Electroweak Physics
Theory

Doreen Wackeroth

dow@ubpheno.physics.buffalo.edu

University at Buffalo
The State University of New York

Aspen 2016 Winter Conference - Particle Physics on the Verge of Another Discovery?
Aspen, Colorado, January 13, 2016

A·S·P·E·N
Center for Physics

A new era of EW precision physics

All SM parameters are known and SM observables can in principle be precisely predicted after choosing a suitable set of SM input parameters:

$$\alpha(0), \alpha(M_Z), \alpha_s(M_z), G_\mu, \Delta\alpha^{(5)}_{had}, M_Z, M_W, M_H, m_t, m_b, m_{u,d,s,c}, m_e, m_\mu, m_\tau, V_{qq'}$$

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

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

We can look forward to increasingly stringent tests of the SM and higher sensitity to new physics. But potential for discovery or constraining new physics models also relies on control of all relevant

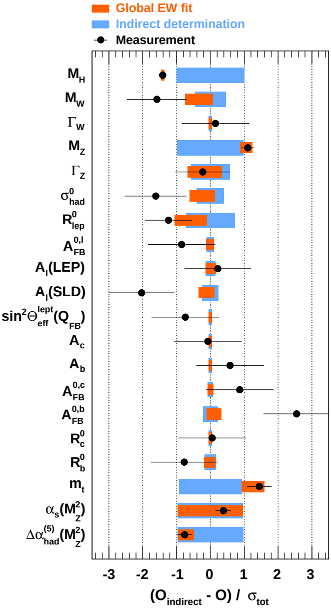
- higher-order contributions in perturbation theory, e. g., at the LHC: NNLO QCD and NLO EW (both in parton shower MCs), combined QCD/EW, resummation (QCD, QED, EW Sudakovs)
- non-perturbative effects ($\Delta\alpha_{had}$, PDFs, ...),
- parametric uncertainties, i. e. due to uncertainties in the measurement of the input parameters ($M_W, M_H, m_t, \ldots$).

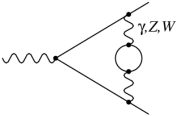
A personal selection of topics in electroweak physics

- Electroweak (EW) precision observables ($M_W, \sin^2\theta^l_{eff}$), global SM fits, sensetivity to BSM physics on the example of MSSM vs NMSSM in M_W and non-standard Higgs couplings from global fits
- Multi-gauge boson production and BSM physics: anomalous couplings, EFT and new resonances
- Electroweak corrections at the LHC: characteristics and relevance
- Towards a per mil precision in the shapes of the $M_{l\nu}, p_T(l)$ distributions in single W boson production: recent advances in precision predictions for the W mass measurement at the Tevatron and LHC
- Recent advances in tools for the calculation of NLO EW corrections (combined with NLO QCD corrections) for multi-particle processes at the LHC on the example of $pp \to l\nu + 0, 1, 2$ jets, $pp \to l^+l^-\gamma$ and $pp \to WW$ production

Not covered: prospects for EW precision physics at future e^+e^- colliders; low-energy experiments; LHCb; B physics

Global SM fit to EW precision observables





from GFITTER M.Baak *et al* arXiv:1407.3792

New: ferm. 2-loop corr. reduce R_b

by approx. exp. error

Freitas, Huang, arXiv:1205.0299

SM input parameters:

$\Delta\alpha^{(5)}_{had}, \alpha_s(M_Z), M_Z, m_f, M_H, G_\mu$

See also: LEPEWWG fit based on ZFITTER

Bardin *et al* (1999)

GPP J.Erler *et al*, PDG 2012

M. Ciuchini *et al.*, arXiv:1306.4644

The role of M_W, M_H, and m_t in precision tests of the SM

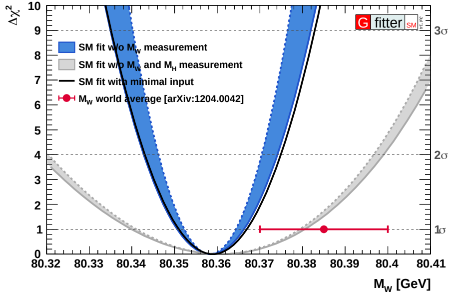
The Standard Model (SM) has proven to be very robust and we need to perform increasingly precise tests of the Standard Model.
M_W, M_H, m_t play important roles in this endeavor both as input parameters and electroweak precision observables (EWPO).
They have been measured with impressive high precision (from PDG and arXiv:1403.4427):

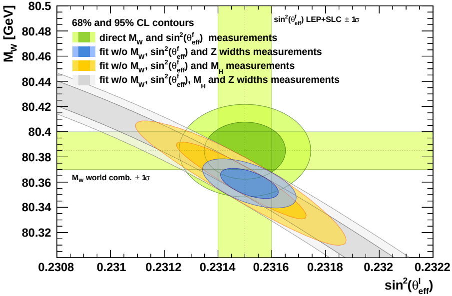
$$M_W = 80385 \pm 15 \; MeV; \; m_t = 173.34 \pm 0.76 \; GeV; \; M_H = 125.09 \pm 0.24 \; GeV$$

Further improved measurements will allow for:

- Decreased parametric uncertainties in precision observables.
- Precise SM predictions for Higgs boson properties, e.g., the Higgs width directly depends on M_H!
- More and more stringent consistency checks of the SM: measurement vs SM prediction of M_W, M_H, m_t.
- Increased sensitivity to loop-induced new physics effects and for discriminating between SM and new physics, or even between different new physics scenarios.
- Precise prediction for the Higgs quartic coupling at high energy scales (EW vacuum stability).

Global SM fit result for M_W and $\sin^2\theta^l_{eff}$





Fit result for M_W

before (gray band) and after (blue)

M_H measurement is included in the fit.

Indirect determination is now more precise than direct measurements!

Fit: $M_W = 80358 \pm 8$ MeV (present)

Exp.: $M_W = 80385 \pm 15$ MeV

Prospect (fit): $\Delta M_W = 5.5$ MeV

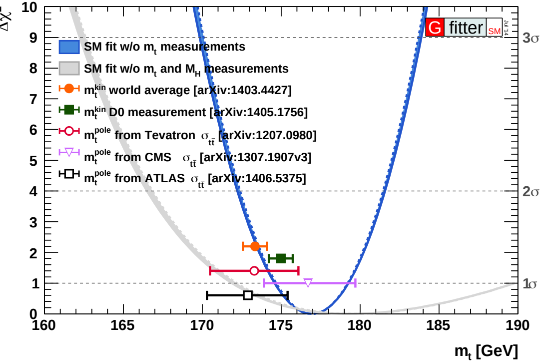
Fit: $\sin^2\theta^l_{eff} = 0.23149 \pm 0.00007$

Exp.: $\sin^2\theta^l_{eff} = 0.23153 \pm 0.00016$

GFITTER, arXiv:1407.3792

see also Snowmass EW WG report, arXiv:1310.6708

Global SM fit result for m_t



Fit result for m_t

before (gray band) and after (blue)

M_H measurement is included in the fit.

Fit: $m_t = 177 \pm 2.4$ GeV (present)

Exp.: $m_t = 173.34 \pm 0.76$ GeV

Prospect (fit): $\Delta m_t = 1.5$ GeV

Improvement mostly driven by ΔM_W.

GFITTER, arXiv:1407.3792

see also Snowmass EW WG report, arXiv:1310.6708

m_t from global fit to flavor observables: $m_t = 175 \pm 8$ GeV G.Giudice *et al*, 1508.05332

Theory and parametric uncertainties in predictions for M_W and $\sin^2\theta^l_{\rm eff}$

Parametric uncertainties (Awramik *et al*, hep-ph/0311148; hep-ph/0608099):

$$M_W = M_W^0 - c_1 \ln\left(\frac{M_H}{100\mathrm{GeV}}\right) + c_6\left(\frac{m_t}{174.3\mathrm{GeV}}\right)^2 + \dots$$

	ΔM_W [MeV]		$\Delta\sin^2\theta^l_{\rm eff}[10^{-5}]$	
	present	future	present	future
$\Delta m_t = 0.9; 0.5(0.1)$ GeV	5.4	3.0(0.6)	2.8	1.6(0.3)
$\Delta(\Delta\alpha_{\rm had}) = 1.38(1.0); 0.5\cdot 10^{-4}$	2.5(1.8)	1.0	4.8(3.5)	1.8
$\Delta M_Z = 2.1$ MeV	2.6	2.6	1.5	1.5
missing h.o.	4.0	1.0	4.5	1.0
total	7.6(7.4)	4.2(3.0)	7.3(6.5)	3.0(2.6)

Theory uncertainty is due to missing 3-loop corrections of $\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$. To match or better exceed the experimental accuracy, EWPOs had to be calculated beyond NLO, some up to leading 4-loop corrections, but complete NNLO EW for all EWPOs is not available (yet).

From Snowmass EW WG report arXiv:1310.6708 [hep-ph].

Projected uncertainties for M_W from $M_T(l\nu)$ at the Tevatron and LHC

ΔM_W [MeV]	present	CDF	D0	combined	LHC		
$\mathcal{L}$[fb]	7.6	10	10	20	20 (8 TeV)	300	3000
PDF	10	5	5	5	10	5	3
QED rad.	4	4	3	3	4	3	2
$p_T(W)$ model	2	2	2	2	2	1	1
other systematics	9	4	11	4	10	5	3
W statistics	9	6	8	5	1	0.2	0
Total	16	10	15	9	15	8	5

From the Snowmass 2013 EW WG report, arXiv:1310.6708.

- CDF, arXiv:1203.0275: δM_W(QED)=4 MeV
  ResBos+PHOTOS, HORACE used to assess the impact of the not included $\mathcal{O}(\alpha)$ corrections
- D0, arXiv:1203.0293: δM_W(QED)=7 MeV
  ResBos+PHOTOS, WGRAD used to assess the impact of the not included EW $\mathcal{O}(\alpha)$ corrections
- How about uncertainties due to *missing* higher-order corrections?
- PDF uncertainty is the limiting factor!
  LHCb measurements with forward muons can help, e.g., 30% improvement in M_W when including LHCb $p_T(l)$ measurement compared to only using ATLAS/CMS measurment
  G.Bozzi *et al*, 1508.06954

Search for indirect signals of BSM physics in EWPOs

- Consider a specific BSM model, which is predictive beyond tree-level, and calculate complete BSM loop contributions to EWPOs (Z pole observables, $M_W(\Delta r)$,. . .). Examples: 2HDM, MSSM, NMSSM
- In many new physics models, the leading BSM contributions to EWPOs are due to modifications of the gauge boson self energies which can be described by the *oblique* parameters S, T, U Peskin, Takeuchi (1991):

$$\Delta r \approx \Delta r^{\mathrm{SM}} + \frac{\alpha}{2 s_W^2} \Delta S - \frac{\alpha c_W^2}{s_W^2} \Delta T + \frac{s_W^2 - c_W^2}{4 s_W^4} \Delta U$$

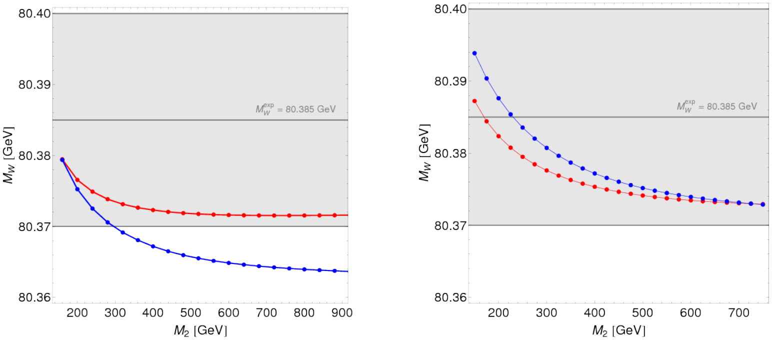
$$\sin^2 \theta^l_{eff} \approx (\sin^2 \theta^l_{eff})^{\mathrm{SM}} + \frac{\alpha}{4(c_W^2 - s_W^2)} \Delta S - \frac{\alpha s_W^2 c_W^2}{c_W^2 - s_W^2} \Delta T$$

  Example: S, T, U from global EW fit
- Non-standard couplings and effective Lagrangians
  Example: Higgs couplings to EW gauge bosons

$M_W(\Delta r)$ in the MSSM and NMSSM

From O.Stal, G.Weiglein, L.Zeune *et al*, arXiv:1506.07465 [hep-ph].

$$\Delta r^{\mathrm{SUSY(h.o.)}} = \Delta r_{\mathrm{red}}^{\mathrm{SUSY}(\alpha^2)} - \frac{c_{\mathrm{w}}^2}{s_{\mathrm{w}}^2}\Delta\rho^{\mathrm{SUSY},(\alpha\alpha_s)} - \frac{c_{\mathrm{w}}^2}{s_{\mathrm{w}}^2}\Delta\rho^{\mathrm{SUSY},(\alpha_t^2,\alpha_t\alpha_b,\alpha_b^2)}$$



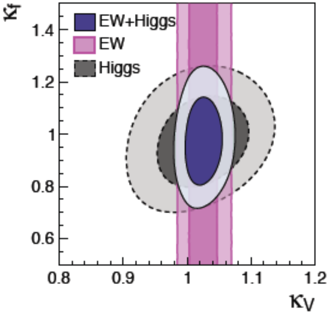
MSSM, NMSSM

$\tan\beta = 3$(*left*); 5.5(*right*), $\mu = 200$ GeV; points allowed by HiggsBounds; $M_{h1} = 125.09 \pm 3.04$ GeV for $M_2 < 725$ GeV from NMSSMTools.

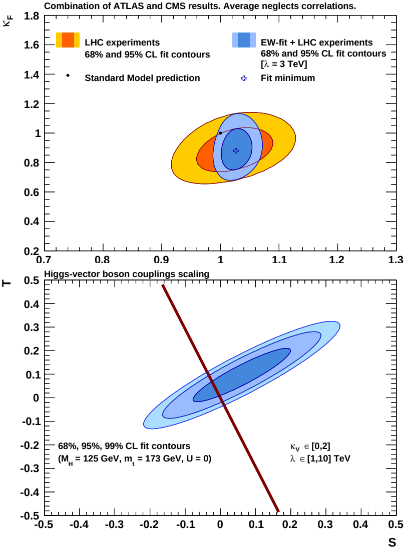
r.h.s. plot: the MSSM and NMSSM Higgs sectors are chosen to be similar.

Limits on non-standard Higgs couplings from EWPOs and ATLAS/CMS measurements

$$\mathcal{L}_{eff} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma)(1 + 2\kappa_V \frac{H}{v} + \ldots$$



Ciuchini *et al.*, arXiv:1410.6940



GFITTER, M.Baak *et al* arXiv:1407.3792

Multiple gauge boson production and non-standard interactions

- The anomalous couplings approach of Hagiwara *et al* (1987) was introduced for LEP physics and is based on the following Lagrangian ($V = \gamma, Z$)

$$\begin{aligned}\mathcal{L} =& ig_{WWV}\Bigg(g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \\ & + ig_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V \epsilon^{\mu\nu\rho\sigma} (W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu) V_\sigma \\ & + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \Bigg)\end{aligned}$$

  SM: $g_1^Z = \kappa_V = 1$; $\lambda_V = \tilde{\lambda}^V = \tilde{\kappa}_V = 0$.

- For LEP-II studies genuine anomalous quartic gauge couplings (aQGCs) involving two photons have been introduced (Sterling *et al* (1999)):

$$\mathcal{L}_0 = -\frac{e^2}{16\pi\Lambda^2} a_0 F_{\mu\nu} F^{\mu\nu} \vec{W}^\alpha \vec{W}_\alpha \; , \; \mathcal{L}_c = -\frac{e^2}{16\pi\Lambda^2} a_c F_{\mu\alpha} F^{\mu\beta} \vec{W}^\alpha \vec{W}_\beta$$

- Effective field theory (EFT): Weinberg (1979); Buchmueller, Wyler (1986)
  Higher-dim. operators describe low–energy effects of possible BSM physics with characteristic energy scale Λ as residual new interactions among light degrees of freedom, i.e. the particles of mass $M \ll \Lambda$:

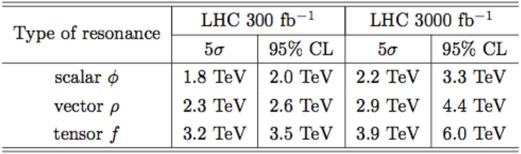
$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4} \mathcal{O}_j + \ldots$$

EFT for multi-boson production and new resonances

- $\mathcal{L}_{\mathcal{EFT}}$ implemented in public codes, e.g., `MadGraph`, `Whizard`, `VBFNLO`, and in dedicated calculations for multiple EW gauge boson production.
- The choice of higher-dimensional operators is not unique (different basis, symmetry group, ...) and different methods to unitarize the cross sections are being used (form factors, K-matrix unitarization, ...).
- Relations between EFT coefficients c_i, f_j and anomalous couplings can be derived for certain processes.
- For strongly coupled, broad resonances, one can then translate bounds for anomalous couplings directly into those of the effective Lagrangian: Snowmass 2013 EW WG report (contribution by J.Reuter and ATLAS study), 1310.6708

$$\alpha_5 \leq \frac{4\pi}{3}\left(\frac{v^4}{M_\sigma^4}\right) \approx \frac{0.015}{(M_\sigma \text{ in TeV})^4} \quad \Rightarrow \quad 16\pi^2\alpha_5 \leq \frac{2.42}{(M_\sigma \text{ in TeV})^4}$$

For example, $W^\pm W^\pm$ scattering at 14 TeV and 3000 fb^{-1} can constrain f_{S0}/Λ^4 to 0.8 TeV^{-4} at 95% CL which translates to



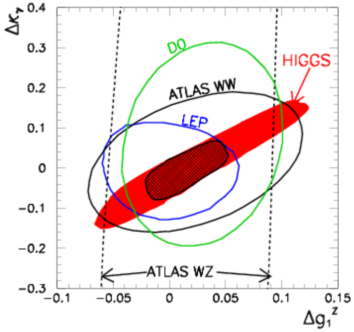
Type of resonance	LHC 300 fb^{-1}		LHC 3000 fb^{-1}	
	5σ	95% CL	5σ	95% CL
scalar ϕ	1.8 TeV	2.0 TeV	2.2 TeV	3.3 TeV
vector ρ	2.3 TeV	2.6 TeV	2.9 TeV	4.4 TeV
tensor f	3.2 TeV	3.5 TeV	3.9 TeV	6.0 TeV

Combined tests of EW gauge and Higgs boson interactions

Anomalous TGC parameters can be related to dim. 6 coefficients c_n of $\mathcal{L}_{eff} = \sum_n \frac{c_n}{\Lambda^2} \mathcal{O}_n$:

$$\Delta\kappa_\gamma \propto (c_W + c_B)\frac{v^2}{\Lambda^2} \quad , \quad \Delta g_1^Z \propto c_W \frac{v^2}{\Lambda^2}$$

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	X	X					X	X	X	X
$\mathcal{O}_W$	X	X	X	X	X		X	X	X	
$\mathcal{O}_B$	X	X		X	X					
$\mathcal{O}_{\Phi d}$			X	X						
$\mathcal{O}_{\Phi W}$			X	X	X	X				
$\mathcal{O}_{\Phi B}$				X	X	X				



Corbett *et al.*, arXiv:1304.1151

EW radiative corrections at the LHC

EW radiative corrections are especially needed

- in modeling signal and background processes for new physics searches either directly or through higher-dimensional operators or the virtual presence of new particles in SM observables,
- in precisely measuring parameters of the SM, e.g., M_W, m_{top}, M_H, $y_{b,t}$, $\ldots$,
- in reducing systematic errors, e.g., improve studies of effects of selection/analysis of data, use $\sigma_{W,Z}$ as luminosity monitor, constrain PDFs (W charge asymmetry, γ, jet production), $\ldots$

Naturally, EW corrections play an especially important role in EW gauge boson production: V, VV, VVV (+jets) gauge boson production.
Even in QCD dominated processes they can be numerically at least as important as NNLO QCD corrections and in certain kinematic regions they may be the dominant corrections.
A nice historic review of the role of radiative corrections in EW precision physics can be found in A.Ferroglia, A.Sirlin, Reviews of Modern Phsyics 85 (2013).

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 PDFs provided by NNPDF coll.

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

Status of EW predictions for $pp \to W \to \nu l, pp \to Z, \gamma \to ll$

- Complete EW $\mathcal{O}(\alpha)$ corrections: `HORACE`, `RADY`, `SANC`, `W/ZGRAD2`
  U.Baur *et al*, PRD65 (2002); C.M.Carloni Calame *et al*, JHEP05 (2005)
  U.Baur, D.W., PRD70 (2004); S.Dittmaier, M.Krämer, PRD65 (2002); A.Andonov *et al*, EPJC46 (2006); Arbuzov *et al*, EPJC54 (2008); S.Dittmaier, M.Huber, JHEP60 (2010).
- Multiple final-state photon radiation: `HORACE`, `RADY`, `WINHAC`, `PHOTOS`
  C.M.Carloni Calame *et al*, PRD69 (2004); S.Brensing *et al*, PRD77 (2008); W.Placzek *et al*, EPJC29 (2003); Golonka, Was (2005,2006)
- EW Sudakov logarithms up to N^3LL Jantzen, Kühn, Penin, Smirnov (2005); brief review: J.H.Kühn, Acta Phys.Polon.B39 (2008); $p_T(V)$ with SCET T.Becher *et al*, 1305.4202
- NLO EW corrections to W production implemented in POWHEG Bernaciak, DW (2012); Barze *et al.* (2012) ⇒ Study of mixed QED-QCD effects
- NLO EW corrections to Z production implemented in POWHEG Barze *et al.* (2013) ⇒ Study of mixed QED-QCD effects
- NLO EW corrections to Z production implemented in FEWZ (NNLO QCD) Li, Petriello (2012)
- $W+1j, Z+1j, Z+2j$ at NLO EW, now with leptonic W, Z decays W.Hollik *et al* (2008); S.Dittmaier *et al* (2009); J.H.Kühn *et al* (2008); A.Denner *et al.* (2010,2014); Actis *et al* (2012); weak Sudakov corr. to $Z+\leq 3$ jets in Alpgen Chiesa *et al* (2013)
- Toward W and Z production at $\mathcal{O}(\alpha\alpha_s)$ Kotikov *et al* (2008); Bonciani (2011); Kilgore, Sturm (2011); S.Dittmaier, A.Huss, C.Schwinn (2014,2015)

Status of QCD predictions for $pp \to W \to \nu l, pp \to Z, \gamma \to ll$

- NLO and NNLO QCD (up to $\mathcal{O}(\alpha_s^2)$): total cross sections ($\sigma_{W,Z}$) and fully differential distributions (DYNNLO, FEWZ):

  R.Hamberg *et al.*, NPB359 (1991); W.L.van Neerven *et al*, NBP382 (1992); W.T.Giele *et al*, NPB403 (1993)

  L.Dixon *et al.*, hep-ph/031226; K.Melnikov, F.Petriello, PRL96, PRD74 (2006); S.Catani *et al.*, PRL103 (2009), JHEP1005 (2010); R.Gavin *et al*, 1011.3540
- NLO QCD corrections matched to an all-order resummation of large logarithms $\ln^n(q_T/Q)$ (at NLL and NNLL accuracy) (Q: W/Z virtuality, q_T: W/Z transverse momentum).

  C.Balazs, C.-P.Yuan, PRD56 (1997) (ResBos); G.Bozzi *et al*, NPB815 (2009), arXiv:1007.2351; S.Catani *et al*, 1209.0158; N.Kidonakis, R.Gonsalves, 1404.4302
- NLO QCD corrections matched to a parton shower (HERWIG, PYTHIA): MC@NLO, POWEG.

  S.Frixione, B.R.Webber, hep-ph/0612272; S.Alioli *et al*, JHEP0807 (2008)
- NNLO QCD corrections matched to a parton shower: SHERPA Hoeche, Li, Prestel, 1405.3607, 1507.05325; POWHEG+MiNLO+DYNNLO Karlberg, Re, Zanderighi, 1407.2940; GENEVA S.Alioli *et al*, 1508.01475.
- $W + n$-jets ($n \leq 5$) and $Z + n$-jets ($n \leq 4$) at NLO QCD (and matched to PS).

  C.F.Berger *et al.* (2010,2009); Z.Bern *et al.* (2013); H.Ita *et al.* (2011); K.Ellis *et al.* (2009); J.Campbell *et al* (2002, 2013 (POWHEG)); B.Jaeger *et al* (2012) (POWHEG); S.Hoeche *et al* (2012)

Status of predictions for $pp \to VV, VVV$ production

QCD corrections:

- VV (TGCs) and VVV (QGCs) production processes known at NLO QCD
  B.Mele *et al* (1991); J.Ohnemus *et al* (1991); S.Frixione *et al* (1992); U.Baur *et al* (1993,1997); L.Dixon *et al* (1992); J.Campbell *et al* (1999) (MCFM)
  A.Lazopolous *et al.* (2007); V.Hankele *et al.* (2008); F. Campanario (2008); T.Binoth *et al* (2008); G.Bozzi *et al.* (2009, 2011); M.Weber *et al* (2010); S.Dawson *et al* (2013)
  WW, WZ, ZZ implementation in POWHEG Melia *et al*, (2011); P.Nason,J.Zanderighi (2013)
- $\gamma\gamma$, $Z\gamma$, ZZ, WW, and $W\gamma$ at NNLO QCD: S.Catani *et al* (2011); M.Grazzini *et al* (2013,2015); F.Cascioli *et al* (2014); T.Gehrmann *et al* (2014); M. Grazzini *et al* (2015) ;
- $WWj, W\gamma j, WZj, ZZj, W\gamma\gamma j$ known at NLO QCD
  J.Campbell *et al* (2007); S.Dittmaier *et al* (2007,2009); F.Campanario *et al* (2009,2010,2011) (VBFNLO); T.Binoth *et al* (2009); see also brief review by G.Bozzi *et al* 1205.2506 (VBFNLO)

Electroweak corrections:

- Logarithmic EW $\mathcal{O}(\alpha)$ corrections to WW, WZ, ZZ production: E.Accomando *et al* (2004,2005)
  W-pair production at NLL+NNLL: J.Kühn *et al.* (2011)
- Complete EW $\mathcal{O}(\alpha)$ corrections to $Z\gamma$, $W\gamma$ and WW, WZ, ZZ production: W.Hollik *et al.* (2004); A.Denner *et al* (2014); Bierweiler *et al* (2012,2013)
  $WW \to 4f$ in DPA M.Biloni *et al* (2013)
  implementation in HERWIG S.Gieseke *et al*, (2013)
- Complete EW $\mathcal{O}(\alpha)$ corrections to WWZ and WZZ production: D.T.Nhung *et al* (2013); S.Yong-Bai *et al* (2015)

$pp \rightarrow W \rightarrow l\nu X$ at NLO EW+QCD+QCD/QED PS with POWHEG

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

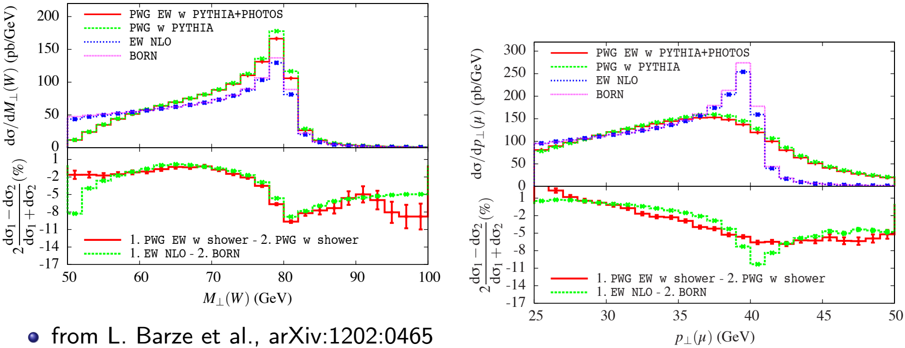
- Virtual $\mathcal{O}(\alpha)$ corrections from S.Dittmaier and M.Krämer, PRD 65 (2002), and checked against HORACE
- soft and collinear photon radiation is treated in the same way as colored parton emission

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 public codes. 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.

See also incorporation of EW $\mathcal{O}(\alpha)$ corrections in `POWHEG-W` by C.Bernaciak, D.W., arXiv:1201.4804.

$M_T(l\nu)$ 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)

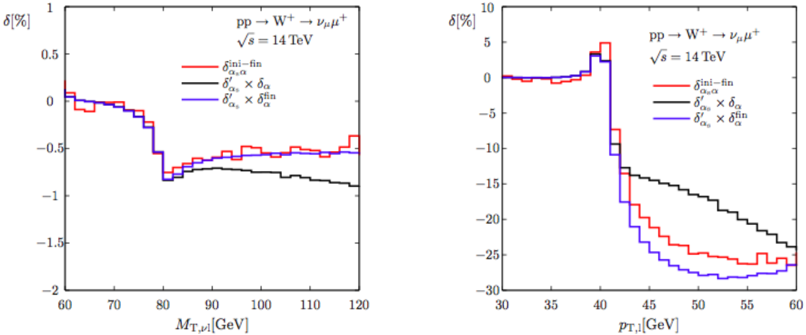
Impact on M_W ? Complete $\mathcal{O}(\alpha\alpha_s)$ corrections needed ?

$pp \to \nu l$ 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; 1511.08016



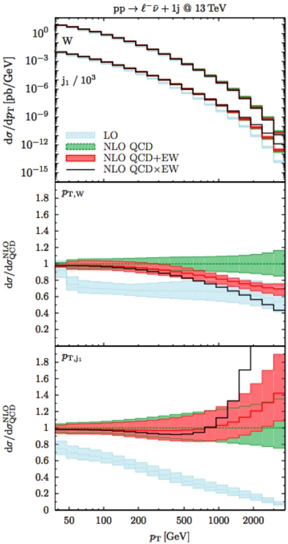
Estimate of additional shift in M_W due to initial-final corrections not described by naive factorization when extracted from $M_T(l\nu)$:
bare muons: -14 MeV; dressed leptons: -4 MeV

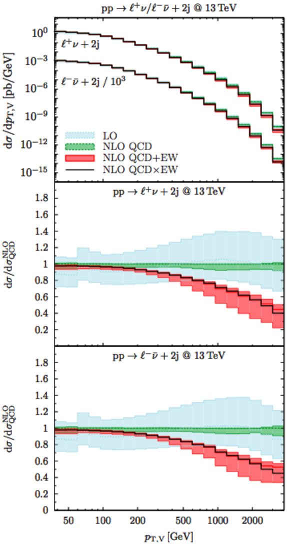
Recent advances in tools for NLO EW+QCD calculations

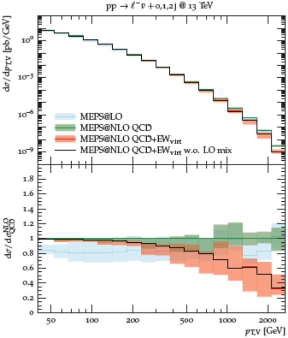
Some new results for multi-particle processes which consistently include higher-order QCD and EW corrections for a given order in perturbation theory:

- `Recola+Collier`; S.Actis *et al*, 1211.6316
  Example: $pp \to l^+ l^- jj$ at $\mathcal{O}(\alpha_s^2 \alpha^3)$, A.Denner *et al*, 1411.00916
- `OpenLoops+Sherpa` (+Collier)
  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
  LO (n jets): $\mathcal{O}(\alpha_s^n \alpha^2)$, NLO: $\mathcal{O}(\alpha_s^{n+1} \alpha^2)$ and $\mathcal{O}(\alpha_s^n \alpha^3)$
- `Madgraph5_AMC@NLO`
  Example: $pp \to t\bar{t} + (H, Z, W)$, S.Frixione *et al*, 1504.03446
  Dominant LO: $\mathcal{O}(\alpha_s^2 \alpha)$, $\mathcal{O}(\alpha_s \alpha^2)$, NLO: $\mathcal{O}(\alpha_s^3 \alpha)$, $\mathcal{O}(\alpha_s^2 \alpha^2)$
- `GOSAM`, G.Cullen *et al*, 1404.7096
  Example: $pp \to W + 2$ jets, M.Chiesa *et al*, `GOSAM+MadDipole`, 1507.08579

Example: $l\nu + 0, 1, 2$ jets at NLO QCD+EW with jet merging



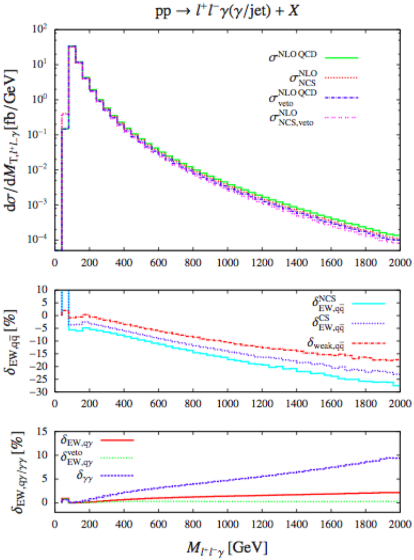




S.Kallweit *et al*, 1511.08692

Example: $pp \rightarrow l^+l^-\gamma$ at NLO QCD+EW

FeynArts+FormCalc+Collier, A.Denner *et al*, 1510.08742



Next steps:

Combination with existing NNLO QCD result.

Anomalous couplings included, but

EFT implementation left to future work.

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

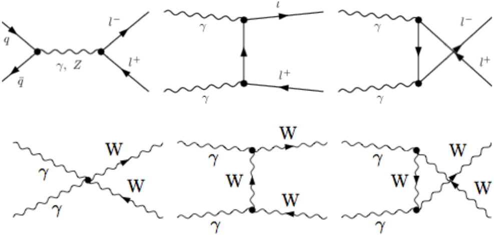
Photon PDF obtained from fit to DIS and DY data:

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

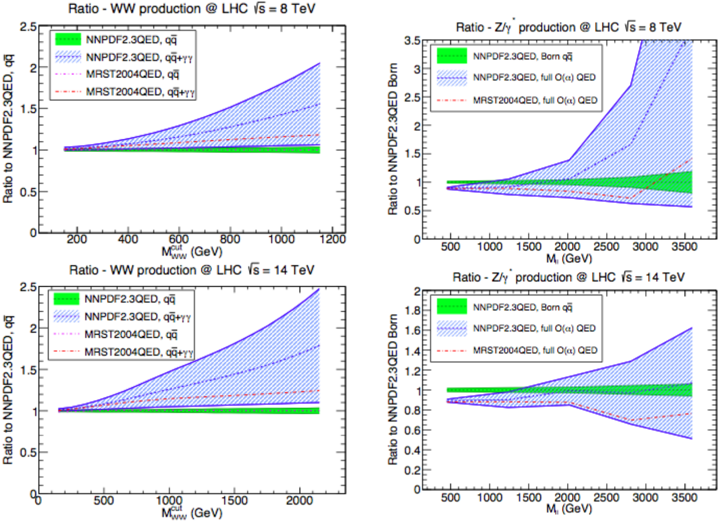
Combined QCD+QED evolution of all parton distributions:

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

Examples of photon-induced processes:



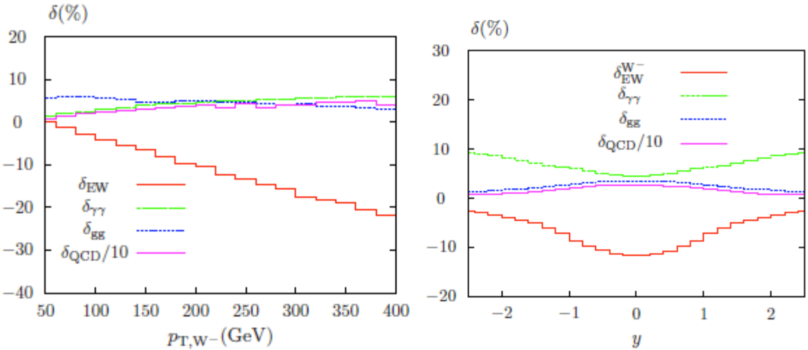
Photon PDF uncertainty in WW production and in Z/γ production



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

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.

Final remarks

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., Snowmass/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)),
- in implementing them in publicly available MC codes, and in matching to QCD/QED parton showers.

More to do:

- Studies of higher dim. operators in EFT for gauge/Higgs boson interactions in the presence of both EW and QCD corrections
- Sudakov approximation vs complete EW corrections; going beyond LL approx.
- Reduction of PDF uncertainties, both quark (e.g., for M_W) and photon PDFs
- Careful assessment of theory uncertainties in combined QCD+EW calculations.