Electroweak Precision Predictions in the LHC Era - Part 2

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Characteristics of EW corrections

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

Possible enhancements:

QED: $\frac{\alpha(0)}{\pi} \log(\frac{m_f^2}{Q^2}) \approx -0.024$ 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)

Weak 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)

NLO EW calculations are available for
$pp, p\bar{p} \to W; Z \to l\nu; l^+l^-; VV; Wj; Zj \to \nu lj; l^+l^-j; t\bar{t}$; single top, $b\bar{b}, jj; \ldots$ (weak); and for dominant Higgs production processes ($gg \to H; W/ZH; VBF; \ldots$); for a review see, e.g., S.Dittmaier's talk at Les Houches 2013.

Renormalization schemes for EW NLO calculations

- On-shell (OS) scheme Böhm, Hollik, Spiesberger (1986)
  Choice of physical parameters (A.Sirlin): $e, m_f, M_Z, M_W, M_H, (V_{ij})$ (with $\cos\theta_w = M_W/M_Z$!)
  Renormalization conditions fix finite parts of renormalization constants:
  - Propagators have their poles at physical(=renormalized) masses, which yields, e.g., the conditions $Re\hat{\Sigma}_T^W(M_W^2) = Re\hat{\Sigma}_T^Z(M_Z^2) = ... = 0$.
  - Properties of the photon and the electromagnetic charge are defined as in QED, e.g., $\hat{\Gamma}_\mu^{\gamma ee}(k^2 = 0) = ie\gamma_\mu$.
  - No tadpoles and poles in the unphysical sector lie at $M_W, M_Z, 0$.

  $\rightarrow$ no renormalization scale dependence (UV divergences subtracted at physical masses).
- $\overline{\mathrm{MS}}$ scheme Bardeen et al (1978): UV poles and $(\gamma_E/4\pi)^\epsilon$ are subtracted
  Example: Calculation of EWPOs in GAPP J.Erler, 0005084; see also G.Degrassi, A.Sirlin (1991,1992)
  Hybrid scheme: OS scheme for masses and $\overline{\mathrm{MS}}$ for couplings.

Difference can serve as an estimate of theoretical uncertainty due to missing higher order corrections.

Choice of EW input parameters in NLO EW calculations

- $\alpha(0), m_f, M_Z, M_W, M_H$
  Contains $\alpha \log(m_f/M_Z)$ terms through the photon vacuum polarization contribution when charge renormalization is performed (δZ_e).
- $\alpha(M_Z), m_f, M_Z, M_W, M_H$

$$\alpha(0) \to \alpha(M_Z) = \frac{\alpha(0)}{[1 - \Delta\alpha(M_Z)]}$$

  Taking into account the running of α from $Q = 0$ to M_Z cancels these mass-singular terms.
- $G_\mu, m_f, \Delta\alpha_{had}, M_Z, M_W, M_H$

$$\alpha(0) \to \alpha_{G_\mu} = \frac{\sqrt{2} G_\mu (1 - M_W^2/M_Z^2) M_W^2}{\pi} [1 - \Delta r(\alpha(0), M_W, M_Z, m_t, M_H, \ldots)]$$

  Δr cancels mass singular logarithms and universal corrections connected to the ρ parameter.

for a brief review see, e.g., S.Dittmaier in Les Houches 2013 SM WG report

Treatment of unstable gauge bosons

- S-matrix theory Eden et al (1965): unstable particles appear as resonances in the interaction of stable particles:

$$\mathcal{M}(s) = \frac{R}{s - M_c^2} + F(s)$$

with a complex pole $M_c^2 = M^2 - iM\Gamma$ and $F(s)$ is an analytic function with no poles. $R, M_c, F(s)$ are separately gauge invariant.

- QFT: resonance is due to pole in Dyson resummed propagator of an unstable particle:

$$D^{\mu\nu} = \frac{-ig^{\mu\nu}}{s - M_0^2 + \Sigma_T(s)} = \frac{-ig^{\mu\nu}}{s - M_0^2 + i\epsilon} \left[1 + \left(\frac{-\Sigma_T(s)}{s - M_0^2 + i\epsilon}\right) + \dots\right]$$

which yields

$$\mathcal{M}(s) = \frac{\hat{V}_i(s)\ \hat{V}_f(s)}{s - M_R^2 + \hat{\Sigma}_T(s)} + B(s)$$

Treatment of unstable gauge bosons

Following an S-matrix theory approach (R.Stuart (1991), H.Veltman (1994)), one can write $\mathcal{M}(s)$ in a gauge invariant way using a Laurent expansion about the complex pole, e.g., at 1-loop order for single W production (W.Hollik, DW (1995) :

$$\mathcal{M}^{(0+1)}(s) = \frac{\mathcal{R}(g^2) + \mathcal{R}(M_W^2, g^4)}{s - M_W^2 + iM_W\,\Gamma_W^{(0+1)}} + \mathcal{O}(g^4)$$

with the residue in next-to-leading order

$$\mathcal{R}(M_W^2, g^4) = \hat{V}_i(M_W^2, g^3)V_f(g) + V_i(g)\hat{V}_f(M_W^2, g^3) - V_i(g)V_f(g)\,\hat{\Pi}_T(M_W^2, g^2)$$

and the width

$$M_W\Gamma_W^{(0+1)} = (1 - \mathcal{R}e\hat{\Pi}_T(M_W^2, g^2))\,\mathcal{I}m\hat{\Sigma}_T(M_W^2, g^2) + \mathcal{I}m\hat{\Sigma}_T(M_W^2, g^4)$$

and a modified 2-loop renormalization condition:

$$M_W^2 = M_R^2$$

if

$$\mathcal{R}e\hat{\Sigma}_T(M_R^2, g^4) + \mathcal{I}m\hat{\Sigma}_T(M_R^2, g^2)\,\mathcal{I}m\hat{\Pi}_T(M_R^2, g^2) = 0$$

Treatment of unstable gauge bosons

$\mathcal{M}^{(0+1)}(s)$ in the s-dependent width approach:

$$\mathcal{M}^{(0+1)}(s) = \frac{\mathcal{R}^{(0+1)}(M_W^2, g^4)}{s - M_W^2 + i\frac{s}{M_W^2}\,\Gamma_W^{(0+1)}} + \mathcal{O}(g^4)$$

with the residue in next-to-leading order

$$\mathcal{R}^{(0+1)} = V_i(g)V_f(g) + \hat{V}_i(M_W^2, g^3)V_f(g) + V_i(g)\hat{V}_f(M_W^2, g^3) - V_i(g)V_f(g)\,(Re\hat{\Pi}_T(M_W^2, g^2) +$$

These two approaches are related by $\gamma = \Gamma_W^{(0+1)}/M_W$:

$$M_W \to \overline{M}_W = M_W\,(1+\gamma^2)^{-\frac{1}{2}}$$

$$\Gamma_W^{(0+1)} \to \overline{\Gamma}_W^{(0+1)} = \Gamma_W^{(0+1)}\,(1+\gamma^2)^{-\frac{1}{2}}$$

$Z(W)$ mass defined in constant width scheme differs from the s-dep. with approach by $\approx 34(27)$ MeV.

Treatment of unstable gauge bosons

Alternatively, one can keep a complex mass as renormalized mass consistently everywhere in the calculation of $\mathcal{M}(s)$, which is called the *complex mass scheme*: A.Denner et al, hep-ph/0605312

$$\mu_V^2 = M_V^2 + iM_V\Gamma_V \to \cos\theta_W = \frac{\mu_W}{\mu_Z}$$

- The bare Lagrangian is not changed, only the renormalization procedure is modified, e.g.,

$$(M_V^0)^2 = \mu_V^2 + \delta\mu_V^2\ ,\ \delta\mu_V^2 = \Sigma_T^V(\mu_V^2)$$

- Unitarity has been proven by deriving modified Cutkosky cutting rules for scalar theories. A.Denner, J.-N. Lang, 1406.6280
- COLLIER: Fortran library for one-loop integrals with complex masses A.Denner et al, 1407.0087

A.Denner et al, hep-ph/9406204 (background field method); A.Sirlin, G.Degrassi, PRD46 (1992) (pinch technique); E.N.Argyres et al, hep-ph/9507216

An example: $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu\gamma$

The total production cross section (in fbarn) for $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu\gamma$ using a constant, running width or a complex mass: A.Denner, S.Dittmaier, M.Roth, D.W.

c.m. energy:	LEP2 189 GeV	LC 500 GeV	LC 2000 GeV
constant width	224.0(7)	83.4(6)	7.02(8)
running width	224.3(7)	84.4(6)	18.9(2)
complex mass	223.9(7)	83.3(6)	7.01(8)

$\Rightarrow$ The running width approach destroys gauge cancellation, which is especially visible at LC energies.

Mass singular logarithms of QED origin

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

- 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); also in Sherpa M. Schoenherr, 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):
  $d\sigma = d\sigma_{LO} \int dz \Gamma(z)\theta_{cut}(zp_l)$; $\beta_l = \frac{2\alpha(0)}{\pi}(L-1)$

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

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

- PHOTOS Golonka, Was (2005,2006)

Initial-state photon radiation (ISR)

Mass singularities always survive but are absorbed by universal collinear counterterms to the parton distribution functions; mass factorization done in complete analogy to QCD:

- introduces dependence on QED factorization scheme (in analogy to QCD there is a *DIS* and $\overline{MS}$ scheme) see, e.g. Baur, Keller, D.W., Phys. Rev. **D59**, 013002 (1999)

$$q_i(x,Q^2) = q_i(x)\ \left[1 + \frac{\alpha}{\pi}\ Q_i^2 \left\{1 - \ln\delta_s - \ln^2\delta_s + \left(\ln\delta_s + \frac{3}{4}\right)\ln\left(\frac{Q^2}{m_i^2}\right) - \frac{1}{4}\lambda_{FC} f_{v+s}\right\}\right.$$

$$\left. + \int_x^{1-\delta_s} \frac{dz}{z}\ q_i\left(\frac{x}{z}\right)\ \frac{\alpha}{2\pi}\ Q_i^2 \left\{\frac{1+z^2}{1-z}\ln\left(\frac{Q^2}{m_i^2}\frac{1}{(1-z)^2}\right) - \frac{1+z^2}{1-z} + \lambda_{FC} f_c\right\}\right]$$

$$f_{v+s} = 9 + \frac{2\pi^2}{3} + 3\ln\delta_s - 2\ln^2\delta_s$$

$$f_c = \frac{1+z^2}{1-z}\ln\left(\frac{1-z}{z}\right) - \frac{3}{2}\frac{1}{1-z} + 2z + 3$$

- PDFs including QED corrections in their evolution have been made available by the MSTR collaboration A.D.Roberts *et al.*, EPJC39 (2005) (outdated), and more recently by the NNPDF collaboration R.D.Ball *et al.*, 1308.0598.
- Photon PDFs allow for inclusion of photon-induced processes.

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

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 Denner, Pozzorini (2001)
- Beyond 1-loop: Resummation techniques based on IR evolution equations (IREE) or SCET yield results up to NNLL ($ln^n(\frac{s}{M_W^2})$, $n = 2, 3, 4$).
    - 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. Fadin, Lipatov, Martin, Melles (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. Chiu, Golf, Kelley, Manohar (2008); Chiu, Fuhrer, Hoang, Kelley, Manohar (2009); Chiu, Fuhrer, Kelley, Manohar (2010); Fuhrer *et al.* (2011); Manohar, Trott (2012)

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

Melles (2000), Hori *et al* (2000), Beenakker, Werthenbach (2000,2002), Pozzorini (2004); Feucht *et al* (2003,2004); Jantzen *et al* (2005,2006); Denner *et al* (2003,2008)

brief review: J.H.Kühn, Acta Phys.Polon.B39 (2008) (brief review)

EW+POWHEG-W+QED PS

Implementation of EW corrections in POWHEG by L. Barze et al., arXiv:1202.0465:

- Virtual $\mathcal{O}(\alpha)$ corrections from S.Dittmaier and M.Krämer, PRD 65 (2002), and checked against HORACE
- soft and collinear photon radiation is treated in the same way as colored parton emission

The implementation

- 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
- consequently, incorporates mixed $\mathcal{O}(\alpha\alpha_s)$ contributions with a better accuracy w.r.t. existing programs. In particular, it can allow to study consistently the interplay between QCD and EW radiation, like *e.g.* the link between a photon emitted after QCD radiation and viceversa.

Resulting public code available within POWHEG-BOX as subprocess W_ew-BMNNP

WGRAD2+POWHEG-W

Incorporation of EW $\mathcal{O}(\alpha)$ corrections into $\bar{\mathrm{B}}$ of `POWHEG-W`[1−2] by C.Bernaciak, D.W., arXiv:1201.4804:

$$d\sigma = \sum_{\text{flavors}} \bar{\mathrm{B}}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) + \sum_{\alpha_r} \frac{\left[d\Phi_{\text{rad}} \Delta(\Phi_n, k_T > p_T^{\min}) R(\Phi_{n+1}) \right]}{B(\Phi_n)} \right\}$$

$$\bar{\mathrm{B}}(\Phi_2) = \mathrm{B}(\Phi_2) + V_{\text{QCD}}(\Phi_2) + V_{\text{EW}}(\Phi_2) + \int_{\oplus} \frac{dz}{z} \left[\mathrm{G}_{\oplus,\text{QCD}}(\Phi_{2,\oplus}) + \mathrm{G}_{\oplus,\text{EW}}(\Phi_{2,\oplus}) \right]$$

$$+ \int_{\ominus} \frac{dz}{z} \left[\mathrm{G}_{\ominus,\text{QCD}}(\Phi_{2,\ominus}) + \mathrm{G}_{\ominus,\text{EW}}(\Phi_{2,\ominus}) \right] + \sum_{\alpha_r \in \text{IS}} \int d\Phi_{\text{rad},IS} \left[\hat{\mathrm{R}}(\Phi_3) + \mathrm{R}_{\text{EW}}(\Phi_3) \right]$$

$\Rightarrow$ $V_{\text{EW}}(\Phi_2)$ virtual + soft finite EW corrections

$\Rightarrow$ $\mathrm{G}_{\text{EW}}(\Phi_2, z)$ IS collinear EW pieces

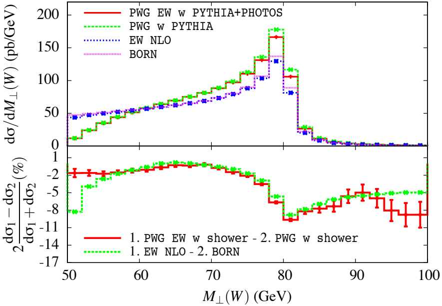
$\Rightarrow$ $\mathrm{R}_{\text{EW}}(\Phi_3)$ finite real piece - IS and FS together

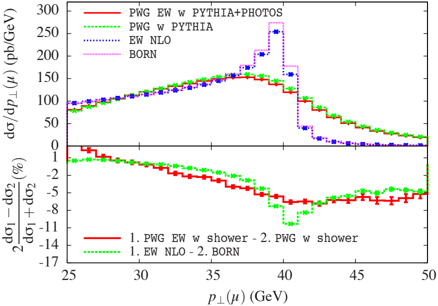
Resulting public code available within POWHEG-BOX as subprocess W_ew-BW

[1] S.Alioli,P.Nason,C. Oleari and E.Re, *JHEP* **1006** (2010) 043, arXiv:1002.2581

[2] S.Alioli,P.Nason,C. Oleari and E.Re, *JHEP* **0807** (2008) 060, arXiv:0805.4802

$M_T(l\nu)$ and $p_T(\mu)$ distributions at the LHC





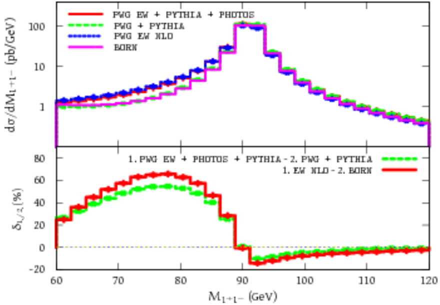
- from L. Barze et al., arXiv:1202:0465
- LHC, $\sqrt{S} = 7$ TeV

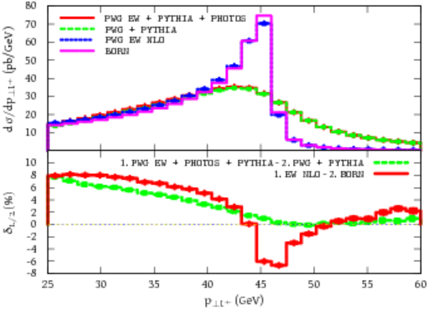
See also earlier studies of mixed QED-QCD effects using HORACE+MC@NLO and ResBos+QED FSR G. Balossini *et al*, arXiv:0907.0276; Cao, Yuan; and B.F.L. Ward *et al* (2008) (HERWIRI)

Impact on M_W ? Complete $\mathcal{O}(\alpha\alpha_s)$ corrections needed ?

EW+POWHEG-Z+QED PS

Implementation of EW corrections to $pp \to Z, \gamma \to l^+ l^-$ in POWHEG by L. Barze et al., arXiv:1302.2716:



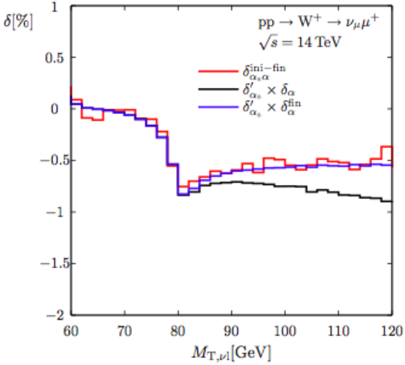


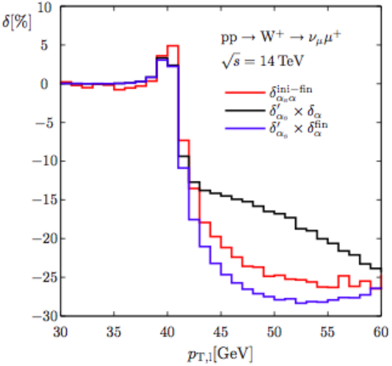
$pp \to \nu l$ at $\mathcal{O}(\alpha\alpha_s)$ in pole approximation

Comparison of initial-final factorizable $\mathcal{O}(\alpha\alpha_s)$ correction in pole approximation and a naive factorization defined as

$$\sigma^{LO}(1+\delta_{\alpha_s})(1+\delta_\alpha)$$

S.Dittmaier, A.Huss, C.Schwinn, arXiv:1405.6897; 1403.3216

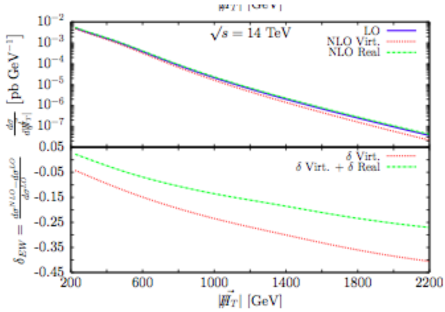




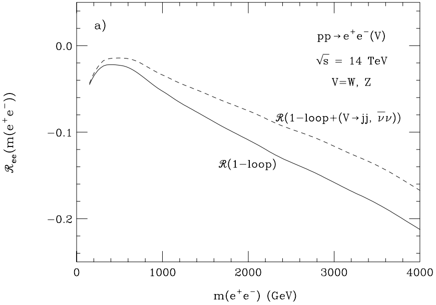
Enhanced EW corrections at high energies: impact of real W/Z radiation

Large virtual corrections may be partially canceled by real W/Z radiation, which strongly depends on the experimental setup. see also G.Bell *et al.*, arXiv:1004.4117; W.Stirling *et al*, arXiv:1212.6537

Impact of real weak gauge boson radiation on $\not{H}_T$ in $Z+3$ jet production and M_{ee} in Z production at the LHC:



M.Chiesa *et al.*, arXiv:1305.6837



U.Baur, PRD75 (2007)

PDFs+QED and Photon PDFs from NNPDF2.3QED

PDFs with QED corrections and photon PDFs are provided by the NNPDF collaboration as follows: R.D.Ball *et al*, 1308.0598

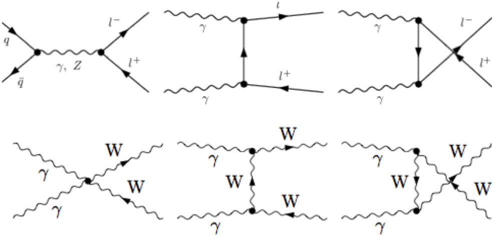
Photon PDF obtained from fit to DIS and DY data:

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

Combined QCD+QED evolution of all parton distributions:

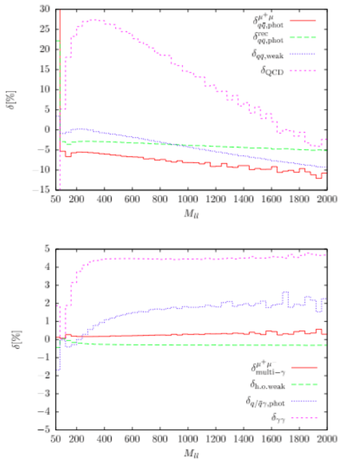
$$Q^2 \frac{\partial}{\partial Q^2} f(x, Q^2) = [\frac{\alpha(Q^2)}{2\pi} P^{QED} + \frac{\alpha_s(Q^2)}{2\pi} P^{QCD}] \otimes f(x, Q^2)$$

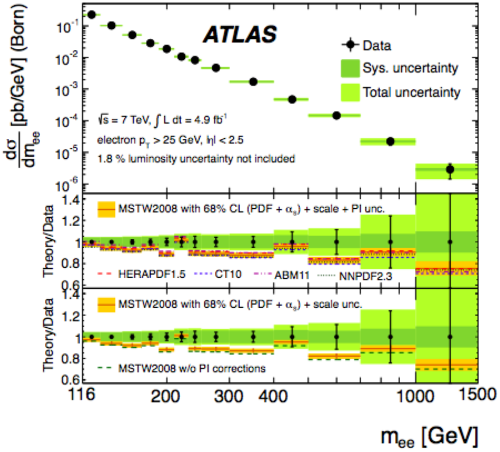
Examples of photon-induced processes:



M_{ll} in $pp \to l^+l^-$ at the LHC

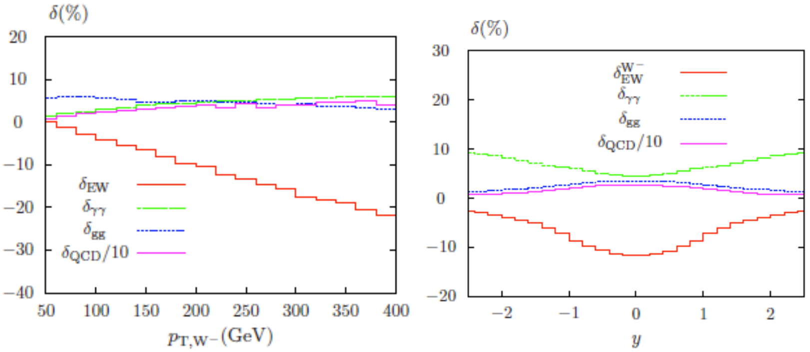
Impact of photon induced processes in Z production at the 14 TeV LHC:
The ATLAS collaboration, arXiv:1305.4192 (Theory: FEWZ NNLO+EW+W/Z rad.+PI)
S.Dittmaier, M.Huber, arXiv:0911.2329





WW production at NLO EW at the 8 TeV LHC

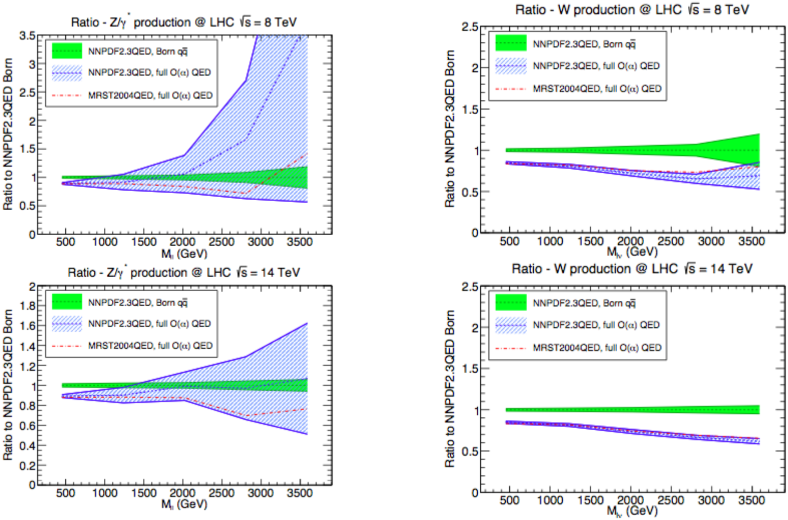
p_T and y_w (with $M_{WW} > 500$ GeV) distributions of W^- at NLO EW at the 8 TeV LHC:



Bierweiler *et al*, arXiv:1208.3147

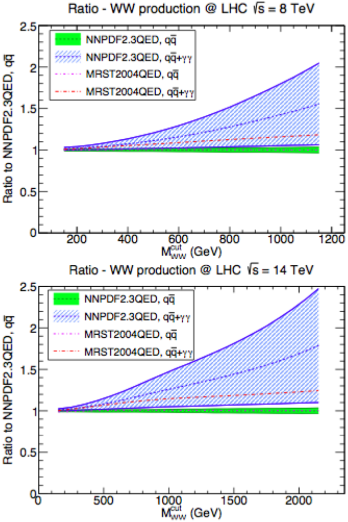
Interesting feature not seen in single-W production: photon-induced processes contribute considerably.

PDF uncertainty in DY-like W and Z production



R.D.Ball *et al*, arXiv:1308.0598

PDF uncertainty in *WW* production



R.D.Ball *et al*, arXiv:1308.0598

Conclusion

LHC Run I has already provided a wealth of EW measurements at very high precision (per mil/percent level) and is probing new kinematic regimes, and we can look forward to much more at Run II.
There has been tremendous effort and is still ongoing (see, e.g., Snomwass/Les Houches 2013 wishlists)

- in calculating higher-order QCD and EW corrections, both complete at fixed order (NNLO QCD, NLO EW and mixed 2-loop QCD-EW) and of logarithmic enhanced corrections (all order resummations up to NNLL in QCD and Sudakov EW logs known at N^3LL accuracy (4f processes)),
- and in bridging the gap between multi-purpose MCs that are needed for modeling hadronization and underlying event (HERWIG,PYTHIA) and fixed-order QCD and EW, parton-level calculations, by matching fixed order and parton shower (MC@NLO, POWHEG-Box, Sherpa).
  Recent progress: Implementation of NLO EW corrections and NNLO+PS matching

But there is still lots of work to be done ...

A personal selection of open questions

- The significance of higher-order corrections strongly depends on details of the experimental definition of observable (cuts etc.), and which kinematic regime is probed.
  EW corrections should be included in PS MCs and mixed EW-QCD effects should be under control as well.
- How can automated tools such as GOSAM, MadGraph help to implement EW one-loop corrections in PS MCs; are they ready ?
- Important and difficult task: reliable estimates of theoretical uncertainties due to missing higher-order corrections. We'll need different approaches to include EW corrections, so there is still need for dedicated calculations for specific processes.
- How do the different prescription to include mixed QCD-EW effects in PS MCs compare and how can we assess their uncertainties?
- How do different prescription to include multiple photon radiation compare, e.g., as implemented in Sherpa, Pythia, Herwig, and Photos?
- How to assess the impact of weak Sudakov logs in realistic observables ? Should we include 2-loop weak effects in PS MCs to improve predictions in the Sudakov regime?
- How to improve PDFs uncertainties for EW precision physics and also for photon unduced processes ?

A personal selection of open questions

- Do we need a tuned comparison of predictions for multi-boson production (including EW and QCD corrections and implemented in PS MCs) including anomalous couplings/EFT approach, and estimate of theoretical uncertainty due to missing-higher order corrections?
- How do different unitarization schemes affect limits on anomalous couplings/higher dim. operators?
- How to compare experimental limits when different parametrizations and unitarization schemes are used?
- How to best perform sensitivity studies on higher dim. operators and interpretation of limits?