EXCLUSIVE $\pi^+\pi^-$ PRODUCTION AT THE LHC WITH FORWARD PROTON TAGGING

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(Received April 29, 2011)

A process of central exclusive $\pi^+\pi^-$ production in proton–proton collisions and its theoretical description is presented. A possibility of its measurement, during the special low luminosity LHC runs, with the help of the ATLAS central detector for measuring pions and the ALFA stations for tagging the scattered protons is studied. A visible cross-section is estimated to be 21 μb for $\sqrt{s} = 7$ TeV, which gives over 2000 events for 100 $\mu\mathrm{b}^{-1}$ of integrated luminosity. Differential distributions in pion pseudorapidities, pion and proton transverse momenta as well as $\pi^+\pi^-$ invariant mass are shown and discussed.

DOI:10.5506/APhysPolB.42.1861
PACS numbers: 13.87.Ce, 13.60.Le, 13.85.Dz, 12.40.Nn

1. Introduction

Processes of central exclusive production have gained a lot of interest in the recent years. Although the attention is paid mainly to high-p_{T} processes that can be used for new physics searches (exclusive Higgs, $\gamma\gamma$ interactions, *etc.*), measurements of low-p_{T} signals are also very important as they can help to constrain models and to understand the backgrounds for the former ones. The aim of this paper is to discuss a measurement possibility of the exclusive $\pi^+\pi^-$ production at the LHC, in which both protons are detected.

This reaction is a natural background for exclusive production of resonances decaying into the $\pi^+\pi^-$ channel, such as: $f_2(1270)$, glueballs, glueball candidates (*e.g.* $f_0(1500)$) or charmonia (*e.g.* $\chi_c(0)$). Since the cross-section for the $pp \to p\pi^+\pi^-p$ process is fairly large [1], its estimation is important for the exotic meson production.

The dominant mechanism of the $pp \to p\pi^+\pi^-p$ reaction is relatively simple compared to that of the $pp \to n\pi^+\pi^+n$ [2] or $pp \to p\pi^0\pi^0p$ processes. However, the only measurements at high energies were performed at the CERN ISR for $\sqrt{s} = 62$ GeV [3, 4] and $\sqrt{s} = 63$ GeV [5]. A measurement at higher energy can add to the understanding of the diffractive reaction mechanism.

2. Theoretical model

The dominant mechanism of the exclusive production of the $\pi^+\pi^-$ pairs at high energies is sketched in Fig. 1. The formalism used in calculations is explained in detail elsewhere [1, 6] and here only the main aspects are discussed.

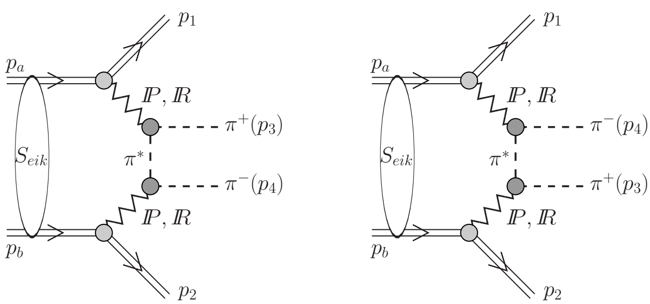

Fig. 1. The double-diffractive mechanism of exclusive production of $\pi^+\pi^-$ pairs including the absorptive corrections.

The full amplitude for the exclusive process $pp \to p\pi^+\pi^-p$ (with four-momenta $p_a + p_b \to p_1 + p_3 + p_4 + p_2$) is a sum of the bare and rescattering amplitudes

$$\mathcal{M}^{\mathrm{full}} = \mathcal{M}^{\mathrm{bare}} + \mathcal{M}^{\mathrm{rescatt}} . \tag{1}$$

The bare amplitude can be written as

$$\begin{aligned} \mathcal{M}^{\mathrm{bare}} &= M_{13}(s_{13}, t_1) F_\pi(t_a) \frac{1}{t_a - m_\pi^2} F_\pi(t_a) M_{24}(s_{24}, t_2) \\ &\quad + M_{14}(s_{14}, t_1) F_\pi(t_b) \frac{1}{t_b - m_\pi^2} F_\pi(t_b) M_{23}(s_{23}, t_2) , \end{aligned} \tag{2}$$

where M_{ik} denotes the coupling between: forward proton ($i=1$) or backward proton ($i=2$) and one of the two pions ($k=3$ for π^+, $k=4$ for π^-). The energy dependence of the πp elastic amplitudes is parameterised in terms of Regge theory by Pomeron and Reggeon exchanges. The values of coupling constants and the Regge trajectory parameters are taken from the Donnachie–Landshoff analysis of the total and elastic cross-sections for πN scattering [7]. The slope parameters of the elastic πp scattering are taken as

$$B(s) = B_i + 2\alpha_i' \ln\left(\frac{s}{s_0}\right) , \tag{3}$$

where $B_{\mathbb{P}} = 5.5\,\text{GeV}^{-2}$, $\alpha'_{\mathbb{P}} = 0.25\,\text{GeV}^{-2}$ and $B_{\mathbb{R}} = 4\ \text{GeV}^{-2}$, $\alpha'_{\mathbb{R}} = 0.93$ GeV^{-2}, for Pomeron and Reggeon exchanges, respectively and $s_0 = 1\ \text{GeV}^2$.

The Donnachie–Landshoff parametrisation is used only for the πp subsystem energy $W_{ik} > 2$ GeV (see Ref. [1]). Below this energy resonance states are present in πp subsystems in single diffractive processes. Their contribution would appear at large rapidities, so it is not discussed here. In order to exclude resonance regions the M_{ik} terms are corrected by purely phenomenological smooth cut-off correction factors which modify the cross-section only at large rapidities [1].

The form factors, $F_\pi(t)$, correct for the off-shellness of the intermediate pions in the middle of the diagrams shown in Fig. 1. In the following they are parameterised as

$$F_\pi(t) = \exp\left(\frac{t - m_\pi^2}{\Lambda_{\text{off}}^2}\right) , \tag{4}$$

where the parameter Λ_{off} is not known precisely. In [6] a fit to the experimental data [4] was performed and $\Lambda^2_{\text{off}} = 2\ \text{GeV}^2$ was obtained. This value was used in the calculations for $pp \to p\pi^+\pi^-p$ production at $\sqrt{s} = 7$ TeV and resulted the cross-section of 234 μb.

The absorptive corrections to the bare amplitude, marked in Fig. 1 by the blob, were taken into account in [6] as

$$\mathcal{M}^{\text{rescat}} = i \int \frac{d^2\boldsymbol{k}_{\text{t}}}{2(2\pi)^2} \frac{A_{pp}\left(s, k_{\text{t}}^2\right)}{s} \mathcal{M}^{\text{bare}}\left(\boldsymbol{p}^*_{a,t} - \boldsymbol{p}_{1,t}, \boldsymbol{p}^*_{b,t} - \boldsymbol{p}_{2,t}\right) , \tag{5}$$

where $\boldsymbol{p}^*_{\text{a}} = \boldsymbol{p}_{\text{a}} - \boldsymbol{k}_{\text{t}}$, $\boldsymbol{p}^*_{\text{b}} = \boldsymbol{p}_{\text{b}} + \boldsymbol{k}_{\text{t}}$ and $\boldsymbol{k}_{\text{t}}$ is the transverse momentum exchanged in the blob. The amplitude for elastic proton–proton scattering is parameterised as

$$A_{pp}\left(s, k_{\text{t}}^2\right) = A_0(s) \exp\left(-Bk_{\text{t}}^2/2\right) . \tag{6}$$

The optical theorem gives: $\text{Im}A_0(s, t=0) = s\sigma_{\text{tot}}(s)$ and the real part is small in the high energy limit. The Donnachie–Landshoff parametrisation of the total and elastic pp or $p\bar{p}$ cross-sections is used to calculate the rescattering amplitude and $B^{pp}_{\mathbb{P}} = 9\ \text{GeV}^{-2}$ value is taken.

The cross-section is obtained by integration over the four-body phase space, which was reduced to 8 dimensions and performed numerically. A weighted Monte Carlo generator based on this model has been developed and was used in the following analysis.

3. Experimental setup

The final state of the $pp \to p\pi^+\pi^- p$ consists of four particles — two protons and two pions. At the LHC the pions are produced in the rapidity range $|y| < 10$, whereas the protons are scattered at very small angles (of the order of microradians) into the accelerator beam pipe. Therefore, to perform a fully exclusive measurement, there is a need of two different types of detectors (see Fig. 2): a central detector (for pion detection) and very forward detectors (for proton tagging). The analysis presented in this paper assumes ATLAS as the central detector and ALFA as the proton tagging detectors.

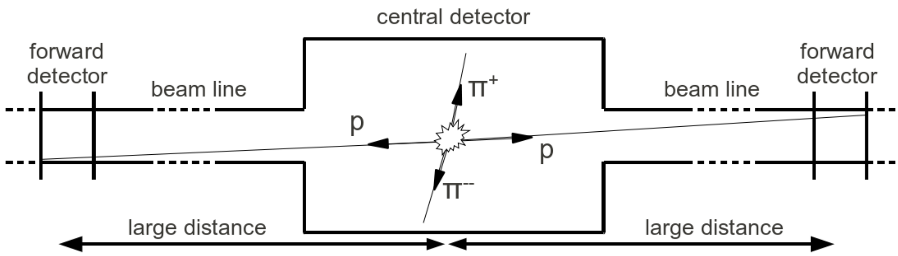

Fig. 2. A scheme of the measurement concept — pions are registered in the central detectors, whereas protons in the very forward detectors.

The ATLAS detector [8] is located at the LHC Interaction Point 1 (IP1). It has been designed as a general purpose detector with a large acceptance in pseudorapidity, full azimuthal angle coverage, good charged particle momentum resolution and a good electromagnetic calorimetry completed by full-coverage hadronic calorimetry. The ATLAS tracking detector provides measurement of charged particles momenta in the $|\eta| < 2.5$ region and the calorimeter covers $|\eta| < 4.9$.

The ALFA (Absolute Luminosity For ATLAS) detectors [9] are designed for proton–proton elastic scattering measurement in the Coulomb-nuclear amplitude interference region. These detectors are placed about 240 m from the IP1, symmetrically on both sides, inside Roman pots. These are special devices that allow to place detectors inside the beam pipe and to control the distance between their edge and the proton beam. This is of primordial importance for the detectors safety, since the proton beam can cause serious radiation damage. Measurement of protons scattered at very small angles (like in the elastic scattering) requires a special tune of the LHC accelerator with very small angular dispersion at the IP. This is granted by a high value of the betatron function (β^*). Due to limited radiation hardness, the ALFA detector will be used only during the dedicated runs.

It is worth mentioning that at the LHC, apart from ALFA, there are also similar stations of the TOTEM [10] experiment placed around the CMS central detector. Although, the present study was carried out for ALFA and ATLAS, similar results can be expected for TOTEM and CMS. In addition, two other proton tagging detectors are presently at the planning stage — AFP (ATLAS Forward Proton) for ATLAS and HPS (High Precision Spectrometer) for CMS. Their purpose is to tag forward protons during high luminosity LHC runs and to look at high-$p_{\rm T}$ signals. The acceptance of these detectors will be completely different than the one of ALFA and TOTEM. Actually, the AFP and HPS detectors will be able to detect protons which lost some part of their initial energy [11] and will not register protons originating from elastic scattering. Since for the $pp \to p\pi^+\pi^-p$ process the energy loss of the protons is rather small, only the tails of this signal could be seen in AFP or HPS. Taking into account the fact that these detectors will work during normal LHC runs, when there will be many independent interactions in one bunch crossing, it is clear that exclusive pion pair production can be measured only with help of ALFA or TOTEM.

4. Results of the simulation

A crucial element of the $pp \to p\pi^+\pi^-p$ measurement is the tagging of the forward protons with the ALFA detectors. Thus, a very important ingredient of this analysis is a proper simulation of the proton transport from the Interaction Point to the ALFA stations through the LHC magnetic lattice. One needs to remember that the ALFA detectors are designed only for the special LHC runs so a corresponding description of the LHC magnets has to be used in the simulation. In this paper the $\sqrt{s} = 7$ TeV and $\beta^* = 90$ m LHC optics was taken, since this is the configuration planned for the ALFA runs in 2011 [12].

The cross-section for exclusive $\pi^+\pi^-$ production at $\sqrt{s} = 7$ TeV is 234 μb (see Sec. 2). The requirement that both protons are tagged in the ALFA stations causes that not all events can be fully registered. This is due to limited acceptance of the detectors. In fact, the visible cross-section depends on the distance between the ALFA detector edge and the beam centre (it will be changed during runs, accordingly to beam conditions). This dependence is presented in Fig. 3, left. For the rest of the present analysis a distance of 4 mm is assumed, which corresponds to 75 μb of cross-section visible in the

ALFA detectors. Figure 3, right presents the distribution of forward proton transverse momentum before and after requesting that protons are tagged in ALFA.

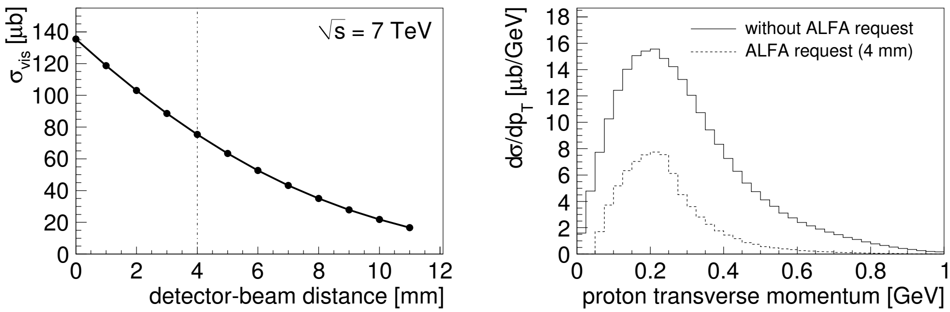

Fig. 3. Left: The cross-section for $pp \to p\pi^+\pi^-p$ with both protons tagged by the ALFA detectors as a function of the distance between the detectors edge and the beam centre (assumed to be identical in all ALFA stations). Right: The proton transverse momentum distribution; the dotted line marks the distribution for the events with both protons tagged by ALFA detectors positioned at 4 mm.

Pions produced in the discussed process will be measured in the central detector. The pion pseudorapidity distribution is presented in Fig. 4, left, whereas the right panel of Fig. 4 shows a correlation between pseudorapidities of both pions. The model used for the simulation predicts a strong correlation between the pseudorapidities of π^+ and π^-, which is not expected for pions originating from $pp \to p\pi^+\pi^0\pi^-p$ or $pp \to p\pi^+\pi^-\pi^+\pi^-p$ processes[1]. Although the majority of the events contains pions with η too large to be detected in ATLAS, the remaining cross-section is still large enough to make the measurement possible.

The pions can be detected in the ATLAS tracking detector ($|\eta| < 2.5$) or in the ATLAS calorimetry system ($|\eta| < 4.9$). From the experimental point of view these are two different measurements, as the tracker enables the particle momentum and charge determination, whereas the calorimeter is sensitive only to the particle energy. One should note that the preferable measurement is the one with the tracker, as it provides very high precision and allows to efficiently discriminate against the like-charge background pairs. Since the correlation between the pseudorapidities of both pions is very large, the following analysis is performed independently for the tracking detector ($|\eta| < 2.5$) and the forward calorimetry ($2.5 < |\eta| < 4.9$).

[1] Such reactions are a natural background, when only two pions are inside the detector acceptance. This contribution can be estimated experimentally by studying the three and four pion final states.

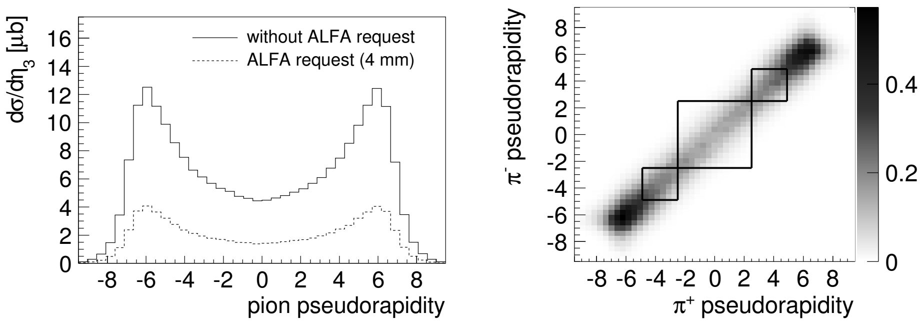

Fig. 4. Left: The total cross-section as a function of pion pseudorapidity. Right: The correlation between the pseudorapidies of the pions, black frames represent regions of tracker and forward calorimeters.

The two adequate distributions: pion transverse momentum in the central region ($|\eta| < 2.5$) and pion energy in the forward region ($2.5 < |\eta| < 4.9$) are presented in Fig. 5, left and Fig. 6, left. Requirement of both protons being tagged in the ALFA detectors influences the shapes of the distributions only very little, but it reduces both by a factor close to three.

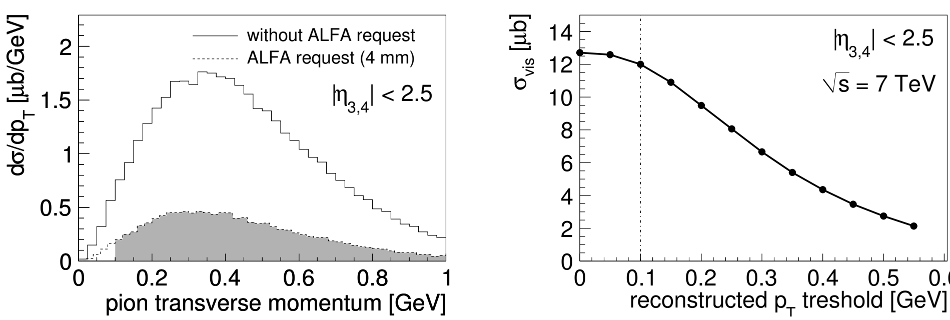

Fig. 5. Left: The pion transverse momentum distribution in the tracking detector. Right: Cross-section for $|\eta| < 2.5$ as a function of p_{T} threshold. The grey area and the dash-dotted line marks the lower boundary of the region accessible by ATLAS.

Obviously, the number of events that can be observed depends on the minimal pion transverse momentum and minimal pion energy that are experimentally accessible. Fig. 5, right and Fig. 6, right show the visible cross-section as a function of reconstruction thresholds for measurements in the tracker and the calorimeter. Clearly, the cross-section falls very steeply with increasing thresholds values. The vertical dash-dotted lines show the thresholds that should be possible to obtain: measurements of $p_{\mathrm{T}} = 100$ MeV were performed for ATLAS minimum bias analysis [13] and particles with energy $E > 4$ GeV were shown to be well above the noise [14]. It should be mentioned that in the minimum bias analysis the efficiency for such low-p_{T} tracks was quite small (about 10%). However, in that analysis, the reconstruction algorithms had to simultaneously deal with many particle tracks. For very clean events that are considered in this work (only two tracks) it should be possible to adjust the reconstruction to obtain a much better efficiency.

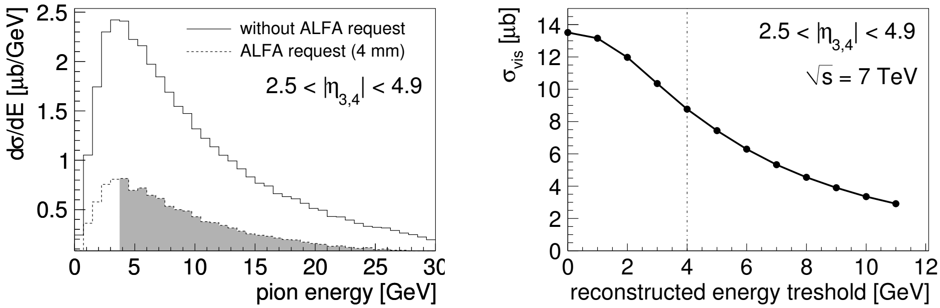

Fig. 6. Left: The pion energy distribution in the calorimeter. Right: Cross-section for $2.5 < |\eta| < 4.9$ as a function of energy threshold. The grey area and the dash-dotted line marks the lower boundary of the region accessible by ATLAS.

An interesting study that can be made when data are collected is the measurement of the $\pi^+\pi^-$ invariant mass distribution. Fig. 7 presents the theoretical predictions and a possible measurement with 100 μb^{-1} integrated luminosity (30 hours of data acquisition time assuming the luminosity value of 10^{27} cm^{-2}s^{-1}) for pions detected in the ATLAS tracker (systematic uncertainty of such a measurement is not considered, only the statistical errors are presented). If the collected statistics is high enough, it should be possible to see resonances, especially the $f_2(1270)$ meson, on top of the presented distribution.

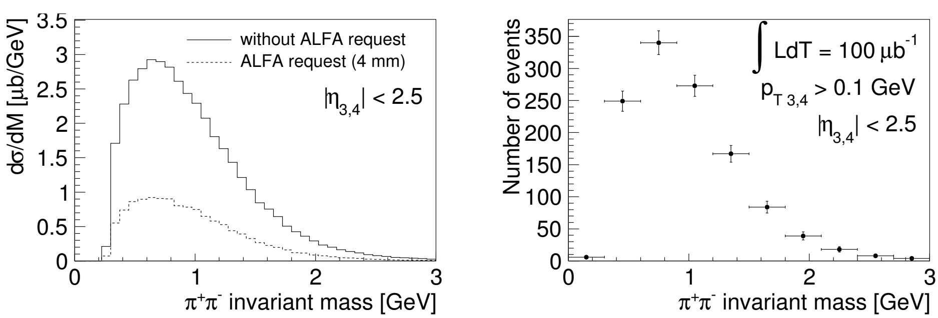

Fig. 7. Left: Distribution of $\pi^+\pi^-$ invariant mass reconstructed in the tracking detector. Right: Possible measurement of the $\pi^+\pi^-$ invariant mass distribution for 100 μb^{-1} integrated luminosity (only the statistical errors are plotted).

5. Summary

A process of exclusive pion pair production in proton–proton collisions was presented and its theoretical description was briefly described. With this theoretical model, a possibility of measuring this process at the LHC was investigated for the ATLAS central detector and the ALFA very forward detectors. There are three main experimental parameters that limit the visible cross-section: the distance between the ALFA detector edge and the proton beam centre, a minimal $p_{\rm T}$ that can be measured in the tracking detector (for pions produced in $|\eta| < 2.5$) and minimal energy that can be measured in the calorimeter (for $2.5 < |\eta| < 4.9$ range). For the values of these parameters set to 4 mm, 0.1 GeV and 4 GeV, respectively, the visible cross-section is 21 μb. For 100 μb^{-1} of integrated luminosity that can be collected during the ALFA runs this gives over 2000 events within the detector acceptance.

R.S. would like to thank J. Turnau for a discussion that triggered this paper and D. Derendarz for his comments about the experimental aspects of the analysis.

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