Diphoton production at the LHC up to NNLO QCD

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Based on:

S. Catani, L. Cieri, D. de Florian, G.F. & M. Grazzini,

arXiv:1110.2375 & **1802.02095**

Motivations

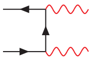
Photon pairs or *diphotons* ($\gamma\gamma$) production at high invariant mass ($M_{\gamma\gamma}$) very relevant at hadron colliders.

- Experimentally very clean finale states. Photon energies/momenta measured with high precision.
- Photons not interact strongly: ideal probes for study Standard Model (SM) interactions.
- At the LHC diphotons final states played a crucial role in the Higgs boson discovery ($H \to \gamma\gamma$).
- Diphotons measurements important in searches for physics beyond the SM.

The above reasons and **precise experimental LHC data** demands for **accurate theoretical predictions** $\Rightarrow$ **computation of higher-order QCD corrections**.

Photon production

- PRIMARY or PROMPT photons
  - DIRECT photons
    Directly produced in the hard scattering



$pQCD(+PDFs)$

  - FRAGMENTATION photons Collinear fragmentation of partons into photons

$pQCD(+PDFs) + PFFs$

Only the sum of Direct + Fragmentation component has a physical meaning, given a proper factorization scheme (e.g. $\overline{MS}$)

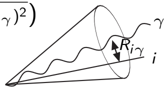
$$\sigma = \sigma_\gamma(M_F^2) + \sum_p \sigma_p(M_F^2) \otimes D_{p/\gamma}(M_F^2)$$

$D_{a/\gamma}(M_F^2)$ Fragmentation function of a parton p in a γ:
non-perturbative initial condition + Altarelli-Parisi perturbative evolution.

- SECONDARY (NON PROMPT) photons From decays of hadrons (π^0, η) at large p_T or faked by jets.
  Several order of magnitude larger than PROMPT photons
  $\Rightarrow$ Photon isolation is necessary to enhance signal-background ratio

Photon Isolation

- Standard Cone: in a cone of radius R around $\mathbf{p}_\gamma$ the hadronic transverse energy
  $E_T^{had}(R) \equiv \sum_i E_{T_i}^{had} \Theta(R - R_{i\gamma})$ $\left(\text{with } R_{i\gamma} = \sqrt{(y_i - y_\gamma)^2 + (\phi - \phi_\gamma)^2}\right)$



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

☹ Not possible to set $E_{T_{max}} = 0$ (to kill fragmentation component):
it is not Infrared Safe (soft gluons cannot be emitted inside the cone).

- Smooth Cone [Frixione('98)]: for ALL cones with radius $r < R$ around $\mathbf{p}_\gamma$

$$E_T^{had}(r) \leq E_{T_{max}}\, \chi(r; R) \xrightarrow{r \to 0} 0$$

☺ It is Infrared Safe (soft gluons can always be emitted inside the cone).

☺ Completely kill (poorly known) Fragmentation component.

☺ Direct component well defined (no parton-photon collinear divergences).

☹ Not easy to implement (a discrete version) in experimental analyses.

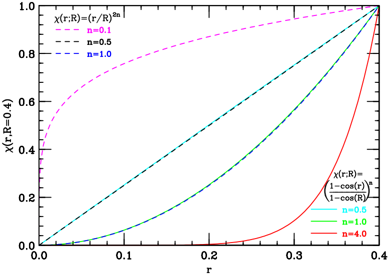
If isolation tight enough NLO QCD predictions with standard and smooth cone are similar (differences smaller than perturbative uncertainties).

Photon Isolation

Isolation functions:

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

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



Shapes $\chi(r;R)$ for various values of power n and $R = 0.4$.

Physical constraints:

- $d\sigma_{smooth}(R;E_{T_{max}}) < d\sigma_{standard}(R;E_{T_{max}})$,
- $d\sigma_{is}(R;E_{T_{max}})$ monotonically decreases as $E_{T_{max}}$ decreases (R fixed) ,
- $d\sigma_{is}(R;E_{T_{max}})$ monotonically increases as R decreases ($E_{T_{max}}$ fixed) ,
- $d\sigma_{smooth}(R;E_{T_{max}};n)$ monotonically decreases as n increases (R and $E_{T_{max}}$ fixed) ,

Diphoton production

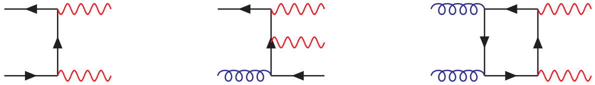
- DIPHOX: NLO QCD for Direct and Fragmentation contributions + part of NNLO ($gg \to \gamma\gamma$ Box) [Binoth,Guillet,Pilon,Werlen('99)].
- gamma2MC: NLO QCD for Direct contribution + part of NNLO ($gg \to \gamma\gamma$ Box) + part of N^{3}LO (corrections to $gg \to \gamma\gamma$ Box) [Bern,Dixon,Schmidt('02)].
- MCFM: LO QCD for Fragmentation contribution + NLO QCD for Direct contribution + part of NNLO ($gg \to \gamma\gamma$ Box) + part of N^{3}LO (corrections to $gg \to \gamma\gamma$ Box) [Campbell,Ellis,Williams('11)].
- NNLL q_T resummation implemented in ResBos [Balazs,Berger,Nadolsky,Yuan ('07)] and in 2γRes [Cieri,Coradeschi,de Florian('15)].
- NLO EW corrections computed [Bierweiler et al.('13)] and [Chiesa et al.('17)].

A complete NNLO in QCD ($\mathcal{O}(\alpha_S^2)$) calculation of both direct and fragmentation components not available. Fragmentation component absent by considering smooth cone isolation. Only direct component needed.

- 2γNNLO: full NNLO QCD calculation for Direct contribution [Catani,Cieri,de Florian, G.F.,Grazzini ('11)] performed within q_T subtraction formalism (independently implemented in the MATRIX generator [Grazzini,Kallweit,Wiesamann('17)]).
- Independent NNLO QCD calculation for direct contribution within N-jettiness subtraction performed by [Campbell,Ellis,Li,Williams('16)].

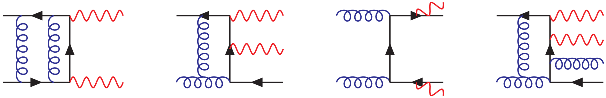
Diphoton production in NNLO QCD: 2γNNLO

The q_T-subtraction formalism cannot deal with IR divergences in the final state
⇒ we rely on Frixione smooth cone isolation (no Fragmentation component) and we calculated the fully exclusive NNLO corrections for Direct component.
Higher order corrections known to be very large:



$\hat{\sigma} \sim \alpha^2;\ \mathcal{L} \sim q\bar{q}$ $\hat{\sigma} \sim \alpha^2\alpha_S;\ \mathcal{L} \sim qg$ $\hat{\sigma} \sim \alpha^2\alpha_S^2;\ \mathcal{L} \sim gg$

Box contribution (part of NNLO) large as Born [Dicus, Willenbrock('88)].
Important to have a full control of all the NNLO ($\mathcal{O}(\alpha_S^2)$) contributions:



$+ \cdots$

Fiducial cross sections at LO and NLO

S. Catani, L. Cieri, D. de Florian, G.F. & M. Grazzini, [arXiv:1802.02095]

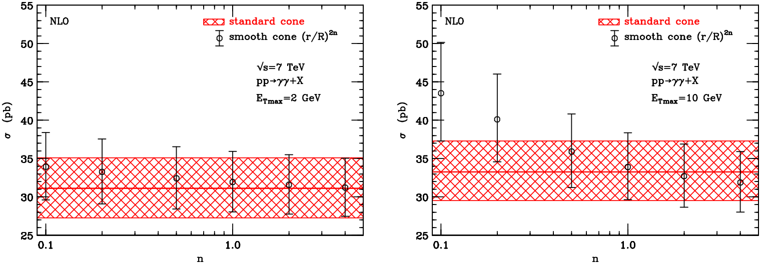
Kinematical cuts (ATLAS):
$p_{T\gamma}^{hard} \geq 25$ GeV, $p_{T\gamma}^{soft} \geq 22$ GeV, $|y_\gamma| < 2.37$, $R_{\gamma\gamma}^{min} = 0.4$.

Set up: $\alpha = 1/137$, MMHT 2014 PDFs, BFG-II photon Frag. Funct.,

Scale choice: $\mu_F = \mu_R = \mu_{frag} = \mu_0 \equiv M_{\gamma\gamma}$

Scale variations: $\{\mu_R = \mu_0/2,\ \mu_F = \mu_{frag} = 2\mu_0\}$ and $\{\mu_R = 2\mu_0\ ,$
$\mu_F = \mu_{frag} = \mu_0/2\}$ (equivalent to independent variation by a factor 2).
Isolation: $R = 0.4$, $n = 1$.

	$E_{T_{max}} = 2$ GeV		$E_{T_{max}} = 10$ GeV	
	$\sigma^{\rm LO}$ (pb)	$\sigma^{\rm NLO}$ (pb)	$\sigma^{\rm LO}$ (pb)	$\sigma^{\rm NLO}$ (pb)
Standard	$12.15\ ^{+14.5\,\%}_{-14.3\,\%}$	$31.1\ ^{+12.8\,\%}_{-12.3\,\%}$	$19.51\ ^{+25.0\,\%}_{-20.8\,\%}$	$33.3\ ^{+12.3\,\%}_{-11.3\,\%}$
[*direct*]	$10.56\ ^{+10.7\,\%}_{-12.0\,\%}$	$27.30\ ^{+7.8\,\%}_{-9.2\,\%}$	$10.56\ ^{+10.7\,\%}_{-12.0\,\%}$	$18.45\ ^{-10.3\,\%}_{+3.8\,\%}$
Smooth	$10.56\ ^{+10.7\,\%}_{-12.0\,\%}$	$31.92\ ^{+12.6\,\%}_{-12.1\,\%}$	$10.56\ ^{+10.7\,\%}_{-12.0\,\%}$	$33.91\ ^{+13.0\,\%}_{-12.6\,\%}$

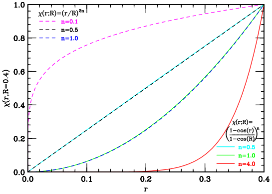


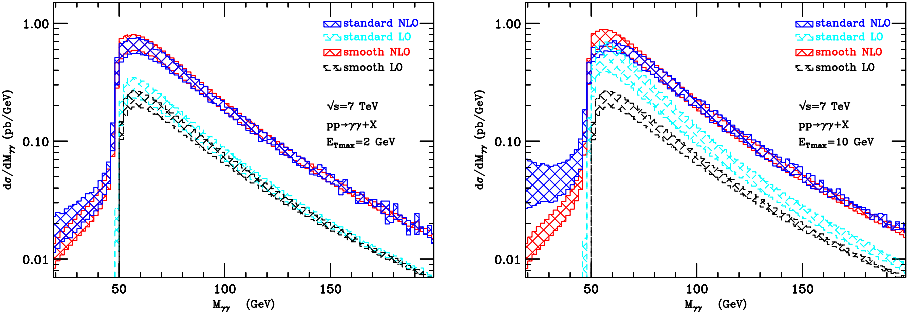
NLO cross section (with scale variation), for standard and smooth isolation with $E_{T_{max}} = 2$ *(left) and 10 GeV (right). Smooth cone isolation function:* $\chi(r;R) = (r/R)^{2n}$ *with* $0.1 \leq n \leq 4$.

Analytic behaviour of NLO correction for smooth cone isolation in the $n \gg 1$ (soft limit) and $n \ll 1$ (collinear limit).

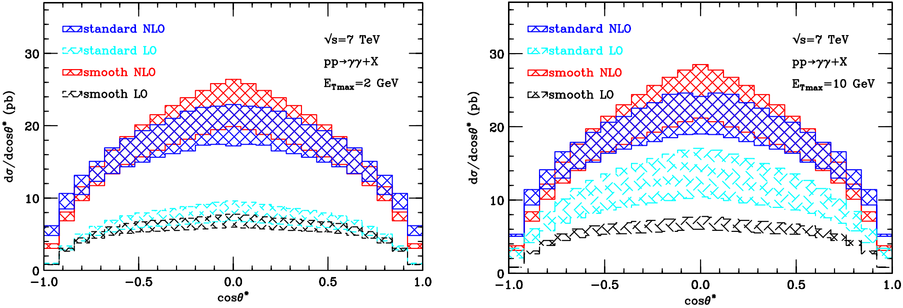
$$\delta^{NLO,soft}_{smooth} \propto -\alpha_S R^2 \left(\ln\left(\frac{Q}{E_{T_{max}}}\right) + n \right) , \qquad (n \gg 1) ,$$

$$\delta^{NLO,coll}_{smooth} \propto +\frac{\alpha_S}{n} \frac{E_{T_{max}}}{Q} , \qquad (n \ll 1) .$$

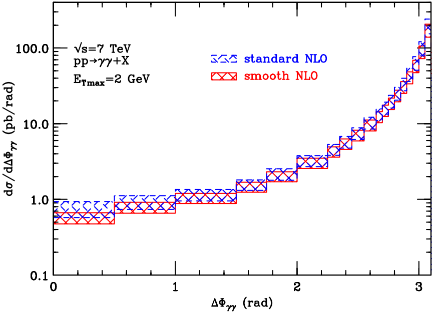


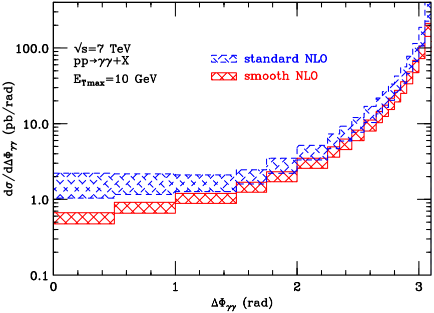


The $M_{\gamma\gamma}$ differential cross section for $E_{T_{max}} = 2$ GeV (left) and $E_{T_{max}} = 10$ GeV (right) at LO and NLO including scale variation bands.

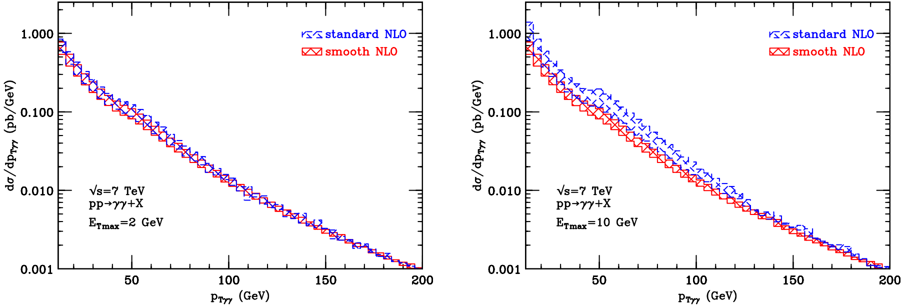


The $\cos\theta^*$ *differential cross section for* $E_{T_{max}} = 2$ *GeV (left) and* $E_{T_{max}} = 10$ *GeV (right) at LO and NLO including scale variation bands. Where* θ^* *is the photon polar angle in the Collins-Soper rest frame of the diphoton system.*

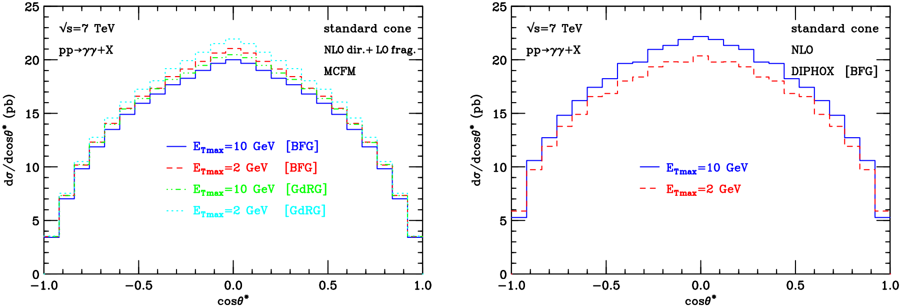




The NLO results (scale variation bands) for the $\Delta\Phi_{\gamma\gamma}$ differential cross section that are obtained by using the smooth (red solid band) and standard (blue dashed band) cone isolation criteria with $E_{T_{max}} = 2$ GeV (left) and $E_{T_{max}} = 10$ GeV (right).



The NLO results (scale variation bands) for the $p_{T\gamma\gamma}$ differential cross section that are obtained by using the smooth (red solid band) and standard (blue dashed band) cone isolation criteria with $E_{T_{max}} = 2$ GeV (left) and $E_{T_{max}} = 10$ GeV (right).



The cos θ^* *differential cross section for standard cone isolation with two different values of* $E_{T_{max}}$ *(2 GeV and 10 GeV). The QCD results are obtained at the central value of the scales* $(\mu_F = \mu_R = \mu_{frag} = \mu_0 \equiv M_{\gamma\gamma})$*. The results with NLO direct + LO fragmentation components (left) use BFG and GdRG_LO fragmentation functions. The NLO results (right) use BFG fragmentation functions.*

Fiducial cross sections at NNLO

S. Catani, L. Cieri, D. de Florian, G.F. & M. Grazzini, [arXiv:1802.02095]

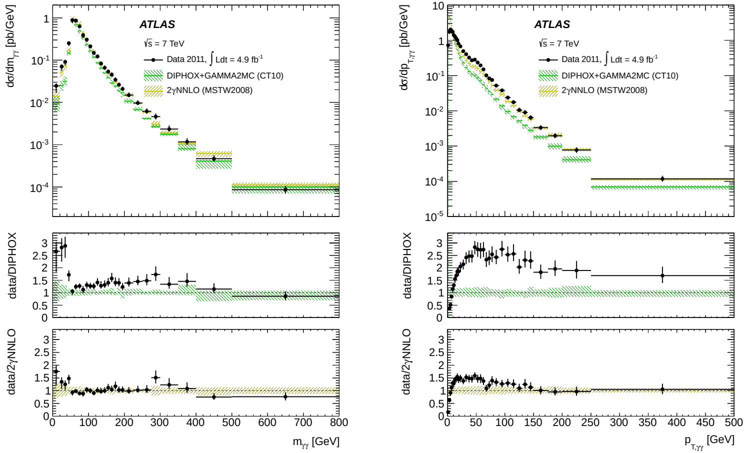
Kinematical cuts (ATLAS): $p_{T\gamma}^{hard} \geq 25$ GeV, $p_{T\gamma}^{soft} \geq 22$ GeV, $|y_\gamma| < 1.37$ and $1.52 < |y_\gamma| \leq 2.37$, $R_{\gamma\gamma}^{min} = 0.4$.

Set up: $\alpha = 1/137$, MMHT 2014 PDFs,

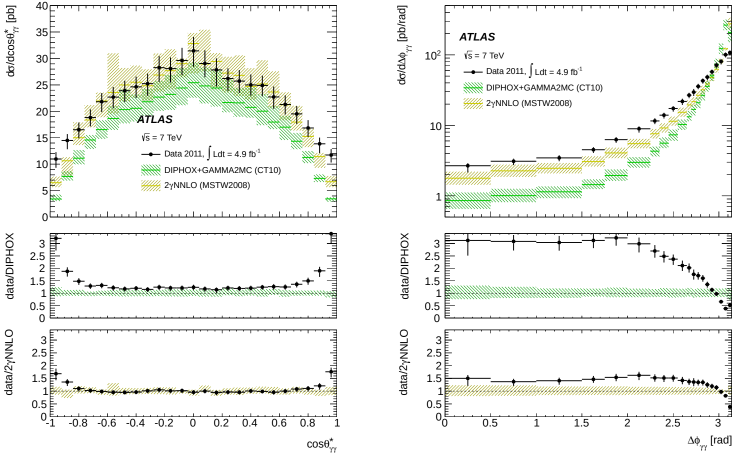
Scale choice: $\mu_F = \mu_R = \mu_{frag} = \mu_0 \equiv \sqrt{{M_{\gamma\gamma}}^2 + p_{T\gamma\gamma}^2} = M_{T\gamma\gamma}$

Scale variations: $\{\mu_R = \mu_0/2,\ \mu_F = \mu_{frag} = 2\mu_0\}$ and $\{\mu_R = 2\mu_0\ ,$ $\mu_F = \mu_{frag} = \mu_0/2\}$ (equivalent to independent variation by a factor 2).
Isolation ATLAS: cone isolation $R = 0.4$ and $E_{T_{max}} = 4$ GeV.
Isolation NNLO: smooth cone isolation $R = 0.4$ and $E_{T_{max}} = 4$ GeV.

	$\sigma^{\rm LO}$ (pb)	$\sigma^{\rm NLO}$ (pb)	$\sigma^{\rm NNLO}$ (pb)
n ind.	$9.293\ ^{+10.9\,\%}_{-11.9\,\%}$		
$n = 0.5$		$29.40\ ^{+12.8\,\%}_{-12.4\,\%}$	$40.98(68)\ ^{+8.3\,\%}_{-8.7\,\%}$
$n = 1$		$28.55\ ^{+12.5\,\%}_{-12.2\,\%}$	$39.50(50)\ ^{+7.9\,\%}_{-8.4\,\%}$
$n = 2$		$27.98\ ^{+12.3\,\%}_{-11.9\,\%}$	$37.53(52)\ ^{+7.0\,\%}_{-7.8\,\%}$



Comparison between ATLAS data at $\sqrt{s} = 7$ TeV with NLO (DIPHOX+GAMMA2MC) and NNLO (2γNNLO) results (with scale dependence) for $d\sigma/dM_{\gamma\gamma}$ (left) and $d\sigma/dp_{T\gamma\gamma}$ (right).



Comparison between ATLAS data at $\sqrt{s} = 7$ TeV with NLO (DIPHOX+GAMMA2MC) and NNLO (2γNNLO) results (with scale dependence) for $\cos\theta^*$ (left) and $d\sigma/\Delta\Phi_{\gamma\gamma}$ (right).

Conclusions

- Detailed study on differences between standard and smooth cone isolation up to NLO: results are consistent within the corresponding scale uncertainties.
- Smooth cone isolation: consistent theoretical framework for NNLO calculation.
- First calculation of full NNLO QCD corrections to direct Diphoton production in hadron collision using the q_T-subtraction formalism.
- Calculation included in a fully-exclusive public available parton-level Monte Carlo code: 2γNNLO.
- NNLO corrections found to be large: $\sim 50\%$ over NLO at the LHC.
- NNLO corrections essential away from the back-to-back region (effectively next-order corrections).
- NNLO uncertainty band: first reliable estimate of perturbative uncertainty in some region underestimate the *true* perturbative uncertainty.
- NNLO corrections clearly improves description of the LHC data.