NNLO Higgs plus Vector boson production at the LHC

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Outline

* Motivation

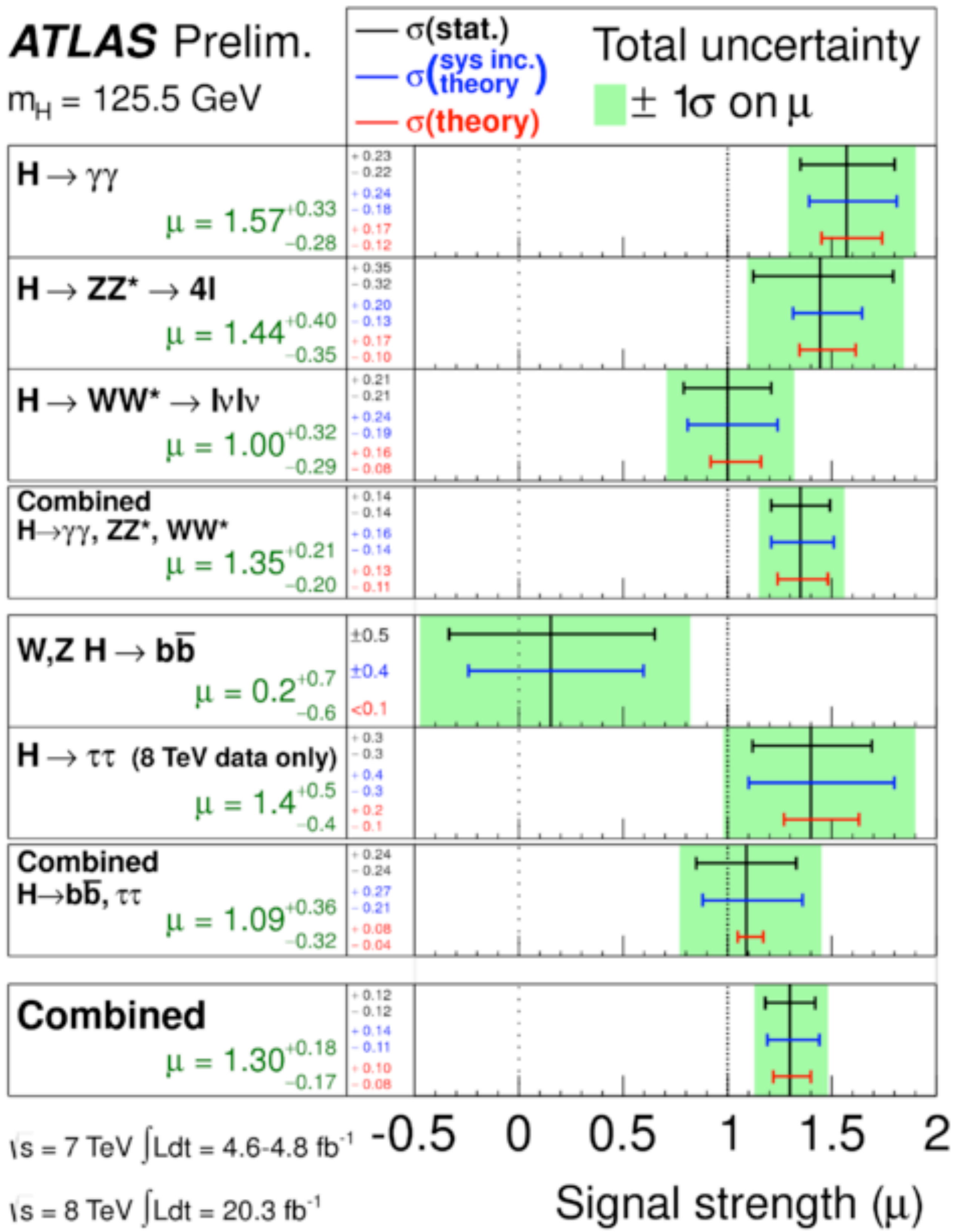
* Higher Order corrections

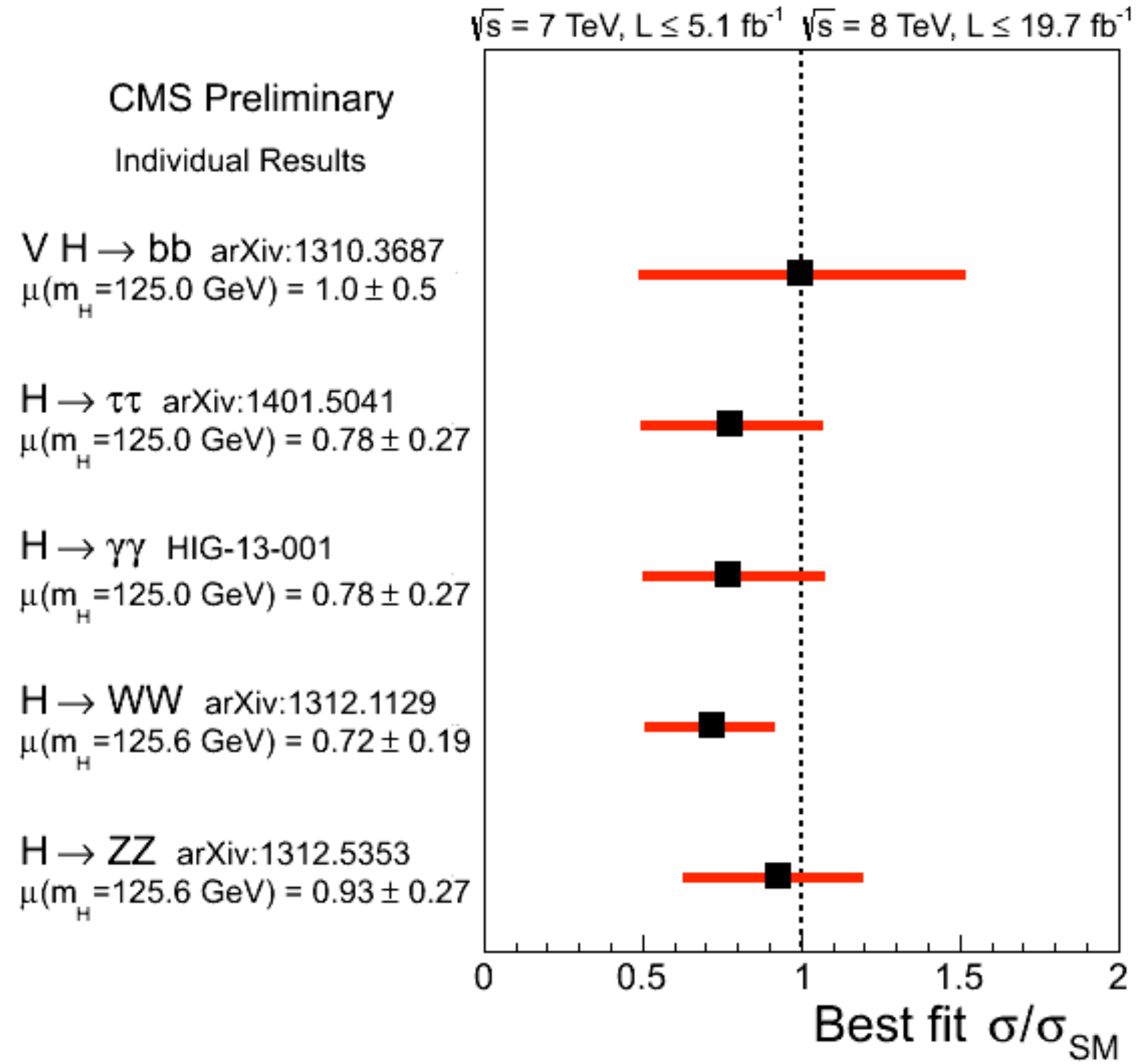
* Results

* Conclusion/Outlook

Motivation

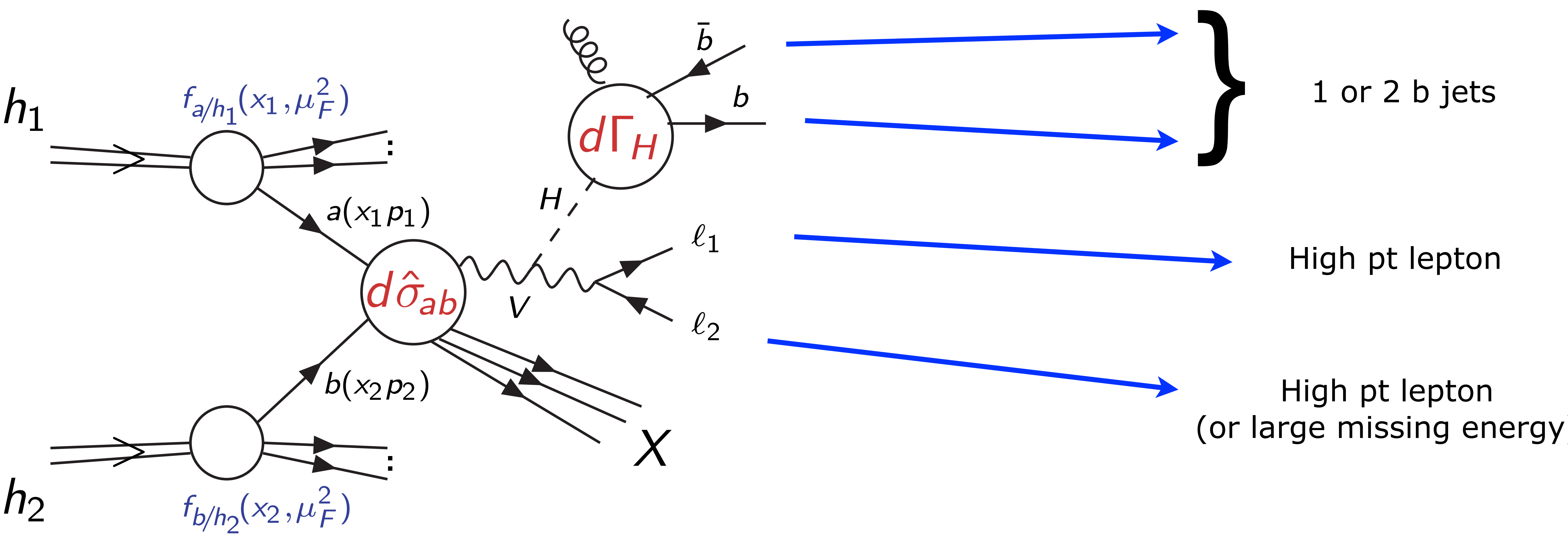
Higgs particle @ ATLAS and CMS





- Direct coupling to fermions possible observing Higgs decay in tau and bottom pairs
- Deviation from the SM are still possible
- VH allows to measure Higgs coupling to bottom
- Need of precise fully differential predictions

VH signal phenomenology



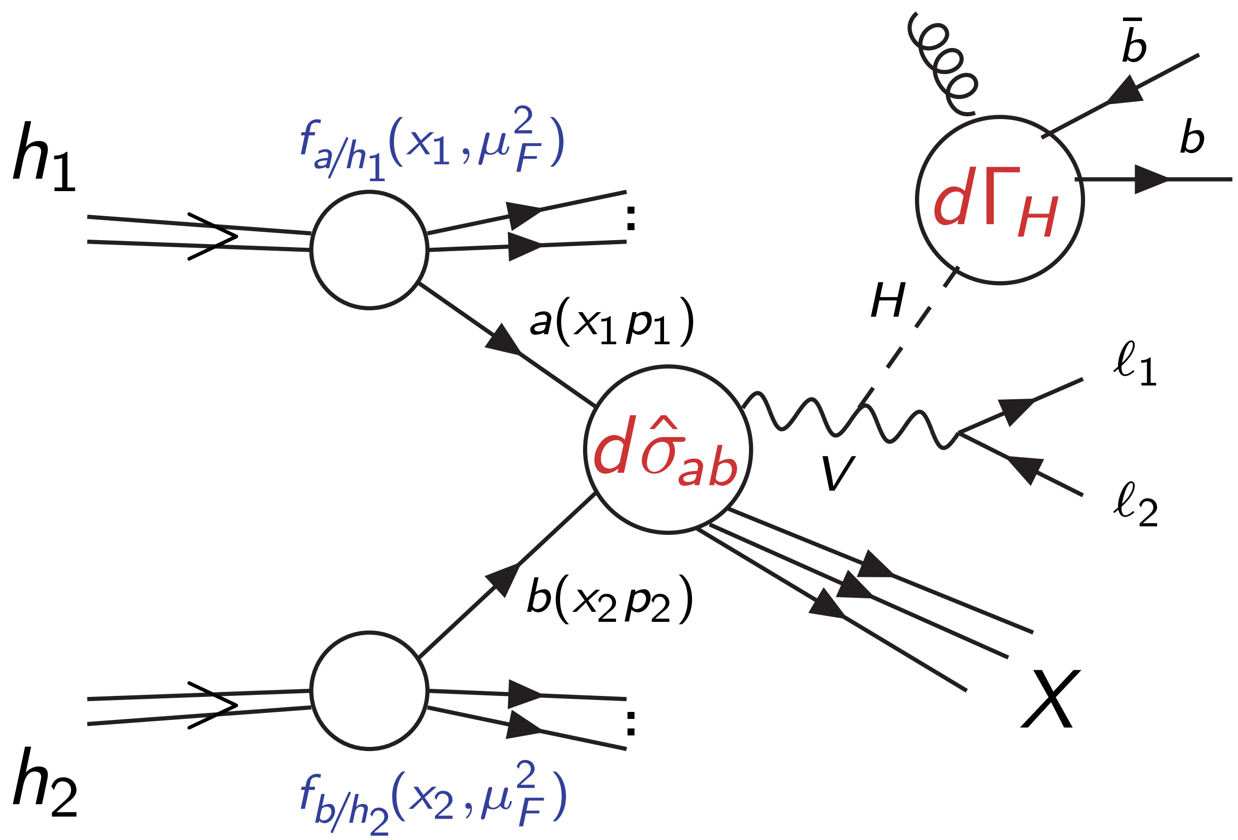
- Large sources of backgrounds from VV, tt, V+jets, V+b, V+bb
- For boosted boson events S/B improve considerably and allows detection at the LHC [Butterworth, Davison, Rubin, Salam 2008]

VH search strategy important to asses the relevance of the corrections to the decay process

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

Higher Order corrections

VH signal computation (QCD)



QCD corrections (inclusive)

- NNLO QCD corrections for VH are basically the same of DY [Van Neerven et al 1991, Brein, Harlander, Djouadi 2000]
- For ZH there is also gg->ZH top-loop [Kniehl 1990]
- NNLO top-mediated constribution [Brei, Halander, Wiesemann, Zirke 2011]
- The inclusive H → bb decay rate is known up to fourth order in QCD [Baikov,Chetyrkin,Kuhn('05)] (and up to NLO [Dabelstein, Hollik; Kniehl ('92)])

QCD corrections (differential)

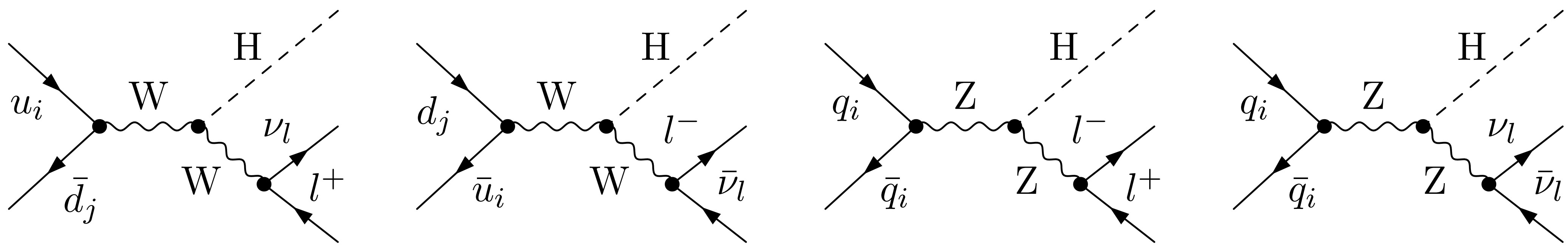
- Fully differential NNLO QCD corrections for VH, including tree-level H and V decays with spin correlations (HVNNLO) [Ferrera, Grazzini, FT (2011, 2014)]
- NLO fully-differential QCD corrections for WH prod. including H → bb NLO decay [Banfi,Cancino('12)]
- NNLO fully-differential decay rate H → bb computed through new non-linear mapping method: [Anastasiou,Herzog,Lazopoulos ('12)] and through Colorful NNLO method see Zoltan's talk [and references therein]
- Resummation of jet-veto and transverse-momentum logarithms performed [Y.Li,Liu('14)][Shao,C.S.Li,H.T.Li('13)], [Dawson,Han,Lai,Leibovich,Lewis('12)]

VH signal computation (EW)

* EW corrections:

NLO EW known differentially, which should be sufficient

→ 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 in YR2 should be ok

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

More can only be achieved by some NNLO QCD-EW calculation

→ currently out of reach

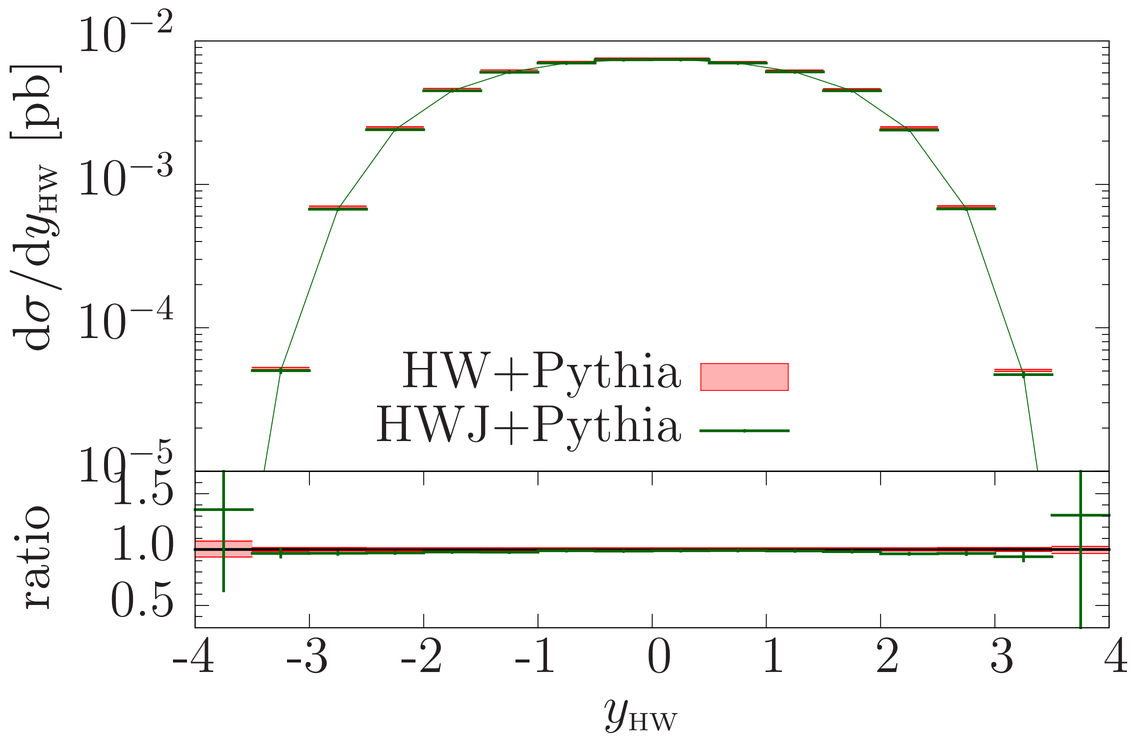
Merging and Matching

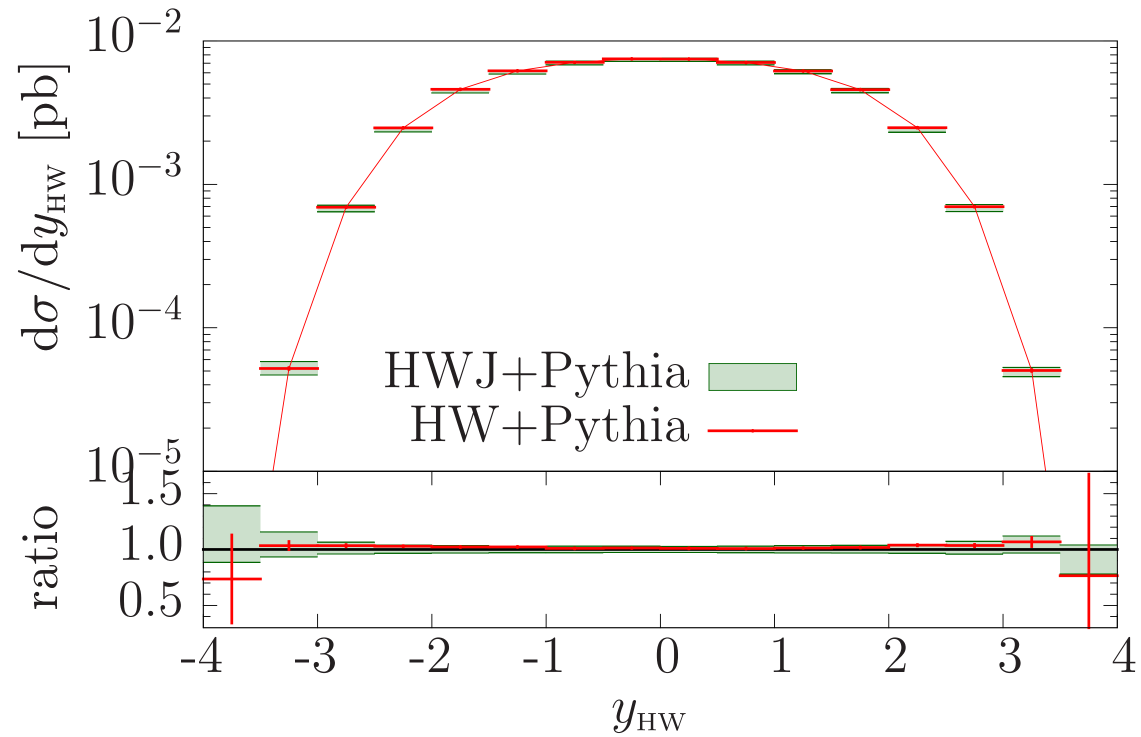
* NLO QCD & parton shower:

  merging and matching for pp→VH(j)

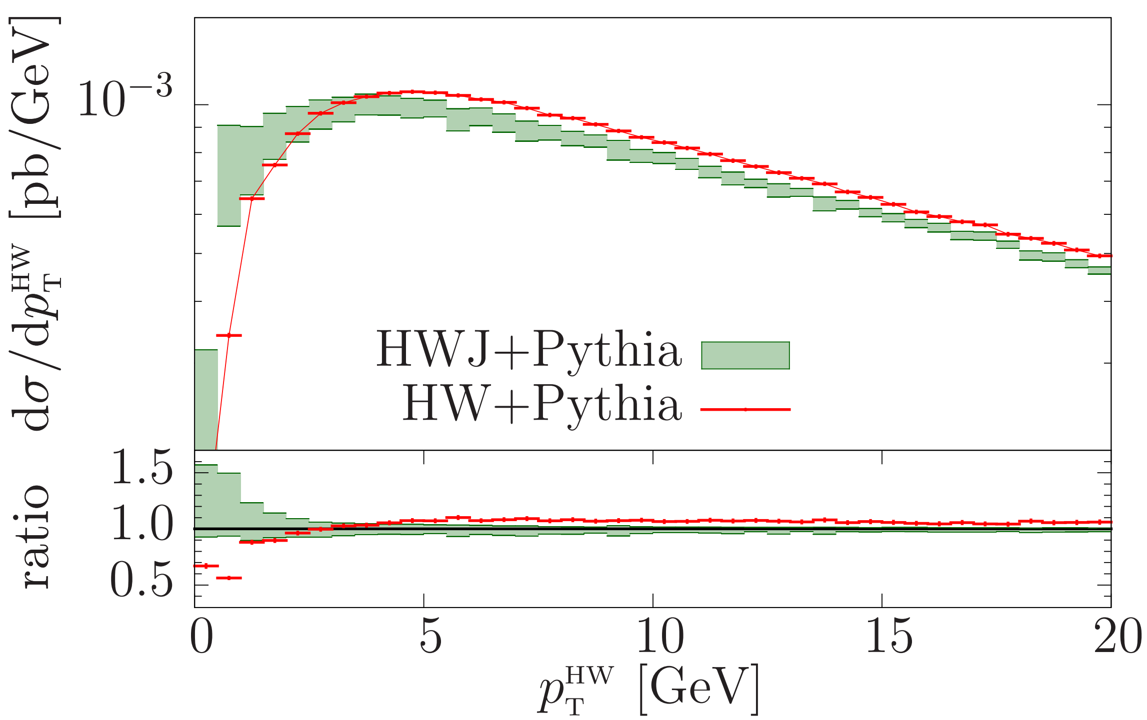
  → available in the POWHEG-BOX framework [Luisoni, Nason, Oleari, FT]
  and in MG5_aMC (FxFx) and Sherpa (MEPS@NLO)

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





LHC8



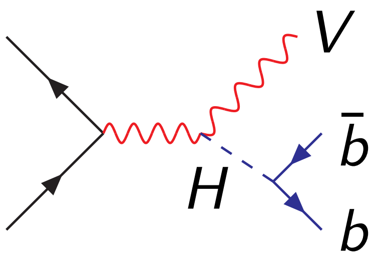
* NNLO matching with PS possible through reweighting of HVj-MINLO with HVNNLO, already worked out for:

  - H production [Hamilton, Nason, Re, Zanderighi]
    reweighting with HNNLO [Grazzini]

  - DY production [Karlberg, Re, Zanderighi]
    reweighting DYNNLO [Catani, Cieri, Ferrera, de Florian, Grazzini]

QCD corrections in the Narrow Width Approximation

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



Including up to NLO corrections

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

Precise knowledge fron YR1

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

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

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

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]

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

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

qT subtraction method [Catani, Grazzini 2007]

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

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

- 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 contain both the double virtual amplitude and the integral of the CT
  - ✓ it's process dependent part can be obtained by the virtual amplitude via a universal process independent factorization 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]

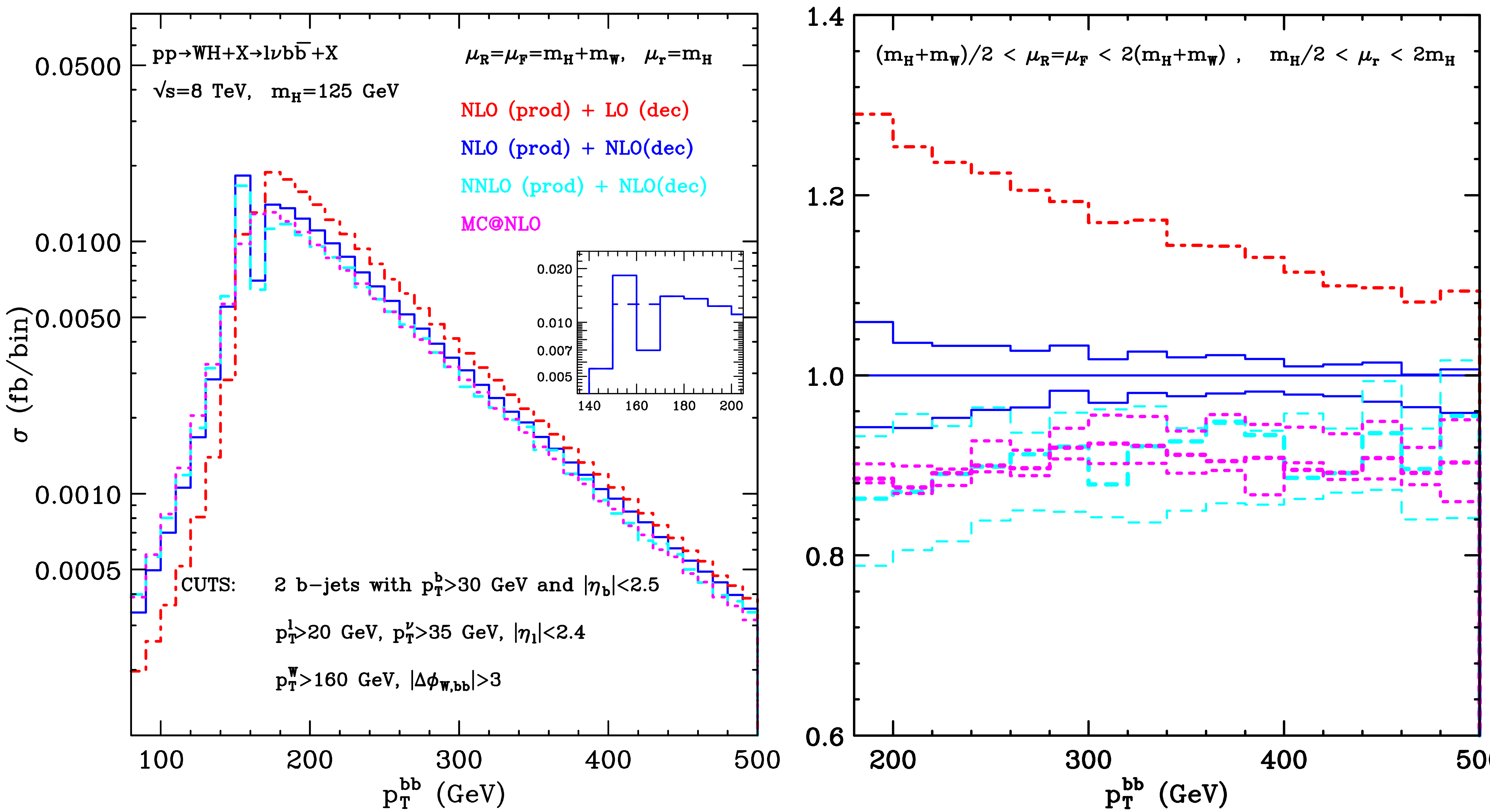
Results

Associated WH production

LHC8 with cuts

Left panel: p_T spectrum of the b-jets pair.

Right panel: Spectra normalized to the full NLO results (perturbative scale - μ_R, μ_F, μ_{Rdec} uncertainty bands are shown).

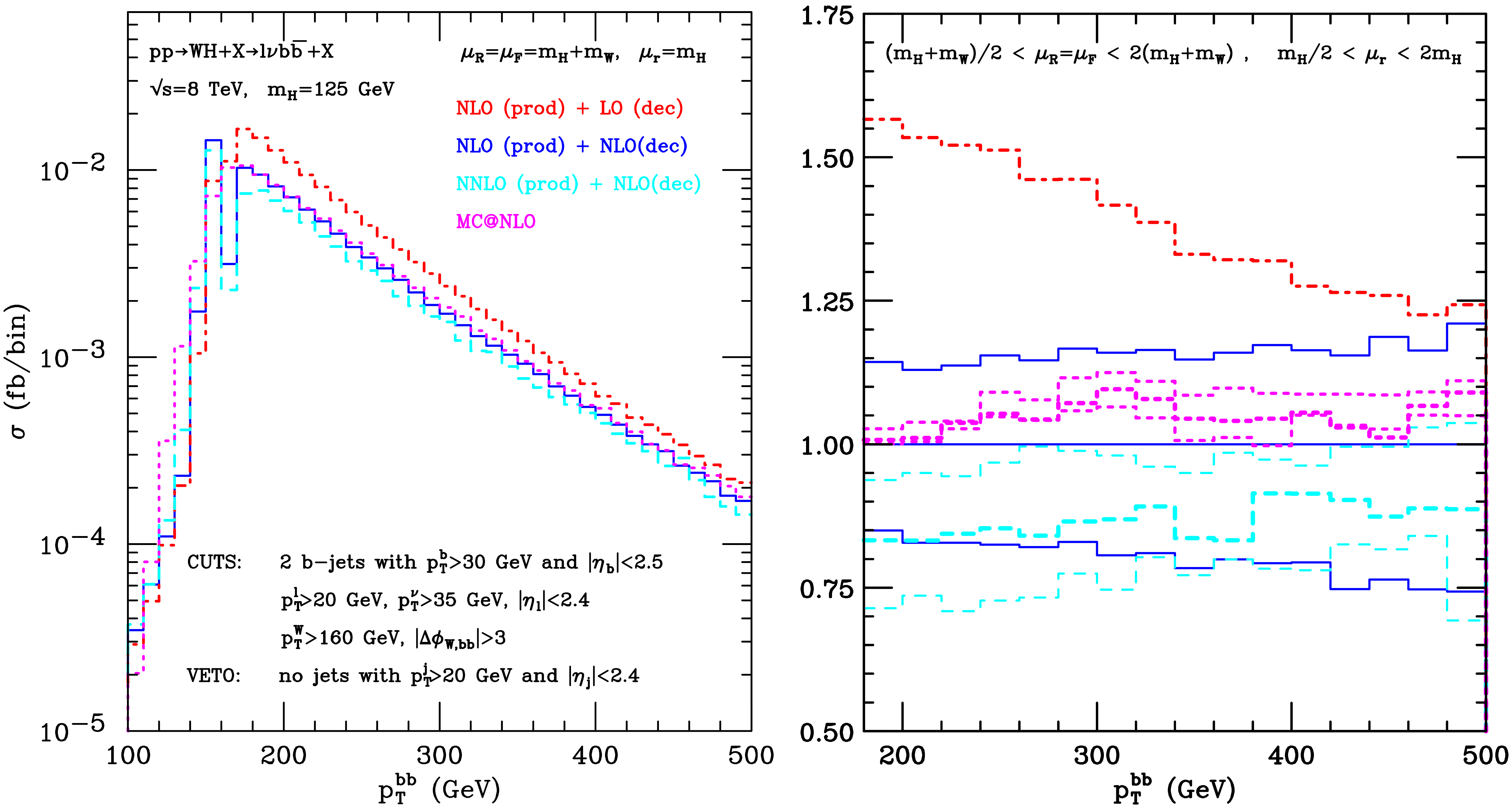


- Acceptance is 4% including NLO in production and is further reduced by 12% including NLO in the decay
- Instability due to the cut on the W transverse momentum (not present for shower MC)
- Large correction below pt 160GeV due to the correction to the decay that are a leading order term
- Effect of the shower similar to NNLO(prod) + NLO(dec)
- Agreement among NNLO(prod) + NLO(dec) and MC@NLO
- NLO scale uncertainty not reliable
- NNLOp+NLOd scale uncertainty larger the NLO one

Associated WH production

LHC8 with cuts

Including a light jet veto

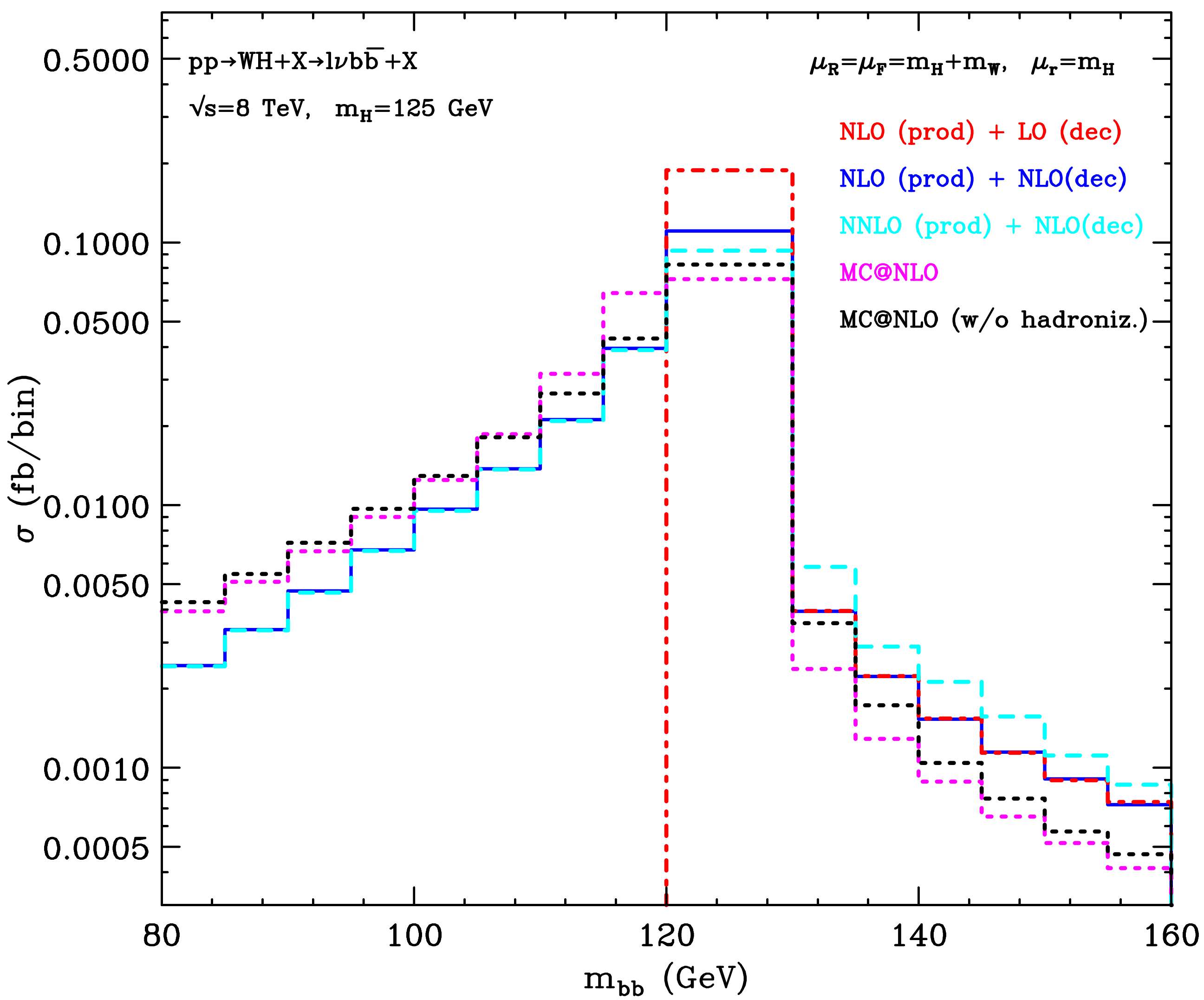


- NNLO having up to two hard radiations is more sensitive to the jet veto
- Acceptance is reduced by 33% for MC@NLO, 41% for NLO and 44% for NNLOp+NLOd

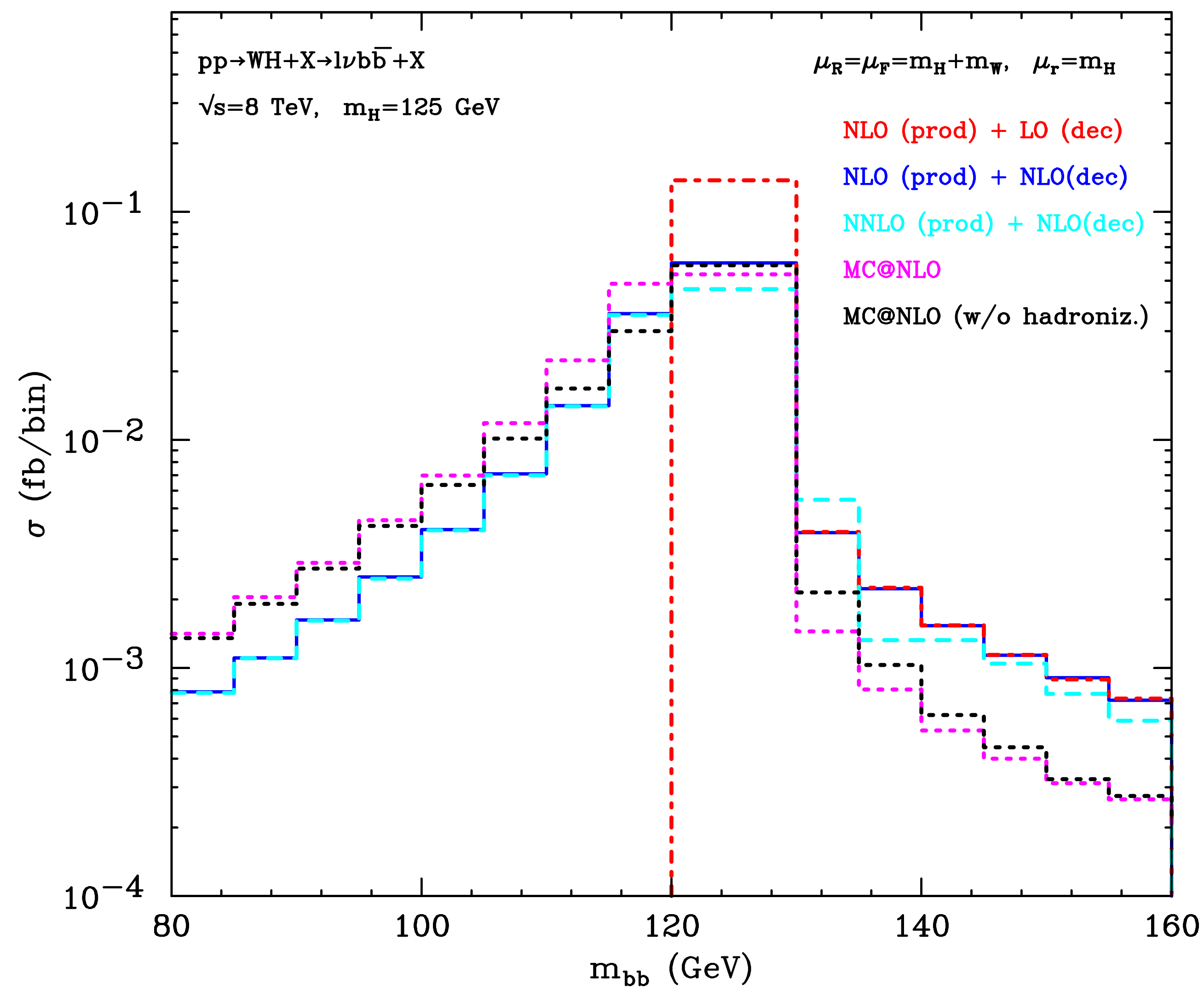
Associated WH production

LHC8 with cuts

Invariant mass distribution



Without a jet veto



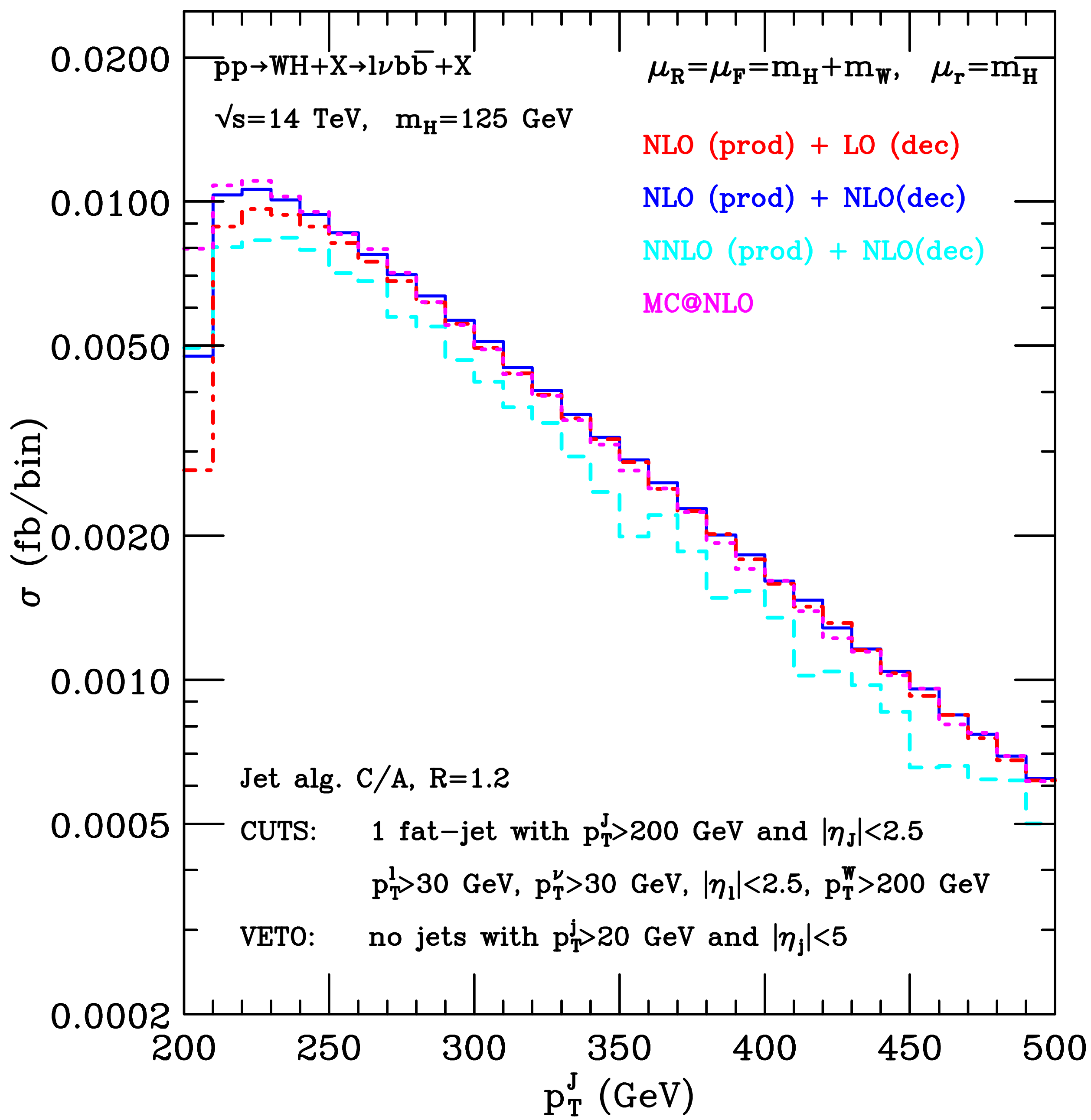
With a jet veto

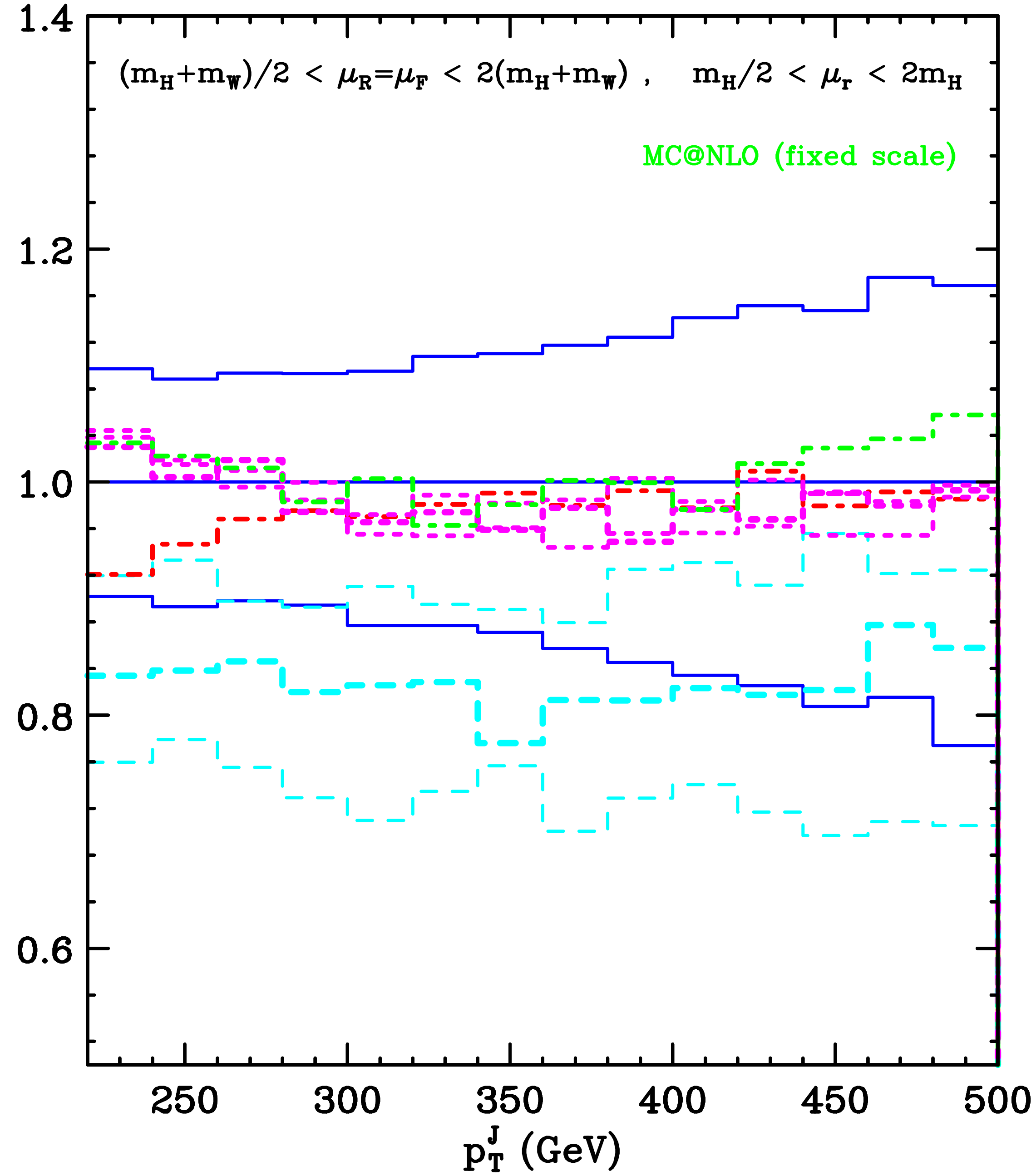
- Correction to production and decay in different regions: high mass and low mass respectively
- High mass region: MC@NLO underestimate the cross section, the NNLO effect is large and positive and partially washed out when the jet veto is applied
- Low mass: MC@NLO more effective in reducing the invariant mass
- Higher order corrections make the invariant mass harder with respect to MC@NLO

Associated WH production

Fat jet

LHC14 with cuts and veto

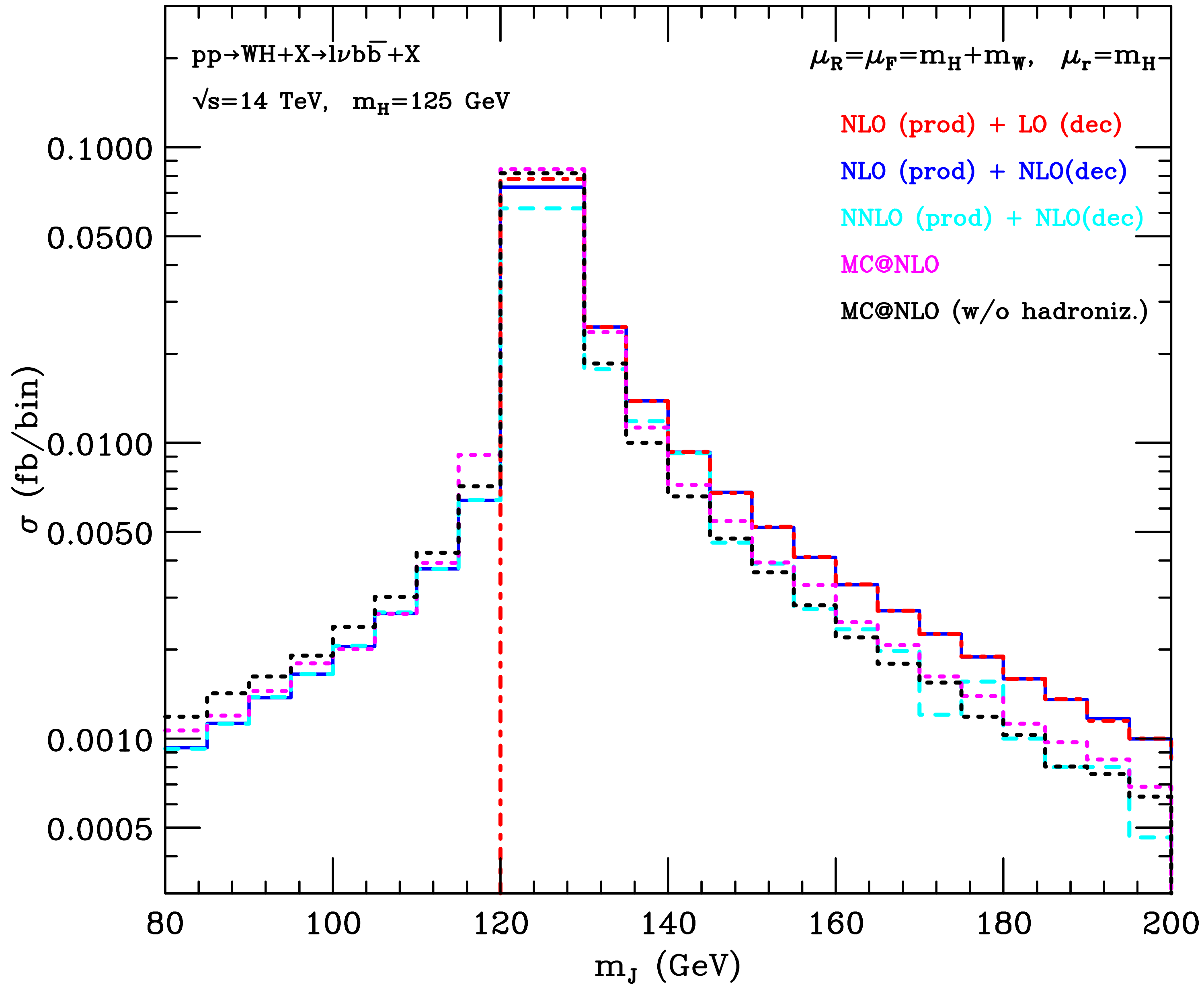




σ (fb)	NLO (with LO dec.)	NLO (full)	NNLO (with NLO dec.)	MC@NLO
w/o jet veto	$2.54^{+1\%}_{-1\%}$	$2.63^{+1\%}_{-1\%}$	$2.52^{+2\%}_{-2\%}$	$2.82^{+1\%}_{-1\%}$
w jet veto	$1.22^{+11\%}_{-14\%}$	$1.29^{+12\%}_{-13\%}$	$1.07^{+8\%}_{-6\%}$	$1.33^{+1\%}_{-1\%}$

Associated WH production

Fat jet LHC14 with cuts

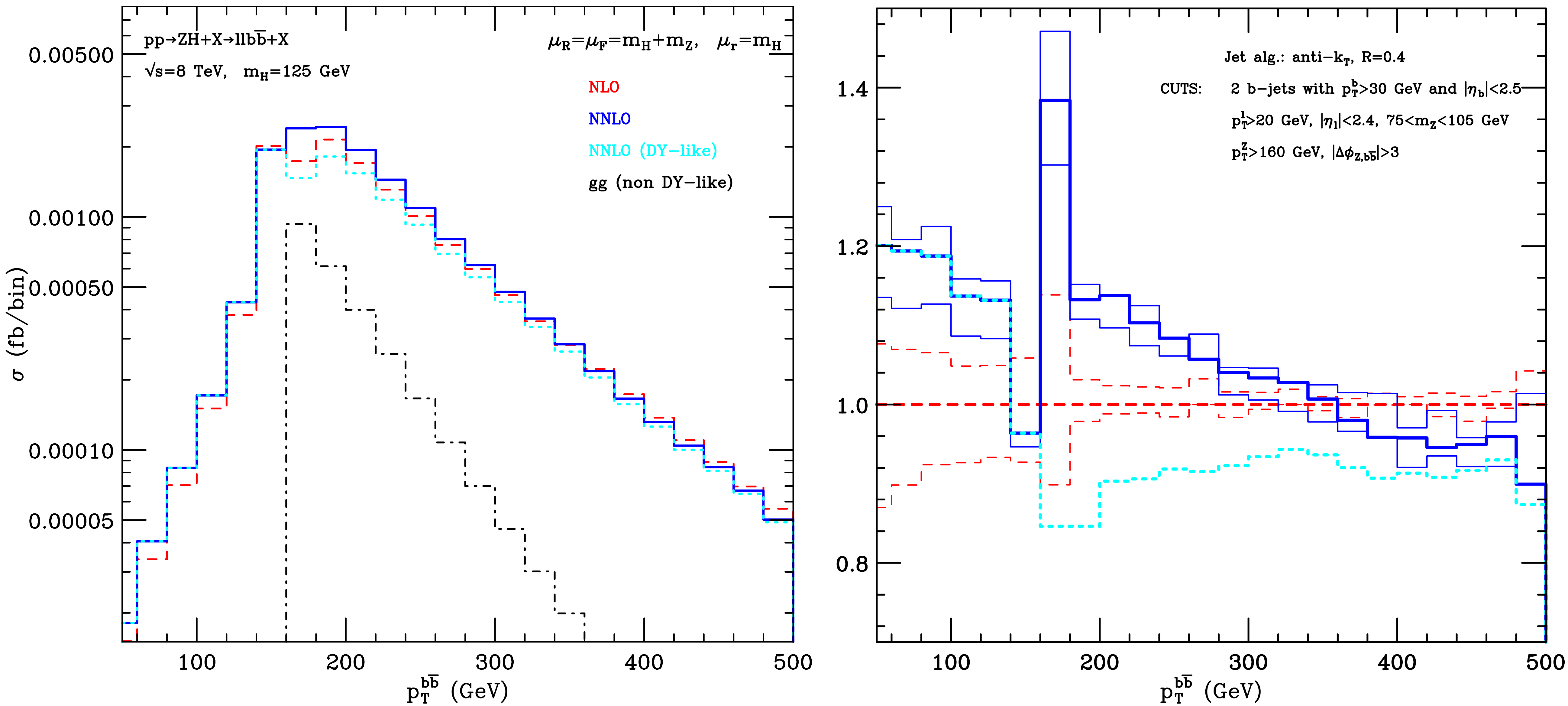


- Radiative corrections to the production are those that are more relevant
- High mass region: reduction due to parton shower similar to the NNLO effect
- Low mass: MC@NLO and fixed order essentially identical
- stable with respect radiative corrections

Associated ZH production

LHC8 with cuts

σ (fb)	NLO	NNLO (DY-like)	NNLO
LHC8	$0.2820^{+2\%}_{-2\%}$	$0.2574^{+3\%}_{-4\%}$	$0.3112^{+3\%}_{-2\%}$



- DY-like contribution not negligible (acceptance reduced by 10%) & Kfactor almost flat at high pt
- Loop induced is positive (+20%) & with a pt dependent Kfactor
- Overall effect is positive
- It is crucial in the experimental analysis to take in proper account the Loop induced gs^4 term

Associated ZH production

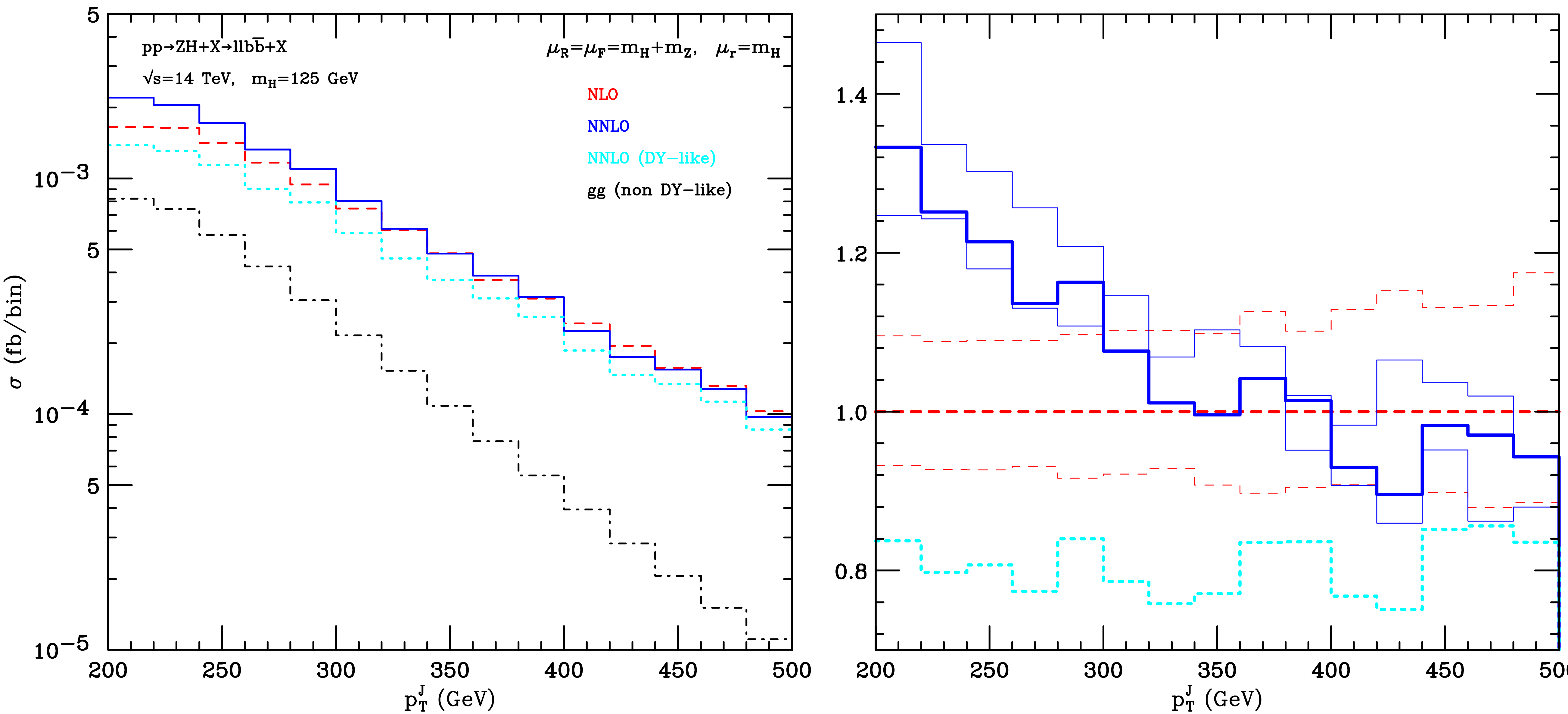
Fat jet LHC14 with cuts and veto

Jet alg. C/A, R=1.2

CUTS: 1 fat−jet with p_T^J>200 GeV and $|\eta_J|$<2.5

p_T^l>30 GeV, $|\eta_l|$<2.5, p_T^Z>160 GeV

VETO: no jets with p_T^j>20 GeV and $|\eta_j|$<5



- DY-like contribution not negligible (acceptance reduced by 20%) & Kfactor almost flat at high pt
- Loop induced is positive (+25%) & with a pt dependent Kfactor
- It is crucial in the experimental analysis to take in proper account the loop induced gs^4 term

Conclusion

- ✳ Calculation of NNLO QCD corrections to VH production with NLO QCD H → bb decay in hadron collision using the qT -subtraction formalism, included in a fully-exclusive parton level Monte Carlo code: VHNNLO
- ✳ Compared perturbative results with NLO parton-shower Monte Carlo predictions. Studied the NNLO(+nlo) uncertainty band: first reliable estimate of perturbative uncertainty
- ✳ Perturbative corrections are important:
  LHC8 analysis: NLO corr. to decay important but well accounted by MC parton shower. Good stability of higher-order corrections for production also with a light-jet veto.
  LHC14 analysis: NLO corr. to decay small. NNLO corrections large and negative: $\sim -20\%$ when a light-jet veto is applied
- ✳ For ZH the loop induced contribution
  - ✓ consistently included together with the other gg initiated subprocesses at the same order
  - ✓ it is crucial that such contribution is properly accounted for in the experimental analyses

Outlook/Work in progress

- ✳ Public release of the parton-level numerical code
- ✳ Extension to the full NNLO corrections for both production and decay
- ✳ Inclusion of H → WW/ZZ → 2l2v/4l decay
- ✳ NNLOPS doable in principle