Higgs Production at High Transverse Momentum

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GLUON FUSION
Motivation

- Study Higgs production at high $p_T \gtrsim 340$ GeV → Explore Higgs in a new kinematic regime.

- Allow us to look inside loop:
  - Probe Higgs couplings to SM quarks;
  - Probe of potential New Physics in loop.

- Studies by ATLAS and CMS.
  [ATL-CONF-2021-010; JHEP 2012 085]
  [Talk by Christina Reissel]

  - Limited by available statistics → looking forward to more data!
Theoretical Calculations

- Calculations of gluon fusion Higgs production use Heavy Effective Field Theory: integrate out top loops.

  ✔ $H \@ N3LO$  [Anastasiou et al., ‘16; Mistlberger, ‘18]


- High-$p_T$: top mass no longer largest scale:
  - HEFT not valid.
  - Full (top) mass effects need to be taken into account.
Current Status

• LO results for $H+j$, $H+jj$, $H+3j$ known.

• NLO corrections to $H+j$ require two-loop massive amplitudes:

  ![Diagram](https://via.placeholder.com/150)

  Extremely challenging!

• Approximate treatments (reweighting, jet merging, ...):

  [Buschmann et al., ’14; Maltoni, Vryonidou, Zaro, ’14; Hamilton, Nason, Zanderighi, ’15; Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier, ’16; Frederix, Frixione, Vryonidou, Wiesemann, ’16; Neumann, Williams, ’17; Neumann, ’18]

• Progress towards exact analytic amplitudes.

  [Bonciani et al., ’16; Frellesvig, Hidding, Maestri, Moriello, Salvatorı, ’20]

• Analytic results using $p_T,H \gg m_t,m_H$

  [Kudashkin, Melnikov, Wever, ’17 + Lindert, ’18]

• Exact numerical results.

  [Jones, Kerner, Luisoni, ’18]
$H+j$: Results at NLO

Exact results

[Jones, Kerner, Luisoni, ‘18]

Approximation $p_{T,H} \gg m_t, m_H$

[Kudashkin, Lindert, Melnikov, Wever, ‘18]

1. K-factors from exact and approximate results show similar behavior → important validation!
$H+j$: Results at NLO

Exact results

[Jones, Kerner, Luisoni, '18]

Approximation $p_{T,H} \gg m_t, m_H$

[Kudashkin, Lindert, Melnikov, Wever, '18]

2. K-factors **slightly larger** than k-factors using HEFT, but **quite flat** in both cases!
**H+j: Results at NLO**

**Exact results**

[Jones, Kerner, Luisoni, ‘18]

**Approximation** $p_T,H \gg m_t, m_H$

[Kudashkin, Lindert, Melnikov, Wever, ‘18]

3. Corrections are large ($k \approx 2$) and scale uncertainty large ($\sim 20\%$)
H+j: Beyond NLO

- Increased precision and reduced theoretical uncertainty: combine HEFT NNLO results with exact NLO results.

- **Flat k-factors**: NLO and NNLO corrections in HEFT and exact NLO corrections don’t alter shape of distribution.

- “Born-improved”: Mass effects at NNLO accounted for by reweighting HEFT results using exact results.

  [Chen, Gehrmann, Glover, Jaquier ‘15]

\[
\Sigma(p_T, \text{cut}) = \int_{p_T^{\text{cut}}}^{\infty} \frac{d\sigma}{dp_T'} dp_T'
\]

\[
\Sigma_{\text{HEFT imp.}(0), \text{NNLO}}(p_T^{\text{cut}}) = \frac{\Sigma_{\text{exact, LO}}(p_T^{\text{cut}})}{\Sigma_{\text{HEFT, LO}}(p_T^{\text{cut}})} \Sigma_{\text{HEFT, NNLO}}(p_T^{\text{cut}})
\]

(Mass effects at LO)

(NNLO corrections in HEFT)

[Becker et al., LHCHXSWG note, ‘20]
Use exact results at NLO

\[ \sum_{\text{HEFT imp.}(1), \text{NNLO}} (p_T^{\text{cut}}) = \frac{\sum_{\text{exact, NLO}} (p_T^{\text{cut}})}{\sum_{\text{HEFT, NLO}} (p_T^{\text{cut}})} \sum_{\text{HEFT, NNLO}} (p_T^{\text{cut}}) \]

[Becker et al., LHCHXSWG note, ’20]
H+j: Beyond NLO

- Use exact results at NLO

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[Becker et al., LHCHXSWG note, ’20]

\[ p_T^{\text{cut}} = 450 \text{ GeV} : \]

\[ \sum_{\text{exact, LO}} = 6.5^{+45\%}_{-29\%} \text{ fb} \quad \sum_{\text{exact, NLO}} = 14.4^{+15\%}_{-21\%} \text{ fb} \]

\[ \sum_{\text{HEFT, NNLO}} = 51^{+9\%}_{-11\%} \text{ fb} \quad \text{Unphysical number} \]

\[ \sum_{\text{EFT imp.}(1), \text{NNLO}} = 18.1^{+11\%}_{-13\%} \text{ fb} \]
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Reduced theoretical uncertainty

\[ \sum_{\text{EFT imp.(1), NNLO}} = 18.1^{+11\%}_{-13\%} \text{ fb} \]
### Generators

<table>
<thead>
<tr>
<th>Fixed order level</th>
<th>Total</th>
<th>$p_T^{cut} &gt; 400$ GeV</th>
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<tbody>
<tr>
<td>$ggh_{m_t=\infty}$</td>
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<td>0.0362</td>
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<td>HJ $m_t = \infty$, 5 GeV gen. cut</td>
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<td>0.0509</td>
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<tr>
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<td>0.0281</td>
<td>0.0153</td>
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Before matching to PS

As expected, small impact from PS (2%-5%)

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After matching to PS

[Becker et al., LHCHXSWG note, ’20]
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- MG5_MC@NLO also includes mass effects:
  - **exact** in Born and real-radiation corrections; through **reweighting** in virtual matrix elements.

- MG5_MC@NLO, HJ-MiNLO and approx. NNLO results **agree** within uncertainties
  - can be used for high-$p_T$ simulations.

[Becker et al., LHCXSWG note, ’20]

[Alwall et al., ’14; Frederix, Frixione, Vryonidou, Wiesemann ’16]
Other source of theoretical uncertainty:

- EW corrections: unknown, expected to be **large**.
- **Scheme and scale choice** for top quark mass in loops.
  - Exact NLO results for $m_t = 173.055$ GeV—pole mass. [Jones, Kerner, Luisoni '18]
  - Different scheme choice: $\overline{\text{MS}}$ mass at given scale, e.g. $\overline{m}_t(\overline{m}_t) \approx 163$ GeV
  - Scheme and scale choice significant for $HH$ production: [Baglio et al., '18; Baglio et al., '20]
    \[
    \frac{d\sigma^{\text{LO}}(gg \rightarrow HH)}{dQ}(Q = 300 \text{ GeV}) = 0.01656^{+62\%}_{-2.4\%} \text{ fb/GeV} \\
    \frac{d\sigma^{\text{NLO}}(gg \rightarrow HH)}{dQ}(Q = 300 \text{ GeV}) = 0.02978^{+6\%}_{-34\%} \text{ fb/GeV}
    \]
  - NLO corrections reduce uncertainty due to scheme and scale choice by factor of $\sim 2$.
  - Still comparable to scale uncertainty for $HH$ production.
Top Mass Scheme Dependence and EW Corrections

Similar situation for high-pT Higgs:

- ~15% at 400 GeV – comparable to scale uncertainty.
- ~30% at 1 TeV.

- NLO corrections might reduce this, but still likely to be an important source of theoretical uncertainty.

[Jones, Spira; LH2019 SMWG Report]
OTHER PRODUCTION MODES
Impact of Different Production Modes

- Other production modes, esp. $VH$, become important at $p_T \sim 1$ TeV.

[Becker et al., LHCHXSWG note, ’20]
Theoretical Uncertainties of Different Production Modes

**Theoretical uncertainties:**

- **VBF:** $< 1\%$.
- **$VH$:** $\sim 5\%$.
  - Further decreased by (known) NNLO corrections.
  - $ZH$: large contribution from gluon fusion; corrections to this unknown but likely sizeable.
  - PS effects may become significant when jet vetoes applied.

  [Astill, Bizoń, Re, Zanderighi, ‘18]

- **$ttH$:** $\sim 10\%-15\%$
  - NNLO corrections unknown.

- EW corrections $\sim 20\%-30\%$ for $VH$ and VBF, $\sim 7\%-12\%$ for $ttH$.

[Becker et al., LHCHXSWG note, ‘20]
SUMMARY
Summary

- Higgs production at high-$p_T$ is important to probe Higgs couplings to quarks and potential BSM effects.

- Dominant contribution from **gluon fusion:**
  - NLO results with **exact top mass dependence** available $\rightarrow$ k-factor of $\sim 2$.
  - Combined with **NNLO results in HEFT** $\rightarrow$ scale uncertainty $\sim 10\%$.
  - Generators available including mass effects at higher orders, allowing for **reliable event simulations**.
  - Other important sources of error: **EW corrections, top mass scheme and scale choice**.

- Other production modes important, especially **$VH$ at $p_T \sim 1$ TeV**.
  - Different patterns of radiative corrections.
THANK YOU FOR YOUR ATTENTION
BACKUP SLIDES
ESTIMATING THEORETICAL UNCERTAINTY

Approx. NNLO results:

\[ \sum_{\text{HEFT imp.(1), NNLO}} (p_T^{\text{cut}}) = \frac{\sum_{\text{exact, NLO}} (p_T^{\text{cut}})}{\sum_{\text{HEFT, NLO}} (p_T^{\text{cut}})} \sum_{\text{HEFT, NNLO}} (p_T^{\text{cut}}) \]

- 7-point envelope by varying scale uncertainties by factor of 2.
- Combine linearly and quadratically.
- Assume uncertainty due to mass effects in NNLO EFT obtained by rescaling by impact of relative mass corrections at NLO:

\[ \delta_{\text{NNLO}} m_t = \frac{\delta \sum_{\text{SM, NLO}} - \delta \sum_{\text{SM, imp.(0), NLO}}}{\delta \sum_{\text{SM, imp.(0), NLO}}} \times \delta \sum_{\text{SM, imp.(0), NNLO}} \]

- Uncertainties added quadratically and linearly.
Additional Plots

• NLO results with full top mass dependence vs. results with reweighted virtual amplitudes, exact Born and real amplitudes.

[Maltoni, Vryonidou, Zaro, ‘14]

• Impact of top mass scheme and scale choice on $Hj$ invariant mass.

[Jones, Spira; LH2019 SMWG Report]