Probing BSM physics in Vh production at LHC

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Based on: arXiv:1409.5449, arXiv:1306.2573

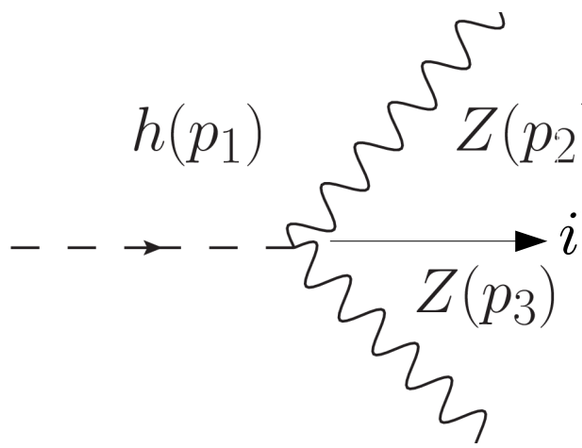
Anomalous hVV Couplings

Higgs-gauge boson coupling

- The most general tensor structure of the hVV vertex.

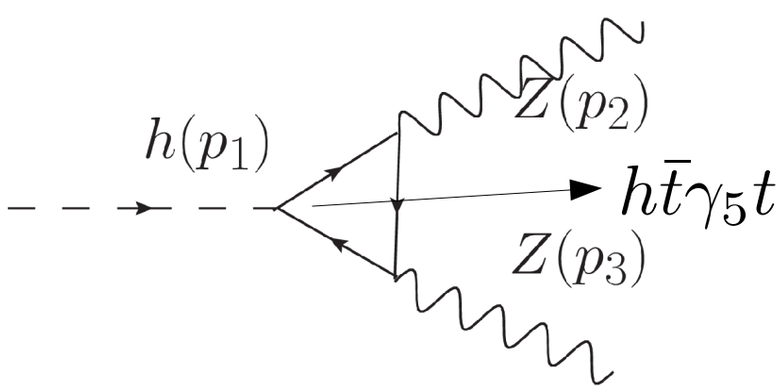
$$p = p_2 + p_3$$

$$q = p_2 - p_3$$

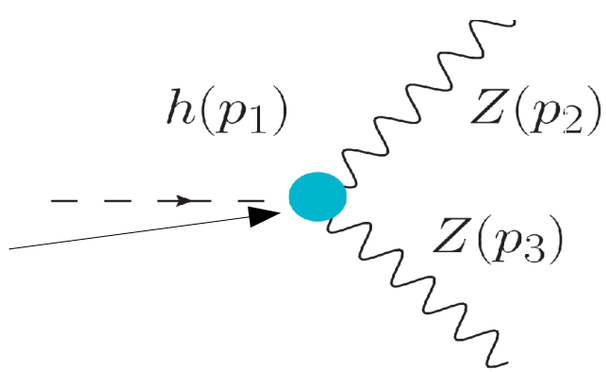


$$i\Gamma^{\mu\nu} = i\frac{gM_Z}{c_W}\left[\underbrace{A\eta^{\mu\nu} + B(p^\mu p^\nu)}_{\text{CP even}} + \underbrace{C\epsilon^{\mu\nu\rho\sigma}p_\rho q_\sigma}_{\text{CP odd}}\right]$$

- A, B, C are momentum dependent form factors.
- In SM A=1, B=C=0.
- Such a vertex may be generated from BSM physics:



$h\tilde{Z}^{\mu\nu}Z_{\mu\nu}$



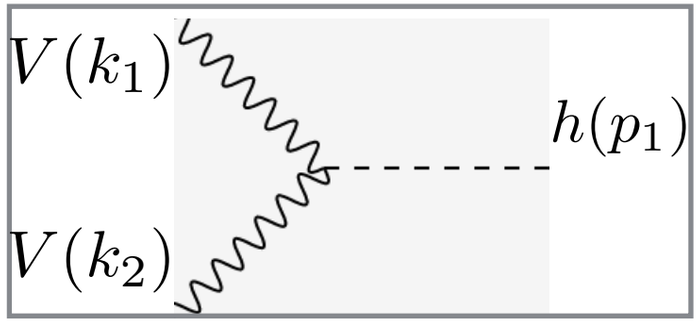
See plenary talk by D. Zeppenfeld

Notation

- Parametrize hVV vertex in terms of $(a_V, b_{V1}, b_{V2}, c_V)$ $V = (W, Z)$

$$i\Gamma^{\mu\nu}_{hWW}(k_1,k_2) = i\,(g_2 m_W)\left[\eta^{\mu\nu}\left(1 + a_W - \frac{b_{W1}}{m_W^2}(k_1\cdot k_2) + \frac{b_{W2}}{m_W^2}(k_1^2 + k_2^2)\right)\right.$$

$$\left. + \frac{b_{W1}}{m_W^2}\,k_1^\nu k_2^\mu - \frac{b_{W2}}{m_W^2}(k_1^\mu k_1^\nu + k_2^\mu k_2^\nu) + \frac{c_W}{m_W^2}\,\epsilon^{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}\right]\;;$$



SM corresponds to $(a_V, b_{V1}, b_{V2}, c_V) = (0,0,0,0)$

In terms of higher dimension operators

$$\mathcal{O}_{WW} = \frac{g_2^2\, b_{WW}}{4\Lambda^2}\Phi^\dagger\Phi W^I_{\mu\nu}W^{I\mu\nu}\,, \qquad \tilde{\mathcal{O}}_{WW} = \frac{g_2^2\, c_{WW}}{4\Lambda^2}\Phi^\dagger\Phi W^I_{\mu\nu}\tilde{W}^{I\mu\nu}\,,$$

$$\mathcal{O}_{hW} = \frac{i g_2\, b_{hW}}{\Lambda^2}\left(D^\nu W_{\mu\nu}\right)^k\left(\Phi^\dagger\sigma^k \overleftrightarrow{D}^\mu\Phi\right).$$

$$b_{W1} = \frac{2\, m_W^2\, b_{WW}}{\Lambda^2}\,, \quad b_{W2} = \frac{2\, m_W^2\, b_{hW}}{\Lambda^2}\,,$$

$$c_W = \frac{2\, m_W^2\, c_{WW}}{\Lambda^2}\,.$$

Theoretical concerns

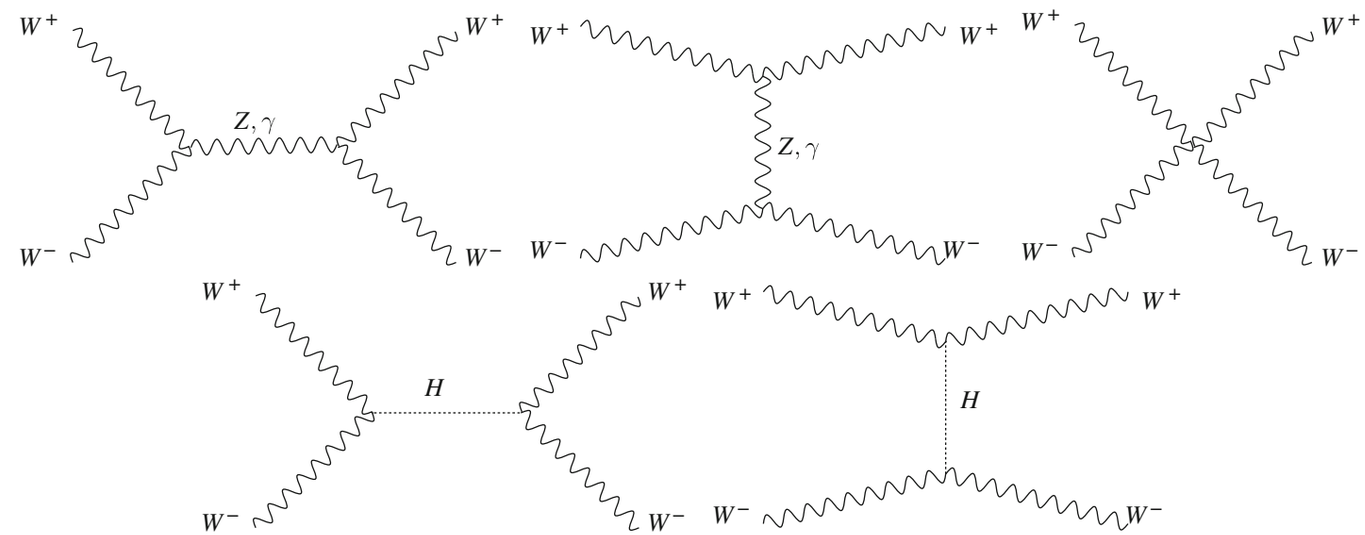
Custodial Symmetry and precision tests

- Do we really need to check the hWW vertex separately? Doesn't custodial symmetry tell us that hWW and hZZ are related?
- Necessary because (global) custodial symmetry is broken by gauging of the hypercharge.
- BSM particles in the loop could give rise to different values for anomalous hWW and hZZ couplings.
- VBF: ~25% contribution from Z mediated production (14 TeV). No clean separation between hZZ and hWW. So use Vh.
- Precision tests can constrain Wilson coefficients of the operators. However, more operators than constraints available. Need to use simplifying assumptions.
- If only one non-zero coefficient then $c_W < 0.85$

Belusca-Maito arXiv: 1507.05657

$$ig_2 m_W \left[\eta^{\mu\nu}\left(1+a_W\right) + \frac{c_W}{m_W^2}\epsilon^{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}\right]$$

Unitarity



$j = 0$ partial wave amplitude for $W_L^+ W_L^- \to W_L^+ W_L^-$ is

$$a_0^{SM} = a_0^{gauge} + a_0^{Higgs} = -\frac{g^2 s}{128\pi m_W^2} + \frac{g^2 s}{128\pi m_W^2} + \mathcal{O}\left(\frac{m_W}{s}\right)$$

Lee, Quigg & Thacker

Unitarity $\implies |Re(a_j)| < 1/2$

For the cp-odd coupling the vertex reduces to: $(\epsilon_1 \times \epsilon_2) \cdot (p_1 - p_2)$

$$s \gg m_W^2 \implies \epsilon_i \propto p_i$$

For cp-odd we use transverse polarization of W boson

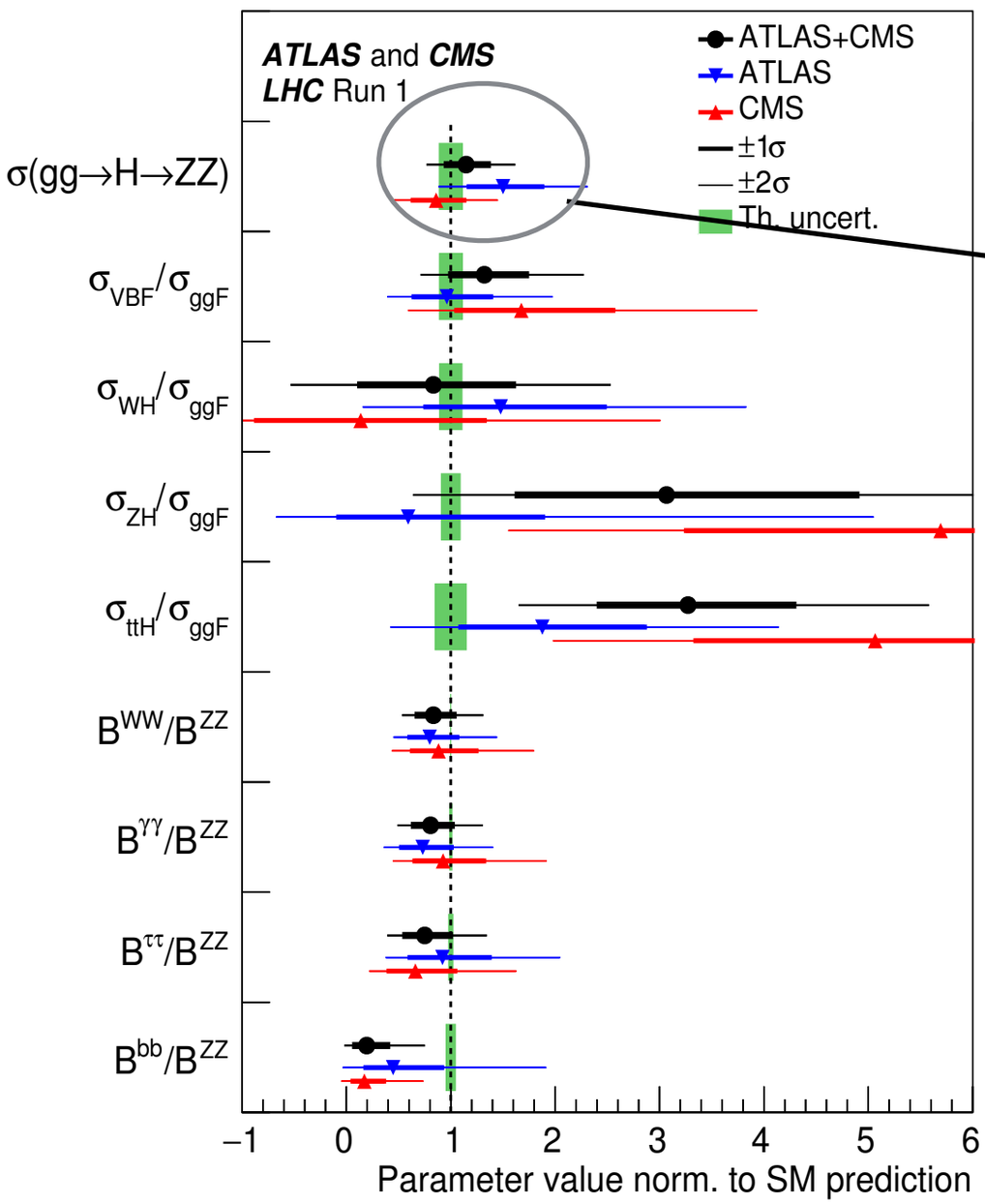
$$\boxed{c_W < \frac{\sqrt{16\pi}\ v}{\sqrt{s}} \simeq \frac{1.75\ \text{TeV}}{\sqrt{s}}}$$

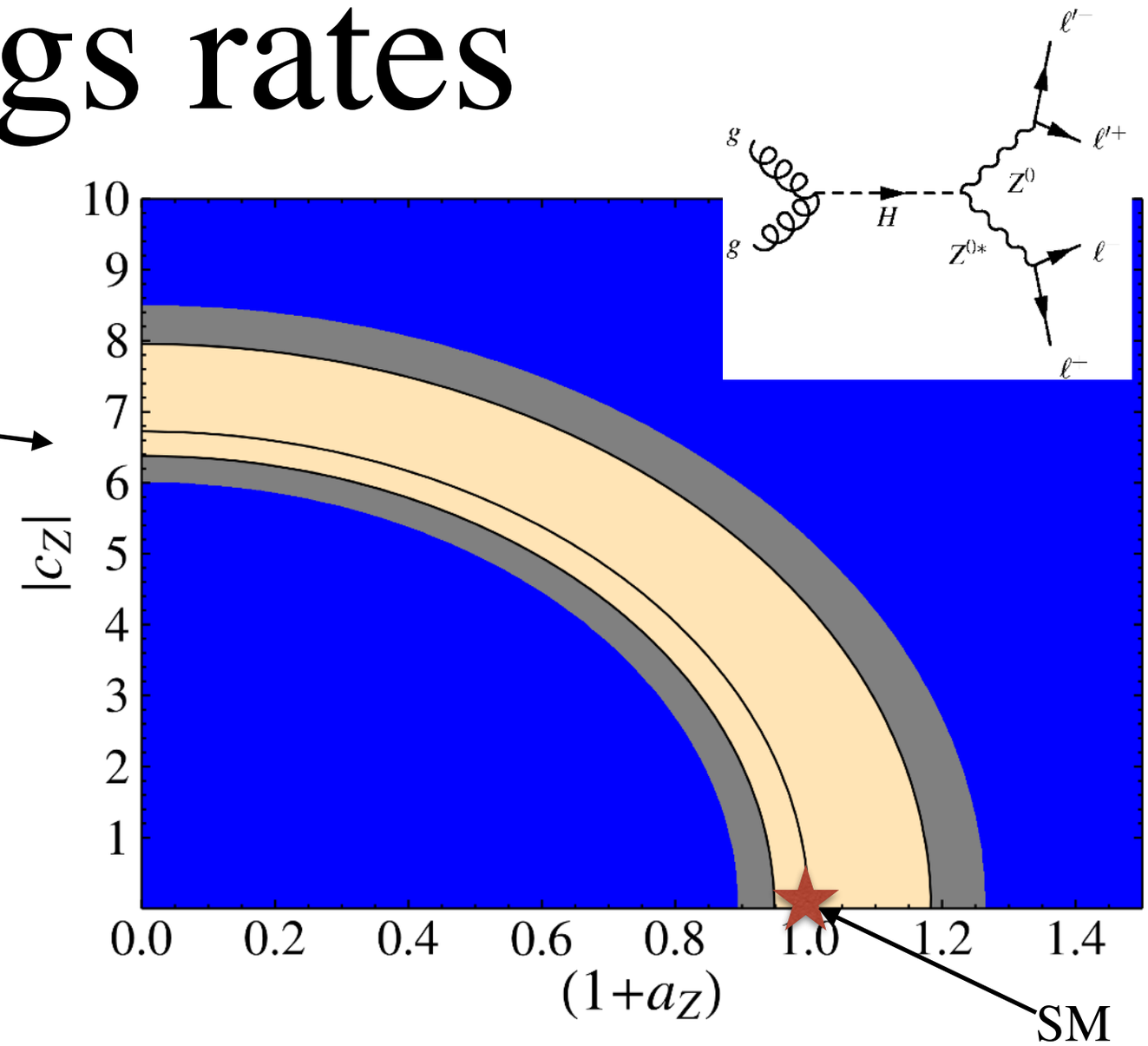
Choose $\sqrt{s} >$ Energy flow through the vertex.

Constraints from Higgs decays

Higgs rates

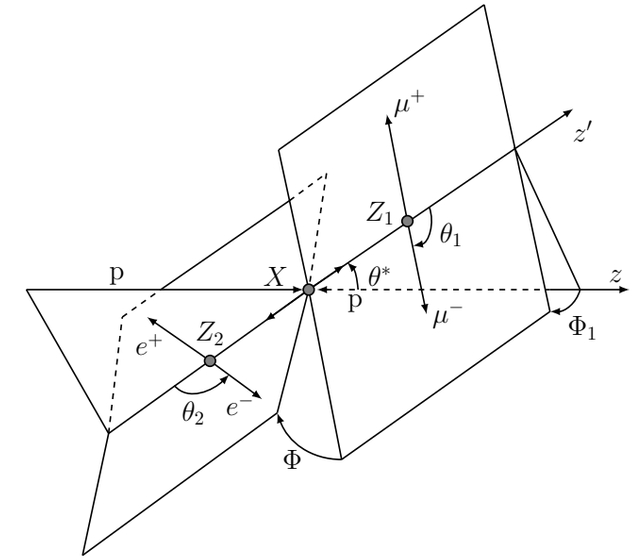
ATLAS+ CMS arXiv:1606.02266





Naive use of Higgs rates does not strongly constrain BSM couplings

Higgs CP analysis in golden channel



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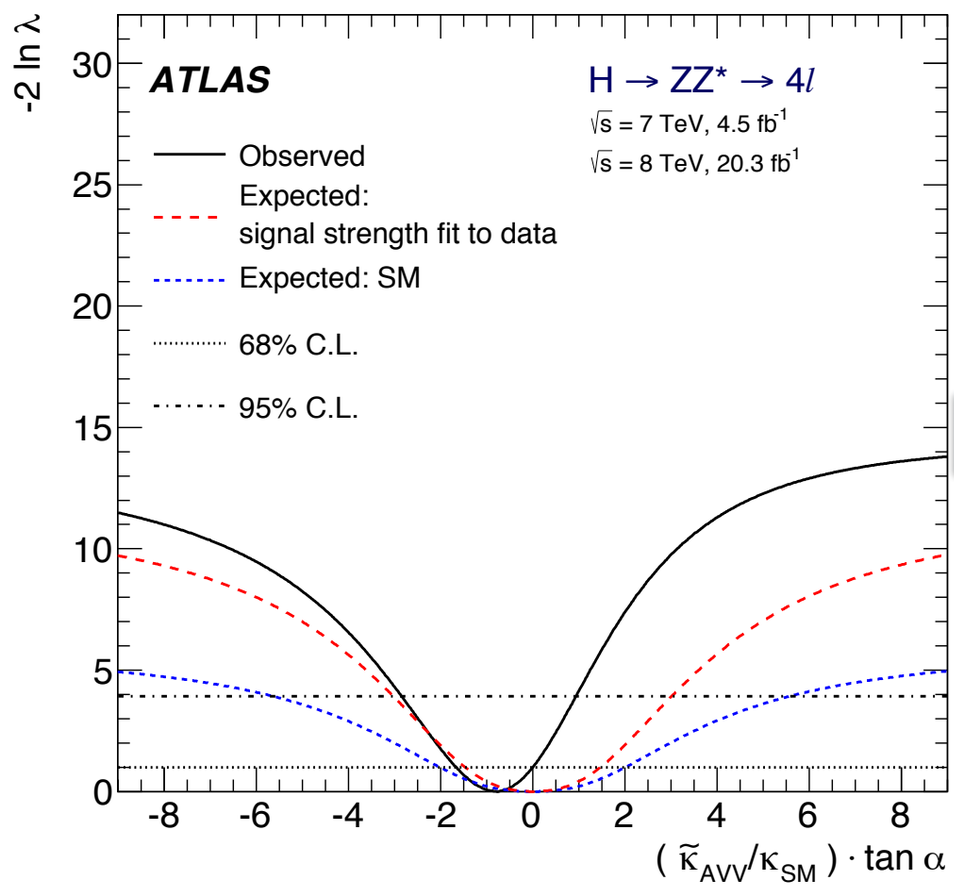
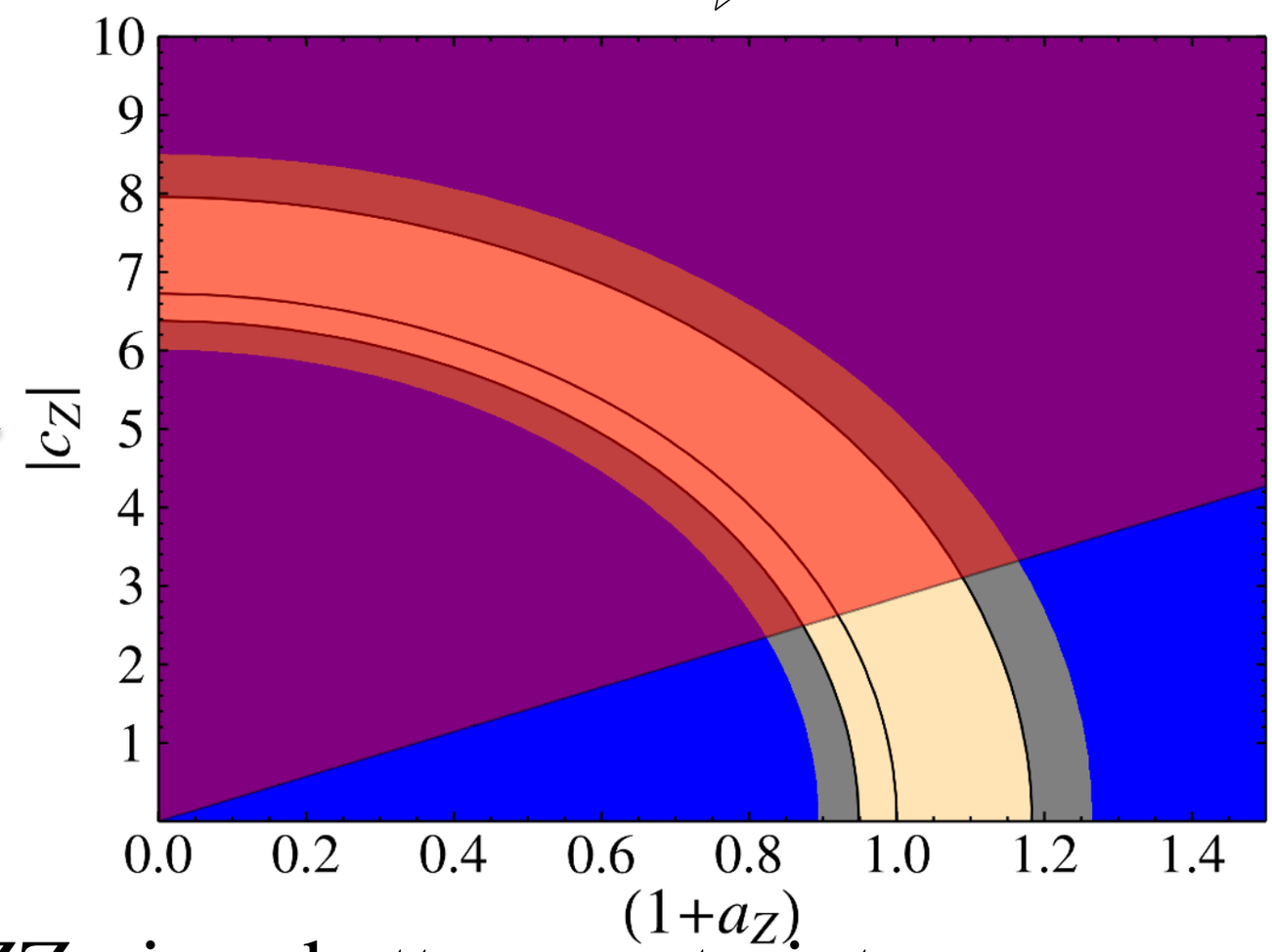
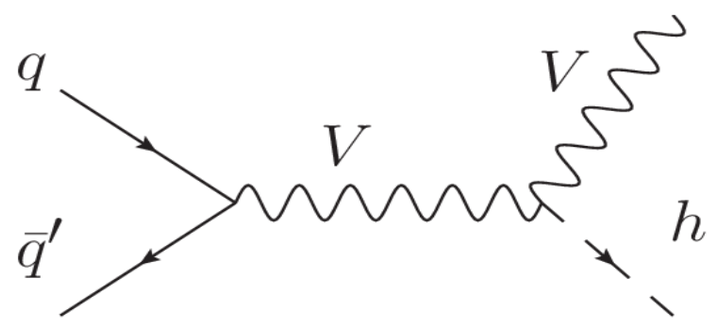




Analysis of Higgs decays to ZZ gives better constraint on BSM couplings though fairly large values are still allowed. Separately analyzing hWW does not give strong constraints.

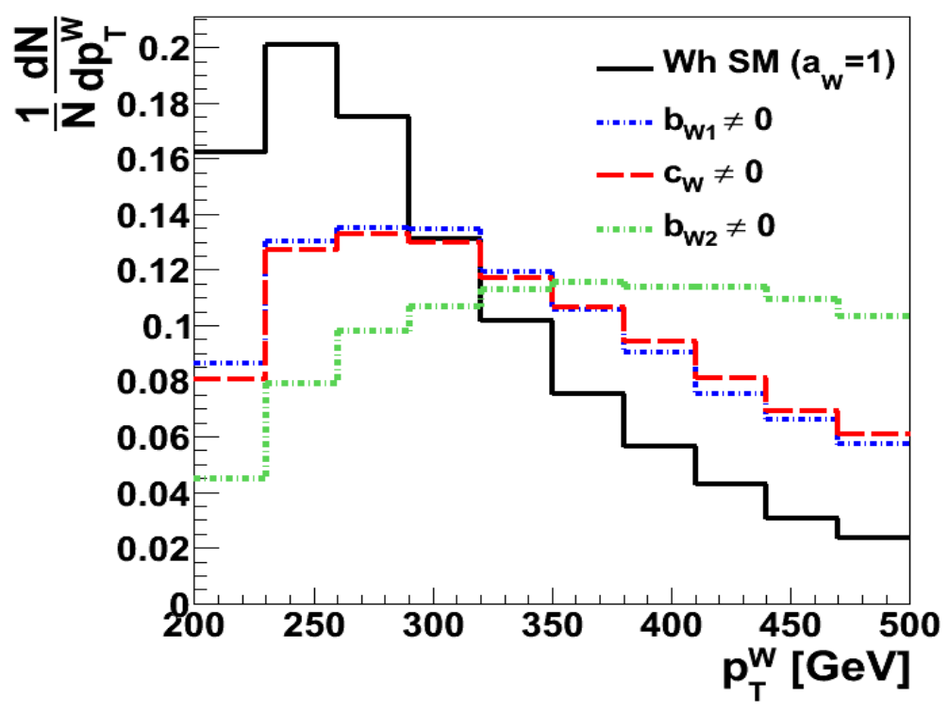
Associated Production

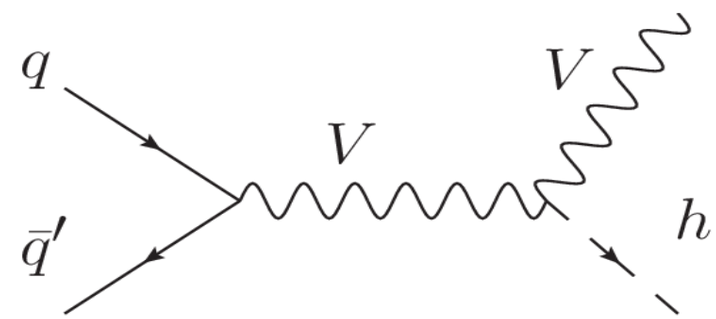


Anomalous couplings in Vh production

- Vh production as can probe separately the hWW and hZZ couplings.
- Vh has a small cross-section: hard to detect at LHC. Detection has been made possible with the use of jet substructure techniques.
- Able to reconstruct the kinematics of the process in both Zh and Wh production.
- Show that probing small values of anomalous couplings well within the reach of LHC.

Vh production kinematics

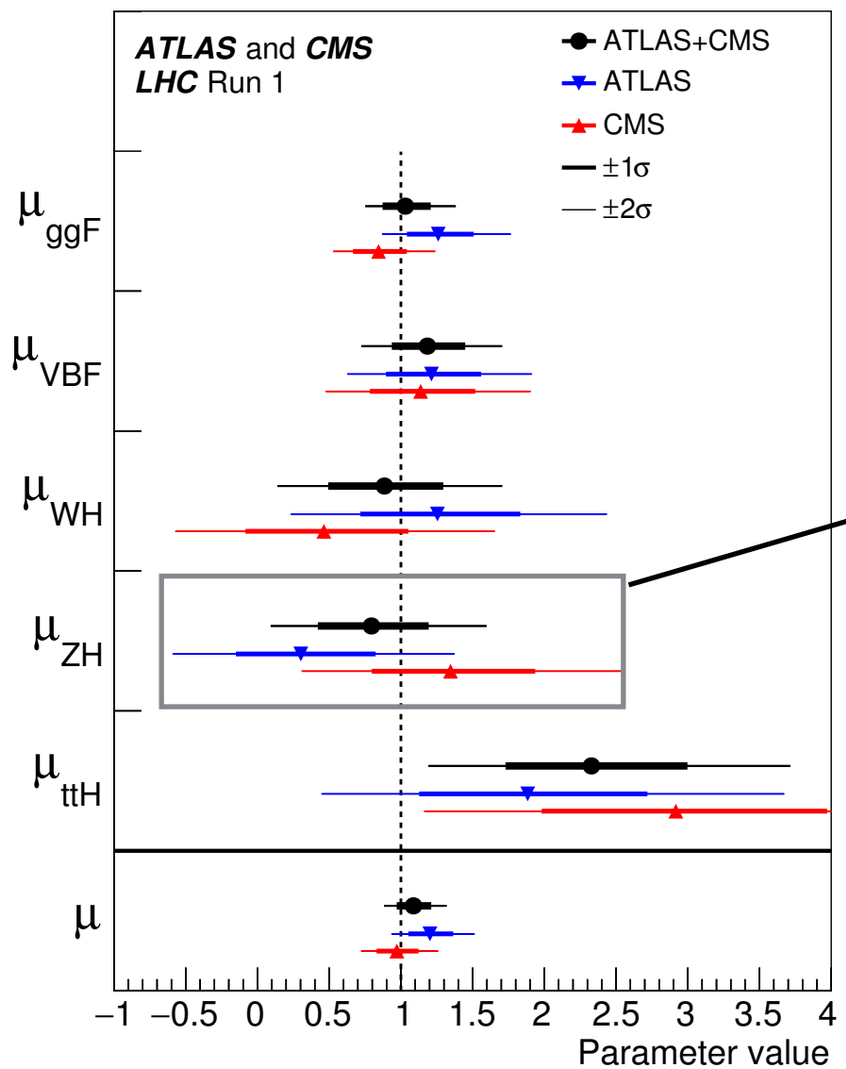


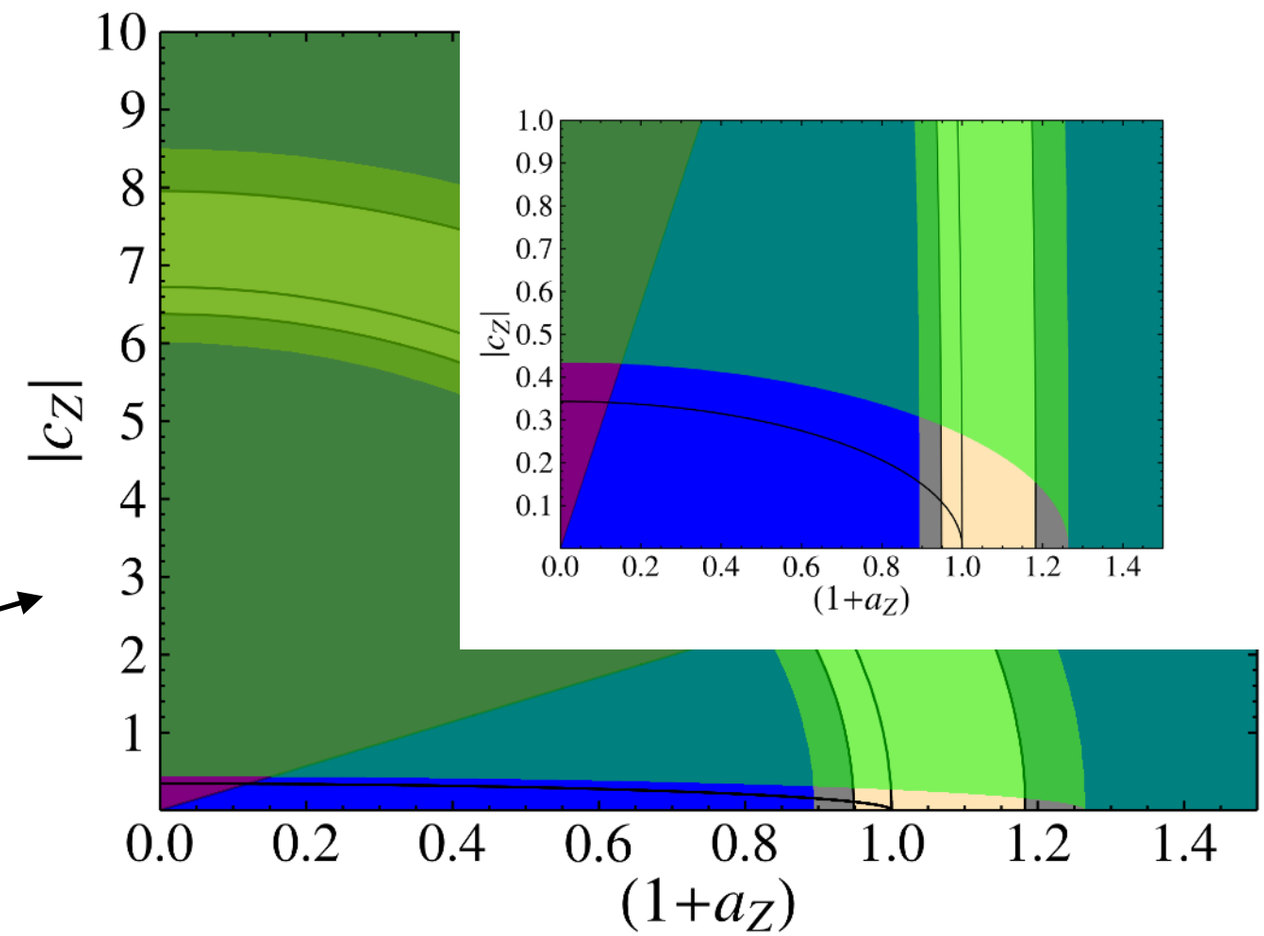


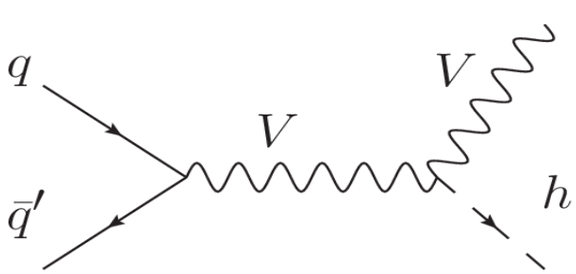
Invariant mass and the transverse momentum distributions show marked differences.
Typically background elimination requires large transverse momentum cuts.
<u>Larger acceptance to non-SM terms: improved sensitivity.</u>

Djouadi, Godbole, Mellado, KM, 2013

Constraints from Higgs rates







Vh production rate alone already constrains the strength of BSM couplings in the hVV vertex.

Polarization of the V bosons

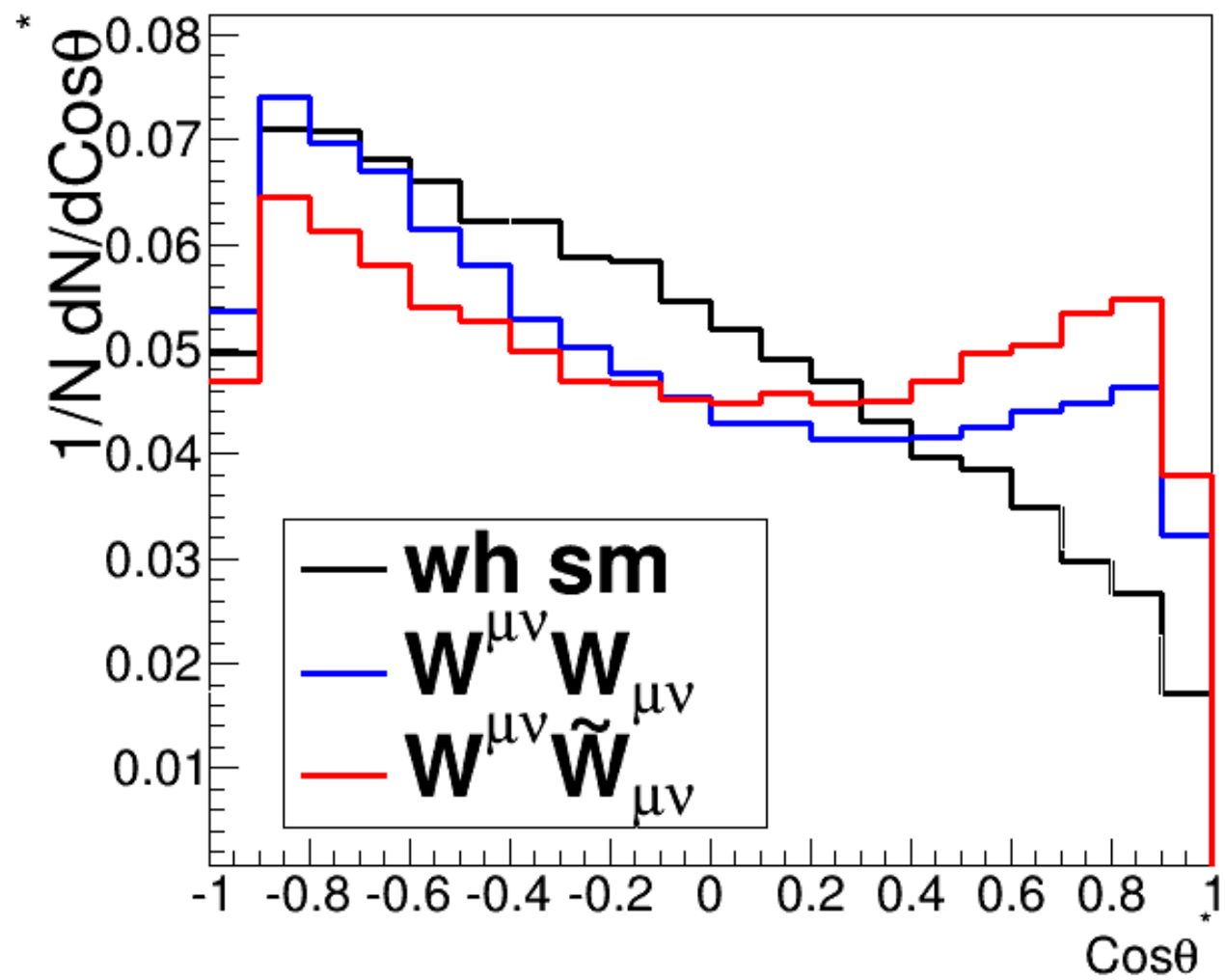
$$\cos\theta^*$$

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



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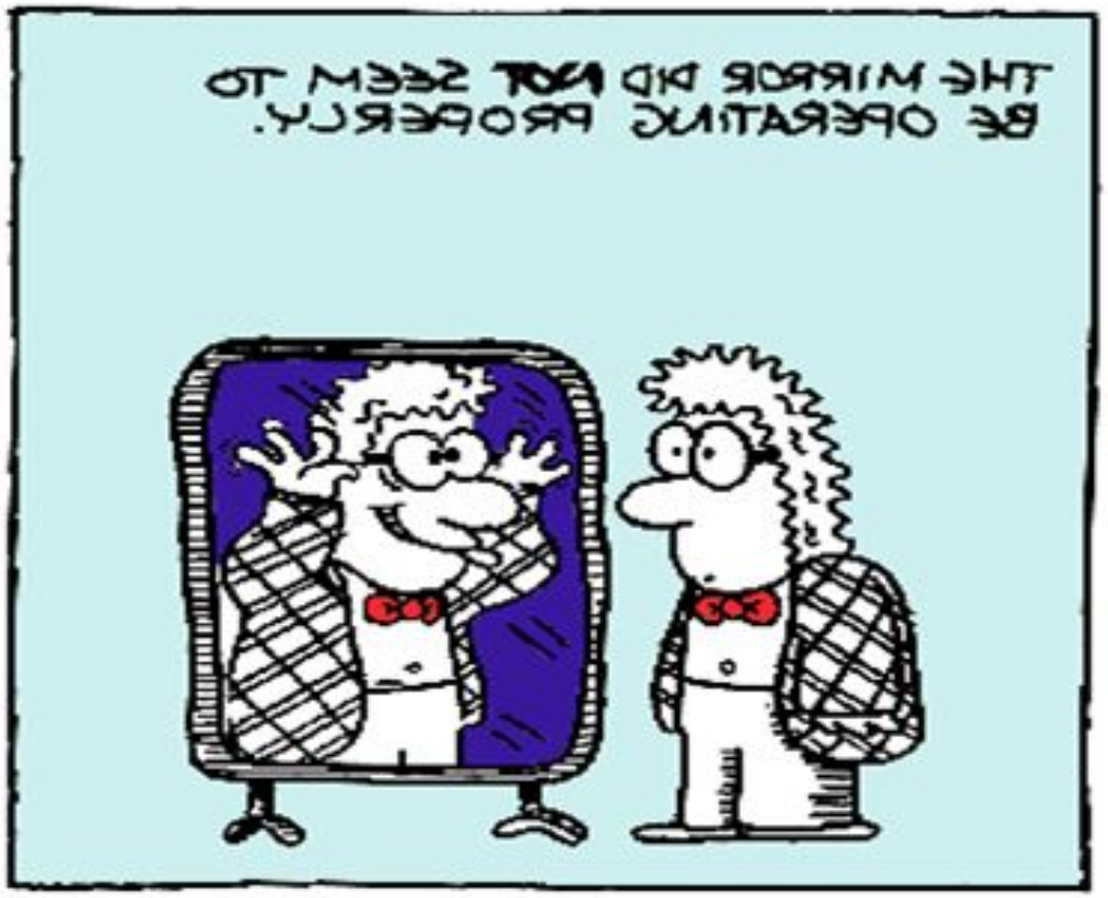
$$q = p_1 - p_2$$

$$i\frac{gM_Z}{c_W}\left[\underbrace{A\eta^{\mu\nu} + B\left(p^\mu q^\nu\right)}_{\text{CP even}} + \underbrace{C\epsilon^{\mu\nu\rho\sigma}p_\rho q_\sigma}_{\text{CP odd}}\right]$$

$$\cos\theta^* = \frac{\vec{p}_{l_1}^{(V)} \cdot \vec{p}_V}{|\vec{p}_{l_1}^{(V)}|\,|\vec{p}_V|}$$

Not a CP odd observable

CP odd (linear) observables:



$$|\mathcal{M}|^2 \to SM^2 + \underbrace{c_W SM}_{\text{Linear term (CP odd)}} + c_W^2$$

CP odd (linear) observables: $(CP)\mathcal{O}(CP)^{-1} \to -\mathcal{O}$

$$\langle f| (CP)^{-1}(CP)\mathcal{O}(CP)^{-1}(CP) |i\rangle \to -\langle f| \mathcal{O} |i\rangle$$

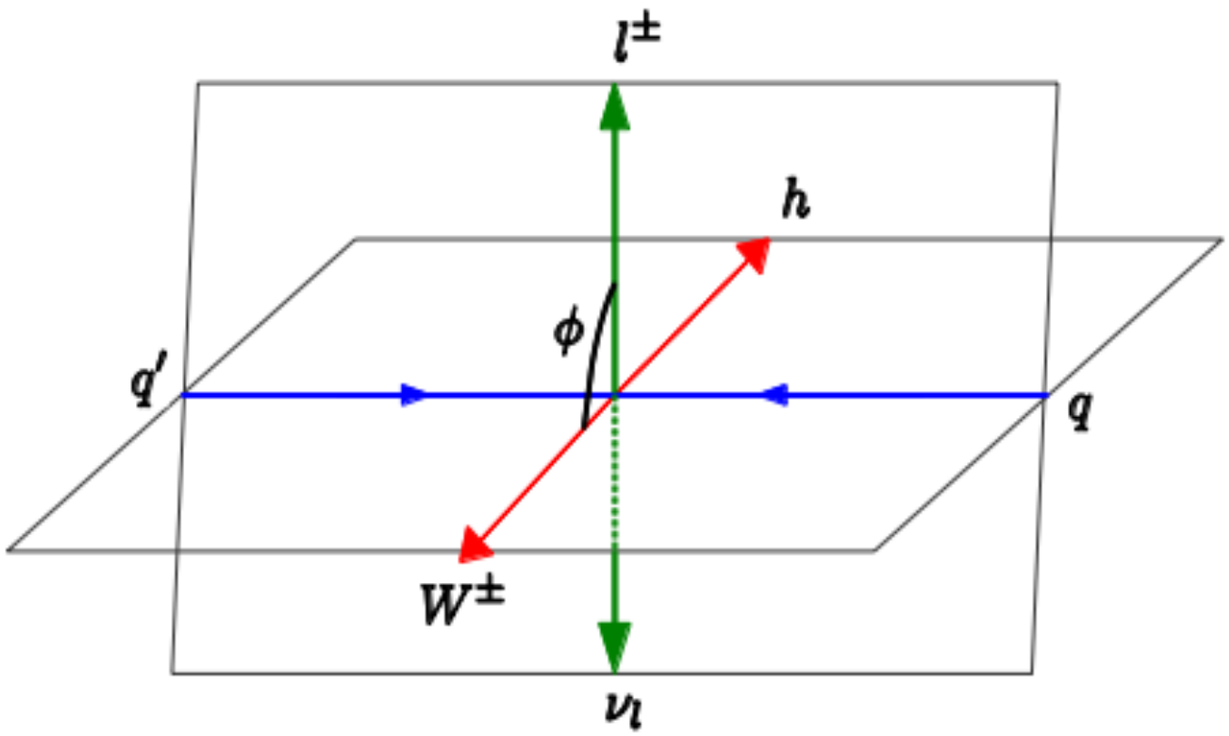
Only possible to construct **truly** CP odd observables for a process if initial and final states are eigenstates of CP.

Eigen state of CP: $CP\,|e^+e^-\rangle_{CMS} = +1\,|e^+e^-\rangle_{CMS}$

LHC: Not an eigen state of CP: $CP\,|P_1, P_2\rangle_{CMS} = |\bar{P}_2, \bar{P}_1\rangle_{CMS}$

Hard but not impossible to find CP odd observables for LHC

Hint: Exploit difference between quark and anti-quark parton distributions.



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

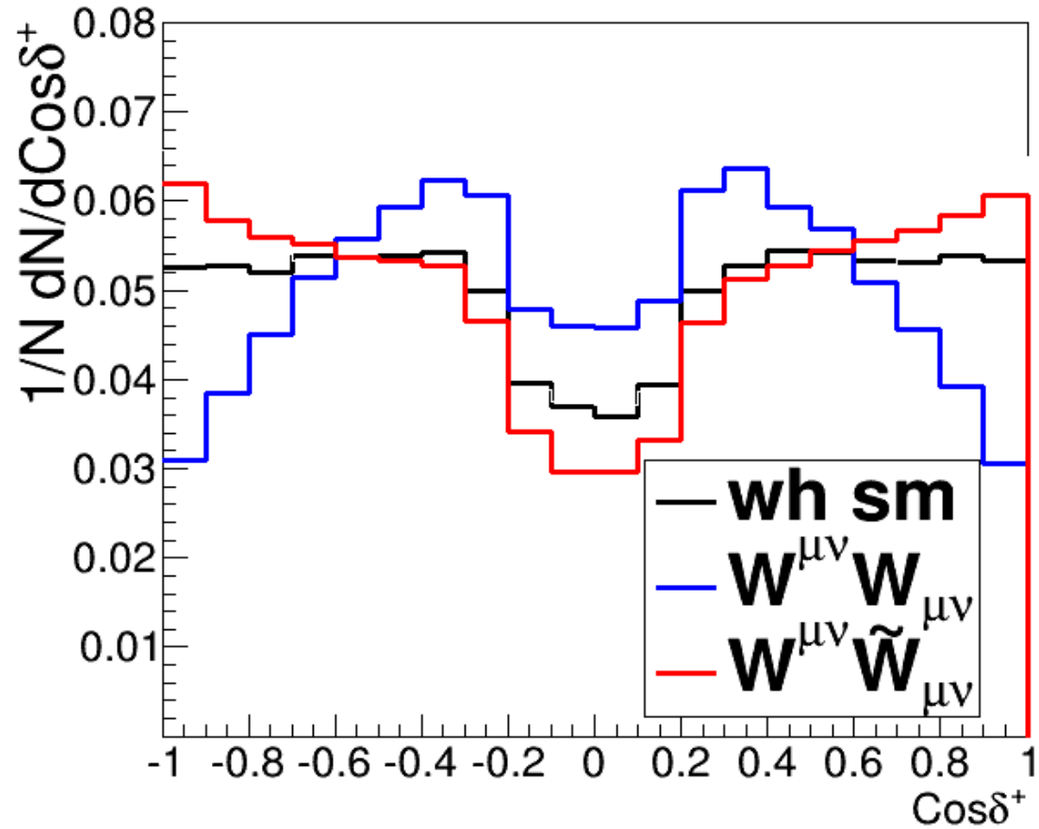
$$\cos\delta^{+} = \frac{\vec{p}_{l_1}^{(V)} \cdot (\vec{p}_V \times \vec{p}_H)}{|\vec{p}_{l_1}^{(V)}|\,|\vec{p}_V \times \vec{p}_H|} \quad , \quad \cos\delta^{-} = \frac{(\vec{p}_{l_1}^{(H-)} \times \vec{p}_{l_2}^{(H-)}) \cdot \vec{p}_V}{|(\vec{p}_{l_1}^{(H-)} \times \vec{p}_{l_2}^{(H-)})||\vec{p}_V|},$$

$$\Delta \quad \phi^{lV} = \Delta\phi(\vec{p}_{l_1}^{(V)}, \vec{p}_V)$$

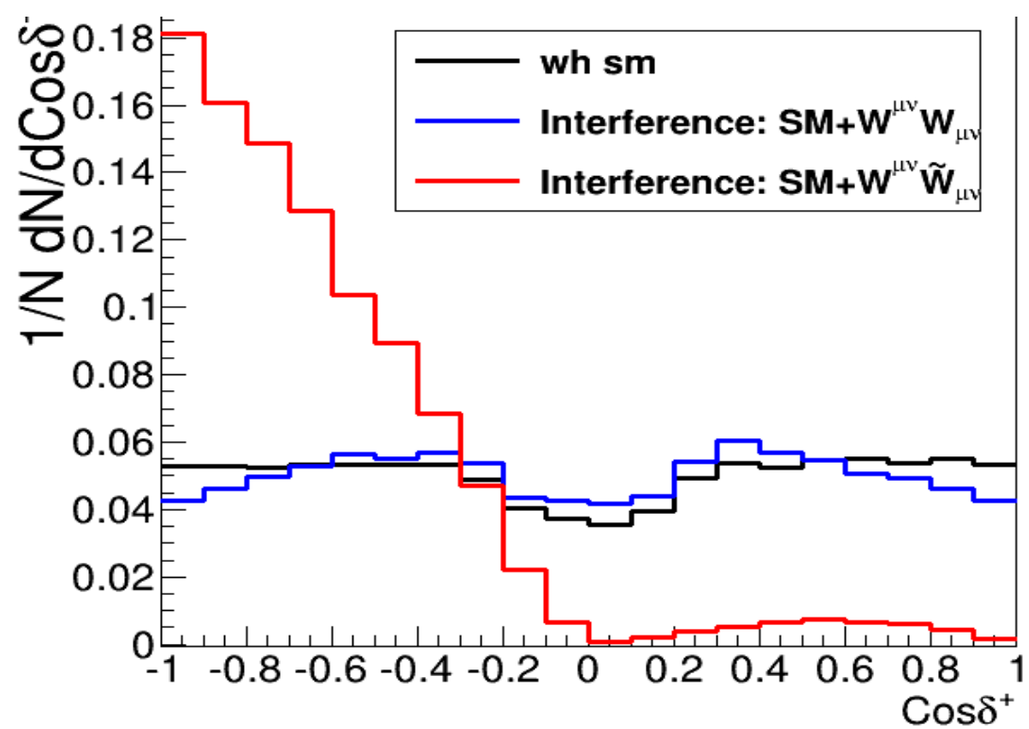
$\cos\delta^+$

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

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



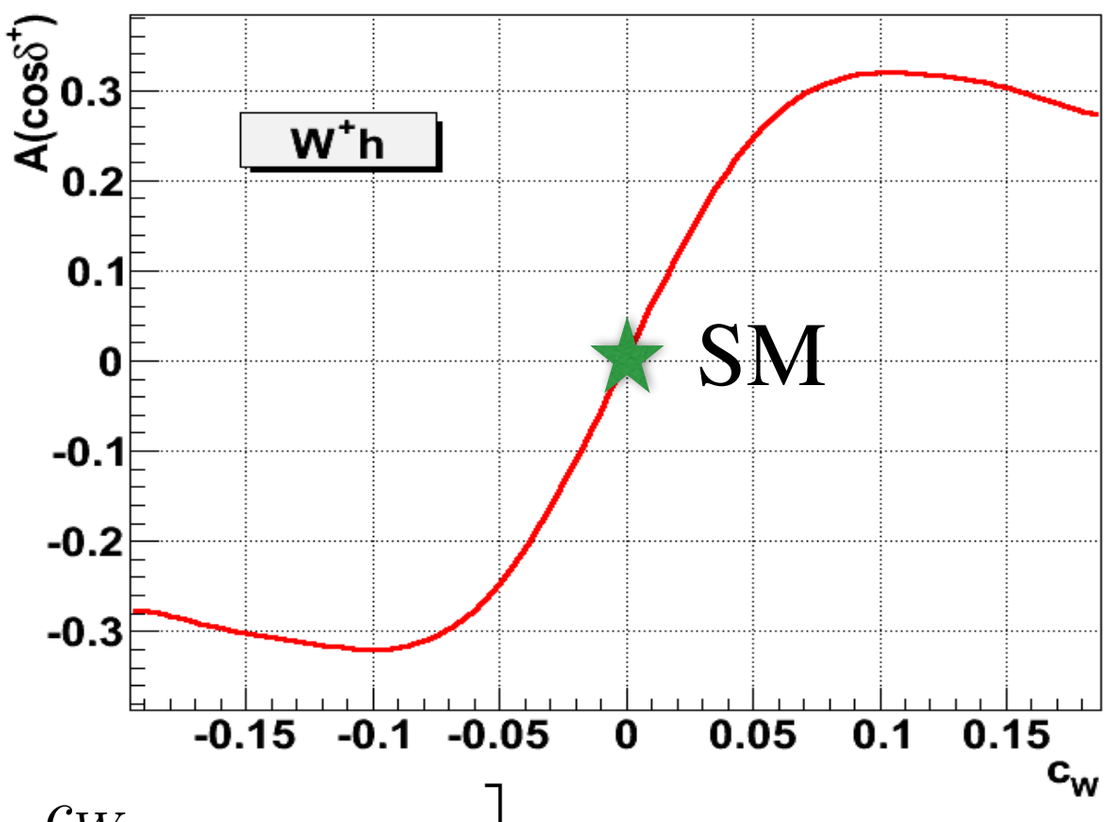
Interference term <u>only</u> between SM and BSM couplings.



CP violation and asymmetries

- Useful to construct an observable that vanishes when CP is conserved.
- Simple counting experiment. Reduced uncertainties.

$$A(\cos\delta^+) = \frac{\sigma(\cos\delta^+ > 0) - \sigma(\cos\delta^+ < 0)}{\sigma(\cos\delta^+ > 0) + \sigma(\cos\delta^+ < 0)}$$



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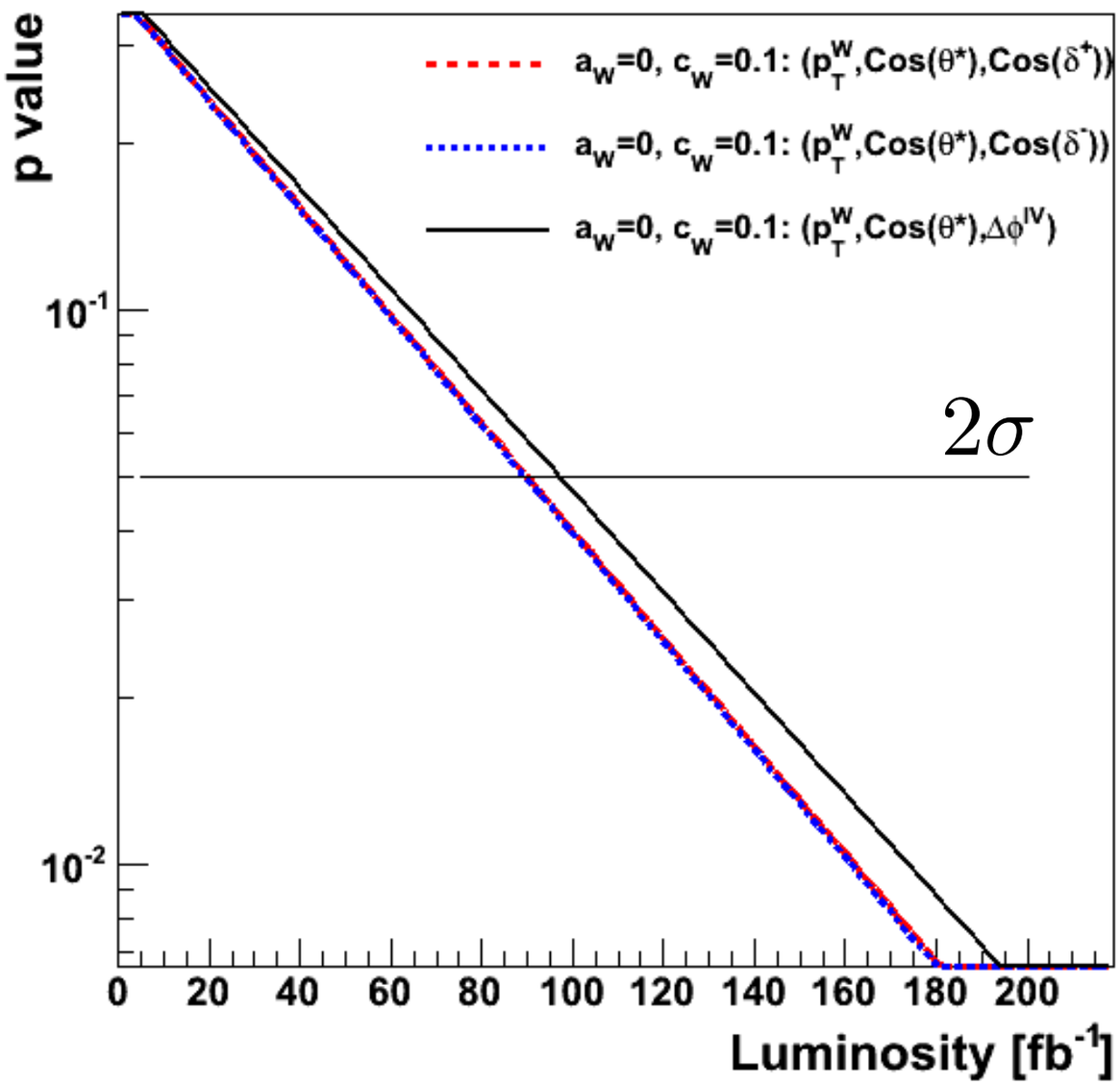
$$ig_2 m_W \left[\eta^{\mu\nu}\left(1 + a_W\right) + \frac{c_W}{m_W^2}\epsilon^{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}\right]$$

Exclusion using a likelihood analysis



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$$ig_2 m_W \left[\eta^{\mu\nu}\left(1+a_W\right)+\frac{c_W}{m_W^2}\epsilon^{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}\right]$$

Summary & Outlook

- Argued the case for testing the hWW and hZZ vertex <u>directly</u> and <u>separately</u> at the LHC.
- Maximum sensitivity comes by combining Higgs decay rates as well Vh production rates.
- Constructed a truly CP-odd observable and asymmetry.
- Currently implementing Vh production with anomalous vertices in RESBOS, including (N)NLO (QCD) & resummation effects.

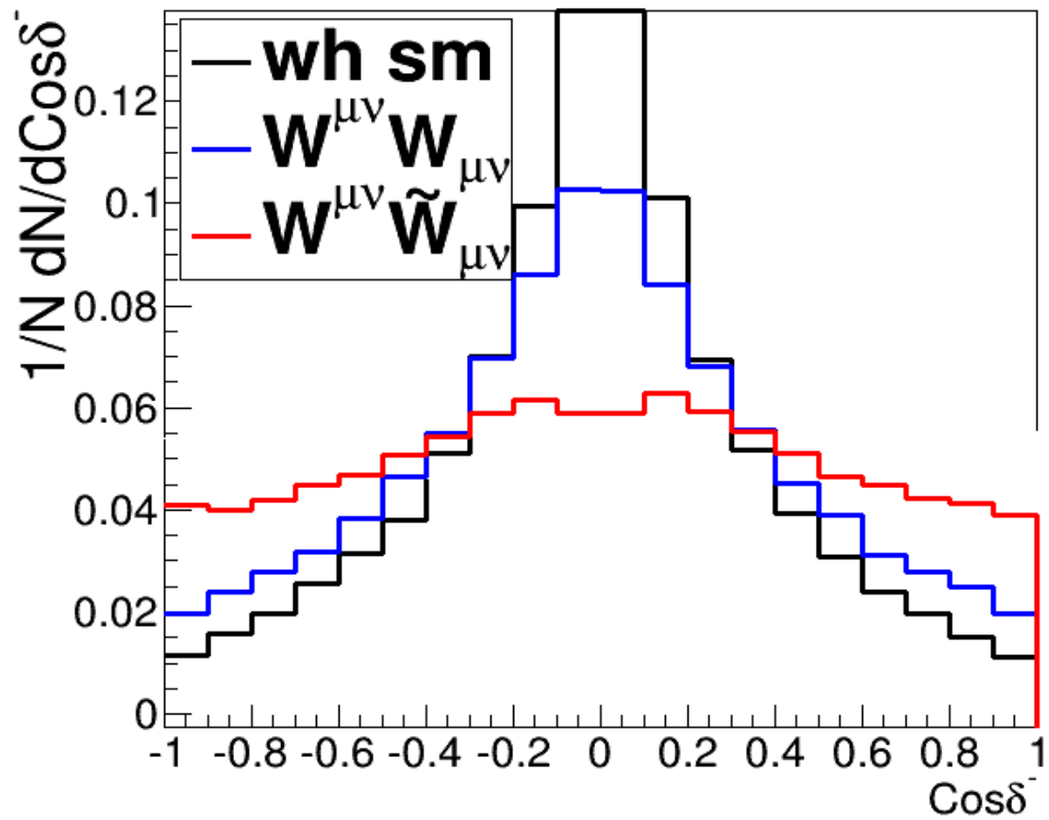
http://hep.pa.msu.edu/resum/

Bonus

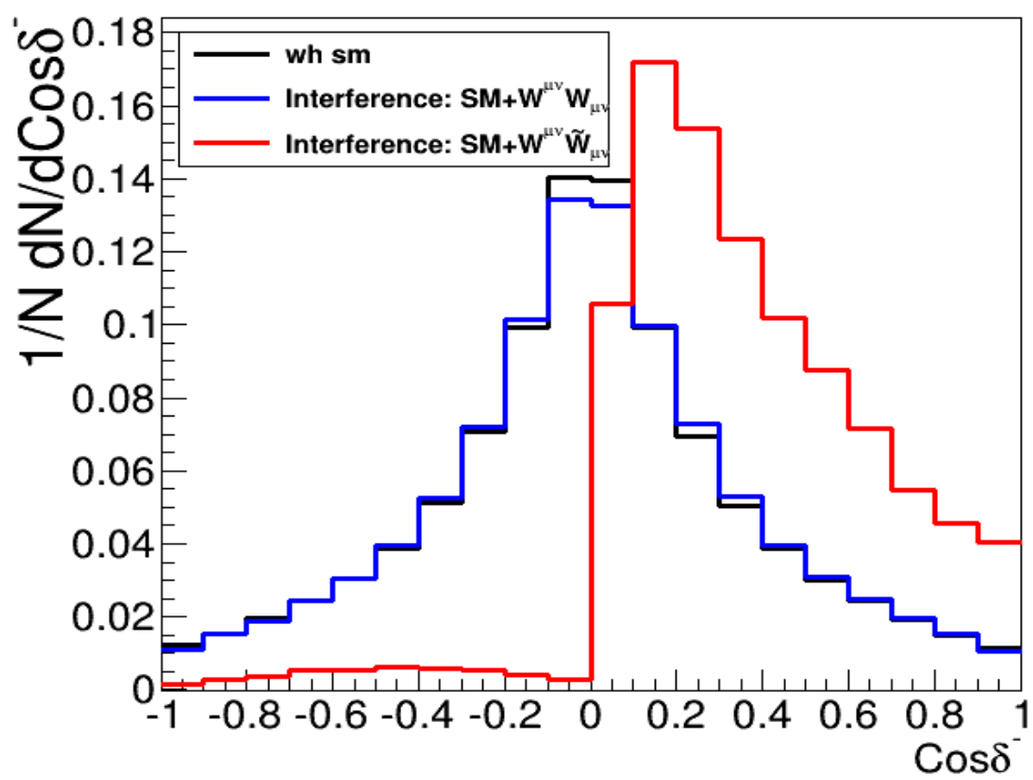
$\cos\delta^-$

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

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



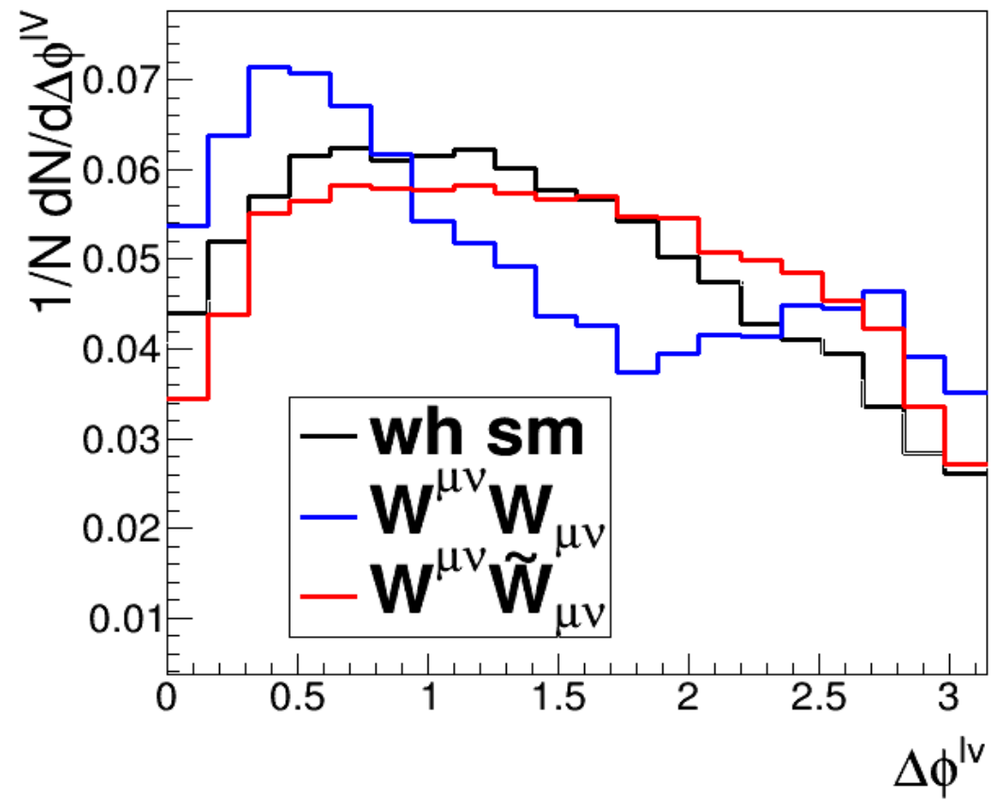
Interference term <u>only</u> between SM and BSM couplings.



$$\Delta\phi^{lV}$$

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

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



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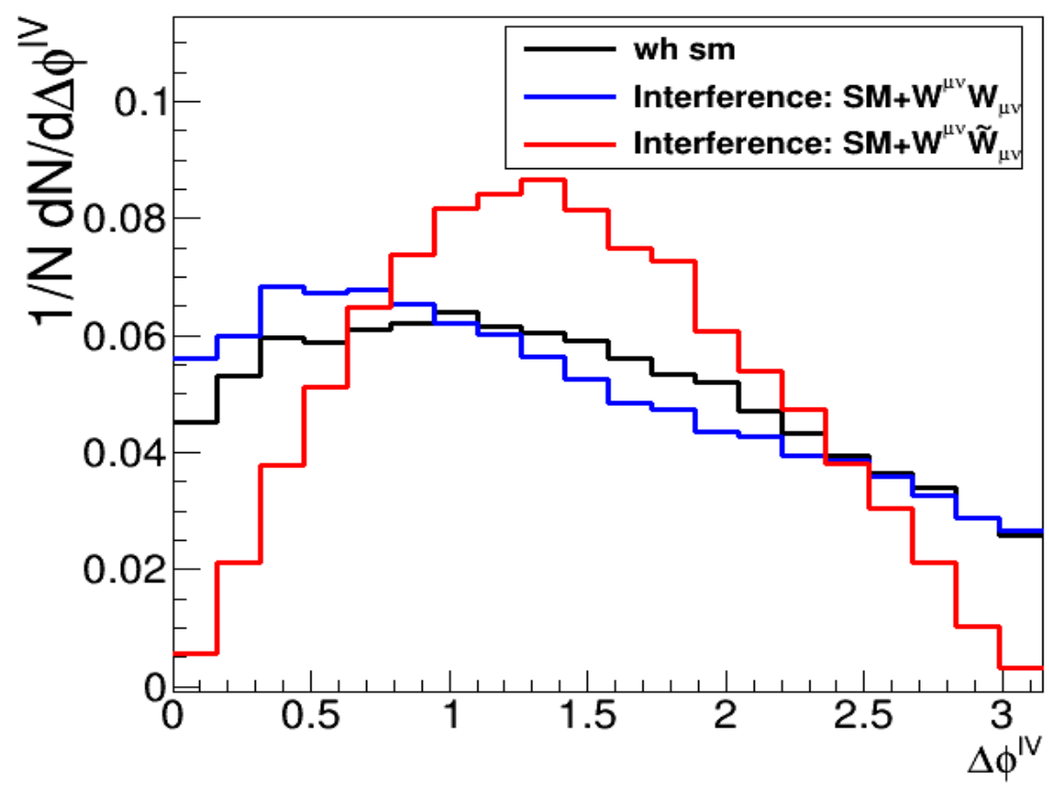
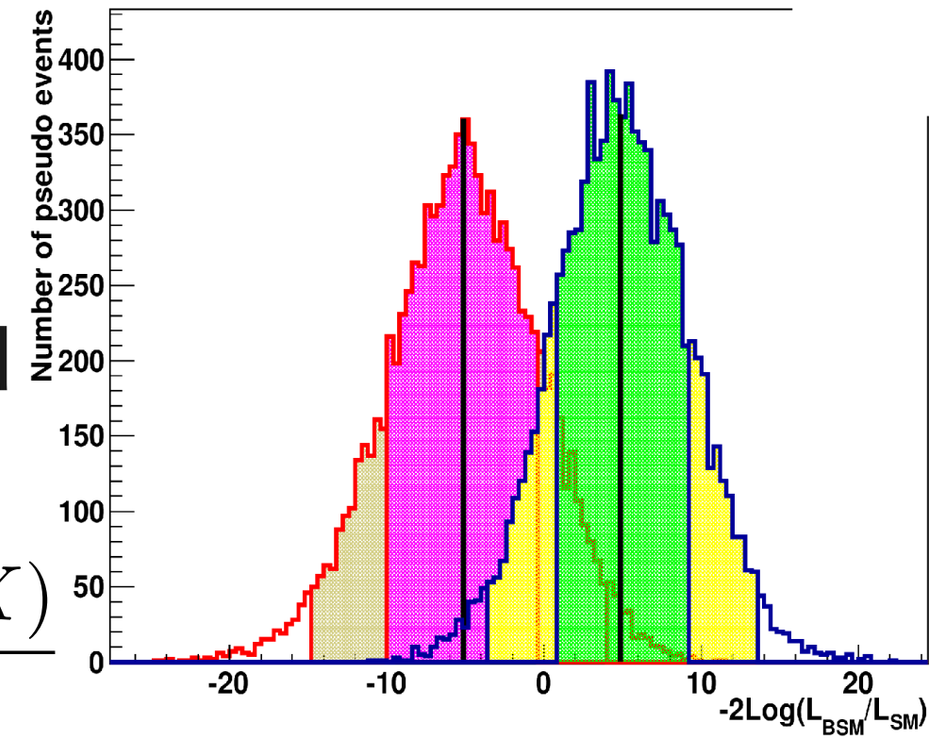


3D-Likelihoods

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

$$\mathcal{Q} = -2log\frac{L(data|hypothesisX)}{L(data|SM)}$$



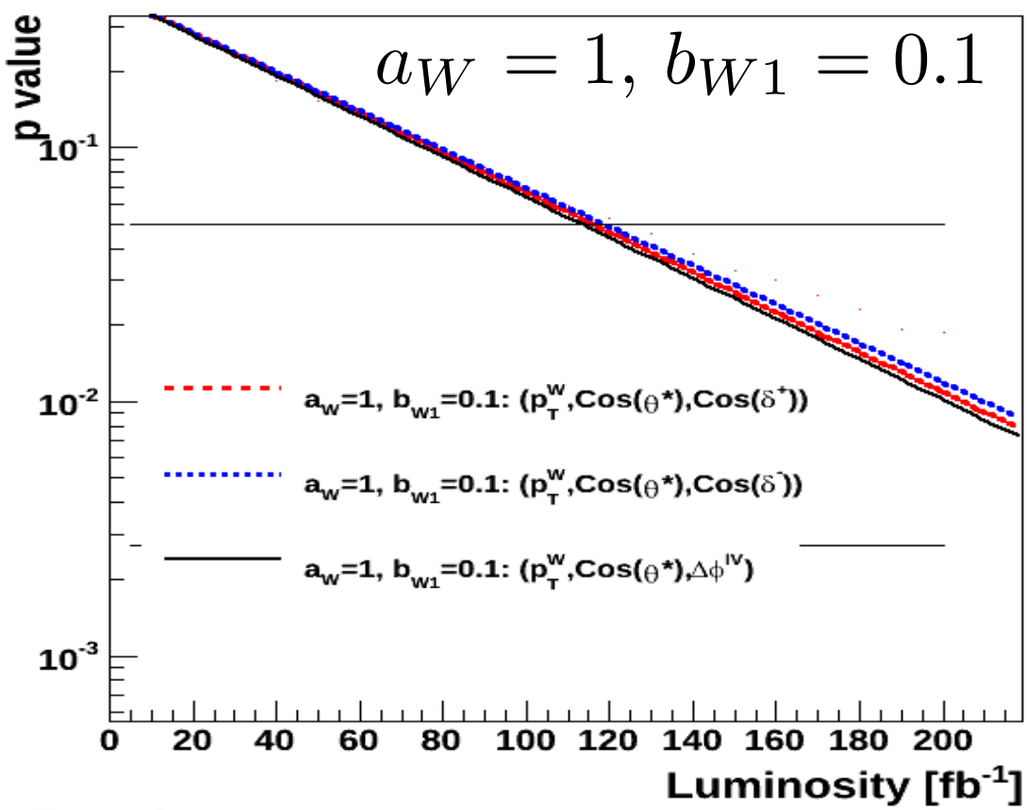
Use 3D binned likelihood.

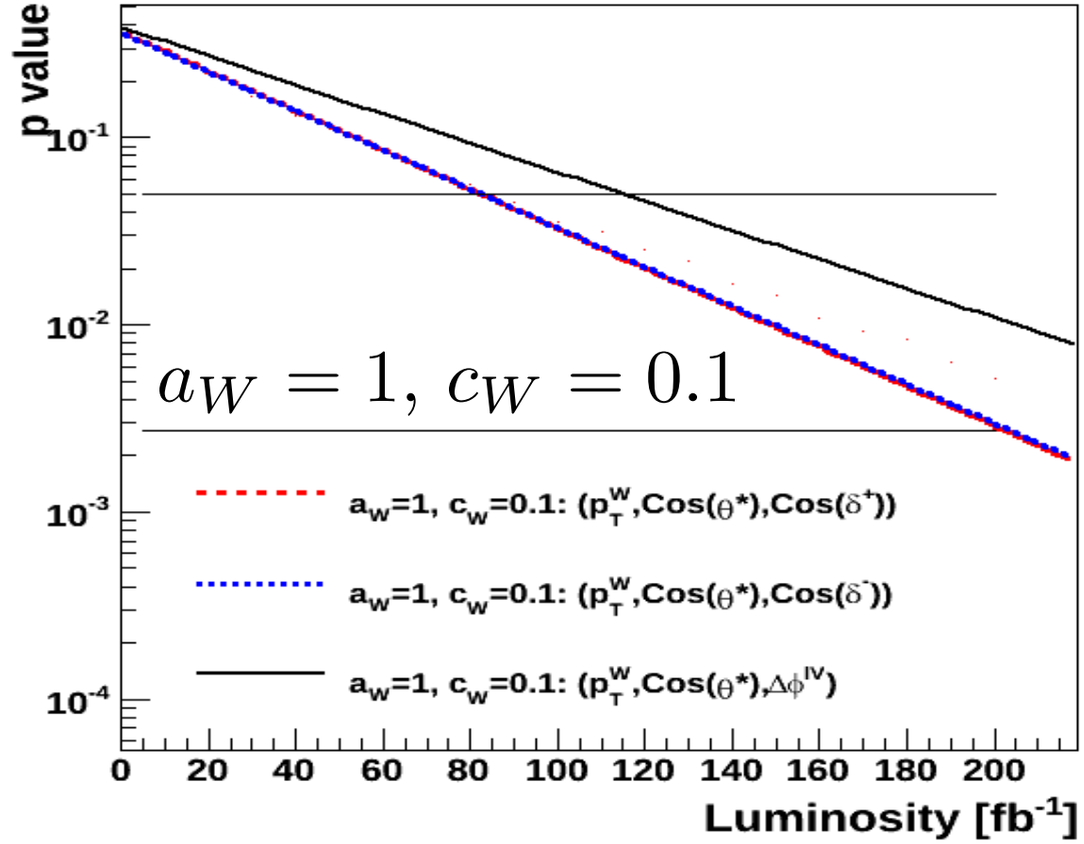
Test 3 different combinations of observables in Likelihood.

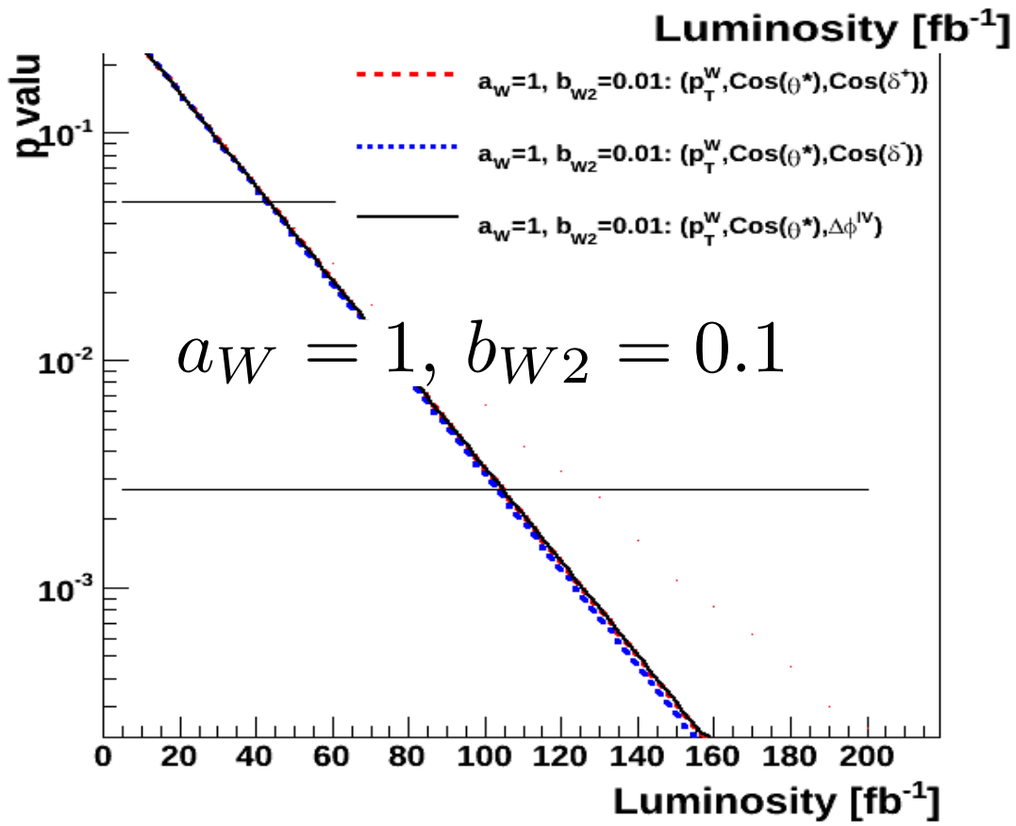
$$\mathcal{L}(p_T^h, \cos\theta^*, \cos\delta^+)$$

$$\mathcal{L}(p_T^h, \cos\theta^*, \cos\delta^-)$$

$$\mathcal{L}(p_T^h, \cos\theta^*, \Delta\phi^{lV})$$



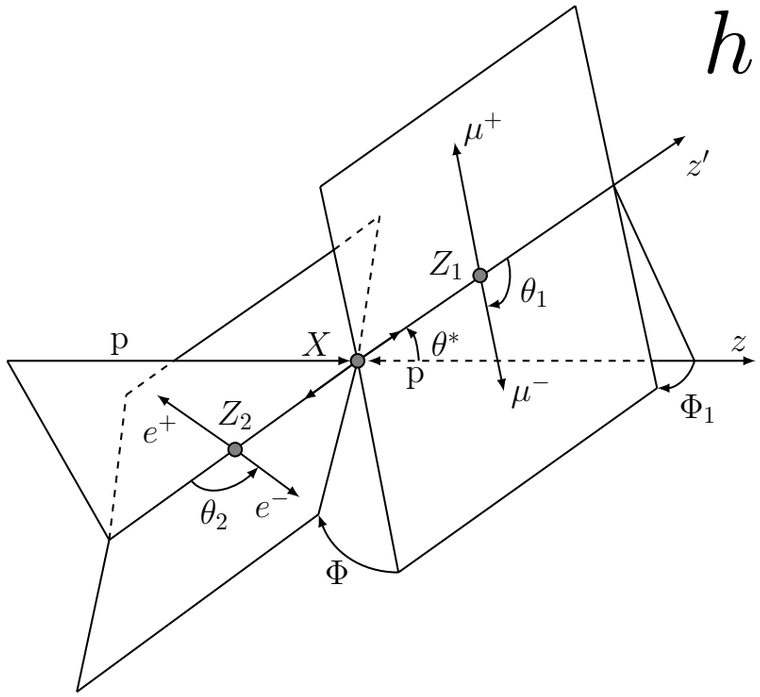




Exclusion at 95%CL well within expected luminosity of first run of 14 TeV LHC.

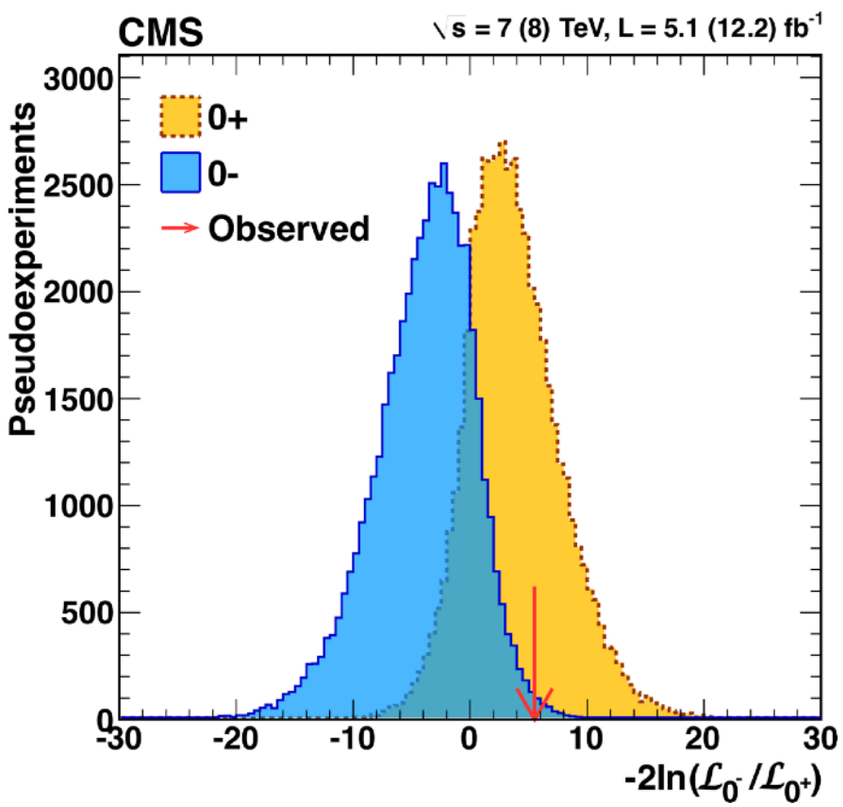
Generated using Feynrules+ MadGraph+ Pythia+ Delphes

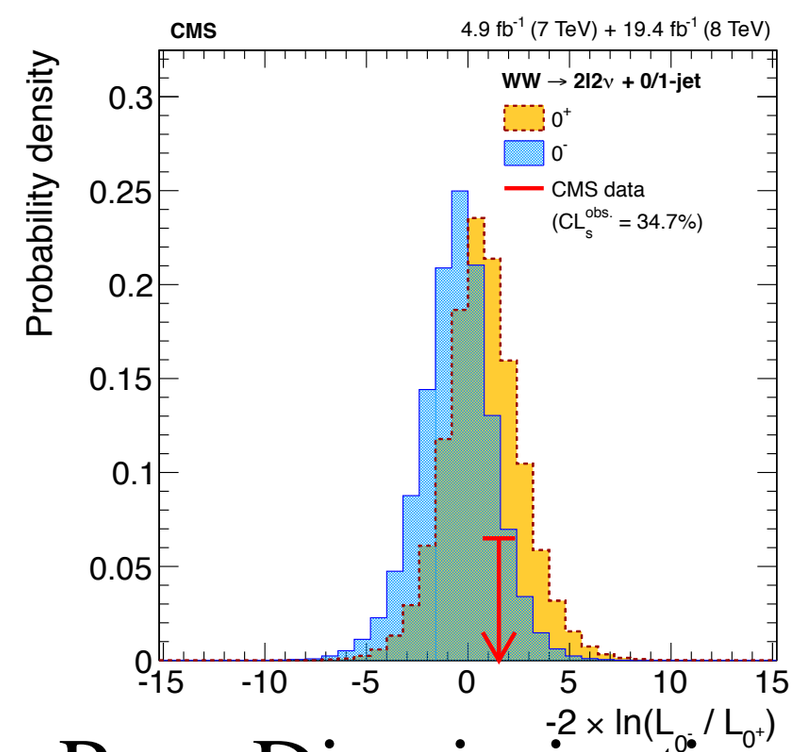
$$h \to V^{(*)}V^{(*)} \to 4l$$



$$\cos\theta_1, \cos\theta_2,$$
$$\cos\theta^*, \cos\phi, M^*_{Z2}$$

Construct a likelihood function out of these observables and discriminate between a SM and a BSM vertex structure.





Poor Discrimination in HWW decays

CMS arXiv:1606.02266, 1312.1129