Precision calculation of Higgs plus one jet at NNLO

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Introduction

Higgs boson discovered [Atlas collaboration 2012, CMS collaboration 2012], what next?

- Establish if it is the SM Higgs Boson or something else.

$\hookrightarrow$ Investigate its coupling to other SM particles.

This requires a very good theoretical knowledge of the new particles's behaviour, in particular its p_T spectrum.

- Understand how the signal behaves under jet cuts, as are applied for $H \to WW$ via VBF to supress $t\bar{t}$ background [Atlas collaboration 2012, CMS collaboration 2012].
- Jet substructure techniques to access $H \to b\bar{b}$ decays [Butterworth, Davison, Rubin, Salam 2008].

Also: better understanding of jet binning in $H \to WW$.

Where do we stand?

- $H + J$ at NLO in HEFT [De Florian, Grazzini, Kunszt 1999, Ravindran, Smith, Van Neerven 2002, Glosser, Schmidt 2002]
  with finite m_t effects [Harlander, Neumann, Ozeren, Wiesemann 2012].
- $gg, qg \to H + J$ at NNLO in HEFT [Boughezal, Caola, Melnikov, Petriello, Schulze 2013]

We provide a second computation of $gg \to H + J$ at NNLO in HEFT

- Important crosscheck
- Distributions in p_T and η

☞ One of the first NNLO processes done with two different subtraction formalisms

$\hookrightarrow$ Opportunity for benchmarking

Long-term goal: full Higgs plus one jet at NNLO.

Setup of the calculation: the leading order

We are interested in evaluating the quantity

$$\sigma_{LO}(H_1, H_2) = \sum_{i,j} \int \frac{\mathrm{d}\xi_1}{\xi_1} \frac{\mathrm{d}\xi_2}{\xi_2} \times f_i(\xi_1, \mu^2) f_j(\xi_2, \mu^2) \mathrm{d}\hat{\sigma}_{ij,LO}(\xi_1 H_1, \xi_2 H_2)$$

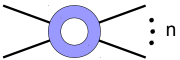
$$\mathrm{d}\hat{\sigma}_{ij,LO}(\xi_1 H_1, \xi_2 H_2) = \int_{\mathrm{d}\Phi_n} \mathrm{d}\hat{\sigma}^B_{ij,LO}(\xi_1 H_1, \xi_2 H_2) J_m^{(n)}$$

Where

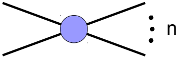
- f_i are the parton distribution functions.
- $J_m^{(n)}$ is the jet function selecting m jets from n partons. At leading order we have $m = n$.

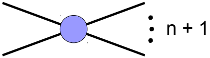
IR divergences and subtraction methods

At higher orders, real radiation and virtual corrections display IR singularities ($D = 4 - 2\epsilon$):



$$\sim \left(\frac{a}{\epsilon^2} + \frac{b}{\epsilon} + c + \mathcal{O}\{\epsilon\} \right)$$





$$\sim \sum_{ij} \frac{c_{ij}}{p_i^0 p_j^0 (1 - \cos(\theta_{ij}))} + \mathcal{O}\{1\}$$

Where, after integration over the unresolved phase-space, the singularities of the real correction become explicit and cancel with the (known) ones of the virtual contribution [Kinoshita 1962, Lee, Nauenberg, 1964].
This is however practically impossible analytically due to the jet function and external particles being on-shell.

IR divergences and subtraction methods

Idea: introduce subtraction terms to render the real and virtual contribution separately finite and perform the integration numerically.

$$\mathrm{d}\hat{\sigma}_{ij,NLO} = \int_{\mathrm{d}\Phi_{n+1}} [\mathrm{d}\hat{\sigma}^{R}_{ij,NLO} - \mathrm{d}\hat{\sigma}^{S}_{ij,NLO}] + \int_{\mathrm{d}\Phi_{n}} [\mathrm{d}\hat{\sigma}^{V}_{ij,NLO} - \mathrm{d}\hat{\sigma}^{T}_{ij,NLO}]$$

$$\mathrm{d}\hat{\sigma}^{T}_{ij,NLO} = -\int_{1_{unresolved}} \mathrm{d}\hat{\sigma}^{S}_{ij,NLO}$$

Where the content of the square brackets is finite and can safely be numerically integrated over.

Subtraction schemes are Antenna subtraction [Gehrmann-De Ridder, Gehrmann, Glover 2007, Kosover 1998], q_T-subtraction [Catani, Grazzini 2007], Residue subtraction [Frixione, Kunszt, Signer 1996], Sector decomposition [Binoth, Heinrich 2000] and STRIPPER [Czakon 2010].

Structure of the subtraction terms at NLO

Real subtraction term includes

$$X_3^0(i,j,k)|M_n^{(0)}(\ldots,I,K,\ldots)|^2 J_m^{(n)}(\ldots,I,K,\ldots)$$

Virtual contribution contains

$$\mathcal{X}_3^0(i,j)|M_n^{(0)}(\ldots,i,j,\ldots)|^2 J_m^{(n)}(\ldots,i,j,\ldots)$$
$$-\int \frac{\mathrm{d}z_1}{z_1}\frac{\mathrm{d}z_2}{z_2}\big(\Gamma(z_1)\delta(1-z_2)+(1\leftrightarrow 2)\big)|M_n^{(0)}(z_1p_1,z_2p_2,\ldots)|^2 J_m^{(n)}(\ldots)$$

where

- $M_n^{(l)}$ is the n-parton l-loop color-ordered amplitude.
- X_3^0 ($\mathcal{X}_3^0$) are the unintegrated (integrated) 3-parton 0-loop antenna funtions.
- The mapping $(i,j,k)\to(I,K)$ interpolates between singular limits.
- Γ is the mass factorisation kernel.

Structure of the subtraction terms at NLO

Recently, progress has been achieved in understanding the structure of the integrated subtraction terms [Currie, Glover, Wells 2013]:

$$\mathcal{X}_3^0(I,J) = \mathcal{J}_2^{(1)}(I,J)$$

$$\mathcal{X}_3^0(1,I) + \Gamma(z_1) = \mathcal{J}_2^{(1)}(1,I)$$

$$\mathcal{X}_3^0(1,2) + \Gamma(z_1)\delta(1-z_2) + \Gamma(z_2)\delta(1-z_1) = \mathcal{J}_2^{(1)}(1,2)$$

and $\mathcal{J}_2^{(1)}(I,J) = \mathcal{I}_2^{(1)}(I,J) + \mathit{Finite}$,

where $\mathcal{I}_2^{(1)}(I,J)$ is catani's IR singularity operator. This correspondence might allow an automatisation of NNLO subtraction starting from the known IR behaviour of loop amplitudes!

Additional features at NNLO

At RR:

- $X_3^0(i,j,k)|M_{n+1}^{(0)}(\ldots,I,K,\ldots)|^2 J_m^{(n+1)}(\ldots,I,K,\ldots)$
- $X_4^0(i,j,k,\ell)|M_n^{(0)}(\ldots,I,L,\ldots)|^2 J_m^{(n)}(\ldots,I,L,\ldots)$
- $X_3^0(i,j,k)X_3^0(I,K,\ell)|M_n^{(0)}(\ldots,\mathbf{I},\mathbf{L},\ldots)|^2 J_m^{(n)}(\ldots,\mathbf{I},\mathbf{L},\ldots)$

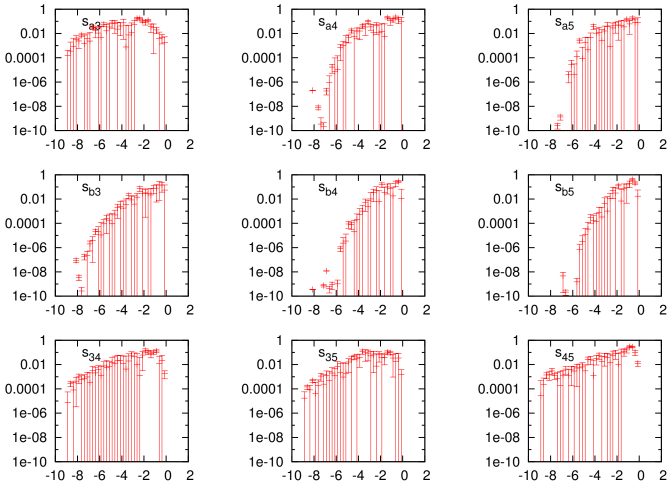
At RV:

- $\mathcal{J}_2^{(1)}(i,j)|M_{n+1}^{(0)}(\ldots,i,j,\ldots)|^2 J_m^{(n+1)}(\ldots,i,j,\ldots)$
- $X_3^0(i,j,k)|M_n^{(1)}(\ldots,I,K,\ldots)|^2 J_m^{(n)}(\ldots,I,K,\ldots)$
- $X_3^1(i,j,k)|M_n^{(0)}(\ldots,I,K,\ldots)|^2 J_m^{(n)}(\ldots,I,K,\ldots)$

At VV:

- $\mathcal{J}_2^{(2)}(i,j)|M_n^{(0)}(\ldots,i,j,\ldots)|^2 J_m^{(n)}(\ldots,i,j,\ldots)$
- $\mathcal{J}_2^{(1)}(i,j)|M_n^{(1)}(\ldots,i,j,\ldots)M_n^{(0)}(\ldots,i,j,\ldots)^\dagger|J_m^{(n)}(\ldots,i,j,\ldots)$
- $\mathcal{J}_2^{(1)}(i,j)^2|M_n^{(0)}(\ldots,i,j,\ldots)|^2 J_m^{(n)}(\ldots,i,j,\ldots)$

Performance of the subtraction terms



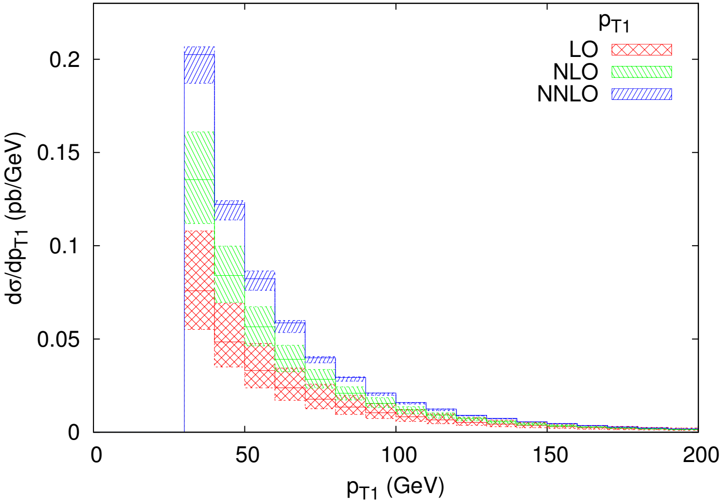
Distribution of subtracted RR weight versus partonic phase-space variables

Result

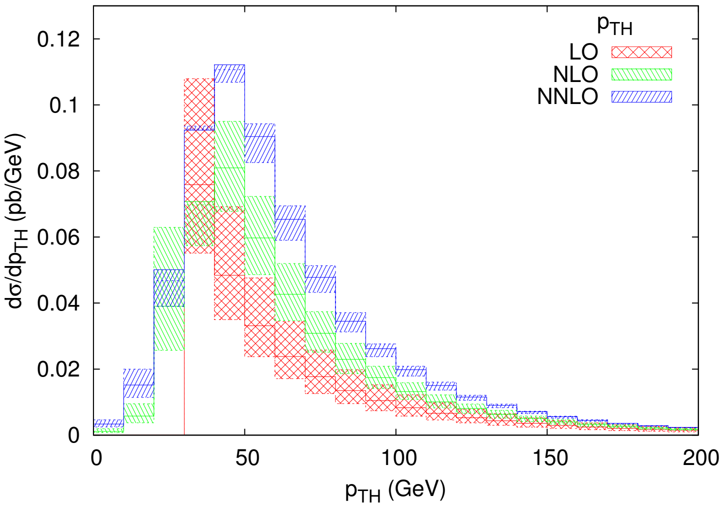
channel	cross section [pb]	approx. processor time
tree	1.9424 ± 0.0004	$\sim$10min
virt	2.8857 ± 0.0003	$\sim$40min
real	-0.5720 ± 0.0022	$<$4h
VV	3.1032 ± 0.0010	$\sim$10min
RV	-1.1616 ± 0.0077	$<$350h
RR	0.1446 ± 0.0290	$<$750h + $\sim$5 days of warmup (2 cores)

$\Rightarrow \sigma_{Tot,NNLO} = 6.342^{+0.282}_{-0.484}$ pb,
with theoretical error from scale variation ($\mu_R = \mu_F = \frac{m_H}{2}, m_H, 2m_H$).

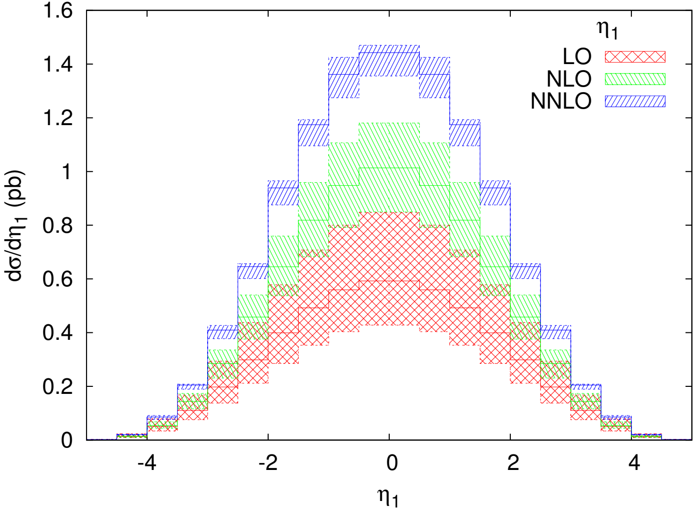
p_T Distributions



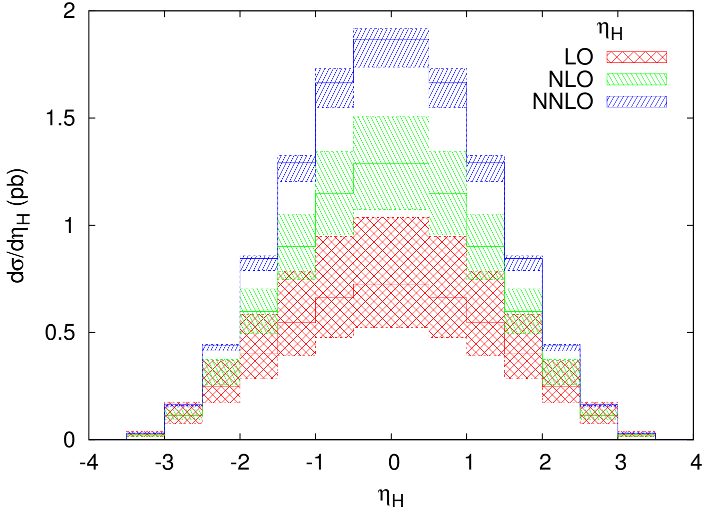
p_T Distributions



η Distributions



η Distributions



Conclusions and outlook

- We presented a computation of $gg \to H + J$ at NNLO QCD in HEFT.
- The handling of IR divergences is successfully carried out by the antenna subtraction formalism.
- We achieve agreement with existing results and provide distributions in p_T and η of the Higgs boson and jets.

- The next step(s) consist in evaluating the remaining qg and $q\bar{q}$ channels to obtain full results.

Thanks!

Technicalities

- Computation for 8TeV LHC
- Gluons only
- VEGAS integration coded up in FORTRAN
- Dedicated Phase-space generator
    - Split in wedges containing only double single collinear or triple collinear limits.
    - 4 rotations per PS point to cancel spurious angular terms in single collinear limits.
- k_T jet algorithm with R=0.5, p_T cut at 30GeV
- Use NNPDF23 set