VH production with $H \to b\bar{b}$ decay in full NNLO QCD

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LHC Higgs Cross Section Working Group
VH subgroup – June 29th 2017

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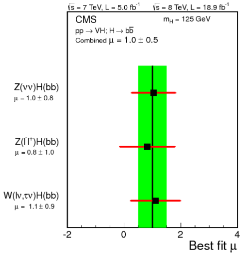
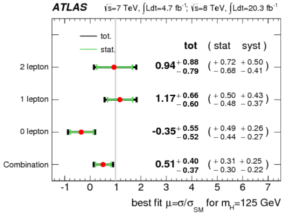
Motivations

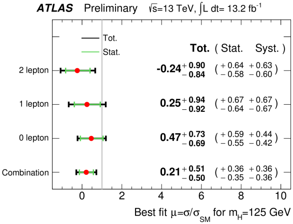
Associated vector boson Higgs (VH) production (with $H \to b\bar{b}$ and $V \to l_1 l_2$ decay)

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

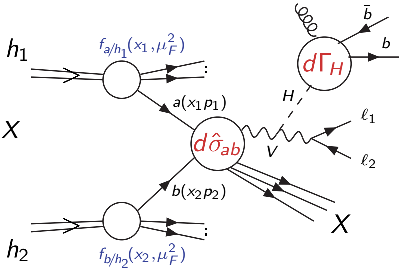
LHC experiments are close to the SM $H \to b\bar{b}$ sensitivity.
To improve these results, precise theoretical predictions are needed
$\Longrightarrow$ computation of higher-order QCD corrections.







Associated VH production with H $\rightarrow$ b$\bar{\text{b}}$ decay



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

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

QCD factorization formula

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

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

$$d\sigma_{VH\rightarrow Vb\bar{b}} = d\sigma_{VH} \times \frac{d\Gamma_{H\rightarrow b\bar{b}}}{\Gamma_H} = d\sigma_{VH} \times \frac{d\Gamma_{H\rightarrow b\bar{b}}}{\Gamma_{H\rightarrow b\bar{b}}} \times \text{Br}(H \rightarrow b\bar{b}),$$

- Perturbative expansion gives

$$d\sigma^{LO+lo}_{VH\rightarrow Vb\bar{b}} = d\sigma^{(0)}_{VH} \times \frac{d\Gamma^{(0)}_{H\rightarrow b\bar{b}}}{\Gamma^{(0)}_{H\rightarrow b\bar{b}}} \times \text{Br}(H \rightarrow b\bar{b}),$$

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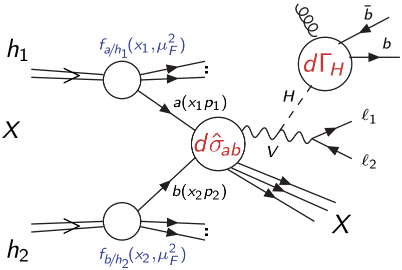

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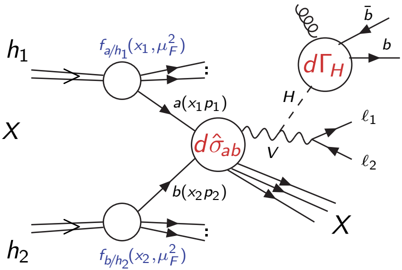

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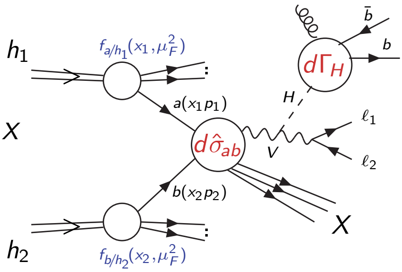
Associated VH production with H $\rightarrow$ b$\bar{\text{b}}$ decay



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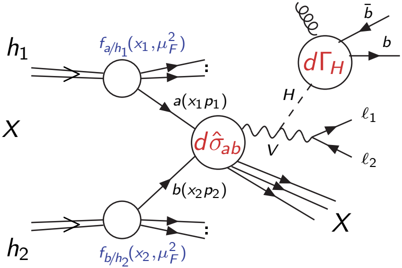
Associated VH production with $H \to b\bar{b}$ decay



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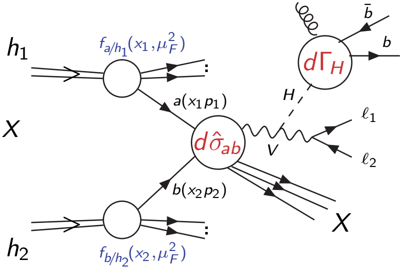

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VH production and decay in full NNLO QCD

G.F.,Somogyi,Tramontano arXiv:1705.0304

Fully differential NNLO calculation for VH production including $H \to b\bar{b}$ at NNLO and $V \to l_1 l_2$ decays with spin correlations.

- NNLO calculation for $h_1 h_2 \to VH + X$ production calculated in [G.F.,Grazzini,Tramontano('11,'15)] within the q_T-subtraction formalism [Catani, Grazzini('07)] requires:
  - Up to $d\sigma_{NLO}^{VH+\mathrm{jets}}$.
  - $\mathcal{H}^{VH(1)}$ 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 coefficients [Bozzi,Catani,de Florian,Grazzini('09,'12)].
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- Fully inclusive QCD effects in the H decay taken into account by normalizing the $Hb\bar{b}$ branching fraction to the LHCHXSWG-YR result.

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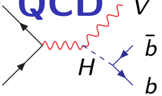
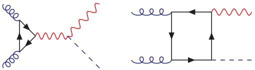
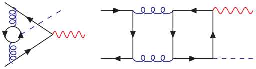


Our fully differential calculation implemented in the parton level code HVNNLO.
For *VH* prod. we have consistently included:

- NNLO DY-like QCD corrections
  (bulk of NNLO correction for *WH*)
  [Van Neerven et al.('91)]
- $gg \to HZ$ top-loop $\sim g^2\lambda_t^2\alpha_S^2$
  (non DY-like) corrections [Kniehl('90)]
  (important at the LHC due to large
  gg luminosity).



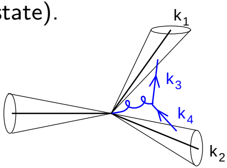
- NNLO top-mediated contributions
  $\sim g^3\lambda_t\alpha_S^2$ to *VH*
  [Brein,Harlander,Wiesemann,Zirke('11)]
  (we included only the terms calculated
  with the full m_t dependence)



b-quark jets identification

We are interested in the identification of the b-quark jet which originate from the Higgs boson (b-quark treated in massless approximation).

- We consistently include b-quark emissions from initial and final state partons (at NNLO up to four b-quarks in the final state).
- Standard jet alg. not infrared and collinear safe definition of flavoured jets: splitting of a gluon in a soft or collinear (massless) $b\bar{b}$ pair affect the flavour of a jet.



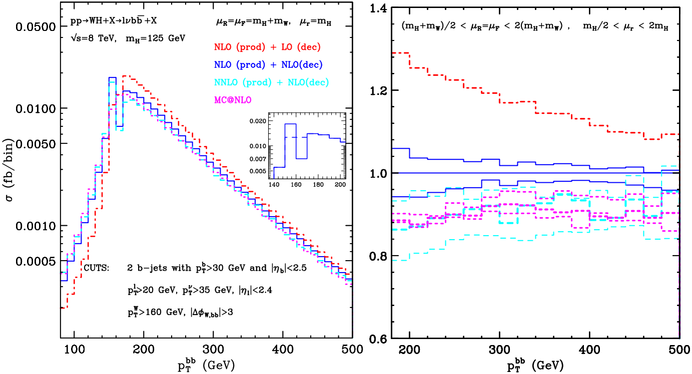
- Collinear unsafety removed by defining "b-jet" if contains $N(b) - N(\bar{b}) \neq 0$.
- Infrared unsafety removed by using the "flavour-k_T" algorithm [Banfi,Salam,Zanderighi('06)]

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

(numerical difference with respect to standard alg. small in our case).

Numerical results at the LHC

WH production

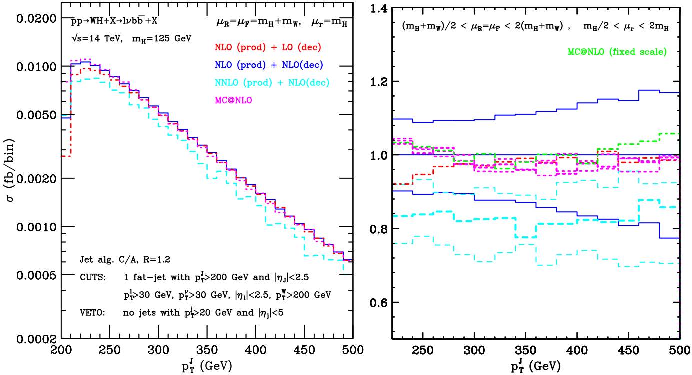


LHC at 8 TeV analysis

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).

WH production

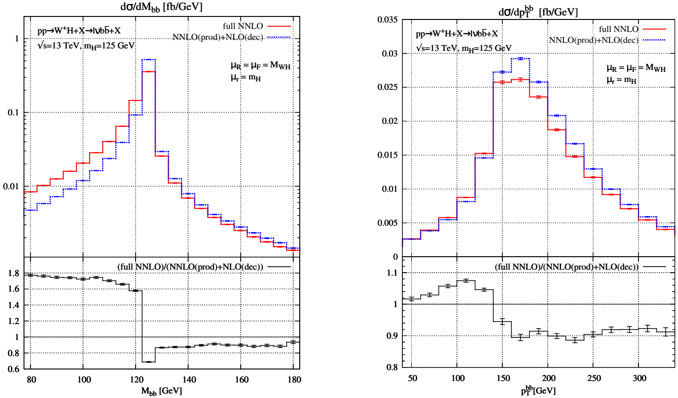


LHC at 14 TeV "fat-jet" analysis. Left panel: p_T spectrum of the fat jet. Right panel: Spectra normalized to the full NLO results (Perturbative scale - μ_R, μ_F, μ_{Rdec} uncertainty bands are shown).

NEW: WH production at full NNLO

σ (fb)	NNLO(prod)+NLO(dec)	full NNLO
W^+H	4.23 ± 0.02	3.96 ± 0.02

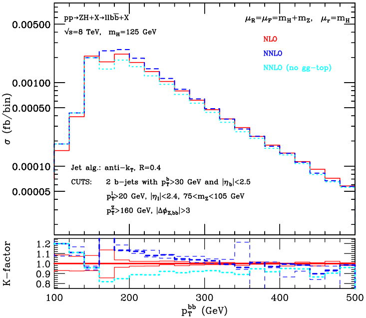
$K_{fact} \sim -6.5\%$



LHC13 analysis: $p_T^l > 15\ GeV$, $|\eta_l| < 2.5$, $p_T^W > 150\ GeV$, 2 *b-jets* $p_T^b > 25 GeV$, $|\eta_b| < 2.5$, flavour-k_T $R = 0.5$.

Left panel: M_{bb} spectrum of the b-jets pair. Right panel: p_T^{bb} spectrum of the b-jets pair. Lower panels: spectra normalized to the NNLO+nlo results.

ZH production

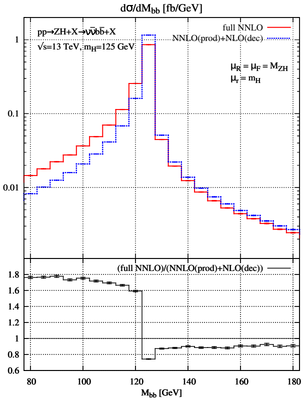


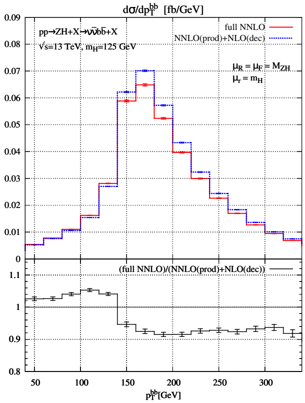
Left panel: LHC8 analysis p_T spectrum of the b-jets pair. Right panel: LHC14 fat-jet analysis p_T spectrum of the fat jet. Lower panels: spectra normalized to the full NLO results (perturbative scale - μ_R, μ_F uncertainty bands are shown).

NEW: ZH production at full NNLO

σ (fb)	NNLO(prod)+NLO(dec)	full NNLO
ZH	8.58 ± 0.02	8.10 ± 0.02

$K_{fact} \sim -5.5\%$





LHC13 analysis: $E_T^{miss} > 150\ GeV$, 2 b-jets $p_T^b > 25 GeV$, $|\eta_b| < 2.5$, flavour-k_T $R = 0.5$.

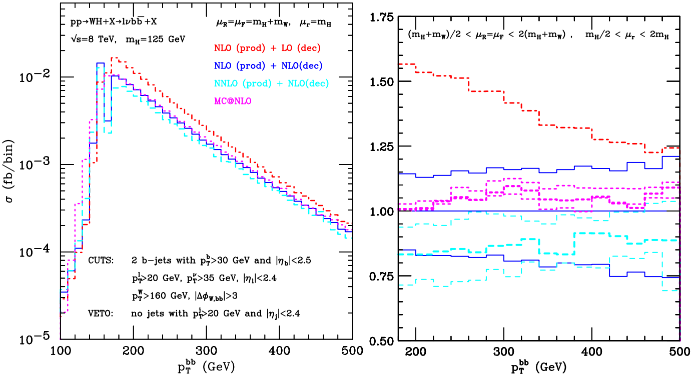
Left panel: M_{bb} spectrum of the b-jets pair. Right panel: p_T^{bb} spectrum of the b-jets pair. Lower panels: spectra normalized to the NNLO+nlo results.

Conclusions

- Associated vector boson Higgs (VH) production important (but challenging) channel at the LHC . ATLAS and CMS experiments are close to the SM sensitivity. Precise theoretical predictions are important.
- Calculation of full NNLO QCD corrections to VH production with $H \to b\bar{b}$ decay in hadron collision using the q_T-subtraction and CoLoRFulNNLO formalism, included in the fully-exclusive parton-level Monte Carlo code `HVNNLO`.
- Perturbative corrections are important and strongly depend on the experimental selection cuts. Illustrative phenomenological results with typical cuts applied in ATLAS and CMS analysis at the LHC.
- Full NNLO QCD corrections significantly reduces the accepted cross section ($\sim -6\%$) and substantially affect the distributions with respect to the partial NNLO result.

Back up slides

Associated *WH* production

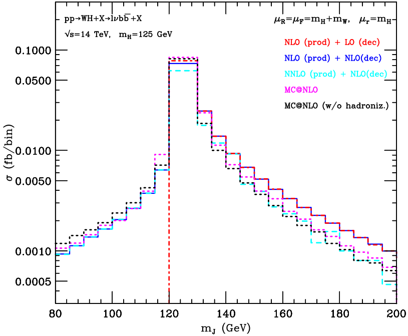


LHC8 with CUTS + VETO (on light jets)

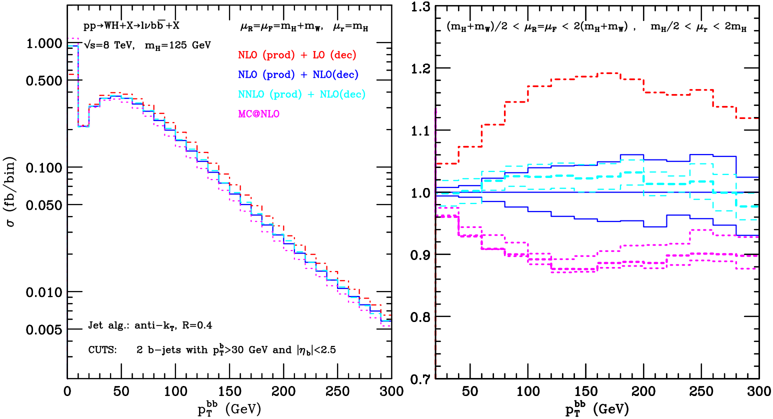
Left panel: p_T spectrum of the b-jets pair.

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

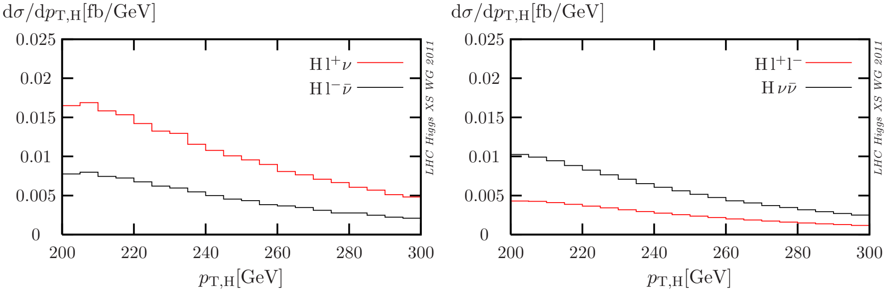
Associated *WH* production



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).



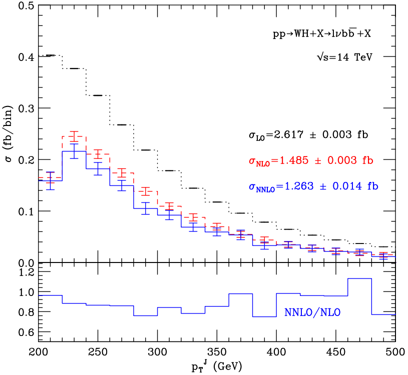
LHC8 with NO CUTS (except the *b*-jet selection).
Left panel: p_T spectrum of the *b*-jets pair.
Right panel: Spectra normalized to the full NLO results (Perturbative scale - μ_R, μ_F, μ_{Rdec} uncertainty bands are shown).



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 ⇒ stability of fixed order calculation challenged.