Mass effects in the Higgs p_T spectrum

Massimiliano Grazzini*

University of Zurich

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*On leave of absence from INFN, Sezione di Firenze

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- Mass effects at fixed order
- Mass effects in the resummed p_T spectrum
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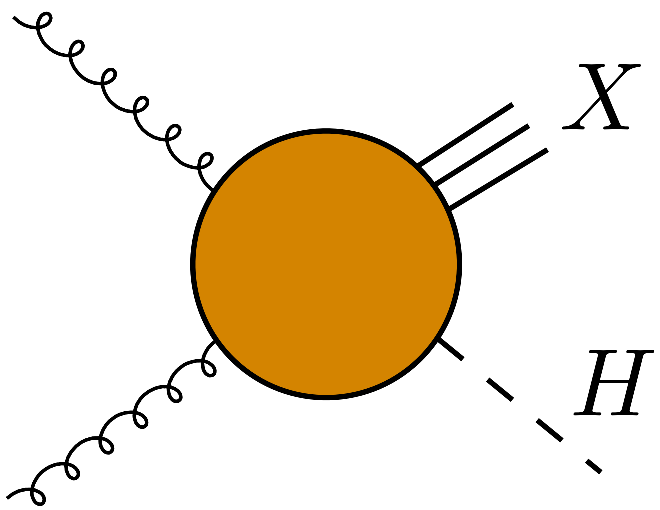
Introduction



Gluon-gluon fusion is the dominant production channel of the Higgs boson at hadron colliders

Enormous activity in the last few years

Total cross section up to NNLO

R.Harlander, W.B. Kilgore (2002)
C. Anastasiou, K. Melnikov (2002)
V. Ravindran, J. Smith, W.L.Van Neerven (2003)

EW corrections

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

NNLO beyond large-m_{top} approximation

R.Harlander et al. (2009)
M.Steinhauser et al. (2009)

Fully exclusive NNLO calculations

→ FEHIP, HNNLO

C.Anastasiou, K.Melnikov, F.Petrello (2005)
S.Catani, MG (2007)
MG (2008)

....

Transverse-momentum spectrum

Among the various distributions an important role is played by the transverse momentum spectrum of the Higgs boson

Transverse momentum (p_T) and rapidity (y) identify the Higgs kinematics

The shape of rapidity distribution mainly determined by PDFs

→ Effect of QCD radiation mainly encoded in the p_T spectrum

Moreover: the Higgs is a scalar → production and decay processes essentially factorized

When considering the transverse momentum spectrum it is important to distinguish two regions of transverse momenta

$p_T \sim m_H$

To have $p_T \neq 0$ the Higgs boson has to recoil against at least one parton ➡ the LO is of relative order α_S

NLO corrections are known

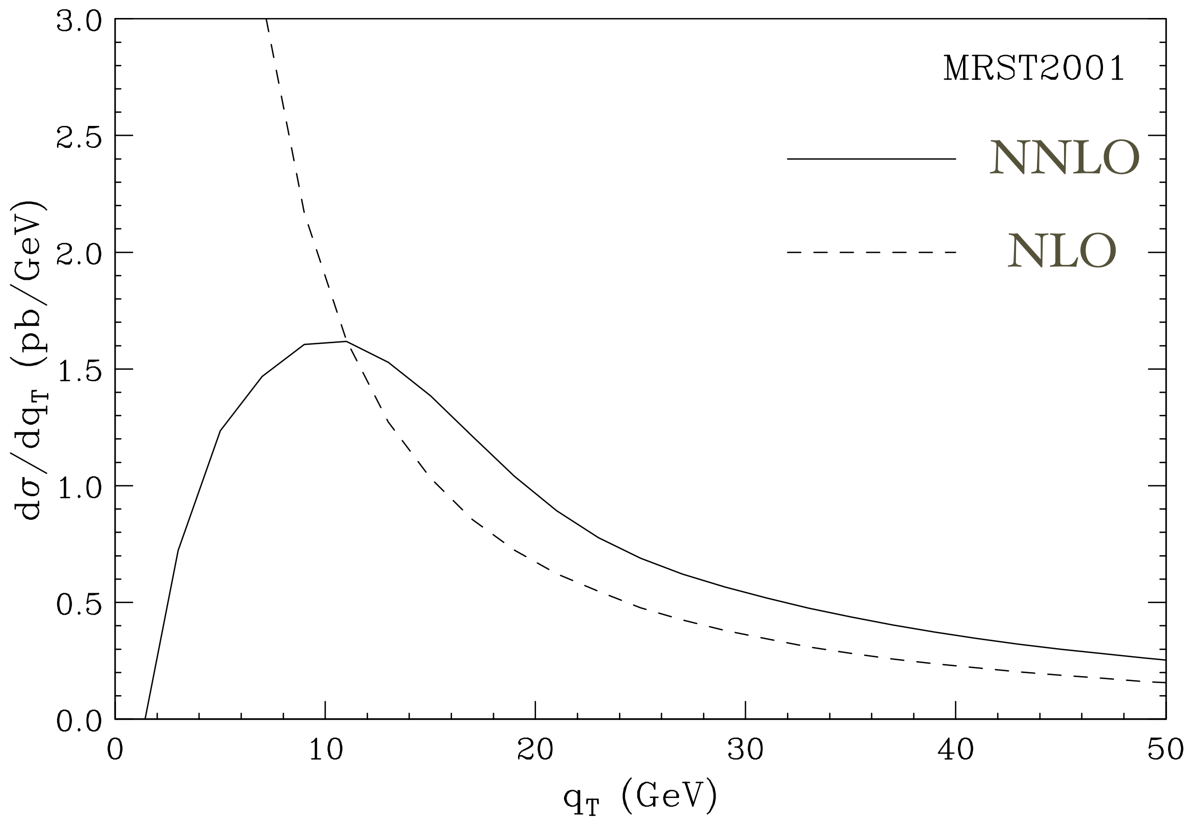
D. de Florian, Z.Kunszt, MG (1999)
V.Ravindran, J.Smith, V.Van Neerven (2002)
C.Glosser, C.Schmidt (2002)

➘ **Part of inclusive NNLO corrections**

$p_T << m_H$

Large logarithmic corrections of the form $\alpha_S^n \ln^{2n} m_H^2/q_T^2$ appear that originate from soft and collinear emission

➡ the perturbative expansion becomes not reliable



NLO: $\frac{d\sigma}{dp_T} \to +\infty$ as $p_T \to 0$

NNLO: $\frac{d\sigma}{dp_T} \to -\infty$ as $p_T \to 0$

➡ RESUMMATION NEEDED (effectively perfomed by standard MC generators)

The resummation formalism has been developed in the eighties

Y.Dokshitzer, D.Diakonov, S.I.Troian (1978)
G. Parisi, R. Petronzio (1979)
G. Curci, M.Greco, Y.Srivastava(1979)
J. Collins, D.E. Soper, G. Sterman (1985)

As it is customary in QCD resummations one has to work in a conjugate space in order to allow the kinematics of multiple gluon emission to factorize

In this case, to exactly implement momentum conservation, the resummation has to be performed in impact parameter b-space

Many phenomenological studies performed at different levels of theoretical accuracy

I.Hinchliffe, S.F.Novaes (1988)
R.P. Kauffmann (1991)
C.P.Yuan (1992)
C.Balazs, C.P.Yuan (2000)
E. Berger, J. Qiu (2003)
A.Kulezsa, J.Stirling (2003)
....

Recent studies also in the context of SCET

S.Mantry, F.Petriello (2009,2010)
T. Becher, M.Neubert (2010)
....

Our formalism

We use a version of the b-space formalism with some appealing features

S.Catani, D. de Florian, MG (2000)
G. Bozzi, S.Catani, D. de Florian, MG(2005)

Parton distributions factorized at $\mu_F \sim M = m_H$

avoids PDF extrapolation to small scales

$$\frac{d\hat{\sigma}_{ac}^{(\mathrm{res.})}}{dp_T^2} = \frac{1}{2}\int_0^\infty db\, b J_0(bp_T)\mathcal{W}_{ac}(b, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)$$

process dependent

$$\mathcal{W}_N^F(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \mathcal{H}_N^F\left(M, \alpha_S(\mu_R^2); M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2\right)$$
$$\times \exp\{\mathcal{G}_N(\alpha_S(\mu_R^2), L; M^2/\mu_R^2, M^2/Q^2)\}$$

universal

where the large logs are organized as:

$$\mathcal{G}_N(\alpha_S, L; M^2/\mu_R^2, M^2/Q^2) = L\, g^{(1)}(\alpha_S L)$$
$$+g_N^{(2)}(\alpha_S L; M^2/\mu_R^2, M^2/Q^2) + \alpha_S\, g_N^{(3)}(\alpha_S L; M^2/\mu_R^2, M^2/Q^2) + \dots$$

with $L = \ln M^2 b^2/b_0^2$ ➡ $\tilde{L} = \ln\left(1 + Q^2 b^2/b_0^2\right)$ and $\alpha_S = \alpha_S(\mu_R)$

resummation scale

- **The form factor takes the same form as in threshold resummation**
- **Unitarity constraint enforces correct total cross section**
- **Allows a consistent study of perturbative uncertainties**

The resummed and fixed order calculations can then be combined to achieve uniform theoretical accuracy over the entire range of p_T

$$\frac{d\hat{\sigma}}{dp_T^2} = \frac{d\hat{\sigma}^{(\mathrm{res.})}}{dp_T^2} + \frac{d\hat{\sigma}^{(\mathrm{fin.})}}{dp_T^2}$$

standard fixed order result minus expansion of resummed formula at the *same* order

The calculation can be done at:

- NLL+NLO: we need the functions $g^{(1)}$, $g_N^{(2)}$ and the coefficient $\mathcal{H}_N^{(1)}$ plus the matching at relative order α_S
- NNLL+NNLO: we also need the function $g_N^{(3)}$ and the coefficient $\mathcal{H}_N^{(2)}$ plus the matching at relative order α_S^2

NNLL+NNLO represents the highest accuracy available to date

→ Implemented in HqT

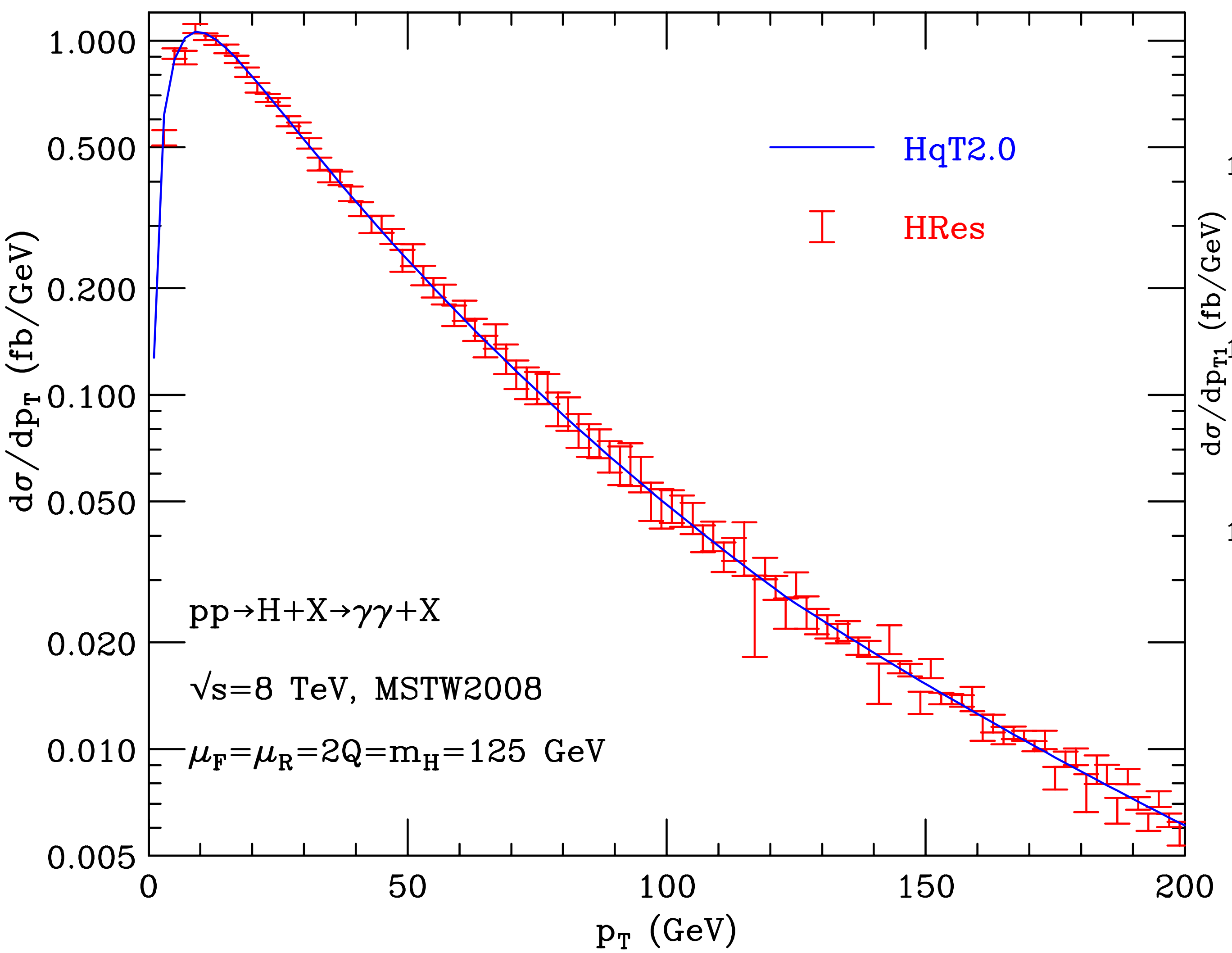
At NLL+NLO the accuracy is roughly the same as in MC@NLO and POWHEG

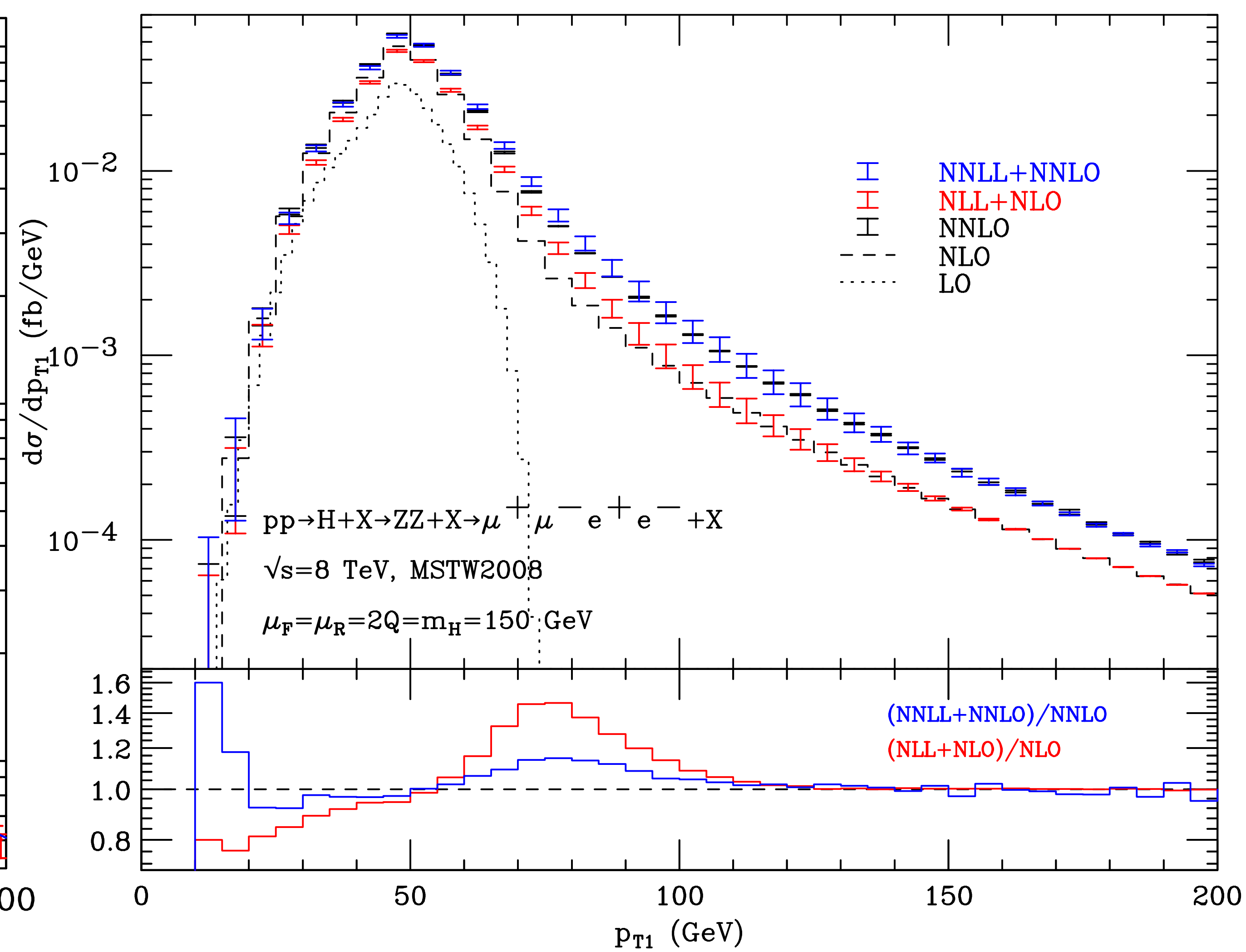
HRes

D. de Florian, G.Ferrera, D. Tommasini, MG (2011)

HRes combines the NNLO calculation in HNNLO with the small-p_T resummation implemented in HqT

It includes the decay $H\to\gamma\gamma$, $H\to WW\to l\nu l\nu$, $H\to ZZ\to 4l$





Mass effects at fixed order

H.Sargsyan, MG (2013)

Let us go back to fixed order for a moment

It is not difficult to extend the fully exclusive calculation in HNNLO to include the exact dependence on the masses of the heavy quarks up to NLO

Two loop virtual corrections available

M.Spira et al. (1991,1995)
R.Harlander , P.Kant (2005)
U.Aglietti, R.Bonciani, G. Degrassi, A.Vicini (2006)

One loop real corrections available

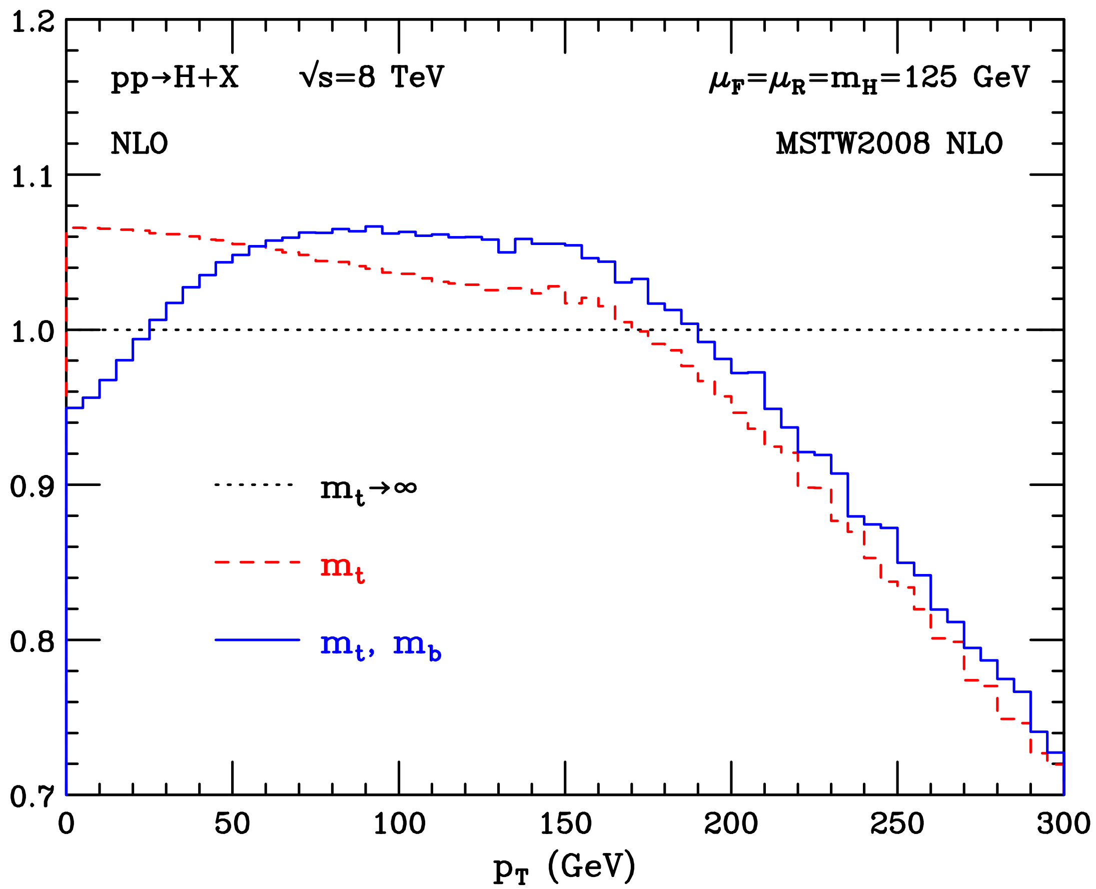
R.K.Ellis,I.Hinchliffe,M.Soldate, J. van der Bij (1988)

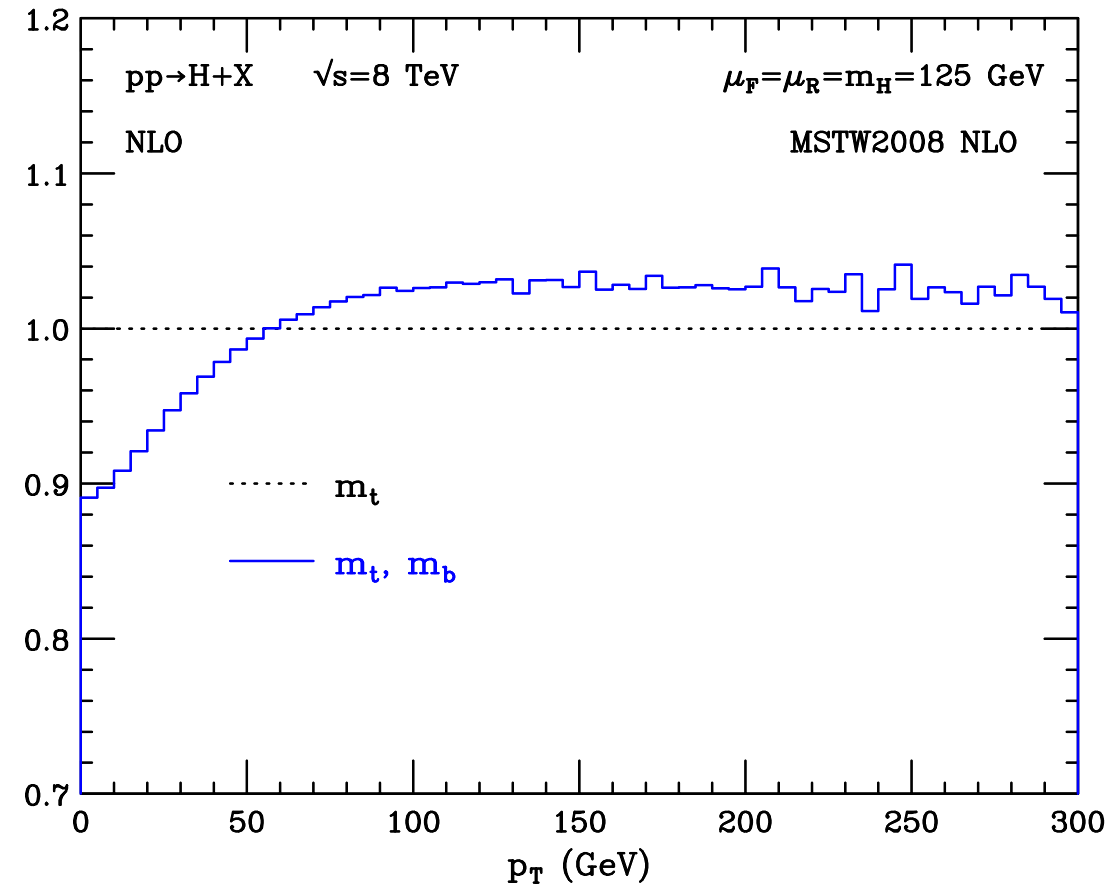
Top and bottom quark contributions exactly taken into account up to NLO
At NNLO we consider only the top-quark contribution and we rescale it with the ratio $\sigma_{LO}(m_t)/\sigma_{LO}(m_t \rightarrow \infty)$

New version of HNNLO now released !

Mass effects at fixed order

Let us look at the mass effects in the NLO p_T spectrum





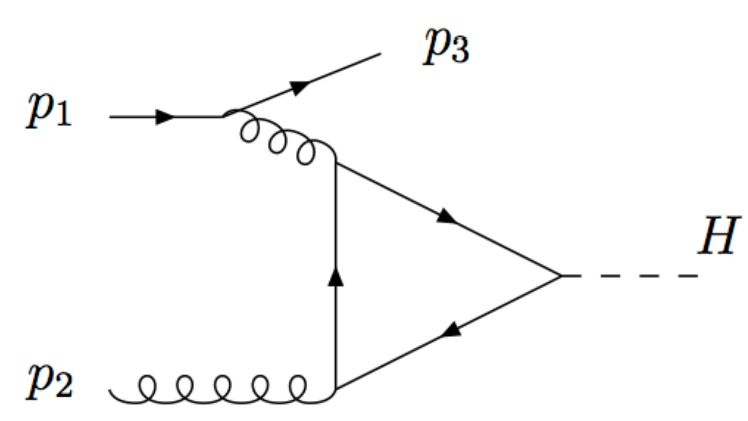
When only the top contribution is considered the shape of the spectrum in the small and intermediate p_T region is similar to the $m_t\to\infty$ result

The bottom contribution significantly distorts the spectrum in the low p_T region

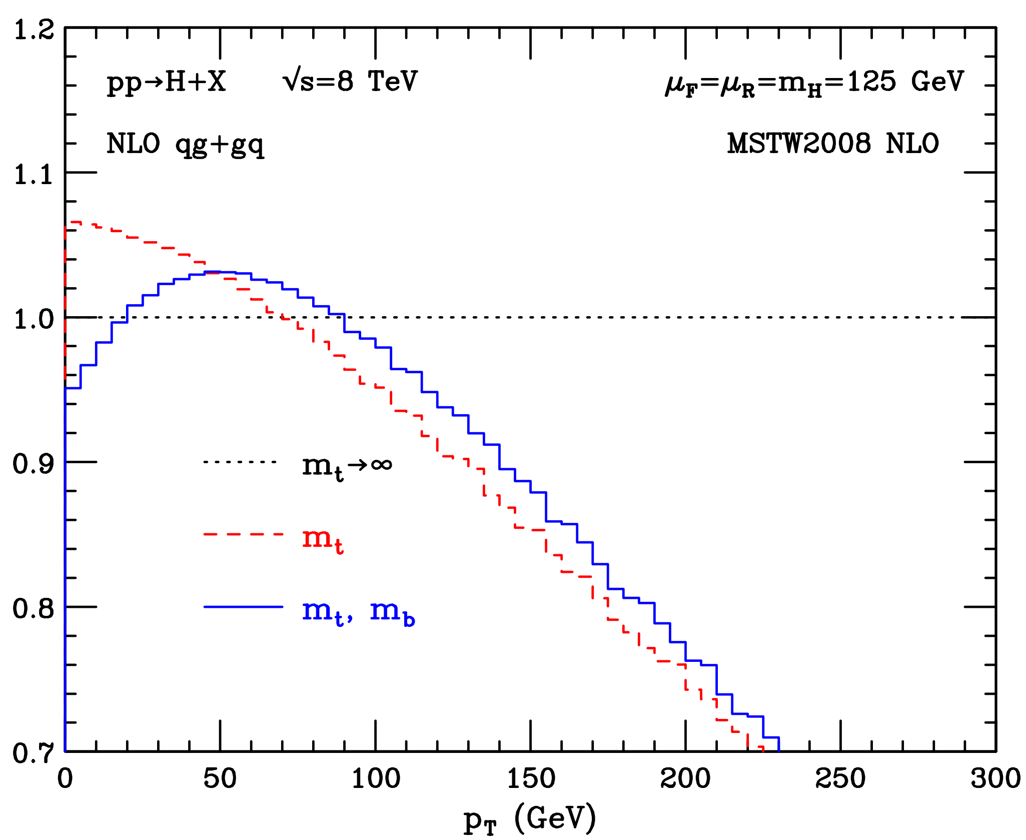
Mass effects at fixed order

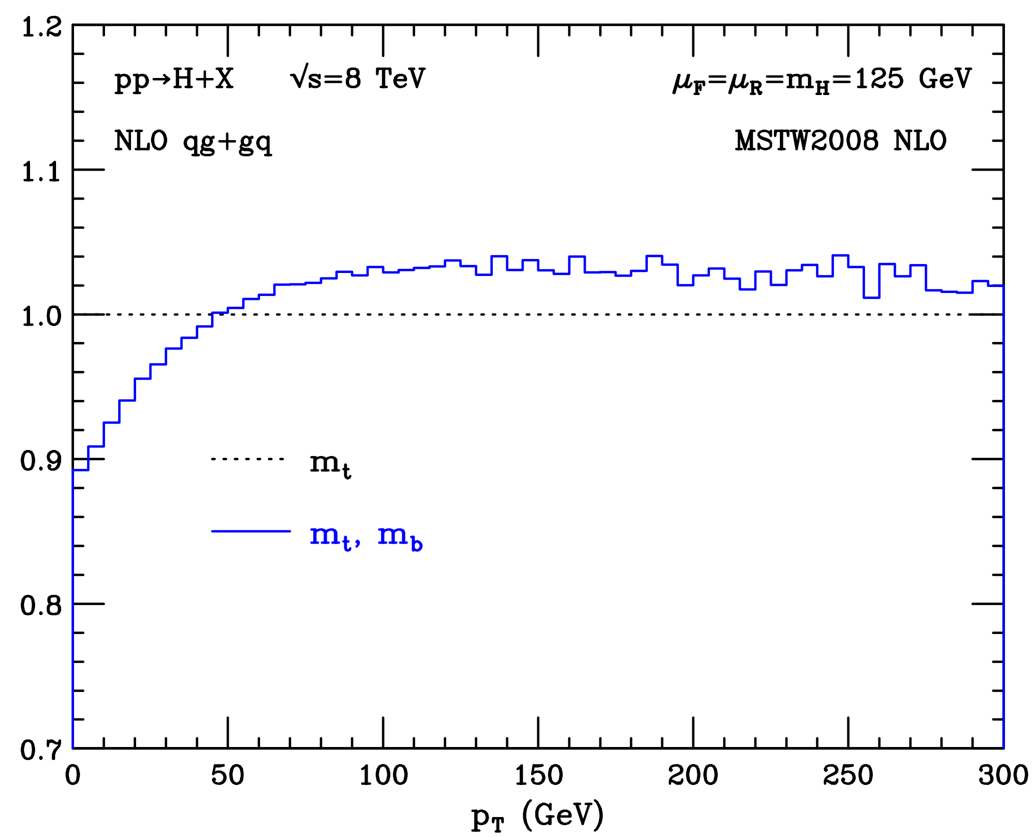
In order to understand what happens let us focus on the qg channel

We may expect that when $p_T << m_H$ the diagram should factorize naively independently on the mass of the heavy quark running in the loop



but this is not the case





Also in this channel the bottom contribution modifies the shape at small p_T

Mass effects in the resummed spectrum

H.Sargsyan, MG (2013)

Studying the analytic behavior of the QCD matrix elements we find that collinear factorization is a good approximation only when $p_T << 2m_b$

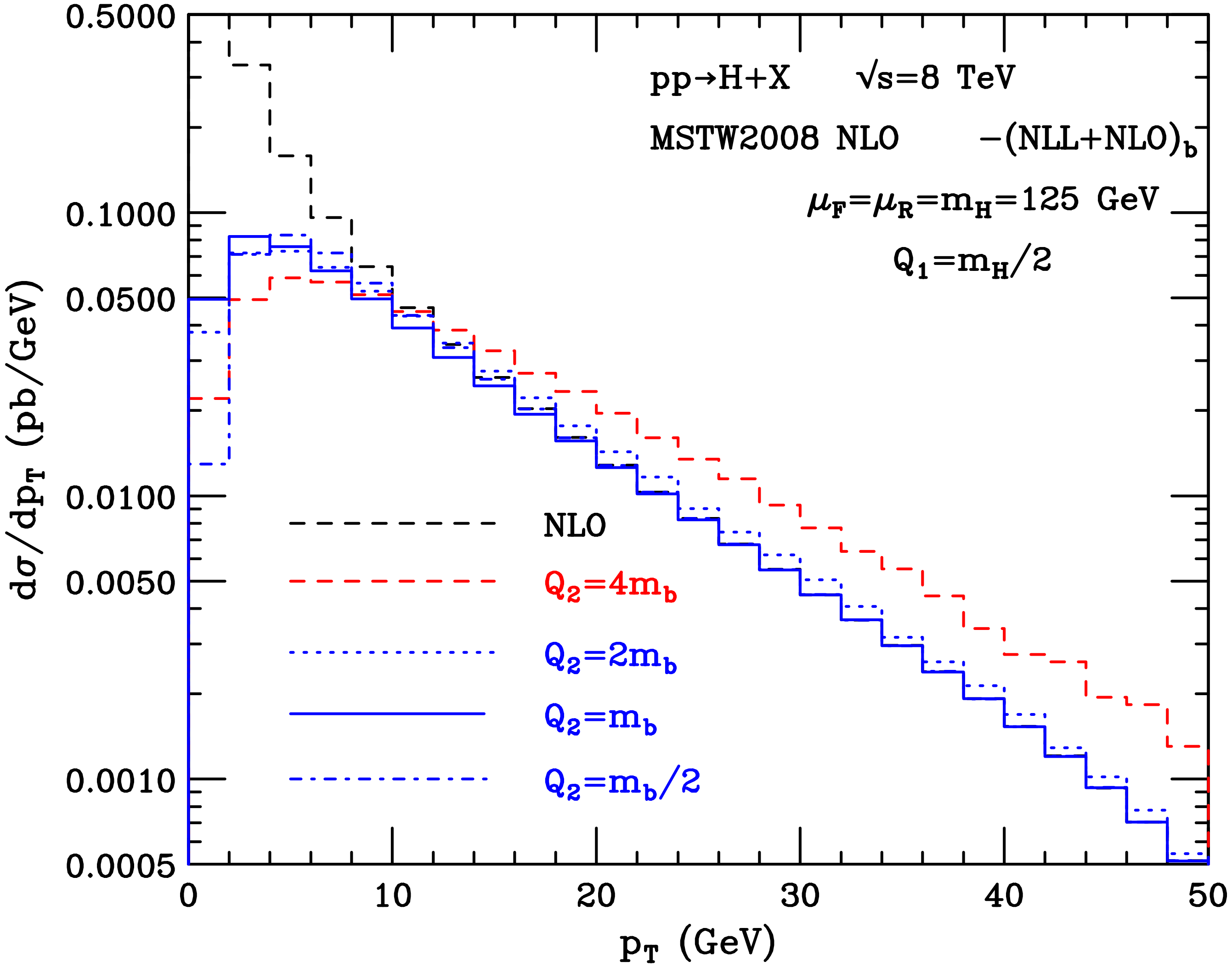
→ the standard resummation procedure cannot be straightforwardly applied to the bottom quark contribution

Our solution:

- 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
- the bottom contributions (and the top-bottom interference) are controlled by an additional resummation scale Q_2 that we choose of the order of the b-mass

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

Numerical results



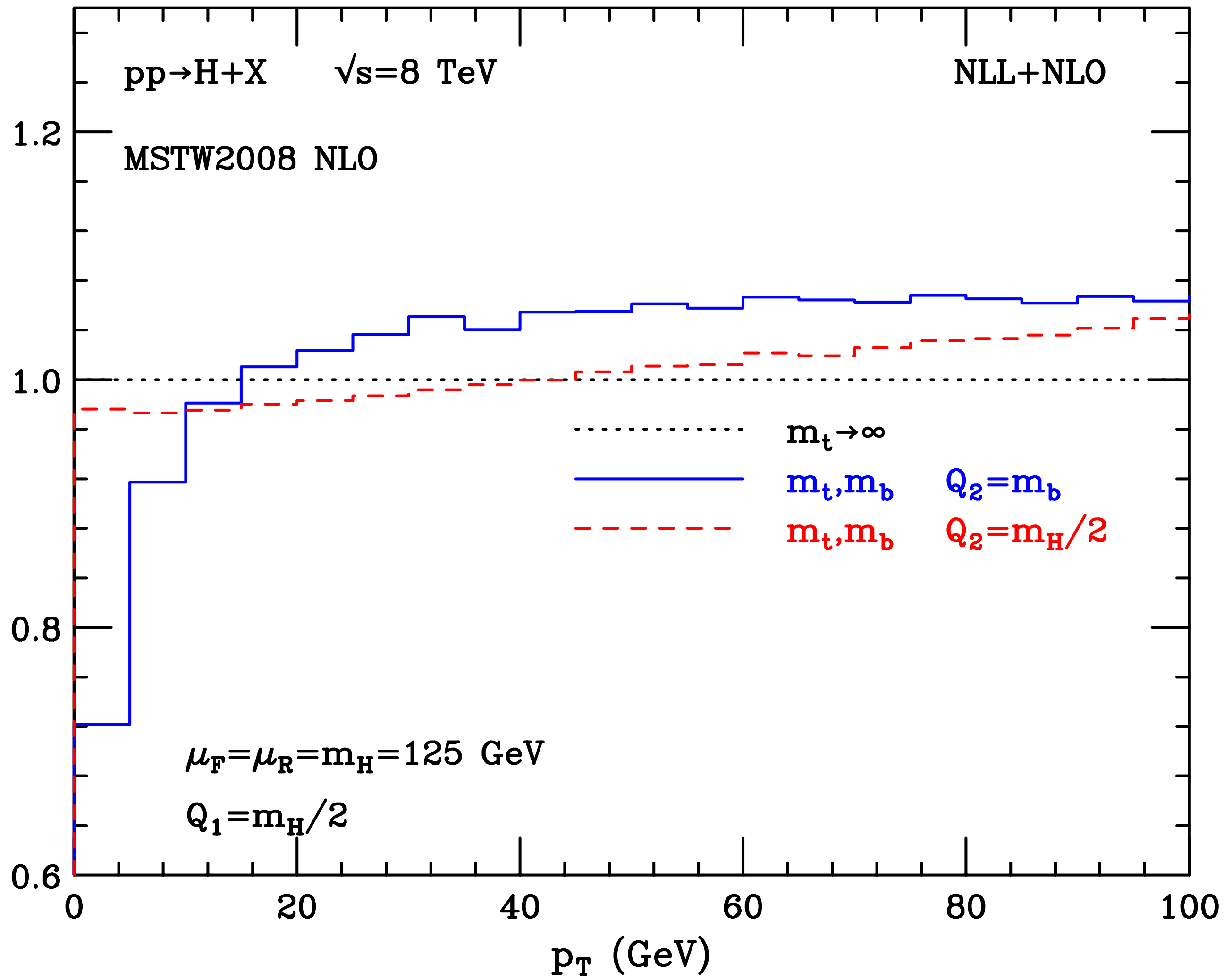
Comparison of resummed spectrum from the bottom quark with the corresponding NLO result for different scales Q_2

We see that for $Q_2=m_b/2$, m_b, $2m_b$ the fixed order is nicely reproduced in the region $p_T>10$ GeV

For $Q_2=4m_b$ instead the resummation deviates from the NLO result

We thus choose $Q_2=m_b$ as central scale and proceed with the full calculation

Numerical results



Comparison of the results obtained with $Q_2=m_b$ and $Q_2=m_H/2$

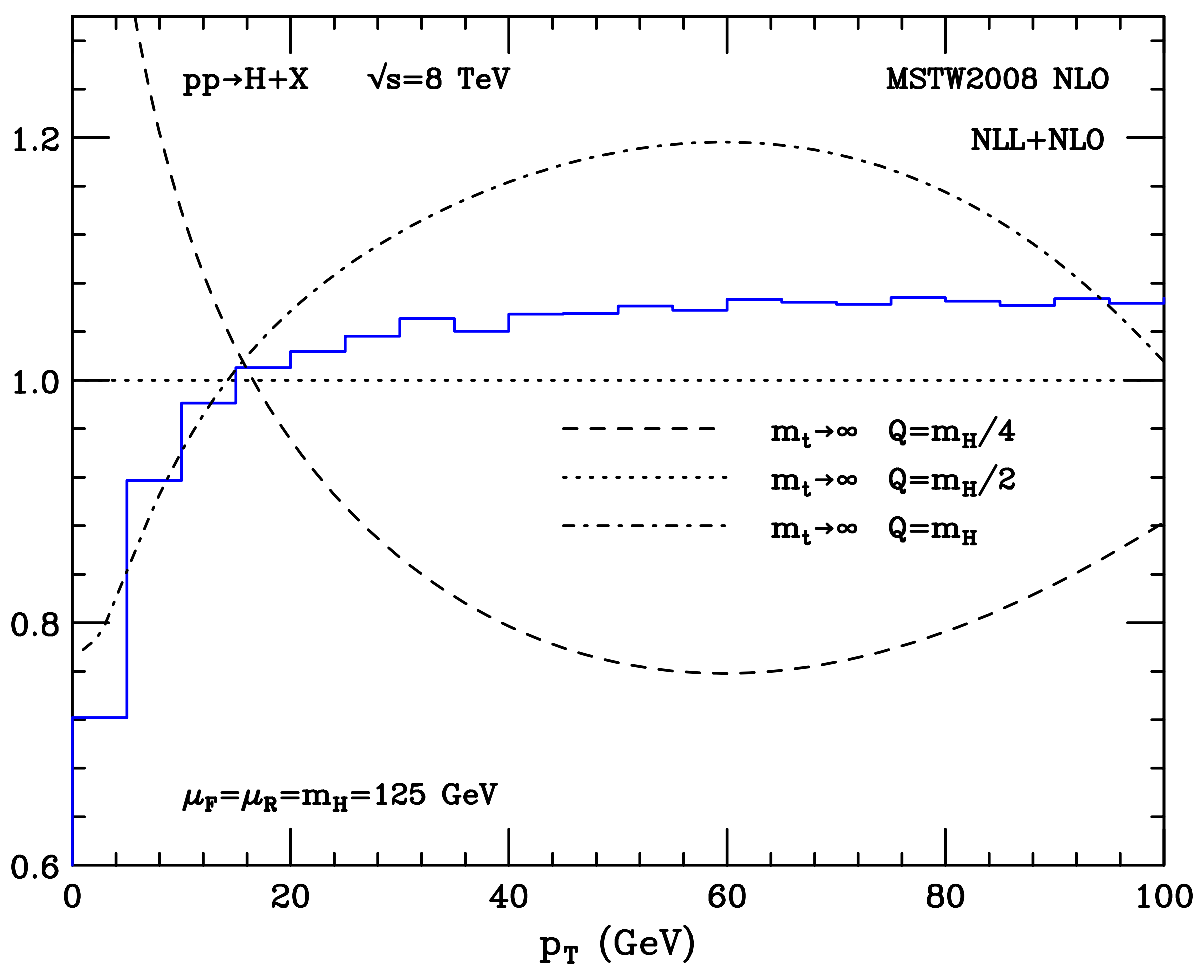
Significant differences in the low-p_T region

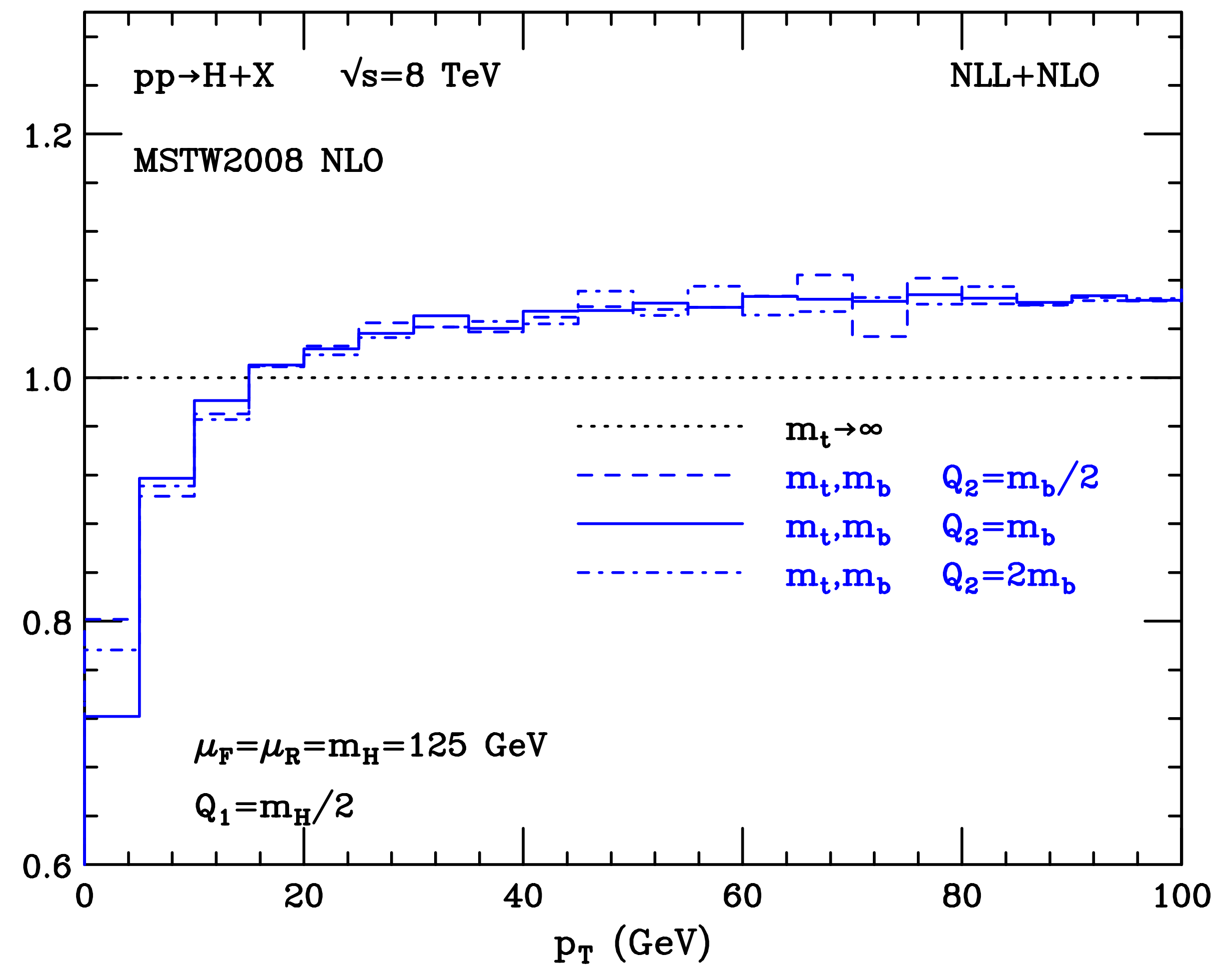
The result with $Q_2=m_H/2$ is in agreement with independent calculation by Mantler-Wiesemann (and with MC@NLO)

Our result for $Q_2=m_b$ somewhat more similar to POWHEG though the distortion is at smaller p_T

But: In order to judge the relevance of this effect we should compare with the perturbative uncertainties affecting the calculation in large-m_t limit

Numerical results

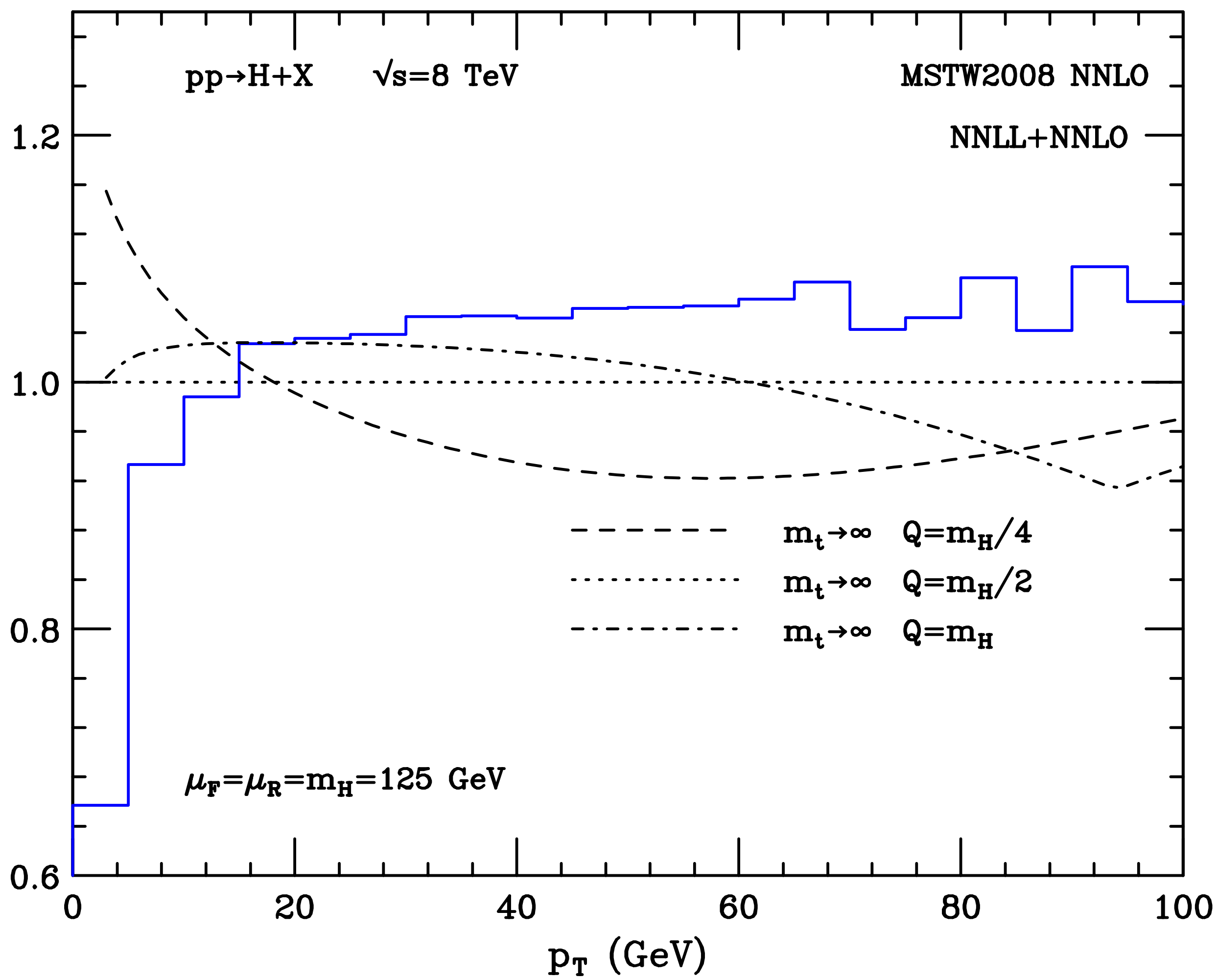


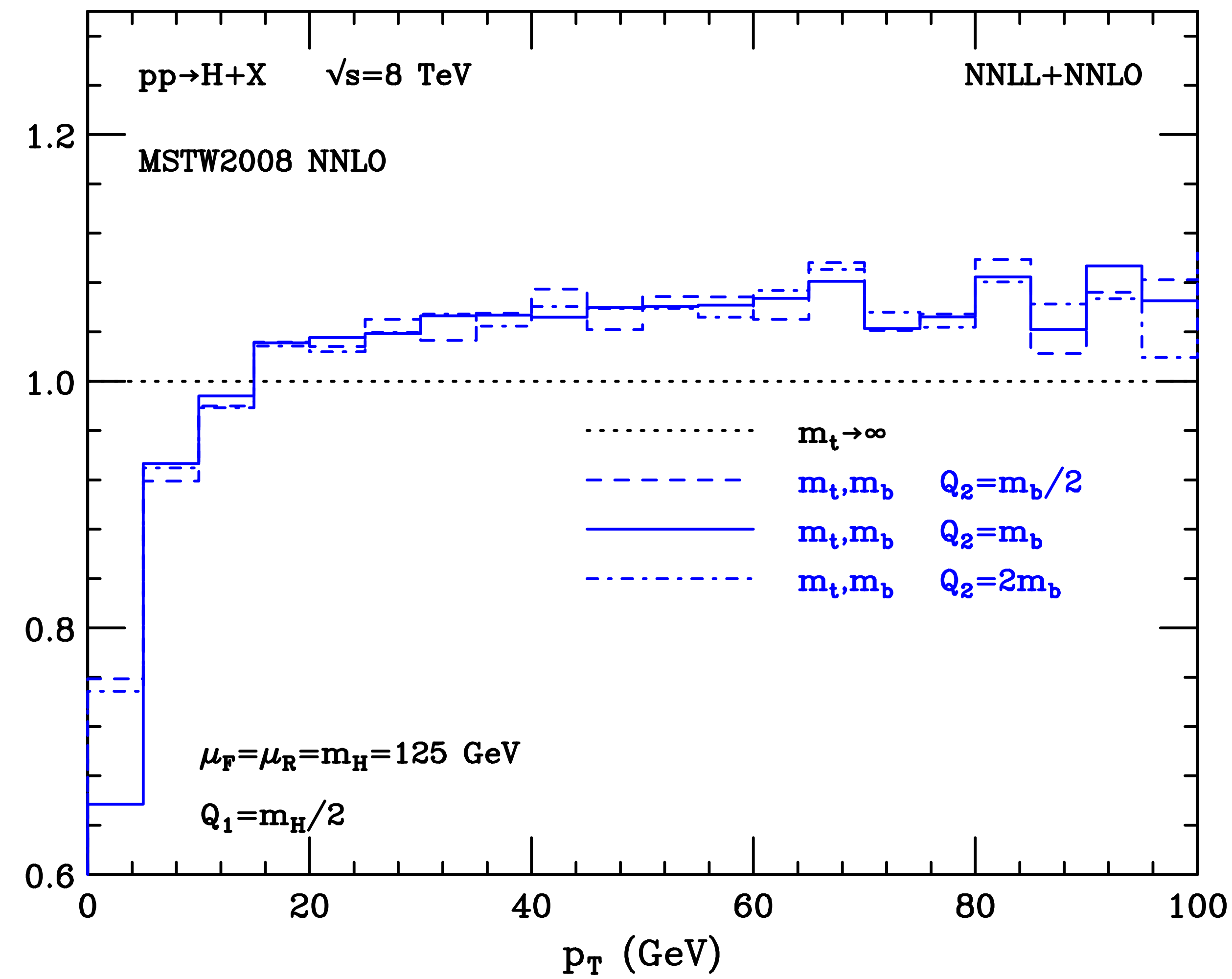


Uncertainties in the shape of the spectrum at NLL+NLO are rather large

On the contrary, our result is rather stable when Q_2 is varied around m_H

Numerical results





At NNLL+NNLO the uncertainties are smaller and the effect we find is similar to NLL+NLO

Summary

- The p_T spectrum of the Higgs boson is an important observable and is being measured by ATLAS and CMS
- HqT computes the spectrum up to NNLL+NNLO but still works in the large-m_t limit
- I have presented a new calculation of the p_T spectrum which includes the finite top and bottom quark masses at full NLL+NLO accuracy NNLL+NNLO effects are included in the large-m_t limit
- The inclusion of the exact dependence on the top mass is straightforward but the bottom quark mass introduces a third scale in the process
- The effect of the bottom-quark mass reduces the range of applicability of the transverse momentum resummation

Summary

- We deal with this problem by splitting the calculation in two parts: the top quark contribution is treated as usual, whereas the bottom contribution is treated by using a resummation scale $Q_2 = O(m_b)$

- This solution has a clear advantage: the bottom quark contribution is treated essentially at fixed order down to the scale to which the p_T resummation is really necessary

- The distortion of the spectrum induced by the bottom quark is significant and, at NNLL+NNLO, it is comparable or larger with respect to the usual perturbative uncertainties

- Our calculations are implemented in updated versions of HNNLO and HRes