Simulation of the MoEDAL-MAPP experiment at the LHC

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Abstract. The MoEDAL (the monopole and exotics detector at the LHC) experiment is located at the interaction point 8 (IP8) of the large hadron collider (LHC). It is an experiment that is dedicated to searches for exotic particles, such as magnetic monopoles and dyons. The experiment is being upgraded with scintillator detectors called as the MAPP (MoEDAL apparatus for penetrating particles). They will extend the physics reach of the experiment by providing sensitivity to millicharged and long-lived exotic particles. The MAPP detectors are planned to be installed, or are already installed in various adjacent tunnels at about 50 to 100 meters from the IP8. To study the physics reach and to support the data analysis of the detectors, we developed a detailed simulation model with Geant4. The model consists of all tunnels, accelerator components between the detectors and the IP8, and of about 100 meters thick ground layer above the tunnels for cosmic ray background studies. In addition to geometry, new physics models that describe the interactions of exotic particles, such as millicharged particles, are implemented into the model.

1 Introduction

The MoEDAL (monopole and exotics detector at the LHC) [1] experiment is dedicated to searches for magnetic monopoles [2] and other exotic particles that would indicate new physics beyond the standard model. The main physics goals of the MoEDAL experiment are complimentary to the other large hadron collider (LHC) general-purpose detectors, such as ATLAS and CMS, since their sensitivity is limited in searches for highly ionizing particles and magnetic monopoles [3].

The MoEDAL detector consists largely of passive sub-detectors. It is deployed at the interaction point 8 (IP8) on the LHC ring, and shares an experimental cavern with the LHCb experiment. The innovative MoEDAL detector consists of three detector subsystems: nuclear track detectors (NTD), magnetic monopole trappers (MMT), and Timepix (TPX) detectors monitoring the beam-related background around the IP.

For Run 3 of the LHC, the MoEDAL experiment was upgraded to MoEDAL-MAPP [4], with MAPP (MoEDAL apparatus for penetrating particles) extension allowing to increase the physics reach to regions of millicharged (mCP) and long-lived exotic particles (LLP). The MAPP detectors are not located at the IP, but in the adjacent tunnels of the LHC accelerator. For the first stage, only a mCP detector subsystem is installed in a service tunnel called underground area 83 (UA83) at about 100 meters from the collision point. This setup is planned to be extended with an array of Outrigger detectors.

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The MoEDAL-experiment is simulated with the LHCb simulation application Gauss [5]. It has the detailed descriptions of the LHCb detectors and its surroundings. In addition we have provided the descriptions of all detector components of the MoEDAL-experiment to the application. For MoEDAL simulations, only the parts of the LHCb experiment that have impact on the MoEDAL sensitivity are used. The simulation model is a combination of external libraries, such as Pythia [6] and Geant4 [7] for event generation and particle transport, and utilizes the functionalities of ROOT for data processing and ntuple construction. Schematic view of the elements of this model is shown in Fig. 1.

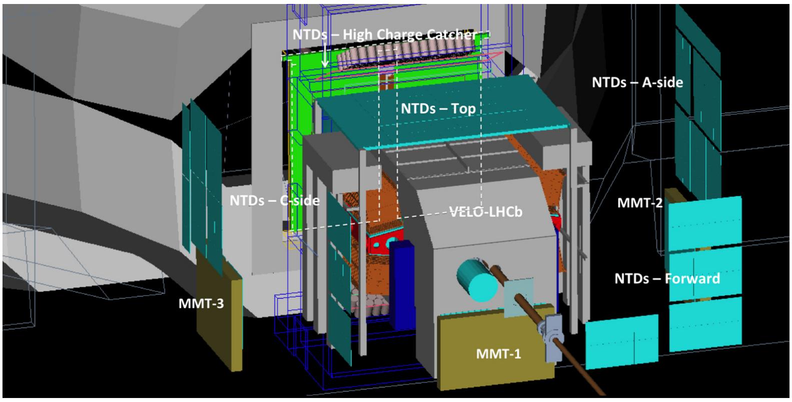

Figure 1. Geant4 model of the MoEDAL experiment within the Gauss application.

However, the simulation arena of the Gauss application is focused around LHCb experiment and is intended to be used only in this location. Thus we use it only in the MoEDAL simulations [8]. In the model, some of the machine components are also included, but materials, such as the outer walls of the caverns are not. To study the detector performance and machine background at MAPP locations, we developed a new simulation model, SUMMA (simulation of the UA83, MoEDAL, MAPP arena) which is built mainly on Geant4 classes to best support transferability between different platforms and systems. The model consists of all tunnel elements, LHC machine components, detector descriptions of the MoEDAL-MAPP detectors, new physics models for LLP and mCP studies, and the material budget for all ground material between the IP and the detectors. In addition a geometry description for the rock overburden can be used with the model. The model is designed to be used as a standalone simulation tool, but allows input from particle generators and Gauss software. In this contribution we will present the SUMMA simulation model and discuss its properties in supporting new physics searches with MoEDAL-MAPP detectors.

2 Simulation of the UA83, MoEDAL, MAPP Arena

SUMMA simulation model was developed to allow studies around the full MoEDAL-MAPP region. The tool is built on standard Geant4 classes to maximally support portability and to limit the dependencies on external packages which might have different versions depending on the platform. The elements of the simulations are written by using Geant4 version 11.1.0 and above. This allows to use more recent features of Geant4 and introduces the support to C++11. However, the selection removes the backwards compatibility of the code with older versions of Geant4. In addition to the requirements for the Geant4 installation, only Xerces-C++ [10] package is needed to run the models. Some external packages, such as Pythia8 and ROOT [9] are needed to produce more detailed primary distributions and to analyse the ntuples.

The full model consists of detailed geometries of the detectors and their surroundings, various particle generators, and new physics models. It is divided in three main parts; the Geant4 based classes, the GDML model tree describing the geometry, and the generators which allow complex inputs for the Geant4 simulations. The structure of the simulation model is shown in Fig. 2.

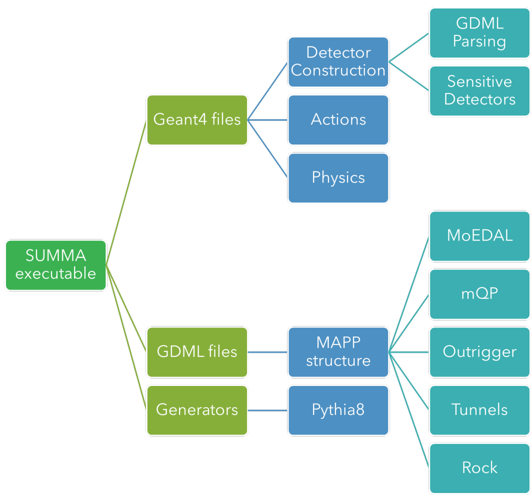

Figure 2. Structure of the SUMMA simulation model.

2.1 Geometry

The SUMMA model is based on combined information from CERN excavations, CAD models of the detector elements, and of various blueprints of the tunnels and accelerator components. It covers an area that corresponds to about 14 000 square meters. The information of different sources is combined to a single CAD model to correctly set the coordinate system and the positions of each element. This model is then exported to STP format from which each element is extracted and stored as individual ASCII stereolithography format (STL) files. The files preserve the material information and their placement in the full model. To pass the geometry to Geant4 `DetectorConstruction`, the files are then converted into geometry description markup language (GDML) geometry description format [11]. The conversion from STL to GDML is done with cad to Geant4 converter [12]. The final geometry is split into sub-branches either by their physical location in the LHC tunnel, or by the detector subsystem.

The selected structures allow modifications to individual elements without the need for rebuilding everything. New additions can be introduced to CAD model by modifying an individual region, and by converting only the new elements into GDML format. The sub-elements follow the naming schema of the LHC tunnel as shown in Fig. 3. After the elements are read into Geant4 through the `G4gdml` parser, the underlying elements are stripped of from their sub-classes and placed under mother volume to remove the overlaps.

The material budget between the IP and the mCP detector is simplified assuming all pipes to aluminium, magnets to iron, and all support structures to stainless steel, soil to a selected

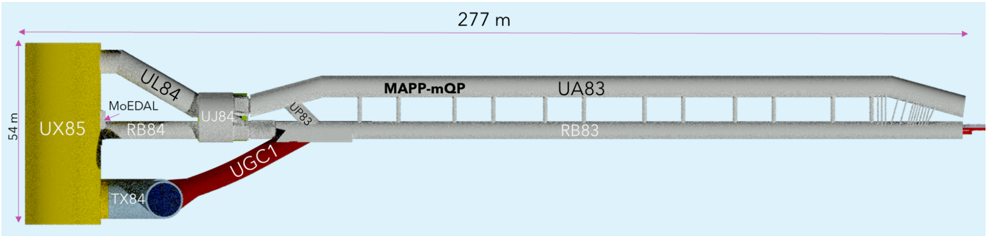

Figure 3. Different regions of the MoEDAL-MAPP arena. The MAPP mCP detector is defined as an individual sub-structure inside UA83 sub-structure.

composition of Molasses, and tunnel walls to concrete. In total there is about 47 meters of material budget composing from 20 different elements between the IP and the mCP detector. In addition an 104 meter thick overburden layer consisting of Molasses is included in the model. This layer can be switched off when it is not needed.

2.2 Detector descriptions

In the Geant4 part, the detector descriptions are generated from the GDML models. In the `DetectorConstruction`, the descriptions are placed in arrays and initialized as sensitive elements. Each element in the full model can be set sensitive. This allows to study for instance rare decays within the rock layers.

The sensitive detector classes control the scoring and filling of the ntuples. The requirement for a hit to be registered is to have energy deposited in the detector volume. In scintillators this would lead into production of secondary light yield, but this is suppressed in the base model. The optical properties of the scintillators are set only in the model extensions.

2.3 Particle generators

By utilizing the standard Geant4 models, loops over single and multiple particle types can be generated. This allows generation of pencil beams, or more complex distributions. In addition the input can be read through Geant4 General Particle Source (GPS), which allows more complex distributions.

However, Geant4 cannot properly simulate decays of exotic particles at the IP, or beam-beam interactions. The GPS distributions have limitations in size and number of bins, and thus more complex input requires different approach. In the SUMMA model, the input from external simulation tools such as Pythia8 is made by using Geant4 HEPEvt parser. The `PrimaryGeneratorAction` can read in a text file containing the information of Pythia8 output by using MUTEX for parallel reading. The input file contains information of the particle through its PDG code, its position in the decay list, xyz-components of its momentum, and its mass. In addition the file lists the number of particles in an event.

Pythia8 will generate particles in all directions around the IP. For MoEDAL-MAPP the interesting particles are the ones that will reach the sensitive detectors. Thus, the primary particle generator is limited to areas which have possibility to reach the sensitive detectors. This is done with simple interpolation between the IP and the detector elements. After the sensitive detectors are selected, the software calculates a target area. If the momentum vector of a particle points to this area, they are tracked. If the momentum vector would move the particle outside the cone, the tracking is killed. The resulting beam profile is a cone where the particles must traverse in order to be simulated. Fig. 6 shows an example of this type of cuts where the primary beam is limited to area around the sensitive detectors.

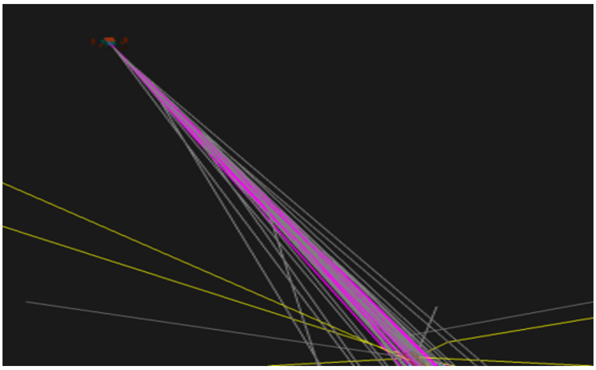

Figure 4. Beam cone consisting of Pythia8 generated soft QCD particles from IP towards the MAPP detectors. In the image, kaons are red, muons and pions are pink, protons and neutrons are gray, and electrons are yellow. In the far distance, the elements of the MoEDAL detector around the IP8 can be seen.

2.4 Physics models

Geant4 includes various physics models for hadronic and electromagnetic interactions. However, new physics models introducing beyond the standard model particles are not fully valid or require modifications. For example, millicharged particles needs to be introduced manually into Geant4.

Millicharged particles (mCPs) are hypothetical free particles with electric charges below the elementary charge. They are predicted by various models beyond the Standard Model. They could be detected through kinetic mixing of the particles with standard photons with the main loss mechanism at the LHC energies being through ionization and excitation.

For the simulation model, the interaction of mCPs is based on modified muon models. The production mechanisms are simulated outside Geant4 with external event generators, such as MadGraph [13], Pythia8 and EPOS-LHC [14] which provide also the kinematics for the particles. This information is pushed to the `ParticleGenerator` at the IP and simulated through the full geometry to the sensitive detectors. To be detected as a millicharged particle, the particle needs to leave a signature that deviates from other charged particles. This can be seen in Fig. 5 where millicharged particle with charge of 0.01 e and mass of 100 MeV traverses the scintillator bars of the MAPP detector at energy of 100 GeV. The simulations consist of a millicharged particle together with muon and kaon background. The millicharged particle leaves only a small trace in the middle of the detector while the other particles produce showers of secondaries.

2.5 Beam background

To understand the detection probabilities, a large number of background event simulations is needed. There will be yield of charged particles which are produced in the proton-proton collisions at the IP, such as $\mu^{\pm}$,$\pi^{\pm}$ and $K^{\pm}$. In addition, high energy muons and showers

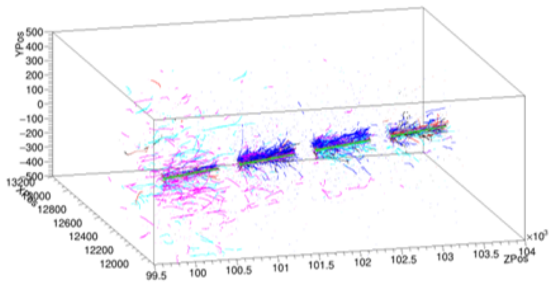

Figure 5. Simulation of millicharged particle and beam background at the MAPP detector. The millicharged particles are shown with a green line, the secondary electrons with blue, and other charged particles with cyan and pink lines.

of secondary particles can be expected from cosmic rays that are interacting with the rock overburden.

Similarly to millicharged particles, proton-proton interactions are simulated with external generators, which allow to select for instance hard or soft-QCD model for the interaction, and produces desired output file in `HepEvt` format. This file is introduced as an input for the `PrimaryGeneratorAction`. An example simulation of 10^7 proton-proton collisions with soft-QCD events at center-of-mass energy of 14 TeV is shown in Fig. 6. The proton-proton collisions produce about 10^9 secondary particles, from which only about 1000 reach the detector.

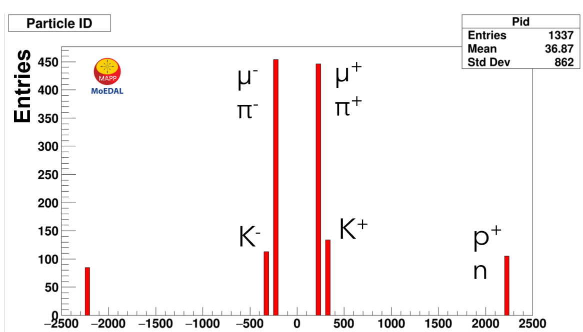

Figure 6. Beam cone consisting of Pythia8 generated soft QCD particles from IP towards the MAPP detectors.

3 Summary

We have developed a detailed model to study the performance and physics reach of MoEDAL-MAPP detectors. The model includes detailed descriptions of the geometry and material budget in the accelerator tunnels between the Interaction Point 8 of the LHC and the detector locations. As an example of the new physics models we have implemented in the tool we presented the millicharged particle simulations.

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