PROCEEDINGS OF SCIENCE

R&D towards the detector for the Muon Collider

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A Muon Collider is being proposed as a next generation facility. This collider would have unique advantages, since clean events as in electron-positron colliders are possible, and high collision energy as in hadron colliders could be reached due to negligible beam radiation losses. The beam-induced background, produced by the muon decays in the beams and subsequent interactions, reaches the interaction region and the detectors, and presents unique features and challenges with respect to other machines. In this talk, the R&D activities for the design of the Muon Collider detector will be presented. In particular, the development of the tracking system, the calorimeter system, and the muon detector will be discussed. Results of detailed simulation studies of the detector in the muon collider environment and of experimental tests on prototypes based on the most promising technologies will be shown.

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1. Introduction to the Muon Collider

The Muon Collider is one of the most promising proposals for future accelerators. It puts together the advantages of having relatively clean events as in lepton colliders, and the possibility to reach high collision energy as in hadron colliders, since radiation losses are very limited. The opportunity of having muon collisions at multi-TeV energies enables an exciting physics potential, that ranges from precision Higgs physics to the search for New Physics at an unexplored energy scale.

The International Muon Collider Collaboration [1] has identified a schedule for the realization of the Muon Collider facility, starting from a demonstrator experiment and moving to a 3 TeV center-of-mass-energy collider. Then the road will be open for a $\sqrt{s}$ =10 TeV collider and to the multi-TeV scale.

The main technological challenges at the accelerator and detector level are due to the short lifetime of the muons (2.2 μs at rest), which should be quickly cooled and accelerated. The limitation factor for the detector is the beam-induced background (BIB) that is produced by the decay in flight of muons in the beams, and subsequent interactions. All kinds of particles are produced, like photons, electrons, and neutrons, and the BIB can be partially mitigated by a proper design of the machine-detector-interface, *e.g.* by using two shielding tungsten nozzles in the detector region [2]. Nevertheless, an order of 10^8 particles enter the detector, therefore the detector design, the technology choices, and the reconstruction strategies must primarily take into account the BIB impact. Most of BIB particles hit the detector asynchronously with respect to the bunch crossing, and they usually have low energy: timing measurements and appropriate energy thresholds are important handles to suppress the BIB at the detector level. It has also been shown that the radiation hardness requirements are similar to what is expected at the High Luminosity LHC (HL-LHC) [3].

2. Muon Collider detector concept

The Muon Collider detector [8] has been designed to suppress the $\sqrt{s}$ =1.5 TeV BIB, since it was the first BIB simulation available and produced with the MARS15 package [4]. All considerations in this paper have been obtained at this center-of-mass energy. Further studies with Fluka [5] have demonstrated that the BIB level at $\sqrt{s}$ =1.5 TeV is similar to $\sqrt{s}$ =3 TeV, therefore this detector concept has been used to assess the physics performance at 3 TeV.

The detector has been developed starting from the CLIC detector concept [6] with a few modifications aimed to adapt it to the machine-detector interface. It is formed by a tracking system, a calorimeter system, a solenoid with a magnetic field of B = 3.57 T, and a return yoke instrumented with muon detectors. The tracking system includes a vertex detector made of silicon pixels with double layers, and inner and outer trackers respectively composed of silicon macropixels and microstrips. The calorimeter system consists of an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL). The former is composed of alternating layers of tungsten absorber and silicon sensors, the latter has alternating layers of steel absorber and scintillating pads. The return yoke is equipped with resistive plate chambers for muon detection. The detector has been simulated and studied with the Muon Collider Software framework [7].

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3. R&D on the tracking system

The occupancy in the first layer of the vertex detector is of about one order of magnitude higher than what was expected at ATLAS/CMS in the HL-LHC era [8], for this reason, a reduction is necessary. However, the Muon Collider features a $\sim$ 100 kHz bunch crossing rate in single bunch mode (at LHC the crossing rate is 40 MHz) therefore there is more time to process the signals. Key features for developing the tracking system are: precise timing measurements, to suppress BIB hits that are out-of-time with respect to the bunch crossing; directional information, since BIB particles do not come from the interaction point; a pulse shape analysis could help in rejecting the soft component. The baseline tracking geometry consists of double layer pixel sensors with a time resolution of 30 ps for the vertex detector, and a time resolution of 60 ps for microstrips and macrostrips in the inner and outer tracker. Promising technologies [9] for such kind of silicon sensors are:

- monolithic devices (CMOS): good timing and spatial resolution, but radiation hardness has to be improved;
- Low Gain Avalanche Detectors (LGAD): large and fast signals (20-30 ps resolution) with moderate radiation hardness;
- hybrid small pixel devices: no gain but fast timing (20-30 ps resolution) and good position resolution, they are intrinsically radiation hard.

It is evident that the development of the silicon sensors for the Muon Collider is in synergy with the R&D for the HL-LHC detectors.

4. R&D on the calorimeter system

A flux of 300 particles per cm^2 passes through the ECAL surface, composed of photons (96%) and neutrons (4%). The average photon energy is 1.7 MeV, and the neutrons that survive the passage in ECAL arrive at the HCAL surface, with a flux of 7.5 kHz/cm^2. A calorimeter system for the Muon Collider should have the following features: timing, since BIB hits are out-of-time, and a resolution in the order of 100 ps is desirable; longitudinal segmentation, since signal and BIB showers have a different longitudinal profile; granularity, that helps in separating BIB particles from the signal, avoiding overlaps in the same cell.

A promising technology for ECAL is Crilin: A CRystal calorImeter with Longitudinal InformatioN for a future Muon Collider [10]. A Crilin module is formed by 5 layers of PbF_2 crystals (10 x 10 x 40 mm^3), and the Cerenkov light is detected with Silicon Photomultipliers. PbF_2 crystals have good light yield (3 photo-electrons per MeV) and fast signals. They are also radiation hard and relatively cheap, potentially much less expensive than the tungsten-silicon calorimeter of the baseline concept (Section 2). In order to assess the physics performance of the Crilin ECAL barrel, the detector has been implemented in the simulation of the Muon Collider experiment, and the result on the photon energy resolution is shown in Figure 1. The obtained energy resolution of $14\%/\sqrt{E\,[\mathrm{GeV}]}$ is close to the target one ($10\%/\sqrt{E\,[\mathrm{GeV}]}$), but more optimization studies are ongoing. To demonstrate the technology concept, a prototype Crilin module has been built at Laboratori Nazionali di Frascati, and tested with beams at CERN [11].

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A promising technology for the HCAL is represented by Micro Pattern Gas Detectors (MPGD). These detectors feature a high rate capability (in the order of MHz/cm^2), a modest time resolution (a few ns) and they are robust against radiation. Their applicability as active sensors in the Muon Collider HCAL has been studied in [12], where iron layers interleaved with MPGDs filled with Argon are simulated, and the energy measurement of pions is studied. An energy resolution of $50\%/\sqrt{E\,[\mathrm{GeV}]}$ is obtained, and these results will be validated in the future with the realization of prototypes.

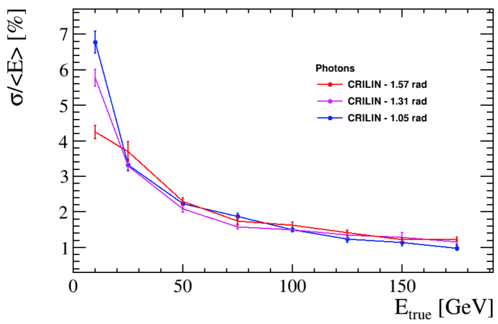

Figure 1: Photon energy resolution as a function of the photon energy, obtained with Crilin as ECAL barrel, and for different photon angles with respect to the beam axis. BIB is included in this simulation.

5. R&D on the muon detector system

In the muon detector BIB hits are concentrated in the forward region [9], as can be seen in Figure 2 (left), where the neutron flux is shown for different detector angles with respect to the beam axis. In the forward region some technologies like resistive plate chambers (RPC), considered for the baseline detector, are already at the sustainable rate limit. The ideal muon detector requires a good spacial resolution (in the order of 100 μm), and possibly a sub-ns time resolution. The neutron sensitivity, *i.e.* the probability for a neutron in the BIB to generate a visible signal, is shown in Figure 2 (right), where several technologies are compared: Triple GEM (Gas Electron Multiplier), RPC, GRPC (Glass RPC), and PicoSec [13]. PicoSec is a new technology based on MICROMEGAS (Micro Mesh Gas Detectors), which could be a valid option for a Muon Collider. First R&D results have shown low neutron sensitivity, a time resolution of 25 ps, and a very high rate capability. Given the novelty of the technology, further simulation studies and experimental characterizations are on-going to evaluate the PicoSec performance at the Muon Collider.

6. Towards a 10 TeV detector

The currently unmatched potential of the Muon Collider will fully emerge at collision energies of $\sqrt{s}$ = 10 TeV and beyond. A new detector concept for $\sqrt{s}$ = 10 TeV has to be designed to ensure the physics reaches from low to high energies. Low energy physics includes Higgs studies: the measurement of HH and HHH production will allow the determination of the Higgs self-couplings with an unprecedented precision. Besides, direct searches for new high mass particles could be performed. Figure 3 (top left) shows the transverse momentum of Higgs decay products

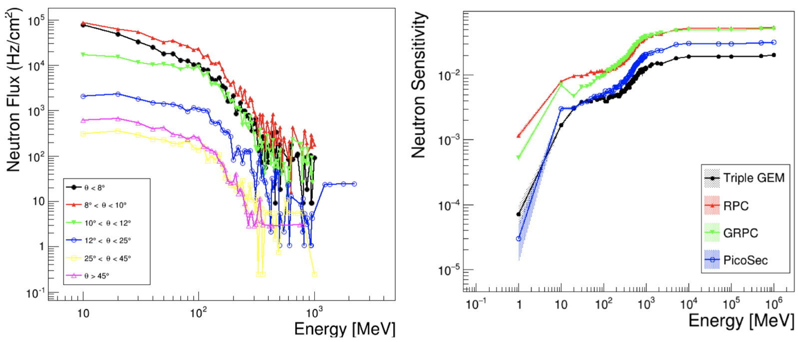

Figure 2: Left: neutron flux in the muon detector shown for different detector angles with respect to the beam axis. Right: The neutron sensitivity for different muon detector technologies [9].

at $\sqrt{s}$ = 3 and $\sqrt{s}$ = 10 TeV: it is evident that the distributions are very similar, with a peak around $p_{\mathrm{T}} \sim$ 100 GeV. An excellent energy/momentum resolution for such low energy particles is necessary to distinguish the Higgs signal from the backgrounds. Figure 3 (top right) shows the transverse momentum of a Z' decay products ($m_{Z'}$ = 9.5 TeV) at 10 TeV, where momenta arrive at the TeV scale. Since at high mass the combinatorial and Standard Model backgrounds could be considered negligible, just a moderate p_{T} resolution for tracks in the TeV range is sufficient.

In order to achieve the adequate p_{T} resolution in this wide range, the tracking system should be designed by choosing accurately several parameters: the tracker radius, the number of tracking layers, the distance of the first layer from the beam axis, and the magnitude of the magnetic field. In particular, the value of the magnetic field determines the superconductive solenoid characteristics and dimensions. Figure 3 (bottom left) shows how the p_{T} resolution for tracks with p_{T} = 5 TeV varies with the magnetic field (B) and the tracker radius (R_{max}), obtained using an analytical extrapolation of the tracking performance with the $\sqrt{s}$ = 3 TeV detector [8]. With very high magnetic fields a deterioration of the tracking performance at low p_{T} is expected: Figure 3 (bottom right) shows the minimum p_{T} required for a charged particle to reach the outermost tracker layer as a function of the magnetic field B, for different tracker radius values (R_{max}). With these considerations, a magnetic field in the 4-5 T range, a bit higher than the field in the 3 TeV detector concept, should be a good compromise, but more studies are necessary.

Showers produced by photons, electrons, and hadrons with TeV energies must be contained in the calorimeter to obtain a good energy measurement resolution. As an example a photon with E = 1 TeV releases less than 95% of its energy in 22 X_0 of ECAL [15], and the rest of the energy spills in HCAL. It is evident that the $\sqrt{s}$ = 10 TeV detector should foresee deeper calorimeters and alternative materials with higher X_0 and interaction lengths should be considered.

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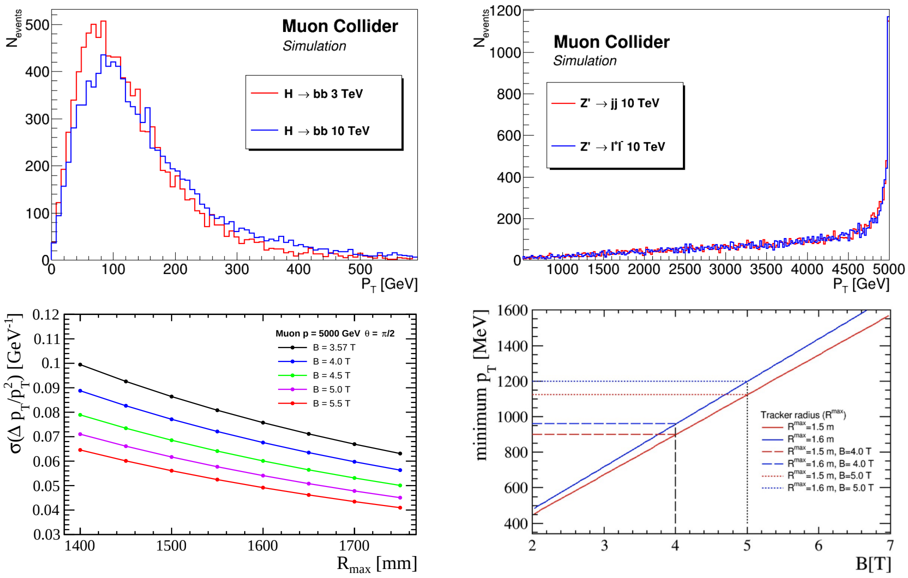

Figure 3: Top left: transverse momenta of b-quarks from the $H \to b\bar{b}$ decay, at $\sqrt{s} = 3$ and $\sqrt{s} = 10$ TeV [14]. Top right: transverse momenta of particle from Z' decays, with $m_{Z'} = 9.5$ TeV [14]. Bottom left: p_{T} resolution for a muon track with $p_{\mathrm{T}} = 5$ TeV as a function of the tracker radius (R_{max}) for different values of the detector magnetic field (B). Bottom right: minimum p_{T} required for a charged particle to reach the outermost tracker layer as a function of B for different tracker radii (R_{max}).

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