Theory predictions for Higgs-boson differential distributions

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The Higgs rapidity distribution

Higgs predictions: forefront of perturbative calculations

Higgs rapidity (ggF)

- Computed @N^3LO in a soft expansion (~inclusive)
- Expected to work very well.
  (apart from end-points)
- Remarkably flat K-factor
  (as expected from previous orders)
- Combined with p_t@NNLO, can give access to N^3LO fiducial volume

Also known at this order for (inclusive) VBF [Karlberg, Dreyer (2016)]
$p_{t,H}$: a major probe for Higgs physics

Low $p_t$
Light Yukawas…

Bulk of the distribution
Highest precision

Boosted
ggH vs ttH, EFT…

Disclaimer: some illustration from each region, mostly focusing on ggF
$p_{t,H}$: a major probe for Higgs physics

**Disclaimer:** some illustration from each region, mostly focusing on ggF
The bulk of the distribution: $NNLO+N^3LL$

- $p_t \ll m_t$: $ggF$, point-like interaction
  ($m_t$-suppressed terms under good control see e.g. [Neumann et al (2016)])

- Very refined theoretical predictions
  - $p_{t,H}$ known at NNLO QCD [Boughezal et al. (2015) x2, Chen et al (2015)].
    Fully validated
  - small $p_t$: matched against resummation to extend down to $p_t \sim 0$. Two different methods
The bulk of the distribution: \( \text{NNLO} + N^3\text{LL} \)

- Same f.o. + resummation accuracy, different matching procedure $\rightarrow$ test for robustness
- By and large: very stable result, f.o. OK down to $\sim 40$ GeV $\rightarrow$ very good control in the bulk of the distribution
Eventually interested in more differential information, e.g. jet-binned $p_t$ distributions
Not the end of the story I: more differential

Jet-vetoed cross-section under very good theoretical control…
[Banfi et al. (2015)]

… but f.o. jet-binned $d\sigma/dp_T$ has unphysical features (would require all-order considerations)
[some work in this direction: Sun et al (2016)]
Not the end of the story II: realistic final states

Consider VH, $H \rightarrow b\bar{b}$

- Typical $p_{t,V} \sim 150-250$ GeV $\rightarrow$ Higgs only semi-boosted
- QCD radiation pattern from $H\rightarrow b\bar{b}$ non trivial
- $\text{NNLO}_{\text{prod}} \times \text{NNLO}_{\text{dec}}$ known [Ferrera et al.; FC et al. (2018)] $\rightarrow$ can explore

$WH$, Reconstructed Higgs $p_t$, $NLO_{\text{dec}}$ vs $NNLO_{\text{dec}}$
VH, $H \rightarrow b\bar{b}$

How well is the radiation pattern described by PS?

\[ WH, \text{NNLO vs off-the-shelf PS} \]

- PS seems to capture some of the radiation pattern
- Delicate issues about HF-identification ($b$-tagging vs flavour $k_t$)
- More apple-to-apple investigations desirable (massive $b$...)

\[ ZH, \text{NNLOPS + NLO}_{\text{dec}} \text{ vs f.o.} \]
Low $p_t$: light quark effects

- For $m_q \ll p_t \ll m_H$: amplitude develops non-Sudakov double logs $y_q m_q / m_H \left[ \ln^2 (m_H^2 / m_q^2), \ln^2 (p_t^2 / m_q^2) \right]$

- Despite $y_{b,c} \ll y_t$, interference effects may be visible → constrain light Yukawas!

**PROBLEM: control over QCD corrections**

- resolved quark loop →
  - difficult loop amplitudes
- low $p_t$ → all-order effects

[Bishara et al. (2017)]
t/b interference: not so long ago

- \(tb\) interference only known at LO
- non trivial interplay with collinear gluons → don’t know how to resume all-order effects at low \(p_t\)
- not enough information for a proper f.o. / resummation matching

A pragmatic approach
- use all the available information
- resum under 2 extreme assumptions:
  * \(b/t\) contributions on the same footing
  * no resummation after \(p_t \sim m_b\)
- Large residual uncertainties
**t/b interference: NLO**

- 2-loop amplitude for $b$ contribution computed in the limit $m_b \ll p_t \ll m_h$
- Approximation expected to be very good for all pheno applications

**Figure 1:** Relative top-bottom interference contribution to the transverse momentum distribution of the Higgs boson at $p_T > 30$ GeV and $+2\%$ at $m_H = 125$ GeV.

- Large $K$-factor…
- … but similar to HEFT
- Large source of unc. from $b$-mass scheme
- Non-trivial logarithmic structure
- Still don’t know how to resum [some work in this direction: Melnikov, Penin (2016); Forte et al (2016); Penin, Liu (2018)]
NLO result allows for a proper matching → resummation ambiguities much less severe
**t/b interference: matching with resummation**

[FC, Monni et al. (2018)]

**Reasonable control over t/b interference**

- Major source of uncertainty from $b$-mass scheme → can only be improved with higher order calculation
- It will be very hard to improve in this direction
• Boosted Higgs very sensitive to BSM contributions, internal structure of ggH coupling

• Problem: very difficult (multi)-loop amplitudes. Going beyond LO non trivial
Boosted Higgs: theoretical picture

- Rates are low, but not insignificant
- Very sensitive to anomalous ggH coupling
- Can help resolving flat directions in ggH, ttH couplings

Unfortunately, we only know it at LO!

NLO would require complicated 2-loop amplitudes, currently under investigation

- Boosted Higgs very sensitive to BSM contributions, internal structure of ggH coupling
- Problem: very difficult (multi)-loop amplitudes. Going beyond LO non-trivial
**Boosted Higgs: NLO**

NLO is finally known. 2 approaches:

- analytic result under the assumption $m_{t,h} \ll p_t$ [Kudashkin et al. (2017-18)]
- exact numerical result [Jones, Kerner, Luisoni (2018)]

They agree within expectation $\rightarrow$ **important validation**

- Large $K$-factor

- Very similar to HEFT $K$-factor confirming expectations from merged samples approach [see e.g. Frederix et al (2016), Greiner et al (2016)], approximate $m_t$ treatment [see e.g. Neumann and Williams (2016)] and resummation analysis [see e.g. Muselli et al (2016)]

**Can combine with NNLO HEFT K-factor**
Boosted Higgs: all channels

Boosted Higgs: other channels become more relevant

- Interesting interplay of different channels. Different pattern of radiative corrections
- NLO EW corrections in ggF? $\ln^2(p_T/m_H)$?
Boosted Higgs: state of the art vs practice

Shower effects small, as they should

<table>
<thead>
<tr>
<th>Fixed order level</th>
<th>Total</th>
<th>$p_T^H &gt; 400$</th>
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<tbody>
<tr>
<td>1</td>
<td>$gg_{\text{hfact}=104}$</td>
<td>30.336 ± 25.6</td>
<td>0.0730</td>
<td>0.0507</td>
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<tr>
<td>2</td>
<td>HJ $m_t = \infty$ 5 GeV gen cut</td>
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<td>0.0643</td>
<td>0.0413</td>
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<td>HJ $m_t = \infty$ 50 GeV gen cut</td>
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<td>4</td>
<td>HJ-MiNLO $m_t = \infty$</td>
<td>32.143 ± 27.2</td>
<td>0.0778</td>
<td>0.0509</td>
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<tr>
<td>5</td>
<td>HJ-MiNLO $m_t = 171.3$</td>
<td>33.845 ± 28.6</td>
<td>0.0281</td>
<td>0.0153</td>
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PS-level

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<tr>
<td>1</td>
<td>$gg_{\text{hfact}=104}$</td>
<td>30.336 ± 25.6</td>
<td>0.08290 ± 0.0563</td>
<td>0.05770 ± 0.0387</td>
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<tr>
<td>2</td>
<td>HJ $m_t = \infty$ 5 GeV gen cut</td>
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<td>0.06510 ± 0.0520</td>
<td>0.04170 ± 0.0333</td>
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<td>4</td>
<td>HJ-MiNLO $m_t = \infty$</td>
<td>32.151 ± 27.2</td>
<td>0.08030 ± 0.0639</td>
<td>0.05240 ± 0.0417</td>
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<tr>
<td>5</td>
<td>HJ-MiNLO $m_t = 171.3$</td>
<td>33.755 ± 28.6</td>
<td>0.0290 ± 0.023</td>
<td>0.01610 ± 0.0128</td>
</tr>
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</table>

Central value for merged samples (✔) and PS (?) in good agreement with state-of-the-art predictions

$|p_T^\text{cut}|$ | NNLO approximate quad. unc. [fb] | HJ-MiNLO [fb] | MG5_MC@NLO [fb] |
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<td>400 GeV</td>
<td>$32.0^{+9.1/-11.6}$</td>
<td>$29^{+24/-21}$</td>
<td>$31.5^{+31/-25}$</td>
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<td>430 GeV</td>
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<td>$21.8^{+31/-25}$</td>
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<tr>
<td>450 GeV</td>
<td>$17.4^{+8.9/-11.5}$</td>
<td>$16.1^{+22/-21}$</td>
<td>$17.1^{+31/-25}$</td>
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Boosted Higgs: an interesting theoretical puzzle

For $q_T < p_T$

(a) $q_T \sim p_T$  
(b) $\ll$

However:

$q^2 \sim m_H^2$ 

Eventually, $K_{full} \neq K_{heft}$

We don’t see it yet… visible at the (HL/HE)-LHC?
Boosted Higgs: a glimpse in the future?

Boosted Higgs at a 27 TeV LHC [LHCHXSWG (2019)]

Radiative corrections
Conclusions

• By and large, Higgs differential distributions under good theoretical control

• There are caveats though
  • going multi-differential
  • complex final states, proper reconstruction
  • loop amplitudes involving massive quarks (low $p_t$, boosted Higgs). All-order structure, higher order corrections…
  • Non-trivial interplays of different channels at high $p_t$, non-trivial patterns of radiative corrections $\rightarrow$ estimate NLO EW for Higgs $p_t$ in ggF?

• Many of these issues not immediately relevant for phenomenology in 2019, but can become issues at the HL-(HE)-LHC…

• … and very interesting from a theoretical point of view
Conclusions

• By and large, Higgs differential distributions under good theoretical control

• There are however:
  • going multi-differential
  • complex final states, proper reconstruction
  • loop amplitudes involving massive quarks (low p_t, boosted Higgs).
    All-order structure, higher order corrections…
  • Non-trivial interplays of different channels at high p_t, non-trivial patterns of radiative corrections

• Many of these issues not immediately relevant for phenomenology in 2019, but…

• … and very interesting from a theoretical point of view
Backup
Higgs differential: rapidity

Soft expansion

NNLO

N^3LO

[Graph showing Higgs boson rapidity distribution with threshold expansion truncated at different orders.]

Note: The graphs illustrate the ratio of the approximate NNLO to the exact result, with different orders of soft expansion. The left panel shows the NNLO prediction obtained in this work, compared to the scale and soft-virtual bands. The right panel shows the N^3LO prediction for the same comparison.
The estimation are known to contribute less than 1% to the total. These contributions have been shown to be much below the permille level after VBF cuts. Contributions from s-channel production, which are known to contribute (5%) of the total cross section. We leave a detailed study of non-factorisable and electroweak effects neglected by the structure function approximations.

In this letter, we have presented the first N3LO contributions to the VBF cross section at NNLO. At the fully inclusive level these contributions are sizeable but they have been calculated up to NLO [10]. Contributions from t-/u-channel interferences which are known to contribute (5%) of the total cross section. At the fully inclusive level these contributions are sizeable but they have been calculated up to NLO [10]. At the inclusive level these contributions are sizeable but they have been calculated up to NLO [10].

Theoretical uncertainties are at the level of 0.25% but are reduced to the permille level after VBF cuts. Contributions along with the heavy-quark loop induced kinematically and colour suppressed. These contributions have been estimated to contribute at the permille level [7].

Contributions have been shown to be much below the permille level after VBF cuts. Contributions from s-channel production, which are known to contribute (5%) of the total cross section. We leave a detailed study of non-factorisable and electroweak effects neglected by the structure function approximations. Theoretical uncertainties are at the level of 0.25% but are reduced to the permille level after VBF cuts.

<table>
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<th>NLO</th>
<th>NNLO</th>
<th>N3LO</th>
</tr>
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<tbody>
<tr>
<td>0.99</td>
<td>1.01</td>
<td>1.02</td>
<td>0.99</td>
</tr>
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TABLE I. Inclusive cross sections at LO, NLO, NNLO and N3LO.

VBF@N3LO