Direct reconstruction of the pp- elastic scattering amplitudes at U70

M.B. Nurusheva[1], A.A. Bogdanov[1], V.A.Chetvertkova[4], A.V. Kozelov[2], V.P. Ladygin[3], V.V.Mochalov[1,2], V.A. Okorokov[1], A.N.Vasiliev[1,2],

[1]National Research Nuclear University (Moscow Engineering Physics Institute), Moscow, 115409, Russia
[2]NRC «Kurchatov Institute» - IHEP, Protvino, Moscow region, 142281, Russia
[3] Joint Institute for Nuclear Research, Dubna, Moscow region, 141980,Russia
[4]GSI, Plankstrasse 1, 64291, Darmstadt, Germany

Introdaction

Newly developing SPASCHARM (SPin Asymmetry in CHARMonia) experiment at U-70 accelerator will give the unique possibility to measure spin effects with the use of polarized proton and antiproton beams and polarized targets. The SPASCHARM experiment also requires polarimetry [1] to verify beam polarization, which will help to study spin effects in elastic processes, since the detectors are the same in both cases.

Here we suggest to carry out the direct reconstruction of pp elastic scattering amplitudes (DRSA)

[1] A A Bogdanov *et al* 2016 *J. Phys.: Conf. Ser.* **678** 012034

Motivation

The scattering matrix concept presented by theorists is convenient for describing the interaction in all its aspects, but, unfortunately, is not available for direct measurement. Therefore, it is necessary to determine a set of observables that allows the direct reconstruction of the scattering matrix.
DRSA is a fully model-independent analysis using only fundamental conservation lows.

The status of the DRSA is as follows:

- The first DRSA analysis was carried out using the 0.429 GeV at the Chicago University (1968) [2]

- Then before 1975, the direct reconstruction was only possible for *pp* elastic scattering at 90^o *(CM)* at a few energies [3].

- The first direct reconstruction over a large angular region was carried out using the 0.59 GeV PSI data and was reported in (1981) [4]. The PSI data below 0.59GeV (1990) [5]

- Similar reconstructions have been subsequently performed using LAMPF data at 0.73 GeV (1989) [6], and LAMPF data at 0.80 GeV (1985) [7].

- The SATURNE II data have also allowed a DRSA analysis at 11 energies between 0.83 and 2.70GeV (1990) [8].

- Finally, at higher energy, an amplitude analysis was performed using the 6 GeV/c ANL-ZGS data (1985-1986) [9,10].

[2] P. Lemon, et al., Phys. Rev. 169 (1968) 1026.
[3] C. Lechanoine-Leluc and F. Lehar, Rev. Mod. Phys. 65,47 (1993)
[4]. E. Aprile,, et al., Phys. Rev. Lett. 46, 1047 (1981) [5]. M.W. McNaughtonet al., Phys. Rev. C 41, 2809 (1990)
[6]. R Hausammann, et al., Phys. Rev. D 40, 22 (1989) [7]. F. Arash, F., et al., Phys. Rev. D 32, 74 (1985)
[8] C.D. Lac, J. Ball, J. Bystricky, et al. Journal de Physique, 1990, 51 (23), pp.2689-2716I
[9]. M. Matsuda, H. Suemitsu, M. Yonezawa, Phys. Rev. D 33, 2563 (1986)
[10].P. Auer, J. Chalmers, E. Colton, R Giese, H. Halpern, et al., Phys. Rev. 032 1609 (1985)

Notation

To discuss the completed experiment, we need to introduce some notation.

We denote a general scattering observable by

$$X_{srbt}$$

where the indices denote the spin direction of the particles:

s = scattered, r = recoil

b = beam, t = target,

$$Xsrbt = \sigma X_{srbt}$$

J. Bystricky, F. Lehar, P. Winternitz. Journal de Physique, 1978, 39 (1), pp.1-32.

Assuming parity conservation, time reversal and isospin invariance, the scattering matrix is written in terms of complex amplitudes *a, b, c, d* and *e*

$$
\begin{aligned}
M(\mathbf{k}_f, \mathbf{k}_i) &= \frac{1}{2}\Big\{(a+b) + (a-b)(\boldsymbol{\sigma}_1, \mathbf{n})(\boldsymbol{\sigma}_2, \mathbf{n}) + \\
&+ (c+d)(\boldsymbol{\sigma}_1, \mathbf{m})(\boldsymbol{\sigma}_2, \mathbf{m}) + \\
&+ (c-d)(\boldsymbol{\sigma}_1, \mathbf{l})(\boldsymbol{\sigma}_2, \mathbf{l}) + e(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2, \mathbf{n})\Big\}.
\end{aligned}
$$

$$
\mathbf{l} = \frac{\mathbf{k}_f + \mathbf{k}_i}{|\mathbf{k}_f + \mathbf{k}_i|}, \quad \mathbf{m} = \frac{\mathbf{k}_f - \mathbf{k}_i}{|\mathbf{k}_f - \mathbf{k}_i|}, \quad \mathbf{n} = \frac{\mathbf{k}_i \times \mathbf{k}_f}{|\mathbf{k}_i \times \mathbf{k}_f|},
$$

Formalism and observables.

The initial conditions are the following. There is a possibility to have polarized proton beam oriented in all 3 directions and vertically and longitudinally polarized targets.

Therefore, the SPASCHARM configuration allow us to measure the following non-vanishing observables:

- **Aoono** - beam analyzing power,
- **Aooon** - target analyzing power,
- **Aoonn**, **Aooll**, **Aooml** - spin correlations.

Next step is to measure the polaization of the recoil particle due to possibility to provide suitable figure of merit for the large aperture of the polarimeter:

- **Ponoo = Aoono = Aooon** - the polarization of the recoil proton Ponoo is the same as analyzing power.
- **Konno, Kommo, Komlo** - 3 polarization transfer coefficients from the beam to the recoil particle in c.m.s
- **Donon, Domol** - 2 depolarization coefficients for the target in c.m.s
- **Nonll, Nonml, Nomnl, Nomln, Nommn** - 5 polarizations of the recoil particle with polarized beam and target in c.m.s

Therefore, 15 deferent observables in total can be measured at U70.

We express the measured observables in terms of scattering amplitudes as follows:

$$
\begin{aligned}
\sigma &= \frac{1}{2}[||a|^2 + |b|^2 + |c|^2 + |d|^2| + |e|^2], \\
\sigma A_{oonn} &= \frac{1}{2}[||a|^2 - |b|^2 - |c|^2 + |d|^2| + |e|^2], \\
\sigma K_{onno} &= \frac{1}{2}[||a|^2 - |b|^2 + |c|^2 - |d|^2| + |e|^2], \\
\sigma D_{onon} &= \frac{1}{2}[||a|^2 + |b|^2 - |c|^2 - |d|^2| + |e|^2],
\end{aligned}
$$

Measuring the cross section of Aoonn, Konno and Donon, allows us to reconstruct the following amplitudes or their combinations :

$$
\begin{aligned}
|b|^2 &= \frac{\sigma}{2}[1 - A_{oonn} - K_{onno} + D_{onon}], \\
|c|^2 &= \frac{\sigma}{2}[1 - A_{oonn} + K_{onno} - D_{onon}], \\
|d|^2 &= \frac{\sigma}{2}[1 + A_{oonn} - K_{onno} - D_{onon}], \\
|a|^2 + |e|^2 &= \frac{\sigma}{2}[1 + A_{oonn} + K_{onno} + D_{onon}].
\end{aligned}
$$

The analyzing powers (or polarization of recoil particle) equal

$$\sigma A_{oono} = \sigma A_{ooon} = \sigma P_{onoo} = \mathrm{Re}\ \bar{a}\, e$$

Lets assume that d amplitude is real ($X_{srbt} = \sigma X_{srbt}$)

$$\mathrm{Re}\ d = d_1, \qquad \mathrm{Im}\ d = 0.$$

$D_{omol} = -\mathrm{Im}\ \bar{b} e$

$N_{ommn} = \mathrm{Re}\ \bar{c} e$

$K_{omlo} = -\mathrm{Im}\ \bar{c} e$

$N_{onll} = -\mathrm{Re}\ \bar{d} e$

$A_{ooml} = -\mathrm{Im}\ \bar{d} e$

$K_{ommo} = \mathrm{Re}(\ \bar{a} c + \bar{b} d\ )$

$N_{omln} = \mathrm{Im}(\ \bar{a} c - \bar{b} d\ )$

$N_{omnl} = \mathrm{Im}(\ \bar{a} b - \bar{c} d\ )$

$N_{onml} = \mathrm{Im}(\ \bar{a} d + \bar{b} c\ )$

$A_{ooll} = -\mathrm{Re}(\ \bar{a} d - \bar{b} c\ )$

$a = a_1 + \mathrm{i} a_2$

$b = b_1 + \mathrm{i} b_2$

$c = c_1 + \mathrm{i} c_2$

$e = e_1 + \mathrm{i} e_2$

We choose the amplitude d to be real and positive and introduce the notations for the real and imaginary parts of each amplitudes

Manipulating these expressions we obtain c(d_1) and e(d_1) :

$$c_1 = \frac{d_1\,(Aooml\,Komlo - Nommn\,Nonll)}{Aooml^2 + Nonll^2}$$

$$c_2 = -\frac{d_1\,(Aooml\,Nommn + Komlo\,Nonll)}{Aooml^2 + Nonll^2}$$

$$e_1 = -\frac{Nonll}{d_1}$$

$$e_2 = -\frac{Aooml}{d_1}$$

From equations for $c(d_1)$ and $e(d_1)$ we obtain $a(d_1)$ and $b(d_1)$:

$$a_1 = \left(-Aooml\,Domol\,d_1^2 - Aoono\,Nommn\,d_1^2 + Aooml^2\,Kommo - Aooml\,Nomln\,Nonll\right) \Big/ \left(d_1\,(Aooml\,Komlo + Nommn\,Nonll)\right)$$

$$a_2 = -\left(Aoono\,Komlo\,d_1^2 - Domol\,Nonll\,d_1^2 + Aooml\,Kommo\,Nonll - Nomln\,Nonll^2\right) \Big/ \left(d_1\,(Aooml\,Komlo + Nommn\,Nonll)\right),$$

$$b_1 = \left(Aooml^2\,Domol\,Komlo\,d_1^2 - Aoono\,Komlo^2\,Nonll\,d_1^2 - Aoono\,Nommn^2\,Nonll\,d_1^2 + Domol\,Komlo\,Nonll^2\,d_1^2 + Aooml^2\,Komlo\,Nomln\,Nonll + Aooml^2\,Kommo\,Nommn\,Nonll + Komlo\,Nomln\,Nonll^3 + Kommo\,Nommn\,Nonll^3\right) \Big/ \left(d_1\,(Aooml^2 + Nonll^2)\,(Aooml\,Komlo + Nommn\,Nonll)\right),$$

$$b_2 = \left(-Aooml^2\,Domol\,Nommn\,d_1^2 - Aooml\,Aoono\,Komlo^2\,d_1^2 - Aooml\,Aoono\,Nommn^2\,d_1^2 - Domol\,Nommn\,Nonll^2\,d_1^2 + Aooml^3\,Komlo\,Nomln + Aooml^3\,Kommo\,Nommn + Aooml\,Komlo\,Nomln\,Nonll^2 + Aooml\,Kommo\,Nommn\,Nonll^2\right) \Big/ \left(d_1\,(Aooml^2 + Nonll^2)\,(Aooml\,Komlo + Nommn\,Nonll)\right)$$

To express d_1 we substitute the found a, b, c, vs d_1 into the equation

$$Norml = a_1 d_2 - a_2 d_1 + b_1 c_2 - b_2 c_1$$

$$d_1 = \Big(\big(Aooml^2 + Komlo^2 + Nommn^2 + Nonll^2\big)\,(Aoono\,Komlo - Domol\,Nonll)\,\big(Aooml^2 + Nonll^2\big)\,\big(Aooml\,Komlo\,Norml - Aooml\,Kommo\,Nonll + Komlo^2\,Nomln + Komlo\,Kommo\,Nommn + Nomln\,Nonll^2 + Nommn\,Nonll\,Norml\big)\Big)^{1/2} \Big/ \Big(\big(Aooml^2 + Komlo^2 + Nommn^2 + Nonll^2\big)\,(Aoono\,Komlo - Domol\,Nonll)\Big)$$

Too complicated !!!

When we choose the amplitude e to be real and positive, we get the following equation for amplitudes:

$$a_1 = \frac{Aoono}{e_1},\ a_2 = -\Big(-Aooml\,Kommo\,e_1^2 + Nomln\,Nonll\,e_1^2 + Aooml^2\,Domol + Aooml\,Aoono\,Nommn - Aoono\,Komlo\,Nonll + Domol\,Nonll^2\Big)\Big/\big((Aooml\,Komlo + Nommn\,Nonll)\,e_1\big)$$

$$b_1 = \Big(-Komlo\,Nomln\,e_1^2 - Kommo\,Nommn\,e_1^2 + Aooml\,Domol\,Nommn + Aoono\,Komlo^2 + Aoono\,Nommn^2 - Domol\,Komlo\,Nonll\Big)\Big/\big(e_1\,(Aooml\,Komlo + Nommn\,Nonll)\big),\ b_2 = \frac{Domol}{e_1}$$

$$c_1 = \frac{Nommn}{e_1},\ c_2 = \frac{Komlo}{e_1} \qquad d_1 = -\frac{Nonll}{e_1},\ d_2 = \frac{Aooml}{e_1}$$

Equation for *e* and minimal set of observables

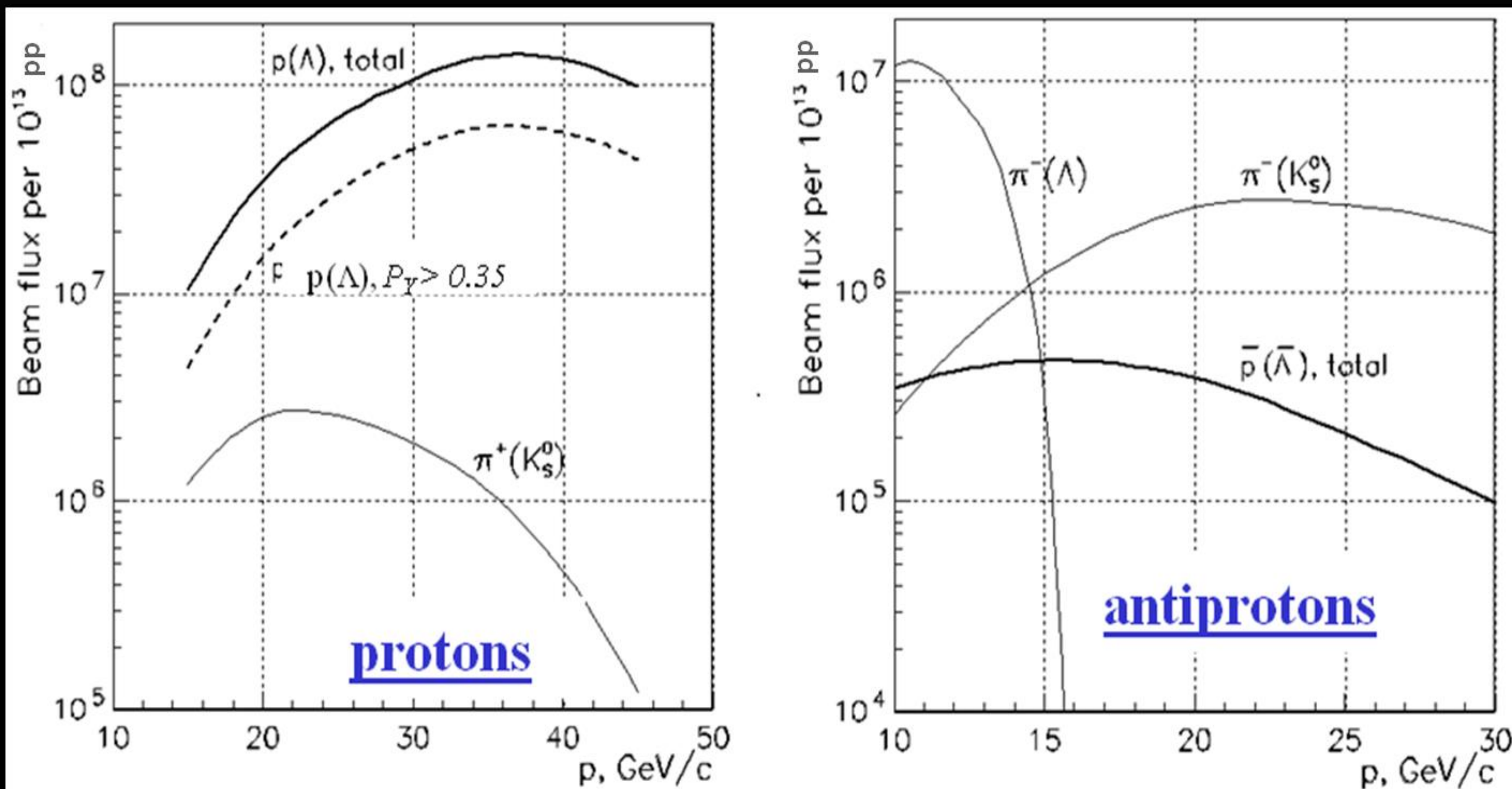
$$
\begin{aligned}
e = \Big(\big(& Aooml\,Komlo\,Nonml - Aooml\,Kommo\,Nonll + Komlo^2\,Nomln \\
& + Komlo\,Kommo\,Nommn + Nomln\,Nonll^2 \\
& + Nommn\,Nonll\,Nonml \big) \left(Aooml^2 + Komlo^2 + Nommn^2 \right. \\
& \left. + Nonll^2 \right) \left(Aoono\,Komlo - Domol\,Nonll \right) \Big)^{1/2} \Big/ \\
\big(& Aooml\,Komlo\,Nonml - Aooml\,Kommo\,Nonll \\
& + Komlo^2\,Nomln + Komlo\,Kommo\,Nommn + Nomln\,Nonll^2 \\
& + Nommn\,Nonll\,Nonml \big)
\end{aligned}
$$

Aoono, Aooml, Komlo, Kommo, Domol, Nomln, Nonml, Nommn, Nonll = 9 spin observables + cross-section

SPASCHARM set up possibility

The use of elastic processes to determine the absolute value of polarization makes it possible to measure the polarization of protons and (anti) protons for any particle energy. But the high pion background to antiprotons from Λ(bar) → p(bar)π^- decays might make it not feasible operating antiproton beam at momenta below 16 GeV/c.

The intensity of polarized proton (left frame) and antiproton (right frame) beams with the maximum Δp/p per 10^{13} of 60 GeV primary protons



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The criteria to select elastic processes

After the Lorentz boost into the laboratory frame transversely polarized portions of the total beam are selected, using the particle's trajectory tagging or collimation.

Tagging system allows for each particle to measure position in both directions (X and Y) in intermediate focus and momentum with an accuracy better than 1%

So we can select the events as elastic on the dual criteria of coplanarity and agreement to the scattering angles with kinematics .

The criteria to select elastic processes

To estimate the S / (S + B) ratio, 10^6 events were simulated using the PYTHIA 6.3 generator. The signal is elastic pp scattering. Background - diffraction processes as A + B → X + B, A + B → A + X in which only two charged particles enter the detector. The geometry and resolution of the detector were taken into account In the simulation. Separation was carried out using the two-dimensional distribution tg1 * tg2 of the difference in angles (phi1-phi2).

The momentum of the incident protons from 16 GeV/c

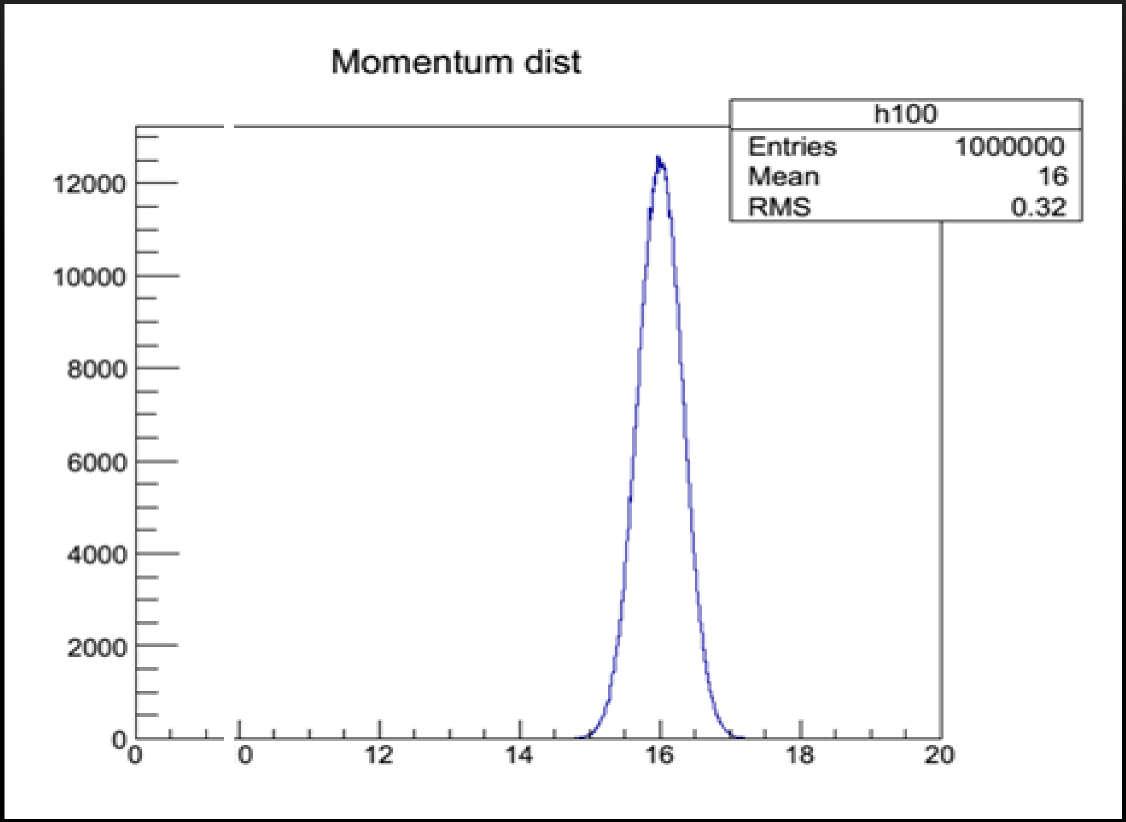


Fig.4. Momentum distribution of incident protons.

The momentum distribution of incident protons of the order of 2% was also taken into account.

Estimating the size of the detector

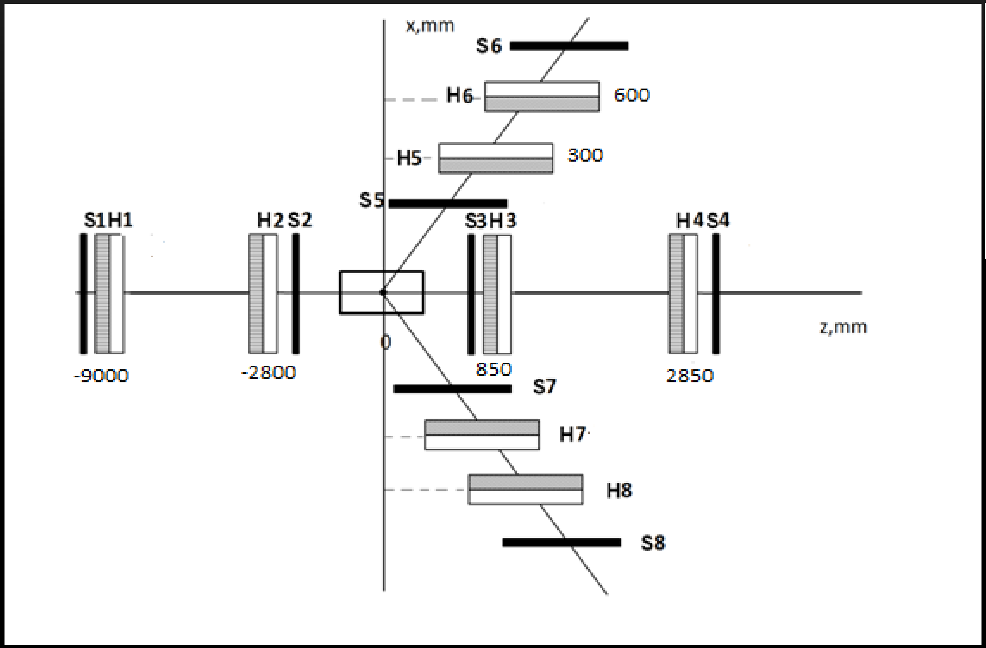


Fig.5 . Scheme of the detector for measuring the elastic processes

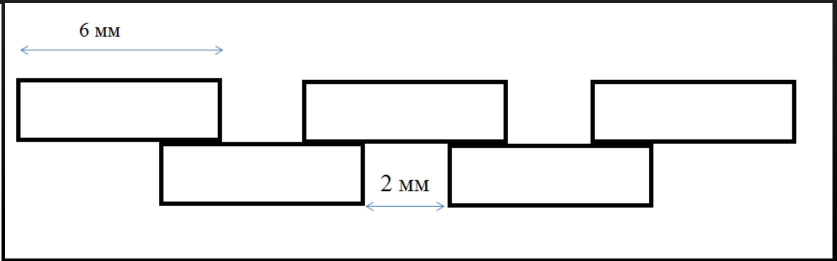


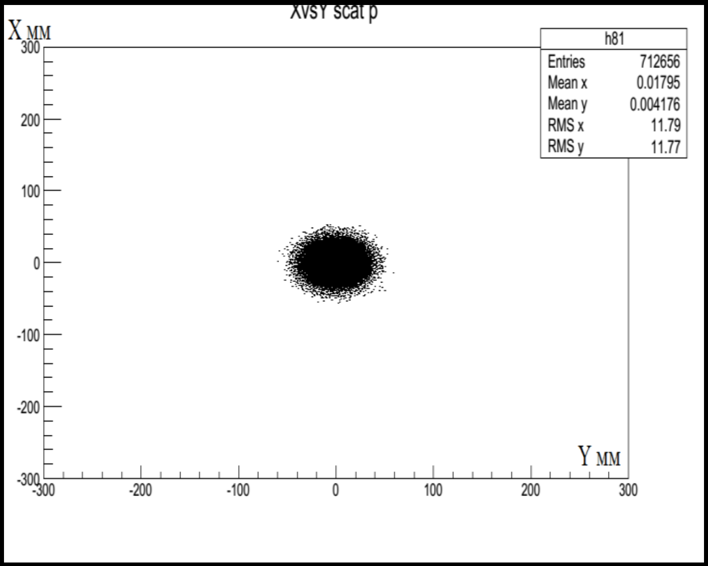
Fig. 6. The overlapping scintillator design of the hodoscope .

The hodoscopes are made of scintillators that are located “comb”, and although the width of each scintillator is 6 mm, this arrangement allows us to know the coordinate of the particle’s impact with an accuracy of 2 mm

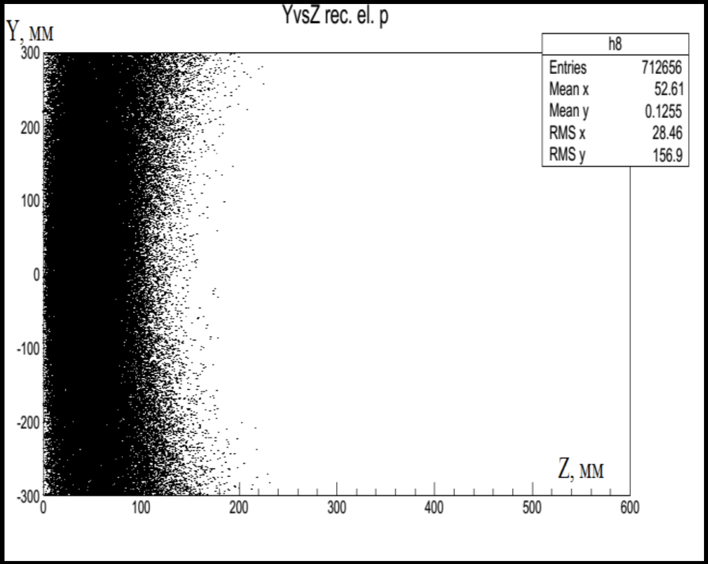
The detector was chosen based on the characteristics of the one presented at [11] that was modeled for registering the elastic processes in scattering of 45 GeV/c protons

[11] V V Abramov et al 2017 J. Phys.: Conf. Ser. 938 012006

Knowing from the simulation of the projection of the particle momentum, it is possible to obtain the exact coordinate of the particle entering the recoil and scattering detector, and accordingly the azimuthal and polar angles of the recoil and scattering particles (ϕ, θ).

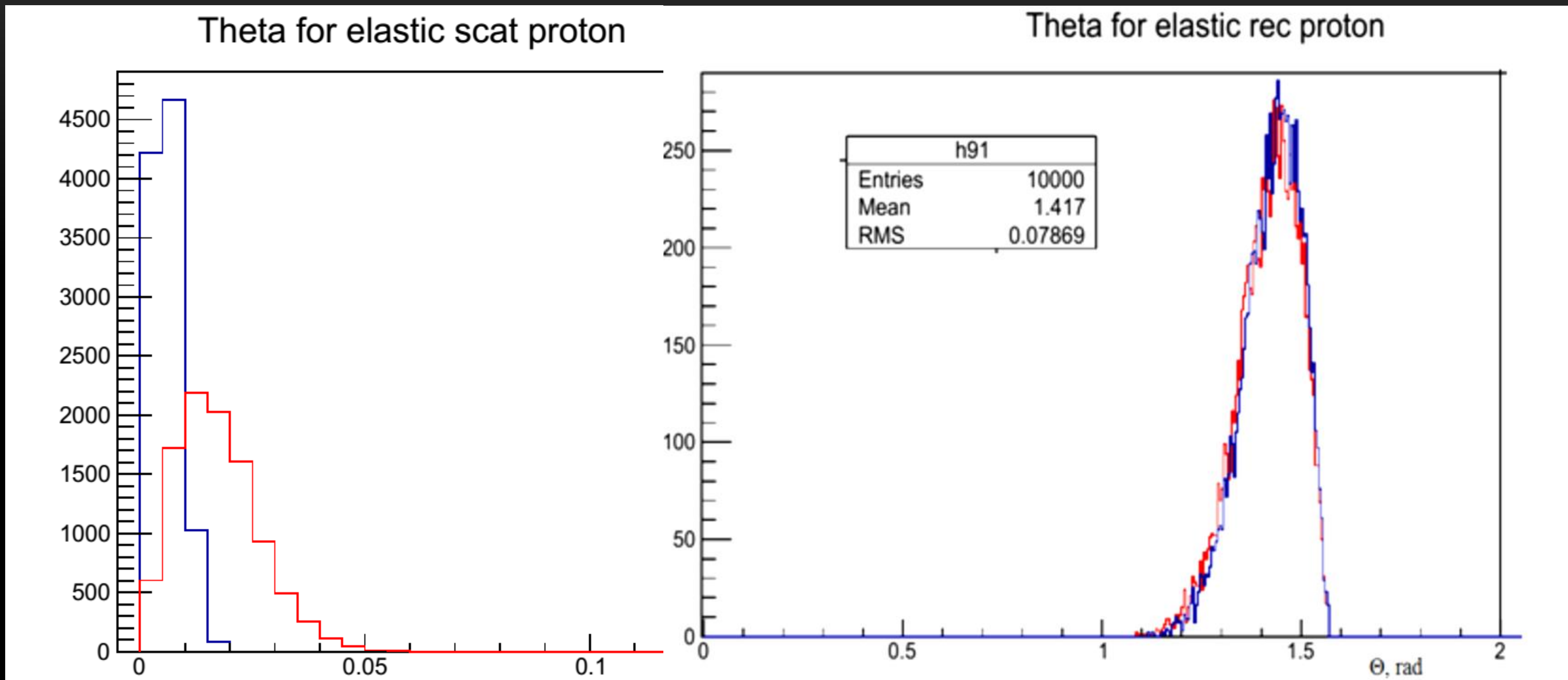


Distribution of scattered protons in the XY plane where the scattered proton hodoscope is located



Distribution of recoil protons in the YZ plane where the recoil proton hodoscope is located

The angles or the recoil protons for 16 and 45 GeV/c.



Angles of the scattering protons Angles of the recoil protons

Red line - for 16 GeV / c, blue - for 45 GeV / c.

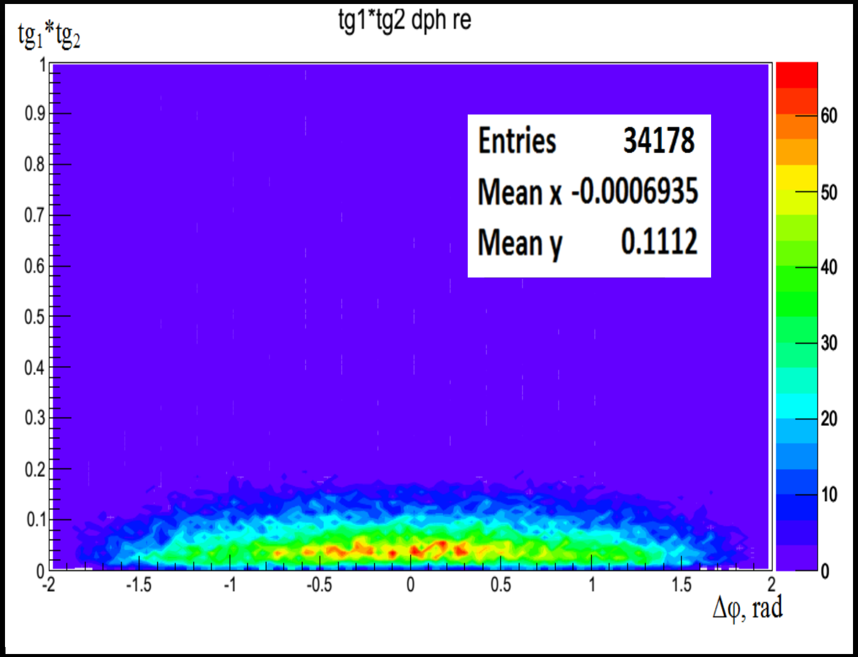
Since the prototype detector was designed for 45 GeV/c, in present studies the sizes were changed based on the comparison of the angles of the recoil protons for 16 and 45 GeV/c.

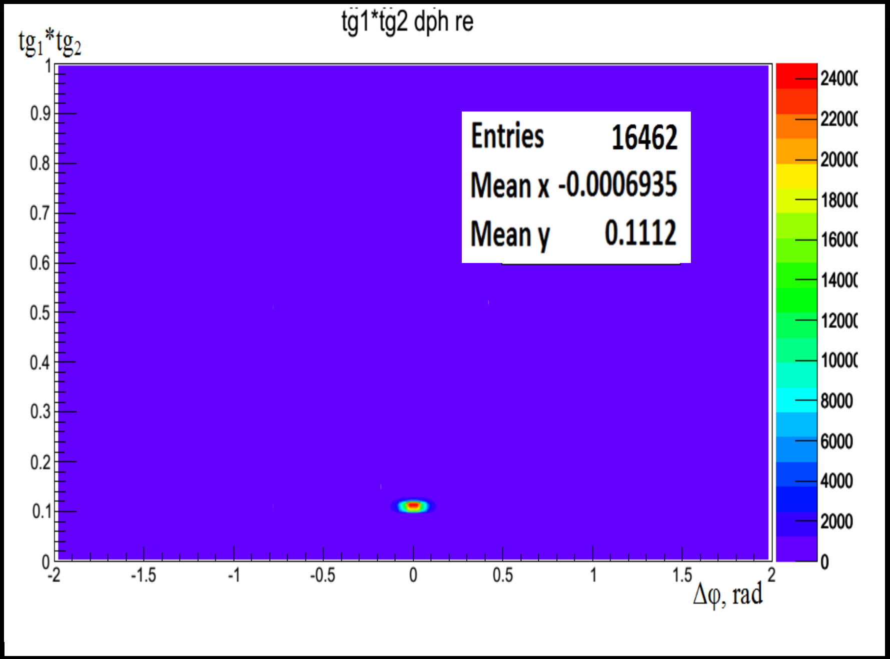
Hodoscopes	Distance from PT (mm)	Total dimensions (mm)	Dimension of scintillator width x thickness x length (mm)		Numbers of PM	
	Z	X × Y	X	Y	X	Y
		Beam	Hodoscopes			
H1	-9000	40 × 40	6 × 3 × 40	6 × 3 × 40	9	9
H2	-2800	40 × 40	6 × 3 × 40	6 × 3 × 40	9	9
		Forward	Hodoscopes			
H3	[illegible]	…45	6 × 3 × 62	6 × 3 × 45	15	11
H4	[illegible]	…86	6 × 3 × 182	6 × 3 × 86	45	21
		Recoil	Hodoscopes			
	X	Z × Y	Z	Y	Z	Y
H5 - H7	300	322 × 228	9 × 5 × 322	9 × 5 × 228	51	37
H6 - H8	600	432 × 430	9 × 5 × 432	9 × 5 × 420	71	69

84 × 84

Design of the hodoscopes

Two-dimensional histogram. The tangent products from the difference in azimuthal angles, taking into account the dimensions of the detectors H3 and H5.





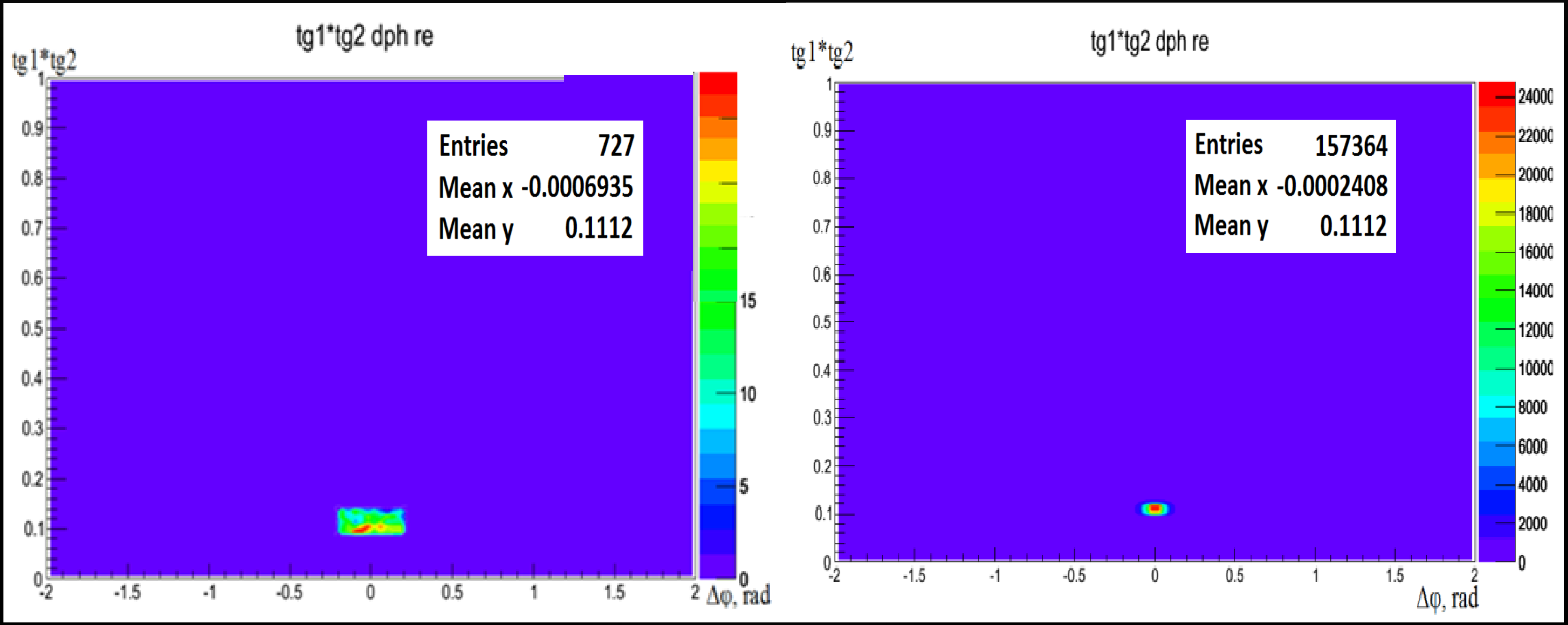
Only for diffraction processes

Background

Only for elastic processes

Signal

Two-dimensional histogram. The tangent products from the difference in azimuthal angles, taking into account the the regions of Δϕ and tg1 * tg2

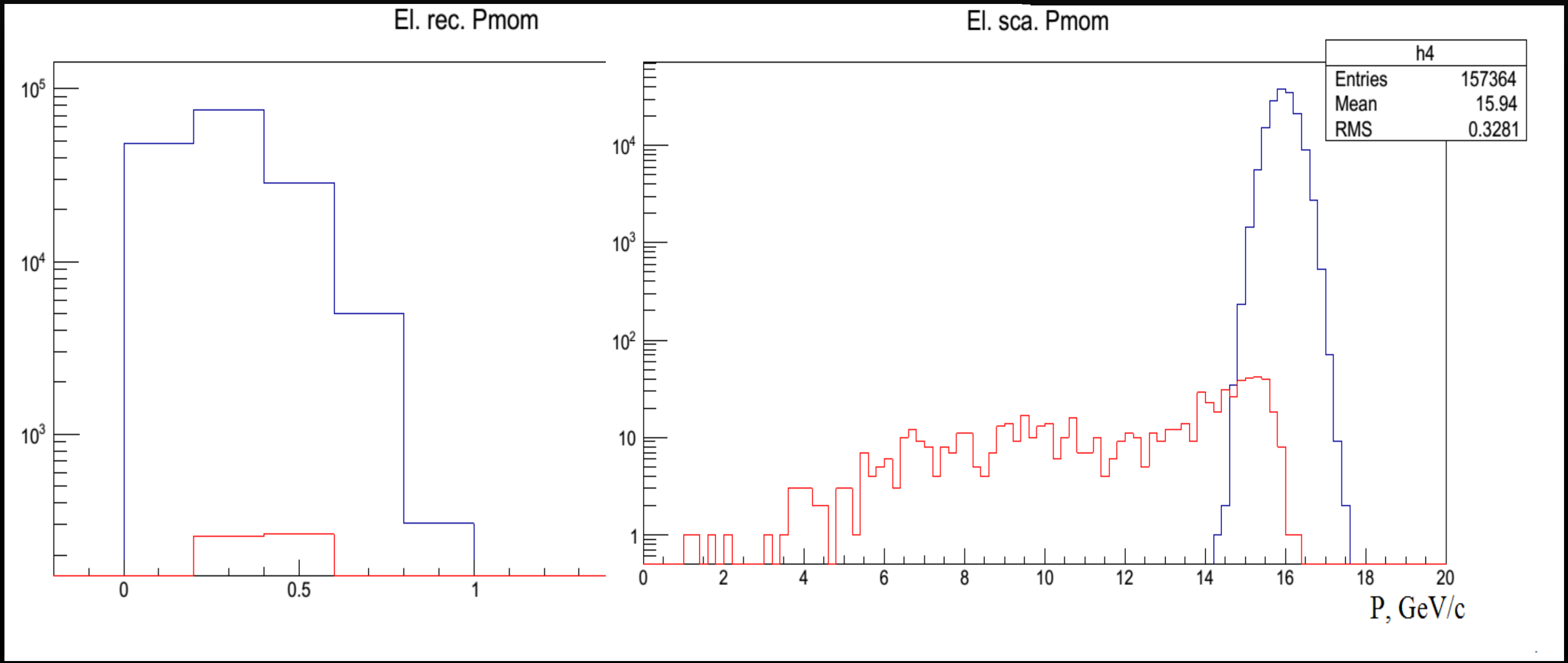


Only for diffraction processes
Background

Only for elastic processes
Signal

$$S/(S+B)=157364/(157364+721)=0.995$$

The momentum distributions of particles entering the recoil and scattering hodoscopes



The recoil particles

The scattered particles.

Blue line is elastic processes, red - diffraction processes

Signal **Background**

$$S / (S + B) = 0.995$$

Conclusion

- We present the direct reconstruction of pp elastic scattering amplitudes at the SPASCHARM experiment.
- The observables are expressed in terms of invariant amplitudes. These amplitudes are deduced analytically   to solve bilinear relations.
- The criteria to select elastic processes are discussed and presented. Monte-Carlo simulations of elastic scattering as well background reactions were carried out
- Elastic and diffraction interactions of protons were simulated by using PYTHIA generator for 16 GeV incident protons, designed Setup geometry and the resolution of the detectors
- Two-dimensional distributions of the product of the tangents of the polar angles of the recoil particle and the scattered particle versus difference of the azimuth angles of these particles, were obtained. The estimated ratio of the signal to background S/(S+B) is about 0.99.

Acknowledgments

The work has been supported in part by the NRNU MEPhI Academic Excellence Project (contract № 02.a03.21.0005, 27.08.2013).

Thank you for attention