EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

DIRAC Note 2016-07
November 7, 2016

The estimation of production rates of K^+K^- and $p\bar{p}$ atoms in proton-nucleus interactions at 450 GeV/c

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GENEVA
2016

1 Introduction

Experimental investigations of the $K^+\pi^-(A_{K\pi})$, $K^-\pi^+(A_{\pi K})$ and $\pi^+\pi^-(A_{2\pi})$ atoms were performed in the DIRAC experiment at the CERN PS at the proton beam momentum of 24 GeV/c [1, 2, 3, 4, 5]. All the dimesoatoms in DIRAC were investigated using a two-arm vacuum magnetic spectrometer with detectors placed in front of and behind the spectrometer magnet [6]. The particles generated in the target by the primary proton beam moved in the solid angle of $1.2 \times 10^{-3} sr$ and crossed all the detectors in front of the magnet. Positive and negative particles that crossed the detectors behind the magnet had the momentum in the interval of 1.2-7 GeV/c.

In the [7] the absolute and relative dimesoatom($A_{K\pi}$, $A_{\pi K}$ and $A_{2\pi}$) yields at proton beam momentum 450 GeV/c and 24 GeV/c as a function of atom angle θ_{lab} and atom momentum were calculated. The calculations were performed using the FTF generator [8], which is a developed version of FTITIOF generator for GEANT4 [9]. It allows obtaining the expected number of detected short-lived dimesoatoms and possible statistical errors.

In the present work the absolute and relative dimesoatom K^+K^+(A_{2K}) and $p\bar{p}$(A_{2p}) yields at the same proton momenta as a function of atom angle θ_{lab} and atom momentum are calculated using the same generator.

2 Basic relations

The atom production probability is proportional to the double inclusive cross section for generation of two constituent particles of this atom with small relative momenta. Calculating the atom production cross section, one should exclude the contribution to the double cross section from those constituents that arise from the decays of long-lived particles and cannot form the atom. When one or both particles in the pair come from these decays the typical range between them is much larger than the Bohr radius of the atom (109 fm for A_{2K} and 58 fm for A_{2p}) and the atom production probability is negligible. The laboratory differential inclusive cross section for the atom production can be written in the form [10]

$$\frac{d\sigma_n^A}{d\vec{p}_A} = (2\pi)^3 \, \frac{E_A}{M_A} \, |\Psi_n(0)|^2 \, \left. \frac{d^2\sigma_s}{d\vec{p}_1 \, d\vec{p}_2} \right|_{\vec{p}_1=\vec{p}_2=\frac{\vec{p}_A}{2}} , \tag{1}$$

where M_A is the atom mass, $\vec{p}_A$ and E_A are the momentum and energy of the atom in the lab system, respectively, $|\Psi_n(0)|^2 = p_B^3/\pi n^3$ is the atomic wave function (without regard for the strong interactions between the particles forming the atom, i.e., it is the pure Coulomb wave function) squared at the origin with the principal quantum number n and the orbital momentum $l = 0$, p_B is the Bohr momentum of the particles in the atom, $d^2\sigma_s^0/d\vec{p}_1 d\vec{p}_2$ is the double inclusive production cross section for the pairs from the short-lived sources (hadronization processes, ρ, ω, Δ, K^*, Σ^*, etc.) without regard for the A_{2K} and A_{2p} Coulomb interaction in the final state, and $\vec{p}_1$ and $\vec{p}_2$ are the momenta of the particles forming the atom in the lab system. The momenta obey the relation $\vec{p}_1 = \vec{p}_2 = \frac{\vec{p}_A}{2}$. The atoms are produced with the orbital momentum $l = 0$, because $|\Psi_{n,l}(0)|^2 = 0$ when $l \neq 0$. The atoms are distributed over n as n^{-3}: $W_1 = 83\%$, $W_2 = 10.4\%$, $W_3 = 3.1\%$, $W_{n\geq 4} = 3.5\%$. Note that $\Sigma_{n=1}^{\infty}|\Psi_n(0)|^2 = 1.202|\Psi_1(0)|^2$.

After substituting the expression for $|\Psi_n(0)|^2$ and summing over n, one can obtain an expression for the inclusive yield of atoms in all S-states through the inclusive yields of positive and negative hadron pairs

$$\frac{d\sigma^A}{d\vec{p}_A} = 1.202 \times 8\,\pi^2\,(\mu\alpha)^3\,\frac{E_A}{M_A}\,\frac{d^2\sigma_s}{d\vec{p}_1\,d\vec{p}_2}\bigg|_{\vec{p}_1=\vec{p}_2=\frac{\vec{p}_A}{2}}\,, \tag{2}$$

where μ is the reduced mass of the atom ($\mu = \frac{m_1 m_2}{m_1+m_2}$), and α is the fine structure constant.

Instead of the differential cross section, it is convenient to introduce the particle production probability per inelastic interaction (yield)

$$\frac{dN}{d\vec{p}} = \frac{d\sigma}{d\vec{p}}\,\frac{1}{\sigma_{in}}, \qquad \frac{d^2N}{d\vec{p}_1 d\vec{p}_2} = \frac{d^2\sigma}{d\vec{p}_1 d\vec{p}_2}\,\frac{1}{\sigma_{in}}, \tag{3}$$

where σ_{in} is the inelastic cross section of hadron production.

Then

$$\frac{dN_A}{d\vec{p}_A} = 1.202 \times 8\,\pi^2\,(\mu\alpha)^3\,\frac{E_A}{M_A}\,\frac{d^2N_s}{d\vec{p}_1\,d\vec{p}_2}\bigg|_{\vec{p}_1=\vec{p}_2=\frac{\vec{p}_A}{2}}\,, \tag{4}$$

The double yield (without regard for the Coulomb interaction) can be presented as [11]:

$$\frac{d^2N_s}{d\vec{p}_1 d\vec{p}_2} = \frac{dN_1}{d\vec{p}_1}\,\frac{dN_2}{d\vec{p}_2}\,R(\vec{p}_1,\vec{p}_2,s), \tag{5}$$

where $dN_1/d\vec{p}_1$ and $dN_2/d\vec{p}_2$ are the single-particle yields, R is a correlation function due to strong interaction only, and s is the c.m.s. energy squared.

2.1 Calculations of inclusive yields of charged particles, K^+K^- and $p\bar{p}$ atoms.

In this subsection the yield is calculated in the solid angle of $10^{-3}sr$ without allowance for the setup acceptance and particle decays.

Figure 1 shows the total yields of the charged particles ($\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$) per pNi interaction event at 450 GeV/c and an emission angles $\theta_{lab} = 0°$, $2°$, $4°$ (right) and at 24 GeV/c and an emission angle $\theta_{lab} = 5.7°$ (left) as a function of their momentum.

The yields of both atoms into solid angle of 10^{-3} sr as a function of their momentum in the interval 2.5-10.5 GeV/c are shown in Fig.2. The chosen interval is the working one of the DIRAC setup in which identification of charged particle is really simple.

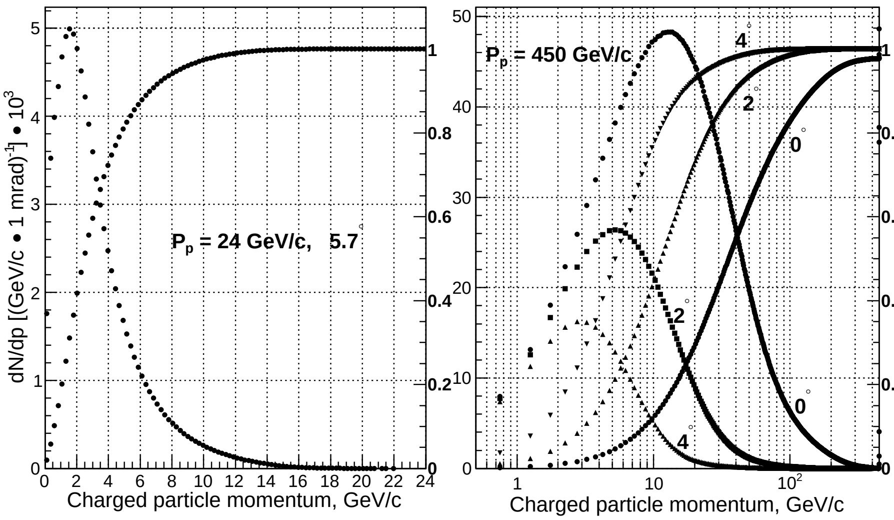

Figure 1: The total yield of the charged particles ($\pi^\pm$, $K^\pm$, p and $\bar{p}$) per pNi interaction event at 450 GeV/c and an emission angles $\theta_{lab} = 0°$, $2°$, $4°$ (right) and at 24 GeV/c and emission angle $\theta_{lab} = 5.7°$ (left) as a function of their momentum in l.s. for the solid angle of 10^{-3} sr. The integrated and normalized to 1 distributions are shown.

Table 1 presents these yields integrated over p_A , where W_{ch} and W_A are the total yields of the charged particles ($\pi^\pm$, $K^\pm$, p, $\bar{p}$) and K^+K^- and $p\bar{p}$ atoms respectively into the aperture of 10^{-3} sr per pNi interaction event at 450 and 24 GeV/c. The relative yields of the charged particles and atoms at 450 and 24 GeV/c are W_{ch}^N=$W_{ch}/W_{ch}(5.7°, 24\ GeV/c)$ and W_A^N=$W_A/W_A(5.7°, 24\ GeV/c)$).

The yields of the K^+K^- and $p\bar{p}$ atoms at $\theta_{lab} = 4°$ and at 450 GeV/c are about 7 and 3 times higher respectively than at 24 GeV/c and $\theta_{lab} = 5.7°$.

2.2 Calculations of inclusive yields of K^+K^- and $p\bar{p}$ atoms detected by the setup

The acceptance of the DIRAC setup for K^+K^- and $p\bar{p}$ atoms detection at 24 GeV/c without allowance for the particle decays is presented in Fig.3. We used the same acceptance at 450 GeV/c to obtain the yield that allows calculating the expected number of K^+K^- and $p\bar{p}$ at 450 GeV/c using the DIRAC experimental data.

The yields of A_{2K} and A_{2p} per pNi interaction event into solid angle of 10^{-3} sr with allowance for the setup acceptance are presented in Fig.4 and 5 as a function of the atom momentum.

These yields integrated over p_A are shown in Table 2. together with the relative yields (the yield at 24 GeV/c and 5.7° is set to 1) and the yields relative to the flux of the charged particles. The latter values are important since the DIRAC forward detectors should operate at this flux of the charged particles. Also this ratio is less sensitive to the accuracy of the meson production inclusive cross sections than the atomic absolute yield.

Table 1: The total yields of charged particles ($\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$) W_{ch} and the K^+K^- and $p\bar{p}$ atoms W_A into the aperture of 10^{-3} sr per pNi interaction event at 24 and 450 GeV/c in the intervals 2.5-10.5 GeV/c versus the emission angle θ_{lab} without taking into account the decays of kaons in the setup. The relative yields of the charged particles and atoms are W_{ch}^N=$W_{ch}/W_{ch}(5.7°, 24\ GeV/c)$ and W_A^N=$W_A/W_A(5.7°, 24\ GeV/c)$.

θ_{lab}	5.7°	4°	2°	0°
p_p	24 GeV/c	450 GeV/c	450 GeV/c	450 GeV/c
Yield of charged particles				
W_{ch}	0.022	0.14	0.50	2.9
W_{ch}^N	1	6.4	22.7	132
Yield of K^+K^- atoms				
$W_A \times 10^9$	0.39	2.9	4.9	6.3
W_A^N	1	7.2	12.4	16.
Yield of $p\bar{p}$ atoms				
$W_A \times 10^9$	2.8	9.0	14.0	16.5
W_A^N	1	3.3	5.1	6.0

2.3 Calculations of the correlation function $R(\vec{p_1}, \vec{p_2}, s)$ at a proton momentum of 24 and 450 GeV/c for the K^+K^- and $p\bar{p}$ pairs with a small relative momentum.

The differential inclusive yield of atom production in (4) is expressed in terms of the double differential yield of two constituent particles. We obtained this yield using the FTF generator. We can also use the FTF to determine the correlation function (5) which allows the uncertainty in the minimum value of W_A^N to be evaluated. This factor for the momentum interval of the DIRAC setup is presented in Fig.6. It shows that the factor R for K^+K^- pairs at 24 GeV/c is higher than for 450 Gev/c. The same takes place for $p\bar{p}$ pairs.

3 Conclusion

The yield of K^+K^- and $p\bar{p}$ in the momentum interval of the DIRAC experiment 2.5-10.5 GeV/c at 450 GeV/c and $\theta_{lab} = 4°$ is 7 and 3 times higher than their production at 24 GeV/c and $\theta_{lab} = 5.7°$ (Table 2).

4 Acknowledgments

We are also grateful to V.Uzhinsky for the discussion on the FTF generator.

Table 2: The yield of the K^+K^- and $p\bar{p}$ atoms W_A into the aperture of 10^{-3} sr with allowance for the setup acceptance and kaon decays per pNi interaction event at 24 and 450 GeV/c versus the emission angle θ_{lab}. W_A^N=$W_A/W_A(5.7°, 24\ GeV/c)$ and $(W_A/W_{ch})^N$=$(W_A/W_{ch})/((W_A/W_{ch})(5.7°, 24\ GeV/c))$.

θ_{lab}	5.7°	4°	2°	0°
E_p	24 GeV/c	450 GeV/c	450 GeV/c	450 GeV
Yield of $K+K^-$ atoms				
$W_A \times 10^9$	0.08	0.59	0.95	1.34
W_A^N	1	7.3	11.8	16.6
$W_A/W_{ch} \times 10^9$	0.28	0.24	0.53	2.2
$(W_A/W_{ch})^N$	1	0.86	1.9	7.9
Yield of $p\bar{p}$ atoms				
$W_A \times 10^9$	1.9	5.4	7.6	9.1
W_A^N	1	2.8	3.9	4.7
$W_A/W_{ch} \times 10^9$	0.037	0.022	0.15	4.2
$(W_A/W_{ch})^N$	1	0.60	3.9	11.2

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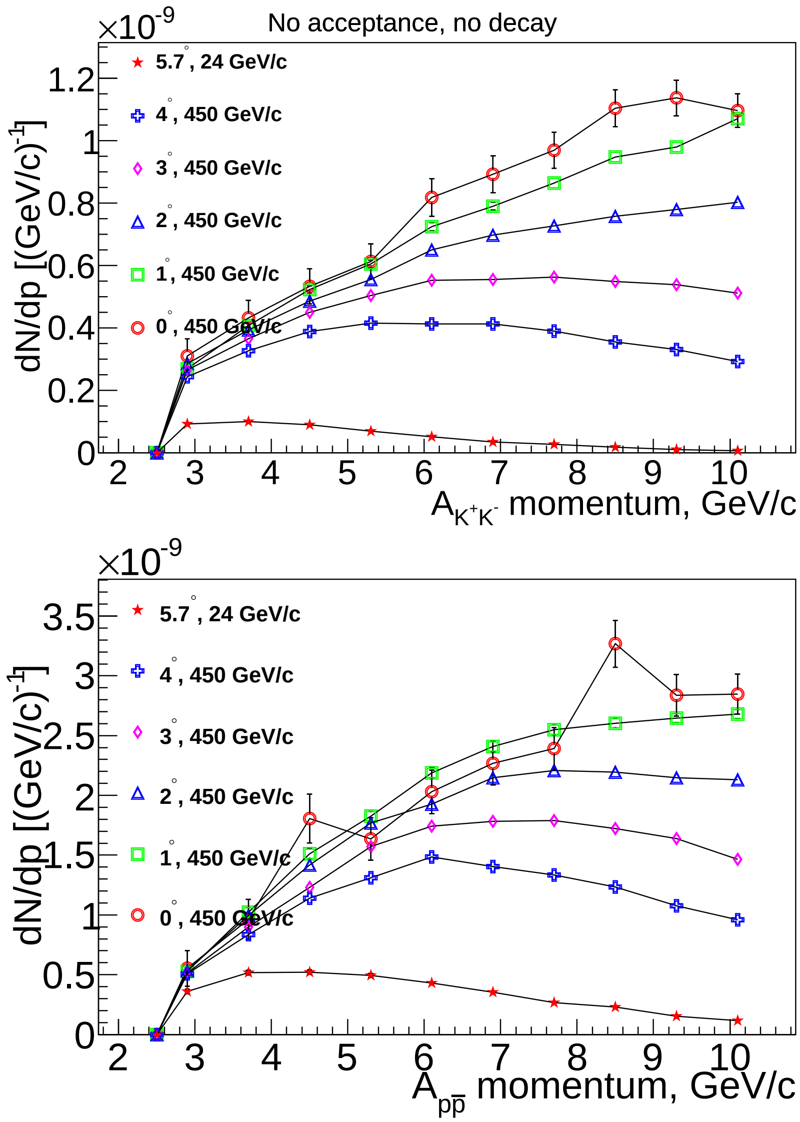

Figure 2: Yields of K^+K^- and $p\bar{p}$ atoms per pNi interaction event at 450 GeV/c and emission angles $\theta_{lab} = 0°$, $2°$, $4°$ and at 24 GeV/c and an emission angle $\theta_{lab} = 5.7°$ as a function of the atom momentum in l.s for the solid angle of 10^{-3} sr. The DIRAC setup acceptance and decays of kaons are ignored.

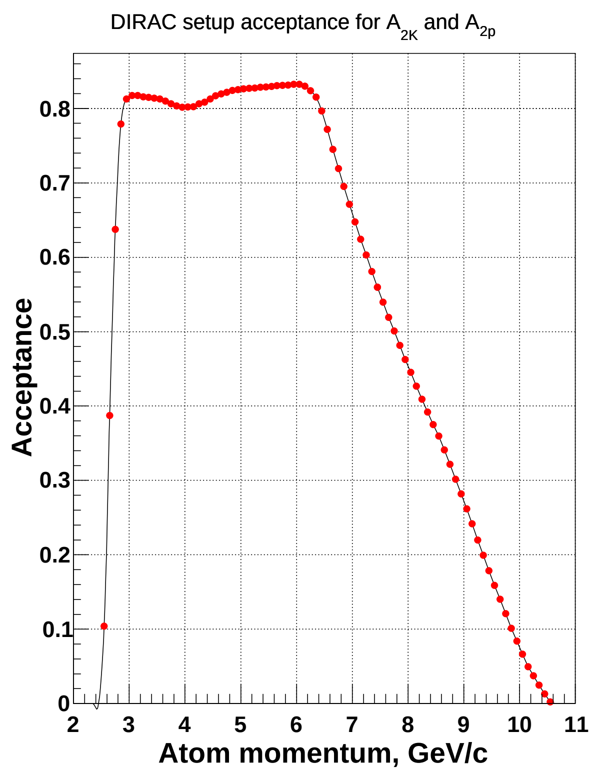

Figure 3: The acceptance of the DIRAC setup at 24 GeV/c for K^+K^- and $p\bar{p}$ as a function of the atom momentum. Decays of kaons are not taken into account.

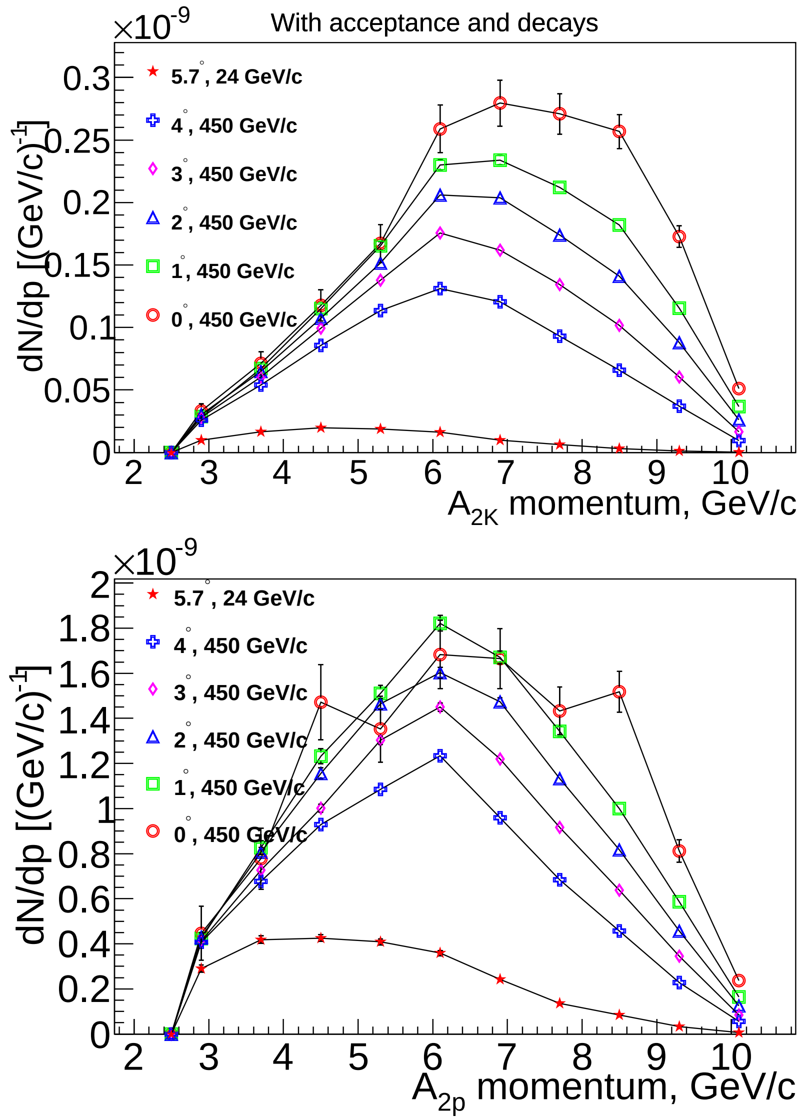

Figure 4: Yields of K^+K^- and $p\bar{p}$ per pNi interaction event at 450 GeV/c and emission angles $\theta_{lab} = 0°$, $2°$, $4°$ and at 24 GeV/c and an emission angle $\theta_{lab} = 5.7°$ as a function of the atom momentum in l.s for the solid angle of 10^{-3} sr. The DIRAC setup acceptance, decays of kaons and the momentum interval of the setup are taken into account.

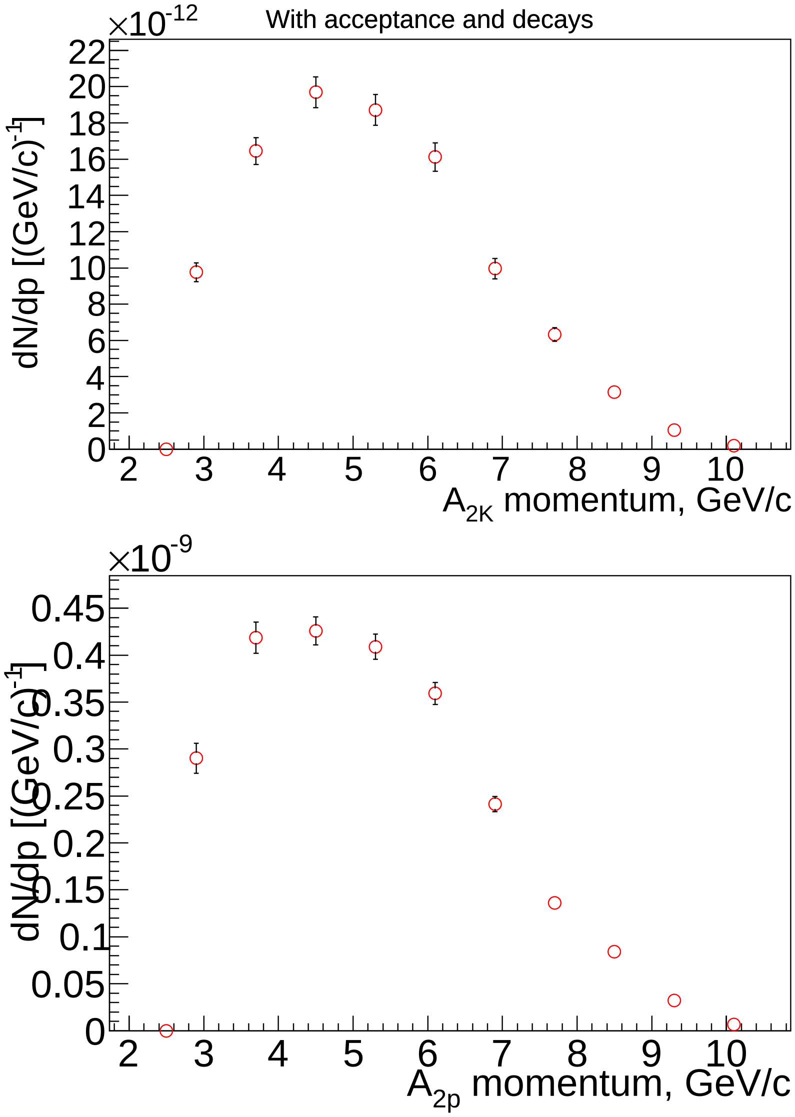

Figure 5: Yields of K^+K^- and $p\bar{p}$ per pNi interaction event at 24 GeV/c and an emission angle $\theta_{lab} = 5.7°$ as a function of the atom momentum in l.s for the solid angle of 10^{-3} sr. The DIRAC setup acceptance, decays of kaons and the momentum interval of the setup are taken into account.

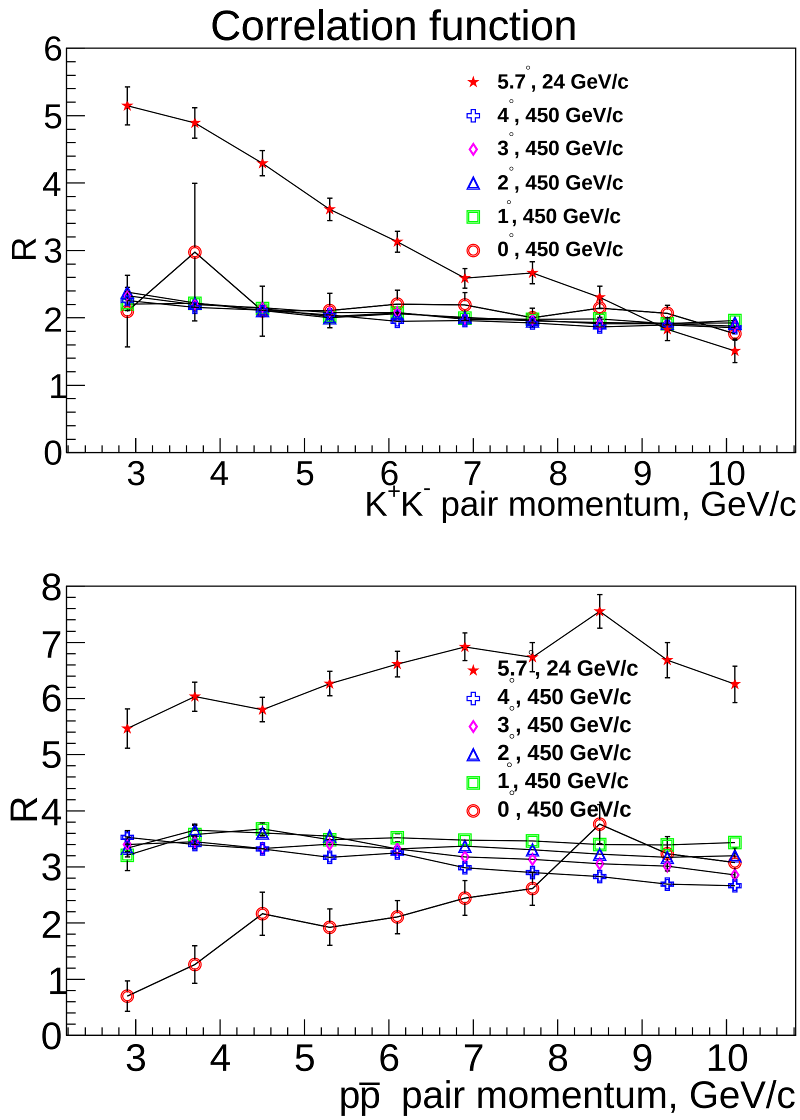

Figure 6: The dependence of correlation factor R for the K^+K^- and $p\bar{p}$ pairs at the DIRAC setup conditions on their momentum in l.s. at 450 GeV/c and emission angles $\theta_{lab} = 0°$, $2°$, $4°$ and at 24 GeV/c and the emission angle $\theta_{lab} = 5.7°$.