PROCEEDINGS OF SCIENCE

Search for $H \to ZZ^* \to 4\mu$ at a Multi-TeV Muon Collider

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A muon collider represents the ideal machine to reach very high center-of-mass energies ($\sqrt{s}$ = 1.5 − 10 TeV) and luminosities $O(0.5 - 10/\text{ab})$. A large number of Higgs bosons will be produced mainly through the Vector Boson Fusion (VBF) processes. The VBF through Z bosons (ZZH) production process could be difficult to disentangle from the dominant WWZ, since the final state VBF muons, produced in the very forward region, could escape the detector. As a consequence, at a multi-TeV muon collider, the $H \to ZZ$ decay process turns out to be favoured to probe exclusively the Higgs boson coupling to Z bosons. In this paper, for the first time, a feasibility study of the search for $H \to ZZ^* \to 4\mu$ at a 1.5 and 3 TeV muon collider is presented. The study of the four muons final state, performed on fully simulated Monte Carlo samples, allows to optimize the muon reconstruction, thus providing feedback for the detector design. Irreducible backgrounds from Standard Model are studied. A first estimate of the senistivity of the Higgs boson coupling to Z bosons in the 4μ channel is provided, along with a preliminary evaluation of the impact of the machine background in the 1.5-TeV scenario.

This work has been performed within the *Muon Collider Detector Design and Performance group* [1].

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1. Introduction

A multi-TeV muon collider is the ideal facility to probe the Higgs boson properties with a much higher precision than that currently achieved and, possibly, to find evidence for new physics. In general, a lepton collider allows to reach higher cross sections than a hadron collider operating at the same energy [2]. Nevertheless, if compared to an electron-positron collider with the same characteristics, a muon collider has the advantage of losing much less energy by synchrotron radiation [3]. However, it suffers from an intense machine background, called Beam Induced Background (BIB), originated by the decay of beam muons. The interaction region and the detector have been carefully designed in order to reduce the impact of the BIB on the detector performance [4] [5]. The detector structure is that of a typical collider. In the very forward region, two shielding nozzles, with an aperture of 10°, have been designed to cover the beam-pipe, in order to mitigate the BIB. Further details about the detector can be found at [6]. The simulation and the reconstruction of events are performed with the software ILCSoft [7].
For the first time, the search for $H \to ZZ^* \to 4\mu$ at a 1.5 (L = 500 fb^{-1}) and 3 TeV (L = 1300 fb^{-1}) muon collider has been investigated. An event selection aimed to discriminate this process from its irreducible Standard Model (SM) background is illustrated and a first evaluation of the impact of the BIB on the signal reconstruction is also provided. The study of the four final state muons has allowed to evaluate the muon reconstruction performance at the designed detector and the main results are reported in this work. Finally, a first evaluation of the precision achievable at a muon collider on the Higgs boson coupling to Z bosons in the 4μ channel is presented.

2. Muon reconstruction

Muons are reconstructed by combining information from all the detectors. At first, tracks are reconstructed by means of the Conformal Tracking [8], a pattern recognition technique based on conformal mapping and cellular automata [9], and the Kalman filter [10] [11], which performs track fitting. For track reconstruction, only hits deposited in the tracking system are used. Reconstructed tracks and hits deposited in the calorimeters and in the muon system are given as input to the Pandora Particle Flow Algorithms (PandoraPFA) [12] [13], for reconstruction and identification of muons. The muon reconstruction performance is evaluated by studying final state muons produced in the $H \to ZZ^* \to 4\mu$ process, generated at 1.5 and 3 TeV center-of-mass energies. Figure 1 shows the muon reconstruction efficiency as function of the transverse momentum (p_T). The efficiency is plotted by dividing the acceptance range of θ in three subranges: 10°-20°, 20°-50°, 50°-90°. The reconstruction efficiency is higher than the 95%. The p_T resolution is plotted in Figure 2 as function of p_T, following the same division in θ intervals introduced above. The resolution results to be smaller than the 0.5% for $\theta > 20°$, and it worsens up to 1-2% in the very forward region. This study has been conducted without taking into account the BIB, since the entire event reconstruction with the BIB overlay is computationally high demanding. In order to provide a preliminary estimate of the impact of the BIB on track reconstruction, a shortcut is used: only hits in narrow cones drown around simulated muons are considered. Figure 3 shows a comparison between the track reconstruction efficiency evaluated with the BIB overlay (blue) and the one evaluated without including it (red).

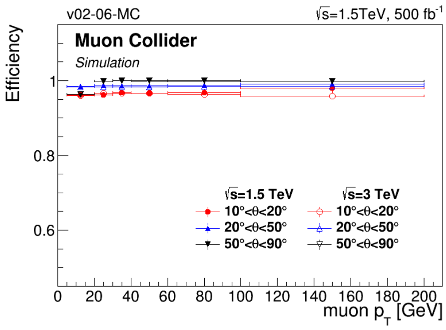

Figure 1: Muon reconstruction efficiency as function of p_T for three ranges of θ.

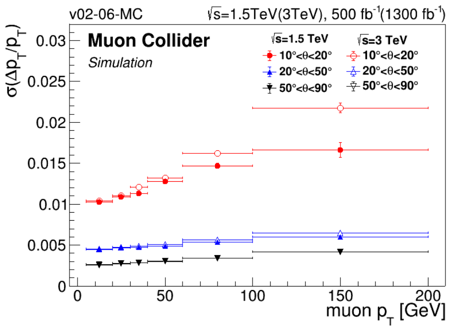

Figure 2: p_T resolution as function of p_T for three ranges of θ.

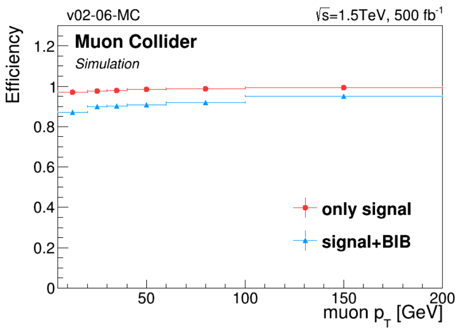

Figure 3: Track reconstruction efficiency as function of p_T. Comparison between the efficiency evaluated with the BIB overlay (blue) and the one evaluated without it (red).

3. Signal and background samples

The signal and the SM background processes have been fully simulated with the latest geometry of the Muon Collider experimental apparatus and reconstructed with the latest version of tracking and PandoraPFA algorithms. The Higgs boson is produced through WW fusion, the dominant production mechanism at a multi-TeV muon collider. The production and the decay chain of the signal process, simulated with Pythia8[14], are represented in 1, while, the SM background, simulated with MadGraph [15], is shown in 2.

$$\mu^+\mu^- \to H\nu_\mu\overline{\nu_\mu} \to ZZ^*\nu_\mu\overline{\nu_\mu} \to 4\mu\nu_\mu\overline{\nu_\mu} \tag{1}$$

$$\mu^+\,\mu^- \to 4\mu\,\nu_\mu\,\overline{\nu_\mu} \tag{2}$$

4. Event selection and final results

The event selection is inspired to that developed by the CMS collaboration in the search for $H \to ZZ^* \to 4l$ at LHC [16]. A pre-selection is applied on final state muons in order to ensure that only events with at least four good-quality reconstruction muons are considered. Muons are required to have: $p_T > 5$ GeV, $|\eta| < 2.5$, $D_0 < 2$ mm and $Z_0 < 10$ mm, where η, D_0 and Z_0 are respectively the pseudorapidity, the transverse and the longitudinal impact parameters. Pre-selected events are then used to build ZZ candidates. A Z candidate is defined as an opposite charge muon pair with invariant mass in the range 12-120 GeV. A ZZ candidate is a combination of non-overlapping Z candidates, where Z_1 is the one with reconstructed mass closest to the nominal

Z boson mass. ZZ candidates are required to have: $\Delta R > 0.02$ between each of the four muons, at least two muons (labelled i and j) with $p_{T,i} > 20$ GeV and $p_{T,j} > 10$ GeV, the Z_1 reconstructed mass greater than 40 GeV and the invariant mass of the 4 muons ($m_{4\mu}$) larger than 70 GeV. If more than one ZZ candidate pass the selection, the one with the Z_1 mass closest to the nominal value is chosen. Figures 4 and 5 show the reconstructed mass of the Z candidates for signal (red) and background (blue).

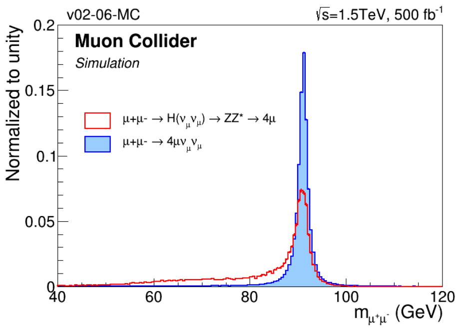

Figure 4: Z_1 reconstructed mass.

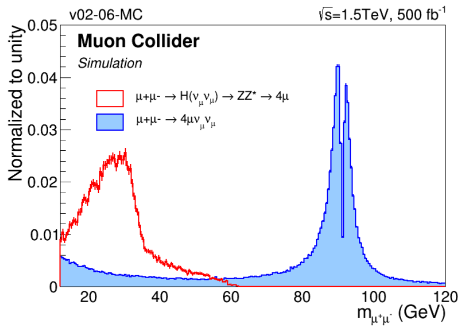

Figure 5: Z_2 reconstructed mass.

In order to select events in the signal-like region, a further cut is applied: $105 < m_{4\mu} < 140$ GeV. Figure 6 shows the reconstructed mass of the Higgs boson in the mentioned interval. The

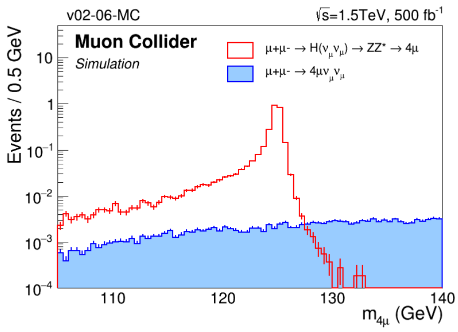

Figure 6: Higgs boson reconstructed mass. Signal (red) and background (blue) distributions are normalized to cross section, luminosity and number of generated events.

significance of the signal, evaluated as described in [17], and the relative precision on the HZZ coupling ($\frac{\Delta g_{HZZ}}{g_{HZZ}}$) are reported in Table 1. A preliminary estimate of the impact of the BIB on final results is provided at $\sqrt{s} = 1.5$ TeV, which represents the worst scenario, being the BIB strongly reduced at higher energy.

Table 1: Significance of the signal and relative precision on the HZZ coupling for a 1.5 and 3 TeV muon collider.

Muon Collider, channel $H \to ZZ^* \to 4\mu$				
Results	$\sqrt{s}$ = 1.5 TeV, L = 500 fb^{-1}		$\sqrt{s}$ = 3 TeV, L = 1300 fb^{-1}	
	significance	$\frac{\Delta g_{HZZ}}{g_{HZZ}}$ (%)	significance	$\frac{\Delta g_{HZZ}}{g_{HZZ}}$ (%)
without BIB	3.61	30.09	6.85	15.83
with BIB	3.08	35.75	-	-

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