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Study of Higgs couplings measurements at muon collider

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Summary. — Muon collisions at multi-TeV center-of-mass energies are ideal for studying Higgs boson properties. At these energies the production rates will allow precise measurements of its couplings to fermions and bosons. In addition, the double (triple) Higgs boson production rate could be sufficiently high to directly measure the parameters of trilinear (quadrilinear) self-couplings, enabling the precise determination of the Higgs potential. In this contribution a study of $\mu^+\mu^- \to H\nu\bar{\nu}$ and $\mu^+\mu^- \to HH\nu\bar{\nu}$ processes, where the Higgs boson decays in $b\bar{b}$, is presented based on the detector full simulation with an evaluation of the beam-induced background.

1. – Introduction

The scientific program concerning the Higgs boson physics at Future Colliders has two main goals. The first one is the improvement of the precision on the Higgs boson couplings to the bosons and fermions below 1%, as deviation from the Standard Model (SM) could reveal New Physics [1]. The second one is the precise measurement of the trilinear (λ_3) and quadrilinear (λ_4) Higgs boson self-couplings, that will allow to determine the shape of the Higgs boson potential. This will be of paramount importance since it rules the electroweak simmetry breaking and will open a window to perform cosmological tests. These parameters will not be directly measured with enough precision at LHC due to the low cross sections of HH and HHH productions. The CLIC Collaboration expects to measure λ_3 with a precision below 10% with e^+e^- collisions at center-of-mass energies of 1.5 TeV and 3 TeV [2]. A limit at 68% Confidence Level in the interval $[-2, 13]$ is expected to be set on λ_4/λ_{SM}, where λ_{SM} is the Higgs self-coupling SM prediction, using *pp* collisions at FCC-hh at 100 TeV [3].

Fenomenological studies show that at a $\mu^+\mu^-$ collider the expected sensitivity for λ_3 is 5% at $\sqrt{s} = 10$ TeV with integrated luminosity $L = 10$ ab^{-1} [4] and for λ_4 is 50% at $\sqrt{s} = 14$ TeV with $L = 33$ ab^{-1} [5]. Colliding muons allow to have clean events

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since they are fundamental particles like e^+e^- and reach high collision energies, as in pp colliders, because of the negligible energy loss by syncrothron and beamstrahlung radiation. However the detector performance at a muon collider can be strongly affected by the presence of the beam-induced background (BIB) if not properly treated.

2. – Beam-induced background

The BIB is generated by the interactions of the electrons/positrons and neutrinos, produced in the decay of muons in circulating beams, with the surrounding machine elements and the machine-detector interface (MDI) components [6]. The result of these interactions is a large number of secondary and tertiary particles that can reach the detector. The amount, the type and the composition of the BIB depend on the collider energy and the machine optics and lattice elements. The Muon Accelerator Program (MAP) Collaboration developed a detailed design of the interaction region and of the MDI for $\sqrt{s} = 125$ GeV and $\sqrt{s} = 1.5$ TeV and found that part of the BIB can be absorbed at the entrance of the detector by two cone-shaped tungsten nozzles [6]. For the $\sqrt{s} = 1.5$ TeV case, $10°$ angular aperture cones provide an average background suppression by a factor of ~ 500. The amount of BIB particles surviving the nozzles is still high ($\sim 10^{10}$ particles) and is composed mostly by photons, electrons/positrons, neutrons and charged hadrons. They have relatively low momentum, and arrival time asynchronous with respect to the beam-crossing time [6]. Further mitigation of the BIB can be achieved with the employment of sensors providing information about the energy released by particles, the position and the time of arrival with respect to the beam crossing at the detector components. Despite these mitigation strategies, the presence of the BIB requires an optimization of the reconstruction and pattern recognition algorithms to avoid fake objects reconstruction due to the BIB and keeping high efficiency. For this reason the evaluation of the detector performances including the BIB is mandatory to determine the physics reaches.

3. – Detector optimization and $H \to b\bar{b}$ reconstruction

The studies presented in sect. **4** are based on the CLIC [7] detector with important modifications to meet the muon collider conditions. These are: the insertion of the tungsten nozzles optimized for $\sqrt{s} = 1.5$ TeV, and the removal of the calorimeters in the forward region. Furthermore the design of the vertex and the tracker detector are changed according to the MAP studies. BIB particles that survive the nozzles release a large number of hits in the innermost layers of the vertex detector (VTX) and the tracker system composed by an inner (IT) and an outer (OT) tracker detectors. The time spread of the hits released on the first layer of the VTX with respect to the beam-crossing time is compared for BIB particles and prompt muons in fig. 1 (left). A time resolution, σ_T, of 50 ps (100 ps) is assumed for the VTX (IT and OT). By applying a $\pm\, 3 \cdot \sigma_T$ time cut, a huge amount of background hits can be rejected. The occupancy on the layers of the VTX and tracker detectors for one beam crossing is shown in fig. 1 (right), before and after the time cut. The average occupancy suppression is $\sim 30\%$. The timing information can be exploited also at the calorimeter level [8]. The optimization of the tracking, jet reconstruction and b-tagging algorithms provided by this simulation framework, in the presence of the BIB, is currently ongoing.

In ref. [8] the $\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ process at 1.5 TeV is fully simulated and reconstructed including the BIB by using a different simulation framework. The jet

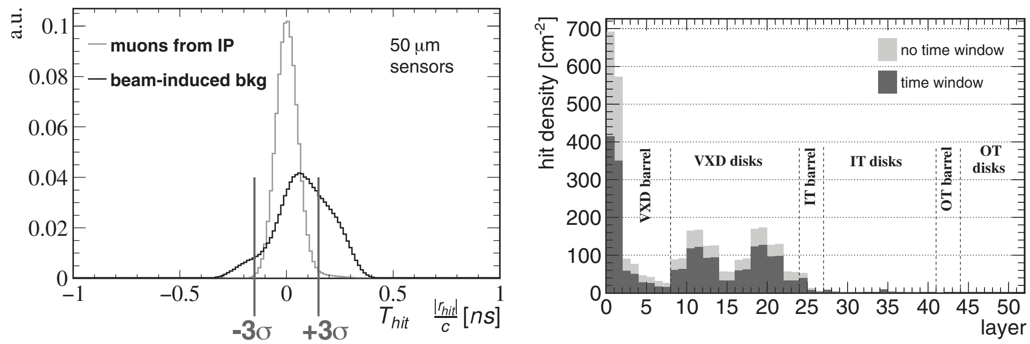

Fig. 1. – Left: time spread of the hits released by muons from the IP (light grey) and BIB particles (dark grey). Right: occupancy as a function of the VTX and tracker layers before (light grey) and after (dark grey) the time cut.

reconstruction and b-tagging algorithms were optimized to reduce the ratio of reconstructed fake jets and fake secondary vertices due to the BIB. The tagging efficiency is found to be around 60% and the mis-tag rate is $\sim$ 1–3%. In these conditions, the uncertainty on the couplings of the Higgs to the b-quark is found to be of the same order as that obtained by CLIC: 1.9% at 1.5 TeV ($L = 0.5$ ab^{-1}), 1% at 3 TeV ($L = 1.3$ ab^{-1}) [9].

4. – Measurement of the double Higgs cross section 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 ($\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$) events are generated with the WHIZARD Monte Carlo [10]. Since one jet per Higgs candidate is required to be tagged, other background sources are considered negligible. The jet reconstruction is performed using the Particle Flow algorithm that exploits both the energy on the calorimeter and the tracks. It is assumed that the jet reconstruction efficiency and p_T resolution are not affected by the presence of the BIB and that the ratio of fake jets is negligible. Since the simulation of the BIB at $\sqrt{s} = 3$ TeV is currently ongoing, in this study the events are weighted for the b-tagging efficiencies obtained in [8] at $\sqrt{s} = 1.5$ TeV. This is a conservative assumption: the BIB level decreases as $\sqrt{s}$ increases, since the muon lifetime is longer, and the detector acceptance is expected to increase with $\sqrt{s}$ [6]. Events with a number of jets $N_{jets} \geq 4$ jets with $p_T > 20$ GeV are selected. Invariant masses between all combinations of jets are calculated. The jets pairs whose invariant masses, m_{12} and m_{34}, minimize the distance D from the Higgs mass m_H are selected and associated to the two Higgs candidates:

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

In order to improve the signal-to-noise ratio a Multivariate Analysis technique [11] is used. Five kinematic variables are selected and given in input to a Boosted Decision Tree (BDT): the invariant mass of the highest p_T dijet pair, the invariant mass of the other dijet pair, the total energy of the four jets, the module of the vector sum of the jets momenta and the maximum angle between the four selected jets. The number of signal (S) and background events (B) are calculated as

$$S = \sigma_{HH} \cdot BR(H \to b\bar{b})^2 \cdot \epsilon_S \cdot L \qquad \text{and} \qquad B = \sigma_{b\bar{b}b\bar{b}\nu\bar{\nu}} \cdot \epsilon_B \cdot L, \tag{2}$$

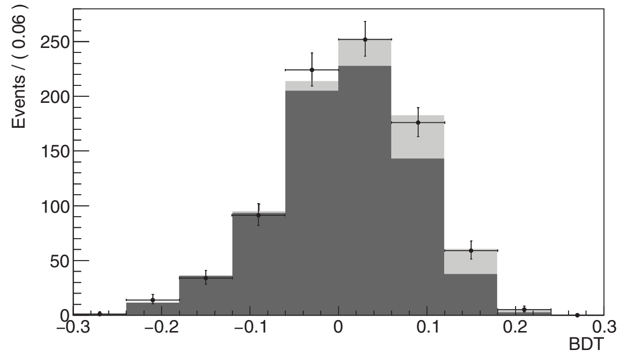

Fig. 2. – Fit results: the signal is in light grey, the background in dark grey, black points with errors bands are the pseudodata.

where σ_{HH} and $\sigma_{b\bar{b}b\bar{b}\nu\bar{\nu}}$ are the signal and the physics background cross sections, $BR(H \to b\bar{b})$ is the $H \to b\bar{b}$ branching ratio, ϵ_s and ϵ_B are the selection efficiencies and $L = 1.3$ ab^{-1} the integrated luminosity. The final numbers of expected events are $S = 67$ and $B = 745$. These estimations and the BDT distributions are used to generate a pseudodataset for the BDT distribution from which the uncertainty on the double Higgs cross section is found to be 33%. Figure 2 shows the result of the fitting procedure.

5. – Conclusions and perspective

The uncertainty on the HH cross section, obtained under conservative assumptions and taking into account the BIB effects, is found to be 33% at $\sqrt{s} = 3$ TeV with $L = 1.3$ ab^{-1}, that corresponds to four years of data taking. This result is comparable to the one obtained in the first analysis on HH by CLIC [9]. With the optimization of algorithms for tracks and jet reconstruction and for b-jet identification, the uncertainty is expected to be largely reduced.

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