Electroweak corrections for LHC physics

Marek Schönherr

IPPP, Durham University

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Introduction

Electroweak corrections come in two variants: virtual corrections and real emission correction.

Virtual electroweak corrections often studied in the context of gauge boson and jet production at large transverse momentum (EW-Sudakov suppression). Usually negative and increasing with $p_{\perp}$.

Real electroweak corrections usually constitute a separate process. However, largest BR of $W/Z$ bosons is hadronic, thus (almost) indistinguishable in jet production. Nonetheless may constitute signal in itself.

When large scale differences occur resummation is needed in either case. Practically at LHC13/14 these scale differences are moderate.

Beware of subleading orders.
Outline

1. Next-to-leading order electroweak corrections
   - Setup, subtleties and automation
   - Selected results

2. Triboson production
   - On-shell vs. Off-shell production
   - Full off-shell results

3. Electroweak corrections in MCs
   - Approximate inclusion in NLO QCD multijet merging
   - Selected results

4. Conclusions
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Higher order corrections

Example: $Vjj$ production

- strictly defined only through order counting
- in principle must differentiate between short-distance objects (partons) and long distance objects (observable objects):
  - well known in QCD (quarks, gluons $\leftrightarrow$ jets)
  - introduce similar concepts in EW sector for photons and leptons
Higher order corrections

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**Example:** $Vjj$ production

- **Tree-level:** $\alpha_s^2 \alpha^2$
- **NLO QCD:** $\alpha_s^3 \alpha^2$
- **NLO EW:** $\alpha_s^2 \alpha^3$
- **Subleading LO:** $\alpha_s \alpha^3$
- **Subleading NLO:** $\alpha^4$

- **QCD**
  - strictly defined only through order counting
  - in principle must differentiate between short-distance objects (partons) and long-distance objects (observable objects):
    - well known in QCD (quarks, gluons ↔ jets)
    - introduce similar concepts in EW sector for photons and leptons
Higher order corrections

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- In principle must differentiate between short-distance objects (partons) and long distance objects (observable objects):
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  - Introduce similar concepts in EW sector for photons and leptons.
Definition of physical objects

What is a jet?

- photons and leptons must be part of a jet, but to what extent?
- **democratic:**
  - straight forward, always well defined
  - many contributions
  → single photons constitute a jet
  → single leptons constitute a jet

- **anti-tagging jets with certain flavour content:**
  - fewer contributions
  - needs a lot of care to be well-defined at all contributing orders
  → anti-tag jets with too large photon content
  → anti-tag jets with net lepton content

- which approach is closer to experiment depends on analysis,
general anti-tagging must proceed through fragmentation functions
Definition of physical objects

What is a photon?

- differentiate: short-distance photon (photon as parton),
  long-distance photon (identified, measurable photon)

a) treat as identified particle, renormalise on-shell ($\alpha(0)$), no $\gamma \rightarrow ff$
  → renormalisation contains IR poles
  → problematic if both identified and unresolved photons in Born

b) treat democratically (just another parton), renormalise in short
distance scheme ($G_\mu$, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...), include $\gamma \rightarrow ff$ splittings
  → pure UV renormalisation
  → identify photon through frag. function $D^p_\gamma(z, \mu)$

i.e. $D^\gamma_\gamma(z, \mu) = \frac{\alpha(0)}{\alpha_{sd}} \delta(1-z) + \mathcal{O}(\alpha^2)$

and $D^q_\gamma(z, \mu) = \mathcal{O}(\alpha)$, $D^g_\gamma(z, \mu) = \mathcal{O}(\alpha^2 \alpha_s)$

• identical at NLO EW, if fragmentation $D^q_\gamma$ on Born is negligible
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  → identify photon through frag. function $D^p_\gamma(z, \mu)$

  i.e. $D^\gamma_\gamma(z, \mu) = \frac{\alpha(0)}{\alpha_{sd}} \delta(1 - z) + O(\alpha^2)$

  and $D^q_\gamma(z, \mu) = O(\alpha)$, $D^g_\gamma(z, \mu) = O(\alpha s^2)$

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  \[ i.e. \ D^\gamma_\gamma(z, \mu) = \frac{\alpha(0)}{\alpha_{sd}} \delta(1 - z) + \mathcal{O}(\alpha^2) \]

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   → pure UV renormalisation
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   and $D^q_\gamma(z, \mu) = \mathcal{O}(\alpha)$, $D^g_\gamma(z, \mu) = \mathcal{O}(\alpha_s \alpha)$

- identical at NLO EW, if fragmentation $D^q_\gamma$ on Born is negligible
Definition of physical objects

What is a lepton?

- in principle, again differentiate between short-distance parton and long-distance identified and measurable object
- simplified as leptons not gauge bosons, thus
  \[ D_{\ell}^{\ell}(z, \mu) = \delta(1 - z) + \text{QED bremsstrahlung} \]
  \[ D_{\gamma}^{\gamma}(z, \mu) = \mathcal{O}(\alpha) \]
  problematic in processes with \( \ell \) and unresolved photons in Born

all other \( D_{\ell}^{q}(z, \mu) = \mathcal{O}(\alpha^2) \), \( D_{\ell}^{g}(z, \mu) = \mathcal{O}(\alpha_s \alpha^2) \)

- dressed lepton: masseless leptons must be dressed for IR safety
- bare lepton: massive leptons may be measured bare
- Born lepton: not an infrared-safe concept
Automation

⇒ emergence of automated frameworks for NLO EW computations along the principles of NLO QCD automation

- Monte-Carlo frameworks (Born and real emission matrix elements, infrared subtraction, phase space generation, process coordination)
  - SHERPA
  - MADGRAPH

- virtual corrections (EW one-loop matrix elements, renormalisation)
  - GOSAM
  - MADLOOP
  - OPENLOOPS
  - RECOLA

- currently generally limited to fixed-order

- a number of dedicated calculations and private codes

- SHERPA
  - MS arXiv:1712.07975

- MADGRAPH
  - Frederix et.al. arXiv:1804.10017

- GOSAM
  - Chiesa et.al. arXiv:1507.08579

- MADLOOP
  - Frixione et.al. arXiv:1407.0823

- OPENLOOPS
  - Kallweit et.al. arXiv:1412.5157

- RECOLA
  - Actis et.al. arXiv:1211.6316
NLO EW calculations with SHERPA

• **SHERPA+OPENLOOPS:**
  - \( pp \rightarrow \gamma/\ell\ell/\ell \nu/\nu + 0, 1, 2(, 3) \text{ jets} \)
    
    Lindert et.al arXiv:1705.04664
    FCC report, EW report, LH’15

  - \( pp \rightarrow Vh \)
    
    FCC report arXiv:1607.01831

  - \( pp \rightarrow 2\ell 2\nu \)
    
    Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

  - \( pp \rightarrow t\bar{t}/t\bar{t}j \)
    
    Gütschow, Lindert, MS arXiv:1803.00950

  - \( pp \rightarrow t\bar{t}h \)
    
    LH’15 arXiv:1605.04692

• **SHERPA+GOSAM**
  - \( pp \rightarrow \gamma\gamma + 0, 1, 2 \text{ jets} \)
    
    Chiesa et.al. arXiv:1706.09022

  - \( pp \rightarrow \gamma\gamma/\gamma\gamma\ell\nu/\gamma\gamma\ell\ell \)
    
    Greiner, MS arXiv:1710.11514

• **SHERPA+RECOLA**
  - \( pp \rightarrow V + 0, 1, 2 \text{ j}, pp \rightarrow 4\ell, pp \rightarrow t\bar{t}h \)
    
    Biedermann et.al. arXiv:1704.05783
    MS arXiv:1806.00307

  - \( pp \rightarrow 3\ell 3\nu \)
    
    Reyer, MS, Schumann arXiv:1902.01763

  - \( pp \rightarrow jj/ jjj \)
NLO EW calculations with SHERPA

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  - $pp \rightarrow \gamma/\ell\ell/\ell\nu/\nu\nu + 0, 1, 2, 3$ jets
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    - $pp \rightarrow 2\ell 2\nu$
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  - LH’15 arXiv:1605.04692

- **SHERPA + GOSAM**
  - $pp \rightarrow \gamma\gamma + 0, 1, 2$ jets
  - $pp \rightarrow \gamma\gamma\gamma / \gamma\gamma\ell\nu / \gamma\gamma\ell\ell$
  - Chiesa et.al. arXiv:1706.09022
  - Greiner, MS arXiv:1710.11514

- **SHERPA + RECOLA**
  - $pp \rightarrow V + 0, 1, 2$ j, $pp \rightarrow 4\ell$, $pp \rightarrow t\bar{t}h$
  - Biedermann et.al. arXiv:1704.05783
  - MS arXiv:1806.00307
  - Reyer, MS, Schumann arXiv:1902.01763
NLO EW calculations with SHERPA

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  - $pp \rightarrow jj/jjj$
Selected results

**General setup**

- work with dressed leptons with $\Delta R_{\text{dress}} = 0.1$
- input parameters for the following calculations

\[
\begin{align*}
G_\mu &= 1.16637 \times 10^{-5} \text{ GeV}^2 \\
m_W &= 80.385 \text{ GeV} \\
m_Z &= 91.1876 \text{ GeV} \\
m_h &= 125.0 \text{ GeV} \\
m_t &= 173.2 \text{ GeV} \\
\Gamma_W &= 2.0897 \text{ GeV} \\
\Gamma_Z &= 2.4955 \text{ GeV} \\
\Gamma_h &= 0.00407 \text{ GeV} \\
\Gamma_t &= 1.3394 \text{ GeV}.
\end{align*}
\]

- EW parameter renormalisation in $G_\mu$-scheme
- photon induced processes considered throughout
Selected results

Diphoton production – $\gamma\gamma$

NLO EW corrections to diphoton production

- peak-like enhancement around $m_{\gamma\gamma} \approx 160$ GeV
- induced by $W$-box creating pseudo-resonant structures
Diphoton production – $\gamma\gamma$

**NLO EW corrections to diphoton production**

- peak-like enhancement around $m_{\gamma\gamma} = 2m_W$
- induced by $W$-box creating pseudo-resonant structures
Selected results

Diboson production – $2\ell 2\nu$ – DF and SF

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

- study $e^+\mu^-\nu\bar{\nu}$ (DF) and $e^+e^-\nu\bar{\nu}$ (SF) production, and $e \leftrightarrow \mu$

| DF | $e^+\mu^-\nu_e\bar{\nu}_\mu$ | WW |
| SF | $e^+e^-\nu_e\bar{\nu}_e$ | $WW + ZZ$ |
|    | $e^+e^-\nu_{\mu/\tau}\bar{\nu}_{\mu/\tau}$ | ZZ |

- incl. event selection w/ standard lepton acceptance cuts, $(p_T,\ell > 20\text{ GeV}), |\eta_\ell| < 2.5)$,
  \[n_f = 4\] and mild jet veto to suppress large NLO QCD corr.
Diboson production – $2\ell 2\nu$ – DF

$\text{pp} \rightarrow e^+\mu^- \nu_e \bar{\nu}_\mu$

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

- Absolute prediction
- Relative correction wrt. LO
- NLO QCD (w/ moderate jet veto)
- LO
- NLO QCD+EW
- NLO QCD×EW
- NLO EW

- Large pos. NLO QCD, large neg. NLO EW
  $\rightarrow$ NLO QCD+EW and NLO QCD×EW differ significantly
Diboson production – $2\ell2\nu$ – DF

Selected results

relative importance of $\gamma$-induced channels wrt. NLO QCD $\times$ EW

- CT14qed (baseline) no $\gamma$PDF
- LUXqed
- NNPDF3.0qed

- all $\gamma$PDF agree that $\gamma$-ind. $> 10\%$ for $p_T > 500 \text{ GeV}$
- very good agreement between CT14qed and LUXqed
Selected results

**Diboson production – $2\ell 2\nu$ – SF**

The relative importance of $\gamma$-induced channels wrt. NLO QCD×EW:

- **CT14qed (baseline)**: no $\gamma$PDF
- **LUXqed**: NNPDF3.0qed

**Relative contributions of $WW$ and $ZZ$ subtops**:
- Coherent $|WW + ZZ|^2$
- Incoherent $|WW|^2 + |ZZ|^2$
- Only $|WW|^2$
- Only $|ZZ|^2$

- $WW$ dominant throughout, $ZZ$ only contribs 10-20%
  → overall very similar to DF case

Graphs showing the distribution of $p_T, \ell_1$ for $pp \to e^+ e^- \nu \bar{\nu}$, $pp \to W^+ [\to e^+ \nu] W^- [\to e^- \bar{\nu}]$, and $pp \to Z/\gamma [\to e^+ e^-] Z [\to \nu \bar{\nu}]$ with incoherent sum.
Diboson production – 2\ell 2\nu – DF

- ZZ dominant at very large \( p_T \)
- \( \rightarrow \) different EW corrections, take care when extrapolating
Diboson production – $2\ell 2\nu$ – SF

- **ZZ** dominant at very large $p_T$
- $\rightarrow$ different EW corrections, take care when extrapolating
Diboson production – $2\ell 2\nu$ – DF

- kinematic suppression for $p_T^{\nu\nu}$ at LO, unlocked at NLO QCD not present in $\gamma$-induced $\Rightarrow$ large contrib
Diboson production – $2\ell 2\nu$ – SF

- Kinematic suppression for $p_T^{\ell \nu}$ for $WW$, but not $ZZ$
- $ZZ$ dominates for MET $> 100$ GeV with large EW corr.
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Triboson production – $3\ell3\nu – 0, 1, 2$ SFOS

- contribs from 0 SFOS ($e^-\mu^+\mu^+\bar{\nu}\nu\nu$), 1 SFOS ($e^-e^+\mu^+\bar{\nu}\nu\nu$) and 2 SFOS ($e^-e^+e^+\bar{\nu}\nu\nu$) processes, and $e \leftrightarrow \mu$

  0 SFOS  \[ e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu \]  WWW  \[ WZ[\rightarrow 2\ell2\nu] \]  Wh

  1 SFOS  \[ e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu \]  WWW + WZZ  \[ WZ[\rightarrow 2\ell2\nu] \]  Wh

  \[ e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu \]  WZZ

  \[ e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu \]  WZZ

  2 SFOS  \[ e^-e^+e^+\bar{\nu}_e\nu_e \]  WWW + WZZ  \[ WZ[\rightarrow 2\ell2\nu] \]  Wh

  \[ e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e \]  WZZ

- standard lepton acceptance cuts, idealised from ATLAS arXiv:1610.05088
Triboson production – $3\ell 3\nu$ – 0, 1, 2 SFOS

- contribs from 0 SFOS ($e^- \mu^+ \mu^+ \bar{\nu} \nu \nu$), 1 SFOS ($e^- e^+ \mu^+ \bar{\nu} \nu \nu$) and 2 SFOS ($e^- e^+ e^+ \bar{\nu} \nu \nu$) processes, and $e \leftrightarrow \mu$

  0 SFOS $e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$  
  1 SFOS $e^- e^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$  
  $e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$  
  $e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$  
  2 SFOS $e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$  
  $e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$

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On-shell vs. Off-shell production

Triboson production – $3\ell 3\nu - 0, 1, 2$ SFOS

- contribs from 0 SFOS ($e^- \mu^+ \mu^+ \nu \nu \nu$), 1 SFOS ($e^- e^+ \mu^+ \nu \nu \nu$) and 2 SFOS ($e^- e^+ e^+ \nu \nu \nu$) processes, and $e\leftrightarrow \mu$

0 SFOS

$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$  

$W_{WW}$  

$WZ[\rightarrow 2 \ell 2\nu]$  

$Wh$

1 SFOS

$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$  

$W_{WW} + W_{ZZ}$  

$W_{ZZ}$  

$WZ[\rightarrow 2 \ell 2\nu]$  

$Wh$

$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$  

$W_{ZZ}$  

$WZ[\rightarrow 2 \ell 2\nu]$  

$Wh$

$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$  

$W_{ZZ}$  

$WZ[\rightarrow 2 \ell 2\nu]$  

$Wh$

2 SFOS

$e^- e^+ e^+ \bar{\nu}_e \nu_e$  

$W_{WW} + W_{ZZ}$  

$W_{ZZ}$  

$WZ[\rightarrow 2 \ell 2\nu]$  

$Wh$

$e^- e^+ e^+ \bar{\nu}_\mu/\tau \nu_\mu/\tau \nu_e$  

$W_{ZZ}$  

$WZ[\rightarrow 2 \ell 2\nu]$  

$Wh$

- standard lepton acceptance cuts, idealised from ATLAS arXiv:1610.05088
NLO EW corrections in off-shell trilepton production

<table>
<thead>
<tr>
<th>Selection</th>
<th>Cut</th>
<th>Value</th>
</tr>
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<tr>
<td>general</td>
<td>$p_T(\ell)$</td>
<td>$[20 \text{ GeV}, \infty)$</td>
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<tr>
<td></td>
<td>$y(\ell)$</td>
<td>$[-2.5, 2.5]$</td>
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<tr>
<td></td>
<td>$\Delta R(\ell, \ell)$</td>
<td>$[0.2, \infty)$</td>
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<tr>
<td>$p_T &gt; 20 \text{ GeV}$</td>
<td>$\Delta \phi(p_T, \ell\ell\ell)$</td>
<td>$[\frac{5}{6} \pi, \pi]$</td>
</tr>
<tr>
<td>1, 2 SFOS</td>
<td>$p_T$</td>
<td>$[50 \text{ GeV}, \infty)$</td>
</tr>
<tr>
<td></td>
<td>$m_{\ell\ell}^{\text{SFOS}}$</td>
<td>$[0, 70 \text{ GeV}] \land [100 \text{ GeV}, \infty)$</td>
</tr>
</tbody>
</table>

- minimise $t\bar{t}W$, $tWW$, $WZ$ backgrounds
- scale choice: $\mu = \sum m_{T,i}^W$ ambiguous in all channels, EW corrections largely scale independent: choose $\mu_R = \mu_F = 3 m_W$
- use NNPDF31_nlo_as_0118_luxqed for reliable $\gamma$PDF
On-shell vs. off-shell triboson production

**On-shell production**

- only triple res. dgrms, threshold at 3 $m_W$
- strong interference between diagrams in which different numbers of gauge bosons couple to quark line
- some kinematic width effects recoverable through BW-shape improved spin-correlated decays
- NLO QCD+EW

Dittmaier, Huss, Knippen arXiv:1705.03722
On-shell vs. Off-shell production

**Off-shell production**

- triple, double and single res. diagrams, importance of single/double resonant topologies as in $WW$
  
  Biedermann et.al. arXiv:1605.03419

- includes on-shell $WWW$ production, $WZ$ production with $Z \to 2\ell 2\nu$, $Wh$ production with $h \to WW^*/ZZ^*$

- thresholds given by acceptance cuts

- NLO QCD
  
  Campanario et.al. arXiv:0809.0790
On-shell vs. off-shell triboson production

$m_{ℓℓℓννν} = m_{WWW}$

- no unique $W$ identification possible in off-shell calculation, even in MC truth, due to occurrence of SF pairs
- on-shell $WWW$ not dominating for incl. xsec
- large cross section from $Wh$, $WZ$ negligible
- at larger $m_{WWW}$ contribs from double (single) resonant

$\rightarrow$ cross checked with off-shell calculation projected on triple $W$ resonant subset of diagrams
On-shell vs. Off-shell production

- on-shell approximation reasonable for $m_{\ell\ell\ell}$
- large single and double resonant contribs for MET
NLO EW corrections in off-shell trilepton production

- at LO: triple and quartic gauge boson self-interactions
- at NLO EW: appearance of octagons, closed fermion loops, Higgs self-interactions, Yukawa couplings, etc
- genuine NLO EW 2 → 6 calculation with 3 resonances
Triboson production

- off-shell $W^+W^+W^-$ production
- includes 0, 1, 2 SFOS processes ($WWW$ and $WZZ$ structures)
- EW correction (incl. $\gamma$-induced) important
- accidental cancellations of EW corr. in $q\bar{q}$ and $q\gamma/\bar{q}\gamma$ channels

Dittmaier, Huss, Knippen
arXiv:1705.03722

but highly obs. dependent
Triboson production – 0, 1, 2 SFOS decomposition

\[ pp \rightarrow \ell_1^+ \ell_2^+ \ell_3^- \bar{\nu}_\ell \nu_\ell \nu_\ell @ 13\,\text{TeV} \]

\[
\begin{align*}
\frac{d\sigma}{dm} &= 10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \quad 10^{-6} \quad 10^{-7} \\
\delta_{\text{EW}} &= -0.1 \quad -0.2 \quad -0.3 \quad -0.4 \\
\frac{d\sigma}{d\sigma_{\text{NLO EW}}} &= 0.1 \quad 0.2 \quad 0.3 \quad 0.4
\end{align*}
\]

MS arXiv:1806.00307
Triboson production – 0, 1, 2 SFOS decomposition

\( pp \rightarrow \ell_1^- \ell_2^+ \ell_3^+ \bar{\ell}_1 \ell_2 \ell_3 @ 13 \text{TeV} \)

**Full off-shell results**

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\[ \frac{d\sigma}{dm} \text{[fb/GeV]} \]

\[ m(3\ell) \text{[GeV]} \]

\[ \delta_{\text{EW}} \]

\[ \delta_{q\bar{q}} \]

\[ \delta q\gamma \]

\[ 50 \quad 100 \quad 200 \quad 500 \quad 1000 \quad 2000 \]

\[ -0.3 \quad -0.2 \quad -0.1 \quad 0 \quad 0.1 \]

Marek Schönherr

Electroweak corrections for LHC physics
Triboson production – 0, 1, 2 SFOS decomposition

$pp \rightarrow \ell_1^- \ell_2^+ \ell_3^+ \bar{\nu}_\ell \nu_\ell \nu_\ell @ 13\text{ TeV}$

$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$ $e^-e^+\bar{\nu}_\mu\nu_\mu\nu_e + \bar{\nu}_\tau\nu_\tau\nu_e$

$pp \rightarrow \ell^-, \ell^+, \ell^+, \bar{\nu}_\ell \nu_\ell \nu_\ell \nu_\ell$

$d\sigma / d\sigma_{NLO EW}$

SHERPA+RECOLA

$\delta_{EW}$

$\delta_{q\bar{q}}$

$\delta_{q\gamma}$

$\delta_{EW}$

$\delta_{q\bar{q}}$

$\delta_{q\gamma}$

$d\sigma / d\sigma_{NLO EW}$

$SHERPA+RECOLA$

$\delta_{EW}$

$\delta_{q\bar{q}}$

$\delta_{q\gamma}$

$\delta_{EW}$

$\delta_{q\bar{q}}$

$\delta_{q\gamma}$

$m(3\ell) [\text{GeV}]$

$d\sigma / d\sigma_{NLO EW}$

$SHERPA+RECOLA$

$\delta_{EW}$

$\delta_{q\bar{q}}$

$\delta_{q\gamma}$

$\delta_{EW}$

$\delta_{q\bar{q}}$

$\delta_{q\gamma}$

$m(3\ell) [\text{GeV}]$

$\delta_{EW}$

$\delta_{q\bar{q}}$

$\delta_{q\gamma}$

$\delta_{EW}$

$\delta_{q\bar{q}}$

$\delta_{q\gamma}$

$m(3\ell) [\text{GeV}]$
Triboson production

- 1, 2 SFOS: req. $p_T > 50$ GeV to suppress $WZ$ background
- substantial $\gamma$-induced contributions
- accidental cancellations
Triboson production

\[ pp \rightarrow \ell_1^- \ell_2^- \ell_3^- \nu_1 \nu_2 \nu_3 \] at 13 TeV

\[ \frac{d\sigma}{dp_T} [fb/GeV] \]

1st lepton

2nd lepton

3rd lepton

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Electroweak corrections for LHC physics

1. Next-to-leading order electroweak corrections
   Setup, subtleties and automation
   Selected results

2. Triboson production
   On-shell vs. Off-shell production
   Full off-shell results

3. Electroweak corrections in MCs
   Approximate inclusion in NLO QCD multijet merging
   Selected results

4. Conclusions
Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA’s NLO QCD multijet merging (MEPS@NLO)
- tailored to large-\(p_T\) regions where EW corrections dominated by virtual \(W/Z\) exchange and RG running
- modify MC@NLO \(\bar{B}\)-function to include NLO EW virtual corrections and integrated approx. real corrections

\[
\bar{B}_{n,QCD+EW_{virt}}(\Phi_n) = \bar{B}_{n,QCD}(\Phi_n) + V_{n,EW}(\Phi_n) + I_{n,EW}(\Phi_n) + B_{n,mix}(\Phi_n)
\]

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA’s NLO QCD multijet merging (MEPS@NLO)
- tailored to large-$p_T$ regions where EW corrections dominated by virtual $W/Z$ exchange and RG running
- modify MC@NLO $\bar{B}$-function to include NLO EW virtual corrections and integrated approx. real corrections

\[ \bar{B}_{n,QCD+EW_{virt}}(\Phi_n) = \bar{B}_{n,QCD}(\Phi_n) + V_{n,EW}(\Phi_n) + I_{n,EW}(\Phi_n) + B_{n,mix}(\Phi_n) \]

exact virtual contribution

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Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
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$$B_{n,QCD+EW_{virt}}(\Phi_n) = B_{n,QCD}(\Phi_n) + V_{n,EW}(\Phi_n) + I_{n,EW}(\Phi_n) + B_{n,mix}(\Phi_n)$$

- exact virtual contribution
- approximate integrated real contribution

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA’s NLO QCD multijet merging (MEPS@NLO)
- tailored to large-$p_T$ regions where EW corrections dominated by virtual $W/Z$ exchange and RG running
- modify MC@NLO $\overline{B}$-function to include NLO EW virtual corrections and integrated approx. real corrections

$$\overline{B}_{n,QCD+EW_{\text{virt}}} (\Phi_n) = \overline{B}_{n,QCD} (\Phi_n) + V_{n,EW} (\Phi_n) + I_{n,EW} (\Phi_n) + B_{n,\text{mix}} (\Phi_n)$$

- optionally include subleading Born

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA’s NLO QCD multijet merging (MEPs@NLO)
- tailored to large-\(p_T\) regions where EW corrections dominated by virtual \(W/Z\) exchange and RG running
- modify MC@NLO \(\mathcal{B}\)-function to include NLO EW virtual corrections and integrated approx. real corrections
  
  \[
  \mathcal{B}_{n,QCD+EW_{virt}}(\Phi_n) = \mathcal{B}_{n,QCD}(\Phi_n) + V_{n,EW}(\Phi_n) + I_{n,EW}(\Phi_n) + B_{n,mix}(\Phi_n)
  \]

  optionally include subleading Born

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
Results: $pp \rightarrow t\bar{t} + \text{jets}$

G"utschow, Lindert, MS in arXiv:1803.00950

- $pp \rightarrow t\bar{t} + 0, 1j@NLO$
  + $2, 3, 4j@LO$
- additional LO multiplicities inherit electroweak corrections through MENLOPs differential $K$-factor
  Höche, Krauss, MS, Siegert
  arXiv:1009.1127
- improved description of data
Conclusions

- Electroweak effects are important at LHC, HE–LHC, FCC, etc.
- Become large whenever the scale is large compared to the EW scale.
- Precise definition of physics objects needed
  ⇒ Differentiate short-distance parton and long-distance measurable object.
- Can be incorporated in multijet-merged particle-level calculations to improve description in those regions
  → Currently tailored to TeV-scale physics.
- Automation of NLO EW follows on the heels of NLO QCD
  → Much more care with consistent schemes and order counting
  → Very rich phenomenology
  → Can induce peaks, edges or kinks in distributions
  → Includes many more pitfalls than NLO QCD.
Thank you for your attention!
Backup
Top pair production in association with jets

Observation: NLO EW factorises from additional jet activity when rather inclusive on jet definition.
Top pair production in association with jets

Gütschow, Lindert, MS in arXiv:1803.00950

Observation: subleading orders important