Electroweak Gauge Boson Production

Doreen Wackeroth

dw24@buffalo.edu

University at Buffalo
The State University of New York

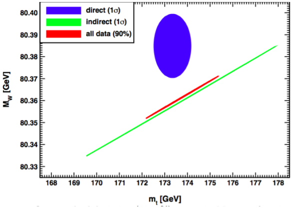
2018 CTEQ Summer School

University of Puerto Rico, Mayaguez, June 24-25, 2018

Outline

Precision physics with

- single W and Z production via the Drell-Yan mechanism at the LHC:
  - EWPO: stress-testing the SM and searching for new physics with M_W, $\sin^2\theta^l_{\rm eff}$ (and a bit of history: the LEP/SLC legacy)



J.Erler, A.Freitas, PDG 2016

  - Precise QCD predictions for relevant observables
  - Electroweak radiative corrections: Characteristics and selected topics (photon-induced processes, finite width and gauge invariance, choice of EW input scheme, EW Sudakov logarithms, ...)
- Direct photon production
- Multiple EW gauge boson production: VV and VVV ($V = \gamma, Z, W$)

blue: 1.lecture, red: 2.lecture

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 EW 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:

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

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 EW 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 EW 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

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

$$V_i(g)V_f(g)\,(Re\hat{\Pi}_T(M_W^2, g^2) + iIm\hat{\Pi}_T^{\gamma})$$

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. width approach by $\approx 34(27)$ MeV.

$\mathcal{M}^{(0+1)}(s)$ 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

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

$$V_i(g)V_f(g)\,\left(Re\hat{\Pi}_T(M_W^2, g^2) + iIm\hat{\Pi}_T^{\gamma}\right)$$

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. width approach by $\approx 34(27)$ MeV.

Treatment of unstable EW gauge bosons: complex-mass scheme

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.

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:

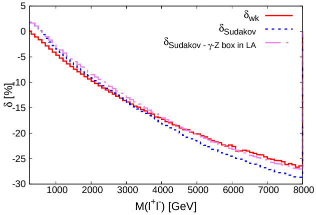
- Results (fixed order and resummed to all orders) are available for hadronic cross sections for, e.g., V(+jets), VV, $t\bar{t}$, bb, cc, jj, and VBF.
  $Z+ \leq 3$ jets in `ALPGEN` Chiesa *et al* (2013)
  $Z, t\bar{t}, jj$ production implemented in `MCFM` Campbell, D.W., Zhou (2016)
- Best studied so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

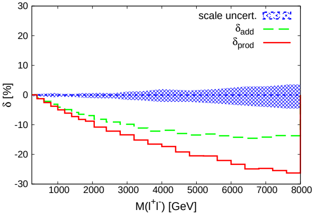
$$\frac{\delta\sigma(e^+e^- \to q\bar{q})(s)}{\sigma_{LO}} = -2.18aL^2 + 20.94aL - 35.07a + \\ +2.79a^2L^4 - 51.98a^2L^3 + 321.20a^2L^2 - 757.35a^2L$$

    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)

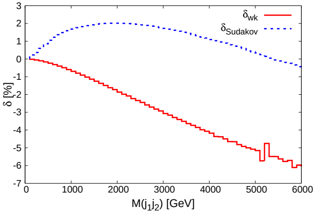
How well does the Sudakov approximation describe NLO EW ?

Very well in the case of the $M(ll)$ distribution in Z boson production:





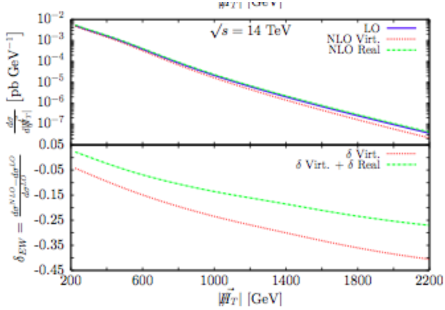
but not so well in the case of the $M(jj)$ distribution in di-jet production:



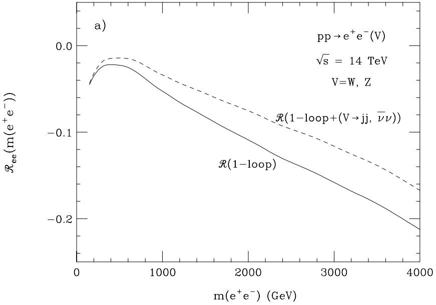
Both calculations are implemented in `MCFM` Campbell, D.W., Zhou (2016)

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:

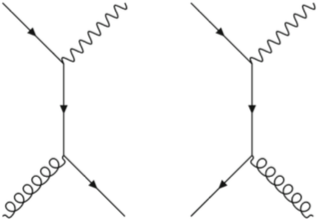


M.Chiesa *et al.*, arXiv:1305.6837

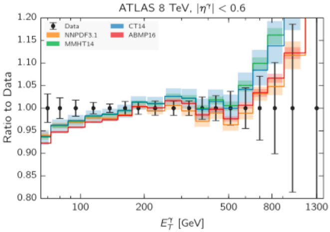


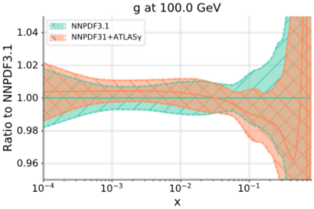
U.Baur, PRD75 (2007)

Direct photon production in $pp \to \gamma j + X$



- Constraints on the gluon PDF.
- Tuning of MCs and testing of description of photons, especially in the presence of jets, e.g., $H \to \gamma\gamma$, BSM searches.
- "Easiest" process involving a jet; high-rate process; used to determine/confirm uncertainty in Jet Energy Scale (JES) at high p_T.

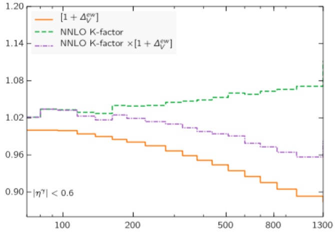




J. Campbell *et al.*, 1802.03021

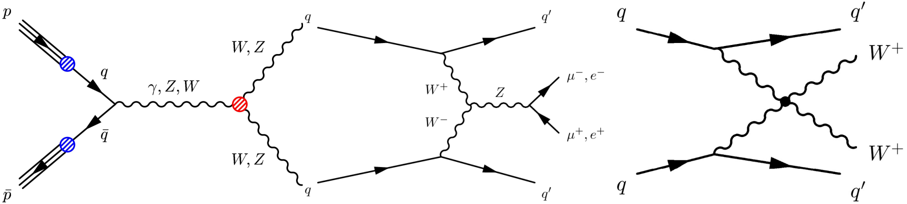
See also lectures by Jeff Owens at the 2015 CTEQ School and by John Campbell at the 2017 CTEQ School.

$$K \equiv \frac{d\sigma^{\mathrm{NNLO}}}{dE_T^\gamma d\eta^\gamma}(\text{NNLO PDFs}) \Big/ \frac{d\sigma^{\mathrm{NLO}}}{dE_T^\gamma d\eta^\gamma}(\text{NNLO PDFs}),$$



J. Campbell *et al.*, 1802.03021 (NNLO QCD based on J.Campbell *et al*, 1612.04333)

- Photons can be well isolated from jets (perturbative) or originate from collinear $q \to q\gamma$ fragmentation described by (non-perturbative) fragmentation functions (measured at LEP):
- How to not jeopordize IR safety when trying to separate photons from jets to obtain a prediction for direct photons only or to minimize the impact of the fragmentation process?
- S. Frixione proposed an algorithm which is *based on a isolation cone and a jet finding algorithm which excludes the photon.* S. Frixione, hep-ph/9801442



Di-boson and triple gauge boson production processes are sensitive probes of the non-abelian EW gauge structure and the EWSB sector of the SM.

- Search for non-standard gauge boson interactions provide an unique indirect way to look for signals of BSM in a model-independent way.
- Improved constraints on anomalous triple-gauge boson couplings (TGCs) and quartic couplings (QGCs) or on higher-dimensional operators in the SM Effective Field Theory (EFT) approach can probe energy scales of new physics in the multi-TeV range.
- Important background to Higgs physics and BSM searches.

Probing the non-abelian gauge structure of the SM: anomalous couplings

There have been a number of different ways introduced in the literature to paramaterize non-standard couplings.

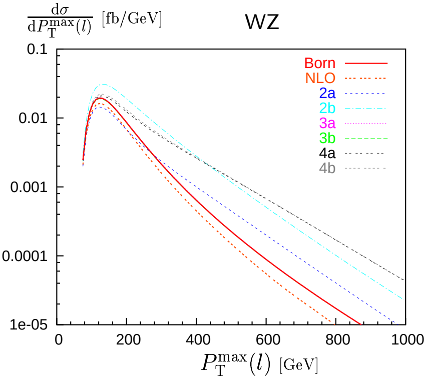
The anomalous couplings approach of Hagiwara et al (1987) was introduced for LEP physics and is based on the Lagrangian ($V = \gamma, Z$)

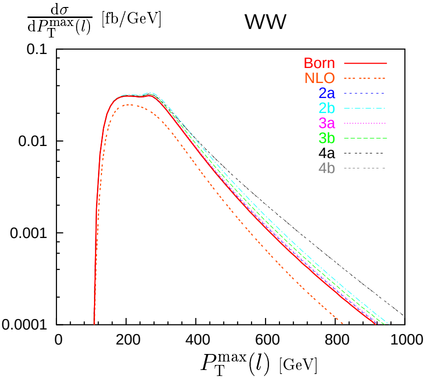
$$\begin{aligned}\mathcal{L} =& i g_{WWV} \left(g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \right. \\ & + i g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - i g_5^V \epsilon^{\mu\nu\rho\sigma} (W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu) V_\sigma \\ & \left. + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \right) ,\end{aligned}$$

$V = \gamma, Z$; $W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $g_{WW\gamma} = -e$ and $g_{WWZ} = -e \cot\theta_W$.

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

SM LO, NLO EW predictions vs. different anomalous couplings scenarios:



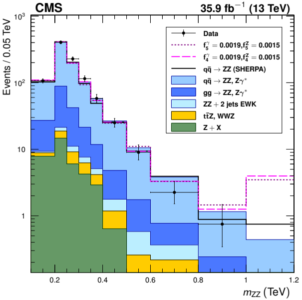


E.Accomando, A.Kaiser, hep-ph/0511088

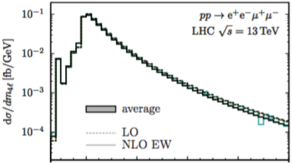
Missing EW corrections in the predictions could be interpreted as signals of new physics !

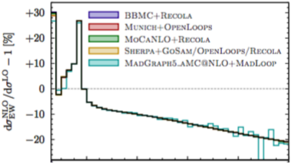
aTGCs in ZZ production

Measurement of $M(ZZ)$ and sensitivity to anomalous TGCs (CMS):



Comparison of NLO EW predictions of $pp \to 4l$ production at the LHC: Report of the Les Houches 2017 SM WG, 1803.07977





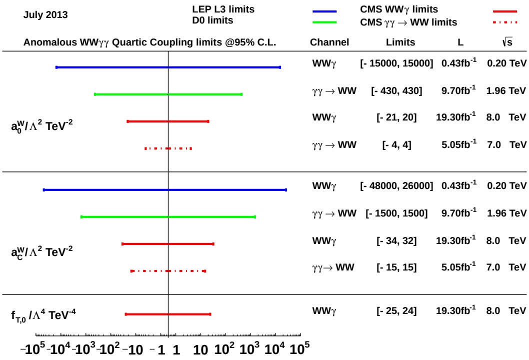
Probing the non-abelian gauge structure of the SM: genuine aQGCs

For LEP-II studies genuine anomalous quartic couplings involving two photons have been introduced as follows (Stirling et al (1999)):

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

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

with $F^{\mu\nu} = \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu}$ and $\vec{W}_{\mu} = \left(\frac{1}{\sqrt{2}}(W^+_{\mu} + W^-_{\mu}), \frac{i}{\sqrt{2}}(W^+_{\mu} - W^-_{\mu}), \frac{Z_{\mu}}{\cos\theta_W}\right)$



Probing BSM physics in multi-boson production: 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:

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

Assumptions: There are no new fields at the EW scale; Su(2) x U(1) breaking via Higgs mechanism, same symmetries as the SM (lepton and baryon number are conserved)

- Implemented in public codes such as MadGraph, Whizard, VBFNLO, and in dedicated calculations for multiple EW gauge boson production.
- In general, 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, ...).
- Warsaw basis: a complete, unique basis for dimension 6 operators (59 operators)

  Grzadkowski *et al.*, 1008.4884

  Feynman rules in R_ξ gauge are provided in form of a Mathematica package for Feynrules: A.Dedes *et al.*, 1704.03888
- Relations between EFT coefficients c_i, f_j and anomalous couplings have been derived.

Snowmass 2013 EW WG report, arXiv:1310.6708; C.Degrande *et al*, arXiv:1309.7890

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.

Examples:

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

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

with $D_\mu \equiv \partial_\mu + i\frac{g'}{2} B_\mu + igW^i_\mu \frac{\tau^i}{2}$; $\Phi = (0, (v+H)/\sqrt{2})$
For the $WW\gamma\gamma$-vertex one finds:

$$\frac{f_{M,0}}{\Lambda^4} = \frac{a_0}{\Lambda^2}\frac{1}{g^2 v^2}$$

$$\frac{f_{M,1}}{\Lambda^4} = -\frac{a_c}{\Lambda^2}\frac{1}{g^2 v^2}$$

$$\frac{f_{M,2}}{\Lambda^4} = \frac{a_0}{\Lambda^2}\frac{2}{g^2 v^2}$$

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. But 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 a Lagrangian given by
$(\mathbf{V} = \Sigma(D\Sigma)^\dagger, \mathbf{T} = \Sigma\tau^3\Sigma^\dagger)$

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

leads to an effective Lagrangian after integrating out the scalar,

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

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:

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

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}	
	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

Final remarks

- The Higgs discovery and a wealth of measurements of electroweak and strong processes at very high precision (per mil/percent level) and in new kinematic regimes are all in agreement with the SM.
- Many new physics scenarios have been probed at new energy regimes, and no signal of new physics has been detected (yet).
- As impressive the progress is in both experiment and theory, this is just the beginning.
- Ideas for new physics models, new and improved experimental analysis techniques, and improved calculational approaches and predictions, all are needed to fully exploit the potential of the LHC for discovery.
- Apart from calculating all relevant higher-order corrections and providing them in MC tools, in order to make the best use of these higher-order calculations and to pin down their uncertainties in the interpretation of LHC data inreasingly close collaboration between theorists and experimentalists is a must.

This is a special time for high-energy physics: the next discovery is going to be a truly unexpected harbinger for the *terra incognita* beyond the Standard Model.

Hic Sunt Dragones