# A NOTE COMPARING TWO LOW-ENERGY HADRONIC INTERACTION MODELS FOR MONTE CARLO SIMULATIONS

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## Summary

The relative merit of two low-energy simulation packages for use with CORSIKA is called into question, including differences in resulting physics as well as an advertised difference in necessary computation time. A brief comparison between the two was thus carried out. They are the FLUctuating Kascade package (FLUKA) [1] and the Gamma Hadron Electron Interaction Shower code (GHEISHA) [2]. Distributions in position and energy were examined for various combinations of parameters and the run-time was compared for a number of simulations. Discrepancies in the resulting particle abundances and energies are demonstrated for certain cases.

## Introduction and Motivation

Of the various low-energy packages available to treat interactions below ~100GeV, GHEISHA has been used predominantly for Milagro MC simulations. FLUKA was developed independently of CORSIKA, modified to work within it, and is purportedly 'more advanced' than GHEISHA, using three different models, applied in different energy regimes, to calculate hadronic cross-sections with atmospheric components, secondary particle production, and to follow the target nucleus. The CORSIKA manual predicts resulting computation times up to 7 times longer than GHEISHA[1]. Here, the goal was to determine if the simulation results justified this increased time and to assess any other noticeable differences in performance and physics.

Trials were carried out in conjunction with the Very Energetic Nuclear Scattering (VENUS) program for high energies, with the assumed transition at 80GeV. Twenty trials were conducted with energies between 10GeV and 50TeV, simulating between 5000 and 30000 events and with an observation altitude set at 4500m. All showers were simulated from zenith and an angle-fitter was used to compare the predicted particle arrival time distributions of the two packages. Identical input was fed to both and the run times, lateral distributions and energy distributions were compared. In addition, I hoped to confirm or deny claims by the CORSIKA authors that the low energy muonic and hadronic components exhibited particular discrepancies.

## Simulation Results

### TIMING OF COMPUTATIONS

In my simulations, the difference in run-time for the two packages was not as pronounced as the CORSIKA authors had claimed. This is due to the fact that most simulations were carried out with gammas as the primary particles and it is expected that the EM-component of the shower represents up to 90% of the run time. Proton showers demonstrated an appreciable timing difference. Over several trials, FLUKA required 1.45 times longer, on average, for energies up to the transition energy for proton showers. Higher transition energies will further increase the run-time and above this energy the timing is a function of the chosen high-energy package. This was confirmed by running below, at, and above the 80GeV transition.

The run time for both FLUKA and GHEISHA was directly proportional

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[1] Corsika Manual, Version 6.200, from October, 2004. Pg. 82

to the number of events at a fixed energy but was especially sensitive to changes in the low end of the simulated energy range, as would be expected.

Finally, for identical, repeated tests, GHEISHA showed a fluctuation in run time of up to 5%, whereas FLUKA appeared more stable, with fluctuations not exceeding 2%. This may be merely a result of other processes running on the machine, although the differences were consistent over several trials.

### LATERAL DISTRIBUTIONS

The lateral particle distributions show relative consistency between the two packages. Similar profiles are seen when plotting position against time as well as arrival time vs. core distance (see figures 1-4). The upturn at the core in figures 2 and 4 is likely due to later particles at the center of the shower increasing the mean at that point. Reference [4], which simulates protons at energies up to $10^7$TeV, claims that the observed lateral particle distributions fall off by 5 orders of magnitude between the two models if one goes out to several km from the core. Any difference is masked at the core because of the predominance of higher-energy interactions, but becomes visible at the fringes where the lower energy particles show up. In the context of Milagro, these differences are likely to be negligible at the distances concerned.

As mentioned, all showers were thrown from zenith. An angle fitter was run as a test to measure discrepancies in curvature and particle arrival-time distributions, with inherent sampling corrections based on the GHEISHA package. The fitter conducts six passes, presumably improving each time and the results (figures 5 and 6) are shown to be comparable for both FLUKA and GHEISHA.

### HADRONIC AND MUONIC SHOWER COMPONENTS

The most pronounced physical difference between FLUKA and GHEISHA is evident in the low energy hadronic and muonic shower components. References [3] and [4] claim that SLAC has provided some patches for GHEISHA which improve its kinematics and eliminate some of its early shortcomings. Some remain, however, and these have a tendency to create an excess in elasticity and thus a "stretching of the low-energy [hadronic] branches" [2]. This manifests itself in the hadronic energy distributions, especially for muons (shown below) and pions. My findings confirm the differences reported in [5], particularly at the lowest energies (see figures 7-14 for tests with both gamma and proton primaries) although the literature notes differences of up to 15% below 30GeV. Thus for any applications where the low-energy muon and hadron components are influential, the increased computation time required by FLUKA is likely merited, as GHEISHA's kinematics are dubious for these energies.

Although unconfirmed here, the references also cite cases in which GHEISHA has produced a sum of secondary particle energy and deposited energy that exceeds the primary energy (by several percent in some cases). Again, users should be wary of this in cases where the low-energy components are of great importance.

## Conclusions

Unless computation time is extremely critical, it seems advisable to use FLUKA over GHEISHA. These simple trials mirrored the trends suggested in the references and seem to support the discrepancies at low energies due to GHEISHA's kinematics. In the case where the primary particles are electromagnetic, the difference in run time is negligible and thus GHEISHA presents no special advantage, nor is there anything to be lost in running FLUKA. For hadronic showers, computation time can be shortened by using GHEISHA, as long as particles below ~30GeV are of little importance to the results.

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[2] Heck, [4], Pg. 4

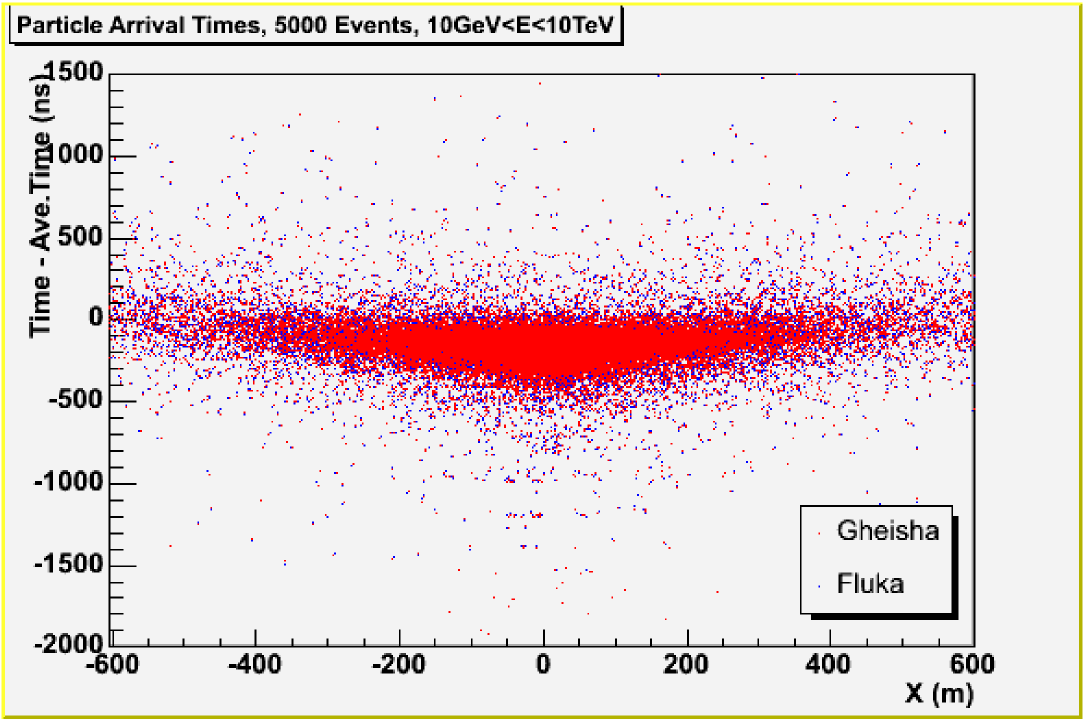

Figure 1: X vs. Time - Average Time for 5000 events with energies from 10GeV to 10TeV, from zenith. GHEISHA is shown in red and FLUKA in blue. The two packages appear comparable.

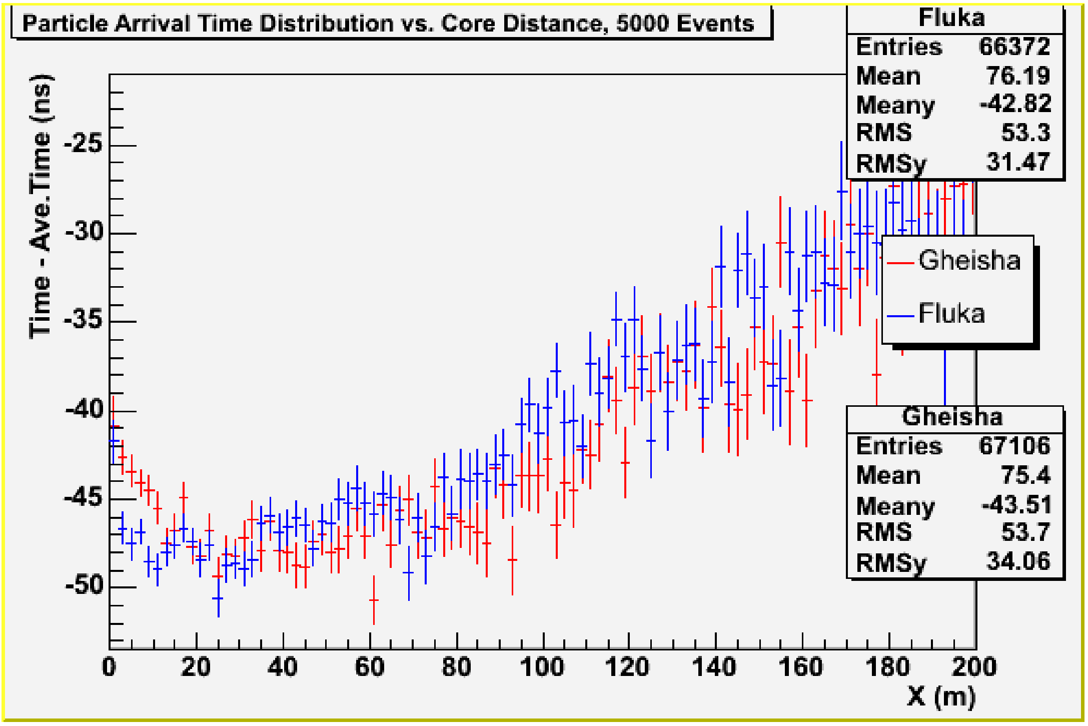

Figure 2: Arrival time vs. core distance for the same simulation, representing the mean in each X bin, along with its RMS. The upturn at the core is thus an artifact of the large number of later particles which pull the mean up.

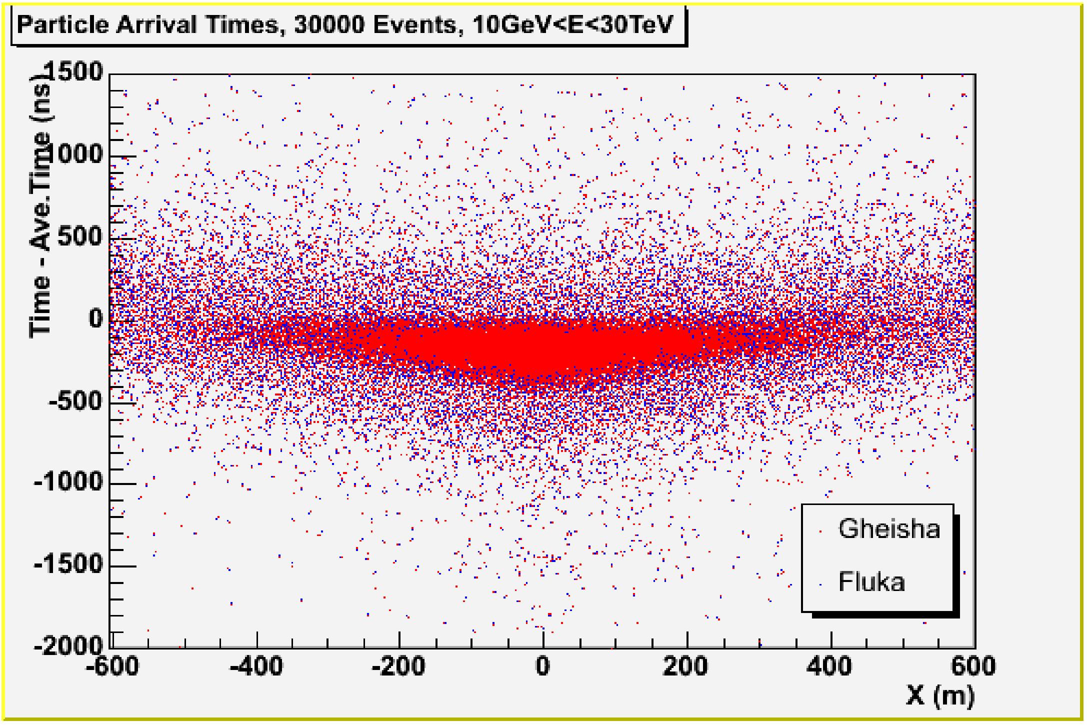

Figure 3: X vs. Time - Average Time for 30000 events with energies from 10GeV to 30TeV, from zenith. GHEISHA is shown in red and FLUKA in blue.

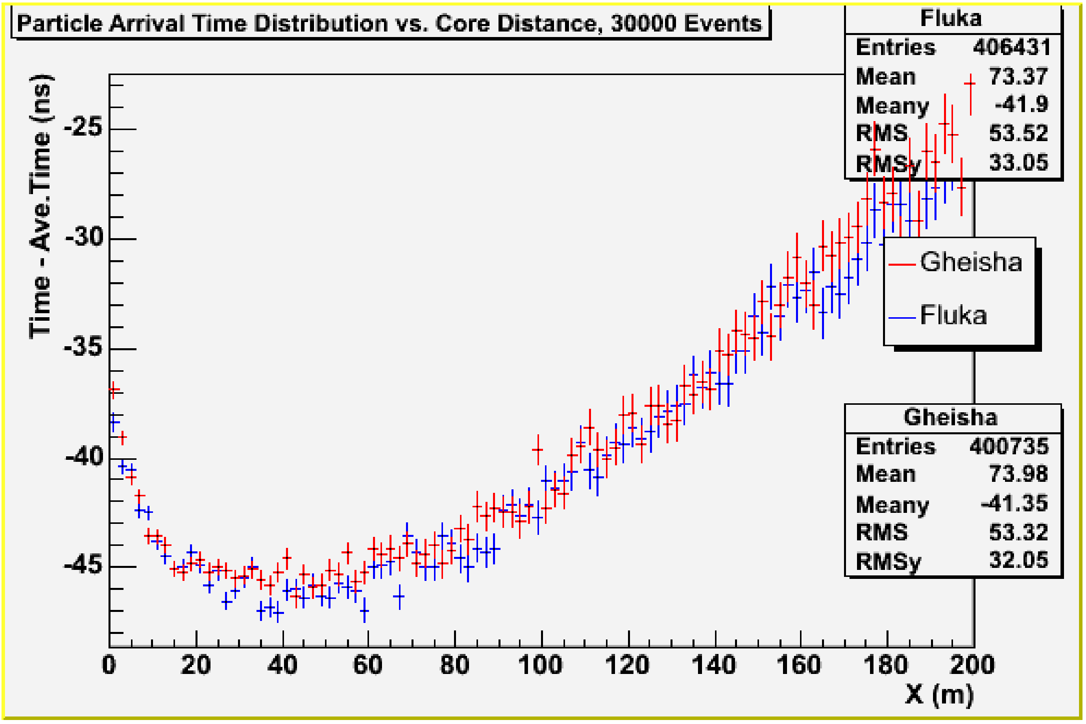

Figure 4: Arrival time vs. core distance for the same simulation, representing the mean in each X bin and the associated RMS.

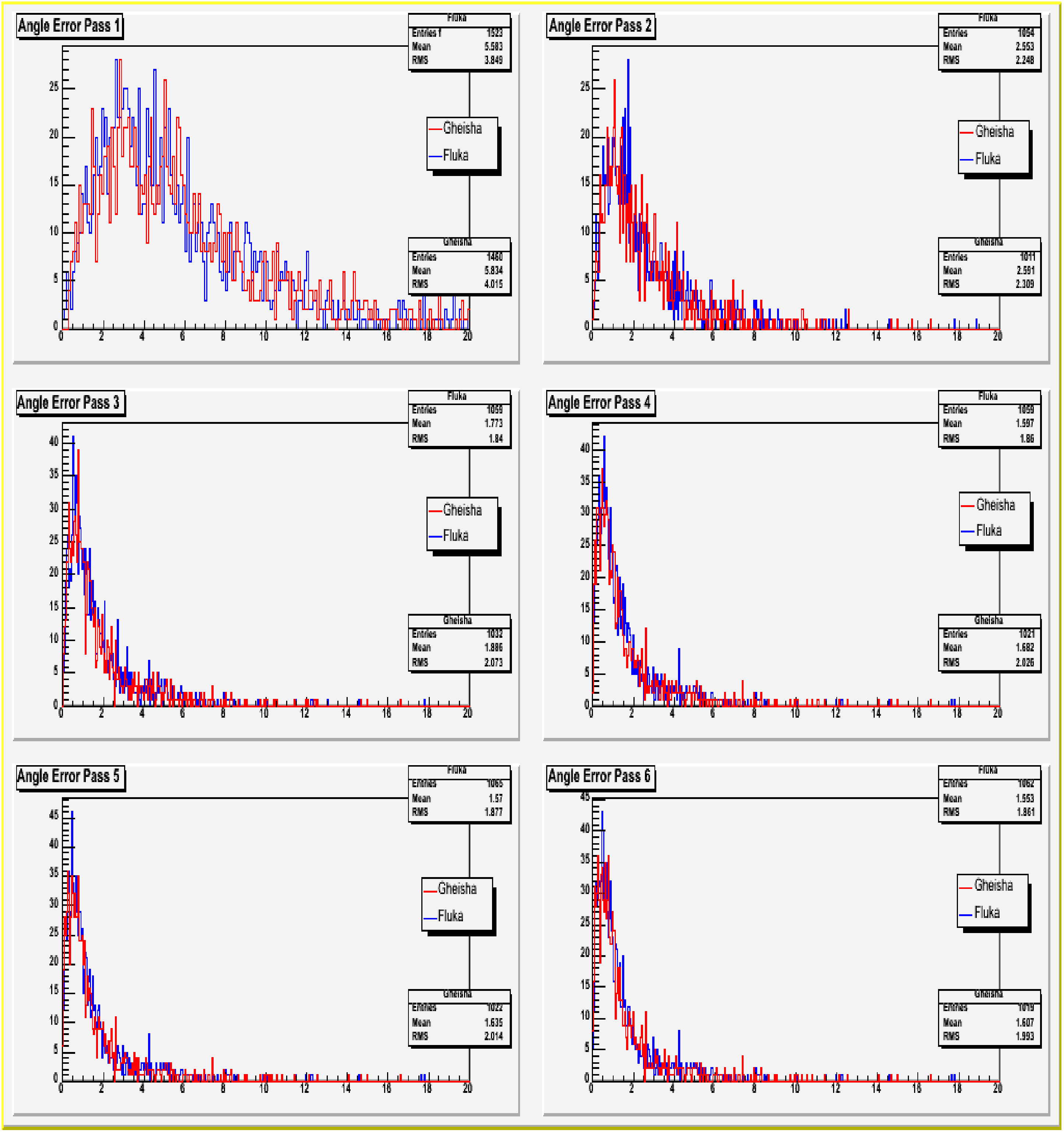

Figure 5: Results of the angle fitter, run on the 5000 event (gamma) simulation from above. For each of the six passes conducted, both models show comparable error from zenith.

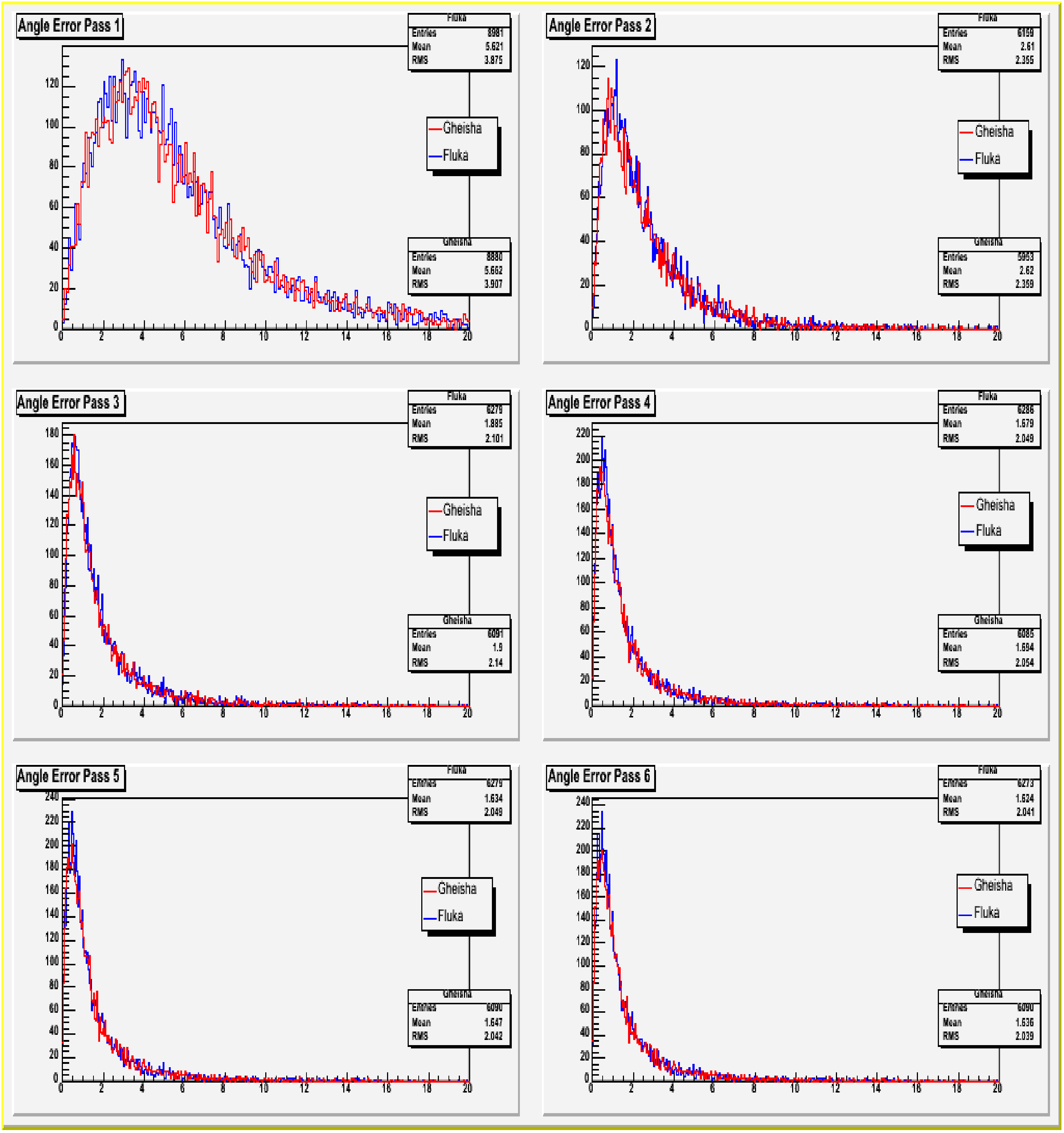

Figure 6: Results of the angle fitter, run on the 30000 event simulation from above. Again, both models show comparable performance and the maximum error in the sixth pass is less than 1 degree.

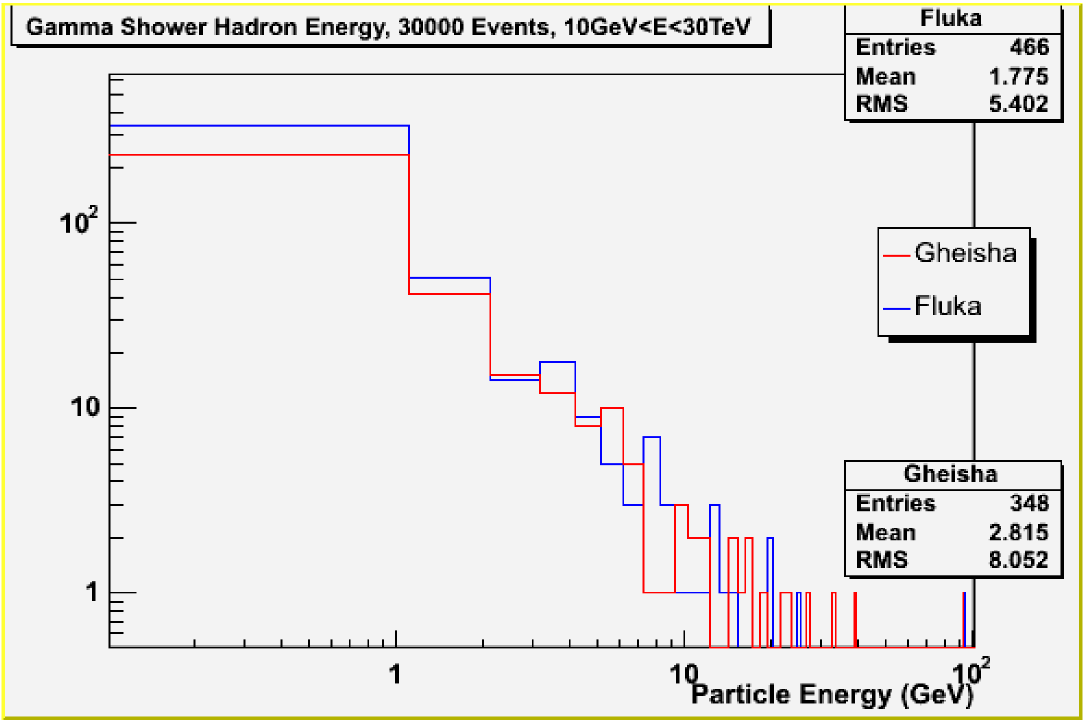

Figure 7: Hadron energies from the 30000 event simulation show that GHEISHA produces a relative deficit of low-energy particles. Included here are $\mu^{\pm}$, $\pi^{\pm,0}$, $K^{\pm}$, $K^{0}_{L}$, $K^{0}_{S}$, $n$, and $p$.

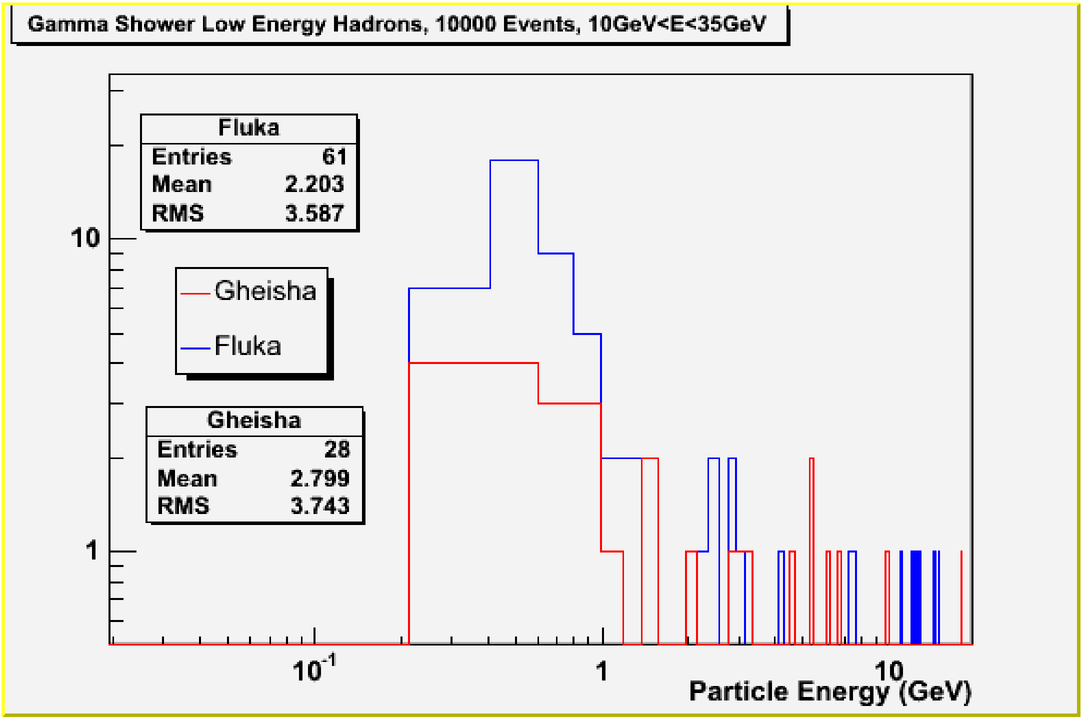

Figure 8: Hadron energies from a low-energy, 10000 event simulation (10GeV<E<35GeV) show the same deficit as above. The same particles are included here: $\mu^{\pm}$, $\pi^{\pm,0}$, $K^{\pm}$, $K^{0}_{L}$, $K^{0}_{S}$, $n$, and $p$.

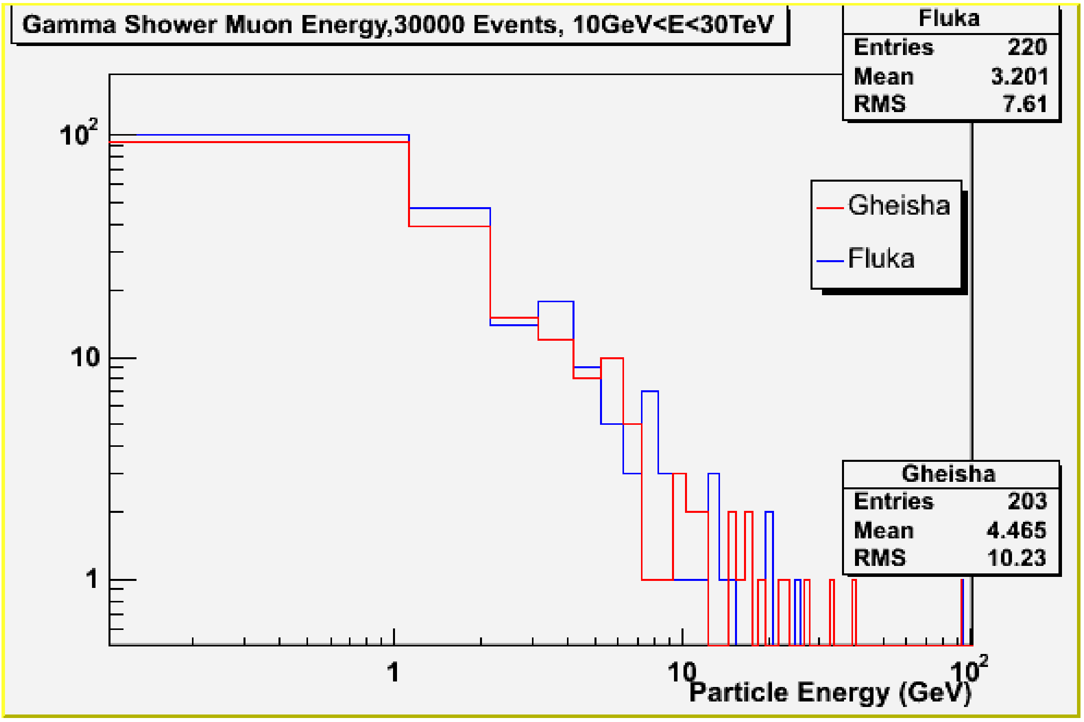

Figure 9: Plotting $\mu^{\pm}$, alone, from the 30000 event simulation (10GeV<E<30TeV) to view the muonic contribution to the low-energy deficit mentioned above.

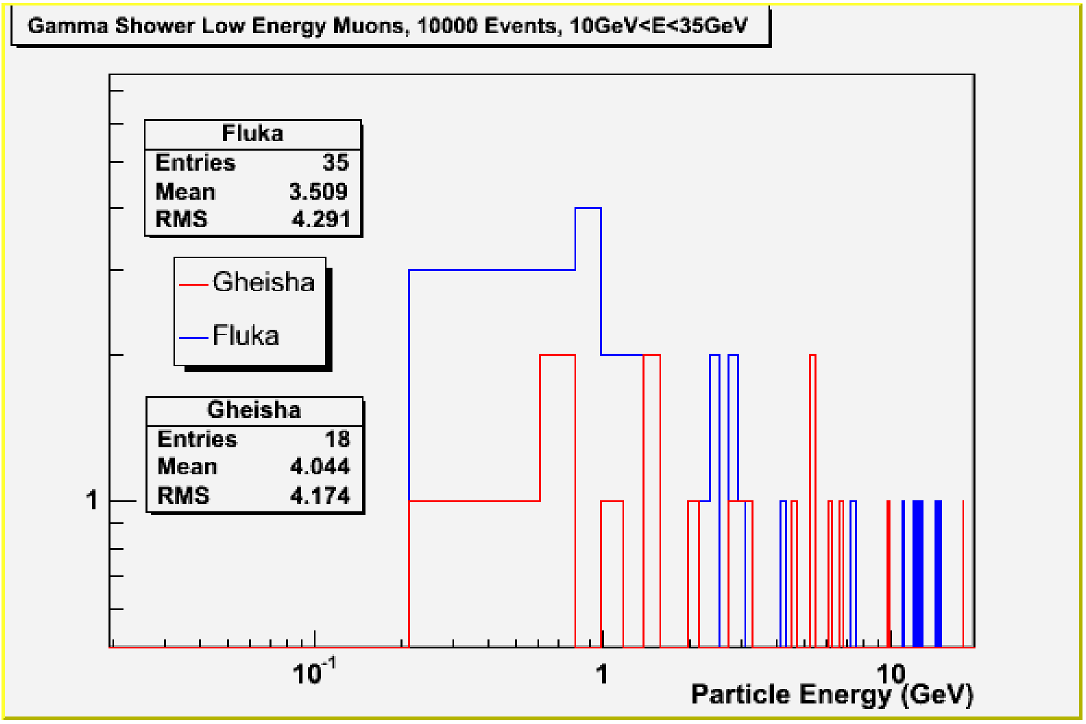

Figure 10: Plotting $\mu^{\pm}$, alone, from the 10000 event simulation with lower energy gammas, as used in figure 8 (10GeV<E<30GeV).

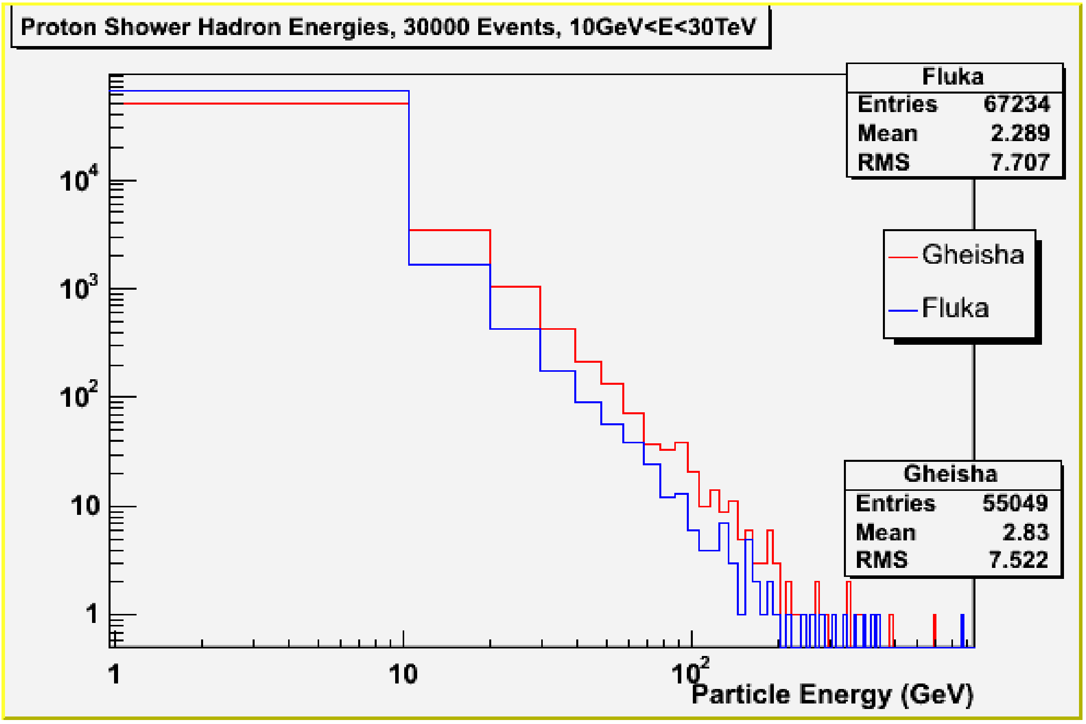

Figure 11: Identical conditions to figure 7, but throwing protons instead of gammas. The same low-energy particle deficit is visible. Note the differing number of entries in the legends. The same particles are included here: $\mu^{\pm}$, $\pi^{\pm,0}$, $K^{\pm}$, $K^0_L$, $K^0_S$, $n$, and $p$.

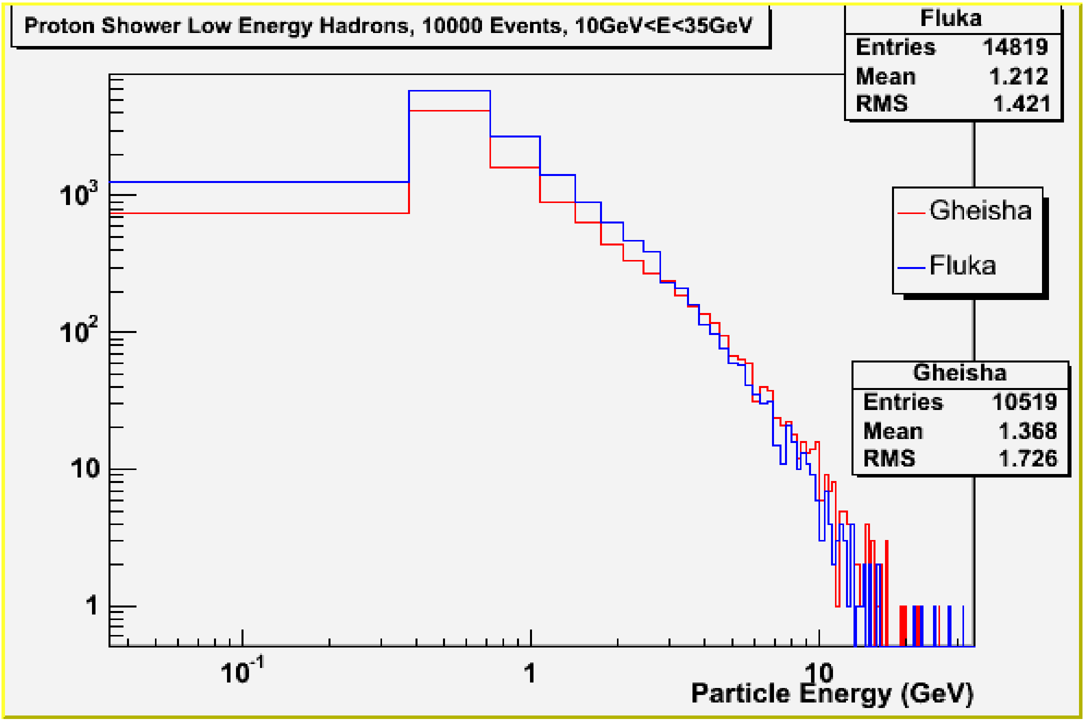

Figure 12: Identical conditions to figure 8, for low energies, but throwing protons instead of gammas. $\mu^{\pm}$, $\pi^{\pm,0}$, $K^{\pm}$, $K^0_L$, $K^0_S$, $n$, and $p$ are included.

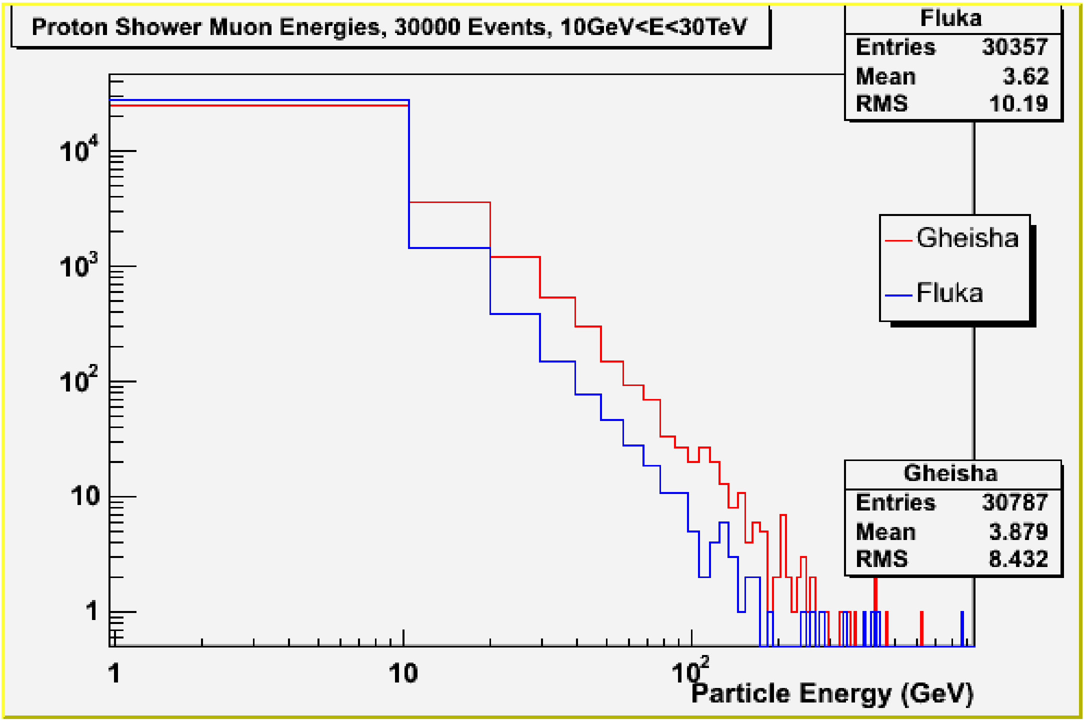

Figure 13: Plotting $\mu^{\pm}$ with conditions identical to figure 9, but throwing protons instead of gammas.

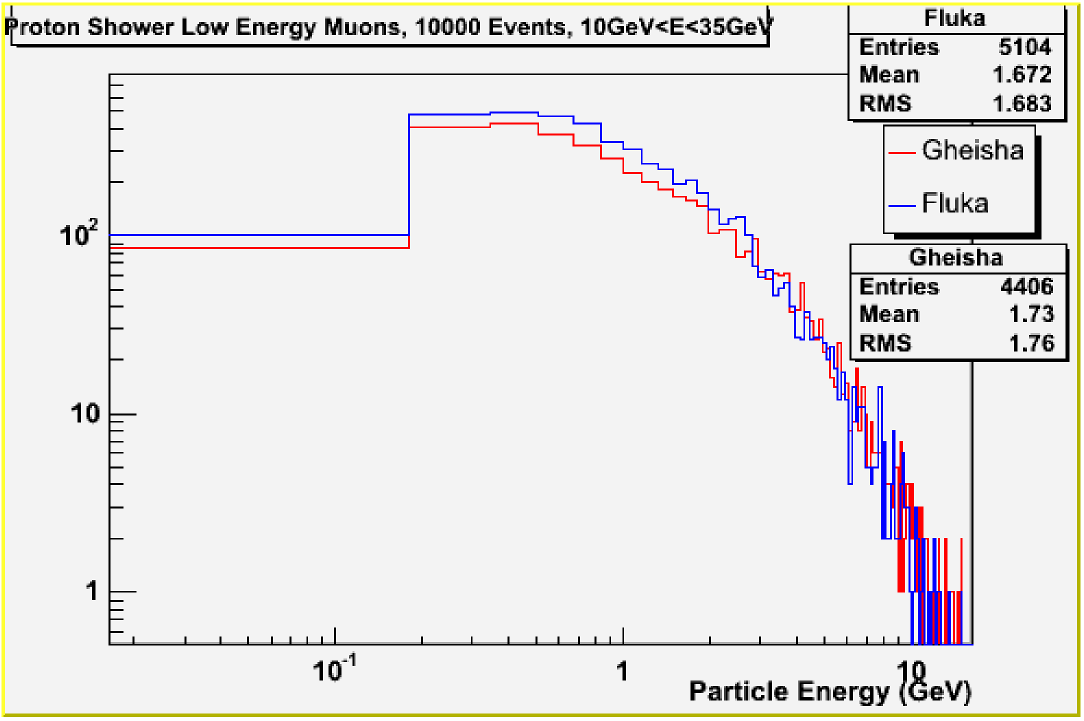

Figure 14: Identical conditions to figure 10, with lower energy protons instead of gammas. The same deficiency of low-energy particles is visible.

# References

[1] A.Fasso', A.Ferrari, J.Ranft, P.R.Sala, "FLUKA: Status and Prospective for Hadronic Applications", Proceedings of the Monte Carlo 2000 Conference, Lisbon, October 23-26 2000, A.Kling, F.Barao, M.Nakagawa, L.Tavora, P.Vaz - eds. , Springer-Verlag Berlin, p.955-960 (2001).

[2] H. C. Fesefeldt, GHEISHA program, Technical Report PITHA 85-02, III Physikalisches Institut, RWTH Aachen Physikzentrum, 5100 Aachen, Germany, September 1985.

[3] D. Heck et al., Report FZKA 6019 (1998), Forschungszentrum Karlsruhe; http://www-ik.fzk.de/~heck/corsika/physics_description/corsika_phys.html.

[4] D. Heck, Low-Energy Hadronic Interaction Models, Proc. XIIIth Int. Symp. on VHE Cosmic Ray Interactions, Pylos, Greece (2004), Nucl. Phys. B (Proc. Suppl.) in print; astro-ph/0410735

[5] D. Heck, R. Engel, G. Battistoni, A. Fasso, A. Ferrari, J. Ranft, P.R. Sala, Influence of Low-Energy Hadronic Interaction Programs on Air Shower Simulations with CORSIKA, Proc. 28th Int. Cosmic Ray Conference, Tsukuba (Japan), 2003, p. 279.