Electroweak corrections for LHC physics

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Introduction

Electroweak sector of the Standard Model is described by a broken $SU(2)_L \times U(1)_Y$ gauge group resulting in $U(1)_{\text{QED}}$ and massive weak gauge bosons ($W^\pm$, $Z$).

Inclusive observables
Electroweak corrections are of $\mathcal{O}(\alpha)$, thus generally of $\mathcal{O}(1\%)$. Roughly, their size can be gauged by $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha^2_s)$. Important to take into account in precision measurements.

TeV scale observables
Incomplete infrared cancellation due to broken structure of the gauge group introduces logarithms of the scale of the process and that of the EW bosons. This introduces EW Sudakov logarithms which are negative and grow with the size of the kinematic invariants, e.g. $p_T$. Thus, $\mathcal{O}(20\%)$ corrections possible already for LHC range.
Electroweak correction can often be separated in QED and genuine weak corrections.

Virtual weak 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 weak 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. Three-jet production
   Contributions
   $R_{32}$

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

- tree-level
  - $\alpha_s^2 \alpha^2$
  - $\alpha_s \alpha^3$
  - $\alpha^4$

- NLO
  - $\alpha_s^3 \alpha^2$
  - $\alpha_s^2 \alpha^3$
  - $\alpha_s \alpha^4$
  - $\alpha^5$

- 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
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- **LO**
  - $\alpha_s^2 \alpha^2$

- **tree-level**
  - $\alpha_s^3 \alpha^2$
  - $\alpha_s^2 \alpha^3$

- **NLO**
  - $\alpha_s^3 \alpha^2$
  - $\alpha_s^2 \alpha^3$

- **NLO QCD**
- **NLO EW**

- $\alpha_s \alpha^3$
- $\alpha_s \alpha^4$
- $\alpha^4$
- $\alpha^5$

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  - \( \alpha_s^2 \alpha^3 \)
- NLO EW
  - \( \alpha_s^3 \alpha^3 \)
  - \( \alpha_s^2 \alpha^4 \)
- subleading NLO
  - \( \alpha^4 \)
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- **subleading NLO**
  - \( \alpha^4 \)
  - \( \alpha^5 \)

- **subleading LO**
  - \( \alpha_s \alpha^3 \)

- **tree-level**
  - \( \alpha^2 \)

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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)
- identify through fragmentation function

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

\( \Rightarrow \) leads to \( \alpha(0) \)-scheme for identified photons

**What is a lepton?**

- simplified as leptons not gauge bosons
- 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
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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
NLO EW calculations with SHERPA

- **SHERPA+OPENLOOPS:**
  - $pp \rightarrow \gamma/\ell\ell/\ell\nu/\nu\nu + 0, 1, 2(, 3)$ jets
    - FCC report, EW report, LH’15
    - Lindert et.al arXiv:1705.04664
  - $pp \rightarrow Vh$
    - FCC report arXiv:1607.01831
  - $pp \rightarrow 2\ell 2\nu$
    - Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598
  - $pp \rightarrow t\bar{t}/t\bar{t}j$
  - $pp \rightarrow t\bar{t}h$

- **SHERPA+GOSAM**
  - $pp \rightarrow \gamma\gamma + 0, 1, 2$ 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**
  - $pp \rightarrow V + 0, 1, 2$ j, $pp \rightarrow 4\ell$, $pp \rightarrow t\bar{t}h$
    - Biedermann et.al. arXiv:1704.05783
    - MS arXiv:1806.00307
  - $pp \rightarrow 3\ell 3\nu$
  - $pp \rightarrow jj/jjj$
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    - Gütschow, Lindert, MS arXiv:1803.00950
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    - LH’15 arXiv:1605.04692

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General setup

- work with dressed leptons with $\Delta R_{\text{dress}} = 0.1$
- input parameters for the following calculations
  
  \[
  G_\mu = 1.16637 \times 10^{-5} \text{ GeV}^2
  \]
  
  \[
  m_W = 80.385 \text{ GeV} \quad \Gamma_W = 2.0897 \text{ GeV}
  \]
  
  \[
  m_Z = 91.1876 \text{ GeV} \quad \Gamma_Z = 2.4955 \text{ GeV}
  \]
  
  \[
  m_h = 125.0 \text{ GeV} \quad \Gamma_h = 0.00407 \text{ GeV}
  \]
  
  \[
  m_t = 173.2 \text{ GeV} \quad \Gamma_t = 1.3394 \text{ GeV}
  \]
- EW parameter renormalisation in $G_\mu$-scheme
- photon induced processes considered throughout
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
- should be accounted for in data-driven background fits in diphoton resonance searches
Diphoton production – $\gamma\gamma$

**NLO EW corrections to diphoton production**

- peak-like enhancement around $m_{\gamma\gamma} = 2 m_W$
- induced by $W$-box creating pseudo-resonant structures
- should be accounted for in data-driven background fits in diphoton resonance searches
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, $(p_T,\ell > 20$ 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

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
  → NLO QCD+EW and NLO QCD×EW differ significantly
Diboson production – $2\ell 2\nu$ – DF

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

CT14qed (baseline) no $\gamma$PDF
LUXqed

$\gamma_{\text{PDF}}$

0.9
1.0
1.1
CT14
LUX
none
NNPDF3.0

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

\[ \frac{d\sigma}{d\sigma_{\text{NLO QCD} \times EW}} \]

- all $\gamma$PDF agree that $\gamma$-ind. $> 10\%$ for $p_T > 500$ GeV
- very good agreement between CT14qed and LUXqed
Diboson production – $2\ell 2\nu$ – SF

$$pp \rightarrow e^+ e^- \nu \bar{\nu}$$

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 – $2\ell2\nu$ – SF

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

- $\gamma$PDF
- CT14
- none
- NNPDF 3.0

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

$\gamma$PDF, CT14, none, NNPDF 3.0

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- $ZZ$ dominant at very large $p_T$
- Different EW corrections, take care when extrapolating

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Electroweak corrections for LHC physics
Selected results

Diboson production – $2\ell2\nu$ – SF

- $ZZ$ dominant at very large $p_T$
  → 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 $p_T^{\nu\nu}$ for $WW$, but not $ZZ$
- $ZZ$ dominates for MET $> 100$ GeV with large EW corr.
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Three-jet production

Dijet production
- NLO QCD
  - Ellis, Kunszt, Soper PRL 69 (1992) 1496-1499
  - Giele, Glover, Kosower hep-ph/9302225
- NLO EW and all subl. corrections
  - Moretti, Nolten, Ross hep-ph/0606201
  - Dittmaier, Huss, Speckner arXiv:1210.0438
  - Frederix et.al. arXiv:1612.06548

Three-jet production
- NLO QCD
  - Nagy hep-ph/0110315
- NLO EW and all subl. corrections
  - Reyer, MS, Schumann arXiv:1902.01763

N-jet production
- NLO QCD known for 4- and 5-jet production
  - Bern et.al. arXiv:1112.3940
  - Badger et.al. arXiv:1309.6585
Contributions

- **define jets completely democratically**, incl. all massless visible particles of the SM \((q, g, \gamma, \ell)\)
  \(p_T(j_1) > 80 \text{ GeV}, \ p_T(j_i) > 60 \text{ GeV} \ (i > 1)\)

- **anti-tag jets against leptons**
  exclude jets with net lepton number within lepton acceptance
  care: jet acceptance and lepton acceptance may differ
  here: \(|\eta(j)| < 2.8, \ |\eta(\ell)| < 2.5\)
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\[\mathcal{O}(\alpha_s^2)\]

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Contributions at NLO

- sensitive to the full SM spectrum, incl. top quark, Higgs boson, all lepton and neutrino flavours
- real emission corrections include: $\ell\nu qg$, $\ell\ell qg$, $\ell\ell\ell$, $\ell\ell\nu$ final states
Leading jet transverse momenta in dijet production

- moderate EW corrections
- overcompensated by subleading orders
Leading jet transverse momenta in 3-jet production

- moderate EW corrections
- overcompensated by subleading orders, can be as large as QCD corr.
- NLO EW reduces x-sec. by \( \approx 15\% \) at \( H_T^{(2)} = 2 \text{ TeV} \)
- again, large accidental compensations between NLO EW and subleading orders
• NLO EW and subleading order contribs very similar between $2j$ and $3j$  
  $\Rightarrow R_{32}$ largely uneffected  

• supports factorisation of NLO QCD and NLO EW correction at large $H_T^{(2)}$  

• scale uncertainty by synchronous scale variation  

$\Rightarrow$ safe to use $R_{32}$ with NLO QCD MCs for $\alpha_s$ extraction
$R_{32}$ in different $\Delta y$-slices

- effects already seen in Dittmaier, Huss, Speckner arXiv:1210.0438
$R_{32}$ in different $\Delta y$-slices

- slightly different in 3-jet production
$R_{32}$ in different $\Delta y$-slices

- different net effects in different rapidity slices
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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

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

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
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- approximate integrated real contribution

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- modify MC@NLO \( B \)-function to include NLO EW virtual corrections and integrated approx. real corrections

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

- 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 $\overline{B}$-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
Results: \( pp \rightarrow t\bar{t} + \text{jets} \)

Gütschow, 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 ME@NLOPs 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.
- NLO EW often not enough, need also subleading contributions.
- 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.
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

Observation: subleading orders important