EFT constraints from precision measurements and prospects

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Precision theory for precise measurements at LHC and future colliders

ICISE, Quy Nhon, Vietnam, 28/09/2016

The Linear SM Effective Field Theory

See talk by Sacha Davidson

Assumptions

Scale of New Physics is high

$$\Lambda_{NP} \gg m_h$$

Higgs is a $SU(2)_L$ doublet

Low energy theory specified by particle content + symmetries

Leading deformations of the SM

+ L and B conservation

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

59 independent dim-6 operators if flavour universality.
2499 parameters for a generic flavour structure.

[Buchmuller and Wyler ’86, Grzadkowski et al. 1008.4884, Alonso et al. 1312.2014]

Observables and the SM EFT

$$\mathcal{L}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

$O(E^2/\Lambda^2)$ $O(E^4/\Lambda^4)$

$$\sigma = \sigma^{\rm SM} + \sum_i \left(\frac{c_i^{(6)}}{\Lambda^2}\sigma_i^{(6\times {\rm SM})} + {\rm h.c.}\right) + \sum_{ij} \frac{c_i^{(6)} c_j^{(6)*}}{\Lambda^4}\sigma_{ij}^{(6\times 6)} + \sum_j \left(\frac{c_j^{(8)}}{\Lambda^4}\sigma_j^{(8\times {\rm SM})} + {\rm h.c.}\right) + \dots$$

Interference (dim-6)*(SM)

quadratic |dim-6|^2

Interference (dim-8)*(SM)

Observables and the SM EFT

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Interference (dim-6)*(SM) | quadratic $|$dim-6$|^2$ | Interference (dim-8)*(SM)

Quadratic $|$dim-6$|^2$ terms are formally of higher order.

If the fit is mostly sensitive to them, validity of the EFT expansion is under question: dim-8 could have similar importance.

In some models it could still be OK, e.g. for: $c_i^{(6)} \sim c_j^{(8)} \sim g_*^2 \gg 1$

See talk on friday - Florian Goertz and D.M.

Basis choice

By using field redefinitions (or SM e.o.m.) it is possible to remove certain operators in favor of others

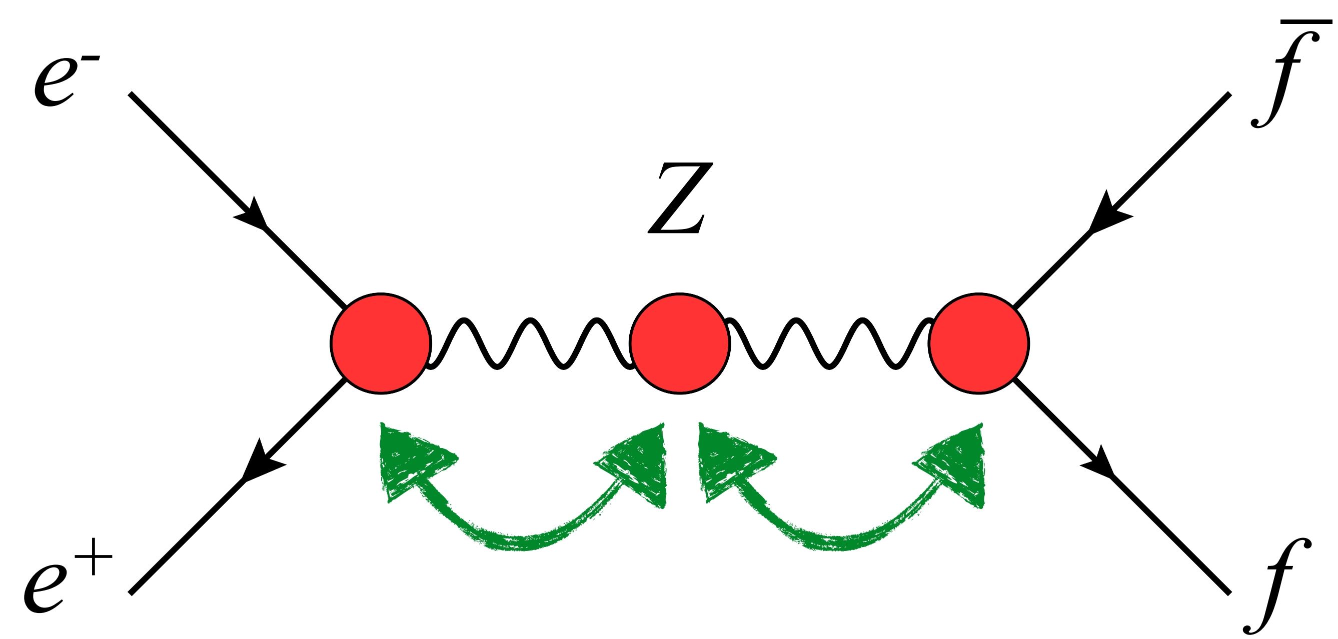
E.g:

$$D^\nu W^a_{\nu\mu} = -\frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) - \frac{g}{2}\Bigg(\underbrace{\sum_i \bar{Q}_i \gamma_\mu \sigma^a Q_i + \bar{L}_i \gamma_\mu \sigma^a L_i}_{J^a_\mu}\Bigg) + \mathcal{O}(1/\Lambda^2)$$

$$\mathcal{O}_W = ig\left(H^\dagger \tau^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu} \longleftrightarrow ig(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) J^a_\mu + \text{dim-8}$$

SILH *Warsaw*

Physical observables are independent on such choices (up to dim-8 effects), but all operators should be considered.



e.g. SILH basis — Giudice et al. [hep-ph/0703164], see HXSWG YR4 - EFT chapter

Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
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Vertex	
$[O_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i \gamma_\mu \ell_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i \sigma^k \gamma_\mu \ell_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{He}]_{ij}$	$\frac{i}{v^2}\bar{e}_i \gamma_\mu \bar{e}_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i \gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i \sigma^k \gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2}\bar{u}_i \gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2}\bar{d}_i \gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2}\bar{u}_i \gamma_\mu d_j \tilde{H}^\dagger D_\mu H$

Except $[O_{H\ell}]_{11}$, $[O'_{H\ell}]_{11}$

(substituted in favor of O_W, O_B)

+ Yukawa, Dipole and 4-fermion operators *e.g.* SILH basis — Giudice et al. [hep-ph/0703164], see HXSWG YR4 - EFT chapter

Bosonic CP-even		Bosonic CP-odd		Vertex	
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O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$			$[O'_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i\sigma^k\gamma_\mu\ell_j H^\dagger\sigma^k \overleftrightarrow{D}_\mu H$
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Operators normalized so that:

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S or TGC are normalized in similar way.
Useful in order to deal with adimensional coefficients.

e.g. SILH basis — Giudice et al. [hep-ph/0703164], see HXSWG YR4 - EFT chapter

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Useful in order to deal with adimensional coefficients.

However, never forget:
EFT is based on a high mass scale Λ.

For O(1) couplings

$\hat{c} \lesssim 10\% \longrightarrow \Lambda \gtrsim 3\, m_W \sim 250\ GeV$

A step-by-step approach

i.e. how to successfully make sense of 2499 parameters

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A step-by-step approach

i.e. how to successfully make sense of 2499 parameters

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  Some observables are much more precise than others.
  Impose these bounds before going on to less precise ones.
  e.g. Pomarol and Riva [1308.2803]

A step-by-step approach

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Example:

Very precise $\hat{S} \lesssim 10^{-3}$ $\hat{S} = \alpha_i \hat{c}_i^{(6)}$

Less precise $\delta g_{1,z} \lesssim 10\%$ $\delta g_{1,z} = \beta_i \hat{c}_i^{(6)} + k(\alpha_i \hat{c}_i^{(6)}) \simeq \beta_i \hat{c}_i^{(6)}$

Selection of relevant processes

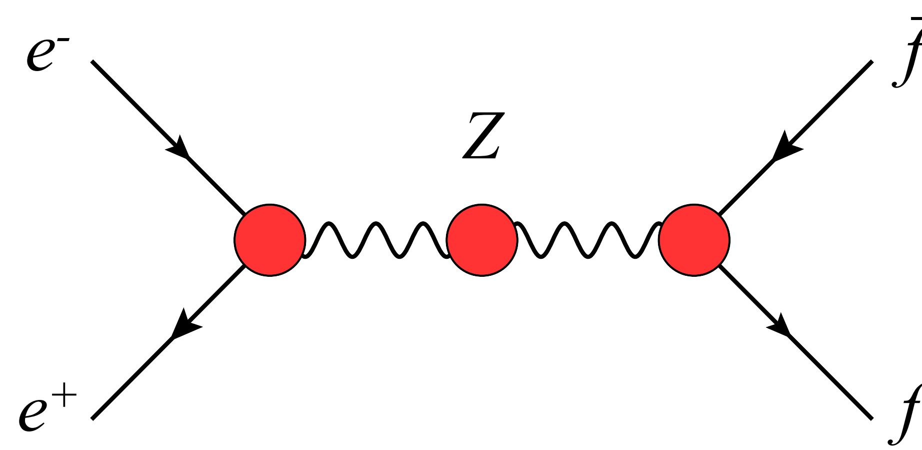
Low-energy measurements
G_F and Flavour

On-shell Z (W) production and decay

High energy $f\bar{f}$ production

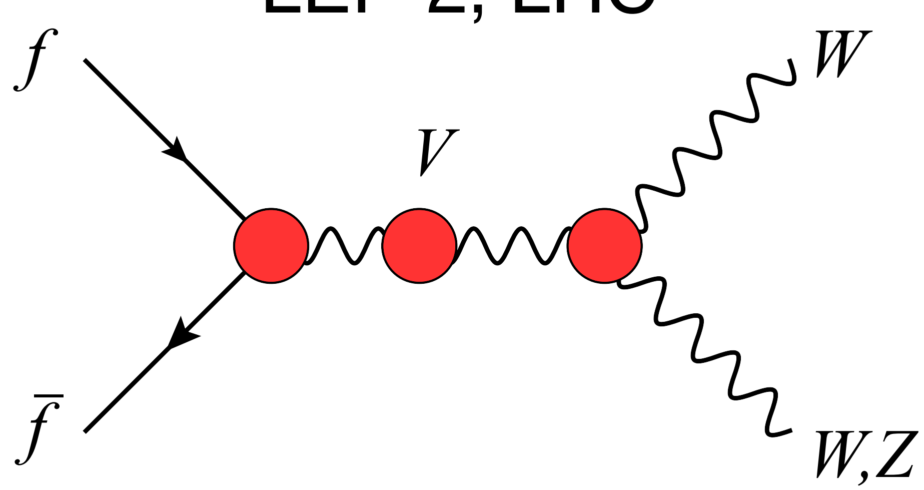
LEP-1

LEP-2



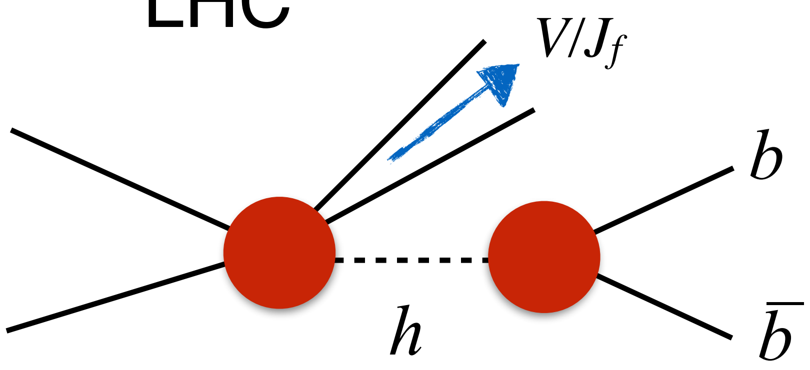
Diboson production

LEP-2, LHC



On-shell Higgs production and decay

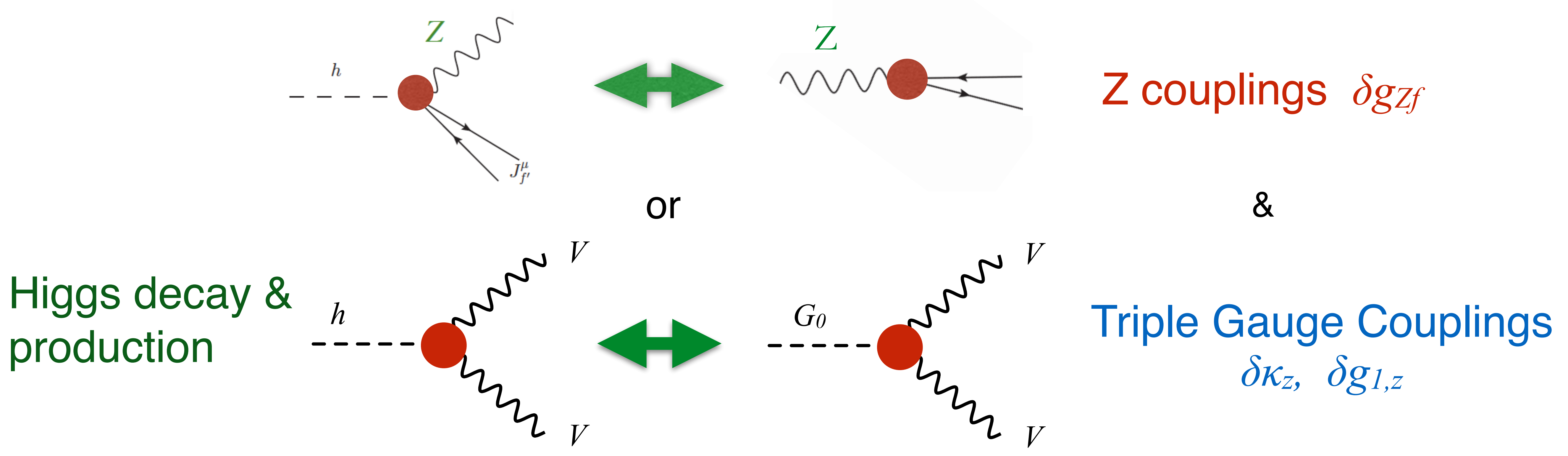
LHC



The power of the SMEFT: relating different observables

The same operator can contribute to different processes.

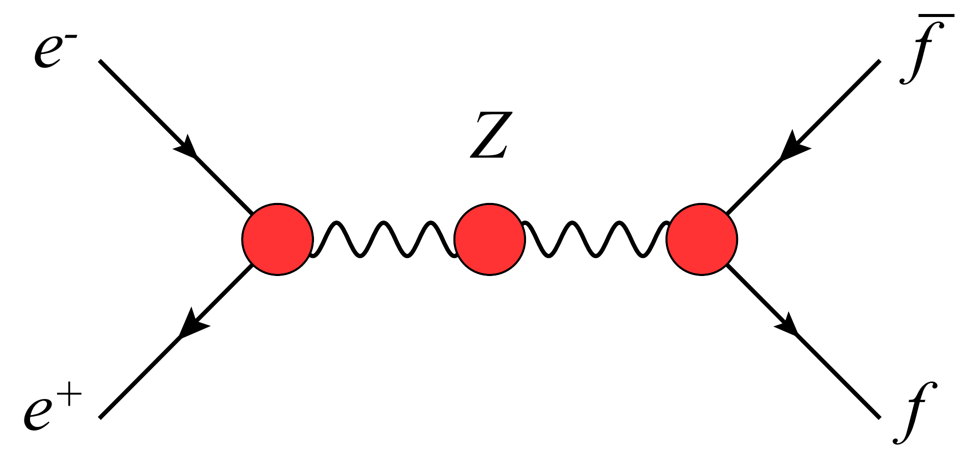
For example: $O_{Hf} = i(H^\dagger \overleftrightarrow{D}_\mu H)\bar{f}\gamma^\mu f = -\frac{1}{2}\sqrt{g^2+g'^2}Z_\mu(v+h)^2\bar{f}\gamma^\mu f$



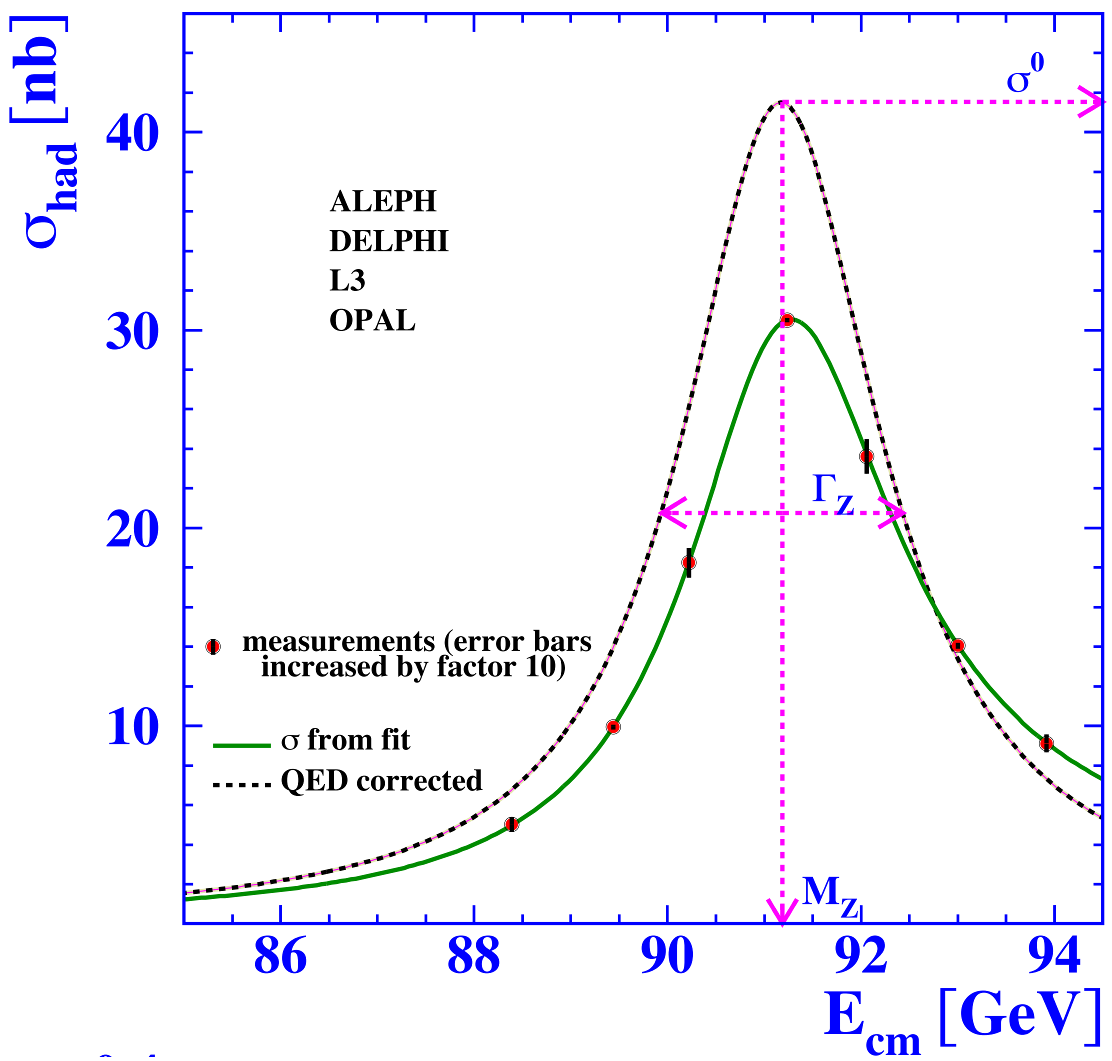
★ Combine different datasets (e.g. LEP-2 + Higgs data) to derive stronger constraints for the EFT.

EFT analysis of EW data

Z-pole



LEP EW WG [hep-ex/0509008]



1) Unfold QED (and/or QCD) soft radiation effect

2) Parametrize the shape with some Pseudo-Observables defined at S-matrix level:

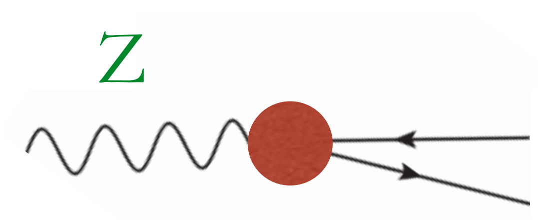
$$m_Z, \Gamma_Z$$

Lineshape

$$\chi(s) = \frac{G_F m_Z^2}{8\pi\sqrt{2}} \frac{s}{s - m_Z^2 + i s \Gamma_Z / m_Z}$$

On-shell $Z\bar{f}f$ vertex in terms of PO

$$\gamma_\mu \left(\mathcal{G}_V^f + \mathcal{G}_A^f \gamma_5 \right)$$



$$g_V^f = \mathrm{Re}\, \mathcal{G}_V^f, \qquad g_A^f = \mathrm{Re}\, \mathcal{G}_A^f$$

Z-pole

Bounds on a set of PO

Observable	Experimental value
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma_{\rm had}$ [nb]	41.541 ± 0.037
R_e	20.804 ± 0.050
R_μ	20.785 ± 0.033
R_τ	20.764 ± 0.045
$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025
$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013
$A_{\rm FB}^{0,\tau}$	0.0188 ± 0.0017
R_b	0.21629 ± 0.00066
R_c	0.1721 ± 0.0030
$A_b^{\rm FB}$	0.0992 ± 0.0016
$A_c^{\rm FB}$	0.0707 ± 0.0035
A_e	0.1516 ± 0.0021
A_μ	0.142 ± 0.015
A_τ	0.136 ± 0.015
A_e	0.1498 ± 0.0049
A_τ	0.1439 ± 0.0043
A_b	0.923 ± 0.020
A_c	0.670 ± 0.027
A_s	0.895 ± 0.091
R_{uc}	0.166 ± 0.009

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

Match the PO to EFT coefficients (e.g. at LO)

→ Very strong constraints on Lepton Flavor Universality and $Zf\bar{f}$ vertex corrections

See e.g. Falkowski et al. 1503.07872

To simplify: assume Flavor Universality

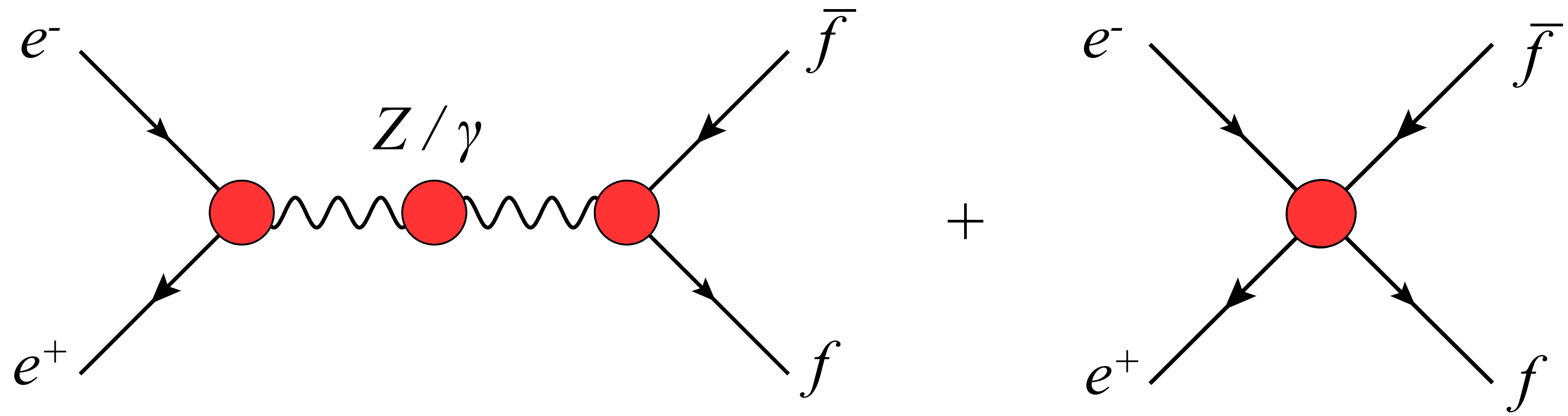
$$\begin{pmatrix} \hat{c}'_{HL} \\ \hat{c}_{HL} \\ \hat{c}_{HE} \\ \hat{c}'_{HQ} \\ \hat{c}_{HQ} \\ \hat{c}_{HU} \\ \hat{c}_{HD} \\ \hat{c}_{ll} \end{pmatrix} = \begin{pmatrix} -1.9 \pm 1.1 \\ 1.1 \pm 0.7 \\ 0.1 \pm 0.6 \\ -4.7 \pm 1.9 \\ 0.2 \pm 2.0 \\ 7.0 \pm 6.9 \\ -31.3 \pm 10.3 \\ -4.7 \pm 3.5 \end{pmatrix} \cdot 10^{-3}$$

Falkowski, Riva 1411.0669

$\sim 10^{-3}$ *precision*

LEP-2 $f\bar{f}$ data

The Z (or γ) is off-shell



This bounds 4-fermion operators

See [Falkowski et al. 1511.07434] for global fit of leptonic 4-fermion operators

as well as the bosonic operators

$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$

W and Y parameters of

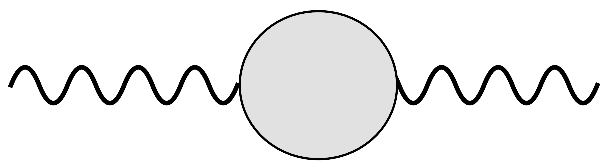
[Barbieri et al. hep-ph/0405040]

$\sim 10^{-3}$ *precision*

Universal Scenario

i.e. oblique corrections

Assuming that New Physics is "universal" — *affects only gauge boson self-energies*



$$\Pi_V(q^2) \simeq \Pi_V(0) + q^2 \Pi'_V(0) + \frac{(q^2)^2}{2!}\Pi''_V(0) + \cdots$$

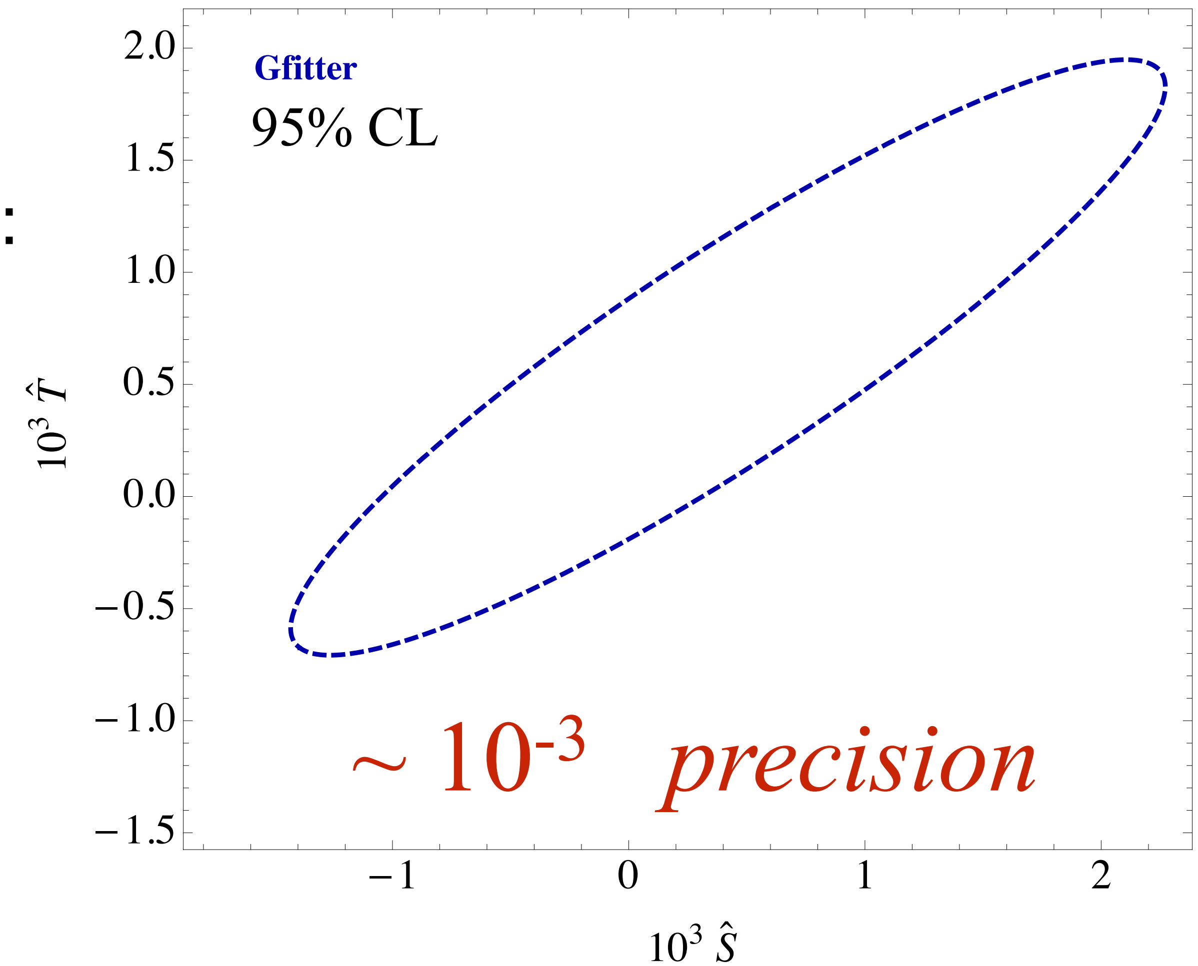
$$\langle V_\mu(-q) V'_\nu(q) \rangle \propto \Pi_{VV'}(q^2)$$

[Altarelli and Barbieri '91, Peskin and Takeuchi '92, Barbieri et al. hep-ph/0405040]

At dim-6 in SM EFT only these are generated:

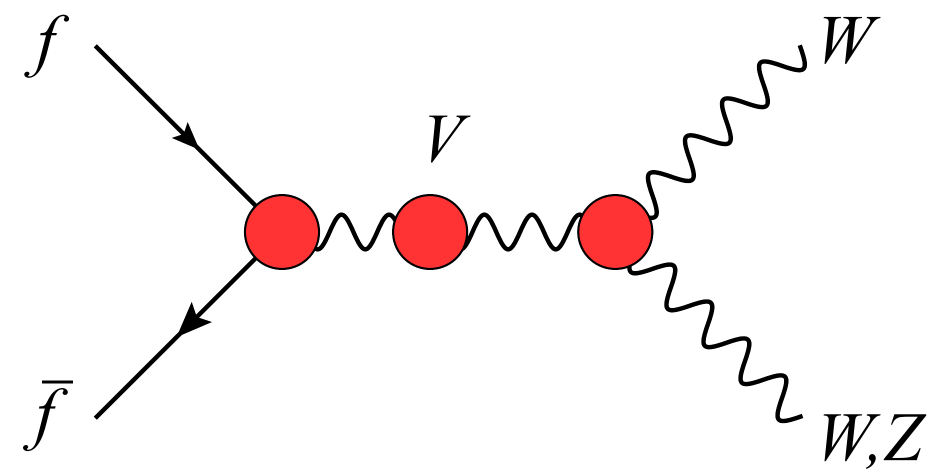
$$
\begin{aligned}
g^{-2}\widehat{S} &= \Pi'_{W_3 B}(0) \\
g^{-2} M_W^2 \widehat{T} &= \Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0) \\
2 g'^{-2} M_W^{-2} Y &= \Pi''_{BB}(0) \\
2 g^{-2} M_W^{-2} W &= \Pi''_{W_3 W_3}(0)
\end{aligned}
$$

$S = 4 s_W^2 \widehat{S}/\alpha \approx 119\,\widehat{S},\ T = \widehat{T}/\alpha \approx 129\,\widehat{T}$



Diboson production

After LEP-1 bounds are imposed, in the SMEFT there are 3 unbounded directions relevant to VV production.



It is always possible to shift these corrections to anomalous triple gauge couplings.

aTGC $\delta g_{1,z}, \ \delta\kappa_\gamma, \ \lambda_z$

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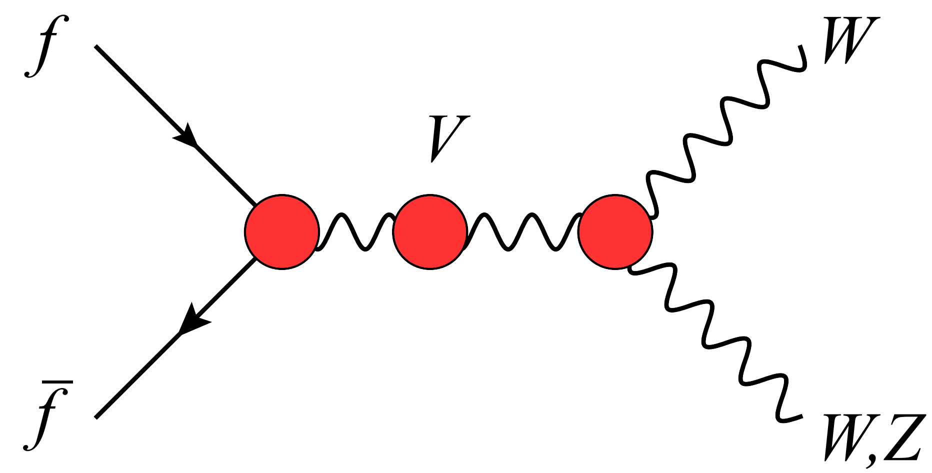


It is always possible to shift these corrections to anomalous triple gauge couplings.

aTGC $\delta g_{1,z}, \ \delta\kappa_\gamma, \ \lambda_z$

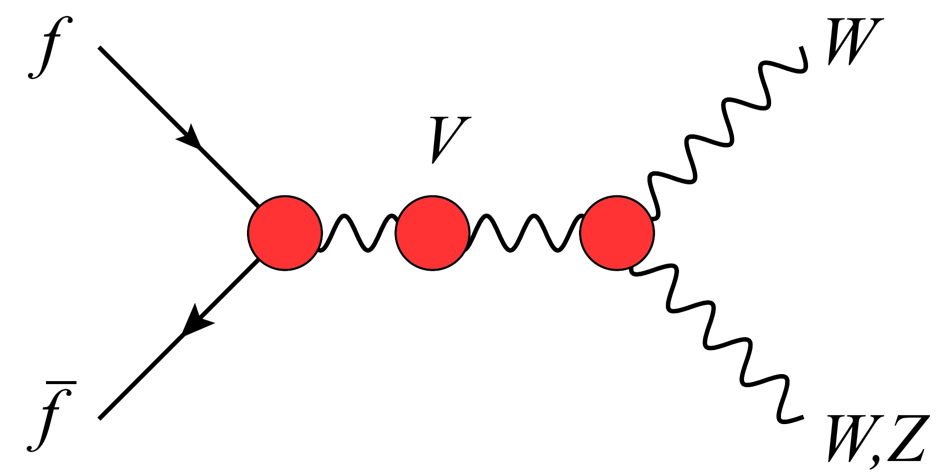
[Hagiwara et al '87]

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

Assumptions: CP conservation, no vertex corrections, no oblique corrections

In [Hagiwara et al '87] this description for $e^+ e^- \to W^+ W^-$ is based on an on-shell amplitude decomposition in terms of form factors and pseudo-observables.

Diboson production



aTGC $\delta g_{1,z},\ \delta\kappa_\gamma,\ \lambda_z$

In the SM EFT these are given by
3 combinations of Wilson coefficients.

$$\delta g_{1z} = -\frac{g_L^2+g_Y^2}{g_L^2-g_Y^2}\left[\frac{g_L^2-g_Y^2}{g_L^2}\bar{c}_{HW}+\bar{c}_W+\bar{c}_{2W}+\frac{g_Y^2}{g_L^2}\bar{c}_B+\frac{g_Y^2}{g_L^2}\bar{c}_{2B}-\frac{1}{2}\bar{c}_T\right]$$

$$\delta\kappa_\gamma = -\bar{c}_{HW}-\bar{c}_{HB}\ , \qquad \lambda_z = -6g_L^2\bar{c}_{3W}\ ,$$

(in SILH basis)

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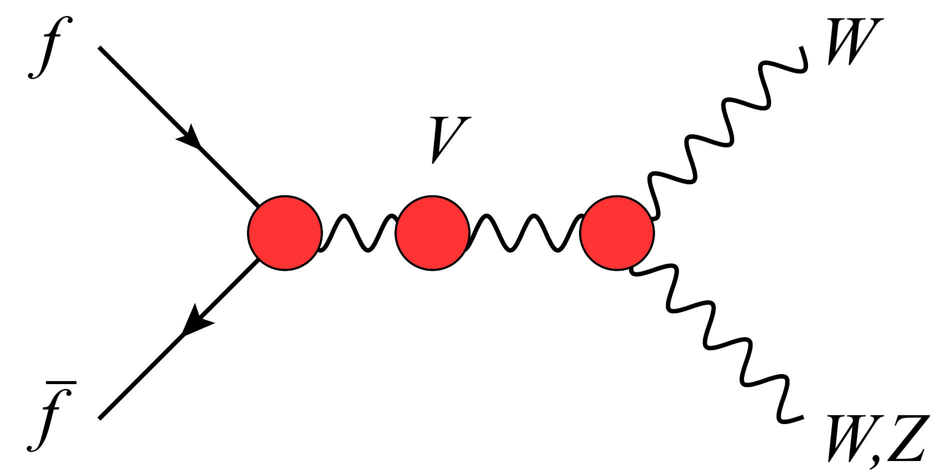

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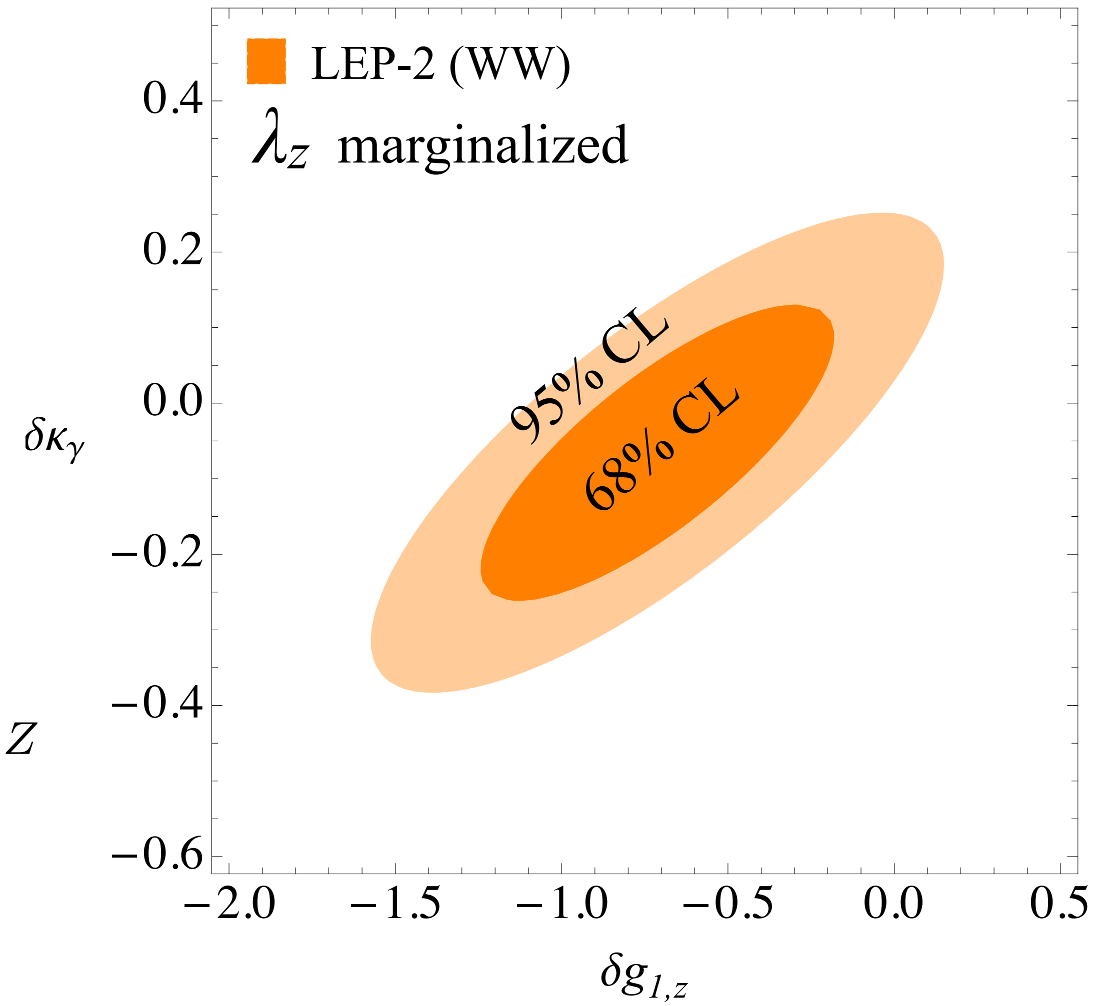
(in SILH basis)

Fit LEP-2 (WW) data:

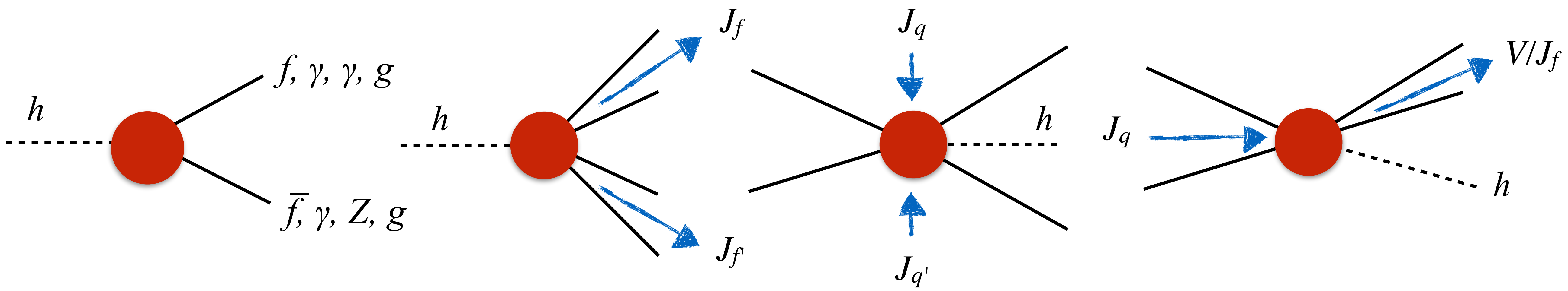
- 3 parameters
- only linear terms $O(1/\Lambda^2)$



1 direction remains unconstrained $\lambda_Z \approx -\delta g_{1.Z}$
(due to an accidental cancellation at LEP-2 energies)

[Contino et al. 1405.1617]

Higgs data



As done for Z boson at LEP-1 (but more complex processes)

1 - Unfold soft QED/QCD (and relevant EW) radiation

2 - Extract a set of pseudo-observables from total rates and differential distributions

3 - Match to SM EFT and extract bounds / combine with EW data

Higgs pseudo-observables

At Run-1 the PO used were the kappas:

$$\sigma(ii \to h+X) \times BR(h \to ff) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_h} = \frac{\kappa_{ii}^2 \, \kappa_{ff}^2}{\kappa_h^2} \sigma_{SM} \times BR_{SM}$$

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Now we want to **go beyond** → PO for kinematical distributions too

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Start from on-shell correlation function, e.g. h → 4ℓ: $\langle 0 | \mathcal{T} \left\{ J_f^\mu(x), J_{f'}^\nu(y), h(0) \right\} |0\rangle$

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Lorentz structures decomposition

$$\mathcal{A} = i \frac{2 m_Z^2}{v_F} (\bar{e} \gamma_\alpha e)(\bar{\mu} \gamma_\beta \mu) \times$$
$$\left[F_L^{e\mu}(q_1^2, q_2^2) g^{\alpha\beta} + F_T^{e\mu}(q_1^2, q_2^2) \frac{q_1 \cdot q_2 \; g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + F_{CP}^{e\mu}(q_1^2, q_2^2) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

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Momentum expansion around physical poles → **PO are the residues**

$$F_X(q_1^2, q_2^2) = \sum_V \frac{(\text{const})_{2V}}{(q_1^2 - m_V^2)(q_2^2 - m_V^2)} + \frac{(\text{const})_{1V}}{(q_{1,2}^2 - m_V^2)} + (\text{const}) + f_{\text{reg}}(q_1^2, q_2^2)$$

Fit to Higgs data

Assuming Minimal Flavor Violation:

After imposing EWPT bounds, at dim-6 in the SM EFT, Higgs data is affected by 9 independent linear combinations of coefficients.

[Corbett et al. 2013; J. Elias-Miro et al. 2013; Pomarol Riva 2013; Gupta et al 2014; Falkowski 2015]

Let us call these combinations as: *'Higgs basis'* [LHCHXSWG 2016]

[Falkowski, Gonzalez-Alonso, Greljo, D.M. 1508.00581]

$$\delta c_z, \quad c_{\gamma\gamma}, \quad c_{z\gamma}, \quad c_{gg}, \quad \delta y_u, \quad \delta y_d, \quad \delta y_e, \quad \delta g_{1,z}, \quad \delta\kappa_\gamma$$

Higgs

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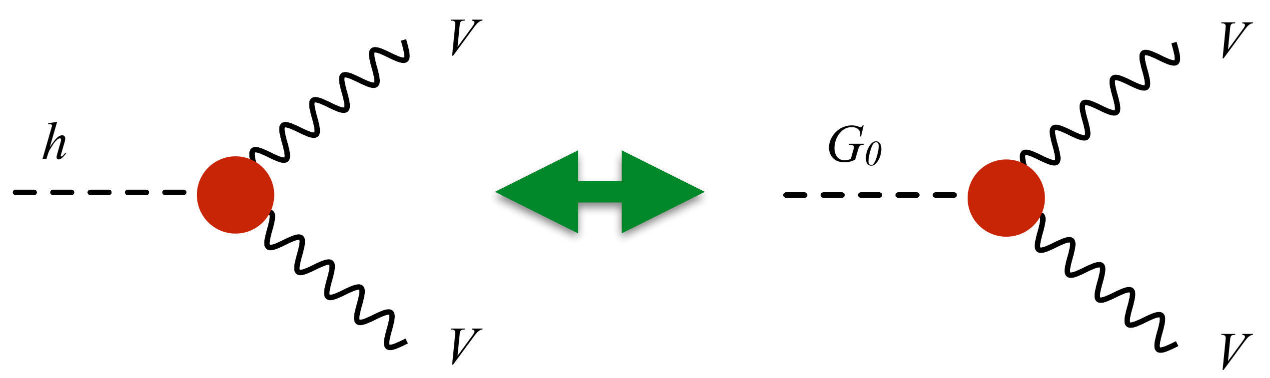
Higgs **TGC**

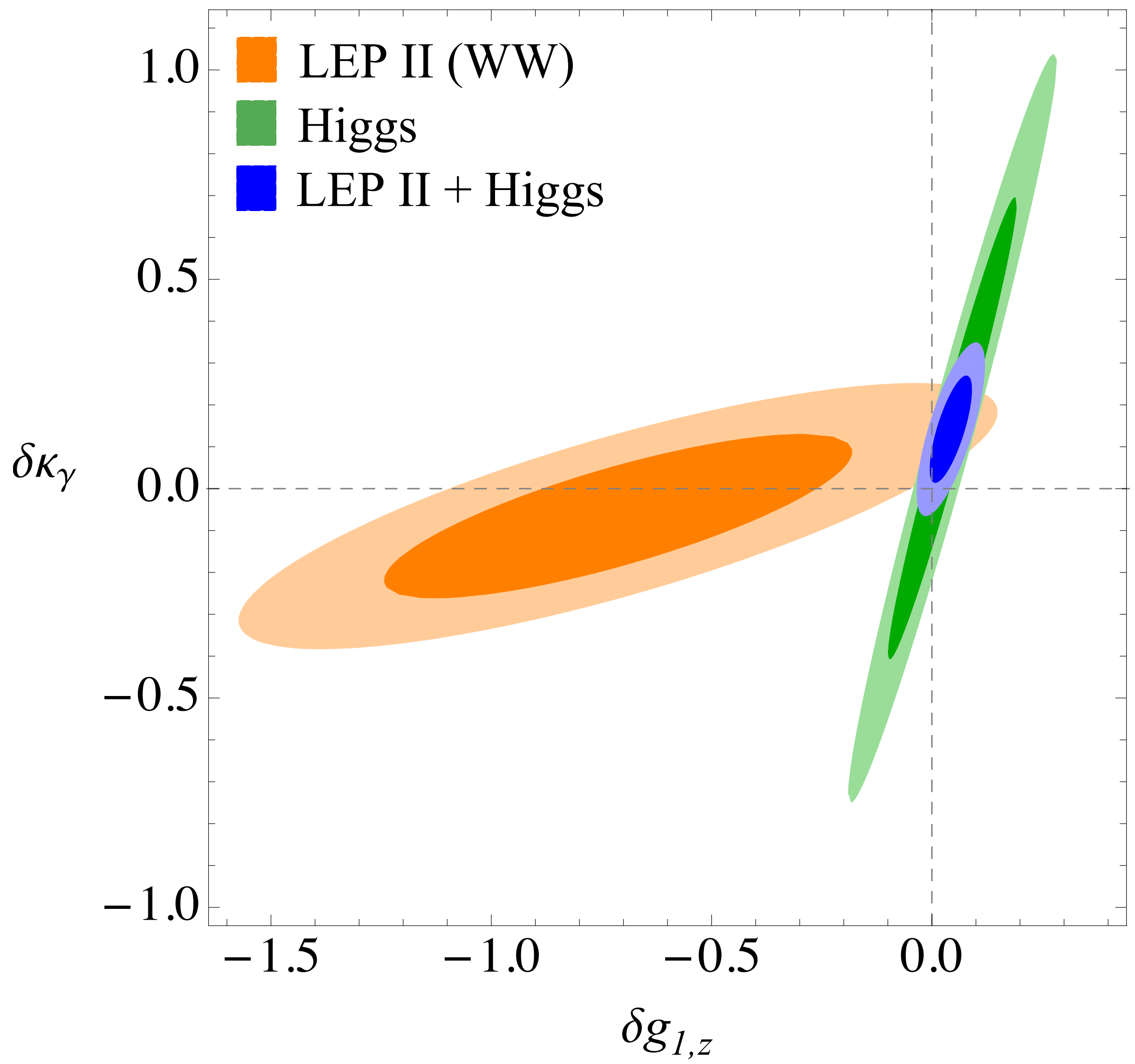
Some aTGC also contribute to Higgs processes: VH and VBF production.



Global fits

Writing the bounds in terms of aTGC:

The other 8 coefficients have been marginalised.



LEP II data alone suffers from a flat direction in the TGC fit. [Contino et al. 1405.1617]

+

Higgs data (mainly via VH and VBF production) is sensitive to a different direction. [Falkowski 1505.00046]

=

Together they provide **strong and robust constraints on the TGC**.

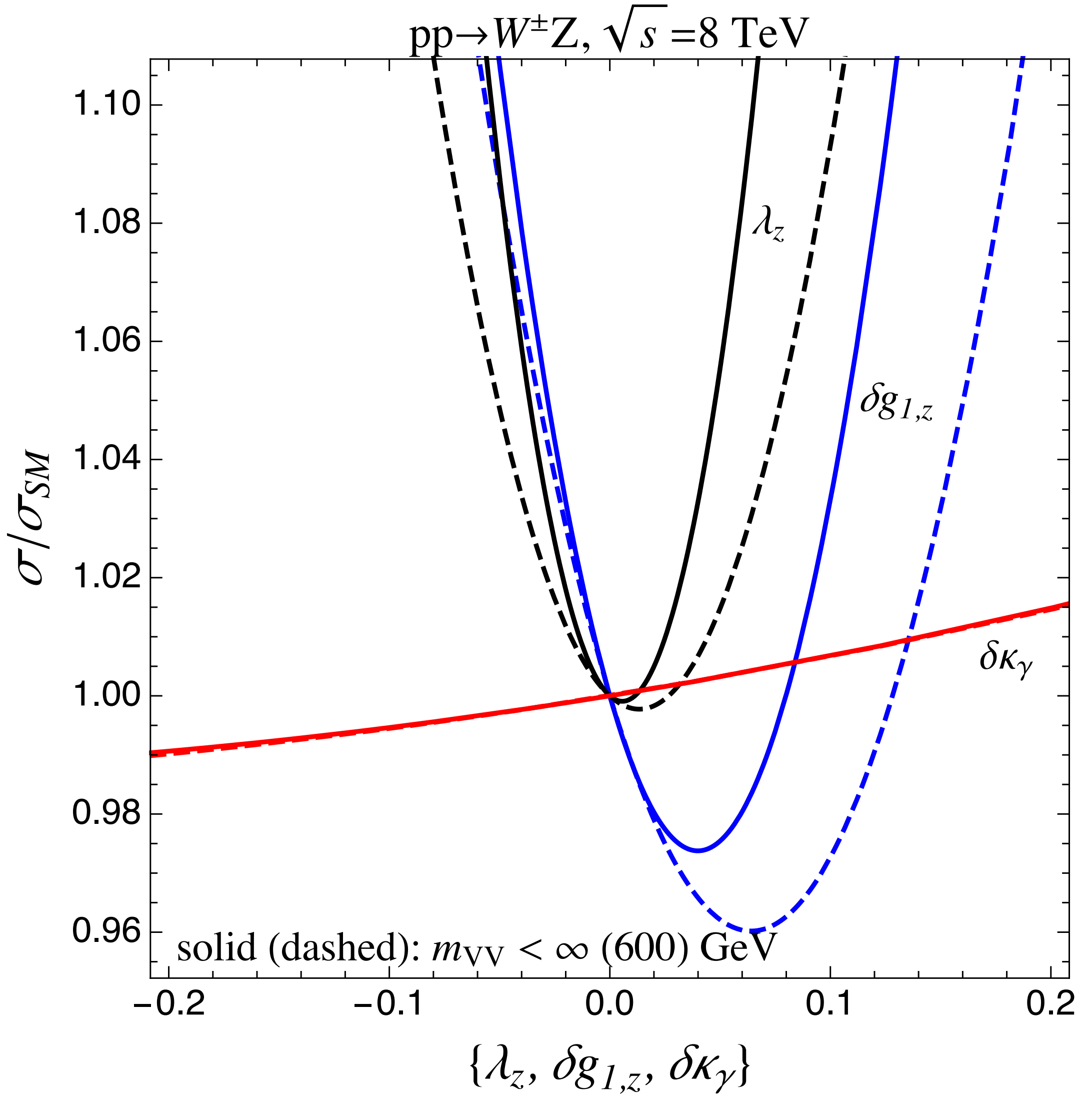
(linear fit ≃ quadratic fit)

Falkowski, Gonzalez-Alonso, Greljo, D.M.
PRL 116, 011801 (2016) [1508.00581]

The role of LHC WW/WZ data

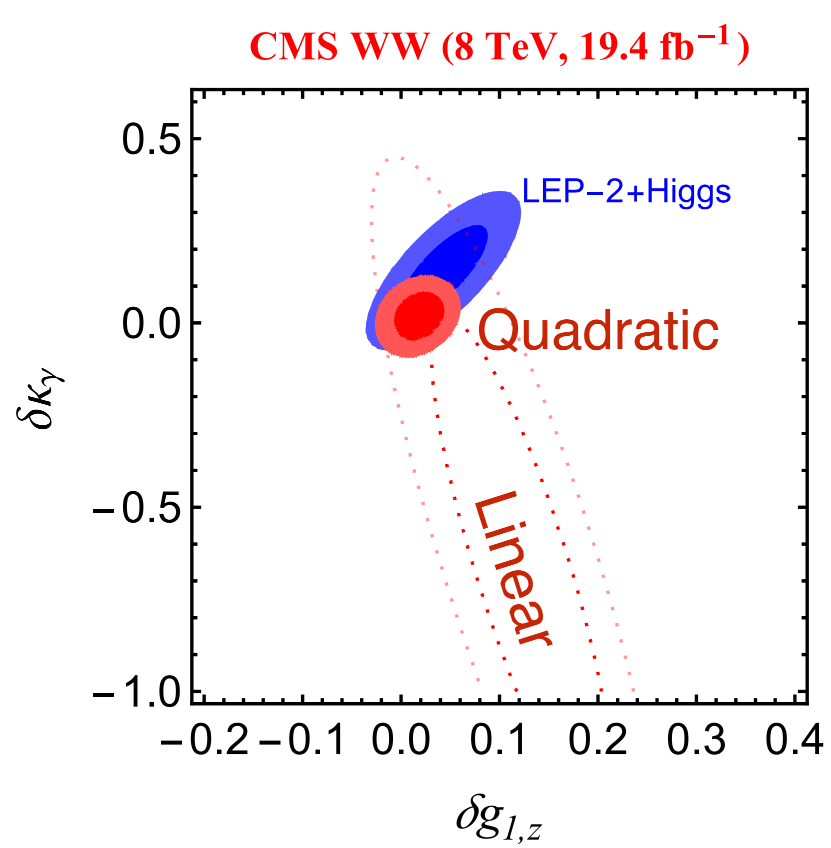
The validity of the EFT (aTGC) analysis is not obvious   See talk on friday - Florian Goertz and D.M.

$$\sigma = \sigma^{\rm SM} + \sum_i \left(\frac{c_i^{(6)}}{\Lambda^2} \sigma_i^{(6\times {\rm SM})} + {\rm h.c.} \right) + \sum_{ij} \frac{c_i^{(6)} c_j^{(6)*}}{\Lambda^4} \sigma_{ij}^{(6\times 6)} + \sum_j \left(\frac{c_j^{(8)}}{\Lambda^4} \sigma_j^{(8\times {\rm SM})} + {\rm h.c.} \right) + \dots$$



Due to SM vs. BSM helicity structure and large E, the (dim-6)² terms dominate.

Expected large sensitivity to dim-8 terms in general EFT approach.



Falkowski, Gonzalez-Alonso, Greljo, D.M., Son [1609.06312]

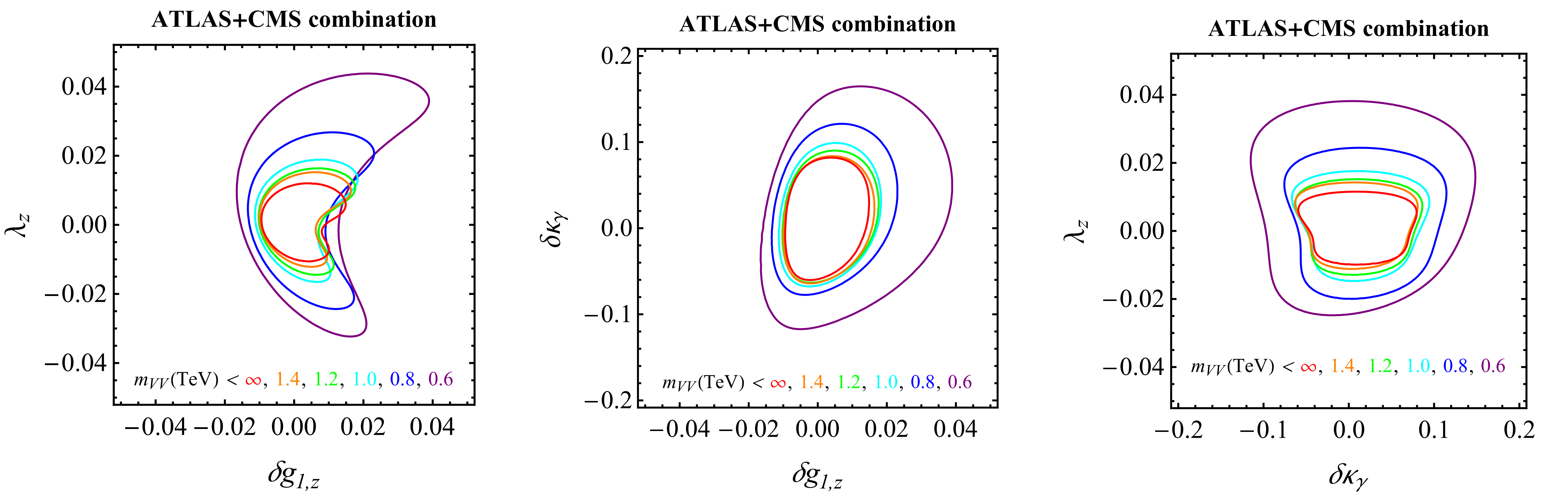
The role of LHC *WW/WZ* data

Set a cut for the high-mass region** $m_{VV} < m_{VV}^{\max}$

Perform different fits for different cut values.

We fit a selection of 8 TeV (20fb^{-1}) +13 TeV (3.2fb^{-1})
ATLAS and CMS WW and WZ data, including quadratic terms.

Falkowski, Gonzalez-Alonso, Greljo, D.M., Son [1609.06312]



Prospects

Explore high scales via precision measurements

Take an observable which we can use to constrain some EFT parameter $\hat{c}$

$$\sigma = \sigma_{SM}\left(1 + \kappa \overbrace{\frac{m_\psi^2}{\Lambda^2}}^{\hat{c}} + O(\Lambda^{-4})\right)$$ with precision δ.

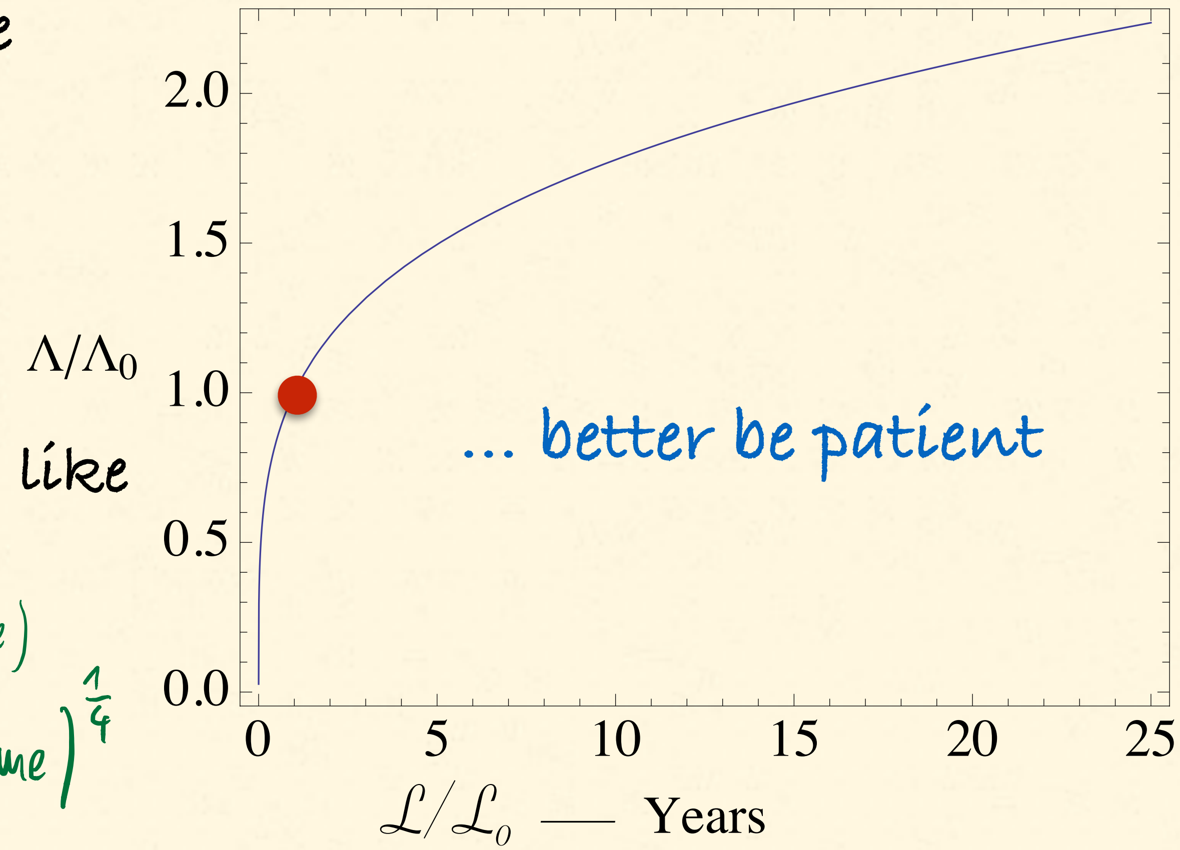
This corresponds to a bound on a mass scale
(I am taking O(1) couplings)

$$\hat{c} < \delta \quad \Rightarrow \quad \Lambda \gtrsim m_\psi\, \delta^{-\frac{1}{2}}$$

The NP scale probed increases with luminosity like

$$\delta \sim \frac{\Delta N}{N} \sim \mathcal{L}^{-\frac{1}{2}} \quad \Rightarrow \quad \Lambda \sim \mathcal{L}^{\frac{1}{4}} \sim (\text{time})^{\frac{1}{4}}$$

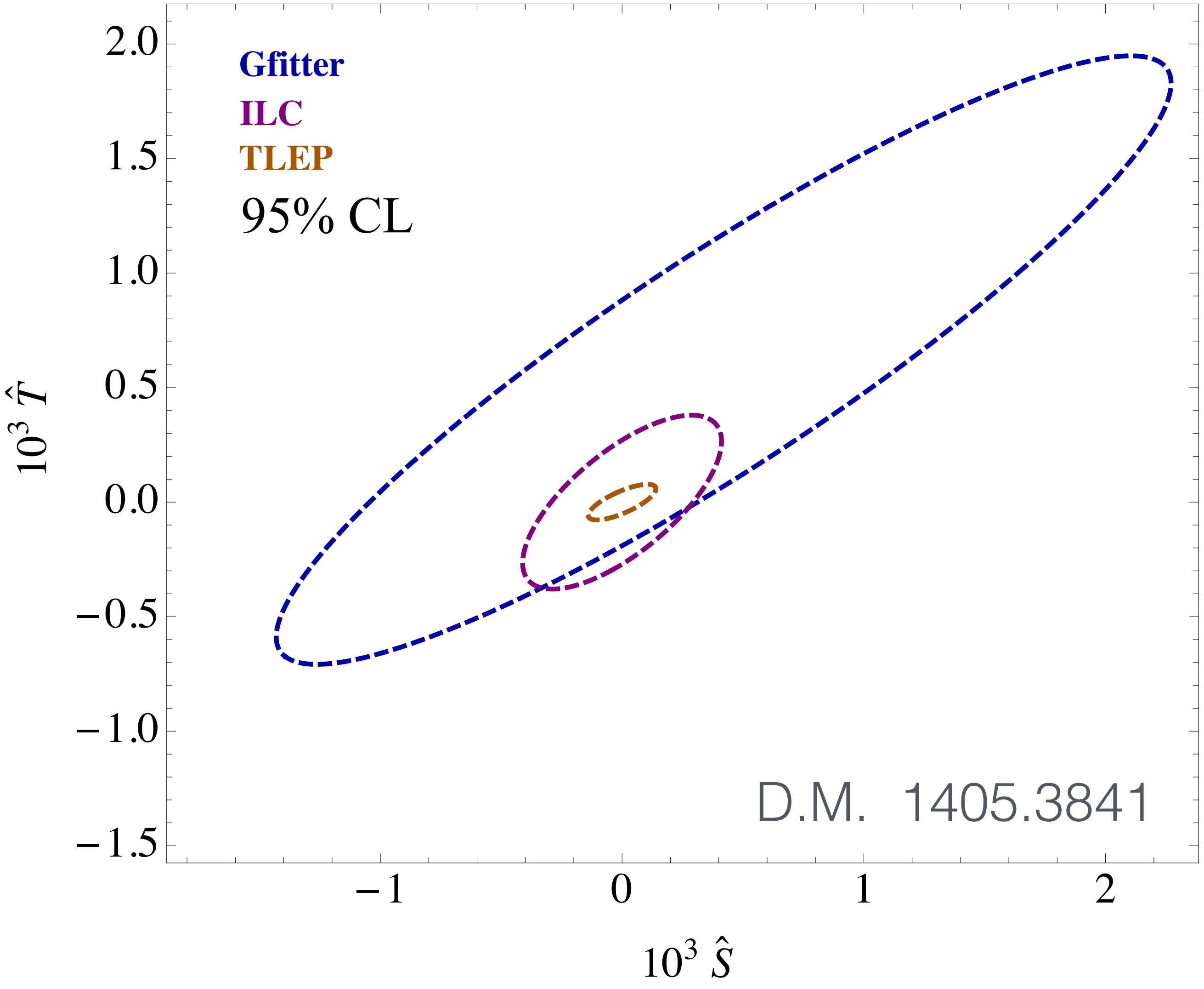
$\mathcal{L} \sim (\text{time})$



Z-pole

ILC / GigaZ [Snowmass, Gfitter 1310.6708] $\sim few \times 10^{-4}$ *precision*

TLEP / TeraZ [TLEP design study group 1308.6176] $\lesssim 10^{-4}$ *precision*



aTGC

HL-LHC

[Gianotti, Mangano, Virdee et al. hep-ph/0204087]

Only 1 parameter varied at a time

Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}
λ_γ	0.0014	0.0006	0.0008	0.0002
λ_Z	0.0028	0.0018	0.0023	0.009
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013
g_1^Z	0.0038	0.0024	0.0023	0.0007

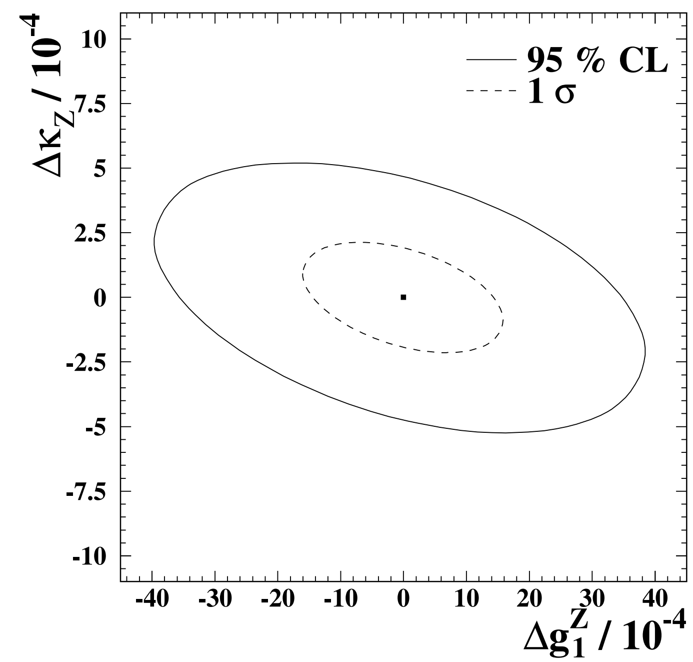
Issues with EFT validity

30 TeV: Higher energy,
higher NP reach from direct searches

ILC [ILC TDR 1306.6352]

~ few×10^-4 precision

coupling	error $\times 10^{-4}$	
	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 800$ GeV
C,P-conserving, $SU(2) \times U(1)$ relations:		
Δg_1^Z	2.8	1.8
$\Delta\kappa_\gamma$	3.1	1.9
λ_γ	4.3	2.6
	$\mathcal{L} = 500$ fb^{-1}	$\mathcal{L} = 1000$ fb^{-1}



EFT-validity under control
(like LEP-2)

Conclusions

SM Effective Theory

- Allows interpretation of precision data in a well defined framework
- Large number of parameters but large number of observables allows to put strong constraints via global fits.
- By construction, better suited for low energy experiments,
  (Z pole, Higgs decays, $e^+ e^-$ machine)
  less for LHC high-p_T processes
  (dijet, dilepton, diboson production, etc..)
- Progress in exploring NP by increasing luminosity is very slow.
  Unlikely to discover NP via precision measurements,
  rather a crucial path for understanding the structure of NP.

Thank you!

Input parameters

The EW sector of the SM depends on 3 parameters: $g,\ g',\ v$

Extracted from inputs, usually: $\boldsymbol{G_\mu,\ M_Z,\ \alpha(0)}$

e.g. $$G_\mu = \frac{1}{\sqrt{2}v^2} \to v^2 = \sqrt{2}G_\mu$$

Effective operators also contribute to these inputs:
redefine SM parameters (and fields) to reabsorb this unphysical shift.

$$G_\mu = \frac{1}{\sqrt{2}v^2} + \frac{k_i c_i^{(6)}}{\Lambda^2} \to v^2 = f(G_\mu, c_i^{(6)})$$

Express SM predictions (and EFT dependence) in terms of physical inputs.

Global fits

Falkowski, Gonzalez-Alonso, Greljo, D.M.
PRL 116, 011801 (2016) [1508.00581]

We performed a global fit of Higgs (8TeV) + LEP-2 (WW) using these 10 parameters (assuming MFV).

Shown here in SILH' basis (others in the paper)
Pomarol, Riva [1308.2803]

We impose exact EWPO bounds:

$$s_T = s_{\ell\ell} = s_{Hf} = s'_{Hf} = 0$$
$$s_W + s_B = 0$$

$$\begin{pmatrix} s_H & = 0.02 \pm 0.17 \\ \frac{1}{2}(s_W - s_B) & = 0.37 \pm 0.30 \\ s_{HW} & = -0.69 \pm 0.43 \\ s_{HB} & = -0.68 \pm 0.42 \\ s_{BB} & = 0.094 \pm 0.015 \\ s_{GG} & = -0.0052 \pm 0.0027 \\ \hat{s}_u & = 0.59 \pm 0.33 \\ \hat{s}_d & = -0.23 \pm 0.22 \\ \hat{s}_e & = -0.10 \pm 0.15 \\ s_{3W} & = 0.63 \pm 0.29 \end{pmatrix}$$

(full correlation matrix in the paper)