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

Leonid AFANASYEV
JOINT INSTITUTE FOR NUCLEAR RESEARCH

on behalf of the DIRAC collaboration

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DIRAC collaboration

CERN
Geneva, Switzerland

Czech Technical University
Prague, Czech Republic

Institute of Physics ASCR
Prague, Czech Republic

Nuclear Physics Institute ASCR
Rez, Czech Republic

INFN-Laboratori Nazionali di Frascati
Frascati, Italy

University of Messina
Messina, Italy

KEK
Tsukuba, Japan

Kyoto Sangyo University
Kyoto, Japan

Kyoto University
Kyoto, Japan

Tokyo Metropolitan University
Tokyo, Japan

IFIN-HH
Bucharest, Romania

JINR
Dubna, Russia

SINP of Moscow State University
Moscow, Russia

IHEP
Protvino, Russia

Santiago de Compostela University
Santiago de Compostela, Spain

Bern University
Bern, Switzerland

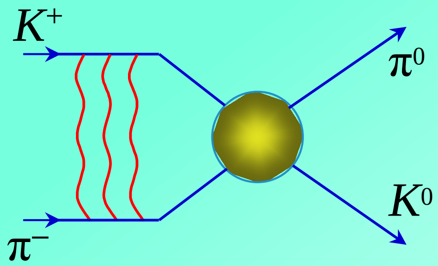
Zurich University
Zurich, Switzerland

totally 68 physicists from 20 Institutes

$K^+\pi^-$ and $K^-\pi^+$ atoms lifetime

$K\pi$-atom ($A_{K\pi}$) is a hydrogen-like atom consisting of $K^{\pm}$ and $\pi^{\mp}$ mesons:

$E_B = -2.9$ keV $r_B = 249$ fm $p_B = 0.79$ MeV



The $K\pi$-atom lifetime ground state 1S, $\tau=1/\Gamma$ is dominated by the annihilation process into $K^0\pi^0$:

$$A_{K^+\pi^-} \to \pi^0 K^0$$
$$A_{\pi^+K^-} \to \pi^0 \overline{K}^0$$

$$\frac{1}{\tau} = \frac{8}{9}\alpha^3\mu^2 p^*\left(a_{1/2} - a_{3/2}\right)^2(1+\delta_K)$$

$\mu = 109\ \mathrm{MeV}/c^2$

$p^* = 11.8\ \mathrm{MeV}/c$

$\delta_k = 0.040 \pm 0.022$

[S.Bilenky et al., Sov. J. Nucl. Phys. 10 (1969) 469]
[J. Schweizer, Phys. Lett. B 587 (2004) 33]

SU(3) ChPT predictions [J. Bijnens et al. JHEP 0405 (2004) 036]

$$\frac{1}{3}M_\pi\left(a_{1/2} - a_{1/3}\right) = M_\pi a_0^- = 0.071(CA) \to 0.079(1l) \to 0.89(2l)$$
$$\to 0.090 \pm 0.005(\text{dispersion}) \to \tau = (3.5 \pm 0.4) \times 10^{-15}\mathrm{s}$$

[P.Buttiker et al., Eur. Phys. J. C33 (2004) 409]

Lattice QCD calculations of ChPT low energy constant

[NPLQCD, Phys. Rev. D74 (2006) 114503] $M_\pi a_0^- = 0.077 \pm 0.001^{+0.002}_{-0.005}$

[Z.Fu, Phys. Rev. D85 (2012) 074501] $M_\pi a_0^- = 0.0777 \pm 0.0013 \pm ?$

[C.B. Lang et al., Phys. Rev. D86 (2012) 054508] $M_\pi a_0^- = 0.0811 \pm 0.0143$

πK scattering

What new will be known if πK scattering length will be measured?

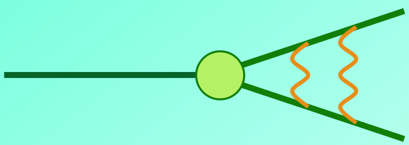
The measurement of the s-wave πK scattering lengths would test our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of *QCD* (u, d and s quarks), while the measurement of $\pi\pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking (u, d quarks).

This is the principal difference between $\pi\pi$ and πK scattering!

Experimental data on the πK low-energy phases are absent

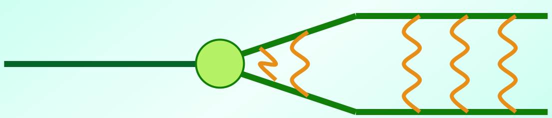
Coulomb pairs and atoms

For the charged pairs from the short-lived sources and small relative momentum Q there is strong Coulomb interaction in the final state. This interaction increases the production yield of the free pairs with Q decreasing and creates atoms.



$\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, K^+K^-, $\pi^+\mu^-$, $\pi^-\mu^+$

Coulomb pairs



$(\pi^+\pi^-)$, $(K^+\pi^-)$, $(K^-\pi^+)$, (K^+K^-), $(\pi^+\mu^-)$, $(\pi^-\mu^+)$

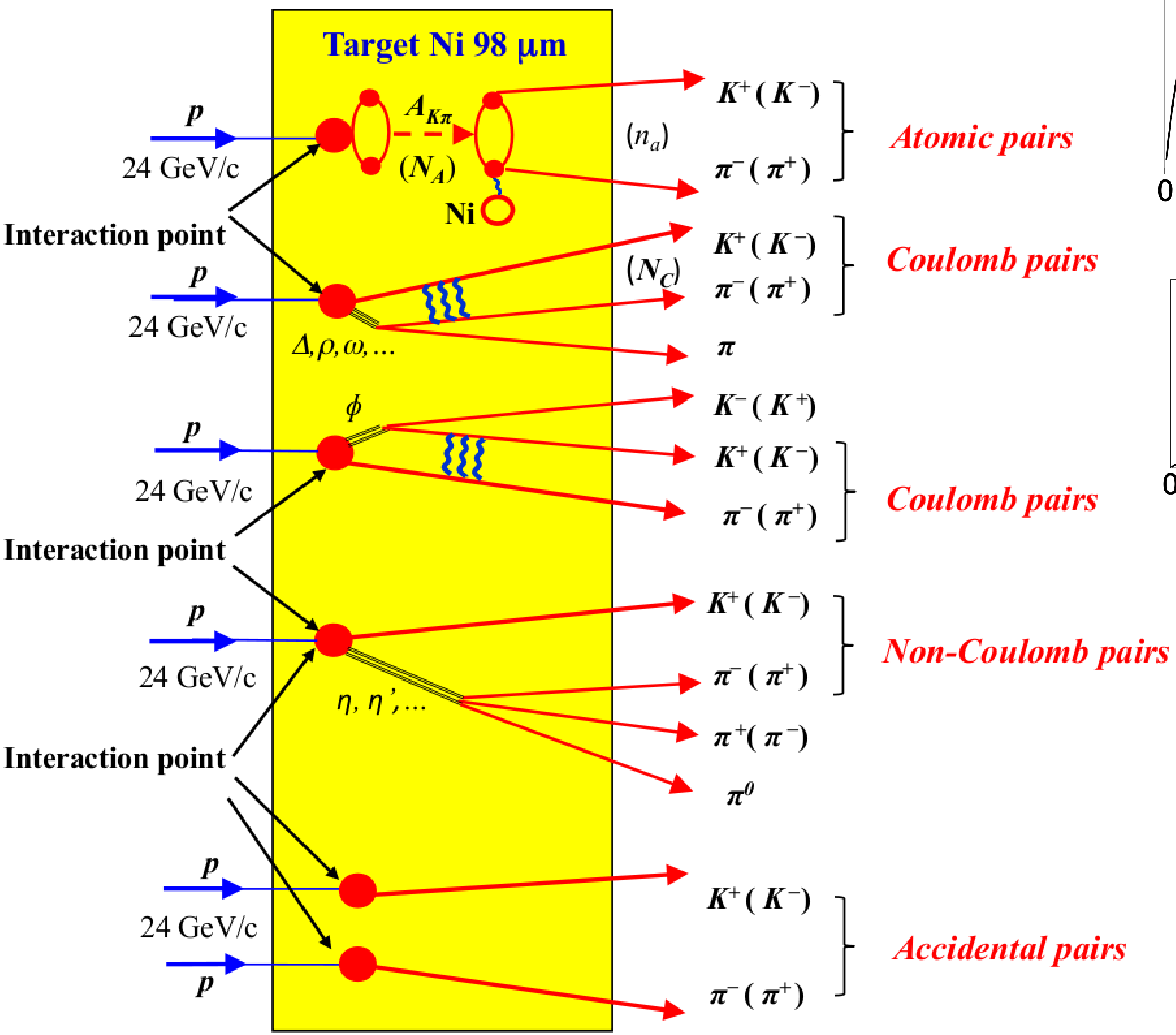
Atoms

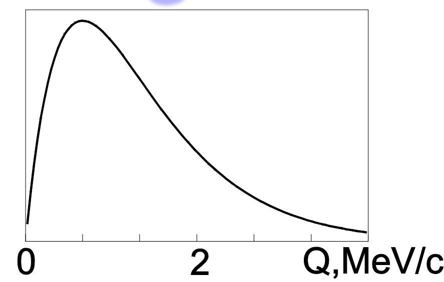
There is precise ratio between the number of produced Coulomb pairs (N_C) with small Q and the number of atoms (N_A) produced simultaneously with these Coulomb pairs:

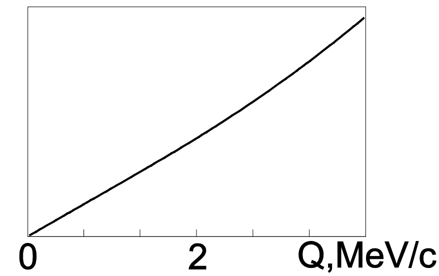
$$N_A = K(Q_0) N_C (Q \le Q_0), \quad \frac{\delta K(Q_0)}{K(Q_0)} \le 10^{-2}$$

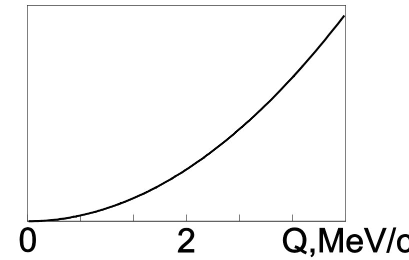
$$n_A \text{ - atomic pairs number,} \quad P_{br} = \frac{n_A}{N_A}$$

Method of Kπ atom observation and investigation





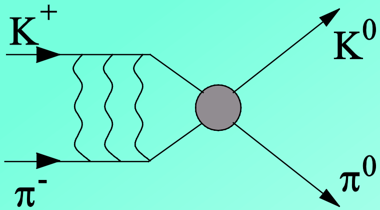




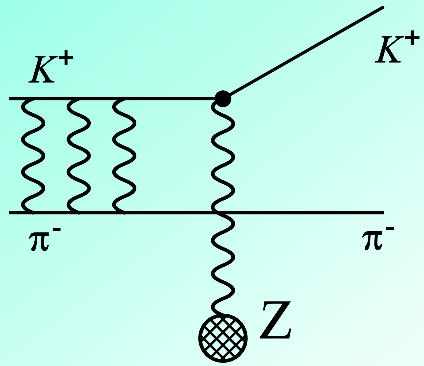
Break-up probability

During propagation in matter $A_{\pi K}$:

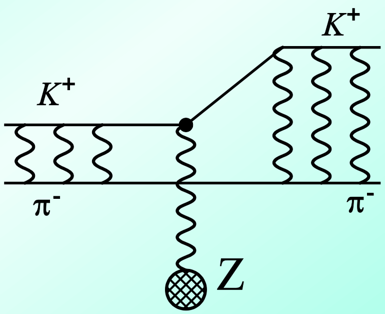
annihilate

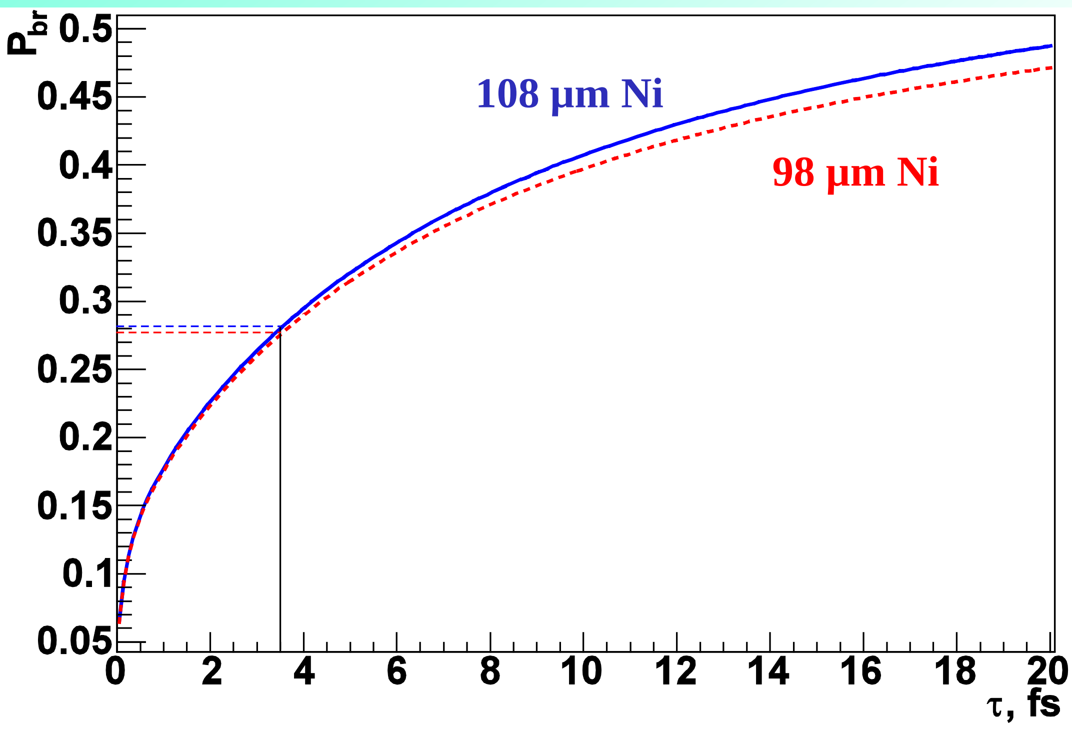


break up(ionized)



excitate

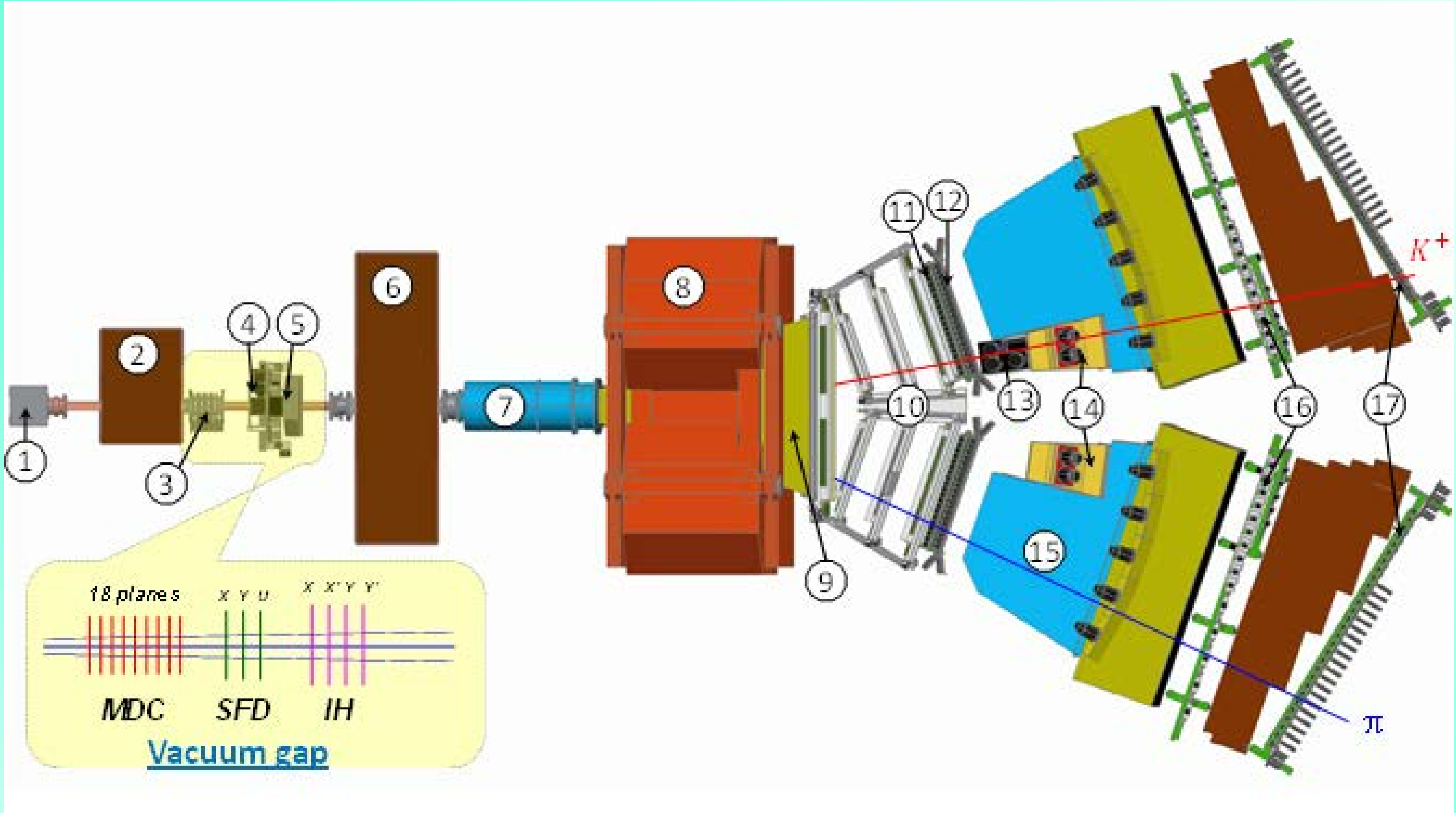




Solution of the transport equations for atomic level populations provides one-to-one dependence of the measured break-up probability (P_{br}) on atom lifetime τ.

Accuracy of P_{br} is better than

Experimental setup



1 Target station with Ni foil; 2 First shielding; 3 Micro Drift Chambers; 4 Scintillating Fiber Detector; 5 Ionization Hodoscope; 6 Second Shielding; 7 Vacuum Tube; 8 Spectrometer Magnet; 9 Vacuum Chamber; 10 Drift Chambers; 11 Vertical Hodoscope; 12 Horizontal Hodoscope; 13 Aerogel Čerenkov; 14 Heavy Gas Čerenkov; 15 Nitrogen Čerenkov; 16 Preshower; 17 Muon Detector

Experimental conditions

SFD			
Coordinate precision	$\sigma_X = 60\ \mu m$	$\sigma_Y = 60\ \mu m$	$\sigma_W = 120\ \mu m$
Time precision	$\sigma^t_X = 380$ ps	$\sigma^t_Y = 512$ ps	$\sigma^t_W = 522$ ps

DC	
Coordinate precision	$\sigma = 85\ \mu m$

VH	
Time precision	$\sigma = 100$ ps

Spectrometer		
Relative resolution on the particle momentum in L.S.	$3 \cdot 10^{-3}$	
Precision on Q-projections	$\sigma_{QX} = \sigma_{QY} = 0.5$ MeV/c	$\sigma_{QL} = 0.5$ MeV/c ($\pi\pi$) $\sigma_{QL} = 0.9$ MeV/c (πK)

Trigger efficiency 98 %	for pairs with $Q_L < 28$ MeV/c $Q_X < 6$ MeV/c $Q_Y < 4$ MeV/c

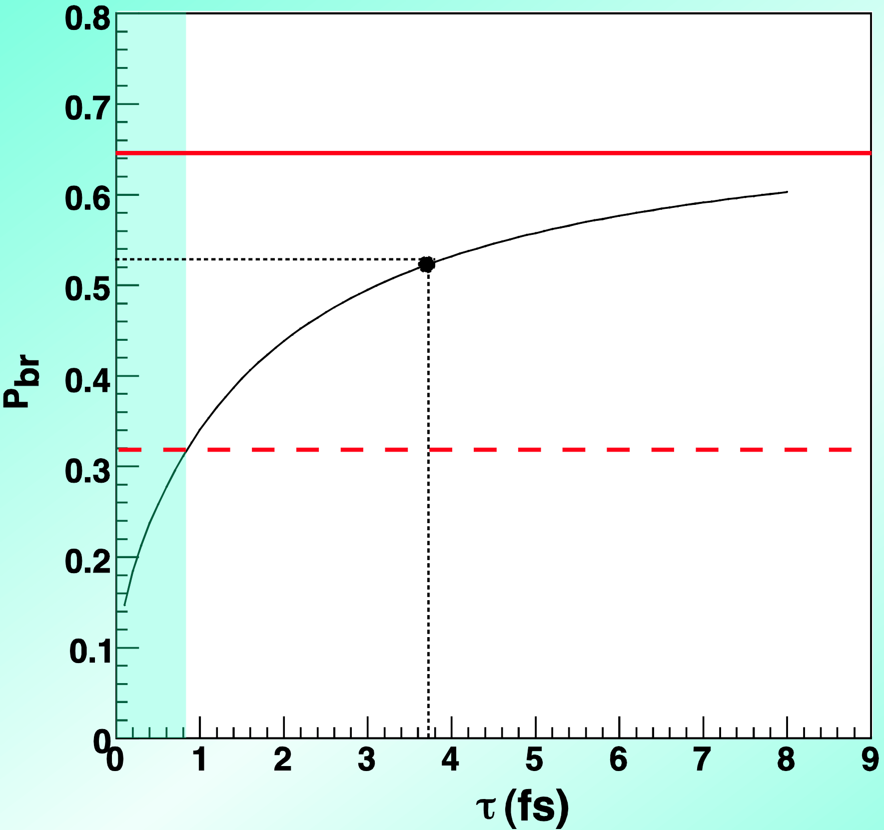
First evidence for πK atoms

2007, Platinum target 28μm:

$$n_A(\pi^- K^+) = 143 \pm 53, \qquad n_A(\pi^+ K^-) = 29 \pm 15$$

Evidence for πK -atoms observation with DIRAC

[Adeva et al. (DIRAC Collaboration) Phys. Lett. B674 (2009) 11]



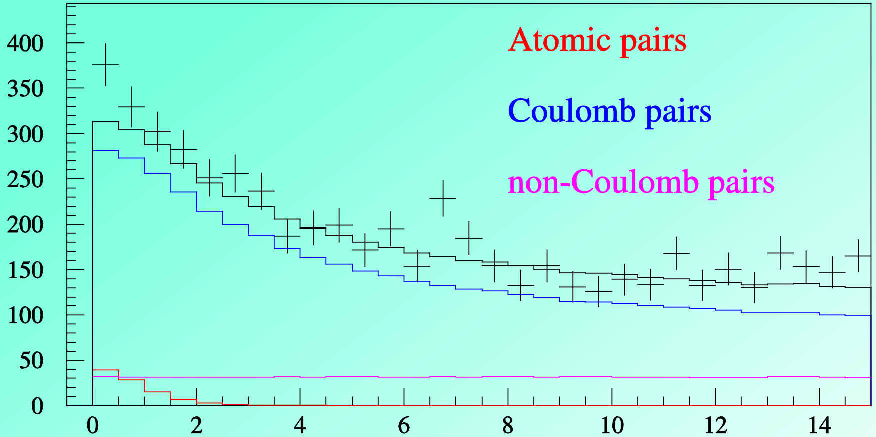
$$n_A(\pi^+ K^- + \pi^- K^+) = 173 \pm 54\ (3.2\sigma)$$

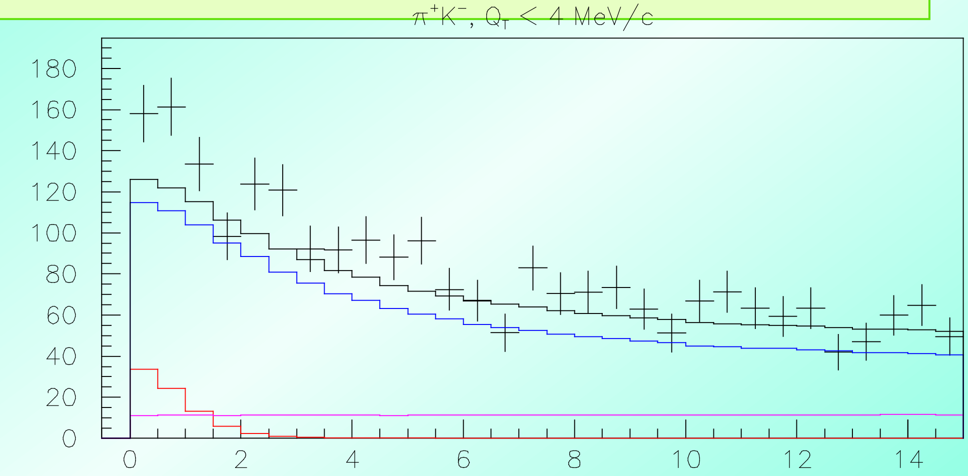
$$N_A(\pi^+ K^- + \pi^- K^+) = kN_c = 280 \pm 70$$

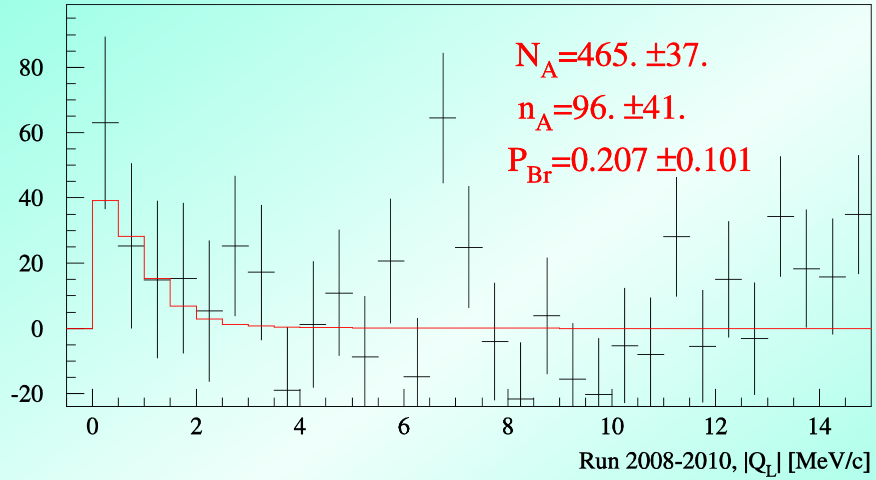
$\tau > 0.8 \times 10^{-15}s$ **(CL=0.9)**

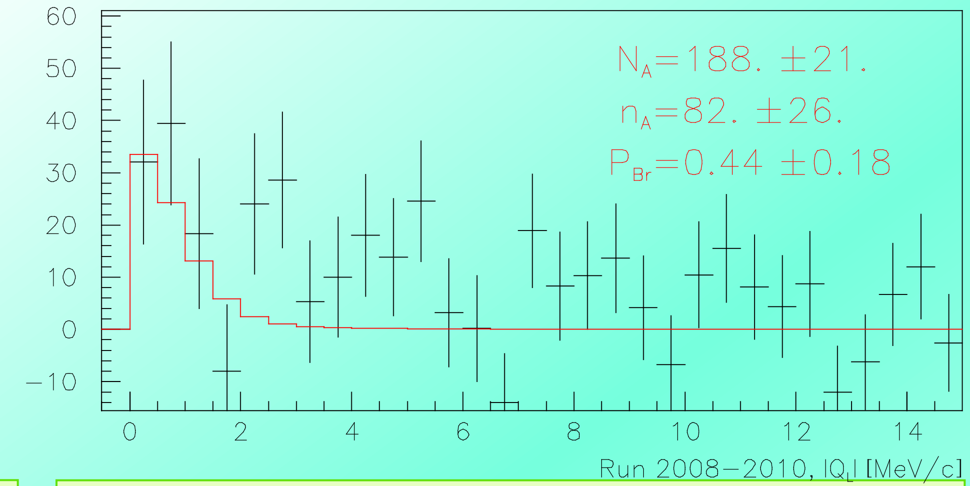
2008-2010 data

Run 2008-2010, statistics with low and medium background (2/3 of all statistics)
100 μm Nickel taget









$K^+\pi^-$ atoms, $|Q_L|$ distribution
analysis on $|Q_L|$ and Q_T for $Q_T < 4$ MeV/c

$K^-\pi^+$ atoms, $|Q_L|$ distribution
analysis on $|Q_L|$ and Q_T for $Q_T < 4$ MeV/c

$K^+\pi^-$ and $K^-\pi^+$ pairs analysis

Year	N_A	n_A	P_{br}
	$K^+\pi^-$		
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
All	465±37	96±41	
	$K^-\pi^+$		
2008	51±11	21±13	0.41±0.33
2009	78±13	26±16	0.34±0.24
2010	60±12	35±16	0.58±0.36
All	188±21	82±26	

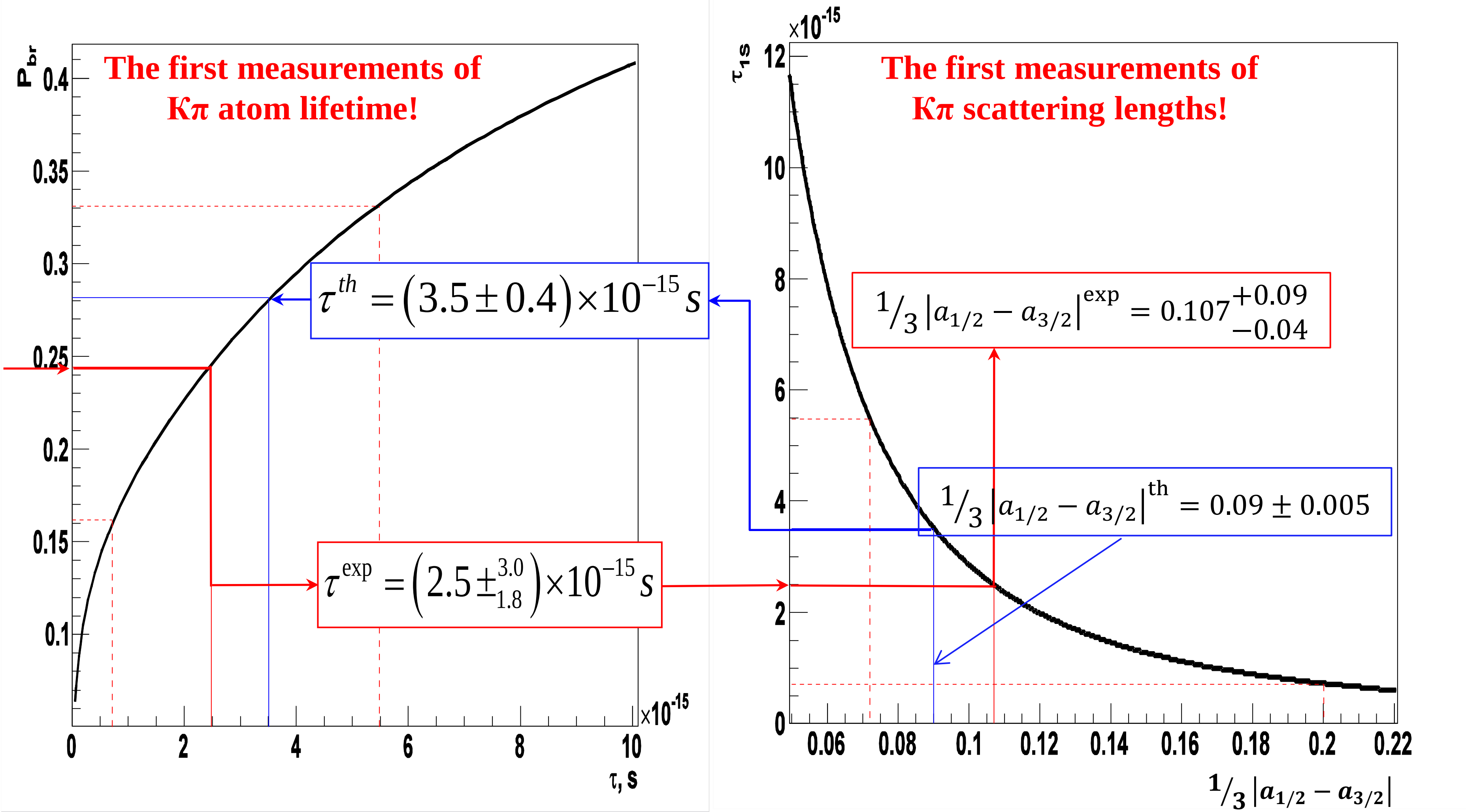
$$n_A(\pi^+K^- + \pi^-K^+) = 178 \pm 49 \ (3.6\sigma)$$

$$\tau = \left(2.5^{+3.0}_{-1.8}|\text{stat}\ ^{+0.3}_{-0.1}|\text{syst}\right) \times 10^{-15}\text{s} = \left(2.5^{+3.0}_{-1.8}|\text{tot}\right)\ \text{fs}$$

[DIRAC, subm. Phys. Lett. B (2014), CERN-PH-EP-2014-030, arXiv:1403.0845]

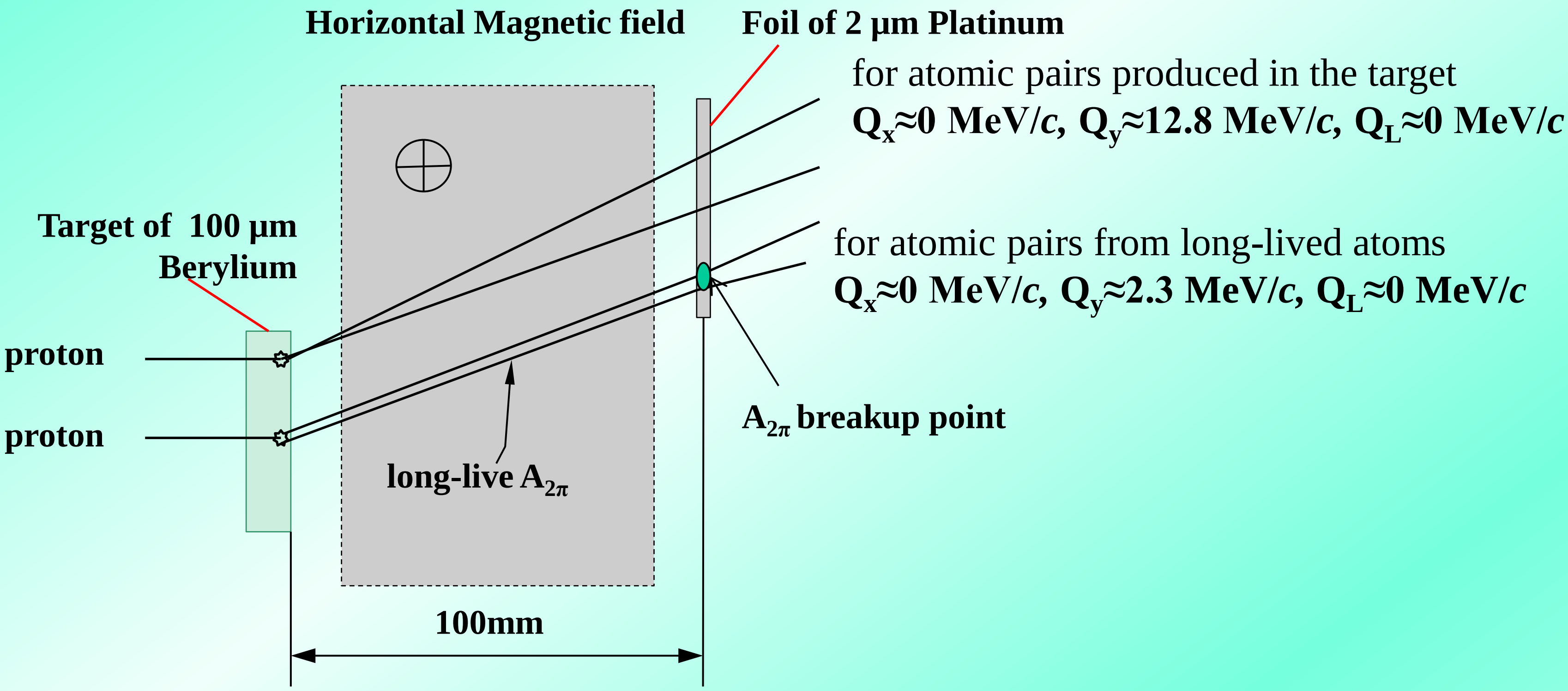
The first measurements of Kπ atom lifetime and Kπ scattering lengths

Basing on 178±49 detected atomic pairs and 653±42 produced atoms we get the first results.

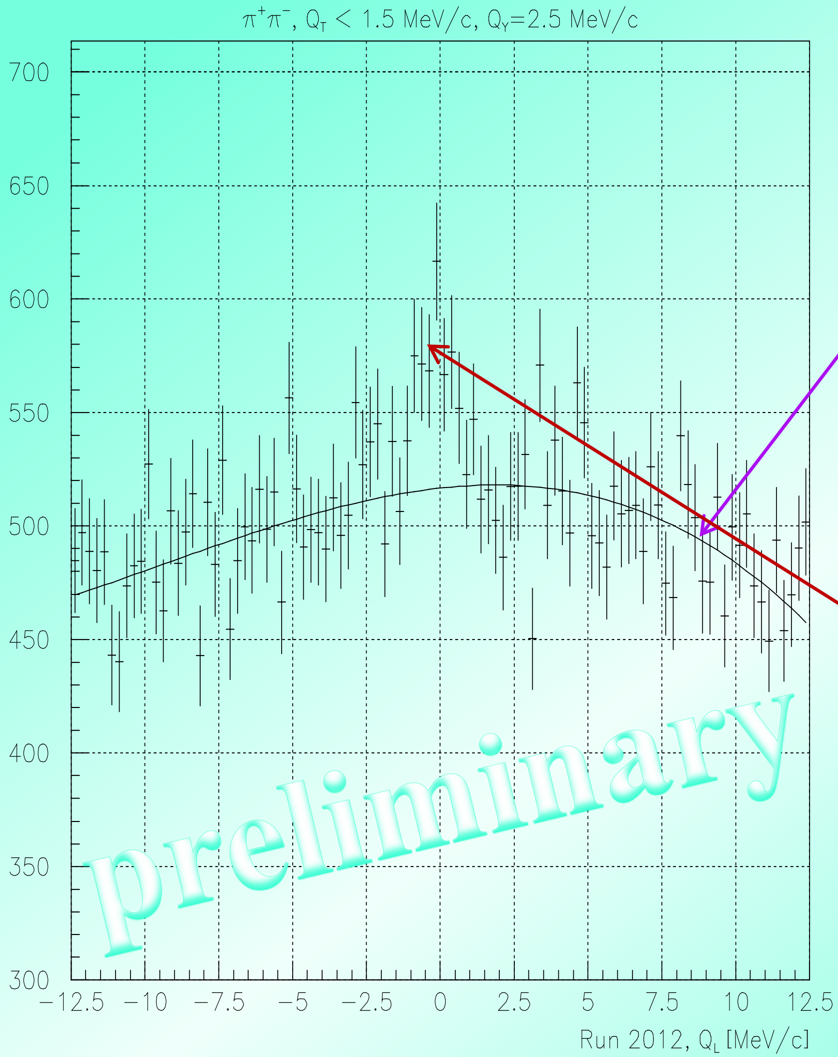


Search for long-lived states of π+π− atoms

During 2011-2012 the data were collected for observation of the long-lived states of $\pi^+\pi^-$ atom. This observation opens the future possibility to measure the energy difference between ns and np states ΔE(ns-np) and the value of ππ scattering length combination $|2a_0+a_2|$.



Search for long-lived states of π+π− atoms



Distribution of $\pi^+\pi^-$ pairs over longitudinal component of relative momentum Q_L with polynomial-fitted background. Cut

$$Q_t = \sqrt{Q_x^2 + (Q_y - 2.5\text{MeV}/c)^2} < 1.5\ \text{MeV}/c$$

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 100mm behind the primary target.

Experiment DIRAC at SPS CERN

In 2013 DIRAC setup has been dismantled from the experimental hall of PS CERN. All detectors are stored for using in the future experiment.

DIRAC collaboration is planning to continue investigation of π^-K^+, π^+K^- and $\pi^+\pi^-$ atoms at SPS accelerator at CERN. The correspondent gains in production rates of these atoms at SPS relative to PS (450 GeV vs. 24 GeV) are 18, 24 and 12. This allows to increase significantly the collected data and to check the precise prediction of Low-Energy QCD at a higher accuracy. Now the collaboration is planning to submit the Letter of Intend for study πK and $\pi^+\pi^-$ atoms at SPS to SPSC CERN.

Results and Outlook

- **Evidence for $\pi^{\pm}K^{\mp}$ atoms on Pt and Ni targets**

  Pt: $n_A = 173 \pm 54$, Ni: $n_A = 178 \pm 49$
- **First measurement of $A_{\pi K}$ lifetime**

  $$\tau = \left(2.5^{+3.0}_{-1.8}\big|_{\text{tot}}\right)\ \text{fs}$$

Main tasks for DIRAC:

- **Analysis of Pt and Ni data to achieve $A_{\pi K}$ observation**
- **Improve precision in pionium lifetime measurement**
- **Observation of long-lived states of $\pi^{+}\pi^{-}$ atoms**
- **Looking forward higher beam momenta (SPS 450 GeV/c)**

Thank you
for your attention!