Massive diphoton production at NNLO

Federico Coro - ICHEP 2024

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J. High Energ. Phys. 2023, 105 (2023)
Ongoing work

Outline of the talk

- Introduction
- Two-loop form factors
- MIs evaluation
- Phenomenological results
- Conclusions

Motivations

- Diphoton is an experimentally clean final state
- QCD background for Higgs
- Important to measure the fundamental parameters within the Standard Model
- Search for new physics

State of the art

- Massless NNLO QCD accuracy (5lf)

  [S.Catani,L.Cieri,D.de Florian,G.Ferrera,M.Grazzini]

  [J.M.Campbell,R.K.Ellis,Y.Li,C.Williams]

  [R.Schuermann,X.Chen,T.Gehrmann,E.W.N.Glover,M.Höfer,A.Huss]

- Elements for N^3LO

  [Z.Bern,A.De Freitas,L.J.Dixon]

  [F.Caola,A.Chakraborty,G.Gambuti,A.Von Manteuffel,L.Tancredi]

  [H.A.Chawdhry,M.Czakon,A.Mitov,R.Poncelet]

  [B.Agarwal,F.Buccioni,A.Von Manteuffel,L.Tancredi]

  [S.Badger,T.Gehrmann,M.Marcoli,R.Moodie]

- First order EW/QED

  [M.Chiesa,N.Greiner,M.Schönherr,F.Tramontano]

  [L.Cieri,G.Sborlini]

- Mass effect for $gg \to \gamma\gamma$

  [F.Maltoni,M.K.Mandal,X.Zhao]

Massive Corrections

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

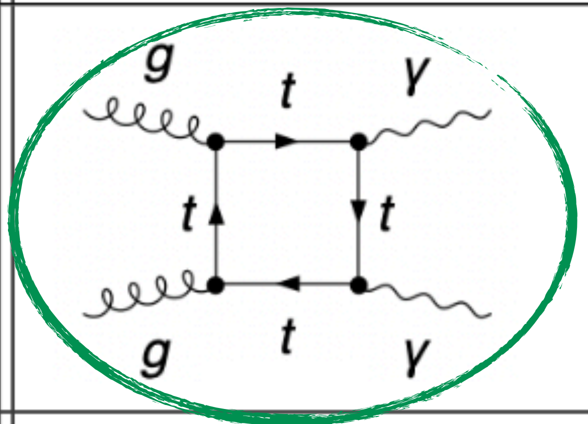
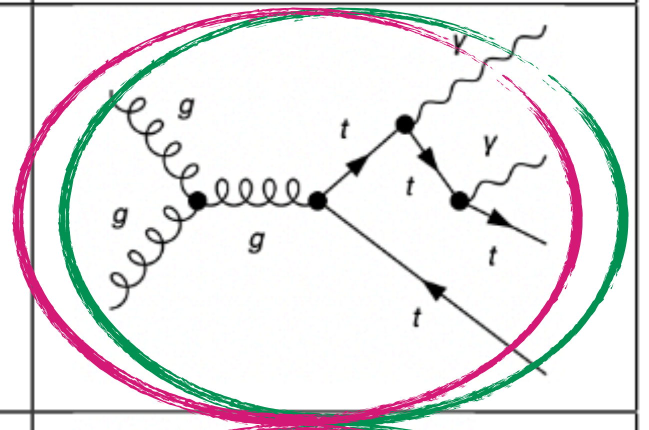
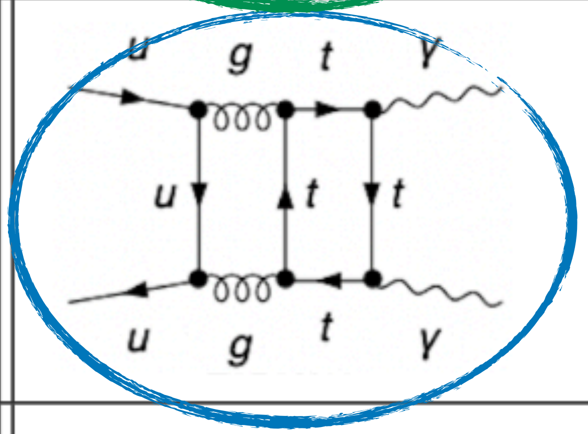
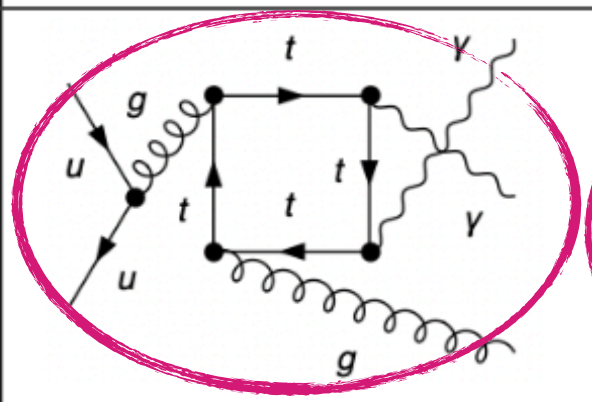
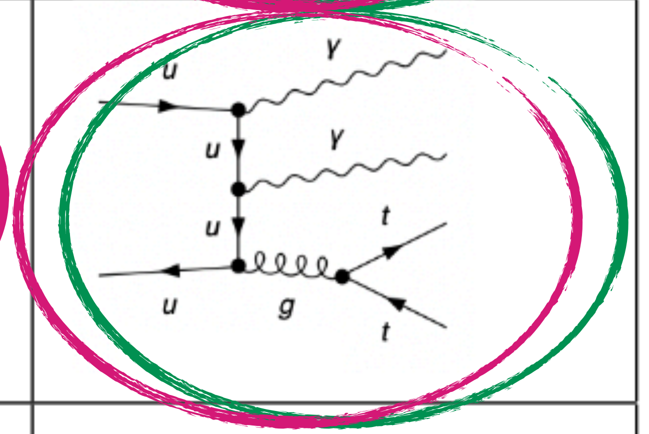
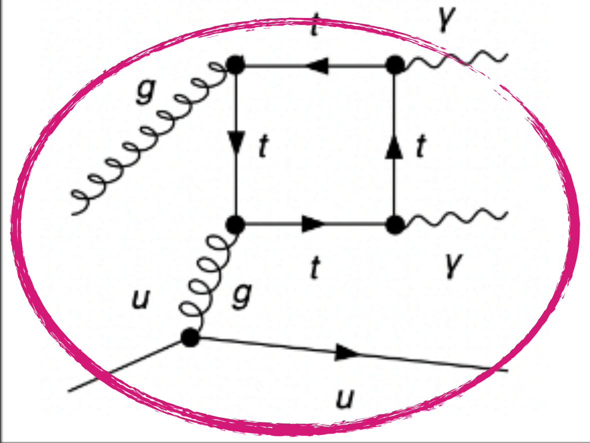
Channels	$\gamma\gamma$	$\gamma\gamma j$	$\gamma\gamma jj$
gg			
$q\bar{q}$			
qg			

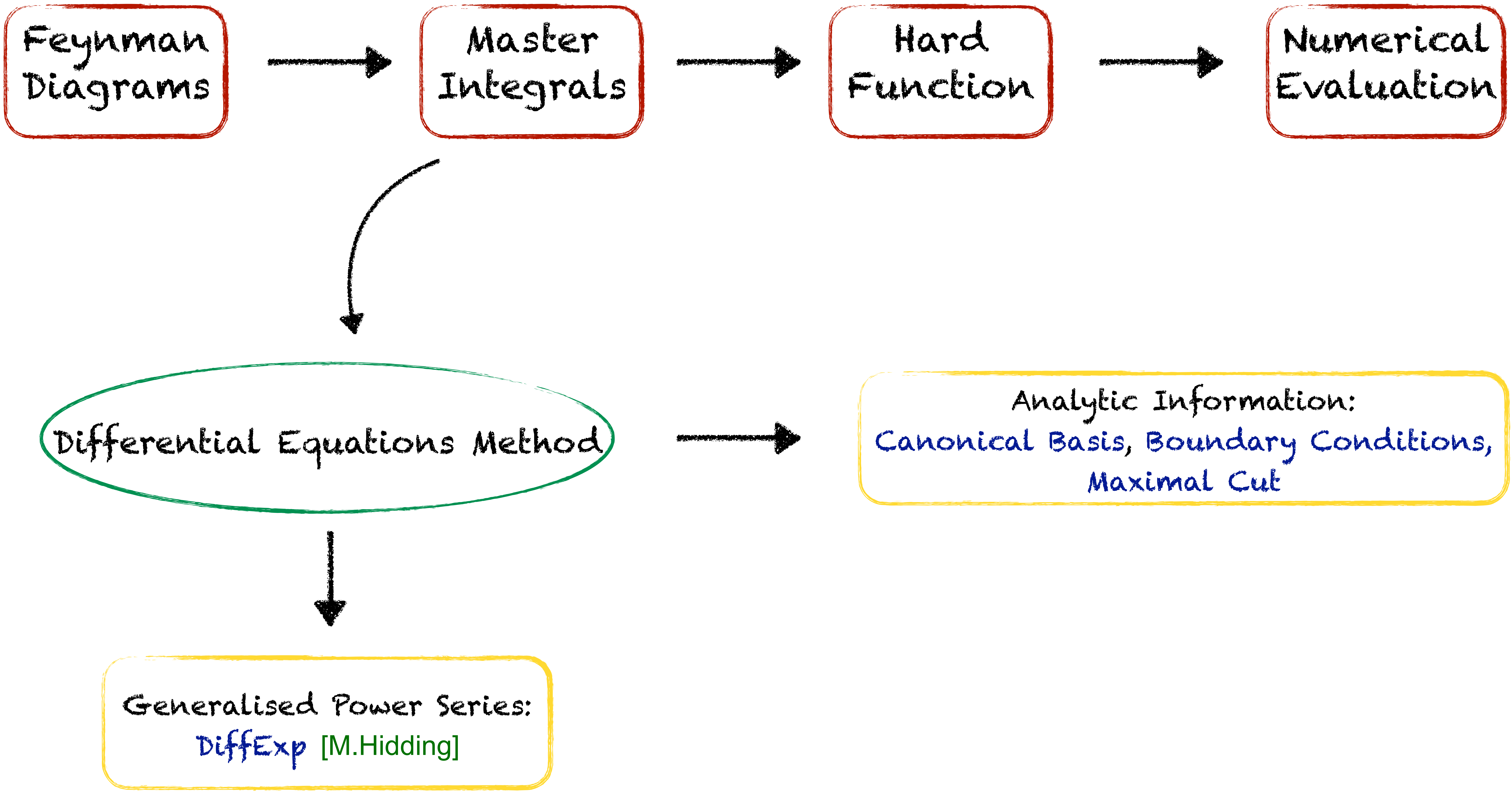
Diagram — [J.M.Campbell,R.K.Ellis,Y.Li,C.Williams]

[F.Buccioni,J-N.Lang,J.M.Lindert,P.Maierhofer, S.Pozzorini,H.Zhang,M.Zoller]

Diagrams — Original results and main focus of the talk

Diagrams — Evaluated for the final result

Computational pipeline



Form factors

The bare scattering amplitude $$\mathscr{A}_{q\bar{q},\gamma\gamma} = \alpha_{em}\delta_{ij}\epsilon^{*\mu}_{\lambda_3}(p_3)\epsilon^{*\nu}_{\lambda_4}(p_4)\bar{v}_{s_2}(p_2)\mathscr{A}_{\mu\nu}(s,t,u,m_t^2)u_{s_1}(p_1)$$

Can be decomposed in terms of a set of four independent tensors $$\mathscr{A}_{q\bar{q},\gamma\gamma}(s,t,m_t^2) = \sum_{i=1}^{4} \mathscr{F}_i(s,t,m_t^2)\bar{v}(p2)\Gamma_i^{\mu\nu}u(p_1)\epsilon_{3,\mu}\epsilon_{4,\nu}$$

$$\Gamma_1^{\mu\nu} = \gamma^\mu p_2^\nu,\ \Gamma_2^{\mu\nu} = \gamma^\nu p_1^\mu,\ \Gamma_3^{\mu\nu} = p_{3,\rho}\gamma^\rho p_1^\mu p_2^\nu,\ \Gamma_4^{\mu\nu} = p_{3,\rho}\gamma^\rho g^{\mu\nu}$$

[F.Caola,A.Von Manteuffel,L.Tancredi]

The form factors admits a perturbative expansion in α_s $$\mathscr{F}_k = \mathscr{F}_k^{(0)} + \left(\frac{\alpha_s^B}{\pi}\right)\mathscr{F}_k^{(1)} + \left(\frac{\alpha_s^B}{\pi}\right)^2\mathscr{F}_k^{(2)} + \cdots$$

Massive contribution appears at $\mathscr{O}(\alpha_s^2)$ $$\mathscr{F}_k^{(2)} = \delta_{ij}C_F(4\pi\alpha_{em})\left[Q_q^2\mathscr{F}^{(2)}_{k,top;0} + Q_t^2\mathscr{F}^{(2)}_{k,top;2}\right]$$

Q_q is the charge of light quark

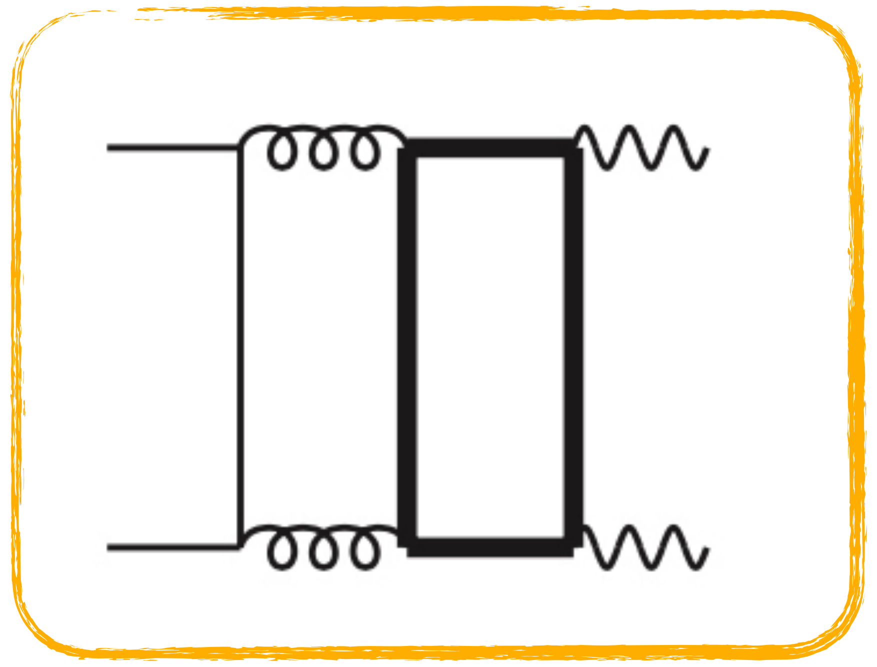
Q_t is the charge of heavy quark

Two-loop Feynman diagrams

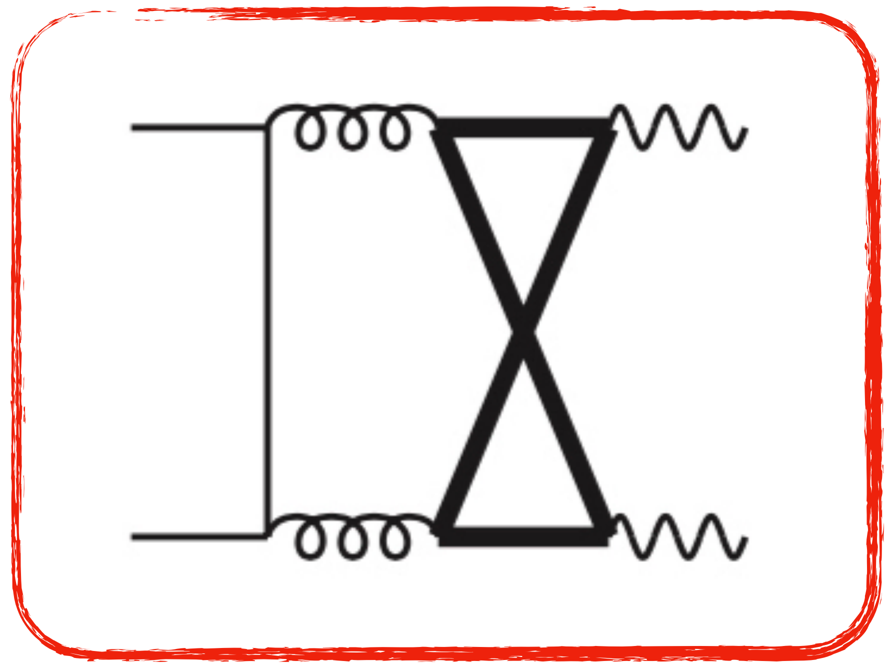
At partonic level the scattering process is: $q(p_1) + \bar{q}(p_2) \to \gamma(p_3) + \gamma(p_4)$

External particles on-shell and the top quark running in the loop

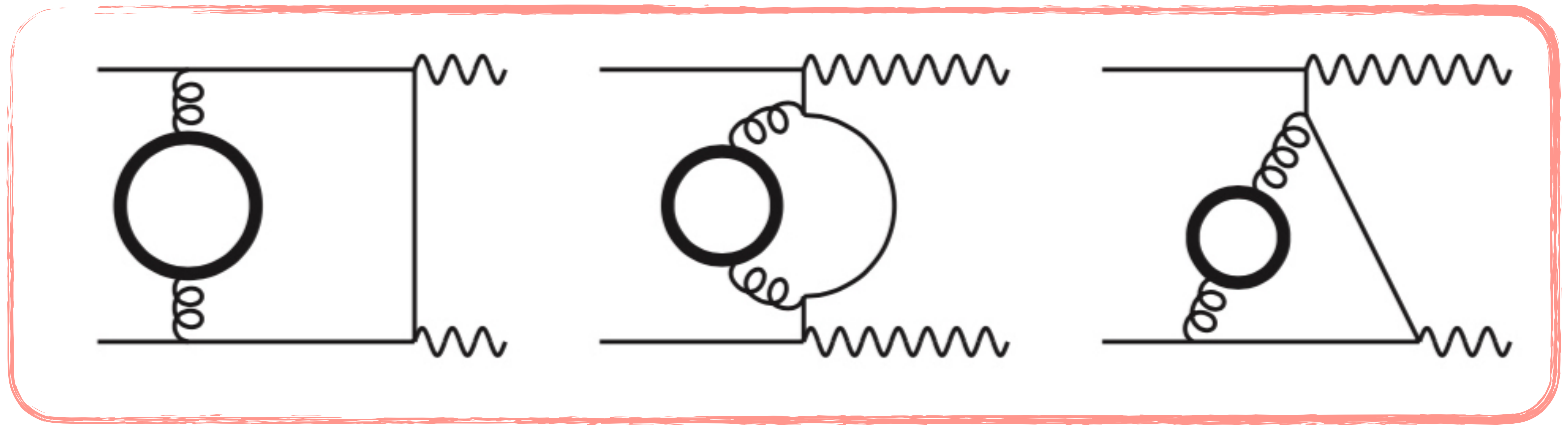
Feynman diagrams generated with **QGRAF** [P. Nogueira] and **FeynArts** [T.Hahn]



PLA



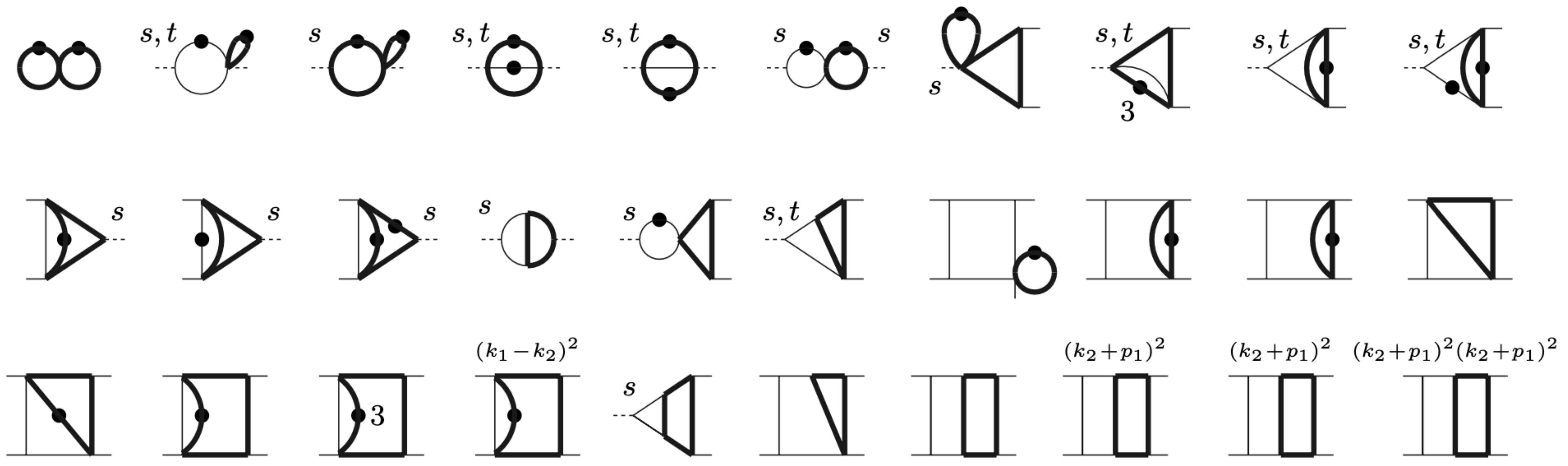
NPL



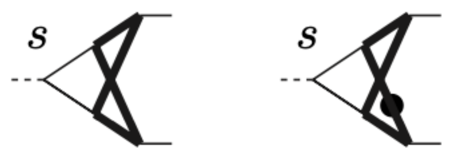
PLB

Master Integrals

PLA and PLB Master Integrals

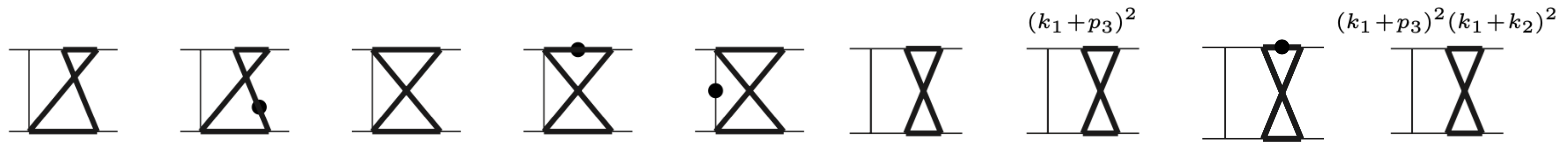


[M.Becchetti,R.Bonciani]



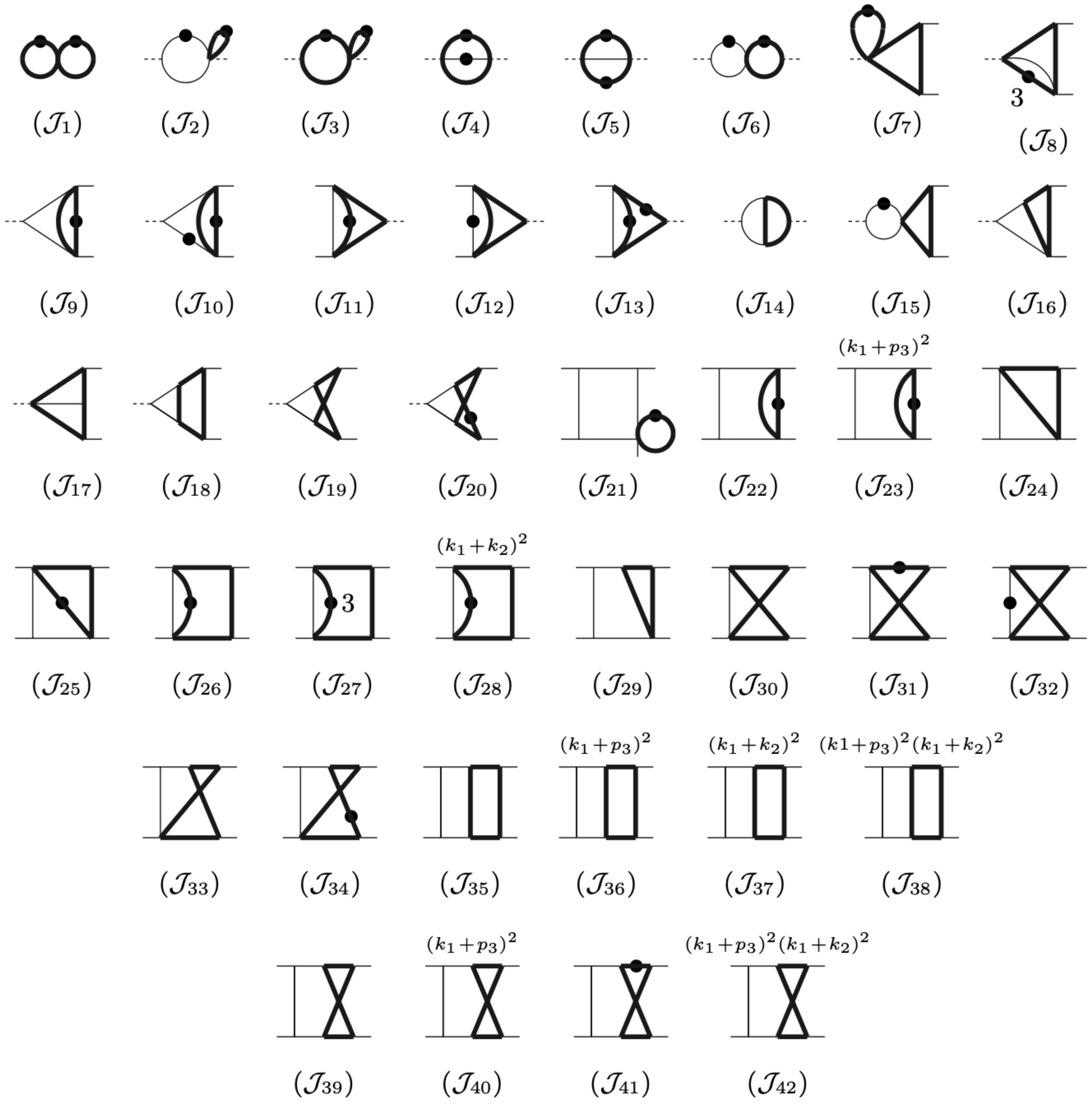
[A.Von Manteuffel,L.Tancredi]

NPL Master Integrals



Original MIs

Master Integrals



Now we have 42 MIs for all the process!

Evaluation of the MIs - PLA family:

The MIs are computed through the differential equations method:

$$df(\underline{x},\epsilon) = \epsilon dA(\underline{x})f(\underline{x},\epsilon)$$

Canonical logarithmic form [J.M.Henn]

with respect to the kinematic invariants: $\underline{x} = \{y, z\}, \quad y = \frac{s}{m_t^2}, \quad z = \frac{t}{m_t^2}$

Boundary Conditions: $\underline{x} = 0$

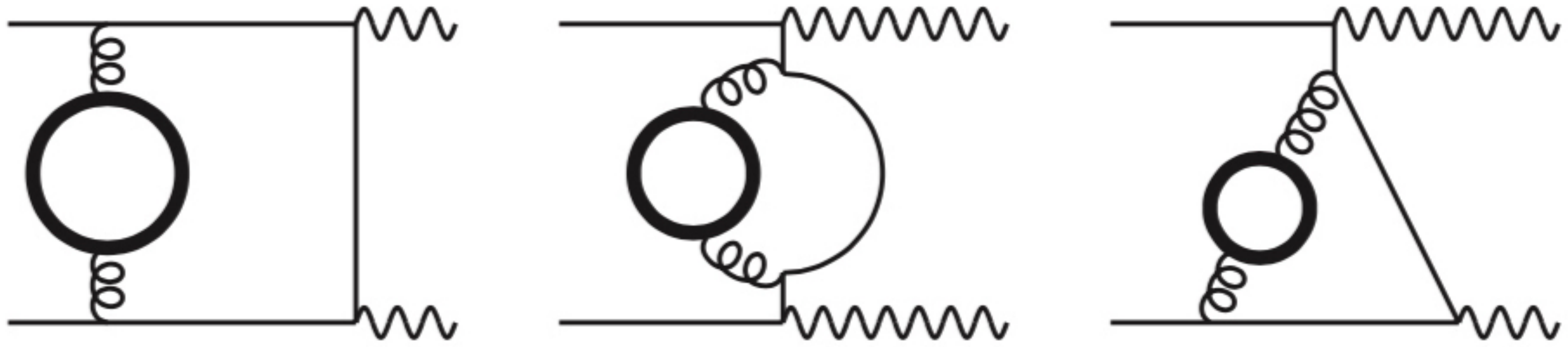
$$A(\underline{x}) = \sum c_i log(w_i(\underline{x}))$$

$W_{PLA} = \{w_i(\underline{x})\}$ → Set of 21 letters

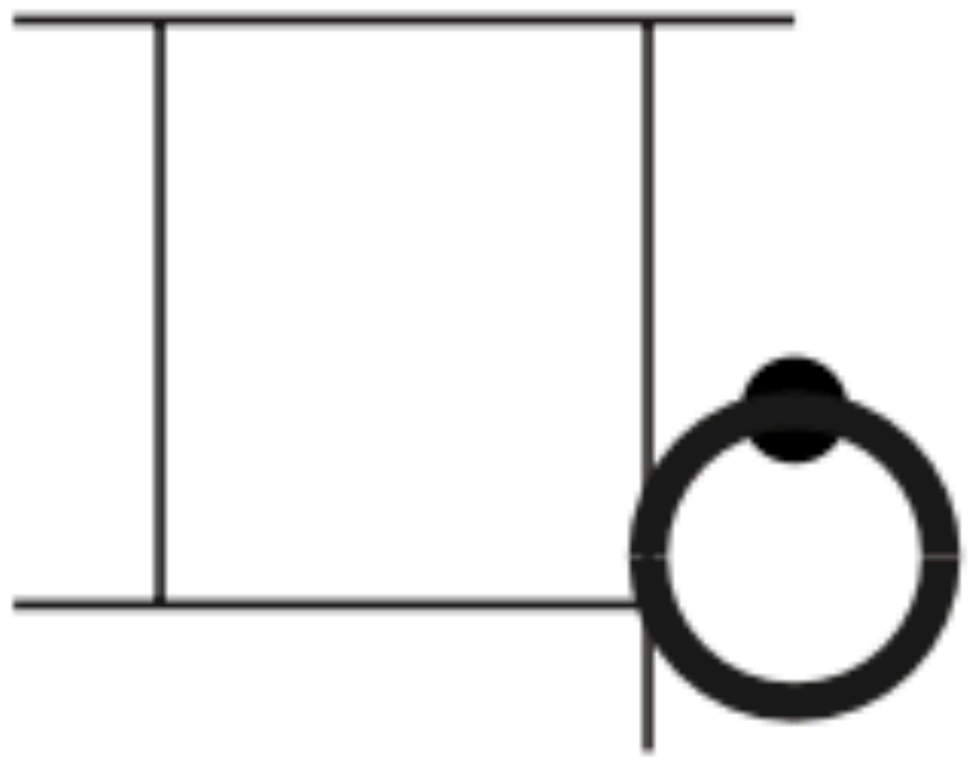
Cons of analytic evaluation :

- 5 non simultaneously linearizable square roots
- Non trivial solution!
- Big expressions!

Evaluation of the MIs - PLB family:



All the MIs coming from the PLB family, except J_{21}, are equal to one of the other two topologies PLA and NPL



Obtained by integrating analytically its differential equations

We dont need to set up a system of DEs for PLB

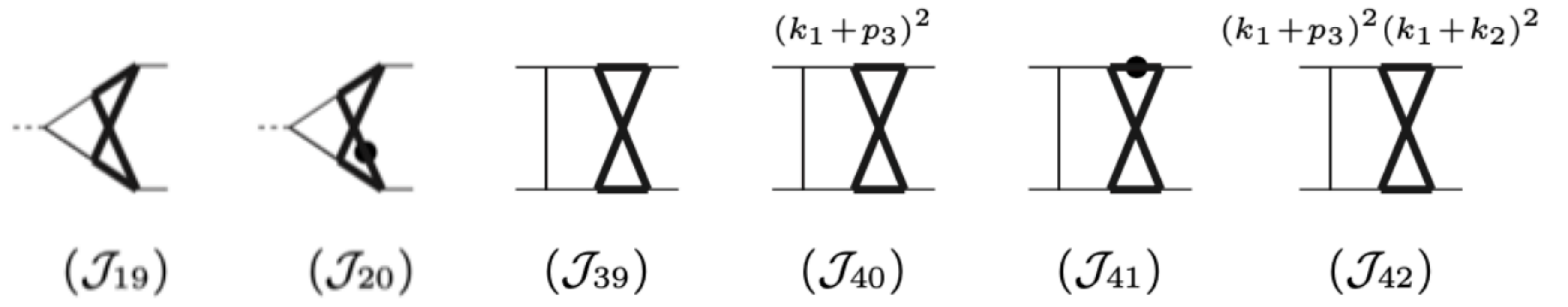
Evaluation of the MIs - NPL family

$$d\underline{g}(\underline{x},\epsilon) = \epsilon dA(\underline{x})\underline{g}(\underline{x},\epsilon) + d\tilde{A}(\underline{x},\epsilon)\underline{g}(\underline{x},\epsilon)$$

Two different subsets

Canonical logarithmic

Elliptic Sectors

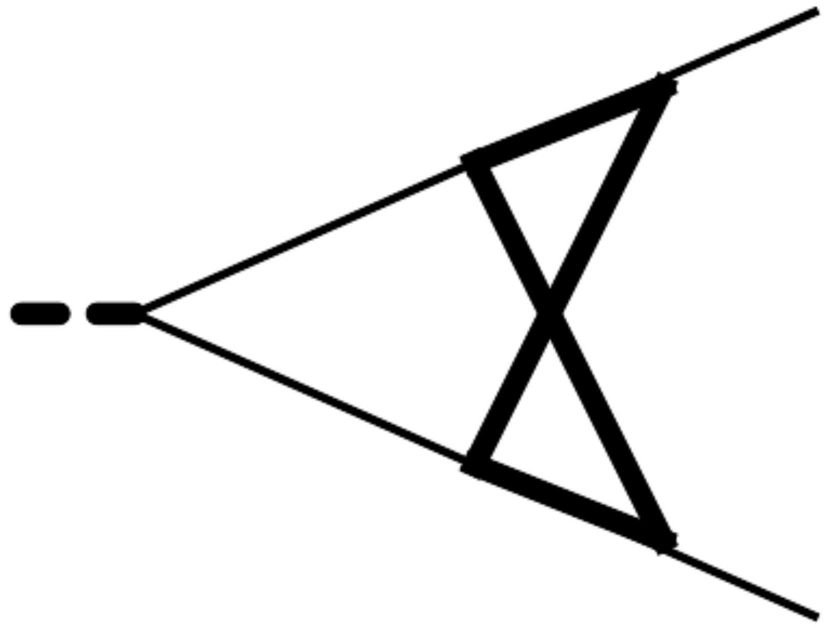


$W_{NPL} = \{w_i(\underline{x})\}$ → Set of 30 letters

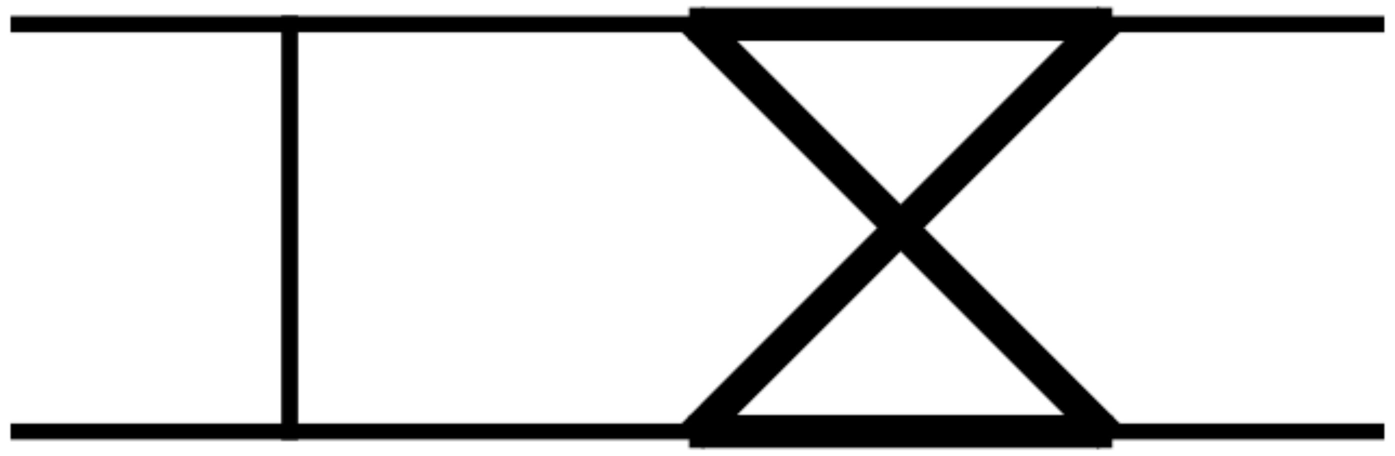
Cons of analytic evaluation :

- Nine square roots in the alphabet
- Non trivial solution!
- Integrals involving eMPLs kernels

Elliptic sectors

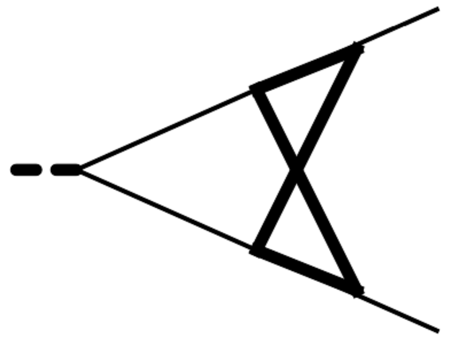


Non-planar triangle



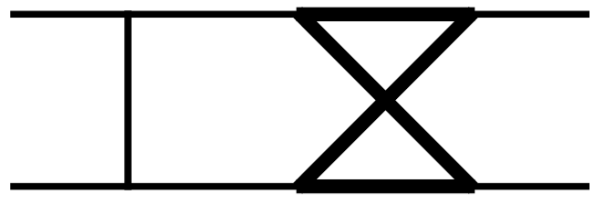
Non-planar double-box

The two sectors $(0,1,1,1,1,1,1,0,0)$ and $(1,1,1,1,1,1,1,0,0)$ for the NPL family are elliptic

$MC($  $) \propto \frac{1}{s}\int \frac{dz}{\sqrt{z(z+s)(z(s+z)-4sm_t^2)}}$

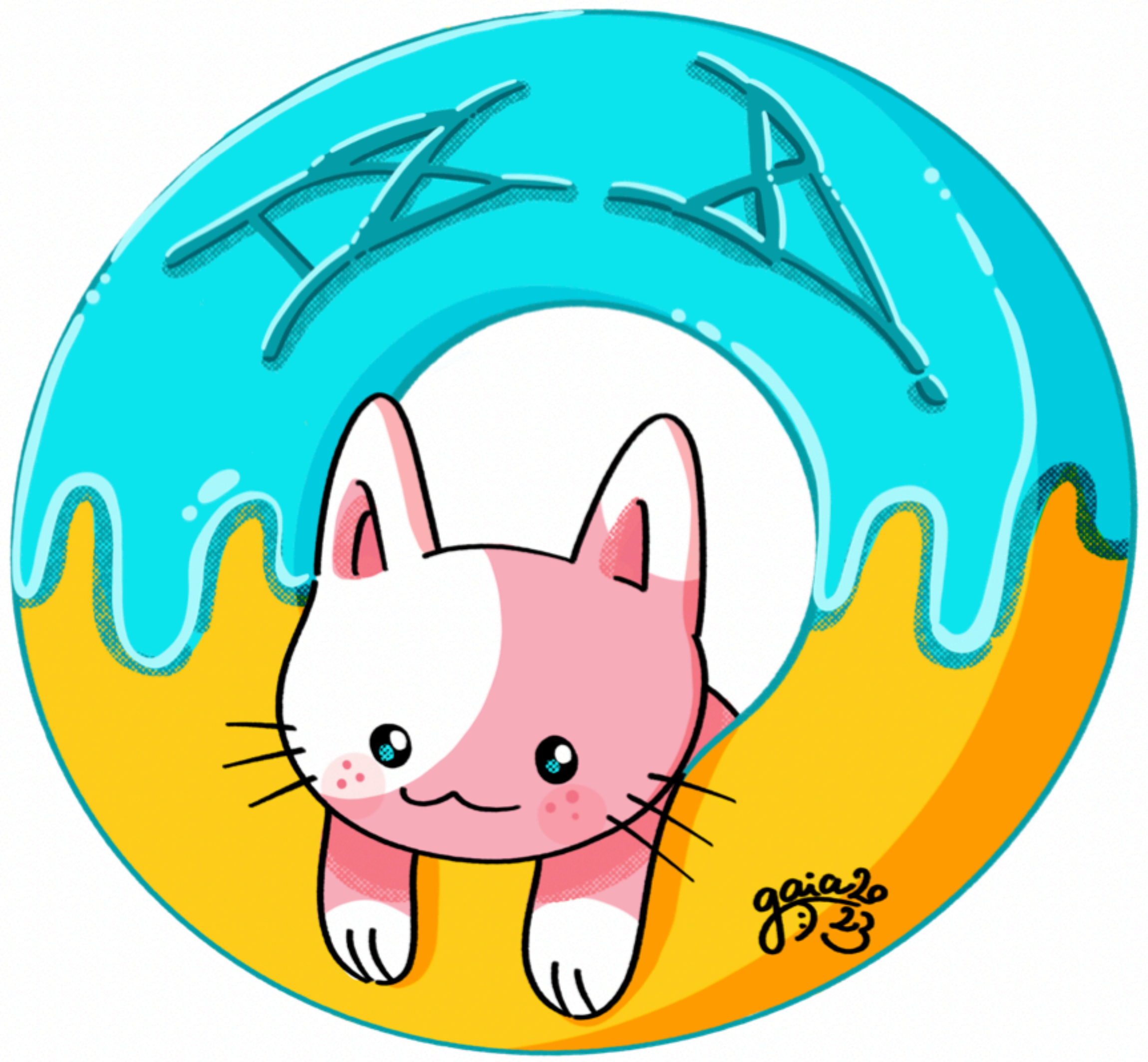
[J.Broedel,C.Duhr,F.Dulat,B.Penante,L.Tancredi]

Elliptic sectors

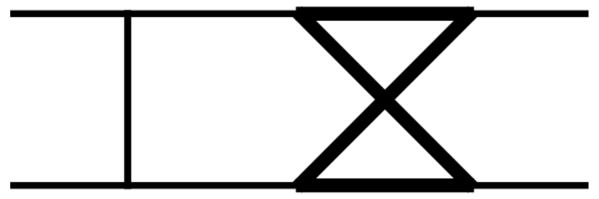
$MC($  $) \propto \frac{1}{s}\int \frac{dz}{z\sqrt{(z+t)(s+t+z)((z+t)(s+t+z)-4sm_t^2)}}$

Möbius transformation: $z \to z - t$

The two elliptic curves are the same!



[G.Fontana]

$MC($  $) \propto \frac{1}{s}\int \frac{dz}{z\sqrt{z(z+s)(z(z+s)-4sm_t^2)}}$

Generalised power series approach

$$\underline{f}(t,\epsilon) = \sum_{k=0}^{\infty} \epsilon^k \sum_{i=0}^{N-1} \rho_i(t) \underline{f}_i^{(k)}(t)$$

$$\rho(t) = \begin{cases} 1 & \text{if } t \in [t_i - r_i, t_i + r_i) \\ 0 & \text{if } t \notin [t_i - r_i, t_i + r_i) \end{cases}$$

$$\underline{f}_i^{(t)} = \sum_{l_1=0}^{\infty} \sum_{l_2=0}^{N_{i,k}} c_k^{(i,l_1,l_2)} (t - t_i)^{l_1/2} log(t - t_i)^{l_2}$$

[R. N. Lee, A. V. Smirnov, V. A. Smirnov]

[M.K.Mandal,X.Zhao]

[F.Moriello]

Series solutions around DEs singular points

Pros:

- It doesn't depend on the function space, so it allows us to avoid elliptic integrals
- Values at arbitrary phase-space points
- Can be used to perform phenomenological studies

Numerical evaluation of the Master Integrals

The numerical evaluation of the Master Integrals has been made with **DiffExp** [M.Hidding]

Several check for the numerical evaluation with **AMFLow** [X.Liu,Y.Ma]

Correspondance up to 200 digits!

For the four elliptic boxes in NPL Topology, at a fixed angle:

Imaginary Part

Real Part

Numerical evaluation of the Hard Function

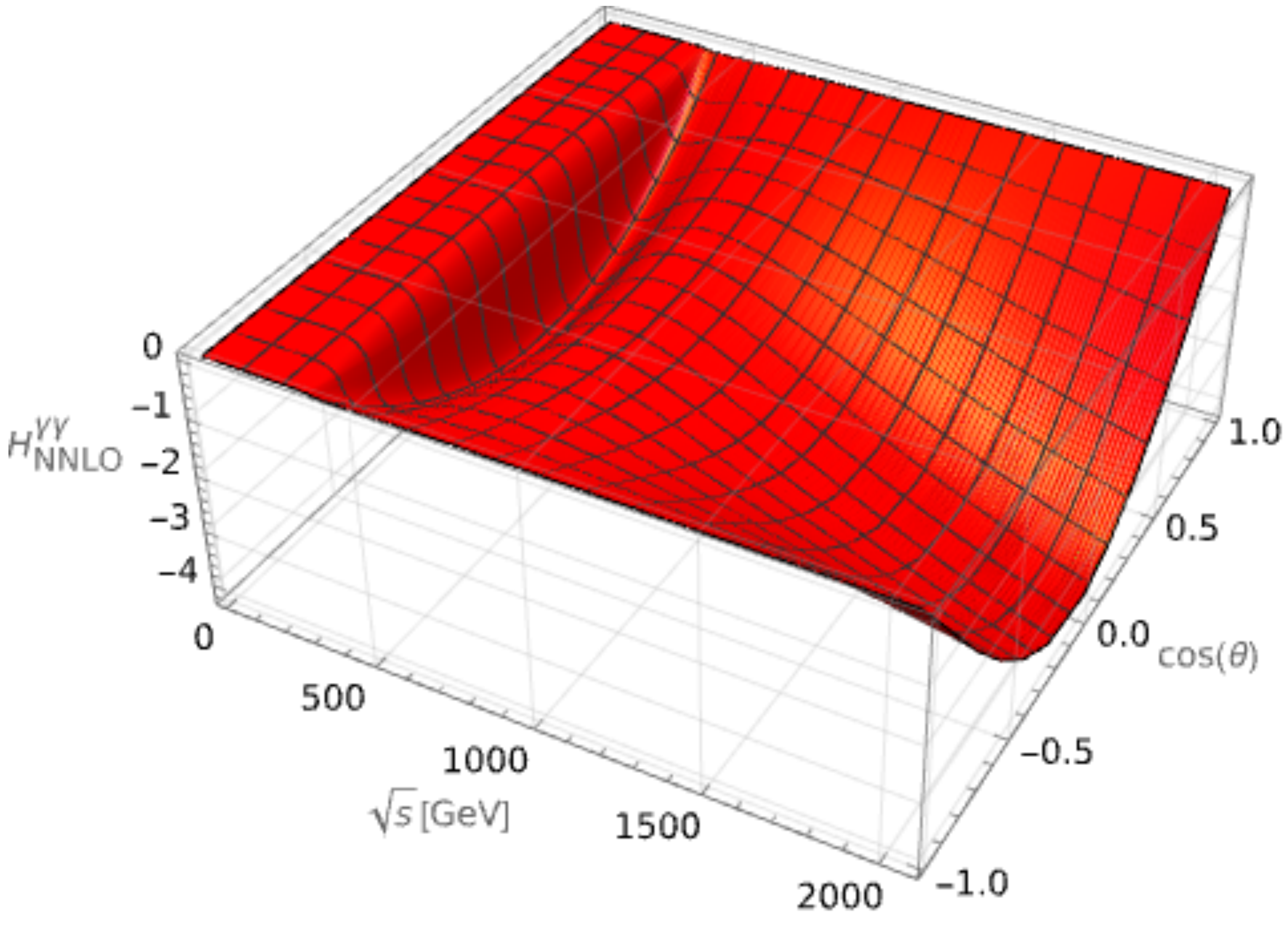
We prepared the numerical grid in the $2 \to 2$ physical phase-space region

$$s > 0, \quad t = -\frac{s}{2}(1 - cos(\theta)), \quad -s < t < 0$$

$-0.99 < cos(\theta) < +0.99$ 24 different values

$8\ GeV < \sqrt{s} < 2.2\ TeV$ 573 different values

13752 points

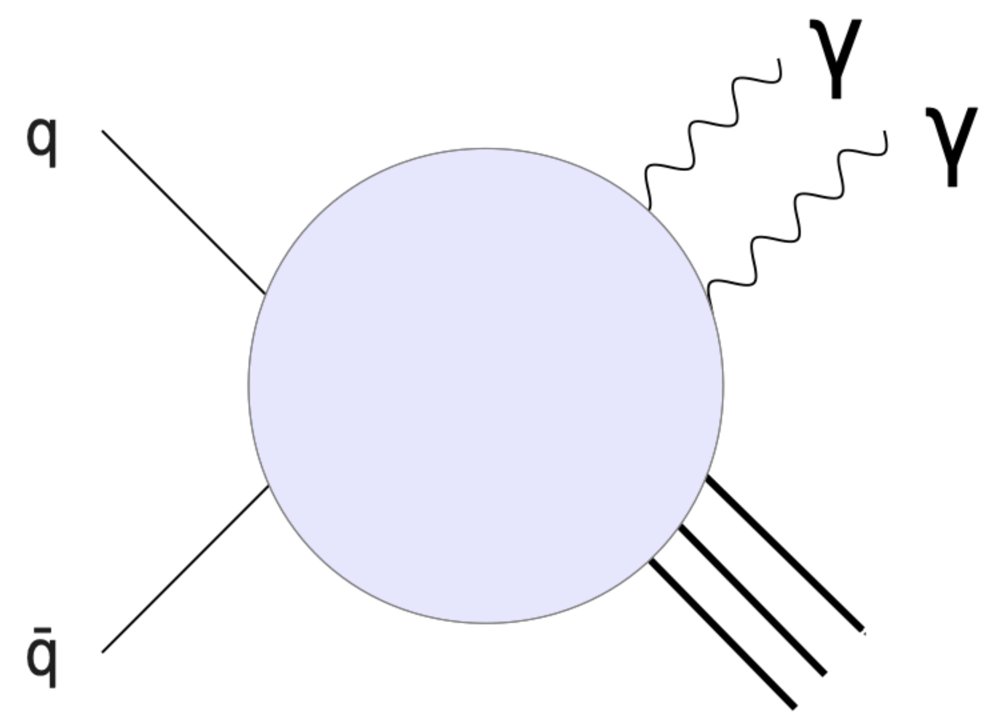


Planar Topology MIs in $\mathcal{O}(2.5\ h)$

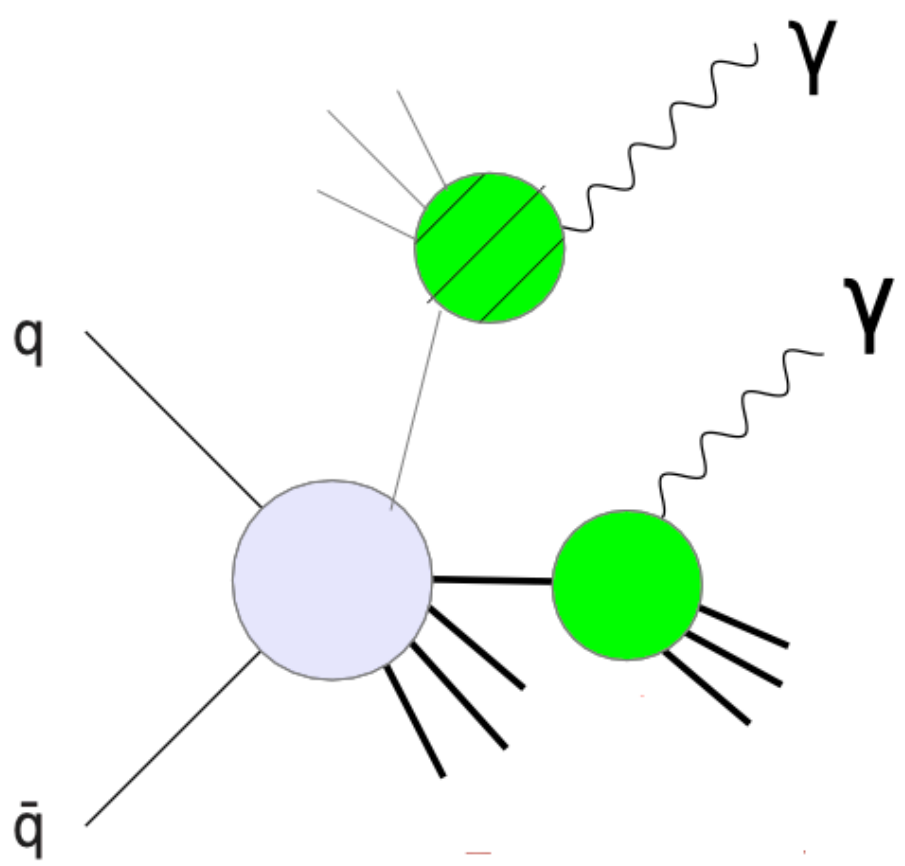
Non-planar Topology MIs in $\mathcal{O}(10.5\ h)$

On a single core!

Photon production and isolation criteria



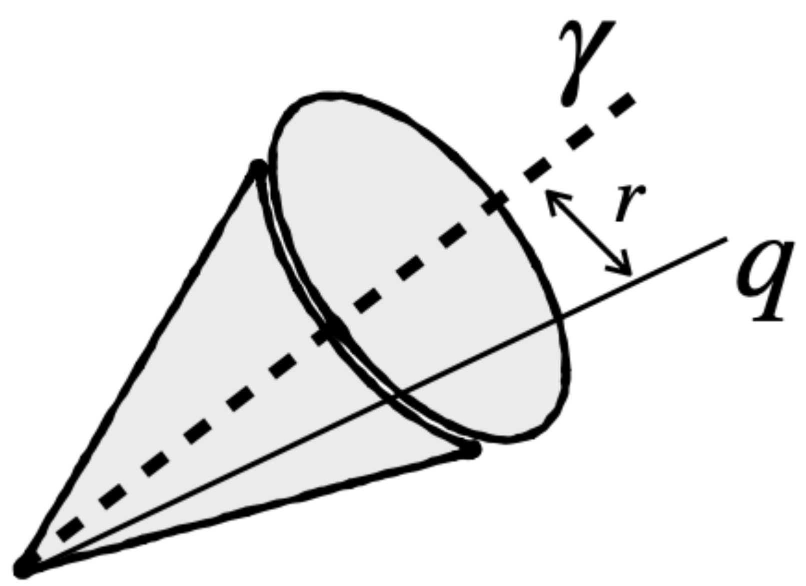
Direct component



Fragmentation component

- Experimentally photons must to be isolated
- Isolation reduces fragmentation component

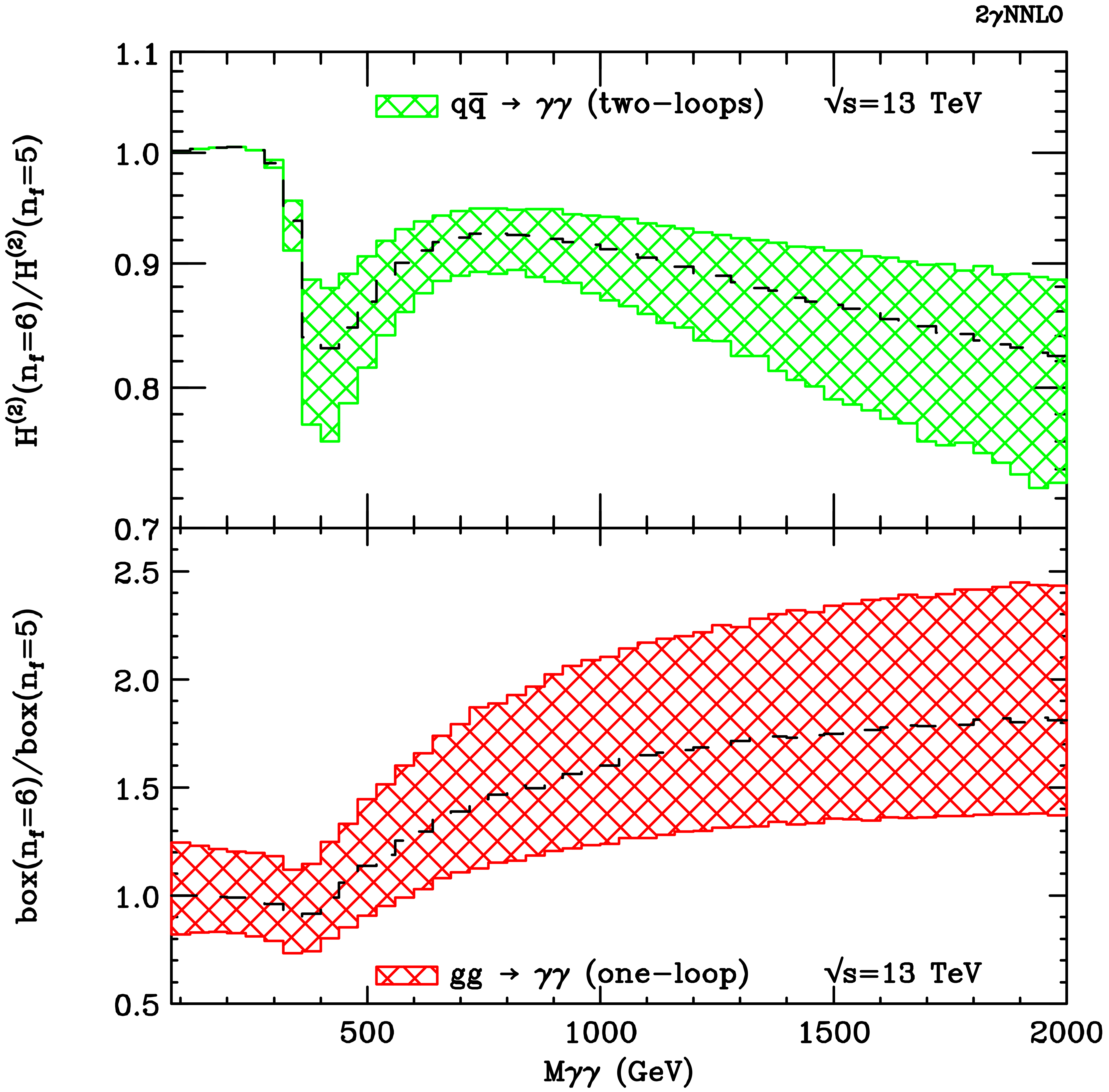
Smooth cone isolation



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

- No quark-photon collinear divergences
- No fragmentation component

Phenomenological Results



Upper panel: ratio between the fully massive and massless NNLO

$M_{\gamma\gamma} \sim 2m_t$ Negative peak → Size of the ratio $\sim -15\,\%$

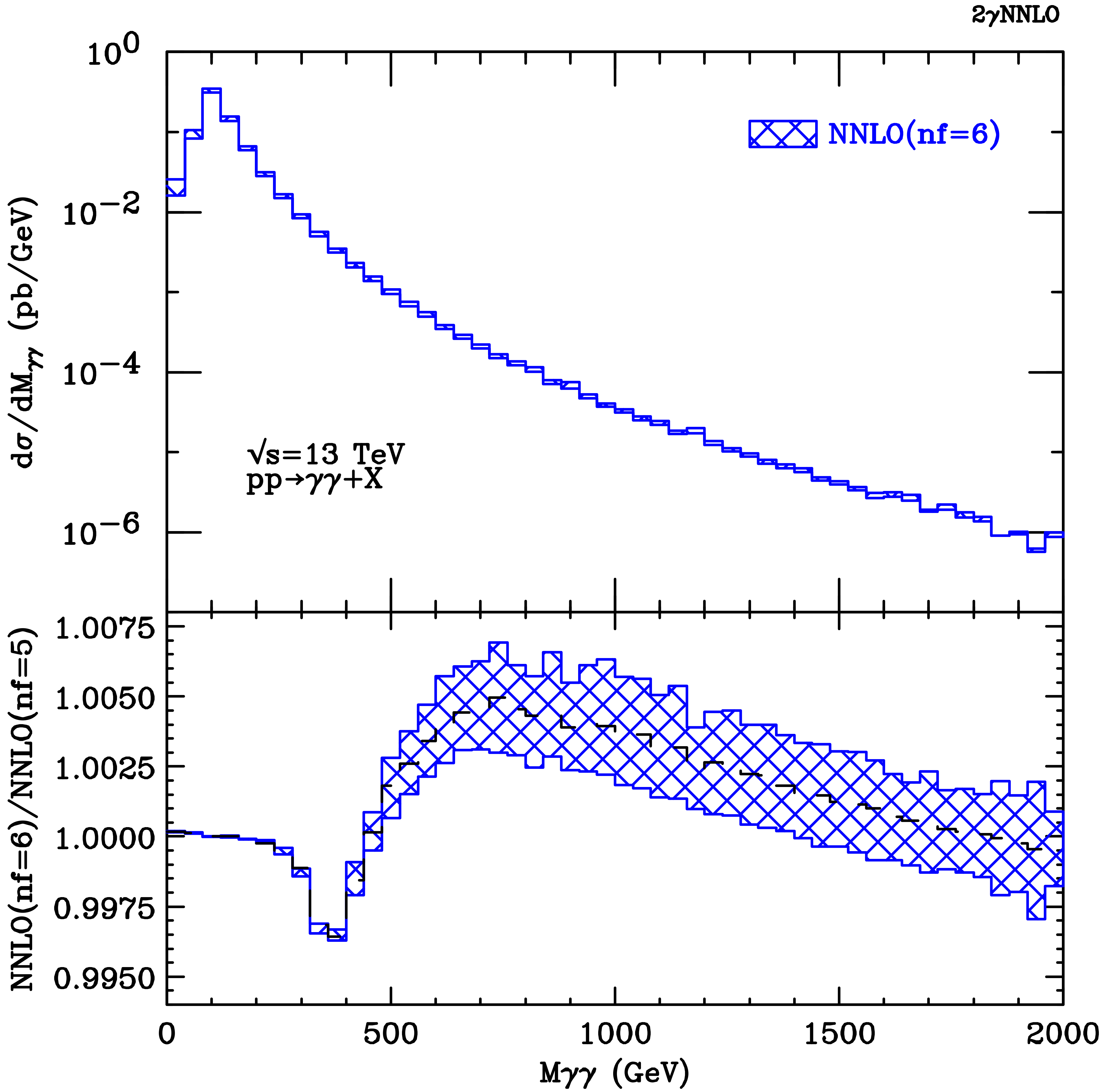
$M_{\gamma\gamma} > 2.3 \cdot 2m_t$ The tail decreases

Lower panel: ratio between the fully massive and massless one-loop box

For $M_{\gamma\gamma} \gg m_t$ the massive one-loop box contribution behaves as if it were composed by 6 light-quark flavors

$$\frac{(\sum_{n_f} e_q^2)^2}{(\sum_{n_f=5} e_q^2)^2} = \frac{225}{121}$$

Phenomenological Results



Ratio between the fully massive and massless invariant mass distribution at NNLO

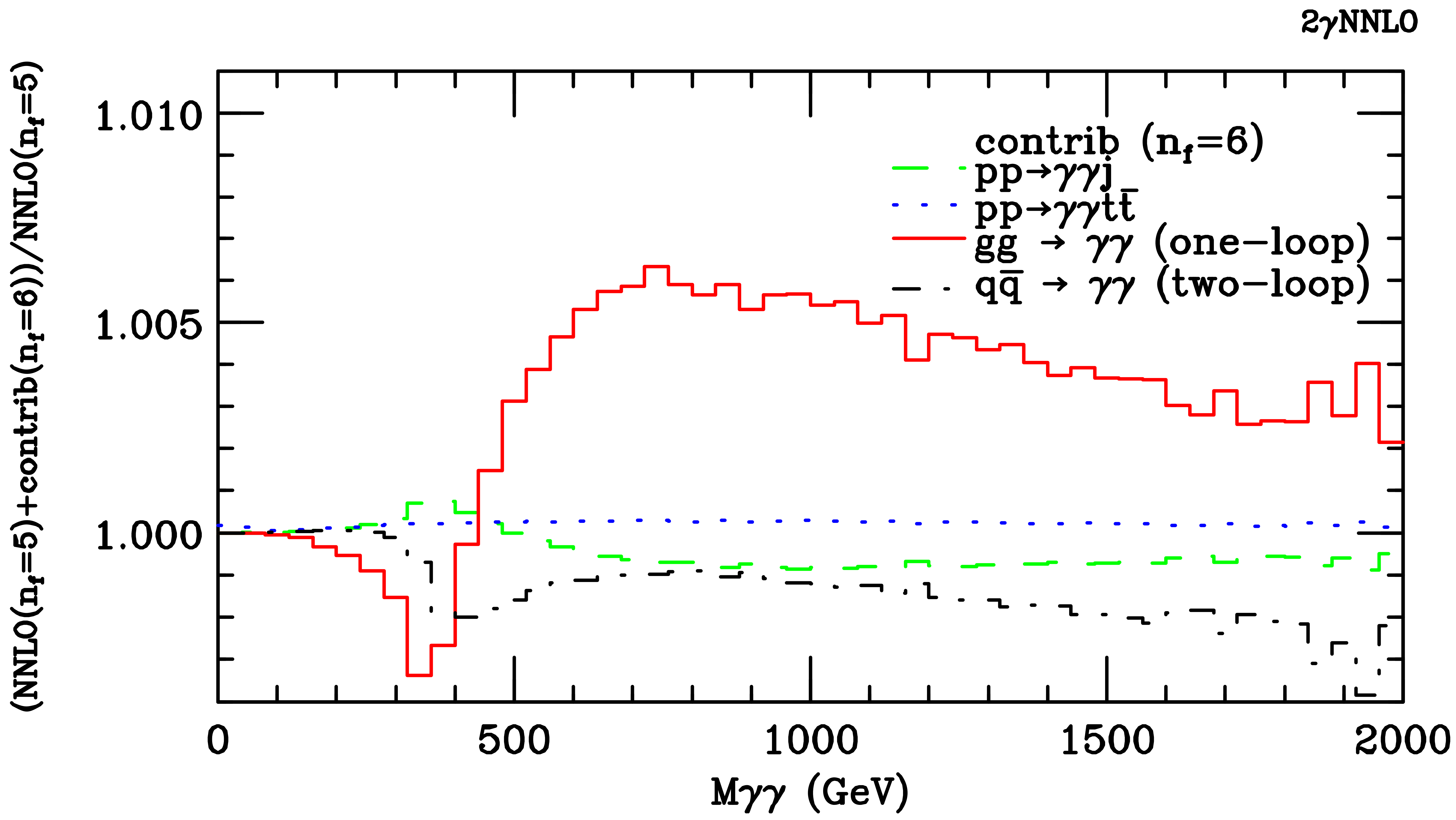
$M_{\gamma\gamma} \sim 2m_t$ Negative peak

$M_{\gamma\gamma} < 2m_t$ Massive corrections smaller than the massless one

$M_{\gamma\gamma} > 2m_t$ Massive corrections larger than the massless one

In the invariant mass region $1\ GeV < M_{\gamma\gamma} < 2\ TeV$ deviation from the massless result in the range $[-0.4\,\%, 0.8\%]$

Phenomenological Results



Ratios of each one of the massive contributions with respect to the NNLO massless cross section as a functions of the invariant mass

Conclusions

- We computed the full NNLO QCD corrections to diphoton production
- The massive two loop $q\overline{q}$-channel is one of the sizeable massive corrections
- Important corrections around the top quark threshold and along the distribution tail

Outlooks

- Analytic computation of the amplitude
- Inclusion of the partial massive N^3LO

Thank you for your attention!