Diboson-VBF-production in VBFNLO

Michael Rauch | Dec 2012

INSTITUTE FOR THEORETICAL PHYSICS

Outline

- Overview of VBFNLO
- Diboson production via vector-boson fusion
  - scale dependence
  - distributions
- BSM extensions
  - anomalous gauge and Higgs couplings
  - heavy spin-2 resonances

Introduction

VBFNLO

- 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

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

  } (including Higgs decays)

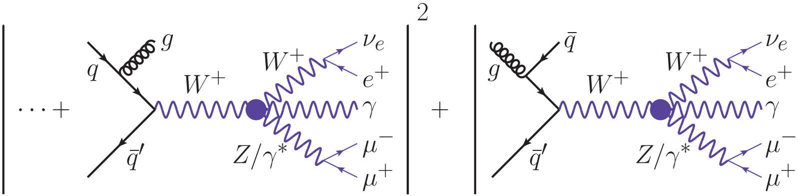
  - vector boson (W, Z, γ)
  - two vector bosons (W^+W^-, $W^\pm W^\pm$, WZ, ZZ; $W\gamma$ in progress)
- diboson production
  - diboson (WW, WZ, ZZ, $W\gamma$, $Z\gamma$, $\gamma\gamma$) (NLO QCD)
  - diboson via gluon fusion (WW, ZZ, $Z\gamma$, $\gamma\gamma$)
    (part of NNLO QCD contribution to diboson)
  - diboson (WZ, $W\gamma$) plus hard jet (NLO QCD)
- triboson production
  - triboson (all combinations of W, Z, γ) (NLO QCD)
  - triboson ($W\gamma\gamma$) plus hard jet (NLO QCD)
- Higgs plus two jets via gluon fusion (one-loop LO)
  (including Higgs decays)

Intermediate state Higgs boson in all processes included where applicable

Implementation Details

[Hagiwara, Zeppenfeld]

- Helicity amplitude method
- 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

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

- Photon isolation à la Frixione
  Processes with real photons in final state can have configurations with photon collinear to final-state quark $\rightarrow$ QED divergence

  Simple (e.g. R) separation cut between photon and jet not infrared safe
  $\rightarrow$ Frixione photon isolation

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  $\Rightarrow$ Efficiently suppresses fragmentation contribution

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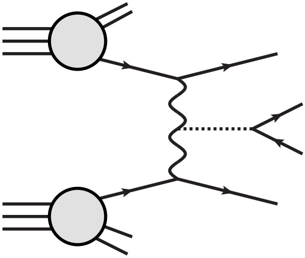
VBF event topology

VBF topology shows distinct signature

- two tagging jets in forward region
- reduced jet activity in central region
- leptonic decay products typically between tagging jets

First studied in context of Higgs searches [Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; . . .]

- $\sim$ 10% compared to main production mode gluon fusion
- NLO QCD corrections moderate ($\mathcal{O}(\lesssim 10\%)$)
- NLO EW same size, opposite sign as QCD for $M_H \sim 126$ GeV [Ciccolini *et al.* , Figy *et al.*]
- NNLO QCD known for subsets: no significant contributions [Harlander *et al.* , Bolzoni *et al.*]
- advantageous scale choice: momentum transfer q^2 of intermediate vector bosons



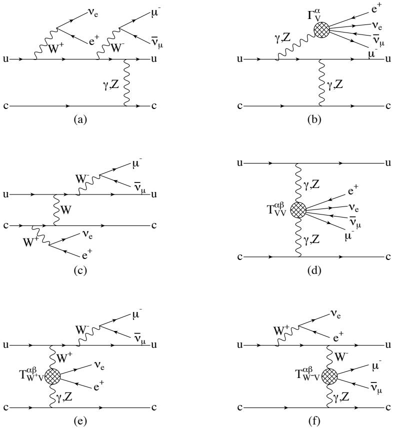
Diboson-VBF production

[Bozzi, Jäger, Oleari, Zeppenfeld; hep-ph/0603177, hep-ph/0604200, hep-ph/0701105]
[Denner, Hosekova, Kallweit (W^+W^+)]

- Part of the NLO wishlist
  [Les Houches 2005]
- background to Higgs searches
- access to anomalous triple and quartic gauge couplings

Implementation:

- modular structure
  $\rightarrow$ reuse building blocks
- leptonic decays included
- only t- and u-channel diagrams (s-channel implemented separately as triboson process)
- no interference effects from identical leptons



Cuts

Cuts used in the following:

- Cuts describing general LHC detector capabilities:

  $p_T(j) > 20$ GeV $\qquad |\eta_j| < 4.5$

  $p_T(\ell) > 20$ GeV $\qquad |\eta_\ell| < 2.5 \qquad \Delta R_{j\ell} > 0.4$

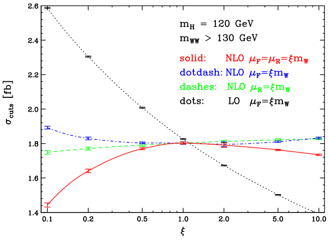
  for WZ additionally: $\quad m_{\ell\ell} > 15$ GeV $\qquad \Delta R_{\ell\ell} > 0.2$

- VBF-specific cuts:
  - two tagging jets well separated in rapidity $\quad \Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4$
  - two tagging jets in opposite detector hemispheres $\quad y_{j_1} \times y_{j_2} < 0$
  - large invariant mass of the two tagging jets $\quad m_{jj} > 600$ GeV
  - final-state leptons between the two tagging jets $\quad y_{j,\text{min}} < \eta_\ell < y_{j,\text{max}}$

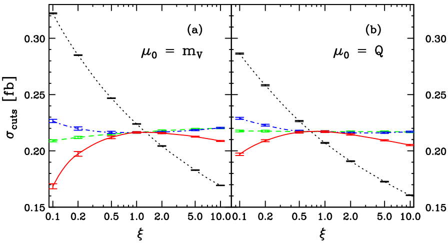
Scale dependence

Dependence on factorization and renormalization scale

$pp \to W^+W^-jj$



$pp \to W^+Zjj$

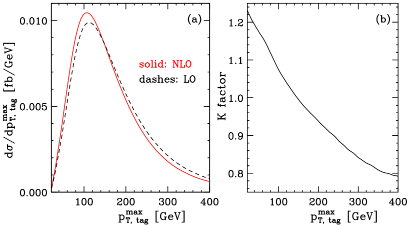


- sizable scale dependence at LO: $\sim \pm$ 10%
- strongly reduced at NLO: $\sim \pm$ 2% (up to 6% in distributions)
- K-factor around 0.98 for $\mu = m_V$, 1.04 for $\mu = Q$ (momentum transfer)

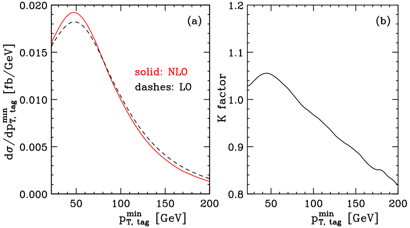
Distributions

Differential distributions: $p_T(j)$ ($W^+ W^-$)

p_T of the leading tagging jet



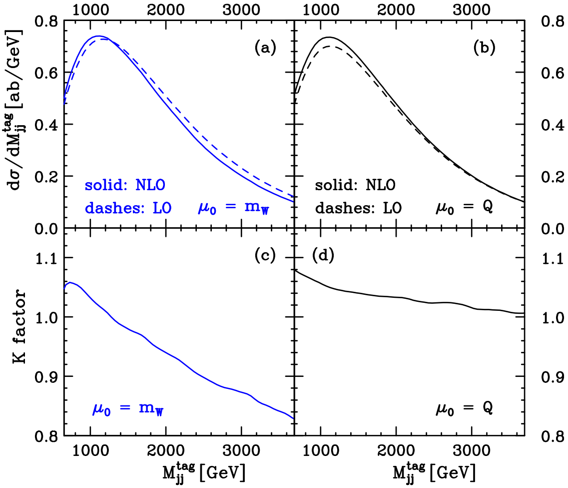
p_T of the second tagging jet



- K factor not constant over range of distribution
- $\rightarrow$ shape of distributions changes
- $\rightarrow$ simple rescaling with K factor not sufficient

Distributions

Differential distributions: m_{jj} ($W^+ W^+$)



→ scale choice $\mu_0 = Q$ leads to flatter differential K factor

Anomalous couplings

New physics at high scale Λ could influence gauge couplings
$\Rightarrow$ anomalous gauge couplings

Different approaches to parametrize effects
$\rightarrow$ Effective field theory

$$\mathcal{L}_{\mathrm{EFT}} = \sum_d \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Operators $\mathcal{O}$ with low energy degrees of freedom respect gauge symmetries

need to consider only lowest (first non-vanishing) order
$\rightarrow$ higher operators suppressed by $\left(\frac{E}{\Lambda}\right)^d$

Building Blocks:

$$\left.\begin{aligned} \hat{W}_{\mu\nu} &= i\frac{g}{2} W^a_{\mu\nu}\sigma^a \\ \hat{B}_{\mu\nu} &= i\frac{g'}{2} B_{\mu\nu} \end{aligned}\right\} [D_\mu, D_\nu] = \hat{W}_{\mu\nu} + \hat{B}_{\mu\nu}$$

$$D_\mu = \partial_\mu + igW^a_\mu \frac{\sigma^a}{2} + i\frac{g'}{2} B_\mu$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

Anomalous gauge couplings

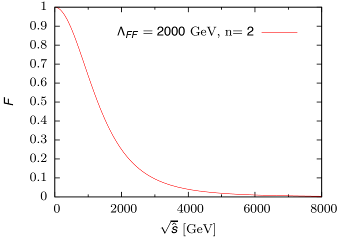
- Anomalous triple gauge couplings:
  8 CP-even operators, e.g.
  - $\mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)$
  - $\mathcal{O}_{WWW} = Tr \left[\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^{\ \mu} \right]$
- Anomalous quartic gauge couplings:
  18 CP-even operators, e.g.
  - $\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$
  - $\mathcal{L}_{M,0} = \mathrm{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$
  - $\mathcal{L}_{T,0} = \mathrm{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \mathrm{Tr} \left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right]$

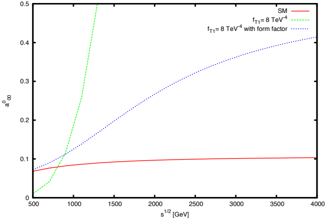
  each term contains at least four gauge bosons
- form factors:
  avoids unitarity violation for scales above Λ_{FF}

$$F(\hat{s}) = \frac{1}{\left(1 + \frac{\hat{s}}{\Lambda_{FF}^2}\right)^n}$$

right: largest helicity contribution to partial wave ($\Re(a) < 0.5$) in VV scattering

$\leftrightarrow$ no over-estimated experimental sensitivity





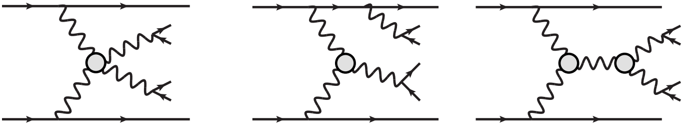
Anomalous gauge couplings

Anomalous gauge couplings implemented in the following processes ($V \in [W, Z, \gamma]$):

- V production via VBF
- VV production via VBF
- WZ, $W\gamma$, WZj, $W\gamma j$ production
- VVV, $W\gamma\gamma j$ production

Results in the following for W^+W^-jj: [New in VBFNLO 2.7beta, O. Schlimpert]

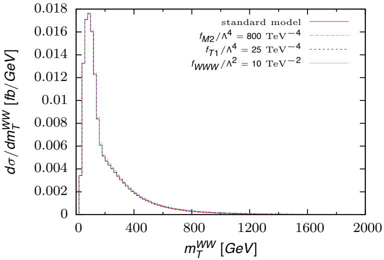
Ideal process to test anomalous quartic gauge couplings

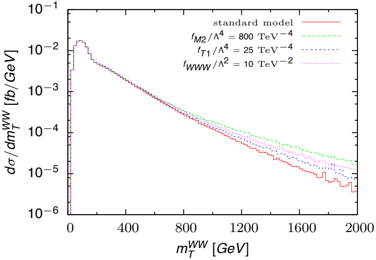


Anomalous quartic gauge couplings

Sensitive region for large transverse mass of the *WW* pair

$$m_T^{WW} = \left(\left(\sqrt{(p_T^{\ell\ell})^2 + m_{\ell\ell}^2} + \sqrt{p_{T,miss}^2 + m_{\ell\ell}^2} \right)^2 - \left(\vec{p}_T^{\,\ell\ell} + \vec{p}_{T,miss} \right)^2 \right)^{\frac{1}{2}}$$



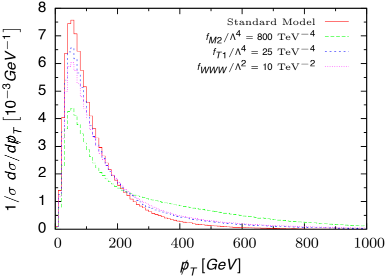


$\Rightarrow$ Require $m_T^{WW} > 800$ GeV

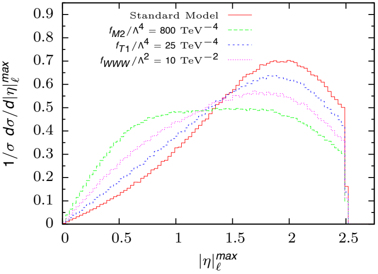
- $\Delta \frac{\sigma_{SM,cut}}{\sigma_{SM}} = -98\,\%$
- $\Delta \frac{\sigma_{M2,cut}}{\sigma_{SM,cut}} = +76.6\,\%$, $\quad \Delta \frac{\sigma_{T1,cut}}{\sigma_{SM,cut}} = +21.7\,\%$, $\quad \Delta \frac{\sigma_{WWW,cut}}{\sigma_{SM,cut}} = +45.9\,\%$

Anomalous quartic gauge couplings

Normalized $\not{p}_t$ distribution



Normalized $|\eta|_\ell^{max}$ distribution



- Anomalous couplings enhance predominantly high-energy region
- Visible changes in distributions, different for individual couplings
- $\rightarrow$ distinguish between different couplings

Anomalous Higgs couplings

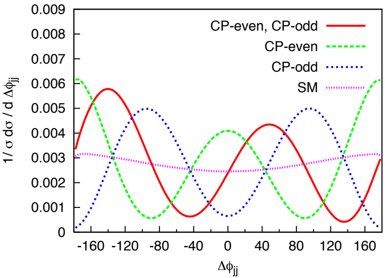
[Buchmüller, Wyler; Hagiwara, Szalapski, Zeppenfeld; Hankele, Klämke, Zeppenfeld; . . .]

Operators for anomalous gauge couplings also induce anomalous Higgs couplings

Alternatively directly as coefficients of (most general) tensor structure

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) \left(q_1 \cdot q_2 \, g^{\mu\nu} - q_2^{\mu} q_1^{\nu}\right) + a_3(q_1, q_2) \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

(q_1, q_2 momenta of vector bosons V^μ, V^ν; SM: $a_2 = a_3 = 0$)



a_2: CP-even coupling
a_3: CP-odd coupling

$\rightarrow \Delta\phi_{jj}$
(azimuthal angle difference between two tagging jets VBF-Higgs production) sensitive observable to distinguish

implemented in ($V \in [W, Z, \gamma]$):

- H production via VBF
- $(gg \rightarrow) VV$
- VVV

Heavy Spin-2 resonances

Effective model for interaction of spin-2 singlet with electroweak gauge bosons

[Frank, MR, Zeppenfeld, arXiv:1211.3658]

- Main motivation: Higgs imposter – test against Higgs spin-0 hypothesis
- also studied phenomenology of heavy resonances ($\mathcal{O}$(1 TeV))
- effective ansatz

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda} T_{\mu\nu} \left(f_1 B^{\alpha\nu} B^{\mu}{}_{\alpha} + f_2 W_i^{\alpha\nu} W^{i,\mu}{}_{\alpha} + 2 f_5 \left(D^\mu \Phi\right)^\dagger \left(D^\nu \Phi\right) \right)$$

- spin-2 $SU(2)$ triplet included similarly
- form factor to preserve unitarity

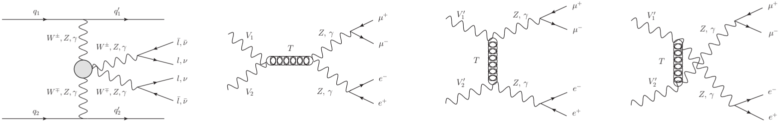
$$F(q_1^2, q_2^2, p_{sp2}^2) = \left(\frac{\Lambda_{ff}^2}{|q_1|^2 + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|q_2|^2 + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_{sp2}|^2 + \Lambda_{ff}^2} \right)^{n_{ff}}$$

(q_1, q_2: momentum transfer of initial electroweak bosons,
p_{sp2}: momentum of spin-2 particle)

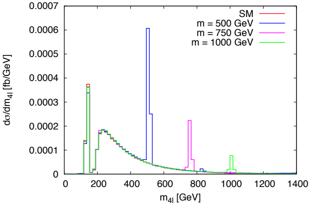
- NLO QCD corrections similar to SM case

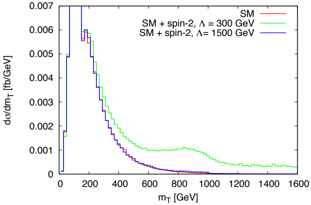
Heavy Spin-2 resonances

- Tree-level diagrams



- signal and SM background included
- ZZjj: nicely visible as peaks (depending on width of resonance)
  WWjj: only transverse mass available





Heavy Spin-2 resonances

Distinguishing from SM and different parameters (ZZjj)

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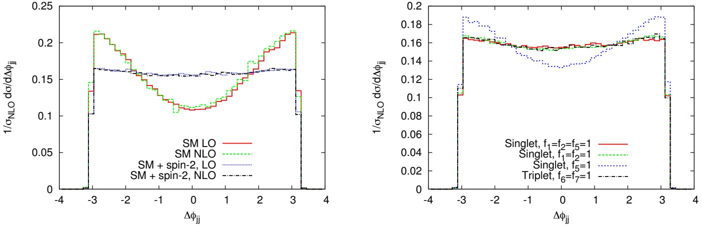
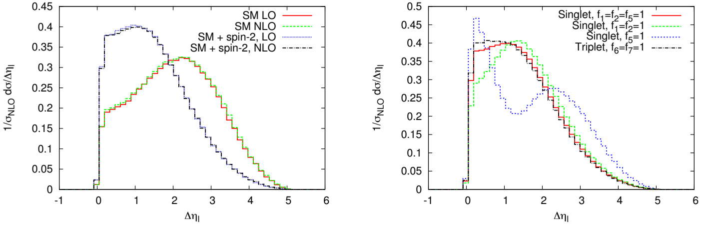
$\Delta\Phi_{jj}$



$\Delta\eta_{\ell^+\ell^+}$



Conclusions

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- Diboson production via VBF theoretically well behaved
  - K factors small, no huge effects in distributions either
  - small scale uncertainty at NLO QCD
- Ideal process to test anomalous couplings
  (quartic gauge couplings and Higgs couplings)
  and heavy electroweak resonances

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

Code available at

`http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb`

VBFNLO is collaborative effort:

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