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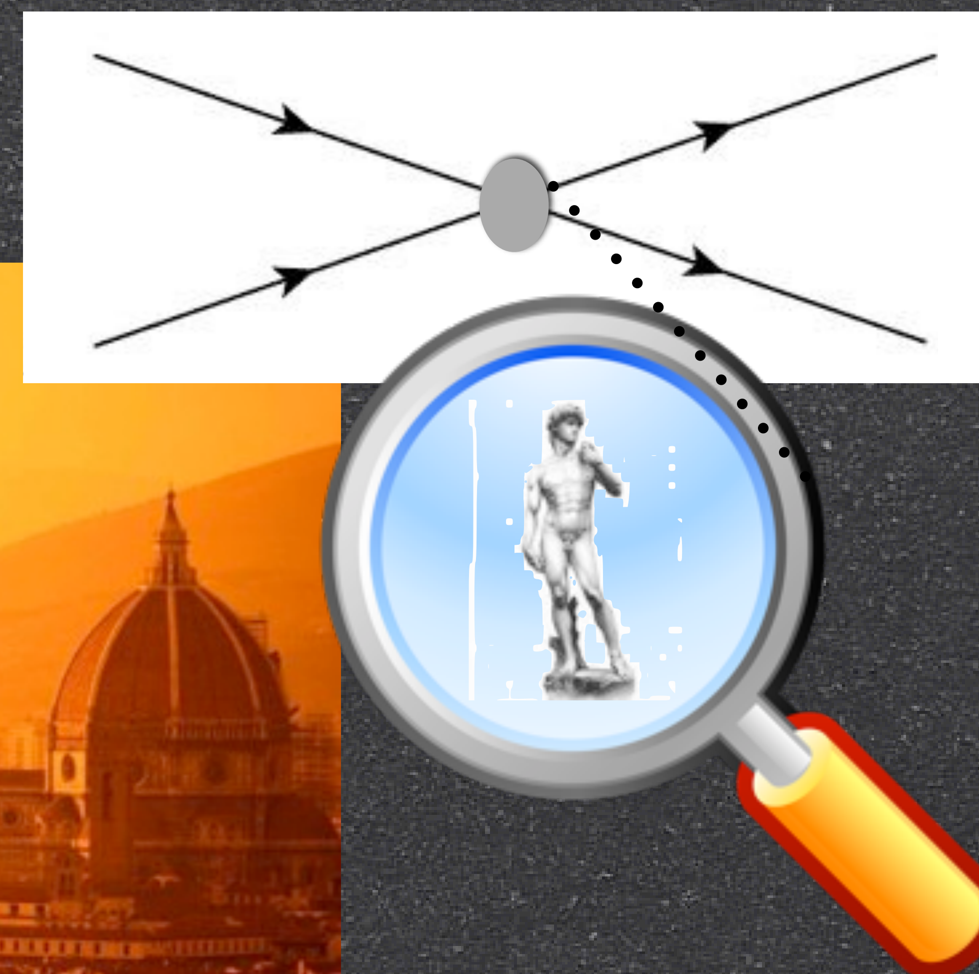
Model Independent Constraints on Physics Beyond the Standard Model



Based on my 1505.00046, 1503.07872 with Aielet Efrati and Yotam Soreq, 1411.0669 with Francesco Riva, and 1508.00581 with Martín Gonzalez-Alonso, Admir Greljo, and David Marzocca

Plan

- Effective field theory approach
  to physics beyond the standard model

- Current precision constraints:
  - from LEP-1 pole observables
  - from LHC Higgs data and LEP-2 WW production
  - from LEP-2 ee->ll scattering (preview)

Effective Field Theory approach to BSM physics

Premise

- SM is probably a correct theory the weak scale, at least as the lowest order term in an effective theory expansion
- If new particles are heavy, their effects can be parametrized by higher-dimensional operators added to the SM Lagrangian
- EFT framework offers a systematic expansion around the SM organized in terms of operator dimensions, with higher dimensional operator suppressed by the mass scale Λ of new physics

Effective Theory Approach to BSM

Basic assumptions

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

- 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

EFT Lagrangian beyond the SM expanded in operator dimension D

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}^{D=5} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \frac{1}{\Lambda^3}\mathcal{L}^{D=7} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \dots$$

Alternatively,
non-linear Lagrangians
with derivative expansion

Effective Theory Approach to BSM

Basic assumptions

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

EFT Lagrangian beyond the SM expanded in operator dimension D

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}^{D=5}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \cancel{\frac{1}{\Lambda^3}\mathcal{L}^{D=7}} + \cancel{\frac{1}{\Lambda^4}\mathcal{L}^{D=8}} + \dots$$

Lepton number violating, hence too small to probe at LHC

By assumption, subleading to D=6

EFT approach to BSM

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

Buchmuller,Wyler pre-arxiv (1986)

- First complete and 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

D=6 Basis

For D=6 Lagrangian several complete non-redundant set of operators (so-called basis) proposed in the literature

SILH basis — Giudice et al hep-ph/0703164, Contino et al 1303.3876

HISZ basis — Hagiwara et al (1993)

$$\mathcal{L}^{D=6}$$

h basis — LHCHXSWG-INT-2015-001

Warsaw Basis — Grządkowski et al. 1008.4884

Primary basis — Gupta et al 1405.0181

- All bases are equivalent, but some may be more ~~equivalent~~ convenient for specific applications
- Physics description (EWPT, Higgs, RG running) in any of these bases contains the same information, provided all operators contributing to that process are taken into account

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

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}	$i\bar{e}\gamma_\mu \bar{e} H^\dagger \overleftrightarrow{D}_\mu H$
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}	$i\bar{u}\gamma_\mu d \widetilde{H}^\dagger D_\mu H$

f^2VHD

O_{eW}	$g\bar{\ell}\sigma_{\mu\nu}e\sigma^i HW^i_{\mu\nu}$
O_{eB}	$g'\bar{\ell}\sigma_{\mu\nu}eHB_{\mu\nu}$
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}	$g_s\bar{q}\sigma_{\mu\nu}T^a dH\, G^a_{\mu\nu}$
O_{dW}	$g\bar{q}\sigma_{\mu\nu}d\sigma^i H\, W^i_{\mu\nu}$
O_{dB}	$g'\bar{q}\sigma_{\mu\nu}dH\, B_{\mu\nu}$

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

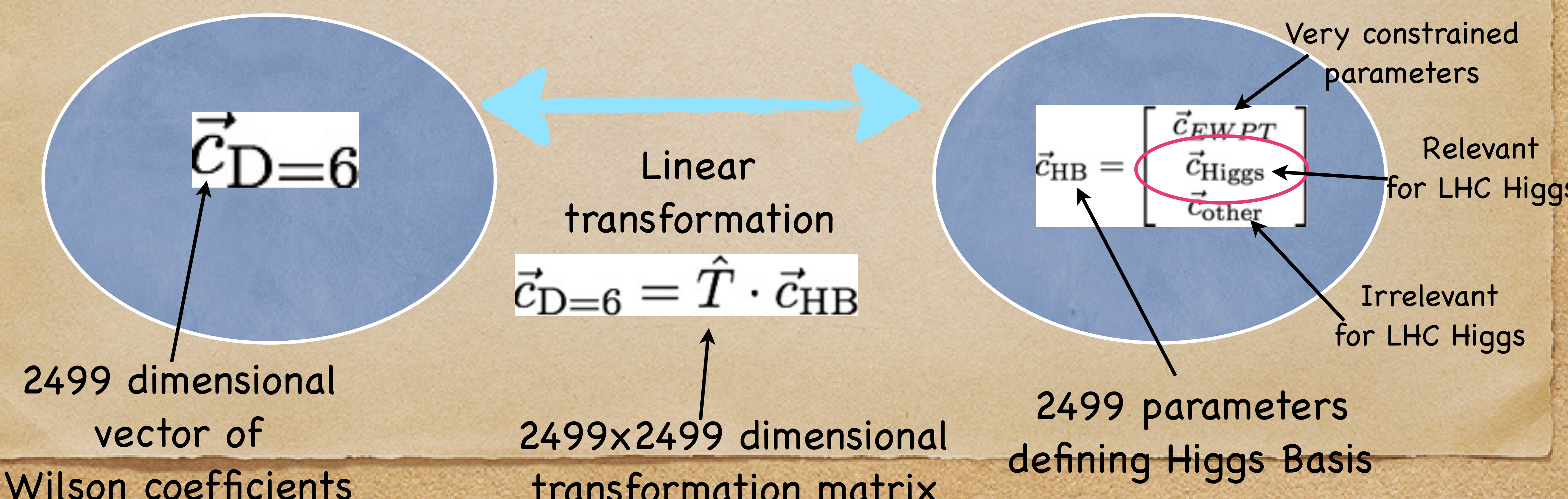
Alonso et al 1312.2014

Similar "EFT Primaries" of Gupta et al 1405.0181

LHCHXSWG-INT-2015-001

h-basis

- Connection between operators and observables a bit obscured in Warsaw or SILH basis. Also, in Warsaw basis EW precision constraints look complicated
- h-basis proposed by LHCHXSWG2 to separate combinations of Wilson coefficients strongly constrained by EWPT from those relevant for LHC Higgs studies
- Rotation of any other D=6 basis such that one isolates linear combinations affecting Higgs observables and not constrained severely by precision tests



h-basis Lagrangian

- h-basis is defined via effective Lagrangian of mass eigenstates after electroweak symmetry breaking (photon,W,Z,Higgs boson, top). SU(3)xSU(2)xU(1) is not manifest but hidden in relations between different couplings

- Feature #1: In the tree-level Lagrangian, all kinetic terms are canonically normalized, and there's no kinetic mixing between mass eigenstates. In particular, all oblique corrections from new physics are zero, except for a correction to the W boson mass

$$\mathcal{L}_{\rm kin} = -\frac{1}{2}W^+_{\mu\nu}W^-_{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z_{\mu\nu} - \frac{1}{4}A_{\mu\nu}A_{\mu\nu} + (1+2\delta m)m_W^2 W^+_\mu W^-_\mu + \frac{m_Z^2}{2}Z_\mu Z_\mu$$

- Feature #2: Tree-level relation between the couplings in the Lagrangian and SM input observables is the same as in the SM. In particular, photon and gluon couple as in SM, and there's no correction to Z mass term

$$m_Z = \frac{\sqrt{g_L^2+g_Y^2}\,v}{2}$$
$$\alpha = \frac{g_L g_Y}{\sqrt{g_L^2+g_Y^2}}$$
$$\tau_\mu = \frac{384\pi^3 v^4}{m_\mu^5}$$

- Features #1 and #2 can always be obtained without any loss of generality, via integration by parts, fields and couplings redefinition

h-Basis: Z and W couplings to fermions

$$\mathcal{L} \supset \frac{g_L g_Y}{\sqrt{g_L^2 + g_Y^2}} Q_f A_\mu \bar{f} \gamma_\mu f + g_s G^a_\mu \bar{q} \gamma_\mu T^a q$$

- By construction, photon and gluon couplings as in the SM. Only W and Z couplings are affected
- Effects of dimension-6 operators are parametrized by a set of vertex corrections

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

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

$$\mathcal{L}_{vff} = \frac{g_L}{\sqrt{2}} \left(W_\mu^+ \bar{u} \bar{\sigma}_\mu (V_{\rm CKM} + \delta g_L^{Wq}) d + W_\mu^+ u^c \sigma_\mu \delta g_R^{Wq} \bar{d}^c + W_\mu^+ \bar{\nu} \bar{\sigma}_\mu (I + \delta g_L^{W\ell}) e + \text{h.c.} \right)$$
$$+ \sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f \in u,d,e,\nu} \bar{f} \bar{\sigma}_\mu (T^3_f - s_\theta^2 Q_f + \delta g_L^{Zf}) f + \sum_{f^c \in u^c, d^c, e^c} f^c \sigma_\mu (-s_\theta^2 Q_f + \delta g_R^{Zf}) \bar{f}^c \right]$$

Dependent Couplings:

Relations enforced by
linearly realized SU(3)xSU(2)xU(1) symmetry
at the level of dimension-6 operators

$$\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{W\ell}$$
$$\delta g_L^{Wq} = \delta g_L^{Zu} V_{\rm CKM} - V_{\rm CKM} \delta g_L^{Zd}$$

h-Basis: Higgs couplings to matter

- In HB, Higgs couplings to gauge bosons described by 6 CP even and 4 CP odd parameters that are unconstrained by LEP-1

$$\text{CP even}: \quad \delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg}$$
$$\text{CP odd}: \quad \tilde{c}_{zz} \quad \tilde{c}_{z\gamma} \quad \tilde{c}_{\gamma\gamma} \quad \tilde{c}_{gg}$$

$$\begin{aligned}
\mathcal{L}_{\rm hvv} =& \frac{h}{v}[2(1+\delta c_w)m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z)m_Z^2 Z_\mu Z_\mu \\
&+ c_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g_L^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\
&+ c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e g_L}{2c_\theta}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}Z_{\mu\nu} \\
&+ c_{z\Box} g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g_L g_Y Z_\mu \partial_\nu A_{\mu\nu} \\
&+ \tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e g_L}{2c_\theta}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}\tilde{Z}_{\mu\nu}]
\end{aligned}$$

- D=6 EFT with linearly realized SU(3)xSU(2)xU(1) enforces relations between Higgs couplings to gauge bosons (otherwise, more parameters)

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

relative correction to W mass

- Corrections to Higgs Yukawa couplings to fermions are also unconstrained by EWPT

- Apart from δm and δg, additional 6+3x3x3 CP-even and 4+3x3x3 CP-odd parameters to parametrize LHC Higgs physics

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$$\text{CP even}: \quad \delta y_u \quad \delta y_d \quad \delta y_e$$
$$\text{CP odd}: \quad \phi_u \quad \phi_d \quad \phi_e$$

$$\mathcal{L}_{\rm hff} = -\sum_{f=u,d,e} m_f f^c (I + \delta y_f e^{i\phi_f}) f + \text{h.c.}$$

h-basis: Triple Gauge Couplings

SM predicts TGCs in terms of gauge couplings
as consequence of SM gauge symmetry and renormalizability:

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

In EFT with D=6 operators, new "anomalous" contributions to TGCs arise

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

These depend on previously introduced h-basis parameters describing Higgs couplings to electroweak gauge bosons, and on 2 new parameters

$$\mathrm{CP-even}: \quad \lambda_z$$

$$\mathrm{CP-odd}: \quad \tilde{\lambda}_z$$

$$\delta g_{1,z} = \frac{1}{2(g_L^2 - g_Y^2)}\left[c_{\gamma\gamma} e^2 g_Y^2 + c_{z\gamma}(g_L^2 - g_Y^2) g_Y^2 - c_{zz}(g_L^2 + g_Y^2) g_Y^2 - c_{z\Box}(g_L^2 + g_Y^2) g_L^2\right]$$

$$\delta\kappa_\gamma = -\frac{g_L^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g_L^2 + g_Y^2} + c_{z\gamma}\frac{g_L^2 - g_Y^2}{g_L^2 + g_Y^2} - c_{zz}\right),$$

$$\tilde{\kappa}_\gamma = -\frac{g_L^2}{2}\left(\tilde{c}_{\gamma\gamma}\frac{e^2}{g_L^2 + g_Y^2} + \tilde{c}_{z\gamma}\frac{g_L^2 - g_Y^2}{g_L^2 + g_Y^2} - \tilde{c}_{zz}\right)$$

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

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

In the rest of the talk I will discuss constraints on the parameters in the h-basis

Model-independent precision constraints on dimension 6 operators

Analysis Assumptions

- Working at order $1/\Lambda^2$ in EFT expansion. Taking into account corrections from D=6 operators, and neglecting D=8 and higher operators. (Only taking into account corrections to observables that are linear in h-basis parameters, that is to say, only interference terms between SM and new physics. Quadratic corrections are formally of order $1/\Lambda^4$, much as D=8 operators that are neglected.)

- Working at tree-level in EFT parameters (SM predictions taken at NLO or NNLO, but only interference of tree-level BSM corrections with tree-level SM amplitude taken into account)

- Except on las slide, restrict to observables that do not depend on 4-fermion operators (they are *not* neglected - just do not contribute at tree-level; constraints on 4-fermion operators left for future work)

- Allowing all dimension-6 operators to be present simultaneously with arbitrary coefficients (within EFT validity range). Constraints are obtained on all parameters affecting EWPT and Higgs at tree level, and correlations matrix is computed.

  Han,Skiba
  hep-ph/0412166

- Unless otherwise noted, dimension-6 operators are allowed with arbitrary flavor structure

  Efrati,AA,Soreq
  1503.07782

Constraints
on Vertex Corrections
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: they are allowed to be arbitrary, flavor dependent, and all can be simultaneously present

$$\mathcal{L}_{vff} = \frac{g_L}{\sqrt{2}}\left(W_\mu^+ \bar{u}\bar{\sigma}_\mu (V_{\rm CKM} + \delta g_L^{Wq}) d + W_\mu^+ u^c \sigma_\mu \delta g_R^{Wq} \bar{d}^c + W_\mu^+ \bar{\nu}\bar{\sigma}_\mu (I + \delta g_L^{W\ell}) e + \text{h.c.}\right)$$
$$+ \sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f\in u,d,e,\nu} \bar{f}\bar{\sigma}_\mu (T_f^3 - s_\theta^2 Q_f + \delta g_L^{Zf}) f + \sum_{f^c \in u^c, d^c, e^c} f^c \sigma_\mu (-s_\theta^2 Q_f + \delta g_R^{Zf}) \bar{f}^c\right]$$

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:

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

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

$$g_{fW,L;\mathrm{eff}} = \frac{g_{L0}}{\sqrt{1 - \delta\Pi'_{WW}(m_W^2)}}\left(1 + \delta g_L^{Wf}\right)$$

$$g_{fZ;\mathrm{eff}} = \frac{\sqrt{g_{L0}^2 + g_{Y0}^2}}{\sqrt{1 - \delta\Pi'_{ZZ}(m_Z^2)}}\left(T_f^3 - s_{\mathrm{eff}}^2 Q_f + \delta g^{Zf}\right)$$

$$s_{\mathrm{eff}}^2 = \frac{g_{Y0}^2}{g_{L0}^2 + g_{Y0}^2}\left(1 - \frac{g_L}{g_Y}\frac{\delta\Pi_{\gamma Z}(m_Z^2)}{m_Z^2}\right)$$

- 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 h-basis, oblique corrections are absent (except for δm) thus δg directly constrained

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

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

Z-pole observables

Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[21]	2.4950	$\sum_f \Gamma(Z \to f\bar{f})$
$\sigma_{\rm had}$ [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	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025	[21]	0.0163	$\frac{3}{4}A_e^2$
$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013	[21]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\rm FB}^{0,\tau}$	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	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
$A_b^{\rm FB}$	0.0992 ± 0.0016	[21]	0.1032	$\frac{3}{4}A_e A_b$
$A_c^{\rm FB}$	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	$\frac{\Gamma(Z\to b_L\bar{b}_L)-\Gamma(Z\to b_R\bar{b}_R)}{\Gamma(Z\to b\bar{b})}$
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	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$

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].

Pole observables - constraints

Efrati,AA,Soreq
1503.07872

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

$$[\delta g_L^{We}]_{ii} = \begin{pmatrix} -1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \end{pmatrix} \times 10^{-2},$$

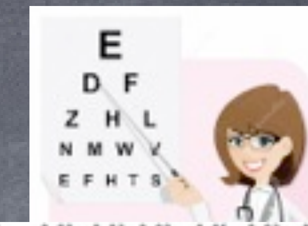
$$[\delta g_L^{Ze}]_{ii} = \begin{pmatrix} -0.26 \pm 0.28 \\ 0.1 \pm 1.1 \\ 0.16 \pm 0.58 \end{pmatrix} \times 10^{-3}, \quad [\delta g_R^{Ze}]_{ii} = \begin{pmatrix} -0.37 \pm 0.27 \\ 0.0 \pm 1.3 \\ 0.39 \pm 0.62 \end{pmatrix} \times 10^{-3},$$

$$[\delta g_L^{Zu}]_{ii} = \begin{pmatrix} -0.8 \pm 3.1 \\ -0.16 \pm 0.36 \\ -0.28 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zu}]_{ii} = \begin{pmatrix} 1.3 \pm 5.1 \\ -0.38 \pm 0.51 \\ \times \end{pmatrix} \times 10^{-2},$$

$$\delta m = (2.6 \pm 1.9) \cdot 10^{-4}. \quad [\delta g_L^{Zd}]_{ii} = \begin{pmatrix} -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.16 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zd}]_{ii} = \begin{pmatrix} 2.9 \pm 16 \\ 3.5 \pm 5.0 \\ 2.30 \pm 0.82 \end{pmatrix} \times 10^{-2}.$$

- Z coupling to charged 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 couplings to light quarks (though their combination affecting *total* hadronic Z-width is strongly constrained)
- Some off-diagonal vertex corrections can also be constrained

Pole constraints - correlations



1.	-0.12	-0.63	-0.1	-0.04	0.01	0.08	-0.06	-0.04	-0.02	0.	0.	-0.03	0.01	0.	-0.02	-0.03	0.02	-0.05	-0.03	0.
-0.12	1.	-0.56	-0.11	-0.05	0.01	0.08	-0.07	-0.04	-0.02	0.	0.	-0.03	0.01	0.	-0.02	-0.03	0.02	-0.05	-0.04	0.
-0.63	-0.56	1.	-0.1	-0.04	0.01	0.07	-0.06	-0.04	0.01	-0.01	0.	0.02	-0.01	0.	0.01	0.03	0.02	0.04	0.03	0.01
-0.1	-0.11	-0.1	1.	-0.08	-0.07	0.15	-0.04	0.04	0.02	0.1	-0.02	0.03	0.09	-0.01	0.02	0.03	-0.36	0.05	0.03	-0.35
-0.04	-0.05	-0.04	-0.08	1.	0.06	-0.04	0.91	-0.04	0.	-0.02	0.	0.	-0.01	0.	0.	0.01	0.07	0.01	0.	0.04
0.01	0.01	0.01	-0.07	0.06	1.	0.02	-0.03	0.41	-0.01	-0.03	0.	-0.01	0.01	0.	0.	0.	0.07	-0.01	-0.01	0.01
0.08	0.08	0.07	0.15	-0.04	0.02	1.	-0.06	-0.04	-0.01	0.09	-0.02	-0.01	0.12	-0.01	-0.01	-0.01	-0.34	-0.02	-0.01	-0.38
-0.06	-0.07	-0.06	-0.04	0.91	-0.03	-0.06	1.	0.04	0.01	0.	0.	0.01	-0.02	0.	0.01	0.01	0.01	0.02	0.02	0.03
-0.04	-0.04	-0.04	0.04	-0.04	0.41	-0.04	0.04	1.	0.01	0.02	0.	0.01	-0.01	0.	0.01	0.01	-0.05	0.02	0.02	0.
-0.02	-0.02	0.01	0.02	0.	-0.01	-0.01	0.01	0.01	1.	-0.04	0.	0.73	0.05	0.	0.79	-0.06	-0.01	0.76	-0.12	0.
0.	0.	-0.01	0.1	-0.02	-0.03	0.09	0.	0.02	-0.04	1.	-0.01	0.03	0.41	0.	-0.03	0.09	-0.15	0.04	0.03	-0.18
0.	0.	0.	-0.02	0.	0.	-0.02	0.	0.	0.	-0.01	1.	0.	-0.01	0.6	0.	0.	0.04	0.	0.	0.04
-0.03	-0.03	0.02	0.03	0.	-0.01	-0.01	0.01	0.01	0.73	0.03	0.	1.	0.03	0.	0.71	-0.21	-0.01	0.92	-0.15	-0.01
0.01	0.01	-0.01	0.09	-0.01	0.01	0.12	-0.02	-0.01	0.05	0.41	-0.01	0.03	1.	0.	0.03	0.04	-0.18	0.07	0.04	-0.16
0.	0.	0.	-0.01	0.	0.	-0.01	0.	0.	0.	0.	0.6	0.	0.	1.	0.	0.	0.03	0.	0.	0.02
-0.02	-0.02	0.01	0.02	0.	0.	-0.01	0.01	0.01	0.79	-0.03	0.	0.71	0.03	0.	1.	-0.62	-0.01	0.67	0.01	0.
-0.03	-0.03	0.03	0.03	0.01	0.	-0.01	0.01	0.01	-0.06	0.09	0.	-0.21	0.04	0.	-0.62	1.	-0.02	-0.03	-0.03	-0.02
0.02	0.02	0.02	-0.36	0.07	0.07	-0.34	0.01	-0.05	-0.01	-0.15	0.04	-0.01	-0.18	0.03	-0.01	-0.02	1.	-0.02	-0.02	0.91
-0.05	-0.05	0.04	0.05	0.01	-0.01	-0.02	0.02	0.02	0.76	0.04	0.	0.92	0.07	0.	0.67	-0.03	-0.02	1.	-0.32	-0.02
-0.03	-0.04	0.03	0.03	0.	-0.01	-0.01	0.02	0.02	-0.12	0.03	0.	-0.15	0.04	0.	0.01	-0.03	-0.02	-0.32	1.	-0.01
0.	0.	0.01	-0.35	0.04	0.01	-0.38	0.03	0.	0.	-0.18	0.04	-0.01	-0.16	0.02	0.	-0.02	0.91	-0.02	-0.01	1.

- Full correlation matrix is also derived
- From that, one can reproduce full likelihood function as function of 21 parameters δg and δm
- If dictionary from h-basis to other bases exists, results can be easily recast to another form
- Similarly, when mapping to d=6 basis from (fewer) parameters of particular BSM models is given, results can be easily recast as constraints on that model

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

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

Correlation Matrix

1σ Errors

Central Values

Pole constraints - recast to Warsaw basis

Results

$$[\hat{c}'_{H\ell}]_{ii} = \begin{pmatrix} -1.09 \pm 0.64 \\ -1.45 \pm 0.59 \\ 1.87 \pm 0.79 \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{H\ell}]_{ii} = \begin{pmatrix} 1.03 \pm 0.63 \\ 1.32 \pm 0.62 \\ -2.01 \pm 0.80 \end{pmatrix} \times 10^{-2},$$

$$[\hat{c}_{He}]_{ii} = \begin{pmatrix} 0.22 \pm 0.66 \\ -0.6 \pm 2.6 \\ -1.4 \pm 1.3 \end{pmatrix} \times 10^{-3}, \quad c'_{\ell\ell} = (-1.21 \pm 0.41) \times 10^{-2},$$

$$\left[\hat{c}'_{Hq}\right]_{ii} = \begin{pmatrix} 0.1 \pm 2.7 \\ -1.2 \pm 2.8 \\ -0.7 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{Hq}]_{ii} = \begin{pmatrix} 1.8 \pm 7.0 \\ -0.8 \pm 2.9 \\ 0.0 \pm 3.8 \end{pmatrix} \times 10^{-2},$$

$$[\hat{c}_{Hu}]_{ii} = \begin{pmatrix} -3 \pm 10 \\ 0.8 \pm 1.0 \\ \times \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{Hd}]_{ii} = \begin{pmatrix} -6 \pm 32 \\ -7 \pm 10 \\ -4.6 \pm 1.6 \end{pmatrix} \times 10^{-2}.$$

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

Dictionary

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

$$f(T^3, Q) = \mathbb{I}\left[-Q c_{WB} \frac{g_L^2 g_Y^2}{g_L^2 - g_Y^2} + (c_T - \delta v)\left(T^3 + Q \frac{g_Y^2}{g_L^2 - g_Y^2}\right)\right].$$

$$\begin{aligned}
\delta g_L^{Wq} &= c'_{Hq} V + f(1/2, 2/3) V - f(-1/2, -1/3) V, \\
\delta g_R^{Wq} &= c_{Hud}, \\
\delta g_L^{Zu} &= \frac{1}{2}\left(c'_{Hq} - c_{Hq}\right) + f(1/2, 2/3), \\
\delta g_L^{Zd} &= -\frac{1}{2} V^\dagger \left(c'_{Hq} + c_{Hq}\right) V + f(-1/2, -1/3), \\
\delta g_R^{Zu} &= -\frac{1}{2} c_{Hu} + f(0, 2/3), \\
\delta g_R^{Zd} &= -\frac{1}{2} c_{Hd} + f(0, -1/3).
\end{aligned}$$

Note in Warsaw basis only combinations of Wilson coefficients are constrained by pole observables

Pole constraints - recast to SILH' basis

Results

$$[s_{\ell\ell}]_{1221} = (4.8 \pm 1.6) \times 10^{-2}, \quad \frac{s_W + s_B}{2} = -0.43 \pm 0.26, \quad s_T = (-1.03 \pm 0.63) \times 10^{-2},$$

$$[s'_{H\ell}]_{ii} = \begin{pmatrix} 0 \\ -0.36 \pm 0.92 \\ 3.0 \pm 1.3 \end{pmatrix} \times 10^{-2}, \quad [s_{H\ell}]_{ii} = \begin{pmatrix} 0 \\ 0.29 \pm 0.95 \\ -3.0 \pm 1.3 \end{pmatrix} \times 10^{-2},$$

$$[s_{He}]_{ii} = \begin{pmatrix} -2.0 \pm 1.3 \\ -2.1 \pm 1.3 \\ -2.2 \pm 1.3 \end{pmatrix} \times 10^{-2},$$

$$[s'_{Hq}]_{ii} = \begin{pmatrix} 1.2 \pm 2.8 \\ -0.1 \pm 2.9 \\ 0.4 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [s_{Hq}]_{ii} = \begin{pmatrix} 2.1 \pm 7.1 \\ -0.4 \pm 2.9 \\ 0.3 \pm 3.8 \end{pmatrix} \times 10^{-2},$$

$$[s_{Hu}]_{ii} = \begin{pmatrix} -1 \pm 10 \\ 2.2 \pm 1.3 \\ \times \end{pmatrix} \times 10^{-2}, \quad [s_{Hd}]_{ii} = \begin{pmatrix} -6 \pm 32 \\ -7 \pm 10 \\ -5.3 \pm 1.7 \end{pmatrix} \times 10^{-2}, \qquad ($$

In SILH basis pole constraints look simpler,
though important correlations remain, notably between cW+cB and leptonic couplings

Pole constraints - flavor blind

$$[\delta g^{Vf}]_{ij} = \delta g^{Vf} \delta_{ij}$$

$$\begin{pmatrix} \delta g_L^{W\ell} \\ \delta g_L^{Ze} \\ \delta g_R^{Ze} \\ \delta g_L^{Zu} \\ \delta g_R^{Zu} \\ \delta g_L^{Zd} \\ \delta g_R^{Zd} \end{pmatrix} = \begin{pmatrix} -0.89 \pm 0.84 \\ -0.20 \pm 0.23 \\ -0.20 \pm 0.24 \\ -1.7 \pm 2.1 \\ -2.3 \pm 4.6 \\ 2.8 \pm 1.5 \\ 19.9 \pm 7.7 \end{pmatrix} \times 10^{-3}$$

- All leptonic couplings constrained at per-mille level, all quark couplings constrained at 1% level or better

Pole constraints - universal theories

Oblique corrections: $\delta\mathcal{M}(V_{1,\mu}\to V_{2,\nu}) = \eta_{\mu\nu}\left(\delta\Pi^{(0)}_{V_1V_2} + \delta\Pi^{(2)}_{V_1V_2}p^2 + \delta\Pi^{(4)}_{V_1V_2}p^4 + \dots\right) + p_\mu p_\nu(\dots)$

$$\alpha S = -4\frac{g_L g_Y}{g_L^2+g_Y^2}\delta\Pi^{(2)}_{3B}$$
$$\alpha T = \frac{\delta\Pi^{(0)}_{11} - \delta\Pi^{(0)}_{33}}{m_W^2}$$
$$\alpha U = \frac{4g_Y^2}{g_L^2+g_Y^2}\left(\delta\Pi^{(2)}_{11} - \delta\Pi^{(2)}_{33}\right)$$

$$\alpha V = m_W^2\left(\delta\Pi^{(4)}_{11} - \delta\Pi^{(4)}_{33}\right)$$
$$\alpha W = -m_W^2\delta\Pi^{(4)}_{33}$$
$$\alpha X = -m_W^2\delta\Pi^{(4)}_{3B}$$
$$\alpha Y = -m_W^2\delta\Pi^{(4)}_{BB}$$

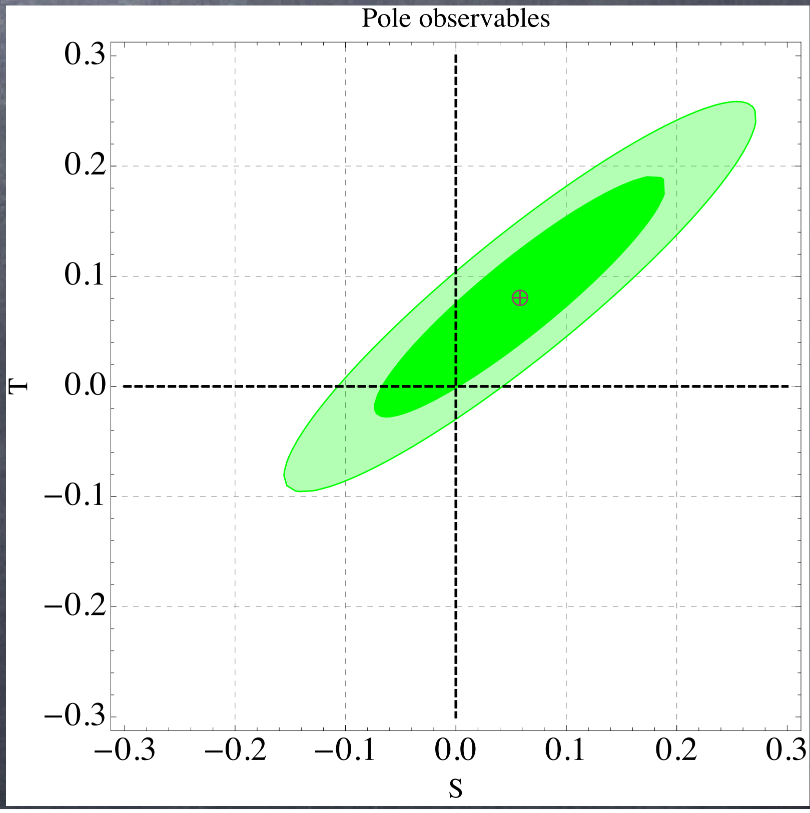
Peskin Takeuchi pre-arxiv

Barbieri et al hep-ph/0405040

Equivalent to restricted form of flavor-diagonal vertex corrections, W-mass corrections, and 4-fermion operators:

$$[\delta g^{Zf}]_{ij} = \delta_{ij}\alpha\left\{T_f^3\frac{2T - W - \frac{g_Y^2}{g_L^2}Y}{4} + Q_f\frac{2g_Y^2T - (g_L^2+g_Y^2)S + g_Y^2W + \frac{g_Y^2(2g_L^2-g_Y^2)}{g_L^2}Y}{4(g_L^2-g_Y^2)}\right\}$$
$$\delta m = \frac{\alpha}{4(g_L^2-g_Y^2)}\left[2g_L^2T - (g_L^2+g_Y^2)S + g_Y^2W + g_Y^2Y\right]$$
$$[c_{\ell\ell}]_{iiii} = -\frac{\alpha}{4}\left[W + \frac{g_Y^2}{g_L^2}Y\right]$$
$$[c_{\ell\ell}]_{iijj} = \frac{\alpha}{2}\left[W - \frac{g_Y^2}{g_L^2}Y\right] \qquad i<j$$
$$[c_{\ell\ell}]_{ijji} = -\alpha W \qquad i<j$$

Same likelihood for pole observables can be used to constrain up to 3 oblique params



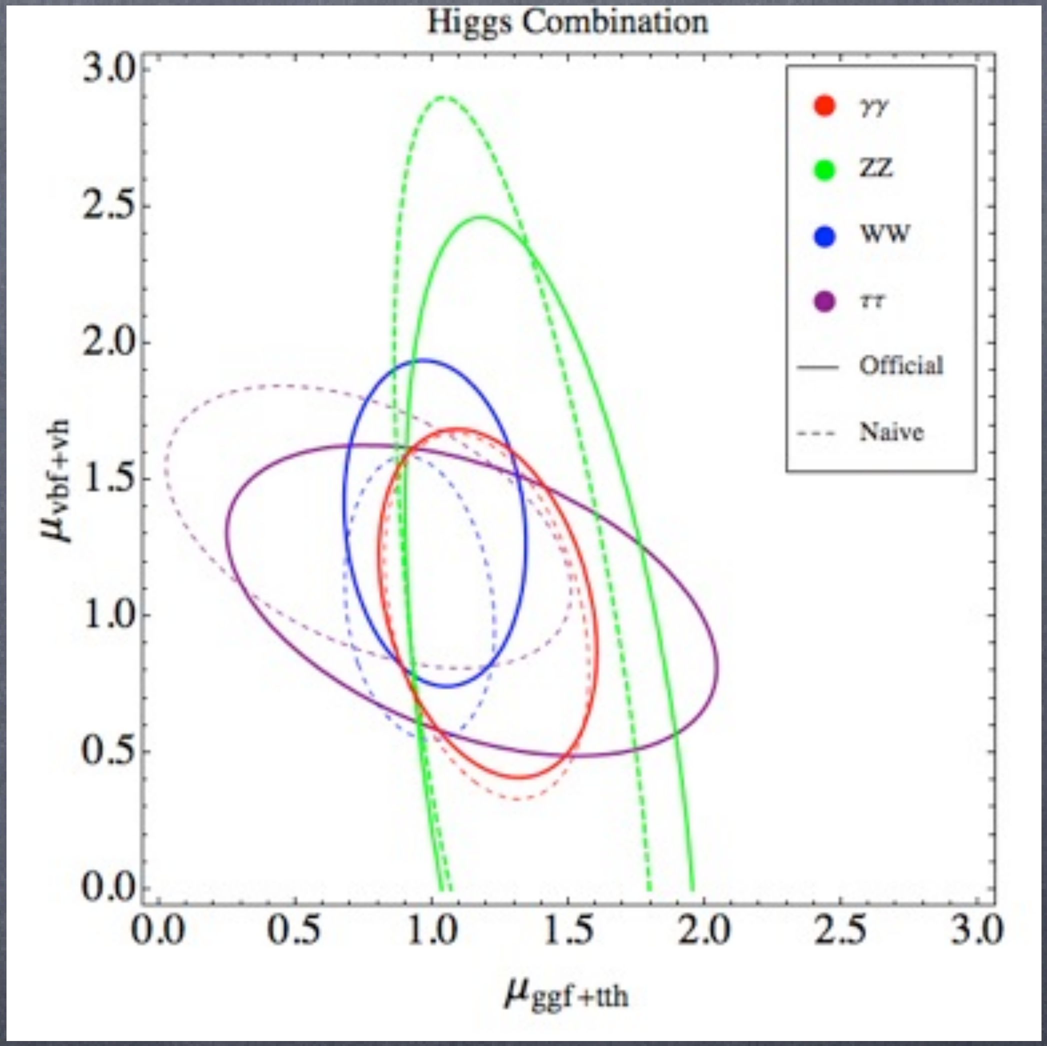
Constraints from LHC Higgs data

Higgs signal strength observables

Channel	μ	Production	Ref.
$\gamma\gamma$	$1.16^{+0.20}_{-0.18}$	2D	[31]
	$1.0^{+1.6}_{-1.6}$	Wh	[34]
	$0.1^{+3.7}_{-0.1}$	Zh	[34]
	$0.58^{+0.93}_{-0.81}$	Vh	[33]
	$1.30^{+2.62}_{-1.75}$ & $2.7^{+2.4}_{-1.7}$	tth	[33, 34]
$Z\gamma$	$2.7^{+4.5}_{-4.3}$ & $-0.2^{+4.9}_{-4.9}$	total	[34, 35]
ZZ^*	$1.31^{+0.27}_{-0.14}$	2D	[31]
WW^*	$1.11^{+0.18}_{-0.17}$	2D	[31]
	$2.1^{+1.9}_{-1.6}$	Wh	[36]
	$5.1^{+4.3}_{-3.1}$	Zh	[36]
	$0.80^{+1.09}_{-0.93}$	Vh	[33]
$\tau\tau$	$1.12^{+0.25}_{-0.23}$	2D	[31]
	$0.87^{+1.00}_{-0.88}$	Vh	[33]
bb	$1.11^{+0.65}_{-0.61}$	Wh	[32]
	$0.05^{+0.52}_{-0.49}$	Zh	[32]
	$0.89^{+0.47}_{-0.44}$	Vh	[33]
	$2.8^{+1.6}_{-1.4}$	VBF	[37]
	$1.5^{+1.1}_{-1.1}$ & $1.2^{+1.6}_{-1.5}$	tth	[38, 39]
$\mu\mu$	$-0.7^{+3.7}_{-3.7}$ & $0.8^{+3.5}_{-3.4}$	total	[34, 40]
multi-ℓ	$2.1^{+1.4}_{-1.2}$ & $3.8^{+1.4}_{-1.4}$	tth	[41, 42]

Including 2D likelihoods from recent ATLAS+CMS combination

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002



Higgs Basis: Higgs couplings to gauge bosons

- In Higgs basis, Higgs couplings to gauge bosons are described by 10 parameters
- These parameters are observables probed by multiple Higgs production (ggF, VBF, VH) and Higgs decay (γγ, Zγ, VV^*→4f) processes
- Linearly realized SU(3)xSU(2)xU(1) with D=6 operators enforces relations between Higgs couplings to gauge bosons (otherwise, 5 more parameters)

CP even : δc_z $\quad c_{z\Box}$ $\quad c_{zz}$ $\quad c_{z\gamma}$ $\quad c_{\gamma\gamma}$ $\quad c_{gg}$

CP odd : $\tilde{c}_{zz}$ $\quad \tilde{c}_{z\gamma}$ $\quad \tilde{c}_{\gamma\gamma}$ $\quad \tilde{c}_{gg}$

$$\begin{aligned}
\mathcal{L}_{\rm hvv} =& \frac{h}{v}[2(1+\delta c_w)m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z)m_Z^2 Z_\mu Z_\mu \\
&+ c_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g_L^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\
&+ c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e g_L}{2c_\theta}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}Z_{\mu\nu} \\
&+ c_{z\Box} g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g_L g_Y Z_\mu \partial_\nu A_{\mu\nu} \\
&+ \tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e g_L}{2c_\theta}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}\tilde{Z}_{\mu\nu}]
\end{aligned}$$

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

Higgs Basis: Higgs couplings to fermions

- In Higgs basis, Higgs couplings to fermions are described by 3 general complex 3x3 matrices
- Here I will assume MFV couplings, thus reducing number of parameters to 2x3
- Without that assumption, couplings to light fermions are unconstrained, leading to flat directions; their effect on other parameters is similar to adding additional invisible width

$$\begin{array}{llll} \text{CP even}: & \delta y_u & \delta y_d & \delta y_e \\ \text{CP odd}: & \phi_u & \phi_d & \phi_e \end{array}$$

$$\Delta \mathcal{L}_{\rm hff}^{D=6} = -\frac{h}{v} \sum_{f \in u,d,e} \delta y_f \, e^{i\phi_f} \, m_f f^c f + \text{h.c.}.$$

Other Higgs couplings to fermions (vertex-like, or dipole-like) are constrained to be small by precision observables and cannot affect LHC Higgs observables given the current level of precision

Higgs observables in the Higgs basis

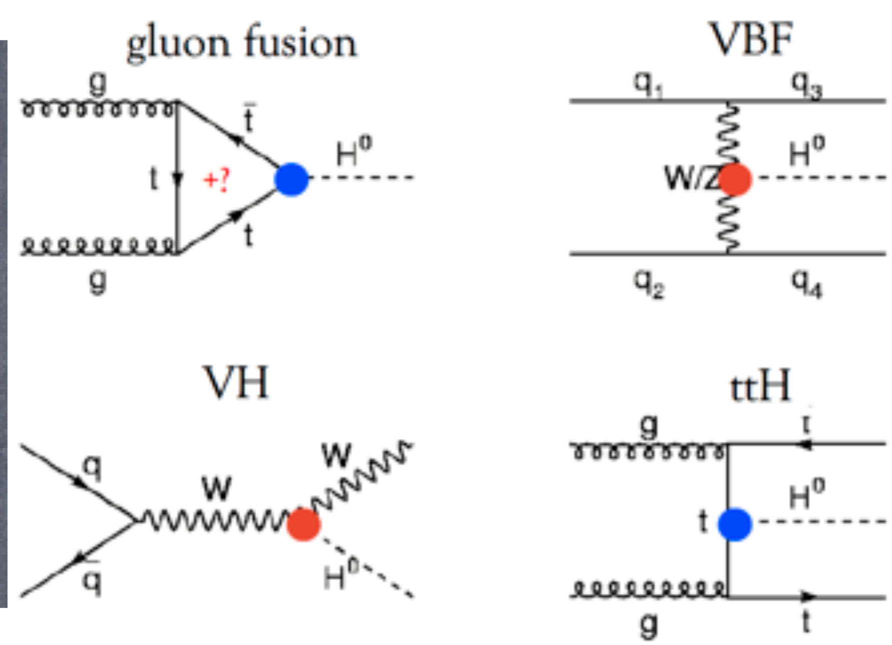
- Higgs signal strength observables at linear level are only sensitive to CP even parameter (CP odd enter only quadratically and are ignored)
- Only couplings unconstrained by precision tests can be relevant at the LHC
- Thus, assuming MFV couplings to fermions, only 9 EFT parameter affect Higgs signal strength measured at LHC

$$\delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg} \quad \delta y_u \quad \delta y_d \quad \delta y_e$$

Higgs production in the Higgs basis

$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq 1 + 237 c_{gg} + 2.06\delta y_u - 0.06\delta y_d.$$

$$\begin{aligned}\frac{\sigma_{VBF}}{\sigma_{VBF}^{\rm SM}} &\simeq 1 + 1.49\delta c_w + 0.51\delta c_z - \begin{pmatrix}1.08\\1.11\\1.23\end{pmatrix} c_{w\Box} - 0.10 c_{ww} - \begin{pmatrix}0.35\\0.35\\0.40\end{pmatrix} c_{z\Box}\\ &\quad -0.04 c_{zz} - 0.10 c_{\gamma\Box} - 0.02 c_{z\gamma}\\ &\to 1 + 2\delta c_z - 2.25 c_{z\Box} - 0.83 c_{zz} + 0.30 c_{z\gamma} + 0.12 c_{\gamma\gamma}.\end{aligned}$$



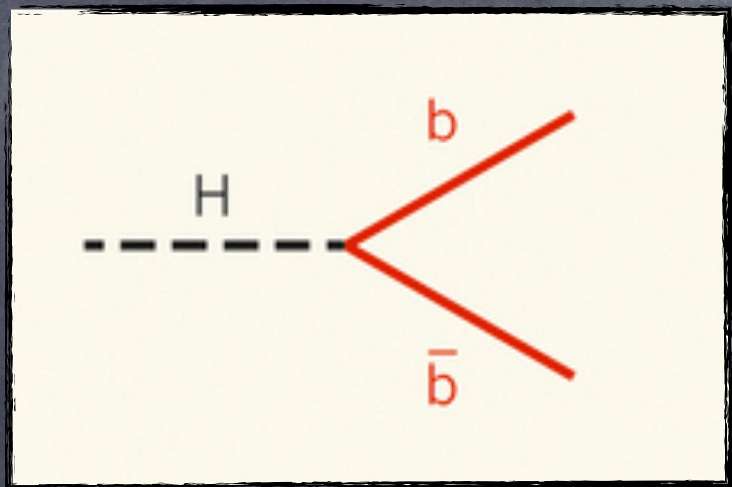
$$\frac{\sigma_{tth}}{\sigma_{tth}^{\rm SM}} \simeq 1 + 2\delta y_u.$$

$$\begin{aligned}\frac{\sigma_{Wh}}{\sigma_{Wh}^{\rm SM}} &\simeq 1 + 2\delta c_w + \begin{pmatrix}6.39\\6.51\\6.96\end{pmatrix} c_{w\Box} + \begin{pmatrix}1.49\\1.49\\1.50\end{pmatrix} c_{ww}\\ &\to 1 + 2\delta c_z + \begin{pmatrix}9.26\\9.43\\10.08\end{pmatrix} c_{z\Box} + \begin{pmatrix}4.35\\4.41\\4.63\end{pmatrix} c_{zz} - \begin{pmatrix}0.81\\0.84\\0.93\end{pmatrix} c_{z\gamma} - \begin{pmatrix}0.43\\0.44\\0.48\end{pmatrix} c_{\gamma\gamma}\\ \frac{\sigma_{Zh}}{\sigma_{Zh}^{\rm SM}} &\simeq 1 + 2\delta c_z + \begin{pmatrix}5.30\\5.40\\5.72\end{pmatrix} c_{z\Box} + \begin{pmatrix}1.79\\1.80\\1.82\end{pmatrix} c_{zz} + \begin{pmatrix}0.80\\0.82\\0.87\end{pmatrix} c_{\gamma\Box} + \begin{pmatrix}0.22\\0.22\\0.22\end{pmatrix} c_{z\gamma},\\ &\to 1 + 2\delta c_z + \begin{pmatrix}7.61\\7.77\\8.24\end{pmatrix} c_{z\Box} + \begin{pmatrix}3.31\\3.35\\3.47\end{pmatrix} c_{zz} - \begin{pmatrix}0.58\\0.60\\0.65\end{pmatrix} c_{z\gamma} + \begin{pmatrix}0.27\\0.28\\0.30\end{pmatrix} c_{\gamma\gamma}.\end{aligned}$$

$\begin{pmatrix}7\\8\\13\end{pmatrix}$ TeV

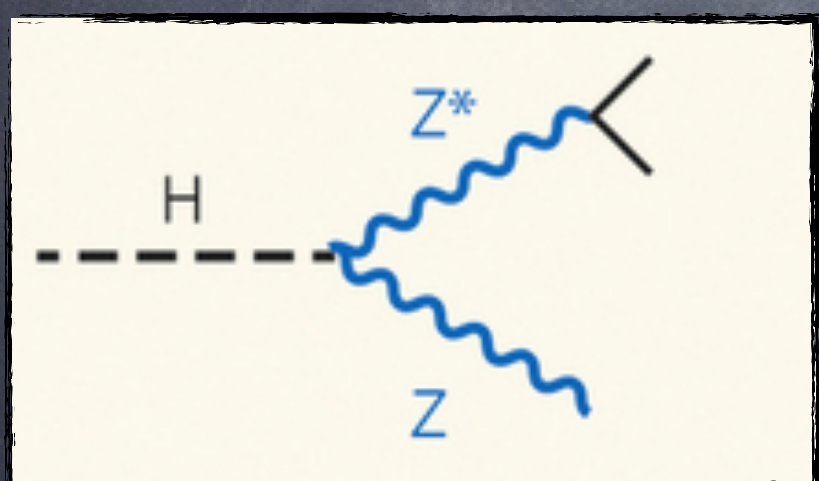
Higgs decay in the Higgs basis

Decays to 2 fermions



$$\frac{\Gamma_{cc}}{\Gamma_{cc}^{\rm SM}} \simeq 1 + 2\delta y_u, \qquad \frac{\Gamma_{bb}}{\Gamma_{bb}^{\rm SM}} \simeq 1 + 2\delta y_d, \qquad \frac{\Gamma_{\tau\tau}}{\Gamma_{\tau\tau}^{\rm SM}} \simeq 1 + 2\delta y_e,$$

Decays to 4 fermions

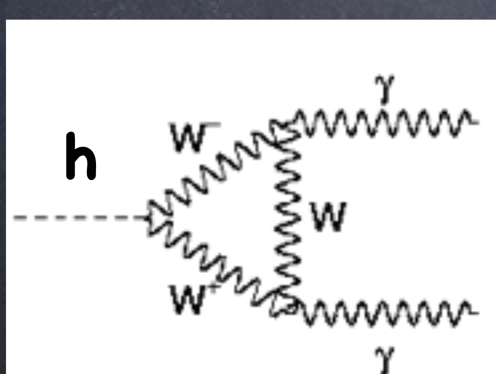


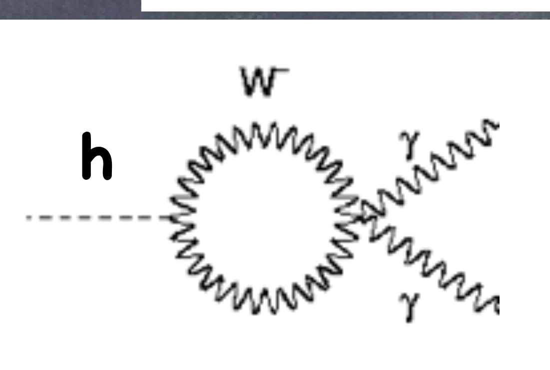
$$\begin{aligned} \frac{\Gamma_{2\ell 2\nu}}{\Gamma_{2\ell 2\nu}^{\rm SM}} &\simeq 1 + 2\delta c_w + 0.46 c_{w\Box} - 0.15 c_{ww} \\ &\to 1 + 2\delta c_z + 0.67 c_{z\Box} + 0.05 c_{zz} - 0.17 c_{z\gamma} - 0.05 c_{\gamma\gamma}. \end{aligned}$$

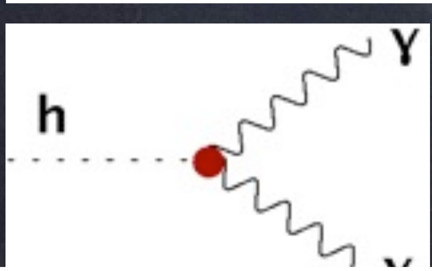
$\begin{pmatrix} \text{2e2μ} \\ \text{4e} \end{pmatrix}$

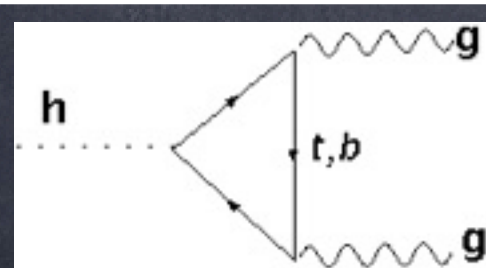
$$\begin{aligned} \frac{\bar\Gamma_{4\ell}}{\bar\Gamma_{4\ell}^{\rm SM}} &\simeq 1 + 2\delta c_z + \begin{pmatrix} 0.41 \\ 0.39 \end{pmatrix} c_{z\Box} - \begin{pmatrix} 0.15 \\ 0.14 \end{pmatrix} c_{zz} + \begin{pmatrix} 0.07 \\ 0.05 \end{pmatrix} c_{z\gamma} - \begin{pmatrix} 0.02 \\ 0.02 \end{pmatrix} c_{\gamma\Box} + \begin{pmatrix} < 0.01 \\ 0.03 \end{pmatrix} c_{\gamma\gamma} \\ &\to 1 + 2\delta c_z + \begin{pmatrix} 0.35 \\ 0.32 \end{pmatrix} c_{z\Box} - \begin{pmatrix} 0.19 \\ 0.19 \end{pmatrix} c_{zz} + \begin{pmatrix} 0.09 \\ 0.08 \end{pmatrix} c_{z\gamma} + \begin{pmatrix} 0.01 \\ 0.02 \end{pmatrix} c_{\gamma\gamma}. \end{aligned} \tag{4.13}$$

Decays to 2 gauge bosons









$$\frac{\Gamma_{VV}}{\Gamma_{VV}^{\rm SM}} \simeq \left| 1 + \frac{\hat c_{vv}}{c_{vv}^{\rm SM}} \right|^2, \qquad vv \in \{gg, \gamma\gamma, z\gamma\},$$

$$\begin{aligned} \hat c_{\gamma\gamma} &= c_{\gamma\gamma}, \qquad c_{\gamma\gamma}^{\rm SM} \simeq -8.3 \times 10^{-2}, \\ \hat c_{z\gamma} &= c_{z\gamma}, \qquad c_{z\gamma}^{\rm SM} \simeq -5.9 \times 10^{-2}, \end{aligned}$$

Higgs observables in the Higgs basis

Signal strength

$$\mu_{X;Y} = \frac{\sigma(pp \to X)}{\sigma(pp \to X)_{\rm SM}} \frac{\Gamma(h \to Y)}{\Gamma(h \to Y)_{\rm SM}} \frac{\Gamma(h \to {\rm all})_{\rm SM}}{\Gamma(h \to {\rm all})}.$$

In EFT, assuming no other degrees of freedom,
so total width is just sum of partial width into SM particle
no invisible width in this analysis

- One can express all measured signal strength in terms of the 9 EFT parameters

$$\delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg} \quad \delta y_u \quad \delta y_d \quad \delta y_e$$

- Using available LHC signal strength data one can obtain constraints on most of these parameters

Higgs constraints on EFT

	$\mathbf{L}$ $(x_0 \pm 1\ \sigma)$
δc_z	-0.12 ± 0.20
c_{zz}	0.6 ± 1.9
$c_{z\Box}$	-0.25 ± 0.83
$c_{\gamma\gamma}$	0.015 ± 0.029
$c_{z\gamma}$	0.01 ± 0.10
c_{gg}	-0.0056 ± 0.0028
δy_u	0.55 ± 0.30
δy_d	-0.42 ± 0.45
δy_e	-0.18 ± 0.36

AA
1505.00046

Flat direction

$$c_{zz} \approx -2.3 c_{z\Box}$$

Needs more data
on differential distributions
in h->4f decays

- Not all parameters yet constrained enough that EFT approach is valid
- Results sensitive to including corrections to Higgs observables quadratic in EFT parameters which are formally O(1/Λ^4). Thus, in general, results may be sensitive to including dimension-8 operators

Combined Constraints from LEP-2 WW and LHC Higgs

Previously

Corbett et al 1304.1151
Dumont et al 1304.3369
Pomarol Riva 1308.2803
Masso 1406.6377
Ellis et al 1410.7703

Now

AA,Gonzalez-Alonso,Greljo,Marzocca 1508.00581

Consistent EFT analysis
at O(1/Λ^2)

TGC - Higgs Synergy

TGC

$$\text{CP even}: \quad \delta\kappa_\gamma \quad \delta g_{1,z} \quad \lambda_z$$
$$\text{CP odd}: \quad \tilde{\kappa}_\gamma \quad \tilde{\lambda}_z$$

Higgs

$$\text{CP even}: \quad \delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg}$$
$$\text{CP odd}: \quad \tilde{c}_{zz} \quad \tilde{c}_{z\gamma} \quad \tilde{c}_{\gamma\gamma} \quad \tilde{c}_{gg}$$

Linearly realized SU(3)xSU(2)xU(1) at D=6 level enforces relations between TGC and Higgs couplings in the Higgs basis

$$\delta g_{1,z} = \frac{1}{2(g_L^2 - g_Y^2)}\left[c_{\gamma\gamma}e^2 g_Y^2 + c_{z\gamma}(g_L^2 - g_Y^2)g'^2 - c_{zz}(g_L^2+g_Y^2)g_Y^2 - c_{z\Box}(g_L^2+g_Y^2)g_L^2\right]$$

$$\delta\kappa_\gamma = -\frac{g_L^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g_L^2+g_Y^2} + c_{z\gamma}\frac{g_L^2-g_Y^2}{g_L^2+g_Y^2} - c_{zz}\right),$$

$$\tilde{\kappa}_\gamma = -\frac{g_L^2}{2}\left(\tilde{c}_{\gamma\gamma}\frac{e^2}{g_L^2+g_Y^2} + \tilde{c}_{z\gamma}\frac{g_L^2-g_Y^2}{g_L^2+g_Y^2} - \tilde{c}_{zz}\right),$$

- 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 constraints on Higgs couplings
- But for that, all TGCs have to be simultaneously constrained in multi-dimensional fit, and correlation matrix should be given
- Note that c_zγ c_zz and c_zBox are difficult to access experimentally in Higgs physics
- Important to combine Higgs and TGC data!

Higgs constraints on EFT

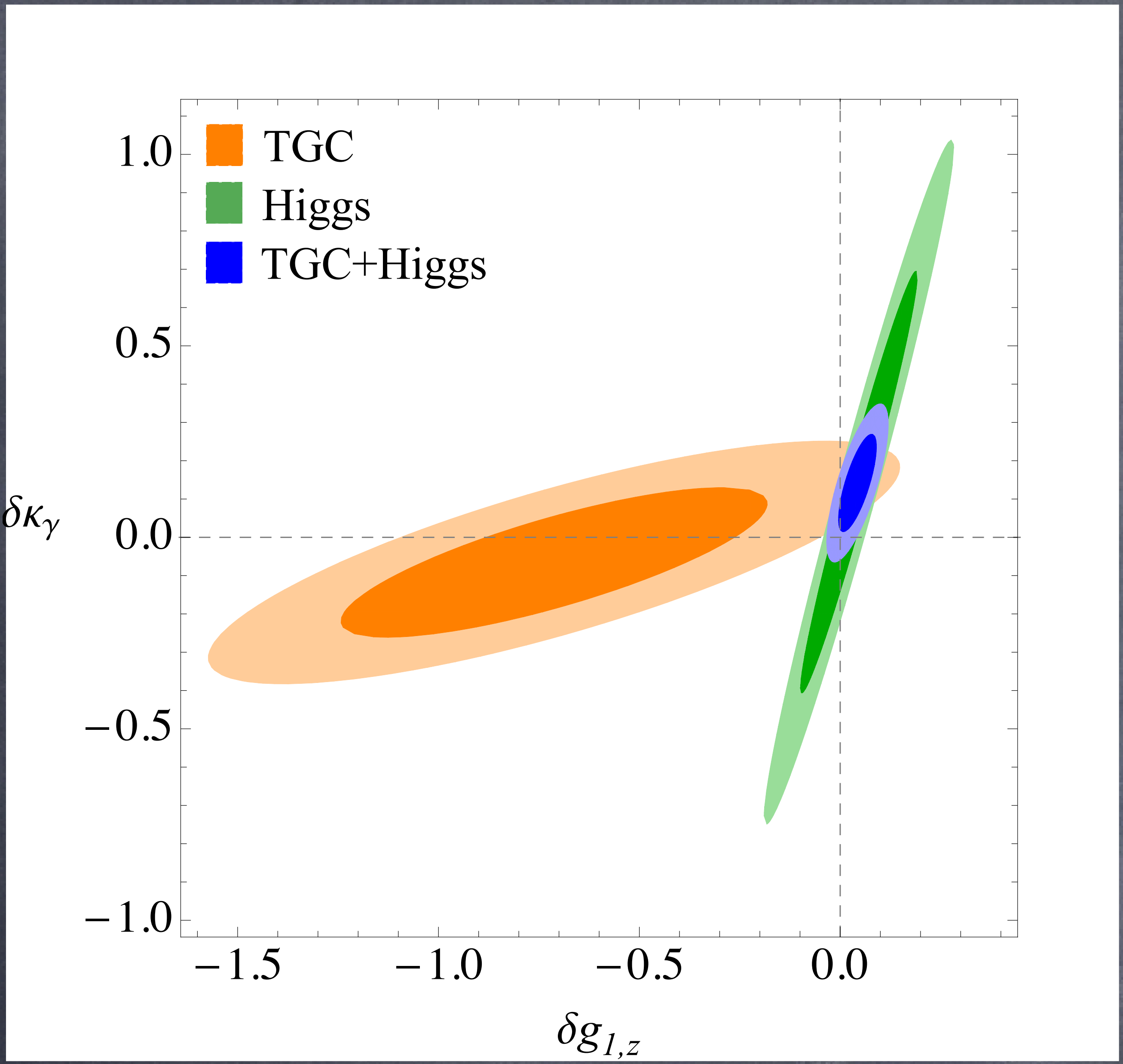
$$
\begin{pmatrix} \delta c_z \\ c_{zz} \\ c_{z\Box} \\ c_{\gamma\gamma} \\ c_{z\gamma} \\ c_{gg} \\ \delta y_u \\ \delta y_d \\ \delta y_e \\ \lambda_z \end{pmatrix}
=
\begin{pmatrix} -0.07 \pm 0.14 \\ 0.65 \pm 0.42 \\ -0.29 \pm 0.21 \\ -0.005 \pm 0.014 \\ -0.005 \pm 0.095 \\ -0.0053 \pm 0.0027 \\ 0.55 \pm 0.30 \\ -0.44 \pm 0.24 \\ -0.22 \pm 0.18 \\ -0.152 \pm 0.080 \end{pmatrix}
$$

Correlation matrix

1.	-0.07	-0.23	0.4	-0.05	-0.05	0.03	0.56	0.49	-0.24
-0.07	1.	-0.92	0.34	0.18	0.	0.02	-0.3	-0.38	-0.85
-0.23	-0.92	1.	-0.43	-0.12	0.03	0.	0.21	0.21	0.94
0.4	0.34	-0.43	1.	0.09	0.4	-0.47	-0.11	-0.12	-0.42
-0.05	0.18	-0.12	0.09	1.	0.01	-0.01	-0.1	-0.13	-0.12
-0.05	0.	0.03	0.4	0.01	1.	-0.89	0.18	0.06	0.03
0.03	0.02	0.	-0.47	-0.01	-0.89	1.	0.1	0.04	0.01
0.56	-0.3	0.21	-0.11	-0.1	0.18	0.1	1.	0.66	0.19
0.49	-0.38	0.21	-0.12	-0.13	0.06	0.04	0.66	1.	0.18
-0.24	-0.85	0.94	-0.42	-0.12	0.03	0.01	0.19	0.18	1.

- Flat direction between c_zz and c_zBox lifted to large extent by WW data!
- Much better constraints on some parameters.
  Most parameters (marginally) within the EFT regime
- Lower sensitivity to the quadratic terms (though still not completely negligible, especially for δcz and δyd)

Corollary: constraints on TGCs

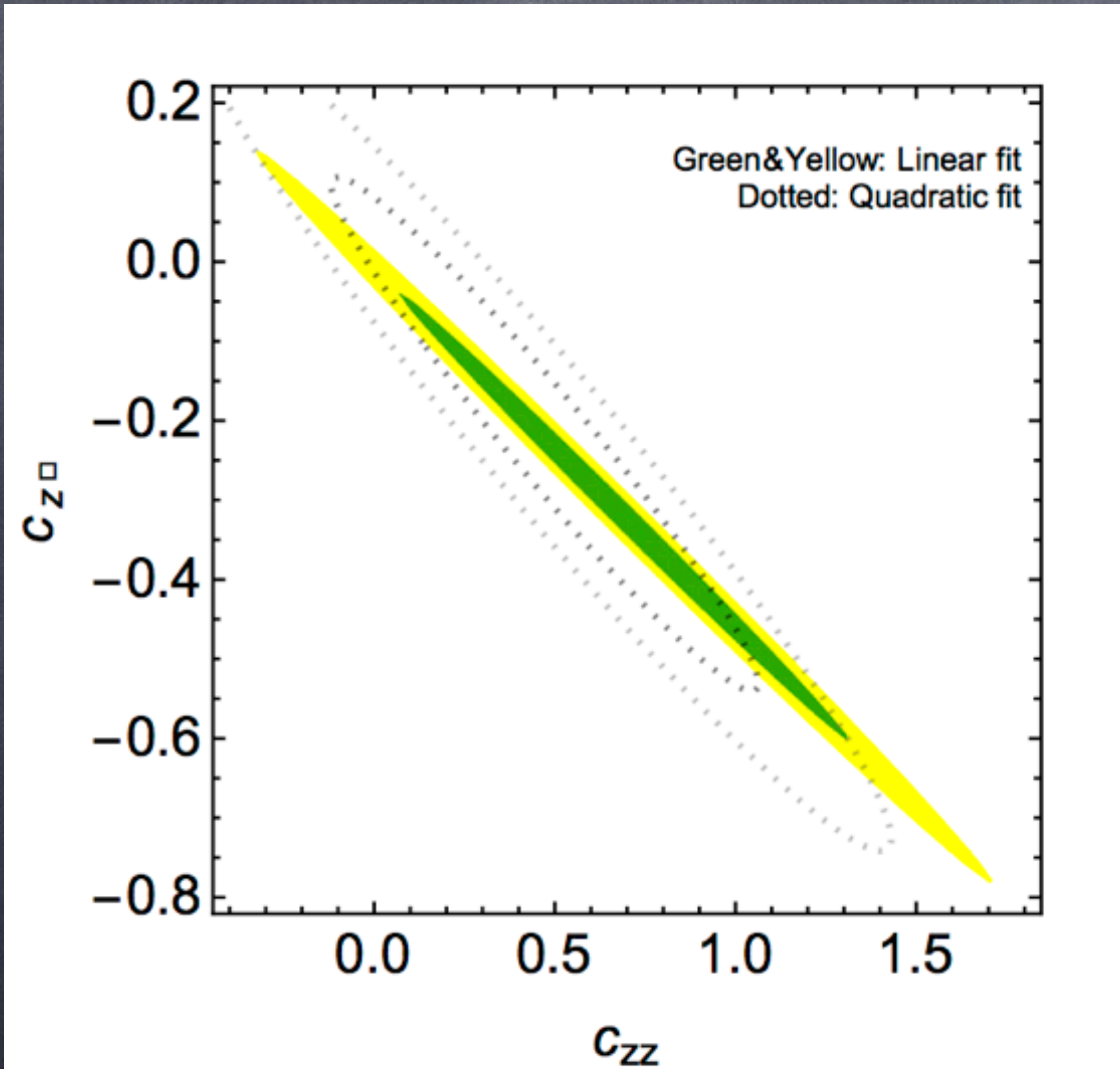


- LHC Higgs and LEP-2 WW data by itself do not constrain TGCs robustly due to each suffering from 1 flat direction in space of 3 TGCs
- However, the flat directions are orthogonal and combined constraints lead to robust O(0.1) limits on aTGCs

$$\begin{pmatrix} \delta g_{1,z} \\ \delta\kappa_\gamma \\ \lambda_z \end{pmatrix} = \begin{pmatrix} 0.037 \pm 0.041 \\ 0.133 \pm 0.087 \\ -0.152 \pm 0.080 \end{pmatrix},$$

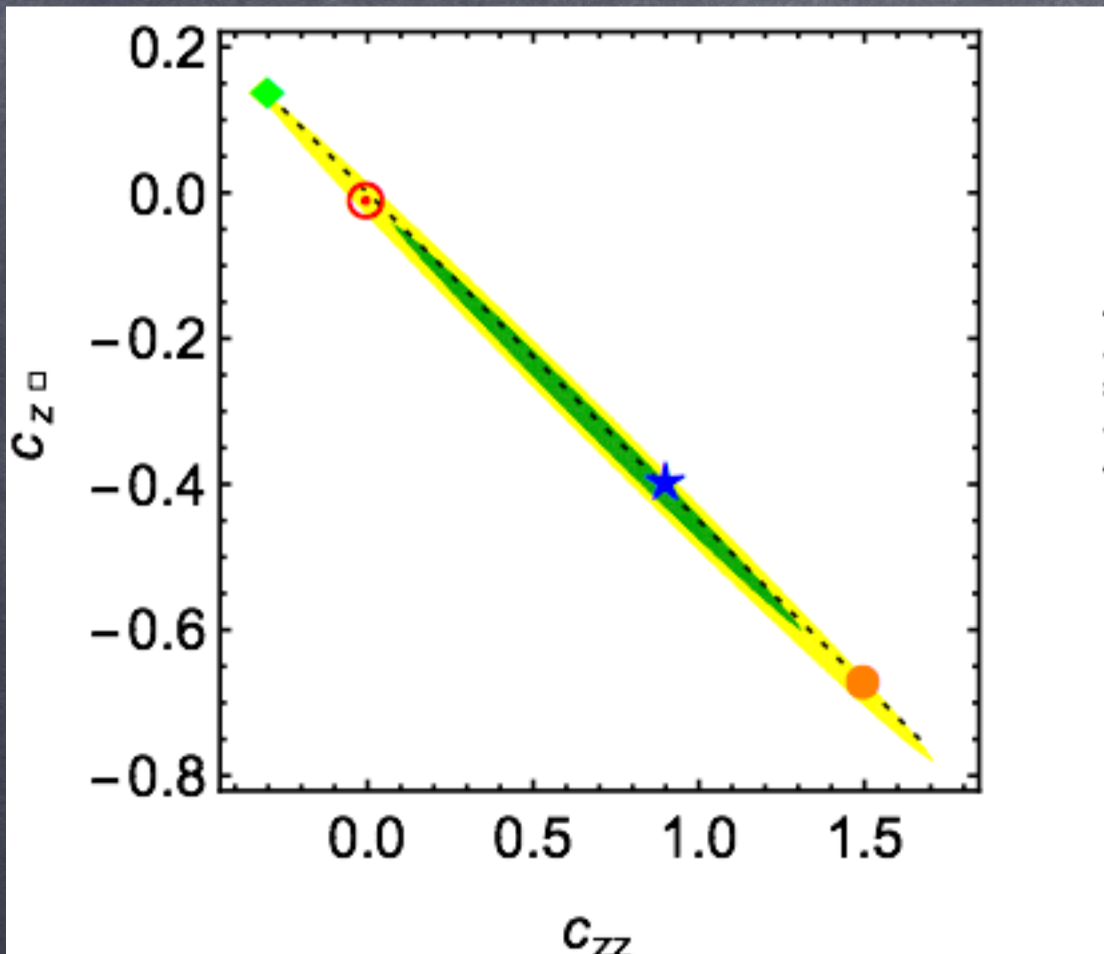
$$\rho = \begin{pmatrix} 1 & 0.62 & -0.84 \\ 0.62 & 1 & -0.85 \\ -0.84 & -0.85 & 1 \end{pmatrix}$$

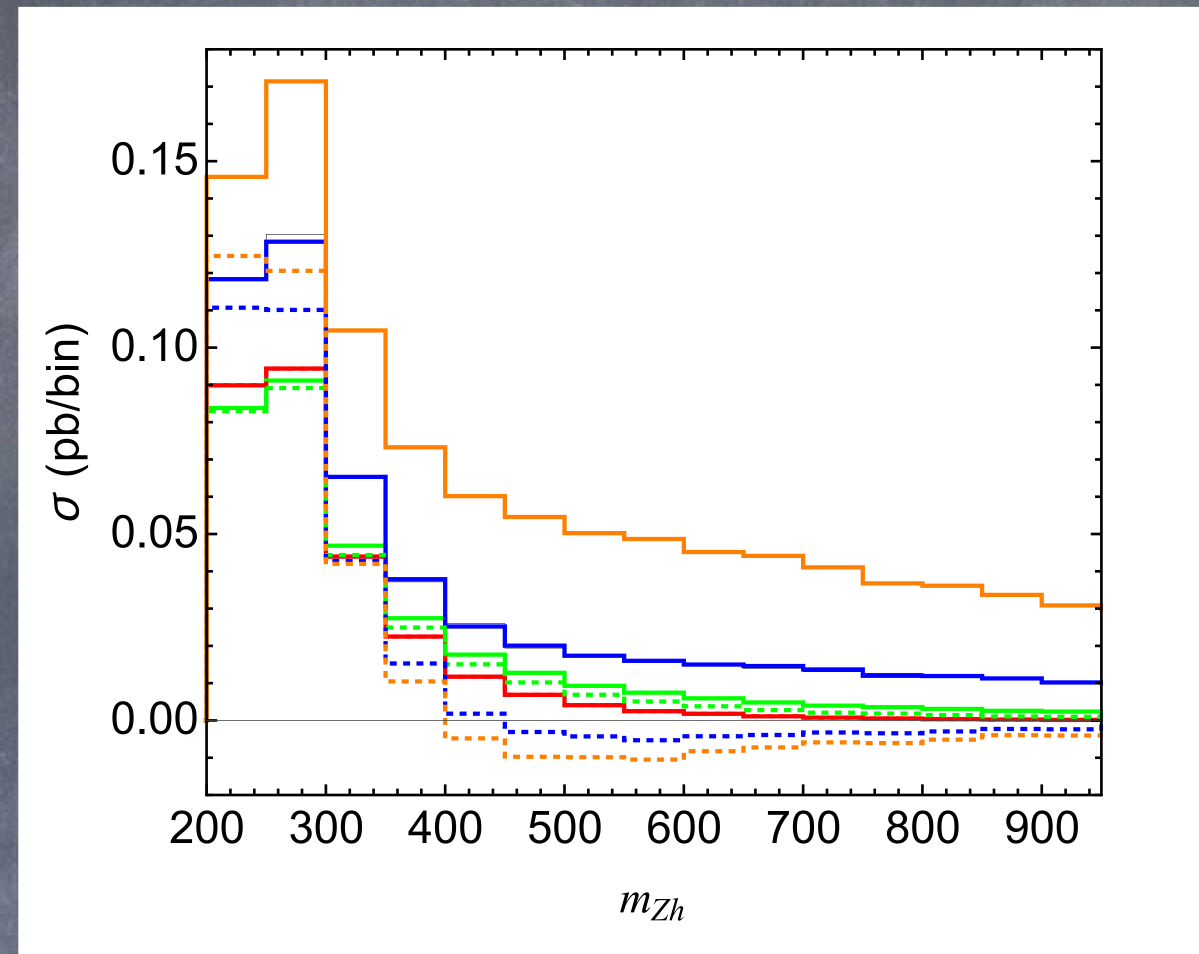
Combined WW+Higgs: robustness



- Non-trivial constraints at linear ($1/\Lambda^2$) level
- Quadratic ($1/\Lambda^4$) terms not completely negligible yet, but they do not change fit qualitatively

Combined WW+Higgs: robustness





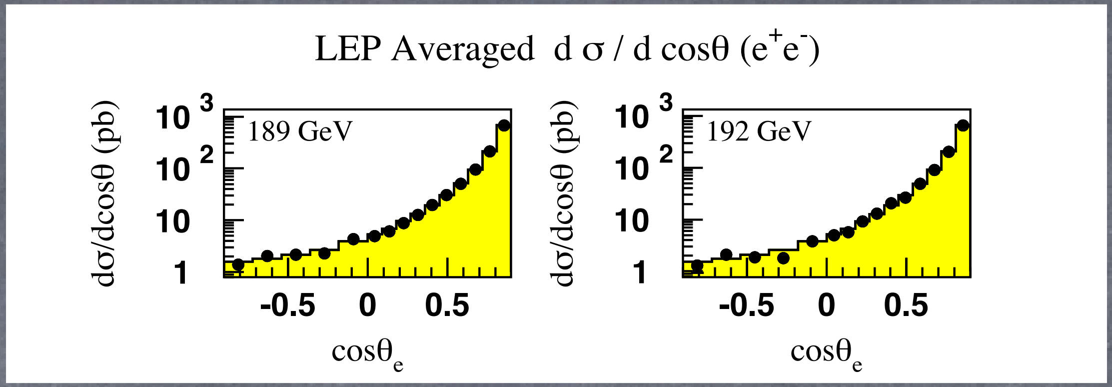
- For VH production, quadratic (1/Λ^4) contributions are comparable to linear (1/Λ^2) ones
- They are numerically important but don't change fit significantly because they constrain similar direction in parameter space as linear ones
- Sensitivity to 1/Λ^4 terms greatly reduced if VH signal strength with cut mVH<400 GeV was quoted

Constraints on 4 fermion operators

Preview: 4-electron operators

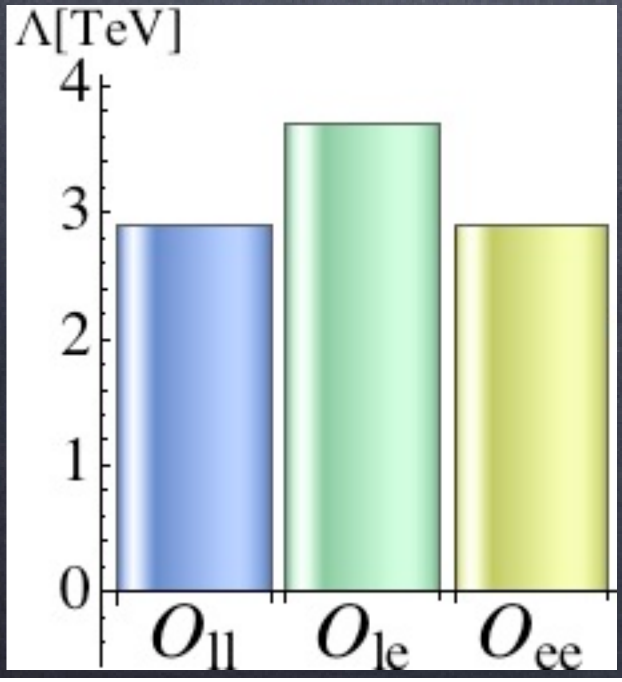
AA, Mimouni, to appear

$$[O_{\ell\ell}]_{1111} = (\bar{\ell}_1\bar{\sigma}_\mu\ell_1)(\bar{\ell}_1\bar{\sigma}_\mu\ell_1),$$
$$[O_{\ell e}]_{1111} = (\bar{\ell}_1\bar{\sigma}_\mu\ell_1)(e_1^c\sigma_\mu\bar{e}_1^c),$$
$$[O_{ee}]_{1111} = (e_1^c\sigma_\mu\bar{e}_1^c)(e_1^c\sigma_\mu\bar{e}_1^c).$$



1-by-1

$$[c_{\ell\ell}]_{1111} = (4.0 \pm 1.6) \times 10^{-3}$$
$$[c_{\ell e}]_{1111} = (1.7 \pm 1.5) \times 10^{-3}$$
$$[c_{ee}]_{1111} = (4.0 \pm 1.7) \times 10^{-3}$$



Simultaneous

$$[c_{\ell\ell}]_{1111} = -0.35 \pm 0.39$$
$$[c_{\ell e}]_{1111} = (-3.7 \pm 2.7) \times 10^{-3}$$
$$[c_{ee}]_{1111} = 0.37 \pm 0.40$$

$$\rho = \begin{pmatrix} 1 & 0.57 & \approx -1 \\ 0.57 & 1 & -0.57 \\ \approx -1 & -0.57 & 1 \end{pmatrix}$$

Take away

- There are strong constraints on certain combinations of dimension-6 operators from the pole observables measured at LEP-1 and other colliders. These can be conveniently presented as correlated constraints on vertex corrections and W mass corrections.
- Assuming MFV, these constraints allow one to describe LO EFT deformations of single Higgs signal strength LHC observables by just 9 parameters
- There are non-trivial constraints on all of these 9 parameters from Higgs and WW data
- Synergy of TGC and Higgs coupling measurements is crucial for deriving meaningful bounds