Heavy Quark Mass Effects in Gluon Fusion

Monte Carlo Treatment with Sherpa

Silvan Kuttimalai

Institute for Particle Physics Phenomenology, Durham

December 9, 2014

Outline

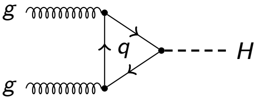
1. Finite Top Mass effects
2. Bottom Quark Effects
3. Conclusions

Outline

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

Gluon Fusion Higgs Production at the LHC

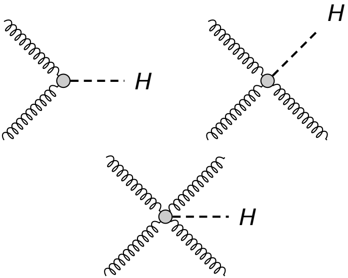
Dominant Prod. Channel at the LHC



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

Effective Lagrangian (HEFT)

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



Available in HEFT

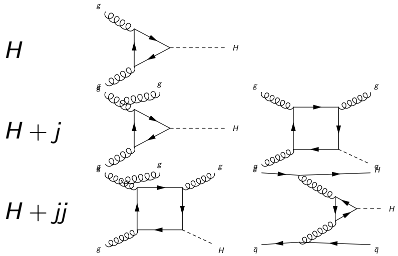
- NNLO fixed order: $H + j$ Boughezal et al.: JHEP 06 (2013) 72
- Parton shower matched: NNLO in UN^{2}LOPS scheme Hoeche, Li, Prestel: arXiv:1407.3773

Beyond the Effective Interaction Approach

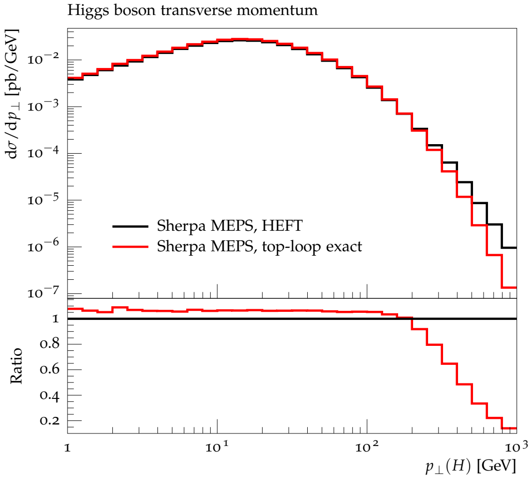
Finite Top Mass Effects

- σ_{incl}: 5% at LO, $\mathcal{O}(1\%)$ at NNLO Pak, Rogal, Steinhauser: JHEP 1109 (2011) 88
- $\frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}$: much larger for $p_\perp > m_t$
- Large effects in phase space regions of hard emissions
- Employ multijet merging to correct parton shower for hard emissions
- Use m_t-exact one-loop MEs from OpenLoops to capture finite mass effects

Cascioli, Maierhöfer, Pozzorini: Scattering Amplitudes with OpenLoops, Phys.Rev.Lett. 108 (2012) 111601



Finite Top Mass Effects at Leading Order



Setup

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

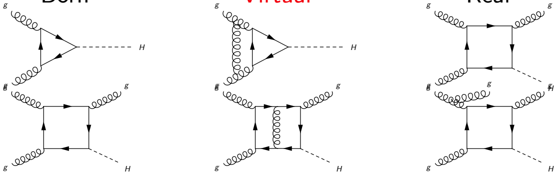
Finite Top Masses at NLO

Sample Feynman Diagrams at NLO

Born | Virtual | Real

Higgs + 0 Jet

Higgs + 1 Jet



$$\mathrm{d}\sigma = \left[B(\phi_B) + V(\phi_B) + I(\phi_B)\right]\mathrm{d}\phi_B + \left[R(\phi_R) - D(\phi_R)\right]\mathrm{d}\phi_R$$

- 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
- Ad hoc hypothesis: finite-mass correction factorizes from α_s correction in ϕ_B:

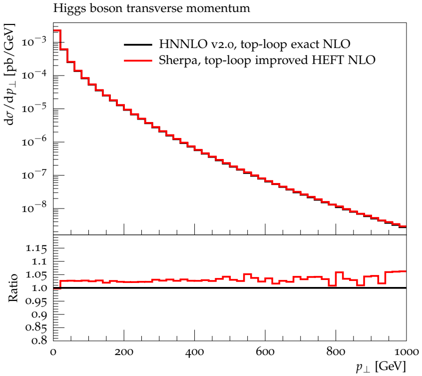
$$V \approx \frac{B}{B_{\mathrm{HEFT}}} V_{\mathrm{HEFT}}$$

Fixed Order NLO: Comparison against HNNLO

HNNLO

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

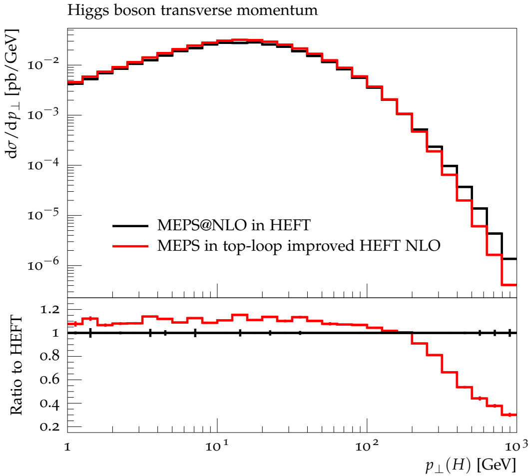
- NNLO Parton-level MC for Higgs production in pp and $p\bar{p}$ collisions
- Finite heavy quark mass effects up to $\mathcal{O}(\alpha_s^3)$ (NLO)
- $\mathcal{O}(\alpha_s^4)$ (NNLO) contributions evaluated in HEFT, rescaled with born-level quark mass correction



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



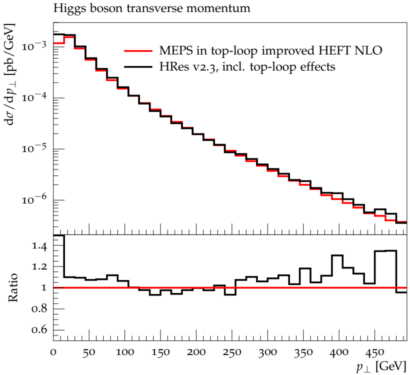
Setup

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

MEPS@NLO: Comparison to HRes

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

- 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

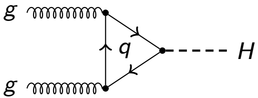


Setup

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

Outline

Taking the Bottom Contribution into Account



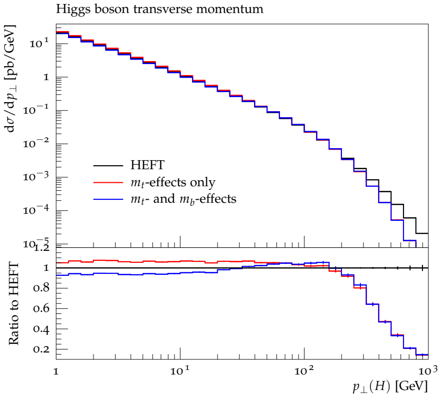
$$|\mathcal{M}|^2 = \underbrace{\mathcal{M}_t^2}_{y_t^2} + \underbrace{2\mathrm{Re}\left\{\mathcal{M}_t\mathcal{M}_b\right\}}_{y_t y_b} + \underbrace{\mathcal{M}_b^2}_{y_b^2} + \dots$$

- 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

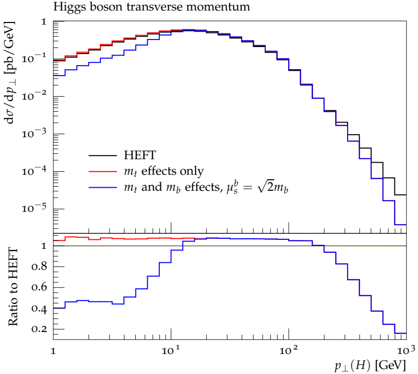
$$m_b << m_H$$

- 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

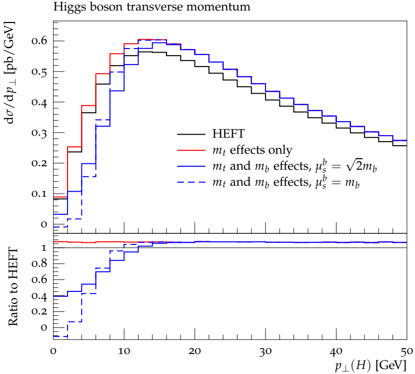
- LHC @ $\sqrt{s} = 13$TeV
- $p\ p \ \to\ H$
- y_t^2-contributions: S-MC@NLO
- Bottom contributions: LO+PS
- $\mu_s^t = m_h$
- $\mu_s^t = \mathcal{O}(m_b)$
- Extremely sensitive to exact choice of μ_s^b

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 $\mu_s^b = \mathcal{O}(m_b)$



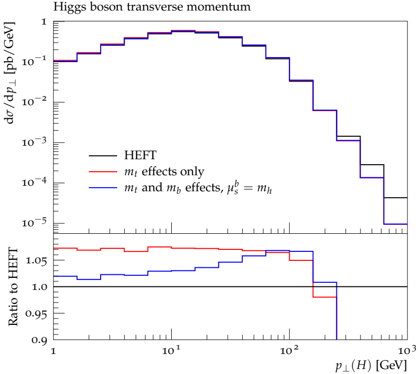
Setup

- LHC @ $\sqrt{s} = 13\text{TeV}$
- $p\ p\ \rightarrow\ H$
- 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

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



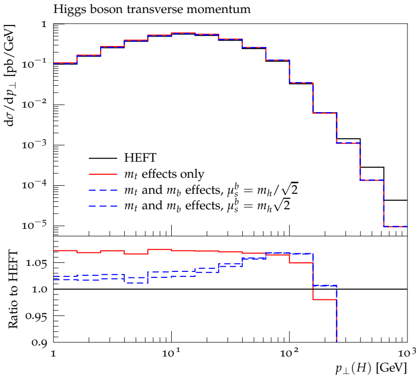
Setup

- LHC @ $\sqrt{s} = 13$TeV
- $\mu_s^t, \mu_s^b = \mathcal{O}(m_h)$
- y_t^2-contributions: S-MC@NLO
  - $p\ p \to H$
- Bottom contributions: LO-merging
  - $p\ p \to H$
  - $p\ p \to H\ j$
  - $Q_{\text{cut}} = m_b$

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



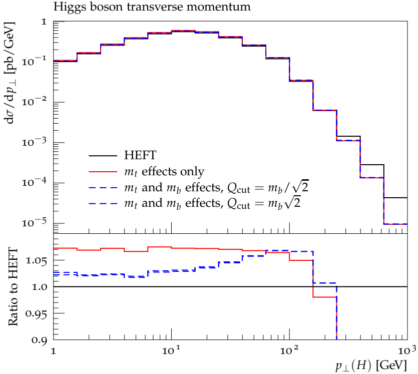
Setup

- LHC @ $\sqrt{s} = 13$TeV
- $\mu_s^t, \mu_s^b = \mathcal{O}(m_h)$
- y_t^2-contributions: S-MC@NLO
  - $p\ p \rightarrow H$
- Bottom contributions: LO-merging
  - $p\ p \rightarrow H$
  - $p\ p \rightarrow H\ j$
  - $Q_{\text{cut}} = m_b$

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



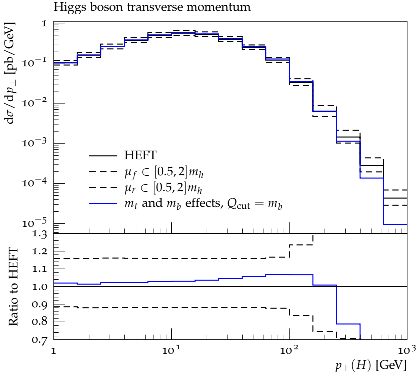
Setup

- LHC @ $\sqrt{s} = 13$TeV
- $\mu_s^t, \mu_s^b = \mathcal{O}(m_h)$
- y_t^2-contributions: S-MC@NLO
  - $p\ p \to H$
- Bottom contributions: LO-merging
  - $p\ p \to H$
  - $p\ p \to H\ j$
  - $Q_{\rm cut} = m_b$

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



Setup

- LHC @ $\sqrt{s} = 13$TeV
- $\mu_s^t, \mu_s^b = \mathcal{O}(m_h)$
- y_t^2-contributions: S-MC@NLO
  - $p\ p \rightarrow H$
- Bottom contributions: LO-merging
  - $p\ p \rightarrow H$
  - $p\ p \rightarrow H\ j$
  - $Q_{\rm cut} = m_b$

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

Backup

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