

# Higgs CP and Boosted Jets

Beyond the LHC Workshop

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[Based on Godbole, DJM, Mohan, White, arXiv:1306.2573]

# Introduction

Everyone is now calling the new resonance at 125 GeV the “Higgs boson”.

But is this the Higgs boson of the Standard Model or something else?

To answer this, we must measure:

- The Higgs boson Spin and CP,
- Its couplings to gauge bosons and fermions,
- The Higgs self couplings.

[\[See talk by A. Papaefstathiou\]](#)

This programme is ultimately **Beyond the LHC** but some initial measurements can be made at the LHC.

Today I will discuss the determination of the **Higgs boson CP** via Higgstrahlung off a  $W/Z$  followed by  $H \rightarrow b\bar{b}$ . We will need to use **jet substructure** [\[See talk by Salam\]](#).

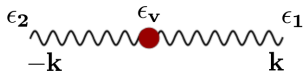
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# Higgs boson CP and Spin so far

**Spin 1** is ruled out by  $H \rightarrow \gamma\gamma$  and the **Landau-Yang theorem**

Imagine a vector decaying  
to two photons



There are 3 possible vertex structures,

$$\begin{aligned} & \epsilon_1 \times \epsilon_2 \cdot \epsilon_v F_1(k^2) \\ & \epsilon_1 \times \epsilon_2 \cdot \mathbf{k} \epsilon_v \cdot \mathbf{k} F_2(k^2) \\ & \epsilon_1 \cdot \epsilon_2 \epsilon_v \cdot \mathbf{k} F_3(k^2) \end{aligned}$$

But Bose symmetry tells us that  $\mathcal{M}(\epsilon_1, \epsilon_2, \mathbf{k}) = \mathcal{M}(\epsilon_2, \epsilon_1, -\mathbf{k})$  so all three terms must be zero.

[Note that this includes an inherent assumption of narrow width.]

**Spin 2** is harder to rule out because we have no convincing model.

- **KK-graviton** [Where are all the other KK states?]  
With democratic couplings predicts  $\Gamma(H \rightarrow gg) = 8\Gamma(H \rightarrow \gamma\gamma)$ .  
[Ellis, Sanz, You, 2012]
- **ATLAS** uses BDTs and  $H \rightarrow WW$  to disfavour “graviton-like”  $2^+$  bosons at  $\sim 2-3\sigma$ .  
ATLAS  $H \rightarrow ZZ$  is a bit weaker ( $2^+$  at 83%,  $2^-$  at 88%)  
[See EPS-HEPP talk by Schaefer]
- **CMS** disfavour  $2^+$  at  $2.7\sigma$  ( $gg$ -production only)  
[See EPS-HEPP talk by Bendavid]
- A **tree-level MC**, JHUGen, is available for spin 0, 1 and 2.  
[See EPS-HEPP talk by Gao]

A more **model independent method** would be to rule out all possible spin-2 tensor structures.

For example, for a general  $2^-$  state the only tensor structures are:

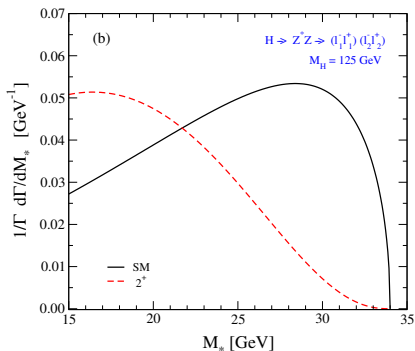
$$c_1 \epsilon^{\mu\nu\beta_1\rho} p_\rho k^{\beta_2} + c_2 \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma k^{\beta_1} k^{\beta_2} + \beta_1 \leftrightarrow \beta_2$$

Here, unlike the SM, every vertex contains a momentum, so the **threshold dependence** is very different.

For other structures in  $2^+$  need angular distributions.

[Choi, DJM, Muhlleitner, Zerwas, 2002;  
Heinemeyer et al., 2013]

[Beware the Velo-Zwanziger problem.]



## Higgs boson CP

- ATLAS and CMS use  $H \rightarrow ZZ$  to disfavour a pure pseudoscalar at the  $\sim 2-3\sigma$  level.

[ATLAS-CONF-2013-013, CMS-PAS-HIG-13-002, Chatrchyan et al. 2013]

However,

- Constraints so far are only for the HZZ vertex (the  $HWW$  vertex is difficult to probe with  $H \rightarrow WW$  due to kinematical cuts to eliminate background).
- There are as yet no limits on Higgs with CP even-odd mixtures.
- In many BSM models (e.g. 2HDM) the pseudoscalar does not couple to gauge bosons.

$\Rightarrow$  These results **do not** prove that the Higgs is  $0^+$ .

# Higher Dimensional Operators

There are two model independent ways one can go about quantifying deviations from the SM.

- Supplement the SM Lagrangian with **higher dimensional operators** that originate from Beyond the SM (BSM) physics:

$$g_W^2 \frac{c_1}{2\Lambda_1^2} \Phi^\dagger \Phi F_{\mu\nu} F^{\mu\nu}, \quad g_W^2 \frac{c_2}{2\Lambda_2^2} \Phi^\dagger \Phi \tilde{F}_{\mu\nu} F^{\mu\nu}. \quad [\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}]$$

These lead to

$$\Rightarrow ig_W M_W \left[ g^{\mu\nu} + \frac{4c_1}{\Lambda_1^2} (p^\mu q^\nu - g^{\mu\nu} p \cdot q) + \frac{8c_2}{\Lambda_2^2} \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

where  $p$  and  $q$  the  $W/Z$  boson momenta.

- Alternatively one could simply regard this as the **most general tensor structure** for spin 0.



# The importance of $WH$ production

How can we investigate the  $HWW$  vertex at the LHC?

- $H \rightarrow WW$  is hard to use due to cuts to remove background.
- In Vector Boson Fusion one cannot separately study the  $Z$  and  $W$  contributions.

Furthermore, non-SM  $HVV$  vertices have a reduced acceptance to VBF-like kinematic cuts.

⇒ At the LHC, one is unavoidably led to **WH production** to probe the  $HWW$  vertex.

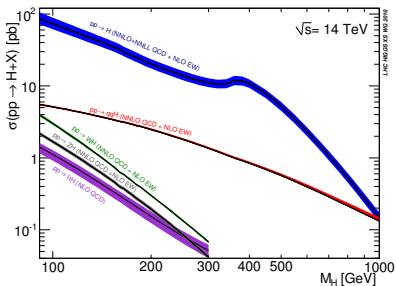
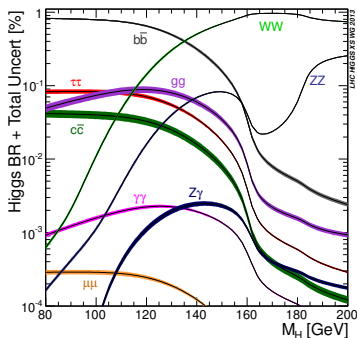


- Production**

$pp \rightarrow HW$  cross-section  $\sim 1.5$  pb  
(cf. gluon fusions  $\sim 50$  pb)

- Decay**

$H \rightarrow b\bar{b}$  provides the highest BR  
Choose  $W/Z$  to decay leptonically



### Problems:

- How do we extract signal from the huge background?
- How do we reconstruct the Higgs?

[Plots from LHC Higgs Cross Section Working Group]

# Jet Substructure

Both of these problems can be overcome by using the substructure of boosted jets. [\[Butterworth, Davison, Ruben, Salam, 2008\]](#)

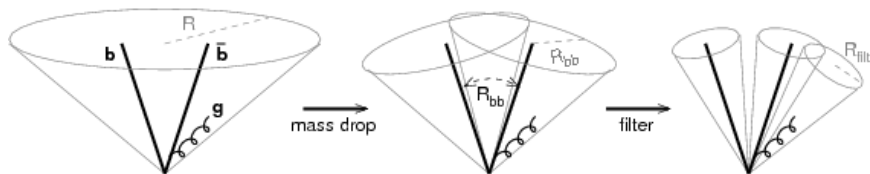
- The Higgs is usually very **boosted**.
- Resulting b-jets combine to look like one fat jet.



[\[Figures stolen from G. Salam's talk\]](#)

- At first sight this looks like a typical QCD jet, but the substructure tells us it is not.
- Note that the need for boosted Higgs prevents us using the threshold dependence.

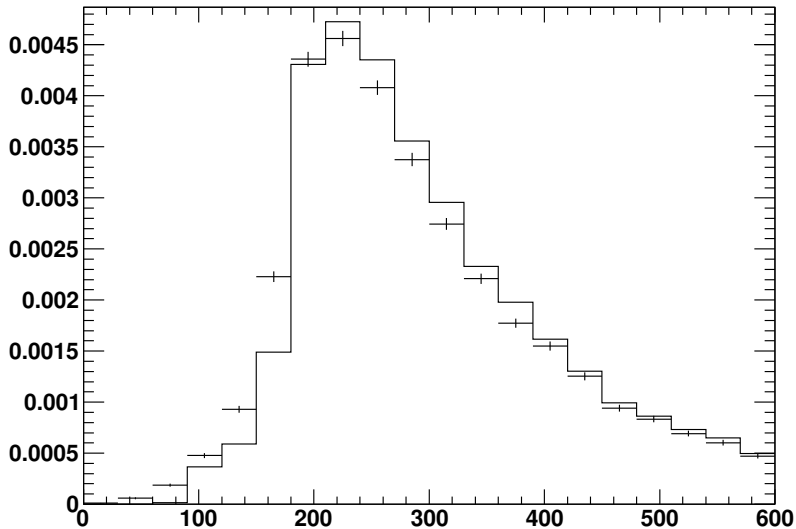
Substructure also lets us remove the parton shower junk from the jet.



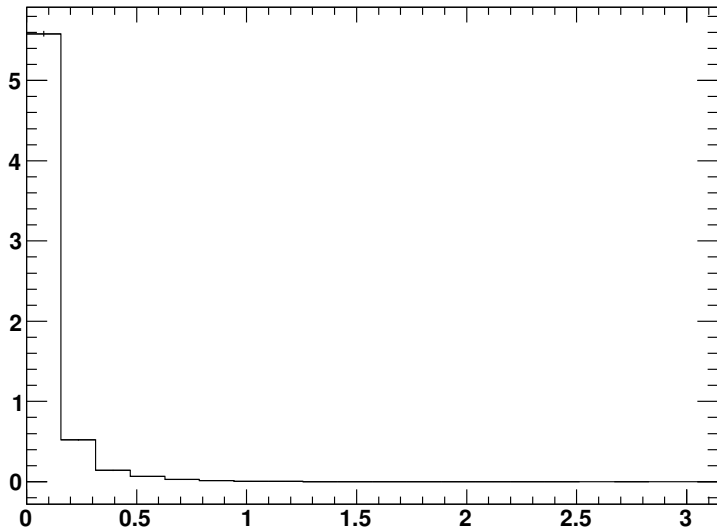
Soft junk is removed  $\Rightarrow$  can reconstruct the Higgs.

We simulate all processes using **MadGraph5** interfaced with **Pythia6** and use the **FastJet** package to cluster the jets. The effective Lagrangian was implemented in **FeynRules**.

All simulations are for a 14 TeV LHC.

**$p_T$  of reconstructed Higgs**

## Angle between reconstructed Higgs and that from hard interaction



# Event Selection

For  $ZH$  production we require:

- A fat jet (radius  $R = 1.2$ ,  $p_T > 200 \text{ GeV}$ )  
After filtering require  $\leq 3$  subjets with  $p_T > 20 \text{ GeV}$ ,  $|\eta| < 2.5$ ,  
radius  $R_{sub} = \min(0.3, R_{bb})$   
 $R_{bb}$  is the two hardest subjets's separation; both must be  $b$ -tagged.
- Exactly 2 leptons (transverse momentum  $p_T > 20 \text{ GeV}$ ,  $|\eta| < 2.5$ ).  
Same flavour and opposite charge.  
 $m_{ll}$  within  $10 \text{ GeV}$  of  $M_Z$ .  
Isolated: the sum of all particle transverse momenta in a cone of  
radius  $R = 0.3$  about each lepton  $< 10\%$  that of the lepton.
- Reconstructed  $Z$  has a  $p_T > 150 \text{ GeV}$  and  $\Delta\phi(Z, H) > 1.2$ .
- $b$ -tagging efficiency is  $\epsilon_b = 0.6$  and light quark jet rejection rate is  
 $r_j = 100$ .

After cuts most backgrounds are eliminated.

### Signal:

SM $ZH$	0.12 fb
CP Even BSM	0.48 fb
CP Odd BSM	0.73 fb

### Backgrounds:

$Z + \text{jets}$	0.23 fb
$t\bar{t}$	0 fb
Single top	0 fb

- $\Lambda_{1,2}$  set to reproduce SM  $\sigma$  before cuts.
- The extra momentum (derivative) in the BSM operators boosts the Higgs more, so the acceptance to selection cuts is much better than the SM.



For  $WH$  production we require:

- The Higgs reconstructed as for ZH.
- Exactly 1 hard lepton ( $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.5$ ), isolated as before.
- Missing transverse momentum  $\cancel{p}_T > 30 \text{ GeV}$ .
- Reconstructed  $W$  has  $p_T > 150 \text{ GeV}$  and  $\Delta\phi(H, W) > 1.2$ .
- No additional jet activity with  $p_T^{jet} > 30 \text{ GeV}$ ,  $|\eta| < 3$   
(to suppress single and top pair production backgrounds).

$WH$  background removal is even better, though some top backgrounds are left.

### Signal:

SM $WH$	0.355 fb
CP Even BSM	1.45 fb
CP Odd BSM	2.14 fb

### Backgrounds:

$W + \text{jets}$	0.28 fb
$t\bar{t}$	0.13 fb
Single top	0.06 fb

- So far we haven't needed to reconstruct the neutrino.
- However, we also need the neutrino to make angular observables.

# Neutrino Reconstruction

- Identify  $\vec{p}_{T\nu}$  with the missing transverse momentum  $\vec{\cancel{p}}_T$ .  
Also use  $p_\nu^2 = 0$ .
- Demand  $(\vec{p}_\nu + \vec{p}_{h_1})^2 = M_W^2$ , solving the quadratic equation.
- Gives two solutions.

We reconstruct the “true” neutrino momentum 50% of the time ( $\simeq 5\%$  give imaginary solutions).

Boosts of Higgs,  $\beta_z^H$ , and  $W$ ,  $\beta_z^W$ , should be similar.

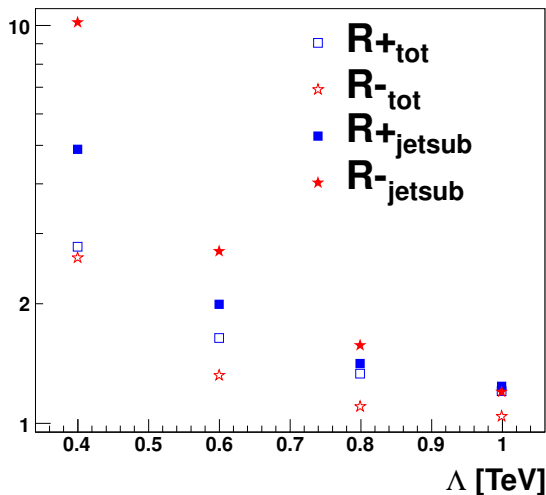
Choose neutrino solution that minimizes  $|\beta_z^W - \beta_z^H|$ .

Gives the true neutrino momentum in 65% of cases.

To check the effect of the neutrino reconstructions, I will (sometimes) present three cases:

- **MCT:** “Monte-Carlo Truth” where the neutrino momentum is reconstructed from the  $p_T$  of the “true” neutrino rather than the  $\cancel{p}_T$ .
- **BT:** Choose the solution by demanding  $|\beta_z^W - \beta_z^H|$  is minimized.
- **BN:** Use both solutions of the quadratic equation.

Ratio of cross-sections for  $WH$ :



Before cuts:

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

After cuts:

$$R_{\text{jetsub}}^{\pm} = \frac{\sigma_{\text{jetsub}}^{\text{SM}+\text{BSM}\pm}}{\sigma_{\text{jetsub}}^{\text{SM}}}$$

Variation with the  $p_T$  cuts can provide information on the presence of BSM physics.

# Angular Observables

We examined lots of different angles to find angles that discriminate between the different operators, and I present three of them here:

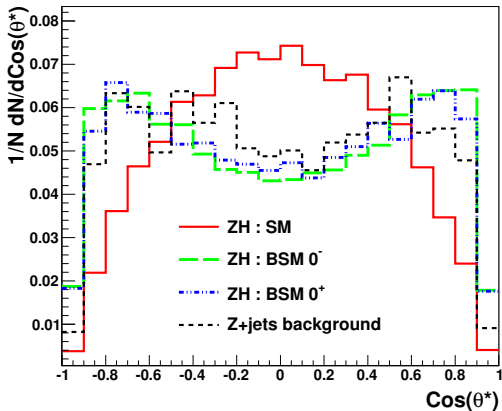
$$\begin{aligned}\cos \theta^* &= \frac{\vec{p}_{l_1}^{(V)} \cdot \vec{p}_V}{|\vec{p}_{l_1}^{(V)}| |\vec{p}_V|} \\ \cos \delta^+ &= \frac{\vec{p}_{l_1}^{(V)} \cdot (\vec{p}_V \times \vec{p}_H)}{|\vec{p}_{l_1}^{(V)}| |\vec{p}_V \times \vec{p}_H|}, \\ \cos \delta^- &= \frac{(\vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)}) \cdot \vec{p}_V}{|(\vec{p}_{l_1}^{(H^-)} \times \vec{p}_{l_2}^{(H^-)})| |\vec{p}_V|}.\end{aligned}$$

- $\vec{p}_X^{(Y)} \equiv$  three-momentum of  $X$  in the rest frame of  $Y$ .
- No  $Y \Rightarrow$  momentum is in the lab frame.
- $H^-$  is the parity inverted Higgs four-momentum, i.e.  $(\vec{p}_H \rightarrow -\vec{p}_H)$
- $V \equiv W^\pm, Z$

ZH:  $\cos \theta^*$ 

$$\cos \theta^* = \frac{\vec{p}_{l_1}^{(Z)} \cdot \vec{p}_Z}{|\vec{p}_{l_1}^{(Z)}| |\vec{p}_Z|}$$

Angle between lepton in parent  $Z$  rest frame and the  $Z$  in the lab frame.

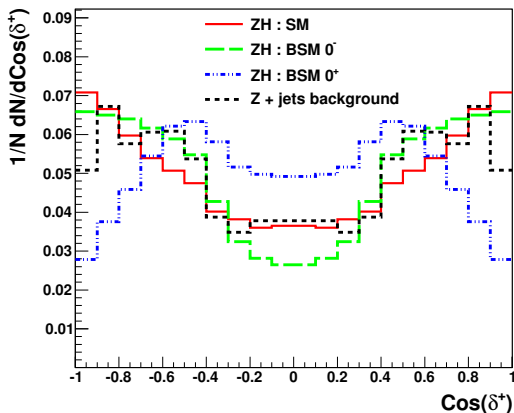


This distinguishes between SM and BSM operators.

ZH:  $\cos \delta^+$ 

$$\cos \delta^+ = \frac{\vec{p}_{l_1}^{(Z)} \cdot (\vec{p}_Z \times \vec{p}_H)}{|\vec{p}_{l_1}^{(Z)}| |\vec{p}_Z \times \vec{p}_H|}$$

Angle between lepton in parent Z rest frame and the normal to the ZH production plane.



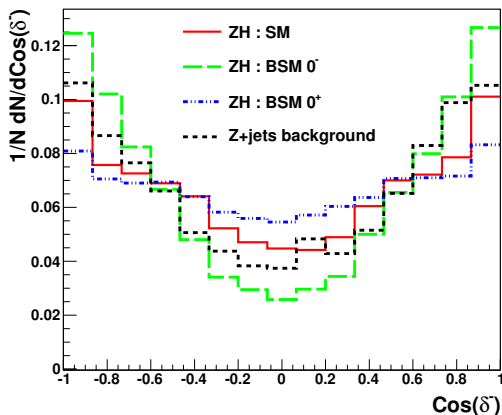
This distinguishes the BSM CP even operator.



ZH:  $\cos \delta^-$ 

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

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

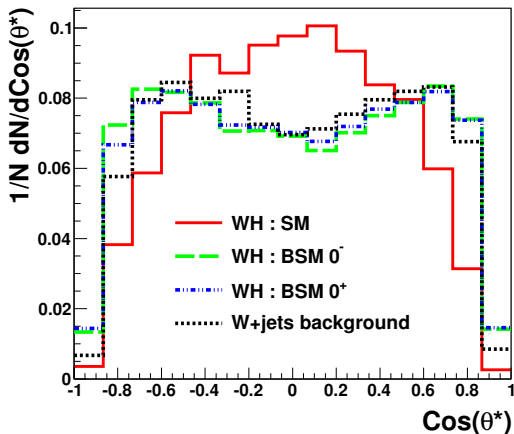


This distinguishes the BSM CP odd operator.

WH:  $\cos \theta^*$ 

$$\cos \theta^* = \frac{\vec{p}_{l_1}^{(W)} \cdot \vec{p}_W}{|\vec{p}_{l_1}^{(W)}| |\vec{p}_W|}$$

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

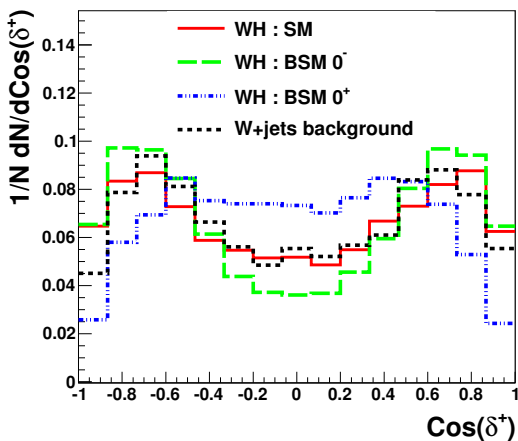


This distinguishes between SM and BSM operators.

WH:  $\cos \delta^+$ 

$$\cos \delta^+ = \frac{\vec{p}_{l_1}^{(W)} \cdot (\vec{p}_W \times \vec{p}_H)}{|\vec{p}_{l_1}^{(W)}| |\vec{p}_W \times \vec{p}_H|}$$

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

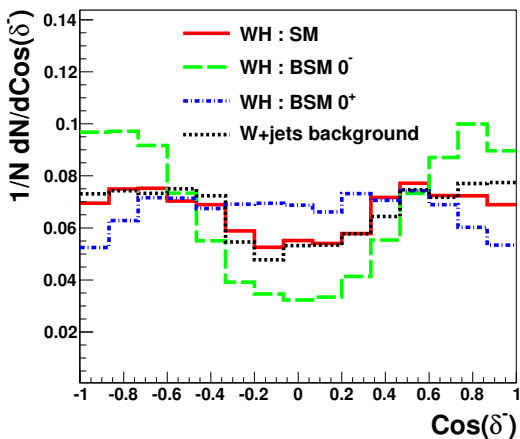


This distinguishes the BSM CP even operator.

WH:  $\cos \delta^-$ 

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

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



This distinguishes the BSM CP odd operator.

# Asymmetries

To quantify these differences, we can construct asymmetries:

$$A(X) = \frac{\sigma(|X| < 0.5) - \sigma(|X| > 0.5)}{\sigma(|X| < 0.5) + \sigma(|X| > 0.5)}$$

where  $X \in \{\cos \theta^*, \cos \delta^+, \cos \delta^-\}$ .

These give:

	$ZH_{SM}$	$ZH_{BSM}^{0-}$	$ZH_{BSM}^{0+}$	Z+jets
$A(\cos \theta^*)$	0.35	-0.05	-0.02	0.07
$A(\cos \delta^+)$	-0.207	-0.262	0.088	-0.188
$A(\cos \delta^-)$	-0.209	-0.435	-0.103	-0.321

For  $WH$  we have 3 ways for reconstructing the neutrino:

		$WH_{SM}$	$WH_{BSM}^{0-}$	$WH_{BSM}^{0+}$	W+jets
<b>MCT:</b>	$A(\cos \theta^*)$	0.413	0.082	0.096	0.152
	$A(\cos \delta^+)$	-0.204	-0.342	0.093	-0.189
	$A(\cos \delta^-)$	-0.104	-0.403	-0.003	-0.173
<b>BT:</b>	$A(\cos \theta^*)$	0.396	0.073	0.100	0.142
	$A(\cos \delta^+)$	-0.150	-0.284	0.142	-0.138
	$A(\cos \delta^-)$	-0.058	-0.353	0.042	-0.118
<b>BN:</b>	$A(\cos \theta^*)$	0.411	0.060	0.095	0.132
	$A(\cos \delta^+)$	-0.161	-0.289	0.141	-0.138
	$A(\cos \delta^-)$	-0.059	-0.367	0.030	-0.135

# Multiple operators

So far, we have seen the pure BSM operators separately from the SM. This is important because no-one has examined the form of the HWW vertex yet.

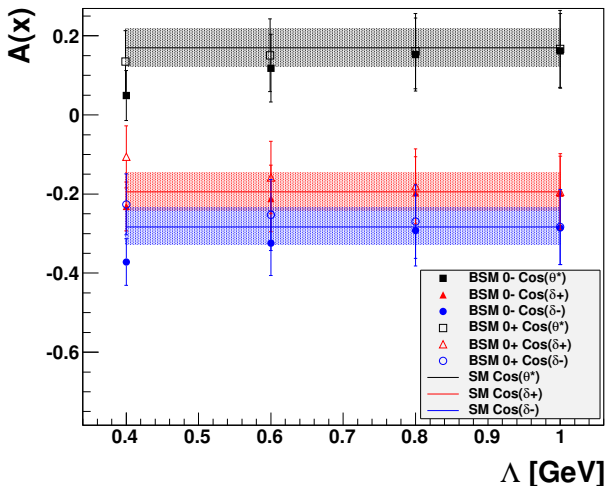
However, it is also interesting to ask if we can distinguish the case where we have the SM **plus** addition higher dimensional operators.

We make a simulation as before and now compare the asymmetries for

- SM + BSM  $0^+$
- SM + BSM  $0^-$

with the SM on its own, taking into account the interference and the dominant  $W/Zjj$  background.

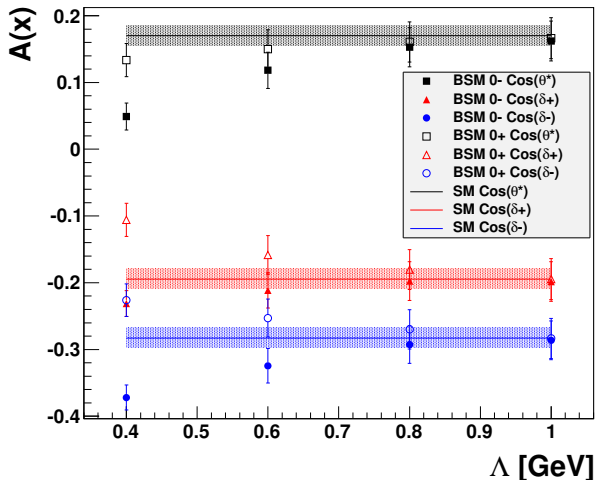
These are again for the 14 TeV LHC, now with  $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$  of luminosity.

ZH asymmetries for  $300 \text{ fb}^{-1}$  of data for 14 TeV LHC

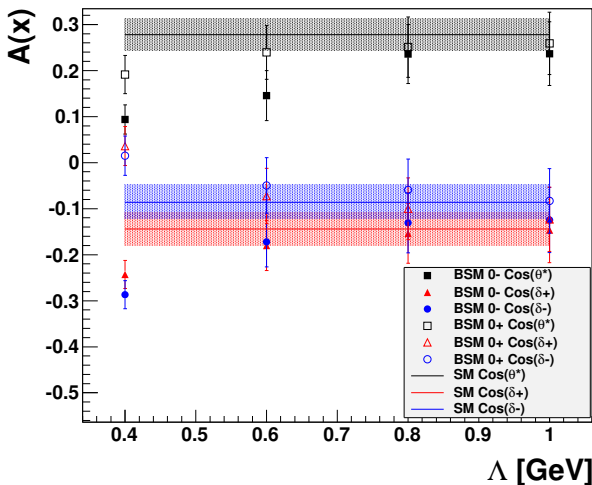
Coloured bands represent statistical uncertainty on SM.



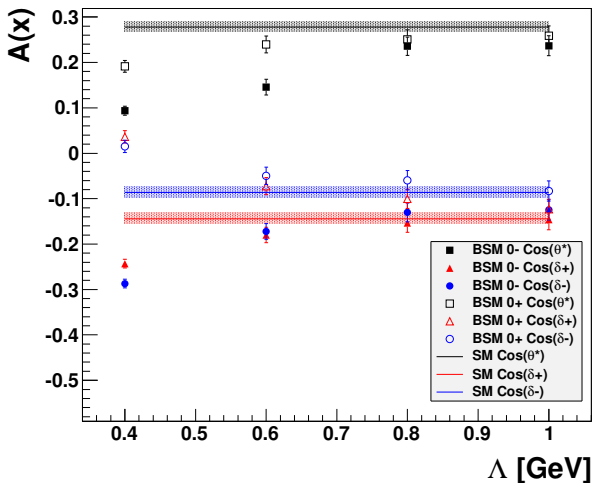
# ZH asymmetries for $3000 \text{ fb}^{-1}$ of data for 14 TeV LHC



# WH asymmetries for $300 \text{ fb}^{-1}$ of data for 14 TeV LHC



# WH asymmetries for 3000 fb<sup>-1</sup> of data for 14 TeV LHC



# Conclusions

- We examined  $ZH$  and  $WH$  production at the LHC, with  $H \rightarrow b\bar{b}$  pair.
- We used **jet structure** to distinguish the signal from the background and reconstruct the Higgs.
- We constructed angular distributions to distinguish between new CP even and CP odd operators coupling the Higgs to vector bosons.
- The  $HWW$  and  $HZZ$  couplings can be studied independently of each other.
- The selection cuts increase sensitivity to BSM physics.
- We can also use this method when both BSM and SM operators are present, and mutually interfere.