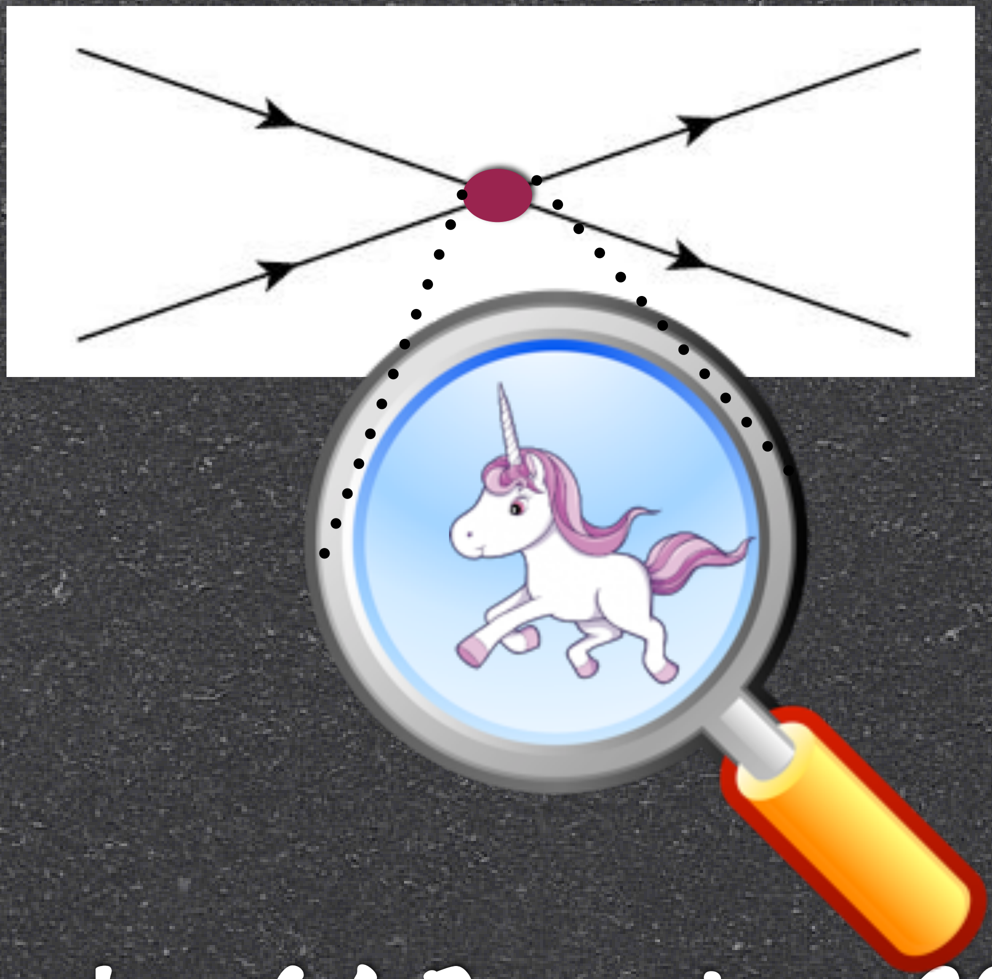
Adam Falkowski

Model Independent Constraints on Physics Beyond the Standard Model



Saclay, 14 December 2015

Based on my 1505.00046, on 1503.07872 with Aielet Efrati and Yotam Soreq, on 1411.0669 with Francesco Riva, on 1508.00581 with Martín Gonzalez-Alonso, Admir Greljo, and David Marzocca, and on 1511.07434 with Kin Mimouni

Effective Field Theory
approach to BSM physics

Several approaches to new physics searches

Model specific

pick one well-defined, motivated,
often UV complete model

E.g. 2HDM, MSSM, NMSSM, NNMSSM, …,
composite Higgs, minimal walking technicolor

Simplified models

pick simple well-defined model
that captures some aspects of phenomenology
of large class of specific models

E.g. singlet scalar, gluino+neutralino, heavy
top quark, vector triplet,

Model independent

parametrize low-energy effects
large class of models as higher-dimensional
contact interaction of light particles

Effective field theory

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

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

Appear when starting from BSM theory,
and integrating out heavy particles with m≈Λ

Cutoff scale of EFT

Alternatively,
non-linear Lagrangians
with derivative expansion

Effective Theory Approach to BSM

Basic assumptions

- New physics scale Λ separated from EW scale v, $\Lambda >> v$
- 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

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

Lepton number or B-L violating,
hence too small to probed 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

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

D=6 Basis

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

HISZ basis — Hagiwara et al (1993)

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

Higgs basis — LHCHXSWG-INT-2015-001

Warsaw Basis — Grządkowski et al. 1008.4884

Primary basis — Gupta et al 1405.0181

One Rosetta
to rule them all

arXiv:1508.05895

- 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

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

Bosonic CP-even		Bosonic CP-odd	
O_H	$[\partial_\mu(H^\dagger H)]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$\lambda(H^\dagger H)^3$		
O_{GG}	$H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
O_{WW}	$H^\dagger H\, W^i_{\mu\nu}W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu}W^i_{\mu\nu}$
O_{BB}	$H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$	$O_{\widetilde{BB}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B_{\mu\nu}$
O_{WB}	$H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$	$O_{\widetilde{WB}}$	$H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu}B_{\mu\nu}$
O_{3W}	$\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
O_{3G}	$f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$f^{abc}\widetilde{G}^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

Yukawa	
$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

+4 fermion operators

Vertex		Dipole	
$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I\bar{\sigma}_\mu\ell_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} e^c_I\sigma_{\mu\nu}H^\dagger\sigma^i\ell_J W^i_{\mu\nu}$
$[O'_{H\ell}]_{IJ}$	$i\bar{\ell}_I\sigma^i\bar{\sigma}_\mu\ell_J H^\dagger\sigma^i \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} e^c_I\sigma_{\mu\nu}H^\dagger\ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$ie^c_I\sigma_\mu\bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} u^c_I\sigma_{\mu\nu}T^a\widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I\bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O'_{Hq}]_{IJ}$	$i\bar{q}_I\sigma^i\bar{\sigma}_\mu q_J H^\dagger\sigma^i \overleftrightarrow{D}_\mu H$	$[O_{uB}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$iu^c_I\sigma_\mu\bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dG}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I\sigma_{\mu\nu}T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$id^c_I\sigma_\mu\bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I\sigma_{\mu\nu}\bar{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$iu^c_I\sigma_\mu\bar{d}^c_J\widetilde{H}^\dagger D_\mu H$	$[O_{dB}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I\sigma_{\mu\nu}H^\dagger q_J\, B_{\mu\nu}$

Example: SILH Basis

Bosonic CP-even		Bosonic CP-odd	
O_H	$\left[\partial_\mu (H^\dagger H)\right]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$(H^\dagger H)^3$		
O_{GG}	$H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{BB}	$H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{i}{2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{i}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$i\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$O_{\widetilde{HW}}$	$i\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$i\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$O_{\widetilde{HB}}$	$i\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{g_L^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{g_Y^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{g_s^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Giudice et al hep-ph/0703164
Contino et al 1303.3876

More bosonic operators,
at the expense of some 2-fermion
and 4-fermion operators
Total still adds up to 2499

Yukawa	
$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

Vertex	
$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar{d}^c_J \widetilde{H}^\dagger D_\mu H$

Dipole	
$[O_{eW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O_{eB}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{uG}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O_{uW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{uB}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{dG}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{dW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{dB}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

+4 fermion operators

Operators to Observables

Less obvious effects of D=6 operators

- Affect relations between couplings and input observables
- Change normalization of kinetic terms
- Introduce non-standard higher-derivative kinetic terms
- Introduce kinetic mixing between photon and Z boson

e.g.

$$\frac{c_T}{v^2} O_T = \frac{c_T}{v^2} (H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\to - c_T \frac{(g_L^2 + g_Y^2) v^2}{4} Z_\mu Z_\mu$$
$$\Rightarrow m_Z^2 = \frac{(g_L^2 + g_Y^2) v^2}{4} (1 - 2 c_T)$$

e.g.

$$\frac{c_{WW}}{v^2} O_{WW} = \frac{c_{WW}}{v^2} g_L^2 H^\dagger H W_{\mu\nu}^i W_{\mu\nu}^i$$
$$\to \frac{c_{WW} g_L^2}{2} W_{\mu\nu}^i W_{\mu\nu}^i$$

e.g.

$$\frac{c_{2W}}{v^2} O_{2W} = \frac{c_{2W}}{v^2} (D_\nu W_{\mu\nu}^i)^2$$
$$\to \frac{c_{2W}}{v^2} W_\mu^i \Box^2 W_\mu^i$$
$$\Rightarrow \langle W^+ W^- \rangle = \frac{i}{p^2 - m_W^2 - c_{2W} \frac{p^4}{v^2}}$$

e.g.

$$\frac{c_{WB}}{v^2} O_{WB} = \frac{c_{WB}}{v^2} g_L g_Y H^\dagger \sigma^i H W_{\mu\nu}^i B_{\mu\nu}$$
$$\to - c_{WB} \frac{g_L g_Y}{2} W_{\mu\nu}^3 B_{\mu\nu}$$

To simplify calculating physical predictions, one can map the theory with dimension-6 operators onto the phenomenological effective Lagrangian

Phenomenological effective Lagrangian

LHCHXSWG-INT-2015-001

- Phenomenological effective Lagrangian is defined using 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.

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

- Feature #3: Photon and gluon couple to matter as in the SM

- Features #1-3 can always be obtained without any loss of generality, starting from any Lagrangian with D=6 operators, using integration by parts, fields and couplings redefinition

$$\mathcal{L} \supset eA_\mu(T^3_f + Y_f)\bar{f}\gamma_\mu f + g_s G^a_\mu \bar{q}\gamma_\mu T^a q$$

Effective Lagrangian: Z and W couplings to fermions

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

- 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

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

Z and W couplings to fermions

Yukawa	
$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
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$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

Vertex	
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$[O_{He}]_{IJ}$	$ie^c_I \sigma_\mu \bar e^c_J H^\dagger \overleftrightarrow{D}_\mu H$
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$[O'_{Hq}]_{IJ}$	$i\bar q_I \sigma^i \bar\sigma_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar u^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar d^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar d^c_J \tilde H^\dagger D_\mu H$

Dipole	
$[O_{eW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O_{eB}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{uG}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J G^a_{\mu\nu}$
$[O_{uW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J W^i_{\mu\nu}$
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$[O_{dG}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J G^a_{\mu\nu}$
$[O_{dW}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} \bar H^\dagger \sigma^i q_J W^i_{\mu\nu}$
$[O_{dB}]_{IJ}$	$\frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} H^\dagger q_J B_{\mu\nu}$

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

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

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

$$\delta v = ([c'_{H\ell}]_{11} + [c'_{H\ell}]_{22})/2 - [c_{\ell\ell}]_{1221}/4$$

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

$$\delta m = \frac{1}{g^2-g'^2}\left[-g^2 g'^2 c_{WB} + g^2 c_T - g'^2\delta v\right]$$

- Observation: vertex correction obtained from Warsaw basis are not independent. Corrections to W vertices are determined by corrections to Z vertices

Effective Lagrangian: Higgs couplings to matter

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

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

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

relative correction to W mass

LHCHXSWG-INT-2015-001

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

Higgs couplings to matter

- Corrections to Higgs couplings in phenomenological effective Lagrangian can be related by linear transformation to Wilson coefficients of any basis of D=6 operators
- Unexpected dependence of fermionic operators due to rescaling of SM couplings
- Corrections to Higgs and other SM couplings are O(1/Λ^2) in EFT expansion. They can be used to define (perhaps more convenient) basis of D=6 operators

Gupta et al 1405.0181

Grządkowski et al. 1008.4884

Example:
from Warsaw Basis
to Higgs couplings

$$\delta c_w = -c_H - c_{WB}\frac{4g_L^2 g_Y^2}{g_L^2 - g_Y^2} + c_T\frac{4g_L^2}{g_L^2 - g_Y^2} - \frac{3g_L^2 + g_Y^2}{4(g_L^2 - g_Y^2)}\left(2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right),$$

$$\delta c_z = -c_H - \frac{3}{4}\left(2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right),$$

$$c_{\gamma\gamma} = c_{WW} + c_{BB} - 4c_{WB},$$

$$c_{zz} = \frac{g_L^4 c_{WW} + g_Y^4 c_{BB} + 4g_L^2 g_Y^2 c_{WB}}{(g_L^2 + g_Y^2)^2},$$

$$c_{z\Box} = -\frac{2}{g_L^2}\left(c_T - \frac{2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}}{4}\right),$$

$$c_{z\gamma} = \frac{g_L^2 c_{WW} - g_Y^2 c_{BB} - 2(g_L^2 - g_Y^2)c_{WB}}{g_L^2 + g_Y^2},$$

$$c_{\gamma\Box} = \frac{4}{g_L^2 - g_Y^2}\left(\frac{g_L^2 + g_Y^2}{2}c_{WB} - c_T + \frac{2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}}{4}\right),$$

$$c_{ww} = c_{WW},$$

$$c_{w\Box} = \frac{2}{g_L^2 - g_Y^2}\left(g_Y^2 c_{WB} - c_T + \frac{2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}}{4}\right).$$

See
LHCHXSWG-INT-2015-001
for full dictionary and other bases

Effective Lagrangian: Triple Gauge Couplings

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

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

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

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

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

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

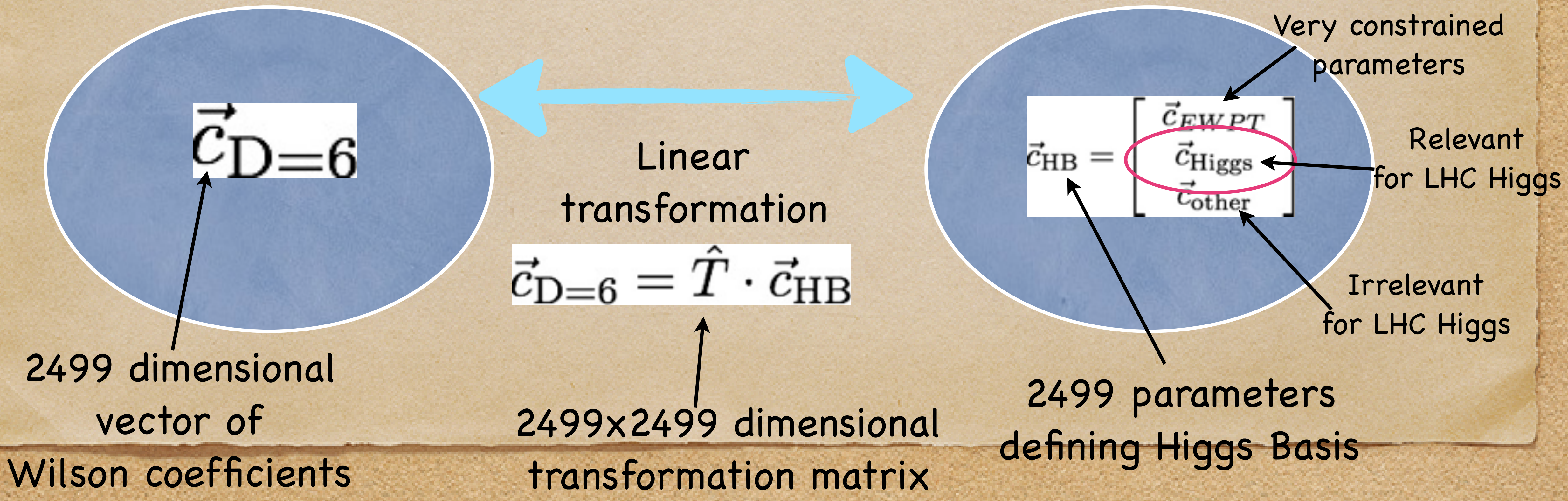
$$\delta\kappa_\gamma = -\frac{g_L^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g_L^2+g_Y^2} + c_{z\gamma}\frac{g_L^2-g_Y^2}{g_L^2+g_Y^2} - c_{zz}\right),$$

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

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

Higgs Basis

- Connection between operators and observables a bit obscured in Warsaw or SILH basis. Also, in Warsaw basis EW precision constraints look complicated.
- Higgs basis proposed by LHCHXSWG2 uses subset of couplings in phenomenological effective Lagrangian to span D=6 basis. Effectively, a rotation of any other D=6 basis
- By construction, one isolates combination of parameters strongly constrained by precision tests, and also the ones affecting Higgs observables and not constrained severely by precision tests



Higgs Basis - parameters

Instead of Wilson coefficients in some basis, use directly a subset of eigenstates couplings to parametrize the D=6 EFT space

Higgs couplings to gauge bosons

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

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

Higgs couplings to fermions

CP even : $\delta y_u \quad \delta y_d \quad \delta y_e$

CP odd : $\phi_u \quad \phi_d \quad \phi_e$

Triple gauge couplings

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

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

Vertex and mass Corrections

$$\delta m,$$

$$\delta g_L^{Ze},\ \delta g_R^{Ze},\ \delta g_L^{W\ell},$$

$$\delta g_L^{Zu},\ \delta g_R^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zd},\ \delta g_R^{Wq}$$

....

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 Higgs 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 Higgs 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)

- 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

- Goal: give you full likelihood in D=6 space, that can be reused for any specific model predicting any particular patter of D=6 operators

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

- Observables can be expressed by Z and W partial widths, and then D=6 corrections can be expressed just by vertex corrections δg

- I will not assume anything about δg: they are allowed to be arbitrary, flavor dependent, and all can be simultaneously present

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

$$\frac{\Gamma(Z \to f_J \bar{f}_J)}{\Gamma(Z \to f\bar{f})_{\rm SM}} = \left(\frac{T_f^3 - s_\theta^2 Q_f + [\delta g^{Zf}]_{JJ}}{T_f^3 - s_\theta^2 Q_f}\right)^2$$
$$\frac{\Gamma(W \to f_{L,J} f'_{L,J})}{\Gamma(W \to f_L f'_L)_{\rm SM}} = \left(1 + [\delta g_L^{Wf}]_{JJ}\right)^2$$
$$\frac{\Gamma(W \to q_{R,J} q'_{R,J})}{\Gamma(W \to q_R q'_R)_{\rm SM}} = \left([\delta g_R^{Wf}]_{JJ}\right)^2$$

Z-pole observables

Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[21]	2.4950	$\sum_f \Gamma(Z \to f\bar{f})$
σ_{had} [nb]	41.541 ± 0.037	[21]	41.484	$\frac{12\pi}{m_Z^2} \frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\text{FB}}^{0,e}$	0.0145 ± 0.0025	[21]	0.0163	$\frac{3}{4} A_e^2$
$A_{\text{FB}}^{0,\mu}$	0.0169 ± 0.0013	[21]	0.0163	$\frac{3}{4} A_e A_\mu$
$A_{\text{FB}}^{0,\tau}$	0.0188 ± 0.0017	[21]	0.0163	$\frac{3}{4} A_e A_\tau$
R_b	0.21629 ± 0.00066	[21]	0.21578	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[21]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b^{FB}	0.0992 ± 0.0016	[21]	0.1032	$\frac{3}{4} A_e A_b$
A_c^{FB}	0.0707 ± 0.0035	[21]	0.0738	$\frac{3}{4} A_e A_c$
A_e	0.1516 ± 0.0021	[21]	0.1472	$\frac{\Gamma(Z\to e_L^+ e_L^-) - \Gamma(Z\to e_R^+ e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[21]	0.1472	$\frac{\Gamma(Z\to \mu_L^+ \mu_L^-) - \Gamma(Z\to e_\mu^+ \mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015	[21]	0.1472	$\frac{\Gamma(Z\to \tau_L^+ \tau_L^-) - \Gamma(Z\to \tau_R^+ \tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020	[21]	0.935	$\frac{\Gamma(Z\to b_L \bar{b}_L) - \Gamma(Z\to b_R \bar{b}_R)}{\Gamma(Z\to b\bar{b})}$
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
$\mathrm{Br}(W \to e\nu)$	0.1071 ± 0.0016	[28]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to ff')}$
$\mathrm{Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[28]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to ff')}$
$\mathrm{Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[28]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to ff')}$
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

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

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

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

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

- 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

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

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

Correlation Matrix

1σ Errors

Central Values

- If dictionary from Higgs 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

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

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

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

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

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

Pole constraints - 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

Constraints on 4-lepton operators from off-pole observables

Off-Pole constraints on 4-lepton observables

AA,Mimouni
1511.07434

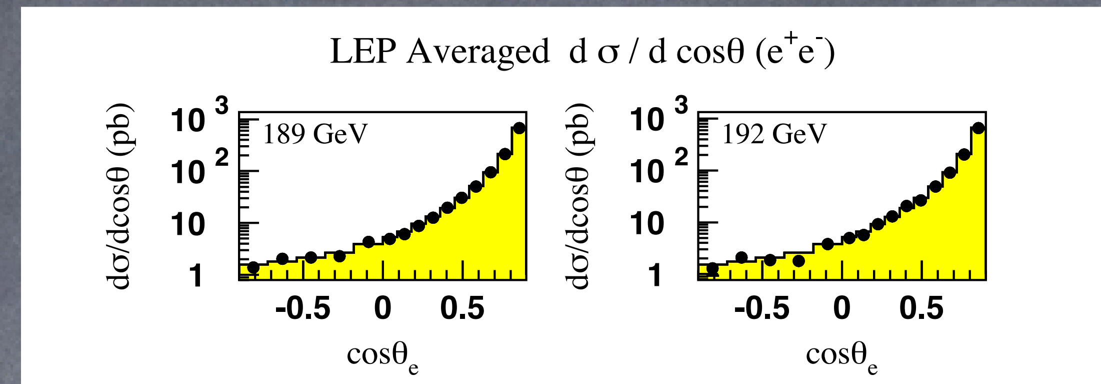
One flavor ($I = 1 \ldots 3$)	Two flavors ($I < J = 1 \ldots 3$)
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{\ell}_I \bar{\sigma}_\mu \ell_I)$	$[O_{\ell\ell}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{\ell}_J \bar{\sigma}_\mu \ell_J)$
	$[O_{\ell\ell}]_{IJJI} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_J)(\bar{\ell}_J \bar{\sigma}_\mu \ell_I)$
$[O_{\ell e}]_{IIII} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(e^c_I \sigma_\mu \bar{e}^c_I)$	$[O_{\ell e}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(e^c_J \sigma_\mu \bar{e}^c_J)$
	$[O_{\ell e}]_{JJII} = (\bar{\ell}_J \bar{\sigma}_\mu \ell_J)(e^c_I \sigma_\mu \bar{e}^c_I)$
	$[O_{\ell e}]_{IJJI} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_J)(e^c_J \sigma_\mu \bar{e}^c_I)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e^c_I \sigma_\mu \bar{e}^c_I)(e^c_I \sigma_\mu \bar{e}^c_I)$	$[O_{ee}]_{IIJJ} = (e^c_I \sigma_\mu \bar{e}^c_I)(e^c_J \sigma_\mu \bar{e}^c_J)$

- There's 27 lepton-flavor conserving 4-lepton operators, 3 of which are complex, however not all are currently probed by experiment
- Using e+e- -> ll scattering in LEP-2, low-energy neutrino scattering on electrons, W mass measurement, low-energy parity violating Moller scattering, and muon and tau decays
- All these observables depend also on leptonic vertex corrections, so combination with previous pole constraints is necessary

$$\delta m = \frac{\delta g_L^{We} + \delta g_L^{W\mu}}{2} - \frac{[c_{\ell\ell}]_{1221}}{4}.$$

Example: LEP-2 constraints on 4-electron operators

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

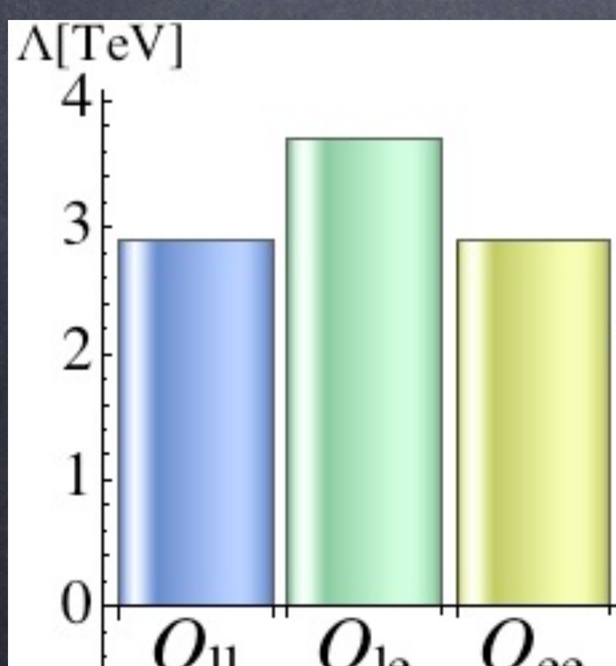


1-by-1

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

Simultaneous

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



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

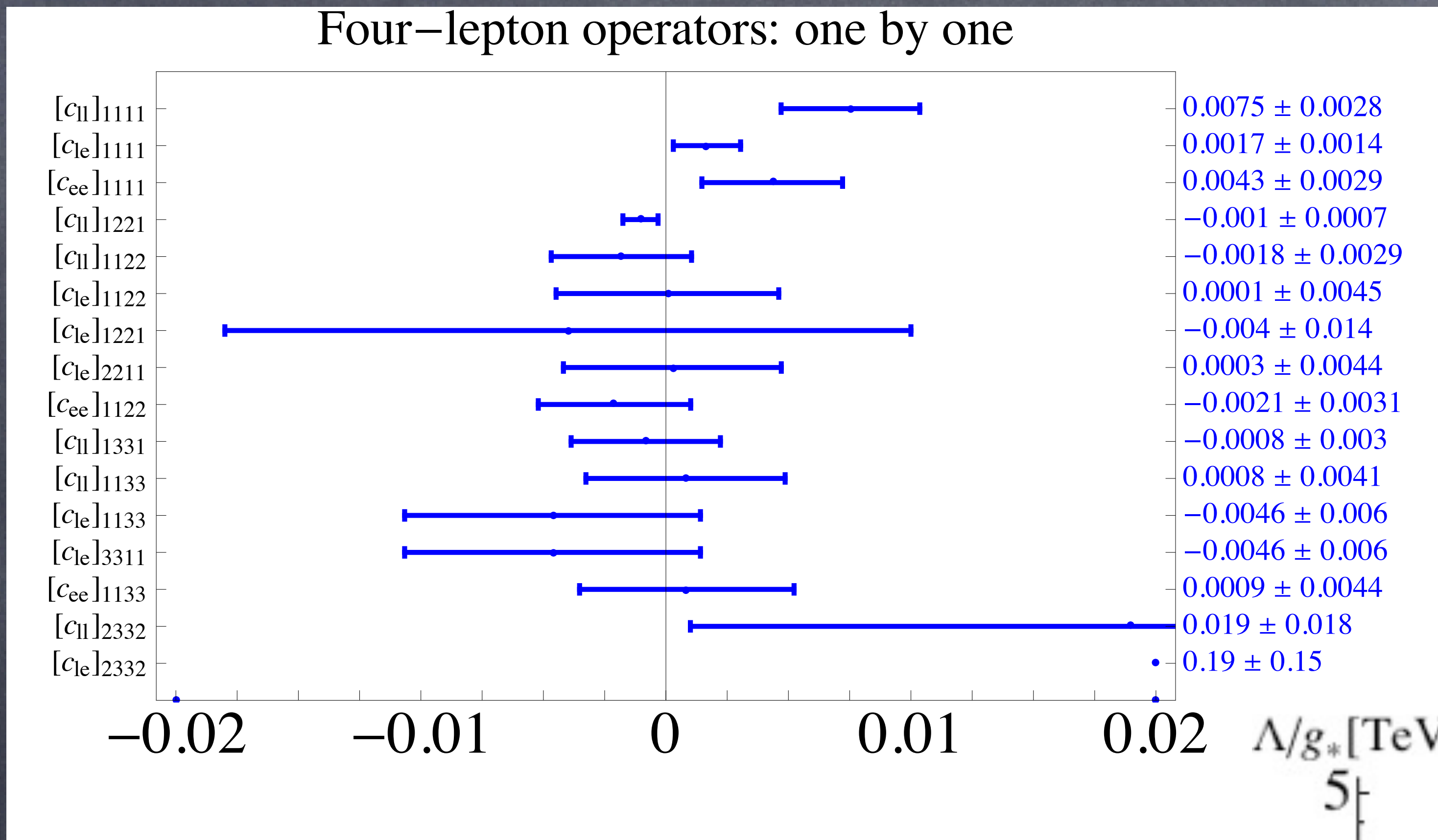
One needs other observables
to break degeneracy

Off-Pole constraints on 4-lepton observables

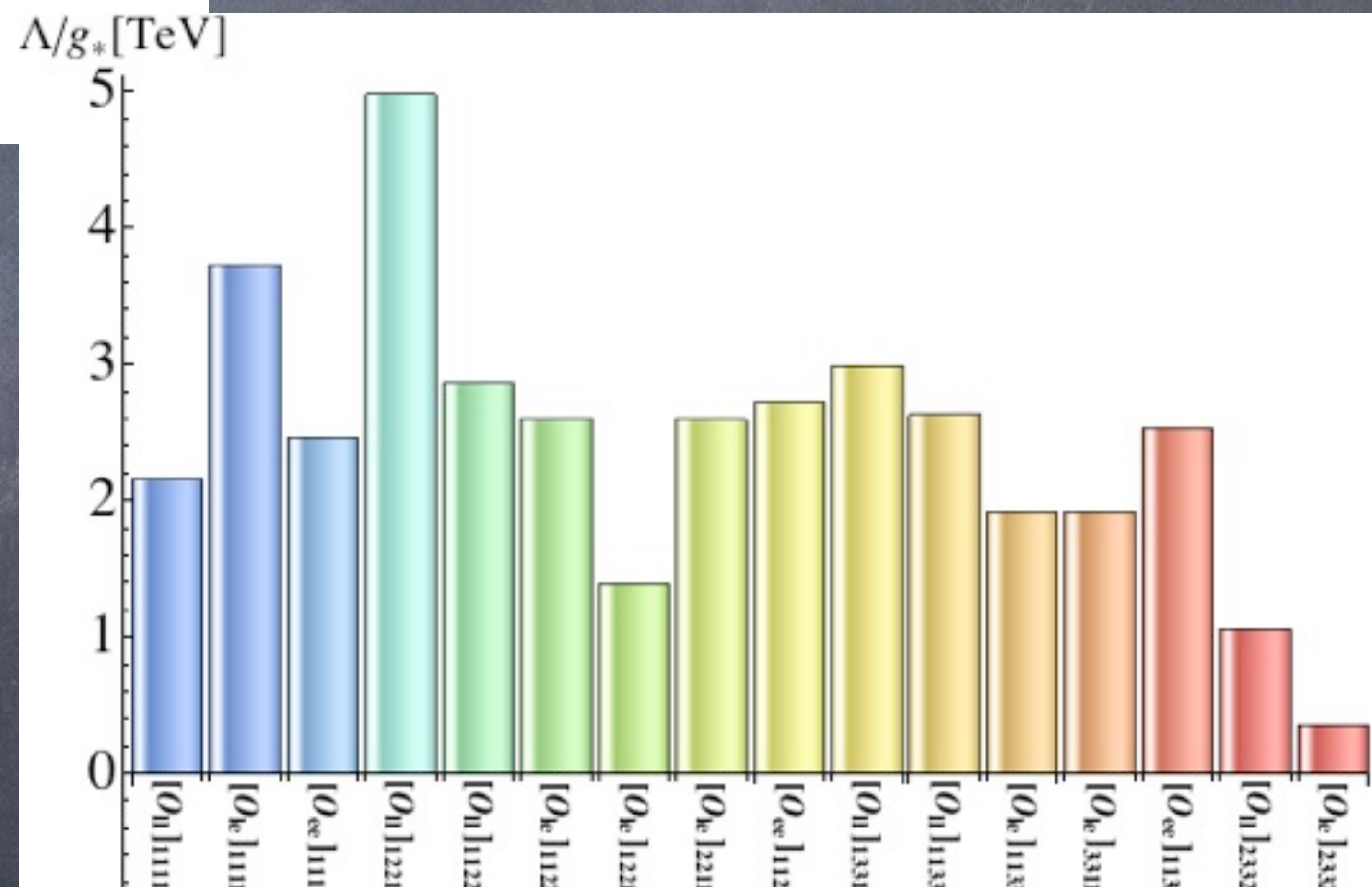
$$
\begin{pmatrix}
\delta g_L^{We} \\
\delta g_L^{W\mu} \\
\delta g_L^{W\tau} \\
\delta g_L^{Ze} \\
\delta g_L^{Z\mu} \\
\delta g_L^{Z\tau} \\
\delta g_R^{Ze} \\
\delta g_R^{Z\mu} \\
\delta g_R^{Z\tau} \\
[c_{\ell\ell}]_{1111} \\
[c_{\ell e}]_{1111} \\
[c_{ee}]_{1111} \\
[c_{\ell\ell}]_{1221} \\
[c_{\ell\ell}]_{1122} \\
[c_{\ell e}]_{1122} \\
[c_{\ell e}]_{2211} \\
[c_{ee}]_{1122} \\
[c_{\ell\ell}]_{1331} \\
[c_{\ell\ell}]_{1133} \\
[c_{\ell e}]_{1133} + [c_{\ell e}]_{3311} \\
[c_{ee}]_{1133} \\
[c_{\ell\ell}]_{2332}
\end{pmatrix}
=
\begin{pmatrix}
-1.00 \pm 0.64 \\
-1.36 \pm 0.59 \\
1.95 \pm 0.79 \\
-0.027 \pm 0.028 \\
0.01 \pm 0.11 \\
0.016 \pm 0.058 \\
-0.037 \pm 0.027 \\
0.00 \pm 0.13 \\
0.039 \pm 0.062 \\
0.99 \pm 0.39 \\
-0.23 \pm 0.22 \\
0.23 \pm 0.39 \\
-4.8 \pm 1.6 \\
2.0 \pm 2.3 \\
0.9 \pm 2.3 \\
-0.8 \pm 2.2 \\
2.8 \pm 2.8 \\
1.5 \pm 1.3 \\
140 \pm 170 \\
-0.55 \pm 0.64 \\
-150 \pm 180 \\
3.0 \pm 2.3
\end{pmatrix}
\times 10^{-2},
$$

- Full correlation matrix also calculated
- Typical constraints at 1% level
- Flat directions for electron-tau operators: no additional observables to break LEP-2 degeneracy

Off-Pole constraints on 4-lepton observables



One-by-one constraints are stronger, especially for electron-muon operators. Experiment probes scales suppressing 4-fermion operators up to 5 TeV



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

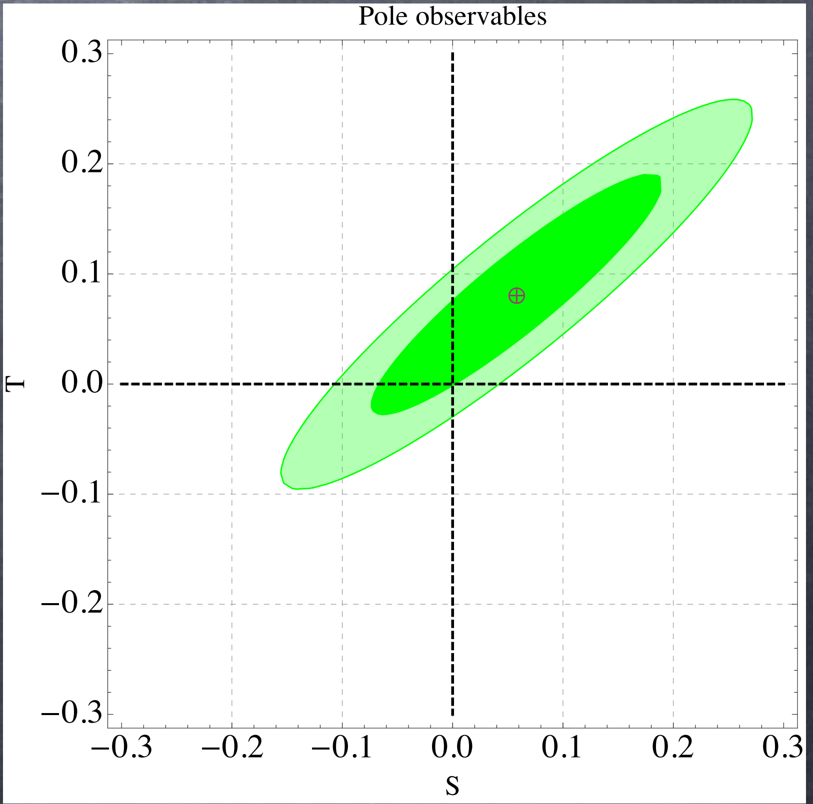
Wells Zhang 1510.08462

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

$$[\delta g^{Zf}]_{ij} = \delta_{ij}\alpha\left\{T_f^3\frac{T - W - \frac{g_Y^2}{g_L^2}Y}{2} + Q_f\frac{2g_Y^2T - (g_L^2+g_Y^2)S + 2g_Y^2W + \frac{2g_Y^2(2g_L^2-g_Y^2)}{g_L^2}Y}{4(g_L^2-g_Y^2)}\right\}$$
$$\delta m = \frac{\alpha}{4(g_L^2-g_Y^2)}\left[2g_L^2T - (g_L^2+g_Y^2)S + 2g_Y^2W + 2g_Y^2Y\right]$$

$$[c_{\ell\ell}]_{IIJJ} = \alpha\left[W - \frac{g_Y^2}{g_L^2}Y\right] \qquad [c_{\ell\ell}]_{IJJI} = -2\alpha W, \qquad I < J$$
$$[c_{\ell\ell}]_{IIII} = -\alpha\left[W + \frac{g_Y^2}{g_L^2}Y\right]$$
$$[c_{\ell e}]_{IIJJ} = -\frac{2g_Y^2}{g_L^2}\alpha Y \qquad [c_{ee}]_{IIJJ} = -\frac{4g_Y^2}{g_L^2}\alpha Y$$

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



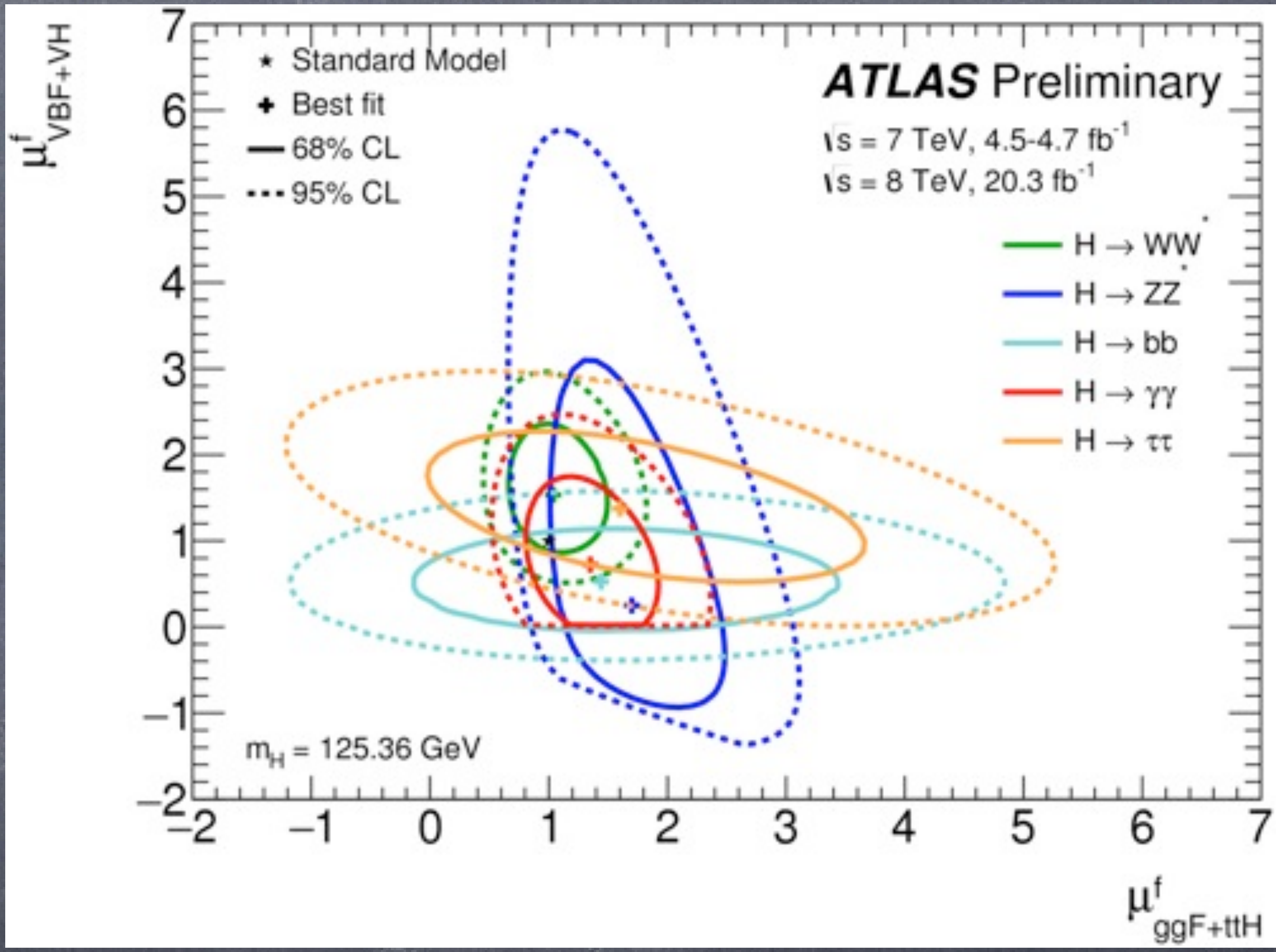
Constraints from LHC Higgs data

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)

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

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

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

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

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

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

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

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

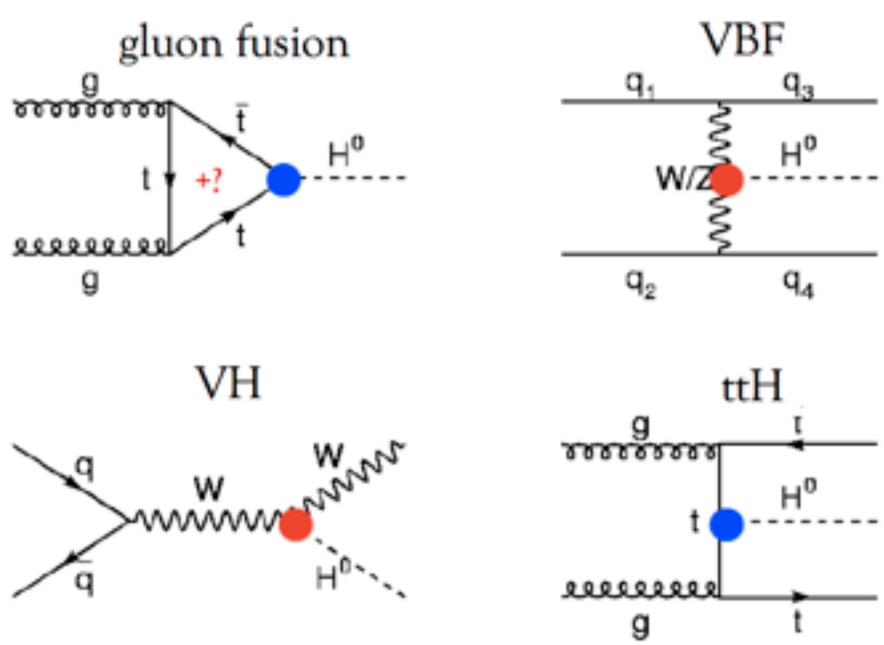
- Higgs signal strength observables at linear level are only sensitive to CP even parameter (CP odd enter only quadratically and are ignored)
- Only couplings unconstrained by precision tests can be relevant at the LHC
- Thus, assuming MFV couplings to fermions, only 9 EFT parameter affect Higgs signal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

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

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



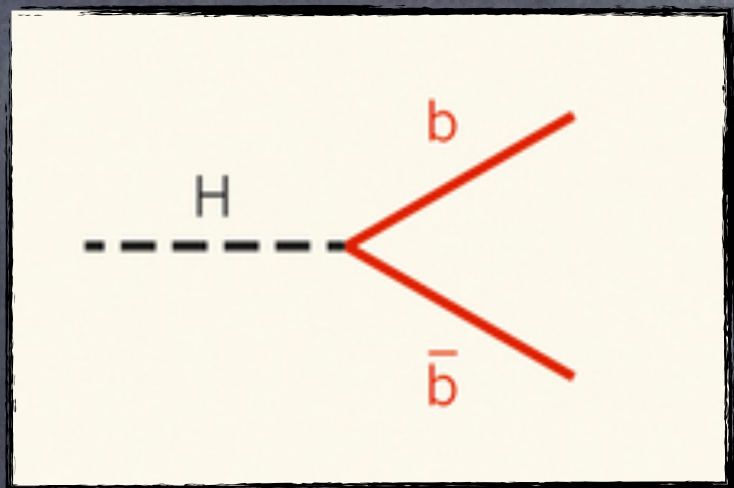
$$\frac{\sigma_{tth}}{\sigma^{\rm SM}_{tth}} \simeq 1 + 2\delta y_u.$$

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

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

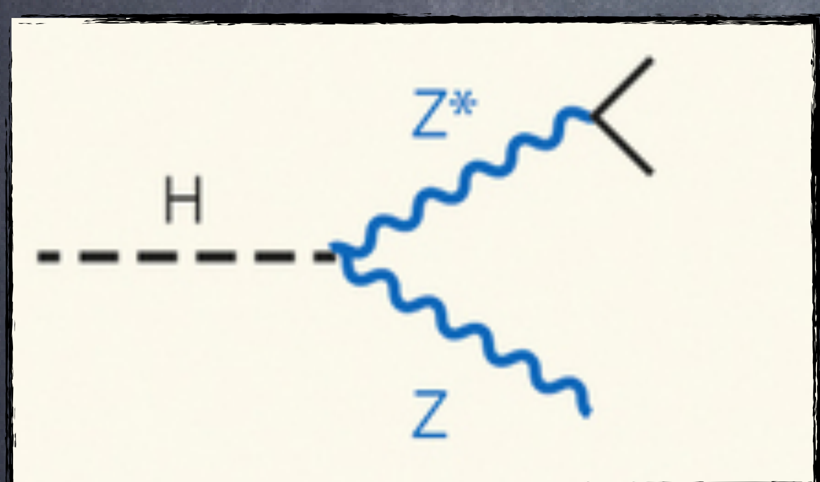
Higgs decay in the Higgs basis

Decays to 2 fermions



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

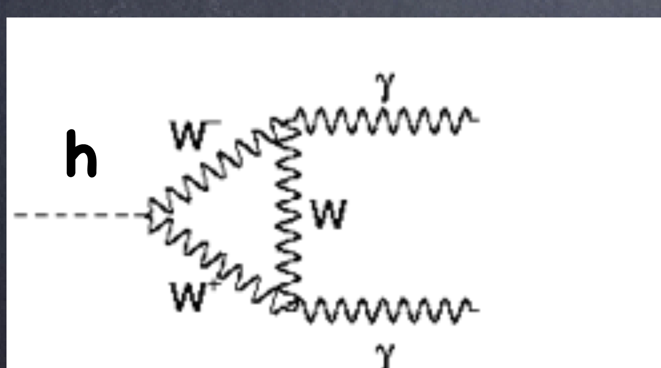
Decays to 4 fermions

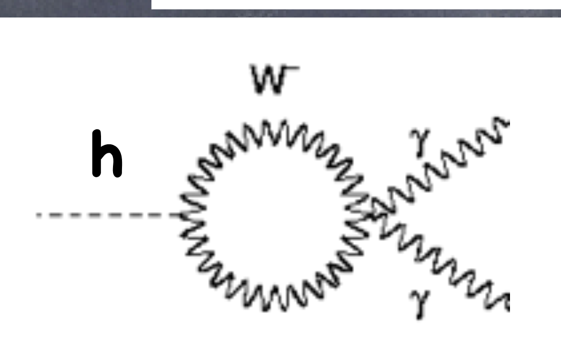


$$\begin{aligned} \frac{\Gamma_{2\ell 2\nu}}{\Gamma_{2\ell 2\nu}^{\rm SM}} \quad &\simeq \quad 1 + 2\delta c_w + 0.46 c_{w\Box} - 0.15 c_{ww} \\ &\to \quad 1 + 2\delta c_z + 0.67 c_{z\Box} + 0.05 c_{zz} - 0.17 c_{z\gamma} - 0.05 c_{\gamma\gamma}. \end{aligned}$$

$$\left(\begin{array}{c} \text{2e2μ} \\ \text{4e} \end{array}\right)$$

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

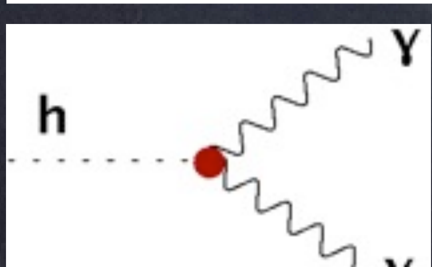


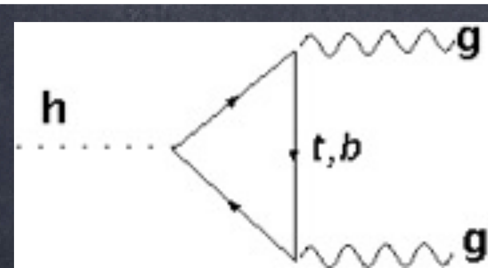


Decays to 2 gauge bosons

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

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





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 $O(1/\Lambda^2)$

TGC - Higgs Synergy

TGC

CP even : $\delta\kappa_\gamma \quad \delta g_{1,z} \quad \lambda_z$

CP odd : $\tilde{\kappa}_\gamma \quad \tilde{\lambda}_z$

$\longleftrightarrow$

Higgs

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

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

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

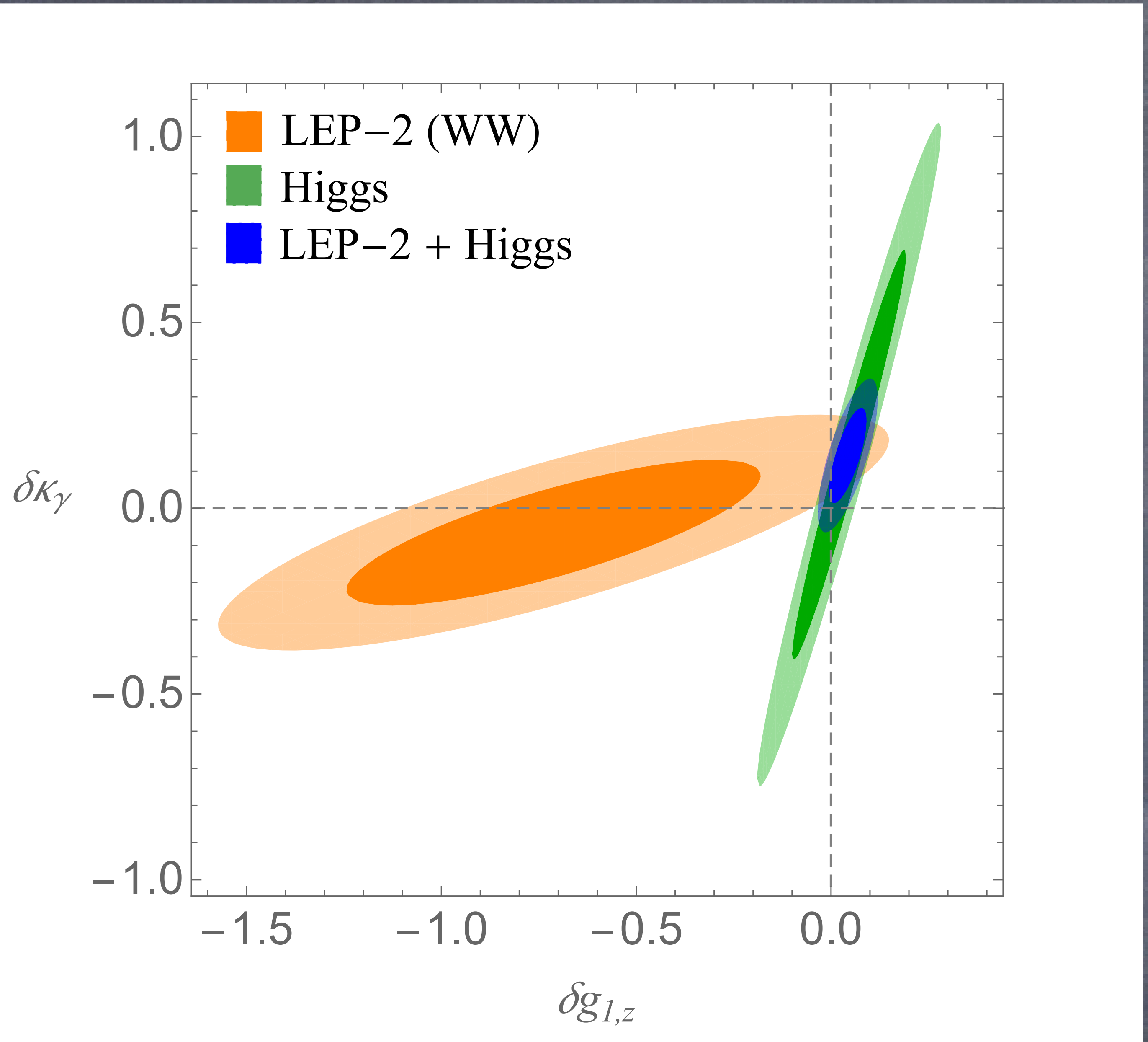
$$
\begin{pmatrix} \delta c_z \\ c_{zz} \\ c_{z\Box} \\ c_{\gamma\gamma} \\ c_{z\gamma} \\ c_{gg} \\ \delta y_u \\ \delta y_d \\ \delta y_e \\ \lambda_z \end{pmatrix} = \begin{pmatrix} -0.07 \pm 0.14 \\ 0.65 \pm 0.42 \\ -0.29 \pm 0.21 \\ -0.005 \pm 0.014 \\ -0.005 \pm 0.095 \\ -0.0053 \pm 0.0027 \\ 0.55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

Correlation matrix

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

- 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

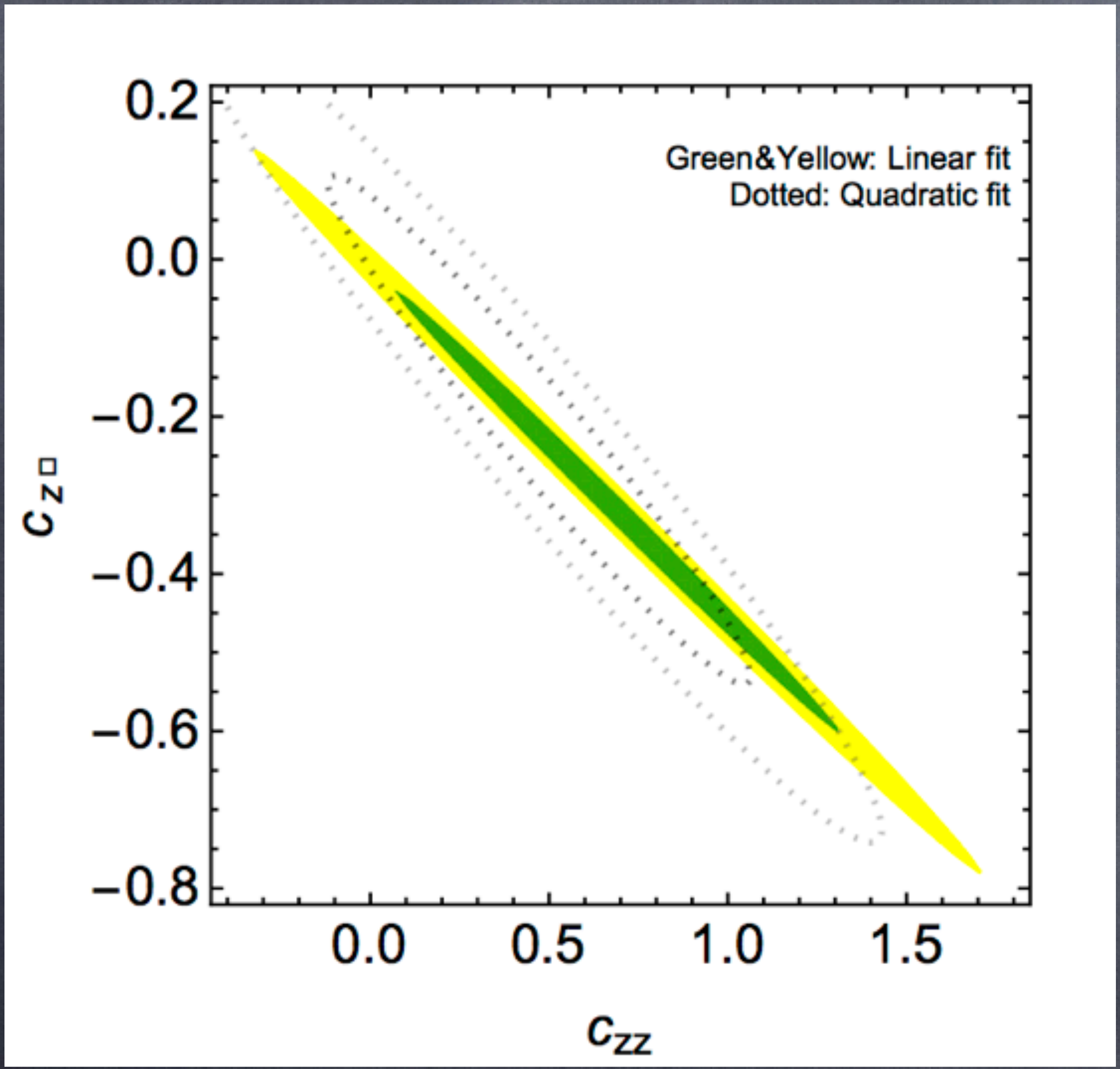


- LHC Higgs and LEP-2 WW data by itself do not constrain TGCs robustly due to each suffering from 1 flat direction in space of 3 TGCs
- However, the flat directions are orthogonal and combined constraints lead to robust O(0.1) limits on aTGCs

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

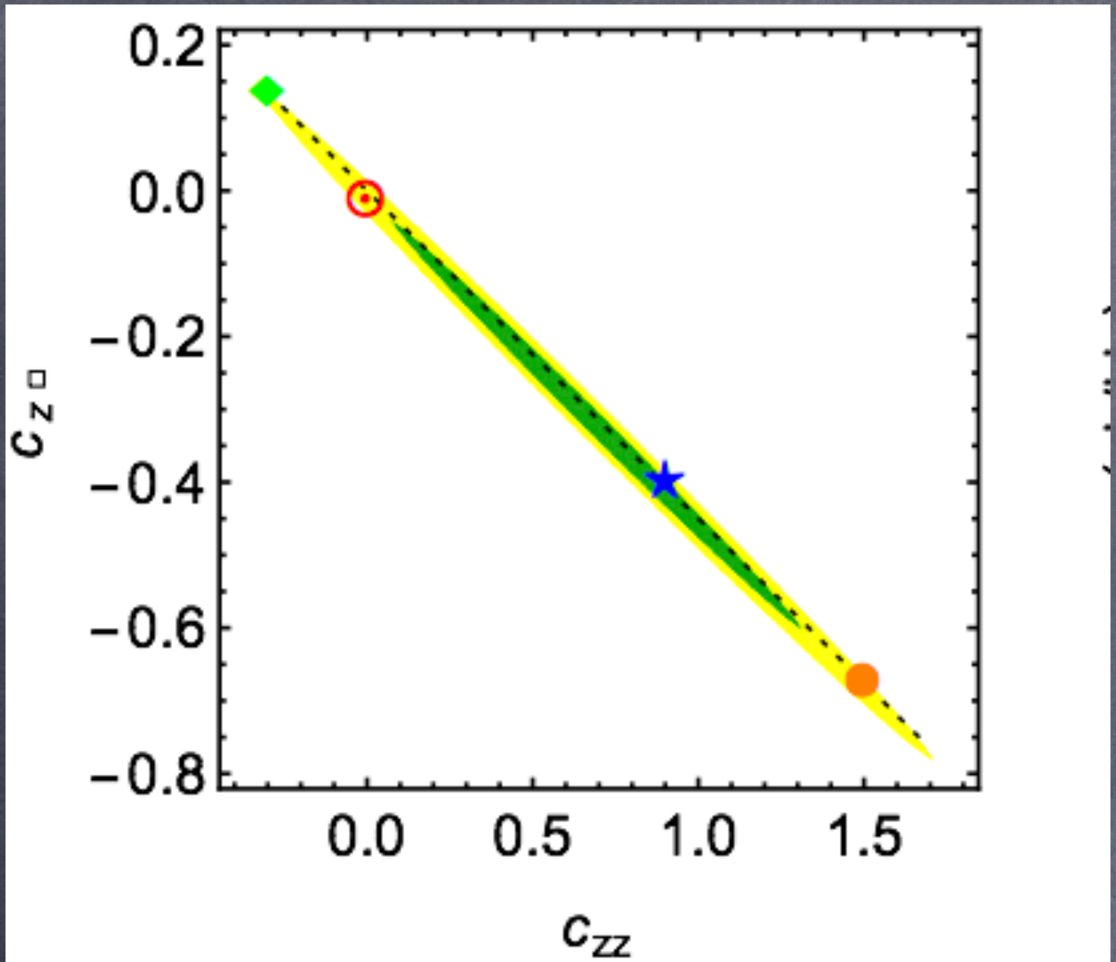
$$\rho = \begin{pmatrix} 1 & 0.62 & -0.84 \\ 0.62 & 1 & -0.85 \\ -0.84 & -0.85 & 1 \end{pmatrix}$$

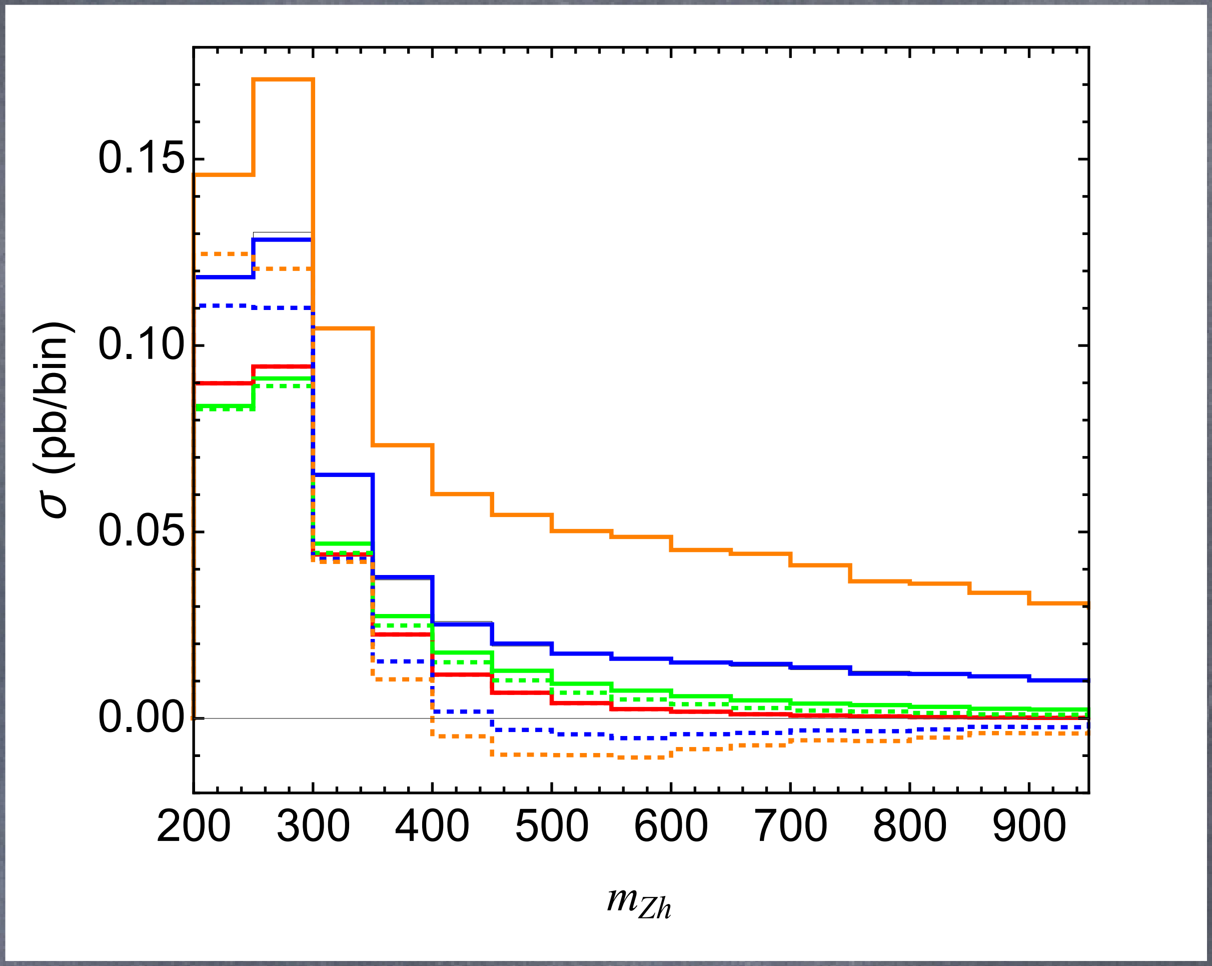
Combined WW+Higgs: robustness



- Non-trivial constraints at linear (1/Λ^2) level
- Quadratic (1/Λ^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

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.

- Adding off-pole observables, one can also constrain 4-fermion operators

- Constraints are given as likelihood in space of D=6 parameters, without assuming anything about flavor structure of higher dimensional operators

- 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 model-independent bounds