Vector Boson Pair Production Processes with Semileptonic Decays in VBFNLO

Pheno 2013, Pittsburgh

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Motivation

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- In discussion of processes with electroweak bosons:
  usually consider leptonic decay modes of vector bosons
  $\Rightarrow$ gives clearer signal, much better background suppression
- But: $BR(W \to \ell\nu) = \mathcal{O}(30\%)$, $BR(Z \to \ell\ell) = \mathcal{O}(10\%)$,
  while $BR(W \to q\bar{q}) \approx BR(Z \to q\bar{q}) = \mathcal{O}(70\%)$
  $\Rightarrow$ purely leptonic decays limit rates, especially for more than one produced vector boson, e.g.

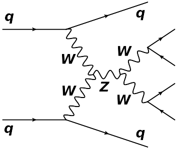
$$pp \to H\,jj \to W^+W^-\,jj \to \ell^+\nu\,\ell^-\bar{\nu}\,jj$$

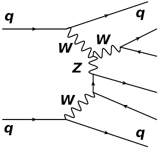
- Experiments extend their analyses and let one vector boson decay hadronically in order to increase sensitivity.
- $\Rightarrow$ Add predictions for the semileptonic case to the program package VBFNLO.

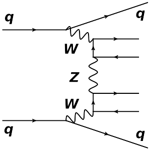
[K. Arnold, M. Bahr, J. Bellm, G. Bozzi, M. Brieg, F. Campanario, C. Englert, BF, T. Figy, J. Frank, F. Geyer, N. Greiner, C. Hackstein, V. Hankele, B. Jager, M. Kerner, G. Klamke, M. Kubocz, C. Oleari, S. Palmer, S. Platzer, S. Prestel, M. Rauch, H. Rzehak, F. Schissler, O. Schlimpert, M. Spannowsky, M. Worek, D. Zeppenfeld; 2008, 2011, 2012]

VBFNLO

- VBFNLO is a parton-level Monte Carlo program that gives predictions in NLO QCD for many processes which involve the production of multiple electroweak bosons:
  - $pp \to Hjj$ in VBF, with $H \to WW/ZZ$
  - $pp \to VVjj$ in VBF, with $V \in \{W, Z\}$
  - $pp \to VV(V)$
  - $gg(\to H) \to VV$ at one-loop (LO QCD)
  - + several other processes
- Also single- and non-resonant contributions giving rise to the specific leptonic final state are included.
- In the current release only the leptonic decay modes of W and Z bosons are available.
- The goal is to extend those processes with semileptonic decay modes, e.g. replace one $\ell\nu$ pair ("hadronic W decay") or one $\ell^+\ell^-$ pair ("hadronic Z decay") with a $q\bar{q}'$ pair.







Implementation in VBFNLO I

- Replacing the electroweak leptonic decay by the corresponding hadronic decay mode at leading order has been done for several processes:
  - $pp \to WW\,jj$ / $ZZ\,jj$ in VBF
  - $pp \to VV$, with $V \in \{W, Z\}$, also gg initiated processes
  - $pp \to WWZ$

Process @ LO in production & decay	fully leptonic	$W^+ \to u\bar{d}$ / $Z \to u\bar{u}$	$W^- \to d\bar{u}$ / $Z \to d\bar{d}$
$pp \to W^+W^-$, 8 TeV, no cuts	$408.86(5)$ fb	$1226.3(1)$ fb	$1226.3(1)$ fb
$pp \to W^+W^-$, 8 TeV, inclusive cuts [1]	$243.46(4)$ fb	$760.3(1)$ fb	$792.3(1)$ fb
$pp \to ZZ$, 8 TeV, inclusive cuts [1]	$5.704(2)$ fb	$23.657(7)$ fb	$29.613(9)$ fb
Process @ NLO in production, LO decay			
$pp \to^{+} W^-$, 8 TeV, inclusive cuts [1]	$363.9(1)$ fb	$1216.9(3)$ fb	$1244.4(3)$ fb
$pp \to ZZ$, 8 TeV, inclusive cuts [1]	$8.024(5)$ fb	$44.14(4)$ fb	$45.88(3)$ fb

[1] $|\eta_j| < 4.5$, $|\eta_l| < 2.5$, $|p_T| > 15\,\text{GeV}$, $\Delta R_{ij} > 0.4$

Implementation in VBFNLO II

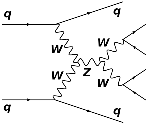
- Further improvements with respect to the 2012 release of VBFNLO:
  - Implementation of anomalous triple and quartic gauge boson couplings extended to all triboson (plus jet) and VVjj in VBF production processes.
  - List of several minor improvements on our website.

- Next beta version:
  - Semileptonic decays in VBF Higgs production signal process with $H \to WW/ZZ$.
  - Full set of anomalous gauge boson couplings are supported also for semileptonic decays.
  - K-factor for $V \to q\bar{q}$ decay $(K = 1 + \frac{\alpha_s}{\pi})$ can be included into semileptonic decay processes as approximation for NLO decay, given that
    - production and decay do not interfere due to lifetime of vector boson
    - resonant vector boson production dominates the process

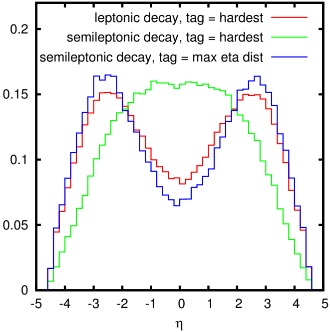
- More information: http://www.itp.kit.edu/vbfnlo .

Tagging Jet Definition I

- in VBF processes, two widely separated forward jets occur.
  $\Rightarrow$ Tagging jets allow for a very efficient background reduction.
- Leptonic decays: Usually use hardest jets as tagging jets.
- No good choice for semileptonic decays: Can originate from the vector boson decay. (bosons with large p_T in heavy Higgs boson search).
- Using the two jets with largest distance in rapidity works for signal process, but is not practicable if backgrounds are considered as well.
  $\Rightarrow$ Need another tagging jet definition.

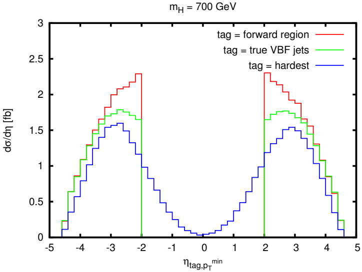


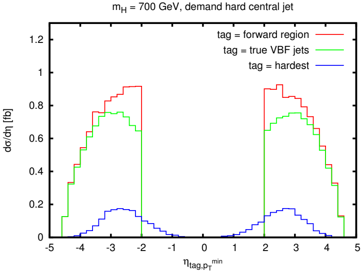
1/σ * dσ/dη for softer tagging jet



$pp \to WWjj$ in VBF, light Higgs, inclusive cuts

Tagging Jet Definition II





- Separate phase space explicitly:
  - tagging jets: $|\eta_{tag}| > \eta_c$, $\eta_1 \cdot \eta_2 < 0$
  - vector boson decay products: $|\eta_{decay}| < \eta_c$
  - require high-p_T jet in the central region
- Tagging jet definition useful for high-mass Higgs boson search. *[Iordanidis, Zeppenfeld; 1998]*
- $\Rightarrow$ much better performance for high m_H than “traditional” tagging jet choice.

Combinatorics in Real Emission I

- When considering the production process at NLO QCD, the K-factor significantly increases when switching from leptonic to semileptonic decay modes.
- For WW production with inclusive cuts:
  - $K = 1.55$ for fully leptonic decays
  - $K = 1.78$ for semileptonic decays
- Due to combinatorics:
  - 2 jets are required, but up to 3 jets available with real emission.
  - Fraction of cross section with visible QCD jet in leptonic decay mode: 31%.
  - $\Rightarrow$ Quite often one decay jet may fail the cuts and the event is still kept.
  - Less stringent cuts for real emission kinematics compared to born kinematics.
- Consistency check: declare only decay jets as visible jets
  $\Rightarrow$ recover $K = 1.52$ of leptonic decay.

Combinatorics in Real Emission II

- Experiments usually will include a cut to check the compatibility of the invariant dijet mass with the decaying vector boson.
- $\Rightarrow$ With the requirement $|m_{jj} - m_W| < 20\,\mathrm{GeV}$ regain the K-factor from the leptonic decay for WW production: $K = 1.57$
- For the VBF processes the K-factor from the leptonic decay is not completely recovered, e.g. $WWjj$ in VBF with a heavy Higgs boson:
  - $K = 0.99$ for fully leptonic decays
  - $K = 1.32$ for semileptonic decays without mass reconstruction
  - $K = 1.20$ for semileptonic decays with mass reconstruction

  $\Rightarrow$ Additional jets in this process still leave some room for jet combinations.

Anomalous Quartic Gauge Boson Couplings I

- VBFNLO supports anomalous triple and quartic gauge boson couplings in almost all processes. [BF, Zeppenfeld; 2009], [Schlimpert, Zeppenfeld; 2012]
- We assume EWSB with a light Higgs boson, possible dim-6 and dim-8 operators discussed in [Hagiwara, Ishihara, Szalapski, Zeppenfeld; 1993], [Eboli, Gonzales-Garcia, Mizukoshi; 2006]

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{L}_j$$

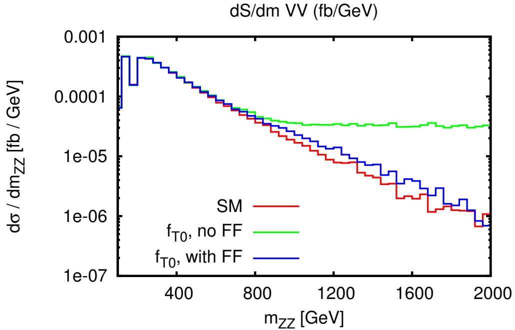
- Conversion from widely used α_4/α_5 parametrisation for quartic couplings is specific for each vertex!
- For aQGC using a form factor or another method that ensures unitarity is mandatory both for triboson production and vector boson scattering processes.
- Use a dipole form factor

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

- Determine the maximal allowed form factor scale with partial-wave analysis in on-shell vector boson scattering.

Anomalous Quartic Gauge Boson Couplings II

- Example: semileptonic $ZZjj$ production in VBF
  - Operator $\mathcal{L}_{T,0} = \text{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \text{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \quad \Rightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{f_{T0}}{\Lambda^4}\mathcal{L}_{T,0}$
  - with $\frac{f_{T0}}{\Lambda^4} = 10\,\text{TeV}^{-4}$
  - Maximal appropriate Λ_{FF} for this parameter with $n = 4$: $\Lambda_{FF} = 2.2\,\text{TeV}$



- Form factor calculation tool publicly available within the next days.

Summary & Outlook

- Electroweak gauge boson production is usually done incorporating leptonic decay of the bosons.
- To gain experimental sensitivity, analyses will include semileptonic decay modes.
- VBFNLO now also provides predictions for semileptonic decays of vector bosons. While the production process is usually at full NLO QCD, the hadronic decay is available at LO QCD with the option to include the K-factor from $V \to q\bar{q}$.
- Study of anomalous gauge and HVV couplings is possible. Unitarity has to be assured when using aQGC.
- Pitfalls in the implementation and study of the semileptonic decay modes are:
  - the tagging jet definition for VBF processes
  - possibly increased K-factor for NLO production due to combinatorics in real emission
- Next steps: Extend implementation to $W^{\pm}W^{\pm}jj$ and $WZjj$ in VBF.

Conversion $\mathcal{L}_{S,0}, \mathcal{L}_{S,1} \leftrightarrow \mathcal{L}_{\alpha_4}, \mathcal{L}_{\alpha_5}$

$$\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi\right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi\right] \quad (1)$$

$$\mathcal{L}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi\right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi\right] \quad (2)$$

$$\mathcal{L}_4^{(4)} = \alpha_4 \left[\mathrm{Tr}\left(V_\mu V_\nu\right)\right]^2, \quad \text{with } V_\mu = (D_\mu \Sigma)\, \Sigma^\dagger \quad (3)$$

$$\mathcal{L}_5^{(4)} = \alpha_5 \left[\mathrm{Tr}\left(V_\mu V^\mu\right)\right]^2 \quad (4)$$

from *[Eboli, Gonzales-Garcia, Mizukoshi; 2006]*

- Our results for the WWWW-Vertex:

$$\alpha_4 = \frac{f_0}{\Lambda^4} \frac{v^4}{8} \quad (5)$$

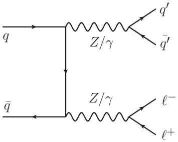
$$\alpha_4 + 2 \cdot \alpha_5 = \frac{f_1}{\Lambda^4} \frac{v^4}{16} \quad (6)$$

- Our results for the WWZZ-Vertex:

$$\alpha_4 = \frac{f_0}{\Lambda^4} \frac{v^4}{16} \quad (7)$$

$$\alpha_5 = \frac{f_1}{\Lambda^4} \frac{v^4}{16} \quad (8)$$

Virtual Photon Decay I

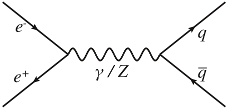


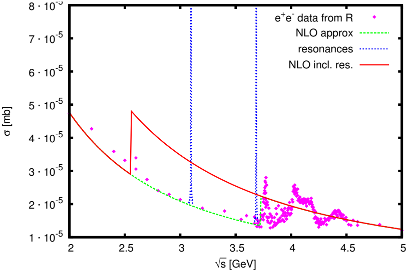
- Hadronic Z decays also include $\gamma^* \rightarrow q\bar{q}$.
- With massless quarks $\Rightarrow$ divergent if not eliminated by cuts.
- Can cause problems in two domains:
  - In real emission both decay quarks may form single jet.
  - Except for this divergence, VBF[1] and VV production finite without jet cuts.
    $\Rightarrow$ Could allow for single decay jets instead of requiring two visible decay jets.
    $\Rightarrow$ Interesting for highly boosted vector bosons.
- In reality divergence regularized by pion mass.
- Need to regularize the virtual photon contribution to get stable results.
- Want to describe virtual photon peak better than just applying a technical cut at some fixed value.
- Description of $q\bar{q}$ resonance structure not necessary, but roughly estimate size of photon peak contribution.

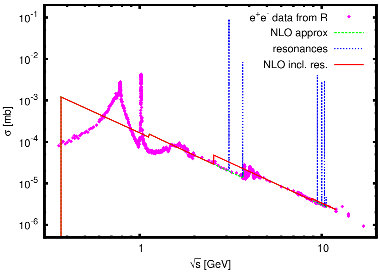
[1] VBF production actually has another one due to t-channel photon exchange. This needs an additional cut on the exchanged q^2 . The effect of this cut is small for final event selection cuts.

Virtual Photon Decay II : $e^+e^- \to hadrons$

- $e^+e^- \to hadrons$ is very similar to $\gamma^* \to q\bar{q}$ in vector boson decay.
- Idea: Cut $q\bar{q}$ final states in hadronic decay at thresholds determined in $e^+e^- \to hadrons$.
- Include resonance contributions by lowering the steps until integrated cross section of the NLO approx. matches data.



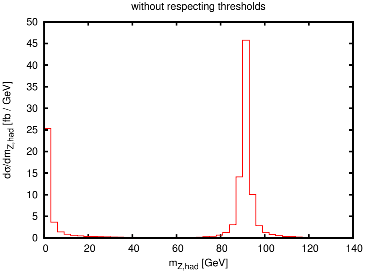


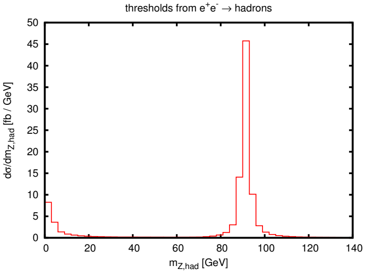


$$\sigma(e^+e^- \to had) = R \cdot \sigma(e^+e^- \to \mu^+\mu^-) = (3\Sigma_q e_q^2)(1 + \alpha_s/\pi) \cdot \sigma(e^+e^- \to \mu^+\mu^-)$$

[PDG; 2012 — Ezhela, Lugovsky, Zenin; 2003]

Virtual Photon Decay III





- Example with thresholds from $e^+e^- \to hadrons$: $pp \to ZZ \to q\bar{q}\,\ell\ell$
  - Inclusive cuts:
  - Allow for single decay decay jet from $q\bar{q}$ pair.
- No divergence in γ^* contribution anymore, result is stable.
- With a vector boson mass reconstruction cut on the jets this contribution disappears.