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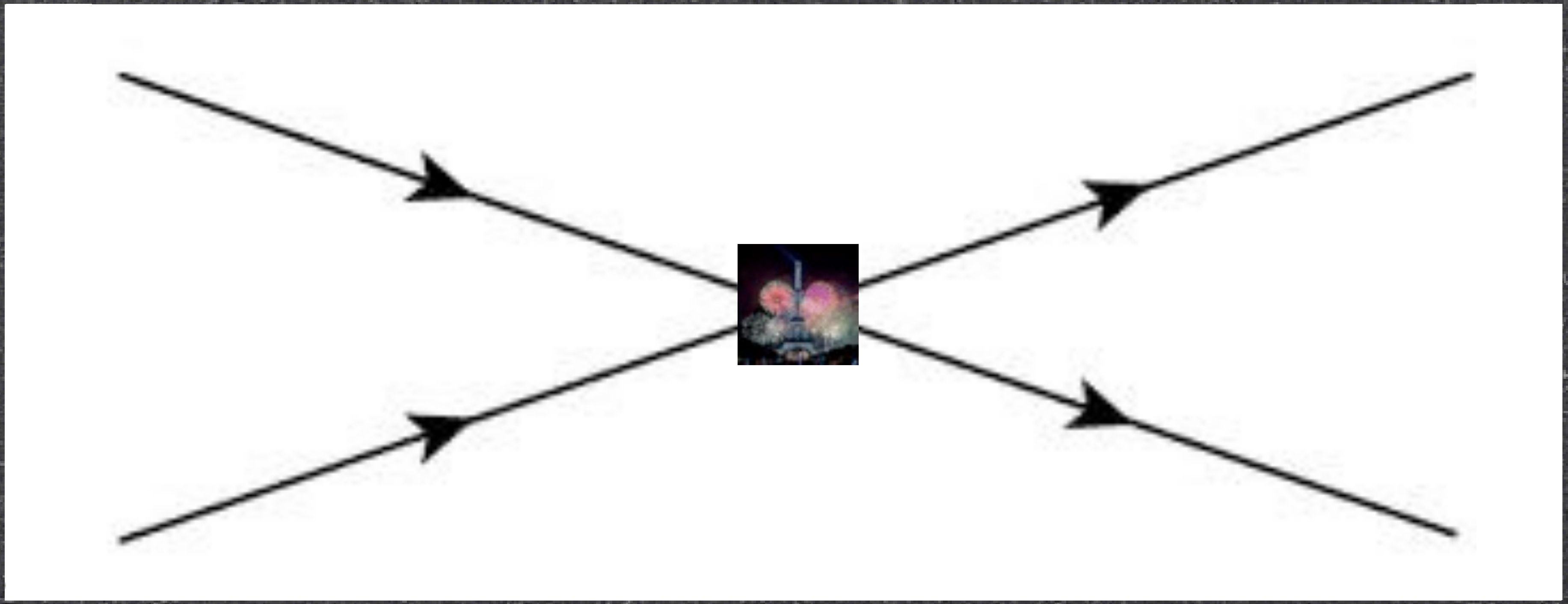
Higgs and Electroweak Precision Observables in Effective Field Theory



1st FCC-ee workshop on
precision observables
and radiative corrections

CERN, 14 July 2015

Based on:
my 1505.00046,
1411.0669 with Francesco Riva,
1503.07872 with Aielet Efrati and Yotam Soreq,
and work in progress with Martin Gonzalez-Alonso, Admir Greljo, and David Marzocca.

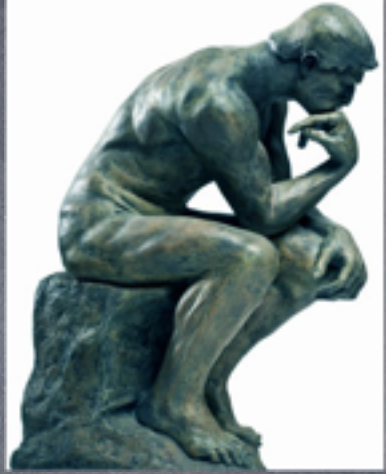
See also talks
of V.Sanz and T.You
for related results
and references

Plan

- Introduction: where do we stand
- Effective field theory approach
  to physics beyond the standard model
- Current precision constraints:
  - from LEP-1 pole observables
  - from LEP-2 WW production
  - from LHC Higgs data

Where do we stand?

Life After Discovery



- Discovery of 125 GeV Higgs boson is the last piece of the puzzle that falls into place
- No more free parameters in the SM
- Overwhelming evidence that particle interactions are dictated by SU(3)xSU(2)xU(1) local symmetry
- All data consistent with the electroweak symmetry breaking SU(2)xU(1)→U(1) proceeding via a single doublet Higgs field

What about new physics?

- We know physics beyond the SM exists (neutrino masses, dark matter, inflation, baryon asymmetry)
- There are also some theoretical hints for new physics (strong CP problem, flavor hierarchies, charge quantization, gauge coupling unifications, naturalness problem)
- But there isn't one model or a class of models that is currently strongly preferred
- How to keep open mind on a large class of new physics models?

Effective Field Theory approach to BSM physics

Effective Theory Approach to BSM

- SM is probably a correct theory the weak scale, at least as the leading order approximation in the effective theory expansion
- If that is the case (in particular, no new light degrees of freedom at weak scale), possible new physics effects can be encoded into higher dimensional operators added to the SM
- EFT framework offers a systematic expansion around the SM organized in terms of operator dimensions, with higher dimensional operator suppressed by the mass scale of new physics

Effective Theory Approach to BSM

Basic assumptions

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

- 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

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

Alternatively,
non-linear Lagrangians
with derivative expansion

Effective Theory Approach to BSM

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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 violating,
hence too small to probe at LHC

Subleading
to D=6

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

Any complete basis leads to
completely equivalent physics description

Warsaw Basis — Grządkowski et al. 1008.4884, Alonso et al 1312.2014

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

Primary/Higgs basis — Gupta et al 1405.0181, LHCHXSWG-INT-2015-001

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

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

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

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

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

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

Grządkowski et al. 1008.4884

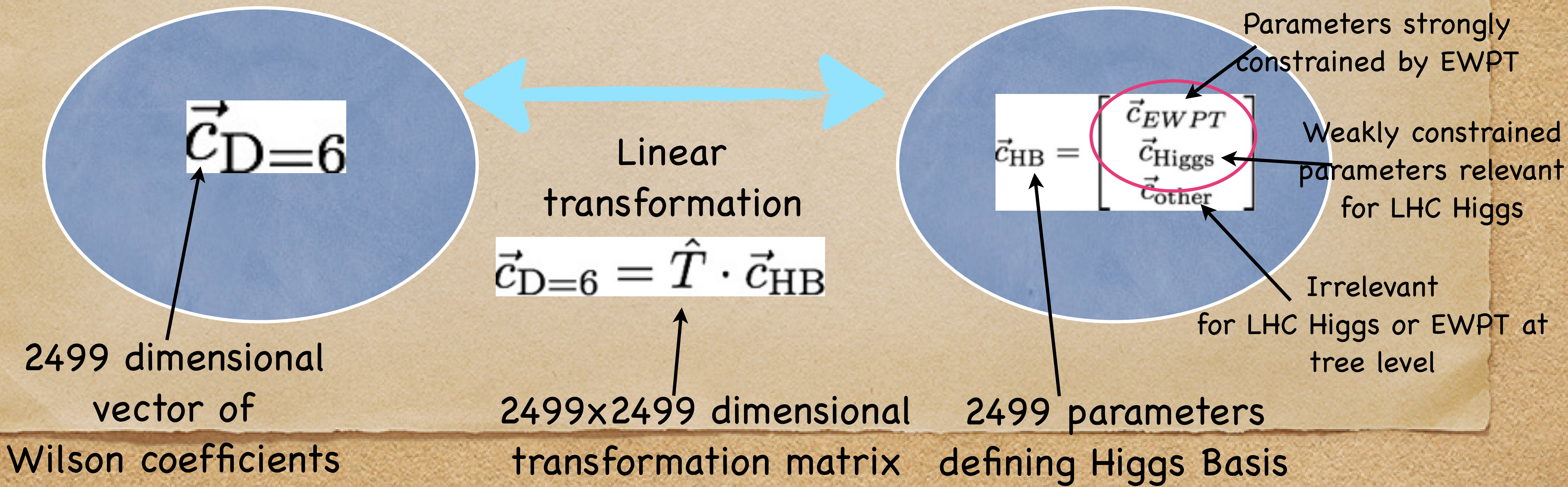
59 different kinds of operators, of which 17 are complex

2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014

Higgs Basis

- Higgs 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 the ones constrained by electroweak precision tests



Higgs Basis Lagrangian

- Higgs 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

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

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

Higgs Basis: Z and W couplings to fermions

- 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

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

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

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

Dependent Couplings:

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

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

Higgs 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
- 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

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

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

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

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

relative correction to W mass

LHCHXSWG-INT-2015-001

$$\text{CP even}: \quad \delta y_u \quad \delta y_d \quad \delta y_e$$

$$\text{CP odd}: \quad \phi_u \quad \phi_d \quad \phi_e$$

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

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 Higgs basis parameters describing Higgs couplings to electroweak gauge bosons, and on 2 new parameters

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

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

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

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

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

Higgs basis summary

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)

- Restrict to observables that do not depend on 4-fermion operators (these are not neglected - just do not contribute at tree-level; constraints on 4-fermion operators are 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

On-shell Z decays: nuts and bolts

Lowest order:

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

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

w/ new physics:

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

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

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

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

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

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

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

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

Pole 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

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

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
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 constraints - Results

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

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

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

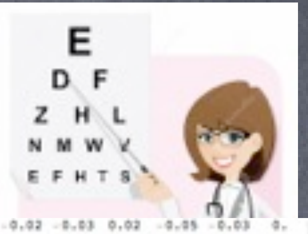
$$[\delta g_L^{Zu}]_{ii} = \begin{pmatrix} -0.8 \pm 3.1 \\ -0.16 \pm 0.36 \\ -0.28 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zu}]_{ii} = \begin{pmatrix} 1.3 \pm 5.1 \\ -0.38 \pm 0.51 \\ \times \end{pmatrix} \times 10^{-2},$$

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

- 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
- Some off-diagonal vertex corrections can also be constrained

Efrati,AA,Soreq
1503.07872

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
- If dictionary from Higgs basis to other bases exists, results can be easily recast
- Similarly, results can be easily recast for particular BSM models in which vertex and mass corrections are functions of (fewer) model parameters

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

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

Correlation Matrix

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

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

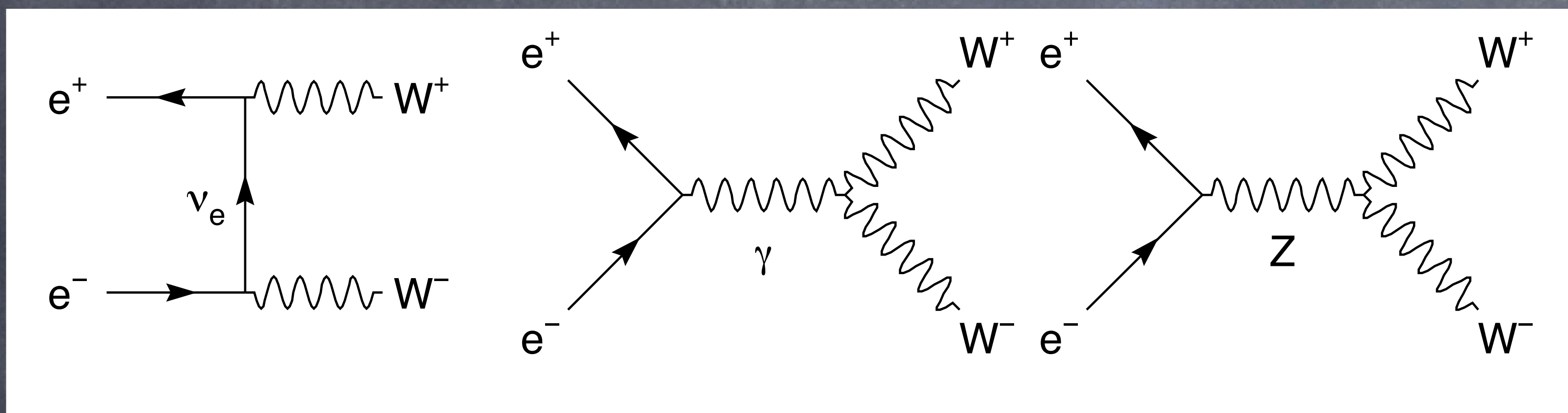
$$f(T^3, Q) = \mathbb{I}\left[-Q c_{WB} \frac{g_L^2 g_Y^2}{g_L^2 - g_Y^2} + (c_T - \delta v)\left(T^3 + Q\frac{g_Y^2}{g_L^2 - g_Y^2}\right)\right].$$

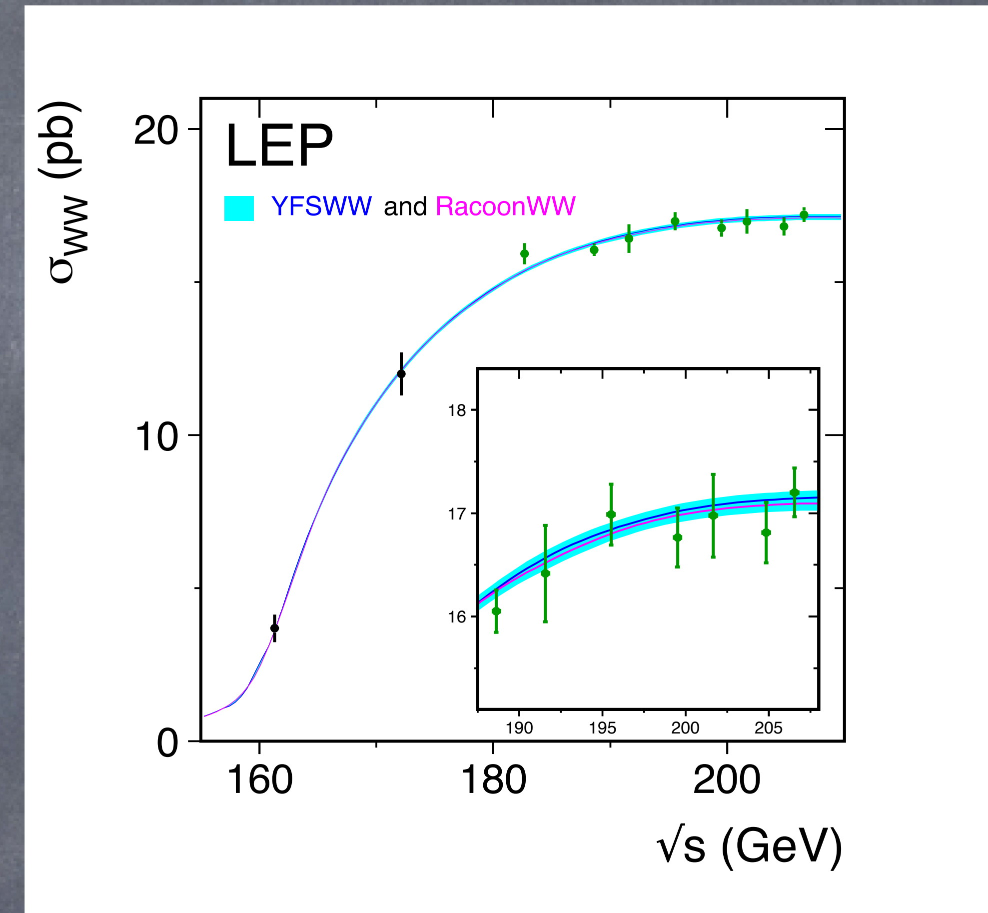
$$\begin{aligned}
\delta g_L^{Wq} &= c'_{Hq} V + f(1/2, 2/3) V - f(-1/2, -1/3) V, \\
\delta g_R^{Wq} &= c_{Hud}, \\
\delta g_L^{Zu} &= \frac{1}{2}\left(c'_{Hq} - c_{Hq}\right) + f(1/2, 2/3), \\
\delta g_L^{Zd} &= -\frac{1}{2} V^\dagger \left(c'_{Hq} + c_{Hq}\right) V + f(-1/2, -1/3), \\
\delta g_R^{Zu}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

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

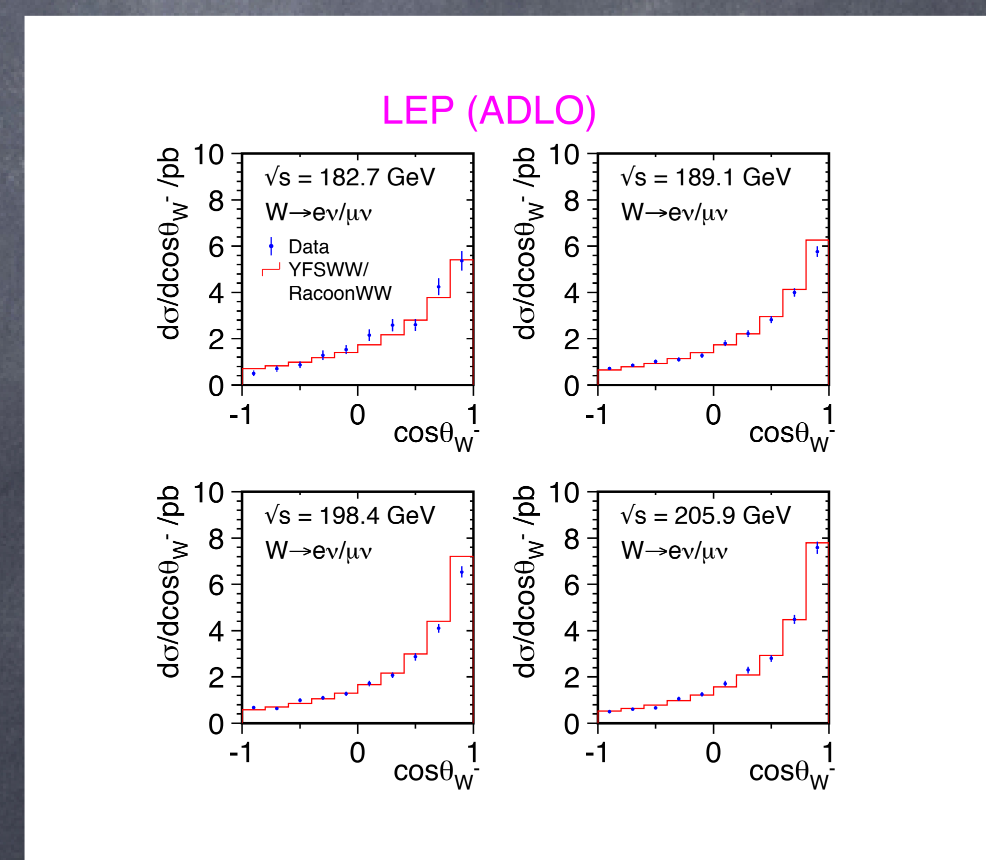
Constraints from WW production at LEP-2

WW production at LEP-2

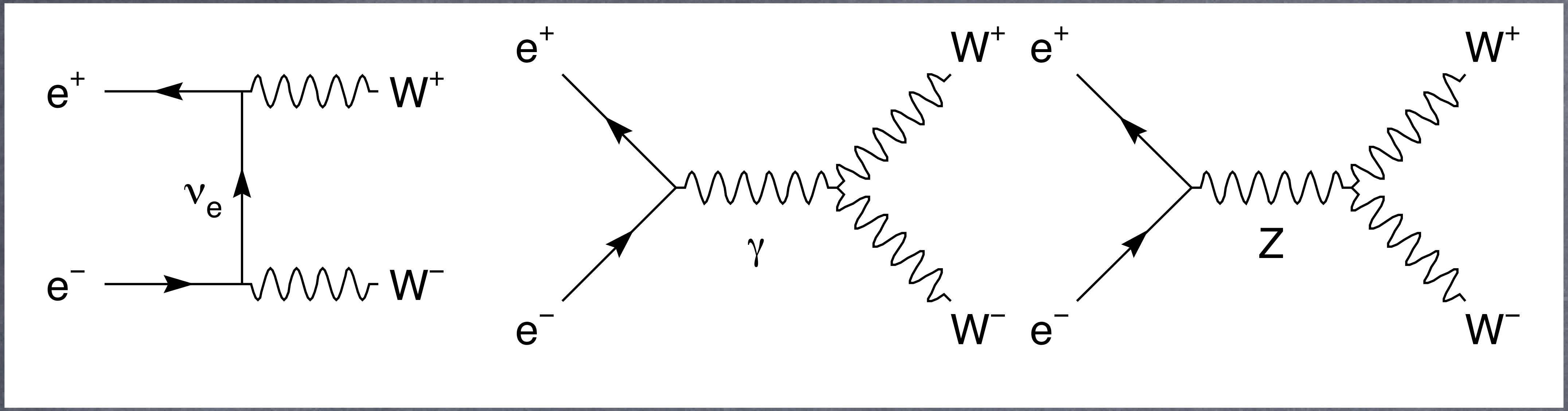




Total and differential WW production cross section measured at different c.o.m. energies in LEP-2



WW production at LEP-2



- In Higgs basis e+ e- > W+ W- cross section at LEP-2 depends at O(1/Λ^2) on several parameters: correction to W mass δm, 3 leptonic vertex corrections δg, and on 3 combinations of parameter contributing to CP-even anomalous triple gauge couplings
- However, δm and δg are already strongly constrained by pole observables, at the level of O(0.1%), whereas precision of WW LEP-2 measurements is only O(1%)
- Therefore, only 3 combinations of parameters: δg1z, δκγ, λz are effectively probed by LEP-2 WW measurements. Same results are obtained if these 3 aTGCs are fit to LEP-2 WW data alone, and when all δm+δg+aTGCs are fit to combined LEP-1+LEP-2 data

Triple Gauge Couplings

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

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

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

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

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

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

Constraints from WW production

Results

AA,Riva 1411.0669;
AA,Gonzalez-Alonso,Greljo,Marzocca to appear

$$\begin{pmatrix} \delta g_{1,z} \\ \delta\kappa_\gamma \\ \lambda_z \end{pmatrix} = \begin{pmatrix} 0.043 \pm 0.031 \\ 0.142 \pm 0.085 \\ -0.162 \pm 0.073 \end{pmatrix}, \qquad \rho = \begin{pmatrix} 1 & 0.74 & -0.85 \\ 0.74 & 1 & -0.88 \\ -0.85 & -0.88 & 1 \end{pmatrix}.$$

- The limits are rather weak, in part due to an accidental flat direction of LEP-2 constraints along λz ≈ -δg1Z
- In fact, the limits are sensitive to whether terms quadratic in dimension-6 operator are included or not
- This in turn implies that the limits might be affected by dimension-8 operators if, as expected from EFT counting, c8~c6^2

Constraints from LHC Higgs data

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 flavor blind 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 pole observables

ATLAS			
Channel	μ	Production	Ref.
$\gamma\gamma$	$1.17^{+0.28}_{-0.26}$	cats.	[9]
$Z\gamma$	$2.7^{+4.6}_{-4.5}$	total	[10]
ZZ^*	$1.46^{+0.40}_{-0.34}$	2D	[11]
WW^*	$1.18^{+0.24}_{-0.21}$	2D	[12]
	$2.1^{+1.9}_{-1.6}$	Wh	[13]
	$5.1^{+4.3}_{-3.1}$	Zh	[13]
$\tau\tau$	$1.44^{+0.42}_{-0.37}$	2D	[14]
bb	$1.11^{+0.65}_{-0.61}$	Wh	[15]
	$0.05^{+0.52}_{-0.49}$	Zh	[15]
	$1.5^{+1.1}_{-1.1}$	tth	[16]
$\mu\mu$	$-0.7^{+3.7}_{-3.7}$	total	[10]
multi-ℓ	$2.1^{+1.4}_{-1.2}$	tth	[17]

CMS			
Channel	μ	Production	Ref.
$\gamma\gamma$	$1.12^{+0.25}_{-0.22}$	cats.	[18]
$Z\gamma$	$-0.2^{+4.9}_{-4.9}$	total	[19]
ZZ^*	$1.00^{+0.29}_{-0.29}$	2D	[20]
WW^*	$0.83^{+0.21}_{-0.21}$	2D	[20]
	$0.80^{+1.09}_{-0.93}$	Vh	[20]
$\tau\tau$	$0.91^{+0.28}_{-0.28}$	2D	[20]
	$0.87^{+1.00}_{-0.88}$	Vh	[20]
	$-1.3^{+6.3}_{-5.5}$	tth	[21]
bb	$0.89^{+0.47}_{-0.44}$	Vh	[20]
	$2.8^{+1.6}_{-1.4}$	VBF	[22]
	$1.2^{+1.6}_{-1.5}$	tth	[23]
$\mu\mu$	$0.8^{+3.5}_{-3.4}$	total	[24]
multi-ℓ	$3.8^{+1.4}_{-1.4}$	tth	[21]

TABLE I. The LHC Higgs results used in the fit.

Higgs constraints on EFT

AA, 1505.00046

	$\mathbf{L}$ $(x_0 \pm 1\ \sigma)$
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

Flat direction

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

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

- Should be treated with a grain of salt
- 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 results are sensitive to including dimension-8 operators

TGC - Higgs Synergy

TGC

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

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

$\longleftrightarrow$

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+WW constraints on EFT

AA, Gonzalez-Alonso, Greljo, Marzocca to appear

$$\begin{pmatrix} \delta c_z \\ c_{zz} \\ c_{z\Box} \\ c_{\gamma\gamma} \\ c_{z\gamma} \\ c_{gg} \\ \delta y_u \\ \delta y_d \\ \delta y_e \\ \lambda_z \end{pmatrix} = \begin{pmatrix} -0.02 \pm 0.17 \\ 0.69 \pm 0.42 \\ -0.32 \pm 0.19 \\ 0.009 \pm 0.015 \\ 0.002 \pm 0.098 \\ -0.0052 \pm 0.0027 \\ 0.57 \pm 0.30 \\ -0.24 \pm 0.35 \\ -0.12 \pm 0.20 \\ -0.162 \pm 0.073 \end{pmatrix},$$

- Flat direction between c_zz and c_zBox lifted by WW data!
- Much better constraints on some parameters. Most parameters (marginally) within the EFT regime
- Lower sensitivity to the quadratic terms (though still non-negligible for δyd)

Take away

- There are strong constraints on certain combinations of dimension-6 operators from the pole observables measured at LEP-1 and other colliders
- There are some meaningful constraints on these parameters from Higgs and WW data
- One (arguably simplest) way to describe them is to use the so-called Higgs basis developed within LHCHXSWG.
- These constraints allow to describe LO EFT deformations of single Higgs signal strength LHC observables by just 9 parameters
- Synergy of TGC and Higgs coupling measurements is crucial to derive meaningful bounds

Outlook (TH)

- More general analysis that includes off-pole observables sensitive to 4-fermion operators
- Model-independent constraints from WW and WZ production at the LHC
- Including NLO EFT effects

Outlook (EXP)

- Z and W boson couplings to light quarks are weakly constrained in model-independent way (light quarks asymmetries and ratios in e+e- colliders, more-general DY studies at LHC)
- Higgs couplings to RH tops are completely unconstrained in model-independent way (ttbar in e+e- machines, model-independent hadron collider studies)
- WW production is extremely important to constrain EFT parameters that are otherwise difficult to access (e+e- machines, EFT studies in LHC, distributions to access CP violating operators)
- EFT approach to LHC Higgs searches to access constrain CP-even and CP-odd 2-derivative Higgs couplings


Merci