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

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0^{st} edition: informal discussion, Les Houches 2017
1^{st} edition: STXS/fiducial meeting, 17^{th} May 2018
2^{nd} edition: Les Houches, 12^{th} June 2019
3^{rd} edition: LHC Higgs XS WG workshop, 17^{th} October 2019

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
  - An expansion can be done and should converge
- Non-trivial information only in $H\rightarrow 4l$, $H\rightarrow l\nu l\nu$, $H\rightarrow \tau\tau$

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.

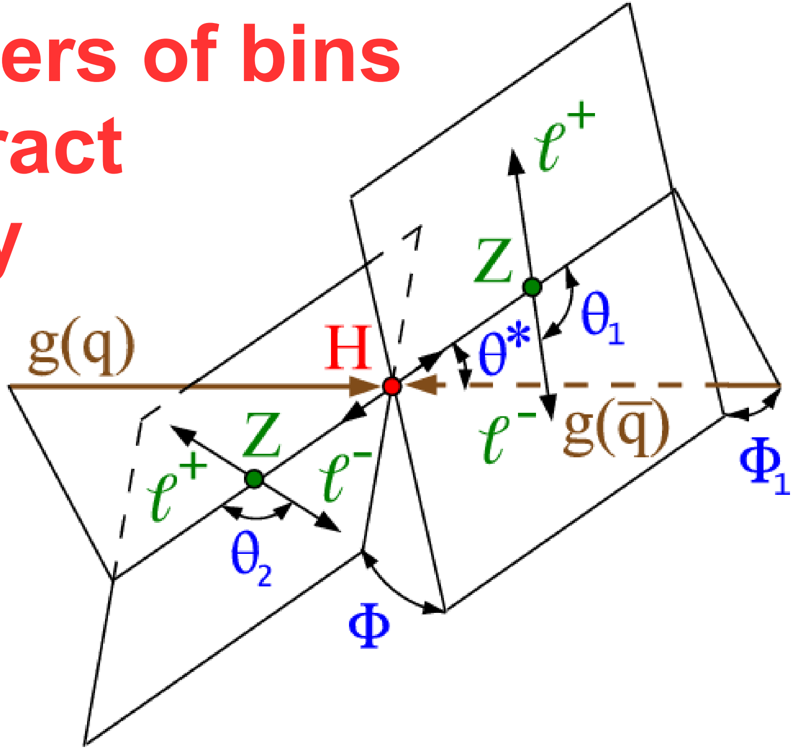
- The parameters should be as sensitive as possible, e.g. not average over large phase space volumes that could provide extra sensitivity
- The parameters should have some intuitive meaning. For example, something directly related to the partial decay width
  - Imagine reading and understanding: "We 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→4l)**
  TO BE CHECKED
  → Les Houches project



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.
$\kappa_f,\ \delta_f^{CP}$	$\Gamma(h \to f\bar{f})$	$= \Gamma(h \to f\bar{f})^{(SM)}[(\kappa_f)^2 + (\delta_f^{CP})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{CP}$	$\Gamma(h \to \gamma\gamma)$	$= \Gamma(h \to \gamma\gamma)^{(SM)}[(\kappa_{\gamma\gamma})^2 + (\delta_{\gamma\gamma}^{CP})^2]$
$\kappa_{Z\gamma},\ \delta_{Z\gamma}^{CP}$	$\Gamma(h \to Z\gamma)$	$= \Gamma(h \to Z\gamma)^{(SM)}[(\kappa_{Z\gamma})^2 + (\delta_{Z\gamma}^{CP})^2]$
κ_{ZZ}	$\Gamma(h \to Z_L Z_L)$	$= (0.209\ \text{MeV}) \times \lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h \to Z_T Z_T)$	$= (1.9 \times 10^{-2}\ \text{MeV}) \times \lvert\epsilon_{ZZ}\rvert^2$
ϵ_{ZZ}^{CP}	$\Gamma^{CPV}(h \to Z_T Z_T)$	$= (8.0 \times 10^{-3}\ \text{MeV}) \times \lvert\epsilon_{ZZ}^{CP}\rvert^2$
ϵ_{Zf}	$\Gamma(h \to Zf\bar{f})$	$= (3.7 \times 10^{-2}\ \text{MeV}) \times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h \to W_L W_L)$	$= (0.84\ \text{MeV}) \times \lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h \to W_T W_T)$	$= (0.16\ \text{MeV}) \times \lvert\epsilon_{WW}\rvert^2$
ϵ_{WW}^{CP}	$\Gamma^{CPV}(h \to W_T W_T)$	$= (6.8 \times 10^{-2}\ \text{MeV}) \times \lvert\epsilon_{WW}^{CP}\rvert^2$
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	$\Gamma_{\text{tot}}(h)$	$= \Gamma_{\text{tot}}^{SM}(h)\kappa_H^2$

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.
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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 $h \rightarrow 4l$)**
- **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**

POs

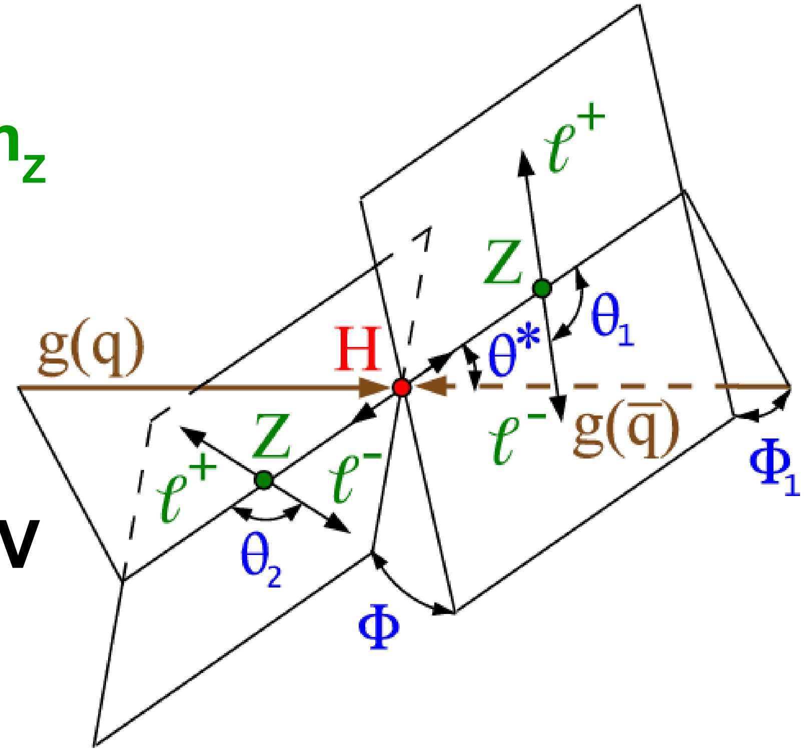
Quadratic (parameters are ~ kappa k_j like)

- 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 could 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 ?

H→4l :

- 1st Z usually ~ on-shell, mass m_{12} ~ m_Z
- 2nd Z off-shell, mass $q^2=m_{34}$
- STXS for q^2 dependence:
  make bins in m_{34}.
  Experiments usually cut m_{34}>~10 GeV
- Within each bin, q^2 is ~ constant
  - Can chose bins or continuous parameters without worry about q^2 expansion
  - Continuous parameters could be stage 2



H→lνlν :

- Want to be as independent from production bins as possible
- Only one Lorentz invariant observable: m_{ll} → Let's make bins

Even more minimal starting point

We have seen in the EFT discussions that acceptance effects in decays play a role. Treat it like $|Y_H|>2.5$ in production

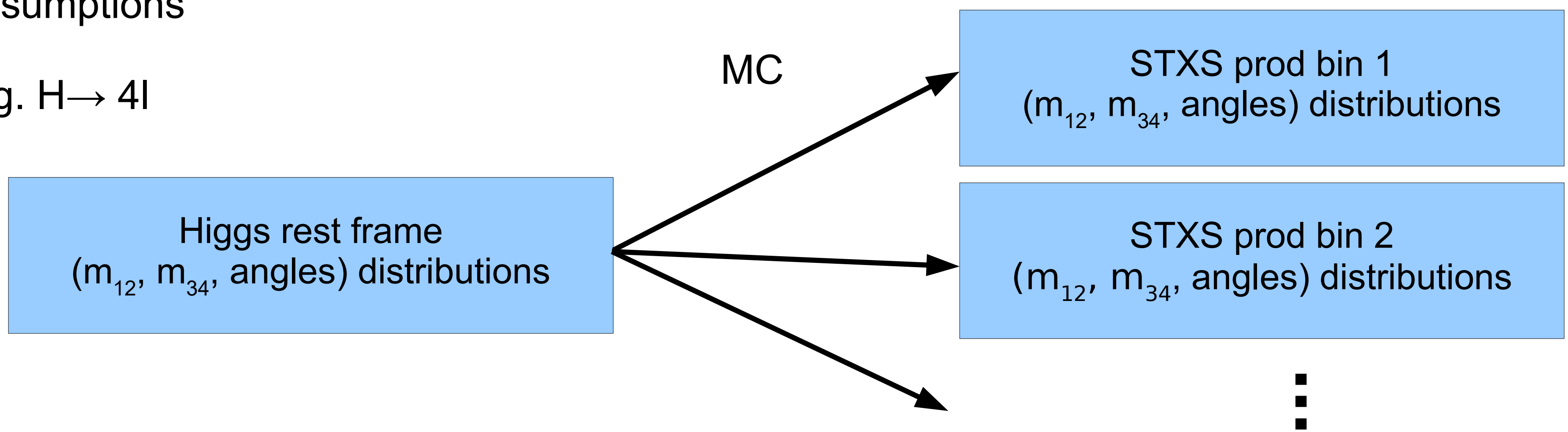
- **H→ZZ***
  - **Add 3 H→ZZ* sub-bins**
    - **H→4l, m_{34} < X (X ~ 10 GeV, not measured region)**
    - **H→4l, X < m_{34} < 62.5 GeV**
    - **H→ZZ*→!4l (populated in ttH multilepton)**
- **H→WW***
  - **Add 4 H→WW* sub-bins**
    - **H→lνlν, m_{ll} < X1 (X1 ~ 10 GeV, not measured region)**
    - **H→lνlν, X1 < m_{ll} < X2 (X2 ~ 50-60 GeV)**
    - **H→lνlν, X2 < m_{ll}**
    - **H→WW*→!lνlν (populated in ttH multilepton, VHWW)**

Production and decay binning

Imagine: O(30) production bins, O(10) decay bins. ⇒ 30 × 10 total bins ?

Truth : Since H is a scalar, can use MC to extrapolate kinematics to each STXS bin without assumptions

e.g. $H \to 4l$



⇒ Only need 30 + 10 truth bins to describe the process

Reco : several possibilities

- Measure binned decay distributions in reco STXS prod bins ⇒ need ~ 30 × 10 bins. Normalization → usual STXS measurement, shapes → decays
- Unfold decay distributions in each prod. bin back to Higgs rest frame, consider inclusively over prod. bins ⇒ 30 + 10 bins to consider
- Unbinned analysis in each reco STXS prod bin (e.g. MLM) ⇒ 30 unbinned models

In all cases seem to need ~30 × 10 templates (or their unbinned equivalent) from signal MC

- An analysis can chose to implement observables for the decay bins only on a small subset of the most sensitive STXS production bins, reducing the problem considerably.

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?