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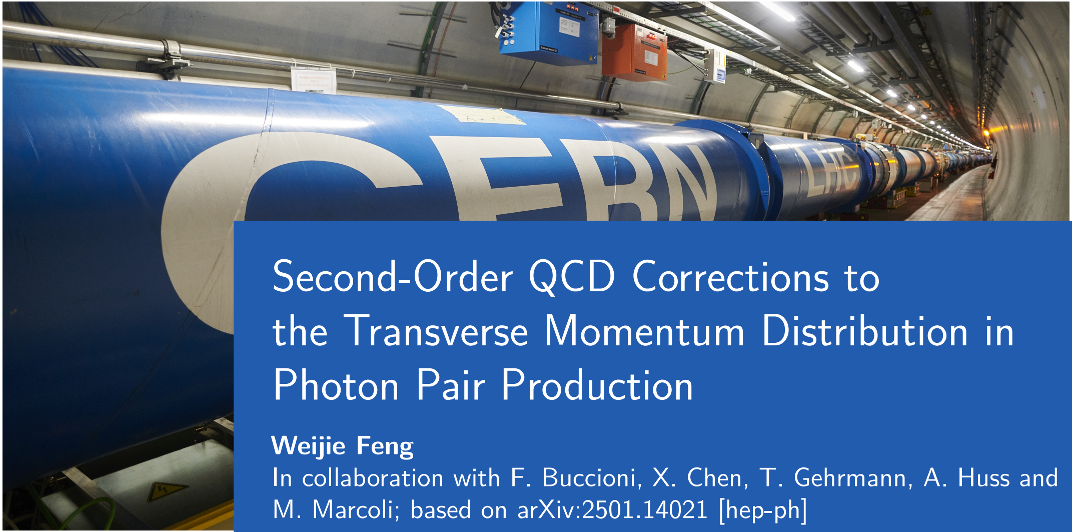

Second-Order QCD Corrections to the Transverse Momentum Distribution in Photon Pair Production

Weijie Feng
In collaboration with F. Buccioni, X. Chen, T. Gehrmann, A. Huss and M. Marcoli; based on arXiv:2501.14021 [hep-ph]

Outline

Motivation

Why should we care about diphoton production?

- A clean final state;
- Main background to the discovery channel of Higgs boson: $H \to \gamma\gamma$;
- Key background to many new physics searches;
- Massless final state: early access to loop-amplitudes;
- Test of the validity of photon isolation.

Previous Work and Challanges

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- $\gamma\gamma$+jet@NNLO in *leading colour approximation* [Czakon, et al, 2105.06940];
- gluon fusion $\gamma\gamma$+jet@NLO [Gehrmann, et al, 2109.12003];
- $\gamma\gamma$+jet two-loop amplitudes in full-colour [Agarwal, et al, 2105.04585];
- Measurement in ATLAS on diphoton observable [ATLAS Collab., 2107.09330].

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Challenges on diphoton production:

- Diphoton@NNLO receives **larger scale uncertainties** than at NLO from new channel opening, depending on scale choice [Gehrmann, et al, 2009.11310];
- Diphoton receives considerable **power corrections** from photon isolation already at NNLO [Campbell, et al, 2408.05265].

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2. The Calculation Setup
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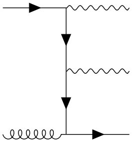
Calculation Components

- The underlying process for diphoton p_T distribution:
  $pp \to \gamma\gamma +$ **QCD recoil**, *e.g.* $qg \to q\gamma\gamma$, Born level at $\mathcal{O}(\alpha_s)$.
- Calculation performed in *perturbative expansion*. At NNLO $\mathcal{O}(\alpha_s^3)$:
  - Double real radiation (RR) and single real with 1-loop correction (RV): `OpenLoops` [Buccioni, et al, 1907.13071].
  - 2-loop correction (VV): **full-colour** expression (*non-planar*) from [Agarwal, et al, 2105.04585].



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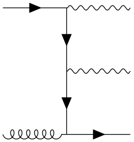
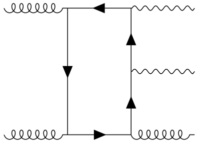
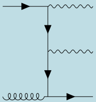


- New channel opening at $\mathcal{O}(\alpha_s^3)$: quark-loop-induced channels (QLI), *e.g.* $gg \to g\gamma\gamma$:
  - Contribution enhanced by the **large gluon luminosity**.
  - $\to$ Full NLO corrections to *all* partonic channels are included, going partly into **N^{3}LO corrections** of the main process (NNLO$^+$).
  - Real corrections: `OpenLoops`.
  - Virtual corrections: NJet library [Badger, et al, 2106.08664].

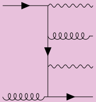


Example Feynman Diagrams

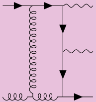
B



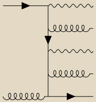
R



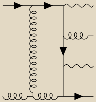
V



RR



RV



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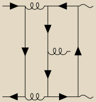
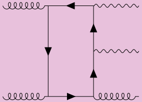
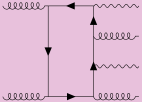


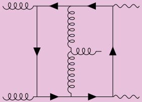
QL-B



QL-R



QL-V



The Calculation

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- Subtraction scheme: **antenna subtraction** [Gehrmann, et al, 0505111, 0612257, 1301.4693].
- Photon isolation: **hybrid** isolation scheme:
  - Fixed-cone isolation with $(R, \epsilon_{T,\gamma}) = (0.2, 0.09)$;
  - Dynamical isolation with smaller cone size $(R_d, \epsilon_d, n) = (0.1, 0.15, 1)$.
- The calculation is performed in **NNLOJET framework** [Huss, et al, 2503.22804].

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- Validation of the calculation:
  - NLO components (+1jet) are compared with `MadGraph5_aMC@NLO`.
  - NNLO LC approx. are compared with [Czakon, et al, 2105.06940].
- Performance:
  - Total core-hours: $\mathcal{O}(10^6)$; bottleneck: RR;
  - VV performance: each phase-space point from $\mathcal{O}(1\ \text{sec})$ (double precision) to $\mathcal{O}(100\ \text{sec})$ (quadrupole precision).

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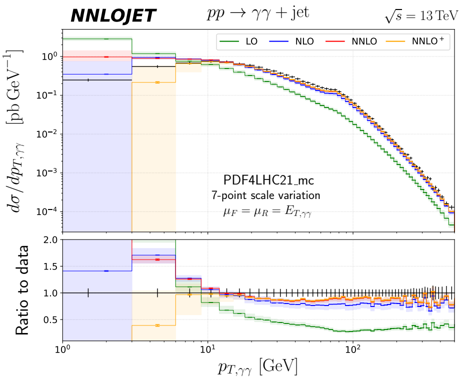
Diphoton Production: ATLAS p_T Event Shapes

- Event shapes of 3 other observables equivalent to $p_T(\gamma\gamma)$ are reproduced: $a_T(\gamma\gamma)$, $\phi^*(\gamma\gamma)$ and $\phi_{\text{acop}}(\gamma\gamma)$ with **higher resolution**.



$$p_{T,\gamma_1} > 40\ \text{GeV}, \quad p_{T,\gamma_2} > 30\ \text{GeV},$$
$$|\eta_\gamma| \in (0, 1.37) \cup (1.52, 2.37),\ \Delta R_{\gamma\gamma} > 0.4\,.$$

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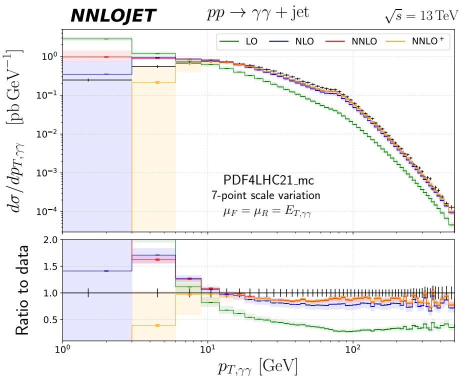

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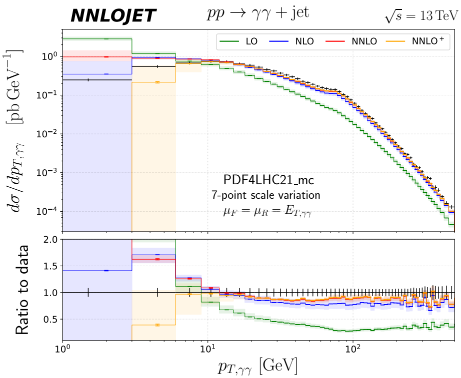

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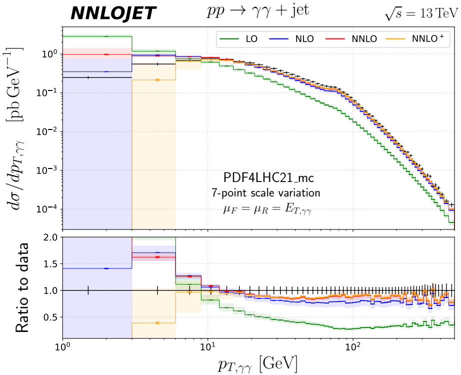
- No jet required; a cut equivalent to $p_{T,\gamma\gamma} = 1\ \text{GeV}$ is applied to avoid going too deep into the infrared region;
- Data comparison:
  - Progressively better agreement from NLO to NNLO;
  - 1.5-2σ undershooting the exp. data: other effects still needed, *e.g.* resummation, hadronisation, etc.



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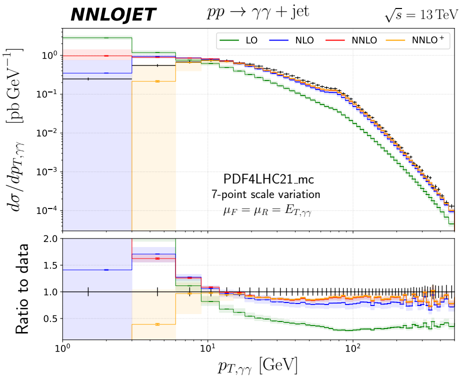

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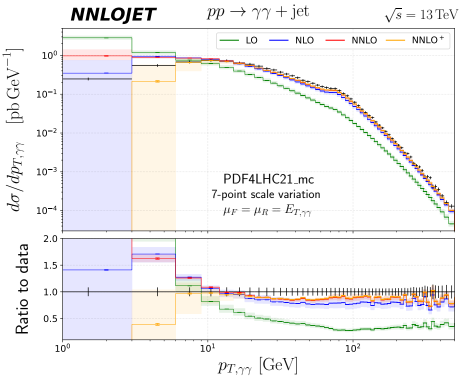

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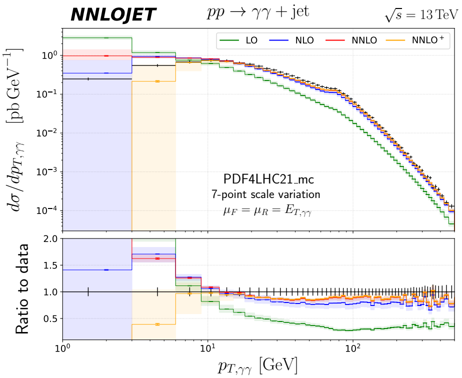
- **Kink** around 80 GeV $(= 2 \cdot p_{T,\gamma_1}^{\text{cut}})$: same-hemisphere events that are previously cut by the individual photon-p_T cuts come into play;



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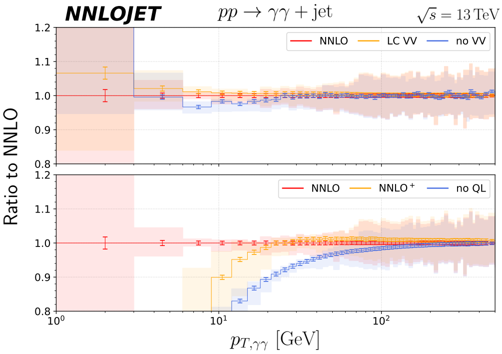
Diphoton Production: Quantifying Loop Effects

- Effects of *2-loop finite remainder* and *loop-induced contributions* are quantified.
- 2L finite remainder $2\Re\left[A_0 \cdot A_2^*\right]$:
  - contributes up to **3%** of some bins;
  - its SLC contribution has less than **0.5%** effect.



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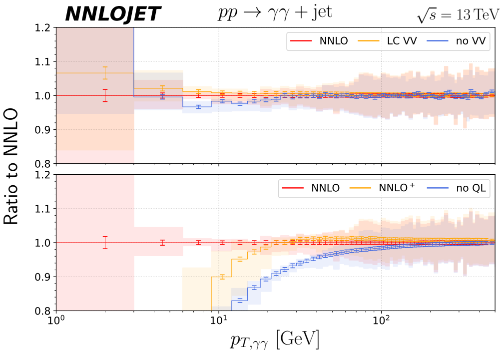
- QLI subprocess:
  - at high p_T, the QL@NLO (NNLO$^+$) contributes less than **0.5%**.
  - at low p_T, either excluding QL altogether, or including up to NLO introduces **large log enhancement**.



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Conclusion and Outlook

- NNLO diphoton p_T event shapes have been computed for the first time in full colour, with the inclusion of quark-loop-induced channels at NLO accuracy, entering NNLO$^+$ contributions.
- The calculation is very performant and optimised, and the numerical stability is under control.

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- The calculation was compared to ATLAS data, and displayed interesting kinematical features.
- Two-loop and quark-loop-induced NLO are quantified, showing that leading-colour approximation is valid for this process.

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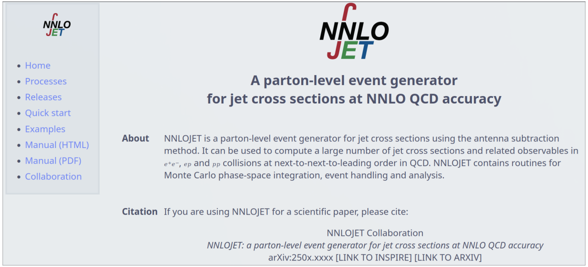
- The calculation was compared to ATLAS data, and displayed interesting kinematical features.
- Two-loop and quark-loop-induced NLO are quantified, showing that leading-colour approximation is valid for this process.
- The results enable precise phenomenology studies of diphoton production at the LHC.
- The calculation paves the way for third-order QCD corrections for more inclusive diphoton observables.

More Outlook...

- **NNLOJET is now public!**
- A wide range of $2 \to 2$ **processes with jets** @LHC is available at NNLO QCD.
- A well-tested and optimised piece of code, with user-friendly workflow.
- Coming soon: `OpenLoops` interface, $\gamma\gamma$+jet@NNLO, and more!



https://nnlojet.hepforge.org

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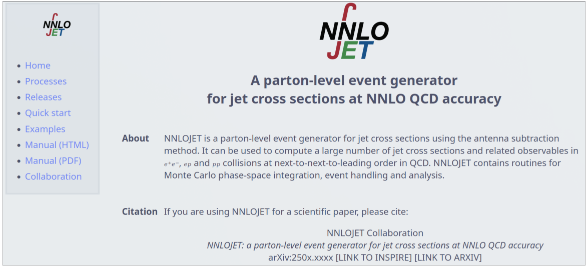

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Thank you!

Backup Slides

Diphoton Production: all ATLAS Event Shapes

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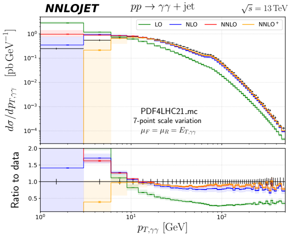

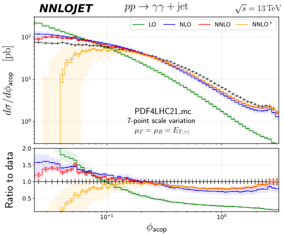

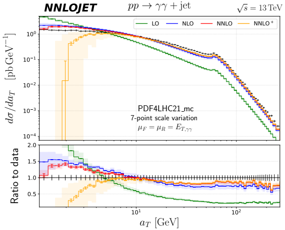

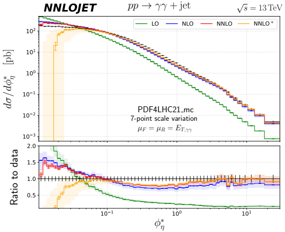

NNLOJET