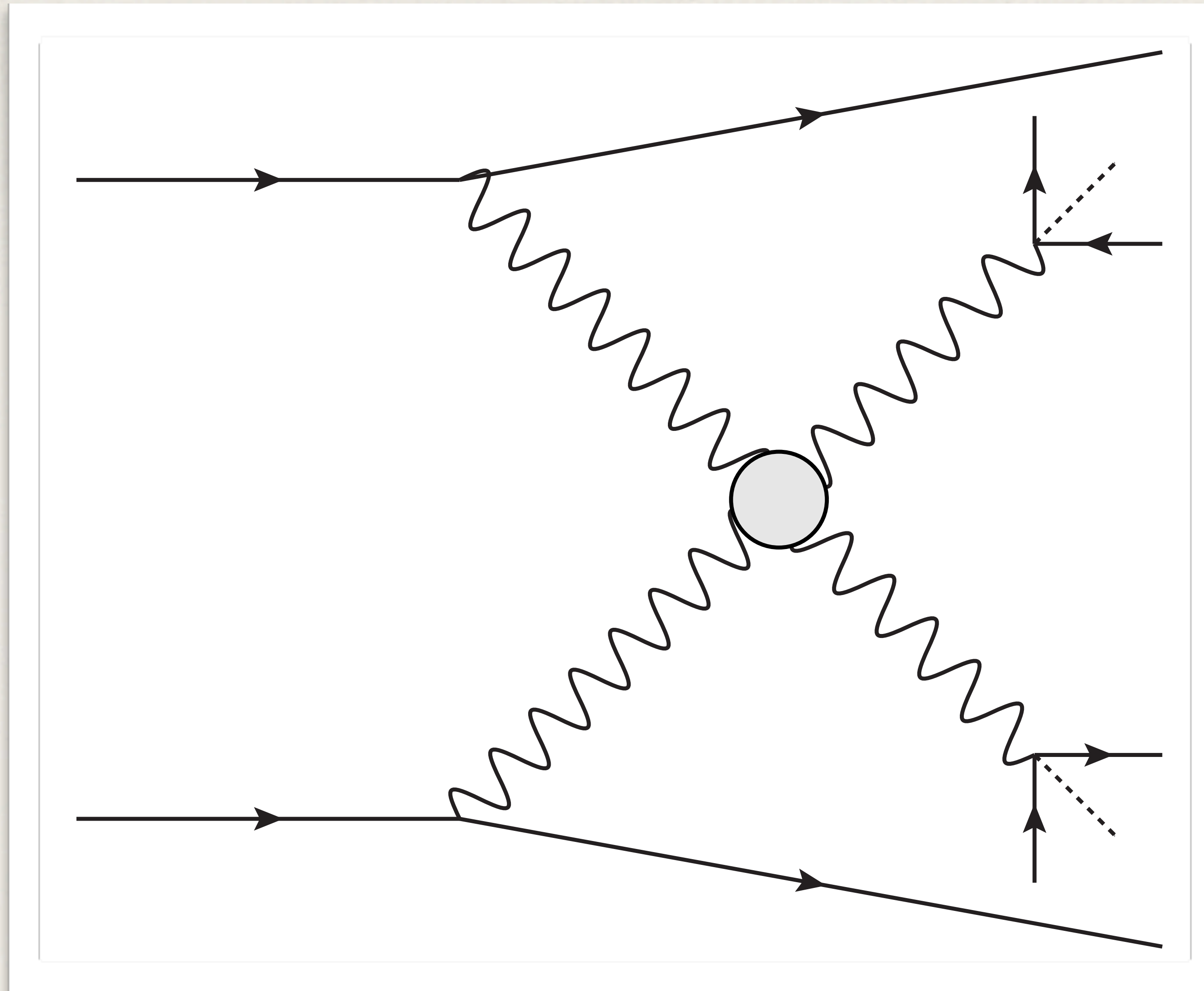

A New Tool for Probing BSM Physics in Vector Boson Fusion

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Based on work with Tao Han (Wisconsin), Lian-Tao Wang (Princeton), and Wenhan Zhu (Princeton)

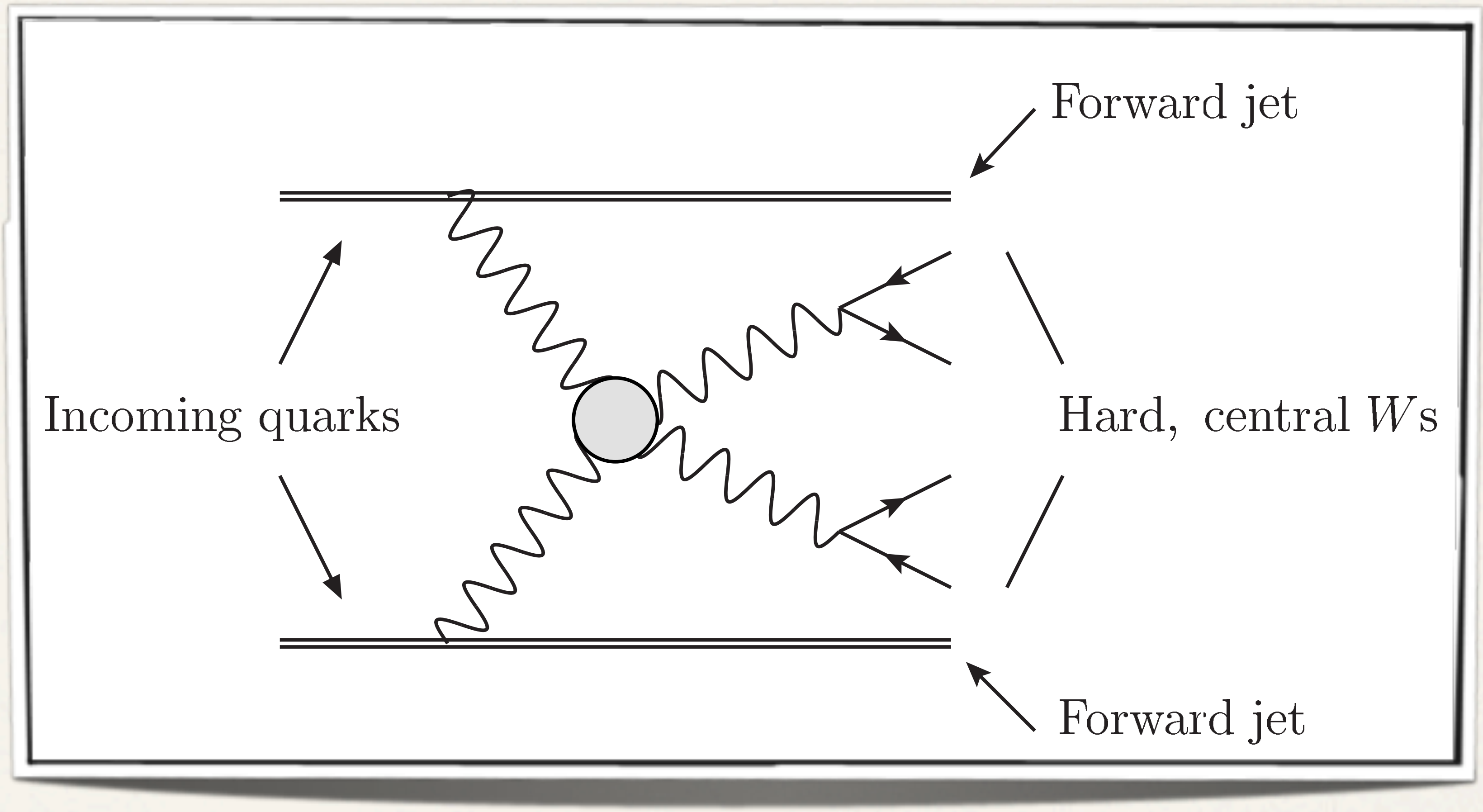
Outline

- Vector boson fusion (VBF) as a probe of new physics
- Using VBF for BSM models with a Higgs
- Factorization scale uncertainties
- Polarization measurements
- Future directions

Takeaway Points

- Vector boson fusion is sensitive to BSM effects even if new particles are beyond the reach of our colliders.
- Measuring these new physics effects through cross section alone can present difficulties.
- Instead, we can see these BSM effects by measuring vector boson polarizations.

Vector Boson Fusion



- Vector boson fusion (VBF) is the process in which vector bosons emitted by energetic quarks scatter back into vector bosons.

VBF as a Probe of BSM Physics

- Some kind of new physics must show up in VBF at the LHC.
  - In the absence of new physics $M(V_L V_L \rightarrow V_L V_L)$ diverges as E^2, violating unitarity at ~1TeV.
  - Therefore, we'll either see new strong interactions in the electroweak sector, or we'll see new particles come in to unitarize the amplitude.

BSM Higgses

- While many BSM models are still feasible, LEP data suggests that there is a particle with the quantum numbers and approximate couplings of the SM Higgs.
- Still, many BSM models can yield such a particle.
- If the states intrinsic to a BSM theory are too heavy to produce we can still infer their presence from modifications to the Higgs couplings.

R. Barbieri, A. Pomarol, R. Rattazzi, and A. Strumia, *Electroweak symmetry breaking after LEP-1 and LEP-2*, Nucl. Phys. B703 (2004) 127–146, [hep-ph/0405040].
G. F. Giudice, C. Grojean, A. Pomarol, and R. Rattazzi, *The Strongly-Interacting Light Higgs*, JHEP 06 (2007) 045, [hep-ph/0703164].

- Therefore, the rest of this analysis will focus on using VBF as a probe of BSM models with a light, Higgs-like particle.
- However, keep in mind the same techniques can be easily extended to probe other models of electroweak symmetry breaking.

See talk by Kentaro Mawatari for another VBF analysis

New Higgs Operators from BSM

- In an effective theory of the Higgs sector, BSM physics enters by generating new dimension six operators.

- All but two of these new operators constrained, and we can only really hope to observe one at the LHC:

$$\mathcal{O}_H \propto \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H)$$

K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, *Low-energy effects of new interactions in the electroweak boson sector*, Phys. Rev. D48 (1993) 2182–2203.
V. Barger, T. Han, P. Langacker, B. McElrath, and P. Zerwas, *Effects of genuine dimension-six Higgs operators*, Phys. Rev. D67 (2003) 115001, [hep-ph/0301097].

Anomalous Couplings

- When the Higgs gets a VEV this operator contributes to its kinetic terms.
- Upon imposing canonical normalization we find the Higgs couplings have shifted from their SM values.

Uncanceled Divergences

- With a SM Higgs, the amplitude $M(V_LV_L\text{->}V_LV_L)$ rises as E^2 until the Higgs scale. Beyond this point the Higgs cancels the divergent behavior and it approaches a constant.

- If the Higgs has non-SM couplings the cancellations in the amplitude will not occur and there will be an E^2 growth until the scale of new physics.

Measuring the E^2 Growth

- So if we can measure the E^2 growth in $V_L V_L$ scattering we can see BSM physics.
- Fortunately, VBF has been well studied and cuts have been developed to isolate the longitudinal scattering signal.

VBF Analysis Cuts

- Nearly all VBF cuts require three basic things:
  - Two high-p_T vector bosons
  - Forward jets
  - Few central jets (to reduce background - in the signal process there is no color exchange)

J. Bagger et al., *CERN LHC analysis of the strongly interacting W W system: Gold plated modes,* Phys. Rev. D52 (1995) 3878–3889, [hep-ph/9504426].
J. M. Butterworth, B. E. Cox, and J. R. Forshaw, *W W scattering at the CERN LHC*, Phys. Rev. D65 (2002) 096014, [hep-ph/0201098].

A Subtlety

- A full calculation of VBF requires that one account for the effects of the parton shower.
- This, in turn, requires one pick a factorization scale μ to characterize the hard scattering. We use:

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

- Where β is an order-one parameter.

Large Scale Sensitivity

- One would hope that the exact choice of factorization scale wouldn't matter too much, and for small differences in β the cross section would be relatively stable.
  - After all, the tree level process is purely electroweak.
- However, this is not the case.

- Here are some example cross sections for a particular set of VBF cuts and for different anomalous couplings (labeled $c_H\xi$, which is 0 for the SM).

	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

Stable before parton shower

Sensitive afterward

- Basically, the central jet veto meant to reduce QCD backgrounds makes the analysis very sensitive to the treatment of the forward jets.

- If this were the best one can do then it would be very hard to see BSM physics in VBF without higher order calculations and/or difficult calibrations.

A New Tool: Polarization

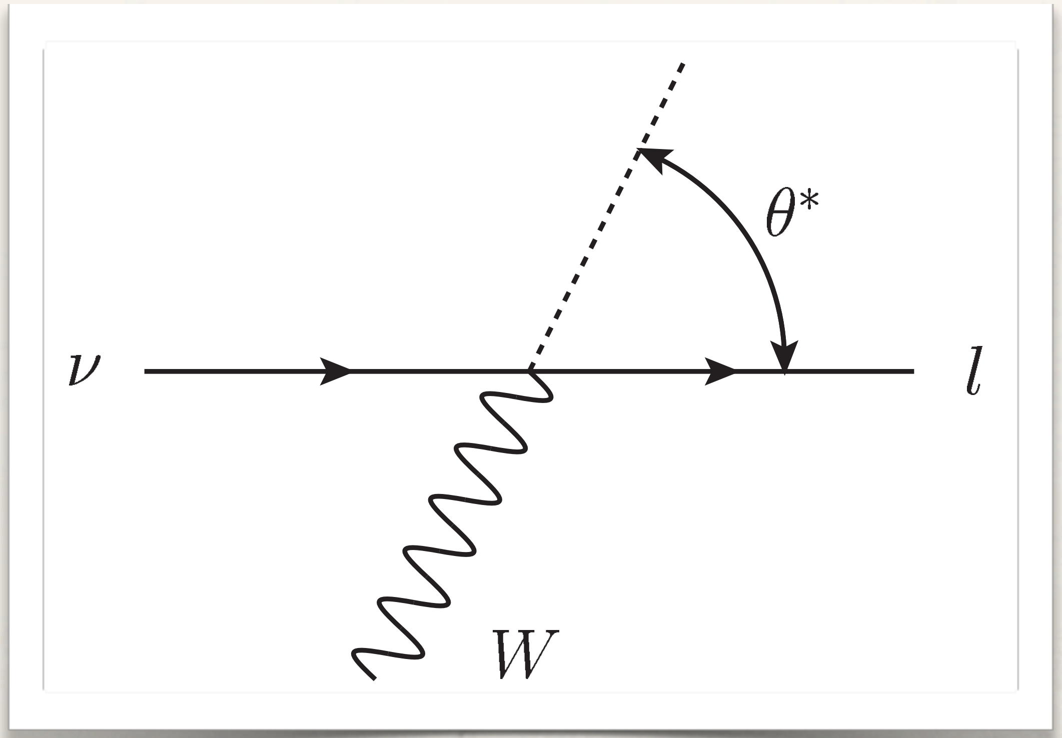
- It turns out we can measure the E^2 behavior of the $V_L V_L$ scattering amplitude by observing its growth relative to the scattering into transversely polarized gauge bosons.
- Because the factorization scale really only affects the behavior of the forward jets, this measurement is quite robust.

Polarization in Practice

- To measure the gauge boson polarizations we can look at the angular distribution of their decay products.
- To pick a consistent reference frame for this measurement we need to fully reconstruct the VV system, so we'll be looking mostly at semi-leptonic VV decays.

Reference Frame

- We need to pick a reference frame.
- One convenient choice is to work in each vector's rest frame and measure the decay angles with respect to the vector direction as seen from the VV center of mass:



Distributions

- A simple spin analysis tells us the decay distributions for different polarizations go as

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

Results

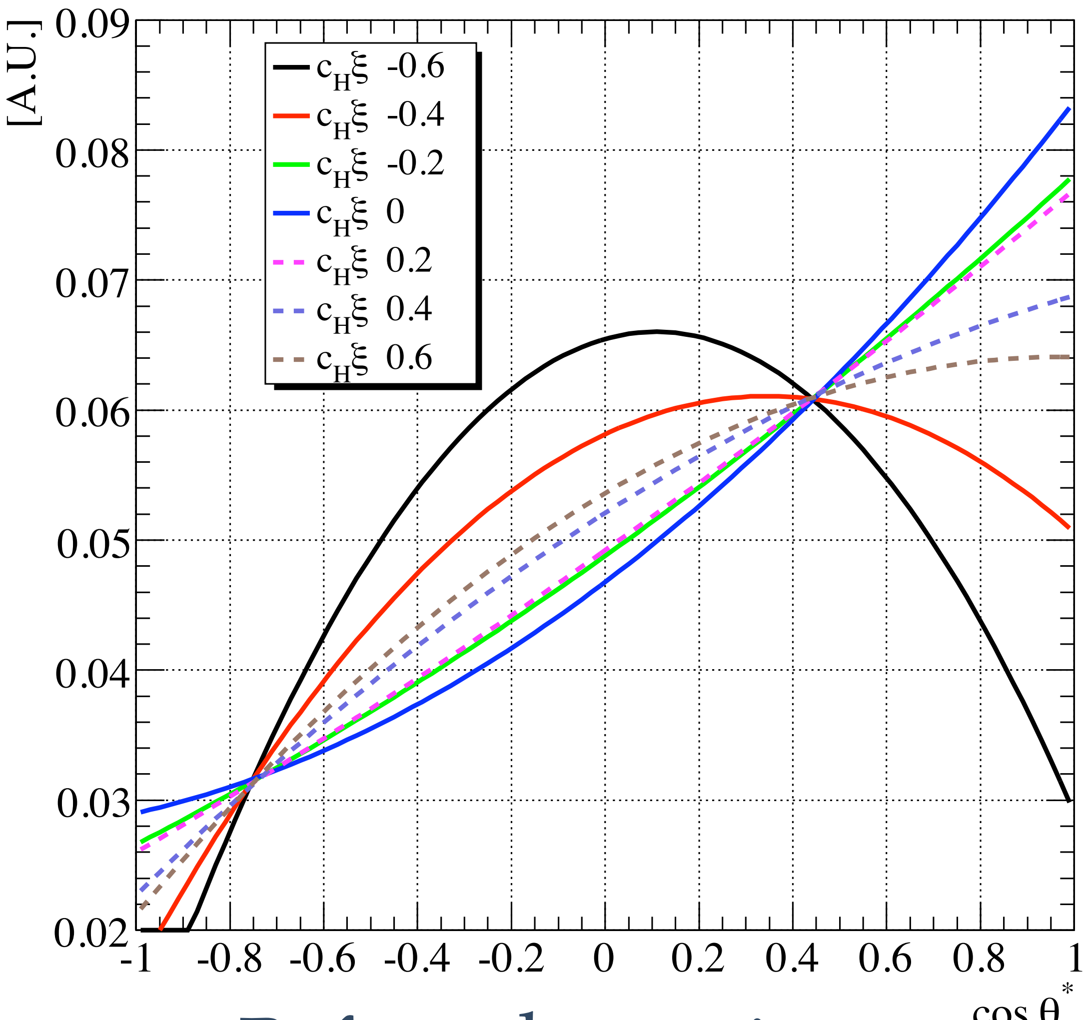
- Our results were generated using a slightly modified version of the cuts from the first semi-leptonic VBF study (Butterworth, Cox, and Forshaw)

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

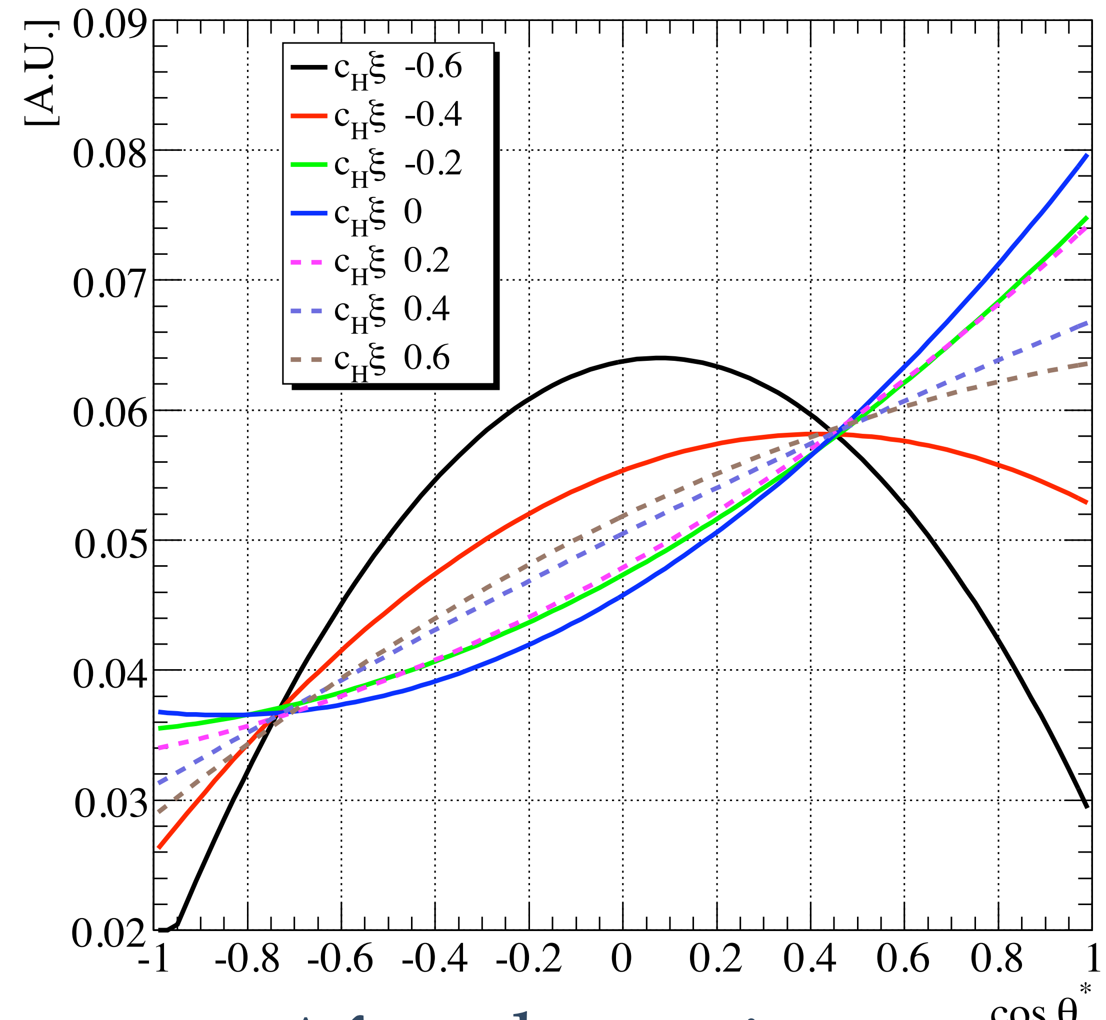
- Matrix element results are showered in Pythia6(Q^2)

J. M. Butterworth, B. E. Cox, and J. R. Forshaw, *W W scattering at the CERN LHC*, Phys. Rev. D65 (2002) 096014, [hep-ph/0201098].

Leptonic Results



Before showering



After showering

Stability

- As promised, the results are quite stable under variations in the factorization scale ($c_H\xi$ parameterizes the deviation from the SM)

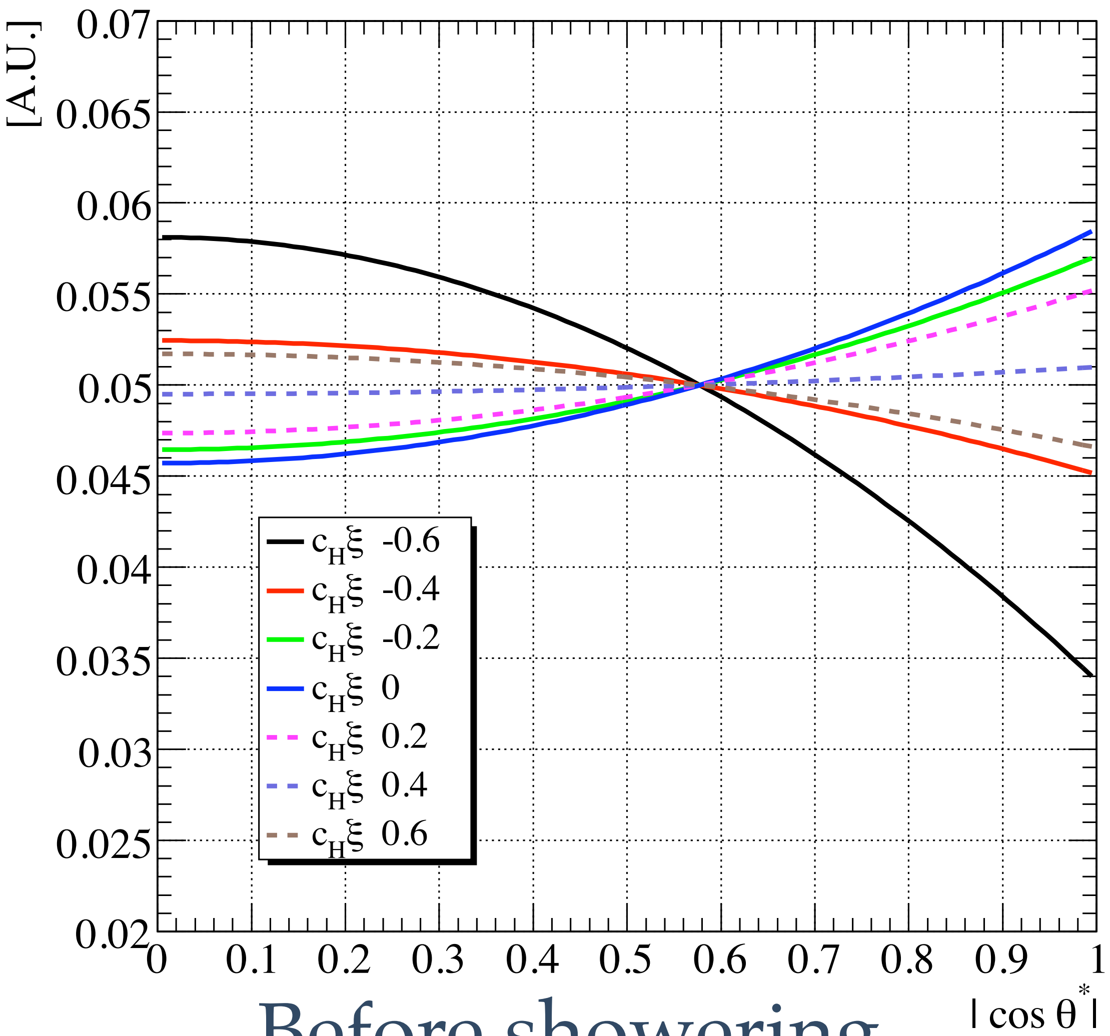
$$P(\cos\theta^*) = f_L P_L(\cos\theta^*) + f_+ P_+(\cos\theta^*) + f_- P_-(\cos\theta^*)$$

	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

Hadronic Vector Polarization

- It's possible to get polarization information out of the hadronically decaying vector as well.
- This is a little more difficult both because it required the use of subjets and because the resulting distributions are symmetrized.

Hadronic Results



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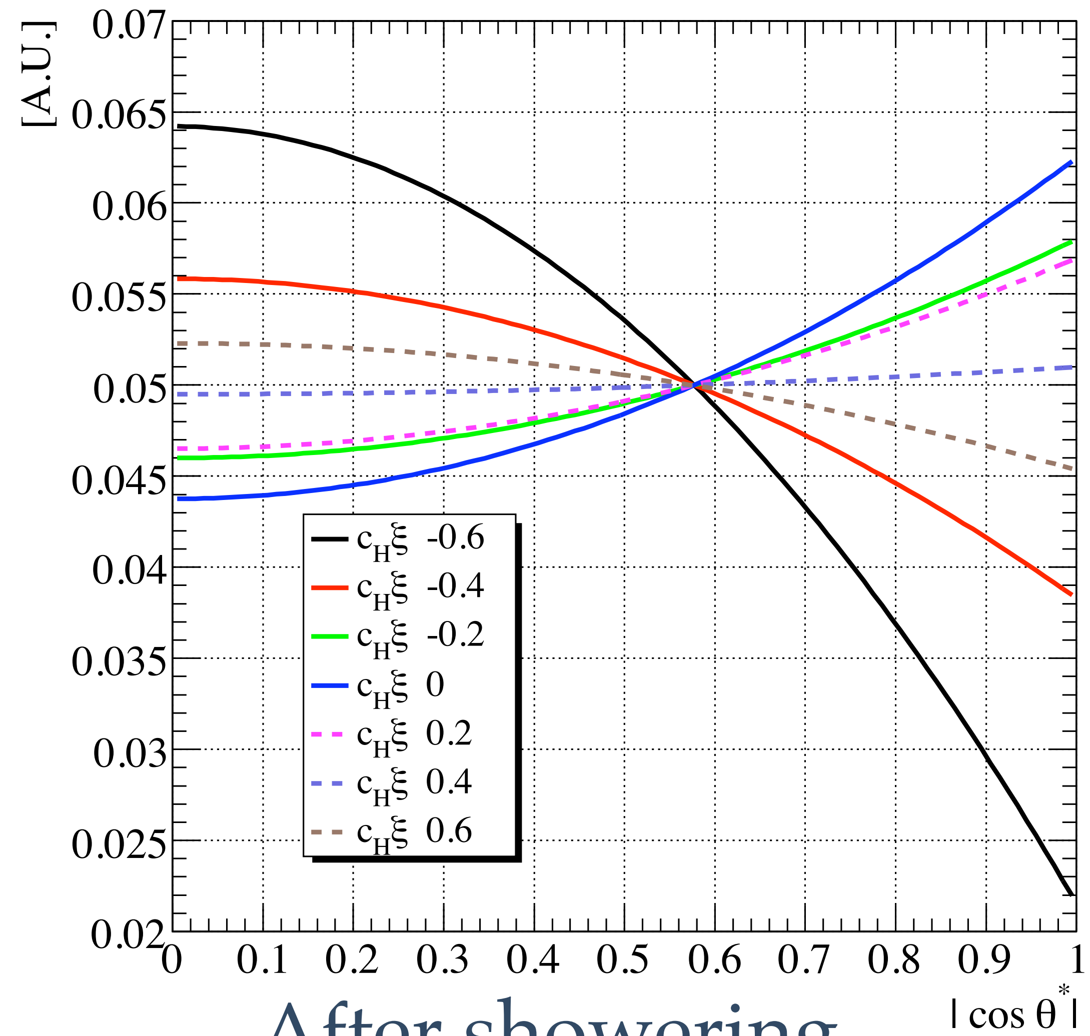
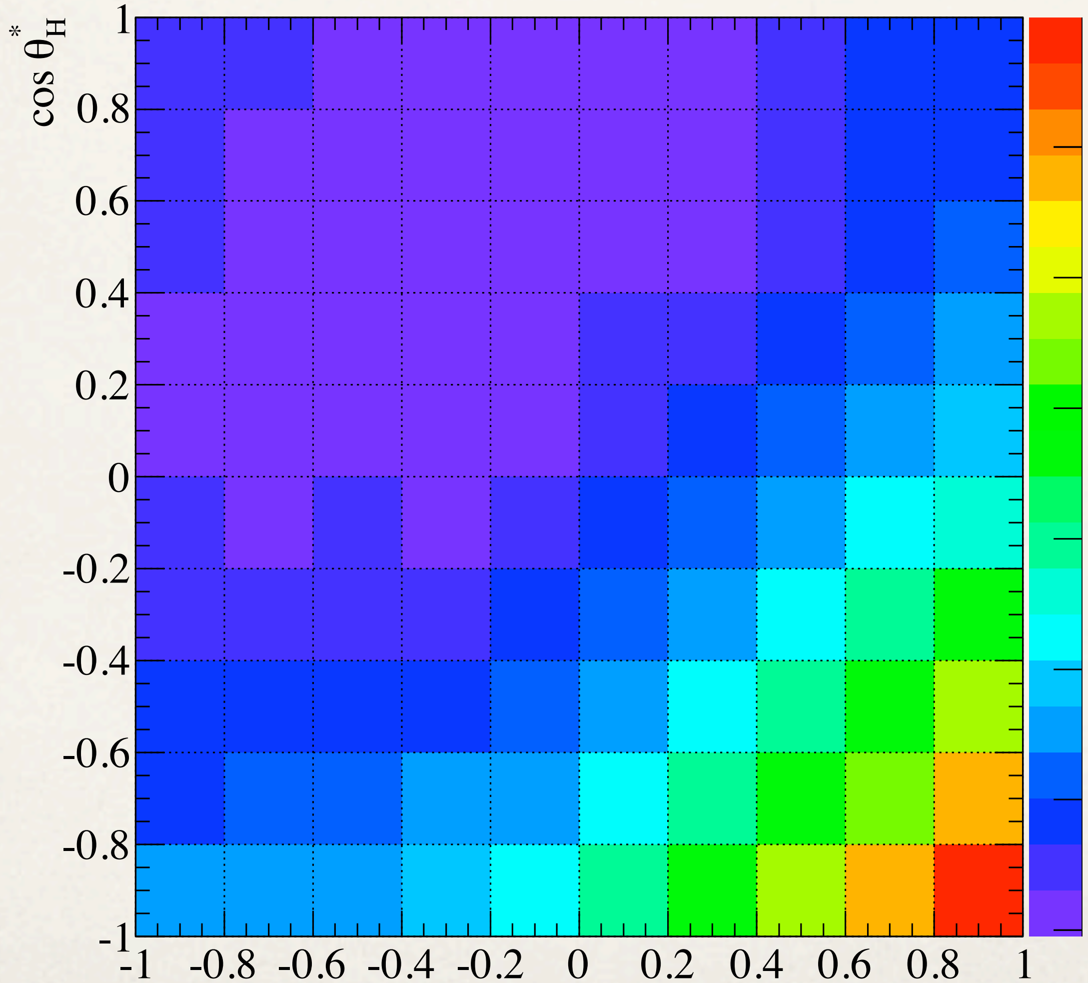


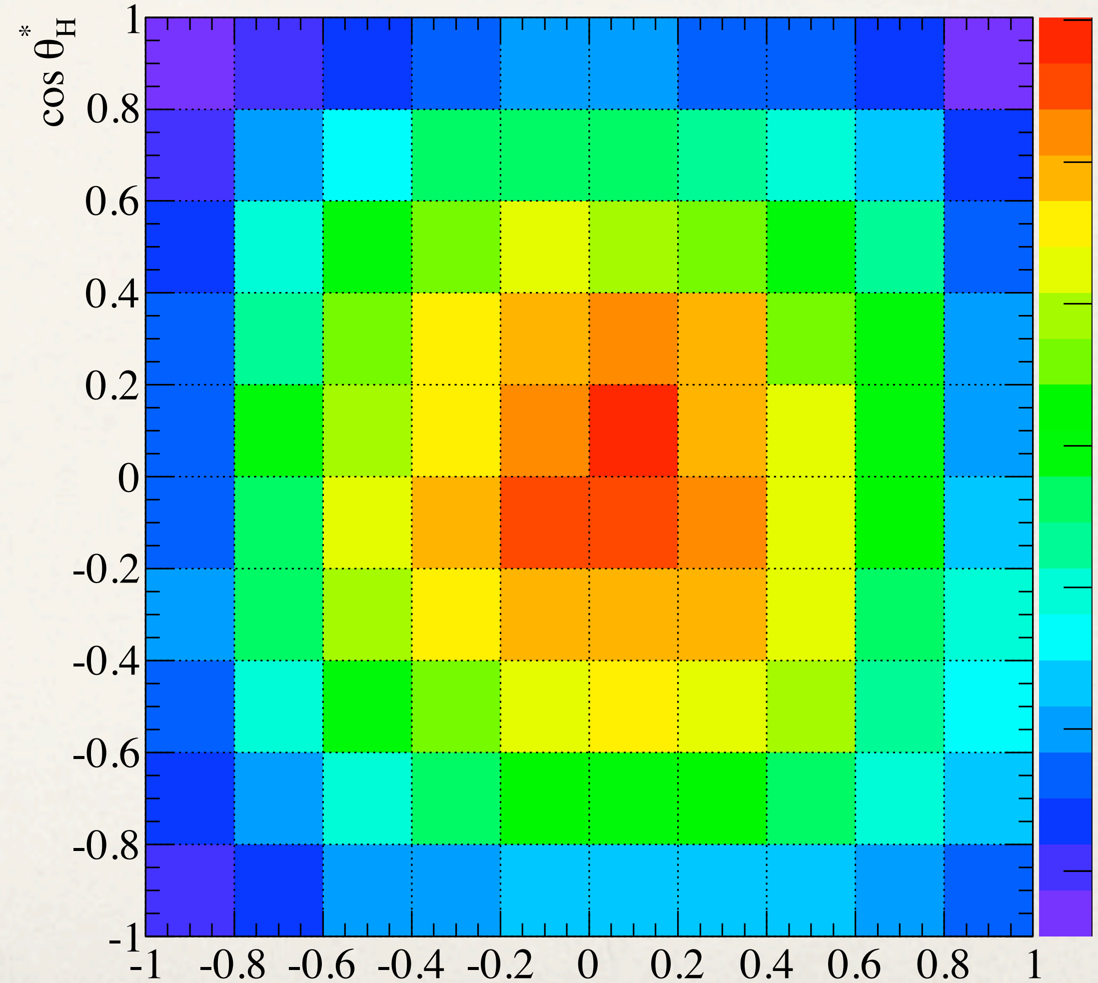
After showering

Combined Results

- By combining results we can increase our discriminating power by looking for correlations.

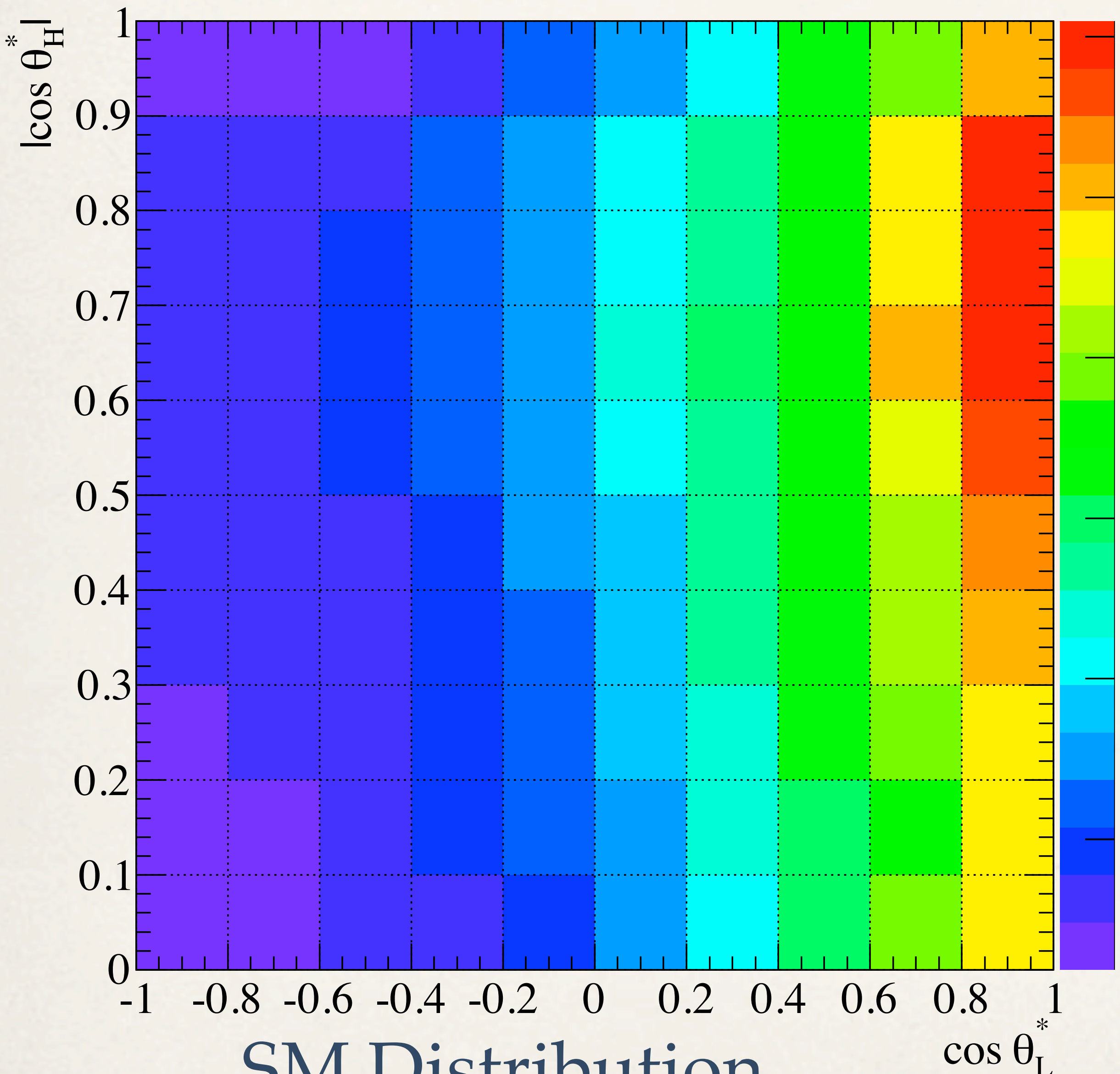


SM Distribution

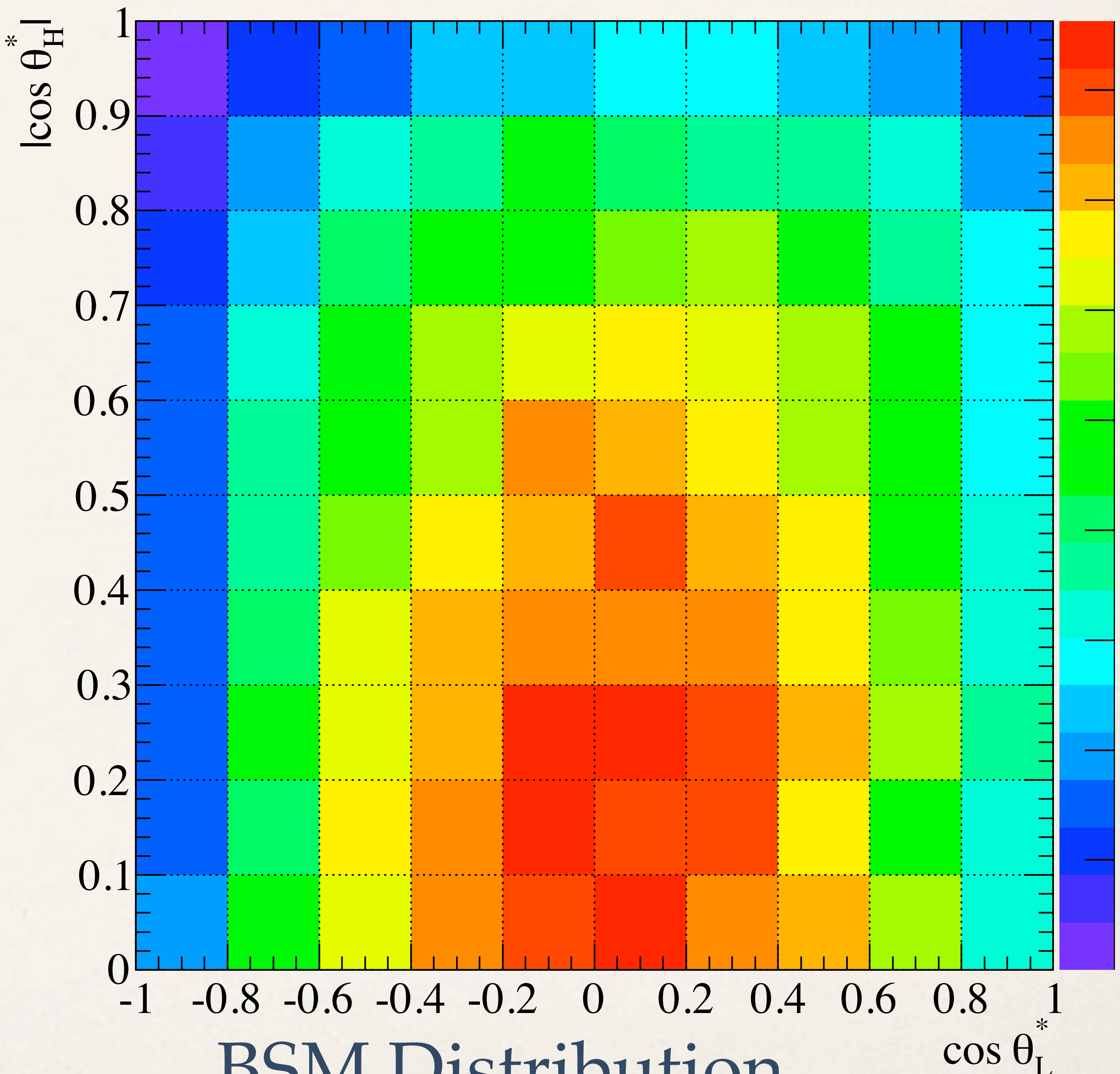


BSM Distribution

Fully Showered & Symmetrized



SM Distribution



BSM Distribution

- In the end we find the leptonic distributions are stable against variations in the factorization scale and in good agreement with the matrix element results.

- The hadronic distributions are more distorted, but presumably this can eventually be understood by analyzing other SM processes.

	Leptonic W		Hadronic W		
$c_H\xi$	f_L^P	f_L^J	f_L^P	f_L^J	σ [fb]
-0.6	0.77	0.74	0.71	0.55	3.38
-0.4	0.58	0.52	0.49	0.40	1.12
-0.2	0.33	0.30	0.23	0.24	0.60
0.0	0.27	0.25	0.17	0.22	0.62
0.2	0.34	0.31	0.24	0.26	0.65
0.4	0.42	0.39	0.32	0.32	0.73
0.6	0.46	0.42	0.40	0.38	0.87

Background

- The overall background rate can usually be cut down to be at or below the signal level.
- Also, because the vectors do not come from the same vertex we don't expect to see any meaningful distributions in their polarizations.
  - Could provide another handle on background

Future Directions

- Better hadronic reconstruction
- Identifying new resonances in VBF
- Differential distributions

Conclusions

- New physics affects VBF amplitudes
- To measure these with rate information alone presents difficulties
- By looking at the polarization distributions we can circumvent these difficulties