The long pending open question: How shall we make general measurements of Higgs decay properties

Long history of approaches

- This is not a complete list, just some examples of what was used in experimental measurements
  - Higgs Characterization model, f_{ai}, EFTs, Pseudo-Observables, …, fiducial differential
- All use some form of q^2 expansion
  - Problematic for initial state → STXS, fiducial
  - OK for on-shell Higgs decays, as q^2<125 GeV
- Still missing: something we can all agree upon to use for general Higgs decay measurements
  - Needs to be sufficiently general
  - Suitable to do measurements, e.g. should be closely related to observable quantities

Linear or Quadractic

Reminder: the observable rate for a Higgs signal is

$$\sigma_i * \Gamma_j \,/\, \Gamma_H$$

Extract decay information

(a) with the rate depending linearly on the parameters, e.g. Γ_j(CP-odd)

(b) with the rate depending quadratically on the parameters, e.g. Γ_j=poly2(κ_m) as in the κ-framework

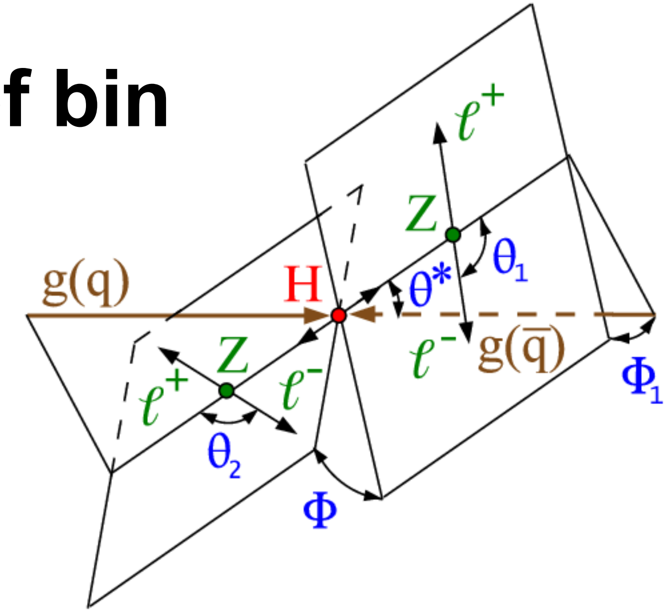
- **In both cases, interference effects between parameters need to be treated correctly**

Trivial: measure in bins

Since none of the proposals so far got wide acceptance, let's try to make a wish list and discuss it. From this it might be easier to converge.

Linear (parameters are ~ partial width Γ_j like)

- Bin the decay phase space into a suitable number of bins to extract all information
- Pro: intuitively understandable
- Con: Need a very large numbers of bin in order to simultaneously extract the information about ~5 decay observables with good sensitivity (for h→4l)



Let's try a wish list

Since none of the proposals so far got wide acceptance, let's try to make a wish list and discuss it. From this it might be easier to converge.

Linear (parameters are ~ partial width Γ_j like)

- **Pro: continuous parameter (so only ~5 for $h \to 4l$)**
- **Pro: closely related to the σ*B==event rate**
- **Pro: intuitively understandable**
- **Con: interference terms ~ ugly/difficult**
- **Condition to make this intuitive:**
  ignoring interference, the sum of these parameters should correspond to the observable (partial) decay width

Let's try a wish list

Since none of the proposals so far got wide acceptance, let’s try to make a wish list and discuss it. From this it might be easier to converge.

Quadratic (parameters are ~ kappa k_j like)

- Pro: more closely related to underlying theory
- Pro: interference terms natural and simple
- Con: value/meaning not necessarily intuitively or directly connected to observable quantities
- Condition to make this intuitive: κ_i, ε_i, c_i, ...==1 should correspond to something well defined (e.g. SM partial width)
- Possible Con: Covariance matrix of a joined measurement with STXS bins could be insufficient

Most general proposal so far: POs

	PO	*Physical* PO	Relation to the eff. coupl.
✓ ✓	$\kappa_f,\ \delta_f^{\rm CP}$	$\Gamma(h\to f\bar f)$	$=\Gamma(h\to f\bar f)^{\rm (SM)}[(\kappa_f)^2+(\delta_f^{\rm CP})^2]$
	$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{\rm CP}$	$\Gamma(h\to\gamma\gamma)$	$=\Gamma(h\to\gamma\gamma)^{\rm (SM)}[(\kappa_{\gamma\gamma})^2+(\delta_{\gamma\gamma}^{\rm CP})^2]$
	$\kappa_{Z\gamma},\ \delta_{Z\gamma}^{\rm CP}$	$\Gamma(h\to Z\gamma)$	$=\Gamma(h\to Z\gamma)^{\rm (SM)}[(\kappa_{Z\gamma})^2+(\delta_{Z\gamma}^{\rm CP})^2]$
? ?	κ_{ZZ}	$\Gamma(h\to Z_L Z_L)$	$=(0.209\ \ {\rm MeV})\times\lvert\kappa_{ZZ}\rvert^2$
	ϵ_{ZZ}	$\Gamma(h\to Z_T Z_T)$	$=(1.9\times10^{-2}\ \ {\rm MeV})\times\lvert\epsilon_{ZZ}\rvert^2$
	$\epsilon_{ZZ}^{\rm CP}$	$\Gamma^{\rm CPV}(h\to Z_T Z_T)$	$=(8.0\times10^{-3}\ \ {\rm MeV})\times\lvert\epsilon_{ZZ}^{\rm CP}\rvert^2$
	ϵ_{Zf}	$\Gamma(h\to Zf\bar f)$	$=(3.7\times10^{-2}\ \ {\rm MeV})\times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
	κ_{WW}	$\Gamma(h\to W_L W_L)$	$=(0.84\ \ {\rm MeV})\times\lvert\kappa_{WW}\rvert^2$
	ϵ_{WW}	$\Gamma(h\to W_T W_T)$	$=(0.16\ \ {\rm MeV})\times\lvert\epsilon_{WW}\rvert^2$
	$\epsilon_{WW}^{\rm CP}$	$\Gamma^{\rm CPV}(h\to W_T W_T)$	$=(6.8\times10^{-2}\ \ {\rm MeV})\times\lvert\epsilon_{WW}^{\rm CP}\rvert^2$
	ϵ_{Wf}	$\Gamma(h\to Wf\bar f')$	$=(0.14\ \ {\rm MeV})\times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$
	κ_g	$\sigma(pp\to h)_{gg-{\rm fusion}}$	$=\sigma(pp\to h)^{\rm SM}_{gg-{\rm fusion}}\kappa_g^2$
	κ_t	$\sigma(pp\to t\bar t h)_{\rm Yukawa}$	$=\sigma(pp\to t\bar t h)^{\rm SM}_{\rm Yukawa}\kappa_t^2$
	κ_H	$\Gamma_{\rm tot}(h)$	$=\Gamma^{\rm SM}_{\rm tot}(h)\kappa_H^2$

Table 110 in YR4:
https://arxiv.org/abs/1610.07922

Most general proposal so far: POs

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

In the SM $\kappa_X \to 1,\ \epsilon_X \to 0,\ \lambda_X^{\mathrm{CP}} \to 0$

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

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

PO	*Physical* PO	Relation to the eff. coupl.
$\kappa_f,\ \delta_f^{\mathrm{CP}}$	$\Gamma(h\to f\bar{f})$	$= \Gamma(h\to f\bar{f})^{(\mathrm{SM})}[(\kappa_f)^2 + (\delta_f^{\mathrm{CP}})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{\mathrm{CP}}$	$\Gamma(h\to\gamma\gamma)$	$= \Gamma(h\to\gamma\gamma)^{(\mathrm{SM})}[(\kappa_{\gamma\gamma})^2 + (\delta_{\gamma\gamma}^{\mathrm{CP}})^2]$
$\kappa_{Z\gamma},\ \delta_{Z\gamma}^{\mathrm{CP}}$	$\Gamma(h\to Z\gamma)$	$= \Gamma(h\to Z\gamma)^{(\mathrm{SM})}[(\kappa_{Z\gamma})^2 + (\delta_{Z\gamma}^{\mathrm{CP}})^2]$
κ_{ZZ}	$\Gamma(h\to Z_L Z_L)$	$= (0.209\ \mathrm{MeV})\times\lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h\to Z_T Z_T)$	$= (1.9\times10^{-2}\ \mathrm{MeV})\times\lvert\epsilon_{ZZ}\rvert^2$
$\epsilon_{ZZ}^{\mathrm{CP}}$	$\Gamma^{\mathrm{CPV}}(h\to Z_T Z_T)$	$= (8.0\times10^{-3}\ \mathrm{MeV})\times\lvert\epsilon_{ZZ}^{\mathrm{CP}}\rvert^2$
ϵ_{Zf}	$\Gamma(h\to Zf\bar{f})$	$= (3.7\times10^{-2}\ \mathrm{MeV})\times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h\to W_L W_L)$	$= (0.84\ \mathrm{MeV})\times\lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h\to W_T W_T)$	$= (0.16\ \mathrm{MeV})\times\lvert\epsilon_{WW}\rvert^2$
$\epsilon_{WW}^{\mathrm{CP}}$	$\Gamma^{\mathrm{CPV}}(h\to W_T W_T)$	$= (6.8\times10^{-2}\ \mathrm{MeV})\times\lvert\epsilon_{WW}^{\mathrm{CP}}\rvert^2$
ϵ_{Wf}	$\Gamma(h\to Wf\bar{f}')$	$= (0.14\ \mathrm{MeV})\times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$
κ_g	$\sigma(pp\to h)_{gg-\mathrm{fusion}}$	$= \sigma(pp\to h)_{gg-\mathrm{fusion}}^{\mathrm{SM}}\kappa_g^2$
κ_t	$\sigma(pp\to t\bar{t}h)_{\mathrm{Yukawa}}$	$= \sigma(pp\to t\bar{t}h)_{\mathrm{Yukawa}}^{\mathrm{SM}}\kappa_t^2$
κ_H	$\Gamma_{\mathrm{tot}}(h)$	$= \Gamma_{\mathrm{tot}}^{\mathrm{SM}}(h)\kappa_H^2$

Table 110 in YR4:
https://arxiv.org/abs/1610.07922

Slides from 17.05.2018

Binned or Continuous

First major question: extract decay information
(a) with measurements in bins of decay observables
(b) with some continuous parameters

a) Most model independent. Difficult to bin in many decay observables simultaneously (e.g. as in $H \rightarrow 4l$). Decay effects are often subtle, so a suitable binning is not easy

b) The mass of the decay system is fixed to 125 GeV for on-shell Higgs decays. Hence the validity of some general physics model expansion should not be an issue for Higgs decays. Continuous parameters also more suited for subtle effects and extracting several parameters simultaneously.

➔ My proposal: use continuous parameters from some general physics model to extract decay information. Use bins only in special cases where it’s sufficient and simpler

Additive or Multiplicative

Second major question: extract decay information

(a) in each STXS bin independently, or

(b) for all bins together?

a) Maximum information. Most model independent. But large experimental challenge with n(STXS)*n(decay) observables to measure simultaneously

b) Higgs is a scalar and a very narrow resonance
=> no cross talk between production and decay
Only Higgs boost influences decay observables, but this can be easily modeled by MC inside each STXS bin

➔ My proposal: measure decay information for all STXS bins together, so experiments have n(STXS)+n(decay) observables to extract

Linear or Quadractic

Reminder: the observable rate for a Higgs signal is

$$\sigma_i * \Gamma_j / \Gamma_H$$

Third major question: extract decay information
(a) with the rate depending linearly on the parameters, e.g. Γ_j(CP-odd)
(b) with the rate depending quadratically on the parameters, e.g. Γ_j=poly2(κ_m) as in the κ-framework

Use pseudo-observables as example in the following, but something else could be used if it provides similar degrees of freedom.

Linear or Quadractic: Example POs

Linear

Quadractic

PO	*Physical* PO	Relation to the eff. coupl.
$\kappa_f,\ \delta_f^{CP}$	$\Gamma(h\to f\bar f)$	$= \Gamma(h\to f\bar f)^{(SM)}[(\kappa_f)^2+(\delta_f^{CP})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{CP}$	$\Gamma(h\to\gamma\gamma)$	$= \Gamma(h\to\gamma\gamma)^{(SM)}[(\kappa_{\gamma\gamma})^2+(\delta_{\gamma\gamma}^{CP})^2]$
$\kappa_{Z\gamma},\ \delta_{Z\gamma}^{CP}$	$\Gamma(h\to Z\gamma)$	$= \Gamma(h\to Z\gamma)^{(SM)}[(\kappa_{Z\gamma})^2+(\delta_{Z\gamma}^{CP})^2]$
κ_{ZZ}	$\Gamma(h\to Z_LZ_L)$	$= (0.209\ \text{MeV})\times\lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h\to Z_TZ_T)$	$= (1.9\times10^{-2}\ \text{MeV})\times\lvert\epsilon_{ZZ}\rvert^2$
ϵ_{ZZ}^{CP}	$\Gamma^{CPV}(h\to Z_TZ_T)$	$= (8.0\times10^{-3}\ \text{MeV})\times\lvert\epsilon_{ZZ}^{CP}\rvert^2$
ϵ_{Zf}	$\Gamma(h\to Zf\bar f)$	$= (3.7\times10^{-2}\ \text{MeV})\times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h\to W_LW_L)$	$= (0.84\ \text{MeV})\times\lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h\to W_TW_T)$	$= (0.16\ \text{MeV})\times\lvert\epsilon_{WW}\rvert^2$
ϵ_{WW}^{CP}	$\Gamma^{CPV}(h\to W_TW_T)$	$= (6.8\times10^{-2}\ \text{MeV})\times\lvert\epsilon_{WW}^{CP}\rvert^2$
ϵ_{Wf}	$\Gamma(h\to Wf\bar f')$	$= (0.14\ \text{MeV})\times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$
κ_g	$\sigma(pp\to h)_{gg-\text{fusion}}$	$= \sigma(pp\to h)_{gg-\text{fusion}}^{SM}\kappa_g^2$
κ_t	$\sigma(pp\to t\bar t h)_{\text{Yukawa}}$	$= \sigma(pp\to t\bar t h)_{\text{Yukawa}}^{SM}\kappa_t^2$
κ_H	$\Gamma_{\text{tot}}(h)$	$= \Gamma_{\text{tot}}^{SM}(h)\kappa_H^2$

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Linear parameters

What could measured parameters look like?

$\sigma(ggH0j)*\Gamma(H\to Z_L\, Z_L)/\Gamma_H$

$\sigma(ggH1j)*\Gamma(H\to Z_L\, Z_L)/\Gamma_H$

...

$\Gamma(H\to Z_T\, Z_T)/\Gamma(H\to Z_L\, Z_L)$

Γ^CPV$(H\to Z_T\, Z_T)/\Gamma(H\to Z_L\, Z_L)$

$\Gamma(H\to Zff)/\Gamma(H\to Z_L\, Z_L)$

$\Gamma(H\to \gamma\gamma)/\Gamma(H\to Z_L\, Z_L)$

So far looks like a nice and simple extension of the known LHC rate measurements

Linear parameters: interference

What happens with interference? Define:

$\Gamma(H\rightarrow Z_T Z_T)/\Gamma(H\rightarrow Z_L Z_L) = c_{TT}*\mathrm{sign}(\varepsilon_{ZZ})*|\varepsilon_{ZZ}|^2 / |k_{ZZ}|^2$

$\Gamma(H\rightarrow Zff)/\Gamma(H\rightarrow Z_L Z_L) = c_{Zff}*\mathrm{sign}(\varepsilon_{Zf})*|\varepsilon_{Zf}|^2 / |k_{ZZ}|^2$

Rate for pure ggH 0j, $H\rightarrow Z_T Z_T$:

$\sigma(ggH0j)*\Gamma(H\rightarrow Z_T Z_T)/\Gamma_H =$
$\sigma(ggH0j)*\Gamma(H\rightarrow Z_L Z_L)/\Gamma_H * |\Gamma(H\rightarrow Z_T Z_T)/\Gamma(H\rightarrow Z_L Z_L)|$

Interference between $H\rightarrow Z_T Z_T$ and $H\rightarrow Zff$ is proportional to:

sign[$\Gamma(H\rightarrow Z_T Z_T)/\Gamma(H\rightarrow Z_L Z_L) * \Gamma(H\rightarrow Zff)/\Gamma(H\rightarrow Z_L Z_L)$] *
sqrt[$|\Gamma(H\rightarrow Z_T Z_T)/\Gamma(H\rightarrow Z_L Z_L)| * |\Gamma(H\rightarrow Zff)/\Gamma(H\rightarrow Z_L Z_L)|$]

The sign(), abs() and sqrt() terms makes this a bit cumbersome to read and might cause problems for fits. To be checked

Alternative: sign[X] * sqrt[X] could be written as X / sqrt[X] if preferred

Quadratic parameters

What could measured parameters look like?

$\sigma(ggH0j) * \Gamma(H \rightarrow Z_L Z_L)/\Gamma_H = \sigma(ggH0j) * c_L * |k_{ZZ}|^2 / \Gamma_H$

$\sigma(ggH1j) * \Gamma(H \rightarrow Z_L Z_L)/\Gamma_H = \sigma(ggH1j) * c_L * |k_{ZZ}|^2 / \Gamma_H$

...

$\varepsilon_{ZZ} / \kappa_{ZZ}$

$\varepsilon_{ZZ}^{CP} / \kappa_{ZZ}$

$\varepsilon_{Zf} / \kappa_{ZZ}$

$\kappa_{\gamma\gamma} / \kappa_{ZZ}$

Effectively some mix between cross section measurements for production and an extended kappa framework for decays.

Quadratic parameters: mix

Rate for pure ggH 0j, $H \rightarrow Z_T Z_T$:

$\sigma(ggH0j) * \Gamma(H \rightarrow Z_T Z_T)/\Gamma_H =$
$\sigma(ggH0j) * \Gamma(H \rightarrow Z_L Z_L)/\Gamma_H * c_T/c_L * (\varepsilon_{ZZ} / \kappa_{ZZ})^2$

Interference between $H \rightarrow Z_T Z_T$ and $H \rightarrow Zff$ is proportional to:

$(\varepsilon_{ZZ} / \kappa_{ZZ}) * (\varepsilon_{Zff} / \kappa_{ZZ})$

Advantage: interference is easy: no sign(), abs() or sqrt() needed

Disadvantage: Uncertainties do not match! κ and ε enter quadratic into rate, STXS bins linear. Relatively speaking, uncertainties for κ and ε parameters will be half the uncertainty for STXS parameters. The correlation matrix will be even more difficult, as it will correlate between linear and quadratic terms. To be checked if such a correlation matrix can be used.

Personal preference

- Use continuous parameters for decay information
- Extract decay information from all STXS bins together, hence measure n(STXS)+n(decay) parameters.
  - For STXS bins with sufficient sensitivity, experiments would need to implement observables that are actually sensitive to decay information (and as many observables as needed and possible)
  - For STXS bins with little sensitivity, the experiments would simply not implement such decay observables and only correct the signal acceptance due to changes in the decay
- Extract information with linear parameters in the rate, as these have a quite intuitive physics meaning and a close relation to known rate measurements. Complications with interference can hopefully be hidden in the fitting code
- Since POs seem to be more general than EFTs, use the physical POs from YR4 as parameters for the decay side

Re-interpretation of STXS and POs

Imagine the measurement:

$\sigma(ggH0j)*\Gamma(H\to Z_L Z_L)/\Gamma_H$ = X1 ± E1 fb

$\sigma(\text{VBF pT}>200)*\Gamma(H\to Z_L Z_L)/\Gamma_H$ = X2 ± E2 fb

$\Gamma(H\to Z_T Z_T)/\Gamma(H\to Z_L Z_L)$ = X3 ± E3

$\Gamma\text{^CPV}(H\to Z_T Z_T)/\Gamma(H\to Z_L Z_L)$ = X4 ± E4

For a re-interpretation to new parameters **p**, do a fit

X1 ± E1 fb = f1(**p**)

X2 ± E2 fb = f2(**p**)

X3 ± E3 = f3(**p**)

X4 ± E4 = f4(**p**)

where fi(**p**) are the expressions for the observables of the STXS+PO fit as function of **p** and correlations should be taken into account. These re-interpretations can extract POs from production+decay, EFTs, …