Longitudinal Polarization fraction measurement in ZZ scattering at the Muon Collider

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Abstract

Measuring longitudinally polarized vector boson scattering in the ZZ channel is a promising way to investigate unitarity restoration with the Higgs mechanism and to search for possible new physics. However, at the LHC, it demands end of the HL-LHC lifetime luminosity (i.e. 3000fb^{-1}) and advanced data analysis technique in order to reach the discovery threshold, due to the small production rates. Instead there could be great potential at future colliders. In this paper, we perform a Monte Carlo study and examine the projected sensitivity of longitudinally polarized ZZ scattering at TeV scale Muon collider using BDT. We find that a 5 standard deviation discovery can be achieved at 14 TeV Muon collider, with 3000fb^{-1} of data collected.

Motivation

Figure 1 shows the current CMS measurements of the longitudinal polarization process [arXiv:2009.09429]. Due to the lack of event brightness, we cannot yet formally declare the discovery.

The muon collider is more like a VBS factory than a hadron collider, so it is very helpful for us to study the VBS longitudinal polarization process. The main principle of VBS at the muon collider is shown in the Feynman diagram below, where two muons each radiate a vector boson and turn into the corresponding leptonic product, and these two vector bosons then interact to form the non-leptonic product X. X can be expressed as $X = nt\bar{t} + mV + kH$, where n, m and k are integers that respectively denote the number of top quark pairs, weak vector bosons V, and Higgs bosons H. According to the different types of V_1V_2 and the corresponding leptons products, we can classify the VBS processes into :

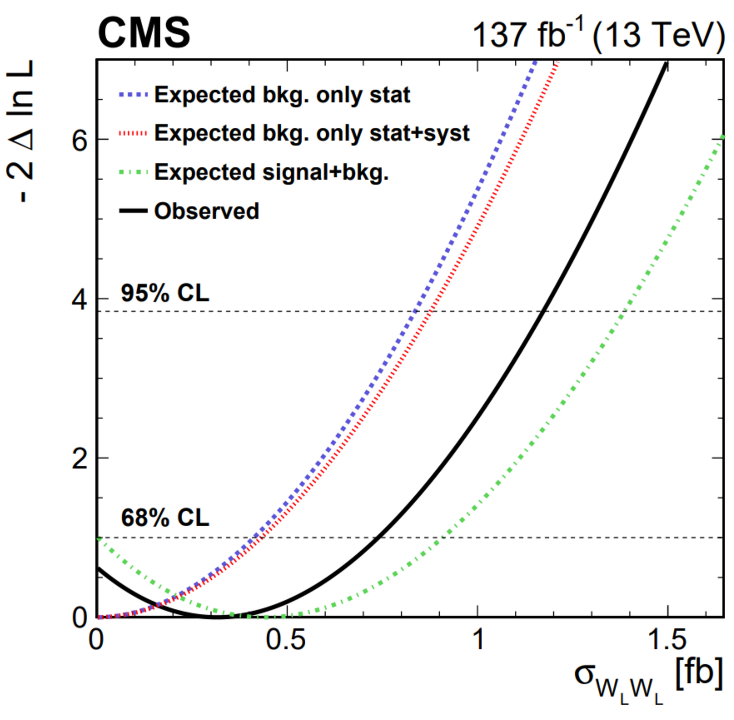

Figure 1: Current longitudinal polarization VBS research at the CMS

- WW_VBS: $V_1V_2 = W^+W^-$; $1,2 = \nu_\mu\overline{\nu_\mu}$
- ZZ_VBS: $V_1V_2 = ZZ/Z\gamma/\gamma\gamma$; $1,2 = \mu^+\mu^-$
- WZ_VBS: $V_1V_2 = WZ/W\gamma$; $1,2 = \mu\nu_\mu$

And the other one type of SM process at the muon collider, s-channel processes, can be expressed as $\mu^+\mu^- \to X$.

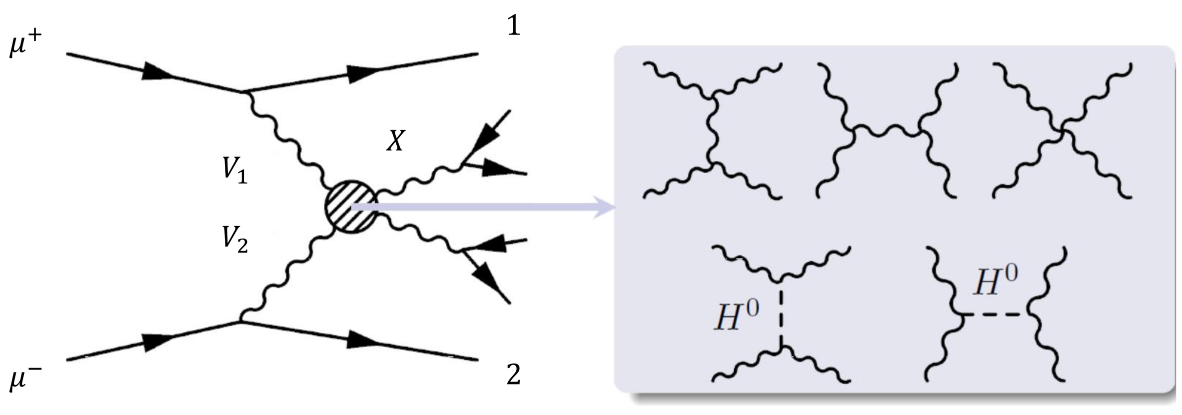
Figure 1: VBS processes at the muon collider

Signal and Backgrounds

We set the collision energy of the muon collider to 14 TeV, with luminosity $L = 20\text{ab}^{-1}$, calculated from:

$$L = 10\text{ab}^{-1} \times \left(\frac{E_{\text{cm}}}{10\text{TeV}}\right)^2$$

The decay of the hadron channel corresponds to more background processes, while the decay of the leptons channel is cleaner. Based on this, we choose $Z_LZ_L \to 4l$ in WW_VBS as our signal. Considering that the final-state products are 4 leptons and 2 neutrino, we need to select all processes that satisfy the following two conditions: (1) has sufficiently large cross section (2) exists the possibility of decay to 4 leptons. The selected background processes are listed in the following table:

SM process type	Selected background
WW_VBS	$H, HZ, HZZ, HWW, HH, WWZ, ZZZ, Z_TZ_T, Z_TZ_L, t\bar{t}Z$
ZZ_VBS	$H, WW, t\bar{t}$
WZ_VBS	WZ, WZH, WH, WWW, WZZ
s-channel	ZZ, WWZ

Table 1: Selected background in 4 types of SM processes at the Muon Collider

Acknowledgement

I would like to thank Mr. Qiang Li for his guidance throughout this work and the students in the group for their discussions and suggestions on the study.

In addition, I would like to thank Snowmass 2022 for giving me this opportunity to present this poster to introduce my work.

Generation and initial selection of MC events

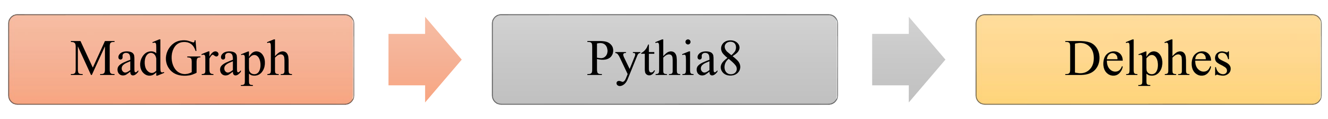

Figure 3: The flow of event generation

With the event generation process shown in Figure 3, we obtain the fast reconstruction events for analysis. In order to get all the events which have the same products as the signal, we adopt the selection method shown in the right figure.

Besides, when the initial selection is done, we finally reconstruct the four leptons into two Z bosons using the following algorithm:

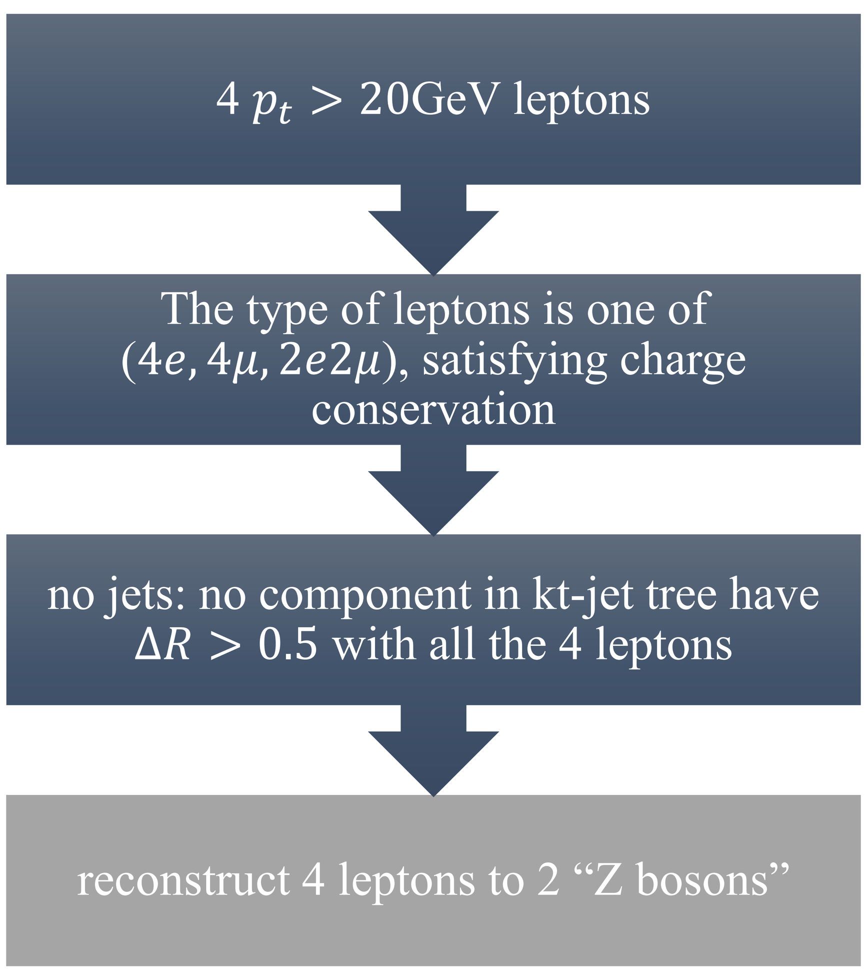

Figure 4: Pre-selection and preprocessing for the reconstructed events

- $l_1^+l_2^+l_3^-l_4^- \to l_1l_3, l_2l_4; l_1l_4, l_2l_3$
- $\Delta M^2 = \left(M_{Z_1'} - M_Z\right)^2 + \left(M_{Z_2'} - M_Z\right)^2$
- $\Delta M^2_{13,24} > \Delta M^2_{14,23} \to$ choose 14,23, vice versa

Features and analysis results of the BDT model

After the initial selection, we finally acquire all the pure 4 leptons events we need. The features we used for training the BDT model are shown in the table 2.

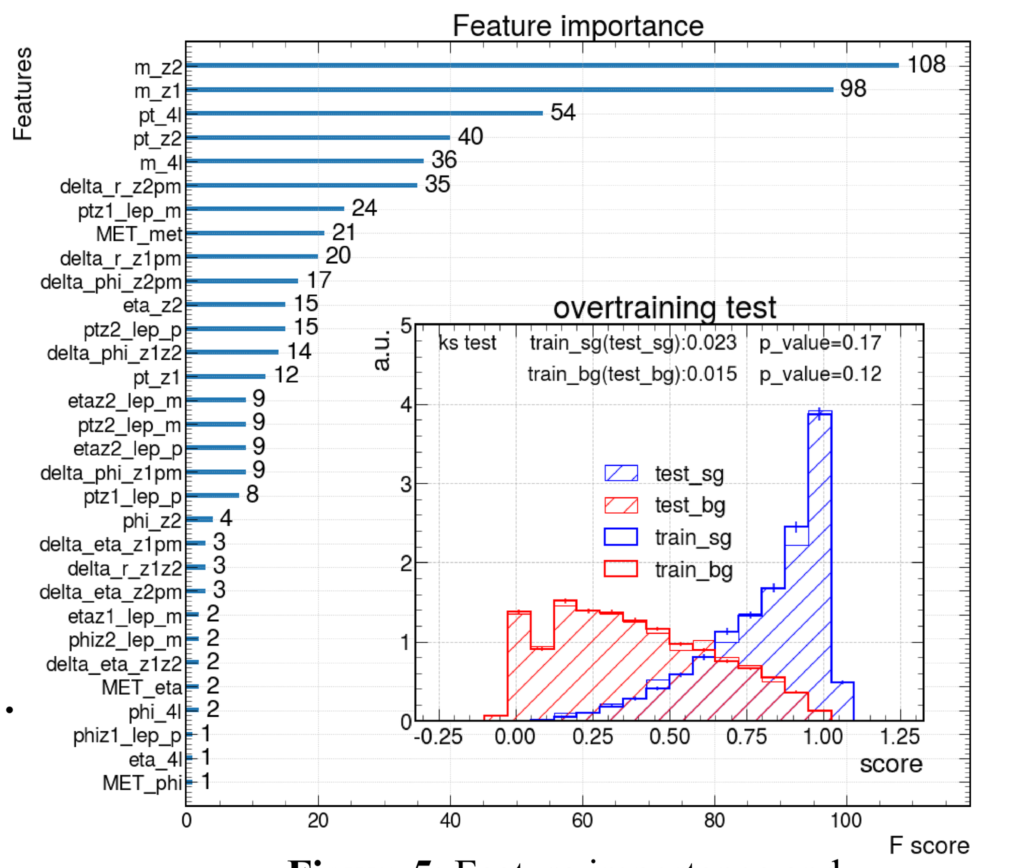

Figure 5: Feature importance and overtraining test

Objective	Features	Number of features
each lepton	(p_t, η, ϕ)	12
each "Z boson"	$(p_t, \eta, \phi, m_{inv})$	8
4 leptons together	$(p_{t4l}, \eta_{4l}, \phi_{4l}, m_{4l})$	4
MissingET	(p_t, η, ϕ)	3
Between 2 Z	$(\Delta\eta, \Delta\phi, \Delta R)$	3
Between 2l of Z_1	$(\Delta\eta, \Delta\phi, \Delta R)$	3
Between 2l of Z_2	$(\Delta\eta, \Delta\phi, \Delta R)$	3
4 leptons type	$(1, -1, 0)$for$(4e, 4\mu, 2e2\mu)$	1
total:		37

Table 2: Features used for training BDT model

The BDT training results is shown in figure 5 and figure 6. We define $n_L = \sigma_X L/N_{G_X}$ to express how many events in the real collider can one event from MG represent. Based on such concept, we can calculate weighted number of signal and background events.

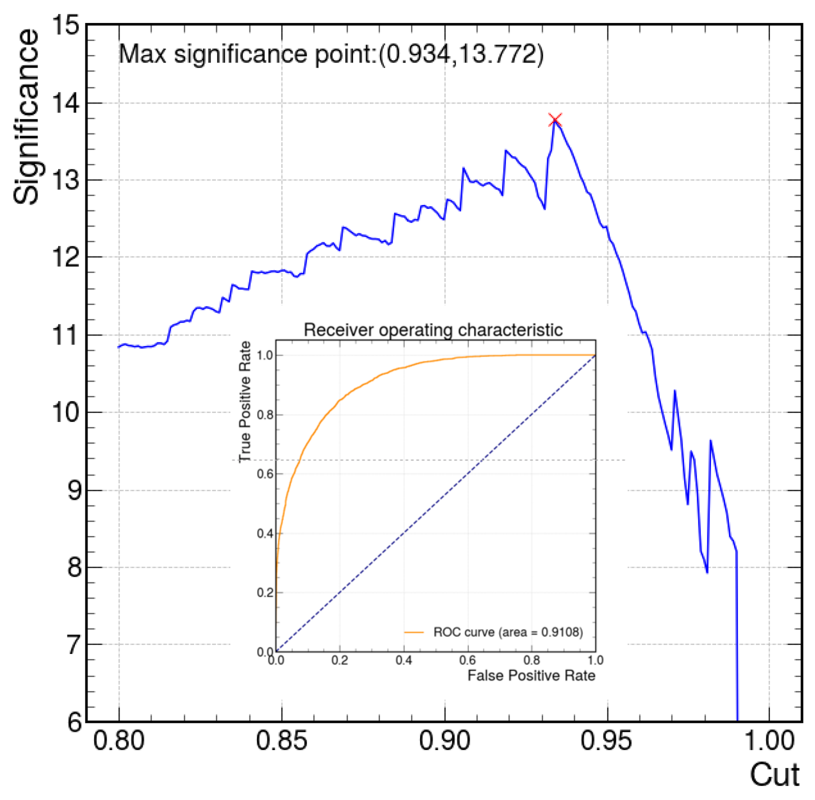

Figure 6: ROC curve and significance over cut scan

The significance is calculated using the following formula:

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

where $s(b)$ means the weighted number of signal(background) events with the score from BDT greater than a certain cut value. Merging 150 different random configurations of training and test sets, we can clearly see that at when cut=0.934, we can get the maximum significance value, which is around 14σ.

Conclusion

As a conclusion, we can find that the maximum significance value is 14σ at $L = 20\text{ab}^{-1}$, obtained at the position of about cut=0.934. From this we can obtain the corresponding luminosity at a maximum significance of 5σ:

$$L' = \frac{5^2}{14^2} L \approx 3\text{ab}^{-1} = 3000\text{fb}^{-1}$$

Considering the statistical errors caused by some large n_L events, the target luminosity is finally set to about 3000fb^{-1}. For muon collider, such luminosity can be achieve in only less than 5 years, which have great advantage over LHC.