Differential Higgs Boson Production

F. Dulat, B. Mistlberger, AP (1710.03016)
F. Dulat, B. Mistlberger, AP (1810.09462)
X. Chen, T.Gehrmann, E.W.N. Glover, A. Huss, B. Mistlberger, AP (2102.07607)

A. Pelloni

12.09.2022

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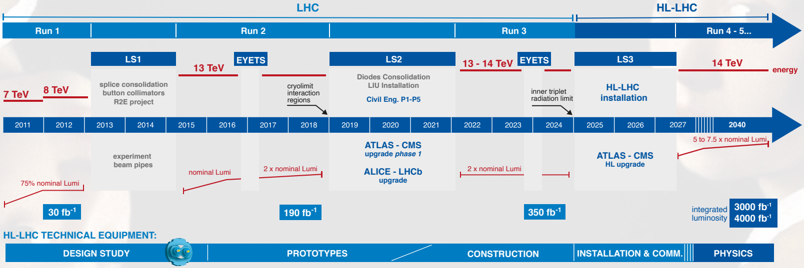
MOTIVATION

- **Theoretical predictions** need to keep up with the ever-increasing precision of **experimental measurements**
- Need to understand the SM background in order to resolve **new physics**



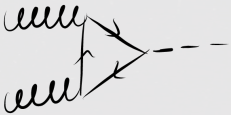
- **Example:** Higgs inclusive: $8\% \rightarrow 3\%$ expected experimental uncertainty at 3000 fb^{-1}. The PDF uncertainty on the theoretical prediction cannot be neglected anymore.

HIGGS AT N3LO

- **2015** : First Prediction for the inclusive Higgs done with threshold expansion at N^3LO **[C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger]**
- **2016** : Vector-Boson Fusion Higgs production in QCD at three loops **[F. A. Dreyer, A. Karlberg]**
- **2018**
  - Exact Higgs inclusive **[B. Mistlberger]**
  - Study of threshold expansion for Differential Higgs **[F. Dulat, B. Mistlberger, AP]**
  - Vector-Boson Fusion Higgs Pair Production **[F. A. Dreyer, A. Karlberg]**
- **2019**
  - Higgs differential using q_T subtraction **[L. Cieri, X. Chen, T. Gehrmann, E. Glover, A. Huss]**
  - Higgs rapidity distribution using threshold expansion **[F. Dulat, B. Mistlberger, AP]**
- **2020**
  - Higgs Boson Production in Bottom-Quark Fusion **[C. Duhr, F. Dulat, B. Mistlberger]**
  - ...matching the 4- and 5-flavour schemes **[C. Duhr, F. Dulat,V. Hirschi, B. Mistlberger]**
- **2021**
  - Fully Differential Higgs Boson Production **[X. Chen, T. Gehrmann, E. Glover, A. Huss, B. Mistlberger, AP]**
  - Higgs pT Spectrum **[G. Billis, B. Dehnadi, M. A. Ebert, J. K. L. Michel, F. J. Tackmann]**

Gluon Fusion

ggH is a **loop-induced** process and represents the largest correction to the cross-section at **13 TeV**



ggH
88.2%

The computation is performed in the **infinite top mass** approximation
Effective theory:

- Remove one loop!
- Good approximation: $\delta_t^{NNLO} \sim 0.7\%$
- To be combined with mass corrections, EW corrections, etc...

Higgs Rapidity Distribution

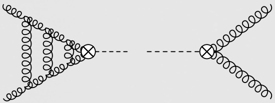
The **real radiation** is treated **inclusively** and the Higgs boson is resolved only in its rapidity

$$\frac{d\hat{\sigma}_{ij\to H+X}}{dY} = \int dp_h \, d\phi_n \left|\mathcal{M}_{ij\to H+X}\right|^2 \delta\left(Y - \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)\right)$$

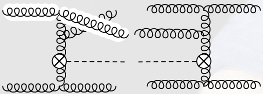
Rapidity

Higgs Rapidity Distribution

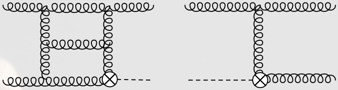
VVV + Born:



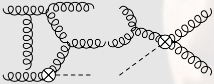
RRR + RRR:



VVR + R:



VRR + RR:



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Rapidity

$$\frac{d\hat{\sigma}_{ij\to H+X}}{dY} = \int dp_h d\phi_n \left| \mathcal{M}_{ij\to H++\,X} \right|^2 \delta\left(Y - \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)\right)$$

Rapidity Distribution

The general form of the rapidity distribution can be written as:

Hadronic

$$\frac{d\sigma_{PP\to H+X}}{dY} = \hat{\sigma}_0 \sum_{ij} \int_0^1 dx_1 dx_2 dy_1 dy_2 f_i(y_1) f_j(y_2) \delta(\tau - x_1 x_2 y_1 y_2)$$

$$\times \delta\left(Y - \frac{1}{2}\log\left(\frac{x_1 y_1}{x_2 y_2}\right)\right) \eta_{ij}(x_1, x_2),$$

Partonic

Where we define the partonic cross-section in terms of a power series in the **strong coupling** constant:

$$\eta_{ij}(x_1, x_2) = \sum_{k=0}^{3} \left(\frac{\alpha_S}{\pi}\right)^k \eta_{ij}^{(k)}(x_1, x_2).$$

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Road to Computation

Computing the rapidity distribution analytically is a hard challenge!

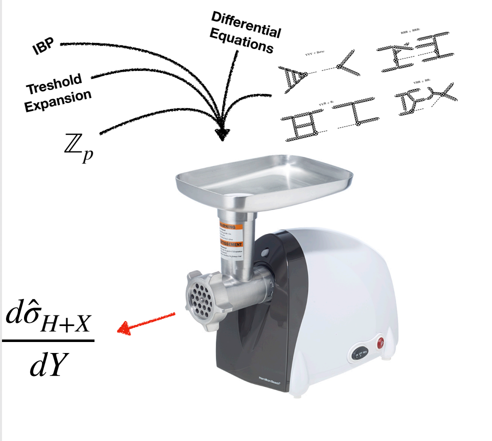
$$\frac{d\hat{\sigma}_{ij\to H+X}}{dY}$$

Divide and Conquer:

- Perform expansion around the production threshold. Already a success for the inclusive **N3LO**

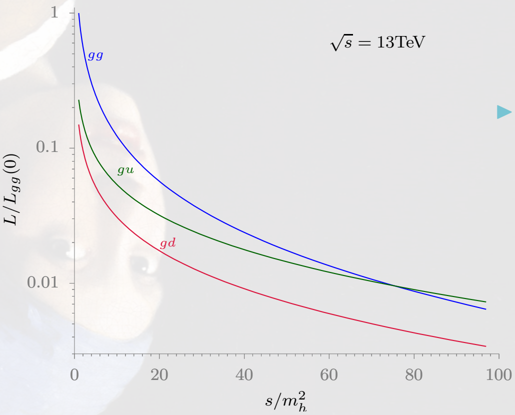
$$\bar{z} = 1 - z = 1 - \frac{m_H^2}{s} \sim 0$$

- Validate the truncation of the threshold expansion



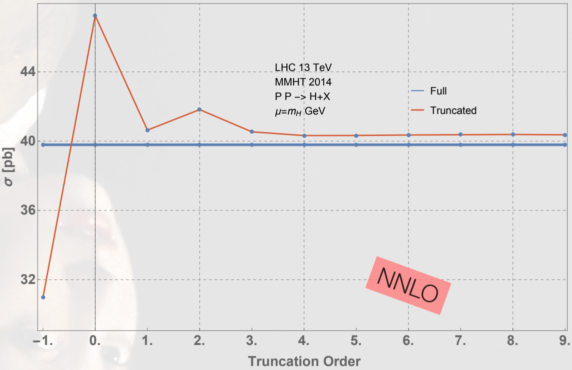
Parton Luminosity

$$L(z) = \int_{\frac{\tau}{z}}^{1} \frac{dx}{x} f_i(x) f_j\left(\frac{\tau}{zx}\right).$$



- The probability of producing the Higgs boson as a function of the partonic center of mass is reduced as the energy moves away from the threshold

Inclusive Threshold Expansion



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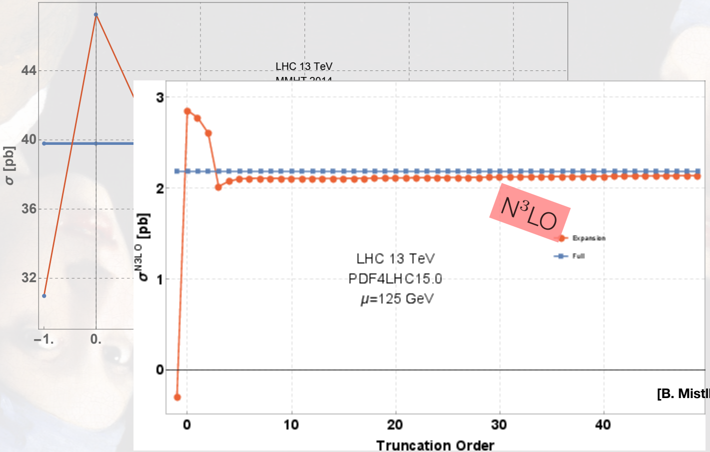
Inclusive Threshold Expansion



[B. Mistlberger '18]

Threshold Expansion

In dimensional regularization the expression for the partonic cross-section takes the form,

$$\eta_{ij}^{(3)}(x_1,x_2) = \eta_{ij}^{(3)}\delta(1-x_1)\delta(1-x_2)$$

Distributions **Holomorphic**

$$+\sum_{n,m=1}^{3} (1-x_1)^{-1-m\epsilon}(1-x_2)^{-1-n\epsilon}\,\eta_{ij}^{(3,m,n)}(x_1,x_2),$$

- Different sectors of the loop momentum give rise to different m ,n exponent

$$\int_0^1 dx(1-x)^{-1+a\epsilon}f(x) = \int_0^1 dx\left[\frac{\delta(1-x)}{a\,\epsilon}+\sum_{n=0}^{\infty}\frac{(a\,\epsilon)^n}{n!}\left[\frac{\log^n(1-x)}{1-x}\right]_+\right]f(x)$$

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Reaching Beyond Threshold Expansion

Obtain finite expressions with a suitable **mass factorization** and **ultraviolet renormalization** counter term $CT_n^{(3)}$:

$$\eta_{ij}^{(3)}(x_1,x_2) = \lim_{\epsilon\to 0}\left[\eta_{ij,bare}^{(3)}(x_1,x_2) + CT_{ij}^{(3)}(x_1,x_2)\right]$$

- Use the fact that poles in the dimensional regulator ϵ cancel to impose further constraints on the partonic functions.
- Fix most of the logarithmically enhanced terms
- Smaller set of expressions that need threshold expansion

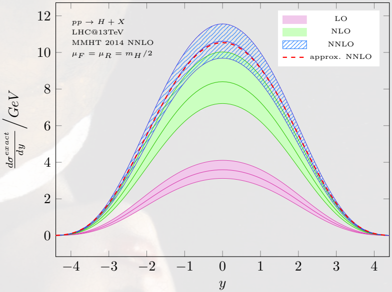
Integrate over the rapidity to **match the inclusive** x-section,

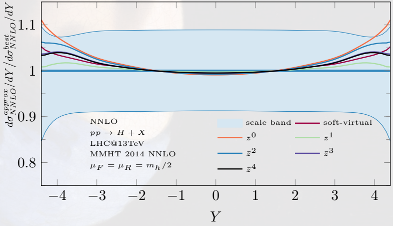
$$\eta_{ij}^{(3),incl.}(z) = \int dY \eta_{ij}^{(3)}(x_1,x_2).$$

- Strong check on the differential partonic cross-section
- Agreement between the two threshold expansions for all computed orders!

RESULTS

Threshold at NNLO:

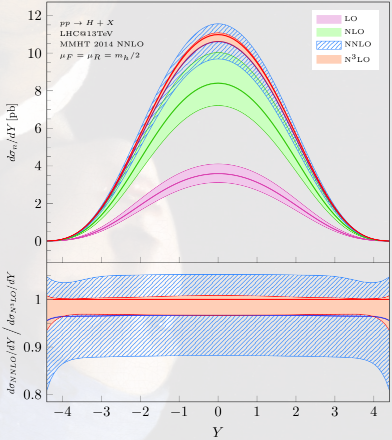


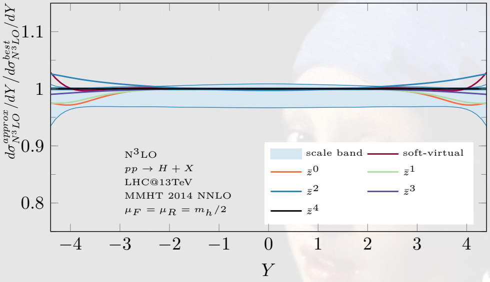


- Threshold expansion using **Differential equations** and **expansion by regions**
- Obtain **6 terms** in the expansion
- **Rescale** to the inclusive result
- The approximation performs well for central rapidities $|Y| < 3$
- Consistent improvement by including more terms
- To access the **missing** information from **high energy** contributions and fill the gap to the exact NNLO we need other tools.

RESULTS

Threshold at N3LO :





- Consistent behaviour between **NNLO** and **N3LO** regarding threshold expansion!
- **uniform** throughout the entire rapidity range
- **Scale variation** uncertainty reduced to [-3.4%,+0.9%]
- **Agreement** with a independent computation relying on q_T-subtraction

[Cieri,Chen,Gehrmann,Glover,Huss]

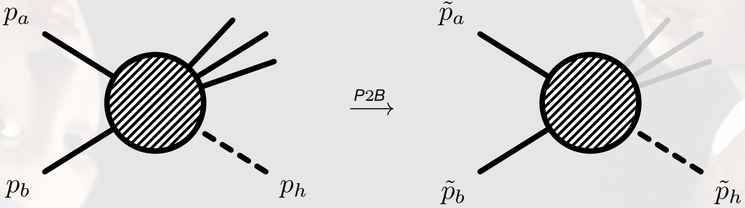
Projection to Born

X. Chen, T.Gehrmann, E.W.N. Glover, A. Huss, B. Mistlberger, AP [2102.07607]

The master formula for the **Projection to Born** (P2B):

$$\frac{\mathrm{d}\sigma_H^{N3LO}}{\mathrm{d}\mathcal{O}} = \left(\frac{\mathrm{d}\sigma_{H+jet}^{N2LO}}{\mathrm{d}\mathcal{O}} - \frac{\mathrm{d}\sigma_{H+jet}^{N2LO}}{\mathrm{d}\tilde{\mathcal{O}}} \right) + \frac{\mathrm{d}\sigma_H^{N3LO}}{\mathrm{d}\tilde{\mathcal{O}}}$$

- **Phase space singularities** associated with fully unresolved configurations are cancelled identically.
- The projection to the born phase space $\mathcal{O} \xrightarrow{P2B} \tilde{\mathcal{O}}$ is defied as:



$$\tilde{p}_a = \xi_a p_a, \quad \tilde{p}_b = \xi_b p_b, \quad \tilde{p}_h = \tilde{p}_a + \tilde{p}_b$$

$$\tilde{p}_a^2 = \tilde{p}_b^2 = 0, \quad \tilde{p}_h^2 = p_h^2, \quad \tilde{y}_h^2 = y_h^2,$$

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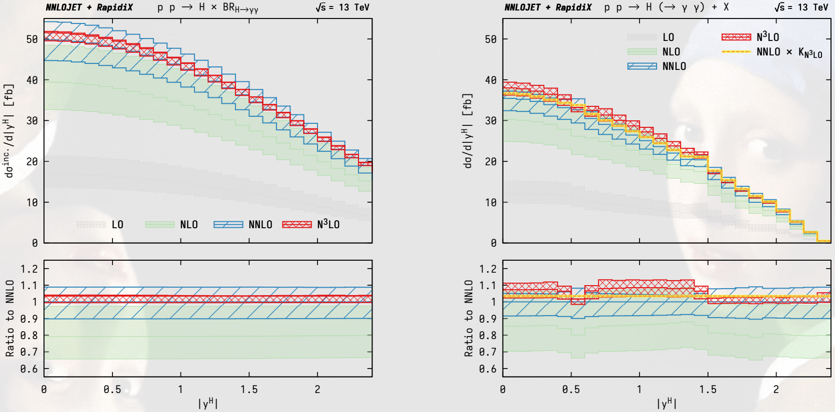
Results: di-Photon Decay



Fiducial cuts :

$$p_T^{\gamma_1} > 0.35 \times m_{\gamma\gamma}, \quad p_T^{\gamma_2} > 0.25 \times m_{\gamma\gamma},$$

$$|\eta^\gamma| < 2.37 \quad \text{excluding} \quad 1.37 < |\eta^\gamma| < 1.52$$

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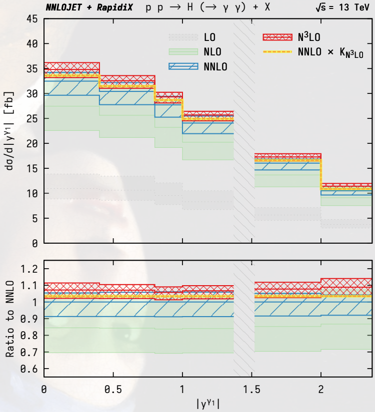

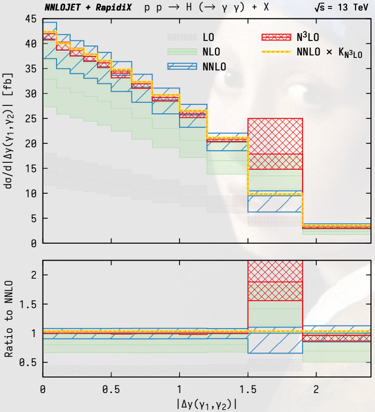

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SUMMARY

- We computed the Higgs boson rapidity distribution at **N3LO**
- We observe **stabilisation** of the perturbative expansion in the strong coupling and a significant reduction in the scale variation of the cross-section to [-3.4%,+0.9%]
- **N3LO** corrections are uniform throughout the entire rapidity range, well estimated by a K-factor
- Combined the rapidity distribution at **N3LO** with the Higgs + jet at **NNLO** distribution using **projection to born** to compute the fully differential Higgs.
- Other uncertainties become relevant (e.g. PDF) and must be addressed in the future.

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Thank you!