Energy dependence of the nucleon-nucleon σ_{tot}*

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ABSTRACT. The nucleon-nucleon total cross section σ_{tot} is an important experimental quantity in the understanding of hadronic interactions. The behavior of the energy dependence of σ_{tot} has changed as the energy has increased. In the 1960's data were consistent with the belief that all cross sections would eventually approach constant values as $s \to \infty$. By the 1970's, as s increased, all cross sections fell, reached a minimum and then rose. Results available in the early and mid 1980's showed that σ_{tot} continued increasing. The most recent data from the Fermilab Tevatron Collider show that σ_{tot} continue to show a rise as the energy increases, consistent with $\log^2 s$. These new results provide an ideal opportunity to present a review of the behavior of σ_{tot}. In this work, the experimental status of the nucleon-nucleon σ_{tot}, with data from the 1960's to the most recent data from the Fermilab Tevatron Collider, is reviewed. I will also outline the open questions for the next higher energy colliders, LHC ($\sqrt{s}$ = 17 TeV) and SSC ($\sqrt{s}$ = 40 TeV). The work emphasizes the importance of new measurements coming from these higher energy colliders.

RESUMEN. La sección transversal total σ_{tot} para nucleón-nucleón es una cantidad experimental importante en el entendimiento de las interacciones hadrónicas. El comportamiento de la dependencia en la energía de σ_{tot} ha cambiado a medida que la energía ha aumentado. En los años 60 los datos eran consistentes con la creencia de que todas las secciones transversales se aproximarían a un valor constante a medida que $s \to \infty$. Para los años 70, a medida que s aumentó, todas las secciones transversales decrecieron, alcanzaron un mínimo y despues aumentaron. Los resultados disponibles a principios y mediados de los años 80 mostraron que σ_{tot} continuó aumentando. Los datos más recientes provenientes del Fermilab Tevatron Collider muestran que σ_{tot} continúa aumentando a medida que la energía aumenta, consistente con $\log^2 s$. Estos nuevos resultados ofrecen una oportunidad ideal para presentar una revisión del comportamiento de σ_{tot}. En este trabajo se revisa el estado experimental de σ_{tot} para nucleón-nucleón con datos desde los años 60 hasta los datos más recientes provenientes del Fermilab Tevatron Collider. Se delinearán también las preguntas aun abiertas para los próximos aceleradores de más alta energía, LHC ($\sqrt{s}$ = 17 TeV) y SSC ($\sqrt{s}$ = 40 TeV). El trabajo enfatiza la importancia de nuevas mediciones provenientes de estos aceleradores.

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1. INTRODUCTION

To understand the dynamics of hadronic interactions at high energies it is essential to know the behavior of the nucleon-nucleon total cross section σ_{tot}. In this context the Fermilab Tevatron Collider experiments (CDF and E-710 collaborations) have recently published

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new results about σ_{tot} and the ratio of the real to the imaginary part of the forward scattering amplitude ρ for $\bar{p}p$ scattering. Also, it is well known that the UA4 measurement of ρ produced an intriguing result ($\rho = 0.24$) larger than the expected ($\rho \approx 0.13$) from lower energy extrapolations. All these reasons added with the Fermilab Tevatron Collider results in hand, provide an ideal opportunity to present a review of the behavior of nucleon-nucleon σ_{tot}. This review covers approximately 30 years of experimental data; from 1960's, data mainly from the CERN PS and the BNL AGS in the range of ≈ 1 GeV to ≈ 50 GeV, to the most recent experimental data from the Fermilab Tevatron Collider at 1.8 TeV.

The structure of this paper is the following. Firstly, it discusses in Sect. 2 some different methods to measure the nucleon-nucleon σ_{tot}. Section 3 is devoted to the discussion of the elastic scattering distribution. Next, in Sect. 4 it does a historical review of the experimental data (from 1960's to 1980's) and it compares the experimental results with predictions of the black disc model. Section 5 is concerned to the analysis of the most recent experimental data from the CDF and E-710 collaborations at the Fermilab Tevatron Collider. Finally, in Sect. 6 it outlines future prospects in the field, specifically for the next higher energy colliders, LHC ($\sqrt{s} = 17$ TeV) and SSC ($\sqrt{s} = 40$ TeV).

2. MEASUREMENT OF σ_{tot}

The nucleon-nucleon σ_{tot} is an experimental quantity which has been measured to very high accuracy. Different techniques can be used to measure σ_{tot}: One relies on a luminosity independent method [1,2], from which σ_{tot} can be determined using the optical theorem, and extrapolating the differential elastic cross section $d\sigma_{\text{el}}/dt$ to $t = 0$,

$$\sigma_{\text{tot}}^2 = 16\pi(\hbar c)^2\left(1+\rho^2\right)^{-1}\left.\frac{d\sigma_{\text{el}}}{dt}\right|_{t=0}. \tag{1}$$

σ_{tot} can also be written as the sum of the elastic N_{el} and inelastic N_{inel} rates as follows:

$$\sigma_{\text{tot}} = \frac{N_{\text{el}} + N_{\text{inel}}}{L}, \tag{2}$$

where L is the integrated luminosity.

On the other hand, the distribution of elastically scattered particles is given by

$$\frac{dN_{\text{el}}}{dt} = L\frac{d\sigma_{\text{el}}}{dt}. \tag{3}$$

So, substituting Eqs. (2) and (3) into Eq. (1), can be obtained a luminosity independent expression for σ_{tot}:

$$\sigma_{\text{tot}} = \frac{16\pi(\hbar c)^2}{(1+\rho^2)(N_{\text{el}}+N_{\text{inel}})}\left.\frac{dN_{\text{el}}}{dt}\right|_{t=0}, \tag{4}$$

where N_{el} is measured using [3] a set of detectors in "Roman Pots" and N_{inel} is measured using a set of scintillators surrounding the interaction region. ρ can be extracted from the interference region using the Coulomb phase [4]. From ρ, the elastic slope, and the inelastic rate, one obtains σ_{tot}. This is the experimental method used by the experiment E-710 at the Fermilab Tevatron Collider and it is similar to that of previous collider experiments at the CERN ISR and SPS.

Thus, with the method described above, one derives σ_{tot} independently of L; the latter is derived from the accelerator parameters.

It is also possible to use dN_{el}/dy in Eq. (4) instead of dN_{el}/dt, where dN_{el}/dy is the number of events in which an elastically scattered particle strikes a strip of detector of width dy. dN_{el}/dy is given by [5] as a function of y, N_{inel}, σ_{tot}, ρ and B as follows:

$$\frac{dN_{el}}{dy} = \sum_i E_i(N_{inel}, \sigma_{tot}, \rho, B) K_i(y), \tag{5}$$

where y is the vertical distance from the beam center, and each y bin cover a specified range [6] of t, and B is the nuclear slope parameter. This function is fitted to the experimental distributions to extract the value of σ_{tot}.

Another technique [7] is to use a direct measurement of the accelerator parameters to calculate L, and hence make a direct extrapolation to $t = 0$. It measures $d\sigma_{el}/dt$, which is given as

$$\frac{d\sigma_{el}}{dt} = L^{-1}\frac{dN_{el}}{dt}. \tag{6}$$

Then, the measured $d\sigma_{el}/dt$ is extrapolated to $t = 0$ and σ_{tot} is calculated using the optical theorem,

$$\sigma^2_{tot} = \frac{16\pi(\hbar c)^2}{(1+\rho^2)} \left.\frac{d\sigma_{el}}{dt}\right|_{t=0}. \tag{1}$$

This is the method used by the CDF collaboration at the Fermilab Tevatron Collider.

3. Elastic scattering distribution

The elastic differential cross section for nucleon-nucleon scattering is given by a sum of three terms:

(i) a Coulomb term, which dominates the scattering at very small values of $|t|$, where t is the 4-momentum transfer squared,

(ii) a nuclear term, which dominates almost entirely at larger values of $|t|$,

(iii) the interference term, which has a significant contribution in some intermediate range around $|t| = 0.001$ (GeV/c)^2.

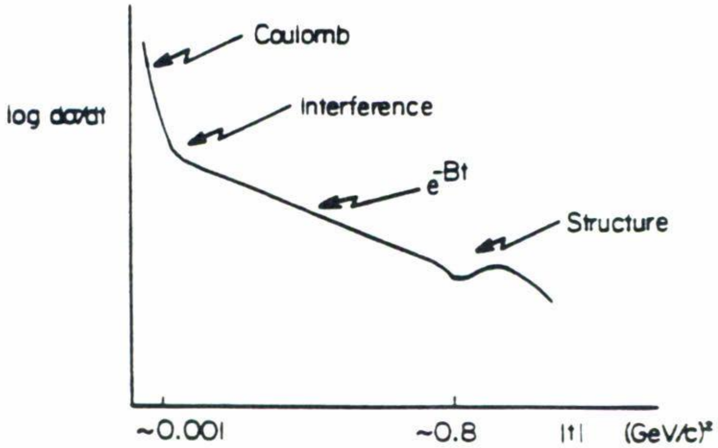

FIGURE 1. Typical elastic scattering distribution at hadron collider energies.

These three terms are given explicitly as follows:
Coulomb term,

$$\frac{d\sigma_{\rm C}}{dt} = \frac{4\pi\alpha^2(\hbar c)^2 G^4(t)}{|t|^2}; \tag{7}$$

Nuclear term,

$$\frac{d\sigma_{\rm n}}{dt} = \frac{\sigma_{\rm tot}^2(1+\rho^2)}{16\pi(\hbar c)^2} e^{-B|t|}; \tag{8}$$

and Interference term,

$$\frac{d\sigma_{\rm Cn}}{dt} = \frac{\alpha(\rho-\alpha\phi)\sigma_{\rm tot}G^2(t)}{|t|} e^{\frac{B|t|}{2}}, \tag{9}$$

where, α is the fine structure constant ($\approx 1/137$), $G(t)$ is the electromagnetic form factor of the proton, written [8] as $G(t) = \left(1 + \frac{|t|}{0.71}\right)^{-2}$, and ϕ is the Coulomb-nuclear relative phase, given by [4] $\ln(0.08|t|^{-1} - 0.577)$. So, the elastic differential cross section can be written as

$$\frac{d\sigma_{\rm el}}{dt} = \frac{d\sigma_{\rm C}}{dt} + \frac{d\sigma_{\rm n}}{dt} + \frac{d\sigma_{\rm Cn}}{dt}. \tag{10}$$

Figure 1 shows a typical elastic scattering distribution in which can be seen:

(a) the Coulomb region, with $d\sigma_{\rm C}/dt \sim \frac{1}{t^2}$, which is used for normalization,

(b) the nuclear region, with $d\sigma_{\rm n}/dt \sim e^{-Bt}$, which is normally called the diffraction peak and can be used to extrapolate to $t = 0$ to obtain $\sigma_{\rm tot}$,

(c) the interference region (also called Coulomb-nuclear interference region), which can be used to obtain ρ, and finally,

(d) the structure region, which is associated to dips and bumps.

4. HISTORICAL REVIEW

In this section we review the evolution of the energy dependence of nucleon-nucleon σ_{tot} from the 1960's to the 1980's. The experimental results are compared with the predictions of the black disc model.

4.1. Evolution through the 1960's

The evolution of nucleon-nucleon σ_{tot} through the 1960's is reviewed with data available from the CERN Proton Synchrotron (PS) [9–15], BNL Alternating Gradient Synchrotron (AGS) [16–26], Lawrence Radiation Laboratory [27–29], Rutherford High Energy Laboratory [30], Cyclotron Laboratory of Harvard [31], and Serpukhov [32]. The measurements are in the range of ≈ 1 GeV to ≈ 30 GeV.

Figure 2a shows the measurements of σ_{tot} for pp (52 points) and $\bar{p}p$ (29 points) interactions through the 1960's. As can be seen, all cross sections lie in the interval ≈ 30 mb to ≈ 80 mb. However, some results up to ≈ 170 mb have been reported [13] for $\bar{p}p$ interactions. The data seem to indicate a smooth behavior of the cross sections as a function of the energy, being consistent with the belief that all cross sections would eventually approach constant values as $s \to \infty$. At least it seems as if the cross sections will not become infinite as the energy increases. There is a theoretical argument supporting this fact, although slightly weak in its formulation. By exploiting the consequences of quantum field theory, it is possible to show that σ_{tot} may grow at most as the second power of $\log(P_{lab})$ as the energy increases

$$\sigma_{tot} < C[\log(P_{lab})]^2, \tag{11}$$

where C is a constant, the value of which is not known. This relation is called the Froissart bound, and was proved [33] in 1961 using unitary and the Mandelstam representation of the scattering amplitude. Another proof based on the axioms of quantum field theory was given by Martin [34] in 1966.

Straightforward extrapolation of the data seem to indicate that σ_{tot} for collisions of a particle and its antiparticle with the same target will eventually become equal. This behavior has a theoretical justification as well. If it is assumed that σ_{tot} of a particle β for a particle α becomes constant beyond an incident energy ϵ such that

$$\sigma_{tot}(\alpha + \beta) = C_1 \quad \text{for energies} > \epsilon_1, \tag{12}$$

and

$$\sigma_{tot}(\bar{\alpha} + \beta) = C_2 \quad \text{for energies} > \epsilon_2, \tag{13}$$

where C_1 and C_2 are constants and $\bar{\alpha}$ is the antiparticle of α, then it can be proved that

$$\sigma_{tot}(\alpha + \beta) = \sigma_{tot}(\bar{\alpha} + \beta) \quad \text{for energies} > \epsilon, \tag{14}$$

where $\epsilon >$ both ϵ_1 and ϵ_2. This result is known as the Pomeranchuk theorem, proved from dispersion relations by Pomeranchuk [35] in 1956, and with less assumptions by

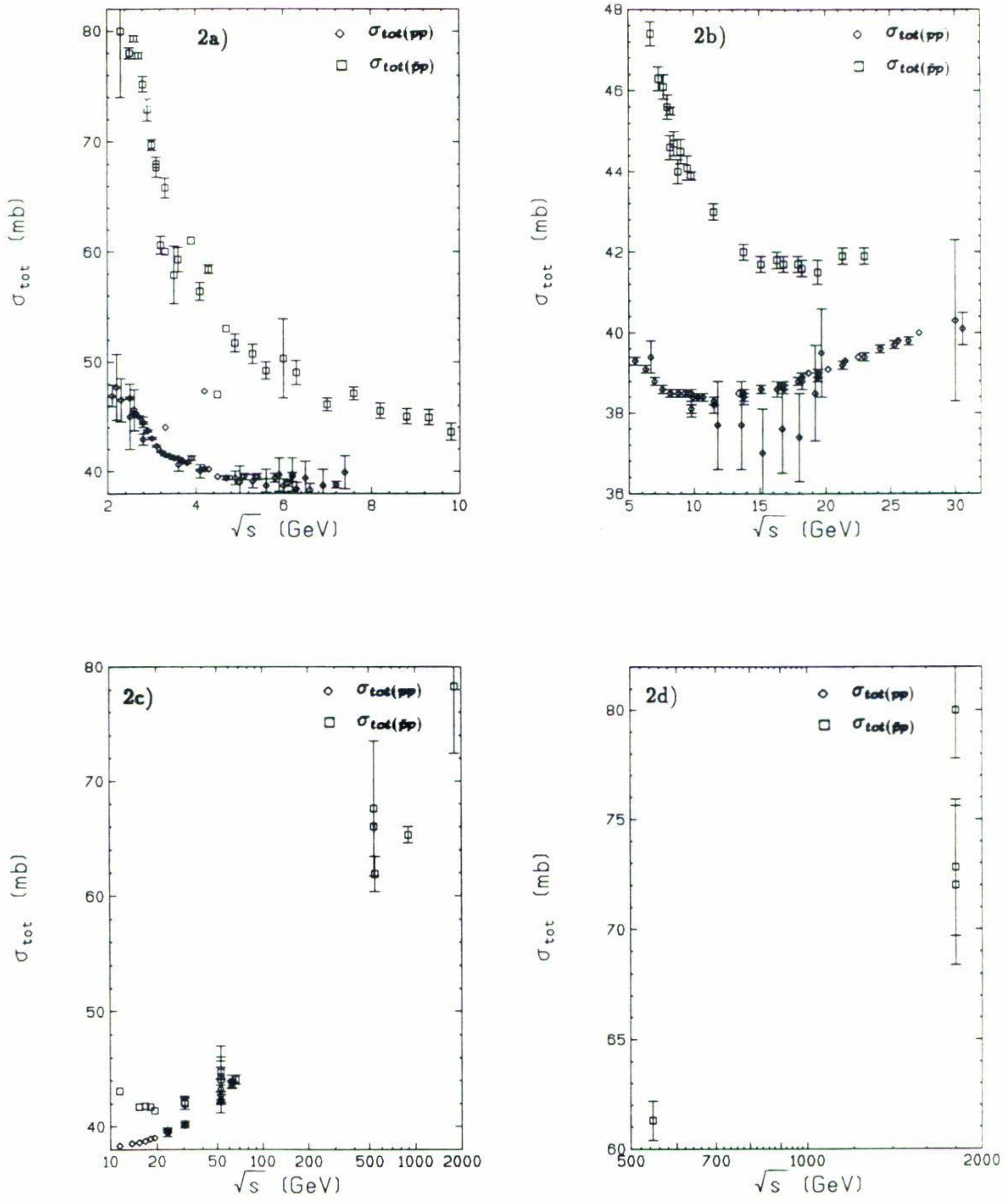

FIGURE 2. Measurements of $\sigma_{\rm tot}$ for both pp and $\bar{p}p$ interactions. (a) Results available in the 1960's. (b) Results available in the 1970's. (c) Results available in the 1980's. (d) Recent results from the Fermilab Tevatron Collider for $\bar{p}p$ interactions.

Martin [36] in 1965. Those energies at which the assumptions and consequences of the Pomeranckuk theorem are satisfied are known as the "asymptotic region". Results by Lindenbaum [37] suggested that the "asymptotic region" could be within reach with a 20 TeV machine.

On the other hand, the experimental data also indicate that σ_{tot} is bigger for $\bar{p}p$ than for pp. This fact is qualitatively explained by the larger number of inelastic channels open in $\bar{p}p$ collisions such as annihilation and baryon-antibaryon final states.

4.2. Evolution through the 1970's

In this section we review the state of nucleon-nucleon σ_{tot} through the 1970's from data of the CERN Intersecting Storage Rings (ISR) [38–43], Fermilab [44–51], and Serpukhov [52–53] with energies between $\approx$ 50 and $\approx$ 500 GeV. Fig. 2b shows these results for pp (59 points) and $\bar{p}p$ (21 points) interactions.

In the 1960's, data were consistent with the belief that all cross sections would eventually approach constant values as $s \to \infty$. However, by the 1970's, the picture had changed. As s increased, all cross sections fell, reached a minimum and then rose.

The rise observed in Fig. 2b is proportional to $\log^2 s$, the fastest possible consistent with the Froissart bound. There have been many explanations for the rising cross sections, these include an increase in diffraction scattering, minijets, and the increasing effect of gluons.

An obvious question in the 1970's was if either σ_{tot} will continue to rise, becoming infinite at infinite energy or if it eventually approach a constant value. Using ISR measurements, predictions [54,58] for σ_{tot} at higher energies have been made using dispersion relations; these showed σ_{tot} rising.

4.3. Evolution through the 1980's

In the early and mid 1980's, results became available from the CERN Super Proton Synchrotron (SPS) [59–62], CERN ISR [63–69], and Fermilab [70,71]. In Fig. 2c the SPS collider values on σ_{tot} both for pp (19 points) and $\bar{p}p$ (20 points) are shown. As can be seen σ_{tot} continue to rise as energy increases. However, the data are not able to distinguish between cross sections which at large s continue as $\log^2 s$, or those which eventually approach a constant.

In the 1980's, data especially relevant are those from the UA4 experiment. The UA4 measured a value [72] of ρ at $\sqrt{s}$ = 546 GeV which does not fall on the general fits to all other existing data. The experimental point is 2.5 standard deviations from the prediction. This discrepancy between the SPS UA4 measurement of ρ at $\sqrt{s} = 546$ GeV and the expected value have been discussed in many theoretical papers [73–78]. There was a general consensus that some new physics was needed to accommodate the value of $\rho = 0.24$. Many models have been produced using this datum point, with many dramatic predictions.

UA4 also measured σ_{el}/σ_{tot}. The value of σ_{el}/σ_{tot} is a measure of nucleon blackness and thus UA4 showed that the nucleon is becoming blacker with increasing energy.

After UA4 results were available, the open questions were:

i) What is the energy dependence of σ_{tot} (as s increases)?, does σ_{tot} go to infinity or to a constant value?

ii) What is the energy dependence of ρ, and in particular can the UA4 result be confirmed?.

4.4. The black disc model

Now we discuss in detail the black disc model, widely used to explain processes of elastic scattering.

The fact that the cross sections are finite as the energy increases can be seen as an indication that the range R of the forces responsible for the interactions is finite. In the crudest of models one expects a σ_{tot} of the order of the geometrical one

$$\sigma_{\text{tot}} \approx \pi R^2. \tag{15}$$

In an impact parameter picture, it could define R as the maximum impact parameter b_{max} for which scattering occurs. For the impact parameter amplitude $B(b, E)$ the above assumption takes the form

$$B(b, E) = 0 \quad \text{for} \quad b > b_{\text{max}} = R. \tag{16}$$

It simply means that all particles that pass the target at a distance larger than R will not feel any influence from the scattering centre and will thus pass untouched.

At high energies it is an experimental fact that inelastic reactions occur very frequently. This means that the absorption parameter $\eta(b)$ might be quite small; roughly speaking it can be assumed that $\eta(b) = 0$ for those b values at which scattering occurs.

So, from the equation

$$B(b, E) = \frac{1}{2i}[\eta(b, E)\exp(2i\delta(b, E)) - 1],$$

the impact parameter amplitude takes the form

$$B(b, E) = \frac{1}{2i}(0 - 1) = \frac{i}{2}, \quad \text{for } b < R. \tag{17}$$

The assumptions given in Eqs. (16) and (17) define the "black disc model".

The result of the black disc model for the elastic scattering amplitude is that

$$F_{\text{el; black disc}}(\cos\theta, E) = iK \int_0^R b\,db\,J_0(b\Delta), \tag{18}$$

where $\Delta = 2K\sin(\theta/2) = \sqrt{-t}$ is the momentum transfer.

From the optical theorem one derives $\sigma_{\rm tot}$ directly,

$$\sigma_{\rm tot} = \frac{4\pi}{K}\,{\rm Im}\left[iK\int_0^R b\,db\right] = 2\pi R^2.$$

As can be seen, $\sigma_{\rm tot}$ is twice the geometrical cross section.

The evaluation of Eq. (18) gives

$$\sigma_{\rm el;\,black\,disc} = \pi R^2 = \tfrac{1}{2}\sigma_{\rm tot;\,black\,disc}.$$

So, the parameter $a = \sigma_{\rm el}/\sigma_{\rm tot}$, which is a measure of the amount of absorption occurring in the interaction, is predicted to be 0.5.

With the predictions of the black disc model in mind, we now turn to the experimental results. As it was mentioned in Sect. 4.3, the energies available in the mid 1980's from the CERN SPS collider showed that the ratio $\sigma_{\rm el}/\sigma_{\rm tot}$ is increasing, as energy increases. However, the value of $\sigma_{\rm el}/\sigma_{\rm tot}$ lies between ≈ 0.15 and 0.30, that is, about half the value predicted by the black disc model; being larger for pp than for $\bar{p}p$, which is connected to the circumstance that more inelastic channels are open for $\bar{p}p$ compared to pp.

Is the proton becoming blacker as energy increases, and eventually can the black disc model prediction for $\sigma_{\rm el}/\sigma_{\rm tot}$ be reached? These still are open questions.

5. Recent data (1990's)

This section is concerned to the analysis of the most recent data from both the CDF [7,79–81] and E-710 [1,5,6,8,82–84] collaborations at the Fermilab Tevatron Collider. Both collaborations have made measurements of $\sigma_{\rm tot}$, ρ, and B for $\bar{p}p$ scattering at $\sqrt{s} = 1.8$ TeV, the highest energy currently available, and with an integrating luminosity $L = 4.0 \pm 0.3$ pb^{-1}.

These new Tevatron results allow a comprehensive review of the field. Particularly interesting, after the UA4 measurement of ρ, is the new measured value of this variable. The CDF collaboration has no reported any measurement of ρ. The E-710 group has made [84] a measurement of $\rho = 0.140 \pm 0.069$, which is in general consistent with the expected behavior based on lower energy data, implying that the UA4 measurement have been interpreted as very anomalous.

The E-710 group had a previous [1] measurement of ρ at the same energy of the UA4 measurement, $\sqrt{s} = 546$ GeV, which had been interpreted as inconsistent with the expected behavior. This situation have been the reason for that new physics phenomena have been invoked in order to explain the apparent discrepancy at this energy.

On the other hand, both the CDF and E-710 groups have reported recently measurements of $\sigma_{\rm tot}$ for $\bar{p}p$ scattering at $\sqrt{s} = 1.8$ TeV. CDF has also reported [81] a measurement at $\sqrt{s} = 546$ GeV. Their results are in general consistent with the expected behavior based on the "$\log^2 s$" physics and also compatible with the Pomeranchuk theorem.

TABLE I. Recent (1990's) experimental results at the Fermilab Tevatron Collider for $\bar{p}p$ scattering. Also is shown a value of ρ from the CERN SPS. (Refs. [1,5–8,79–85]).

Collaboration	$\sqrt{s}$ (GeV)	$\sigma_{\rm tot}$ (mb)	ρ	B (GeV/c)$^{-2}$	$\sigma_{\rm el}/\sigma_{\rm tot}$
E-710	1800	72.8 ± 3.1	0.140 ± 0.069	16.99 ± 0.47	0.233 ± 0.012
CDF	1800	72.0 ± 3.6	—	16.50 ± 0.76	0.299 ± 0.020
CDF	1800	80.0 ± 2.2	—	—	—
CDF	546	61.3 ± 0.9	—	—	—
CERN SPS	541	—	0.135 ± 0.015	—	—

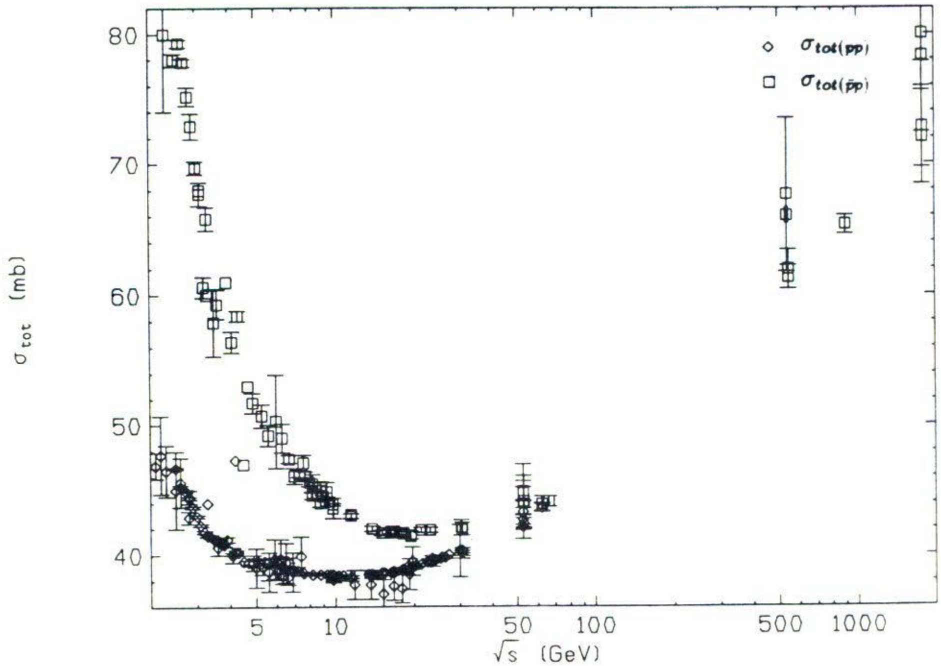

FIGURE 3. Measurements of $\sigma_{\rm tot}$ for pp and $\bar{p}p$ interactions since 1960's up to now.

Table I shows the results of $\sigma_{\rm tot}$ and ρ, and also B and $\sigma_{\rm el}/\sigma_{\rm tot}$ for $\bar{p}p$ scattering from both CDF and E-710 collaborations. There are not reported data for pp scattering. Table I shows also a reported [85] value of ρ from CERN SPS at $\sqrt{s} = 541$ GeV for $\bar{p}p$.

Figure 2d shows the recent Tevatron results. Figure 3 shows together the Tevatron results and measurements since 1960's. It can be concluded from Fig. 2d and Table I, that $\sigma_{\rm tot}$ and ρ continue to rise as energy increases. Also, the values of $\sigma_{\rm el}/\sigma_{\rm tot}$ reported in Table I, show an increase with respect to results at lower energies.

Finally, it is important to mention that the UA4 collaboration has recently [86] published a new measurement of ρ, finding that the new results no longer disagree with the expected value.

TABLE II. Predictions of several models for $\sigma_{tot}(\bar{p}p)$ at the LHC and SSC energies (Refs. [78,87]). Also is shown the Akeno prediction for $\sigma_{tot}(pp)$ at the SSC energy (Ref. [101]).

Collider	$\sqrt{s}$ (TeV)	$\sigma_{tot}(\bar{p}p)$(mb)	Model
LHC	17	107 ± 4	Block, Halzen, and Margolis (QCD)
SSC	40	121 ± 5	Block, Halzen, and Margolis (QCD)
SSC	40	135	Gotsman, Levin, and Maor (a_{II})
SSC	40	106	Gotsman, Levin, and Maor (Ω_{II})
SSC	40	134	Gotsman, Levin, and Maor (Ω_{IV})
SSC	40	191	Gotsman, Levin, and Maor (Ω_{V})
SSC	40	132	Gotsman, Levin, and Maor (Ω_{VI})
SSC	40	133	Akeno prediction for *pp* (Durand and Pi method)

6. FUTURE PROSPECTS

From all the results presented, both recent from the CDF and E-710 collaborations and from lower energy data, we attempt to outline future possibilities for the LHC ($\sqrt{s}$ = 17 TeV) and SSC ($\sqrt{s} = 40$ TeV) colliders.

The wide class of models that have made predictions for σ_{tot} at the future energies, as 'QCD' predictions [87–91], rising mini-jet cross section [92–95], or the "odderon" [96–100], might suggest substantially new physics at the LHC and SSC colliders.

The unanswered questions for the future can be summarized as follows:

(i) Does σ_{tot} go to infinity or to a constant value as energy increases?

(ii) Is the proton becoming blacker as energy increases?

These forthcoming machines should give the first experimental glimpse of these questions.

In Table II are shown predictions of several models [78,87] for σ_{tot} at the LHC and SSC energies. Note the disagreement and the wide range of predictions for σ_{tot} at SSC energy.

6.1. Cosmic ray experiments

At present, accelerator data are available only up to $\sqrt{s} = 1.8$ TeV for $\bar{p}p$ interactions. No data are reported at these energies for *pp*. Now, with the recent problems associated to the construction of the SCC, the possibilities to get accelerator data in the near future to energies greater than $\sqrt{s} = 17$ TeV (LHC energy) are really uncertain.

Recent cosmic ray experiments [101–103] held at the Akeno Cosmic Ray Observatory in Tokyo, provide us with the unique opportunity to measure the *pp* total cross section at ultra high energies ($E \approx 10^{17}$ eV). For the reasons mentioned above, these experiments acquire great importance.

Using recent results from the Akeoo collaboration and a method given by Durand and Pi [104], it is shown that σ_{tot} for *pp* increases with energy as

$$\sigma_{tot}(pp) = 38.5 + 1.37 \ln^2(\sqrt{s}/10 \text{ GeV}) \text{ mb}. \quad (19)$$

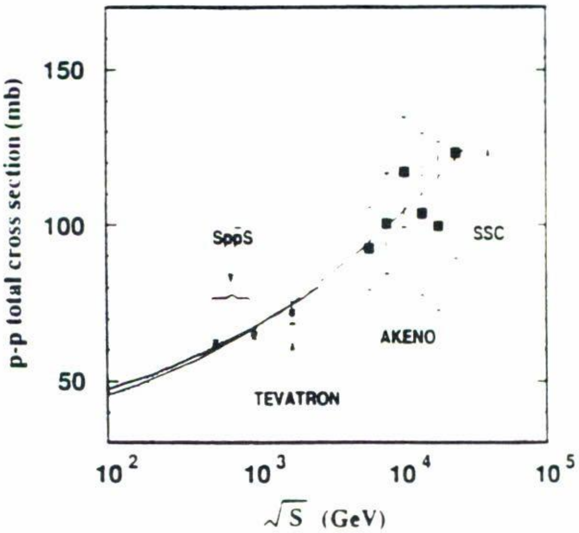

FIGURE 4. Energy dependence of $\sigma_{\rm tot}(pp)$ obtained using the Durand and Pi method. Figure shows the Akeno results along accelerator data. The solid line shows the fit in the form $\sigma_{\rm tot}(pp) = 38.5 + 1.37\ln^2(\sqrt{s}/10\ \text{GeV})$. (Ref. [101]).

From this expression they were able to obtain the value $\sigma_{\rm tot}(pp) \approx 120$ mb, for an energy of $\approx 10^4$ GeV. The Akeno results are shown in Fig. 4 along with indications of SPS, Tevatron, and the SSC energy ranges.

From the relation (19), the value expected for $\sigma_{\rm tot}(pp)$ at the SSC ($\sqrt{s} = 40$ TeV) is 133 ± 10 mb.

7. CONCLUSIONS

The behavior of the energy dependence of $\sigma_{\rm tot}$ has changed as energy has increased. In the 1960's data were consistent with the belief that all cross sections would eventually approach constant values as $s \to \infty$. By the 1970's, as s increased, all cross sections fell, reached a minimum and then rose. Since the 1980's $\sigma_{\rm tot}$ continues to rise, consistent with $\log^2 s$. Also ρ, B, and $\sigma_{\rm el}$ continue increasing as s increases. The same behavior shows $\sigma_{\rm el}/\sigma_{\rm tot}$ showing that the nucleon is getting blacker, but has not yet reached the black disc value of 0.5.

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