Towards Higgs plus one jet at NNLO

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Based on work with X. Chen, T. Gehrmann and E.W.N. Glover

Introduction

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

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

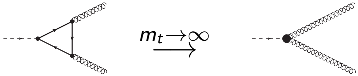
$\hookrightarrow$ Investigate its coupling to other SM particles.

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 $H \to WW$.

Introduction



Where do we stand?

- $H + J$ at NLO [De Florian, Grazzini, Kunszt 1999, Ravindran, Smith, Van Neerven 2002, Glosser, Schmidt 2002] in Higgs effective field theory (HEFT) [Wilczek 1977, Shifman, Vainshtein, Zakharov 1978, Inami, Kubota, Okada 1083] 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 computation of purely gluonic ($N_f = 0$) $H + J$ at NNLO in HEFT. This is expected to contribute by $\sim 60\%$ to the total cross section.

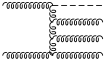
- Independent crosscheck

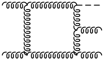
☞ One of the first NNLO processes done with two different subtraction formalisms

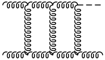
$\hookrightarrow$ Opportunity for benchmarking

IR subtraction at NNLO

$$
\begin{aligned}
\mathrm{d}\hat{\sigma}_{ij,NNLO} = & \int_{\mathrm{d}\Phi_{n+2}} \left[\mathrm{d}\hat{\sigma}^{RR}_{ij,NNLO} - \mathrm{d}\hat{\sigma}^{S}_{ij,NNLO}\right] \\
& + \int_{\mathrm{d}\Phi_{n+1}} \left[\mathrm{d}\hat{\sigma}^{RV}_{ij,NNLO} - \mathrm{d}\hat{\sigma}^{T}_{ij,NNLO}\right] \\
& + \int_{\mathrm{d}\Phi_{n}} \left[\mathrm{d}\hat{\sigma}^{VV}_{ij,NNLO} - \mathrm{d}\hat{\sigma}^{U}_{ij,NNLO}\right]
\end{aligned}
$$







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, Heymes 2014].

Structure of the subtraction terms at NLO

Real subtraction term includes

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

Integrated subtraction term contains

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

where

- 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.
- J_n is the measurement function selecting n jets.
- 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]:

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

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

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:

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

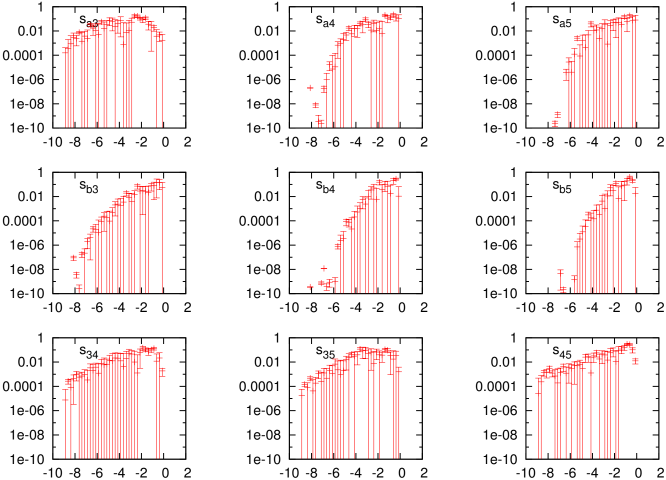
At RV:

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

At VV:

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

Performance of the subtraction terms



Distribution of subtracted RR weight versus partonic phase-space variables

Technicalities

- Computation for 8TeV LHC
- Gluons only
- Use NNPDF23 set
- VEGAS integration coded up in FORTRAN
- Higgs decay matrix element included
- Production of user defined distributions

Comparison with ATLAS

We use

- $m_H = 125\text{GeV}$
- Anti-k_T jet algorithm R=0.4
- Jet p_T cut at 30GeV, Jet η cut at 4.4
- Leading/Subleading photon p_T cut at $0.35/0.25 \cdot m_{\gamma\gamma}$
- Photon η cut at 2.37
- $\Delta_{J\gamma} < 0.4$
- $105\text{GeV} < m_{\gamma\gamma} < 16\text{GeV}$
- Photon isolation and hadronisation corrections estimated from MC [ATLAS 2014]
- Correction to $H \to \gamma\gamma$ branching ratio included.

Comparison with ATLAS

channel	cross section [fb]	approx. processor time
tree	5.118 ± 0.003	1min
virt	5.755 ± 0.019	20min
real	-2.616 ± 0.008	3h
VV	4.251 ± 0.005	4min
RV	-3.158 ± 0.032	220h
RR	1.004 ± 0.145	540h + ∼4 days warmup (2 cores)

$$\sigma^{LO}_{N\geq 1} = 6.61^{+3.18}_{-1.99}\mathrm{fb}$$
$$\sigma^{NLO}_{N\geq 1} = 8.43^{+0.26}_{-1.03}\mathrm{fb}$$
$$\sigma^{NNLO}_{N\geq 1} = 10.35^{-0.45}_{-0.46}\mathrm{fb},$$

To be compared with $\sigma^{ATLAS}_{N\geq 1} = 21.5 \pm 5.3(\mathrm{stat.})^{+2.4}_{-2.2}(\mathrm{syst.}) \pm 0.6(\mathrm{lumi})$

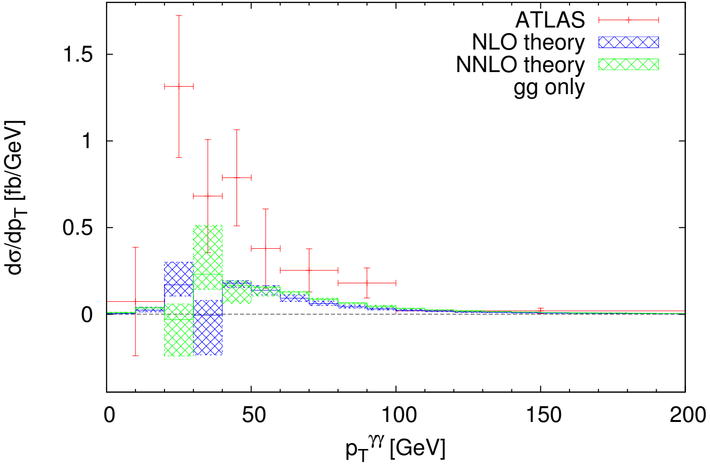
[ATLAS 2014]

$$\sigma_{N\geq 1}^{LO} = 6.61^{+3.18}_{-1.99}\mathrm{fb}$$
$$\sigma_{N\geq 1}^{NLO} = 8.43^{+0.26}_{-1.03}\mathrm{fb}$$
$$\sigma_{N\geq 1}^{NNLO} = 10.35^{-0.45}_{-0.46}\mathrm{fb}.$$

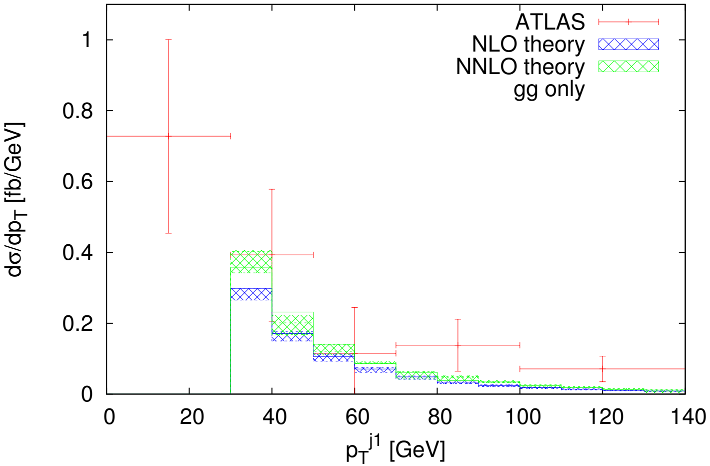
We set H_T as central scale and vary it by factors of 2 and $\frac{1}{2}$ to estimate the error from missing higher orders.

μ_R,μ_F	$m_H/2, m_H/2$	$m_H/2, 2m_H$	m_H, m_H	$2m_H, m_H/2$	$2m_H, 2m_H$
$\sigma_{N\geq 1}^{LO}$	9.79	9.60	6.61	4.73	4.62
$\sigma_{N\geq 1}^{NLO}$	8.69	8.81	8.43	7.62	7.40
$\sigma_{N\geq 1}^{NNLO}$	9.90	10.00	10.35	10.16	9.90

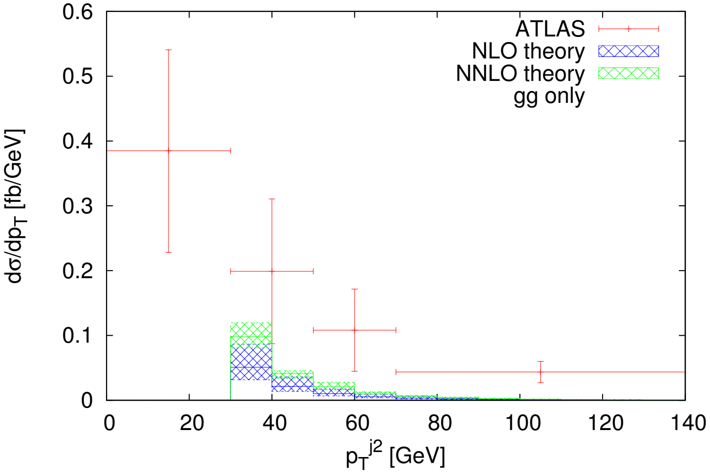
p_T Distributions: diphoton system (preliminary)



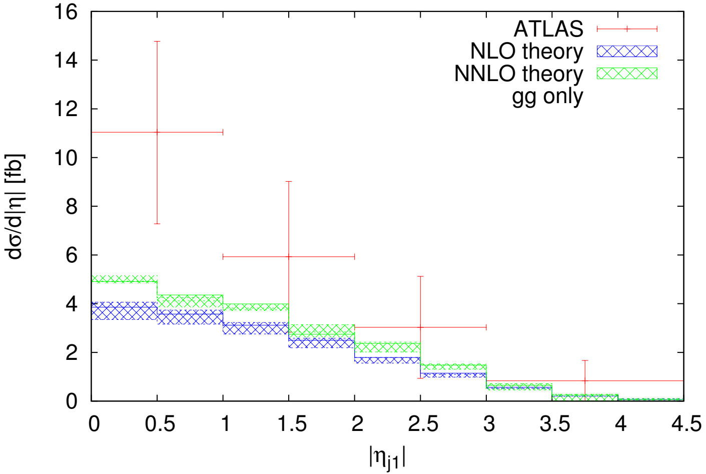
p_T Distributions: leading jet (preliminary)



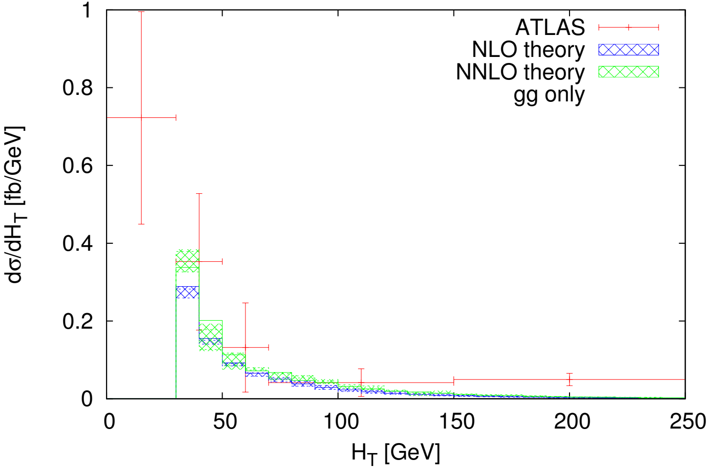
p_T Distributions: subleading jet (preliminary)



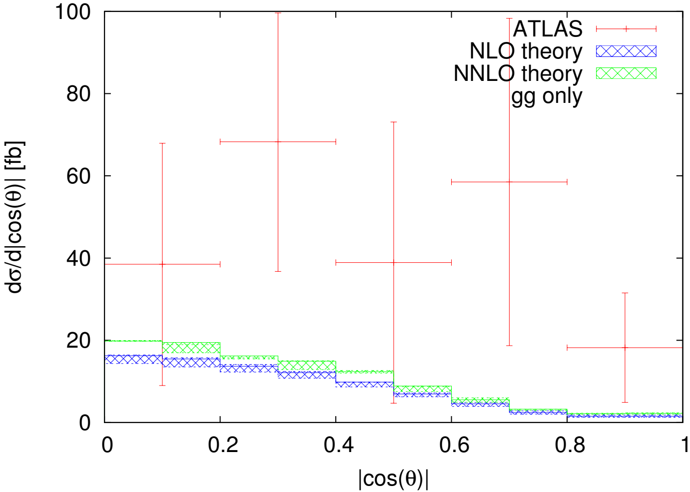
η Distribution of the leading jet (preliminary)



H_T Distribution (preliminary)



$|\cos(\theta)^\star|$ Distribution (preliminary)



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.
- We implemented the setup of ATLAS and compare distributions with experimental results.

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

Thanks!