Mass Dependence of Higgs Production at Large P_T

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based on arXiv:1704.06620, 1707.xxxxx

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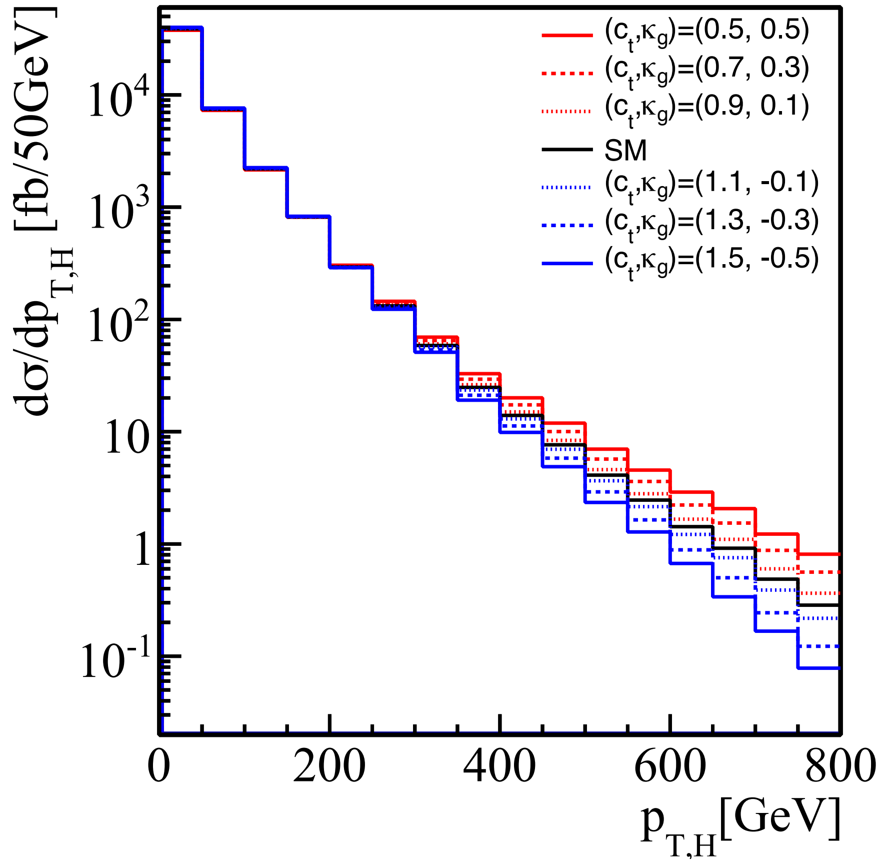
Higgs P_T Distribution

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

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



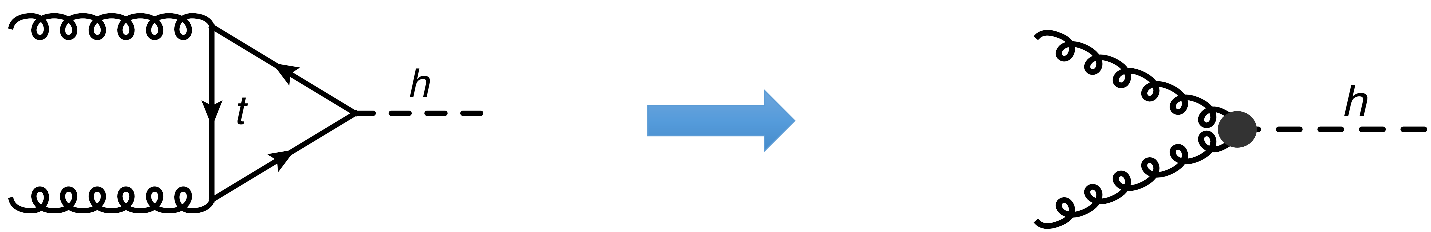
- lack of reliable SM prediction could compromise search for new physics

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

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 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 + ≥ 2 jet: **NLO** Campbell, Ellis, Williams, PRD 2010

Higgs P_T Distribution

- calculation is complicated by many scales $(\sqrt{s}, P_T, m_t, m_H)$
  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 $1/s$, $1/P_T^2$

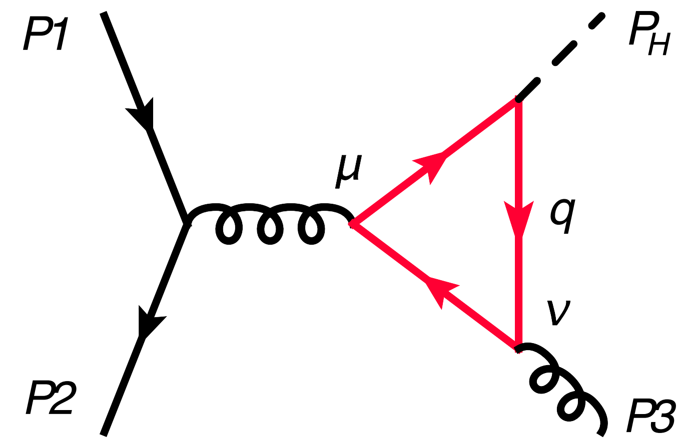
complicated by mass singularities

increasingly accurate as P_T increases

complimentary to HEFT

Simple Illustration

$q\bar{q} \rightarrow H + g$ 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

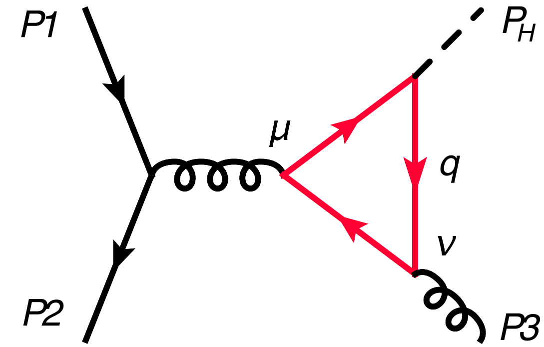
leading term in expansion in powers of m_t^2/s, m_H^2/s

factorization formula motivated by QCD factorization

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

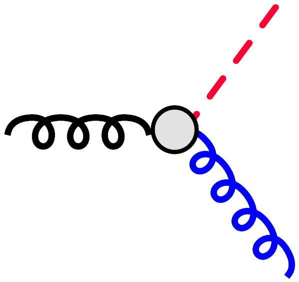
Each diagram simpler to calculate due to fewer scales.

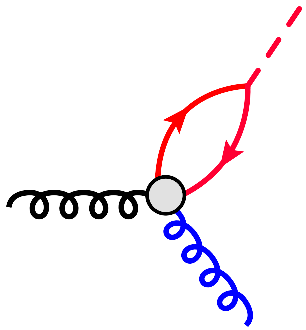
Leading Power Regions

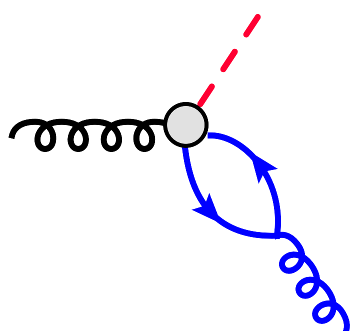


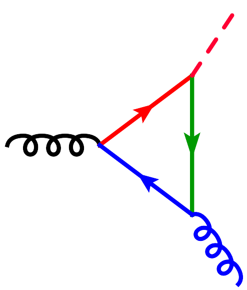
- four regions of loop momentum that contribute at Leading Power of *1/s*

<u>scales</u>

Hard  $\left(\sqrt{s}\right)$

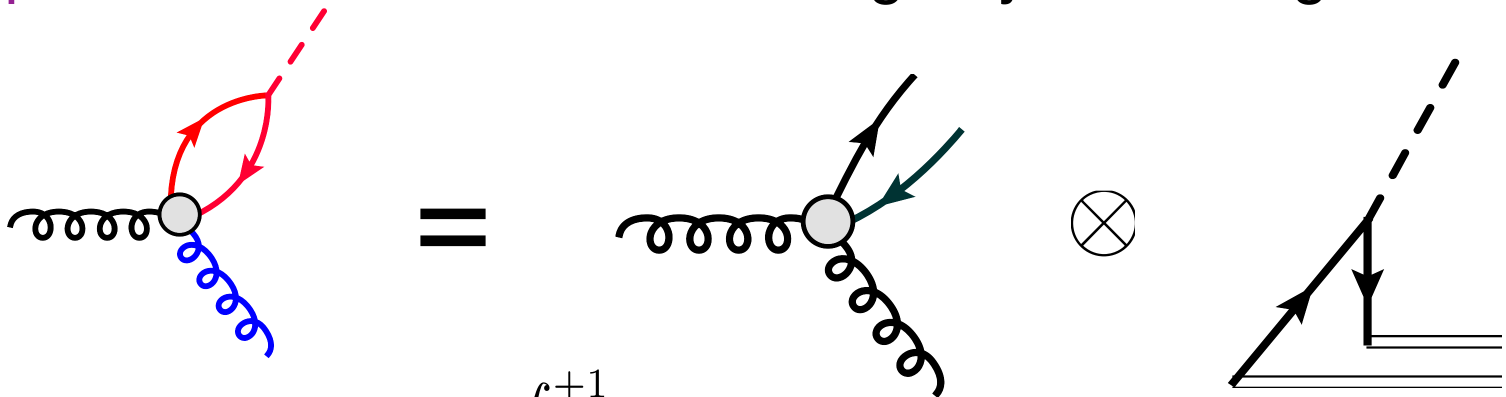
Higgs Collinear  $\left(\sqrt{s}, m_t, m_H\right)$

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

Soft  $\left(m_t\right)$

Higgs Collinear Region

- separate scales before calculating Feynman diagrams



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

➢ 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

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

- Error in LP form factor decreases as *1/s*

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

Top-quark Mass Improvement

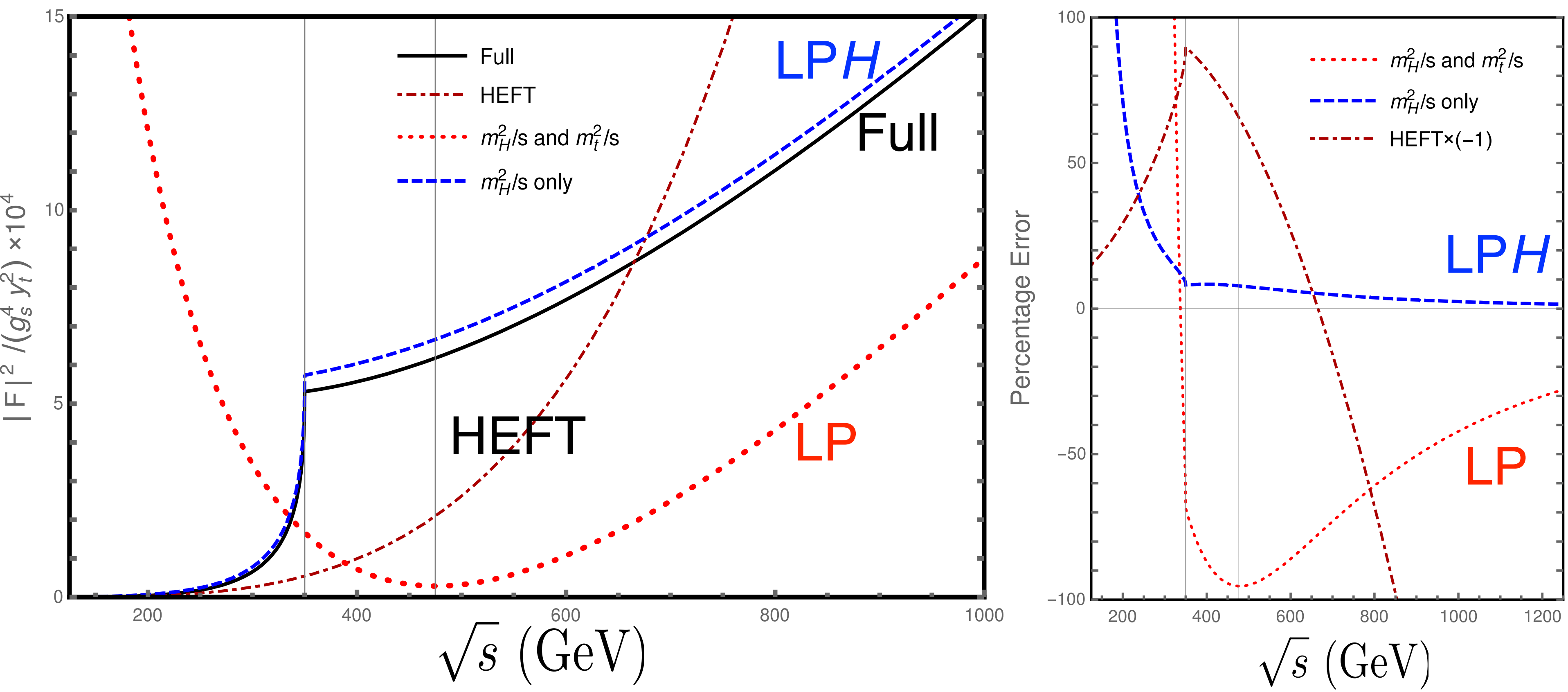
$$\frac{m_H^2}{4m_t^2} = 0.13$$

LP*H* 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

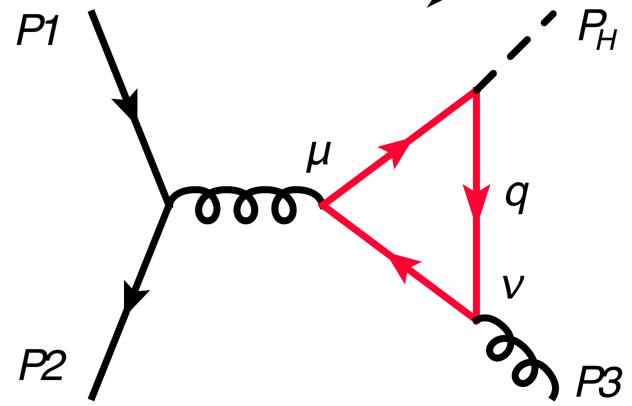
For more details, see Braaten, Zhang, and Zhang, arXiv:1704.06620

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

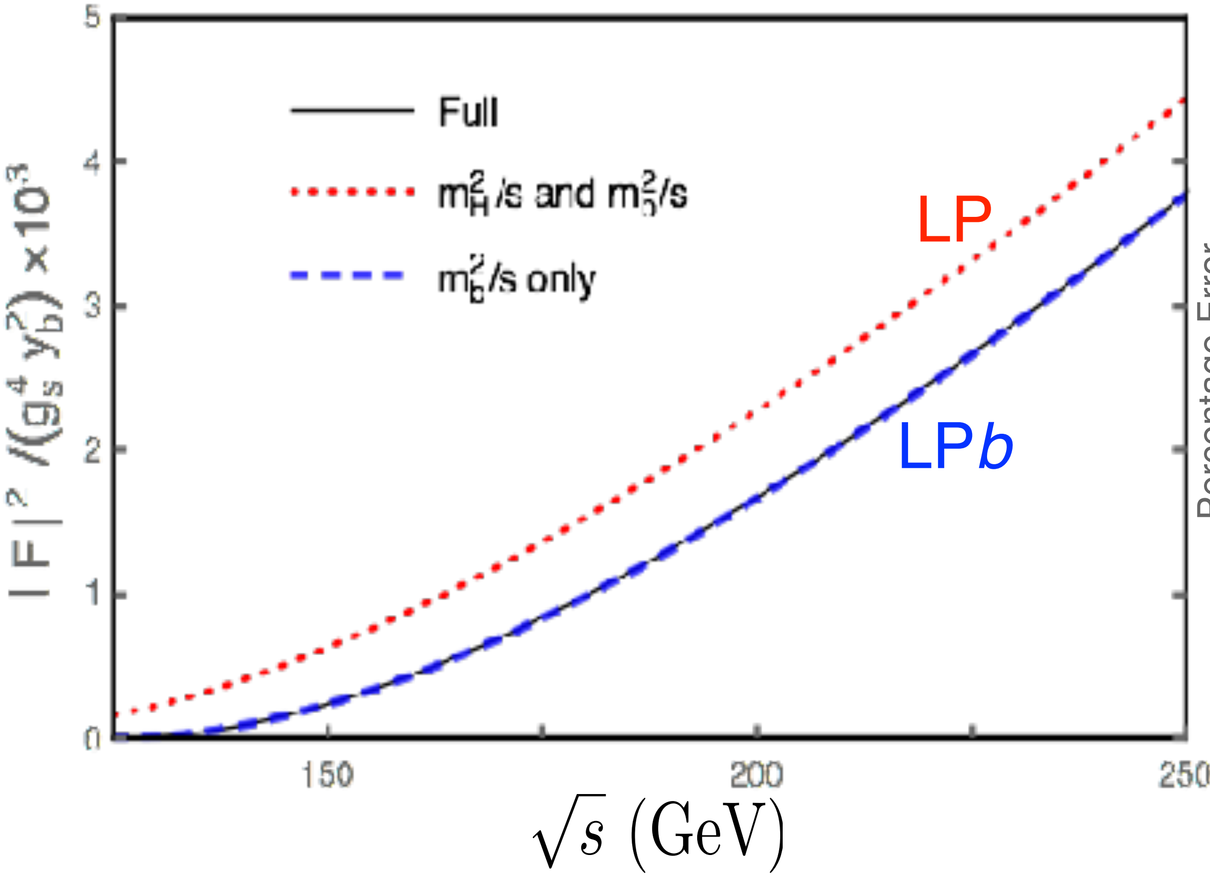
- leading power in m_b^2/s and m_H^2/s
- error in LP form factor decreases as $1/s$

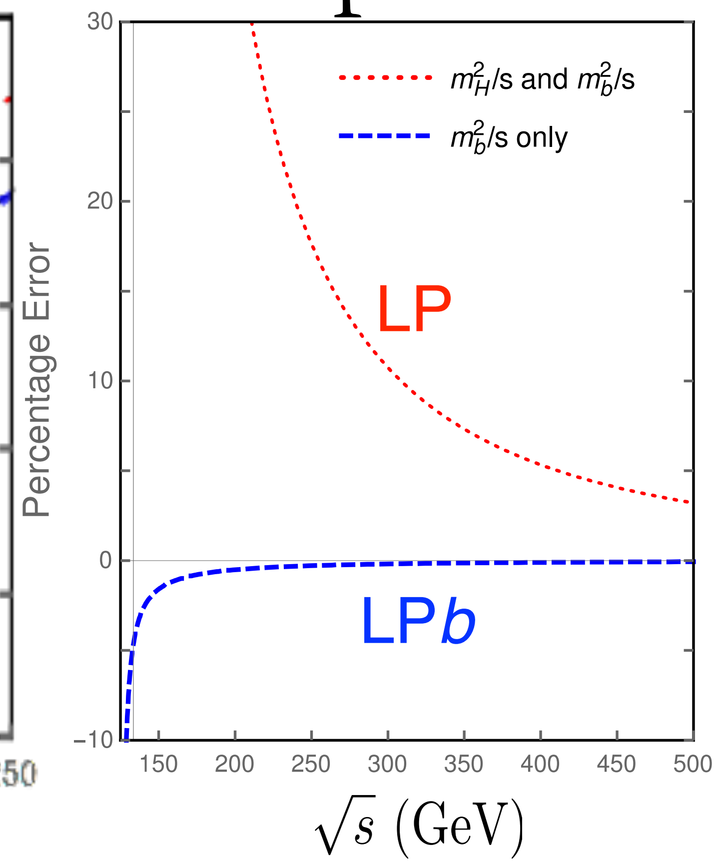
improved dependence on Higgs mass:

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 <u>leading power</u> in $1/P_T^2$

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

top-quark mass improvement:

LP*H* factorization formula for <u>leading power</u> 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 $q\,\bar{q} \longrightarrow H + g$ at LO

from top-quark loop arXiv:1704.06620

bottom-quark loop arXiv:1707.xxxxx

other parton processes at LO: straightforward

$$g\,g \longrightarrow H + g$$

$$g\,g \longrightarrow H + Z^0$$

Next-to-Leading Order: more challenging

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