EAS-TOP:The proton-air inelastic cross-section at $\sqrt{s} \approx$ 2 TeV

G.C. Trinchero[1,2] *on behalf of the EAS-TOP Collaboration*
[1]Istituto di Fisica dello Spazio Interplanetario, INAF, Torino, Italy,
[2]Istituto Nazionale di Fisica Nucleare, Torino, Italy

Abstract
The proton-air inelastic cross section measurement at $\sqrt{s} \approx 2$ TeV from the EAS-TOP Extensive Air Shower experiment is reported. The technique exploits cosmic ray proton primaries in the energy region $E_0 = (1.5 \div 2.5) \cdot 10^{15}$ eV, studying the absorption length of their cascades when detected at maximum development. Primary energies are selected through the EAS muon number (N$_\mu$), and proton originated cascades at maximum development by means of the shower size (N$_e$). The obtained value of the *p*-air inelastic cross section at $\sqrt{s} \approx 2$ TeV is $\sigma^{inel}_{p-\mathrm{air}}$=365±24(*stat*)-28(*sys*) mb. The statistical and systematic uncertainties, as well as the connections with the *pp* total cross section measurements are discussed.

1 Introduction

Hadronic cross section measurements at energies above the accelerators' limits have to be performed by exploiting the cosmic ray beam. This holds in particular for nucleus-nucleus interactions as the typical *p*-N, *p*-O ("*p*-air") ones, which rule the development of Extensive Air Showers (EAS).

The most relevant datum to which the EAS development is sensitive, is the *p*-air inelastic cross section ($\sigma^{inel}_{p-\mathrm{air}}$). In the present work we will address to its measurement. We will focus on primary energies $\sqrt{s} \approx 2$ TeV, which are of particular interest, as discussed in the following.

The *pp* total cross section, $\sigma^{tot}_{p\bar{p}}$, and $\sigma^{inel}_{p-\mathrm{air}}$ are related and can be inferred from each other by means of Glauber theory [1]. The whole procedure is model dependent, the results [2–7] differing of about 20% for $\sqrt{s}$ values in the TeV energy range. It is therefore of primary interest to have experimental measurements of $\sigma^{inel}_{p-\mathrm{air}}$ and $\sigma^{tot}_{p\bar{p}}$ at the same CM energies, i.e. around $\sqrt{s} \approx 2$ TeV, at which collider data are still available.

At the highest energies, the direct accelerator measurements themselves can be affected by systematic uncertainties of difficult evaluation, and, as a matter of fact, the available *pp* ($\bar{p}p$) cross section data at energies of $\sqrt{s} = 1.8$ TeV differ of about 10%, which exceeds the statistical uncertainties of the individual measurements [8–10] introducing further uncertanties in the *p*-nucleus cross section determination.

From the point of view of cosmic ray physics, the interpretation of Extensive Air Shower measurements (and therefore the energy determinations and the studies of primary composition) rely on simulations based on hadronic interaction models. Such models are based on theoretically guided extrapolations of the accelerator data obtained at lower energies (and usually restricted to limited kinematical regions).

A direct measurement of $\sigma^{inel}_{p-\mathrm{air}}$ and the comparison of basic quantities as obtained from measurements and model based simulations, in the same conditions, is therefore highly desirable for the validation of the methodology. This can be best performed at primary energies below the steepening (*knee*) of the primary spectrum (i.e. E$_0 < 3 \cdot 10^{15}$ eV, $\sqrt{s} < 2.5$), where, in particular conditions, proton primaries can be reliably selected.

Following the particle array technique [11–13], the primary energy is first selected from the muon number (N$_\mu$). Proton induced showers at maximum development are selected from the shower size (dominated by the electron number, N$_e$). The absorption in the atmosphere of such showers is related to the cross section of the primary. The observed absorption length (λ_{obs}), obtained through their angular distribution at observation level, is also affected by the fluctuations in the longitudinal development of the cascades and in the detector response. Such fluctuations can be studied through simulations, providing the conversion factor *k* between the observed absorption length and the interaction length of primary protons (*k*=$\lambda_{obs}/\lambda_{int}$).

2 The experiment and the simulation

The EAS-TOP array was located at Campo Imperatore, National Gran Sasso Laboratories, 2005 m a.s.l., 820 $\mathrm{g/cm}^2$ atmospheric depth.

The e.m. detector consisted of 35 modules $10\ \mathrm{m}^2$ each of plastic scintillators, 4 cm thick, distributed over an area of $10^5\ \mathrm{m}^2$. In the present work, events with at least six modules fired in a compact configuration, and the largest number of particles recorded by a module internal to the edges of the array are selected. Such triggering condition is fully efficient for N$_e > 10^5$, i.e. for primary energies $E_0 > 3 \cdot 10^{14}$ eV for primary protons. Core location (X_c, Y_c), shower size (N$_e$), and slope of the lateral distribution function (s) are obtained by fitting the recorded number of particles in each module with the Nishimura-Kamata-Greisen (NKG) expression [14]. The resolutions of such measurements for N$_e > 2 \cdot 10^5$ are: $\sigma_{N_e}/\mathrm{N}_e \simeq 0.1$; $\sigma_{X_c} = \sigma_{Y_c} \simeq 5$ m; $\sigma_s \simeq 0.1$. The arrival direction of the shower is measured from the times of flight among the modules with resolution $\sigma_\theta \simeq 0.9^o$. A detailed discussion of the performances of the e.m. detector is reported in Ref. [15].

The muon-hadron detector (MHD), located at an edge of the e.m. array, for the present analysis is used as a tracking module of 9 active planes. Each plane includes two layers of streamer tubes (12 m length, $3 \times 3\ \mathrm{cm}^2$ section) and is shielded by 13 cm of iron. The total height of the detector is 280 cm and the surface is $12 \times 12\ \mathrm{m}^2$. A muon track is defined by the alignment of at least 6 fired wires in different streamer tube layers defining an energy threshold of $E^{th}_\mu \approx 1$ GeV. The muon counting accuracy is $\Delta N_\mu < 1$ for $N_\mu < 15$ reaching $\Delta N_\mu < 2$ for $N_\mu < 30$.

Events with core distance from the muon detector 50 m $< r <$ 100 m, and up to zenith angle θ = 33.6^o are used ("r–θ" selection), for a total of 1.7$\cdot 10^6$ events.

Simulations are performed in order to obtain the event selection parameters (muon number for primary energy and shower size for proton shower at maximum development) and the *k*=$\lambda_{obs}/\lambda_{int}$ value, relating the observed absorption length to the interaction length, i.e. the contribution of fluctuations in the shower development and detector response.

In the present analysis we use the CORSIKA EAS simulation program [16] with the

QGSJET (QGSJET 01) high energy hadronic interaction model [17], that has shown to provide consistent descriptions of different shower parameters in the considered energy range both at sea level and mountain altitudes [18, 19]. Hadrons with energies below 80 GeV are treated with GHEISHA 2002 [20] interaction model.

The full response of the muon detector is included by means of simulations based on the GEANT code [21] taking into account the measured experimental efficiencies of the streamer tubes.

For the e.m. detector, parameterized expressions of the fluctuations and experimental uncertainties have been included, as well as trigger requirements. The muon contribution to N_e is added by using the average ldf (its overall contribution being anyway lower than 5%).
Poissonian fluctuations and parameterized expressions of experimental uncertainties have been included, as well as trigger requirements.

Simulated events have been treated following the same procedure as the experimental data. More than 10^6 proton showers have been simulated with energy threshold 10^{15} eV, spectral index $\gamma = 2.7$ (from which KASCADE spectra [22] have been afterward sampled), and uniform angular distribution. Every shower has been sampled over an area of $4.4 \cdot 10^5$ m^2 till the event fulfills the "$r-\theta$" and trigger requirements. The number of trials ($n_T(\theta)$) is recorded and used to obtain the angular acceptance.

3 The method and the analysis

The frequency of showers of given primary energy ($E_{0,1} < E_0 < E_{0,2}$) selected through their muon number N_μ ($N_{\mu,1} < N_\mu < N_{\mu,2}$) and shower size N_e corresponding to maximum development ($N_{e,1} < N_e < N_{e,2}$) is expected and observed to decrease exponentially with atmospheric depth through its zenith angle dependence:

$$f(\theta) = G(\theta) f(0) \exp[-x_0(\sec\theta - 1)/\lambda_{\rm obs}] \tag{1}$$

where x_0 is the vertical atmospheric depth of the detector, and $G(\theta)$ the angular acceptance.

The observed absorption length $\lambda_{\rm obs}$, obtained from (1), is a combination of the interaction mean free path ($\lambda_{\rm int}$), and of the shower development and detector response fluctuations. Fluctuation effects are evaluated through simulations, by comparing the observed (λ_{obs}^{sim}) and interaction (λ_{int}^{sim}, which is known from the interaction model) lengths, and are expressed through the factor $k = \lambda_{obs}^{sim}/\lambda_{int}^{sim}$. Such factor is used to convert the observed experimental absorption length λ_{obs}^{exp} into the interaction one λ_{int}^{exp}.
The physical quantities required for the analysis are obtained through simulations as described in the following.
Events in the desired proton primary energy range ($E_0 = (1.5 \div 2.5) \cdot 10^{15}$ eV) are selected by means of a matrix of minimum ($N_{\mu,1}$) and maximum ($N_{\mu,2}$) detected muon numbers for each possible combination of zenith angle and core distance from the muon detector. The selection table is obtained from simulated data for 5 m bins in core distance (50 m $\leq$ r $\leq$ 100 m) and 0.025 $\sec\theta$ bins ($1.0 \leq \sec\theta \leq 1.2$) for zenith angle. $N_{\mu,1}$ and $N_{\mu,2}$ correspond respectively to the average muon numbers for $1.5 \cdot 10^{15}$ eV and $2.5 \cdot 10^{15}$ eV. The selection of proton initiated

cascades near maximum development is based on the simulated distribution of the shower size at maximum development N_e^{max} independently of the atmospheric depth at which it is reached. Choosing the shower size interval $\overline{LogN_e^{max}} \pm \sigma_{LogN_e^{max}}$ (i.e. 6.01< Log N_e < 6.16) provides the selection of the peak of the distribution and of about 65% of the events.
The effective energy distribution of the selected primaries, obtained following the KASCADE spectra, is shown in Fig. 1, the median value being $E_0^{median} = 2.3 \cdot 10^{15}$ eV with HWHM $0.7 \cdot 10^{15}$ eV and systematic uncertainty lower than 10%.

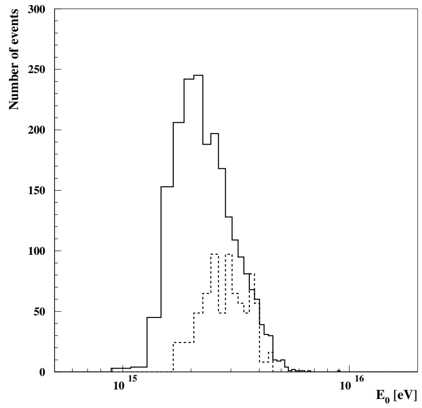

Fig. 1: Primary energy distribution of simulated proton events selected with the N_μ-N_e cuts (continuous line). The energy distribution of helium primaries satisfying the selection criteria is also shown (dashed line).

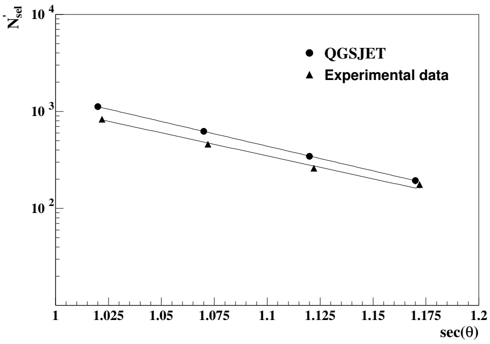

Fig. 2: Acceptance corrected event numbers vs. secθ for the simulated and experimental data selected with the N_μ-N_e cuts. The fits with expression (1) providing the λ_{obs} values are also shown (continuous lines).

The interaction length λ_{int}^{sim} is obtained as the average proton interaction depth in the selected energy range ($E_0 = (1.5 \div 2.5) \cdot 10^{15}$ eV), and results to be $\lambda_{int}^{sim} = 61.2 \pm 0.1$ g/cm^2.

The acceptance corrected numbers of selected events N'_{sel} vs. zenith angle are shown in Fig. 2. The fit with expression (1) provides $\lambda_{obs}^{sim} = 70.4 \pm 3.0$ g/cm^2, and therefore k = $\lambda_{obs}^{sim}/\lambda_{int}^{sim} = 1.15 \pm 0.05$.
The contamination due to heavier primary particles has been evaluated by simulating the helium contribution, assuming the KASCADE spectrum and composition, which accounts for a flux about twice the proton one in the energy range of interest (see Fig. 1).

4 Results and discussion

The same procedure as discussed for the simulation is applied to the experimental data. The corresponding event numbers as a function of sec(θ) are shown in Fig. 2, together with their fit providing $\lambda_{obs}^{exp} = 76.0 \pm 3.8$ g/cm^2. From λ_{int}^{exp}=λ_{obs}^{exp}/k, we obtain $\lambda_{int}^{exp} = \lambda_{p-\mathrm{air}} = 66.1 \pm 4.4$ g/cm^2 where the uncertainties are due to the statistics of the measurement and of the simulation (of the same order).

The p-air inelastic cross section is obtained from: $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}(\mathrm{mb}) = 2.41 \cdot 10^4/\lambda_{p-\mathrm{air}}$, and results to be $\sigma_{p-\mathrm{air}}^{\mathrm{inel}} = 365 \pm 24\mathrm{mb}$. Such value is plotted together with other experimental data and the values derived from the current hadronic interaction models in Fig. 3, resulting respectively about 10% and 15% smaller than QGSJET and SIBYLL [23] cross sections and in better agreement with the QGSJET modified version of Ref. [24].

Predicted $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$ values, that were obtained from different $\sigma_{p\bar{p}}^{tot}$ Tevatron measurements at $\sqrt{s} = 1.8$ TeV by using different calculations based on the Glauber theory, are reported in Fig. 4. The present measurement is in better agreement with the smaller values of the $\bar{p}p$ total cross section ($\sigma_{p\bar{p}}^{tot}$=72.8$\pm$3.1 mb [9], and $\sigma_{p\bar{p}}^{tot}$=71$\pm$2 mb [10]), and the *pp* to *p*-air cross section conversions of Refs. [3, 5, 6].

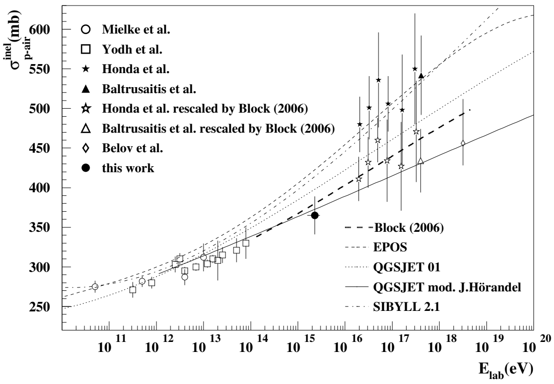

Fig. 3: *p*-air inelastic cross section data, including the present measurement, and values in use from hadronic interaction models.

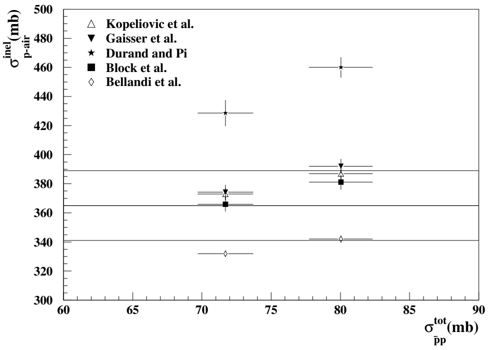

Fig. 4: Present measurement of the *p*-air inelastic cross section ($\pm$ 1 s.d., solid lines) vs. the $\bar{p}p$ data reported at $\sqrt{s} = 1.8$ TeV. Results of different calculations are also shown.

Taking into account helium primaries, the overall simulated observed absorption length becomes $\lambda_{obs}^{sim(p+He)}$ = 65.2$\pm$3.6 g/cm^2, which implies k$^{(p+He)}$ = 1.07$\pm$0.06 , and $\lambda_{int}^{exp(p+He)}$ = 71.4 $\pm$5.3 g/cm^2, i.e. increased of about 8%. Due to the uncertainty of the relative proton/helium flux we will not introduce such a correction, but rather consider it as a systematic uncertainty, possibly increasing the interaction length, and therefore leading to an overestimated cross section value expressed as:

$\sigma_{p-\mathrm{air}}^{inel}(\sqrt{s} \approx 2$ TeV)=365$\pm$24(*stat*)-28(*sys*)mb.

Independently from the cross-section analysis, the measured value of the absorption length ($\lambda_{obs}^{exp} = 76.0 \pm 3.8$ g/cm^2) can be directly compared with the analogous one obtained, for the same experimental conditions, from simulations based on QGSJET ($\lambda_{obs}^{sim} = 70.4 \pm 3.0$ g/cm^2). Inside the still large uncertainties, the measured value results nearly 10% larger than the simulated one (and it would be even larger including the helium contribution), showing a deeper penetration of showers in the atmosphere than predicted by the interaction model, as reflected in the corresponding smaller value of the *p*-air inelastic cross section (see also ref. [24]).

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