Mass Dependence of Higgs Production at Large $P_T$

Eric Braaten

The Ohio State University

in collaboration with

Hong Zhang (Ohio State U ⇒ T U Munich)

Jia-Wei Zhang (Chongqing U)

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Higgs $P_T$ Distribution

- Higgs at large $P_T$ is an important probe of BSM physics

- lack of reliable SM prediction could compromise search for new physics

- complete calculation of Higgs $P_T$ distribution with physical top quark mass is available only at LO!

Ellis, Hinchliffe, Soldate, & van der Bij, NPB 1988; Baur & Glover, NPB 1990

- calculation is complicated by many scales $(\sqrt{s}, P_T, m_t, m_H)$ can be simplified by separating scales
Higgs Effective Field Theory

Standard Model
\[ \mathcal{L} = -\frac{m_t}{v} \bar{t} t h \]

HEFT
\[ \mathcal{L}_{\text{eff}} = \frac{\alpha_s}{12\pi v} G_{\mu\nu} G_{\mu\nu, A} h \]

- eliminate the scale \( m_t \)
- reduce number of loops by 1

Calculations of Higgs production with Higgs EFT

- Inclusive Higgs cross section: **NNNLO**
  Anastasiou, Duhr, Dulat, Herzog, Mistlberger, PRL 2015

- Higgs + 1 jet: **NNLO**
  Boughezal, Focke, Giele, Liu, Petriello, PLB 2015

- Higgs + \( \geq 2 \) jet: **NLO**
  Campbell, Ellis, Williams, PRD 2010
Higgs $P_T$ Distribution

• calculation is complicated by many scales
  can be simplified by separating scales

Large $m_t$  \[ m_H, \sqrt{s}, P_T \ll m_t \]
expand in powers of $1/m_t^2$
Higgs EFT!
cannot be applied at large $P_T$ (resolves top quark loop)

Large $P_T$  \[ m_H, m_t \ll \sqrt{s}, P_T \]
expand in powers of $1/s, 1/P_T^2$
complicated by mass singularities
increasingly accurate as $P_T$ increases
complimentary to HEFT

$(\sqrt{s}, P_T, m_t, m_H)$
Simple Illustration

\[ q\bar{q} \rightarrow H + g \text{ at LO} \]

can be reduced to one relevant form factor \( \mathcal{F}(s, m_H^2, m_t^2) \) that depends on one kinematic variable \( s \)

**Leading Power (LP) form factor**

leading term in expansion in powers of \( m_t^2/s, m_H^2/s \)

factorization formula motivated by QCD factorization

- separate **hard scale** \( s \) from **soft scales** \( m_t, m_H \)
before calculating Feynman diagrams

Each diagram simpler to calculate due to fewer scales.
Leading Power Regions

- four regions of loop momentum that contribute at Leading Power of $1/s$

Hard scales $(\sqrt{s})$

Higgs Collinear scales $(\sqrt{s}, m_t, m_H)$

Gluon Collinear scales $(\sqrt{s}, m_t)$

Soft $(m_t)$
Higgs Collinear Region

- separate scales before calculating Feynman diagrams

\[ \int_{-1}^{+1} d\zeta \tilde{F}_{t\bar{t}V} + g(\zeta) \]

- integral over relative longitudinal momentum fraction of \( t\bar{t} \)

- hard form factor for producing \( t\bar{t} \)

in color-singlet Lorentz-vector channel

depends on hard scale \( \sqrt{s} \)

- distribution amplitude for \( t\bar{t} \) in the Higgs

depends on soft scales \( m_t, m_H \)
LP Factorization Formula

• Contribution from each region is UV divergent: regularize with dimensional regularization and rapidity regularization. Divergences cancel when four terms are added.

• All pieces calculated directly from Feynman diagrams. Each piece involves fewer scales: \( m_t, m_H \) OR \( s \)

• Each piece can be renormalized separately by minimal subtraction of poles from regularization

\[
\mathcal{F}_{\text{LP}}(s, m_t^2, m_H^2) = \tilde{F}_{H+g}(s) + \int_{-1}^{+1} d\zeta \tilde{F}_{t\bar{t}1V+g}(\zeta)d_{t\bar{t}1V\to H}(\zeta; m_t^2, m_H^2, P.n)
\]
\[
+ \int_{-1}^{+1} d\zeta \tilde{F}_{H+t\bar{t}8T}(\zeta)d_{t\bar{t}8T\to g}(\zeta; m_t^2, p_3, \bar{n}) + \mathcal{F}_{\text{soft}}(m_t^2)
\]

• Error in LP form factor decreases as \( 1/s \)

For more details, see Braaten, Zhang, and Zhang, arXiv:1704.06620
Top-quark Mass Improvement

\[
\frac{m_H^2}{4m_t^2} = 0.13
\]

**LPH factorization formula**

- **leading power** in \( m_H^2/s \), keep all powers of \( m_t^2/s \)
- same form as LP factorization formula
- Higgs collinear, gluon collinear, soft terms are the same
- hard term is different (requires additional calculations with \( m_H = 0 \))
- error is decreased to order \( m_H^2/s \)

For more details, see Braaten, Zhang, and Zhang, arXiv:1704.06620
Compare with Full Form Factor

- error of LP, LPH factorization formulas decreases as $1/s$
- LP factorization formula is not useful until extremely large $s$
- LPH factorization formula is accurate even below $t\bar{t}$ threshold
Bottom-quark Loop Contribution

**LP factorization formula**

can also be applied to Higgs production from *b*-quark loop

relevant scales: $\sqrt{s}, m_H, m_b$

• leading power in $m_b^2/s$ and $m_H^2/s$

• error in LP form factor decreases as $1/s$

improved dependence on Higgs mass:

**LP*b* factorization formula**

• *leading power* in $m_b^2/s$, keep all powers of $m_H^2/s$

• much smaller error of order $m_b^2/s$
Compare to Full Form Factor from $b$ loop

- error of LP, LP$b$ factorization formula decreases as $1/s$
- LP factorization formula is not useful until extremely large $s$
- LP$b$ factorization formula is always good approximation
Summary

Higgs production at large $P_T$: complete NLO result still unavailable 30 years after LO!

LP factorization formula for the leading power in $1/P_T^2$

- separates large kinematic scales from mass scales before calculating Feynman diagrams
- each piece in the factorization formula is easier to calculate because it depends on fewer scales

top-quark mass improvement:

LPH factorization formula for leading power in $m_H^2/P_T^2$

- includes all powers of $m_t^2/P_T^2$
- reduces error to order $m_H^2/P_T^2$
Summary

LP factorization formula

applied to $q \bar{q} \rightarrow H + g$ at LO

from top-quark loop arXiv:1704.06620
from bottom-quark loop arXiv:1707.xxxxx

other parton processes at LO: straightforward

$g g \rightarrow H + g$
$g g \rightarrow H + Z^0$

Next-to-Leading Order: more challenging

resum leading logarithms of $P_T^2/m^2$ to all orders?