Recent developments in inclusive and differential Higgs cross sections

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Higgstools: first annual meeting
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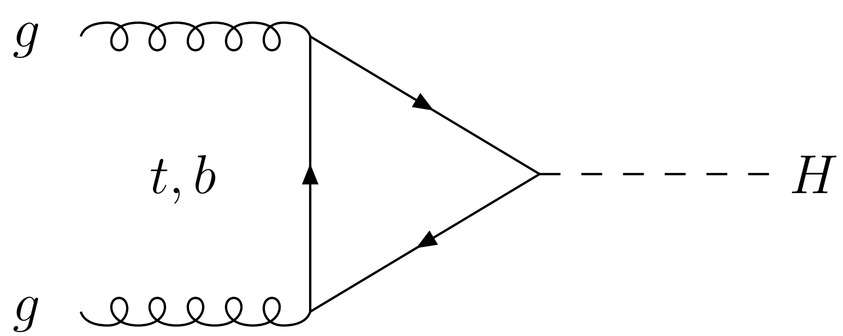
Outline

- ggF
  - N3LO result and quantitative impact
  - Higgs p_T spectrum
  - NNLO+PS matching
- VH+VBF
- ttH
- Summary

gg fusion



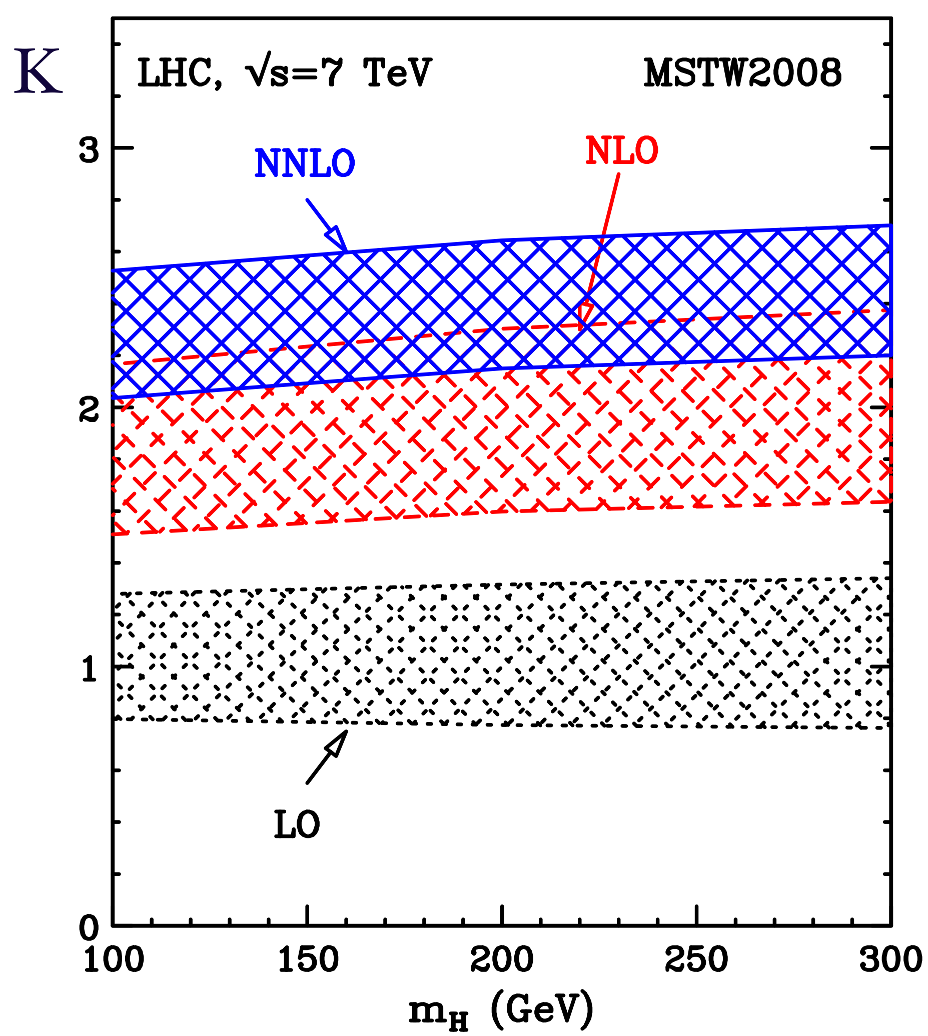
The Higgs coupling is proportional to the quark mass

→ 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 $1/2 < \mu_F/\mu_R < 2$

gg fusion

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about +6-9% 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)

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

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

The large-m_{top} approximation

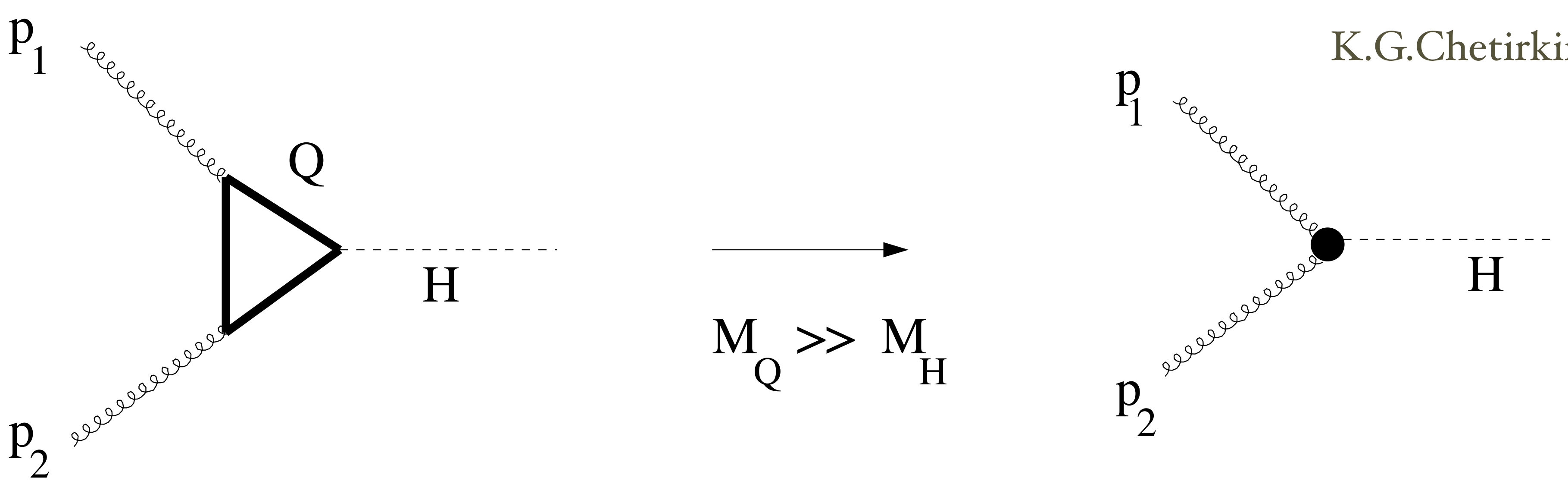
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

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**

Approximated N3LO

The N3LO race started with the computation of SV corrections about one year ago

C.Anastasiou, C.Duhr, F.Dulat, E.Furlan, T.Gehrmann, F.Herzog, B.Mistlberger (2014)

$$\hat{\sigma}_{ij}^{(3)} = \delta_{ig}\,\delta_{jg}\hat{\sigma}_{SV}^{(3)} + \sum_n c_{ij}^{(3,n)}(1-z)^n$$

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

"distance" from partonic threshold

Approximated N3LO result based on analyticity in Mellin space

M.Bonvini,R.Ball, S.Forte, S.Marzani, G.Ridolfi (2014)

Logarithmic corrections beyond SV approximation obtained and used to present N3LO approximated results

D. de Florian, J.Mazzitelli, S.Moch, A.Vogt (2014)

Next-to-soft corrections presented five-months ago

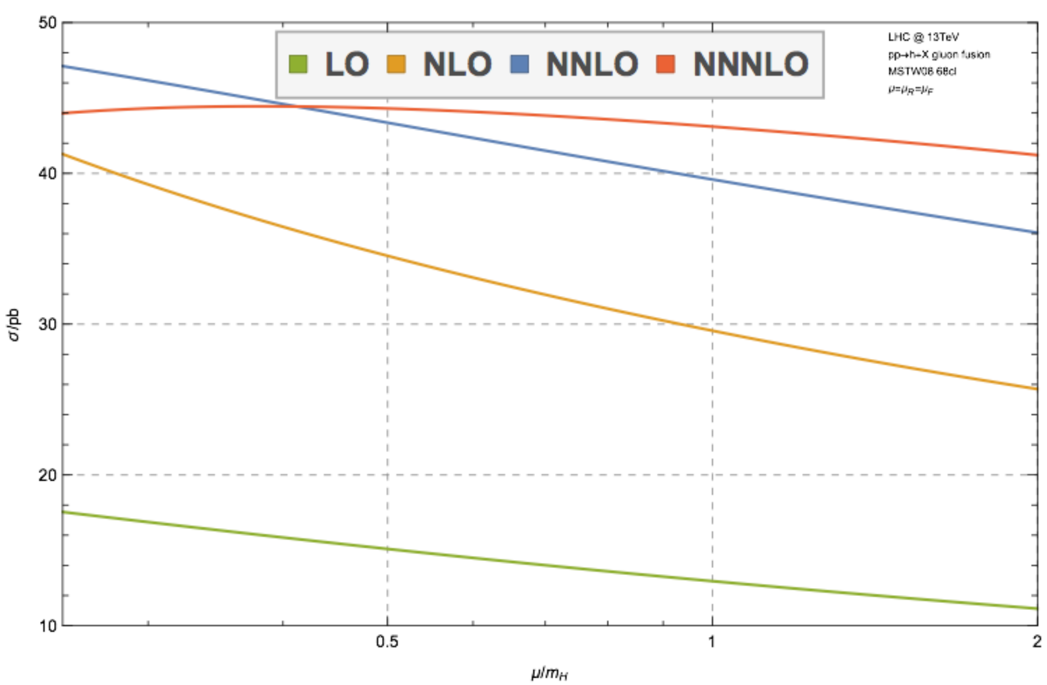
C.Anastasiou, C.Duhr, F.Dulat, E.Furlan, T.Gehrmann, F.Herzog, B.Mistlberger (2014)

Full N3LO

C.Anastasiou, C.Duhr, F.Dulat, F.Herzog, B.Mistlberger (2015)

Full calculation completed through the evaluation of 30 terms in the soft-expansion: first complete calculation at N3LO in hadronic collisions !

see talk by F.Dulat



Nice stabilisation of scale dependence around $\mu=m_H/2$

N3LO effect +2.2% at $\mu=m_H/2$

σ/pb	2 TeV	7 TeV	8 TeV	13 TeV	14 TeV
$\mu = \frac{m_H}{2}$	$0.99^{+0.43\%}_{-4.65\%}$	$15.31^{+0.31\%}_{-3.08\%}$	$19.47^{+0.32\%}_{-2.99\%}$	$44.31^{+0.31\%}_{-2.64\%}$	$49.87^{+0.32\%}_{-2.61\%}$
$\mu = m_H$	$0.94^{+4.87\%}_{-7.35\%}$	$14.84^{+3.18\%}_{-5.27\%}$	$18.90^{+3.08\%}_{-5.02\%}$	$43.14^{+2.71\%}_{-4.45\%}$	$48.57^{+2.68\%}_{-4.24\%}$

→ What is the impact on phenomenology ?

N3LO impact: a simple exercise

To obtain a state-of-the-art prediction it is essential to include heavy-quark mass effects and EW corrections

This can be done by using HIGLU and well known results in the large m_t limit

Let us focus on $\sqrt{s}$=8 TeV: from N3LO result in the large-m_t limit one can easily extract the contribution $\Delta\sigma$ of $O(\alpha_S^4+\alpha_S^5)$ terms and combine it with the NLO result with exact dependence on heavy quark masses

m_t=172.5 GeV

m_b=4.75 GeV

m_c=1.42 GeV

σ_{NLO}=15.22 pb

$\mu_F=\mu_R=m_H/2$

$\Delta\sigma$=4.25 pb → rescale it with exact $\sigma_{LO}(m_t)$

$\sigma_{NLO}(m_t,m_b,m_c)/\sigma_{NLO}(m_t \to \infty)=0.983$ $\quad$ $\sigma_{LO}(m_t)/\sigma_{LO}(m_t \to \infty)=1.066$

→ $\sigma_{N3LO}=(15.22*0.983+4.25*1.066)*1.0514$ pb=20.49 pb

EW correction (G.Passarino et al. 2008)

N^3LO impact: a simple exercise

Analogous calculation done at $\mu=m_H$ gives: $\sigma_{N3LO}=19.94$ pb

(3% smaller than at $\mu=m_H/2$)

Current recommendation gives $\sigma_{NNLL+NNLO}=19.27^{+1.39}_{-1.50}$ pb (scale)

D. de Florian, MG (2012)

→ **N^3LO prediction at $\mu=m_H/2$ higher by 6% with respect to the current recommendation but perfectly consistent with it within scale uncertainties**

(note that 4% comes from NNLO !)

- ggF cross section seems to be under better control (but we still should be conservative about uncertainties !)
- It will be important now to reassess the uncertainties coming from EW effects, large-m_t approximation, PDFs.......

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

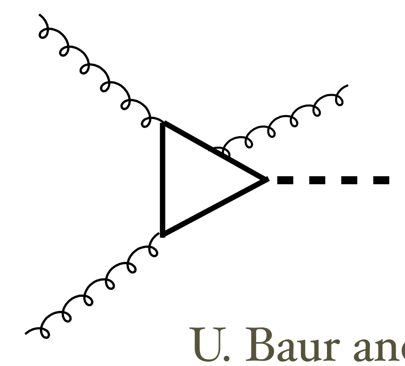
→ Effect of QCD radiation mainly encoded in the p_T spectrum

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

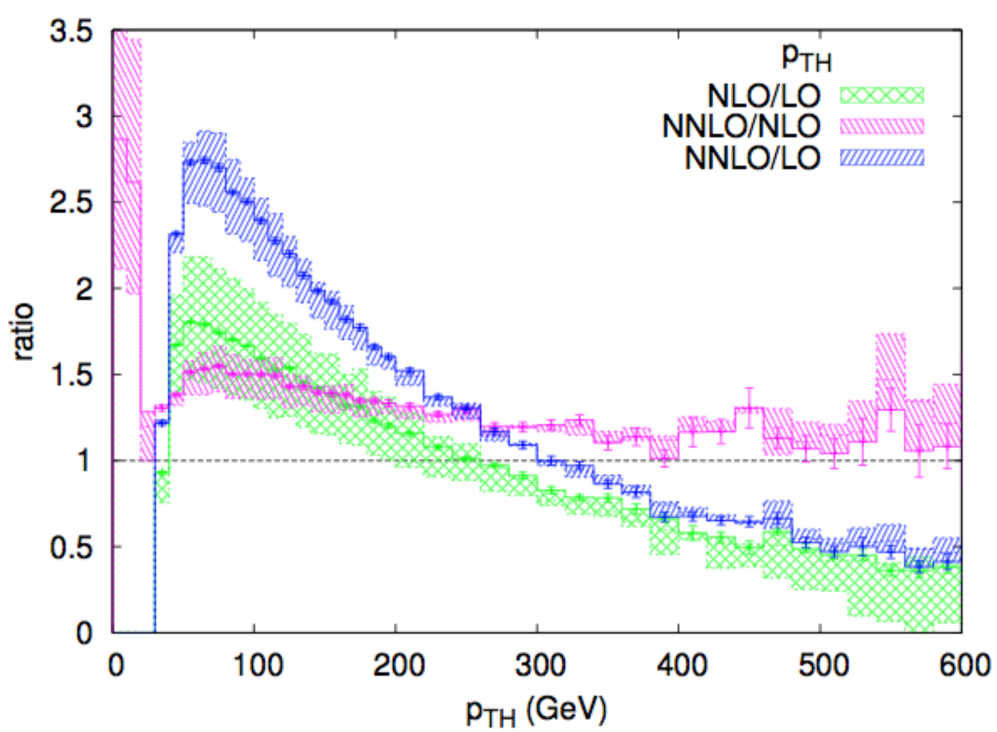


➡ the LO is of relative order α_S
exact result known for many years

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

NLO corrections are known only in the large-m_t 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

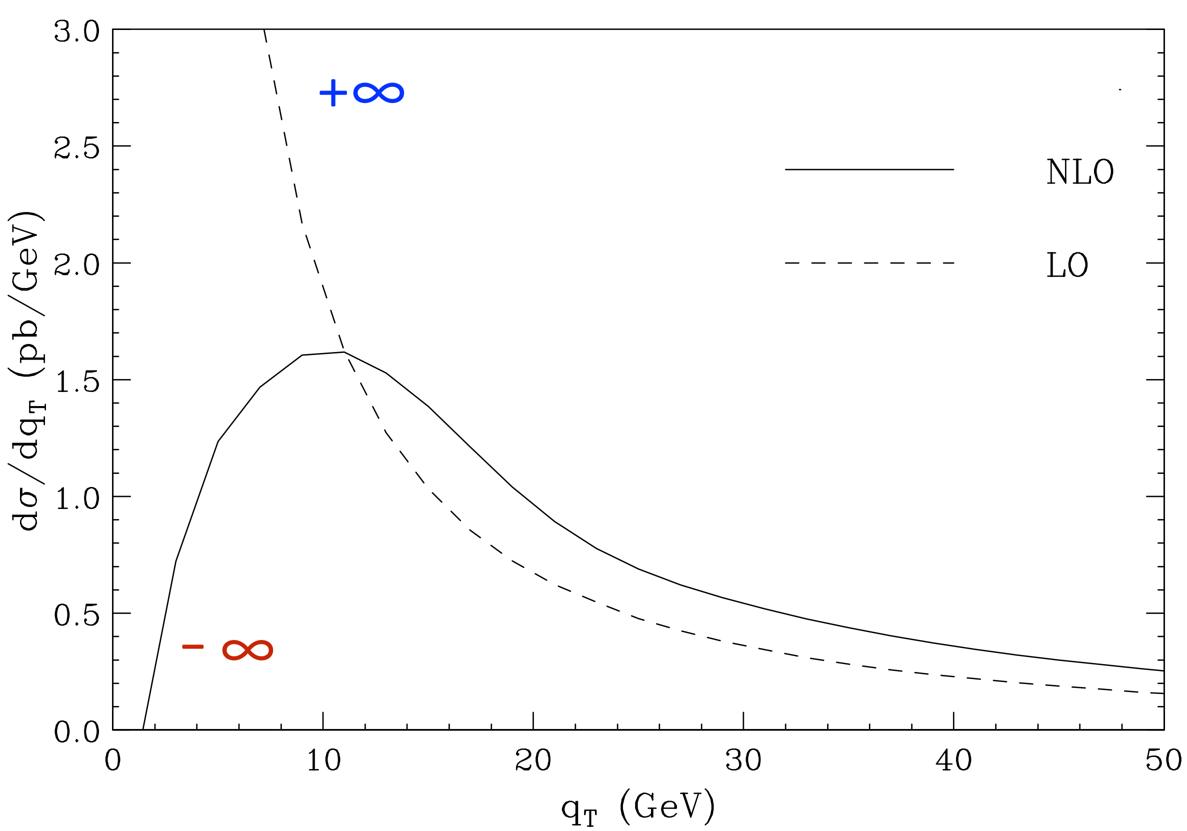
➡ quantitative effect appears to be large

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

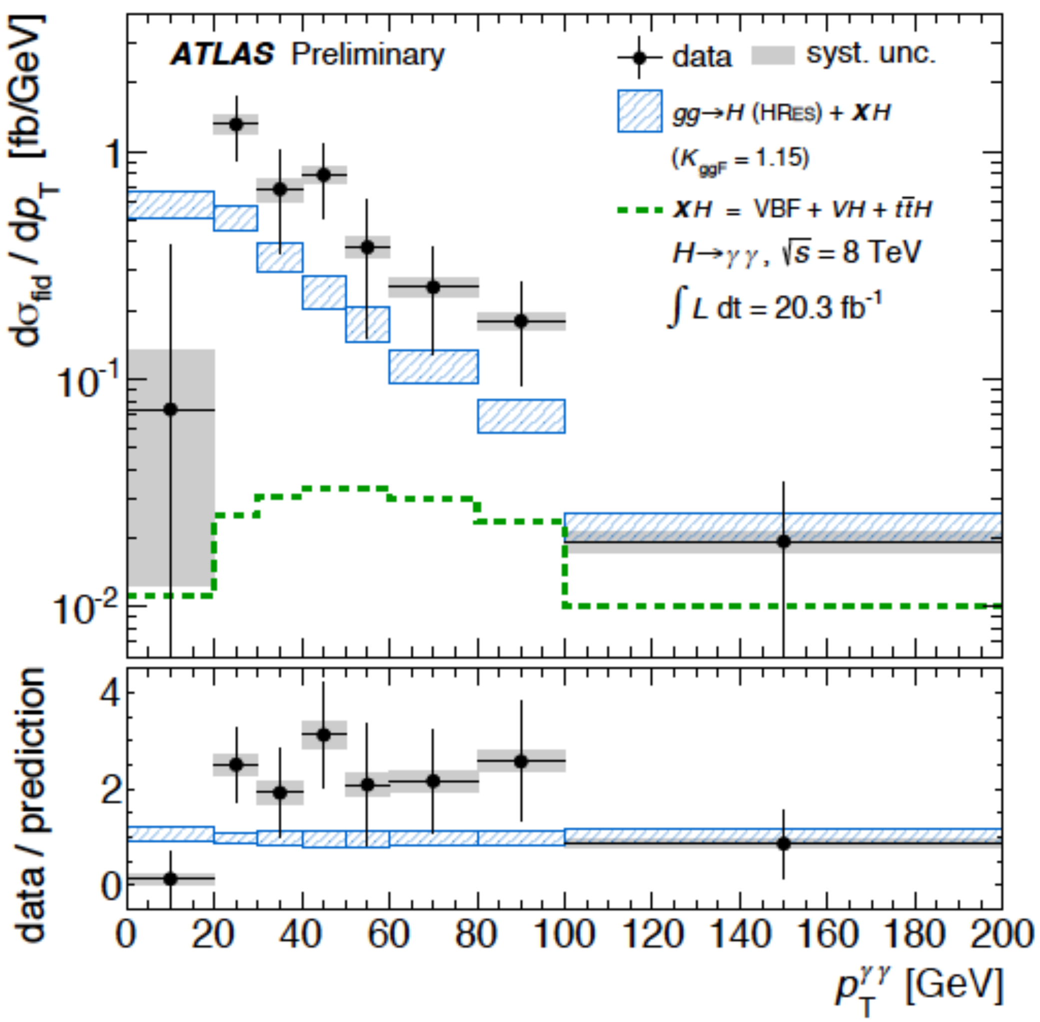
NLO: $\frac{d\sigma}{dp_T} \to -\infty$ as $p_T \to 0$

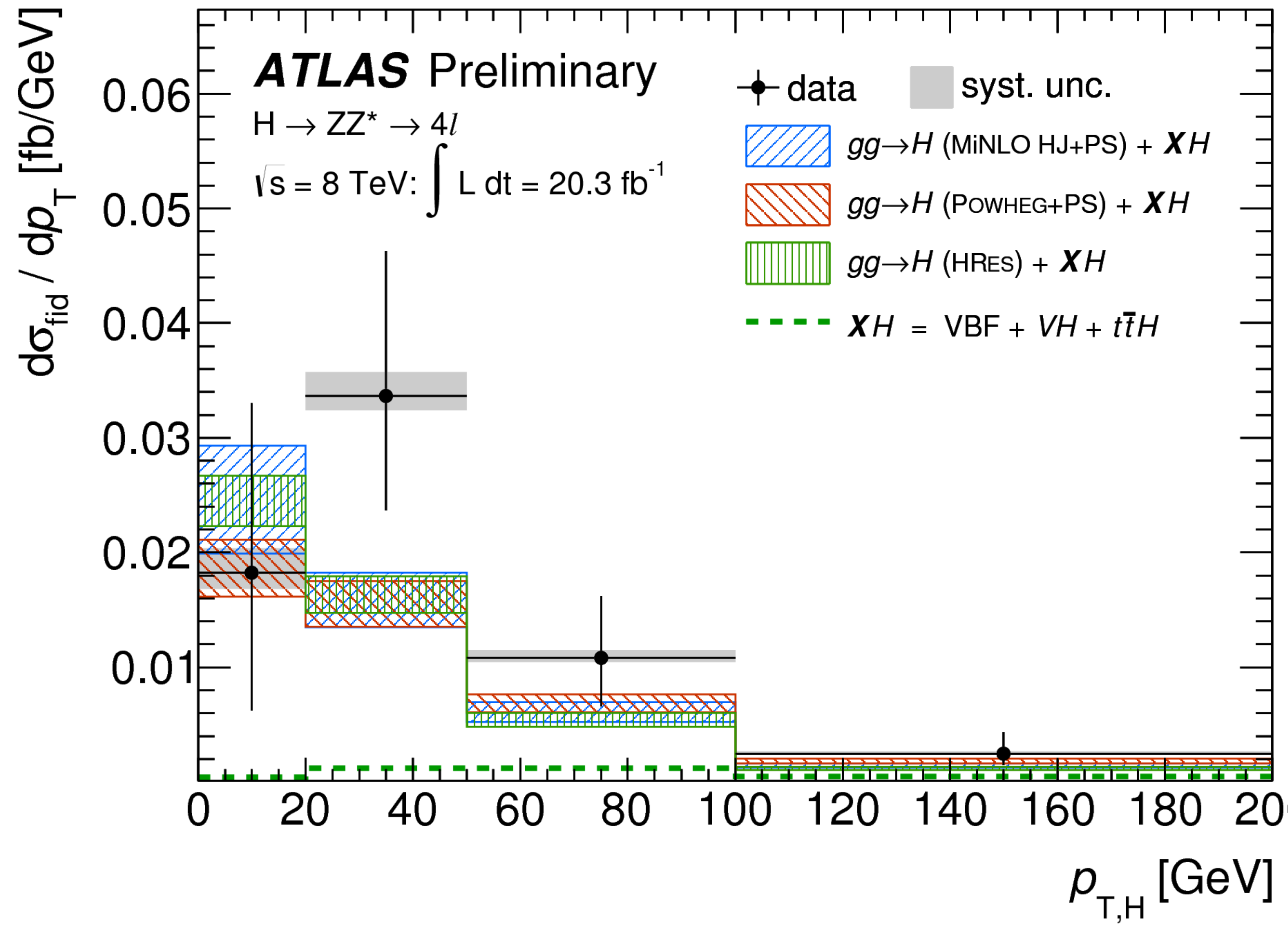
→ RESUMMATION NEEDED
(effectively performed by standard MC generators)

State of the art NNLL+NNLO results including mass effects available from HRes

D. de Florian, G.Ferrera, D. Tommasini, MG (2011)
H.Sargsyan, MG (2013)

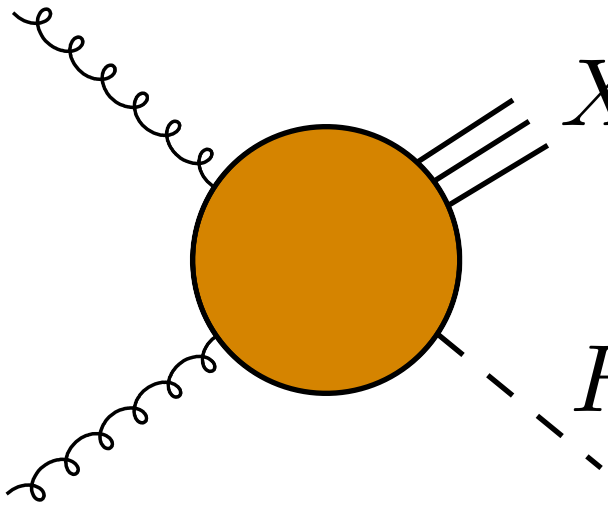
The first data





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

p_T spectrum: what else ?



Higgs production at high-p_T can be useful to test new physics scenarios

- models with modified couplings to gluons and top quark
- models with fermionic top partners

....

A.Azatov, A.Paul (2013)

A.Banfi et al. (2013)

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

$$\mathcal{L} = -c_t \frac{m_{top}}{v} \bar{\psi}\psi + \frac{\alpha_S}{12\pi} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

SM: $c_t = 1 \quad c_g = 0$

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

➡ Study their impact on the (resummed) p_T spectrum !

see talk by A.Ilnicka

A new player: NNLO matching

NLO matching well established (MC@NLO, POWHEG, Sherpa....)
NNLO matching still in its infancy

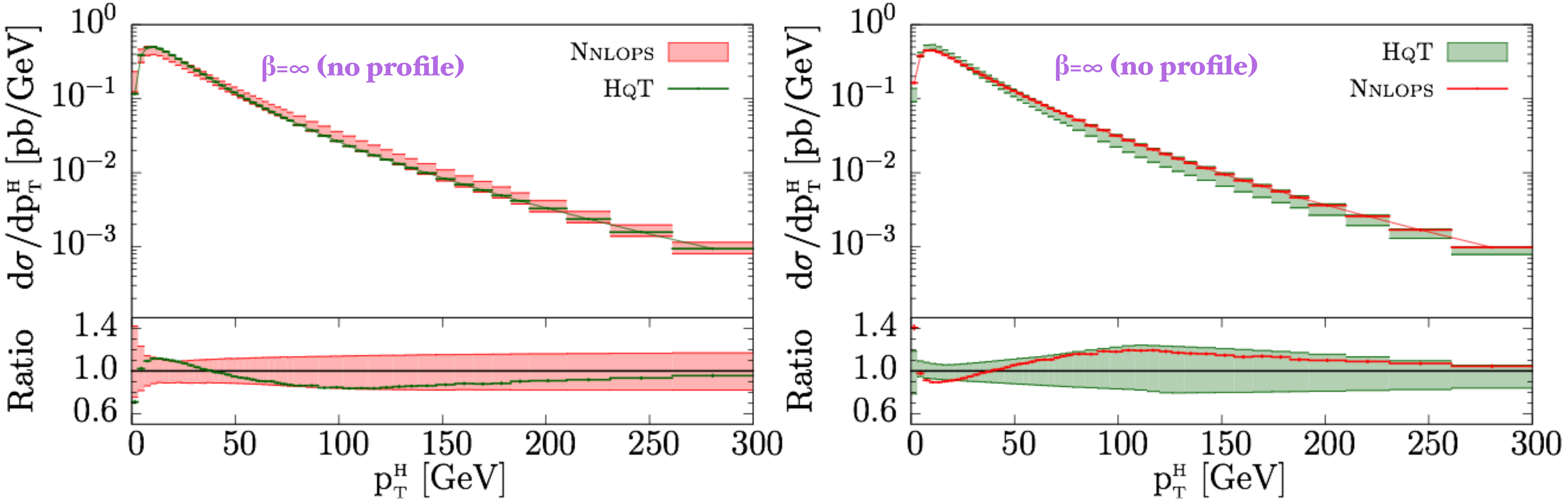
NNLOPS: use MINLO to obtain a NLO generator for both H and H+jet(s)

Enforce correct NNLO normalisation by reweighing the inclusive rapidity distribution to HNNLO

K.Hamilton, P.Nason, G.Zanderighi (2014,2015)

→ This is enough to achieve NNLO accuracy

Mass effects recently included HNNLO2.0

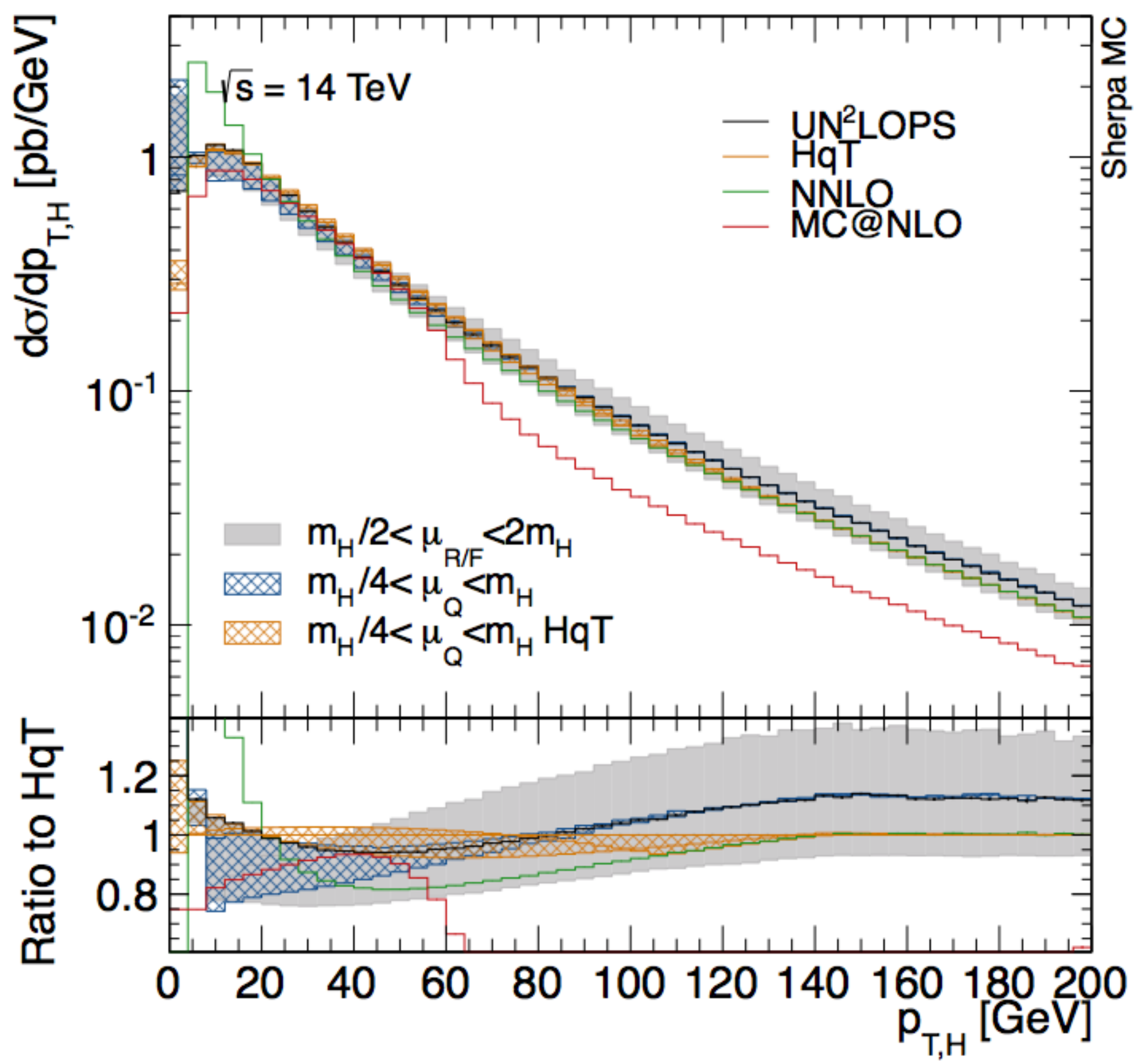


A new player: NNLO matching

UN²LOPS: use S-MC@NLO + UNLOPS + q_T slicing

N.Lavesson, L.Lonnblad (2008)
S.Hoeche, Y.Li, S.Prestel (2014)

Start from S-MC@NLO simulation for H+jet(s) for $p_T > p_{T\,cut}$ and complement it with NNLO information below the cut



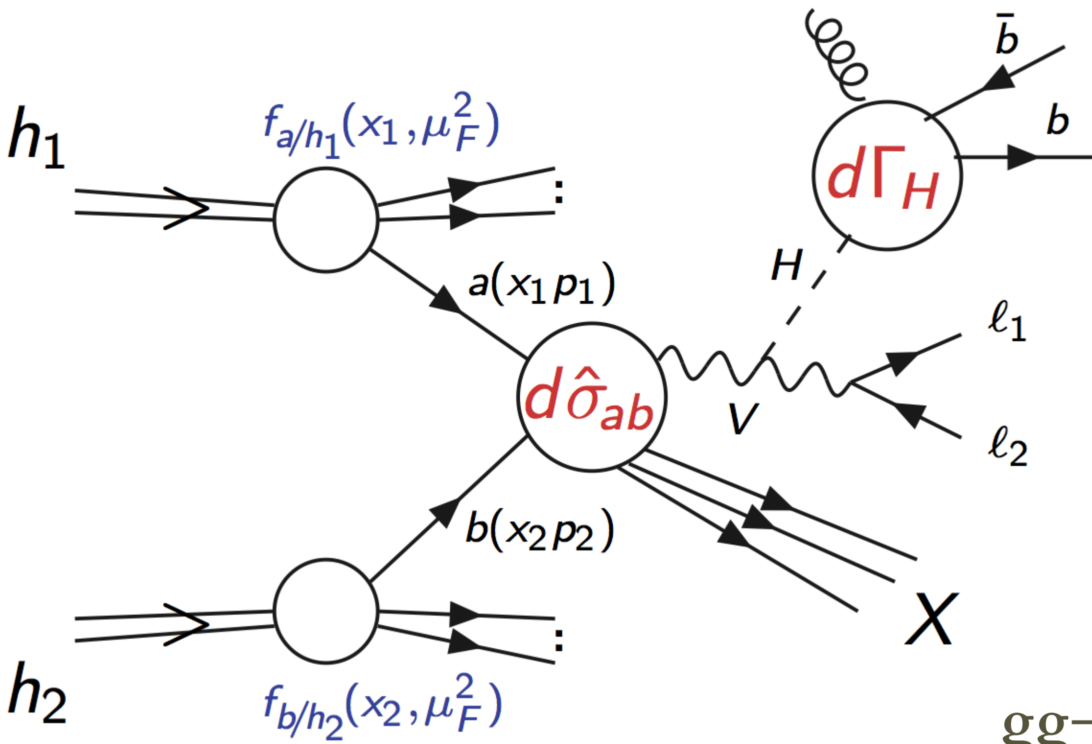
NNLO virtual corrections confined in the low p_T region while in the POWHEG-MINLO approach they are spread over the whole p_T region

A third approach is not implemented yet

S.Alioli et al. (2013)

➡ It would be interesting to carry out a quantitative comparison of the two approaches and a careful study of uncertainties

VH



Total cross section well under control (NNLO effects roughly the same as for Drell-Yan)

W.Van Neerven et al. (1991)
O.Brein, R.Harlander, A.Djouadi (2000)

Top mediated contributions (1-3%)

O.Brein, R.Harlander, M.Wiesemann, T.Zirke (2012)

gg→ZH loop induced (~ 5%) but crucial in boosted kinematics

B.Kniehl (1990)

NLO corrections known only in large m_t limit (~100%)

L.Altenkamp et al. (2012)

Fully differential NNLO corrections available, also including H→bb decay at NLO

G.Ferrera, F.Tramontano, MG (2011,2014)

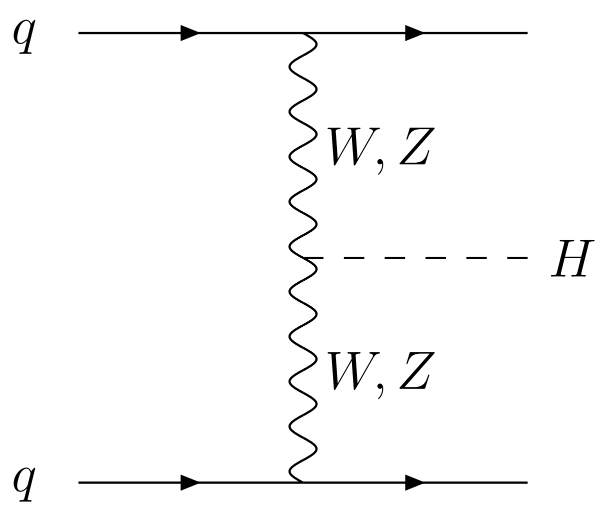
Fully differential H→bb decay at NNLO available

C.Anastasiou et al. (2012)
Z.Trocsanyi et al (2014)

NLO QCD+EW corrections available in HAWK

A.Denner, S.Dittmaier, S.Kallweit,A.Muck (2012)

VBF



QCD corrections at NLO of O(10%)

T. Han, S. Willenbrock (1991)
T. Figy, C. Oleari, D. Zeppenfeld (2003)
J. Campbell, K. Ellis (2003)

NLO QCD and EW interactions implemented in HAWK and VBFNLO: they tend to compensate each other

M.Ciccolini, A.Denner, S.Dittmaier (2007)

Other radiative contributions:

Interference with gluon fusion

Andersen, Binoth, Heinrich, Smillie (2007)
Andersen, Smillie (2008)
Bredenstein, Hagiwara, Jäger (2008)

Other refinements include some NNLO contributions like gluon-induced diagrams (well below 1%)

R.Harlander, J.Vollinga,M.Weber (2008)

and the more relevant DIS like NNLO contributions computed within the structure function approach (1% effect)

P.Bolzoni, F.Maltoni, S.Moch, M. Zaro (2010)

Hjj in NLO+PS implemented in POWHEG and aMC@NLO

ttH

Total cross section known at NLO: uncertainties at the level of 9% (scale) and 8% (PDF+α_S)

W.Beenhakker et al. (2001)
S.Dawson, L.Reina (2002)

NLO+PS implementations:

- MG5_aMC@NLO
- POWHEL samples
- POWHEG box (Jager et al. 2015)

For both signal and backgrounds it is crucial to account for spin correlations

R.Frederix et al (2014)

Included in MG5_aMC@NLO, POWHEG and SHERPA

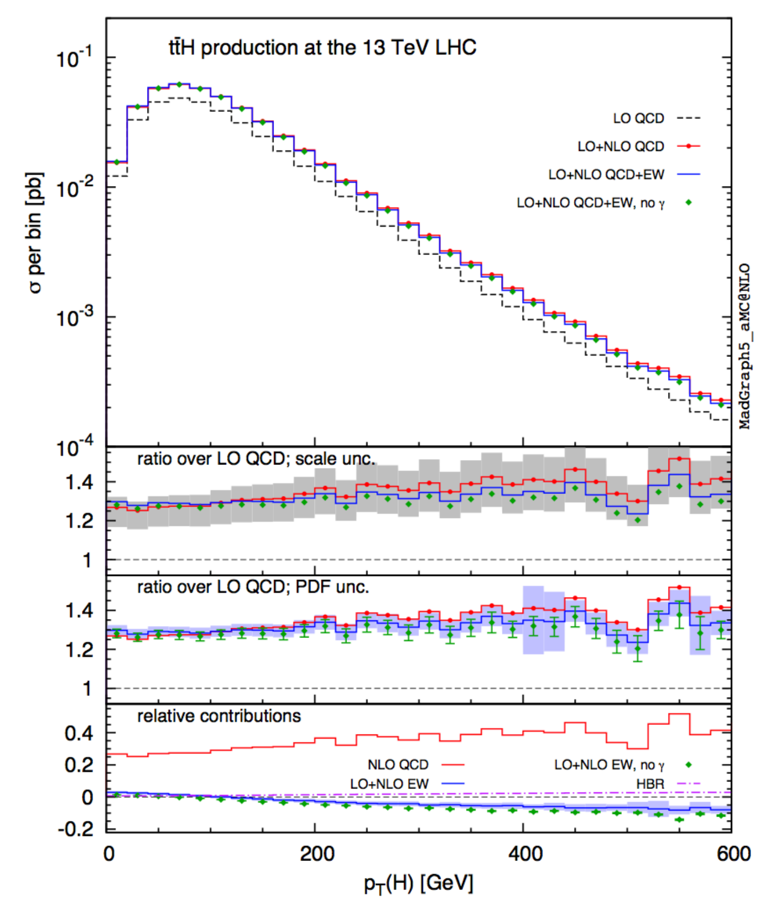
Important progress in EW corrections

- EW corrections in MG5_aMC@NLO

  ➡ -10% at high p_T

S.Frixione et al (2015)
see also Y.Zhang et al (2014)

- EW automation in Openloops underway



Summary

- I have presented a (personal) selection of recent results in the main Higgs production channels
- In gluon fusion the great news is the completion of the N^{3}LO: first ever calculation at this order in hadron collisions !

  - N^{3}LO perfectly consistent with current HXSWG recommendation

  - N^{3}LO corrections are moderate but important reduction in scale uncertainties

  - We look forward for the publication of the explicit N^{3}LO result

  - Higgs p_T spectrum can provide a handle to test new physics scenarios

  - I have discussed two NNLO+PS tools: interesting possibility to incorporate NNLO effects in the MC tools but still limited logarithmic accuracy

- I have flashed a selection of recent results in VH, VBF and ttH