Study of hadronic hydrogen-like atoms in DIRAC experiment at PS CERN

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DIRAC collaboration

DImeson Relativistic Atomic Complexes

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Santiago de Compostela University
Santiago de Compostela, Spain

Bern University
Bern, Switzerland

Zurich University
Zurich, Switzerland

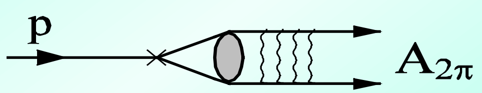
totally 68 physicists from 20 Institutes

Production of pionium

Atoms are Coulomb bound state of two pions produced in one proton-nucleus collision

Nemenov 1985

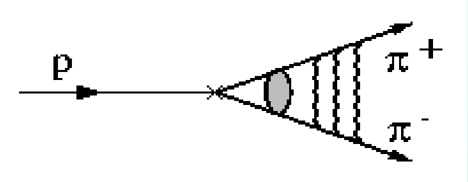
$$\frac{d\sigma_{nlm}^{A}}{d\vec{P}} = (2\pi)^3 \frac{E_A}{M_A} \left|\psi_{nlm}^{(C)}(0)\right|^2 \frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}\bigg|_{\vec{p}_+=\vec{p}_-} \qquad \sigma_A = k\sigma_C(Q<Q_0)$$



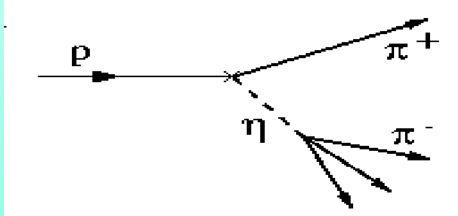
Background processes:

Coulomb pairs. They are produced in one proton nucleus collision from fragmentation or short lived resonances and exhibit Coulomb interaction in the final state

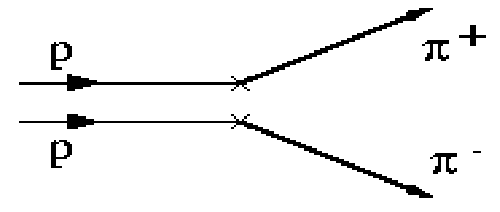
$$\frac{d^2\sigma_C}{d\vec{p}_+ d\vec{p}_-} = A_C(q)\frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}, \qquad A_C(q) = \frac{2\pi m_\pi \alpha / q}{1-\exp(-2\pi m_\pi \alpha / q)}$$



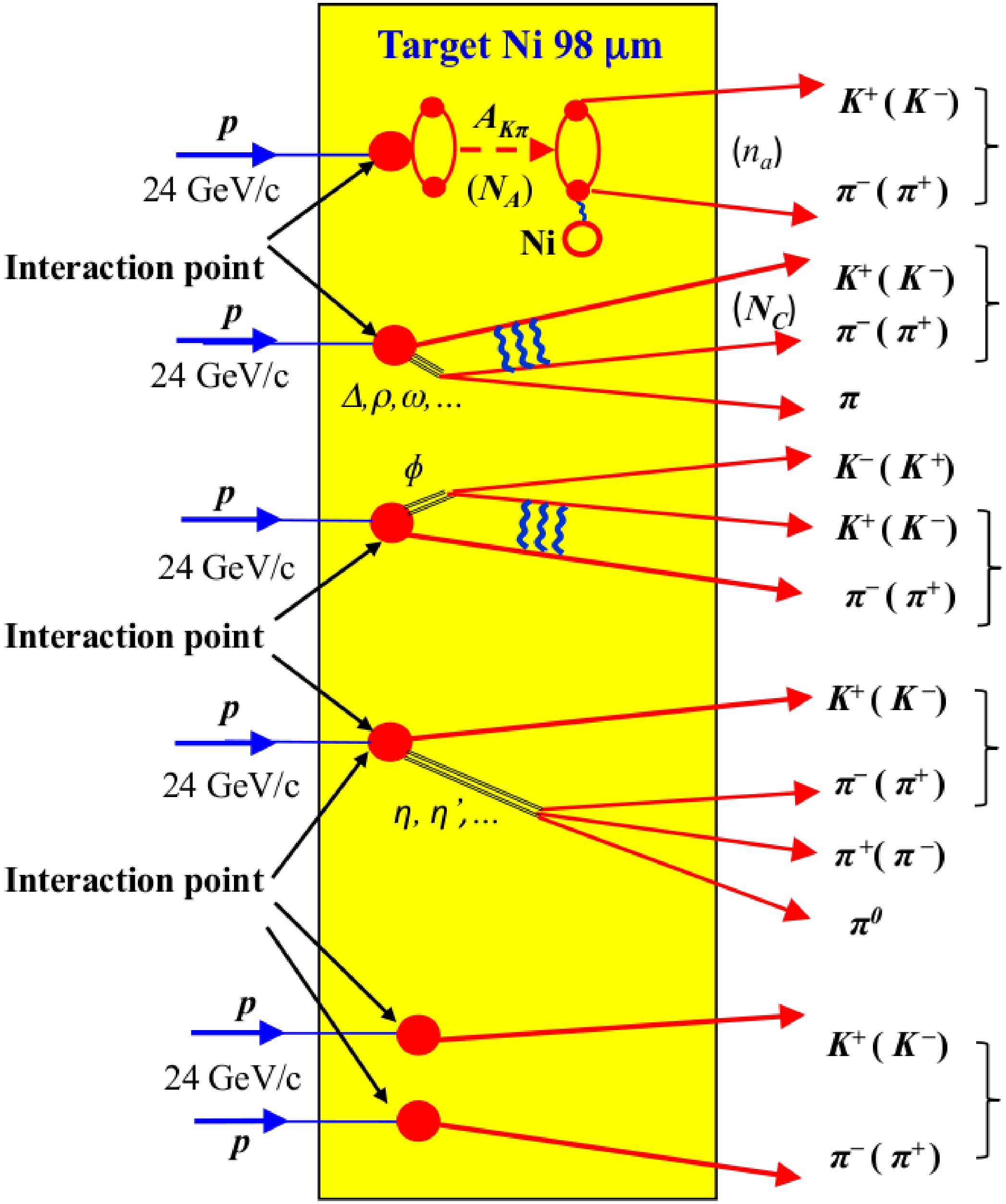
Non-Coulomb pairs. They are produced in one proton nucleus collision. At least one pion originates from a long lived resonance. No Coulomb interaction in the final state



Accidental pairs. They are produced in two independent proton nucleus collision. They do not exhibit Coulomb interaction in the final state



Method of πK (ππ) atom observation and investigation



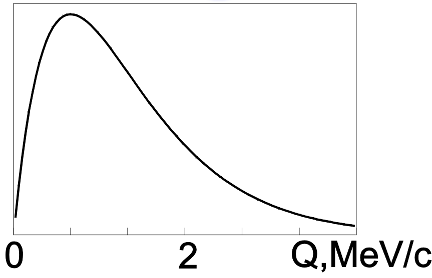
Atomic pairs

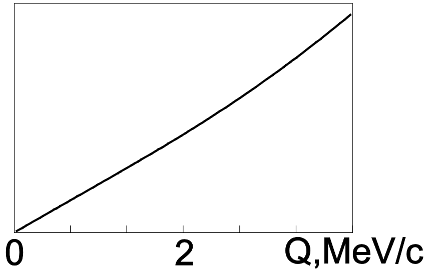
Coulomb pairs

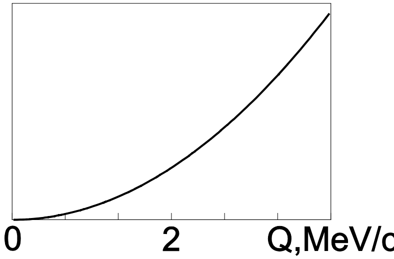
Coulomb pairs

Non-Coulomb pairs

Accidental pairs



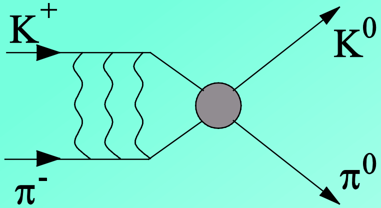




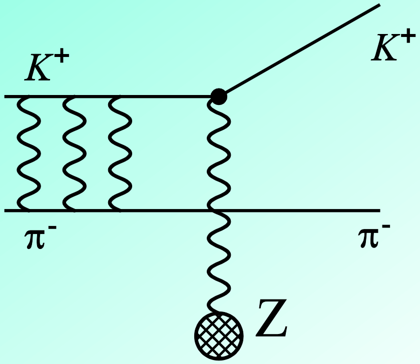
Break-up probability

During propagation in matter atoms:

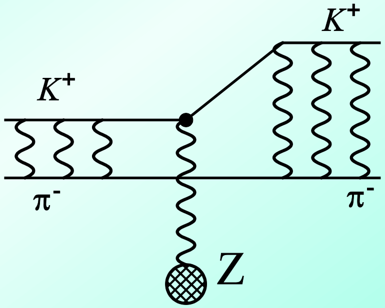
annihilate



break up(ionized)



excitate



result in production of πK ($\pi^+\pi^-$) atomic pairs n_A

$$\frac{\sigma_A}{\sigma_C} = \frac{\left|\psi^{(C)}_{nlm}\right|^2}{\left|\psi^{(C)}_{\vec{q}}\right|^2}$$

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

n_A *- atomic pairs number,* $\quad P_{br} = \dfrac{n_A}{N_A}$

Lifetime and breakup probability

The P_{br} value depends on the lifetime value, τ. To obtain the precise $P_{br}(\tau)$ curve a large differential equation system must be solved:

$$\frac{dp_{nlm}(s)}{ds} = \sum_{n'l'm'} a_{nlm}^{n'l'm'} p_{n'l'm'}(s)$$

where s is the position in the target, p_{nlm} is the population of a definite hydrogen-like state of pionium. The $a_{nlm}^{n'l'm'}$ coefficients are given by:

$$a_{nlm}^{n'l'm'} = \frac{\sigma_{nlm}^{n'l'm'} \rho N_0}{A}$$

if $nlm \neq n'l'm'$,

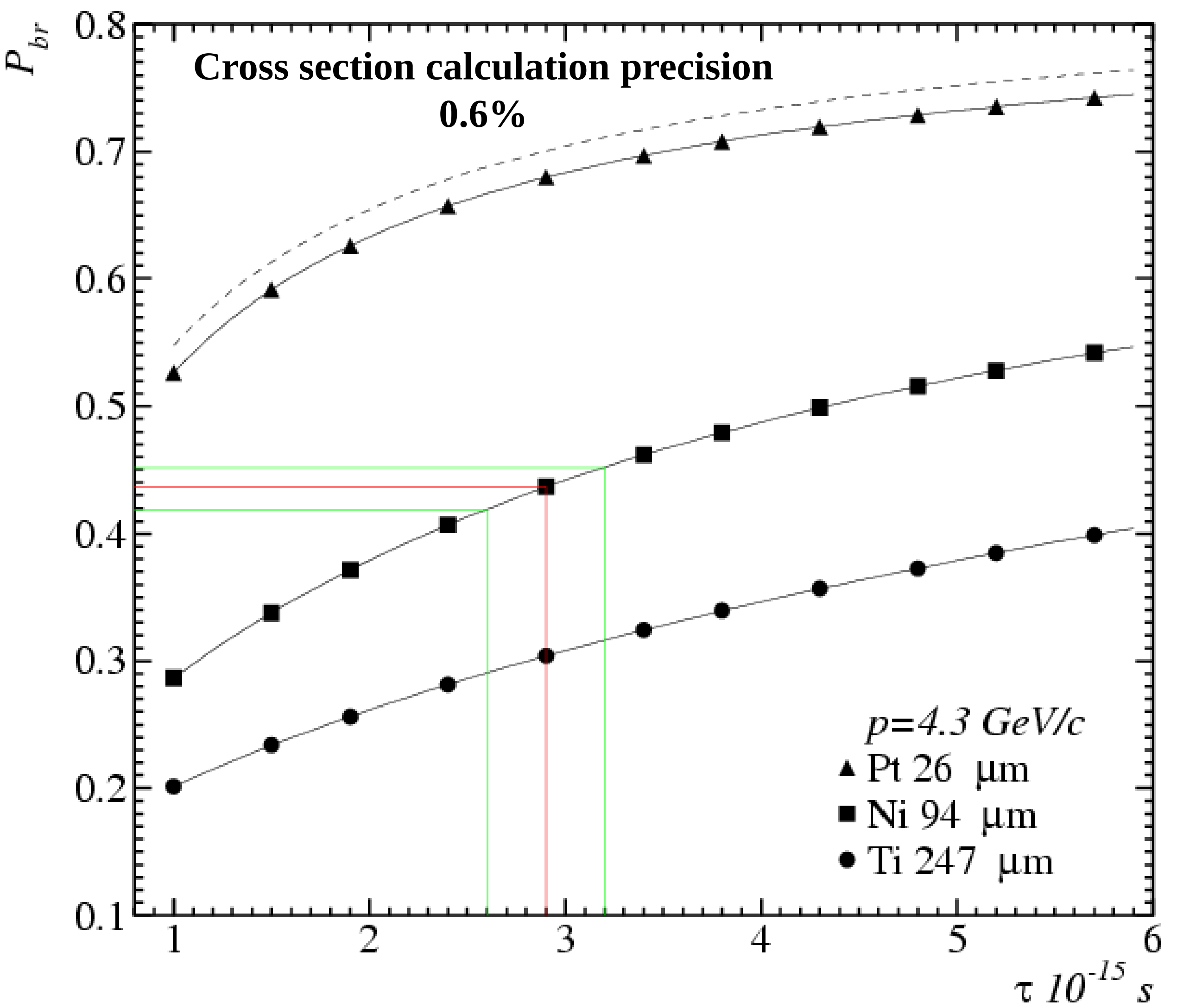
$$a_{nlm}^{nlm} = -\frac{\sigma_{nlm}^{tot} \rho N_0}{A} - \begin{cases} 2M_\pi / Pc\tau_n & l=0. \\ 0 & l \neq 0. \end{cases}$$

$\sigma_{nlm}^{n'l'm'}$ being the pionium-target atom cross section, N_0 the Avogadro Number, ρ the material density and A its atomic weight.

The detailed knowledge of the cross sections (Afanasyev&Tarasov, Trautmann et al) (Born and Glauber approach) together with the accurate solution of the differential equation system permits us to know the curves within 1%.

Break-up probability

Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on pionium lifetime τ



$\delta\tau=10\% \rightarrow \delta Pbr=4\%$

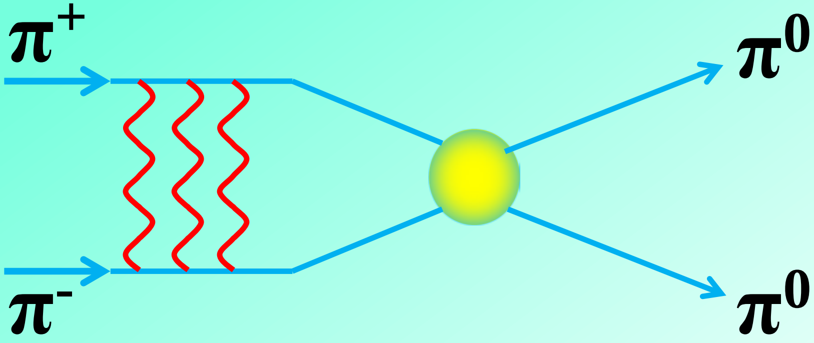
All targets have the same thickness in radiation lengths $6.7*10^{-3}\ X_0$

There is an optimal target material for a given lifetime

$\pi^+\pi^-$ atom lifetime

$\pi^+\pi^-$ atom (pionium) is a hydrogen-like atom consisting of π^+ and π^- mesons:

$E_B = -1.86$ keV, $r_B = 387$ fm, $p_B \approx 0.5$ MeV/c



The lifetime of $\pi^+\pi^-$ atom is dominated by the decay into $\pi^0\,\pi^0$ mesons:

$$\Gamma = \frac{1}{\tau} = \Gamma_{2\pi^0} + \Gamma_{2\gamma} \qquad \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4\times10^{-3}$$

$$\boxed{\Gamma_{ns\to2\pi^0} = R\left|\psi_{ns}(0)\right|^2\left|a_0 - a_2\right|^2}$$

$$\boxed{\tau_{1s} = \left(2.9\pm0.1\right)\times10^{-15}\,s}$$

a_0 and a_2 are the $\pi\pi$ *s*-wave scattering lengths for isospin I=0 and I=2.

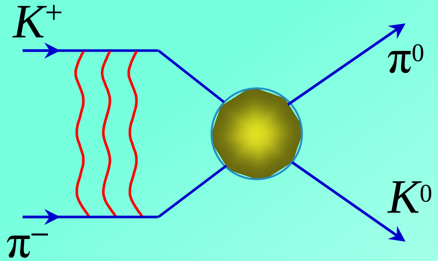
$$\psi_{nl}\begin{cases}\neq 0 \text{ for } l = 0 & A_{2\pi}(1s, 2s,\ldots,(n-1)s) \longrightarrow \pi^0\pi^0\\ = 0 \text{ for } l \neq 0 & A_{2\pi}(np) \xrightarrow{\gamma} A_{2\pi}(1s, 2s,\ldots(n-1)s) \longrightarrow \pi^0\pi^0\end{cases}$$

The lifetime of *np* states depends on transition *np* ⟶ 1*s*, 2*s*,…,(*n*-1)*s* probability
This probability is about three orders less than *ns* ⟶ $\pi^0\pi^0$ decay into $\pi^0\,\pi^0$

$K^+\pi^-$ 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]

$$\frac{1}{3}M_\pi\left(a_{1/2} - a_{1/3}\right) = M_\pi a_0^- = 0.071(CA) \to 0.079(1l) \to 0.89(2l)$$

$$\to 0.090 \pm 0.005(\text{dispersion}) \to \tau = (3.5 \pm 0.4) \times 10^{-15}\text{s}$$

[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] $M_\pi a_0^- = 0.0811 \pm 0.0143$

Theoretical motivation

ElectroWeak

L_{EW}

$SU(2)_L \times U(1)$

Standard Model

local gauge theory

strong:

L_{QCD}

$SU(3)_c$

Strong interaction: $L_{QCD} = L_{sym} + L_{sym\text{-}break}$ $(m_q \neq 0)$

(chiral symmetry)

HIGH energy
(small distance)

Q>>

Q<<

LOW energy
(large distance)

perturbative QCD:

L_{QCD} (q,g)

Interaction → „weak“ (asympt. freedom)
Method: expansion in coupling

Checks only L_{sym} $(m_q \ll 0)$!

non-perturbative QCD:

L_{eff} (GB: π,K,η); $L_{lattice}$ (q,g)

Interaction → „strong“ (confinement)
Methods: 1) Chiral Perturbation Theory 2) Lattice Gauge Theory

Checks L_{sym} as well as $L_{sym\text{-}break}$!

spontaneously broken symmetry ← quark-condensate

Theoretical motivation

ππ scattering length

In ChPT the effective Lagrangian, which describes the ππ interaction, is an expansion in terms:

$$L_{eff} = \underset{\text{(tree)}}{L^{(2)}} + \underset{\text{(1-loop)}}{L^{(4)}} + \underset{\text{(2-loop)}}{L^{(6)}} + \square$$

G. Colangelo, J. Gasser and H. Leutwyler, Nucl. Phys. B603 (2001) 125, using ChPT (2-loop) & Roy equations:

$$\left.\begin{aligned} a_0 &= \quad 0.220 \pm 2.3\% \\ a_2 &= -0.0444 \pm 2.3\% \end{aligned}\right\} \quad a_0 - a_2 = 0.265 \pm 1.5\%$$

These results (precision) depend on the low-energy constants (LEC) $\bar{l}_3$ and $\bar{l}_4$:
Lattice gauge calculations from **2006** provided values for these $\bar{l}_3$ and $\bar{l}_4$.

Theoretical motivation

Lattice calculations of $\bar{l}_3, \bar{l}_4$

- 2006: $\bar{l}_3, \bar{l}_4$ … first lattice calculations

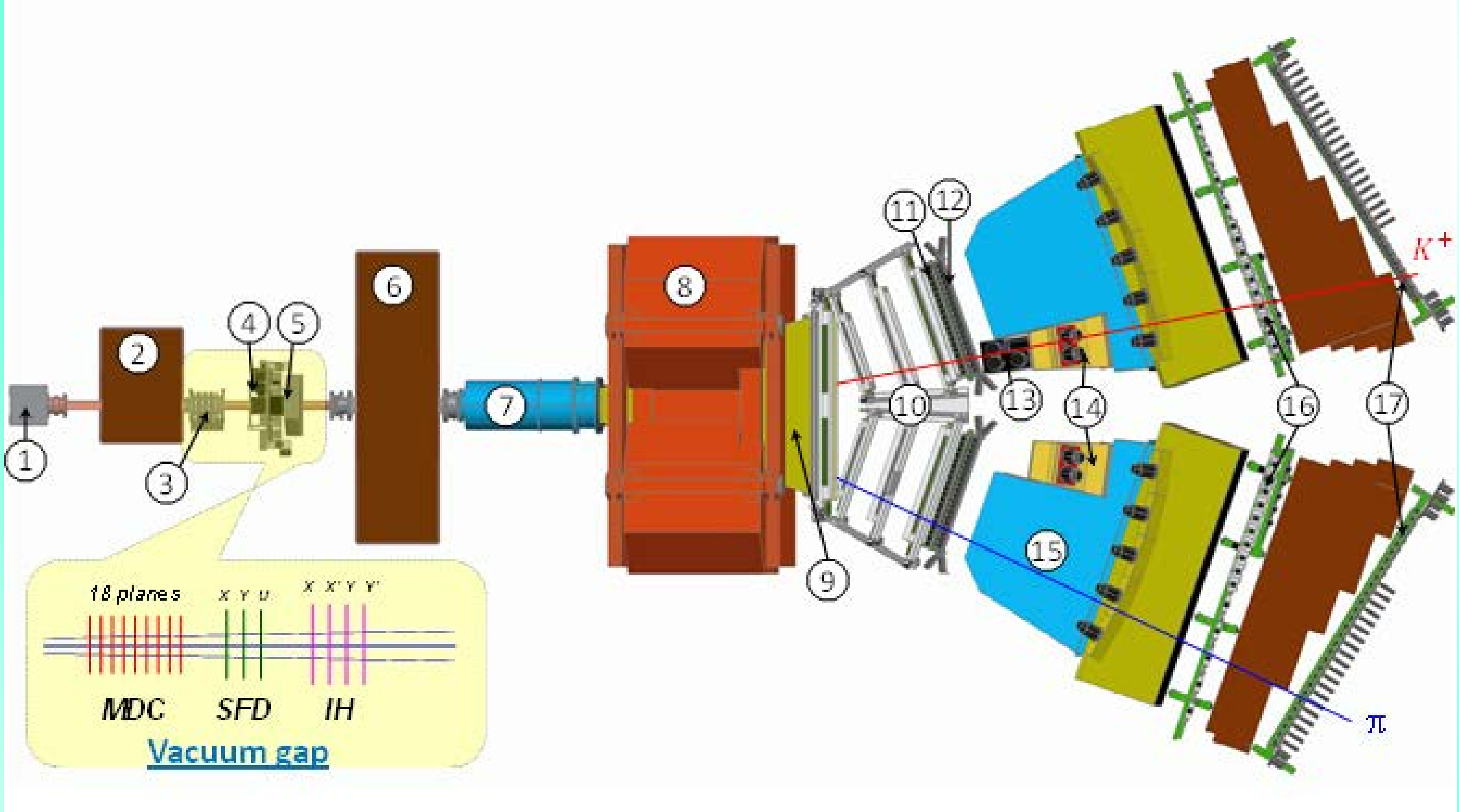
- 2012: 10 collaborations: 3 in USA, 5 in Europe and 2 in Japan

- J. Gasser, H. Leutwyler: model calculation (1985)
  $\bar{l}_3$=2.9±2.4, $\bar{l}_4$ =4.3 ±0.9

- Lattice calculations of these constants have been done in 20 works.
  Best result: $\bar{l}_3$=2.6±0.5st ±0.4sy, $\bar{l}_4$ =3.8 ±0.4st ±0.2sy

Therefore, the theoretical pion-pion scattering length precision can be improved.
The best experimental results on the scattering length have a precision not better than 4%.

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

Spectrometer resolutions

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

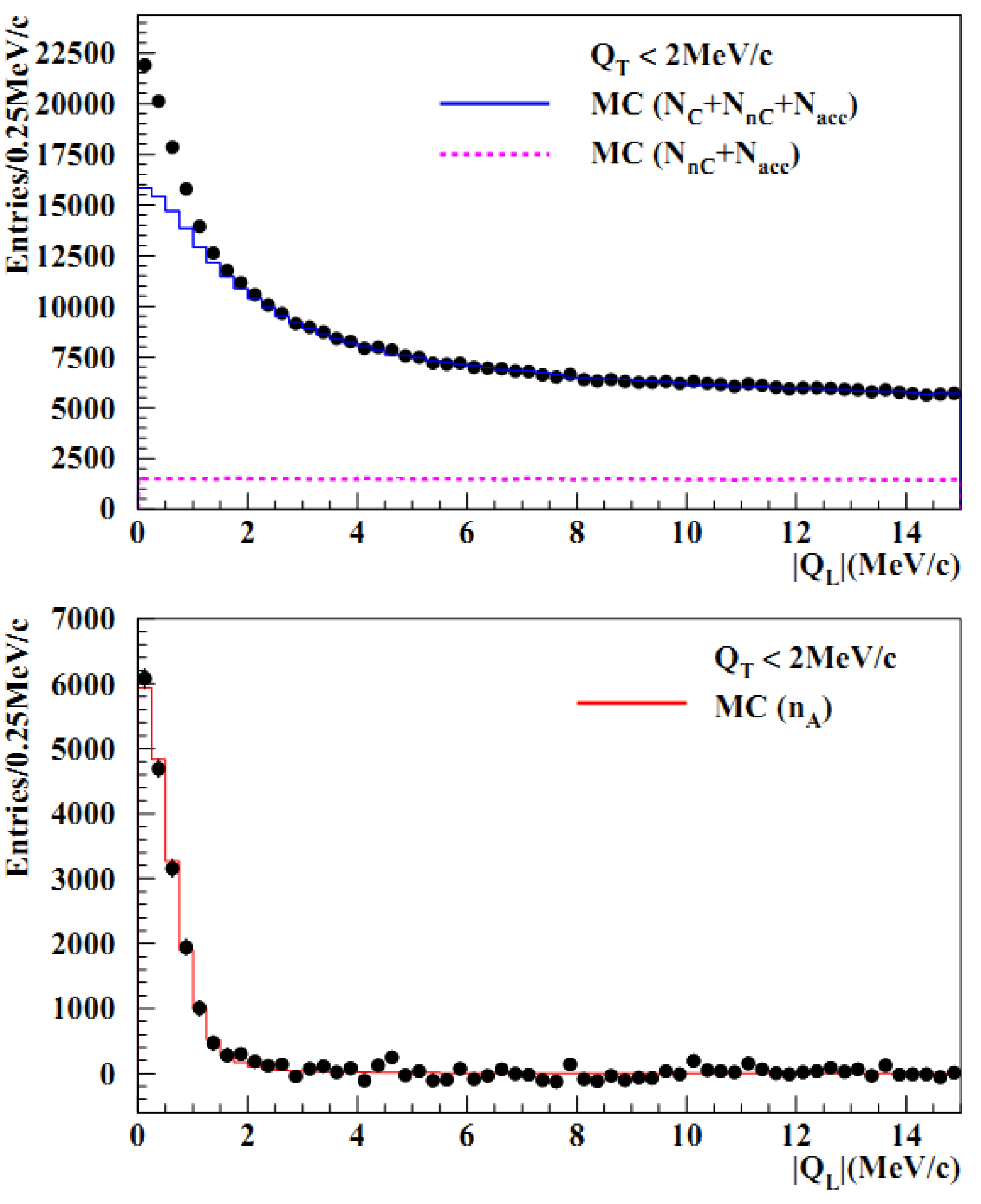
DC	
Coordinate precision	$\sigma = 85\ \mu m$

VH	
Time precision	$\sigma = 100$ ps

Spectrometer		
Relative resolution on the particle momentum in L.S.		$3\cdot10^{-3}$
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

$\pi^+\pi^-$ atoms 2001-2003

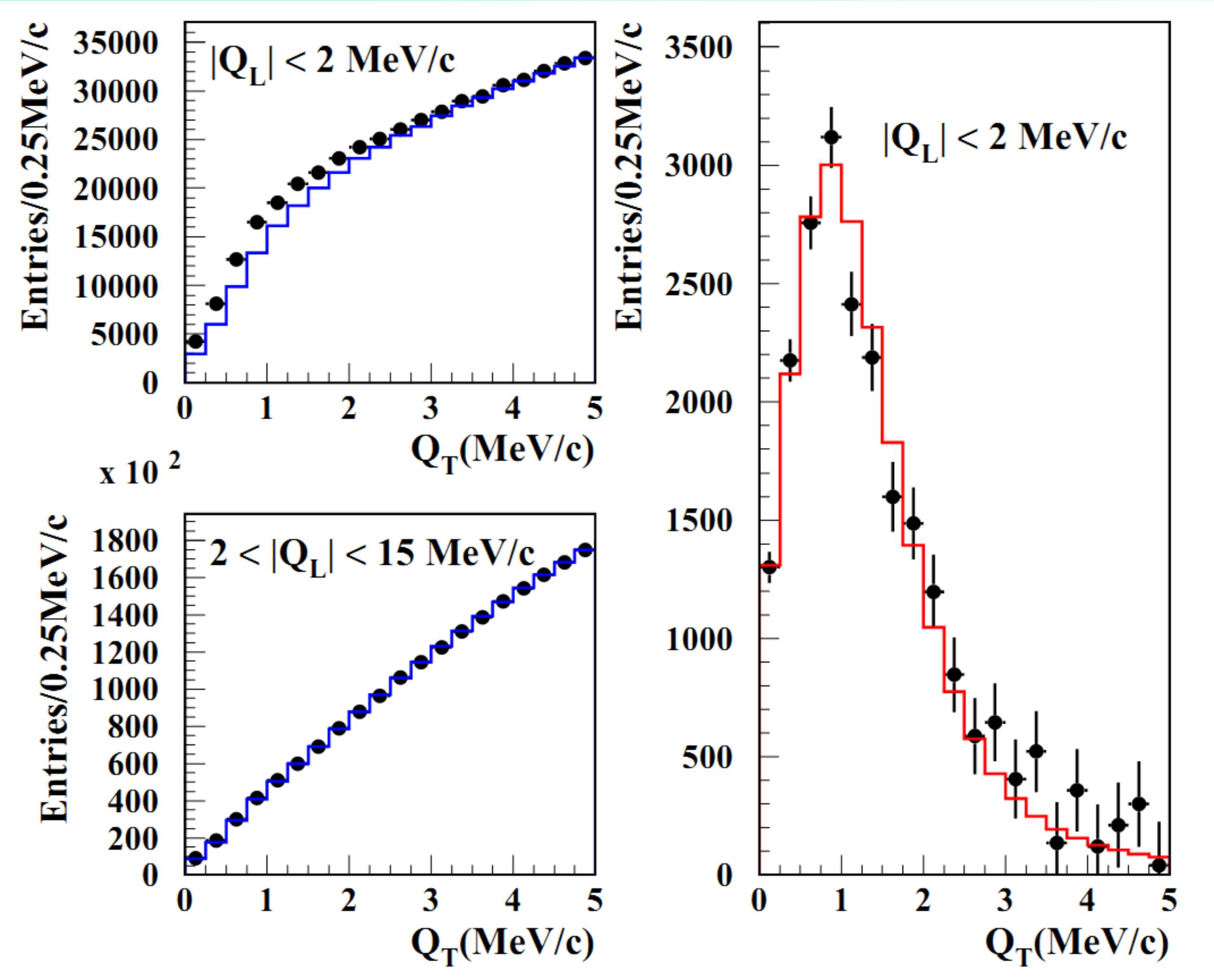


Q_L distribution

←All events

←After background subtraction

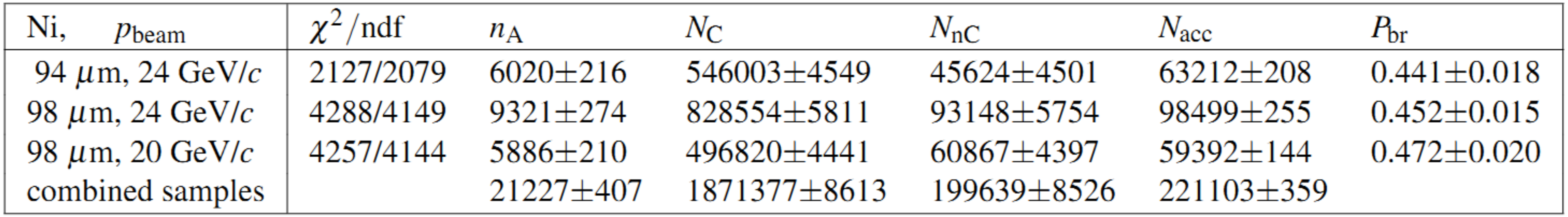
$\pi^+\pi^-$ atoms 2001-2003



Q_T distribution

←After background subtraction for Q_L<2MeV/c

$\pi^+\pi^-$ atoms 2001-2003



Ni, p_{beam}	χ^2/ndf	n_A	N_C	N_{nC}	N_{acc}	P_{br}
94 μm, 24 GeV/c	2127/2079	6020±216	546003±4549	45624±4501	63212±208	0.441±0.018
98 μm, 24 GeV/c	4288/4149	9321±274	828554±5811	93148±5754	98499±255	0.452±0.015
98 μm, 20 GeV/c	4257/4144	5886±210	496820±4441	60867±4397	59392±144	0.472±0.020
combined samples		21227±407	1871377±8613	199639±8526	221103±359	

DIRAC data	τ_{1s} $(10^{-15}$ s) value	stat	syst	*theo**	tot	$\|a_0-a_2\|$ value	stat	syst	*theo**	tot	**Reference**
2001	**2.91**	$^{+0.45}_{-0.38}$	$^{+0.19}_{-0.49}$		$\left[^{+0.49}_{-0.62}\right]$	**0.264**	$^{+0.017}_{-0.020}$	$^{+0.022}_{-0.009}$		$\left[^{+0.033}_{-0.020}\right]$	PL B 619 (2005) 50
2001-03	**3.15**	$^{+0.20}_{-0.19}$	$^{+0.20}_{-0.18}$		$\left[^{+0.28}_{-0.26}\right]$	**0.2533**	$^{+0.0078}_{-0.0080}$	$^{+0.0072}_{-0.0077}$		$\left[^{+0.0106}_{-0.0111}\right]$	PL B 704 (2011) 24

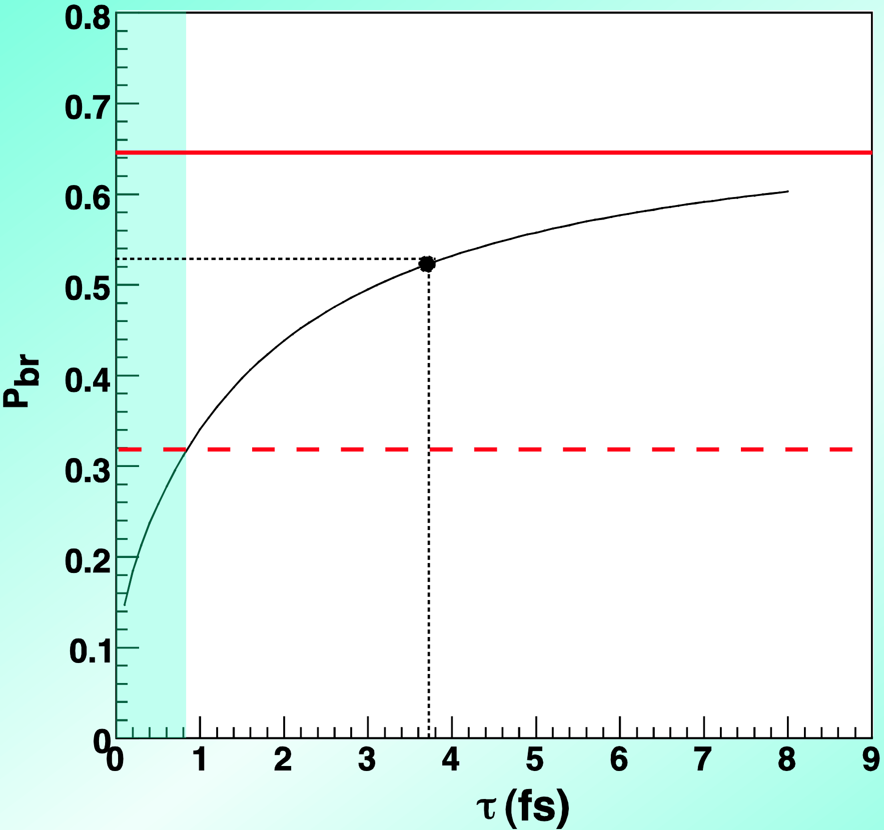
First evidence for πK atoms

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]



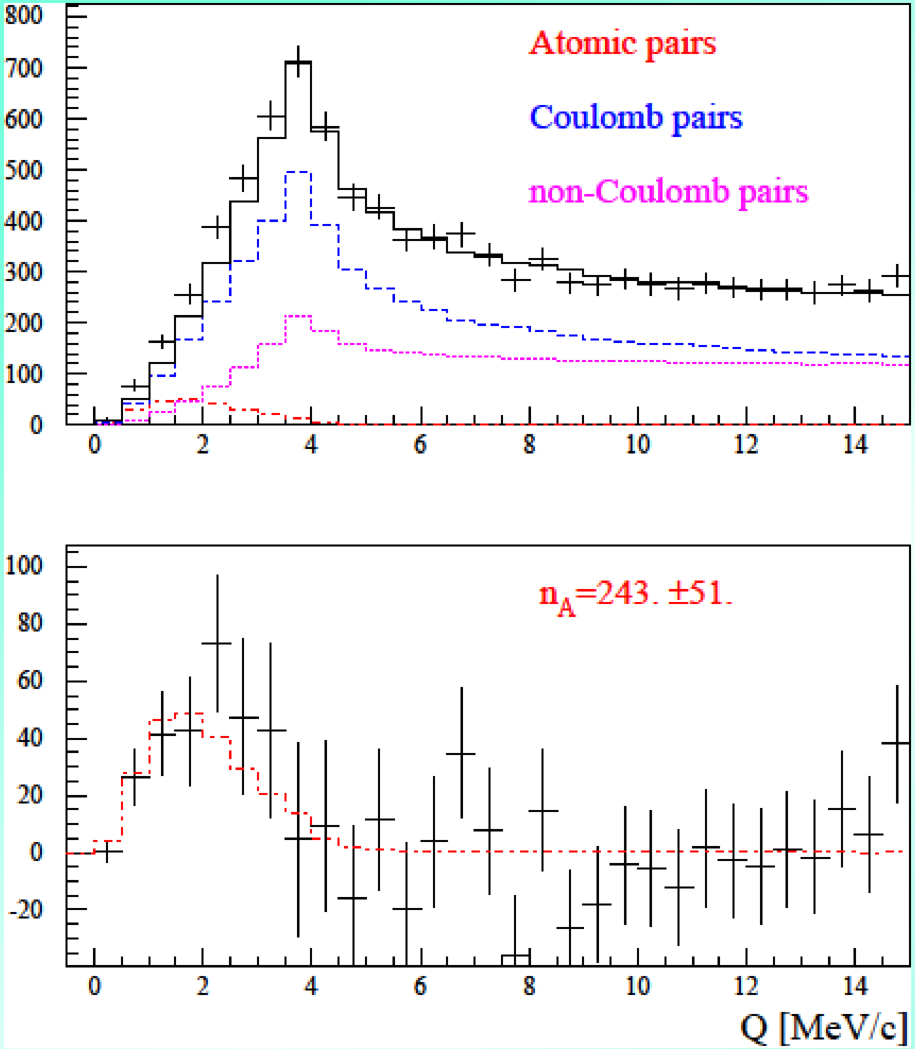
$$n_A(\pi^+ K^- + \pi^- K^+) = 173 \pm 54\ (3.2\sigma)$$

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

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

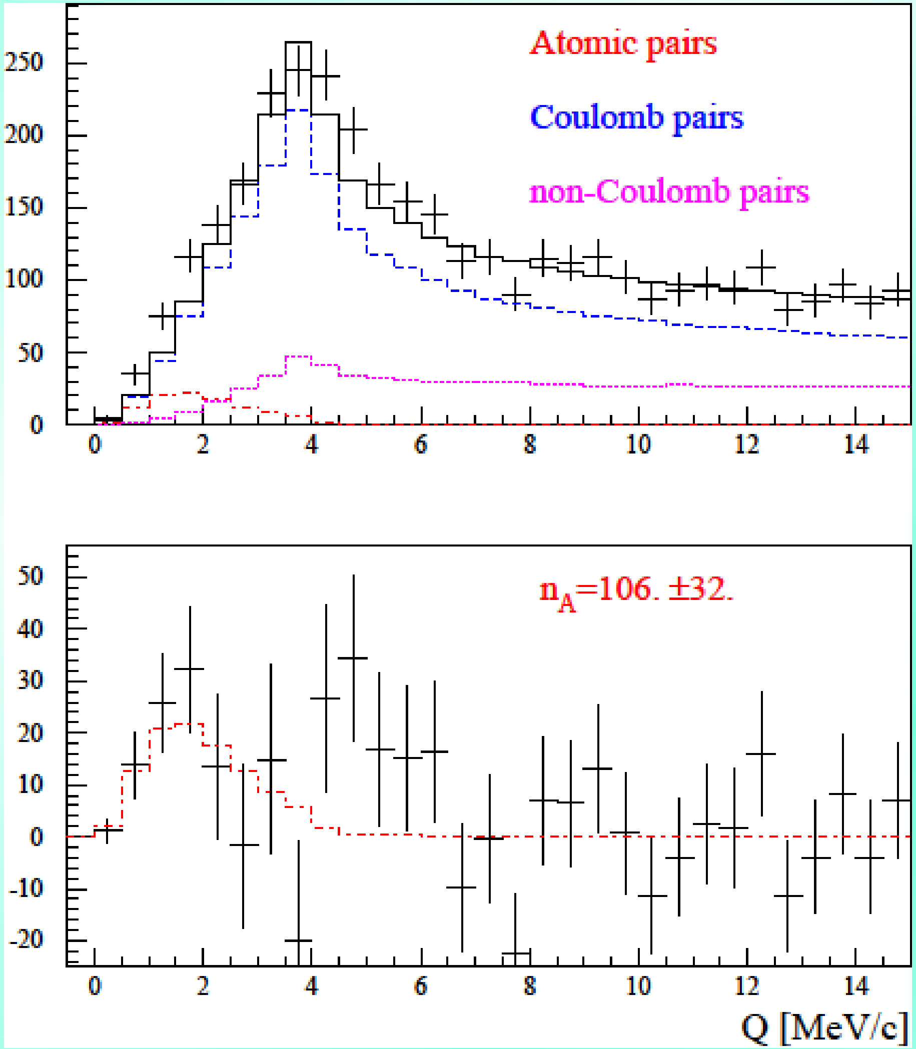
πK atoms observation

All data Platinum and Nickel targets



***$K^+\pi^-$* atoms**

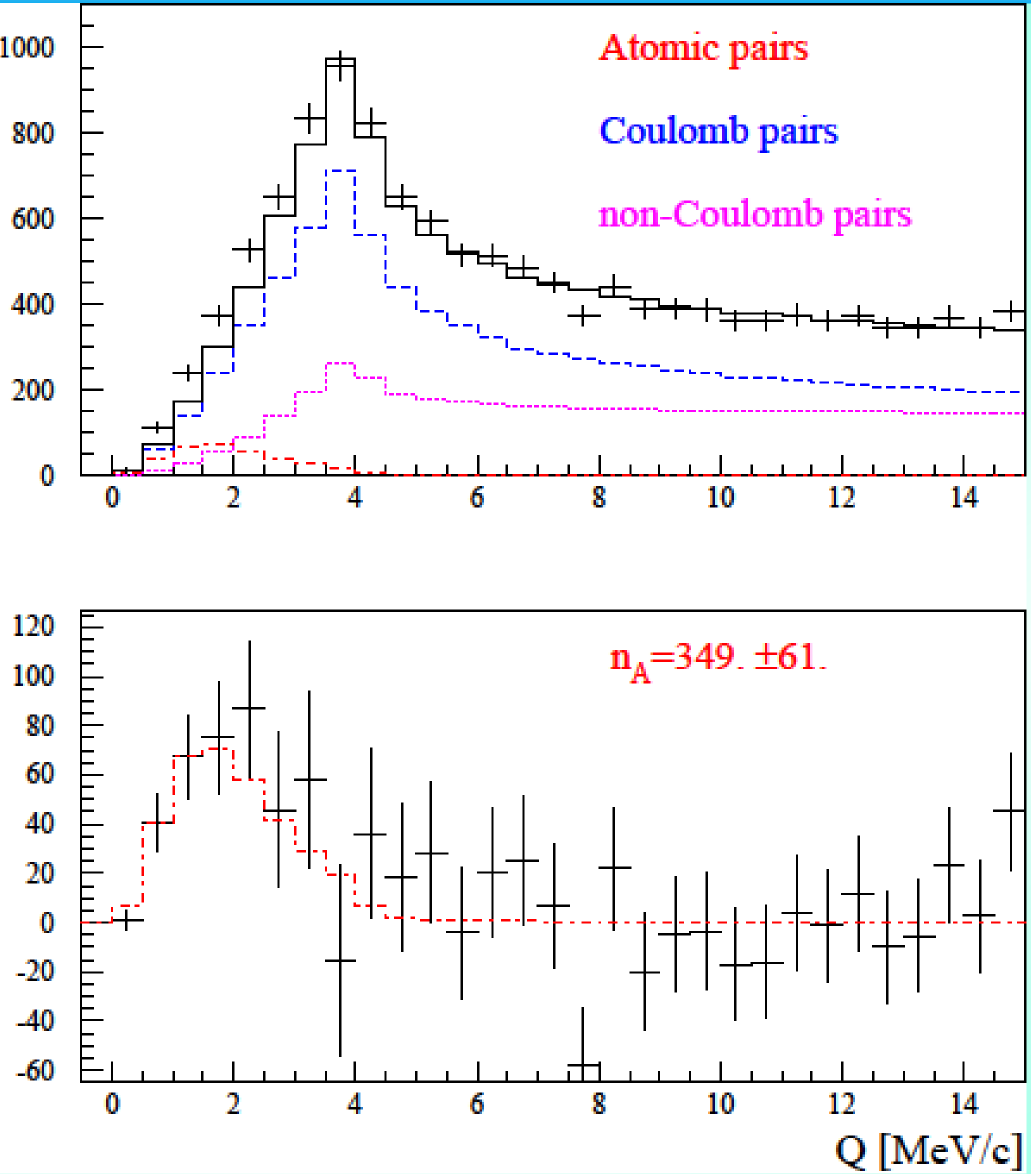
Q distribution for $Q_T < 4$ MeV/c



***$K^-\pi^+$* atoms**

Q distribution for $Q_T < 4$ MeV/c

πK atoms observation



All data Platinum and Nickel targets

$K^+\pi^-$ and $K^-\pi^+$ atoms , Q_L distribution for $Q_T < 4$ MeV/c χ^2 /ndf = 41/37
In absense of “atomic pairs” χ 2 /ndf = 73/38

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

Analysis	π^-K^+	π^+K^-	$\pi^+K^- + \pi^-K^+$
Q	243 ± 51 (4.7σ)	106 ± 32 (3.3σ)	349 ± 61 (5.7σ)
$\lvert Q_L \rvert$	164 ± 79 (2.1σ)	67 ± 47 (1.4σ)	230 ± 92 (2.5σ)
$\lvert Q_L \rvert$, Q_T	237 ± 50 (4.7σ)	78 ± 32 (2.5σ)	314 ± 59 (5.3σ)

Analysis with $|Q_L|$, Q_T

$n_A = 314 \pm 59(\text{stat}) \pm 10(\text{syst}) = 314 \pm 60(\text{tot})$
5.2 standard deviations

Analysis with Q

$n_A = 349 \pm 61(\text{stat}) \pm 9(\text{syst}) = 349 \pm 62(\text{tot})$
5.6 standard deviations

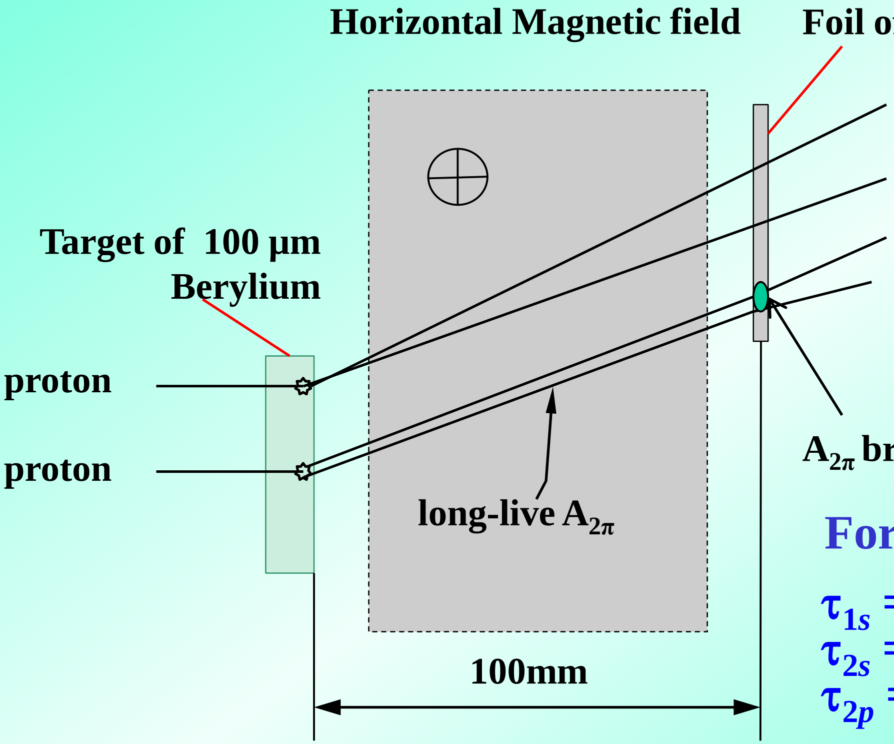
[DIRAC, Physical Review Letters 117, 112001 (2016)
CERN-EP-2016-128 ; arXiv:1605.06103]

Preliminary

$$\tau = \left(5.5^{+5.0}_{-2.8}|\text{tot}\right)\ \text{fs} \qquad 1/3\left|a_{1/2} - a_{3/2}\right| = \left(0.072^{+0.031}_{-0.020}\right) M_{\pi^+}^{-1}$$

Search for long-lived states of $\pi^+\pi^-$ 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 $\Delta E(ns\text{-}np)$ and the value of $\pi\pi$ scattering length combination $|2a_0+a_2|$.



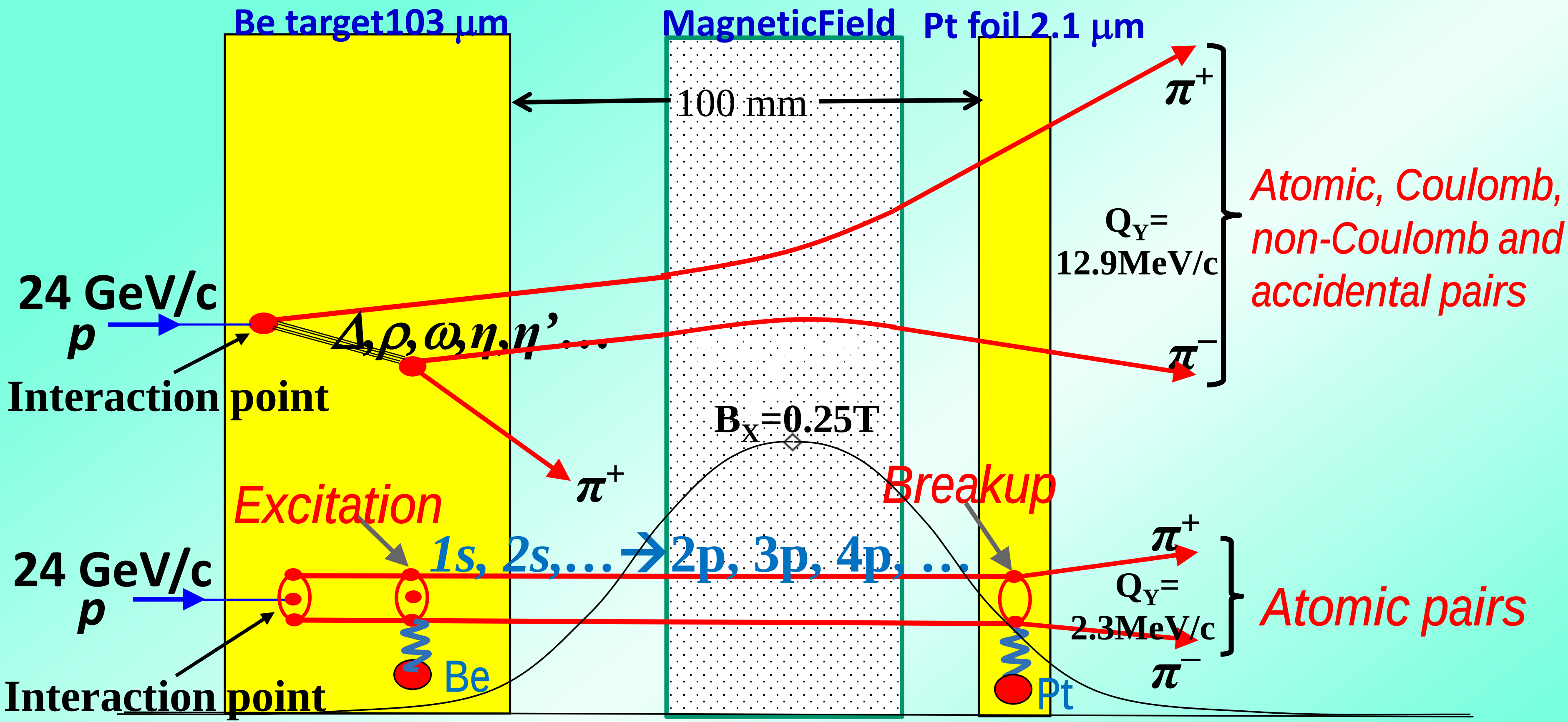
for atomic pairs produced in the target
$Q_x \approx 0$ MeV/c, $Q_y \approx 12.8$ MeV/c, $Q_L \approx 0$ MeV/c

for atomic pairs from long-lived atoms
$Q_x \approx 0$ MeV/c, $Q_y \approx 2.3$ MeV/c, $Q_L \approx 0$ MeV/c

For $p_A = 5.6$ GeV/c and $\gamma = 20$

$\tau_{1s} = 2.9 \times 10^{-15}$ s ,	$\lambda_{1s} = 1.7 \times 10^{-3}$ cm
$\tau_{2s} = 2.3 \times 10^{-14}$ s ,	$\lambda_{2s} = 1.4 \times 10^{-2}$ cm
$\tau_{2p} = 1.17 \times 10^{-11}$ s ,	$\lambda_{2p} = 7$ cm
	$\lambda_{3p} \approx 23$ cm
	$\lambda_{4p} \approx 54$ cm

Method for observing long-lived $\pi^+\pi^-$ atom with breakup Pt foil



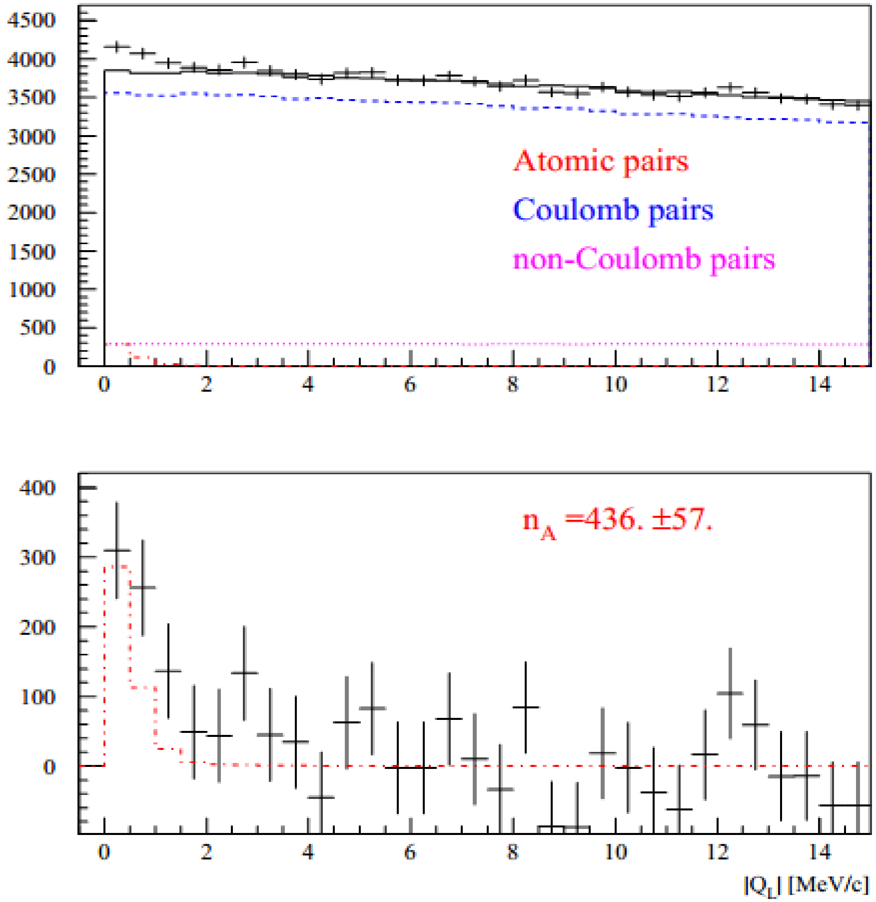
for
$\gamma = 16$

$l(2p) = 5.6$ cm, $l(3p) = 19$ cm, $l(4p) = 43$ cm, $l(5p) = 84$ cm
$l(2s) = 0.11$ mm, $l(3s) = 0.38$ mm, $l(4s) = 0.89$ mm, $l(5s) = 1.74$ mm

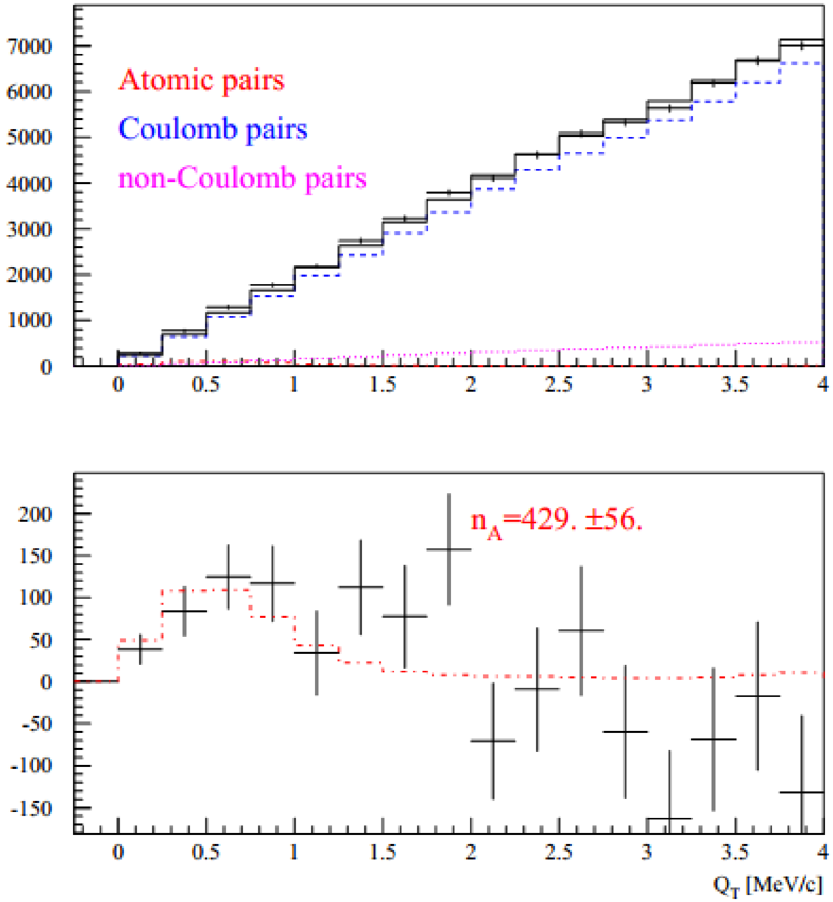
n	2	3	4	5	>2
$\varepsilon_n(\mathrm{Be}) \times 10^2$	$2.48 \pm O(10^{-3})$	1.54 ± 0.01	0.86 ± 0.03	0.56 ± 0.06	7.1 ± 0.8
$\varepsilon_n(\mathrm{Pt}) \times 10^2$	$0.52 \pm O(10^{-4})$	$1.10 \pm O(10^{-3})$	0.78 ± 0.03	0.54 ± 0.06	4.6 ± 0.8

Observation of long-lived $\pi^+\pi^-$ atoms

Two-dimensional distribution over $|Q_L|$ Q_T, have been fitted with χ^2/ndf = 138/140. Projections to $|Q_L|$ and Q_T are presented.



$|Q_L|$ for Q_T<2.0 MeV/c



Q_T for $|Q_L|$<2.0 MeV/c

Observation of long-lived $\pi^+\pi^-$ atoms

Q_T cut	n_A	n_A^{tot}	Background	χ^2/ndf
$Q_T<2.0\ MeV/c$	436±57 (~7.6σ)	488±64	16719	138/140
1-dimensional fit over Q_L				
$Q_T<0.5\ MeV/c$	152±29 (~5.2σ)	467±88	971	29/27
$Q_T<1.0\ MeV/c$	349±53 (~6.6σ)	489±75	3692	19/27
$Q_T<1.5\ MeV/c$	386±78 (~4.9σ)	454±91	9302	22/27
$Q_T<2.0\ MeV/c$	442±105 (~4.2σ)	495±117	16774	22/27

Observation of long-lived $\pi^+\pi^-$ atoms

Systematic errors of number of long-lived "atomic pairs"

Sources of systematic errors	σ^{syst}
Uncertainty in correction on Λ-width	4.4
Uncertainty of Platinum foil thickness	22
Total	23

$$n_A^L = 436 \pm 57(\text{stat}) \pm 23(\text{syst}) = 436 \pm 61(\text{tot})$$

Expected number → 653 ± 110 (453 ÷ 845)

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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.

Thank you
for your attention!

$\pi^+\pi^-$ experimental results

$K\to 3\pi$:

$$\left(\text{scattering length in } m_\pi^{-1}\right)$$

2009 NA48/2 (EPJ C64, 589)

$$\Rightarrow a_0 - a_2 = 0.2571 \pm 0.0048\big|_{stat} \pm 0.0025\big|_{syst} \pm 0.0014\big|_{ext} = \ldots \pm 2.2\%$$

plus additional 3.4% theory uncertainty

Ke4:

2010 NA48/2 (EPJ C70, 635)

$$\Rightarrow a_0 = 0.2220 \pm 0.0128\big|_{stat} \pm 0.0050\big|_{syst} \pm 0.0037\big|_{theo} = \ldots \pm 6.4\%$$

$$\Rightarrow a_2 = -0.0432 \pm 0.0086\big|_{stat} \pm 0.0034\big|_{syst} \pm 0.0028\big|_{theo} = \ldots \pm 22\%$$

$\pi^+\pi^-$ atom:

2011 DIRAC (PLB 704, 24)

$$\Rightarrow \left|a_0 - a_2\right| = 0.2533 \begin{matrix} +0.0078 \\ -0.0080 \end{matrix}\Big|_{stat} \begin{matrix} +0.0072 \\ -0.0077 \end{matrix}\Big|_{syst} = \ldots \begin{matrix} +4.2\% \\ -4.4\% \end{matrix}$$