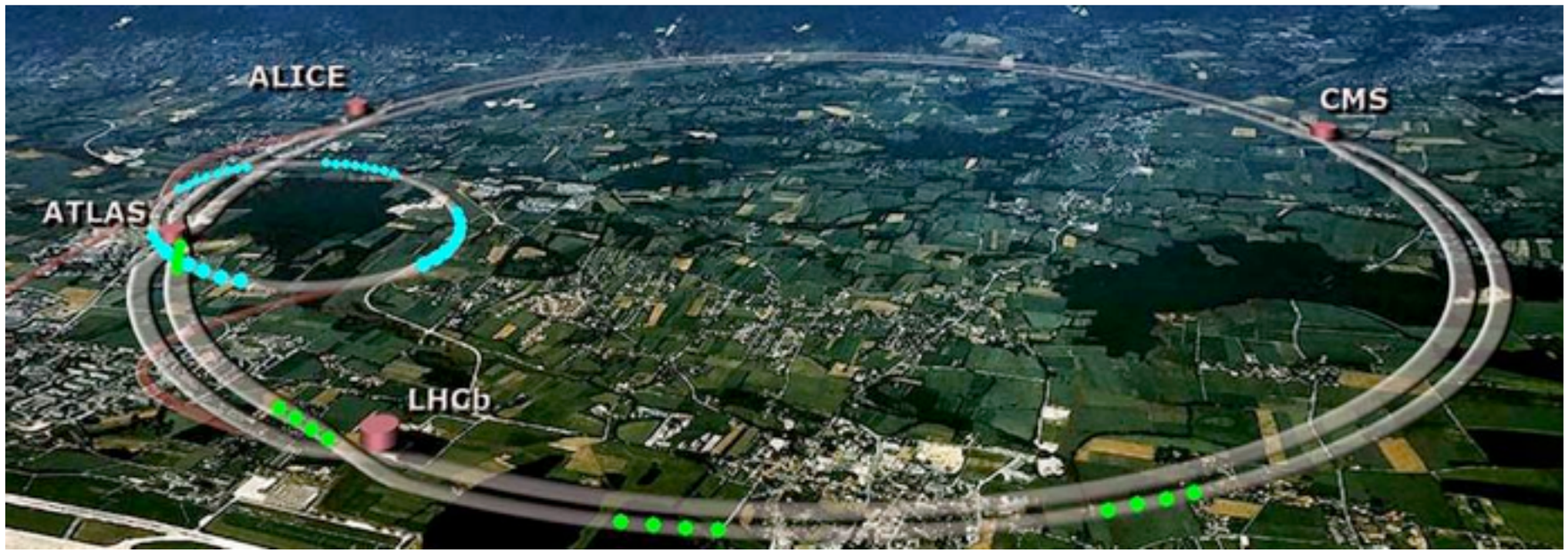
VBF+VH theory summary



Francesco Tramontano
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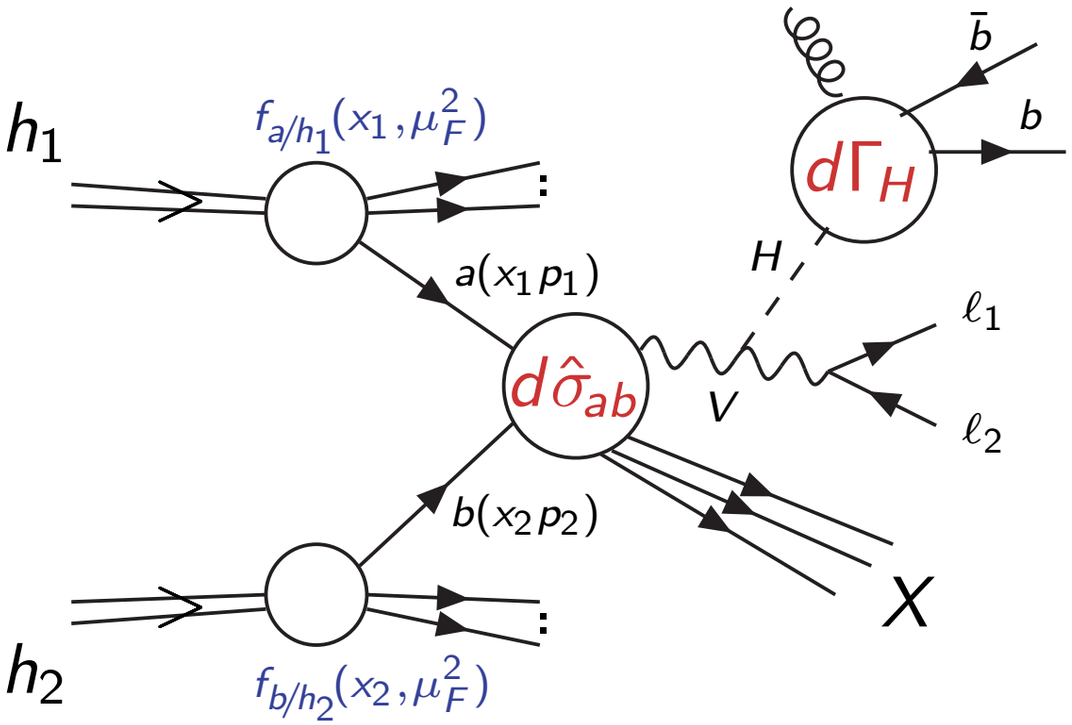
On behalf of the WG1 VBF+VH subgroup
EX: P. Govoni, J. Nielsen, E. Pianori, A. Rizzi
TH: S.Dittmaier, B. Jaeger, F. Tramontano

LHC Higgs XS WG general assembly - CERN - Jan 22th 2015

VH

VH Higher Order Corrections (QCD)



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 '12]
- NNLO top-mediated contribution (1~2% at the LHC)
  [Brei, Halander, Wiesemann, Zirke 2011]
- N3LO threshold corrections computed
  [Kumal, Mandal, Ravindran ('14)]
- 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 ('92)])

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)] done with the qT subtraction method [Catani, Grazzini ('07)]
- NNLO fully-differential decay rate H → bb computed: through new non-linear mapping method [Anastasiou,Herzog,Lazopoulos ('12)]
- 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)]

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

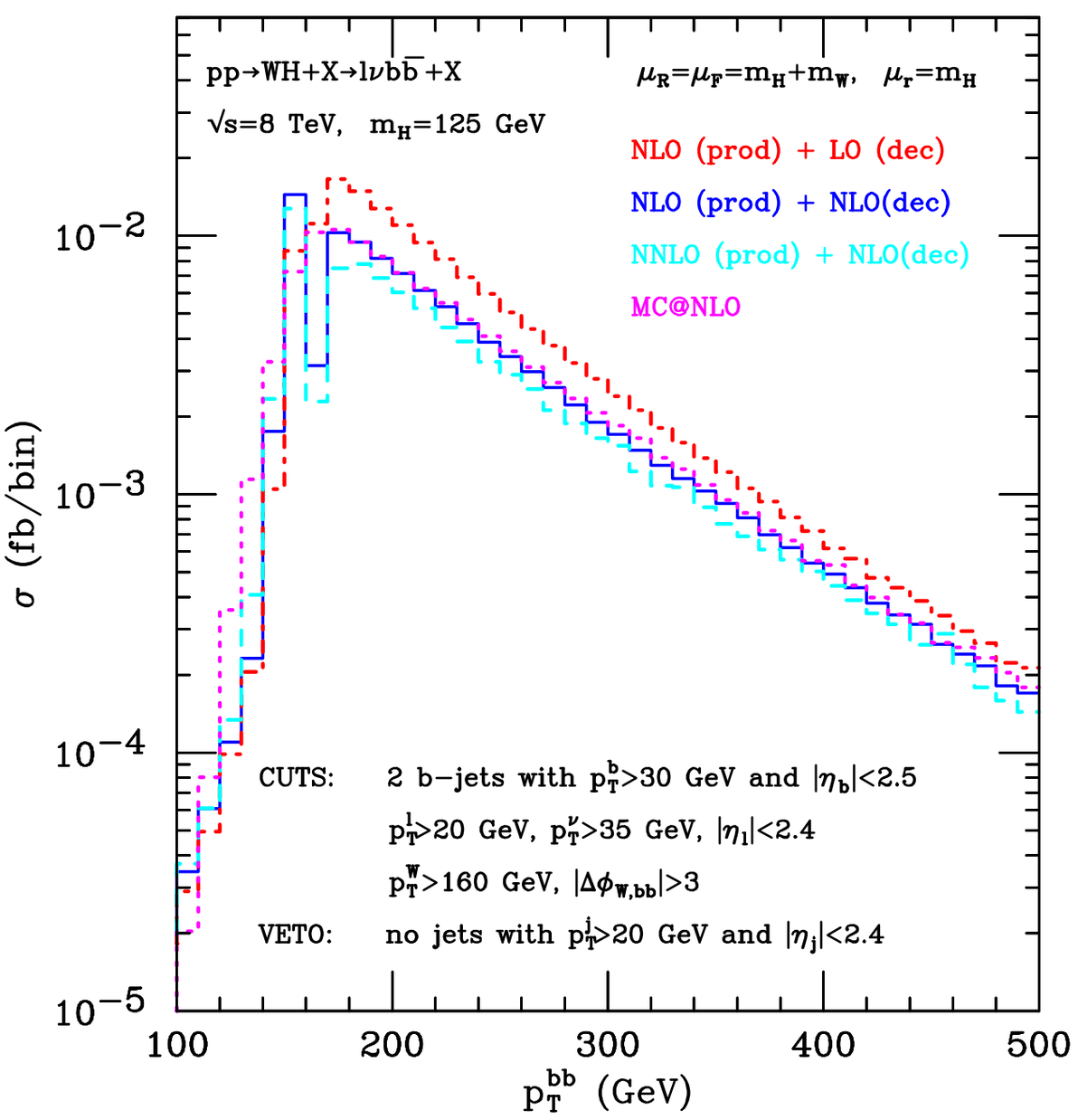
$$d\sigma^{\mathrm{NLO(prod)+NLO(dec)}}_{pp\to VH+X\to Vb\bar{b}+X} = \left[d\sigma^{(0)}_{pp\to VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} + d\sigma^{(1)}_{pp\to VH+X} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to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

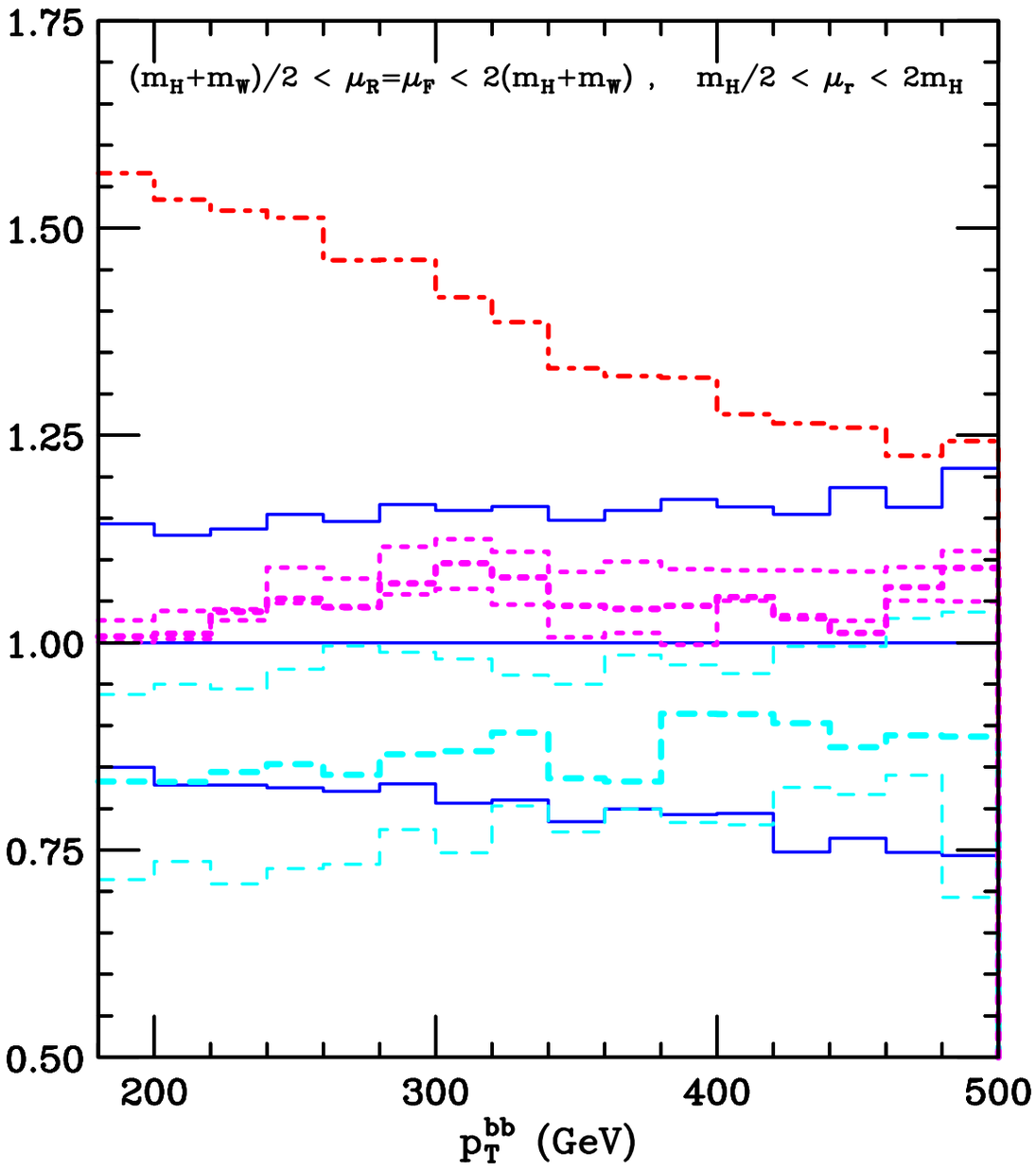
Including up to NNLO corrections for the production and up to NLO for the decay

$$d\sigma^{\mathrm{NNLO(prod)+NLO(dec)}}_{pp\to VH+X\to l\nu b\bar{b}+X} = \left[d\sigma^{(0)}_{pp\to VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} + \left(d\sigma^{(1)}_{pp\to VH+X} + d\sigma^{(2)}_{pp\to VH+X}\right) \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}}\right] \times Br(H\to b\bar{b})$$

- QCD corrections to the decay might be large depending on the search strategy
- for boosted searches NLO QCD corrections are huge and captured by LO decay plus shower MC

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



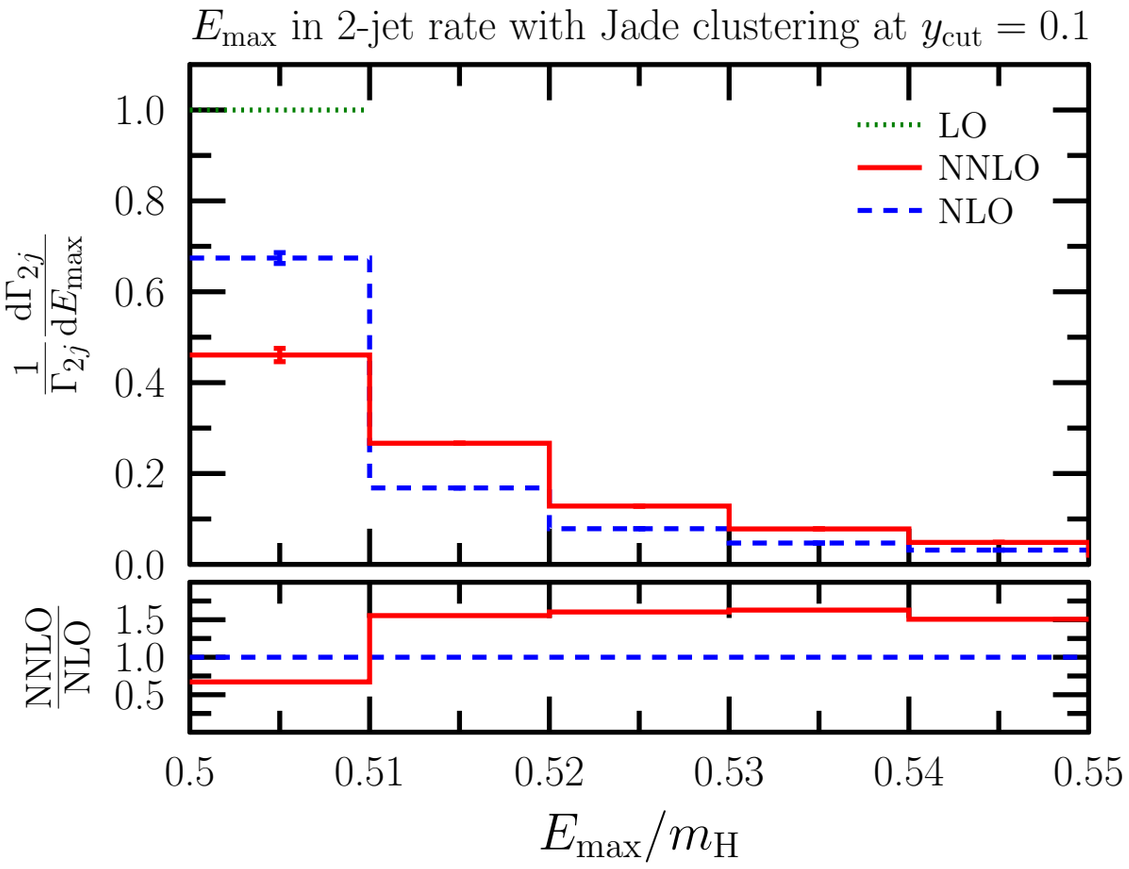


Improving on the fixed order prediction: fully differential H decay to bb@NNLO

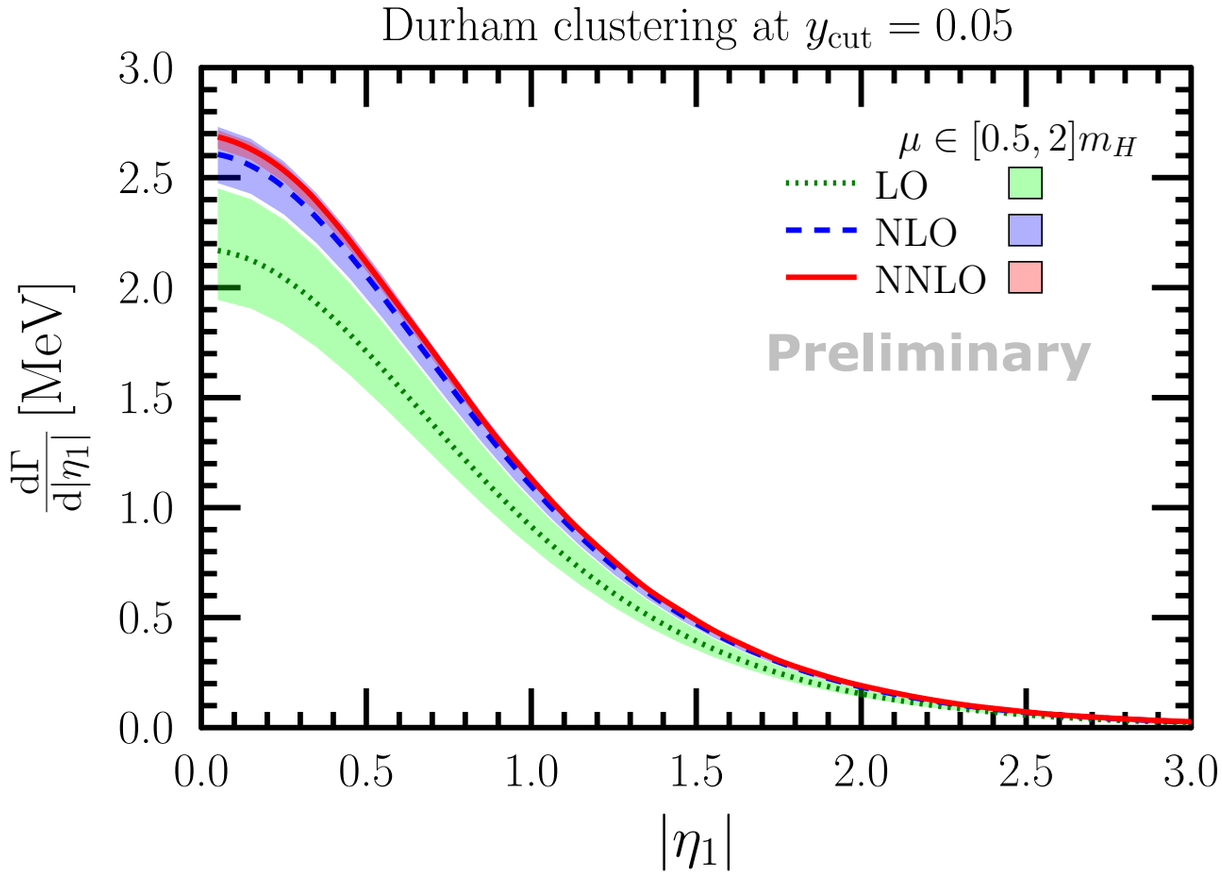
[Anastasiou, Herzog, Lazopoulos '12]

Computation also performed via the NNLO subtraction method of [Del Duca, Somogyi, Trocsanyi '07]

[Del Duca, Duhr, Somogyi, FT, Trocsanyi in preparation]



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

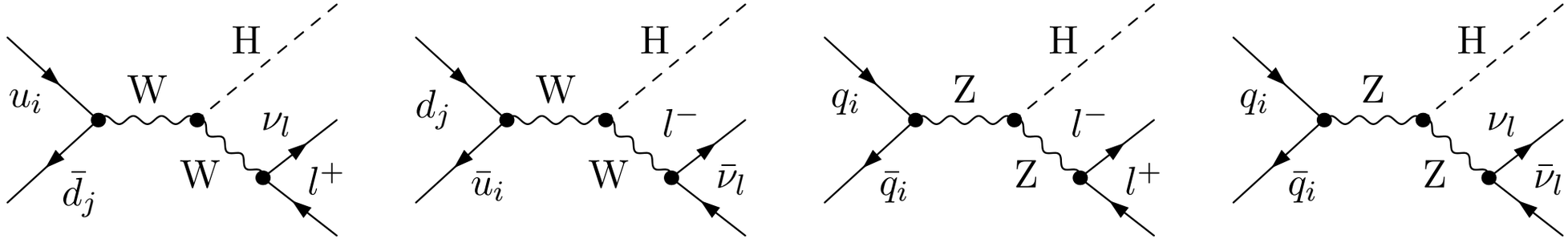
VH Higher Order Corrections (EW)

* 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 in YR2 should be ok

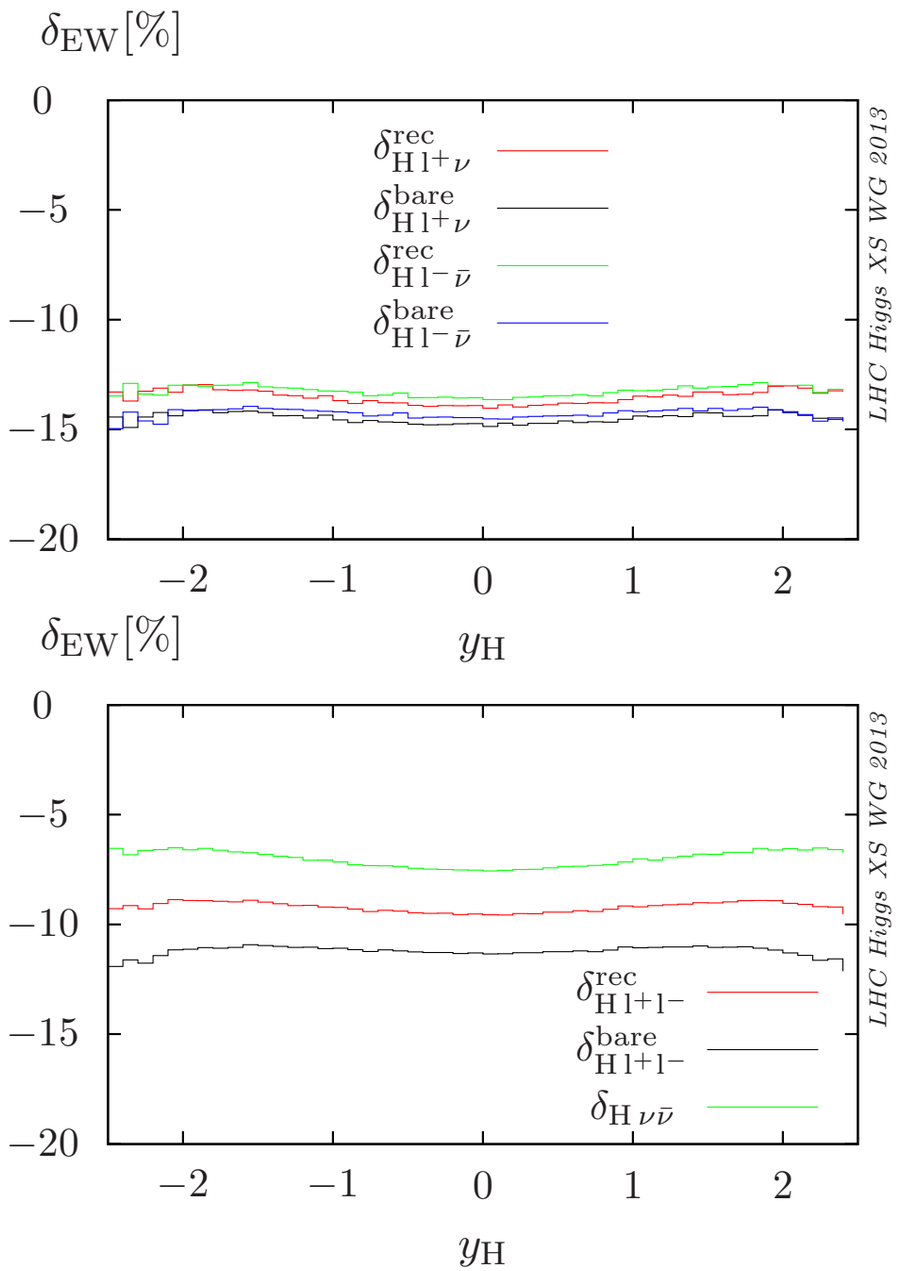
$$\sigma = \sigma^{\mathrm{QCD}} \times (1 + \delta_{\mathrm{EW}}^{\mathrm{rec}}) + \sigma_\gamma$$

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

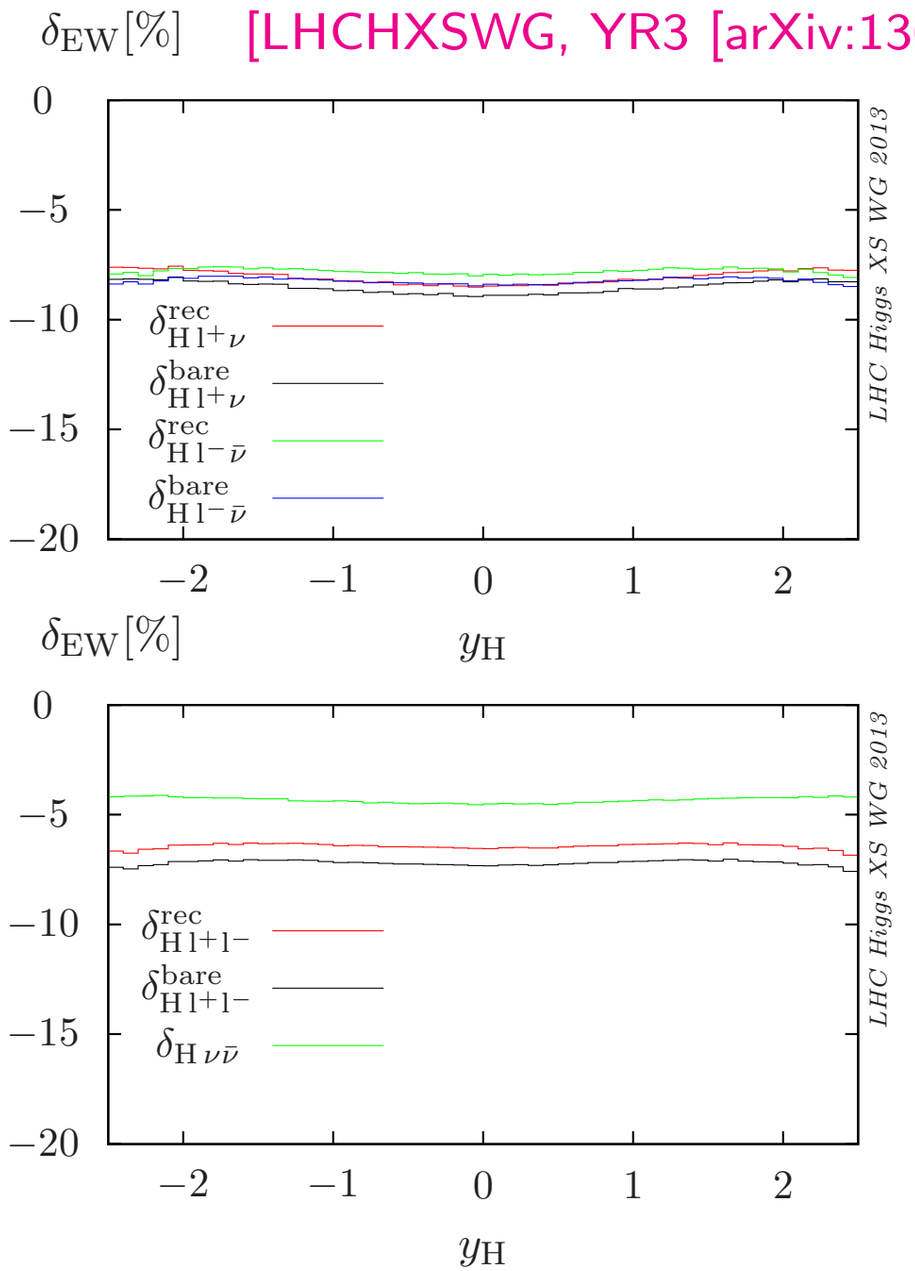
→ currently out of reach

VH Higher Order Corrections (EW)

boosted ($p_T > 200$ GeV)



no $p_{\mathrm{T,H/V}}$ cuts



[LHCHXSWG, YR3 [arXiv:1307.1347]]

- larger EW corrections for boosted Higgs, up to −15% for WH

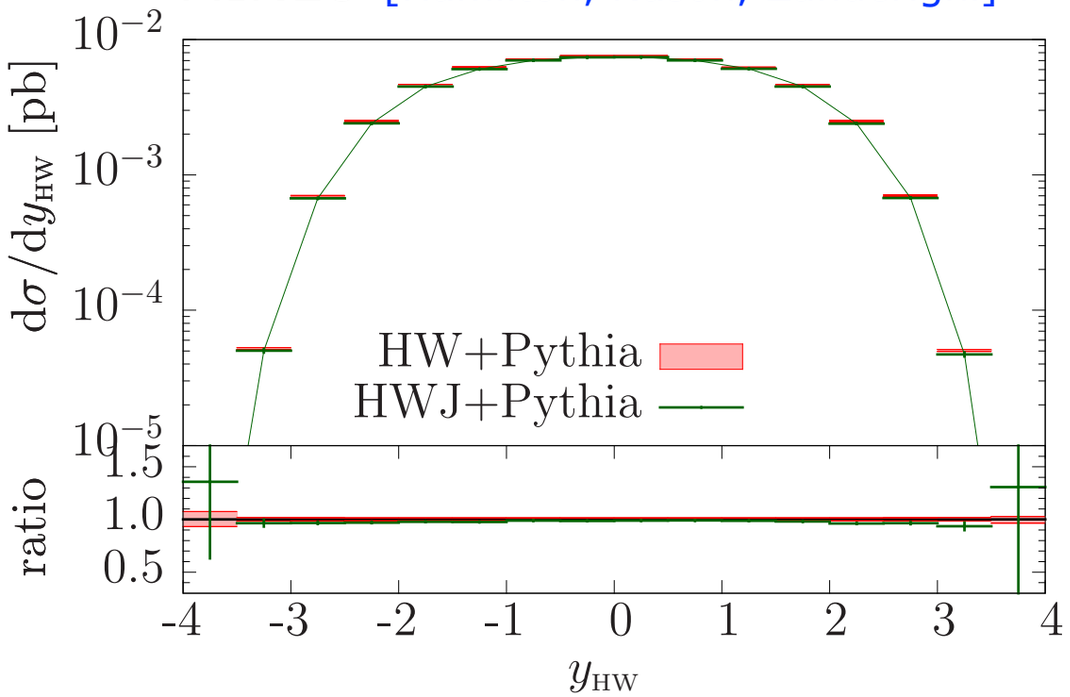
Merging and Matching

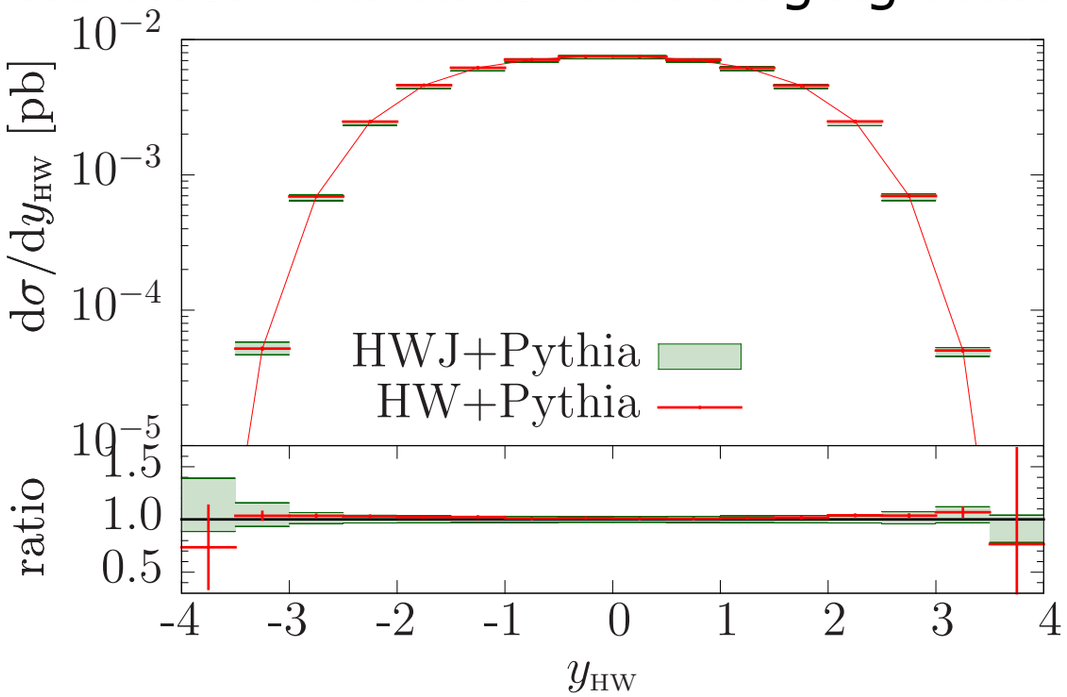
* NLO QCD & parton shower:

  merging and matching for pp→VH(j)

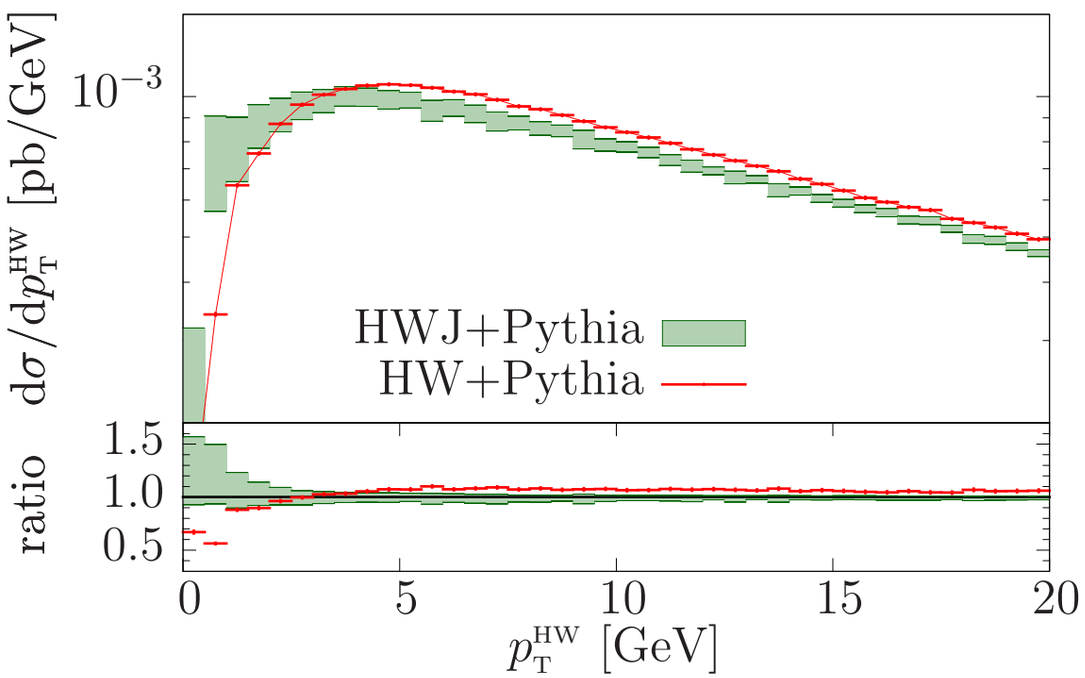
  → available in the POWHEG-BOX framework [Luisoni, Nason, Oleari, FT]
  and in MG5_aMC (FxFx) and Sherpa (MEPS@NLO)
  also with anomalous couplings

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





LHC8

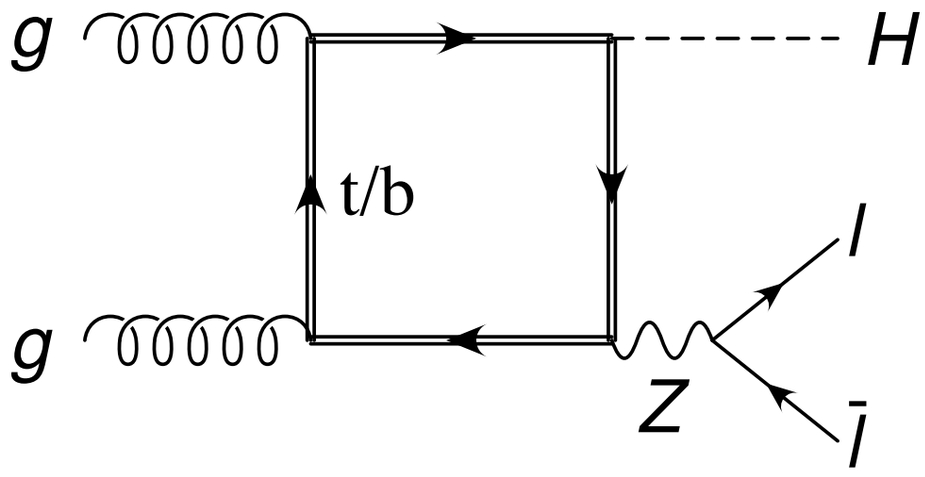


* NNLO matching with PS possible through reweighting of HVj-MINLO with HVNNLO, already worked out for:

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

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

gg to ZH



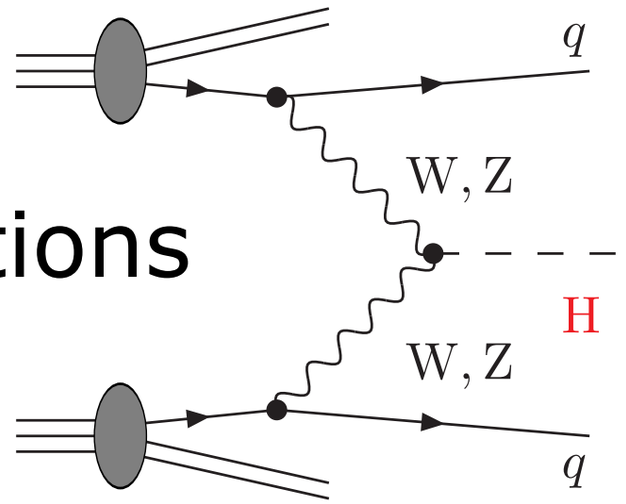
- α_S^2 contribution sensitive to gg luminosity
  - ★ Consistently included differentially in NNLO differential computation
    [Ferrera, Grazzini, FT '14]
  - ★ pt dependent k-factor
  - ★ tend to compensate DY-like corrections

- most accurate prediction known is approx. (large mt) NLO correction
  [Altenkamp, Dittmaier, Harlander, Rzehak, Zirke '12]
  - ★ large k-factor in the boosted region (~2)
  - ★ smaller scale dependence

- Matching of LO with PS included at least in POWHEG-BOX and MG5_aMC

VBF

VBF Hjj production: higher order corrections



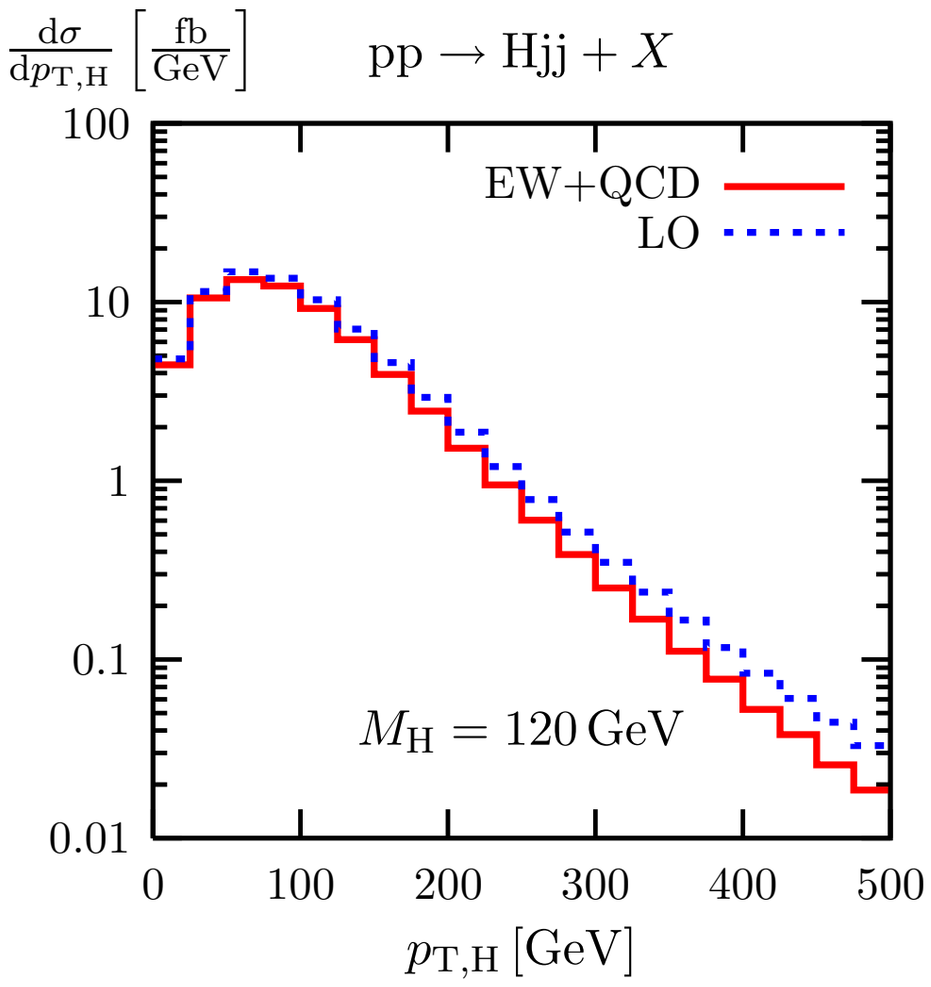
* higher order QCD corrections:
  - ✔ NLO-QCD: σ_{tot} and differential distributions
    incl. (~10% at the LHC) [Han, Valencia, Willenbrock '92]
    [Figy, Oleari, Zeppenfeld '03]
    [Berger, Campbell '04]
  - ✦ NNLO-QCD: DIS approximation for σ_{tot}, no differential distributions yet
    [Bolzoni, Maltoni, Moch, Zaro '10]
    incl. (~1% at the LHC)

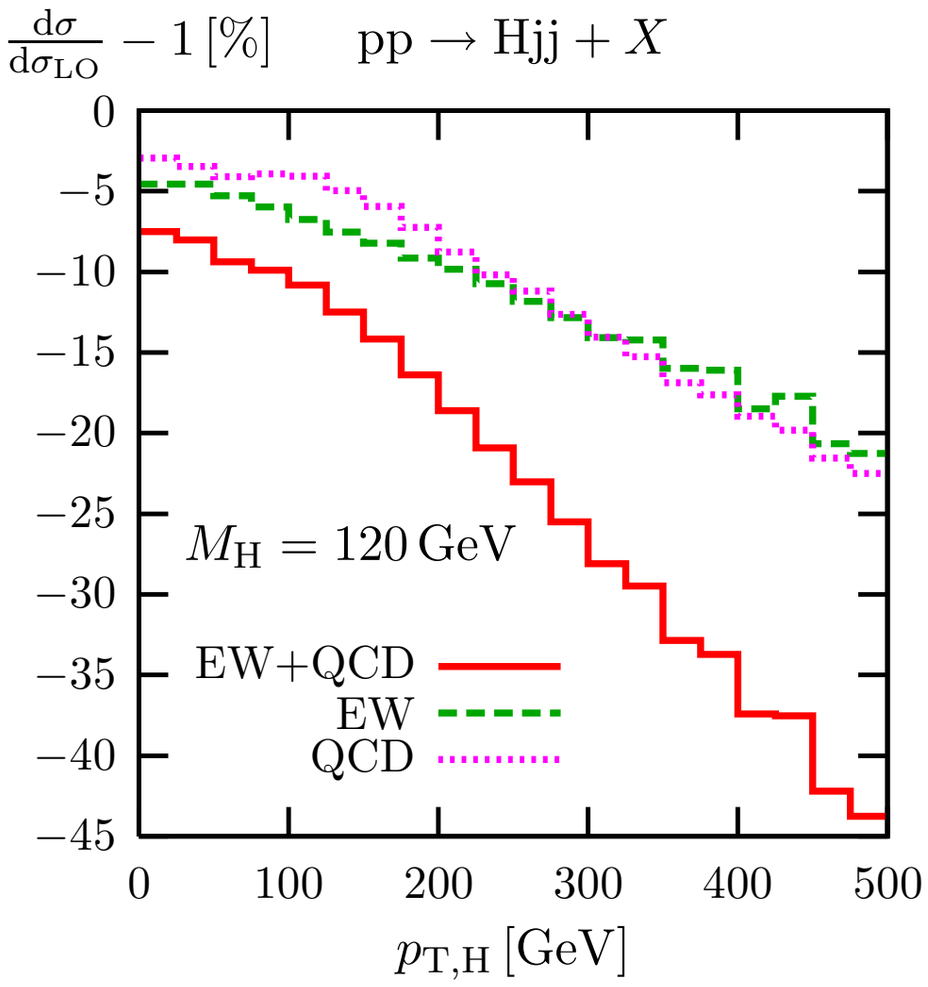
* electroweak corrections:
  - ✔ NLO-EW: σ_{tot} and differential distributions
    incl. (~10% at the LHC)
    [Ciccolini, Denner, Dittmaier '07]
    [Figy, Palmer, Weiglein '10]

* combination of NLO QCD and EW corrections:
  - ✔ available at NLO in `HAWK` and `VBFNLO` (← YR2)

VBF Higher Order Corrections (EW)

EW effects on Higgs p_{T} distribution (results for VBF cuts)





[Ciccolini, Denner, Dittmaier [arXiv:0710.4749]]

- QCD and EW corrections distort shapes of distributions
- Size of EW corrections $\sim -20\%$ at $p_{\mathrm{T,H}} = 500$ GeV
  - ↪ electroweak Sudakov logarithms

VBF Hjj production: matching with parton shower

- VBF Hjj production:

  NLO-QCD matched with parton shower default by now

  `(POWHEG-BOX, aMC@NLO, HERWIG++ ...)`

- VBF $Hjjj$ production:

  NLO-QCD matched with parton shower available

  `(POWHEG-BOX, MadGraph5_aMC@NLO)`

- ✘ merging different jet multiplicities

  has not been studied systematically

- ✘ NLO-EW matching with parton shower not available

VBF+VH precision and uncertainty estimation

* use NLO-QCD matched with parton shower

  reweighted with NNLO when possible

* use NLO EW results → combine with best QCD prediction

  by reweighting procedure

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

* estimate of theoretical uncertainties:

  - missing higher order QCD corrections: scale variation
  - missing higher order EW and mixed QCD-EW corrections:

$$\boldsymbol{\Delta\sigma} \sim \mathbf{Max}\left(1\%, \boldsymbol{\delta}_{\mathbf{EW}}^{\mathbf{2}}, \boldsymbol{\delta}_{\mathbf{QCD}}\boldsymbol{\delta}_{\mathbf{EW}}\right)$$

  δ_{EW} here means non-universal EW corrections

  otherwise the estimated uncertainty is too conservative

  - matching uncertainty: compare results of different generators

backgrounds

background processes that could be addressed in the VBF/VH working group:

- Hjj production via gluon fusion

  ($\rightarrow$ overlap with ggF subgroup?)

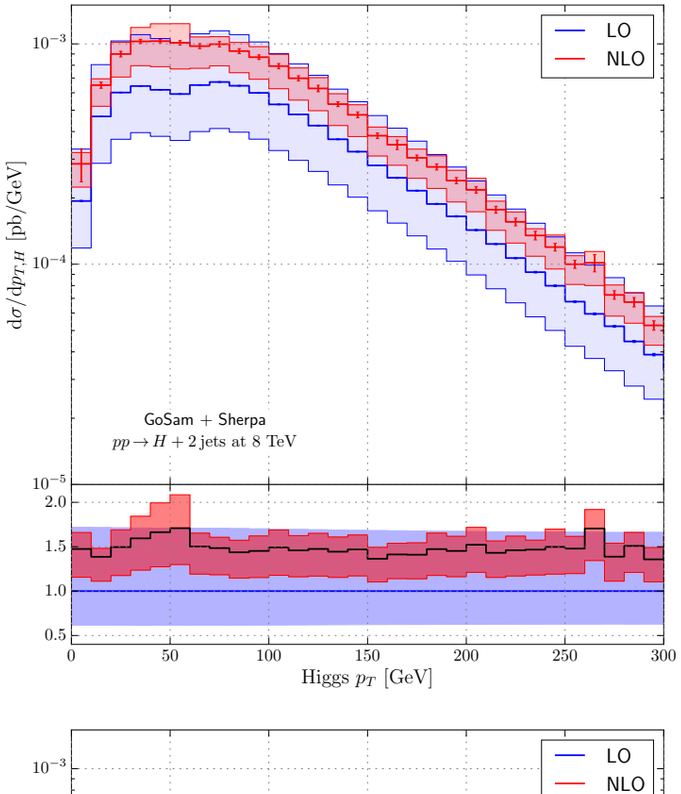
- $VVjj$ production: particularly important for off-shell coupling measurements

The number of background processes to VBF and VH is quite large and most of them are already studied by other groups.

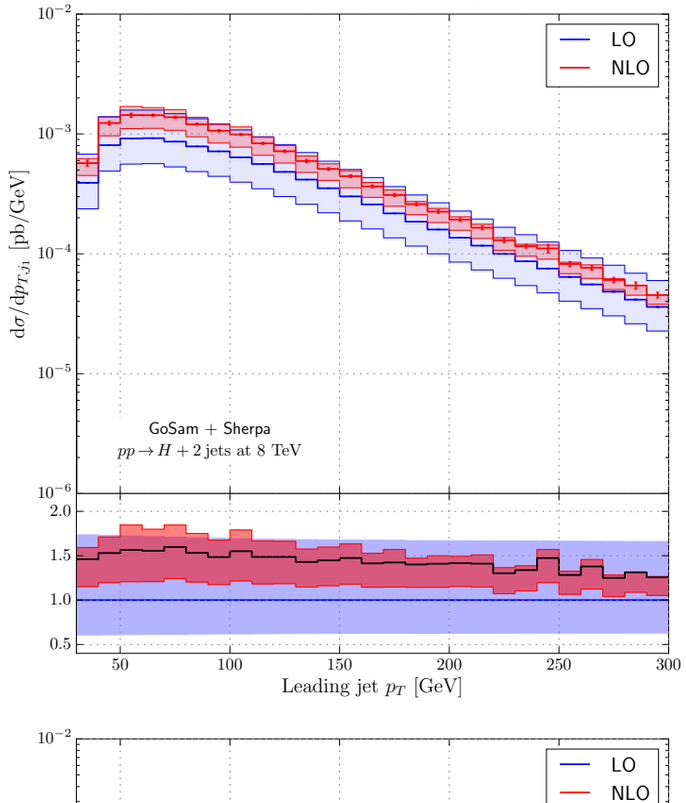
Results with VBF-like cuts (7% of events) H+3j in gluon fusion

Higgs + 2 jets (VBF-cuts)

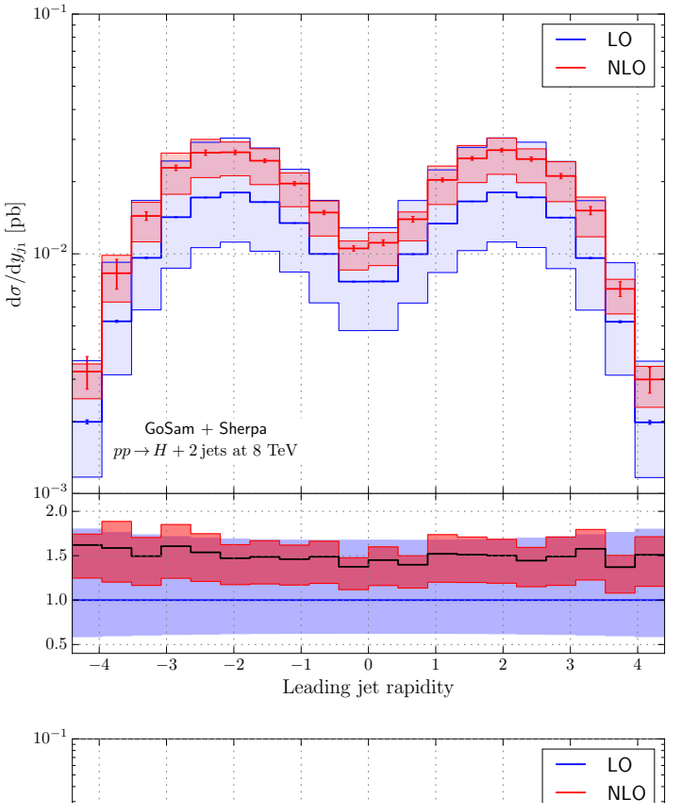
Higgs p_T



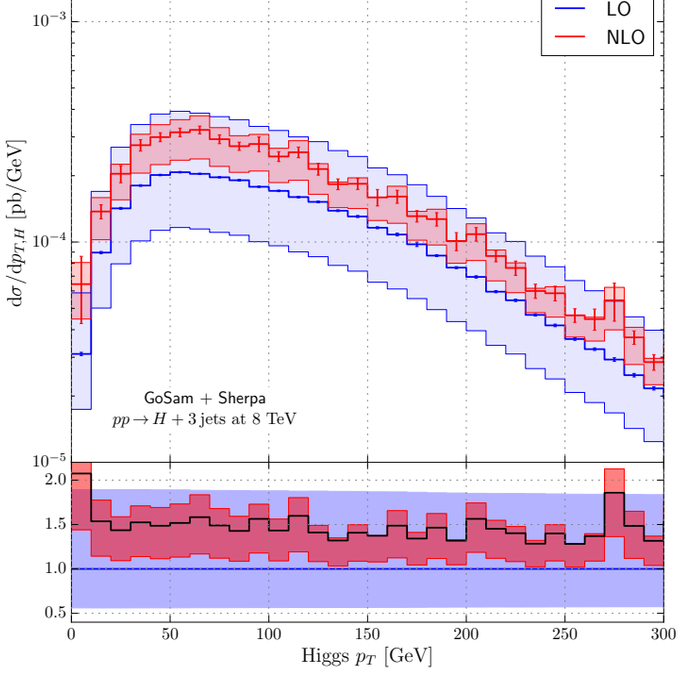
First jet p_T

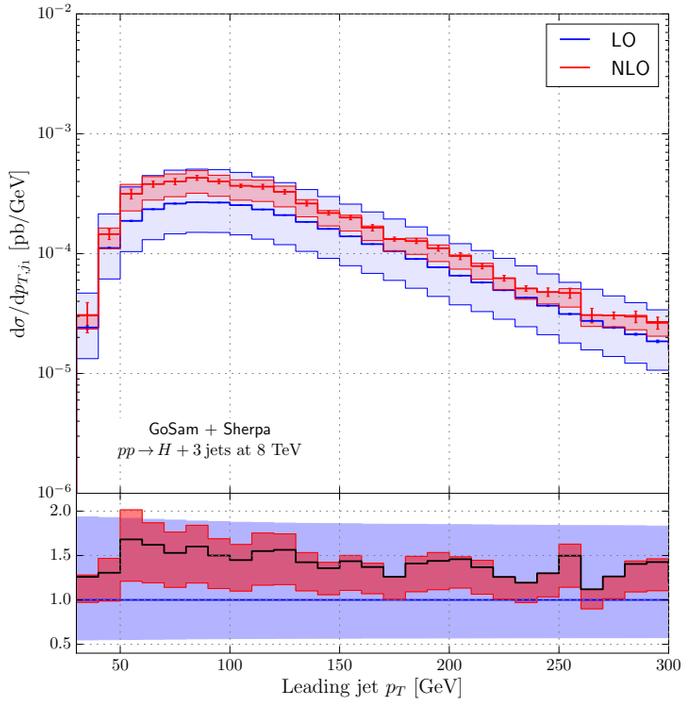


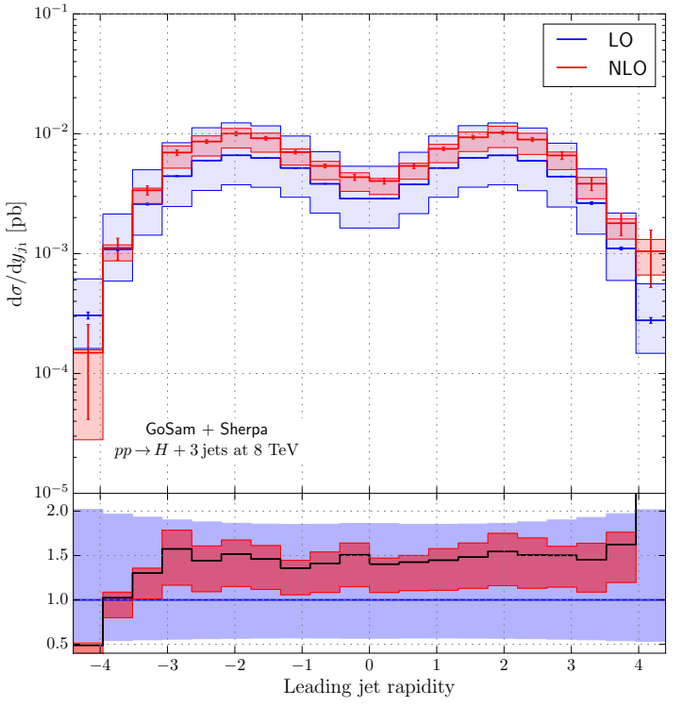
First jet y



Higgs + 3 jets (VBF-cuts)







pp → H + 2,3 jets with GoSam + Sherpa (Comix)

- Cuts: 8 TeV, anti-kt $R = 0.4$ jets with $p_T > 30$ GeV, $|\eta| < 4.4$
- PDF: CT10nlo for LO, CT10nlo for NLO

Yundin's talk at the ATLAS (N)NLO MC tools WS
[Greiner, Hoeche, Luisoni, Schoenherr, Yundin, Winter]

Conclusion

* NLO EW available for both VH and VBF

* Fully differential NNLO QCD available for VH production

* Inclusive NNLO QCD corrections available for VBF

* Matched NLO QCD computations available since long with both MC@NLO and POWHEG

* For VH, merging done for the lowest multiplicity with POWHEG-MINLO and also available within MG5_aMC and Sherpa

* Anomalous couplings implemented at the parton level in both HAWK and VBFNLO, and for NLO QCD matched at least in VH(j) MINLO and VH+VBF in MG5_MC

Outlook

* Improvements on VH & VBF prediction are doable:
  VH: NNLOPS
  NWA @ NNLO

  VBF: H+jj/jjj merging could be studied systematically

* Backgrounds:

  - Hjjj in gluon fusion is being studied
  - VVjj important for off-shell coupling measurements and certainly doable with several of the tools available

* Future plans: agreement on a “general strategy” for uncertainty estimation