FALKO DULAT

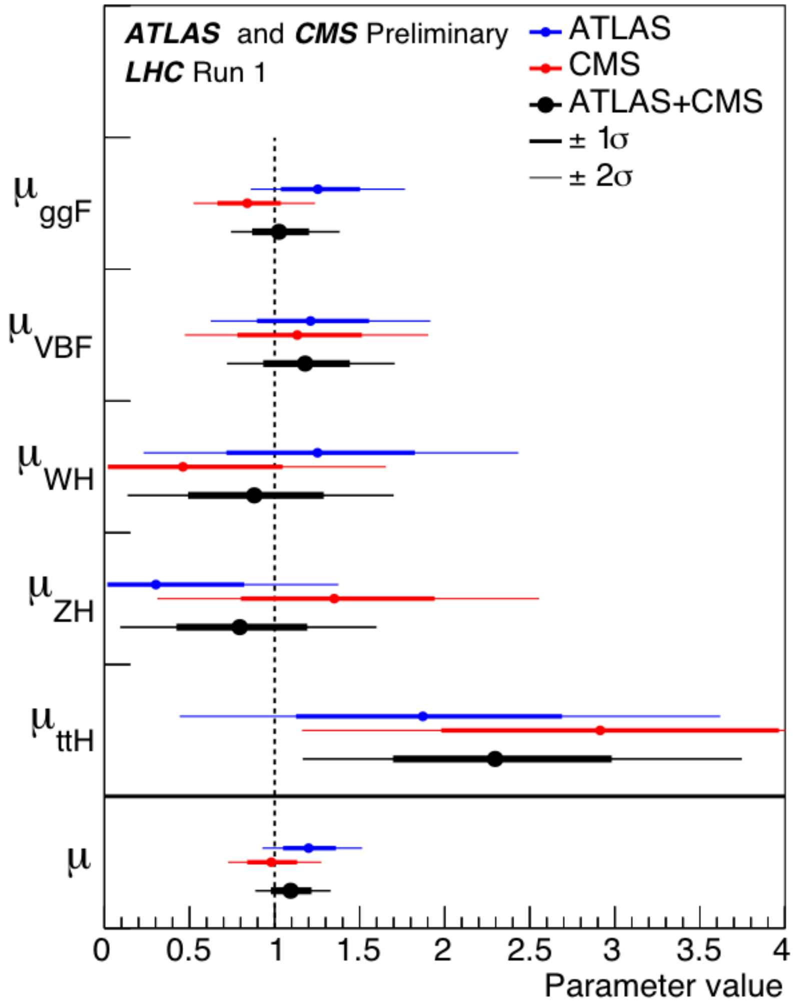
SLAC

TOWARDS DIFFERENTIAL HIGGS PRODUCTION AT N3LO

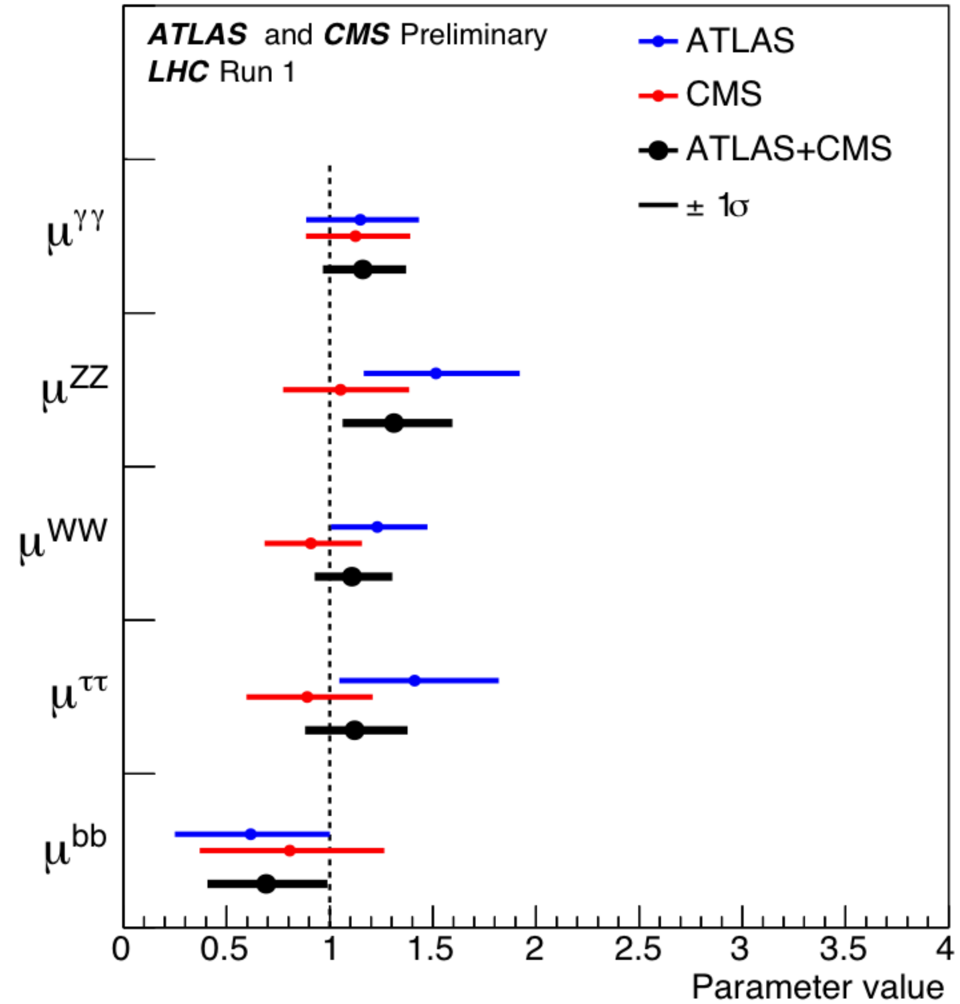
IN COLLABORATION WITH

SIMONE LIONETTI, BERNHARD MISTLBERGER, ANDREA PELLONI, CATERINA SPECCHIA

$$\mu_i = \sigma_i/(\sigma_i)_{SM}$$

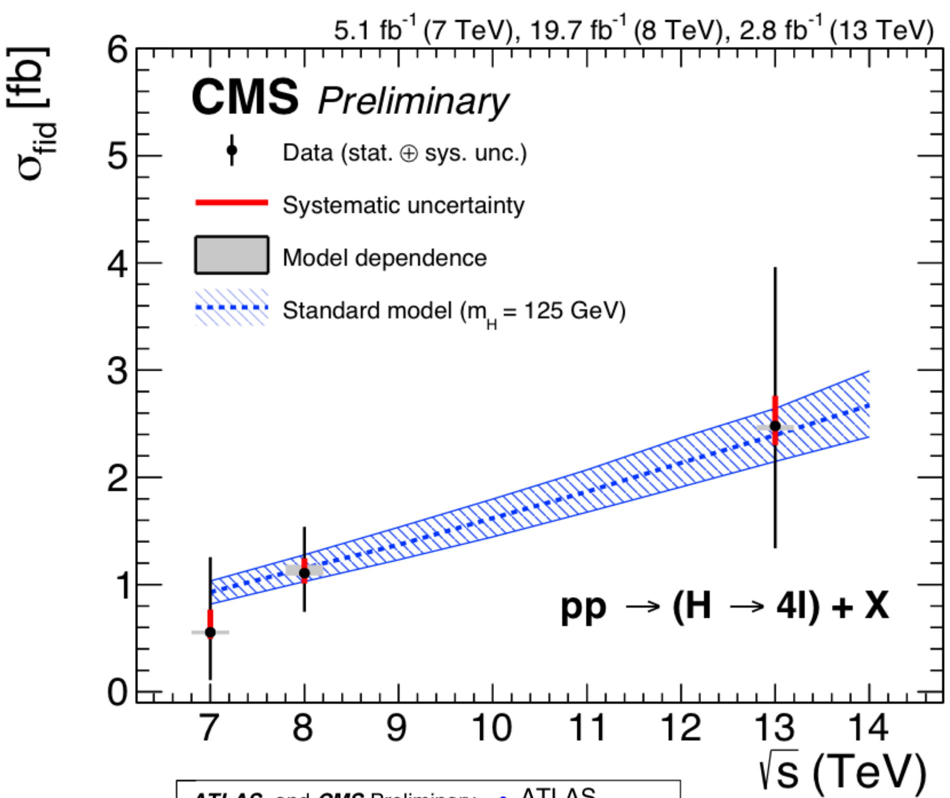


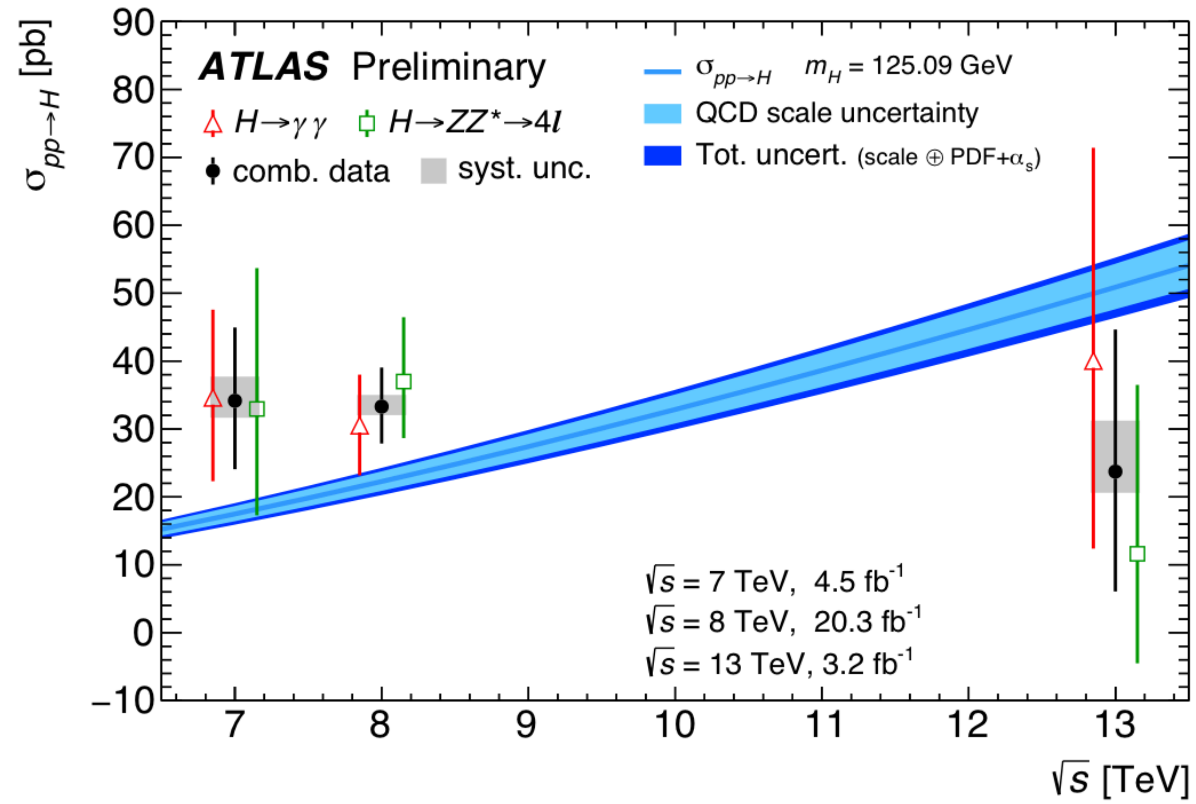
$$\mu_f = \mathrm{BR}_f/(\mathrm{BR}_f)_{SM}$$

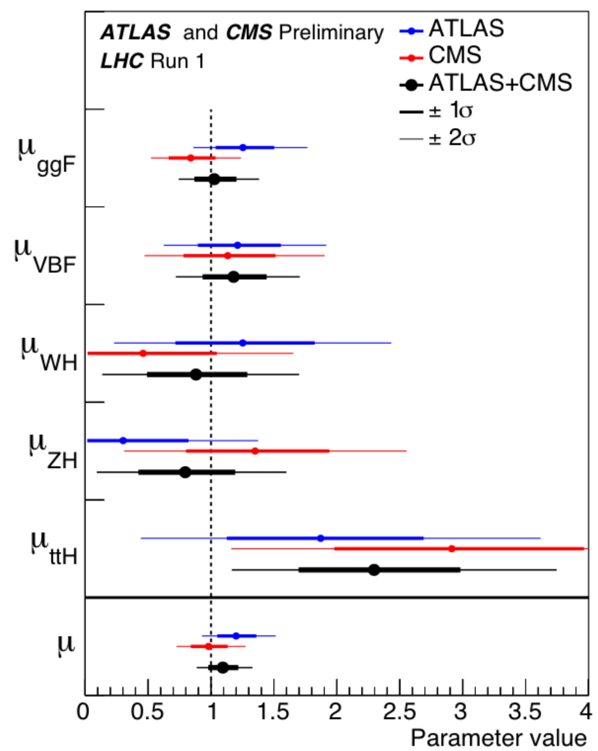


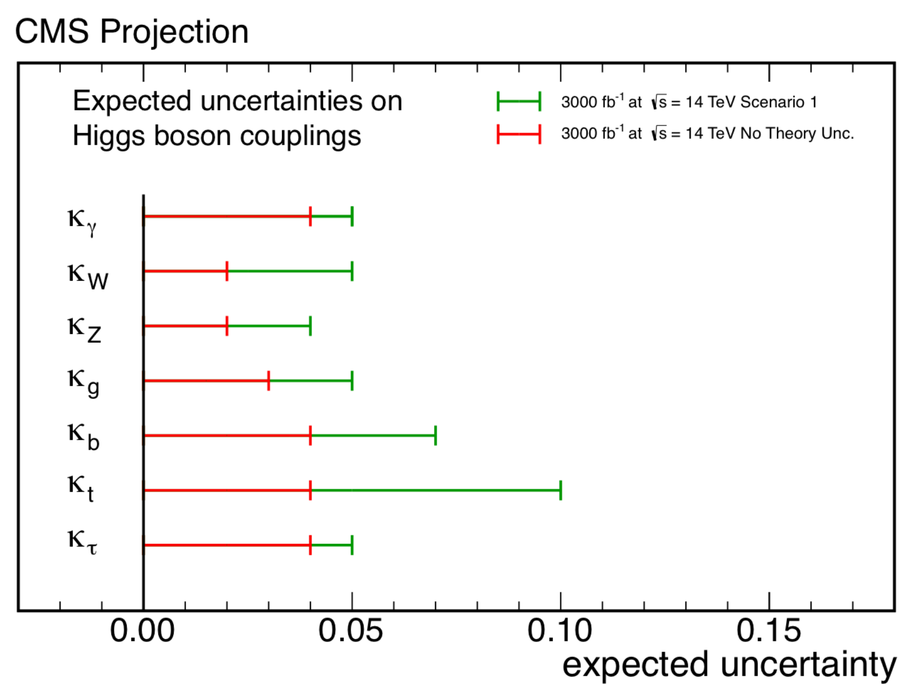
Global signal strength for all prod. and decay modes measured with ~10% accuracy

$$\mu = 1.09 \pm 0.07_{\text{stat}} \pm 0.04_{\text{exp syst.}} \pm 0.03_{\text{th. bkg}} \pm 0.07_{\text{th. signal}}$$



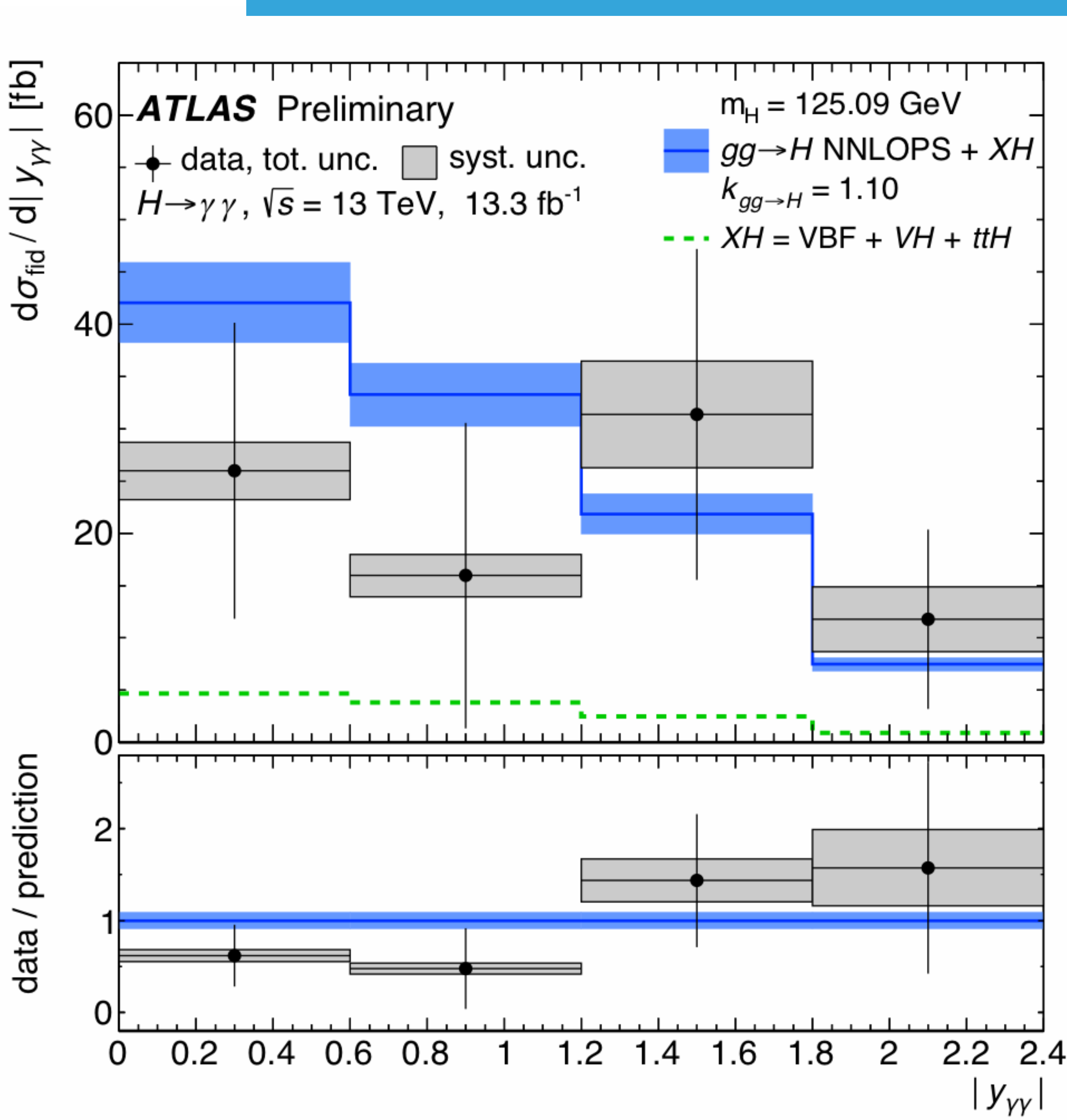


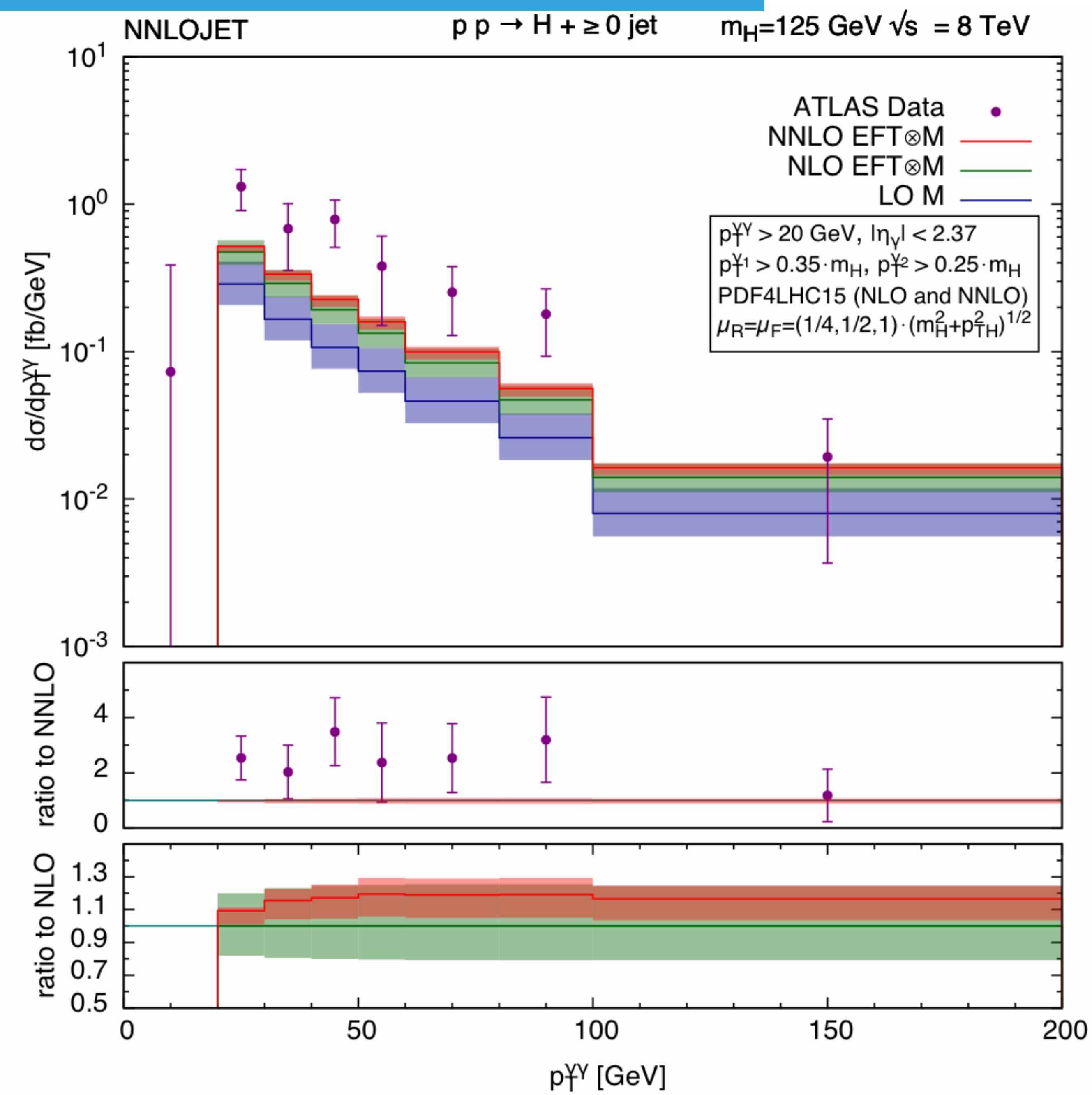




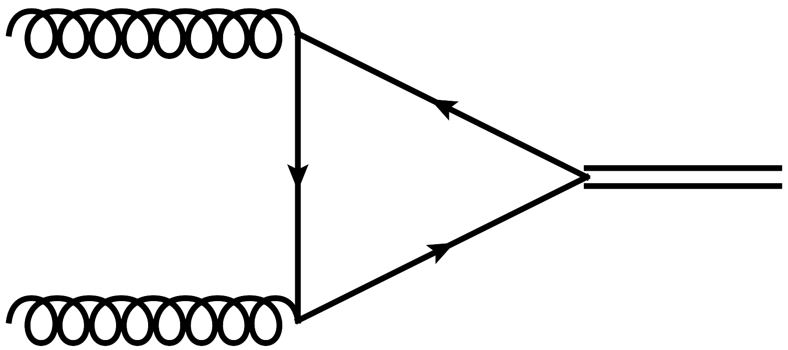
REDUCTION OF THEORETICAL UNCERTAINTIES IS CRUCIAL

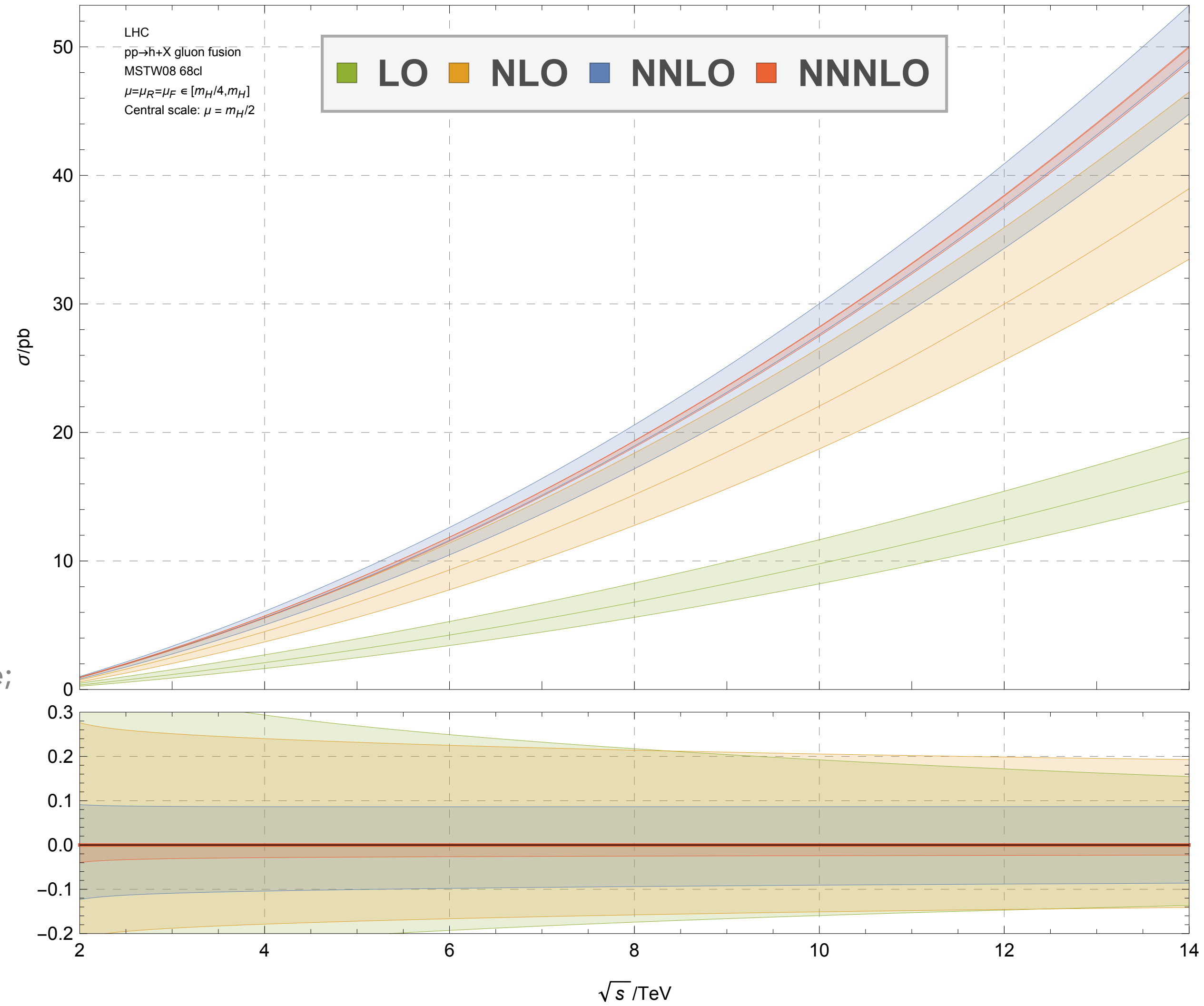
EXPERIMENTS DON'T MEASURE TOTAL XSECTIONS





WE NEED HIGH PRECISION DIFFERENTIAL PREDICTIONS FOR HIGGS PRODUCTION





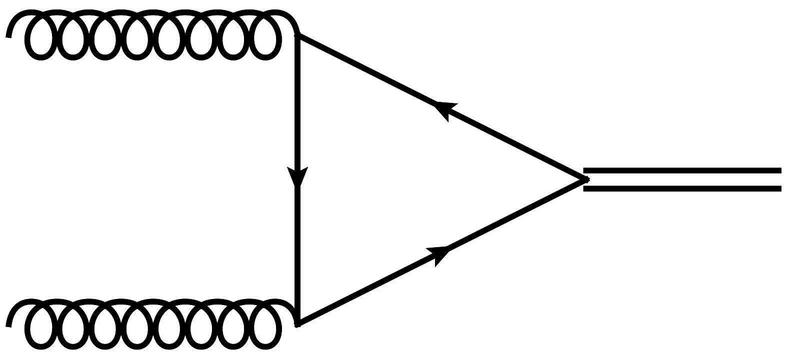
- Heroic NNLO calculations for differential Higgs and Higgs+Jet [Anastasiou, Melnikov, Petriello; Catani, Grazzini; Chen, Gehrmann, Glover, Jaquier; Boughezal, Caola, Melnikov, Petrikello, Schiulze; Boughezal, Focke, Giele, Liu, Petriello;...]
- Very successful calculation of ggF @ N3LO [Anastasiou, Duhr, FD, Furlan, Herzog, Mistlberger]
- Stabilization of scale dependence and higher order corrections
- Can we obtain the same for differential observables?

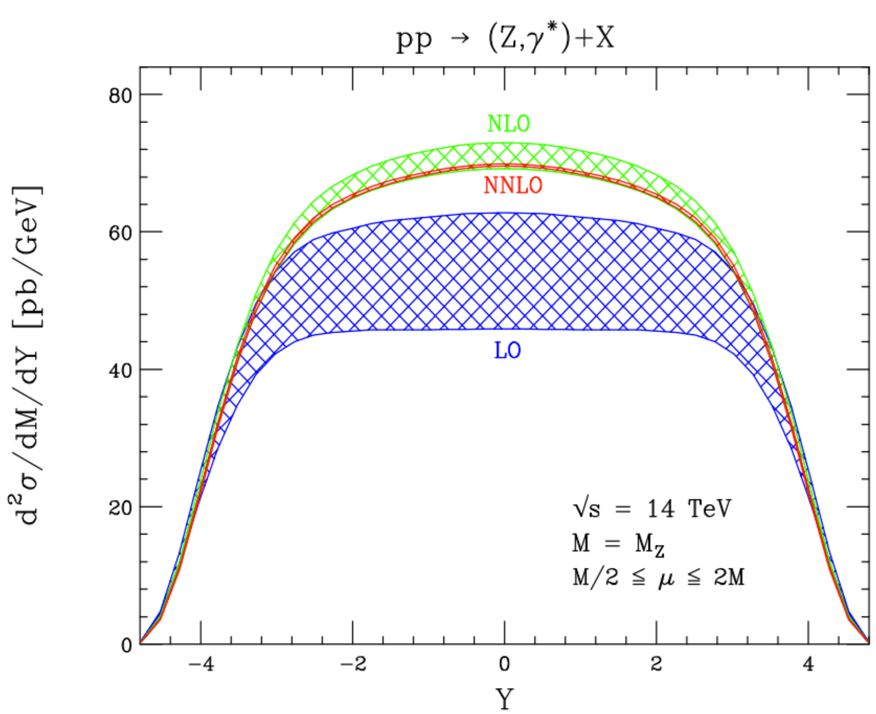
- Analytic complexity of higher order matrix elements (loop corrections, multi-leg amplitudes):
  - Algebraic complexity, coupled differential equations, new mathematical functions: Elliptic generalizations of multiple polylogarithms...
- "Numerical complexity": Monte-Carlo integral over highly divergent final state configurations
  - Infrared subtractions
  - Many successful methods
  - Challenging beyond two loops

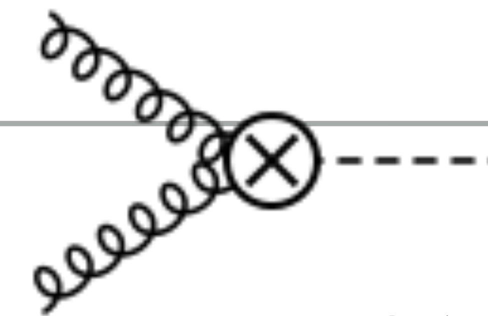
- **Sector decomposition**
- **Non-Linear Mappings**
- **qT**
- **FKS+**
- **N-Jettiness** H+J
- **Antenna**
- **Colourful**
- **Projection-To-Born** VBF
- **…**

- Can we circumvent some problems of subtraction methods?
- Make use of some of the tools from our inclusive calculation.
- Focus on some relevant LHC observables:

$$P\ P \to H + X \to \gamma\gamma + X$$



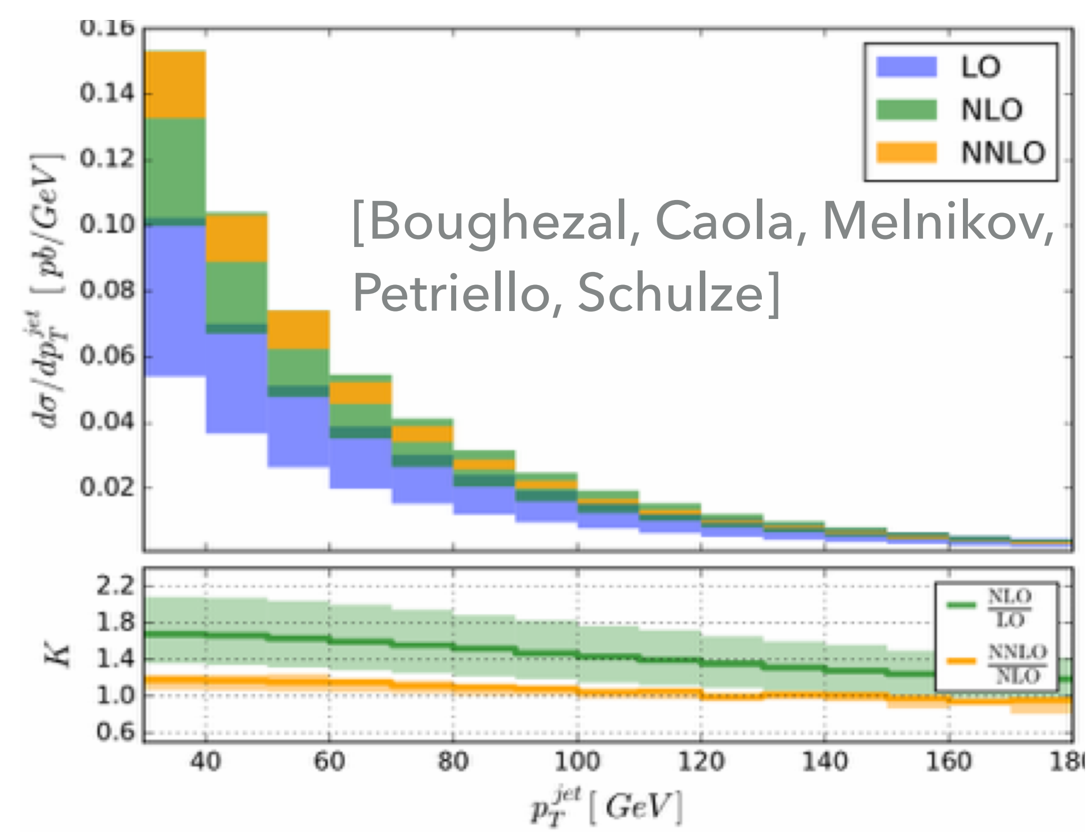


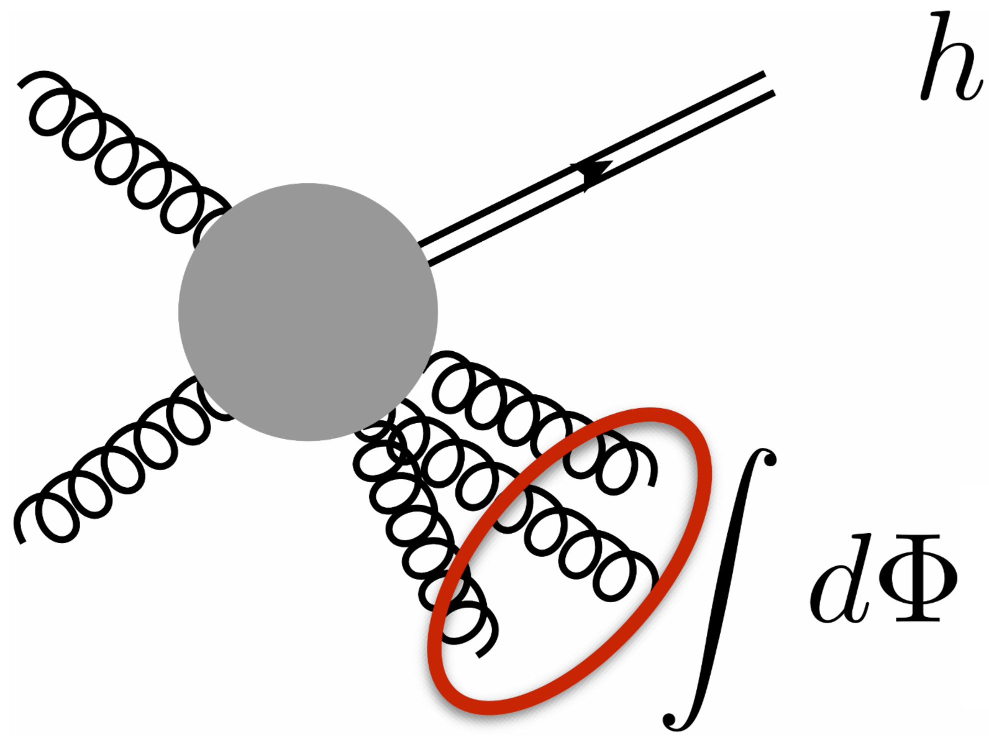


- We want a complete picture of Higgs production at $O(\alpha^5)$
- Part of this picture is Higgs+Jet @ NNLO
- What is missing is the rapidity spectrum at N3LO

FULLY DIFFERENTIAL N3LO

1. Compute rapidity distribution at N3LO
2. Combine with Higgs+Jet @ NNLO using qT subtraction or nJettiness





Y	Rapidity
p_T	Transverse momentum
m_h	Mass / Virtuality
ϕ	Azimutal angle

- Inclusive in radiation - exclusive in the Higgs
- Integrate out all extra QCD radiation
- Jet observables at this order are described by H+Jet @ NNLO

$$\sigma_{PP\to H+X}\left[\mathcal{O}\right] = \sum_{i,j} \int_{-\infty}^{+\infty} dY \int_0^{\infty} dp_T^2 \int_0^{2\pi} \frac{d\phi}{2\pi} \int_0^1 dx_1 dx_2 f_i(x_1) f_j(x_2)$$

$$\times \frac{d^2\hat{\sigma}_{ij}}{dY\, dp_T^2}(S, x_1, x_2, m_h^2, Y, p_T^2)\, \mathcal{J}_{\mathcal{O}(Y,p_T^2,\phi,m_h^2)}$$

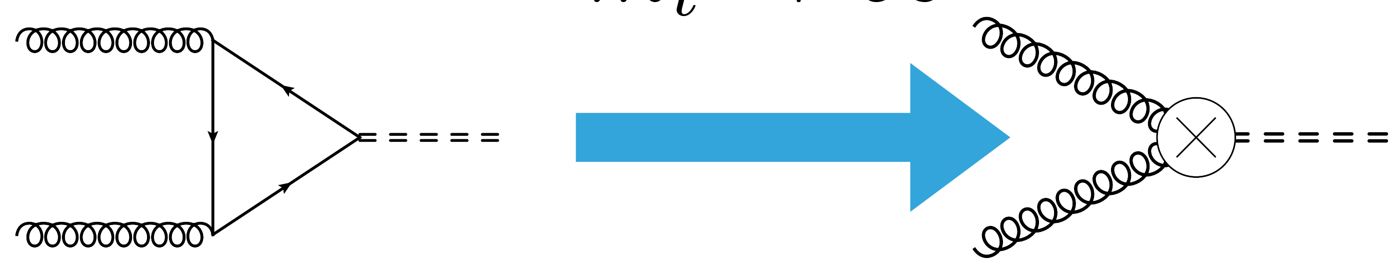
example observable:

$$\mathcal{J}_{(Y,p_T^2,\phi,m_h^2)} = \theta(p_T^2 > 20GeV)$$

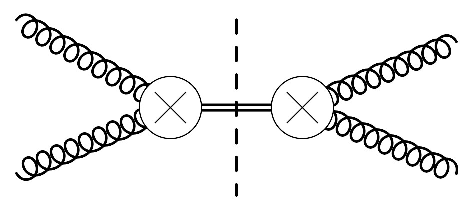
$$\frac{d^2\hat{\sigma}_{ij}}{dY\,dp_T^2} \sim \sum_X \int d\Phi_n \left|\mathcal{M}_{ij\to H+X}\right|^2$$

$$\mathcal{L} = \mathcal{L}_{QCD,5} - \frac{1}{4v} C_1 \, H \, G^a_{\mu\nu} \, G_a^{\mu\nu}$$

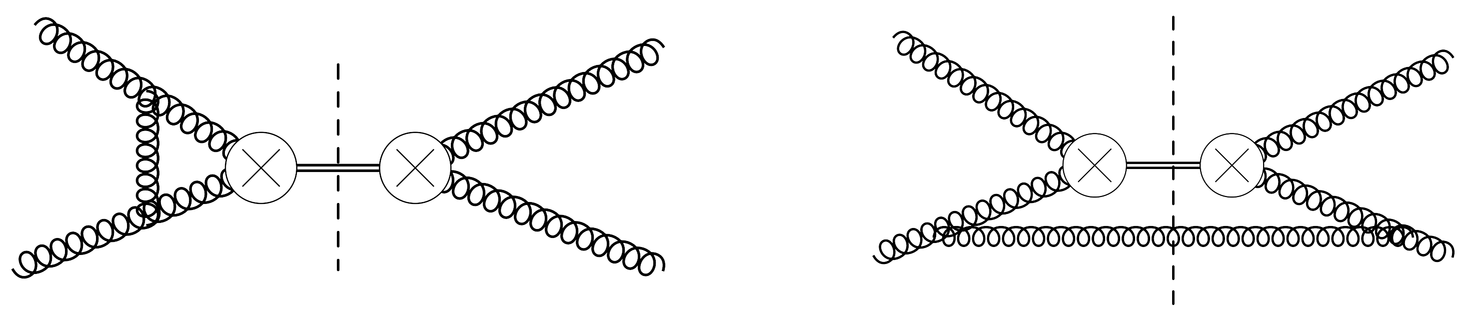
$$m_t \to \infty$$



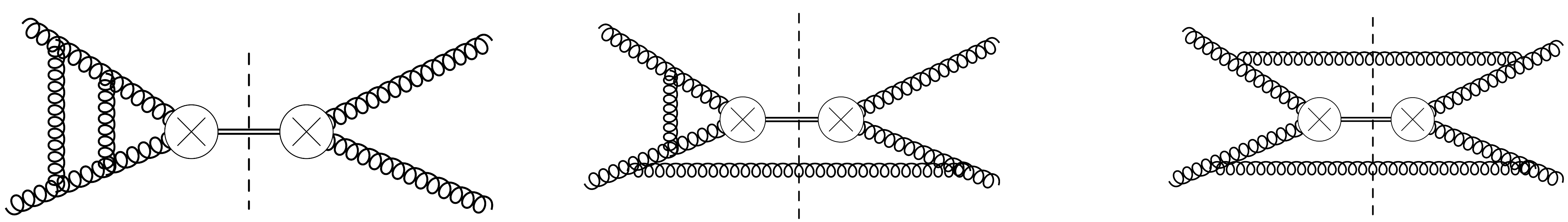
LO:



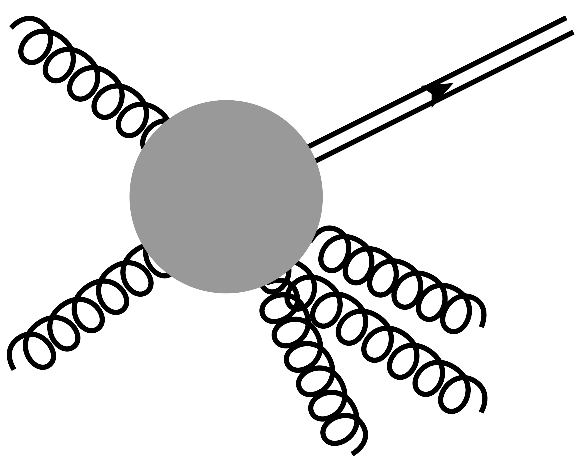
NLO:



NNLO:



$$\frac{d^2\hat{\sigma}_{ij}}{dY\,dp_T^2} \sim \sum_X \int d\Phi_n \left|\mathcal{M}_{ij\to H+X}\right|^2$$



h

$$\int d\Phi_n$$

- Inclusive final state integral over QCD radiation
- Analytic integration
- Use techniques from inclusive N3LO calculation

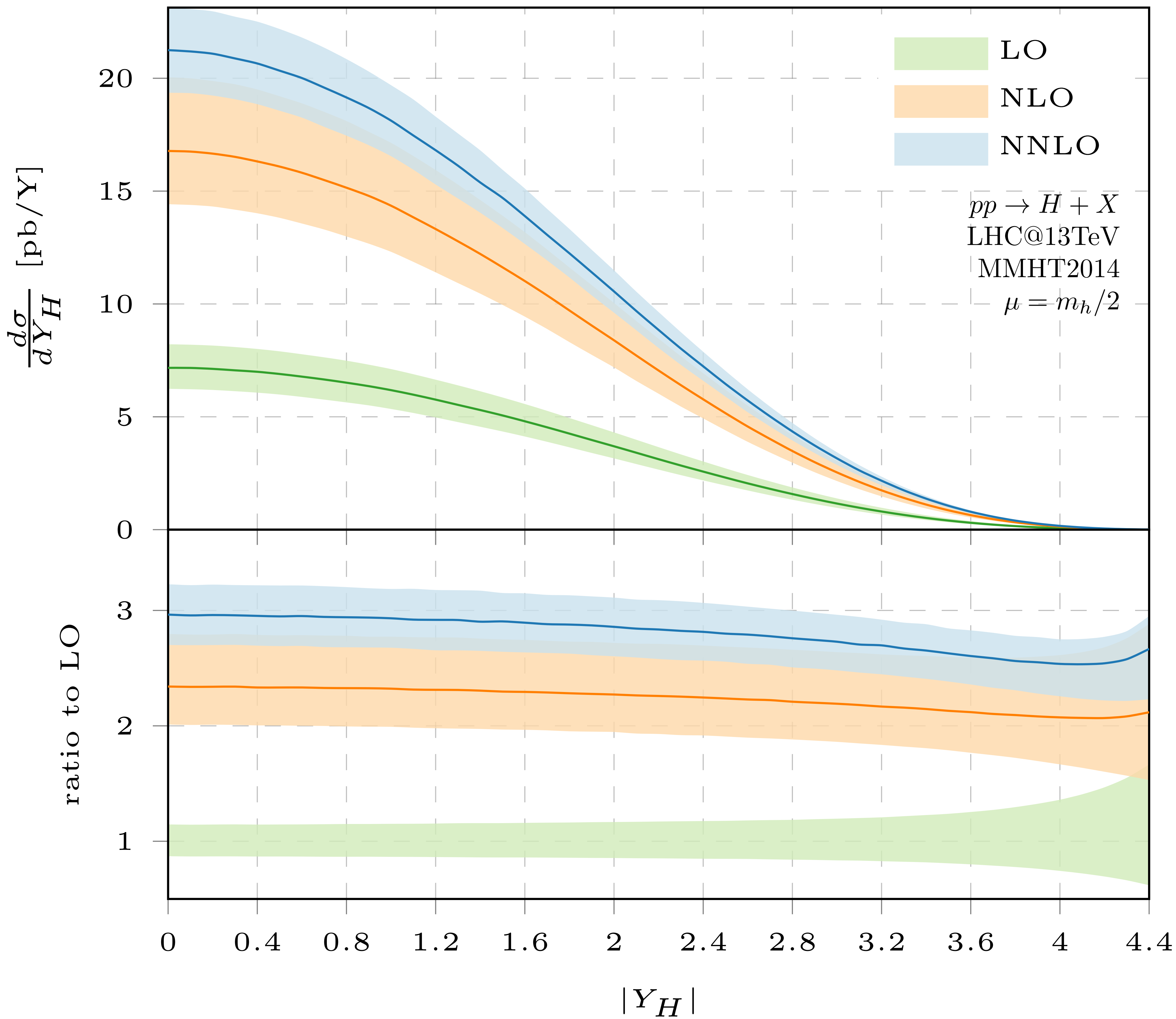
$$\delta\left(y - \frac{1}{2}\log\left(\frac{E-p_z}{E+p_z}\right)\right)$$

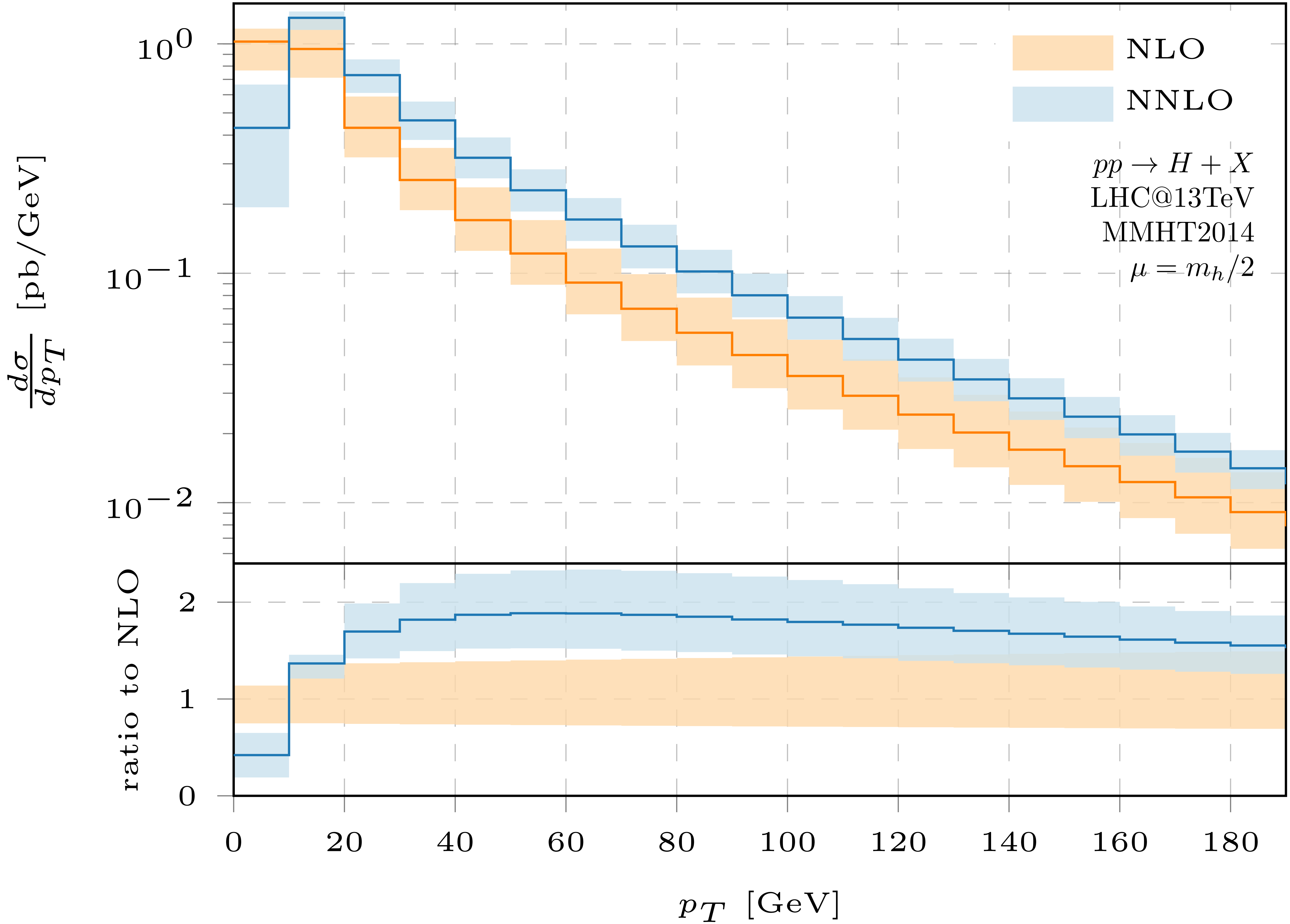
$$\delta\left(p_T - \sqrt{E^2 - p_z^2 - m_h^2}\right)$$

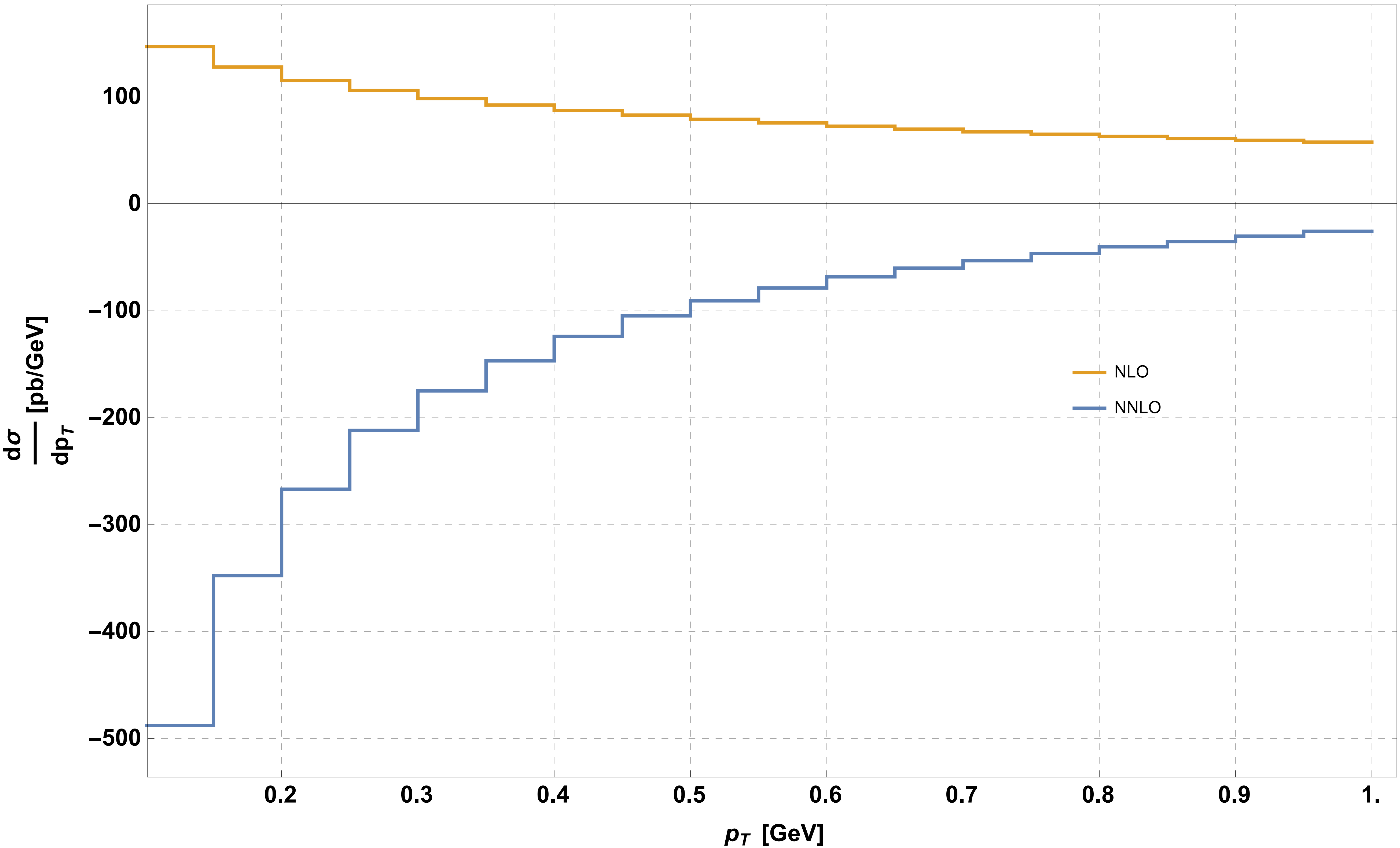
$$\delta_+(p_i^2) \sim \lim_{\delta\to 0}\left[\frac{1}{p_i^2 + i\delta} - \frac{1}{p_i^2 - i\delta}\right] = \left[\frac{1}{p_i^2}\right]_c$$

REVERSE UNITARITY

[Anastasiou, Menikov; Anastasiou, Dixon, Melnikov, Petriello]


LO
NLO
NNLO
$pp \to H + X$
LHC@13TeV
MMHT2014
$\mu = m_h/2$
$\frac{d\sigma}{dY_H}$ [pb/Y]
ratio to LO
$|Y_H|$
0
5
10
15
20
1
2
3
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.4


NLO
NNLO
$pp \to H + X$
LHC@13TeV
MMHT2014
$\mu = m_h/2$
$\frac{d\sigma}{dp_T}$ [pb/GeV]
10^0
10^{-1}
10^{-2}
ratio to NLO
0
1
2
0 20 40 60 80 100 120 140 160 180
p_T [GeV]


100
0
−100
−200
−300
−400
−500
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.
p_T [GeV]
$\frac{d\sigma}{dp_T}$ [pb/GeV]
NLO
NNLO

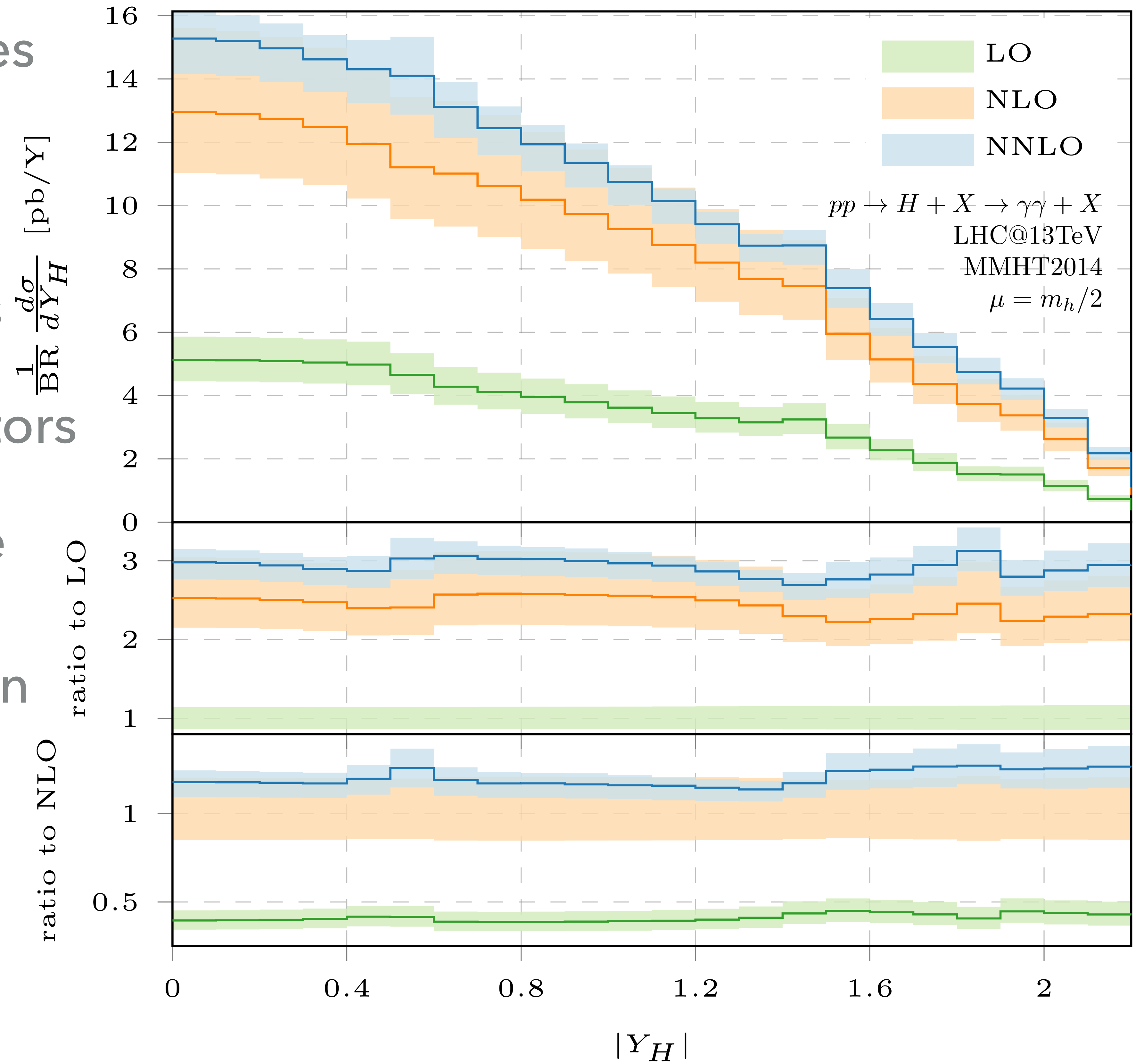
- Realistic observables (ATLAS cuts)
- Non-trivial features induced by the cuts
- Relatively flat K-factors
- Similar perturbative progression as the inclusive distribution

$$\eta_\gamma < 2.37$$

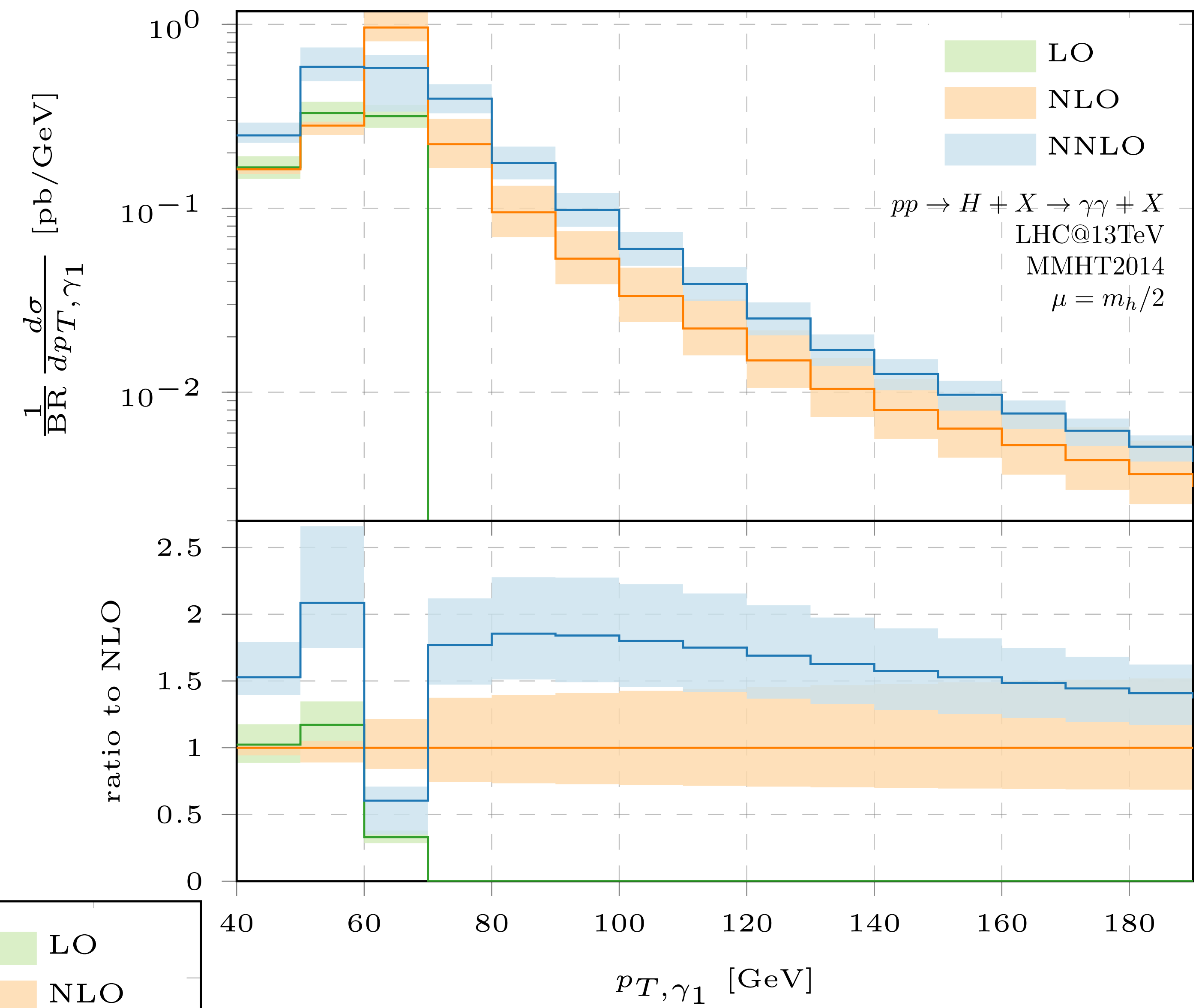
$$\eta_\gamma \notin [1.37, 1.52]$$

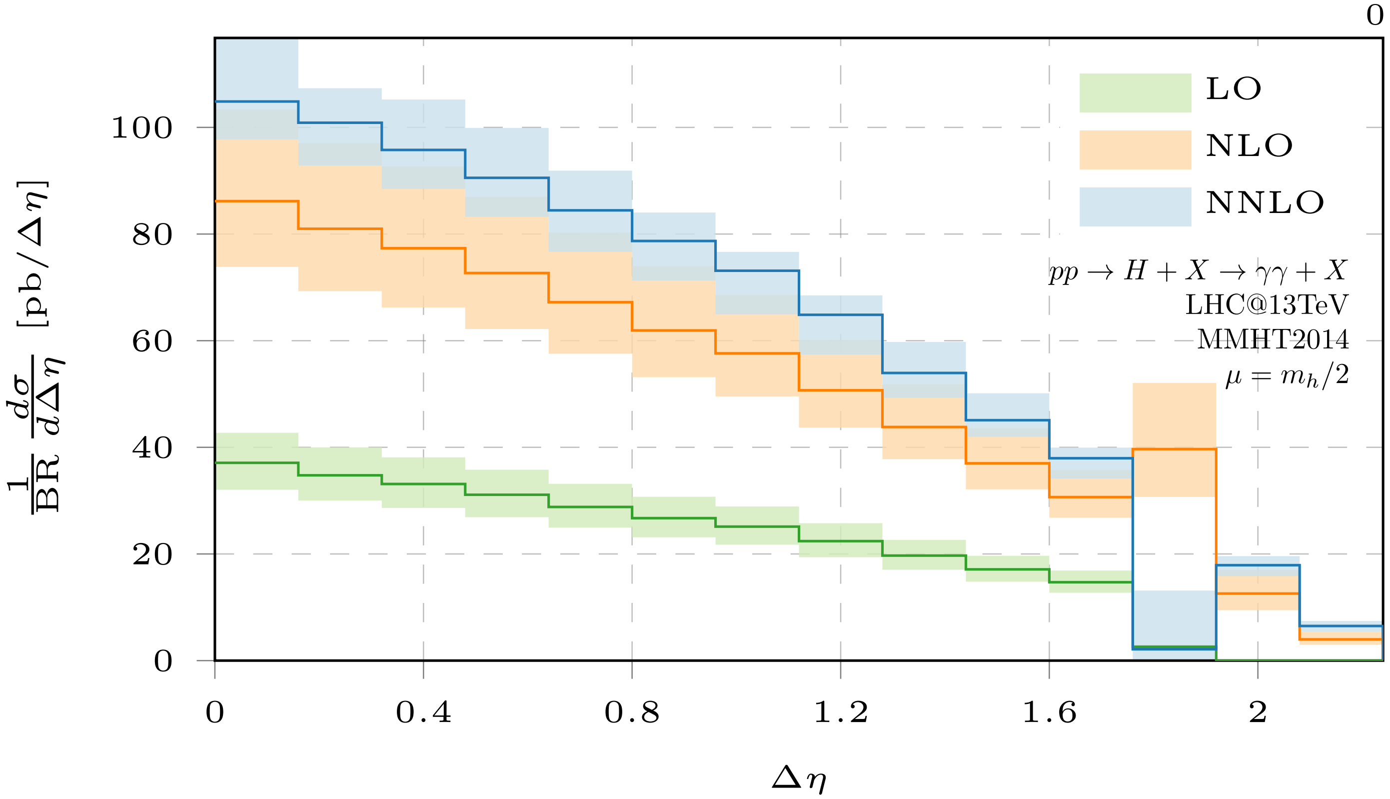
$$p_{T,\gamma_1} > 0.35\, m_h$$

$$p_{T,\gamma_2} > 0.25\, m_h$$



- Distributions of final state momenta:
- Leading photon pT
- Rapidity difference



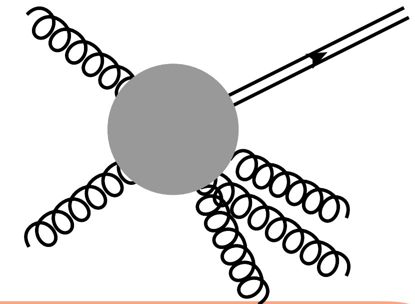


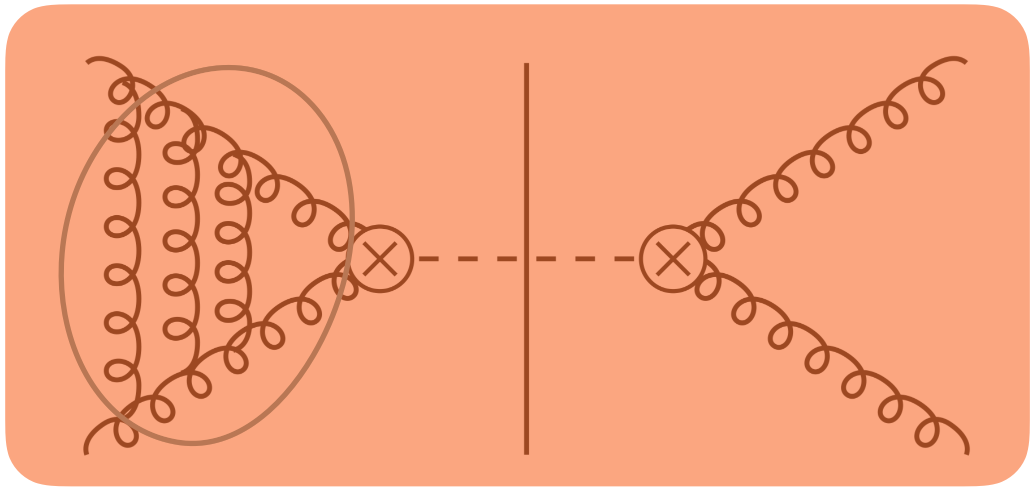
$$\Delta\eta = |\eta_{\gamma_1} - \eta_{\gamma_2}|$$

TOWARDS N3LO

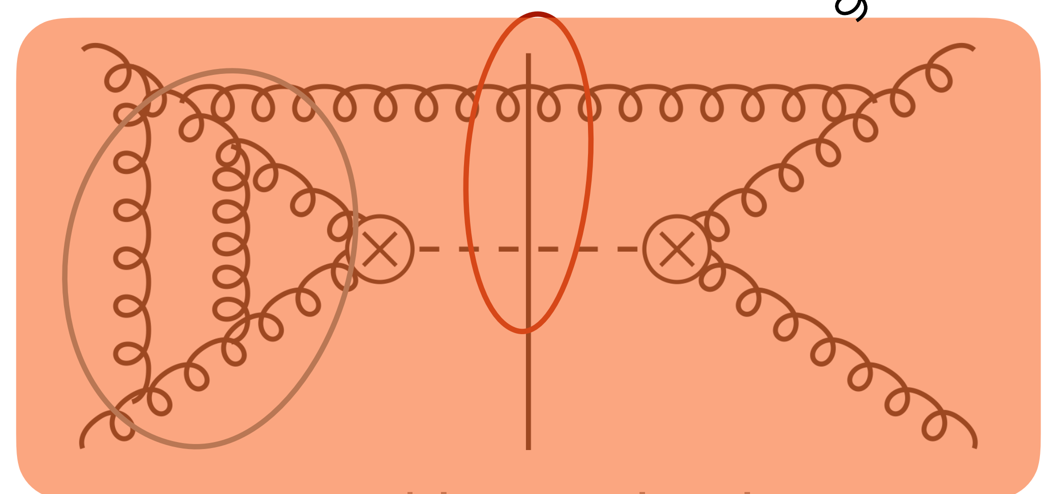
ALL ORDER STRUCTURE

$$\frac{d^2\hat{\sigma}_{ij}}{dY\,dp_T^2} \sim \sum_X \int d\Phi_n \left|\mathcal{M}_{ij\to H+X}\right|^2$$

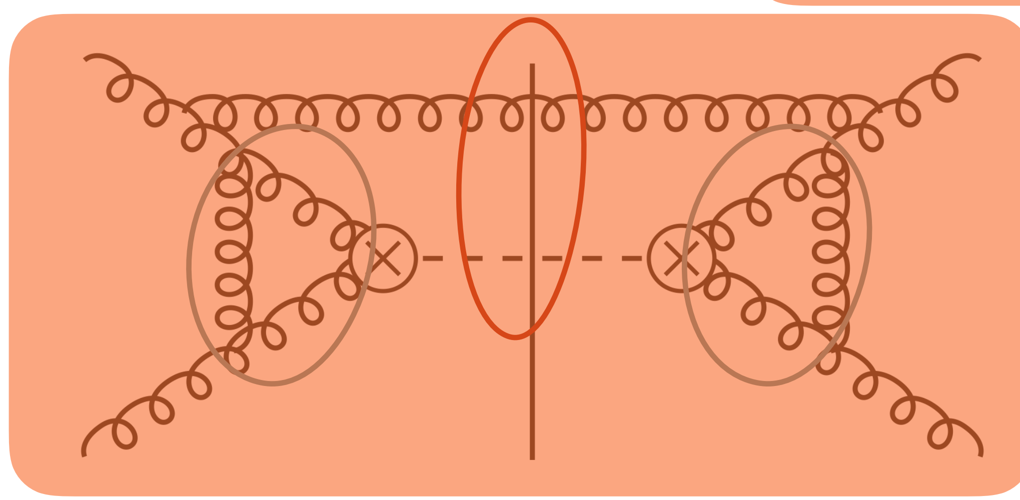




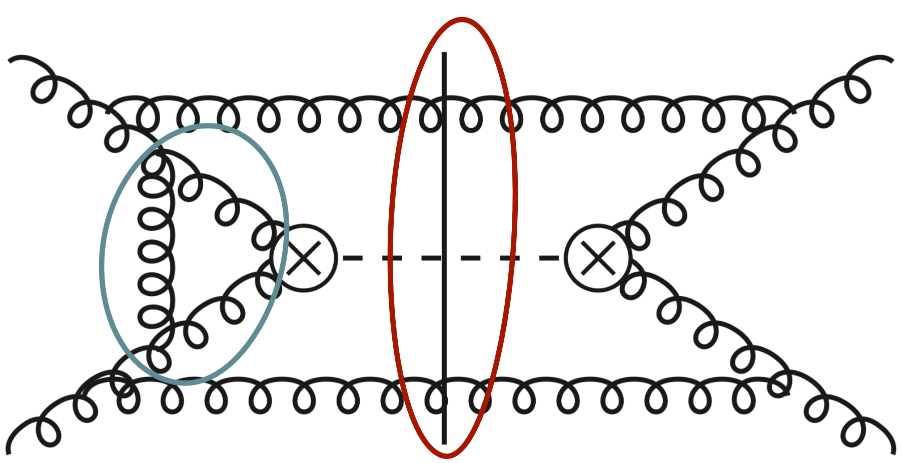
Triple virtual



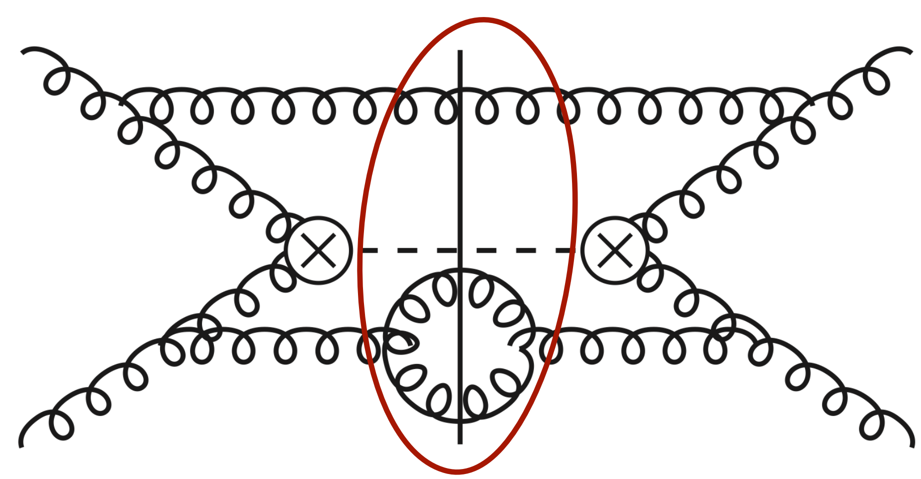
Double-virtual real



Real-virtual²



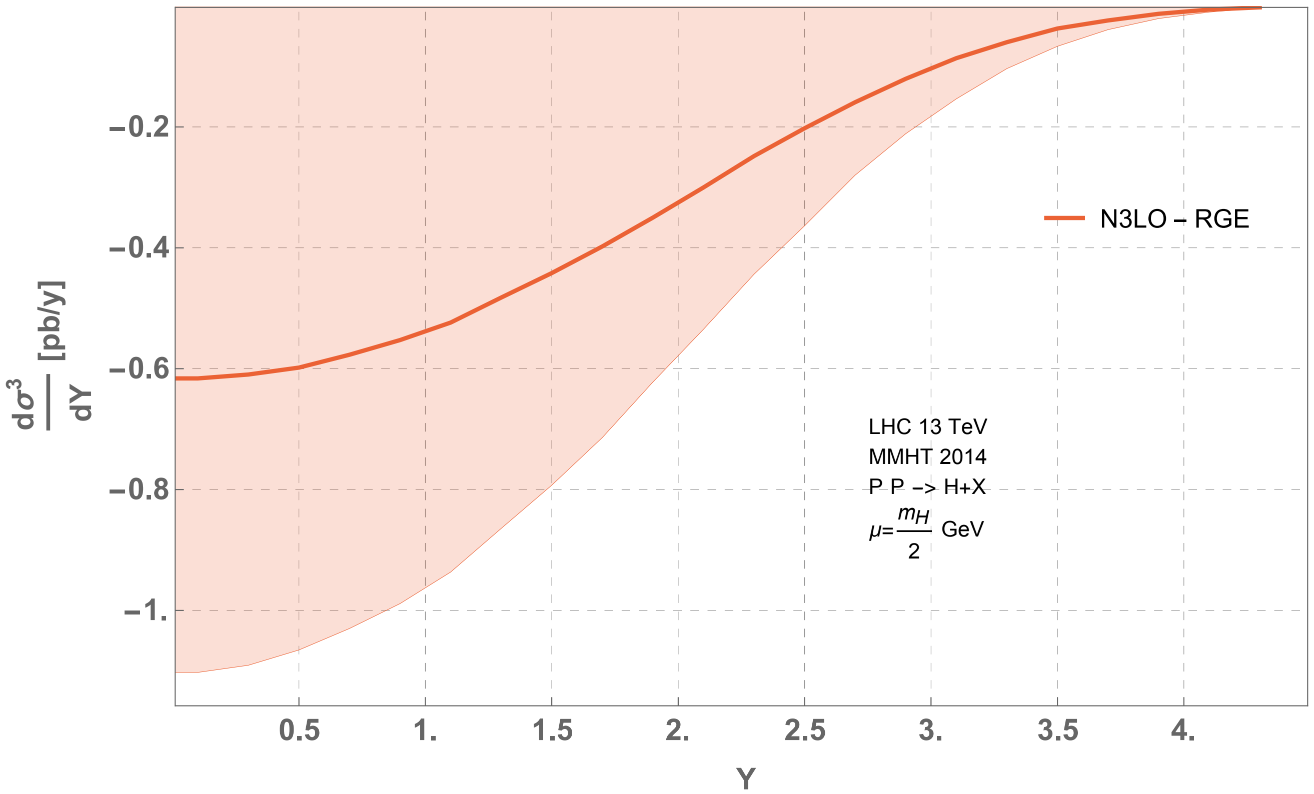
Double-real virtual

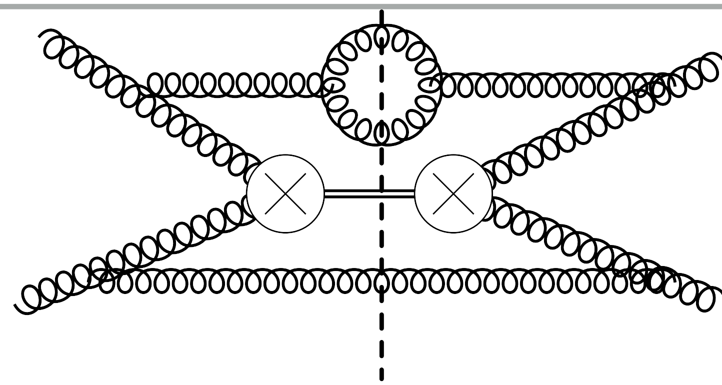


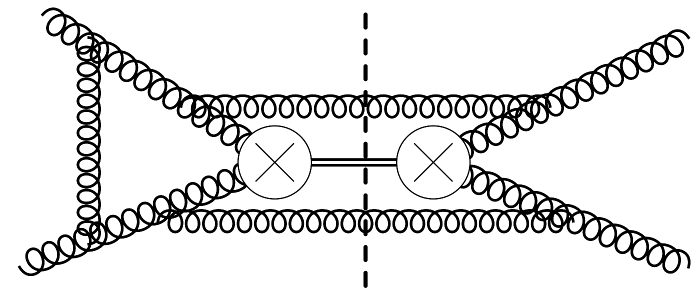
Triple real

- UV and collinear counter terms for the N3LO cross section require the NNLO cross section to $\mathcal{O}(\epsilon^1)$
- N3LO scale variation can be derived from DGLAP

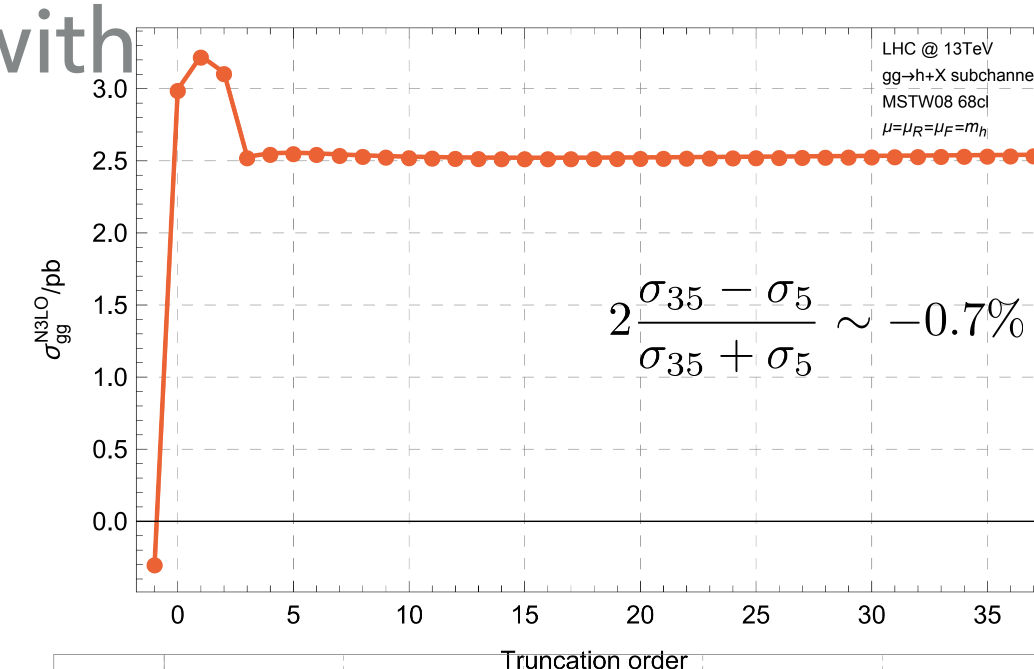
$$\hat{\sigma}^{(3)} = \hat{\sigma}_0^{(3)} + \hat{\sigma}_1^{(3)} \log\left(\frac{m_h^2}{\mu^2}\right) + \hat{\sigma}_2^{(3)} \log^2\left(\frac{m_h^2}{\mu^2}\right) + \hat{\sigma}_3^{(3)} \log^3\left(\frac{m_h^2}{\mu^2}\right)$$





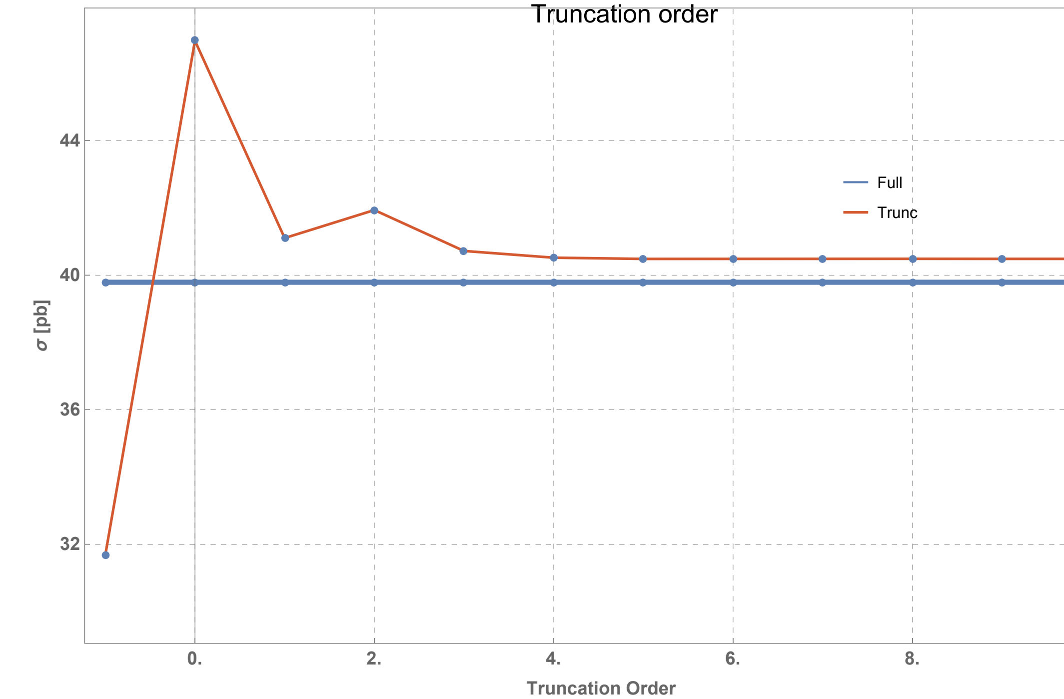


- Need to compute matrix elements with two or more final state partons

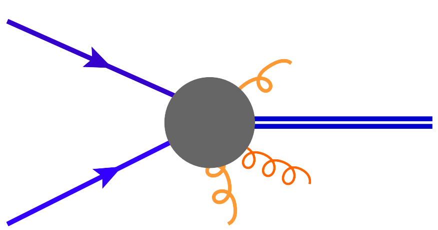


- Compute using reverse unitarity, differential equations …

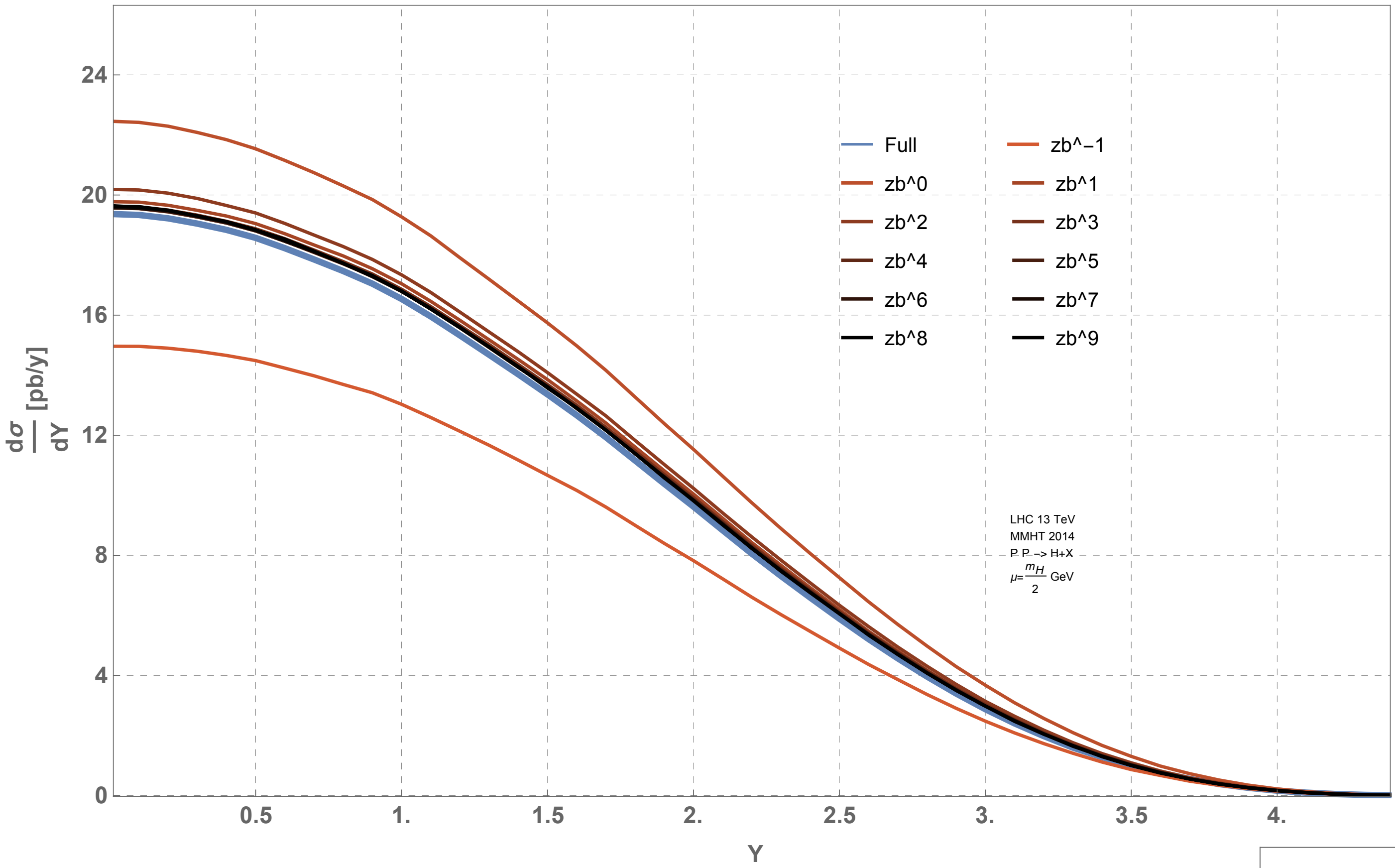
- O(1000) master integrals required



- First step: threshold expansion

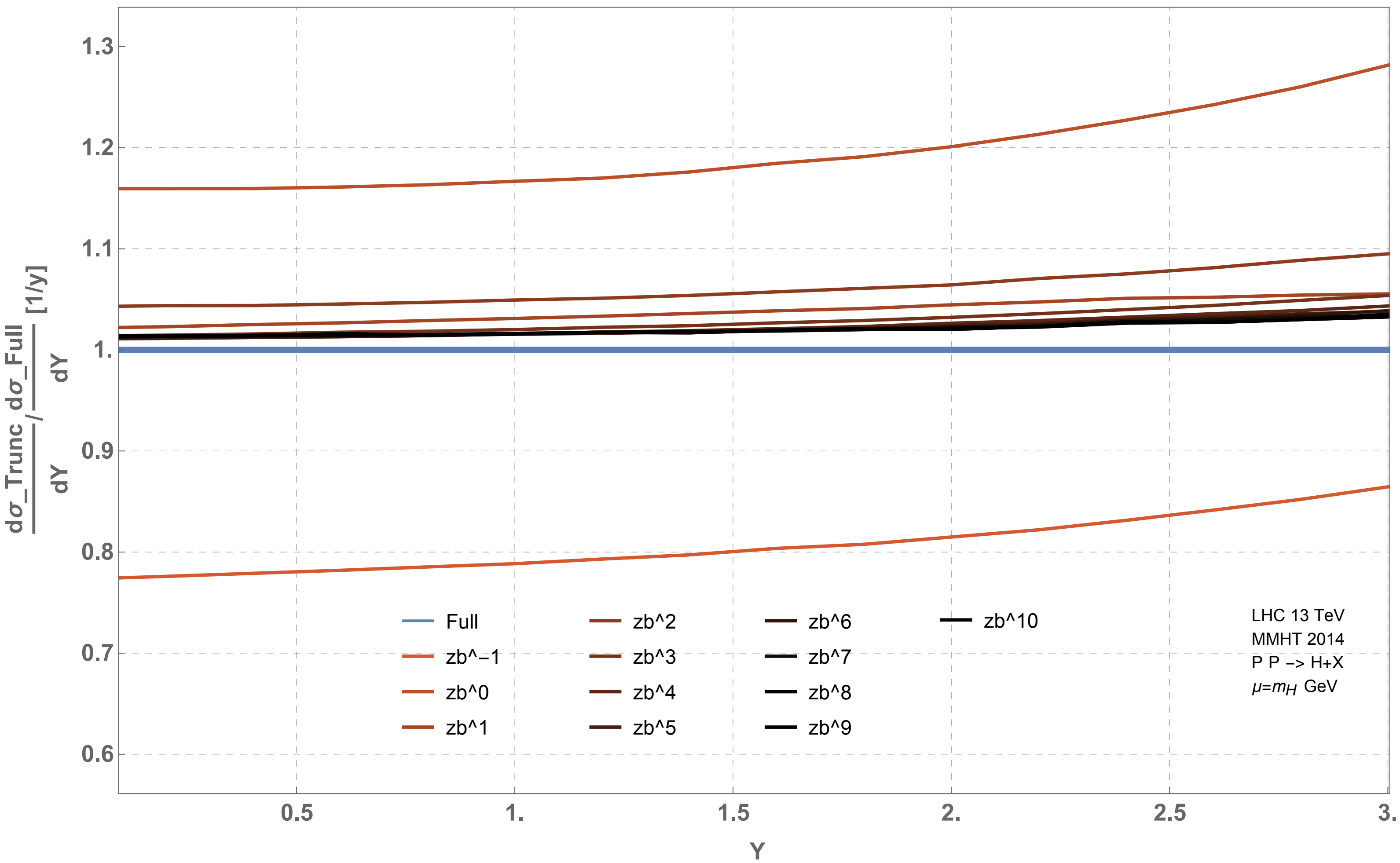


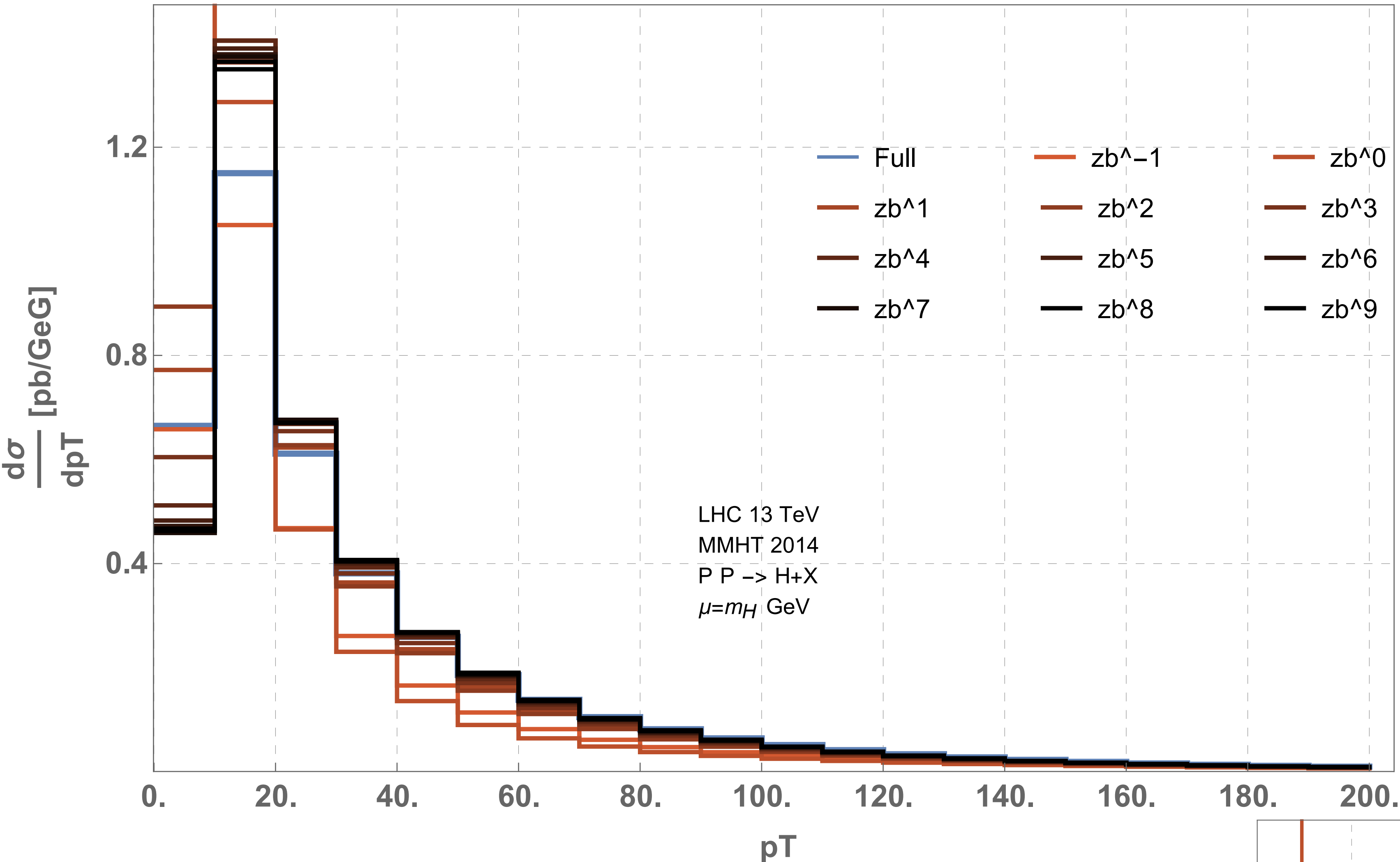
$$z = \frac{m_H^2}{\hat{s}} \sim 1$$



- Test at NNLO

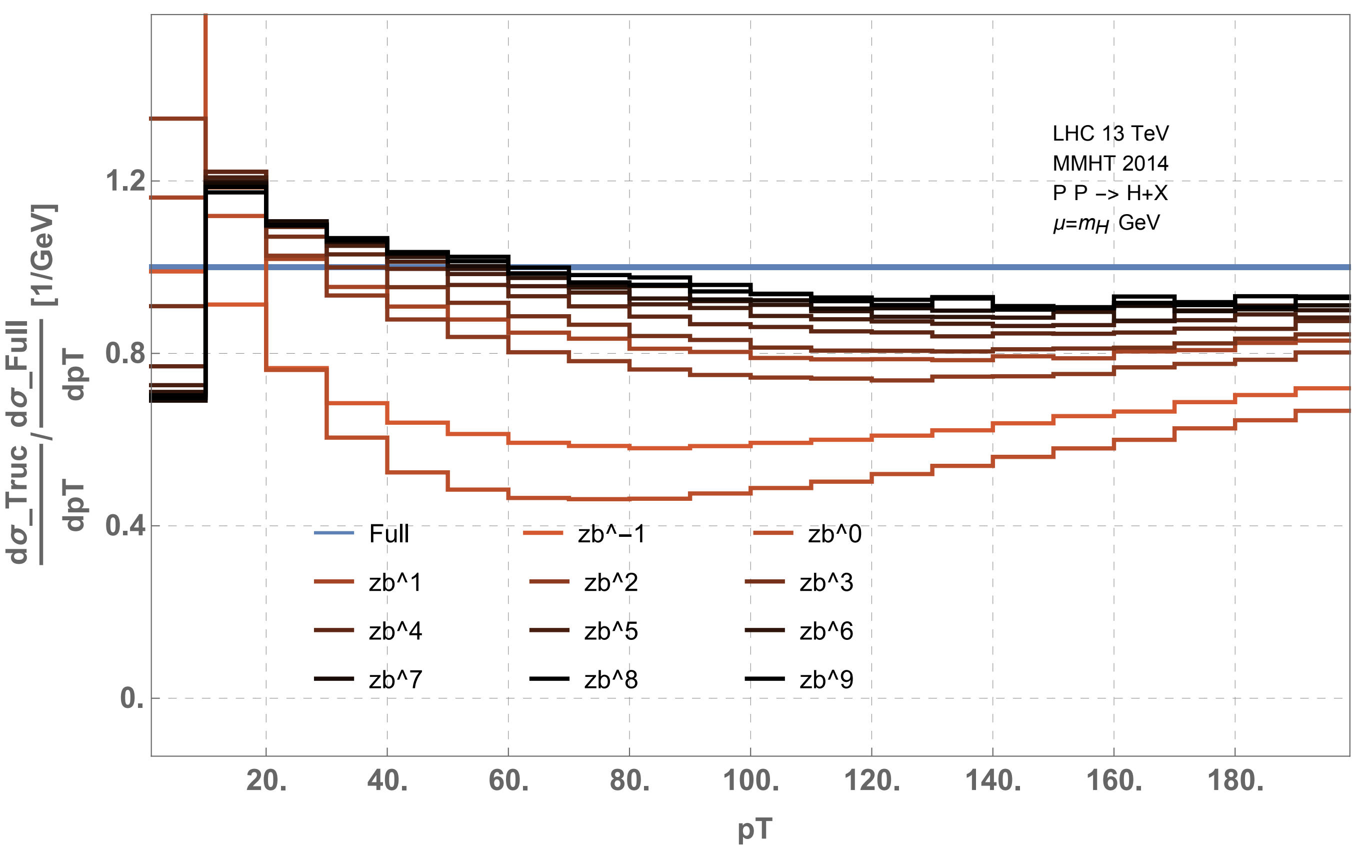
- Bulk of the cross section is described reasonably within a few terms

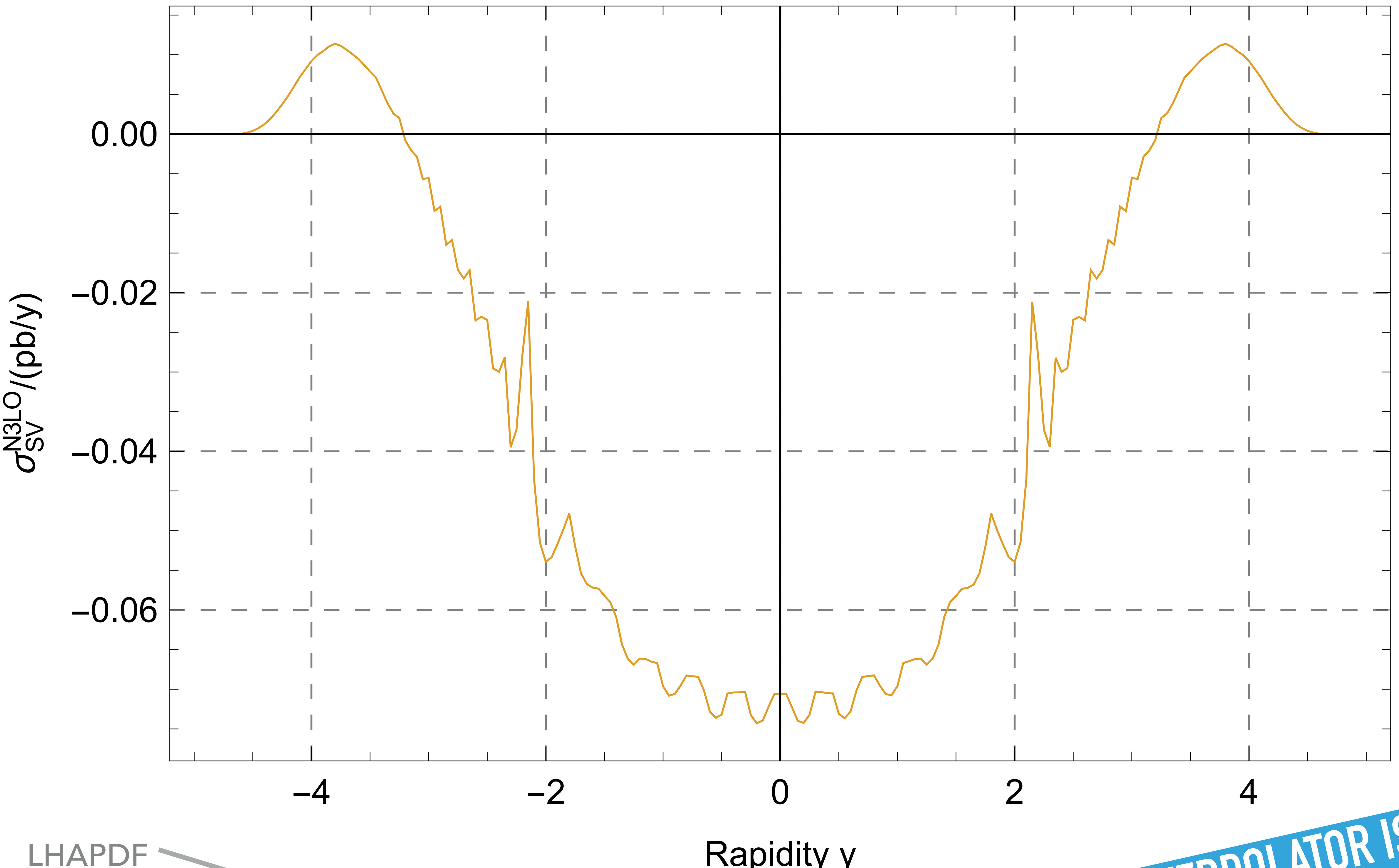




- Bad convergence at low pT
- Generally slow convergence
- Barely within 20% with 10 terms

- pT is a NLO observable
- Threshold expansion falls back to Born level kinematics

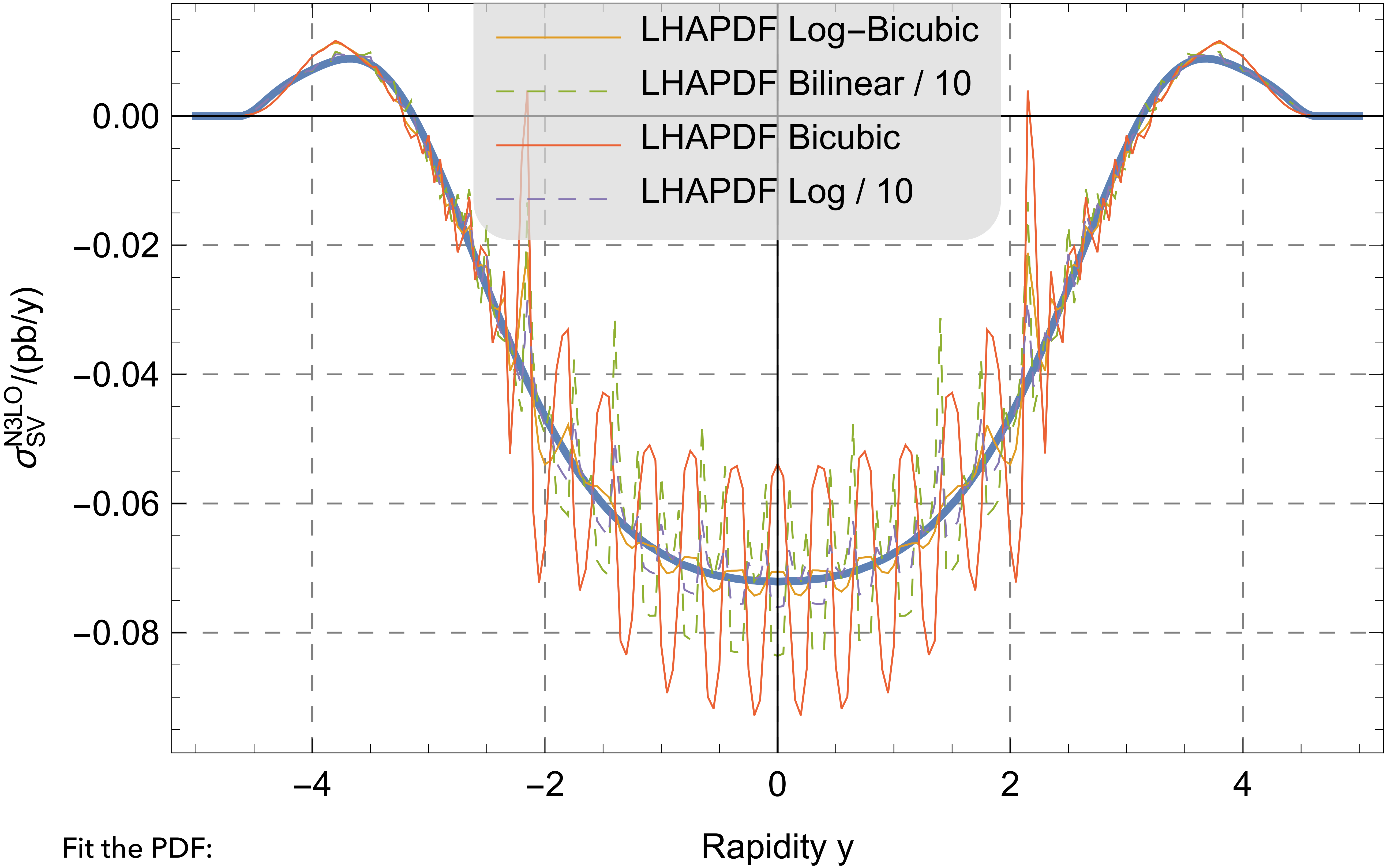




LHAPDF

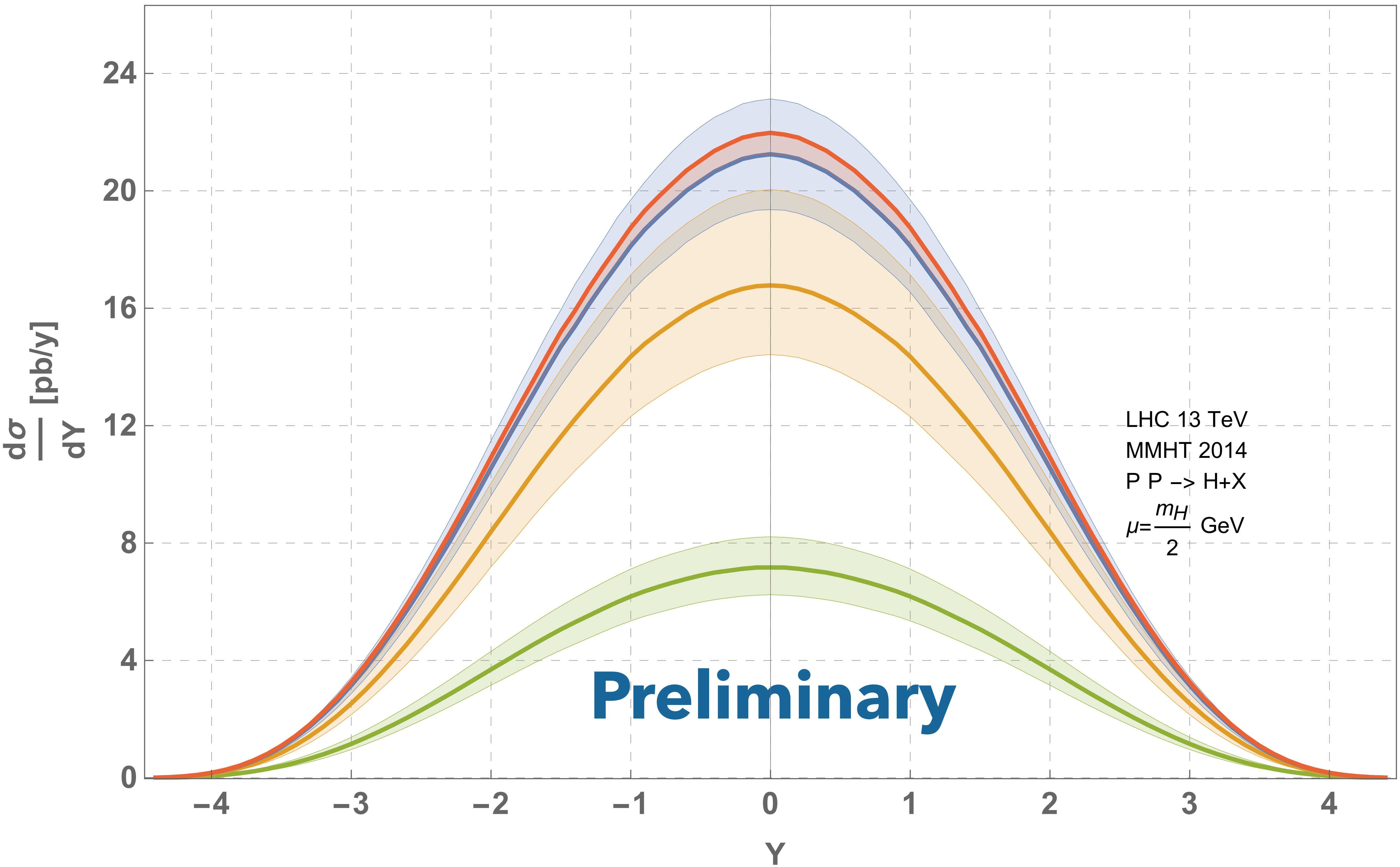
$$\sigma \sim \int dz\, \mathcal{L}_{gg}(z) \left[\frac{log^5(1-z)}{1-z} \right]_+$$

LHAPDF INTERPOLATOR IS NOT SMOOTH ENOUGH FOR N3LO



Fit the PDF:

$$f(x, Q = 125) = c_1(1-x)^{e_1}x^{e_2} + c_2(1-x)^{e_3}(1 - c_3\sqrt{x}) + c_4 x + c_5 \log^2(x) + c_6 \log^4(x) + c_7 \log^4(x)$$



$\frac{d\sigma}{dY}$ [pb/y]
24
20
16
12
8
4
0
−4
−3
−2
−1
0
1
2
3
4
Y
LHC 13 TeV
MMHT 2014
P P −> H+X
$\mu=\frac{m_H}{2}$ GeV
Preliminary

CONCLUSIONS

- Good progress towards differential distributions for gluon fusion at N3LO
- "Higgs-differential" framework is able to describe realistic final state observables
- Further progress towards N3LO is systematic, we need to compute a few more integrals
- Threshold expansion is feasible for some differential observables
- Interesting lessons to be learned when doing higher order differential calculations