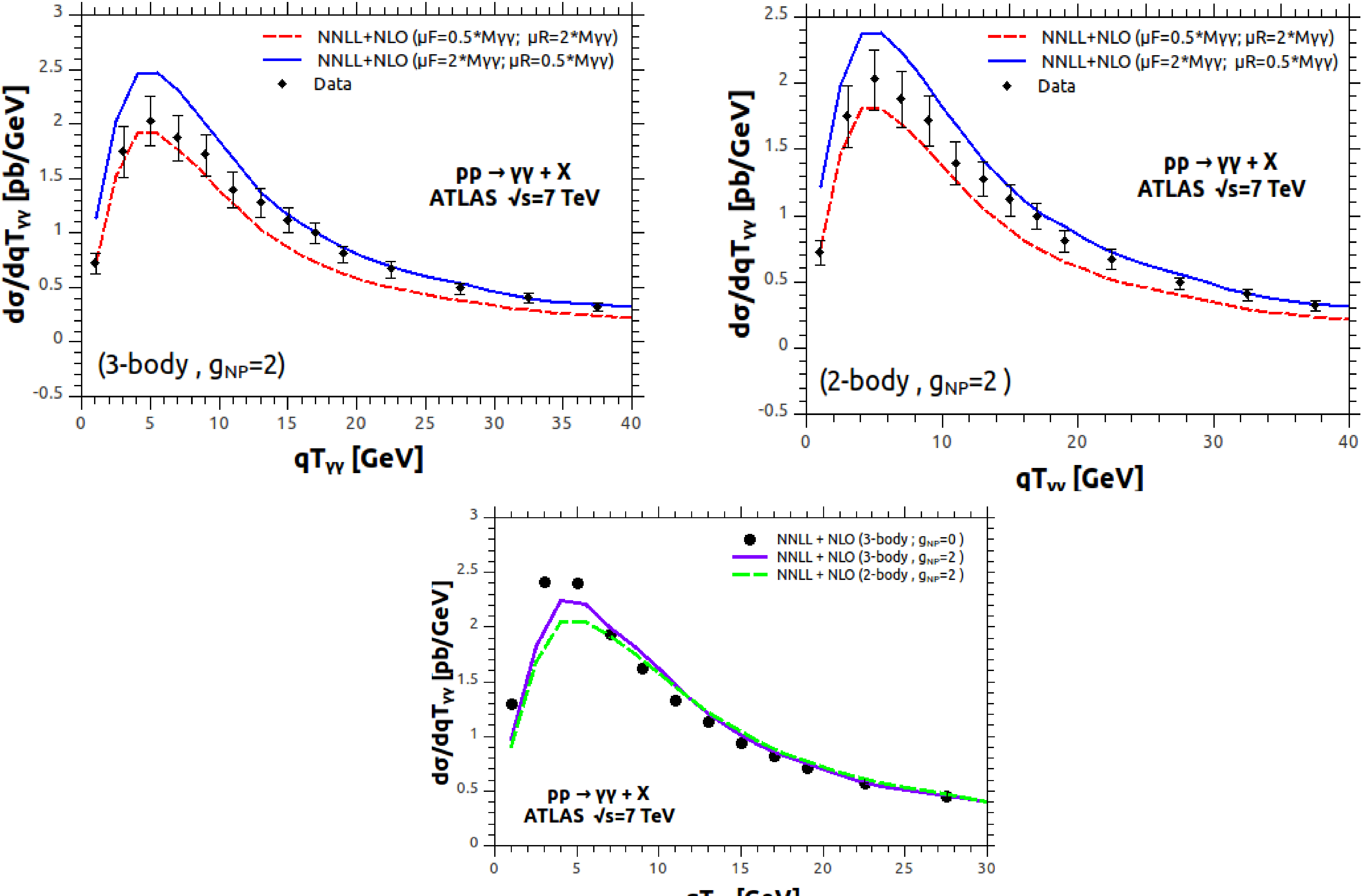
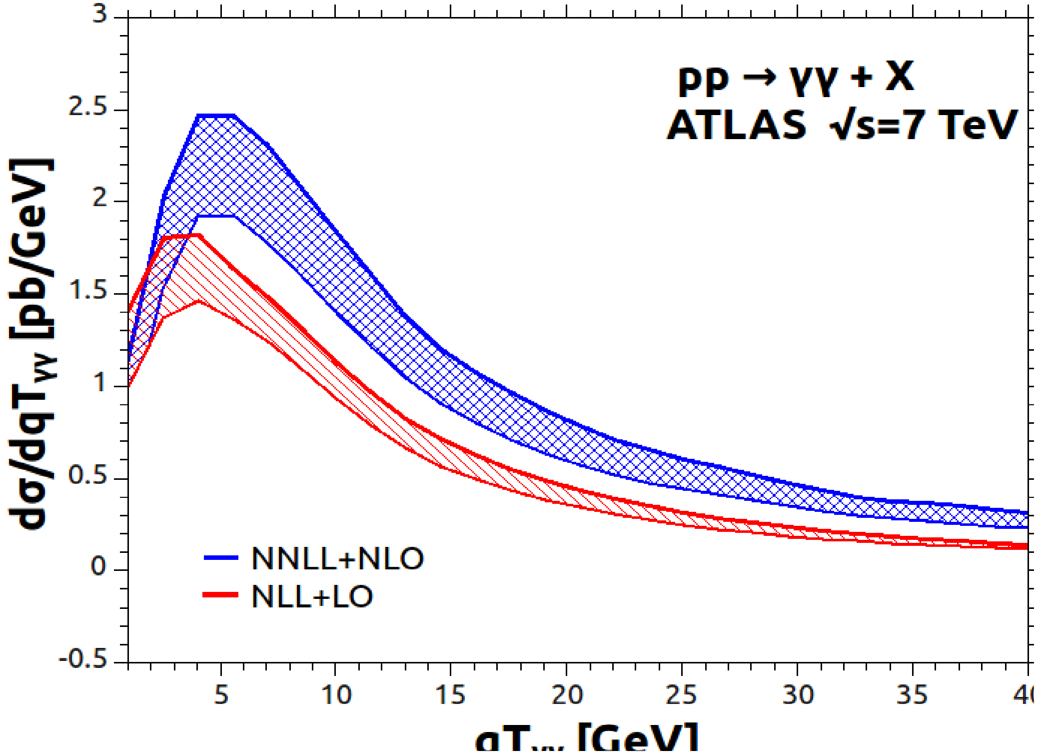
Tighter criteria

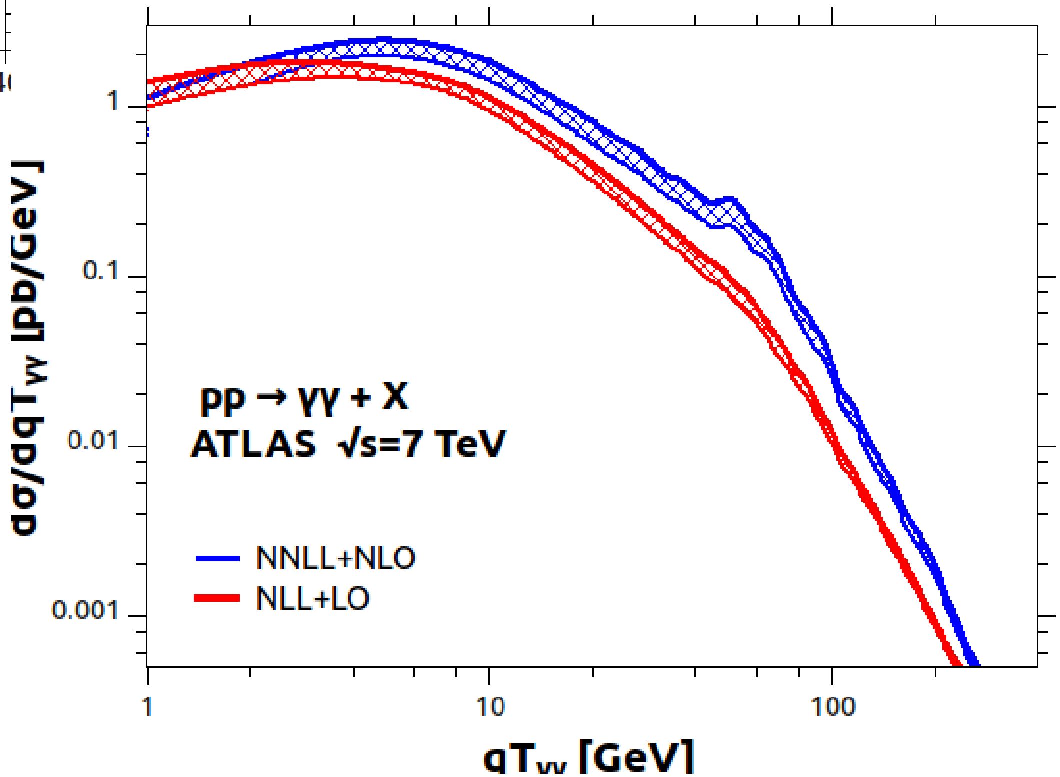
Direct component increasing

Resummation

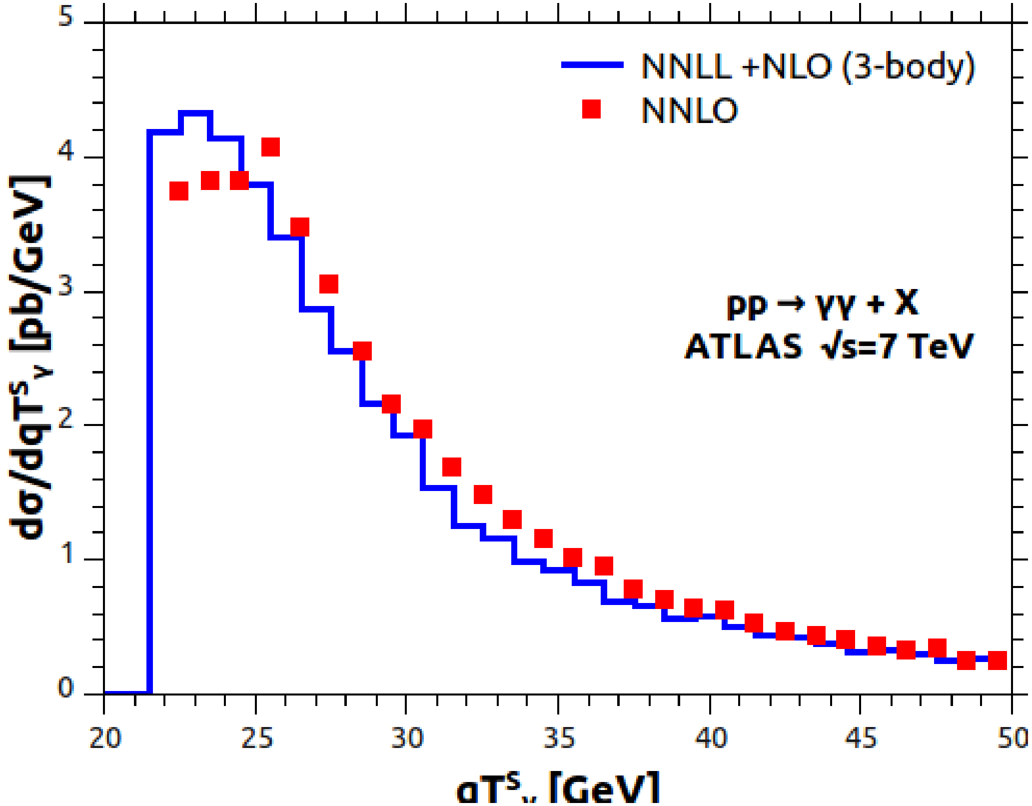


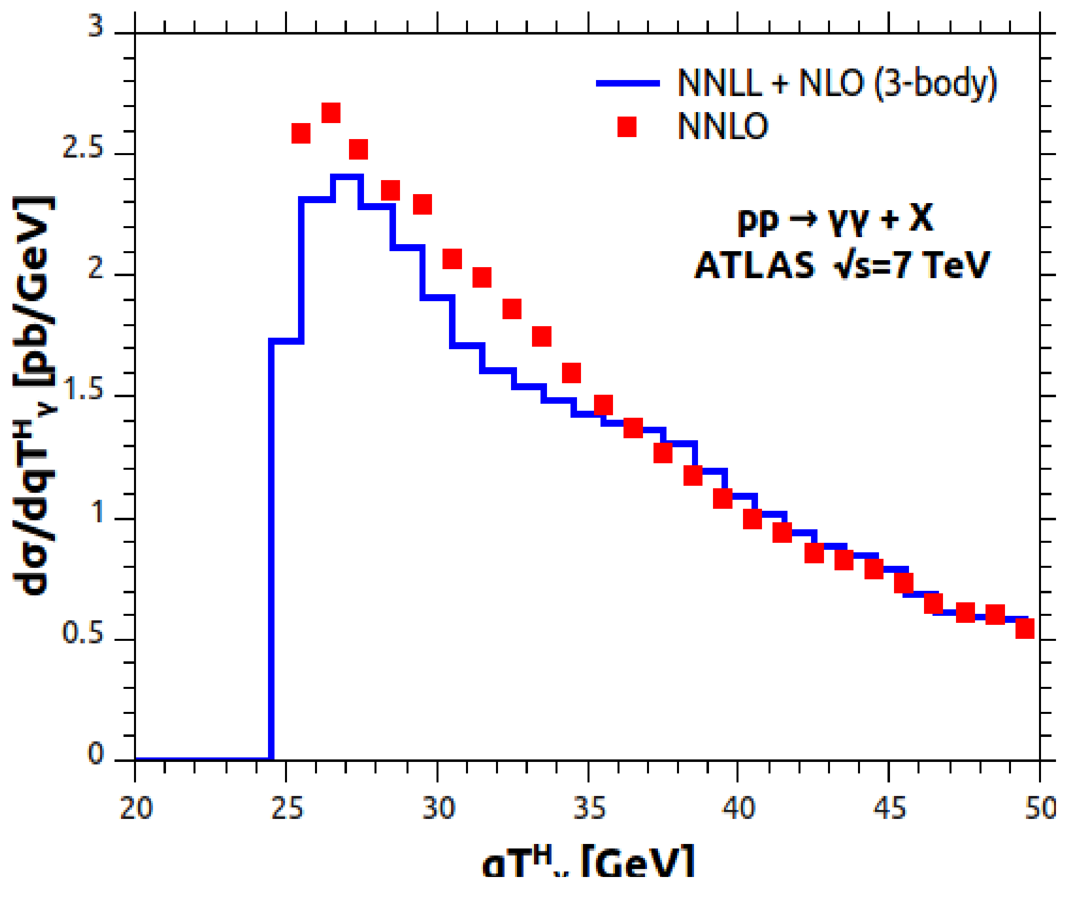
Resummation



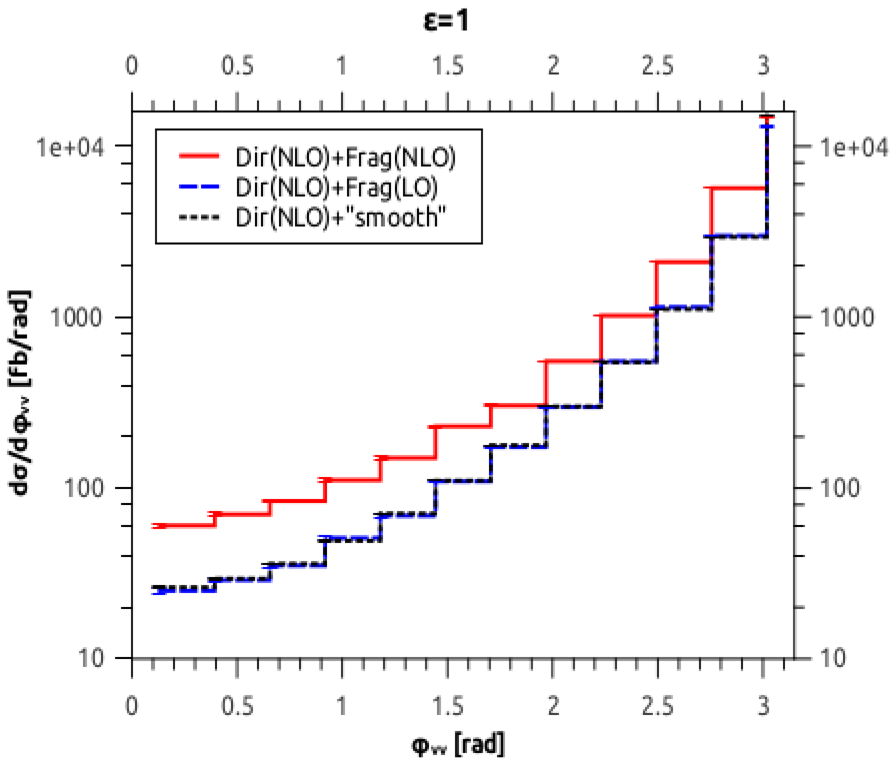


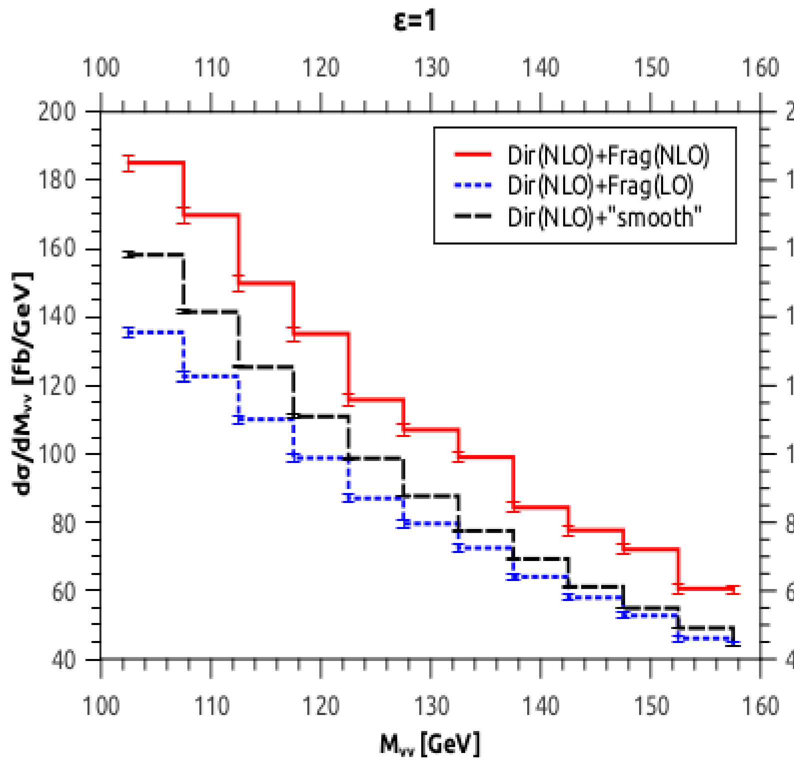
Resummation





What we learnt from γγ





Fragmentation could be very relevant!!!!

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

Vγ ATLAS

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

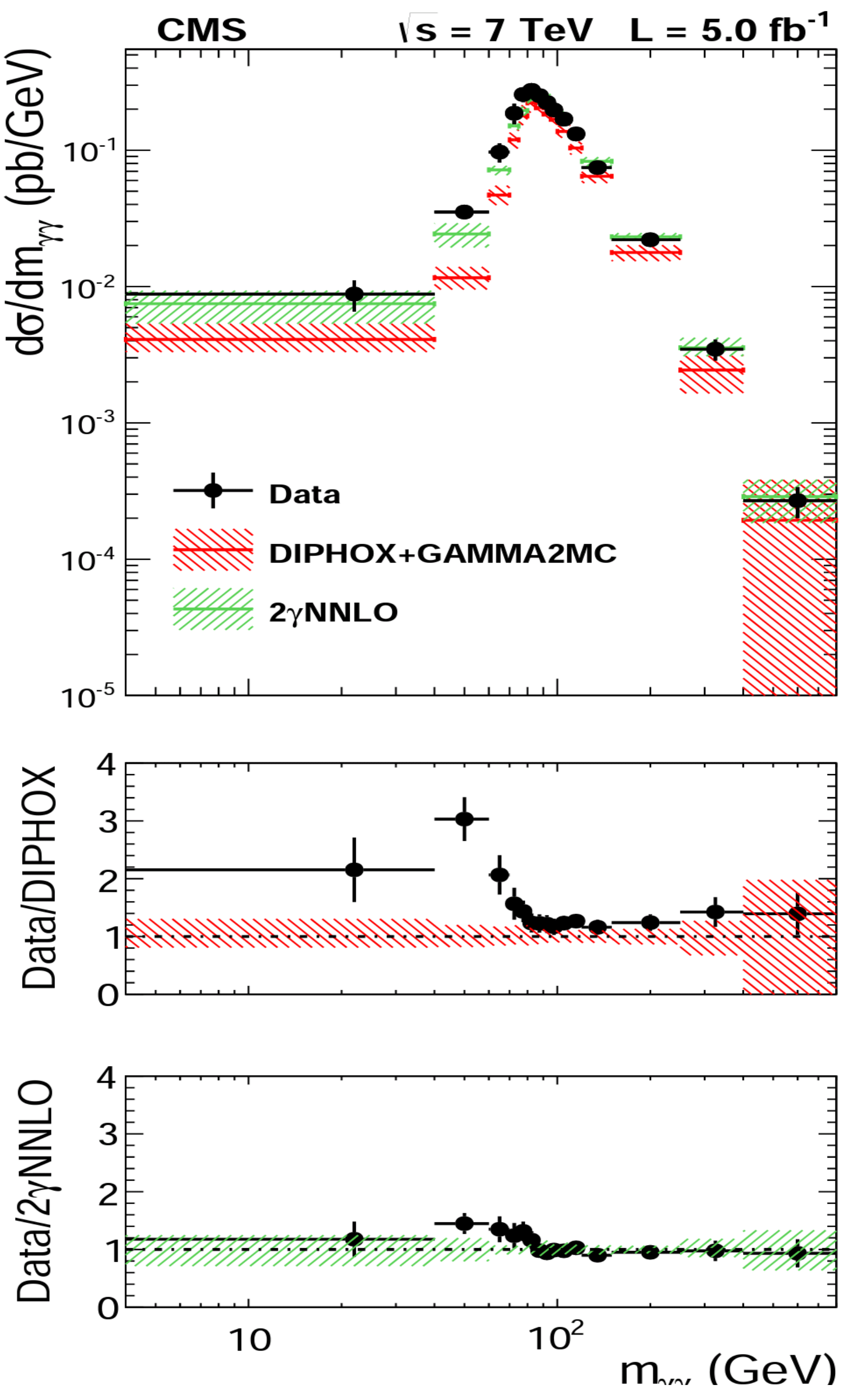
CMS results γγ

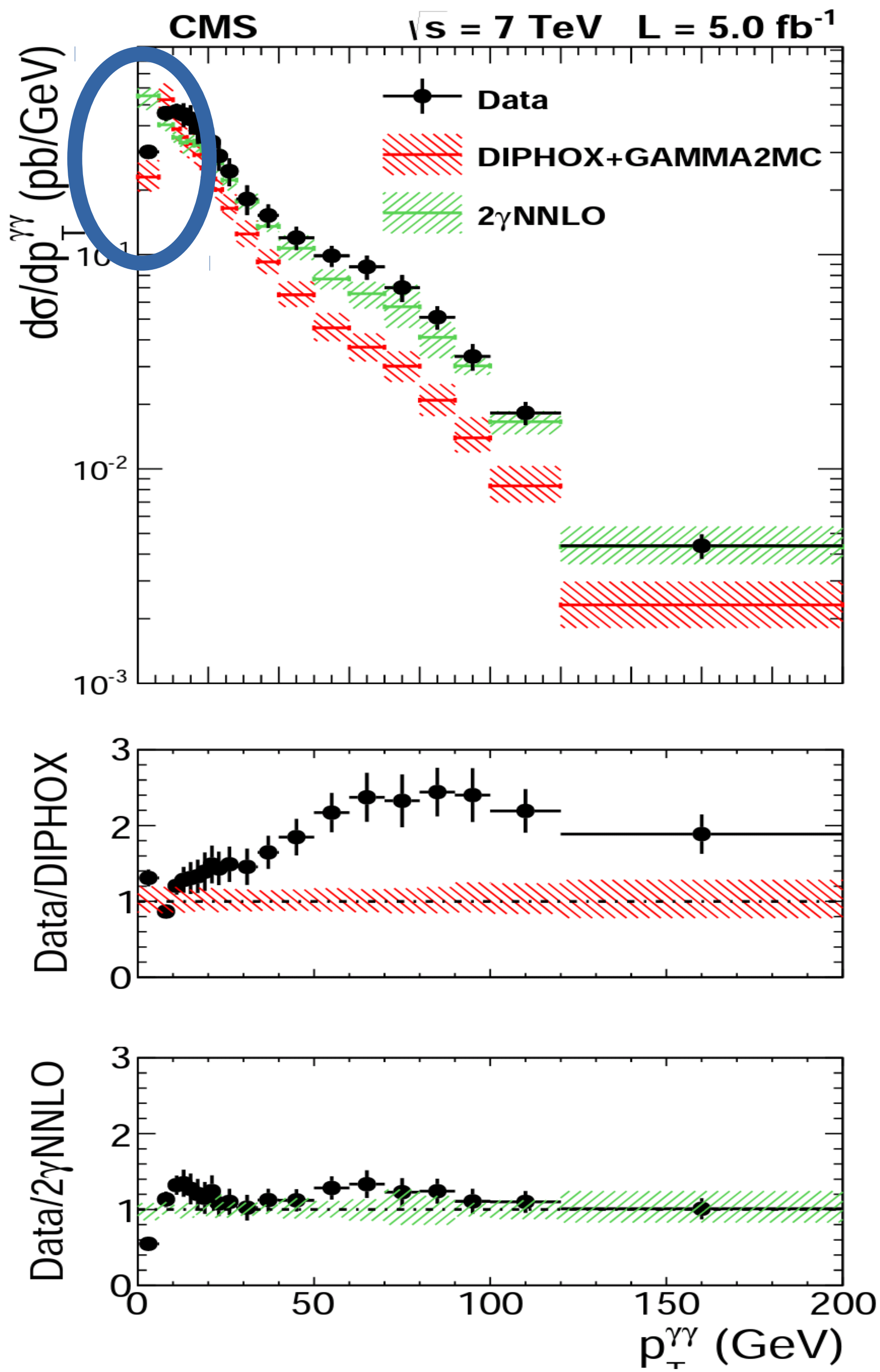
arXiv:1405.7225

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

CMS results γγ

arXiv:1405.7225





CMS results γγ

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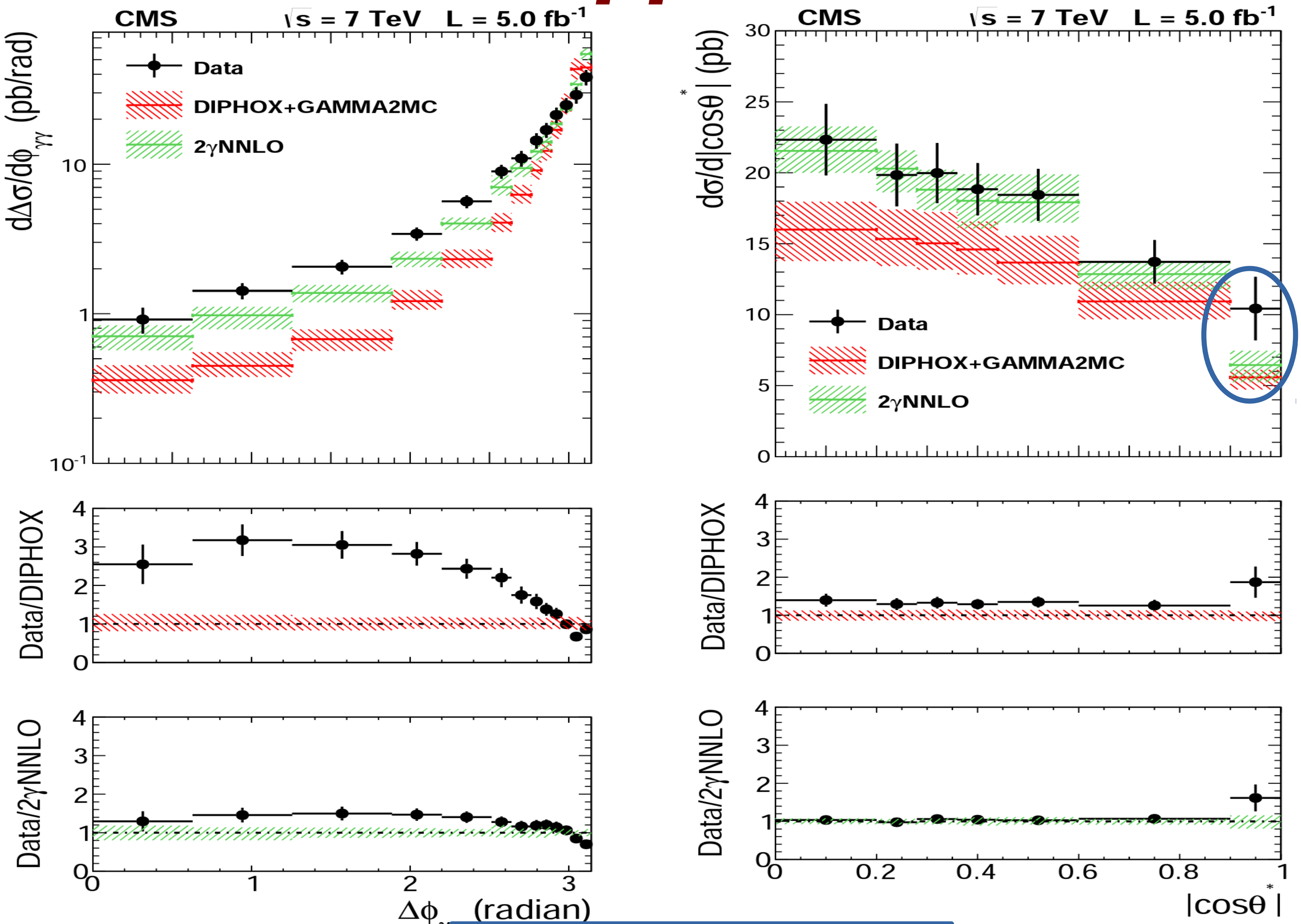

Uncertainties → 6% - 8%