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

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Long history of approaches

- This is not a complete list, just some examples of what was used in experimental measurements
  - Effective Lagrangian, Higgs Characterization model, f_{ai}, EFTs, Pseudo-Observables, …, fiducial differential
- 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
  - If possible, assumptions needed for interpretations should be avoided for the measurements

Some general statements

- The Higgs is a scalar: no information is transferred between production and decay!
  - Anything learned about Higgs decays in one Higgs production mode or production kinematics is generally valid for all Higgs
  - If we want to measure *n* STXS bins in production and *m* parameters for decay, we need to measure in total *n*+*m* parameters, not *n***m*
    => Measuring production and decay is feasible!
- We are discussing on-shell Higgs decays
  - $q^2=(125\text{ GeV})^2$, independent of kinematics
  - A q^2 expansion can be done and converges in all corners of the phase space

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.

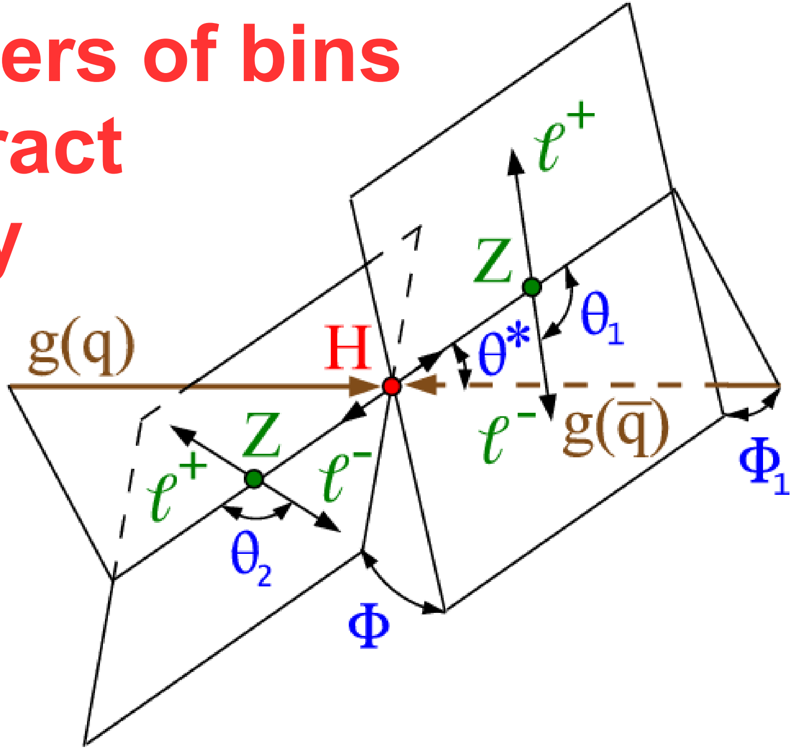
- **The parameters should be as sensitive as possible, e.g. not average over large phase space volumes that could provide extra sensitivity**
- **The parameters should have some intuitive meaning. For example, something directly related to the partial decay width**
  - **Imagine reading and understanding: "We measure the CP-even part of $H \to \tau\tau$ as 230±30 keV and the CP-odd part is <50 keV @ 95% CL. The SM prediction (CP-even) is 256±5 keV"**
- **As general as needed with as few parameters as possible**
- **We know there is interference in decays. Whatever is chosen should make dealing with interference not too complicated**
- **Can be well measured together with production STXS bins**
- **More?**

Some more inspiration
to get you thinking

Trivial: measure in bins (STXS)?

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, well defined**
- **Pro: Interference enters in the interpretation step**
- **Con: Likely need a large numbers of bins in order to simultaneously extract the information about ~5 decay observables with good sensitivity (for $h \rightarrow 4l$) TO BE CHECKED!**



Continues: Linear or Quadractic?

Reminder: the observable rate for a Higgs signal is

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

Extract decay information with continuous parameters

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

(b) with the decay 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**

Most general proposal so far: POs

(b) PO	(a) *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}	$\Gamma(h\to Z_LZ_L)$	$= (0.209\ \ {\rm MeV})\times|\kappa_{ZZ}|^2$
ϵ_{ZZ}	$\Gamma(h\to Z_TZ_T)$	$= (1.9\times10^{-2}\ \ {\rm MeV})\times|\epsilon_{ZZ}|^2$
$\epsilon_{ZZ}^{\rm CP}$	$\Gamma^{\rm CPV}(h\to Z_TZ_T)$	$= (8.0\times10^{-3}\ \ {\rm MeV})\times|\epsilon_{ZZ}^{\rm CP}|^2$
ϵ_{Zf}	$\Gamma(h\to Zf\bar f)$	$= (3.7\times10^{-2}\ \ {\rm MeV})\times N_c^f\ |\epsilon_{Zf}|^2$
κ_{WW}	$\Gamma(h\to W_LW_L)$	$= (0.84\ \ {\rm MeV})\times|\kappa_{WW}|^2$
ϵ_{WW}	$\Gamma(h\to W_TW_T)$	$= (0.16\ \ {\rm MeV})\times|\epsilon_{WW}|^2$
$\epsilon_{WW}^{\rm CP}$	$\Gamma^{\rm CPV}(h\to W_TW_T)$	$= (6.8\times10^{-2}\ \ {\rm MeV})\times|\epsilon_{WW}^{\rm CP}|^2$
ϵ_{Wf}	$\Gamma(h\to Wf\bar f')$	$= (0.14\ \ {\rm MeV})\times N_c^f\ |\epsilon_{Wf}|^2$
κ_g	$\sigma(pp\to h)_{gg-{\rm fusion}}$	$= \sigma(pp\to h)_{gg-{\rm fusion}}^{\rm SM}\kappa_g^2$
κ_t	$\sigma(pp\to t\bar th)_{\rm Yukawa}$	$= \sigma(pp\to t\bar th)_{\rm Yukawa}^{\rm SM}\kappa_t^2$
κ_H	$\Gamma_{\rm tot}(h)$	$= \Gamma_{\rm tot}^{\rm SM}(h)\kappa_H^2$

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 $\kappa_X \to 1,\ \epsilon_X \to 0,\ \lambda_X^{\rm CP} \to 0$

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

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

PO	*Physical* PO	Relation to the eff. coupl.
$\kappa_f,\ \delta_f^{\rm CP}$	$\Gamma(h\to f\bar f)$	$= \Gamma(h\to f\bar f)^{\rm (SM)}[(\kappa_f)^2 + (\delta_f^{\rm CP})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{\rm CP}$	$\Gamma(h\to\gamma\gamma)$	$= \Gamma(h\to\gamma\gamma)^{\rm (SM)}[(\kappa_{\gamma\gamma})^2 + (\delta_{\gamma\gamma}^{\rm CP})^2]$
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κ_t	$\sigma(pp\to t\bar t h)_{\rm Yukawa}$	$= \sigma(pp\to t\bar t h)_{\rm Yukawa}^{\rm SM}\kappa_t^2$
κ_H	$\Gamma_{\rm tot}(h)$	$= \Gamma_{\rm tot}^{\rm SM}(h)\kappa_H^2$

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Physical POs

Linear (parameters are ~ partial width Γ_j like)

- **Pro: continuous parameter (so only ~5 for h→4l)**
- **Pro: closely related to the σ*B==event rate**
- **Mixed: Appears to be intuitively understandable (its like a partial width), but because of interference the partial width components in the same decay mode do not sum up to the observable partial width!**
- **Con: interference terms ~ ugly/difficult**
- **Con: Authors don't think these physics POs are a good basis for the fundamental parameters of a measurement.**
  Authors recommend the POs (next slide)

POs

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
  - Factors of 2, π, … (any constant) can be put into the definition of the parameters without changing physics
  - Option to make this more intuitive: κ_i, ε_i, c_i, ...==1 should correspond to something well defined
- Possible Con: Covariance matrix of a joined measurement with STXS bins could be insufficient (TO BE CHECKED!), if κ^2, ε^2 terms dominate

A compromise ?

Linear, the *n* parameters are

- **1 * partial width of SM decay template**
- **(*n*-1) * partial widths of interference terms between SM and BSM decay modes (with a well defined physics meaning)**
- **Inside experimental fit, also add *n**(*n-1*)/2 BSM^2 templates with partial width calculated from SM and interferences**
- **Pro: continuous parameter (so only ~5 for $h\rightarrow 4l$),intuitive if one thinks of small admixtures to the SM**
- **Pro: related to the σ*B==event rate. Close to the SM the parameters sum up to the observed width**
- **Con: what to do if the partial width of interference == 0?**
- **Con: for large BSM^2 terms, parameters do not sum up**
- **Possible Con: covariance matrix of a measurement with STXS bins could be insufficient if BSM^2 terms are large**

What about ...

- fiducial/differential decay measurements?
  - Usually only 1-dimensional, at most 2-dimensional
  - So far only $\gamma\gamma$ can combine measurements of different observables, but $\gamma\gamma$ doesn’t provide decay information
  - Can't be combined with SXTS production measurements

- a direct fit to SMEFT Wilson coefficients just for decays?
  - A bit far from the experimental observables, but “far” is subjective (SMEFT is an interpretation, not a measurement)
  - ~same PROs and CONs as POs
  - But possible
  - Are all possible degrees of freedom (every Lorentz Structure allowed in Higgs decays) included in SMEFT?

Backup:

Slides from LHC Higgs STXS/fiducial meeting on 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.
$\kappa_f,\ \delta_f^{CP}$	$\Gamma(h \to f\bar{f})$	$= \Gamma(h \to f\bar{f})^{(SM)}[(\kappa_f)^2 + (\delta_f^{CP})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{CP}$	$\Gamma(h \to \gamma\gamma)$	$= \Gamma(h \to \gamma\gamma)^{(SM)}[(\kappa_{\gamma\gamma})^2 + (\delta_{\gamma\gamma}^{CP})^2]$
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ϵ_{Zf}	$\Gamma(h \to Zf\bar{f})$	$= (3.7 \times 10^{-2}\ \text{MeV}) \times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
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ϵ_{Wf}	$\Gamma(h \to Wf\bar{f}')$	$= (0.14\ \text{MeV}) \times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$
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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	$\Gamma_{\text{tot}}(h)$	$= \Gamma_{\text{tot}}^{SM}(h)\kappa_H^2$

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

Linear parameters

What could measured parameters look like?

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

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

...

$\Gamma(H\rightarrow Z_T Z_T)/\Gamma(H\rightarrow Z_L Z_L)$

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

$\Gamma(H\rightarrow Zff)/\Gamma(H\rightarrow Z_L Z_L)$

$\Gamma(H\rightarrow \gamma\gamma)/\Gamma(H\rightarrow Z_L Z_L)$

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

Linear parameters: interference

What happens with interference? Define:

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

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

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

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

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

$\text{sign}[\ \Gamma(H\to Z_T Z_T)/\Gamma(H\to Z_L Z_L) * \Gamma(H\to Zff)/\Gamma(H\to Z_L Z_L)\ ] *$
$\text{sqrt}[\ |\Gamma(H\to Z_T Z_T)/\Gamma(H\to Z_L Z_L)| * |\Gamma(H\to Zff)/\Gamma(H\to Z_L Z_L)|\ ]$

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.