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# Model Independent Constraints on Dimension Six Operators



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



- 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

 $H = \frac{1}{\sqrt{2}} \begin{pmatrix} \cdots \\ v + h + \cdots \end{pmatrix}$ Alternatively, non-linear Lagrangians

with derivative expansion

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 of higher dimensional operators are O(1), Λ corresponds to mass scale on BSM theory with couplings of order 1 [more generally,  $\Lambda \sim$  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∼(v/Λ)^(d-4)

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

# Standard Model Lagrangian

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

Some predictions at lowest order

- Couplings of gauge bosons to fermions universal and  $\bullet$ fixed by fermion's quantum numbers
- Z and W boson mass ratio related to Weinberg angle  $\bigcirc$
- Higgs coupling to gauge bosons proportional to their  $\bigcirc$ mass squared
- Higgs coupling to fermions proportional to their mass  $\bigcirc$
- Triple and quartic vector boson couplings proportional  $\bigcirc$  ${\cal L}_{\rm TGC}^{\rm SM} =ie\left[A_{\mu\nu}\,W^+_\mu W^-_\nu + \left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu\right]$ to gauge couplings  $+ig_Lc_\theta\left[\left(W_{\mu\nu}^+W_\mu^- - W_{\mu\nu}^-W_\mu^+\right)Z_\nu + Z_{\mu\nu}\,W_\mu^+W_\nu^-\right]$

All these predictions can be perturbed by higher-dimensional operators

$$
\mathcal{L}_{\rm SM} = -\frac{1}{4g_s^2} G_{\mu\nu,a}^2 - \frac{1}{4g_L^2} W_{\mu\nu,i}^2 - \frac{1}{4g_Y^2} B_{\mu\nu}^2
$$
  
+
$$
i \sum_{f=q,\ell} \bar{f} \bar{\sigma}_{\mu} D_{\mu} f + i \sum_{f=u,d,e} f^c \sigma_{\mu} D_{\mu} \bar{f}^c
$$

$$
-Hq Y_u u^c - H^{\dagger} q Y_d d^c - H^{\dagger} \ell Y_e e^c + \text{h.c.}
$$

$$
+ D_{\mu} H^{\dagger} D_{\mu} H + m_H^2 H^{\dagger} H - \lambda (H^{\dagger} H)^2
$$

 $g^{Af}=Q_f \frac{g_Lg_Y}{\sqrt{g_L^2+g_Y^2}}\equiv eQ_f$  $g_L^{Wf}=g_L$  $\int_{gZf}^{gL}=\sqrt{g_L^2+g_Y^2}\left(T_f^3-s_\theta^2Q_f\right)$  $\frac{m_W}{m_Z} = \frac{g_L}{\sqrt{g_L^2 + g_Y^2}} \equiv c_\theta$  $\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left(2m_W^2\,W_\mu^+W_\mu^- +m_Z^2\,Z_\mu Z_\mu\right)$ 

 $-\frac{h}{v}\sum_{\epsilon}m_f\bar{f}f$ 

# Dimension 5 Lagrangian

$$
\mathcal{L}_{\textrm{eff}}=\mathcal{L}_{\textrm{SM}}+\frac{1}{v}\!\!\left(\!\mathcal{L}^{D=5}\!\right)\!\!+\frac{1}{v^2}\mathcal{L}^{D=6}+\ldots
$$

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

At dimension 5, only operators one can construct are so- $\bigcirc$ called Weinberg operators, which violate lepton number

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

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

- Neutrino oscillation experiments strongly suggest these  $\circledcirc$ operators are present
- However, to match the measurements, their coefficients  $\bullet$ have to be extremely small,  $c \sim 10^{\circ}$ -11
- Therefore dimension 5 operators can have no observable  $\bigcirc$ impact on LHC phenomenology

$$
L = \frac{1}{2} \sum_{\substack{i=0 \text{odd } k}}^{\text{Lipses}} \frac{1}{k} \sum_{\substack{i=0 \text{odd } k}}^{\text{Higgs}} \frac{1}{n} \sum_{\substack{i=0 \text{odd } k}}^{\text{Higgs}} \frac{1}{n
$$

## EFT approach to BSM

First attempt to classify dimension-6 operators back in 1986

Buchmuller,Wyler Nucl.Phys. B268 (1986)

Grządkowski et al.

[1008.4884](http://arxiv.org/abs/1303.3876)

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

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](http://arxiv.org/abs/1303.3876) Giudice et al [hep-ph/0703164](http://arxiv.org/abs/hep-ph/0703164) Contino et al [1303.3876](http://arxiv.org/abs/arXiv:1303.3876)

All bases are equivalent, but some are more equivalent convenient

# Example: Warsaw Basis



 $O_{\ell edq}$   $(\bar{\ell}^je)(\bar{d}q^j)$ 

Grządkowski et al. [1008.4884](http://arxiv.org/abs/1303.3876)

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

- Generally, EFT has maaaaany parameters
- After imposing baryon and lepton number conservation, there are  $\circledcirc$ 2499 non-redundant parameters at dimension-6 level

Alonso et al 1312.2014

- Flavor symmetries dramatically reduce number of parameters. E.g.,  $\odot$ 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 J … … is interested by while EWPT constrains combinations of while EWPT constrains combinations of  $c_H, c_T, c_{WB}, c_{WW}, c_{BB}$  $c_{H\ell_1}, c_{H\ell_2}, c_{H\ell_1}', c_{H\ell_2}', c_{He}, c_{H\mu}, c_{4F} \vert$ 



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

# Higgs Basis Inspired by

"EFT Primaries" of Gupta et al 1405.0181

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



## Higgs Basis: independent and dependent couplings

- For practical reasons, more convenient to introduce the Higgs basis via coefficients of  $\bullet$ 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  $\bullet$ greatly simplifies connection between couplings and observables.
- Since a typical dimension-6 operator spawns several different Lagrangian terms,  $\circledcirc$ 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  $\bullet$ 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  $\bullet$ 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 in the second line of Eq. (3.3) are 3 ⇥ 3 real matrices each, defined via the Higgs boson  $\mathcal{L}$  and we coup Wiggs Rasis: 7 and W couplings by convenience. in our case, the independent couplings are more easily mapped to by convenience. In our case, the independent couplings are more easily mapped to independent couplings are more observables constrained by electrowing constrained by electroweak precision tests and  $\mathsf{H}$  in  $\mathsf{H}$

- By construction, photon and gluon couplings as in the SM. Only W and Z couplings are affected  $\ddot{\phantom{1}}$ <sup>ø</sup> By construction, photon and gluon couplings as in the SM. Only W and Z couplings are affected in the precision of precision of precision of precision of precision of precision of precision of<br>The coupling of precision of pre
- Strongly constrained by single Z and W production and decay at LEP, and W mass measurements (see later in this talk) I and W production and decay at  $F$ FD and W mass *h* and it production and decay are bet, and it mass and electric moments of fermions) in planets of  $\mathcal{A}$  that these couplings must be suppressed at the suppresse we choose the following set of independent and dependent and dependent control in the following relevant of the magnetic r level, for precision observables related to Z and W boson decays:  $\bullet$  Stronaly constrained by single Z and W productic *L Industrial (See taler in this lain)*

 $\mathcal{S}_{\alpha}Zu \quad \mathcal{S}_{\alpha}Zu \quad \mathcal{S}_{\alpha}Zd \quad \mathcal{S}_{\alpha}Zd \quad \mathcal{S}_{\alpha}Wq \quad \mathcal{S}_{\alpha}w$  $\overline{C}$  ,  $\overline{C}$  ,  $\overline{C}$  and  $\overline{C}$   $\overline{C$  $c_{\mathbf{z}} \cdot \mathbf{z} = \sum_{i=1}^{n} \mathbf{z} \cdot \mathbf{z} \cdot \mathbf{w}$  $\begin{array}{cccc} \text{etc.} & \text{og}_L, & \text{og}_L, \\ \end{array}$  $\textbf{Independent}:~~ \delta g_L^{Ze},~ \delta g_R^{Ze},~ \delta g_L^{W\ell},~ \delta g_L^{Zu},~ \delta g_R^{Zu},~ \delta g_L^{Zd},~ \delta g_R^{Zd},~ \delta g_R^{Wq},~ \delta m,$  $\textbf{Dependent}: \quad \delta g^{Z\nu}_L, \,\, \delta g^{Wq}_L$  $\frac{W}{L}$ ,  $\delta q_{P}^{Ze}$ ,  $\delta q_{I}^{W\ell}$ ,  $\delta q_{I}^{Zu}$ ,  $\delta q_{P}^{Zd}$ ,  $\delta q_{P}^{Zd}$ ,  $\delta q_{P}^{Wq}$ ,  $\delta m$ ,  $\mathbf{D}$  are are 3 and  $\mathbf{v} \cdot Z\nu \in W_q$ **parameter couplings** and  $\log_L^{2\nu}$ ,  $\log_L^{2\nu}$ ,

where all  $g$  are 3  $\mu$  3

$$
\mathcal{L}_{\text{ewpt}}^{D=6} = \frac{g}{\sqrt{2}} \left( W_{\mu}^{+} \bar{\nu}_{L} \gamma_{\mu} \delta g_{L}^{W\ell} e_{L} + W_{\mu}^{+} \bar{u} \gamma_{\mu} \delta g_{L}^{Wq} V_{\text{CKM}} d_{L} + W_{\mu}^{+} \bar{u}_{R} \gamma_{\mu} \delta g_{R}^{Wq} d_{R} + \text{h.c.} \right) + \sqrt{g^{2} + g'^{2}} Z_{\mu} \left[ \sum_{f \in u, d, e, \nu} \bar{f}_{L} \gamma_{\mu} \delta g_{L}^{Zf} f_{L} + \sum_{f \in u, d, e} \bar{f}_{R} \gamma_{\mu} \delta g_{R}^{Zf} f_{R} \right] + 2 \delta m \frac{g^{2} v^{2}}{4} W_{\mu}^{+} W_{\mu}^{-},
$$
(3)

### Dependent Couplings which can be expressed by the independent couplings as independent couplings as:  $\mathcal{L}(\mathcal{L})$ <sup>4</sup> *<sup>W</sup>*<sup>+</sup>  $Dependent Couplings$

*<sup>µ</sup> W*

 $S_{\rm eff}$  fermions in Eq. (2.3) and to the W boson mass in Eq. (2.3) and to the W boson mass in Eq. (2.2):  $\alpha$ 

+ 2*m*

as:

where the dependent couplings *g<sup>Z</sup>*⌫

(z)x0(1) symmetry to leptons (rather than the Z couplings to neutri-------------Relations enforced by  $\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{W\ell}$ ,  $\delta$ linearly realized SU(3)xSU(2)xU(1) symmetry *<sup>L</sup>* = *gZu*

**Couplings**  
\n
$$
\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{W\ell}, \qquad \delta g_L^{Wq} =
$$

*<sup>µ</sup> ,* (3.3)

*<sup>L</sup>* can be expressed by the independent couplings

*<sup>L</sup> gZd*

 $\delta g_L^{Wq} = \delta g_L^{Zu} - \delta g_L^{Zd}$  $L^2$   $\cdot$   $\cdot$   $\cdot$ 

level that makes them unobservable at the LHC. Moreover, the contribution from the

At the level of the dimension-formation-formation-formation-formation-formation-formation-formation-formation-

 $\setminus$ 

*<sup>L</sup>* ⌫*<sup>L</sup>* +

*<sup>L</sup> .* (3.4)

### Higgs Basis: Higgs couplings to gauge bosons *y<sup>u</sup> , y<sup>d</sup> , y<sup>e</sup> ,* sin *<sup>u</sup> ,* sin *<sup>d</sup> ,* sin ` *.* (3.5) Independent : *cw, cz, cgg, c, cz, czz, c*˜*gg, c*˜*, c*˜*z, c*˜*zz, y<sup>u</sup> , y<sup>d</sup> , y<sup>e</sup> ,* sin *<sup>u</sup> ,* sin *<sup>d</sup> ,* sin ` *.* (3.5)

### as to gay as hosons are probad by multing Higgs couplings to gauge bosons are probed by multiple Higgs production and decay  $\bullet$  $\mu$ ge bosons are probed by multiple Higgs p processes (ggF, VBF, VH; γγ, Zγ, VV^\*→4f)  $\sim$  -4+)  $\mathbf{J}_{\text{in}}$  independent and dependent and dependent and dependent and dependent and dependent couplings:

where *y<sup>f</sup>* , sin *<sup>f</sup>* , and *cV f* are 3 ⇥ 3 real matrices. These couplings do not a↵ect the  $\textbf{Independent}: \qquad \delta c_w, \; \delta c_z, \; c_{gg}, \; c_{\gamma \gamma}, \; c_{z \gamma}, \; \tilde{c}_{gg}, \; \tilde{c}_{\gamma \gamma}, \; \tilde{c}_{z \gamma}, \; \tilde{c}_{zz},$ **independent**.  $\sigma v_w$ ,  $\sigma v_z$ ,  $c_{gg}$ ,  $c_{\gamma\gamma}$ ,  $c_{zz}$ ,  $c_{gg}$ ,  $c_{\gamma\gamma}$ ,  $c_{z\gamma}$ ,  $c_{zz}$ ,

Higgs boson couplings to the SM gauge bosons: Dependent :

Higgs studies at the LHC.

+*cww*

+*cgg*

*cz*2*g*<sup>2</sup>

+˜*cgg*

expressed by the independent couplings as  $200$  for independent couplings as

Typically, the strongest limits on the independent couplings in Eq. (3.5) comes from  $\mathcal{L}$ 

 $\textbf{Dependent}: \hspace{25pt} c_{ww}, \hspace{20pt} \tilde{c}_{ww}, \hspace{20pt} c_{w\Box}, \hspace{20pt} \tilde{c}_{z\Box}, \hspace{20pt}$ 

Typically, the strongest limits on the independent couplings in Eq. (3.5) come from  $\mathbb{R}^2$ 

$$
\Delta \mathcal{L}_{\text{hvv}}^{D=6} = \frac{h}{v} \left[ 2 \delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu \right.\n+ c_{ww} \frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww} \frac{g^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g^2 (W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}) \n+ c_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma} \frac{eg}{2c_\theta} Z_{\mu\nu} A_{\mu\nu} + c_{zz} \frac{g^2}{4c_\theta^2} Z_{\mu\nu} Z_{\mu\nu} \nc_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} gg' Z_\mu \partial_\nu A_{\mu\nu} \n+ \tilde{c}_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma} \frac{eg}{2c_\theta} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz} \frac{g^2}{4c_\theta^2} Z_{\mu\nu} \tilde{Z}_{\mu\nu} \right].
$$

*Aµ*⌫*Aµ*⌫ + *cz*

*eg*

*Zµ*⌫*Aµ*⌫ + *czz*

SU(3)xSU(2)xU(1) symmetry Here *<sup>X</sup>µ*⌫ <sup>=</sup> @*µX*⌫ @⌫*Xµ*, and *<sup>X</sup>*˜*µ*⌫ <sup>=</sup> ✏*µ*⌫⇢@⇢*X*. The dependent couplings can be *cww* = *czz* + 2*s*<sup>2</sup> ✓*cz* + *s*<sup>4</sup> ✓*c, c*˜*ww* = ˜*czz* + 2*s*<sup>2</sup> ✓*c*˜*z* + *s*<sup>4</sup> ✓*c*˜*. cw*<sup>2</sup> = *c e*2 *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> <sup>+</sup> *<sup>c</sup>z g*<sup>2</sup> *g*0<sup>2</sup> *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> *<sup>c</sup>zz* + 1 <sup>2</sup>*g*0<sup>2</sup> [*c<sup>w</sup> c<sup>z</sup>* <sup>4</sup>*m*] *cz*<sup>2</sup> = *c e*2 *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> <sup>+</sup> *<sup>c</sup>z g*<sup>2</sup> *g*0<sup>2</sup> *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> *<sup>c</sup>zz* + 1 2 ✓ 1 *<sup>g</sup>*0<sup>2</sup> <sup>1</sup> *g*2 ◆ [*c<sup>w</sup> c<sup>z</sup>* 4*m*] *c*<sup>2</sup> = *c e*2 *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> <sup>+</sup> *<sup>c</sup>z g*<sup>2</sup> *g*0<sup>2</sup> *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> *<sup>c</sup>zz* + 1 *<sup>g</sup>*0<sup>2</sup> [*c<sup>w</sup> c<sup>z</sup>* <sup>4</sup>*m*] (3.8) <sup>4</sup> *<sup>G</sup><sup>a</sup>* +˜*cgg* <sup>4</sup> *<sup>G</sup><sup>a</sup> µ*⌫*G*˜*<sup>a</sup> <sup>µ</sup>*⌫ + ˜*c* 4 *Aµ*⌫*A*˜*µ*⌫ + ˜*cz* expressed by the independent couplings as<sup>2</sup> *cww* = *czz* + 2*s*<sup>2</sup> ✓*cz* + *s*<sup>4</sup> Here *<sup>X</sup>µ*⌫ <sup>=</sup> @*µX*⌫ @⌫*Xµ*, and *<sup>X</sup>*˜*µ*⌫ <sup>=</sup> ✏*µ*⌫⇢@⇢*X*. The dependent couplings can be expressed by the independent couplings as<sup>2</sup> *cww* = *czz* + 2*s*<sup>2</sup> ✓*cz* + *s*<sup>4</sup> ✓*c, c*˜*ww* = ˜*czz* + 2*s*<sup>2</sup> ✓*c*˜*z* + *s*<sup>4</sup> ✓*c*˜*. cw*<sup>2</sup> = *c e*2 *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> <sup>+</sup> *<sup>c</sup>z g*<sup>2</sup> *g*0<sup>2</sup> *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> *<sup>c</sup>zz* + *cz*<sup>2</sup> = *c e*2 *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> <sup>+</sup> *<sup>c</sup>z g*<sup>2</sup> *g*0<sup>2</sup> *<sup>g</sup>*<sup>2</sup> <sup>+</sup> *<sup>g</sup>*0<sup>2</sup> *<sup>c</sup>zz*

+*cgg*

*g*2 *s*

*µ*⌫*G<sup>a</sup>*

*<sup>µ</sup>*⌫ + *c*

*e*2

### Dependent Couplings *Zµ*⌫*A*˜*µ*⌫ + ˜*czz g*2 *Zµ*⌫*Z*˜*µ*⌫  $\mathbf{I}$

*Zµ*⌫*Zµ*⌫

(3.7)

*g*2

*<sup>R</sup> ,* (3.6)

Enforced by linearly realized  $SU(3)$ xSU(2)xl

### Higgs Basis: triple gauge couplings . It iple gauge coupling  $T$  interactions would than be traded for couplings in Eq. (3.10), which would change the relation between *friple* gauge couplings. We find the couplings more convenient in practice. Namely, since *gV f* are strongly constrained by precision

- 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 interaction terms are consequently also set to zero. cribed b
- Only 2 of those are independent couplings; the other are dependent couplings: they can be expressed by Higgs couplings to gauge bosons Cnly 2 of those are independent couplings: the other are dependent

the couplings are defined the coupling to the specific part of the specific thrower the state of the stat

Independent:	
\n $\mathcal{L}_{\text{tgc}}^{\text{D=6}} = ie \left[ \delta \kappa_{\gamma} A_{\mu\nu} W_{\mu}^+ W_{\nu}^- + \tilde{\kappa}_{\gamma} \tilde{A}_{\mu\nu} W_{\mu}^+ W_{\nu}^- \right]$ \n	\n <b>Dependent:</b> \n $\delta g_{1,z}, \delta \kappa_{\gamma}, \delta \kappa_{z}, \lambda_{\gamma}, \tilde{\kappa}_{\gamma}, \tilde{\kappa}_{z}, \tilde{\lambda}_{\gamma}.$ \n
\n $+ ig c_{\theta} \left[ \delta g_{1,z} \left( W_{\mu\nu}^+ W_{\mu}^- - W_{\mu\nu}^- W_{\mu}^+ \right) Z_{\nu} + \delta \kappa_{z} Z_{\mu\nu} W_{\mu}^+ W_{\nu}^- + \tilde{\kappa}_{z} \tilde{Z}_{\mu\nu} W_{\mu}^+ W_{\nu}^- \right]$ \n	
\n $+ i \frac{e}{m_W^2} \left[ \lambda_{\gamma} W_{\mu\nu}^+ W_{\nu\rho}^- A_{\rho\mu} + \tilde{\lambda}_{\gamma} W_{\mu\nu}^+ W_{\nu\rho}^- \tilde{A}_{\rho\mu} \right] + i \frac{g c_{\theta}}{m_W^2} \left[ \lambda_{z} W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu} + \tilde{\lambda}_{z} W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu} \right],$ \n	

⌫ + ˜*<sup>z</sup> Z*˜*µ*⌫ *W*<sup>+</sup>

⌫⇢*Z*⇢*<sup>µ</sup>* + ˜*zW*<sup>+</sup>

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

### Translation to dimension-6 operators takes the same form as *L*Higgs Basis. The dictionary between the coecients of dimension-Franslation to dimension-6 operator  $\frac{1}{2}$ where *v* = ([*c*<sup>0</sup> *<sup>H</sup>*`]<sup>11</sup> + [*c*<sup>0</sup> *<sup>H</sup>*`]22)*/*2 *c*<sup>0</sup> ``. *n*-6 operators *c<sup>B</sup>BB*

*c<sup>Z</sup>*⌫

*<sup>L</sup>* <sup>=</sup> <sup>1</sup>

*c*0

*<sup>H</sup>*` <sup>1</sup>

*cH*`*, cZe*

*<sup>L</sup>* <sup>=</sup> <sup>1</sup>

 $= \left( \left[ c_{H\ell}^{\prime} \right] \right)$ 

*c*0

*<sup>H</sup>*` <sup>1</sup>

 $c'_{H\ell}|_{22}$ 

*cH*`*, cZe*

*<sup>R</sup>* <sup>=</sup> <sup>1</sup>

*cHe,* (4.17)

 $\mathcal{A}^{\text{max}}_{\text{max}}$ 

**g** 

*<sup>H</sup>*` <sup>1</sup>

2

*v* ! *v* (1 + *v*)*,* (4.8)

*cHe* + *f*(0*,* 1)*,* (4.10)

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

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

where

*QcW B*

*g*<sup>2</sup>*g*0<sup>2</sup>

*<sup>L</sup>* <sup>=</sup> <sup>1</sup>

*c*0

*Hq* <sup>1</sup>

*gZu*

*, Q*) = *I*<sup>3</sup>

The shift of  $W$  and  $Z$  boson couplings to leptons are given by  $\mathbb{R}^n$  and  $\mathbb{R}^n$  are given by  $\mathbb{R}^n$ 

where  
\n
$$
f(T^3, Q) = I_3 \left[ -Qc_{WB} \frac{g^2 g'^2}{g^2 - g'^2} + (c_T - \delta v) \left( T^3 + Q \frac{g'^2}{g^2 - g'^2} \right) \right],
$$
\n
$$
\lambda_z = -\frac{3}{2} g^4 c_{3W},
$$
\n
$$
\tilde{\kappa}_{\gamma} = g^2 \tilde{c}_{WB},
$$
\n
$$
\tilde{\kappa}_z = -g'^2 \tilde{c}_{WB},
$$
\n
$$
\tilde{\lambda}_{\gamma} = -\frac{3}{2} g^4 \tilde{c}_{3W},
$$
\n
$$
\tilde{\lambda}_{\gamma} = -\frac{3}{2} g^4 \tilde{c}_{3W},
$$

✓

*cHq* + *f*(1*/*2*,* 2*/*3)*,*

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

*<sup>g</sup>*<sup>2</sup> *<sup>g</sup>*0<sup>2</sup> + (*c<sup>T</sup> v*) *g*<sup>2</sup> *g*0<sup>2</sup> *gZd <sup>L</sup>* <sup>=</sup> <sup>1</sup> 2 and *II*3 incudual cu cupungu cui reupund tu nun nine *c*0 *Hq* <sup>1</sup> 2 *cHq* + *f*(1*/*2*,* 1*/*3)*,*  $\overline{\text{measured}}$  cou 2 1binations of SU3xSU2xU1 in *F*  $\overline{A}$ Directly measured couplings correspond to non-trivial linear combinations of SU3xSU2xU1 invariant operators

*<sup>T</sup>*<sup>3</sup> <sup>+</sup> *<sup>Q</sup> <sup>g</sup>*0<sup>2</sup>

# Warsaw Basis





## Higgs Basis: Pros and Cons

Pros Cons



- 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  $\bigcirc$ 

- 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  $\bullet$ 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) the opservapies (FFI T CC AF)  $t_{\text{max}}$  section for the independent couplings in the independent coupling in terms of  $t_{\text{max}}$  in the independent coupling in terms of  $t_{\text{max}}$ LE ODSEI VUDLES (FFL-T

- 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 concretered is suppressed by  $\Gamma/m$  and sep he neelested operators is suppressed by 17m and can be hegiected. couplings displayed below *hold at the level of the dimension-6 Lagrangian*, and they are vables with  $\boldsymbol{\Sigma}$  of vy bosons on-shell, interference between sive and where operators is suppressed by  $\Gamma/\mathsf{m}$  and can be neqlected
- observables constrained by electroweak precision tests and Higgs searches. However,  $\mathbf{H} = \mathbf{H} \cdot \mathbf{H}$ Corrections from dimension-6 Lagrangian to pole observables can be expressed just by  $\bullet$ is from annehsion-o Lagrangian to pole observables can be exp vertex corrections δg and W mass correction δm other choices can be envisaged, and may be more convenient for other applications.
- I will not assume anything about δg and δm: they are allowed to be arbitrary, flavor dependent, and all can be simultaneously present assume any ining about og and om: they are allowed to be arbitr<br>We can all about a size there are always relevant We choose the following set of independent and dependent couplings relevant, at tree-

level, for precision observables related to Z and W boson decays:

 $S_{\rm eff}$  fermions in Eq. (2.3) and to the W boson mass in Eq. (2.3) and to the W boson mass in Eq. (2.2):  $\alpha$ 

+ 2*m*

as:

where the dependent couplings *g<sup>Z</sup>*⌫

<sup>4</sup> *<sup>W</sup>*<sup>+</sup>

*<sup>µ</sup> W*

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

where all  $g$  are 3  $\mu$  3

*<sup>µ</sup> ,* (3.3)

*<sup>L</sup>* can be expressed by the independent couplings

$$
\mathcal{L}_{\text{ewpt}}^{D=6} = \frac{g}{\sqrt{2}} \left( W_{\mu}^{+} \bar{\nu}_{L} \gamma_{\mu} \delta g_{L}^{W\ell} e_{L} + W_{\mu}^{+} \bar{u} \gamma_{\mu} \delta g_{L}^{Wq} V_{\text{CKM}} d_{L} + W_{\mu}^{+} \bar{u}_{R} \gamma_{\mu} \delta g_{R}^{Wq} d_{R} + \text{h.c.} \right)
$$
  
+ 
$$
\sqrt{g^{2} + g'^{2}} Z_{\mu} \left[ \sum_{f \in u, d, e, \nu} \bar{f}_{L} \gamma_{\mu} \delta g_{L}^{Zf} f_{L} + \sum_{f \in u, d, e} \bar{f}_{R} \gamma_{\mu} \delta g_{R}^{Zf} f_{R} \right]
$$
  
+ 
$$
2 \delta m \frac{g^{2} v^{2}}{4} W_{\mu}^{+} W_{\mu}^{-}, \qquad (3
$$

## Pole observables (LEP-1 et al)

- For observables with Z or W bosons on-shell, interference between SM amplitudes and  $\circledcirc$ 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,  $\alpha$ , Γμ,  $\Rightarrow$  [ Couplings: gL, gY, v

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

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

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

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

# Z-pole observables



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



Table 2: W-boson pole observables. Measurements of the 3 leptonic branching fractions are correlated. For the theoretical predictions of  $m_W$  and  $\Gamma_W$ , 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:

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

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

# w/ new physics:  $\Gamma(Z \to f\bar{f}) = \frac{N_f m_Z}{24\pi} g_{fZ;eff}^2 \Gamma(W \to f\bar{f}') = \frac{N_f m_W}{48\pi} g_{fW,L;eff}^2$

- Including leading order new physics corrections  $\circledcirc$ amount to replacing Z coupling to fermions with effective couplings
- These effective couplings encode the effect of  $\bullet$ 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  $\bullet$ combinations of coefficients of dimension-6 operators
- However, in Higgs basis, oblique corrections are  $\circledcirc$ absent (except for δm) thus δg directly constrained

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

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

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

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

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

### **Pole constraints** correlated. For the theoretical predictions of *m<sup>W</sup>* and *<sup>W</sup>* , we use the best fit SM values from  $\sum_{n=1}^{\infty}$  of  $\sum_{n=1}^{\infty}$  of  $\sum_{n=1}^{\infty}$ contribution vanishes (such as lepton- or quark-flavor violating Z decays), we take into ac-

All diagonal vertex corrections except for δgWqR simultaneously constrained in a completely model-independent way correlations ⇢*ij,*exp (whenever they are quoted). Minimizing <sup>2</sup> with respect to *g* we obtain the count quadratic corrections in *g* because they are the leading ones. In these case, possible corrections from dimension-8 operators are of order *O*(*v*<sup>6</sup>*/*⇤<sup>6</sup>). *••* We suppress the action of the *g* and *m*. In particular, we only the *mass* 

$$
[\delta g_L^{We}]_{ii} = \begin{pmatrix} -1.01 \pm 0.64 \\ -1.37 \pm 0.59 \\ 1.95 \pm 0.79 \end{pmatrix} \cdot 10^{-2}, [\delta g_L^{Ze}]_{ii} = \begin{pmatrix} -0.22 \pm 0.28 \\ 0.1 \pm 1.2 \\ 0.18 \pm 0.58 \end{pmatrix} \cdot 10^{-3}, [\delta g_R^{Ze}]_{ii} = \begin{pmatrix} -0.33 \pm 0.27 \\ 0.0 \pm 1.4 \\ 0.42 \pm 0.62 \end{pmatrix} \cdot 10^{-3},
$$
\n
$$
[\delta g_L^{Zu}]_{ii} = \begin{pmatrix} -0.8 \pm 3.1 \\ -0.17 \pm 0.31 \\ -0.3 \pm 3.8 \end{pmatrix} \cdot 10^{-2}, [\delta g_R^{Zu}]_{ii} = \begin{pmatrix} 1.3 \pm 5.1 \\ -0.37 \pm 0.52 \\ 8 \pm 14 \end{pmatrix} \cdot 10^{-2},
$$
\n
$$
(3.5)
$$
\n
$$
[\delta g_L^{Zd}]_{ii} = \begin{pmatrix} -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \end{pmatrix} \cdot 10^{-2}, [\delta g_R^{Zd}]_{ii} = \begin{pmatrix} 2 \pm 16 \\ 3.4 \pm 4.9 \\ 2.30 \pm 0.87 \end{pmatrix} \cdot 10^{-2}.
$$
\n
$$
(3.6)
$$
\n
$$
\delta m = (2.6 \pm 1.9) \cdot 10^{-4}.
$$

 $\odot$  Z coupling to leptons constrained at 0.1% level Using these central values *g*0, uncertainties *g* and the correlation matrix ⇢ one can re-

*ij* [*g* Efrati,AA,Soreq 1. In concrete extensions of the SM, the vertex of the vertex of the vertex of the  $\sim 1$  H 1503.0xxxx

- W couplings to leptons constrained at 1% level  $\ell$  corrections will be functions of a model parameters. In this case  $\ell$  $\sigma$  couplings to reptons constrained at 1% lever observables depend only on diagonal elements of *g*. Furthermore, corrections proportional to *gW q R* do not interfere with the SM amplitudes; therefore they enter only quadratically and are neglected.
- Some couplings to quarks (bottom, charm) also constrained at 1% level letter coapings to quarks (bortoni, charing also constrained ar *the level*  $A$ l in all, at the tree level, the pole observables depend linearly on  $21$   $\pm$ *<sup>R</sup>* , *gZd*  $\bullet$  Some couplings to quarks (bottom, charm) als
- Some couplings very weakly constrained in a model-independent way, in particular Z coupling to right-handed quarks, and to light quarks  $\overline{z}$  and in the flavor universal case. Due to the relation in Eq. (2.4), the  $\overline{z}$ articular 2 coupling to right-handed yours, and to light you is *Oi,*th = *ONNLO i,*SM <sup>+</sup> ~*<sup>g</sup> · <sup>O</sup>*<sup>~</sup> LO *i*, *i*, *i*, *didn't*, *bonontantoa in* a The state-of-art SM predictions *ONNLO i*, SM are provided in the literature, while the tree-level new trees

# Pole constraints



- 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



Е D<sub>F</sub>



### combinations of the latter can be constrained by the pole observables. We define Pole constraints in Warsaw basis (ˆ*cHU* )*ij* = (*cHU* )*ij* + *c<sup>T</sup> ij ,* (ˆ*cHD*)*ij* = (*cHD*)*ij* <sup>2</sup> *c<sup>T</sup> ij ,* (1.5)

following central values and 1-sigma errors:

$$
(\hat{c}_{HL}^{\prime})_{ij} = (c_{HL}^{\prime})_{ij} + (g_L^2 c_{WB} - \frac{g_L^2}{g_Y^2} c_T) \delta_{ij},
$$
  
\n
$$
(\hat{c}_{HL})_{ij} = (c_{HL})_{ij} - c_T \delta_{ij},
$$
  
\n
$$
(\hat{c}_{HE})_{ij} = (c_{HE})_{ij} - 2c_T \delta_{ij},
$$
  
\n
$$
(\hat{c}_{HQ}^{\prime})_{ij} = (c_{HQ})_{ij} + (g_L^2 c_{WB} - \frac{g_L^2}{g_Y^2} c_T) \delta_{ij},
$$
  
\n
$$
(\hat{c}_{HQ})_{ij} = (c_{HQ})_{ij} + \frac{1}{3} c_T \delta_{ij},
$$
  
\n
$$
(\hat{c}_{HU})_{ij} = (c_{HU})_{ij} + \frac{4}{3} c_T \delta_{ij},
$$
  
\n
$$
(\hat{c}_{HD})_{ij} = (c_{HD})_{ij} - \frac{2}{3} c_T \delta_{ij},
$$
  
\n
$$
(\hat{c}_{HD})_{ij} = (c_{HD})_{ij} - \frac{2}{3} c_T \delta_{ij},
$$
  
\n
$$
(\hat{c}_{HD})_{ij} = (c_{HD})_{ij} - \frac{2}{3} c_T \delta_{ij},
$$
  
\n
$$
(c_{HD})_{ij} = (c_{HD})_{ij} - \frac{2}{3} c_T \delta_{ij},
$$

The pole observable constrain all 21 diagonal elements of ˆ*c*. For these combinations, we obtain the

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

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

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

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

We stress that only the combinations in Eq. (1.5) are stress that observables. In Eq. (1.5) are stress that  $\mathcal{C}$ Conversely, the pole observables calculated in the Warsaw basis are completely independent on the Wilson coecients along the flat directions defined by [ˆ*cHF* ]*ii* = 0. Therefore, individually, *cHF* ,

The pole observable constrain all 21 diagonal elements of ˆ*c*. For these combinations, we obtain the

### Only c-hat combinations can be constrained! @ 0nlv 1*.*4 *±* 1*.*3 *c*-hat combinations can be constrained! *Standard Model Lagrangian*, *JHEP* 1010 (2010) 085, [arXiv:1008.4884].

# Flat directions of pole observables

Gupta et al, [1405.0181](http://arxiv.org/abs/arXiv:1405.0181)

- Pole observables depend, at linear level, on 30  $\circledcirc$ dimension-6 operators in Warsaw basis
- One can constrain only 27 combinations of EFT  $\bigcirc$ parameters: c-hats to the right
- Only combinations of vertex and oblique  $\circledcirc$ corrections are constrained, not separately The pole observable constrain all 21 diagonal elements of ˆ*c*. For these combinations, we obtain the
- This leaves 2 flat EFT directions  $\bullet$
- These 2 directions are related to usual S and T  $\circledcirc$ parameters
- From pole observables alone there's no model  $\bigcirc$ independent constraints on S and T!

Cacciapaglia et al hep-ph/0604111

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

combinations of the latter can be constrained by the pole observables. We define

# The flat directions arise due to EFT operator identities Flat directions of pole observables

$$
O_W = iH^{\dagger} \sigma^i \overleftrightarrow{D_{\mu}} H D_{\nu} W_{\mu\nu}^i = \frac{g_L^2}{2} O_{Hq}^{\prime} + \frac{g_L^2}{2} O_{H\ell}^{\prime}.
$$
  
\n
$$
O_B = iH^{\dagger} \overleftrightarrow{D_{\mu}} H \partial_{\nu} B_{\mu\nu} = -g_Y^2 \left( -2O_T + \frac{1}{6} O_{Hq} + \frac{2}{3} O_{Hu} - \frac{1}{3} O_{Hd} - \frac{1}{2} O_{H\ell} - O_{He} \right)
$$

- Obviously, operators OW and OB do not affect Z and W couplings to fermions  $\circledcirc$
- They only affect gauge boson propagators (same way as OWB) and Higgs couplings to  $\circledcirc$ gauge bosons. Moreover, OW affects triple gauge couplings
- They are not part of Warsaw basis, because they are redundant with vertex  $\odot$ corrections.
- Conversely, this means that there are 2 combinations of vertex corrections whose  $\bullet$ 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  $\bigcirc$

Constraints from WW production at LEP-2

# WW production

## WW production at LEP-2



Figure 1.4: Feynman diagrams (Constitute 1.4: Februar 1.4: Feynman diagrams (CO23) for the Process et the Born Level. Depends on triple gauge couplings

- $\epsilon^{\scriptscriptstyle +}$ ana  $\angle\!\!\!\!\sqrt{ \rho}$ osons ana on opera e e W and Z bosons and on operators modifying EW Also depends on electron and neutrino couplings to gauge boson propagators
- ndirectly,∧depe Z Indirectly, depends on operators shifting the SM reference parameters (GF, α, mZ)

### $e+e \rightarrow$  W+W- nuts and bolts W+W− nuts and bolts  $\mathbf{M}$ where t = (pe<sup>−</sup> − pW<sup>−</sup>)<sup>2</sup> , "'s are polarization vectors of W<sup>±</sup>, and x, y are spinor wave-functions of

$$
\mathcal{M} = \mathcal{M}_t + \sum_{\mathbf{V} = \boldsymbol{\gamma}, \mathbf{Z}} \mathcal{M}_s^{\mathbf{V}} \qquad \qquad \mathcal{M}_t = -\frac{g_{\ell W, L; \text{eff}}^2}{2t} \bar{\epsilon}_{\mu}(p_{W^-}) \bar{\epsilon}_{\nu}(p_{W^+}) \bar{y}(p_{e^+}) \bar{\sigma}_{\nu} \sigma \cdot (p_{e^-} -
$$

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

It is the same coupling that determines the W decay width into leptons, therefore this part of the

 $\mathcal{L}_\mathcal{D}$  ,  $\mathcal{L}_\mathcal{D}$  , performing is generally diagram, the effective coupling is gev; effective coupling  $\mathcal{L}_\mathcal{D}$ 

where  $\omega$  is given the effective TGCs are defined as a gluenos of equations of  $\omega$  . The effective TGCs are defined as a gluenos of  $\omega$ 

where t = (pe<sup>−</sup> − pW<sup>−</sup>)<sup>2</sup>  $\mathcal{M}^V_s=-\frac{1}{2}\left[g_{eV,L;{\rm eff}}\bar y(p_{e^+})\bar\sigma_o x(p_{e^-})+g_{eV,R;{\rm eff}}x(p_{e^+})\sigma_o\bar y(p_{e^-})\right]\bar\epsilon_u(p_{W^-})\bar\epsilon_\nu(p_{W^+})F^V_{\mu\nu o},$  $t = m_V$  ${\cal M}^V_s=-\frac{1}{s-s}$  $s - m_V^2$  $\left[g_{eV,L;\text{eff}}\bar{y}(p_{e^+})\bar{\sigma}_\rho x(p_{e^-})+g_{eV,R;\text{eff}}x(p_{e^+})\sigma_\rho\bar{y}(p_{e^-})\right]\bar{\epsilon}_\mu(p_{W^-})\bar{\epsilon}_\nu(p_{W^+})F^V_{\mu\nu\rho},$  $\mathcal{M}^V = \frac{1}{(q_{\text{max}} - \bar{q}(p_{\text{min}}) \bar{\sigma} x(p_{\text{min}}) + q_{\text{max}} - \bar{q}(p_{\text{min}}) \bar{\sigma} (p_{\text{min}}) \bar{\sigma} (p_{$  $\int s - m_V^2 \int \frac{1}{2} eV, L; \text{erf } g \left( Pe^+ \right) \circ \rho^{\omega} \left( Pe^- \right) + \int \frac{1}{2} eV, R; \text{erf } \omega \left( Pe^+ \right) \circ \rho g \left( Pe^- \right) \left[ \frac{1}{2} \rho \left( Pe^+ \right) \right]$ the triple gauge boson vertex function:

where s = (pe+ )2. For the photon diagram, the photon diagram, the effective coupling is gev;effective coupling is g<br>The effective coupling is general to the effective coupling is general to the effective coupling is get

 $\mathcal{L}=\mathcal{L}^2+\mathcal{L}$ 

The remaining part of the amplitude describes the s-channel photon and Z exchange:  $\mathcal{L}(\mathcal{L})$ 

$$
F_{\mu\nu\rho}^{V} = g_{1,V;\text{eff}} \left[ \eta_{\rho\mu} p_{W^{-}}^{\nu} - \eta_{\rho\nu} p_{W^{+}}^{\mu} + \eta_{\mu\nu} (p_{W^{+}} - p_{W^{-}})_{\rho} \right] + \kappa_{V;\text{eff}} \left[ \eta_{\rho\mu} (p_{W^{+}} + p_{W^{-}})_{\nu} - \eta_{\rho\nu} (p_{W^{+}} + p_{W^{-}})_{\mu} \right] + \frac{g_{VWW}\lambda_{V}}{m_{W}^{2}} \left[ \eta_{\rho\mu} (p_{W^{+}}(p_{W^{+}} + p_{W^{-}}) p_{W^{-}}^{\nu} - p_{W^{+}} p_{W^{-}}(p_{W^{+}} + p_{W^{-}})_{\nu} \right) + \eta_{\rho\nu} (p_{W^{+}}p_{W^{-}}(p_{W^{+}} + p_{W^{-}})_{\mu} - p_{W^{-}}(p_{W^{+}} + p_{W^{-}}) p_{W^{+}}^{\mu}) \right].
$$
\n(21)

WW production amplitude depends on the  $e_{\text{eff}} = \frac{3L3T}{\sqrt{2+2}}$ 0  $\overline{\mathsf{eff}}$ Mand g∨ same effective couplings gZeff and gWeff as  $\sqrt{g^2_L+g^2_{Y}}\,\sqrt{1-\delta\Pi_{\infty}^{(2)}}$  $\cdot$  9.100 the pole observables and avoids dealing with the complicated tensor structure of gauge boson self-interactions introduced by O2<sup>W</sup> .

where grows are grown as equipment of the equipment of the equipment of the effective Table as a construction

- It also depends on effective electromagnetic  $\int g_{1,\gamma;\text{eff}} = e_\text{eff}, \quad \kappa_{\gamma;\text{eff}} = e_\text{eff}$  [1 - $\circledcirc$ couplings which does not change in the  $q_{1,2,eff} = \frac{g_L \cos \theta_W}{\sqrt{1 + e \delta}} [1 + e \delta]$ go winch does not change in the  $g_{1,Z;eff} = \frac{1 + e^{-\lambda t}}{\sqrt{2\pi}} [1 + e^{-\lambda t}]$ presence of dimension-6 operators
- Finally, it depends on 3 effective triple gauge lU Ô couplings This accounts for the correction to the Correction to the WW production cross section due to oblique corrections  $\mathcal{E}_{\mathcal{E}}$

tude depends on the  
ngs gZeff and gWeff as  

$$
\cos \frac{f}{f} = \frac{g_L g_Y}{\sqrt{g_L^2 + g_Y^2}} \frac{1}{\sqrt{1 - \delta \Pi_{\gamma\gamma}^{(2)}}}
$$

, "where  $\sim$  are polarization vectors of W $_{\rm{eff}}$  and  $\sim$  and  $\sim$  and  $\sim$   $\sim$   $\sim$   $\sim$   $\sim$ 

e

**nagnetic**

\n
$$
g_{1,\gamma; \text{eff}} = e_{\text{eff}}, \quad \kappa_{\gamma; \text{eff}} = e_{\text{eff}} \left[ 1 + \delta \kappa_{\gamma} \right],
$$
\n**he**

\n
$$
g_{1,Z; \text{eff}} = \frac{g_L \cos \theta_W}{\sqrt{1 - \delta \Pi_{ZZ}^{(2)}}} \left[ 1 + e \delta \Pi_{\gamma Z}^{(2)} \right] \left[ 1 + \delta g_{1,Z} \right],
$$
\n**he**

\n
$$
\kappa_{Z; \text{eff}} = \frac{g_L \cos \theta_W}{\sqrt{1 - \delta \Pi_{ZZ}^{(2)}}} \left[ 1 + e \delta \Pi_{\gamma Z}^{(2)} \right] \left[ 1 + \delta \kappa_Z \right].
$$

to the propagators of electroweak gauge bosons and Z-γ mixing, while vertex corrections are

accounted for in the definition of gas with an experimental generators the presence of dimension-6 operators t

# e+e-→W+W- in Higgs basis

- Again, in Higgs basis things greatly simplify thanks to lack of oblique corrections  $\circledcirc$
- Usual triple gauge couplings become directly related to observable WW production  $\circledcirc$ cross section
- At dimension-6 level, the process depends on 3 vertex corrections to Z and W  $\circledcirc$ 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  $\circledcirc$ enter quadratically and can be ignored, leaving only 3 TGCs

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

 $\Gamma$ 

 $D$   $c$ 

$$
\begin{aligned} \delta \kappa_z =& \delta g_{1,z} - t_\theta^2 \delta \kappa_\gamma \\ \tilde{\kappa}_z =& - t_\theta^2 \tilde{\kappa}_\gamma \\ \lambda_\gamma =& \lambda_z \\ \tilde{\lambda}_\gamma =& \tilde{\lambda}_z \end{aligned}
$$

$$
\mathcal{L}_{\text{tgc}}^{\text{D=6}} = ie \left[ \delta \kappa_{\gamma} A_{\mu\nu} W_{\mu}^{+} W_{\nu}^{-} + \tilde{\kappa}_{\gamma} A_{\mu\nu} W_{\mu}^{+} W_{\nu}^{-} \right]
$$
\n
$$
+ ig_{L} c_{\theta} \left[ \delta g_{1,z} \left( W_{\mu\nu}^{+} W_{\mu}^{-} - W_{\mu\nu}^{-} W_{\mu}^{+} \right) Z_{\nu} + \delta \kappa_{z} Z_{\mu\nu} W_{\mu}^{+} W_{\nu}^{-} + \tilde{\kappa}_{z} \tilde{Z}_{\mu\nu} W_{\mu}^{+} W_{\nu}^{-} \right]
$$
\n
$$
+ i \frac{e}{m_{W}^{2}} \left[ \lambda_{\gamma} W_{\mu\nu}^{+} W_{\nu\rho}^{-} A_{\rho\mu} + \tilde{\lambda}_{\gamma} W_{\mu\nu}^{+} W_{\nu\rho}^{-} \tilde{A}_{\rho\mu} \right] + i \frac{g_{L} c_{\theta}}{m_{W}^{2}} \left[ \lambda_{z} W_{\mu\nu}^{+} W_{\nu\rho}^{-} Z_{\rho\mu} + \tilde{\lambda}_{z} W_{\mu\nu}^{+} W_{\nu\rho}^{-} Z_{\rho\mu} \right]
$$

 $\mathbf{r}$ 

# WW production constraints

- Precision of WW measurements is only O(1)% in LEP-2, compared with O(0.1%)  $\bullet$ precision of LEP measurement of leptonic vertex corrections
- Therefore the relevant vertex corrections are already strongly constrained in a  $\odot$ 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  $\bigcirc$ section at different energies of LEP-2
- Single W production cross section at different  $\bullet$ energies of LEP-2



Figure 1.4: Feynman diagrams (CC03) for the process e<sup>+</sup>e<sup>−</sup> → W<sup>+</sup>W<sup>−</sup> at the Born level.





## Constraints from VV production Fitting to following data: 204.9 0.34 + 0.34 + 0.31 + 0.33 + 0.33 + 0.31 + 0.33 + 0.31 + 0.33 + 0.33 + 0.33 + 0.35 + 0.31 + 0.31 + 0.31 +  $2000U$ CTION $2000$

 $e^+$ 

 $W^+$ 

γ Total and differential WW production cross  $\circledcirc$ section at different energies of LEP-2 e− W<sup>−</sup> e−

Single W production cross section at different energies of LEP-2  $\frac{1}{2}$  imaging the production diagrams section at university examples  $\frac{1}{2}$ involving quartic electroweak-gauge-boson vertices.





e<sub>+</sub>





## Constraints from WW production Central values and 1 sigma errors: AA,Riva 1411.0669

 $\delta g_{1,Z} = -0.83 \pm 0.34, \ \delta \kappa_\gamma = 0.14 \pm 0.05, \ \lambda_Z = 0.86 \pm 0.38, \quad \rho = \left( \begin{array}{ccc} 1 & -0.71 & -0.997 \ . & 1 & 0.69 \ . & . & 1 \end{array} \right)$ 

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

[see also](http://arxiv.org/abs/arXiv:1405.1617) [1405.1617](http://arxiv.org/abs/arXiv:1405.1617)

- This implies that dimension-6 operator coefficients are constrained at the  $\ddot{\circ}$ O(1) level
- In fact, the limits are sensitive to whether terms quadratic in dimension-6  $\circledcirc$ operator are included or not
- This in turn implies that the limits might be affected by dimension-8  $\circledcirc$ operators if, as expected from EFT counting, c8∼c6^2

# Constraints from WW production Central values and 1 sigma errors:

 $\delta g_{1,Z} = -0.83 \pm 0.34, \; \delta \kappa_\gamma = 0.14 \pm 0.05, \; \lambda_Z = 0.86 \pm 0.38, \quad \rho = \left( \begin{array}{ccc} 1 & -0.71 & -0.997 \ . & 1 & 0.69 \ . & . & 1 \end{array} \right)$ 

- These limits can be affected by dimension-8 operators if, as expected from  $\circledcirc$ 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  $\bullet$ corresponding operator O3W can be generated only at the loop level
- For λZ=0 much stronger limits follow:

 $\delta \hat{g}_{1,Z} = -0.06 \pm 0.03, \quad \delta \hat{\kappa}_{\gamma} = 0.06 \pm 0.04, \quad \rho = \left( \begin{array}{cc} 1 & -0.50 \ . & 1 \end{array} \right)$ 

### TGC - Higgs Synergy duction In order to describe WW and WZ production processes we need, apart from the vertex correction introduced introduced in Section 3.1, the following independent and dependent and dependent couplings: Independent : *z,* ˜*z,* Dependent : *g*1*,z, , z, ,* ˜*,* ˜*z,* ˜*.* (3.12)

**Independent**:  
\n
$$
\mathcal{L}_{\text{tgc}}^{\text{D=6}} = ie \left[ \delta \kappa_{\gamma} A_{\mu\nu} W_{\mu}^{+} W_{\nu}^{-} + \tilde{\kappa}_{\gamma} \tilde{A}_{\mu\nu} W_{\mu}^{+} W_{\nu}^{-} \right]
$$
\n**Dependent**:  
\n
$$
ig_{1,z}, \delta \kappa_{\gamma}, \delta \kappa_{z}, \lambda_{\gamma}, \tilde{\kappa}_{\gamma}, \tilde{\kappa}_{z}, \tilde{\lambda}_{\gamma}.
$$
\n+ 
$$
ig_{\mathcal{C}\theta} \left[ \delta g_{1,z} \left( W_{\mu\nu}^{+} W_{\mu}^{-} - W_{\mu\nu}^{-} W_{\mu}^{+} \right) Z_{\nu} + \delta \kappa_{z} Z_{\mu\nu} W_{\mu}^{+} W_{\nu}^{-} + \tilde{\kappa}_{z} \tilde{Z}_{\mu\nu} W_{\mu}^{+} W_{\nu}^{-} \right]
$$
\n+ 
$$
i \frac{e}{m_W^2} \left[ \lambda_{\gamma} W_{\mu\nu}^{+} W_{\nu\rho}^{-} A_{\rho\mu} + \tilde{\lambda}_{\gamma} W_{\mu\nu}^{+} W_{\nu\rho}^{-} \tilde{A}_{\rho\mu} \right] + i \frac{g_{\mathcal{C}\theta}}{m_W^2} \left[ \lambda_{z} W_{\mu\nu}^{+} W_{\nu\rho}^{-} Z_{\rho\mu} + \tilde{\lambda}_{z} W_{\mu\nu}^{+} W_{\nu\rho}^{-} Z_{\rho\mu} \right],
$$
\n
$$
\delta g_{1,z} = -\frac{g^2 + g'^2}{2} \left( c_{\gamma \gamma} \frac{e^2}{g^2 + g'^2} + c_{z \gamma} \frac{g^2 - g'^2}{g^2 + g'^2} - c_{z z} \right) + \frac{g^2 + g'^2}{2g'^2} (\delta c_{z} - \delta c_{w} + 4\delta m),
$$
\n
$$
\delta \kappa_{\gamma} = -\frac{g^2}{2} \left( c_{\gamma \gamma} \frac{e^2}{g^2 + g'^2} + c_{z \gamma} \frac{g^2 - g'^2}{g^2 + g'^2} - c_{z z} \right),
$$
\n
$$
\tilde{\kappa}_{\gamma} = -\
$$

- In Higgs basis formalism, all but 2 TGCs are dependent couplings and can be  $\circledcirc$ acio romanom, an sar super cos are appendent coapmigo at expressed by Higgs couplings to gauge bosons
- motivation is that the Higgs basis should be parametrized such that the connection Therefore constraints on δg1z and δκγ imply constraint on Higgs couplings. Note  $\circledcirc$ constraints on Oqlz and OKY imply constraint on Higgs co that cZY and cZZ are especially difficult to access experimentally in Higgs physics example, one could chose the independent couplings as *g*1*,z*, , *z*, ˜, ˜*z*, and consider
- Important to combine Higgs and TGC data!  $\ddot{\circ}$ 3.4 Couplings relevant for Higgs pair production



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