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Accelerator measurements desired to improve cosmic ray Monte Carlos

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Abstract. The Monte Carlo models which are the basis for the interpretation of ground-based cosmic ray observations in terms of primary composition and the physics of the primary interaction are mostly based on data from accelerator experiments in the range of 100 GeV. The extrapolation to the PeV energies of cosmic rays in the knee region is certainly suspect, as the broad spectrum of conclusions regarding composition, for example,illustrates. With the operation of the Fermilab Tevatron, the Brookhaven Relativistic Heavy Ion Collider, and (in about 5 years) the CERN Large Hadron Collider, it should be possible to collect data on interactions which would greatly improve these models. However our cosmic ray community must clearly articulate the measurements which are necessary and work with the accelerator community to obtain these desired data. This presentation is an attempt to initiate such a discussion.

1 Introduction

This paper is a continuation of a discussion begun informally at the Utah ICRC (1999) and more explicitly articulated at the Campinas International Symposium on Very High Energy Cosmic Ray Interactions in July, 2000 (Jones, 2000). To briefly recapitulate, it was noted that the current and near-future generation of colliding beam hadron accelerators has the potential to explore particle interactions at energies which have previously been the exclusive domain of the cosmic ray community. Cosmic ray physicists are interested in data from these accelerators for three reasons; 1) to verify and understand phenomena reported by the cosmic ray community (Centauros, Chirons, the Long-Flying Component, Aligned Events, etc. etc.), 2) to explore the new domain of energy and pseudorapidity to search for new physics, and 3) to collect data which would form the basis for more reliable Monte Carlo models of the first interaction of cosmic rays at energies where the low flux precludes direct observation. As noted in the Campinas paper, John Ellis, a senior theorist at CERN, strongly recommended 3) as a basis for communicating with the accelerator community. Early this year, copies of the Campinas paper and a covering letter were circulated to a broad spectrum of the cosmic ray community who have been active in developing the cosmic ray Monte Carlo models, with the objective of stimulating discussion and of developing a proposed program of accelerator measurements on which the cosmic ray community could agree.

It is worth recalling that the primary cosmic ray flux above 10 PeV ($10^{16} eV$) is only one per square meter per steradian per year. Therefore the direct study of primary interactions in this energy range from balloon or satellite observations is clearly impractical for the foreseeable future, hence the importance of the accelerator-based measurements.

2 Collider Parameters

The Brookhaven Relativistic Heavy Ion Collider (RHIC) has colliding beams of particles with momenta per unit charge of 250 GeV/c, so that two protons achieve a c.m. collision energy of 500 GeV, equivalent to a cosmic ray proton of 133 TeV ($1.33 \times 10^{14} eV$) colliding with a stationary proton. A proton colliding with a nitrogen nucleus in RHIC would have 354 GeV in the nucleon-nucleon c.m., corresponding to a cosmic ray proton of 67 PeV incident on a stationary nitrogen (e.g. air) nucleus. And the beam-beam collision between two nitrogen nuclei, with 250 GeV nucleon-nucleon c.m. energy, would be equivalent to a primary cosmic ray nitrogen nucleus of 462 TeV on an air nucleus.

The corresponding numbers for the CERN Large Hadron Collider (LHC), with 7 TeV/c per unit charge particles, will be: 14 TeV c.m. for a proton-proton collision, equivalent to a cosmic ray proton of 104 PeV (about $10^{17} eV$) incident on a stationary nucleon; 9.9 TeV in the nucleon-nucleon c.m. for a proton-nitrogen collision, equivalent to a 52 PeV cosmic ray proton incident on an air nucleus, and 7 TeV nucleon-nucleon c.m. energy for a nitrogen-nitrogen collision, equivalent to a

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cosmic ray nitrogen primary of 364 PeV incident on an air nucleus.

The Fermilab Tevatron collides only protons and antiprotons (no heavier nuclei). Its 1.8 TeV c.m. is equivalent to a 2 PeV cosmic ray antiproton incident on a stationary proton. Of course the energies of any of these machines can be lowered, so that continuous energy coverage would not be a problem. At RHIC and the LHC, proton-proton collisions and collisions of like nuclei (e.g. nitrogen-nitrogen) are practical, and at the LHC it is possible that proton-nitrogen collisions could be studied. However collisions between dissimilar heavy nuclei are not practical.

Each of these colliders employs very large 4π detectors to study reaction products, and it is tempting to believe that therefore they cover the full range of physics relevant to cosmic ray interactions below $10^{17} eV$. However the problem is that these huge, elegant detectors (involving international collaborations numbering over 1000 physicists) do not cover very small angles, i.e. within one or two degrees of the beam lines. While this certainly leaves them with coverage of over 99% of the 4π steradian solid angle, in terms of rapidity or pseudorapidity, a great deal is missing. A coverage down to 28 mr (about 1.5^o) corresponds to a pseudorapidity $\eta = 4.25$, while a 7 TeV proton (in the LHC) at 0^o has a rapidity, $y = 9.6$.

3 Forward Physics

The evolution of the ground-level observables from primary cosmic ray interactions depends critically on the energy flow in the first (and early) interactions, and this in turn is dominated by the secondaries produced at high rapidities (equivalent to pseudorapidities, for all practical purposes). Wlodarczyk has pointed out that a Tevatron Collider detector covering down to $\eta = 4.25$ misses 80% of the final state energy flow, and a similar coverage at the LHC will miss 95% of the energy flow. It is easy to see why this is so; for example, an inelastic, final state nucleon at the LHC with an energy of a 700 GeV (i.e. an inelasticity of 0.9) scattered with a rather large transverse momentum of 700 MeV/c leaves the collision at only one mr relative to its initial direction, equivalent to a pseudorapidity $\eta = 7.6$.

During the 1970s, bubble chambers at Fermilab and at CERN collected data over the complete solid angle - through 0^o - by imaging entire events. Other fixed-target, counter experiments also looked at particle production and spectra in the forward direction. But these experiments were all done at energies of a few hundred GeV; well below a TeV, and about 4 orders of magnitude below the cosmic ray "knee". And it is these data on which the current Monte Carlo models are based. However, increasingly, cosmic ray observations are not consistant with the current Monte Carlo models (Antoni, 1999). The current state of affairs is nicely illustrated by the chaos of "experimental" values of <lnA> through the knee region from different observations. Very clearly, good experimental data from accelerators should be obtained through these small forward angles at energies equivalent to those of the primary cosmic rays being simulated.

The above discussion is not new; it has been repeated at many earlier conferences, seminars, and papers. The question is; what to do now? If the cosmic ray community can agree on specific measurements and data which are necessary for the construction of the first-interaction Monte Carlo models, and if this consensus is conveyed to the experimental collaborations and administrations of the major laboratories, there is reason to hope that it will be heeded and that the relevant experiments can be undertaken.

4 Karlsruhe Correspondence

A very substantive response to the letter cited earlier was received from H. Rebel and 7 of his colleagues at Karlsuhe. The "shopping list" below is a brief summary of their four page letter. They suggest, as a top priority, inclusive, minimum-bias differential hadron spectra with respect to Feynman x, dn/dx, over the range $0.1 < x < 1.0$ for the common hadrons; protons, neutrons, charged and neutral pions, and charged kaons. Both pA and pp collision data would be of interest. The data could be collected in two x regions: $0.1 < x < 0.8$, of interest for the determination of inelasticity; and $0.8 < x < 1.0$, the diffraction region, relevant for fluctuations in atmospheric cascade development and for the high energy hadrons which penetrate deep in the atmosphere. The hadronic spectra for $0 < x < 0.1$ and the transverse momentum distributions of the hadrons is also of interest, although secondary to the differential x spectra discussed above. As a second priority, they recommended the pion-nucleus and pion-proton inclusive differential spectra over the same range of x and for the range of final state hadrons noted above. They suggest a third priority which would be A-A (nucleus-nucleus) collisions, but note that models which work for p-A collisions generally do not have difficulty with minumum bias A-A. Again, nitrogen is the most appropriate target nucleus.

At a lower priority, they suggest collecting 'centrality dependent' spectra, using veto-calorimetric measurements in the backward hemisphere, to select the subset of very peripheral interactions. This again would provide a severe consistency check of model predictions. Also clean data on p-A, π-A, and A-A total cross sections would be valuable. They cite the fact that the two values of the proton-proton total cross section from different Fermilab experiments at 1.8 TeV c.m., 72 and 80 mb, result in a difference of $15 g/cm^2$ in the atmospheric depth of shower mximum at $E_o = 10^{10}$ GeV. And finally, they note the desirability of better low energy spectra and cross sections ($E < 10GeV$), in the context of detector behavior. These data are also relevant to the properties of the detectors used at the colliding beam facilities.

5 ALICE and CASTOR

There have been discussions with members of the ALICE collaboration at the CERN LHC; they have expressed an interest in physics which would contribute to cosmic ray studies. A subset of that collaboration has planned a far-forward detector, CASTOR, specifically to study forward particle production. CASTOR is basically a well-instrumented calorimeter preceeded by silicon tracking chambers and tungsten radiators (CASTOR, 2000). It will cover angles corresponding to $5.6 \leq \eta \leq 7.2$, i.e. between about 7.4 mr and 1.5 mr. Although its primary objectives are to search for evidence of the Centauro phenomena and for evidence of ‘Stragelets’ (hadronic states containing equal numbers of up, down, and strange quarks), it could contribute data relevant to some of the shopping list discussed above. Certainly, it could give π^o production data analogous to the very useful UA7 data from the earlier CERN antiproton-proton collider, although at the much higher LHC energies. Although distinguishing incident neutrons from charged hadrons, it would not be able to separate protons from charged mesons. And, of course, there is still much pseudorapidity phase space within the 1.5 mr minimum angle. But the CASTOR measurements will certainly be welcome, and the cosmic ray community should maintain close liason with this group.

6 Conclusions

With the excellent, thoughtful input from the Karlsruhe group as a useful starting point, it would be valuable if, at this International Cosmic Ray Conference, the international community of experts on Monte Carlo models for cosmic ray calculations, could develop a paper to which all would agree. This communication, carrying the weight of this community of scholars, could then be transmitted to the three laboratories at which these beam-beam collisions can be observed and studied, at energies relevant to cosmic ray measurements and beyond the energies accessible to direct observation. While the thoughts of individual experts would be heard with ‘interest’ by the laboratories, it is improbable that this would lead to any action or change in the experimental program. However a paper carrying the signatures of a large number of the members of this global community could have a significant impact. The objective of this report is to initiate such a process.

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