GAP-98-036, Auger project technical note. Shower Model Comparison II : Ground Particles in MOCCA and CORSIKA

C. Pryke

Enrico Fermi Institute, University of Chicago, USA

email: pryke@hep.uchicago.edu

March 10, 1999

Abstract

This paper presents a comparison of the air shower simulation codes MOCCA and CORSIKA, using three high energy hadronic models. The mean values and the fluctuations of the lateral distribution are given. This is extremely computationally intensive and hence only a single energy (10^{19} eV), and primary type (proton), have been calculated. The combinations considered yield mean water Čerenkov signals at 1 km which vary by $\sim 50\%$. The fluctuations are of order 10% in each case. Some characteristics of the shower particles at large core distances are also investigated — they are broadly similar with a few differences.

1 Introduction

Air shower simulations codes are complex, and the high energy hadronic models uncertain. Comparisons of the models are rare, and of the shower framework programs rarer still.

The MOCCA program with the Sibyll high energy hadronic interaction model has been used extensively for Auger simulations and experimental performance predictions. The technique of Hybrid Cross Calibration means

Tag name	Program frame	High E Hadronic	Low E Hadronic	Electromag.
mocspl	MOCCA	Internal	Internal	Internal
mocsib	MOCCA	Sibyll	Internal	Internal
corsib	CORSIKA	Sibyll	GEISHA	EGS4
corqgs	CORSIKA	QGSjet	GEISHA	EGS4

Table 1: Summary of the four program-frame / interaction-model combinations investigated in this paper.

that the absolute accuracy of the shower code is much less important that it would otherwise be — it does not translate directly into systematic energy error [1]. However, if fluctuations were dramatically greater in other programs this would be a cause for concern, as it would lead to increased random energy error.

In this paper four combinations of framework program and high energy hadronic interaction model are investigated; these are summarized in table 1. The "tag names" will be used to refer to these throughout.

CORSIKA is a well documented and thorough program prepared originally for the Kascade experiment [2]. It has the attractive feature of using the well established HEP codes EGS4 [3] and GEISHA [4] for the lower energy modeling, thus hopefully keeping the uncertainty in the high energy hadronic model where it is unavoidable. This is of considerable advantage when dealing with the psychology of sceptical outsiders to the air-shower field.

2 Detailed Run Conditions

The "Michigan version" of MOCCA-Sibyll was used, and it was not subject to the problem with random seeding of Sibyll which had affected some previous runs. Version 5.610 of CORSIKA was used (16 March '98); this includes a very similar thinning algorithm to MOCCA, and the LPM effect is correctly implemented [5].

In all cases the high energy hadronic interaction model is used with the set of inelastic cross sections provided by it's authors. Three hundred showers were run at thinning levels of 10^{-5}, 10^{-6} and 10^{-7}.

The run conditions were the same as far as possible:

- Primary proton arriving at 30 degrees from the zenith.
- Ground level at 870 g cm^{-2} (Auger site altitude).
- Electromagnetic particle energy cutoff at 0.2 MeV.

Known differences between the run conditions are as follows:

- In CORSIKA the transition between the High Energy and Low Energy interaction model (GEISHA) and cross sections takes place at 80 GeV. In MOCCA the corresponding threshold was set to 200 GeV, as this was the value used in the '97 shower library production. Testing revealed that changing the transition energy by this amount makes a negligible difference.
- The version of Sibyll used with MOCCA was 1.5; with CORSIKA it was 1.6.

The mean value and fluctuation of the lateral distribution will be compared, followed by the mean features of the ground level particles at large core distance.

3 The Lateral Distribution

3.1 Average

The Average lateral distribution is compared in figure 1. The upper left plot shows the density of gammas, electrons and muons versus core distance for the "reference" **mocsib** ccombination. The energy spectra of these particles are used to calculate the signal yield in a 1.2 m deep water Čerenkov detector and this is plotted in units of Vertical Equivalent Muons (VEM).

The prediction of all combinations is very similar. The gross shape of the lateral distribution is a steep power law ($\rho \propto r^{-\gamma}$, where $\gamma \sim 3$). Hence to make comparisons it is necessary to plot ratios; the upper right and lower plots in figure 1 show results for **mocspl**, **corsib** and **corqgs**.

Note that the differences between **corsib** and **mocsib** are qualitatively as significant as those between **mocspl** and **mocsib**. EGS4 produces 40% more gamma rays at large core distance than the electromagnetic code in MOCCA.

The density of muons in **mocsib** and **corsib** should presumably be the same, and the 10% difference at large core distance may be due to the inadequate treatment of Kaons in **mocsib** (or differences in the muon scattering code). **corqgs** shows similar behavior in the electromagnetic particles to **corsib** but the density of muons is increased by $\sim 50\%$.

The Auger array will make its best estimate of the water Čerenkov signal size at ~ 1 km from the core (due to the reconstruction effect of a power law lateral distribution with unknown slope on a sparse array of detectors) The Hybrid cross calibration plan means that the $\sim 50\%$ range of the models for this parameter is actually no cause for concern.

3.2 Fluctuations

The thinning technique which is used to accelerate air shower simulations introduces artificial fluctuations, since only a sample of the total particles are tracked. As already mentioned, the lateral distribution is to first order a r^{-3} power law, and thus the bulk of the shower particles are close to the core. These two statements imply that the thinning-induced fluctuations grow with core distance. Figure 2 shows the lateral distributions of 300 individual showers thinned at 10^{-7} of primary energy. In an annular bin far from core there only a few particles arriving, each carrying a high ($\sim 10^4$) weight, and bin-to-bin "noisy" fluctuations result. This is clearly seen in the gamma and electron plots of figure 2.

The way in which the accuracy of the calculations improve with decreasing thinning level has been investigated previously [6]. Figure 3 shows the now expected result; at a thinning level of 10^{-7} the artificial fluctuations do not start to dominate until a core distance of > 1 km. (It is probable that some fraction of the rise beyond this distance is not artificial.)

Figure 4 shows the fractional fluctuations for $10-7$ thinning and each combination of framework program and high energy hadronic model. **mocsib** and **corsib** are nearly identical. **mocspl** shows less fluctuation in electromagnetic particles, and more in muons; for **corqgs** the situation is reversed. The fluctuation of gammas and electrons is typically $\leq 10\%$, and that of muons $\sim 15\%$. It is encouraging to note that the fluctuation of the water Čerenkov signal is $\sim 10\%$ for all combinations at ~ 1 km.

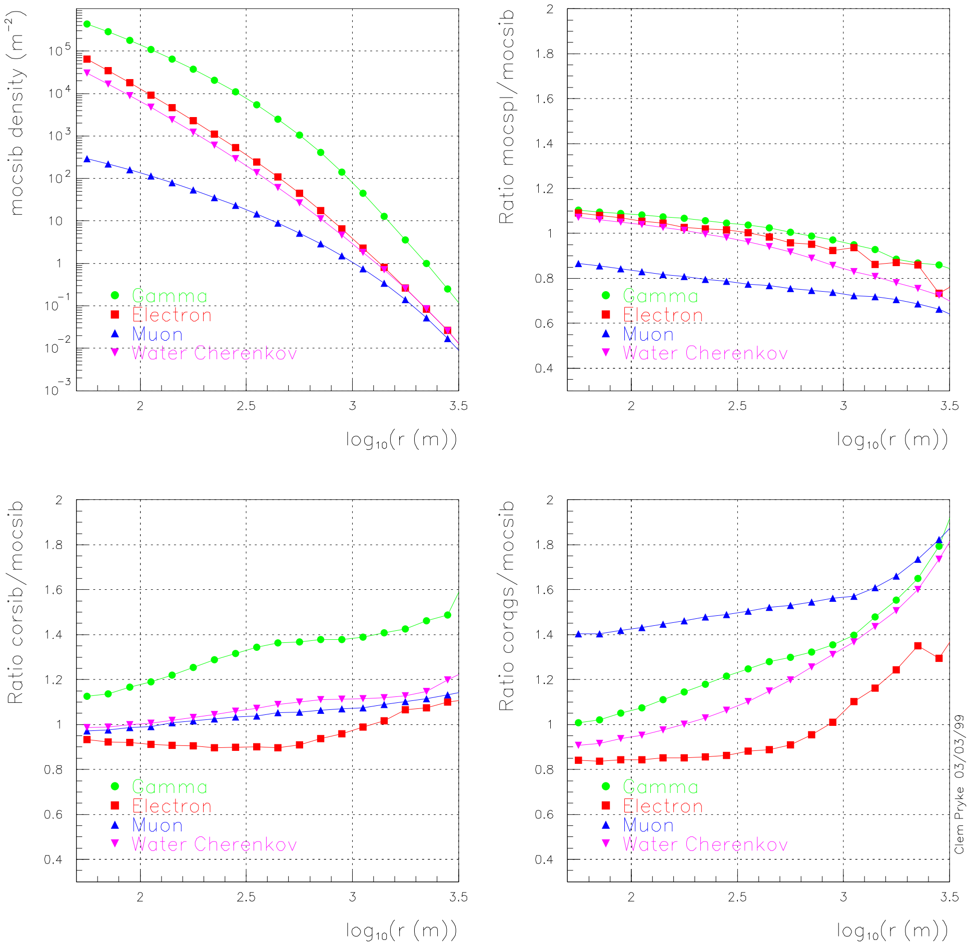

Figure 1: The average lateral distribution from **mocsib** and comparison with the results of 3 other combinations of framework program and high energy hadronic model. (Each an average over 300 showers thinned at 10^{-7}.)

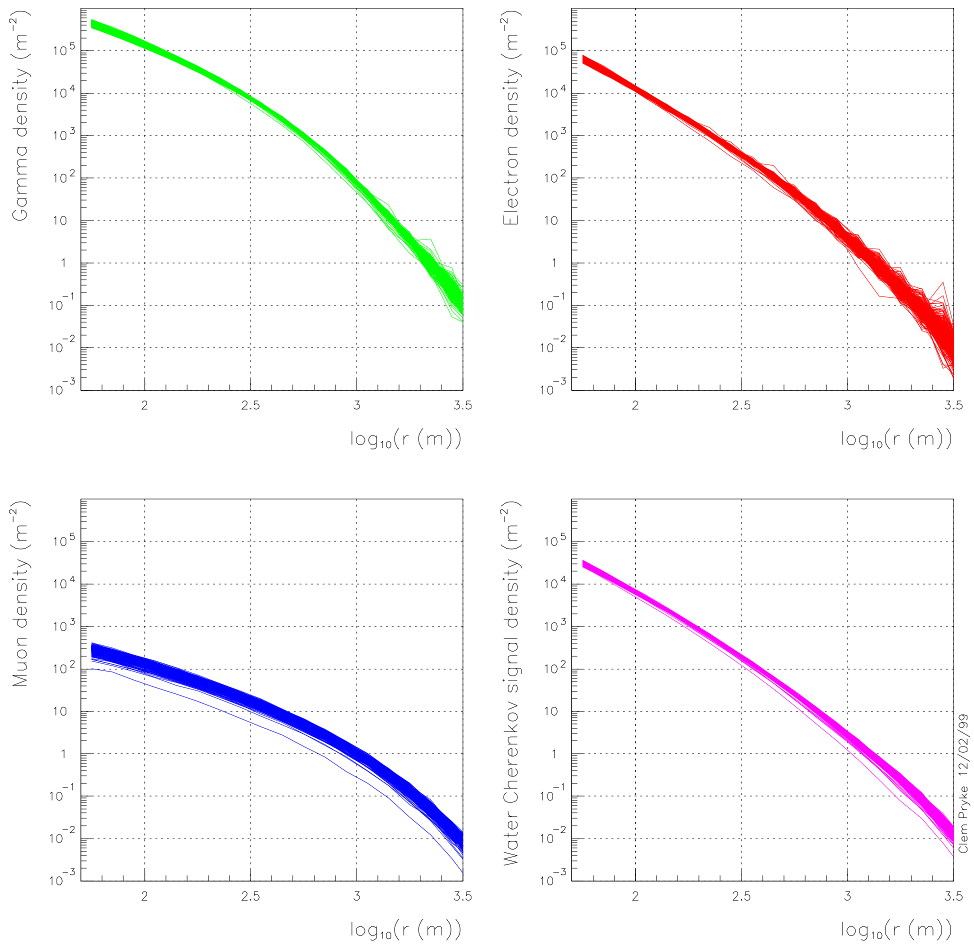

Figure 2: The lateral distributions of 300 individual **mocsib** showers thinned at 10^{-7} of primary energy.

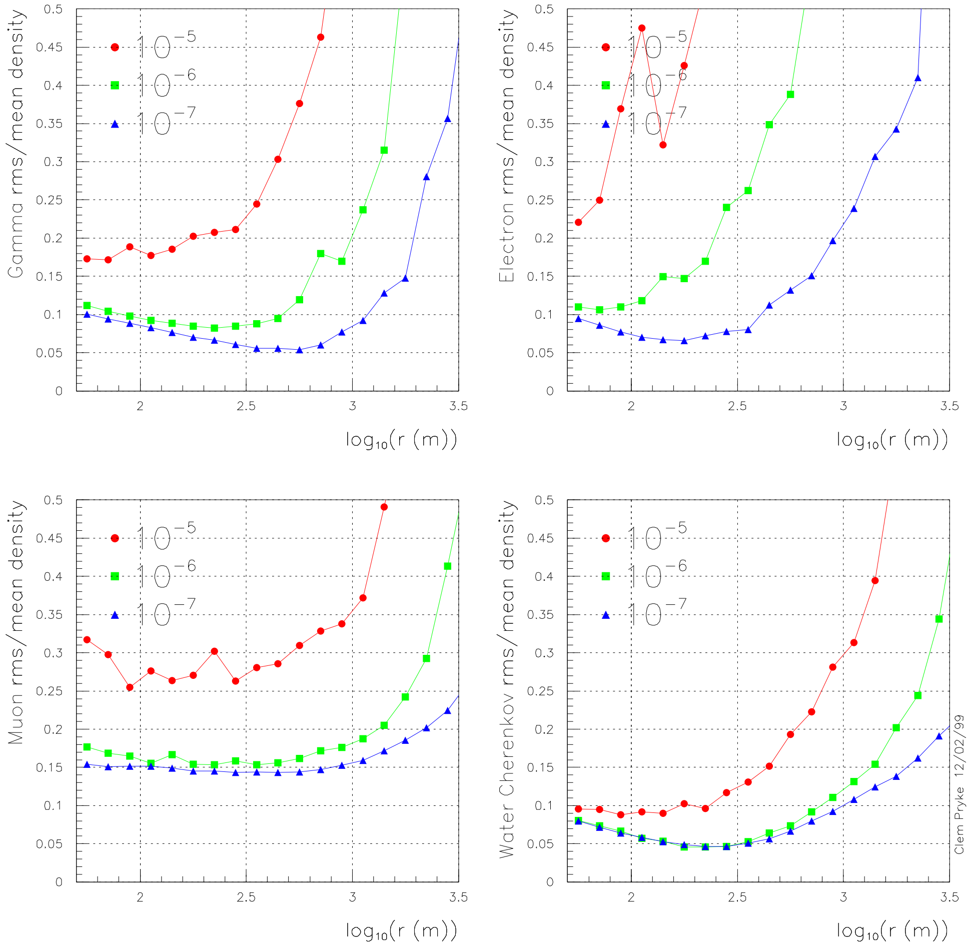

Figure 3: The fractional fluctuation in the lateral distribution of **mocsib** showers at three thinning levels.

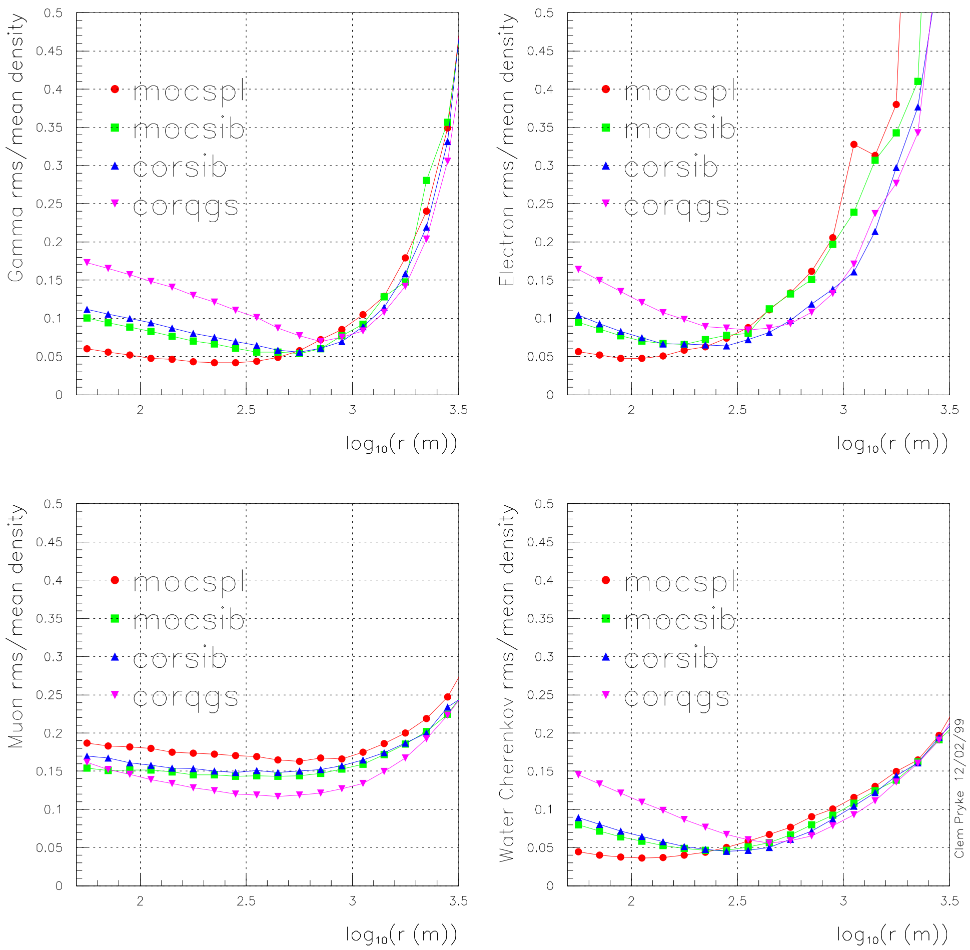

Figure 4: The fractional fluctuation in the lateral distribution of showers from four combinations of framework program and high energy hadronic model (10^{-7} thinning).

4 Particle Characteristic far from the Shower Core

The following comparisons are made for an average over the complete set of 300 showers thinned at 10^{-7}. Hence they do not necessarily reflect the distribution for any individual shower. Additionally each has been normalized to have the same area — the objective is to compare the distribution shapes — the absolute numbers having been compared above.

The particles which arrive at the ground far from the shower core are the product of low energy processes; ie. they might depend on the details of the *low* energy interaction models. Therefore we might expect **mocspl** and **mocsib**to be similar, and **corsib** and **corqgs** to be similar.

4.1 Energy Distribution

When calculating the signal yield in a thick detector it is necessary to know the energy spectra of the shower particles, and not just their numerical density; figure 5 shows a comparison. CORSIKA produces a bigger fraction of soft gamma rays; this is very probably more correct as the ability of EGS4 to describe low energy interactions correctly is proven. CORSIKA also produces a bigger fraction of soft muons which may be significant when calculating the number of muons which stop in a water Čerenkov detector, and the effect which their subsequent decay has on the apparent time dispersion of the signal.

4.2 Arrival Time Distribution

Figure 6 shows the arrival time dispersion of the shower particles. Notice that for gammas and electrons all models are practically identical. CORSIKA produces a bigger fraction of late muons (probably the soft ones noted in the previous section).

4.3 Angle Distribution

Figure 7 shows the angular distributions of the shower particles arriving at ground level. The arrival angle is split into two components; θ_{plane} is the angle projected into the plane defined by the shower axis and the arrival

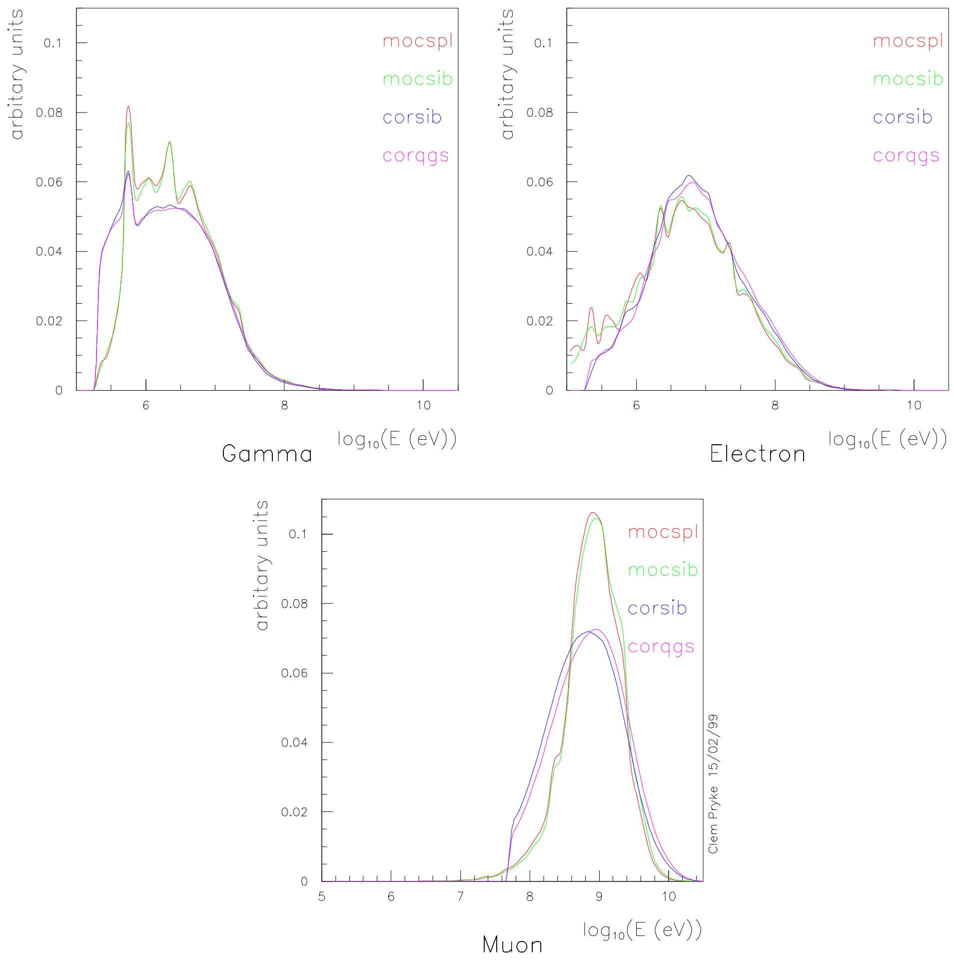

Figure 5: Particle energy spectra for four combinations of shower framework and high energy hadronic model. (Taken in the core distance range $1 < r < 2$ km for 300 showers thinned at 10^{-7}, and normalized to have equal area.)

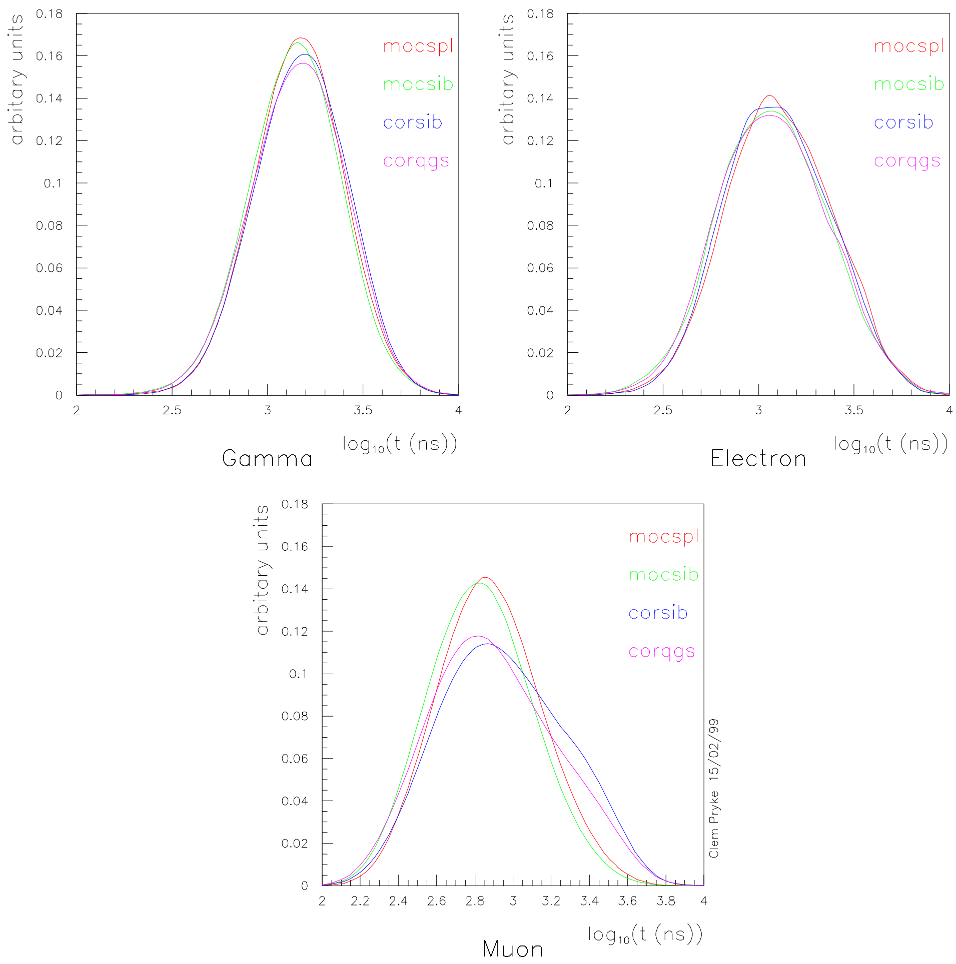

Figure 6: Particle arrival time distributions for four combinations of shower framework and high energy hadronic model. (Taken in the core distance range $1 < r < 2$ km for 300 showers thinned at 10^{-7}, and normalized to have equal area.)

position on the ground, while θ_{perp} is the angle in the plane perpendicular to this. θ_{plane} is a measure of the point along the shower axis that a ground particle "points back to", and is a product of emission angle and scattering; θ_{perp} presumably results from scattering alone. Note that all models produce practically identical results for these parameters.

4.4 Weight Distribution

The thinning algorithm as implemented in CORSIKA 5.2 was non-optimal. In CORSIKA 5.6 it is now nearly identical to that of MOCCA [5]. Figure 8 shows the distribution of particle weights for the four combinations of framework program and high energy hadronic model. A log scale on the vertical axis is appropriate since higher weight particles will dominate unless γ is greater than 1 in $\frac{dN}{d\log W} \propto (\log W)^{-\gamma}$. This is seen to be the case for instance for the electron weights below 10^4, and in fact these lower weight particles simply increase the size of the output file, while contributing very little to the result.

5 Runtimes

Figure 9 shows the run times for the four combinations of hadronic-model and framework program. Notice that CORSIKA runs at approximately half the speed of MOCCA, and that both programs scale with thinning level in the same way. The total run time for the showers used in this paper was ~ 1000 days on 180 MHz R10000 CPUs.

6 Online Materials

The entire set of runs generated for this paper are available online at this time. However the raw output files occupy over 22 GB of space and it is almost certainly impractical to move them through the Internet; tapes could be made upon request. These file will very probably be deleted in the not too distant future.

Reduced HBOOK files occupy only 6 MB. Both sets of files are available at: `ftp://aupc1.uchicago.edu` — once there proceed to the directory `auger/showlib/modcomp/latrdist/pro/gap-98-036`. Putting the above

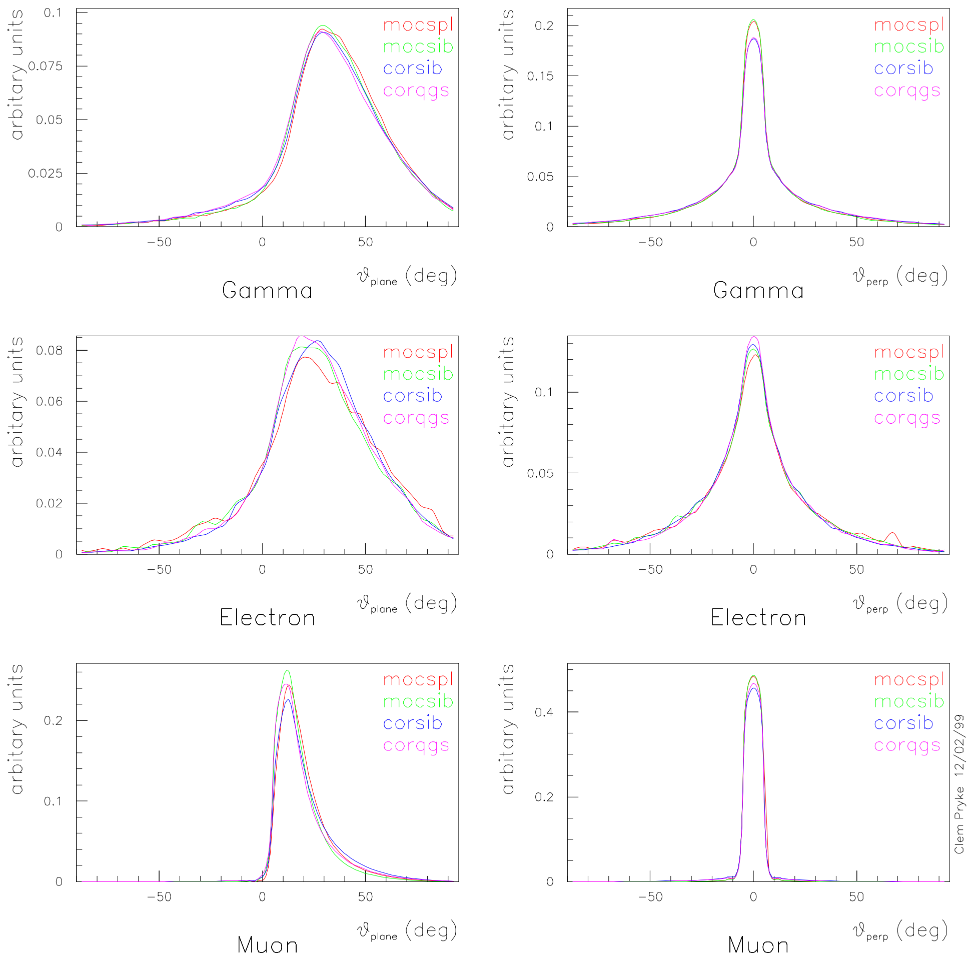

Figure 7: Particle arrival angle distributions for four combinations of shower framework and high energy hadronic model. (Taken in the core distance range $1 < r < 2$ km for 300 showers thinned at 10^{-7}, and normalized to have equal area.)

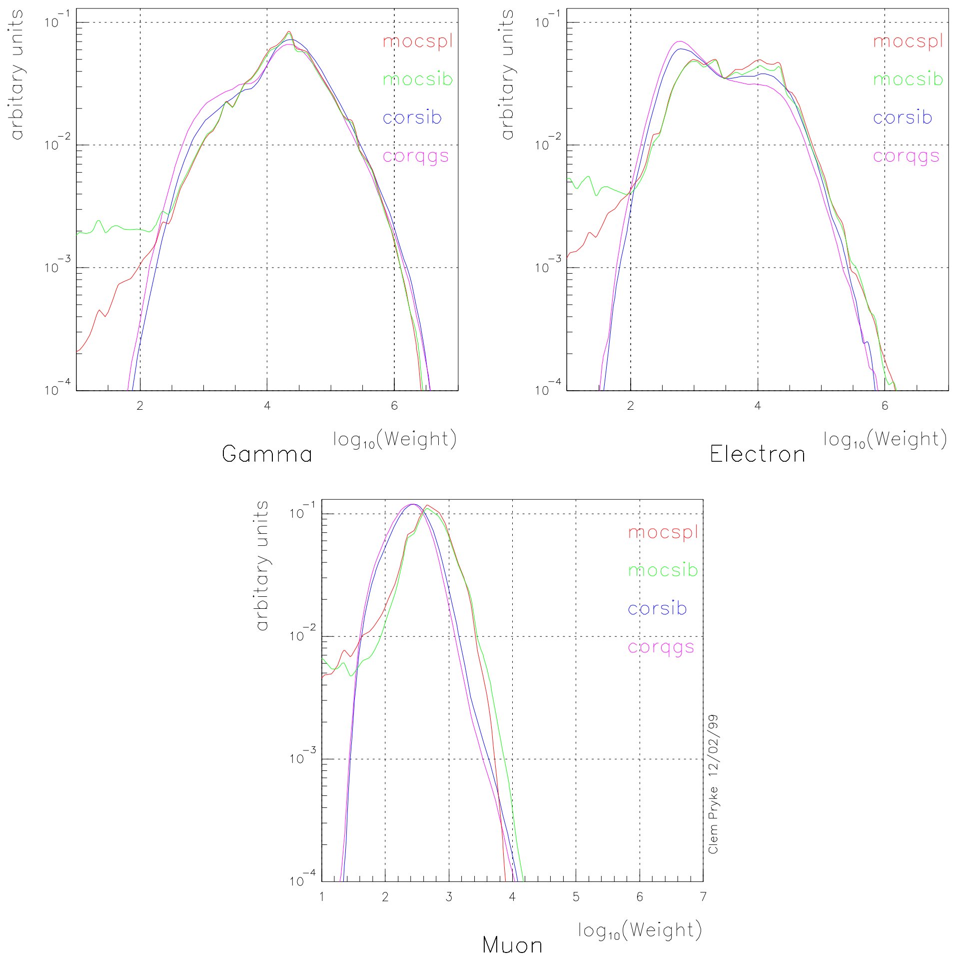

Figure 8: Particle weight distributions for four combinations of shower framework and high energy hadronic model. (Taken in the core distance range $1 < r < 2$ km for 300 showers thinned at 10^{-7}, and normalized to have equal area.)

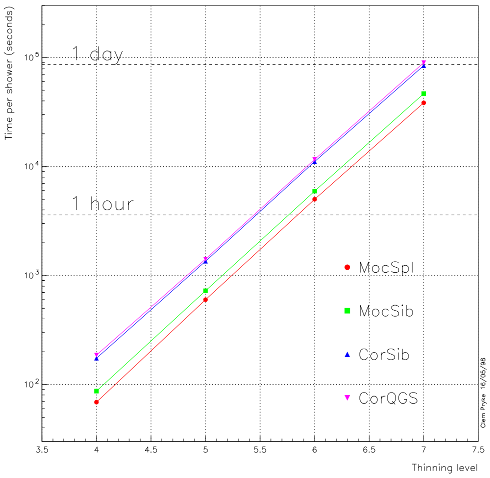

Figure 9: The run time of the four combinations of shower framework and high energy hadronic model plotted as a function of thinning level.

address into Netscape is recommended as informational messages will display for each directory. (Once the ftp site has been explored batches of files can be downloaded with a standard ftp client.)

7 Conclusions

By exploiting hybrid cross calibration the Auger ground detectors will depend only minimally on air shower simulations for energy calibration. This is a big step forward compared to current experiments such as the AGASA which is entirely dependent on the absolute accuracy of shower code.

Nevertheless the possibility remains that interaction physics at the highest energies leads to increasing fluctuations. This would be very harmful to any ground array's ability to measure a steeply falling energy spectrum, regardless of calibration technique. Existing experiments are not really able to rule out increasing fluctuations, although they show no evidence for it.

It is hence encouraging that the models investigated in this paper show such similar fluctuation behavior at 10^{19} eV. This does not prove that they are right, but does increase confidence somewhat.

Additionally it is very encouraging to note that two entirely independent shower simulation "frameworks" — MOCCA and CORSIKA — produce such similar results. Both programs are complex and there is much room for errors, both trivial and insidious. The AIRES program, which has been previously compared to MOCCA [7], is in fact a derivative of it. CORSIKA, however, is an entirely independent code and so the fact that it produces such similar results is perhaps more interesting.

8 Acknowledgements

The Fermilab computing department are thanked profusely for the use of their machines. Thanks to Jim Matthews and Lou Voyvodic for reading the manuscript.

References

[1] C. Pryke presentation to SAGENAP committee November 97, "Simulated Performance of the Auger Observatory Hybrid Detectors". Available at `http://aupc1.uchicago.edu/~pryke/auger/documents/`

[2] D. Knapp *et al*, "CORSIKA: A Monte Carlo Code to Simulate Air Showers", Forschungszentrum Karlsruhe Report FZKA 6019 (1998).

J. Knapp, D. Heck and G. Schatz, "Comparison of Hadronic Interaction Models Used in Air Shower Simulations and Their Influence on Shower Development and Observables", Forschungszentrum Karlsruhe Report FZKA 5828 (December 1996).

J. Knapp, D. Heck and G. Schatz, "Inelastic Cross Sections and Their Influence on Air Shower Development", Forschungszentrum Karlsruhe (June 1997).

J. Knapp and D. Heck, "Extensive Air Shower Simulation with CORSIKA: A User's Guide", Forschungszentrum Karlsruhe.

Available at `http://www-ik3.fzk.de/~heck/corsika/`

[3] W.R. Nelson, H. Hirayama, D.W.O. Rogers, Report **SLAC 265** (1985), Stanford Linear Accelerator Center.

[4] H. Fesefeldt, Report **PITHA-85/02** (1985), RWTH Aachen.

[5] D. Heck and J. Knapp, "Upgrade of the Monte Carlo Code CORSIKA to Simulate Extensive Air Showers with Energies $> 10^{20}$ eV", Forschungszentrum Karlsruhe. Report FZK6067B (Draft April 98).

[6] D. Ravignan, F. Hasenbalg, and C. Hojvat "Cosmic Ray Shower Simulations with MOCCA: Artificial Fluctuations due to Thinning" Auger tech. note GAP-96-020.

D. Ravignani and C. Hojvat, "Fluctuations in the Lateral Distribution from MOCCA Simulations at 10^{-7} Thinning Level", Auger tech. note GAP-96-032.

[7] M.T. Dova and S.J. Sciutto, "Air Shower Simulations: Comparison Between AIRES and MOCCA", Auger tech. note GAP-97-053.