Air Shower Simulation with new Hadronic Interaction Models in CORSIKA

T. PIEROG[1] D. HECK[1]

[1] *Karlsruhe Institute of Technology (KIT), IKP, D-76021 Karlsruhe, Germany*

tanguy.pierog@kit.edu

Abstract: The interpretation of EAS measurements strongly depends on detailed air shower simulations. CORSIKA is one of the most commonly used air shower Monte Carlo programs. The main source of uncertainty in the prediction of shower observables for different primary particles and energies being currently dominated by differences between hadronic interaction models, two models, EPOS and QGSJETII, have been updated taking into account LHC data. After briefly reviewing major technical improvements implemented in the latest release, version 7.37, such as optional hybrid or massively parallel simulation, the impact of the improved hadronic interaction models on shower predictions will be presented. The performance of the new EPOS LHC and QGSJETII-04 models in comparison to LHC data is discussed and the impact on standard air shower observables derived. As a direct consequence of the tuning of the model to LHC data, the predictions obtained with these two models show small differences on the full energy range.

Keywords: EAS, LHC, CORSIKA, CONEX, EPOS, QGSJETII, Simulations.

1 Introduction

The experimental method of studying ultra-high energy cosmic rays is an indirect one. Typically, one investigates various characteristics of extensive air showers (EAS), a huge nuclear-electromagnetic cascade induced by a primary particle in the atmosphere, and uses the obtained information to infer the properties of the original particle, its energy, type, direction, etc. Hence, the reliability of ultra-high energy cosmic ray analyzes depends on the use of proper theoretical and phenomenological descriptions of the cascade processes.

The most natural way to predict atmospheric particle cascading in detail seems to be a direct Monte Carlo (MC) simulation of EAS development, like it is done, for example, in the CORSIKA program [1]. As very large computation times are required at ultra-high energy, a parallelization of the sub-showers of the cascade on big CPU clusters is now possible. An alternative procedure was developed to describe EAS development numerically, based on the solution of the corresponding cascade equations (CE). Combining this with an explicit MC simulation of the most energetic part of an EAS allows us to obtain accurate results both for average EAS characteristics and for their fluctuations in the CONEX program [2]. Combining the two programs not only a complete 3D simulation can be achieved with a reduced computation time but new analysis possibilities are open.

On fundamental ingredient of the MC process is the hadronic interaction models which generate the hadronic cascade at the origin of the electromagnetic cascade. Since 2009, the Large Hadron Collider (LHC) provide a lot of very precise data which have been used to improve two of the hadronic models used for air shower simulations: EPOS [3] and QGSJETII [4].

In this article, we will discuss changes in the hadronic model predictions after LHC data and their consequences on air shower observables. In the first section, we will compare the results of the newly available hadronic interaction models, EPOS LHC and QGSJETII-04 with LHC data for the main observables relevant for air shower development. Then the main new options available in the last release of CORSIKA v7.37 and CONEX v4.37 will be reviewed. Finally using detailed Monte Carlo simulations done with these air shower simulation models, the new predictions for X_{max} and for the number of muons will be presented.

2 Hadronic interaction models and LHC data

To qualitatively describe the dependence of shower development based on some basic parameters of particle interaction, decay and production, a very simple toy model can be used. Although initially developed for electromagnetic (EM) showers [5] it can also be applied to hadronic showers [6].

It is clear that such a model is only giving a very much over-simplified account of air shower physics. However, the model allows us to qualitatively understand the dependence of many air shower observables on the characteristics of hadronic particle production. Accordingly the parameters of hadron production being most important for air shower development are the cross section (or mean free path), the multiplicity of secondary particles of high energy, and the production ratio of neutral to charged particles. Until the start of LHC, these parameters were not well constrained by particle production measurements at accelerators. As a consequence, depending on the assumptions of how to extrapolate existing accelerator data, the predictions of hadronic interaction models differ considerably.

There are several hadronic interaction models commonly used to simulate air showers. Here we will focus on the two high energy models which were updated to take into account LHC data at 7 TeV: QGSJETII-03 [7] changed into QGSJETII-04 [8] and EPOS 1.99 [9] replaced by EPOS LHC [10]. There is no major change in these models but in addition to some technical improvements, some parameters were changed to reproduce TOTEM [11] cross sections. Both are based on Gribov-Regge multiple scattering, perturbative QCD and string fragmentation.

The former versions reproduce accelerator data and even first LHC data reasonably well [12] and Figs. 1 but predict different extrapolations above $E_{\text{cms}} \sim$1.8 TeV ($E_{\text{lab}} \sim 10^{15}$ eV) that lead to very different results at high energy [13, 14]. This can be improved using LHC data. In all the figures EPOS LHC is represented by a full (blue) line, QGSJETII-04 by a dotted (red) line, EPOS 1.99 by a dashed (black) line and QGSJETII-03 by a dashed-dotted (green) line.

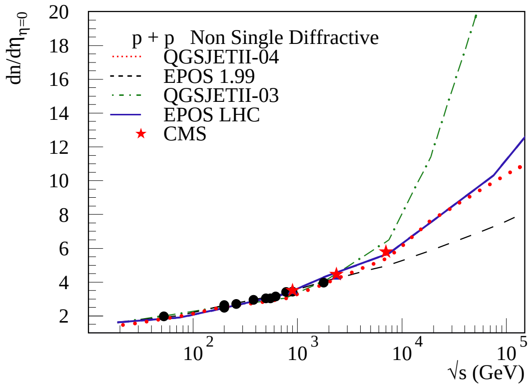

Figure 1: Measurement of particle density at $\eta = 0$ for non single diffractive events (NSD) from old experiments and from CMS experiment [17] (stars) as a function of center of mass energy. Simulations are done with EPOS LHC (full line), QGSJETII-04 (dotted line), EPOS 1.99 (dashed line) and QGSJETII-03 (dashed-dotted line).

2.1 Cross section

The cross section is very important for the development of air showers and in particular for the depth of shower maximum. As a consequence, the number of electromagnetic particles at ground is strongly correlated to this observable (if the shower maximum is closer to ground, the number of particles is higher).

The proton-proton scattering total cross section is usually used as an input to fix basic parameters in all hadronic interaction models. Therefore it is very well described by all the models at low energy, where data exist [15]. And then it diverges above 2 TeV center-of-mass (cms) energy because of different model assumptions. The new point measured by the TOTEM experiment at 7 TeV reduces the difference between the models by a factor of 5 (50 to 10 mb) at the highest energy.

2.2 Multiplicity

According to the generalized Heitler model, the multiplicity plays a similar kind of role as the cross section, but with a weaker dependence (log). On the other hand, the predictions from the models had much larger differences for the multiplicity compared to the cross section. As shown Fig. 1, the particle density at mid-rapidity is well reproduced by all the models up to 2 TeV where Tevatron data [16] constrain the results, but at the highest energies, the difference can be as high as a factor of 10. After retuning at 7 TeV to be compatible with CMS data [17] or ALICE data [18], the difference is now negligible.

So for both cross section and multiplicity, when the models are constrained by LHC data up to 7 TeV, the extrapolation to the highest energy is not so different any more. This will have a strong impact on X_{max} uncertainty in air shower simulations.

2.3 Baryon production

Another important observable for EAS is the number of muons reaching the ground. It has been shown in [19] that the number of muons in EAS is sensitive to the number of (anti)baryons produced in the hadronic interactions and it is important to check the production of such particles in LHC data.

Both ALICE [20] and CMS [21] experiments published very nice results on identified spectra used to constrain models used for air shower simulations. As shown in Fig. 2, these data helped a lot to reduce the differences between the models especially because it could resolve an ambiguity on the phase space used to produce some anti-proton over pion ratio with Tevatron data at 1.8 TeV. LHC data are much better defined and can be used to constrain the production of baryon pairs at mid-rapidity (largely dominated by string fragmentation).

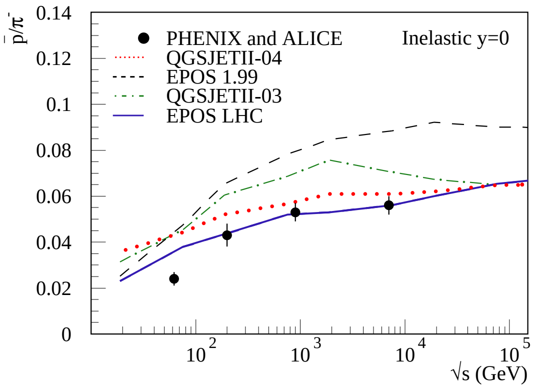

Figure 2: Measurement of pion over anti-proton ratio at $y = 0$ for p-p collisions by ALICE and PHENIX [20] experiments (right-hand side) as a function of center of mass energy. Simulations are done with EPOS LHC (full line), QGSJETII-04 (dotted line), EPOS 1.99 (dashed line) and QGSJETII-03 (dashed-dotted line).

It is important to notice that all particles which do not decay into an electromagnetic particle can play a similar role and keep the energy of the shower into the hadronic channel to produce muons. For instance in QGSJETII-04 the newly introduced ρ^0 resonance as excited state of the pion remnant in pion interactions has a very strong influence on the muon production. Since forward π^0, transferring a lot of energy in the electromagnetic channel, are replaced by particles which decay in charged pions, the energy is kept in the hadronic channel [22]. The leading ρ^0 production was already in EPOS 1.99, being one source of difference between the 2 models. On the other hand in EPOS 1.99 another process producing forward (anti)baryons was missing at high energy. As a consequence the reduced rate of (anti)baryons production at mid-rapidity is compensated by more forward (anti)baryons production which is even more important for muon production.

3 EAS simulations

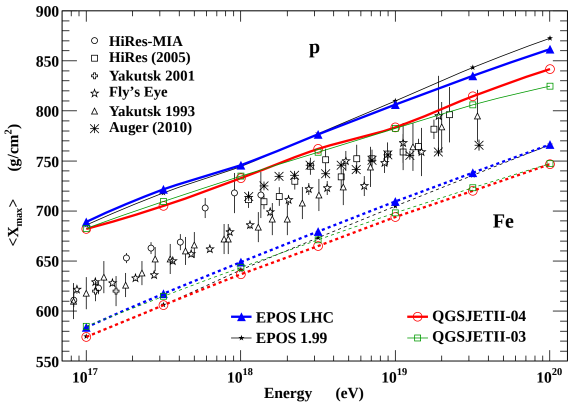

Figure 3: Mean X_{max} for proton and iron induced showers as a function of the primary energy. Predictions of different high-energy hadronic interaction models, full lines for proton and dashed lines for iron with full triangles for EPOS LHC, open squares for QGSJETII-03, open circles for QGSJETII-04, and full stars for EPOS 1.99, are compared to data. Refs. to the data can be found in [29] and [30].

3.1 CORSIKA v7.37

CORSIKA 7.37 has been released in April 2013 including post-LHC hadronic models EPOS LHC and QGSJETII-04. The main new option is the possibility to replace the thinning procedure by numerical cascade equations as implemented in CONEX. The detailed process is described in [23] and was first implemented in the SENECA model [24].

As a result, simulations can be done either in 1D (only the longitudinal profile) or in 3D (lateral distribution function (LDF)) or even 3D only for the muons depending on keyword used in the steering file (automatic threshold management). For an equivalent precision level, a minimum gain factor of 5 to 10 in time can be expected using this method instead of standard thinning. When only the longitudinal development is needed, the simulation time is reduced to a couple of minutes for all primary energies.

Using the new option, a new approach is possible to analyze air shower data. Until now, only statistical analyzes were possible because of the large shower-by-shower fluctuations and the large computation time. But since the same first sequence of hadronic interactions are realized independly of the selected option (1D or 3D full MC) for a given random seed, the fluctuations induced by the low energy MC are really limited (not affecting X_{max} for instance). Using hybrid simulation (CORSIKA + CONEX) together with the new hybrid detectors (fluorescence+surface (PAO [25], TA [26]), radio+surface (PAO, KASCADE [27]), ...) it is possible to study data shower-by-shower.

Another new option available in CORSIKA 7.37 is the possibility to run unthinned shower using massive parallelization with MPI management.

3.2 CONEX v4.37

The corresponding version of CONEX linked to ROOT has been released with version number 4.37 for 1D use only. New hadronic models EPOS LHC and QGSJETII-04 are available and the low energy model GHEISHA has been replaced by URQMD 1.3 [28] as used in CORSIKA.

3.3 Results

In the following EAS simulation results using EPOS LHC and QGSJETII-04 are presented and compared to former results using QGSJETII-03 and EPOS 1.99.

As shown in Fig. 3, the mean depth of shower maximum, X_{max}, for proton and iron induced showers simulated with CONEX is still different for EPOS LHC and QGSJETII-04. But now the elongation rate (the slope of the mean X_{max} as function of the primary energy) is the same in both cases while EPOS 1.99 had an elongation rate larger than QGSJETII-03. The difference between the 2 models is a constant shift of about $20 g/cm^2$ (close to the experimental systematic error in PAO [30]) while before the difference was increasing up to $50 g/cm^2$ at the highest energies

This is very important to study the primary cosmic ray composition. If the models converge to a similar elongation rate, it will allow us to have a more precise idea on possible changes in composition at the "ankle" for instance where the PAO measured a break in the elongation rate of the data.

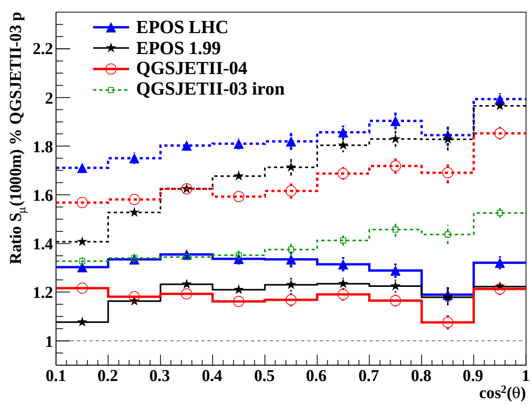

Figure 4: Ratio of muon signal at 1000 m at ground as measured by PAO with respect to QGSJETII-03 proton showers for proton and iron induced showers at 10^{19} eV as a function of the zenith angle ($\cos^2\theta$). Predictions of different high-energy hadronic interaction models: full lines for proton and dashed lines for iron with full stars for EPOS LHC, open squares for QGSJETII-03, open circles for QGSJETII-04, and full triangles for the results of EPOS 1.99.

Concerning the muon signal at ground as measured by PAO experiment (at 1000 m from the shower core for an primary energy of 10^{19} eV and ground height at 1500 m), the difference between the new QGSJETII-04 and the old QGSJETII-03 is even more impressive. We can see on Fig. 4, where the muon signal of each model is divided by the one of QGSJETII-03, that QGSJETII-04 predicts now about the same number of muons than EPOS 1.99 which is about 20% more than QGSJETII-03. It is due to the change in baryon, strangeness and mostly resonance production as described in section 2.3. Concerning the predictions of EPOS LHC, the number of muons is very similar to the one in EPOS 1.99 for vertical showers but the attenuation length is larger (similar to QGSJETII-04 now) the difference at large angle is as large as 20%. This is probably due to the leading baryon production compensating the reduction of (anti)baryon production at mid-rapidity but for a different phase space. So, even if the number of muons is much more similar now for the two most recent hadronic models, there is still an uncertainty of about 10% but with the same attenuation length. Furthermore the energy spectrum of the muons at ground is different between the models. This is important for the calculation of the invisible energy for fluorescence detection. The average energy of the muons is larger in QGSJETII-04 than in EPOS resulting in a slightly larger (1% to 2%) invisible energy correction in QGSJETII-04 (same value for EPOS LHC and EPOS 1.99). These changes are observed at all primary energies.

4 Summary

Using recent LHC data at 7 TeV it is possible to reduce the uncertainty in the extrapolation of the hadronic interaction models used for EAS simulations. Using pre- and post-LHC versions of the QGSJETII and EPOS models included in the last release of CORSIKA v7.37 and CONEX v4.37, it has been showed that the difference in multiplicity between these models has been reduced by a factor of 5 at the highest energy, resulting in a very similar elongation rate. There is still a systematic shift in X_{max} of about $20 g/cm^2$ due to remaining differences in the multiplicity (and elasticity) of the models. This uncertainty is comparable to the experimental uncertainty in the measurement of X_{max}. As a consequence the interpretation of the data using post-LHC data will be more reliable especially concerning the possible change in mass composition with energy as summarized in [31].

For the number of muons, the ratio between particles producing hadronic sub-showers and the total number of particles is very important. LHC data are important to constrain (anti)baryon and strangeness production at mid-rapidity. Lower energy data of fixed target experiment are also important to measure forward production of π^0 for instance. Taking into account both aspect, the new version of the QGSJETII and EPOS models predict very similar results close to EPOS 1.99 model (less than 10% difference) but with a flatter attenuation length.

Compared to QGSJETII-03, using both post-LHC hadronic models to interpret cosmic ray data will result in a slightly lighter composition around the "knee" [32] and heavier composition above the "ankle" [33].

References

[1] D. Heck et al., *Forschungszentrum Karlsruhe Report FZKA* **6019** (1998).
[2] T. Bergmann, et al., *Astropart. Phys.* **26**, 420–432 (2007), [astro-ph/0606564].
[3] K. Werner, F.-M. Liu, and T. Pierog, *Phys. Rev.* **C74**, 044902 (2006), [hep-ph/0506232].
[4] S. Ostapchenko, *Phys. Rev.* **D74**, 014026 (2006), [hep-ph/0505259].
[5] W. Heitler, *Quantum Theory of Radiation*, Oxford University Press, Oxford, 1944, 2nd edition.
[6] J. Matthews, *Astropart. Phys.* **22**, 387–397 (2005).
[7] S. Ostapchenko, *Phys. Lett.* **B636**, 40–45 (2006), [hep-ph/0602139].
[8] S. Ostapchenko, Phys. Rev. D **83** (2011) 014018 [arXiv:1010.1869 [hep-ph]].
[9] T. Pierog, and K. Werner, *Nucl. Phys. Proc. Suppl.* **196**, 102–105 (2009), [arXiv:0905.1198 [hep-ph]].
[10] T. Pierog, et al., [arXiv:1306.0121 [hep-ph]].
[11] T. C̃sörgö, et al., [TOTEM Collaboration], *Prog. Theor. Phys. Suppl.* **193**, 180 (2012).
[12] D. d'Enterria, R. Engel, T. Pierog, S. Ostapchenko and K. Werner, Astropart. Phys. **35** (2011) 98 [arXiv:1101.5596 [astro-ph.HE]].
[13] J. Knapp, D. Heck, S. J. Sciutto, M. T. Dova, and M. Risse, *Astropart. Phys.* **19**, 77–99 (2003), [astro-ph/0206414].
[14] R. Engel, and H. Rebel, *Acta Phys. Polon.* **B35**, 321–330 (2004).
[15] H. Jung, et al. (2009), [arXiv:0903.3861 [hep-ph]].
[16] F. Abe, et al., *Phys. Rev.* **D41**, 2330 (1990).
[17] V. Khachatryan, et al. [CMS Collaboration], *Phys. Rev. Lett.* **105**, 022002 (2010), [arXiv:1005.3299 [hep-ex]].
[18] K. Aamodt, et al., [ALICE Collaboration], *Eur. Phys. J. C* **68**, 345 (2010).
[19] T. Pierog, and K. Werner, *Phys. Rev. Lett.* **101**, 171101 (2008).
[20] M. Chojnacki [ALICE Collaboration], *J. Phys. G* **38** 124074 (2011), [arXiv:1109.6744 [hep-ex]].
[21] S. Chatrchyan, et al., [CMS Collaboration], [arXiv:1207.4724 [hep-ex]].
[22] T. Pierog, et al., *I*SVHECRI Berlin Proceedings (2012).
[23] T. Pierog, et al., *I*CRC proceedings ID 1170 (2011)
[24] H. J. Drescher and G. R. Farrar, *P*hys. Rev. **D67**, 116001 (2003).
[25] J. Abraham, et al. [Pierre Auger Observatory], *Nucl. Instrum. Meth.* **A523**, 50–95 (2004).
[26] H. Kawai et al. [Telescope Array Collaboration], *N*ucl. Phys. B (Proc. Suppl.) **175-176** 221–226 (2008).
[27] T. Antoni et al. [KASCADE Collaboration], *N*ucl. Instrum. Meth. **A513**, 490–510 (2003).
[28] S.A. Bass et al., *P*rog. Part. Nucl. Phys. **41**, 225 (1998); M. Bleicher et al., *J*. Phys. G: Nucl. Part. Phys. **25**, 1859 (1999); http://urqmd.org/
[29] J. Blümer, R. Engel, and J. R. Hörandel, *Prog. Part. Nucl. Phys.* **63**, 293–338 (2009), [arXiv:0904.0725 [astro-ph.HE]].
[30] J. Abraham, et al. [Pierre Auger Observatory], *Phys. Rev. Lett.* **104**, 091101 (2010), [arXiv:1002.0699 [astro-ph.HE]].
[31] K.-H. Kampert and M. Unger, Astropart. Phys. **35** (2012) 660 [arXiv:1201.0018 [astro-ph.HE]].
[32] M. Bertaina, et al. [KASCADE Grande Collaboration] *T*hese proceedings (2013)
[33] A. Letessier-Selvon, et al. [Pierre Auger Observatory] *T*hese proceedings (2013)