KIT
Karlsruher Institut für Technologie

POWHEG & VBFNLO

Weak boson production via vector-boson fusion @ NLO matched with POWHEG

Carlo Oleari, Franziska Schissler, Dieter Zeppenfeld | 5/8/2012, PHENO 2012

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Outline

VBFNLO

[Arnold et al 2011, 2008]

Fully flexible parton level Monte-Carlo program for processes with electroweak bosons at NLO-QCD

- Various weak boson fusion processes
- Diboson production
- Triboson production
- Beyond the Standard Model:
  - MSSM with real or complex parameters
  - Anomalous Higgs and gauge boson couplings
  - ...
- ...

Goal: Matching to Parton Shower

avoid double counting → POWHEG-BOX [Alioli, Nason, Oleari, Re 2010]

POWHEG master formula

[Nason 2004], [Frixione, Nason, Oleari 2007]

Subtraction formalism

- NLO cross section for $2 \to n$ process,

$$d\Phi_{n+1} = d\Phi_n \, d\Phi_{rad}, \; d\Phi_{rad} \propto dt\, dz\, d\varphi$$

$$d\sigma_{NLO} = \Big[\mathcal{B}(\Phi_n) + \underbrace{\overbrace{\mathcal{V}_{\rm b}(\Phi_n)}^{\text{UV finite}} + \mathcal{R}(\Phi_{n+1}) d\Phi_{rad}}_{\text{seprately IR divergent}}\Big] d\Phi_n, \;\; \mathcal{V}_{\rm b} = 2\mathrm{Re}\left(\mathcal{M}_B^* \mathcal{M}_V\right)$$

- add local Counterterms to cancel IR divergencies (KLN theorem)

[Kinoshita 1962], [Lee, Nauenberg 1964]

$$\mathcal{R}(\Phi_n, \Phi_{rad}) - \mathcal{C}(\Phi_n, \Phi_{rad}) \to \text{finite}$$

$$\mathcal{V}(\Phi_n) = \mathcal{V}_{\rm b}(\Phi_n) + \int \mathcal{C}(\Phi_n, \Phi_{rad}) d\Phi_{rad} \to \text{finite}$$

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$\overline{B}$-function

$$\overline{\mathcal{B}} = \Big[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \int \big[\mathcal{R}(\Phi_n, \Phi_{rad}) - \mathcal{C}(\Phi_n, \Phi_{rad})\big] d\Phi_{rad}\Big]$$

Inclusive NLO cross section at fixed underlying Born kinematics

- POWHEG first emission

$$d\sigma_{PWG} = \overline{\mathcal{B}}(\Phi_n)\, d\Phi_n \left[\Delta_{PWG}(\Phi_n, p_T^{min}) + \Delta_{PWG}(\Phi_n, k_T)\frac{\mathcal{R}(\Phi_n, \Phi_{rad})}{\mathcal{B}(\Phi_n)}\theta(k_T - p_T^{min})d\Phi_{rad}\right]$$

- POWHEG Sudakov factor: Probability of not emitting a parton with transverse momentum harder than p_T

$$\Delta_{PWG}(\Phi_n, p_T) = exp\left[-\int d\Phi'_{rad}\frac{\mathcal{R}(\Phi_n,\Phi_{rad})}{\mathcal{B}(\Phi_n)}\theta(k_T(\Phi_n, \Phi'_{rad}) - p_T)\right]$$

- NLO accuracy preserved in the hard region, $\Delta_{PWG}(\Phi_n, p_T) \approx 1$

$$d\sigma_{PWG} \approx \frac{\overline{\mathcal{B}}(\Phi_n)}{\mathcal{B}(\Phi_n)}\mathcal{R}(\Phi_n, \Phi_{rad})d\Phi_n d\Phi_{rad} \approx \mathcal{R}(\Phi_n, \Phi_{rad})\left(1 + \mathcal{O}(\alpha_s)\right)\, d\Phi_n\, d\Phi_{rad}$$

- Leading-Log accuracy of a Shower Monte Carlo program in the soft/collinear limit $k_T \longrightarrow 0$

$$\frac{\mathcal{R}(\Phi_n, \Phi_{rad})}{\mathcal{B}(\Phi_n)}d\Phi_{rad} \approx \frac{\alpha_s}{2\pi}\frac{1}{t}P(z)\, dt\, dz\frac{d\varphi}{2\pi}, \quad \overline{\mathcal{B}} \approx \mathcal{B}\left(1 + \mathcal{O}(\alpha_s)\right)$$

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The POWHEG-BOX

[Alioli, Nason, Oleari, Re 2010]

- FORTRAN code
- Projection of real cross section into singular regions
- Counter terms (soft/coll. approximation) & radiation phase space
  FKS subtraction method [Frixione, Kunszt, Signer 1996], [Frixione 1997]
- pdfs (LHAPDF)
- NLO differential cross section $\longrightarrow$ comparison to VBFNLO
- LesHouches event files (unweighted events)
  - Calculate upper bounds for efficient generation of Sudakov suppressed events
  - Hardest emission according to POWHEG Sudakov factor

Needed ingredients

obtained from VBFNLO-subroutines, converted into POWHEG-BOX format

1. Flavour structures of Born & Real processes
2. Coupling constants (conversion to POWHEG-format) [Jäger, Zanderighi 2011]
3. Born phase space (PS)
4. Born squared amplitudes $\mathcal{B}$
   - color-correlated $\mathcal{B}_{ij}$
   - spin-correlated $\mathcal{B}_{\mu\nu}$
5. Born color structures in $N_c \to \infty$ limit
6. Real matrix elements squared
7. Virtual finite part $2\,\mathrm{Re}\left[\mathcal{M}_{\mathcal{V}}\mathcal{M}^*_{\mathcal{B}}\right]$

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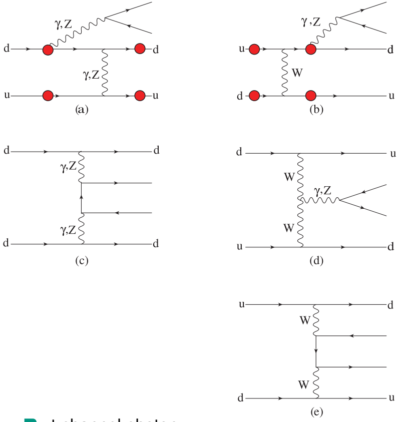
$Z \to l^+ l^-$ Production in Vector Boson Fusion

Details of the Implementation

Born & Real contributions, full off-shell effects [Oleari, Zeppenfeld 2003]



- t-channel photon

- (a),(b) Vector boson pair production, neglected, strongly suppressed in VBF region
- (c),(d) $g \to q\bar{q}$ splittings, included
- treat upper and lower quark line distinct (no interaction due to color flow)
- tagging of parton lines [Nason, Oleari 2009]

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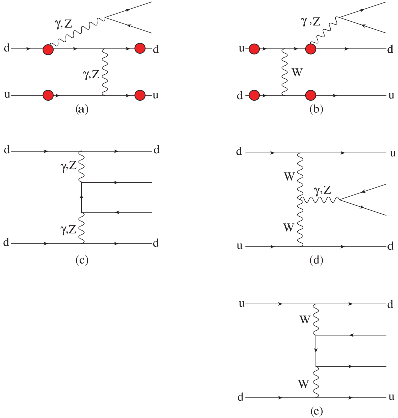

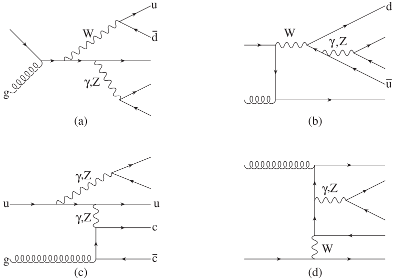

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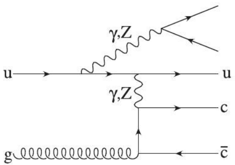


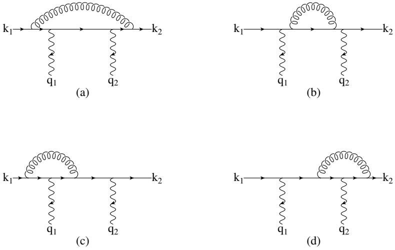
- $c\bar{c}$ lead to visible jets $\longrightarrow$ vanishing momentum transfer of γ
- collinear singularity $\rightarrow$ QED correction to $g\gamma \rightarrow c\bar{c}Z$
- absorbed in Photon PDF
- HERE: impose cut $|t| > Q^2_{\gamma,min} = 4\ \text{GeV}^2$
- replace missing piece by $p\gamma \rightarrow ZjjX$ (quite small)
- in VBF region: $Q^2_{\gamma,min} = 4\ \text{GeV}^2$, $Q^2_{\gamma,min} = 0.1\ \text{GeV}^2$ $\rightarrow$ 2‰ effect

Phase space

- use 'unweighted' events generated by VBFNLO (weight $= \frac{\sigma_{LO}}{\mathcal{M}_B^2}$)
- already optimized, flat $\rightarrow$ no integration needed
- cuts, caution with migration effects - check fixed order distributions

Virtual Contributions

- one vector boson attached to quarkline: Vertex corrections
- two vector bosons, boxes
- $Q^2 = 2\, k_1 \cdot k_2$



Virtual contribution per fermion line:

$$2\,\mathrm{Re}\left[\mathcal{M}_V \mathcal{M}_B^*\right] = |\mathcal{M}_B|^2 \frac{\alpha_s(\mu_R)}{2\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon)\left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 8\right] + 2\,\mathrm{Re}\left[\tilde{\mathcal{M}}_V \mathcal{M}_B^*\right]$$

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$$+\,2\,\mathrm{Re}\left[\tilde{\mathcal{M}}_V \mathcal{M}_B^*\right]$$

Finite part in POWHEG-BOX convention:

$$\mathcal{N} = \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu_R^2}{Q_P^2}\right)^\epsilon, Q_P = \mu_R.$$

$$2\,\mathrm{Re}\left[\mathcal{M}_V^{fin} \mathcal{M}_B^*\right] = |\mathcal{M}_B|^2 \frac{\alpha_s(\mu_R)}{2\pi} C_F \left[-\ln^2\left(\frac{\mu_R^2}{Q^2}\right) - 3\ln\left(\frac{\mu_R^2}{Q^2}\right) - 8\right]$$
$$+\,2\,\mathrm{Re}\left[\tilde{\mathcal{M}}_V \mathcal{M}_B^*\right]$$

Preliminary Results

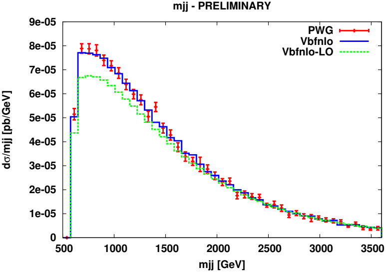
- diagonal CKM-matrix $\rightarrow$ no tagging of flavor
- only massless external partons, *b*-contributions neglected ($\approx \mathcal{O}(1\%)$ for neutral bosons in t-channel)
- (modified) complex mass scheme [Denner, Dittmaier, Roth, Wackeroth, 1999]
- PDF: CT10 [Lai et al, 2010]
- FASTJET 2.4.4 [Cacciari, Salam, Soyez, 2006]
- $\mu_R = \mu_F = M_Z$

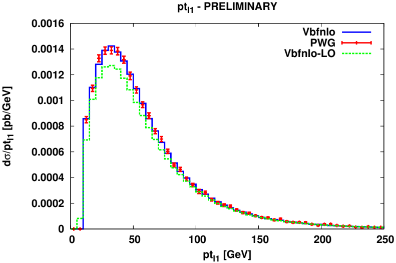
CUTS:

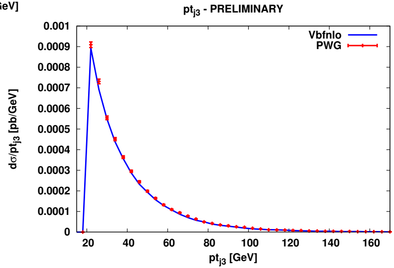
- Basic: $p_T^j \geq 20$ GeV, $|\eta_j| \leq 4.5$, $R_{jj} \geq 0.8$
- Leptons: $p_T^l > 10$ GeV, $|\eta_l| \leq 2.5$, $m_{ll} \geq 15$ GeV, $R_{ll} \geq 0.6$, $R_{jl} \geq 0.8$
- VBF: $m_{jj} \geq 600$ GeV, $\Delta\eta_{jj} > 4.2$, $\eta_{j1} \cdot \eta_{j2} < 0$, $\eta_{j,min} + 0.6 \leq \eta_l \leq \eta_{j,max} - 0.6$

Fixed order, preliminary

$\sigma = 96.95$ fb, $K = 1.1$







Conclusion & Outlook

- unweighted events as phase space generator $\surd$
- Vector boson fusion
  - *Zjj*: good agreement on parton level
  - next step: Parton shower
  - *Hjj* (VBF) checked against POWHEG-BOX [Nason, Oleari 2009]
  - plenty of other VBF processes
  - anomalous couplings
  - BSM Models
- other weak processes
  - $WW \to e^+ \nu_e \; \mu^- \; \overline{\nu}_\mu$ finished and checked [Melia et al, 2011]
  - anomalous couplings
  - WZ, $W\gamma$
  - Triboson processes