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Vertex and tracking detector developments for Muon Collider

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A Muon Collider has been proposed as the next-generation collider facility after the High Luminosity LHC program completes. It is believed that colliding muons at $\sqrt{s} = 10$ TeV can meet the desired physics goals of future experiments. The clean initial state allows for precision measurements of the Higgs boson and other Standard Model processes. At the same time, the high beam energy allows for direct searches for new physics beyond the LHC reach. The main detector challenge at the Muon Collider is the Beam Induced Background (BIB) coming from the decay of muons in the colliding bunches. The result is a large cloud of low energy particles striking the detector along with the bunch. The tracking detector will experience a hit density ten times that of the HL-LHC, most coming from the BIB.

The R&D for the tracking detector follows a similar path of the FCChh, with requirements on high density, high power, radiation hard and precision timing. The precision timing information, roughly 30 ps per hit in the vertex, will play a critical role in reducing the BIB-induced hits. However, the low energy of the BIB particles means that the innermost layer will only experience a fluence of 10^{16} neq/cm^2.

The contribution summarizes the state of the simulation of an experiment at a Muon Collider and the derived requirements on the tracking detector.

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1. Introduction

Next generation of energy frontier experiments have two goals: precision measurements of the Higgs boson properties (couplings and mass) to less than 1% accuracy and perform direct searches for new physics at the 1 TeV scale. Lepton colliders, due to the fully defined initial state and low backgrounds, are ideal environments for precision measurements. The power of electron colliders as "Higgs factories" has been extensively motivated. The elementary nature of leptons also provides an advantage when probing for new physics at high energies; the full beam energy participates in the collisions. A 10 TeV lepton collider is equivalent to a 50-100 TeV proton collider. However accelerating electrons to sup-TeV energies is difficult.

A proposed novel future collider facility is a Muon Collider. Muons are leptons and thus retain the advantages of a lepton collider described above. Being heavier than electrons, muons can be accelerated in circular rings to high energies without considerable Bremsstrahlung radiation losses.

The International Muon Collider Collaboration is developing two proposals. The first is a 3 TeV collider targeting an integrated luminosity of 1 ab^{-1}. The second is a 10 TeV collider with an integrated luminosity of 10 ab^{-1}. Both would operate for 5 years. Studies [1] have shown that a collider with at least $\sqrt{s} = 10$ TeV is necessary to reach the physics goals stated at the beginning. The 3 TeV collider option is an intermediately stage to demonstrate the new technology required to reach even higher energies.

The construction of a Muon Collider has several challenges that require an extensive R&D program. On the detector side, the main challenge is dealing with the Beam Induced Background (BIB) [2]. The results of muon decays result in a collimated beam of high energy electrons that strike the beam optics and other equipment in the way. This results in further secondary particles that enter the detector and deposit energy into the sensing elements (hits). The BIB is very different from pile-up present at hadron colliders. The pile-up background is a result of multiple simultaneous collisions. The reconstructed pile-up particles are real particles that originate from a distinct vertex in the collision region. On the other hand, the BIB consists of a swath of particles originating from outside the detector and don't follow the trajectory typical of a collision product.

New techniques, including advancements in instrumentation, are needed to separate the BIB hits from those created by particles coming from collisions. Failing to do so will create reconstructed ghost particles and reduce the energy resolution of reconstructed collision particles. Precision timing, to validate the time of flight (ToF) compatibility with primary interactions, plays an important role throughout all sub-detectors.

This contribution focuses on the requirements of the sub-detector used to reconstruct the trajectory of charged particles (Tracking Detector or tracker). Details on the full detector are available in [3].

The presented results use BIB expected at $\sqrt{s} = 1.5$ TeV as that was only available at the time of the study. New BIB overlays are being created for the center-of-mass energies descried earlier.

2. Tracking Detector

The proposed Tracking Detector utilises a general silicon-based tracker design. At this stage, no further explicit technology decisions have been made. The tracker is divided into three parts.

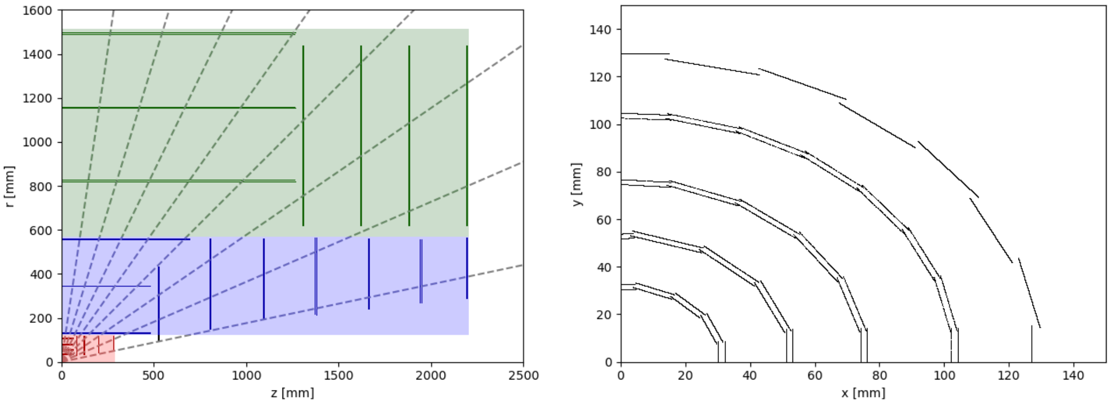

Figure 1: The layout of the silicon sensor layers in the Tracking Detector. Left plot shows the r-z projection with the VTX (red), IT (blue) and OT (green) highlighted. Right plot shows an x-y projection of the VTX barrel, highlighting the doublet layers.

	Vertex Detector	**Inner Tracker**	**Outer Tracker**
Cell Type	pixels	macropixels	microstrips
Cell Size	$25\,\mu\text{m} \times 25\,\mu\text{m}$	$50\,\mu\text{m} \times 1\,\text{mm}$	$50\,\mu\text{m} \times 10\,\text{mm}$
Sensor Thickness	$50\,\mu\text{m}$	$100\,\mu\text{m}$	$100\,\mu\text{m}$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\,\mu\text{m} \times 5\,\mu\text{m}$	$7\,\mu\text{m} \times 90\,\mu\text{m}$	$7\,\mu\text{m} \times 90\,\mu\text{m}$

Table 1: The pixel sizes and timing resolution in each tracker sub-detector. There is no difference between the barrel and end-cap regions.

Going from inside out, they are the Vertex Detector (VTX), the Inner Tracker (IT) and the Outer Tracker (OT). Each consists of a barrel region with sensors parallel to the beam and an end-cap region with sensors perpendicular to the beam. The Vertex Detector employs a doublet layer concept with two pixel sensors separated by 2 mm in each layer. The Tracking Detector layout is shown in figure 1. The tracker is placed in a 3.57 T magnetic field.

All sub-detectors are assumed be "4D trackers". In addition to precision space position measurement, they also provide a Time of Arrival (ToA) with $O(10$ ps$)$ resolution. The pixel size and timing resolution of each sub-detector is summarized in table 1. The values were chosen to ensure per-pixel occupancy below 1% .

The layout has been implemented using DD4hep for simulation using the GEANT4 program. A nominal amount of services has been included to provide a realistic amount of material, as shown in figure 2. Simulated hits are digitized by smearing their position and ToA using a gaussian distribution with the listed resolutions. The software is available as part of the *MuonColliderSoft* framework. The Beam Induced Background overlay is applied by the procedure described in [2].

An implementation of a realistic digitization algorithm is well advanced, but is not yet part of the standard workflow. Preliminary studies show that the pointing information stored in the hit cluster shapes can reduce the amount of BIB hits by half while maintaining 99% signal efficiency.

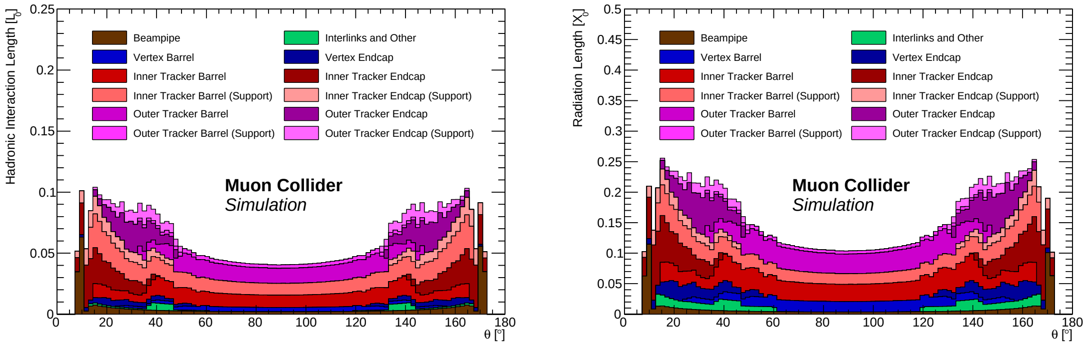

Figure 2: Amount of material inside the simulation of the Tracking Detector as shown via the hadronic interaction (left) and radiation lengths (right).

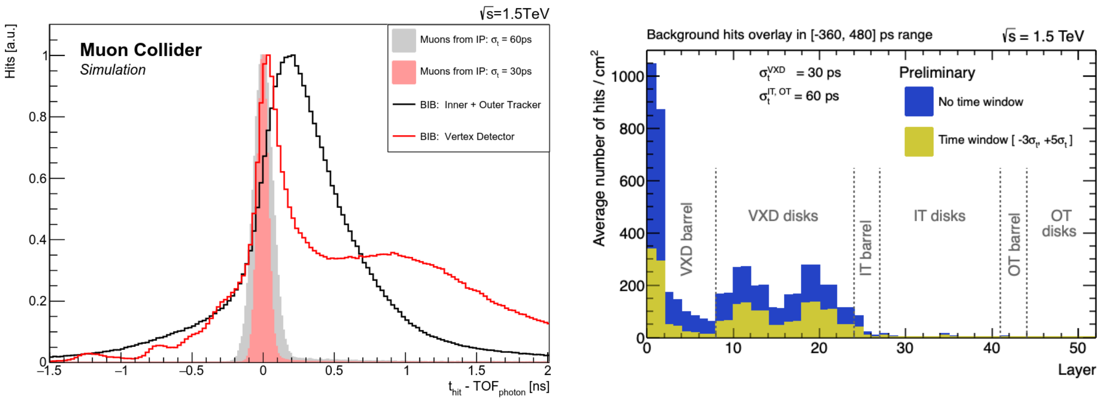

Figure 3: The impact of precision timing in reducing BIB hits. Left plot is the Time of Flight corrected timing measurement of hits originating from collision products (single muons) versus BIB. Right plot is hit density in the different tracking layers before and after filtering hits based on the corrected ToA information. The ToA is smeared the assumed resolution in each layer.

The precision measurement of the ToA is critical for separating BIB hits from those deposited by the collision products (collision hits). Figure 3 shows the Time of Flight (ToF) corrected ToA of the two sources, with a muon gun used for the collision hits. The ToF correction assumes the charged particle has travelled in a straight line at the speed of light from the center of the detector. A clear seperation is observed. The figure also shows the hit density per tracking layer before and after filtering using smeared ToA information. The timing cuts select hits within a $[-3\sigma, +5\sigma]$ time window. This reduces the hit density by a factor of two while keeping more than 99% of collision hits.

The hit density, after timing cuts, is around a factor of ten higher than in the corresponding layers of the ATLAS and CMS tracking detectors expected during the HL-LHC data taking. However most of the hits come from the low energy BIB particles. Thus the expected radiation damage is comparable to the HL-LHC environment. The Tracking Detector expects a 1-MeV-neq fluence of $\approx 10^{14-15}$ cm^{-2} y^{-1} and total ionising dose of $\approx 10^{-3}$ Grad/y. Both values decrease with radius.

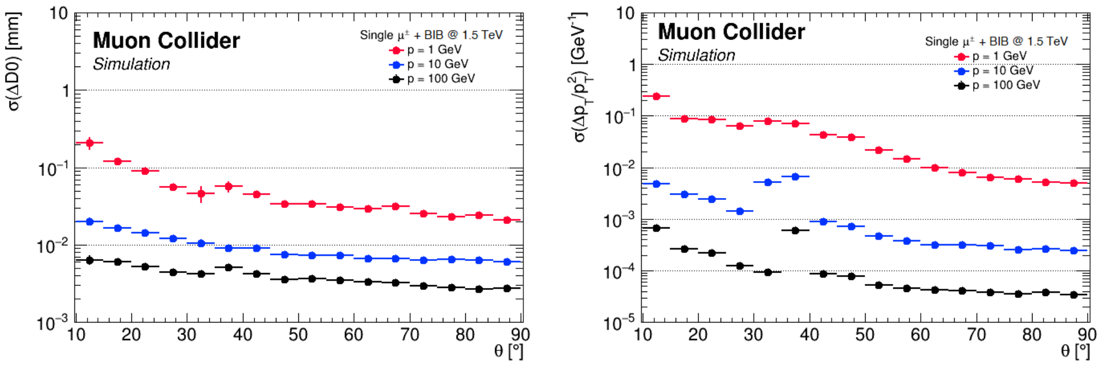

Figure 4: The resolution of track parameters for single-muon events reconstructed using Conformal Tracking and a Region-of-Interest hit filter. Left plot shows relative transverse momentum resolution and right plot shows the impact parameter resolution. The angle θ is with respect to the beam. More plots are available in [3].

3. Track Reconstruction

The simulated and digitized hits passing timing selection are used to reconstruct the trajectory of charged particles (tracks). The timing selection removes hits with a ToF not within $[-3\sigma_t, +5\sigma_t]$, where σ_t is the timing resolution of the layer. Two algorithms have been used for track reconstruction studies; one based on the Conformal Tracking (CT) [4] and second using a Combinatorial Kalman Filter (CKF). The reason for the two algorithms is historic. The CT algorithm implementation was already present in the software framework and used for most of the initial studies. The CKF algorithm was implemented later due to significant improvements in the computational performance and has only recently entered the standard workflow.

The Conformal Tracking algorithm is described in [4]. Its design and implementation target the clean environment of an electron collider. The muon collider has a much higher hit multiplicity due to the Beam Induced Background. This significantly increases the combinatorics at the pattern recognition stage. It takes about 2 weeks to reconstruct a single event in these conditions. To improve reconstruction time, two strategies were implemented to further reduce the number of hits entering the pattern recognition stage. The first strategy employs a Region of Interest (RoI) approach where only hits within the radius of a calorimeter jet or close to a muon reconstructed in the moun system are used. The resolution of select reconstructed track parameters in single-muon events is shown in figure 4. The resolution mainly depends on the detector material and not the algorithm. Thus similar values are expected for the other algorithms.

The second strategy exploits the doublet layers of the Vertex Detector to look for pairs of hits that point towards the origin. By using a tight criterion on the hit doublets, the time to reconstruct a single event is reduced to $\approx$ 2 min/event. No extra filtering is performed in the IT or OT as they have a much lower BIB density. The downside is that not all valid tracks originate from the origin. The filter discriminates against non-prompt decays (ie: b-meson decays) or a realistically sized beamspot. For this reason, the use of a doublet layer filter is not preferred. But it does provide another potential handle for dealing with the BIB.

The Combinatorial Kalman Filter algorithm is described in [5, 6]. The used steering parameters

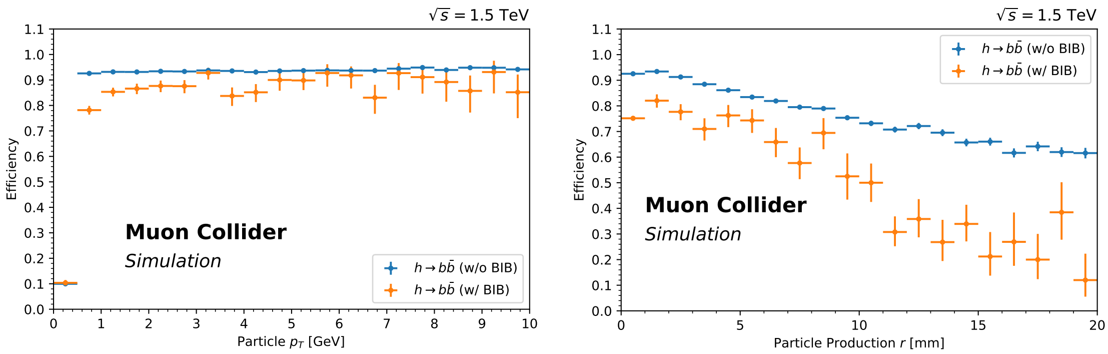

Figure 5: The CKF track reconstruction efficiency for charged particles in events containing a higgs boson decaying to two b-quarks. Left plot shows the efficiency as function of the charged particle transverse momentum and right plot as a function of its particle production radius. Efficiencies with (orange) and without (blue) BIB overlay are shown. More plots are available in [3].

CKF are documented in [3]. An important choice is that only the closest hit is included at each layer (meaning that there is no splitting) to allow for short processing time. The track reconstruction takes $\approx$ 4 min/event with no additional hit filtering past timing cuts.

The CKF was implemented inside the *MuonColliderSoft* framework using the A Common Tracking Software (ACTS) library [7]. The ACTS library is an experiment-independent implementation of common tracking algorithms. A large amount of work has gone into optimizing the performance of their code, giving performance boosts past the algorithm choices. For example, the ACTS implementation of the Kalman Filter performs almost two orders of magnitude faster than the original *MuonColliderSoft* implementation. ACTS is also a playground for next-generation tracking algorithms and acceleration platforms, helping to make the track reconstruction "future-proof".

The track reconstruction efficiency for events containing a higgs boson decaying to two b-quarks is shown in figure 5. A charged particle is considered reconstructed if more than a half of any track's hits can be truth-matched to it. Over 90% of charged particles with $p_T > 1$GeV are reconstructed. The inefficiency is due to charged particles produced at a radius greater than 5 cm. The efficiency drops by a few percent in the presence of a BIB overlay. Improvements are possible with an optimization of the CKF steering parameters. Single-muon events are reconstructed with an efficiency greater than 95% for $p_T > 1$ GeV.

The raw output of CKF algorithm also contains a $\approx$ 100k ghost tracks per event when applied in the presence of Beam Induced Background. Ghost tracks are reconstructed tracks where the majority of the hits is not truth-matched to a single charged particle. The ghost tracks can be reduced to less than one per event using the hits per track and keeping only tracks with $p_T > 1$ GeV. The selection is still missing a few handles (ie: reduced χ^2) and can be optimized further.

4. A Word on the Needed R&D

None of the current, operational or prototype, tracking detectors satisfy the requirements presented here. There is no complete system with a fine pixel size and precision ToA information. Significant research and development would be required to build the detector proposed here. How-

Technology	**Pitch** [μm^2]	**Rad Hard** [n − eq/cm^2]	**Timing Res [ps]**
AC/TI/DC LGAD	$\approx 100 \times 100$	2.5×10^{15}	20-30
3D (TIMESPOT)	55×55	2.5×10^{16}	10
Planar (TimePix4)	55×55	-	50
Planar (NA62)	300×300	1.3×10^{14}	130

Table 2: State of the art sensor technologies presented at the VERTEX2023 conference.

ever the requirements are not too different from other proposed future facilities [8]. The proposed FCC-hh collider, a facility alternative to the Muon Collider, will require a 4D tracker with similar specifications. As will the planned upgrade of the VErtex LOcator at the LHCb experiment. The main difference being that the Muon Collider will experience a radiation environment orders of magnitude smaller, making the development an "easier" challenge.

The needed R&D path is independent of what the next-generation flagship energy frontier facility will be. A lot of progress already exists on 4D trackers for collider experiments. Table 2 shows the current state of the art sensor technologies presented at this conference. Ignoring the (not simple!) challenges of mechanics, integration and readout, some sensor technologies come close. The 3D pixels from the TIMESPOT collaboration could already be used for the Vertex Detector, even if the pixel size is still twice what would be needed in the Muon Collider. However their their current cost makes them not be practical for the large area of the Inner and Outer Trackers. This is where cheaper LGAD sensors could be employed. The LGAD sensors are radiation hard enough for this region of the detector and are mainly limited by their large pixel size, which is less of a problem in the IT/OT. Exploring "strip" LGAD sensors with a fine pitch along one axis is an uncovered R&D path.

5. Conclusion

The Muon Collider can shed the light on form of the higgs boson and search for Beyond the Standard Model physics in the same next-generation facility. Recently there has been progress on understanding the impact that detector resolutions will have on the key measurements. A detector concept has been implemented in a simulation and object reconstruction algorithms are being studied. The main challenge is dealing with the Beam Induced Background coming from the decay products of the beam muons. The BIB results in a high occupancy inside the detector system. The Tracking Detector employs a "4D tracker" to reject BIB hits using precision Time of Arrival information. Then a Combinatorial Kalman Filter algorithm can reconstruct charged particles with a reasonable efficiency. Using the experiment-independent ACTS library allows the CKF to run in a computationally efficient manner.

While significant R&D is required to make 4D trackers for collider experiment a reality, this path is shared among many future projects. However the radiation environment at the Muon Collider is much lower than the other projects, making the R&D slightly easier and the necessary technology progress within reach.

PoS(VERTEX2023)039

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