Heavy quark mass effects in the Higgs p_T spectrum

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Massimiliano Grazzini, Hayk Sargsyan, arXiv:1306.4581 [hep-ph]

Outline

- Introduction
- Mass effects in the resummed p_T spectrum
- The bottom quark loop
- Results
- Summary

Transverse-momentum spectrum

At hadron colliders the production of an (on shell) Higgs boson is characterized by its transverse momentum p_T and rapidity y

- shape of rapidity spectrum is mainly driven by PDFs
- Effect of QCD radiation is mainly encoded in p_T spectrum

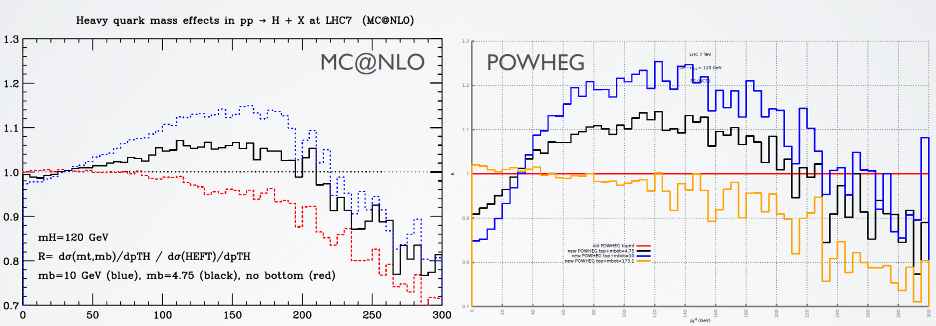
- When $p_T \sim m_H$ the QCD radiative corrections can be evaluated through the standard fixed-order expansion
- When $p_T \ll m_H$ large logarithmic terms appear

  $\Rightarrow$ spoil the perturbative expansion

To obtain reliable perturbative predictions over the whole range of transverse momenta, such terms must be resummed to all orders, and the result has to be consistently matched to the standard fixed-order result

p_T spectrum

Such resummation is effectively performed by MC event generators



S.Frixione, LHC Higgs XS Meeting (december, 2012)

- Good agreement when only the top quark contribution is considered
- Inclusion of the bottom quark introduces large differences at small p_T
- MC@NLO agrees well with the analytical resummation
- POWHEG amplifies the effect of the bottom mass

Fixed order results

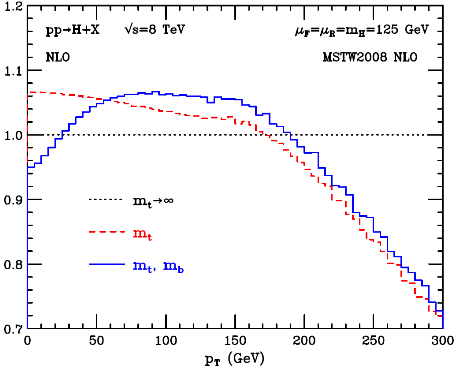
The exact heavy-quark mass dependence is known up to NLO

R. K. Ellis, I. Hinchliffe, M. Soldate, J. van der Bij (1988)

M. Spira, A. Djouadi, D. Graudenz, P. Zerwas (1995)

We have implemented the exact heavy-quark mass dependence in a new version of the numerical program HNNLO

- At large p_T the top quark contribution dominates and reduces the cross section with respect to the result in the large-m_t limit
- At small p_T the bottom contribution is significant and changes the shape of the spectrum



Resummation procedure at small p_T

The series expansion of the partonic cross section $d\hat{\sigma}_{ab}$ in α_s contains logarithmic-enhanced terms $(\alpha_s^n/p_T^2)ln^m(m_H^2/p_T^2)$ $\longrightarrow$ should be resummed

$$\frac{d\hat{\sigma}_{a_1 a_2}}{d\hat{y}dp_T^2} = \frac{d\hat{\sigma}^{(res.)}_{a_1 a_2}}{d\hat{y}dp_T^2} + \frac{d\hat{\sigma}^{(fin.)}_{a_1 a_2}}{d\hat{y}dp_T^2}$$

$$\left[\frac{d\hat{\sigma}^{(fin.)}_{a_1 a_2}}{d\hat{y}dp_T^2}\right]_{f.o.} = \left[\frac{d\hat{\sigma}_{a_1 a_2}}{d\hat{y}dp_T^2}\right]_{f.o.} - \left[\frac{d\hat{\sigma}^{(res.)}_{a_1 a_2}}{d\hat{y}dp_T^2}\right]_{f.o.}$$

- The resummed component is obtained by working in impact parameter b space

$$\frac{d\hat{\sigma}^{(res.)}_{a_1 a_2}}{d\hat{y}dp_T^2}(\hat{y}, p_T, m_H, \hat{s}; \alpha_s) = \frac{m_H^2}{\hat{s}} \int_0^\infty db \frac{b}{2} J_0(bp_T) \mathcal{W}_{a_1 a_2}(\hat{y}, b, m_H, \hat{s}; \alpha_s)$$

$$\mathcal{W}^{N_1,N_2}(b, m_H) = \sigma_0(m_H)\mathcal{H}^{N_1,N_2}(m_H; m_H^2/Q^2) \times exp\left[\mathcal{G}^{N_1,N_2}(\tilde{L}; m_H^2/Q^2)\right]$$

resummation scale

$$\tilde{L} = ln\left(\frac{Q^2 b^2}{b_0^2} + 1\right), \quad b_0 = 2e^{-\gamma_E}, \quad \gamma_E \text{ is the Euler number}$$

Mass effects in the resummed spectrum

- Since $m_t \sim m_H$, as far as only the top quark is considered we have only 2 physical scales m_H and p_T
- The inclusion of the bottom quark introduces the third physical scale m_b Studying the analytic behaviour of the QCD matrix elements we find that, for the bottom quark contribution the collinear factorization is a good approximation only when $p_T \ll 2m_b$

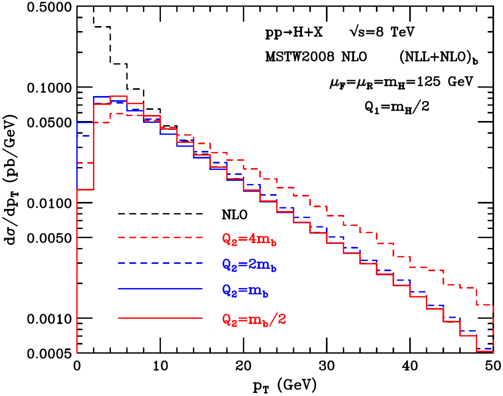
$\Longrightarrow$ the standard resummation procedure cannot be straightforwardly applied to the bottom quark contribution

- Our resummation formalism introduces an unphysical scale Q (resummation scale) which sets the scale up to which the resummation is effective
- the top quark gives the dominant contribution to the p_T cross section and we treat it as usual with a resummation scale $Q_1 \sim m_H/2$
- the bottom contributions (and the top-bottom interference) are controlled by an additional resummation scale Q_2 that we choose of the order of m_b

In this way we limit the resummation for the bottom contribution only to the region in which it is really justified (and needed)

Results

We have implemented the exact heavy-quark mass dependence in a new version of the numerical program HRes



We focus on the bottom contribution

The p_T spectra for $Q_2 = m_b/2$, $Q_2 = m_b$ and $Q_2 = 2m_b$ agree well with the fixed order spectrum, while for $Q_2 = 4m_b$ the resummed and fixed order spectra do not match

→ We choose $Q_2 = m_b$ as a central value of the second resummation scale

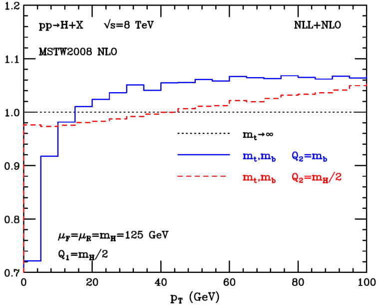
Results

The naive implementation of the the bottom quark mass leads to a result very similar to MC@NLO
Good agreement with independent calculation by Wiesmann, Mantler (2012)

The inclusion of the second resummation scale increases the effect of the bottom quark in the low p_T region

→ result is more similar to the POWHEG result, though in our case the effects of the bottom quark are confined to smaller values of p_T

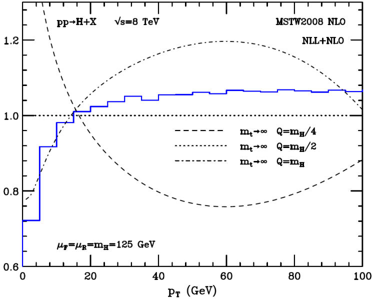
Large effects!

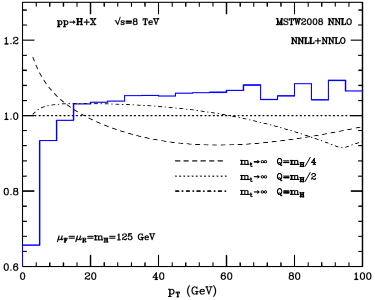


Results

The scale uncertainties are computed with HqT

- At NLL+NLO the effect of resummation scale variations is large, well beyond the effect of heavy-quark masses for $p_T \gtrsim 20$ GeV In the region $p_T \lesssim 20$ GeV the effect of bottom-quark mass and of resummation scale variation are comparable
- As it was expected, the impact of the heavy-quark mass effects in the NNLL+NNLO result is similar to what was observed at NLL+NLO
- The effect of resummation scale variations at this order is much smaller mass effects in the low p_T region are even more important





Summary

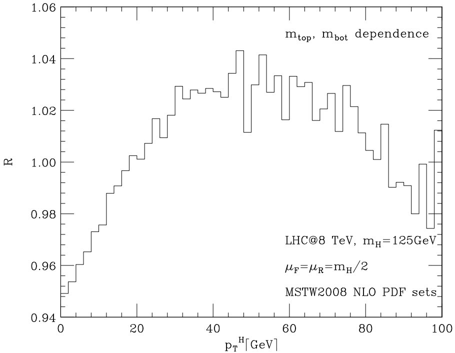
- We have considered heavy-quark mass effects in Higgs boson production through gluon-gluon fusion at the LHC
- The bottom quark plays an important role and leads to relatively large differences in the shape of the p_T spectrum between MC@NLO and POWHEG
- The inclusion of the exact bottom mass dependence in the p_T spectrum beyond fixed order implies the solution of a difficult three scale problem
- We have provided a simple solution of this issue by controlling the resummed bottom-quark contribution through an additional resummation scale $Q_2 \sim m_b$
- At NLL+NLO the perturbative uncertainties are large and comparable to the bottom quark mass effects in the low p_T region
- At NNLL+NNLO the distortion induced by the bottom quark is significant and well beyond of the perturbative uncertainties
- Our results are implemented in updated versions of the HNNLO and HRes numerical programs
- Recently MC@NLO and POWHEG have implemented our prescription in their codes and the results are in a good agreement with HRes

Backup slides

Bottom quark loop

Consider $qg \to Hq$ channel

The qualitative behaviour of the p_T shape in this channel is the same as for the full calculation



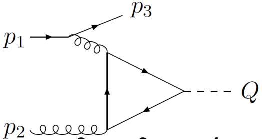
Bottom quark loop

Consider the amplitude of the Higgs production in the $qg \to Hq$ channel

$$s = (p_1 + p_2)^2$$

$$t = (p_1 - p_3)^2$$

$$u = (p_2 - p_3)^2$$



$$|\mathcal{M}_{qg\to Hq}(s,t,u)|^2 = \alpha_W \alpha_S^3 C_F C_A \frac{u^2+s^2}{-tM_W^2}\frac{m_H^4}{(u+s)^2}|A_5(t,s,u)|^2$$

$$s+u+t = m_H^2, \quad ut = sp_T^2$$

$$A_5(t,s,u) = \sum_{f=b,t}\frac{m_f^2}{m_H^2}\Big[4 + \frac{4t}{u+s}\left[W_1(t) - W_1(m_H^2)\right] + \left[1 - \frac{4m_f^2}{u+s}\right]\left[W_2(t) - W_2(m_H^2)\right]\Big],$$

R.K. Ellis, I. Hinchliffe, M. Soldate, J. van der Bij (1988)

In the small p_T region we have $t \to 0$ and $u \to -s(1-z)$, $z = m_H^2/s$

Bottom quark loop

In the limit $p_T \to 0$ (naive collinear factorization)

$$|\mathcal{M}_{qg\to Hq}(s,t,u)|^2 = \alpha_W \alpha_S^3 C_F C_A \frac{1+(1-z)^2}{z^2} \frac{m_H^4}{M_W^2} \frac{1}{-t} |A_1(m_H^2)|^2,$$

where $A_1(m_H^2)$ is the Born $gg \to H$ amplitude

$$A_1(m_H^2) = \sum_{f=b,t} \frac{m_f^2}{m_H^2} \left[4 - W_2(m_H^2)\left(1 - \frac{4m_f^2}{m_H^2}\right)\right]$$

$$A_{5b}(t,s,u) = \frac{m_b^2}{m_H^2} \left[4 - \left(W_2(m_H^2) - W_2(t)\right)\left(1 - \frac{4m_b^2}{m_H^2}\right)\right]$$

$$W_2(t) = 4\left(\mathrm{arcsinh}\left(\frac{\sqrt{-t}}{2m_b}\right)\right)^2$$

$$A_{5b} \xrightarrow{p_T\to 0} A_{1b}$$

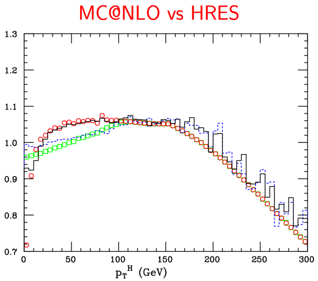
Bottom quark loop

This does not hold when $p_T \sim m_b$

$|t| \sim 4m_b^2 \Rightarrow W_2(t) \sim 1$

- The naive collinear factorization, which would lead us to recover the Born result, does not hold here
- $W_2(t)$ is an increasing function of $-t$, and hence, of p_T, thus explaining the steep behaviour in p_T distribution

MC@NLO vs HRes



S. Frixione, Higgs XS WG Meeting, 23-7-2013

histograms: MC@NLO symbols: HRes

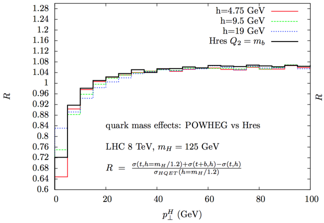
solid and circles: $Q_2 = \mathcal{O}(m_b)$ dashed and boxes: $Q_2 = \mathcal{O}(m_H)$

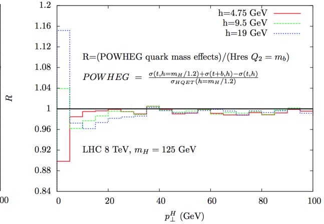
POWHEG vs HRes

A. Vicini, Higgs XS WG Meeting, 23-7-2013

Numerical comparison with Hres

- Hres results (arXiv:1306.4581) kindly provided by M. Grazzini





- Significant suppression due to bottom mass effects in the first two bins, rather flat and positive corrections above 30 GeV