Electroweak Corrections

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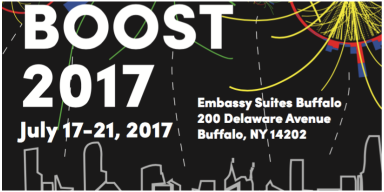
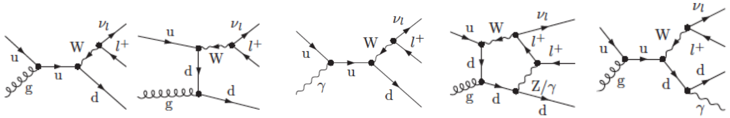


Buffalo, NY, July 18, 2017

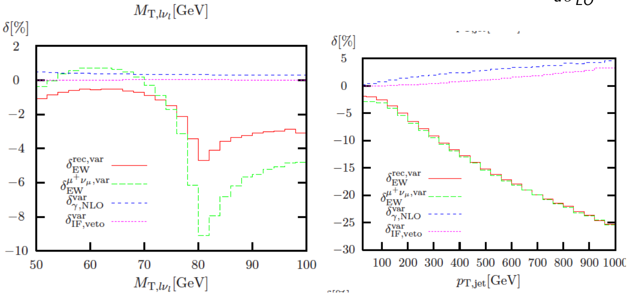
Electroweak corrections at hadron colliders: a prelude

Fixed order prediction for $pp \to W(l\nu) + 1\text{jet} + X$ up to $\mathcal{O}(\alpha_s\alpha^3)$: A.Denner, S.Dittmaier, T.Kasprzik, A .Mück, arXiv:0906.1656

$$d\sigma_{NLO} = d\sigma_{LO}(\alpha_s\alpha^2) + d\sigma_{LO,\gamma}(\alpha^3) + (d\sigma_{virtual} + d\sigma_{real})_{EW}(\alpha_s\alpha^3) + d\sigma_{NLOQCD,\gamma}(\alpha_s\alpha^3)$$



Impact on observables usually shown as relative correction: $\delta(\%) = \frac{d\sigma_{NLO}}{d\sigma_{LO}}$



Electroweak corrections at hadron colliders: some resources

- Recent Les Houches workshop reports
  - Dictonary of electroweak (EW) corrections: S.Dittmaier
    EW input schemes, EW Sudakov logs, mass-singular logs, QED corrections in PDFs, photon-induced processes, treatment of unstable W, Z bosons, photon-jet separation, combination of QCD and EW corrections arXiv:1405.1067
  - High-precision wishlist and status of automation: arXiv:1605.04692
- Precision studies of observables in $pp \to W \to l_l$ and $pp \to \gamma, Z \to l^+ l$ processes at the LHC: arXiv:1606.02330
  and
  Precision Measurement of the W-Boson Mass: Theoretical Contributions and Uncertainties C. M. Carloni Calame,M. Chiesa, H.Martinez, G.Montagna, O.Nicrosini, F.Piccinini, A.Vicini
  arXiv:1612.02841
- Precise predictions for V+jets dark matter backgrounds J. M. Lindert, S. Pozzorini, R. Boughezal, J. M. Campbell, A. Denner, S. Dittmaier, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, S. Kallweit, P. Maierhöfer, M. L. Mangano, T.A. Morgan, A. Mück, F. Petriello, G.P. Salam, M.Schönherr, C.Williams
  arXiv:1705.04664

Electroweak corrections at hadron colliders

EW corrections are needed for

- precisely extracting SM input parameters from observables: M_W, $\sin^2\theta_{eff}$, m_t, $y_{b,t}$, ..., Example: M_W extracted from transverse lepton-pair mass or lepton momentum in single W production via Drell-Yan:

$$M_T(l\nu_l) = \sqrt{p_T^l p_T^\nu (1 - \cos(\Phi_l - \Phi_\nu))}$$

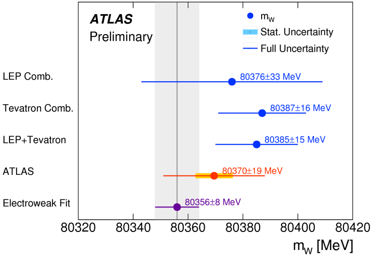
- precisely predicting SM input parameters, e.g., $M_w(theory)$ from

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha(0)M_Z^2}{2(M_Z^2 - M_W^2)M_W^2}[1 + \Delta r]$$

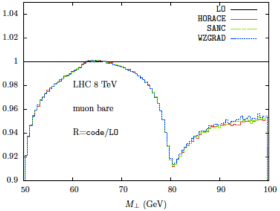
  $\Delta r(M_W, m_t, M_H, \ldots)$ describes the loop corrections to muon decay. For a review of the role of radiative corrections in EW precision physics see, e. g., A.Ferroglia, A.Sirlin (2013).

- reducing systematic uncertainties, e.g., W, Z observables are important for constraining quark PDFs.

First W mass measurement at the LHC (ATLAS) arXiv:1701.07240



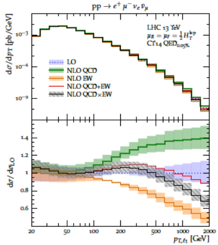
Impact of EW corrections on $M_T(\mu\nu_\mu)$ in $pp \to W^+ \to \mu^+\nu_\mu$: arXiv:1606.02330

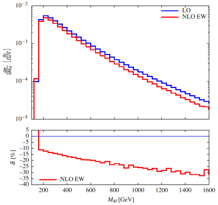


Electroweak corrections at hadron colliders

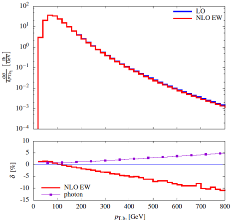
- EW corrections are relevant for modeling signal and background processes for searches of signals of new physics, either due to direct production, higher-dimensional operators, or the virtual presence of new particles in SM observables.
- EW corrections play an especially important role in EW gauge boson production processes: V, VV, VVV (+jets) with $V = \gamma, Z, W^{\pm}$.
- EW corrections can be numerically at least as important as NNLO QCD corrections and for certain processes and in certain kinematic regions they may even be the dominant corrections.

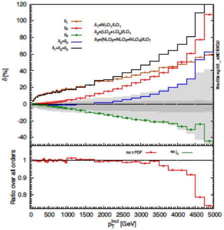
$pp \to e^+\mu^-\nu_e\bar{\nu}_\mu$: S.Kallweit, J.Lindert, S. Pozzorini, M.Schönherr, arXiv:1705.00598; $pp \to \mu^+\nu_\mu e^+\nu_e jj$: B. Biedermann, A.Denner, M.Pellen, arXiv:1611.02951





$pp \to e^+\nu_e\mu^-\nu_\mu b\bar{b}$: A.Denner, M.Pellen, arXiv:1607.05571; $pp \to jj$: R.Frederix *et al*, arXiv:1612.06548





Characteristics of EW corrections

Naive estimate of relative size of EW and QCD corrections:

$\frac{\alpha(M_Z)}{\pi} \approx 0.0025$ vs. $\frac{\alpha_s(M_Z)}{\pi} \approx 0.037$ and $(\frac{\alpha_s(M_Z)}{\pi})^2 \approx 0.0014$

Possible enhancements:

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

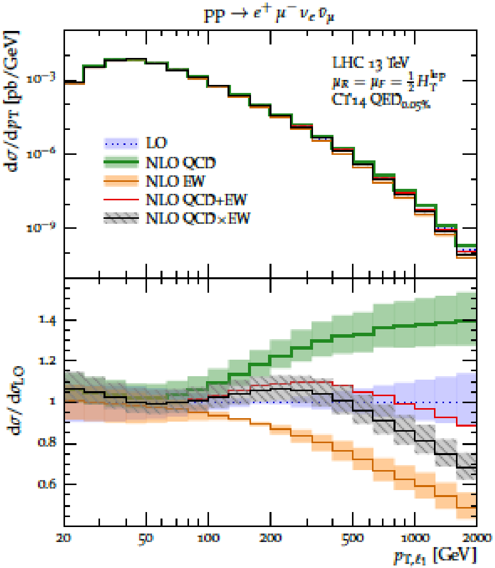
Origin: Soft/collinear FS photon radiation
In sufficiently inclusive observables these mass singularities completely cancel. Kinoshita, Lee, Nauenberg (1962,1964)
Depending on the experimental lepton identification cuts they can significantly affect the shape of distributions.
IS mass singularities are factorized into PDFs which introduces a QED factorization scheme; PDFs with QED corrections and photon PDF A.Manohar, 1607.04266 (LUXqed

Weak Sudakov corrections, e.g., at LL: $-\frac{\alpha}{\pi s_w^2} \log^2(\frac{M_V^2}{Q^2}) \approx -0.052$ for Q=2 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. M.Ciafaloni, P.Ciafaloni, D.Comelli (2000,2001) see, e.g., K.Mishra *et al*, 1308.1430; J.H.Kühn, Acta Phys.Polon.B39 (2008) for examples and a brief review

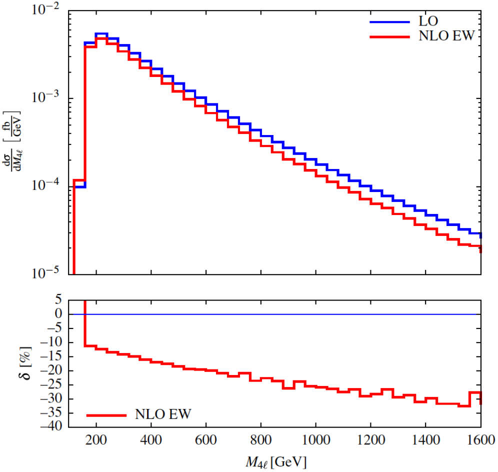
$pp \to e^+\mu^-\nu_e\bar{\nu}_\mu$ at NLO(EW+QCD)

S.Kallweit, J.Lindert, S. Pozzorini, M.Schönherr; arXiv:1705. 00598



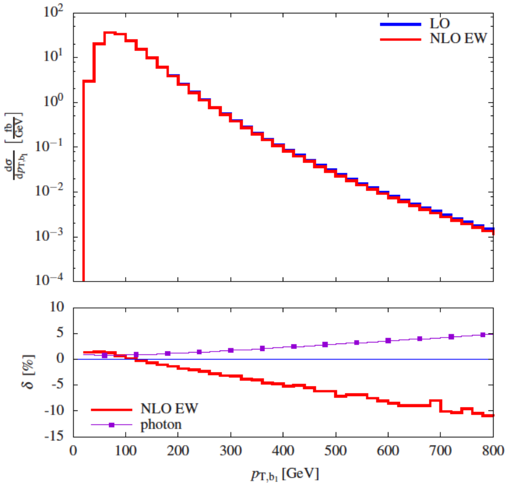
$pp \to \mu^+\nu_\mu e^+\nu_e jj$ at NLO EW (VBS)

B. Biedermann, A.Denner, M.Pellen arXiv:1611.02951



$pp \to e^+\nu_e\mu^-\nu_\mu b\bar{b}$ at NLO EW

A.Denner, M.Pellen arXiv:1607.05571;

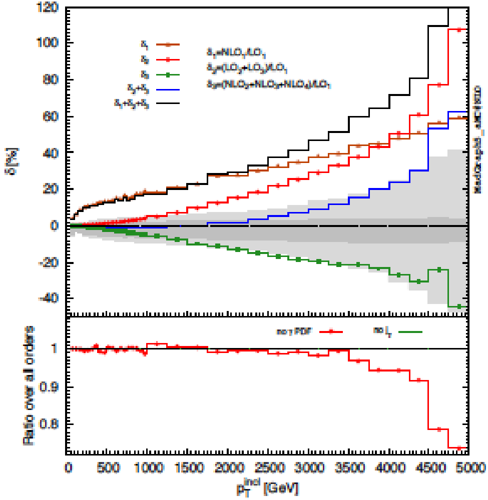


$pp \to jj$

R.Frederix *et al* arXiv:1612.06548

LO: $\mathcal{O}(\alpha_s^2)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha\alpha_s)$

NLO: $\mathcal{O}(\alpha_s^3)$, $\mathcal{O}(\alpha_s^2\alpha)$, $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha^3)$



Mass-singular logarithms of QED origin

Multiple FS photon radiation and exponentiation at LL, $L = \log(\frac{Q^2}{m_l^2})$:

- Exponentiation of YFS form factor Yennie,Frautschi,Suura (1961):

$$Y(m \ll Q) = \frac{\alpha}{\pi}\left\{2(L-1)\ln(\frac{2\Delta E_\gamma}{Q}) + \frac{1}{2}L - \frac{1}{2} - \frac{\pi^2}{6}\right\}$$

  Implemented in `WINHAC` for W production Placzek *et al* (2003), matched to NLO EW of `SANC` Bardin *et al* (2008); and in `Sherpa` M. Schönherr, F.Krauss (2008).

- QED parton shower: emission of n photons ($I_+ = \int_0^{1-\epsilon} dz P(z)$)

$$d\sigma = \exp[-\frac{\alpha}{2\pi} I_+ L] \sum_n^\infty |M_n^{LL}|^2 d\Phi_n$$

  Implemented in `HORACE` Carloni-Calame et al (2003,2004,2006), matched to full NLO EW.

- QED structure function Kuraev, Fadin (1985):
  $d\sigma = d\sigma_{LO} \int dz \Gamma(z)\theta_{cut}(zp_l)$; $\beta_l = \frac{2\alpha(0)}{\pi}(L-1)$

$$\Gamma(z, Q^2)) = \frac{\exp[-\beta_l/2\gamma_E + \frac{3}{8}\beta_l]}{\Gamma(1+\beta_l/2)} \frac{\beta_l}{2}(1-z)^{\beta_l/2-1} + \ldots + \mathcal{O}(\beta_l^4)$$

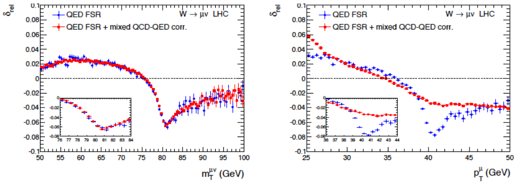
  Implemented in W production Brensing, Dittmaier, Krämer, Mück (2008) and Z production Dittmaier, Huber (2009), matched to full NLO EW.

- `POWHEG`(NLO QCD+EW)$\otimes$ (QCD+QED) PS; QED PS with `PHOTOS` (Golonka, Was (2005,2006)) or with `PYTHIA 8` for W production Carloni Calame *et al*, 1612.02841.

$pp \to W \to l\nu X$ at NLO(EW+QCD)$\otimes$ QCD/QED PS in POWHEG BOX V2

The implementation of EW corrections in the POWHEG BOX Barze *et al.*, 1202.0465; Carloni Calame *et al*, 1612.02841

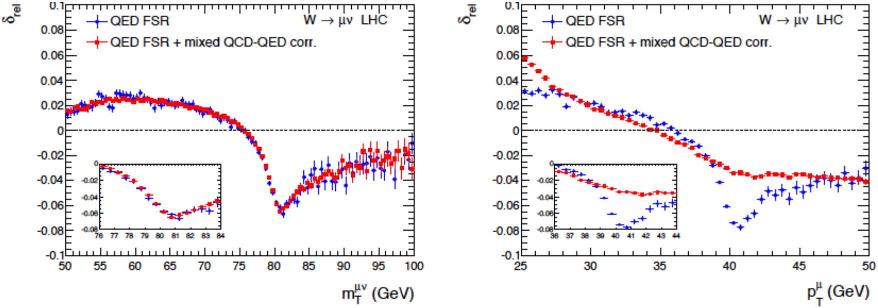
- ensures normalization with NLO QCD + EW accuracy,
- combines the complete SM NLO corrections with a mixed QCD$\otimes$QED parton cascade, where the particles present in the shower are coloured particles or photons, and
- consequently, incorporates mixed $\mathcal{O}(\alpha\alpha_s)$ contributions and allows to study consistently the interplay between QCD and EW radiation, *e.g.*, the link between a photon emitted after QCD radiation and viceversa.



See also C.Bernaciak, D.W., arXiv:1201.4804

$pp \to l^+l^-X$ and $pp \to \nu lX$ at $\mathcal{O}(\alpha\alpha_s)$ in pole approximation: S.Dittmaier, A.Huss, C.Schwinn, arXiv:1405.6897; 1403.3216; 1511.08016

Carloni Calame *et al*, 1612.02841



EW Sudakov logarithms $\alpha_w^l \log^n(Q^2/M^2)$, $n \leq 2l$

When the characteristic energies are larger than $M_{W,Z}$ higher-order EW corrections may be approximated as an expansion in EW Sudakov logs:

- Results (fixed order and resummed to all orders) are available for hadronic cross sections for, e.g., V(+jets), VV, $t\bar{t}$, bb, cc, jj, and VBF.
  $Z+\leq 3$ jets in ALPGEN Chiesa *et al* (2013)
  $Z, t\bar{t}, jj$ production implemented in MCFM Campbell, D.W., Zhou (2016)
- Best studied so far for four-fermion process $f\bar{f} \to f'\bar{f}'$:
  - up to N^3LL for massless fermions ($a = \frac{\alpha}{4\pi s_w^2}$, $L = \log(s/M_W^2)$):

$$\frac{\delta\sigma(e^+e^- \to q\bar{q})(s)}{\sigma_{LO}} = -2.18aL^2 + 20.94aL - 35.07a + \\ +2.79a^2L^4 - 51.98a^2L^3 + 321.20a^2L^2 - 757.35a^2L$$

    Jantzen, Kühn, Penin, Smirnov, hep-ph/0509157
  - up to NNLL for massive fermions Denner, Jantzen, Pozzorini (2008).
  - up to NLL for $V + jets$ J. H. Kuhn, A. Kulesza, S. Pozzorini, M. Schulze (2005,2007); see also J.Lindert *et al*, 1705.04664
- Impact of real W, Z radiation Baur (2006); Bell *et al* (2010); Manohar *et al* (2014)
- Resummation with SCET Chiu et al, (2008,2009); Manohar, Trott (2012); Bauer,Ferland (2017)

Automation of NLO EW (+QCD) calculations

"Amplitude calculators":

- Recola S.Actis *et al*, 1605.01090+ Collier A.Denner *et al* 1604.06792
- OpenLoops F.Cascioli *et al*, 1111.5206
- Gosam M.Chiesa *et al*, 1507.08579 + MadDipole T.Gehrmann *et al*, 1011.0321
- `Madgraph5_aMC@NLO` J.Alwall *et al*, 1405.0301

Some recent results for multi-particle processes which consistently include higher-order QCD and EW corrections implemented in PS MCs:

- `Recola+Sherpa` B.Biedermann *et al*, 1704.05783
  Examples: $pp \to V+$ jets, $pp \to ZZ \to 4$ leptons, $pp \to t\bar{t}H$
- `OpenLoops+Munich/Sherpa`
  Examples: $pp \to W + 1, 2, 3$ jets, S.Kallweit *et al*, 1412.5157, and $V + 1, 2$ jets with $V \to ll'$ and MEPS@NLO jet merging, S.Kallweit *et al*, 1511.08692; $pp \to 2\nu 2l$, S.Kallweit *et al*, 1705:00598
- `GOSAM+Sherpa` M.Chiesa *et al*, 1706.09022
  Examples: $pp \to \gamma\gamma + 0, 1, 2$ jets
- `Madgraph5_aMC@NLO`
  Examples: $pp \to t\bar{t} + (H, Z, W)$, S.Frixione *et al*, 1504.03446; $pp \to jj$, Frederix *et al*, 1612.06548

Final Remarks

- Electroweak corrections have a reach structure and their numerical impact strongly depend on the kinematic regime, details of the lepton identification/analysis cuts, interplay with QCD radiation, etc.
- Predictions for a selected number of SM processes have reached a high level of sophistication.
- Automated calculations of NLO EW+QCD corrections are becoming available, matched to PS Monte Carlo programs.
- We can look forward to a new era of EW phenomenology.