Exhancing New Physics Signals in Vector Boson Scattering at the LHC

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- Anomalous Coupling of Vector Boson to Higgs Boson
- Previous study in Vector Boson Scattering and factorization scale uncertainty
- New measurement method proposed to reduce factorization scale uncertainty using modern jet substructure techniques

Unitarity in Vector Boson Scattering

- In high energy limit, the polarization tensor for the W boson $\epsilon_L \sim \frac{k}{M_W}$.
- Without a higgs boson, the amplitude for longitudinal vector boson scattering scales as s/M_W^2. Unitarity will be violated.
- In the absence of higgs, the conditions for partial wave unitarity are violated for $s > 16\pi v^2 \approx (1.2 Tev)^2$.
- Higgs exchange will cancel this bad high energy bahavior. For SM Higgs, unitarity gives an upper bound on the Higgs mass which is about 1.2 TeV.

Vector Boson anomalous coupling to Higgs Boson

- Many BSM EWSB Models(Little Higgs, Holographic Higgs, etc.) often include a SM-like Higgs with new higher dimensional couplings.
- The dominant dimension-6 effective operator for VV scattering is:

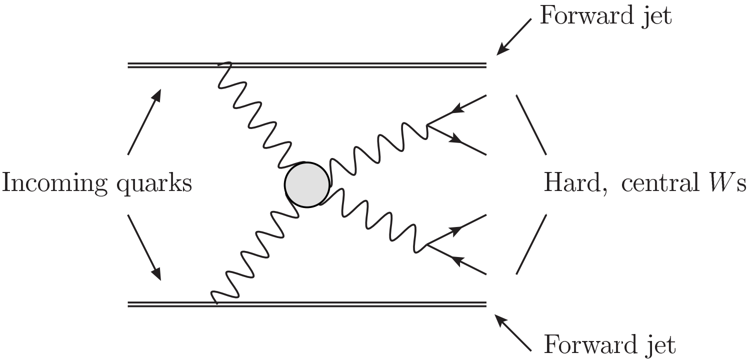
$$\mathcal{O}_H = \frac{c_H}{2f^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H)$$

$$\xi = \frac{v^2}{f^2}$$

- The effective couplings generated from this operator is:

$$g_{\text{eff}} = \frac{g_{\text{SM}}}{\sqrt{1 + c_H\xi}} \approx g_{\text{SM}}\left(1 - \frac{c_H}{2}\xi\right)$$

Vector Boson Scattering



Semi-Leptonic Channel

This channel is studied in [hep-ph] 0201098, again we will use the cut in this paper to do the analysis.

Pass conditions	Veto conditions
$E(j_{\text{tag}}) > 300\ \text{GeV}$	$p_T(j_{\text{mini}}) > 25\ \text{GeV}$
$2 < \lvert y(j_{\text{tag}})\rvert < 5$	$\lvert y(j_{\text{mini}})\rvert < 2$
$p_T(j_{\text{tag}}) > 20\ \text{GeV}$	$130\ \text{GeV} < m_{WJ} < 240\ \text{GeV}$
$p_T(W_{\text{recon.}}) > 320\ \text{GeV}$	
$\lvert y(W_{\text{had}})\rvert < 4$	

Dependence on factorization scale

The factorization scale employed in this study is:

$$\mu^2 = \beta^2 \left(m_W^2 + \frac{1}{2} \sum_{\text{jets}} p_T^2 \right)$$

β is a prefactor to vary the factorization scale.

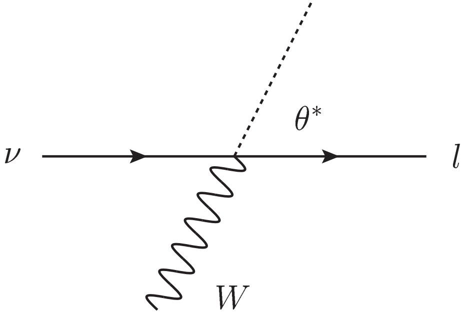
	Parton Level [fb]			Jet Level [fb]		
$c_H\xi$	$\beta = 0.5$	$\beta = 1.0$	$\beta = 2.0$	$\beta = 0.5$	$\beta = 1.0$	$\beta = 2.0$
0.4	0.95	0.81	0.73	0.53	0.38	0.26
0.2	0.82	0.72	0.64	0.43	0.33	0.24
0.0	0.73	0.64	0.57	0.40	0.29	0.21

The uncertainty at Parton Level is $\mathcal{O}(10\%)$ and increases to $\mathcal{O}(100\%)$ at jet level.

New measurement method needed!

- Rate measurement will suffer from factorization scale uncertainty because of the tough tag and veto cuts.
- The new physics will make the unitarization incomplete, we are expecting to see more longitudinally polarized vector boson.
- The polarization measurement is a distribution measurement, and it is independent of the factorization scale. In that case, we only have a overall normalization.

Polarization measurement



$$P_{\pm}(\cos\theta^*) = \frac{3}{8}(1 \pm \cos\theta^*)^2, \; P_L(\cos\theta^*) = \frac{3}{4}(1 - \cos^2\theta^*)$$

$$P(\cos\theta^*) = f_L P_L(\cos\theta^*) + f_+ P_+(\cos\theta^*) + f_- P_-(\cos\theta^*)$$

Polarization measurement

- To measure this polarization angles, we have to fully reconstruct the vector boson four momentum. Therefore, we will look into semi-leptonic channels.
- The neutrino p_T is reconstructed from the missing energy. And p_z is calculated assuming the vector boson is on-shell.
- The daughters of the hadronic W is reconstructed using modern substructure technique.

Leptonic *W* Boson Polarization

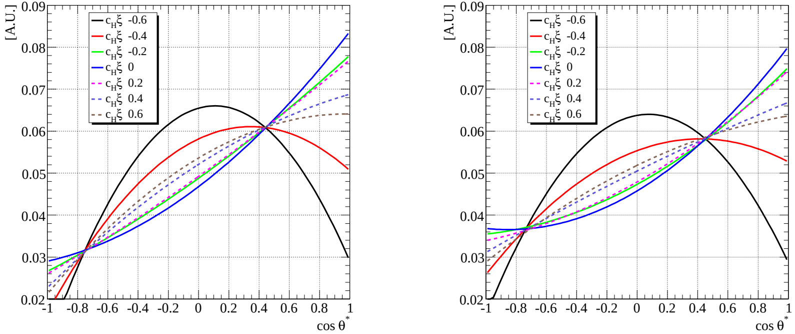


Figure: Left plot is parton level samples , while the one on the right is fully showered, hadronized samples. The jet and parton level distribution agrees with each other well, though the rate is different.

Hadronic *W* boson Polarization

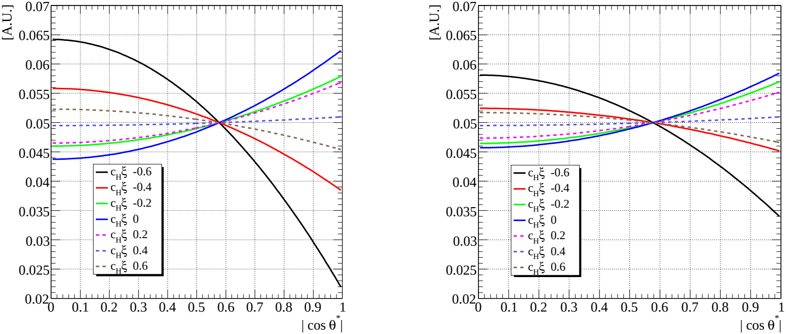


Figure: The plot on the left is parton level samples , while the one on the right is fully showered, hadronized samples.

Longitudinal Fractions and Anomalous Coupling

$c_H\xi$	f_L^P	f_L^J	σ [fb]
-0.6	0.77	0.74	3.38
-0.4	0.58	0.52	1.12
-0.2	0.33	0.30	0.60
0.0	0.27	0.25	0.62
0.2	0.34	0.31	0.65
0.4	0.42	0.39	0.73
0.6	0.46	0.42	0.87

$c_H\xi$	f_L^P	f_L^J
-0.6	0.77	0.70
-0.4	0.58	0.48
-0.2	0.33	0.26
0.0	0.27	0.22
0.2	0.34	0.27
0.4	0.42	0.35
0.6	0.46	0.38

Table: The table on the left is for leptonically decaying bosons and The table on the right is for hadronically decaying bosons.

VV polarization correlation at Parton Level

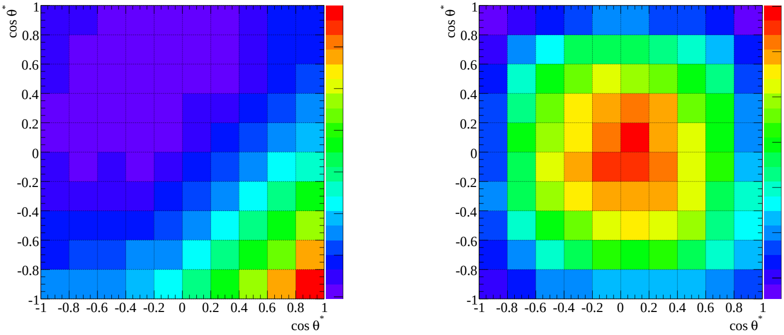


Figure: The plot on the left is for the Higgs with SM couplings, while the one on the right is for $c_H\xi = -0.6$.

VV polarization correlation at Jet Level

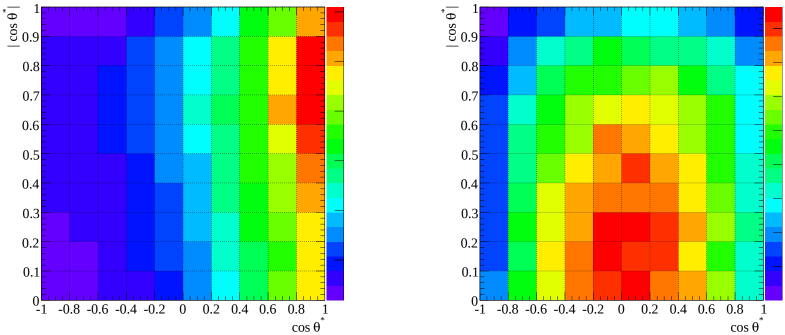


Figure: The plot on the left is for the Higgs with SM couplings, while the one on the right is for $c_H \xi = -0.6$.

Scale insensitivity of the polarization measurement

The largest advantage of this technique is scale insensitivity to the factorization scale, which is our original motivation.

	Longitudinal Fraction		
$c_H\xi$	$\beta = 0.5$	$\beta = 1.0$	$\beta = 2.0$
0.0	0.25	0.26	0.25
0.2	0.33	0.33	0.33
0.4	0.40	0.40	0.41

Reach Plot

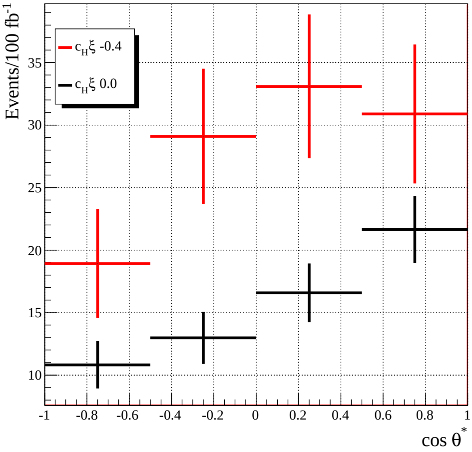


Figure: Projected distribution and associated statistical uncertainties of $\cos\theta^*$ for the leptonically decaying vector using 100 fb^{-1} of luminosity.

Future Directions

- Improvement of the subjet reconstruction of the Hadronic W Boson.
- Application of this polarization measurement technique in other models,for instance, Higgsless Models with a spin one resonance.
- Application for finding missing resonance due to a broad width or PDF convolution.

Conclusion

- Precision measurements prefer a light Higgs, many new physics models already include it with anomalous couplings to Vector Bosons.
- Rate Measurement will suffer from scale uncertainty to find new physics models for EWSB.
- Polarization measurement will cure this problem, and discriminate various anomalous coupling scenarios.

Event Generation and Reconstruction

- The parton level event is generated by our private code using Helicity Amplitude Method, both for leptonic and semi-leptonic channel.
- We will use a 100 GeV SM-like Higgs which has an anomalous coupling to the vector bosons, and the beams are pp at 14TeV .
- The parton level event is showered by Pythia and the final state particles are preclustered into 0.1×0.1 energy cells between $-5 \leq y \leq 5$ to produce $R = 0.7$ anti-k_T jets using FastJet.
- The factorization scale employed in this study is:

$$\mu^2 = \beta^2 \left(m_W^2 + \frac{1}{2} \sum_{\mathrm{jets}} p_T^2 \right)$$

Fully Leptonic Channel Revisited (W^+W^-)

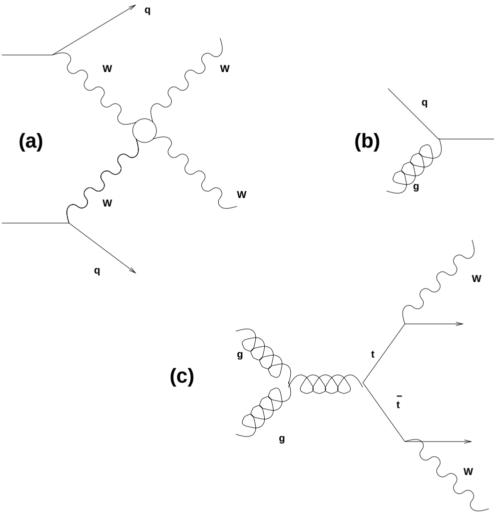
This channel is studied in [hep-ph]9306256, and we will use the cut in this paper to analyze the sample.

Leptonic Cuts	Jet Cuts
$\lvert y(l)\rvert < 2.0$	$E(j_{\rm tag}) > 0.8$ TeV
$p_T(l) > 100$ GeV	$3.0 < \lvert j_{\rm tag}\rvert < 5.0$
$\Delta p_T(ll) > 440$ GeV	$p_T(j_{\rm tag}) > 40$ GeV
$\cos\phi_{ll} < -0.8$	$p_T(j_{\rm veto}) > 30$ GeV
$M(ll) > 250$ GeV	$\lvert y(j_{\rm veto})\rvert < 3.0$

	Parton Level [fb]			Jet Level [fb]		
$c_H\xi$	$\beta = 0.5$	$\beta = 1.0$	$\beta = 2.0$	$\beta = 0.5$	$\beta = 1.0$	$\beta = 2.0$
0.4	0.015	0.013	0.012	0.015	0.009	0.005
0.2	0.013	0.011	0.010	0.013	0.006	0.004
0.0	0.011	0.090	0.008	0.012	0.007	0.004

The uncertainty at Parton Level is $\mathcal{O}(10\%)$ and increases to $\mathcal{O}(100\%)$ at jet level.

VBF and Background



Background...

- A full treatment of the background is beyond the scope of this work.
- From arxiv:0201098 [hep-ph] by Buttorworth and Forshaw, with a similar cuts as we use, the total background is estimated around 0.3 fb.
- The background will definitely changed the rate of VV scattering. However, it may not contaminate our polarization measurement very much.
- Also further suppression might be possible by looking at the correlation between the polarization between the two vector bosons.