Higgs WG: theory

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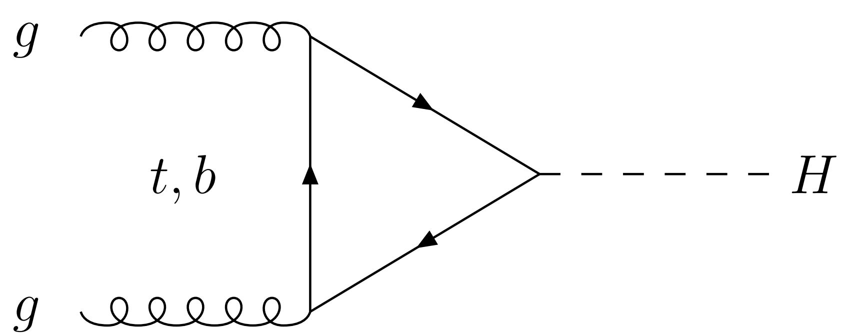
Outline

- gluon fusion
  - N3LO result and quantitative impact
  - H+jet(s) at NNLO
  - Higgs p_T spectrum
  - NNLO+PS matching
- VH, VBF, ttH
- Higgs decays
- Off-Shell/Interference
- Double Higgs production
- Items for discussion

gg fusion



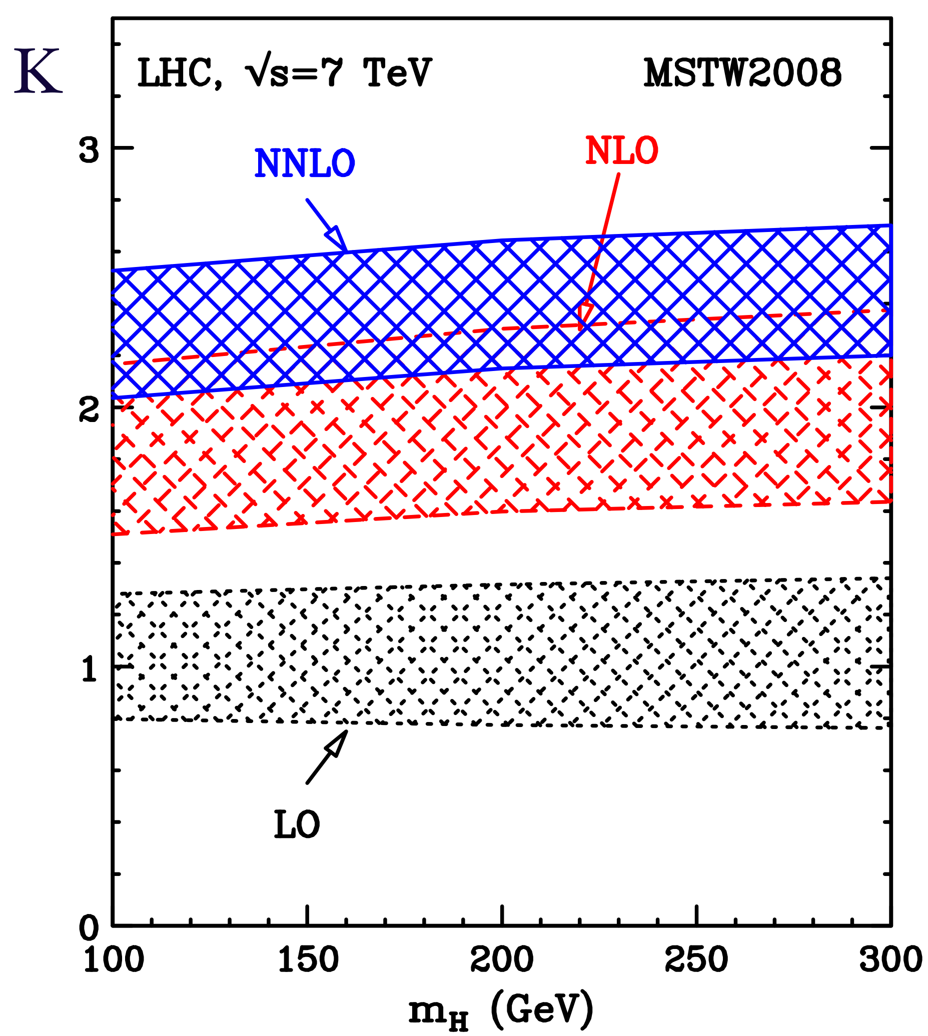
The Higgs coupling is proportional to the quark mass

→ 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

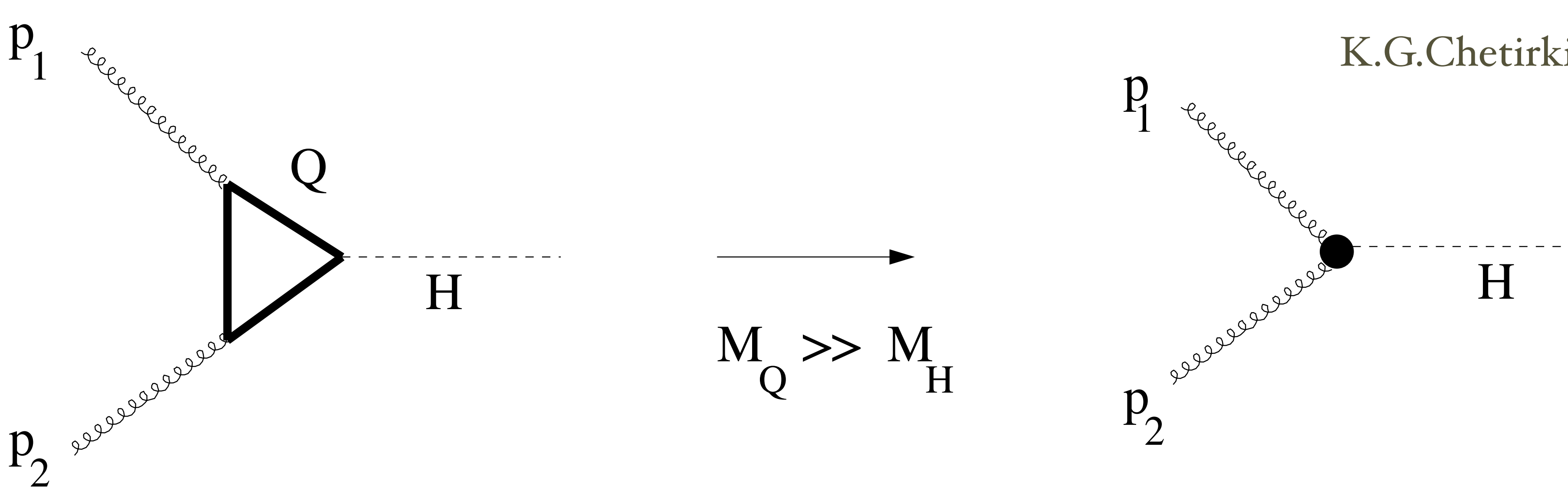
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

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)

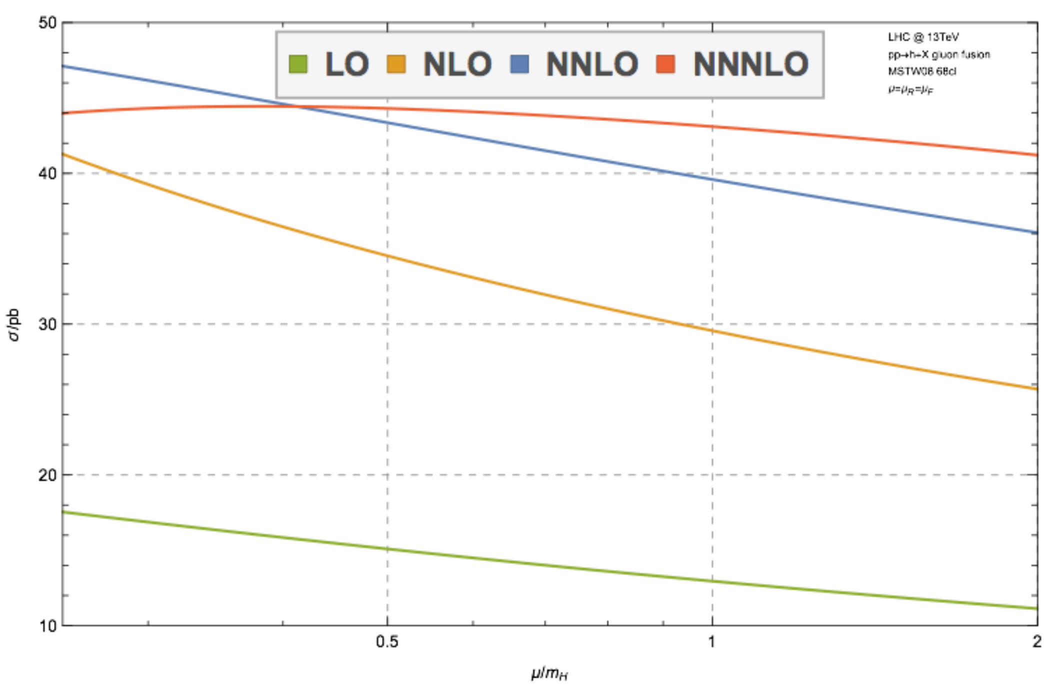
Next-to-soft corrections presented few months ago

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 !



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

Waiting for a throughout assessment of the newly computed corrections from Anastasiou et al. we can easily obtain a first estimate of their impact

This can be done by using exact NLO (obtained for example from 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 $\sigma_{LO}(m_t)$

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

$\sigma_{LO}(m_t)/\sigma_{LO}(m_t \to \infty)=1.066$

→ $\sigma_{N3LO}=(15.22*0.983+4.25*1.066)*1.0514$ 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 (at $\mu=m_H$ the effect is 3%)

- 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, α_S.......

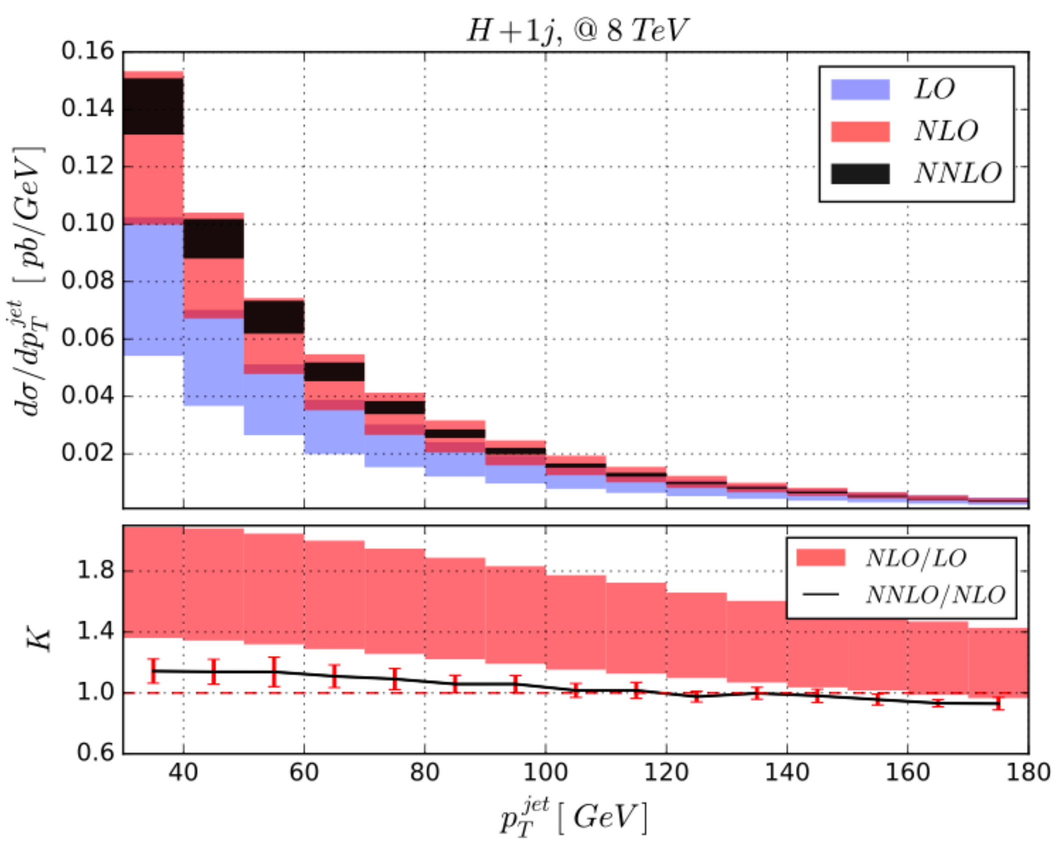
→ **A meeting on these issues is scheduled for june 8 14.30-16.30**

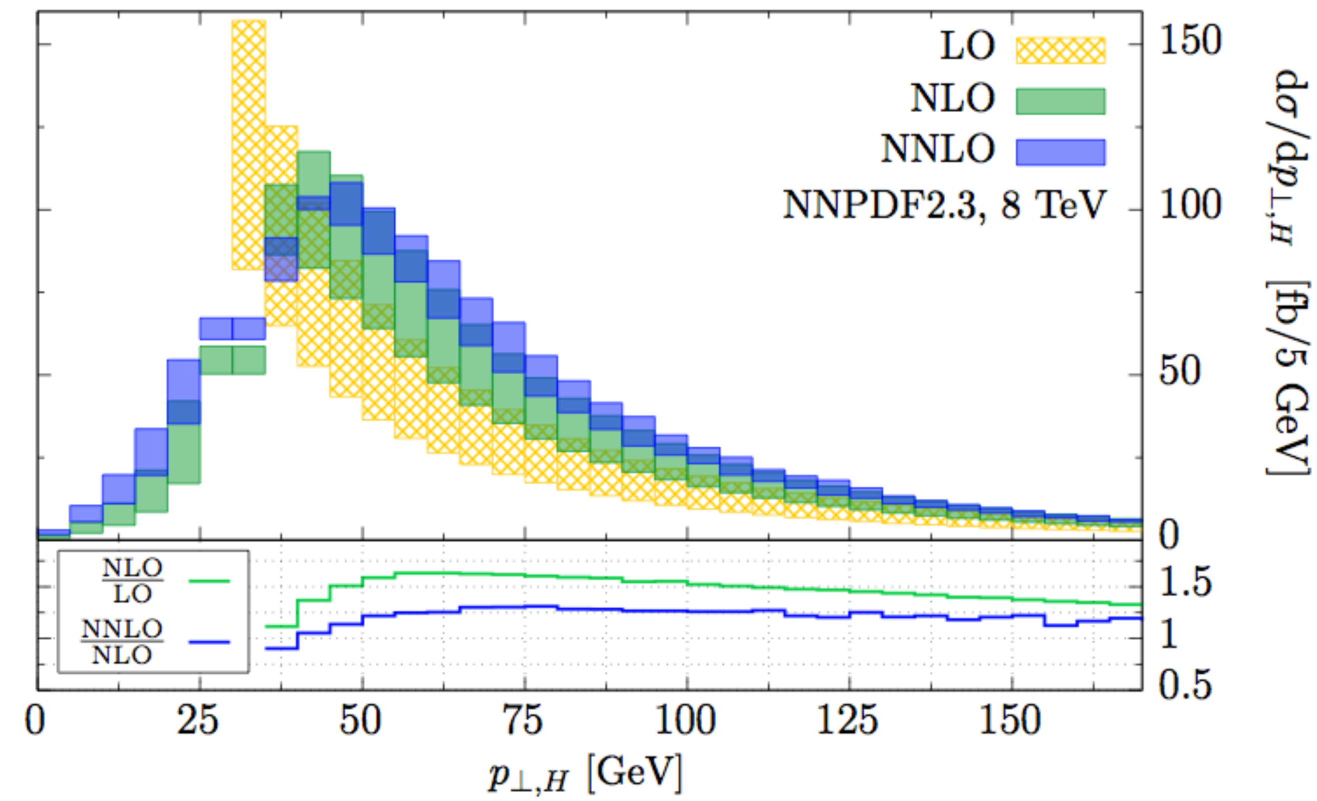
H+jet(s) at NNLO

R.Boughezal, F.Caola, K.Melnikov, ,F.Petriello, M.Schulze (2015)
R.Boughezal, C.Focke, W.Giele ,X.Liu, F.Petriello (2015)
(see also X. Chen, T. Gehrmann, E.W.N. Glover, M. Jaquier (2014))

The N3LO calculation of the inclusive cross section is followed by the NNLO computation of the H+jet cross section (note: both $O(\alpha_S^5)$)

Calculation carried out with three independent methods !





quantitative effect smaller than previously anticipated from gg only: at the 20% level ($\mu=m_H$)

H+jet(s) at NNLO

R.Boughezal, F.Caola, K.Melnikov, ,F.Petriello, M.Schulze (2015)
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(see also X. Chen, T. Gehrmann, E.W.N. Glover, M. Jaquier (2014))

The cross section in the 0-jet bin at a given order can be obtained by subtracting the H+jet cross section at the same order in α_S (started in Les Houches 2001 !)

S.Catani, D. de Florian, MG (2002)

➡ It is now possible to obtain the 0-jet cross section at N³LO

$\sqrt{s}$=13 TeV p_T = 30 GeV   anti-kt R=0.5

0-jet bin

ord	$\sigma_{0-\mathrm{jet}}^{\mathrm{f.o.}}$ (JVE)	$\sigma_{0-\mathrm{jet}}^{\mathrm{f.o.+NNLL}}$ (JVE)	$\sigma_{0-\mathrm{jet}}^{\mathrm{f.o.+NNLL}}$ (scales)
NNLO	$26.2^{+4.0}_{-4.0}$ pb	$25.8^{+3.8}_{-3.8}$	$25.8^{+1.6}_{-1.6}$
N^{3}LO	$27.2^{+2.7}_{-2.7}$ pb	$27.2^{+1.4}_{-1.4}$	$27.2^{+0.9}_{-0.9}$

≥1-jet bin

ord	$\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{f.o.}}$ (scales)	$\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{f.o.}}$ (JVE)	$\sigma_{\geq 1-\mathrm{jet}}^{\mathrm{f.o.+NNLL}}$ (JVE)
NLO	$14.7^{+2.8}_{-2.8}$ pb	$14.7^{+3.4}_{-3.4}$	$15.1^{+2.7}_{-2.7}$
NNLO	$17.5^{+1.3}_{-1.3}$ pb	$17.5^{+2.6}_{-2.6}$	$17.5^{+1.1}_{-1.1}$

F.Caola, HXSWG meeting, CERN, may 7

No breakdown of fixed-order calculation for p_T = 30 GeV

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

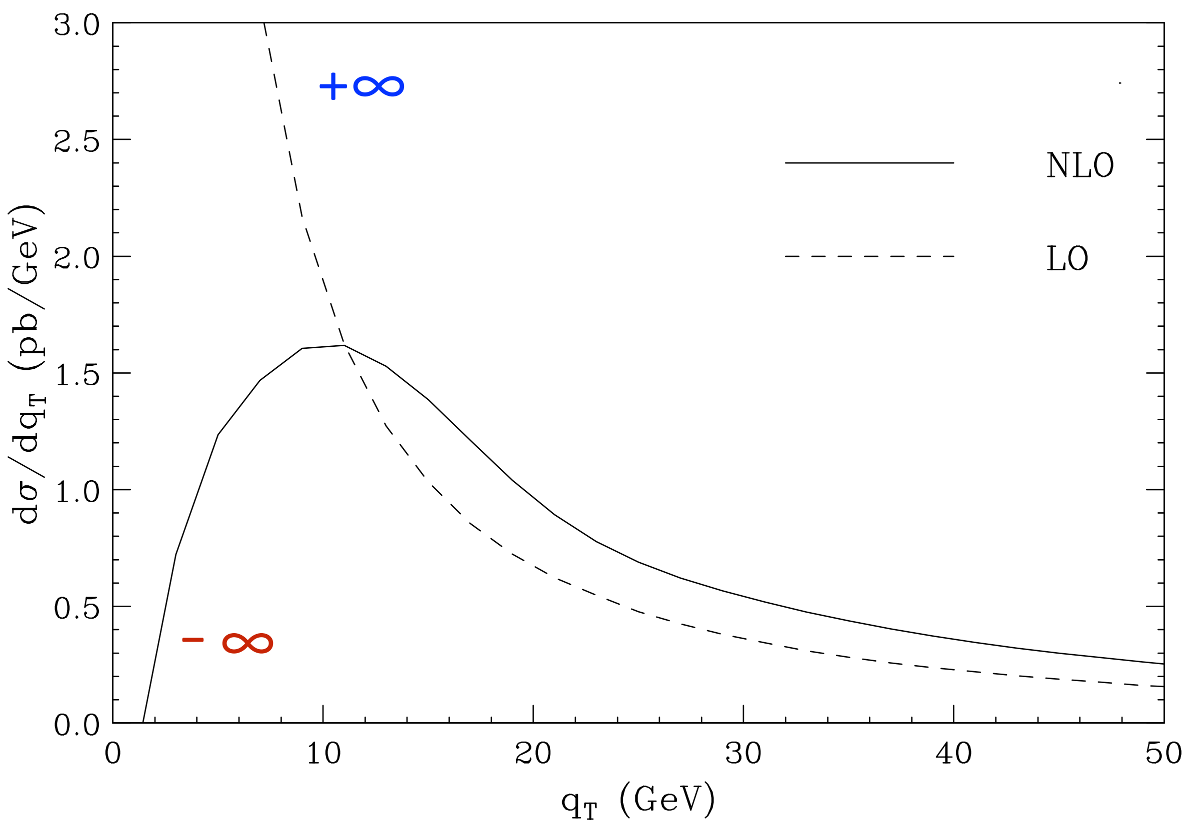
Moreover: the Higgs is a scalar → production and decay processes essentially factorised

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

The region $p_T \ll m_H$

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)

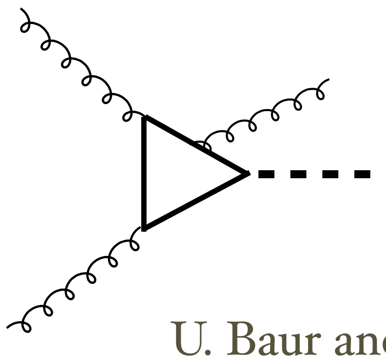
State of the art NNLL+NNLO results including mass effects available from HRes: used for reweighing by ATLAS and CMS

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

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)

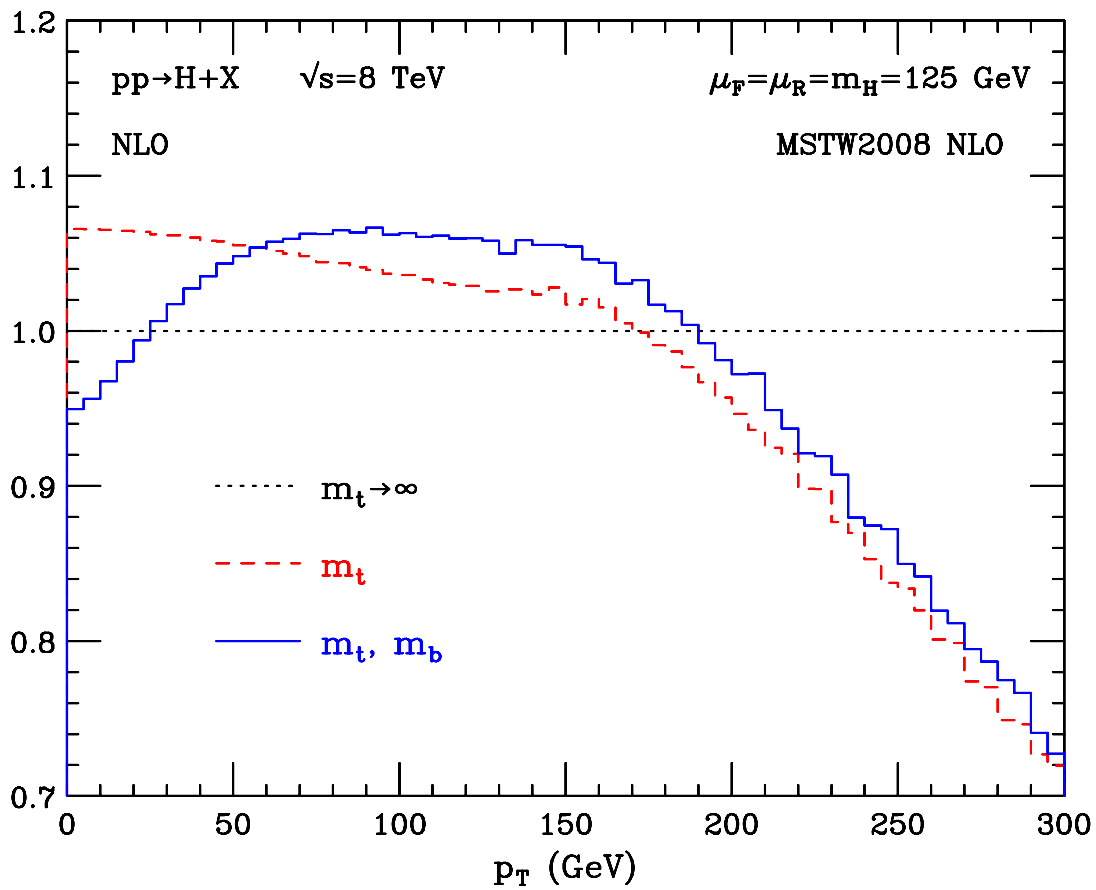
QCD radiative corrections in this region can be obtained from calculation of H+jet(s)

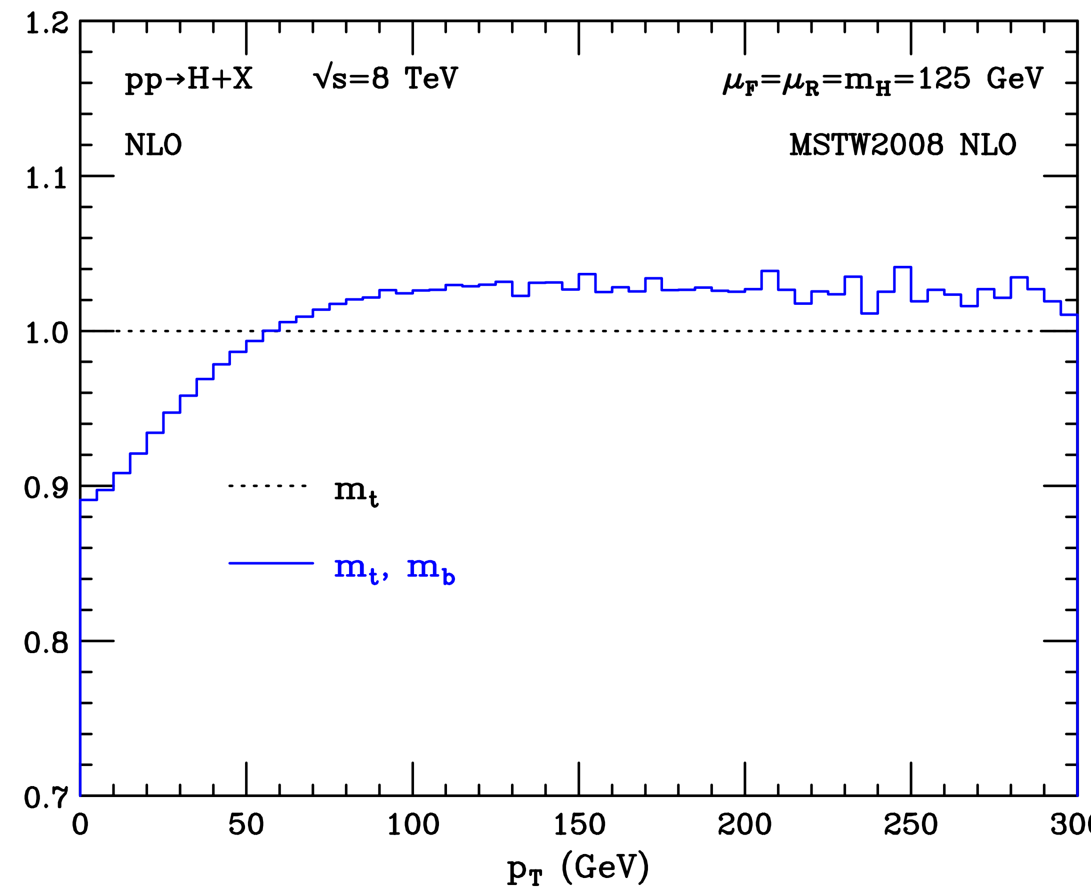
D. de Florian, Z.Kunszt, MG (1999)
V.Ravindran, J.Smith, V.Van Neerven (2002)
C.Glosser, C.Schmidt (2002)

NLO corrections are known only in the large-m_t approximation (part of inclusive NNLO cross section)

- Impact of recently computed NNLO corrections in H+jets ?
- Matching at $O(\alpha_S^5)$? N^{3}LL+N^{3}LO in the future ?

Mass effects



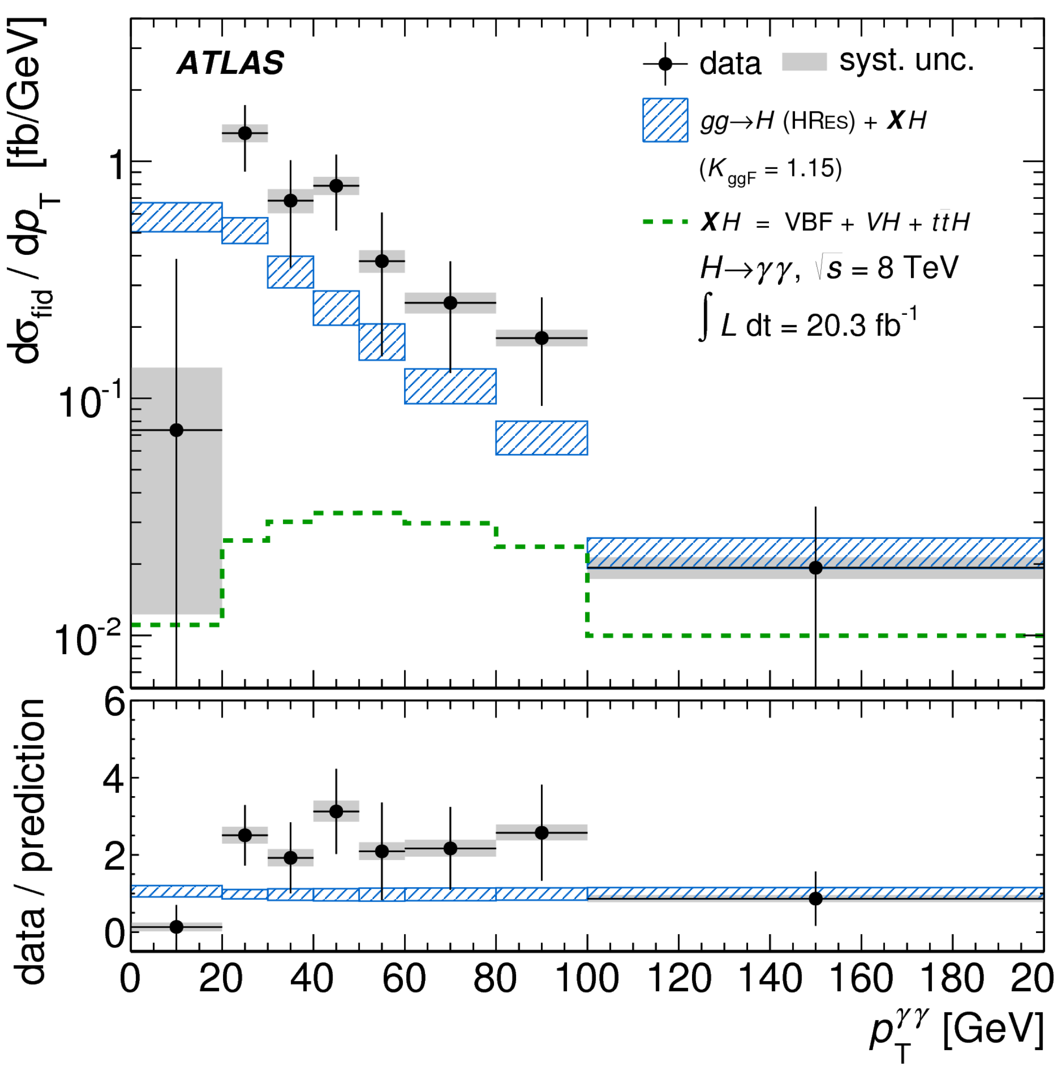


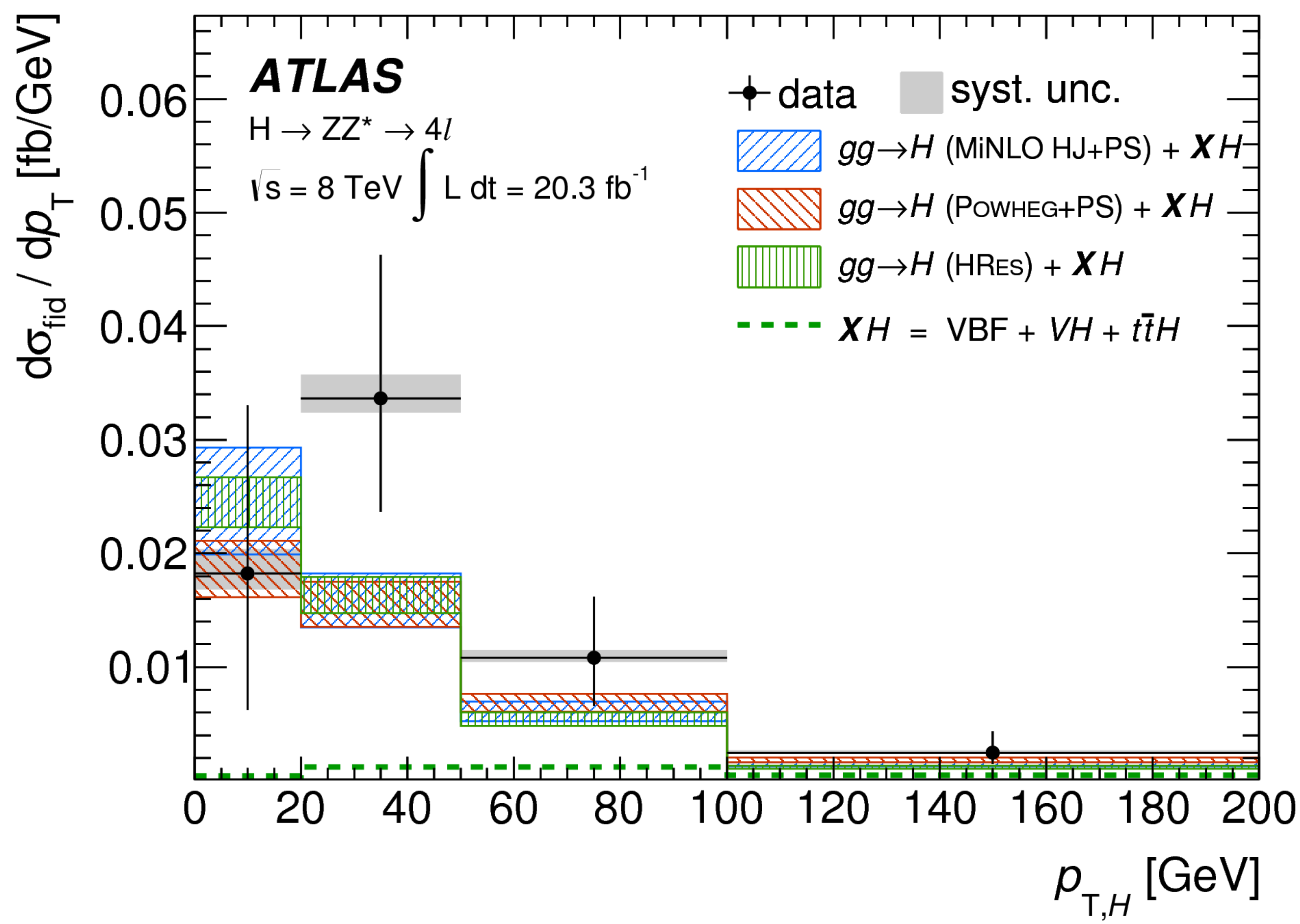
In the low p_T region finite m_t effects don't change the shape significantly (but finite m_b effects do it !)

At high-p_T finite m_t effects are crucial → Exact NLO highly demanded

Same topology as for W+jet at NNLO but with massive particles in the loop (feasible ?)

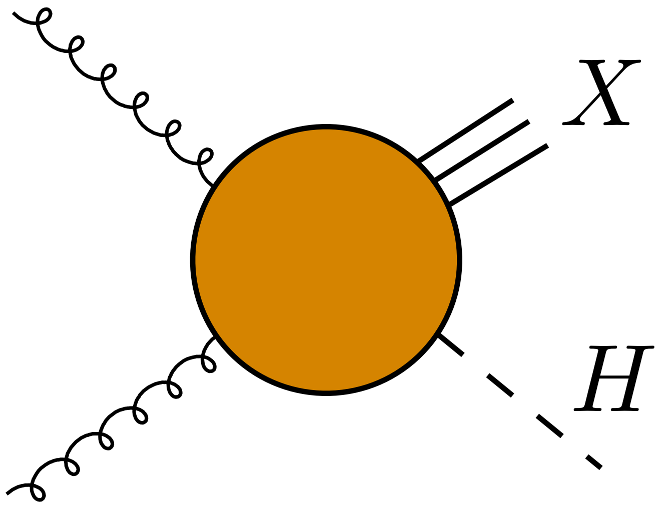
The first data





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 p_T spectrum in HqT

A.Ilnicka, M.Wiesemann, M.Spira, MG (to appear)

A new player: NNLO matching

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

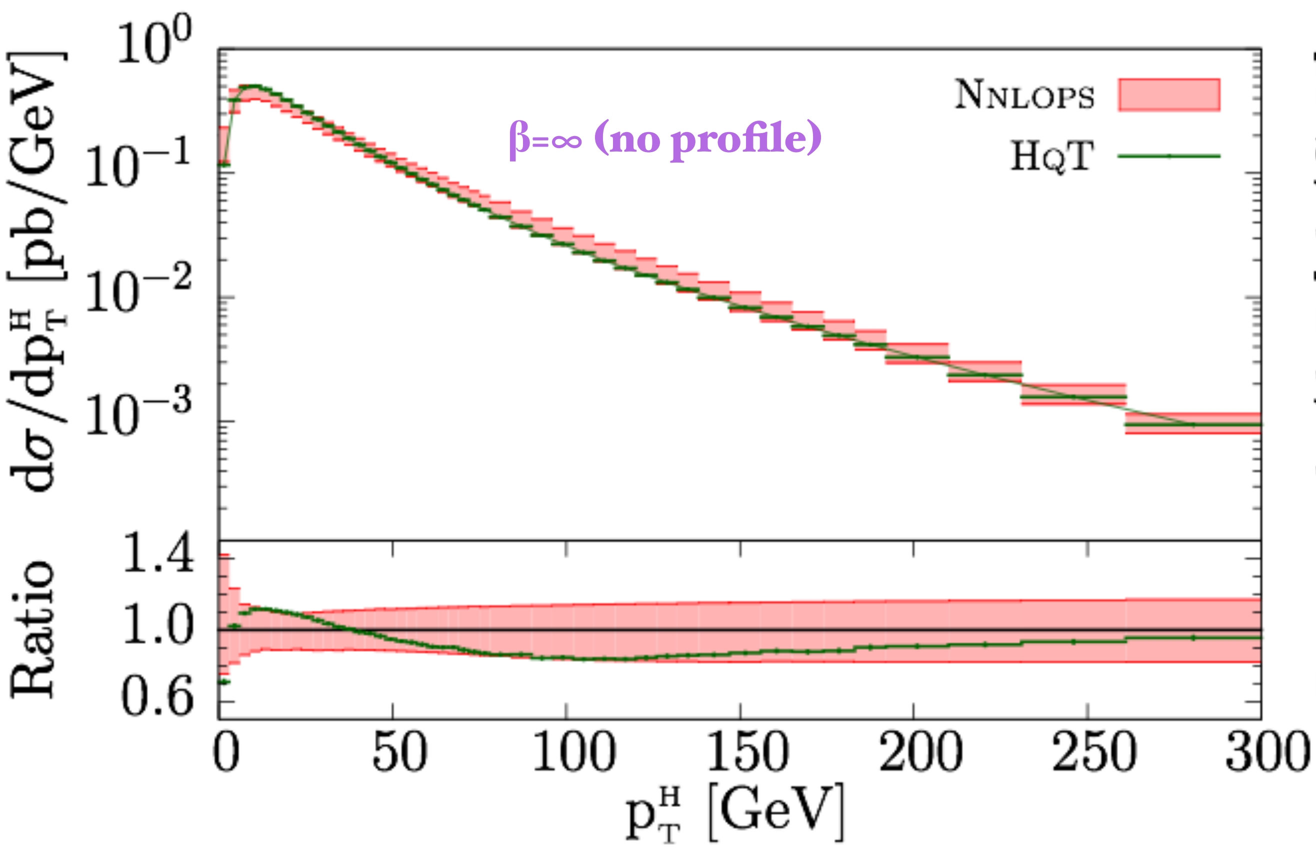
NNLOPS: use MINLO to obtain a NLO generator for both H and H+jet(s)

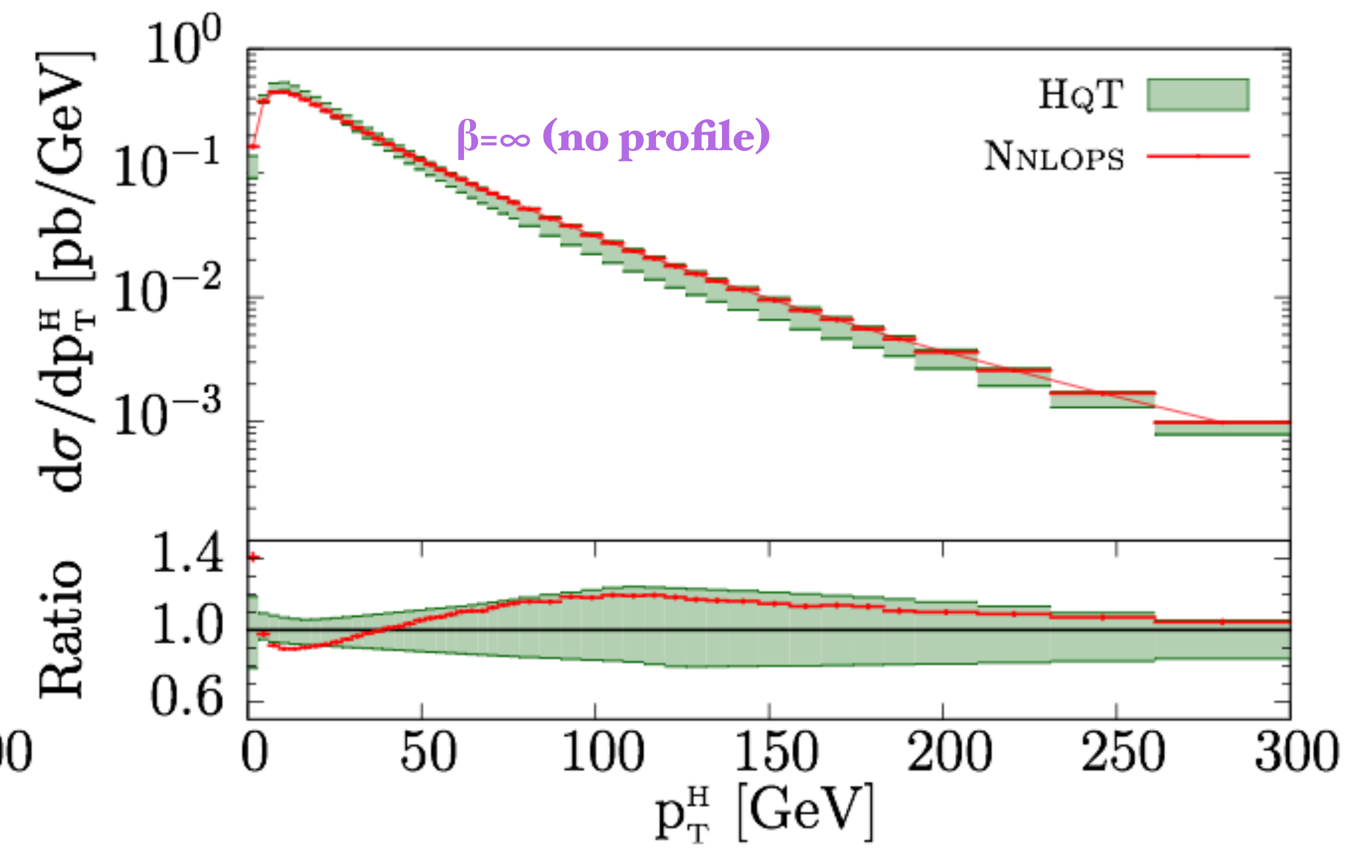
Enforce correct NNLO normalisation by reweighing the inclusive rapidity distribution to HNNLO

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

→ This is enough to achieve NNLO accuracy

Mass effects recently included from HNNLO2.0





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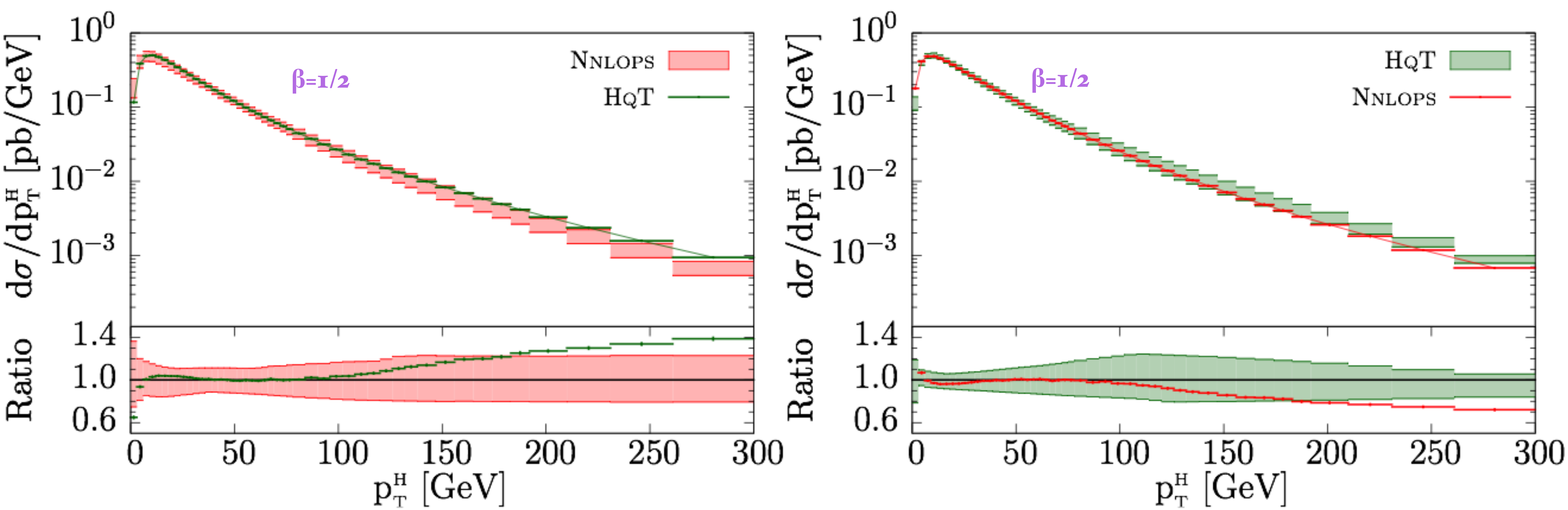
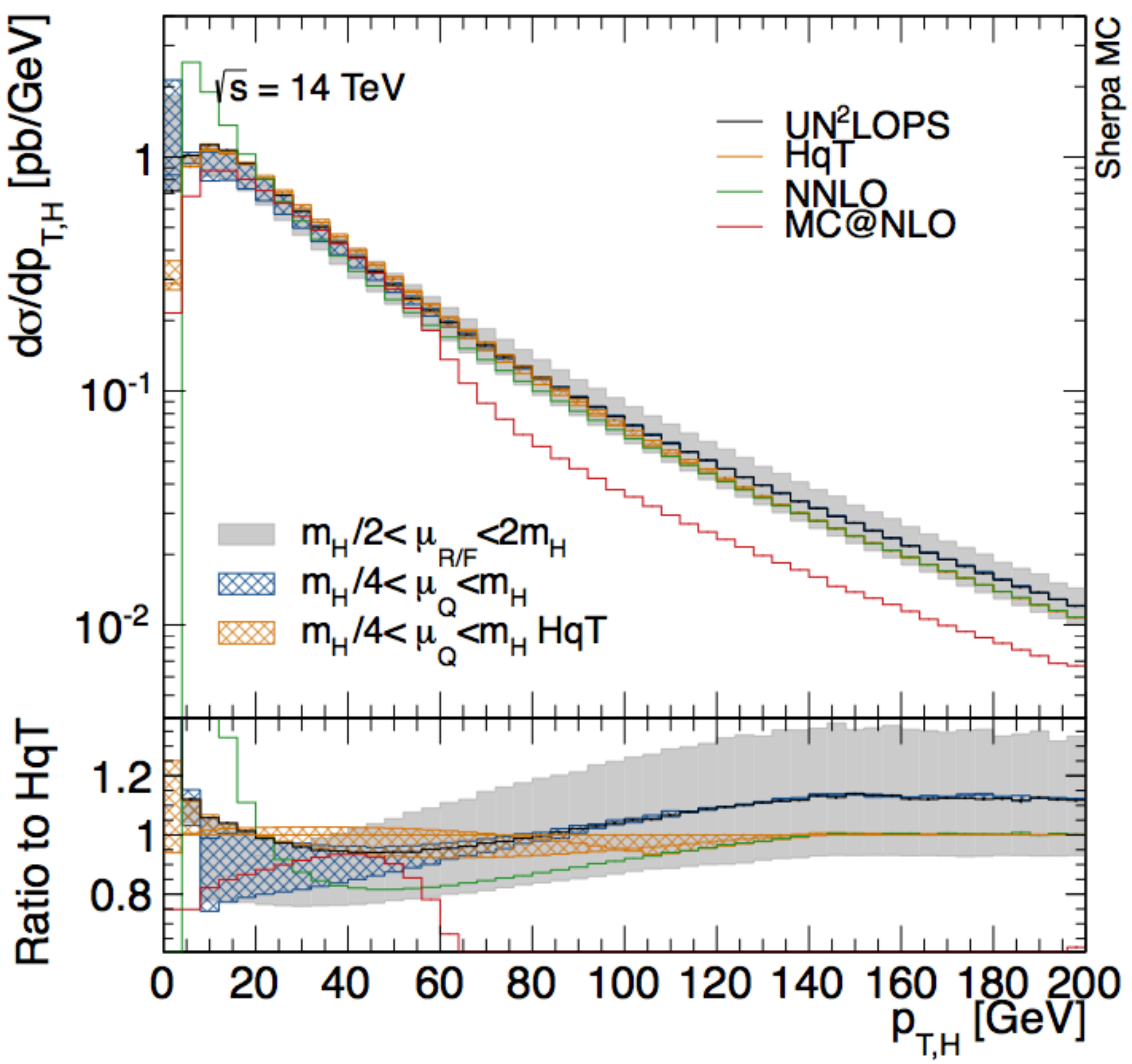


A new player: NNLO matching

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



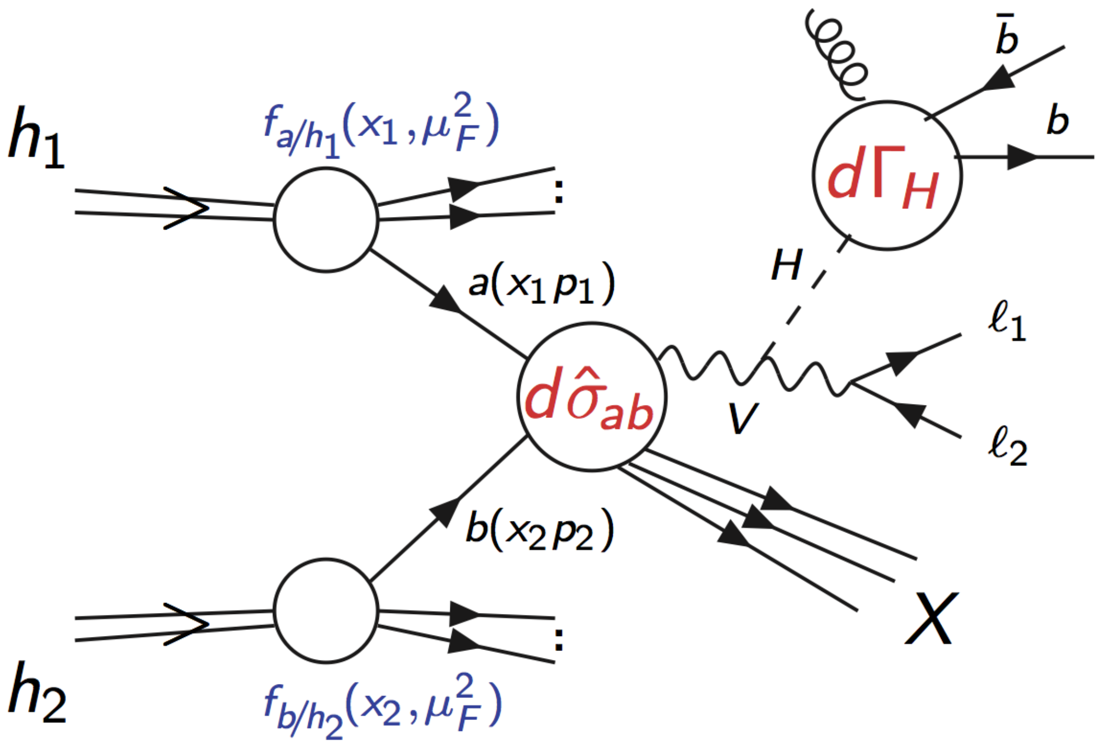
NNLO virtual corrections confined in the low p_T region while in the POWHEG-MINLO approach they are spread over the whole p_T region

A third approach is not implemented yet

S.Alioli et al. (2013)

→ It would be interesting to carry out a quantitative comparison of the 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%)

B.Kniehl (1990)

N3LO at threshold

M.Kumar, M.Mandal, V.Ravindran (2014)

Inclusive H →bbar known to $O(\alpha_S^4)$; EW corrections known

P. Baikov, K.Chetyrkin,J.Kuhn (2006)
A.Dabelstein,W.Hollik (1992)
B.Kniehl (1992)

NLO QCD+EW corrections available in HAWK A.Denner, S.Dittmaier, S.Kallweit,A.Muck (2012)

VH

Fully differential NLO corrections to production and H→bb decay known

A.Banfi, J.Cancino (2012)

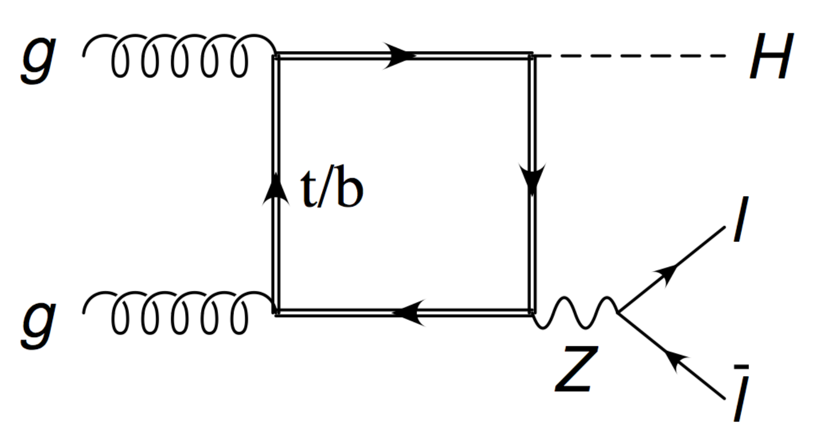
Fully differential NNLO corrections available, also including H→bb decay at NLO

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)

The major problem for ZH is the gg induced loop contribution (now implemented in NNLO calculation)



Impact of QCD corrections:

σ (fb)	NLO	NNLO (DY-like)	NNLO	
LHC8	$0.2820^{+2\%}_{-2\%}$	$0.2574^{+3\%}_{-4\%}$	$0.3112^{+3\%}_{-2\%}$	+21%
LHC14	$0.2130^{+10\%}_{-12\%}$	$0.1770^{+7\%}_{-6\%}$	$0.2496^{+5\%}_{-2\%}$	+41%

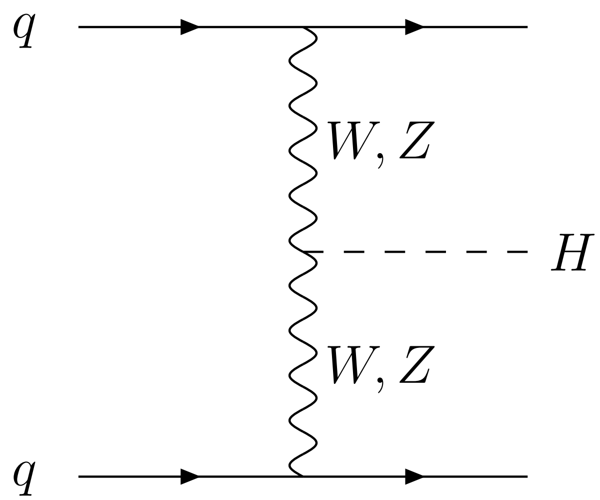
→ Very important in the boosted region

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

L.Altenkamp et al. (2012)

Two-loop corrections beyond current possibilities (too many scales !)

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

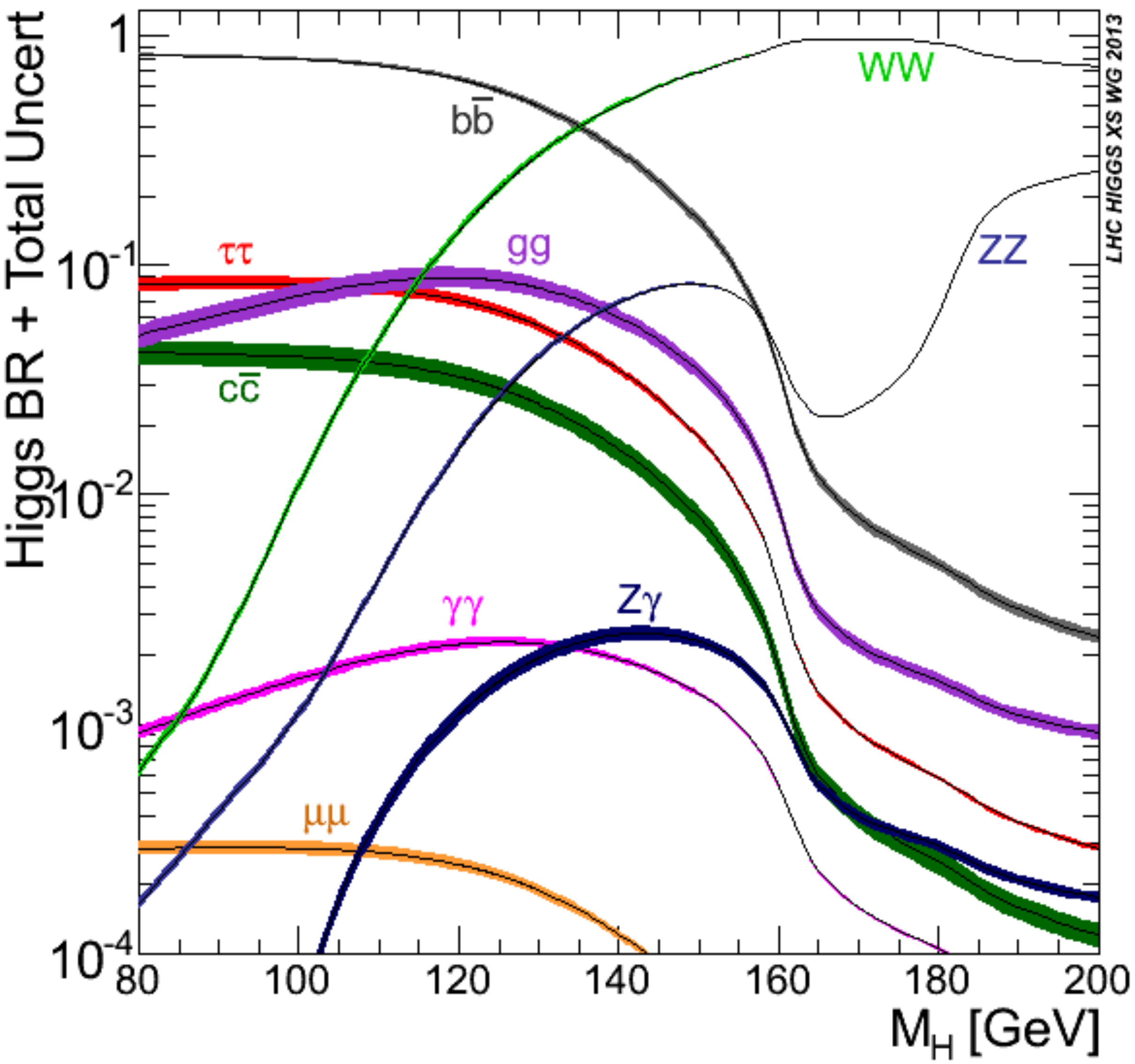
Progress in EW corrections (MG5_aMC@NLO and also Openloops)

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

Main problem is to reach a good understanding of backgrounds

Higgs decays

A.Denner, S.Heinemeyer, D.Rebuzzi,I.Puljak,M.Spira (2013)
A. Bredenstein, A. Denner, S. Dittmaier, and M. Weber (2006)



Uncertainty in H→bbar decay at the 3% level

Uncertainty in H→γγ, ZZ,WW decays at the 4-5% level

m_H (GeV)	$H \to b\bar{b}$	$H \to \tau\tau$	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$
125	$57.7^{+3.2\%}_{-3.3\%}$	$6.32^{+5.7\%}_{-5.7\%}$	$0.22^{+5.0\%}_{-4.9\%}$	$21.5^{+4.3\%}_{-4.2\%}$	$2.64^{+4.3\%}_{-4.2\%}$

HDECAY and Prophecy4f

New version of HDECAY includes EW corrections in fermionic decays. This will decrease a bit the uncertainties, which, however, are dominated by parametric uncertainties.

Off-shell Higgs

Most of Higgs studies performed so far involve on-shell Higgs bosons

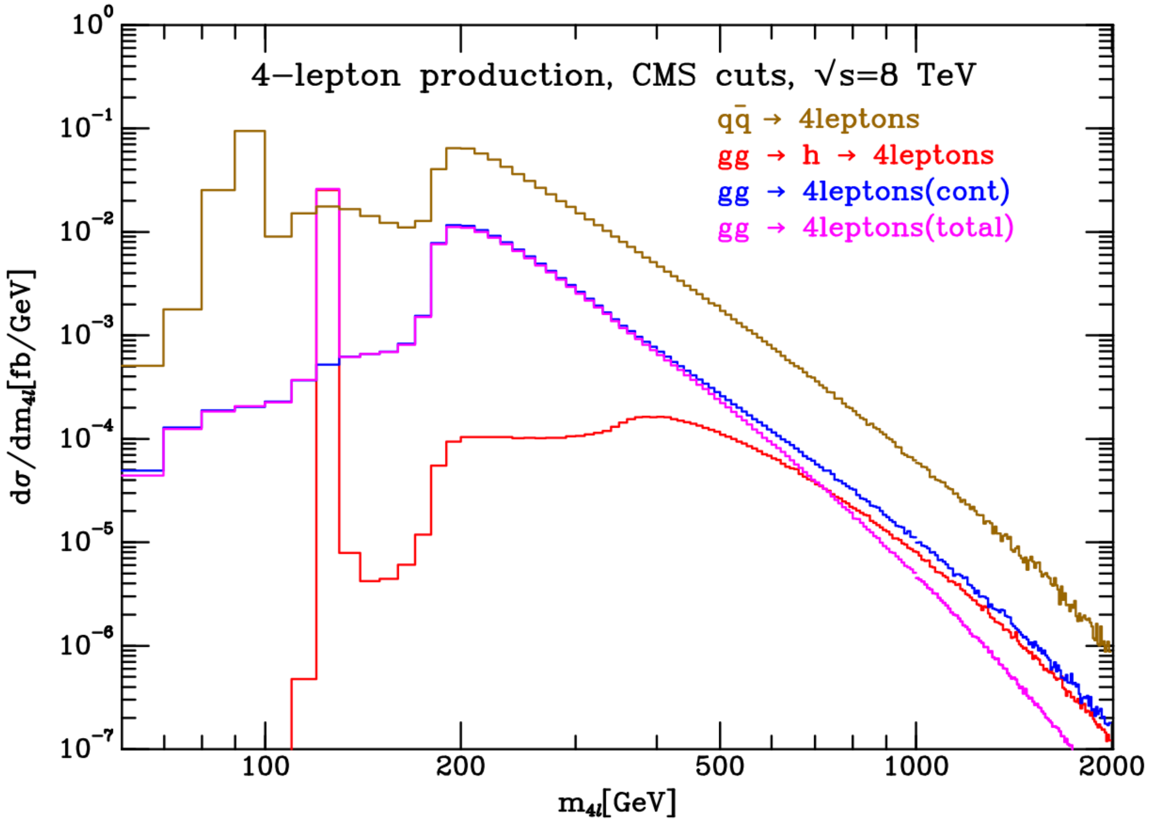
→ This is because the on-shell signal is by far the cleanest and dominant

But for the process $i \to H \to j$ the on-shell cross section is $\sigma_{\text{on-shell}} \sim (g_i\, g_j)^2 / \Gamma_H$: impossible to study Higgs couplings and width separately

Off-shell production allows us to break this degeneracy since the corresponding cross section is independent on the width $\sigma_{\text{off-shell}} \sim (g_i\, g_j)^2$

→ Ratio $\sigma_{\text{off-shell}} / \sigma_{\text{on-shell}}$ is thus sensitive to Γ_H

F.Caola,K.Melnikov (2013)



In the off-shell region the effect of the interference is large and negative

Off-shell measurements thus rely on good knowledge of SM prediction in this region

N.Kauer, G.Passarino (2012)
J.Campbell,K.Ellis,C.Williams (2013)

Off-shell Higgs

Further progress in the off-shell region requires improved predictions for ZZ background and signal background interference

T.Gehrmann et al. (2014)

NNLO predictions for qqbar→ZZ

F.Caola et al. (2015)
A. von Manteuffel, L.Tancredi (2015)

Two-loop amplitudes for gg→ZZ

→ NLO calculations for gg→ZZ and interference now possible (with massless quarks in the two-loop diagrams)

QCD corrections expected to be large

M.Bonvini, F.Caola,S.Forte,K.Melnikov, G.Ridolfi (2013)

Top-quark contributions are expected to be important for the interference and to have a large K-factor

M.Dowling, K.Melnikov (2015)

Recent proposal: study same effects in VBF

J.Campbell and K.Ellis (2015)

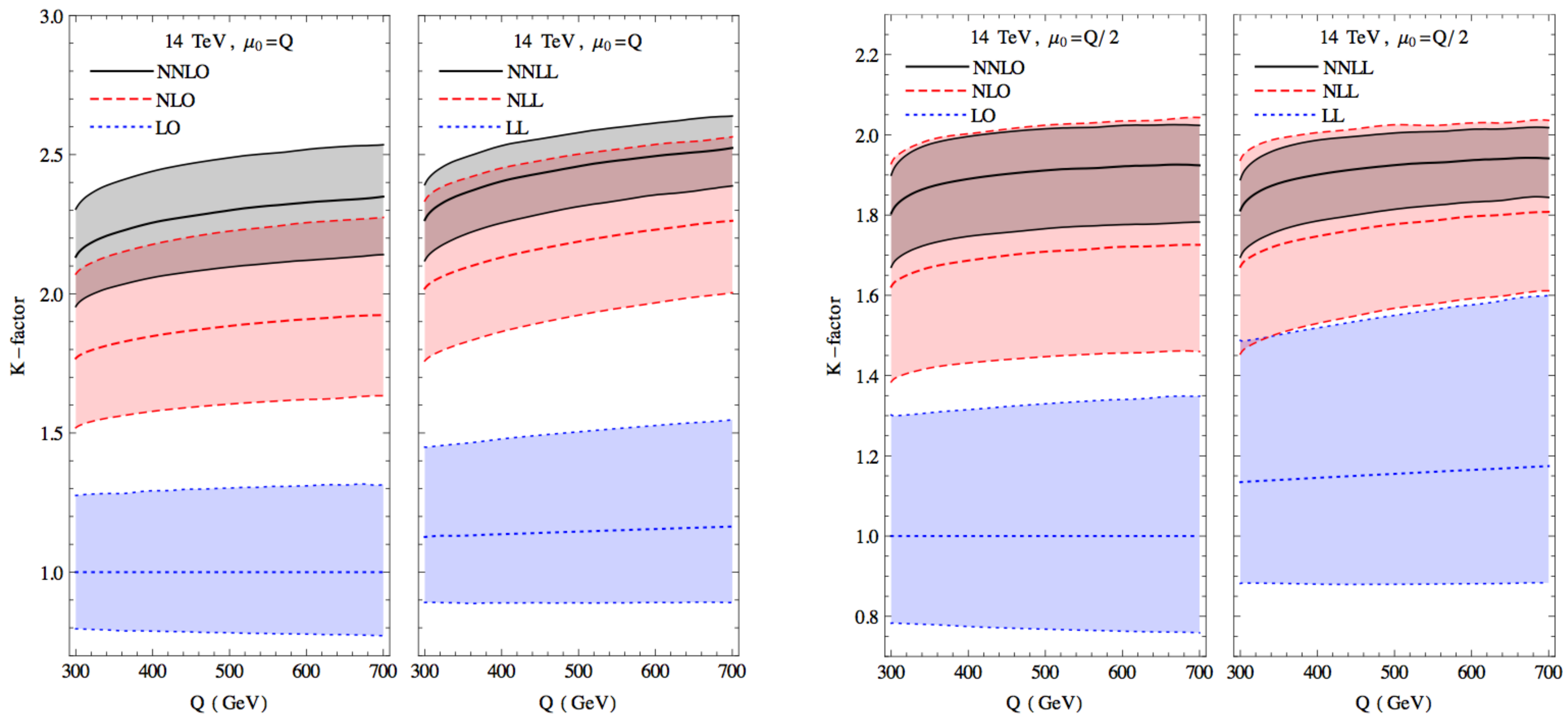
Double Higgs production

It is the process that gives direct access to the Higgs self coupling λ

QCD corrections at NLO and NNLO known only in the large-m_{top} approximation

S.Dawson,S.Dittmaier,M.Spira (1998)

D. de Florian, J.Mazzitelli (2013)



NNLL resummation recently completed

D. de Florian, J.Mazzitelli (2015)

nice reduction of scale uncertainties

Main issue: large-m_{top} approximation known not to work so well

J.Grigo et al. (2013)

Include mass effects for the contributions for which they are available

F.Maltoni,E.Vyronidou,M.Zaro (2014)

What we want to discuss

- Inclusive ggF cross section: what after the N^3LO ?

  - N^3LO corrections are moderate but important reduction in scale uncertainties
  - What about the other uncertainties ? PDFs, α_S, EW corrections, large-m_{top} ?

  A meeting is scheduled for june 8 14.30-16.30

- Higgs p_T spectrum:

  - Impact of H+jet at NNLO ?
  - Effects of finite heavy quark masses ?
  - NNLO matching ?
  - Reweighting or not reweighing ?

- Signal-Background interference: what else can we learn ?

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