Sensitivity to longitudinal vector boson scattering in $W^{\pm}W^{\pm}jj$ at future hadron colliders

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Abstract

We study the sensitivity to longitudinal vector boson scattering at a 27, 50 and 100 TeV pp collider using events containing two leptonically-decaying same-electric-charge W bosons produced in association with two jets.

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I. INTRODUCTION

Vector boson scattering (VBS) processes are important probes of the non-Abelian gauge structure of the electroweak (EW) interactions and the EW symmetry breaking mechanism. The unitarity of the tree-level amplitude of the scattering of longitudinally polarized gauge bosons at high energies [1–3] *could* be restored by the Higgs-like boson observed at the CERN LHC with a mass of about 125 GeV [4–6]. However, modifications of the cross sections of processes involving scattering of longitudinally polarized gauge bosons with respect to the Standard Model (SM) expectations are predicted in physics beyond the SM models via the presence of additional new resonances or via modifications of the Higgs boson couplings to gauge bosons [7–9].

The VBS processes at proton-proton (pp) colliders are characterized by the presence of two gauge bosons in association with a forward/backward pair of jets. The goal of this note is to study the prospects for measuring the polarized scattering of same-sign $W^{\pm}W^{\pm}jj$ production at a future high energy pp machine [10, 11]. In particular, our studies focus on future hadron colliders operating at a \sqrt{s} of 27, 50 and 100 TeV (the latter of which corresponding to the FCC-hh collider [10]) with an integrated luminosity of 30 ab⁻¹. The leptonic decay mode of pure EW production of same-sign $W^{\pm}W^{\pm}jj$, where both W bosons decay into electrons or muons, is a promising final state as the background contribution from the strong (QCD-induced) production of $W^{\pm}W^{\pm}jj$ is small. The ATLAS and CMS Collaborations have measured the EW production of the $W^{\pm}W^{\pm}jj$ process at $\sqrt{s} = 8$ and 13 TeV [12–16].

The W boson can be polarized either longitudinally (W_L) or transversely (W_T). This leads to three contributions $W_L^{\pm}W_L^{\pm}jj$, $W_L^{\pm}W_T^{\pm}jj$, and $W_T^{\pm}W_T^{\pm}jj$ to the overall $W^{\pm}W^{\pm}jj$ production. In this study, the candidate $W^{\pm}W^{\pm}jj$ events contain exactly two same-sign leptons, missing transverse momentum, and two jets with a large rapidity separation and a high dijet invariant mass. The helicity eigenstates are defined in the WW center-of-mass reference frame. Studies of changes in polarization fractions and in kinematic distributions arising from defining the helicity eigenstates in different reference frames at the LHC are reported in Ref. [17]. A maximum-likelihood fit is performed using the distribution of events as a function of the separation between the two jets in azimuthal angle, $\Delta \phi_{jj}$, to extract the cross sections of the $W_L^{\pm}W_L^{\pm}jj$, $W_L^{\pm}W_T^{\pm}jj$, and $W_T^{\pm}W_T^{\pm}jj$ contributions.

A first measurement attempt of the production cross sections of polarized scattering

in the same-sign $W^{\pm}W^{\pm}jj$ process was performed by the CMS Collaboration using a data sample corresponding to an integrated luminosity of 137 fb⁻¹ at $\sqrt{s} = 13$ TeV [18], with an observed significance of about one standard deviation for the $W_L^{\pm}W_L^{\pm}jj$ component. There have been a number of studies focusing on techniques to maximize the sensitivity to the purely longitudinal contributions at the High-Luminosity LHC (HL-LHC) [19–21]. The CMS Collaboration recently projected the result in Ref. [18] to an integrated luminosity of 3000 fb⁻¹, expected at the end of the HL-LHC, to obtain an expected significance of about four standard deviations for $W_L^{\pm}W_L^{\pm}jj$ production [22]. Beyond the LHC, studies focusing on the prospects of measuring longitudinally polarized ZZ scattering at a future high-energy muon collider were performed in Ref. [23].

II. EVENT SIMULATION

The $W^{\pm}W^{\pm}jj$ events are modeled at leading order in QCD using the Monte Carlo event generator MADGRAPH5_aMC@NLO version 3.1.1 [24, 25] with the NNPDF2.3 PDF set [26] interfaced with PYTHIA version 8 [27] for parton showering. Events where either both W bosons are longitudinally polarized ($W_L^{\pm}W_L^{\pm}jj$ events), both W bosons are transversely polarized ($W_T^{\pm}W_T^{\pm}jj$ events), or those where one of the W bosons is longitudinally polarized and the other is transversely polarized ($W_L^{\pm}W_T^{\pm}jj$ events) are generated separately.

Background processes considered in this analysis include the production of $W^{\pm}W^{\pm}jj$ via the strong interaction, the production of WZjj via the electroweak and strong interactions, and the production of tl^+l^-j , referred to as tZq. These processes are simulated with MADGRAPH5_aMC@NLO as well.

The Delphes [28] program, using a generic FCC detector card, is then used to simulate detector effects for all samples. Jets are clustered from the reconstructed objects using FASTJET [29] with the anti-kt clustering algorithm [30], using a distance parameter of 0.4. For the validation of the signal samples, an inclusive $W^{\pm}W^{\pm}jj$ electroweak sample was generated using the same generator and settings as well as Delphes for detector effects, and good agreement was observed with respect to the sum of the polarized signal samples. Detector-specific backgrounds such as those in which lepton charge is misidentified or those in which jets mimic leptons were not considered in this analysis as they are highly detector-specific.

III. EVENT SELECTION

Signal $(W^{\pm}W^{\pm}jj)$ events are characterized by the presence of two high transverse momentum (p_T) same-charge leptons (electrons or muons, denoted by l), large missing transverse momentum (E_T^{miss}) and two forward/backward jets with large di-jet invariant mass (M_{jj}) . In this analysis, events with τ leptons are only considered when the τ decays leptonically. The event selection was optimized for $\sqrt{s} = 100$ TeV to maximize the background rejection and enhance the signal, and then applied to all \sqrt{s} values under study. Table I gives a summary of all object and event selection cuts applied in this analysis. The distributions of events as a function of the invariant mass of the two jets with leading $p_T(M_{jj})$, the invariant mass of the two leptons (M_{ll}) , the separation in azimuthal angle ϕ between the two leading jets in $p_T(\Delta \phi_{jj})$ and the separation in pseudorapidity η between the two leading jets in $p_T(\Delta \eta_{jj})$ after the full selection requirements are shown in Figure 1 for $\sqrt{s} = 27$ TeV, in Figure 2 for $\sqrt{s} = 50$ TeV and in Figure 3 for $\sqrt{s} = 100$ TeV.

Selection type	Requirement
Number of leptons	Exactly 2 same-charge leptons
Lepton p_T	$p_T \ge 15 \text{ GeV}$
Number of jets	≥ 2
Jet p_T	$p_T \ge 50 \mathrm{GeV}$
Di-lepton invariant mass	$M_{ll} \ge 60 {\rm GeV}$
Z-veto	$ M_{ll} - M_Z > 10 \text{ GeV}$
Di-jet invariant mass	$M_{jj} \ge 2 \text{ TeV}$
Missing transverse momentum	$E_T^{miss} \ge 50 \text{ GeV}$

TABLE I. Selection criteria used for $W^{\pm}W^{\pm}jj$ events.

IV. SENSITIVITY ANALYSIS

The sensitivity to the $W^{\pm}W^{\pm}jj$ polarization contributions is estimated using a profile likelihood fit as implemented in the RooFit [31] and RooStats [32] packages. We consider three signal strength parameters, μ_{LL} , μ_{LT} and μ_{TT} corresponding to each of the $W^{\pm}W^{\pm}jj$



FIG. 1. The distribution of events as a function of M_{jj} , M_{ll} , $\Delta \phi_{jj}$ and $\Delta \eta_{jj}$ after the full selection shown in Table I for $\sqrt{s} = 27$ TeV.

polarization states. We assume a normalization uncertainty of 2% for all the processes due to uncertainties in the integrated luminosity. The uncertainties associated with limited number of simulated events are also included in the profile likelihood fit and the results are dominated by these uncertainties. We do not consider any other sources of systematic uncertainties in this study.

Table II shows the signal strengths μ , defined as the ratio to the SM cross-section, and the corresponding uncertainties for each $W^{\pm}W^{\pm}jj$ polarization state for all \sqrt{s} values under study. The values are expected to be unity because the Asimov dataset is used in the fit. Table III gives the event yields obtained after the fit for all \sqrt{s} values under study.



FIG. 2. The distribution of events as a function of M_{jj} , M_{ll} , $\Delta \phi_{jj}$ and $\Delta \eta_{jj}$ after the full selection shown in Table I for $\sqrt{s} = 50$ TeV.

Polarization	Signal Strength			
	$\sqrt{s} = 27 \text{ TeV}$	$\sqrt{s} = 50 \text{ TeV}$	$\sqrt{s} = 100 \text{ TeV}$	
μ_{LL}	1 ± 0.39	1 ± 0.22	1 ± 0.17	
μ_{LT}	1 ± 0.11	1 ± 0.10	1 ± 0.04	
μ_{TT}	1 ± 0.08	1 ± 0.05	1 ± 0.02	

TABLE II. Signal strengths μ after the fit for each $W^{\pm}W^{\pm}jj$ polarization state and all \sqrt{s} values under study.



FIG. 3. The distribution of events as a function of M_{jj} , M_{ll} , $\Delta \phi_{jj}$ and $\Delta \eta_{jj}$ after the full selection shown in Table I for $\sqrt{s} = 100$ TeV.

Process	Signal Region			
	$\sqrt{s} = 27 \text{ TeV}$	$\sqrt{s} = 50 \text{ TeV}$	$\sqrt{s} = 100 \text{ TeV}$	
$W_L W_L$	12503.6 ± 4795.85	48531.4 ± 10527.6	163489 ± 26922.9	
$W_L W_T$	52144.3 ± 5574.84	203074 ± 18270.4	688367 ± 26560.9	
$W_T W_T$	95923.2 ± 6455.61	396749 ± 19167.6	1423190 ± 26148.2	
WW QCD	138386 ± 2488.8	577235 ± 4828.33	2099750 ± 12029	
tZq	5203.87 ± 93.9418	32999.1 ± 275.972	153951 ± 860.373	
WZ EW	26343.7 ± 475.701	115216 ± 964.227	425249 ± 2412.36	
WZ QCD	28343.9 ± 505.25	174787 ± 1457.15	1002530 ± 5522.47	
Total	198277 ± 598.02	900238 ± 1249.77	3681480 ± 2437.95	

TABLE III. Event yields after the fit for all \sqrt{s} values under study.

V. CONCLUSIONS

Cross section measurements of the polarized scattering of same-sign W[±]W[±]jj production using the leptonic decay mode at a future high energy pp collider with an integrated luminosity of 30 ab⁻¹ should be possible with a relative precision around 39% at $\sqrt{s} = 27$ TeV, 22% at $\sqrt{s} = 50$ TeV and 17% at $\sqrt{s} = 100$ TeV for the purely longitudinal contribution and better for the other contributions.

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- M. J. G. Veltman, "Second Threshold in Weak Interactions," Acta Phys. Pol. B, vol. 8, p. 475, 1977.
- [2] B. W. Lee, C. Quigg, and H. B. Thacker, "The strength of weak interactions at very highenergies and the Higgs boson mass," *Phys. Rev. Lett.*, vol. 38, p. 883, 1977.
- [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. D*, vol. 16, p. 1519, 1977.
- [4] G. Aad et al., "Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC," Phys. Lett. B, vol. 716, p. 1, 2012.
- [5] S. Chatrchyan *et al.*, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC," *Phys. Lett. B*, vol. 716, p. 30, 2012.
- [6] S. Chatrchyan *et al.*, "Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV," *JHEP*, vol. 06, p. 081, 2013.
- [7] D. Espriu and B. Yencho, "Longitudinal WW scattering in light of the Higgs boson discovery," *Phys. Rev. D*, vol. 87, p. 055017, 2013.

- [8] J. Chang, K. Cheung, C.-T. Lu, and T.-C. Yuan, "WW scattering in the era of post-Higgsboson discovery," *Phys. Rev. D*, vol. 87, p. 093005, 2013.
- [9] S. J. Lee, M. Park, and Z. Qian, "Probing unitarity violation in the tail of the off-shell Higgs boson in V_LV_L mode," Phys. Rev. D, vol. 100, p. 011702, 2019.
- [10] A. Abada *et al.*, "FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3," *Eur. Phys. J. ST*, vol. 228, p. 755, 2019.
- [11] "CEPC Conceptual Design Report: Volume 1 Accelerator," 9 2018.
- [12] G. Aad *et al.*, "Evidence for electroweak production of $W^{\pm}W^{\pm}jj$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," *Phys. Rev. Lett.*, vol. 113, p. 141803, 2014.
- [13] V. Khachatryan *et al.*, "Study of vector boson scattering and search for new physics in events with two same-sign leptons and two jets," *Phys. Rev. Lett.*, vol. 114, p. 051801, 2015.
- [14] A. M. Sirunyan *et al.*, "Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Phys. Rev. Lett.*, vol. 120, p. 081801, 2018.
- [15] M. Aaboud *et al.*, "Observation of electroweak production of a same-sign W boson pair in association with two jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," *Phys. Rev. Lett.*, vol. 123, p. 161801, 2019.
- [16] A. M. Sirunyan *et al.*, "Measurements of production cross sections of WZ and same-sign WW boson pairs in association with two jets in proton-proton collisions at √s = 13 TeV," *Phys. Lett. B*, vol. 809, p. 135710, 2020.
- [17] A. Ballestrero, E. Maina, and G. Pelliccioli, "Different polarization definitions in same-sign WW scattering at the LHC," *Phys. Lett. B*, vol. 811, p. 135856, 2020.
- [18] A. M. Sirunyan *et al.*, "Measurements of production cross sections of polarized same-sign W boson pairs in association with two jets in proton-proton collisions at √s = 13 TeV," *Phys. Lett. B*, vol. 812, p. 136018, 2021.
- [19] J. Searcy, L. Huang, M.-A. Pleier, and J. Zhu, "Determination of the WW polarization fractions in pp → W[±]W[±]jj using a deep machine learning technique," Phys. Rev. D, vol. 93, p. 094033, 2016.
- [20] J. Lee, N. Chanon, A. Levin, J. Li, M. Lu, Q. Li, and Y. Mao, "Polarization fraction measurement in same-sign WW scattering using deep learning," *Phys. Rev. D*, vol. 99, no. 3, p. 033004, 2019.

- [21] J. Roloff, V. Cavaliere, M.-A. Pleier, and L. Xu, "Sensitivity to longitudinal vector boson scattering in semileptonic final states at the HL-LHC," *Phys. Rev. D*, vol. 104, p. 093002, 2021.
- [22] CMS Collaboration, "Prospects for the measurement of vector boson scattering production in leptonic $W^{\pm}W^{\pm}$ and WZ diboson events at $\sqrt{s} = 14$ TeV at the High-Luminosity LHC," tech. rep., CERN, Geneva, 2021.
- [23] T. Yang, S. Qian, Z. Guan, C. Li, F. Meng, J. Xiao, M. Lu, and Q. Li, "Longitudinally polarized ZZ scattering at a muon collider," *Phys. Rev. D*, vol. 104, p. 093003, 2021.
- [24] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations," JHEP, vol. 07, no. 79, 2014.
- [25] D. Buarque Franzosi, O. Mattelaer, R. Ruiz, and S. Shil, "Automated predictions from polarized matrix elements," *JHEP*, vol. 04, p. 082, 2020.
- [26] R. Ball et al., "Parton distributions with LHC data," Nuclear Physics B, vol. 867, no. 244, 2013.
- [27] T. o. Sjöstrand, "An Introduction to PYTHIA 8.2," Computer Physics Communications, vol. 191, no. 159, 2015.
- [28] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi, "DELPHES 3, A modular framework for fast simulation of a generic collider experiment," *JHEP*, vol. 02, p. 057, 2014.
- [29] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual," Eur. Phys. J. C, vol. 72, p. 1896, 2012.
- [30] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-kt jet clustering algorithm," JHEP, vol. 04, p. 063, 2008.
- [31] W. Verkerke and D. P. Kirkby, "The RooFit toolkit for data modeling," *eConf*, vol. C0303241, p. MOLT007, 2003.
- [32] L. Moneta, K. Belasco, K. S. Cranmer, S. Kreiss, A. Lazzaro, D. Piparo, G. Schott, W. Verkerke, and M. Wolf, "The RooStats Project," *PoS*, vol. ACAT2010, p. 057, 2010.
- [33] R. Pordes, D. Petravick, B. Kramer, D. Olson, M. Livny, A. Roy, P. Avery, K. Blackburn, T. Wenaus, F. Würthwein, I. Foster, R. Gardner, M. Wilde, A. Blatecky, J. McGee, and R. Quick, "The open science grid," in *J. Phys. Conf. Ser.*, vol. 78 of 78, p. 012057, 2007.

[34] I. Sfiligoi, D. C. Bradley, B. Holzman, P. Mhashilkar, S. Padhi, and F. Wurthwein, "The pilot way to grid resources using glideinwms," in 2009 WRI World Congress on Computer Science and Information Engineering, vol. 2 of 2, pp. 428–432, 2009.