Full NNLO QCD corrections to diphoton production

Federico Coro

IFIC - Universitat de Valencia

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

Outline of the talk

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

State of art

T. Binoth, J. P. Guillet, E. Pilon and M. Werlen, *A Full next-to-leading order study of direct photon pair production in hadronic collisions*, *Eur. Phys. J. C* **16** (2000) 311–330, [hep-ph/9911340].

Z. Bern, L. J. Dixon and C. Schmidt, *Isolating a light Higgs boson from the diphoton background at the CERN LHC*, *Phys. Rev. D* **66** (2002) 074018, [hep-ph/0206194].

S. Catani, L. Cieri, D. de Florian, G. Ferrera and M. Grazzini, *Diphoton production at hadron colliders: a fully-differential QCD calculation at NNLO*, *Phys. Rev. Lett.* **108** (2012) 072001, [1110.2375].

V. Del Duca, F. Maltoni, Z. Nagy and Z. Trocsanyi, *QCD radiative corrections to prompt diphoton production in association with a jet at hadron colliders*, *JHEP* **04** (2003) 059, [hep-ph/0303012].

Z. Bern, A. De Freitas and L. J. Dixon, *Two loop amplitudes for gluon fusion into two photons*, *JHEP* **0109** (2001) 037 [hep-ph/0109078].

J. M. Campbell and C. Williams, *Triphoton production at hadron colliders*, *Phys.Rev.* **D89** (2014) 113001 [1403.2641].

P. Bargiela, A. Chakraborty and G. Gambuti, *Three-loop helicity amplitudes for photon+jet production*, *Phys. Rev. D* **107** (2023) L051502 [2212.14069].

P. Bargiela, F. Buccioni, F. Caola, F. Devoto, A. von Manteuffel and L. Tancredi, *Signal-background interference effects in Higgs-mediated diphoton production beyond NLO*, *Eur. Phys. J. C* **83** (2023) 174 [2212.06287].

J. M. Campbell, R. K. Ellis, Y. Li and C. Williams, *Predictions for diphoton production at the LHC through NNLO in QCD*, *JHEP* **07** (2016) 148, [1603.02663].

S. Frixione, *Isolated photons in perturbative QCD*, *Phys. Lett. B* **429** (1998) 369–374, [hep-ph/9801442].

M. Becchetti and R. Bonciani, *Two-Loop Master Integrals for the Planar QCD Massive Corrections to Di-photon and Di-jet Hadro-production*, *JHEP* **01** (2018) 048, [1712.02537].

F. Maltoni, M. K. Mandal and X. Zhao, *Top-quark effects in diphoton production through gluon fusion at next-to-leading order in QCD*, *Phys. Rev. D* **100** (2019) 071501, [1812.08703].

V. Del Duca, W. B. Kilgore and F. Maltoni, *Multiphoton amplitudes for next-to-leading order QCD*, *Nucl.Phys.* **B566** (2000) 252–274 [hep-ph/9910253].

F. Caola, A. Von Manteuffel and L. Tancredi, *Diphoton Amplitudes in Three-Loop Quantum Chromodynamics*, *Phys. Rev. Lett.* **126** (2021) 112004, [2011.13946].

P. Bargiela, F. Caola, A. von Manteuffel and L. Tancredi, *Three-loop helicity amplitudes for diphoton production in gluon fusion*, *JHEP* **02** (2022) 153 [2111.13595].

H. A. Chawdhry, M. Czakon, A. Mitov and R. Poncelet, *NNLO QCD corrections to diphoton production with an additional jet at the LHC*, *JHEP* **09** (2021) 093 [2105.06940].

Massive Corrections

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

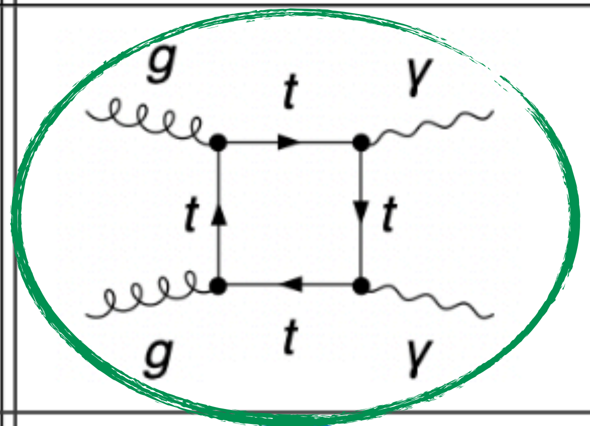
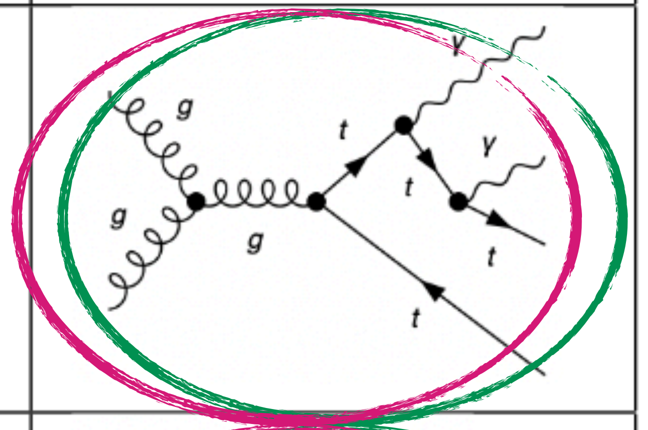
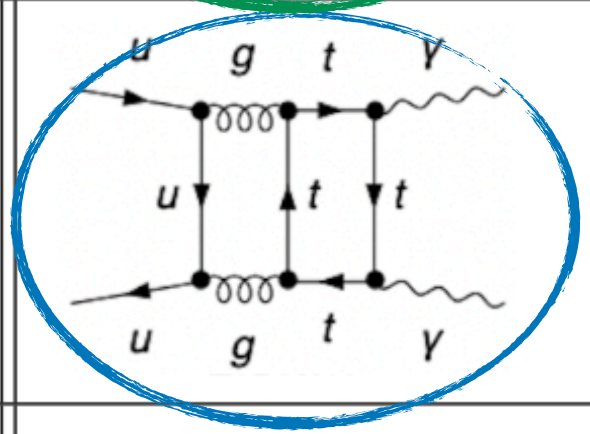
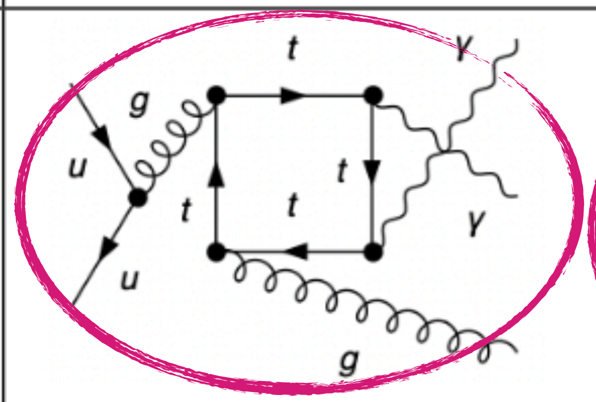
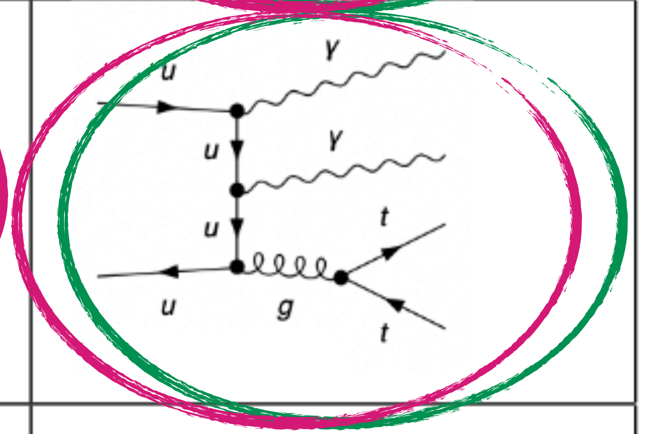
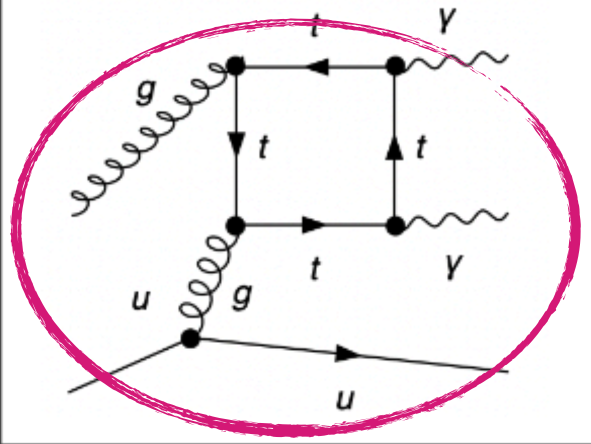
Channels	$\gamma\gamma$	$\gamma\gamma j$	$\gamma\gamma jj$
gg			
$q\bar{q}$			
qg			

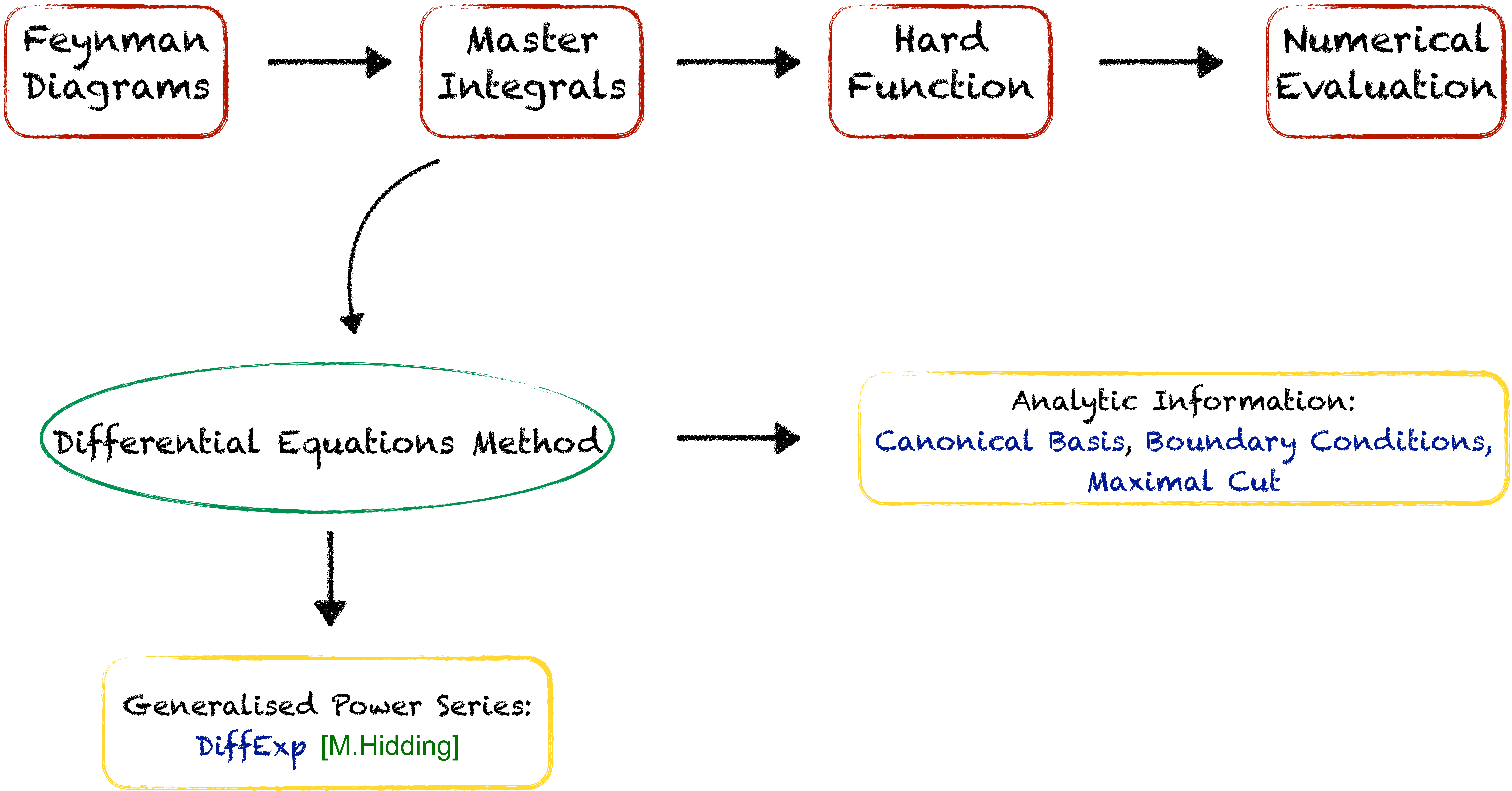
Diagram — [J.M.Campbell,R.K.Ellis,Y.Li,C.Williams]

[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 $\mathcal{O}(\alpha_s^2)$:

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

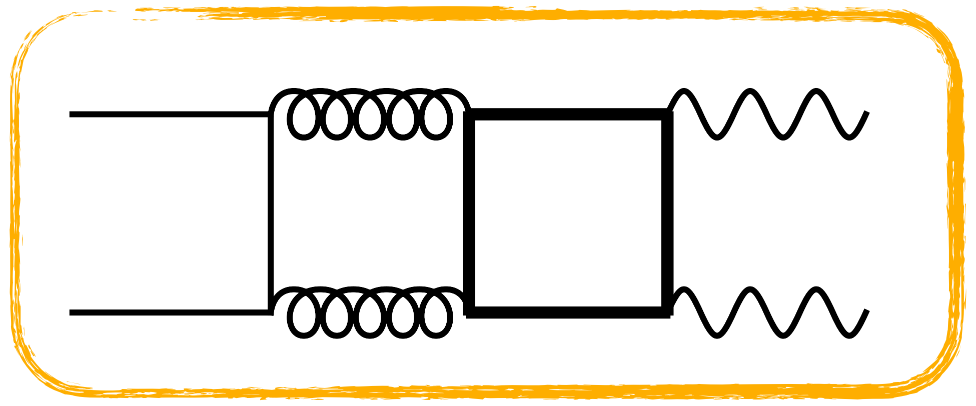
Q_q is the charge of light quark
Q_t is the charge of heavy quark

Two-loop Feynman diagrams

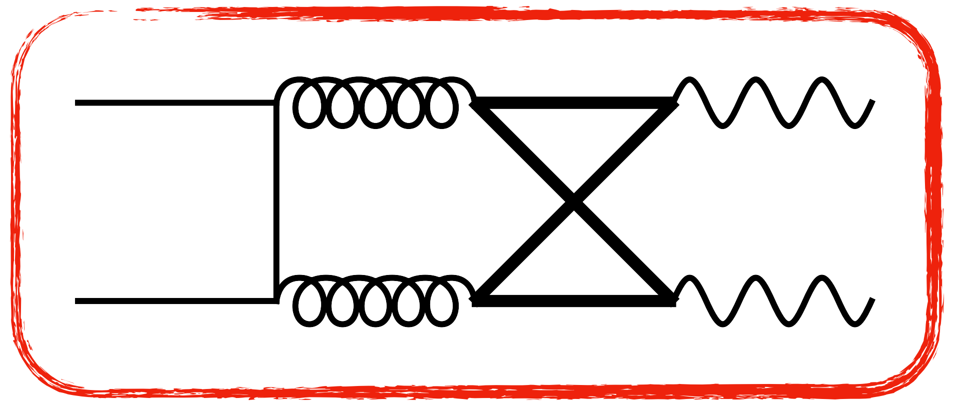
At partonic level the scattering process is: $q(p_1) + \bar{q}(p_2) \rightarrow \gamma(p_3) + \gamma(p_4)$

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

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

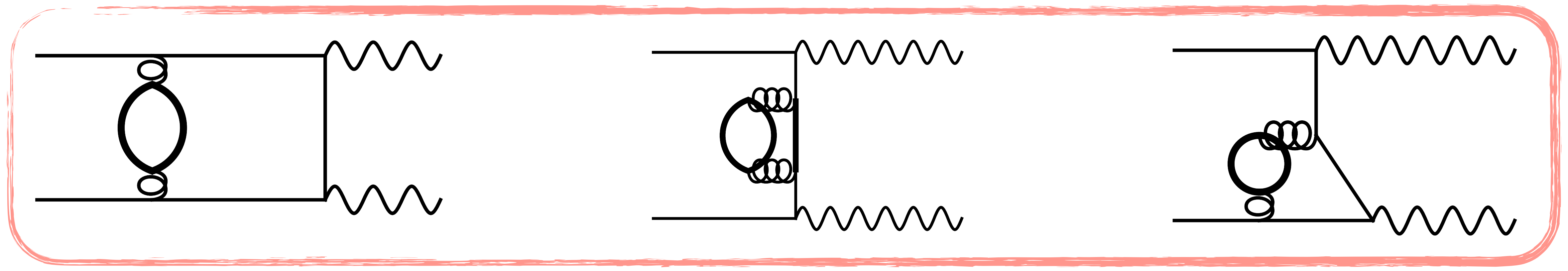


PLA



NPL

The MIs for the top-sector
NPL are an original result

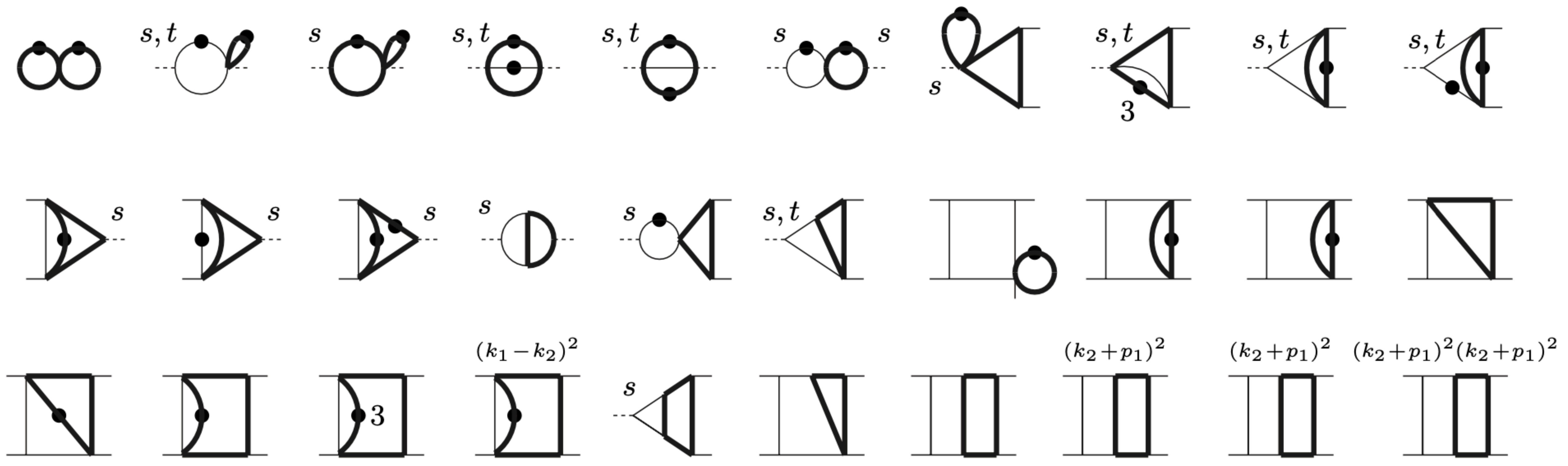


PLB

Form factors → Scalar integrals → IBPs reduction → **PLA: 32 MIs** **NPL: 36 MIs** **PLB: 10 MIs**

Master Integrals

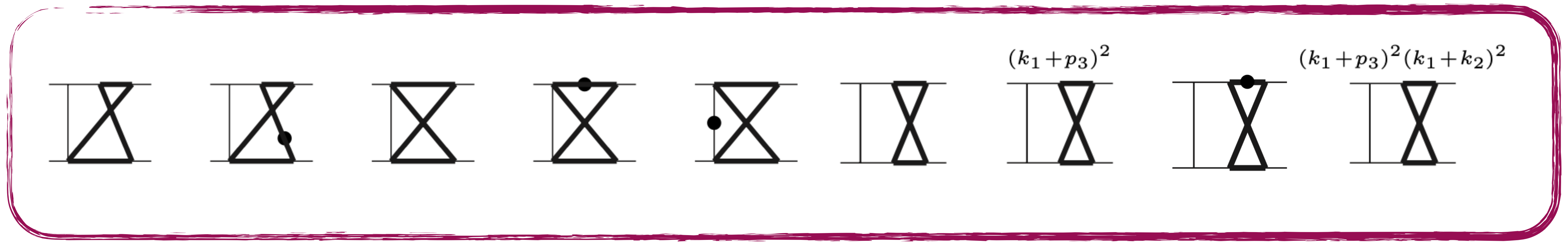
PLA and PLB
Master Integrals



[M.Becchetti,R.Bonciani]

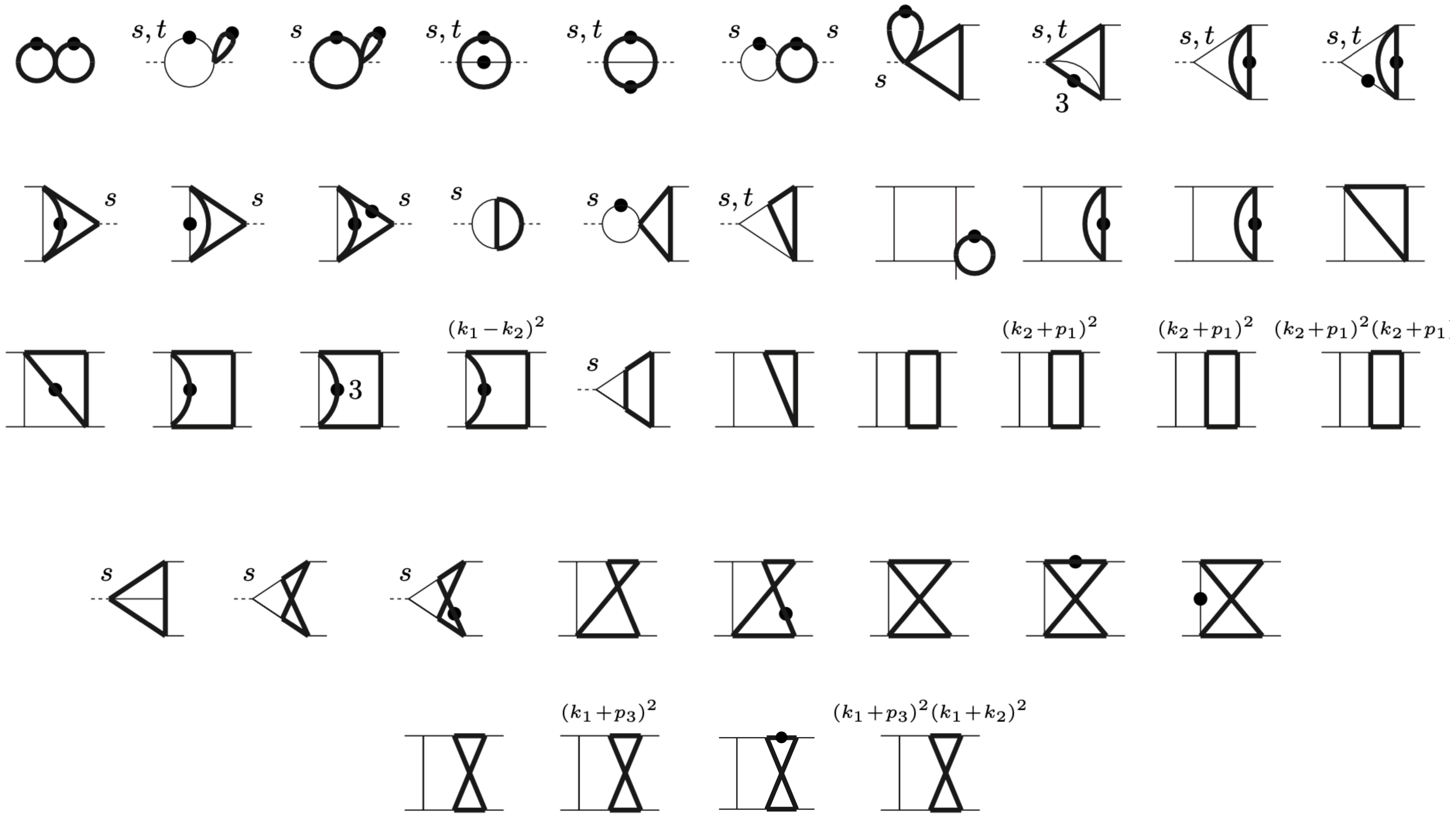
[A.Von Manteuffel,L.Tancredi]

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

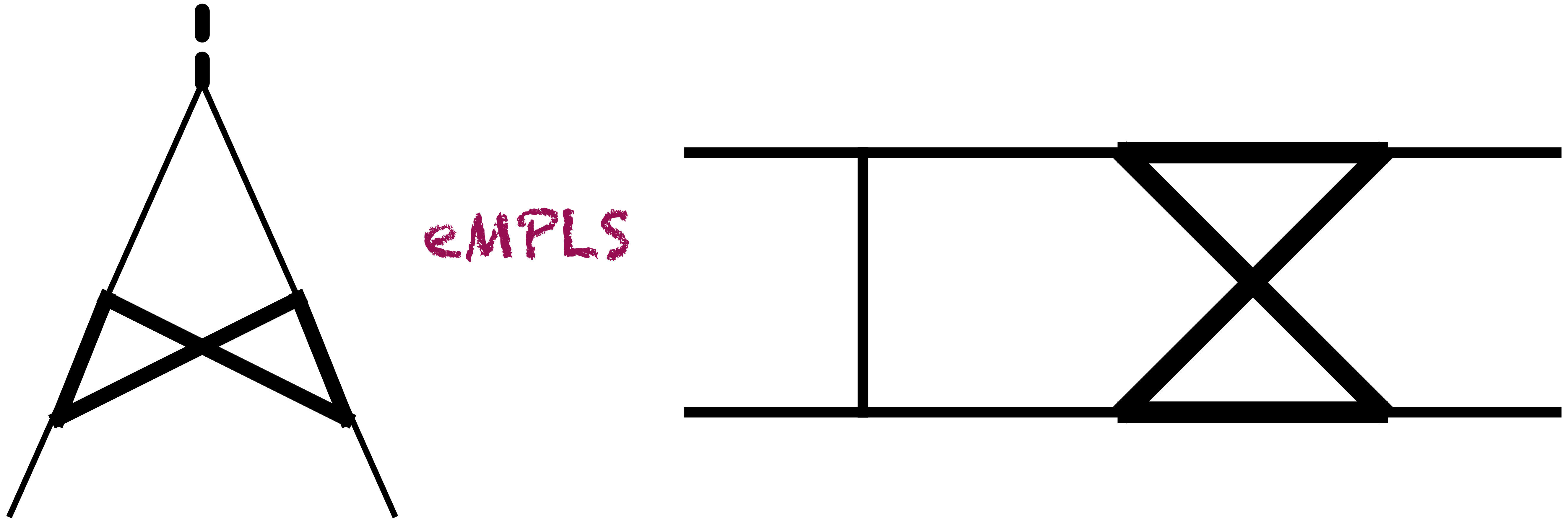
NPL family:

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

Two different subsets

Canonical logarithmic

Elliptic Sectors

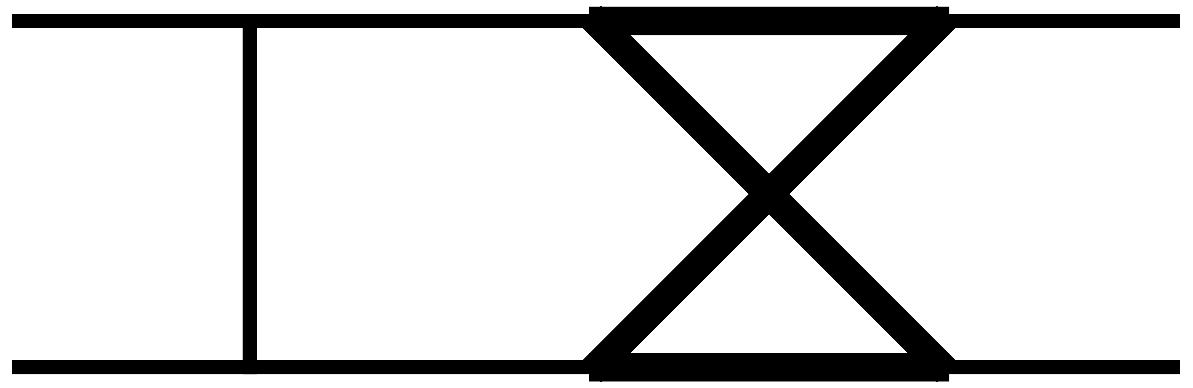


- Non trivial solution!
- Nine square roots in the alphabet
- Integrals involving eMPLs kernels

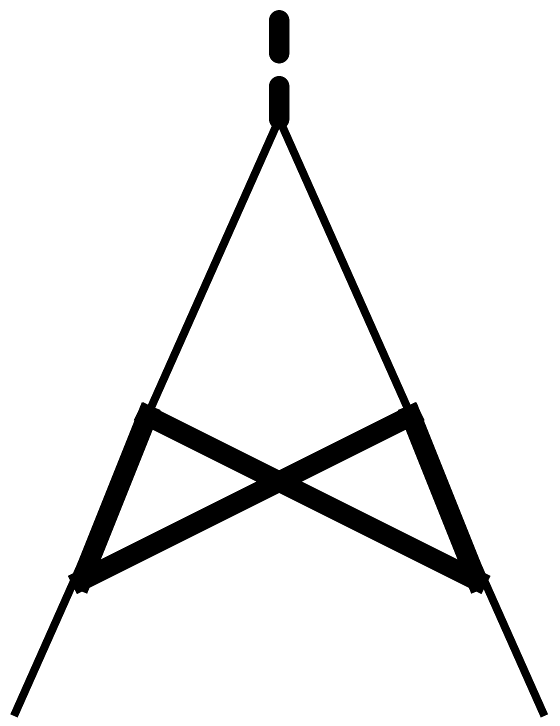
[A.Von Manteuffel,L.Tancredi]

Maximal Cut

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



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



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

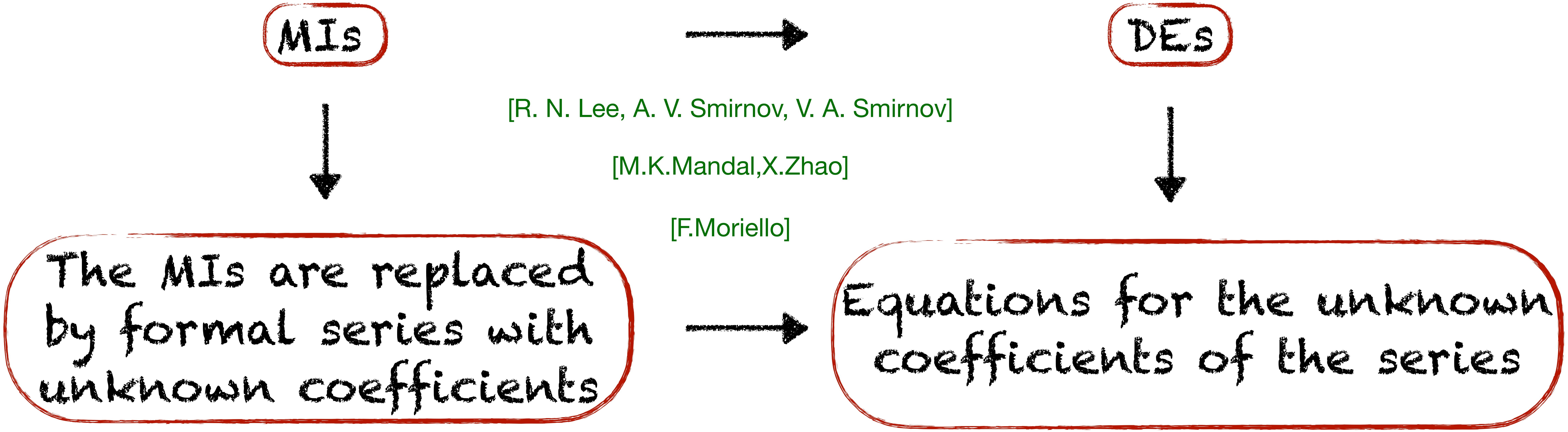
[J.Broedel,C.Duhr,F.Dulat,B.Penante,L.Tancredi]

$$z_\pm = \frac{1}{2}\left(-s - 2t \pm \sqrt{s}\sqrt{s + 16m_t^2}\right), \; b_\pm = \frac{1}{2}(1 \pm \sqrt{1 - 16a}), \; a = \frac{m^2}{-(p_1 + p_2)^2}$$

Genus one

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

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 50 digits!

Imaginary Part

Real Part

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

Renormalisation

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

We remove the UV poles by adopting a mixed renormalisation scheme:

- $\overline{MS}$ for α_s
- On-shell for the external fields

Renormalised form factor: $\overline{\mathscr{F}}_i = Z_q \mathscr{F}_i(\alpha_s^B \to \alpha_s^R)$ $\xrightarrow{\text{Perturbative expansion}}$ $\overline{\mathscr{F}}_i = \overline{\mathscr{F}}_i^{(0)} + \left(\frac{\alpha_s}{\pi}\right)\overline{\mathscr{F}}_i^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \overline{\mathscr{F}}_i^{(2)} + \cdots$

Then, for the two-loop:

$$\overline{\mathscr{F}}_i^{(2)} = C_F N_h \left(\frac{1}{32\epsilon} - \frac{5}{192}\right)\mathscr{F}_i^{(0)} + \frac{N_h}{6\epsilon}\mathscr{F}_i^{(1)} + \mathscr{F}_i^{(2)}$$

Hard Function

In q_T - subtraction scheme:

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

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:

$$\mathscr{H}^{\gamma\gamma} = 1 + \frac{\alpha_S}{\pi}\mathscr{H}^{\gamma\gamma}_{\mathrm{NLO}} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathscr{H}^{\gamma\gamma}_{\mathrm{NNLO}} + \cdots$$

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

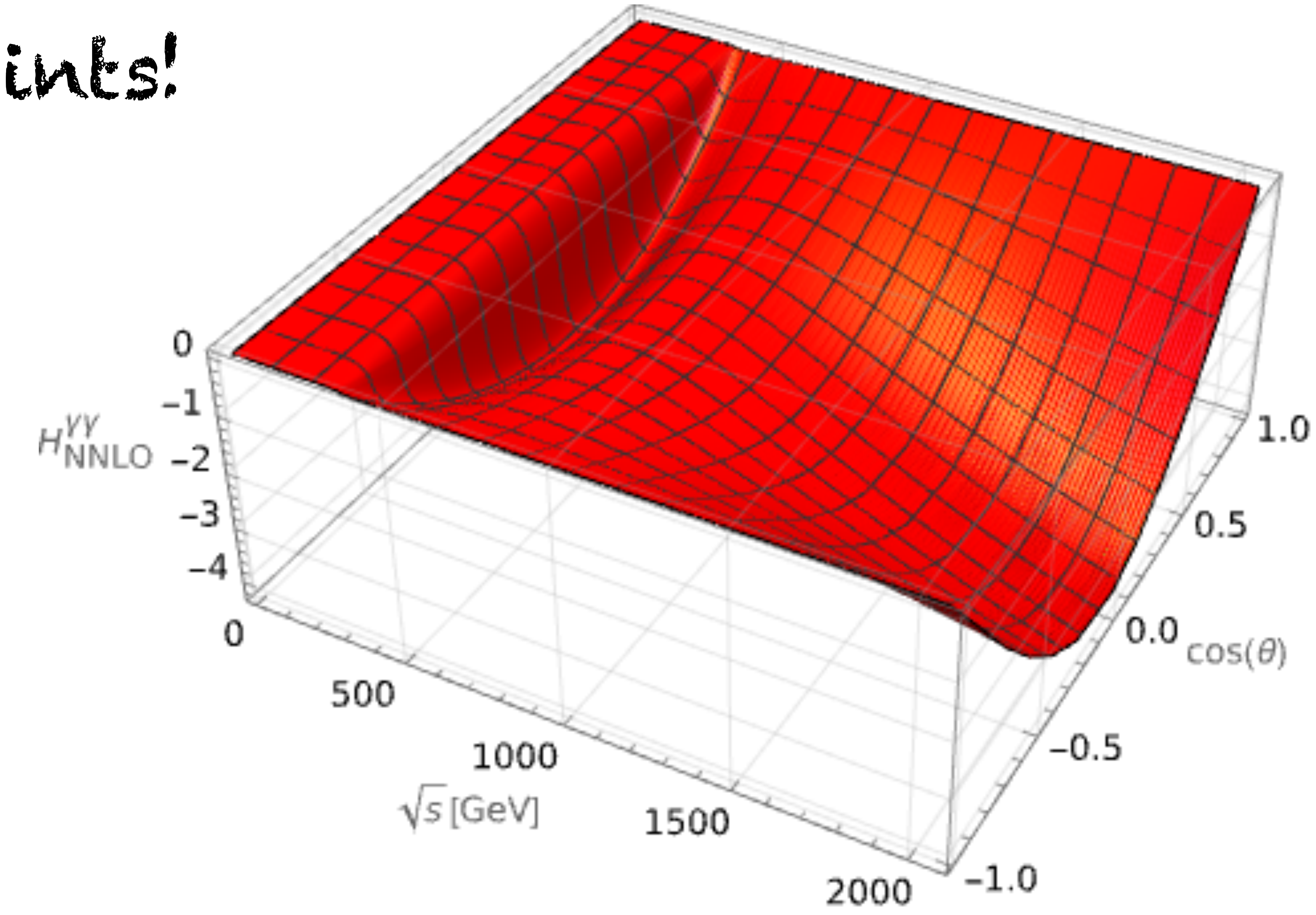
13752 points!

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

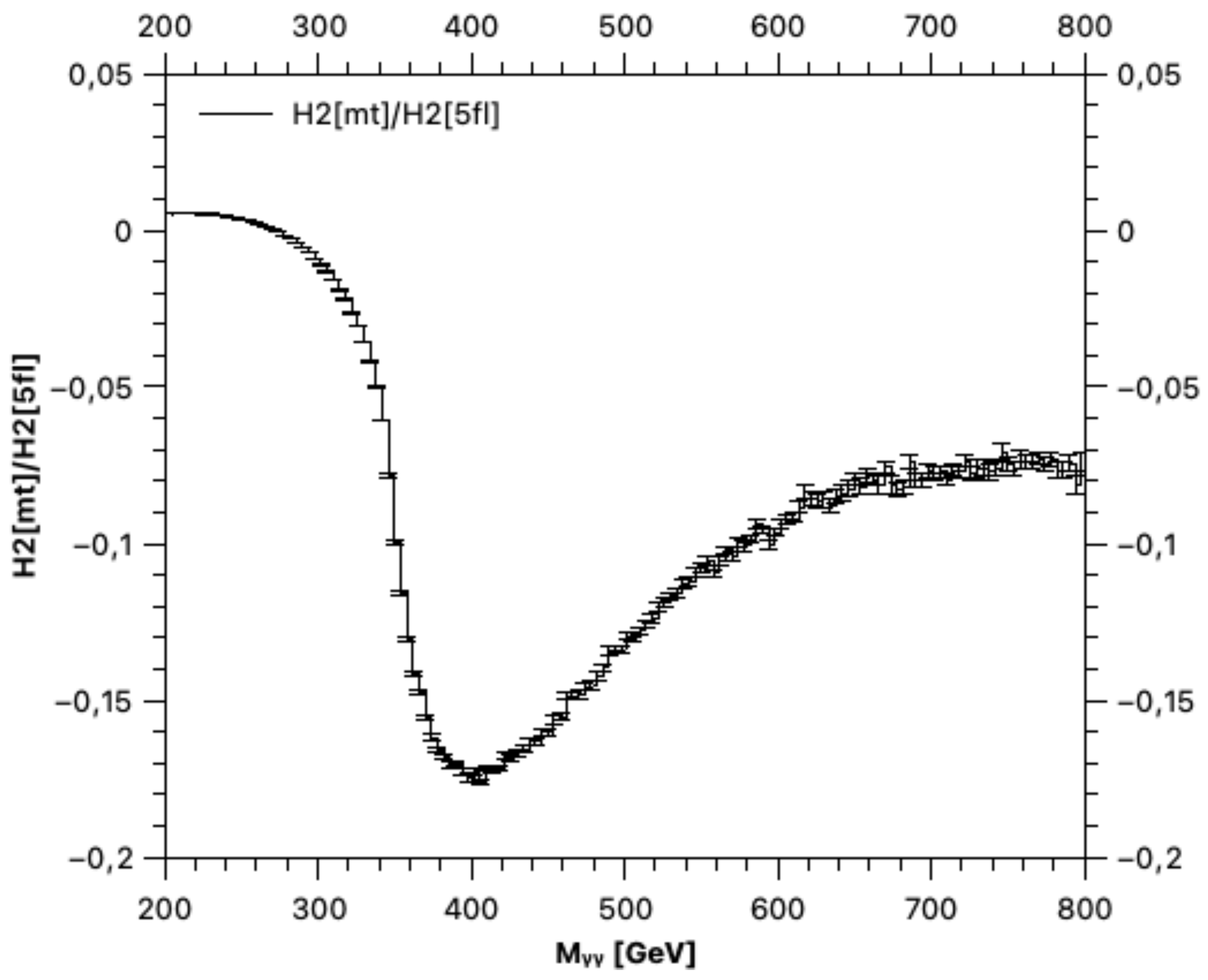
PLA Topology: 32 MIs in $\mathcal{O}(2.5h)$

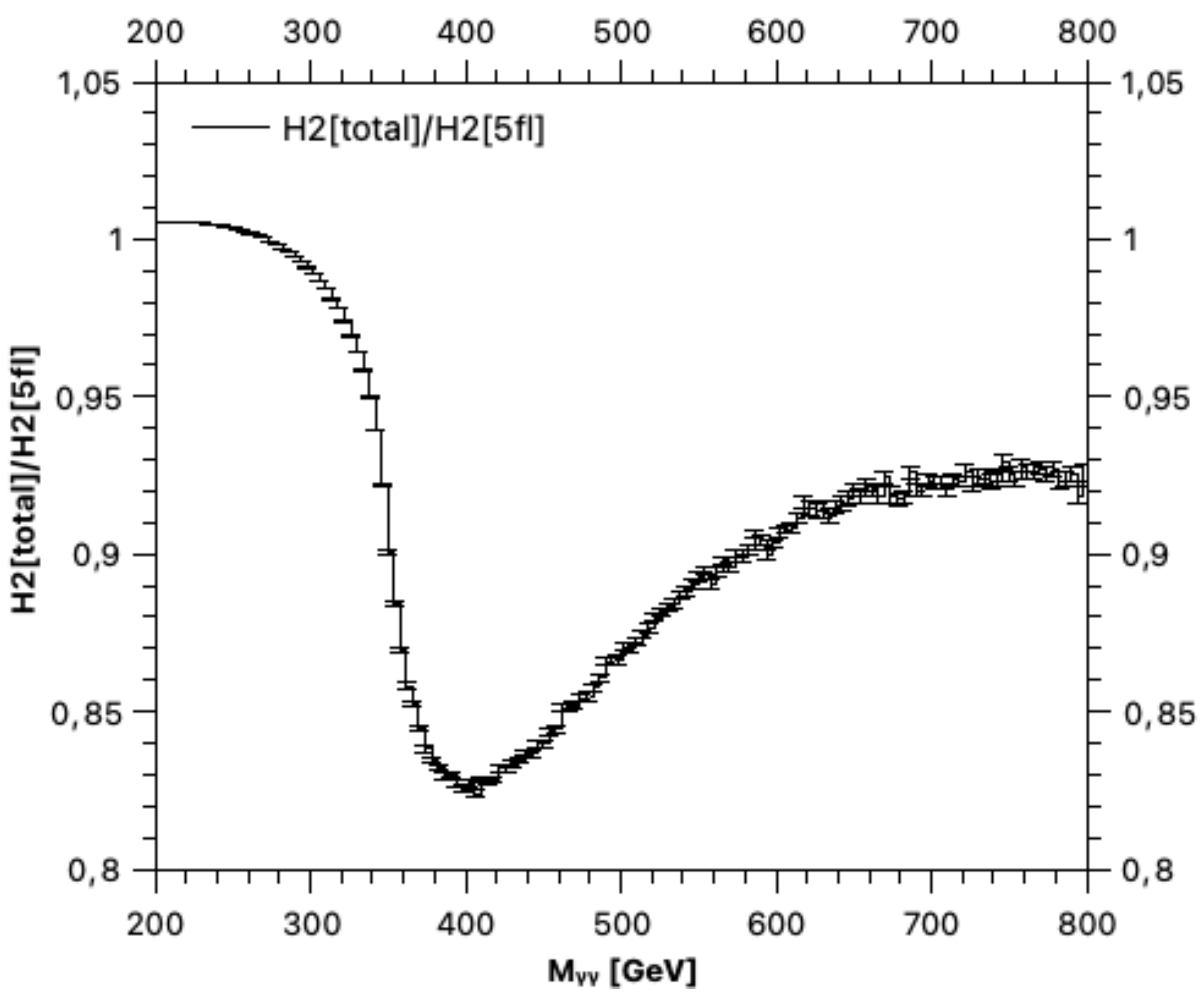
NPL Topology: 36 MIs in $\mathcal{O}(10.5h)$

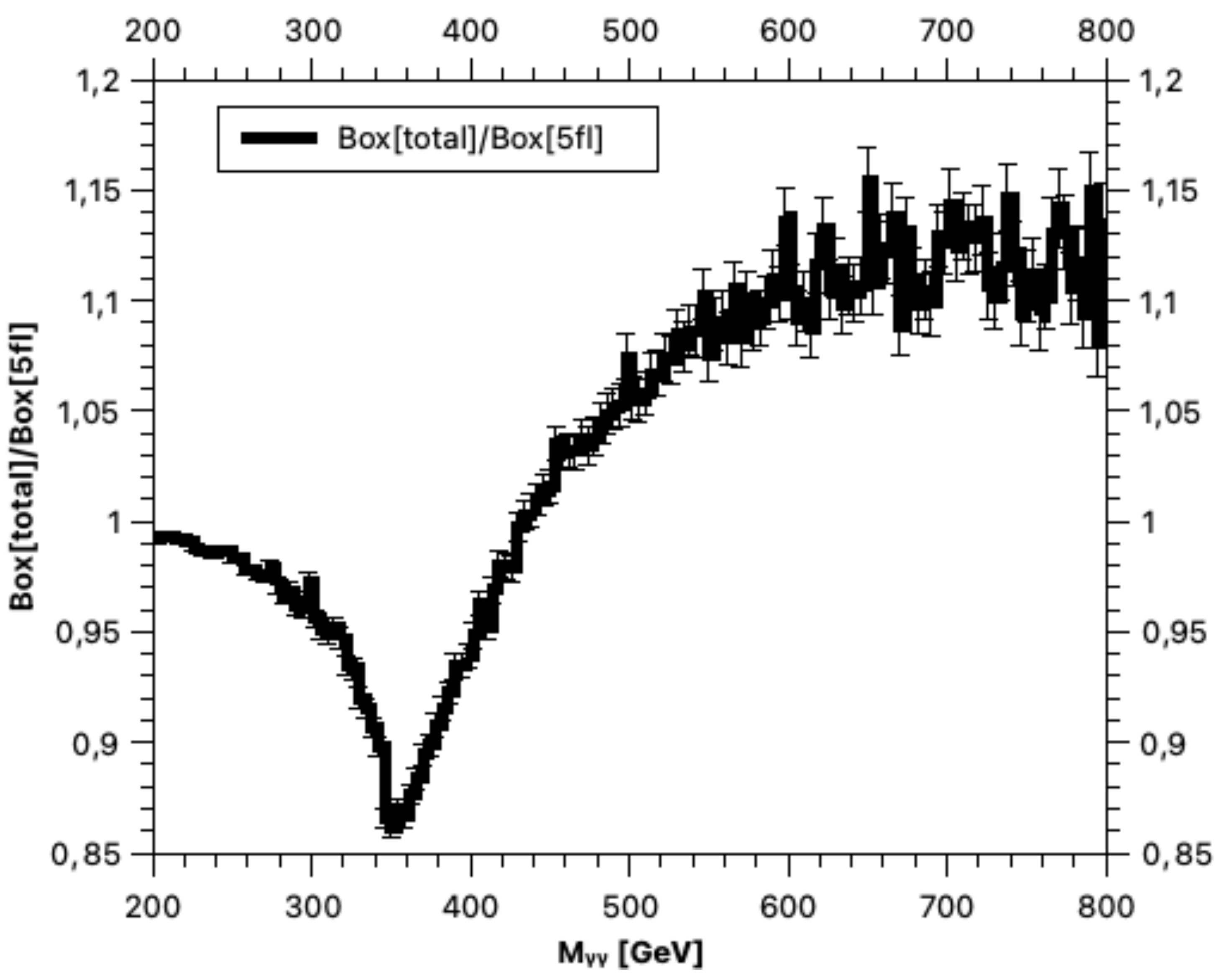
On a single core!



Results







Fiducial cuts

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

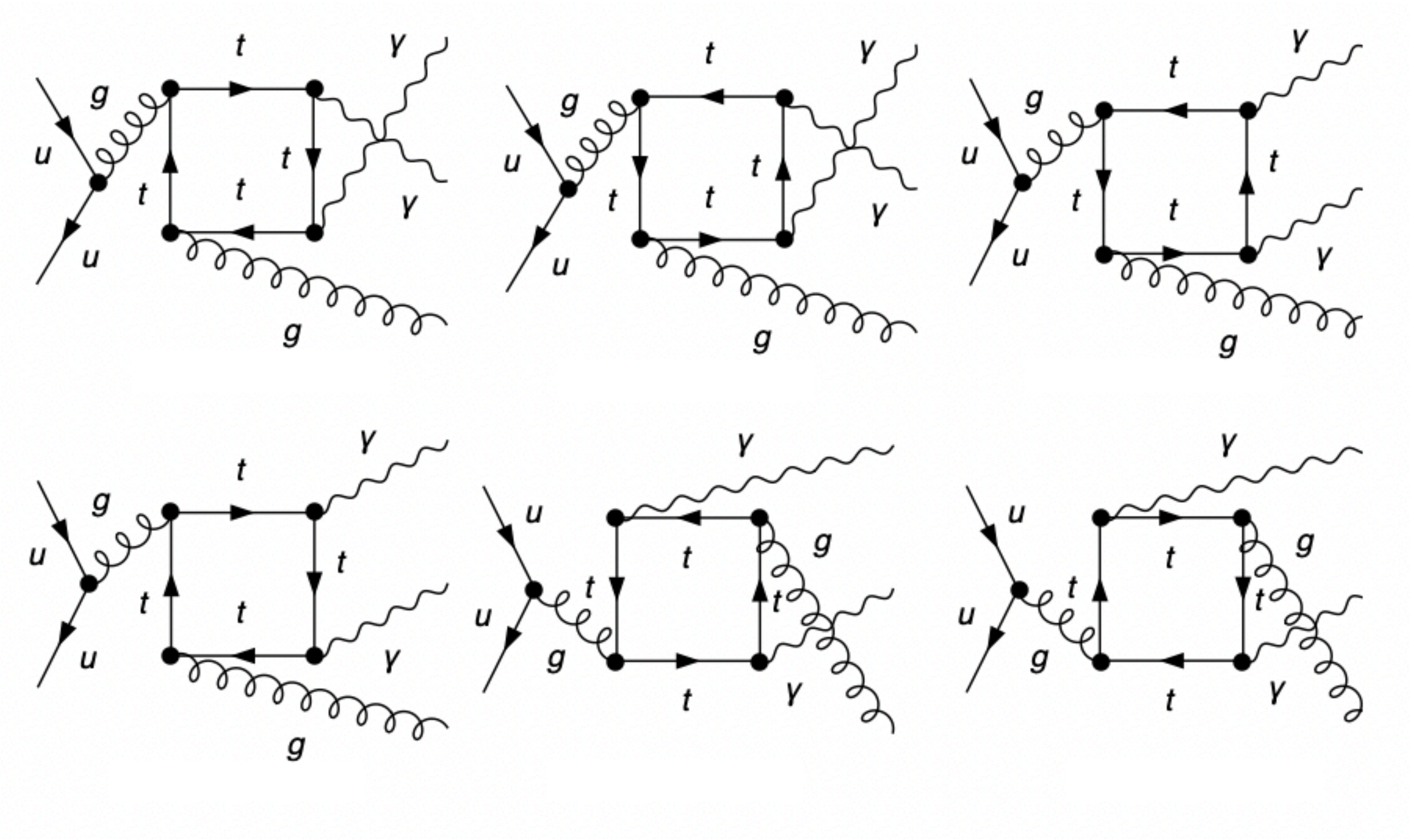
[The ATLAS Collaboration]

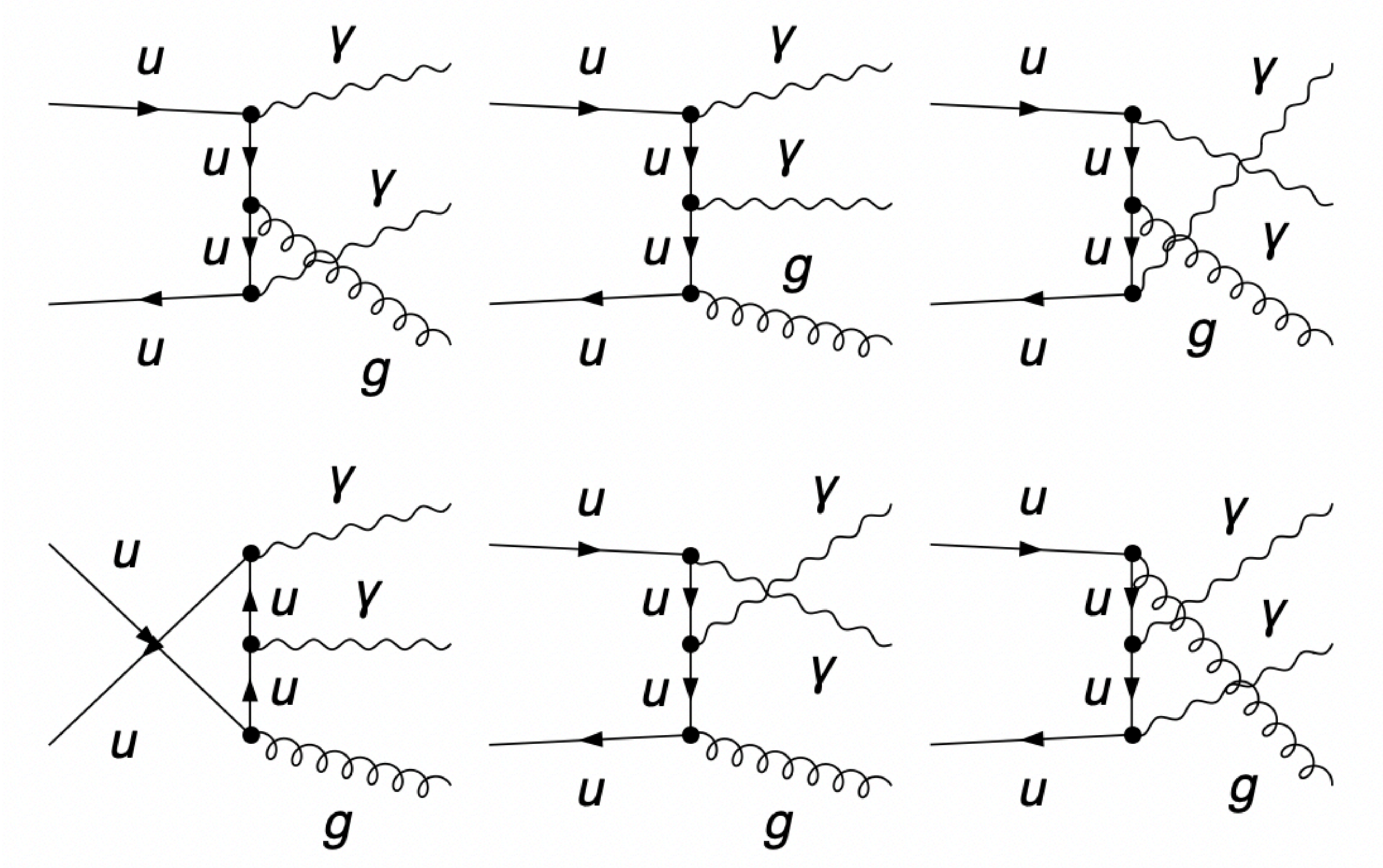
Smooth isolation cone

- $E_T^{had}(\delta) \leq E_{T_{max}}^{had} \chi(\delta)$
- $\Delta R = 0.2$
  $\Delta R_{\gamma\gamma} > 0.4$

Real-Virtual Contributions

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





$q\bar{q}$ - channel

Analytic Computation of the Master Integrals

[G.'t Hooft,M.Veltman]

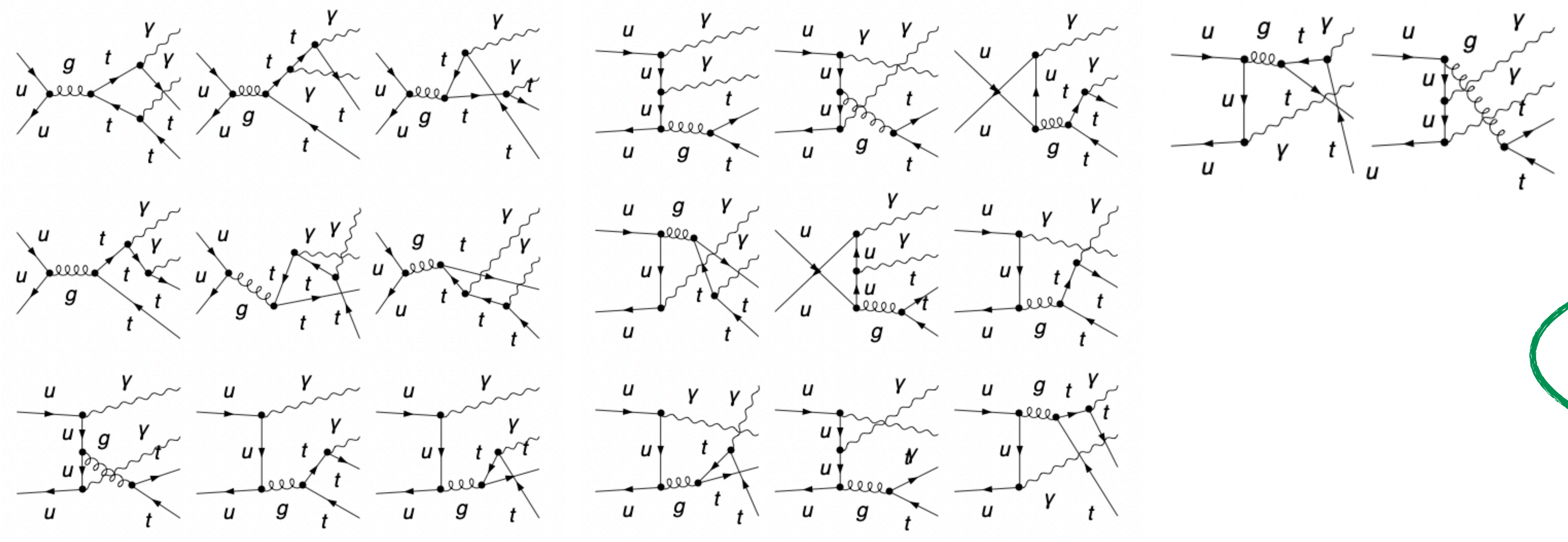
[R.K.Ellis,G.Zanderighi]

[A.Denner,S.Dittmaier]

qg - channel is considered as well!

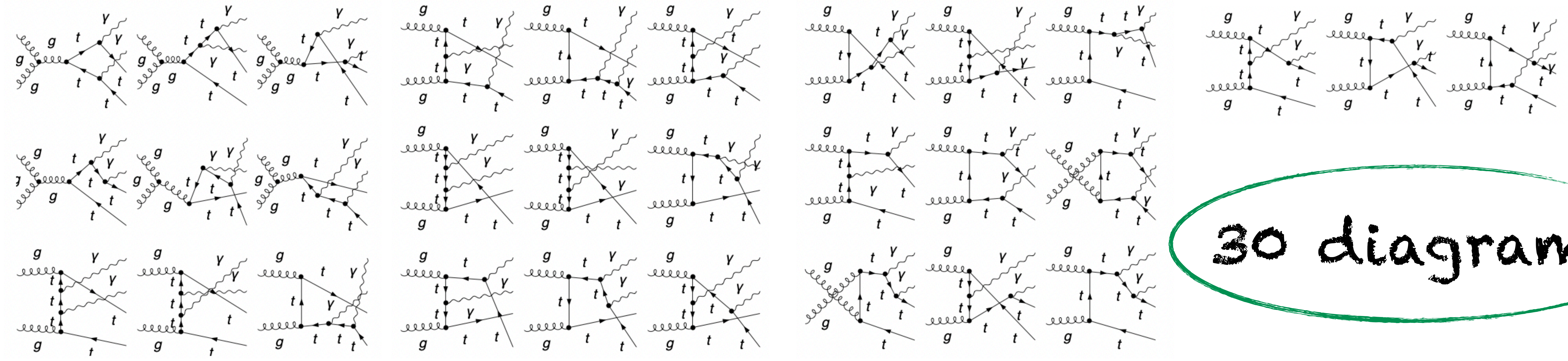
Double Real Contributions

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



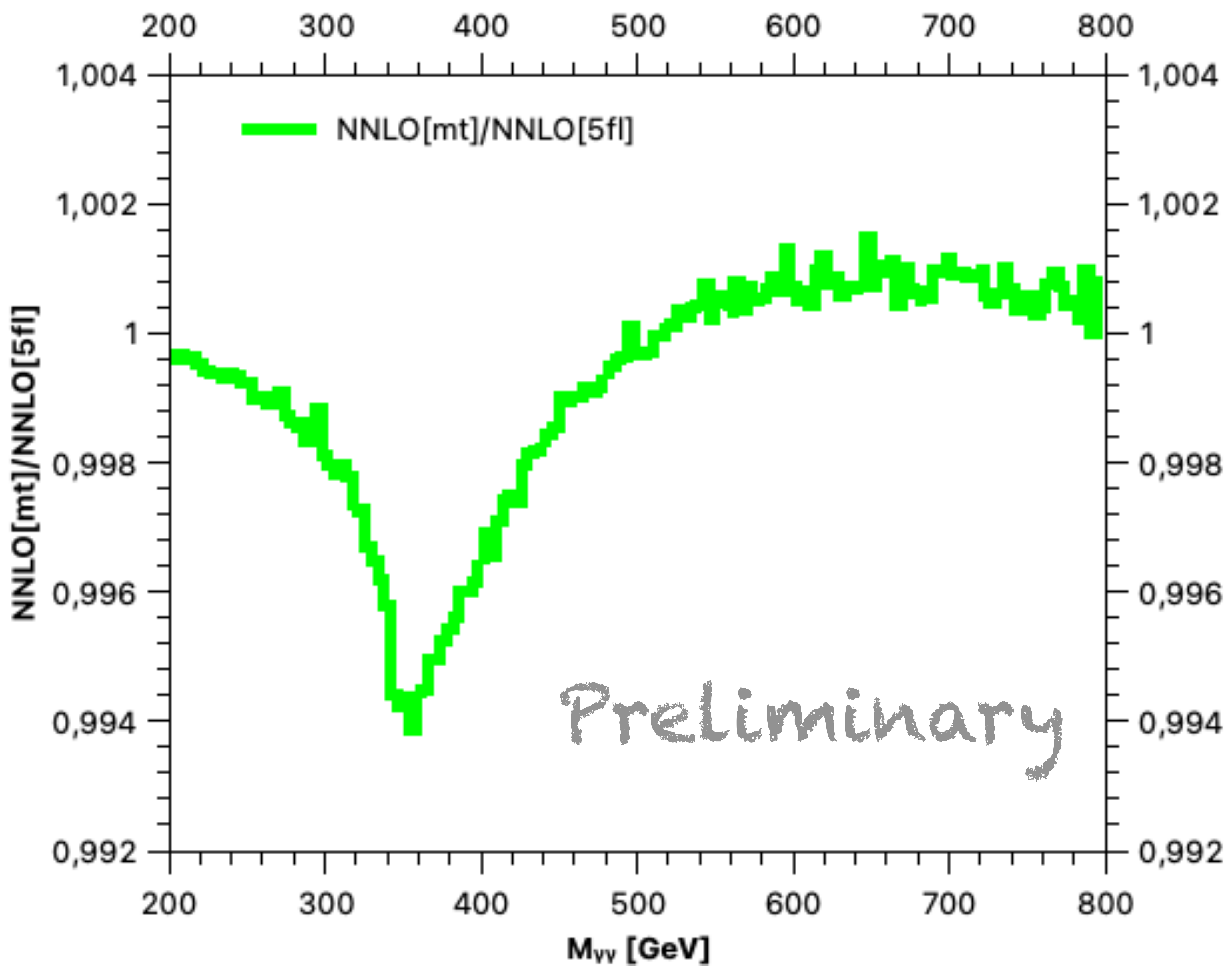
20 diagrams

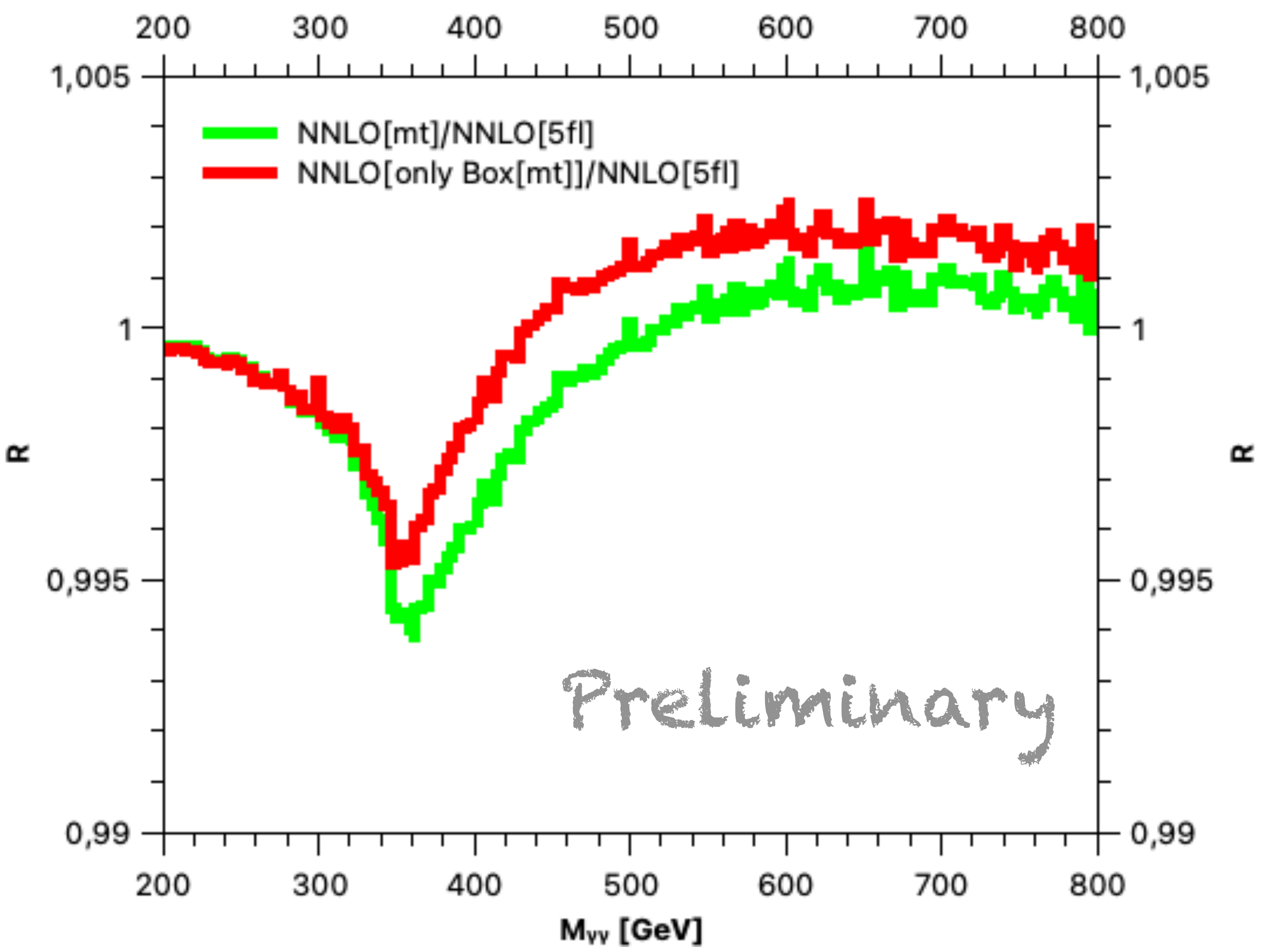
$gg \to t\bar{t}\gamma\gamma$



30 diagrams

Final Results





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 some preliminary results for the phenomenological part

Outlooks

- We are about to finish a complete study of the phenomenology with all the massive contributions that until now have not been considered