Some general comments about

EFT analyses of NP searches & applications to Higgs physics

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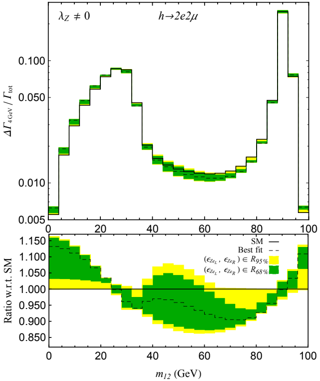


Outline

- Intro: searching for NP;
- EFT: General comments.
  - What's an EFT?
  - Illustrative example: W boson & the (V-A)(V-A) effective theory
  - EFT at the EW scale? Linear EFT?
- Higgs physics:
  - Generalizing the kappa framework: Higgs pseudo-observables
  - New Physics room in h → 4 leptons ?

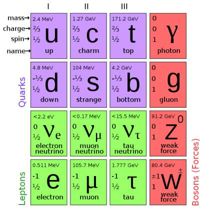
[MGA & Isidori, PLB733 (2014)]

[MGA, Greljo, Isidori & Marzocca, EPJC75 (2015)]

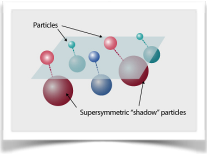
[MGA, Greljo, Isidori & Marzocca, arXiv:1504.xxxx]

Intro: the search for 'New Physics'

NEW PHYSICS : a new theory that completes the SM and solves (at least some of) the current puzzles.

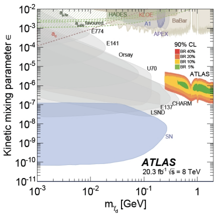


- Every experiment has a discovery potential... but we cannot make them all!

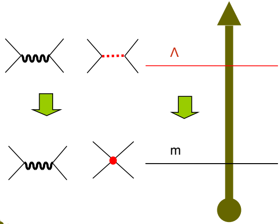


- Theory can provide some guidance… useful to prioritize & interpret results.

- Which theory?
  - Simple option: specific NP model
  - Can we be more general? Yes: Effective Field Theories. Caveat: Model-indep., but not assumption-indep.;



What's an EFT?



$$\mathcal{L} = \mathcal{L}(\phi, \phi_\Lambda)$$

$$\mathcal{L}_{eff} = \mathcal{L}_4(\phi) + \frac{1}{\Lambda}\mathcal{L}_5(\phi) + \frac{1}{\Lambda^2}\mathcal{L}_6(\phi) + \ldots \;\Rightarrow\; \sum \alpha_i\, \mathcal{O}_i$$

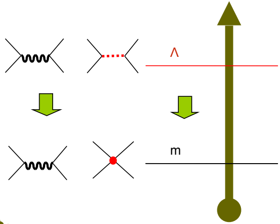
α_i : Wilson coefficients. They encode the Λ-scale (known?) physics.

Effective Field Theory = Fields + Symmetries + Power counting

- n, p, e, ν;
- u, d, e, ν;
- W, Z, …
- h SU(2) doublet?
- bSM? (DM!)

- Lorentz;
- QED;
- SU(2) x U(1);
- Flavour sym.;
- B, L;

What's an EFT?



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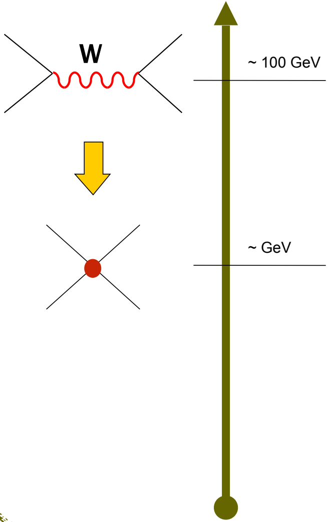
α_i : Wilson coefficients. They encode the Λ-scale (known?) physics.

Effective Field Theory = Fields + Symmetries + Power counting

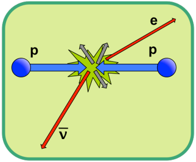
- Observables: $$\mathcal{R} = \mathcal{R}_0 \left(1 + \frac{\mathcal{O}(m,E)}{\Lambda} + \frac{\mathcal{O}(m^2,E^2,mE)}{\Lambda^2} + \ldots\right)$$

Validity of the EFT: E << Λ

Simple example: beta decays



$\mathcal{L}_{SM}$ (EW theory)

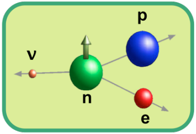


$$\mathcal{L}^{eff}_{d\to ue^-\bar{\nu}_e} = -\frac{4G_F V_{ud}}{\sqrt{2}}\,\bar{e}\gamma_\mu(1-\gamma_5)\nu\cdot\bar{u}\gamma^\mu(1-\gamma_5)d$$

+ higher-dim terms

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient



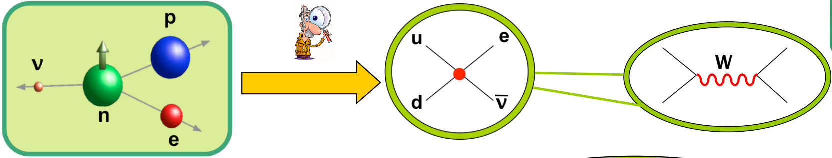
Simple example: beta decays

- In real life, the process is the other way around:

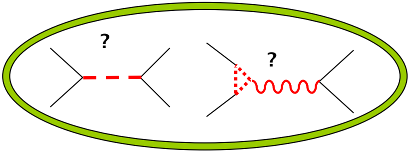
$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{e}\gamma_\mu(1-\gamma_5)\nu\cdot\ \bar{u}\gamma_\mu(1-\gamma_5)d\ +\ \sum_i \varepsilon_i\ \bar{e}\,\Gamma\nu\cdot\bar{u}\Gamma\right]$$

$$G_F \sim \frac{1}{M_W^2}$$

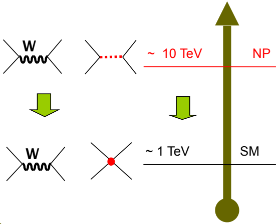
$$G_F\varepsilon_i \sim \frac{1}{M_{NP}^2}$$



- Discovery of V-A structure!
- Very active field nowadays!
- Complementary to collider searches.



EFT at the EW scale



$\mathbf{L}^{TeV}(x) = \mathbf{L}(\text{SM-fields, bSM-fields})$

$$\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda}\mathcal{L}_5(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \ldots$$

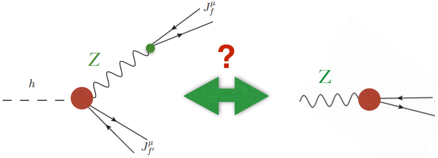
EFT = Symmetries + Fields

- Lorentz;
- SU(2) x U(1);
- Flavour sym?
- B, L;

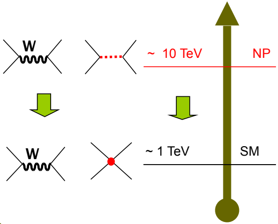
- q, u, d, l, e
- W, Z, γ, g
- h SU(2) doublet?
- No light NP

linear vs non-linear EFT

$$\varphi \overset{?}{=} \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



EFT at the EW scale: linear EFT

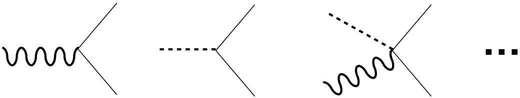


$$\mathbf{L}^{TeV}(x) = \mathbf{L}(\text{SM-fields}, \text{bSM-fields})$$

$$\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda}\mathcal{L}_5(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \ldots \rightarrow \sum \alpha_i \mathcal{O}_i$$

[Buchmuller & Wyler, 1986]
[Leung et al., 1986]
[Grzadkowksi et al., 2010]

- Minimal & complete basis: 59 dim-6 operators.
- E.g. $(\varphi^\dagger i D_\mu \varphi)(l_p \gamma^\mu l_r)$

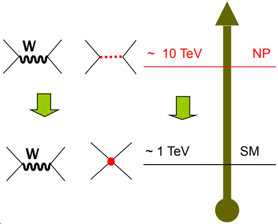


$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$D_\mu = I\partial_\mu - i g_s \frac{\lambda^A}{2} G_\mu^A - i g \frac{\sigma^a}{2} W_\mu^a - i g' Y B_\mu$$

EFT at the EW scale: *linear EFT*



$\mathbf{L}^{TeV}(x) = \mathbf{L}(\text{SM-fields, bSM-fields})$

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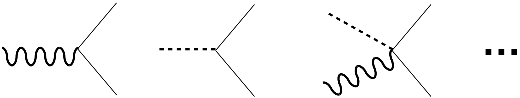


- Parametrization of BSM effects in any given process (#dof). E.g. $\frac{d\Gamma}{dq^2} = \frac{d\Gamma_{SM}}{dq^2} + f(\alpha_4; q^2)$

EFT at the EW scale:

Correlating measurements (or how to play the EFT game)

- Choose your EFT, *e.g. linear EFT*
- Choose an operator basis $\{O_1, O_2, \ldots, O_n\}$, *e.g. the Warsaw basis*
  $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Sigma\, \alpha_i O_i$
- Calculate the observable you like in the EFT,
  e.g. $O = O_{SM} + \Sigma\, c_i\, \alpha_i = O_{SM} + 3\alpha_1 - \alpha_6$
- What are the known limits on the Wilson coefficients?
  e.g. from LEP… $\alpha_1 = 0.001(3)$, α_2 *unkown, …*
  More precisely: χ^2 with (*LEP*) measurements gives you central values and error matrix
- Implications for your observable?
  e.g. error matrix $\rightarrow 3\alpha_1 - \alpha_6 = 0.02(4)$
  - ~ 4% sensitivity (th+exp) to be competitive (or to check a LEP anomaly);
  - A deviation larger than that indicates some wrong assumptions in your EFT!

Application to Higgs physics

A) Pseudo-observables in Higgs decays (EFT-inspired)
B) Linear EFT: $h \to 4l$

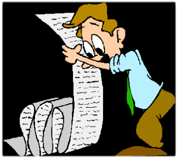
[MGA, Greljo, Isidori & Marzocca, EPJC75 (2015)]

[MGA, Greljo, Isidori & Marzocca, arXiv:1504.xxxx]

Application to Higgs physics

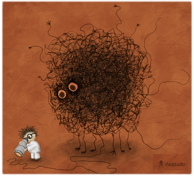
- After the discovery,
  we enter a high-precision Higgs physics era.

- How to analyze exp results?
  How to pass them to the theory community?



  - Extreme case (no theory bias):
    all available experimental info…
    we wouldn't know what todo!

  - The other extreme (max theory bias):
    assume a simple model with 1 free parameter P, analyze all Higgs data and extract P.



Application to Higgs physics

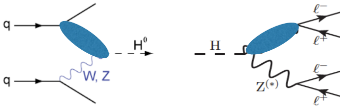
- What was done in run 1? Kappa framework

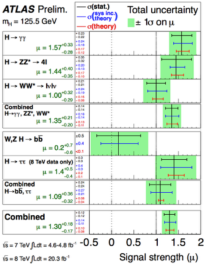
$$\sigma(ii \to h+X) \times BR(h \to ff) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_h} = \frac{\kappa_{ii}^2 \kappa_{ff}^2}{\kappa_h^2} \sigma_{SM} \times BR_{SM}$$

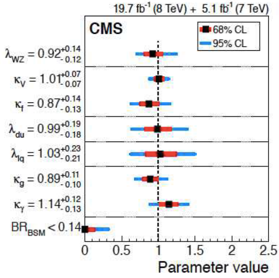
Virtues: Clean SM limit (k→1), well-def. exp & th, quite general.

Limitations:

- What about NP affecting mainly diff. distr? (easy to conceive, e.g. CPV)
- What about hVff terms? (diff. in production & decay)







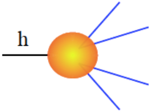
Application to Higgs physics

- We need a larger set of "pseudo-observables" able to characterize NP in the Higgs sector with the least theory bias.

  Let's focus on h→4l
  (where the limitations of the kappa framework are more relevant)

  Assumption #1: Chirality-conserving interactions

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times T^{\alpha\beta}(q_1,q_2)$$



  Lorentz symmetry:

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

==> One could simply extract FFs but it requires an enormous amount of data & general considerations (EFT-inspired) tells us quite a lot about them…

[MGA, Greljo, Isidori & Marzocca, 2014]

Pseudo-observables in Higgs decays

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

[MGA, Greljo, Isidori & Marzocca, 2014]

Leading NP effects (linear & non-linear EFT):

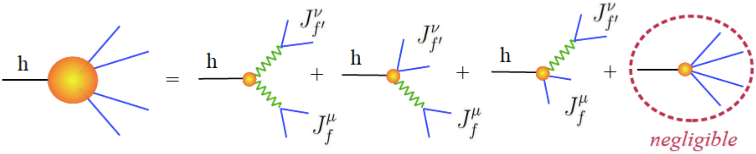
$$\mathcal{A} = i\frac{2m_Z^2}{v_F} \sum_{e=e_L,e_R} \sum_{\mu=\mu_L,\mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu) \times$$

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

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

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

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



PS: Absence of light states is crucial…

Pseudo-observables in Higgs decays

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

[MGA, Greljo, Isidori & Marzocca, 2014]

Leading NP effects (linear & non-linear EFT):

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

$h \to \gamma\gamma$

$$
\mathcal{A}\left[h \to \gamma(q,\epsilon)\gamma(q',\epsilon')\right] = i\frac{2}{v_F}\epsilon'_\mu \epsilon_\nu \left[\kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{SM-1L} (g^{\mu\nu}\; q\cdot q' - q^\mu q'^\nu) + \epsilon_{\gamma\gamma}^{CP} \varepsilon^{\mu\nu\rho\sigma} q_\rho q'_\sigma \right],
$$

Pseudo-observables in Higgs decays

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

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

- 11 pseudo-observables;
- No new POs needed to describe… →
- What about the h→2l2ν channels? ==> 9 more PO needed.

$h \to 4\mu$

$h \to 4e$

$h \to \gamma\gamma$

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

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

Pseudo-observables in Higgs decays

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

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

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

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

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

- g_Z^f are LEP pseudo-observables (Z→ff); → $\mathcal{A} = i \sum_{f=f_L,f_R} g_Z^f \, \varepsilon_\mu \, \bar{f}\gamma^\mu f$
- POs defined at the amplitude level (PO ≠ WC);
- κ-framework limit: $\varepsilon_i = 0$;
- SM limit: $\kappa_i = 1$, $\varepsilon_i = O(0.001) \sim 0$;

Pseudo-observables in Higgs decays

- General comments:
  - PO = general encoding of the exp. results in terms of a finite number of simplified "observables" of easy th. interpretation;
  - Their determination helps (but not replaces) model-dep. / EFT studies: PO = $PO_{SM} + f(\alpha_i) + \ldots$
  - PO example: Z-mass;

- Higgs decays well within EFT validity: (not so for production…)

$$\mathcal{R} = \mathcal{R}_0 \left(1 + \frac{\mathcal{O}(m, E)}{\Lambda} + \frac{\mathcal{O}(m^2, E^2, mE)}{\Lambda^2} + \ldots \right)$$

Validity of the EFT:
E << Λ

- Signal strengths only give us certain combinations; Distributions are necessary! (Montecarlo!)

Parameter counting & symmetry limits

[From talk by A. Greljo at Portoroz'2015]

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

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

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

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

$\epsilon_{W e_L}, \epsilon_{W \mu_L}$ (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

Parameter counting & symmetry limits

[From talk by A. Greljo at Portoroz'2015]

Neutral currents

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

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

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

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

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

$h \to \gamma\gamma$

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

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

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

9

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)

5

N. & C. interference

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

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

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

1

Flavour universality

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

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

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

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

Parameter counting & symmetry limits

[From talk by A. Greljo at Portoroz'2015]

Neutral currents

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

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

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

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

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

$h \to \gamma\gamma$

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

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

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

6

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)

3

N. & C. interference

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

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

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

1

Flavour universality

$$\epsilon_{Ze_L} =$$
$$\epsilon_{Ze_R} =$$
$$\epsilon_{Z\nu_e} =$$
$$\epsilon_{We_L} = \epsilon_{W\mu_L} \; .$$

CP conservation

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

Parameter counting & symmetry limits

[From talk by A. Greljo at Portoroz'2015]

Neutral currents

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

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

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

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

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

$h \to \gamma\gamma$

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

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

6

Charged currents

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

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

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

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

1

N. & C. interference

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

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

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

0

Flavour universality

$$\epsilon_{Ze_L} = $$
$$\epsilon_{Ze_R} = $$
$$\epsilon_{Z\nu_e} = $$
$$\epsilon_{We_L} = \epsilon_{W\mu_L} \, .$$

CP co[...]

$$\epsilon^{CP}_{ZZ} = \epsilon^{CP}_{Z\gamma} = \epsilon^{CP}_{\gamma\gamma} = \epsilon^{CP}_{W[...]}$$

Custodial symmetry

$$★\ \epsilon_{WW} = c_w^2\epsilon_{ZZ} + 2c_w s_w \epsilon_{Z\gamma} + s_w^2 \epsilon_{\gamma\gamma} \, ,$$
$$★\ \epsilon^{CP}_{WW} = c_w^2\epsilon^{CP}_{ZZ} + 2c_w s_w \epsilon^{CP}_{Z\gamma} + s_w^2 \epsilon^{CP}_{\gamma\gamma} \, ,$$
$$\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\epsilon_{We^i_L} + 2c_w\epsilon_{Ze^i_L}\right) \, ,$$
$$★\ \epsilon_{We^i_L} = \frac{c_w}{\sqrt{2}}\left(\epsilon_{Z\nu^i_L} - \epsilon_{Ze^i_L}\right) \, ,$$

★ (Accidentally) true in the linear EFT

Linear-EFT can be ruled out using only Higgs data!

[MGA, Greljo, Isidori & Marzocca, arXiv:1504.xxxx]

Pseudo-observables in Higgs decays (linear EFT)

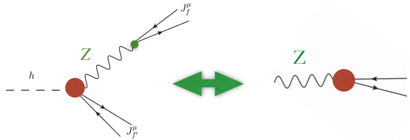
What's the room for NP in Higgs decays taking into account LEP results?

Example:

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

$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,
$\epsilon_{Z\gamma}^{CP}, \epsilon_{\gamma\gamma}^{CP}, \epsilon_{ZZ}^{CP}$,
$\epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



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

$$\epsilon_{Zf} = \sqrt{g^2 + g'^2}\,\left(\delta g^{Zf} - (c_\theta^2 T_f^3 + s_\theta^2 Y_f)\mathbb{1}\,\delta g_{1,z} + t_\theta^2 Y_f \mathbb{1}\,\delta\kappa_\gamma\right),$$

LEP I

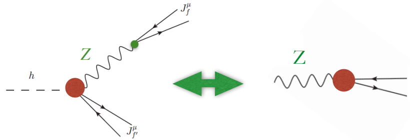
LEP II

Only flavor dep.

$\mathcal{O}(10^{-3})$ [Efrati, Falkowski & Soreq'2015]

Flavour univ. derived from data (not imposed!)

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



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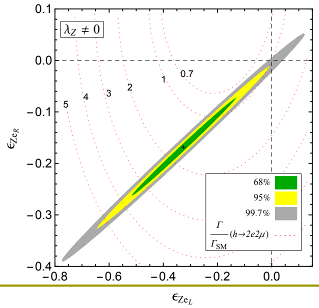
$$\epsilon_{Zf} = \sqrt{g^2 + g'^2}\left(\delta g^{Zf} - (c_\theta^2 T_f^3 + s_\theta^2 Y_f)\mathbb{1}\,\delta g_{1,z} + t_\theta^2 Y_f \mathbb{1}\,\delta\kappa_\gamma\right),$$

LEP I

LEP II [Falkowski & Riva'2014]



[MGA, Greljo, Isidori & Marzocca, arXiv:1504.xxxx]

Pseudo-observables in Higgs decays (linear EFT)

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$$\epsilon_{Zf} = \sqrt{g^2 + g'^2}\, \delta g^{Zf} - (c_\theta^2 T_f^3 + s_\theta^2 Y_f) \delta g_{1,z} + t_\theta^2 Y_f (\delta\kappa_\gamma),$$

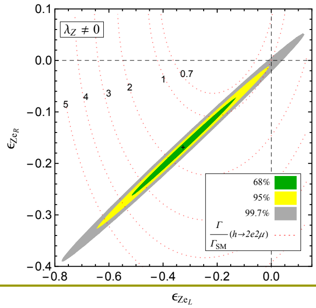
LEP I

LEP II [Falkowski & Riva'2014]

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

$h \to \gamma\gamma$ $\sim 10^{-3}$

$h \to Z\gamma$ $\sim 10^{-2}$



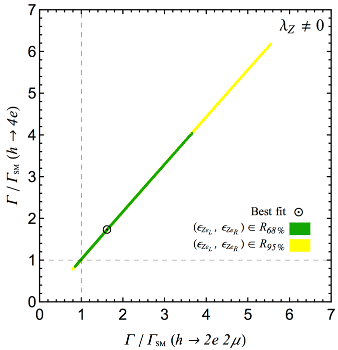
Linear EFT predictions for h → 4ℓ

What's the room for NP in Higgs decays taking into account LEP results?

Example:

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

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



Large effects on total decay rates allowed,
but huge correlation between 4e, 4μ and 2e2μ
(consequence of flavor univ,
which in turn is a consequence of the linear EFT!)

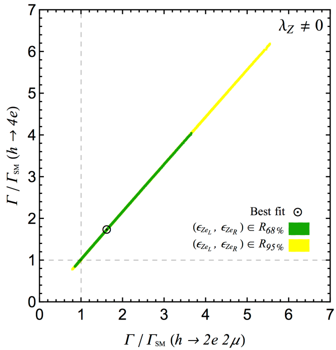
Linear EFT predictions for h $\to 4\ell$

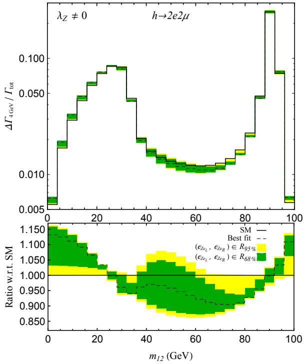
What's the room for NP in Higgs decays taking into account LEP results?

Example:

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

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





Small effects in the shape!

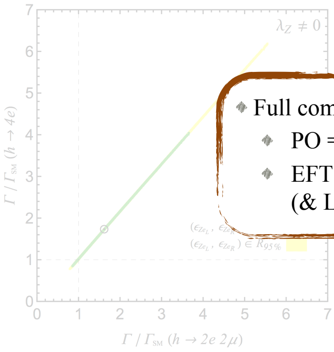
Linear EFT predictions for $h \to 4\ell$

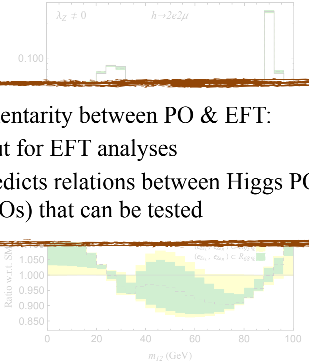
What's the room for NP in Higgs decays taking into account LEP results?

Example:

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

$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,
$\epsilon_{Z\gamma}^{CP}, \epsilon_{\gamma\gamma}^{CP}, \epsilon_{ZZ}^{CP}$,
$\epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$





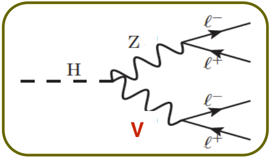
- Full complementarity between PO & EFT:
  - PO = input for EFT analyses
  - EFT = predicts relations between Higgs POs (& LEP POs) that can be tested

Small effects in the shape!

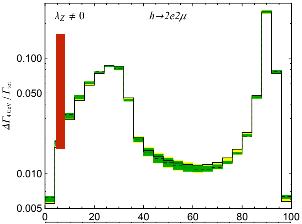
Not assumption-independent…

- All these approaches neglect new light states…
  which are not ruled out & indeed deserve their own separate attention
  (Exotic Higgs decays)

- Discovery potential: worth searching!
  Current cuts: 12 GeV!



More spectacular signals!



[Davoudiasl et al'2012-2013,
Curtin et al'2013,
MGA & G. Isidori, 2014
Falkowski & Vega-Morales, 2014, ...]

Summary

- Introd. to EFT analysis of NP searches
  NP encoded in Wilson coefficients;

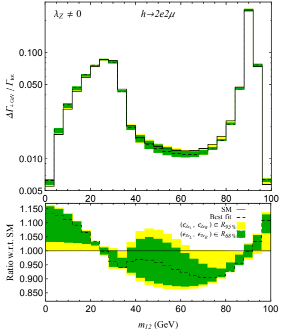
- Higgs decays:

  - Pseudo-observables as a convenient & general way to encode the experimental results; (generalization of the kappa framework)

  - Many NP hypothesis testable;

  - LEP implications for Higgs decays analyzed.

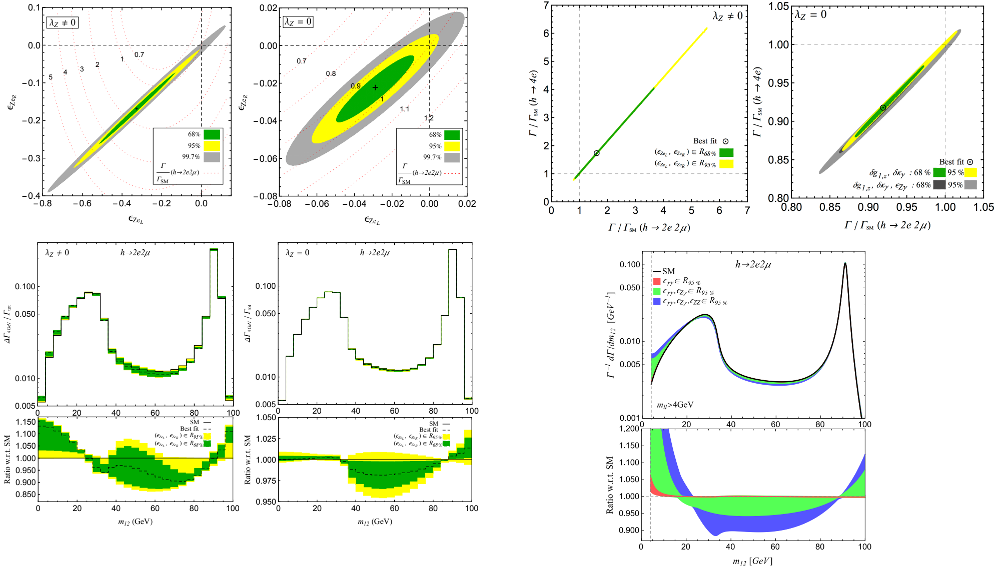
Effective Field Theory
=
Fields + Symmetries



Merci beaucoup!

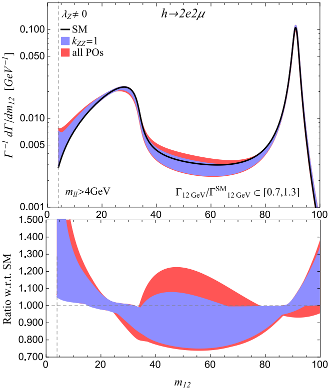
Backup slides

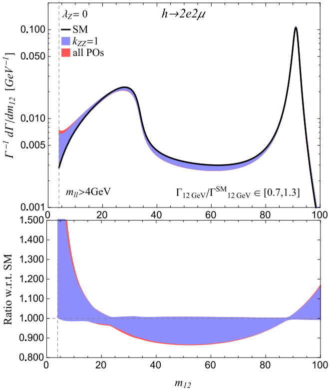
Pseudo-observables in Higgs decays (linear EFT)



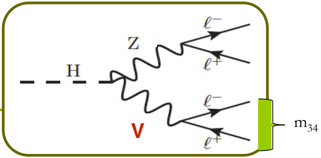
Linear EFT predictions for h → 4ℓ

Taking into account the other PO, there is still limited room for NP.





EFT limitations…

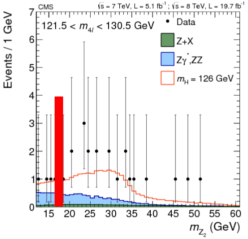


- Light new particles are not ruled out!
  (historical example: neutrino!)

- Exotic Higgs decays?
  - Tiny Γ_h ;
  - O(500,000) Higgses produced at LHC7+LHC8!
  - BR(h➔BSM) could be as large as O(20-50%);
    [Belanger et al'2013, Giardino et al'2013, Ellis & You'2013, ...]
  - Can be connected with some anomalies (g-2).

- Low-energy QCD effects can be important;

- Discovery potential: worth searching!
  Current cuts: 12 GeV!



More spectacular signals!

[MGA & G. Isidori, 2014
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