Mass Dependence of Higgs Production at large P_T

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Higgs Effective Field Theory

Standard Model $\mathcal{L} = -\frac{m_t}{v}\bar{t}th$

HEFT $\mathcal{L}_{\text{eff}} = \frac{\alpha_s}{12\pi v} G^A_{\mu\nu} G^{\mu\nu,A} h$

- Eliminate the scale m_t
- Reduce the number of loops by 1.
- Inclusive Higgs production cross section from gluon fusion has been calculated to **NNNLO** with Higgs EFT.

  Anastasiou, Duhr, Dulat, Herzog, Mistlberger, PRL 2015
- Higgs + 1 jet, **NNLO**

  Boughezal, Focke, Giele, Liu, Petriello, PLB 2015
- Higgs + ≥ 2 jet, **NLO**

  Campbell, Ellis, Williams, PRD 2010

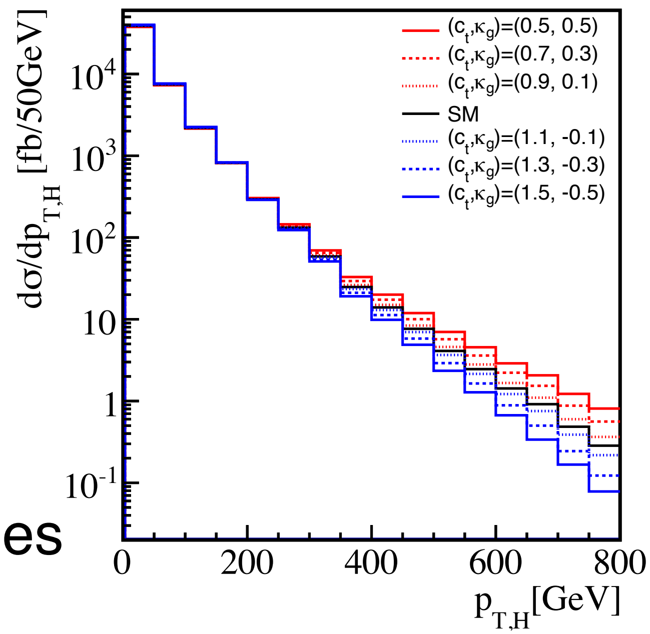
Higgs P_T Distribution

- Higgs EFT cannot be applied to large P_T

  Large $\sqrt{s}$ and P_T can resolve the *t*-quark

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

  e.g. Schlaffer et al, Eur.Phys.J C 2014



- Calculation is very difficult with many scales $(\sqrt{s}, P_T, m_t, m_H)$

  Higgs P_T distribution with physical top mass is available only at LO.

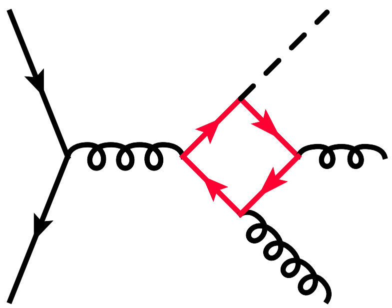
  Ellis et.al., NPB **1988**; Baur et.al., NPB **1990**

- Lack of reliable SM prediction may compromise the search for new physics.

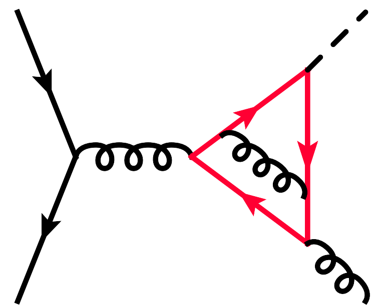
NLO Calculation with Massive Top

- Include both real and virtual corrections (e.g. $q\bar{q} \to H + g$)

  Relevant scales: $\sqrt{s}, m_t, m_H$



1-loop
Already calculated



2-loop

- Separate scales to simplify NLO calculation

Limit 1: $2m_t \gg \sqrt{s}, m_H$ Expand in $s/4m_t^2$ and $m_H^2/4m_t^2$ ***HEFT***

Limit 2: $\sqrt{s} \gg 2m_t, m_H$ Expand in m_H^2/s and m_t^2/s

Limit 3: m_t is arbitrary and $\sqrt{s} \gg m_H$ Expand in m_H^2/s

An “EFT” complementary to HEFT!

Mass Singularity

- Expansion is nontrivial due to mass singularity

  Relevant scales: $\sqrt{s}, m_t, m_H$ Expand in m_H^2/s and m_t^2/s

  - Non-analytic, e.g. $\log(s/m_H^2)$
  - Ratio of mass scales, e.g. $m_H^2/4m_t^2$

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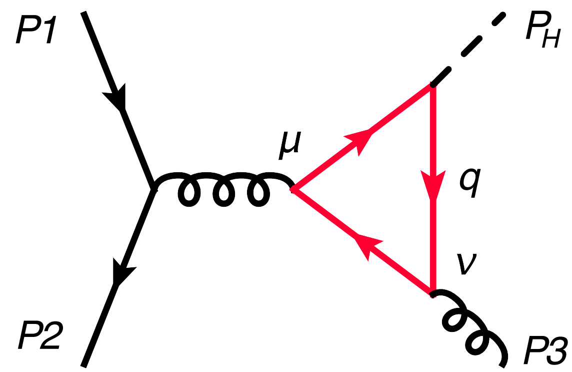
- More ambitiously, we want the expansion (scale separation) before calculating Feynman diagrams.

  Each diagram is simpler to calculate due to fewer scales.

- QCD factorization is a systematic framework to remove the small mass scales.

Setup of the Calculation

- As an example, we have calculated $q\bar{q} \to H + g$ at LO
  - Easy to calculate.
  - Can compare with the full LO analytically.



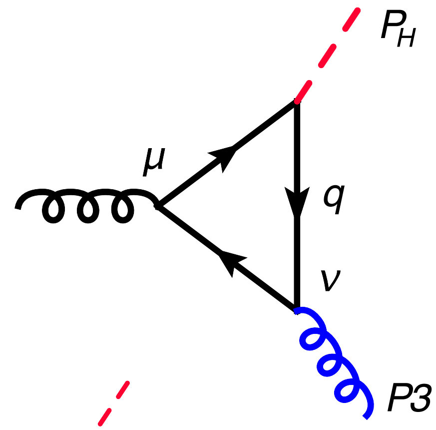
- One relevant form factor at LO

$$\frac{1}{4N_c^2}\sum|\mathcal{M}|^2 = \frac{2(N_c^2-1)g_s^2 m_t^2}{N_c^2}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}(\hat{s}-m_H^2)^2}\,|\mathcal{F}(\hat{s},m_t^2,m_H^2)|^2$$

Only need to separate the scales in the form factor.

Leading Regions

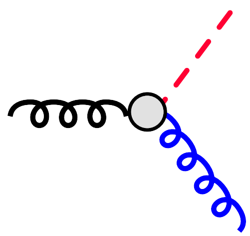
- The leading terms in the expansion of the full form factor are called "leading power terms (LP)".
- The regions of loop momentum integral giving LP terms are called "leading regions".



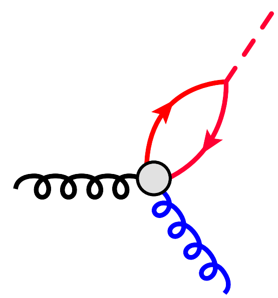
First consider expanding in both m_H^2/s and m_t^2/s

- Four leading regions: $(\sqrt{s} \gg m_t, m_H)$

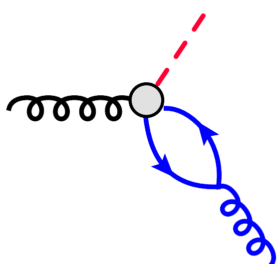
Hard
$(\sqrt{s})$



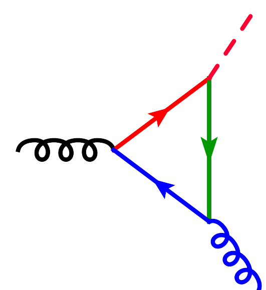
Higgs Collinear
$(\sqrt{s}, m_t, m_H)$



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

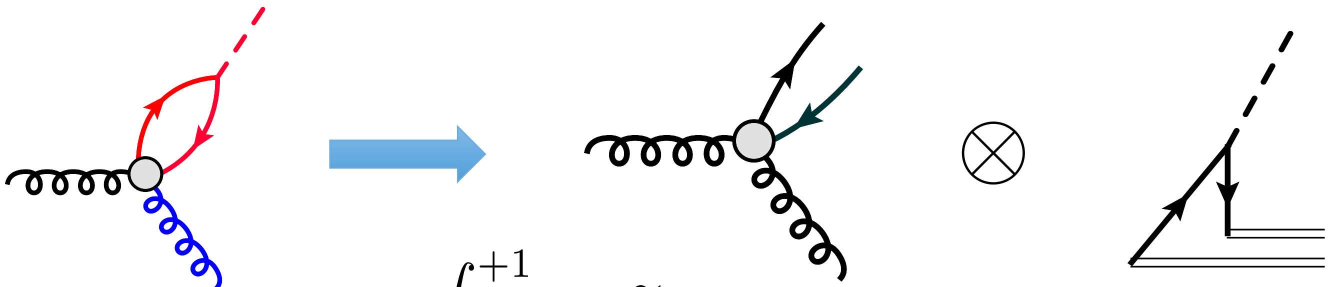


Soft
(m_t)



Factorization of Collinear Regions

- Higgs Collinear Region



$$\int_{-1}^{+1} d\zeta \quad \widetilde{\mathcal{F}}_{t\bar{t}_{1V}+g}(\zeta) \qquad\qquad d_{t\bar{t}_{1V}\to H}(\zeta; m_t^2, m_H^2, P.n)$$

  - Hard production of massless $t\bar{t}$ in color-singlet Lorentz-vector channel

    Only depends on hard scale $\sqrt{s}$

  - Collinear $t\bar{t}$ interact and produce the Higgs

    Only depends on soft scales m_t, m_H

  - Integrate over the relative longitudinal momentum of $t\bar{t}$ pair

- After factorization, we separate the scales before the calculation of Feynman diagrams

Factorization Formula

- LP factorization formula (Expand by both m_H^2/s and m_t^2/s)

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

- All pieces can be calculated directly from Feynman diagrams with fewer scales.
- Although the full form factor is finite, each region is divergent. Dimensional regularization and rapidity regularization are used.
- Comparing with the full form factor, all LP terms are preserved, including the mass singularities.

For more details, see Braaten, HZ and Zhang, arXiv:1704.06620

Improved Top Mass Dependence

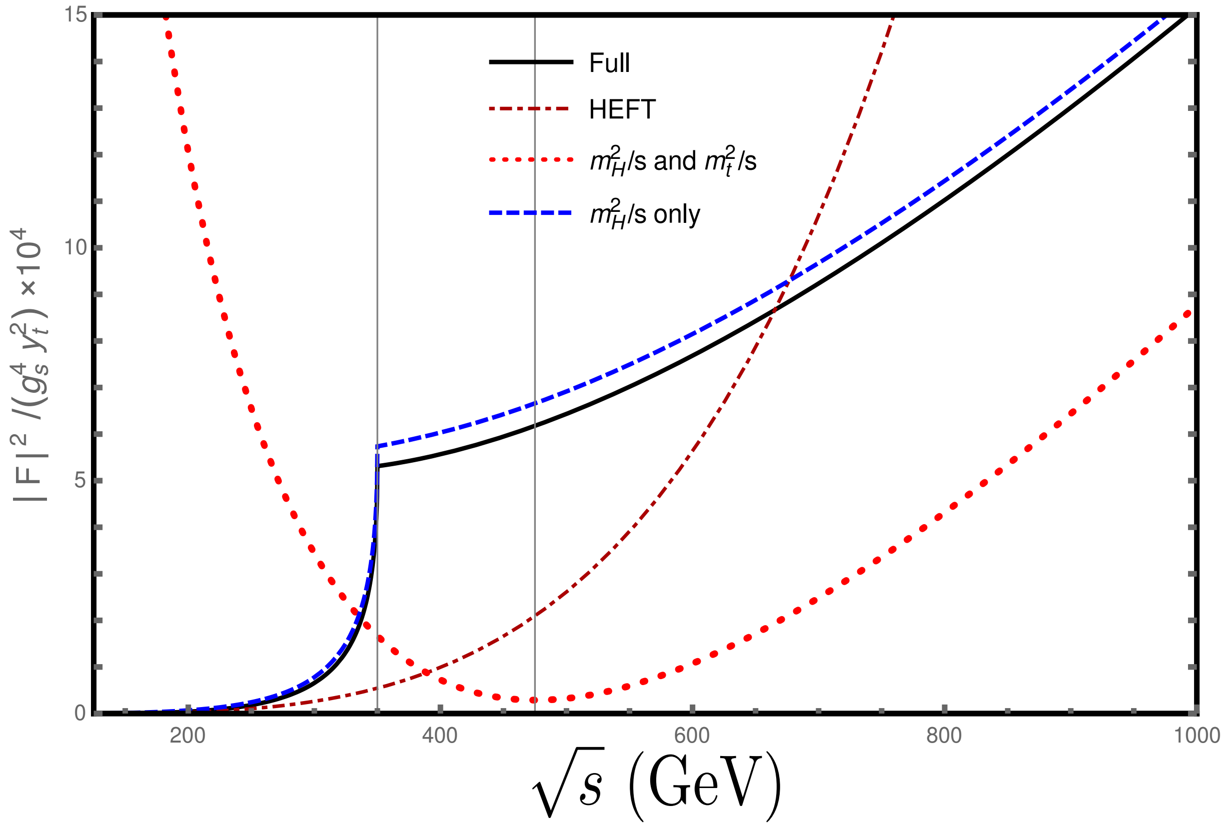
- Only expand by m_H^2/s, keep m_t an arbitrary scale

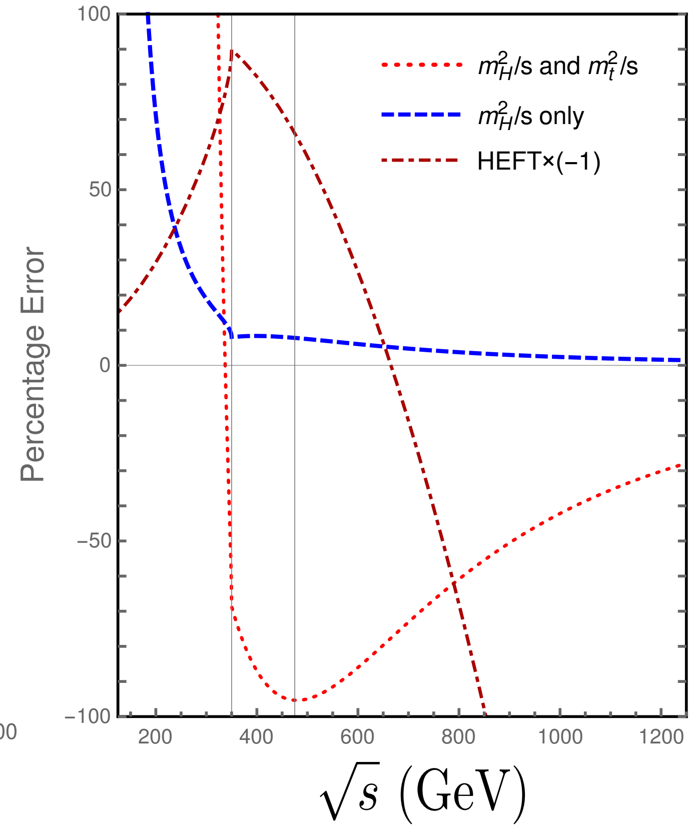
  Don't expand in m_t^2/s or m_H^2/m_t^2

- Same factorization formula, only the hard region needs to be modified

For more details, see Braaten, HZ and Zhang, arXiv:1704.06620

Compare with Full Result





- The error of factorization formula decreases as $\sqrt{s}$ increases.
- Reliable prediction for all kinematic regions can be obtained by combining the factorization formula with HEFT.

Bottom Loop Contribution

- The factorization formula can also be used to calculate the contribution from a *b*-quark loop

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

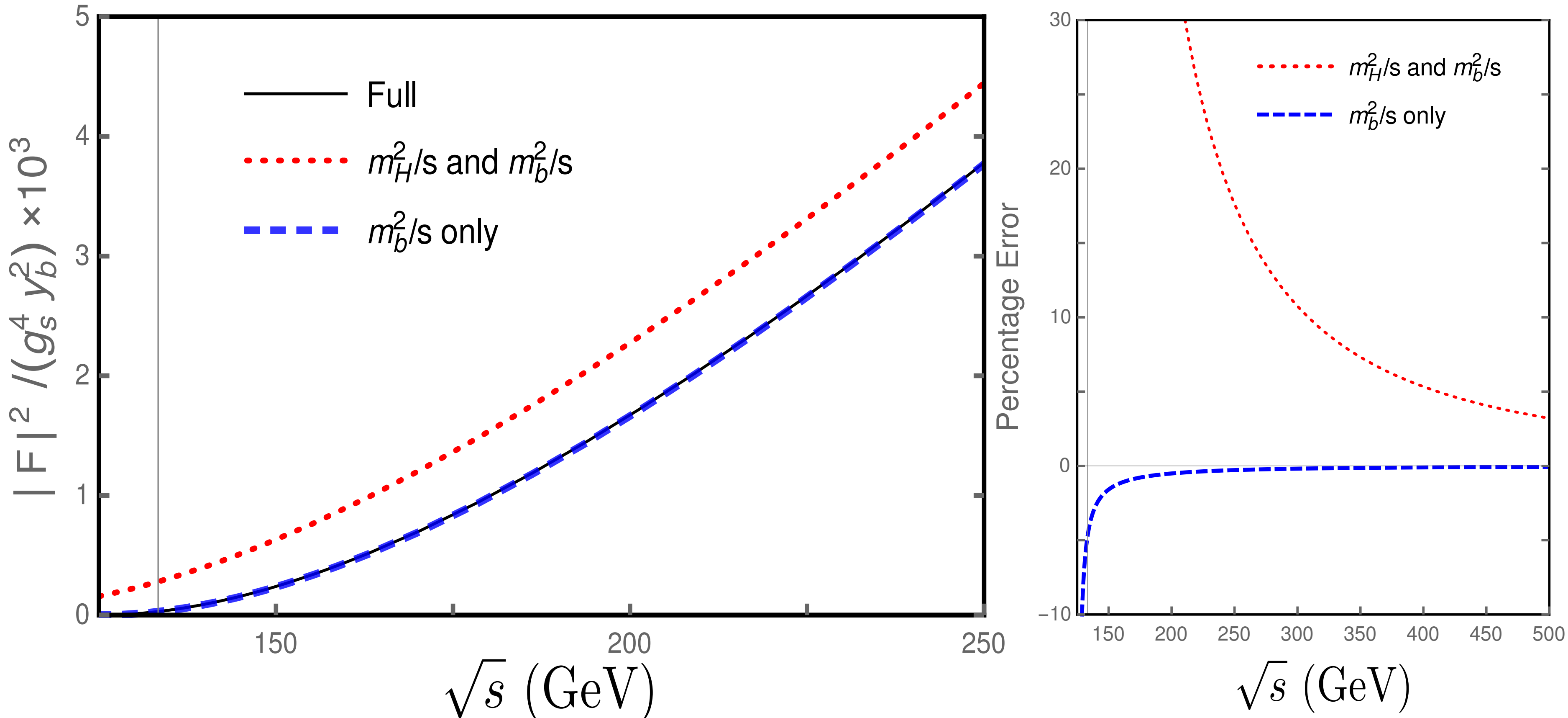
  Limit 1: Expand in both m_H^2/s and m_b^2/s

  Limit 2: Expand only in m_b^2/s

- Separate the scales before calculating the Feynman diagrams. Much simpler to calculate.

- Comparing with the full form factor, all LP terms are preserved, including the mass singularities.

Compare with Full Result (b-quark loop)



- The error of factorization formula quickly decreases as $\sqrt{s}$ increases.
- The expansion in only m_b^2/s gives a very good approximation to the full result (<10% error over all kinematic region)

Summary

- For Higgs produced at large P_T, NLO result is still unavailable 30 years after LO.
- We have proposed a factorization formula which separates different scales before calculating Feynman diagrams.
- Each piece in the factorization formula at LO is already available or easy to calculate.
- With the example $q\bar{q} \to H + g$, we show the factorization formula gives a very good approximation of the full result.
- Combined with HEFT, a reliable prediction of Higgs P_T distribution can be obtained at higher orders.
- The same method also shows great power to study the b-quark loop contribution.

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Thank you!