NNLOPS

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Outline

**MOTIVATION**

**MiNLO: Multiscale improved NLO**
- Nason, Zanderighi, k.h. - JHEP 1210
- Nason, Oleari, Zanderighi, k.h. - JHEP 1305

**NNLOPS**
- Nason, Zanderighi, Re, k.h. - JHEP 1310/JHEP 1505
- Karlberg, Re, Zanderighi - JHEP 1409

**RESULTS**

**SUMMARY**
NNLO needed for processes where NLO/LO corrs are large ...

E.g. Higgs production

For exploiting Higgs data we rather know the NNLO than NLO/LO ...
Motivation: NNLO

- NNLO needed for HIGH precision signal measurements ...
- E.g. DY: constrains PDFs, detector calibrations, BSM searches

You’d rather know this with O(1%) than O(10%) unc ...

Left: Anastasiou, Dixon, Melnikov, Petriello 2004 PRD 69
Right: ATLAS PLB 725
Motivation: NNLOPS

- **Differential NNLO DY and gg → Higgs achieved ~10yrs ago**
  Anastasiou, Dixon, Melnikov, Petriello ; Catani, Grazzini
  Generalised in more recent years:
  Del Duca, Somogyi, Trocsanyi ; Gehrmann, Glover, Pires et al. ; Czakon ;
  Boughezal, Caola, Melnikov, Petriello, Schulze ; Boughezal, Focke, Giele, Liu, Petriello ;
  Gaunt, Stahlhofen, Tackmann, Walsh

- **Unquestionably outstanding & progress**

- **Description of highest multiplicity events in e.g. NNLO gg → Higgs, is**

Anastasiou, Dixon, Melnikov, Petriello 2003 PRL 91
Catani, Grazzini 2007 PRL 98

Friday, 4 September 15
Meanwhile in ATLAS ...
Motivation: NNLOPS

NNLOPS takes fully inclusive fixed order NNLO as input ...
Motivation: NNLOPS

- NNLOPS outputs NNLO+[N]LL resummed, hadronized, fully exclusive, particle-level, unweighted events, with MPI, with QED ...

- No need for extrapolations, acceptance corrs, effy corrs, shower corrs, non-perturbative corrs, MPI, QED ...
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Results

Summary
Conventional NLO H + jet vs NLOPS H

\begin{align*}
\frac{d\sigma}{dp_T^H} \text{[pb/GeV]} & \\
\begin{array}{c}
\text{H PWG} \\
\text{HJ RUN} \\
\text{HJ FXD}
\end{array} & \\
\begin{array}{c}
\text{H PWG} \\
\text{HJ RUN} \\
\text{HJ FXD}
\end{array}
\end{align*}

\begin{align*}
\text{Ratio} & \\
\begin{array}{c}
\text{H PWG} \\
\text{HJ RUN} \\
\text{HJ FXD}
\end{array} & \\
\begin{array}{c}
\text{H PWG} \\
\text{HJ RUN} \\
\text{HJ FXD}
\end{array}
\end{align*}

- H PWG: \( gg \to \text{Higgs at NLO Powheg+Pythia } \)
- HJ RUN: NLO H+1 jet with \( \mu_R = \mu_F = p_{T,H} \)
- HJ FXD: NLO H+1 jet with \( \mu_R = \mu_F = M_H \)
- Conventional HJ calc\( n \)s diverge to -infinity as \( p_T \to 0 \)

Nason, Zanderighi, k.h. 2012 JHEP 1210
MiNLO \( H + \) jet in a nutshell

- In a nutshell MiNLO adds Sudakov resummation to \( H + \) jet configs.
- MiNLO recipe applied to the NLO \( H + \) jet goes

\[
\frac{d\sigma_M}{dp_T^2 dy} = \Delta^2 (Q, p_T) \frac{\alpha_S (p_T)}{\alpha_S (Q)} \left[ \frac{d\sigma}{dp_T^2 dy} + \frac{d\sigma}{dp_T^2 dy} \right]_{\alpha_S^{NLO}} \left[ A_1 L^2 + 2B_1 L - b_0 L \right]
\]

- With MiNLO, the initial \( pp \to H + \) jet kinematic goes from being divergent as \( p_T \to 0 \) to having physical Sudakov suppression.
**MiNLO H + jet v Conventional NLO v NLOPS H**

### d\sigma/dp_T^H [pb/GeV]

- **H PWG**: Essentially parton shower x NLO K-fact [≡ 1 in ratios]
- **HJ RUN**: NLO H + 1 jet with \( \mu_R = \mu_F = p_{T,H} \)
- **HJ FXD**: NLO H + 1 jet with \( \mu_R = \mu_F = M_H \)
- **HJ-MiNLO**: conventional NLO H + 1 jet at high \( p_T \)
- **HJ-MiNLO** parton shower result at low \( p_T \), no divergences
- **HJ-MiNLO** sensible scale unc. band [doesn’t shrink as \( p_T \to 0 \)]
MiNLO H + jet: NLO for H + jet & NLO for H

MiNLO gives physical predictions for multi-jet spectra all through $p_T$ spectra [as opposed to $\infty$] so it gives physical predictions for fully inclusive Higgs observables too.

JHEP 1305 proved with the NNLL$_\sigma$ Sudakov of Ellis & Veseli

HJ-MiNLO is NLO for H + jet AND inclusive Higgs observables: two NLO calculations from one ["NLO x NLO"]

Nason, Oleari, Zanderighi, k.h. 2012 JHEP 1305 Ellis, Veseli 1997 NPB 503
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RESULTS

SUMMARY
NNLOPS

- **HJ NLO:**
  - Unphysical NLO 0-jet obs
  - NLO 1-jet obs
  - LO 2-jet obs
  - 0 everything else

- **HJ-MINLO [NLO x NLO]:**
  - NLO 0-jet obs
  - NLO 1-jet obs
  - LO 2-jet obs
  - 0 everything else

- **HJ-MINLO + PS for \( q < q_0 \):**
  - NLO 0-jet obs
  - NLO 1-jet obs
  - LO 2-jet obs
  - PS everything else

- **NNLOPS:**
  - **NNLO** 0-jet obs
  - NLO 1-jet obs
  - LO 2-jet obs
  - PS everything else

Achieved by NNLO/NLO weighting the NLO x NLO version of HJ-MiNLO

Nason, Oleari, Zanderighi, k.h. 2012 *JHEP 1305*  
Nason, Re, Zanderighi, k.h. *JHEP 1310*

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In its most basic form:

$$d\sigma_{\text{NNLOPS}} = d\sigma_{\text{MiNLO}} \times W(y_H) \quad \text{with} \quad W(y_H) = \frac{d\sigma_{\text{NNLO}}}{dy_H}$$

Since $$\frac{d\sigma_{\text{MiNLO}}}{dy_H} = \frac{d\sigma_{\text{NNLO}}}{dy_H}$$ at NLO \,

\Rightarrow \quad W(y_H) = 1 + O(\alpha_s^2)

so $$W(y_H)$$ factor only affects $$d\sigma_{\text{MiNLO}}$$ by NNLO terms.

So multiplying $$d\sigma_{\text{MiNLO}}$$ by the $$W(y_H)$$ factor for NNLO accuracy doesn’t spoil NLO accuracy already in $$d\sigma_{\text{MiNLO}}$$ for $$\geq 1$$ jet obs!

If $$\frac{d\sigma_{\text{MiNLO}}}{dy_H} \neq \frac{d\sigma_{\text{NNLO}}}{dy_H}$$ at NLO $$W(y_H)$$ spoils NLO of $$d\sigma_{\text{MiNLO}}$$ for $$\geq 1$$ jet obs.

Apart from NNLO calc, catch for NNLOPS is making the NLO x NLO MiNLO calc ...

\[\text{HNNLO is fixed order NNLO code of Catani, Grazzini, Sargsyan 2007/2013 \ PRL 98/JHEP 1309} \]
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**RESULTS**

**SUMMARY**
The lower panel shows the ratio relative to the latter.

Here, to begin with, we wish to discuss the evolution of the Higgs boson transverse momentum with its central scale choice.

In figure 2 we show how the Higgs boson transverse momentum spectrum is a exclusive, realistic, hadron level, final-states

**HNNLO**: state-of-the-art fixed order Higgs production calculation [Catani, Grazzini, Sargsyan 2007/2013 PRL 98/JHEP 1309]

**HNNLOPS**: as above but with resummed, parton showered, fully exclusive, realistic, hadron level, final-states

Nason, Re, Zanderighi, k.h. JHEP 1310
Jet veto efficiency: HNNLOPS vs NNLO+NNLL

- **0-jet xsec efficiency**: $\varepsilon(p_{T,\text{veto}}) = \frac{\sigma(p_{T,\text{veto}})}{\sigma_{\text{tot}}}$
- **JETVHETO**: state-of-the-art NNLO+NNLL 0-jet xsec effy
  [Banfi, Monni, Salam, Zanderighi 2012 *PRL* 109]
- **HNNLOPS**: agreement at level of $\leq 3\%$ everywhere
Jet bins & Jet $p_T$: HNNLOPS vs ATLAS data

- Jet bins low for all MCs; HNNLOPS expectedly better in 0-jet bin
- “...poorest agreement with data ... in the inclusive and exclusive 1-jet bins, with p-values ranging between 0.1% and 3.6%.”
- Normalised lead jet $p_T$ agreeing well between data & all MCs

Nason, Re, Zanderighi, k.h. JHEP 1310  ATLAS arXiv:1504.05833
Figure 6: Distribution of the photon decay angle in the Collins-Soper frame at the 8 TeV LHC. The inset shows ratios of dijet cross sections in different production modes.

Left: NNLOPS vs 20.3 fb⁻¹ ATLAS PRL 2015, H → γγ △, H → ZZ □, H → ZZ ⊕ γγ  •

Right: NNLO H+1 jet vs 20.3 fb⁻¹ ATLAS JHEP 1409 H → γγ

HNNLOPS & state-of-the-art NNLO H+1 jet calcⁿ appear to do a similar job for lead jet p_T w.r.t data
\( y_H \) \( p_{T,H} \): HNNLOPS t & b mass effects

- \( y_H \): mass effect flat, finite \( m_t \to +6\% \), finite \( m_t+m_b \to +6\%-6\% = 0\% \)
- \( p_{T,H} < 120 \) GeV: \( m_t \) effect mild and \( \sim \) flat
- \( p_{T,H} > 220 \) GeV: \( m_t \) effect sizable, -ve & NOT flat w.r.t large \( m_t \)
- \( p_{T,H} > 70 \) GeV: \( m_b \) effect v.small [t-b-loop interference v.small]
- \( p_{T,H} < 40 \) GeV: \( m_b \) effect sizable but not far from large \( m_t \) limit

Nason, Zanderighi, k.h. 2015 JHEP 1501
Jet veto efficiency: DYNNLOPS vs NNLO+NNLL

**0-jet xsec efficiency:** $\varepsilon(p_{T,veto}) = \sigma(p_{T,veto}) / \sigma_{tot}$

**JETVHETO:** state-of-the-art NNLO+NNLL 0-jet xsec effy

[Banfi, Monni, Salam, Zanderighi 2012 PRL 109]

**DYNNLOPS:** agreement at level of $\leq 3\%$ everywhere [as for HNNLOPS]

Karlberg, Re, Zanderighi 2014 JHEP 1409
**Z rapidity: DYNLOPS on ATLAS data**

- **ATLAS late 2011 incl. Z analysis** [PRD 85](#)
- **Left:** DYNLOPS v data. Right: FEWZ with various PDFs v data ...
- **Good agreement for central region, less so at high |y_z|**
- **DYNLOPS v. compatible with independent fixed order FEWZ NNLO**

Karlberg, Re, Zanderighi 2014 [JHEP 1409](#) ATLAS 2011 [PRD 85](#)
**MOTIVATION**

Maximising reach & potential of NNLO & NLO calcns requires matching to fully excl. resummation, hadronization, MPI, QED, particle-level PS’s

**MiNLO: Multiscale improved NLO**

Get NLO for lower multiplicity calcns ‘for free’ from higher multiplicity ones: exponentiate NNNLL_{soft} soft terms in NLO xsecn

**NNLOPS**

Depends on NNLO code from NNLO groups

In its most basic variant: \( \frac{d\sigma_{NNLOPS}}{d\Phi_B} = \frac{d\sigma_{NNLO}}{d\Phi_B} \times \frac{d\sigma_{MiNLO}}{d\Phi_B} \)

**RESULTS**

Someone will have a new idea/extend this idea but NNLOPS does the job today & it does it well
improving $HJJ \rightarrow HJJ^*$

In pipeline, Rikkert Frederix, k.h.
Suppose MC gives integral at NNLO i.e. including $O(\alpha_s^4)$ terms [HJ-MiNLO rwgted to HNNLO [Catani, Grazzini] $d\sigma/dy$ does this]

Suppose MC also predicts spectrum at NLO i.e. distribution to right of green cut including $O(\alpha_s^4)$ terms [HJ-MiNLO does this]

Plainly the MC then also gives the area to the left at NNLO i.e. including $O(\alpha_s^4)$ terms [HJ-MiNLO rwgted to NNLO $d\sigma/dy$ does this]

Some arbitrary cut in radiation phase space

In infinitesimal element of $gg \rightarrow$ Higgs Born ph. space $[y, y+dy]$
**0-jet xsec	extsuperscript{n}** and **0-jet xsec	extsuperscript{n} effy**: net effect of finite \( m_t + m_b \) corrections is very small [2-3\%] in region of practical interest

- Little difference on exponentiating [RMB] or not [MEMB] non-factorizing terms

- Cumulative nature of observables diminishes \( m_b \) effect at low \( p_T \)