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# CMS: Cosmic muons in simulation and measured data

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A dedicated cosmic muon Monte-Carlo event generator CMSCGEN has been developed for the CMS experiment. The simulation relies on parameterisations of the muon energy and the incidence angle, based on measured and simulated data of the cosmic muon flux. The geometry and material density of the CMS infrastructure underground and surrounding geological layers are also taken into account. The event generator is integrated into the CMS detector simulation chain of the existing software framework. Cosmic muons can be generated on earth's surface as well as for the detector located 90 m underground. Many million cosmic muon events have been generated and compared to measured data, taken with the CMS detector at its nominal magnetic field of 3.8 T.

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## 1. Muon flux parameterisation and normalisation

The cosmic muon generator of the CMS experiment [1] is based on a parameterised differential muon flux obtained by means of the air shower program CORSIKA [3] which in turn has been operated making use of the EPOS interaction model for high energy interactions and the GHEISHA interaction model for low energy hadronic interactions. The CORSIKA simulation results have been fitted with polynomials [4] to describe the differential flux at earth's surface as a function $\frac{d\Phi}{dp\, d\cos\theta\, d\phi}$ of the azimuth angle $\phi$, the incidence angle $\theta$ and the muon momentum $p$. The flux is normalised to vertical muons from measured data with an energy of 100 GeV. The maximally allowed phase space in azimuth angle is $\phi \in [0, 2\pi)$, whereas azimuthal isotropy has been assumed. The phase space for incidence angles is given by $0^\circ < \theta < 84^\circ$. For incidence angles of $\theta > 75^\circ$ the parameterisation is extrapolated. In momentum the phase space is restricted to $3 < p_\mu < 3000$ GeV. The lower limit is driven by the existence of new physical processes which set in at such low momenta which makes the extrapolation invalid. The upper limit of muon momenta is driven by strongly decreased flux in this regime. The muon momentum is approximated by a polynomial of the expression

$$L = \log_{10}(p/\mathrm{GeV}) \tag{1.1}$$

which is slowly varying in muon momentum. The muon momentum spectrum is then fitted by a polynomial of the form

$$s(L) = a_0 + a_1 L + ... + a_6 L^6. \tag{1.2}$$

The momentum dependent zenith angle is taken into account by a polynomial of the cosine of the incident angle

$$z(\cos\theta, L) = b_0(L) + b_1(L)\cos\theta + b_2(L)\cos^2\theta. \tag{1.3}$$

Finally the differential flux is given by

$$\frac{d\Phi}{dp\, d\cos\theta\, d\phi} = C_{\mathrm{norm}} \cdot \frac{1}{p^3} \cdot s(L) \cdot z(\cos\theta, L) \cdot \frac{1}{2\pi}. \tag{1.4}$$

## 2. Muon energy loss in material

A random vertex on a disk at the surface is assigned to a generated single muon. The size of the disk which is centred around the vertical symmetry axis of the detector is determined by the chosen maximal incidence angle such, that a muon whose extrapolated direction does hit the CMS detector does necessarily have a vertex inside the disk. In the case the muon direction is pointing to the CMS detector the muon is propagated through the different material densities of the geological environment between the surface and the CMS detector, located at 90 m underground to obtain an integrated amount of water equivalents. This amount determines the energy loss of a given muon as a parameterised function [5] of the energy of the incident muon at surface. If the direction is not pointing to the CMS detector a new random vertex at the surface is chosen. A material map describes the diverse materials from earth's surface to the CMS detector. In concrete, the fundament of the hall at surface, the three vertical access shafts, a movable plug of the main shaft as well as the collision and service caverns including the adjacent parts of the LHC tunnel are taken into account. Two different average densities are assigned to the geological layers surrounding the

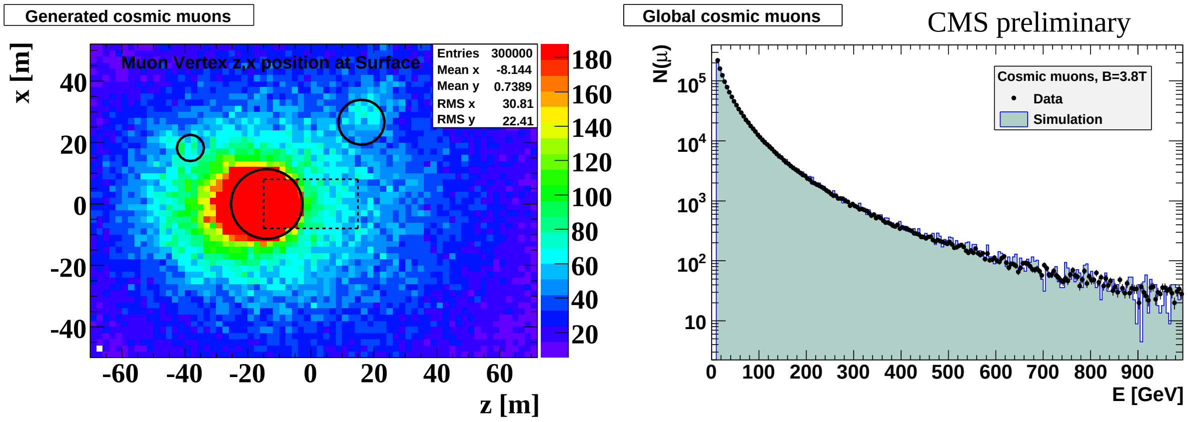

**Figure 1:** Left plot: Entrance vertex at the surface of the generated muons which arrive at the CMS detector (indicated by the dashed rectangle) 90 m underground. The three vertical shafts are indicated by black circles. There is clearly a correlation between muon intensity and shafts visible. Right plot: Energy spectrum of muons in data (black points) measured with the CMS detector. In comparison the GEANT simulation (green/blue histogram) is shown. The simulation has been normalised to the number of events of the data.

CMS infrastructure. The upper half consists of sand, clay, gravels and water while the lower half consists of rock. In Fig. 1 the vertex position of the muons at the surface which reach the CMS detector are shown. Lower energetic muons are responsible for the enhanced intensities at the vertical access shafts. After the generated muons have been propagated to the CMS detector a full GEANT [2] simulation of the detector processes the muons further.

## 3. Simulation and data comparison

In the cosmic data taking period 2008 three hundred million events have been recorded with a solenoid magnetic field of $B = 3.8$ T. Global cosmic muons, which are reconstructed in the muon chambers and the central tracking system are chosen. A mixture of four different triggers is used in the simulation. The momentum of the reconstructed global muons is required to exceed a momentum threshold of $p = 10$ GeV. The incidence angle is restricted to the interval $0 \leq \theta < 60^\circ$ to ensure that the parametrisation is applied far away from its regime of extrapolation. Fig. 1 right plot shows the energy spectrum of the cosmic muon data taken in 2008 in black points. The simulation is superposed as a green/blue shaded histogram and normalised to the number of entries in data. The decrease of the data distribution by the power of -2.7 is very well described by the simulation.

## References

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