

## Proton-proton cross section at $\sqrt{s} \sim 30$ TeV

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(Received 23 February 1998; published 9 June 1998)

There are both theoretical and experimental uncertainties in using data from cosmic-ray air showers to estimate hadronic cross sections above accelerator energies. We outline these problems and compare the physics used to extract  $\sigma_{pp}^{\text{tot}}$  from air shower data to the widely used parametrization of the proton-proton cross section of Donnachie and Landshoff and other contemporary models. We conclude that the published cosmic-ray cross section values do not strongly constrain  $\sigma_{pp}^{\text{tot}}$  fits from lower energy accelerator data.  
[S0556-2821(98)00715-2]

PACS number(s): 13.85.Lg, 13.85.Tp

### I. INTRODUCTION

New and proposed experiments to study the cosmic-ray spectrum up to  $10^{20}$  eV and beyond [2–7] will depend for their interpretation on extrapolations of models of hadronic interactions more than two orders of magnitude in a center of mass energy beyond what is accessible with present colliders. The interaction length of hadrons in the atmosphere, and hence their cross sections, are the most obvious determining factors in the rate at which the showers develop. An extra source of model dependence is the relation between hadron cross sections in air and the more basic hadron-hadron cross sections.

Cosmic-ray measurements have been used in the past to determine  $\sigma_{p\text{-air}}^{\text{inel}}$  and, with the help of Glauber multiple scattering theory [8], to estimate  $\sigma_{pp}^{\text{tot}}$ . Frequently quoted examples are the Fly's Eye experiment [9,10] and the Akeno experiment [11]. Both experiments find rather large central values of  $\sigma_{p\text{-air}}^{\text{inel}}$  ( $\approx 540$  mb [9] and  $\approx 570$  mb [11] at lab energy  $E_0 \sim 4 \times 10^8$  GeV). In both experiments, the proton-air cross section has to be inferred from some measure of the attenuation of the rate of showers deep in the atmosphere. The measured attenuation depends on the cross section which determines the depth at which showers are initiated, but it also depends very significantly on the rate at which energy is dissipated in the subsequent atmospheric cascades. For this reason, a simulation which includes a full representation of the hadronic interactions in the cascade is needed. Because these two experiments measure the attenuation in quite different ways, the fact that their inferred values of  $\sigma_{p\text{-air}}^{\text{inel}}$  agree is a non-trivial result.

Having determined  $\sigma_{p\text{-air}}^{\text{inel}}$ , the experimental groups go on to derive corresponding values for  $\sigma_{pp}^{\text{tot}}$  of 120 mb [9,10] and 125 mb [11] at  $\sqrt{s}$  about 30 TeV. As noted by the Particle Data Group [12],  $\sigma_{pp}^{\text{tot}} \sim 120$  mb is in good agreement with extrapolation of the parametrization of Donnachie and Landshoff (DL) [1]. As we discuss in the next section, however, the cosmic-ray values of  $\sigma_{pp}^{\text{tot}}$  are based on a parametrization of the nucleon-nucleon scattering amplitude that is in disagreement with high energy collider data. Therefore, the quoted values cannot be used to pin down a high energy extrapolation of the  $pp$  cross section.

Indeed, it has been pointed out in the past [13,14] that such large values of  $\sigma_{p\text{-air}}^{\text{inel}}$  ( $\sim 550$  mb) would require significantly larger values of  $\sigma_{pp}^{\text{tot}}$  than that predicted by the parametrization of Ref. [1]. Conversely, if that predicted behavior of the hadronic cross section is correct, then the hadron-air cross sections should be smaller, and this could have important consequences for development of high energy cascades.

The plan of the paper is as follows. In the next section we discuss the relation between the nucleon-nucleon cross section and the nucleon-nucleus cross section, in particular, how it depends on the slope of the elastic  $pp$  cross section. Next we review how the hadron-air cross sections are inferred from air shower experiments and discuss the resulting uncertainties in  $\sigma_{p\text{-air}}^{\text{inel}}$  and their implications for  $\sigma_{pp}^{\text{tot}}$ .

### II. PROTON-PROTON VS PROTON-AIR CROSS SECTION

The relation between the hadron-nucleon cross section and the corresponding hadron-nucleus cross section depends significantly on the elastic slope parameter  $B(s)$ :

$$B(s) = \frac{d}{dt} \left[ \ln \left( \frac{d\sigma_{pp}^{\text{el}}}{dt} \right) \right]_{t=0}. \quad (1)$$

This relation is discussed in the context of cosmic-ray cascades in detail in Ref. [13]. Qualitatively, the relation is such that for a given value of  $\sigma_{pp}^{\text{tot}}$ , a larger value of the slope parameter corresponds to a larger proton-air cross section. Conversely for a given value of  $\sigma_{p\text{-air}}^{\text{inel}}$ , a larger value of  $B(s)$  leads to a smaller value of  $\sigma_{pp}^{\text{tot}}$ . In addition, the smaller the slope parameter, the larger is the uncertainty in the derived proton-proton cross section.

For example, the Fly's Eye value of  $\sigma_{pp}^{\text{tot}} = 122 \pm 11$  mb at  $\sqrt{s} = 30$  TeV [9,10] is obtained using an outdated geometrical scaling fit [15,16] to extrapolate the slope parameter to this energy. This results in a large value of  $B > 30$  GeV<sup>-2</sup> and hence (for a measured value of  $\sigma_{p\text{-air}}^{\text{inel}} \approx 540 \pm 50$  mb) a small value of  $\sigma_{pp}^{\text{tot}}$ . Using a different model for the slope parameter [17,18], for example, as advocated in the review article of Block and Cahn [19], leads to a slower increase in

$B(s)$  and to a considerably larger value of  $\sigma_{pp}^{\text{tot}} \approx 175_{-30}^{+40}$  mb [13]. The same applies to the Akeno analysis and numbers [11].

Before discussing the slope parameter further, it is useful to review briefly the basis of the very successful DL fits of cross sections, which are based on a one-pomeron exchange model (e.g., [20] and references therein). In such a model, the energy dependence of the total cross section for  $AB$  scattering is given by [1]

$$\sigma_{AB}^{\text{tot}}(s) = X_{AB} \left( \frac{s}{s_0} \right)^{\Delta} + Y_{AB} \left( \frac{s}{s_0} \right)^{-\epsilon}. \quad (2)$$

The constants  $X_{AB}$  and  $Y_{AB}$  are target and projectile specific whereas the effective powers  $\Delta \approx 0.08$  and  $\epsilon \approx 0.45$  are independent of the considered particles  $A$  and  $B$ . Within the uncertainties of the measurements, this parametrization is in agreement with almost all currently available data on  $pp$ ,  $p\bar{p}$ ,  $\pi p$ ,  $\gamma p$ , and  $\gamma\gamma$  total cross sections. It should be noted that the high energy  $p\bar{p}$  data are not fully self-consistent. There is some disagreement between measurements of the total cross section at  $\sqrt{s} = 1800$  GeV. Whereas the E710 [21] and the preliminary E811 [22] data are in perfect agreement with the DL prediction [1], the Collider Detector at Fermilab (CDF) measurement [23] shows a steeper rise of the total  $p\bar{p}$  cross section. New data from the DESY  $ep$  collider HERA ( $\sigma_{\gamma p}^{\text{tot}}$  [24]) and CERN  $e^+e^-$  collider LEP2 ( $\sigma_{\gamma\gamma}^{\text{tot}}$  [25]), although being compatible with an energy dependence of  $\Delta \approx 0.08$ , indicate that the cross section may rise faster with energy than assumed in the DL fit. Furthermore, in a recent fit to  $pp$  and  $p\bar{p}$  data [26] a slightly higher value of  $\Delta = 0.096_{-0.009}^{+0.012}$  was found.

Given the success of the one-pomeron exchange model in predicting the total cross section, one might apply it to derive further predictions. The one-pomeron amplitude can be written as

$$A(s, t) = g_{AB}(t) \left( \frac{s}{s_0} \right)^{\alpha(t)} \quad (3)$$

with  $\alpha(t=0) = 1 + \Delta$ . Collider data on elastic scattering suggest for small  $|t|$  the functional dependence  $g_{AB}(t) = X_{AB} \exp\{\frac{1}{2}B_0 t\}$ . Following the predictions of Regge theory,  $B_0$  is an energy-independent constant. Consequently, the elastic slope  $B(s)$  is given by

$$B(s) = B_0 + 2\alpha'(0) \ln \left( \frac{s}{s_0} \right) \quad (4)$$

where the parameter  $\alpha'(0)$  is a constant and has to be determined from data [20]. The elastic cross section follows from

$$\sigma_{AB}^{\text{el}} = (1 + \rho^2) \frac{(\sigma_{AB}^{\text{tot}})^2}{16\pi B(s)}. \quad (5)$$

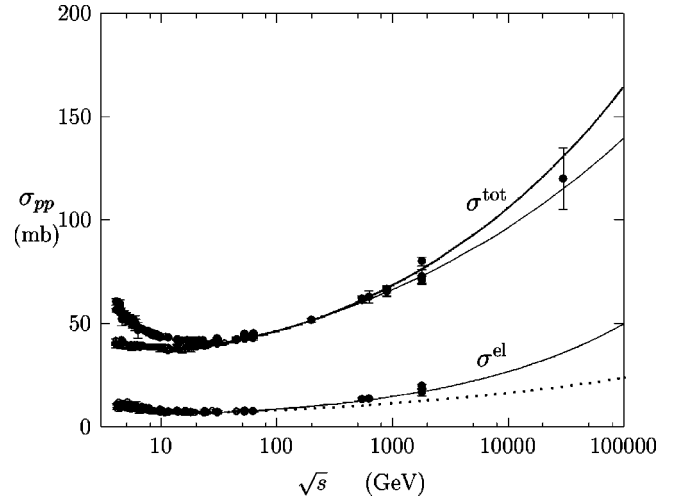


FIG. 1. Data on  $pp$  and  $p\bar{p}$  interactions [12] are compared with the DL parametrization [1] (lower curve) and the fit of Ref. [26] (upper curve). The predictions for the elastic cross section from Eq. (5) and in the case of geometrical scaling (dotted curve) are also shown. The data point at  $\sqrt{s} = 30$  TeV is the original Fly's Eye estimate [9].

At high energies the ratio  $\rho$  between the real and the imaginary part of the forward scattering amplitude is small and  $\rho^2$  can be neglected.

In a model with geometrical scaling it is assumed that the increase of the total cross section stems entirely from an increase of the transverse size of the scattering particles. The opacity of the particles is considered as constant. A direct consequence of this assumption is the energy independence of the ratio  $R = \sigma_{pp}^{\text{el}}(s) / \sigma_{pp}^{\text{tot}}(s)$ , which, in combination with Eq. (5), leads to the relation

$$B(s) = (1 + \rho^2) \frac{\sigma_{pp}^{\text{tot}}(s)}{16\pi R}. \quad (6)$$

Over the CERN Intersecting Storage Rings (ISR) energy range  $R \approx 0.17$ , which was the value used in Eq. (6) in Refs. [9,11].

In Fig. 1 the parametrizations of Refs. [1] and [26] are compared to data. The data point at  $\sqrt{s} = 30$  TeV is the original Fly's Eye estimate [9]. The prediction for geometrical scaling has been calculated using the DL model for the total cross section. Whereas both Regge parametrizations are in agreement with data on total as well as elastic cross sections, the geometrical scaling model fails to describe the elastic scattering data. This becomes even more obvious if one considers the predictions for the energy dependence of the elastic slope parameter as shown in Fig. 2. In contrast, the single pomeron exchange model is in very good agreement with collider data. Such an  $a + b \ln(s)$  extrapolation of the slope parameter is often used to fit data (for example, [27]) and also to estimate cross sections and interaction lengths for cascade calculations [28,29]. Remarkably, the minijet calculation of Block, Halzen and Margolis [30] (BHM) predicts a slope parameter that almost coincides with the one-pomeron model extrapolation using  $\alpha'(0) = 0.3 \text{ GeV}^{-2}$ .

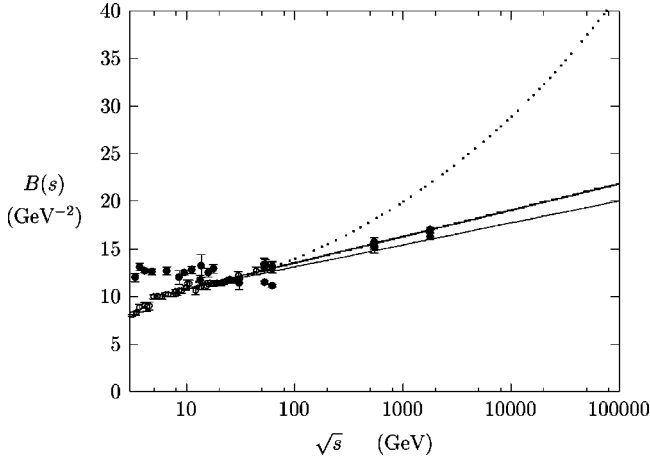


FIG. 2. Elastic slope parameter for  $pp$  and  $p\bar{p}$  interactions. The solid lines are the predictions of the one-pomeron exchange model with  $\alpha'(0)=0.25$  and  $0.3 \text{ GeV}^{-2}$ . The dotted line corresponds to geometrical scaling. The data are taken from Refs. [31–33].

As recognized by DL the single pomeron exchange model is not consistent with unitarity. One way to see this is to note from Eqs. (2), (4), and (5), that at asymptotically high energy the unitarity requirement

$$\frac{\sigma_{AB}^{\text{el}}}{\sigma_{AB}^{\text{tot}}} < \frac{1}{2} \quad (7)$$

is violated. We point out, however, that the model of Block, Halzen, and Margolis (BHM) [30] does satisfy unitarity and it gives a similar prediction to the single pomeron fit over the energy range shown in Fig. 2.

We summarize some of the results of this section in Fig. 3, by displaying them in the  $(\sigma_{pp}^{\text{tot}}-B)$  plane. The shaded region corresponds to the region excluded by the unitarity constraint of Eq. (7). The points represent experimental measurements at ISR (triangles) and  $p\bar{p}$  collider (squares). The dotted line indicates the relation between  $B$  and  $\sigma_{pp}^{\text{tot}}$  predicted by geometrical scaling with  $R=0.17$  in Eq. (6). This line fails to describe the highest energy measurements. The dashed line corresponds to the DL fit to  $\sigma_{pp}^{\text{tot}}$  together with Eq. (4) for the energy dependence of the slope [with  $\alpha'(0) = 0.3 \text{ GeV}^{-2}$ ]. Each point on the dashed line corresponds to a value of the center of mass energy of the  $pp$  (or  $p\bar{p}$ ) reaction. We have indicated with a circle the point for  $\sqrt{s} = 30 \text{ TeV}$ .

Using the Glauber formalism a fixed value of the  $p$ -air cross section can be represented as a curve in the  $(\sigma_{pp}^{\text{tot}}-B)$  plane. The five curved lines in Fig. 3 indicate the set of values of  $\sigma_{pp}^{\text{tot}}$  and  $B$  that result in a proton-air cross section of  $\sigma_{p\text{-air}}^{\text{inel}}$  of  $540$ ,  $540 \pm 50$  and  $540 \pm 100 \text{ mb}$ , that is the central value and  $\pm 1,2$  standard deviations of the Fly’s Eye measurement at  $\sqrt{s} = 30 \text{ TeV}$ . The intersections of the curves corresponding to  $590$  and  $490 \text{ mb}$  with the dotted line that describes geometrical scaling give the (one standard deviation) allowed interval for  $\sigma_{pp}^{\text{tot}}$ , as estimated in the original Fly’s Eye publication. However it is clear that any reason-

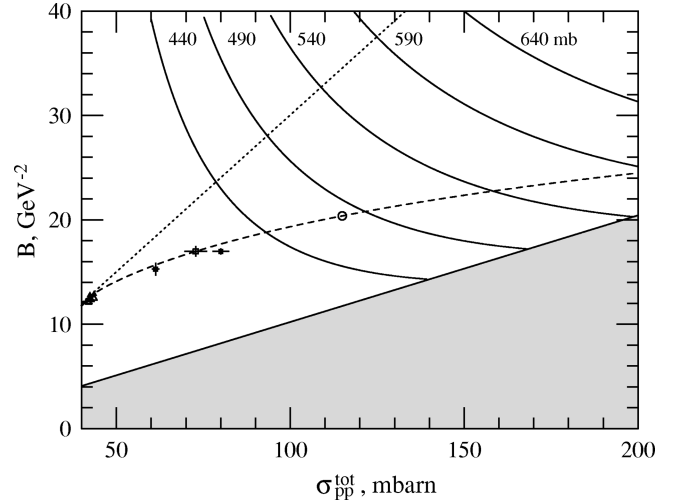


FIG. 3.  $B$  dependence on  $\sigma_{pp}^{\text{tot}}$  and the values of  $\sigma_{pp}^{\text{tot}}$  allowed by the Fly’s Eye measurement. The shaded area is excluded by the unitarity constraint. Solid symbols give experimental data points. Dashed line shows  $B$  as in DL fit; dotted line shows geometrical scaling. The open point indicates  $\sigma_{pp}^{\text{tot}}$  at  $\sqrt{s} = 30 \text{ TeV}$  from the DL fit. The five curved lines show the region allowed by  $\sigma_{p\text{-air}}^{\text{prod}} = 540 \text{ mb} \pm 1\sigma$  and  $\pm 2\sigma$  (see text).

able extrapolation of the collider data (for the  $B-\sigma_{pp}^{\text{tot}}$ ) will result in the estimate of a higher central value for the  $pp$  cross and in larger uncertainty. Nominally the prediction of Donnachie and Landshoff for  $\sigma_{pp}^{\text{tot}}$  at  $\sqrt{s} = 30 \text{ TeV}$  is one standard deviation below the Fly’s Eye measurement.

It is important to notice that the experimentally measured and published inelastic  $p$ -air cross section is only that part of the total cross section which belongs to particle production. Following [13] we write this cross section as

$$\sigma_{p\text{-air}}^{\text{prod}} = \sigma_{p\text{-air}}^{\text{tot}} - \sigma_{p\text{-air}}^{\text{el}} - \sigma_{p\text{-air}}^{\text{q-el}}, \quad (8)$$

where  $\sigma_{p\text{-air}}^{\text{q-el}}$  is the quasielastic  $p$ -air cross section corresponding to scattering processes where the nucleus gets excited without direct particle production. The Glauber formalism [8] gives explicit expressions for all terms in Eq. (8). Unfortunately, there is ambiguity in the literature about the designation of the production cross section. It has also been called  $\sigma_{p\text{-air}}^{\text{inel}}$  in experimental [9–11] and theoretical [13] papers and it is also often referred to as absorptive cross section [34–36,14]. In the hope of removing this confusion, we introduce the notation ‘‘prod’’ to represent the inelastic cross section in which at least one new hadron is produced in addition to nuclear fragments.

### III. UNCERTAINTIES IN THE $p$ -AIR CROSS SECTION MEASUREMENT

In addition to uncertainties in converting from  $\sigma_{p\text{-air}}^{\text{prod}}$  to  $\sigma_{pp}^{\text{tot}}$ , there are significant uncertainties in the determination of  $\sigma_{p\text{-air}}^{\text{prod}}$  itself. Both at Fly’s Eye [9] and at Akeno [11], the approach is to look at the frequency of deeply penetrating showers and to assign a corresponding attenuation length ( $\Lambda$ ) on the assumption that, for a given energy, the most deeply

penetrating showers are initiated by protons.

The Fly’s Eye group measures the depth of maximum development ( $X_{\max}$ ) distribution for air showers in a relatively narrow interval of  $S_{\max}$ , where  $S_{\max} \propto E_0$  is the shower size at maximum. The tail of that distribution, well after its peak, is a measure of the depth of the first interaction convoluted with the intrinsic fluctuations in the shower development.

The Akeno group selects deeply penetrating showers by cutting on showers with the highest size,  $S$ , at the observation level in narrow bins of the shower muon size  $S_\mu$ . The reason for this procedure is that  $S_\mu$  is nearly proportional to the primary energy  $E_0$ .  $\Lambda$  is then derived from the frequency of such showers at different zenith angles, i.e., from the decrease of the frequency with atmospheric depth, which is a different measure of attenuation from that used in the Fly’s Eye approach.

The model-dependence then is compressed into a single parameter  $a > 1$  in the relation

$$\Lambda = a \times \lambda_{p\text{-air}} = a \times \frac{14.5 m_p}{\sigma_{p\text{-air}}^{\text{prod}}}. \quad (9)$$

Here  $\lambda_{p\text{-air}}$  is the interaction length of protons in air, which has a mean atomic mass of 14.5. The effective value of  $a$  for proton initiated showers depends on the pion inelastic cross section in air and on the inclusive cross sections in the proton and pion inelastic interactions [37,38].

The Fly’s Eye proton air cross section value of  $540 \pm 50$  mb is derived by fitting the tail of the  $X_{\max}$  distribution to an exponential with a slope of  $\Lambda = 70 \pm 6$  g/cm<sup>2</sup> and then using  $a \approx 1.60$ , which is similar to the value calculated in Ref. [39]. The  $\Lambda$  values in Ref. [39] are calculated by simulating air showers assuming different energy dependences of  $\sigma_{p\text{-air}}^{\text{prod}}$  and fitting the tails of the resulting  $X_{\max}$  distributions.  $\Lambda$  values are then compared to  $\sigma_{p\text{-air}}^{\text{prod}}$  at primary energy  $E_0 > 3 \times 10^{17}$  eV. The calculation was performed with an essentially  $pp$  scaling interaction model [40].

Models with even very modest scaling violation, that also account for the nuclear target effect yield smaller values of  $a$ . It is not possible to separate the effects of the energy dependence of the inelastic cross section from those of the scaling violation in the ‘‘one parameter’’ approach. The relevant parameter in  $p$ -air interactions is the rate of energy dissipation by the primary proton  $K_{p\text{-air}}^{\text{inel}}/\lambda_{p\text{-air}}$ . The inelasticity coefficient  $K_{p\text{-air}}^{\text{inel}} = (E_0 - \langle E_L \rangle)/E_0$ , where  $E_0$  is the primary proton energy in the lab system and  $\langle E_L \rangle$  is the average lab system energy of the leading nucleon. The equally strong contribution of  $\pi$ -air collisions is even more difficult to quantify in simple terms. On the other hand  $a$  tends to saturate for very strong scaling violation models, because the nuclear target effects in such models are small.

The Akeno experiment uses calculations [41] made also with a model implementing radial scaling. In Ref. [38] the results of Akeno have been reanalyzed making use of an interaction model with scaling violations, resulting in the derivation of lower values for  $a$  that used by the Akeno experiment.

TABLE I. Cross section values that can be extracted from the measured  $\Lambda = 70 \pm 6$  g/cm<sup>2</sup> with different interaction models.

Model	$\langle K_{pp}^{\text{inel}} \rangle$	$\langle K_{p\text{-air}}^{\text{inel}} \rangle$	$a(\sqrt{s} = 30 \text{ TeV})$	$\sigma_{p\text{-air}}^{\text{prod}}$ , mb
Hillas	—	0.50	$1.47 \pm 0.05$	504
SIBYLL	0.57	0.67	$1.20 \pm 0.05$	411
High-K	0.64	0.74	$1.12 \pm 0.05$	384

We have updated the calculations of Ref. [39] to illustrate how different values of  $\sigma_{p\text{-air}}^{\text{prod}}$  can be extracted from the same measured value of  $\Lambda$  depending on the inclusive cross sections of the interaction model. The calculations were performed with three interaction models characterized by  $K_{p\text{-air}}^{\text{inel}}$ : the scaling model of Hillas [40], SIBYLL [42] and a SIBYLL-based model with significantly stronger scaling violation in  $pp$  interactions (high-K). All three calculations use the same input  $\sigma_{p\text{-air}}^{\text{prod}} = 520$  mb ( $\lambda_{p\text{-air}} = 46$  g/cm<sup>2</sup>) at  $\sqrt{s} = 30$  TeV. The resulting values of  $a$  are given in Table I. The last column of the table gives the values of  $\sigma_{p\text{-air}}^{\text{prod}}$  that would be inferred from the Fly’s Eye measurements if the corresponding value of  $a$  had been used. The effects of scaling violation on the shower attenuation rate used by the Akeno experiment [11] are similar, although the numerical values of  $a$  are somewhat different.

#### IV. DISCUSSION

Cosmic-ray experiments detect air showers that result from interactions of particles with energy up to and exceeding  $10^{11}$  GeV. Such observations have the potential to provide information about the growth of  $\sigma_{p\text{-air}}^{\text{prod}}$  up to  $\sqrt{s} \approx 10^5$  GeV. The long lever arm would be helpful for discriminating among models that give nearly identical results at lower energy. Here we attempt to summarize the problems and complications involved in the measurement and interpretation of  $\sigma_{p\text{-air}}^{\text{prod}}$  in cosmic ray experiments.

The experimental shower sets are inevitably contaminated by showers initiated by heavier nuclei. Neglecting this contamination would result in an overestimate of  $\sigma_{p\text{-air}}^{\text{prod}}$ . To minimize this contamination, the Fly’s Eye cross section was estimated by analyzing only the most penetrating showers, that is a subset of 20% of the entire data sample, strongly enriched in protons. A subsequent analysis [43] found that the composition of primary cosmic rays may be very heavy in the energy region considered. If so, the contamination of heavy primaries could be larger than what was estimated in the original work leading to an overestimate of  $\sigma_{p\text{-air}}^{\text{prod}}$ .

The cross section estimates in Refs. [9–11] were based on interaction models with scaling particle momentum distributions. Models with scaling violations predict faster shower development (e.g., smaller values of  $a$ ). If such models were used they would imply a smaller  $p$ -air cross section (as illustrated in Table I). In addition, such models could also be consistent with a smaller fraction of heavy nuclei. If the shower development is described with a single parameter, as done in the first generation cross section estimates, it is impossible to distinguish between the effects of the proton and

pion cross sections and the inclusive distributions of the secondary particles.

Once  $\sigma_{p-air}^{prod}$  is determined, the Glauber formalism can be used to infer  $\sigma_{pp}^{tot}$  with extrapolations for  $B(s)$  based on all available collider data. Previous analyses [9–11] used a parametrization based on data up through ISR energies which fails to describe recent high energy measurements and leads to an underestimation of  $\sigma_{pp}^{tot}$ .

Our basic conclusion is that cosmic-ray values of  $\sigma_{pp}^{tot}$  do not at present strongly constrain extrapolations of fits of this cross section up to collider energies. With the prospect of much more precise experimental measurements forthcoming from the high-resolution Fly's Eye and other proposed experiments [44] there is the potential for much better estimates of the proton-proton cross section. Realizing this potential will depend also on the use of a new generation [45]

of shower simulations based on interaction models that incorporate all the physics of minimum bias interactions up to collider energies and a correspondingly detailed treatment of nuclear effects. The corresponding analysis should involve a full Monte Carlo simulation of each experimental data set rather than characterizing the simulation with a single parameter.

#### ACKNOWLEDGMENTS

One of the authors (P.L.) wishes to thank the Bartol Research Institute for hospitality during the time this work was completed. One of the authors (R.E.) is grateful to J. Ranft and S. Roesler for many discussions. This research was supported in part by the U.S. Department of Energy under Grant No. DE FG02 01 ER 40626.

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- [1] A. Donnachie and P. V. Landshoff, Phys. Lett. B **296**, 227 (1992).
- [2] T. Abu-Zayyad *et al.*, in *Proceedings of the 25th International Cosmic Ray Conference*, Durban, South Africa, 1997, edited by M. S. Potgieter, B. C. Rankenheimer, and D. J. van der Walt (Potchefstroom, South Africa, 1997), Vol. 5, p. 321.
- [3] M. Boratav *et al.*, in *Cosmic Rays Above  $10^{19}$  eV*, Proceedings of the International Workshop, Paris, France, 1992, edited by J. Cronin *et al.* [Nucl. Phys. B (Proc. Suppl.) **28B**, 1 (1992)].
- [4] Telescope Array Collaboration, M. Teshima *et al.*, in *Proceedings of the 25th International Cosmic Ray Conference* [2], Vol. 5, p. 369.
- [5] J. Ormes *et al.*, <http://lheawww.gsfc.nasa.gov/docs/gamcosray/hecr/owl>
- [6] J. Linsley *et al.*, in *Proceedings of the 25th International Cosmic Ray Conference* [2], Vol. 5, p. 381.
- [7] J. Linsley *et al.*, in *Proceedings of the 25th International Cosmic Ray Conference* [2], Vol. 5, p. 385.
- [8] R. J. Glauber and G. Matthiae, Nucl. Phys. **B21**, 135 (1970).
- [9] Fly's Eye Collaboration, R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **52**, 1380 (1984).
- [10] Fly's Eye Collaboration, R. M. Baltrusaitis *et al.*, in *Proceedings of the 19th International Cosmic Ray Conference*, edited by F. C. Jones, J. Adams, and S. M. Mason (NASA Conference Publication 2376), La Jolla, California, 1985, Vol. 5, p. 5.
- [11] Akeno Collaboration, M. Honda *et al.*, Phys. Rev. Lett. **70**, 525 (1993).
- [12] Particle Data Group, R. M. Barnett *et al.*, Phys. Rev. D **54**, 1 (1996).
- [13] T. K. Gaisser, U. P. Sukhatme and G. B. Yodh, Phys. Rev. D **36**, 1350 (1987).
- [14] N. N. Nikolaev, Phys. Rev. D **48**, R1904 (1993).
- [15] J. Dias de Deus and P. Kroll, Acta Phys. Pol. B **9**, 157 (1978).
- [16] A. J. Buras and J. Dias de Deus, Nucl. Phys. **B71**, 481 (1974).
- [17] T. T. Chou and C. N. Yang, Phys. Rev. **170**, 1591 (1968).
- [18] C. Bourrely, J. Soffer and T. T. Wu, Phys. Rev. Lett. **54**, 757 (1984).
- [19] M. M. Block and R. N. Cahn, Rev. Mod. Phys. **57**, 563 (1985).
- [20] A. Donnachie and P. V. Landshoff, Nucl. Phys. **B231**, 189 (1983).
- [21] E710 Collaboration, N. A. Amos *et al.*, Phys. Lett. B **243**, 158 (1990).
- [22] E811 Collaboration, C. Avila *et al.*, in Proceedings of the VII Blois Workshop on Elastic and Diffractive Scattering, Seoul, Korea, 1997.
- [23] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **50**, 5550 (1994).
- [24] H1 Collaboration, S. Aid *et al.*, Z. Phys. C **69**, 27 (1995).
- [25] L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. B **408**, 450 (1997).
- [26] J. Cudell, K. Kang and S. K. Kim, Phys. Lett. B **395**, 311 (1997).
- [27] K. Goulianos, Phys. Rep. **101**, 169 (1983).
- [28] N. N. Kalmykov and S. S. Ostapchenko, Phys. At. Nucl. **56** (3), 346 (1993).
- [29] J. Ranft, Phys. Rev. D **51**, 64 (1995).
- [30] M. M. Block, F. Halzen and B. Margolis, Phys. Rev. D **45**, 839 (1992).
- [31] R. Castaldi and G. Sanguinetti, Annu. Rev. Nucl. Part. Sci. **35**, 351 (1985).
- [32] E710 Collaboration, N. A. Amos *et al.*, Phys. Lett. B **247**, 127 (1990).
- [33] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **50**, 5518 (1994).
- [34] N. N. Nikolaev, Z. Phys. C **32**, 537 (1986).
- [35] L. Durand and H. Pi, Phys. Rev. D **38**, 78 (1988).
- [36] B. Z. Kopeliovich, N. N. Nikolaev and I. K. Potashnikova, Phys. Rev. D **39**, 769 (1989).
- [37] T. Stanev and T. K. Gaisser, in Proceedings of the Workshop on Very High Energy Interactions in Cosmic Rays, Philadelphia, PA, 1982, edited by M. L. Cherry and R. I. Steinberg, p. 125.
- [38] J. Bellandi, R. J. M. Covolan and A. L. Godoi, Phys. Lett. B **343**, 410 (1995).
- [39] R. W. Ellsworth, T. K. Gaisser, T. Stanev and G. B. Yodh, Phys. Rev. D **26**, 336 (1982).

- [40] A. M. Hillas, in *Proceedings of the 17th International Cosmic Ray Conference*, Paris, France, 1981 (CEN, Saclay, 1981), Vol. 8, p. 193.
- [41] K. Kasahara, S. Torii and T. Yuda, in *Proceedings of the 16th International Cosmic Ray Conference*, Tokyo, Japan, 1979 (University of Tokyo, Tokyo, 1979), Vol. 13, p. 70.
- [42] R. S. Fletcher, T. K. Gaisser, P. Lipari and T. Stanev, *Phys. Rev. D* **50**, 5710 (1994).
- [43] T. K. Gaisser *et al.*, *Phys. Rev. D* **47**, 1919 (1993).
- [44] The Hi-Res Collaboration, T. Abu-Zayyad *et al.*, several papers in the *Proceedings of the 25th International Cosmic Ray Conference* [2], Vol. 5, pp. 321–367; The Telescope Array Collaboration, S. Aiso *et al.*, *ibid.*, pp. 369–376; The Auger Collaboration, M. Boratav *et al.*, *ibid.*, p. 205; Auger Design Report, 2nd edition, FNAL, Chicago, 1997, available at <http://www-td-auger.fnal.gov:82>
- [45] J. Knapp, D. Heck and G. Schatz, FZKA 5828, Wissenschaftliche Berichte, Forschungszentrum Karlsruhe, 1996.