Electroweak Corrections for off-shell $W^+W^-$ Scattering

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RADCOR & LoopFest
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What is Vector Boson Scattering?

- interesting field to check the validity of
  - the standard model in general
  - especially electroweak symmetry breaking

\[
W^+ W^+ W^- W^- = \cdots + h + \gamma, Z + \cdots
\]

- exact cancellation of unitarity-violating high-energy behaviour of longitudinal modes
- very sensitive to BSM physics
- need of precise SM predictions
Previous work

- 2006: corrections $\mathcal{O}(\alpha_1^1 \alpha_6^6)$ in VBS approximation [Jäger, Oleari, Zeppenfeld; arXiv:hep-ph/0603177]

- 2011/12: corrections $\mathcal{O}(\alpha_3^3 \alpha_4^4)$ [Melia, Melnikow, Röntsch, Zanderighi; arXiv:1104.2327] [Greiner et al.; arXiv:1202.6004]

- 2013/16: corrections $\mathcal{O}(\alpha_1^1 \alpha_6^6) + \text{parton shower}$ [Jäger, Zanderighi; arXiv:1301.1695] [Rauch, Plätzer; arXiv:1605.07851]

$\Rightarrow$ no electroewak corrections yet
Motivation and introduction
Differences to other VBS processes
Setup and (preliminary) results
Summary & outlook

Opposite sign WW scattering

- experimentally interesting
  - high cross section ($> 10 \times$ larger) compared to other VBS processes $\sigma_{W^+ W^-} \sim 10 \text{ fb}$
  - but also large background from (misidentified) $t \bar{t}$ production
    $\sigma_{t\bar{t}} \sim 1 \text{ nb}$ [ATLAS; arXiv:1910.08819]
  - not measured yet, measurements are forthcoming
- includes EW Higgs production via VBF and Higgs decay to $W$ bosons
  - problematic: we cannot cut it out via physical cuts
  - interesting process also for Higgs physics

\[ h 

\]
Details of the calculation

\[ pp \rightarrow e^+ \mu^- \nu_e \bar{\nu}_\mu jj + X \]

- Monte Carlo integration with BBMC (in-house Monte Carlo)
- Calculation of matrix elements with \textsc{Recola} [Actis, Denner, Hofer, Lang, Scharf, Uccirati; arXiv:1605.01090] and \textsc{Collier} [Denner, Dittmaier, Hofer; arXiv:1604.06792]
  - Dimensional regularisation for IR singularities
  - Renormalisation in on-shell scheme

- Input:
  - Pdf set \textsc{NNPDF3.1luxQED} [Bertone, Carrazza, Hartland, Rojo; arXiv:1712.07053]
  - Running of $\alpha_S$ from pdfs
  - Determination of $\alpha$ in $G_\mu$ scheme
Signal diagrams

\[ u \rightarrow \mu^- \rightarrow \bar{\nu}_\mu \rightarrow d \rightarrow \bar{\nu}_\mu \rightarrow \nu_e \rightarrow e^+ \rightarrow u \]

\[ d \rightarrow \mu^- \rightarrow \bar{\nu}_\mu \rightarrow u \rightarrow \nu_e \rightarrow e^+ \rightarrow d \]

\[ d \rightarrow \mu^- \rightarrow \bar{\nu}_\mu \rightarrow u \rightarrow \nu_e \rightarrow e^+ \rightarrow d \]

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Process structure

\[
\begin{align*}
\text{LO} & \quad \mathcal{O}(\alpha^6) & \quad \mathcal{O}(\alpha_s \alpha^5) & \quad \mathcal{O}(\alpha_s^2 \alpha^4) \\
\text{EW} & \quad \text{QCD} & \quad \text{QCD} & \quad \text{QCD} \\
NLO & \quad \mathcal{O}(\alpha^7) & \quad \mathcal{O}(\alpha_s \alpha^6) & \quad \mathcal{O}(\alpha_s^2 \alpha^5) & \quad \mathcal{O}(\alpha_s^3 \alpha^4)
\end{align*}
\]

<table>
<thead>
<tr>
<th>(W^+ W^+)</th>
<th>(\sigma_{\alpha_s^0 \alpha^6}/\text{fb})</th>
<th>(\sigma_{\alpha_s^1 \alpha^5}/\text{fb})</th>
<th>(\sigma_{\alpha_s^2 \alpha^4}/\text{fb})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W^+ Z)</td>
<td>0.25511(1)</td>
<td>0.006824(1)</td>
<td>1.0973(1)</td>
</tr>
<tr>
<td>(Z Z)</td>
<td>0.097683(2)</td>
<td>0.008628(1)</td>
<td>1.06248(5)</td>
</tr>
<tr>
<td>(W^+ W^-)</td>
<td>2.67(3)</td>
<td>0.066(4)</td>
<td>6.93(1)</td>
</tr>
</tbody>
</table>

The Higgs resonance (I)

- first appearance in the fiducial phase space region:

\[ Z, W_{\pm} \rightarrow W_{\pm}, W_{\mp} \rightarrow h \rightarrow 120, 24, 96, 32, 64, 16, 8, 4, 1 \]

- with its very sharp resonance peak

- problem of our Monte Carlo: mapping of invariants in fixed order back-to-front \( s_{24} \rightarrow s_{96} \rightarrow s_{120} \)
The Higgs resonance (II)

- both $W$ bosons mapped resonant $\Rightarrow h$ almost never resonant

\[ s_{16} = (p_8 + p_{16})^2 \approx m_W^2, \quad s_{96} = (p_{32} + p_{64})^2 \approx m_W^2 \]

$\Rightarrow s_{120} > (\sqrt{s_{24}} + \sqrt{s_{96}})^2 > m_H^2$ mostly
The Higgs resonance (III)

- Problem enhanced at NLO in Catani-Seymour algorithm:
  - Used to subtract divergencies in collinear and soft regions
  - Redistributions momenta of emitter $p_i$, emissus $p_j$ and some spectator $p_k$ to a reduced $n-1$ particle PS with momenta $\tilde{p}_{ij}, \tilde{p}_{k}$
  - Normally no severe impact on “non-dangerous” PSP . . .
  - . . . but it may shift the momenta in the reduced PS to the Higgs resonance
    $\Rightarrow$ real ME and subtracted ME do not match

- Monte Carlo signature: events with extremely large weights
  $\Rightarrow$ unstable integration
The Higgs resonance (IV)

real ME \quad \Rightarrow \quad \text{subtracted ME}

\begin{align*}
&\begin{array}{c}
\begin{array}{c}
\hat{p}_k \ 4 \\
\hat{p}_i \ 8 \\
\hat{p}_j \ 256 \\
\end{array}
\end{array} \\
&\begin{array}{c}
\begin{array}{c}
h^* \ 376 \\
W^* \ 280 \\
96 \\
\end{array}
\end{array} \\
&\begin{array}{c}
\begin{array}{c}
W^* \ 16 \\
\end{array}
\end{array}
\end{align*}

\begin{align*}
&\begin{array}{c}
\begin{array}{c}
\hat{\tilde{p}}_k \ 4 \\
\hat{\tilde{p}}_{ij} \ 8 \\
\end{array}
\end{array} \\
&\begin{array}{c}
\begin{array}{c}
h^* \ 120 \\
W^* \ 24 \\
96 \\
\end{array}
\end{array} \\
&\begin{array}{c}
\begin{array}{c}
W^* \ 16 \\
\end{array}
\end{array}
\end{align*}

\begin{align*}
s_{280} &\approx m_W^2,  \\
s_{96} &\approx m_W^2 \\
s_{376} &> m_H^2
\end{align*}

\Rightarrow \quad \begin{align*}
&\begin{array}{c}
\tilde{s}_{24} \not\approx m_W^2,  \\
\tilde{s}_{96} &\approx m_W^2 \\
\tilde{s}_{120} &\approx m_H^2 \text{ possible}
\end{array}
\end{align*}

depending on the combination of momenta of emitter, emissus and spectator, formerly non-resonant particles can become resonant.
**Solution**

- introduction of additional integration channels
- 3 steps:
  - determine all (free) s-channel invariants back to front
  - separate massive and massless s-channel invariants
  - do a cyclic permutation of massive s-channel invariants

\[
(s_{96} \rightarrow s_{280} \rightarrow s_{376}), \quad (s_{280} \rightarrow s_{376} \rightarrow s_{96}), \quad (s_{376} \rightarrow s_{96} \rightarrow s_{280})
\]

- for every possibly resonant propagator: at least 1 integration channel that maps this propagator first
- let the channel weight optimisation do the rest
  \Rightarrow \text{dominant integration channels with resonant Higgs}
General setup

- simulate $pp$ collider at $\sqrt{s} = 13$ TeV
- only light jets; b-jet veto
- cluster jets with anti-\(k_T\) algorithm \cite{Cacciari:2008gp}, resolution parameter $R = 0.4$
- consider only particles with $|y| < 5$ for recombination
- recombination $j\gamma \to j, \ell\gamma \to \ell$, resolution parameter $R = 0.4$
- use scales $\mu_F = \mu_R = \sqrt{p_{T,j_1} p_{T,j_2}}$
## Two experimental cut setups

<table>
<thead>
<tr>
<th>inspired by</th>
<th>“VBS setup”</th>
<th>“Higgs setup”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T,\ell\ell$</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>$p_T,j_1, p_T,j_2$</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>$p_T,\ell 1$</td>
<td>$&gt; 25$ GeV</td>
<td>$&gt; 25$ GeV</td>
</tr>
<tr>
<td>$p_T,\ell 2$</td>
<td>$&gt; 13$ GeV</td>
<td>$&gt; 10$ GeV</td>
</tr>
<tr>
<td>$p_T,\text{miss}$</td>
<td>$&gt; 20$ GeV</td>
<td>$&gt; 20$ GeV</td>
</tr>
<tr>
<td>$\Delta R_{j\ell}$</td>
<td>$&gt; 0.4$</td>
<td>$&gt; 0.4$</td>
</tr>
<tr>
<td>$\Delta R_{\ell\ell}$</td>
<td>$-$</td>
<td>$&gt; 0.4$</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$&gt; 50$ GeV</td>
<td>$&gt; 12$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>y_{\ell}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>y_{j}</td>
<td>$</td>
</tr>
<tr>
<td>$M_{jj}$</td>
<td>$&gt; 300$ GeV</td>
<td>$&gt; 400$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y_{jj}</td>
<td>$</td>
</tr>
<tr>
<td>$m_{T,4,\ell}$</td>
<td>$-$</td>
<td>$\in [60$ GeV, $125$ GeV]</td>
</tr>
<tr>
<td>$</td>
<td>z_{\ell jj}</td>
<td>$</td>
</tr>
<tr>
<td>jet veto: $p_T,j_3$</td>
<td>$-$</td>
<td>$&lt; 30$ GeV</td>
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<td>$p_T,j_1, p_T,j_2$</td>
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</tr>
<tr>
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<td>&gt; 25 GeV</td>
<td>&gt; 25 GeV</td>
</tr>
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<tr>
<td>$\Delta R_{\ell\ell}$</td>
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</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>&gt; 50 GeV</td>
<td>&gt; 12 GeV</td>
</tr>
<tr>
<td>$</td>
<td>y_\ell</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>y_j</td>
<td>$</td>
</tr>
<tr>
<td>$M_{jj}$</td>
<td>&gt; 300 GeV</td>
<td>&gt; 400 GeV</td>
</tr>
<tr>
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<td>\Delta y_{jj}</td>
<td>$</td>
</tr>
<tr>
<td>$m_{T,4\ell}$</td>
<td>–</td>
<td>$\in [60 \text{ GeV}, 125 \text{ GeV}]$</td>
</tr>
<tr>
<td>$</td>
<td>z_{\ell jj}</td>
<td>$</td>
</tr>
<tr>
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</table>
Differential distributions (I) – preliminary

(a) $p_{T,j_1}$

(b) $p_{T,e^+}$

• typical VBS signature: large corrections (up to $-40\%$) at high energies due to Sudakov logarithms
same behaviour of the corrections, but: bulk of the cross section at low lepton invariant masses
Differential distributions (III) – preliminary

(a) $\gamma_{j_1}$

(b) $\gamma_{e^+}$

- small jet rapidities very suppressed
- corrections in lepton rapidity almost constant
Differential distributions (IV) – preliminary

\( (a) \ \Delta R_{j_1j_2} \)

\( (b) \ \Delta R_{j_1e^+} \)

- again typical VBS signatures: clearly separated particles
## Electroweak corrections in different VBS processes

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{\alpha^6}/fb$</th>
<th>$\delta\sigma_{\alpha^7}/fb$</th>
<th>$\delta\sigma_{\alpha^7}/\sigma_{\alpha^6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ W^+$</td>
<td>1.4178(2)</td>
<td>−0.2169(3)</td>
<td>−15.3%</td>
</tr>
<tr>
<td>$W^+ Z$</td>
<td>0.25511(1)</td>
<td>−0.04091(2)</td>
<td>−16.0%</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.097683(2)</td>
<td>−0.015573(5)</td>
<td>−15.9%</td>
</tr>
<tr>
<td>$W^+ W^-$ (Higgs setup)</td>
<td>1.5322(2)</td>
<td>−0.115(3)</td>
<td>−7.5%</td>
</tr>
</tbody>
</table>

Summary & outlook

- $W^+ W^-$ scattering is *different* from other VBS processes.
- Higgs resonance plays an important role:
  - has severe impact on the behaviour of NLO cross sections
  - different setups for Higgs and VBS
- We plan to investigate a further setup in which we eliminate the Higgs resonance.
- Checks against other Monte Carlos (MoCaNLO) ongoing.
- Better statistics, additional setups and other orders in $\alpha_S$ coming soon.

Stay tuned ;-)
SM input parameters

\begin{align*}
m^\text{OS}_W &= 80.379 \text{ GeV} & \Gamma^\text{OS}_W &= 2.085 \text{ GeV} \\
m^\text{OS}_Z &= 91.1876 \text{ GeV} & \Gamma^\text{OS}_Z &= 2.4952 \text{ GeV} \\
m_h &= 125.0 \text{ GeV} & \Gamma_h &= 4.07 \cdot 10^{-3} \text{ GeV} \\
G_\mu &= 1.16638 \cdot 10^{-5} \text{ GeV}^{-2} & \alpha_S(m^2_Z) &= 0.118
\end{align*}
Definition of non-standard cut variables

\[ z_{\ell jj}^* = \frac{y_{\ell} - \frac{y_{j_1} + y_{j_2}}{2}}{y_{j_1} - y_{j_2}} \]

\[ m_{T,4\ell} = \sqrt{2 p_{T,\ell\ell} p_{T,\text{miss}}} [1 - \cos \Delta \phi \Sigma_{\ell\ell} \Sigma_{\nu\nu}] \]