Towards Extraction of $\pi^+ p$ and $\pi^+\pi^+$ cross-sections from Charge Exchange Processes at the LHC.

R.A. Ryutin, V.A. Petrov, A.E. Sobol

Institute for High Energy Physics 142 281 Protvino, Russia

Abstract

We study the possibilities to analyse the data on leading neutrons production at first LHC runs. These data could be used to extract from it $\pi^+ p$ and $\pi^+\pi^+$ cross-sections. In this note we estimate relative contributions of $\pi$, $\rho$ and $a_2$ reggeons to charge exchanges and discuss related problems of measurements.

Keywords

Leading Neutron Spectra – Elastic and total cross-section – Absorption – Regge-eikonal model - pion-proton and pion-pion collider
1 Introduction

In recent papers [1],[2] we pushed forward (and discussed) the idea of using the Zero Degree Calorimeters [3], ZDCs, designed for different uses at several of the LHC collaborations, to extract the total and elastic 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 at effective c.m.s. energies about 1-5 TeV. For further motivation and technical details we refer the reader to Refs. [1],[2].

In this paper we concentrate on quite a serious problem of the $\rho$- and $a_2$-exchanges in the processes $p+p \to n+X$ and $p+p \to n+X+n$ which compete with the $\pi^+$-exchange and are to be considered in detail.

2 The basic model of charge exchange processes and extraction of $\pi^+ p$ and $\pi^+ \pi^+$ cross-sections.

We consider processes presented in Fig. 1. Signal processes of Single (S$\pi$E) and double (D$\pi$E) pion exchanges are depicted in Fig. 1a), e). In the previous articles [1],[2] we estimated contributions to the background of reactions depicted in Fig. 1d)g)h) and also minimum bias (MB) and single dissociation (SD) with forward neutrons production. In the present work we give calculations of events from Fig. 1b), f), which are called single (SRE) and double (DRE) reggeon exchanges. In the DRE contributions of $\pi \rho$ and $\pi a_2$ collisions dominate over $\rho \rho$, $\rho a_2$ and $a_2 a_2$ processes.

Details of calculations can be found in [1],[2]. Here we show only basic issues. As an approximation for $\pi$ exchanges we use the formulas shown graphically in Fig. 2. If we take into account absorptive corrections, which were calculated in the Regge-eikonal model [4], these formulas can be rewritten as

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

![Figure 1: Signal and background processes: a) S$\pi$E signal; b) SRE background; c) Double Dissociative (DD) background; e) D$\pi$E signal; f) DRE background (contributions from $\pi \rho$ and $\pi a_2$ collisions dominate); g)j) Central Diffractive (CD) background.](image)
Figure 2: Amplitudes squared and cross-sections of the processes: a) $p + p \rightarrow n + X$ ($S\pi E$), b) $p + p \rightarrow n + X + n$ ($D\pi E$). $S$ represents soft rescattering corrections.

\[
\frac{d\sigma_{D\pi E}}{d\xi_1 d\xi_2 dt_1 dt_2} = F_0(\xi_1, t_1) F_0(\xi_2, t_2) S_2(s/s_0, \{\xi_i\}, \{t_i\}) \sigma_{\pi^+\pi^+}(\xi_1\xi_2s),
\]

where the pion trajectory is $\alpha_\pi(t) = \alpha'_\pi(t - m^2_\pi)$. The slope $\alpha'_\pi \simeq 0.9$ GeV$^{-2}$, $\xi = 1 - x_L$, where $x_L$ is the fraction of the initial proton’s longitudinal momentum carried by the neutron, and $G^2_{\pi^0pp}/(4\pi) = G^2_{\pi^+pn}/(8\pi) = 13.75$ [5]. From recent data [6], [7], we expect $b \simeq 0.3$ GeV$^{-2}$. We are interested in the kinematical range $0.01 \text{ GeV}^2 < |t_i| < 0.5 \text{ GeV}^2$, $\xi_i < 0.4$, where formulae (1), (2) dominate according to [8] and [9].

Rescattering corrections $S$ and $S_2$ are calculated in [1], [2]. Behaviour of $S t/m^2_\pi$ is shown in the Fig. 3. It is clear from the figure that $|S| \sim 1$ at $|t| \sim m^2_\pi$ (the situation is similar for $S_2$), which is an argument for the possible model-independent extraction of $\pi p$ and $\pi\pi$ cross-sections by the use of (1) and (2) [2].

Figure 3: Function $S(\xi, t) t/m^2_\pi$ versus $t/m^2_\pi$ at fixed $\xi = 0.05$. The boundary of the physical region $t_0 = -m^2_p \xi^2/(1 - \xi)$ is represented by vertical dashed line in b).
The present design of detectors does not allow \( t \) measurements, it gives only restrictions
\[ |t| < \sim 1 \text{ GeV}^2 \text{ at } 7 \text{ TeV} \ (|t| < 0.3 \text{ GeV}^2 \text{ at } 0.9 \text{ TeV}). \]
If to assume a weak enough \( t \)-dependence of \( \pi p \) and \( \pi \pi \) cross-sections, i.e.
\[ \sigma_{\pi p}^+ \left( s; \{ m^2_p, t \} \right) \simeq \sigma_{\pi p}^+ \left( s; \{ m^2_p, m^2_\pi \} \right), \]
\[ \sigma_{\pi p}^{\pi \pi} \left( s; \{ t_1, t_2 \} \right) \simeq \sigma_{\pi p}^{\pi \pi} \left( s; \{ m^2_\pi, m^2_\pi \} \right), \] (4)
then we could hope to extract these cross-sections (though, with big errors) by the following procedure:
\[ \tilde{S}(s) = \int_{t_{\text{min}}}^{t_{\text{max}}} dt \frac{d \sigma_{\pi p}}{d \xi} \bigg|_{\xi=t} F_0(\xi, t), \]
\[ \sigma_{\pi p}^+(s, \xi) = \frac{d \sigma_{\pi p}}{d \xi} \bigg|_{\xi=t} \xi \simeq \frac{M^2_{\pi p}}{s}, \] (5)
\[ \tilde{S}_2(\xi_0) = \int_{t_{\text{min}}}^{t_{\text{max}}} dt_1 dt_2 \int_{y_0}^{y_0} dy S_2(s/s_0, \{ \xi_0 e^{\pm y} \}, \{ t_i \}) F_0(\xi_0 e^{y}, t_1) F_0(\xi_0 e^{-y}, t_2), \]
\[ \sigma_{\pi \pi}^+(\xi_0^2 s) = \frac{d \sigma_{\pi \pi}}{d \xi_0} \bigg|_{\xi_0=t} \xi_0 = \frac{M_{\pi \pi}}{\sqrt{s}}, \]
\[ y_0 = \ln \frac{\xi_{\text{max}} \sqrt{s}}{M_{\pi \pi}}. \] (6)

Functions \( \tilde{S}_2(s, \xi_0) \) and \( \tilde{S}(s, \xi) \) are depicted in Fig. 4. To suppress theoretical errors of \( \tilde{S} \) and \( \tilde{S}_2 \) we have to measure total and elastic \( pp \) rates at energies greater than 2 TeV, since all the models for absorptive corrections are normalized to \( pp \) cross-sections. At present we can estimate the theoretical error to be less than 20% at \( \sim 10 \text{ TeV} \) for this method from predicted values of total \( pp \) cross-sections in the most popular models [2].

Figure 4: Rescattering corrections integrated with formfactors for \( \sqrt{s} = 0.9 \text{ TeV} \) (solid) and \( \sqrt{s} = 7 \text{ TeV} \) (dashed): a) \( \tilde{S}(s, \xi) \); b) \( \tilde{S}_2(s, \xi_0) \).
For \( \rho \) and \( a_2 \) contributions we can write formulae similar to (1), (2):

\[
\frac{d\sigma_{SRE}}{d\xi dt} = F_R(\xi, t)S_R(s/s_0, \xi, t) \sigma_{R+p}(\xi s),
\]

\[
\frac{d\sigma_{DR\pi E}}{d\xi_1 d\xi_2 dt_1 dt_2} = F_{R\pi}(\xi_1, \xi_2, t_1, t_2)S_{R,2}(s/s_0, \{\xi_i\}, \{t_i\}) \sigma_{R+\pi}(\xi_1 \xi_2 s),
\]

\[
F_R(\xi, t) = \frac{|\eta_R|^2 \bar{G}_{R+pn}^2}{16\pi^2} e^{2\eta_R t \xi^{1-2\alpha_R(t)}} \left( 1 + \frac{\kappa_R^2 \bar{q}^2}{4m_p^2} \right),
\]

\[
F_{R\pi}(\{\xi_i\}, \{t_i\}) = F_0(1)F_R(2) + F_0(2)F_R(1) + 2 \sqrt{\frac{F_0(1)F_0(2)F_R(1)F_R(2)}{t_1 t_2 (1 - \xi_1)(1 - \xi_2)}} \times \left( \frac{m_p \xi_1 + \bar{q}_{1}^2 \frac{\kappa_R}{2m_p}}{1 + \bar{q}_{1}^2 \frac{\kappa_R}{4m_p^2}} \right) \left( \frac{m_p \xi_2 + \bar{q}_{2}^2 \frac{\kappa_R}{2m_p}}{1 + \bar{q}_{2}^2 \frac{\kappa_R}{4m_p^2}} \right),
\]

\[
F_{0,R}(i) = F_{0,R}(\xi_i, t_i), \quad \bar{q}_i^2 \simeq -t_i (1 - \xi_i) - m_p^2 \xi_i^2.
\]

Here \( \kappa_R = 8 \) is the ratio of spin-flip to nonflip amplitude, \( \alpha_R(t) \simeq 0.5 + 0.9t \) and parameters for \( \rho, a_2 \) mesons are [10]

\[
\eta_{\rho} = -i + 1, \quad \eta_{a_2} = i + 1, \quad (12)
\]

\[
b_{\rho} = 2 \text{ GeV}^{-2}, \quad b_{a_2} = 1 \text{ GeV}^{-2}, \quad (13)
\]

\[
\frac{\bar{G}_{\rho+pn}^2}{8\pi} = 0.18 \text{ GeV}^{-2}, \quad \frac{\bar{G}_{a_2+pm}^2}{8\pi} = 0.405 \text{ GeV}^{-2}. \quad (14)
\]

Rescattering corrections \( S_R \) and \( S_{R,2} \) are calculated by the method used in [1], [2]. Basic assumptions in our calculations are:

- \( \rho, \rho, a_2 \) and \( a_2 \) contributions are small;
- interference terms of the type \( T_{SRE}^* T_{SRE}, T_{DR\pi E}^* T_{DR\pi E} \) are small [7], \( R, R' = \pi, \rho, a_2, \)
- \( R \neq R' \), where \( T \) are amplitudes of the corresponding processes;
- approximate relations \( \sigma_{R+p} \simeq \sigma_{\pi+p}, \sigma_{R+\pi} \simeq \sigma_{\pi+\pi} \) [7].

### 3 Relative contributions of \( \pi, \rho \) and \( a_2 \) exchanges to charge exchanges

Let us consider meson exchange contributions as a source of additional backgrounds for \( S\pi E \) and \( D\pi E \). In Figs. 5 and 6 you can see contributions of pion and reggeon (sum of \( \rho \) and \( a_2 \)) exchanges to single (CE) and double (DCE) charge exchange processes. Here we use the kinematical variable \( r \) which is equal to the transverse distance from the beam and directly related to the pseudorapidity \( r = L/sh(\eta) \). \( L = 14000 \text{ cm} \) is the longitudinal distance from the interaction point to the detector. The best situation is observed at
\( \sqrt{s} = 900 \text{ GeV} \). Since the geometrical acceptance of the detector is \( r \leq 5 \text{ cm} \) it cuts off reggeon background almost at all for the CE (Fig. 5b) and the significant part for the DCE (Fig. 5d). At 7 TeV the situation is not so good for DCE even if we perform a cut \( r \leq 1 \text{ cm} \) (see Fig. 6d). It is difficult to separate different reggeon contributions from DCE in this case.

Figure 5: Cross-sections \( \frac{d\sigma}{d\xi dr} \) in \( \text{mb} \cdot \text{cm}^{-1} \) at \( \sqrt{s} = 0.9 \text{ TeV} \) for: a) \( S\pi E \); b) \( S\rho E + Sa_2 E \); c) \( D\pi E \); d) \( D\rho E + Da_2\pi E \).

Figure 6: Cross-sections \( \frac{d\sigma}{d\xi dr} \) in \( \text{mb} \cdot \text{cm}^{-1} \) at \( \sqrt{s} = 7 \text{ TeV} \) for: a) \( S\pi E \); b) \( S\rho E + Sa_2 E \); c) \( D\pi E \); d) \( D\rho E + Da_2\pi E \).
Figure 7: Ratios of reggeon exchange events to pion exchange events in the ZDC acceptance versus the invariant mass of reggeon-proton (reggeon-reggeon) systems: a) \( (N_{S\rho E} + N_{S\sigma_2 E})/N_{S\pi E} \), \( \sqrt{s} = 900 \text{ GeV} \); b) \( (N_{S\rho E} + N_{S\sigma_2 E})/N_{S\pi E} \), \( \sqrt{s} = 7 \text{ TeV} \); c) \( (N_{D\rho E} + N_{D\sigma_2 E})/N_{D\pi E} \), \( \sqrt{s} = 900 \text{ GeV} \); d) \( (N_{D\rho E} + N_{D\sigma_2 E})/N_{D\pi E} \), \( \sqrt{s} = 7 \text{ TeV} \). Results for different models are similar.

Table 1: Relative contributions of reggeons to CE and DCE in the ZDC acceptance.

| \( \sqrt{s}, \text{ TeV} \) | 0.9 | 7 |
|-----------------------------|-----|---|
| \( (\sigma_{S\rho E} + \sigma_{S\sigma_2 E})/\sigma_{S\pi E}, \% \) | 10.7 | 8.2 |
| ZDC acceptance, % | S\pi E | 27.8 | 86.6 |
| | S\rho E | 10.8 | 86.8 |
| | S\sigma_2 E | 6.7 | 86.7 |
| \( \langle (N_{S\rho E} + N_{S\sigma_2 E})/N_{S\pi E} \rangle, \% \) | 3.0 | 8.2 |
| \( (\sigma_{D\rho E} + \sigma_{D\sigma_2 E})/\sigma_{D\pi E}, \% \) | 47.3 | 43.4 |
| ZDC acceptance, % | D\pi E | 4.80 | 99.6 |
| | D\rho E | 0.28 | 99.8 |
| | D\sigma_2 E | 0.65 | 99.7 |
| \( \langle (N_{D\rho E} + N_{D\sigma_2 E})/N_{D\pi E} \rangle, \% \) | 19.3 | 43.4 |

Monte-carlo simulation shows relative contributions in detail (see Fig. 7 and Table 1). For CE situation is quiet encouraging, since reggeon background is less than 10\% for large invariant masses (or \( \xi \)), and for DCE it can reach 19.3 (43.4)\% at \( \sqrt{s} = 0.9(7) \text{ TeV} \) due to similar distributions in \( r \).

4 Conclusions

In this article we have considered the problems due to extra reggeon exchanges which arise when trying to extract \( \pi^+ p \) and \( \pi^+ \pi^+ \) cross-sections from the data on leading neutrons at the LHC. After the estimation of reggeon exchange contributions to the background
we can conclude that at present time we have some chances to extract total $\pi^+ p$ cross-
sections from the first LHC data at 900 GeV (7 TeV) but with rather big errors (about
20-30%). With the data on $p p$ total and elastic cross-sections at 7 TeV and higher
theoretical errors can be reduced significantly.

At present our preliminary analysis shows that the 900 GeV data are too poor to come
to some valuable results. This is the reason that detectors like ZDC need modernization
to improve their performance for the reach of $\pi p$ and $\pi \pi$ collisions at the LHC.

**Acknowledgements**

This work is supported by the grant RFBR-10-02-00372-a.

**References**

[1] V. Petrov, R. Ryutin and A. Sobol, *LHC as $\pi p$ and $\pi \pi$ collider*, Eur. Phys. J. C 65 (2010) 637.

[2] A. Sobol, R. Ryutin, V. Petrov, M. Murray, *Elastic $\pi^+ p$ and $\pi^+ \pi^+$ scattering at LHC*,
Eur. Phys. J. C 69 (2010) 641.

[3] A.S. Ayan et. al., *ZDC Technical Design Report*, CMS-IN-2006/54.

[4] V. A. Petrov and A. V.Prokudin, *The first three Pomeron*, Eur.Phys.J. C 23 (2002) 135.

[5] V. Stoks, R. Timmermans and J.J. de Swart, *On the pion - nucleon coupling con-
stant*, Phys. Rev. C 47 (1993) 512; R.A. Arndt, I.I. Strakovsky, R.L. Workman and
M.M. Pavan, *Updated analysis of $\pi N$ elastic scattering data to 2.1-GeV: The Baryon
spectrum*, Phys. Rev. C 52 (1995) 2120.

[6] ZEUS Collab., S Chekanov et al., *Leading neutron production in $e^+$ $p$ collisions at
HERA*, Nucl. Phys. B 637 (2002) 3.

[7] B.Z. Kopeliovich, B. Povh and I. Potashnikova, *Deep inelastic electroproduction of
neutrons in the proton fragmentation region*, Z. Phys. C 73 (1996) 125.

[8] K.G. Boreskov, A.B. Kaidalov and L.A. Ponomarev, *Nucleon spectra in $p p$ collisions
and the reggeized pi-meson exchange model*, Sov. J. Nucl. Phys. 19 (1974) 565.

[9] K.G. Boreskov, A.B. Kaidalov, V.I. Lisin, E.S. Nikolaevskii, L.A. Ponomarev, *Model
of reggeized one pion exchange and reaction $p p \rightarrow p n\pi^+*$, Sov.J.Nucl.Phys. 15
(1972) 203.

[10] P.E. Volkovitsky, A.M. Lapidus, V.I. Lisin, K.A. Ter-Martirosian, *Experimental Data
FIT in the Theory of Pomeron with $\alpha_{IP}(0) > 1$ and Some of Its Consequences*, Sov.
J. Nucl. Phys. 24 (1976) 648.
