Different-sign Longitudinally Polarized WW Scattering at the Muon Collider

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Abstract

Longitudinally polarized Vector Boson Scattering (VBS) process provides us with a perfect probe to precisely measure electroweak observables and Higgs coupling as massive vector bosons have longitudinally polarized components originating from the Higgs mechanism. A TeV-scaled muon collider that would effectively be a "high-luminosity weak boson collider", has great potential to measure VBS processes. In this research, we choose W^+W^- scattering to validate the feasibility of the muon collider from the physical side using multi-variable analysis method. The significance of longitudinally polarized W^+W^- can obtain a 5 standard deviation discovery at a 14 TeV muon collider, which shows good potential to reach the first longitudinally polarized WW scattering discovery on a muon collider.

Introduction

Recently interests on the Muon Collider are revived due to several reasons. Firstly, several anomalies related to muon were found including lepton unitarity violation from LHCb and muon g-2 anomaly from FermiLab. Besides, the technology of muon source has made some progress. Furthermore, the muon collider has intrinsic pros involving a clean background as an electron-positron collider and high energy as a hadron collider. Based on these advantages and some preliminary research, the Update of the European Strategy for Particle Physics recommended integrating an international design study for a muon collider in the European Roadmap for accelerator R&D.

Monte Carlo Simulation

Analysis Framework

- Generate Processes: Both signal and background events are simulated by MadGraph5_aMC@NLO(MG) that is one of the key tools for Monte Carlo event generation in Compact Muon Solenoid (CMS) experiment in this research.
- Parton Shower and Hadronization: The events from MG are showered and hadronized by PYTHIA8.
- Detector Fast Simulation: DELPHES version 3.5.0 is used to simulate detector effects with the default card for the muon collider detector.

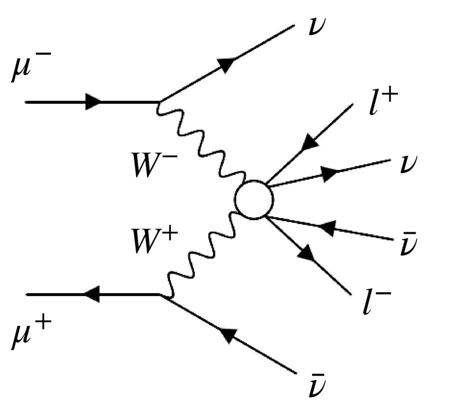


FIG. 1: Example diagram of signal process at the muon collider.

Signal and Background Processes

C.M. 14 TeV	Processes	Cross Section / fb
Signal	$\mu^+ + \mu^- \to W_L^+ + W_L^- + \nu + \bar{\nu}, W_L^+ \to l^+ + \nu, W_L^- \to l^- + \bar{\nu}$	3.549
Backgrounds	$\mu^+ + \mu^- \to W_L^+ + W_T^- + \nu + \bar{\nu}, W_L^+ \to l^+ + \nu, W_T^- \to l^- + \bar{\nu}$	3.728
	$\mu^+ + \mu^- \to W_T^+ + W_L^- + \nu + \bar{\nu}, W_T^+ \to l^+ + \nu, W_L^- \to l^- + \bar{\nu}$	3.728
	$\mu^+ + \mu^- \to W_T^+ + W_T^- + \nu + \bar{\nu}, W_T^+ \to l^+ + \nu, W_T^- \to l^- + \bar{\nu}$	16.92
	$\mu^+ + \mu^- \to W^+ + W^-, W^+ \to l^+ + \nu, W^- \to l^- + \bar{\nu}$	0.6562
	$\mu^+ + \mu^- \to H + \nu + \bar{\nu}, H \to l^+ + l^-$	20.79
	$\mu^+ + \mu^- \to H + Z + \nu + \bar{\nu}, H \to l^+ + l^-, Z \to \nu + \bar{\nu}$	0.2156
	$\mu^+ + \mu^- \to Z_1 + Z_2 + \nu + \bar{\nu}, Z_1 \to l^+ + l^-, Z_2 \to \nu + \bar{\nu}$	5.852
	$\mu^+ + \mu^- \to H + \gamma + \nu + \bar{\nu}, H \to l^+ + l^-$	1.079
	$\mu^+ + \mu^- \to Z + \gamma + \nu + \bar{\nu}, Z \to l^+ + l^-$	16.53
	$\mu^+ + \mu^- \to Z + \nu + \bar{\nu}, Z \to l^+ + l^-$	226.8
	$\mu^+ + \mu^- \to Z + Z + \nu + \bar{\nu}, Z \to l^+ + l^-$	0.7564
	$\mu^+ + \mu^- \to W^+ + W^- + \mu^+ + \mu^-, W^+ \to l^+ + \nu, W^- \to l^- + \bar{\nu}$	0.4835
	$\mu^+ + \mu^- \to W^- + Z + \nu + \mu^+, W^- \to l^- + \bar{\nu}, Z \to l^+ + l^-$	0.1114
	$\mu^+ + \mu^- \to W^+ + Z + \bar{\nu} + \mu^-, W^+ \to l^+ + \nu, Z \to l^+ + l^-$	0.1114

Multi-variable Analysis

Multi-variable Analysis(MVA) Observables Selection

As the two final state leptons of the signal process are from two different W bosons, the kinematic observables of the two leptons and two W bosons have intrinsic shape discrepancies. The observables selected to participate in the multi-variable analysis are as below:

Name	Definition	Name	Definition	Name	Definition
electron_pt	Electron transverse momentum	electron_eta	Electron pseudorapidity	electron_phi	Electron azimuthal angle
muon_pt	Muon transverse momentum	muon_eta	Muon pseudorapidity	muon_phi	Muon azimuthal angle
delta_eta	Pseudorapidity between two leptons	delta_phi	Azimuthal angle between two leptons	delta_r	$\sqrt{(\Delta\phi)^2+(\Delta\eta)^2}$
invariant_mass	Invariant mass of two leptons	missinget_eta	Missing energy pseudorapidity	missinget_phi	Missing transverse energy azimuthal angle

MVA Framework

We train a Gradient Boosted Decision Tree (GBDT) model with the Toolkit for Multivariate Analysis (TMVA) and XGBoost for better discrimination of the signal and all background components. The previous kinematic observables are input features.

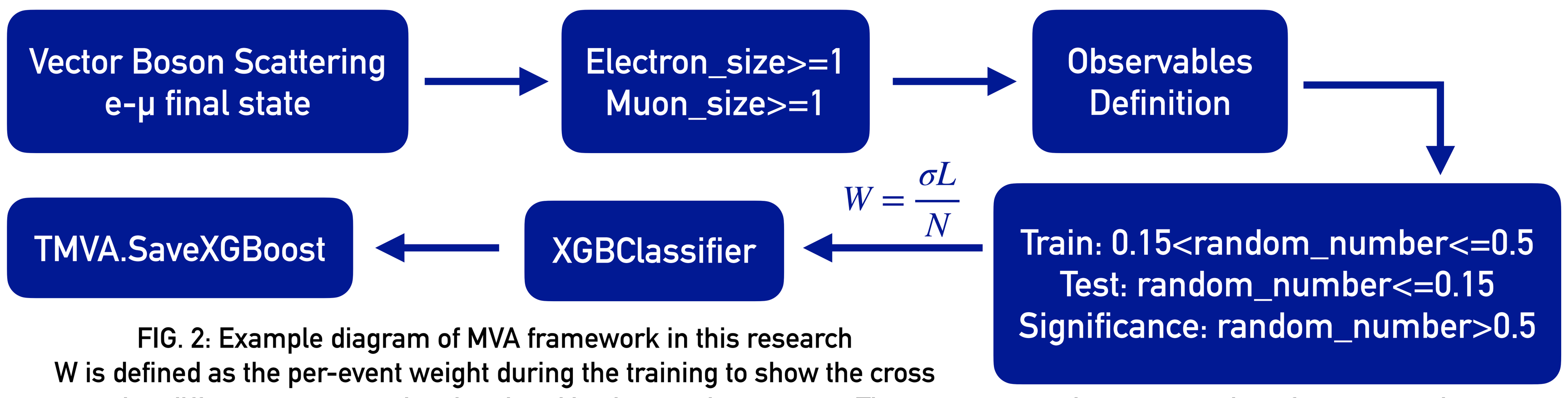


FIG. 2: Example diagram of MVA framework in this research
W is defined as the per-event weight during the training to show the cross section differences among the signal and background processes. The σ represents the cross section of a process, the L represents the default target luminosity of the 14 TeV muon collider, and the N represents the number of events.

MVA Training and Testing Results

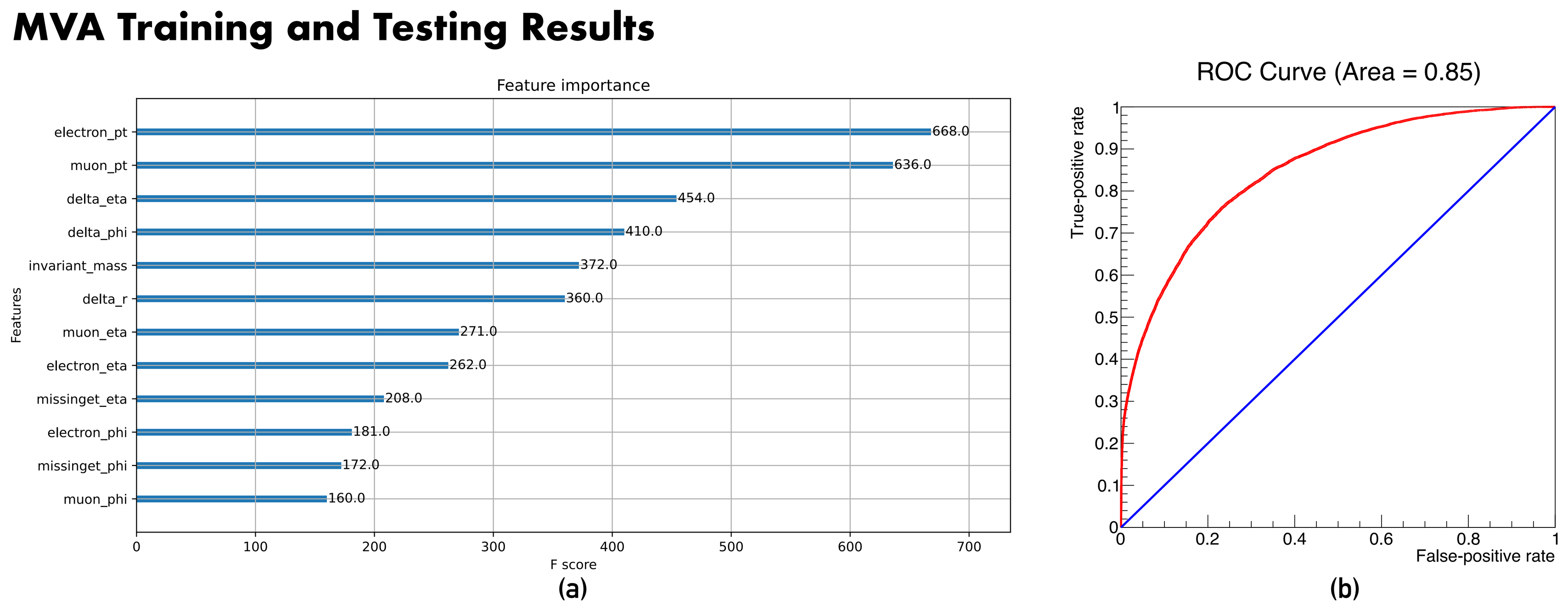
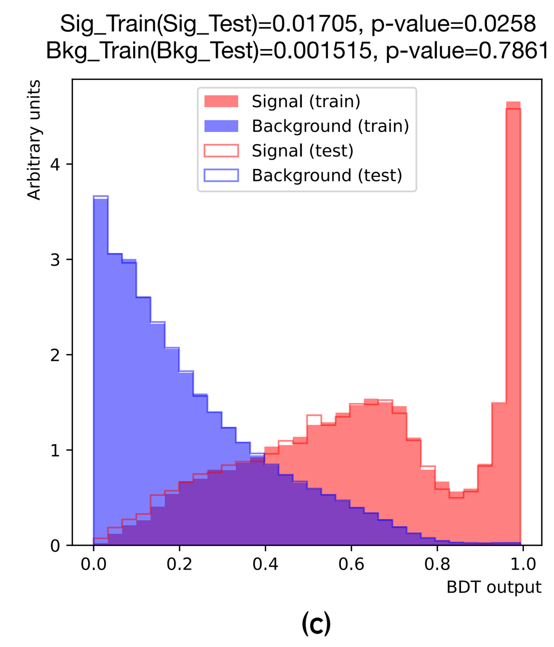


FIG. 3: The results of the MVA.



We endow the signal and background events with random numbers and separate them as the training, test, and significance calculation sets with the event ratio of 7:3:10. The BDT with 600 trees, a maximum depth of 3, and learning rate of 0.1 is trained. The results of the MVA are shown in some figures.

- Feature importance (a) — transverse momentum of two leptons are the two most vital importance observables in discriminating the signal and backgrounds.
- Receiver operating characteristic (ROC) curve (b) — a graph showing the performance of a classification model at all classification thresholds.
- Area under the ROC Curve (AUC) (b) — a model whose predictions are 100% wrong has an AUC of 0.0; one whose predictions are 100% correct has an AUC of 1.0.
- BDT score (c) — the signal and background peaks are well-separated.

Corresponding Significance

The corresponding significance is calculated at different BDT selection cut, using the formula

$$S=\sqrt{2(s+b)ln(1+\frac{s}{b})-2s},$$

where s (b) represents the weighted signal (background) yield that their BDT scores are between a certain cut and 1.
The perfect cut value is around 0.56, with the corresponding significance of around 18 σ.

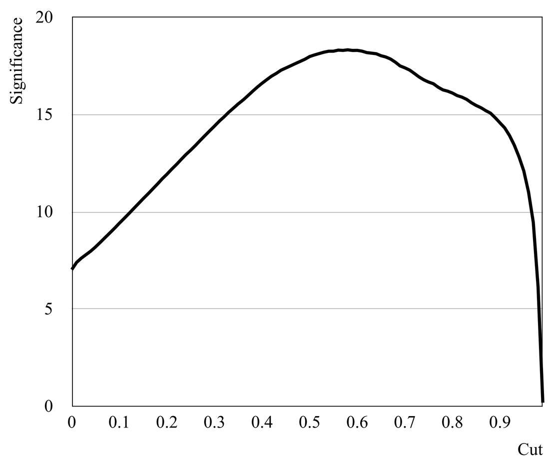


FIG. 4: Significance dependence on the BDT cut.

Conclusion and Expectation

In this research, we use Monte Carlo simulation and MVA method to examine the significance of different-sign longitudinally polarized WW vector boson scattering at a TeV scale muon collider. The current results show that the conservative estimation of the MVA method can obtain a 5 standard deviation discovery at a 14 TeV muon collider. It shows good potential to reach the first different-sign longitudinally polarized WW scattering discovery on the future muon collider.
This research is in the final stage. The explanation of the unusual bulge of the signal in the BDT score image is in progress.

References

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