Total pion-proton cross-section from the new LHCf data on leading neutrons spectra.

R.A. Ryutin

Institute for High Energy Physics, NRC “Kurchatov Institute”, Protvino 142 281, Russia

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Abstract. In the light of the latest data by LHCf collaboration of the LHC on leading neutrons spectra it is possible to obtain total pion-proton cross-sections in the TeV energy region. In this work the exact extraction procedure is shown. Final numbers for the pion-proton cross-section are collected at several different values of the colliding energy and compared with some popular theoretical predictions. Errors of results are estimated.

PACS. 11.55.Jy Regge formalism – 12.40.Nn Regge theory, duality, absorptive/optical models – 13.85.Ni Inclusive production with identified hadrons – 13.85.Lg Total cross sections

Introduction

In previous papers we pushed forward (and discussed) the idea of using the leading neutrons spectra at LHC to extract the total [1], elastic [2] and inclusive di-jet [3] cross-sections of the $\pi^+p$ and $\pi^+\pi^+$ scattering processes. Actually, this could allow the use of the LHC as a $\pi p$ and $\pi\pi$ collider. Certainly, at LHC it would be difficult to measure exclusive channels but, instead, inclusive spectra of fast leading neutrons seem to give an excellent occasion to get pion cross-sections at unimaginable energies 1-5 TeV in the c.m.s. For further motivation and technical details we refer the reader to Refs. [1]-[4].

The process of leading neutron production has been studied at several experiments in photon-hadron [5]-[11] and hadron-hadron [12]-[18] colliders. In this paper we consider process of the type $p + p \rightarrow n + X$ in the light of new data from the LHCf collaboration [19]. Recently some calculations were made in [20]-[23]. In these works authors paid attention basically to the photon-proton reaction, while for hadron collisions the situation was estimated to be not so clear (see [22],[23]).

The leading neutron production is dominated by $\pi$ exchange [20]-[23] and we have a chance to extract total $\pi^+p$ cross-sections.

Since the energy becomes large, we have to take into account effects of soft rescattering which can be calculated as corrections to the Born approximation. In the calculations of such absorptive effects we use Regge-eikonal approach [24], which is corrected by the use of new data from TOTEM [25].

In the first part of the paper the outlook of the method is given, while in the last section this method is applied to the recent data from the LHCf collaboration [19].

The result shows that our previous proposals to use this method in CMS ZDC look rather realistic.

Single pion exchange and a method to extract pion-proton total cross-section

Details of calculations can be found in [1],[2]. Here we give an outlook of basic methods. As an approximation for $\pi$ exchanges we use the formulas shown graphically in Fig. 1.

In the model we have to take into account absorptive corrections depicted as $S$ in Fig. 1. In our previous papers we used the model [24] with three pomerons for this task. In the present work we apply the Regge-eikonal model [24] with three pomerons and two odderon, since it better fits the data, including also the latest results from TOTEM [25]. Although in the region of the Single Charge Exchange (SCE) process [3] at the LHC almost

Fig. 1. Amplitude squared and the cross-section of the process $p + p \rightarrow n + X$ (Single pion Exchange, S$\pi E$). $S$ represents soft rescattering corrections.
all the models describe the data rather well, and possible theoretical errors are small.

We consider only absorption in the initial state (elastic absorption), since other corrections are not so important at very low values of t. Arguments in favour of this statement can be found, for example, in the Ref. [20], where different types of corrections were analysed. Although, some authors [22,27,28] argued that there is an additional suppression due to interactions of “color octet states” in proton remnants with the final neutron. But we have some doubts that the lifetime of final state fluctuations is large enough and interaction between colorless neutron with “color octets” is important, at least, at low momentum transfer squared.

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![Fig. 2](image)

**Fig. 2.** Function \( S(\xi, t)/m_{\pi}^2 \) versus \( t/m_{\pi}^2 \) at fixed \( \xi = 0.107 \) (upper figure) and \( \xi = 0.179 \) (lower figure). The boundary of the physical region \( t_0 = -m_{\pi}^2/\xi^2/(1 - \xi) \) is represented by vertical dashed line.

Finally we have the expression for the single pion exchange (S\( \pi \)E) cross-section

\[
\frac{d\sigma_{S\pi E}}{d\xi dt} = F_0(\xi, t) S(s/s_0, \xi, t) \sigma_{\pi^+ p}(s; \{m_{\pi}^2, t\}), \quad (1)
\]

\[
F_0(\xi, t) = \frac{G_{\pi^+ p}^2}{16\pi^2} \frac{-t}{(t - m_{\pi}^2)^2} e^{2\eta t} \xi^{1 - 2\alpha_s(t)}, \quad (2)
\]

where the pion trajectory is \( \alpha_s(t) = \alpha_s'(t - m_{\pi}^2) \). The slope \( \alpha_s' \approx 0.9 \text{ GeV}^{-2}, \xi = 1 - x_L \), where \( x_L \) is the fraction of the initial proton’s longitudinal momentum carried by the neutron, and \( G_{\pi^+ p}^2/(4\pi) = G_{\pi^+ p}^2/(8\pi) = 13.75 \). From recent data [5,31], we expect \( b \approx 0.3 \text{ GeV}^{-2} \).

are interested in the kinematical range

\[
0.01 \text{ GeV}^2 < |t| < 0.5 \text{ GeV}^2, \xi < 0.4, \quad (3)
\]

where formulae (1) dominate according to [32] and [33].

Behaviour of \( S(t/m_{\pi}^2) \) is shown in the Fig. 2. It is clear from the figure that \( |S| \sim 1 \) at \( |t| \sim m_{\pi}^2 \), which is an argument for the possible almost model-independent extraction of \( \pi p \) cross-sections by the use of (1) [2].

The present design of detectors does not allow exact \( t \) measuremetns, it gives only integrated cross-sections in some interval \( t_{\text{min}} < t < t_{\text{max}} \). If to assume a weak enough \( t \)-dependence of \( \pi p \) cross-sections, i.e.

\[
\sigma_{\pi^+ p}(s; \{m_{\pi}^2, m_{\eta}^2, m_{\pi}^2\}) \approx \sigma_{\pi^+ p}(s; \{m_{\pi}^2, m_{\eta}^2\}), \quad (4)
\]

then we could hope to extract these cross-sections (though, with big errors) by the following procedure:

\[
\tilde{S}(s, \xi) = \int_{t_{\text{min}}}^{t_{\text{max}}} dt \ S(s/s_0, \xi, t) F_0(\xi, t), \quad (5)
\]

\[
\sigma_{\pi^+ p}(s) \approx \frac{d\sigma_{S\pi E}/s}{\tilde{S}(s, \xi)} \approx \frac{M_{\pi p}^2}{s}. \quad (6)
\]

Function \( \tilde{S}(s, \xi) \) is depicted in Fig. 3. To suppress theoretical errors of \( \tilde{S} \) we have to use total and elastic \( pp \) cross-sections at 7 TeV, since all the models for absorptive corrections are normalized to \( pp \) cross-sections. At present we can estimate these errors to be less than several percent at 7 TeV since we have precise data from TOTEM [23].

![Fig. 3](image)

**Fig. 3.** Rescattering corrections multiplied by formfactors for \( \sqrt{s} = 7 \text{ TeV} \) (\( \tilde{S}(s, \xi) \)) integrated in the whole \( t \) regions of the LHCf data [19]: \( \eta > 10.76 \). Dashed vertical lines mark \( \xi = 0.107, 0.179, 0.28 \), which are used to extract \( \sigma_{\pi p} \) cross-sections.

**LHCf data analysis and values of pion-proton total cross-sections in TeV domain**

Our method developed in [1] was successfully applied to the extraction of \( \pi^+ p \) total cross-sections at low energies (see Fig. 4).
In this section we show results of the procedure [6] applied to the latest data on neutrons spectra by LHCf [19].

Let us first consider the data on $d\sigma_{\pi}/dE_{\pi}$ from the table A.5 of [19] in three rapidity ranges:

$$
\eta > 10.76,
8.99 < \eta < 9.22,
8.81 < \eta < 8.99.
$$

The first one corresponds to very low $t \sim m_{\pi}^2$ values, where the flux factor $\hat{S}$ is small, and we can use [5] to extract pion-proton cross-sections. For this region we can analyze the behaviour of functions $St/m_{\pi}^2$ (Fig. 2) and $\hat{S}$ (Fig. 3). In next two regions $|t| \sim 0.1 \rightarrow 0.4 \text{ GeV}^2$. In principle we could calculate $\hat{S}$, but absorptive effects are very significant for these regions, and we should calculate them with unprecedented accuracy. This will be considered in further publications.

![Fig. 4. Total $\pi^+ p$ cross-sections versus different parametrizations: $[34]$ (solid), $[35]$ (dashed), $[36]$ (dotted) and $[37], [38]$ (dash-dotted). Real data are taken from PDG (triangles) up to $\sqrt{s} = 25 \text{ GeV}$ and extracted values (boxes) up to $\sqrt{s} = 70 \text{ GeV}$ (see [11]).](image_url)

**Table 1.** Values of the $\pi p$ total cross-sections extracted from the LHCf data [19] and also depicted in the Fig. 6. Corresponding average $|t|$ values and $q_0$ ($q < q_0$) are also shown. Backgrounds from $\rho$ and $\alpha_2$ exchanges are taken into account.

| $\sqrt{s}, \text{ TeV}$ | $|t|/m_{\pi}$ | $q_0, \text{ GeV}$ | $\sigma^{\text{tot}}_{\pi p}, \text{ mb}$ |
|------------------------|----------------|-------------------|-------------------------------|
| 2.291 ± 0.382          | 0.91 ± 0.29    | 0.132             | 33.15 ± 13.1                 |
| 2.958 ± 0.296          | 1.41 ± 0.166   | 0.12              | 40.22 ± 7.76                 |
| 3.5 ± 0.25             | 1.99 ± 0.11    | 0.112             | 65.43 ± 15.15                |

![Fig. 6. Extracted total $\pi^+ p$ cross-sections presented in the table 1 versus different parametrizations: $[34]$ (solid), $[35]$ (dashed), $[36]$ (dotted) and $[37], [38]$ (dash-dotted). The interval of $t$ related to the $\eta$ region of the LHCf is $\eta > 10.76$.](image_url)

We also discard the data at large values of $\xi > 0.25$, since the model may not work properly for large $\xi$. Finally we use six data values from LHCf, which are reliable for our method [6].

Results of calculations by the method [6] are presented in the table 1 and also shown in the Fig. 6. Corrections that correspond to backgrounds depicted in the Fig. 5 are taken into account in these results.

Although errors of results are rather large, we can see following facts:

- Results are described well by popular models at the 3rd point at 3.5 TeV. But two other points are at the low edge of predictions. The possible reason for the underestimation is the fact that we have to take into account some other absorptive effects (see [39] for example) that reduce $\hat{S}$ (making extracted cross-sections higher).
- Cross-section continues to rise with $s$.
- The pion-proton cross-section decreases with $|t|$ (virtuality of the pion) increasing. Experimental errors are rather big, but preliminary calculations (which are not presented here) show the tendency. Our assumption was that this $t$ dependence is rather weak. The data confirms it rather well.

**Conclusions**

This paper was inspired by the latest LHCf data [19] on the SCE process at 7 TeV. The analysis of these data is the first attempt to extract pion-proton total cross-section at
TeV energies. The observation of SCE confirms that our expectations [12,34] were realistic.

With the data on $p p$ total and elastic cross-sections at 7 TeV and higher [25], theoretical errors of absorptive corrections have been reduced significantly, since parameters of the model for these corrections are obtained by fitting the total and elastic cross-sections. There are some disagreements with other authors [24,25], who propose stronger suppression factor. They considered scattering of higher Fock components of the projectile proton, which contain a color octet dipole. In this case absorption occurs due to pomeron exchanges between this components and initial (final) hadron, as depicted in the Fig.5c of Ref. [22]. Since they have no calculations for single pion exchange at LHC, we can estimate their result from calculations for double pion exchange in [22]. They use the flux factor, which is equal to our function $\tilde{S}$ with $|s_{\min}| \approx m_p^2 \xi^2/(1 - \xi)$ and $|s_{\max}| = \infty$ in [5]. In their case $\tilde{S}$ is approximately 15% smaller than our result. So we can suppose that extracted values of the pion-proton cross-sections will be about 15% higher than in the table. Since calculation of absorptive corrections is the critical point, we will discuss this question in details further, especially in processes like $\gamma^* p \to X n$ or $\gamma^* p \to p \pi n$., where we have experimental data.

Unfortunately, experimental errors of the LHCF are huge. Nevertheless, we can try our method to extract the pion-proton total cross-section in the TeV energy region and make preliminary conclusions on its behaviour at different values of $t$.

If measurements are done more accurately then we will have additional, more rich, data in the high energy region to check predictions of different models for strong interactions, quark counting rules, ”asymptopia” hypothesis and so on.

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