Recent progress on VH associated production at the LHC

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Based on:

- G. Ferrera, M. Grazzini, FT [Phys. Rev. Lett. 2011, JHEP 2014, Phys. Lett. 2015]
- G. Luisoni, P. Nason, C. Oleari, FT [JHEP 2013]
- V. Del Duca, C. Duhr, G. Somogyi, FT, Z. Trocsanyi [JHEP 2015]
- G. Ferrera, G. Somogyi, FT [to appear]

LHCTheory ERC meeting, 22-24 March 2017, Brussels

Outline

* Motivation

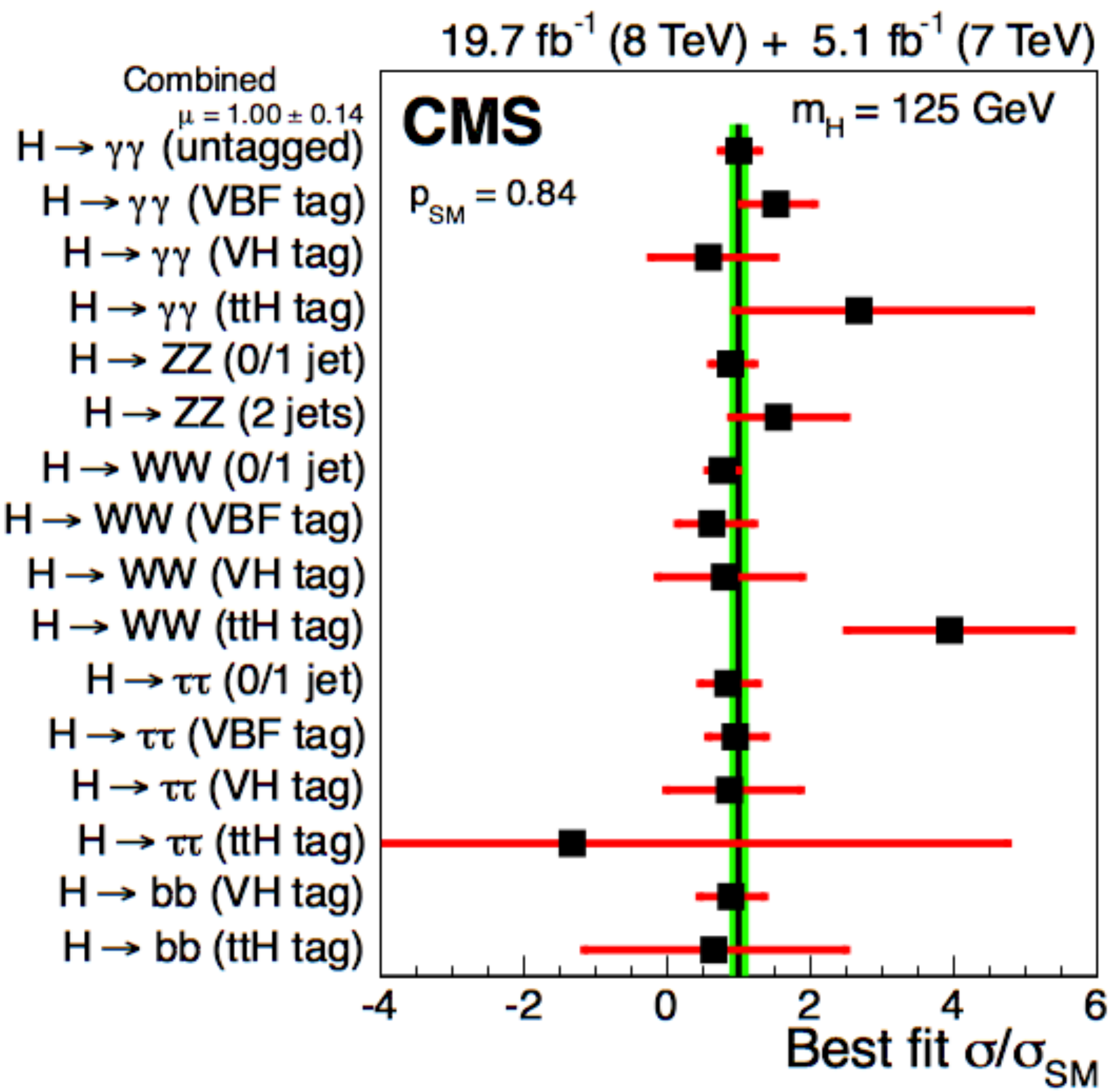
* Higher order corrections

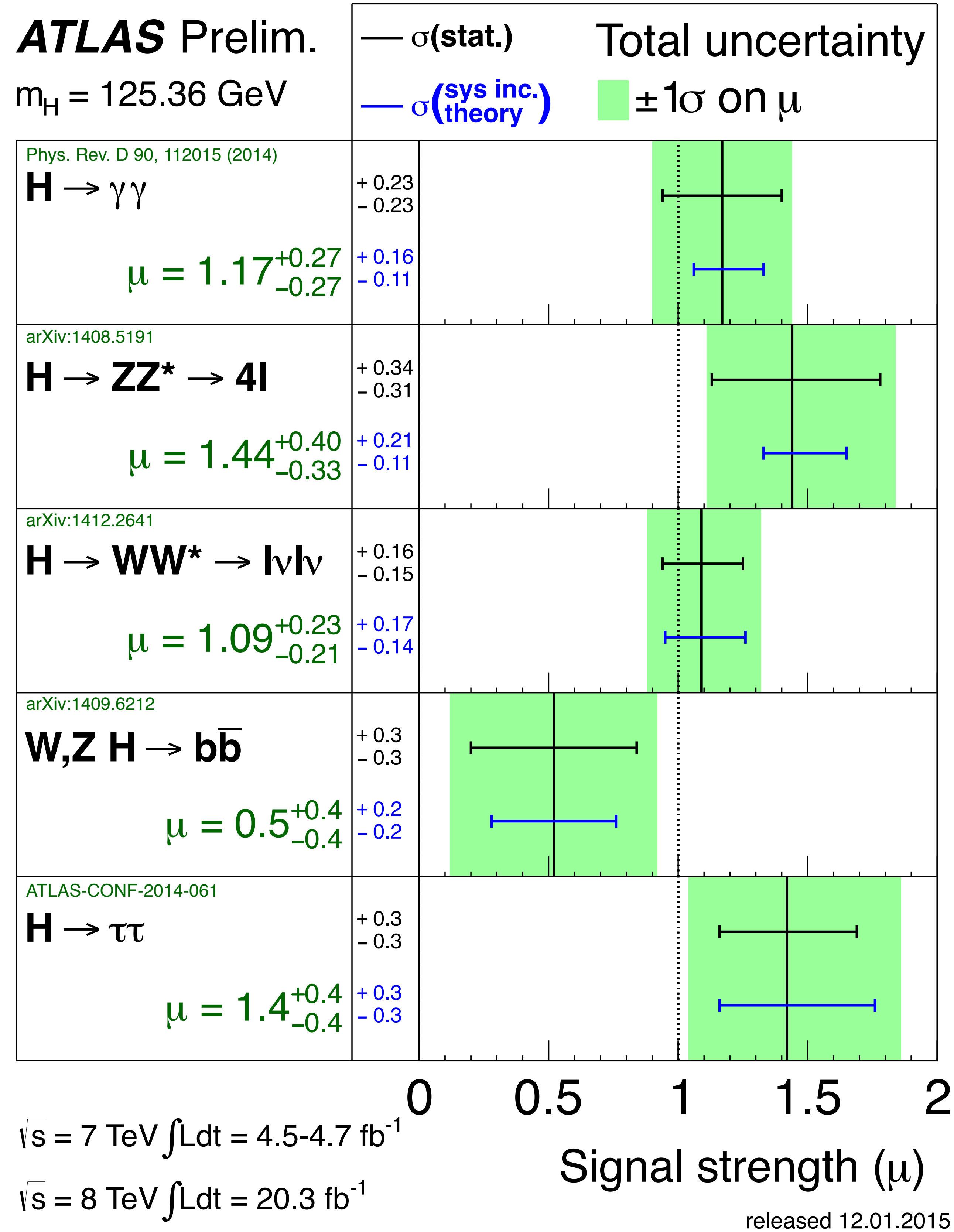
* Results

* Conclusion/Outlook

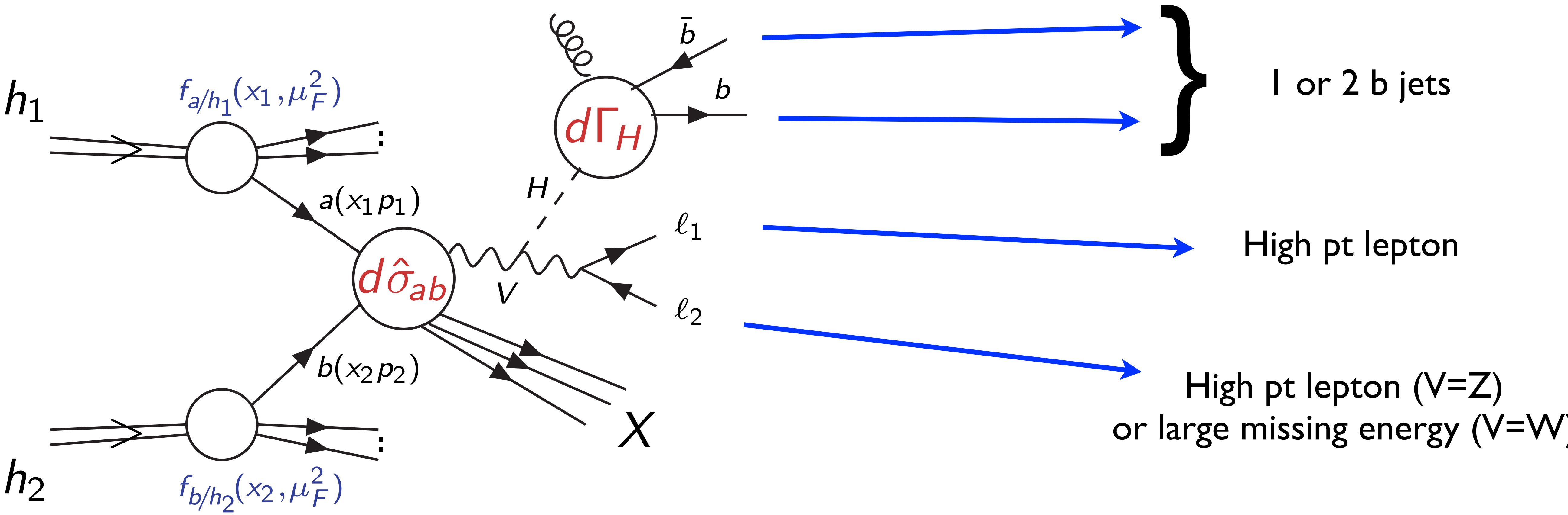
Higgs particle @ ATLAS and CMS

- VH allows to measure Higgs coupling to beauty
- Deviation from the SM still possible
- Need of precise fully differential predictions





VH(bb) signal phenomenology



- Large sources of backgrounds from V+bb, V+b, V+jets, tt, VV

- For boosted events S/B ratio improve considerably and allows detection at the LHC
[Butterworth, Davison, Rubin, Salam 2008]

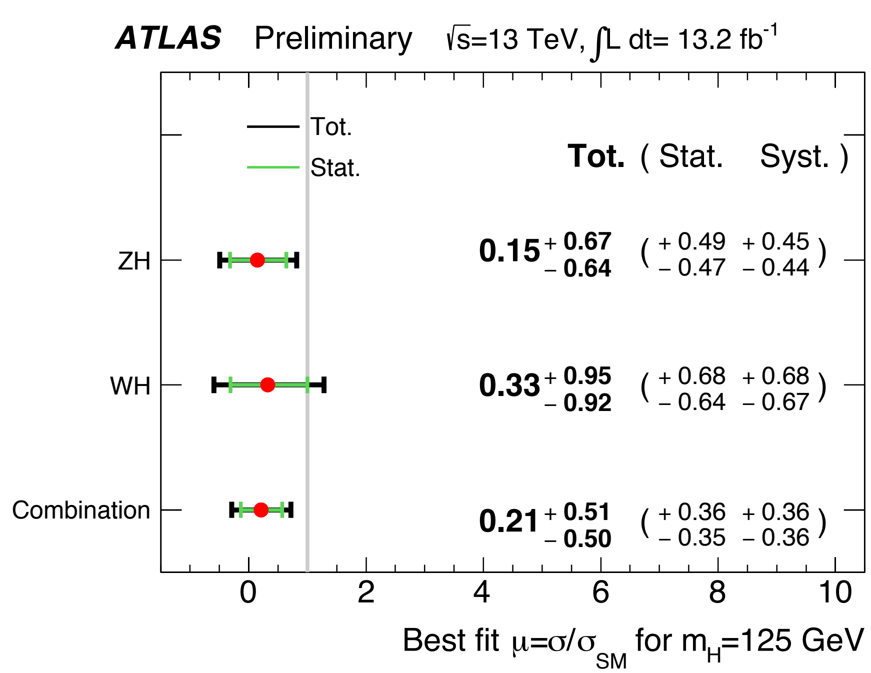
- Search strategy for VH production important to asses the relevance of the corrections to the decay process

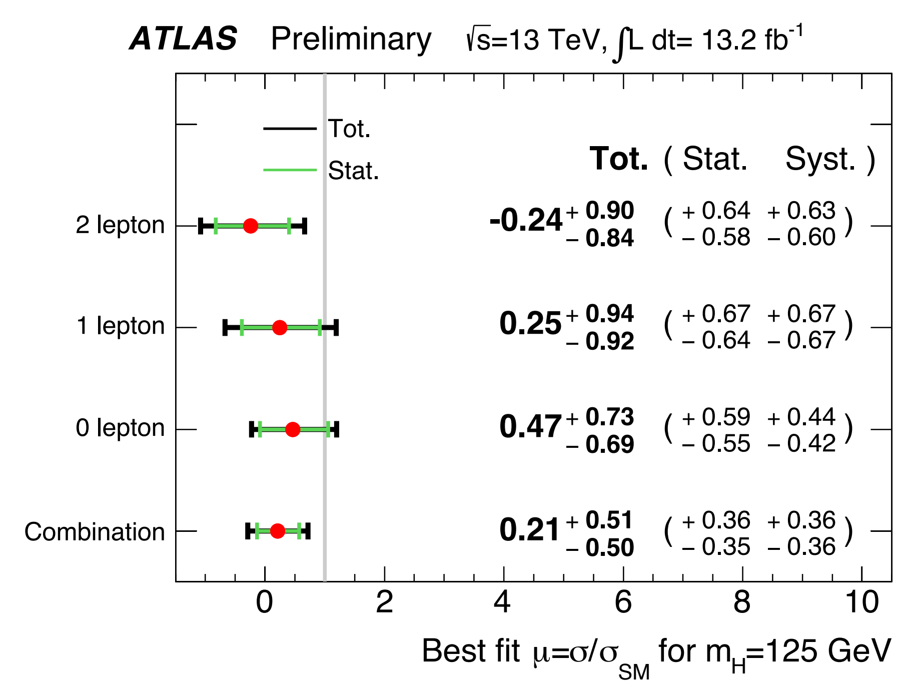
$$R_{bb} \gtrsim 2\frac{m_H}{p_T} \qquad (p_T \gg m_H)$$

Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-bbar pair in pp collisions at 13 TeV using the ATLAS detector

ATLAS-CONF-2016-091

Selection	0-lepton	1-lepton	2-lepton
Trigger	E_T^{miss}	E_T^{miss} (μ sub-channel)	
		Lowest unprescaled single lepton	
Leptons	0 loose lepton	1 tight lepton	2 loose leptons ($\geq$ 1 medium lepton)
Lepton pair	-	-	Same flavour opposite-charge for $\mu\mu$
E_T^{miss}	> 150 GeV	> 30 GeV (e sub-channel)	-
m_{ll}	-	-	$71 < m_{ll} < 121$ GeV
S_T	> 120 (2 jets), >150 GeV (3 jets)	-	-
Jets	Exactly 2 or 3 signal jets		Exactly 2 or $\geq$ 3 signal jets
b-jets	2 b-tagged signal jets		
Leading jet p_T	> 45 GeV		
$\min\Delta\phi(E_T^{miss}, \text{jet})$	$> 20°$	-	-
$\Delta\phi(E_T^{miss}, h)$	$> 120°$	-	-
$\Delta\phi$(jet1,jet2)	$< 140°$	-	-
$\Delta\phi(E_T^{miss}, E_{T,trk}^{miss})$	$< 90°$	-	-
p_T^V regions	[0, 150] GeV (2-lepton), [150, ∞] GeV		





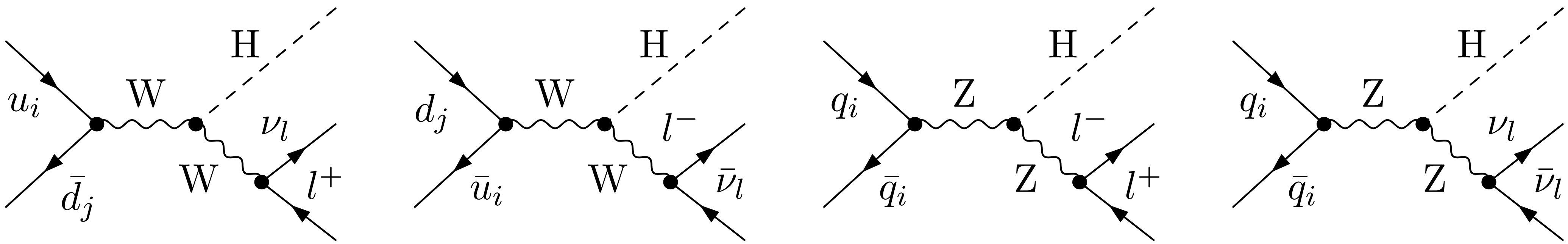
- too early to claim the need of NP, but…
- quite large negative fluctuation

- with combined ATLAS and CMS 2016 data H-b-b coupling will be measured with high accuracy

Higher order corrections

VH higher Order Corrections (EW)

* EW corrections:
  NLO EW total cross section (5~10% at the LHC) [Ciccolini, Dittmaier, Kramer '03]
  NLO EW known differentially (5~10% or more at the LHC)
  → HAWK [Denner, Dittmaier, Kallweit, Mück]



✓ Fully differential 2→3 NLO EW computation

✓ Implemented through the Complex Mass Scheme@NLO [Denner, Dittmaier]

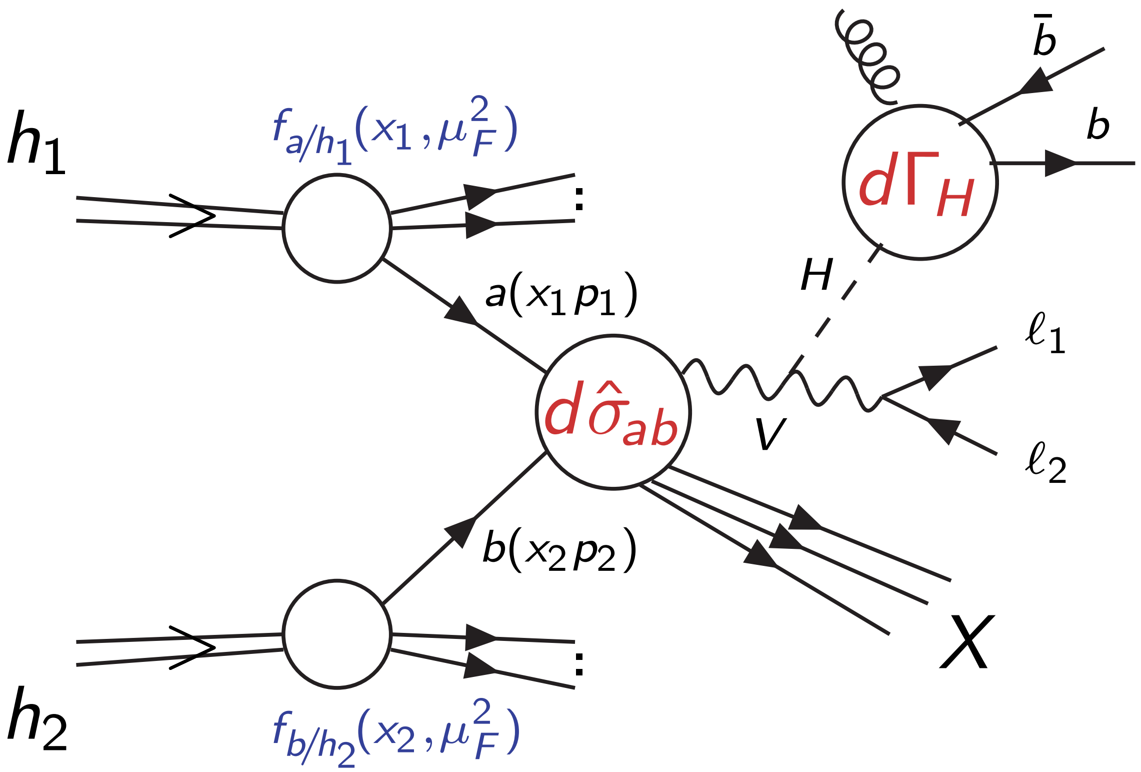
* Combination of QCD and EW corrections

✓ as done already in YR2, also at differential level

$$\sigma = \sigma^{\mathrm{QCD}} \times (1 + \delta_{\mathrm{EW}}^{\mathrm{rec}}) + \sigma_\gamma$$

✓ More can only be achieved by some NNLO QCD-EW calculation: currently out of reach

VH higher order Corrections (QCD)
(parton level)



QCD corrections (inclusive)

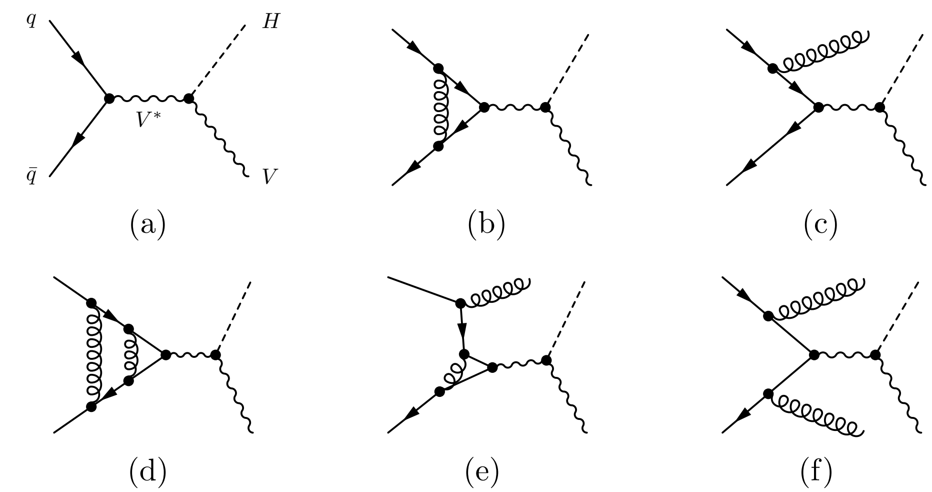
- NNLO QCD corrections for VH are basically the same of DY (1~3% at the LHC) [Van Neerven et al 1991, Brein, Harlander, Djouadi 2000]
- For ZH there is also gg->ZH top-loop, the most accurate prediction covers gg->ZH @ NLO QCD in the heavy-top limit (5% at the LHC) [Altenkamp, Dittmaier, Harlander, Rzehak, Zirke 2012]
- NNLO top-mediated contribution (1~2% at the LHC) [Brei, Harlander, Wiesemann, Zirke 2011]
- N3LO threshold corrections computed [Kumal, Mandal, Ravindran (2014)]
- The inclusive H → bb decay rate is known up to fourth order in QCD (0.1%) [Baikov,Chetyrkin,Kuhn('05)] (and up to NLO EW (1~2%) [Dabelstein, Hollik; Kniehl (1992)])

QCD corrections (differential)

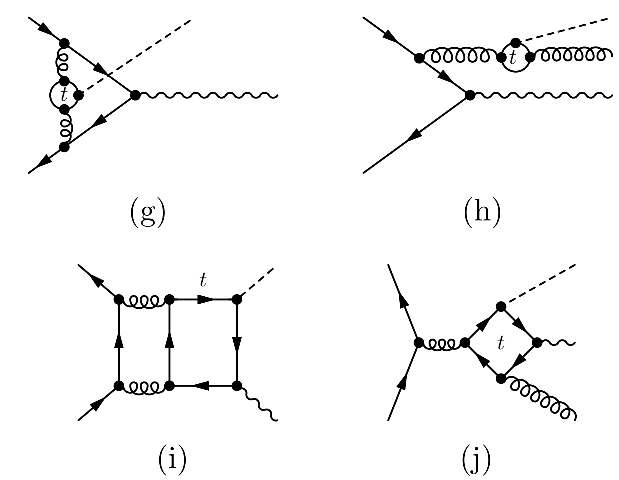
- Fully differential NNLO QCD corrections for VH, including leptonic V decays with spin correlations and NLO H decay
  HVNNLO [Ferrera, Grazzini, FT (2011, 2014)] (qT subtraction method)
  MCFM [Campbell, Ellis, Giele, Williams (2016)] (N-jettiness method) + top-loop contributions from [Brein et al (2011)]
- NNLO fully-differential decay rate H → bb computed through new non-linear mapping method [Anastasiou,Herzog,Lazopoulos (2012)] and the Colourful (dipole) method [Del Duca,Duhr,Somogyi,FT,Trocsanyi (2015)]
- Resummation of jet-veto and transverse-momentum logarithms performed [Y.Li,Liu(2014)][Shao,C.S.Li,H.T.Li(2013)], [Dawson,Han,Lai,Leibovich,Lewis(2012)]

Higgs boson associated production

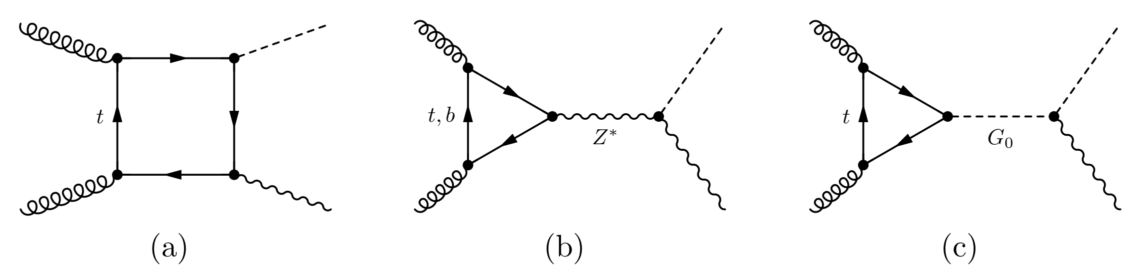
- Drell–Yan type contribution
- They contribute to the cross section at order $g^4 \alpha_s^n$ (n = 0, 1, 2)
- increase the cross section by about 30% with respect to LO



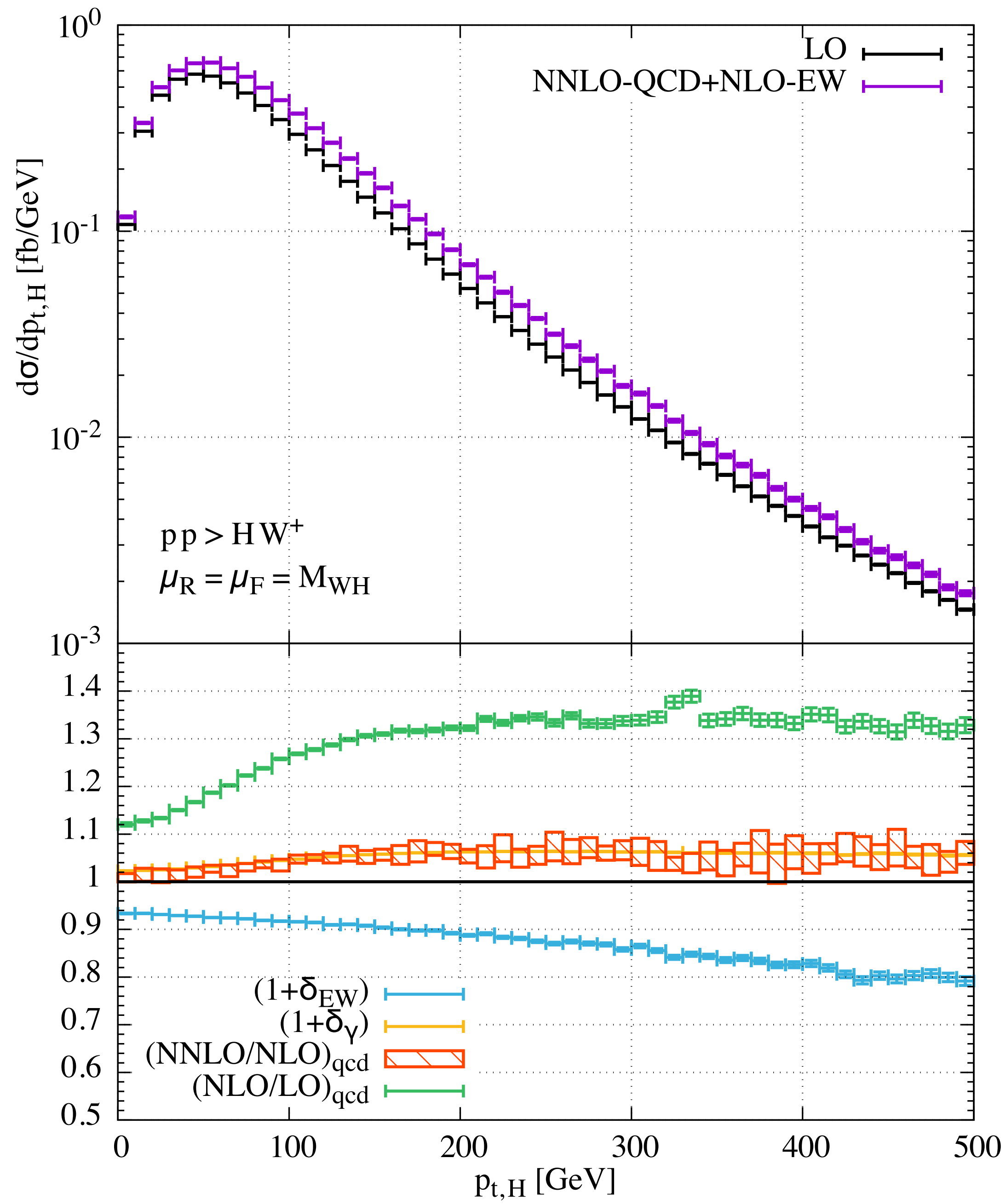
- top-loop-induced contributions
- Interference with the LO and the real-emission
  NLO amplitude is of order $\lambda_t\, g^3\, \alpha_s^2$
- numerical impact is at the percent level.

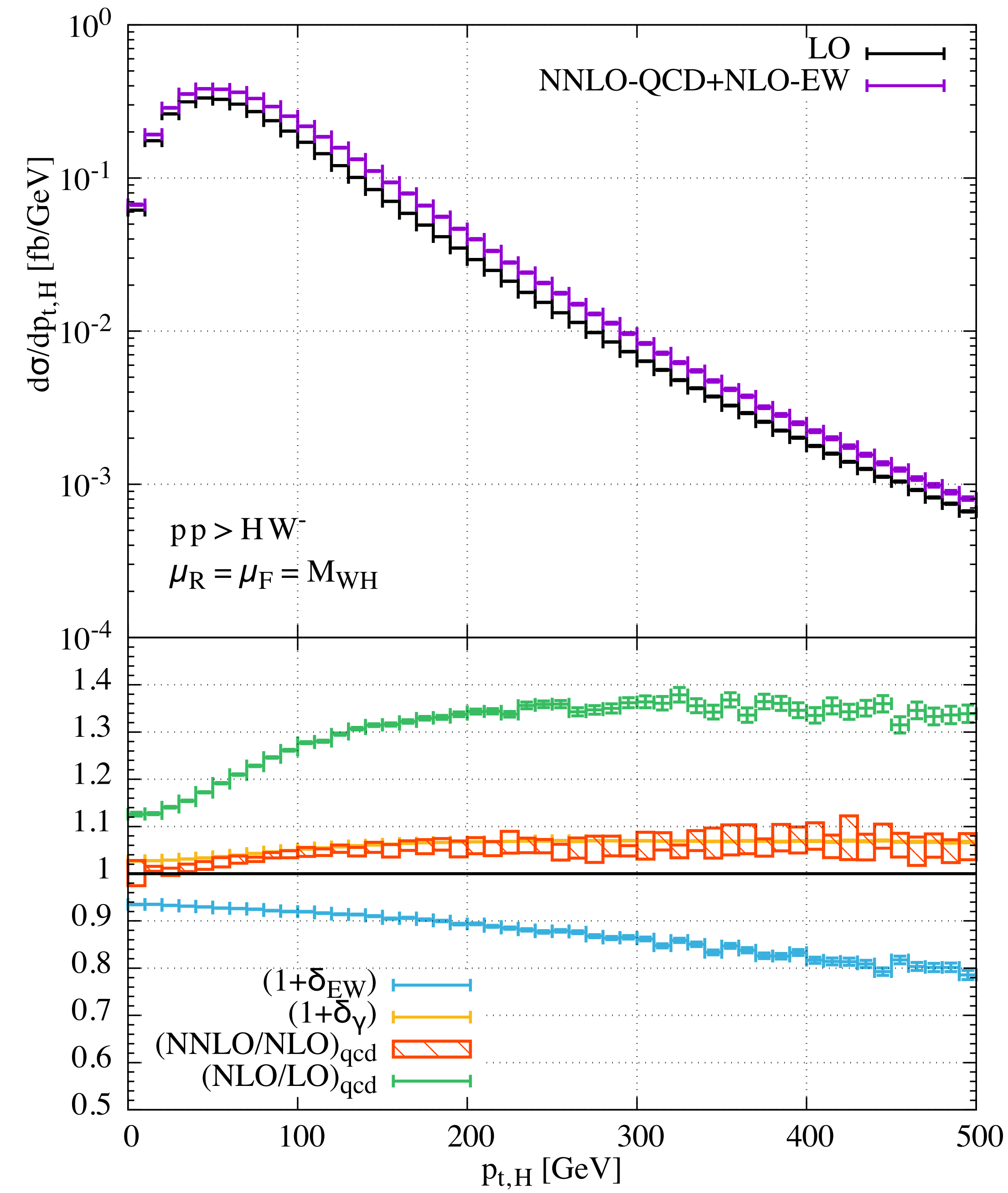


- Contributes to the cross section at order $\lambda_t^2\, g^2\, \alpha_s^2$
- At one-loop order it amounts to about 4% (6%) of the total Higgs strahlung cross section at the LHC with 8TeV (14TeV)
- Rather strong renormalisation and factorisation scale dependence of about 30%
  - increase the theoretical uncertainty of the HZ relative to the WH process



WH higher order corrections (YR4)
(parton level)





$$\delta_{EW} = \sigma_{EW}/\sigma_{LO}$$

$$\delta_{\gamma} = \sigma_{\gamma}/\sigma_{LO}$$

- LHC13
- anti-kt with R=0.4

$$p_{\mathrm{T}l} > 15\ \mathrm{GeV}, \qquad |y_l| < 2.5\,.$$

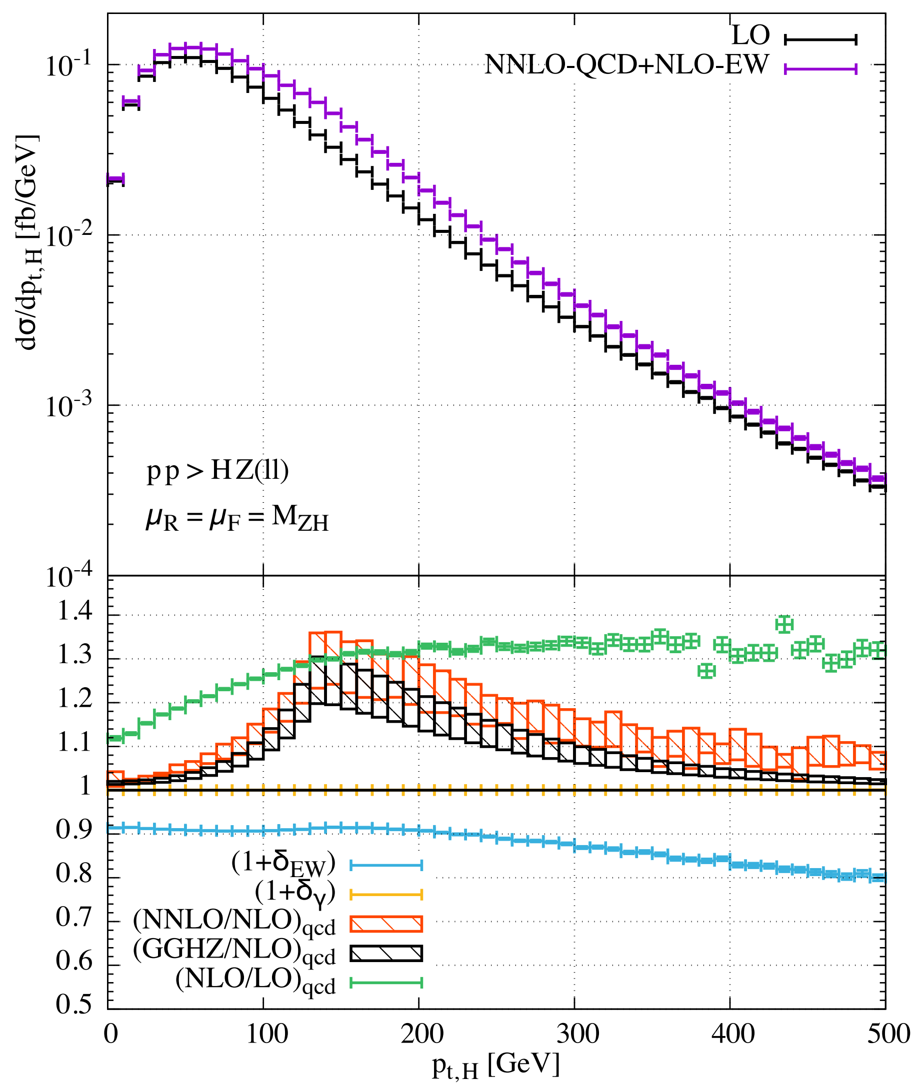
ZH associated production

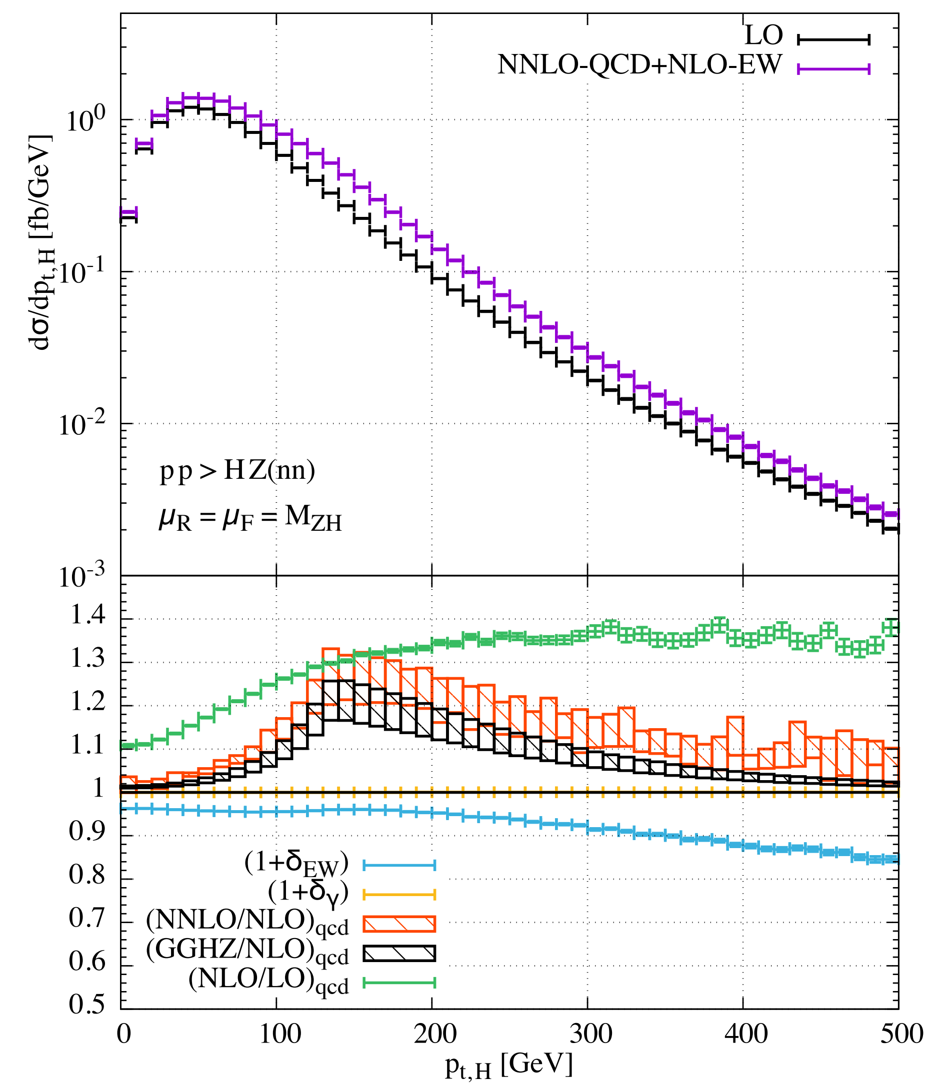
Inclusive Cross Section

$\sqrt{s}$[GeV]	σ[fb]	$\Delta_{\rm scale}$[%]	$\Delta_{{\rm PDF}/\alpha_s/{\rm PDF}\oplus\alpha_s}$[%]	$\sigma^{\rm DY}_{\rm NNLOQCD}$[fb]	$\sigma^{\rm ggZH}_{\rm NLO+NLL}$[fb]	$\sigma_{\rm t\text{-}loop}$[fb]	$\delta_{\rm EW}$[%]	σ_γ[fb]
7	11.43	$^{+2.6}_{-2.4}$	$\pm1.6/\pm0.7/\pm1.7$	10.91	0.94	0.11	-5.2	$0.03^{+0.04}_{-0.00}$
8	14.18	$^{+2.9}_{-2.4}$	$\pm1.5/\pm0.8/\pm1.7$	13.36	1.33	0.14	-5.2	$0.04^{+0.05}_{-0.00}$
13	29.82	$^{+3.8}_{-3.1}$	$\pm1.3/\pm0.9/\pm1.6$	26.66	4.14	0.31	-5.3	$0.11^{+0.12}_{-0.01}$
14	33.27	$^{+3.8}_{-3.3}$	$\pm1.3/\pm1.0/\pm1.6$	29.47	4.87	0.36	-5.3	$0.12^{+0.13}_{-0.01}$

Differential Cross Section

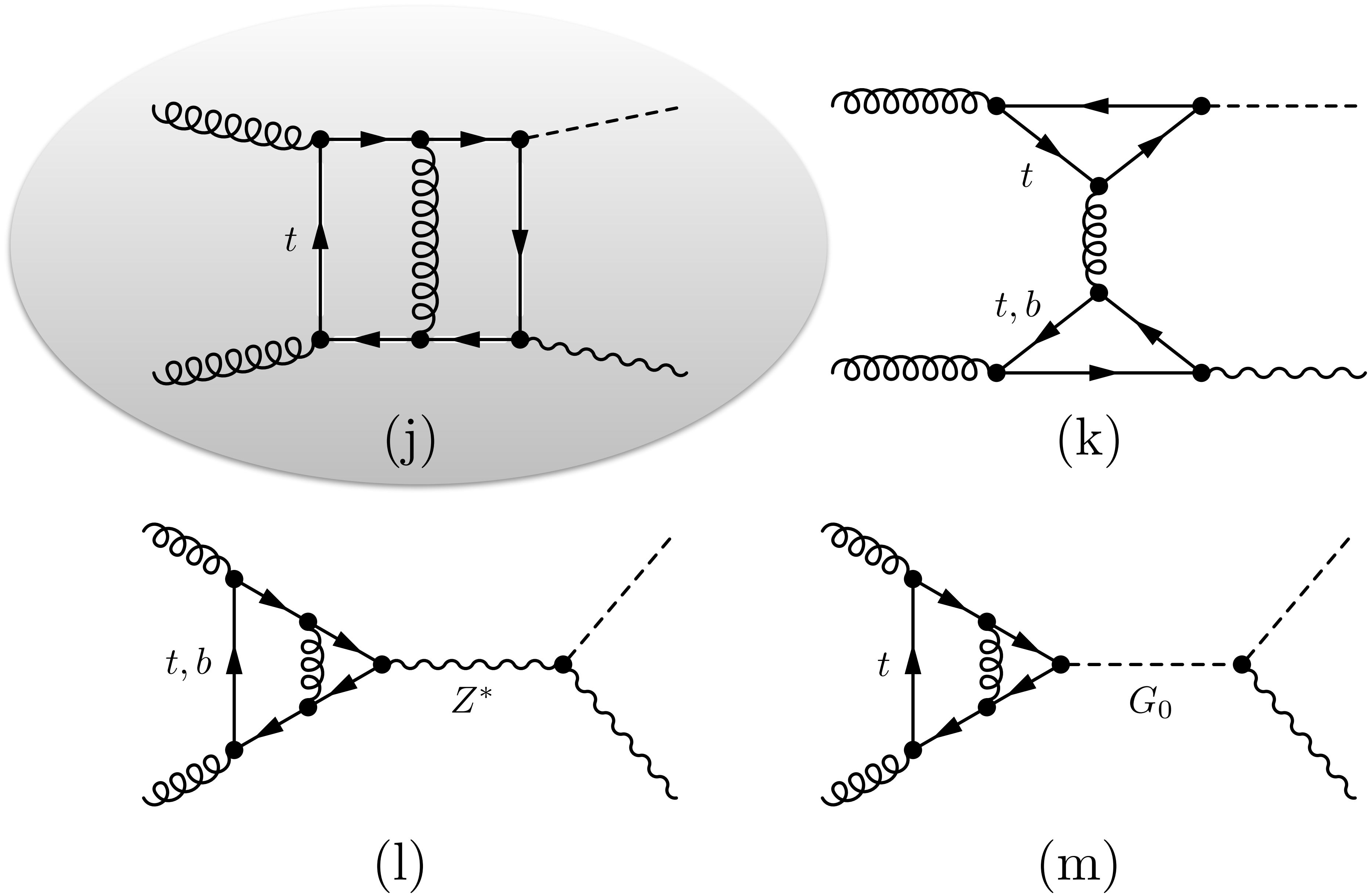
75 GeV $< M_{ll} <$ 105 GeV.





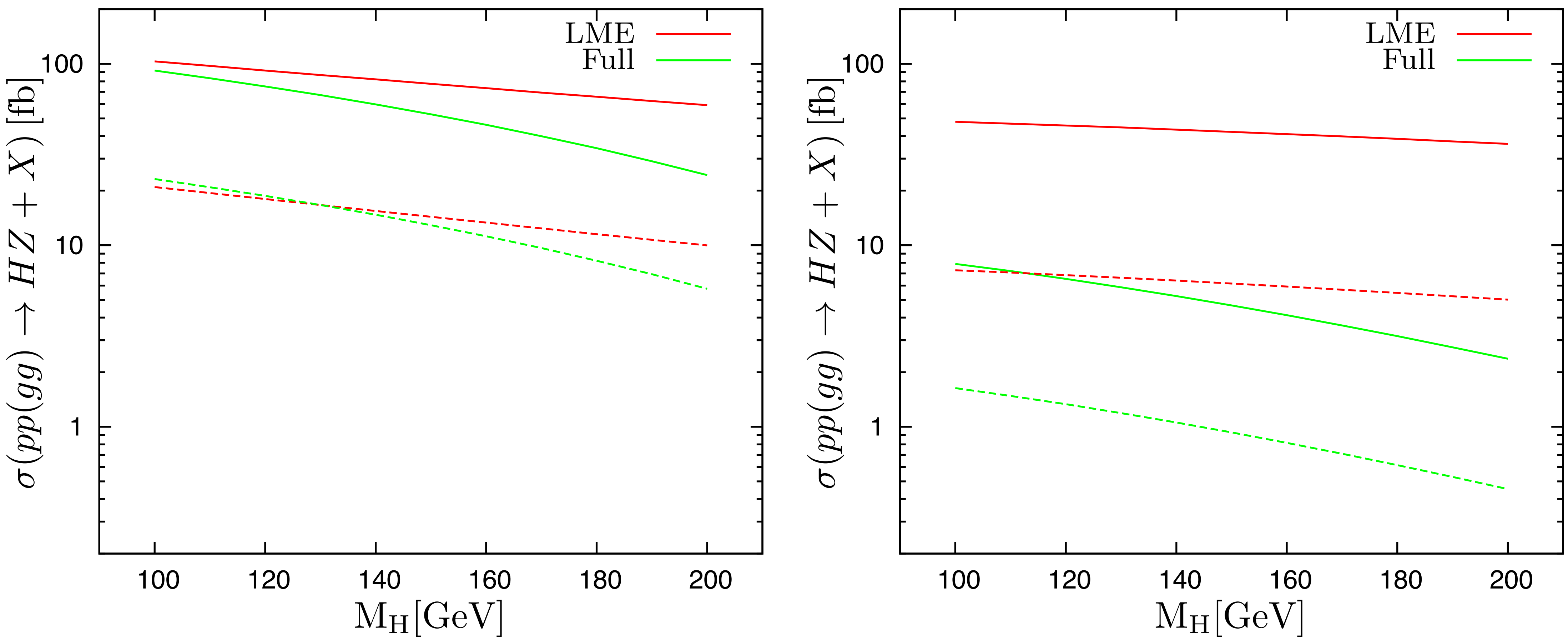
Higgs cross section working group

ggZH associated production at NNLO



ggZH contribution to the associated production

$\sqrt{s}$ = 8 TeV (dashed) and 14 TeV (solid)



(a) Inclusive cross section

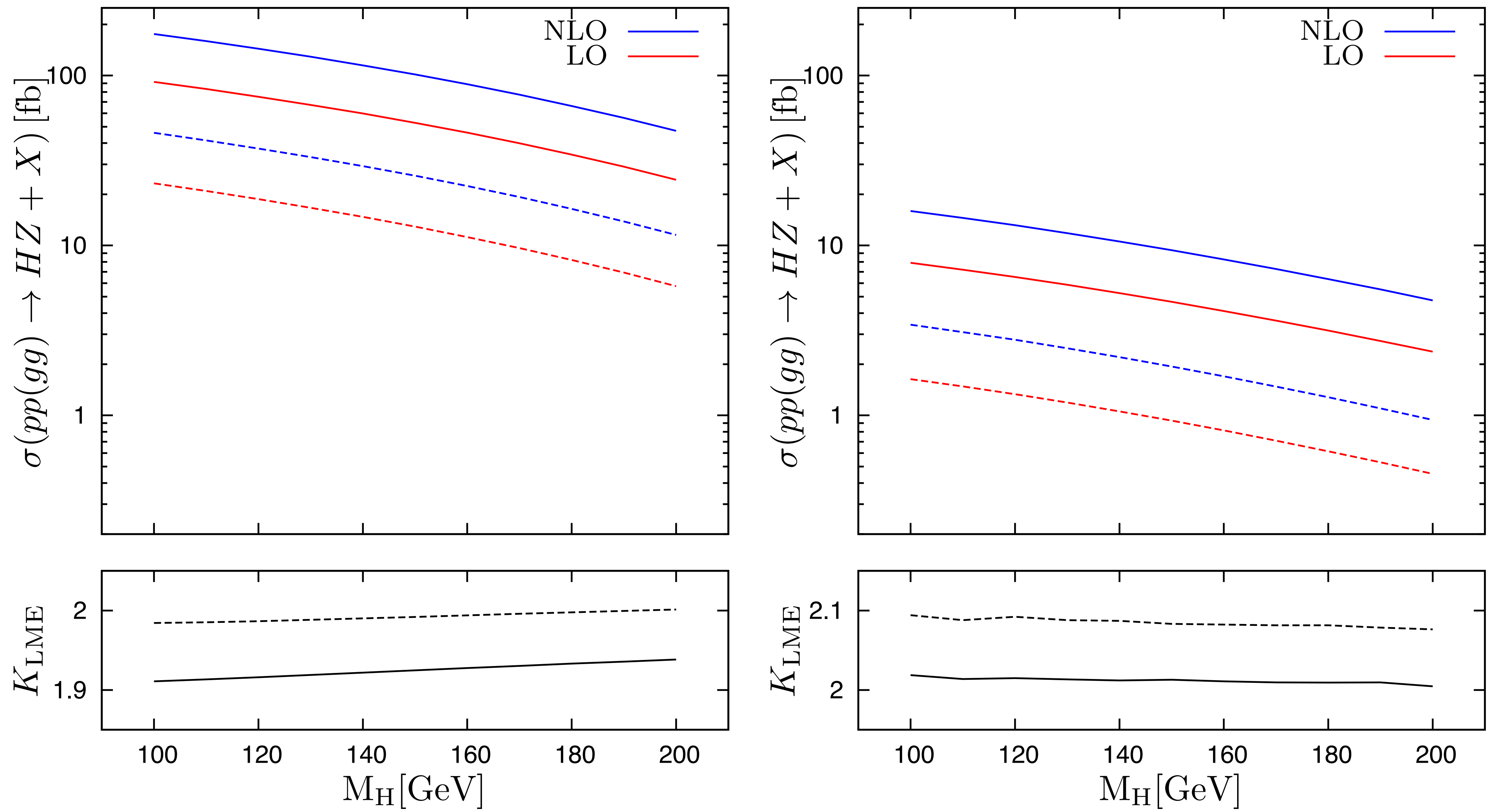
(b) $p_{T,H} > 200$ GeV

Large Mass Expansion for the LO

[Altenkamp, Dittmaier, Harlander, Rzehak, Zirke 2012]

ggZH contribution to the associated production

$\sqrt{s}$ = 8 TeV (dashed) and 14 TeV (solid)



(a) Inclusive cross section

(b) $p_{\mathrm{T,H}} > 200\,\mathrm{GeV}$

$$\sigma^{\mathrm{NLO}}_{\mathrm{approx}}(m_{\mathrm{t}}, m_{\mathrm{b}}) = \sigma^{\mathrm{LO}}(m_{\mathrm{t}}, m_{\mathrm{b}}) K(m_{\mathrm{t}} \to \infty, m_{\mathrm{b}} = 0)$$

$$= \frac{\sigma^{\mathrm{LO}}(m_{\mathrm{t}}, m_{\mathrm{b}})}{\sigma^{\mathrm{LO}}(m_{\mathrm{t}} \to \infty, m_{\mathrm{b}} = 0)} \sigma^{\mathrm{NLO}}(m_{\mathrm{t}} \to \infty, m_{\mathrm{b}} = 0)$$

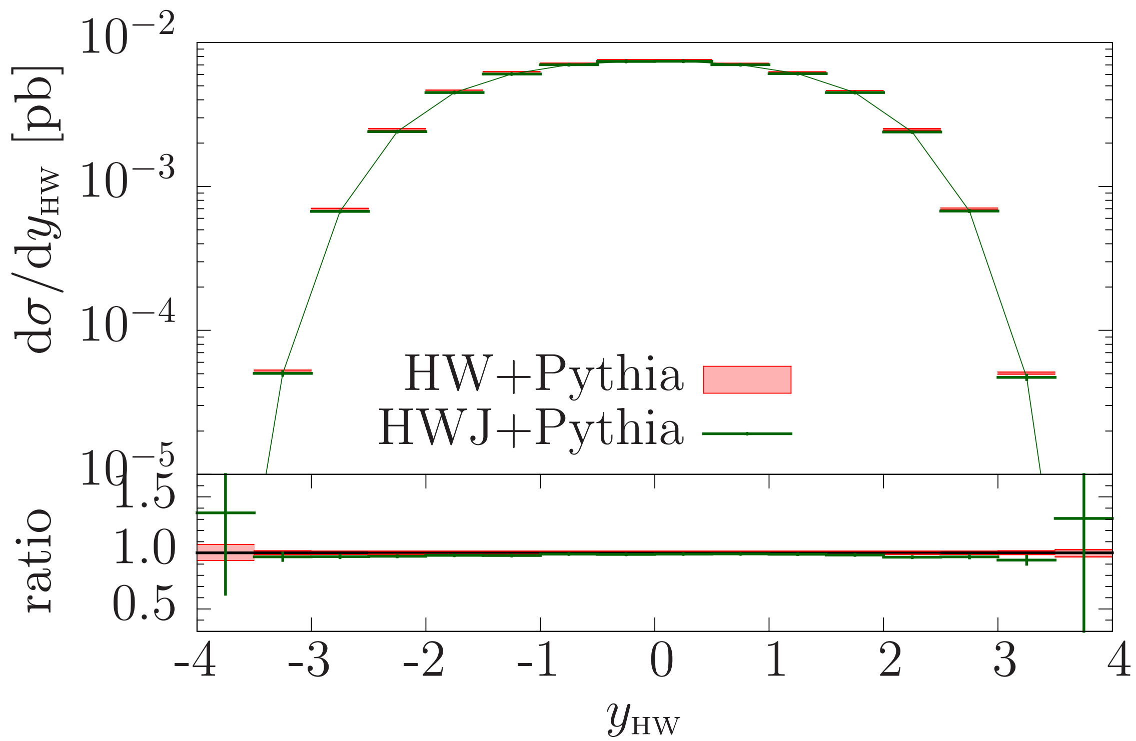
[Altenkamp, Dittmaier, Harlander, Rzehak, Zirke 2012]

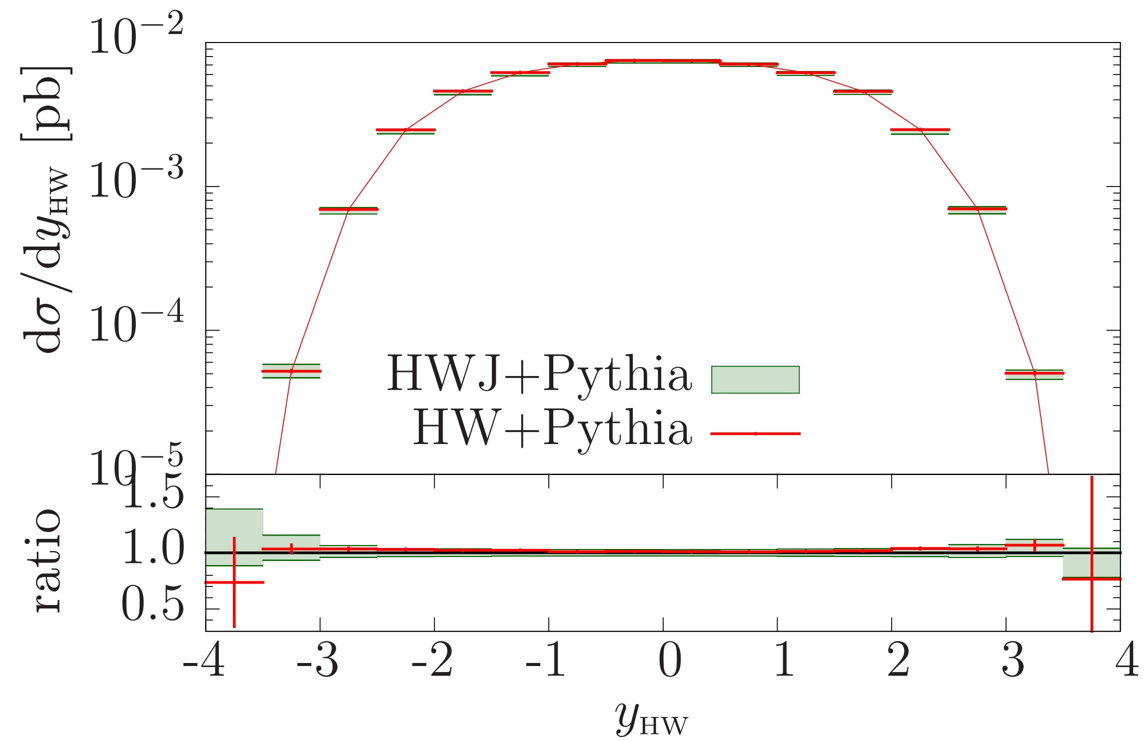
Merging and Matching

* NLO QCD & parton shower:

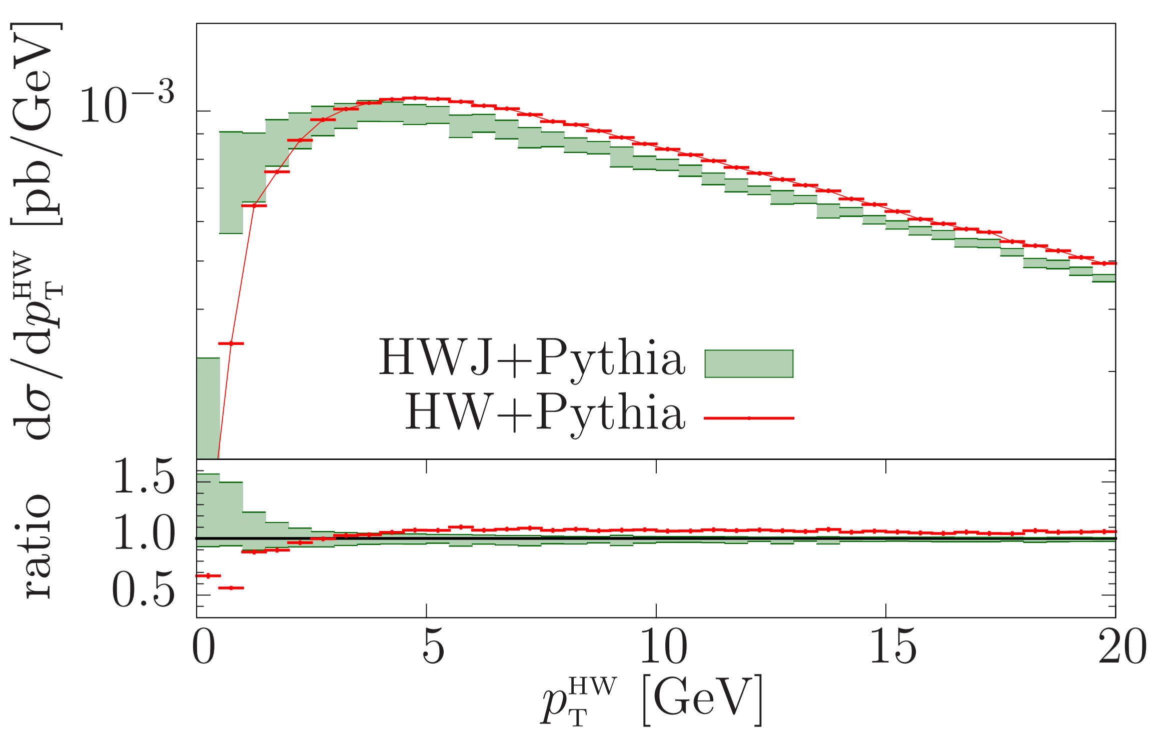
- ✓ merging and matching for pp→VH(j) available in the POWHEG-BOX framework [Luisoni, Nason, Oleari, FT]
- ✓ also in MG5_aMC (FxFx) and Sherpa (MEPS@NLO)
- ✓ also with anomalous couplings

MINLO [Hamilton, Nason, Zanderighi] → No error related to the merging scale





LHC8

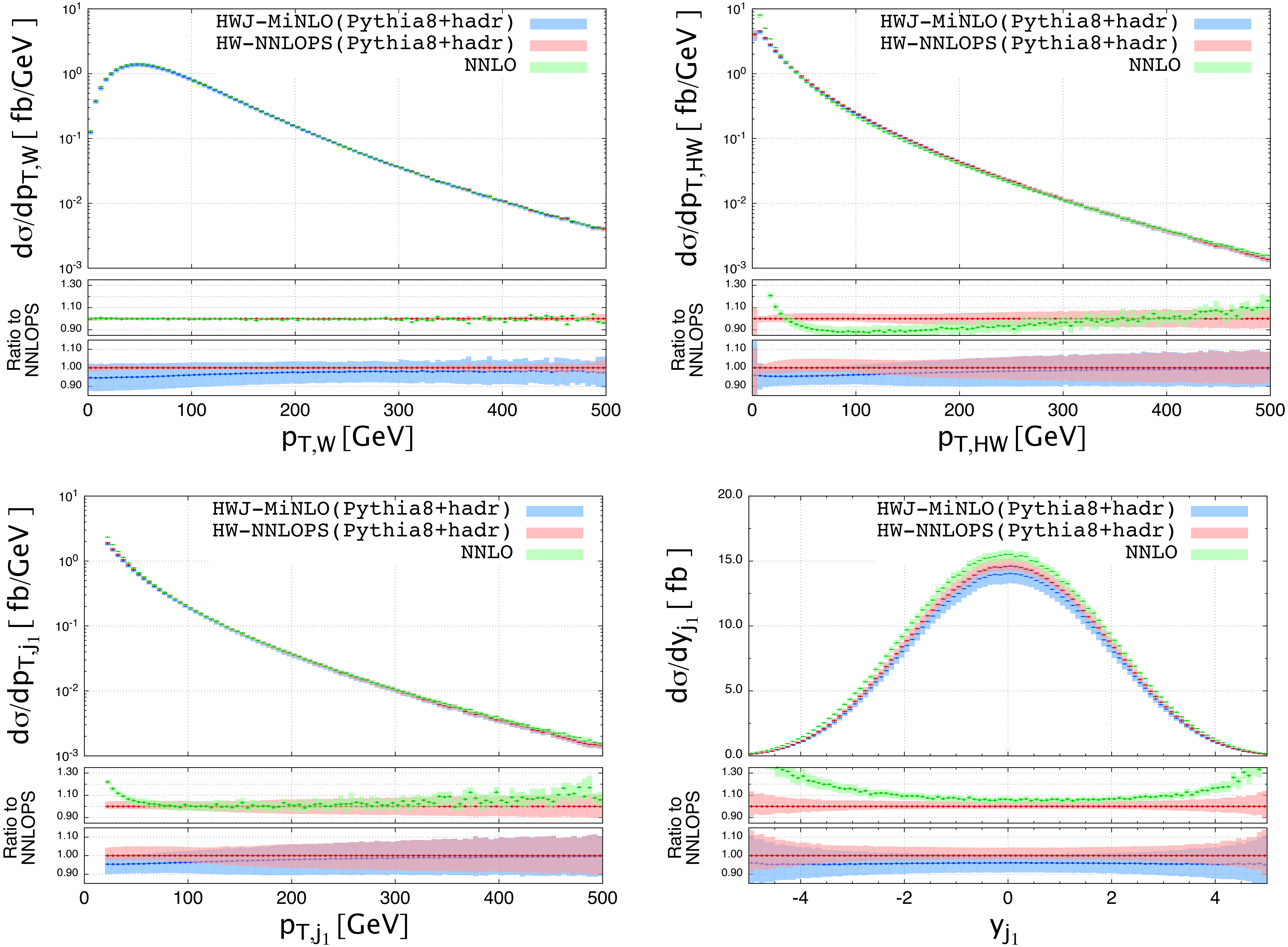


* NNLO matching with PS possible through reweighting of HVj-MINLO with HVNNLO. Already worked out for:

- ✓ H production [Hamilton, Nason, Re, Zanderighi] reweighting with HNNLO [Grazzini]
- ✓ DY production [Karlberg, Re, Zanderighi] reweighting with DYNNLO [Catani, Cieri, Ferrera, de Florian, Grazzini]

WH @ NNLOPS

$p_T(\text{jet}) > 20$ GeV, $|\eta(\text{jet})| < 4.5$ [Astill, Bizon, Re, Zanderighi 2016]



$(pp \to VH) \otimes (H \to bb)$

QCD corrections in the Narrow Width Approximation

$$d\sigma_{pp\to VH+X\to Vb\bar{b}+X} = \left[\sum_{k=0}^{\infty} d\sigma^{(k)}_{pp\to VH+X}\right] \times \left[\frac{\sum_{k=0}^{\infty} d\Gamma^{(k)}_{H\to b\bar{b}}}{\sum_{k=0}^{\infty} \Gamma^{(k)}_{H\to b\bar{b}}}\right] \times Br(H\to b\bar{b})$$

Precise knowledge from YR1

Including up to NLO corrections

$$d\sigma^{\mathrm{NLO(prod)+NLO(dec)}}_{pp\to VH+X\to Vb\bar{b}+X} = \left[d\sigma^{(0)}_{pp\to VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} + d\sigma^{(1)}_{pp\to VH+X} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}}\right] \times Br(H\to b\bar{b})$$

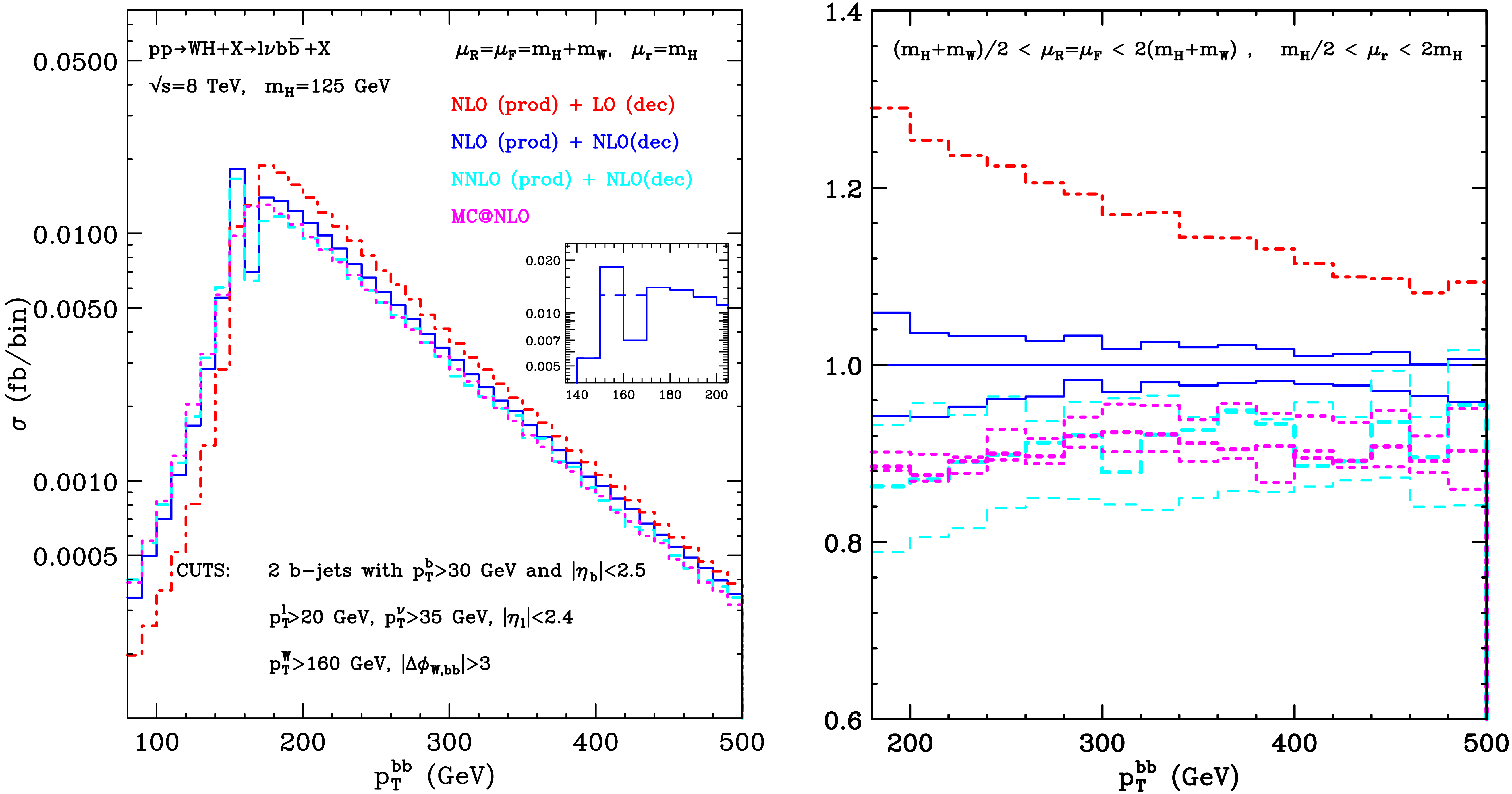
Including up to NNLO corrections for the production and up to NLO for the decay

$$d\sigma^{\mathrm{NNLO(prod)+NLO(dec)}}_{pp\to VH+X\to l\nu b\bar{b}+X} = \Bigg[d\sigma^{(0)}_{pp\to VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}}$$

$$+ \left(d\sigma^{(1)}_{pp\to VH+X} + d\sigma^{(2)}_{pp\to VH+X}\right) \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}}\Bigg] \times Br(H\to b\bar{b})$$

NNLO($pp \to VH$) $\otimes$ nlo($H \to bb$)

LHC8 with standard WH search cuts



Including up to NNLO corrections for both the Higgs production and its decay

$$
\begin{aligned}
d\sigma^{\mathrm{NNLO(prod)+NNLO(dec)}}_{pp\to WH+X\to l\nu b\bar{b}+X} = \Bigg[& d\sigma^{(0)}_{pp\to WH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}} + d\Gamma^{(2)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}} + \Gamma^{(2)}_{H\to b\bar{b}}} \\
& + d\sigma^{(1)}_{pp\to WH+X} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} \\
& + d\sigma^{(2)}_{pp\to WH+X} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}} \Bigg] \times Br(H\to b\bar{b})
\end{aligned}
$$

- combine NNLO in the production and nnlo in the decay stages
- inclusion of NLO(prod) x NLO(dec) contribution relevant

Production: qT subtraction method [Catani, Grazzini 2007]

$$h_1\, h_2 \to F$$ a colorless system

- qT is the transverse momentum of the colorless system (F), it is exactly zero at the leading order

- for qT.ne.0 there can be only divergences from single unresolved parton configurations

  ✓ can be treated with NLO subtraction methods like CS dipoles

- double unres. singularities are **all** associated with qT = 0 configurations

  ✓ can be treated by an additional subtraction defined exploiting the knowledge of the logarithmically enhanced contributions from the qT resummation formalism [Catani, De Florian, Grazzini 2000]

$$d\sigma^F_{N^nLO} \xrightarrow{q_T \to 0} d\sigma^F_{LO} \otimes \Sigma(q_T/M) dq_T^2 = d\sigma^F_{LO} \otimes \sum_{n=1}^{\infty} \sum_{k=1}^{2n} \left(\frac{\alpha_S}{\pi}\right)^n \Sigma^{(n,k)} \frac{M^2}{q_T^2} \ln^{k-1} \frac{M^2}{q_T^2}\, dq_T^2$$

$$d\sigma^{CT} \xrightarrow{q_T \to 0} d\sigma^F_{LO} \otimes \Sigma(q_T/M) dq_T^2$$

Production: qT subtraction method [Catani, Grazzini 2007]

Fully differential cross section: $d\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\mathrm{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$

where $\mathcal{H}^{F}_{NNLO} = \left[1 + \frac{\alpha_S}{\pi} \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi} \right)^2 \mathcal{H}^{F(2)} \right]$

- the choice of the counter term (CT) has arbitrariness but the qT→0 limit behavior is universal
- CT regularize simultaneously the real-virtual and the double real integration that have to be run together
- the Hard function H contains both the double virtual amplitude and the integral of the CT
  - ✓ its process dependent part can be obtained by the virtual amplitude via a universal process independent factorisation formula [Catani, Cieri, De Florian, Ferrera, Grazzini 2009]
- the method has been used for:
  ggF Higgs production [Catani, Grazzini 2007],
  DY and **Diphoton** [Catani, Cieri, De Florian, Ferrera, Grazzini 2009],
  VV' production [Grazzini,Kallweit,Rathlev,Torre 2013] and
  [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi 2014]

Decay: Colourful method [Del Duca, Somogyi and Trocsanyi 2007, 2009]

- completely local method
- based on the universal infrared factorization of QCD squared matrix elements
- local subtraction terms for regulating the singularities
- Phase space factorization
- O(300) integrals to account of the final state singularities

$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{m+2} = \left\{\mathrm{d}\sigma^{\mathrm{RR}}_{m+2} J_{m+2} - \mathrm{d}\sigma^{\mathrm{RR,A_2}}_{m+2} J_m - \left[\mathrm{d}\sigma^{\mathrm{RR,A_1}}_{m+2} J_{m+1} - \mathrm{d}\sigma^{\mathrm{RR,A_{12}}}_{m+2} J_m\right]\right\}_{\epsilon=0},$$

$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{m+1} = \left\{\left[\mathrm{d}\sigma^{\mathrm{RV}}_{m+1} + \int_1 \mathrm{d}\sigma^{\mathrm{RR,A_1}}_{m+2}\right] J_{m+1} - \left[\mathrm{d}\sigma^{\mathrm{RV,A_1}}_{m+1} + \left(\int_1 \mathrm{d}\sigma^{\mathrm{RR,A_1}}_{m+2}\right)^{\mathrm{A_1}}\right] J_m\right\}_{\epsilon=0},$$

$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{m} = \left\{\mathrm{d}\sigma^{\mathrm{VV}}_{m} + \int_2 \left[\mathrm{d}\sigma^{\mathrm{RR,A_2}}_{m+2} - \mathrm{d}\sigma^{\mathrm{RR,A_{12}}}_{m+2}\right] + \int_1 \left[\mathrm{d}\sigma^{\mathrm{RV,A_1}}_{m+1} + \left(\int_1 \mathrm{d}\sigma^{\mathrm{RR,A_1}}_{m+2}\right)^{\mathrm{A_1}}\right]\right\}_{\epsilon=0} J_m\,.$$

Status of (287) integrals

Int	status
$\mathcal{I}^{(k)}_{1\mathcal{C},0}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},1}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},2}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},3}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},4}$	✔
$\mathcal{I}^{(k,l)}_{1\mathcal{C},5}$	✔
$\mathcal{I}^{(k,l)}_{1\mathcal{C},6}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},7}$	✔
$\mathcal{I}_{1\mathcal{C},8}$	✔

Int	status
$\mathcal{I}_{1\mathcal{S},0}$	✔
$\mathcal{I}_{1\mathcal{S},1}$	✔
$\mathcal{I}_{1\mathcal{S},2}$	$(m > 3)$ ✔
$\mathcal{I}^{(k)}_{1\mathcal{S},3}$	✔
$\mathcal{I}_{1\mathcal{S},4}$	✔
$\mathcal{I}_{1\mathcal{S},5}$	✔
$\mathcal{I}_{1\mathcal{S},6}$	✔
$\mathcal{I}_{1\mathcal{S},7}$	✔

Int	status
$\mathcal{I}_{1\mathcal{CS},0}$	✔
$\mathcal{I}_{1\mathcal{CS},1}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{CS},2}$	✔
$\mathcal{I}_{1\mathcal{CS},3}$	✔
$\mathcal{I}_{1\mathcal{CS},4}$	✔

Int	status
$\mathcal{I}^{(k,l)}_{12\mathcal{C},1}$	✔
$\mathcal{I}^{(k,l)}_{12\mathcal{C},2}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},3}$	✔
$\mathcal{I}^{(k,l)}_{12\mathcal{C},4}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},5}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},6}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},7}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},8}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},9}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},10}$	✔

Int	status
$\mathcal{I}_{2\mathcal{S},1}$	✔
$\mathcal{I}_{2\mathcal{S},2}$	✔
$\mathcal{I}_{2\mathcal{S},3}$	✔
$\mathcal{I}_{2\mathcal{S},4}$	✔
$\mathcal{I}_{2\mathcal{S},5}$	✔
$\mathcal{I}_{2\mathcal{S},6}$	✔
$\mathcal{I}_{2\mathcal{S},7}$	✔
$\mathcal{I}_{2\mathcal{S},8}$	✔
$\mathcal{I}_{2\mathcal{S},9}$	✔
$\mathcal{I}_{2\mathcal{S},10}$	✔
$\mathcal{I}_{2\mathcal{S},11}$	✔
$\mathcal{I}_{2\mathcal{S},12}$	✔
$\mathcal{I}_{2\mathcal{S},13}$	✔
$\mathcal{I}_{2\mathcal{S},14}$	✔
$\mathcal{I}_{2\mathcal{S},15}$	✔
$\mathcal{I}_{2\mathcal{S},16}$	✔
$\mathcal{I}_{2\mathcal{S},17}$	✔
$\mathcal{I}_{2\mathcal{S},18}$	✔
$\mathcal{I}_{2\mathcal{S},19}$	✔
$\mathcal{I}_{2\mathcal{S},20}$	✔
$\mathcal{I}_{2\mathcal{S},21}$	✔
$\mathcal{I}_{2\mathcal{S},22}$	✔
$\mathcal{I}_{2\mathcal{S},23}$	✔

Int	status
$\mathcal{I}^{(k)}_{12\mathcal{S},1}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{S},2}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{S},3}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{S},4}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{S},5}$	✔
$\mathcal{I}_{12\mathcal{S},6}$	✔
$\mathcal{I}_{12\mathcal{S},7}$	✔
$\mathcal{I}_{12\mathcal{S},8}$	✔
$\mathcal{I}_{12\mathcal{S},9}$	✔
$\mathcal{I}_{12\mathcal{S},10}$	✔
$\mathcal{I}_{12\mathcal{S},11}$	✔
$\mathcal{I}_{12\mathcal{S},12}$	✔
$\mathcal{I}_{12\mathcal{S},13}$	✔

Int	status
$\mathcal{I}^{(k)}_{12\mathcal{CS},1}$	✔
$\mathcal{I}_{12\mathcal{CS},2}$	✔
$\mathcal{I}_{12\mathcal{CS},3}$	✔

Int	status	Int	status
$\mathcal{I}^{(j,k,l,m)}_{2\mathcal{C},1}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},1}$	✔
$\mathcal{I}^{(j,k,l,m)}_{2\mathcal{C},2}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},2}$	✔
$\mathcal{I}^{(j,k,l,m)}_{2\mathcal{C},3}$	✔	$\mathcal{I}^{(2)}_{2\mathcal{CS},2}$	✔
$\mathcal{I}^{(j,k,l,m)}_{2\mathcal{C},4}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},3}$	✔
$\mathcal{I}^{(-1,-1,-1,-1)}_{2\mathcal{C},5}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},4}$	✔
$\mathcal{I}^{(k,l)}_{2\mathcal{C},6}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},5}$	✔

✓: pole coefficients are known analytically, finite numerically, in some cases analytically

Fully analytic determination of all the singularities for $H \to b\bar{b}$

$$\sigma_m^{\mathrm{NNLO}} = \int_m \left\{ \mathrm{d}\sigma_m^{\mathrm{VV}} + \int_2 \left[\mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_2}} - \mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_{12}}} \right] + \int_1 \left[\mathrm{d}\sigma_{m+1}^{\mathrm{RV,A_1}} + \left(\int_1 \mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_1}} \right)^{\mathrm{A_1}} \right] \right\} J_m$$

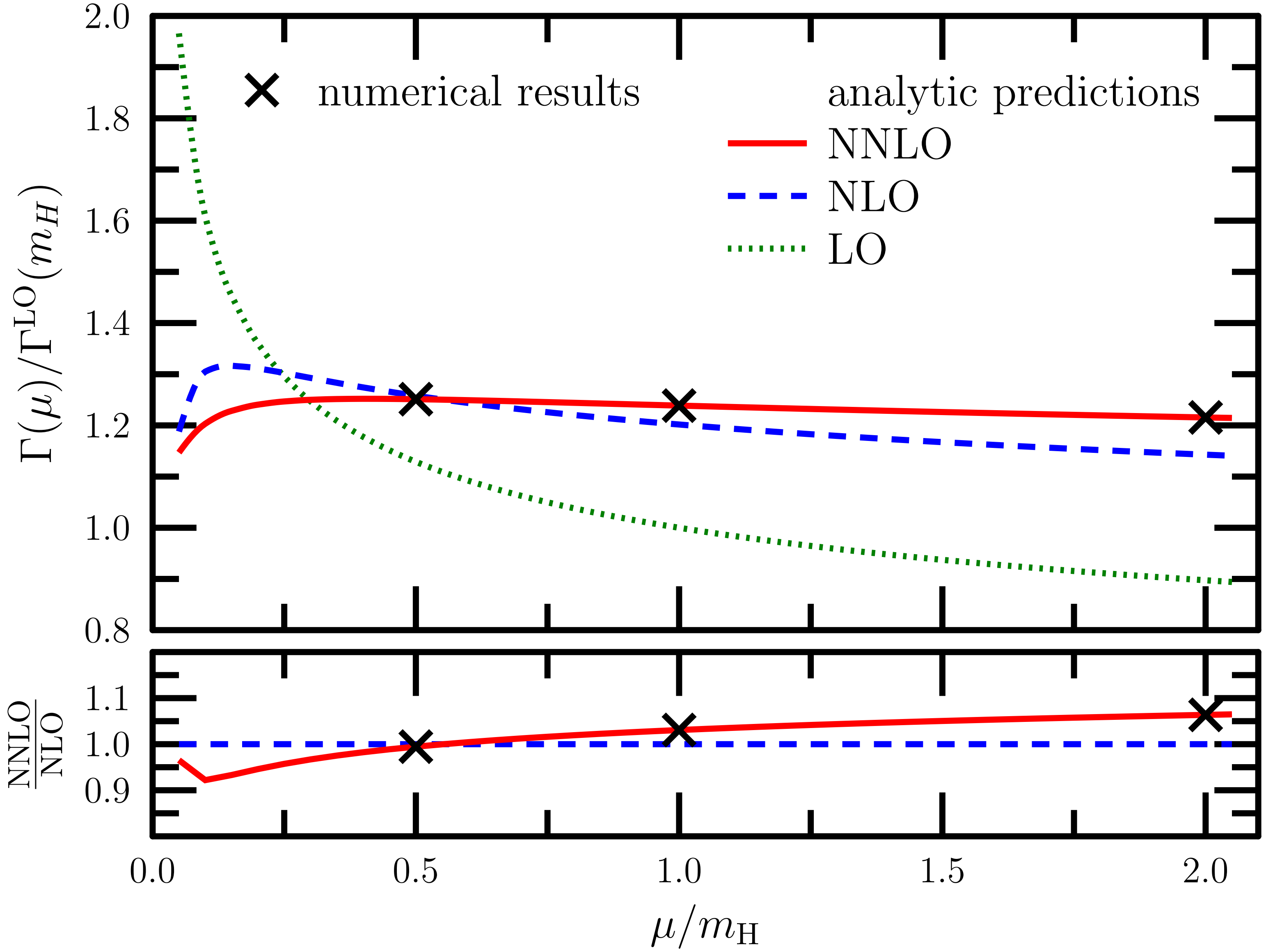
$$\mathrm{d}\sigma_{H\to b\bar{b}}^{\mathrm{VV}} = \left(\frac{\alpha_\mathrm{s}(\mu^2)}{2\pi} \right)^2 \mathrm{d}\sigma_{H\to b\bar{b}}^{\mathrm{B}} \left\{ + \frac{2C_\mathrm{F}^2}{\epsilon^4} + \left(\frac{11 C_\mathrm{A} C_\mathrm{F}}{4} + 6 C_\mathrm{F}^2 - \frac{C_\mathrm{F} n_\mathrm{f}}{2} \right) \frac{1}{\epsilon^3} \right.$$
$$+ \left[\left(\frac{8}{9} + \frac{\pi^2}{12} \right) C_\mathrm{A} C_\mathrm{F} + \left(\frac{17}{2} - 2\pi^2 \right) C_\mathrm{F}^2 - \frac{2 C_\mathrm{F} n_\mathrm{f}}{9} \right] \frac{1}{\epsilon^2}$$
$$\left. + \left[\left(-\frac{961}{216} + \frac{13\zeta_3}{2} \right) C_\mathrm{A} C_\mathrm{F} + \left(\frac{109}{8} - 2\pi^2 - 14\zeta_3 \right) C_\mathrm{F}^2 + \frac{65 C_\mathrm{F} n_\mathrm{f}}{108} \right] \frac{1}{\epsilon} \right\}$$

C. Anastasiou, F. Herzog, A. Lazopoulos, arXiv:0111.2368

$$\sum \int \mathrm{d}\sigma^{\mathrm{A}} = \left(\frac{\alpha_\mathrm{s}(\mu^2)}{2\pi} \right)^2 \mathrm{d}\sigma_{H\to b\bar{b}}^{\mathrm{B}} \left\{ - \frac{2C_\mathrm{F}^2}{\epsilon^4} - \left(\frac{11 C_\mathrm{A} C_\mathrm{F}}{4} + 6 C_\mathrm{F}^2 + \frac{C_\mathrm{F} n_\mathrm{f}}{2} \right) \frac{1}{\epsilon^3} \right.$$
$$- \left[\left(\frac{8}{9} + \frac{\pi^2}{12} \right) C_\mathrm{A} C_\mathrm{F} + \left(\frac{17}{2} - 2\pi^2 \right) C_\mathrm{F}^2 - \frac{2 C_\mathrm{F} n_\mathrm{f}}{9} \right] \frac{1}{\epsilon^2}$$
$$\left. - \left[\left(-\frac{961}{216} + \frac{13\zeta_3}{2} \right) C_\mathrm{A} C_\mathrm{F} + \left(\frac{109}{8} - 2\pi^2 - 14\zeta_3 \right) C_\mathrm{F}^2 + \frac{65 C_\mathrm{F} n_\mathrm{f}}{108} \right] \frac{1}{\epsilon} \right\}$$

V. Del Duca, C. Duhr, G. Somogyi, FT, Z. Trocsanyi, arXiv:1501.07226

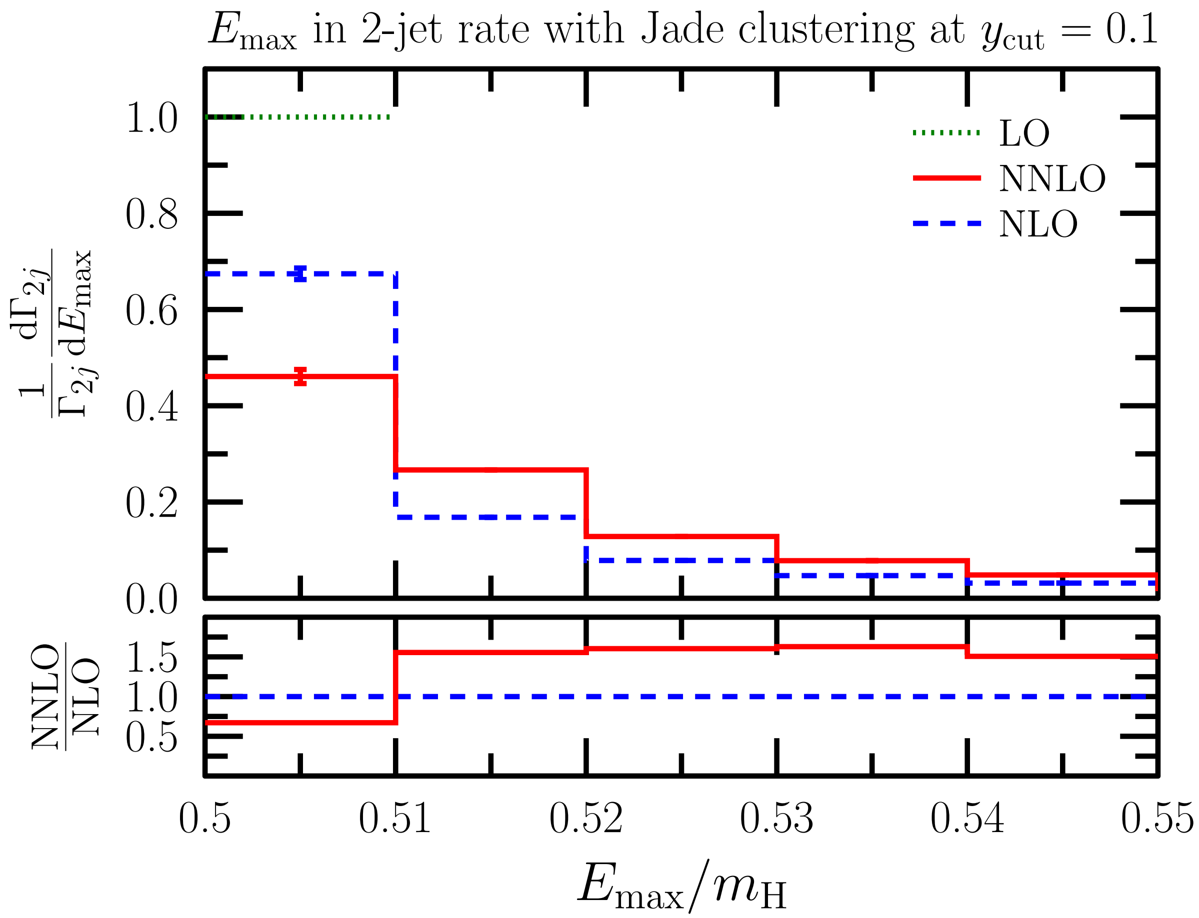
Inclusive result



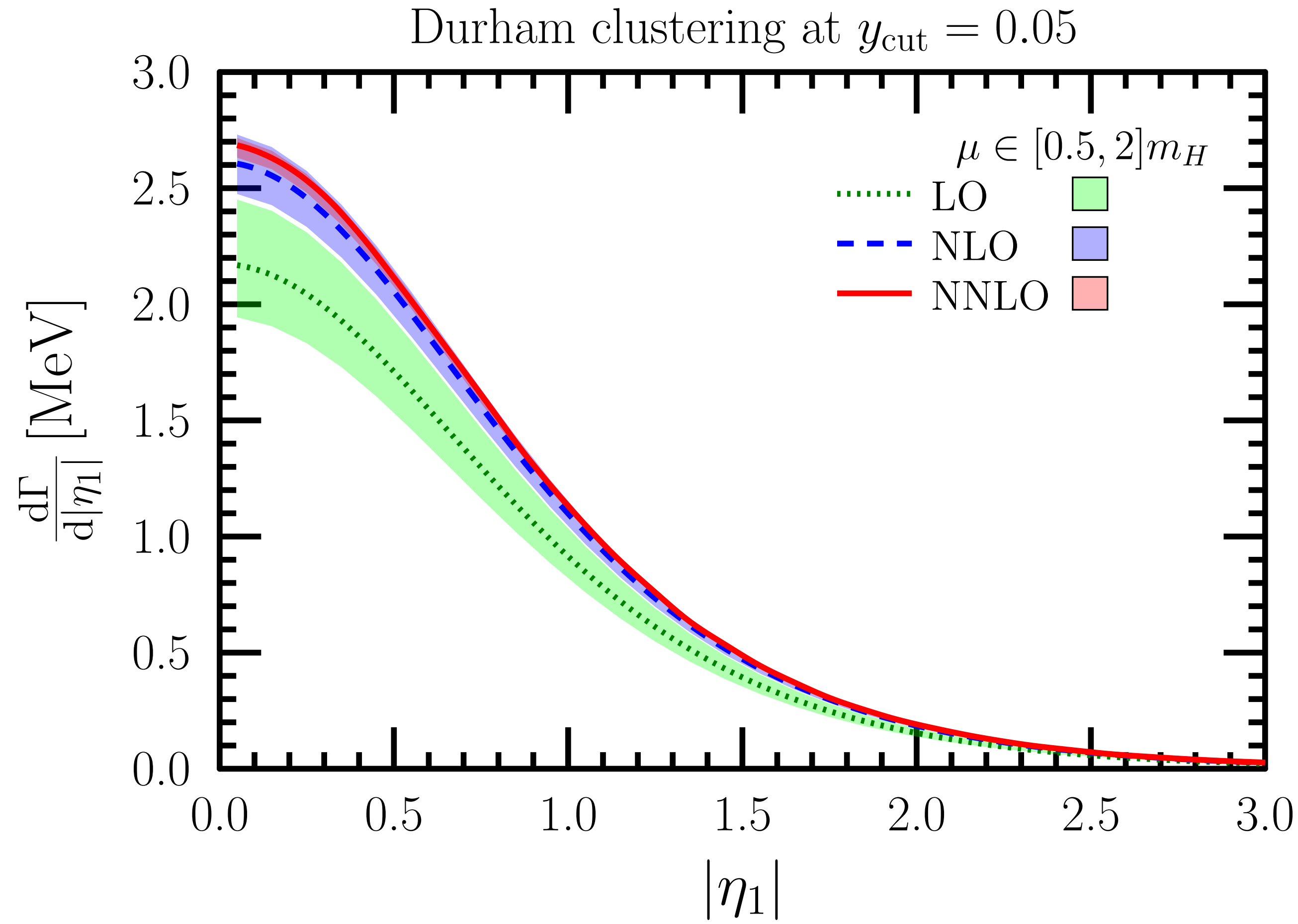
In perfect agreement with:
[Gorishnii, Kataev, Larin, Surguladze 1990]
[Baikov, Chetyrkin, Kuhn 2006]

[Del Duca, Duhr, Somogyi, FT, Trocsanyi 2015]

Differential results



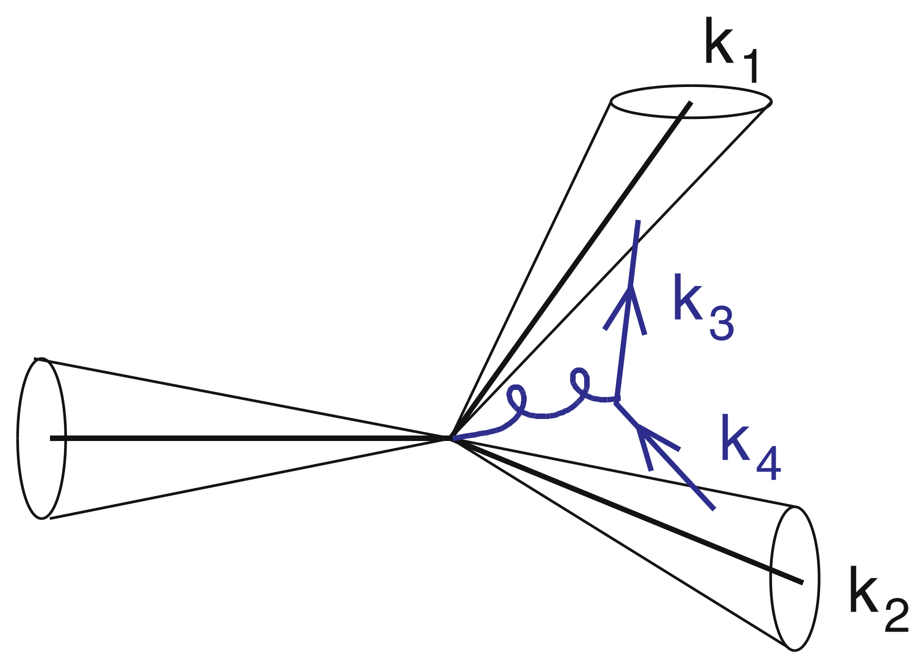
Energy spectrum of the leading jet in the rest frame of the Higgs boson for 2j events.
Excellent agreement with
[Anastasiou, Herzog, Lazopoulos '12]



Absolute value of the pseudorapidity of the leading jet in the rest frame of the Higgs boson

[Del Duca, Duhr, Somogyi, FT, Trocsanyi 2015]

Jet algorithm



Flavor-kT provides an IRC safe definition of jet flavour

[Banfi, Salam, Zanderighi 2006]

$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavourless,} \end{cases}$$

$$d_{iB}^{(F)} = \begin{cases} \max(k_{ti}^2, k_{tB}^2)\,, & i \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tB}^2)\,, & i \text{ is flavourless.} \end{cases}$$

$$k_{tB}(\eta) = \sum_i k_{ti}\left(\Theta(\eta_i - \eta) + \Theta(\eta - \eta_i)e^{\eta_i - \eta}\right)$$

$$k_{t\bar{B}}(\eta) = \sum_i k_{ti}\left(\Theta(\eta - \eta_i) + \Theta(\eta_i - \eta)e^{\eta - \eta_i}\right)$$

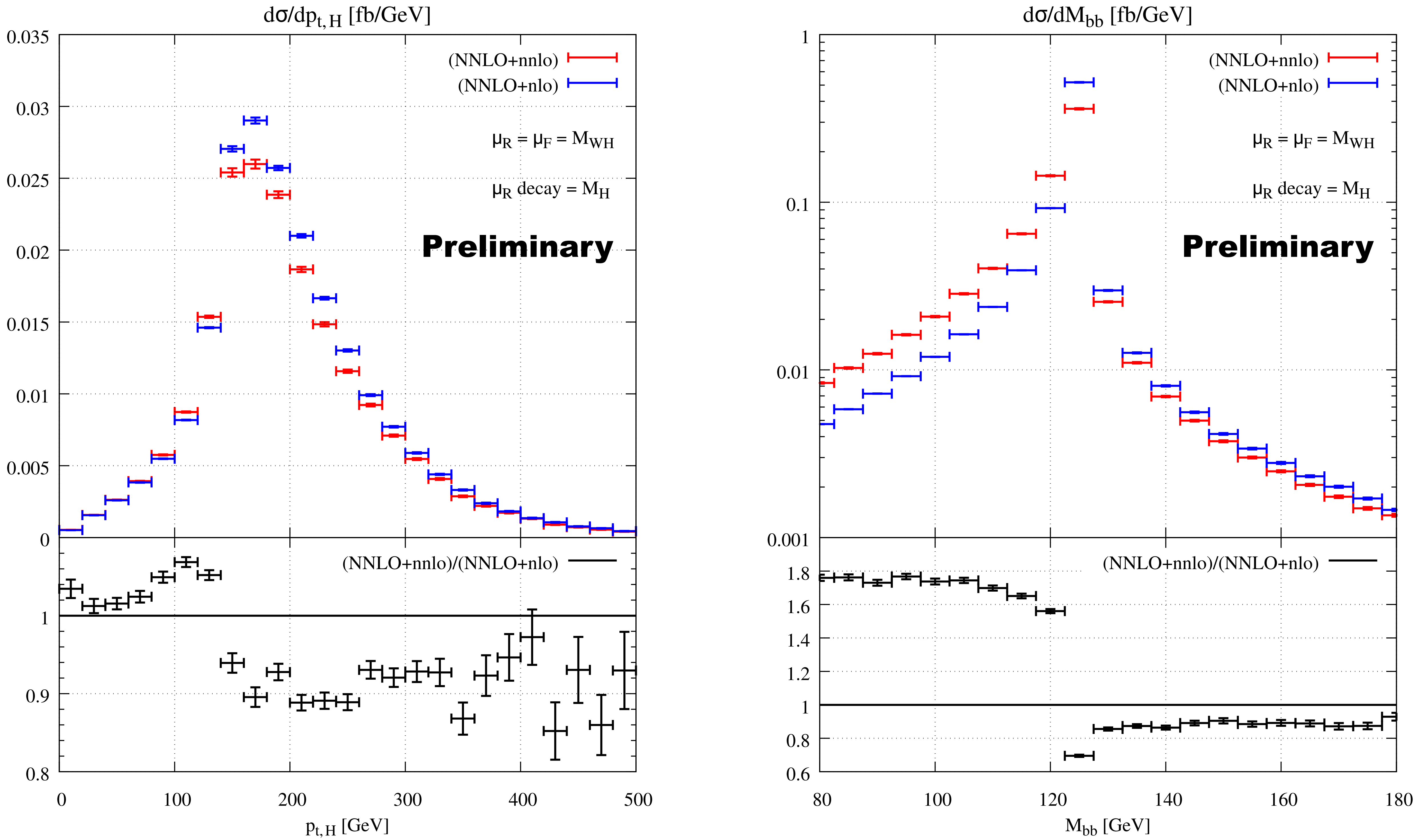
Results

WH(bb)@NNLO in both production and decay

[G. Ferrera, G. Somogyi, FT(to appear)]

LHC13 with standard WH search cuts

ptW > 150GeV



Conclusion

- ✳ Calculation of NNLO QCD corrections to VH production with nnlo QCD $H \to bb$ decay in hadron collision included in a fully-exclusive parton level Monte Carlo code: HVNNLO
- ✳ Perturbative corrections are important
- ✳ first reliable estimate of perturbative uncertainty possible

Outlook/Work in progress

- ✳ Public release of the HVNNLO parton-level numerical code
- ✳ Inclusion of other Higgs boson decay channels, es. $H \to WW/ZZ \to 2l2\nu/4l$ decay
- ✳ Further comparisons among fixed order and computations matched to the PS
- ✳ Would be important to have a NLOPS event generator with both QCD and EW effects
- ✳ NNLOPS (?)

Backup

NNLO(pp → VH) ⊗ nlo(H → bb)

LHC8 with standard WH search cuts and a jet veto