Electroweak corrections to vector-boson scattering

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Outline

1. Introduction

2. Complete NLO corrections to $pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj$

3. Large NLO EW corrections to VBS

4. Conclusion
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2 Complete NLO corrections to \( pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj \)

3 Large NLO EW corrections to VBS

4 Conclusion
Physics issues of vector-boson scattering (VBS): \((V = W, Z)\)

- crucial test of electroweak (EW) symmetry breaking mechanism
  - Higgs boson important for unitarity of process
- search for anomalous quartic-gauge-boson couplings
  - sensitivity grows with energy of vector bosons
  - \(\rightarrow\) EW corrections (EWC) significant \(\propto \alpha \log^2(E/M_W)\)
- experimental signature
  - two forward/backward jets at large rapidities
  - large rapidity separation between jets
  - large di-jet invariant mass
  - final-state vector bosons in central region
- VBS purely EW process \((\mathcal{O}(\alpha^4)\) for stable \(V\)s)
Irreducible background to VBS

Final state: $VV + 2j$  
$(4l + 2j)$

- Full EW process  \( (\mathcal{O}(\alpha^4) \text{ for stable } V\text{s as above}) \)  
  not separable from VBS
- QCD process  \( (\mathcal{O}(\alpha_s^2\alpha^2) \text{ for stable } V\text{s}) \)  
  gauge-invariant contribution
- Interferences between EW and QCD contributions  
  \( (\mathcal{O}(\alpha_s\alpha^3) \text{ for stable } V\text{s}) \)  
  appear only for channels with identical or weak-isospin partner quarks
- Gluonic channels for neutral final states
- Irreducible background can be suppressed by cuts on $M_{jj}$ and $|\Delta y_{jj}|$
Existing calculations for $VV + 2$ jet production

**EW production:** $\mathcal{O}(\alpha^6)$

**QCD-induced production:** $\mathcal{O}(\alpha_s^2 \alpha^4)$

- Full LO predictions: Ballestrero, Franzosi, Maina ’10 (PHANTOM)
- NLO QCD corrections to EW diagrams:
  - Jäger, Oleari, Zeppenfeld (+ Bozzi) ’06, ’07, ’09 (VBFNLO);
  - Denner, Hosekova, Kallweit ’12
  - PS matching: Zanderighi, Jäger ’11, ’13 + Karlberg ’14
  - Rauch, Plätzer ’16 ($W^+W^-, ZZ$)
  - ($W^+W^+$)
- NLO QCD corrections to QCD diagrams:
  - Melia, Melnikov, Röntsch, Zanderighi ’10, ’11; Greiner et al. ’12;
  - Campanario, Kerner, Ninh, Zeppenfeld ’13, ’14 (VBFNLO)
  - PS matching: Melia, Nason, Röntsch, Zanderighi ’11
- NLO EW corrections
  - For on-shell VBS: Denner, Dittmaier, Hahn ’97; Denner, Hahn ’98
  - First results for a full $2 \rightarrow 6$ process: Denner et al. ’16, ’17
Process: \( pp \rightarrow W^+W^+jj \rightarrow \ell^+\nu\ell'^+\nu\ell'jj \)

- distinct signature: same-sign di-leptons + \( E_T \) + 2 jets
  - same-sign leptons reduce SM background significantly
- no contributions of gluonic channels
- largest cross section ratio EW to QCD production
  - EW production mode dominates QCD production for VBF cuts
- experimental evidence:
  - ATLAS '14, ’16 (4.5\(\sigma\) for WWjj, 3.6\(\sigma\) for EW contribution)
  - CMS ’14 (2.0\(\sigma\) for WWjj, 1.9\(\sigma\) for EW contribution)
  - observation: CMS ’16 5.5\(\sigma\) for EW WWjj
- background for New Physics leading to same-sign lepton final states
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Recent calculation  Biedermann, Denner, Pellen ’17

LO EW process:  \( pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj \quad \mathcal{O}(\alpha^6) \)

- all partonic channels included

  - \( uu \rightarrow \mu^+ \nu_\mu e^+ \nu_e dd \)  \( (t, u) \)  \[67\%\]
  - \( cc \rightarrow \mu^+ \nu_\mu e^+ \nu_e ss \)  \( (t, u) \)
  - \( ud \rightarrow \mu^+ \nu_\mu e^+ \nu_e d\bar{u} \)  \( (t, s) \)  \[16\%\]
  - \( cs \rightarrow \mu^+ \nu_\mu e^+ \nu_e s\bar{c} \)  \( (t, s) \)
  - \( \bar{d}\bar{d} \rightarrow \mu^+ \nu_\mu e^+ \nu_e \bar{u}\bar{u} \)  \( (t, u) \)
  - \( \bar{s}\bar{s} \rightarrow \mu^+ \nu_\mu e^+ \nu_e \bar{c}\bar{c} \)  \( (t, u) \)

- no bottom-induced contributions (no final state top quarks)
- real corrections upon adding additional photon/gluon
- photon/gluon-induced contributions upon crossing photon/gluon
- complete matrix elements taken into account
Details on $pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj$ at LO

**Vector-boson scattering (VBS) topologies:** $\mathcal{O}(g^6)$ all $t$ channel

**Irreducible background to VBS:**

$t$ channel: incoming quarks/antiquarks connected to outgoing quarks/antiquarks

$u$ channel: exchange identical quarks/antiquarks

$s$ channel: incoming quark and anti-quark connected

all boson propagators time like
Contributions to cross section for \(pp \rightarrow \mu^+ \nu \mu^+ \nu \) \(jj\)

**LO:**
- \(\mathcal{O}(\alpha^6)\): EW contribution including VBS and irreducible background
- \(\mathcal{O}(\alpha_s \alpha^5)\): interference between different kinematic channels
- \(\mathcal{O}(\alpha_s^2 \alpha^4)\): irreducible QCD background

**NLO:**
- \(\mathcal{O}(\alpha^7)\): EW corrections to EW LO process
- \(\mathcal{O}(\alpha_s \alpha^6)\): QCD corrections to LO EW and EW corrections to LO interference
- \(\mathcal{O}(\alpha_s^2 \alpha^5)\): EW corrections to LO QCD and QCD corrections to LO interference
- \(\mathcal{O}(\alpha_s^3 \alpha^4)\): QCD corrections to QCD LO process
Virtual diagrams mix QCD and EW corrections:
- EW correction to LO QCD amplitude
- QCD correction to LO EW amplitude

⇒ QCD and EW corrections mix at $\mathcal{O}(\alpha_s \alpha^6)$ and $\mathcal{O}(\alpha_s^2 \alpha^5)$

(1) QCD corrections to EW LO cross section
(1) EW corrections to interference between LO QCD and EW
(2) EW correction to LO EW amplitude interfered with QCD amplitude

⇒ separation into QCD and EW is not well-defined at NLO
Details on virtual EW corrections

- Complete one-loop matrix elements included \( \mathcal{O}(\alpha^7), \mathcal{O}(\alpha_s\alpha^6), \mathcal{O}(\alpha_s^2\alpha^5), \mathcal{O}(\alpha_s^3\alpha^4) \) terms
- On-shell renormalization scheme
- \( G_\mu \) scheme for electromagnetic coupling:

\[
\alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_W^2}{\pi} \left( 1 - \frac{M_W^2}{M_Z^2} \right)
\]

absorbs running of \( \alpha \) to EW scale and universal corrections \( \propto m_t^2 \)

- Complex-mass scheme for vector-boson resonances
  - Denner, Dittmaier, Roth, Wackeroth, Wieders ’99, ’05
  - Complex poles: \( \mu_W^2 = M_W^2 - i M_W \Gamma_W, \mu_Z^2 = M_Z^2 - i M_Z \Gamma_Z \)
  - Complex EW mixing angle
  - Gauge-invariant amplitudes

- All matrix elements calculated with RECOLA Actis et al. ’13, ’16 and COLLIER Denner, Dittmaier, Hofer ’16
soft and collinear singularities

- **Catani–Seymour dipole subtraction** (Catani, Seymour ’96; Dittmaier ’99)
- recombination of collinear parton–photon/gluon and lepton–photon pairs (jet clustering)
  - $\Rightarrow$ cancellation of singularities from soft and final-state collinear photon/gluon emission
- initial-state collinear singularities cancelled by $\overline{\text{MS}}$ redefinition of PDFs

phase-space integration with multi-channel Monte Carlo programs (e.g. **MOCANLO** Feger)
Tree-level matrix elements and LO hadronic cross section successfully compared with MG5@NLO Alwall et al. '14

IR-singularities, Monte Carlo integration
  - variation of $\alpha$ parameter in subtraction terms Nagy, Trócsányi '98
  - variation of IR scale
  - two independent implementations of Monte Carlo integration

one-loop matrix elements
  - comparison against double-pole approximation for two dominant partonic channels ($uu$, $u\bar{d}$) agreement within 1%
  - $O(\alpha_s^3 \alpha^4)$ contributions for $uu$ channel compared against MG5@NLO
  - RECOLA has been checked for many other processes
Setup for $W^+W^+$ scattering

Energy: 13 TeV

PDFs

NNPDF3.0QED  Ball et al. '13, '14
factorization and renormalization scales: $\mu_F = \mu_R = \sqrt{p_{T,j_1}, p_{T,j_2}}$

recombination / jet clustering

anti-$k_T$ algorithm with $R = 0.4$  Cacciari, Salam, Soyez ’08
recombination of photons with charged partons with $R = 0.1$

cuts: inspired by ATLAS 1405.6241, 1611.02428 and CMS 1410.6315

$p_{T,\ell} > 20$ GeV,  $|y_\ell| < 2.5$,  $\Delta R_{j\ell} > 0.3$
$p_{T,j} > 30$ GeV,  $|y_j| < 4.5$,  $\Delta R_{\ell\ell} > 0.3$
$E_{T,\text{miss}} > 40$ GeV

for 2 leading jets: $M_{jj} > 500$ GeV,  $|\Delta y_{jj}| > 2.5$  (VBF cuts)

$\Delta R_{ij} = \sqrt{(\Delta y_{ij})^2 + (\Delta \phi_{ij})^2}$
LO fiducial cross section

Scale uncertainty:

\[ \sigma_{\text{LO}} = 1.6383(2)^{+11.66(2)}_{-9.44(2)} \text{ fb} \]

central scale scaled by factors

\[ (\xi_{\text{fac}}, \xi_{\text{ren}}) \in \{ (1/2, 1/2), (1/2, 1), (1, 1/2), (1, 1), (1, 2), (2, 1), (2, 2) \} \]

results for separate orders:

<table>
<thead>
<tr>
<th>order</th>
<th>( \mathcal{O}(\alpha^6) )</th>
<th>( \mathcal{O}(\alpha_s\alpha^5) )</th>
<th>( \mathcal{O}(\alpha_s^2\alpha^4) )</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{LO}} ) [fb]</td>
<td>1.4178(2)</td>
<td>0.04815(2)</td>
<td>0.17229(5)</td>
<td>1.6383(2)</td>
</tr>
</tbody>
</table>

- LO EW contribution dominates (87%) (owing to VBS cuts)
- QCD-induced contribution 10%
- interference 3% (larger for individual channels)
Scale uncertainty reduced by factor 5:

\[ \sigma_{\text{NLO}} = 1.3577(7)^{+1.2(1)\%}_{-2.7(1)\%} \text{ fb} \]

results for separate orders:

<table>
<thead>
<tr>
<th>Order</th>
<th>( \mathcal{O}(\alpha^7) )</th>
<th>( \mathcal{O}(\alpha_s \alpha^6) )</th>
<th>( \mathcal{O}(\alpha_s^2 \alpha^5) )</th>
<th>( \mathcal{O}(\alpha_s^3 \alpha^4) )</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta \sigma_{\text{NLO}} ) [fb]</td>
<td>−0.2169(3)</td>
<td>−0.0568(5)</td>
<td>−0.00032(13)</td>
<td>−0.0063(4)</td>
<td>−0.2804(7)</td>
</tr>
<tr>
<td>( \delta \sigma_{\text{NLO}} / \sigma_{\text{LO}} ) [%]</td>
<td>−13.2</td>
<td>−3.5</td>
<td>0.0</td>
<td>−0.4</td>
<td>−17.1</td>
</tr>
</tbody>
</table>

- surprisingly large EW corrections at \( \mathcal{O}(\alpha^7) \)
- small negative corrections at \( \mathcal{O}(\alpha_s \alpha^6) \):
  - \( \sim 0.6\% \) difference with respect to VBS approximation
    (neglecting \( s \)-channel and \( t-/u \)-channel interferences)
  - tuned comparison against Denner et al. '12 and Jäger et al. '09
    and VBS approximation in RECOLA
- very small \( \mathcal{O}(\alpha_s^2 \alpha^5) \) and \( \mathcal{O}(\alpha_s^3 \alpha^4) \) corrections (LO suppressed)
- photon-induced contribution at NLO \( +1.5\% \) with LUXqed Manohar et al. '16
  (not included in NLO cross section, dominated by \( \mathcal{O}(\alpha^7) \) )
Distribution in transverse momentum of the anti-muon

- EW contribution dominates everywhere
- $\mathcal{O}(\alpha^7) - 40\%$ at 800 GeV (Sudakov logarithms)
- $\mathcal{O}(\alpha_s \alpha^6) - 4\% - 0\%$
- $\mathcal{O}(\alpha_s^2 \alpha^5)$, $\mathcal{O}(\alpha_s^3 \alpha^4)$ between $-2\%$ and $+2\%$ cancelling for large $p_{T\mu^+}$
- photon-induced corrections increase to $4\%$ at $p_{T\mu^+} = 800$ GeV
Di-jet invariant-mass distribution

- Large cross section also for high $M_{jj}$
- QCD-induced contrib. drops much faster
  - $O(\alpha^7) - 6\% - 17\%$
  - $O(\alpha_s \alpha^6) + 5\% - 5\%$
  - $O(\alpha_s^2 \alpha^5), O(\alpha_s^3 \alpha^4)$ tiny
- photon-induced corrections decrease with $M_{jj}$
Distribution in cosine of angle between charged leptons

- LO QCD produces dominantly back-to-back charged leptons
  \[ \Rightarrow \text{relatively large fraction for small } \cos\theta_{e^+\mu^+} \]

- \( \mathcal{O}(\alpha^7) \) between \(-11\%\) and \(-14\%\)
- \( \mathcal{O}(\alpha_s\alpha^6) \) between \(-3\%\) and \(-4\%\)
- \( \mathcal{O}(\alpha_s^3\alpha^4) \) reaches \(-6\%\) for small \(\cos\theta_{e^+\mu^+}\)
  (enhanced LO)
Distribution in the invariant mass of the charged leptons

- Scale uncertainty decreases significantly from LO to NLO
- NLO scale uncertainty band outside LO scale uncertainty band owing to large EW corrections not included in QCD scale uncertainty
  ⇒ need to include EWC
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Process: \(pp \rightarrow \mu^+ \nu \mu e^+ \nu_{e, jj}\)

EW contributions only, \(\mu_F = \mu_R = M_W\)

<table>
<thead>
<tr>
<th>(\sigma^{LO} ,[\text{fb}])</th>
<th>(\sigma^{NLO}_{EW} ,[\text{fb}])</th>
<th>(\delta_{EW} ,[%])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.5348(2))</td>
<td>(1.2895(6))</td>
<td>(-16.0)</td>
</tr>
</tbody>
</table>

- surprisingly large EW corrections for fiducial cross section
- large EWC arise from bosonic virtual corrections
- leading behaviour of EWC usually dominated by Sudakov logarithms, 
  \(\log^2 \left( \frac{Q^2}{M_W^2} \right)\)
  - appear usually in the tails of distributions (suppressed)
  - usually small for total cross section
- large corrections not due to VBS cuts
  - remove \(m_{jj} > 500 \text{ GeV}\) and \(|\Delta y_{jj}| > 2.5\)
  - relax \(p_{T,j}\) and \(E_{T,miss}\) \(\Rightarrow\) still large EWC
  \(\Rightarrow\) intrinsic feature of VBS process
Double-pole approximation (DPA)

Leading contribution in expansion about poles of $W$ resonances

- factorisable corrections: production $\times$ decay
- nonfactorisable corrections \textit{Accomando et al. '04, Dittmaier, Schwan '15}

DPA only applied to virtual corrections

DPA agrees within 1\% with full calculation

EWC dominated by factorisable corrections (95\%)

large corrections driven by $WW$ scattering process?
Effective vector-boson approximation (EVBA)

- EVBA reduces discussion to $W^+ W^+ \to W^+ W^+$
- Crude approximation but sufficient to understand dominant effects

**leading-logarithmic approximation for $WW \to WW$**  
Denner, Pozzorini ’00

$$\sigma_{\text{LL}} = \sigma_{\text{LO}} \left[ 1 - \frac{\alpha}{4\pi} 4C_{\text{W}}^{\text{ew}} \log^2 \left( \frac{Q^2}{M_W^2} \right) + \frac{\alpha}{4\pi} 2b_{\text{W}}^{\text{ew}} \log \left( \frac{Q^2}{M_W^2} \right) \right]$$

$$C_{\text{W}}^{\text{ew}} = \frac{2}{s_w^2}, \quad b_{\text{W}}^{\text{ew}} = \frac{19}{6s_w^2}$$

(Double EW logs, collinear single EW logs, and single logs from parameter renormalisation included) (angular-dependent logarithms omitted)
Source of large EW corrections

Simple formula for total cross section

\[
\sigma_{\text{LL}} = \sigma_{\text{LO}} \left[ 1 - \frac{\alpha}{4\pi} 4C_{\text{ew}}^W \log^2 \left( \frac{Q^2}{M_W^2} \right) + \frac{\alpha}{4\pi} 2b_{\text{ew}}^W \log \left( \frac{Q^2}{M_W^2} \right) \right]
\]

- for \( Q = \langle m_{4\ell} \rangle \sim 390 \text{ GeV} \) (from MC run)

\[
\delta_{\text{EW}}^{\text{LL}} = -16\% \ (!)
\]

surprisingly good agreement with complete calculation

⇒ corrections 3–4 times larger than for \( q\bar{q} \to W^+W^+ \)

- \( C_{\text{ew}}^W \) larger for bosons than fermions
- \( \langle m_{4\ell} \rangle \) larger for VBS (massive \( t \)-channel exchange Denner, Hahn '97)
  - \( \langle m_{4\ell} \rangle \sim 250 \text{ GeV} \) for \( q\bar{q} \to W^+W^+ \)
- less cancellation between double and single logs

large NLO EW corrections intrinsic feature of VBS
Distribution in the rapidity of the leading jet pair

Biedermann et al. ’17

- $y_{j_1j_2} \approx 0$: two jets back-to-back, VBS configuration
  $\Rightarrow$ bulk of cross section
  $E_{WC} \sim -16\%$

- band: $\pm 1/\sqrt{N_{obs}}$
  for $3000 \text{ fb}^{-1}$
  $\Rightarrow$ EWC necessary for adequate predictions
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Complete NLO QCD and EW corrections calculated for \( pp \rightarrow \mu^+\nu_\mu e^+\nu_e jj \)  
Biedermann, Denner, Pellen 1708.00268

- Matrix elements from RECOLA and loop integrals from COLLIER complete irreducible background included
- DPA provides approximation within 1%
- \(-13\%\) EW corrections for fiducial cross section
  intrinsic feature of VBS process
  result from Sudakov logarithms in combination with large scale of WW scattering process and large vector-boson couplings
  Biedermann, Denner, Pellen 1611.02951

- EW corrections in distributions even larger
  \(-40\%\) for \( p_{T,j_1} = 800 \text{ GeV} \)
- Predictions available in terms of flexible MC programs
Backup
Jäger, Zanderighi ’11

\( \sqrt{s} = 7 \text{ TeV}, \) NLO QCD, basic cuts: \( p_{T,j} > 20 \text{ GeV} \)

**EW production:**
- large rapidity separation \( \Delta y_{jj} \)
- dominant for large \( M_{jj} \)
- \( \sigma_{\text{EW}}^{\text{inclusive}} = 1.10 \text{ fb} \)
- \( \sigma_{\text{EW}}^{\text{VBF cuts}} = 0.201 \text{ fb} \)

**QCD production:**
- small rapidity separation \( \Delta y_{jj} \)
- prefers small \( M_{jj} \)
- \( \sigma_{\text{QCD}}^{\text{inclusive}} = 2.12 \text{ fb} \) \( \times \) 192% 
- \( \sigma_{\text{QCD}}^{\text{VBF cuts}} = 0.0074 \text{ fb} \) \( \times \) 3.7%

VBF cuts: \( M_{jj} > 600 \text{ GeV}, \) \( |\Delta y_{jj}| > 4, \) \( y_{j1} \times y_{j2} < 0 \)
Double-pole approximation

Leading order:

\[ M_{LO, DPA}^{qq \rightarrow WW qq \rightarrow 4f qq} = \sum_{\lambda_{W_1}, \lambda_{W_2}} \frac{[M_{LO}^{qq \rightarrow WW qq}(\lambda_{W_1}, \lambda_{W_2})M_{LO}^{W \rightarrow 2f}(\lambda_{W_1})M_{LO}^{W \rightarrow 2f}(\lambda_{W_2})]}{(p_{W_1}^2 - M_W^2 + iM_W\Gamma_W)(p_{W_2}^2 - M_W^2 + iM_W\Gamma_W)} \]

- only contributions with two resonant W bosons \( \Rightarrow \) dominant contribution
- momenta in numerator projected on shell \( \Rightarrow \) gauge invariance
Double-pole approximation for $pp \rightarrow e^+ \nu_e \mu^+ \bar{\nu}_\mu b \bar{b}$

NLO:

- **factorisable corrections:**
  corrections to production or decay matrix elements

- **non-factorisable corrections:**
  IR-singular corrections connecting production and decay
  $\Rightarrow$ universal correction factors
  Denner et al. '00; Accomando et al. '04;
  Dittmaier, Schwan '15

Implementation

- DPA applied only to squared matrix element for (subtracted) virtual corrections
- leading order and real corrections treated exactly
- phase-space integration treated exactly
- naive error estimate: $\mathcal{O}(\Gamma_W/M_W) \times \delta_{EW} \sim \mathcal{O}(0.2\%)$
- DPA worse, where non-doubly-resonant contributions sizeable