QCD and Higgs physics: theoretical issues

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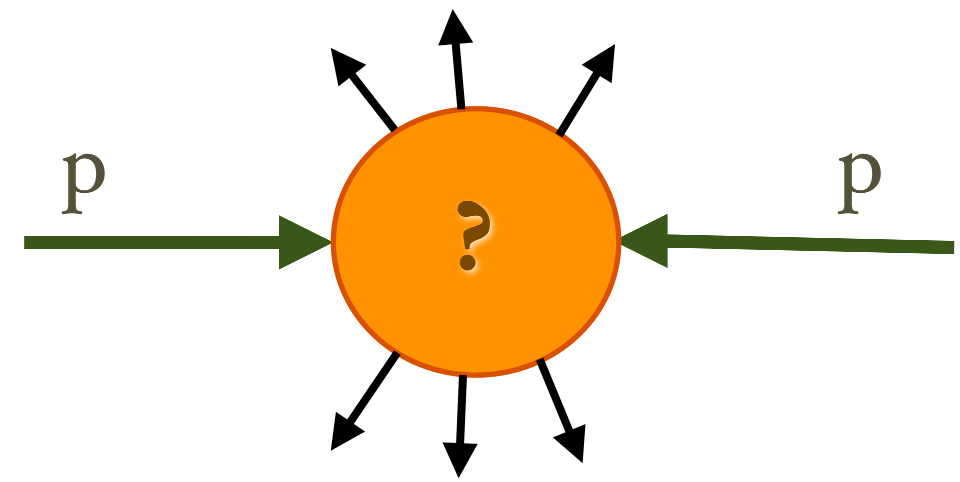
Outline

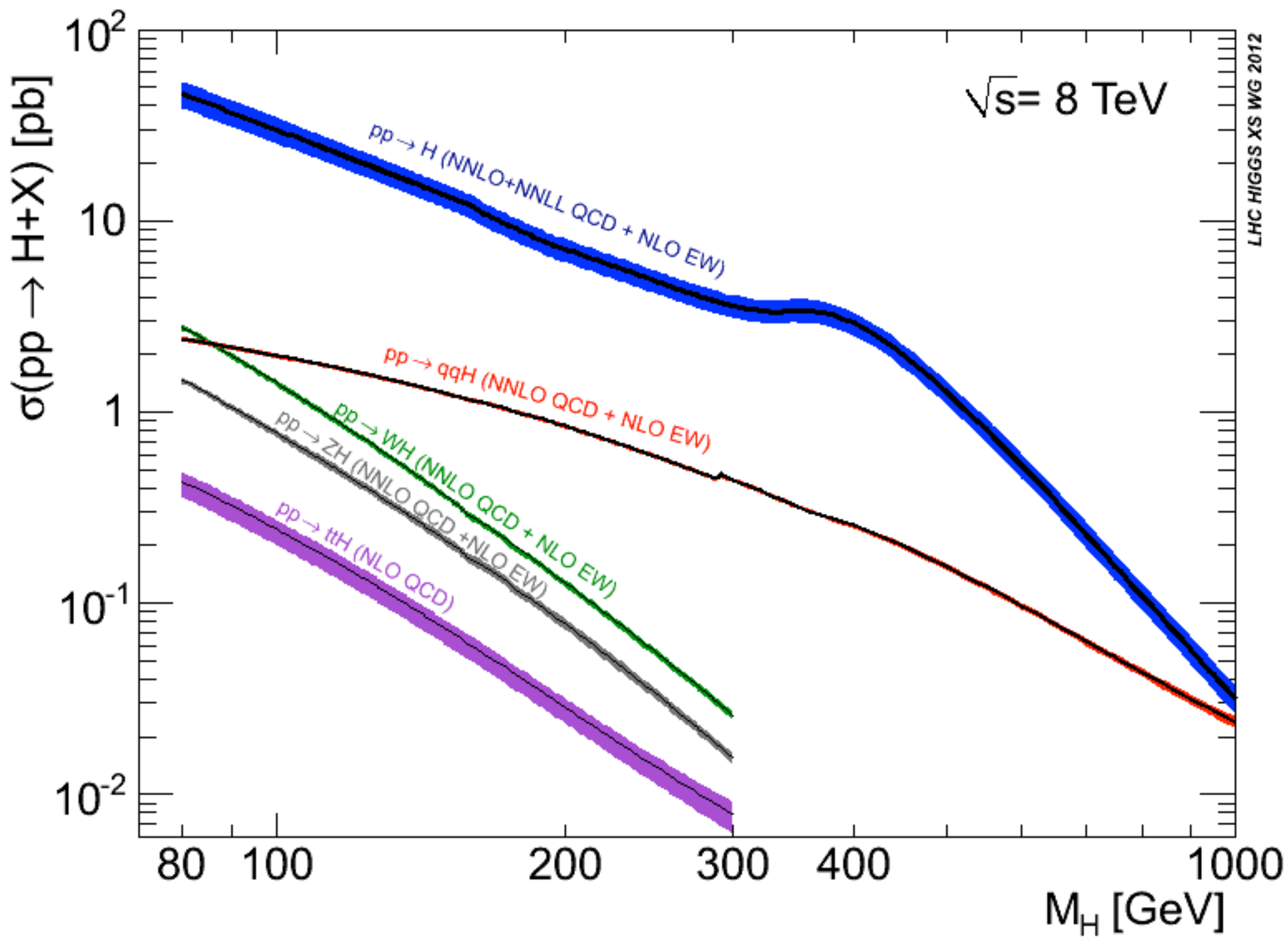
- Introduction
- Inclusive cross section
  - Review of existing calculations
  - The issue of the gluon distribution
  - N^3LO ?
- Transverse momentum spectrum
  - Heavy quark mass effects
  - spectrum for spin 2 ?
- Jet veto
- Summary and Outlook

Introduction

QCD ubiquitous at hadron colliders

This applies also to Higgs production



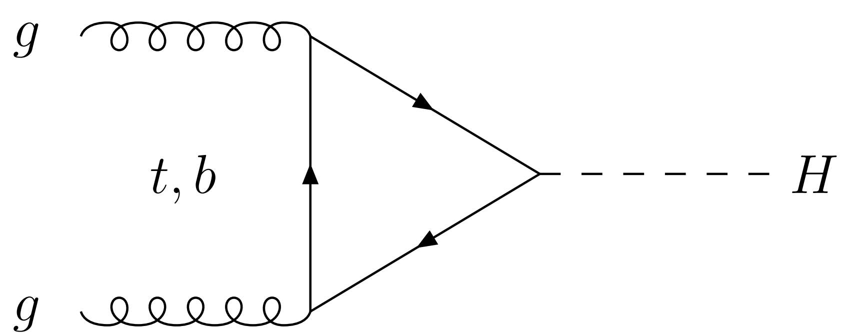


Large gluon luminosity:

gg fusion is the dominant production channel over the whole range of m_H

→ Focus on gg fusion in this talk

gg fusion



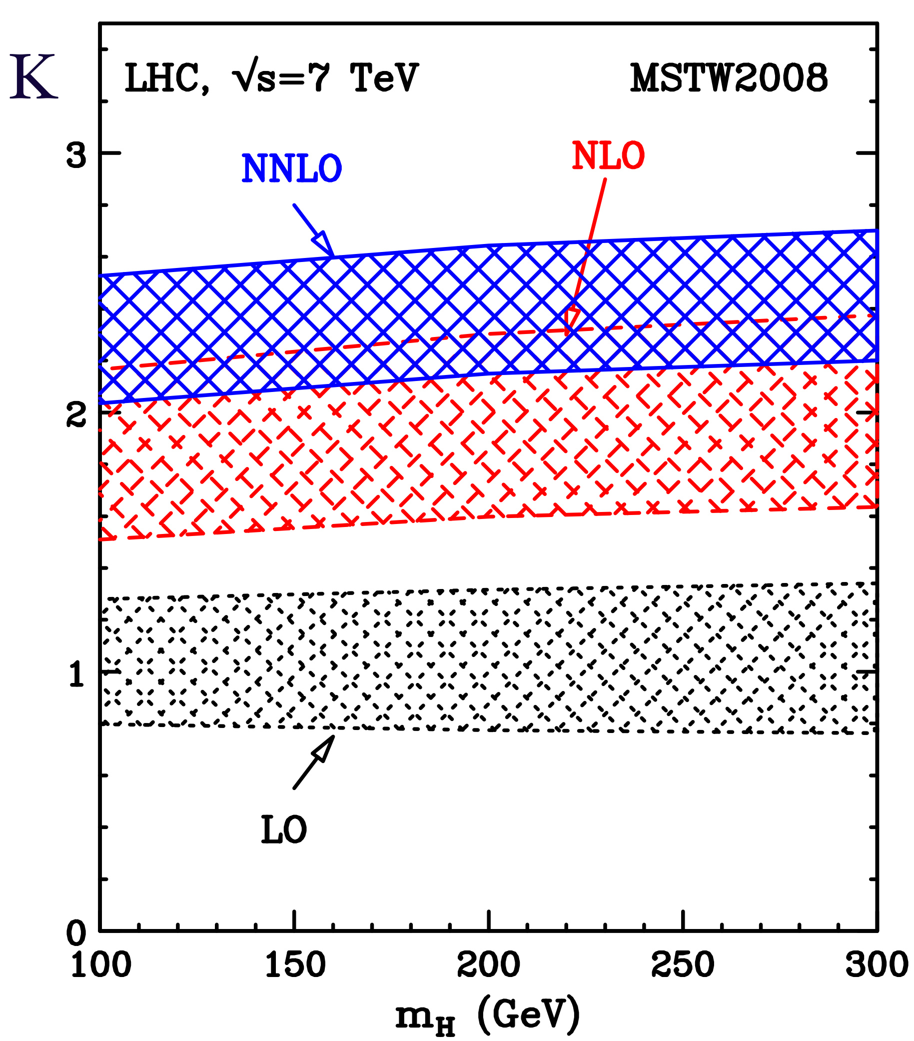
The Higgs coupling is proportional to the quark mass

→ top-loop dominates

$O(\alpha_S^2)$ process already at Born level

QCD corrections to the total rate computed 20 years ago and found to be large → O(100 %) effect !

A. Djouadi, D. Graudenz, M. Spira, P. Zerwas (1991)



Next-to-next-to leading order (NNLO) corrections computed in the large-m_{top} limit (+25 % at the LHC, +30 % at the Tevatron)

R.Harlander (2000); S. Catani, D. De Florian, MG (2001)
R.Harlander, W.B. Kilgore (2001,2002)
C. Anastasiou, K. Melnikov (2002)
V. Ravindran, J. Smith, W.L.Van Neerven (2003)

scale uncertainty computed with $m_H/2 < \mu_F, \mu_R < 2\, m_H$ and $1/2 < \mu_F/\mu_R < 2$

The large-m_{top} approximation

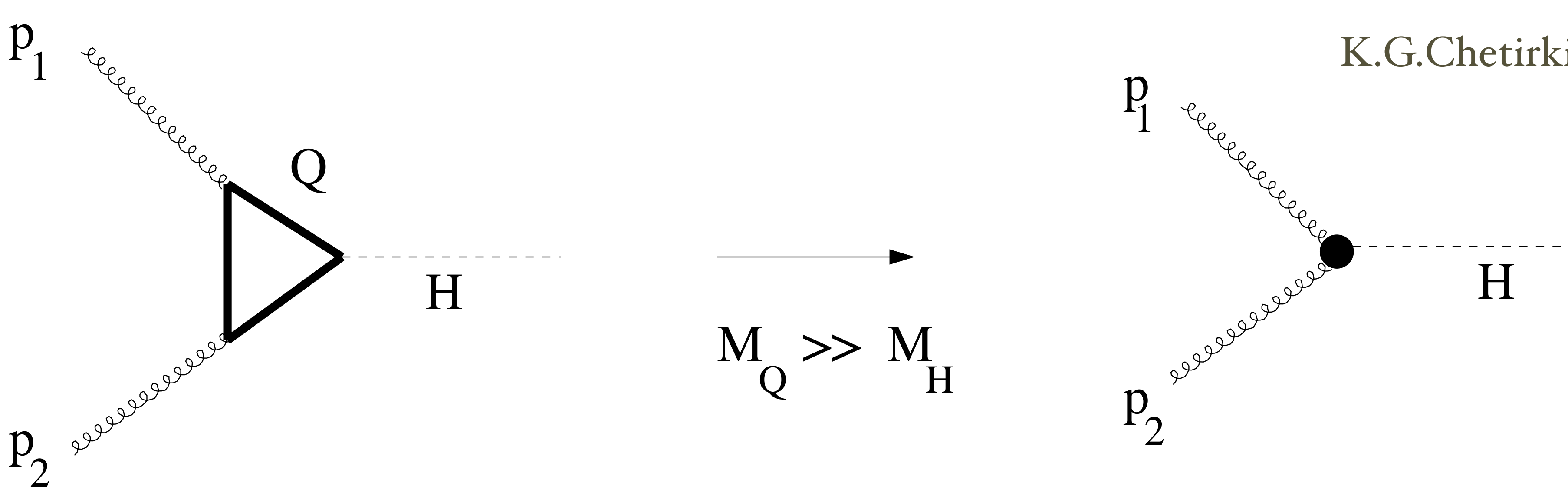
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

J.Ellis, M.K.Gaillard, D.V.Nanopoulos (1976)
M.Voloshin, V.Zakharov, M.Shifman (1979)

$$\mathcal{L}_{eff} = -\frac{1}{4}\left[1 - \frac{\alpha_S}{3\pi}\frac{H}{v}(1+\Delta)\right] \mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$$

Known to $\mathcal{O}(\alpha_S^3)$

K.G.Chetirkin, M.Steinhauser, B.A.Kniehl (1997)



Effective vertex: one loop less !

Recently the subleading terms in large-m_{top} limit at NNLO have been evaluated

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

→ **The approximation works to better than 0.5 % for m_H < 300 GeV**

gg fusion

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about +9-10% at the LHC, +13% at the Tevatron, with slight reduction of scale unc.)

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

→ Nicely confirmed by computation of soft terms at N^3LO

S. Moch, A. Vogt (2005), E. Laenen, L. Magnea (2005)

Two-loop EW corrections are also known (effect is about O(5%))

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

Mixed QCD-EW effects evaluated in EFT approach (effect O(1%))

Anastasiou et al. (2008)

→ support "complete factorization": EW correction multiplies the full QCD corrected cross section

EW effects for real radiation (effect O(1%))

W.Keung, F.Petriello, (2009)
O.Brein (2010)
C.Anastasiou et al. (2011)

Results

Quite an amount of work has been done in the last few years to provide updated results that include all the available theoretical information

- **NNLO Calculation implemented in iHixs** C.Anastasiou et. al. (2012)

  - Start from exact NLO and include NNLO in the large-m_{top} limit
  - Effect of resummation is mimicked by choosing $\mu_F = \mu_R = m_H/2$ as central scale (choice motivated by apparent better convergence of the perturbative series)
  - Includes EFT estimate of mixed QCD-EW effects and some effects from EW corrections to real radiation (at the percent level or smaller)

- **Our NNLL+NNLO calculation:** D. de Florian, MG (2009)

  - Improvement of the calculation by Catani et al. (2003)
  - Start from exact NLO result and add soft-gluon resummation at NLL
  - Perform NNLL+NNLO calculation in the large-m_{top} limit
  - Include two-loop EW effects

→ **Recommended result by the LHC Higgs XS WG and used as reference theoretical prediction by ATLAS and CMS**

(corresponding results for the Tevatron still used by CDF+D0)

Our latest update (2012)

D. de Florian, MG (2012)

- Effect of the charm quark included (typically neglected so far)

This is a -2.5 % effect at Born level (reduced to -1.2% at NNLL+NNLO) !

Finite width effects according to complex-mass scheme included (irrelevant for m_H=125 GeV)

G. Passarino et al. (2011)

PDF uncertainties computed with PDF4LHC recommendation (roughly equivalent to consider 90% CL)

Scale uncertainties computed with $m_H/2 < \mu_F, \mu_R < 2\, m_H$ and $1/2 < \mu_F/\mu_R < 2$

$$\sigma = 19.31^{+7.2\%}_{-7.8\%}\,(\text{scale})^{+7.5\%}_{-6.9\%}\,(\text{PDF}+\alpha_S)\ \text{pb}$$

- Compare with result by iHixs

Anastasiou et al. (2012)

$$\sigma = 20.69^{+8.4\%}_{-9.3\%}\,(\text{scale})^{+7.8\%}_{-7.5\%}\,(\text{PDF}+\alpha_S)\ \text{pb}$$

→ 7% higher than our result but still compatible within scale uncertainties

Other Results

- Calculation by Baglio-Djouadi

J.Baglio,A.Djouadi (2010)

- Detailed (and very) conservative study of the various sources of uncertainties → about±25-30 % at 7 TeV

- Further update for the Tevatron uses $\mu_F = \mu_F = m_H/2$ as central scale: agreement with the other calculations

→ Recently used to provide possible explanation of $\gamma\gamma$ excess

A.Djouadi (2012)

- Calculation by Neubert et al.

V.Ahrens et al. (2010)

- Based on the so called "π^2-resummation"

- Numerical results agree with the other calculations

- Perturbative uncertainties of about 3% or smaller → largely underestimated !

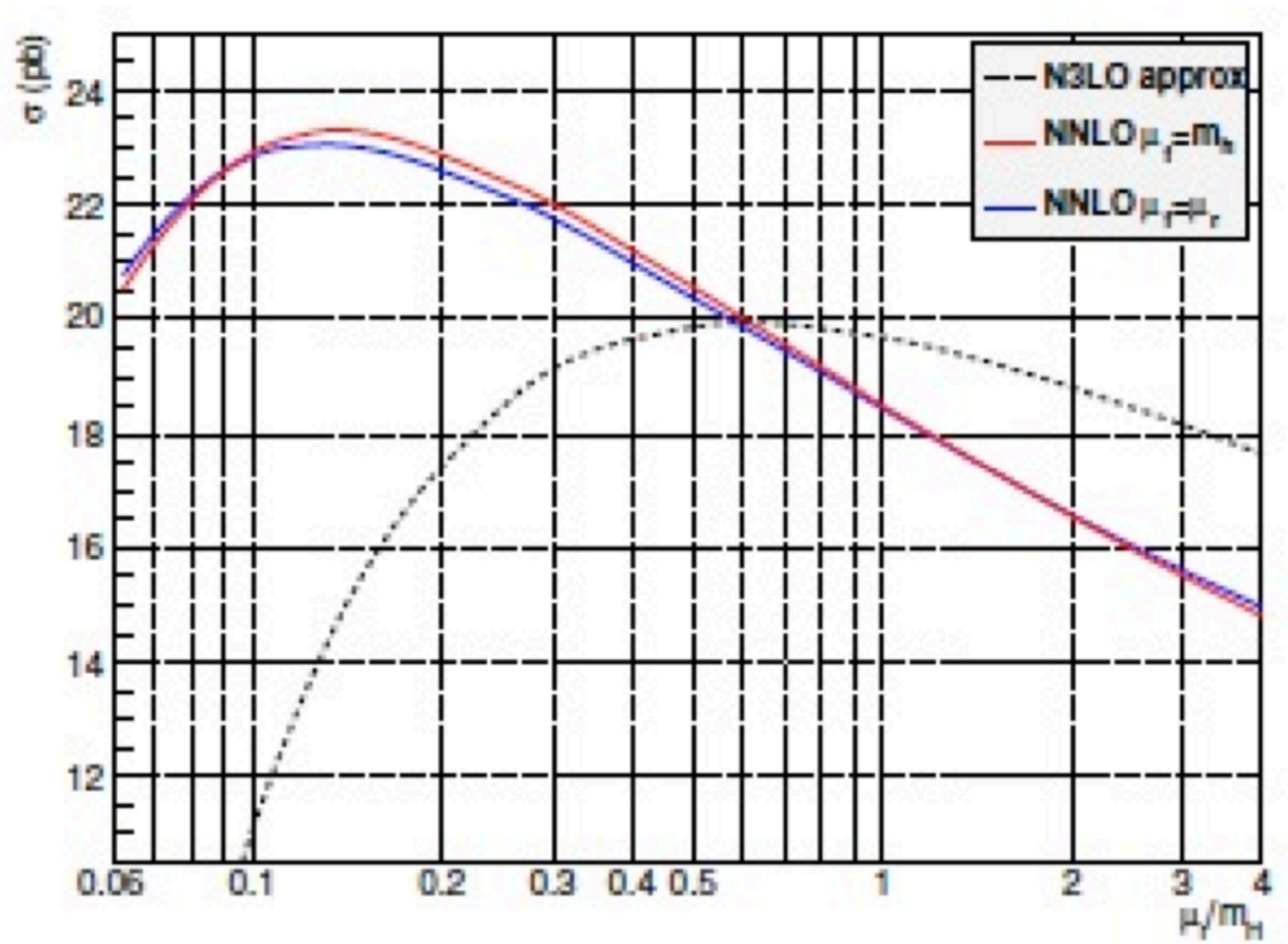
The issue of the scale choice

Our calculation uses $\mu_F = \mu_R = m_H$ as central value for the renormalization and factorization scales whereas Anastasiou and collaborators use $\mu_F = \mu_R = m_H/2$

The central scale choice is somewhat arbitrary and both choices make sense

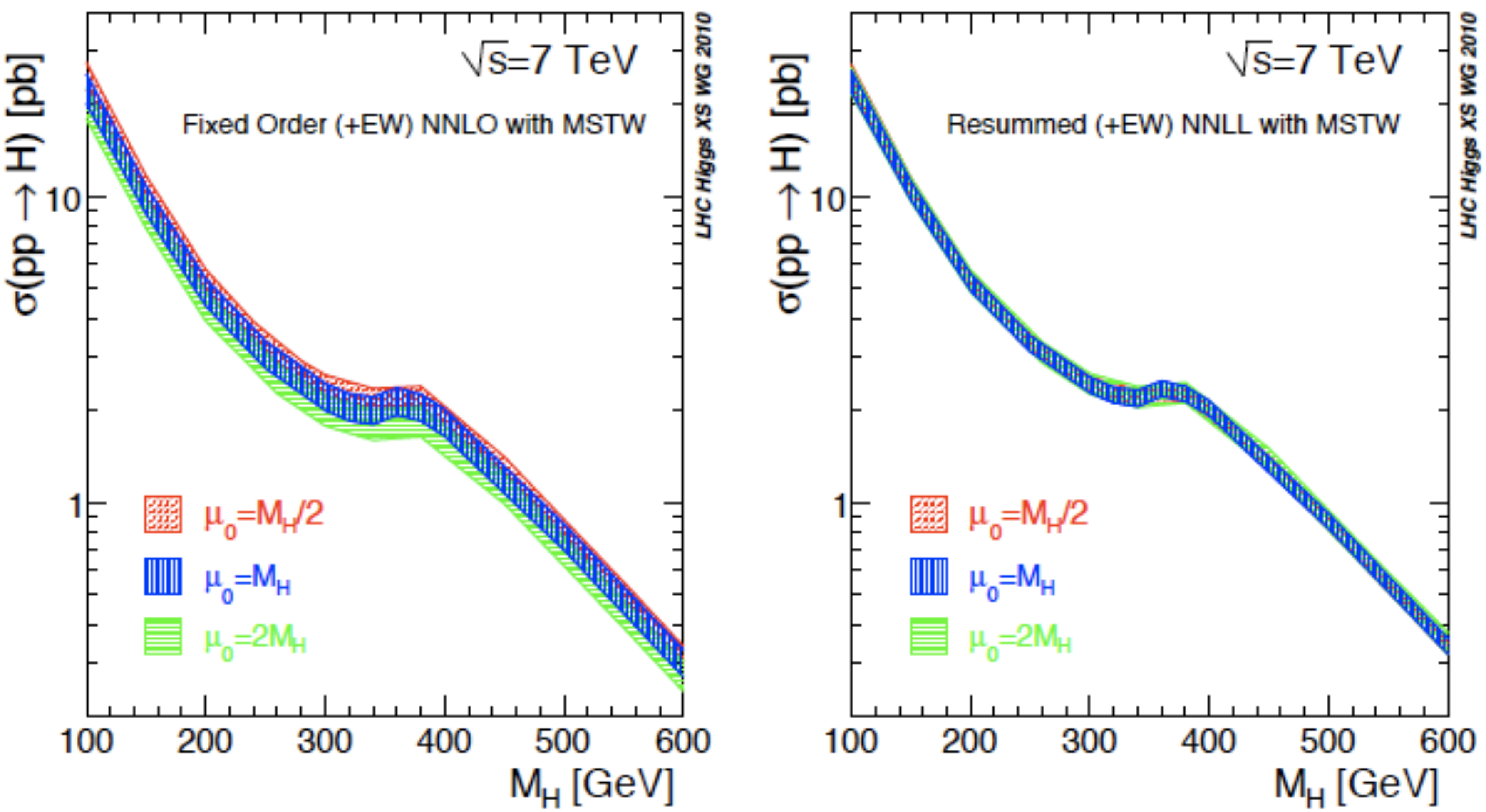
One argument that has been used to support the choice of $m_H/2$ is that the NNLO is stationary for $\mu \sim 0.1\text{-}0.2\ m_H$

Note that at N^3LO the stationary point moves to $\mu \sim 0.6\ m_H$



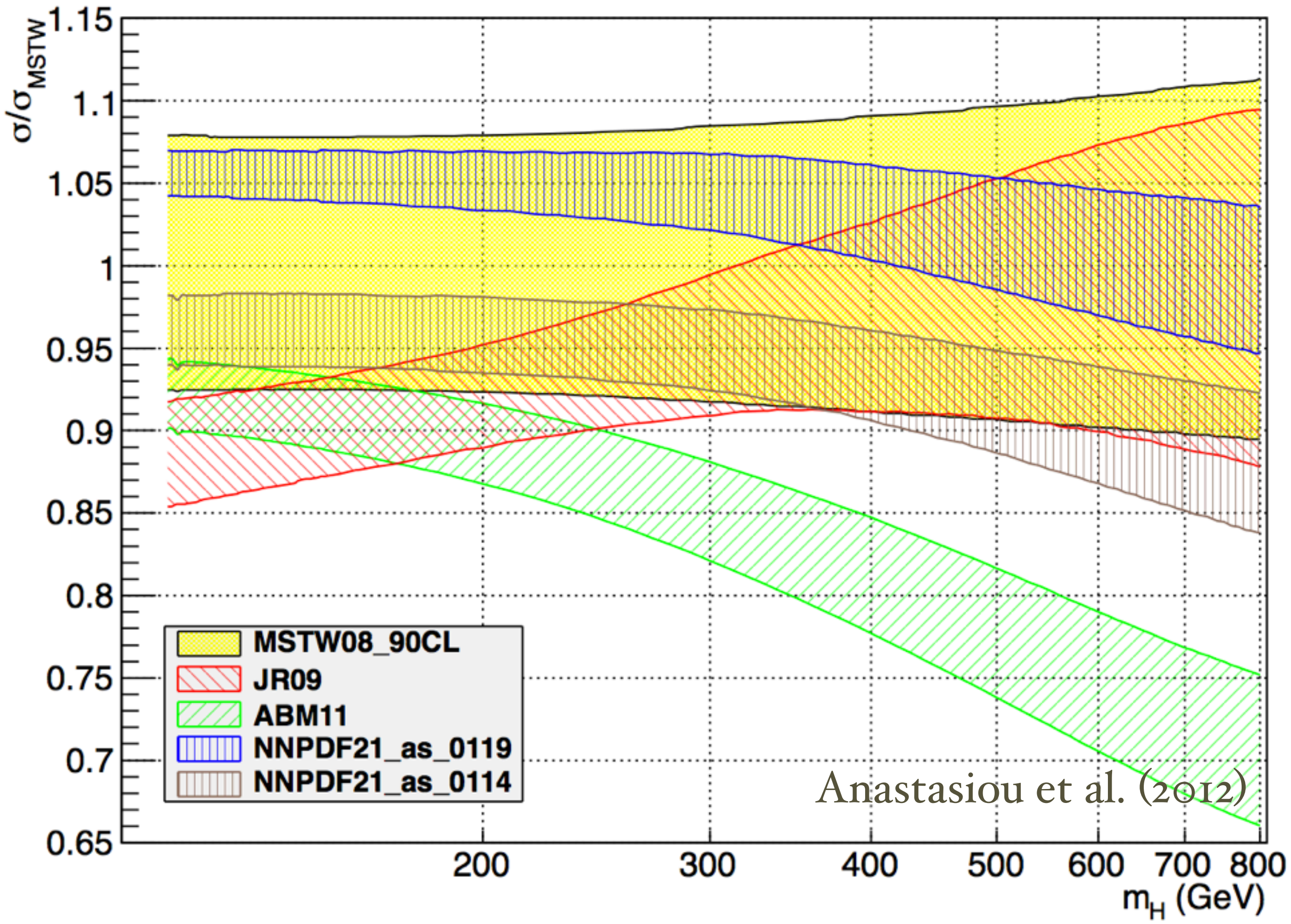
C.Anastasiou (2012)

The issue of the scale choice



It is remarkable that the NNLL resummed calculation is basically insensitive to the central scale choice !

The gluon density issue



Various NNLO sets have become available in the last few years

New CT10 NNLO fit agrees with MSTW within 5 %

At m_H=125 GeV things appear under control

ABM11 set does not include Tevatron jet data and it has α_S much smaller than the world average → large difference at high m_H (relevant for exclusion)

Jet data give important constraint on the gluon distribution but known only at NLO at present

NNLO calculation in progress: first result for gg channel at leading color just presented

T.Gehrmann et al. (2013)

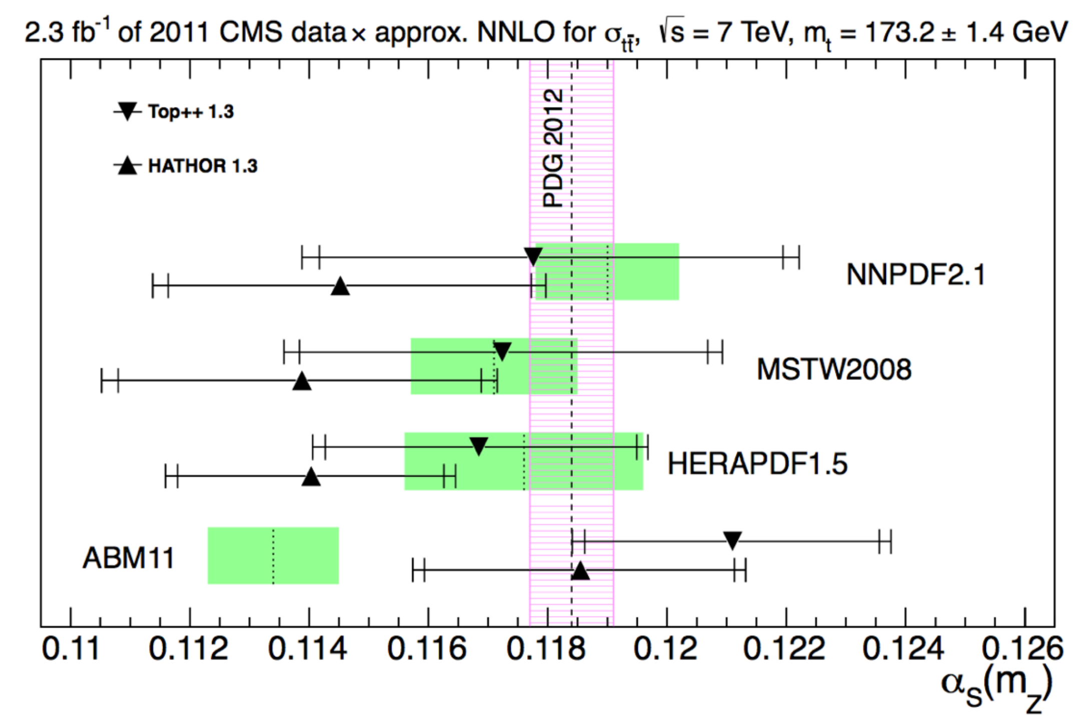
The gluon density issue

The ttbar cross section is also sensitive to the gluon density

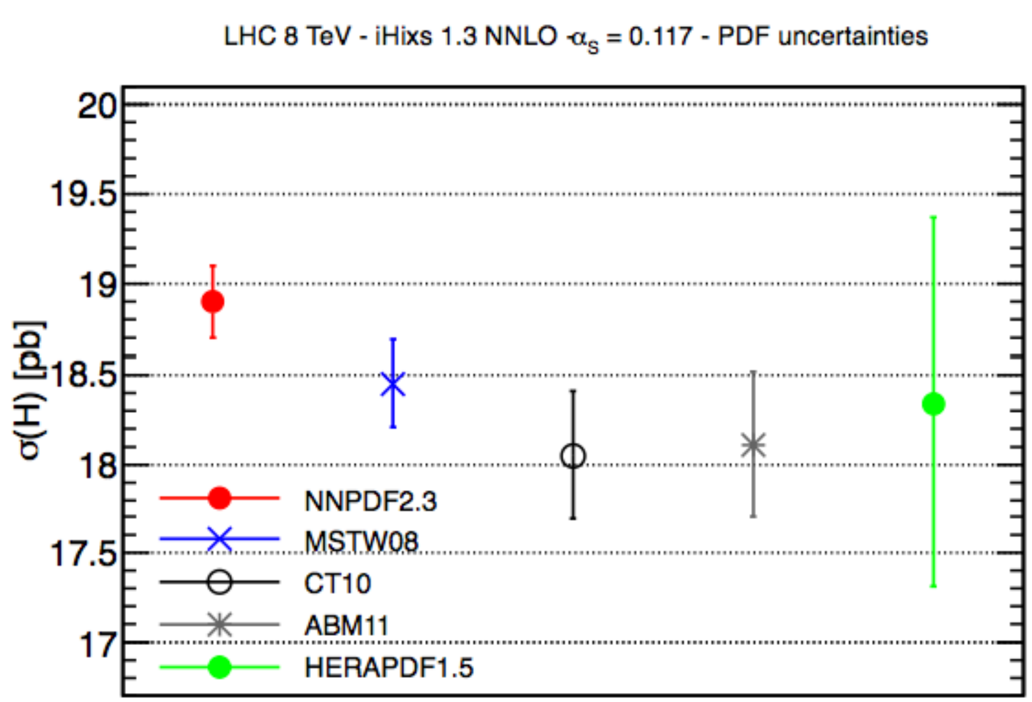
CMS-PAS-TOP-12-022

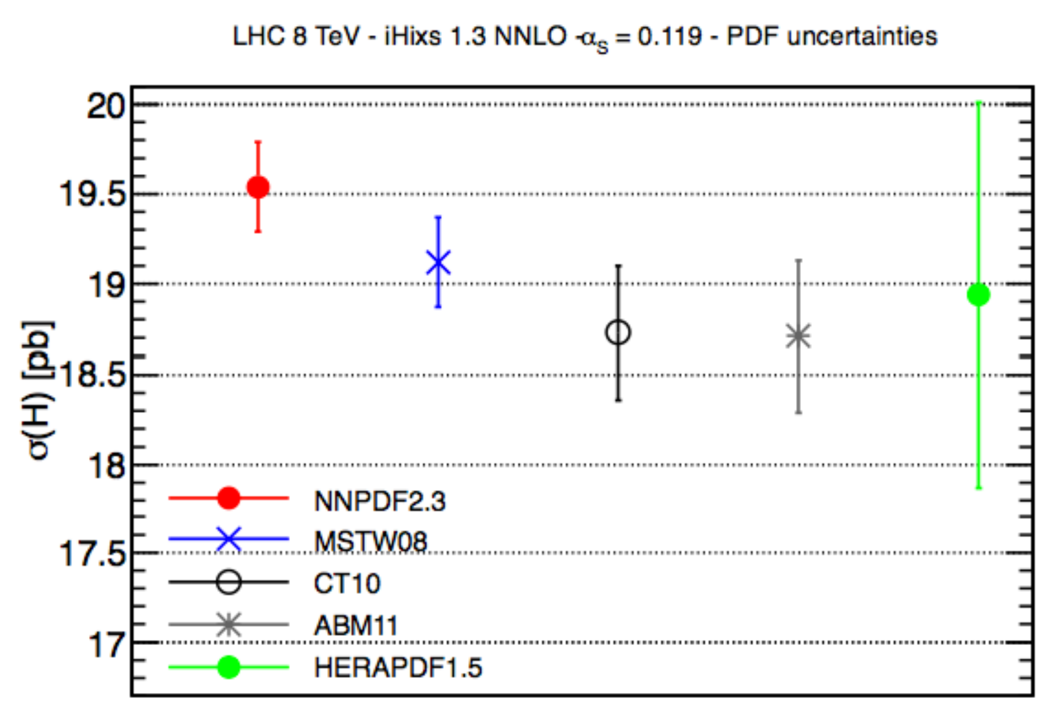
Once m_{top} is fixed it is possible to extract α_S from the measured cross section and compare it with the preferred value for the set

→ Consistency check for the PDFs !



NNLO predictions are compatible if a common value of α_S is used





J.Rojo et al. (2012)

N^3LO ?

Some brave colleagues are working to extend the calculation to N^3LO

Scale uncertainty would go down from about *7%* to about *5%*: is it worth ?

S.Moch and A.Vogt (2005)

Consistent N^3LO calculation would require N^3LO PDFs.....

but...... N^3LO result would be an impressive achievement anyway !

Experience at NNLO tells us that the first step would be to compute the soft-virtual part first

W. van Neerven et al. (1988)

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

- NNLO Partonic cross section to $O(\varepsilon)$

M.Steinhauser et al . (2012)

- NNLO master integrals to $O(\varepsilon)$ and to all orders in ε at threshold

C.Anastasiou et al . (2012)

N3LO ?

Important new result from the ETH group:

$$\sigma_{ij\to H+X}(s,\bar{z}) = \bar{z}^{-1-6\epsilon} s^{3\epsilon} \sum_{k=0}^{\infty} \bar{z}^k \sigma^{S(k)}_{ij\to H+X}$$

$$\bar{z} = 1 - z \quad z = m_H^2/s$$

C.Anastasiou. C. Duhr, F.Dulat, B.Mistlberger (2013)

First two terms of the threshold expansion for triple-real contribution (SV plus its first correction)

Note that soft-gluon resummation predicts the first term in the soft expansion $\sigma^{S(0)}_{ij\to H+X}$ (except its δ(1-z) part)

S.Catani, D. de Florian, P.Nason, MG (2003)
S.Moch, A. Vogt (2005)

Still missing: contribution of the known two-loop H+1 parton and one-loop H+2 parton amplitudes

L.Dixon, Y.Sofianatos (2009)
S.Badger et al. (2009)
T.Gehrmann et al. (2011)

To be combined with known three-loop result to get a finite cross section

→ Result seems within reach !

P.A.Baikov et al. (2009)
R.N.Lee, A.V.Smirnov and V.A.Smirnov (2010)
T.Gehrmann et al . (2010)

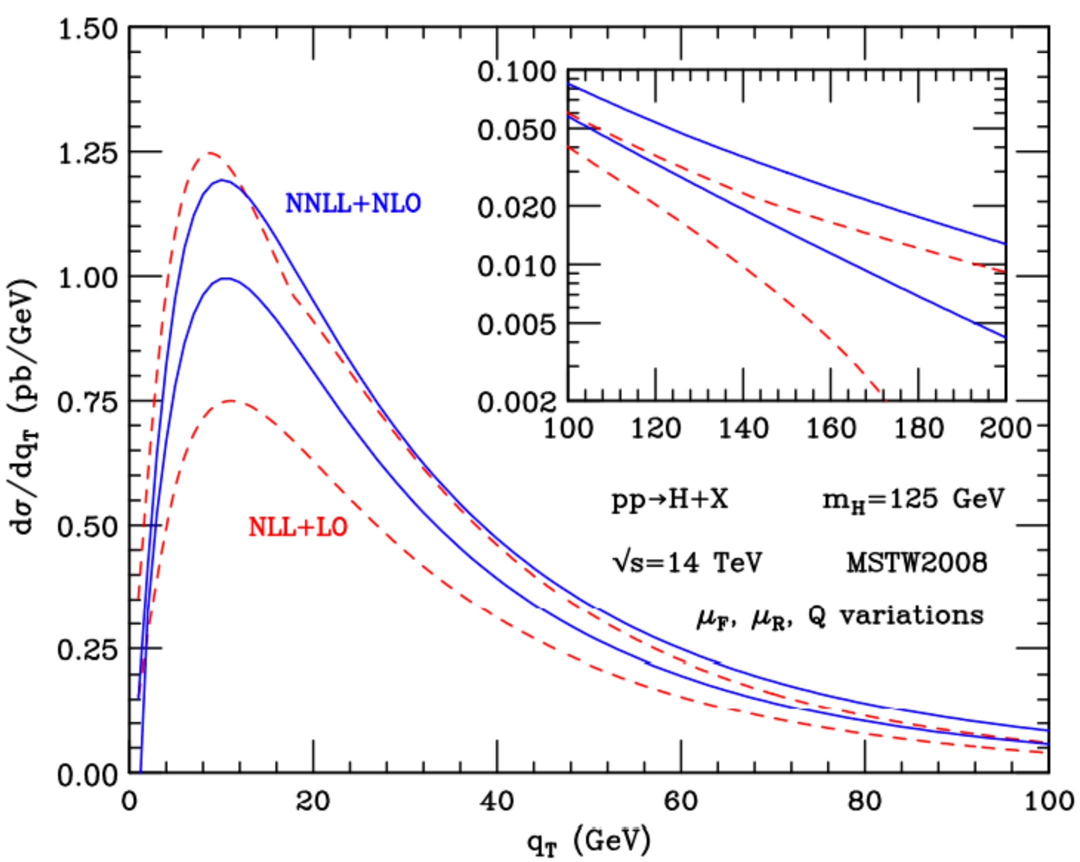
Going differential: p_T spectrum

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



HqT: soft gluon resummation at $p_T \ll m_H$ matched to fixed order result at $p_T \sim m_H$

In the last few years HqT became the reference tool to compare with

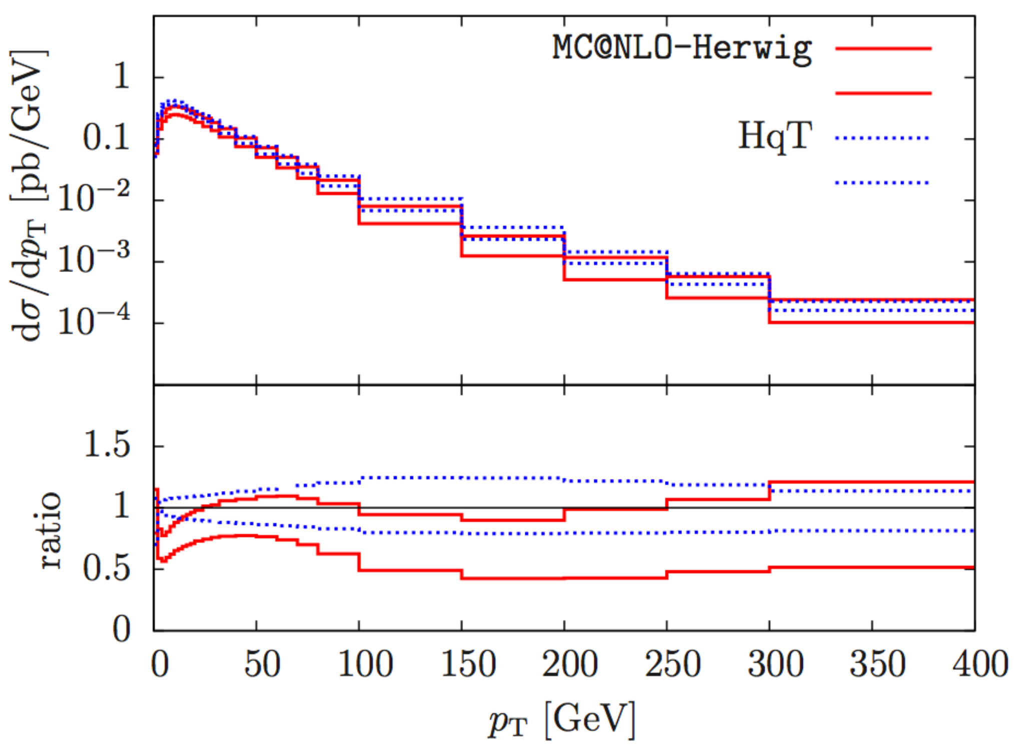
New program HRes includes Higgs decay

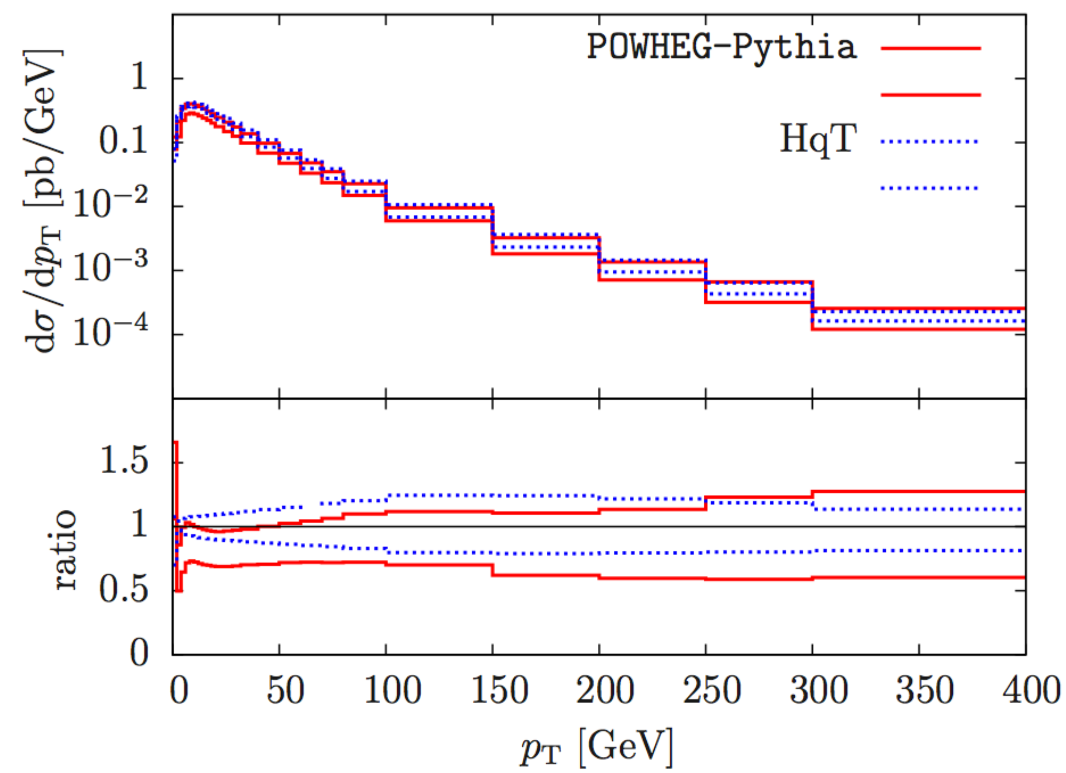
G. Bozzi, S.Catani, D. de Florian, MG (2005,2007)
D. de Florian, G.Ferrera, D.Tommasini, MG (2011,2012)

Going differential: p_T spectrum

Resummation "effectively" performed (less accurately) by standard MC event generators

Reasonably good agreement with MC@NLO and now also POWHEG (with h=1.2)





h controls amount of real radiation that is exponentiated ($h=\infty$ in default POWHEG)

C.Oleari, Higgs Hunting 2012

But the spectrum is still in the large-mtop limit: bound to fail when p_T is very large

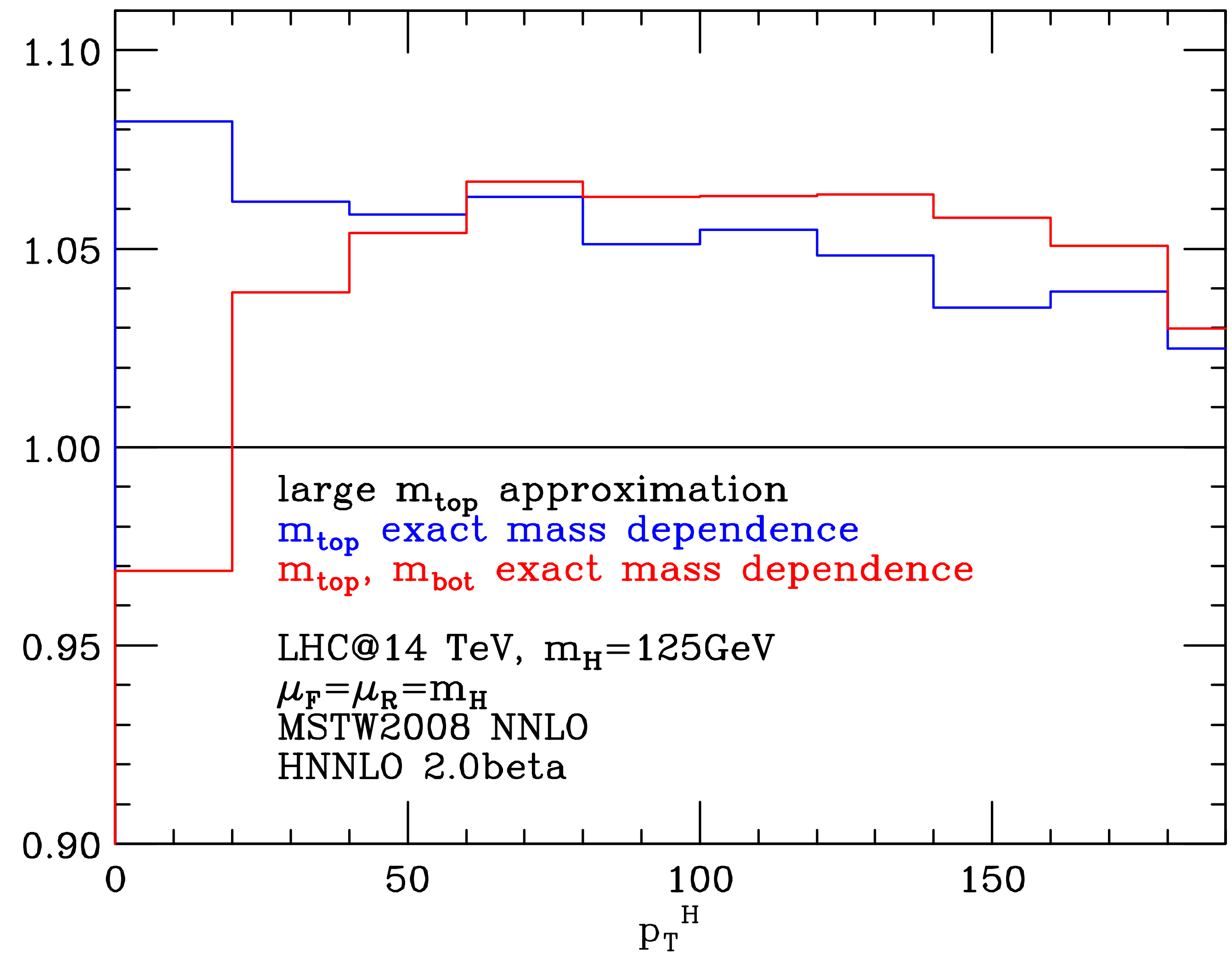
Heavy quark mass effects now included in POWHEG and MC@NLO

E.Bagnaschi et al. (2012)
S.Frixione (2012)

Going differential: p_T spectrum

Exact dependence on the masses of top and bottom quarks known up to NLO

M. Spira et al. (1995)
K.Ellis, Hinchliffe, van der Bij (1988)



Now implemented in NNLO fully-exclusive calculation

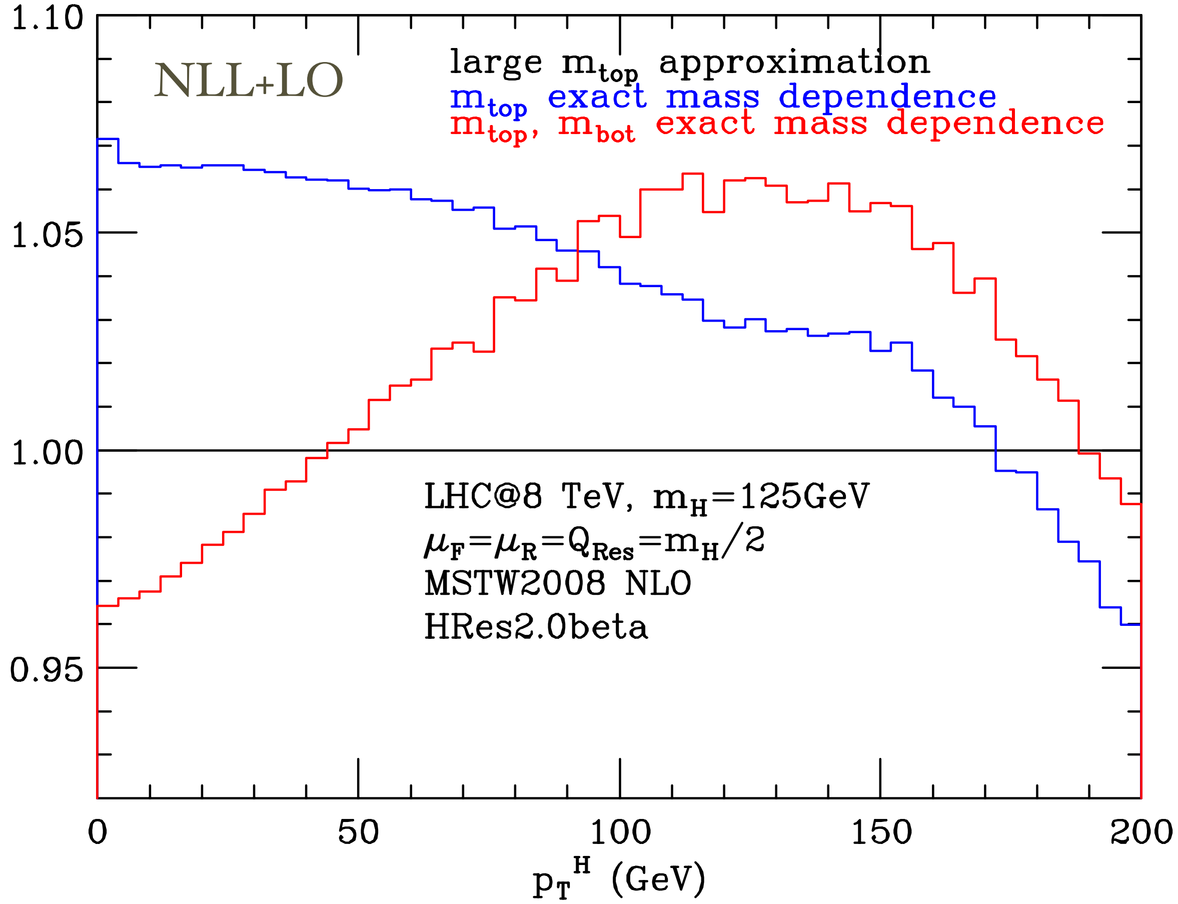
New version of HNNLO ready to be released

H.Sargsyan, MG (2013)

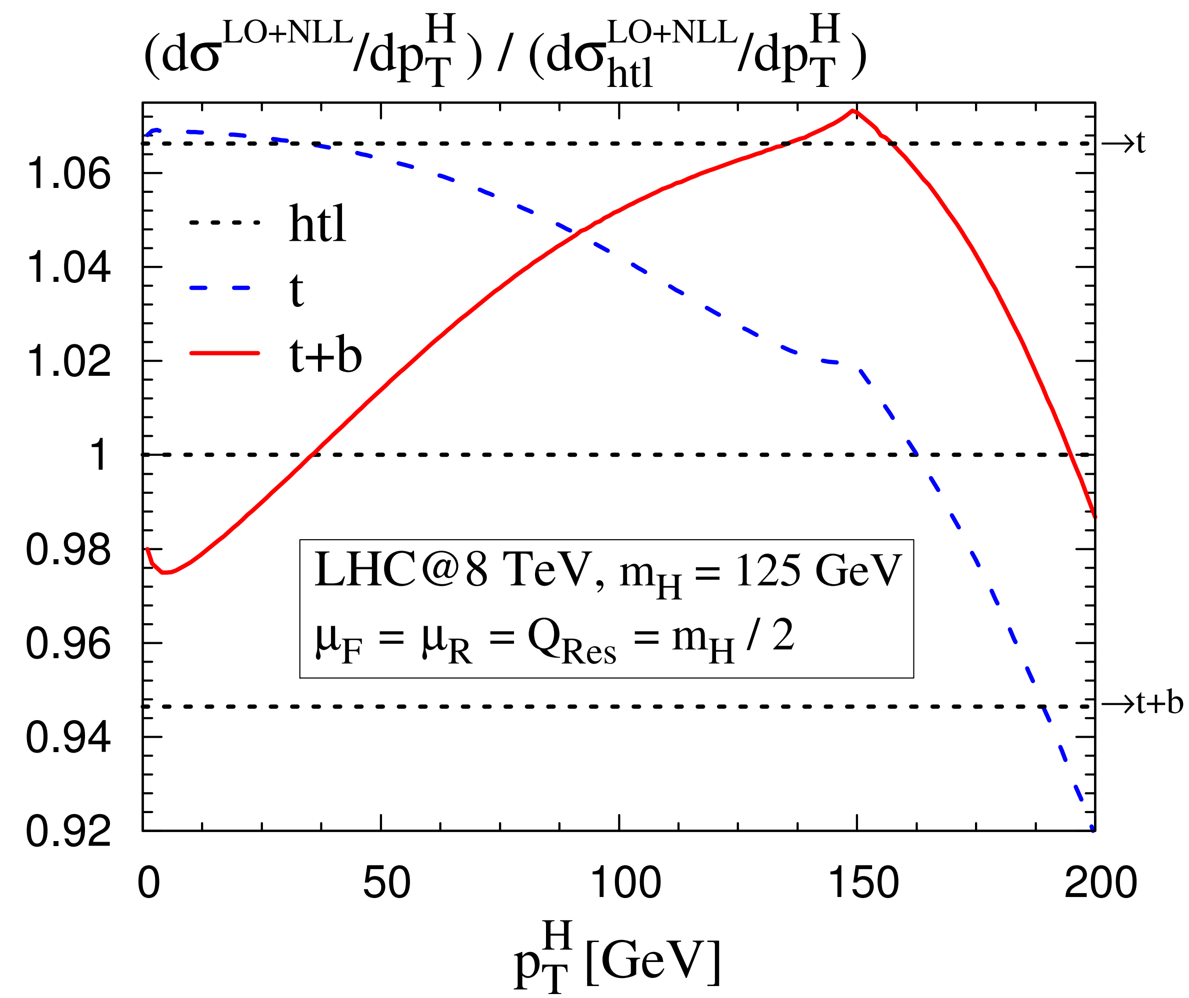
Good agreement with results of other authors

Anastasiou et al. (2009); E. Bagnaschi et al. (2012)

Going differential: p_T spectrum



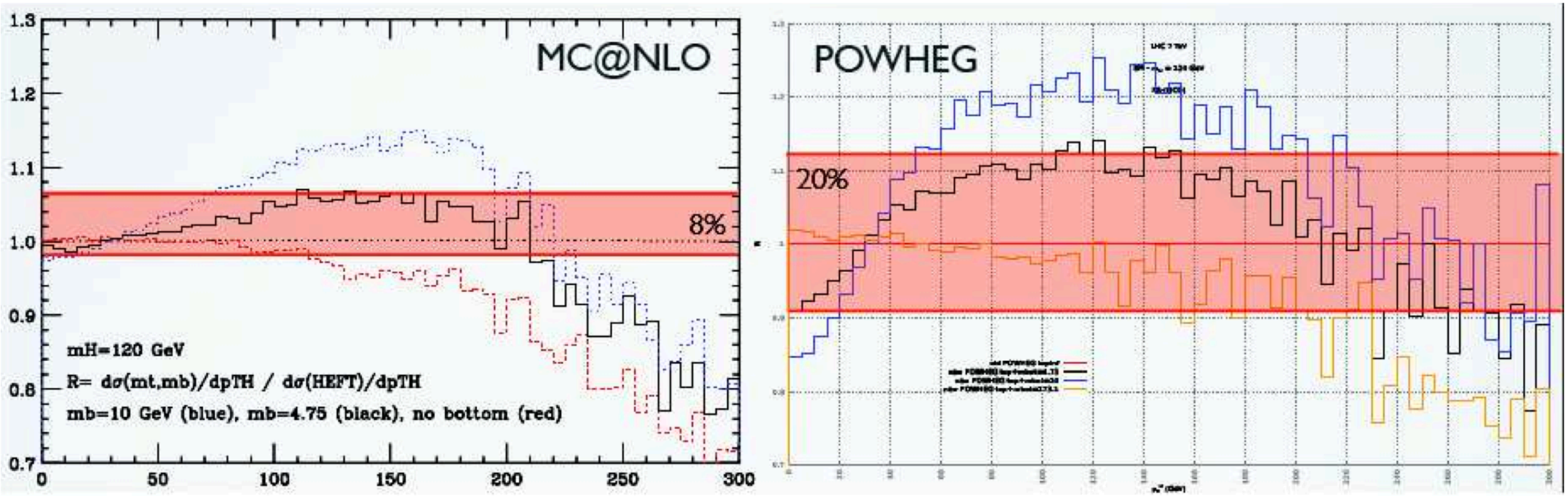
H.Sargsyan, MG



H.Mantler, M.Wiesemann (2012)

Similar work done on resummed p_T spectrum in HRes: good agreement with similar calculation appeared recently

Going differential: p_T spectrum



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

But what seems a trivial implementation of the exact real and virtual NLO matrix elements lead to large differences in MC@NLO vs POWEG

MC@NLO agrees rather well with analytic resummation whereas POWHEG appears to “amplify” the effect of the bottom mass

- Without bottom $p_T << m_H \sim m_{top}$ still 2-scale problem
- With bottom p_T, m_b, $m_H \sim m_{top}$ 3-scale problem !

The implementation of the bottom quark in the spectrum is non trivial

What if it is not spin zero ?

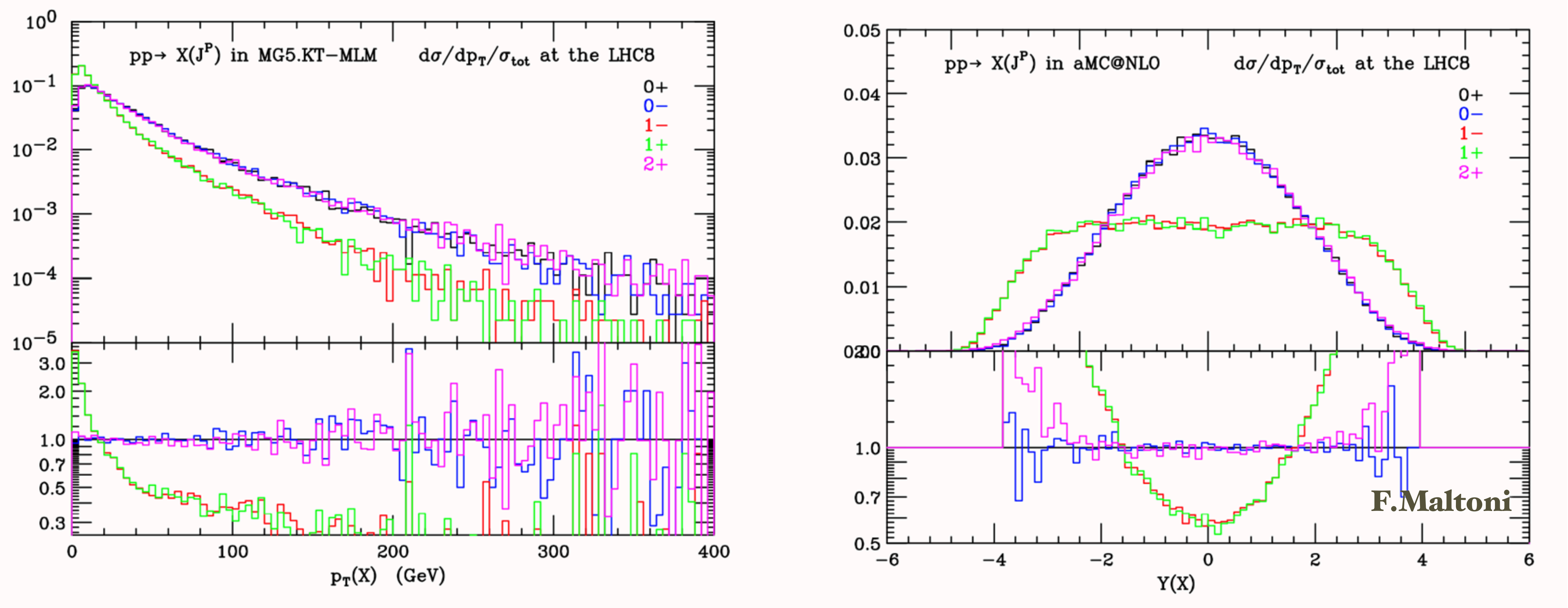
One of the most frequent questions asked by experimentalists in the last period is:

- How would the shape of the spectrum change in case the Higgs has spin 2 ?

This question is not well posed, since the shape is strongly driven by the production channel (so it has actually little to do with the spin)

Gluons radiate more than quarks → The gg initial state tends to produce harder spectra than the qqb initial state

What if it is not spin zero ?



gg or qqbar initial state is of great importance.

→ Better to choose a benchmark model and study it !

Going differential: jet bins

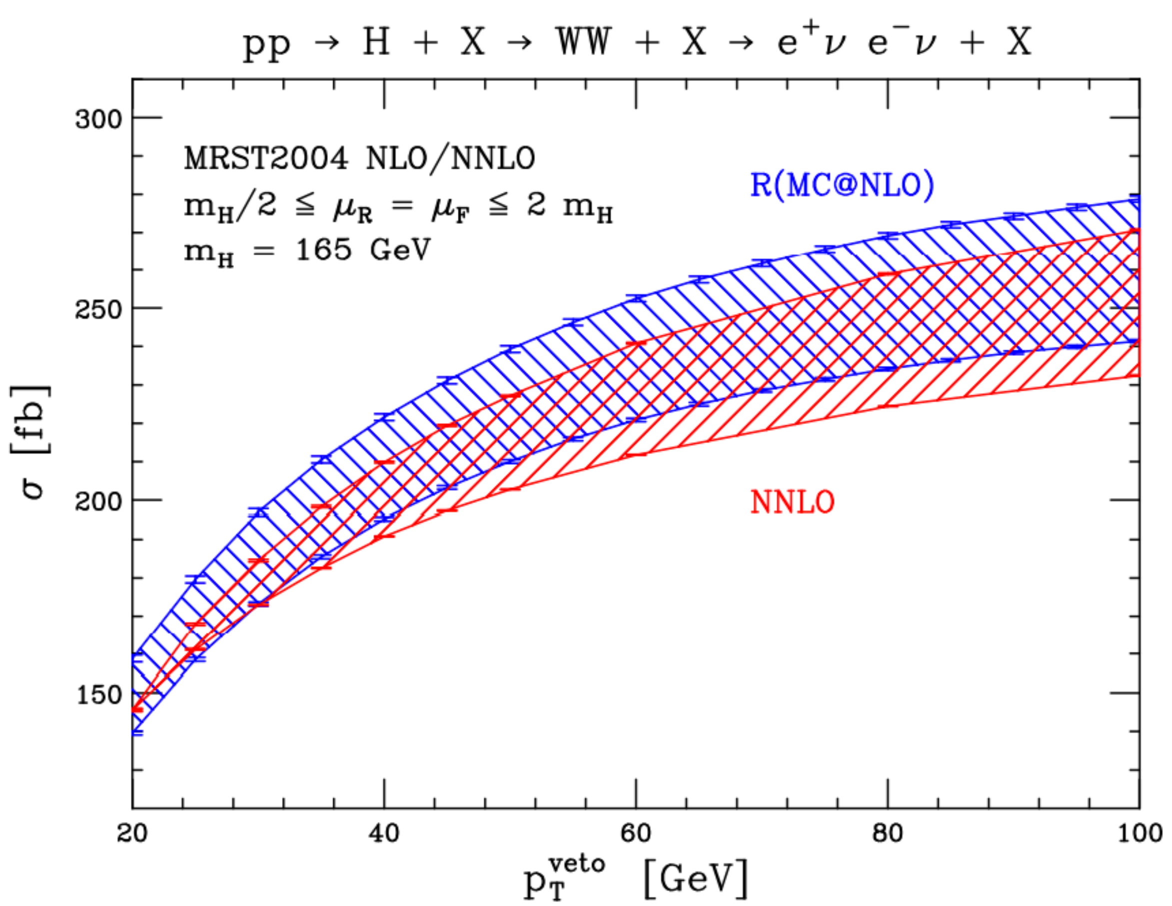
Experimental analysis often split into jet bins → Introduce a scale p_{Tveto}

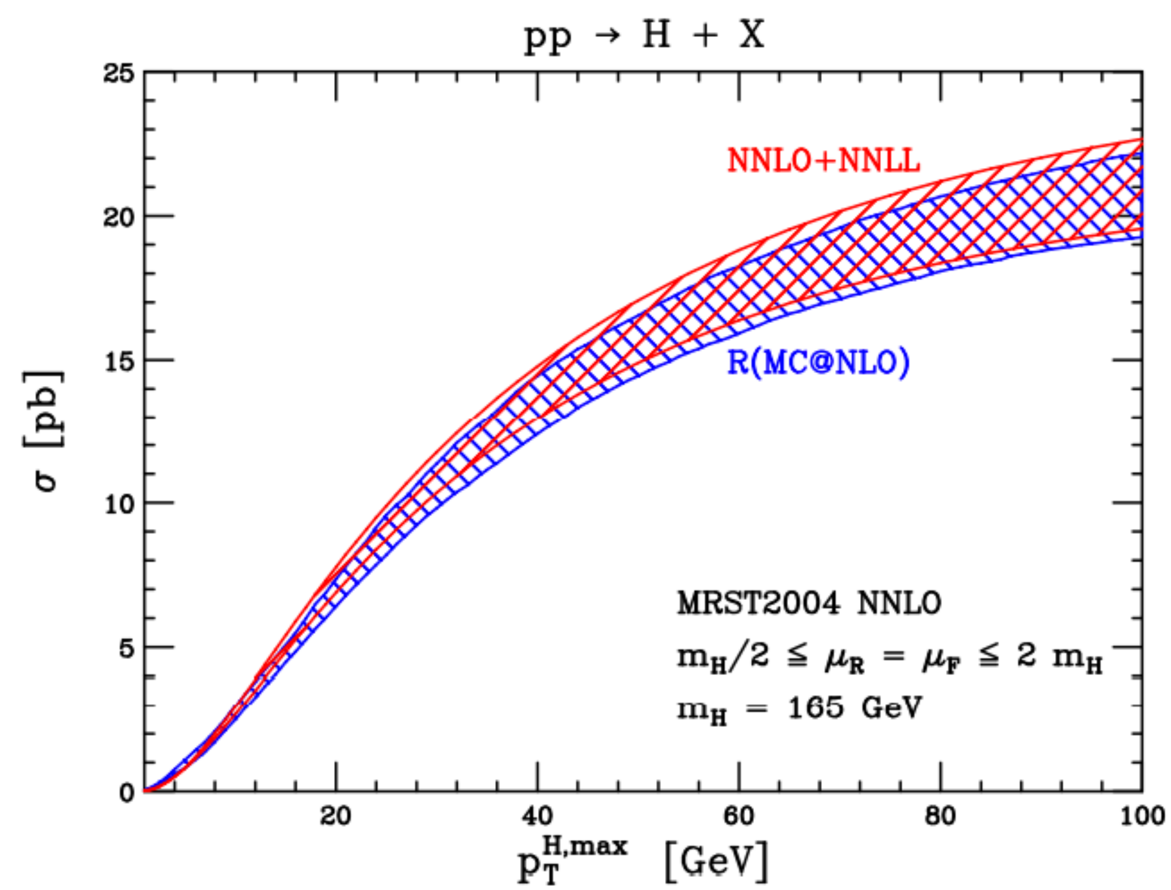
Large logarithmic terms could spoil perturbative convergence

Is theoretical description under control ?

Detailed comparison between MC, p_T resummed and NNLO results performed few years ago

→ Good agreement found





C.Anastasiou, G.Dissertori, F.Stoeckli, B.Webber (2008)

C.Anastasiou, G.Dissertori, MG, F.Stoeckli, B.Webber (2009)

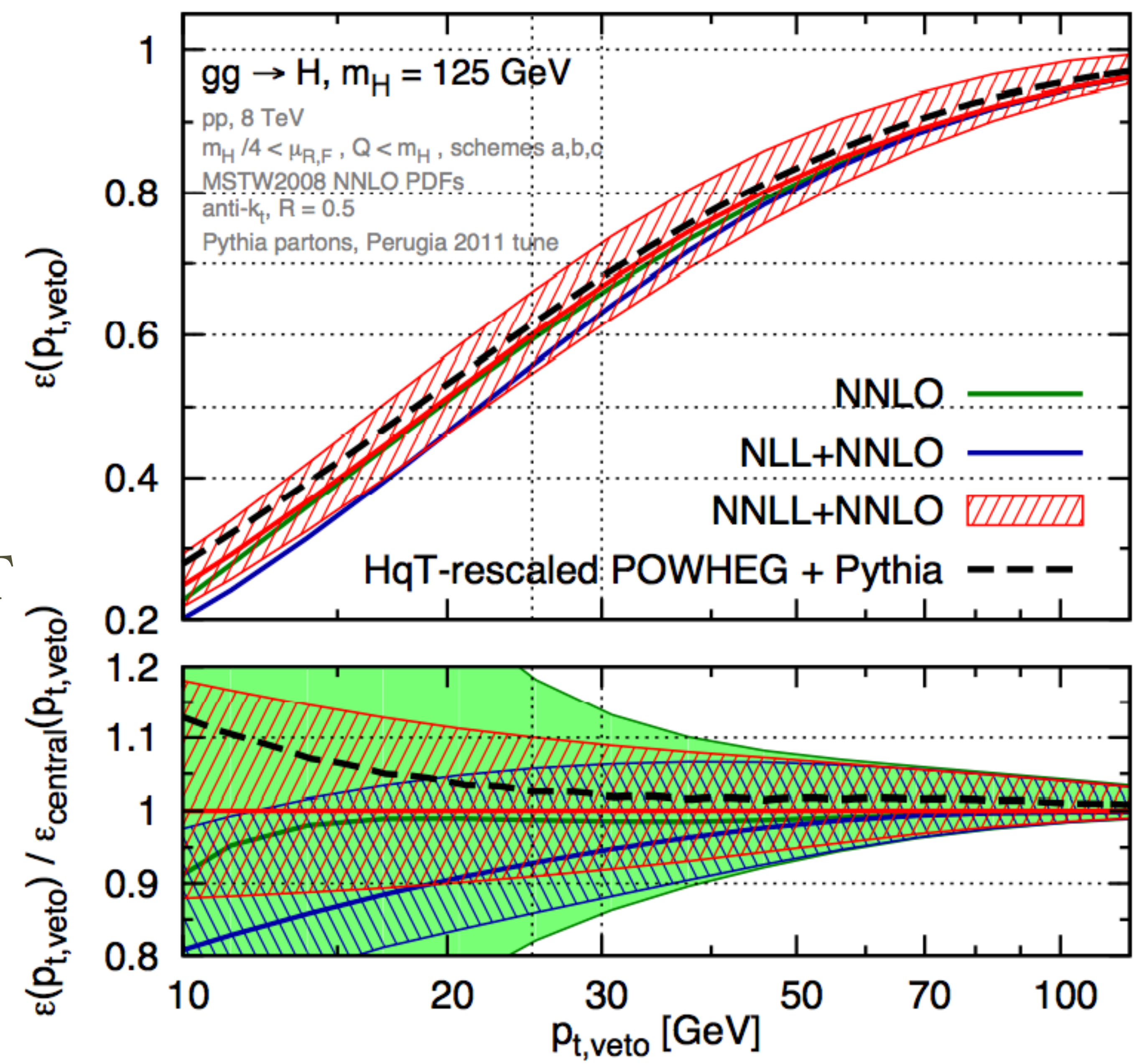
Going differential: jet bins

But uncertainties obtained from naive scale variations of the jet vetoed cross section typically too small to be realistic I.Stewart, F.Tackmann (2011)

Now resummation for jet vetoed cross section is available !

Good agreement obtained by using naive rescaling with NNLL+NNLO calculation of p_T spectrum with HqT

For values of p_{Tveto} used by ATLAS and CMS the large logs are not so large !



A.Banfi, P.Monni, G.Salam, G.Zanderighi (2012)

(see also related work by Becher-Neubert and Tackmann et al.)

Summary & Outlook

- Gluon fusion is the main production channel of the SM Higgs boson
- Theoretical predictions seem in good shape and it is unlikely that big higher order effects have been missed
- Nonetheless a renewed effort is being put in extending the calculation of the inclusive cross section to N^3LO
- Among the various kinematical distributions the p_T spectrum is one of the most important for the analyses
- Inclusion of previously neglected heavy-quark mass effects leads to relatively large difference in the shape between MC@NLO and POWEG

  → Still to be understood and presently limiting the accuracy

- New calculations of the jet vetoed cross section help in better quantifying the theoretical uncertainties in the analyses split into jet bins

BACKUP SLIDES

Uncertainties on ggF

- Scale uncertainty: ±7-8 % at 8 TeV

- Implementation of EW corrections:
  changing to the "partial" factorization scheme would lead to an effect going from -3 % (m_H=115 GeV) to +1 % (m_H=300 GeV)

- Large-m_{top} approximation:
  recent work by Harlander, Steinhauser and collaborators shows that it works to better than 0.5 % for $m_H \leq 300$ GeV
  → important confirmation of the accuracy of this approximation

  For a heavier Higgs the uncertainty increases and should not be neglected

- PDF uncertainties: ±7-8 %