Karlsruher Institut für Technologie

EFT in VBFNLO

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Area 2 meeting: predictions and tools

KIT Center Elementary Particle and Astroparticle Physics - KCETA

VBFNLO is a collection of many mixed QCD/EW processes with NLO QCD corrections

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3.1 VBF Higgs boson production in association with 2 jets
3.2 VBF Higgs boson production in association with 3jets
3.3 VBF Higgs boson production with a photon and two jets
3.4 VBF production of a single vector boson and two jets
3.5 VBF production of a spin-2 particle
3.6 VBF production of two vector bosons and two jets
3.7 VBF production of two Higgs bosons and two jets
3.8 *W* production with up to one jet
3.9 Double vector boson production
3.10 Triple vector boson production
3.11 Double vector boson production in association with a hadronic jet
3.12 Triple vector boson production in association with a hadronic jet
3.13 Higgs production in association with a *W*
3.14 Higgs production in association with a *W* and a hadronic jet
3.15 QCD-induced production of a vector boson in association with two jets
3.16 QCD-induced diboson production in association with two jets
3.17 Higgs boson production in gluon fusion with two jets
3.18 Gluon-induced diboson production
3.19 Gluon-induced diboson production in association with a hadronic jet

VBF Higgs

VBF Z,W,photon

VBS

V, VV, VVV

V, VV, VVV +1 jet

V, VV + 2 jets

Gluon fusion at LO

BSM effects included in many processes

ProcId	Process	Bsm
100	$\overset{(-)}{p}p \to H\,jj$	anomalous HVV couplings, MSSM
101	$\overset{(-)}{p}p \to H\,jj \to \gamma\gamma\,jj$	
102	$\overset{(-)}{p}p \to H\,jj \to \mu^+\mu^-\,jj$	
103	$\overset{(-)}{p}p \to H\,jj \to \tau^+\tau^-\,jj$	
104	$\overset{(-)}{p}p \to H\,jj \to b\bar{b}\,jj$	
105	$\overset{(-)}{p}p \to H\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	
106	$\overset{(-)}{p}p \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	
107	$\overset{(-)}{p}p \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	

Anomalous couplings included in various forms:

- General form factors
- Dimension 6 EFT
- ….

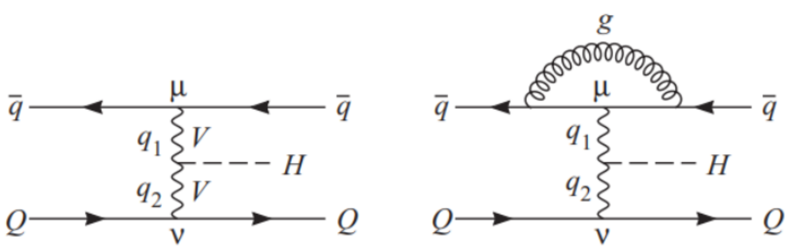
ProcId	Process	Bsm
120	$\overset{(-)}{p}p \to Z\,jj \to \ell^+\ell^-\,jj$	anomalous couplings
121	$\overset{(-)}{p}p \to Z\,jj \to \nu_\ell\bar{\nu}_\ell\,jj$	
130	$\overset{(-)}{p}p \to W^+\,jj \to \ell^+\nu_\ell\,jj$	
140	$\overset{(-)}{p}p \to W^-\,jj \to \ell^-\bar{\nu}_\ell\,jj$	
150	$\overset{(-)}{p}p \to \gamma\,jj$	

…. and dimension-8 EFT operators for VBS

ProcId	Process	BSM
200	$p \overset{(-)}{p} \to W^+W^- jj \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} jj$	anomalous couplings, two-Higgs model, Kaluza-Klein models, spin-2 models
210	$p \overset{(-)}{p} \to ZZ jj \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- jj$	
211	$p \overset{(-)}{p} \to ZZ jj \to \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2} jj$	
220	$p \overset{(-)}{p} \to W^+Z jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^- jj$	
230	$p \overset{(-)}{p} \to W^-Z jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^- jj$	
250	$p \overset{(-)}{p} \to W^+W^+ jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \nu_{\ell_2} jj$	anomalous couplings, two-Higgs model
260	$p \overset{(-)}{p} \to W^-W^- jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} jj$	
270	$p \overset{(-)}{p} \to W^+\gamma jj \to \ell^+ \nu_\ell \gamma jj$	anomalous couplings
280	$p \overset{(-)}{p} \to W^-\gamma jj \to \ell^- \bar{\nu}_\ell \gamma jj$	
290	$p \overset{(-)}{p} \to Z\gamma jj \to \ell^+ \ell^- \gamma jj$	
291	$p \overset{(-)}{p} \to Z\gamma jj \to \nu_\ell \bar{\nu}_\ell \gamma jj$	

Example: tensor structure of HVV coupling

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



(a) (b)

Physical interpretation of terms:

SM Higgs $\mathcal{L}_I \sim HV_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

CP even $\mathcal{L}_{eff} \sim HV_{\mu\nu}V^{\mu\nu} \longrightarrow a_2$

CP odd $\mathcal{L}_{eff} \sim HV_{\mu\nu}\tilde{V}^{\mu\nu} \longrightarrow a_3$

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

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Connection to EFT description

We need model of the underlying UV physics to determine the form factors $a_i(q_1, q_2)$

Approximate its low-energy effects by an effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{f_{WW}}{\Lambda^2}\phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi + \frac{f_\phi}{\Lambda^2}\left(\phi^\dagger\phi - \frac{v^2}{2}\right)(D_\mu\phi)^\dagger D^\mu\phi + \cdots + \sum_i \frac{f_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

Gives leading terms for form factors, e.g. for hWW coupling

$$a_1 = \frac{2m_W^2}{v}\left(1 + \frac{f_\phi}{\Lambda^2}\frac{v^2}{2}\right) + \sum_i c_i^{(1)}\frac{f_i^{(8)}}{\Lambda^4}v^2q^2 + \cdots$$

$$a_2 = c^{(2)}\frac{f_{WW}}{\Lambda^2}v + \sum_i c_i^{(2)}\frac{f_i^{(8)}}{\Lambda^4}vq^2 + \cdots$$

$$a_3 = c^{(3)}\frac{\tilde{f}_{WW}}{\Lambda^2}v + \sum_i c_i^{(3)}\frac{\tilde{f}_i^{(8)}}{\Lambda^4}vq^2 + \cdots$$

Describe same physics (for a particular vertex) by taking some minimal set of effective Lagrangian coefficients f_i as form factors

Implementation in VBFNLO

Start from effective Lagrangians

$$\begin{aligned}\mathcal{L} \;=\; & \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W_-^{\mu\nu} + \\ & \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}\end{aligned}$$

or , alternatively,

$$\mathcal{L}_{\text{eff}} \;=\; \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{ CP-odd part} + \cdots$$

Implementation in VBFNLO

Start from effective Lagrangians (set PARAMETR1=.true. in anom_HVV.dat)

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}$$

or , alternatively, (set PARAMETR3=.true. in anom_HVV.dat)

$$\mathcal{L}_{\rm eff} = \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{CP-odd part} + \cdots$$

see VBFNLO manual for details on how to set the anomalous coupling choices

Remember to choose form factors in anom_HVV.dat

$$F_1 = \frac{M^2}{q_1^2 - M^2} \frac{M^2}{q_2^2 - M^2} \quad \text{or} \quad F_2 = -2\, M^2\, C_0\left(q_1^2, q_2^2, (q_1+q_2)^2, M^2\right)$$

EFT operators for HVV and VVV couplings

- VBFNLO provides only for a restricted set of dimension 6 operators

$$\begin{aligned} \mathcal{O}_W &= (D_\mu\phi^\dagger)\widehat{W}^{\mu\nu}(D_\nu\phi) \\ \mathcal{O}_B &= (D_\mu\phi^\dagger)\widehat{B}^{\mu\nu}(D_\nu\phi) \\ \mathcal{O}_{WW} &= \phi^\dagger\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\phi \\ \mathcal{O}_{BB} &= \phi^\dagger\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\phi\,, \end{aligned}$$

with

$$\begin{aligned} \widehat{W}_{\mu\nu} &= igT^aW^a_{\mu\nu} \\ \widehat{B}_{\mu\nu} &= ig'YB_{\mu\nu}, \end{aligned}$$

$$O_{WWW} = \mathrm{Tr}\left(\hat{W}^\mu{}_\nu\hat{W}^\nu{}_\rho\hat{W}^\rho{}_\mu\right)$$

- Parameters are set in anom_HVV.dat and anomV.dat which also provides switch to lambda, kappa, g_1 notation

$$\mathcal{L}_{WWZ} = -ie\cot\theta_w\left[g_1^Z\left(W^\dagger_{\mu\nu}W^\mu Z^\nu - W^\dagger_\mu Z_\nu W^{\mu\nu}\right) + \kappa_Z W^\dagger_\mu W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W^\dagger_{\sigma\mu}W^\mu_\nu Z^{\nu\sigma}\right]$$

- See manual for details: https://www.itp.kit.edu/vbfnlo/wiki/doku.php

For aQGC: full set of dimension 8 operators (Eboli et al.)

- Distinguish by dominant set of vector boson helicities
- Longitudinal operators: derivatives of Higgs doublet field

$$\mathcal{O}_{S_0} = \left[\left(D_\mu \Phi \right)^\dagger D_\nu \Phi \right] \times \left[\left(D^\mu \Phi \right)^\dagger D^\nu \Phi \right]$$
$$\mathcal{O}_{S_1} = \left[\left(D_\mu \Phi \right)^\dagger D^\mu \Phi \right] \times \left[\left(D_\nu \Phi \right)^\dagger D^\nu \Phi \right]$$
$$\mathcal{O}_{S_2} = \left[\left(D_\mu \Phi \right)^\dagger D_\nu \Phi \right] \times \left[\left(D^\nu \Phi \right)^\dagger D^\mu \Phi \right]$$

Wilson coefficients for these operators and analogous transverse dimension-8 operators can be set in anomV.dat

Field strength ←→ transverse polarizations

Transverse operators

$$\mathcal{O}_{T_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
$$\mathcal{O}_{T_1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$
$$\mathcal{O}_{T_2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right]$$
$$\mathcal{O}_{T_5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta},$$
$$\mathcal{O}_{T_6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu},$$
$$\mathcal{O}_{T_7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha},$$
$$\mathcal{O}_{T_8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta},$$
$$\mathcal{O}_{T_9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$$

$$O_{T_3} = \mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}^{\alpha\beta}\right)\mathrm{Tr}\left(\hat{W}_{\nu\alpha}\hat{W}_{\beta\mu}\right)$$
$$O_{T_X} = \mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}^{\alpha\beta}\right)\hat{B}_{\nu\alpha}\hat{B}_{\beta\mu}$$

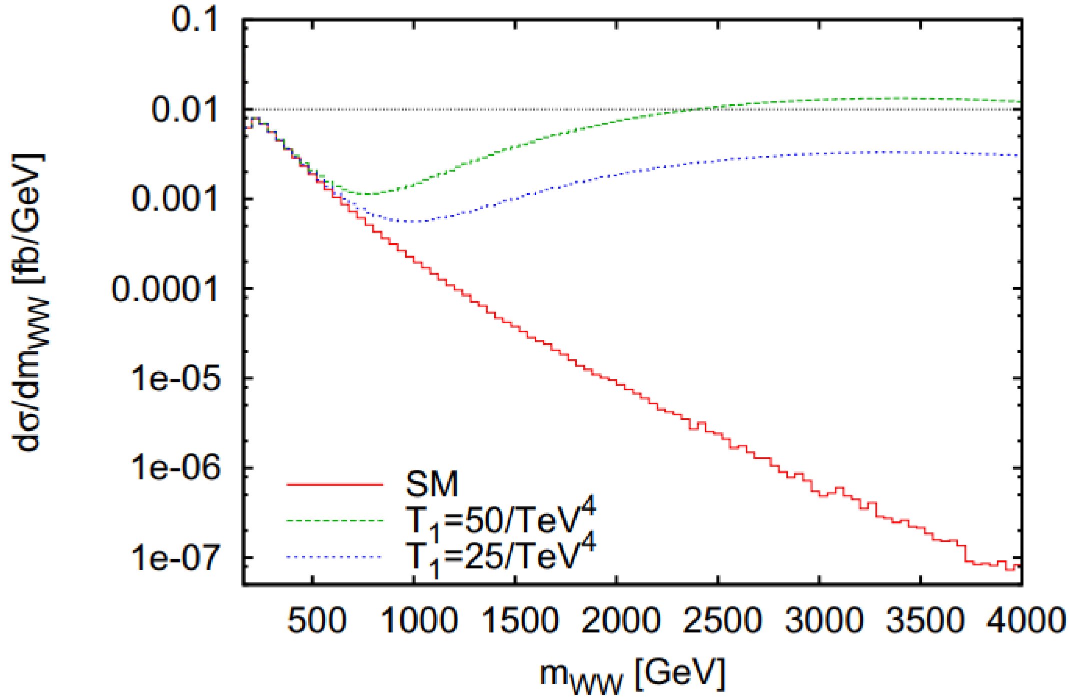
←To be added in VBFNLO 3.0 release

Mixed: transverse-longitudinal

$$\mathcal{O}_{M_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M_1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M_2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M_3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M_4} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu},$$
$$\mathcal{O}_{M_5} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu},$$
$$\mathcal{O}_{M_7} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right].$$

$VV \to W^+W^-$ with dimension 8 operators

Effect of constant $T_1 = \frac{f_{M,1}}{\Lambda^4}$ on $pp \to W^+W^- jj \to e^+ \nu_e \mu^- \bar{\nu}_\mu jj$



- Huge increase in cross section at high m_{WW} is completely unphysical
- Need form factor for analysis or some other unitarization procedure

Unitarization of tree level amplitude: $T_0 \rightarrow T_u$

- K-matrix (also called T-matrix) procedure for on-shell hermitian T_0

$$\mathbf{T}_L = \left(\mathbb{1} - \frac{\mathrm{i}}{2}\mathbf{T}_0^\dagger\right)^{-1} \frac{1}{2}\left(\mathbf{T}_0 + \mathbf{T}_0^\dagger\right) = \left(\mathbb{1} + \frac{1}{4}\mathbf{T}_0\mathbf{T}_0\right)^{-1}\left(\mathbf{T}_0 + \frac{\mathrm{i}}{2}\mathbf{T}_0\mathbf{T}_0\right)$$

- General virtualities → T_0 not normal for off-shell VV→VV

  Must distinguish

$$\mathbf{A}_{t\leftarrow s} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_3,q_4;q_1,q_2)$$
$$\mathbf{A}_{s\leftarrow t} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(k_3,k_4;k_1,k_2)$$
$$\mathbf{A}_{t\leftarrow t} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_3,q_4;k_1,k_2)$$

- Use

$$\mathbf{A}^{\text{unit}}_{t\leftarrow s} = \left(\mathbb{1} + \frac{1}{4}\mathbf{A}_{t\leftarrow s}\mathbf{A}_{s\leftarrow t}\right)^{-1}\left(\mathbf{A}_{t\leftarrow s} + \frac{\mathrm{i}}{2}\mathbf{A}_{t\leftarrow t}\mathbf{A}_{t\leftarrow s}\right)$$

- Alignment problems avoided by using largest eigenvalue of denominator

$$\mathbf{A}^{\text{unit}}_{t\leftarrow s} = \left(\mathbb{1} + \frac{1}{4}a^2_{\max}\right)^{-1}\left(\mathbf{A}_{t\leftarrow s} + \frac{\mathrm{i}}{2}\mathbf{A}_{t\leftarrow t}\mathbf{A}_{t\leftarrow s}\right)$$

Defines T_u model

T_u model unitarization now implemented for all VBS processes in VBFNLO

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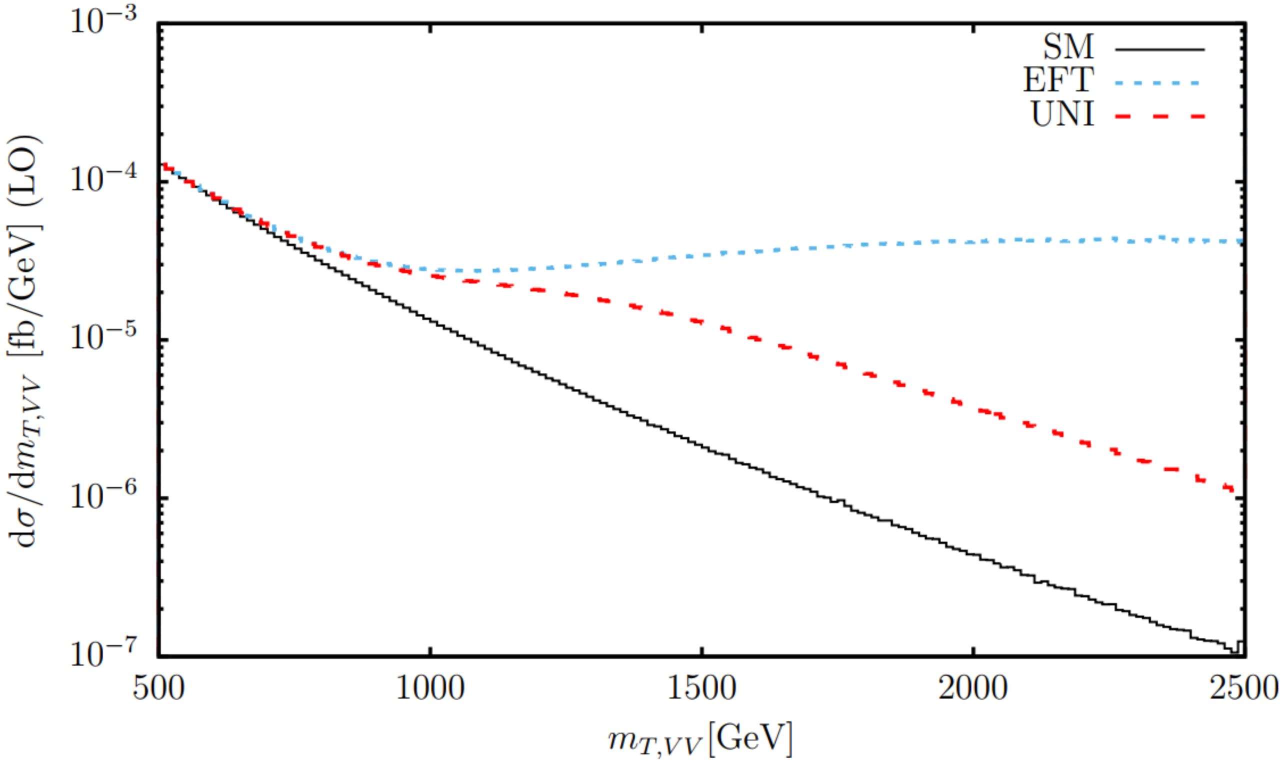
$$qq \to W^+Zjj \to l^+l^-l^+\nu_l jj,$$



Will be made available in new release 3.0 of VBFNLO in 2021

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