Theory improvements for Run 2 and beyond

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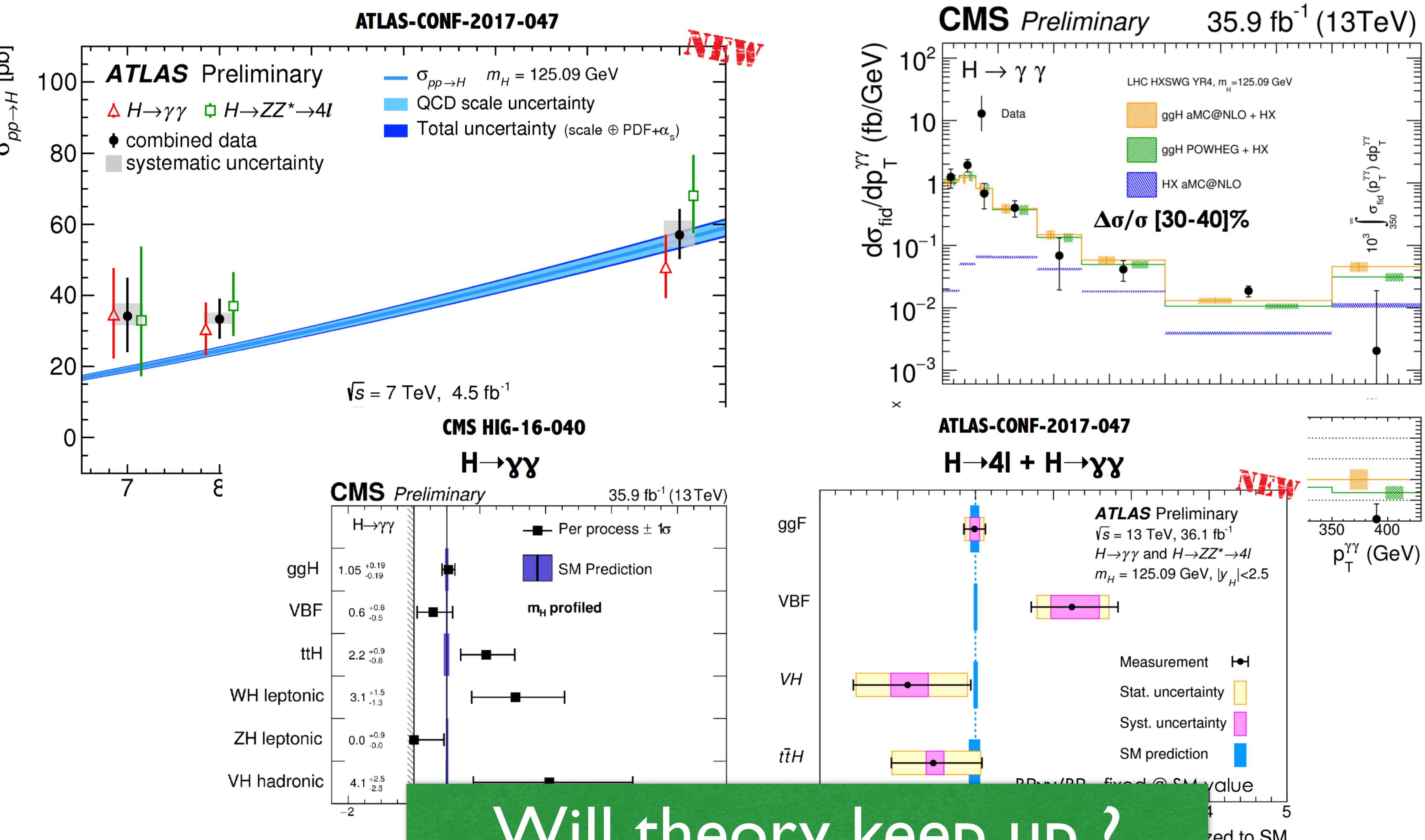
University of Zurich

Higgs Hunting 2017
Paris, july 26 2017

The latest results



Will theory keep up ?

Outline

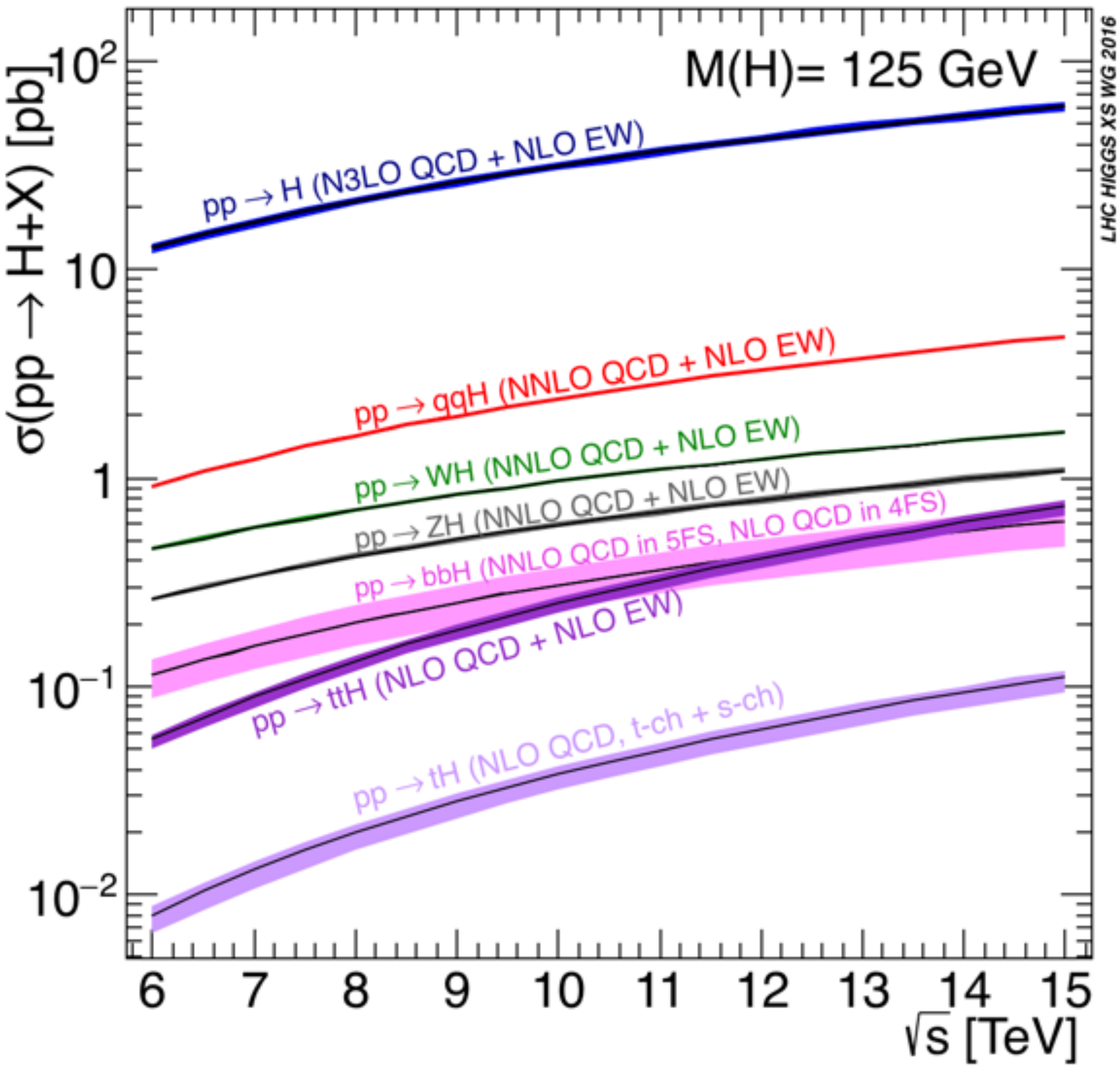
- gluon fusion
  - Inclusive cross section
  - H+jet(s) and jet-vetoed cross section
  - Transverse-momentum spectrum
- VH, VBF, ttH
- Higgs decays
- Backgrounds
- Summary

MC tools → talk by Hamilton

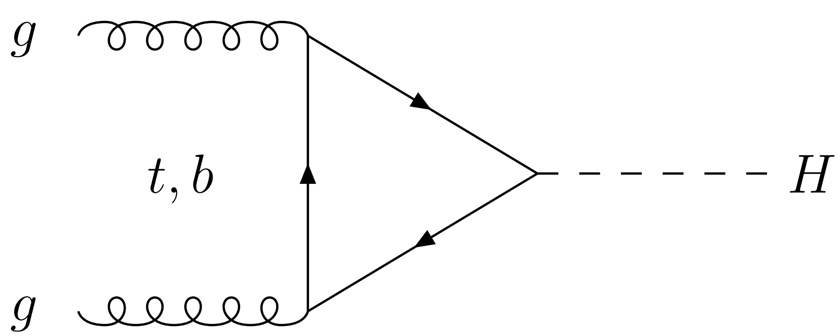
Off-shell → talk by Kauer

HH → talk by Low

Production channels



gg→H



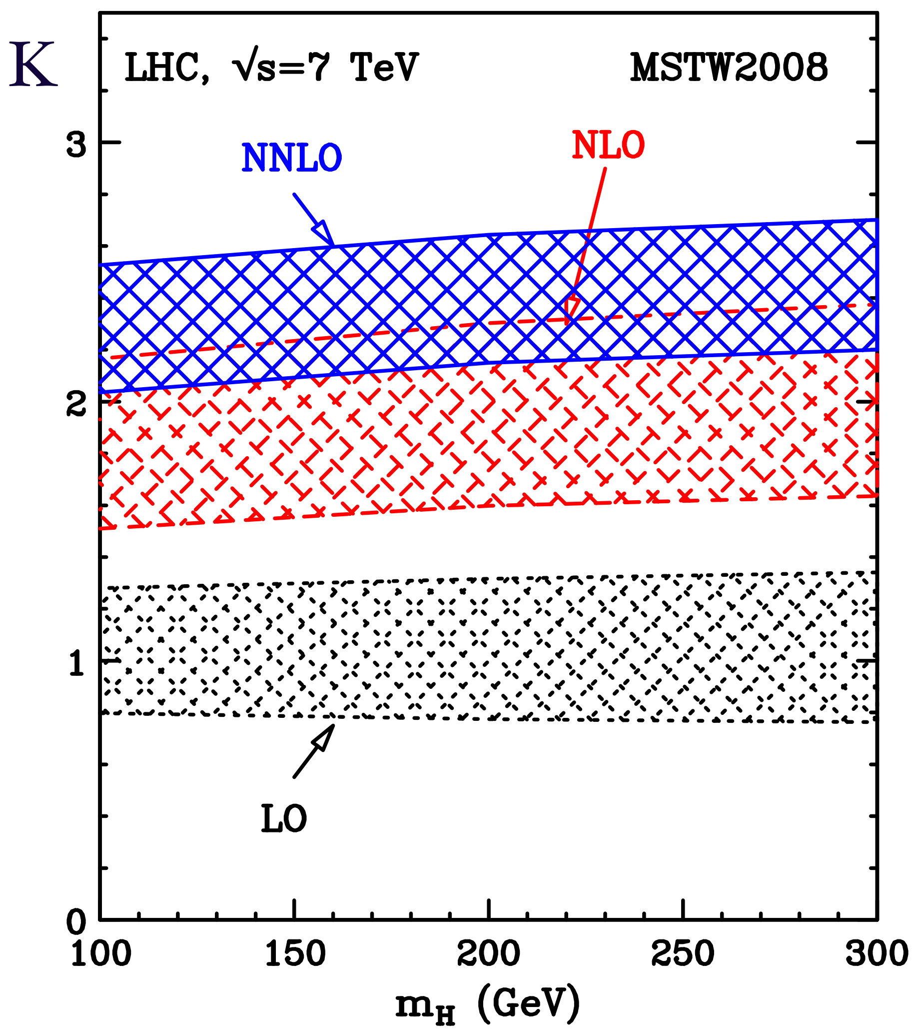
The Higgs coupling is proportional to the quark mass

→ top-loop dominates

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

QCD corrections to the total rate computed 25 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, W.B. Kilgore (2001)
C. Anastasiou, K. Melnikov (2002)
V. Ravindran, J. Smith, W.L.Van Neerven (2003)

Soft-gluon effects included

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

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

gg→H

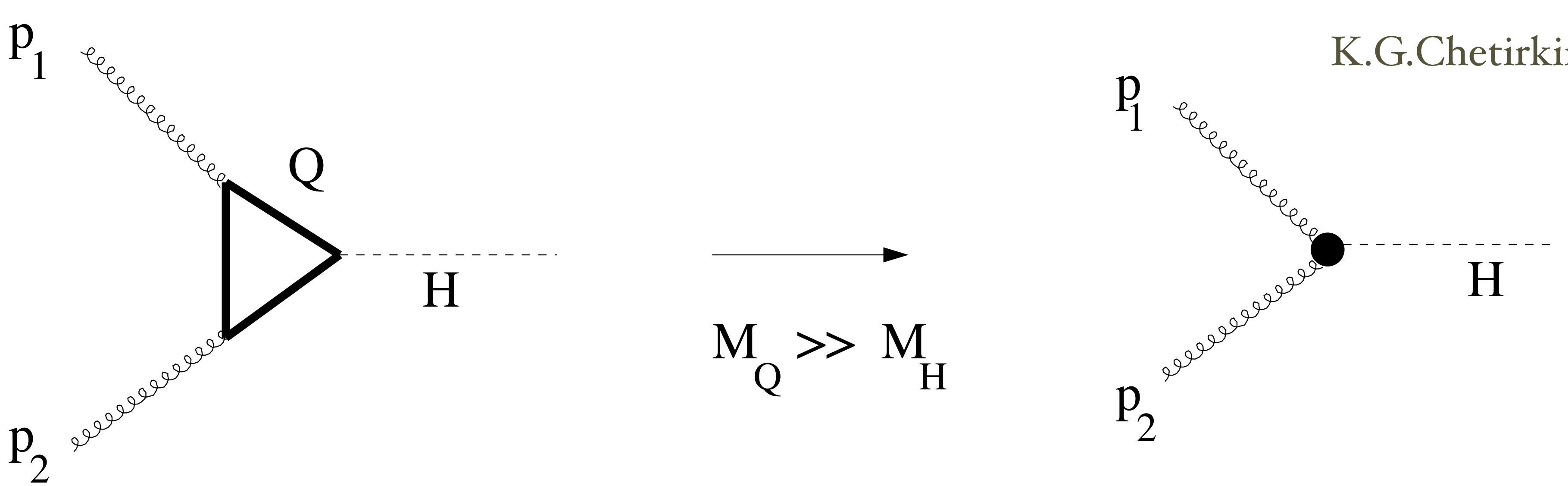
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

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 !

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)

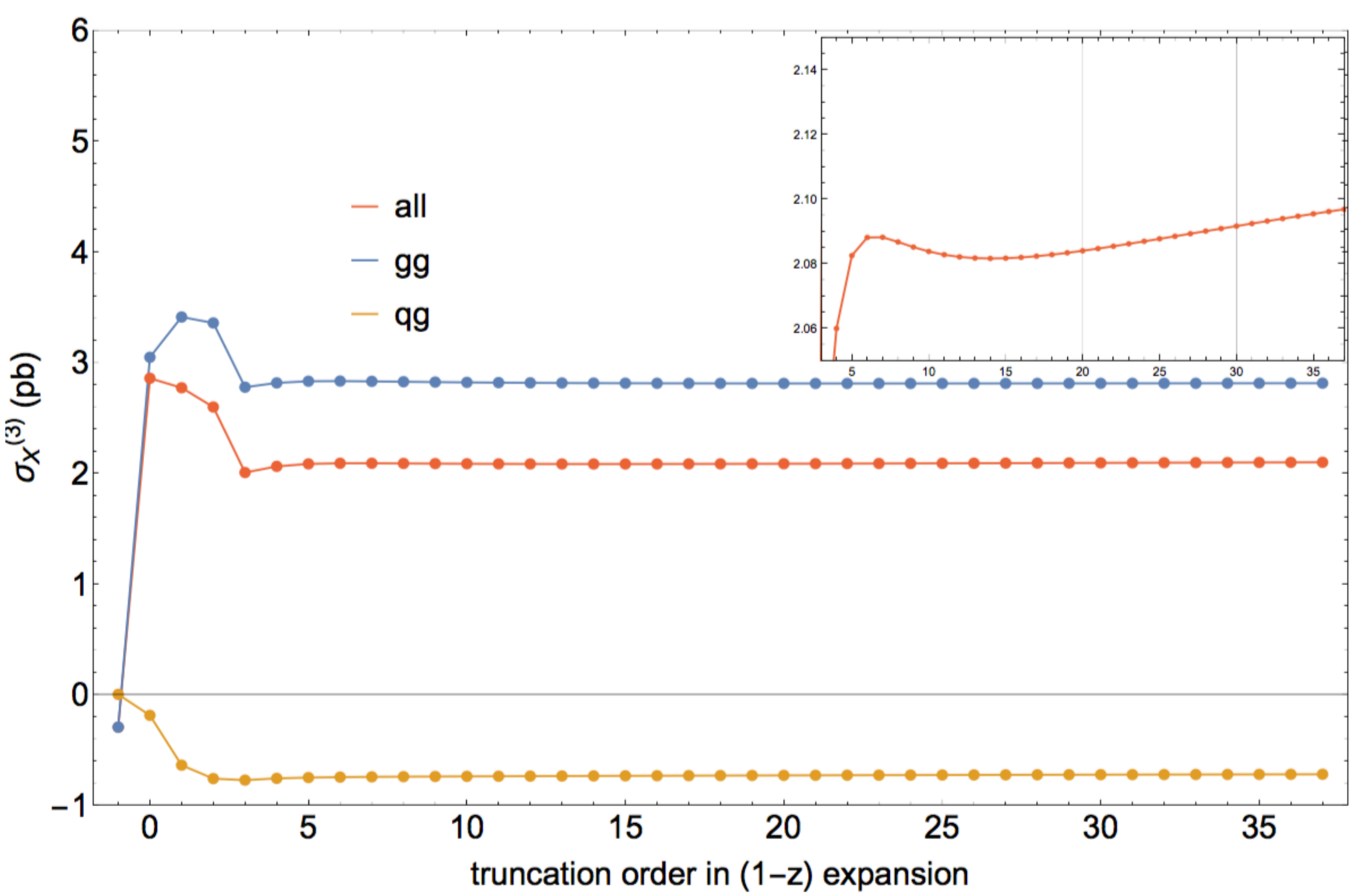
The approximation works to better than 0.5 % for $m_H < 300$ GeV

gg→H at N3LO

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

Really impressive achievement:

- first complete calculation at N3LO in hadronic collisions !
- O(105) diagrams; O(103) master integrals



Obtained through a series expansion around the soft limit (37 terms !)

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

"distance" from partonic threshold

Important reduction of perturbative uncertainties

Impact of N3LL resummation on top of N3LO very small

M.Bonvini et al. (2016) (see also M.Spira, T.Schmidt (2015))

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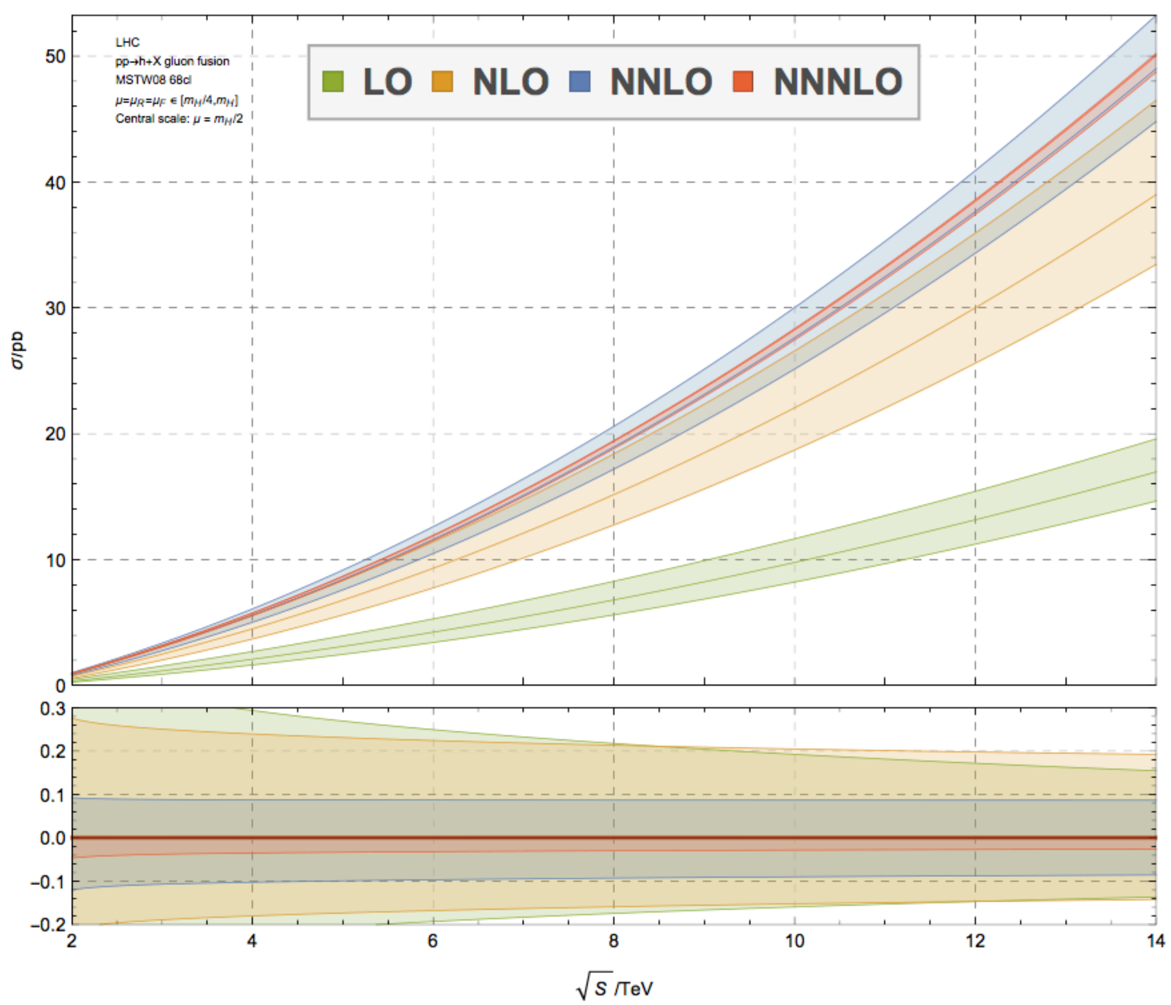

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C.Anastasiou, C.Duhr, F.Dulat, E.Furlan, T.Gehrmann, F.Herzog, A.Lazopoulos, B.Mistlberger (2016)

N3LO calculation accompanied by a thorough study of the remaining theoretical uncertainties

$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

missing higher-orders

uncertainty from the soft expansion

missing N3LO PDFs

missing mixed QCD-EW corrections

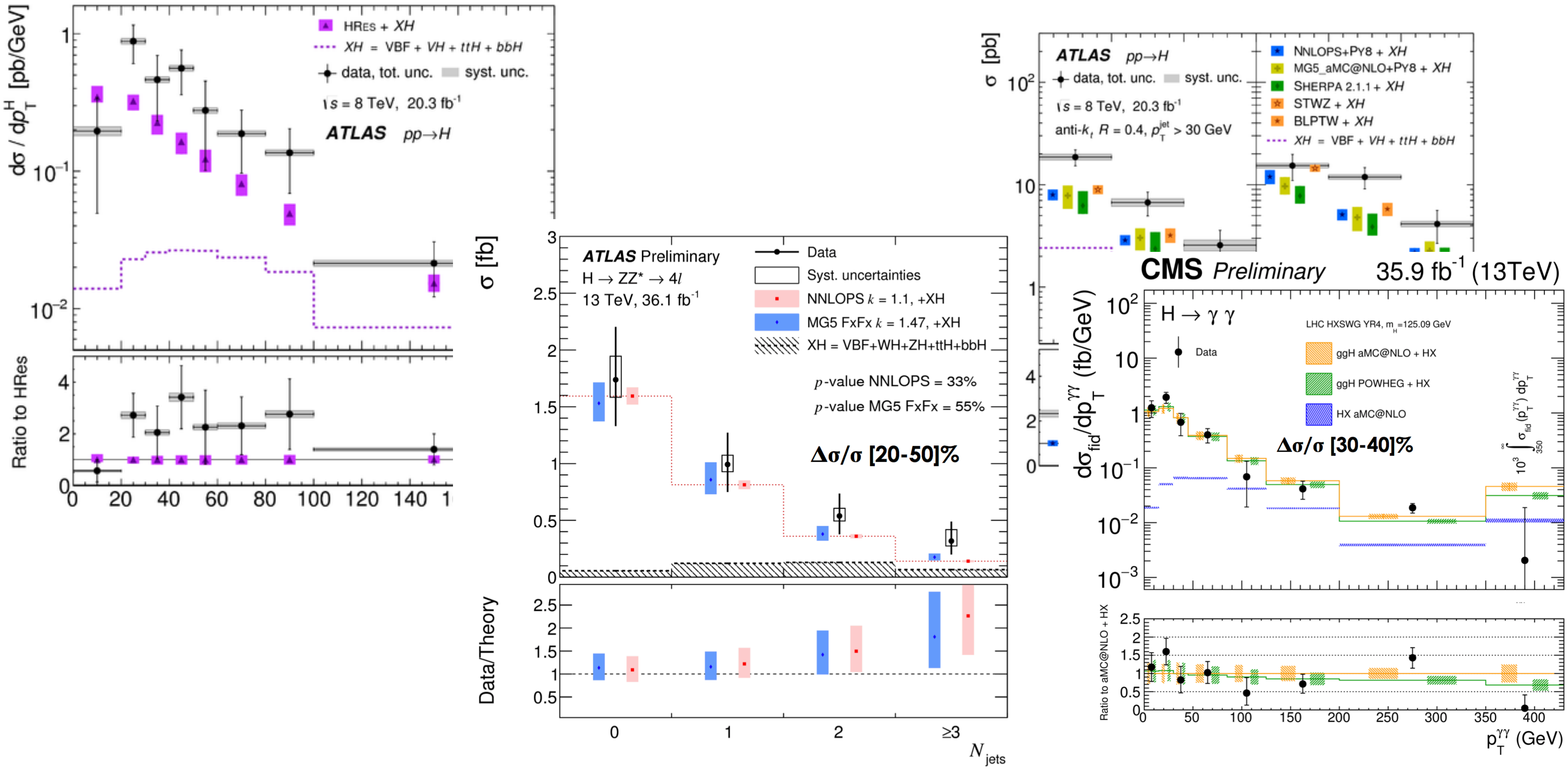
uncertainty from heavy-quark mass dependence

uncertainty in the $1/m_t$ included corrections

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

New HXSWG recommendation

Differential distributions



Will current theoretical accuracy be enough ? TH improvements in ggF may come from:

- going beyond the large-m_{top} limit
- compute further terms in the perturbative expansion

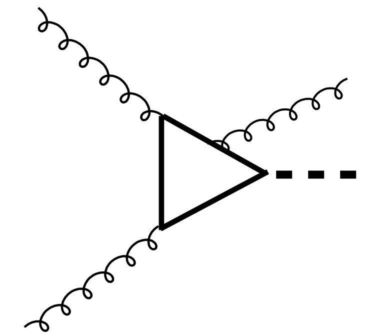
H+jet(s)

When the Higgs recoils against one parton the LO is of relative order α_S

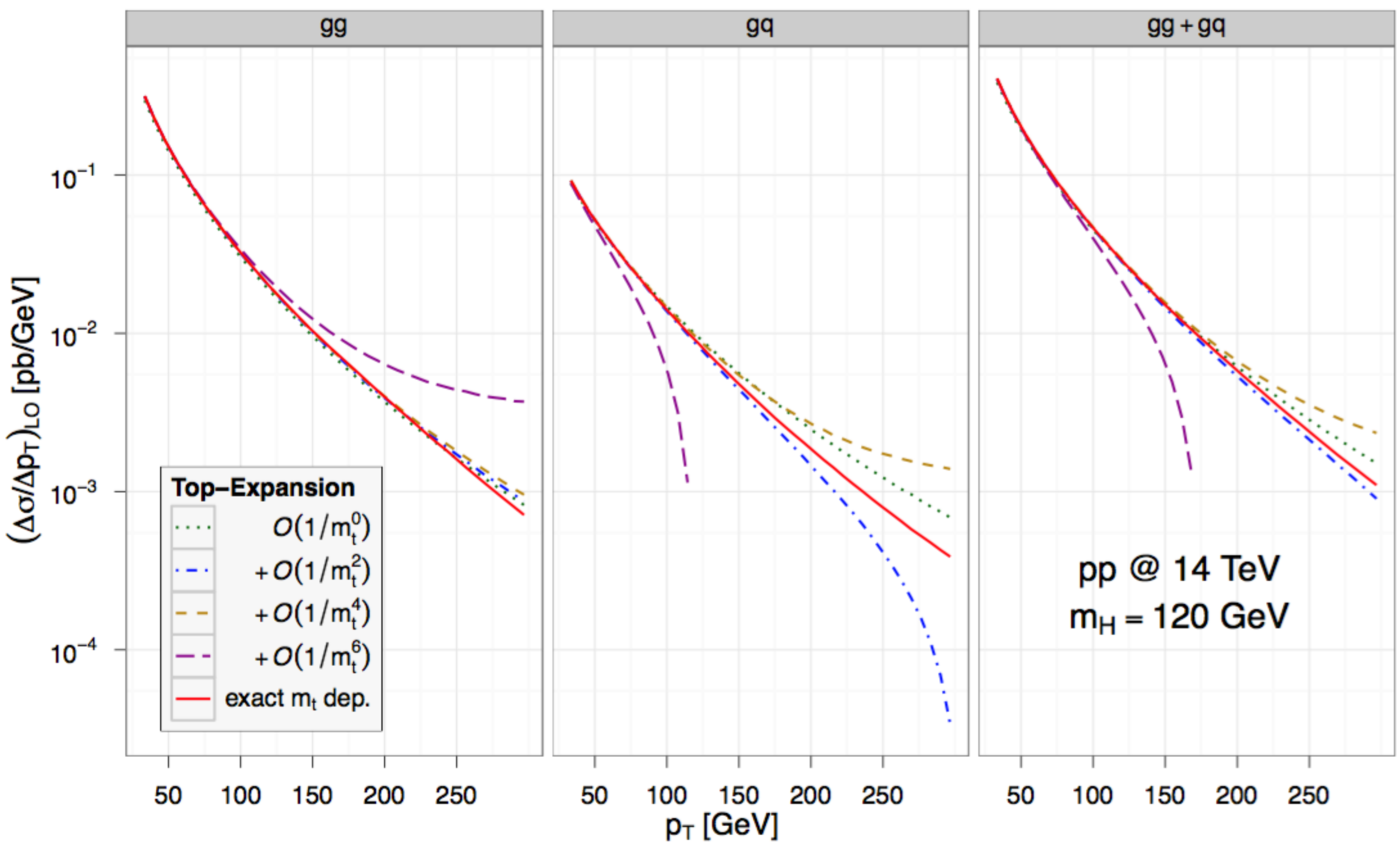
Exact result including mass dependence known for many years

Large-m_t expansion does not work so well as in the inclusive case

Bound to fail at high p_T (recoiling radiation resolves the heavy-quark loop)



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



R.Harlander, T.Neumann,K.Ozeren, M.Wiesemann (2012)

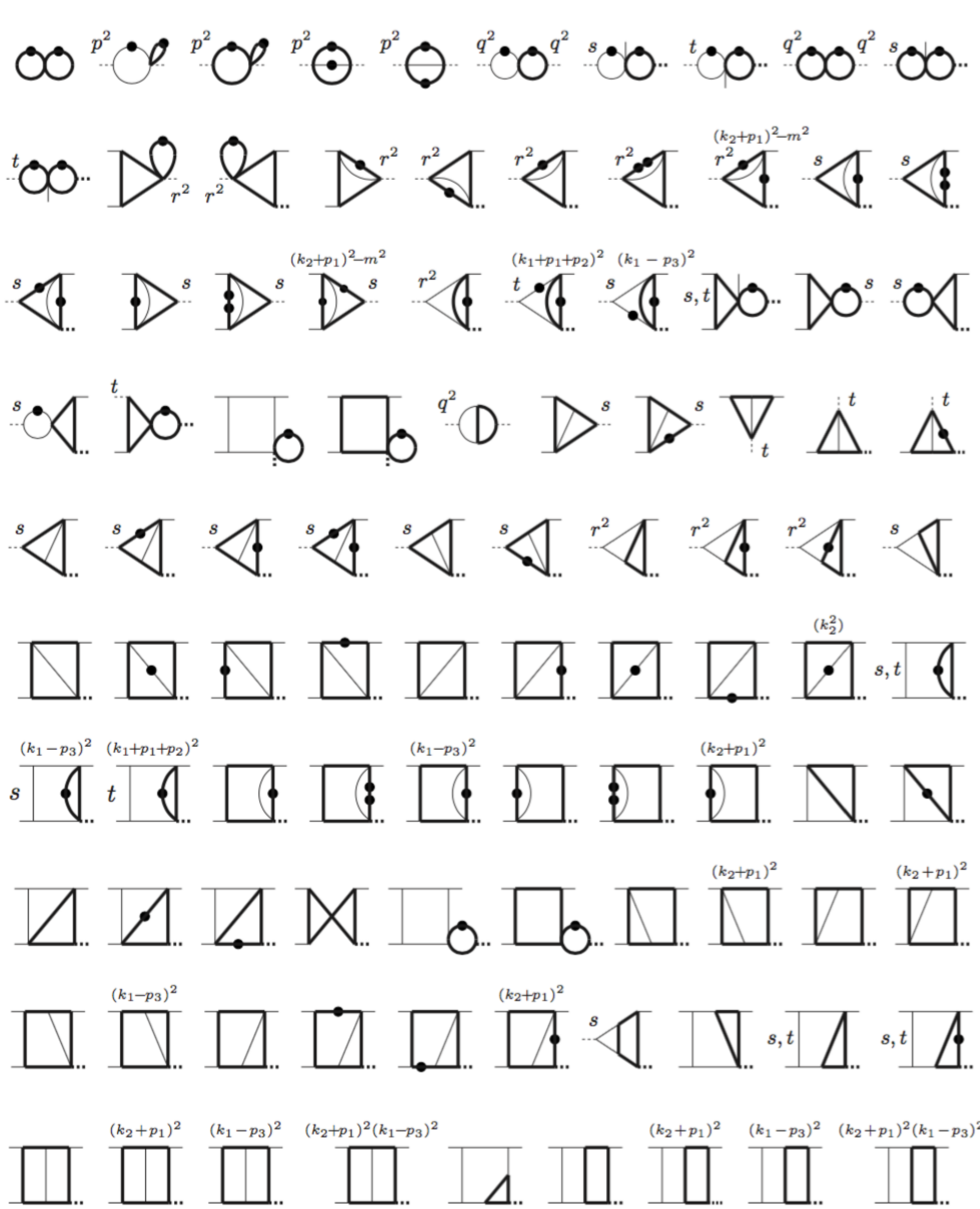
NLO corrections are known only in the large-m_{top} approximation (part of inclusive NNLO cross section)

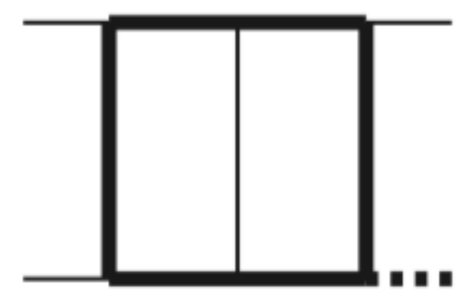
D. de Florian, Z.Kunszt, MG (1999)
V.Ravindran, J.Smith, V.Van Neerven (2002)
C.Glosser, C.Schmidt (2002)

Beyond the large-m_{top} limit

$$d\sigma = d\sigma_{tt} + d\sigma_{tb} + d\sigma_{bb}$$

Exact calculation requires 2-loop amplitudes with different mass scales: this is at the forefront of current technologies !





H

Two-loop planar master integrals recently computed in terms of elliptic functions: this is an important first step

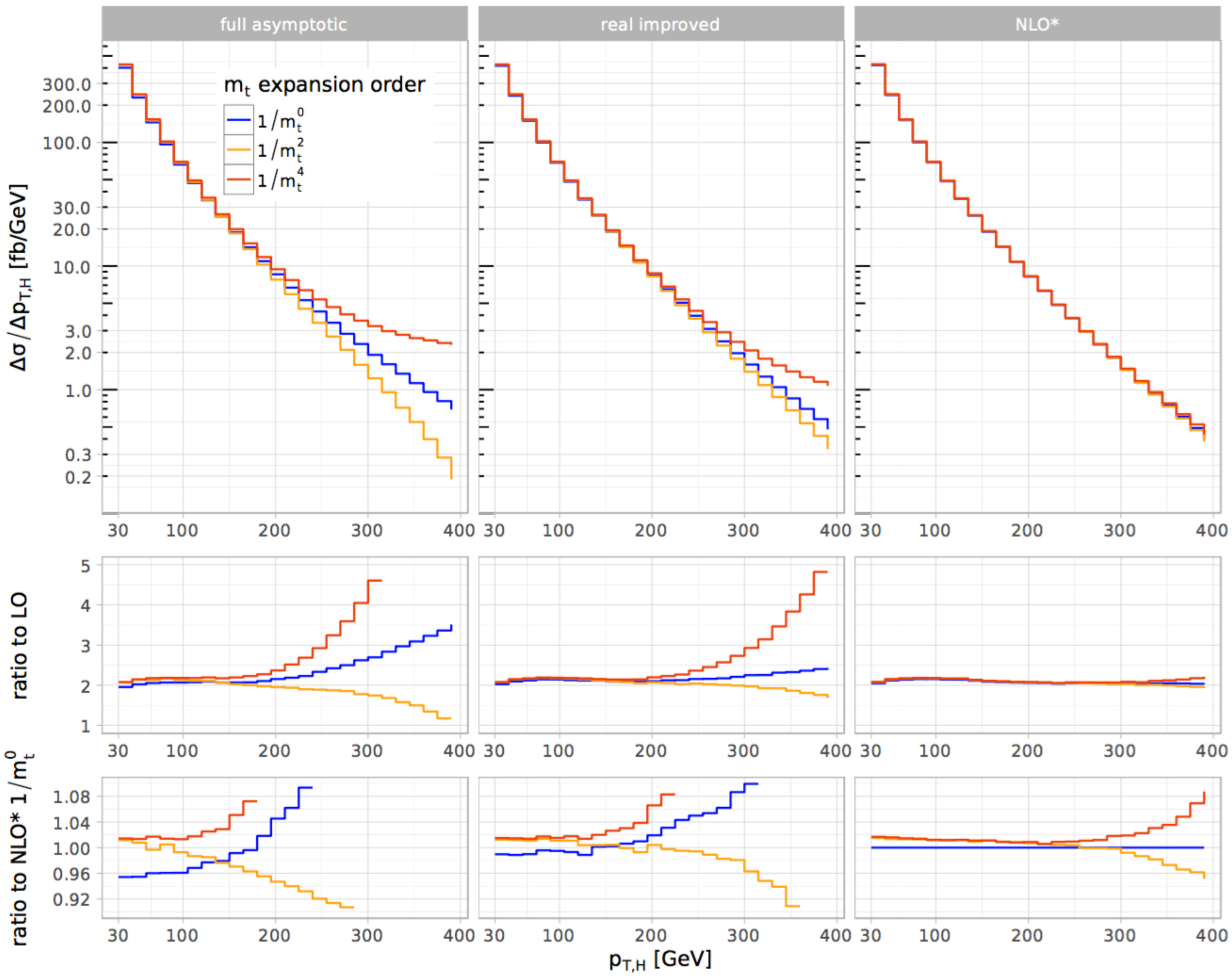
R.Bonciani et al. (2016)

Exciting but….not even enough to get the leading color contribution !

H+jet(s)

In the meanwhile: make the best use of what is available

T.Neumann, C.Williams (2016)



Compute the NLO corrections by using exact amplitudes when possible (plus expansion in $1/m_{top}$) for the finite part of the missing two loop amplitude

It pushes the reliability of the large-m_{top} approximation a bit further !

But at high-p_T the exact result is really needed !

Beyond the large-m_{top} limit

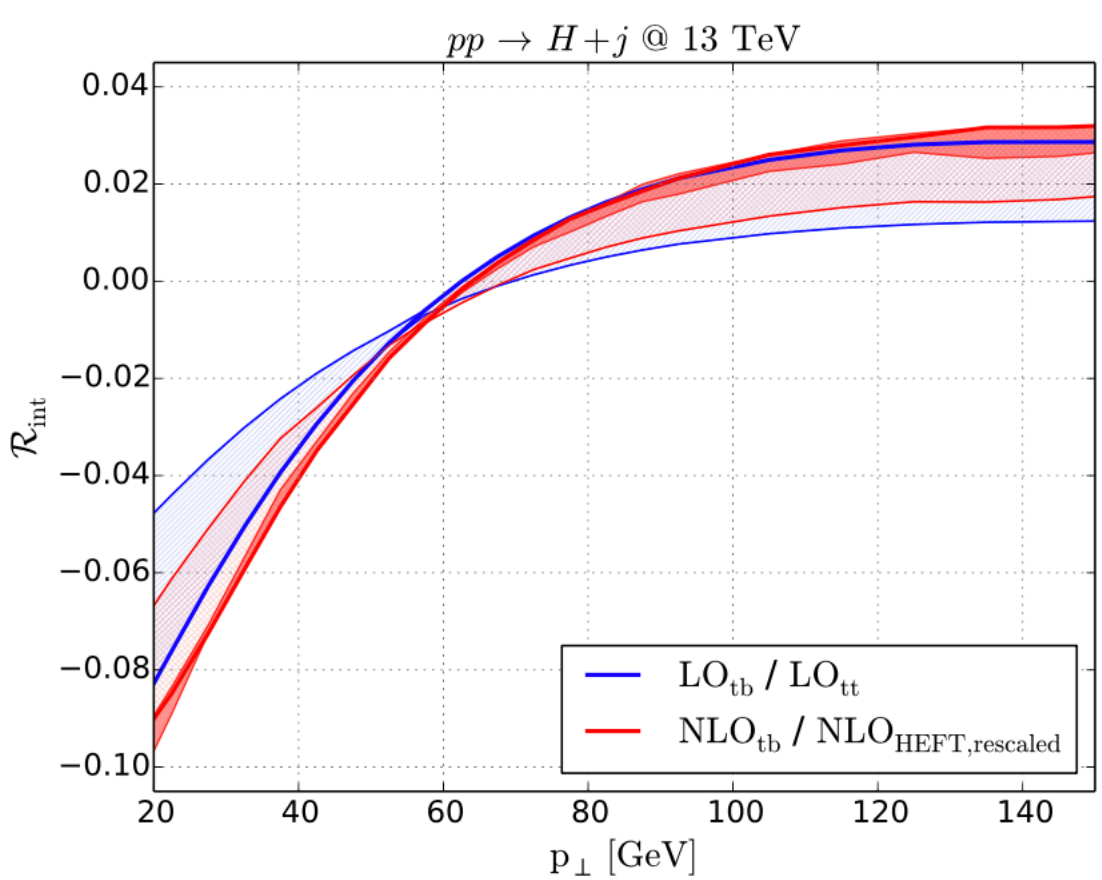
$$d\sigma = d\sigma_{tt} + d\sigma_{tb} + d\sigma_{bb}$$

J.Lindert, K.Melnikov, L.Tancredi, C.Wever (2017)

In the meanwhile: NLO corrections to top-bottom interference completed

Virtual: bottom contribution in the small m_b limit $\times$ HEFT contribution for m_{top}

Real: massive one-loop amplitudes with Openloops



Similar method used in analytic computation of top-bottom interference at NLO

R.Mueller, G.Ozturk (2016)

NLO corrections to the interference are sizeable and similar to those for the top contribution in the HEFT

Strong dependence on the scheme

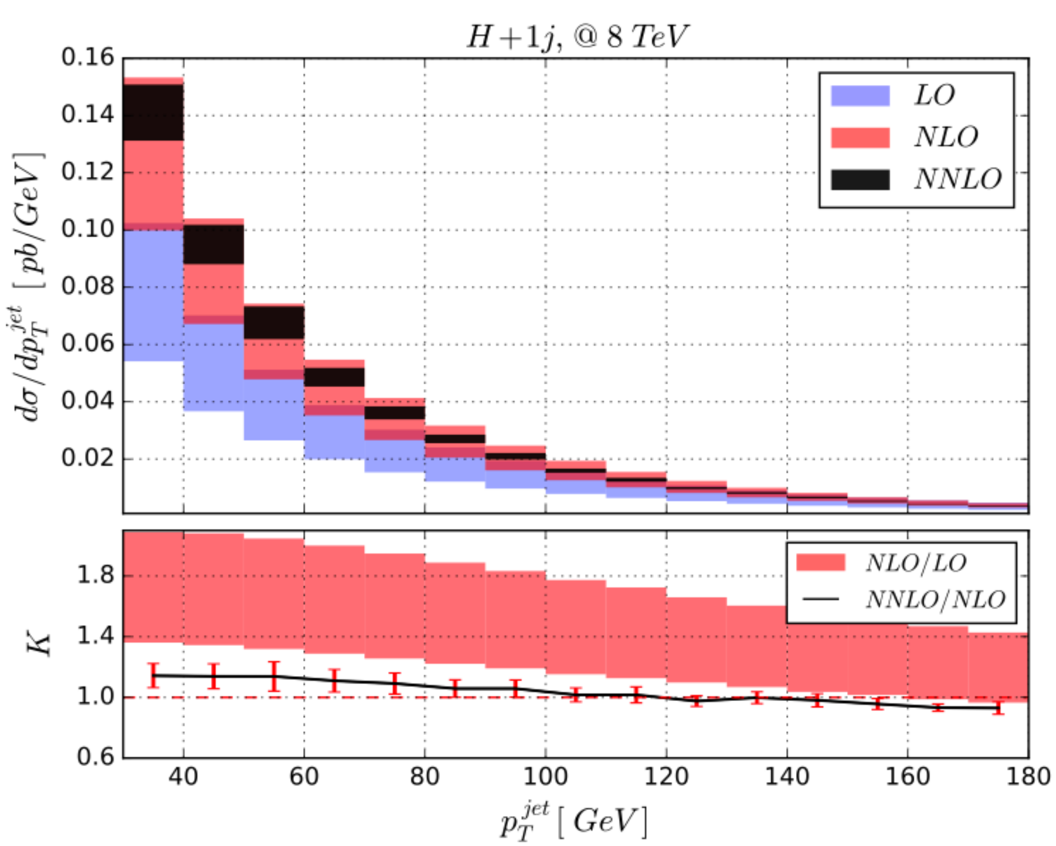
H+jet(s) at NNLO

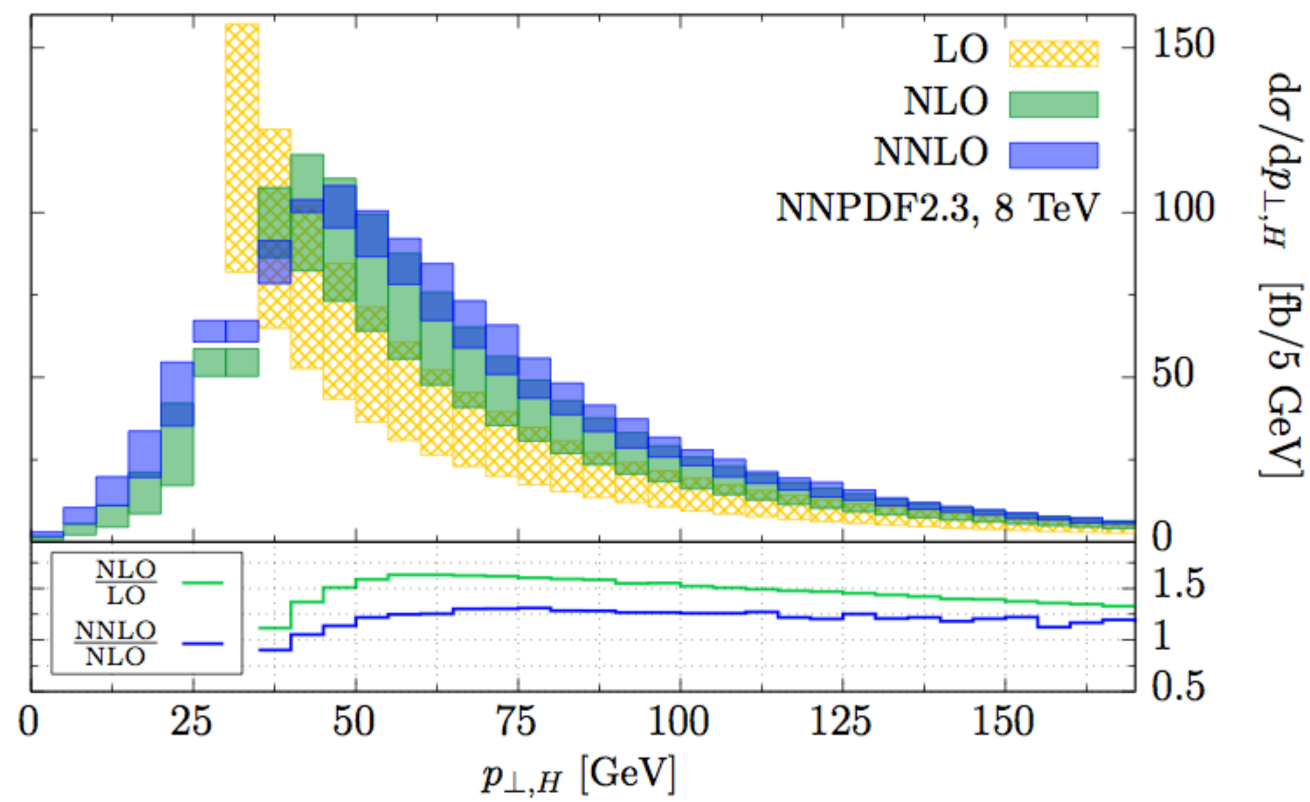
X. Chen, T. Gehrmann, N. Glover, M. Jaquier (2014,2016)
R.Boughezal, F.Caola, K.Melnikov, ,F.Petriello, M.Schulze (2015)
R.Boughezal, C.Focke, W.Giele ,X.Liu, F.Petriello (2015)

Go one order higher: Fully differential NNLO computation in the HEFT

Calculation carried out with three independent methods (N-jettiness, antenna subtraction, sector improved residue subtraction)

Important to validate NNLO results for such a complex final state

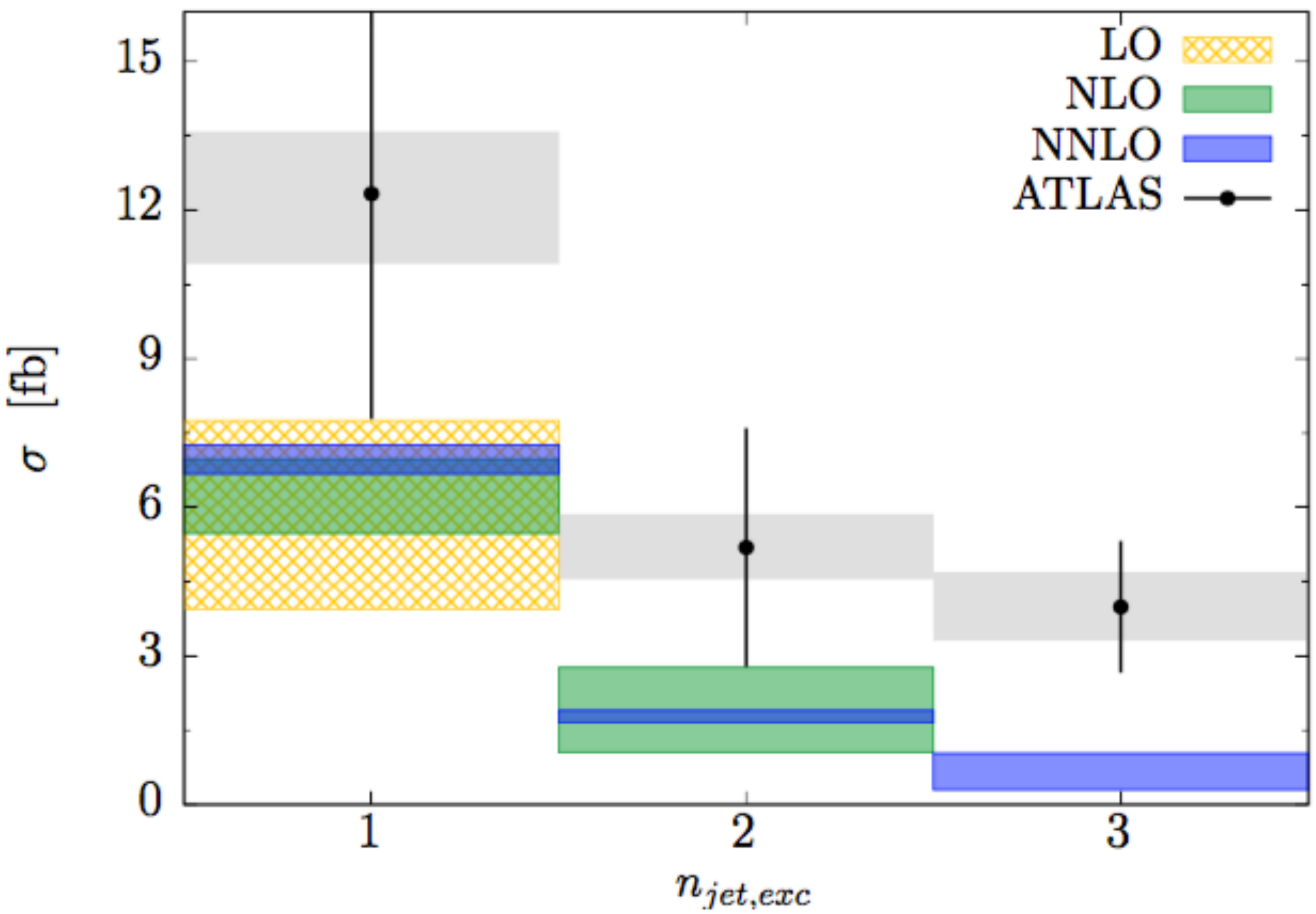




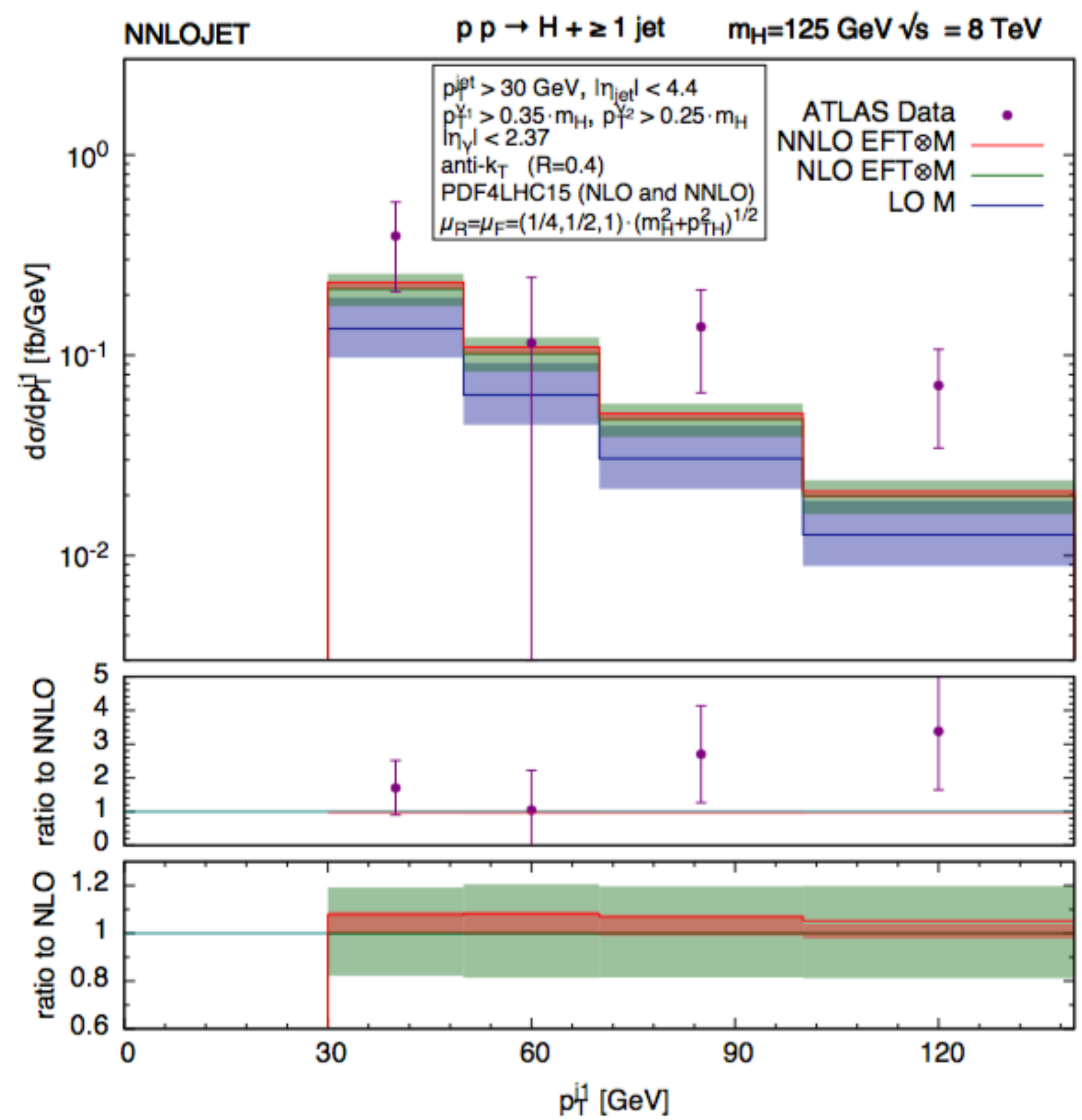
Same order in α_S as N3LO for the inclusive cross section

H+jet(s) at NNLO

Being fully differential the computation permits a direct comparison with data



F.Caola, K.Melnikov, M.Schulze (2015)



X. Chen, T. Gehrmann, N. Glover, M. Jaquier (2016)

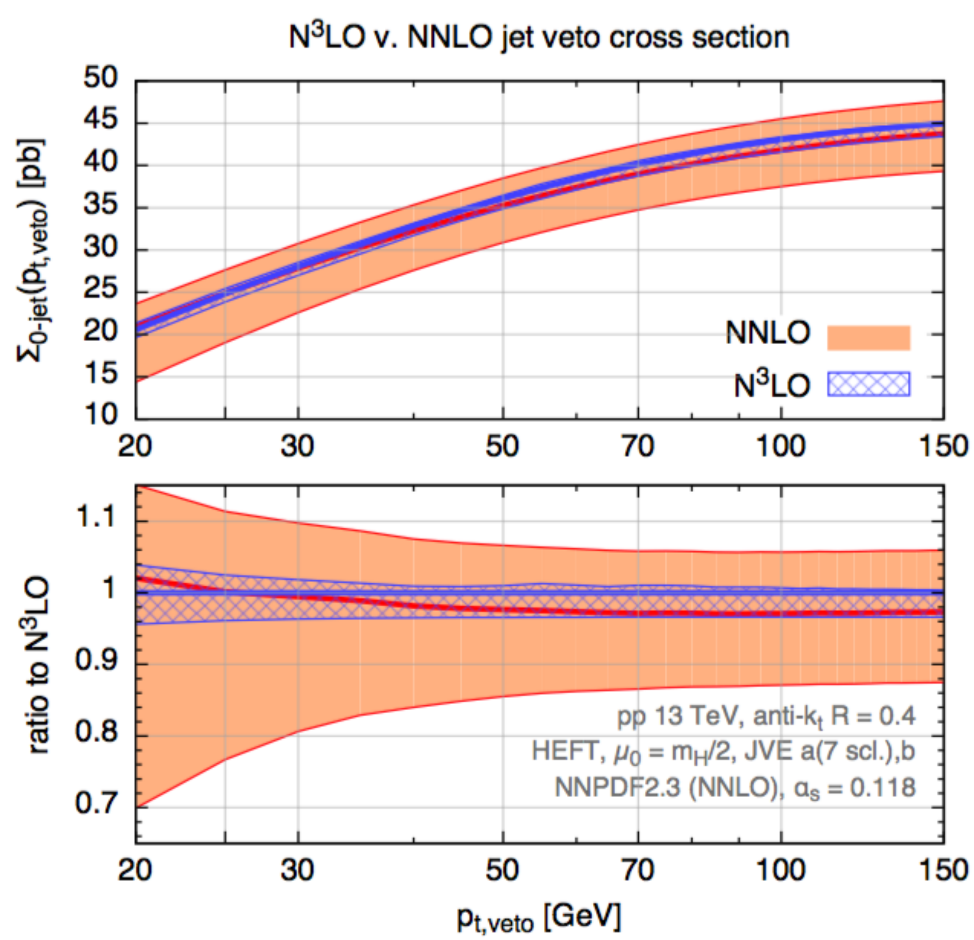
Jet-veto

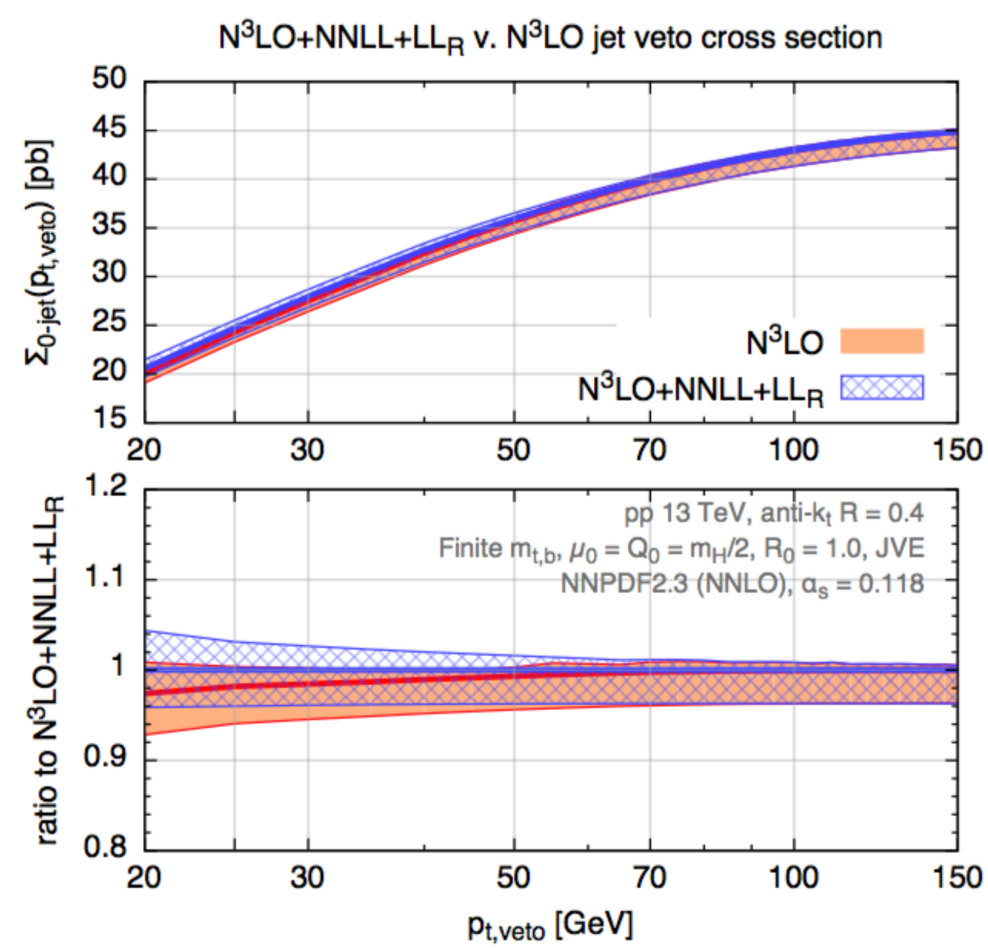
A. Banfi, F. Caola, F.A. Dreyer, P.F. Monni,
G.P. Salam, G. Zanderighi, F. Dulat (2016)

The cross section in the 0-jet bin can be obtained from the inclusive cross section by subtracting the H+jet(s) cross section at the same order in α_S

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

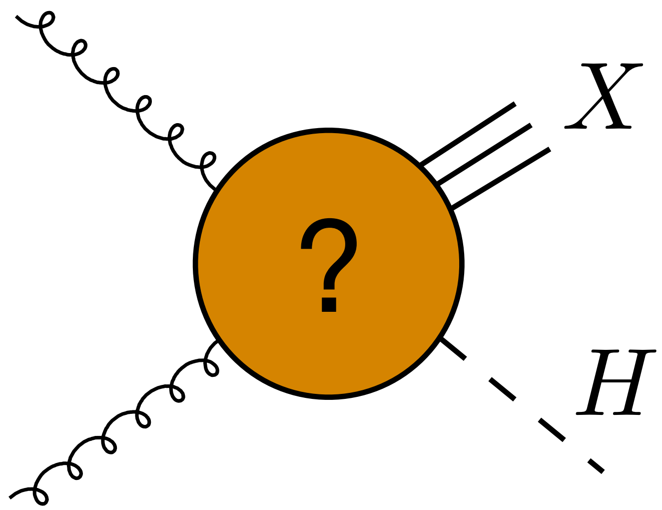
Combine with the jet-veto resummation at NNLL and LL resummation for the jet radius dependence





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

Transverse-momentum spectrum



When we are inclusive over the radiation recoiling against the Higgs boson we measure the p_T spectrum

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

For example: current constraints on the charm Yukawa y_c are rather weak but if y_c is very different from its SM value → effect on Higgs p_T distribution

Rapidity distribution mainly driven by PDFs

see e.g. F.Bishara, U.Haisch,P.Monni, E.Re (2016)

→ Effect of QCD radiation mainly encoded in the p_T spectrum

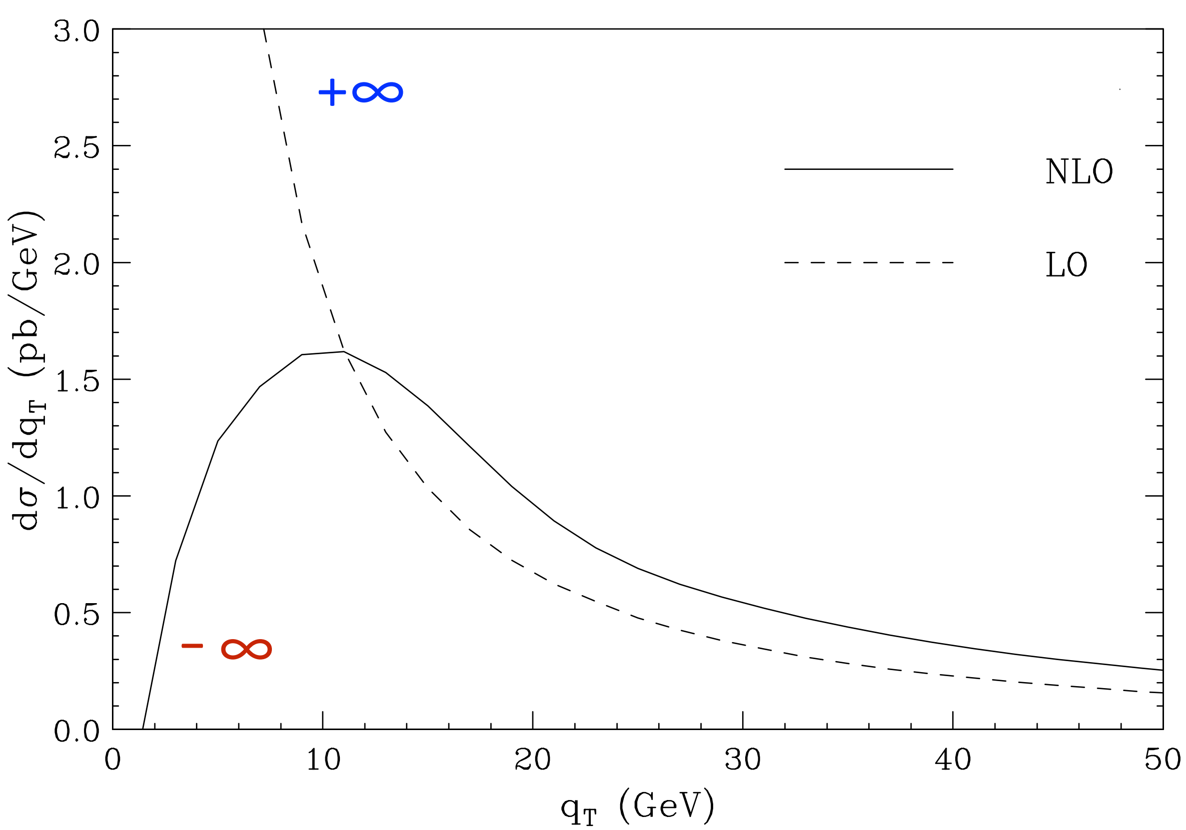
When considering the transverse momentum spectrum it is important to distinguish two regions of transverse momenta

The region $p_T \sim m_H$ can be described by fixed order H+jet(s) calculations

Transverse-momentum spectrum

In the region $p_T << m_H$ large logarithmic corrections of the form $\alpha_S^n \ln^m m_H^2/p_T^2$ 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)

NNLL+NNLO results including mass effects available in HRes: includes Higgs decays

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

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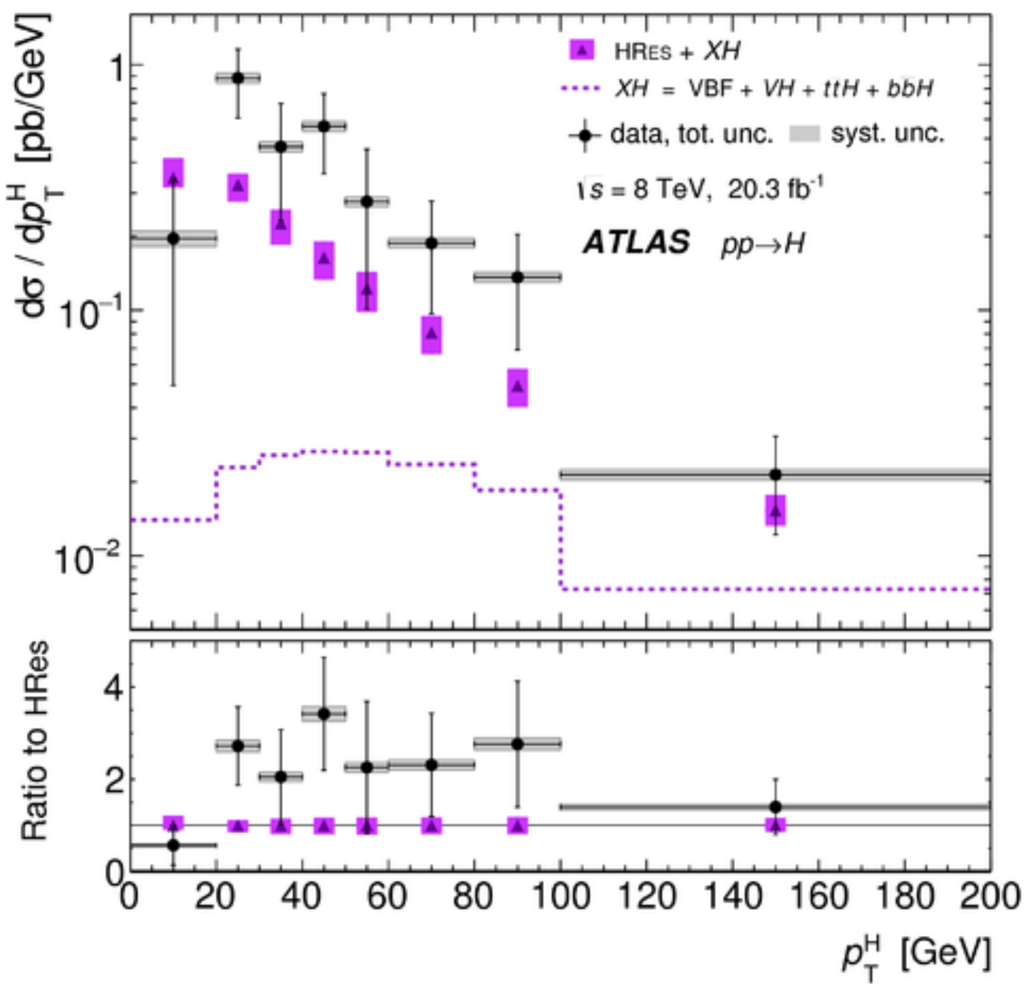

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Beyond current accuracy

- Combine threshold at fixed p_T and p_T resummation at small p_T such that the integral of the resummed spectrum coincides with the threshold resummed inclusive cross section at NNLL+NNLO

S.Forte, C.Muselli, G.Ridolfi (2017)

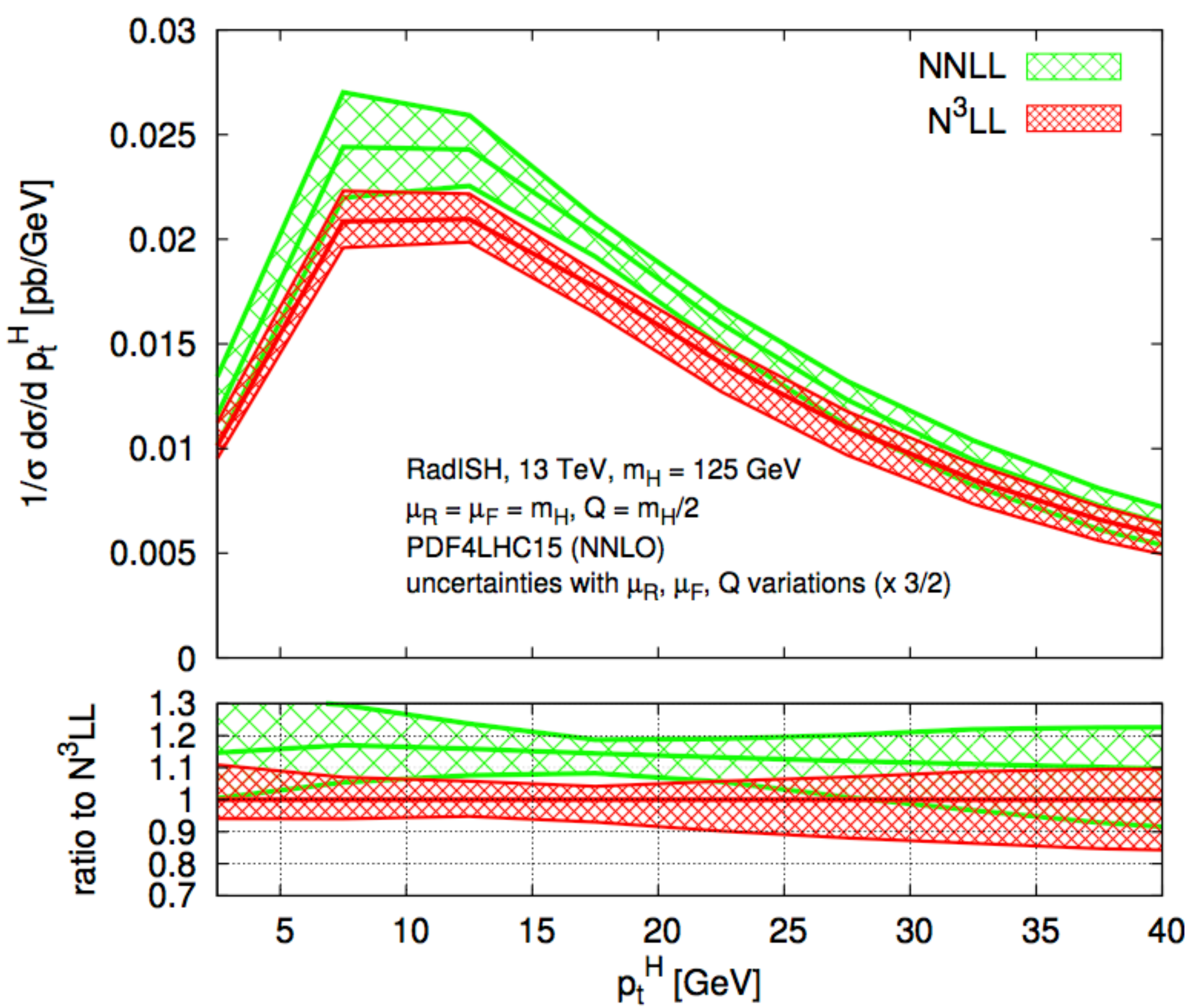
- Extend logarithmic accuracy of the resummed computation

The required resummation coefficient has been recently computed

Y. Li and H. X. Zhu (2016)
A.Vladimirov (2016)

Calculation done by using a new formulation directly in q_T space

P.Monni et al. (2017)

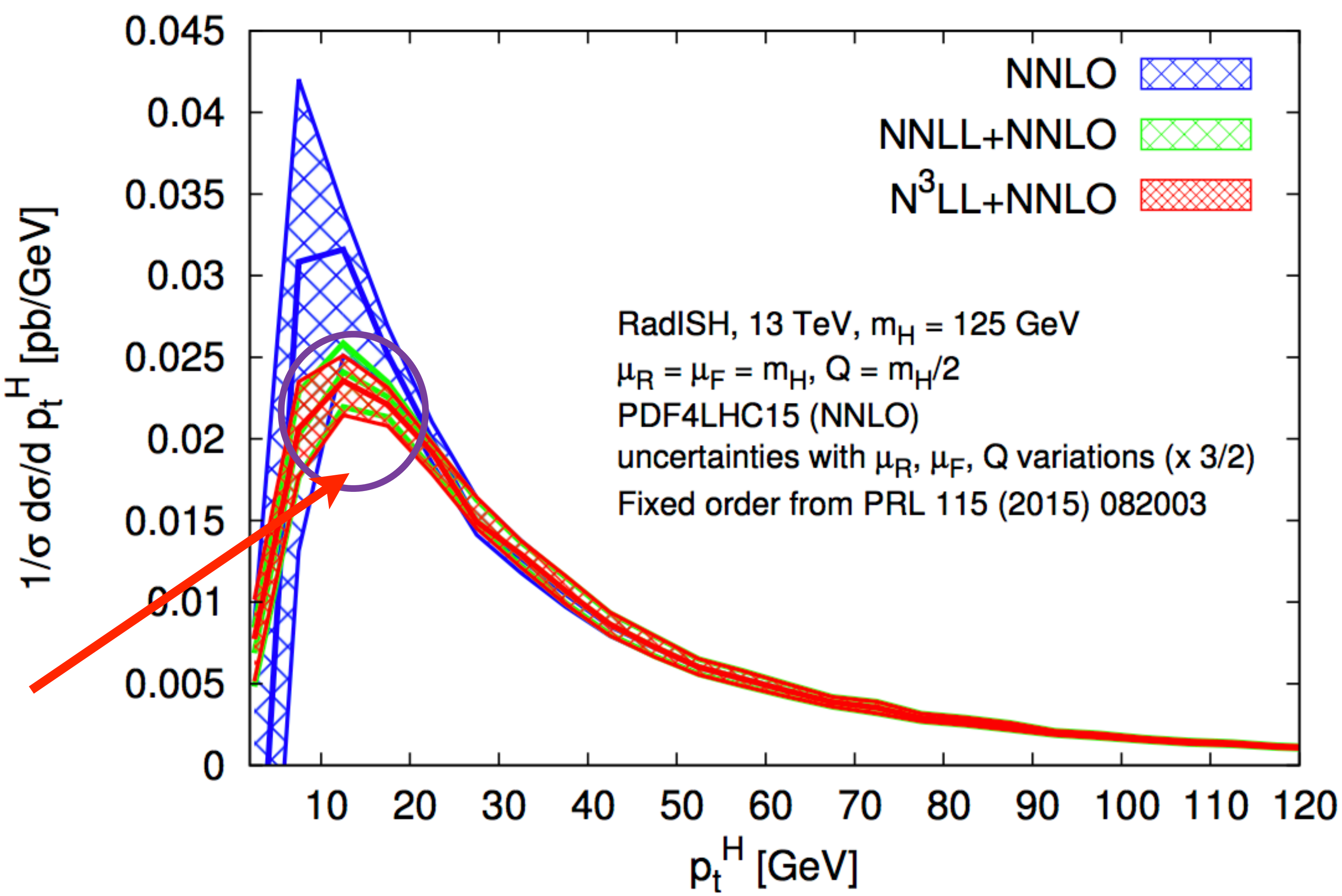


Beyond current accuracy

The H+jet calculation at NNLO can be used to improve the matching

First resummed predictions at (almost) N3LL+N3LO

P.Monni et al. (2017)



Matching accuracy currently limited by numerical instabilities of fixed order calculations

BSM effects on Higgs p_T

A.Ilnicka, M.Spira, M.Wiesemann, MG (2016)

Small deviations from the SM predictions could be due to new-physics effects → Parametrize them with an EFT approach $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$

$$\mathcal{O}_1 = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu} \longrightarrow \frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}$$

$$\mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c. \longrightarrow \frac{m_t}{v} c_t h \bar{t} t$$

$$\mathcal{O}_3 = |H|^2 \bar{Q}_L H d_R + h.c. \longrightarrow \frac{m_b}{v} c_b h \bar{b} b$$

$$\mathcal{O}_4 = \bar{Q}_L H \sigma^{\mu\nu} T^a u_R G^a_{\mu\nu} + h.c. \longrightarrow c_{tg} \frac{g_S m_t}{2v^3} (v+h) G^a_{\mu\nu} (\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c)$$

NLL+NLO computation which consistently includes the effect of O_1 O_2 and O_3 operators

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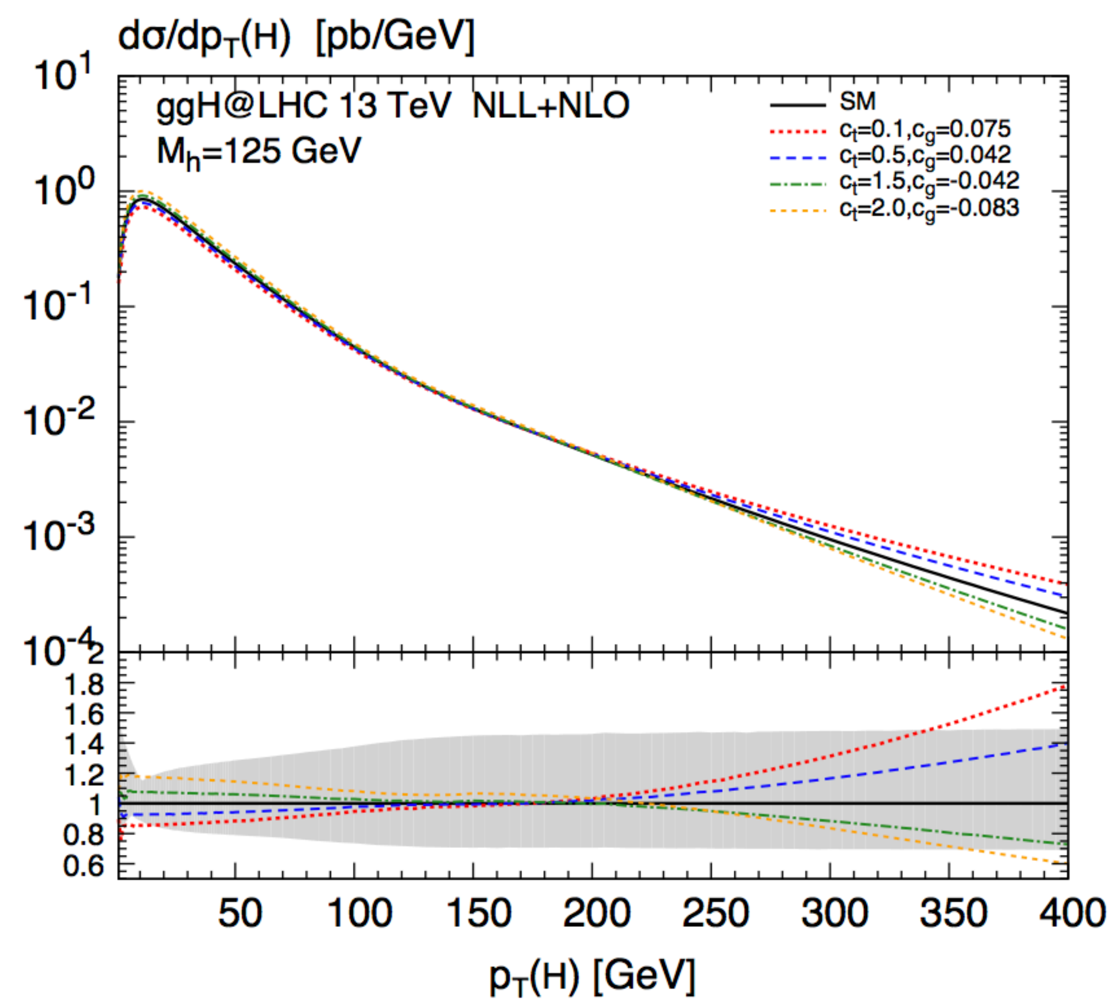
$$\mathcal{O}_4 = \bar{Q}_L H \sigma^{\mu\nu} T^a u_R G^a_{\mu\nu} + h.c. \longrightarrow c_{tg} \frac{g_S m_t}{2v^3}(v + h$$

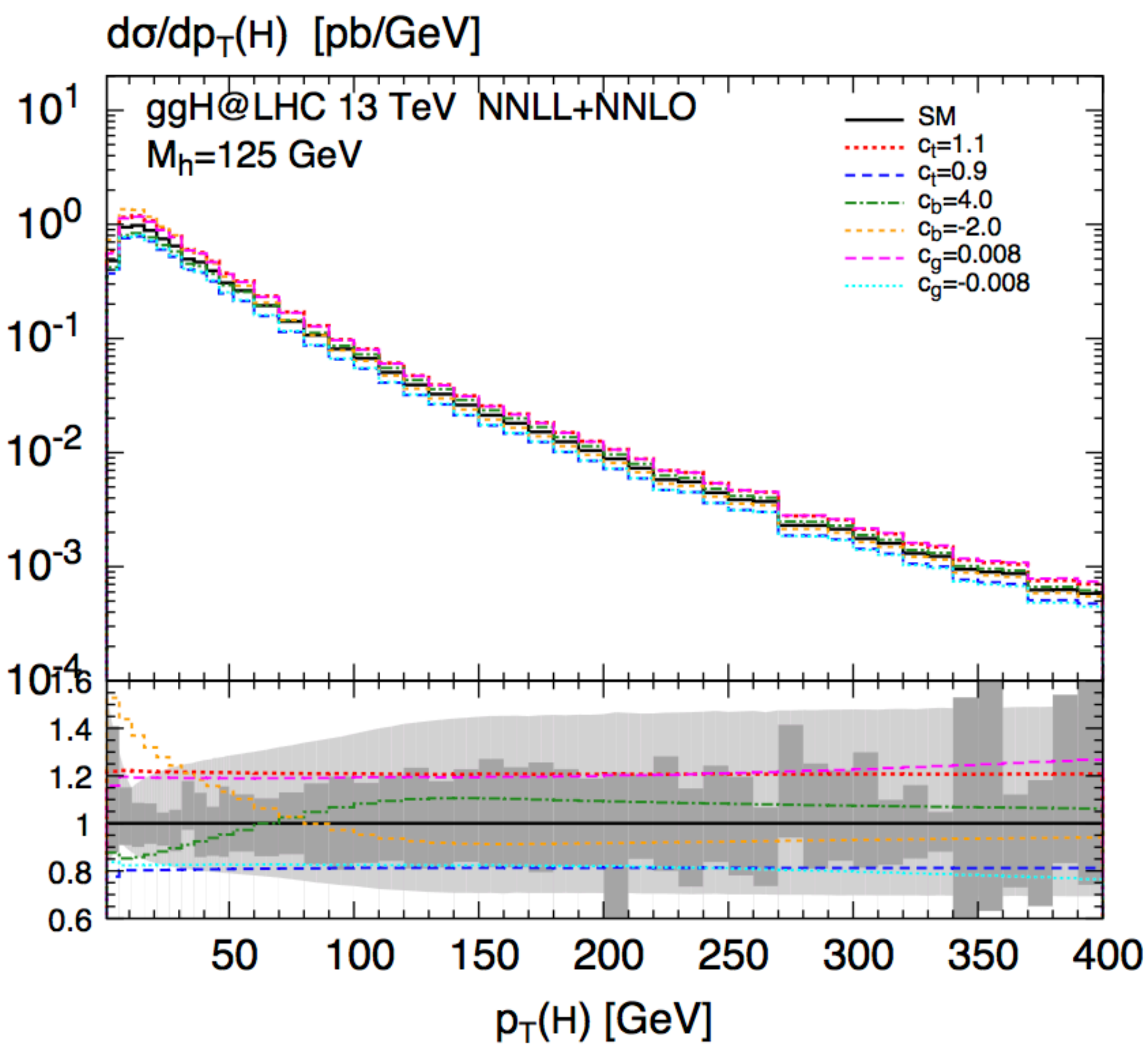
NLL+NLO computation which consistently includes the effect of O_1 O_2 and O_3 operators

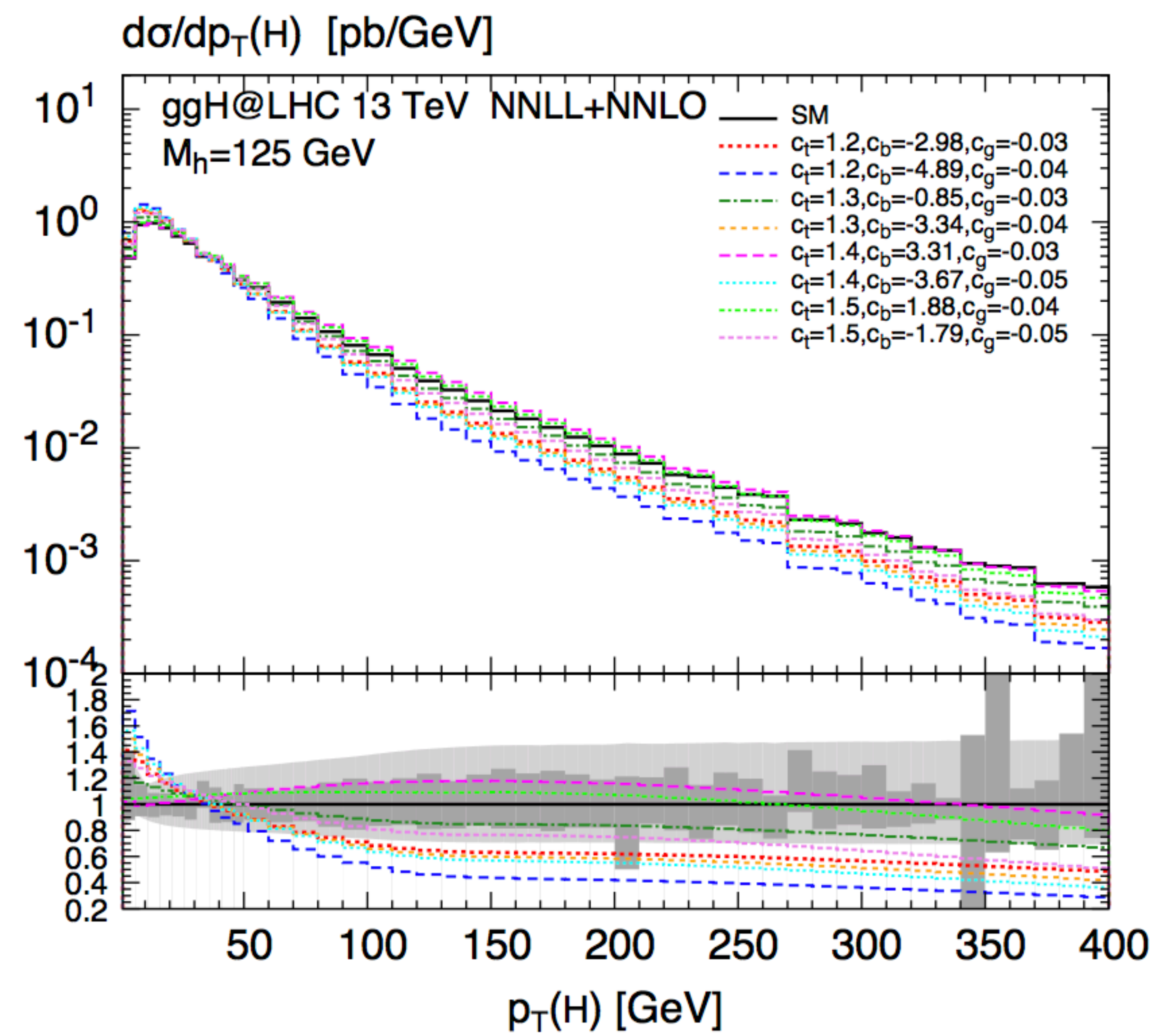


the simultaneous effect of two or more operators can significantly distort the spectrum, still keeping the total rate consistent with the SM prediction

BSM effects on Higgs p_T

A.Ilnicka,M.Spira, M.Wiesemann, MG (2016)



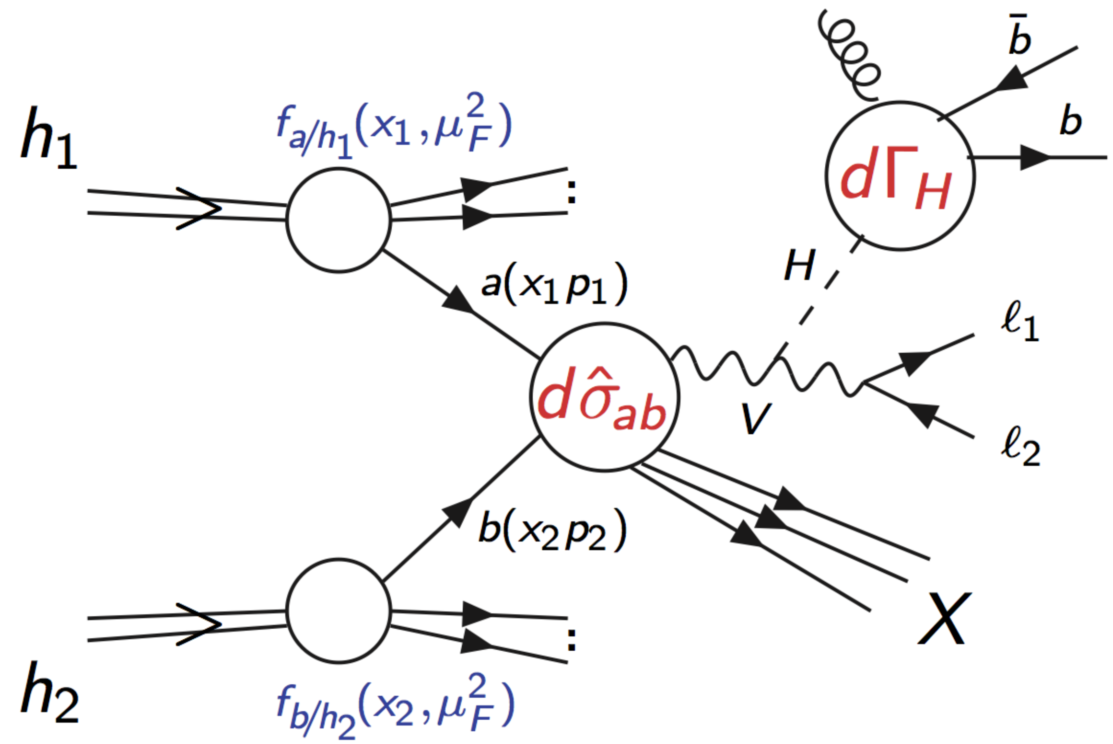


Relative BSM effects computed in this way can be used to rescale benchmark NNLL+NNLO effects

Similar results (including chromomagnetic operator) in the MG5_aMC framework

talk by Deutschmann

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)

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

Fully differential NNLO corrections available in the program VHNNLO, also including H→bb decay at NLO

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

Differential NNLO H→bb decay rate also available

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

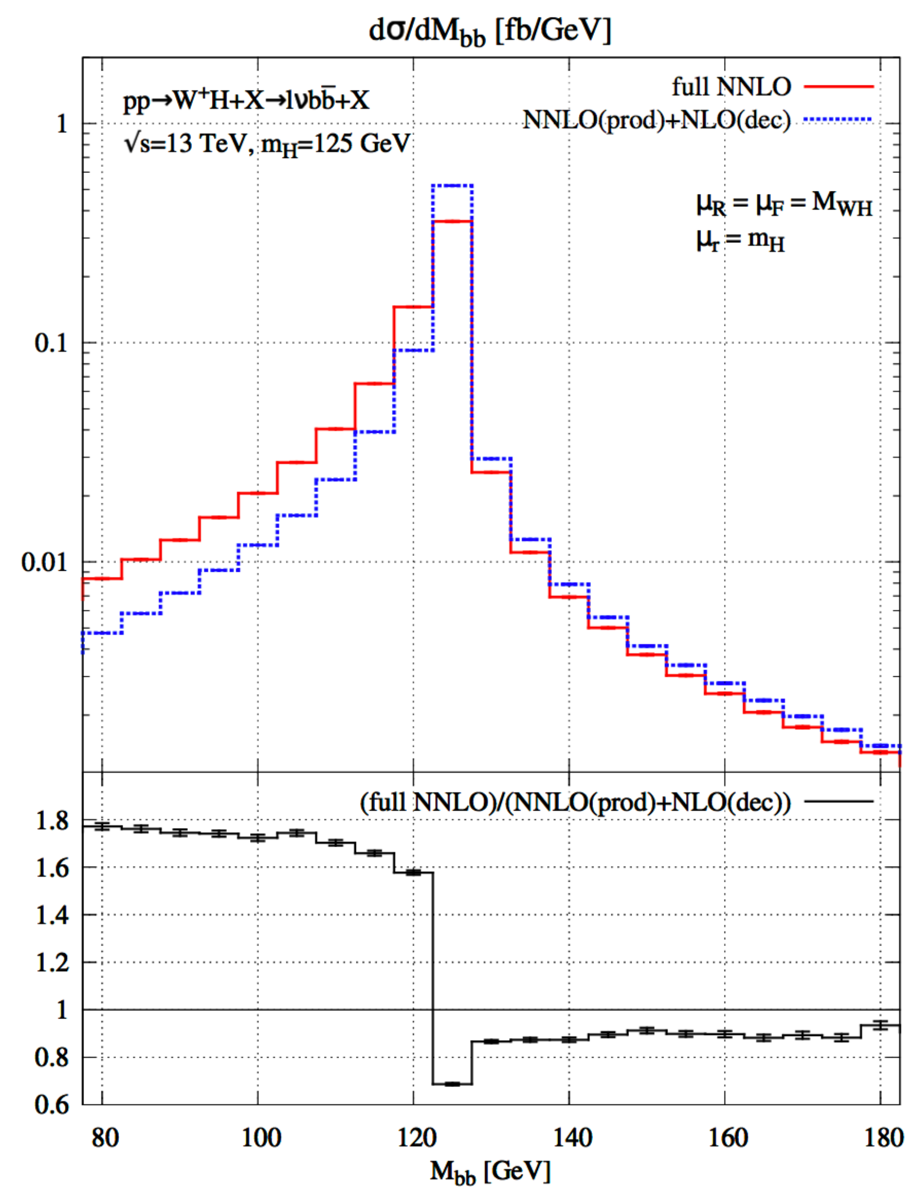
NNLO corrections for production + NLO decay now also in MCFM

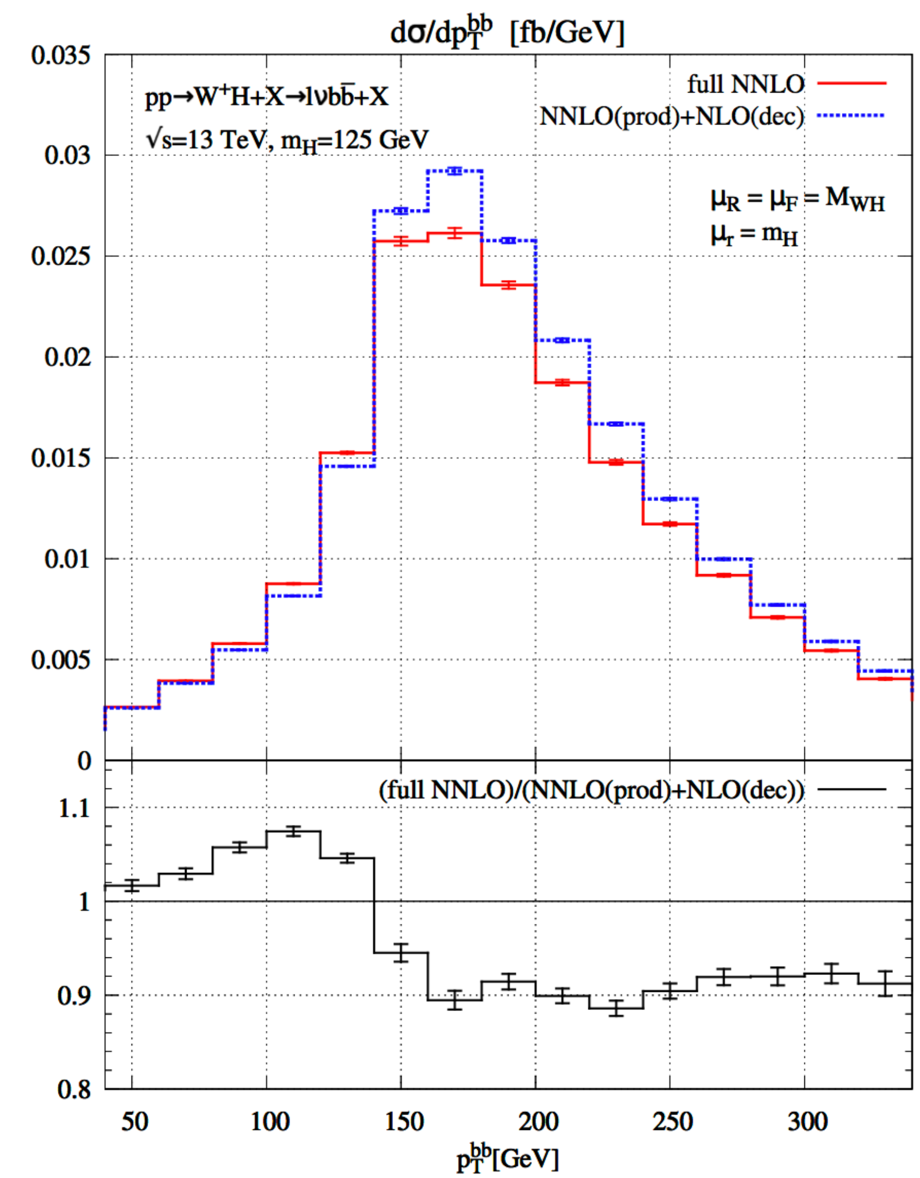
R.Boughezal et al (2016)

VH

G.Ferrera, G.Somogyi, F.Tramontano (2017)

Full NNLO QCD calculation (production and decay) recently completed: combines q_T subtraction for production and colourful subtraction for decay





Relatively large effects (-6%) from newly computed effects

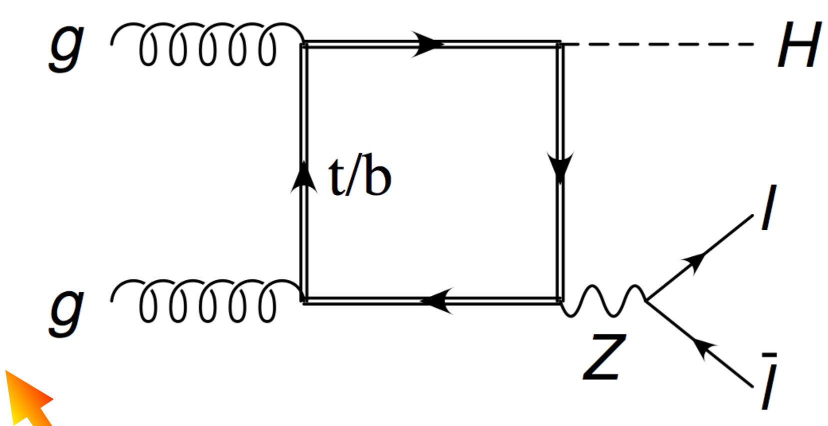
VH

The ZH bottleneck

The loop induced gg contribution, which first appears at NNLO, is strongly enhanced at high p_T

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%

$p_T^Z > 160$ GeV $\quad \Delta\phi_{Z,b\bar{b}} > 3$



Impact of gg → ZH

→ Increasingly important in the boosted region

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

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

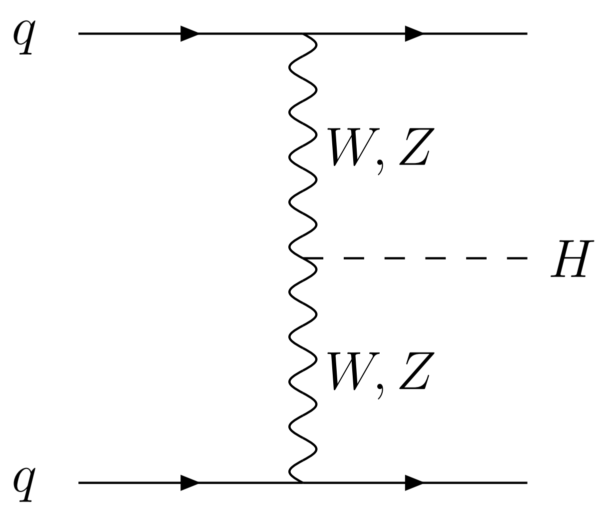
L.Altenkamp et al. (2012)

Use numerical techniques as in NLO calculation for HH ?

S.Borowka et al (2016)

The presence of one additional scale (Q~ m_Z) makes reduction to master integrals much more involved

VBF



Second important production channel: distinctive signature with little jet activity in the central rapidity region

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)

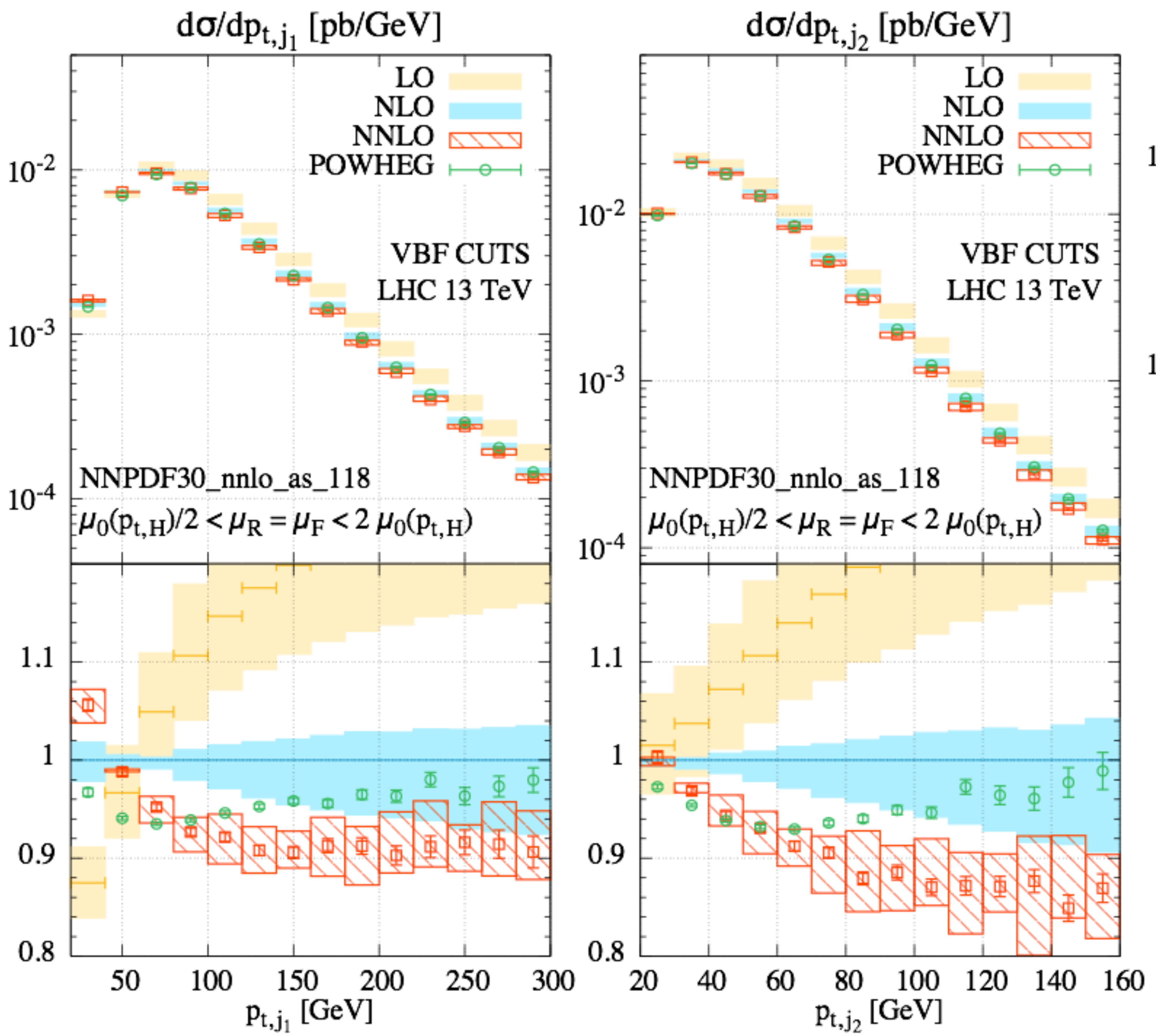
and the more relevant DIS like NNLO contributions computed within the structure function approach (1% effect)

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

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

VBF

Theoretical control appears to be at the level of accuracy to which the process itself can be defined but....



Fully exclusive NNLO computation recently completed shows that NNLO corrections make p_T spectra softer

➡ larger impact when VBF cuts are applied

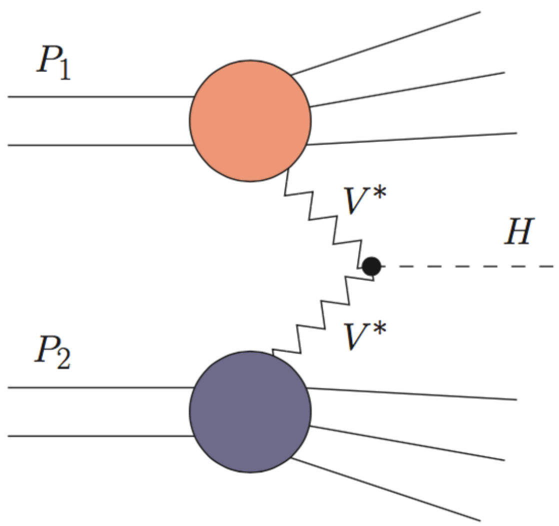
	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032\,^{+0.057}_{-0.069}$	$0.957\,^{+0.066}_{-0.059}$
NLO	$3.929\,^{+0.024}_{-0.023}$	$0.876\,^{+0.008}_{-0.018}$
NNLO	$3.888\,^{+0.016}_{-0.012}$	$0.826\,^{+0.013}_{-0.014}$
	-1%	-6%

M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)

VBF

Inclusive N3LO calculation recently completed (structure function approach: neglecting color connections between the upper and lower part of the diagrams)

F.Dreyer, A.Karlberg (2016)



Residual scale uncertainty at the per mille level

Could potentially lead to a differential N3LO calculation with the same method adopted at NNLO

→ talk by A.Karlberg

Remaining issues:

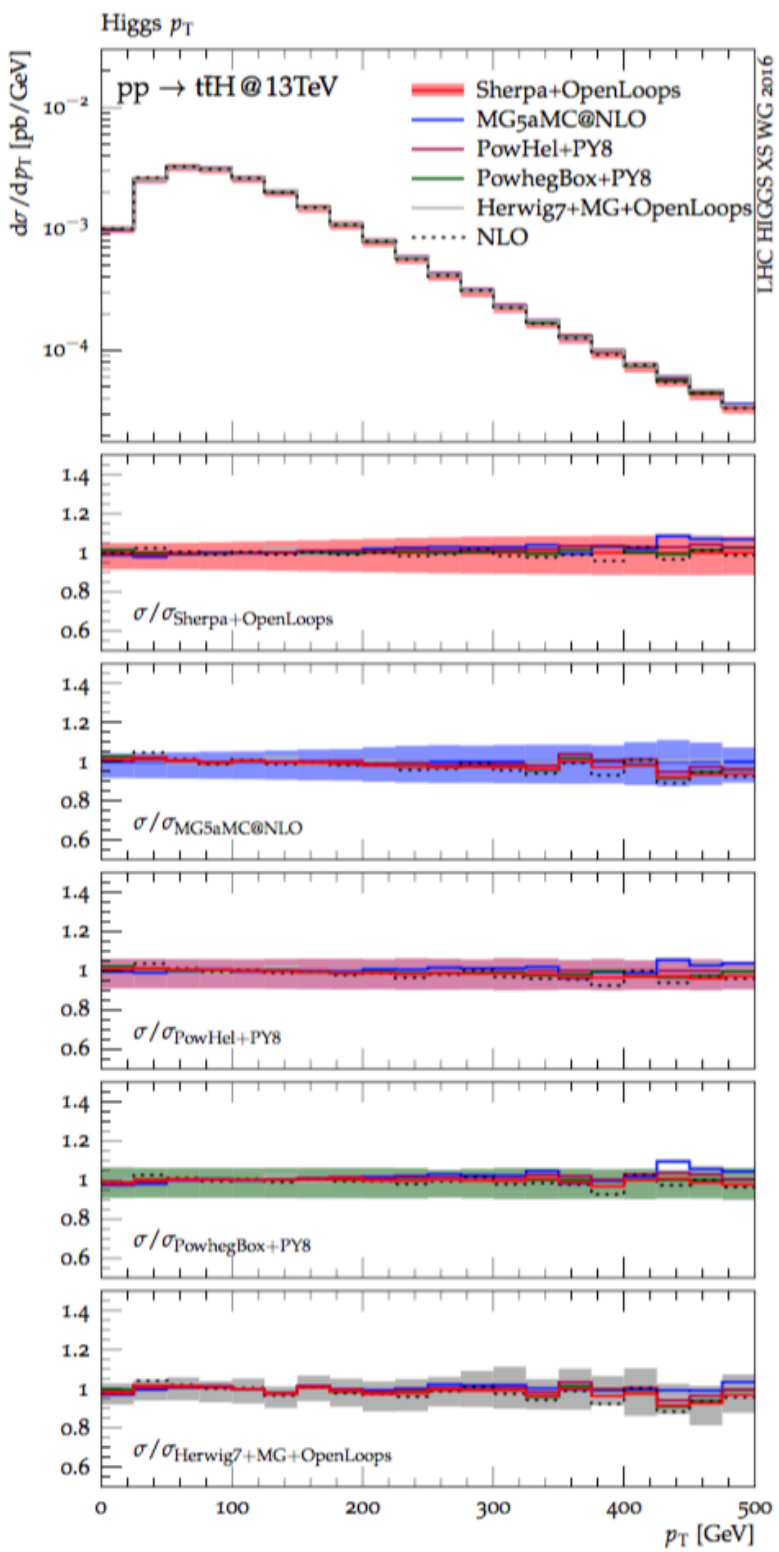
- ggF contamination: in run 2 will use NNLOPS → Large uncertainties
- central jet veto: when matching to PS different showers give significantly different results

When it comes to realistic studies more work is needed !

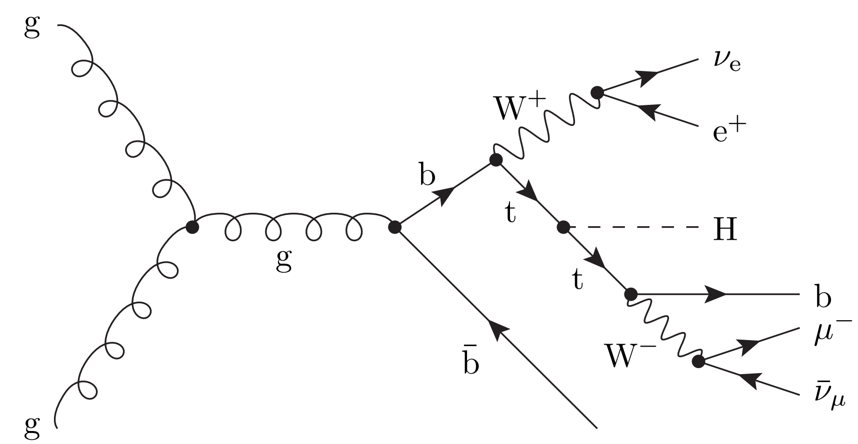
ttH

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)



Realistic parton level simulations including top decays and all non-resonant contributions, off-shell effects and interferences



A.Denner , R.Feger (2015)

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

R.Frederix et al (2014)

Various NLO+PS implementations:

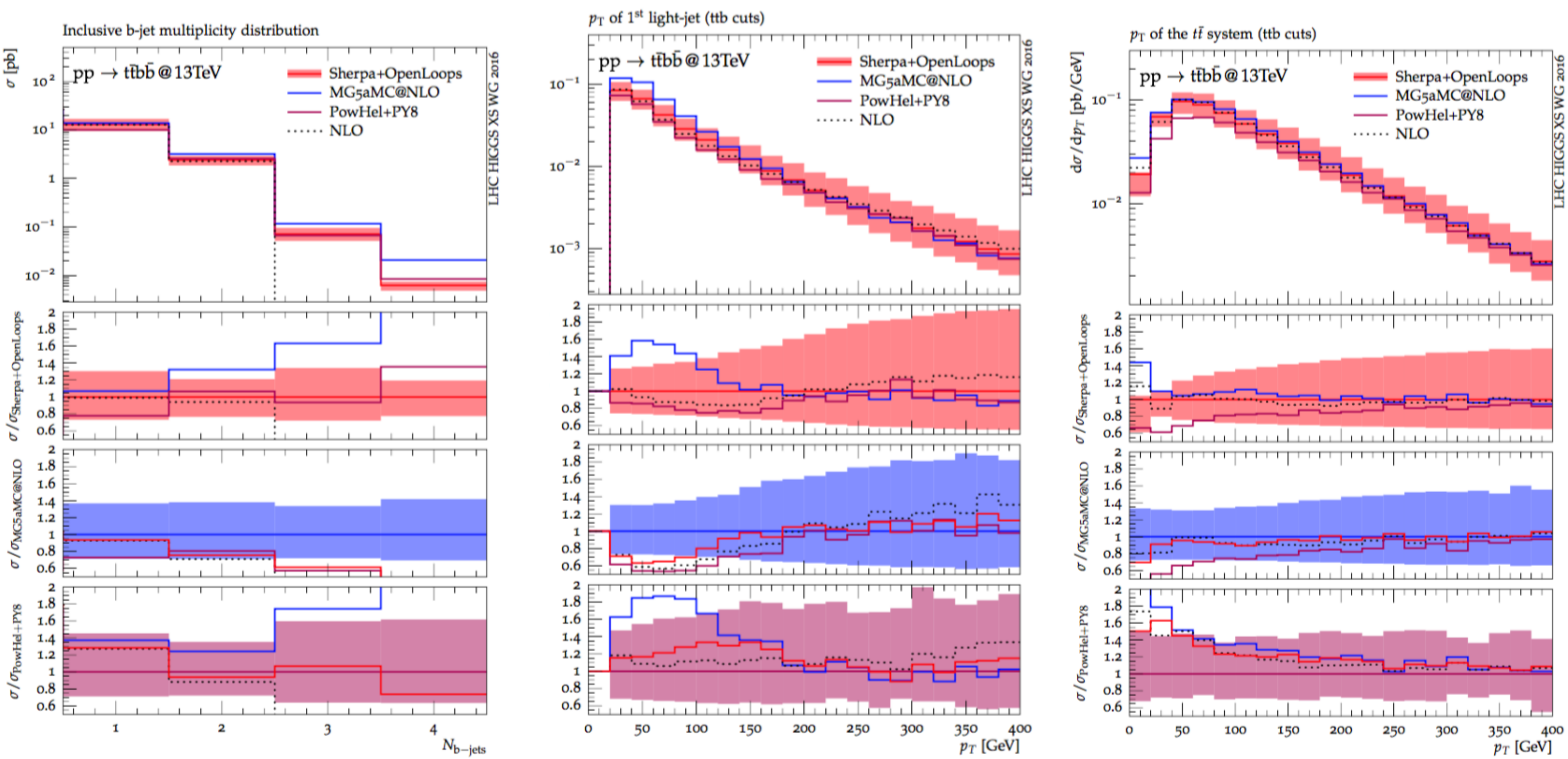
Validation for HXSWG YR4 → Good compatibility

QCD+EW corrections

S.Frixione et al (2014, 2015)
see also Z.Yu et al (2014)

ttH

Main problem is to reach a good understanding of backgrounds

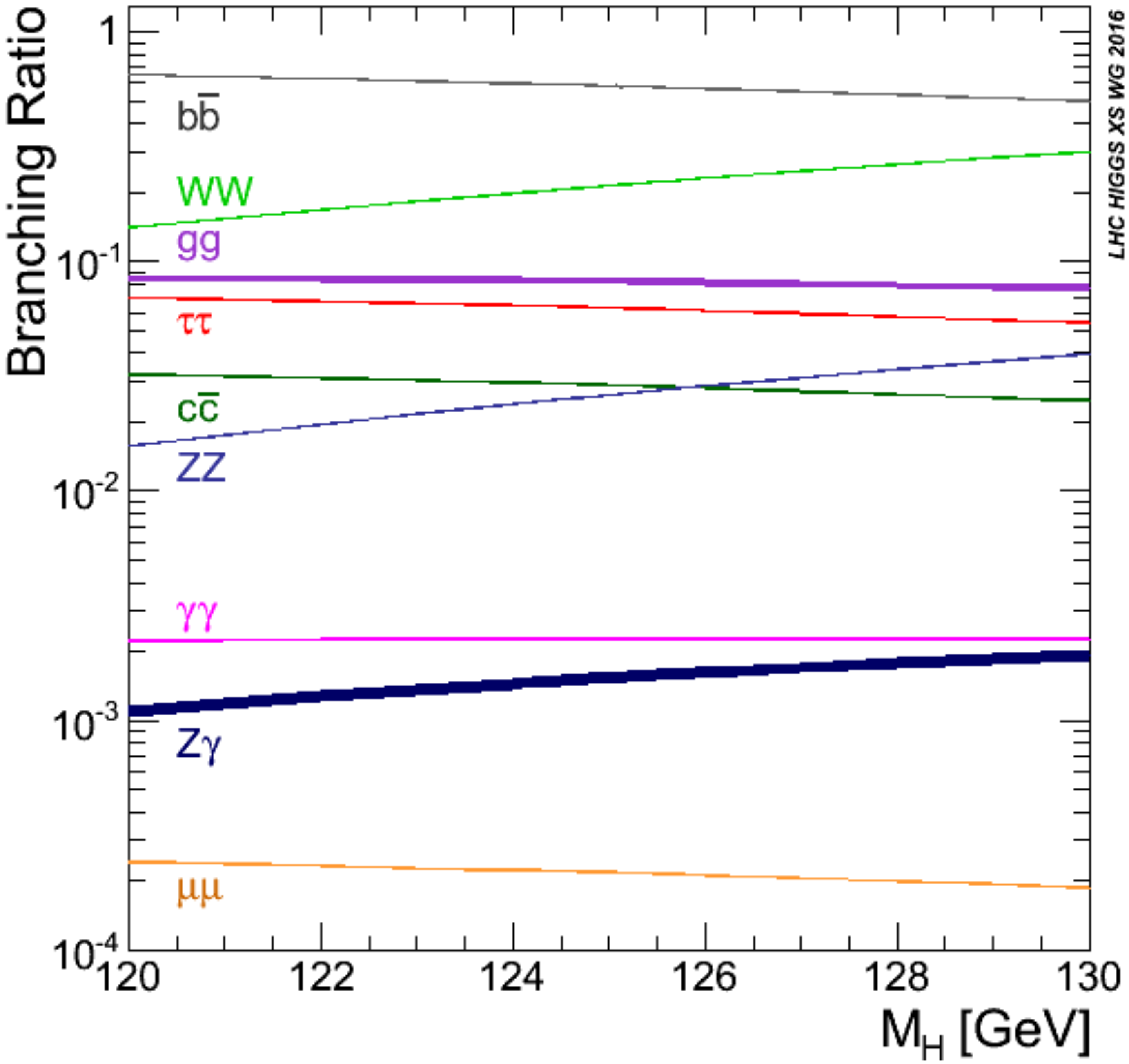


S.Guidon, C.Neu , S.Pozzorini, L.Reina, YR4 HXSWG (2016)

NLO+PS simulations show some discrepancies: to be understood

Higgs decays

A.Denner, S.Heinemeyer, A. Mück,
I.Puljak, D.Rebuzzi (HXSWG YR4, 2016)



Results based on HDECAY and Prophecy4f which include all relevant QCD and EW corrections

$$\Gamma_{\mathrm{H}} = \Gamma^{\mathrm{HD}} - \Gamma^{\mathrm{HD}}_{\mathrm{ZZ}} - \Gamma^{\mathrm{HD}}_{\mathrm{WW}} + \Gamma^{\mathrm{Proph.}}_{\mathrm{4f}}$$

New version of HDECAY includes EW corrections in fermionic decays and MSbar input masses

Higgs decays

For M_H = 125 GeV

YR3 → YR4

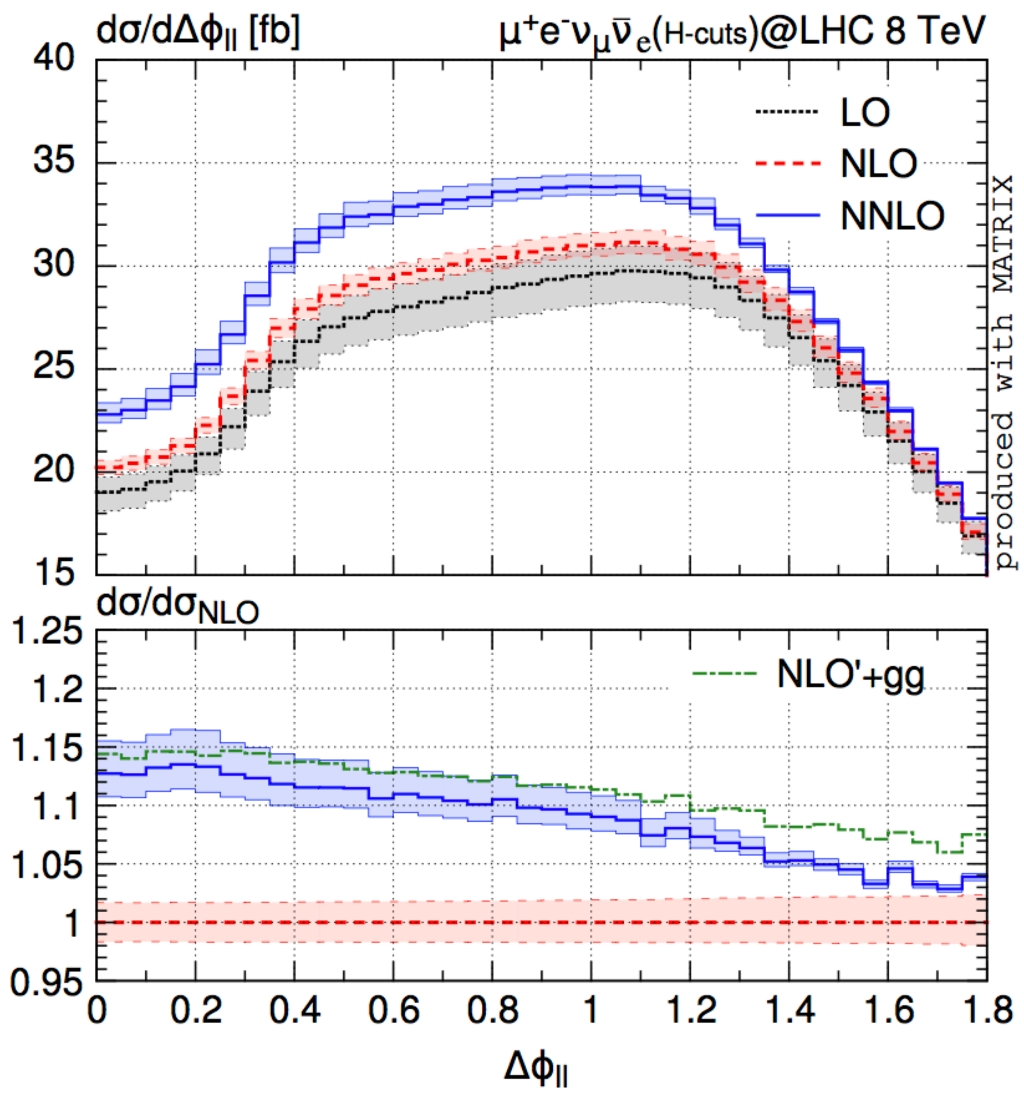
Channel	$\Delta\alpha_S$	Δm_b	Δm_c	THU
$b\bar{b}$	$^{-2.3\%}_{+2.3\%} \rightarrow ^{-1.4\%}_{+1.4\%}$	$^{+3.3\%}_{-3.2\%} \rightarrow ^{+1.7\%}_{-1.7\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+2.0\%}_{-2.0\%} \rightarrow ^{+0.5\%}_{-0.5\%}$
$\tau\tau$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+2.0\%}_{-2.0\%} \rightarrow ^{+0.5\%}_{-0.5\%}$
$\mu\mu$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+2.0\%}_{-2.0\%} \rightarrow ^{+0.5\%}_{-0.5\%}$
$c\bar{c}$	$^{-7.1\%}_{+7.0\%} \rightarrow ^{-1.9\%}_{+1.9\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+6.2\%}_{-6.1\%} \rightarrow ^{+5.3\%}_{-5.2\%}$	$^{+2.0\%}_{-2.0\%} \rightarrow ^{+0.5\%}_{-0.5\%}$
gg	$^{+4.2\%}_{-4.1\%} \rightarrow ^{+3.0\%}_{-3.0\%}$	$^{+0.1\%}_{-0.1\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+3.0\%}_{-3.0\%}$
$\gamma\gamma$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+1.0\%}_{-1.0\%}$
$Z\gamma$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+5.0\%}_{-5.0\%}$
WW	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$
ZZ	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$

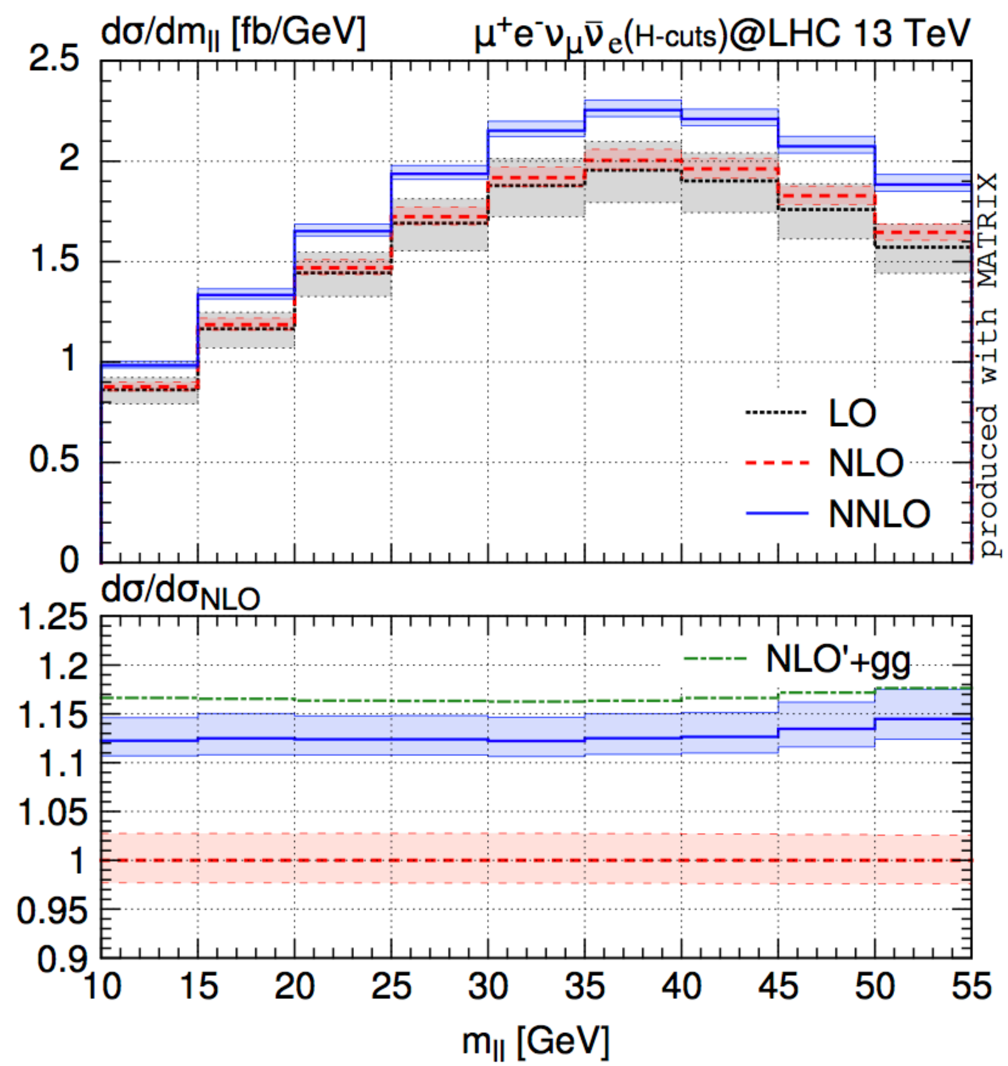
D.Rebuzzi, HXSWG meeting, july 2016

Significant reduction of PU and TH uncertainties on the partial widths

Diboson backgrounds

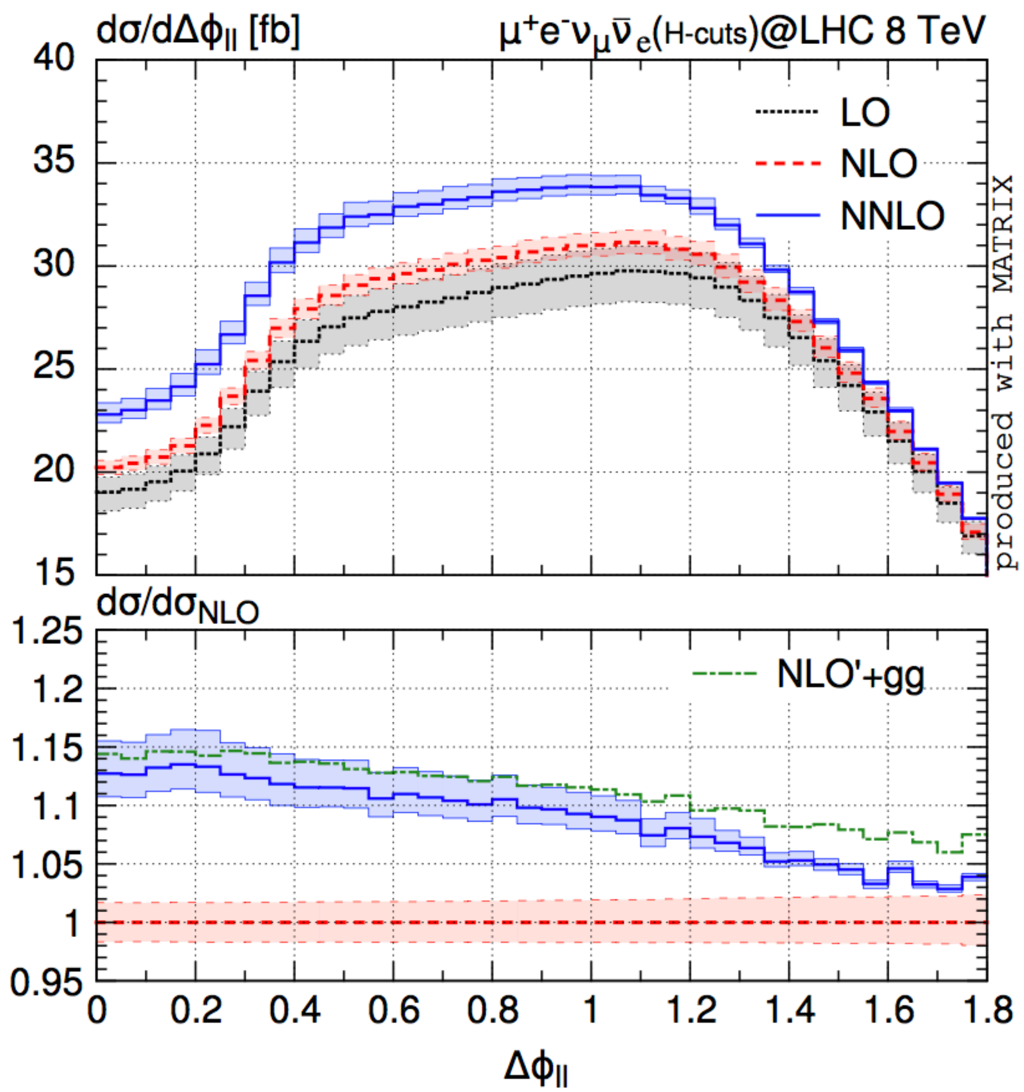
All diboson backgrounds computed to NNLO QCD

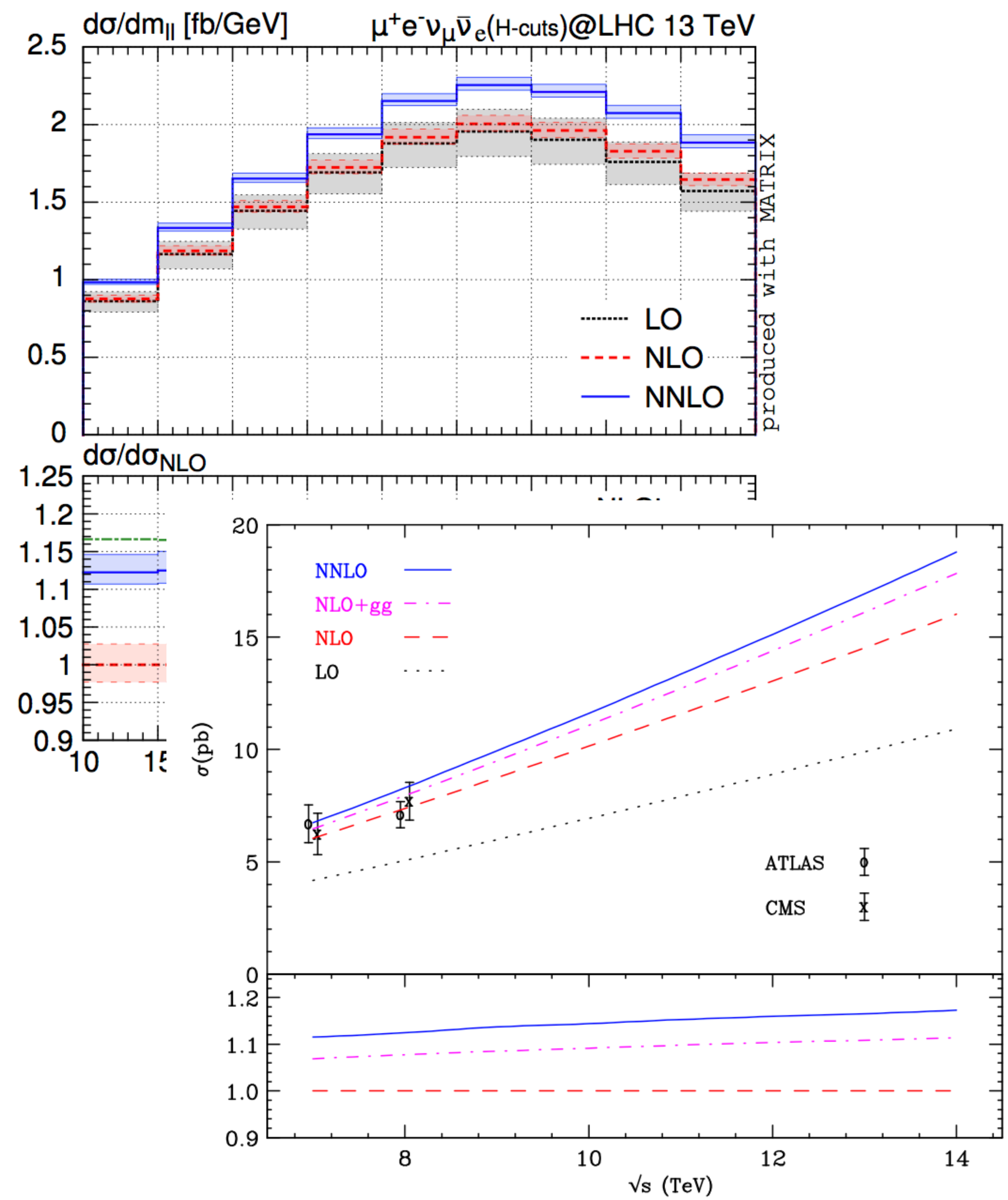




Diboson backgrounds

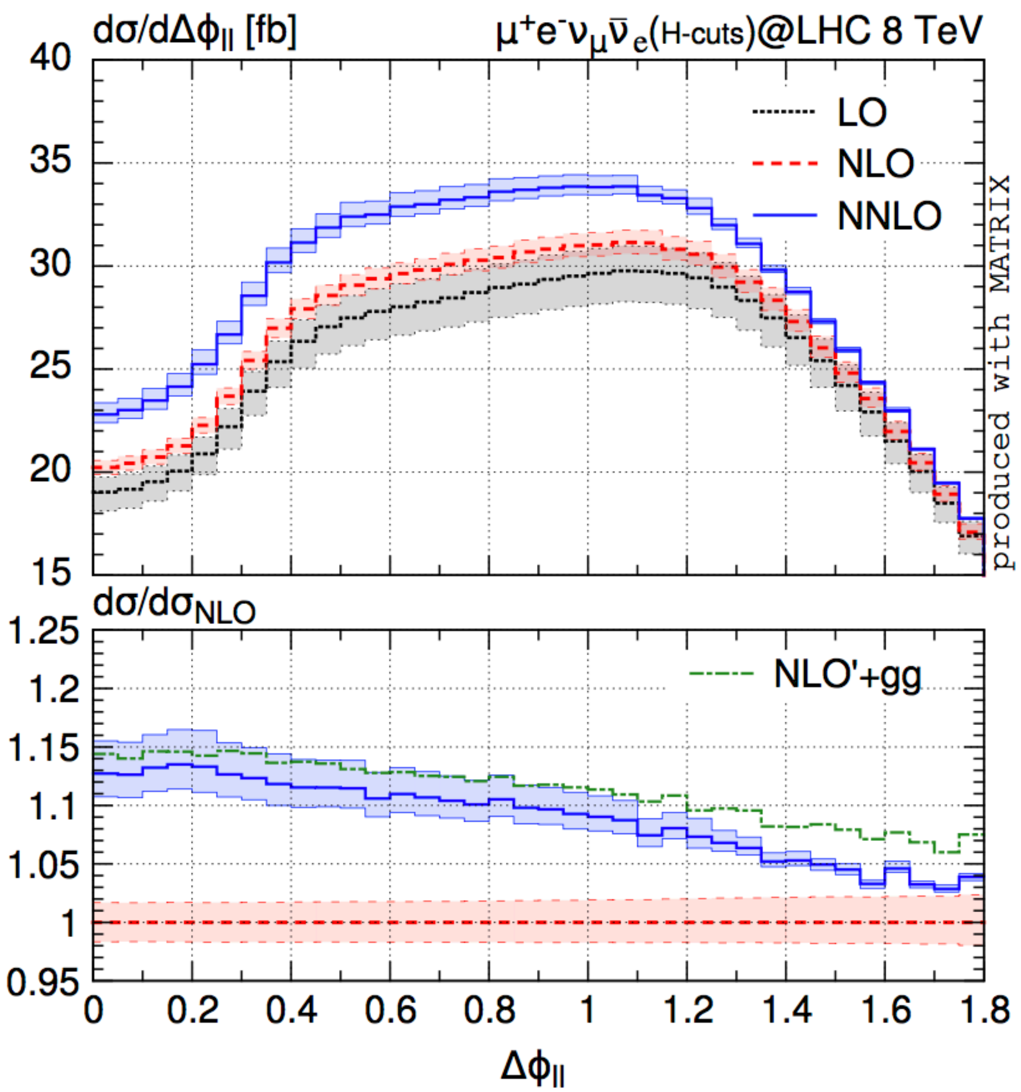
All diboson backgrounds computed to NNLO QCD

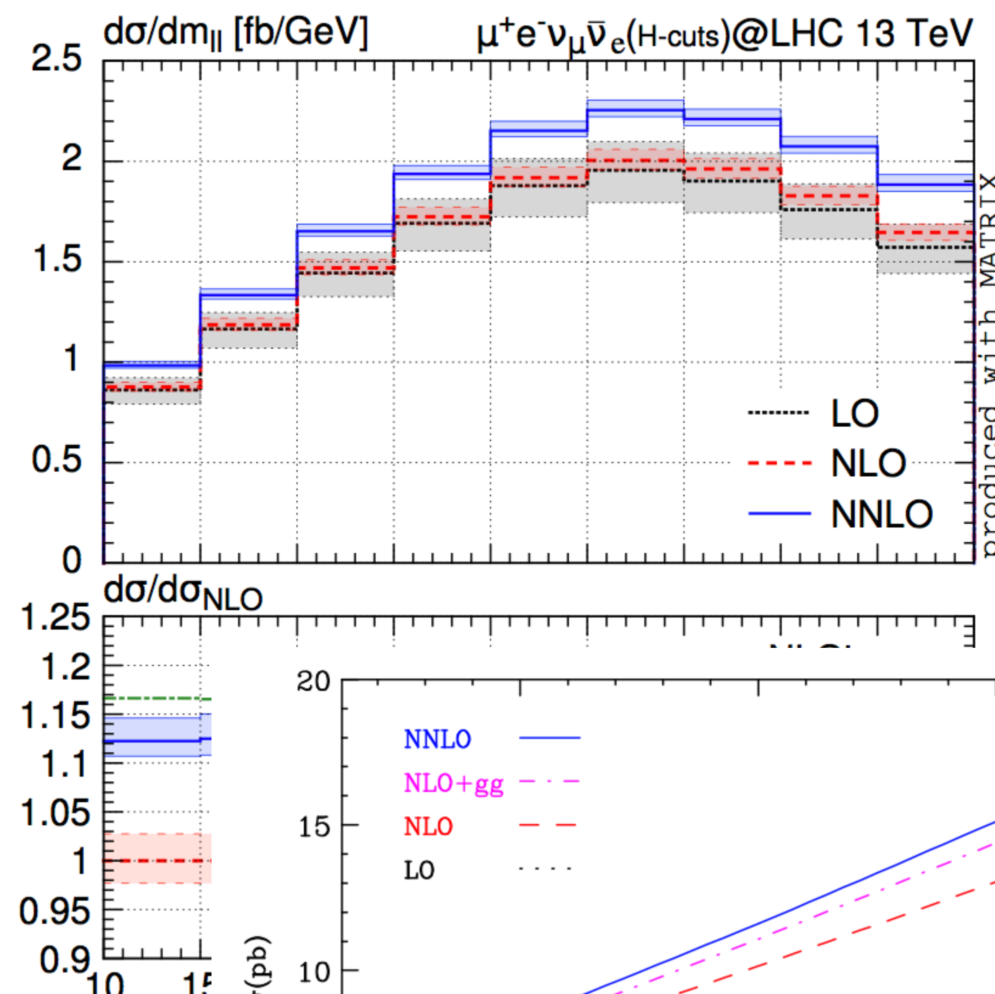


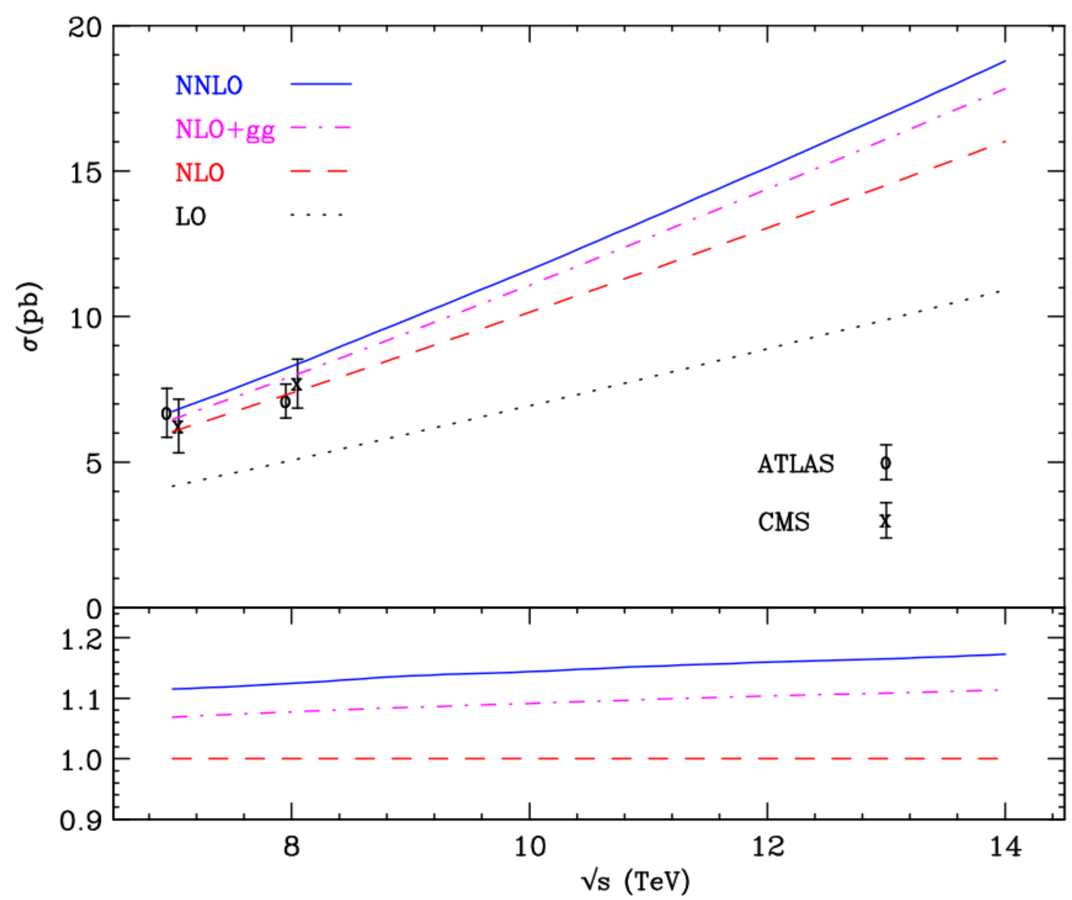


Diboson backgrounds

All diboson backgrounds computed to NNLO QCD







Now available in a general purpose parton level Montecarlo program: MATRIX

S.Kallweit, D.Rathlev, M.Wiesemann, MG (to appear)

Diboson backgrounds

Terminal — ssh mucky.physik.uzh.ch — 202×74

```
[grazzini:~/munich/MATRIX] ./matrix

 MATRIX: A fully-differential NNLO(+NNLL) process library

         Version: 1.0.0.release_candidate2      Apr 2017

 Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
 Automates qT-subtraction and Resummation to Integrate X-sections

 M. Grazzini                                (grazzini@physik.uzh.ch)
 S. Kallweit                               (stefan.kallweit@cern.ch)
 D. Rathlev                                  (rathlev@physik.uzh.ch)
 M. Wiesemann                             (marius.wiesemann@cern.ch)

 MATRIX is based on a number of different computations and tools
 from various people and groups. Please acknowledge their efforts
 by citing the list of references which is created with every run.

<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
|============>> list
------------------------------------------------------------------------------------------------------------------
process_id    ||  process                          ||  description
------------------------------------------------------------------------------------------------------------------
pph21         >>  p p --> H                        >>  on-shell Higgs production
ppz01         >>  p p --> Z                        >>  on-shell Z production
ppw01         >>  p p --> W^-                      >>  on-shell W- production
ppwx01        >>  p p --> W^+                      >>  on-shell W+ production
ppw01ckm      >>  p p --> W^-  (with CKM)          >>  on-shell W- production with CKM
ppwx01ckm     >>  p p --> W^+  (with CKM)          >>  on-shell W+ production with CKM
ppeex02       >>  p p --> e^- e^+                  >>  Z production with decay
ppnenex02     >>  p p --> v_e^- v_e^+              >>  Z production with decay
ppenex02      >>  p p --> e^- v_e^+                >>  W- production with decay
ppexne02      >>  p p --> e^+ v_e^-                >>  W+ production with decay
ppenex02ckm   >>  p p --> e^- v_e^+  (with CKM)    >>  W- production with decay and CKM
ppexne02ckm   >>  p p --> e^+ v_e^-  (with CKM)    >>  W+ production with decay and CKM
pphh22        >>  p p --> H H                      >>  on-shell double Higgs production
ppaa02        >>  p p --> gamma gamma              >>  gamma gamma production
ppzz02        >>  p p --> Z Z                      >>  on-shell ZZ production
ppwxw02       >>  p p --> W^+ W^-                  >>  on-shell WW production
ppeexa03      >>  p p --> e^- e^+ gamma            >>  Z gamma production with decay
ppnenexa03    >>  p p --> v_e^- v_e^+ gamma        >>  Z gamma production with decay
ppenexa03     >>  p p --> e^- v_e^+ gamma          >>  W- gamma production with decay
ppexnea03     >>  p p --> e^+ v_e^- gamma          >>  W+ gamma production with decay
ppemexmx04    >>  p p --> e^- mu^- e^+ mu^+        >>  ZZ production with decay
ppeeexex04    >>  p p --> e^- e^- e^+ e^+          >>  ZZ production with decay
ppeexnmnmx04  >>  p p --> e^- e^+ v_mu^- v_mu^+    >>  ZZ production with decay
ppemxnmnex04  >>  p p --> e^- mu^+ v_mu^- v_e^+    >>  WW production with decay
ppeexnenex04  >>  p p --> e^- e^+ v_e^- v_e^+      >>  ZZ/WW production with decay
ppemexnmx04   >>  p p --> e^- mu^- e^+ v_mu^+      >>  W-Z production with decay
ppeeexnex04   >>  p p --> e^- e^- e^+ v_e^+        >>  W-Z production with decay
ppeexmxnm04   >>  p p --> e^- e^+ mu^+ v_mu^-      >>  W+Z production with decay
ppeexexne04   >>  p p --> e^- e^+ e^+ v_e^-        >>  W+Z production with decay
ppzzz03       >>  p p --> Z Z Z                    >>  no description available, PROCESS POSSIBLY NOT SUPPORTED
ppttx20       >>  p p --> top anti-top             >>  no description available, PROCESS POSSIBLY NOT SUPPORTED
ppyyx22       >>  p p --> tau^- tau^+              >>  no description available, PROCESS POSSIBLY NOT SUPPORTED
ppmmx22       >>  p p --> mu^- mu^+                >>  no description available, PROCESS POSSIBLY NOT SUPPORTED
ppttxh21      >>  p p --> top anti-topH            >>  no description available, PROCESS POSSIBLY NOT SUPPORTED
|============>>
```

$pp \to ZZ+X$ at NNLO: the Higgs background region

S. Kallweit, D. Rathlev, MG (2016)

YR4 ZZ cuts:

- $p_{T1} > 20$ GeV $p_{T2} > 10$ GeV
  $p_{Te} > 7$ GeV $|\eta_e| < 2.5$ $p_{T\mu} > 5$ GeV $|\eta_\mu| < 2.5$
  $\Delta R(l,l) > 0.1$
- lepton isolation: Σ (p_{Ti} of all particles i with $\Delta R(l,i) < 0.4$) $< 0.4\, p_{Tl}$
  Jets: anti-kt with R=0.4
- Leading pair: same flavour pair with smallest $|m-m_Z|$ $\to$ m_1
  Subleading pair: remaining same flavour pair with smallest $|m-m_Z|$ $\to$ m_2
  $40 \text{ GeV} < m_1 < 120 \text{ GeV}$ $12 \text{ GeV} < m_2 < 120 \text{ GeV}$
- $120 \text{ GeV} < m_{4l} < 130 \text{ GeV}$
- Use PDF4LHC15 at NLO and NNLO with $\mu_F = \mu_R = m4l$ as central scale

pp→ZZ+X at NNLO: the Higgs background region

S. Kallweit, D. Rathlev, MG (2016)

Since the cuts are not very aggressive we would expect the impact of radiative corrections not to change

Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NLO+gg} (fb)	σ_{NNLO} (fb)
$e^+e^-e^+e^-$	$0.1347(1)^{+10\%}_{-11\%}$	$0.1485(2)^{+2.4\%}_{-3.6\%}$	$0.1584(2)^{+2.4\%}_{-3.6\%}$	$0.159(1)^{+0.7\%}_{-0.9\%}$
$\mu^+\mu^-\mu^+\mu^-$	$0.1946(2)^{+10\%}_{-11\%}$	$0.2150(2)^{+2.4\%}_{-3.6\%}$	$0.2291(2)^{+2.4\%}_{-3.6\%}$	$0.230(1)^{+0.9\%}_{-0.8\%}$
$e^+e^-\mu^+\mu^-$	$0.3165(3)^{+10\%}_{-11\%}$	$0.3457(3)^{+2.4\%}_{-3.6\%}$	$0.3677(2)^{+2.3\%}_{-3.5\%}$	$0.3690(6)^{+0.5\%}_{-0.8\%}$

+9-10% +6-7% 0-1%

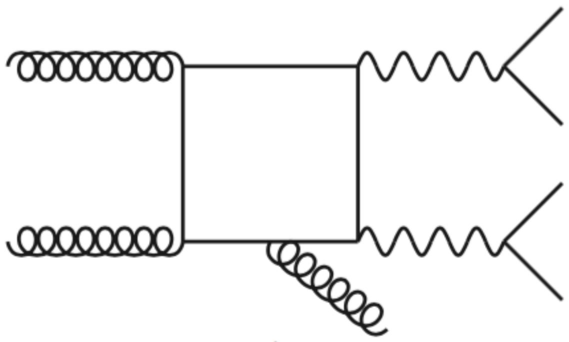
With this choice of parameters NLO corrections for on shell inclusive ZZ production amount to +23%

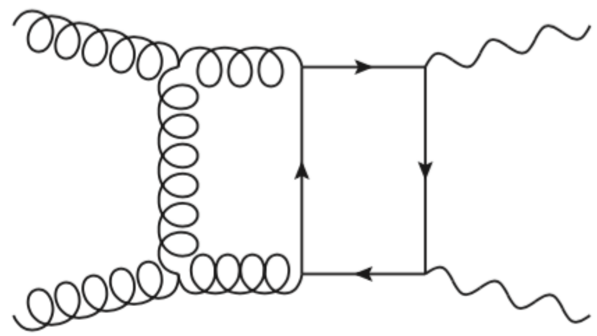
The combination of the cuts acts to reduce the impact of radiative corrections !

gg contribution provides almost the entire NNLO corrections

gg→ZZ+X at NLO

F.Caola, K.Melnikov, R.Röntsch, L.Tancredi (2015)





NLO corrections to the gluon channel are known to be large

NLO corrections to gg→ZZ recently completed (no fermionic channels) and found to be large, as happens for Higgs production

By using our NNLO setup they get an additional +6% shift of the ZZ cross section at 8 TeV (+7% at 13 TeV) which exceeds the O(3%) scale uncertainty at NNLO

QCD corrections to qqbar and gg channels should be treated in the same consistent framework

Summary

- The current LHC data indicate that the Higgs boson is perfectly consistent with what predicted by the SM

- This conclusion is based on a good control on SM predictions to which the data are compared, including radiative corrections

- I have reviewed the current status of theoretical predictions for Higgs boson production and decay, focusing on the most recent developments

- The general picture is that SM predictions are in good shape

  - For the dominant $gg \to H$ channel QCD predictions are essentially pushed to the next order ➡ reduction of perturbative uncertainties

  - Still important limitations come from the use of HEFT

- All diboson backgrounds now available at NNLO

  To be done: combination with NLO gg and NLO EW