Chapter 3

EAS Simulation Techniques

3.1 Introduction

Many quantitative problems in astrophysics are nowadays solved via statistical sampling on a computer. Such Monte Carlo(MC) methods can be used in three different ways:

(1) to generate random objects and processes in order to observe their behavior,

(2) to estimate numerical quantities by repeated sampling, and

(3) to solve complicated optimization problems through randomized algorithms.

This part of the present manuscript describes the importance of Monte Carlo programs used for both estimation and optimization purposes in Astrophysical problems as in the case of cosmic ray air shower simulation programs. A range of established MC programs as well as some of the latest adaptive techniques are also discussed in later part of this chapter.

3.2 Importance of MC programs and high energy interaction models

As mentioned before, direct measurement of primary cosmic rays are not possible above few hundred TeV as its flux decreases with increase in energy, following a power law spectrum. That is why above this energy, ground based detector arrays are used to study various observables of EAS produced by the interaction of primary cosmic ray particles with air nuclei. Few such important observables are cross-section of the interactions (that determines the shower depth), particle multiplicity (that determines the number secondary particles produced), pseudorapidity (that determines the longitudinal momentum of the secondary particles) and transverse momentum (p_T) distribution (which is related to lateral development of the shower). After that, various Monte Carlo simulation programs like MOCCA [87], COSMOS [117], GEANT4 [118, 119], CORSIKA [91, 92] and AIRES [125] containing high energy hadronic interaction models like QCDJET [126], QGSJET [93–95], VENUS [106], NEXUS [127, 128], DPMJET [129–132], SIBYLL [88–90], HDPM [91], EPOS [107] and low energy hadronic interaction models like GHEISHA [105], UrQMD [133, 134] and FLUKA [135, 136], are used to study the hadron production processes in EAS and informations related to them so that the primary particles can be traced back. But computation of hadron production, particularly at low transverse momenta, is not yet possible from first principles within QCD framework. One, therefore, relies on phenomenological models that are appropriately turned to match with the prevailing experimental data. Even a parametrization of such models may be difficult as the accelerator data for the relevant target-projectile combinations covering the whole kinematic region are not available. Experimental data on hadron-hadron interactions in the forward kinematic region at high energies and the data on hadron-nucleus and nucleus-nucleus interactions at all energies covering the whole kinematic range are particularly scarce. One has to resort to theoretical models of particle interactions in such cases. Microscopic models are preferred over the parametrized inclusive models in view of the preservation of correlations such that the basic conservation laws are maintained at every single interaction level. Moreover, such microscopic models have predictive power in the regions in which experimental data are not available.

Hadronic interactions are well described by resonance production and subsequent resonance decay near the particle production threshold; whereas, such particle production scenario becomes too complex at higher ($E_{lab} > 5$GeV) energies. In the latter situation, most of the particles are produced with low transverse momenta and, therefore, along the projectile direction so that a very large number of resonances of very short lifetimes have to be considered to describe particle production that may not be possible in practice. Such a difficulty gives rise to a number of attempts to develop various hadronic interaction models.

Most of the high energy hadronic interaction models are based on parton interactions or Gribov-Regge theory where particle productions are explained using fragmentation of strings with other effects taken into account differently. So the largest uncertainty in the results of air shower simulation comes from the use of different hadronic interaction models which interpret hadronic interactions differently at high energies. Therefore, testing of these high energy interaction models at the highest energies is very important for the understanding of hadronic interactions and interpretation of air shower data. This testing is done by comparing the model predictions with various LHC data.

A brief description of these codes with models and comparison of these model predictions with LHC data is given below.

3.2.1 MOCCA

MOCCA [87] is Monte Carlo simulation program that simulates the cascade generated when a Cosmic Ray particle enters into Earth's atmosphere and detectors. It also uses thinning techniques to make the simulation faster at higher energies up to 10^{20} eV. It can be used to study secondary particles including Cerenkov radiation. Because of its special feature it was used widely in various shower experiments. Some special features of this program is outlined here. The height of the atmosphere is considered to be 100 km at which a cosmic ray particle (nucleus, nucleon, electron or gammas) enters into Earth's atmosphere. The secondary particles are traced down to 50 KeV and they can be traced into the scintillation detectors and absorbers Monte Carlo techniques are directly used for generating particles instead of looking for interaction libraries. The Thinning process is done by following all particles down to a fixed energy E_1 and beyond that only certain particles are followed with a given weight > 1 which is inverse of the probability of the particle with the energy E_2 ($probability = E_1/E_2$) to compensate for this incompleteness. Because of this the accuracy is reduced in the results. An "energy-splitting' basis simple but accurate high energy hadronic interaction model is employed to study high energy hadron interactions. Due to the non-inclusion of low energy nucleon cascading of nucleons, this program is inadequate to study the large flux of slow neutrons. The Nishimura-Kamata analytic treatment for electron-photon cascades becomes inadequate at high energies because of the inclusion of the process which describes production of Pions by photons. The Landau-Pomeranchuk-Midgal effect in air and neutral Pion non-decay at very high energies is also included. This program allows to calculate detector signals along with the complete Monte Carlo Simulation of air showers. It also allows to study parentage of particles arriving at the detector level. The longitudinal and lateral development of the shower can also be studied by this program. Other hadronic interaction models can also be called form this program in order to study hadronic interactions. This program is in Pascal language. The upgraded version of this model is called ARIES [125] which is in FORTRAN language.

3.2.2 COSMOS

The program COSMOS [117] was first written in assembly language. It was changed to Fortran language in late 1970's. Gradually, improvements were made by adding heavy iron and their breaking processes, QCD jet production process, Lund Monte Carlo code Jetset, Fritiof, Nucrin, Hadrin and an improved multiple production model at high energies etc. In 1995, the main version was re-written. In 2001, a new interaction model DPMJET3 [132] was introduced in COSMOS. Also low energy phenomena such as atmospheric neutrino problems taking the muon polarization into account, or very high energy air showers in the GZK cuto region with magnetic bremsstrahlung and pair creation effects or the LPM effects are included into the code. The DPMJET3 [132] model will be discussed later.

3.2.3 GEANT4

GEANT4 [118, 119] is a 3-D detector simulation program written in the C++ language. It is used widely to simulate various types of particle detectors. It can also be used for the simulation of extensive air-shower [120–122]. Its a completely new detector simulation toolkit for which the reader is assumed to have a basic knowledge of object-oriented programming using C++. Although GEANT4 is a fairly complicated software system, only a relatively small part of it needs to be understood in order to begin developing detector simulation and air shower applications.

It is a free software package composed of tools which can be used to accurately simulate the passage of particles through any matter. The aspects of simulation process which have been included in it are given below :

• the geometry of the system, in which the user can define the geometry of the medium in which the particle will pass. It can be the atmosphere, a detector or any other material. User can use Detector Construction class to define and construct all these geometry related things.

• the materials involved, in which the user can define the material through which the particle pass through. It can be the air with its composition, or a detector with materials. The user can select the materials of the medium.

• the fundamental particles of interest, in which the user can select a primary particle which has to pass through the medium.

• the generation of primary events, in which the user can select the no. of primary events, their energy and flux.

• the tracking of particles through materials and electromagnetic fields, in which the user can track a particle up to certain energy and can define the electromagnetic field.

• the physics processes governing particle interactions, in which a user can select different hadronic interaction models and electromagnetic processes.

• the response of sensitive detector components, in which a user can select a particular portion of the detector as sensitive.

• the generation of event data, in which a user can select number events, the type of data to be generated etc.

• the storage of events and tracks, in which the user can select the tracks and data and store them in different formats.

• the visualization of the detector and particle trajectories, in which the user can generate the image of a detector, particles and their trajectories.

• the capture and analysis of simulation data at different levels of detail and refinement which can be done also in GEANT4.

The user may creates its own application based on the GEANT4 framework too. GEANT4 contains lots of different interaction models which can be used to handle the interactions of particles with matter across a wide range of energies. Because of the inclusion of data and expertise from various sources around the globe, GEANT4 can be considered as a scientific repository that incorporates most of the known particle interaction processes. Since it is written in C++ language and has advanced software engineering features, the user can build its own application by choosing different options and implementing it in user action class. Also new interaction models from outside can be added in GEANT4 by the user. Some of the hadronic interaction models, present in GEANT4 are discussed below.

All the hadronic interaction models used in GEANT4 can be classified into the following 3 categories.

3.2.3.1 Data driven models

When sufficient data like cross-section, angular distribution, multiplicity etc are available the data driven approach is the ultimate way to explain hadronic interactions. These models simply interpolate the available data in order to calculate interaction length and final state of a hadronic interaction. Usually linear interpolation of cross-section and Legendre's polynomials are used for these purposes in these models. Examples of interactions in which this data driven approach is used are coherent elastic scattering (pp, np, nn), radioactive decays and neutron decay (E < 20 MeV). The classes G4LEpp and G4LEnp provide data-driven models for coherent elastic scattering over the range 10-1200 MeV. At high and inter mediate energy, an alternative model (The Glauber model [124]) is used for elastic and quasi-elastic hadron-nucleus scattering. Corrections for inelastic screening and the excitation of a discrete level or a state in the continuum for quasi-elastic scattering is considered at high energies. The Binary Cascade model is one such model which is described below.

The Binary Cascade model [123] : The Binary Cascade is a data driven intranuclear cascade model which explains the propagation of primary and secondary particles inside a nucleus. cross-section data are used to select collisions between primary and the nucleus and subsequent interactions. Equation of motions are solved numerically in order to explain the propagation of particles is the nuclear field. A threshold is set beyond which the cascade stops. It is designed for incident energy between 100 MeV to 5 GeV. The modeling sequence is similar to the Bertni cascade model except that

• Nucleus is considered to be consists of nucleons.

• Hadron-nucleon reactions are handled by resonance formations which then decay according to their quantum numbers. Elastic scattering on nucleons are also taken into consideration.

• The secondary particles follow curved trajectories in nuclear potential.

• De-excitation is handled by Pre-compound model [123].

3.2.3.2 Parametrization driven models

The models of these category depends both on data and theory. Large amount of data is used to parametrized cross-sections, multiplicities and angular distributions of hadronic interactions. The final state of every hadronic interaction is determined by theory with data sampling in which conservation laws were used to get charge, energy etc. The interactions which are used by such approach is nuclear fission, nuclear capture etc. In GEANT4 mainly 2 sets of parametrized models are given in order to explain these hadronic interactions.

The low energy models [123] : These models work in the energy range of 1 GeV to 25 GeV.

The high energy models [123] : These models work in the energy range of 25 GeV to 10 TeV.

Both of these type of models are based on GHEISHA package of GEANT3 (a previous version of GEANT4). In these models, the final state of a collision of an incident particle with a nucleon inside the nucleus consists of a recoil nucleon, the scattered incident particle, and possibly many hadronic secondaries. Formation of real particles are approximated by the quark-parton interactions over some time. These newly formed hadrons are able to form intra nuclear cascades inside the nucleus because of their interactions with each other. That is why in these models only the parent hadron-nucleon collision is simulated in detail. The simulation of the intra nuclear cascade is done by by generating additional secondary hadrons from the initial collision. The distribution, multiplicity and their type is determined by theory (functions) which were fitted to experimental data or which reproduce general trends in hadron-nucleus collisions. It is difficult to explain the physical significance of the parameters that are used through out these models to obtain reasonable physical behavior. Because of this the use of these models as generators of hadron-nucleus interaction is restricted. On the other hand these models are fast and precise with significant predictive power. Two such parametrization driven model are given below.

The LEP model [123] : This is a low energy parametrized model derived from GHEISHA . The model is designed to work up to incident energy below 20 GeV.

The HEP model [123] : This is a high energy parametrized model derived from GHEISHA . The model is designed to work up to incident energy above 25 GeV.

3.2.3.3 Theory driven models

These models are based on various theories (QCD, strings, chiral perturbation theory) in order to explain hadronic interactions of different energy ranges. Here experimental data are used for normalization of the result and validation of the model. In these models, the final state of a hadronic interaction is determined sampling of theoretical distributions. Based on energy range, these models can be classified into three categories :

The low energy models ($<$ 5 GeV) [123] : intra-nuclear cascade models at medium to low energies.

The high energy models ($>$ 5 GeV) [123] : diffractive string model, dual parton model, quark gluon string model, parton string models at medium to high energies.

The very low energy models (MeV range) : nuclear evaporation model [123], fission models [123] in MeV ranges.

Few such theory driven models used in GEANT4 are described below.

The CHIPS model [123] : It is a theory driven, quark level, non-perturbative and three-dimensional event generator for the fragmentation of hadronic system into hadrons which is based on the Chiral Invariant Phase Space model [123] that uses a 3D quark-level SU(3) approach. Here only light (u, d, s) quarks are considered which in turn can create other (c, b, t) quarks by the gluon-gluon or photo-gluon fusion. The most important parameter of this model is the critical temperature T_c (≈200 M eV) which defines the number of 3D partons with a fixed energy W. Since the probability of finding a quark with energy E decreases exponentially with increase in temperature, heavier quarks are suppressed. So it can be said that the critical temperature in CHIPS model defines the mass of the hadron. Isgur quark-exchange diagrams are used to explain the hadron-hadron interactions where as the fusion of quark-antiquark or quark-diquark partons treat the decay of excited hadronic systems in vacuum. The CHIPS model may be considered as a generalization of the hadronic phase space distribution since it considers the homogeneous distribution of asymptotically free quark-partons over the invariant phase space, as applied to the fragmentation of various types of excited hadronic systems. It generates angular momentum distributions as well as multiplicity distributions for a given set of hadrons, defined by multi-step energy dissipation process like decay.

It handles a hadronic or nuclear interaction above few hundred MeV by considering the creation of an intermediate state of excited hadronic matter (quasmon) which dissipates energy by radiating particles in vacuum or by quark exchange with surrounding nucleons or clusters of nucleons in addition to the vacuum quark fusion mechanism inside a material. It can be applied to to nucleon excitations, hadronic systems produced in e^+e^- and $p\bar{p}$ annihilation, and high energy nuclear excitations. Exclusive modelling of hadron cascades in materials is possible by CHIPS model, since it validates photon and hadron projectiles for hadron and nuclear targets.

The PreCompound model [123] : The GEANT4 precompound model gives a possibility to extend the low energy range of the intra nuclear transport model for nucleon-nucleus inelastic collision and it provides a “smooth” transition from kinetic stage of reaction described by the hadron kinetic model to the equilibrium stage of reaction described by the equilibrium de-excitation models. The energy range of this 0 to 100 MeV.

The Bertini cascade model [123] : This model is a collection of theory driven models with parametrization feature. It includes the Bertini intra-nuclear cascade model which is a solution of Boltzmann equation on average with excitons, a pre-equilibrium model, a nucleus explosion model, a fission model, and an evaporation model. It is intended to treat nuclear reactions initiated by long-lived hadrons such as p, n,π,K, Λ, Σ, Ξ, Ω and γ with energies between 0 to 10 GeV. The target nucleus is considered to be made up of six concentric shells of constant density in order to explain the continuously changing density distribution of nuclear matter within nuclei. The cascade starts when an incident particle interacts with a nucleon in the target nucleus followed by production of secondaries. The secondaries are also allowed to interact with other nucleons or get absorbed. When all the secondaries escape the nucleus, the cascade ends. Energy conservation is checked at that point. The calculations are done by relativistic kinematics throughout the cascade.

3.2.4 CORSIKA

CORSIKA (COsmic Ray Simulations for Kascade) [91, 92] is a 3-dimensional simulation program which is used widely to study the evolution and properties of air shower. It was developed to simulate interactions and decays of nuclei, hadrons, muons, electrons, and photons in the atmosphere up to energies of some 10^{20} eV. The out put contains informations such as type, energy, location, direction and arrival times of all secondary particles of an air shower at a selected observation level. CORSIKA is a complete set of standard FORTRAN routines that consists basically of 4 parts. The first part is a general program frame that handles the in and output, decay of unstable particles and particle tracking considering ionization energy loss, multiple scattering and the Earth's magnetic field. The second part treats high energy hadronic interactions where as the third part simulates low energy hadronic interactions. The fourth part simulates particle transport and interaction of electrons, positrons, and photons.

For later three parts., CORSIKA uses several interaction models, which may be activated optionally depending on the precision of the simulation. High energy hadronic interactions are handled by one of the following models : The Dual Parton Model DPMJET [129, 132], the HDPM [91], the quark-gluon-string model QGSJET [93–95], the mini-jet model SIBYLL [88–90], VENUS [106], the NEXUS model [127, 128] and the EPOS [107] model. The low energy hadronic interactions are simulated using models like GHEISHA [105], UrQMD [133, 134] and FLUKA [135, 136]. The electromagnetic showers are treated using EGS4 [104] code which tracks each particle and its reactions. Also the analytic NKG [137, 138] code is used in order to simulate electromagnetic simulations to obtain electron densities at selected observation level. Few of these models are described below.

3.2.4.1 The VENUS model

The VENUS (Very Energetic Nuclear Scattering) [106] model is based on the Gribov-Regge theory [139], in which single or multiple Pomeron exchange is considered as the basis of high energy hadron-hadron interaction. Particle production in inelastic collision is explained by cutting Pomerons (which are essentially cylinders of gluons and quark loops), that give rise to colored strings which in turn forms neutral hadrons after fragmentation. Also, formation of massive quark droplets in collisions of heavy nuclei at high densities are considered. Same formalism is used for the explanation of diffractive and non-diffractive collisions as well as mesonic projectiles. In all these case, the final state interactions are taken into account. Because of this the VENUS model can treat all types of hadronic interactions involved in an air shower cascade. Because of the absence of jets, this model is not recommended at energies above 20 PeV.

3.2.4.2 The DPMJET model

The DPMJET (Dual Parton Model with JETs) [129, 132] is based on Gribov-Regge theory [139] with interactions described by multiple pomeron exchange that contains and contains multiple soft chains as well as multiple mini-jets. Here a supercritical Pomeron is introduced to explain soft processes where as hard processes are explained by introducing hard Pomerons. Triple Pomerons and Pomeron loops are used in order to describe high mass diffractive events where as low mass diffractive events are simulated outside Gribov-Regge theory. Two strings are produced by cutting a Pomeron, which are again fragmented by the JET-SET routines [140] on the basis of the Lund algorithm [141, 142]. Glauber theory is used in order to calculate the number of nuclei involved in a collision as well as the number of interactions. Intranuclear cascade model [143] is used for the of treatment of the residual nuclei with the nuclear excitation energy, models nuclear evaporation, high energy fission and break-up of light nuclei, and emission of de-excitation photons for projectile and target nuclei being taken into consideration.

DPMJET ensures the decay of short living secondaries. Since CORSIKA can not treat charmed hadrons, the produced charmed hadrons are replaced by strange hadrons In DPMJET which are tracked and undergoes decay or interactions within CORSIKA.

3.2.4.3 The QGSJET model

In QGSJET (Quark Gluon String model with JETs) [93–95] hadronic interactions are described on the basis of exchanging supercritical Pomerons which are divided into two strings each according the Abramovski-Gribov-Kancheli rule. After that fragmentation of these strings are done with an algorithm like Lund algorithm but with deviating treatment of the momenta at the string ends. Also mini-jets are included in QGSJET in order to describe the hard interactions at the highest energies. Glauber calculations are used to determine participants in a nucleus-nucleus collisions by assuming a Gaussian distribution of the nuclear density for light nuclei with $A \leq 10$ and a Woods-Saxon distribution for the heavier nuclei. The peripheral collisions are considered to be spallation like reaction where as central collisions are considered to be more or less like fragmentation. After that various fragmentation options available in CORSIKA can be applied.

3.2.4.4 The SIBYLL model

Contrary to the VENUS model, SIBYLL [88–90] is a mini-jet model designed to handle hadronic interactions in EAS Monte Carlo programs. Here it is considered that triplets and anti-triplets of colour are formed from the fragmentation of of both projectile and target hadrons in a hadronic soft collision. After that combination of the opposite colour of the two hadrons leads to the formation of two colour strings , the fragmentation of which leads to particle production. This fragmentation of the two colour strings is done by modified Lund algorithm [141, 142]. Hard collisions are explained with minijet production having high transverse momenta. The number of mini-jets are increased with energy which explains the increase in inelastic scattering cross-section with energy where as the contribution of the soft component is assumed to be energy independent. This model explains diffractive events independently of soft or hard collisions. The hadron-nucleus collisions are explained by the formation and fragmentation of string pairs of opposite colour while nucleus-nucleus collisions are treated with Glauber theory [144, 145] and thermal model [88]. In SIBYLL , the shot lived seconadry particles are decayed into known particles that are known to CORSIKA . If the secondary particles are nucleons and anti-nucleons, charged pions, and all four species of kaons, they are be treated as projectiles by SIBYLL and further collisions are considered. Decay of strange baryons after tracking and substitution of photon with a charged pion in photo-nuclear reactions are two other important aspects of SIBYLL. The SIBYLL model contains its own nucleus-nucleus cross-section table including an interpolation routine.

3.2.4.5 The HDPM model

The HDPM [91] is a phenomenological generators which describes the hadronic interactions between hadrons and nuclei at high energies. It is inspired by the Dual Parton Model which is based on the assumption that in an hadronic interaction, interacting quarks of two hadrons form two dominant colour strings which after separation and fragmentation produce jets of many colour neutral secondaries around the primary quark directions. These jets are observed in many high energy physics experiments. Since the particles emitted in extreme forward directions are important in understanding the EAS, this model is built to reproduce collider data by correlating many quantities, such as the number and type of secondaries, the longitudinal and transverse momentum distributions and the spatial energy flow with the available energy. This model is valid up to 100 PeV.

3.2.4.6 The NEXUS model

While non of the above mentioned models violates important theoretical principles, NEXUS [127, 128] model is the first model in which the theoretically predicted energy-momentum sharing between the hadron constituents is consistently implemented in construction of scattering amplitudes. Being based on Gribov-Regge theory with soft, semi-hard and hard pomerons, this model for the first time employs the multiple scattering approach through a “three object picture”- a parton-ladder between a interacting parton and a diquark, one of which is from the projectile and the other is from the target, along with two excited colorless remnants formed by the spectator parton and diquark of the projectile and the target nucleons. The parton-ladder describes successive parton emission through the soft and the hard interactions with the soft interaction being described by the traditional soft pomeron exchange; where as, the hard interaction is realized through perturbative QCD within the concept of the semi-hard pomeron. According to the number of quarks and anti-quarks, to the phase space and to an excitation probability, a remnant may decay into mesons, baryons and anti-baryons [146]. The remnant produce particles mostly at large rapidities whereas the parton-ladders emit particles at central rapidities. Such "three object picture" of the parton-ladder and the two remnants solve the multi strange problem of conventional high energy problems [147].

To implement energy conserving multiple scattering, this model consider both the open parton-ladders as well as closed parton-ladders, the latter being an important player in the calculation of partial cross-sections through interfering contributions. The NEXUS model uses relativistic string approach to obtain observable hadrons from partons *via.* two steps, namely, the formation of strings from the partons and then the string fragmentation into hadrons.

3.2.4.7 The EPOS model

The EPOS [148, 149] model, being the successor to NEXUS, is also based on parton based Gribov-Regge theory with special emphasis given on high parton densities for proton-nucleus or nucleus-nucleus collisions which are taken care of by the fragmentation of Pomerons in Pomeron-Pomeron interactions. This new multiple scattering approach, EPOS, stands for [148]

• Energy conserving quantum mechanical multiple scattering approach, on the basis of

• Partons (Pomerons)

• Off-shell remnants

• Splitting of Pomerons.

The outline of this model is given below :

1. In parton models it is considered that in case of a proton-proton collision, two partons, one from the projectile and one from the target interacts with each other leaving behind colored remnants (the diquarks) at the string ends. Just like NEXUS, in EPOS model, it is considered that in the case of a hadronic interaction, two fold objects like quark-diquark or quark-antiquark take part directly leaving behind colorless excited (off-shell) remnants. So finally three colorless objects will remain, the two off-shell remnants and one parton-ladder (also called as Pomerons : the whole structure of the dynamical process of successive emission of partons in case of hadronic interactions).

2. Just like NEXUS, the energy independent contribution from the remnants is responsible for the production of particles at large rapidities where as the parton-ladders mainly contribute at central rapidities which grows with energy. An energy conserving multiple scattering treatment [127] is applied to this scenario considering both open parton-ladders (representing inelastic scattering) as well as closed parton-ladders (representing elastic scattering) in order to calculate the partial cross-sections.

3. Finally the relativistic string approach is employed in order to explain the formation of colorless "strings" and its fragmentation into hadrons.

The EPOS model has adopted some additional aspects such as the nuclear effects related to Cronin transverse momentum broadening, parton saturation and screening. The particle production scenario is also expected to be very different depending on whether the interaction is with a peripheral nucleon or with a nucleon from the high density central part. This aspect has been accomplished in EPOS by allowing splitting (as well as merging) of parton-ladders based on an effective treatment of lowest order Pomeron-Pomeron interaction graphs with the corresponding parameters being adjusted from the comparision with accelerator data. In the case of meson projectile, the EPOS model leads to an increase of baryon and anti baryon production in the forward direction in agreement with the low energy pion-nucleus data [150].

3.2.4.8 The GHEISHA model

The GHEISHA [105] model is a data driven model, that treats hadronic interactions up to 80 GeV. This can handle all the baryonic projectiles with strangeness ±1, ±2, and ±3 except nuclear evaporation products like deuteron, tritium and alpha particles. This package contains cross-sections for elastic and inelastic interactions obtained from interpolation and extrapolation of. tabulated experimental data. Nuclear fission routines are removed too. The interaction cross-section of projectiles with air (which contains elements like N, O, Ar) is derived from interpolation of cross-section data because of which some accuracy is lost. That is why validity of this model must be checked before simulation.

3.2.4.9 The FLUKA model

The interaction model FLUKA [135, 136] employs resonance superposition from threshold to about 5 GeV but incorporates the two string interaction model(DPM) at higher energies. In this model, the resonance energies, widths, cross-sections and the branching ratios are extracted from data and from the conservation laws by making explicit use of the spin and isospin relations. For high energy hadron-nucleus interactions, the model exploits the Glauber-Gribov cascade [151, 152]; whereas, it uses the pre-equilibrium-cascade model PEANUT [153, 154] below about 5 GeV. The nucleus-nucleus interactions above a few GeV/n are treated in FLUKA (version 2008.3b) by interfacing with the DPMJET-III [132] model. It may be added here that FLUKA describes the fixed target data reasonably well.

3.2.4.10 The UrQMD model

The UrQMD (Ultra-relativistic Quantum Molecular Dynamics) [133, 134] model was originally designed for simulating the relativistic heavy ion collisions in the *cms* (center of mass) energy range from around 1 AGeV to a few hundred AGeV for the RHIC experiment. This particular model inherits the basic treatment of the baryonic equation of motion in quantum molecular dynamic approach and describes the phenomenology of hadronic interactions at low to intermediate energies in terms of the interactions between known hadrons and their resonances. The model does not use an intrinsic cross-section calculation. Instead, the projectile is allowed to hit a sufficiently large disk involving maximum collision parameters as a result of which the program consumes rather a long CPU time. Like FLUKA, UrQMD also explains the fixed-target data reasonably well.

3.3 Comparison between predictions of high energy hadronic interaction models of CORSIKA with LHC data

The cross-section is a very important observable which is strongly correlated with shower depth of individual EAS. In all hadronic interaction models p-p scattering cross-section is used as the basis for understanding hadronic interactions. All

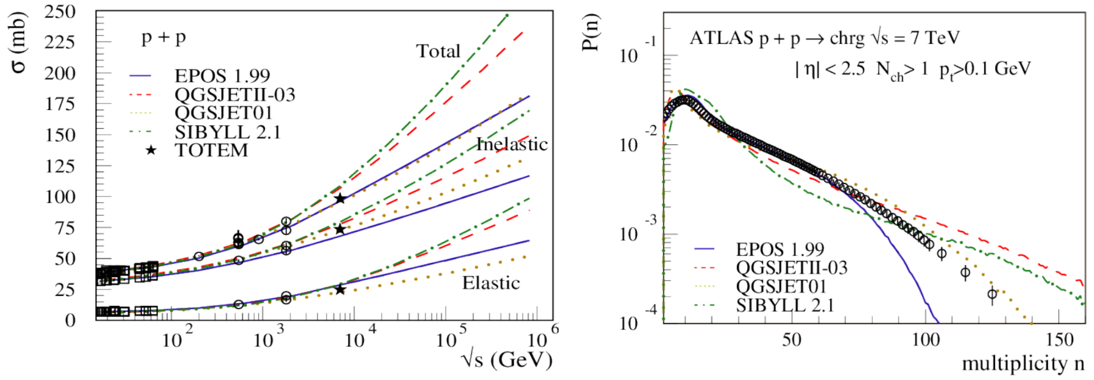

FIGURE 3.1: Comparison of model predicted cross-section (σ) and multiplicity (n) with LHC Data (figure taken from [160, 161]).

the models agrees well with experimental cross-section data at lower energies and start diverging at around 2 TeV cms energy. The TOTEM experiment [158] at 7 TeV cms reduces the differences between the models by 10-50 mb. Comparison [160, 161] of cross-sections predicted by the models with ALICE [155, 156], ATLAS [157] and TOTEM [158] data shows that QGSJET 01c agrees better with the data than EPOS 1.99, QGSJET-II-03 and SIBYLL 2.1 for inelastic and elastic scattering cross-section. Both EPOS 1.99 and QGSJET 01c are in good agreement with data for total scattering cross-section.

Just like the cross-section, the multiplicity is also an important observable in EAS which has a logarithmic dependence on particle production. Comparison of model predictions with ATLAS data [160, 161] for multiplicity distribution of charged particles at 7 TeV cms shows that EPOS 1.99 starts deviating sharply after multiplicity but it agrees well at lower multiplicities. SIBYLL 2.1 does not agree well with the entire data set whereas QGSJET-II-03 has better agreement at multiplicities below 80 than SIBYLL 2.1. The prediction by QGSJET 01c agrees better with the entire data set than prdeictions of other models, though it shows slight deviation above multiplicity 60.

The transverse momentum plays an important role in the development of the EAS. It is associated with the spread of hadronic and muonic showers in an EAS. Comparision of model predictions with CMS data [162] for transverse momentum (p_T) distribution of charged particles at 7 TeV shows a significant deviation of EPOS 1.99 predictions with the data after 5 GeV/c whereas predictions by QGSJET 01c and QGSJET-II matches well with the entire data set. Significant deviation can

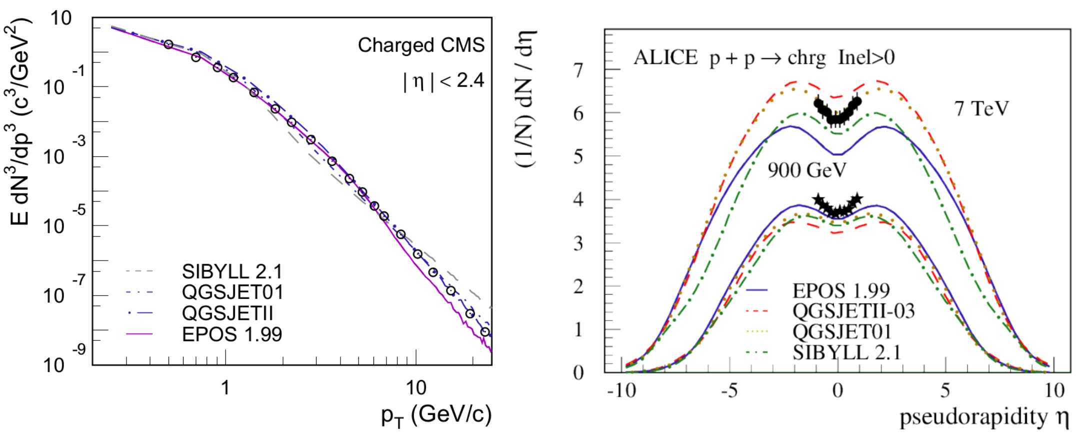

FIGURE 3.2: Comparison of model predicted transverse momentum (p_T) and pseudorapidity (η) with LHC Data (figure taken from [159–161]).

also be seen in the predicted values of p_T by SIBYLL 2.1 with the data set above 1 GeV/c.

The EAS observable pseudorapidity is strongly related with the longitudinal momentum distribution of secondary particles. Comparison of model predictions with ALICE data [163] for pseudorapidity distribution of charged particles at 7 TeV cms shows a complete mismatch of EPOS 1.99 predictions with the entire data set. Predictions by SIBYLL 2.1 as well as QGSJET-II-03 does not agree well with the entire data set whereas QGSJET 01c has a very close agreement with the data.

3.4 Comparison between predictions of high energy hadronic interaction models of CORSIKA with GEANT4

Accurate reproduction of EAS is an essential part of the air shower experiments. Most of the experiments have relied simulations from CORSIKA which is an EAS simulation program with low and high energy interaction models. Because of the limited understanding of hadronic interactions at high energy, uncertainty in muon number is expected from the model predictions. In fact, most of the CORSIKA interaction models predict lower muon number than expected. It also can not simulate low energy particles. On the other hand, GEANT4 is a detector simulation program having different high and low energy interaction models. Recently

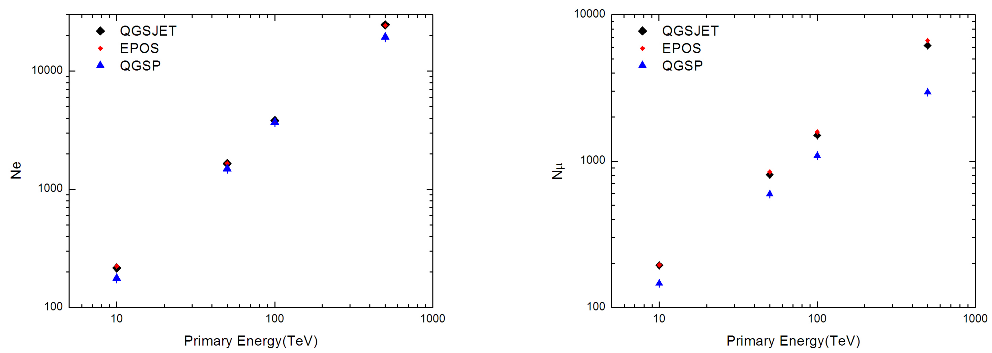

FIGURE 3.3: Shower size (N_e) and muon size (N_μ) predicted by models of CORSIKA and GEANT4.

GEANT4 has also been used for simulation of air shower. So comparison of interaction models of GEANT4 and CORSIKA may throw some light towards the shortcomings of hadronic interaction models and hence can give some idea about this uncertainty of muon numbers.

In GEANT4, the atmosphere was realized by constructing a volume of 1000 km length, 1000 km width and 100 km altitude. The altitude was divided into 1000 layers, each with thickness 0.1 km. Each layer was made up of air with density and composition varying with altitude as per US Standard atmospheric model. Observation level is set at 4300 m which was the altitude of EAS-TOP experiment and magnetic field was set accordingly. QGS model was selected to simulate high energy hadronic interactions $<$ 500 GeV where as BiC model was used to handle low energy hadronic interactions. Electromagnetic interactions were simulated by STANDARD electromagnetic model of GEANT4 and cut off energy was set to 300 MeV.

In CORSIKA, observation level, magnetic field and cut off energy were set to the same values as GEANT4. Also QGSJET 1c and EPOS model were choosen to simulate high energy hadronic interactions, where as low energy interactions were handled by GHEISHA. EGS4 routine was used to simulate the electromagnetic interaction.

Both in GEANT4 and CORSIKA, proton is chosen as primary particle at energies 10 TeV, 50 TeV, 100 TeV and 1000 TeV. In case of GEANT4, 1000 showers were considered at each energy where as in CORSIKA, 50000 showers were considered at

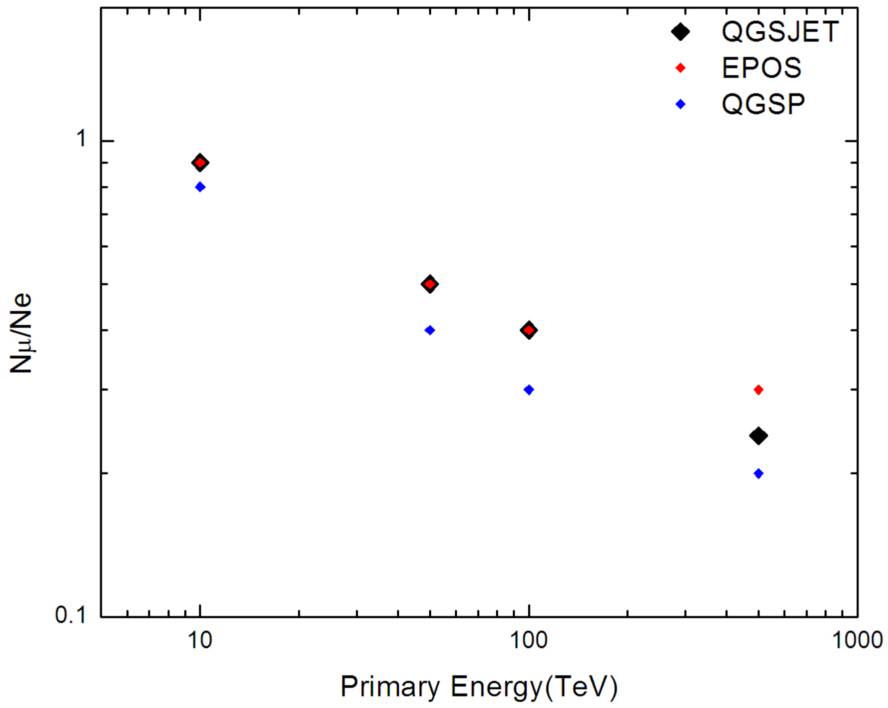

FIGURE 3.4: Ratio of shower size (N_e) and muon size (N_μ) predicted by models of CORSIKA and GEANT4.

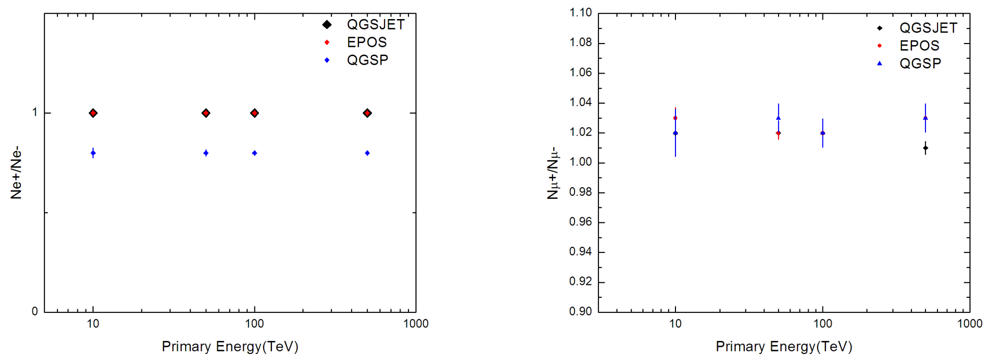

FIGURE 3.5: Comparison between shower size (N_e) and muon size (N_μ) predicted by models of CORSIKA and GEANT4.

each energies. Average number of electrons and muons, produced at each primary energy were studied.

The results were discussed below:

It can be seen from figure 3.3 that GEANT4 produces less number of electrons and muons compared to those in CORSIKA even for the same hadronic interaction(QGS) model.

The GEANT4 gives persistently smaller muon size to electron size ratio than that given by CORSIKA. The positron to electron ratio is substantial lower in GEANT4 than in CORSIKA. The reasons for such discrepancies are not clear at all.