SOFT-GLUON RESUMMATION FOR HIGGS PRODUCTION AT THE LHC

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Loop and Legs 2004

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Outline

- Inclusive cross section for $gg \to H$
  - QCD cross section at NNLO
  - Soft gluon resummation
  - Residual theoretical uncertainty
- Transverse momentum distribution
  - NNLL+NLO results

$gg \to H$ at NNLO

NNLO corrections computed in the large-m_{top} approximation

We can identify three kinds of contributions as $z = M_H^2/\hat{s} \to 1$

- Soft and virtual (SV) contributions: dominant as $z \to 1$

S. Catani, D. De Florian, MG (2001)
R.Harlander, W.B. Kilgore (2001)

- Purely collinear contributions: next-to-dominant as $z \to 1$

M.Kramer, E. Laenen, M. Spira (1998)

- Hard effects: finite as $z \to 1$

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

The bulk of the effects is given by SV(C) contributions

Hard effects are only about 2% at the LHC and 4% at the Tevatron

→ This is reassuring because these are the effects that are most sensitive to the heavy quark-loop

Soft gluon resummation

S. Catani, D. De Florian, P. Nason, MG (2003)

The inclusive cross section is dominated by soft emission
Multiple soft gluon emission beyond NNLO can be important

In N space the large logs appear as $\alpha_S^n \ln^{2n} N$

They can be resummed to all orders:

G. Sterman (1987)
S.Catani, L.Trentadue (1989)
S.Catani, M. Mangano, P. Nason, L.Trentadue (1996)

$$G_{gg\to H,N}(\alpha_S) = C(\alpha_S) \exp\left\{ \ln N g_1(\beta_0\alpha_S \ln N) + g_2(\beta_0\alpha_S \ln N) + \alpha_S\, g_3(\beta_0\alpha_S \ln N) + \dots \right\}$$

The functions g_1, g_2, g_3 control LL, NLL, NNLL contributions

At NNLL three new coefficients appear:

- $D^{(2)}, C^{(2)}$ extracted from NNLO calculation
- $A^{(3)}$ known numerically (now also analytically !)

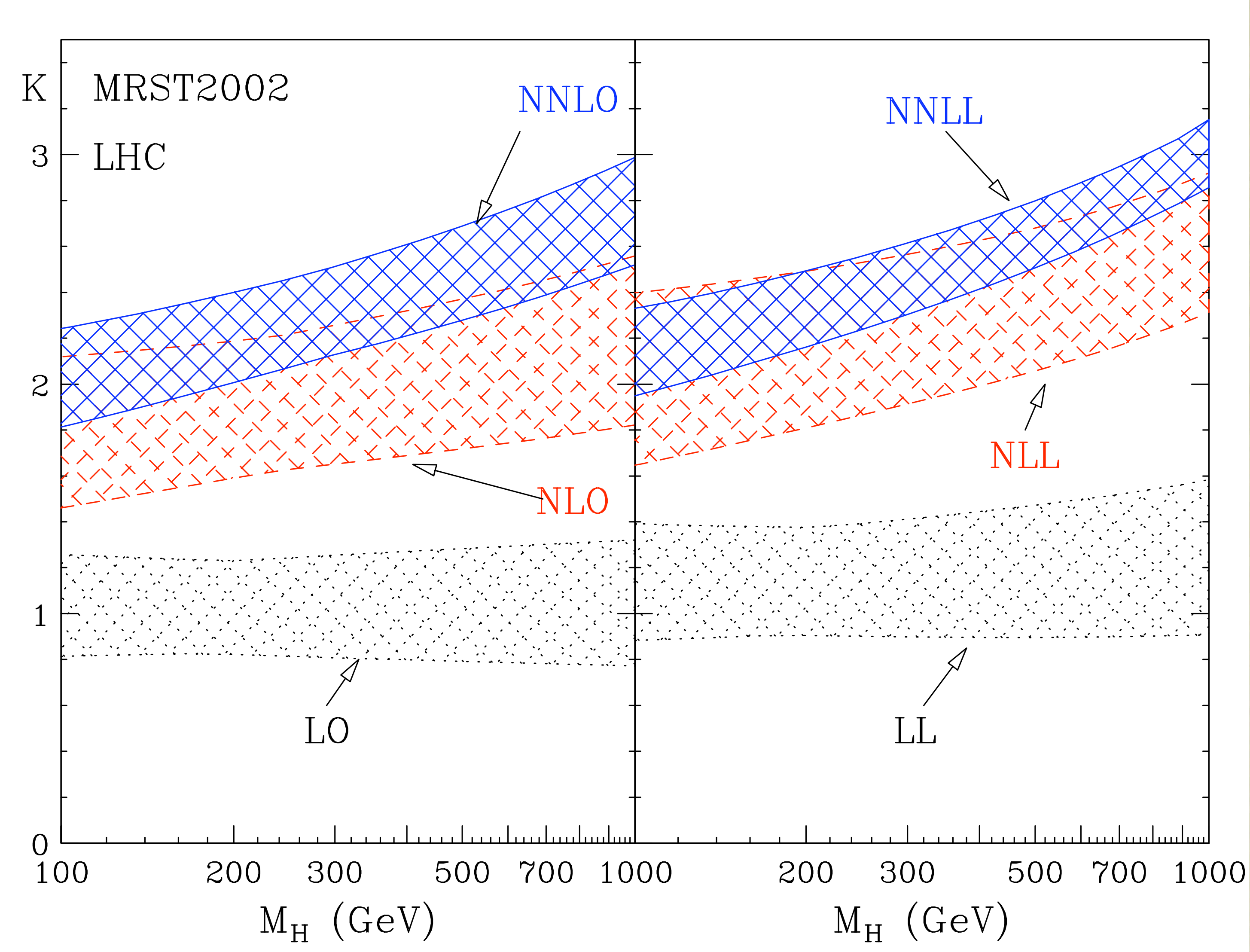
A. Vogt (2000)
A.Vogt, S.Moch, J.A.M. Vermaseren (2004)

→ We can go to NNLL+NNLO

Results at the LHC

For a light Higgs:

NNLL effect $+6\%$
Scale unc. $\sim 8\%$



- Resummed results matched to corresponding fixed order
- K-factors defined with respect $\sigma_{LO}(\mu_F = \mu_R = M_H)$
- With $\mu_{F(R)} = \chi_{L(R)} M_H$ and $0.5 \leq \chi_{L(R)} \leq 2$ but $0.5 \leq \chi_F/\chi_R \leq 2$

What is the residual theoretical uncertainty on σ_H ?

- Scale dependence
- Large m_{top} approximation:
  - At NLO the approximation works well BECAUSE the cross section is dominated by soft emission, which is weakly sensible to the top-loop
  - The dominance of soft gluons persists at NNLO

→ It is natural to expect the large m_{top} approximation to work well also at higher orders

  - Message from NLO: use exact Born cross section to normalize the result → uncertainty $\lesssim 5\%$

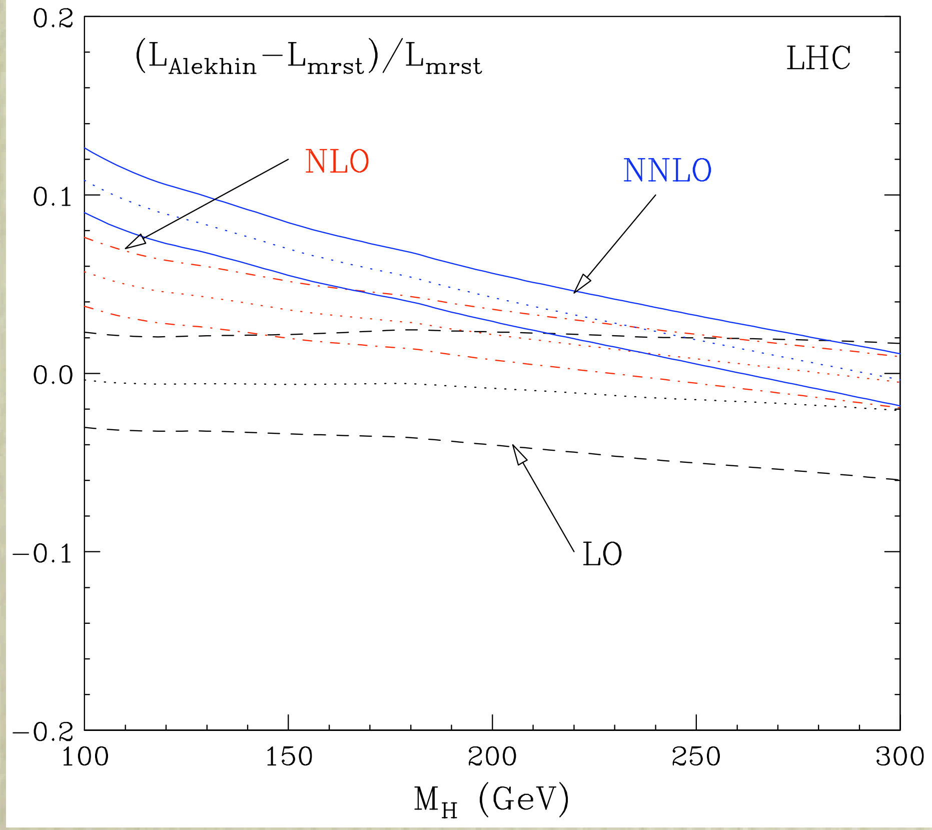
NEW: EW two-loop contributions of light fermions computed the effect can reach about 9%

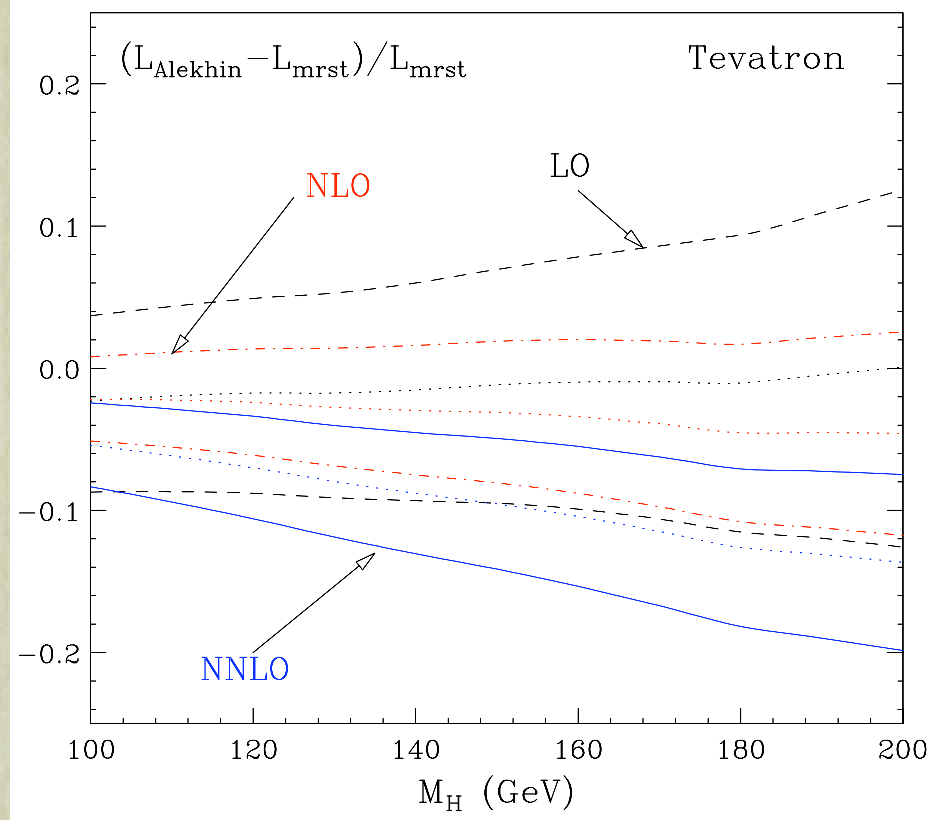
U. Aglietti, R. Bonciani, G. Degrassi, A. Vicini (2004)

Consistency requires NNLO pdf ➡ MRST, Alekhin

- At the LHC Alekhin results are larger than MRST: differences from about 8% for $M_H = 100$ GeV to about 2% for $M_H = 200$ GeV
- At the Tevatron Alekhin results are smaller than MRST, difference from 7% for $M_H = 100$ GeV to about 14% for $M_H = 200$ GeV

Differences due to gg luminosities





➡ Theoretical accuracy of about 10% can be reached once problems with pdf will be solved

The q_T spectrum of the Higgs boson

G. Bozzi, S. Catani, D. de Florian, MG (2003)

Signal and background have different shape in q_T

→ a precise knowledge of the spectrum can help to devise strategies to improve statistical significance

Studies of the Higgs q_T distribution have been performed at various levels of accuracy

I. Hinchliffe, S.F. Novaes (1988)
R.P. Kauffman (1992)
C.P. Yuan (1992)
C. Balazs, C.P. Yuan (2000)
E.L. Berger, J. Qiu (2002)

Our work →

- Include the best information available now: NNLL resummation at small q_T and NLO pert. theory at large q_T
- Improve the resummation formalism

The region $q_T \sim M_H$

To have $q_T \neq 0$ the Higgs has to recoil against at least one parton ➡ the LO is $\mathcal{O}(\alpha_S^3)$

The LO calculation shows that the large m_{top} approximation works well if both M_H and q_T are smaller than m_{top}

R.K.Ellis, I.Hinchliffe, M.Soldate, J.J.van der Bij (1988)
U. Baur, E.W.Glover (1990)

NLO corrections computed in this limit

D. de Florian, Z.Kunszt, MG (1999)

Amplitudes used at NLO:

- One loop: $gg \to gH$, $q\bar{q} \to gH$

C.Schmidt (1997)

- Bremssstrahlung: $gg \to ggH$, $q\bar{q} \to q\bar{q}H$, $q\bar{q} \to ggH$

R. Kauffmann, S.Desai, D.Risal (1997)

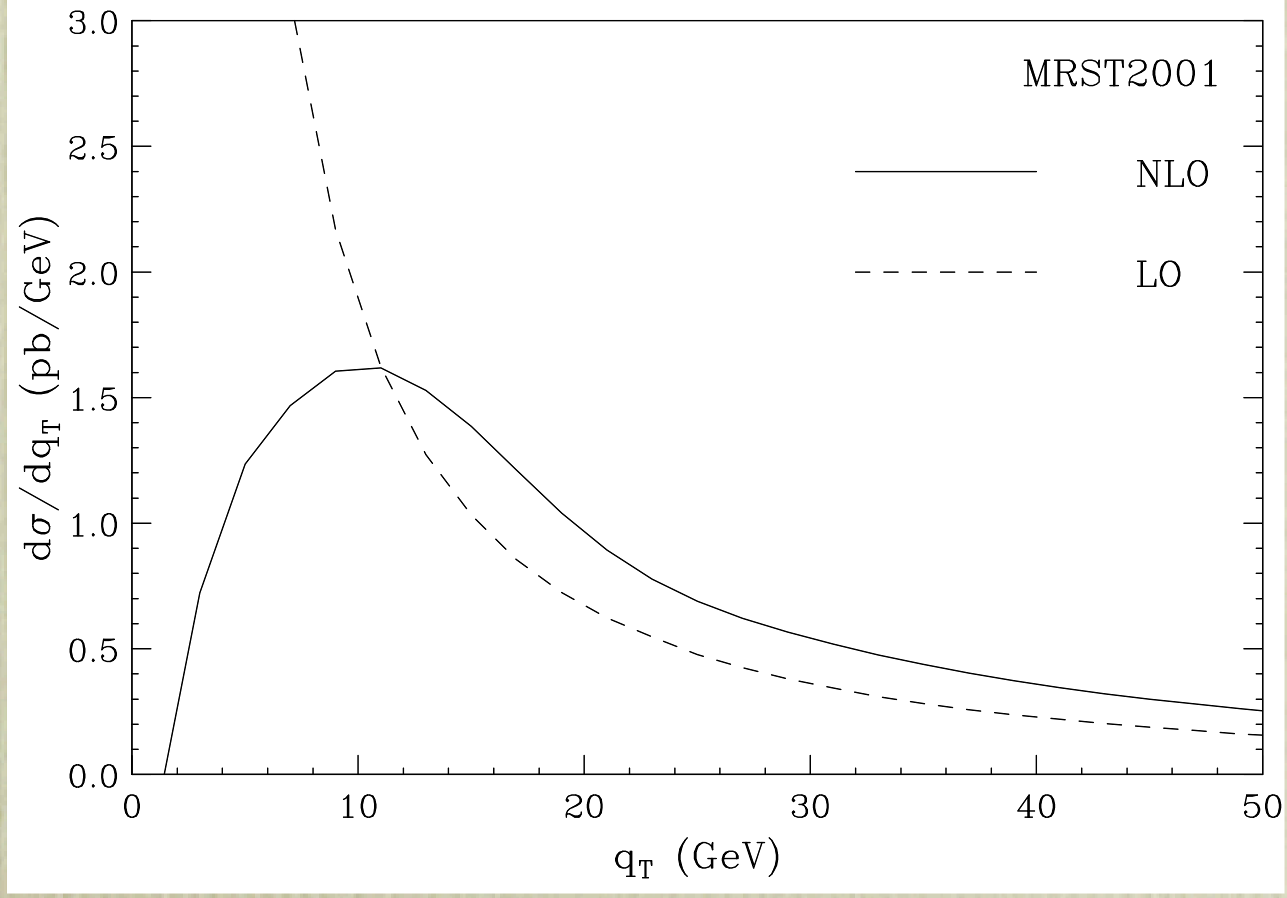
By using the subtraction method they were implemented in a parton level MC ➡ HIGGSJET NLO code
It is possible to compute any IR safe observable with Higgs + jet(s)

The region $q_T \ll M_H$

The small q_T region is the most important because it is here that the bulk of events is expected

When $q_T \ll M_H$ 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



LO: $\frac{d\sigma}{dq_T} \to +\infty$ as $q_T \to 0$

NLO: $\frac{d\sigma}{dq_T} \to -\infty$ as $q_T \to 0$

This is a general problem in the production of systems of high mass Q^2 in hadronic collisions (DY, $\gamma\gamma$ .....) → RESUMMATION

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. Kodaira, L. Trentadue (1982)
J. Collins, D.E. Soper, G. Sterman (1985)

As usual in QCD resummations one has to work in a conjugate space 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

The standard (CSS) formalism has several disadvantages:

- The resummation coefficients are process dependent

  D. de Florian, MG (2000)

- The integral over b involves and extrapolation of the pdf to the NP region

- The resummation effects are large also at small b

→ - No control on the normalization
  - Problems in the matching to the PT result

Our formalism

A version of the b-space formalism has been proposed that overcomes all these problems

S. Catani, D. de Florian, MG (2000)

Parton distributions are factorized at $\mu_F \sim M_H$

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

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

where the large logs are organized as:

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

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

➡
- The form factor takes the same form as in threshold resummation
- Unitarity constraint enforces correct total cross section

Numerical results

I present NLL results matched to LO (NLL+LO) and NNLL results matched to NLO (NNLL+NLO) → we use MRST2002 pdf

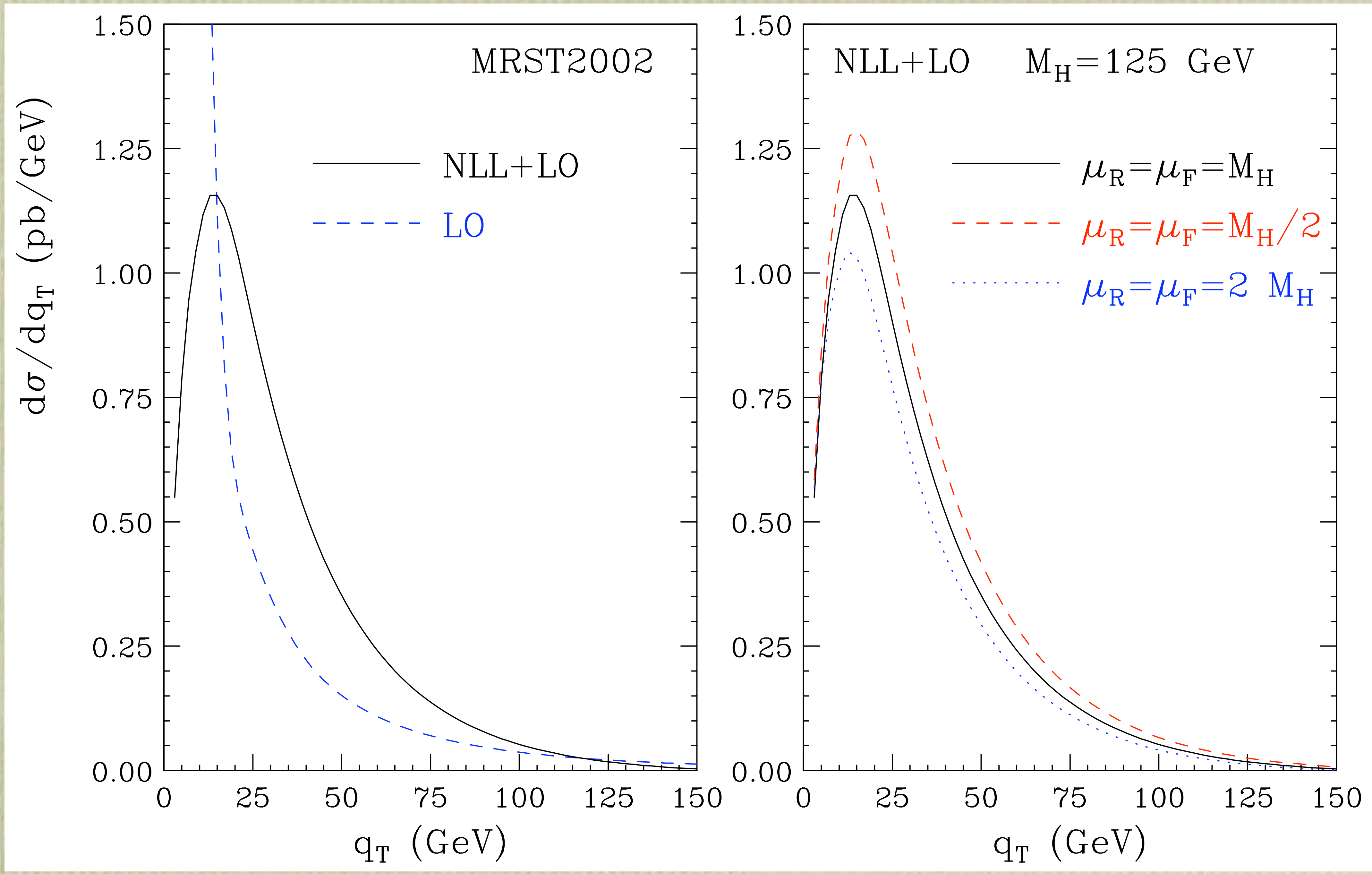
- NLL+LO: LO pdf +1-loop α_S
- NNLL+NLO: NLO pdf +2-loop α_S

At NNLL+NLO the coefficients $A^{(3)}, \mathcal{H}^{(2)}$ are not known

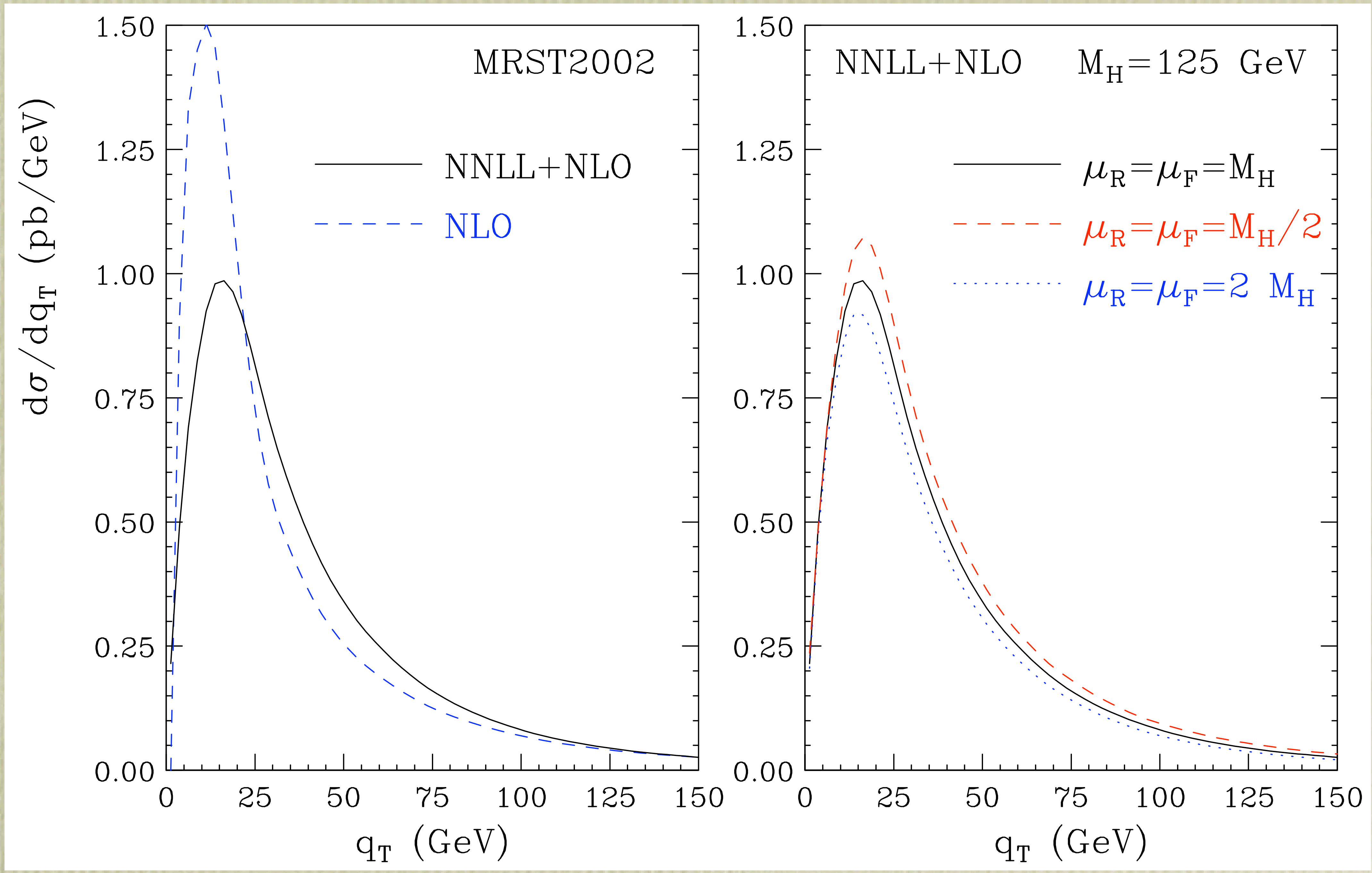
For the coefficient $A^{(3)}$ we use the result available for threshold resummation

A.Vogt (2000)
A.Vogt, S.Moch, J.A.M. Vermaseren (2004)

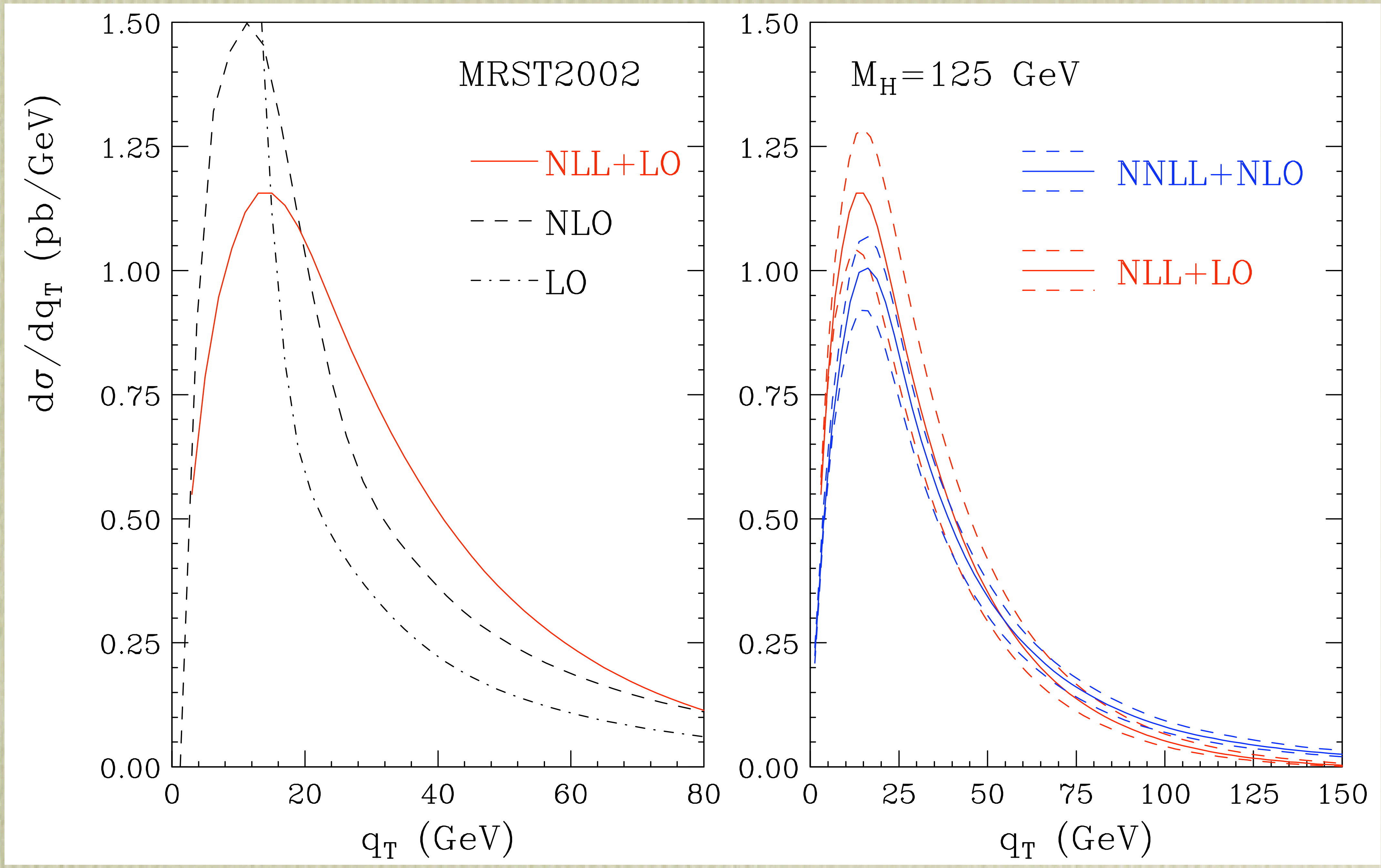
The effect of $\mathcal{H}^{(2)}$ is included in approximated form using the result for the total NNLO cross section



- The LO result diverges to $+\infty$ as $q_T \to 0$
- The effect of resummation is relevant already below $100\ \text{GeV}$
- The integral of the spectrum in good agreement with the total NLO cross section



- The NLO result diverges to $-\infty$ (unphysical peak) as $q_T \to 0$
- The effect of $A^{(3)}$ is neglible, whereas $\mathcal{H}^{(2)}$ gives $+20\%$
- Scale dependence reduced with respect to NLL+LO: it is about 10% at the peak



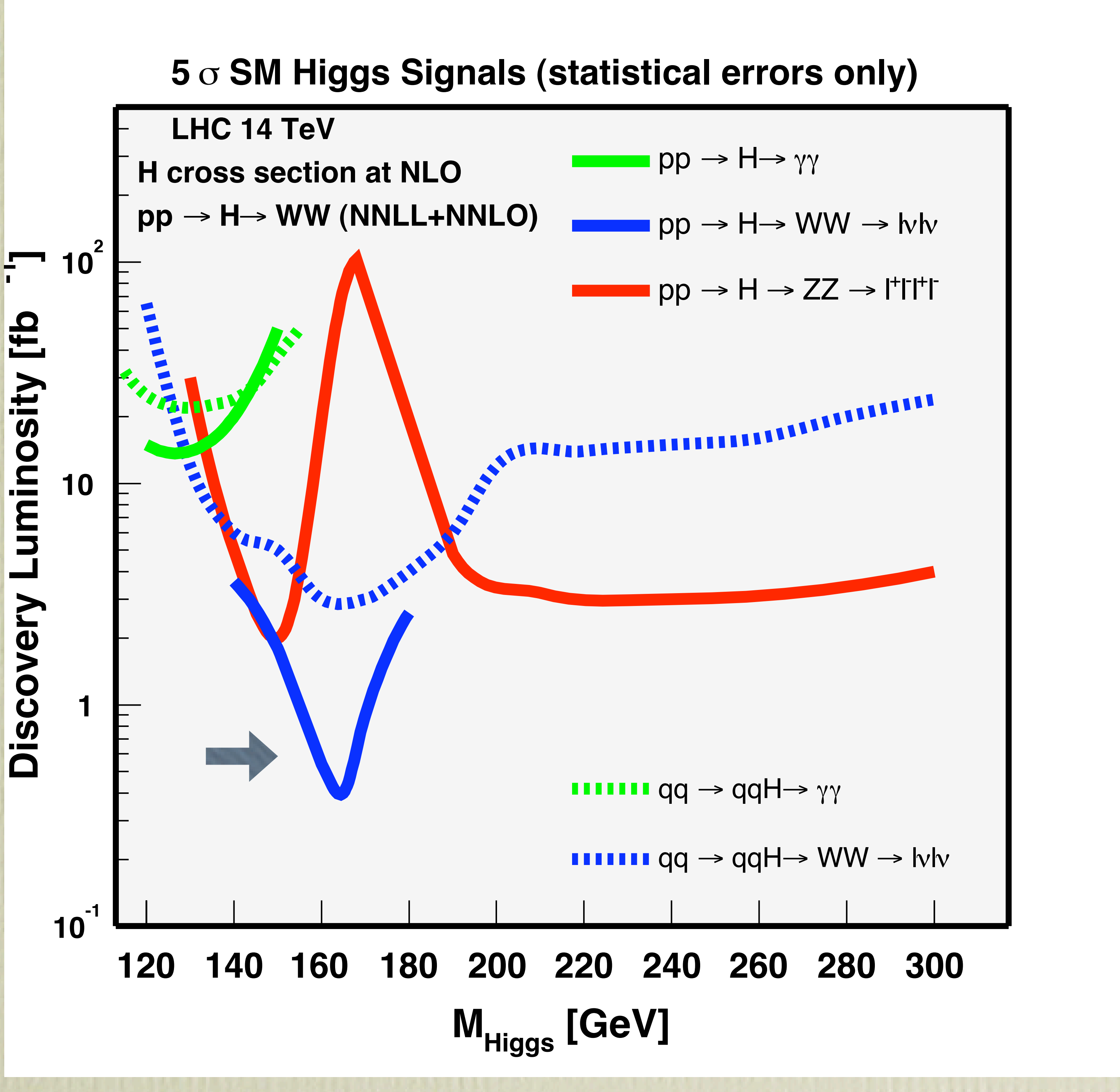
- In the intermediate region the cross section sizeably increases going from LO to NLO and from NLO to NLL+LO ➡ there are important contributions that must be resummed to all orders and not simply evaluated to the next order
- Bands overlap for $q_T \lesssim 100$ GeV
  ➡ Good stability of perturbative result

A recent application in $gg \to H \to WW \to l\nu l\nu$

G. Davatz, G. Dissertori, M. Dittmar, F. Pauss, MG (2004)

Use results for $gg \to H$ spectrum at NNLL+NLO to correct (reweight) events generated with PYTHIA

Apply the resummation formalism to WW pair production → NLL+LO results used to correct PYTHIA main background



Summary

We have evaluated the effect of multiple soft-gluon emission to $gg \to H$

- Effect moderate at LHC:
  for a light Higgs $+6\%$ with respect to NNLO
- Perturbative result under better control now but...
  still problems with NNLO pdf !

We have computed the q_T spectrum of the Higgs boson at the LHC

- We have implemented the most complete information available at present: all-order resummation of large logs at small q_T at NNLL level combined with NLO perturbation theory at large q_T
- Our approach allows a consistent study of th. uncertainties and implements a unitarity constraint such that the total cross section at the nominal accuracy is recovered by integration
- Results appear to be stable