PROCEEDINGS OF SCIENCE

Higgs boson couplings at muon collider

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Muon collisions at multi-TeV center of mass energies are the ideal place to study Higgs boson properties. At these energies the high production rates and the clean environment will allow precise measurements of its couplings to fermions and bosons. In addition, the double Higgs boson production rate could be sufficiently high to directly measure the trilinear self-couplings strength, giving access to the determination of the Higgs field potential. This proceeding gives an overview of the results that have been obtained so far on Higgs couplings by studying the $\mu^+\mu^- \to \mathrm{H}\nu\,\bar{\nu}$ and $\mu^+\mu^- \to \mathrm{HH}\nu\,\bar{\nu}$ processes. All the studies have been performed by simulating the signal and physics background samples and by evaluating the effects of the beam-induced background on the detector performances. The evaluations on Higgs boson couplings sensitivities and the most recent results on the uncertainty on double Higgs production cross section, together with the trilinear self-coupling, will be discussed at $\sqrt{s} = 3$ TeV.

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1. Introduction

The measurements of the Higgs boson couplings to bosons and fermions carried out so far at LHC, are in agreement with the Standard Model (SM). The measurement of the trilinear (λ_3) and the quadrilinear (λ_4) Higgs self-couplings, are mandatory to determine Higgs boson potential shape and to test the electroweak simmetry breaking mechanism. Such parameters cannot be directly measured with enough precision at LHC due to the low statistics. The two main goals of the scientific program of the Higgs boson physics at Future Colliders are then: the determination of the Higgs boson couplings to fermions and boson with uncertainty below 1% [1], since deviations from the SM could reveal New Physics, and the measurement of the Higgs self-couplings with precision of few percent. The muon collider is a project where muons will collide at multi-TeV center of mass energies. Such high center of mass energies can be reached since muons are $\sim$ 200 times heavier than electrons, so the energy loss via syncrothron and beamstrahlung radiation is negligible. Furthermore muons are elementary particles, then all the beam energy is available for the collision. At $\sqrt{s}$ = 10 TeV with integrated luminosity of L=10 ab^{-1}, 10^8 single Higgs bosons and $3.6{\cdot}10^4$ Higgs pairs are expected [2]. Preliminary theoretical estimations on Higgs couplings have been performed in [3], considering only $\sqrt{s}$= 10 TeV and L=10 ab^{-1}. Most of them are found to satisfy the required (<1%) precision and are competitive compared to other Future Colliders [1]. The uncertainty on λ_3, is expected to be ~25% at $\sqrt{s}$ = 3 TeV and L=1 ab^{-1} and ~5% at $\sqrt{s}$ = 10 TeV and L=10 ab^{-1}[2] at 95% Confidence Level. The uncertainty on λ_4, is expected to be ~50% at $\sqrt{s}$ = 14 TeV and L=33 ab^{-1} [4]. In these theoretical estimations the beam-induced background (BIB) effects on the detector performances are not included. In this paper results obtained so far on Higgs couplings and on the trilinear Higgs self-couplings are presented, including the BIB.

2. Beam-induced background

The BIB is generated by electrons/positrons and neutrinos coming from the muons decay in circulating beams. Such decay products can interact with the surrounding machine elements and can produce high flux of secondary and tertiary particles that might reach the detector and affect its performances. The characteristics of BIB particles reaching the detector depend on the design of the machine optics, the lattice elements, the interaction region and the machine-detector interface (MDI). A detailed simulation of the BIB was done in [5] at $\sqrt{s}$= 1.5 TeV by using the machine design developed by the Muon Accelerator Program [6] collaboration. In order to absorb part of the BIB particles, two 10° aperture cone-shaped tungsten nozzles are inserted in the detector. Despite of the presence of the tungsten cones, $\sim 10^{10}$ BIB particles reach the detector, mainly low energy photons and e^+/e^-, neutrons and hadrons. In order to study the BIB effects on the detector components, detailed simulation of the muon collider detector, described in [7], is required. The amount of BIB particles reaching the detector can be reduced by using sensors exploiting information on the energy released by the particles, position and time of arrival at the sub-detectors. For example, since BIB particles are partially asynchronous with respect to the bunch-crossing time, a cut on the arrival time of the particles at the detector can reject part of them. Detailed studies on the application of a time cut to the vertex and the tracker systems and its effects on the tracking performances can be found in [7]. The main issue in track reconstruction with BIB is the large number of hits surviving the time cut, that leads to a huge number of hits combinatorial fits making the tracking procedure computationally demanding. In the electromagnetic (ECAL) and hadronic calorimeters (HCAL), the BIB generates a diffused energy distribution [8]. The BIB effects on reconstruction and identification of jets coming from b-quarks have been studied via simulation of b-dijet samples generated with Pythia [9] Monte Carlo, including the BIB at $\sqrt{s}$= 1.5 TeV. The average energy deposited by BIB in the ECAL cells is subtracted from the actual energy for each calorimeter cell. Jets are reconstructed with Pandora Particle Flow [10], that exploits both the calorimeter and the tracks information to reconstruct particles in the jet. The jet cone is R=0.5. The b-jet reconstruction efficiency is shown in figure 1 left as a function of the jet trasverse momentum p_T. It is above 80% for jets with $p_T > 40$ GeV, and ~50-60% for lower p_T jets. The jet p_T resolution is shown in figure 1 right and is found below 30% for jets with $p_T > 40$ GeV, it increase to 15% for jet $p_T \sim$ 100 GeV, while it decrease up to 50 % for jets with lower p_T. The worsen of the reconstruction efficiency and the p_T resolution at low p_T is due to the jet reconstruction procedure not optimized. The LCFIPlus algorithm [11] is used to reconstruct primary and secondary vertices inside the jet cones. Preliminary results shows that the tagging efficiency is around 55% for jet $p_T > 20$ GeV and the b-jet misidentification, evaluated on light di-jets samples is in the range 0.2% at low p_T, up to ~10% at high p_T.

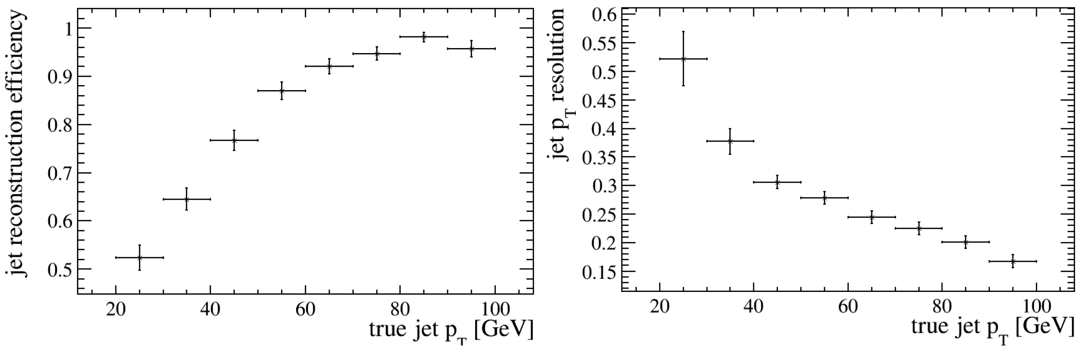

Figure 1: Jet reconstruction efficiency (left) and jet p_T resolution (right) as a function of jet p_T.

3. Measurement of the Higgs couplings to fermions at $\sqrt{s}$=3 TeV

The evaluation of the uncertainty on the Higgs coupling to b-quark at $\sqrt{s}$=3 TeV is currently ongoing. Preliminary studies on the evaluation of the uncertainty on the $\sigma(\mu^+ \mu^- \to$H$) \cdot$ BR(H$\to b\bar{b}$) at 3 TeV were recently presented in the Higgs2021 conference [12]. The signal $\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ and the physics background, inclusive $\mu^+\mu^- \to b\bar{b} + X$, have been generated with Pythia Monte Carlo and simulated including BIB effects. The expected number of events after kinematic cuts on the jet $p_T > 20$ GeV, the requirement of a pair of b tagged jets in the final state and the jet pair invariant mass $m_{inv} < 300$ GeV, is 79000 for the signal and 3600 for the background, assuming L=1 ab^{-1}. The expected yields of signal and background events and the invariant mass distribution are used to generate a pseudodataset for the invariant mass distribution. A fit to the invariant mass distribution is performed to estimate the uncertainty on $\sigma(\mu^+ \mu^- \to$H$) \cdot$ BR(H$\to b\bar{b}$), that is found to be $\sim$ 0.4%. The fit result is shown in figure 2.

Studies to evaluate the Higgs coupling to the muon at $\sqrt{3}$ TeV muon collider are presented in [13], where the sensitivity on the $\sigma(\mu^+\mu^- \to \mathrm{H}) \cdot \mathrm{BR}(\mathrm{H} \to \mu\mu)$ is found ~ 38 %. Further studies on the Higgs coupling to the c quark and the W boson are currently ongoing.

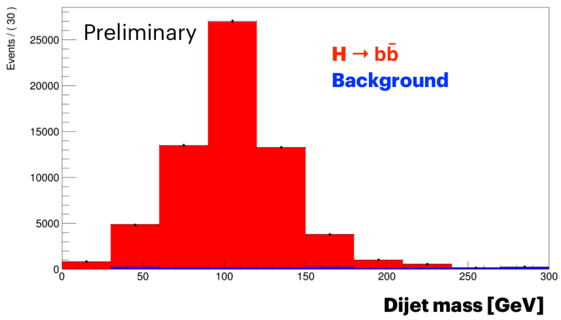

Figure 2: Result of the fit to the invariant mass. In red the signal distribution, in blue the background distribution, black dots with error bars are pseudodataset.

4. Evaluation of the precision on the double Higgs cross section and trilinear Higgs self-coupling sensitivity at $\sqrt{s}$=3 TeV

The signal $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ and physics background samples $\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$, where b quarks in the final state are not produced by Higgs pair decays, and $\mu^+\mu^- \to Hb\bar{b}\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$, that includes HH signal, are generated with the WHIZARD [14] Monte Carlo at $\sqrt{s}$=3 TeV. Final state jets are reconstructed with the Particle Flow algorithm. Events with at least 4 jets in the final state with $p_T > 20$ GeV are selected. The invariant masses of all possible jet pairs are calculated and the jet pair invariant masses m_{12} and m_{34} that minimize the distance D from the mass of the Higgs m_H are then associated to the two Higgs candidate:

$$D = \sqrt{(m_{12} - m_H)^2 + (m_{34} - m_H)^2} \tag{1}$$

Five kinematic and angular variables have been selected to train a multivariate classifier based on a Boosted Decision Tree (BDT) to separate the signal from the physics background $\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$. BIB effects on b-jet identification are taken into account by weighting events with the tagging efficiencies described in section 2. At least one jet for each jet pair associated to Higgs candidates is required to be tagged. Assuming L=1 ab^{-1} at $\sqrt{s}$=3 TeV, 50 signal and 432 background events are expected to be selected. Pseudodatasets have been generated assuming these number of signal and background events and BDT distribution and from the fit of the BDT an uncertainty of ~30 % is obtained on the cross section. Figure 3 left shows the result of the fitting procedure.

The determination of the uncertainty on the trilinear Higgs self-coupling exploits the characteristics of $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ containing only Higgs pairs produced via H^*. By comparing this sample with the inclusive double Higgs is it possible to see differences in angular observables: for example as is shown in figure 3 right the angle between the Higgs pair from H^* is lower with respect to the two Higgs produced via other electroweak interactions. Such characteristic is exploited to maximize the selection of the double Higgs events sensitive to the trilinear coupling. The event

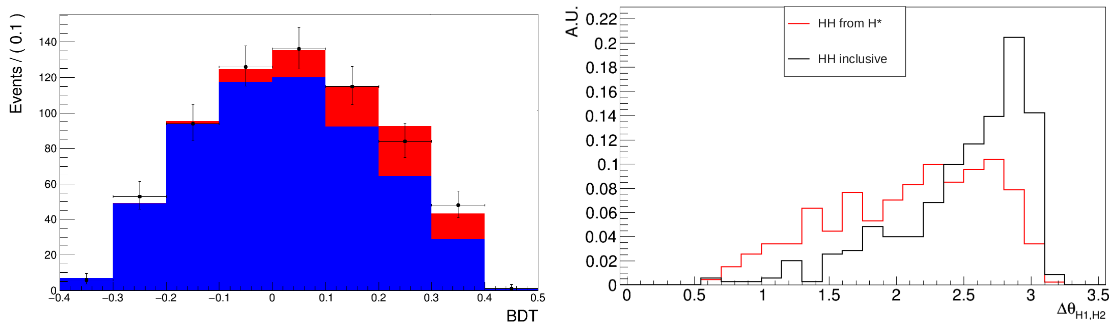

Figure 3: Left: fit result of the BDT. The signal contribution is coloured in red, the total physics background is coloured in blue, black dots with error bars represent the pseudodataset. Right: distribution of the angle between the two Higgs at Monte Carlo level for the inclusive HH (black) and the HH from H^* (red) samples.

classification is carried out using two multivariate classifiers based on Multi-Layers Perceptrons (MLP), trained independently. The first one is trained on nine kinematic and angular variables, to separate the HH events from the physics background $\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$. The output distributions, once it is applied to the four samples of inclusive HH, the two physics background and the HH from trilinear, can be seen in figure 4 left. The second one is trained on seven kinematic and angular variables to separate the HH from H^* from the inclusive HH sample. Figure 4 right shows its output distributions for the four samples. The $b\bar{b}H$ physics background MLP distribution (yellow) partially overlap with the inclusive HH distribution (blue), since it includes the HH.

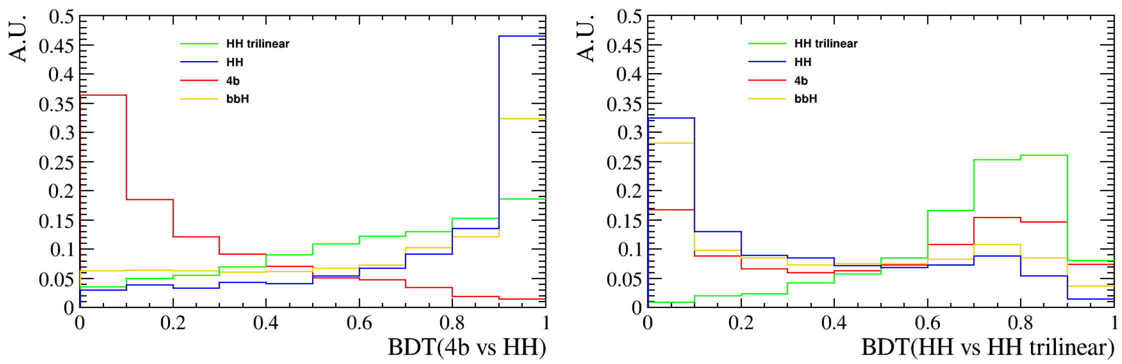

Figure 4: MLP outputs for the HH from H^* (green), the inclusive HH (blue) and the two physics backgrounds ($\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$ in red and $\mu^+\mu^- \to Hb\bar{b}\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ in yellow) samples. Left: MLP trained to separate the four b jets ($\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$) background from the HH. Right: MLP trained to separate the HH from H^* (HH trilinear) sample from the inclusive HH.

The uncertainty on the trilinear Higgs self-coupling is determined in the following way: samples of double Higgs events are generated for different $\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$ =(0.4, 0.6, 0.8, 1.2, 1.4, 1.6). The two MLP scores on these samples, the HH signal (κ_λ= 1) and the physics backgrounds are arranged in 2D histograms. A binned likelihood analysis based on pseudoexperiments, generated assuming the expected signal and background yields and the 2D histogram MLP distribution, gives a final uncertainty on κ_λ, assuming L=1 ab^{-1}, of $\sim$ 20% at 68 % C.L. .

5. Conclusions

Studies performed in the different hypothesis show that a muon collider can be the ideal machine to study Higgs physics. In this paper results, obtained for $\sqrt{s}$= 3 TeV and L=1 ab^{-1}, on the uncertainty on the double Higgs cross section (∼ 30 %), the trilinear Higgs self-coupling (∼ 20 %) and on $\sigma(\mu^+ \mu^- \to$H) · BR(H$\to b\bar{b}$) (0.4 %) have been presented. These results are comparable to the one obtained in the first analysis by CLIC [15].

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