NNLO QCD Predictions for Triphoton Production

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based on
Stefan Kallweit, VS, Marius Wiesemann [Phys. Lett. B 812 (2021) 136013]

Standard Model at the LHC 2021 (Online)

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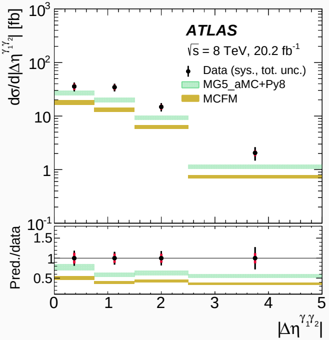
Motivation for $pp \to \gamma\gamma\gamma + X$

- Tensions between NLO QCD predictions and ATLAS 8 TeV measurement [arXiv:1712.07291]
- Main irreducible background for anomalous quartic gauge (e.g. $Z \to \gamma\gamma\gamma$) and anomalous Higgs ($H\gamma\gamma$) couplings
- Fixed order predictions: clean theoretical framework



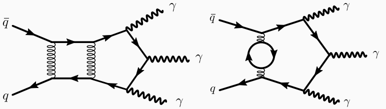
Studied earlier in [Chawdry, Czakon, Mitov, Poncelet '19] within STRIPPER framework [Czakon '10,'11]

- Very challenging $\implies$ independent calculation crucial
- We achieve flexible and public implementation

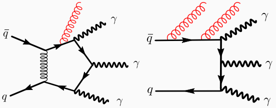
NNLO QCD multiplicity frontier

Triphoton is the first and only $2 \to 3$ process at LHC known to NNLO QCD so far

Why?



Two-loop amplitudes



IR divergences

Astoundingly more complex than $2 \to 2$!

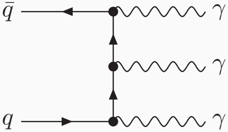
Tools and techniques for lower multiplicity do not scale well

$\Downarrow$

new approaches and frameworks

- Transcendental functions (Feynman integrals) [Papadopoulos, Tommasini, Wever '15] [Gehrmann, Henn, Lo Presti '18] [Abreu, Dixon, Herrmann, Page, Zeng '18] [Chicherin, Gehrmann, Henn, Wasser, Zhang, Zoia '18] [Abreu, Page, Zeng '18] [Chicherin, VS '20] [Abreu, Ita, Moriello, Page, Tschernow, Zeng '20] [Canko, Papadopoulos, Syrrakos '20]
- Taming algebraic complexity [Gehrmann, Henn, Lo Presti '15] [Dunbar, Perkins '16] [Peraro '16] [Badger, Brønnum-Hansen, Hartanto, Peraro '18] [Abreu, Febres Cordero, Ita, Page, VS '18] [Abreu, Dormans, Febres Cordero, Ita, Page '18] [Abreu, Dormans, Febres Cordero, Ita, Page, VS '19] [Badger, Chicherin, Gehrmann, Heinrich, Henn, Peraro, Wasser, Zhang, Zoia '19] [Abreu, Dixon, Herrmann, Page, Zeng '18] [Chicherin, Gehrmann, Henn, Wasser, Zhang, Zoia '18] [Chawdry, Lim, Mitov '18] [Boels, Jin, Luo '18] [Böhm, Georgoudis, Larsen, Schönemann, Zhang '18] [Wang, Li, Basat '19] [Guan, Liu, Ma '19] [Chawdry, Czakon, Mitov, Poncelet '19] [Hartanto, Badger, Brønnum-Hansen '19] [Laurentis, Maître '20] [Badger, Hartanto, Zoia '21], [Bendlea, Boehm, Heymann, Ma, Rahn, Ristau, Wittmann, Wu, Zhang '21]

Setup



- Five-flavor number scheme (5FNS), no top loops
- Full color, except in double-virtual contributions, missing contributions expected numerically subleading [Chawdry, Czakon, Mitov, Poncelet '19] [Kallweit, VS, Wiesemann '20]

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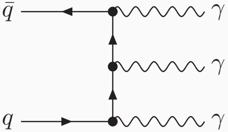

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Calculation within MATRIX framework [Grazzini, Kallweit, Wiesemann '17]

- q_T-subtraction formalism, phase space integration
- NLO $pp \to \gamma\gamma\gamma\, j + X$ through Catani-Seymour [Catani, Seymour '96 '97]
- Tree-level, one-loop from OPENLOOPS [Cascioli, Maierhöfer, Pozzorini '11]
- Two-loop analytic results [Abreu, Page, Pascual, VS '20], employing `PentagonFunctions++` [Chicherin, VS '20] for special functions

Phase space and parameters

$\sqrt{s} = 7, 8, 13, 14, 27, 100$ TeV

G_μ scheme for the EW parameters, $\alpha_s(m_Z) = 0.118$, NNPDF3.1

Dynamical central scale $\quad \mu_R = \mu_F = \frac{1}{4}\,(p_{T,\gamma_1} + p_{T,\gamma_2} + p_{T,\gamma_3})$

Fiducial phase space from ATLAS 8 TeV analysis [arXiv:1712.07291]:

$p_{T,\gamma_1} \geq 27\,\text{GeV}, \quad p_{T,\gamma_2} \geq 22\,\text{GeV}, \quad p_{T,\gamma_3} \geq 15\,\text{GeV}, \quad m_{\gamma\gamma\gamma} \geq 50$

$0 \leq |\eta_\gamma| \leq 1.37$ or $1.56 \leq |\eta_\gamma| \leq 2.37$

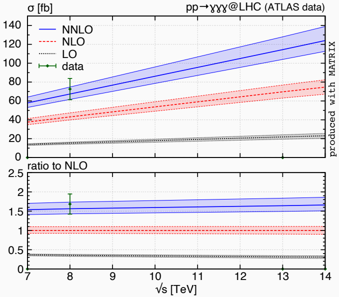
$\Delta R_{\gamma\gamma} \geq 0.45$

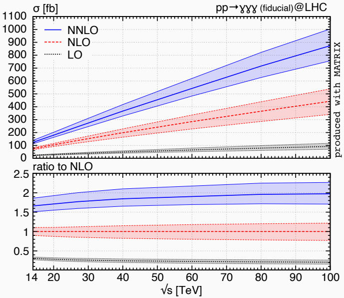
Suppress fragmentation photons: smooth-cone isolation [Frixione '98]
($n = 1$, $\delta_0 = 0.4$, fixed $E_T^{\text{ref}} = 10\,\text{GeV}$)

Uncertainties

- Missing higher orders: 7-point scale variation $0.5 \leq \mu_R/\mu_F \leq 2$
- Slicing parameter extrapolation ($r_{\text{cut}} = \left(\frac{q_T}{m}\right)_{\gamma\gamma\gamma} \to 0$) $\implies$ subleading
- PDF uncertainty 2-3% at NLO [arXiv:1712.07291] $\implies$ negligible at NNLO

Fiducial cross sections

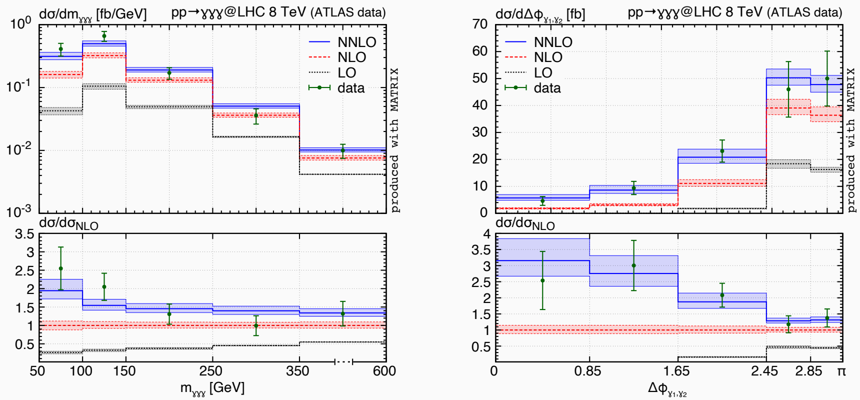




$\sqrt{s}$, TeV	$\sigma_{\rm NNLO}$, fb	$K_{\rm NLO}$	$K_{\rm NNLO}$
7	$57.84(20)^{+10.7\%}_{-\ 8.3\%}$	2.72	1.54
8	$67.42(20)^{+11.0\%}_{-\ 8.5\%}$	2.82	1.56
13	$114.60(43)^{+11.9\%}_{-\ 9.1\%}$	3.18	1.65
14	$123.83(24)^{+12.0\%}_{-\ 9.2\%}$	3.24	1.66
27	$245.91(48)^{+13.2\%}_{-\ 9.9\%}$	3.76	1.77
100	$878.9(24)\ ^{+15.0\%}_{-13.5\%}$	4.79	1.99

- Full agreement with 8 TeV results of [Chawdry, Czakon, Mitov, Poncelet '19]
- Consistent with ATLAS 8 TeV measurement $72.6\ ^{+6.5}_{-6.5}(\text{stat})\ ^{+9.2}_{-9.2}(\text{syst})$ fb
- Huge $K_{\rm NLO}$ and $K_{\rm NNLO}$ factors

Differential cross sections $\sqrt{s} = 8$ TeV

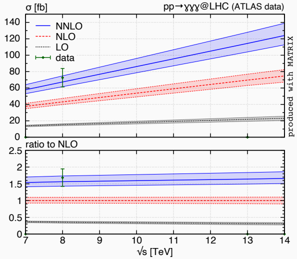


- Major shape differences w.r.t. NLO
- Excellent agreement with data (and [Chawdry, Czakon, Mitov, Poncelet '19]) across all differential distributions
- At higher $\sqrt{s}$ similar pattern, corrections slightly increase

Perturbative convergence?

Symptoms

- Giant K_{NLO} and K_{NNLO} factors
- No overlap in uncertainty bands



Lifting fixed-order constraints

- opening of channels
  NLO $qg \to \gamma\gamma\gamma q$
  NNLO $qq' \to \gamma\gamma\gamma qq'$, $gg \to \gamma\gamma\gamma q\bar{q}$
- degenerate LO kinematics

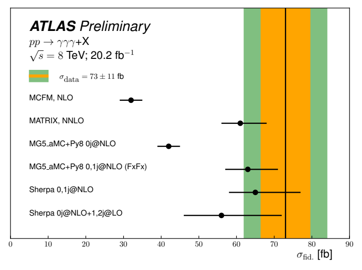
Other examples: $\gamma\gamma$, $Wb\bar{b}$, H, ...

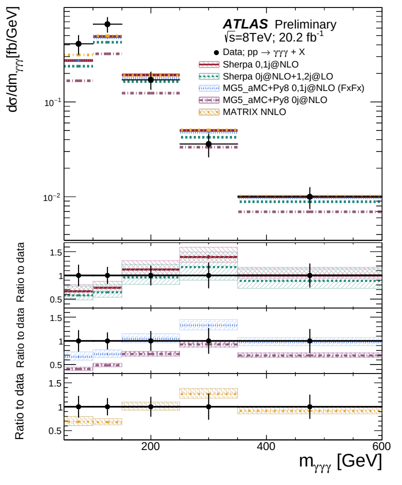
$\Downarrow$

- Scale uncertainties unreliable until all constraints are lifted
- For triphoton reasonable uncertainties expected at NNLO

Perturbative convergence?

Comparison to merged 0,1j NLO sheds some light [ATL-PHYS-PUB-2021-001]





Summary & outlook

Summary

Triphoton production in NNLO QCD with q_T-subtraction in Matrix

- First on-the-fly NNLO calculation of a $2 \to 3$ process, publicly available in the next release of Matrix
- NNLO corrections large and essential for precision phenomenology

Outlook

- NNLO+PS
- EW corrections, subleading-color contributions
- Better understanding of uncertainties, e.g. interplay of scale choice and isolation criteria [Gehrmann, Glover, Huss, Whitehead '20], etc.

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Self-promotion corner

Double-virtual contributions for NNLO QCD three-jet are now available [arXiv:2102.13609]!

Acknowledgments

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Backup

q_T subtraction (slicing)

[Catani, Grazzini '07]

$$h_1 + h_2 \to F + X$$

q_T — transverse momentum of color singlet system F, $\quad r = \frac{q_T}{m_F}$

$q_T = 0$ in LO kinematics

$$\sigma^F_{\rm NNLO} = \int_{\Phi_F} {\rm d}\sigma_{\rm B} + \int_{\Phi_F} {\rm d}\sigma_{\rm V} + \int_{\Phi_{F+1}} {\rm d}\sigma_{\rm R} + \int_{\Phi_{F+2}} {\rm d}\sigma_{\rm RR} + \int_{\Phi_{F+1}} {\rm d}\sigma_{\rm RV} + \int_{\Phi_F} {\rm d}\sigma_{\rm VV}$$

$$ {\rm d}\sigma^{\rm F}_{\rm NNLO} = \mathcal{H}_{\rm NNLO} \otimes {\rm d}\sigma_{\rm B} \;+\; \left({\rm d}\sigma^{F+{\rm jet}}_{\rm NLO} - {\rm d}\sigma^{\rm CT}_{\rm NNLO}\right)$$

$$\to \mathcal{H}_{\rm NNLO} \otimes {\rm d}\sigma_{\rm B} \;+\; \left({\rm d}\sigma^{F+{\rm jet}}_{\rm NLO} - {\rm d}\sigma^{\rm CT}_{\rm NNLO}\right)\theta(r - r_{\rm cut}) + \mathcal{O}(r_{\rm cut})$$

${\rm d}\sigma^{F+\text{jet}}_{\text{NLO}}$ finite with $r > 0 \implies$ Catani-Seymour calculation [Catani, Seymour '96 '97]

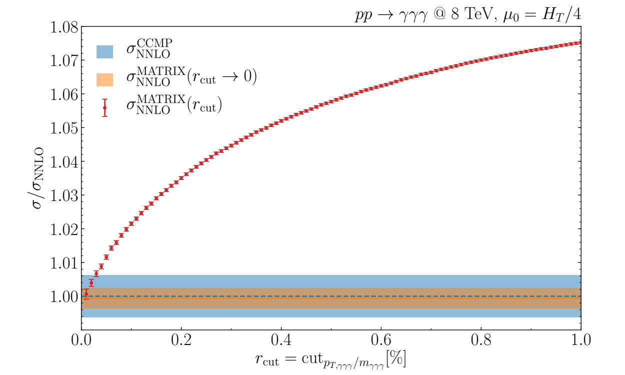
${\rm d}\sigma^{\text{CT}}_{\text{NNLO}}$ universal counterterm, known from small q_T resummation [Bozzi, Catani, de Florian, Grazzini '05]

$\mathcal{H}_{\text{NNLO}}$ particular IR renormalization of loop corrections [Catani, Cieri, de Florian, Ferrera, Grazzini '13]

$r_{\text{cut}} \to 0$ extrapolation automated in MATRIX [Grazzini, Kallweit, Wiesemann '17]

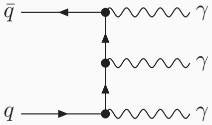
$r_{\text{cut}} \to 0$ extrapolation

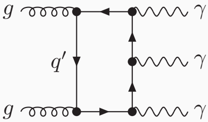
Three smooth-cone isolated photons, intricate interplay with r_{cut}
$\implies$ potentially large uncertainties

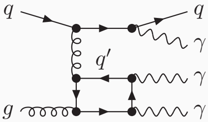


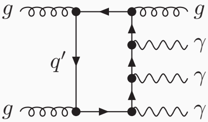
- q_T subtraction fully capable dealing with $2 \to 3$ color singlet!
- extrapolation uncertainties controlled, few ‰, mild phase-space dependence

Loop-induced contributions





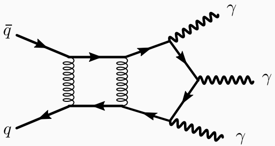




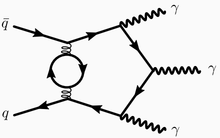
$= 0$

finite (formally N^{3}LO), small $\lesssim 1\%$

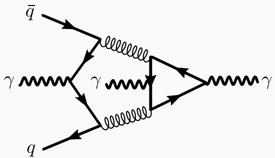
Contributions to two-loop hard function $\mathcal{H}^{(2)}$



$A^{(2,0)}$



$A^{(2,N_\mathrm{f})}$

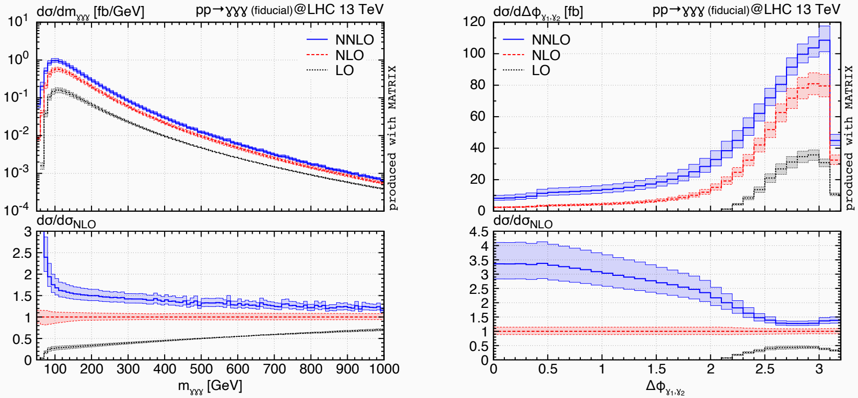


$A^{(2,\tilde{N}_\mathrm{f})}$

$$\mathcal{H}^{(2)} = \frac{N_\mathrm{c}^2}{4}\left(\mathcal{H}^{(2,0)} - \frac{1}{N_\mathrm{c}^2}(\mathcal{H}^{(2,0)} + \mathcal{H}^{(2,1)}) + \frac{1}{N_\mathrm{c}^4}\mathcal{H}^{(2,1)}\right) + C_\mathrm{F}T_\mathrm{F}N_\mathrm{f}\,\mathcal{H}^{(2,N_\mathrm{f})} + C_\mathrm{F}T_\mathrm{F}\left(\sum_{f=1}^{N_\mathrm{f}} Q_f^2\right)\mathcal{H}^{(2,\tilde{N}_\mathrm{f})} \quad \longrightarrow \quad \frac{N_\mathrm{c}^2}{4}\mathcal{H}^{(2,0)}$$

- $\mathcal{H}^{(2,1)}$, $\mathcal{H}^{(2,\tilde{N}_\mathrm{f})}$ include non-planar two-loop contributions (difficult, WIP)
- $\mathcal{H}^{(2,N_\mathrm{f})}$, $\mathcal{H}^{(2,\tilde{N}_\mathrm{f})}$ contributions expected numerically subleading

Differential cross sections $\sqrt{s} = 13$ TeV



- Similar pattern as in 8 TeV, corrections generally increase
- Efficient calculation allows fine binning, predictions for high-energy tails