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Update on Pseudo Observables for Higgs Decays

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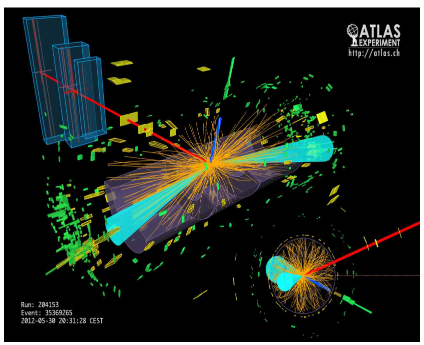
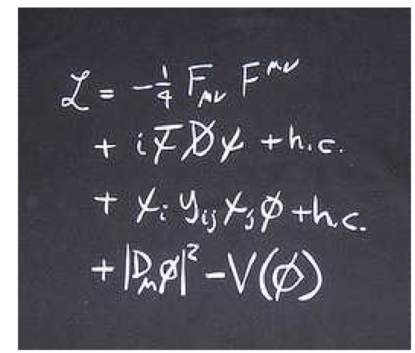
- General comments about PO
- Recent progress (I): radiative corrections in $h \to 4f$
- Recent progress (II): “physical PO” for $h \to 4f$

General comments about PO

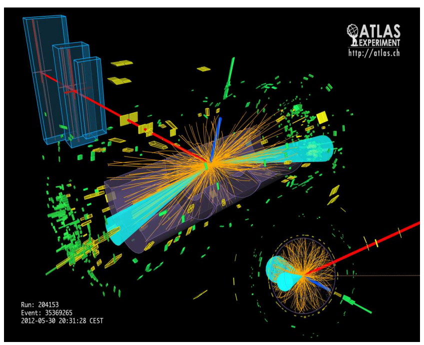


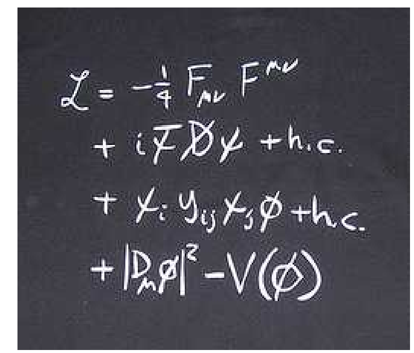


Experimental data	Pseudo Observables	Lagrangian parameters
raw data, fiducial cross-sections, ...	masses, widths, slopes, ...	Wilson coefficients, renormalization scale, running masses, ...

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 <u>on-shell processes</u> (*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 (*at least as far as decays are concerned*):

A) "Ideal observables" or "physical PO"

M_W, $\Gamma(Z \to ll)$, … M_h, $\Gamma(h \to \gamma\gamma)$, $\Gamma(h \to 4\mu)$, …

B) "Effective on-shell couplings"

g_Z^f, g_W^f, … κ_i & ε_i

- 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 [→ *see talk by Admir*]

General comments about PO

Multi-body modes

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

↓

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

↓

There is more to extract from data other than the κ_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 κ_i ($\leftrightarrow \Gamma_i$) is all what one can extract from data

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

General comments about PO

Multi-body modes

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

↓

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

↓

Momentum expansion of the *f.f.* around leading poles

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

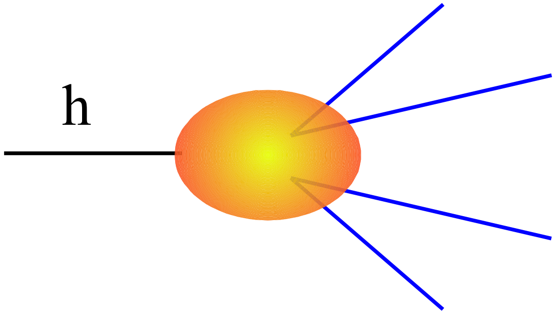
Two-body (on-shell) decays

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

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

- No need to specify any detail about the EFT, but for the absence of light new particles → momentum expansion very well justified 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 (and necessary...)

Radiative corrections & "physical PO" in $h \to 4f$



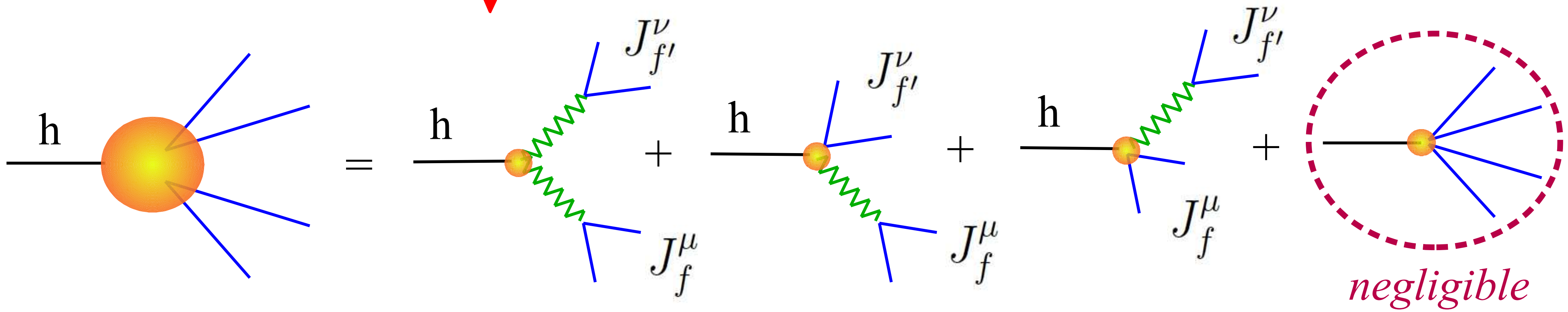
The $h \to 4f$ case

Two main hypotheses:

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

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.:

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

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

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

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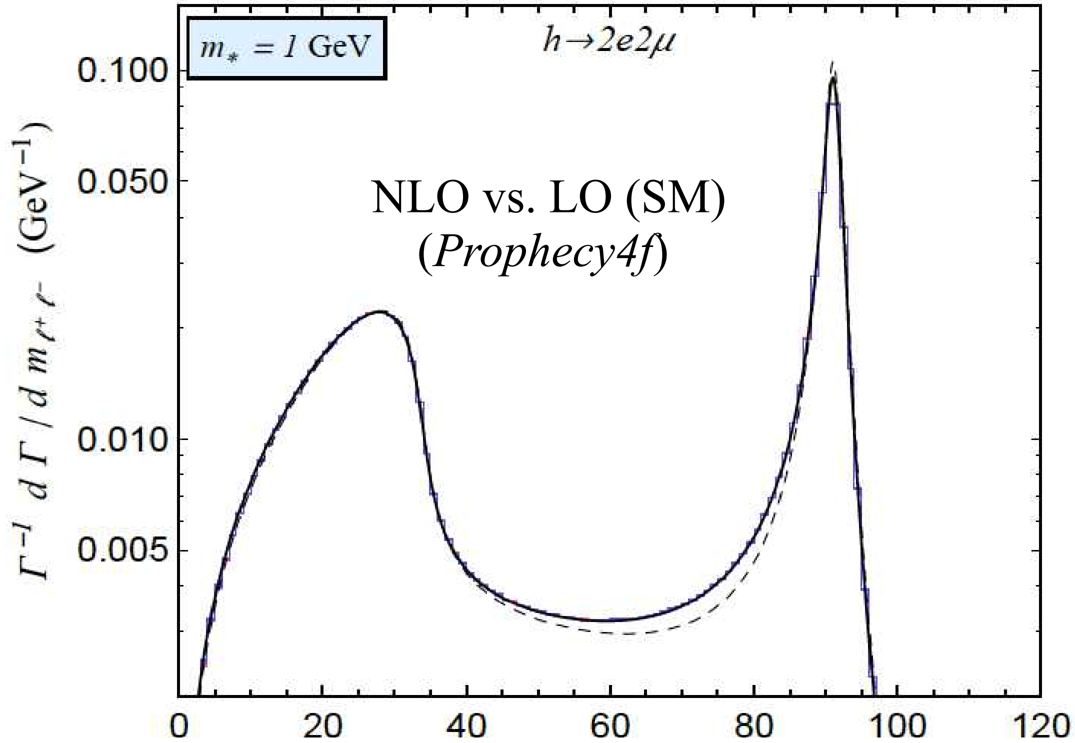
$$\begin{aligned}\mathcal{A} = & i\frac{2m_Z^2}{v_F} \sum_{e=e_L,e_R} \sum_{\mu=\mu_L,\mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu) \times \\ & \left[\left(\kappa_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2} \frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}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

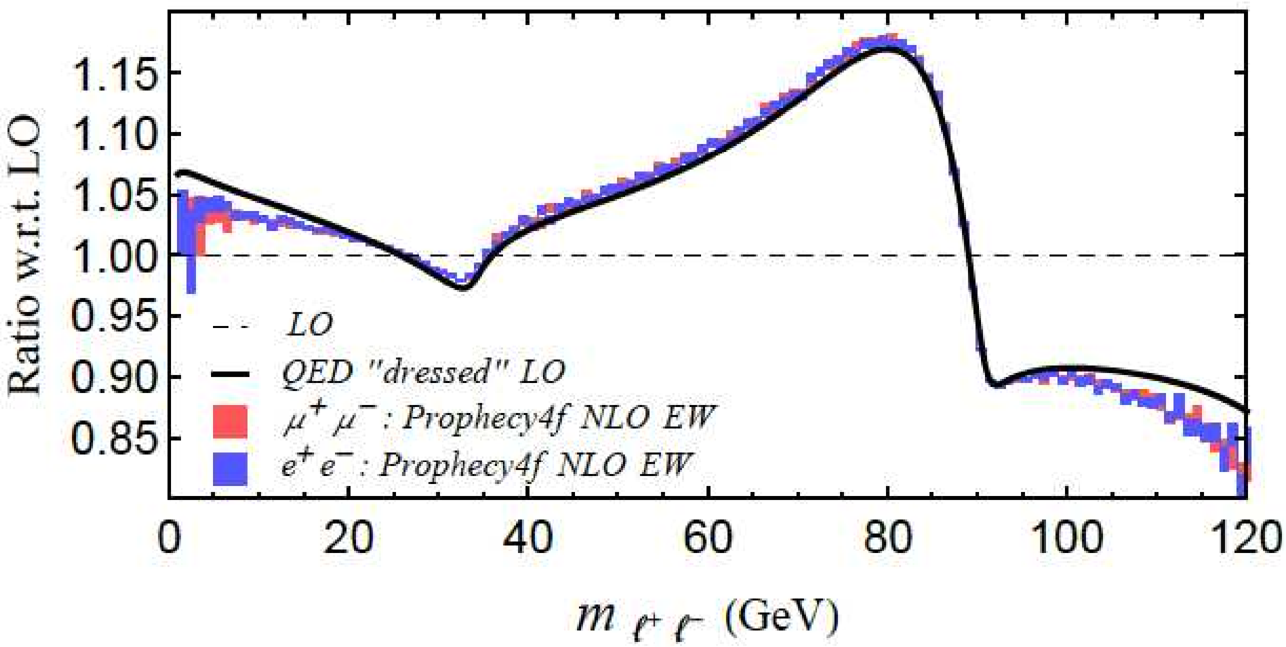
$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

- The κ_i are normalized such that the SM is recovered in the limit $\kappa_i \to 1$
- The ε_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



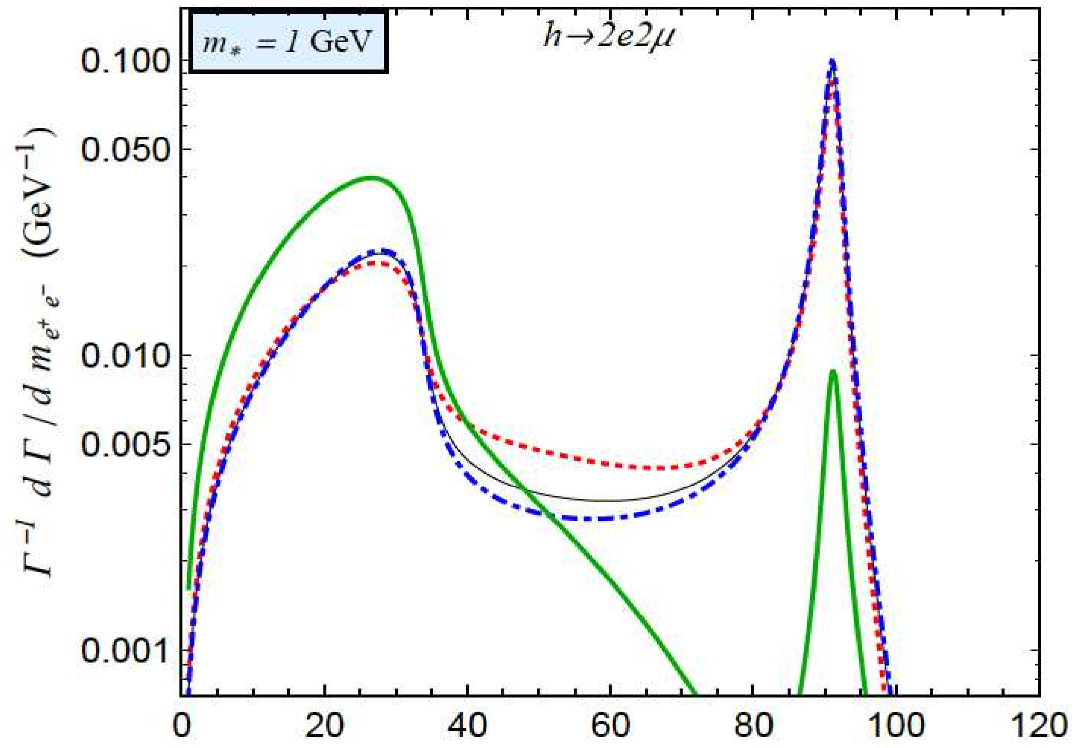
"Dressing" with QED radiation → excellent description of SM beyond the tree level

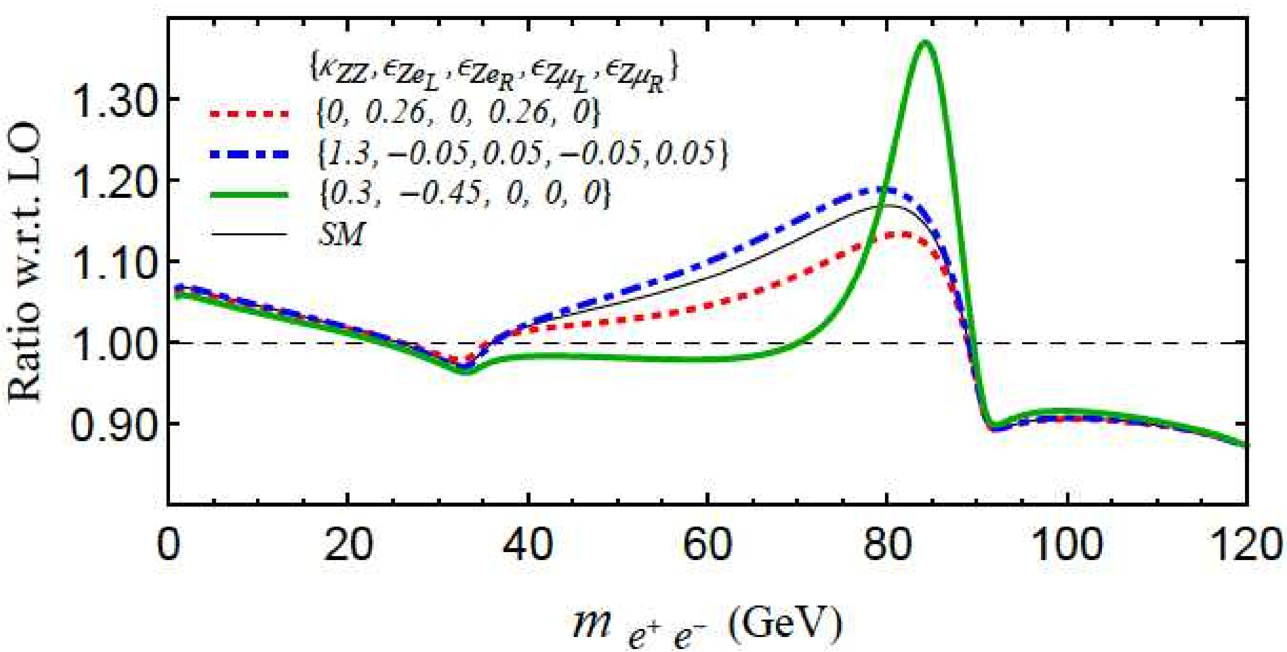


Bordone, Greljo, G.I., Marzocca, Pattori, to appear

The $h \to 4f$ case

"Dressing" with QED radiation → excellent description of SM beyond the tree level & relevant impact for BSM @ NLO





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

Physical PO for $h \to 4f$

The "physical meaning" of the parameters appearing in this decomposition is not obvious at first sight, but it is actually quite simple:

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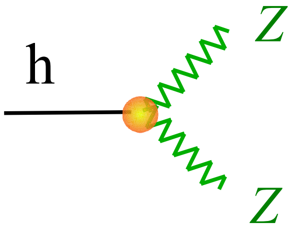
&+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)}+\kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)}+\frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right)+\kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot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

"double Z-pole"



$$\Gamma(h\to Z_L Z_L)\equiv\frac{\Gamma(h\to 2e2\mu)[\kappa_{ZZ}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z\to 2\mu)}=0.209\ |\kappa_{ZZ}|^2\ \text{MeV}$$

$$\Gamma(h\to Z_T Z_T)\equiv\frac{\Gamma(h\to 2e2\mu)[\epsilon_{ZZ}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z\to 2\mu)}=0.0189\ |\epsilon_{ZZ}|^2\ \text{MeV}$$

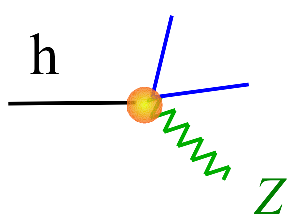
$$\Gamma^{\text{CPV}}(h\to Z_T Z_T)\equiv\frac{\Gamma(h\to 2e2\mu)[\epsilon_{ZZ}^{\text{CP}}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z\to 2\mu)}=0.00799\ |\epsilon_{ZZ}^{\text{CP}}|^2\ \text{MeV}$$

Physical PO for $h \to 4f$

The "physical meaning" of the parameters appearing in this decomposition is not obvious at first sight, but it is actually quite simple:

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

"single Z-pole"



$$\Gamma(h \to Z\ell^+\ell^-) = 0.0366 |\epsilon_{Z\ell}|^2 \ \text{MeV}$$

Physical PO for $h \to 4f$

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

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

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

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

"Z & γ pole" → $\Gamma(h \to Z\gamma)$

"double γ-pole" → $\Gamma(h \to \gamma\gamma)$

Note on "continuous PO" for $pp \to hZ(W)$:

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

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

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

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

N.B.: These are the only terms that change when going from decay to production, and that in production should be considered as ŝ-dependent terms