VH production at the LHC: recent theory progress

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LHC Higgs Cross Section Working Group
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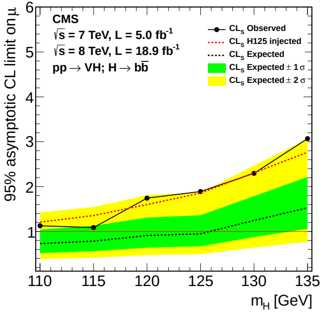
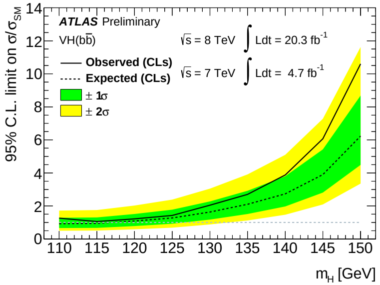
Motivations

Associated vector boson Higgs (VH) production (with $H \to b\bar{b}$ and $V \to l_1 l_2$ decay)

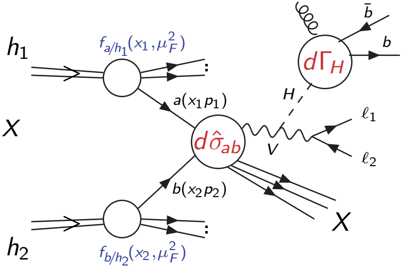
- Important channel at the LHC (access to $Hb\bar{b}$ coupling) but challenging.

LHC experiments are close to the SM $H \to b\bar{b}$ sensitivity.
To improve these results, precise theoretical predictions are needed
$\Longrightarrow$ computation of higher-order QCD corrections.





Associated VH production and $H \to b\bar{b}$ decay



$$h_1(p_1) + h_2(p_2) \;\to\; V + H + X \;\to\; \ell_1\ell_2 + b\bar{b} + X$$

where $\quad V = Z^0, W^\pm \quad$ and $\quad \ell_1\ell_2 = \ell^+\ell^-, \ell\nu_\ell$

The framework: QCD factorization formula

$$d\sigma_{VH} = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 \; f_{a/h_1}(x_1, \mu_F^2)\; f_{b/h_2}(x_2, \mu_F^2)\; d\hat{\sigma}_{ab}(x_1 p_1, x_2 p_2; \mu_F^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^p$$

- $\left(\frac{\Lambda_{QCD}}{Q}\right)^p$ (with $p \geq 1$): Non perturbative power-corrections (higher-twist).
- $f_{a/h}(x, \mu_F^2)$: Non perturbative universal parton densities (PDFs), $\mu_F \sim Q$.
- $d\hat{\sigma}_{ab}$: Hard scattering cross section. calculable with a perturbative expansion in $\alpha_S(Q)$

$$d\hat{\sigma}_{ab} = d\hat{\sigma}_{ab}^{(0)} + d\hat{\sigma}_{ab}^{(1)}(\mu_R^2) + d\hat{\sigma}_{ab}^{(2)}(\mu_R^2) + \mathcal{O}(\alpha_S^3)\,.$$

Precise predictions for σ depend on good knowledge of both $\hat{\sigma}_{ab}$ and $f_{a/h}(x, \mu_F^2)$

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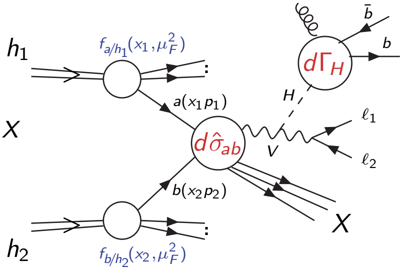

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- By using the zero width approximation ($\Gamma_H \ll m_H$)

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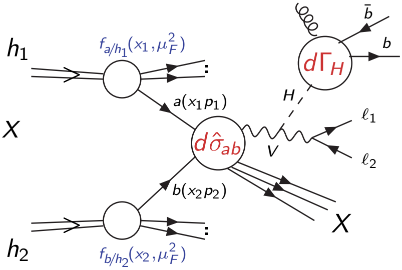

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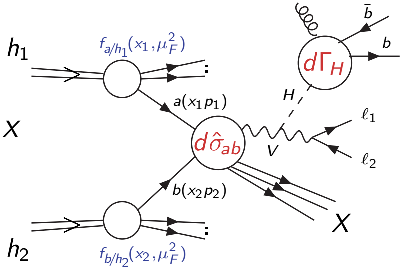

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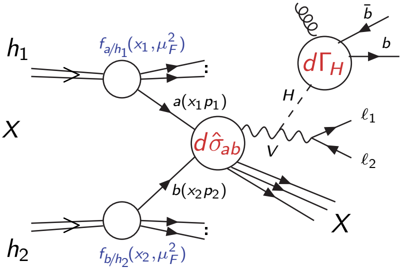

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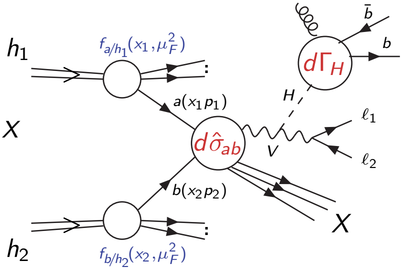

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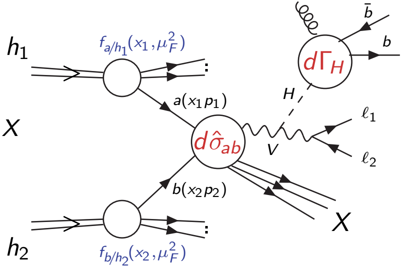

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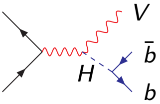
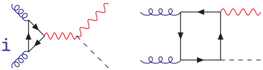
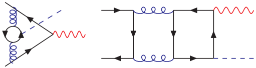
$pp \to VH \to l\nu b\bar{b}$: total cross section



- NNLO QCD corrections for WH are basically the same of DY ($\sim$ 1-3% at the LHC) [Van Neerven et al.('91)],[Brein,Harlander,Djouadi('00)]→vh@nnlo
- For ZH, $gg \to HZ$ top-loop $\sim g^2\lambda_t^2\alpha_S^2$ (non DY-like) corr. (+5% at the LHC) [Kniehl('90)],[Brein,Harlander,Djouadi('00)]→vh@nnlo, [Englert,McCullough,Spannowsky('14)].

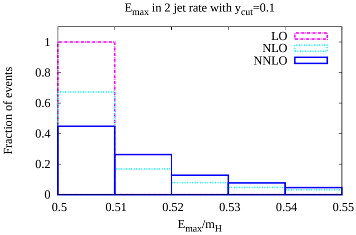


- N^{3}LO, $gg \to HZ$ top-loop corrections (in the large-m_{top} limit) also large: correction factor $K \simeq 2$ [Altenkamp,Dittmaier,Harlander,Rzehak,Zirke('13)].
- NNLO top-mediated contributions $\sim g^3\lambda_t\alpha_S^2$ to VH ($\sim$ 1-2% at the LHC) recently computed: [Brein,Harlander,Wiesemann,Zirke('11)].



- NLO EW corrections ($\sim$ 5-10%) [Ciccolini,Dittmaier,Krämer('03)] [Denner,Dittmaier,Kallweit,Mück('11)]
- The inclusive $H \to b\bar{b}$ decay rate is known up to α_S^4 in QCD ($\sim$ 0.1%) [Baikov,Chetyrkin,Kuhn('05)], and up to NLO in the EW theory ($\sim$ 1-2%) [Dabelstein, Hollik; Kniehl ('92)].

$pp \to VH \to l\nu b\bar{b}$: differential distributions



Energy spectrum of the leading jet in the $H \to b\bar{b}$ decay. Jet clustering: JADE alg. $y_{cut} = 0.1$.

- NNLO fully-differential decay rate $H \to b\bar{b}$ through non-linear mapping method: [Anastasiou,Herzog,Lazopoulos('12)].
- HV + 0/1 jet at NLO with the POWHEG BOX interfaced to GoSam and merged within Multiscale Improved NLO (MiNLO) method [Luisoni,Oleari,Nason,Tramontano('13)].
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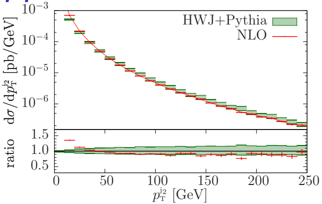

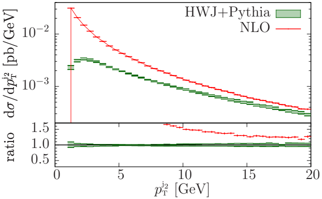

HWJ-MiNLO+PYTHIA and the NLO HWJ result for the p_T of the 2nd hardest jet, at the LHC at 8 TeV.

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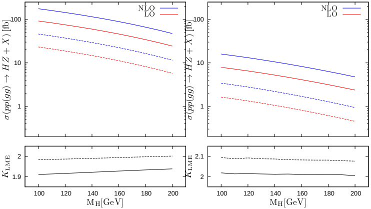
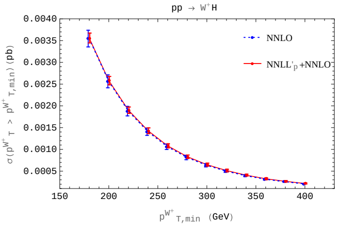


NLO hadronic cross section (upper), and NLO K-factor (lower) for $\sqrt{s} = 8\,TeV$ (dashed) and $\sqrt{s} = 14\,TeV$ (solid) in the inclusive (left) and *boosted* (right) case.

$pp \to VH \to l\nu b\bar{b}$: differential distributions



NNLO cross sections with (red solid) and without (blue dotted) the NNLL jet-veto resummation for W^+H production at LHC14. The error bars reflect the scale uncertainties (anti-k_T, $R = 1.2$, $p_{T,veto} = 25 GeV$). [Y.Li,Liu('14)].

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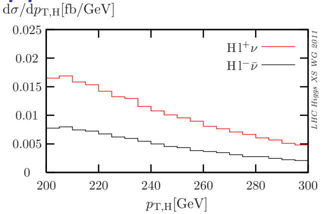

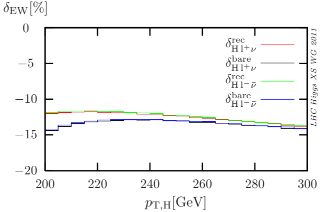

$p_{T,H}$ spectra for WH (NNLO QCD + NLO EW) at $\sqrt{s} = 7$ TeV in the boosted region (from Yellow Rep. II).

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VH production and decay in higher-order QCD

G.F.,Grazzini,Tramontano arXiv:1107.1164, arXiv:1312.1669

Fully differential NNLO QCD calculation for VH (both DY like and $gg \to HZ$ top-loop corrections), including NLO $H \to b\bar{b}$ and $V \to l_1 l_2$ decays with spin correlations.

- NNLO calculation for $h_1 h_2 \to VH + X$ production within q_T-subtraction formalism [Catani, Grazzini('07)] requires:
  - Up to $d\sigma_{NLO}^{VH+\text{jets}}$.
  - $\mathcal{H}^{VH(1)}$ and $\mathcal{H}^{VH(2)}$ [Catani,Cieri,de Florian,G.F.,Grazzini('09,'12)]: contains the finite-part of the one- and two-loops amplitude $c\bar{c} \to VH$.
  - Up to $d\sigma_{NLO}^{CT}$: depends by the (universal) q_T-resummation coeff. A_1, B_1, A_2 and B_2.
- $H \to b\bar{b}$ decay at NLO calculated with dipole subtraction. Fully inclusive QCD effects in the H decay taken into account by normalizing the $Hb\bar{b}$ branching fraction to the precise result from the LHCHXSWG-YR.
  Fully exclusive calculation at NNLO for production and NLO for $H \to b\bar{b}$ decay, implemented in a parton-level Monte Carlo code.

VH production and decay in higher-order QCD

G.F.,Grazzini,Tramontano arXiv:1107.1164, arXiv:1312.1669

Fully differential NNLO QCD calculation for VH (both DY like and $gg \to HZ$ top-loop corrections), including NLO $H \to b\bar{b}$ and $V \to l_1 l_2$ decays with spin correlations.

- NNLO calculation for $h_1 h_2 \to VH + X$ production within q_T-subtraction formalism [Catani, Grazzini('07)] requires:
    - Up to $d\sigma^{VH+\mathrm{jets}}_{NLO}$.
    - $\mathcal{H}^{VH(1)}$ and $\mathcal{H}^{VH(2)}$ [Catani,Cieri,de Florian,G.F.,Grazzini('09,'12)]: contains the finite-part of the one- and two-loops amplitude $c\bar{c} \to VH$.
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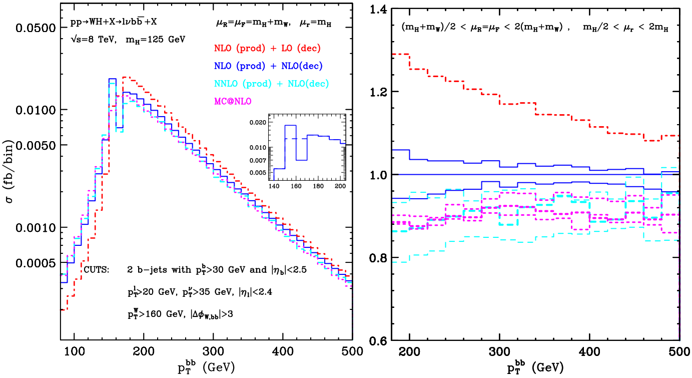
Associated *WH* production

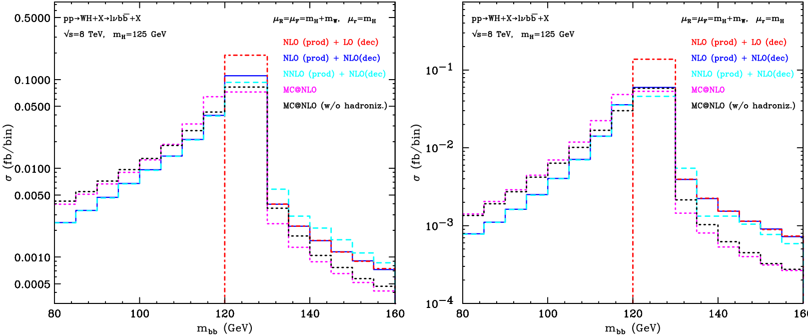


LHC8 with CUTS

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

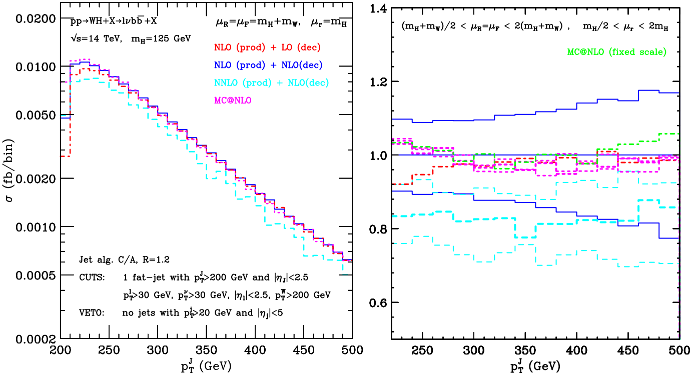
Right panel: Spectra normalized to the full NLO results (perturbative scale - μ_R, μ_F, μ_{Rdec} uncertainty bands are shown).

Associated *WH* production



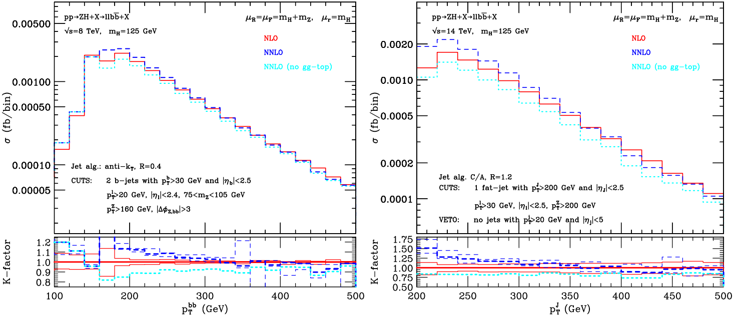
LHC8: Invariant mass distribution of the *b*-jets pair. Left panel: without jet veto. Right panel: with jet veto.

Associated *WH* production



LHC14 fat-jet analysis. Left panel: p_T spectrum of the fat jet. Right panel: Spectra normalized to the full NLO results (Perturbative scale - μ_R, μ_F, μ_{Rdec} uncertainty bands are shown). MC@NLO result (green dots) with fixed scale is also shown.

Associated *ZH* production



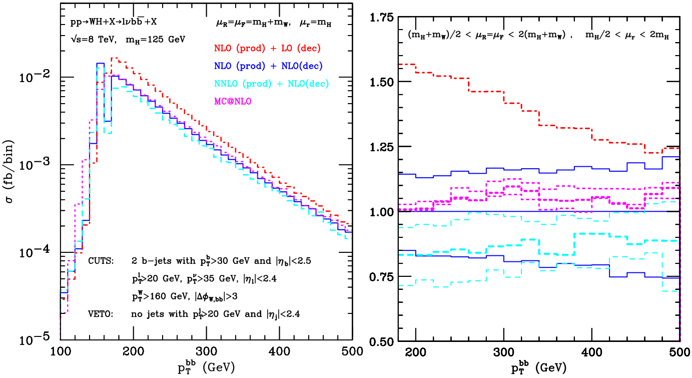
Left panel: LHC8 analysis p_T spectrum of the b-jets pair. Right panel: LHC14 fat-jet analysis p_T spectrum of the fat jet. Lower panels: spectra normalized to the full NLO results (perturbative scale - μ_R, μ_F uncertainty bands are shown).

Conclusions

- Associated vector boson Higgs (VH) production important channel at the LHC (access to $Hb\bar{b}$ coupling) but challenging. LHC experiments are close to the SM sensitivity.
- To improve these results, precise theoretical predictions are already available (and more are needed).
- Calculation of NNLO QCD corrections to VH production with NLO QCD $H \to \bar{b}b$ decay in hadron collision using the q_T-subtraction formalism, included in a fully-exclusive parton-level Monte Carlo code.
- 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 and strongly depend on the experimental selection cuts.

Back up slides

Associated *WH* production

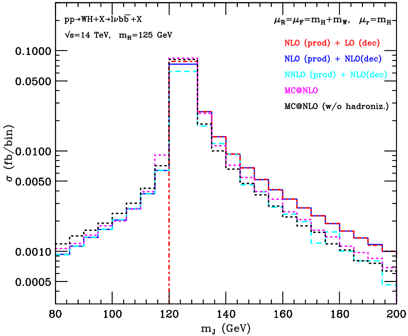


LHC8 with CUTS + VETO (on light jets)

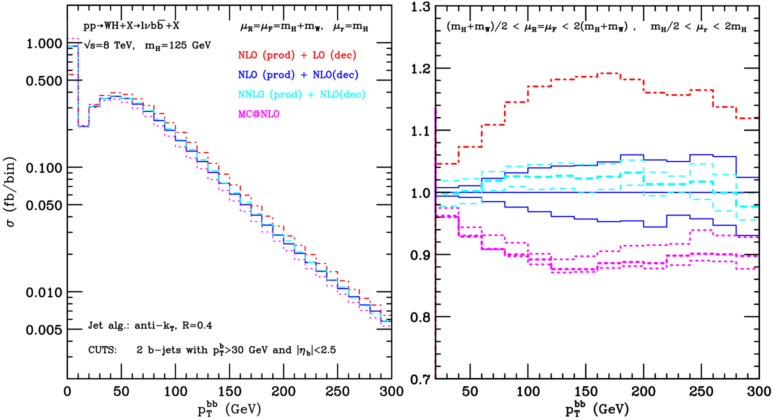
Left panel: p_T spectrum of the b-jets pair.

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

Associated *WH* production



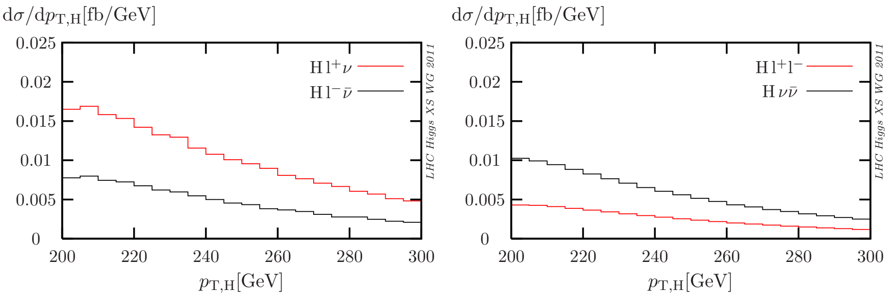
LHC14 fat-jet analysis. Invariant mass distribution of the fat jet computed at fixed-order QCD and at MC@NLO without hadronization (black dots) and with default MC@NLO (magenta dots).



LHC8 with NO CUTS (except the *b*-jet selection).

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

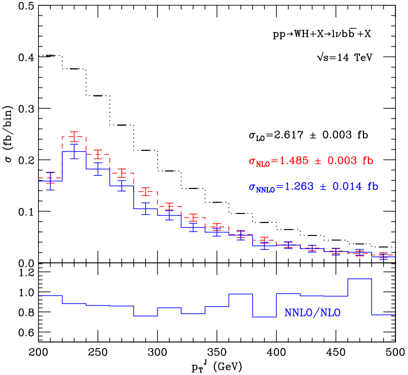
Right panel: Spectra normalized to the full NLO results (Perturbative scale - μ_R, μ_F, μ_{Rdec} uncertainty bands are shown).



Yellow Report II:arXiv:1201.3084

Distributions in $p_{T,H}$ for $pp \to WH \to l\nu H$ (NNLO QCD + NLO EW) and for $pp \to ZH \to ll/\nu\nu H$ (NLO QCD + NLO EW) at $\sqrt{s} = 7$ TeV.
Boosted setup: $|\eta_l| < 2.5$, $p_{T,l} > 20$ GeV, $p_{T,\nu} > 25$ GeV, $p_{T,H} > 200$ GeV, $p_{T,W/Z} > 190$ GeV.

We produced similar results at $\sqrt{s} = 8$ TeV.



$pp \to WH(\to l\nu\, b\bar{b})$
p_T spectra of the fat jet at the LHC@14TeV for $m_H = 120 GeV$ at LO (dots), NLO (dashes) and NNLO (solid).

- Selection strategy of [Butterworth et al.('08)]: search a large-p_T Higgs boson thorough a collimated $b\bar{b}$ pair decay.
  Cuts:
  Leptons: $p_T^l > 30 GeV$, $|\eta^l| < 2.5$, $p_T^{miss} > 30 GeV$, $p_T^W > 200 GeV$.
  Jets: Cambridge/Aachen algorithm with R=1.2.
  Fat jet (contain the $b\bar{b}$) $p_T^J > 200 GeV$, $|\eta^J| < 2.5$
  Jet veto: No other jets with $p_T > 20 GeV$ and $|\eta| < 5$.
- Large negative higher-order corrections: NLO (NNLO) effects -52%/-36% (-6%/-19%), depending on the scale choice (factor two around $\mu_F = \mu_R = m_W + m_H$).
- Jet veto strongly affect the higher order corrections $\Rightarrow$ stability of fixed order calculation challenged.