CP violation in the Higgs sector at the LHC

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Introduction:

- What do we do now that we have found the Higgs?
- One answer: study its couplings in detail.
- But then experimentalists show this great plot of couplings vs masses and tell us that we have the SM Higgs (almost!)

- **SM predicts two things**
- **Coupling strengths of the Higgs to all the SM particles**

  AND

- **Tensor structure of the coupling**
Largest couplings of the Higgs to pair of vector bosons and the heaviest fermion the top quark.

- If at all these will carry glimpses of BSM!
- In this talk study these two couplings with a focus on CP violation.

**HVV coupling:**

VBF, VH production

**Htt coupling:**

Associated production of Higgs with a $tt$ pair and inclusive production of Higgs.
References:
These studies were foreseen as the step after discovery!


References which I will use in this talk:
Anom. VVH and and the ttH vertex at the LHC:
1) **ZZH:**
2) **VBF:**
3) **VH**
4) **ttH:** *Contribution to Les Houches proceedings,* F. Boudjema, R.G, D. Guadagnoli and K. Mohan, 1408.xyzw
References which I will use in this talk:
Anom. VVH and the $ttH$ vertex at the $ILC$:

VVH:


$ttH$:

(Bhupal Dev, A.Djoaudi, R.G. et al)

4) EPJC, 71 (2011) 168,
(C. Hangst, R.G., Margarete Muehelleitner et al)
Just the discovery of the Higgs boson is not sufficient to validate the minimal SM.

We need to establish the strength and the tensor structure of the Higgs couplings to all the matter and gauge particles.

To this end just using rates is not enough, but studying kinematic distributions and constructing variables that are sensitive to anomalous vertices, preferably linearly using INTERFERENCE EFFECTS.
Ways to probe the Tensor structure and CP violation:

0) Decay through ZZ to 4 lepton pairs.

0) Decay to a gamma gamma pair. (happening now)

1) Production in WW fusion
2) Production of Higgs in association with a vector boson
   (Upcoming run)

Completely unambiguous:
3) Associated production of a Higgs with a ttbar pair. Low rates! Once we have seen the signal
   This will be the order of the day!
Higgs-Gauge Boson Coupling

- The most general Lorentz structure of the hVV vertex:

\[ i\Gamma^{\mu\nu} = i \frac{gM_Z}{c_W} \left[ A\eta^{\mu\nu} + B(p^{\mu}q^{\nu}) + C\varepsilon^{\mu\nu\rho\sigma}p_\rho q_\sigma \right] \]

- A, B, C are momentum dependent form factors.
- In SM A=1, B=0=C.
- Such a vertex may be generated from BSM physics:
Momentum dependence of Form Factors (A, B, C)

- Structure of Form Factors depend on nature of BSM.
- Infinite possibilities.
- If BSM scale is large, massive particles can be integrated out.

- Supplement SM Lagrangian with higher dimension operators

\[ \mathcal{L}_H = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \frac{\lambda}{2} (\Phi^\dagger \Phi - (v/2)^2)^2 \]

\[ \mathcal{O}_W = 2ig[\Phi^\dagger T^a_2 D^\mu \Phi] D^\nu W^{a\nu}_\mu , \]

\[ \mathcal{O}_{WW} = \frac{g^2}{4} H^\dagger H W^a_\mu W^{a\nu}_\mu , \]

\[ \mathcal{O}_{BB} = \frac{g'^2}{4} H^\dagger H B_\mu B^{\nu} , \]

\[ \tilde{\mathcal{O}}_{WW} = \frac{g^2}{4} H^\dagger H W^{a\nu}_\mu \tilde{W}^{a\mu}_\nu , \]

\[ \tilde{\mathcal{O}}_{BB} = \frac{g'^2}{4} H^\dagger H B_\mu \tilde{B}^{\nu} , \]

\[ \tilde{\mathcal{O}}_{WB} = gg' H^\dagger \sigma^a H W^a_\mu \tilde{B}^{\nu} . \]

Buchmuller, D. Wyler (1986) & Grzadkowski et. al. (2010)
Effective Lagrangian

- Supplement the SM lagrangian with the following terms (unitary gauge)

\[ \mathcal{L}_h^{\text{zz}} = -\frac{1}{4} g_{hZZ} Z_{\mu\nu} Z_{\mu\nu} h - g_{hZZ} Z_\nu \partial_\mu Z_{\mu\nu} h - \frac{1}{4} c Z_{\mu\nu} \tilde{Z}_{\mu\nu} h \]

- This gives rise to a vertex of the form

\[ \Gamma^{\mu\nu}(p_2, p_3) = i\eta^{\mu\nu} \left( a \left( gM_Z / c_W \right) + g_{hZZ}^{(1)} (p_2 \cdot p_3) + g_{hZZ}^{(2)} (p_2^2 + p_3^2) \right) \]

\[ - ig_{hZZ}^{(1)} p_2^\nu p_3^\mu - ig_{hZZ}^{(2)} (p_2^\mu p_2^\nu + p_3^\mu p_3^\nu) \]

\[ - i c c_{\mu\nu}^{\rho\sigma} p_2^\rho p_3^\sigma \]

- \( a, g_{hZZ}, c \) are constants

- \( g_{hZZ}, c \) suppressed by the scale of new physics \( 1/\Lambda_i^2 \)

\[ g_{hZZ}, c \rightarrow \frac{2 g M_Z}{c_W \Lambda_i^2} \]
Use observables to discriminate between the various vertex structures.

CMS & ATLAS use a likelihood constructed out of these.

h $\rightarrow$ ZZ*(4l) decays

Godbole, Miller, Muhlleitner, 2007. Rates CP conserving and only can delineate regions in |c|--a plane.

2007: sensitivity of rates alone need to use distributions for further Discrimination, 2014!

\[
\begin{align*}
cos(\theta_1), \cos(\theta_2), \\
cos(\theta^*), \cos(\phi), \\
M^*_Z
\end{align*}
\]
Identify observables which have specific CP and T transformation properties and construct asymmetries proportional to each of the anomalous couplings.

\( h \rightarrow ZZ^*(4l) \) decays

Godbole, Miller, Muhlleitner, 2007 Rates CP conserving and only can delineate regions in \(|c|--a\) plane.

\[ \cos(\theta_1), \cos(\theta_2), \cos(\theta^*), \cos(\phi), M^*_Z \]
Vector Boson Fusion (VBF)

- **Typical VBF cuts**
  - Two forward jets with a large rapidity gap $\Delta \eta_{jj} > 4$.
  - Invariant mass of the jets $M_{jj} > 600$ GeV.

Djouadi, Godbole, Mellado, Mohan, 2013

Plehn, Rainwater, Zeppenfeld, 2001
VBF: ~25% contribution from Z mediated production
Phase space populated by ggF and QCD background similar to that of BSM couplings
VBF general comments

The study points out kinematical distributions in addition to phi\(_{jj}\) which distinguishes the SM from the BSM operators. If both CPV and CPV Higher Dimensional operators are present the structure in phi distribution can go away!

New phase space region for probing the BSM operators in EW Higgs + 2jets production.

But no capability of separating WWH from ZZH

Also apart from phi\(_{jj}\) no capability of separation between the 0+ and 0- operators.

The momentum dependence of the higher dimensional operators makes the Pt distributions harder and hence possible to use the low delta-eta\(_{jj}\) region. (Analysis with B. Mellado for spin 2 case!)
Next go to VH production:

Momentum dependence of the anomalous vertex makes the $p_T$ distributions and $\Delta_{HY}$ distributions harder.

This is in addition to the change in HV invariant mass distribution (Noticed and studied also by Ellis, Veronica Sanz and You)

A detailed study also by Plehn, Englert et al.
A study of Boosted VH process.

Higgs with a large boost (or $p_T$): Decay $b\bar{b}$ collimated and form a single jet. This 'fat' jet looks different from a QCD jet.

Use boosted Higgs decays to $b\bar{b}$ and jet substructure analysis. Use the jet direction as the direction of the Higgs.

Using the information on the $V$ and $H$ momentum one can reconstruct the hard scattering rest frame and construct different angles, just like in $e^+e^-$ case.

In addition this also increases sensitivity to the anomalous operators, but does not have much to say about CP violation. Hence I dont discuss it here further.
One angle from the e+e- case

CONSTRUCT MORE SUCH ANGLES.
$\cos \theta^*$

Angle between lepton in parent W rest frame and the W in the lab frame.

A measure of polarization of the W.

Differentiates A from B and C.

Cannot strongly differentiate between different non-SM operators.

$$\cos \theta^* = \frac{\hat{p}_{l_1}^{(V)} \cdot \hat{p}_V}{|\hat{p}_{l_1}^{(V)}| |\hat{p}_V|}$$
Variables that explore the angular distribution between the plane of production of the decaying leptons and the plane of production of Wh are linear and can discriminate between different BSM couplings.

Test three such angles

\[
\cos \delta^+ = \frac{\vec{p}_{l_1}^{(V)} \cdot (\vec{p}_V \times \vec{p}_H)}{|\vec{p}_{l_1}^{(V)}||\vec{p}_V \times \vec{p}_H|} , \quad \cos \delta^- = \frac{(\vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)}) \cdot \vec{p}_V}{|(\vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)})||\vec{p}_V|} ,
\]

\[
\Delta \phi^{LV} = \Delta \phi(\vec{p}_{l_1}^{(V)}, \vec{p}_V)
\]
\[ \cos \delta^+ \]

Angle between lepton in parent W rest frame and the normal to the WH production plane.

\[
\cos \delta^+ = \frac{\vec{p}_{l_1}^{(V)} \cdot (\vec{p}_V \times \vec{p}_H)}{|\vec{p}_{l_1}^{(V)}| \, |\vec{p}_V \times \vec{p}_H|}
\]

Interference term only between SM and BSM couplings.
Comparison with backgrounds
## CONSTRUCT ASYMMETRIES

<table>
<thead>
<tr>
<th>Asymmetries</th>
<th>$ZH_{SM}$</th>
<th>$ZH_{BSM}^{0-}$</th>
<th>$ZH_{BSM}^{0+}$</th>
<th>$Z+$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A(\cos \theta^*)$</td>
<td>0.35</td>
<td>-0.05</td>
<td>-0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>$A(\cos \delta^+)$</td>
<td>-0.207</td>
<td>-0.262</td>
<td>0.088</td>
<td>-0.188</td>
</tr>
<tr>
<td>$A(\cos \delta^-)$</td>
<td>-0.209</td>
<td>-0.435</td>
<td>-0.103</td>
<td>-0.321</td>
</tr>
</tbody>
</table>
WH Asymmetry, errors for 3000 $fb^{-1}$.
$\alpha = 1, \Lambda_i = 1 \, TeV$

About 80-100 fb$^{-1}$ data for 95% exclusion limits using Zh production.

$\Delta \phi^{lV}$ is stronger discriminant.

Analysis for Wh in progress.
Higgs coupling to top quarks

\[ \mathcal{L}_{ttth} = g_{ttth} \bar{t}(a + ib\gamma_5)\phi t \]

\[ g_{ttth} = \frac{m_t}{v} \]

In SM \( a = 1 \) and \( b = 0 \).

For a pure pseudoscalar \( a = 0 \) and \( b \neq 0 \).

Higgs of mixed CP properties \( a \neq 0 \) and \( b \neq 0 \).

Non-SM couplings will affect higgs production and decay rates
This is what we see all the time!
Higgs rates

- Higgs production and decay rates can provide information about the strength of $g_{ttH}$
- Unambiguous determination of the nature of the interaction requires a more direct probe.

\[
\frac{\sigma(gg \rightarrow h)}{\sigma(gg \rightarrow h)^{SM}} = \frac{\Gamma(h \rightarrow gg)}{\Gamma(h \rightarrow gg)^{SM}} = a^2 + b^2 \frac{|A_t^b(\tau_t)|^2}{|A_t^a(\tau_t)|^2} .
\]

\[
\frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow \gamma\gamma)^{SM}} = \frac{|\kappa_W A_W^a(\tau_W) + a \frac{4}{3} A_t^a(\tau_t)|^2 + |b \frac{4}{3} A_t^b(\tau_t)|^2}{|A_W^a(\tau_W) + \frac{4}{3} A_t^a(\tau_t)|^2} .
\]
Effect on kinematic distributions

• To probe directly the nature of the coupling scalar or pseudoscalar look at the kinematic distributions of decay products
• Also look at the spin spin correlations between the top and the anti-top.
• How to probe these correlations?
Reminder of a result from $e^+e^-$

The energy dependence of cross-section depends on $a$ and $b$.

Top curve $a = 1$, $b = 0$, Pure Scalar
Bottom curve $a = 0$, $b = 1$, pure pseudoscalar.

(Bhupal Dev, A.Djoaudi, R.G. et al)

and

EPJC, 71 (2011) 1681
(C. Hangst, R.G., Margarete Muehelleitner et al)
Threshold behaviour of $tth$ production

For $qq$ initiated process angular momentum provide hints to origin of suppression.
For scalar overall angular momentum of $tth = 0$.
For pseudoscalar overall angular momentum of $tth = 1$.

Dominant $gg$ initiated process also suppressed but not as strongly.

$pp \rightarrow tth$
Pt distribution of Higgs

Noticed also by Maltoni et al:

The gamma\(_5\) in the vertex makes a difference in the momentum flow at the vertex. Difference seen even in normalised distributions.
Spin correlations of the top and anti-top affected by the nature of interaction.

Difficult angle to reconstruct at LHC.

\[
\cos(\Delta \phi^{\ell\ell}(\ell^+, \ell^-)) = \frac{(\hat{z} \times \vec{p}_{\ell^-}^t) \cdot (\hat{z} \times \vec{p}_{\ell^+}^t)}{|\vec{p}_{\ell^-}^t||\vec{p}_{\ell^+}^t|},
\]
Azimuthal angle between t and tbar

Pseudoscalar case larger pt of Higgs makes the distribution flatter.
Simpler Alternatives

- Difference in azimuthal angle of the leptons in the rest frame of the higgs.
- Azimuthal angle difference between the top pair.
- Simpler to reconstruct and can be extended to all decay modes of the top.
Another angle: in terms of lab obs.

\[ \cos(\Delta \theta^{lh}(\ell^-, \ell^+)) = \frac{(p_h \times p_{\ell^-}) \cdot (p_h \times p_{\ell^+})}{|p_h \times p_{\ell^-}| |p_h \times p_{\ell^+}|} \]

Similar observables using W momenta.
They can discriminate well but...

- These distributions can discriminate well but do not work so well for determination of CP violation if there is mixing between CP even and CP odd state.

- The overall order of magnitude agreement WW, ZZ and gamma gamma rates clearly says that the dominant part of the observed Higgs is certainly CP even.

- Need observables sensitive to mixing and also CP violating in character! Observables shown so far NOT LINEAR in b!
One observable Linear in $b$

$$\beta \equiv \text{sgn}\left( (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell^- \times \vec{p}_\ell^+) \right).$$

The red and blue have different behaviour wrt sign of beta.

Indeed an effect linear in $b$

Completely in terms of lab observables.

No need to construct any particular frame.
Other studies

- Pt spectrum dependency on the CP even nature noticed by Maltoni and collaborators. [PLB701 (2011) 427-433 AND 1407.5089](http://www.elsevier.com)
  Concentrated on using the distribution shapes to establish the CP property of the Higgs and used AMC @ NLO.

- Using the spin spin correlations for the ttHiggs signal: Gabrielli and collaborators.: [1403.1790](https://arxiv.org/)
  Concentrated on using the spin spin correlations for getting the background under control

- CP violation studies: Ellis and collaborators [1312.5736](https://arxiv.org/)
  Observables defined for lab frame in our analysis. Ellis et al defined similar observable but in the ttbar rest frame.
CPV observable in ttbar rest frame

\[ \alpha \equiv \text{sgn} \left( p_{t+}^{\tilde{t}} \cdot (p_{\ell-}^{\tilde{t}} \times p_{\ell+}^{\tilde{t}}) \right). \]
Asymmetry: Linear behaviour in $b$, Uniquely CP violating.

Asymmetry of lab variables (blue) is smaller but easier to construct. Less systematic uncertainties.
Summary

- The order of the day to analyse the CP structure of the HVV and Htt vertices, and hence probe the BSM, study of both rates and interference effects is necessary.
- The next round will be able to probe the WWH vertex separately in VBF and VH production and add to our knowledge
- Htt production and study of spin, spin correlations are the next order.
- Electron positron colliders are really great for many of these studies.
h $\rightarrow$ WW* decays

- Although the branching ratio is larger than h ZZ*, plagued by backgrounds.
- Not easy to reconstruct the momenta of all decaying particles.
- However rate information in this channel can be used in correlation with other channels to extract some amount of information.
What about the hWW vertex?

- We already know that the vertex structure of hZZ can be probed. Do we need to do this same with hWW?
- The couplings of h to W could arise from independent higher dimensional operators.
- Custodial Symmetry? This is already violated in SM by gauging of the hypercharge.
- The extra operators violate this symmetry in the same manner. Discrepancies in the hWW and hZZ couplings may arise naturally without new sources of custodial symmetry violation.
- Imperative to determine both the hWW and hZZ couplings explicitly.
\[ \Delta \phi^{lv} \]

Azimuthal angle between lepton in parent W rest frame and the W in the lab frame.

\[
\cos \delta^- = \frac{(\vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)}) \cdot \vec{p}_V}{|\vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)}||\vec{p}_V|}
\]

Interference term only between SM and BSM couplings.
\[ \cos \delta^- \]

Angle between the boosted W decay plane and the W in the lab frame.

\[
\cos \delta^- = \frac{\left( \vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)} \right) \cdot \vec{p}_V}{\left| \left( \vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)} \right) \right| \left| \vec{p}_V \right|}
\]

Interference term only between SM and BSM couplings.
Comparison with backgrounds
3D-Likelihoods

- We can combine all this information in a likelihood analysis.

\[ Q = -2 \log \frac{L(data|hypothesis X)}{L(data|SM)} \]

Use 3D binned likelihood.

Test 3 different combinations of observables in Likelihood.

\[ \mathcal{L}(p_T^h, \cos \theta^*, \cos \delta^+) \]
\[ \mathcal{L}(p_T^h, \cos \theta^*, \cos \delta^-) \]
\[ \mathcal{L}(p_T^h, \cos \theta^*, \Delta \phi^{lV}) \]
Vh production kinematics

- Invariant mass and the transverse momentum distributions show marked differences.
- Typically background elimination requires large $P_t$ cuts.
- Larger acceptance to non-SM terms.
Higher acceptance of $Vh$ to anomalous couplings

- Boosted analysis in $Vh$ production has an increased acceptance to non-SM couplings
- For example: set $A=1$ and vary $B$ or $C$ & plot ratio of cross-sections

Ratio of cross-sections:

$$R_{\text{jet-sub}}^{\pm} = \frac{\sigma^{SM+BSM\pm}}{\sigma_{\text{jetsub}}}$$

$$R_{\text{tot}}^{\pm} = \frac{\sigma_{\text{tot}}^{SM+BSM\pm}}{\sigma_{\text{tot}}^{SM}} - C + B$$

$\Lambda(TeV)$

Godbole, Miller, KM, White, 2013
NLO effects on pt distributions

Z boson pt

\[
\frac{d\sigma}{dp_T^Z} \quad (fb)
\]

\[
p_T^Z (GeV)
\]

MCFM
- LO SM
- \( c_W = 0.05 \)
- \( c_W = 0.01 \)
- NLO SM