Status of higher-order electroweak calculations

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QCD Tools for LHC Physics:
From 8 to 14 TeV
"What's needed and why?"
Fermilab
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Electroweak corrections for LHC physics

For a recent review see, e.g., talk by S. Dittmaier at Les Houches 2013 at

This talk: a selection of recent results with emphasize on open issues:

• Combination of QCD and EW corrections
• Beyond 1-loop
• Photon PDFs
• Assessment of theory uncertainties

Motivation: see Snowmass report of the QCD working group, including an updated wishlist.

Anderson et al, 1310.5189
## Excerpt of Snowmass wishlist

<table>
<thead>
<tr>
<th>Process</th>
<th>known</th>
<th>desired</th>
<th>details</th>
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<tbody>
<tr>
<td>H</td>
<td>$d\sigma$ @ NNLO QCD</td>
<td>$d\sigma$ @ NNLO QCD + NLO EW</td>
<td>H branching ratios and couplings</td>
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<td>$d\sigma$ @ NLO EW</td>
<td>$MC@NNLO$</td>
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<td>finite quark mass effects @ NLO</td>
<td>finite quark mass effects @ NNLO</td>
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<td>H + j</td>
<td>$d\sigma$ @ NNLO QCD (g only)</td>
<td>$d\sigma$ @ NNLO QCD + NLO EW</td>
<td>$H_{p_t}$</td>
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<td>$d\sigma$ @ NLO EW</td>
<td>$MC@NNLO$</td>
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<td>finite quark mass effects @ LO</td>
<td>finite quark mass effects @ NLO</td>
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<td>H + 2j</td>
<td>$\sigma_{tot}(VBF)$ @ NNLO(DIS) QCD</td>
<td>$d\sigma$ @ NNLO QCD + NLO EW</td>
<td>$H$ couplings</td>
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<td>$d\sigma(gg)$ @ NLO QCD</td>
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<td>$d\sigma(VBF)$ @ NLO EW</td>
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<td>H + V</td>
<td>$d\sigma$ @ NNLO QCD</td>
<td>with $H \to b\bar{b}$ @ same accuracy</td>
<td>$H$ couplings</td>
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<td>$d\sigma$ @ NLO EW</td>
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<td>$d\sigma$(stable tops) @ NLO QCD</td>
<td>$d\sigma$(top decays)</td>
<td>top Yukawa coupling</td>
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<td>$d\sigma$ @ NLO QCD + NLO EW</td>
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<td>HH</td>
<td>$d\sigma$ @ LO QCD (full $m_t$ dependence)</td>
<td>$d\sigma$ @ NLO QCD (full $m_t$ dependence)</td>
<td>Higgs self coupling</td>
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<td>$d\sigma$ @ NLO QCD (infinite $m_t$ limit)</td>
<td>$d\sigma$ @ NNLO QCD (infinite $m_t$ limit)</td>
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</table>

Anderson et al, 1310.5189
Characteristics of EW corrections

\[ \frac{\alpha(M_Z)}{\pi} \approx 0.0025 \text{ vs. } \frac{\alpha_s(M_Z)}{\pi} \approx 0.037 \]

Possible enhancements:

**QED:** \( \frac{\alpha(0)}{\pi} \log \left( \frac{m_f^2}{Q^2} \right) \approx -0.024 \) for \( Q = M_W, f = \mu \)

*Origin:* Soft/collinear FS photon radiation
In sufficiently inclusive observables these mass singularities completely cancel. *Kinoshita, Lee, Nauenberg (1962,1964)*

**Weak at LL:** \(-\frac{\alpha}{\pi s_w^2} \log^2 \left( \frac{M_V^2}{Q^2} \right) \approx -0.052 \) for \( Q = 2 \text{ TeV} \)

*Origin:* Remnants of UV singularities after renormalization and soft/collinear IS and FS emission of virtual and real \( W \) and \( Z \) bosons.
In contrast to QED and QCD, also in inclusive observables these corrections do not completely cancel. *Ciafaloni, Ciafaloni, Comelli (2000)*

NLO EW calculations are available for
\( pp, p\bar{p} \rightarrow W; Z \rightarrow l\nu; l^+l^-; VV; Wj; Zj \rightarrow \nu l j; l^+l^-j; t\bar{t}; \) single top, and \( b\bar{b},jj \) (weak);
and for dominant Higgs production processes \( (gg \rightarrow H; W/ZH; VBF, \) for a review see, e.g., *Higgs cross section WG report, arXiv:1101.0593*)
Weak Sudakov logs: \( \alpha^l_W \ln^n \left( \frac{Q^2}{M^2_W} \right) ; n \leq 2l \)

In the high-energy limit, \( \frac{Q}{M_{W,Z}} \to \infty \), EW Sudakov logarithms have been studied in analogy to soft/collinear logarithms in QED,QCD.

- 1-loop: LL and NLL are universal and factorize \cite{Denner_2001}
- Beyond 1-loop: Resummation techniques based on IR evolution equations (IREE) or SCET yield results up to NNLL \( (\ln^n(\frac{s}{M^2_W}), n = 2, 3, 4) \).
  - IREE: EW theory splits into symmetric \( SU(2) \times U(1) \) \( (M_W = M_Z = M_\gamma = M \) for \( \mu > M \)) and QED regime and effect of EW symmetry breaking neglected. \cite{Fadin_2000}
  - SCET: At \( \mu = Q \) match full theory to SCET(\( M = 0 \)), evolve to \( \mu = M \) SCET(\( M \neq 0 \)), match to SCET with no gauge bosons.
  - SCET and IREE Sudakov form factors are equivalent. \cite{Chiu_2008, Chiu_2009, Chiu_2010, Fuhrer_2011}

Resummation results at LL and NLL confirmed by explicit diagramatic one-loop and two-loop calculations.

Higgs production via gluon fusion

‘Best’ prediction of the total cross section for Higgs production in gluon fusion (in pb):
NNLO+NNLL+EW

\[ \sigma = 19.31^{+7.2\%}_{-7.8\%} \text{(scale)}^{+7.5\%}_{-6.9\%} \text{(PDF + } \alpha_s) \]

N^3LO QCD work in progress! Grazzini, de Florian, 1206.4133

NLO EW corrections shift the NNLO QCD result by about +5% (complete factorization) and by +1% (partial factorization). Actis et al, 0809.1301

Explicit calculation of mixed EW-QCD corrections is close to result obtained with complete factorization. Anastasiou et al, 0811.3458
Relative weak corrections to leading jet $k_T$ distribution to $pp \rightarrow jj+X$ at the 8 TeV LHC

Impact of weak 1-loop corrections in top-pair production at the 8 TeV LHC

$M_H = 126$ GeV

$M_H = 126$ GeV, $g_Y = 2 \times g_Y^{SM}$

$M_H = 1$ TeV

$\delta \sigma_{NLO}^{tot}/\sigma_{LO}^{tot} [%]$ vs LHC Energy [TeV]

H.Kühn, A. Scharf and P. Uwer, arXiv:1305.5773
Impact of weak 1-loop corrections in top-pair production at the 8 TeV LHC

H. Kühn, A. Scharf and P. Uwer, arXiv:1305.5773
**pp→W⁺W⁻ at NLO EW at the LHC**

W rapidity distributions at LO and relative NLO EW corrections for different initial states:

![Graph showing rapidity distributions and corrections](image)

Bierweiler *et al*, 1208.3147; WZ,ZZ: 1305.5402
\[ pp \rightarrow WW \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e \]

at NLO EW in DPA

Biloni et al, 1310.1564
NLO EW correction to $WW, ZZ, WZ$ in HERWIG

$$d\hat{\sigma}_{\text{EW} \times \text{QCD}} = K_{qq'}^{V_1 V_2}(\hat{s}, \hat{t}) \times d\hat{\sigma}_{\text{QCD}}$$

Gieseke et al, 1310.2843
WW production at EW NLL and NNLL in the high energy limit

J.H. Kuhn et al, 1101.2563

Large cancellations between NLL and NNLL in transverse case (LL dominated) and between LL, NLL, and NNLL in the $W_L W_L$ production process.

See also results obtained in the EFT approach by Chiu et al. (2008)
QED in NNPDF

Combined QED-QCD evolution equation:

\[ Q^2 \frac{\partial}{\partial Q^2} f(x, Q^2) = \left[ \frac{\alpha(Q^2)}{2\pi} P_{\text{QED}} + \frac{\alpha_s(Q^2)}{2\pi} P_{\text{QCD}} \right] \otimes f(x, Q^2) \]

Photon PDF:

\[ \gamma(x, Q_0^2) = (1 - x)^{m_\gamma} x^{-n_\gamma} NN_\gamma(x) \]

Implications for:

Ball et al, 1308.0598
NNPDF Photon PDF from DIS data

Photon PDF at $Q^2 = 2.0$ GeV$^2$

LHC data constrain shape and normalization.

Ball et al, 1308.0598
Ball et al., 1308.0598
Electroweak 1-loop corrections to Z/W+n jets

• Exact 1-loop EW corrections are known for W/Z+1 jet Kuhn et al, hep-ph/057178, 0708.0476; Denner et al, 1211.507,0906.1656

• and for Z+2 jet (only gluonic contributions, 4-quark contributions in progress) Actis et al, arXiv:1211.6316

• At energy scales above the electroweak scale EW corrections are dominated by weak Sudakov logarithms
  for a review see, e.g., H.Kuhn, Acta Physica Polonia B39(2008); talk by S.Dittmaier at Les Houches 2013

• Weak 1-loop Sudakov corrections to Z+1,2,3 jets production are now implemented in Alpgen 1.4.1.2, Chiesa et al. arXiv:1305.6837
Z+2j @ NLO EW at the 8 TeV LHC

Based on REcola: Fortran90 code for the recursive calculation of one-loop amplitudes

Actis et al, arXiv:1211.6316

\[ p_{T,jet} > 25 \text{ GeV}, \quad |y_{jet}| < 4.5 \]
Z+3j: Weak 1-loop Sudakov corrections in Alpgen

\[ H_T > 500 \text{ GeV} \quad \quad |\vec{H}_T| > 200 \text{ GeV} \]
\[ p_T^j > 50 \text{ GeV} \quad \quad |\eta_j| < 2.5 \quad \Delta R_{(j_i,j_k)} > 0.5 \]
\[ \Delta \phi(\vec{p}_{T}^{j_1,j_2},\vec{H}_T) > 0.5 \quad \Delta \phi(\vec{p}_{T}^{j_3},\vec{H}_T) > 0.3 \]

\[ \sqrt{s} = 7 \text{ TeV} \]

NLO Virt. \quad NLO Real

\[ \delta \text{ Virt.} + \delta \text{ Real} \]

Chiesa et al. arXiv:1305.6837
NLO EW×QCD to W and Z production in POWHEG

• Implementation in POWHEG-W by Bernaciak et al 1201.4804 and Barze et al. 1202.0465

• Implementation in POWHEG-Z by Barze et al, 1302.4606

• Implementation by Barze et al: NLO QCD and EW both interfaced to QCD and QED shower MCs.

Implementation by Bernaciak et al:

\[
\begin{align*}
    d\sigma &= \sum_{\text{flavors}} \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\text{min}}) + \sum_{\alpha_r} \frac{d\Phi_{\text{rad}} \Delta(\Phi_n, k_T > p_T^{\text{min}}) R(\Phi_{n+1})}{B(\Phi_n)} \right\} \\
    \bar{B}(\Phi_2) &= B(\Phi_2) + V_{\text{QCD}}(\Phi_2) + V_{\text{EW}}(\Phi_2) + \int_{\oplus} \frac{dz}{z} \left[ G_{\oplus, \text{QCD}}(\Phi_2, \oplus) + G_{\oplus, \text{EW}}(\Phi_2, \oplus) \right] \\
    &+ \int_{\ominus} \frac{dz}{z} \left[ G_{\ominus, \text{QCD}}(\Phi_2, \ominus) + G_{\ominus, \text{EW}}(\Phi_2, \ominus) \right] + \sum_{\alpha_r \in IS} \int d\Phi_{\text{rad}, IS} \left[ \hat{R}(\Phi_3) + R_{\text{EW}}(\Phi_3) \right]
\end{align*}
\]
Impact of NLO EW in presence of QCD corrections on $P_T$(lepton) in $pp\rightarrow\gamma,Z\rightarrow l^+l^-$

Barze et al, 1302.4606

Calculation of mixed 2-loop QCD-EW corrections is work in progress. See talk by S.Dittmaier at Radcor 2013.
Getting ready for the 14 TeV Run

• The community has identified what is needed.
• The calculational tools needed to achieve the necessary precision in LHC predictions are in place.
• Impressive progress has been made already.
• But (much) more work is ahead of us and hopefully this important bread and butter physics will find continued support.