Karlsruhe Institute of Technology

Computational Theoretical Particle Physics
SFB TR9

VBFNLO

Michael Rauch | LHC Higgs XS&BR WG1 VBF+VH subgroup, Oct 2014

INSTITUTE FOR THEORETICAL PHYSICS

Introduction

VBFNLO

F
~~Ph~~ysics
Vector-Boson-~~Fusion~~ at Next-to-Leading Order

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons
  - accurate predictions needed for LHC
    (both signal and background)
  - MC efficient solution for high number of final-state particles
    (decays of electroweak bosons included)
- general cuts and distributions of final-state particles
- various choices for renormalization and factorization scales
- any pdf set available from LHAPDF
  (or hard-wired CTEQ6L1, CT10, MRST2004qed, MSTW2008)
- event files in Les Houches Accord (LHA) or HepMC format (LO only)

Process overview

List of implemented processes

(New in VBFNLO 2.7.0)

- vector-boson fusion production at NLO QCD of
  - Higgs (+NLO EW, NLO SUSY)
  - Higgs plus third hard jet
  - Higgs plus photon
  - Higgs pair

  } (including Higgs decays)

  - vector boson (W, Z, γ)
  - two vector bosons (W^+W^-, $W^\pm W^\pm$, WZ, ZZ; $W\gamma$)
- diboson production
  - diboson (WW, WZ, ZZ, $W\gamma$, $Z\gamma$, $\gamma\gamma$) (NLO QCD)
  - diboson via gluon fusion (WW, ZZ, $Z\gamma$, $\gamma\gamma$) (part of NNLO QCD contribution to diboson)
  - diboson (WZ, $W\gamma$) plus hard jet (NLO QCD)
  - diboson ($W^\pm W^\pm$, WZ, $W\gamma$) plus two hard jets (NLO QCD)
- triboson production (NLO QCD)
  - triboson (all combinations of W, Z, γ)
  - triboson ($W\gamma\gamma$) plus hard jet
- Higgs plus vector boson (NLO QCD) (including Higgs decays)
  - Higgs plus vector boson (WH)
  - Higgs plus vector boson plus hard jet (WH)
- Higgs plus two jets via gluon fusion (one-loop LO) (including Higgs decays)
- new physics models
  - anomalous Higgs couplings
  - anomalous triple and quartic gauge couplings
  - Higgsless and spin-2 models
  - Two-Higgs model

Intermediate state Higgs boson in all processes included where applicable

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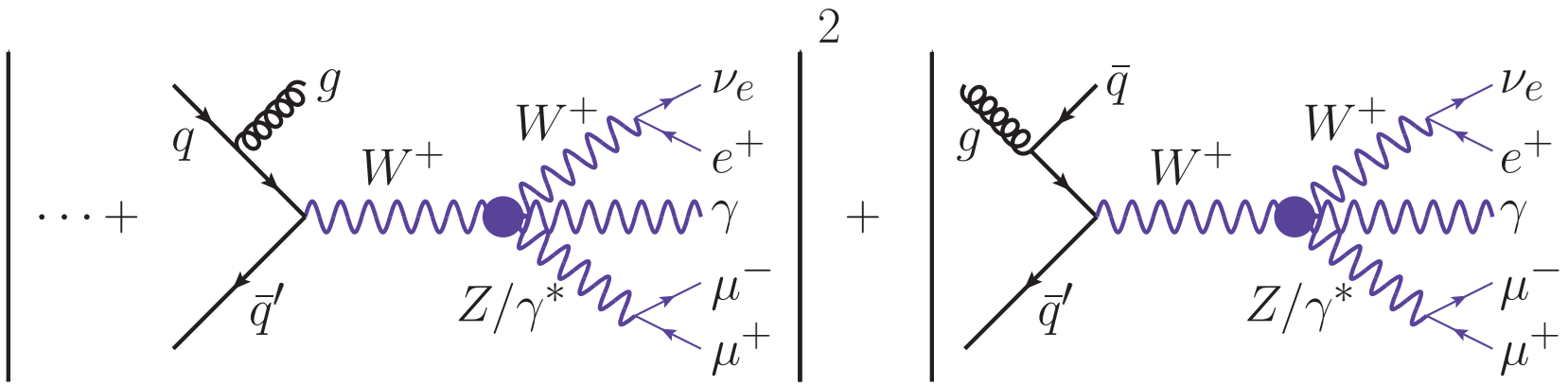
Implementation Details

- Helicity amplitude method [Hagiwara, Zeppenfeld]
- Same building blocks for different Feynman graphs
  $\Rightarrow$ Compute only once per phase-space point and reuse (”leptonic tensors”)
  $\rightarrow$ Significantly faster than generated code (up to factor 10)

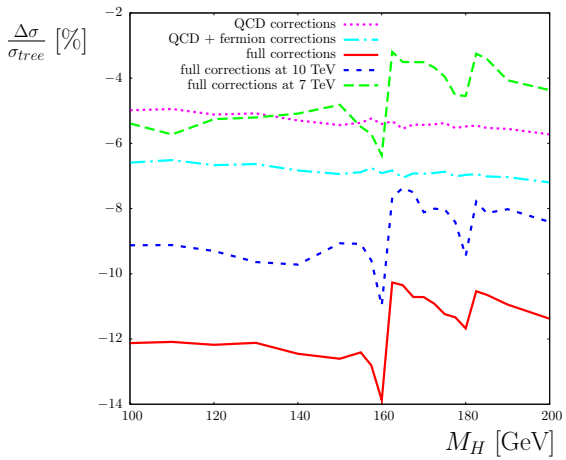


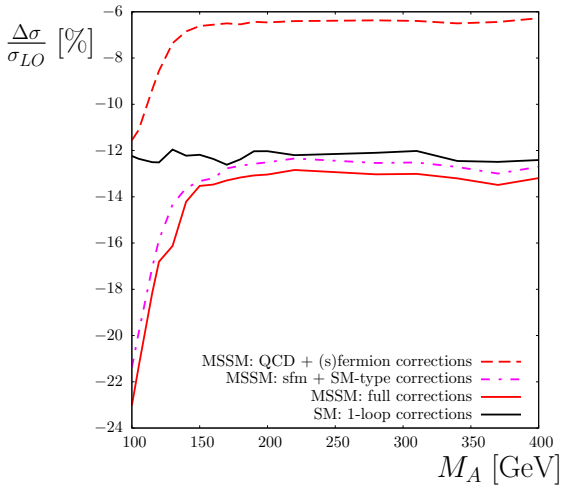
- Catani-Seymour dipole subtraction scheme

$$\sigma_{\mathrm{NLO}} = = \underbrace{\int_{m+1} [\mathrm{d}\sigma^R|_{\epsilon=0} - \mathrm{d}\sigma^A|_{\epsilon=0}]}_{\text{real emission}} + \underbrace{\int_m [\mathrm{d}\sigma^V + \int_1 \mathrm{d}\sigma^A]_{\epsilon=0}}_{\text{virtual contributions}} + \underbrace{\int_m \mathrm{d}\sigma^C}_{\text{finite collinear term}}$$

Vector-boson-fusion Higgs

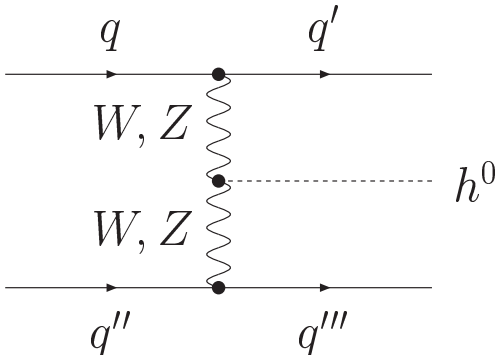
[Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; Campbell, Ellis, Berger]





- Clear signature due to two tagging jets
- QCD corrections relatively small $\sim 5\%$
- EW corrections of same size

  [Ciccolinni, Denner, Dittmaier; Figy, Palmer, Weiglein]



- SM (QCD+EW) corrections
- SUSY (QCD+EW) corrections

  [Hollik, Plehn, MR, Rzehak; Figy, Palmer, Weiglein]
- available for all Higgs bosons (h^0, H^0, A^0)
- CP-conserving and -violating scenario
- Higgs boson decays in narrow-width approximation
- For $H \to WW/ZZ \to 4\ell$ full spin information and off-shell effects included

Two-Higgs Model

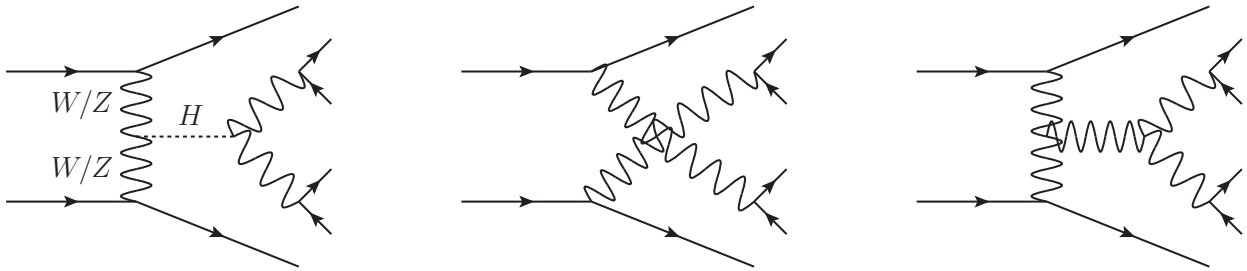
Two Higgs model for VBF processes [New in VBFNLO 2.7.0: MR]

Search for heavy Higgs bosons:

- width becomes large (Γ_H^{OS} =123 (304, 647) GeV at m_H = 600 (800, 1000) GeV)
- significant signal-background interference
- What defines “background”?

  $B = \int d\Phi |\mathcal{M}_B|^2$ or
  $S = \int d\Phi \left[|\mathcal{M}_H|^2 + 2\mathrm{Re}\mathcal{M}_H\mathcal{M}_B^*\right]$ violate unitarity at large s

  Notation: $\mathcal{M}_H \sim \frac{s}{v^2}$ Signal amplitude for s-, t- and u-channel exchange of H
  $\mathcal{M}_B \sim \frac{-s}{v^2}$ continuum electroweak background amplitude

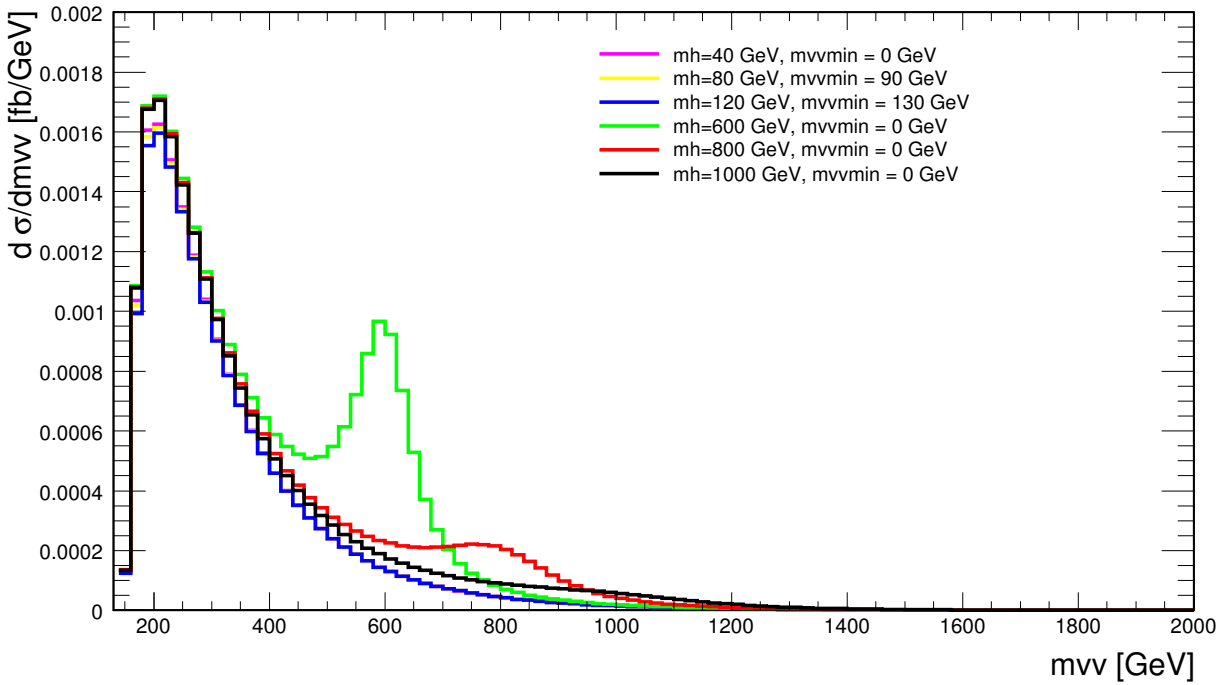


- $\leftrightarrow$ 125 GeV Higgs well established

Continuum-Higgs interference

$\Rightarrow$ Compare to SM light Higgs scenario

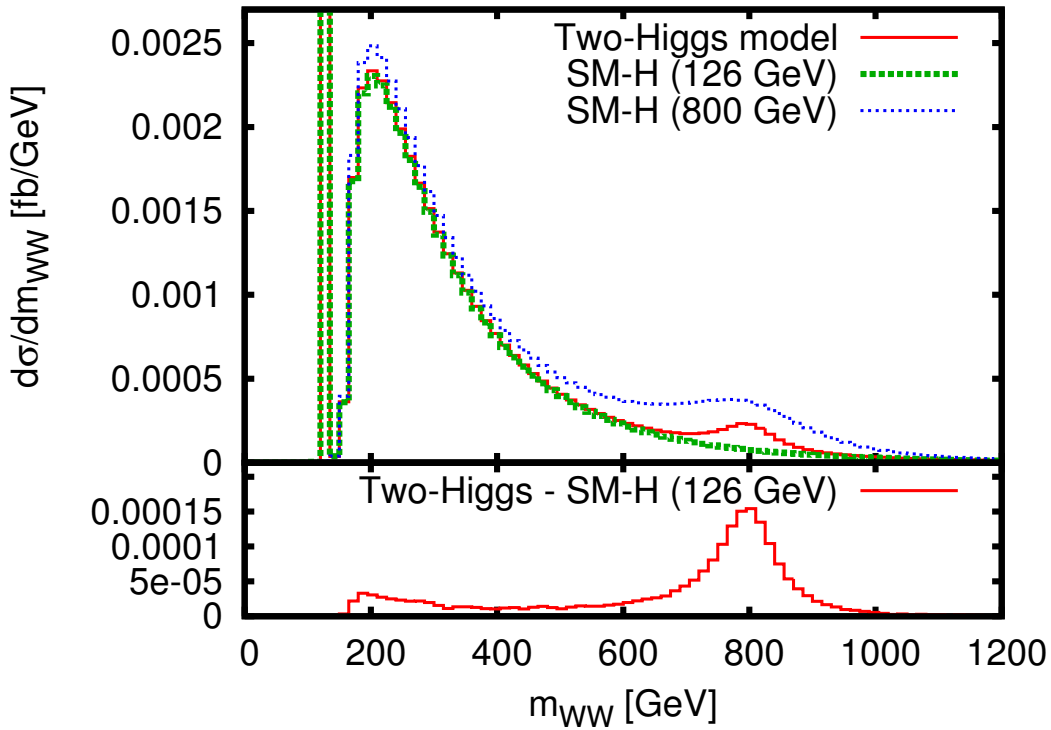
- Define $S = \int d\Phi |\mathcal{M}_B + \mathcal{M}_H(m_H)|^2 - B$ with $B = \int d\Phi |\mathcal{M}_B + \mathcal{M}_h(m_h)|^2$
- Integrate over suitable mass range $[m_H - \Gamma_1, m_H + \Gamma_2]$
- $\Rightarrow$ S and B well defined and do not violate unitarity



$\rightarrow$ light-Higgs curves indistinguishable at large m_{VV}

Two-Higgs Model

→ Model with two Higgs resonances



Example:

- h_0: M_{h_0}=126 GeV, $\quad g^2_{h_0 VV}/g^2_{HVV,SM} = 0.7$
- H_0: M_{H_0}=800 GeV, $\quad g^2_{H_0 VV}/g^2_{HVV,SM} = 0.3$

→ Consistent definition possible

Reweighting events (REPOLO)

[F. Schissler, available on request]

Generating events at detector-level time-consuming (shower, detector simulation, . . .)

→ Reuse SM Higgs events and reweight for different BSM scenarios

→ REPOLO (REweighting POwheg events at Leading Order)

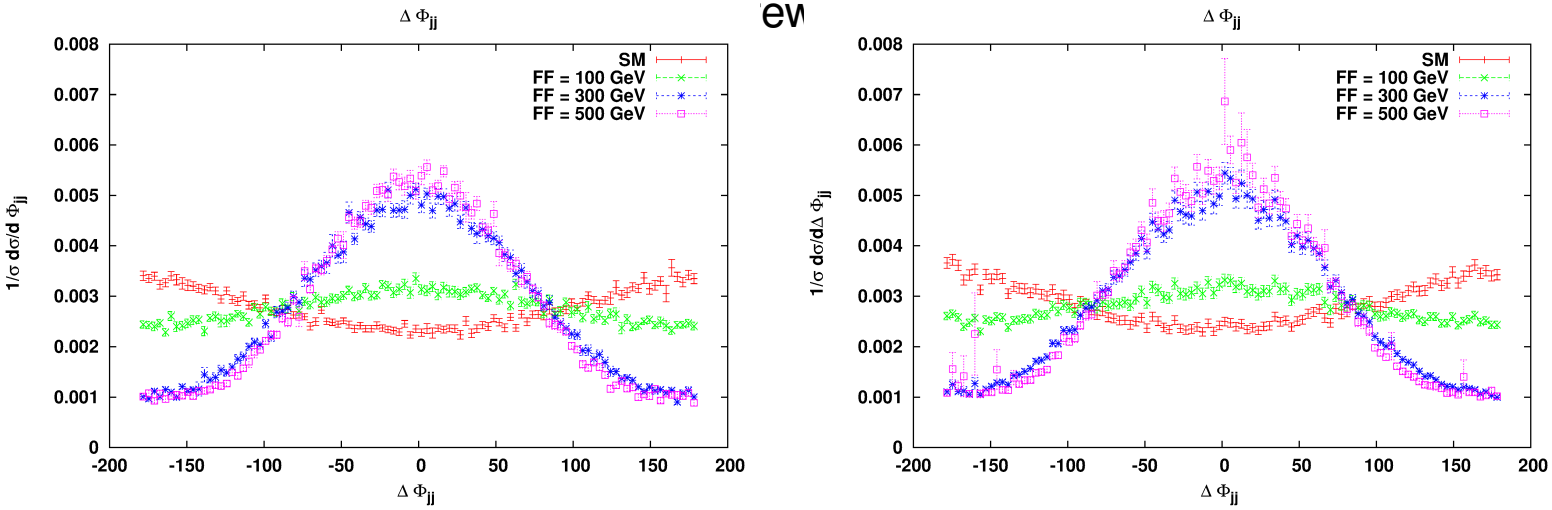
uses VBFNLO framework to multiply each event by a factor $\frac{|\mathcal{M}_{\text{BSM}}|^2}{|\mathcal{M}_{\text{SM}}|^2}$

Limitation:

event with high reweighting factor ($|\mathcal{M}_{\text{SM}}|^2 \ll |\mathcal{M}_{\text{BSM}}|^2$) can destroy distributions

→ only SM-like distributions can be safely reweighted

Example: VBF-$H \to \gamma\gamma$, SM → anomalous Higgs couplings ($+HW^{\mu\nu}_{+} W^{-}_{\mu\nu}$, $HZ^{\mu\nu} Z_{\mu\nu}$)

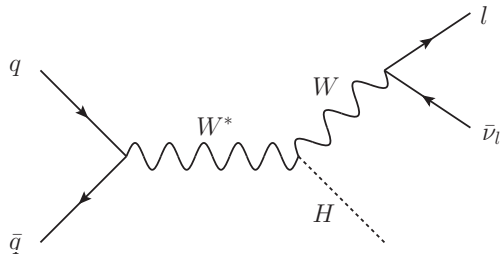


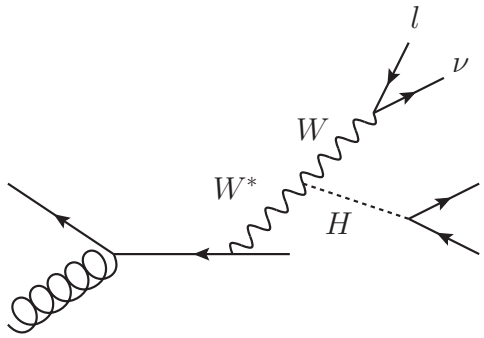
⇒ distributions correctly reproduced, larger errors in SM-suppressed regions

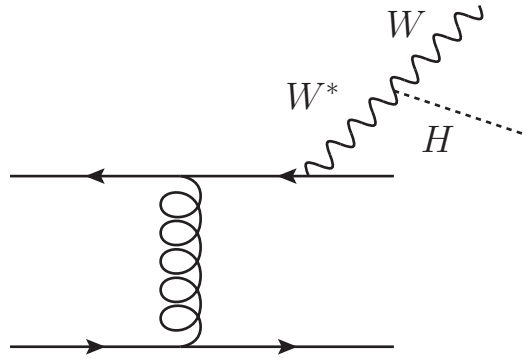
$WH(j)$ production at NLO QCD

Implementation of WH and $WH(j)$ at NLO QCD

[Campanario, Roth, Zeppenfeld; see also Ji-Juan et al.; Luisoni et al.]

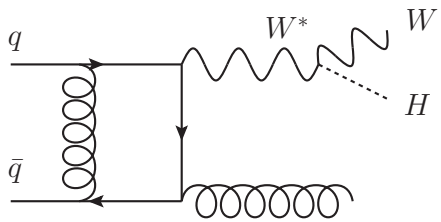


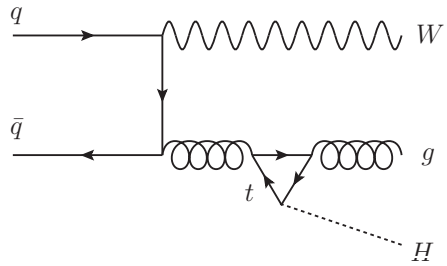




two types of virtual contributions:

- Drell-Yan-like diagrams ($W^* \to WH$)
- Higgs coupling to heavy quark (top) loop (2-3% effect)



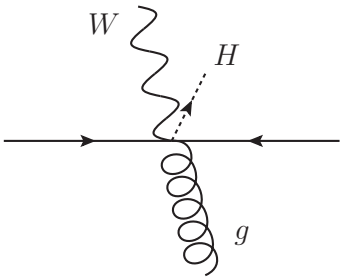


- including leptonic decays of W boson and off-shell effects
- allows including decay of Higgs boson
- anomalous WWH couplings from dimension-6 operators implemented

Boosted Higgs

- experimental analysis require high p_T to reduce background
- $p_{T,W} = p_{T,H}$ for WH (LO), but deviates with additional radiation
- large NLO effects on distributions in boosted phase space region

Inclusive cuts



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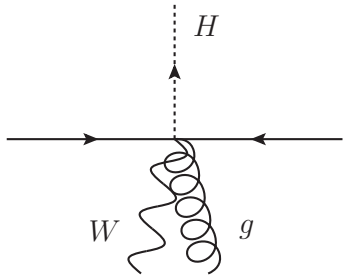
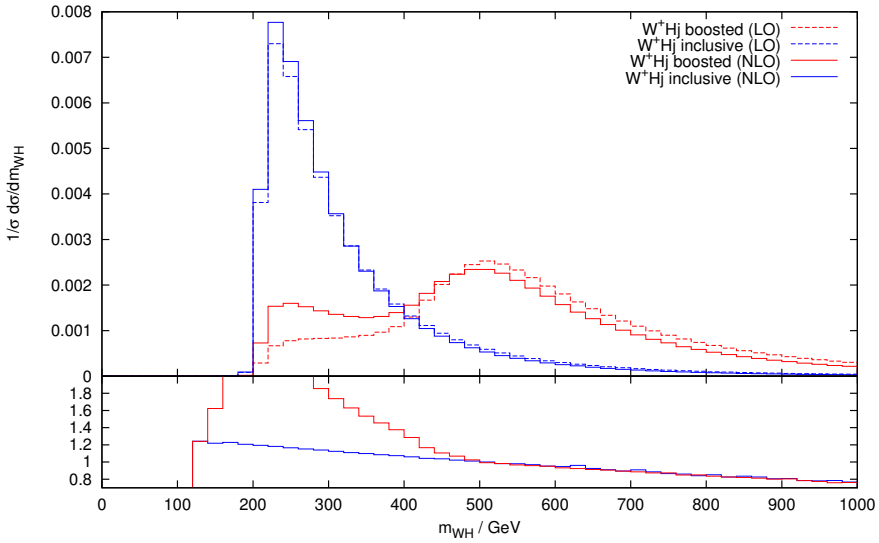
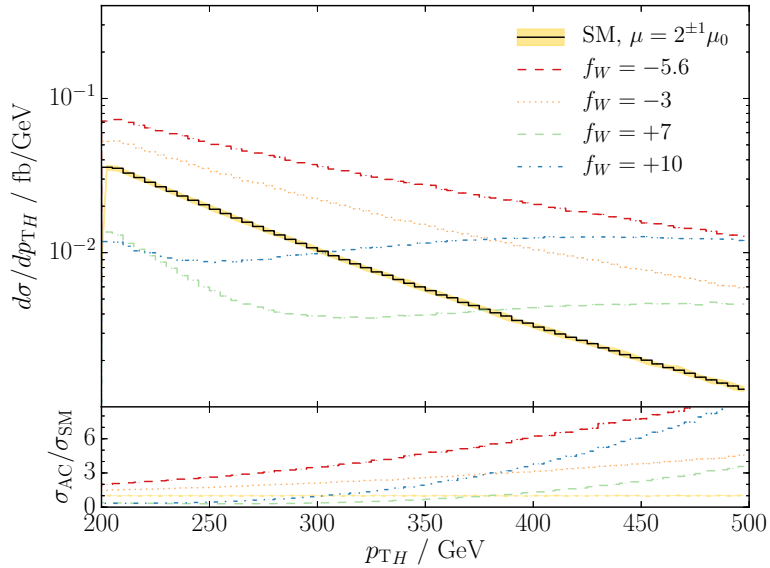


Cuts	Cross Section (fb) LO	NLO	K
inclusive	25	28	1.11
$p_{T,H} > 200$ GeV	3.5	3.7	1.08

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \hat{W}^{\mu\nu} \, (D_\nu \Phi)$$

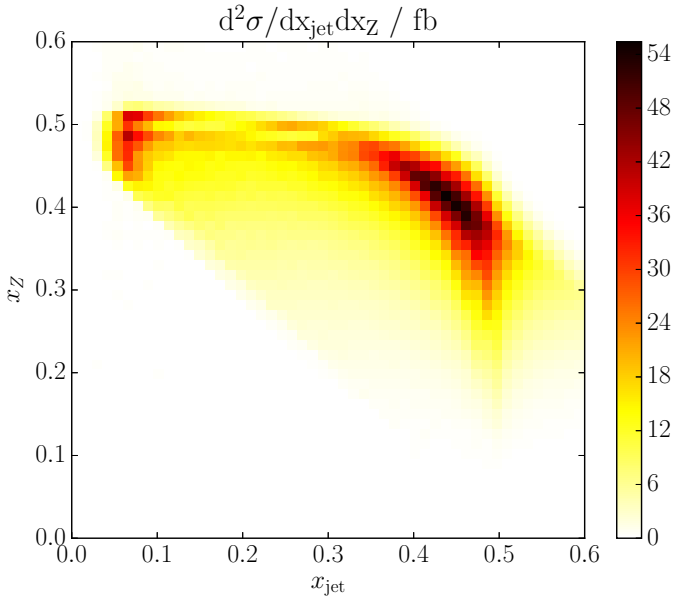




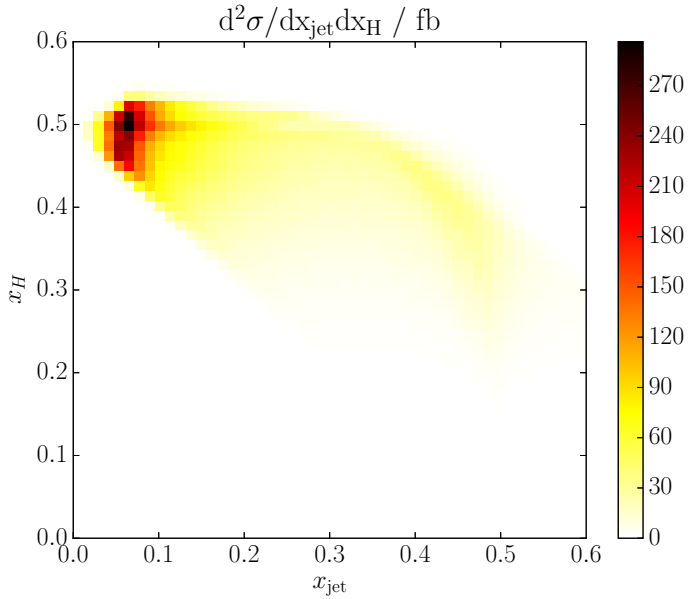
QCD Patterns in WZj vs. WHj

[Campanario, Roth, Zeppenfeld]

$$x_V = \frac{E_{TV}}{\sum_{\text{jets}} E_{T,i} + \sum_{W,Z/H} E_{T,i}}, \qquad x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + \sum_{W,Z/H} E_{T,i}}$$



WZj



WHj

- *WHj* has mainly soft jets, while *WZj* also has a phase space region with hard *Vj* and a soft second vector boson

Conclusions

- VBF-H available at NLO QCD+EW in SM and MSSM (h^0, H^0, A^0)
- WH and WHj available at NLO QCD in SM and with D6 anomalous couplings
- Two-Higgs model for diboson-VBF processes
  $\rightarrow$ allows for consistent definition of signal+interference in heavy-Higgs scenarios
- Reweighting of VBF-H events to account for BSM effects

VBFNLO is a flexible parton-level Monte Carlo for processes with electro-weak bosons

Code available at `http://www.itp.kit.edu/vbfnlo`

VBFNLO is collaborative effort:

K. Arnold, J. Baglio, J. Bellm, G. Bozzi, M. Brieg, F. Campanario, C. Englert, B. Feigl, J. Frank, T. Figy, F. Geyer, N. Greiner, C. Hackstein, V. Hankele, B. Jäger, N. Kaiser, M. Kerner, G. Klämke, M. Kubocz, L.D. Ninh, C. Oleari, S. Palmer, S. Plätzer, S. Prestel, MR, R. Roth, H. Rzehak, F. Schissler, O. Schlimpert, M. Spannowsky, M. Worek, D. Zeppenfeld

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