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

EAS-TOP COLLABORATION
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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 shower longitudinal development and detection fluctuations are determined by means of simulations performed using the CORSIKA code and the QGSJET interaction model. The simulations provide the conversion factor (*k*=1.15±0.05) from the observed attenuation length (λ_{obs}^{exp}=76.0±3.8 g/cm^2) to the interaction length ($\lambda_{p-\mathrm{air}}$=λ_{int}^{exp}=66.1±4.4 g/cm^2). The obtained value of the *p*-air inelastic cross section at $\sqrt{s} \approx 2$ TeV is $\sigma_{p-\mathrm{air}}^{inel}$=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.

Introduction

We present the final results on the proton-air inelastic cross section measured at primary energy $E_0 = (1.5 \div 2.5) \cdot 10^{15}$ eV (i.e. $\sqrt{s} \approx 2$ TeV) obtained from the analysis of the EAS-TOP experiment complete data set. The considered energy range is below the knee of the primary spectrum ($E_0 \approx 3 \cdot 10^{15}$ eV), above which the proton flux is strongly depressed [1, 2, 3], and allows a direct comparison with the Tevatron $\bar{p}p$ total cross section data [4, 5, 6]. Exploiting the constant N$_e$-N$_\mu$cuts method [7, 8], 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*=$\lambda_{obs}/\lambda_{int}$).

Systematic uncertainties due to the contamination from heavier primaries are discussed assuming as a reference the recent KASCADE spectra [3].

The experiment and the simulation

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

The e.m. detector [9] consisted of 35 modules $10\ \mathrm{m}^2$ each of plastic scintillators distributed over an area of $10^5\ \mathrm{m}^2$. 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 . The resolutions of such measurements for $N_e > 2 \cdot 10^5$ are: $\sigma_{N_e}/N_e \simeq 0.1$; $\sigma_{X_c} = \sigma_{Y_c} \simeq 5$ m; $\sigma_s \simeq 0.1$. The arrival direction of the shower is measured from the times of flight among the modules with resolution $\sigma_\theta \simeq 0.9^o$.

The muon-hadron detector (MHD), is used as a tracking module of 9 active planes. Each plane includes two layers of streamer tubes (12m 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 $E_\mu^{th} \approx 1$ 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).

Simulations have been performed with the CORSIKA code [10] using QGSJET [11] as high energy hadronic interaction model and the NKG analytic treatment of the e.m. component.

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 in the e.m. array is added on average, including fluctuations.

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

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 γ = 2.7 (from which KASCADE spectra[1] have been afterwards 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–θ"* and trigger requirements. The number of trials ($n_T(\theta)$) is recorded and used to obtain the angular acceptance.

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:

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

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

The observed absorption length λ_{obs}, obtained from (1), is a combination of the interaction mean free path (λ_{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 dis-

1. The KASCADE spectra are the ones based on QGSJET analysis and result from our own fits. The power law indexes of proton and helium spectra are respectively $\gamma_{p,1}(E_0 < 2 \cdot 10^{15}$ eV$) = 2.6$, $\gamma_{p,2}(2 \cdot 10^{15}$ eV$< E_0 < 4.5 \cdot 10^{15}$ eV$) = 3.3$, $\gamma_{p,3}(E_0 > 4.5 \cdot 10^{15}$ eV$) = 5.0$, and $\gamma_{He} = 2.65$.

tance (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} in the desired energy interval 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 average energy of the selected primaries, obtained following the KASCADE spectra, is $\bar{E_0} = 2.67 \cdot 10^{15}$ eV with r.m.s. $0.83 \cdot 10^{15}$ eV.

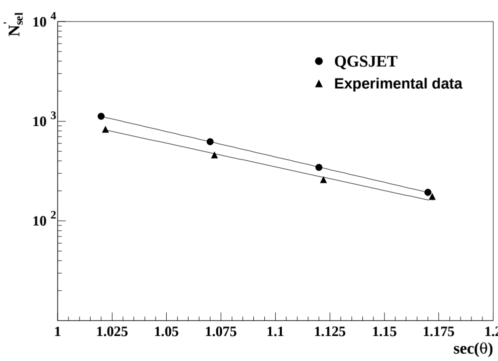

Figure 1: Acceptance corrected event numbers vs. secθ for the simulated and experimental data selected with the N_μ-N_e cuts. The fits with expression (1) providing the λ_{obs} values are also shown (continuous lines).

The interaction length λ_{int}^{sim} is obtained as the average proton interaction depth in the selected energy range (and results to be $\lambda_{int}^{sim} = 61.2 \pm 0.1$ g/cm^2.

The acceptance corrected numbers of selected events vs. zenith angle are shown in fig. 1. 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 primaries 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 [2].

Results and discussion

The same procedure discussed for the simulation is applied to the experimental data. The corresponding event numbers as a function of sec(θ) are shown in fig. 1, together with their fit providing λ_{obs}^{exp}=76.0±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:

$\sigma_{p-\mathrm{air}}^{inel}$=365±24(*stat*)

Such value is plotted together with other experimental data and the values derived from the current hadronic interaction models in fig. 2, resulting respectively about 10% and 15% smaller than QGSJET and SIBYLL [12] cross sections and in better agreement the QGSJET modified version of ref.[13].

Predicted $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$ values, that were obtained from different $\sigma_{\bar{p}p}^{tot}$ Tevatron measurements at $\sqrt{s} = 1.8$ TeV by using different calculations based on the Glauber theory [14], are reported in fig. 3. The present measurement is in better agreement with the smaller values of the $\bar{p}p$ total cross section (and the *pp* to *p*-air cross section conversions of refs. [15, 16, 17].

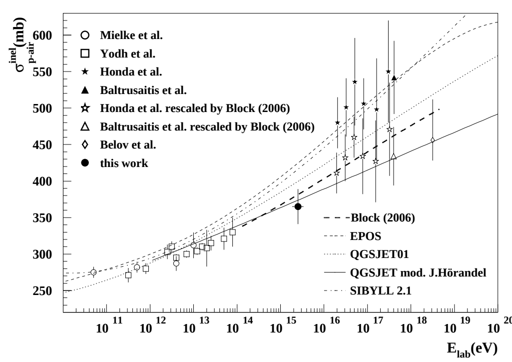

Figure 2: *p*-air inelastic cross section data, including the present measurement, and values in use from hadronic interaction models.

2. Heavier primaries, as e.g. CNO, hardly pass the N_μ-N_e cuts and result in an additional effect smaller than 1%

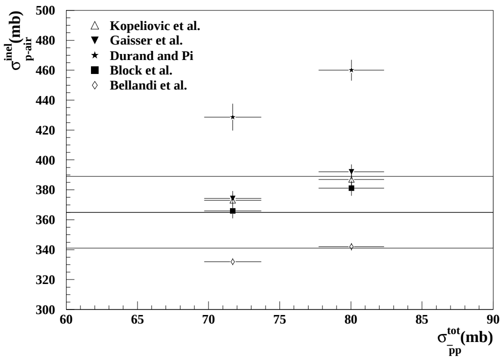

Figure 3: Present measurement of the *p*-air inelastic cross section ($\pm$ 1 s.d., solid lines) vs. the $\bar{p}p$ data reported at $\sqrt{s} = 1.8$ TeV. Results of different calculations [15, 18, 16, 17, 19] are also shown.

Taking into account helium primaries, the overall simulated observed absorption length increases of about 8%. Due to the uncertainty of the relative proton/helium flux we will not introduce such correction, but rather consider it as a systematic uncertainty, possibly increasing the interaction length, and therefore leading to an overestimated cross section value therefore:

$\sigma^{inel}_{p-\mathrm{air}}$=365$\pm$24(*stat*)-28(*sys*)mb

Independently from the cross-section analysis, the measured value of the absorption length ($\lambda^{exp}_{obs} = 76.0 \pm 3.8$ g/cm^2) can be directly compared with the analogous one obtained, for the same experimental conditions, from simulations based on QGSJET ($\lambda^{sim}_{obs} = 70.4 \pm 3.0$ 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. [13]).

References

[1] M. Aglietta et al., Astrop. Phys., **10** (1999) 1-9.

[2] M. Aglietta et al. Astrop. Phys., **21** (2004) 583-596.

[3] T. Antoni et al, Astrop. Phys., **24** (2005) 1-25.

[4] F. Abe et al., Phys. Rev. D, **50** (1994) 5550.

[5] N. A. Amos et al., Phys. Lett. B, **243** (1990) 158.

[6] C. Avila et al., Phys. Lett. B, **445** (1999) 419.

[7] M. Honda et al., Phys. Rev. Lett., **70** (1993) 525.

[8] M. Aglietta et al., Proc. 26$^{\mathrm{th}}$ Int. Cosmic Ray Conf., Salt Lake City (USA), **1** (1999) 143.

[9] M. Aglietta et al., Nucl. Inst. Meth. Phys. Res. A, **336** (1993) 310.

[10] D. Heck et al., Report **FZKA 6019**, Forschungszentrum Karlsruhe (1998).

[11] N. N. Kalmykov, S. S. Ostapchenko and A. J. Pavlov, Nucl. Phys. B, **52** (1997) 17.

[12] R. Engel et al., Proc. 26$^{\mathrm{th}}$ Int. Cosmic Ray Conf., Salt Lake City (USA), **1** (1999) 415.

[13] J.R. Hörandel, J. Phys. G: Nucl. Part. Phys. **29** (2002) 2439

[14] R. J. Glauber and G. Matthiae, Nucl. Phys. B., **21** (1970) 135.

[15] T. K. Gaisser et al., Phys. Rev. D, **36** (1987) 1350.

[16] B. Z. Kopeliovich, Phys. Rev. D, **39** (1989) 769-779.

[17] M. M. Block, Phys. Rep., **436** (2006) 71-215.

[18] L. Durand and H. Pi, Phys. Rev. D, **38** (1988) 78-84

[19] J. Bellandi et al., Phys. Lett. B **343** (1995) 410.