

## SHOWER SIMULATIONS FOR THE FLY'S EYE

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**1. Introduction.** The analysis of the Fly's Eye data, especially in terms of the cosmic ray composition at ultra-high energy, sets specific requirements on the simulation programs necessary to derive the desired results. On one hand, because of the extremely high energy of the detected showers, the interaction model and the shower codes have to be simplified enough to make the task feasible. On the other hand they have to give a good representation of the energy dependence of the inelastic interactions. Since the experiment explores the full energy range of the cosmic ray flux we must also study the sensitivity of the derived cosmic ray composition to the main characteristics of the interaction model.

The task is then to compile models that describe equally well the results of accelerator collider experiments, but predict different energy behavior at  $10^{17}$  eV and higher energy. A central question is how the scaling violation observed in collider experiments affects the fragmentation region of interaction high energy interactions, which is important for the development of cosmic ray cascades. An added theoretical complication is the transition from proton-proton interactions with nuclei, which has to reflect the basic physics of the models.

**2. Basic Interaction Models** We have chosen <sup>1,2</sup> the following representative models of high-energy inelastic interactions:

A. Statistical model. Related to the Landau Hydrodynamical model, versions of a statistical model have been widely used in cosmic ray cascade calculations<sup>3-5</sup>. Its main feature is that the multiplicity is proportional to a power of the available center of mass energy.  $\langle n \rangle = Const (K_{inel} s)^a$ , where  $K_{inel}$  is the inelasticity coefficient showing the fraction of the energy not carried away by the leading nucleon. To match the observed rise of the rapidity density from  $s = 53$  to  $1800$  GeV, the power law increase of the multiplicity must be compensated for<sup>5</sup> by a decrease in  $K_{inel}$ . At  $s$  of  $540$  GeV  $K_{inel}$  has to be decreased to  $0.3$  from the canonical low energy value of  $0.5$ . A further decrease to  $0.2$  is necessary to explain the multiplicity at  $s$  of  $1.8$  TeV.

B. QCD Pomeron Model. The interaction features are controlled by the properties of the Pomeron. At low energy one cut Pomeron is exchanged, which corresponds to a constant soft cross-section. At higher energy the cross-section rises due to exchange of  $n$  cut Pomerons. We are using the KNP<sup>6</sup> version of the Pomeron model, where the leading particle spectrum is derived from the leading particle cascade<sup>7</sup> model. The average fractional leading nucleon energy with  $n$  cut Pomeron exchanges is given by a recurrence relation to the single cut Pomeron case. Thus  $\langle x \rangle_n = (\langle x \rangle_1)^n$ . This gives a rapid decrease with  $x$  of the leading nucleon spectrum and a correspondingly strong increase of  $K_{inel}$ . The secondary particles  $x$  spectra are relatively unchanged, however, because of the effect of successive interactions of the leading nucleon.

C. Minijet model. The minijet model relates the increase of the interaction cross-section

**4. Program Implementation and Results for p-Nucleus Collisions.** The simplified cascade interaction routines consist of two major components that govern respectively the leading particle distribution and the production of secondary mesons. The leading particle  $x$  spectra were sampled from a  $x dn / dx = \hat{\lambda} x^{\lambda}$  distribution as suggested by KNP. For the minijet model the energy taken away in sea-quark interactions was actually sampled from sea quark structure functions. The average resulting  $K_{inel}$  for p-Air collisions on Fig. 1 for the three models as a function of the incident energy. All models exhibit an increased  $K_{inel}$  compared to pp collisions. The biggest change is in the statistical model because of its hard nucleon spectrum.

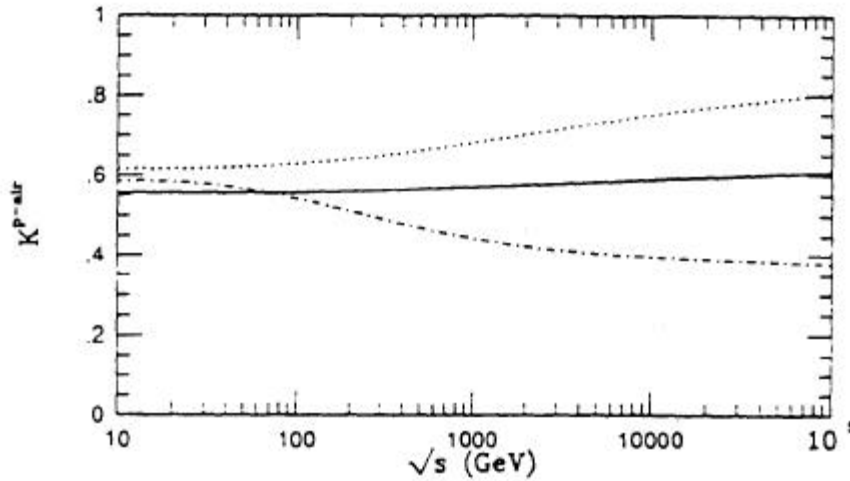


Fig. 1 Inelasticity of p-Air interactions predicted by: KNP(dotted), Minijet(solid), and Statistical(dot-dash) models

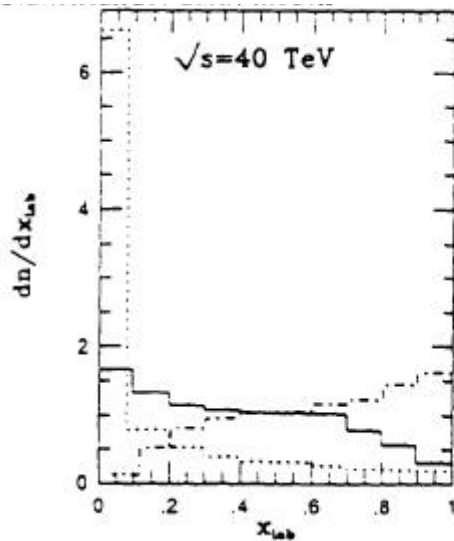


Fig. 2  $x_{lab}$  for the leading nucleon in inelastic non-diffractive p-Air interactions.

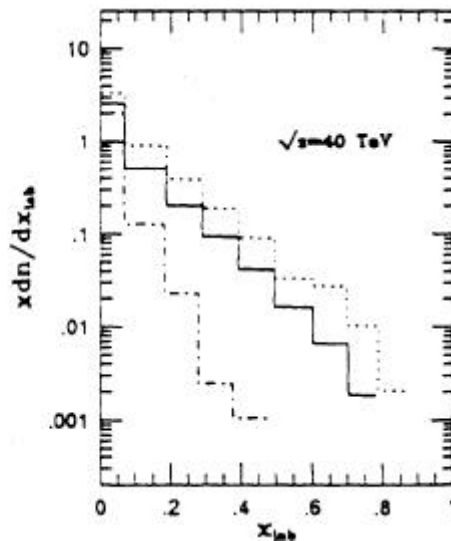


Fig. 3  $x_{lab}$  for charged pions in inelastic non-diffractive p-Air interactions.

The secondary meson production was simulated with Hillas' splitting algorithm" with an energy dependent number of pre-splittings. The energy dependence was chosen to fit the accelerator data on the pseudorapidity density in the central region, and then applied to p-nucleus collisions. Figs. 2 and 3 show the  $x$  distributions produced by the code for the leading nucleon (Fig.2) and for the charged pions at  $s = 40$  TeV in p -air interactions. In spite of the different  $x_{ldng}$  for the mini-jet and the KNP models, both of them show moderate scaling violation in the fragmentation region in Fig. 3. The statistical MO ,,, on the other hand, shows a much softer spectrum for the secondary pions. A combination

with interactions of sea quarks and gluons that become more prominent at high energy.<sup>8,9</sup> The fractional energy of the interacting partons has to be subtracted from the energy carried by the beam particles. The leading particle  $x$  is then decreased by to the energy carried by parton jets:  $\langle x \rangle = 0.5(1 - \langle x \rangle_{\text{jet}} \langle n \rangle_{\text{jet}})$ . The number of jets increases with energy while the fractional energy of each jet decreases. The resulting scaling violation in the fragmentation region is small compared to the strong scaling violation in the central region.<sup>10</sup>

**3. Nuclear Target Effects** One can use Glauber's multiple scattering theory to calculate the inelastic cross-section for hadron-nucleus interactions:<sup>11</sup>

$$\sigma_{\text{inel}}^{hA}(s) = 2\pi \int b db [1 - e^{-\sigma_{\text{inel}}^{hh}(s)T(b)}]$$

where  $T(b)$  is the nuclear profile.  $\sigma_{\text{inel}}^{hA}(s)$  can be expressed as a sum of cross sections for having  $\nu$  wounded nucleons in the target with the average number of wounded nucleons

$$\langle \nu \rangle = A \sigma_{\text{inel}}^{hh} / \sigma_{\text{inel}}^{hA}$$

Since we use in our calculation the same form of  $\sigma^{\text{PP}}$  that fits the collider results, we end up with the same wounded nucleon distributions for all three models. The difference is in the treatment of the beam interactions inside the target.

KNP treat p-nucleus interactions in the same way they treat multiple Pomeron exchanges in p-p scattering:

$$\langle x_{\text{ldng}} \rangle^{pA} = \sum_{\nu=1}^A P_{\nu} (\langle x_{\text{ldng}} \rangle^{\text{PP}})^{\nu}$$

The beauty of this model is that there is actually only one parameter, the pp cross-section, that determines all properties of the interaction, and the scaling violation and cross-section are strongly correlated. We have used the same approach to implement the nuclear target effects in the statistical model. The results for p-nucleus interactions we obtained from our model are very close to the examples given by Wilk.<sup>12</sup>

For the minijet model we implemented the scheme of the Dual Topological Unitarization model<sup>13</sup>. While the p-nucleus interactions for  $\nu = 1$  are the same as pp interactions, subsequent beam collisions involve sea quark pairs, associated with the beam. Since the structure functions of sea quarks are softer than these of valence quarks, the beam loses less energy in these additional collisions.  $x_{\text{ldng}}$  can then be calculated as

$$\langle x \rangle^{pA} = \langle x \rangle^{\text{PP}} \times \left[ 1 - \sum_{\nu=2}^A P_{\nu} \langle x_{\text{sea}}(2(\nu - 1)) \rangle \right],$$

where  $\langle x_{\text{sea}}, Q(2(\nu - 1)) \rangle$  is the total fractional energy carried by the interacting sea quarks in the projectile.<sup>2</sup> 7r- and K- nucleus interactions were treated in analogous way, with a different number of wounded nucleons corresponding to the appropriate cross-sections on protons and nuclei. This whole scheme has a qualitative advantage over our previous attempts to model hadron-nucleus collisions which were generally pp models scaled to p-nucleus according to the experimental results at low energy, and were underestimating the nuclear target effects at very high energy.

of these two pictures can be observed for  $\pi$ -nucleus collisions, where the statistical model gives a higher inclusive cross section *at high as well as low x* values because of the hard leading pion distribution.

**5. Shower profiles.** Using the three interaction models described above, and p-Air inelastic cross-section as in KNP, we have calculated a set of showers for fixed primary energies above  $10^{16}$  eV. The results of the KNP and the mini-jet models are quite similar, while the statistical model predicts, expectedly, slower shower development. The elongation rates between  $10^{16}$  and  $10^{19}$  eV are respectively  $60 \pm 2$ ,  $55 \pm 1$  and  $52 \pm 2$  g/cm<sup>2</sup> for the statistical, minijet, and KNP models. The average depths of shower maximum  $\langle X_{\max} \rangle$  at proton energy of  $1.25 \times 10^{18}$  eV are  $807 \pm 6$ ,  $775 \pm 4$ , and  $762 \pm 4$  g/cm<sup>2</sup> in the same order. These are values that come directly from shower Monte Carlo calculations and cannot be compared to experimental data without accounting for the detector efficiency and detection biases.

We also simulated a set of showers with energy distribution following that measured by Fly's Eye<sup>15</sup> in an attempt to study the shape of the  $X_{\max}$  distribution. The tails of the  $X_{\max}$  distributions depend on the interaction model, with the biggest absorption for the KNP model and the most penetration for the statistical model.

In conclusion, we have developed three models of high energy inelastic interactions for shower calculations up to  $10^{20}$  eV, which give quite different extrapolations of accelerator data. Calculations of shower profiles with these three models show that the observable shower parameters are quite sensitive to the main properties of the inelastic collisions. The statistical model gives the most deeply penetrating showers, while the KNP model showers develop most rapidly. In particular, a statistical type model<sup>3-5</sup> would require a larger fraction of heavy nuclei in the primary flux to compensate for the slow energy dissipation in the cascades.

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