Pseudo-observables in Higgs decays

IFAC seminar — April 2015

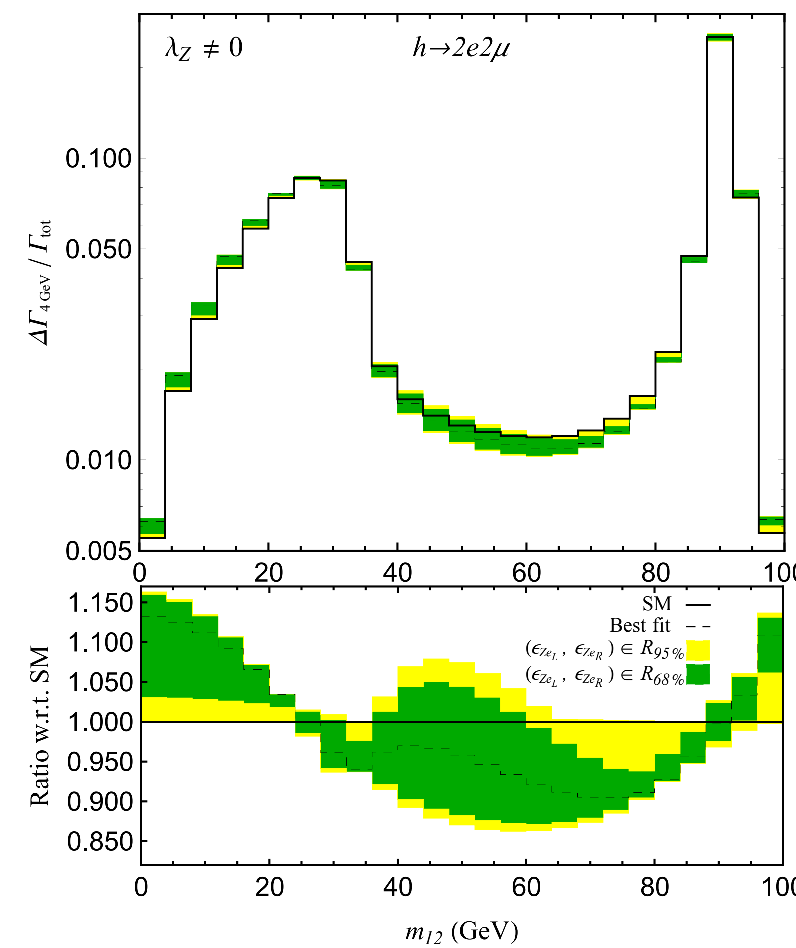
Martín González-Alonso

Lyon Institute of Origins

Institut de Physique Nucléaire de Lyon

Labex LIO Institut des Origines de Lyon

UNIVERSITÉ DE LYON



Outline

- Introduction & EFTs
- Generalizing the kappa framework to analyze Higgs data:
  Pseudo-observables in Higgs decays
- Linear EFT:
  - EW bounds on Higgs PO;
  - New Physics room in h → 4l?
  - What about h → 2l2ν ?
- Conclusions

[MGA & Isidori, PLB733 (2014)]
[MGA, Greljo, Isidori & Marzocca, EPJC75 (2015)]
[MGA, Greljo, Isidori & Marzocca, arXiv:1504.04018]

Introduction

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

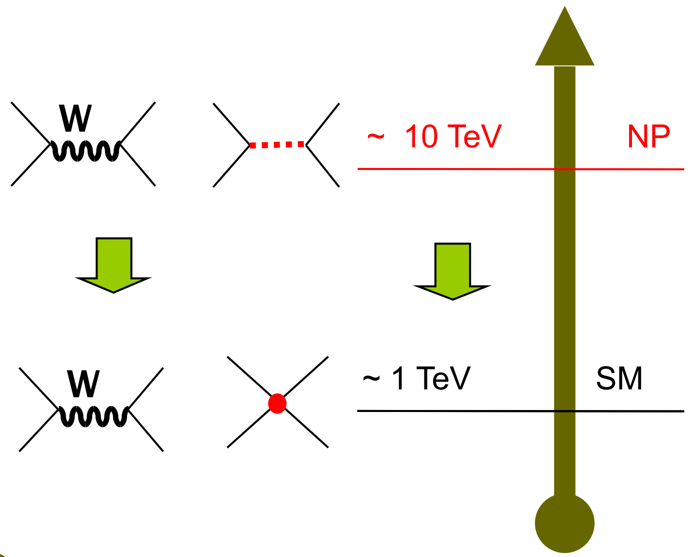
- How to analyze exp results?
  How to pass them to the theory community?

  - 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.

EFT approach is useful…

EFT at the EW scale



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

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

$$\sum \alpha_i \mathcal{O}_i$$

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

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

(+ Power counting)

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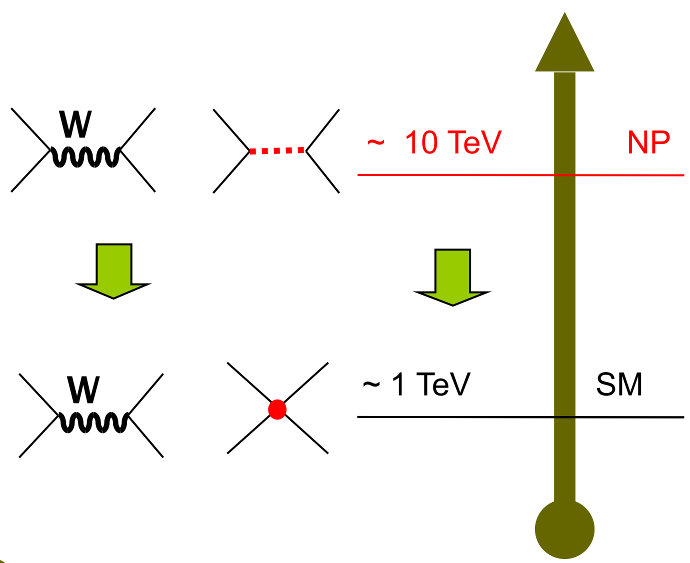

$$\mathcal{L} = \mathcal{L}(\phi, {\color{red}\phi_\Lambda})$$

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

Validity of the EFT:
$E \ll \Lambda$

(Higgs decays: $E \ll M_h \ll \Lambda$)

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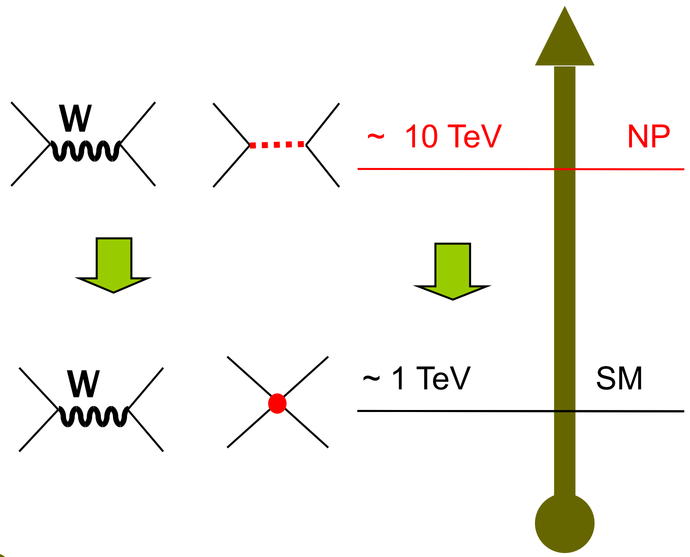

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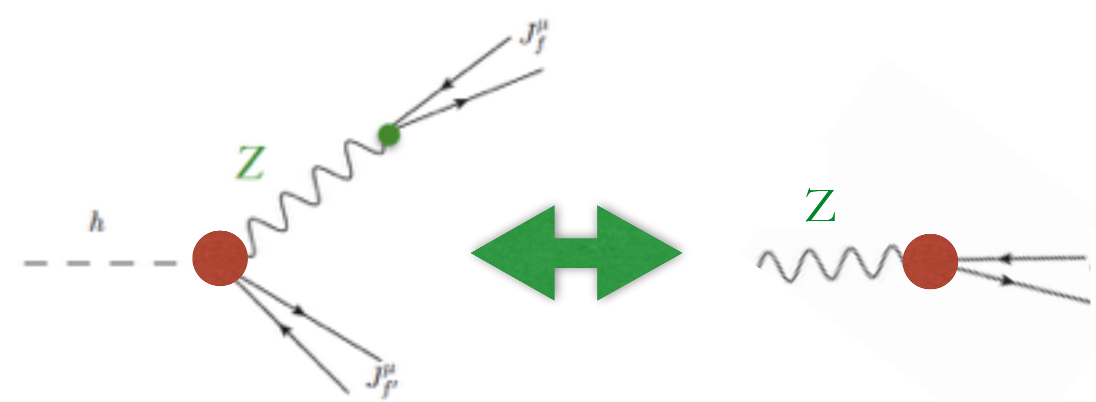
Linear EFT

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



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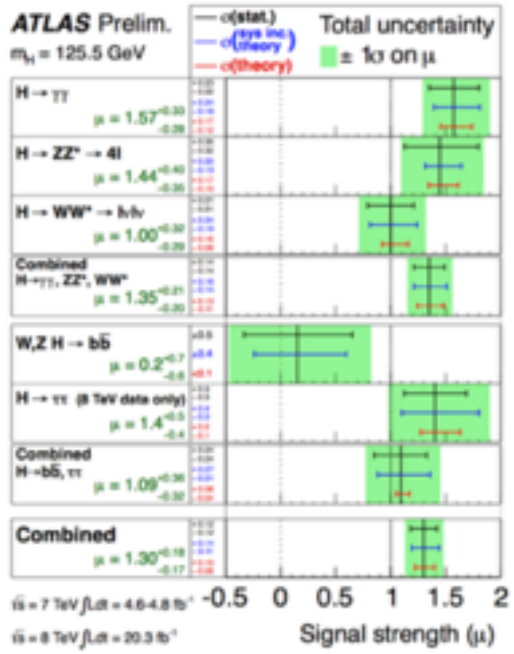
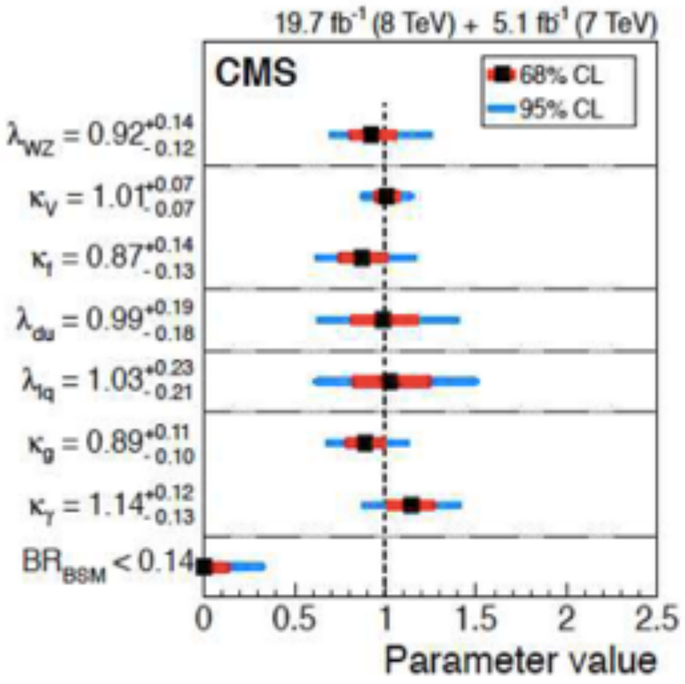
$$\sigma(ii \to h+X) \times BR(h \to ff) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_h} = \frac{\kappa_{ii}^2 \kappa_{ff}^2}{\kappa_h^2} \sigma_{SM} \times BR_{SM}$$

Higgs characteristic footprint:

$$g_F = \kappa_F \frac{\sqrt{2} m_F}{v}$$

$$g_V = \kappa_V \frac{2 m_V^2}{v}$$





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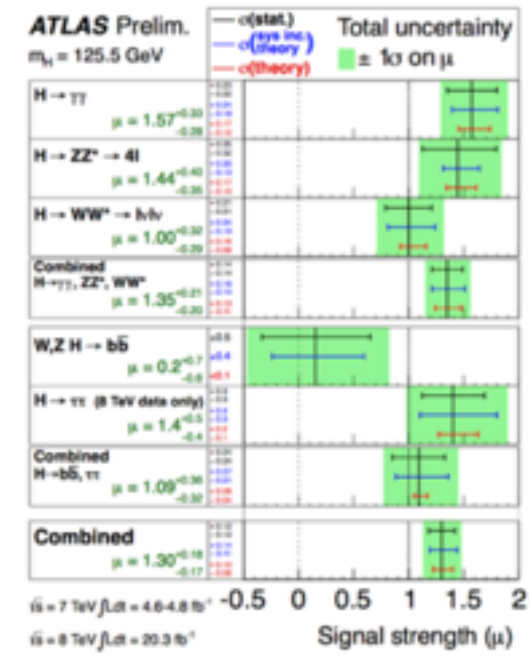
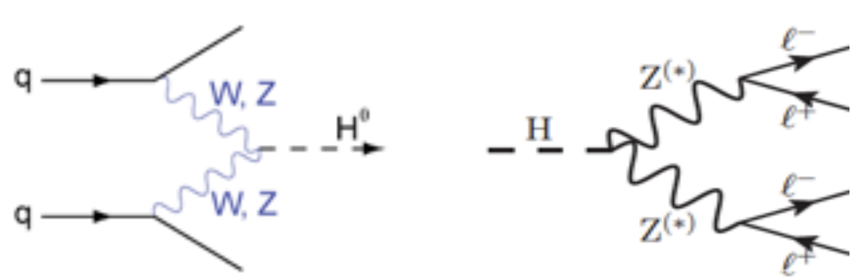
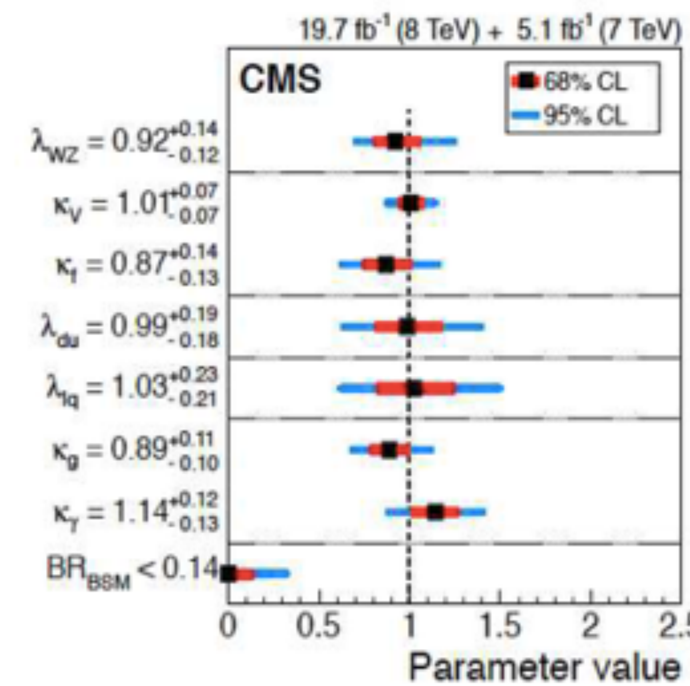


Virtues: Clean SM limit (k→1), well-def. exp & th, quite general.

Limitations:

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





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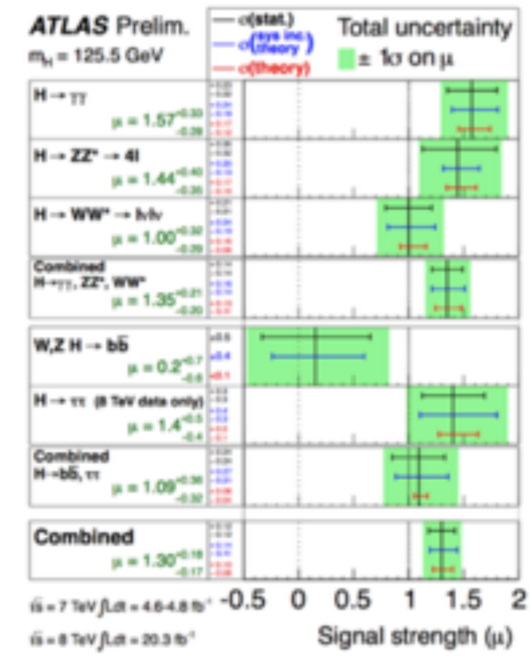

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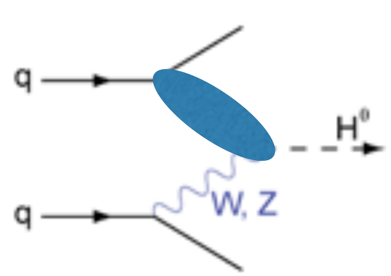
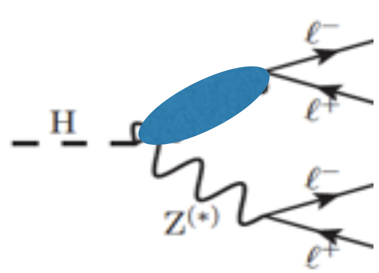
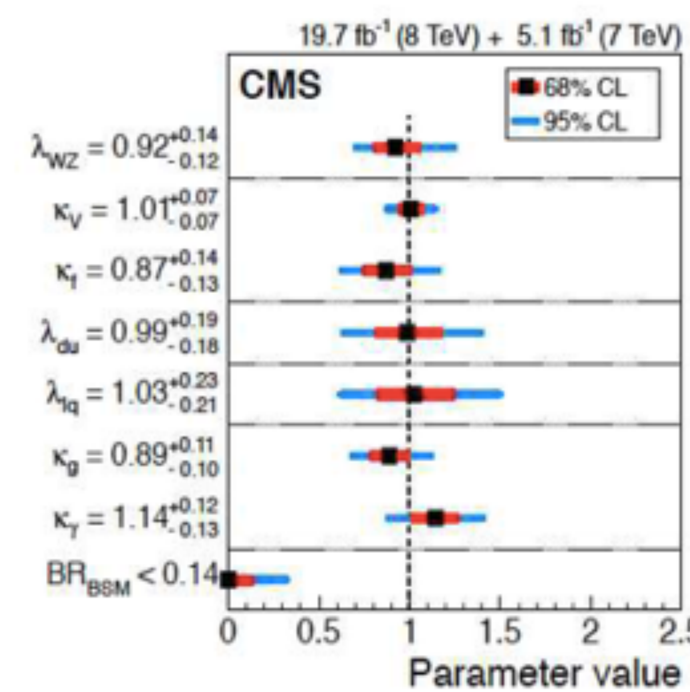


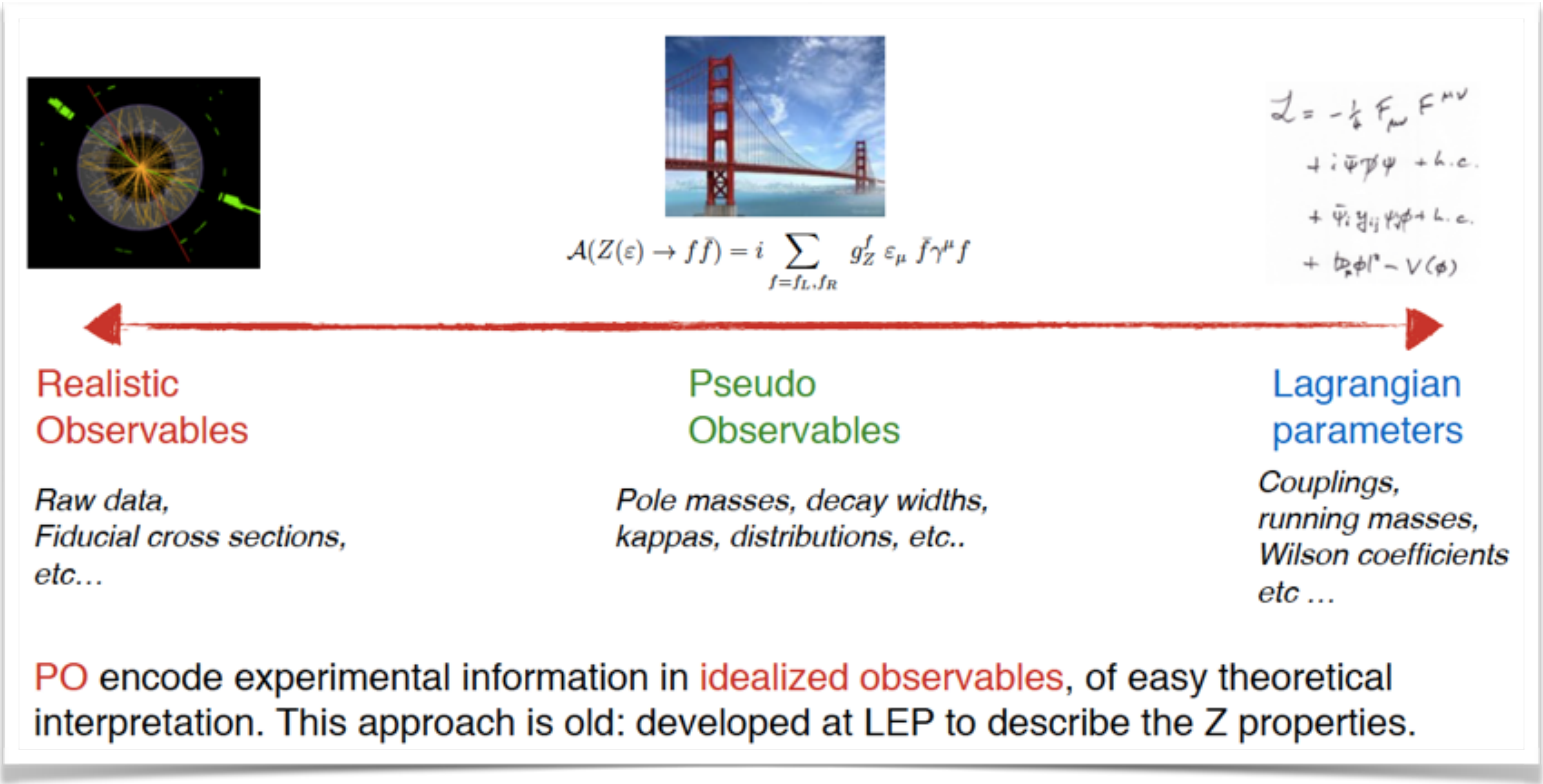




Higgs pseudo-observables

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

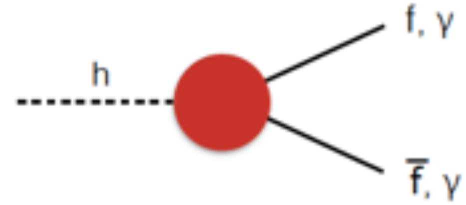
[D. Marzocca, DIS2015]



Pseudo-observables in Higgs decays

[MGA, Greljo, Isidori & Marzocca, 2014]

2-body decays:



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

$\Gamma(h\to\gamma\gamma)$ → $|\epsilon_{\gamma\gamma}|^2 + |\epsilon^{\rm CP}_{\gamma\gamma}|^2$

$$\mathcal{A}(h \to f\bar{f}) = -\frac{i}{\sqrt{2}}\left[(y^f_S + i y^f_P)\bar{f}_L f_R + (y^f_S - i y^f_P)\bar{f}_R f_L\right]$$

$\Gamma(h\to ff)$ → $|y^f_S|^2 + |y^f_P|^2$

- Polarization information needed to disentangle both contributions. If the total rate is all we have ==> kappa is enough.

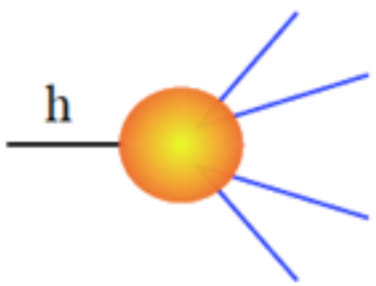
Pseudo-observables in Higgs decays

[MGA, Greljo, Isidori & Marzocca, 2014]

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

  Assumption #1: Chirality-conserving interactions

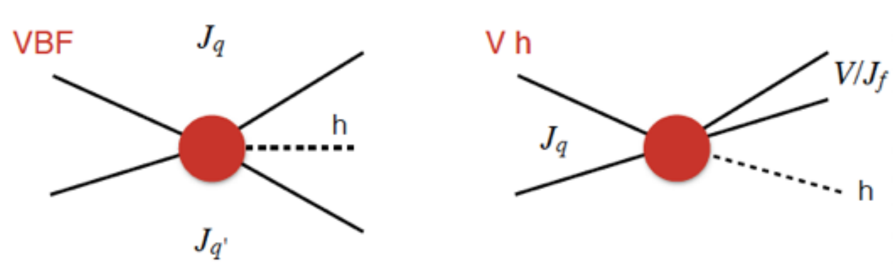
$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times T^{\alpha\beta}(q_1,q_2)$$



Process described by the Green function of onshell states:

$$\langle 0|\mathcal{T}\left\{J_f^\mu(x), J_{f'}^\nu(y), h(0)\right\}|0\rangle\,, \qquad J_f^\mu(x) = \bar{f}(x)\gamma^\mu f(x)$$

... which also affect production (VBF, Vh)



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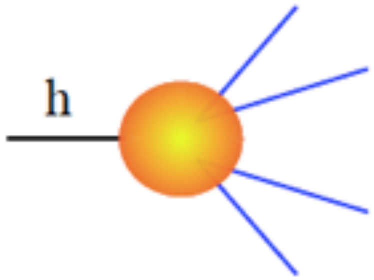


  Lorentz symmetry:

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

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

Pseudo-observables in Higgs decays

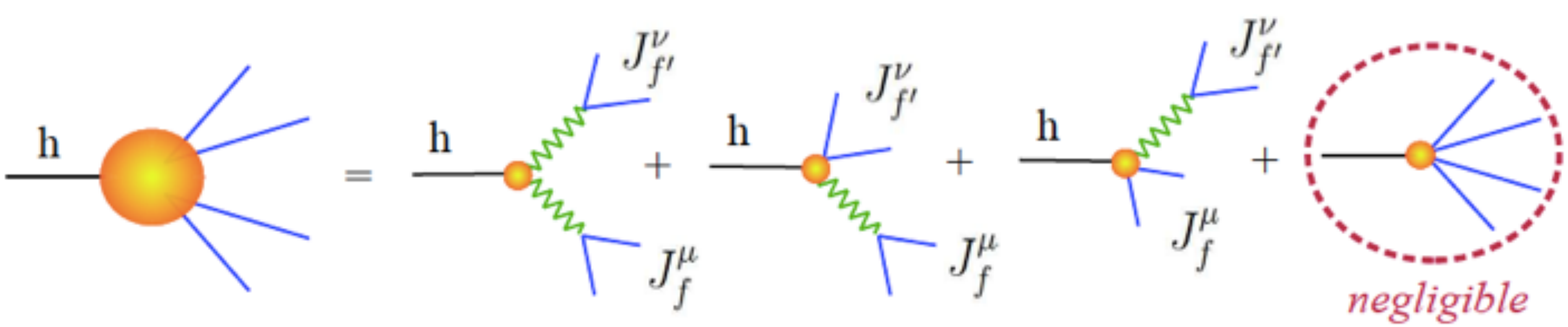
[MGA, Greljo, Isidori & Marzocca, 2014]

- FF form?

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

$$\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}$$

Pole decomposition
+ EFT expansion



PS: Absence of light states is crucial...

Pseudo-observables in Higgs decays

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

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

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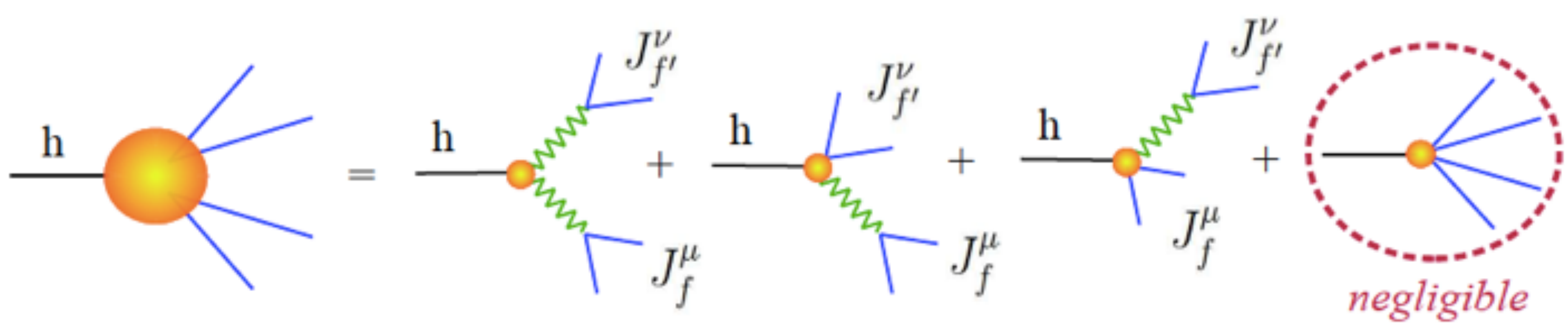
$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} + \right.$$

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

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

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



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$$
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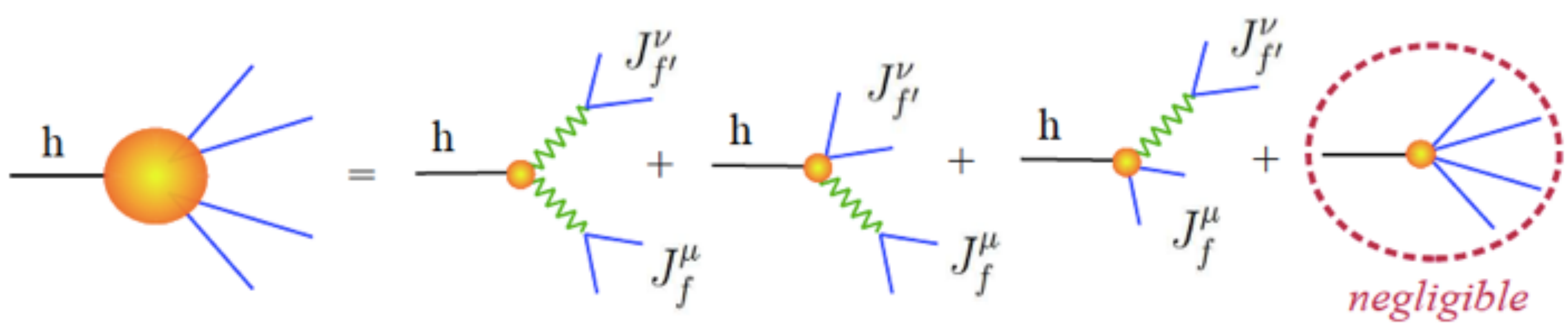
\end{aligned}
$$

Only source of flavor dep. (ϵ_{Ze}, $\epsilon_{Z\mu}$)

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



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- 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: $\kappa_i = 1$, $\varepsilon_i = O(0.001) \sim 0$;
- Diff. distr. modified!

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

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

$h \to \gamma\gamma$

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

Pseudo-observables in Higgs decays

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

[MGA, Greljo, Isidori & Marzocca, 2014]

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

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

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

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

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

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

$h \to 4\mu$

$h \to 4e$

$h \to \gamma\gamma$

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

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

Parameter counting & symmetry limits

[A. Greljo's talk 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

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

$\kappa_{WW}, \epsilon_{WW}, \epsilon_{WW}^{CP}$,
$\epsilon_{W_e}, \epsilon_{W_\mu}$, (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

[A. Greljo's talk 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

[A. Greljo's talk 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

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

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

[A. Greljo's talk at Portoroz'2015]

Neutral currents		
$h \to e^+e^-\mu^+\mu^-$		
$h \to \mu^+\mu^-\mu^+\mu^-$	$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,	
$h \to e^+e^-e^+e^-$	$\epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}, \epsilon^{CP}_{ZZ}$,	
$h \to \gamma e^+e^-$	$\epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$	
$h \to \gamma\mu^+\mu^-$		6
$h \to \gamma\gamma$		

Charged currents		
$h \to e^+\mu^-\nu\nu$	$\kappa_{WW}, \epsilon_{WW}, \epsilon^{CP}_{WW}$,	
$h \to e^-\mu^+\nu\nu$	$\epsilon_{We_L}, \epsilon_{W\mu_L}$ (complex)	1

N. & C. interference		
$h \to e^+e^-\nu\nu$	$\epsilon_{Z\nu_e}, \epsilon_{Z\nu_\mu}$	
$h \to \mu^-\mu^+\nu\nu$		0

Flavour universality

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

CP co...

$$\epsilon^{CP}_{ZZ} = \epsilon^{CP}_{Z\gamma} = \epsilon^{CP}_{\gamma\gamma} = \epsilon^{CP}_{WW}$$

Custodial symmetry

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

★ (Accidentally) true in the linear EFT

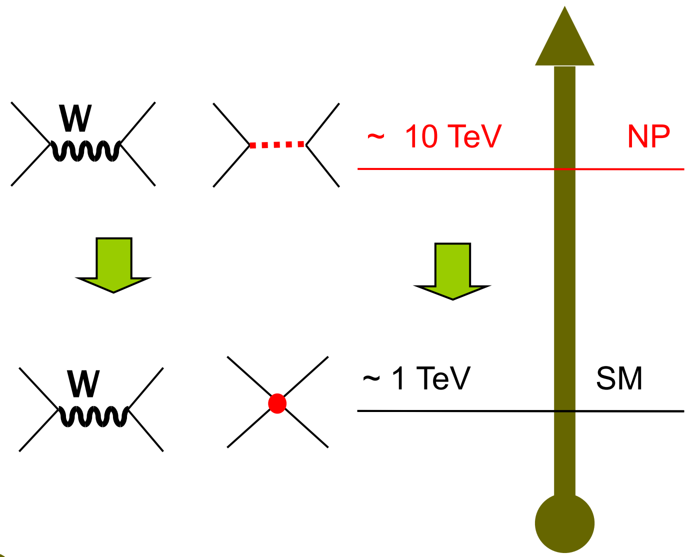
Linear-EFT can be ruled out using only Higgs data!

Relation with Higgs-less processes: Linear EFT

* EW bounds on Higgs PO;
* New Physics room in $h \to 4l$?
* What about $h \to 2l2\nu$?

[MGA, Greljo, Isidori & Marzocca, arXiv:1504.04018]

EFT at the EW scale: *linear EFT*



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

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

EFT = Symmetries + Fields

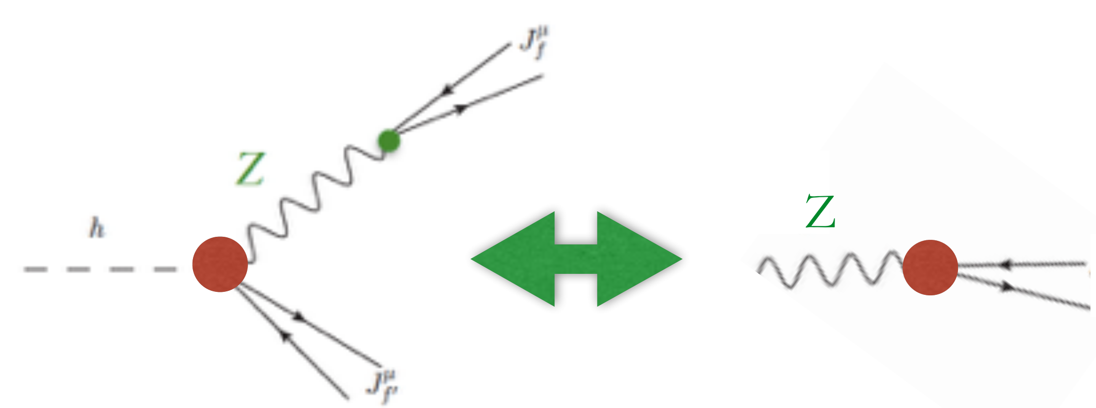
- Lorentz;
- SU(2) x U(1);
- Flavour sym?
- B, L;

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

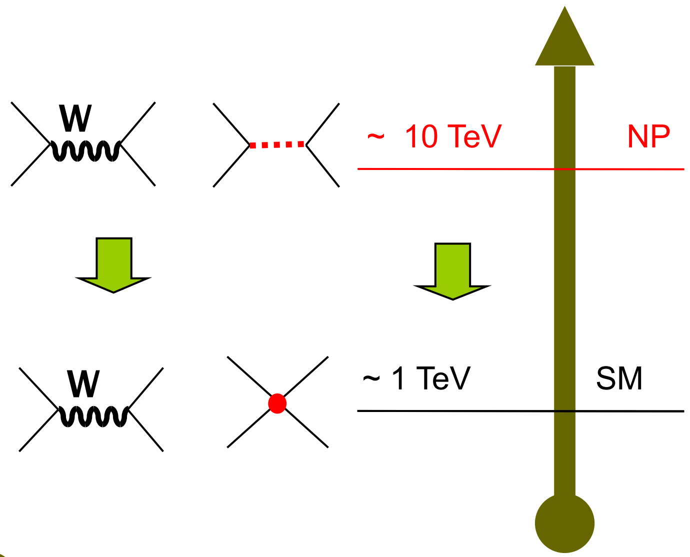
(+ Power counting)

Linear EFT

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



EFT at the EW scale: linear EFT

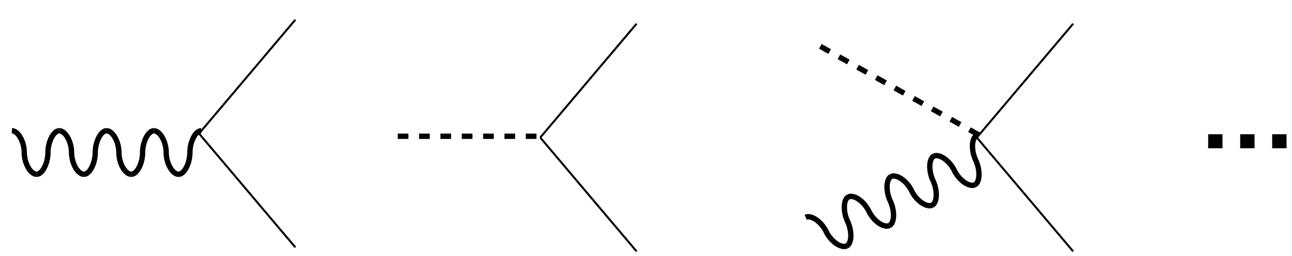


$$\mathcal{L} = \mathcal{L}(\phi, \phi_\Lambda)$$

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

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

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



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

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

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

EFT at the EW scale: linear EFT

H^4D^2 and H^6	
O_H	$[\partial_\mu(H^\dagger H)]^2$
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}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$
$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$
O_{3W}	$g^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
$O_{\widetilde{3W}}$	$g^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$

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}	$i\bar{e}\gamma_\mu \bar{e} H^\dagger \overleftrightarrow{D}_\mu H$
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}	$i\bar{u}\gamma_\mu d \widetilde{H}^\dagger D_\mu H$

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}	$(\bar{q}\gamma_\mu T^a q)(\bar{d}\gamma_\mu T^a d)$

Warsaw basis:

59 ops;

2499 real couplings;

[Grzadkowksi et al., 2010]

[Alonso et al., 2013]

EFT at the EW scale: linear EFT

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. $\Gamma(h\to 4e) = \Gamma(h\to 4e)_{SM} + \Sigma\, c_i\, \alpha_i = \Gamma(h\to 4e)_{SM} + 3\alpha_1 - \alpha_6$
- 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 $\to 3\alpha_1 - \alpha_6 = 0.02(4)$
  - ~ 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!

EFT at the EW scale: *linear EFT*

Correlating measurements (or how to play the EFT game)

- Choose your EFT, *e.g. linear EFT*
- Choose an operator basis {O_1, O_2, …, O_n}, *e.g. the Warsaw basis*
  $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \Sigma\, \alpha_i\, O_i$
- Calculate the observable you like in the EFT,
  e.g. $\Gamma(h\to 4e) = \Gamma(h\to 4e)_{SM} + \Sigma\, c_i\, \alpha_i = \Gamma(h\to 4e)_{SM} + 3\alpha_1 - \alpha_6$
- What
  e.g. f
  More … d error matrix
- Implications for your observable?
  e.g. error matrix $\to 3\alpha_1 - \alpha_6 = 0.02(4)$
  - ~ 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!

Equivalently (& more transparent)

- Show analytical relations between pseudo-observables;
- Do the error analysis afterwards;

Pseudo-observables in Higgs decays (linear EFT)

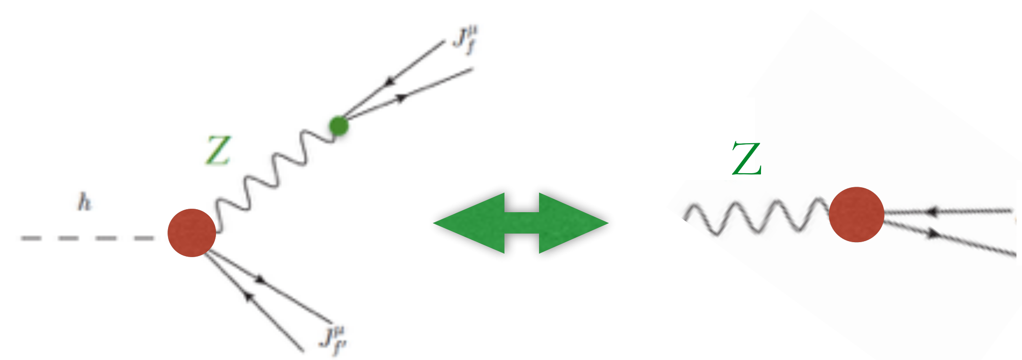
What's the room for NP in Higgs decays taking into account LEP results?

Example:

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

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

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



Pseudo-observables in Higgs decays (linear EFT)

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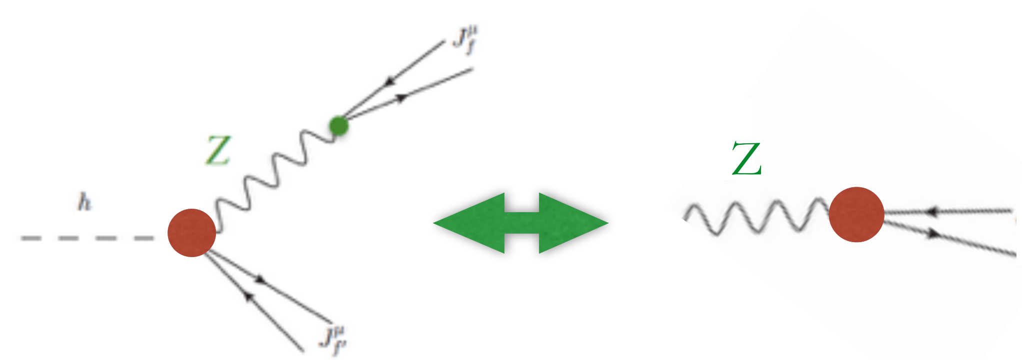
$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,
$\epsilon_{Z\gamma}^{CP}, \epsilon_{\gamma\gamma}^{CP}, \epsilon_{ZZ}^{CP}$,
$\epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$

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

LEPI pseudo-obs.
A(Z->ff)

LEPII pseudo-obs.
A(e⁻e⁺->W⁻W⁺)

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



Pseudo-observables in Higgs decays (linear EFT)

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

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

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

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

LEP I

LEP II

Only flavor dep.

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

Flavour univ. derived from data (not imposed!)

Pseudo-observables in Higgs decays (linear EFT)

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

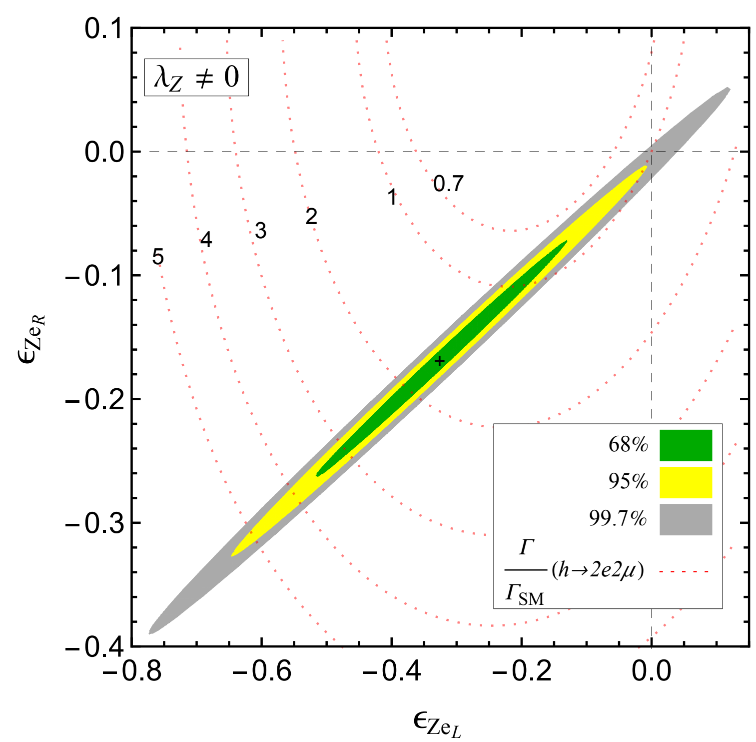
Example: $h \to e^+e^-\mu^+\mu^-$

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

LEP I

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

LEP II [Falkowski & Riva'2014]



$$\begin{pmatrix}\delta g_{1Z}\\ \delta\kappa_\gamma \\ \lambda_Z\end{pmatrix} = \begin{pmatrix}-0.83\pm0.34\\ 0.14\pm0.05\\ 0.86\pm0.38\end{pmatrix},$$

$$\rho = \begin{pmatrix}1 & -0.71 & -0.997\\ . & 1 & 0.69\\ . & . & 1\end{pmatrix}.$$

Accidental blind direction:

$$\lambda_Z \approx -\delta g_{1,z}$$

Pseudo-observables in Higgs decays (linear EFT)

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

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

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

LEP I

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

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

LEP II [Falkowski & Riva'2014]

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

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

$$\begin{pmatrix} \varepsilon_{Ze_L} \\ \varepsilon_{Ze_R} \\ \varepsilon_{ZZ} \\ \varepsilon_{Z\gamma} \\ \varepsilon_{\gamma\gamma} \end{pmatrix} = \begin{pmatrix} -0.32(13) \\ -0.17(7) \\ -0.19(7) \\ 0.000(11) \\ 0.003(1) \end{pmatrix}; \quad \rho = \begin{pmatrix} 1 & 0.996 & 0.72 & 0 & 0 \\ \cdot & 1 & 0.77 & 0 & 0 \\ \cdot & \cdot & 1 & 0.19 & 0.01 \\ \cdot & \cdot & \cdot & 1 & 0 \\ \cdot & \cdot & \cdot & \cdot & 1 \end{pmatrix};$$

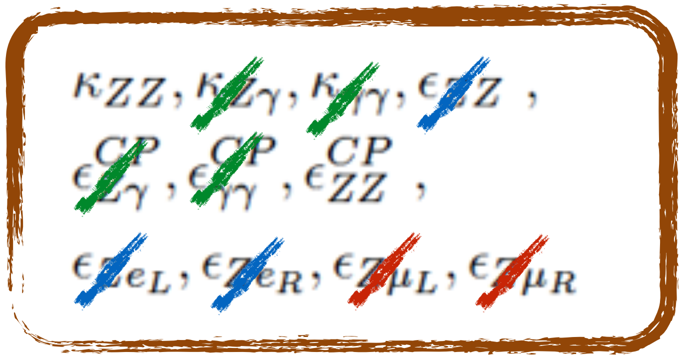
[MGA, Greljo, Isidori & Marzocca, arXiv:1504.04018]

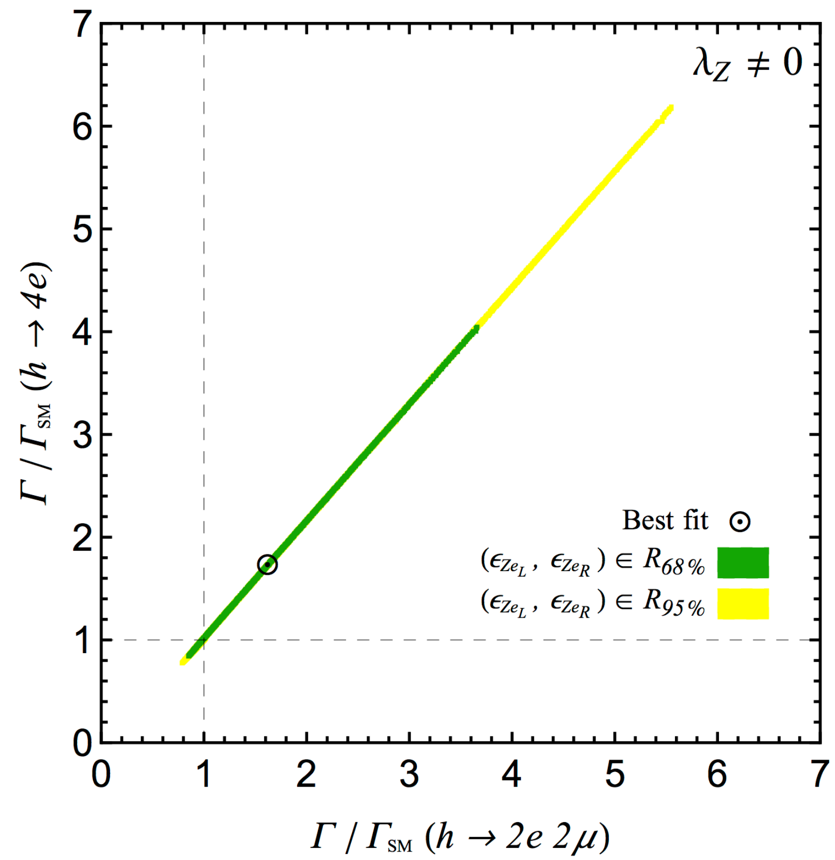
Linear EFT predictions for h → 4ℓ

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

Example:

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





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!)

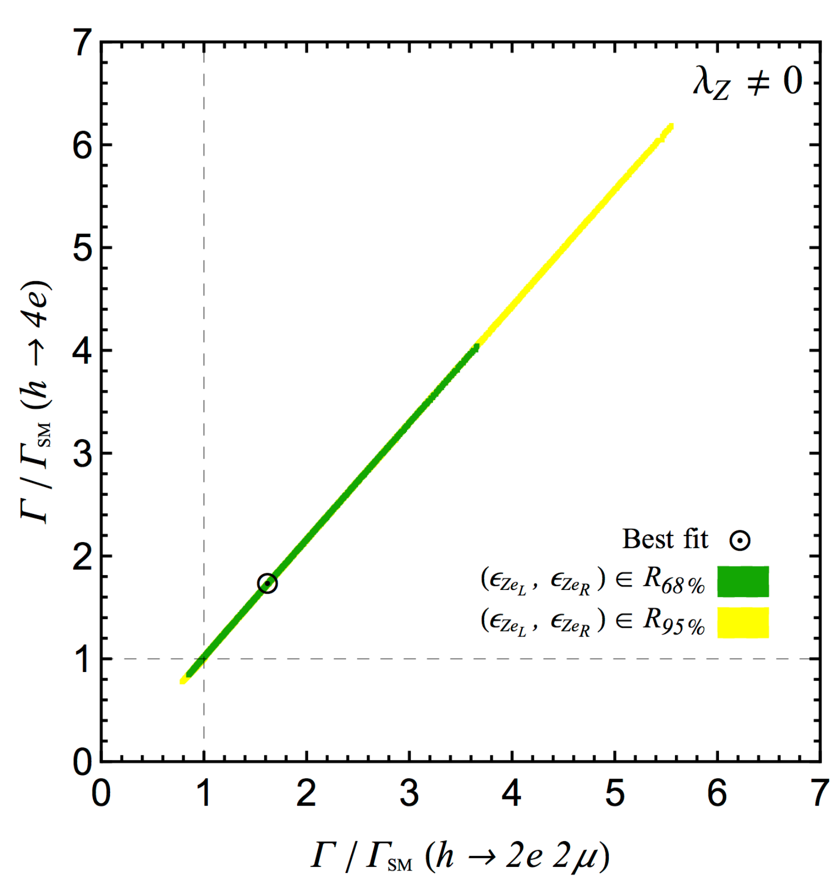
Linear EFT predictions for $h \to 4\ell$

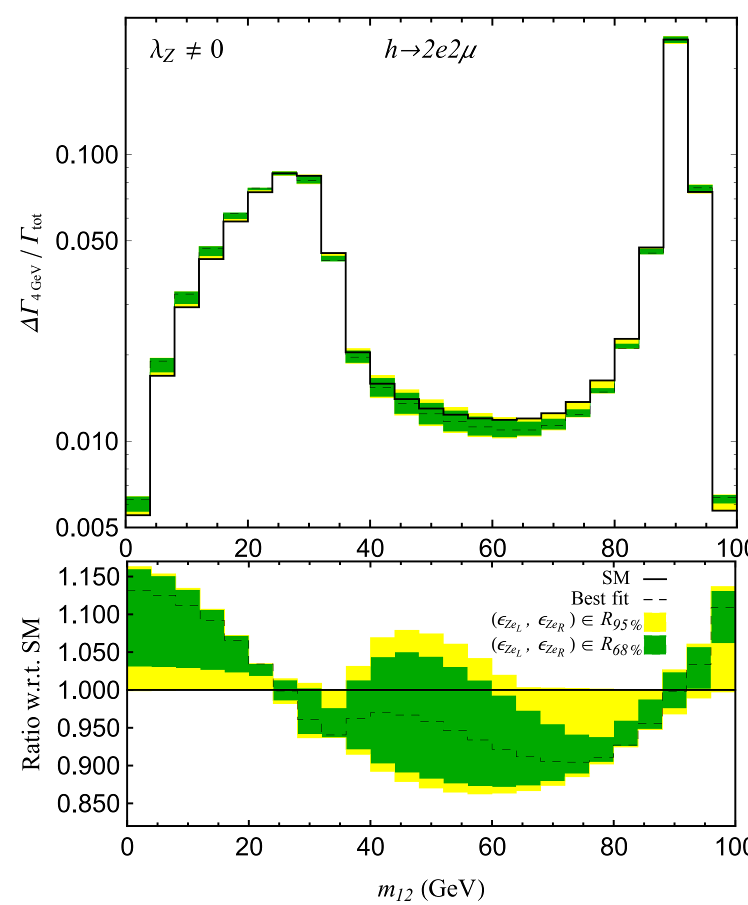
What's the room for NP in Higgs decays taking into account LEP results?

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!

What about h → 2ℓ2ν ?

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

Charged currents $h \to e^+\mu^-\nu\nu$ $h \to e^-\mu^+\nu\nu$	κ_{WW} $(\epsilon_{WW}, \epsilon^{CP}_{WW})$, $\epsilon_{W\ell_e}, \epsilon_{W\ell_\mu}$, ~~(complex)~~	3
N. & C. interference $h \to e^+e^-\nu\nu$ $h \to \mu^-\mu^+\nu\nu$	$(\epsilon_{Z\nu_e}, \epsilon_{Z\nu_\mu})$	0

$$\epsilon_{WW} = c_w^2 \epsilon_{ZZ} + 2c_w s_w \epsilon_{Z\gamma} + s_w^2 \epsilon_{\gamma\gamma} = f(\text{TGC}, h \to \gamma\gamma/Z\gamma)$$

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

$$\epsilon_{We^i_L} = \frac{c_w}{\sqrt{2}} \left(\epsilon_{Z\nu^i_L} - \epsilon_{Ze^i_L} \right)$$

What about h → 2ℓ2ν ?

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

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

κ_{WW} (ϵ_{WW}, ϵ_{WW}^{CP}),
ϵ_{We}, $\epsilon_{W\mu}$, ~~(complex)~~

3

N. & C. interference
$h \to e^+e^-\nu\nu$
$h \to \mu^-\mu^+\nu\nu$

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

0

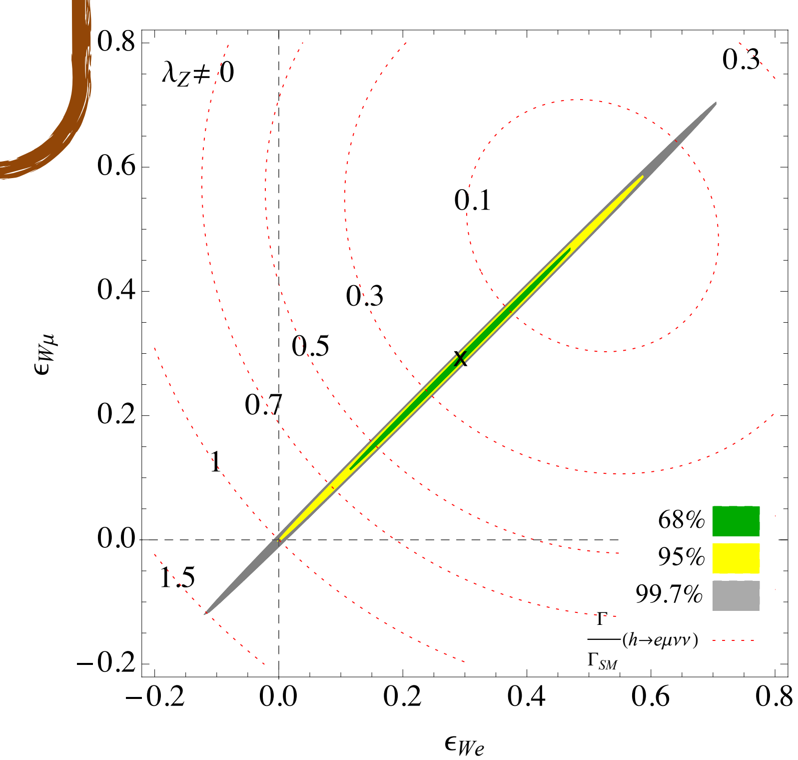
$$\epsilon_{WW} = c_w^2\epsilon_{ZZ} + 2c_w s_w \epsilon_{Z\gamma} + s_w^2 \epsilon_{\gamma\gamma} = f(\text{TGC}, h\to\gamma\gamma/Z\gamma)$$

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

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

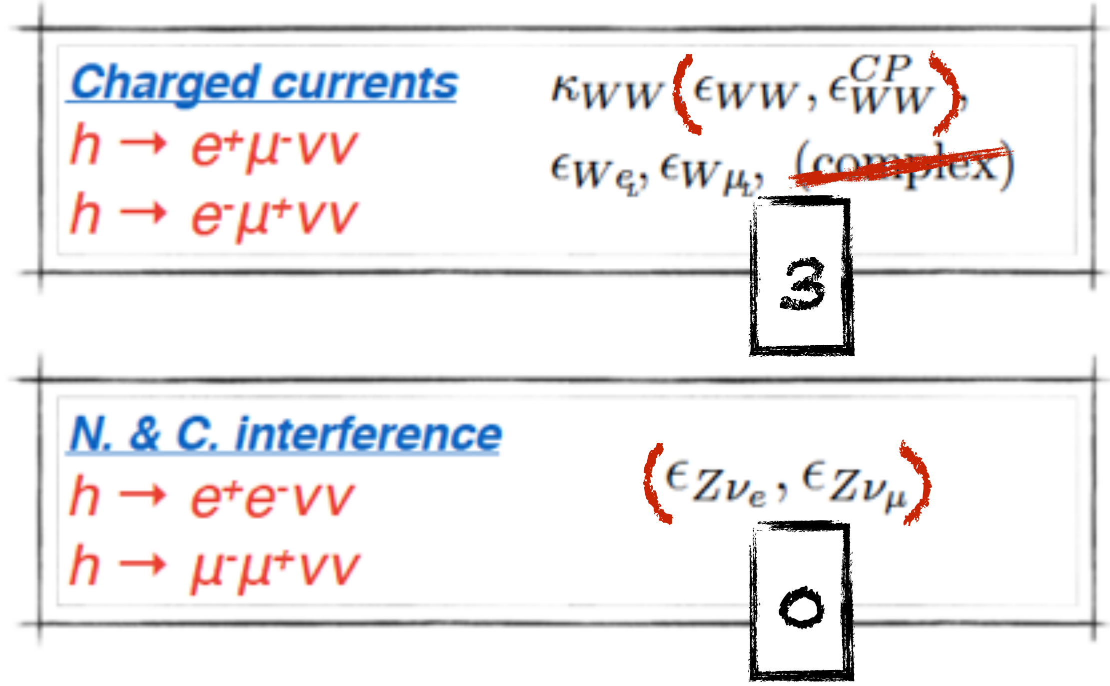
$$\varepsilon_{Wf} = \frac{\sqrt{2}m_W}{v}\left(\delta g^{Wf} - c_\theta^2 \mathbf{1}\,\delta g_{1,z}\right)$$

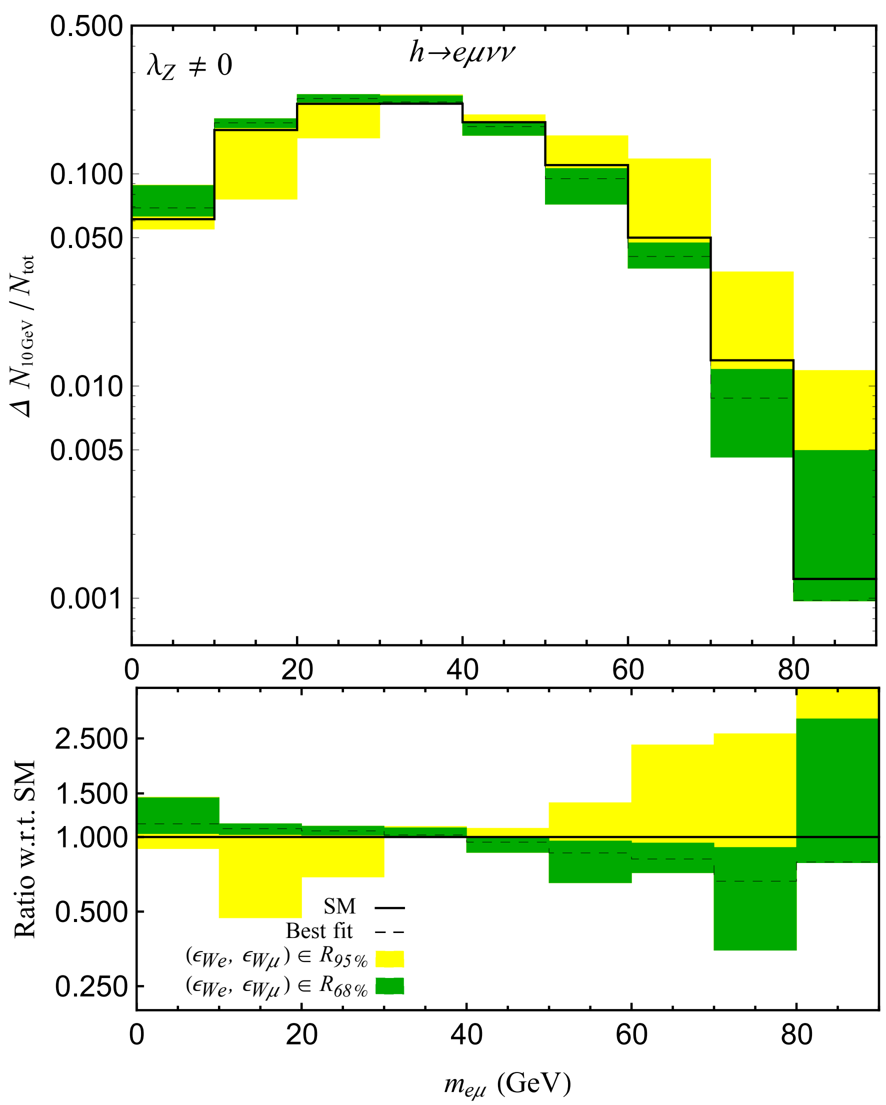
$$\kappa_{WW} - \kappa_{ZZ} = -2s_\theta^2\delta g_{1,z} + 2t_\theta^2\delta\kappa_\gamma + \cancel{4\delta m}$$



What about h → 2ℓ2ν ?

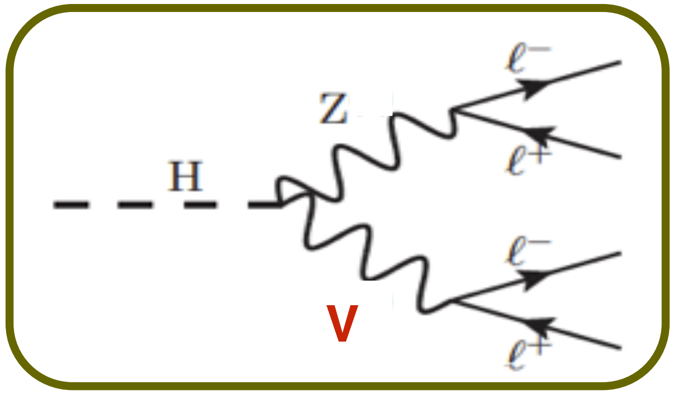
What's the room for NP taking into account LEP results?





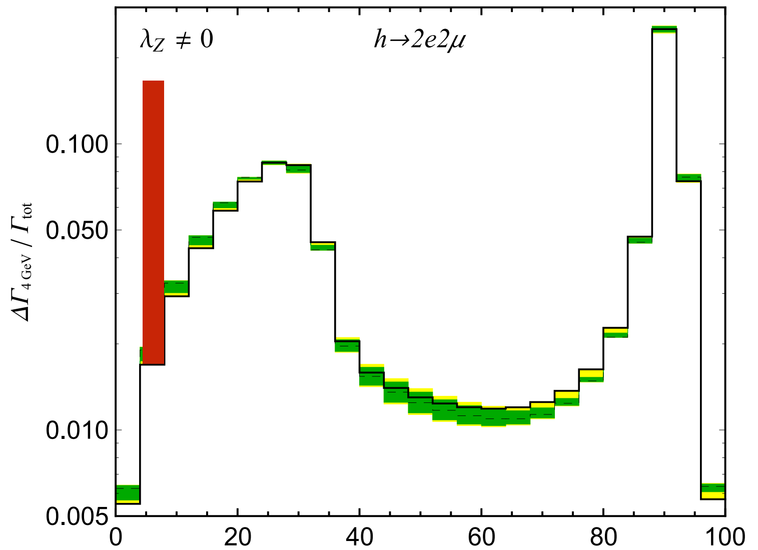
Not small effects!

Not assumption-independent… Exotic Higgs decays



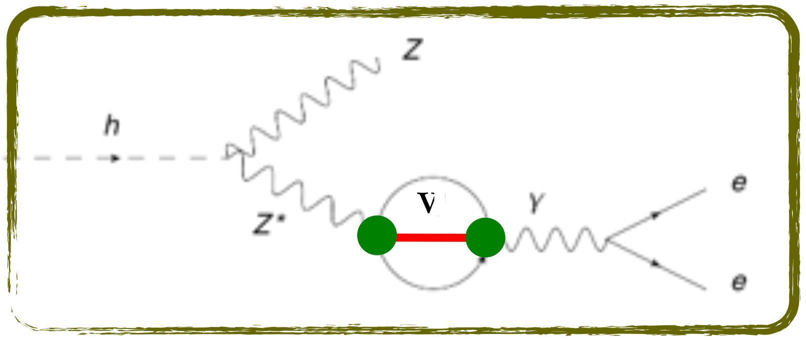
- EFT-based approaches neglect new light states…
  which are not ruled out & indeed deserve their own separate attention
  - Tiny Γ_h ;
  - O(500,000) Higgses produced at LHC7+LHC8!
  - BR(h➔BSM) could be as large as O(20-50%);
  - Can be connected with some anomalies (g-2).

More spectacular signals!



- Low-energy QCD effects under control;

[MGA & G. Isidori, 2014]



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

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

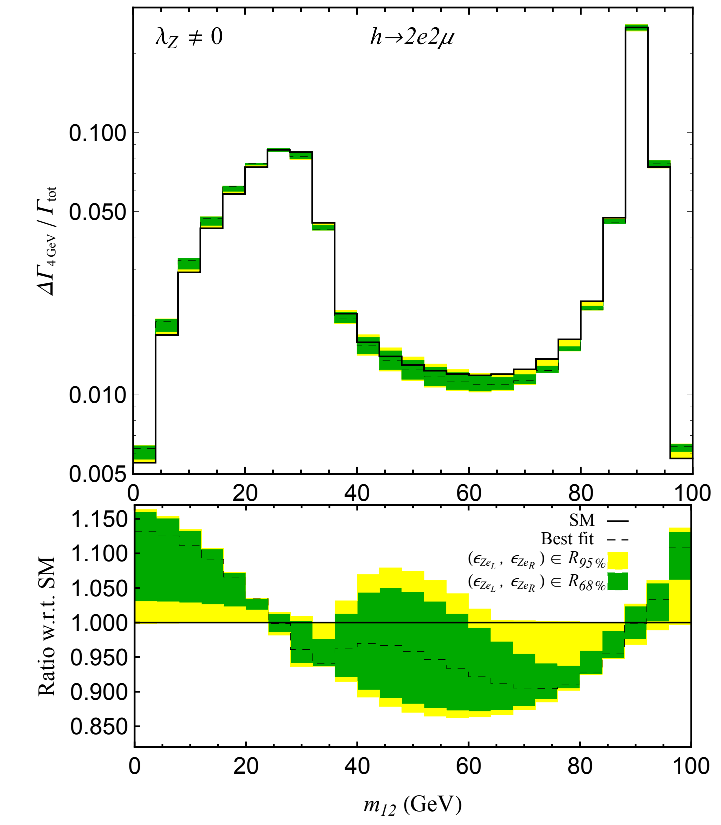
Summary

- Set of PO in Higgs decays as a convenient & general way to encode the experimental results; (generalization of the kappa framework)
- Different NP hypothesis testable;
- LEP implications for some Higgs decays analyzed:
  - strong correlations between channels;
  - implications of the LEP2 flat direction;
- Full complementarity between PO & EFT:
  - PO = input for EFT analyses
  - EFT = predicts relations between Higgs POs (& LEP POs) that can be tested

Effective Field Theory

=

Fields + Symmetries

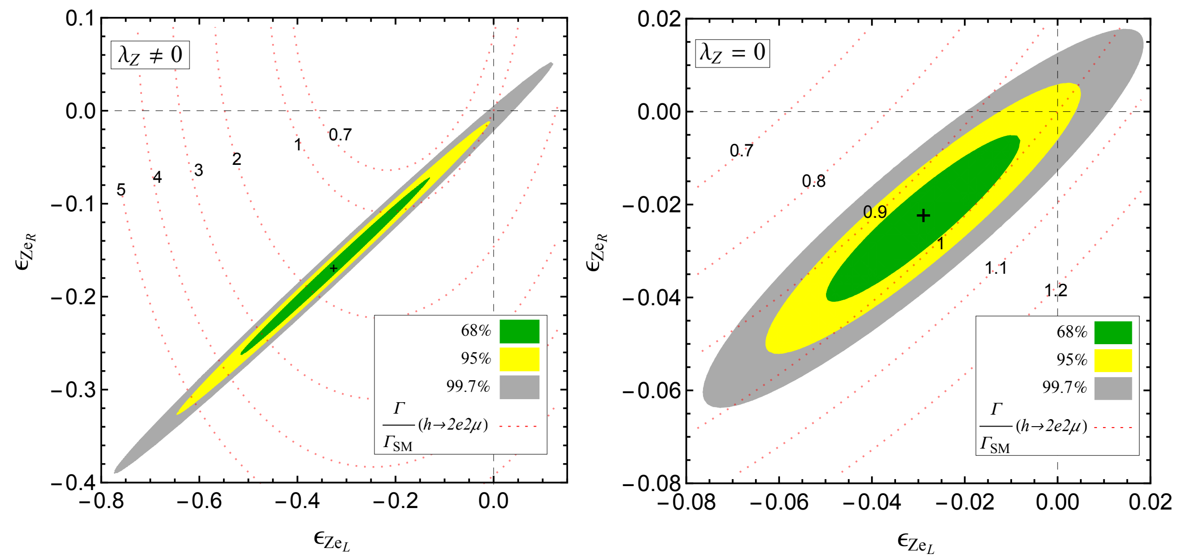


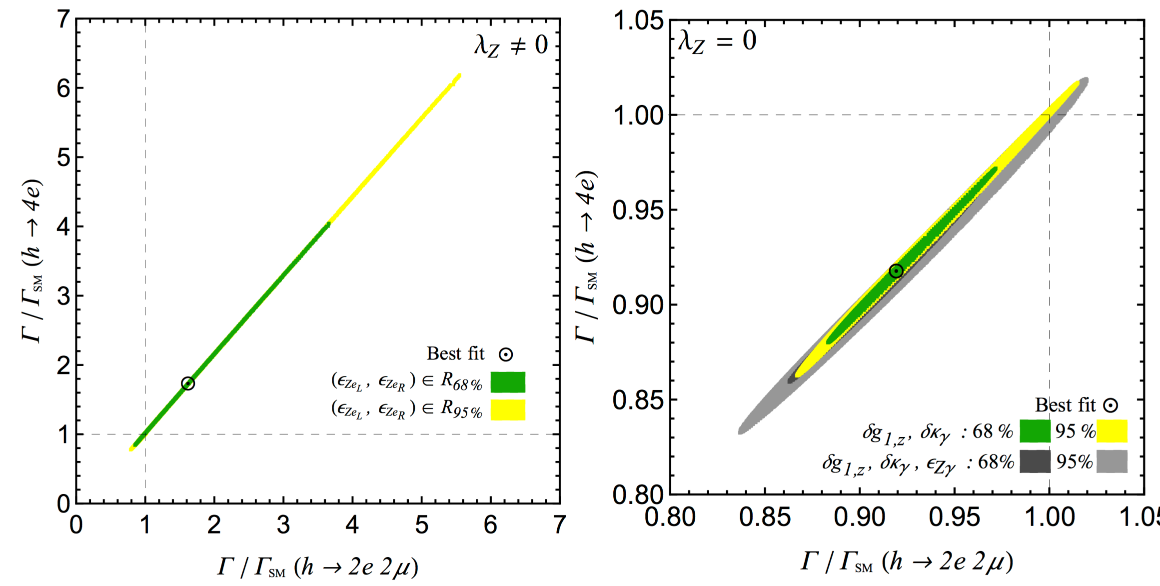
Merci beaucoup!

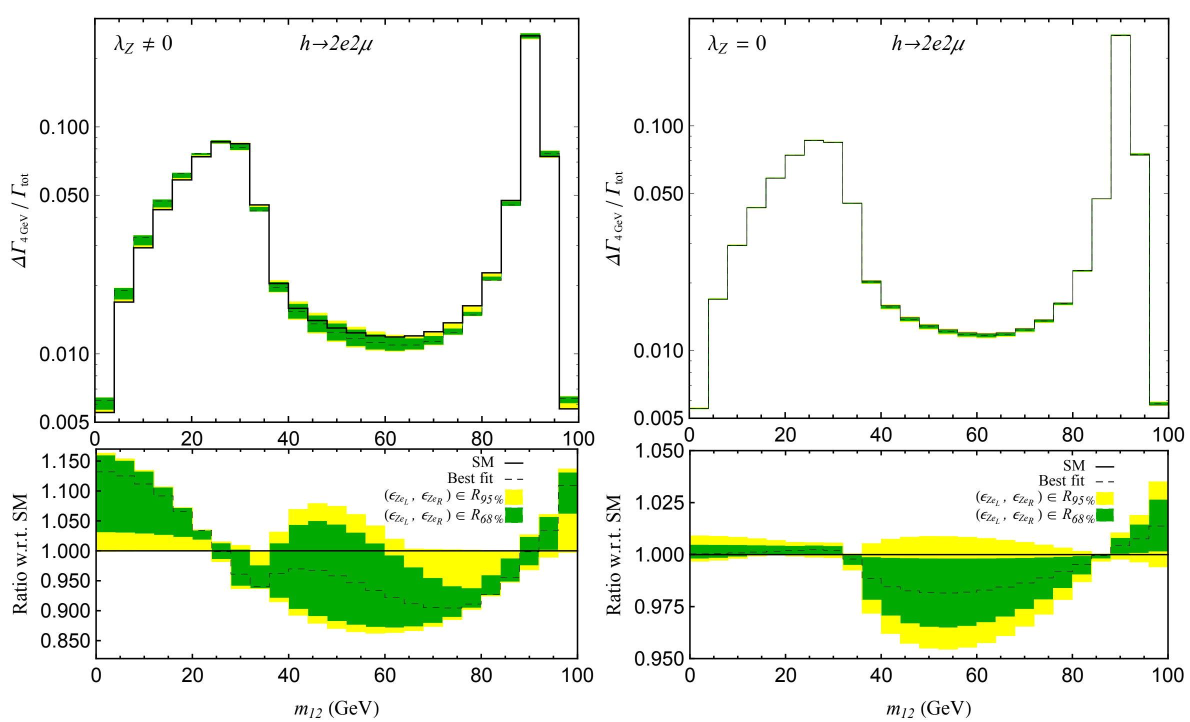
Backup slides

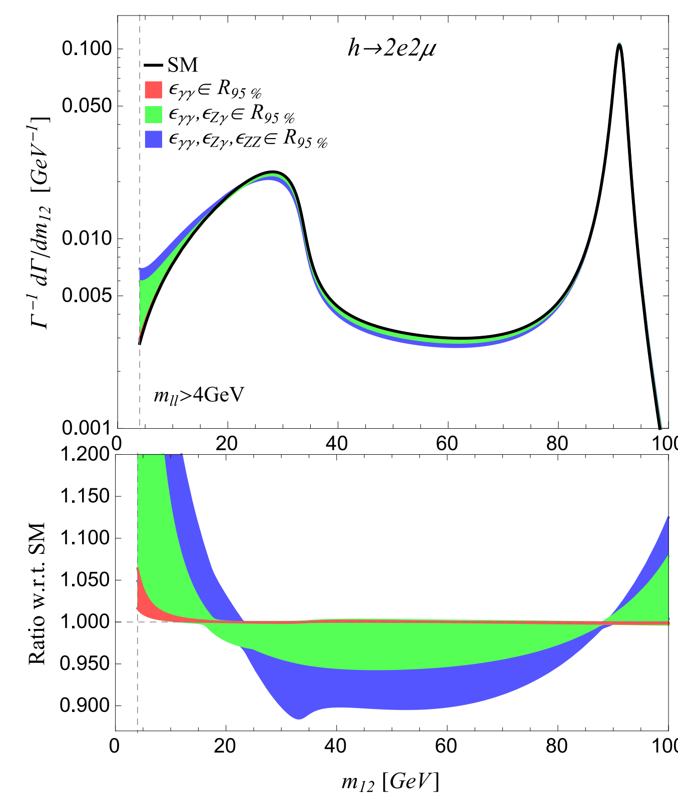
[MGA, Greljo, Isidori & Marzocca, arXiv:1504.04018]

Pseudo-observables in Higgs decays (linear EFT)









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

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