Precision calculation of Higgs plus one jet at NNLO

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Higgs + Jets, Durham
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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.

↪ 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 (BCMPS) [Boughezal, Caola, Melnikov, Petriello, Schulze 2013]

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

- Independent crosscheck
- One of the first NNLO processes done with two different subtraction formalisms

  $\hookrightarrow$ Opportunity for benchmarking

Antenna subtraction

Numerical programs don't like infinities...

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

[Gehrmann-De Ridder, Gehrmann, Glover 2007, Kosover 1998]

Other formalisms are 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

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

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

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:

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

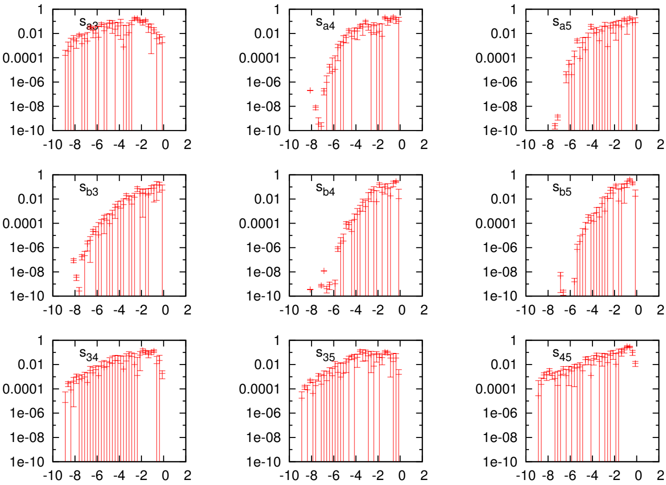
At RV:

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

At VV:

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

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

- $m_H = 125$ 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
- $\Delta_{J\gamma} < 0.4$
- $105\text{GeV} < m_{\gamma\gamma} < 160\text{GeV}$
- Photon isolation and hadronisation corrections estimated from MC [ATLAS 2014]
- Correction to $H \rightarrow \gamma\gamma$ branching ratio included.

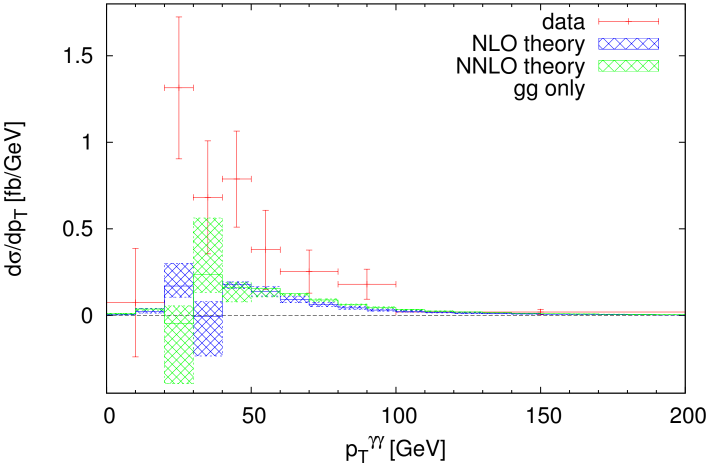
Comparison with ATLAS

channel	cross section [fb]	approx. processor time
tree	5.118 ± 0.001	1min
virt	5.755 ± 0.007	20min
real	-2.604 ± 0.005	3h
VV	4.251 ± 0.002	4min
RV	-3.153 ± 0.067	220h
RR	1.156 ± 0.222	2500h + ∼4 days warmup (2 cores)

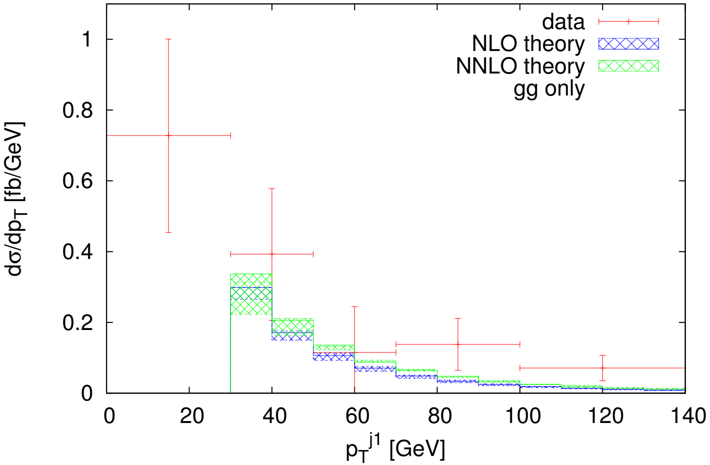
$$
\begin{aligned}
\sigma^{LO}_{N\geq 1} &= 6.61^{+3.18}_{-1.99} fb \\
\sigma^{NLO}_{N\geq 1} &= 8.43^{+0.26}_{-1.03} fb \\
\sigma^{NNLO}_{N\geq 1} &= 10.05^{+0.55}_{-0.53} fb,
\end{aligned}
$$

where 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.

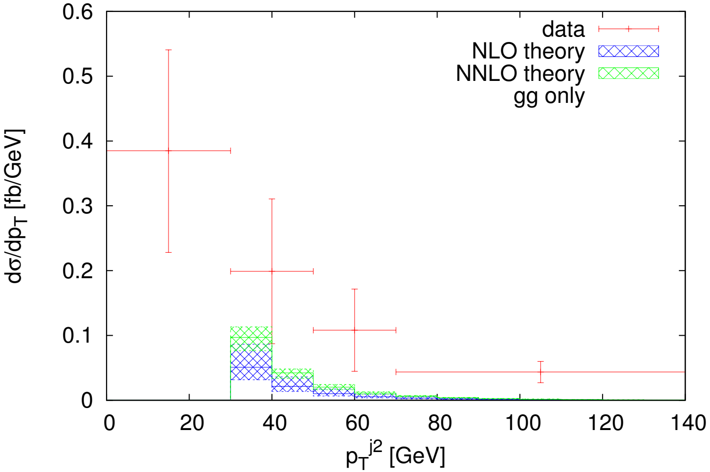
p_T Distributions: diphoton system (preliminary)



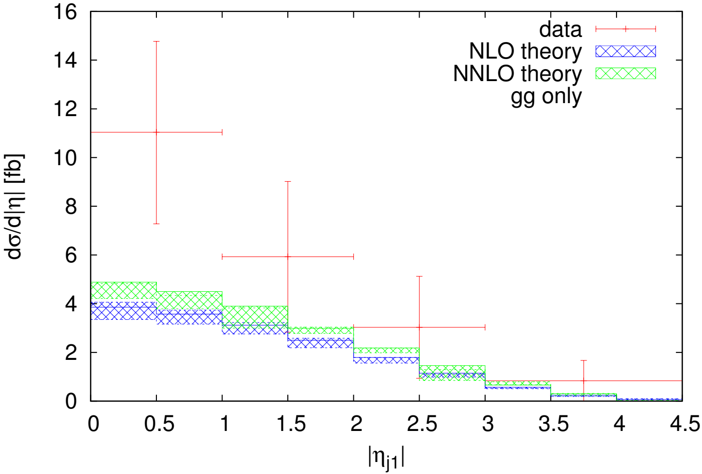
p_T Distributions: leading jet (preliminary)



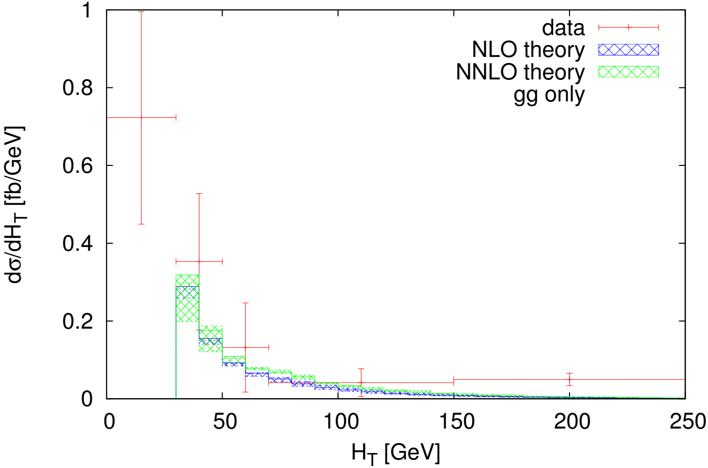
p_T Distributions: subleading jet (preliminary)



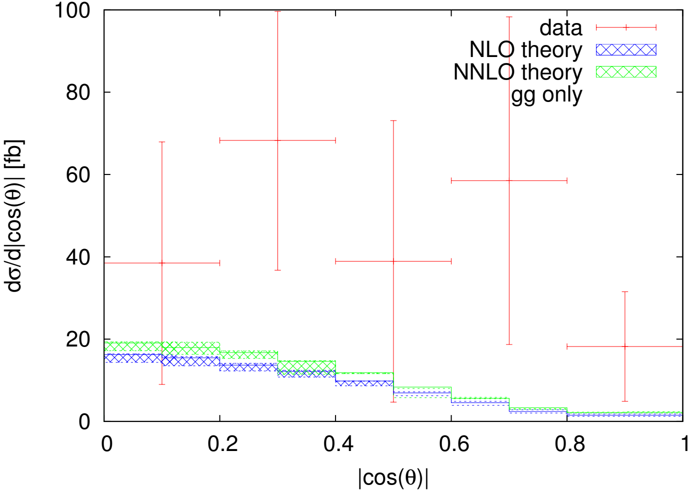
η Distribution of the leading jet (preliminary)



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 theoretical predictions.
- 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!