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The Compact Muon Solenoid Experiment

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The CMS nominal FLUKA Model; version 1.0.0.0

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Abstract

For a physics experiment such as CMS the understanding of the radiation environment is of great interest. It is necessary for the evaluation of the detector performance, effectiveness of shielding or to assess radiation damage. Monte Carlo simulations have been performed for CMS with various simulation tools. FLUKA is one of these tools used to understand the particle rates inside CMS and in the whole experimental cavern. It is not realistic to implement every detail of the actual detector in a FLUKA geometry. However, there is the need to have a geometry which reflects the layout of the real detector by using the correct material composition and the correct mass. The work presented here builds on an existing FLUKA model describing the CMS geometry. It includes modifications of the Preshower detector, CASTOR, the pixel detector and BCM2. TOTEM T1 and T2 were also implemented. Between 2010 and 2011 the LHC ran with a beam energy of 3.5 TeV, while during 2012 a 4.0 TeV beam energy was used. For this reason simulations using 3.5 TeV and 4.0 TeV as proton energy have been performed and will be presented as an example application of this geometry.

1 Introduction

For a physics experiment such as CMS [1], the understanding of the radiation environment is of great interest. It is necessary for the evaluation of the detector performance, effectiveness of shielding or to assess radiation damage. Monte Carlo simulations have been done for CMS with various simulation tools. FLUKA [2, 3] is one of these tools to understand the particle rates inside CMS and in the whole experimental cavern.

It is not realistic to implement every detail of the actual detector in a FLUKA geometry. However, there is the need to have a geometry which reflects the layout of the real detector by using the correct material composition and the correct mass. A FLUKA model describing the CMS geometry in a simplified way was first developed by Mika Huhtinen [4]. In 1996, all geometry models, for the various codes (FLUKA, MARS and GCALOR) which are used to perform radiation transport simulations at CMS, were synchronized. During work on the CMS subsystem technical design reports (1997-1998), all the main features of subdetector projects were introduced to this model, and in 2000-2003, details of the CMS forward shielding design were implemented. Since then, several people made custom changes to study particular problems. The latest publication of results prior to the updates described in this note is by Steffen Müller [5]. The work presented here describes developments of this geometry model. It includes modifications to the Preshower detector, CASTOR, the pixel detector and BCM2. TOTEM T1 and T2 were also implemented.

Between 2010 and 2011 the LHC ran with a beam energy of 3.5 TeV, while during 2012 a 4.0 TeV beam energy was used. For this reason simulations using 3.5 TeV and 4.0 TeV as proton energy have been performed and will be presented as an example application of this geometry.

2 FLUKA Geometry

Since the last publication of data, several details of the geometry have been changed. These parts are described in this section together with a general overview of the features of the CMS geometry. It should be noted that the CMS FLUKA model refers to a collection of settings used in simulations, which include the CMS geometry. The 'geometry' or 'geometry model' refers specifically to the definition of regions and materials that are assigned to them.

2.1 CMS Geometry

In order to understand the particle rates inside the CMS detector and in the whole experimental cavern, simulations with the complete detector must be performed. The CMS FLUKA geometry was originally set up by M. Huhtinen [4] and refined by various authors. The previous publication of simulation data with an updated geometry was done by S. Müller in 2011 [5]. For a coarse understanding a fine detailed geometry is not necessary as long as the mass and the material composition is correct. Hence an average material composition is used for many parts of the detector. To reduce the necessary running time to obtain results with small statistical error the geometry is symmetric in Z and in ϕ with certain exceptions. The Z-symmetry is implemented by using the FLUKA lattice option. Only the positive end of the cavern is modeled and the negative end is automatically included in the simulation as a 180° rotation around the y-axis.

Various parts of the geometry have been updated recently. Figure 1 shows a 3D picture of CMS and the cavern as implemented. To facilitate elements only present on one end of CMS, certain parts of the lattice region can be excluded and the volume filled with a dedicated geometry element. In this version of the CMS geometry, the region describing the CASTOR detector and

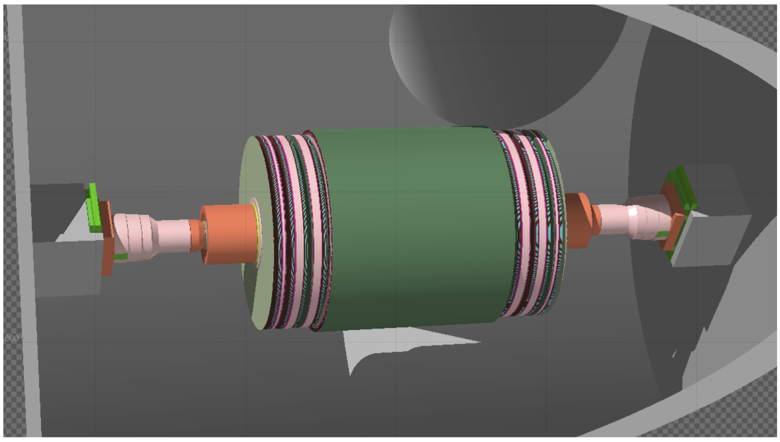


Figure 1: 3D representation of the CMS geometry v.1.0.0.0. While most of the geometry is symmetric in ϕ, the blockhouse is an exception to this. The cavern was enlarged for this picture to allow for a better view.

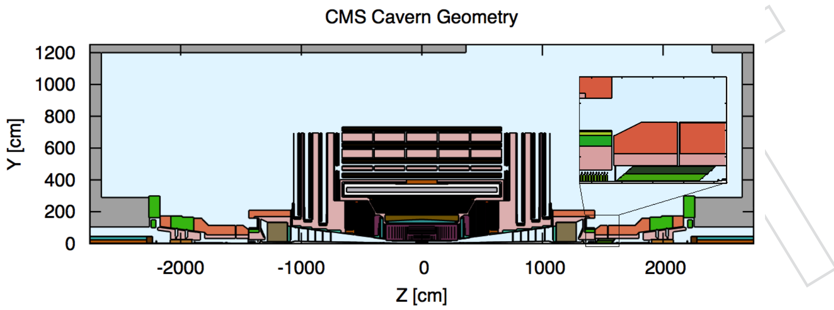


Figure 2: Geometry of CMS detector v.1.0.0.0., including a zoom in to the forward region.

the shaft, which are both only present on one end of the detector, are excluded from this lattice, as shown in Fig. 2. The modifications for this version of the geometry are described in the following paragraphs:

The pixel detector: The mechanical design and material budget of the CMS barrel pixel and forward pixel detectors can be found in the papers [6]. In accordance with [6], the FLUKA pixel detector model was subdivided into logical parts: the central barrel detector, the inner and outer shielding, the end flange, power and signal cables, the supply tube, supply box, the forward pixel detector and service cylinder. A schematic geometry of the CMS pixel detector for FLUKA simulation is shown in Fig. 3. The central barrel detector consists of three layers at the mean radii of 4.4, 7.7 and 10.2 cm, respectively, with a length of 53 cm. The central barrel region is defined by inner and outer shielding at radii of 3.7 and 18.6 cm extending over the full barrel length of 57 cm. The signal and power cables run parallel to the modules along the z-direction. They are fed through the spacing in the end-flange and then radially distributed until they are connected to the printed circuit boards (PCBs). The barrel pixel detector is completed by two forward pixel disks on each side from IP5, located along the beam axis at Z = 34.5 cm and Z = 46.5 cm, and extending from R = 5.87 cm to 14.5 cm. The total mass of the pixel detector consists of about 66.4 kg. The chemical compositions of all used materials correspond to the mechanical design and material budget [6].

Preshower: The preshower detector is installed in front of the endcap electromagnetic calorimeters. Its purpose is to improve the shower position measurements. It consists of two detection layers; a lead absorber followed by a silicon sensor. A cooling screen consisting of aluminum

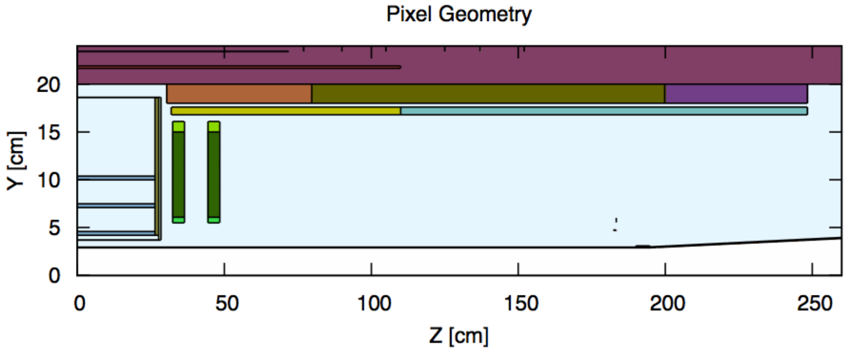


Figure 3: The CMS pixel detector in CMS FLUKA geometry v.1.0.0.0.

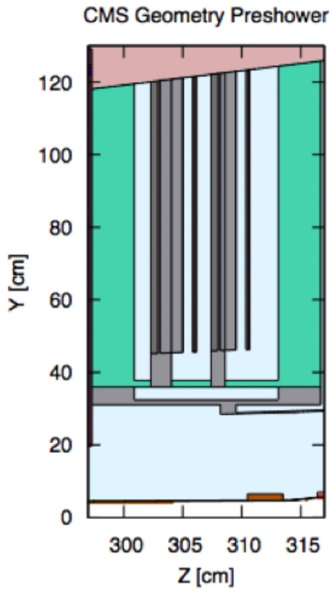


Figure 4: CMS preshower detector in CMS FLUKA geometry v.1.0.0.0.

tubes filled with cooling water is attached to the lead layer. In front and behind the two detection layers is a 3.6 cm thick layer of polyethylene. The previous model of the Preshower detector was based on drawings from an early design stage. An update to fit the actual installed version was performed for the purpose of a detailed study of the radiation environment at the Preshower detector position [7]. A picture of the geometry can be found in Fig. 4. The FLUKA model consists of layers of material confined in R by two cones with η of 1.653 and 2.6. The cooling screen is modelled with an average material with a density of 2.93 g/cm^3, consisting of 70 % aluminum and 30 % C_6F_{14} cooling liquid. The support structures made out of aluminum under the detection layers are also implemented.

BCM2: A layer of aluminum was included in front and behind the BCM2 diamond detectors at Z = 14.39 m to represent the support structure. This modification has a rather low influence on the overall CMS simulation, however for specific interest, a more detailed BCM2 region was implemented to gain more realistic results at lower energies. The aluminum layers range from 3 to 33 cm and are 1 mm thick facing the interaction point and 2 mm behind the diamonds.

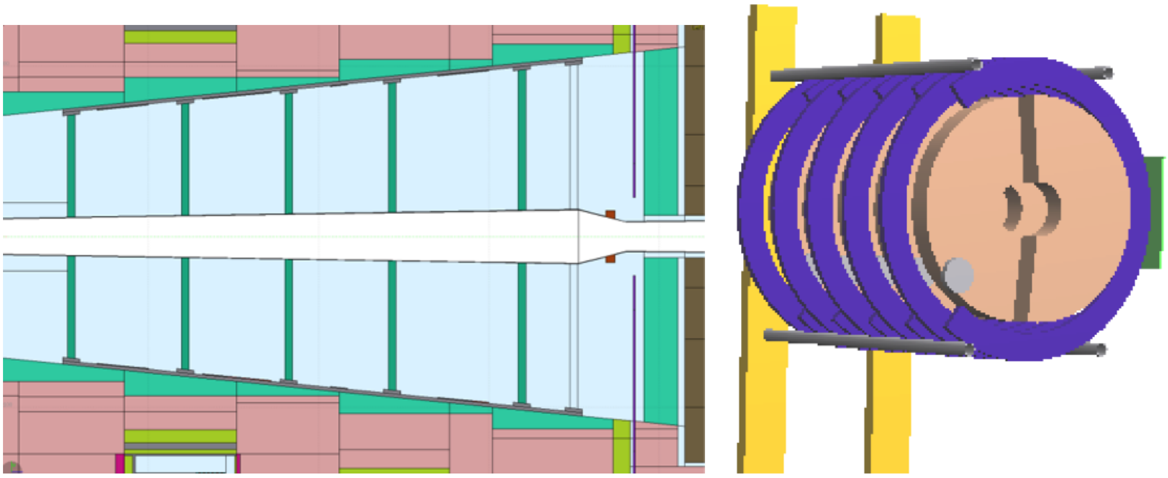
TOTEM T1 and T2 inelastic telescopes: TOTEM is an independent LHC experiment located at the same interaction point as CMS. It was not previously implemented in any version of the FLUKA geometry before. Instead the region was filled only with air. The TOTEM geometry was introduced to the CMS geometry as described in section 2.2.

CASTOR: The region of the CASTOR detector [8] was updated to better represent the outer shape of the detector, and surrounding material was included. The lattice exclusion to implement CASTOR only on one end was implemented. Details of the update are described in section 2.3.

2.2 TOTEM Geometry

The TOTEM Experiment [9] is dedicated to the measurement of the total pp (proton-proton) cross section with a luminosity independent method, and the study of elastic scattering and diffractive processes at the LHC in combination with the CMS experiment. To achieve an optimum forward coverage for charged particles inelastically produced by the pp collisions in IP5, two tracking telescopes T1 and T2, are installed on both sides of IP5 in the pseudo-rapidity region $3.1 \leq \eta \leq 6.5$. T1 and T2 are complemented by detector stations installed in special movable beam-pipe insertions (so-called 'Roman Pots') placed in the LHC tunnel and designed to detect leading protons [10]. TOTEM is therefore an independent experiment but, for about 2/3 of its size, technically integrated into CMS. The telescope closest to the interaction point (T1, centered at Z = 9 m) consists of Cathode Strip Chambers CSC, while the second one (T2, centered at Z = 13.5 m) exploits Gas Electron Multipliers GEM [11].

The two arms of the T1 telescope, one on either side of the IP5, fit in the space between two conical surfaces, the beam pipe and the inner envelope of the flux return yoke of the CMS end-cap. The T1 telescopes are the last to be inserted when closing and the first to be removed when opening the CMS detector. Each telescope consists of five planes of CSCs, equally spaced along the z axis. In reality a detector plane is composed of six CSC wire chambers covering a region of approximately 60° in ϕ; however, in this FLUKA model, the T1 CSC wire chambers are considered to be ϕ-symmetric. The chambers are composite structures, sandwich panels of standard glass-epoxy laminate (G10) with a core of honeycomb and are flushed with a gas mixture Ar/CO2 (50/50). In the FLUKA model, an average material combining the previous three constituents in the proportion 20/60/20%-weight respectively, for a total mass of 25 kg, represents the CSC chamber. Each of the five detector planes (half telescope), plus a sixth frame (layer visible in Fig. 5a) which supports patch panels for the connectivity of the services, are fixed separately to conical aluminum rails. The rails, which serve as mechanical support structure, have a total weight of 200 kg. In the FLUKA model, the support structure is modeled by a thin ϕ-symmetric conical surface of equivalent mass. Finally, in the peripheral region between the CSC planes, a series of support plates host the cathode readout electronics. These plates are also included in the FLUKA model as concentric rings of metal and electronic material (Al/Cu/FR4) with a thickness chosen to maintain the total mass equivalent to 30 kg/ring. The T2 telescopes are installed in the forward shielding of CMS between the vacuum chamber and the inner shielding of the HF calorimeter. There is a vacuum pump unit in front of T2 and the CMS CASTOR calorimeter is located behind it (on the negative end of the CMS detector only). In each T2 arm, 20 semi-circular GEM planes, with overlapping regions, are interleaved on both sides of the beam pipe to form 10 detector planes of full azimuthal coverage. The GEMs are mounted as pairs with a back-to-back configuration. For the purpose of maintaining a simple FLUKA geometry, the paired chambers are modeled as a unique one with double thickness as shown in Fig. 5b. The material budget of T2, minimized by using low-Z construction materials and honeycomb structures in the manufacturing the mechanical support, has been finely reproduced in the FLUKA model. The material definition of the GEM chambers takes into account the real detector structure: three GEM amplification stages realized by three perforated and Cu-clad polyimide foils ($1.6\,\%_{\mathrm{w}}$) supported by honeycomb plates ($42.3\,\%_{\mathrm{w}}$). The GEM foils are



(a) Telescope T1 (longitudinal view) (b) Telescope T2 (3D view)

Figure 5: TOTEM forward telescopes implemented in the CMS FLUKA geometry v.1.0.0.0.

then separated by a 3 mm drift space followed by two 2 mm deep charge transfer regions and a 2 mm charge induction space as shown in detail in [9]. These drift spaces are flushed with a gas mixture Ar/CO2 (70/30) that constitutes the remnant part of the material budget (56.1 $\%_W$). The front-end electronics of the GEM detector is mounted at the periphery of the chamber, on a concentrical printed circuit board named ”horseshoe card” after its geometrical shape. Since the cooling lines and the readout board are also located in the same spatial region, an equivalent region made of different materials has been defined in FLUKA. The ”horseshoe cards” of the 10 detectors from one T2 telescope half arm are connected to the so-called ”11th card” which provides the interface to the outside world and is also present in the simulated FLUKA model. Finally, the FLUKA geometry of T2 also includes the detector support structures, two massive bars and four small cylindrical tubes, made of stainless steel, as shown in Fig. 5b.

2.3 The CASTOR Detector

The CASTOR calorimeter [8] is located behind the hadronic forward calorimeter of CMS and the T2 tracking station of TOTEM. In the old model CASTOR was a simple tungsten cylinder. In order to be only present on one end in the FLUKA model, a user routine modifies the material composition according to whether the particle is within the normal (positive) region or the (negative) lattice region.

In the release of the FLUKA model described here, the calorimeter is implemented with two concentric cylindrical layers which are cut with an angle of about 45° along the Z-axis in order to reproduce the shape of the high-Z material sampling plates:

- The inner cylinder has a radius from 4 cm to 18 cm and represents the active volume of the detector. It is composed of an average material made of 95.2 % tungsten and 4.8 % quartz. An equivalent material with the density of 12.88 g/cm^3 has been used to describe the total mass of the active volume which is about 1682 kg.
- The outer cylinder reaches the ultimate radius of 31.8 cm and represents the external stainless steel support skeleton weighing about 300 kg.

The CASTOR volume has been removed from the lattice definition, and a real region on the negative end included. In the normal CMS definition of positive and negative ends, CASTOR, as well as the shaft, is located on the negative or ”minus” end of the CMS detector. In this geometry release, CASTOR is located only at positive Z values since the shaft is likewise implemented on this end. The corresponding detector volume at negative Z is instead replaced by air.

2.4 Magnetic field

The map used as an input for these FLUKA simulations is extracted from CMSSW and based on the latest version of the magnetic field (CMSSW version 5.01). The versions of the magnetic field used for all previous runs were based only on simulations, and the newer version of the field incorporates findings from cosmic ray data. The newer model is more realistic, especially in the forward regions. The field definition is, like the geometry, symmetric in ϕ and ranges in Z from 0 to 1600 cm and in R from 0 to 900 cm. The bin size is 2.5 cm.

3 Example Runs with 2011 and 2012 conditions

The CMS FLUKA model can be used for many types of analysis. As an example, a run with various multi-purpose scorings was performed. The conditions for these simulation were chosen to be the typical LHC and CMS configurations for 2011 and 2012. For 2011, a beam energy of 3.5 TeV and a geometry model with the CASTOR detector installed was used. For 2012, a beam energy of 4.0 TeV and a geometry model without CASTOR (volume set to to air) was used since CASTOR was removed during the shutdown period. The 2011 simulation results are obtained by averaging 15,000 simulated proton-proton collisions, and the 2012 results averaging over 10,500 simulated collisions.

3.1 FLUKA Settings

Used cards

- The set of defaults was applied by using the option PRECISION in the DEFAULTS card.
- Primary proton-proton events are generated by the SPECSOUR card which invokes DPMJET-III [12].

Cutoffs

The cutoffs have not been modified with the geometry. They are as defined in [5].

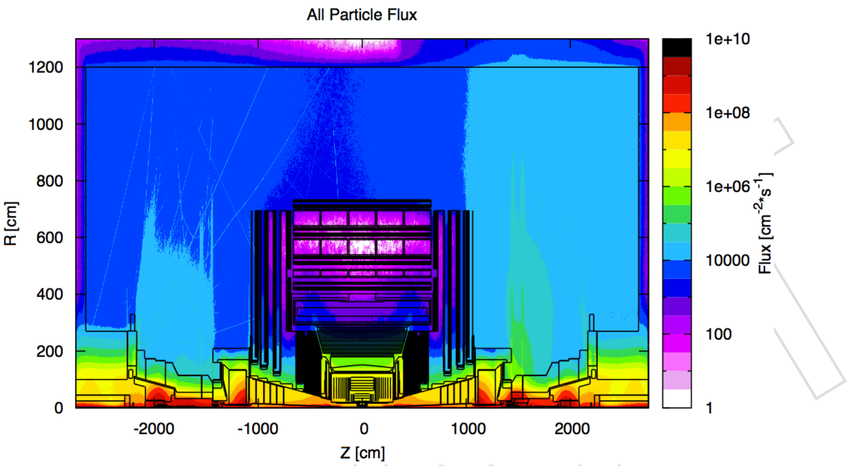
- The cutoff for neutrons is 0.01 meV. This is the lowest energy handled by the low energy neutron library.
- The cutoff for charged hadrons is 1 keV.
- The cutoff for electrons is mostly 30 keV and for photons mostly 3 keV. In some regions with high density material it is higher to avoid too high CPU load.

3.2 Scorings

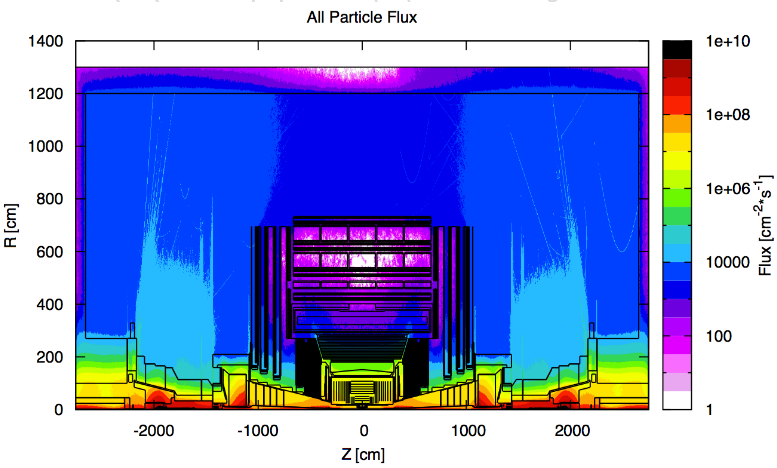
A scoring is a FLUKA option that determines the output format. The main scoring used is a USRBIN scoring, with cylindrical coordinates over the whole cavern and a 2 cm resolution in Z and in R. There is only one bin in ϕ. A splitting over the ϕ angle is not necessary since the geometry is symmetrical. The particle types and groups scored are: All particles, all charged particles, neutral hadrons, charged hadrons, charged hadrons with $E > 20$ MeV, neutrons, neutrons with $E > 20$ MeV, protons, photons, electrons, charged pions, dose, non ionizing energy loss, 1 MeV neutron equivalent in silicon, number of inelastic interactions.

3.3 Results

The R/Z plot over the whole cavern for the all particle flux, normalised per cm^2 per second at nominal luminosity (10^{34} cm^{-2} s^{-1}) as shown in Fig. 6. Figure 6a shows the results from the 2011 run, Fig. 6b shows the results from the 2012 run. For the normalisation of both runs to nominal luminosity a inelastic collision cross section of 73.5 mb as measured by the TOTEM collaborations is used [13]. The flux at the negative Z axis (corresponding to the positive end in the CMS axis frame) is almost the same for 2011 and 2012. The increased flux of particles on the positive Z axis (corresponding to the negative end in the CMS axis frame) of the 2011 run is clearly visible. Particles hitting the CASTOR detector, which was only installed in 2011, produce many secondary particles that can leak out of the forward shielding and flood the cavern. All CMS approved plots based on these simulations can be found here:
`https://twiki.cern.ch/twiki/bin/view/CMSPublic/BRILRadiationSimulation`



(a) All Particle Flux, 2011 Situation, CMS FLUKA Study v.1.2.0.0., [14]



(b) All Particle Flux, 2012 situation, CMS FLUKA Study v.1.0.6.0., [14]

Figure 6: Particle Flux per cm^2 per second of all particles for nominal luminosity (10^{34} cm^{-2} s^{-1}) in the 2011 and the 2012 case.

4 Introduction of a Version System for CMS FLUKA Results

Results based on various developments of the CMS FLUKA model originally created by Mika Huhtinen [4] are used throughout the CMS collaboration. However, until recently, a tagging system for these results and their corresponding input files has not been implemented. This makes it difficult to account for potential inconsistencies in values predicted with CMS FLUKA simulations. In addition, the maintenance of the CMS FLUKA input can be inefficient when there is no record of the date and motive for prior updates. The tagging system that is now in place is described in the following paragraphs. Ideally, all CMS FLUKA results should be captioned with a version number. FLUKA input files should be developed, stored and tagged in a GIT repository created by BRIL, and various other details related to the simulation study should be recorded on a shared website.

The BRIL tagging system contains four numerical digits. It is not only the geometry that is tagged, since a result is also influenced by other parameters such as the radiation source, cut-offs, magnetic field, etc. Therefore a change in any simulation parameter leading to a different result invokes a new individual tag number. The recommended use of the tagging system is shown in Fig. 7 and is described below. Due to the nature of developing FLUKA studies, there is some flexibility in the use of the last three digits, however the main requirement is that each study has its own unique tag.

4.1 Description of Digits

First Digit - A Nominal Release Version A change in the first digit reflects a collection of major updates. When all other digits are zero, this is a representation of an actual installed geometry or a 'final planning' model. High statistics, multi-purpose results are produced.

Second Digit - Major Update or Subversion A change in the second digit usually represents a single nominal geometry update. An example would be the addition of a planned upgrade, e.g. a new central beam pipe should be tagged v.1.1.0.0, or a model update of a particular region, e.g. the addition of the cavern floor to the cavern model, or simply a simulation with CASTOR included (v.1.2.0.0). In most cases, therefore, it represents the an up-to-date 'final planning' model to be included in the merge for a new release. However it can also be used to represent a very major geometry modification in a future potential configuration.

Third Digit - Modification Study Version or Minor Update A non-zero number implies a more standard 'speculative' study for a potential future configurations, for example a shielding study. It is also used for activation studies, where there are not necessarily geometry modifications, but many other input settings are altered. It can also be used for a more minor modification to a nominal geometry update which is already tagged with a non-zero 2nd digit.

Fourth Digit - Internal Working Number or Minor Study Modification This was intended to be used for internal working number of unfinished or unconfirmed work. However, officially a non zero number is also used for a minor geometry variation within a speculative study (where the first 3 digits are are non-zero values), e.g. for a shielding study, a change in this digit would reflect a different shielding material or thickness.

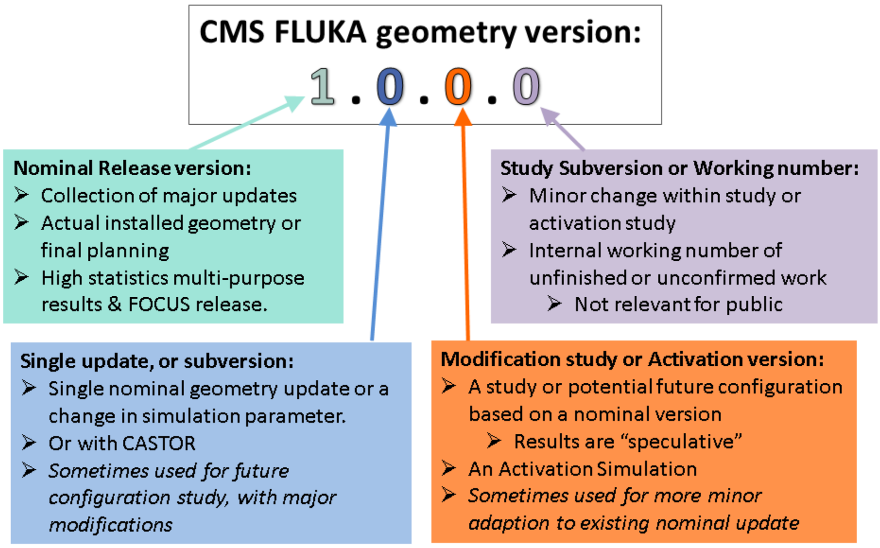


Figure 7: CMS FLUKA Version Scheme

5 Summary

The implementation of the geometry of the CMS detector for FLUKA simulations has been improved by adding missing detector parts, like TOTEM, and modifying the geometry of some parts of the model. Particle flux maps and dose rates with this new geometry have been simulated. Future improvements to the model could include:

- New beam pipe geometry after LS1.
- Adding structure in the cavern like the floor, balconies or HF risers.
- Improvement the geometry of the forward shielding, especially the cracks between the collar and the rotating shielding is not realistic. In addition, the crack between the two halves of the rotating shielding should be implemented.

A Acknowledgements

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