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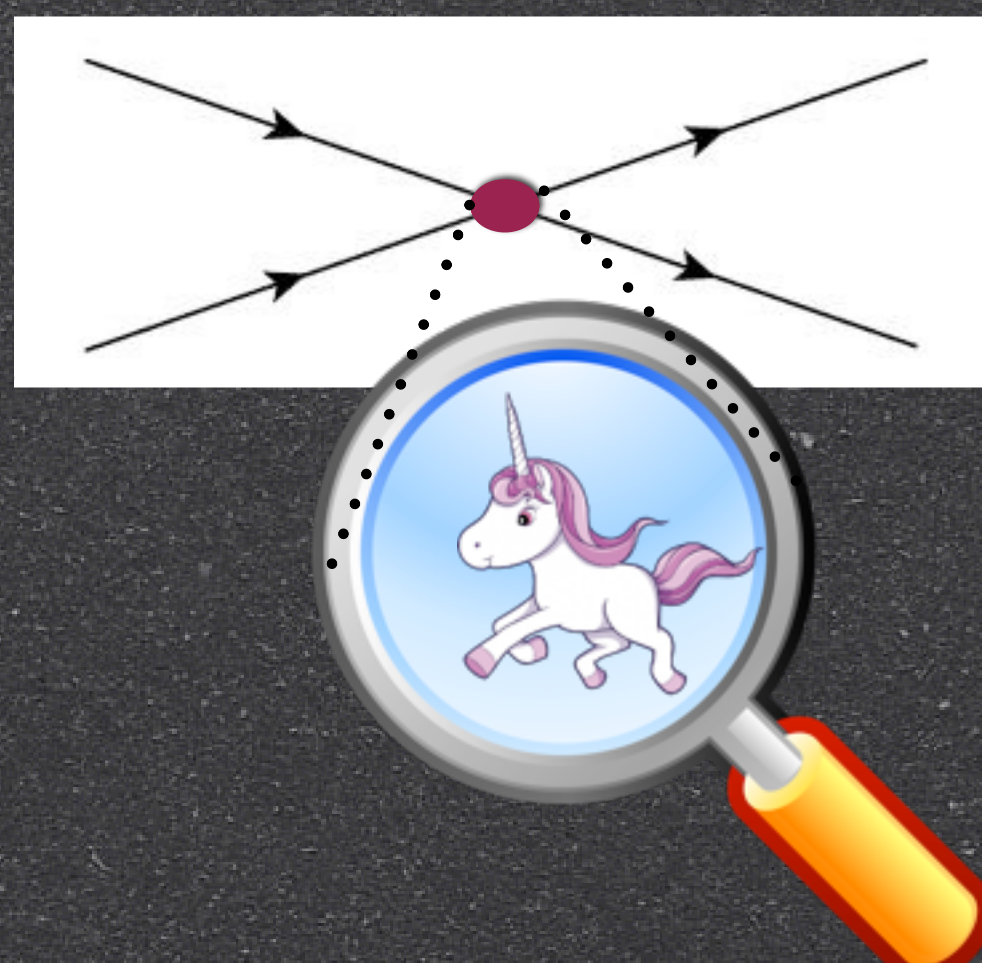
Effective Lagrangian approach to physics beyond the standard model



Plan

- Introduction and motivations
- Philosophy of effective field theory approach
- Effective Lagrangian for physics beyond the SM
- Synergy between Higgs data and electroweak precision observables
- Model independent precision constraints on effective theory operators

Introduction and Motivations

After Higgs discovery

- Discovery of 125 GeV Higgs boson is last piece of puzzle that falls into place
- No more free parameters in SM
- Overwhelming evidence that particle interactions are dictated by linearly realized SU(3)xSU(2)xU(1) local symmetry
- All data consistent with electroweak symmetry breaking SU(2)xU(1)→U(1) proceeding via a single doublet Higgs field

What about new physics?

- We know physics beyond SM exists (neutrino masses, dark matter, inflation, baryon asymmetry)
- There are also some theoretical hints for new physics (strong CP problem, flavor hierarchies, gauge coupling unifications, naturalness problem)
- But there isn't one model or a class of models that is strongly preferred
- How to keep open mind on many possible forms of new physics?

Effective Field Theory Framework

- EFT framework is QFT for low energy degrees of freedom, where heavy particles that cannot be directly produced have been integrated out
- Effects of heavy particles are encoded into contact interactions of low energy particles
- Under certain assumptions, EFT framework allows one to describe effects of new physics beyond SM in a model independent way

Philosophy
of
EFT framework

Effective Field Theory Philosphy

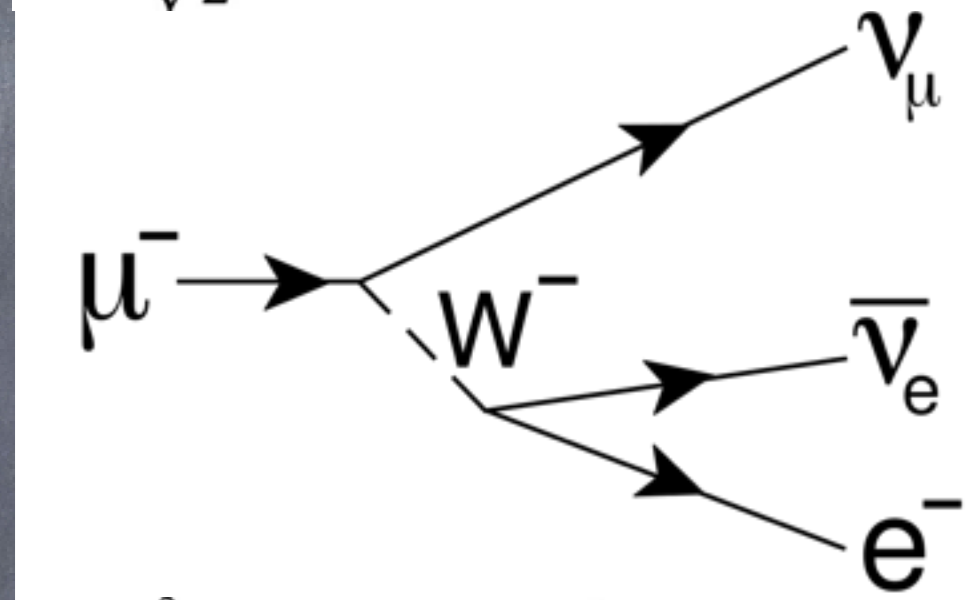
- EFT framework is commonly used to describe physics at low energies, keeping only relevant degrees of freedom at these energies
- EFT can also be used when high energy theory is unknown, or when matching between high and low energy theories is not calculable

EFT example 1

Fermi Theory of weak interactions

- In SM, charged current interactions mediating weak decays are mediated by W bosons
- At low energies below W mass, W boson can be integrated out, leading to effective theory with 4-fermion interactions
- In particular, muon decay can be described by effective theory with 4-fermion interactions between muon, electron, and 2 neutrinos

$$\mathcal{L} = \frac{g_L}{\sqrt{2}} \left(\bar{\nu}_\mu \bar{\sigma}_\rho \mu + \bar{\nu}_e \bar{\sigma}_\rho e\right) W^+_\rho + \text{h.c.}$$

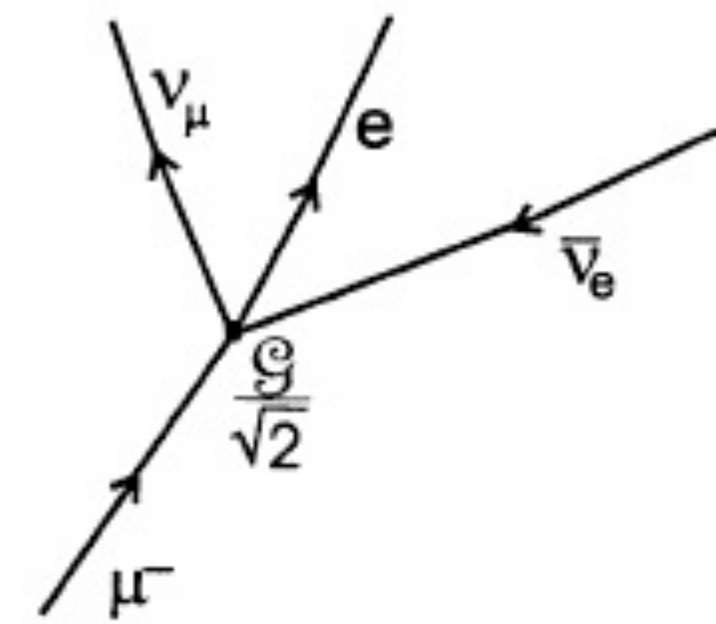


$$\mathcal{M} = \frac{g_L^2}{2} \bar{x}(k_{\nu_\mu}) \bar{\sigma}_\rho x(k_\mu) \frac{1}{q^2 - m_W^2} \bar{x}(k_e) \bar{\sigma}_\rho y(k_{\nu_e})$$

$$q = k_\mu - k_{\nu_\mu}$$

$$\mathcal{M} \approx -\frac{1}{\Lambda^2} \bar{x}(k_{\nu_\mu}) \bar{\sigma}_\rho x(k_\mu) \bar{x}(k_e) \bar{\sigma}_\rho y(k_{\nu_e})$$

$$\Lambda = \frac{\sqrt{2} m_W}{g_L} = \frac{v}{\sqrt{2}}$$

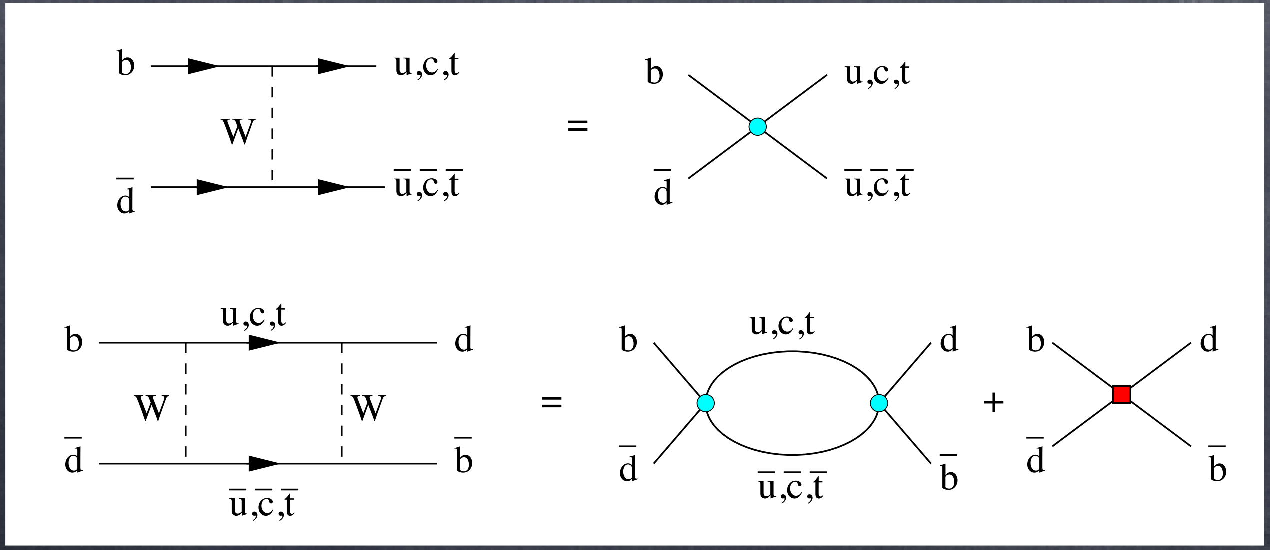


$$\mathcal{L}_{\text{eff}} = -\frac{1}{\Lambda^2} \left(\bar{\nu}_\mu \bar{\sigma}_\rho \mu\right) \bar{e} \bar{\sigma}_\rho \nu_e + \text{h.c.}$$

EFT example 2

Weak quark decays

- At low energies below W mass, W boson can be integrated out, leading to effective theory with 4-fermion interactions
- Some flavor violating operators are loops and CKM suppressed, therefore their coefficients are suppressed by more than heavy mass scale
- Note that loops can and have to be computed on EFT side as well



Phenomenologically important EFT examples

- Chiral perturbation theory. Describes low energy interactions of pions. Underlying theory is QCD, but coefficients of EFT operators cannot be calculated analytically. Approximate symmetries inherited from QCD provide some guidance.
- Heavy Quark Effective Theory. Describes mesons with one heavy quark (charm or bottom).
- Non-relativistic QED. Describes bound states of electrons, positrons, muons, etc.
- Soft-collinear effective theory. Describes light-like interaction of light quarks.

Summary of Introduction

- EFTs emerge naturally in particle physics and elsewhere, at vastly different scales and kinematical regimes
- Even when UV theory is known, and matching to IR EFT is calculable, EFT is important tool for calculations (simplicity, resummation of large logs)
- When IR Lagrangian cannot be calculated, EFT framework is important tool to organize physics description of low energy theory.
- We expect Standard Model is low-energy effective theory to some yet unknown UV theory

Effective Lagrangian for BSM physics

Effective Theory Approach to BSM

Basic assumptions

- No new particles at energies probed by LHC
- Poincare invariance (Lorentz+translations)
- Linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by Higgs doublet field vev
- Later, more assumptions about approximate global symmetries

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \dots \\ v + h + \dots \end{pmatrix}$$

Alternatively, non-linear Lagrangians with derivative expansion

Effective Theory Approach to BSM

Building effective Lagrangian

- Start with SM Lagrangian as lowest order approximation.
- Possible new physics effects can be encoded into higher dimensional operators added to SM
- Systematic expansion around the SM organized in terms of operator dimensions == expansion in new physics scale

Effective Theory Approach to BSM

- EFT comes with many free parameters. But in spite of that it predicts correlations between different observables

- Framework to combine constraints on new physics from Higgs searches, electroweak precision observables, gauge boson pair production, fermion pair production, dijet production, atomic parity violations, magnetic and electric dipole moments, and more...

- In case of a signal, offers unbiased hint about possible form of new physics

Effective Theory Approach to BSM

Building effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}^{D=5} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \ldots$$

$$\Lambda \gg v$$

- If coefficients c of higher dimensional operators are order 1, Λ corresponds to mass scale on BSM theory with couplings of order 1 (more generally, Λ ~ m/g)

- Slightly simpler (and completely equivalent) is to use EW scale v in denominators and work with small coefficients of higher dimensional operators c~(v/Λ)^(d-4)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

Standard Model Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

$$\begin{aligned}\mathcal{L}_{\text{SM}} = & -\frac{1}{4g_s^2}G^2_{\mu\nu,a} - \frac{1}{4g_L^2}W^2_{\mu\nu,i} - \frac{1}{4g_Y^2}B^2_{\mu\nu} \\ & + i\sum_{f=q,\ell}\bar{f}\bar{\sigma}_\mu D_\mu f + i\sum_{f=u,d,e} f^c\sigma_\mu D_\mu \bar{f}^c \\ & - HqY_u u^c - H^\dagger qY_d d^c - H^\dagger \ell Y_e e^c \text{ +h.c.} \\ & + D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda(H^\dagger H)^2\end{aligned}$$

- Operators up to dimension 4 (renormalizable)
- 18 free parameters (19 with θqcd), all measured (constrained)
- Fits in T-shirt

Standard Model Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

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Some predictions at lowest order

- Z and W boson mass ratio related to Weinberg angle

$$\frac{m_W}{m_Z} = \frac{g_L}{\sqrt{g_L^2 + g_Y^2}} = \cos\theta_W$$

- Higgs coupling to gauge bosons proportional to their mass squared
- Higgs coupling to fermions proportional to their mass
- Triple and quartic gauge couplings proportional to gauge couplings

Standard Model Lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

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Some predictions at lowest order

- Z and W boson mass ratio related to Weinberg angle
- Higgs coupling to gauge bosons proportional to their mass squared

$$\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)\left(2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right)$$

- Higgs coupling to fermions proportional to their mass
- Triple and quartic gauge couplings proportional to gauge couplings

Standard Model Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

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Some predictions at lowest order

- Z and W boson mass ratio related to Weinberg angle
- Higgs coupling to gauge bosons proportional to their mass squared
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- Triple and quartic gauge couplings proportional to gauge couplings

$$-\frac{h}{v}\sum_f m_f \bar{f} f$$

Standard Model Lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

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Some predictions at lowest order

- Z and W boson mass ratio related to Weinberg angle
- Higgs coupling to gauge bosons proportional to their mass squared
- Higgs coupling to fermions proportional to their mass
- Triple and quartic gauge couplings proportional to gauge couplings

$$\begin{aligned}\mathcal{L}_{\rm TGC} =& ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\,A_{\mu\nu}\,W^+_\mu W^-_\nu \\ &+ i\frac{g_L^2}{\sqrt{g_L^2+g_Y^2}}\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + i\frac{g_L^2}{\sqrt{g_L^2+g_Y^2}}Z_{\mu\nu}\,W^+_\mu W^-_\nu\end{aligned}$$

Dimension 5 Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

$$\mathcal{L}^{D=5} = -(L_i H)c_{ij}(L_j H) + \text{h.c.}$$

- At dimension 5, only operators one can construct are so-called Weinberg operators

- After EW breaking they give rise to Majorana mass terms for SM (left-handed) neutrinos

$$\mathcal{L}^{D=5} = -\frac{1}{2}(v+h)^2 \nu_i c_{ij} \nu_j$$

- They have been shown to be present by neutrino oscillation experiments

- However, to match the measurements, their coefficients have to be extremely small, c ~ 10^-11

- Therefore dimension 5 operators have no observable impact on collider phenomenology

Dimension 6 Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

- At dimension 6 level all hell breaks loose
- First attempt to enumerate dimension-6 operators back in the 80s, but only recently complete non-redundant set was identified

  Buchmuller,Wyler Nucl.Phys. B268 (1986)

- After imposing baryon and lepton number conservation, there are 2499 non-redundant parameters at dimension-6 level

  Alonso et al 1312.2014

- Flavor symmetries dramatically reduce number of parameters
- E.g., assuming flavor blind couplings the number of parameters is reduced down to 76

  Grządkowski et al. 1008.4884

Dimension 6 Lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

$$\mathcal{L}^{D=6} = \mathcal{L}^{D=6}_{\rm H} + \mathcal{L}^{D=6}_{\rm V} + \mathcal{L}^{D=6}_{\rm HV} + \mathcal{L}^{D=6}_{\rm 2FV} + \mathcal{L}^{D=6}_{\rm 2FY} + \mathcal{L}^{D=6}_{\rm 2FD} + \mathcal{L}^{D=6}_{4F}$$

Higgs interactions with itself — e.g.

$$O_H = \partial_\mu(H^\dagger H)\partial_\mu(H^\dagger H)$$

Self-interactions of gauge bosons — e.g.

$$O_{3W} = \epsilon^{ijk} W^{i\,\nu}_{\mu} W^{j\,\rho}_{\nu} W^{k\,\mu}_{\rho}$$

Higgs interactions with gauge bosons — e.g.

$$O_{WB} = B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$

2-fermion vertex corrections — e.g.

$$O'_{HL} = \bar{\ell}\sigma^i\bar{\sigma}_\mu l H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$$

2-fermion Yukawa interactions — e.g.

$$O_u = H^\dagger H H q Y_u u^c$$

2-fermion dipole operators — e.g.

$$O_{BE} = H^\dagger \bar{\sigma}_{\mu\nu} \ell e^c B_{\mu\nu}$$

4-fermion operators — e.g.

$$O'_{e\mu} = (\bar{e}\sigma_\rho \nu_e)(\bar{\nu}_\mu \sigma_\rho \mu)$$

Dimension 6 Lagrangian

$$\rangle H^\dagger H \langle \equiv H^\dagger H - \frac{v^2}{2}$$

Higgs only operators

$$\mathcal{L}_{\mathrm{H}}^{D=6} = c_H \, \partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) - c_6 \left(\rangle H^\dagger H \langle\right)^3$$

- First operator OH shifts kinetic term of Higgs bosons

$$\begin{aligned} \Delta\mathcal{L} &= c_H \partial_\mu h \partial_\mu h \\ h &\to (1 - c_H) h \\ 2\frac{h}{v} m_W^2 W_\mu^+ W_\mu^- &\to 2(1 - c_H)\frac{h}{v} m_W^2 W_\mu^+ W_\mu^- \\ \frac{h}{v} m_Z^2 Z_\mu Z_\mu &\to (1 - c_H)\frac{h}{v} m_Z^2 Z_\mu Z_\mu \\ \frac{h}{v} m_f f f^c &\to (1 - c_H)\frac{h}{v} m_f f f^c \end{aligned}$$

- After normalizing Higgs boson field properly, universal shift by cH of all SM Higgs coupling to matter

- Second operator O6 modifies Higgs boson self-couplings

$$\mathcal{L}_h = -\left(\frac{m_h^2}{2v} + c_6 v\right) h^3 - \left(\frac{m_h^2}{8v^2} + \frac{3c_6}{2}\right) h^4 - \frac{3c_6}{4v} h^5 - \frac{c_6}{8v^2} h^6$$

- One prediction (but difficult to test): if triple Higgs couplings modified, correlated shift of higher self-couplings

Dimension 6 Lagrangian

Gauge only operators

$$\mathcal{L}_{\rm V}^{D=6} = c_{3W}\ \epsilon^{ijk} W_{\mu}^{i\,\nu} W_{\nu}^{j\,\rho} W_{\rho}^{k\,\mu} + \tilde{c}_{3W}\ \epsilon^{ijk} W_{\mu}^{i\,\nu} W_{\nu}^{j\,\rho} \tilde{W}_{\rho}^{k\,\mu} + c_{3G}\, f^{abc} G_{\mu}^{a\,\nu} G_{\nu}^{b\,\rho} G_{\rho}^{c\,\mu} + \tilde{c}_{3G}\, f^{abc} G_{\mu}^{a\,\nu} G_{\nu}^{b\,\rho} \tilde{G}_{\rho}^{c\,\mu},$$

- Induces new (not present in SM), 3-derivative coupling between charged and neutral gauge bosons
- New sources of CP violation at dimension 6 level

$$\lambda_Z = -\frac{3}{2} g_L^4 c_{3W}$$

$$\begin{aligned}\mathcal{L}_{\rm TGC} =& ie\,\left(W_{\mu\nu}^{+} W_{\mu}^{-} - W_{\mu\nu}^{-} W_{\mu}^{+}\right) A_{\nu} + ie(1+\delta\kappa_{\gamma})\, A_{\mu\nu}\, W_{\mu}^{+} W_{\nu}^{-} + ie \frac{\lambda_Z}{m_W^2} W_{\mu\nu}^{+} W_{\nu\rho}^{-} A_{\rho\mu} \\ &+ i g_L \cos\theta_W (1+\delta g_1^Z)\,\left(W_{\mu\nu}^{+} W_{\mu}^{-} - W_{\mu\nu}^{-} W_{\mu}^{+}\right) Z_{\nu} + i g_L \cos\theta_W \left(1 + \delta g_{1,Z} - \frac{g_Y^2}{g_L^2}\delta\kappa_{\gamma}\right) Z_{\mu\nu}\, W_{\mu}^{+} W_{\nu}^{-} \\ &+ i g_L \cos\theta_W \frac{\lambda_Z}{m_W^2} W_{\mu\nu}^{+} W_{\nu\rho}^{-} Z_{\rho\mu}\end{aligned}$$

Dimension 6 Lagrangian

Higgs-Gauge operators

$$\mathcal{L}_{\rm HV}^{D=6} = c_T \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$+ c_{GG} \rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW} \rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB} \rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu}$$
$$+ \tilde{c}_{GG} \rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$

$$H^\dagger \overleftrightarrow{D^\mu} H \equiv H^\dagger D_\mu H - D_\mu H^\dagger H \qquad \rangle H^\dagger H \langle \equiv H^\dagger H - \frac{v^2}{2}$$

- These operators modify Higgs couplings to gauge bosons
- OT modifies Higgs couplings to Z boson mass only (custodial symmetry breaking)
- OWW, OBB and OS introduce new 2-derivative Higgs couplings to γγ and Zγ, WW and ZZ. Prediction:3 parameters to describe 4 of these couplings
- CP violating Higgs couplings appear

$$\begin{aligned}
c_w &= 1 - c_H, \\
c_z &= 1 - c_H - 4 c_T, \\
c_{gg} &= 4 c_{GG}, \\
c_{\gamma\gamma} &= -4\left(c_{WW} + c_{BB} - c_S\right), \\
c_{z\gamma} &= -\frac{2}{g_L^2 + g_Y^2}\left(2 g_L^2 c_{WW} - 2 g_Y^2 c_{BB} - (g_L^2 - g_Y^2) c_S\right) \\
c_{zz} &= -\frac{4}{(g_L^2 + g_Y^2)^2}\left(g_L^4 c_{WW} + g_Y^4 c_{BB} + 2 g_L^2 g_Y^2 c_S\right), \\
c_{ww} &= -4 c_{WW}.
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{h,g} = \; & \frac{h}{v}\Big\{ 2 c_w m_W^2 W^+_\mu W^-_\mu + c_z m_Z^2 Z_\mu Z_\mu \\
& + \frac{g_s^2}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{g_L^2}{2} c_{ww} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{e^2}{4} c_{\gamma\gamma} A_{\mu\nu} A_{\mu\nu} - \frac{g_L^2}{4\cos^2\theta_W} c_{zz} Z_{\mu\nu} Z_{\mu\nu} - \frac{e g_L}{2\cos\theta_W} c_{z\gamma} A_{\mu\nu} Z_{\mu\nu} \\
& + \frac{g_s^2}{4} \tilde{c}_{gg} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{g_L^2}{2} \tilde{c}_{ww} W^+_{\mu\nu} \tilde{W}^-_{\mu\nu} - \frac{e^2}{4} \tilde{c}_{\gamma\gamma} A_{\mu\nu} \tilde{A}_{\mu\nu} - \frac{g_L^2}{4\cos^2\theta_W} \tilde{c}_{zz} Z_{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{e g_L}{2\cos\theta_W} \tilde{c}_{z\gamma} A_{\mu\nu} \tilde{Z}_{\mu\nu} \Big\}
\end{aligned}$$

Dimension 6 Lagrangian

Vertex Operators

$$\begin{aligned}
\mathcal{L}_{2\mathrm{FV}}^{D=6} &= ic'_{HQ}\bar{q}\sigma^i\bar{\sigma}_\mu q H^\dagger\sigma^i \overleftrightarrow{D_\mu} H + \left(ic_{HUD}u^c\sigma_\mu\bar{d}^c\epsilon H D_\mu H + \mathrm{h.c.}\right) \\
&+ ic_{HQ}\bar{q}\bar{\sigma}_\mu q H^\dagger \overleftrightarrow{D_\mu} H + ic_{HU}u^c\sigma_\mu\bar{u}^c H^\dagger \overleftrightarrow{D_\mu} H + ic_{HD}d^c\sigma_\mu\bar{d}^c H^\dagger \overleftrightarrow{D_\mu} H \\
&+ ic'_{HL}\bar{\ell}\sigma^i\bar{\sigma}_\mu l H^\dagger\sigma^i \overleftrightarrow{D_\mu} H + ic_{HL}\bar{\ell}\bar{\sigma}_\mu l H^\dagger \overleftrightarrow{D_\mu} H + ic_{HE}e^c\sigma_\mu\bar{e}^c H^\dagger \overleftrightarrow{D_\mu} H.
\end{aligned}$$

- These operators shift Z and W boson couplings to leptons and quarks
- Prediction: corrections to W and Z boson couplings are correlated

$$\begin{aligned}
\delta g_{\ell W,L} &= c'_{HL}, \\
\delta g_{\nu Z,L} &= \frac{c'_{HL}}{2} - \frac{c_{HL}}{2}, \\
\delta g_{eZ,L} &= -\frac{c'_{HL}}{2} - \frac{c_{HL}}{2}, \\
\delta g_{eZ,R} &= -\frac{c_{HE}}{2}.
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{ffV} &= eA_\mu \sum_{f=u,d,e} Q_f\left(\bar{f}\bar{\sigma}_\mu f + f^c\sigma_\mu\bar{f}^c\right) \\
&+ \frac{g_L}{\sqrt{2}}W_\mu^+\left[(1+\delta g_{qW,L})\bar{u}\bar{\sigma}_\mu V_{\mathrm{CKM}}d + \delta g_{qW,R}u^c\sigma_\mu\bar{d}^c + (1+\delta g_{\ell W,L})\bar{e}\bar{\sigma}_\mu\nu\right] + \mathrm{h.c.} \\
&+ \sqrt{g_L^2+g_Y^2}Z_\mu \sum_{f=u,d,e,\nu}(T_f^3 - \sin^2\theta_W Q_f + \delta g_{fZ,L})\bar{f}\bar{\sigma}_\mu f \\
&+ \sqrt{g_L^2+g_Y^2}Z_\mu \sum_{f=u,d,e}(-\sin^2\theta_W Q_f + \delta g_{fZ,R})f^c\sigma_\mu\bar{f}^c \qquad (3.14)
\end{aligned}$$

Dimension 6 Lagrangian

Remaining Operators

$$\mathcal{L}_{\rm 2FY}^{D=6} = -\rangle H^\dagger H \langle \left[c_U H q Y_u u^c + c_D H^\dagger q Y_d d^c + c_L H^\dagger \ell Y_\ell e^c \right] + \text{h.c.}$$

- 2-fermion Yukawa operators modify Higgs couplings to fermions
- 2-fermion dipole operators contribute to anomalous magnetic and electric moments of quark and leptons

$$c_{BE} H^\dagger L \bar{\sigma}_{\mu\nu} e^c B_{\mu\nu} + \text{h.c.}$$

- 4-fermion operators contribute to non-resonant electron and quark scattering

$$O'_{e\mu} = (\bar{e}\sigma_\rho \nu_e)(\bar{\nu}_\mu \sigma_\rho \mu)$$

Dimension 6 Lagrangian

- Dimension 6 operators can modify all couplings present in the SM
- They also introduce new couplings with a new tensor structure that is not present in the SM

Basis choice

- Operators can be traded for other operators using integration by parts and equations of motion

- Because of that, one can choose many different bases == non-redundant sets of operators

- All bases are equivalent, but some are more ~~equivalent~~ convenient.

- Here I stick to the so-called Warsaw basis. It is distinguished by the simplest tensor structure of Higgs and matter couplings

Grządkowski et al. 1008.4884

- Other basis choices exist in the literature, they may be more convenient for particular applications, or they may connect better to certain classes of BSM model

see e.g.
Giudice et al hep-ph/0703164
Contino et al 1303.3876

Synergy

between Higgs and EWPT

Higgs gauge operators and Higgs couplings

$$\mathcal{L}_{\rm HV}^{D=6} = c_T \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$+ c_{GG}\, \rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW}\, \rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB}\, \rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu}$$
$$+ \tilde{c}_{GG}\, \rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$

$$H^\dagger \overleftrightarrow{D^\mu} H \equiv H^\dagger D_\mu H - D_\mu H^\dagger H \qquad \rangle H^\dagger H \langle \equiv H^\dagger H - \frac{v^2}{2}$$

- OT modifies Higgs couplings to Z boson mass only (custodial symmetry breaking)
- OWW, OBB and OS introduce new 2-derivative Higgs couplings to γγ and Zγ, WW and ZZ

$$\begin{aligned}
c_w &= 1 - c_H, \\
c_z &= 1 - c_H - 4c_T, \\
c_{gg} &= 4c_{GG}, \\
c_{\gamma\gamma} &= -4\left(c_{WW} + c_{BB} - c_S\right), \\
c_{z\gamma} &= -\frac{2}{g_L^2 + g_Y^2}\left(2g_L^2 c_{WW} - 2g_Y^2 c_{BB} - (g_L^2 - g_Y^2) c_S\right) \\
c_{zz} &= -\frac{4}{(g_L^2 + g_Y^2)^2}\left(g_L^4 c_{WW} + g_Y^4 c_{BB} + 2g_L^2 g_Y^2 c_S\right), \\
c_{ww} &= -4c_{WW}.
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{h,g} = \frac{h}{v}\Big\{ & 2c_w m_W^2 W^+_\mu W^-_\mu + c_z m_Z^2 Z_\mu Z_\mu \\
+ & \frac{g_s^2}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{g_L^2}{2} c_{ww} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{e^2}{4} c_{\gamma\gamma} A_{\mu\nu} A_{\mu\nu} - \frac{g_L^2}{4\cos^2\theta_W} c_{zz} Z_{\mu\nu} Z_{\mu\nu} - \frac{e g_L}{2\cos\theta_W} c_{z\gamma} A_{\mu\nu} Z_{\mu\nu} \\
+ & \frac{g_s^2}{4} \tilde{c}_{gg} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{g_L^2}{2} \tilde{c}_{ww} W^+_{\mu\nu} \tilde{W}^-_{\mu\nu} - \frac{e^2}{4} \tilde{c}_{\gamma\gamma} A_{\mu\nu} \tilde{A}_{\mu\nu} - \frac{g_L^2}{4\cos^2\theta_W} \tilde{c}_{zz} Z_{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{e g_L}{2\cos\theta_W} \tilde{c}_{z\gamma} A_{\mu\nu} \tilde{Z}_{\mu\nu} \Big\}
\end{aligned}$$

Higgs gauge operators and oblique corrections

$$\mathcal{L}_{\rm HV}^{D=6} = c_T \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$+ c_{GG}\,) H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW}\,) H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB}\,) H^\dagger H \langle B_{\mu\nu} B_{\mu\nu}$$
$$+ \tilde{c}_{GG}\,) H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$

$$\Delta\mathcal{L} = -\frac{c_S}{2}\left(\partial_\mu W^3_\nu - \partial_\nu W^3_\mu\right)\left(\partial_\mu B_\nu - \partial_\nu B_\mu\right) - c_T \frac{v^2}{4}(W^3_\mu - B_\mu)^2.$$

- Two of these operators contribute to EW precision observables
- OT and OS affect propagators of EW gauge bosons (equivalent to Peskin-Takeuchi T and S parameters)
- Therefore these 2 operators are probed by V-pole measurements, in particular Z-pole measurements at LEP-1 and W mass measurements at LEP-2 and Tevatron

$$\Delta S = 16\pi c_S$$
$$\Delta T = \frac{8\pi(g_L^2 + g_Y^2)}{g_L^2 g_Y^2} c_T$$
$$\Delta U = 0$$

Higgs gauge operators and VV production

$$\mathcal{L}_{\mathrm{HV}}^{D=6} = c_T \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$+ c_{GG}\, \rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW}\, \rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB}\, \rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu}$$
$$+ \tilde{c}_{GG}\, \rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$

- One of these operators contributes to vector boson pair production
- OS induces anomalous triple gauge couplings κγ and g1Z in the standard Hagiwara et al parametrization

Hagiwara et al, Phys.Rev. D48 (1993)

- Therefore this parameter can be probed by WW and WZ production at LEP-2 and LHC

$$\delta g_1^Z = 0$$
$$\delta \kappa_\gamma = g_L^2 c_S$$
$$\lambda_Z = -\frac{3}{2} g_L^4 c_{3W}$$

$$\mathcal{L}_{\mathrm{TGC}} = ie\left(W^+_{\mu\nu} W^-_\mu - W^-_{\mu\nu} W^+_\mu\right) A_\nu + ie(1+\delta\kappa_\gamma)\, A_{\mu\nu} W^+_\mu W^-_\nu + ie\frac{\lambda_Z}{m_W^2} W^+_{\mu\nu} W^-_{\nu\rho} A_{\rho\mu}$$
$$+ ig_L \cos\theta_W (1+\delta g_1^Z)\left(W^+_{\mu\nu} W^-_\mu - W^-_{\mu\nu} W^+_\mu\right) Z_\nu + ig_L \cos\theta_W \left(1 + \delta g_{1,Z} - \frac{g_Y^2}{g_L^2}\delta\kappa_\gamma\right) Z_{\mu\nu} W^+_\mu W^-_\nu$$
$$+ ig_L \cos\theta_W \frac{\lambda_Z}{m_W^2} W^+_{\mu\nu} W^-_{\nu\rho} Z_{\rho\mu}$$

$$O_{3W} = \epsilon^{ijk} W^{i\,\nu}_{\mu} W^{j\,\rho}_{\nu} W^{k\,\mu}_{\rho}$$

Vertex operators and fermion couplings

$$\begin{aligned}
\mathcal{L}_{\rm 2FV}^{D=6} &= i c'_{HQ} \bar q \sigma^i \bar\sigma_\mu q H^\dagger \sigma^i \overleftrightarrow{D_\mu} H + \left(i c_{HUD} u^c \sigma_\mu \bar d^c \epsilon H D_\mu H + \text{h.c.} \right) \\
&+ i c_{HQ} \bar q \bar\sigma_\mu q H^\dagger \overleftrightarrow{D_\mu} H + i c_{HU} u^c \sigma_\mu \bar u^c H^\dagger \overleftrightarrow{D_\mu} H + i c_{HD} d^c \sigma_\mu \bar d^c H^\dagger \overleftrightarrow{D_\mu} H \\
&+ i c'_{HL} \bar\ell \sigma^i \bar\sigma_\mu l H^\dagger \sigma^i \overleftrightarrow{D_\mu} H + i c_{HL} \bar\ell \bar\sigma_\mu l H^\dagger \overleftrightarrow{D_\mu} H + i c_{HE} e^c \sigma_\mu \bar e^c H^\dagger \overleftrightarrow{D_\mu} H.
\end{aligned}$$

- These operators contribute to EW precision observables
- They shift the Z and W boson couplings to leptons and quarks
- Therefore they can be probed by V-pole measurements

$$\begin{aligned}
\delta g_{\ell W,L} &= c'_{HL}, \\
\delta g_{\nu Z,L} &= \frac{c'_{HL}}{2} - \frac{c_{HL}}{2}, \\
\delta g_{eZ,L} &= -\frac{c'_{HL}}{2} - \frac{c_{HL}}{2}, \\
\delta g_{eZ,R} &= -\frac{c_{HE}}{2}.
\end{aligned}$$

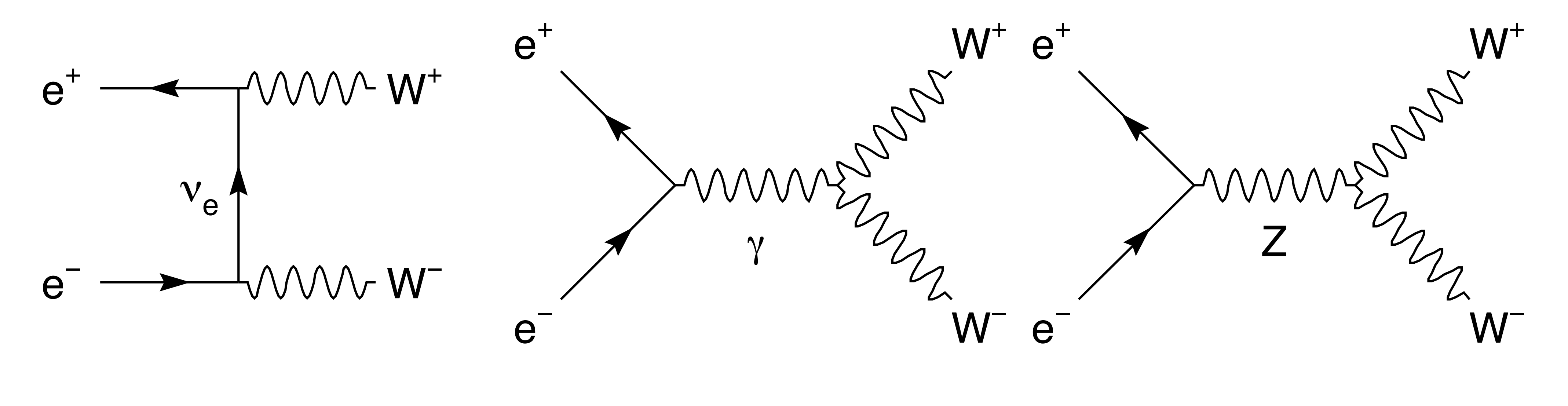
$$\begin{aligned}
\mathcal{L}_{ffV} &= e A_\mu \sum_{f=u,d,e} Q_f \left(\bar f \bar\sigma_\mu f + f^c \sigma_\mu \bar f^c \right) \\
&+ \frac{g_L}{\sqrt{2}} W_\mu^+ \left[(1+\delta g_{qW,L}) \bar u \bar\sigma_\mu V_{\rm CKM} d + \delta g_{qW,R} u^c \sigma_\mu \bar d^c + (1+\delta g_{\ell W,L}) \bar e \bar\sigma_\mu \nu \right] + \text{h.c.} \\
&+ \sqrt{g_L^2 + g_Y^2} Z_\mu \sum_{f=u,d,e,\nu} (T_f^3 - \sin^2\theta_W Q_f + \delta g_{fZ,L}) \bar f \bar\sigma_\mu f \\
&+ \sqrt{g_L^2 + g_Y^2} Z_\mu \sum_{f=u,d,e} (-\sin^2\theta_W Q_f + \delta g_{fZ,R}) f^c \sigma_\mu \bar f^c \qquad (3.14)
\end{aligned}$$

Vertex operators and VV production

$$\begin{aligned}\mathcal{L}_{2\mathrm{FV}}^{D=6} &= i c'_{HQ} \bar{q} \sigma^i \bar{\sigma}_\mu q H^\dagger \sigma^i \overleftrightarrow{D_\mu} H + \left(i c_{HUD} u^c \sigma_\mu \bar{d}^c \epsilon H D_\mu H + \mathrm{h.c.}\right) \\ &+ i c_{HQ} \bar{q} \bar{\sigma}_\mu q H^\dagger \overleftrightarrow{D_\mu} H + i c_{HU} u^c \sigma_\mu \bar{u}^c H^\dagger \overleftrightarrow{D_\mu} H + i c_{HD} d^c \sigma_\mu \bar{d}^c H^\dagger \overleftrightarrow{D_\mu} H \\ &+ i c'_{HL} \bar{\ell} \sigma^i \bar{\sigma}_\mu l H^\dagger \sigma^i \overleftrightarrow{D_\mu} H + i c_{HL} \bar{\ell} \bar{\sigma}_\mu l H^\dagger \overleftrightarrow{D_\mu} H + i c_{HE} e^c \sigma_\mu \bar{e}^c H^\dagger \overleftrightarrow{D_\mu} H.\end{aligned}$$

- These operators contribute to vector boson pair production, by shifting electron and quark couplings to W and Z
- Therefore they can be probed by by WW and WZ production at LEP-2 and LHC

$$\begin{aligned}\delta g_{\ell W,L} &= c'_{HL}, \\ \delta g_{\nu Z,L} &= \frac{c'_{HL}}{2} - \frac{c_{HL}}{2}, \\ \delta g_{eZ,L} &= -\frac{c'_{HL}}{2} - \frac{c_{HL}}{2}, \\ \delta g_{eZ,R} &= -\frac{c_{HE}}{2}.\end{aligned}$$

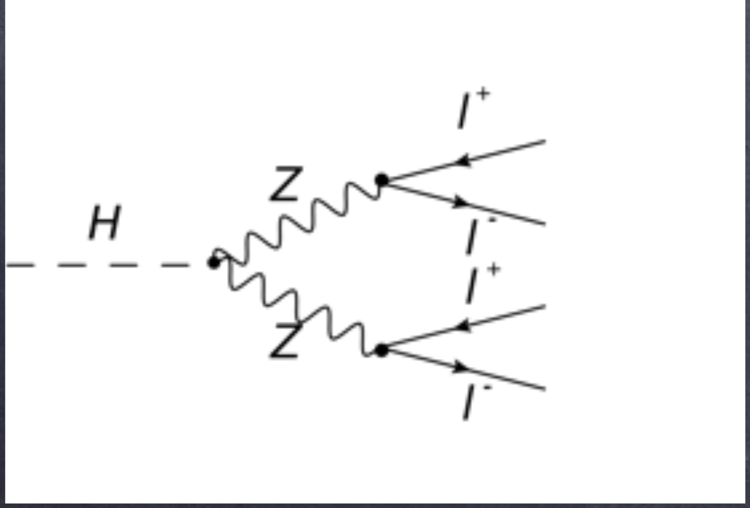


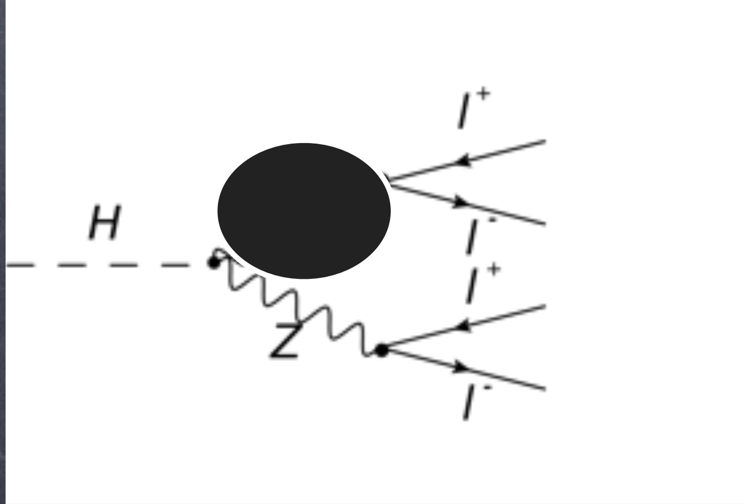
Vertex operators and Higgs couplings

$$\begin{aligned}\mathcal{L}^{D=6}_{2\mathrm{FV}} &= ic'_{HQ}\bar{q}\sigma^i\bar{\sigma}_\mu q H^\dagger\sigma^i\overleftrightarrow{D_\mu}H + \left(ic_{HUD}u^c\sigma_\mu\bar{d}^c\epsilon H D_\mu H + \mathrm{h.c.}\right)\\ &+ ic_{HQ}\bar{q}\bar{\sigma}_\mu q H^\dagger\overleftrightarrow{D_\mu}H + ic_{HU}u^c\sigma_\mu\bar{u}^c H^\dagger\overleftrightarrow{D_\mu}H + ic_{HD}d^c\sigma_\mu\bar{d}^c H^\dagger\overleftrightarrow{D_\mu}H\\ &+ ic'_{HL}\bar{\ell}\sigma^i\bar{\sigma}_\mu l H^\dagger\sigma^i\overleftrightarrow{D_\mu}H + ic_{HL}\bar{\ell}\bar{\sigma}_\mu l H^\dagger\overleftrightarrow{D_\mu}H + ic_{HE}e^c\sigma_\mu\bar{e}^c H^\dagger\overleftrightarrow{D_\mu}H.\end{aligned}$$

- These operators also affect Higgs searches
- On one hand, they contribute to Higgs decays via intermediate gauge bosons, by shifting couplings of the latter to fermions
- On the other hand, they also induce new h V f f contact interactions

$$\begin{aligned}\delta g_{\ell W,L} &= c'_{HL},\\ \delta g_{\nu Z,L} &= \frac{c'_{HL}}{2} - \frac{c_{HL}}{2},\\ \delta g_{eZ,L} &= -\frac{c'_{HL}}{2} - \frac{c_{HL}}{2},\\ \delta g_{eZ,R} &= -\frac{c_{HE}}{2}.\end{aligned}$$





Synergy

- The same operators are probed by Higgs physics, Z-pole measurements and vector boson pair production
- Starting from precision measurement one can formulate model independent predictions concerning what kind of Higgs signals are possible

Current precision constraints

on dimension 6 operators

Current precision constraints on dimension 6 operators

Preliminary

EFT approach to BSM

In this talk:

- Taking into account coefficients of dimension-6 operators at the linear level (except at the very end)
- I'm assuming flavor blind vertex corrections (more general approach left for future work)
- Restrict to observables that do not depend on 4-fermion operators (more general approach left for future work)

V-pole constraints

Z pole

Observable	Experimental value	SM prediction
Γ_Z [GeV]	2.4952 ± 0.0023	2.4954
$\sigma_{\rm had}$ [nb]	41.540 ± 0.037	41.478
R_ℓ	20.767 ± 0.025	20.741
A_ℓ	0.1499 ± 0.0018	0.1473
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0162
R_b	0.21629 ± 0.00066	0.21474
A_b	0.923 ± 0.020	0.935
$A_b^{\rm FB}$	0.0992 ± 0.0016	0.1032
R_c	0.1721 ± 0.0030	0.1724
A_c	0.670 ± 0.027	0.667
$A_c^{\rm FB}$	0.0707 ± 0.0035	0.073

W pole

Observable	Experimental value	SM prediction
m_W [GeV]	80.385 ± 0.015 [12]	80.3602
Γ_W [GeV]	2.085 ± 0.042 [13]	2.091
Br($W \to$ had) [%]	67.41 ± 0.27 [?]	67.51

Input: mZ, α(0), Γμ

- For V-pole observables, interference between SM and 4-fermion operators is suppressed by Γ/m
- Corrections can be expressed by Higgs-gauge and vertex operators only (+1 four-fermion operator contributing to Γμ). For example:

For example

$$\delta m_W = \frac{m_W}{g_L^2 - g_Y^2}\left(g_L^2 c_T - g_L^2 g_Y^2 c_S - g_Y^2 c'_{HL} - \frac{g_Y^2}{4} c_{4F}\right)$$

V-pole constraints

$$\mathcal{L}^{D=6}_{\rm HV} = c_T \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$+ c_{GG} \rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW} \rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB} \rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu}$$
$$+ \tilde{c}_{GG} \rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$

- Assume first new physics affects only oblique operators OS and OT
- Then V-pole measurements imply very strong limits on these operators
- In other words, new physics scale suppressing these operators is in few-10 TeV ballpark
- If that is the case:
  - Higgs coupling to W and Z mass (set by cT) mismatch must be unobservably small
  - 2-derivative Higgs couplings to WW, ZZ are tightly correlated with couplings to Zγ and γγ

$$c_S = (1.26 \pm 1.72) \times 10^{-3}$$
$$c_T = (3.52 \pm 2.80) \times 10^{-4}$$

But this is not robust conclusion!

$$\begin{aligned}
\mathcal{L}_{h,g} &= \frac{h}{v}\Big\{2c_w m_W^2 W^+_\mu W^-_\mu + c_z m_Z^2 Z_\mu Z_\mu \\
&+ \frac{g_s^2}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{g_L^2}{2} c_{ww} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{e^2}{4} c_{\gamma\gamma} A_{\mu\nu} A_{\mu\nu} - \frac{g_L^2}{4\cos^2\theta_W} c_{zz} Z_{\mu\nu} Z_{\mu\nu} - \frac{e g_L}{2\cos\theta_W} c_{z\gamma} A_{\mu\nu} Z_{\mu\nu} \\
&+ \frac{g_s^2}{4} \tilde{c}_{gg} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{g_L^2}{2} \tilde{c}_{ww} W^+_{\mu\nu} \tilde{W}^-_{\mu\nu} - \frac{e^2}{4} \tilde{c}_{\gamma\gamma} A_{\mu\nu} \tilde{A}_{\mu\nu} - \frac{g_L^2}{4\cos^2\theta_W} \tilde{c}_{zz} Z_{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{e g_L}{2\cos\theta_W} \tilde{c}_{z\gamma} A_{\mu\nu} \tilde{Z}_{\mu\nu}\Big\}
\end{aligned}$$

V-pole constraints

$$\mathcal{L}^{D=6}_{\rm HV} = c_T \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$+ c_{GG} \rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW} \rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB} \rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu}$$
$$+ \tilde{c}_{GG} \rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$

$$O'_{e\mu} = (\bar{e}\sigma_\rho \nu_e)(\bar{\nu}_\mu \sigma_\rho \mu)$$

$$\begin{aligned} \mathcal{L}^{D=6}_{\rm 2FV} \;=\;& i c'_{HQ} \bar{q} \sigma^i \bar{\sigma}_\mu q H^\dagger \sigma^i \overleftrightarrow{D_\mu} H + \left(i c_{HUD} u^c \sigma_\mu \bar{d}^c \epsilon H D_\mu H + \text{h.c.}\right) \\ &+ i c_{HQ} \bar{q} \bar{\sigma}_\mu q H^\dagger \overleftrightarrow{D_\mu} H + i c_{HU} u^c \sigma_\mu \bar{u}^c H^\dagger \overleftrightarrow{D_\mu} H + i c_{HD} d^c \sigma_\mu \bar{d}^c H^\dagger \overleftrightarrow{D_\mu} H \\ &+ i c'_{HL} \bar{\ell} \sigma^i \bar{\sigma}_\mu l H^\dagger \sigma^i \overleftrightarrow{D_\mu} H + i c_{HL} \bar{\ell} \bar{\sigma}_\mu l H^\dagger \overleftrightarrow{D_\mu} H + i c_{HE} e^c \sigma_\mu \bar{e}^c H^\dagger \overleftrightarrow{D_\mu} H. \end{aligned}$$

- Assuming flavor blind vertex corrections here.
- V-pole observables depend on 10 effective theory parameters
- We have 11 precisely measured independent V-pole observables
- So we can constrain all these parameters ? No...

V-pole flat directions

Gupta et al, 1405.0181

- In general, V pole measurements depend at linear level on 10 dimension-six operators
- One can show that LEP constrains 8 combinations of EFT parameters: c-hats to the right
- Limits on these combinations are O(0.001) for leptonic vertex corrections and O(0.01) for quark ones, much better than the precision of WW cross section measurements
- This leaves 2 EFT directions that can visibly affect Higgs searches at the linear level
- These 2 directions can be parameterized by cT, cS, simply related to usual S and T parameters
- From LEP-1 and Tevatron V-pole data alone there's no model independent constraints on S and T! In particular, custodial symmetry breaking is not constrained at all!

$$
\begin{aligned}
\hat{c}'_{HL} &= c'_{HL} + g_L^2 c_S - \frac{g_L^2}{g_Y^2} c_T \\
\hat{c}_{HL} &= c_{HL} - c_T \\
\hat{c}_{HE} &= c_{HE} - 2c_T \\
\hat{c}'_{HQ} &= c'_{HQ} + g_L^2 c_S - \frac{g_L^2}{g_Y^2} c_T \\
\hat{c}_{HQ} &= c_{HQ} + \frac{1}{3} c_T \\
\hat{c}_{HU} &= c_{HU} + \frac{4}{3} c_T \\
\hat{c}_{HD} &= c_{HD} - \frac{2}{3} c_T \\
& c_{4F}
\end{aligned}
$$

V-pole flat directions

- The flat directions arise due to EFT operator identities

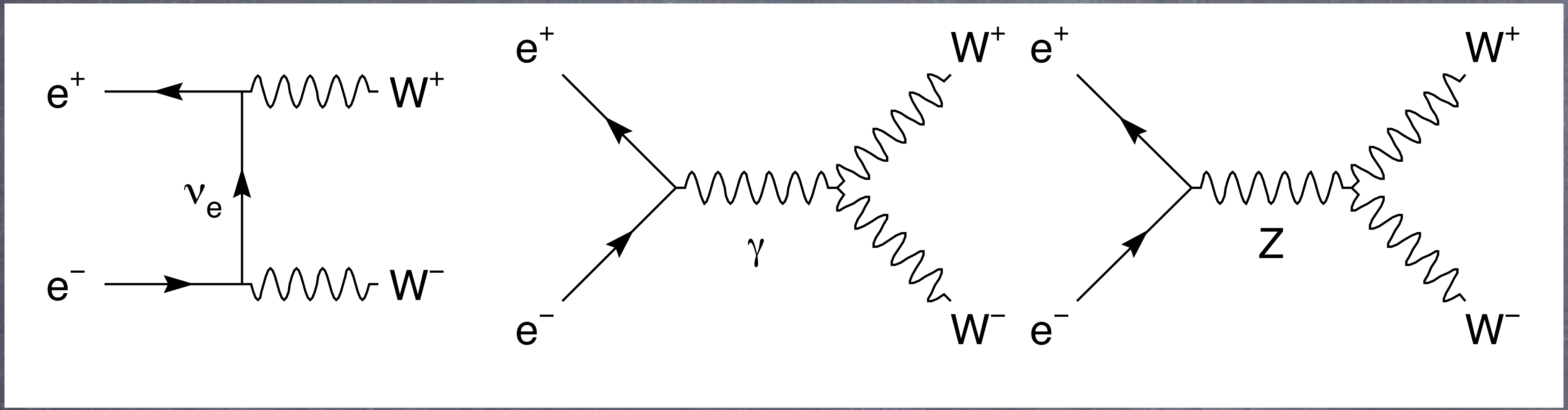
$$O_W = iH^\dagger \sigma^i \overleftrightarrow{D}_\mu H \, D_\nu W^i_{\mu\nu} = \frac{g_L^2}{2} O'_{Hq} + \frac{g_L^2}{2} O'_{H\ell}.$$

$$O_B = iH^\dagger \overleftrightarrow{D}_\mu H \, \partial_\nu B_{\mu\nu} = -g_Y^2 \left(-\frac{1}{2} O_T + \frac{1}{6} O_{Hq} + \frac{2}{3} O_{Hu} - \frac{1}{3} O_{Hd} - \frac{1}{2} O_{H\ell} - O_{He} \right)$$

- Obviously, operators OW and OB do not affect Z and W couplings to fermions
- They only affect gauge boson propagators (S parameter) and Higgs couplings to gauge bosons. Moreover, OW affects triple gauge couplings
- They are not part of Warsaw basis, because they are redundant with vertex corrections.
- Conversely, this means that there are 2 combinations of vertex corrections whose effect on V-pole observables is identical to that of S and T parameter!
- These 2 flat directions are lifted only when VV production data are included

VV production

WW production at LEP and LHC



- Depends on triple gauge couplings
- Also depends on electron/quark couplings to W and Z bosons and on operators modifying EW gauge boson propagators
- Indirectly, depends on operators shifting the SM reference parameters (GF, α, mZ)

WW production in effective theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \dots$$

Using Warsaw basis. Showing only operators affecting WW cross section at linear level. For simplicity, assuming flavor blind couplings.

- 2 operators (in Warsaw basis) affecting TGCs
- 7 operators (in Warsaw basis) affecting electron/quark couplings to W/Z
- 2 operators entering indirectly by affecting SM parameters
- In total, 11 dimension-six operators affecting WW production
- 8 combinations of 10 operators are constrained by V-pole measurements, while c3W is not constrained

$$\mathcal{L}^{D=6}_{\text{TGC}} = c_S B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H + c_{3W}\ \epsilon^{ijk} W^{i\,\nu}_{\mu} W^{j\,\rho}_{\nu} W^{k\,\mu}_{\rho}$$

$$\begin{aligned}\mathcal{L}^{D=6}_{\text{vertex}} =& i c'_{HQ} \bar{q}\sigma^i\bar{\sigma}_\mu q H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + i c_{HQ} \bar{q}\bar{\sigma}_\mu q H^\dagger \overleftrightarrow{D}_\mu H \\ &+ i c_{HU} u^c \sigma_\mu \bar{u}^c H^\dagger \overleftrightarrow{D}_\mu H + i c_{HD} d^c \sigma_\mu \bar{d}^c H^\dagger \overleftrightarrow{D}_\mu H \\ &+ i c'_{HL} \bar{\ell}\sigma^i\bar{\sigma}_\mu l H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + i c_{HL} \bar{\ell}\bar{\sigma}_\mu l H^\dagger \overleftrightarrow{D}_\mu H \\ &+ i c_{HE} e^c \sigma_\mu \bar{e}^c H^\dagger \overleftrightarrow{D}_\mu H.\end{aligned}$$

$$\mathcal{L}^{D=6}_{\text{EWPT}} = c_T \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \left[c_{4F} (\bar{e}\sigma_\rho \nu_e)(\bar{\nu}_\mu \sigma_\rho \mu) + \text{h.c.}\right]$$

V-pole constraints

- 11 parameters affecting WW and WZ production at linear level
- 8 combinations of 10 parameters are constrained by V-pole measurements, while c3W is not constrained by those
- Precision of WW measurements is only O(1)% in LEP and O(10%) in LHC, compared with O(0.1%) precision of LEP measurement of leptonic vertex corrections and oblique corrections
- Thus, these 8 EFT directions constrained by V-pole measurements are hardly relevant for WW and WZ measurements, given existing constraints
- We can use a simplified treatment of WW and WZ production, with only 3 free parameters

Simplified EFT for WW production

$$\begin{aligned}\mathcal{L}_{\rm TGC} =& ie\,\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie(1+\delta\kappa_\gamma)\,A_{\mu\nu}\,W^+_\mu W^-_\nu + ie\frac{\lambda_Z}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu}\\ &+ig_L\cos\theta_W(1+\delta g_1^Z)\,\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + ig_L\cos\theta_W\left(1+\delta g_{1,Z} - \frac{g_Y^2}{g_L^2}\delta\kappa_\gamma\right)Z_{\mu\nu}\,W^+_\mu W^-_\nu\\ &+ig_L\cos\theta_W\frac{\lambda_Z}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}\end{aligned}$$

$$\begin{aligned}\delta g_{1,Z} =&(g_L^2+g_Y^2)c_S - \frac{g_L^2+g_Y^2}{g_Y^2}c_T\\ \delta\kappa_\gamma =&g_L^2 c_S\\ \lambda_Z =& -\frac{3}{2}g_L^4 c_{3W}\end{aligned}$$

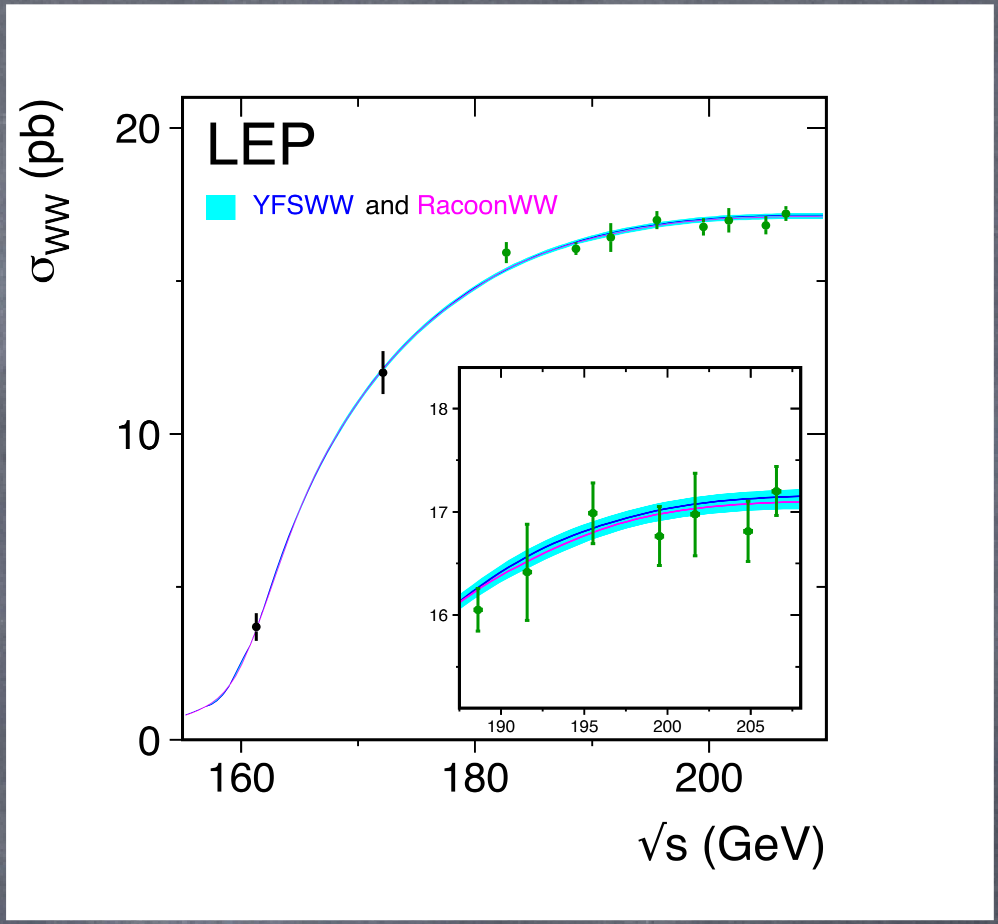
- One can prove that these 3 EFT directions are EQUIVALENT to the usual 3 dimensional TGC parameterization
- cT, cS, c3W can be mapped to g1Z, κγ and λZ
- Constraining these 3 TGCs gives a decent approximation of the constraints on EFT parameters cT, cS, c3W
- Constraint on vertex corrections can be obtained, again to a decent accuracy, assuming c-hats are zero

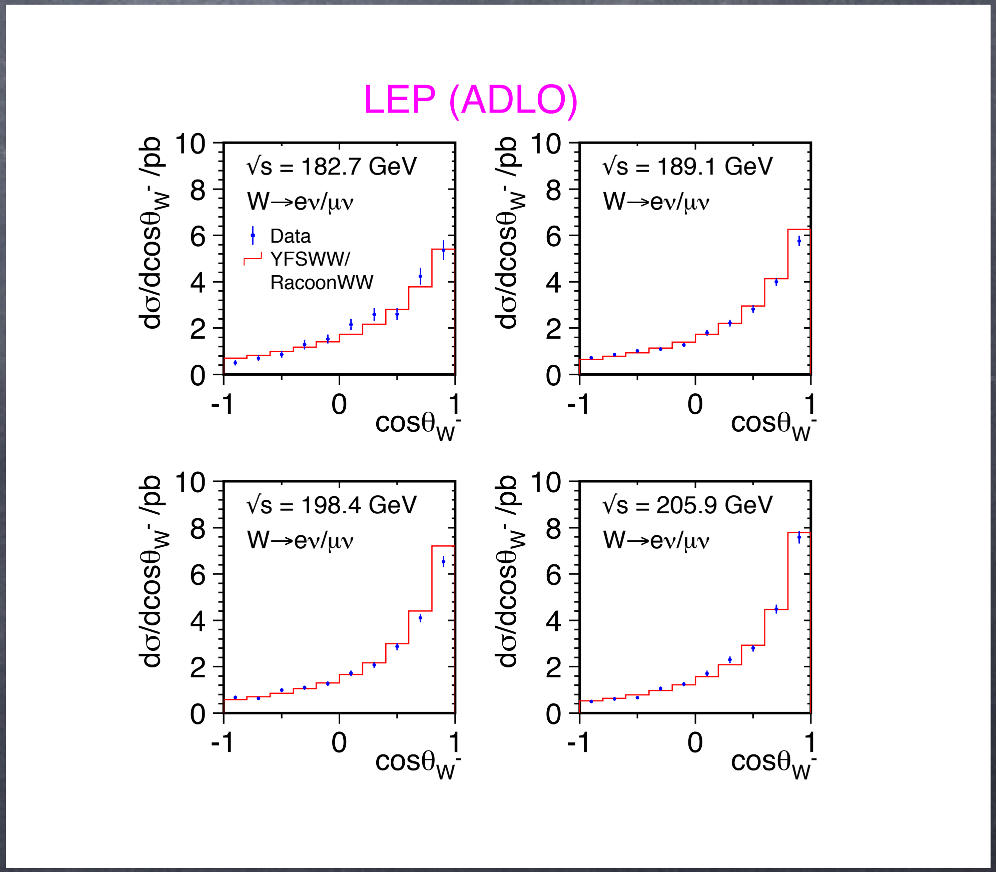
$$\begin{aligned}\hat{c}'_{HL} =&c'_{HL} + g_L^2 c_S - \frac{g_L^2}{g_Y^2}c_T\\ \hat{c}_{HL} =&c_{HL} - c_T\\ \hat{c}_{HE} =&c_{HE} - 2c_T\\ \hat{c}'_{HQ} =&c'_{HQ} + g_L^2 c_S - \frac{g_L^2}{g_Y^2}c_T\\ \hat{c}_{HQ} =&c_{HQ} + \frac{1}{3}c_T\\ \hat{c}_{HU} =&c_{HU} + \frac{4}{3}c_T\\ \hat{c}_{HD} =&c_{HD} - \frac{2}{3}c_T\\ &c_{4F}\end{aligned}$$

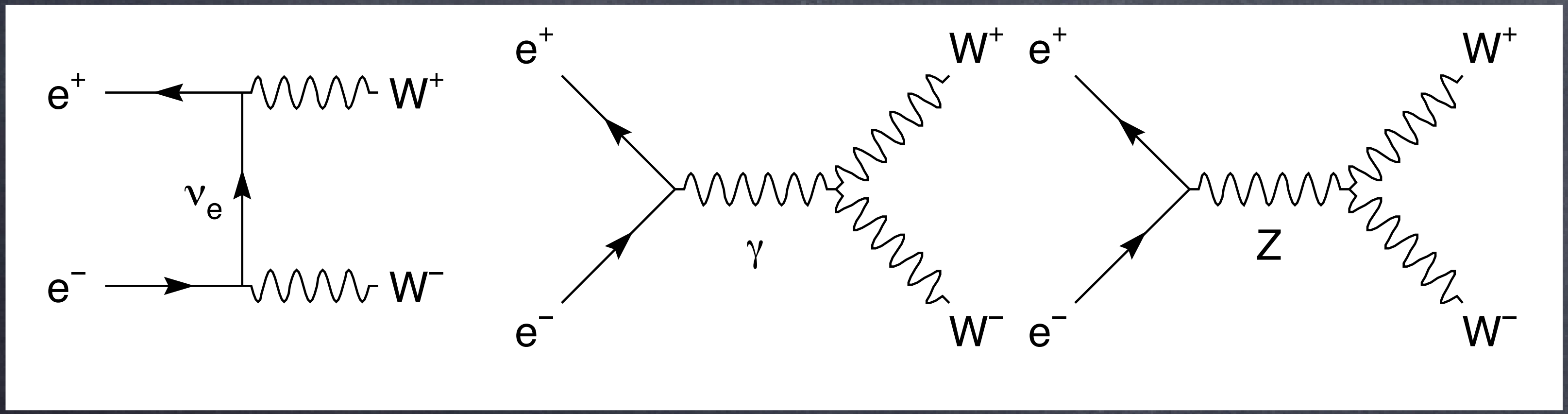
Constraints from VV production

Fitting to following data:

- Total and differential WW production cross section at different energies of LEP-2
- Single W production cross section at different energies of LEP-2
- Total WW and WZ production cross section at 7 and 8 TeV LHC







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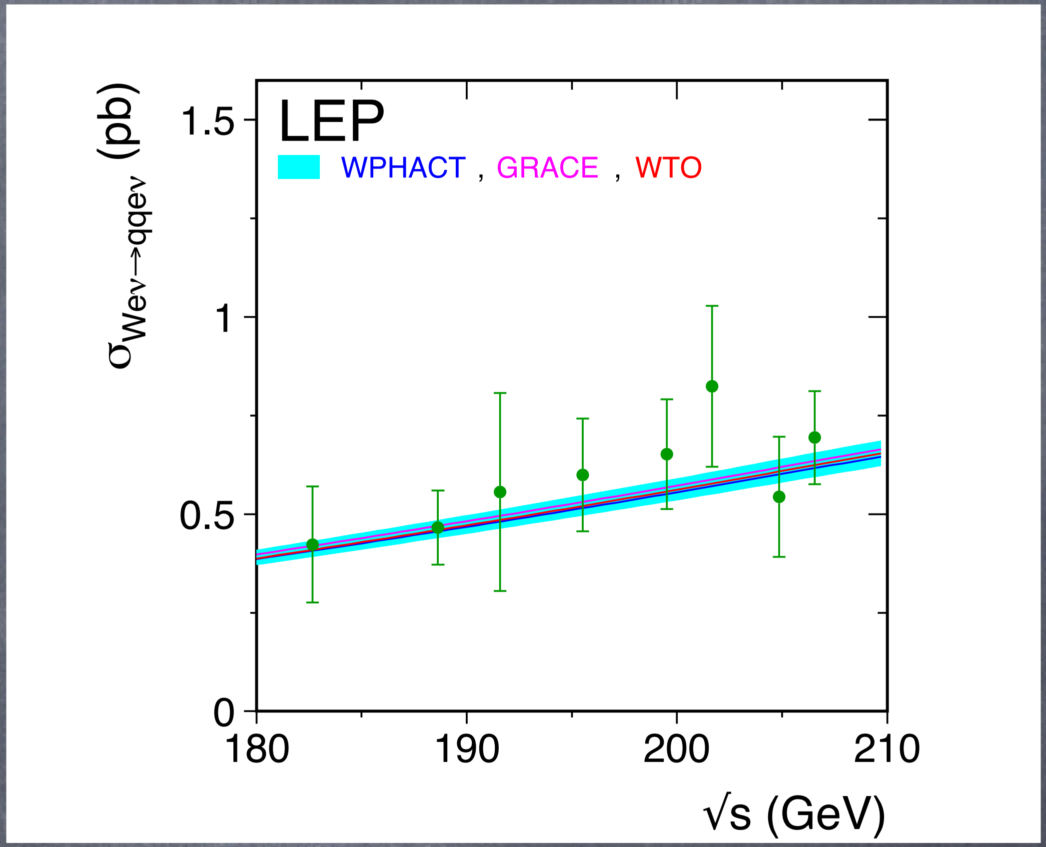
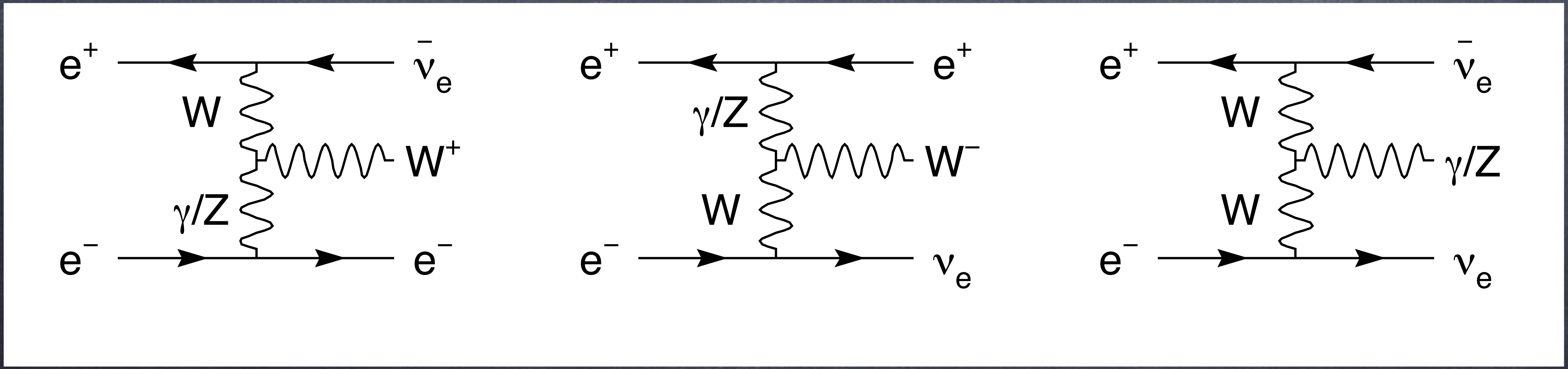




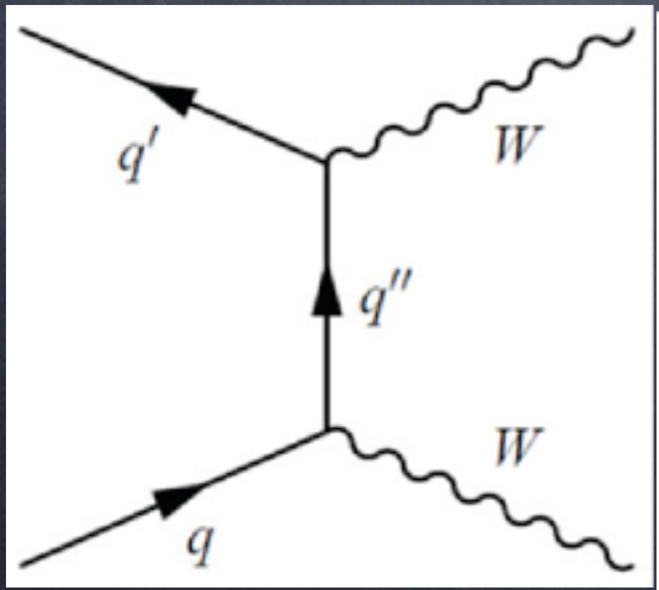
Constraints from VV production

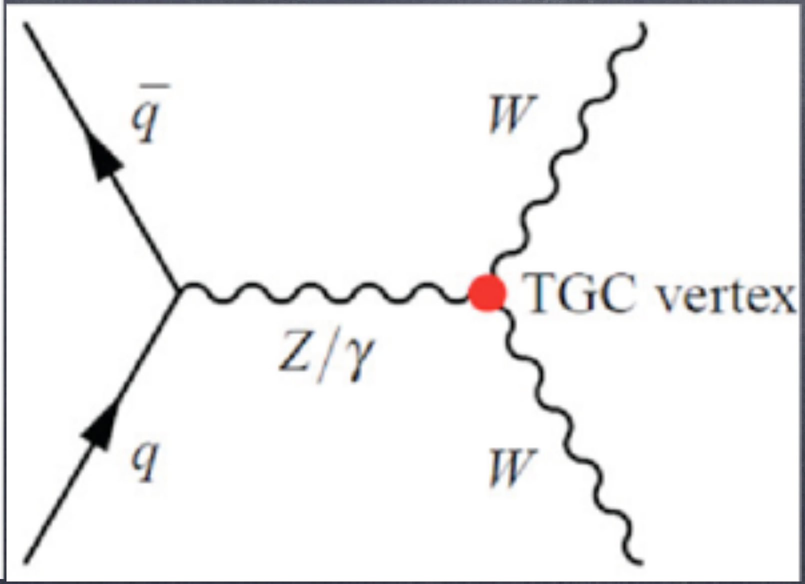
Fitting to following data:

- Total and differential WW production cross section at different energies of LEP-2
- Single W production cross section at different energies of LEP-2
- Total WW and WZ production cross section at 7 and 8 TeV LHC

Observable	ATLAS	CMS	SM
$\sigma_{WW}^{\text{LHC7}}$ [pb]	51.9 ± 4.8 [17]	52.4 ± 5.1 [18]	44.7
$\sigma_{WW}^{\text{LHC8}}$ [pb]	71.4 ± 5.6 [19]	69.9 ± 7.0 [20]	58.7
$\sigma_{WZ}^{\text{LHC7}}$ [pb]	19.0 ± 1.7 [21]	20.8 ± 1.8 [22]	17.6
$\sigma_{WZ}^{\text{LHC8}}$ [pb]	20.3 ± 1.6 [23]	24.6 ± 1.7 [22]	20.3

Table 4: *Total WW and WZ cross sections at the LHC.*





Constraints from VV production

Comments

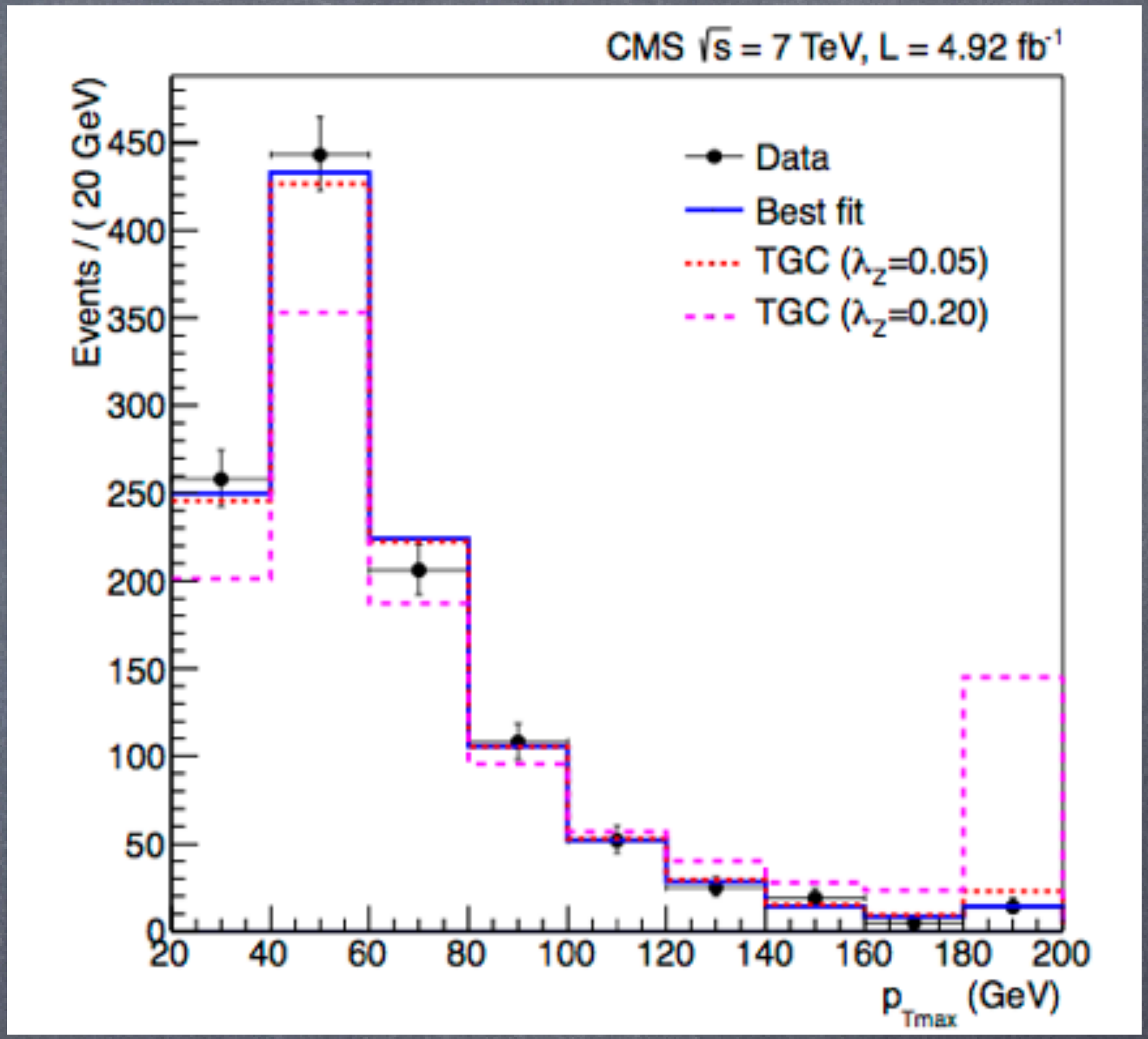
- The limits are rather weak, in part due to an accidental flat direction of LEP-2 constraints along $\lambda z \approx -\delta g1Z$ 1405.1617
- This implies that the limits are sensitive to whether quadratic term in dimension-6 operator are included or not
- In other words, the limits can be affected by dimension-8 operators if $c8 \sim c6^2$

Central values and 1 sigma errors:

$$\begin{pmatrix} c_S \\ c_T \\ c_{3W} \end{pmatrix} = \begin{pmatrix} 0.16 \\ 0.062 \\ 0.58 \end{pmatrix} \pm \begin{pmatrix} 0.084 \\ 0.019 \\ 0.31 \end{pmatrix}$$

Constraints from LHC tails VV production

- One can include constraints from high pT tails of WW and WZ production at LHC (standard TGC probe)
- However, one should remember these tails are dominated by quadratic terms in dimension-6 operators (or in aTGCs)
- Thus limits obtained using these tails have implicit model-dependent assumption that dimension-8 operators can be neglected, that is to say c8 << c6^2



$$
\begin{aligned}
\frac{\sigma^{\rm lastbin}_{\rm CMS7}}{\rm fb} \approx\; & 2.9 - 11.9\delta g_{1,Z} - 4.3\delta\kappa_\gamma - 14.5\lambda_Z \\
& +275\delta g_{1,Z}^2 + 49.4\delta\kappa_\gamma^2 + 822\lambda_Z^2 \\
& -63.6\delta g_{1,Z}\delta\kappa_\gamma + 57.5\delta g_{1,Z}\lambda_Z - 0.14\delta\kappa_\gamma\lambda_Z
\end{aligned}
$$

Constraints from LHC tails VV production

- Combining LEP-2 and LHC constraints including tail one obtains better 95% CL limits on coefficients of dimension-6 operators

$$c_S \in [-0.06, 0.26]$$

$$c_T \in [-0.01, 0.04]$$

$$c_{3W} \in [-0.04.0.17]$$

Consequences for Higgs physics

$$
\begin{aligned}
\mathcal{L}_{\rm HV}^{D=6} =& c_T \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H \\
& + c_{GG}\, \rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW}\, \rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB}\, \rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu} \\
& + \tilde{c}_{GG}\, \rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H
\end{aligned}
$$

- Another constraint on CP conserving higher derivative Higgs couplings to γγ, Zγ, ZZ and WW (effectively, 2 parameters for 4 couplings)

- Model independent constraint on custodial symmetry violation in Higgs sector:
  -0.04 < cw-cz < 0.16 at 95% CL

$$
\begin{aligned}
c_w =& 1 - c_H, \\
c_z =& 1 - c_H - 4c_T, \\
c_{gg} =& 4c_{GG}, \\
c_{\gamma\gamma} =& -4\left(c_{WW} + c_{BB} - c_S\right), \\
c_{z\gamma} =& -\frac{2}{g_L^2 + g_Y^2}\left(2g_L^2 c_{WW} - 2g_Y^2 c_{BB} - (g_L^2 - g_Y^2)c_S\right), \\
c_{zz} =& -\frac{4}{(g_L^2 + g_Y^2)^2}\left(g_L^4 c_{WW} + g_Y^4 c_{BB} + 2g_L^2 g_Y^2 c_S\right), \\
c_{ww} =& -4c_{WW}.
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{h,g} =& \frac{h}{v}\Big\{2c_w m_W^2 W_\mu^+ W_\mu^- + c_z m_Z^2 Z_\mu Z_\mu \\
& + \frac{g_s^2}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{g_L^2}{2} c_{ww} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{e^2}{4} c_{\gamma\gamma} A_{\mu\nu} A_{\mu\nu} - \frac{g_L^2}{4\cos^2\theta_W} c_{zz} Z_{\mu\nu} Z_{\mu\nu} - \frac{e g_L}{2\cos\theta_W} c_{z\gamma} A_{\mu\nu} Z_{\mu\nu} \\
& + \frac{g_s^2}{4} \tilde{c}_{gg} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{g_L^2}{2} \tilde{c}_{ww} W^+_{\mu\nu} \tilde{W}^-_{\mu\nu} - \frac{e^2}{4} \tilde{c}_{\gamma\gamma} A_{\mu\nu} \tilde{A}_{\mu\nu} - \frac{g_L^2}{4\cos^2\theta_W} \tilde{c}_{zz} Z_{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{e g_L}{2\cos\theta_W} \tilde{c}_{z\gamma} A_{\mu\nu} \tilde{Z}_{\mu\nu}\Big\}
\end{aligned}
$$

Summary

- Effective field theory approach allows one, under certain general assumptions, to study BSM physics in a model independent way
- EFT is a convenient tool to combine constraints on new physics from Higgs data and other precision measurements
- In case deviations from SM are seen, EFT predicts correlations between different observables that can be tested