Full NNLO QCD corrections to diphoton production

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Based on: arXiv:2308.10885

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

Outline of the talk

- **Introduction**
  - Motivations
  - State of the art
- **Double Virtual Contribution**
  - Form factors
  - Master Integrals
  - Hard Function
- **Final Results**
  - Double Virtual
  - Double Real
  - Real-Virtual
- **Conclusions**

Motivations

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

State of the art

- Full NLO
- QCD NNLO
- $\gamma\gamma + jets$
- Form factors up to 3 loops

Massive Corrections

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

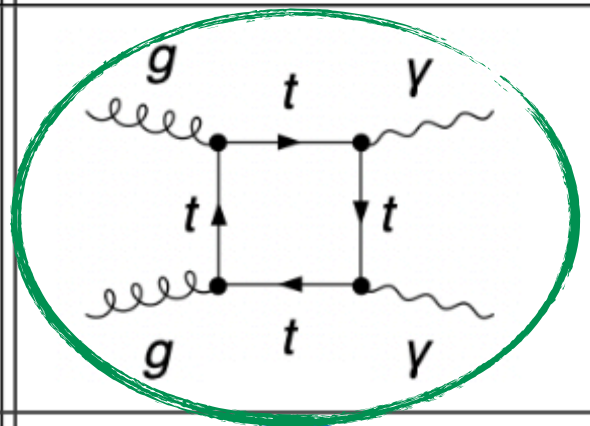
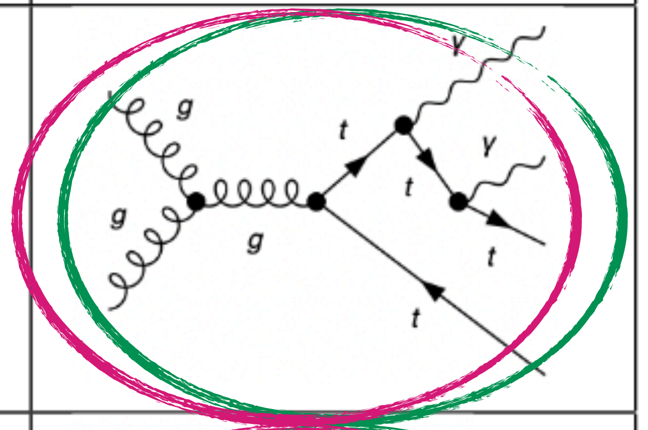
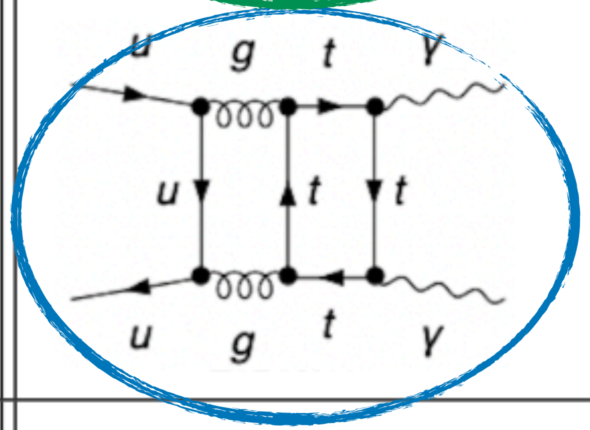
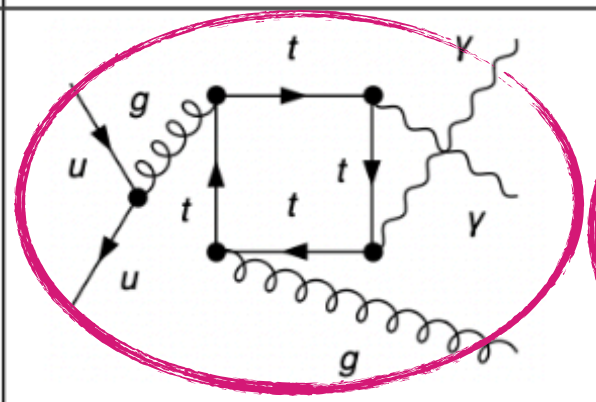
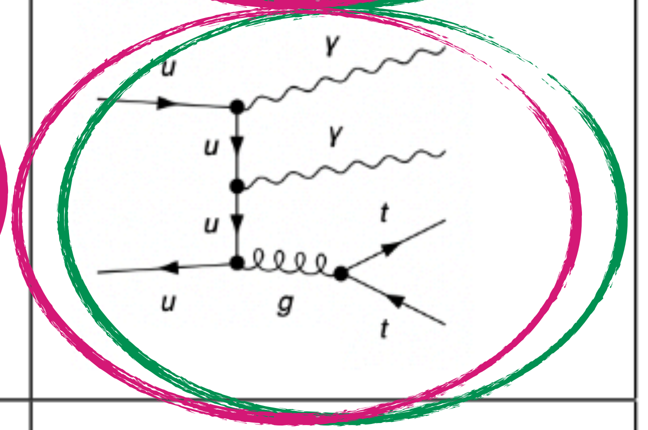
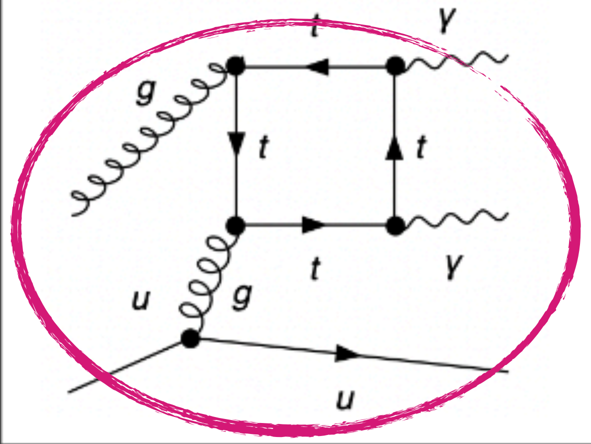
Channels	$\gamma\gamma$	$\gamma\gamma j$	$\gamma\gamma jj$
gg			
$q\bar{q}$			
qg			

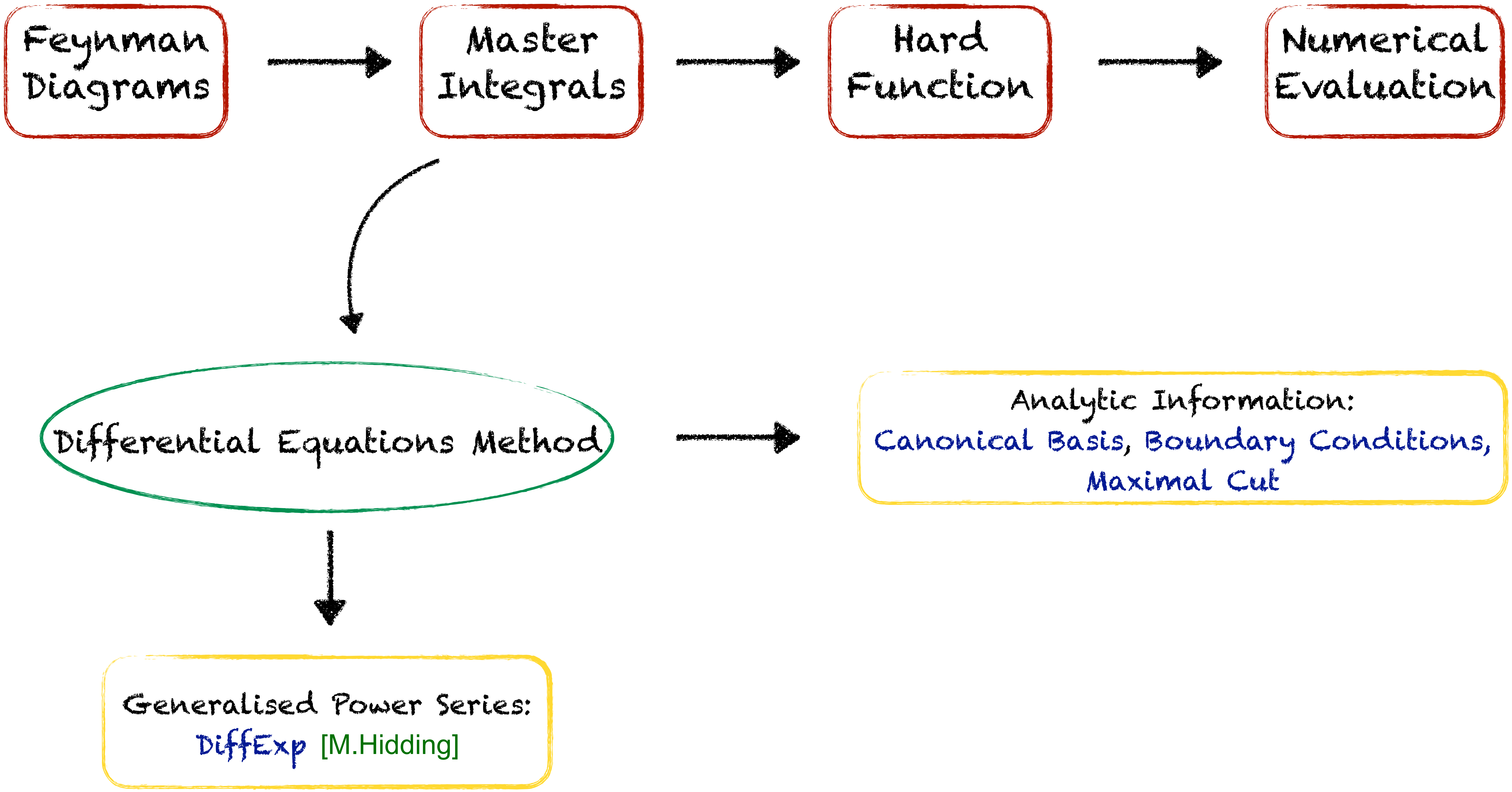
Diagram — [J.M.Campbell,R.K.Ellis,Y.Li,C.Williams]

[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

At any order in QCD perturbation theory, the amplitude can be decomposed as:

$$\mathscr{A}_{q\bar{q},\gamma\gamma}(s,t,m_t^2) = \sum_{i=1}^{4} \mathscr{F}_i(s,t,m_t^2)\bar{v}(p2)\Gamma_i^{\mu\nu}u(p_1)\epsilon_{3,\mu}\epsilon_{4,\nu}$$

In dimensional regularisation:

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

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

The form factors admits a perturbative expansion:

$$\mathscr{F}_i = \mathscr{F}_i^{(0)} + \left(\frac{\alpha_s^B}{\pi}\right)\mathscr{F}_i^{(1)} + \left(\frac{\alpha_s^B}{\pi}\right)^2 \mathscr{F}_i^{(2)} + \cdots$$

Massive contribution appears at $\mathcal{O}(\alpha_s^2)$:

$$\mathscr{F}_i^{(2)} = \delta_{kl}C_F(4\pi\alpha_{em})\left[Q_q^2\mathscr{F}_{i;0}^{(2)} + Q_t^2\mathscr{F}_{i;2}^{(2)}\right]$$

Q_q is the charge of light quark

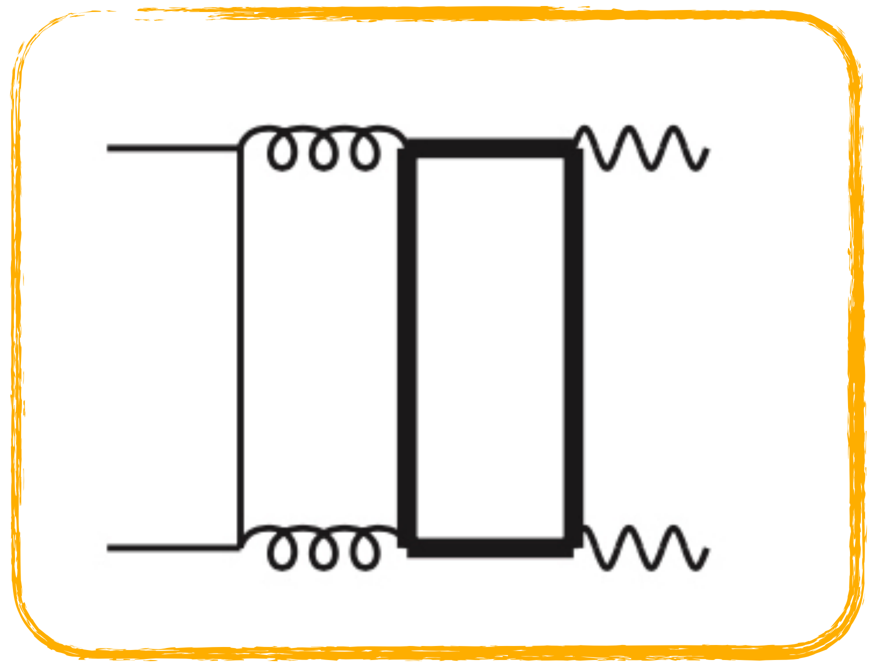
Q_t is the charge of heavy quark

Two-loop Feynman diagrams

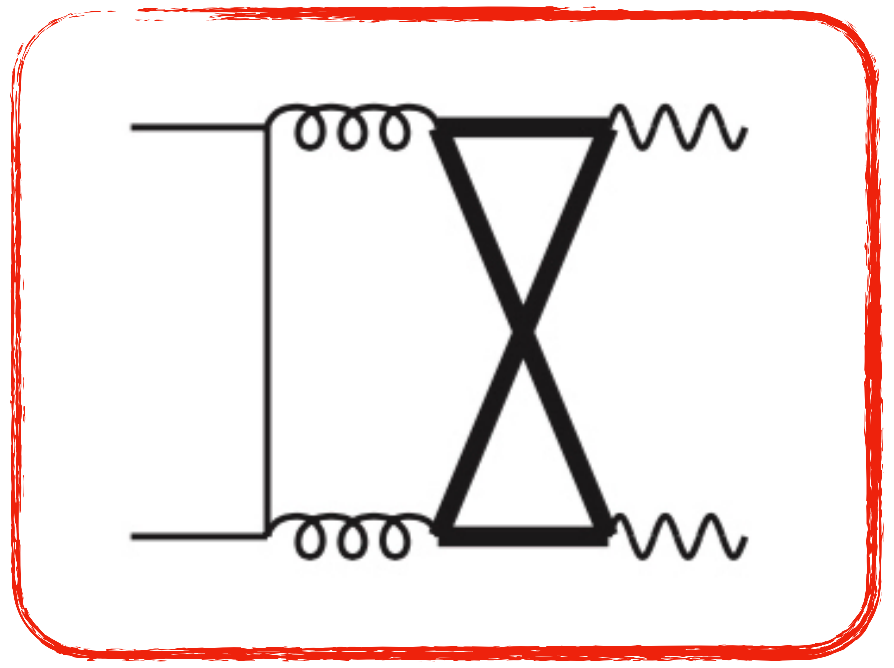
At partonic level the scattering process is: $q(p_1) + \bar{q}(p_2) \to \gamma(p_3) + \gamma(p_4)$

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

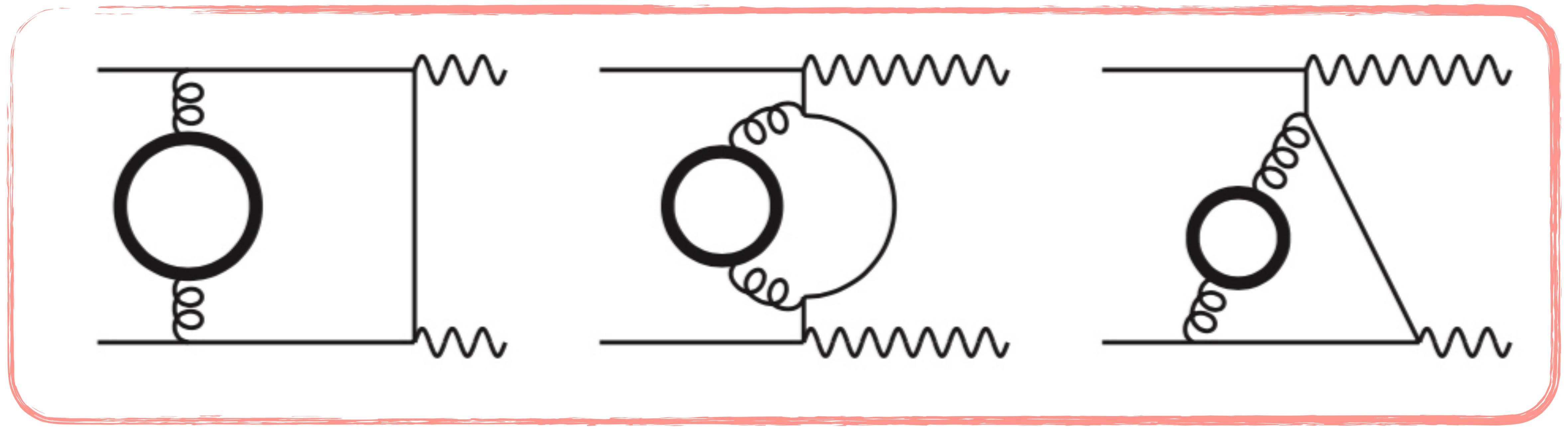
Feynman diagrams generated with **FeynArts** [T.Hahn]



PLA



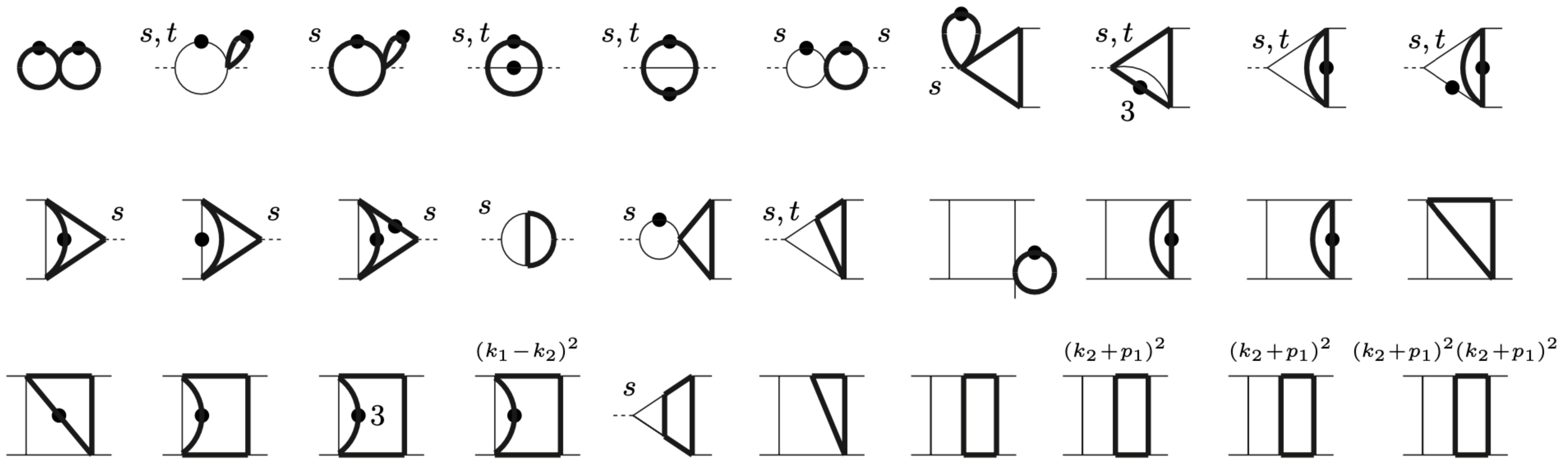
NPL



PLB

Master Integrals

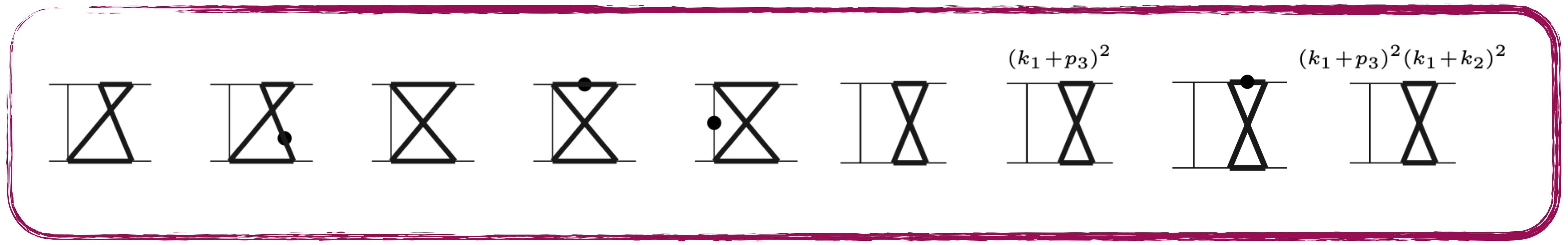
PLA and PLB Master Integrals



[M.Becchetti,R.Bonciani]

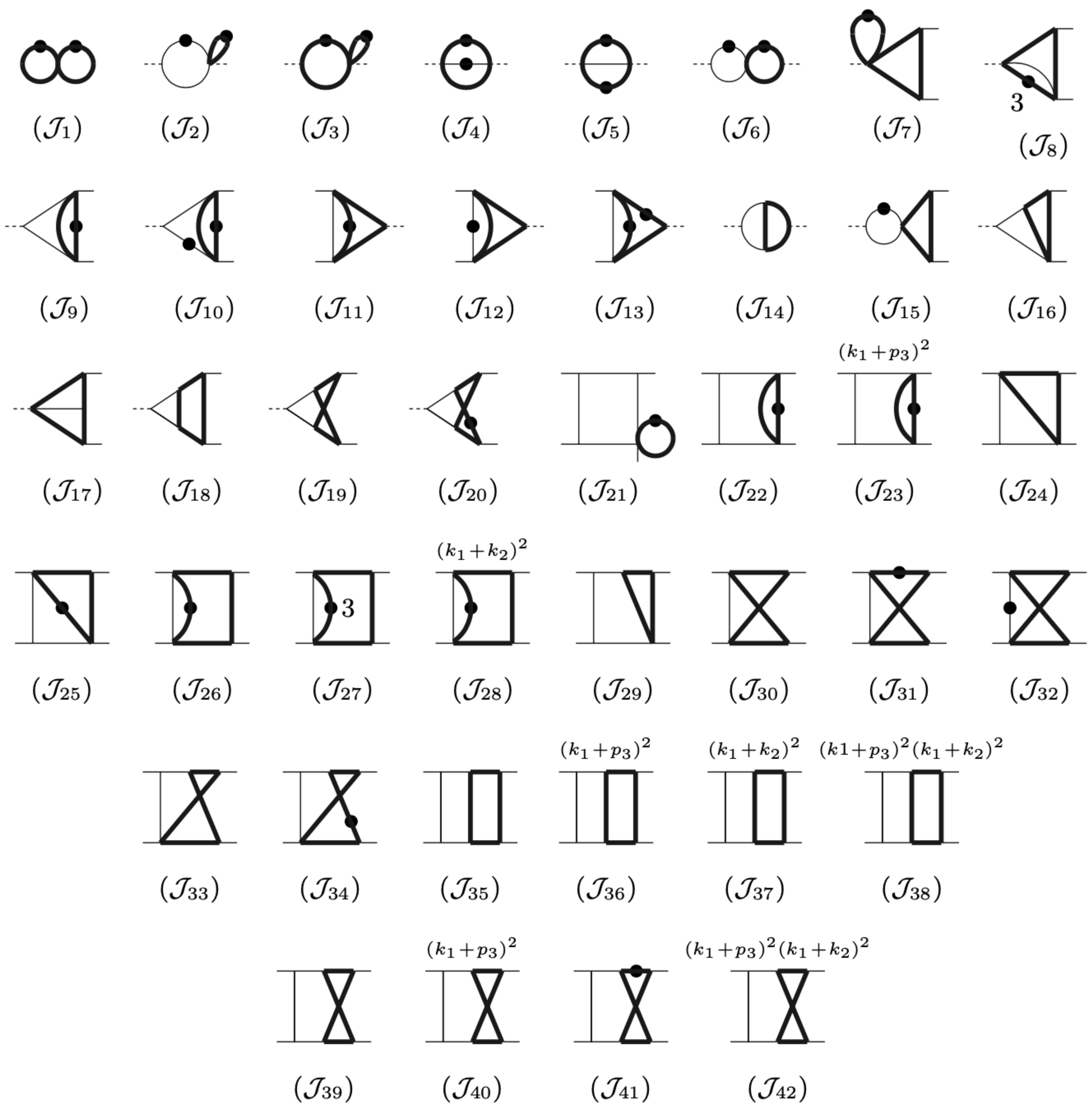
[A.Von Manteuffel,L.Tancredi]

NPL Master Integrals



Original MIs

Master Integrals



Now we have
42 MIs
for all the
process!

Evaluation of the Master Integrals

The MIs are computed through the differential equations method:

PLA family: $d\underline{f}(\underline{x},\epsilon) = \epsilon dA(\underline{x})\underline{f}(\underline{x},\epsilon)$ 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: $\underline{x} = 0$

Five different square roots in the letters

- ❖ Non linearizable square roots
- ❖ Non trivial solution!
- ❖ Big expressions!

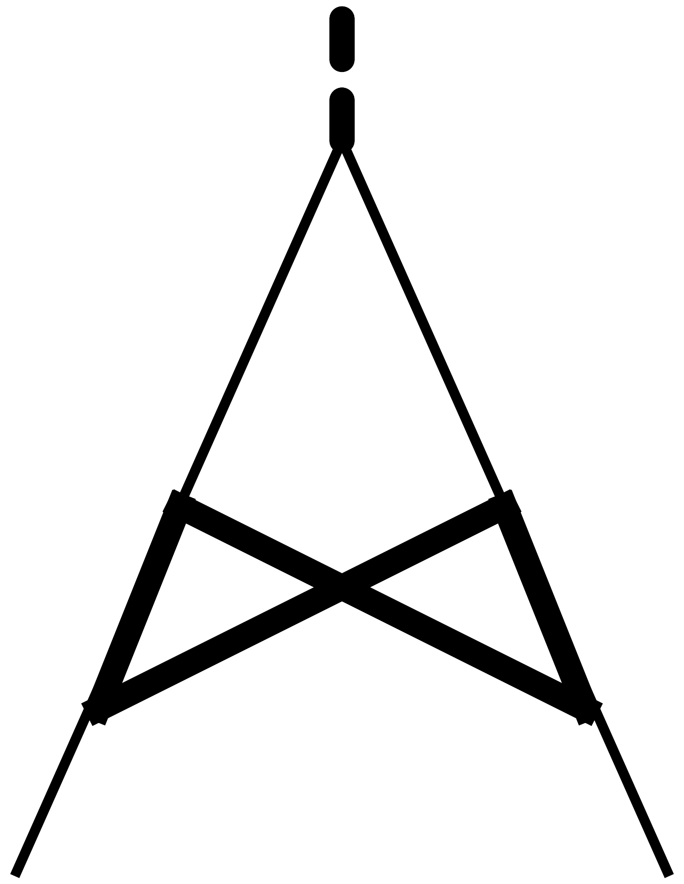
PLB family: This topology contains only one different MIs from the other two topologies, which was computed analytically

Evaluation of the Master Integrals

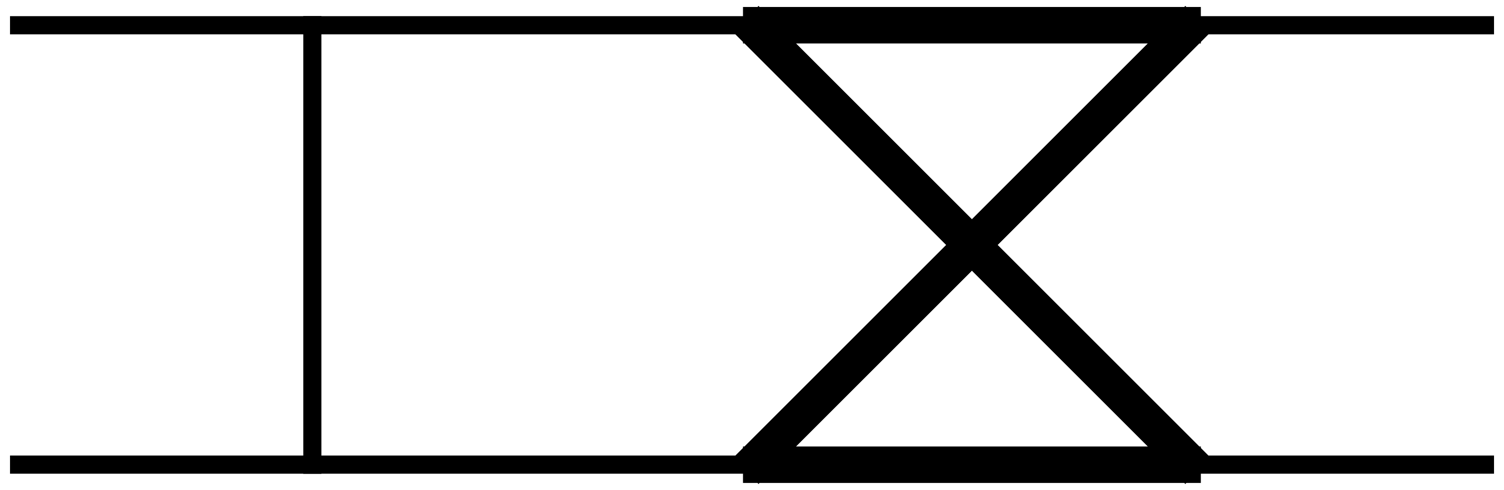
NPL family: $d\underline{f}(\underline{x},\epsilon) = \epsilon dA(\underline{x})\underline{f}(\underline{x},\epsilon) + d\tilde{A}(\underline{x},\epsilon)\underline{f}(\underline{x},\epsilon)$

Two different subsets

- Canonical logarithmic
- Elliptic Sectors



eMPLS



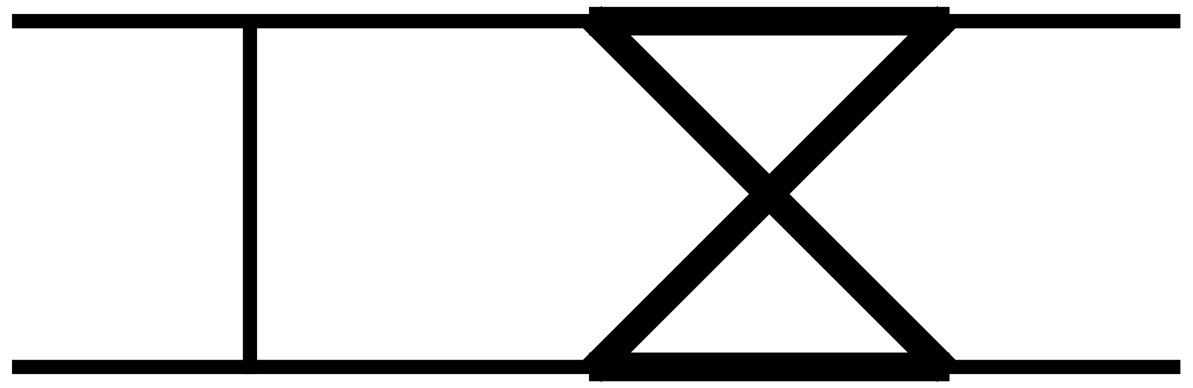
- ❖ Non trivial solution!
- ❖ Nine square roots in the alphabet
- ❖ Integrals involving eMPLs kernels

[A.Von Manteuffel,L.Tancredi]

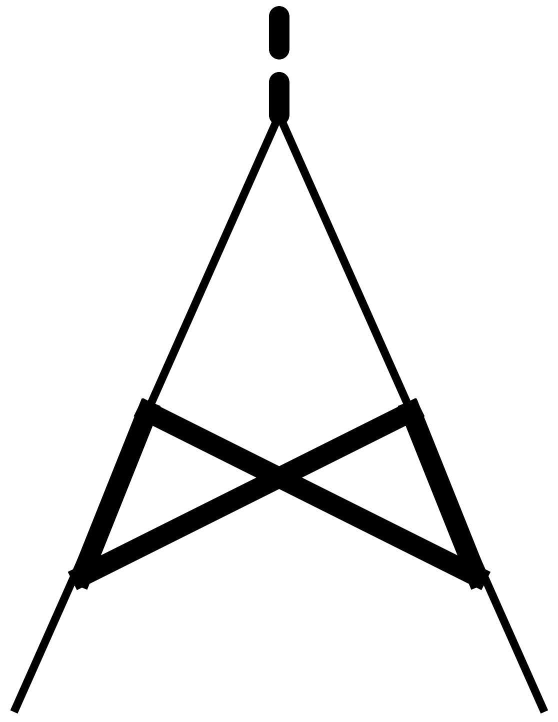
Maximal Cut

The homogeneous part of the DEs contains elliptic functions → This is verified by the **Maximal Cut**

Genus one



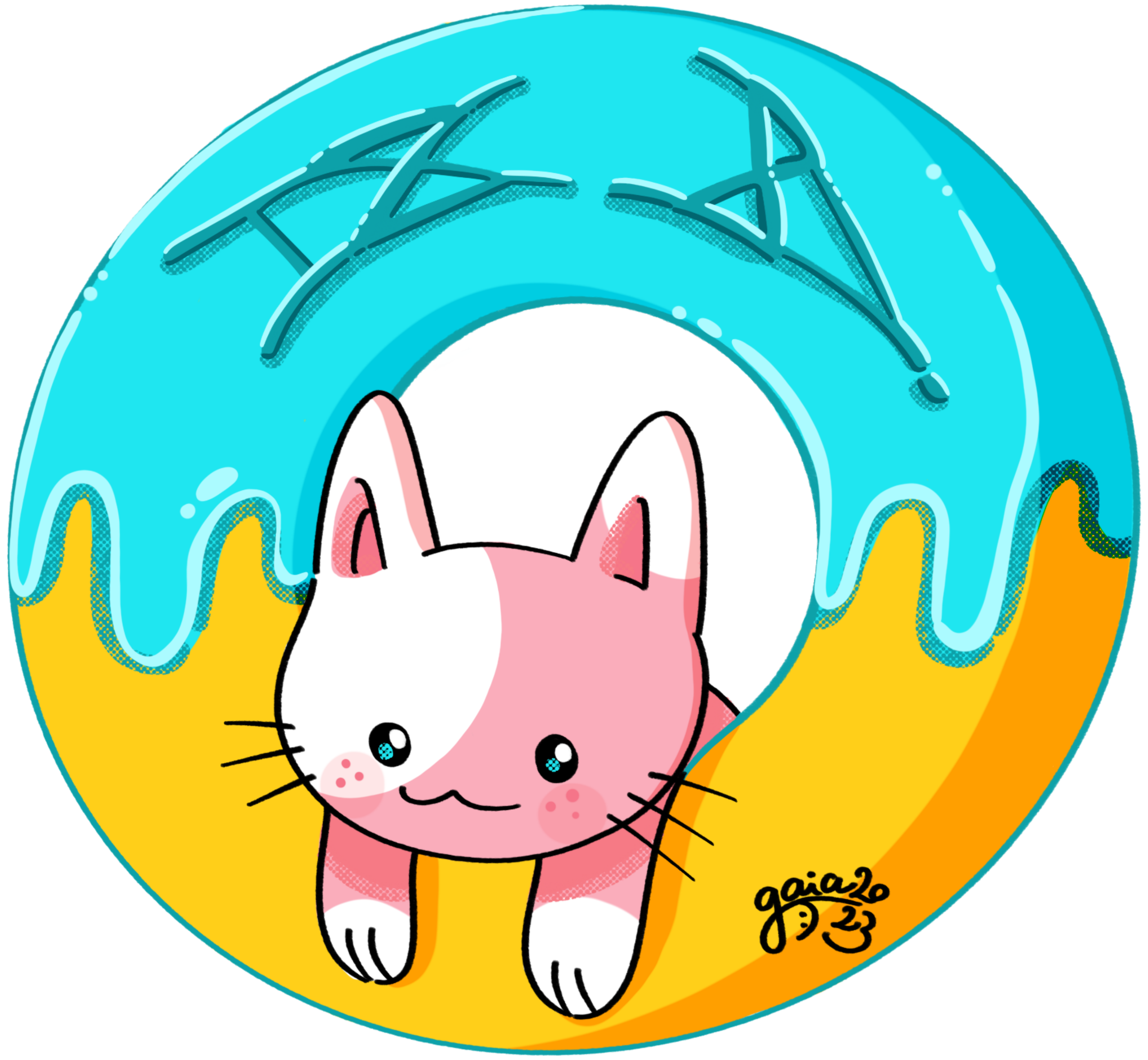
$$y_c^2 = (z_8 + t)(z_8 + s + t)(z_8 - z_+)(z_8 - z_-)$$



$$y^2 = \bar{x}_2(\bar{x}_2 - 1)(\bar{x}_2 - b_+)(\bar{x}_2 - b_-)$$

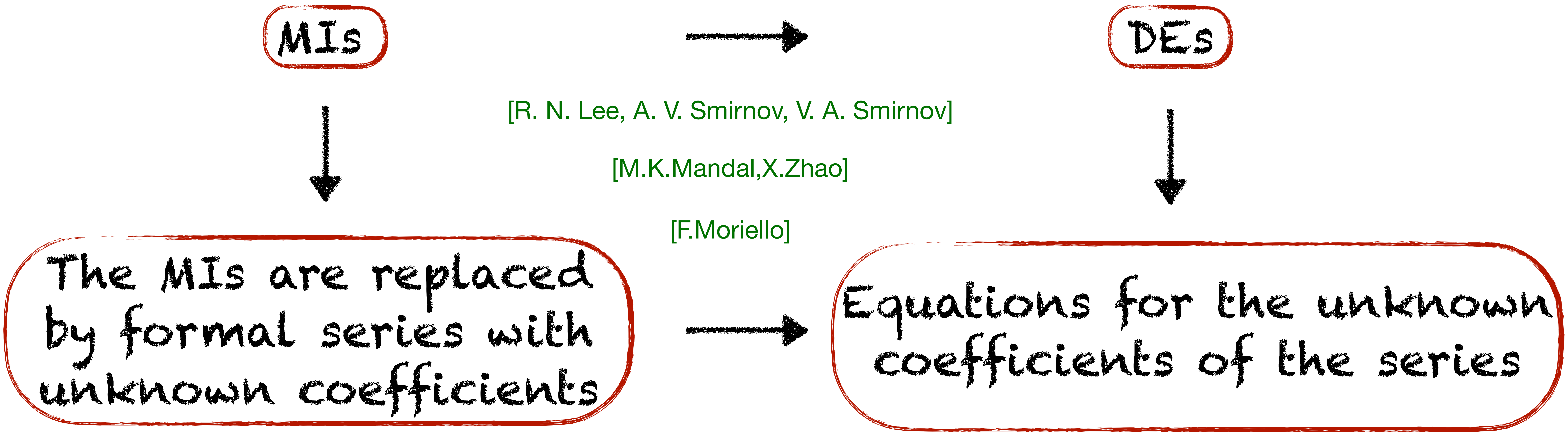
[J.Broedel,C.Duhr,F.Dulat,B.Penante,L.Tancredi]

The elliptic curve y_c^2 degenerates to y in the forward limit $t = 0$



[G.Fontana]

Generalised power series approach



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!

Imaginary Part

Real Part

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

Hard Function

$\mathcal{F}_i^{(2)}$ does not have IR poles!

After remove the UV poles, we can compute the NNLO Hard Function

In q_T - subtraction scheme:

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

Contains our massive contribution

LO cross section

NLO cross section for $\gamma\gamma + jet$

CT needed to cancel the IR singularities

The Hard function admit a perturbative expansion: $\mathcal{H}^{\gamma\gamma} = 1 + \frac{\alpha_S}{\pi}\mathcal{H}^{\gamma\gamma}_{\text{NLO}} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{\gamma\gamma}_{\text{NNLO}} + \cdots$

Numerical evaluation of the Hard Function

A numerical grid has been prepared for all the MIs of the PLA and NPL, covering the $2 \to 2$ physical space:

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

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

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

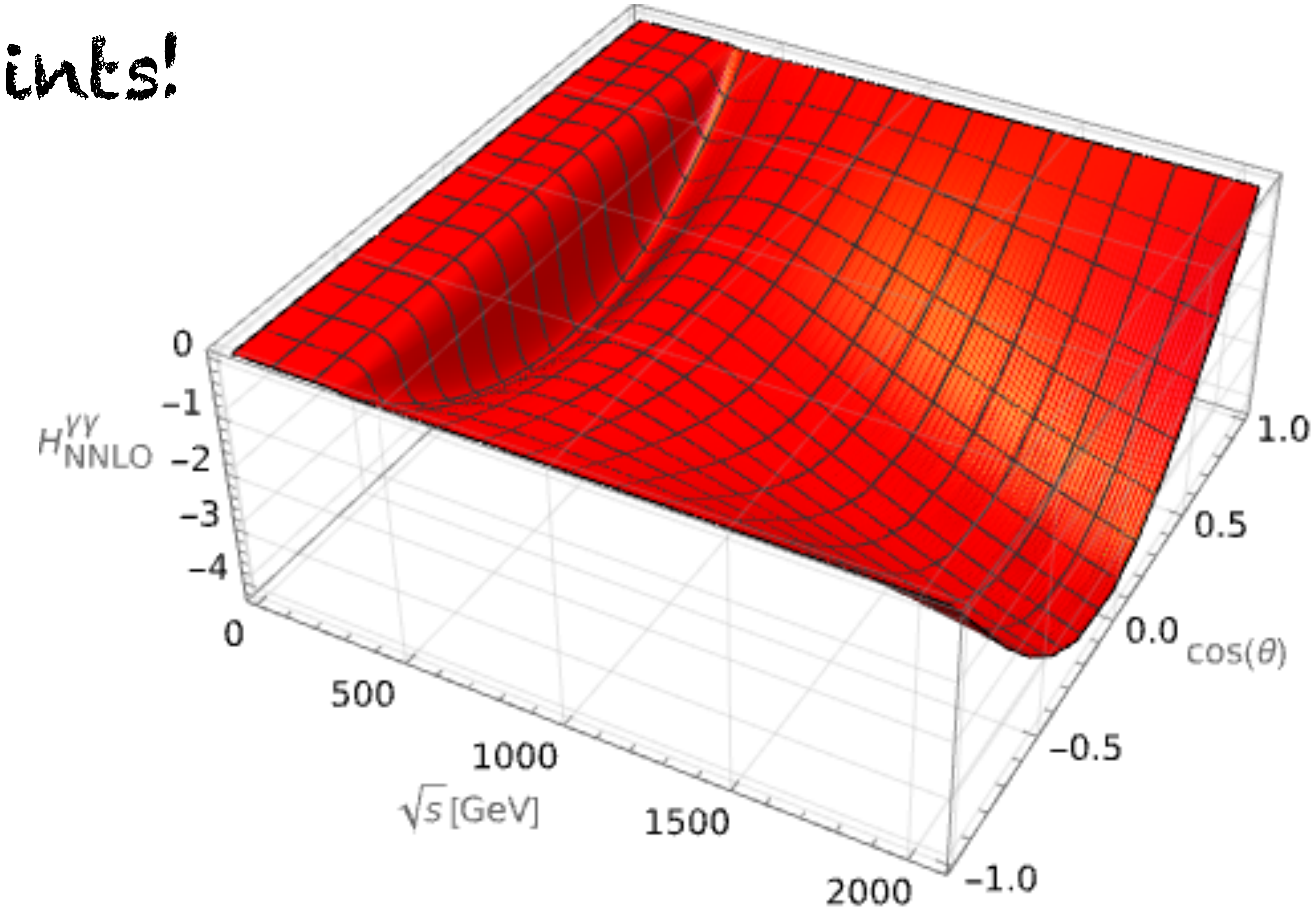
13752 points!

DiffExp time for the $H^{\gamma\gamma}_{NNLO}$ MIs evaluation:

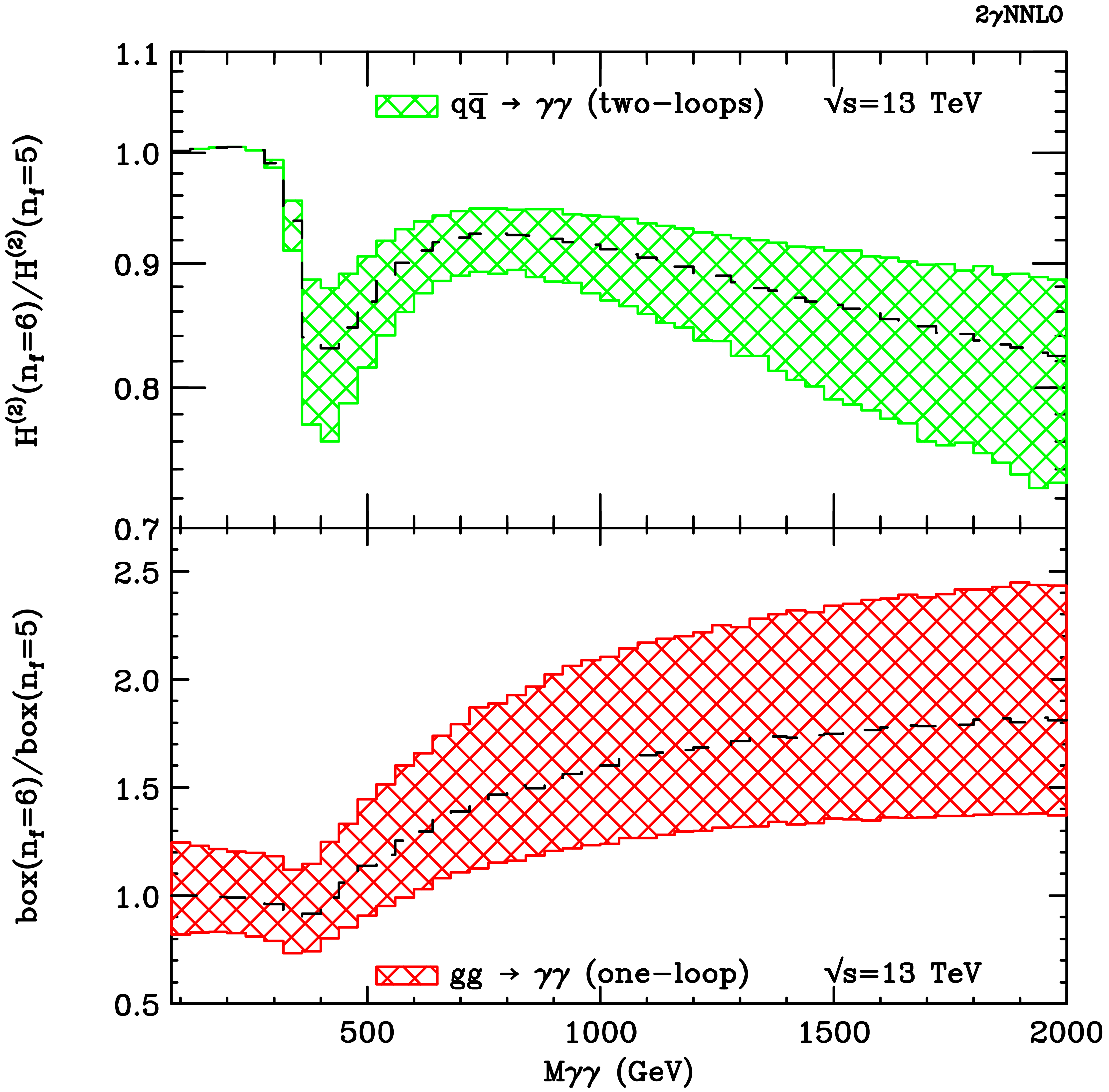
PLA Topology: 32 MIs in $\mathcal{O}(2.5h)$

NPL Topology: 36 MIs in $\mathcal{O}(10.5h)$

On a single core!



Final Results



Fiducial cuts

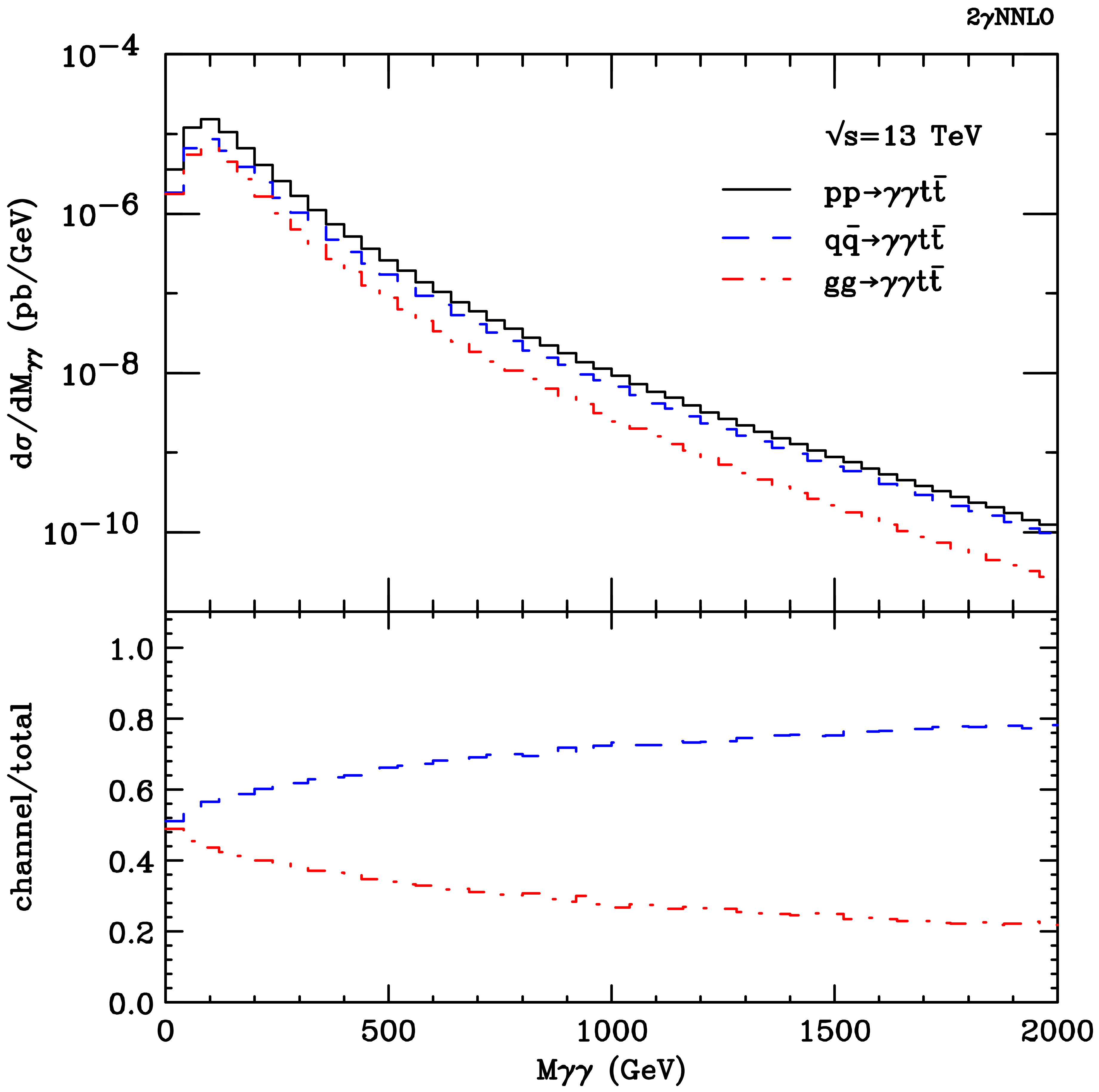
- $\sqrt{s} = 13\ TeV$
- $p_{T_\gamma}^{Hard} \geq 40\ GeV$
- $p_{T_\gamma}^{Soft} \geq 30\ GeV$
- $|y_\gamma| < 2.37$ Excluding $1.37 < |y_\gamma| < 1.52$

[The ATLAS Collaboration]

Smooth isolation cone

- $E_T^{had}(r) \leq \epsilon p_{T_\gamma} \chi(r; R)$
- $\chi(r; R) = \left(\frac{r}{R}\right)^{2n}$
- $R = 0.4$
- $\epsilon = 0.09$
- $n = 1$

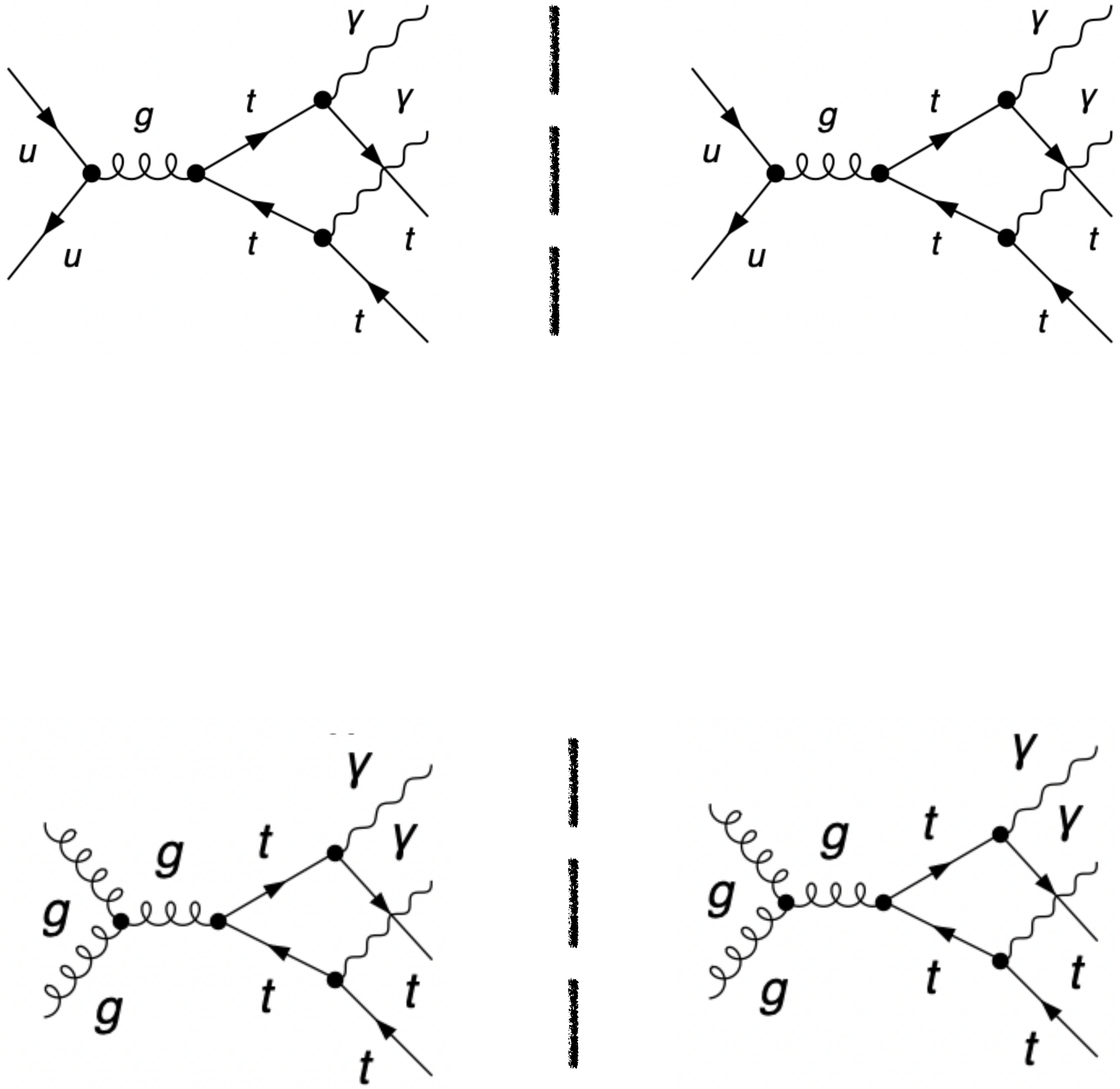
Final Results



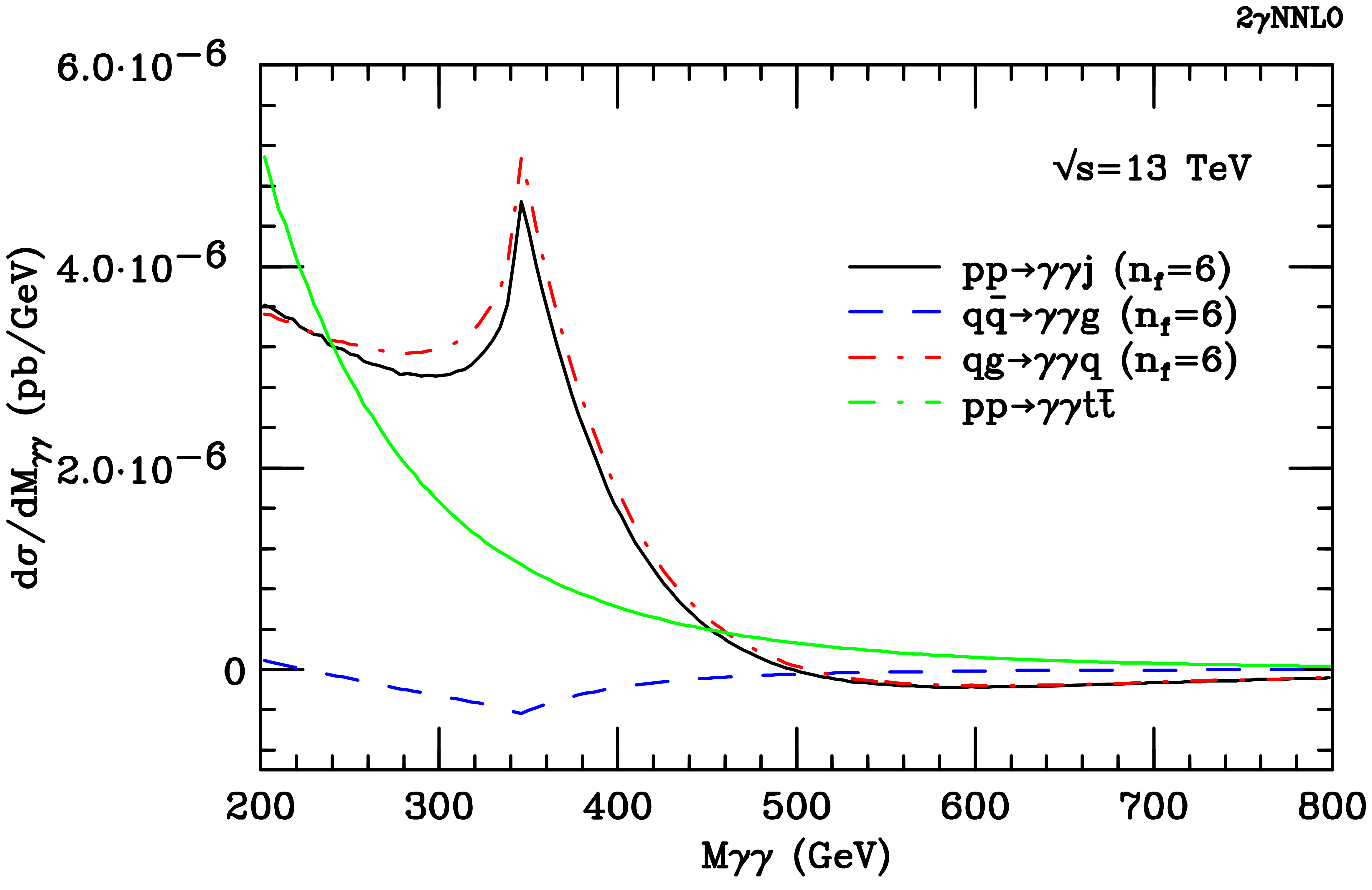
Invariant mass distribution of the Double-Real contribution to the NNLO fully massive result

$q\bar{q} \to t\bar{t}\gamma\gamma$

$gg \to t\bar{t}\gamma\gamma$

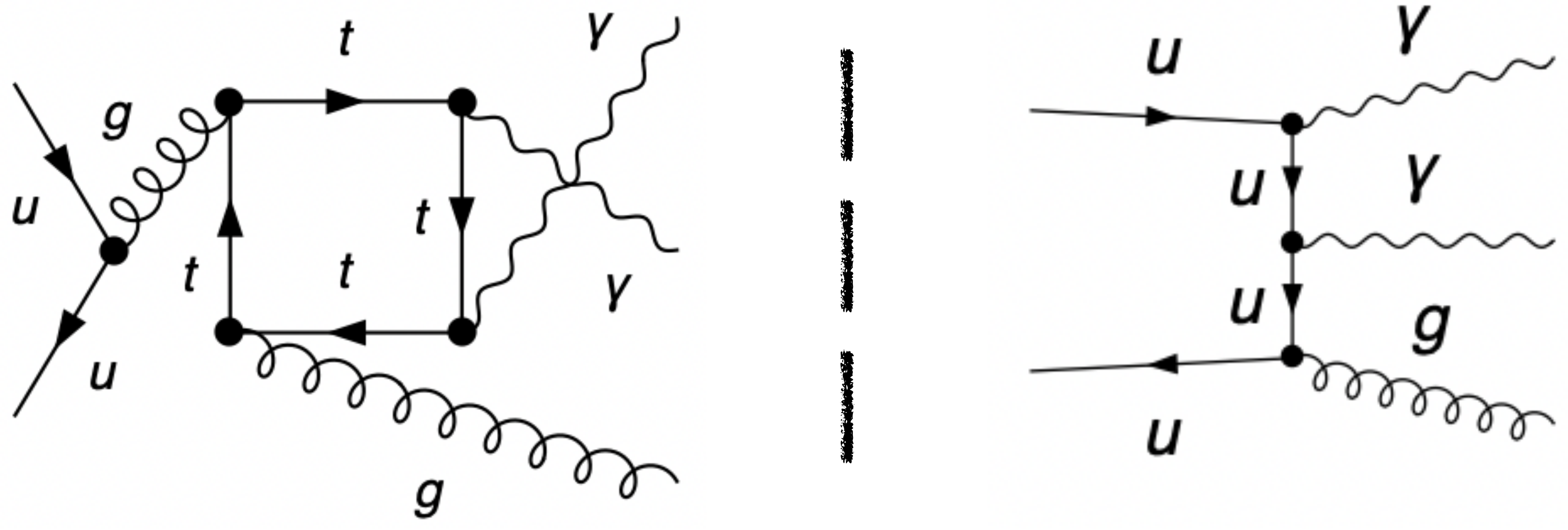


Final Results

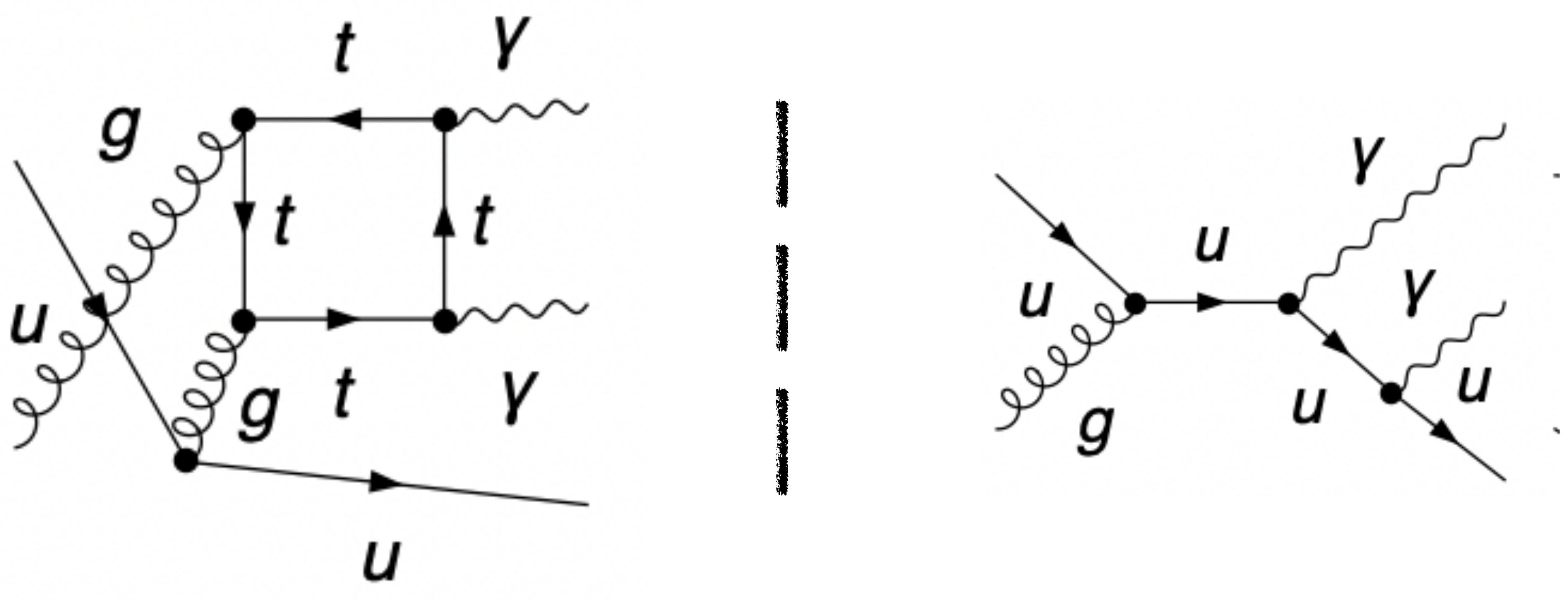


Invariant mass distribution of the one-loop massive contribution at NNLO

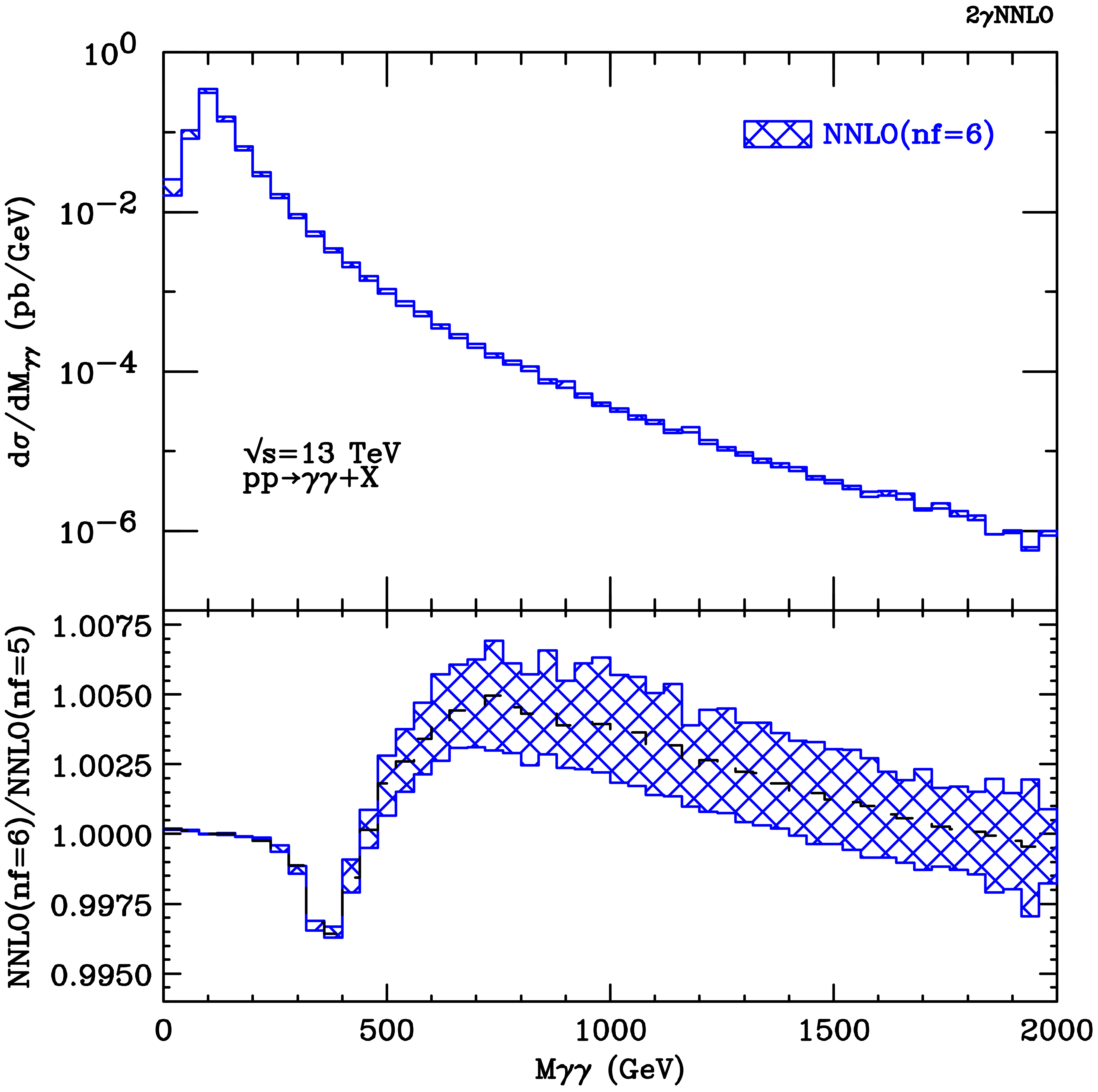
$q\bar{q} \to \gamma\gamma g$



$qg \to \gamma\gamma q$



Final Results



NNLO invariant mass distribution with full top quark mass depencence

Conclusions

- We computed the massive two-loop form factors
- The MIs were evaluated using the generalised power series method
- Computation of the Massive Hard Function NNLO
- We obtained the first phenomenological results for the full massive NNLO diphoton production

THANKS FOR YOUR ATTENTION!