Talk @INFN Welcome day

Federico Ripani

PostDoc @Dipartimento di Fisica, Torino 10/24-09/26

PhD in Rome 11/21-09/24, supervisor: R. Bonciani

Cavoretto (TO), 03/11/2024

Iniziativa Specifica: Amplitudes

analytic structure, loop methods and pertubative gravity

LNF (Del Duca, RN)
TO (Badger)
NA (Tramontano)
BO (Peraro)
PA (Mastrolia)
FI (Bonciani)

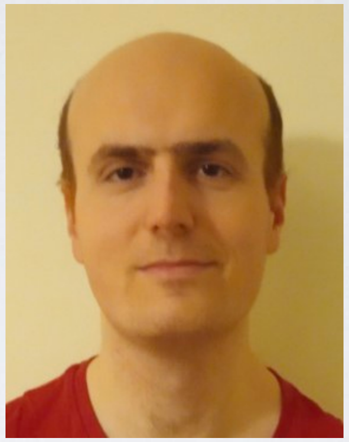
"**Modern amplitude methods** have made a huge impact on our **understanding of quantum field theory** and our ability to make precise predictions for physical observables. Their remarkable **mathematical structure** has led to new results in an enormous range of subjects from gravitational waves, condensed matter systems and collider experiments.

Our team members have contributed to cutting-edge computations of amplitudes, and our aim is to keep INFN to the forefront of amplitude evaluations both for **collider** and for **gravitational-wave observables**."

Amplitudes in Torino

Simon Badger

PD (**FARE2020**):
Colomba Brancaccio
(PhD, Aachen)
10/23 - 09/26



F (**MCSA global, Zurich**)
Guilo Falcioni
10/24 - 9/27

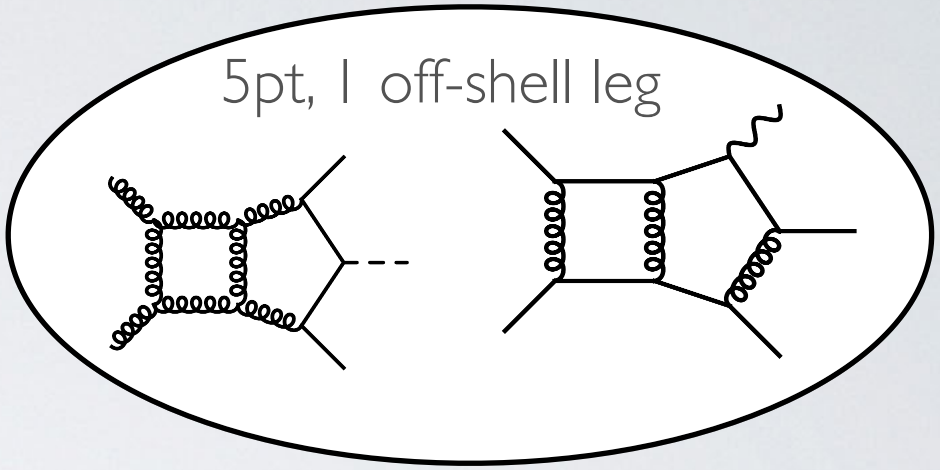
↓

RTT Torino

PD (**FARE2020**):
Federico Ripani
10/24 - 09/26

PhD
(sup. Badger/Torrielli)
Yashsvee Goel
11/24 - 10/27

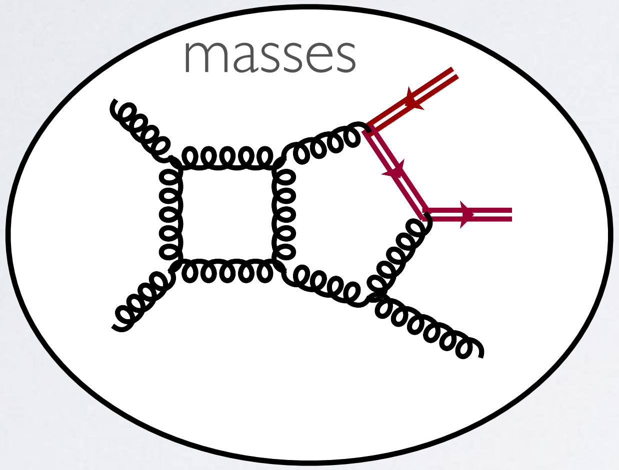
Recent projects



first **full colour** amplitudes

pp→Wγγ arXiv:2409.08146

pp→Hbb arXiv:24xx.xxxxx



pp→ttj leading colour integral basis

JHEP 07 (2024) 066

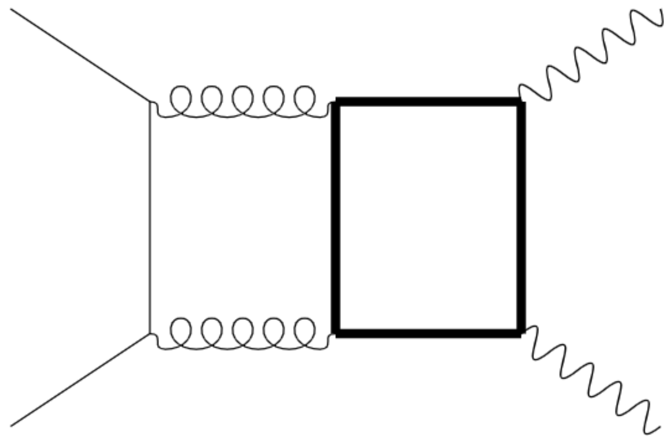
pp→ttj leading colour amplitudes

first numerical evaluations coming soon:
(see Brancaccio talk at TOP24)

Project of my PhD: top quark contribution to diphoton @NNLO

Phys. Lett. B 848 (2024) 138362 and *J. High Energ. Phys.* ***2023****, 105 (2023)*

In collaboration with: M. Becchetti, R. Bonciani, L. Cieri and F. Coro



Outline

- Motivation for diphoton and state of the art
- Two-loop Amplitude with a top-quark loop
- Phenomenology

Motivation

- Diphoton production, $pp \to \gamma\gamma + X$ is a probe for the SM, and check of the validity of pQCD

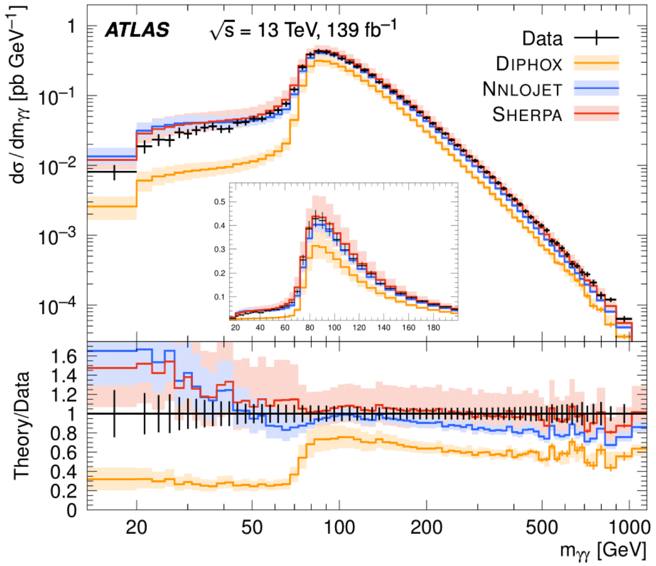
- It is an important channel for studies of the Higgs boson. In diphoton channel the signal is O(0.2%) of the background, which requires accurate theoretical prediction.

- Searches for New Physics (pair-produced Higgsinos that decay to LLPs, axion-like particles with masses between 10 and 70 GeV, supersymmetry, spin-0 and spin-2 resonances with masses between 0.5 and 4.5 TeV)

- Possible alternative channel for measuring top quark mass

[Kawabat, Yokoya '17; Dugad, Jain, Mitra, Sanyal, Verma '18]

- Interesting framework to evaluate massive corrections at NNLO



[ATLAS (2017) arXiv:2107.09330]

State of the art

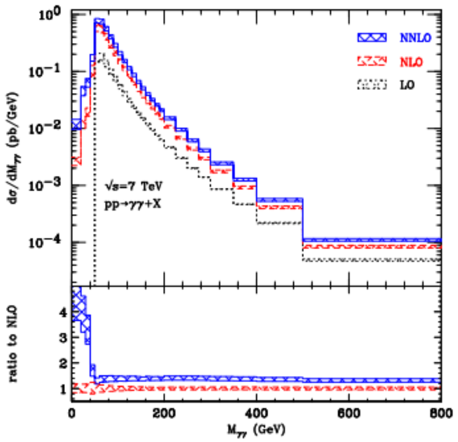
- NNLO QCD corrections with five light quark flavours

  [Catani, Cieri, de Florian, Ferrera, Grazzini '12 '18]

  [Campbell, Ellis, Li, Williams '16]

  [Chen, Gehrmann, Glover, Höfer, Huss, Schürmann '22]

  Enhance the NLO prediction of 40% for $M_{\gamma\gamma} > 50$ GeV



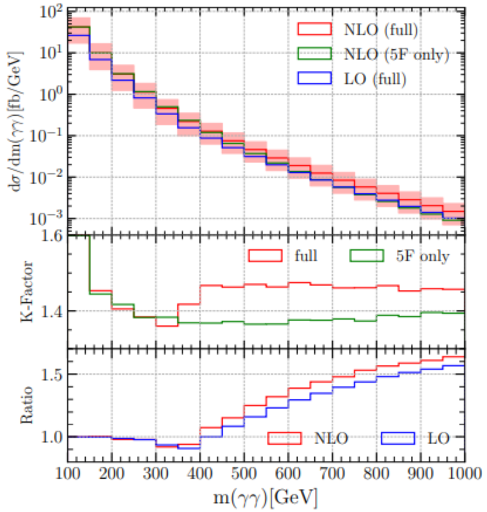
[Catani, Cieri, de Florian, Ferrera, Grazzini '18]

- Necessary scattering amplitude elements for N3LO analysis (massless case)
  - Two-Loop Amplitudes for Gluon Fusion into Two Photons — [Bern, De Freitas, Dixon '01]
  - Three-loop helicity amplitudes for quark-gluon scattering in QCD — [Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi '22]
  - Two-Loop Helicity Amplitudes for Diphoton Plus Jet Production in Full Color — [Agarwal, Buccioni, von Manteuffel, Tancredi '21]
  - NNLO QCD corrections to diphoton production with an additional jet at the LHC — [Chawdhry, Czakon, Mitov, Poncelet '21]
  - Next-to-leading order QCD corrections to diphoton-plus-jet production through gluon fusion at the LHC — [Badger, Gehrmann, Marcoli, Moodie '22]

State of the art

- **First-order Electroweak\QED corrections**
  - Next-to-leading order electroweak corrections to the production of a photon pair in association with zero, one and two jets at the LHC [Chiesa, Greiner, Schonherr, Tramontano '17]
  - NLO QED Effects to Diphoton Production at Hadron Colliders [Cieri, Sborlini '21]
- **Transverse-momentum resummation**
  - NNLL+NLO accuracy [Cieri, Coradeschi, de Florian '15]
  - N3LL+NNLO accuracy [Becher, Neumann '20]

Effective NLO top-quark correction to gluon fusion channel enhances the NLO massless prediction of 7% for $M_{\gamma\gamma} > 400$ GeV

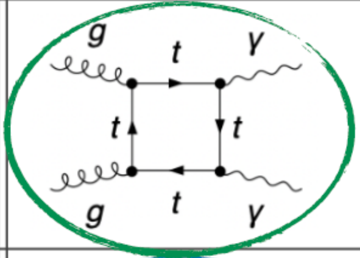
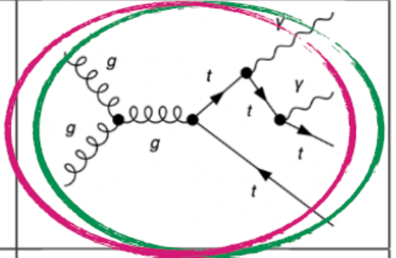
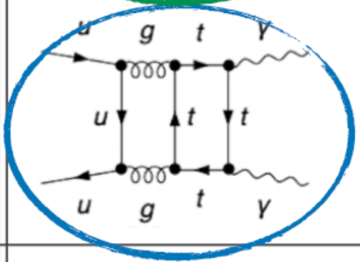
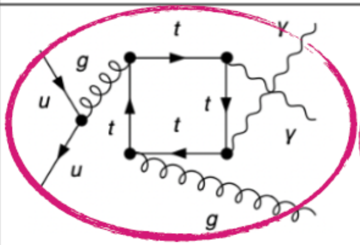
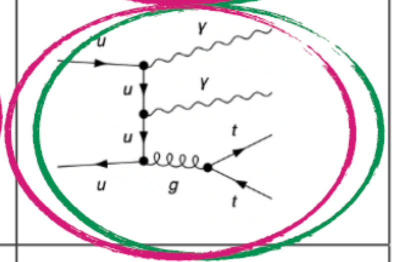
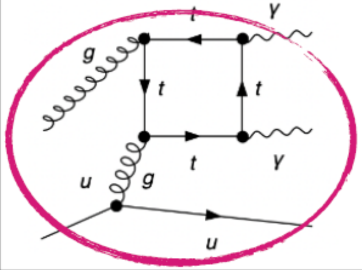


[Maltoni, Mandal, Zhao '18]

- **Massive QCD contributions**
  - One-loop $gg \to \gamma\gamma$ scattering amplitude with the top quark mass dependence (formally NNLO) [Campbell, Ellis, Li, Williams '16]
  - Top-quark effects in diphoton production through gluon fusion at NLO in QCD. They are formally part of N3LO, but of the order of NNLO because of the luminosity of the gluon. [Maltoni, Mandal, Zhao '18] [Chen, Heinrich, Jahn, Jones, Kerner, Schlenk, Yokoya '20]
  - Full top-quark mass dependence in diphoton production at NNLO in QCD [Becchetti, Bonciani, Cieri, Coro, Ripani '23]

Massive contributions @ NNLO

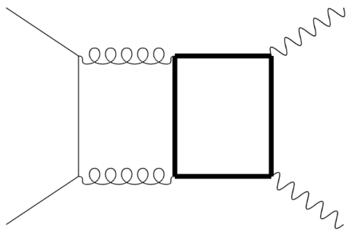
Massive corrections $\mathcal{O}(\alpha_s^2)$

Channels	$\gamma\gamma$	$\gamma\gamma j$	$\gamma\gamma jj$
gg			
$q\bar{q}$			
qg			

- Two-loop contribution
- One-loop box contribution
- Real-Virtual contribution
- Double-Real contribution

Two-loop Amplitude with a top-quark loop

Computation of the Amplitude



Generation of Feynman diagrams (**QGRAF** or **FeynArts)**

[Nogueira] [Hahn]

Amplitude= rational coefficients X Feynman Integrals

(O(10^5) Integrals)

IBP reduction [Laporta]

- Huge linear system to solve
- Bottleneck
- FiniteFlow, Kira, Reduze, FIRE,...

[Klappert, Lange, Maierhöfer, Usovitsch '21] [Manteuffel, Studerus '12] [Peraro] [Smirnov, Chukarev '19]

(for our case Kira)

Amplitude= rational coefficients X **Master Integrals**

(O(10^2) Integrals, in our case 63)

Epsilon expansion

UV renormalization and **IR** subtraction

[Catani]

(in our case only UV poles)

Finite remainder

FINAL RESULT

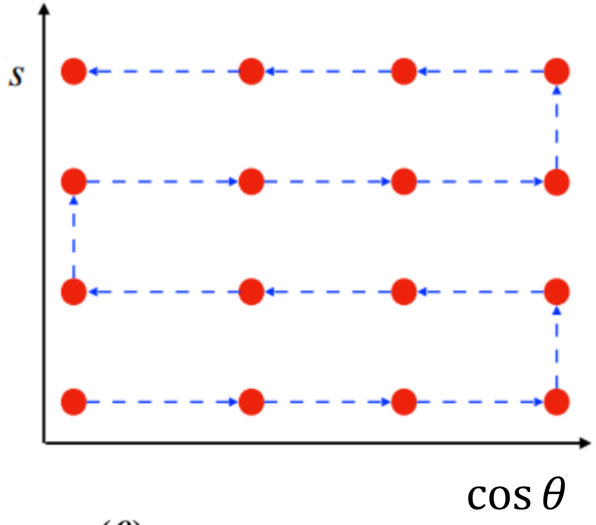
Solution to Master Integrals

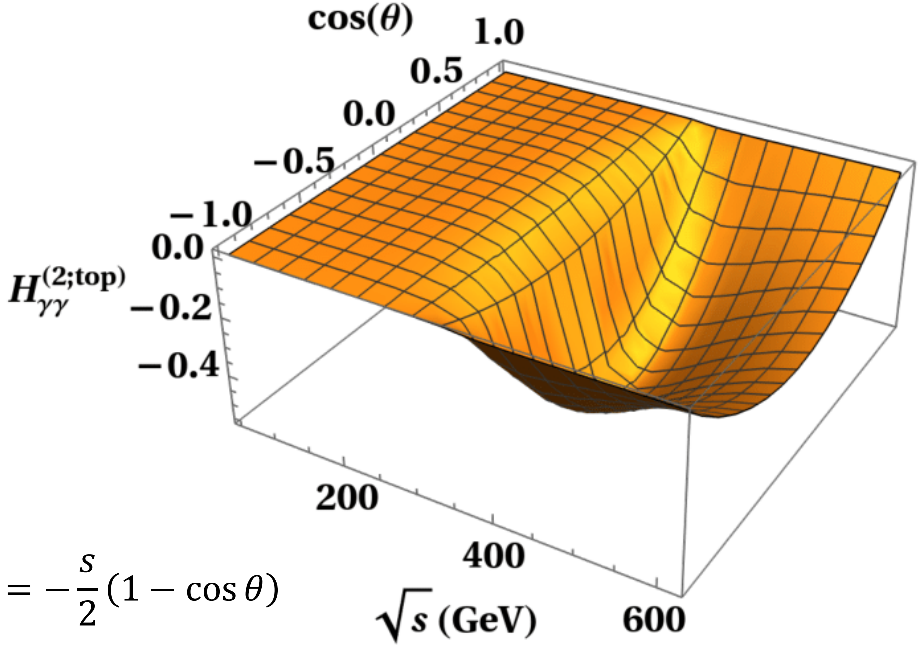
- ***analytical*** or **numerical**
- Masses introduce complex mathematical structures
- Bottleneck

(in our case semi-analytical, i.e. generalised power series expansions)

Hard function and Numerical Evaluation

- We built a grid which covers the space defined by the centre-of-mass energy and the scattering angle
- The entire grid is evaluated in O(13h) on a single core laptop (13752 points from 8 GeV to 2.2 TeV)
- The grid is interpolated with cubic splines which allow fast numerical evaluations
- The interpolation introduces an error of O(0.3%)





$$|\mathcal{M}^{(\text{fin})}_{q\bar{q},\gamma\gamma}|^2 = |\mathcal{M}^{(0)}_{q\bar{q},\gamma\gamma}|^2 \left(1 + \left(\frac{\alpha_s}{\pi}\right)\mathcal{H}^{(1)}_{\gamma\gamma} + \left(\frac{\alpha_s}{\pi}\right)^2 \left(\mathcal{H}^{(2;\text{top})}_{\gamma\gamma} + \mathcal{H}^{(2;5\text{f})}_{\gamma\gamma}\right) + \cdots\right)$$

$$t = -\frac{s}{2}(1 - \cos\theta)$$

Phenomenology

Setup

- Massive corrections encoded in new version of 2γNNLO

[Catani, Cieri, de Florian, Ferrera, Grazzini '16]

- NNLO cross section in qT subtraction scheme:

$$d\sigma^{\gamma\gamma}_{\rm NNLO} = \mathcal{H}^{\gamma\gamma}_{\rm NNLO} \otimes d\sigma^{\gamma\gamma}_{\rm LO} + \left[d\sigma^{\gamma\gamma+{\rm jets}}_{\rm NLO} - d\sigma^{CT}_{\rm NLO}\right]$$

[Catani, Grazzini '07]

Kinematical parameters

- $\sqrt{s}$ =13 TeV
- Photon transverse momentum:

  $p_{T_\gamma}^{hard} \geq 40$ GeV $p_{T_\gamma}^{soft} \geq 30$ GeV
- Photon rapidity:

  $|y_\gamma| < 2.37$ excluding $1.37 < |y_\gamma| < 1.52$

Smooth isolation cone parameters

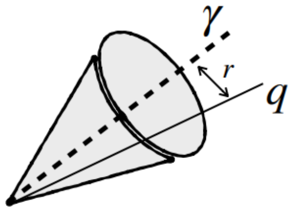
$$E_T^{had}(r) \leq \epsilon p_{T_\gamma} \chi(r; R)$$

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

$R = 0.4$

$\epsilon = 0.09$

$n = 1$

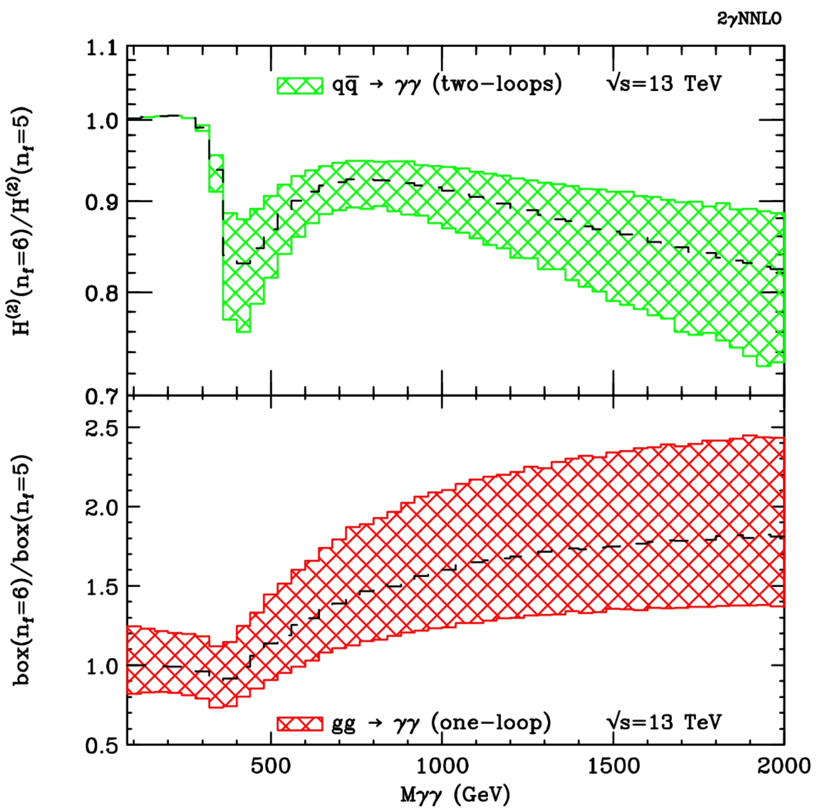


Scale choice

- Central value:

  $\mu_F = \mu_R = M_{\gamma\gamma}$
- Theoretical uncertainty: seven-point variation scale by factors {1/2,2}

Double-Virtual contributions



Upper Panel: ratio between fully massive and massless two-loop correction.
Smaller than massless 5 flavour two-loop correction in the whole invariant mass range

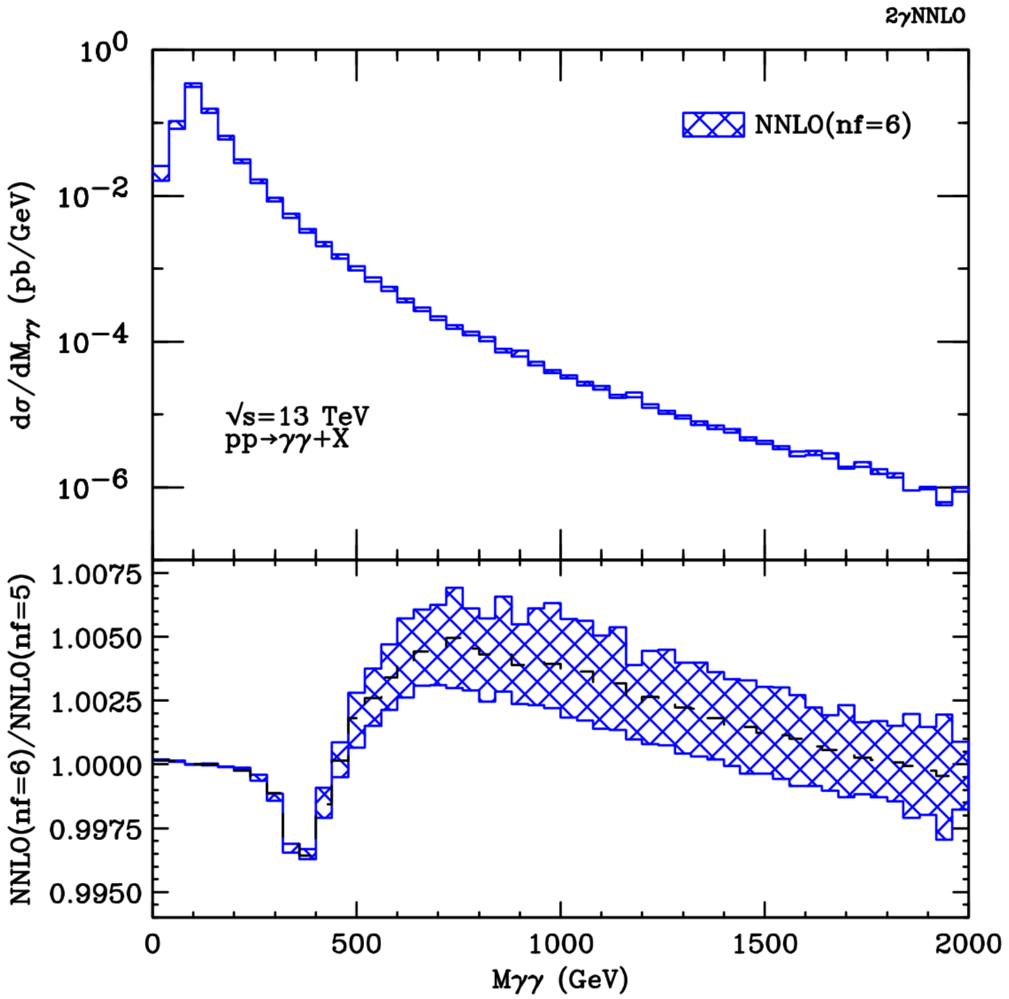
Lower Panel: ratio between fully massive and massless one-loop box.
The asymptotic behaviour as a 6 light quark contribution is manifest:

$$\left(\sum_{n_f=6} e_q^2\right)^2 \Big/ \left(\sum_{n_f=5} e_q^2\right)^2 = 225/121 = 1.8595\ldots$$

The mass inhibits the effect of a 6th massless flavour below the top-quark threshold

Two top produced on-shell enhance the cross-section + Destructive interference between massive and massless → Both have a negative peak of size -15% around the top-quark threshold

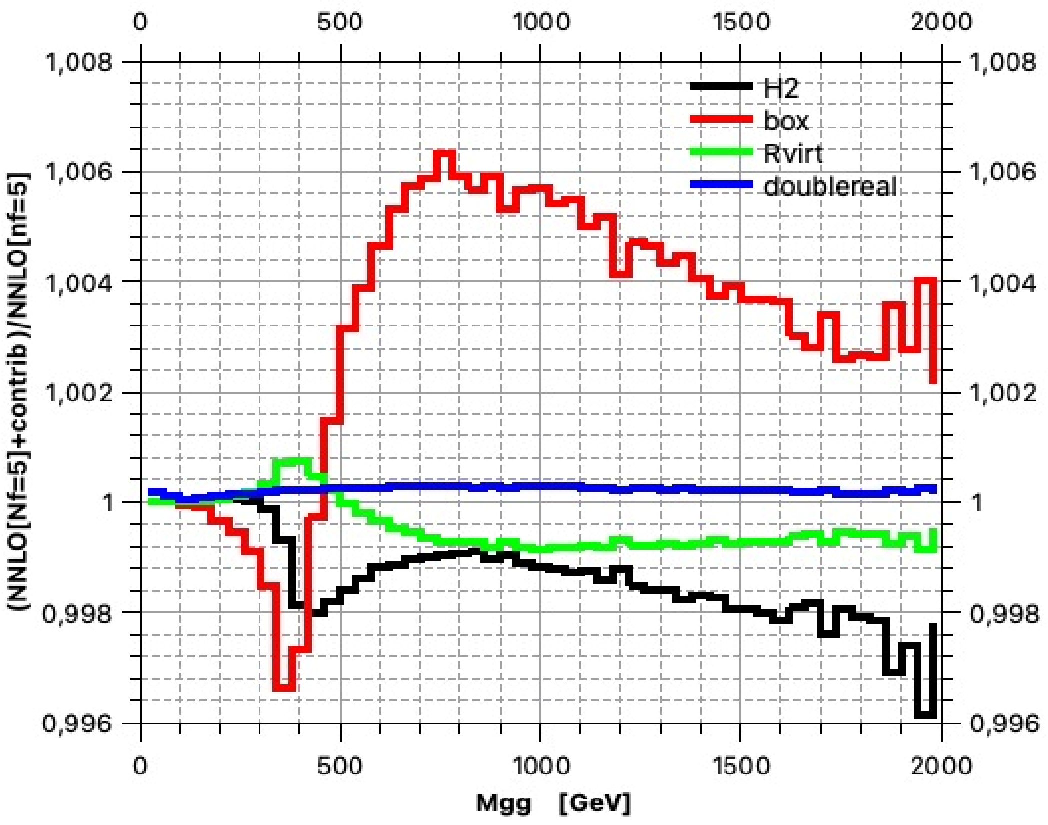
NNLO invariant mass distribution



- Lower Panel: ratio between fully massive and massless 5 flavour NNLO invariant mass distribution
- There is a negative peak around twice the top-quark mass
- Effect of massive corrections: deviation from 5 flavour massless prediction in the range [-0.4%,0.8%]

Summary of massive contributions

Ratios of each massive contribution with respect to massless NNLO invariant mass distribution



- Double-Virtual dominant massive contributions:
  - The box determines a positive contribution with a maximum around 2.3 times top-quark threshold
  - At high invariant mass there is a tension between positive one-loop box and negative two-loop quark annihilation channel
- Real-Virtual contribution subdominant
- Double-Real contribution not relevant for phenomenology

Conclusions

- Relevance of Amplitudes:
  - Fundamental ingredients to make precise predictions for physical observables
  - Are a portal to study the mathematical structure of the microscopic world
- Diphoton:
  - We computed the two-loop amplitude with a loop of top quark
  - We used the result to compute the cross section for diphoton production retaining the full top-quark mass dependence at NNLO in QCD
- Some future projects:
  - 5 pt, 1 off-shell leg amplitudes (e+e-→4j, pp→Hjj,...)
  - pp→ttj leading colour amplitudes (analytical reconstruction)
  - Mixed QCD-Electroweak corrections to pp→Hj and pp→γγ

Thank you for your attention!