Electroweak Restoration at the LHC and Beyond

Li Huang,[1,*] Samuel D. Lane,[1,2,†] Ian M. Lewis,[1,‡] and Zhen Liu[3,§]

[1]*Department of Physics and Astronomy,*

University of Kansas, Lawrence, Kansas 66045 U.S.A.

[2]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973 U.S.A*

[3]*Maryland Center for Fundamental Physics, Department of Physics,*

University of Maryland, College Park, MD, 20742 U.S.A.

The LHC and proposed future colliders will thoroughly explore the nature of electroweak (EW) symmetry breaking. As energies are pushed far above the EW scale, it will be possible to observe the restoration of EW symmetry. There is a long history of studying how to observe EW symmetry restoration in longitudinal vector boson scattering [1–16]. By the Goldstone boson equivalence theorem, longitudinal vector boson scattering is equivalent to two-to-two scattering of Goldstone bosons, which originate from the Higgs potential.

We propose to study EW restoration in di-boson final processes: $q\bar{q}' \to VV'/Vh$, where $V, V' = W^\pm, Z$ and h is the SM Higgs. At high energies, the longitudinal vector boson processes originate from the Higgs kinetic term:

$$\mathcal{L}_{Kin} = |D_\mu \Phi|^2, \quad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ v + h + i\, G^0 \end{pmatrix}, \tag{1}$$

where $v = 246$ GeV is the Higgs vev. To see the restoration of EW symmetry, we propose to observe the convergence of longitudinal to the applicable Goldstone boson production rates in the $v \to 0$ limit.

To observe this convergence, we necessarily need to represent the reach in longitudinally polarized vector bosons. In Fig. 1 we show the polarization composition of the various di-boson processes. As is clear, Wh and Zh are very quickly dominated by longitudinally polarized vector boson. Our analyses of these processes are soon to appear in a paper. We

*Electronic address: huangli@ku.edu

†Electronic address: samuel.lane@ku.edu

‡Electronic address: ian.lewis@ku.edu

§Electronic address: zliuphys@umd.edu

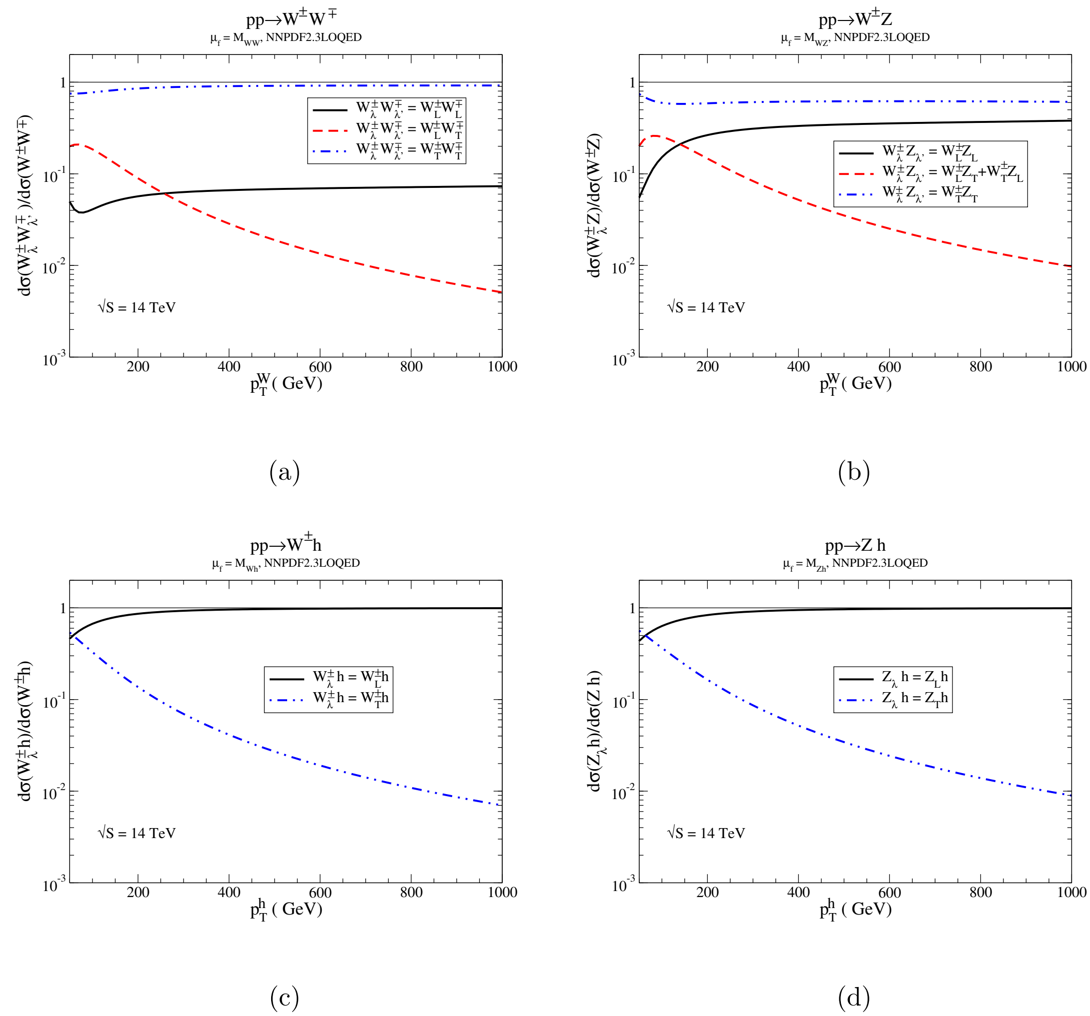

FIG. 1: Ratio of transverse momentum, p_T, distributions of (blue dash-dot-dot) fully longitudinal, (black solid) fully transverse, and (red dashed) longitidunial+transversely polarized gauge bosons to the total distrbution summed over polarizations for (a) $W^\pm W^\mp$, (b) $W^\pm Z$, (c) $W^\pm h$, and (d) Zh production. The lab frame energy is the HL-LHC energy of $\sqrt{S} = 14$ TeV.

propose to expand that analysis to 100 TeV collider, and seek collaboration on high energy lepton colliders. For WW and WZ final states, which are dominated by transverse polarization at high energies, we propose to use machine learning techniques to get a signal sample rich in longitiduinally polarized vector bosons, to see the restoration of EW symmetry. We will conduct these studies for the LHC and future colliders.

[1] C. H. Llewellyn Smith, *High-Energy Behavior and Gauge Symmetry*, *Phys. Lett.* **46B** (1973) 233–236.

[2] M. J. G. Veltman, *Second Threshold in Weak Interactions*, *Acta Phys. Polon.* **B8** (1977) 475.

[3] B. W. Lee, C. Quigg, and H. B. Thacker, *Weak Interactions at Very High-Energies: The Role of the Higgs Boson Mass*, *Phys. Rev.* **D16** (1977) 1519.

[4] M. S. Chanowitz and M. K. Gaillard, *The TeV Physics of Strongly Interacting W's and Z's*, *Nucl. Phys.* **B261** (1985) 379–431.

[5] D. A. Dicus, J. F. Gunion, and R. Vega, *Isolating the scattering of longitudinal W+'s at the SSC using like sign dileptons*, *Phys. Lett.* **B258** (1991) 475–481.

[6] V. D. Barger, K.-m. Cheung, T. Han, and R. J. N. Phillips, *Strong W^+W^+ scattering signals at pp supercolliders*, *Phys. Rev.* **D42** (1990) 3052–3077.

[7] J. Bagger, S. Dawson, and G. Valencia, *Effective field theory calculation of p p —¿ V(L) V(L) X*, *Nucl. Phys.* **B399** (1993) 364–394, `arXiv:hep-ph/9204211 [hep-ph]`.

[8] D. A. Dicus and V. S. Mathur, *Upper bounds on the values of masses in unified gauge theories*, *Phys. Rev.* **D7** (1973) 3111–3114.

[9] J. Bagger, V. D. Barger, K.-m. Cheung, J. F. Gunion, T. Han, G. A. Ladinsky, R. Rosenfeld, and C. P. Yuan, *The Strongly interacting W W system: Gold plated modes*, *Phys. Rev.* **D49** (1994) 1246–1264, `arXiv:hep-ph/9306256 [hep-ph]`.

[10] J. Bagger, V. D. Barger, K.-m. Cheung, J. F. Gunion, T. Han, G. A. Ladinsky, R. Rosenfeld, and C. P. Yuan, *CERN LHC analysis of the strongly interacting W W system: Gold plated modes*, *Phys. Rev.* **D52** (1995) 3878–3889, `arXiv:hep-ph/9504426 [hep-ph]`.

[11] M. S. Chanowitz, *Strong W W scattering at the end of the 90's: Theory and experimental prospects*, in *Hidden symmetries and Higgs phenomena. Proceedings, Summer School, Zuoz, Switzerland, August 16-22, 1998*, pp. 81–109. 1998. `arXiv:hep-ph/9812215 [hep-ph]`.

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

[13] T. Han, D. Krohn, L.-T. Wang, and W. Zhu, *New Physics Signals in Longitudinal Gauge Boson Scattering at the LHC*, *JHEP* **03** (2010) 082, `arXiv:0911.3656 [hep-ph]`.

[14] J. Brehmer, J. Jaeckel, and T. Plehn, *Polarized WW Scattering on the Higgs Pole*, *Phys.*

Rev. **D90** no. 5, (2014) 054023, arXiv:1404.5951 [hep-ph].

[15] B. Henning, D. Lombardo, M. Riembau, and F. Riva, *Measuring Higgs Couplings without Higgs Bosons*, *Phys. Rev. Lett.* **123** no. 18, (2019) 181801, arXiv:1812.09299 [hep-ph].

[16] G. Cuomo, L. Vecchi, and A. Wulzer, *Goldstone Equivalence and High Energy Electroweak Physics*, *SciPost Phys.* **8** no. 5, (2020) 078, arXiv:1911.12366 [hep-ph].