Diphoton production in gluon fusion: Top quark threshold effects

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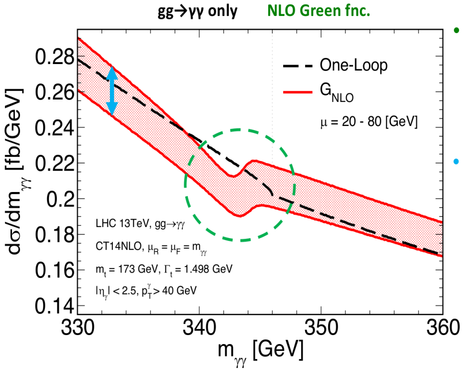
in collaboration with G. Heinrich, S. Jahn, S. Jones, M. Kerner, J. Schlenk, H. Yokoya, based on [$1909.XXXX$]

Being experimentally clean, the diphoton production is very important for phenomenological studies at LHC.

- One of the discovery channels for the Higgs with highest mass sensitivity
- An important place to look for signals from beyond Standard Model physics
- . . . . . .
- Sensitive to the top quark mass m_t around $t\bar{t}$ production threshold [S.Kawabata, H.Yokoya; 17]



Many theoretical works done ...

The "irreducible diphoton background" at LHC:

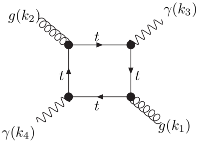
- $q\bar{q} \to \gamma\gamma + X$ of order $\alpha_e^2\,\alpha_s^N$ with $N \geq 0$
  - $\alpha_e^2\,\alpha_s$ order, implemented in **Diphox** [T. Binoth, J. Guillet, E. Pilon, M. Werlen; 00]
  - $\alpha_e^2\,\alpha_s^2$ order, [S. Catani, L. Cieri, D. de Florian, G. Ferrera, M. Grazzini], implemented in **MCFM** [J. Campbell, R. Ellis, Y. Li, C. Williams; 16] and in **MATRIX** [M. Grazzini, S. Kallweit, M. Wiesemann; 18]
  - ......

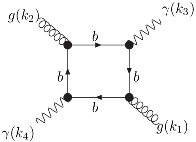
- $gg \to \gamma\gamma + X$ of order $\alpha_e^2\,\alpha_s^{2+N}$ with $N \geq 0$
  - $\alpha_e^2\,\alpha_s^2$ (LO) order, massless + massive quarks [D. Dicus and S. Willenbrock; 88]
  - $\alpha_e^2\,\alpha_s^3$ (NLO) order, massless quarks: [Z. Bern, A. De Freitas, L. Dixon; 01] implemented in $2\gamma MC$ [Z. Bern, L. Dixon, C. Schmidt; 02] , in **MCFM** [J. Campbell, R. Ellis, C. Williams; 11] and also in **MATRIX** [M. Grazzini, S. Kallweit, M. Wiesemann; 18]
  - $\alpha_e^2\,\alpha_s^3$ (NLO) order, massless + massive quarks: [F. Maltoni, M. Mandal, X. Zhao, 18]

(see talk by Xiaoran Zhao)

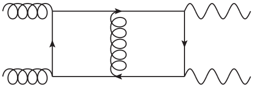
Examples of diagrams involved in the work:

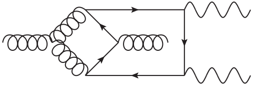
- Born ($\alpha_e^2\, \alpha_s^2$)



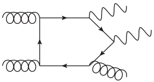


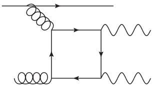
- NLO ($\alpha_e^2\, \alpha_s^3$)
  - Virtual:

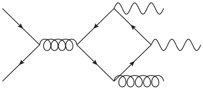




  - Real:







Form Factor Decomposition

- For a scattering amplitude $\hat{\mathcal{M}}$ at a fixed perturbative order,

$$\hat{\mathcal{M}} = \sum_{n=1}^{N} c_n \, \hat{T}_n \, ,$$

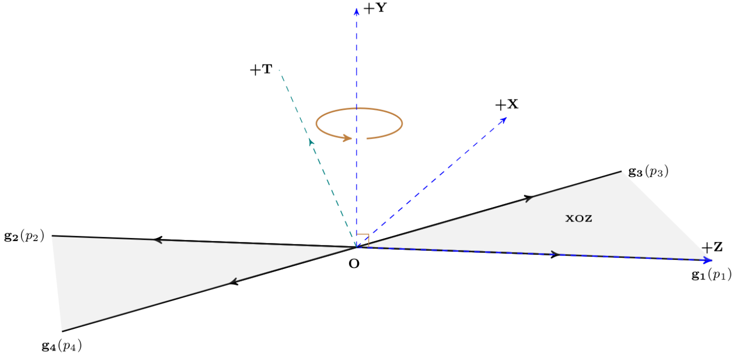
compute the **Gram matrix** $\hat{\mathbf{G}}$

$$\hat{\mathbf{G}}_{ij} = \langle \hat{T}_i^\dagger, \hat{T}_j \rangle \, ,$$

whose inverse gives us the formulae for projectors $\hat{\mathbf{G}}_{ij}^{-1} \, \hat{T}_j^\dagger$ to project out c_n.

- The number of Lorentz tensor structures in $gg \to \gamma\gamma$ amplitudes
  - 137 assuming only P-invariance (and momentum conservation)
  - 57 after imposing transversality condition (i.e. $\varepsilon_i \cdot p_i = 0$)
  - $\mathcal{O}(10)$ imposing additional conditions from choosing a specific gauge (additional constraints on ε_i) **or** Bose-symmetries (kinematic crossings) and Ward-Identities.

Projecting D-dimensional amplitudes directly to the *linear polarization basis*
[**LC**, 19 (arXiv: 1904.00705)] :



Momentum basis representations of elementary linear polarization state vectors:

$$\varepsilon_X^\mu = c_1^X p_1^\mu + c_2^X p_2^\mu + c_3^X p_3^\mu \,,$$
$$\varepsilon_T^\mu = c_1^T p_1^\mu + c_2^T p_2^\mu + c_3^T p_3^\mu \,,$$
$$\varepsilon_Y^\mu = \mathcal{N}_Y \, \epsilon^{\nu\rho\sigma\mu} p_{1\nu} p_{2\rho} p_{3\sigma}.$$

Projectors for linearly polarized amplitudes

- For 2-to-2 P-even scattering of massless gauge bosons, we need only
$$\varepsilon^{\mu}_{[X,Y]}\varepsilon^{\nu}_{[X,Y]}\varepsilon^{\rho}_{[T,Y]}\varepsilon^{\sigma}_{[T,Y]}$$
where all open Lorentz indices are *D-dimensional* by definition and all pairs of $\epsilon^{\nu\rho\sigma\mu}$ should be contracted first (in one definite ordering).

- Upon pulling out the overall normalization factors, all projectors thus constructed have only *polynomial* dependence in kinematics and algebraic constants, and it is always $g_{\mu\nu}$ used in index contraction.

- Resulting polarized amplitudes are different from those defined under CDR, HV, FDH, $\cdots$.

- The usual helicity amplitudes can be constructed optionally, as circular polarization states from the linear ones, e.g.
$$\varepsilon^{\mu}_{\pm}(p_1) = \frac{1}{\sqrt{2}}\left(\varepsilon^{\mu}_{X} \pm i\varepsilon^{\mu}_{Y}\right).$$

Applications to $b\bar{b} \to ZH$ @ 2-loop: $\to$ (talk by T. Ahmed)

Flowchart of our virtual amplitude evaluation

- Unreduced (projected) amplitudes: an extended version of **GoSam**

  [G. Cullen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, G. Ossola, T. Reiter, F. Tramontano; S. Jahn, S. Jones, M. Kerner]

- IBP-tables: **Reduze** [A. von Manteuffel, C. Studerus; 12] and **Kira** [P. Maierhofer, J. Usovitsch; 18]
  - 39 masters in 2-loop massless $gg \to \gamma\gamma$;
  - 162 masters in 2-loop massive $gg \to \gamma\gamma$.

- Simplifying rational coefficients of masters: **mathematica** + **fermat**

  [R. Lewis; 09]

- Rotating to a basis of *finite* master integrals [A. von Manteuffel, E. Panzer, R. Schabinger; 14] suitable for **pySecDec** [S. Borowka, G. Heinrich, S. Jahn, S. Jones, M. Kerner, J. Schlenk; 18]

(see talks by A. von Manteuffel, R. Schabinger, M. Kerner)

- Virtual interference:
  - $\overline{\text{MS}}$ renormalization for α_s with $n_f = 5$ and top-quark loops renormalized on-shell.
  - Reweighting *unweighted* Born events:

$$\sigma_V = \sum_{i=1}^{N} \frac{2\,\text{Re}\left[M_B^\dagger M_V\right]}{|M_B|^2} \frac{\sigma_B}{N}$$

  - Accuracy goal: 1 per-mille for each linearly polarized amplitude. $\sim 6 * 10^3$ points in $[s, t]$-plane collected for doing phenomenology.
- Real radiations:
  - IR subtraction: FKS-scheme [S. Frixione, Z. Kunszt, A. Signer] as implemented in **POWHEG** setup [S. Alioli, S. Frixione, P. Nason, C. Oleari, E. Re]

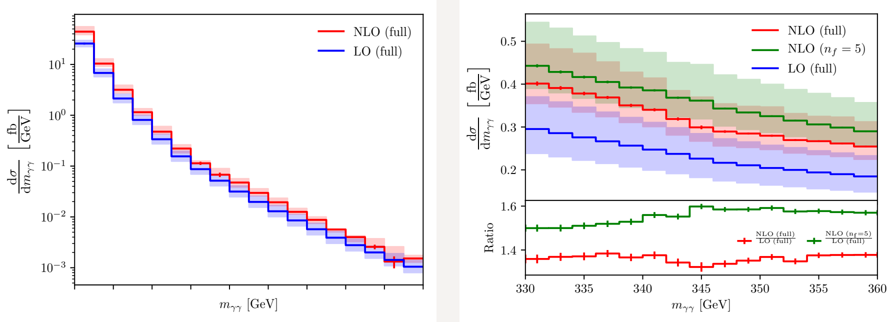
(see talk by M. Kerner)

LHC@13 TeV (PDF4LHC15_nlo_30):

$p_T(\gamma_1) > 40$ GeV, $p_T(\gamma_2) > 20$ GeV, $|\eta_\Gamma| < 2.5$.

Central $\mu_R = \mu_F = \frac{m_{\gamma\gamma}}{2}$ (varied simultaneously)

Preliminary

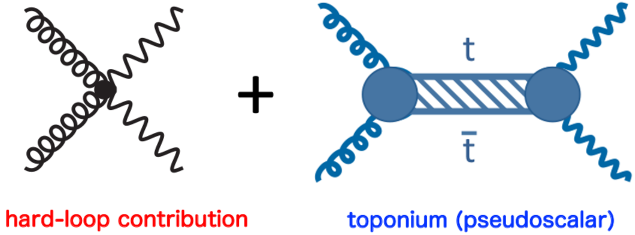


In the **(P)NRQCD**, $gg \to \gamma\gamma$ amplitude with $\beta \ll 1$ [K. Melnikov, M. Spira, O. Yakovlev; 94]

$$\mathcal{M}_t = \mathcal{A}_t(\theta) + \mathcal{B}_t(\theta, \beta)\, G(0; \mathcal{E}) + \cdots$$

(where $\mathcal{E} = E + i\Gamma_t$).

[figure by H.Yokoya]



The $G(0; \mathcal{E}, \mu)$ is defined through

$$\left(-\frac{\nabla^2}{m_t} + V(r, \mu) - \mathcal{E} \right) G(r; \mathcal{E}, \mu) = \delta(\vec{r}) \, .$$

At the amplitude level,

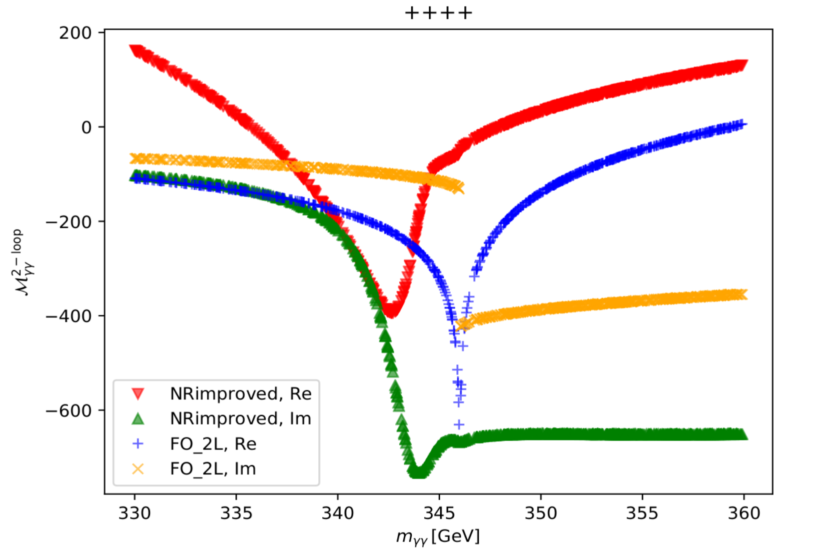
$$\mathcal{M}_t = \mathcal{A}_t(\theta) + \mathcal{B}_t(\theta,\beta)\, G(0;\mathcal{E}) + \cdots$$
$$\Downarrow$$
$$\mathcal{M}_t^{match} \equiv \left(M_t^{FO} - M_t^{OC}\right) + \mathcal{B}_t(\theta,\beta)\, G(0;\mathcal{E}) + \cdots$$

where $M_t^{OC} \equiv \mathcal{B}_t(\theta,\beta)\, G(0;E)|_{FO}$

At the level of cross sections, schematically we **use**

$$\sigma \sim \int \mathrm{PDF}(\mu_F) \otimes \alpha_e^2\, \alpha_s^2(\mu_R) \left(\left| \mathcal{M}_B + \mathcal{B}_t(\mu)\, G(0;\mathcal{E},\mu) - M_{t,LO}^{OC} \right|^2 \right.$$
$$+ \alpha_s(\mu_R)\, 2\mathrm{Re}\left[\mathcal{M}_B^\dagger \left(\mathcal{M}_V(\mu_R) - M_{t,NLO}^{OC}(\mu) \right) \right]$$
$$\left. + \alpha_s(\mu_R) \left| \mathcal{M}_R \right|^2 + \alpha_s(\mu_R)\, C.T._{IC}(\mu_F) \right)$$

An example of IR-subtracted $\mathcal{M}_t^{match}$: ($\log[\beta]$ only at 2-loop)



Our remake of the "LO-matched" diphoton spectrum [S. Kawabata, H. Yokoya; 17]

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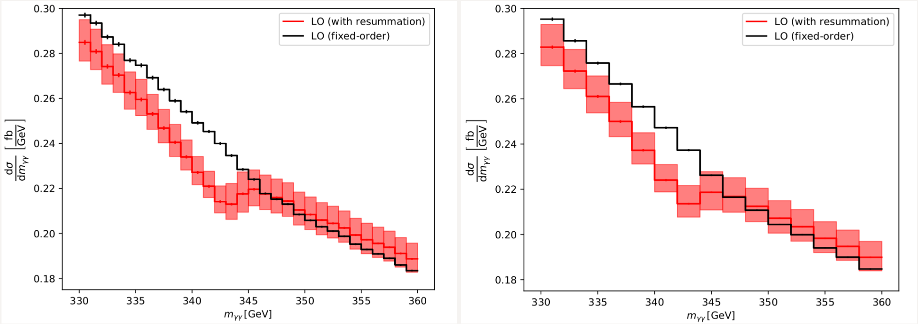
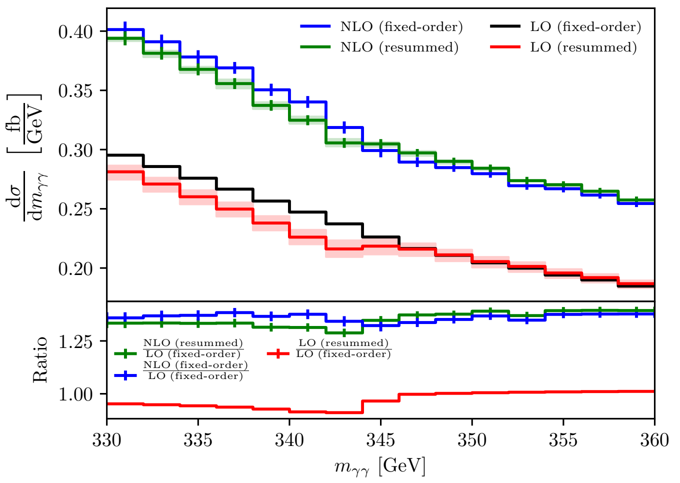
Central $\mu_R = \mu_F = \frac{m_{\gamma\gamma}}{2}$ and $\mu = 80$ GeV; Scale-band $\mu \in [40, 160]$ GeV.



(0.5 GeV bins) (2 GeV bins)

NLO-matched diphoton spectrum

Preliminary



Summary and Outlook

- ☑ An independent computation of $gg \to \gamma\gamma$ at order $\alpha_e^2 \alpha_s^3$ at LHC including top quark is done, using different methodology (e.g. *linear polarization projectors* and pySecDec).

- ☑ This process has been implemented in the POWHEG setup to facilitate future analysis.

- ☑ An improved description of $\gamma\gamma$ production around the $t\bar{t}$ threshold is achieved via combining the full NLO result with (P)NRQCD threshold resummation. A significant reduction in the dependence on μ of the (P)NRQCD Green function is observed compared to the previous computation.

- ☒ Investigating variations under different top quark pole mass values and trying out different top-quark schemes

- ☒ Making predictions for future hadron colliders (such as FCC @ 100 TeV) with more realistic experimental cuts (e.g. with photon-isolation cuts)

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THANK YOU