Some comments about Pseudo Observables in Higgs Physics

Gino Isidori
[*University of Zürich*]

- Clarifications of issues raised during the plenary meeting
  - *The role of PO (PO vs. EFT)*
  - *The two main categories of PO*
  - *Worries about form factors and consistency with QFT*
- Some comments about Vh (and VBF)

Clarifications of issues raised during the plenary meeting

I. The role of PO (PO vs. EFT)

talk by Marzocca
(plenary meeting)

EXP

TH

Clear connection to
measurable distributions.

Easy to match to any EFT
in any basis.

The PO can be computed in terms of Lagrangian parameters
in any specific th. framework (SM, SM-EFT, SUSY, ...)

- The goal is to provide a general encoding of the exp. results in terms of a limited number of “simplified” observables of easy th. interpretation.
- The PO approach will “help” and not “replace” the EFT approach (*no contradiction*)

Clarifications of issues raised during the plenary meeting

The goal is to provide a general encoding of the exp. results in terms of a limited number of "simplified" observables of easy th. interpretation.

Example: The mass of a particle is a PO

Not always obvious how to extract it from data (→ *debate on Z line-shape*) and how to make it in a way that is useful for theoreticians (→ *top mass*).

The M_Z, M_W, M_h, determined by experiments are 3 well-defined PO and not fundamental couplings of the SM Lagrangian (or BSM models)

Either we predict them (*at a certain order*) in terms of other couplings or we use them to extract the couplings (*at a given order and at a given scale....*). This does not affect their experimental determination, while the way they are defined from data affect the way we compute them.

Clarifications of issues raised during the plenary meeting

I. The role of PO (PO vs. 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*)

Clarifications of issues raised during the plenary meeting

I. The role of PO (PO vs. 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*)

In the limit where one
- considers Higgs decay only
- works at tree-level in the EFT

then there is a 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 at some point we want to go beyond these limitations…

Clarifications of issues raised during the plenary meeting

II. The two main categories of PO:

A) "Ideal observables" [better name?]

M_h, $\Gamma(h \to \gamma\gamma)$, $\Gamma(h \to gg)$, $\Gamma(h \to 4\mu)$, ...

but also $d\sigma(pp \to hZ)/dm_{hZ}$ ...

B) "Effective on-shell couplings" [κ-ε framework, extended κ's, ...]

$\kappa_{\gamma\gamma}$, κ_{gg}, ...	eff. coupl., normalized to SM, for $h \to$ 2-body
κ_{ZZ}, κ_{WW}, ...	eff. coupl., normalized to SM – assuming SM kin. dependence
ε_{ZZ}, ε_{Zf}, ...	eff. coupl. for kin. dep. not present in the SM at the tree level

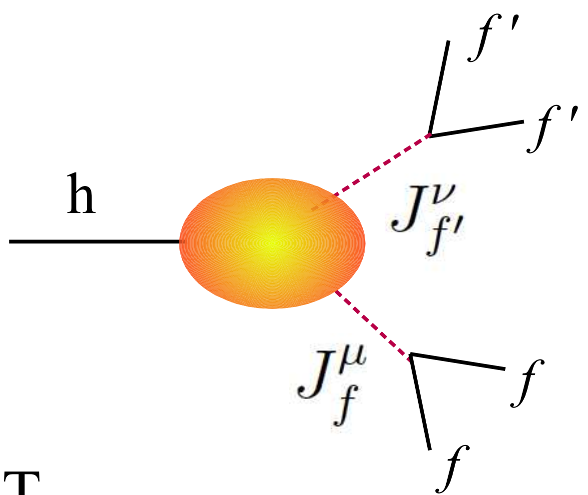
- Both of them are useful.
- For B) one can write an effective Feynman rule, not to be used beyond tree-level

▶ *Clarifications of issues raised during the plenary meeting*

III. Worries about form factors and consistency with QFT

From a theoretical point of view, the "effective on-shell couplings" are nothing but a parameterization (after momentum expansion) of well-defined correlation functions, e.g.:

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



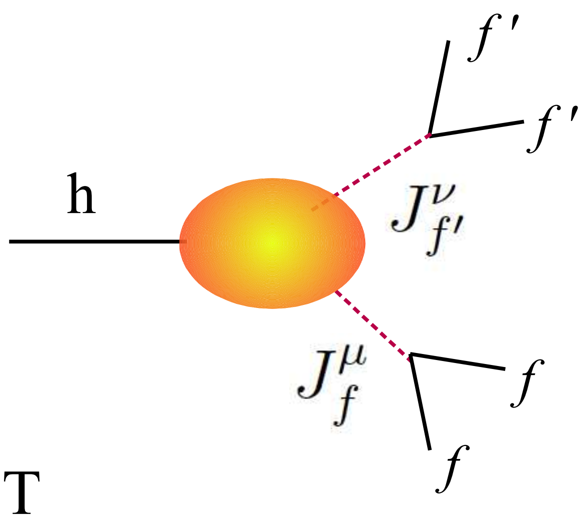
for $h \to 4f$, $qq \to (ff)_V + h$, $qq \to (q'q'+h)_{VBF}$

- This is something perfectly well-defined in QFT (*according to QFT "rules", this is the most appropriate quantity for th.-exp. comparison...*)

▶ Clarifications of issues raised during the plenary meeting

III. Worries about form factors and consistency with QFT

From a theoretical point of view, the "effective on-shell couplings" are nothing but a parameterization (after momentum expansion) of well-defined correlation functions, e.g.:



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

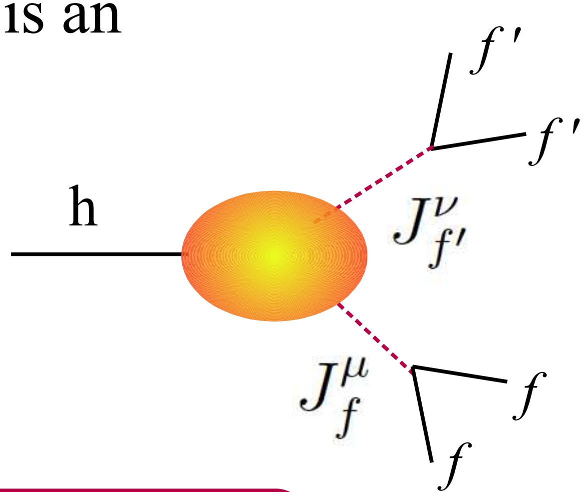
for h → 4f, qq → (ff)$_V$+h, qq → (q'q'+h)$_{VBF}$

- This is something perfectly well-defined in QFT
- Same is true if we decompose the correlation functions in terms of Lorentz-invariant form-factors.
- What is not well-defined are the hVV* form-factors (*often used both in th. & exp. papers...*), but that is not we are discussing here...

Some comments about Vh (and VBF)

What has been proposed in [Gonzales-Alonso *et al.*, 1412.6038] is an "EFT-inspired" momentum expansion of

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



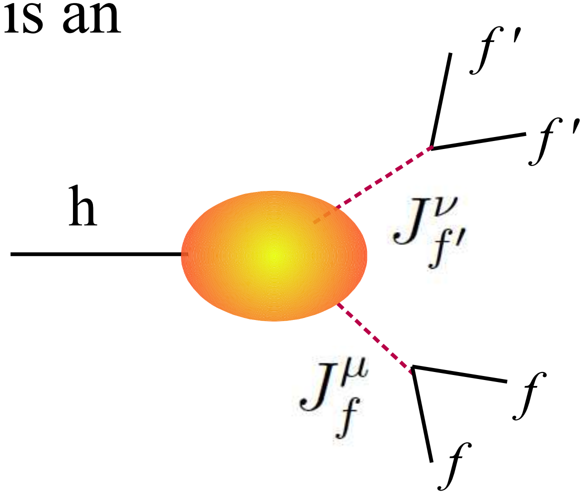
up to to terms of O(p^2) × A_{SM}

- Parameter counting for h → 4ℓ (ℓ=e,μ,ν) + ℓℓγ + γγ:
  20 (no symmetries) → 7 (CP + Lepton Univ + Custodial)

Some comments about Vh (and VBF)

What has been proposed in [Gonzales-Alonso *et al.*, 1412.6038] is an "EFT-inspired" momentum expansion of

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



up to to terms of $O(p^2) \times A_{SM}$

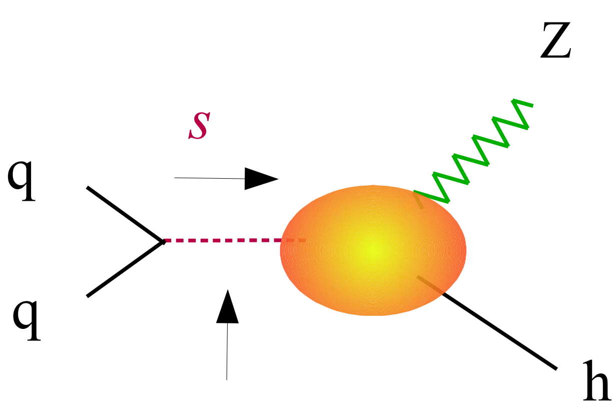
- Parameter counting for $h \to 4\ell$ (ℓ=e,μ,ν) + $\ell\ell\gamma$ + $\gamma\gamma$: 20 (no symmetries) → 7 (CP + Lepton Univ + Custodial)

Same correlation function accessible in hV and VBF but...

- different flavor composition ($q \leftrightarrow \ell$) → 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*)

Some comments about Vh (and VBF)



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.

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

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*)

$$\boxed{[d\sigma(pp \to hZ)/dm_{hZ}]_{exp} / [d\sigma(pp \to hZ)/dm_{hZ}]_{SM}}$$


Backup

Constant terms within (d=6) EFT $\rightarrow$ ε_i

General structure of $HV_1^\mu V_2^\nu$ vertex ($V = W, Z, \gamma, g$) [Figy, Zeppenfeld]

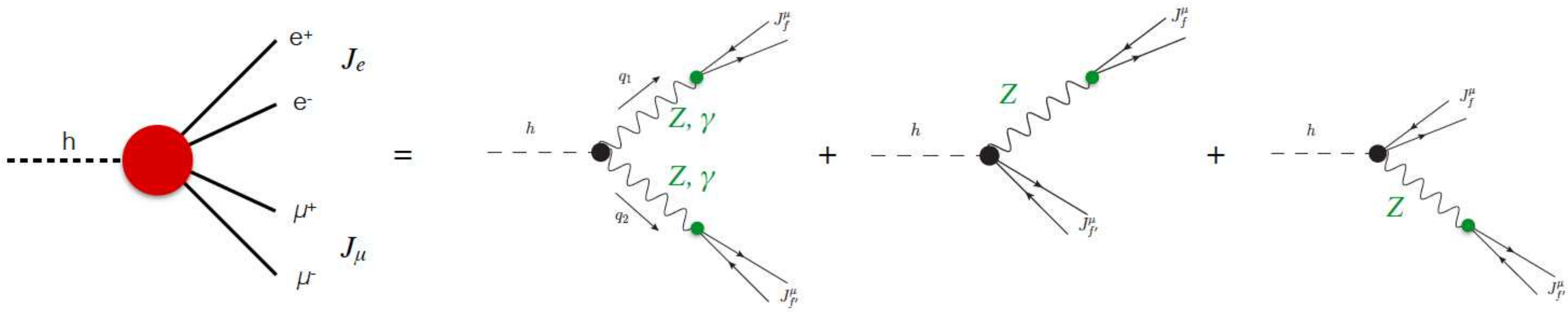
$$T^{\mu\nu} = a_1(p_1, p_2) g^{\mu\nu} + a_2(p_1, p_2)[p_1 \cdot p_2 g^{\mu\nu} - p_2^\mu p_1^\nu] + a_3(p_1, p_2)\varepsilon^{\mu\nu\rho\sigma} p_{1\,\rho} p_{2\,\sigma}$$

+ *"contact terms"*

SM (LO):

$HWW, HZZ \propto a_1,\ a_2 = a_3 = 0$

κ_i & ε_i [p_i^2 "slopes"]



We expand around the poles and keep only terms wihich can arise at dim ≤ 6:

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

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

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

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

In the SM $\kappa_X \to 1,\ \epsilon_X \to 0$

Parameter counting

10 processes:

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

11 real observables

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

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

7 real observables

$\kappa_{WW}, \epsilon_{WW}, \epsilon^{CP}_{WW}$,
$\epsilon_{We}, \epsilon_{W\mu}$, (complex)

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

above + 2 real ones

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

Symmetries impose relations — which can be tested — among these observables:

	General case	Flavour univ.	CP + Flavour univ.	Custodial symmetry + CP + Flavour univ.
# of independent pseudo-observables	**20**	**15**	**10**	**7**
E.g.:		$\epsilon_{Ze_L} = \epsilon_{Z\mu_L}$ $\epsilon_{Ze_R} = \epsilon_{Z\mu_R}$	$\epsilon^{CP}_X = \mathrm{Im}\,\epsilon_{W\ell_L} = 0$	$\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\epsilon_{We_L} + 2c_w\epsilon_{Ze_L}\right)$

[see 1412.6038 for more details]