Summary of Precision Electroweak Measurements

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

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FCC Week 2015 - Georgetown, D.C., March 24, 2015

See also Roberto Tenchini's talk on Thursday

A new era of EW precision physics

With the discovery of a Higgs boson with SM-like properties and access to multi-boson processes such as WW scattering in vector boson fusion at the LHC, precision physics with W and Z boson has entered a new era.

- Electroweak Precision observables (EWPO), such as m_{top}, M_W, $\sin^2\theta^l_{eff}$, M_H (and Z pole observables), provide even more precise probes of the SM and sensitivity to indirect signals of new physics.
  For example, in the SM we can obtain very precise predictions for the W boson mass:
  $$M_W(\mathrm{SM}) = 80358 \pm 8\ \mathrm{MeV}$$
  compared to the current experimental accuracy in M_W:
  $$M_W(\exp) = 80385 \pm 15\ \mathrm{MeV}$$
- Vector boson fusion (VBS) processes, e.g. $WW \to WW$ scattering, directly probe the EWSB sector of the SM.
- Search for non-standard gauge boson interactions provide an unique indirect way to look for signals of new physics in a model-independent way.
- Improved constraints on anomalous triple-gauge boson couplings (TGCs) and quartic couplings (QGCs) can probe scales of new physics in the multi-TeV range.

These were the two themes of the 2013 Snowmass EW WG study of the potential of the LHC and future colliders (HE-LHC, HL-LHC, ILC, TLEP (now FCC-ee)) to look for manifestations of new physics in quantum loops in EWPOs and access new physics scales in VBS and tri-boson production.

Many thanks to the 2013 Snowmass EW WG Contributors!

M. Baak, A. Blondel, A. Bodek, R. Caputo, T. Corbett, C. Degrande, O. Eboli, J. Erler, B. Feigl, A. Freitas, J. Gonzalez Fraile, M.C. Gonzalez-Garcia, J. Haller, J. Han, S. Heinemeyer, A. Hoecker, J. L. Holzbauer, S.-C. Hsu, R. Kogler, B. Jäger, W. Kilian, P. Langacker, S. Li, L. Linssen, M. Marx, O. Mattelaer, J. Metcalfe, K. Mönig, G. Moortgat-Pick, M.-A. Pleier, C. Pollard, M. Ramsey-Musolf, M. Rauch, J. Reuter, M. Rominsky, J. Rojo, W. Sakumoto, M. Schott, C. Schwinn, M. Sekulla, J. Stelzer, E. Torrence, A. Vicini, G. Weiglein, G. Wilson, L. Zeune

Conveners: A. Kotwal, D.W.

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

EW (Pseudo-)Observables around the Z resonance

Taken from D.Bardin *et al.*, hep-ph/9902452

Pseudo-observables are extracted from "real" observables (cross sections, asymmetries) by de-convoluting them of QED and QCD radiation and by neglecting terms ($\mathcal{O}(\alpha\Gamma_Z/M_Z)$) that would spoil factorization (γ, Z interference, t-dependent radiative corrections).

The $Zf\bar{f}$ vertex is parametrized as $\gamma_\mu(G_V^f + G_A^f\gamma_5)$ with formfactors $G_{V,A}^f$, so that the partial Z width reads:

$$\Gamma_f = 4N_c^f\Gamma_0(|G_V^f|^2 R_V^f + |G_A^f|^2 R_A^f) + \Delta_{EW/QCD}$$

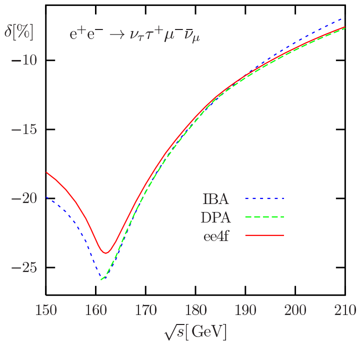
$R_{V,A}^f$ describe QED, QCD radiation and Δ non-factorizable radiative corrections.

Pseudo-observables are then defined as ($g_{V,A}^f = ReG_{V,A}^f$)

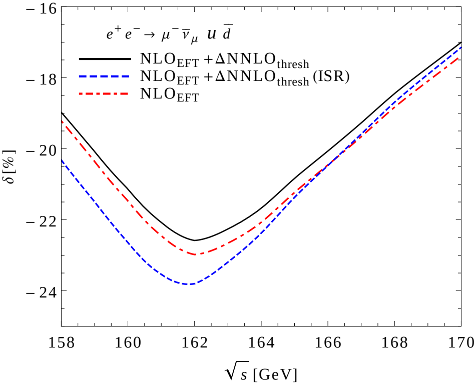
- $\sigma_h^0 = 12\pi\frac{\Gamma_e\Gamma_h}{M_Z^2\Gamma_Z^2}$, $R_{q,l} = \Gamma_{q,h}/\Gamma_{h,l}$
- $A_{FB}^f = \frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} \rightarrow A_{FB}^{f,0} = \frac{3}{4}A_e A_f, A_f = 2\frac{g_V^f g_A^f}{(g_V^f)^2+(g_A^f)^2}$
- $A_{LR}(SLD) = \frac{N_L-N_R}{N_L+N_R}\frac{1}{<P_e>} \rightarrow A_{LR}^0(SLD) = A_e$

and $4|Q_f|\sin^2\theta_{eff}^f = 1 - \frac{g_V^f}{g_A^f}$ with $g_{V,A}^f$ being *effective* couplings including radiative corrections.

Extracting M_W from W pairs in e^+e^- collisions at threshold



A.Denner *et al*, hep-ph/0502063

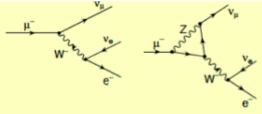


S.Actis *et al*, arXiv:0807.0102 [hep-ph]

One needs NLO EW to $e^+e^- \to 4f$ and dominant NNLO corr. at threshold.

Theory uncert. due to missing NNLO corr.: $\Delta M_W \approx 3$ MeV at threshold

see discussion by C.Schwinn in Snowmass EW WG report



Implicit equation for M_W:

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

Δr describes the loop corrections to muon decay ($c_W = M_W/M_Z$):

$$\Delta r = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho(0) + 2\Delta_1 + \frac{s_w^2 - c_W^2}{s_w^2}\Delta_2 + \text{boxes, vertices, higher orders}$$

$\Delta\rho(0)$ at 1-loop is given in terms of 1-PI EW gauge boson self energies, $\Pi^T_{V_1V_2}$:

$$\Delta\rho(0) = \frac{\Pi^T_{WW}(0)}{M_W^2} - \frac{\Pi^T_{ZZ}(0)}{M_Z^2} - 2\frac{s_W}{c_W}\frac{\Pi^T_{Z\gamma}(0)}{M_Z^2}$$

$\Delta\alpha$ describes contributions to the running of α: $\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{top} + \Delta\alpha^{(5)}_{had} + \ldots$

Status of predictions for EWPOs

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).
Some of the most important EWPOs and their present-day and future estimated theory errors: see discussion by A.Freitas in EW WG Snowmass report, arXiv:1310.6708

Quantity	Current theory error	Leading missing terms	Est. future theory error
$\sin^2\theta^l_{\rm eff}$	4.5×10^{-5}	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$1...1.5\times10^{-5}$
R_b	$\sim 2\times10^{-4}$	$\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$\sim 1\times10^{-4}$
Γ_Z	few MeV	$\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	< 1 MeV
M_W	4 MeV	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$<\sim 1$ MeV

New: Fermionic 2-loop order is now complete: $\Delta\Gamma_Z \sim 0.5 MeV$ A.Freitas, arXiv:1401.2477 [hep-ph], and projected is 0.2 MeV (see LL 2014 contribution)
Precise predictions for EWPOs for global fits are provided for instance by the LEPEWWG based on ZFITTER by Bardin et al., using the following set of input parameters:

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

GFITTER by M.Baak *et al* arXiv:1407.3792,
and also J.Erler *et al* PDG 2012, Ciuchini *et al.*, arXiv:1306.4644.

Parametric and theory uncertainties: M_W and $\sin^2\theta^l_{\rm eff}$

Theory uncertainty are due to missing 3-loop corrections of $\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$.
Parametric uncertainties (Awramik *et al*, hep-ph/0311148; hep-ph/0608099):

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

	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)

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

Projected uncertainties in the measurement of M_W at the Tevatron

ΔM_W [MeV]	CDF	D0	combined	final CDF	final D0	combined
$\mathcal{L}$[fb]	2.2	4.3 (+1.1)	7.6	10	10	20
PDF	10	11	10	5	5	5
QED rad.	4	7	4	4	3	3
$p_T(W)$ model	5	2	2	2	2	2
other systematics	10	18	9	4	11	4
W statistics	12	13	9	6	8	5
Total	19	26 (23)	16	10	15	9

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 missing $\mathcal{O}(\alpha)$ corrections
- D0, arXiv:1203.0293: δM_W(QED)=7 MeV
  ResBos+PHOTOS, WGRAD used to assess the impact of the missing EW $\mathcal{O}(\alpha)$ corrections
- How about uncertainties due to missing higher-order corrections?
- PDF uncertainty is the limiting factor!

Projected uncertainties in the measurement of M_W at the LHC

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}$[fb]	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

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

Current and projected uncertainties in the measurement of M_W at e^+e^- colliders

ΔM_W [MeV]	LEP2	ILC	ILC	e^+e^-	TLEP
$\sqrt{s}$ [GeV]	161	161	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480	600	3000×4
$P(e^-)$ [%]	0	90	90	0	0
$P(e^+)$ [%]	0	60	60	0	0
systematics	70			?	$<$0.5
statistics	200			2.3?	0.5
experimental total	210	3.9	1.9	$>$2.3	$<$0.7
beam energy	13	0.8-2.0	0.8-2.0	0.8-2.0	0.1
radiative corrections	-	1.0	1.0	1.0	1.0
total	210	4.1-4.5	2.3-2.9	$>$2.6-3.2	$<$1.2

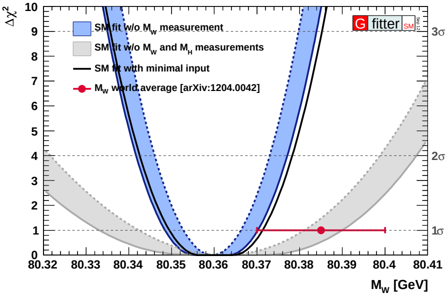
From the Snowmass 2013 EW WG report, arXiv:1310.6708.

Summary of target uncertainties in measurements of $M_W, \sin^2\theta^l_{\rm eff}, \Gamma_Z, R_b$

	LHC	LHC	ILC/GigaZ	ILC	ILC	ILC	TLEP
$\sqrt{s}$ [TeV]	14	14	0.091	0.161	0.161	0.250	0.161
Ł[fb]	300	3000		100	480	500	3000×4
ΔM_W [MeV]	8	5	-	4.1-4.5	2.3-2.9	3.6	$<$1.2
$\Delta\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	36	21	1.3	-	-	-	0.3

Estimated theory uncertainties in SM predictions: $\Delta M_W = 4.2(3.0)$ MeV,
$\Delta\sin^2\theta^\ell_{\rm eff} = 3.0(2.6)\times 10^{-5}$
Preliminary target uncertainty on M_Z, Γ_Z and R_b at TLEP: 0.1 MeV, 0.1 MeV, and
$2-5\times 10^{-5}$
Estimate of present(future) theory uncertainty on Γ_Z, R_b: 0.5(0.2) MeV, $2(1)\times 10^{-4}$.
From Snowmass EW WG report arXiv:1310.6708 [hep-ph]; A.Freitas, 1401.2477 [hep-ph]
Assuming theoretical uncertainties in the measurements are under control at that level, e.g., $\Delta M_W \sim 1$ MeV when extracted from W pair cross section!

Prospects for M_W from global EW fits

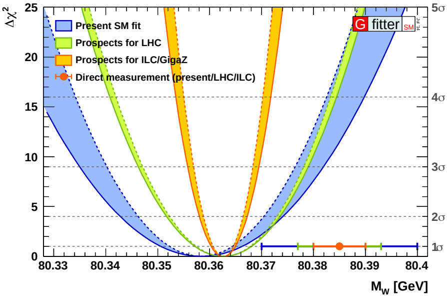


M_W from global EW fit

before (gray band) and after (blue)

M_H measurement is included in the fit.

GFITTER, arXiv:1310.6708



Fit result: $\Delta M_W = 7.8$ MeV (present)

Fit result: $\Delta M_W = 5.5$ MeV (LHC)

Fit result: $\Delta M_W = 2.3$ MeV (GigaZ)

GFITTER, arXiv:1407.3792

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, ...).
  Example: MSSM
- 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):

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

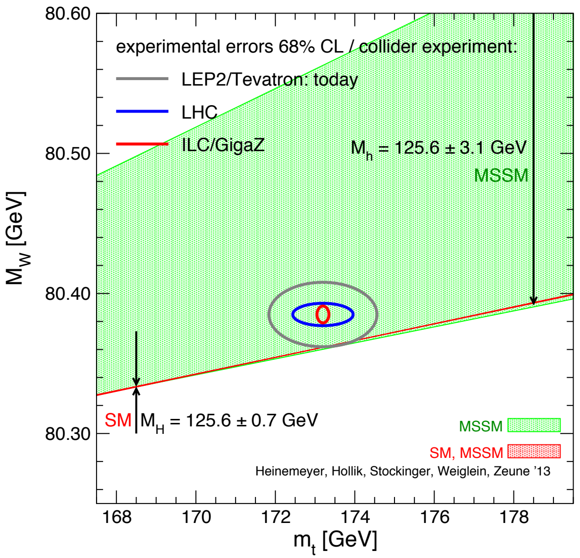
$$\sin^2 \theta^l_{eff} \approx (\sin^2 \theta^l_{eff})^{\mathrm{SM}} + \frac{\alpha}{4(c_W^2 - s_W^2)} \Delta S - \frac{\alpha s_W^2 c_W^2}{c_W^2 - s_W^2} \Delta T$$

- Effective field theory: Weinberg (1979); Buchmueller, Wyler (1986)
  Effective Lagrangians parametrize in a model independent way the low–energy effects of possible BSM physics with characteristic energy scale Λ. Residual new interactions among light degrees of freedom, ie among particles of mass $M << \Lambda$, can then be described by higher-dimensional operators:

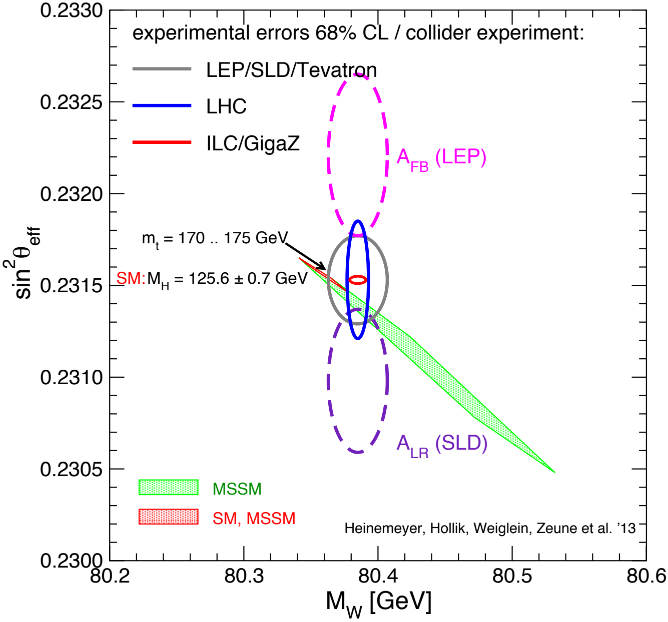
$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4} \mathcal{O}_j + \ldots$$

  Example: Higgs couplings to gauge bosons and impact on S,T,U.

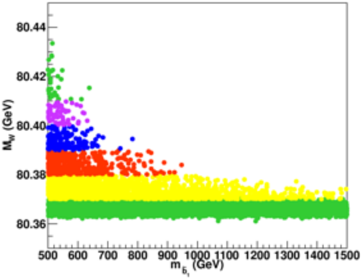
$M_W(m_{top}, M_{susy}, \ldots)$ in the MSSM

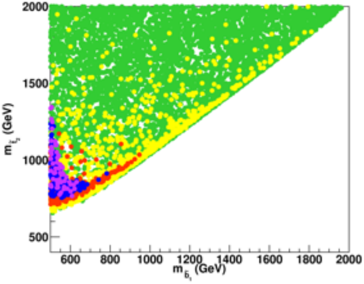


M_W and $\sin^2\theta^l_{eff}$ within the MSSM



What else can be learned from a more precise M_W measurement?





Assumption: a light stop is found with $m_{\tilde{t}_1} = 400 \pm 40$ GeV: green points: all points in the scan with $M_h = 125.6 \pm 3.1$ GeV and $m_{\tilde{t}_1} = 400 \pm 40$ GeV, and $M_W = 80.375 \pm 0.005$ GeV (yellow), $M_W = 80.385 \pm 0.005$ GeV (red), $M_W = 80.395 \pm 0.005$ GeV (blue), and $M_W = 80.405 \pm 0.005$ GeV (purple).
S.Heinemeyer *et al*, Snowmass EW WG report arXiv:1310.6708 [hep-ph].

Parameterizing BSM physics in multi-boson production using the EFT approach

Effective field theory (EFT): Weinberg (1979); Buchmueller, Wyler (1986)

EFT Lagrangians parametrize in a model independent way the low–energy effects of possible BSM physics with characteristic energy scale Λ. Residual new interactions among light degrees of freedom, ie the particles of mass $M << \Lambda$, can then be described by higher-dimensional operators:

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

- Implemented in public codes MadGraph, Whizard, VBFNLO, and in dedicated calculations for multiple EW gauge boson production.
- Higher order EW and QCD corrections have to be included (missing h.o. corr. can mimick anomalous couplings).
- The choice of higher-dimensional operators is not unique (different basis, symmetry group, ...) and different methods to unitarize the cross sections have been used (form factors, K-matrix unitarization, ...).
- Relations between EFT coefficients c_i, f_j and anomalous coupling parameters $(\lambda, \kappa, a_0, a_c)$ can be derived.

Snowmass 2013 EW WG report, arXiv:1310.6708, and whitepapers.

Genuine dimension eight operators

- The lowest dimension operator that leads to quartic interactions but does not exhibit two or three weak gauge boson vertices is of dimension eight.
- Effective operators possessing QCGs but no TGCs can be generated at tree level by new physics at a higher scale (see Arzt et al.(1995)), in contrast to operators containing TGCs that are generated at loop level.
  Example:

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu}\right] \times \left[\left(D_\beta \Phi\right)^\dagger D^\beta \Phi\right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu} W^{\nu\beta}\right] \times \left[\left(D_\beta \Phi\right)^\dagger D^\mu \Phi\right]$$

  with $D_\mu \equiv \partial_\mu + i\frac{g'}{2} B_\mu + igW^i_\mu \frac{\tau^i}{2}$
- Vector boson scattering and tri-boson production can now be studied at the LHC. They uniquely probe the EWSB sector of the SM.

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

Prospects for 5σ discovery of higher dim. operators in $pp \to W^\pm W^\pm + 2j \to l\nu l\nu + 2j$ and $pp \to WWW \to 3l + 3\nu$

Parameter	channel	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	5σ [TeV^{-4}]
f_{S0}/Λ^4	$W^\pm W^\pm$	14	300	10
f_{S0}/Λ^4	$W^\pm W^\pm$	14	3000	4.5
f_{T1}/Λ^4	$W^\pm W^\pm$	14	300	0.2 (0.4)
f_{T1}/Λ^4	$W^\pm W^\pm$	14	3000	0.1 (0.2)
f_{T1}/Λ^4	$W^\pm W^\pm$	100	3000	0.001 (0.001)
f_{T0}/Λ^4	WWW	14	3000	0.6
f_{T0}/Λ^4	WWW	33	3000	0.05
f_{T0}/Λ^4	WWW	100	3000	0.002

Snowmass 2013 EW WG report, arXiv:1310.6708, and whitepapers.

aQGCs and heavy resonances

See Snowmass 2013 EW WG report (contribution by J.Reuter), arXiv:1310.6708

BSM physics could enter in the EW sector in form of very heavy resonances that leave only traces in the form of deviations in the SM couplings, ie they are not directly observable. Such deviations can be translated into higher-dimensional operators that affect triple and quartic gauge couplings in multi-boson processes.

For example, a scalar resonance σ with the following Lagrangian:
$(\mathbf{V} = \Sigma(D\Sigma)^\dagger, \mathbf{T} = \Sigma\tau^3\Sigma^\dagger)$

$$\mathcal{L}_\sigma = -\frac{1}{2}\left[\sigma(M_\sigma^2 + \partial^2)\sigma - g_\sigma v \mathbf{V}_\mu \mathbf{V}^\mu - h_\sigma \mathbf{T}\mathbf{V}_\mu \mathbf{T}\mathbf{V}^\mu\right]$$

leads to the effective Lagrangian after integrating out the scalar,

$$\mathcal{L}_\sigma^{\mathrm{eff}} = \frac{v^2}{8M_\sigma^2}\left[g_\sigma \mathbf{V}_\mu \mathbf{V}^\mu + h_\sigma \mathbf{T}\mathbf{V}_\mu \mathbf{T}\mathbf{V}^\mu\right]^2$$

ie integrating out σ generates the following anomalous quartic couplings

$$\alpha_5 = g_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_7 = 2g_\sigma h_\sigma\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_{10} = 2h_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right)$$

aQGCs and heavy resonances

For strongly coupled, broad resonances, one can then translate bounds for anomalous couplings directly into those of the effective Lagrangian:

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

From the Snowmass 2013 EW WG report (ATLAS study):

For a different choice of operator basis:

$$\alpha_4 = \frac{f_{S0}}{\Lambda^4}\frac{v^4}{16} \quad ; \quad \alpha_5 = \frac{f_{S1}}{\Lambda^4}\frac{v^4}{16}$$

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}		1 TeV ILC 1 ab^{-1}
	5σ	95% CL	5σ	95% CL	95% CL
scalar ϕ	1.8 TeV	2.0 TeV	2.2 TeV	3.3 TeV	1.64 TeV
vector ρ	2.3 TeV	2.6 TeV	2.9 TeV	4.4 TeV	2.09 TeV
tensor f	3.2 TeV	3.5 TeV	3.9 TeV	6.0 TeV	2.76 TeV

Preliminary conclusion:

TGCs introduced by dimension 6 operators are better probed at a high-energy ILC than at the LHC, whereas in case of QGCs induced by dimension 8 operators the situation is reversed.

Conclusions

Lesson from the LHC (so far): again the SM has proven to be very robust!

- Precision physics with W and Z boson provides a unique and very sensitive probe of the SM, especially of the EWSB sector, and can access high scales of new physics complementary to the direct production of new particles.
- The exploration of the full potential of EW measurements at the LHC and at future colliders requires also much effort in the assessment of the theory uncertainties and the need for theoretical improvements.
- This should go hand-in-hand with an effort to provide appealing examples of what can be learned from these measurements in either case, when the SM keeps holding or when deviations are found.
- In any case, we can look forward to exciting times for EW precision physics!