Finite Heavy Quark Mass Effects in Gluon Fusion Higgs Production

Effects on the Transverse Momentum Spectrum

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Outline

1. Finite Top Mass effects
2. Bottom Quark Effects
3. Conclusions

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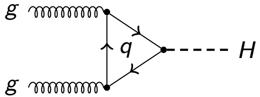
Gluon Fusion Higgs Production at the LHC

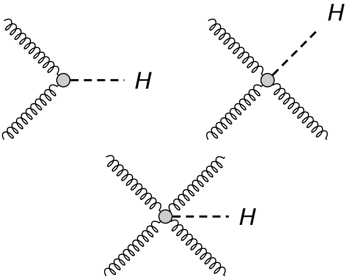
Dominant Prod. Channel at the LHC



- Large corrections to total cross section beyond leading order $\mathcal{O}\left(100\,\%\right)$
- At leading order: $p_\perp = 0$
- $p_\perp$ distribution driven by QCD corrections
- Rapidity distribution driven by PDFs

Effective Lagrangian

$$\mathcal{L}_{ggh} \propto G^{\mu\nu} G_{\mu\nu} H$$



Beyond the Effective Interaction Approach

Finite Top Mass Effects

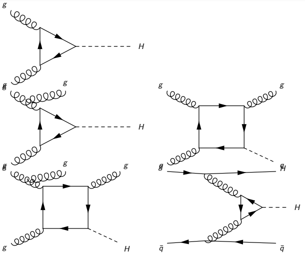
- Top mass effect on total inclusive cross section: 5% at leading order
- Effect on $p_\perp$ distribution can be larger for $p_\perp \approx m_t$

Sample Feynman Diagrams at Leading Order

Higgs + 0 Jet

Higgs + 1 Jet

Higgs + 2 Jet



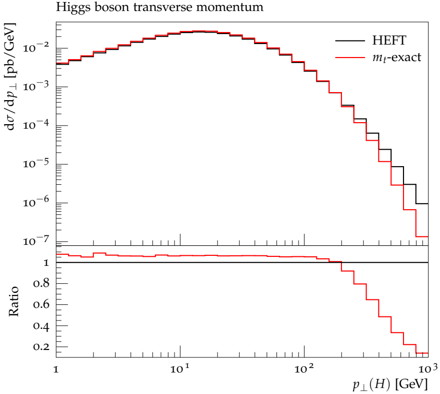
Can be obtained from automatic one-loop providers e.g. OpenLoops

Finite Top Mass Effects at Leading Order

- Expect effect at high $p_\perp > m_t$
- Employ multijet merging to properly account for hard emissions
- Requires diagrammatic ME information, use tree-level ME generators (Comix/AMEGIC++) in effective theory (HEFT)
- Account for mass effects by correcting tree-level MEs with OpenLoops MEs
- Apply correction factors of the form

$$\frac{|\mathcal{M}_{1-\text{loop}}|^2}{|\mathcal{M}_{\text{HEFT}}|^2}$$

Finite Top Mass Effects at Leading Order

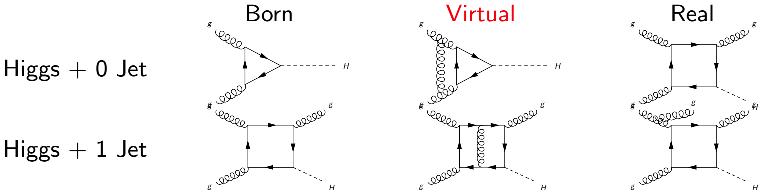


Setup

- LHC @ $\sqrt{s} = 13$TeV
- Merging at $Q_{\mathrm{cut}} = 30$GeV
  - $p\ p \to H$
  - $p\ p \to H\ j$
  - $p\ p \to H\ j\ j$
- $\mu_f = m_H$
- $\mu_r = m_H$
- $\mu_s = m_H$

Finite Top Masses at NLO

Sample Feynman Diagrams at NLO



- Born and real emission contributions: 1-loop MEs
- Virtual corrections are two-loop in an m_t-exact treatment
- For Higgs + 1 or more jets, two-loop calculation currently not available

Correcting for Finite Top Mass by Reweighting: NLO

$\mathbb{S}$-events (MC@NLO)

$$\overline{B}(\phi_B) = B(\phi_B) + V(\phi_B) + I^S(\phi_B) + \int \left[D^A(\phi_B, \phi_1) - D^S(\phi_B, \phi_1) \right] \mathrm{d}\phi_1$$

- Unintegrated Catani-Seymour dipole terms $D^{A/S} = \sum B \otimes V$
- Integrated Catani-Seymour dipole terms $I^S = \sum B \otimes I$
- Virtual contribution V contains two-loop matrix for finite quark masses, approximation: assume factorization of mass correction
- Reweight all contributions by ratios of matrix elements with born kinematics

$$\frac{|\mathcal{M}^B_{1-\mathrm{loop}}(\phi_B)|^2}{|\mathcal{M}^B_{HEFT}(\phi_B)|^2}$$

Correcting for Finite Top Mass by Reweighting: NLO

$\mathbb{H}$-events (MC@NLO)

$$H(\phi_R) = R(\phi_R) - D^A(\phi_B, \phi_1)$$

- Reweight real emission term R with real emission matrix elements

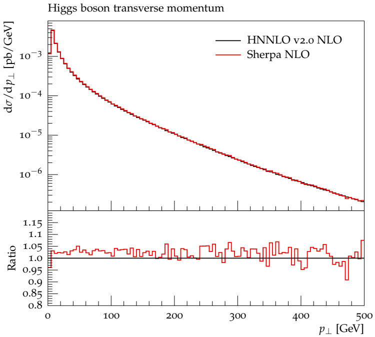
$$\frac{|\mathcal{M}^R_{1-\text{loop}}(\phi_R)|^2}{|\mathcal{M}^R_{\text{HEFT}}(\phi_R)|^2}$$

- Reweight subtraction terms D^A with born-ratios as in the case of $\mathbb{S}$-events

Fixed Order NLO: Comparison against HNNLO

HNNLO Grazzini, Sargsyan: Heavy-Quark Mass Effects in Higgs Boson Production at the LHC, arXiv:1306.4581

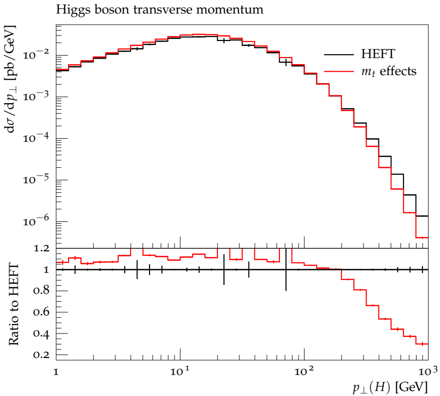
- Parton-level MC for Higgs production in pp and $p\bar{p}$ collisions
- Finite heavy quark mass effects up to $\mathcal{O}(\alpha_s^3)$ (NLO)
- Up to NNLO accuracy
- $\mathcal{O}(\alpha_s^4)$ (NNLO) contributions evaluated in HEFT, rescaled with born-level quark mass correction



Setup

- LHC @ $\sqrt{s} = 13$TeV
- $p\ p\ \rightarrow\ H$ @ NLO fixed order (no shower)
- Finite top quark mass

MEPS@NLO with Finite Top Mass Effects



Setup

- LHC @ $\sqrt{s} = 13$TeV
- Merging at $Q_{\text{cut}} = 30$GeV:
  - $p\ p \rightarrow H$ NLO
  - $p\ p \rightarrow H\ j$ NLO
  - $p\ p \rightarrow H\ j\ j$ LO
- $\mu_f = m_H$
- $\mu_r = m_H$
- $\mu_s = m_H/2$

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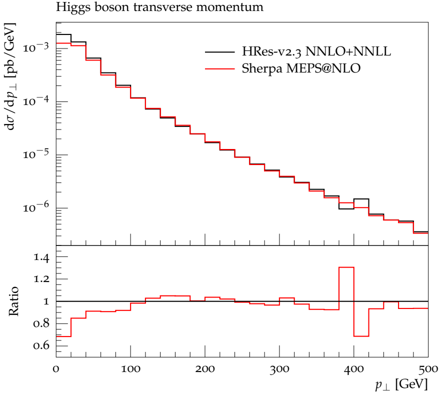
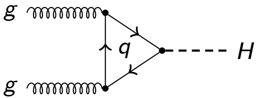


HRes

- Fully differential XS for Higgs production
- Up to NNLO accuracy with NNLL resummation
- Exact m_t dependence up to NLO
- Approximate m_t dependence of α_s^4 contributions

Outline

Taking the Bottom Contribution into Account



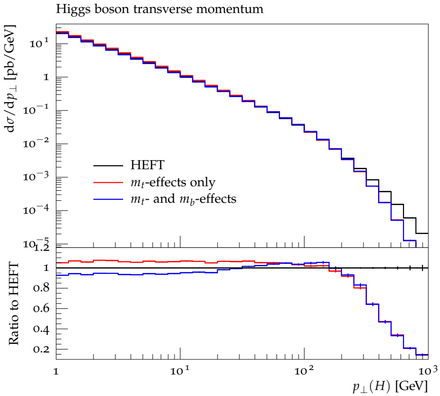
$$|\mathcal{M}|^2 = \underbrace{\mathcal{M}_t^2}_{y_t^2} + \underbrace{2\mathrm{Re}\left\{\mathcal{M}_t\mathcal{M}_b\right\}}_{y_t y_b} + \underbrace{\mathcal{M}_b^2}_{y_b^2} + \dots$$

- So far, only top contribution considered
- Top-bottom interference contribution is Yukawa-suppressed $\frac{y_t y_b}{y_t^2} \approx 3\%$
- Effects might be larger around $p_\perp(H) \approx m_b$

Implementing Bottom Quark Corrections

- HEFT not applicable for light bottom quark
- Cannot approximate virtual corrections as in case of top quark
- Split up matrix elements into terms proportional to y_t^2 and the remaining terms proportional to $y_t y_b$ or y_b^2 (OpenLoops)
- Generate contributions involving y_b at LO
- Generate top squared contributions separately at LO or NLO

Top- and Bottom Mass Effects at fixed Leading Order



Setup

- LHC @ $\sqrt{s} = 13\text{TeV}$
- $p\ p \rightarrow H + j$ @ LO fixed order (no shower)
- Finite top mass
- Finite top mass + bottom contributions

Bottom Contributions beyond Fixed Order

- At low $p_\perp$, large logarithms arise in the preturbative expansion

$$\ln^m(m_H/p_\perp)$$

- Need to resum them to all orders $\Longrightarrow$ Monte Carlo Shower
- Resummation based on factorization of real emission matrix elements for

$$p_\perp < \mu_s$$

- Top contributions factorize below $m_t \approx m_H$

$$\mu_s = \mathcal{O}(m_h)$$

- Bottom quark adds third scale to resummation problem

$$m_b << m_H$$

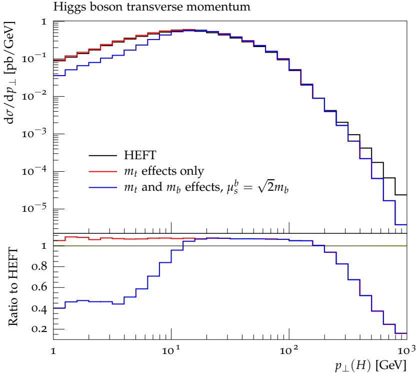
- Bottom contributions factorize around m_b, well below the hard scale m_H

Bottom Contributions beyond Fixed Order

A Different Resummation Scale for the Bottom

- Idea: restrict resummation to phase space where underlying approximations are valid

  Grazzini, Sargsyan: Heavy-Quark Mass Effects in Higgs Boson Production at the LHC, arXiv:1306.4581
- Treat y_t^2 contributions as usual, $\mu_s^t = \mathcal{O}(m_h)$
- Choose lower resummation scale for bottom contributions $\mu_s^b = \mathcal{O}(m_b)$



Setup

- LHC @ $\sqrt{s} = 13$TeV
- $p\ p \ \rightarrow \ H$
- y_t^2-contributions: S-MC@NLO
- Bottom contributions: LO+PS
- $\mu_s^t = m_h$
- $\mu_s^t = \mathcal{O}(m_b)$
- Extremely sensitive to exact choice of μ_s^b

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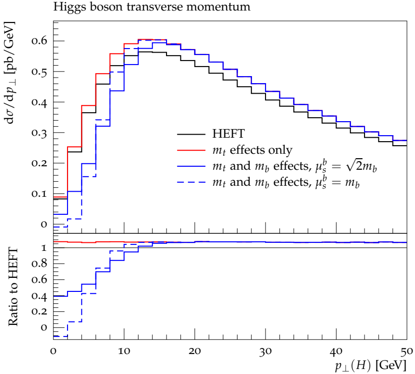

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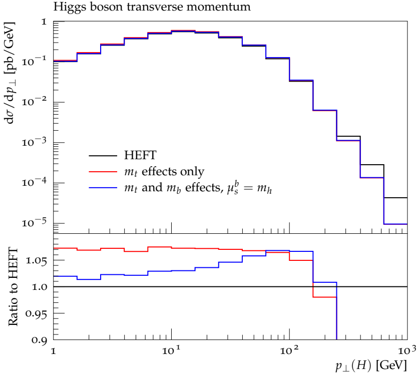
Bottom Contributions beyond Fixed Order

Utilizing Multijet Merging for the Bottom Contributions

- Start shower for all contributions at the same scale $\mu_s = \mathcal{O}(m_h)$
- Bottom contributions: correct emission above m_b with higher multiplicity MEs



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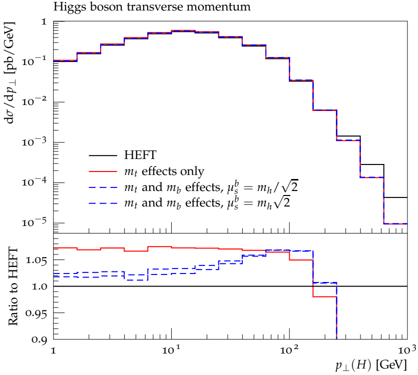

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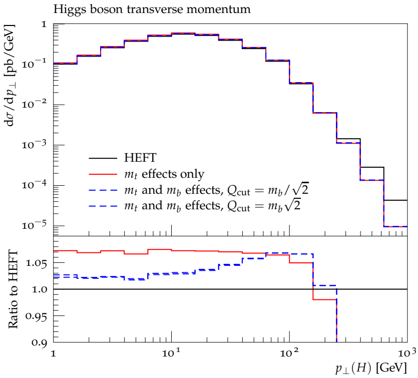

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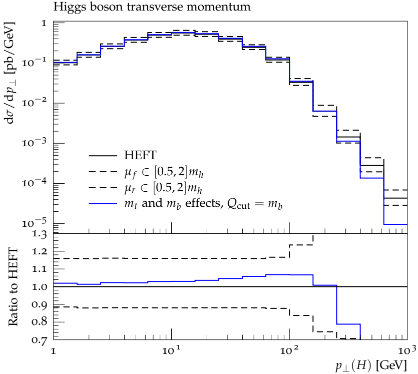

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  - $p\ p \rightarrow H$
  - $p\ p \rightarrow H\ j$
  - $Q_{\mathrm{cut}} = m_b$

Conclusions

- Finite top mass effects significantly suppress $p_\perp$ spectrum in the tail
- Implemented top mass corrections for H and Hj processes at NLO
  - approximate for virtual corrections
  - exact for real emission contributions
  - exact for H, Hj, Hjj at LO
- Bottom contributions alter the spectrum at lower scales
- Obtained stable (against scale variations) predictions by applying ME corrections instead of lowering shower scale for bottom contribution
- Effects are within perturbative uncertainties