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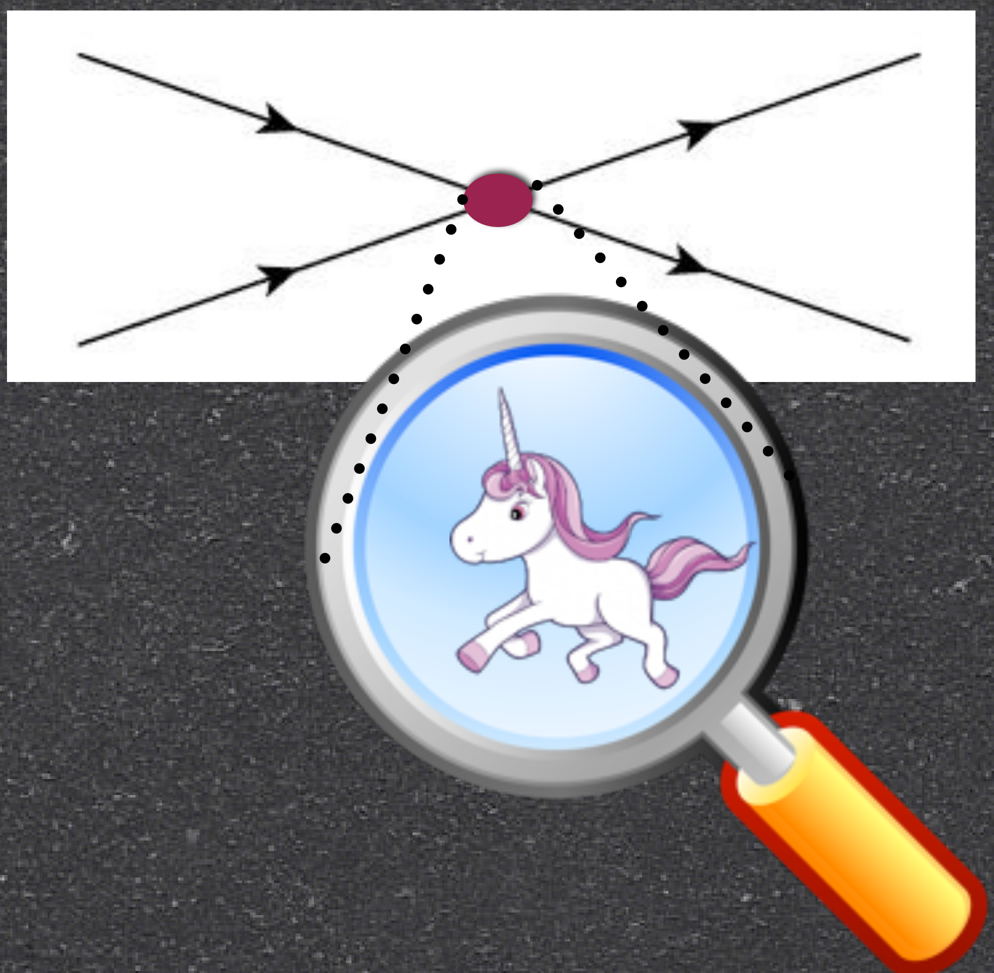
Higgs data and electroweak precision data



Mainz, 10 November 2014

Based on 1411.0669 with Francesco Riva

Plan

- Effective field theory approach
  to physics beyond the SM
- Synergy between Higgs data
  and electroweak precision observables
- Current precision constraints

Where do we stand

- SM is a very good approximation of fundamental physics at weak scale, including the Higgs sector
- There's no sign of new light particles from BSM
- In other words, SM is a good effective theory at the weak scale
- In such a case, possible new physics effects can be encoded into higher dimensional operators added to the SM
- EFT framework offers a systematic expansion around the SM organized in terms of operator dimensions, with higher dimensional operator suppressed by the mass scale of new physics

Where do we go

- 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 information about new physics

Effective Field Theory approach to BSM physics

Effective Theory Approach to BSM

Basic assumptions

- No new particles at energies probed by LHC
- Linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by Higgs doublet field vev

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

Alternatively, non-linear Lagrangians with derivative expansion

- Later, more assumptions about approximate global symmetries (for practical reason only)

Effective Theory Approach to BSM

Building effective Lagrangian

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

$$\Lambda \gg v$$

- 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)

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

Standard Model Lagrangian

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

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

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 vector boson couplings proportional to gauge couplings

All these predictions can be perturbed by higher-dimensional operators

Dimension 5 Lagrangian

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

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

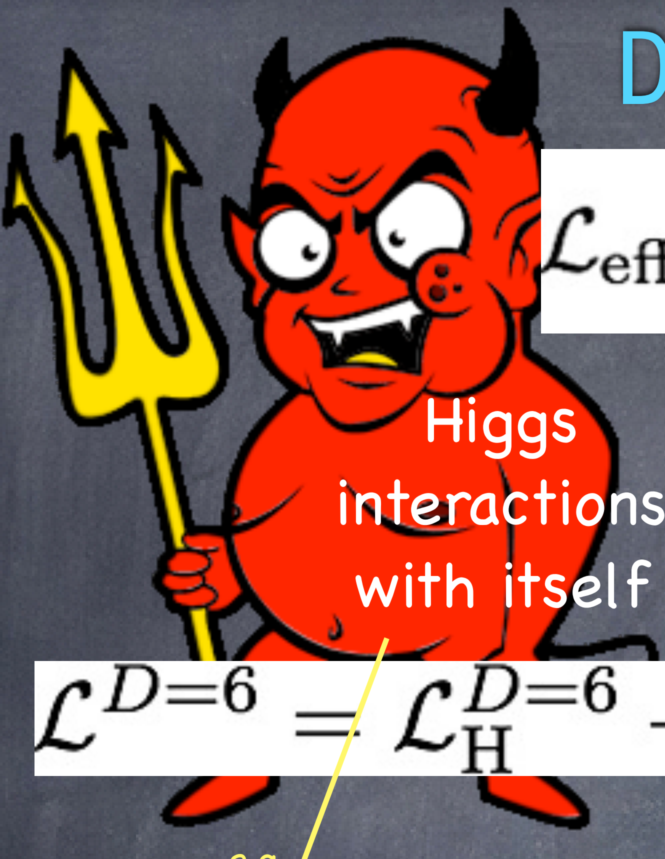
- At dimension 5, only operators one can construct are so-called Weinberg operators, which violate lepton number
- After EW breaking they give rise to Majorana mass terms for SM (left-handed) neutrinos

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

- 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 LHC phenomenology

Dimension 6 Lagrangian

(all hell breaks loose)



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

Higgs interactions with itself

Higgs interactions with gauge bosons

2-fermion Yukawa interactions

4-fermion operators

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

Self-interactions of gauge bosons

2-fermion vertex corrections

2-fermion dipole operators

e.g.

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

e.g.

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

e.g.

$$O_S = B_{\mu\nu} W_{\mu\nu}^i H^\dagger \sigma^i H$$

e.g.

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

e.g.

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

e.g.

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

e.g.

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

EFT approach to BSM

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

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

- Generally, EFT has maaaaany parameters
- 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
- Some of these couplings are constrained by Higgs searches, some by dijet measurements, some by measurements of W and Z boson production, some by LEP electroweak precision observables, etc.
- Important to explore synergies between different measurements and different colliders to get the most out of existing data

EFT approach to BSM

Buchmuller,Wyler
Nucl.Phys. B268 (1986)

- First attempt to classify dimension-6 operators back in 1986

Grządkowski et al.
1008.4884

- First fully non-redundant set of operators explicitly written down only in 2010
- 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

EFT approach to BSM

In this talk:

Assumptions

- I'm taking into account coefficients of dimension-6 operators at the linear level
- 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)

Goals

- Identify which combinations of dimension-6 operators are constrained
- What do these constraints imply for Higgs physics at the LHC

Synergy
between Higgs and EWPT

Dimension 6 Lagrangian

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

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

Higgs couplings

- First operator OH shifts kinetic term of Higgs bosons
- 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

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

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

Dimension 6 Lagrangian

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

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

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

Triple Gauge Couplings

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

$$H^\dagger \overleftrightarrow{D^\mu} H \quad \equiv \quad H^\dagger D_\mu H - D_\mu H^\dagger H$$

Higgs-gauge operators

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

$$\begin{aligned}\mathcal{L}_{\rm HV}^{D=6} =& \frac{c_T}{4}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H \\ &+ c_{GG}\,\rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW}\,\rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB}\,\rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu} \\ &+ \tilde{c}_{GG}\,\rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H\end{aligned}$$

- 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

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

Contino et al
1303.3876

Higgs Couplings

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

$$H^\dagger \overleftrightarrow{D^\mu} H \equiv H^\dagger D_\mu H - D_\mu H^\dagger H$$

Higgs gauge operators

$$\begin{aligned}
\mathcal{L}^{D=6}_{\rm HV} = & \frac{c_T}{4}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H \\
& + c_{GG}\,\rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW}\,\rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB}\,\rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu} \\
& + \tilde{c}_{GG}\,\rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H
\end{aligned}$$

- Two of these operators contribute to EW precision observables
- OS and OT affect propagators of EW gauge bosons (equivalent to Peskin-Takeuchi S and T 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

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

Oblique Corrections

Higgs gauge operators

$$\mathcal{L}_{\rm HV}^{D=6} = \frac{c_T}{4}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$+ c_{GG}\, \rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW}\, \rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB}\, \rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu}$$
$$+ \tilde{c}_{GG}\, \rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$

- One of these operators contributes to vector boson pair production
- OS induces anomalous triple gauge couplings κγ in the standard Hagiwara et al parametrization
- Therefore this parameter can be probed by WW and WZ production at LEP-2 and LHC

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

Triple Gauge Couplings

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

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

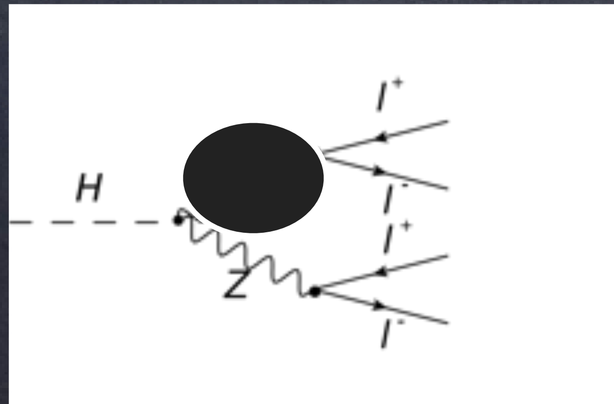
$$O_{3W} = \epsilon^{ijk} W^{i\,\nu}_{\mu} W^{j\,\rho}_{\nu} W^{k\,\mu}_{\rho}$$

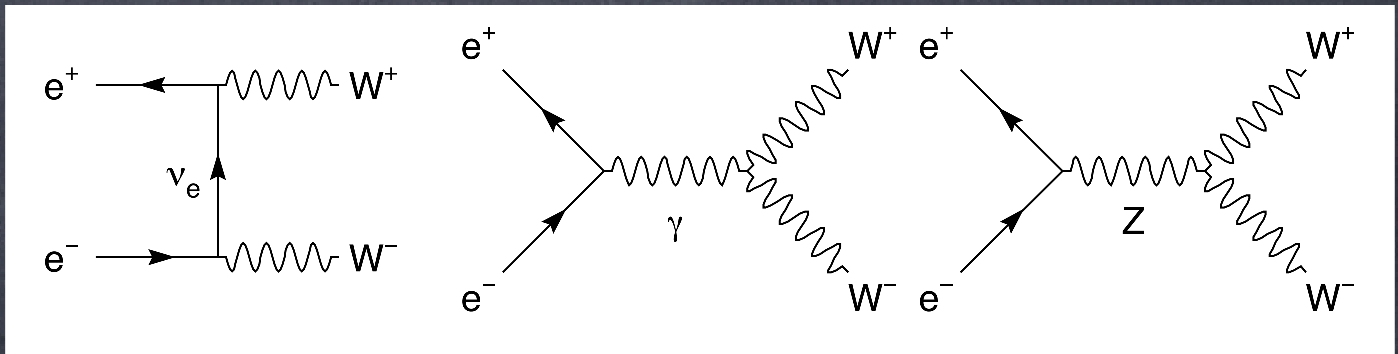
Vertex operators

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

For vertex operators, similar story as for Higgs-gauge operators:

- Contribute to EW precision observables by shift the Z and W boson couplings to leptons and quarks
- Contribute to vector boson pair production and H>4f decays, by shifting electron and quark couplings to W and Z
- They also introduce new vertices between Higgs, vector boson and two leptons





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

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
$\mathrm{Br}(W \to \mathrm{had})$ [%]	67.41 ± 0.27 [?]	67.51

Input: mZ, α(0), Γμ

- For 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:

Z-pole constraints: nuts and bolts

Lowest order: $\Gamma(Z \to f\bar{f}) = \frac{N_f m_Z}{24\pi} g_{fZ}^2 \qquad g_{fZ} = \sqrt{g_L^2 + g_Y^2}\,(T_f^3 - \sin^2\theta_W Q_f)$

w/ new physics: $\Gamma(Z \to f\bar{f}) = \frac{N_f \hat{m}_Z}{24\pi} {g_{fZ;\mathrm{eff}}}^2 \qquad g_{fZ;\mathrm{eff}} = g_{Z,\mathrm{eff}}\,(T_f^3 - s_{\mathrm{eff}}^2 Q_f + \delta g_{fZ})$

$$g_{Z,\mathrm{eff}} = \frac{\sqrt{g_L^2 + g_Y^2}}{\sqrt{1 - \delta\Pi'_{ZZ}(m_Z^2)}}$$

$$s_{\mathrm{eff}}^2 = \sin\theta_W^2 \left(1 - \frac{g_L}{g_Y}\frac{\delta\Pi_{\gamma Z}(m_Z^2)}{m_Z^2}\right)$$

- Including leading order new physics corrections amount to replacing Z coupling to fermions with effective couplings
- These effective couplings encode the effect of vertex and oblique correction
- Shift of the effective couplings in the presence of dimension-6 operators allows one to read off the dependence of observables on dimension-6 operators

e.g.

$$\delta g_{eZ,L;\mathrm{eff}} = \frac{\sqrt{g_L^2 + g_Y^2}}{g_L^2 - g_Y^2}\left[g_Y^2\left(c'_{HL} + g_L^2 c_S - \frac{g_L^2}{4g_Y^2}c_T\right) - \frac{(g_L^2 - g_Y^2)(4c_{HL} - c_T)}{8} - \frac{(g_Y^2 + g_L^2)c_{4F}}{8}\right]$$

$$\delta g_{eZ,R;\mathrm{eff}} = \frac{\sqrt{g_L^2 + g_Y^2}}{g_L^2 - g_Y^2}\left[g_Y^2\left(c'_{HL} + g_L^2 c_S - \frac{g_L^2}{4g_Y^2}c_T\right) - \frac{(g_L^2 - g_Y^2)(2c_{HL} - c_T)}{4} - \frac{g_Y^2 c_{4F}}{4}\right]$$

Pole constraints

$$\mathcal{L}_{\rm HV}^{D=6} = \frac{c_T}{4}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$\cancel{+ c_{GG} \rangle H^\dagger H \langle G^a_{\mu\nu} G^a_{\mu\nu} + c_{WW} \rangle H^\dagger H \langle W^i_{\mu\nu} W^i_{\mu\nu} + c_{BB} \rangle H^\dagger H \langle B_{\mu\nu} B_{\mu\nu}}$$
$$\cancel{+ \tilde{c}_{GG} \rangle H^\dagger H \langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \tilde{c}_{WW}\, H^\dagger H W^i_{\mu\nu} \tilde{W}^i_{\mu\nu} + \tilde{c}_{BB}\, H^\dagger H B_{\mu\nu} \tilde{B}_{\mu\nu} + \tilde{c}_{WB}\, \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H}$$

- First, assume that BSM affects only oblique operators OS and OT but no vertex corrections
- 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

$$c_S = (0.7 \pm 1.8) \times 10^{-3}$$
$$c_T = (1.0 \pm 1.1) \times 10^{-3}$$

But this is not robust conclusion!

Pole constraints

$$\mathcal{L}^{D=6}_{\rm HV} = \frac{c_T}{4}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S\, B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H$$
$$\cancel{+ c_{GG}\rangle H^\dagger H\langle G^a_{\mu\nu}G^a_{\mu\nu} + c_{WW}\rangle H^\dagger H\langle W^i_{\mu\nu}W^i_{\mu\nu} + c_{BB}\rangle H^\dagger H\langle B_{\mu\nu}B_{\mu\nu}}$$
$$\cancel{+ \tilde{c}_{GG}\rangle H^\dagger H\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \tilde{c}_{WW} H^\dagger H W^i_{\mu\nu}\tilde{W}^i_{\mu\nu} + \tilde{c}_{BB} H^\dagger H B_{\mu\nu}\tilde{B}_{\mu\nu} + \tilde{c}_{WB}\tilde{B}_{\mu\nu}W^i_{\mu\nu}H^\dagger\sigma^i H}$$

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

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

- Assuming flavor blind vertex corrections here.
- Pole observables depend on 10 effective theory parameters
  (7 vertex corrections, 2 oblique corrections, 1 four-fermion operator)
- We have 10 independent and precisely measured pole observables
  (7 partial widths of Z, 2 partial width of W, W mass)
- So we can constrain all these parameters ? No...

Flat directions of pole observables

Gupta et al, 1405.0181

- Pole observables depend, at linear level, on 10 dimension-6 operators in Warsaw basis
- One can show that LEP constrains 8 combinations of EFT parameters: c-hats to the right
- Only combinations of vertex and oblique corrections are constrained, not separately
- 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 pole data alone there's no model independent constraints on S and T!

Cacciapaglia et al
hep-ph/0604111

$$\hat{c}'_{HL} = c'_{HL} + g_L^2 c_S - \frac{g_L^2}{4 g_Y^2} c_T$$

$$\hat{c}_{HL} = c_{HL} - \frac{1}{4} c_T$$

$$\hat{c}_{HE} = c_{HE} - \frac{1}{2} c_T$$

$$\hat{c}'_{HQ} = c'_{HQ} + g_L^2 c_S - \frac{g_L^2}{4 g_Y^2} c_T$$

$$\hat{c}_{HQ} = c_{HQ} + \frac{1}{12} c_T$$

$$\hat{c}_{HU} = c_{HU} + \frac{1}{3} c_T$$

$$\hat{c}_{HD} = c_{HD} - \frac{1}{6} c_T$$

$$c_{4F}$$

Flat directions of pole observables

- The flat directions arise due to EFT operator identities

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

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

- Obviously, operators OW and OB do not affect Z and W couplings to fermions
- They only affect gauge boson propagators (same way as OS) 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 pole observables is identical to that of S and T parameter!
- These 2 flat directions are lifted only when VV production data are included

Pole constraints

AA,Riva
1411.0669

$$\begin{pmatrix} \hat{c}'_{HL} \\ \hat{c}_{HL} \\ \hat{c}_{HE} \\ \hat{c}'_{HQ} \\ \hat{c}_{HQ} \\ \hat{c}_{HU} \\ \hat{c}_{HD} \\ c_{ll} \end{pmatrix} = \begin{pmatrix} -1.9 \pm 1.1 \\ 1.1 \pm 0.7 \\ 0.1 \pm 0.6 \\ -4.7 \pm 1.9 \\ 0.2 \pm 2.0 \\ 7.0 \pm 6.9 \\ -31.3 \pm 10.3 \\ -4.7 \pm 3.5 \end{pmatrix} \cdot 10^{-3},$$

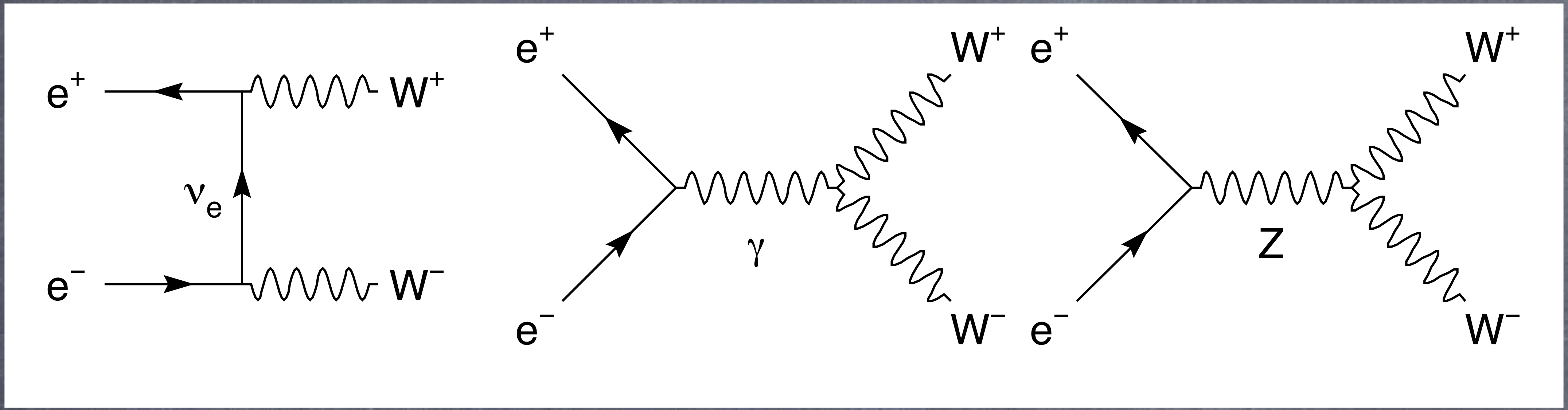
$$\boxed{\chi^2_{\rm pole} = \sum_{ij} \frac{(\hat{c}_i - \hat{c}_i^0)\rho_{ij}(\hat{c}_j - \hat{c}_j^0)}{\delta\hat{c}_i \delta\hat{c}_j}}$$

$$\rho = \begin{pmatrix} 1 & -0.49 & 0.31 & 0.17 & -0.05 & -0.03 & -0.04 & 0.89 \\ \cdot & 1 & 0.42 & 0.08 & 0.00 & 0.06 & -0.12 & -0.76 \\ \cdot & \cdot & 1 & -0.04 & -0.09 & 0.09 & -0.32 & 0.03 \\ \cdot & \cdot & \cdot & 1 & -0.39 & -0.73 & 0.59 & 0.01 \\ \cdot & \cdot & \cdot & \cdot & 1 & 0.43 & 0.22 & -0.04 \\ \cdot & \cdot & \cdot & \cdot & \cdot & 1 & -0.15 & -0.01 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & 1 & -0.06 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & 1 \end{pmatrix}$$

- From this once can reconstruct the χ^2 function of pole observables as a function of coefficients of dimension-6 operators
- If in particular model only a subset of operators are generated, one can constrain χ^2 and minimize wrt to the new parameter set
- This way, from above one can quickly derive constrains on any model of new physics

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)

e+e-→W+W- nuts and bolts

$$\mathcal{M} = \mathcal{M}_t + \sum_{V=\gamma,Z} \mathcal{M}_s^V$$

$$\mathcal{M}_t = -\frac{g^2_{\ell W,L;\mathrm{eff}}}{2t}\bar\epsilon_\mu(p_{W^-})\bar\epsilon_\nu(p_{W^+})\bar y(p_{e^+})\bar\sigma_\nu\sigma\cdot(p_{e^-}-p_{W^-})\bar\sigma_\mu x(p_{e^-}),$$

$$\mathcal{M}_s^V = -\frac{1}{s-m_V^2}\left[g_{eV,L;\mathrm{eff}}\bar y(p_{e^+})\bar\sigma_\rho x(p_{e^-}) + g_{eV,R;\mathrm{eff}} x(p_{e^+})\sigma_\rho \bar y(p_{e^-})\right]\bar\epsilon_\mu(p_{W^-})\bar\epsilon_\nu(p_{W^+})F^V_{\mu\nu\rho},$$

$$\begin{aligned} F^V_{\mu\nu\rho} &= g_{1,V;\mathrm{eff}}\left[\eta_{\rho\mu}p^\nu_{W^-} - \eta_{\rho\nu}p^\mu_{W^+} + \eta_{\mu\nu}(p_{W^+}-p_{W^-})_\rho\right] + \kappa_{V;\mathrm{eff}}\left[\eta_{\rho\mu}(p_{W^+}+p_{W^-})_\nu - \eta_{\rho\nu}(p_{W^+}+p_{W^-})_\mu\right] \\ &+ \frac{g_{VWW}\lambda_V}{m_W^2}\left[\eta_{\rho\mu}\left(p_{W^+}(p_{W^+}+p_{W^-})p^\nu_{W^-} - p_{W^+}p_{W^-}(p_{W^+}+p_{W^-})_\nu\right)\right. \\ &+ \left.\eta_{\rho\nu}\left(p_{W^+}p_{W^-}(p_{W^+}+p_{W^-})_\mu - p_{W^-}(p_{W^+}+p_{W^-})p^\mu_{W^+}\right)\right]. \end{aligned} \tag{21}$$

- WW production amplitude depends on the same effective couplings gZeff and gWeff as the pole observables
- It also depends on effective electromagnetic couplings which does not change in the presence of dimension-6 operators
- Finally, it depends on 3 effective triple gauge couplings whose shift in the presence of dimension-6 operators is different than for pole observables

$$e_{\mathrm{eff}} = \frac{g_L g_Y}{\sqrt{g_L^2+g_Y^2}}\frac{1}{\sqrt{1-\delta\Pi^{(2)}_{\gamma\gamma}}}$$

$$\begin{aligned} g_{1,\gamma;\mathrm{eff}} &= e_{\mathrm{eff}}, \quad \kappa_{\gamma;\mathrm{eff}} = e_{\mathrm{eff}}\left[1+\delta\kappa_\gamma\right], \\ g_{1,Z;\mathrm{eff}} &= \frac{g_L\cos\theta_W}{\sqrt{1-\delta\Pi^{(2)}_{ZZ}}}\left[1+e\delta\Pi^{(2)}_{\gamma Z}\right]\left[1+\delta g_{1,Z}\right], \\ \kappa_{Z;\mathrm{eff}} &= \frac{g_L\cos\theta_W}{\sqrt{1-\delta\Pi^{(2)}_{ZZ}}}\left[1+e\delta\Pi^{(2)}_{\gamma Z}\right]\left[1+\delta\kappa_Z\right]. \end{aligned}$$

e+e-→W+W- nuts and bolts

$$\frac{\delta g_{1,Z;\mathrm{eff}}}{g_L \cos\theta_W} \equiv \delta\hat{g}_{1,Z} = (g_L^2 + g_Y^2)\left[c_S - \frac{c_T}{4g_Y^2} - \frac{\hat{c}_{HL} - c_{ll}/4}{g_L^2 - g_Y^2}\right]$$

$$\frac{\delta\kappa_{\gamma;\mathrm{eff}}}{e} \equiv \delta\hat{\kappa}_\gamma = g_L^2 c_S$$

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

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

Effective TGCs are not the same as TGCs in the Lagrangian !

- WW production amplitude depends on the same effective couplings gZeff and gWeff as the pole observables

$$e_{\mathrm{eff}} = \frac{g_L g_Y}{\sqrt{g_L^2 + g_Y^2}} \frac{1}{\sqrt{1 - \delta\Pi^{(2)}_{\gamma\gamma}}}$$

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- Finally, it depends on 3 effective triple gauge couplings whose shift in the presence of dimension-6 operators is different than for pole observables

$$\begin{aligned}
g_{1,\gamma;\mathrm{eff}} &= e_{\mathrm{eff}}, \quad \kappa_{\gamma;\mathrm{eff}} = e_{\mathrm{eff}}\left[1 + \delta\kappa_\gamma\right], \\
g_{1,Z;\mathrm{eff}} &= \frac{g_L \cos\theta_W}{\sqrt{1 - \delta\Pi^{(2)}_{ZZ}}}\left[1 + e\delta\Pi^{(2)}_{\gamma Z}\right]\left[1 + \delta g_{1,Z}\right], \\
\kappa_{Z;\mathrm{eff}} &= \frac{g_L \cos\theta_W}{\sqrt{1 - \delta\Pi^{(2)}_{ZZ}}}\left[1 + e\delta\Pi^{(2)}_{\gamma Z}\right]\left[1 + \delta\kappa_Z\right].
\end{aligned}$$

VV production constraints

- 11 parameters affecting WW and WZ production at linear level (previous 10 plus O3W which affects only TGCs)
- However, 8 combinations of these 11 parameters are already constrained by pole measurements
- 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 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 VV production

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

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

- 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

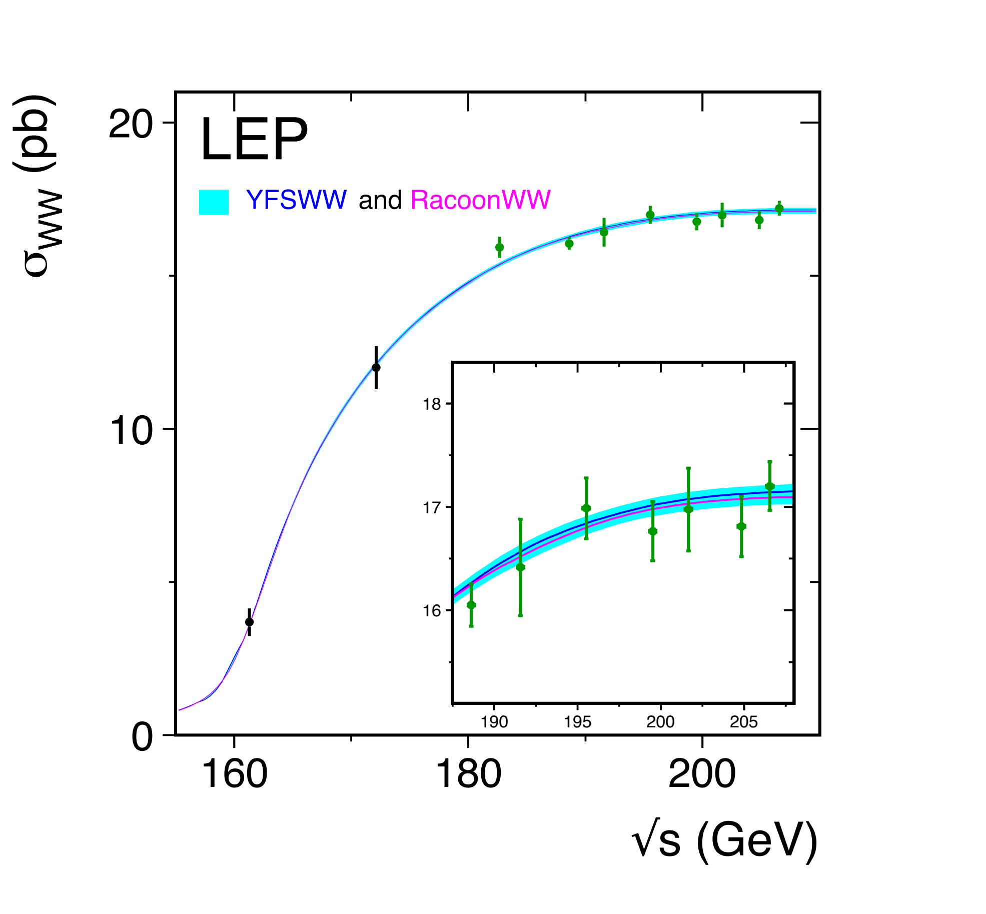
$$\hat{c}'_{HL} = c'_{HL} + g_L^2 c_S - \frac{g_L^2}{4g_Y^2}c_T$$
$$\hat{c}_{HL} = c_{HL} - \frac{1}{4}c_T$$
$$\hat{c}_{HE} = c_{HE} - \frac{1}{2}c_T$$
$$\hat{c}'_{HQ} = c'_{HQ} + g_L^2 c_S - \frac{g_L^2}{4g_Y^2}c_T$$
$$\hat{c}_{HQ} = c_{HQ} + \frac{1}{12}c_T$$
$$\hat{c}_{HU} = c_{HU} + \frac{1}{3}c_T$$
$$\hat{c}_{HD} = c_{HD} - \frac{1}{6}c_T$$

c_{4F}

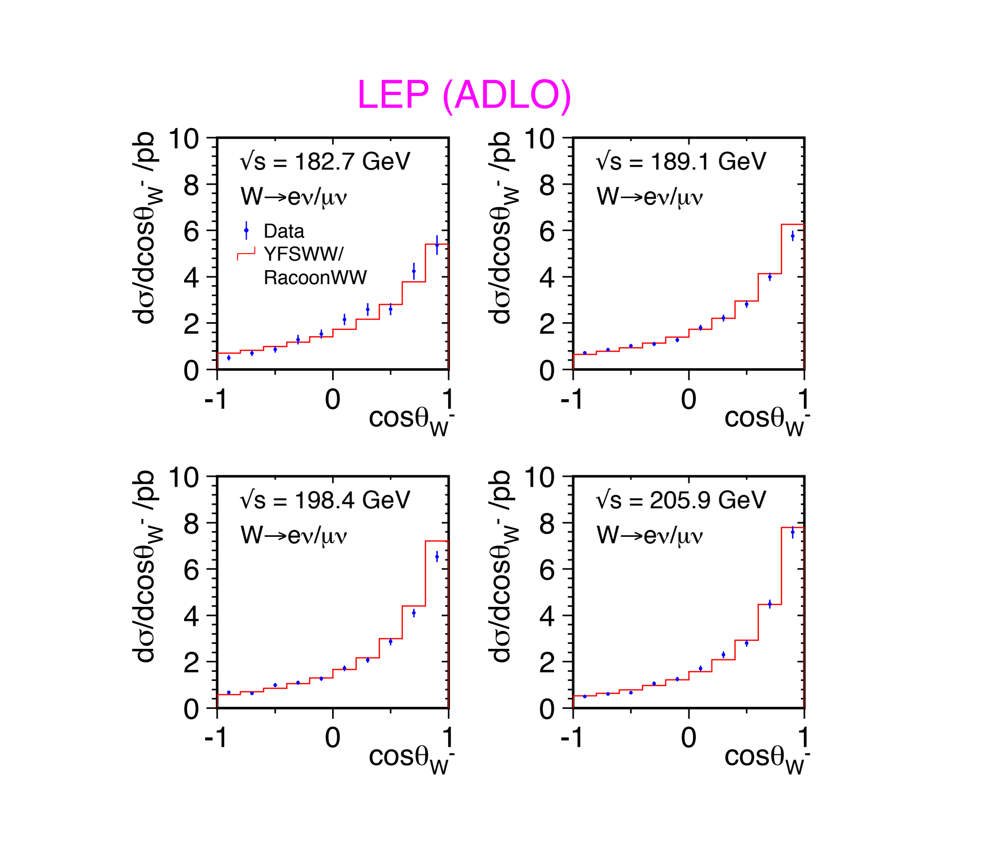
$$\mathcal{L}^{D=6} \supset \frac{c_T}{4}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + c_S B_{\mu\nu}W^i_{\mu\nu}H^\dagger\sigma^i H + c_{3W}\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$$

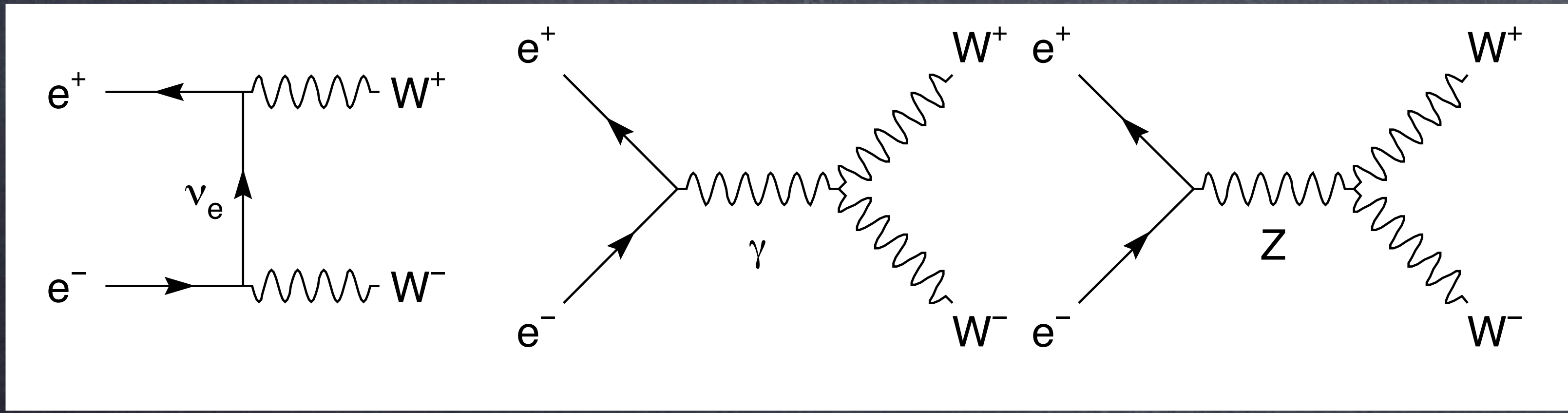
Constraints from VV production

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

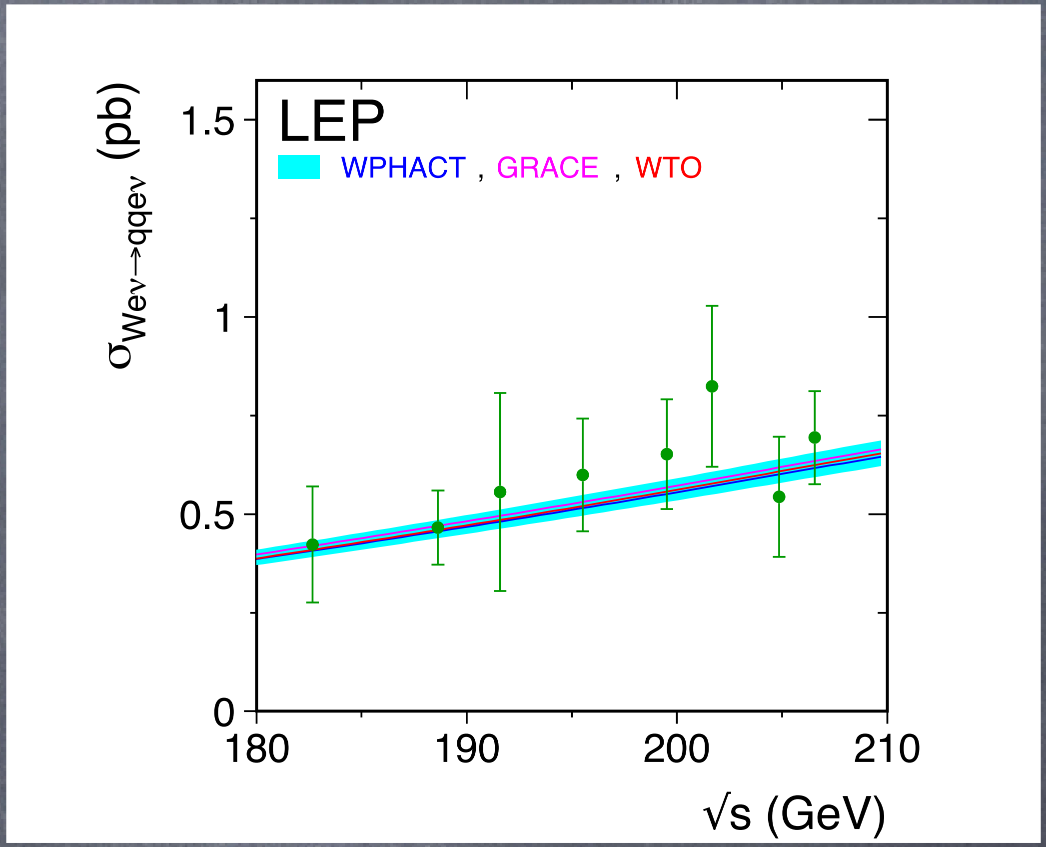


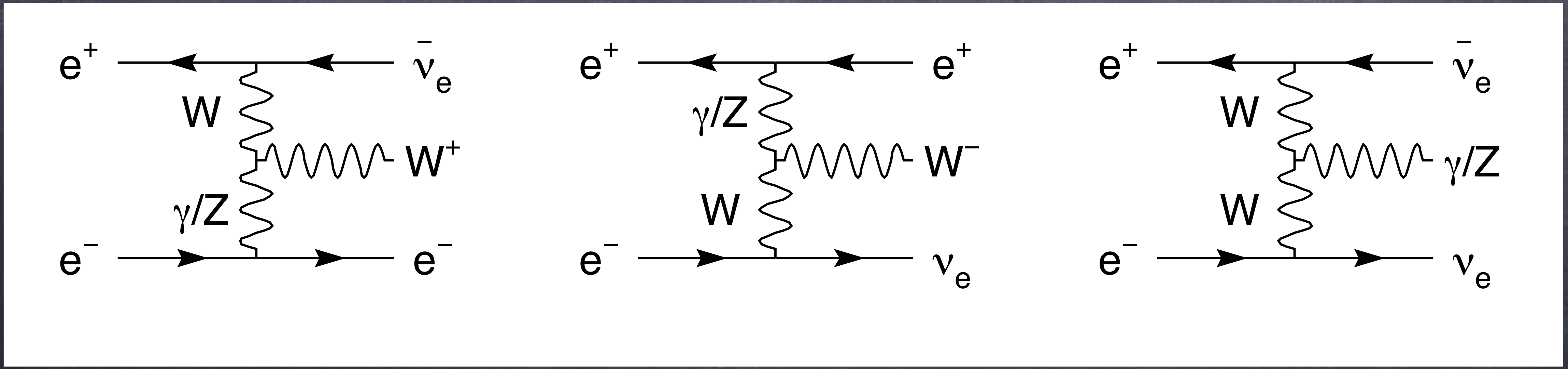


Constraints from VV production

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





Constraints from WW production

AA,Riva
1411.0669

Central values and 1 sigma errors:

$$\delta g_{1,Z} = -0.83 \pm 0.34, \;\; \delta\kappa_\gamma = 0.14 \pm 0.05, \;\; \lambda_Z = 0.86 \pm 0.38, \quad \rho = \begin{pmatrix} 1 & -0.71 & -0.997 \\ \cdot & 1 & 0.69 \\ \cdot & \cdot & 1 \end{pmatrix}$$

- The limits are rather weak, in part due to an accidental flat direction of LEP-2 constraints along λz ≈ -δg1Z

see also
1405.1617

- This implies that dimension-6 operator coefficients are constrained at the O(1) level

- In fact, the limits are sensitive to whether terms quadratic in dimension-6 operator are included or not

- This in turn implies that the limits can be affected by dimension-8 operators if, as expected from EFT counting, c8~c6^2

Constraints from WW production

Central values and 1 sigma errors:

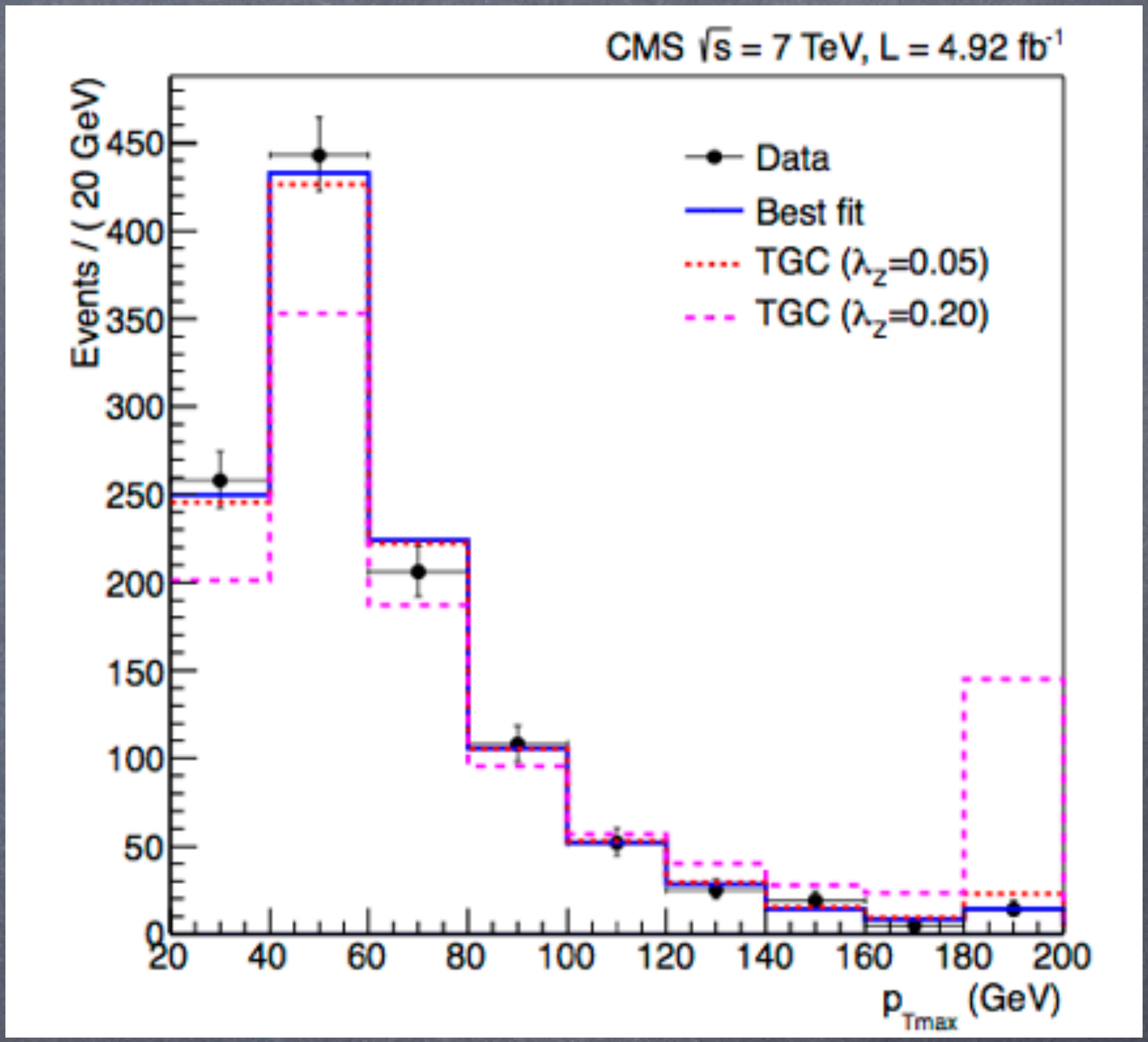
$$\delta g_{1,Z} = -0.83 \pm 0.34, \;\; \delta\kappa_\gamma = 0.14 \pm 0.05, \;\; \lambda_Z = 0.86 \pm 0.38, \quad \rho = \begin{pmatrix} 1 & -0.71 & -0.997 \\ \cdot & 1 & 0.69 \\ \cdot & \cdot & 1 \end{pmatrix}$$

- These limits can be affected by dimension-8 operators if, as expected from EFT counting, c8~c6^2
- Still, they are useful to constrain specific BSM models that predict TGCs away from the flat direction
- In particular, many models predict $\lambda Z \ll \delta g1Z$, $\kappa\gamma$, because the corresponding operator O3W can be generated only at the loop level
- For $\lambda Z=0$ much stronger limits follow:

$$\delta \hat{g}_{1,Z} = -0.06 \pm 0.03, \quad \delta\hat{\kappa}_\gamma = 0.06 \pm 0.04, \quad \rho = \begin{pmatrix} 1 & -0.50 \\ \cdot & 1 \end{pmatrix}$$

Comments on LHC constraints

- One can include constraints from high pT tails of WW and WZ production at LHC (standard TGC probe)
- These tails are dominated by quadratic terms in dimension-6 operators (or in aTGCs), rather than by linear interference terms as in the case of LEP-2
- For the magnitude of TGCs being probed by LHC, operators with dimensions higher than 6 are expected to contribute comparably or more, if these operators have natural coefficients from the EFT point of view
- In other words, in the regime where LHC currently probes the TGCs, the EFT expansion is not valid



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

Consequences for Higgs physics

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

- Another constraint on CP conserving higher derivative Higgs couplings to γγ, Zγ, ZZ and WW (effectively, 2 parameters for 4 couplings)
- For any model predicting c3W≈0, constraints on custodial symmetry violation of Higgs couplings to W and Z:
  -0.06 < cw-cz < 0.24 at 95% CL

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

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

To take away

- There are strong constraints on certain combinations of dimension-6 operators from the pole observables measured at LEP-1 and other colliders
- WW production process is extremely important, because it lifts flat directions of the pole observables
- Current model independent LEP-2 constrain are weak, due to an accidental flat directions
- Better probes of dimension-6 operators in WW production should be designed for future e+e- colliders

Outlook

- Better probes of dimension-6 operators in VV production at the LHC?
- Drop the assumption of flavor blindness (MFV? SU(2)?)
- Full set of precision constraints, including off-pole observables