Universität Zürich[UZH]

Pseudo-observables in Higgs decays

Admir Greljo

based on:
(1) Gonzalez-Alonso, AG, Isidori, Marzocca, **Eur. Phys. J. C75 (2015) 3, 128**
(2) Gonzalez-Alonso, AG, Isidori, Marzocca, **work in progress**

Portorož 2015 workshop, 08/04/2015

The idea is to provide **general** and yet **simple** parameterisation of New Physics (NP) effects in Higgs decays…

Outline

- “kappa” formalism and beyond
- **P**seudo-**O**bservables (**PO**s) in Higgs decays
- Parameter counting
- Symmetry limits
- Higgs **PO**s from LEP data in the linear EFT

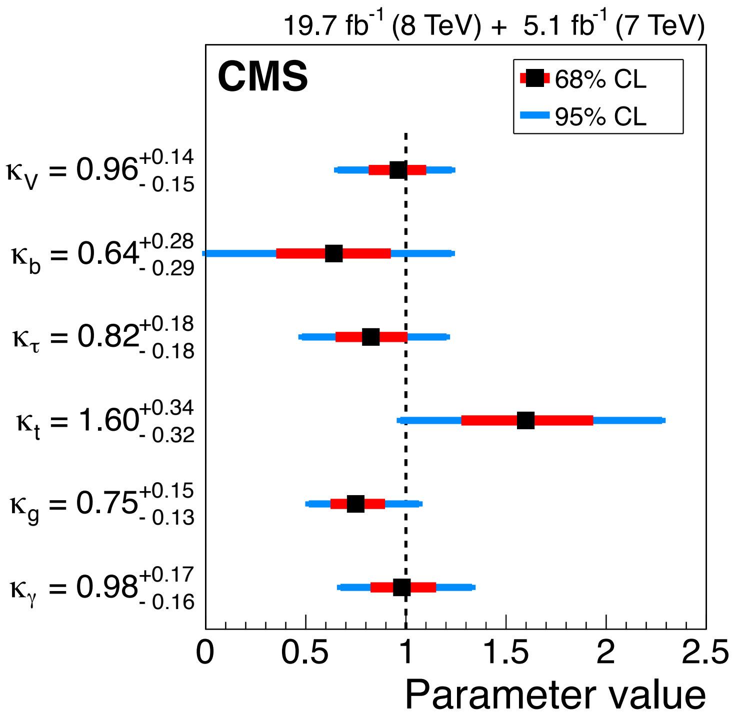
“kappa” formalism

- Interim framework for the analysis of Higgs couplings **(CERN Yellow Report 3, 1307.1347)**
  - Single narrow resonance with a mass ~ 125 GeV
  - The production and decay kinematics are SM-like
  - Introduce “coupling strength” scaling factors $\boldsymbol{\kappa_i}$, i.e.,

$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

  - SM limit recovered for $\boldsymbol{\kappa_i \to 1}$

“kappa” formalism



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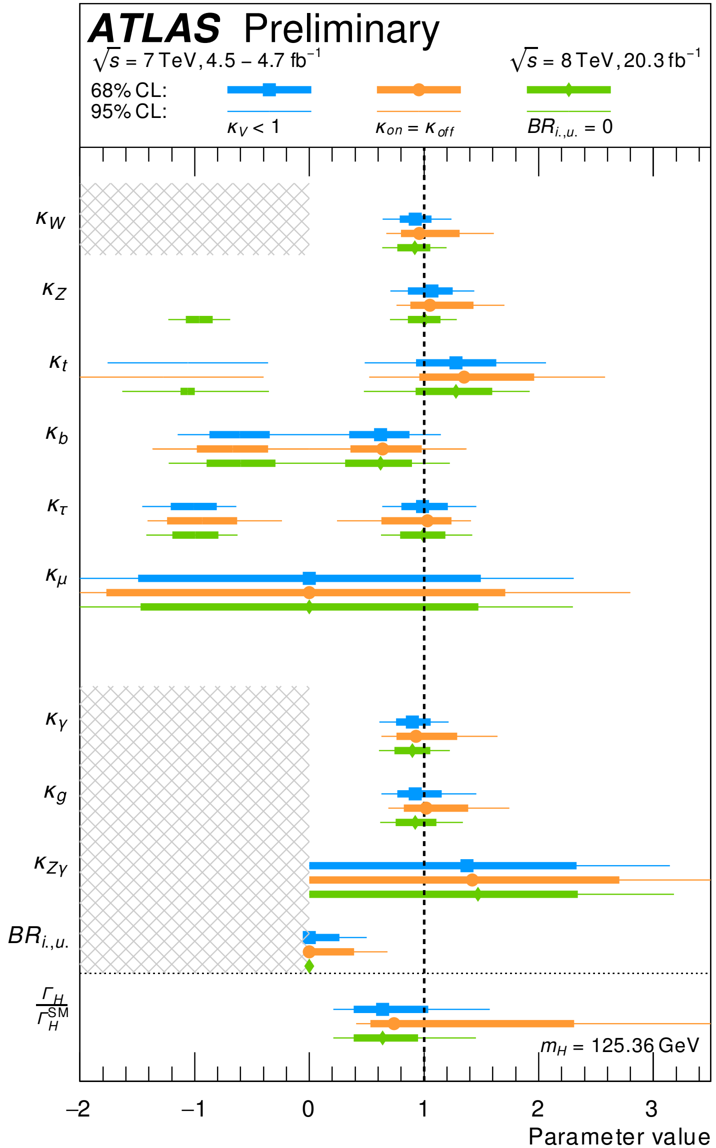


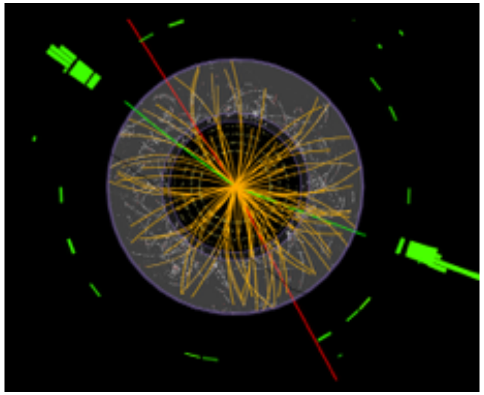
ATLAS-CONF-2015-007

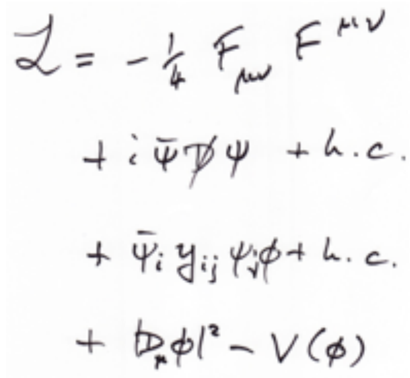
Beyond “kappa” formalism

- Higgs physics is entering a precision era
- LHC Run II: Precise measurements of the observed Higgs processes
- $\mathcal{O}(100)$ events expected soon in $h \rightarrow 4\ell$
- Exploit full kinematics of the events
  (not only the total rate)
- ***Extended “kappa” formalism needed***

Pseudo-Observables

Marzocca, HXSWG plenary meeting - Jan 2015





Experimental data

Fiducial cross sections, distributions, …

Pseudo Observables

Lagrangian parameters

Couplings, bare masses, Wilson coeff., …

- **PO**s are limited set of “idealised” observables defined from “on-shell” amplitudes
- Ideally, **PO**s should:
  1. provide general encoding of the experimental data
  2. be computable and encode all possible predictions of large set of theories

POs in Higgs decays

Assumptions:

- h(125) is a spin 0 particle
- Zero width approximation, “on-shell” single Higgs processes
  (factorisation of new physics effects in production and decay)
- No light New Physics

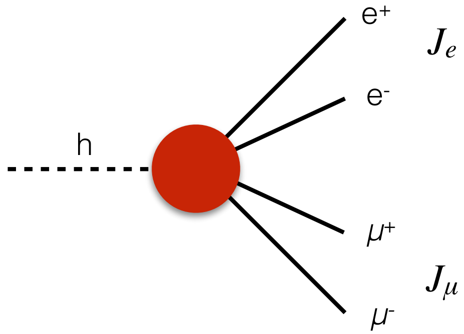
  Notion of an underlining Effective Field Theory (EFT), smooth kinematical distortions from the SM,
  Momentum expansion of the on-shell Higgs amplitudes.
- Power counting based on the canonical dimension:
  (1) Higgs, gauge bosons, derivatives (momenta) ~ 1
  (2) Fermions ~ 3/2
- Neglect contributions with dimension > 6
- General enough to accommodate all the effect from next-to-leading order terms in the expansions of a generic linear **and** non-linear EFT
- No assumptions on custodial symmetry, CP, flavour universality or $SU(2)_L$ properties of the Higgs, **we rather want to test it from data!**

$h \to e^+e^- \mu^+\mu^-$

The most generic structure of the amplitude (helicity conserving):

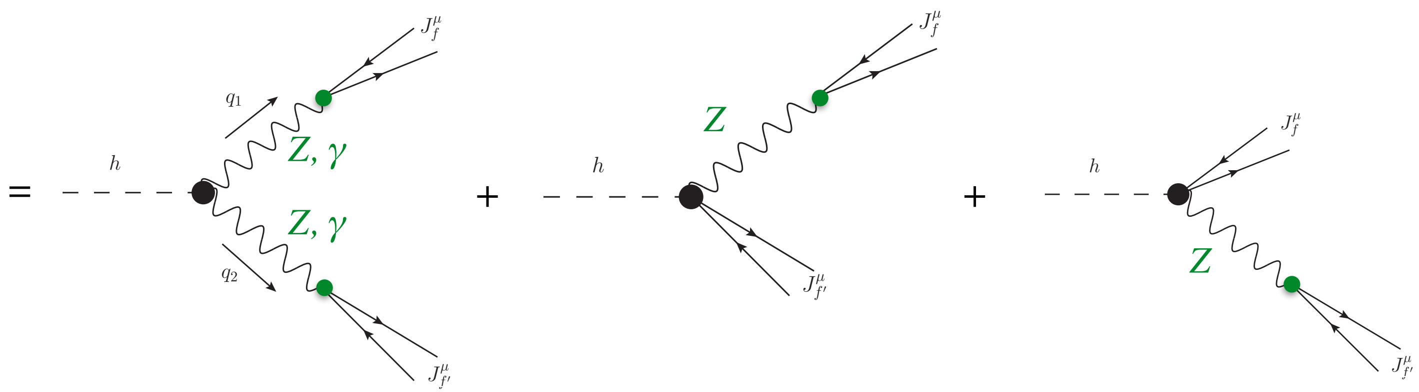
Marzocca, HXSWG plenary meeting - Jan 2015

Gonzalez-Alonso, AG, Isidori, Marzocca



$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$
$$\left[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\; g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

Momentum expansion of the form factors around the physical poles



$h \to e^+e^- \mu^+\mu^-$

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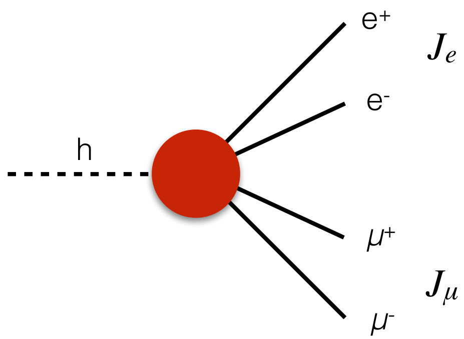

$$\mathcal{A} = i\frac{2m_Z^2}{v_F} \sum_{e=e_L,e_R} \sum_{\mu=\mu_L,\mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu) \times \left[F_1^{e\mu}(q_1^2, q_2^2) g^{\alpha\beta} + F_3^{e\mu}(q_1^2, q_2^2) \frac{q_1 \cdot q_2 \; g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2, q_2^2) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

Momentum expansion of the form factors around the physical poles

$$\mathcal{A} = i\frac{2m_Z^2}{v_F} \sum_{e=e_L,e_R} \sum_{\mu=\mu_L,\mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu) \times$$
$$\left[\left(\kappa_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2} \frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2} \frac{g_Z^e}{P_Z(q_1^2)} \right) g^{\alpha\beta} + \right.$$
$$+ \left(\epsilon_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \kappa_{Z\gamma} \epsilon_{Z\gamma}^{\text{SM-1L}} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \kappa_{\gamma\gamma} \epsilon_{\gamma\gamma}^{\text{SM-1L}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{q_1 \cdot q_2 \; g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} +$$
$$\left. + \left(\epsilon_{ZZ}^{\text{CP}} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{\text{CP}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

In the SM at tree level: $\kappa_X \to 1, \;\; \epsilon_X \to 0$

NLO EW - Prophecy4F code, hep-ph/0604011

Systematic inclusion of radiative QED corrections possible

Isidori et al, work in progress

$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

$$\epsilon_{\gamma\gamma}^{\text{SM-1L}} \simeq 3.8 \times 10^{-3} \, ,$$
$$\epsilon_{Z\gamma}^{\text{SM-1L}} \simeq 6.7 \times 10^{-3}$$

$h \to e^+ e^- \mu^+ \mu^-$

The most generic structure of the amplitude:

Marzocca, HXSWG plenary meeting - Jan 2015

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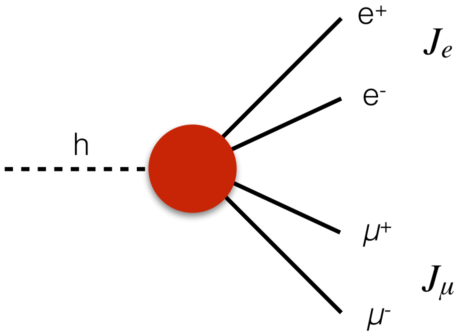


$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$

$$\left[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

Momentum expansion of the form factors around the physical poles

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$

$hZ_\mu \bar{f}\gamma^\mu f,\ hZ^\mu\partial^\nu V_{\mu\nu}$ $\quad V = Z,\gamma$

$hZ_\mu Z^\mu,\ hZ^\mu\partial^\nu V_{\mu\nu}$

$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} +\right.$$

$hV_{\mu\nu}V^{\mu\nu}$

$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} +$$

$h\varepsilon^{\mu\nu\rho\sigma}V_{\mu\nu}V_{\rho\sigma}$

$$\left.+\left(\epsilon_{ZZ}^{\text{CP}}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\text{CP}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

Parameter counting

Consider decays: ***h* → *WW****, ***h* → *ZZ****, ***h* → *Zγ***, ***h* → *γγ***

Neutral currents

$h \to e^+e^-\mu^+\mu^-$

$h \to \mu^+\mu^-\mu^+\mu^-$

$h \to e^+e^-e^+e^-$

$h \to \gamma e^+e^-$

$h \to \gamma\mu^+\mu^-$

$h \to \gamma\gamma$

$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,

$\epsilon_{Z\gamma}^{CP}, \epsilon_{\gamma\gamma}^{CP}, \epsilon_{ZZ}^{CP}$,

$\epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$

11

Charged currents

$h \to e^+\mu^-\nu\nu$

$h \to e^-\mu^+\nu\nu$

$\kappa_{WW}, \epsilon_{WW}, \epsilon_{WW}^{CP}$,

$\epsilon_{We_L}, \epsilon_{W\mu_L}$ (complex)

7

N. & C. interference

$h \to e^+e^-\nu\nu$

$h \to \mu^-\mu^+\nu\nu$

$\epsilon_{Z\nu_e}, \epsilon_{Z\nu_\mu}$

2

- Compared to only 4 parameter in the present “kappa” formalism
- Easy to implement in MC event generator,
  AG, Marzocca, private code

Symmetry limits

Consider decays: $h \to WW^*$, $h \to ZZ^*$, $h \to Z\gamma$, $h \to \gamma\gamma$

Neutral currents

$h \to e^+e^-\mu^+\mu^-$
$h \to \mu^+\mu^-\mu^+\mu^-$
$h \to e^+e^-e^+e^-$
$h \to \gamma e^+e^-$
$h \to \gamma\mu^+\mu^-$
$h \to \gamma\gamma$

$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,
$\epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}, \epsilon^{CP}_{ZZ}$,
$\epsilon_{Ze_L}, \epsilon_{Ze_R}$

9

Charged currents

$h \to e^+\mu^-\nu\nu$
$h \to e^-\mu^+\nu\nu$

$\kappa_{WW}, \epsilon_{WW}, \epsilon^{CP}_{WW}$,
ϵ_{We_L} (complex)

5

N. & C. interference

$h \to e^+e^-\nu\nu$
$h \to \mu^-\mu^+\nu\nu$

$\epsilon_{Z\nu_e}$

1

FU

Flavour universality

$$\epsilon_{Ze_L} = \epsilon_{Z\mu_L} \ ,$$

$$\epsilon_{Ze_R} = \epsilon_{Z\mu_R} \ ,$$

$$\epsilon_{Z\nu_e} = \epsilon_{Z\nu_\mu} \ ,$$

$$\epsilon_{We_L} = \epsilon_{W\mu_L} \ .$$

Symmetry limits

Consider decays: ***h* → *WW****, ***h* → *ZZ****, ***h* → *Zγ***, ***h* → *γγ***

Neutral currents

h → $e^+e^-\mu^+\mu^-$

h → $\mu^+\mu^-\mu^+\mu^-$

h → $e^+e^-e^+e^-$

h → γe^+e^-

h → $\gamma\mu^+\mu^-$

h → $\gamma\gamma$

$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,

$\epsilon_{Ze_L}, \epsilon_{Ze_R}$

6

FU + CP

Charged currents

h → $e^+\mu^-\nu\nu$

h → $e^-\mu^+\nu\nu$

$\kappa_{WW}, \epsilon_{WW},$

$\mathrm{Re}(\epsilon_{We_L})$ (complex)

3

N. & C. interference

h → $e^+e^-\nu\nu$

h → $\mu^-\mu^+\nu\nu$

$\epsilon_{Z\nu_e}$

1

CP conservation

$$\epsilon^{CP}_{ZZ} = \epsilon^{CP}_{Z\gamma} = \epsilon^{CP}_{\gamma\gamma} = \epsilon^{CP}_{WW} = \mathrm{Im}\epsilon_{We_L} = \mathrm{Im}\epsilon_{W\mu_L} = 0$$

Symmetry limits

Consider decays: ***h* → *WW****, ***h* → *ZZ****, ***h* → *Zγ***, ***h* → *γγ***

Neutral currents

h → $e^+e^-\mu^+\mu^-$
h → $\mu^+\mu^-\mu^+\mu^-$
h → $e^+e^-e^+e^-$
h → γe^+e^-
h → $\gamma\mu^+\mu^-$
h → $\gamma\gamma$

$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,

$\epsilon_{Ze_L}, \epsilon_{Ze_R}$

6

FU + CP + cust. symm.

Charged currents

h → $e^+\mu^-\nu\nu$
h → $e^-\mu^+\nu\nu$

$\mathrm{Re}(\epsilon_{We_L})$ (complex)

1

N. & C. interference

h → $e^+e^-\nu\nu$
h → $\mu^-\mu^+\nu\nu$

0

Custodial symmetry

$$\epsilon_{WW} = c_w^2\epsilon_{ZZ} + 2c_w s_w \epsilon_{Z\gamma} + s_w^2 \epsilon_{\gamma\gamma} \ ,$$

$$\epsilon_{WW}^{CP} = c_w^2\epsilon_{ZZ}^{CP} + 2c_w s_w \epsilon_{Z\gamma}^{CP} + s_w^2 \epsilon_{\gamma\gamma}^{CP} \ ,$$

$$\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\epsilon_{We_L^i} + 2c_w\epsilon_{Ze_L^i}\right) \ ,$$

$$\epsilon_{We_L^i} = \frac{c_w}{\sqrt{2}}\left(\epsilon_{Z\nu_L^i} - \epsilon_{Ze_L^i}\right) \ ,$$

*The BSM sector is invariant under the custodial symmetry group

$G = \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X$,

spontaneously broken to

$H = \mathrm{SU}(2)_{L+R} \times \mathrm{U}(1)_X$.

Linear vs *Non-linear* EFT

- **Non-linear EFT:**
  An effective decoupling of the Higgs boson from the Goldstone-boson components of the **$SU(2)_L \times U(1)_Y / U(1)_{em}$** symmetry breaking.

- EW symmetry is non-linearly realised, derivative expansion over the cutoff

- All Higgs **PO**s independent

- **Linear EFT:**
  Higgs boson is part of an $SU(2)_L$ doublet field **H**. Higher-dimensional operators are constructed in terms of the **H** field. The physical Higgs boson appears in operators contributing also to non-Higgs processes.

- **(1)** Some Higgs **PO**s constrained from LEP data

- **(2)** Relations among Higgs **PO**s due to the accidental custodial symmetry present in some of the D = 6 operators

$$
\begin{aligned}
\epsilon_{WW} &= c_w^2 \epsilon_{ZZ} + 2 c_w s_w \epsilon_{Z\gamma} + s_w^2 \epsilon_{\gamma\gamma} \; , \\
\epsilon_{WW}^{CP} &= c_w^2 \epsilon_{ZZ}^{CP} + 2 c_w s_w \epsilon_{Z\gamma}^{CP} + s_w^2 \epsilon_{\gamma\gamma}^{CP} \; , \\
\epsilon_{We_L^i} &= \frac{c_w}{\sqrt{2}} (\epsilon_{Z\nu_L^i} - \epsilon_{Ze_L^i})
\end{aligned}
$$

Violation of (1) and (2) would point towards non-linear realisation of EW symmetry!

Test from Higgs data!!!

Higgs POs from *LEP* data

Gonzalez-Alonso, AG,
Isidori, Marzocca,
work in progress

Assuming linear EFT with dimension 6 operators:

$$\varepsilon_{Zf} = \frac{2m_Z}{v}\left(\delta g^{Zf} - (c_\theta^2 T_f^3 + s_\theta^2 Y_f)\mathbf{1}_3 \underline{\delta g_{1,z}} + t_\theta^2 Y_f \mathbf{1}_3 \underline{\delta \kappa_\gamma}\right) ,$$

$$\varepsilon_{Wf} = \frac{\sqrt{2}m_W}{v}\left(\delta g^{Wf} - c_\theta^2 \mathbf{1}_3 \underline{\delta g_{1,z}}\right)$$

LEP I

LEP II

$$\delta\varepsilon_{ZZ} = \delta\varepsilon_{\gamma\gamma} + \frac{c_{2\theta}}{s_\theta c_\theta}\delta\varepsilon_{Z\gamma} - \frac{1}{c_\theta^2}\underline{\delta\kappa_\gamma} ,$$

LEP II

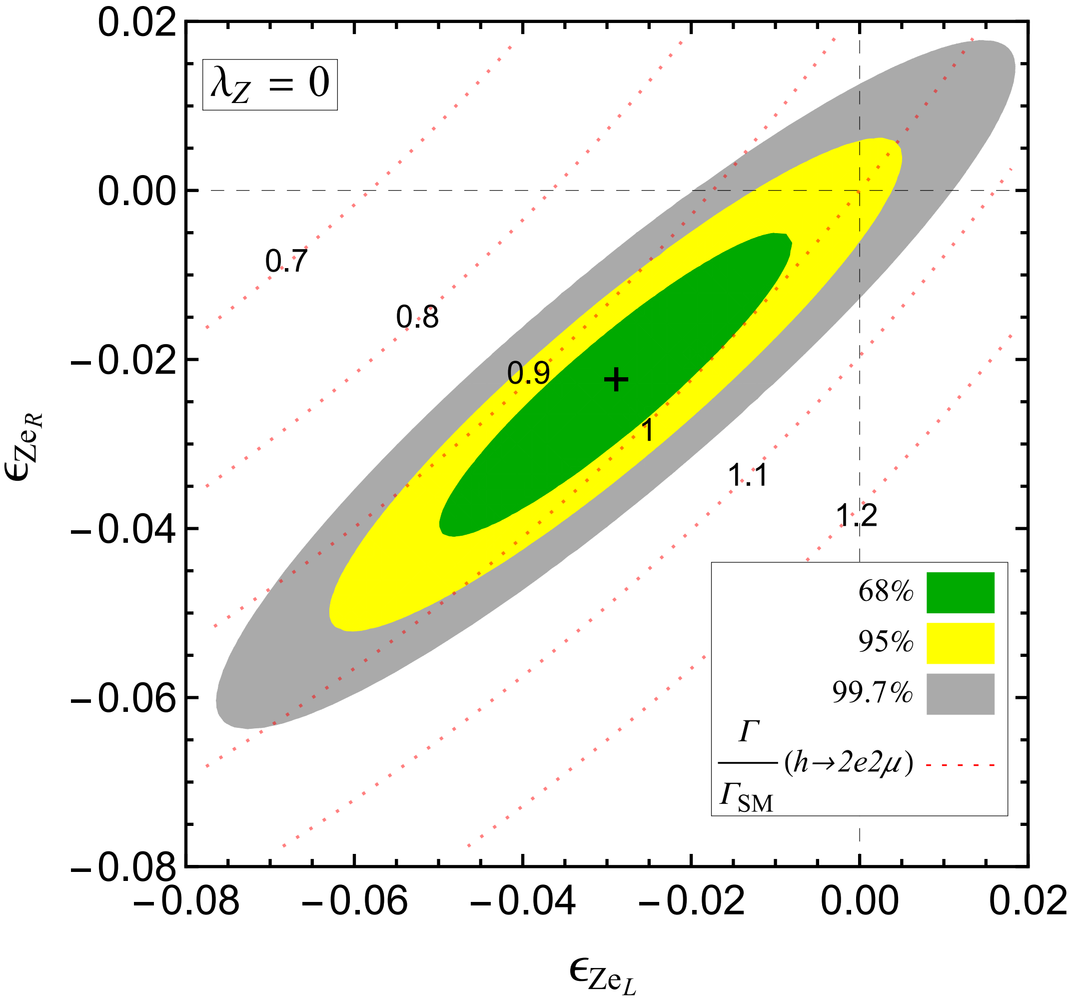
Higgs POs from *LEP* data

Gonzalez-Alonso, AG, Isidori, Marzocca, work in progress

Assuming linear EFT with dimension 6 operators:

Using the EW fits from Falkowski, Riva and Efrati, Falkowski, Soreq we find:

$\epsilon_{Ze_R} = \epsilon_{Z\mu_R}$



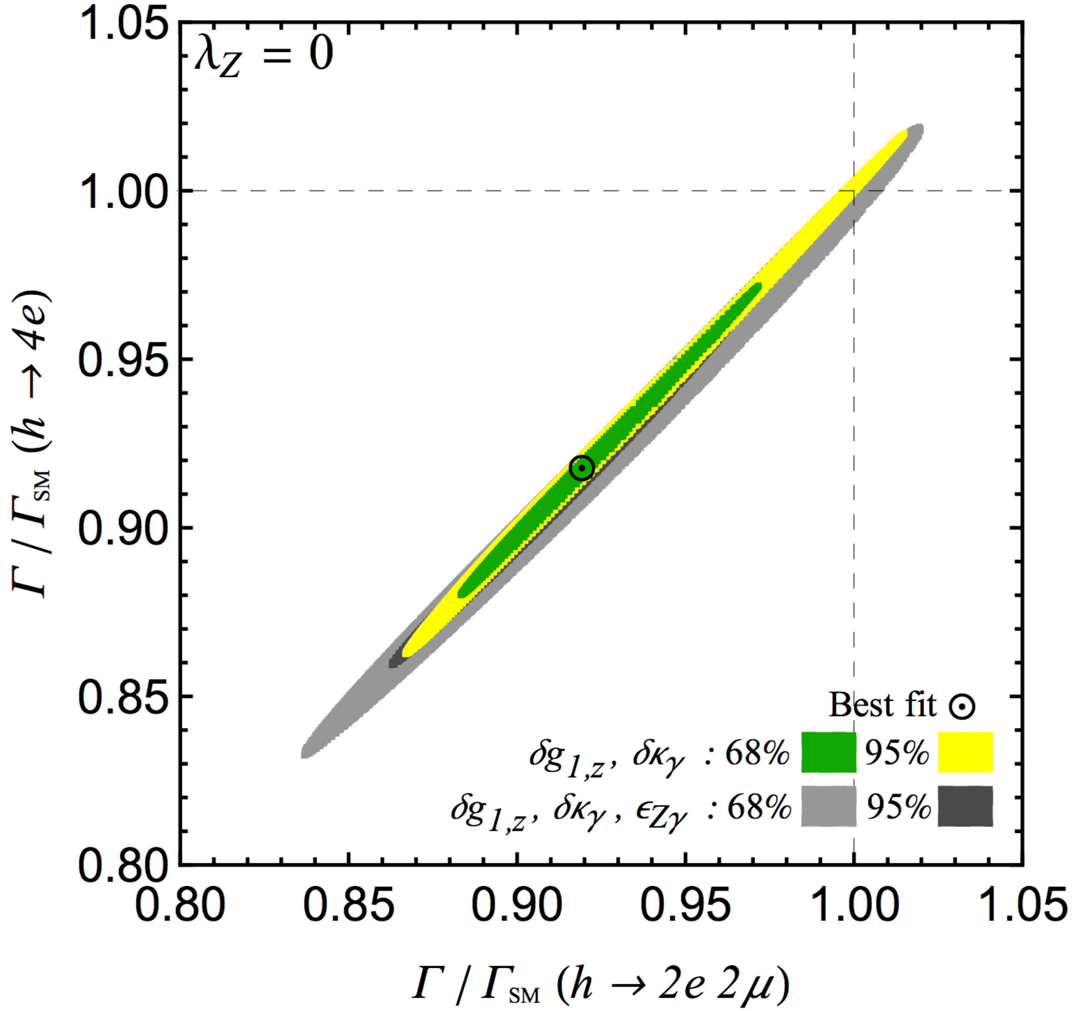
$\epsilon_{Ze_L} = \epsilon_{Z\mu_L}$

Flavour universality

Higgs POs from *LEP* data

Gonzalez-Alonso, AG, Isidori, Marzocca, work in progress

Assuming linear EFT with dimension 6 operators:



Higgs POs from *LEP* data

Gonzalez-Alonso, AG,
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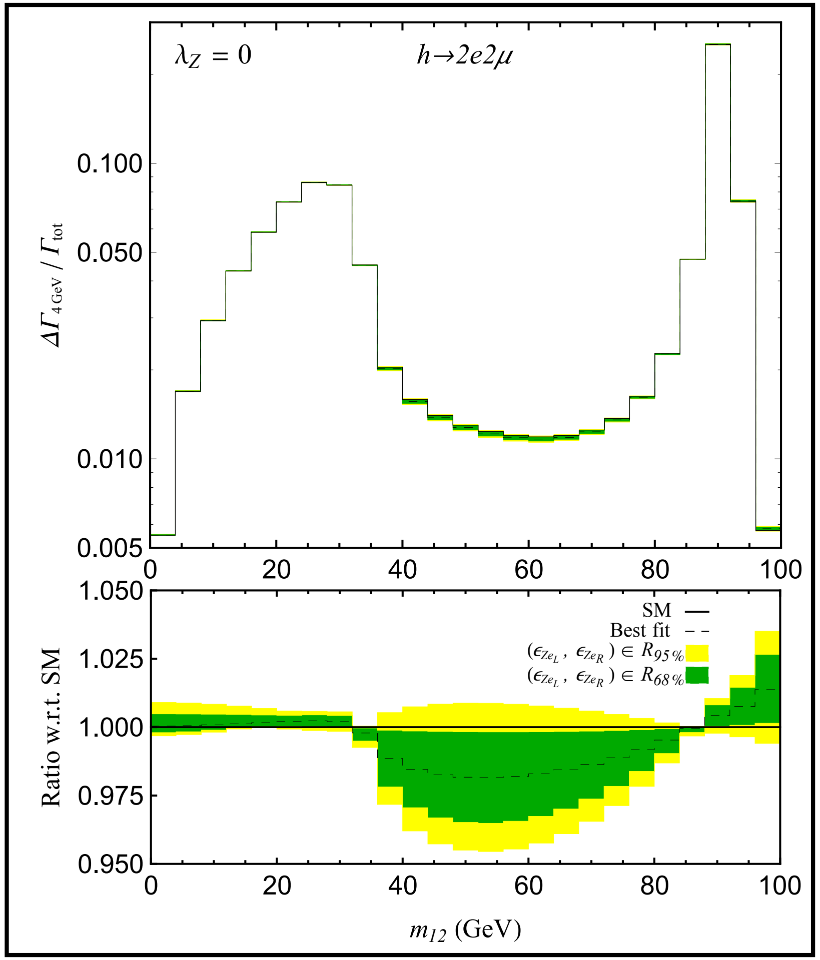

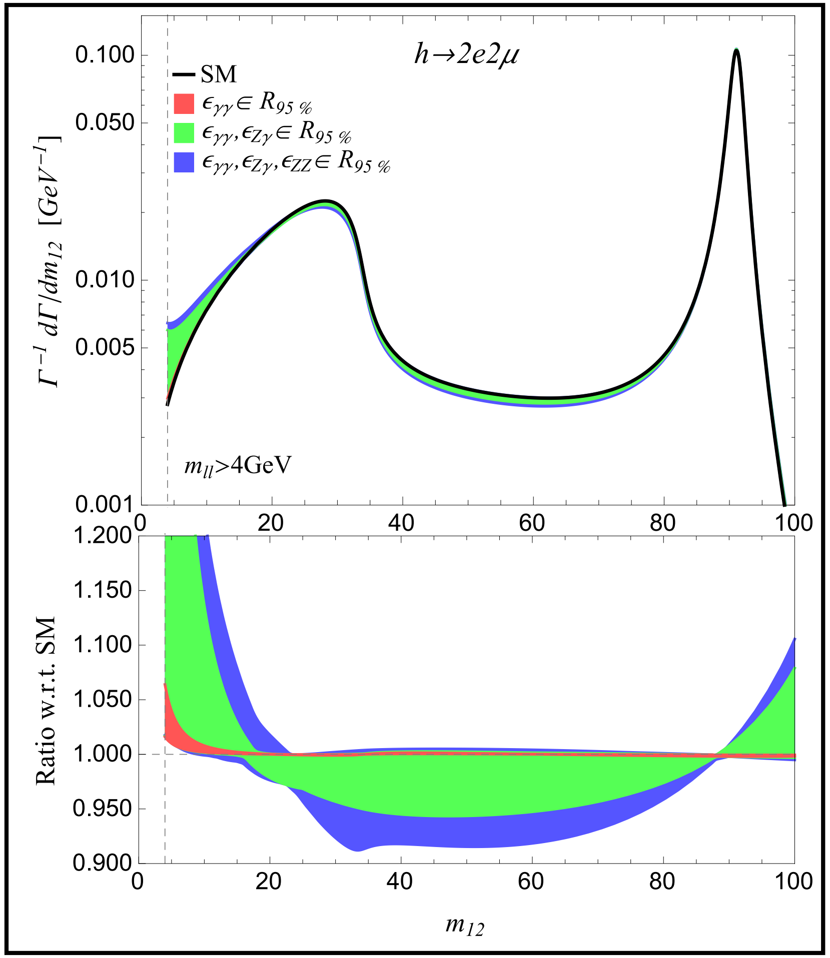

Small deviations in the shape expected.

Conclusions

- We propose a set of **PO**s to characterise NP in Higgs decays
    A. General encoding of the experimental results
    B. Easily computable in large set of theories
    C. Not a substitute (or competition) to **EFT** approach, rather an intermediate step
    D. Dressing with QED radiation possible

- FU, CP, custodial symmetry, linear or non-linear EFT not assumed!
  We should keep our eyes open.

- Linear EFT > firm predictions on $h \to 4\ell$ shape & LFU
  (possibility to falsify them with Higgs data would be a "double discovery": NP + h(125) non-pure $SU(2)_L$ doublet)

- Work to do: compute the projections for LHC run 2
  (in collaboration with experimental groups)