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Last results of DIRAC experiment on study hadronic hydrogen-like atoms at PS CERN

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Abstract

Results on study the hydrogen-like atoms consisting of charged pions and Kaons are presented. The first measurement of $K^+\pi$ and $K\pi^+$ atoms lifetime was fulfilled basing on identification of 178 ± 49 $K\pi$ pairs from the atom breakup. The measured lifetime is $\tau = \left(2.5^{+3.0}_{-1.8}\right)$ fs. This value is dictated by properties of the strong πK-interaction at low energy, namely S-wave πK scattering length. The first experimental value of the isospin-odd combination of S-wave πK scattering length was obtained $|a_0^-| = \frac{1}{3}|a_{1/2} - a_{3/2}| = \left(0.11^{+0.09}_{-0.04}\right) M_\pi^{-1}$ (a_I for isospin I).

A dedicated experiment with $\pi^+\pi$ atoms allows further study of these already observed atoms. The preliminary results on observation of the long-lived (metastable) states of $\pi^+\pi$ atoms are presented. The observation of long-lived states opens the possibility to measure the energy difference between ns and np states — the Lamb shift.

Keywords: DIRAC experiment, elementary atom, hadronic atom, pion pion scattering, pion Kaon scattering

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1. Introduction

The DIRAC experiment aims to observe and study hydrogen-like atoms formed by pairs of $\pi^+\pi^-$ and $\pi^\pm K^\mp$ mesons using the 24 GeV extracted beam of PS CERN. The lifetime of these atoms is dictated by the strong interaction between the components. Thus combining of hadrons into a hydrogen-like atom opens a unique possibility to study a property of the strong interaction at the very low relative momenta which are of order of the atom Bohr momentum. For $\pi^+\pi^-$ atom it is 0.5 MeV, for πK — 0.8 MeV. Hence the region of QCD confinement becomes available for investigation.

The ground-state lifetime of $\pi^+\pi^-$ atom $\tau_{2\pi}$ is governed by the $\pi\pi$ S-wave scattering lengths a_I, with isospin $I = 0, 2$ [1, 2, 3]: $1/\tau_{2\pi} \propto |a_0 - a_2|^2$. For the πK atom the lifetime $\tau_{\pi K}$ depends on the πK S-wave scattering lengths with isospin 1/2 and 3/2 [4]: $1/\tau_{\pi K} \propto |a_{1/2} - a_{3/2}|^2$. The values of these scattering lengths can be rigorously calculated in Chiral Perturbation Theory (ChPT) [5, 6]. Thus the measurement of the hadronic hydrogen-like atom lifetimes provides an experimental test of the low-energy QCD perditions.

Moving after the production in the target, the $\pi^+\pi^-$ ($\pi^\pm K^\mp$) atoms may either decay into $\pi^0\pi^0$ ($\pi^0 K^0$, $\pi^0 \bar{K}^0$) or evolve by excitation (de-excitation) to different quantum states and finally decay or survive (long-lived states) or break up (be ionized) by the electric field of the target atoms [8]. In the case of breakup, characteristic "atomic pairs" emerge with a low relative momentum Q in their center of mass ($Q < 3\ MeV/c$), and small opening angle in the laboratory frame (< 3 mrad). These pairs are the subject of observation.

A high-resolution magnetic spectrometer ($\Delta p/p \sim 3 \cdot 10^{-3}$) is used [9] (Fig. 1) to identify the pairs and measure Q with sufficient precision to detect the pionium signal. This signal lies above a continuum background from free (unbound) "Coulomb pairs" produced from short lived sources ($\rho, \Delta \ldots$) . Other background sources are "non-Coulomb pairs" where one or both pions originate from a long-lived source ($\eta, \eta', \Lambda, \ldots$) and accidental coincidences from different proton-nucleus interactions.

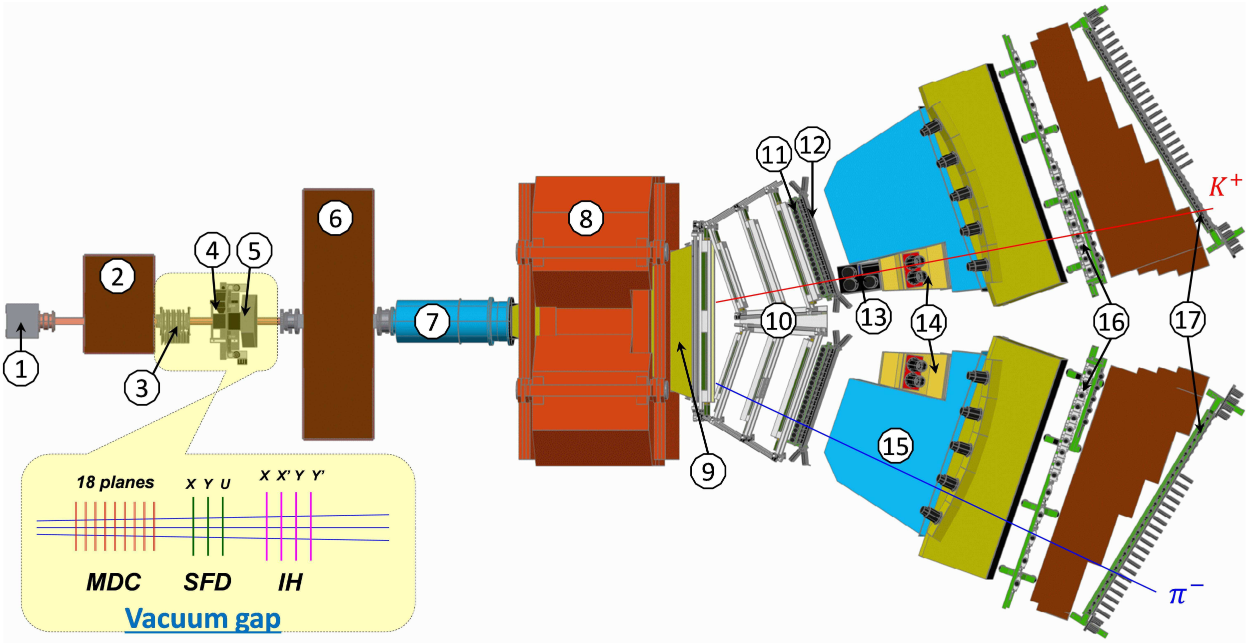

Figure 1: General view of the DIRAC setup: 1 – target station; 2 – first shielding; 3 – microdrift chambers; 4 – scintillating fiber detector; 5 – ionisation hodoscope; 6 – second shielding; 7 – vacuum tube; 8 – spectrometer magnet; 9 – vacuum chamber; 10 – drift chambers; 11 – vertical hodoscope; 12 – horizontal hodoscope; 13 – aerogel Cherenkov; 14 – heavy gas Cherenkov; 15 – nitrogen Cherenkov; 16 – preshower; 17 – muon detector.

2. Results

Basing on 2008–2010 data the collaboration has doubled the number of observed “atomic pairs” n_A (see Fig. 2) compared to the already published results [10]. Processing of these data is in progress. The final expected accuracy in $|a_0 - a_2|$ is about 3%.

Processing of the same data allows to extract 178 ± 49 πK “atomic pairs” (3.6σ significance) (see Fig 3) and to get the first estimation of its lifetime

$$\tau = \left(2.5^{+3.0}_{-1.8}\Big|_{\mathrm{stat}}\;{}^{+0.3}_{-0.1}\Big|_{\mathrm{syst}}\right)\mathrm{fs} = \left(2.5^{+3.0}_{-1.8}\Big|_{\mathrm{tot}}\right)\mathrm{fs}. \tag{1}$$

and evaluation of πK S-wave scattering length difference $1/3|a_{1/2} - a_{3/2}| = 0.107^{+0.09}_{-0.04}$ (see Fig 4) [11]. Details about number of observed “atomic pairs” n_A, number of produced atoms N_A and their breakup probability P_{br} for different year and atom types is given in Table 1.

The evaluation of the breakup probability P_{br} is affected by several sources of systematic errors [12]. Most of them are induced by imperfections in the simulation of the different πK pairs, the atomic, Coulomb, non-Coulomb and misidentified pairs. Shape differences of experimental and simulated distributions in the fit procedure lead to biases on parameters, including breakup probability. The influence of error sources is different for the (Q_T, Q_L) and Q_L analyses. Table 2 shows systematic errors common to $\pi^- K^+$ and $\pi^+ K^-$, collected from 2008 to 2010. Other sources of systematic errors are uncertainties of the experimental lab momentum spectra of πK and background pairs. These spectra have been measured individually for the different run periods, producing systematic errors $\sigma^{syst}_{\pi K}$ and σ^{syst}_{back} in P_{br} (Table 3). The presented systematic errors have been included in the above estimation of πK atom lifetime.

During the 2011–2012 data taking DIRAC had as objective the observation of long-lived states of $\pi^+\pi^-$ atoms [13]. The long-lived states are the states with non-zero orbital momenta, for which the strong interaction is suppressed. As result the lifetime and mean path of such states are a few order higher compared to the ground state. For example at $\gamma = 17$ the mean paths of 2p and 3p states are 5.7 cm and 19 cm correspondingly, compared to 0.02 mm for the ground state. To observe the objects with such macroscopic path, behind the Beryllium foil of 100 μm installed in the primary proton beam, we have placed a Platinum foil of $2\mu m$ over the primary beam at the distance of 10 cm between them. The long-lived states of $\pi^+\pi^-$ atoms produced in the Beryllium then break up in the Plat-

Table 1: Results for N_A (number of produced atoms), n_A (number of "atomic pairs") and P_{br} (breakup probability) by analysing 2-dimensional (Q_T, Q_L) and 1-dimensional (Q_L) distributions.

Year	N_A	n_A	P_{br}
$\pi^- K^+$ over Q_T, Q_L			
2008	132 ± 16	14 ± 19	0.11 ± 0.15
2009	169 ± 24	33 ± 26	0.20 ± 0.17
2010	164 ± 23	49 ± 26	0.30 ± 0.19
$\pi^- K^+$ over Q_L			
2008	125 ± 19	25 ± 30	0.20 ± 0.26
2009	151 ± 28	54 ± 42	0.36 ± 0.33
2010	155 ± 28	61 ± 42	0.39 ± 0.32
$\pi^+ K^-$ over Q_T, Q_L			
2008	51 ± 11	21 ± 13	0.41 ± 0.33
2009	77 ± 13	26 ± 16	0.34 ± 0.24
2010	60 ± 12	35 ± 16	0.58 ± 0.36
$\pi^+ K^-$ over Q_L			
2008	47 ± 13	35 ± 21	0.75 ± 0.62
2009	76 ± 15	28 ± 24	0.37 ± 0.37
2010	83 ± 15	-4 ± 22	-0.04 ± 0.26

inum resulting in observation of extra "atomic pairs" (see Fig 5). For significant suppression of the background of $\pi^+\pi^-$ pairs produced in the first foil a permanent magnet of 0.02 Tm bending power had been placed between the foils. The distribution of detected $\pi^+\pi^-$ pairs over longitudinal component of relative momentum Q_L with polynomial-fitted background is shown on Fig 6. Zero at this distribution is shifted by 2.5 MeV/c to account the residual field of the permanent magnet which goes behind the Platimun foil. The transverse component of the relative momentum was cutted as $Q_T = \sqrt{Q_x^2 + (Q_y - 2.5\,\mathrm{MeV}/c)^2} < 1.5\,\mathrm{MeV}/c$ The peak at zero with significance of 5σ is expected to originate form breakup of the long-lived $\pi^+\pi^-$ atoms inside the Platinum foil.

Table 2: Systematic errors in P_{br} common to all data collected from 2008 to 2010.

Sources of systematic errors	$\sigma^{\text{syst}}_{Q_T,Q_L}$	$\sigma^{\text{syst}}_{Q_L}$
Uncertainty in Λ width correction	$3.9 \cdot 10^{-3}$	$7.1 \cdot 10^{-3}$
Uncertainty of multiple scattering in Ni target	$3.2 \cdot 10^{-3}$	$5.4 \cdot 10^{-4}$
Accuracy of SFD simulation	$7.5 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$
Correction of Coulomb correlation function on finite size production region	$5.8 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
Uncertainty in $P_{br}(\tau)$ dependence	$5.0 \cdot 10^{-3}$	$5.0 \cdot 10^{-3}$
Uncertainty in target thickness	$3.0 \cdot 10^{-4}$	$< 3.0 \cdot 10^{-4}$

Table 3: Systematic errors in P_{br} specific to the data samples collected in 2008, 2009 and 2010.

Year	$\sigma^{\text{syst}}_{\pi K}$	$\sigma^{\text{syst}}_{\text{back}}$
$K^+\pi^-$ over Q_T, Q_L		
2008	0.0028	0.0015
2009	0.0044	0.0025
2010	0.0036	0.0022
$K^+\pi^-$ over Q_L		
2008	0.0030	0.0028
2009	0.0053	0.0044
2010	0.0046	0.0036
$\pi^+ K^-$ over Q_T, Q_L		
2008	0.0072	0.0067
2009	0.0048	0.0028
2010	0.0017	0.0043
$\pi^+ K^-$ over Q_L		
2008	0.0093	0.0072
2009	0.0047	0.0048
2010	0.0021	0.0017

For the future, DIRAC plans to continue the experiment at the SPS CERN accelerator. We expect to gain about 20 in the detection rate of $\pi^+\pi^-$ and πK atoms.

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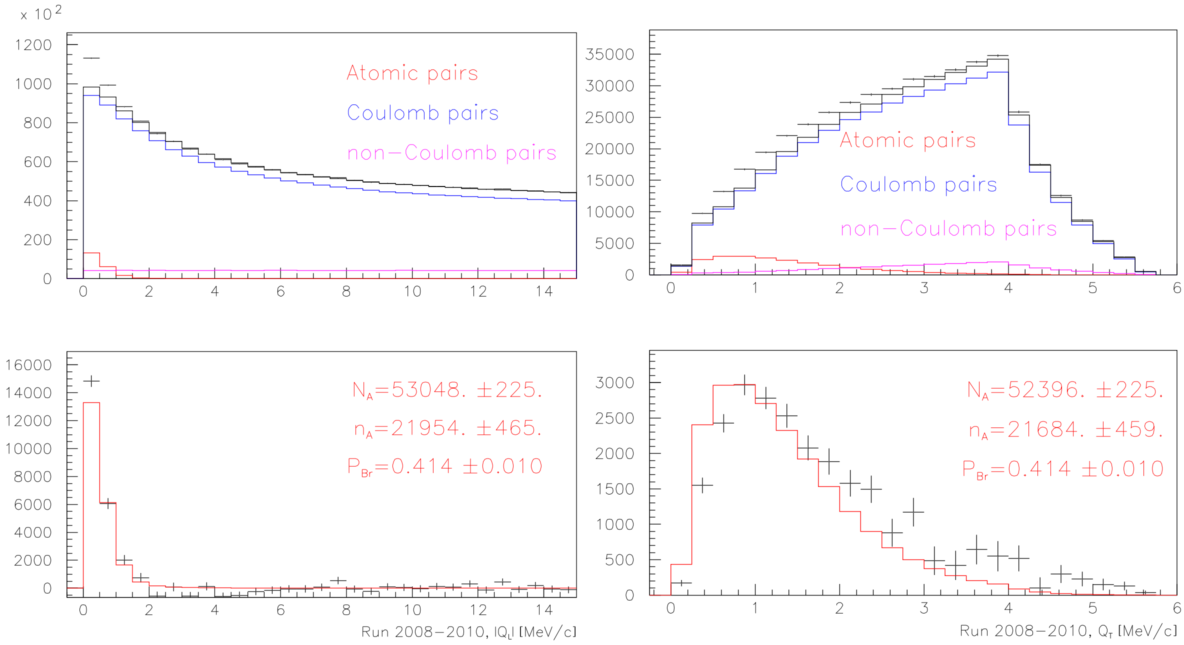

Figure 2: Upper: experimental distributions of $\pi^+\pi^-$ pairs (points with error bars) over the longitudinal (Q_L) (left) and transverse (Q_T) (right) components of the pair CMS relative momentum Q, are fitted by a sum of simulated distributions of “atomic”, “Coulomb” and “non-Coulomb” pairs. Free pairs (“Coulomb” and “non-Coulomb”) shown by black line. Lower: difference of experimental and simulated distribution of “free” pairs comparing with simulated distributions of “atomic pairs”

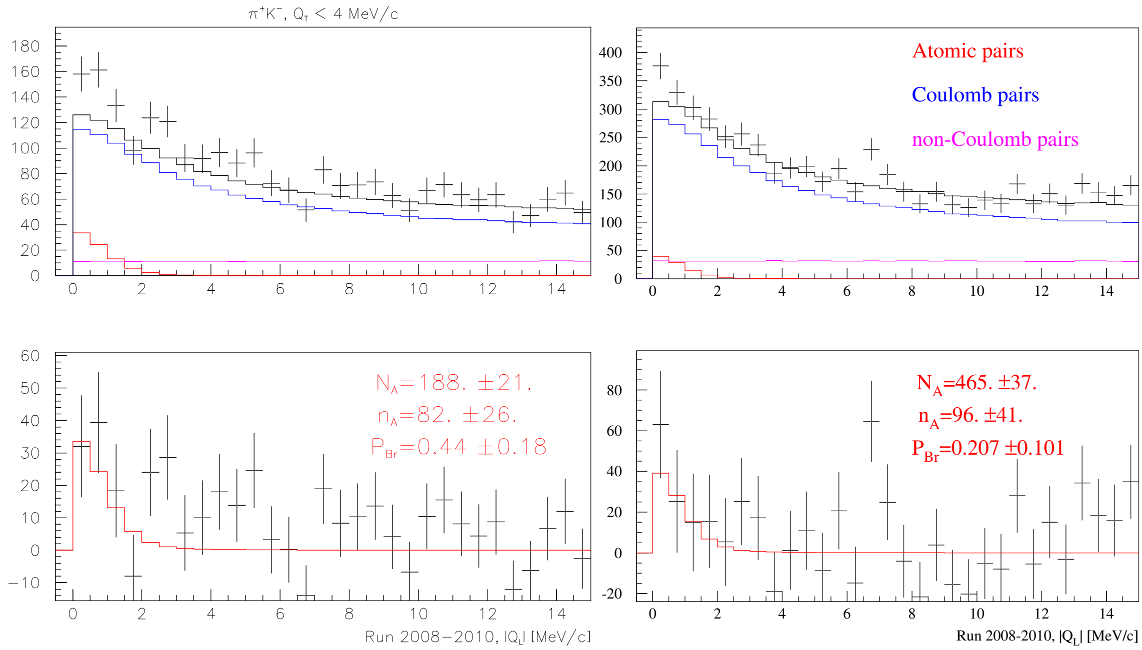

Figure 3: Upper: experimental distribution over the longitudinal components of the pair CMS relative momentum (Q_L) of π^+K^- pairs (left) (points with error bars) and $K^+\pi^-$ (right) are fitted by a sum of simulated distributions of “atomic”, “Coulomb” and “non-Coulomb” pairs. Free pairs (“Coulomb” and “non-Coulomb”) shown by black line. Lower: difference of experimental and simulated distribution of “free” pairs comparing with simulated distributions of “atomic pairs”.

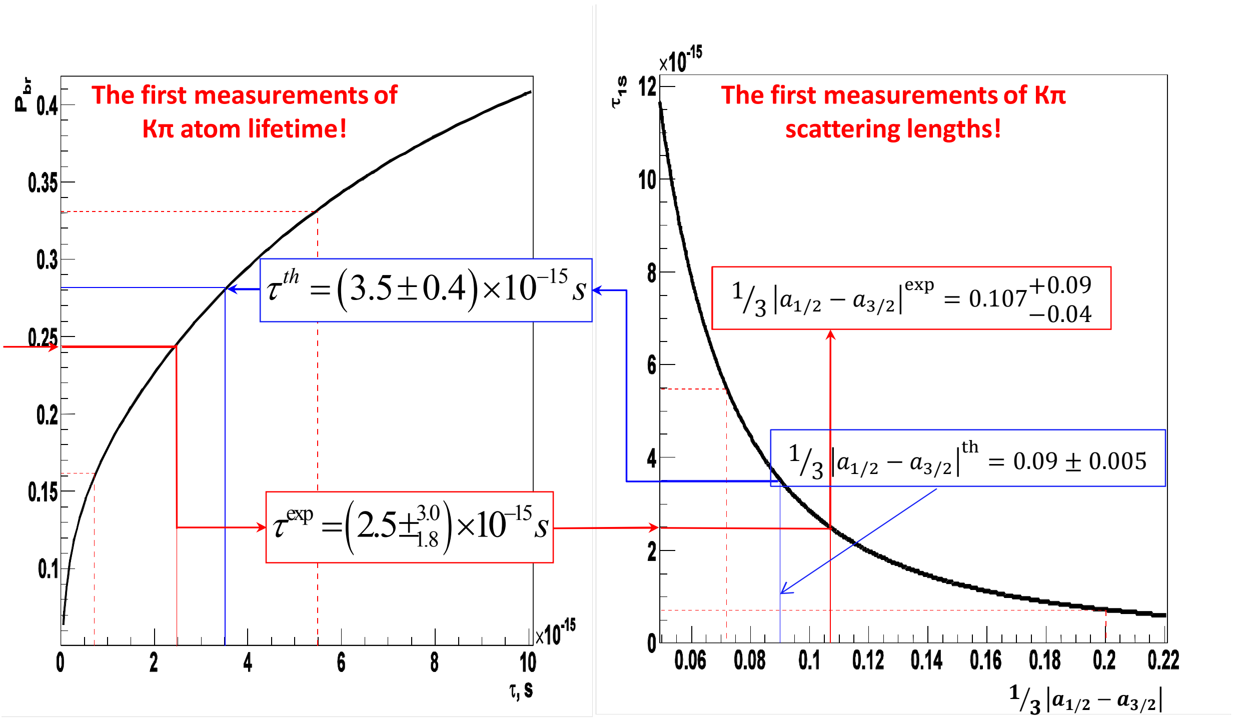

Figure 4: Left: Probability of πK atom breakup as a function its lifetime allows extracting the lifetime from the experimental value the breakup probability (red line) and compare with the theoretical prediction (blue line).
Right: Dependence of the lifetime on the scattering lengths allows extracting the result for the scattering lengths.

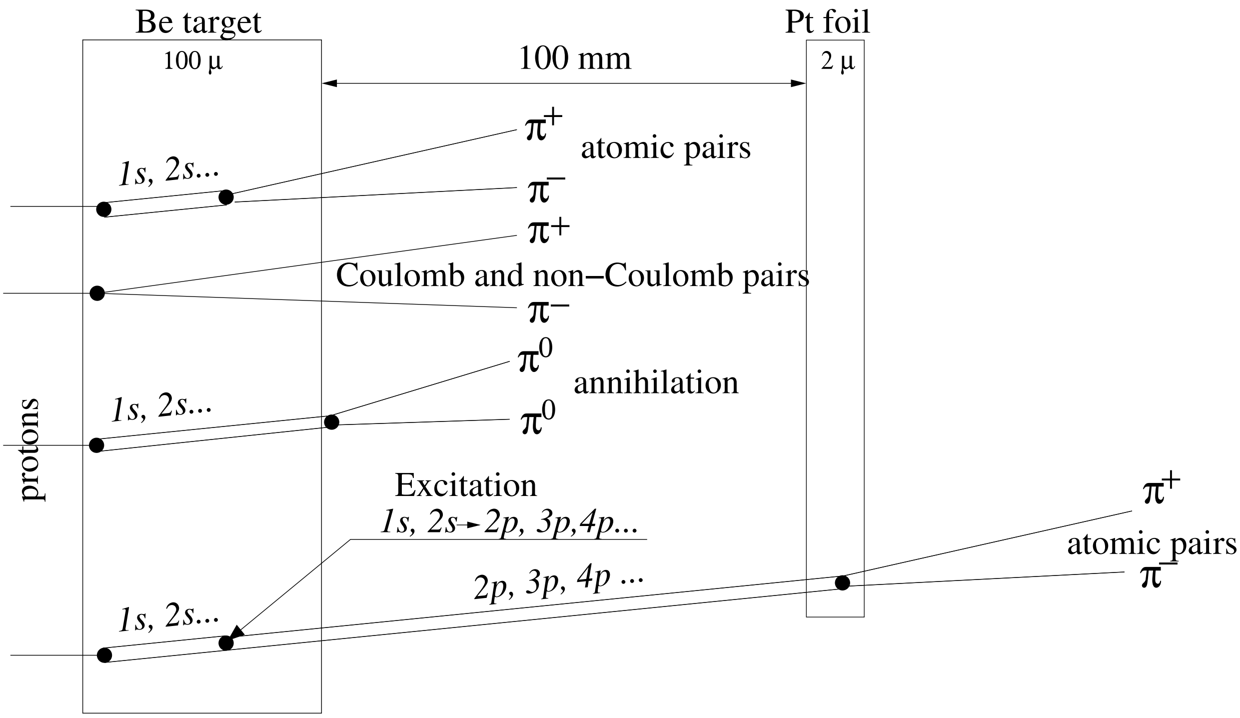

Figure 5: Method to observe long-lived states of $\pi^+\pi^-$ atoms by means of a breakup foil (Pt).

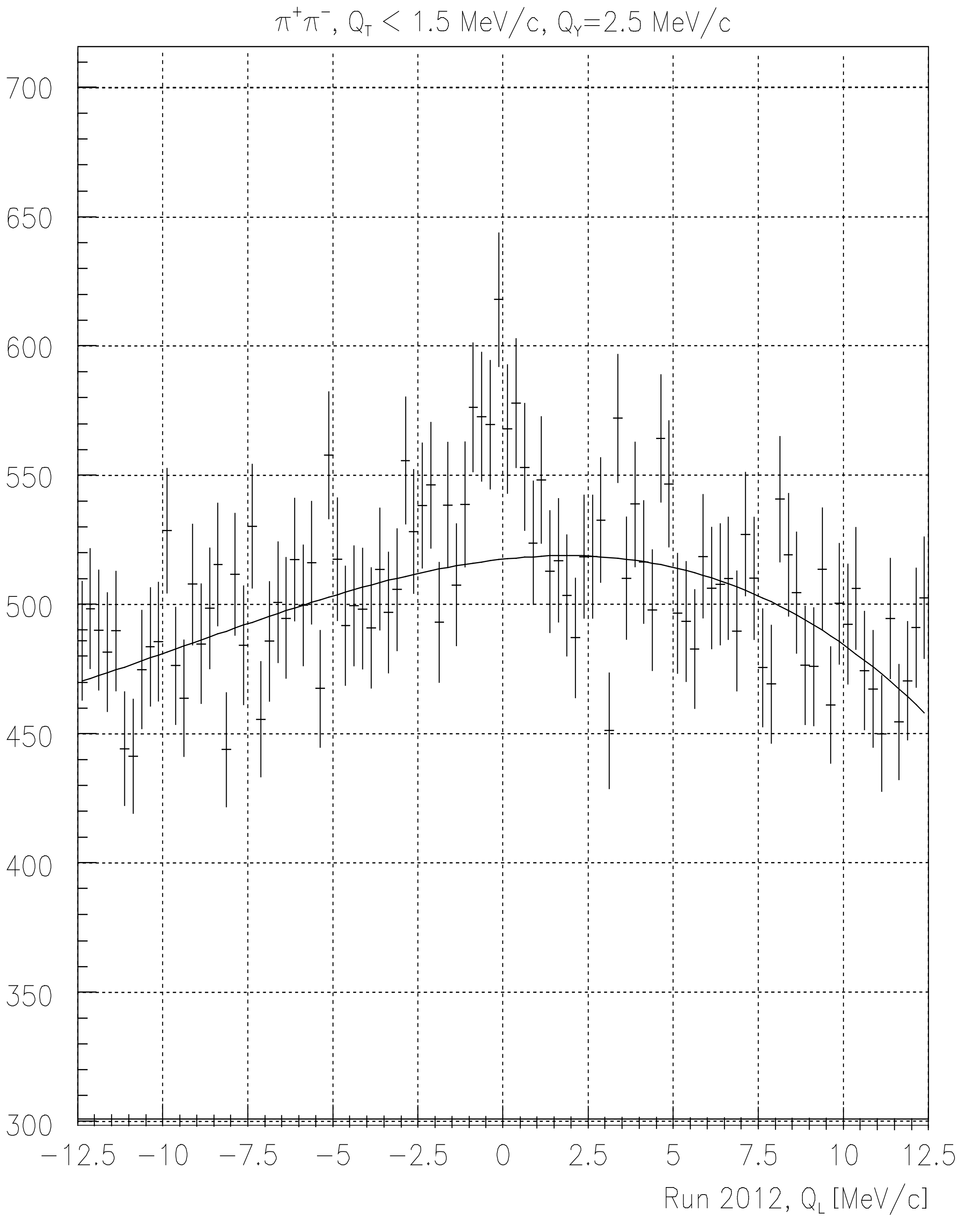

Figure 6: Distribution of $\pi^+\pi^-$ pairs over longitudinal component of relative momentum Q_L with polynomial-fitted background. The peak at zero at the level of 5σ is expected to be originate form breakup of the long-lived $\pi^+\pi^-$ atoms inside the Platinum foil of 2 μm placed at 100 mm behind the primary Beryllium target.