Eur. Phys. J. C (2011) 71:1667
DOI 10.1140/epjc/s10052-011-1667-5

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

Towards extraction of $\pi^+ p$ and $\pi^+\pi^+$ cross-sections from charge exchange processes at the LHC

R.A. Ryutin[a], **V.A. Petrov**[b], **A.E. Sobol**[c]

Institute for High Energy Physics, 142 281 Protvino, Russia

Received: 6 February 2011 / Revised: 30 March 2011 / Published online: 27 May 2011

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 π, ρ and a_2 reggeons to charge exchanges and discuss related problems of measurements.

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 πp 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 ρ- and a_2-exchanges in the processes $p + p \to n + X$ and $p + p \to n + X + n$ which compete with the π^+-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 (SπE) and double (DπE) pion exchanges are depicted in Fig. 1(a), (e). In the previous articles [1, 2] we estimated contributions to the background of reactions depicted in Fig. 1(c), (d), (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. 1(b), (f), which are called single (SRE) and double (DRE) reggeon exchanges. In the DRE contributions of $\pi\rho$ and πa_2 collisions dominate over $\rho\rho$, ρa_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 π 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

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

$$\frac{d\sigma_{\mathrm{D}\pi\mathrm{E}}}{d\xi_1\, d\xi_2\, dt_1\, dt_2} = F_0(\xi_1, t_1) F_0(\xi_2, t_2) S_2\big(s/s_0, \{\xi_i\}, \{t_i\}\big) \times \sigma_{\pi^+\pi^+}(\xi_1\xi_2 s), \quad (2)$$

$$F_0(\xi, t) = \frac{G^2_{\pi^+ pn}}{16\pi^2} \frac{-t}{(t - m_\pi^2)^2} \mathrm{e}^{2bt} \xi^{1-2\alpha_\pi(t)}, \quad (3)$$

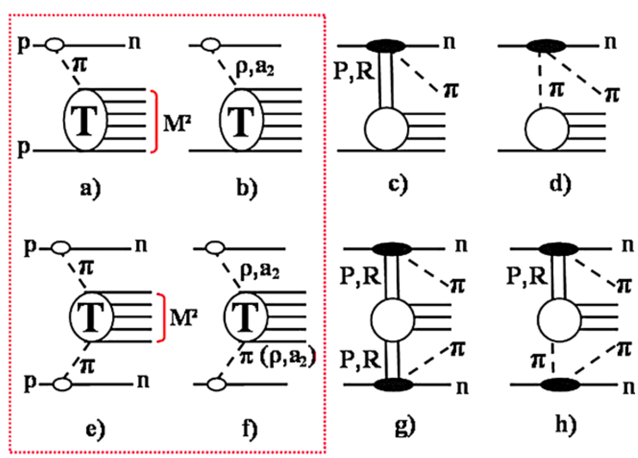


Fig. 1 Signal and background processes: (**a**) SπE signal; (**b**) SRE background; (**c**), (**d**) Double Dissociative (DD) background; (**e**) DπE signal; (**f**) DRE background (contributions from $\pi\rho$ and πa_2 collisions dominate); (**g**), (**h**) Central Diffractive (CD) background

[a] e-mail: Roman.Rioutine@cern.ch
[b] e-mail: Vladimir.Petrov@cern.ch
[c] e-mail: Andrei.Sobol@cern.ch

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

$$0.01\ \text{GeV}^2 < |t_i| < 0.5\ \text{GeV}^2, \qquad \xi_i < 0.4,$$

where formulaes (1), (2) dominate according to [9] and [10]. Rescattering corrections S and S_2 are calculated in [1, 2]. Behaviour of St/m_π^2 is shown in Fig. 3. It is clear from the figure that $|S| \sim 1$ at $|t| \sim m_\pi^2$ (the situation is similar for S_2), which is an argument for the possible model-independent extraction of πp and $\pi\pi$ cross-sections by the use of (1) and (2) [2].

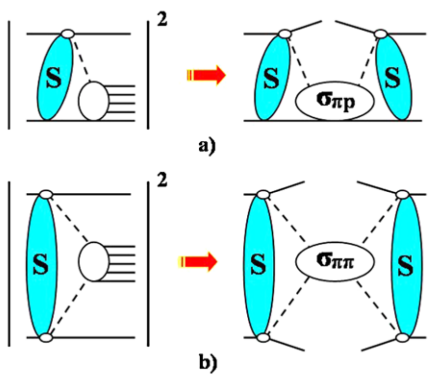


Fig. 2 Amplitudes squared and cross-sections of the processes: (**a**) $p + p \to n + X$ (SπE), (**b**) $p + p \to n + X + n$ (DπE). S represents soft rescattering corrections

The present design of detectors does not allow t measurements, it gives only restrictions $|t| <\sim 1\ \text{GeV}^2$ at 7 TeV ($|t| < 0.3\ \text{GeV}^2$ at 0.9 TeV). If to assume a weak enough t-dependence of πp and $\pi\pi$ cross-sections, i.e.

$$\sigma_{\pi^+_{\text{virt}} p}\big(s; \{m_p^2, t\}\big) \simeq \sigma_{\pi^+ p}\big(s; \{m_p^2, m_\pi^2\}\big),$$
$$\sigma_{\pi^+_{\text{virt}}\pi^+_{\text{virt}}}\big(s; \{t_1, t_2\}\big) |\simeq \sigma_{\pi^+\pi^+}\big(s; \{m_\pi^2, m_\pi^2\}\big), \qquad (4)$$

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

$$\tilde{S}(\xi) = \int_{t_{\min}}^{t_{\max}} dt\, S(s/s_0, \xi, t) F_0(\xi, t),$$
$$\sigma_{\pi^+ p}(\xi s) = \frac{\frac{d\sigma_{\text{S}\pi\text{E}}}{d\xi}}{\tilde{S}(s, \xi)}, \quad \xi \simeq \frac{M^2_{\pi p}}{s}, \qquad (5)$$
$$\tilde{S}_2(\xi_0) = \int_{t_{\min}}^{t_{\max}} dt_1\, dt_2 \int_{-y_0}^{y_0} dy\, S_2\big(s/s_0, \{\xi_0 e^{\pm y}\}, \{t_i\}\big)$$
$$\times F_0\big(\xi_0 e^{y}, t_1\big) F_0\big(\xi_0 e^{-y}, t_2\big),$$
$$\sigma_{\pi^+\pi^+}\big(\xi_0^2 s\big) = \frac{\frac{d\sigma_{\text{D}\pi\text{E}}}{d\xi_0}}{\tilde{S}_2(s, \xi_0)}, \qquad \xi_0 = \frac{M_{\pi\pi}}{\sqrt{s}},$$
$$y_0 = \ln \frac{\xi_{\max}\sqrt{s}}{M_{\pi\pi}}. \qquad (6)$$

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

Fig. 3 Function $S(\xi, t)t/m_\pi^2$ versus t/m_π^2 at fixed $\xi = 0.05$. The boundary of the physical region $t_0 = -m_p^2\xi^2/(1-\xi)$ is represented by *vertical dashed line* in (**b**)

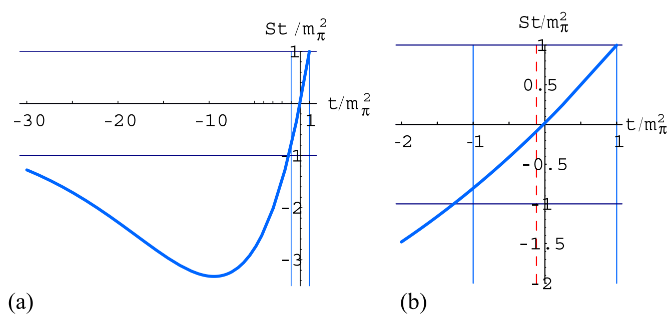
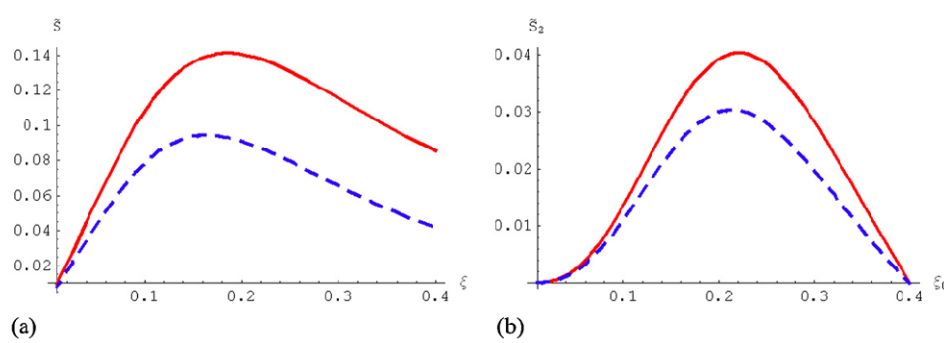


Fig. 4 Rescattering corrections integrated with formfactors for $\sqrt{s} = 0.9$ TeV (*solid*) and $\sqrt{s} = 7$ TeV (*dashed*): (**a**) $\tilde{S}(s, \xi)$; (**b**) $\tilde{S}_2(s, \xi_0)$



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 ~ 10 TeV for this method from predicted values of total pp cross-sections in the most popular models [2].

For ρ and a_2 contributions we can write formulaes similar to (1), (2):

$$\frac{d\sigma_{\mathrm{SRE}}}{d\xi\, dt} = F_R(\xi, t) S_R(s/s_0, \xi, t)\sigma_{R^+p}(\xi s), \tag{7}$$

$$\frac{d\sigma_{\mathrm{DR}\pi\mathrm{E}}}{d\xi_1\, d\xi_2\, dt_1\, dt_2} = F_{R\pi}(\xi_1, \xi_2, t_1, t_2) S_{R,2}\big(s/s_0, \{\xi_i\}, \{t_i\}\big) \times \sigma_{R^+\pi^+}(\xi_1\xi_2 s), \tag{8}$$

$$F_R(\xi, t) = \frac{|\eta_R|^2 \tilde{G}^2_{R^+pn}}{16\pi^2} \mathrm{e}^{2b_R t} \xi^{1-2\alpha_R(t)} \left(1 + \kappa_R^2 \frac{\boldsymbol{q}^2}{4m_p^2}\right), \tag{9}$$

$$F_{R\pi}\big(\{\xi_i\}, \{t_i\}\big) = F_0(1) F_R(2) + F_0(2) F_R(1) + 2\sqrt{\frac{F_0(1)F_0(2)F_R(1)F_R(2)}{t_1 t_2 (1-\xi_1)(1-\xi_2)}} \times \frac{(m_p\xi_1 + \boldsymbol{q}_1^2 \frac{\kappa_R}{2m_p})(m_p\xi_2 + \boldsymbol{q}_2^2 \frac{\kappa_R}{2m_p})}{(1 + \boldsymbol{q}_1^2 \frac{\kappa_R^2}{4m_p^2})(1 + \boldsymbol{q}_2^2 \frac{\kappa_R^2}{4m_p^2})}, \tag{10}$$

$$F_{0,R}(i) = F_{0,R}(\xi_i, t_i), \qquad \boldsymbol{q}_i^2 \simeq -t_i(1-\xi_i) - m_p^2 \xi_i^2. \tag{11}$$

Here $\kappa_R = 8$ is the ratio of spin-flip to nonflip amplitude, $\alpha_R(t) \simeq 0.5 + 0.9t$ and parameters for ρ, a_2 mesons are [11]

$$\eta_\rho = -\imath + 1, \qquad \eta_{a_2} = \imath + 1, \tag{12}$$

$$b_\rho = 2\ \mathrm{GeV}^{-2}, \qquad b_{a_2} = 1\ \mathrm{GeV}^{-2}, \tag{13}$$

$$\frac{\tilde{G}^2_{\rho^+pn}}{8\pi} = 0.18\ \mathrm{GeV}^{-2}, \qquad \frac{\tilde{G}^2_{a_2^+pn}}{8\pi} = 0.405\ \mathrm{GeV}^{-2}. \tag{14}$$

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

– $\rho\ \rho$, $\rho\ a_2$ and $a_2\ a_2$ contributions are small;
– interference terms of the type $T^*_{\mathrm{S}\pi\mathrm{E}} T_{\mathrm{SRE}}$, $T^*_{\mathrm{DR}\pi\mathrm{E}} T_{\mathrm{DR}'\pi\mathrm{E}}$ are small [8], R, R$' = \pi, \rho, a_2$, R $\neq$ R$'$, where T are amplitudes of the corresponding processes;
– approximate relations $\sigma_{R^+p} \simeq \sigma_{\pi^+p}$, $\sigma_{R^+\pi^+} \simeq \sigma_{\pi^+\pi^+}$ [8].

3 Relative contributions of π, ρ and a_2 exchanges to charge exchanges

Let us consider meson exchange contributions as a source of additional backgrounds for SπE and DπE. In Figs. 5 and 6

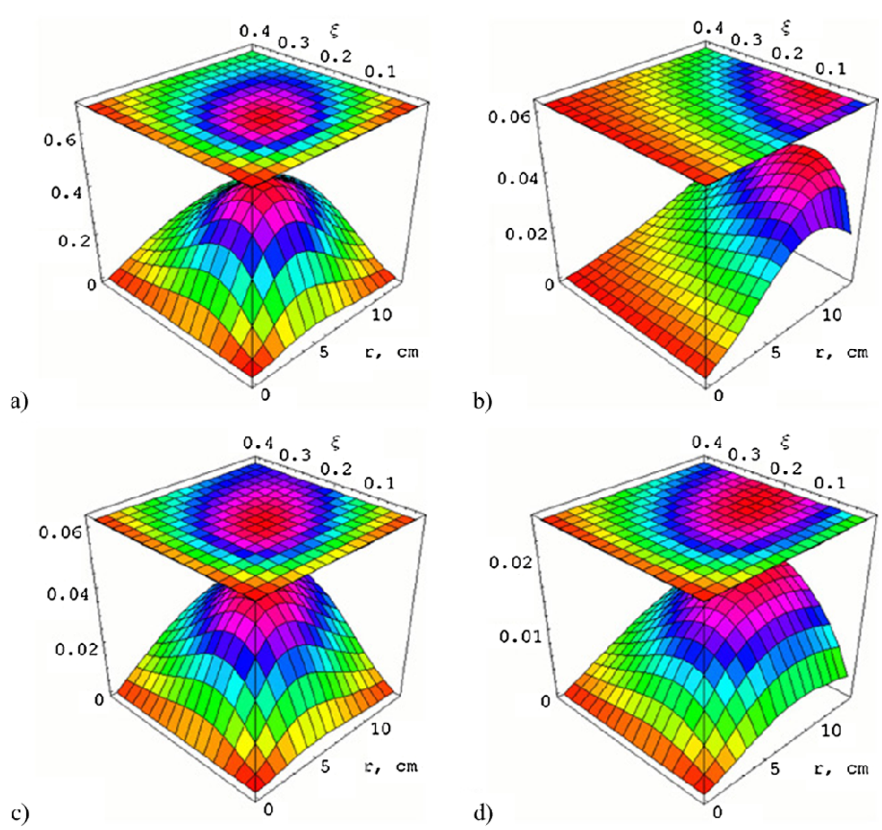


Fig. 5 Cross-sections $\frac{d\sigma}{d\xi dr}$ in mb cm^{-1} at $\sqrt{s} = 0.9$ TeV for: (**a**) SπE; (**b**) SρE + Sa_2E; (**c**) DπE; (**d**) D$\rho\pi$E + D$a_2\pi$E

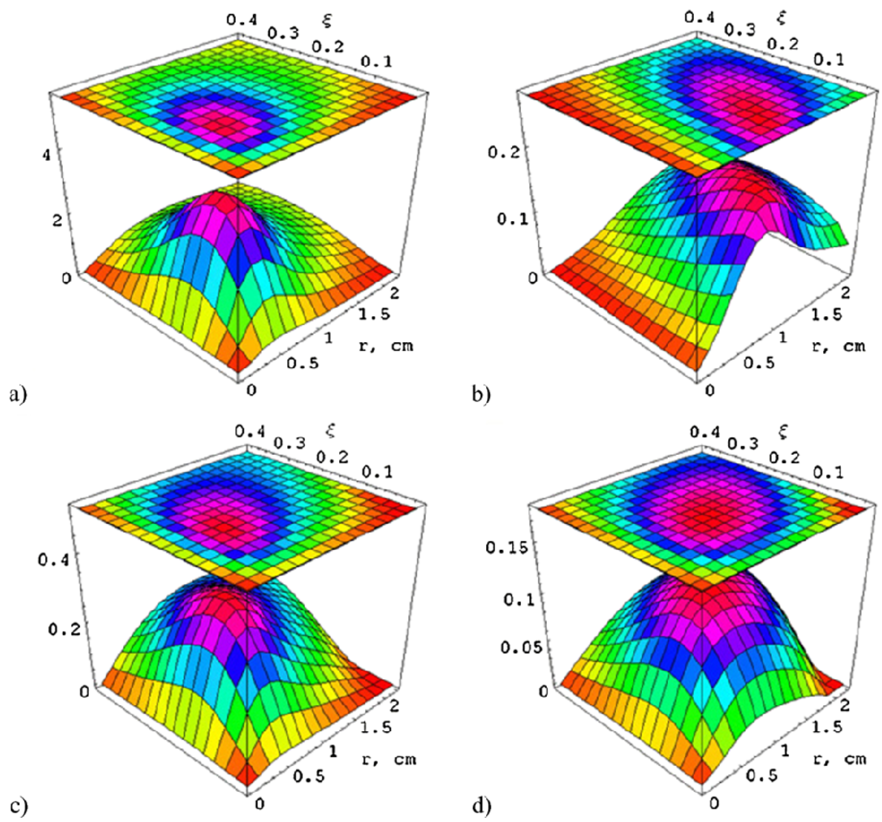


Fig. 6 Cross-sections $\frac{d\sigma}{d\xi dr}$ in mb cm^{-1} at $\sqrt{s} = 7$ TeV for: (**a**) SπE; (**b**) SρE + Sa_2E; (**c**) DπE; (**d**) D$\rho\pi$E + D$a_2\pi$E

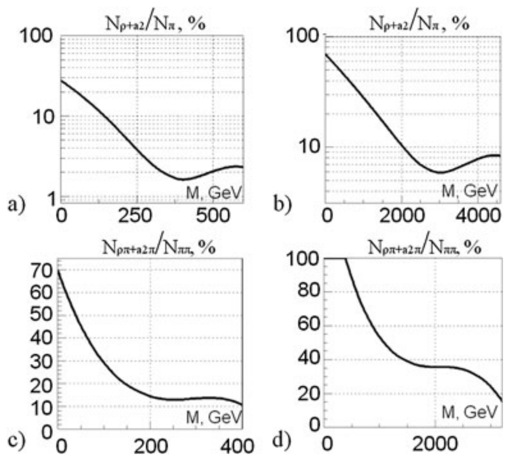


Fig. 7 Ratios of reggeon exchange events to pion exchange events in the ZDC acceptance versus the invariant mass of reggeon–proton (reggeon–reggeon) systems: (**a**) $(N_{\mathrm{S}\rho\mathrm{E}} + N_{\mathrm{S}a_2\mathrm{E}})/N_{\mathrm{S}\pi\mathrm{E}}$, $\sqrt{s} = 900$ GeV; (**b**) $(N_{\mathrm{S}\rho\mathrm{E}} + N_{\mathrm{S}a_2\mathrm{E}})/N_{\mathrm{S}\pi\mathrm{E}}$, $\sqrt{s} = 7$ TeV; (**c**) $(N_{\mathrm{D}\rho\pi\mathrm{E}} + N_{\mathrm{D}a_2\pi\mathrm{E}})/N_{\mathrm{D}\pi\mathrm{E}}$, $\sqrt{s} = 900$ GeV; (**d**) $(N_{\mathrm{D}\rho\pi\mathrm{E}} + N_{\mathrm{D}a_2\pi\mathrm{E}})/N_{\mathrm{D}\pi\mathrm{E}}$, $\sqrt{s} = 7$ TeV. Results for different models are similar

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

$\sqrt{s}$, TeV		0.9	7
$(\sigma_{\mathrm{S}\rho\mathrm{E}} + \sigma_{\mathrm{S}a_2\mathrm{E}})/\sigma_{\mathrm{S}\pi\mathrm{E}}$, %		10.7	8.2
ZDC acceptance, %	SπE	27.8	86.6
	SρE	10.8	86.8
	Sa_2E	6.7	86.7
$\langle(N_{\mathrm{S}\rho\mathrm{E}} + N_{\mathrm{S}a_2\mathrm{E}})/N_{\mathrm{S}\pi\mathrm{E}}\rangle$, %		3.0	8.2
$(\sigma_{\mathrm{D}\rho\pi\mathrm{E}} + \sigma_{\mathrm{D}a_2\pi\mathrm{E}})/\sigma_{\mathrm{D}\pi\pi\mathrm{E}}$, %		47.3	43.4
ZDC acceptance, %	D$\pi\pi$E	4.80	99.6
	D$\rho\pi$E	0.28	99.8
	D$a_2\pi$E	0.65	99.7
$\langle(N_{\mathrm{D}\rho\pi\mathrm{E}} + N_{\mathrm{D}a_2\pi\mathrm{E}})/N_{\mathrm{D}\pi\pi\mathrm{E}}\rangle$, %		19.3	43.4

you can see contributions of pion and reggeon (sum of ρ 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 $r = L/\mathrm{sh}(\eta)$. $L = 14000$ cm is the longitudinal distance from the interaction point to the detector. The best situation is observed at $\sqrt{s} = 900$ GeV. Since the geometrical acceptance of the detector is $r \le 5$ cm it cuts off reggeon background almost at all for the CE (Fig. 5(b)) and the significant part for the DCE (Fig. 5(d)). At 7 TeV the situation is not so good for DCE even if we perform a cut $r \le 1$ cm (see Fig. 6(d)). It is difficult to separate different reggeon contributions from DCE in this case.

Monte-Carlo simulation shows relative contributions in detail (see Fig. 7 and Table 1). For CE situation it is quite encouraging, since reggeon background is less than 10% for large invariant masses (or ξ), and for DCE it can reach 19.3 (43.4)% at $\sqrt{s} = 0.9(7)$ 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%) due to instrumental uncertainties in measurements of neutrons energy (ξ) and also theoretical errors for energies greater than 2 TeV. With the data on pp total and elastic cross-sections at 7 TeV and higher theoretical errors can be reduced significantly, since parameters of the model for rescattering corrections are obtained by fitting the total and elastic cross-sections.

At present our preliminary analysis shows that the 900 GeV data are too poor to come to some valuable results due to instrumental errors from detectors (insufficient calibration, instability of results and so on). This is the reason that detectors like ZDC need modernization to improve their performance for the reach of πp 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, A. Sobol, Eur. Phys. J. C **65**, 637 (2010)
2. A. Sobol, R. Ryutin, V. Petrov, M. Murray, Eur. Phys. J. C **69**, 641 (2010)
3. A.S. Ayan et al., CMS-IN-2006/54
4. V.A. Petrov, A.V. Prokudin, Eur. Phys. J. C **23**, 135 (2002)
5. V. Stoks, R. Timmermans, J.J. de Swart, Phys. Rev. C **47**, 512 (1993)
6. R.A. Arndt, I.I. Strakovsky, R.L. Workman, M.M. Pavan, Phys. Rev. C **52**, 2120 (1995)
7. ZEUS Collab., S. Chekanov et al., Nucl. Phys. B **637**, 3 (2002)
8. B.Z. Kopeliovich, B. Povh, I. Potashnikova, Z. Phys. C **73**, 125 (1996)
9. K.G. Boreskov, A.B. Kaidalov, L.A. Ponomarev, Sov. J. Nucl. Phys. **19**, 565 (1974)
10. K.G. Boreskov, A.B. Kaidalov, V.I. Lisin, E.S. Nikolaevskii, L.A. Ponomarev, Sov. J. Nucl. Phys. **15**, 203 (1972)
11. P.E. Volkovitsky, A.M. Lapidus, V.I. Lisin, K.A. Ter-Martirosian, Sov. J. Nucl. Phys. **24**, 648 (1976)