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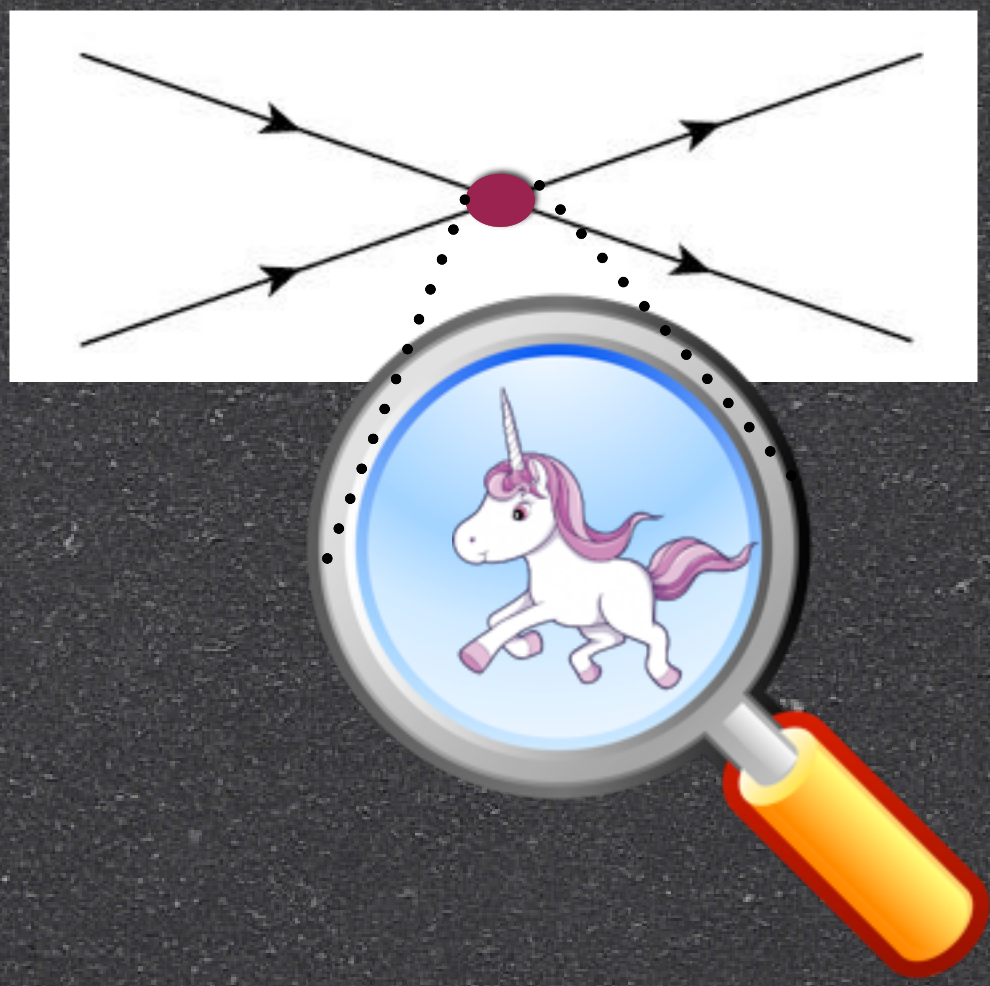
Model Independent Constraints on Dimension Six Operators



Warszawa, 9 Marca 2015

Based on 1411.0669 with Francesco Riva, and on 1503.0xxxx with Aielet Efrati and Yotam Soreq

Plan

- Effective field theory approach to physics beyond the SM
- EFT Higgs basis developed within LHCHXSWG
- Current precision constraints from LEP-1 pole observables and from LEP-2 WW production

Effective Field Theory approach to BSM physics

Where do we stand

- SM is a very good approximation of fundamental physics at the weak scale, including the Higgs sector
- There's no sign of new light particles from BSM
- In other words, SM is probably a correct 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

Effective Theory Approach to BSM

Basic assumptions

- New physics scale Λ separated from EW scale v, Λ >> v
- Linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

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

Alternatively, non-linear Lagrangians with derivative expansion

Effective Theory Approach to BSM

Building effective Lagrangian

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

$$\Lambda \gg v$$

- If coefficients of higher dimensional operators are O(1), Λ corresponds to mass scale on BSM theory with couplings of order 1
[more generally, Λ ~ Mass f(couplings)]

- Slightly simpler (and completely equivalent) is to use EW scale v in denominators and work with small coefficients of higher dimensional operators $c \sim (v/\Lambda)^{(d-4)}$

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

Standard Model Lagrangian

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

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

Some predictions at lowest order

- Couplings of gauge bosons to fermions universal and fixed by fermion's quantum numbers

$$\begin{aligned} g^{Af} &= Q_f \frac{g_L g_Y}{\sqrt{g_L^2+g_Y^2}} \equiv eQ_f \\ g_L^{Wf} &= g_L \\ g^{Zf} &= \sqrt{g_L^2+g_Y^2}\,(T_f^3 - s_\theta^2 Q_f) \end{aligned}$$

- Z and W boson mass ratio related to Weinberg angle

$$\frac{m_W}{m_Z} = \frac{g_L}{\sqrt{g_L^2+g_Y^2}} \equiv c_\theta$$

- Higgs coupling to gauge bosons proportional to their mass squared

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

- Higgs coupling to fermions proportional to their mass

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

- Triple and quartic vector boson couplings proportional to gauge couplings

$$\begin{aligned}\mathcal{L}_{\rm TGC}^{\rm SM} = & ie\left[A_{\mu\nu}W_\mu^+ W_\nu^- + (W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+)A_\nu\right] \\ & + ig_L c_\theta\left[(W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+)Z_\nu + Z_{\mu\nu}W_\mu^+ W_\nu^-\right]\end{aligned}$$

All these predictions can be perturbed by higher-dimensional operators

Dimension 5 Lagrangian

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

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

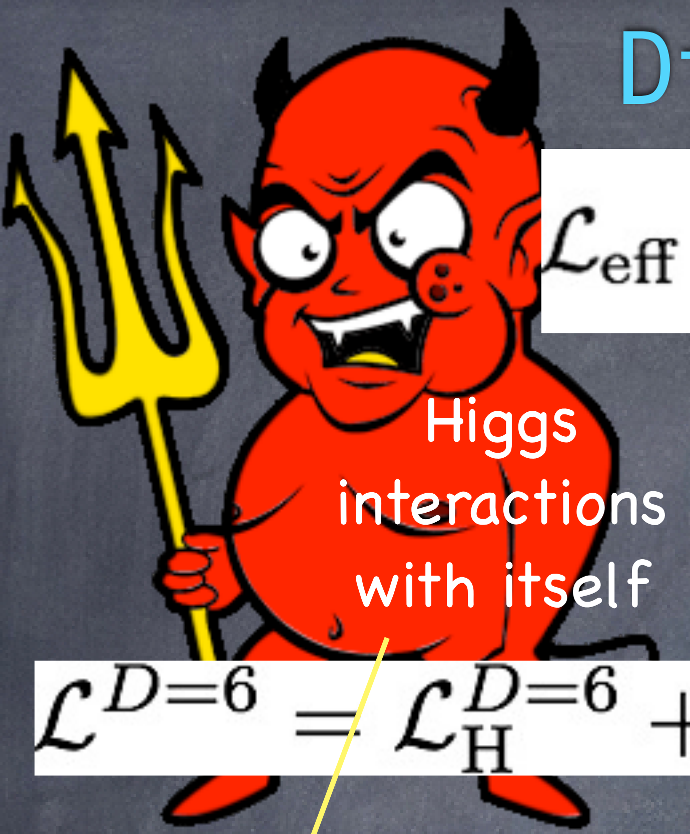
- At dimension 5, only operators one can construct are so-called Weinberg operators, which violate lepton number
- After EW breaking they give rise to Majorana mass terms for SM (left-handed) neutrinos

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

- Neutrino oscillation experiments strongly suggest these operators are present
- However, to match the measurements, their coefficients have to be extremely small, c ~ 10^-11
- Therefore dimension 5 operators can have no observable impact on LHC phenomenology

Dimension 6 Lagrangian

(all hell breaks loose)



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

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

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.

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

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.

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

EFT approach to BSM

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

Buchmuller,Wyler
Nucl.Phys. B268 (1986)

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

Grządkowski et al.
1008.4884

- Operators can be traded for other operators using integration by parts, field redefinition, equations of motion, Fierz transformation, etc

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

see e.g.
Grządkowski et al. 1008.4884
Giudice et al hep-ph/0703164
Contino et al 1303.3876

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

Example: Warsaw Basis

H^4D^2 and H^6

O_H	$[\partial_\mu(H^\dagger H)]^2$
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
O_{6H}	$(H^\dagger H)^3$

f^2H^3

O_e	$-(H^\dagger H - \frac{v^2}{2})\bar{e}H^\dagger \ell$
O_u	$-(H^\dagger H - \frac{v^2}{2})\bar{u}\widetilde{H}^\dagger q$
O_d	$-(H^\dagger H - \frac{v^2}{2})\bar{d}H^\dagger q$

V^3D^3

O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$
$O_{3\widetilde{G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$
O_{3W}	$g^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
$O_{3\widetilde{W}}$	$g^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$

V^2H^2

O_{GG}	$\frac{g_s^2}{4} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$
$O_{\widetilde{G}G}$	$\frac{g_s^2}{4} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$\frac{g^2}{4} H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$
$O_{\widetilde{W}W}$	$\frac{g^2}{4} H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$\frac{g'^2}{4} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$
$O_{\widetilde{B}B}$	$\frac{g'^2}{4} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g g' H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$
$O_{\widetilde{W}B}$	$g g' H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$

f^2H^2D

$O_{H\ell}$	$i\bar{\ell}\gamma_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$
$O'_{H\ell}$	$i\bar{\ell}\sigma^i \gamma_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
O_{He}	$i\bar{e}\gamma_\mu e H^\dagger \overleftrightarrow{D}_\mu H$
O_{Hq}	$i\bar{q}\gamma_\mu q H^\dagger \overleftrightarrow{D}_\mu H$
O'_{Hq}	$i\bar{q}\sigma^i \gamma_\mu q H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
O_{Hu}	$i\bar{u}\gamma_\mu u H^\dagger \overleftrightarrow{D}_\mu H$
O_{Hd}	$i\bar{d}\gamma_\mu d H^\dagger \overleftrightarrow{D}_\mu H$
O_{Hud}	$i\bar{u}\gamma_\mu d \tilde{H}^\dagger D_\mu H$

f^2VHD

O_{eW}	$g\bar{\ell}\sigma_{\mu\nu} e \sigma^i H W^i_{\mu\nu}$
O_{eB}	$g'\bar{\ell}\sigma_{\mu\nu} e H B_{\mu\nu}$
O_{uG}	$g_s \bar{q}\sigma_{\mu\nu} T^a u \widetilde{H}\, G^a_{\mu\nu}$
O_{uW}	$g\bar{q}\sigma_{\mu\nu} u \sigma^i \widetilde{H}\, W^i_{\mu\nu}$
O_{uB}	$g'\bar{q}\sigma_{\mu\nu} u \widetilde{H}\, B_{\mu\nu}$
O_{dG}	$g_s \bar{q}\sigma_{\mu\nu} T^a d H\, G^a_{\mu\nu}$
O_{dW}	$g\bar{q}\sigma_{\mu\nu} d \sigma^i H\, W^i_{\mu\nu}$
O_{dB}	$g'\bar{q}\sigma_{\mu\nu} d H\, B_{\mu\nu}$

$(\bar{L}L)(\bar{L}L)$ and $(\bar{L}R)(\bar{L}R)$

$O_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma_\mu \ell)$
O_{qq}	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma_\mu q)$
O'_{qq}	$(\bar{q}\gamma_\mu \sigma^i q)(\bar{q}\gamma_\mu \sigma^i q)$
$O_{\ell q}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma_\mu q)$
$O'_{\ell q}$	$(\bar{\ell}\gamma_\mu \sigma^i \ell)(\bar{q}\gamma_\mu \sigma^i q)$
O_{quqd}	$(\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)$
O'_{quqd}	$(\bar{q}^j T^a u)\epsilon_{jk}(\bar{q}^k T^a d)$
$O_{\ell equ}$	$(\bar{\ell}^j e)\epsilon_{jk}(\bar{q}^k u)$
$O'_{\ell equ}$	$(\bar{\ell}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$
$O_{\ell edq}$	$(\bar{\ell}^j e)(\bar{d} q^j)$

$(\bar{R}R)(\bar{R}R)$

O_{ee}	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma_\mu e)$
O_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma_\mu u)$
O_{dd}	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma_\mu d)$
O_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma_\mu u)$
O_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma_\mu d)$
O_{ud}	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma_\mu d)$
O'_{ud}	$(\bar{u}\gamma_\mu T^a u)(\bar{d}\gamma_\mu T^a d)$

$(\bar{L}L)(\bar{R}R)$

$O_{\ell e}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma_\mu e)$
$O_{\ell u}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma_\mu u)$
$O_{\ell d}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma_\mu d)$
O_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma_\mu e)$
O_{qu}	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma_\mu u)$
O'_{qu}	$(\bar{q}\gamma_\mu T^a q)(\bar{u}\gamma_\mu T^a u)$
O_{qd}	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma_\mu d)$
O'_{qd}	$(\bar{q}\gamma_\mu T^a q)(\bar{d}\gamma_\mu T^a d)$

Grządkowski et al. 1008.4884

59 different kinds of operators, of which 17 are complex

2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014

EFT approach to BSM

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

- 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

Higgs Basis
for LHCXSWG

Possible practical problems

- There's so many coefficients. Which ones do I vary in my analysis?
- Maybe the operator I'm probing is already strongly constrained by another analysis. How could I know?
- How do I treat non-canonical normalization and kinetic mixing induced by dimension-6 operators?

E.g in the Warsaw basis $h \to 4l$ is affected by

$$c_H, c_T, c_{WB}, c_{WW}, c_{BB}$$
$$c_{H\ell_1}, c_{H\ell_2}, c'_{H\ell_1}, c'_{H\ell_2}, c_{He}, c_{H\mu}, c_{4F}$$

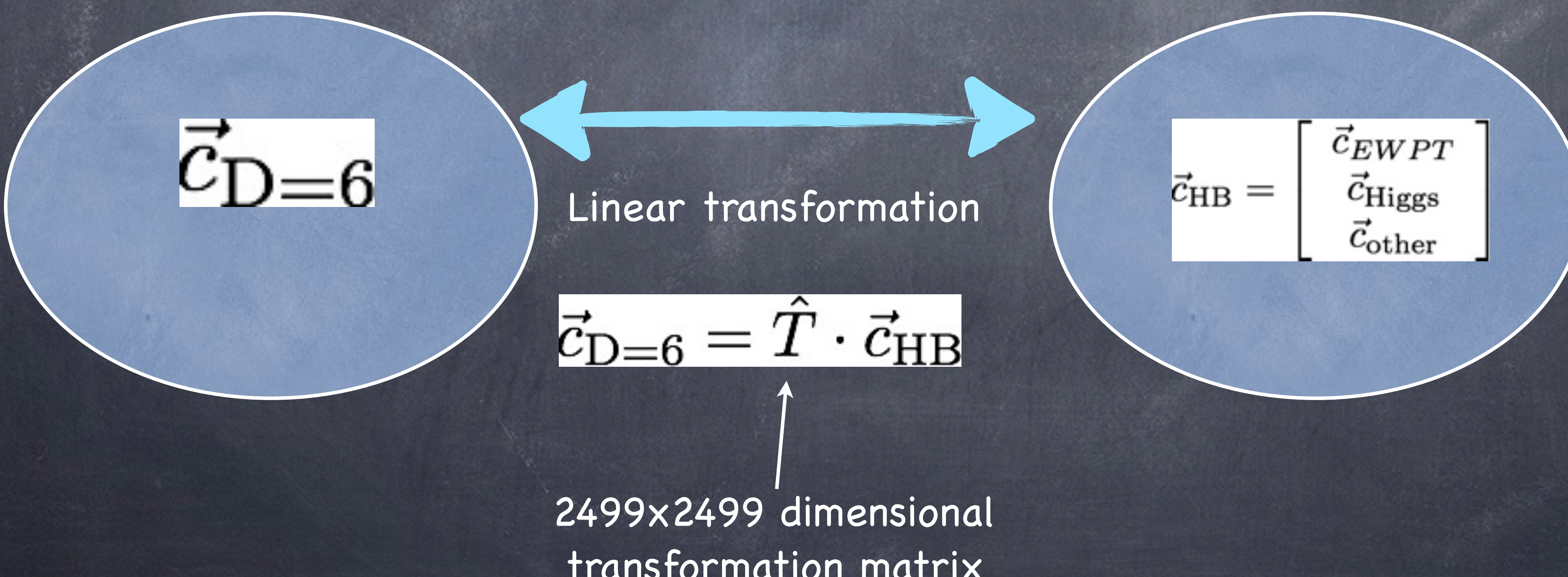
while EWPT constrains combinations of

$$c_T, c_{WB}$$
$$c_{H\ell_1}, c_{H\ell_2}, c'_{H\ell_1}, c'_{H\ell_2}, c_{He}, c_{H\mu}, c_{4F}$$

Higgs Basis

Inspired by "EFT Primaries" of Gupta et al 1405.0181

- Map a basis of dimension-6 operators into equivalent set of variables that is more directly connected to collider observables
- Also, isolate parameters strongly constrained by electroweak precision tests
- I call it the **Higgs basis** (because developed for LHC Higgs studies)



Higgs Basis: independent and dependent couplings

- For practical reasons, more convenient to introduce the Higgs basis via coefficients of Lagrangian terms expressed by mass eigenstates after electroweak symmetry breaking (rather than via SU(3)xSU(2)xU(1) invariant dimension-6 operators).
- By construction, all eigenstates canonically normalized, and no kinetic mixing. This greatly simplifies connection between couplings and observables.
- Since a typical dimension-6 operator spawns several different Lagrangian terms, there will be relations between coefficients of different Lagrangian terms (much as in the SM there are, e.g., relations between Higgs boson couplings and particle masses)
- We single out a set of (2499) coefficients that define the Higgs basis and call them the independent couplings. Coefficients of remaining terms are expressed by the independent couplings. We call them the dependent couplings.
- It is a matter of convention and convenience which couplings are chosen to as independent and which are chosen as dependent.

Higgs basis summary

- In the next few slides, I discuss the Lagrangian in the Higgs basis

- Only a subset of interactions relevant for this talk (Higgs couplings to gauge bosons, vertex correction to Z and W boson couplings, triple gauge couplings) is presented. For more details and the rest of the Lagrangian, see LHCHXSWG-INT-2015-001

Higgs Basis: Z and W couplings

- By construction, photon and gluon couplings as in the SM. Only W and Z couplings are affected
- Strongly constrained by single Z and W production and decay at LEP, and W mass measurements (see later in this talk)

$$\textbf{Independent}: \quad \delta g_L^{Ze},\ \delta g_R^{Ze},\ \delta g_L^{W\ell},\ \delta g_L^{Zu},\ \delta g_R^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zd},\ \delta g_R^{Wq},\ \delta m,$$

$$\textbf{Dependent}: \quad \delta g_L^{Z\nu},\ \delta g_L^{Wq},$$

$$\begin{aligned}\mathcal{L}_{\rm ewpt}^{D=6} &= \frac{g}{\sqrt{2}}\left(W_\mu^+\bar{\nu}_L\gamma_\mu\delta g_L^{W\ell}e_L + W_\mu^+\bar{u}\gamma_\mu\delta g_L^{Wq}V_{\rm CKM}d_L + W_\mu^+\bar{u}_R\gamma_\mu\delta g_R^{Wq}d_R + \text{h.c.}\right)\\ &+ \sqrt{g^2+g'^2}Z_\mu\left[\sum_{f\in u,d,e,\nu}\bar{f}_L\gamma_\mu\delta g_L^{Zf}f_L + \sum_{f\in u,d,e}\bar{f}_R\gamma_\mu\delta g_R^{Zf}f_R\right]\\ &+ 2\delta m\frac{g^2v^2}{4}W_\mu^+W_\mu^-, \qquad (3\end{aligned}$$

Dependent Couplings

Relations enforced by
linearly realized SU(3)xSU(2)xU(1) symmetry

$$\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{W\ell}, \qquad \delta g_L^{Wq} = \delta g_L^{Zu} - \delta g_L^{Zd}.$$

Higgs Basis: Higgs couplings to gauge bosons

- Higgs couplings to gauge bosons are probed by multiple Higgs production and decay processes (ggF, VBF, VH; γγ, Zγ, VV^*→4f)

Independent : $\delta c_w,\ \delta c_z,\ c_{gg},\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ \tilde c_{gg},\ \tilde c_{\gamma\gamma},\ \tilde c_{z\gamma},\ \tilde c_{zz},$

Dependent : $c_{ww},\ \tilde c_{ww},\ c_{w\Box},\ \tilde c_{\gamma\Box},\ \tilde c_{z\Box},$

$$
\begin{aligned}
\Delta\mathcal{L}^{D=6}_{\rm hvv} \;=\; & \frac{h}{v}\Big[2\delta c_w m_W^2 W^+_\mu W^-_\mu + \delta c_z m_Z^2 Z_\mu Z_\mu \\
& + c_{ww}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu} + \tilde c_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde W^-_{\mu\nu} + c_{w\Box}g^2\left(W^-_\mu\partial_\nu W^+_{\mu\nu} + \text{h.c.}\right) \\
& + c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{eg}{2c_\theta}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2}{4c_\theta^2}Z_{\mu\nu}Z_{\mu\nu} \\
& c_{z\Box}g^2 Z_\mu\partial_\nu Z_{\mu\nu} + c_{\gamma\Box}gg' Z_\mu\partial_\nu A_{\mu\nu} \\
& + \tilde c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde G^a_{\mu\nu} + \tilde c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde A_{\mu\nu} + \tilde c_{z\gamma}\frac{eg}{2c_\theta}Z_{\mu\nu}\tilde A_{\mu\nu} + \tilde c_{zz}\frac{g^2}{4c_\theta^2}Z_{\mu\nu}\tilde Z_{\mu\nu}\Big].
\end{aligned}
$$

$$
\begin{aligned}
c_{ww} &= c_{zz} + 2s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma}, \\
\tilde c_{ww} &= \tilde c_{zz} + 2s_\theta^2 \tilde c_{z\gamma} + s_\theta^4 \tilde c_{\gamma\gamma}. \\
c_{w\Box} &= \left[c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right] + \frac{1}{2g'^2}\left[\delta c_w - \delta c_z - 4\delta m\right] \\
c_{z\Box} &= \left[c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right] + \frac{1}{2}\left(\frac{1}{g'^2} - \frac{1}{g^2}\right)\left[\delta c_w - \delta c_z - 4\delta m\right] \\
c_{\gamma\Box} &= \left[c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right] + \frac{1}{g'^2}\left[\delta c_w - \delta c_z - 4\delta m\right]
\end{aligned}
$$

Dependent Couplings

Enforced by linearly realized SU(3)xSU(2)xU(1) symmetry

Higgs Basis: triple gauge couplings

- Cubic couplings of EW gauge bosons that appear at dimension-6 level can be described by 9 parameters: 5 CP even and 4 CP odd

- Only 2 of those are independent couplings; the other are dependent couplings: they can be expressed by Higgs couplings to gauge bosons

$$\textbf{Independent}: \quad \lambda_z,\ \tilde{\lambda}_z,$$
$$\textbf{Dependent}: \quad \delta g_{1,z},\ \delta\kappa_\gamma,\ \delta\kappa_z,\ \lambda_\gamma,\ \tilde{\kappa}_\gamma,\ \tilde{\kappa}_z,\ \tilde{\lambda}_\gamma.$$

$$\begin{aligned}
\mathcal{L}_{\rm tgc}^{\rm D=6} &= ie\left[\delta\kappa_\gamma A_{\mu\nu}W_\mu^+W_\nu^- + \tilde{\kappa}_\gamma \tilde{A}_{\mu\nu}W_\mu^+W_\nu^-\right] \\
&+ igc_\theta\left[\delta g_{1,z}\left(W_{\mu\nu}^+W_\mu^- - W_{\mu\nu}^-W_\mu^+\right)Z_\nu + \delta\kappa_z Z_{\mu\nu}W_\mu^+W_\nu^- + \tilde{\kappa}_z\tilde{Z}_{\mu\nu}W_\mu^+W_\nu^-\right] \\
&+ i\frac{e}{m_W^2}\left[\lambda_\gamma W_{\mu\nu}^+W_{\nu\rho}^-A_{\rho\mu} + \tilde{\lambda}_\gamma W_{\mu\nu}^+W_{\nu\rho}^-\tilde{A}_{\rho\mu}\right] + i\frac{gc_\theta}{m_W^2}\left[\lambda_z W_{\mu\nu}^+W_{\nu\rho}^-Z_{\rho\mu} + \tilde{\lambda}_z W_{\mu\nu}^+W_{\nu\rho}^-Z_{\rho\mu}\right],
\end{aligned}$$

$$\begin{aligned}
\delta g_{1,z} &= -\frac{g^2+g'^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right) + \frac{g^2+g'^2}{2g'^2}\left(\delta c_z - \delta c_w + 4\delta m\right), \\
\delta\kappa_\gamma &= -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right), \\
\tilde{\kappa}_\gamma &= -\frac{g^2}{2}\left(\tilde{c}_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + \tilde{c}_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - \tilde{c}_{zz}\right), \\
\delta\kappa_z &= \delta g_{1,z} - t_\theta^2\delta\kappa_\gamma, \qquad \tilde{\kappa}_z = -t_\theta^2\tilde{\kappa}_\gamma, \\
\lambda_\gamma &= \lambda_z, \quad \tilde{\lambda}_\gamma = \tilde{\lambda}_z.
\end{aligned} \tag{3.14}$$

Translation to dimension-6 operators

$$\delta m = \frac{1}{g^2 - g'^2}\left[-g^2 g'^2 c_{WB} + g^2 c_T - g'^2 \delta v\right] \qquad \delta v = ([c'_{H\ell}]_{11} + [c'_{H\ell}]_{22})/2 - c'_{\ell\ell}.$$

$$\begin{aligned}
\delta g_L^{W\ell} &= c'_{H\ell} + f(1/2, 0) - f(-1/2, -1), \\
\delta g_L^{Z\nu} &= \frac{1}{2} c'_{H\ell} - \frac{1}{2} c_{H\ell} + f(1/2, 0), \\
\delta g_L^{Ze} &= -\frac{1}{2} c'_{H\ell} - \frac{1}{2} c_{H\ell} + f(-1/2, -1), \\
\delta g_R^{Ze} &= -\frac{1}{2} c_{He} + f(0, -1),
\end{aligned}$$

where

$$f(T^3, Q) = I_3\left[-Q c_{WB} \frac{g^2 g'^2}{g^2 - g'^2} + (c_T - \delta v)\left(T^3 + Q \frac{g'^2}{g^2 - g'^2}\right)\right],$$

$$\begin{aligned}
\delta g_{1,z} &= \frac{g^2 + g'^2}{g^2 - g'^2}\left(-g'^2 c_{WB} + c_T - \delta v\right), \\
\delta \kappa_\gamma &= g^2 c_{WB}, \\
\delta \kappa_z &= -2 c_{WB} \frac{g^2 g'^2}{g^2 - g'^2} + \frac{g^2 + g'^2}{g^2 - g'^2}\left(c_T - \delta v\right), \\
\lambda_\gamma &= -\frac{3}{2} g^4 c_{3W}, \\
\lambda_z &= -\frac{3}{2} g^4 c_{3W}, \\
\tilde{\kappa}_\gamma &= g^2 \tilde{c}_{WB}, \\
\tilde{\kappa}_z &= -g'^2 \tilde{c}_{WB}, \\
\tilde{\lambda}_\gamma &= -\frac{3}{2} g^4 \tilde{c}_{3W}, \\
\tilde{\lambda}_z &= -\frac{3}{2} g^4 \tilde{c}_{3W}.
\end{aligned}$$

Directly measured couplings correspond to non-trivial linear combinations of SU3xSU2xU1 invariant operators

Warsaw Basis

H^4D^2 and H^6	
O_H	$\left[\partial_\mu(H^\dagger H)\right]^2$
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
O_{6H}	$(H^\dagger H)^3$

f^2H^3	
O_e	$-(H^\dagger H - \frac{v^2}{2})\bar{e}H^\dagger \ell$
O_u	$-(H^\dagger H - \frac{v^2}{2})\bar{u}\widetilde{H}^\dagger q$
O_d	$-(H^\dagger H - \frac{v^2}{2})\bar{d}H^\dagger q$

V^3D^3	
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$
$O_{3\widetilde{G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$
O_{3W}	$g^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
$O_{3\widetilde{W}}$	$g^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$

V^2H^2	
O_{GG}	$\frac{g_s^2}{4} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$
$O_{\widetilde{G}G}$	$\frac{g_s^2}{4} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$\frac{g^2}{4} H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$
$O_{\widetilde{W}W}$	$\frac{g^2}{4} H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$\frac{g'^2}{4} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$
$O_{\widetilde{B}B}$	$\frac{g'^2}{4} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g g' H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$
$O_{\widetilde{W}B}$	$g g' H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$

f^2H^2D	
$O_{H\ell}$	$i\bar{\ell}\gamma_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$
$O'_{H\ell}$	$i\bar{\ell}\sigma^i\gamma_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
O_{He}	$i\bar{e}\gamma_\mu e H^\dagger \overleftrightarrow{D}_\mu H$
O_{Hq}	$i\bar{q}\gamma_\mu q H^\dagger \overleftrightarrow{D}_\mu H$
O'_{Hq}	$i\bar{q}\sigma^i\gamma_\mu q H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
O_{Hu}	$i\bar{u}\gamma_\mu u H^\dagger \overleftrightarrow{D}_\mu H$
O_{Hd}	$i\bar{d}\gamma_\mu d H^\dagger \overleftrightarrow{D}_\mu H$
O_{Hud}	$i\bar{u}\gamma_\mu d \tilde{H}^\dagger D_\mu H$

f^2VHD	
O_{eW}	$g\bar{\ell}\sigma_{\mu\nu} e \sigma^i H W^i_{\mu\nu}$
O_{eB}	$g'\bar{\ell}\sigma_{\mu\nu} e H B_{\mu\nu}$
O_{uG}	$g_s\bar{q}\sigma_{\mu\nu} T^a u \widetilde{H}\, G^a_{\mu\nu}$
O_{uW}	$g\bar{q}\sigma_{\mu\nu} u \sigma^i \widetilde{H}\, W^i_{\mu\nu}$
O_{uB}	$g'\bar{q}\sigma_{\mu\nu} u \widetilde{H}\, B_{\mu\nu}$
O_{dG}	$g_s\bar{q}\sigma_{\mu\nu} T^a d H\, G^a_{\mu\nu}$
O_{dW}	$g\bar{q}\sigma_{\mu\nu} d \sigma^i H\, W^i_{\mu\nu}$
O_{dB}	$g'\bar{q}\sigma_{\mu\nu} d H\, B_{\mu\nu}$

$(\bar{L}L)(\bar{L}L)$ and $(\bar{L}R)(\bar{L}R)$	
$O_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma_\mu \ell)$
O_{qq}	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma_\mu q)$
O'_{qq}	$(\bar{q}\gamma_\mu \sigma^i q)(\bar{q}\gamma_\mu \sigma^i q)$
$O_{\ell q}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma_\mu q)$
$O'_{\ell q}$	$(\bar{\ell}\gamma_\mu \sigma^i \ell)(\bar{q}\gamma_\mu \sigma^i q)$
O_{quqd}	$(\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)$
O'_{quqd}	$(\bar{q}^j T^a u)\epsilon_{jk}(\bar{q}^k T^a d)$
$O_{\ell equ}$	$(\bar{\ell}^j e)\epsilon_{jk}(\bar{q}^k u)$
$O'_{\ell equ}$	$(\bar{\ell}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$
$O_{\ell edq}$	$(\bar{\ell}^j e)(\bar{d} q^j)$

$(\bar{R}R)(\bar{R}R)$	
O_{ee}	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma_\mu e)$
O_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma_\mu u)$
O_{dd}	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma_\mu d)$
O_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma_\mu u)$
O_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma_\mu d)$
O_{ud}	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma_\mu d)$
O'_{ud}	$(\bar{u}\gamma_\mu T^a u)(\bar{d}\gamma_\mu T^a d)$

$(\bar{L}L)(\bar{R}R)$	
$O_{\ell e}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma_\mu e)$
$O_{\ell u}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma_\mu u)$
$O_{\ell d}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma_\mu d)$
O_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma_\mu e)$
O_{qu}	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma_\mu u)$
O'_{qu}	$(\bar{q}\gamma_\mu T^a q)(\bar{u}\gamma_\mu T^a u)$
O_{qd}	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma_\mu d)$
O'_{qd}	$(\bar{q}\gamma_\mu T^a q)(\bar{d}\gamma_\mu T^a d)$

Higgs Basis: Pros and Cons

Pros

- Simple enough that should be accessible for those not acquainted with nuts and bolts of EFTs
- Transparent connection between independent couplings and (pseudo-)observables
- Constraints on EFT parameters from electroweak precision observables can be easily imposed, which greatly reduces the number of parameters and should simplify LHC analyses
- Simple to implement in monte carlo codes

Cons

- SU(3)xSU(2)xU(1) not manifest (hidden in relations between dependent and independent couplings)
- Connection to BSM models less straightforward than in other existing bases. Mixes tree and loop induced couplings
- Renormalization group running of the couplings less straightforward to compute than in other bases

Higgs basis summary

For more details and the rest of the Lagrangian, see LHCHXSWG-INT-2015-001

In the rest if the talk I will discuss electroweak constraints on the parameters in the Higgs basis

Assumptions

- I'm only taking into account corrections to observables who are linear in new physics parameters, that is to say, only interference terms between SM and new physics. Quadratic corrections are formally of the same order as dimension-8 operators.
- I restrict to observables that do not depend on 4-fermion operators (more general approach left for future work)

Model-independent EW precision constraints on dimension 6 operators

Constraints from Pole Observables

Pole observables (LEP-1 et al)

- For observables with Z or W bosons on-shell, interference between SM amplitudes and 4-fermion operators is suppressed by Γ/m and can be neglected
- Corrections from dimension-6 Lagrangian to pole observables can be expressed just by vertex corrections δg and W mass correction δm
- I will not assume anything about δg and δm: they are allowed to be arbitrary, flavor dependent, and all can be simultaneously present

$$\textbf{Independent}: \quad \delta g_L^{Ze},\ \delta g_R^{Ze},\ \delta g_L^{W\ell},\ \delta g_L^{Zu},\ \delta g_R^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zd},\ \delta g_R^{Wq},\ \delta m,$$

$$\textbf{Dependent}: \quad \delta g_L^{Z\nu},\ \delta g_L^{Wq},$$

$$\begin{aligned}
\mathcal{L}_{\rm ewpt}^{D=6} &= \frac{g}{\sqrt{2}}\left(W_\mu^+ \bar\nu_L \gamma_\mu \delta g_L^{W\ell} e_L + W_\mu^+ \bar u \gamma_\mu \delta g_L^{Wq} V_{\rm CKM} d_L + W_\mu^+ \bar u_R \gamma_\mu \delta g_R^{Wq} d_R + \text{h.c.}\right) \\
&+ \sqrt{g^2+g'^2} Z_\mu \left[\sum_{f\in u,d,e,\nu} \bar f_L \gamma_\mu \delta g_L^{Zf} f_L + \sum_{f\in u,d,e} \bar f_R \gamma_\mu \delta g_R^{Zf} f_R\right] \\
&+ 2\delta m \frac{g^2 v^2}{4} W_\mu^+ W_\mu^-, \qquad (3
\end{aligned}$$

Pole observables (LEP-1 et al)

- For observables with Z or W bosons on-shell, interference between SM amplitudes and 4-fermion operators is suppressed by Γ/m and can be neglected
- Corrections from dimension-6 Lagrangian to pole observables can be expressed just by vertex corrections δg and W mass correction δm
- I will not assume anything about δg and δm: they are allowed to be arbitrary, flavor dependent, and all can be simultaneously present

Input: mZ, α, Γμ ⇒ **Couplings: gL, gY, v**

$$m_Z = \frac{\sqrt{g_L^2 + g_Y^2} v}{2}$$

$$\alpha = \frac{g_L g_Y}{\sqrt{g_L^2 + g_Y^2}}$$

$$\tau_\mu = \frac{384\pi^3 v^4}{m_\mu^5}$$

In Higgs basis, by construction, the SM relation between input and couplings is unchanged

Z-pole observables

Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[21]	2.4950	$\sum_f \Gamma(Z \to f\bar{f})$
σ_{had} [nb]	41.541 ± 0.037	[21]	41.484	$\frac{12\pi}{m_Z^2} \frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\text{FB}}^{0,e}$	0.0145 ± 0.0025	[21]	0.0163	$\frac{3}{4} A_e^2$
$A_{\text{FB}}^{0,\mu}$	0.0169 ± 0.0013	[21]	0.0163	$\frac{3}{4} A_e A_\mu$
$A_{\text{FB}}^{0,\tau}$	0.0188 ± 0.0017	[21]	0.0163	$\frac{3}{4} A_e A_\tau$
R_b	0.21629 ± 0.00066	[21]	0.21578	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[21]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b^{FB}	0.0992 ± 0.0016	[21]	0.1032	$\frac{3}{4} A_e A_b$
A_c^{FB}	0.0707 ± 0.0035	[21]	0.0738	$\frac{3}{4} A_e A_c$
A_e	0.1516 ± 0.0021	[21]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[21]	0.1472	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to e_\mu^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015	[21]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020	[21]	0.935	$\frac{\Gamma(Z\to b_L b_L)-\Gamma(Z\to b_R b_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027	[21]	0.668	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091	[22]	0.935	$\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	0.166 ± 0.009	[23]	0.1724	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$
μ_{ttZ}	0.81 ± 0.24	[24, 25]	1.00	$\frac{(g_L^{Zt})^2+(g_R^{Zt})^2}{(g_{L,\text{SM}}^{Zu})^2+(g_{R,\text{SM}}^{Zu})^2}$

Table 1: **Z boson pole observables**. The experimental errors of the observables between the double lines are correlated, which is taken into account in the fit. The results for $A_{e,\mu,\tau}$ listed above come from the combination of leptonic polarization and left-right asymmetry measurements at the SLD; we also include the results $A_\tau = 0.1439 \pm 0.0043$, $A_e = 0.1498 \pm 0.0049$ from tau polarization measurements at LEP-1 [21]. For the theoretical predictions we use the best fit SM values from GFitter [20]. We also include the model-independent measurement of on-shell Z boson couplings to light quarks in D0 [26].

W-pole observables

Observable	Experimental value	Ref.	SM prediction	Definition
m_W [GeV]	80.385 ± 0.015	[27]	80.364	$\frac{g_L v}{2}(1+\delta m)$
Γ_W [GeV]	2.085 ± 0.042	[23]	2.091	$\sum_f \Gamma(W \to f f')$
$\mathrm{Br}(W \to e\nu)$	0.1071 ± 0.0016	[28]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to f f')}$
$\mathrm{Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[28]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to f f')}$
$\mathrm{Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[28]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to f f')}$
R_{Wc}	0.49 ± 0.04	[23]	0.50	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$
R_σ	0.998 ± 0.041	[29]	1.000	$g_L^{Wq_3}/g_{L,\mathrm{SM}}^{Wq_3}$

Table 2: **W-boson pole observables**. Measurements of the 3 leptonic branching fractions are correlated. For the theoretical predictions of m_W and Γ_W, we use the best fit SM values from GFitter [20], while for the leptonic branching fractions we take the value quoted in [28].

On-shell Z decays: nuts and bolts

Lowest order:

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

$$\Gamma(W \to f\bar{f}') = \frac{N_f m_W}{48\pi} g_{fW,L}^2 \qquad g_{fW,L} = g_L$$

w/ new physics:

$$\Gamma(Z \to f\bar{f}) = \frac{N_f m_Z}{24\pi} {g_{fZ;\text{eff}}}^2 \quad \Gamma(W \to f\bar{f}') = \frac{N_f m_W}{48\pi} {g_{fW,L;\text{eff}}}^2$$

- Including leading order new physics corrections amount to replacing Z coupling to fermions with effective couplings

$$g_{fW,L;\text{eff}} = \frac{g_L}{\sqrt{1 - \delta\Pi'_{WW}(m_W^2)}}\left(1 + \delta g_L^{Wf}\right)$$

$$g_{fZ;\text{eff}} = \frac{\sqrt{g_L^2 + g_Y^2}}{\sqrt{1 - \delta\Pi'_{ZZ}(m_Z^2)}}\left(T_f^3 - s_{\text{eff}}^2 Q_f + \delta g^{Zf}\right)$$

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

- These effective couplings encode the effect of vertex and oblique corrections
- 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
- In general, pole observables constrain complicated combinations of coefficients of dimension-6 operators
- However, in Higgs basis, oblique corrections are absent (except for δm) thus δg directly constrained

$$g_{fW,L;eff} = g_L\left(1 + \delta g_L^{Wf}\right)$$

$$g_{fZ;eff} = \sqrt{g_L^2 + g_Y^2}\,\left(T_f^3 - s_\theta^2 Q_f + \delta g^{Zf}\right)$$

Pole constraints

All diagonal vertex corrections except for δgWqR simultaneously constrained in a completely model-independent way

$$[\delta g_L^{We}]_{ii} = \begin{pmatrix} -1.01 \pm 0.64 \\ -1.37 \pm 0.59 \\ 1.95 \pm 0.79 \end{pmatrix} \cdot 10^{-2}, \; [\delta g_L^{Ze}]_{ii} = \begin{pmatrix} -0.22 \pm 0.28 \\ 0.1 \pm 1.2 \\ 0.18 \pm 0.58 \end{pmatrix} \cdot 10^{-3}, \; [\delta g_R^{Ze}]_{ii} = \begin{pmatrix} -0.33 \pm 0.27 \\ 0.0 \pm 1.4 \\ 0.42 \pm 0.62 \end{pmatrix} \cdot 10^{-3}, \tag{3.4}$$

$$[\delta g_L^{Zu}]_{ii} = \begin{pmatrix} -0.8 \pm 3.1 \\ -0.17 \pm 0.31 \\ -0.3 \pm 3.8 \end{pmatrix} \cdot 10^{-2}, \quad [\delta g_R^{Zu}]_{ii} = \begin{pmatrix} 1.3 \pm 5.1 \\ -0.37 \pm 0.52 \\ 8 \pm 14 \end{pmatrix} \cdot 10^{-2}, \tag{3.5}$$

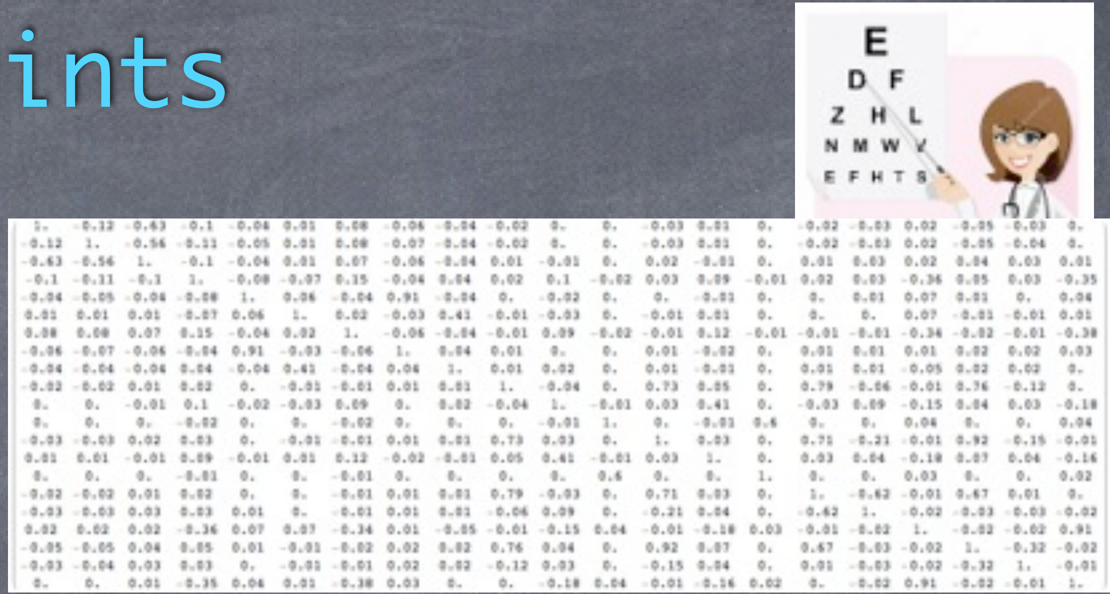
$$[\delta g_L^{Zd}]_{ii} = \begin{pmatrix} -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \end{pmatrix} \cdot 10^{-2}, \quad [\delta g_R^{Zd}]_{ii} = \begin{pmatrix} 2 \pm 16 \\ 3.4 \pm 4.9 \\ 2.30 \pm 0.87 \end{pmatrix} \cdot 10^{-2}. \tag{3.6}$$

$$\delta m = (2.6 \pm 1.9) \cdot 10^{-4}.$$

- Z coupling to leptons constrained at 0.1% level
- W couplings to leptons constrained at 1% level
- Some couplings to quarks (bottom, charm) also constrained at 1% level
- Some couplings very weakly constrained in a model-independent way, in particular Z coupling to right-handed quarks, and to light quarks

Efrati,AA,Soreq
1503.0xxxx

Pole constraints



- Full correlation matrix is also derived
- From that, one can reproduce full likelihood function
- If dictionary from Higgs basis to other bases exists, results can be easily recast
- Similarly, results can be easily recast for particular BSM models in which vertex and mass corrections are functions of (fewer) model parameters

$$\chi^2_{\rm pole} = \sum_{ij} (\delta g_i - \delta g_i^0) \Delta^{-1}_{ij} (\delta g_j - \delta g_j^0),$$

$$\Delta_{ij} = \delta g_i^{\rm err} \rho_{ij} \delta g_j^{\rm err}$$

Correlation Matrix (ρ_{ij}) · 1σ Errors ($\delta g^{\rm err}$) · Central Values (δg^0)

Pole constraints in Warsaw basis

$$
\begin{aligned}
(\hat{c}'_{HL})_{ij} &= (c'_{HL})_{ij} + \left(g_L^2 c_{WB} - \frac{g_L^2}{g_Y^2} c_T \right) \delta_{ij}, \\
(\hat{c}_{HL})_{ij} &= (c_{HL})_{ij} - c_T \delta_{ij}, \\
(\hat{c}_{HE})_{ij} &= (c_{HE})_{ij} - 2 c_T \delta_{ij}, \\
(\hat{c}'_{HQ})_{ij} &= (c'_{HQ})_{ij} + \left(g_L^2 c_{WB} - \frac{g_L^2}{g_Y^2} c_T \right) \delta_{ij}, \\
(\hat{c}_{HQ})_{ij} &= (c_{HQ})_{ij} + \frac{1}{3} c_T \delta_{ij}, \\
(\hat{c}_{HU})_{ij} &= (c_{HU})_{ij} + \frac{4}{3} c_T \delta_{ij}, \\
(\hat{c}_{HD})_{ij} &= (c_{HD})_{ij} - \frac{2}{3} c_T \delta_{ij},
\end{aligned}
$$

$$
(\hat{c}'_{HL})_{ii} = \begin{pmatrix} -1.09 \pm 0.64 \\ -1.46 \pm 0.59 \\ 1.86 \pm 0.79 \end{pmatrix} \cdot 10^{-2}, \quad (\hat{c}_{HL})_{ii} = \begin{pmatrix} 1.02 \pm 0.63 \\ 1.32 \pm 0.63 \\ -2.01 \pm 0.80 \end{pmatrix} \cdot 10^{-2},
$$

$$
(\hat{c}_{HE})_{ii} = \begin{pmatrix} 0.13 \pm 0.66 \\ -0.6 \pm 2.7 \\ -1.4 \pm 1.3 \end{pmatrix} \cdot 10^{-3}, \quad c'_{ll} = (-1.21 \pm 0.41) \cdot 10^{-2},
$$

$$
(\hat{c}'_{HQ})_{ii} = \begin{pmatrix} 0.1 \pm 2.7 \\ -1.2 \pm 2.8 \\ -0.7 \pm 3.8 \end{pmatrix} \cdot 10^{-2}, \quad (\hat{c}_{HQ})_{ii} == \begin{pmatrix} 1.7 \pm 7.1 \\ -0.8 \pm 2.9 \\ -0.1 \pm 3.8 \end{pmatrix} \cdot 10^{-2},
$$

$$
(\hat{c}_{HU})_{ii} = \begin{pmatrix} -2 \pm 10 \\ 0.8 \pm 1.0 \\ -16 \pm 28 \end{pmatrix} \cdot 10^{-2}, \quad (\hat{c}_{HD})_{ii} = \begin{pmatrix} -6 \pm 32 \\ -6.9 \pm 9.8 \\ -4.6 \pm 1.7 \end{pmatrix} \cdot 10^{-2}.
$$

- Only c-hat combinations can be constrained!

Flat directions of pole observables

Gupta et al, 1405.0181

- Pole observables depend, at linear level, on 30 dimension-6 operators in Warsaw basis
- One can constrain only 27 combinations of EFT parameters: c-hats to the right
- Only combinations of vertex and oblique corrections are constrained, not separately
- This leaves 2 flat EFT directions
- These 2 directions are related to usual S and T parameters
- From pole observables alone there's no model independent constraints on S and T!

$$
\begin{aligned}
(\hat{c}'_{HL})_{ij} &= (c'_{HL})_{ij} + \left(g_L^2 c_{WB} - \frac{g_L^2}{g_Y^2} c_T \right) \delta_{ij}, \\
(\hat{c}_{HL})_{ij} &= (c_{HL})_{ij} - c_T \delta_{ij}, \\
(\hat{c}_{HE})_{ij} &= (c_{HE})_{ij} - 2 c_T \delta_{ij}, \\
(\hat{c}'_{HQ})_{ij} &= (c'_{HQ})_{ij} + \left(g_L^2 c_{WB} - \frac{g_L^2}{g_Y^2} c_T \right) \delta_{ij}, \\
(\hat{c}_{HQ})_{ij} &= (c_{HQ})_{ij} + \frac{1}{3} c_T \delta_{ij}, \\
(\hat{c}_{HU})_{ij} &= (c_{HU})_{ij} + \frac{4}{3} c_T \delta_{ij}, \\
(\hat{c}_{HD})_{ij} &= (c_{HD})_{ij} - \frac{2}{3} c_T \delta_{ij},
\end{aligned}
$$

Cacciapaglia et al
hep-ph/0604111

Flat directions of pole observables

- The flat directions arise due to EFT operator identities

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

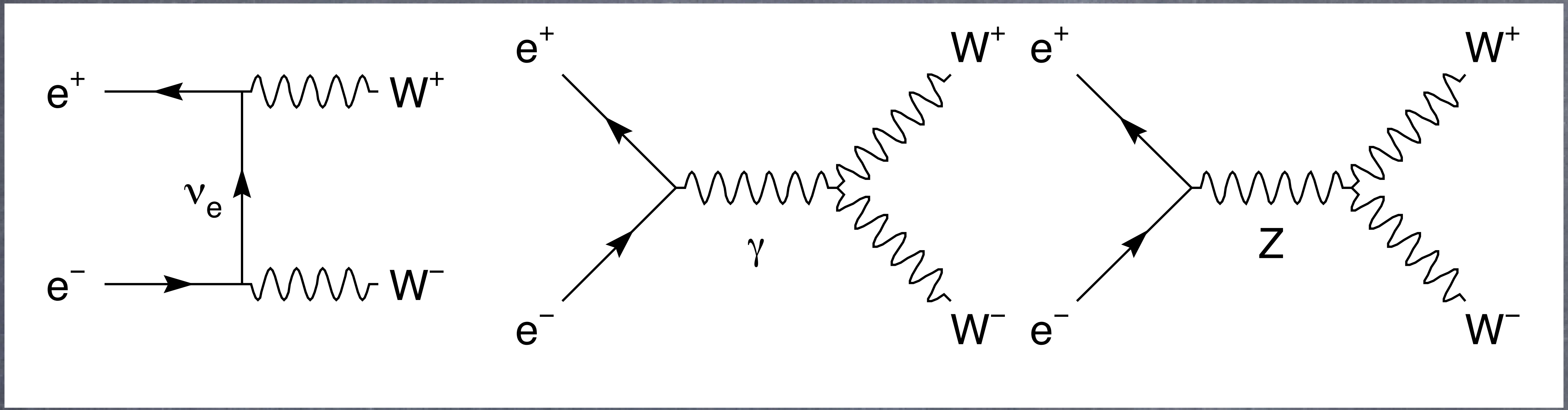
$$O_B = iH^\dagger \overleftrightarrow{D}_\mu H \, \partial_\nu B_{\mu\nu} = -g_Y^2 \left(-2O_T + \frac{1}{6} O_{Hq} + \frac{2}{3} O_{Hu} - \frac{1}{3} O_{Hd} - \frac{1}{2} O_{H\ell} - O_{He} \right)$$

- Obviously, operators OW and OB do not affect Z and W couplings to fermions
- They only affect gauge boson propagators (same way as OWB) 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 non-W/Z pole data are included

Constraints from WW production at LEP-2

WW production

WW production at LEP-2



- Depends on triple gauge couplings
- Also depends on electron and neutrino 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

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

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

e+e-→W+W- in Higgs basis

- Again, in Higgs basis things greatly simplify thanks to lack of oblique corrections
- Usual triple gauge couplings become directly related to observable WW production cross section
- At dimension-6 level, the process depends on 3 vertex corrections to Z and W couplings to electrons and neutrinos, and 5 TGCs: 3 CP even and 2 CP odd
- If we focus on WW differential distributions only (ignoring decays), CP odd TGCs enter quadratically and can be ignored, leaving only 3 TGCs

$$\mathcal{L}_{\rm TGC}^{\rm SM} = ie\left[A_{\mu\nu}W_\mu^+W_\nu^- + \left(W_{\mu\nu}^+W_\mu^- - W_{\mu\nu}^-W_\mu^+\right)A_\nu\right] + ig_Lc_\theta\left[\left(W_{\mu\nu}^+W_\mu^- - W_{\mu\nu}^-W_\mu^+\right)Z_\nu + Z_{\mu\nu}W_\mu^+W_\nu^-\right]$$

$$\delta\kappa_z = \delta g_{1,z} - t_\theta^2\delta\kappa_\gamma$$
$$\tilde\kappa_z = -t_\theta^2\tilde\kappa_\gamma$$
$$\lambda_\gamma = \lambda_z$$
$$\tilde\lambda_\gamma = \tilde\lambda_z$$

$$\mathcal{L}_{\rm tgc}^{\rm D=6} = ie\left[\delta\kappa_\gamma A_{\mu\nu}W_\mu^+W_\nu^- + \tilde\kappa_\gamma\tilde A_{\mu\nu}W_\mu^+W_\nu^-\right] + ig_Lc_\theta\left[\delta g_{1,z}\left(W_{\mu\nu}^+W_\mu^- - W_{\mu\nu}^-W_\mu^+\right)Z_\nu + \delta\kappa_z Z_{\mu\nu}W_\mu^+W_\nu^- + \tilde\kappa_z\tilde Z_{\mu\nu}W_\mu^+W_\nu^-\right] + i\frac{e}{m_W^2}\left[\lambda_\gamma W_{\mu\nu}^+W_{\nu\rho}^-A_{\rho\mu} + \tilde\lambda_\gamma W_{\mu\nu}^+W_{\nu\rho}^-\tilde A_{\rho\mu}\right] + i\frac{g_Lc_\theta}{m_W^2}\left[\lambda_z W_{\mu\nu}^+W_{\nu\rho}^-Z_{\rho\mu} + \tilde\lambda_z W_{\mu\nu}^+W_{\nu\rho}^-Z_{\rho\mu}\right]$$

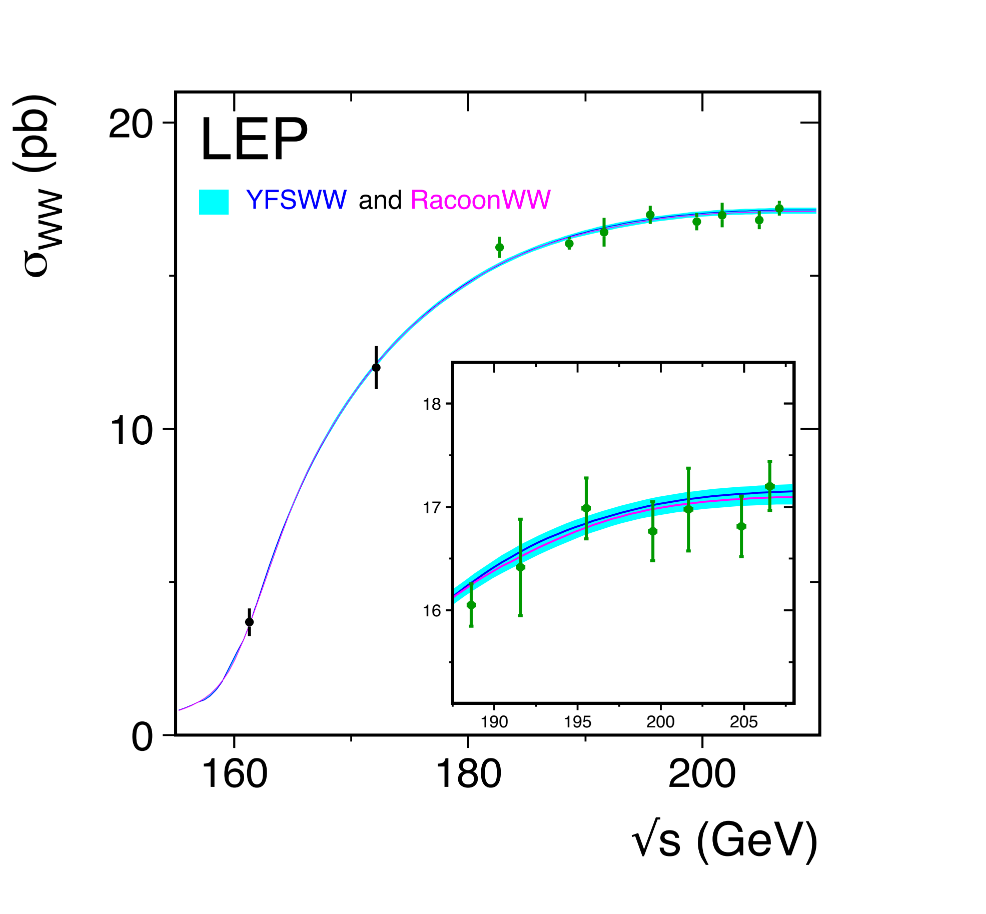
WW production constraints

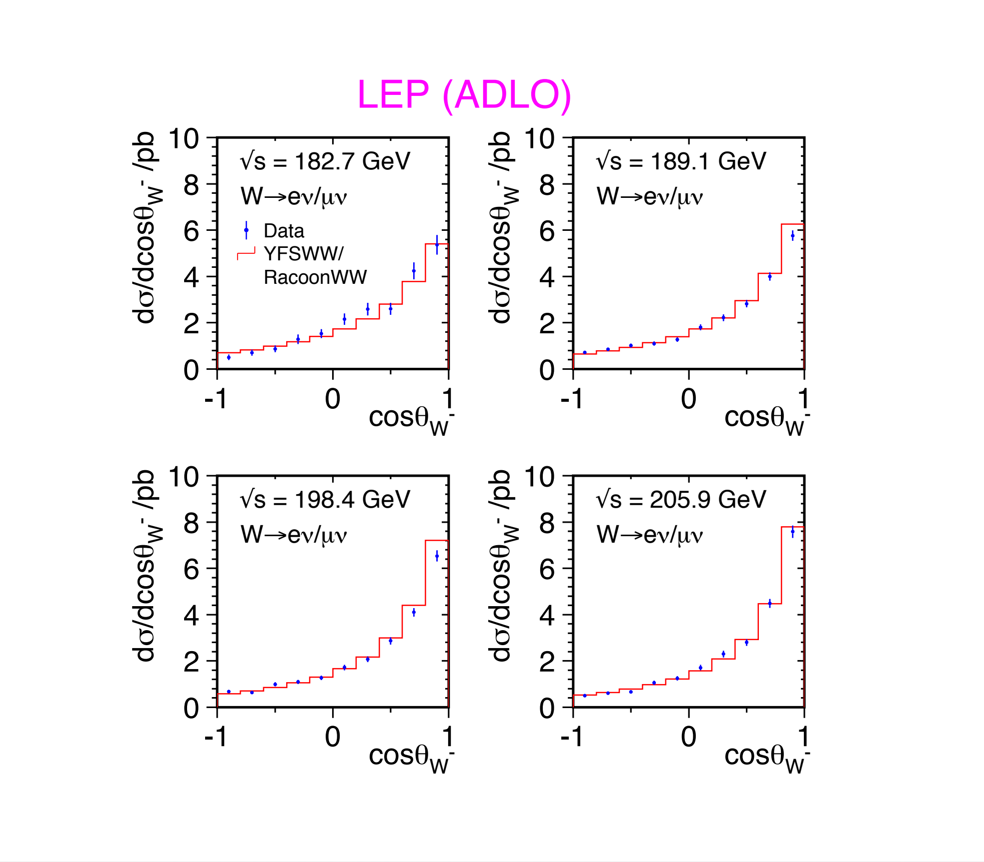
- Precision of WW measurements is only O(1)% in LEP-2, compared with O(0.1%) precision of LEP measurement of leptonic vertex corrections
- Therefore the relevant vertex corrections are already strongly constrained in a model independent way and can be safely set to zero in this analysis
- Then we can use a simplified treatment of WW production, with only 3 triple gauge couplings as free parameters

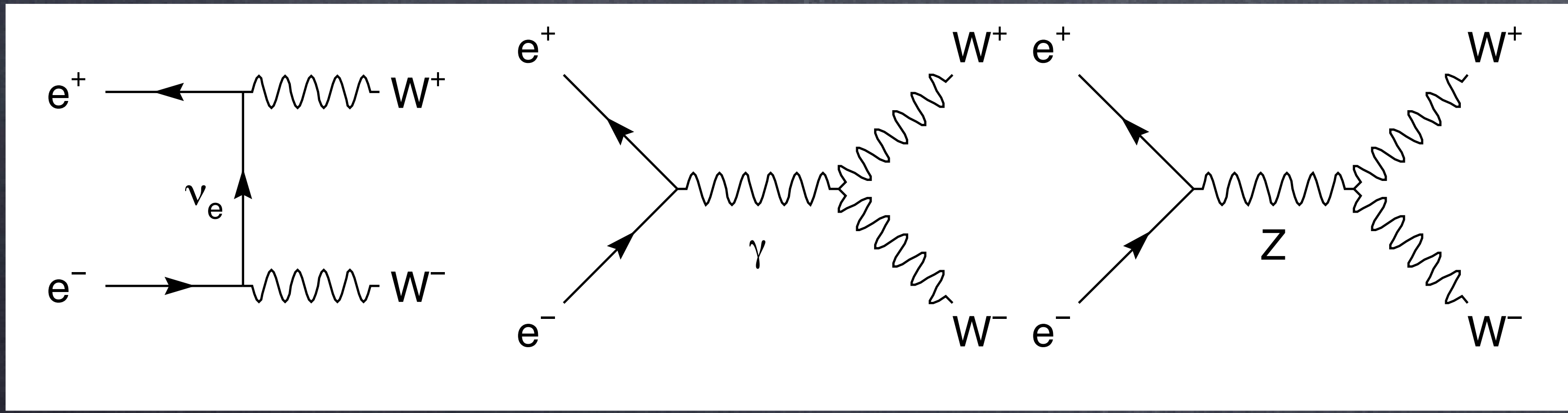
Constraints from VV production

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:

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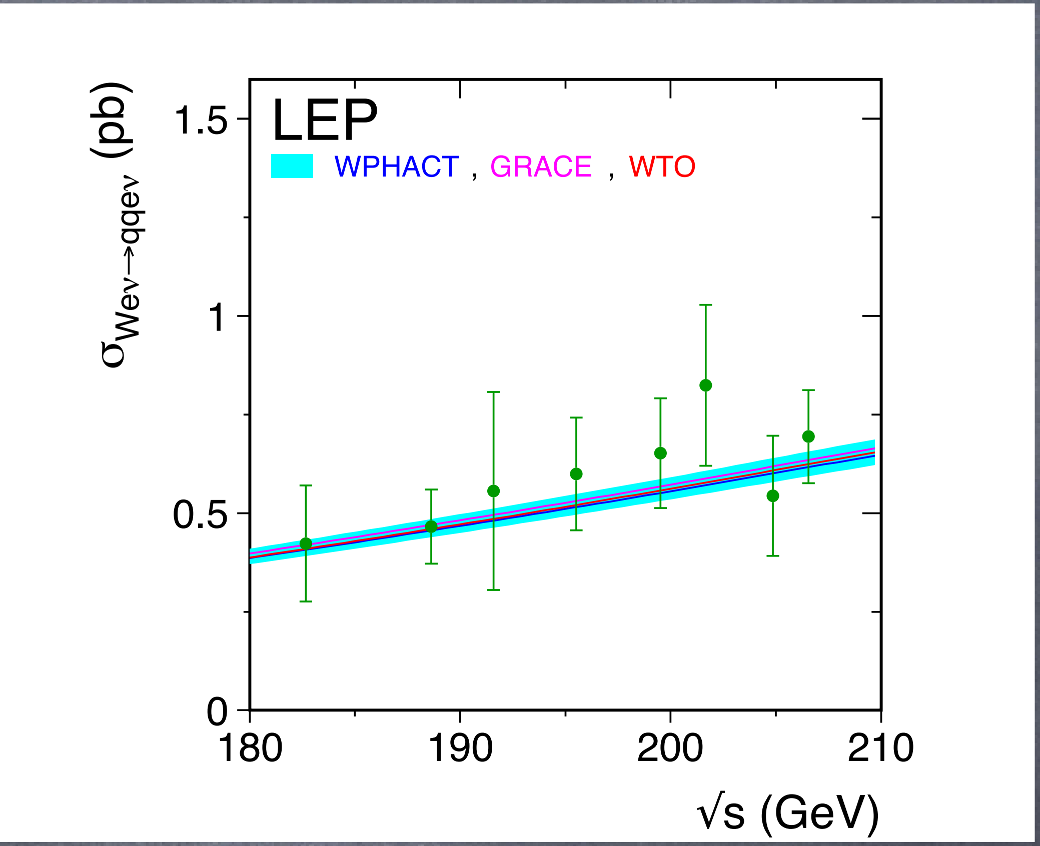
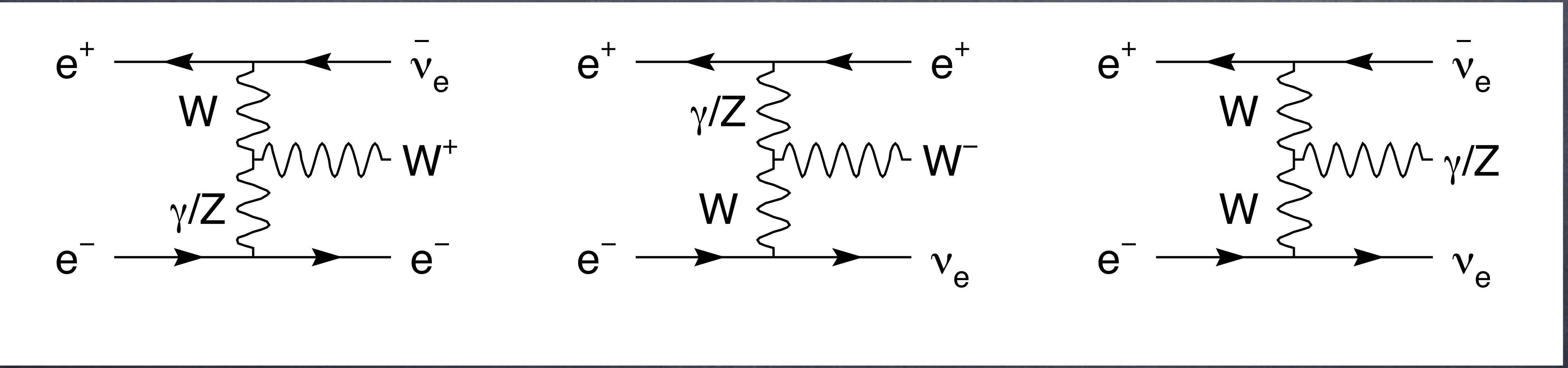
- Single W production cross section at different energies of LEP-2





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 might 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 λZ<< δg1Z, κγ, because the corresponding operator O3W can be generated only at the loop level
- For λZ=0 much stronger limits follow:

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

TGC - Higgs Synergy

$$\text{Independent}: \quad \lambda_z,\ \tilde{\lambda}_z,$$
$$\text{Dependent}: \quad \delta g_{1,z},\ \delta\kappa_\gamma,\ \delta\kappa_z,\ \lambda_\gamma,\ \tilde{\kappa}_\gamma,\ \tilde{\kappa}_z,\ \tilde{\lambda}_\gamma.$$

$$\begin{aligned}
\mathcal{L}_{\rm tgc}^{\rm D=6} &= ie\left[\delta\kappa_\gamma A_{\mu\nu}\, W_\mu^+ W_\nu^- + \tilde{\kappa}_\gamma \tilde{A}_{\mu\nu}\, W_\mu^+ W_\nu^-\right] \\
&+ igc_\theta\left[\delta g_{1,z}\left(W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+\right) Z_\nu + \delta\kappa_z\, Z_{\mu\nu}\, W_\mu^+ W_\nu^- + \tilde{\kappa}_z\, \tilde{Z}_{\mu\nu}\, W_\mu^+ W_\nu^-\right] \\
&+ i\frac{e}{m_W^2}\left[\lambda_\gamma W_{\mu\nu}^+ W_{\nu\rho}^- A_{\rho\mu} + \tilde{\lambda}_\gamma W_{\mu\nu}^+ W_{\nu\rho}^- \tilde{A}_{\rho\mu}\right] + i\frac{gc_\theta}{m_W^2}\left[\lambda_z W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu} + \tilde{\lambda}_z W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu}\right],
\end{aligned}$$

$$\begin{aligned}
\delta g_{1,z} &= -\frac{g^2+g'^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right) + \frac{g^2+g'^2}{2g'^2}\left(\delta c_z - \delta c_w + 4\delta m\right), \\
\delta\kappa_\gamma &= -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right), \\
\tilde{\kappa}_\gamma &= -\frac{g^2}{2}\left(\tilde{c}_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + \tilde{c}_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - \tilde{c}_{zz}\right), \\
\delta\kappa_z &= \delta g_{1,z} - t_\theta^2\delta\kappa_\gamma, \qquad \tilde{\kappa}_z = -t_\theta^2\tilde{\kappa}_\gamma, \\
\lambda_\gamma &= \lambda_z, \quad \tilde{\lambda}_\gamma = \tilde{\lambda}_z. \qquad (3.14)
\end{aligned}$$

- In Higgs basis formalism, all but 2 TGCs are dependent couplings and can be expressed by Higgs couplings to gauge bosons
- Therefore constraints on δg1z and δκγ imply constraint on Higgs couplings. Note that cZγ and cZZ are especially difficult to access experimentally in Higgs physics
- Important to combine Higgs and TGC data!

Take away

- There are strong constraints on certain combinations of dimension-6 operators from the pole observables measured at LEP-1 and other colliders
- Simplest way to describe them is to use the so-called Higgs basis developed within LHCXSWG
- In this language, model-independent constraints on vertex corrections and triple gauge couplings
- Current model independent LEP-2 constraints on triple gauge couplings are weak, due to an accidental flat direction. But they can still be useful in combination with other measurements or additional assumptions
- Synergy of TGC and Higgs coupling measurements

Outlook

- More general analysis that includes off-pole observables sensitive to 4-fermion operators
- Constraints on EFT parameters from Higgs data in the Higgs basis language
- Model-independent constraints from WW and WZ production at the LHC