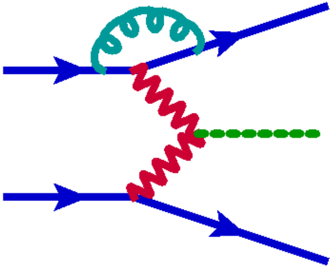
VBS in VBFNLO

Marco Sekulla

HL/HE-LHC WG1 Meeting **January 19, 2018**

Institute for Theoretical Physics (ITP)



VBFNLO

Vector-**B**oson-**F**~~usion~~ysics at **N**ext-To-**L**eading **O**rder

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons at NLO QCD
- general cuts and distributions of final-state particles
- various choices for renormalization and factorization scales
- any pdf set available from LHAPDF
- event files in Les Houches Accord (LHA) or HepMC format (LO only)
- BLHA interface to Monte-Carlo event generators (for VBF processes with leptonic final states)

→ NLO event output

- process optimized implementation

Process overview

- VBF-processes (VBF-approximation)
  - vector bosons (W,Z,γ)
  - vector boson scattering
    - fully leptonic incl. $(\ell\bar{\ell}\gamma jj)$
    - all weak semi-leptonic states
    - VBF-approximation: negligible error for $\Delta y(jj) \gtrapprox 2$

    VBSCAN: in preparation
  - Higgs (+NLO EW, including Higgs decays)
  - Higgs pair
- triboson
- diboson (+ 1 or 2 hard jets)
- Higgs + vector boson
- Higgs + two jets via gluon fusion

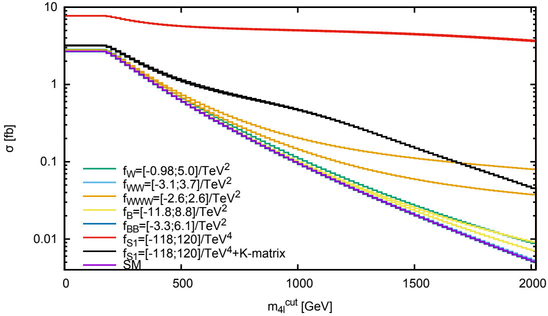
Full list : `https://www.itp.kit.edu/vbfnlo`

New Physics

- Dimension six and eight EFT operators containing bosons
- unitarization methods (for VBS)
  - Form Factor including tool to calculate needed parameters
  - generic T-Matrix unitarisation
    - respecting highest involved scale:
      M_{VV} or space-like momenta of incoming vector bosons
    - double and single charged final states: in validation
    - neutral final states: work in progress
- Two Higgs model

Example: Fiducial cross section for VBS

$$pp \to W^+(\ell^+\nu)W^+(\ell^+\nu)jj$$



by M. Rauch

- for processes
  $W^\pm W^\pm$, $W^\pm\gamma$, W^+W^-, ZZ, $W^\pm Z$, $Z\gamma$
- scan over lower cut on invariant mass m_{4l}

⇒ estimation of expected number of events

Backup

Vertex Contributions

frame:M.Rauch

List of Operators (only gauge and Higgs couplings)

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger \widehat{W}^{\mu\nu} (D_\nu\Phi) \qquad \mathcal{O}_B = (D_\mu\Phi)^\dagger \widehat{B}^{\mu\nu} (D_\nu\Phi)$$

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{BB} = \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}^{\mu}{}_{\nu} \widehat{W}^{\nu}{}_{\rho} \widehat{W}^{\rho}{}_{\mu}\right] \qquad \mathcal{O}_{\phi,2} = \partial_\mu \left(\Phi^\dagger\Phi\right) \partial^\mu \left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{\widetilde{W}} = (D_\mu\Phi)^\dagger \widetilde{W}^{\mu\nu} (D_\nu\Phi) \qquad \mathcal{O}_{\widetilde{B}} = (D_\mu\Phi)^\dagger \widetilde{B}^{\mu\nu} (D_\nu\Phi)$$

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger \widetilde{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{\widetilde{B}B} = \Phi^\dagger \widetilde{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}\left[\widetilde{W}^{\mu}{}_{\nu} \widehat{W}^{\nu}{}_{\rho} \widehat{W}^{\rho}{}_{\mu}\right]$$

Modification of corresponding triple-gauge-coupling vertices:

	$\mathcal{O}_{WWW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{B}$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{\phi,2}$	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\widetilde{W}}$	$\mathcal{O}_{\widetilde{B}}$	$\mathcal{O}_{\widetilde{W}W}$	$\mathcal{O}_{\widetilde{B}B}$
WWZ	X	X	X				X	X	X		
$WW\gamma$	X	X	X				X	X	X		
HWW		X		X		X		X		X	
HZZ		X	X	X	X	X		X	X	X	X
$HZ\gamma$		X	X	X	X	(X)		X	X	X	X
$H\gamma\gamma$				X	X	(X)				X	X
$WWWW$	X	X					X				
$WWZZ$	X	X					X				
$WWZ\gamma$	X	X					X				
$WW\gamma\gamma$	X						X				

Dimension-8

frame:M.Rauch

Bosonic dimension-8 operators [Eboli, Gonzalez-Garcia]

(D6 could be loop-induced → D8 effects can become sizable [Arzt, Einhorn, Wudka])

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,2} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,3} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\mu\Phi\right] \times \widehat{B}^{\beta\nu}$$

$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\nu\Phi\right] \times \widehat{B}^{\beta\mu}$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right]$$

$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right]$$

$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\mu\beta}\widehat{B}^{\alpha\nu}$$

$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$$

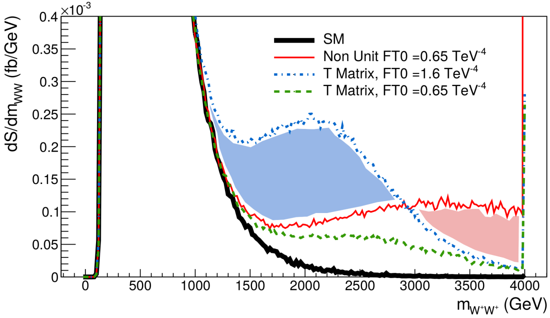
$$\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = \widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta}\widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$$

→ each operators contains at least four bosons

⇒ leading contribution to quartic gauge coupling

T-matrix (VBFNLO) for $pp \to W^+W^+jj$



G. Perez

- Non-unitarized: Events for experimental bounds originate from unphysical prediction of EFT
- T-matrix: Factor 2 – 3 lower bounds for EFT couplings
- Unitarisation methods are important

T-matrix (VBFNLO) for $pp \to W^+W^+jj$

Coupling (TeV^{-4})	CMS (13 TeV)	New limits
f_{S_1}/Λ^4	[-21.6,21.8]	[-50.0,60.3]
f_{M_0}/Λ^4	[-8.7,9.1]	[-20.0,14.5]
f_{T_0}/Λ^4	[-0.62,0.65]	[-1.35,1.60]

- Non-unitarized: Events for experimental bounds originate from unphysical prediction of EFT
- T-matrix: Factor 2 – 3 lower bounds for EFT couplings
- Unitarisation methods are important