Finite mass effects in Higgs boson production in association with jets

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Based on: JHEP 1601 (2016) 169 (1506.01016) and JHEP 1701 (2017) 091 (1608.01195)
H+jets in gluon-gluon fusion at NLO

• LHC Run II is collecting data very fast. This will soon allow for precise Higgs boson studies at 13 TeV

• Higher order corrections are particularly sizable in Higgs boson production in gluon-gluon fusion

• For a precise determination of the most important observables (e.g. the Higgs transverse momentum spectrum) a good control over higher multiplicities is relevant

• Furthermore:
  • How large are finite mass corrections, what is their dominant effect?
  • Which observables are most affected and where do the effective field predictions break down?
State of the art of the theoretical predictions

- Gluon fusion calculations in effective and full theory:

  - ME level
  - Shower/Hadron level
  - Approximate
  - New result (2015-2017)

Latest results:

[H: 1503.06056, 1602.00695]
[H+1j: 1504.07922, 1505.03893, 1508.02684, 1607.08817]
[H+3j: 1307.4737, 1506.01016]

[I tried not to miss any contribution, my apologies for any omission]
Computational setup

• Amplitudes in HEFT computed with **GoSam+Sherpa** via BLHA
  
  
  [Gleisberg, Höche, Krauss, Schönherr, Schumann, Siegert]

  • Virtual amplitudes: **GoSam** with **Ninja**
    - > scalar loop integrals evaluated using **OneLoop**

  • Tree amplitudes and integration: **Sherpa** with **Comix**

• Phenomenological analysis via generation of ROOT Ntuple files:

  • Events for: **H+1 / 2 / 3 jets** → **2 TB** per CM energy set

  ✓ Available for 8, 13, 14 and 100 TeV

  ✓ For kt/anti-kt algorithm and R=0.1, 0.2, …, 1.0

  ✓ Ntuples for **LO/NLO HEFT** and **LO full SM**

• Full theory result generated by **reweighting** the Born HEFT Ntuples with the amplitude carrying the full quark mass dependence.
Root Ntuples and timing

- Ntuples allow for fast analysis, change of **scale, pdf, cuts, jet radius**
  - on average 50 CPU hours per analysis for H+3 jets

Investigating different scale choices, performing the scale variation, varying the radii and changing selection cuts takes time:

- If we would run from scratch every time:
  \[(3 \text{ scale variations }) \times (4 \text{ scales }) \times (5 \text{ jet radii }) \times (2 \text{ cuts }) = 120\]

- which means approx. 4 million CPU hours (4.6 years on 100 cores)

**NOW:** Publicly available on:

https://eospublichttp.cern.ch/eos/theory/project/GoSam/
Physical setup

For both 13 and 100 TeV:

- Scale choice: 
  $\mu_F = \mu_R = \frac{H_T}{2} = \frac{1}{2} \left( \sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}| \right)$

- PDFs: CT14nlo

- Masses: 
  $m_H = 125.0$ GeV,  
  $m_t = 172.3$ GeV,  
  $m_b(m_H) = 3.38$ GeV

- Baseline cuts: anti-kt with 
  $p_T > 30$ GeV,  
  $|\eta| < 4.4$

- Additional VBF cuts: 
  $m_{j_1 j_2} > 400$ GeV,  
  $|\Delta y_{j_1, j_2}| > 2.8$

- **Remark**: basic Ntuples sets have events with $p_T > 25$ GeV, $|\eta| < 4.5$ for the jets at the generation level
Total cross section: 13 TeV

Total inclusive cross section with gluon fusion cuts at 13 TeV

Higgs effective field theory

GoSam+Sherpa

\[ r_{2/1} = \frac{\sigma_{\text{tot}}(H+2\text{jets})}{\sigma_{\text{tot}}(H+1\text{jet})} \]

\[ r_{3/2} = \frac{\sigma_{\text{tot}}(H+3\text{jets})}{\sigma_{\text{tot}}(H+2\text{jets})} \]

Powers are for H+3j
**Total cross section: 13 TeV**

**Total inclusive cross section with gluon fusion cuts at 13 TeV**

<table>
<thead>
<tr>
<th>H+1 jet LO</th>
<th>H+2 jets LO</th>
<th>H+3 jets LO</th>
<th>H+1 jet NLO</th>
<th>H+2 jets NLO</th>
<th>H+3 jets NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>1</td>
<td>100</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

**Higgs effective field theory**

<table>
<thead>
<tr>
<th>Ratio</th>
<th>$\alpha_s\left(\frac{H_H}{2}\right)^3\alpha_s(m_H)^2$</th>
<th>$\alpha_s\left(\frac{H_H}{2}\right)^5$</th>
<th>$\alpha_s(m_H)^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80</td>
<td>$r_2/1$</td>
<td>$r_3/2$</td>
<td></td>
</tr>
<tr>
<td>0.70</td>
<td>$r_2/1$</td>
<td>$r_3/2$</td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>$r_2/1$</td>
<td>$r_3/2$</td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>$r_2/1$</td>
<td>$r_3/2$</td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>$r_2/1$</td>
<td>$r_3/2$</td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>$r_2/1$</td>
<td>$r_3/2$</td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>$r_2/1$</td>
<td>$r_3/2$</td>
<td></td>
</tr>
</tbody>
</table>
Total cross section: 13 TeV

- $\sigma_{LO}, m_{t,b}$: top- and bottom-quark loops
- $\sigma_{LO}, m_t$: top-quark loops only

- Reduction of the size of NLO corrections for higher multiplicity
- Relative difference due to bottom-quark O(1%)
Total cross section: 13 TeV

- $\sigma_{LO, m_{t,b}}$ : top- and bottom-quark loops
- $\sigma_{LO, m_t}$ : top-quark loops only

\[
\sigma_{LO, m_{t,b}} = |M_t|^2 + |M_b|^2 + 2\Re(M_t M_b)
\]

positive definite

potentially negative
Total cross section: 13 TeV

- $\sigma_{LO, m_{t,b}}$: top- and bottom-quark loops
- $\sigma_{LO, m_t}$: top-quark loops only

$$\sigma_{LO, m_{t,b}} = |M_t|^2 + |M_b|^2 + 2\Re(M_t M_b)$$

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positive definite
potentially negative
Total cross section: 13 TeV

- $\sigma_{LO}, m_{t,b}$: top- and bottom-quark loops
- $\sigma_{LO}, m_t$: top-quark loops only

- Reduction of the size of NLO corrections for higher multiplicity
- Relative difference due to bottom-quark O(1%)
- Sign flip in corrections due to bottom-top quark interference in H+1j
Higgs boson $p_T$

- Transverse momentum related observables known to receive significant corrections.

*04/04/2017 - Gionata Luisoni*  
DIS2017, Birmingham
Higgs boson $p_T$

- Transverse momentum related observables known to receive significant corrections.

- Effective theory starts to break down at $p_T, H \approx 200$ GeV and NLO corrections start to become subdominant compared to mass effects.
Interludio: Effective vs. Full theory scaling

- Breakdown of effective theory can be understood comparing the high energy limit of a pointlike ggH interaction with that of a loop-mediated one:

  - Consider the **transverse momentum** behaviour of the g*g* --> H amplitude (i.e. when gluons are **off shell**) [Catani, Ciafaloni, Hautmann, ‘91] [Hautmann, ‘02] [Pasechnik, Teryaev, Szczurek, ‘06] [Marzani, Ball, Del Duca, Forte, Vicini, ‘08]

    ![Diagram](image)

    Transverse momenta can reach kinematic limit given by CM energy

    Contribution from large transverse momenta suppressed by massive quark loop

    \[ \hat{\sigma} \sim \begin{cases} \sum_{k=1}^{\infty} \alpha_s^k \ln^{2k-1} \left( \frac{s}{m_H^2} \right) & \text{pointlike: } m_t \to \infty \\ \sum_{k=1}^{\infty} \alpha_s^k \ln^{k-1} \left( \frac{s}{m_H^2} \right) & \text{resolved: finite } m_t \end{cases} \]

    Corresponding scaling in Higgs p_T computed recently:

    - as \( p_T, H \to \infty \) differential cross section (in \( p_T^2 \)):
      
      drops like \( (p_T^2, H)^{-1} \)

      drops like \( (p_T^2, H)^{-2} \)
Higgs boson $p_T$

- Transverse momentum related observables known to receive significant corrections.

- Effective theory starts to break down at about $p_T, H \approx 200$ GeV and NLO corrections start to become subdominant compared to mass effects.
Higgs boson $p_T$

- Transverse momentum related observables known to receive significant corrections

- Effective theory starts to break down at about $p_{T,H} \approx 200$ GeV and NLO corrections start to become subdominant compared to mass effects.

- Define $R_{m_t,b}(O) \equiv \frac{d\sigma}{dO} \bigg|_{m_t,b} - \frac{d\sigma}{dO} \bigg|_{\text{eff}}$ then the rough scaling behavior from plots is given by

  $$ \frac{R_{m_t,b}(p_{T,H} = 1.0 \text{ TeV})}{R_{m_t,b}(p_{T,H} = 0.4 \text{ TeV})} \approx \frac{10\%}{60\%} = \frac{1}{6} = 0.167 $$

  while the high energy limit prediction is

  $$ \left( \frac{400 \text{ GeV}}{1000 \text{ GeV}} \right)^2 = \frac{4}{25} = 0.16 $$

  $\implies$ Very similar behavior for the three different multiplicities
• Importance of H+2j and H+3j contributions in Higgs $p_T$ spectrum:

Higgs effective field theory
Higgs boson $p_T$

- Ratios of successive differential cross sections:
  
  $R_n(O) = \frac{\frac{d\sigma}{dO}(H+n\text{ jets})}{\frac{d\sigma}{dO}(H+(n-1)\text{ jets})}$

  - suggests that the different transverse momentum scaling of effective and full theory also holds for higher multiplicities

  - relative importance of higher multiplicities remains stable under mass corrections
Leading jet $p_T$

- For $H+1j$ at LO: $p_T, H = p_T, j_1$

- However a very similar behaviour is observed also for the higher multiplicities

- We can compare them directly ...
GoSam + Sherpa

$pp \rightarrow H + 1, 2, 3$ jets at 13 TeV

CT14nlo, $R = 0.4$ anti-kT, $|\eta_{jet}| < 4.4$, $p_{T,jet} = 30$ GeV

Ratio wrt. LO using $m_z \rightarrow \infty$ approximation.

only H+1

only H+2

only H+3

Higgs boson transverse momentum: $p_{T,H}$ [GeV]

Leading-jet transverse momentum: $p_{T,j1}$ [GeV]
Seems to support the hypothesis that

The resolution of the effective vertex is driven by a quantity, which is strongly correlated with the event’s hardest single particle $p_T$, and a leading role is played by the Higgs boson.

Inner structure of $ggH$ vertex probed with any interaction where the leading particle-$p_T$ exceeds the top-quark mass (here Higgs or leading jet).

This can be checked by imposing a veto on the Higgs transverse momentum...
Applying a veto on the Higgs for $H+2j$: $p_{T,H} < 100$ GeV:

**Preliminary DIS2017, Birmingham 04/04/2017 - Gionata Luisoni**
Applying a veto on the Higgs for H+3j: $p_T, H \lesssim 100$ GeV:

**Preliminary**

**DIS2017, Birmingham**

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more investigation ongoing...
Higgs boson rapidity

- Mass corrections small over full kinematical range:
  - Regions of phase space where quark-loop is resolved are smeared over the entire range
  - For the bulk of the cross sections mass effects are small
Massless bottom quark

- Mass effects from bottom quark become important for
  \[ m_b < p_T < m_H \]

due to the enhancement caused by terms which scale like

\[ \sim \frac{1}{p_T^2 m_H^2} \log^2 \left( \frac{m_b^2}{p_T^2} \right) \]

- The more jets are present, the more the \( p_T \) involved gets diluted among more jets, leading to ratio closer to 1 in the logarithm

- Bottom mass effects expected to be smaller for larger multiplicities
Massless bottom quarks

- Comparison between top- and bottom-quark predictions and top-quark only results:
  - difference is well below scale uncertainty and never exceeds 5%
  - primarily concerns soft region
  - is multiplicity dependent
  - destructive interference observed in the total $H+1j$ cross section stems from the soft region, whereas net contribution becomes positive in regions where the bottom quark can be considered as massless.
  - Similar behavior for Higgs and leading jet $p_T$
Conclusions and Outlook

- Higher order QCD corrections to Higgs boson production in association with jets in ggf are large and therefore need to be considered in order to reach a reasonable theoretical accuracy
  - A lot of work was put and is still put in improving these predictions

- Depending on the kinematical cuts (especially $p_T$ requirements), mass effects can play a major role in differential distributions
  - Even if this may not be highly relevant for LHC Run II, future runs and future colliders will be very sensitive to this (FCC is the extreme case)
  - Important driver for the break down of the effective theory seems to be the transverse momentum of the Higgs boson, and in general of the hardest particle in the event
  - Lots of effort lately are put into improving the accuracy of finite mass corrections (NLO will be needed in future!)
Backup
# Total cross sections in number

<table>
<thead>
<tr>
<th>Numbers in [pb]</th>
<th>$p_{T,\text{jet}} &gt; 30$ GeV</th>
<th>$p_{T,\text{jet}} &gt; 100$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$</td>
<td>13 TeV</td>
<td>100 TeV</td>
</tr>
<tr>
<td>H+1 jet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{LO, eff.}}$</td>
<td>$8.06^{+38%}_{-26%}$</td>
<td>$196^{+21%}_{-17%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{NLO, eff.}}$</td>
<td>$13.3^{+15%}_{-15%}$</td>
<td>$315^{+11%}_{-10%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{LO, } m_{t,b}}$</td>
<td>$8.35^{+38%}_{-26%}$</td>
<td>$200^{+20%}_{-17%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{LO, } m_t}$</td>
<td>$8.40^{+38%}_{-26%}$</td>
<td>$201^{+20%}_{-17%}$</td>
</tr>
<tr>
<td>H+2 jets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{LO, eff.}}$</td>
<td>$2.99^{+58%}_{-34%}$</td>
<td>$124^{+39%}_{-27%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{NLO, eff.}}$</td>
<td>$4.55^{+13%}_{-18%}$</td>
<td>$156^{+3%}_{-10%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{LO, } m_{t,b}}$</td>
<td>$3.08^{+58%}_{-34%}$</td>
<td>$121^{+39%}_{-26%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{LO, } m_t}$</td>
<td>$3.05^{+58%}_{-34%}$</td>
<td>$120^{+39%}_{-26%}$</td>
</tr>
<tr>
<td>H+3 jets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{LO, eff.}}$</td>
<td>$0.98^{+76%}_{-41%}$</td>
<td>$70.4^{+56%}_{-34%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{NLO, eff.}}$</td>
<td>$1.45^{+11%}_{-22%}$</td>
<td>$72.0^{+16%}_{-7%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{LO, } m_{t,b}}$</td>
<td>$1.00^{+77%}_{-41%}$</td>
<td>$63.3^{+56%}_{-34%}$</td>
</tr>
<tr>
<td>$\sigma_{\text{LO, } m_t}$</td>
<td>$0.99^{+77%}_{-41%}$</td>
<td>$62.7^{+56%}_{-34%}$</td>
</tr>
</tbody>
</table>
Wimpiest jet $p_T$

- Full theory predictions start to deviate from effective one even earlier for H+2j and H+3j

- consequence of the $p_T$ ordering of the jets:
  
  - There hast to be 1 or 2 harder jets that drive the breakdown of the effective theory approach