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Search for the Higgs boson decaying to a pair of charm quarks at a future Multi-TeV Muon Collider

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Summary. — This paper presents a feasibility study aiming to estimate the precision achievable on the Higgs-to-charm-quark coupling at a future Muon Collider. The accurate measurement of the Yukawa couplings is of invaluable importance in High Energy Particle Physics, as it sheds light on the Electroweak Symmetry Breaking mechanism. In particular, the couplings to the second generations of fermions are of extreme interest due to sensitivity to a whole class of new physics models, but their measurement is extremely challenging, because of the small branching ratio. The coupling to charm quark, especially, is currently not accessible at LHC but could be probed at future lepton colliders. Within this work, the search for $H \to c\bar{c}$ at Muon Collider has been performed. The $\mu^+\mu^- \to H\nu\bar{\nu} \to c\bar{c}\nu\bar{\nu}$ signal process has been fully simulated and reconstructed at $\sqrt{s} = 1.5$ TeV, along with the main physics backgrounds. The machine background originating from the decay of muons in the beam, the so-called Beam Induced Background, is not included in this preliminary study. With the aim of improving the rejection of jets coming from b-quark and u-d-s-g hadronization, a charm quark tagging algorithm has been developed by employing Machine Learning techniques. Finally, the relative uncertainty on the coupling at $\sqrt{s} = 1.5$ TeV is estimated to be 5.5%. A projection to $\sqrt{s} = 3$ TeV shows that precision improves with increasing energy, reaching the value of 2.6%.

1. – Introduction

Since its discovery in 2012, the Higgs boson has been at the center of the scientific community effort in the context of Particle Physics. Indeed, the Higgs boson is considered

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a powerful tool to explore the manifestations of the Standard Model (SM) and to probe the physics landscape beyond it. The precise measurement of Higgs properties and couplings to SM particles has, thus, become the primary goal of the proposed Future Colliders, as even small deviations of these values from SM expectation could possibly reveal New Physics. In this context, a Multi-TeV ($\sqrt{s} = 1.5$–$10\,\text{TeV}$) Muon Collider has been proposed as an unconventional machine with several advantages with respect to the traditional hadronic and e^+e^- colliders [1]. Nonetheless, this novel approach poses some new technical challenges, as the mitigation of the Beam Induced Background (BIB) [2].

In this work, the search for the Higgs boson decaying into charm quarks at Muon Collider is simulated for the first time, and a preliminary estimate of the precision achievable on the Higgs-to-charm-quark coupling is given, for the time being without the BIB overlay. The core feature of this analysis is the identification of charm quark jets. In order to fully exploit differences between flavours of jets, good vertexing capability and jet energy resolution are necessary. The former is accomplished through a $5\,\mu\text{m} \times 5\,\mu\text{m}$-resolution vertex detector, while the latter is accomplished by using high granularity calorimeters and a new Particle Flow algorithm for particle reconstruction and identification. Detailed information on the detector and reconstruction algorithm can be found in refs. [3] and [4].

2. – Simulated samples

The signal process is the Higgs decay into charm quarks, where the Higgs Boson is produced through WW fusion, that is the dominant Higgs production mechanism at this energy ($\sqrt{s} = 1.5\,\text{TeV}$) [5]. The resonant background consists of Higgs Boson decays to a pair of bottom quarks ($H \to b\bar{b}$) and to a pair of gluons ($H \to gg$), whose branching ratios are respectively 20 and 3 times higher than the signal one. The non-resonant background is represented by processes with two jets and two leptons of any kind in the final states. Signal and background processes are generated using Pythia8 [6] and MadGraph5 [7]. All the samples produced are exhaustively described in ref. [8]. The Muon Collider detector response simulation and reconstruction are performed with ILCSoft [9].

3. – The c jet tagger

In order to discriminate c jets from b jets and light-flavour jets, a dedicate tagger has been implemented, exploiting the properties of heavy-flavour hadrons resulting from radiation and hadronization of charm quarks. The sizeable lifetime of these hadrons together with their relativistic boost give rise to displaced tracks (large signed impact parameter, SIP) and secondary vertices (SVs) millimetres or more away from the primary one. Moreover, the semi-leptonic decays of heavy hadrons lead to the presence of non-isolated low-energy electrons and muons, collectively called soft leptons. For these reasons, the tagger relies on three types of variables: secondary vertex related variables (examples in fig. 1), track related variables (example in fig. 2 (left)) and soft lepton related variables (example in fig. 2 (right)). A comprehensive description of all the features utilized in the tagger can be found in ref. [8].

Two binary Boosted Decision Tree classifiers have been trained: one for discriminating c jets from b jets (*CvsB*) and the other for discriminating c jets against light-flavour jets (*CvsL*). The performances of the two separate classifiers compared to the CMS and CLIC ones are reported in ref. [10]. Since the two discriminators are applied together in the analysis, it is helpful to evaluate their combined effect on signal and backgrounds

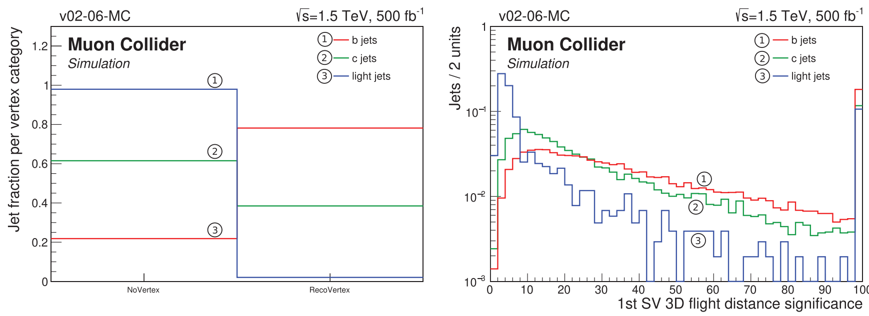

Fig. 1. – Left: jet fraction per vertex category. The "NoVertex" category contains jets with no SV, while the "RecoVertex" category contains jets with at least a SV. Right: 3D flight distance divided by its uncertainty (significance) for the first SV. SVs are ordered by increasing uncertainty on their 3D flight distance. Distributions are reported for b/c/light jets for comparison.

and calculate the total tagging efficiency and mis-tagging probability as shown in fig. 3 (left). The working point chosen for the analysis lies on the 40% charm efficiency curve (magenta line, labeled with "3") in correspondence of 5% light-flavour and 13% bottom contamination.

4. – Event selection and final results

The highest-p_T-jets surviving the flavour tagging are used to build the Higgs candidates. Several topological selections are applied in order to suppress the prompt jet background: the separation between jets in the $\eta - \phi$ plane is required to be smaller than 3, the Higgs candidate is required to have energy greater than 130 GeV, p_T greater than 30 GeV, and invariant mass in the range $[110, 130]$ GeV. Figure 3 (right) shows the mass distribution for the signal and backgrounds surviving the event selection, *i.e.*, the resonant component and the prompt c jet production.

The final number of expected signal events (S) and background events (B) are used for computing approximatively the relative uncertainty on the $H \to c\bar{c}$ production cross section and on the Higgs-to-c-quark coupling, following ref. [11]. Table I summarizes the results and shows the projection at $\sqrt{s} = 3\,\text{TeV}$, $\mathcal{L} = 1300\,\text{fb}^{-1}$, obtained assuming the same fraction of surviving events per each sample and scaling the results to cross

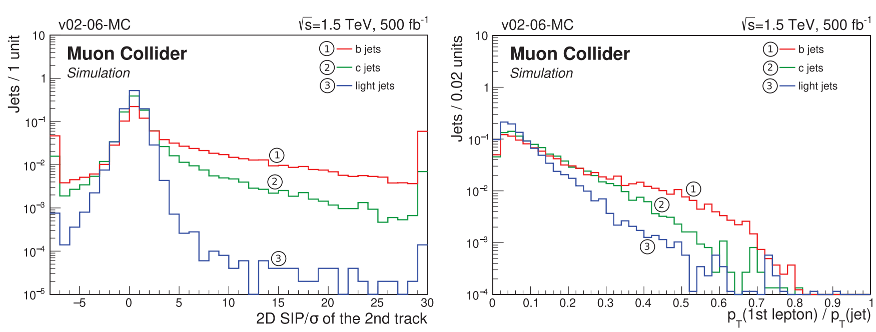

Fig. 2. – Left: 2D SIP divided by its uncertainty (significance) for the second track. Tracks are ordered by decreasing 2D SIP significance. Right: transverse momentum of the first lepton divided by jet transverse momentum. Leptons are ordered as tracks.

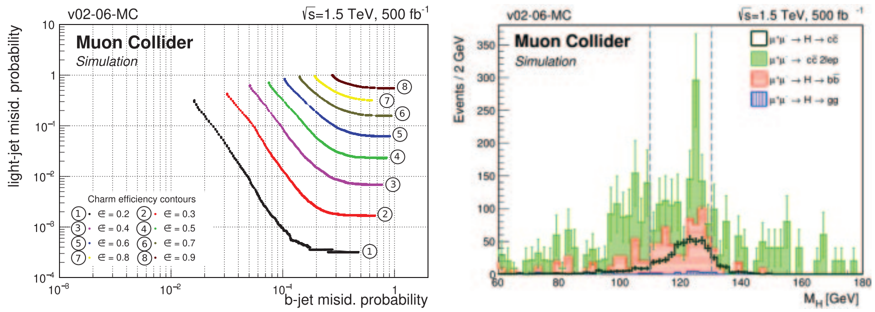

Fig. 3. – Left: misidentification probability for light-flavour jets *vs.* misidentification probability for b jets for several constant c jet efficiencies. Right: invariant mass of the di-jet system for signal and background processes surviving the selections. The selected mass range is indicated by the vertical dashed lines. Histograms are scaled to cross section and luminosity.

TABLE I. – *Signal and background yields, signal significance, relative uncertainty on $H \to c\bar{c}$ production cross section and relative uncertainty on the Hcc coupling at 1.5 and 3 TeV, without BIB overlay.*

$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	S	B	$S/\sqrt{S+B}$	$\Delta\sigma/\sigma$	$\Delta g_{Hcc}/g_{Hcc}$
1.5	500	378	1205	9.5	10.5 %	5.5 %
3.0	1300	1565	4337	20.4	4.9 %	2.6 %

section and luminosity at the increased center of mass energy. These estimates are very preliminary but already show the potential of the Muon Collider, if an efficient machine background mitigation strategy is adopted.

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