

# Heavy quark mass effects in the Higgs $p_T$ spectrum

Hayk Sargsyan

University of Zurich


LHCPhenoNet annual meeting, 2-5 December 2013, CERN

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

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

# Transverse-momentum spectrum

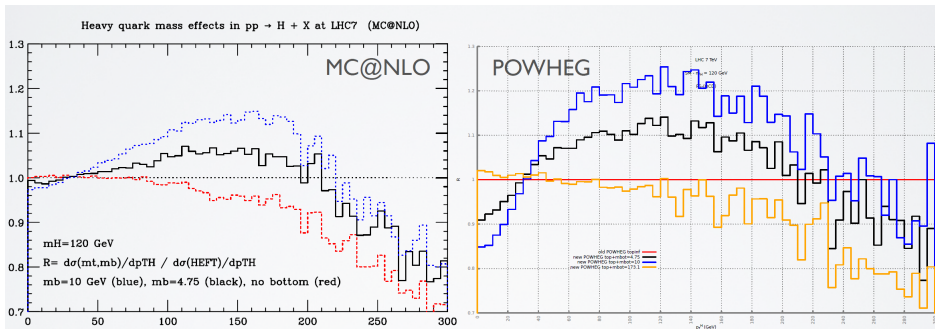
At hadron colliders the production of an (on shell) Higgs boson is characterized by its transverse momentum  $p_T$  and rapidity  $y$

- 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  
 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

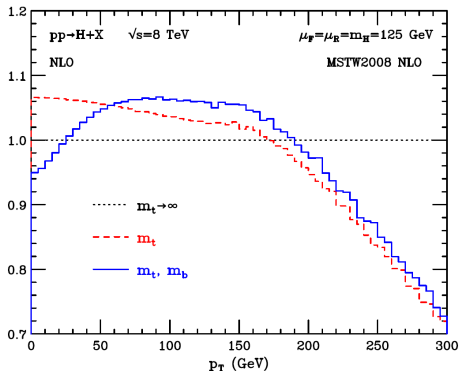
The exact heavy-quark mass dependence is known up to NLO

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  $\alpha_s$  contains logarithmic-enhanced terms  $(\alpha_s^n/p_T^2)\ln^m(m_H^2/p_T^2)$   **should be resummed**

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

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

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

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

resummation  
scale 

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

# Bottom quark loop

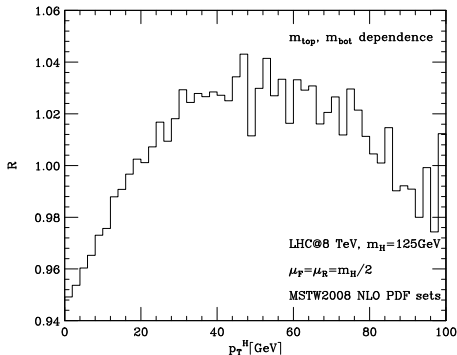
The resummation procedure involves an additional unphysical parameter  $Q$  (resummation scale) which sets the scale up to which the resummation is effective

- If we consider only the top mass contribution we have only 2 physical scales  $m_H$  and  $m_t$   
Since  $m_t$  is of the order of  $m_H$  we can safely do the resummation at small  $p_T$
- Once we consider the bottom quark contribution we have 1 additional physical scale  $m_b$ , since  $m_b \ll m_H$   
The possible problem might arise in the region  $m_b \sim p_T \ll m_H$

# Bottom quark loop

Consider  $qg \rightarrow Hq$  channel

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





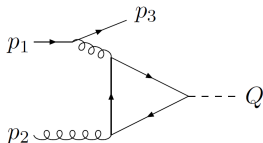
# Bottom quark loop

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

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

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

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



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

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

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

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

# Bottom quark loop

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

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

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

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

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

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


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

# Bottom quark loop

This does not hold when  $p_T \sim m_b$

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

- 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

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

# Possible solution

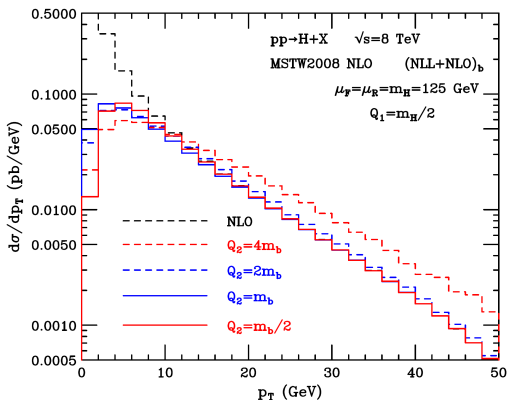
- Our resummation formalism introduces an unphysical scale  $Q$  (resummation scale) which sets the scale up to which the resummation is effective
- the top quark gives the dominant contribution to the  $p_T$  cross section and we treat it as usual with a resummation scale  $Q_1 \sim m_H/2$
- the bottom 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

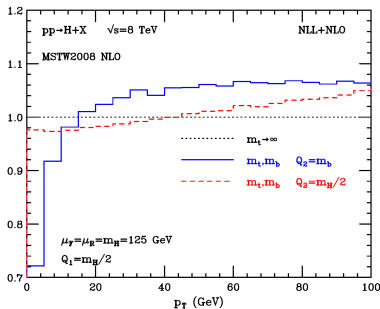
The naive implementation of the the bottom quark mass leads to a result very similar to MC@NLO  
Good agreement with independent calculation by [Wiesmann, Mantler \(2012\)](#)

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  $p_T$

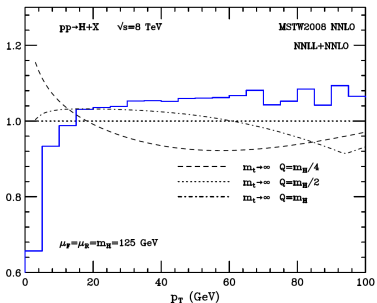
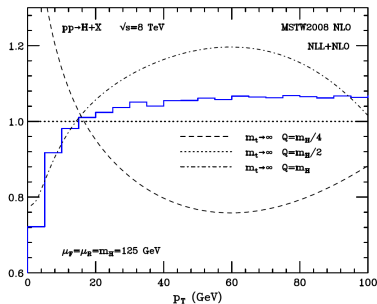
Large effects!



# 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



# Efficiency

$$\epsilon(p_T^{cut}) = \frac{\sigma(p_T^{cut})}{\sigma_{tot}}$$

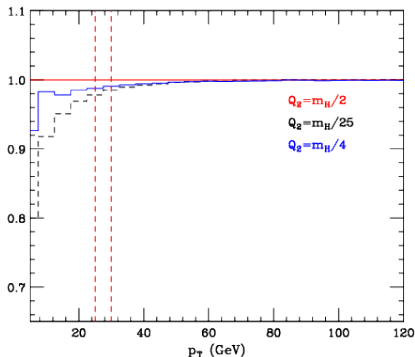
$$\sigma(p_T^{cut}) = \int d\Phi \frac{d\sigma}{d\Phi} \Theta(p_T^{cut} - p_T)$$

Large effect at low  $p_T$

1.5-2.3% effect at  $p_T = 25 - 30$  GeV  
for  $Q_2 = 5$  GeV

Similar effect was observed for  
Higgs production with jet-veto

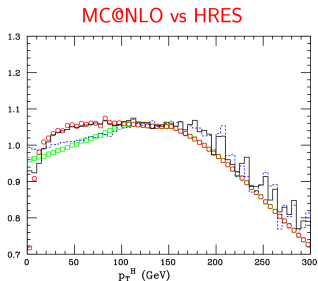
A. Banfi, P.F Monni, G. Zanderighi





# MC@NLO vs HRes

Recently MC@NLO and POWHEG used our prescription to control bottom-induced contributions separately  
Both are in a relatively good agreement with HRes



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

histograms: MC@NLO

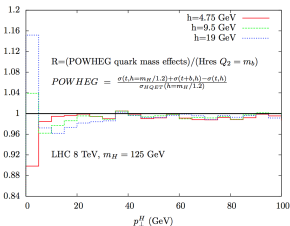
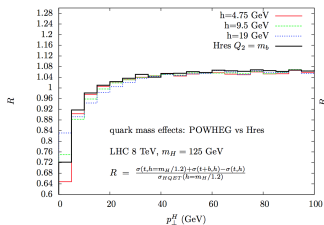
symbols: HRes

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

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

## Numerical comparison with Hres

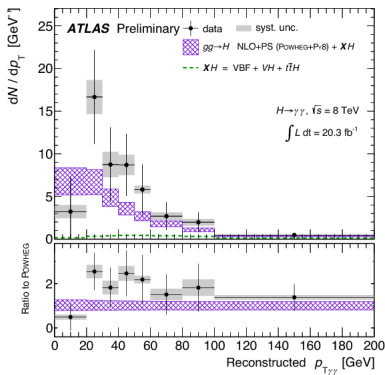
- Hres results (arXiv:1306.4581) kindly provided by M. Grazzini



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

# First experimental results

First experimental measurement of the Higgs  $p_T$  spectrum provided by ATLAS. It is compatible with theory predictions but suggests a possibly harder spectrum.



Still too early to draw a definite conclusion. Looking forward for the new data!

# 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 relatively good agreement with HRes