University of Zurich[UZH]

# Pseudo Observables in Higgs Decays

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- Introduction
- General comments about PO
- PO in Higgs decays
- The $h \to 4f$ case
- Parameter counting, symmetry limits, dynamical constraints
- PO beyond decays
- Conclusions

*based on*
*Several discussions within the LHC-HXSWG2...*
+ a few specific hep-ph works [Gonzales-Alonso *et al.* arXiv:1412.6038; arXiv:1504.04018; Bordone *et al.* to appear]

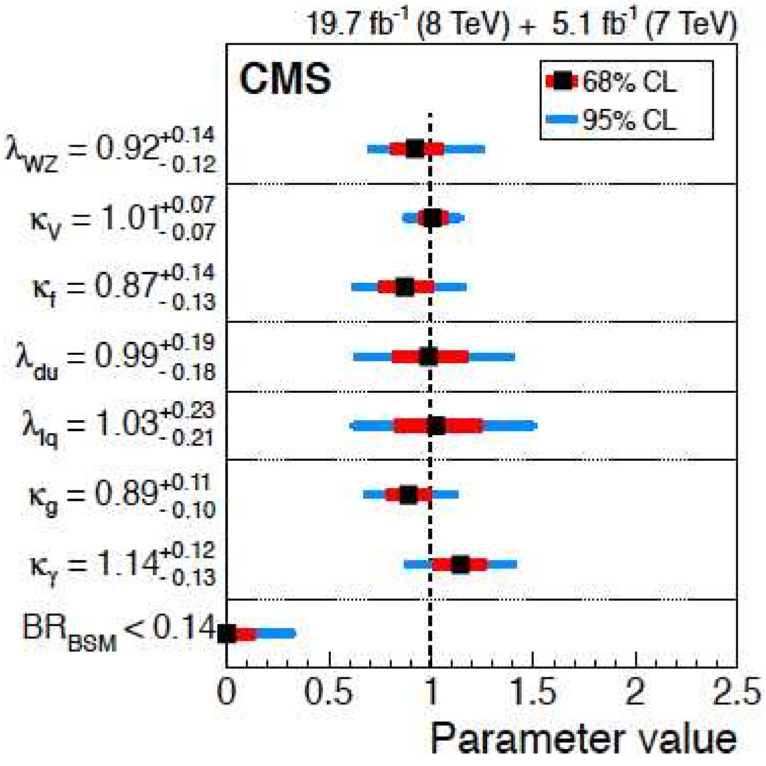
## Introduction

So far, possible non-standard properties of the Higgs boson (in process with a leading SM amplitude) have been analyzed from the experimental point of view using the so-called "kappa-formalism":

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

Main virtues:

- Clean SM limit [best up-to-date TH predictions recovered for $\kappa_i \to 1$]
- Well-defined both on TH and EXP sides
- (*almost*) Model independent



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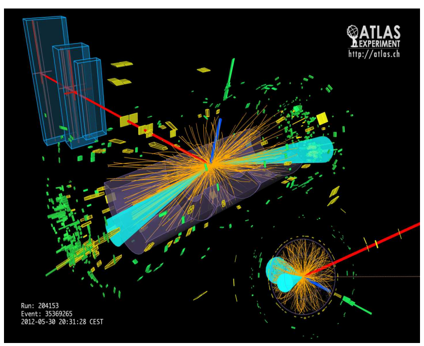
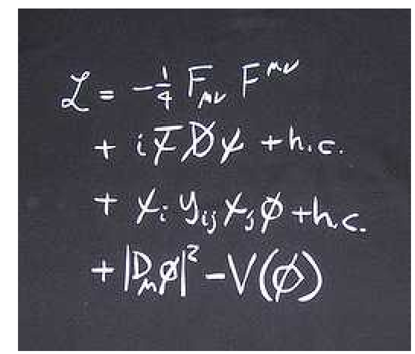
Main problem:

- Loss of information on possible NP effects modifying the kinematical distributions

We need to identify a larger set of "pseudo-observables" able to characterize NP in the Higgs sector in general terms

# General comments about Pseudo Observables




**Experimental data**

raw data,
fiducial cross-sections,
...

**Pseudo Observables**

masses, widths,
slopes, ...

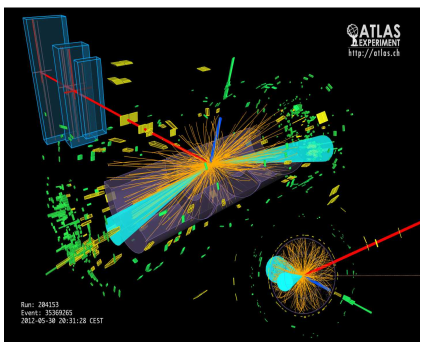
**Lagrangian parameters**

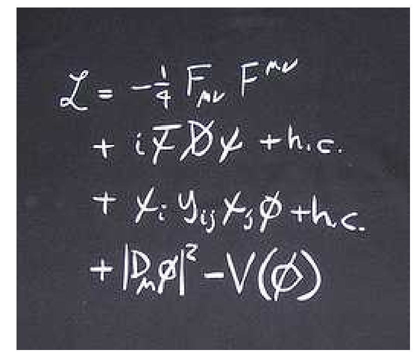
Wilson coefficients,
renormalization scale,
running masses, ...

## General comments about PO

- The goal of the PO is to provide a general encoding of the exp. results in terms of a limited number of "simplified" (idealized) observables of easy th. interpretation [*old idea - heavily used and developed at LEP times*]

- The experimental determination of an appropriate set of PO will "help" and not "replace" any explicit NP approach to Higgs physics (*including the EFT* )




- The PO should be defined from kinematical properties of on-shell processes (*no problems of renormalization, scale dependence,…* )

- The theory corrections applied to extract them should be universally accepted as "NP-free" (*soft QCD and QED radiation*)

## *General comments about PO*

There are two main categories:

A) "Ideal observables"

$M_W$, $\Gamma(Z \to ll)$, …

$M_h$, $\Gamma(h \to \gamma\gamma)$, $\Gamma(h \to 4\mu)$, …
but also $d\sigma(pp \to hZ)/dm_{hZ}$ ...

B) "Effective on-shell couplings"

$g_Z^f$, $g_W^f$, ...

*This is the category we want to "extend" in order to describe non-standard effects in the Higgs sector*

- Both categories are useful
(*there is redundancy having both, but that's not an issue...*).
- For B) one can write an effective Feynman rule, not to be used beyond tree-level

## <u>*PO in Higgs decays*</u>

Multi-body modes
e.g. $h \to 4\ell$, $\ell\ell\gamma$, ...

↓

*There is more to extract from data other than the* $\kappa_i$

Two-body (on-shell) decays
[*no polarization properties of the final state accessible*]
e.g. $h \to \gamma\gamma$, $\mu\mu$, $\tau\tau$, $bb$

↓

*The* $\kappa_i$ $(\leftrightarrow\Gamma_i)$ *is* <u>*all what one can extract*</u> *from data*

[+ *one more parameter if the polarization is accessible*]

## *PO in Higgs decays*

**Multi-body modes**

e.g. $h \to 4\ell$, $\ell\ell\gamma$, ...

$\downarrow$

Form factors $\to f_i(s)$ [E.g.: $s = m^2_{\ell\ell}$]

**Two-body (on-shell) decays**

[*no polarization properties of the final state accessible*]

e.g. $h \to \gamma\gamma$, $\mu\mu$, $\tau\tau$, bb

E.g.: $\mathcal{A}(h \to Z\, ee) \sim$

$$\varepsilon^{Z}_{\mu} J^{e_L}_{\mu} \left[ f_1^{Z e_L}(q^2)\, g^{\mu\nu} + f_3^{Z e_L}(q^2)\left(pq\, g^{\mu\nu} - q^{\mu} p^{\nu}\right) + \ldots \right]$$

N.B.: There is noting "wrong" or "dangerous" in using *f.f.*, provided

- they are defined from on-shell amplitudes [*hill-defined for* $h \to WW^*$, $ZZ^*$ *but perfectly ok for* $h \to 4\ell$ ]
- no model-dependent assumptions are made on their functional form

## PO in Higgs decays

**Multi-body modes**

e.g. $h \to 4\ell,\ \ell\ell\gamma,\ \ldots$

↓

Form factors $\to f_i(s)$ [E.g.: $s = m^2_{\ell\ell}$]

↓

"EFT (QFT)-inspired" momentum expansion of the *f.f.*

$$\text{E.g.:}\quad f_i^{SM+NP} = \frac{\kappa_i}{s - m_Z^2 + i m_Z \Gamma_Z} + \frac{\varepsilon_i}{m_Z^2} + O(s/m_Z^4)$$

**Two-body (on-shell) decays**

[*no polarization properties of the final state accessible*]

e.g. $h \to \gamma\gamma,\ \mu\mu,\ \tau\tau,\ bb$

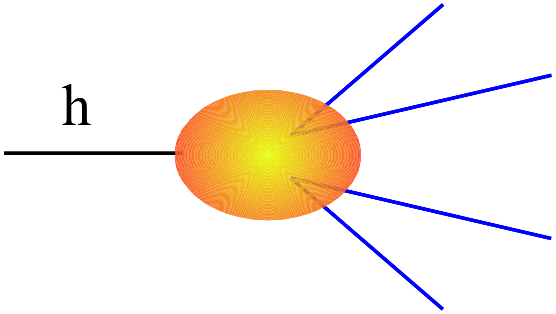
↓

$\kappa_i\ (\leftrightarrow \Gamma_i)$

- No need to specify any detail about the EFT, but for the absence of light new particles → momentum expansion <u>very well justified</u> by the Higgs kinematic

- The $\{\kappa_i, \varepsilon_i\}$ thus defined are well-defined PO → systematic inclusion of higher-order QED and QCD (soft) corrections possible (<u>and necessary...</u>)

## The $h \to 4f$ case

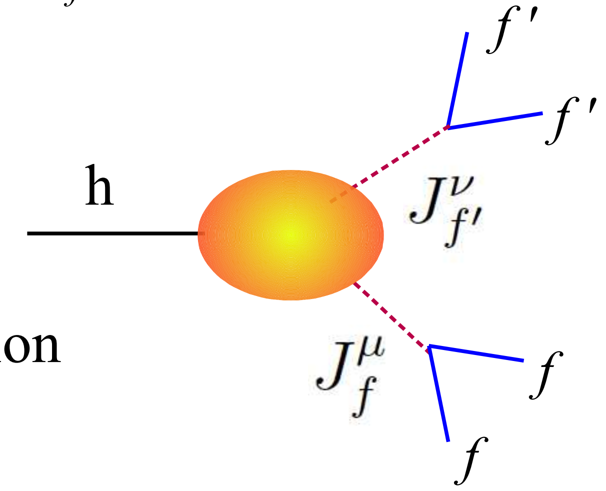


## The $h \to 4f$ case

Two main hypotheses:

I. Fermion couples to the Higgs via helicity-conserving local currents
[$\leftrightarrow$ neglect helicity-violating interactions, naturally linked to $m_f$ also BSM]

$$G_{[JJh]} = \langle 0 | \mathcal{T} \left\{ J_f^\mu(x), J_{f'}^\nu(y), h(0) \right\} |0\rangle$$




The amplitude is fully determined by this Green function that contains long-distance modes ($\leftrightarrow$ non-local terms in $x$ and $y$ due to the exchange of EW gauge bosons) & short-distance modes ($\leftrightarrow$ contact terms for $x$ or $y \to 0$)

Only 3 Lorentz structures allowed, e.g.:

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

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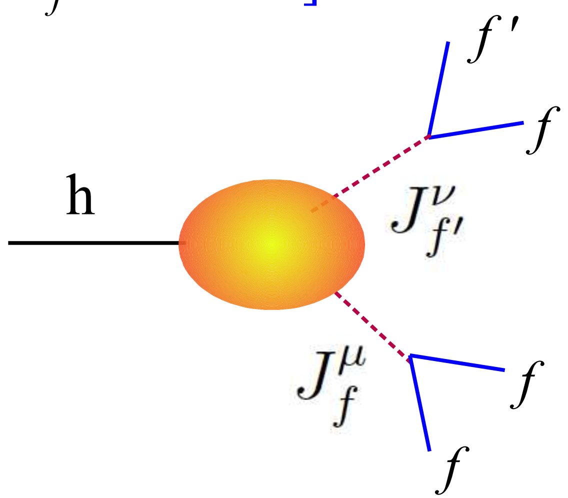
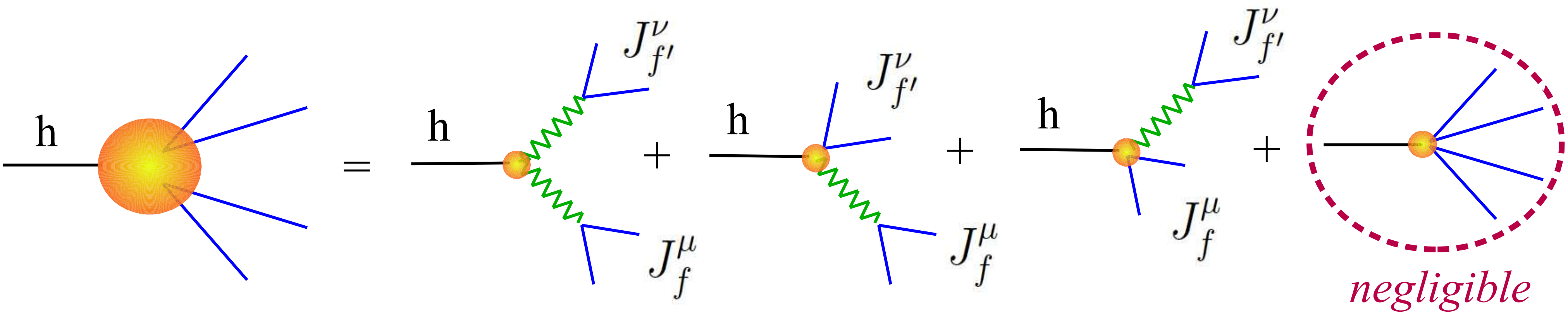



II. Expansion of $G_{[JJh]}$ neglecting short-distance modes corresponding to local operators with d > 6

*non-local amplitude at the EW scale:*

↓



## ▶ The $h \to 4f$ case

Following these hypotheses we can expand the form factors around the physical poles and retain only the leading terms (in the momentum expansion), e.g.:

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

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

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

- The $\{\kappa_i, \varepsilon_i\}$ are defined from the residues of the amplitude on the physical poles → well-defined PO that can be extracted from data and computed to desired accuracy in a given BSM framework

- By construction, the $g_Z^f$ are the PO from Z-pole measurements, while $\kappa_{\gamma\gamma}$ and $\kappa_{Z\gamma}$ are the standard "kappas" from <u>on-shell</u> $h \to \gamma\gamma$ and $h \to Z\gamma$

## The $h \to 4f$ case

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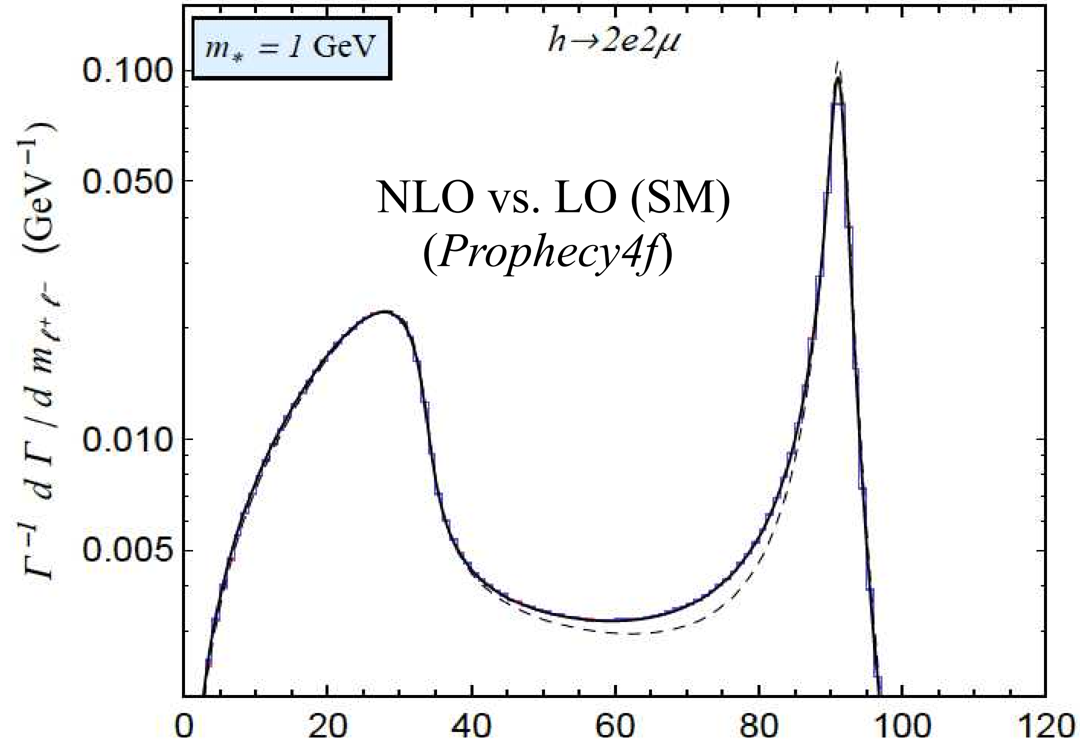
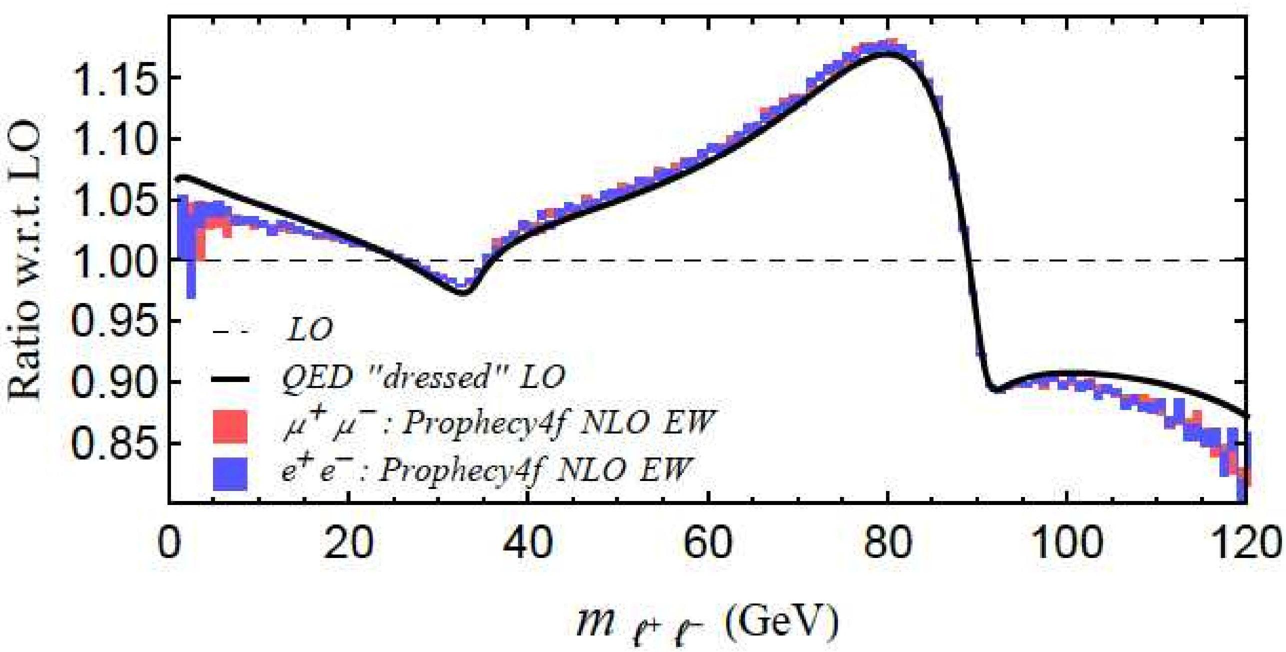
$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

- The $\kappa_i$ are normalized such that the SM is recovered in the limit $\kappa_i \to 1$
- The $\varepsilon_i$ describe terms not present in the SM at the tree level (*and always sub-leading*): SM recovered for $\varepsilon_i^{(SM)} = O(10^{-3}) \to 0$
- To this amplitude we can apply a "radiation function" to take into account QED radiation → excellent description of SM (and NP) beyond the tree level.

## *The $h \to 4f$ case*

"Dressing" with QED radiation → excellent description of SM beyond the tree level.




Bordone, Greljo, G.I., Marzocca, Pattori, to appear

## The $h \to 4f$ case

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$$\Bigg[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} +$$
$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\; g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} +$$
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$$\epsilon_{\gamma\gamma}^{\text{SM-1L}} \simeq 3.8\times 10^{-3}$$
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$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

These PO are calculable in the (various) Higgs-EFT approaches.

In the limit where we consider Higgs-processes only, and we work at the tree-level in the EFT → simple linear relation between PO and EFT couplings: one-to-one correspondence between PO and combinations of couplings of the most general Higgs EFT (*non-linear EW symm. breaking, no custodial symm., no flavor symm., no CP symmetry*). But this does not hold beyond the tree-level.

## Parameter counting, symmetry limits, dynamical constraints

## *Parameter counting, symmetry limits, dynamical constraints*

Number of independent PO for h → 4ℓ (ℓ=e,μ,ν) + ℓℓγ + γγ:

| Decay modes | *flavor +CP symm.* | *flavor non univ.* | *CP violation* |
|---|---|---|---|
| $h \to \gamma\gamma, 2e\gamma, 2\mu\gamma$<br>$4e, 4\mu, 2e2\mu$ | $\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}$<br>$\epsilon_{ZZ}, \epsilon_{Ze_L}, \epsilon_{Ze_R}$ (6) | $\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$ (2) | $\epsilon^{CP}_{ZZ}, \epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}$ (3) |
| $h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$ | $\kappa_{WW}$<br>$\epsilon_{WW}, \epsilon_{Z\nu_e}, \mathrm{Re}(\epsilon_{We_L})$ (4) | $\epsilon_{Z\nu_\mu}, \mathrm{Re}(\epsilon_{W\mu_L})$<br>$\mathrm{Im}(\epsilon_{W\mu_L})$ (5) | $\epsilon^{CP}_{WW}, \mathrm{Im}(\epsilon_{We_L})$ |
| all modes<br>*with custodial symmetry* | $\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}$<br>$\epsilon_{ZZ}, \epsilon_{Ze_L}, \epsilon_{Ze_R}$<br>$\mathrm{Re}(\epsilon_{We_L})$ (7) | $\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$ | $\epsilon^{CP}_{ZZ}, \epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}$ |

20 (no symmetries) → 7 (CP + Lepton Univ + Custodial)

## *Parameter counting, symmetry limits, dynamical constraints*

Number of independent PO for $h \to 4\ell$ ($\ell$=e,μ,ν) + $\ell\ell\gamma$ + $\gamma\gamma$:

| Decay modes | *flavor +CP symm.* | *flavor non univ.* | *CP violation* |
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| $h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$ | $\kappa_{WW}$ (4)<br>$\epsilon_{WW}, \epsilon_{Z\nu_e}, \mathrm{Re}(\epsilon_{We_L})$ | $\epsilon_{Z\nu_\mu}, \mathrm{Re}(\epsilon_{W\mu_L})$ | $\epsilon^{CP}_{WW}, \mathrm{Im}(\epsilon_{We_L})$<br>$\mathrm{Im}(\epsilon_{W\mu_L})$ (5) |
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The symmetry assumptions can be directly tested from data, focusing on specific kinematical distributions sensitive to the relevant PO's [e.g. CPV-violating observables & LFU tests → key role played by the "contact terms" ($\epsilon_{Zl}$)]

## *Parameter counting, symmetry limits, dynamical constraints*

Computing the PO in specific EFT (e.g.: *the linear EFT*) we get additional dynamical constraints dictated by the specific extra dynamical assumption of the EFT employed (e.g.: *h belongs to the $SU(2)_L$-doublet breaking the EW symmetry*)

The most powerful of such constraints is the link between the contact terms and EW precision measurements performed at LEP

EPWO + Linear EFT $\longrightarrow$ small (tiny) & flavor-universal $\varepsilon_{Zl}$

Contino *et al.*, 1303.3876
Pomarol & Riva, 1308.2803

$\downarrow$

Excellent opportunity to test from data (via $h \to 4l$)
if h belongs to a pure $SU(2)_L$ doublet

G.I., Manohar, Trott, 1305.0663
G.I., Trott, 1307.4051

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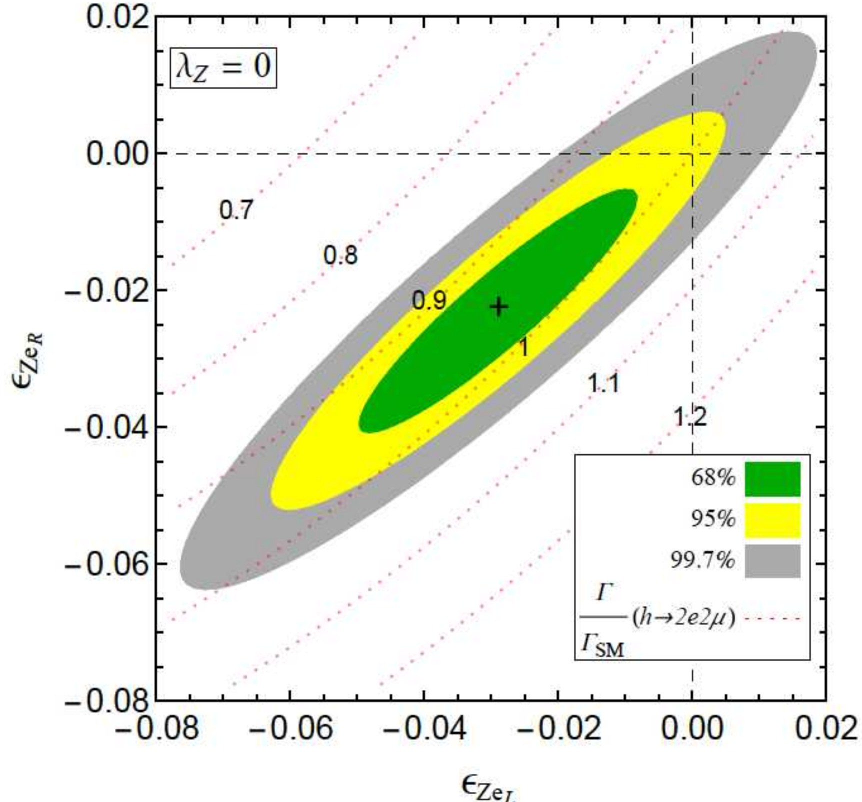


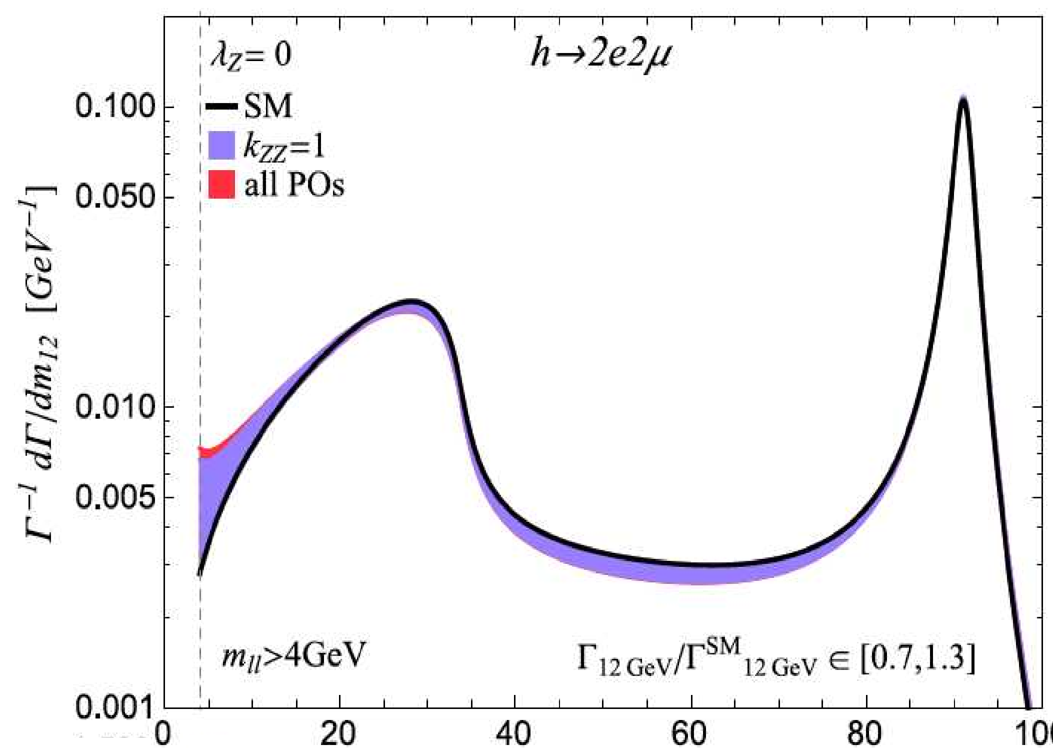


Gonzales-Alonso, Greljo, G.I., Marzocca, arXiv:1504.04018

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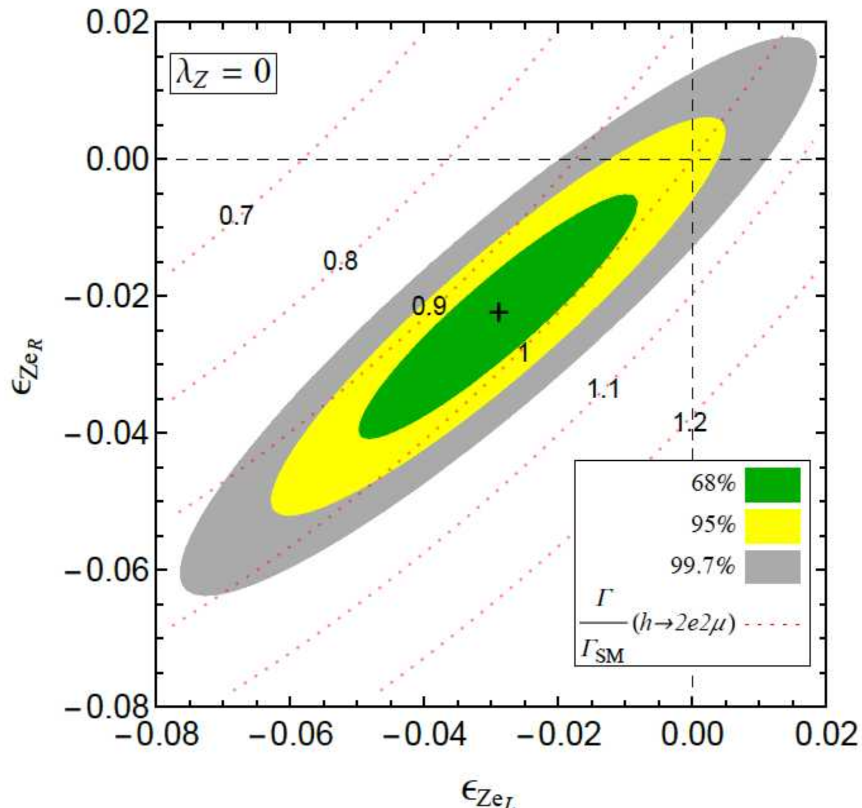


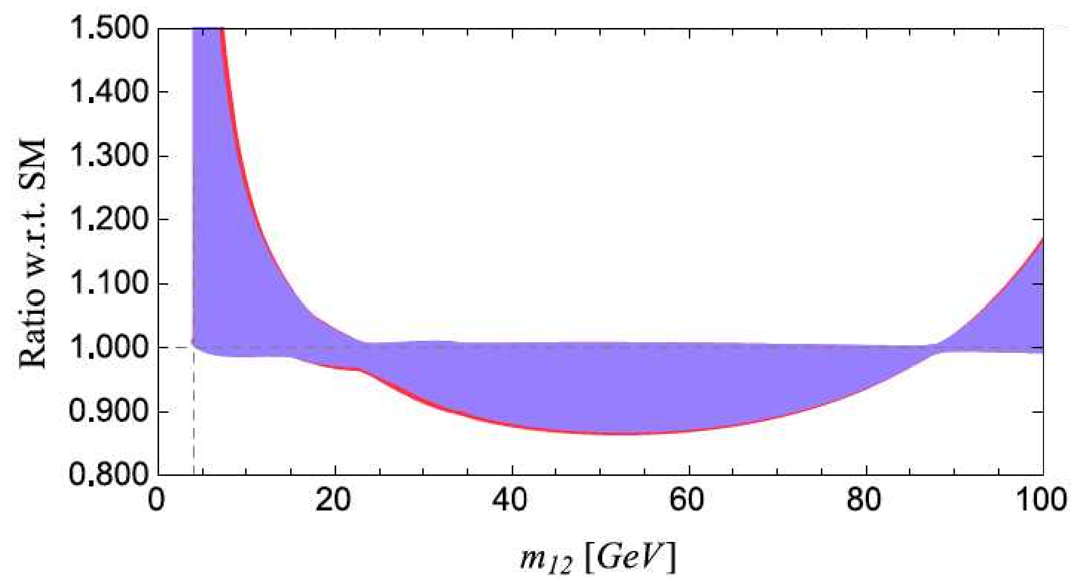


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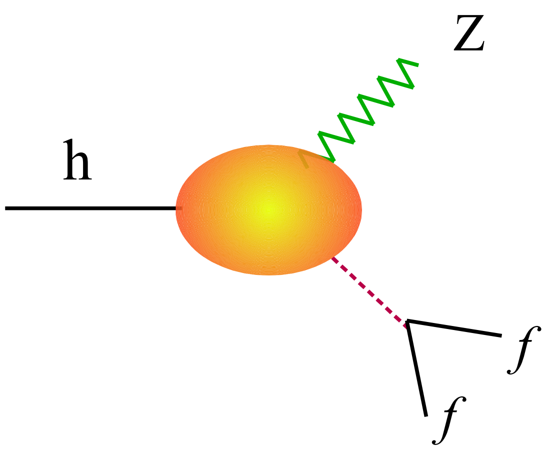
The most powerful of such constraints is the link between the contact terms and EW precision measurements performed at LEP:

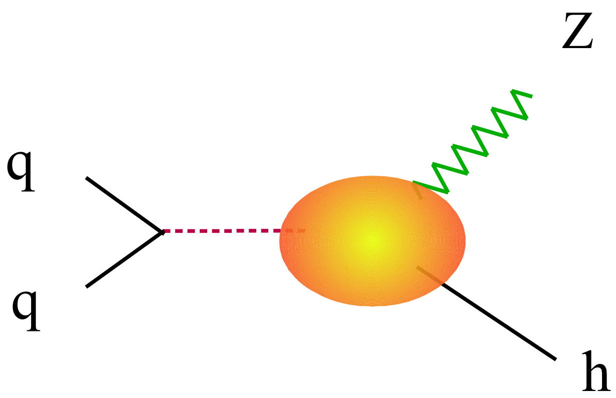
Maim message: full complementary between PO approach and EFT.

- PO → inputs for EFT coupling fits
- EFT → predictions of relations between different PO sets (that can be tested)

# PO beyond decays




vs.



## PO beyond decays

The same Green Function controlling h → 4*f* decays is accessible also in pp → hV and pp → h via VBF, i.e. the two leading EW-type Higgs production processes (*N.B.: this follows from "plain QFT" no need to invoke any EFT...*)

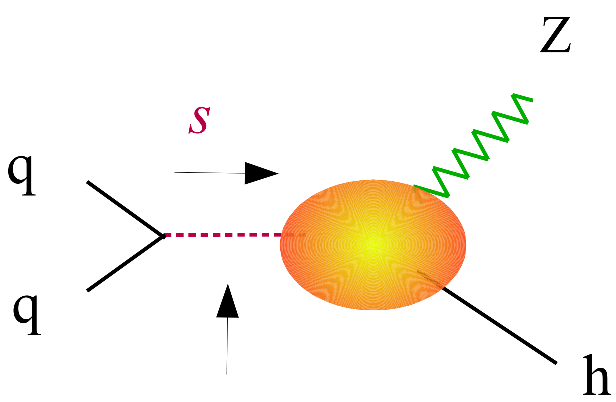
$$G_{[JJh]} = \langle 0|\mathcal{T}\left\{J^{\mu}_{f}(x), J^{\nu}_{f'}(y), h(0)\right\}|0\rangle$$

But for two important differences:

- different flavor composition (q ↔ ℓ) → 4 more param. for hZ + 4 for hW and VBF (no symm.) → <u>only 2 eff. combinations easily accessible</u>

- different kinematical regime: <u>momentum exp. not always justified</u> (*large momentum transfer*)

## PO beyond decays




The new parameters to be introduced are related to the momentum transfer associated to the quark-current ↔ variable related to the possible break-down of the momentum expansion.

$$\frac{1}{s - m_Z^2}\left[\, g^Z{}_q\, \kappa_{ZZ} + \varepsilon_{Zq}\,(s - m_Z^2)/m_Z^2 \;+ \dots \right] \qquad s = (m_{hZ})^2$$

Two (complementary) approaches:

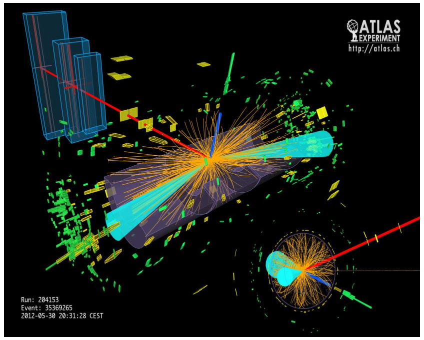
- design kinematical cuts to remain in the region where the expansion works & introduce diagnostic tools to validate the result
- "ideal solution": extract the shape of the distribution from data (*only for the variables that can go into the large-momentum transfer region*)

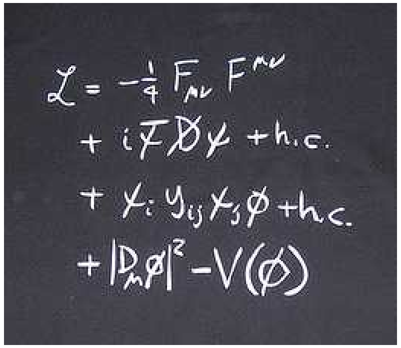
$$\boxed{d\sigma(pp \to hZ)/dm_{hZ}}$$

# Conclusions

The 125 GeV scalar is certainly compatible with the properties of the SM Higgs boson, but we are still far from having explored its properties in great detail.

The PO represent a general tool for the exploration of such properties (in view of high-statistics data), with minimum loss of information and minimum theoretical bias.




Experimental data Pseudo Observables Lagrangian parameters