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The Ultimate Monte Carlo: Studying Cross-Sections With Cosmic Rays

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Abstract: The high-energy physics community has been discussing for years the need to bring together the three principal disciplines that study hadron cross-section physics - ground-based accelerators, cosmic-ray experiments in space, and air shower research. Only recently have NASA investigators begun discussing the use of cosmic-ray payloads to bridge the gap between accelerator physics and air shower work using space-borne cosmic-ray measurements. The common tool used in these three realms of high-energy hadron physics is the Monte Carlo. Yet the obvious has apparently not been considered in earnest - using a single Monte Carlo as a “mathematical experiment” for simulating the entire range of energy (GeV to EeV) while calculating cross-sections when these are not available. The task is daunting due to a large disparity in accelerator, space, and shower measurements. Uncertainties involve inclusive versus exclusive cross-section measurements, primary shower composition, hadron interaction dynamics, and possible new physics beyond the standard model. However, the discussion of a common tool or ultimate Monte Carlo might be something that could begin to unify these independent groups into a common purpose. The Offline ALICE concept at CERN’s Large Hadron Collider (LHC) will be discussed as a rudimentary beginning of this idea, and a possible forum for carrying it forward in the future as LHC data emerges.

Introduction

The cosmic ray (CR) community has been concerned for years about the problem of reconciling accelerator cross-section data with cosmic-ray measurements made in space or taken from cosmic-ray initiated air showers and atmospheric fluorescence. The energy range is phenomenal, from 100 MeV to 100 EeV covering nucleon-nucleon and heavy-ion collisions (e.g., *p-p*, *p-A*, and *A-A*) of all kinds.

These energies take us to the threshold of our understanding of hadron physics and the frontier that lies beyond. As the Large Hadron Collider (LHC) at CERN comes online this year, basic questions in fundamental particle physics will be addressed having to do with experimental verification of the Standard Model and its limitations. Without question, cosmic rays are closely connected to any new physics that arises within and lies beyond the Standard Model.

One of the important parameters in particle physics to be measured is total cross-section, σ_T. Historically, the data on cross-sections has derived from hadron colliders like CERN and Fermilab, and their predecessors [1]. Since these ground-based observations are limited in energy and luminosity, the intriguing question of how to determine cross-sections, theoretically and experimentally, from high-energy cosmic-ray measurements has occurred to a number of groups.

The real issue is one of unification. Three different disciplines in high-energy physics collect data on heavy-ion collisions. How can this research be made consistent, and why won’t consistency reduce the total cost?

The extraction of the *p-p* cross-section from cosmic-ray data has been the subject of a number of studies [2-6]. The use of air-shower data is first confronted by the problem that the identity of the nucleus initiating an air shower is unknown. Also, an incident proton *p* interacts with air resulting in a *p-air* cross-section $\sigma_{p\text{-}air}$ which has no direct bearing with hadron collider measurements. Hence, obtaining cross-sections directly from extensive air showers (EASs) is not possible. The solution, therefore, must be a phenomenological one.

Secondly, the inelastic component of $\sigma_{p\text{-}air}$ must be identified in order to apply Glauber theory [7, 8] and determine the *p-p* total cross-section σ_{pp}. The next complication is that the $\sigma_{p\text{-}air}$ data must be transformed into the center-of-mass frame for consolidation into the ground-based accelerator data based upon $\sqrt{s}$ energies [6]. These steps necessarily involve a number of assumptions: the air-to-center-of-mass frame transformation per se (e.g., Fig. 3 of [2]), the Glauber approximation itself [7, 8], and "optical" properties of hadrons that help define the phase shift χ in the scattering amplitude using the optical theorem. Gribov theory [9] is also used as well as multiple scattering approximations [6]. A brief discussion of EAS versus CR physics is available in [10].

Needless to say, the physical properties of hadrons are essentially unknown except at low and medium (nonrelativistic) energies and such assumptions are very limited. The principal source of inspiration for confronting hadron collisions is QCD[1] and the quark-parton physics of the Standard Model.

Nevertheless, the evolution of important atmospheric cascade experiments such as Auger [11], Fly's Eye [12], and CORSIKA [13] has presented a challenge that accelerator physics needs to support air-shower research more vigorously. To this one can add the subject of space-borne CR calorimeter-based detectors, and how these can address the common goal of understanding hadron and nuclear physics by making measurements in space at energies beyond those attainable at the LHC. In such a case, no air-shower physics is involved (unless air-shower photodetectors are orbited above the atmosphere, proposed for OWL).

The idea of utilizing the proposed next-generation space-borne CR detector ACCESS [14] for analyzing cross-sections has been put forward by the ACCESS collaboration [15]. One of the stated purposes of ACCESS is "to help calibrate the air-shower arrays."

A different approach, namely using Monte Carlos for calculating ultra-high energy hadron cross-sections is presented here. It will now be discussed.

Hadron Colliders & Air-Shower Physics

A principal argument for using the Earth's atmosphere as a CR calorimeter is one of statistics. At and below the "knee" around 1 PeV (10^{15} eV), the CR flux becomes so low that only a large-scale array can collect enough statistics within a reasonable period of time. Therefore, the air-shower arrays emerged as the practical means for studying the PeV and EeV energy region. However, there exist no test beams for calibrating these arrays unless a particle accelerator is placed in low-Earth orbit. The calibration problem has since been inherited by the hadron simulation codes, where the largest uncertainties arise in the first place. The electromagnetic and weak interactions are fairly well understood. Although a space-based detector such as ACCESS might be conceivable, its collection power cannot compete with the air-shower arrays except through years of observation time.

Monte Carlos

A summary of some of the popular Monte Carlo models through 1999 used to simulate hadronic and nuclear interactions up to $E_{lab} = 10^{21}$ eV ($\sqrt{s}$ = 2000 TeV) has been given by Ranft [16], who describes the disparity in their predictions. See also [17]. Ranft argues that EAS data can only be reliably interpreted by sampling the EAS cascade using more than one model. These models predict a rise of all hadronic and nuclear cross sections with energy, using Gribov-Regge and Gribov-Glauber theory in a quark-gluon string model to construct multi-string production in hadron-hadron and nuclear collisions.

As the principal author of DPMJET, Ranft was concerned with its extension to air-shower energies. The latest version of DPMJET (DPMJET-3) [18] is available in FLUKA [19] in 2007.

CORSIKA

More recent comparisons of air-shower simulations from the point of view of CORSIKA are given in Heck [20, 21]. Higher cross-sections necessarily predict higher secondary-particle multiplicities. Using data from the KASKADE

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[1] Quantum Chromodynamics.

calorimeter, further comparisons have been compiled by Mielke [22].

An example of the hadron simulation codes versus data and other studies regarding the *p-air* cross-section $\sigma_{p\text{-}air}$ transformation to lab frame energies E_{lab} is shown in Figure 1.

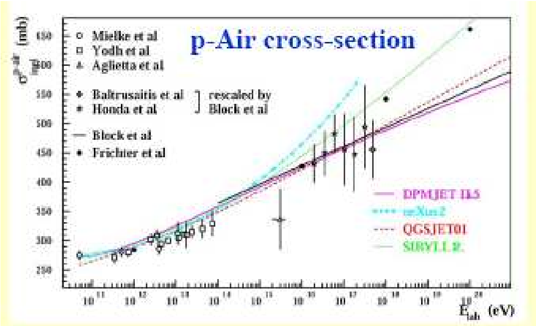

Figure 1: Air-to-Lab transformation [21]

Experimental data from KASCADE has been used to analyze hadron physics at the CR knee [23], with comparisons to various models. A knee was found in the KASCADE data. An impressive summary is given in Figure 2.

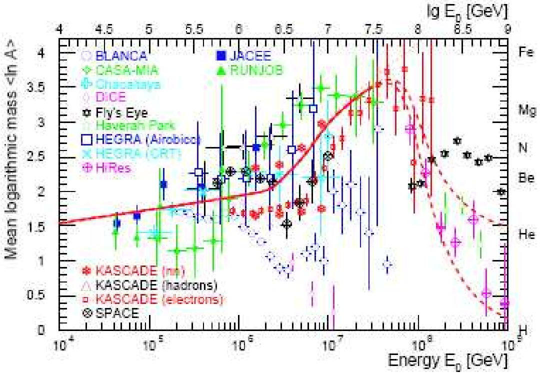

Figure 2: World data on CR mass composition, from [23]

The NEEDS Workshop

One step forward in the unification of cross-section physics has been the discussion of running ground-based accelerator experiments for the purpose of helping tune and calibrate the air-shower Monte Carlos. This effort has been led by Jones [24-28], and resulted in the NEEDS workshop in 2002 in Karlsruhe, Germany [25].

The Mathematical Experiment

The Monte Carlo can be thought of as a "mathematical experiment" [29]. With this perspective in mind, one can view the Monte Carlo as a powerful tool for calculating cross-sections when accelerator data is not available. This is the inverse of the standard Monte Carlo method where cross-sections are given and dynamical physics is derived instead. In fact, this very technique was originally used by Bertini [30] in studying what he called theoretical reaction and geometric cross-sections. The geometric cross-sections were determined by intranuclear-cascade model parameters.

By circumstance, the evolution of air-shower arrays necessitated Monte Carlos that had no experimental cross-sections for the energies involved. Pragmatically, the codes were still developed using quark-gluon string models where hadron structure was represented by parton distribution functions (PDFs). Experimental collisional data is as much about the structure of particle distribution functions as it is about cross-sections. Hence, PDFs are equally as important as cross-sections at energies where most quarks/partons are spectators anyway and do not interact. For example, the input "cross-section" σ_h (before unitarization applied by the models) is calculated by applying the QCD-improved parton model [16].

Therefore, the ultimate Monte Carlo that derives its own cross-sections virtually exists at the present time. The point of this paper is to emphasize the importance of the "mathematical experiment" as a means of advertising the answer to challenge the hadron-collider community to try and find it experimentally. We still need the LHC (!) because its task is to find new physics, the Higgs, and much more. These goals have little to do with cross-sections.

Aliroot

One naturally might be concerned about where to run such a Monte Carlo. Pieces already exist as event generators in CORSIKA, and FLUKA is by far the best end-to-end transport code for all energies by virtues of that fact that it contains DPMJET-3. However, none of these codes is actually designed for such a purpose. They would

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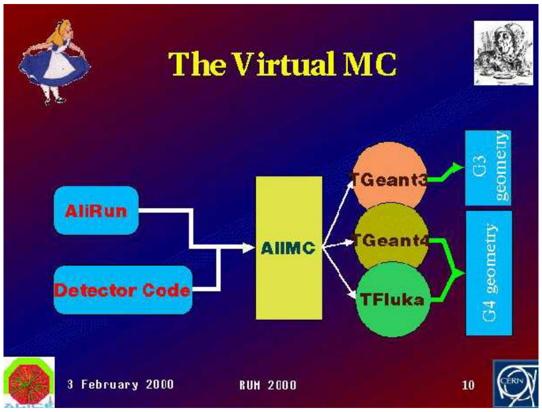
Since FLUKA is the transport engine of choice for ALICE (A Large Ion Collision Experiment) at the LHC, it can run as “Tfluka” in the Virtual MC Offline ALICE system known as Aliroot, illustrated in Figure 3 [31]. Such an architecture is one conceivable place that might serve as a test-bed for predicting PDFs and hadron cross-sections for experimental verification.



The Virtual MC

AliRun

Detector Code

AliMC

TGeant3

TGeant4

TFluka

G3 geometry

G4 geometry

3 February 2000

RUN 2000

10

Figure 3: Aliroot [31]

Summary

The use of Monte Carlos in high-energy hadron physics as a tool for calculating collisional cross-sections in the absence of experimental accelerator data has been discussed.

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