The Higgs p_T spectrum in the SM and beyond

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Outline

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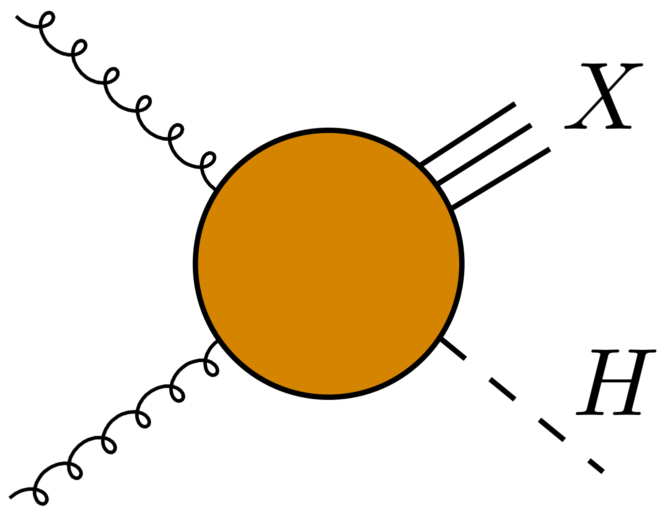
- The p_T spectrum: high-p_T and low-p_T
- Transverse momentum resummation and the HRes program
- Mass effects
- Higgs p_T and BSM effects
- Summary

Introduction



Gluon-gluon fusion is the dominant production channel of the Higgs boson at hadron colliders: enormous activity in the last 15 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

S.Marzani et al. (2008)
R.Harlander et al. (2009,2010)
M.Steinhauser et al. (2009)

Partial N^3LO and approximations

Anastasiou et al. (2014); de Florian et al. (2014)
S.Forte et al (2013, 2014)

Threshold resummations

S.Catani, D. de Florian, P. Nason, MG (2003)
M.Neubert et al. (2011)
M.Bonvini, S.Marzani (2014)

Fully exclusive NNLO calculations

→ FEHIPro, HNNLO

C.Anastasiou et al. (2005, 2009)
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

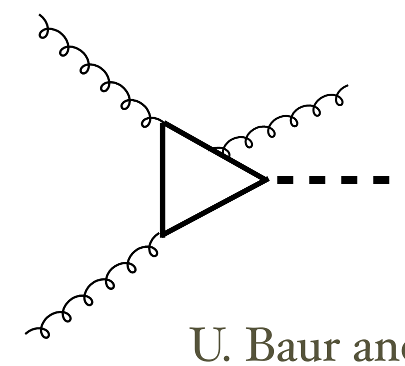
Moreover: the Higgs is a scalar → production and decay processes essentially factorised

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

The region $p_T \sim m_H$

To have $p_T \neq 0$ the Higgs boson has to recoil against at least one parton

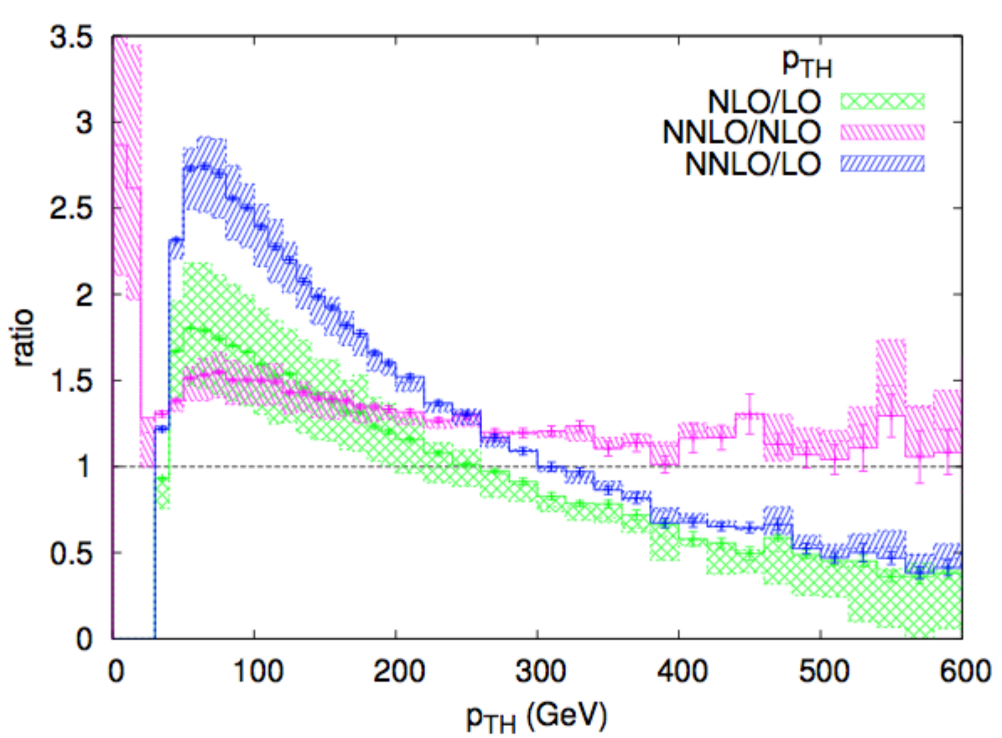
→ the LO is of relative order α_S
exact result known for many years



R.K.Ellis et al (1988);
U. Baur and E.W.N.Glover (1990)

NLO corrections are known only in the large m_{top} approximation
(part of inclusive NNLO cross section !)

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



Recently NNLO (i.e. $O(\alpha_S^5)$) contribution from the gg channel has been evaluated

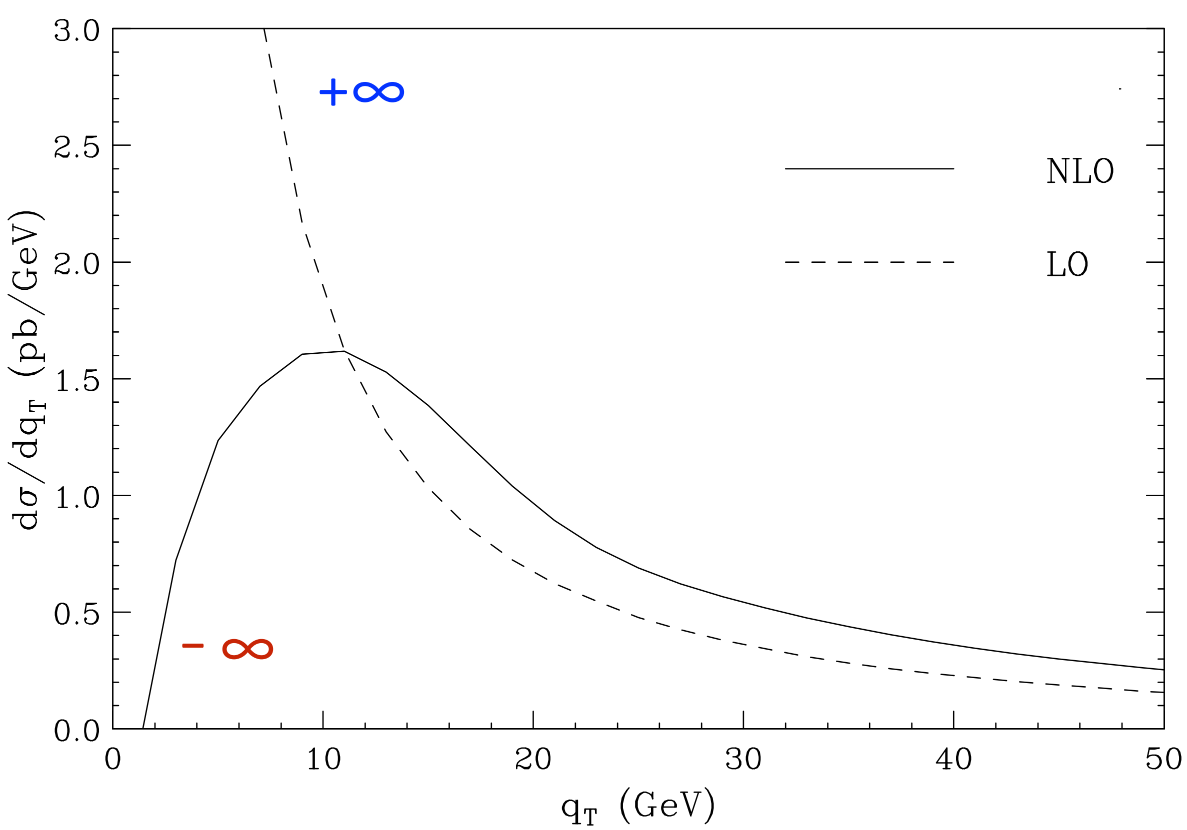
→ quantitative effect appears to be large

X. Chen, T. Gehrmann, E.W.N. Glover, M. Jaquier (2014)
(see also R.Boughezal, F.Petriello, K.Melnikov, M.Schulze (2013))

The region $p_T << m_H$

In this region 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



LO: $\dfrac{d\sigma}{dp_T} \to +\infty$ as $p_T \to 0$

NLO: $\dfrac{d\sigma}{dp_T} \to -\infty$ 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:

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

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

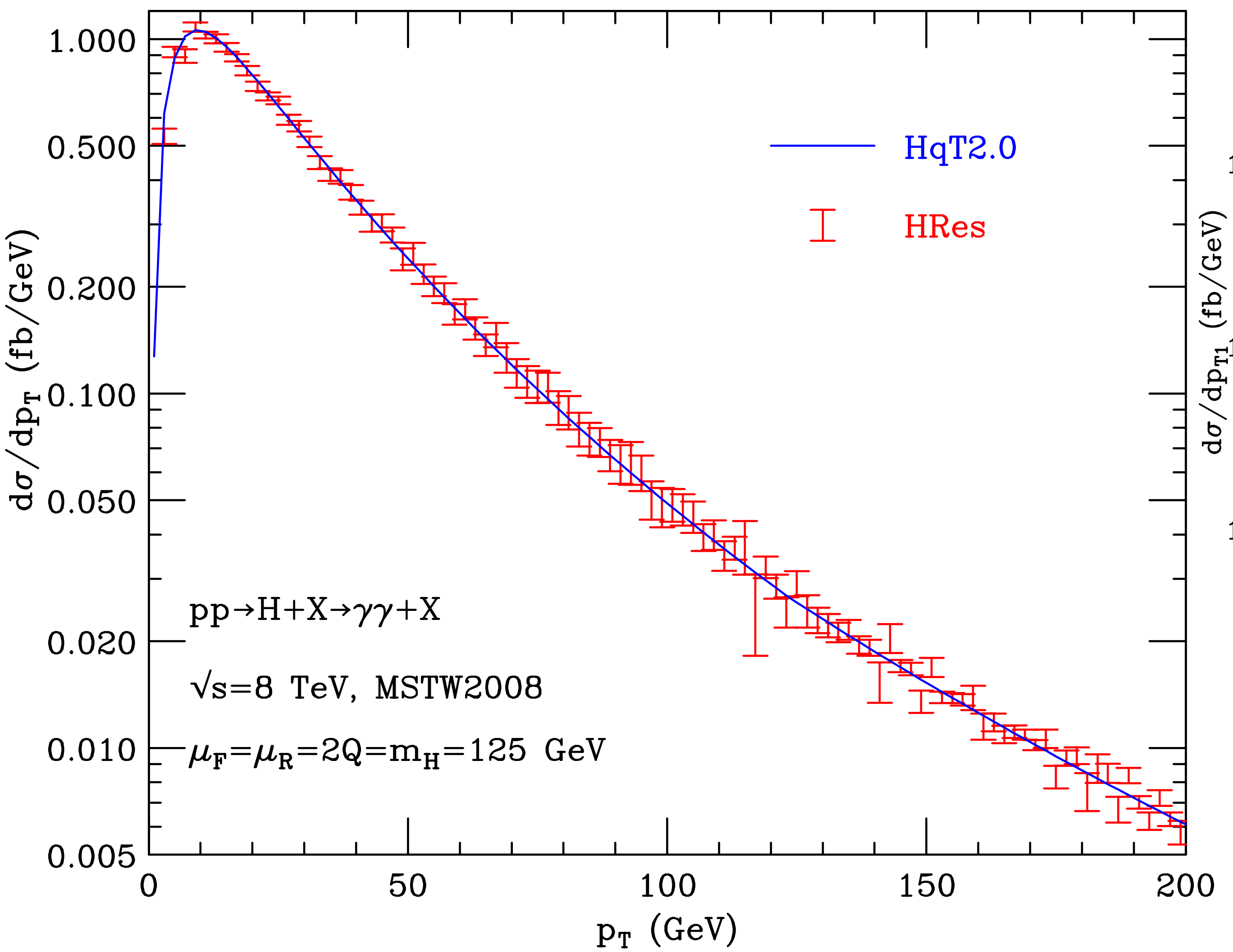
At NLL+NLO the accuracy is roughly the same as in MC@NLO and POWHEG

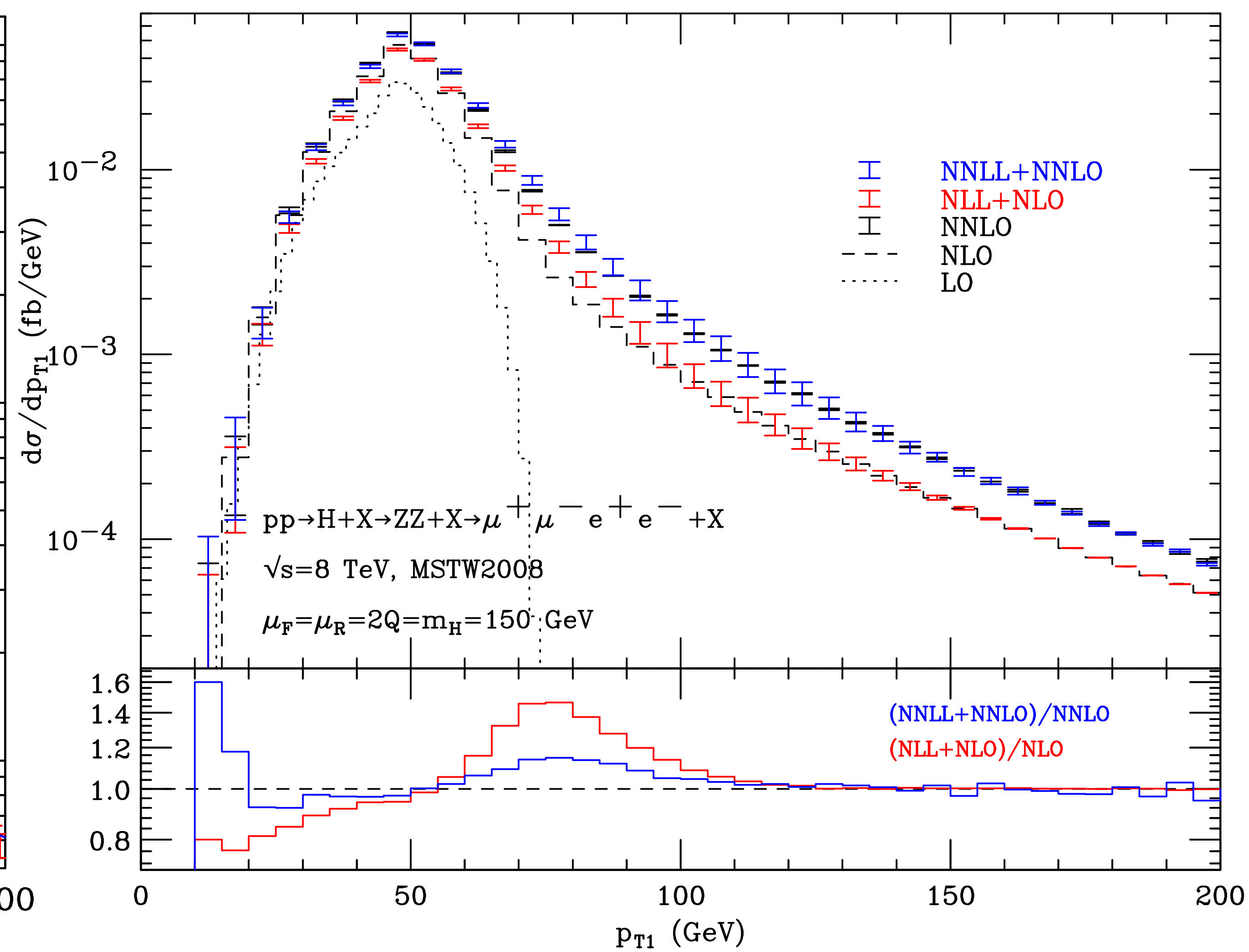
HRes

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 ➡ "Higgs event generator"

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

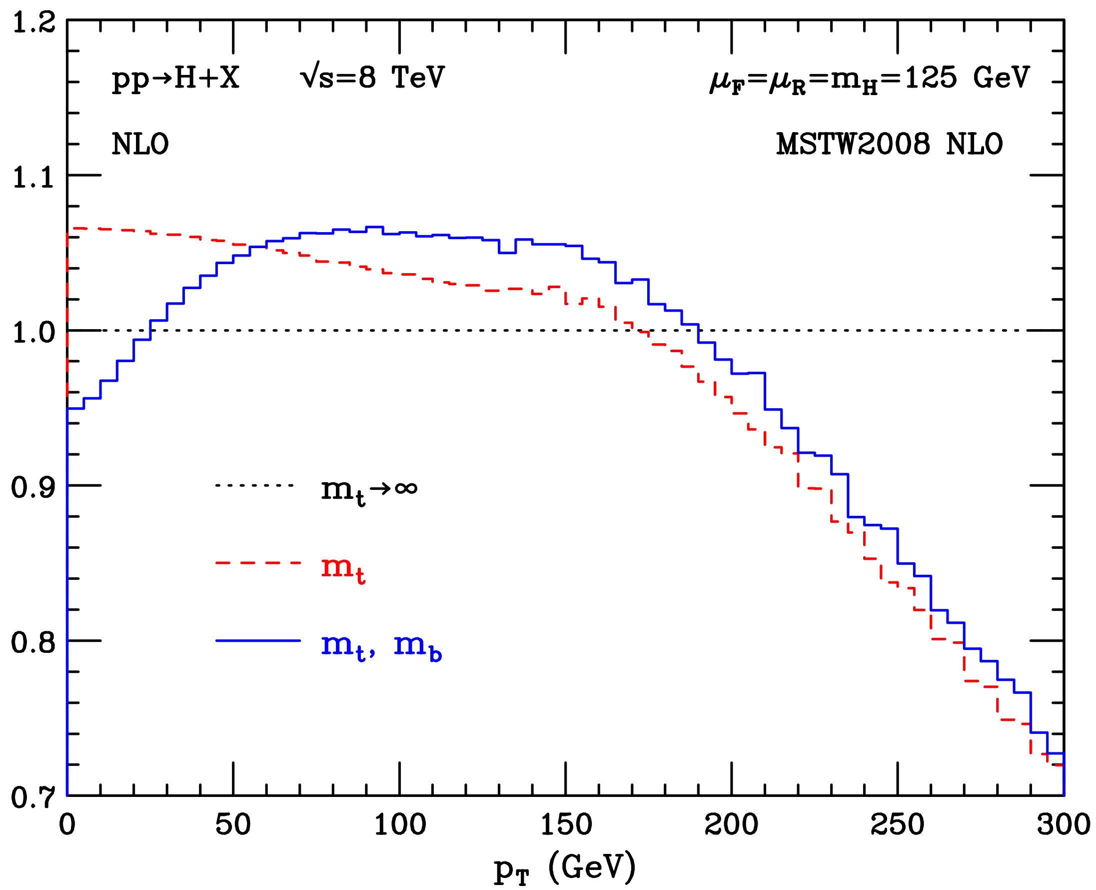
R.K.Ellis,I.Hinchliffe,M.Soldate, J. van der Bij (1988)

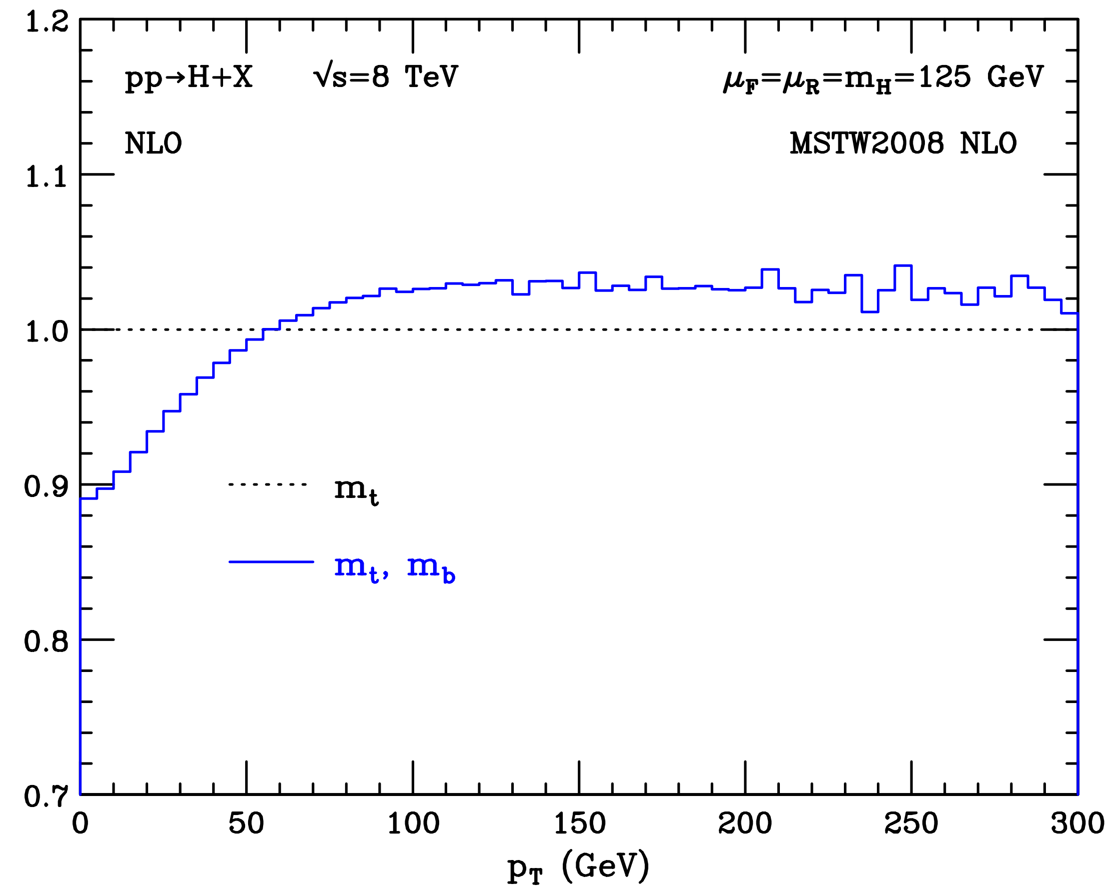
Top and bottom quark contributions exactly taken into account up to NLO
At NNLO we consider only the top-quark contribution and we rescale it with the ratio $\sigma_{LO}(m_t)/\sigma_{LO}(m_t \to \infty)$

→ HNNLO now includes NLO mass effects

Mass effects at fixed order

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





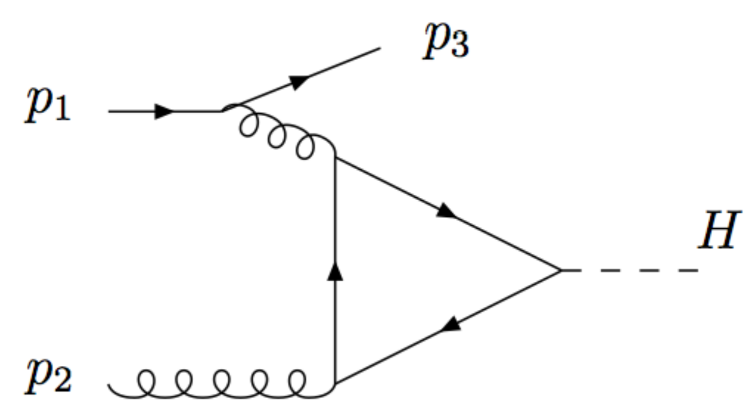
When only the top contribution is considered the shape of the spectrum in the small and intermediate p_T region is similar to the $m_t \to \infty$ result

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

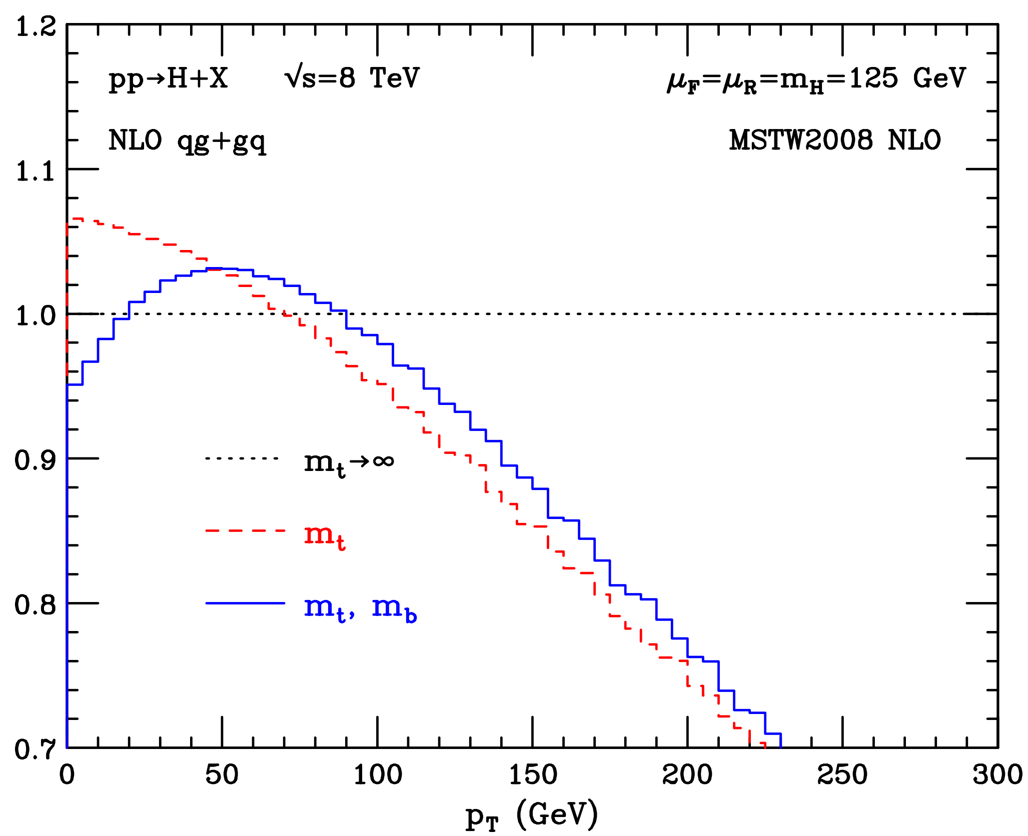
Mass effects at fixed order

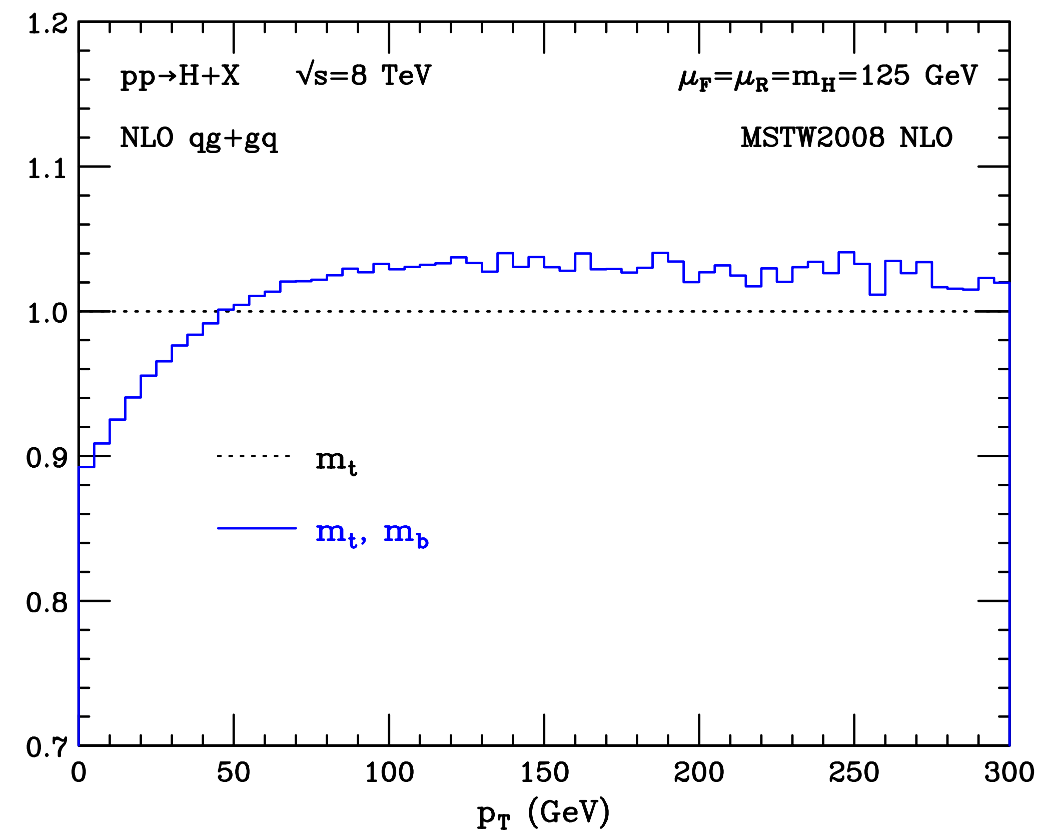
In order to understand what happens let us focus on the qg channel

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 $p_T << 2m_b$

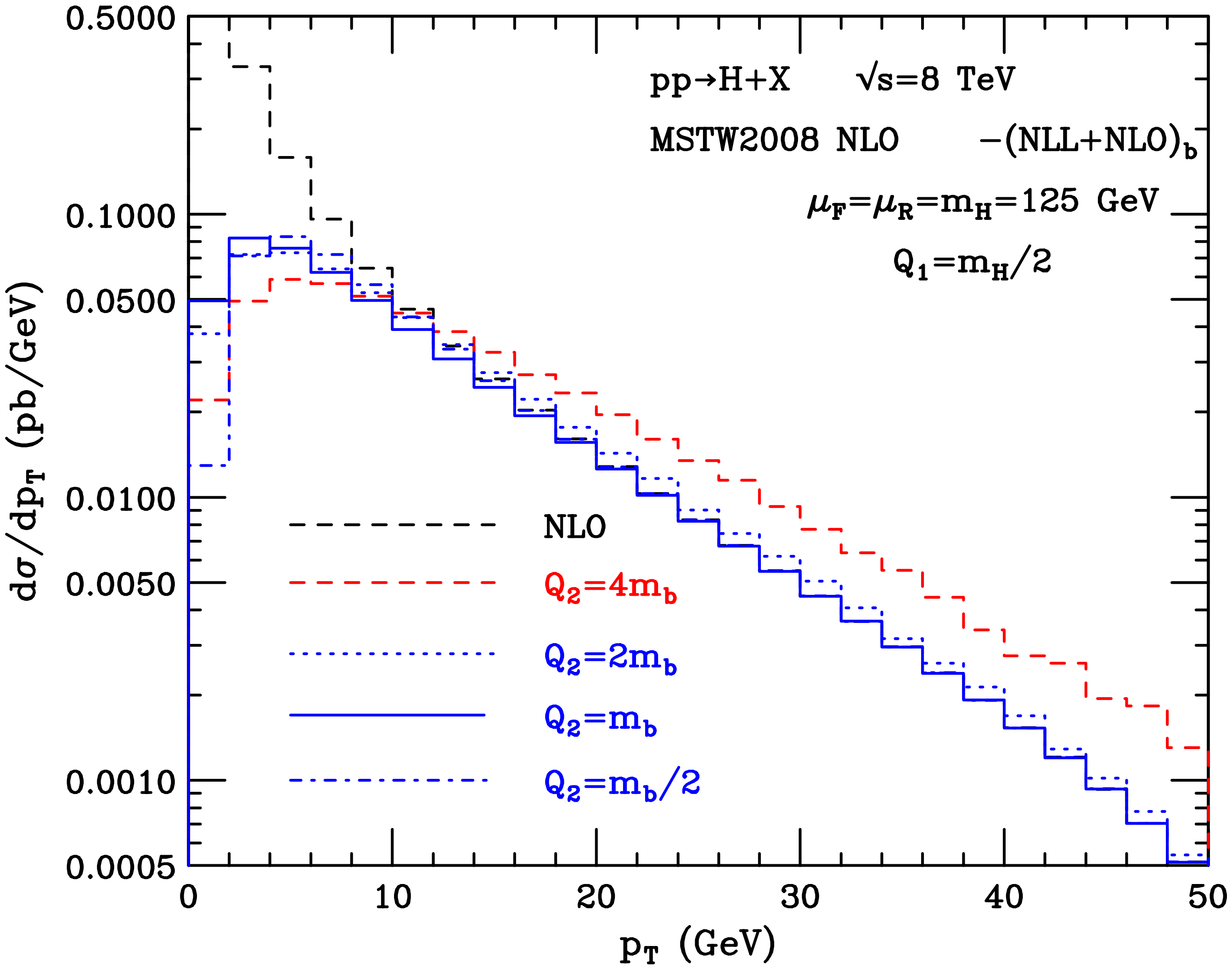
→ the standard resummation procedure cannot be straightforwardly applied to the bottom quark contribution

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)

Mass effects in the resummed spectrum



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

Mass effects in the resummed spectrum

Recently the choice of the central value and range of the second resummation scale has been the subject of discussion

It has been argued that the factorisation breaking terms are small and could be treated as a finite remainder

A.Banfi, P.F.Monni, G.Zanderighi (2013)

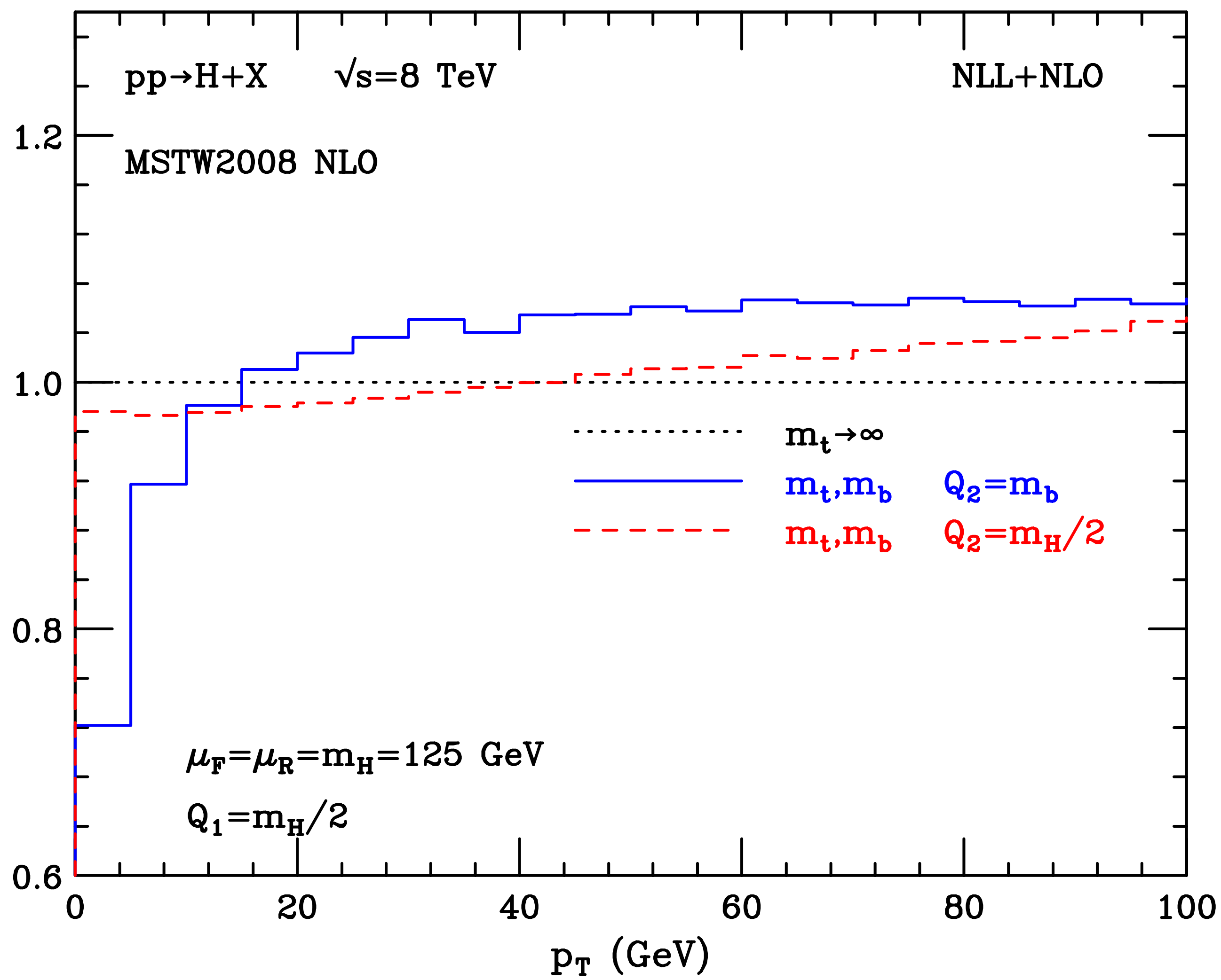
This point of view has been recently taken by Harlander et al. who suggest to choose Q_2 so as to let the resummed spectrum agree (with 100%) with the fixed order at $p_T \sim m_H$

R.Harlander, R.Mantler,M.Wiesemann (2014)

This is to be contrasted with our choice to carry our this comparison in the intermediate region

In this way one is lead to consider values of the second resummation scale Q_2 larger than what suggested in our analysis (but still smaller than Q_1)

Numerical results



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

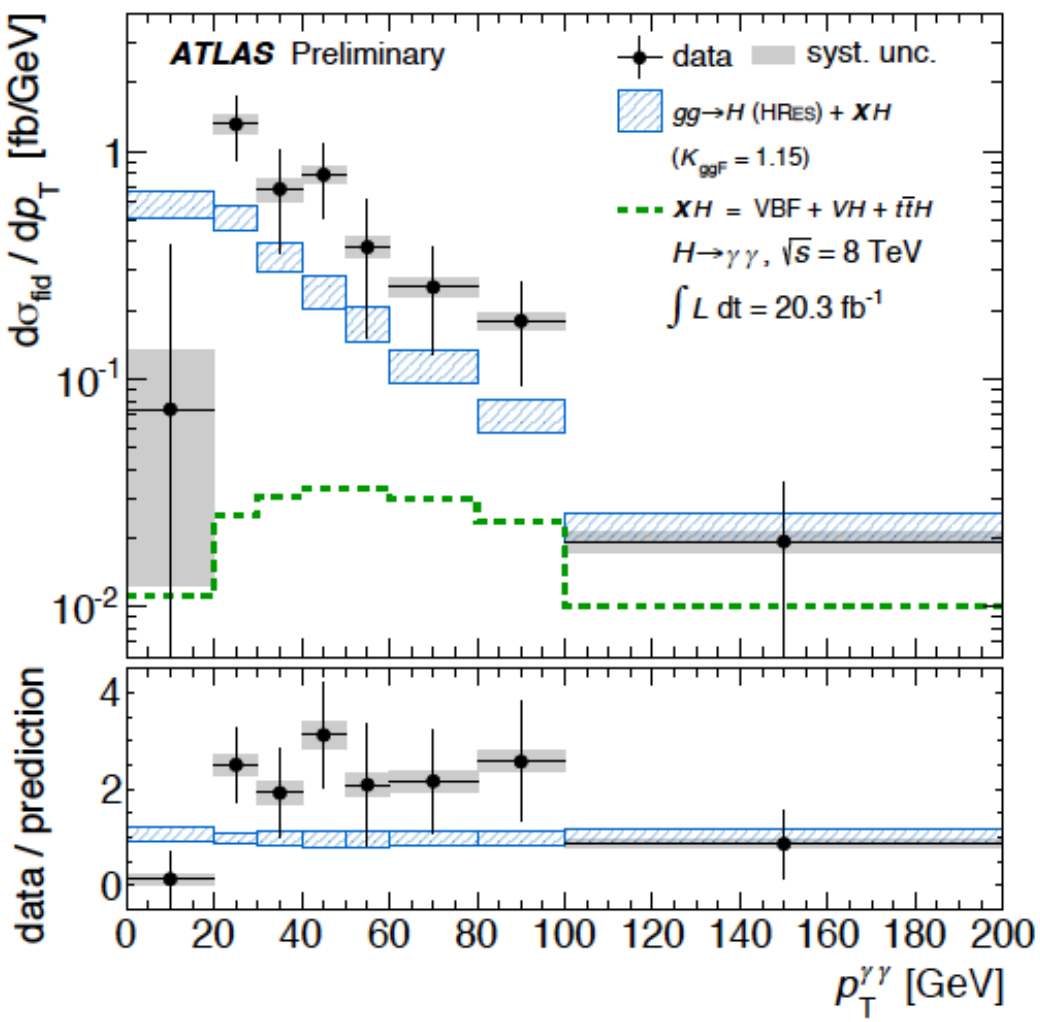
Significant differences in the low-p_T region

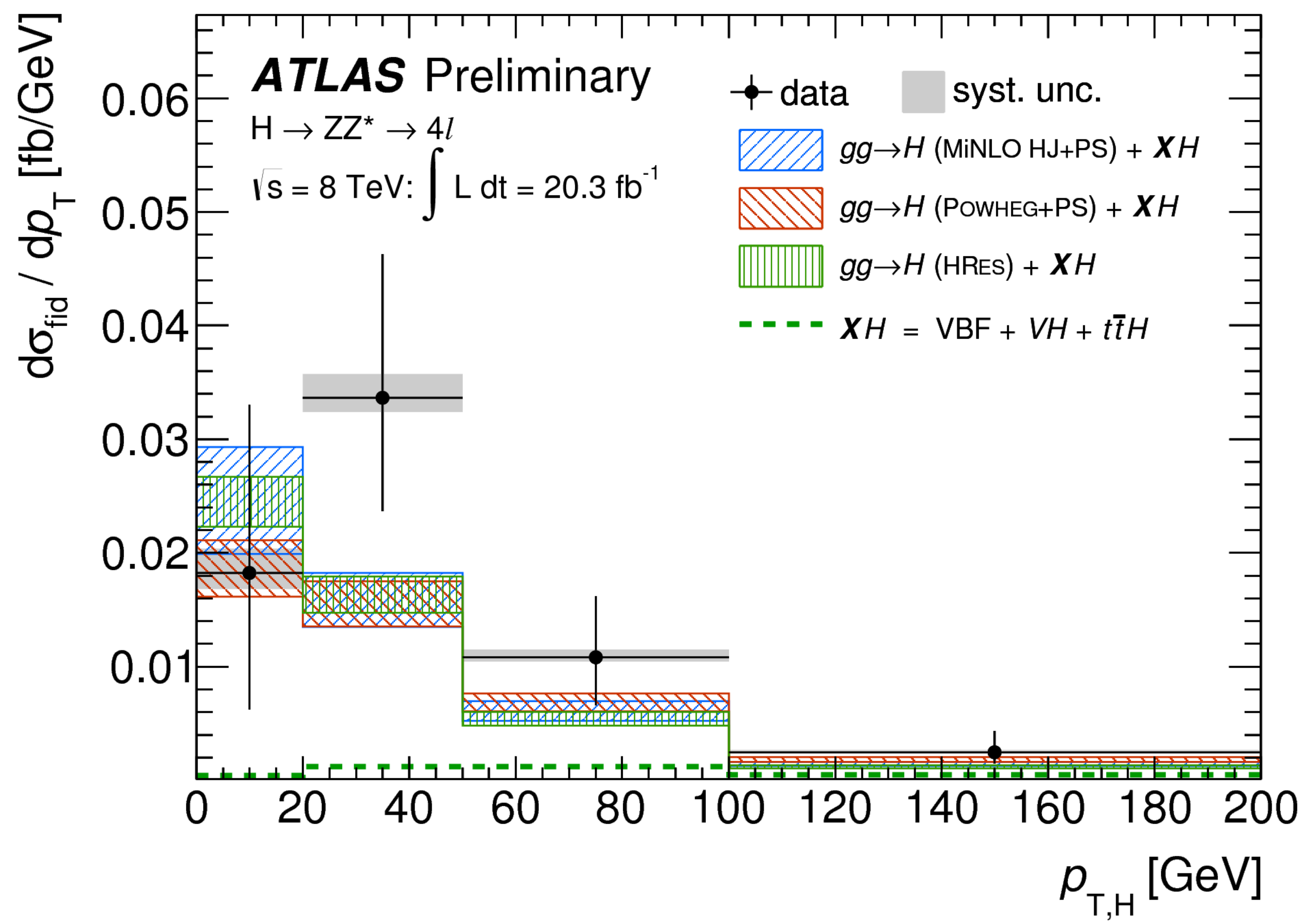
The result with $Q_2=m_H/2$ is in agreement with independent calculation by Mantler-Wiesemann (and with MC@NLO)

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 NLL+NLO calculation (which are large)

The first data





ATLAS data seem to suggest a harder spectrum (but still very large uncertainties !)

Higgs p_T and BSM

Modifications of the Higgs couplings to gluons and the top quark can be parametrised as

$$\mathcal{L} = -c_t \frac{m_{top}}{v} \bar{\psi}\psi + \frac{\alpha_S}{12\pi} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu} \qquad \text{SM:} \quad c_t = 1 \qquad c_g = 0$$

neglecting CP violation

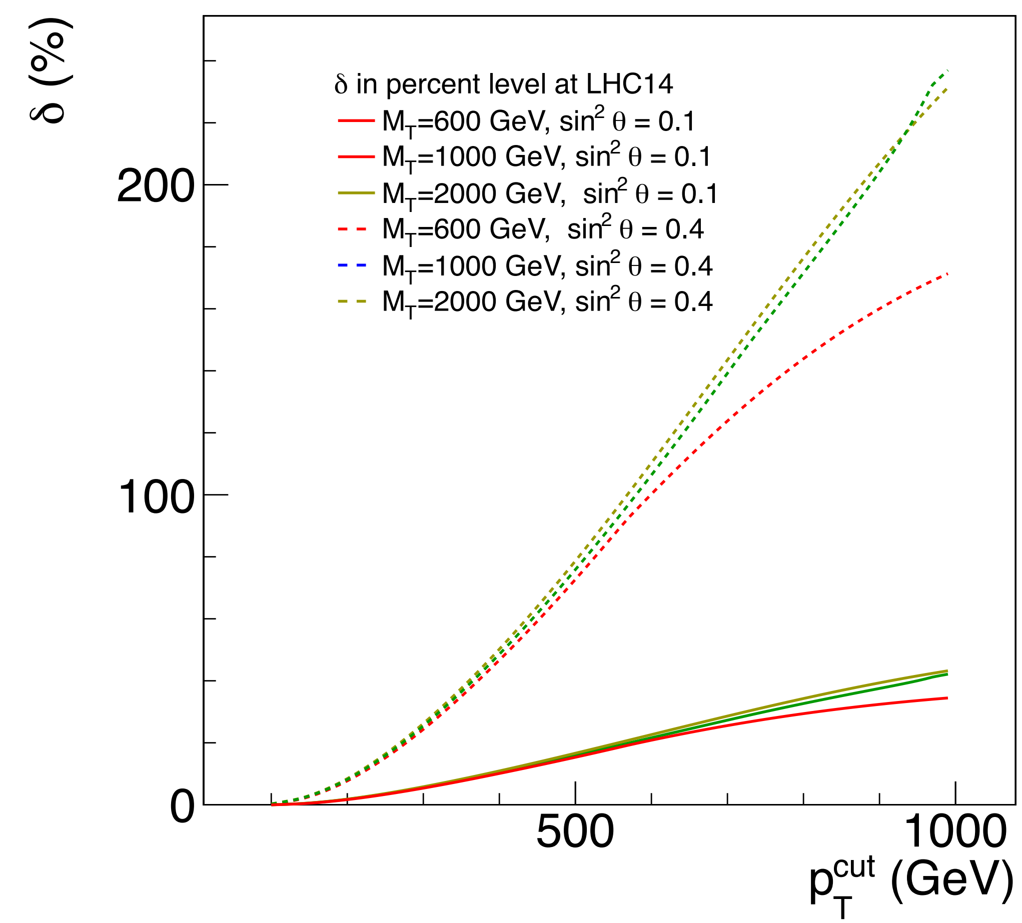
$$\sigma_H \sim |c_t + c_g|^2 \, \sigma_H^{SM}$$

➡ not possible to disentangle c_t and c_g in the inclusive rate

Direct access to top Yukawa coupling is offered by tth production but low sensitivity

Looking at high-p_T events allows us to break this degeneracy

Relative effect of top partners on high-p_T cross section can be very large



A.Banfi, A.Martin, V.Sanz (2013)

Higgs p_T and BSM

However one is forced to look at the tail of the distribution where few events are expected

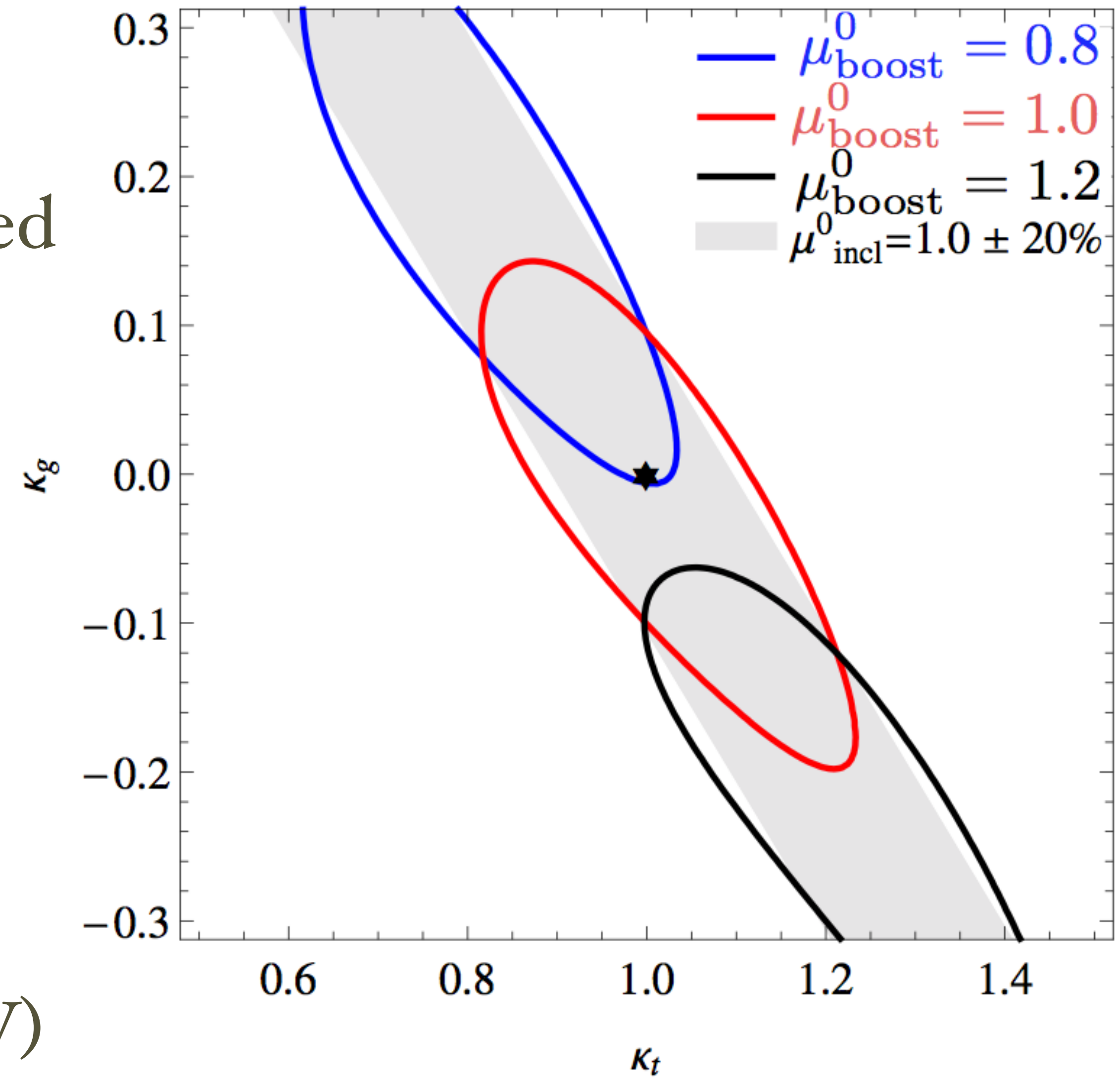
Small rate: need to focus on high BR decays

Recent study by Grojean et al. in $H \to \tau\tau$

Assume high luminosity LHC at 14 TeV with 3 ab^{-1} and 10% systematics

Consider ratio $\sigma(p_T>650\ \mathrm{GeV})/\sigma(p_T>150\ \mathrm{GeV})$ and include NLO K-factors in the EFT

Even if the inclusive rate shows no deviation a 20% deviation of the tth coupling can be resolved



C.Grojean et al. (2013)

see also Azatov, Paul (2013)
S.Dawson,I.Lewis,M.Zeng (2014)

Effects in the MSSM → talk by A.Vicini

Summary

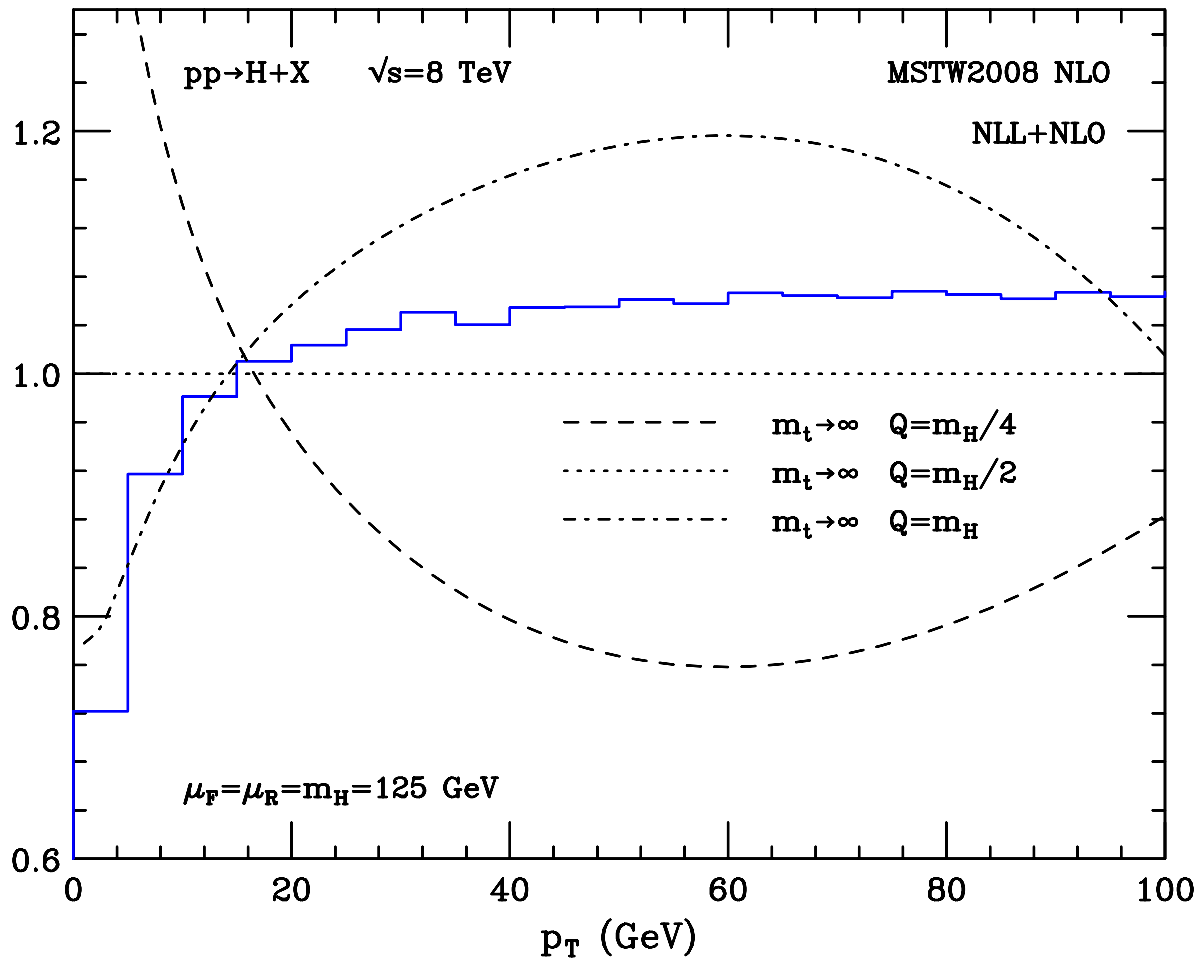
- The p_T spectrum of the Higgs boson is an important observable and is being measured by ATLAS and CMS
- HqT computes the spectrum up to NNLL+NNLO but still works in the large-m_{top} limit
- HRes includes the finite top and bottom quark masses at full NLL+NLO accuracy NNLL+NNLO effects are included in the large-m_{top} 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 (three-scale problem)

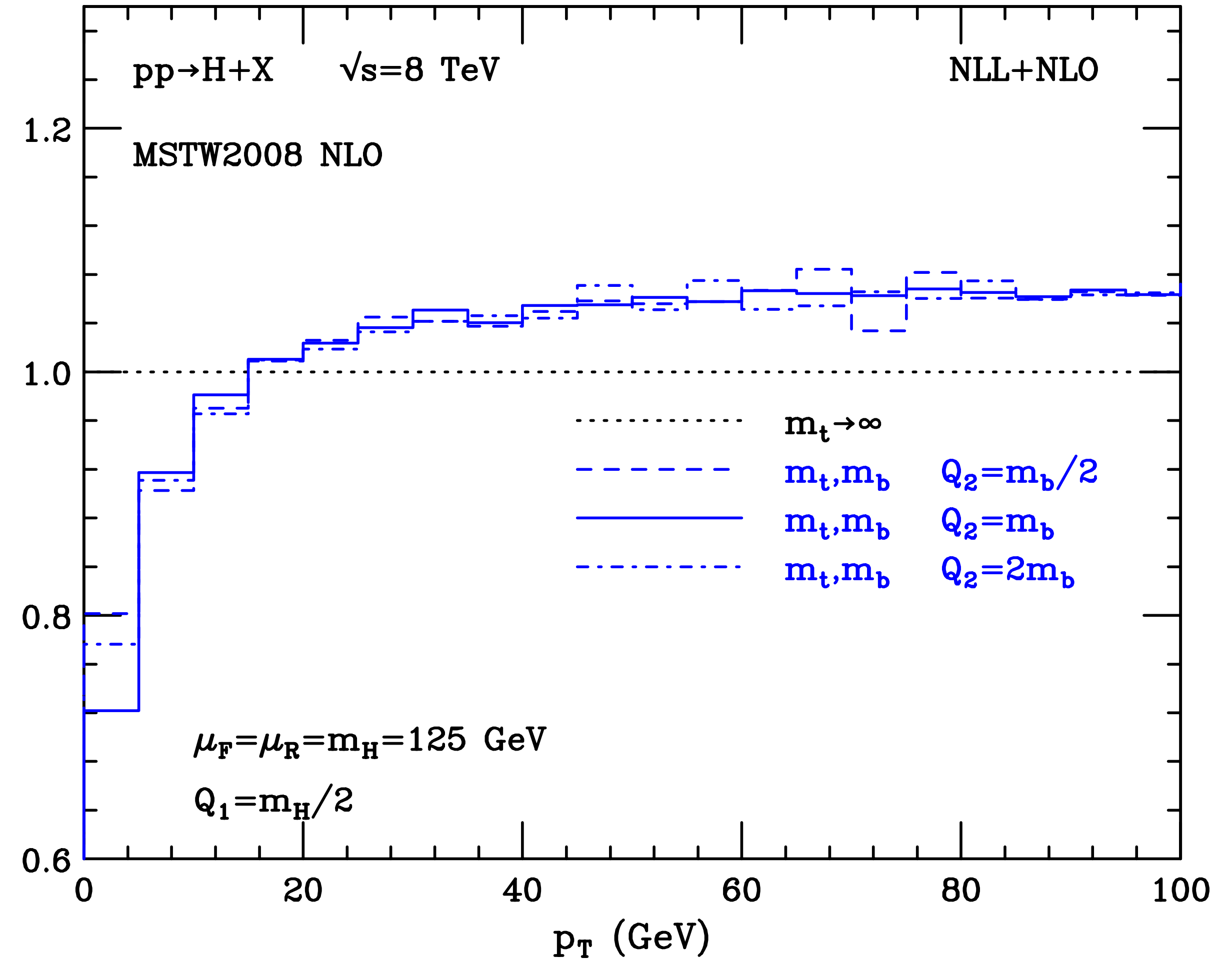
Summary

- 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
- First ATLAS data show a spectrum which is significantly harder than the SM prediction, though still with very large uncertainties
- High-p_T Higgs events offer the possibility to explore BSM scenarios in which large deviations appear that are not visible in the inclusive rate
- The case of models with top partners is a clear example

Backup

Numerical results

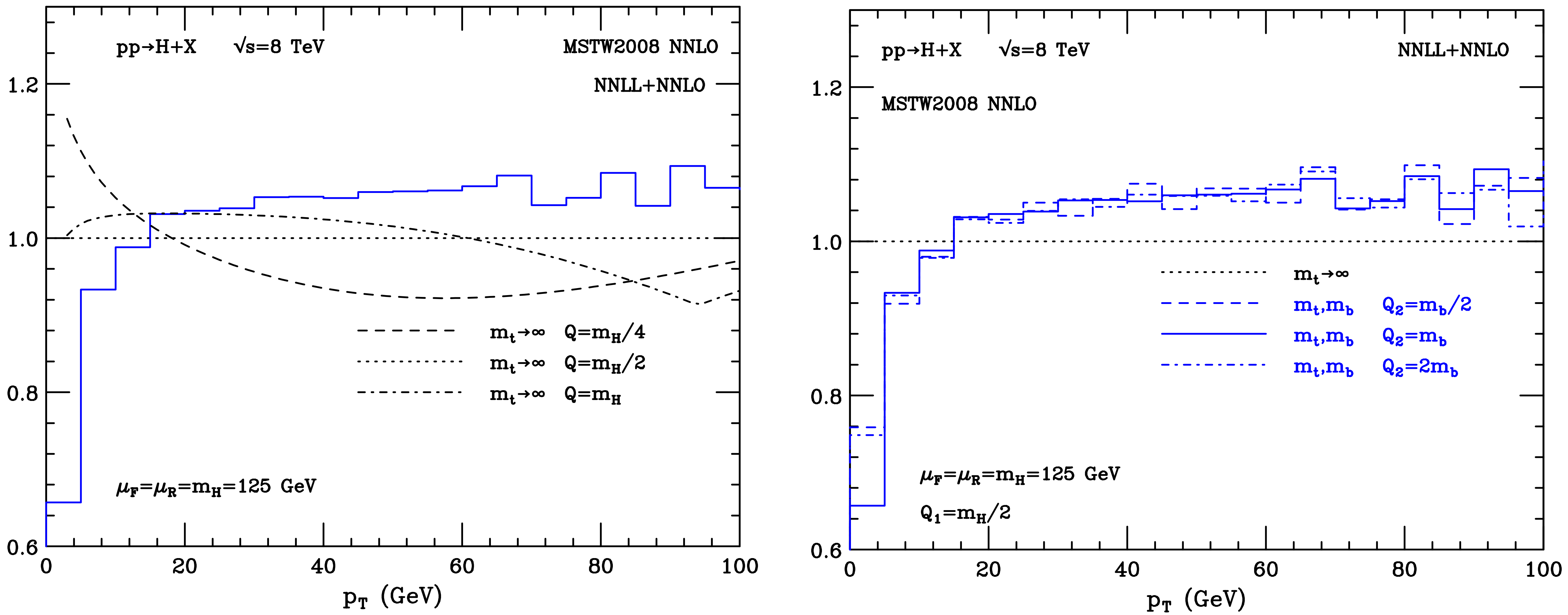




Uncertainties in the shape of the spectrum at NLL+NLO are rather large

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

Numerical results



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