Investigation of $\pi^+\pi^-$ and πK atoms at DIRAC

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on Chiral Dynamics
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DIRAC collaboration

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Tokyo Metropolitan University
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IFIN-HH
Bucharest, Romania

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Moscow, Russia

Santiago de Compostela University
Santiago de Compostela, Spain

Bern University
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Zurich University
Zurich, Switzerland

Theoretical status

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History of Chiral Perturbation Theory (ChPT) :
- S. Weinberg 1966 - 1979
- J. Gasser & H. Leutwyler 1983 – 1985

Colangelo et al. in 2001, using ChPT (2-loop) & Roy equations:

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

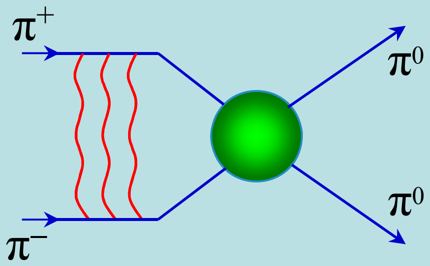
These results (precision) depend on the low-energy constants (LEC) l_3 and l_4:
Lattice gauge calculations from **2006** provided values for these l_3 and l_4.

Because l_3 and l_4 are sensitive to the quark condensate,
precision measurements of a_0, a_2 are a way
to study the **structure** of the QCD vacuum.

Pionium lifetime

Pionium ($A_{2\pi}$) 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



The lifetime of $\pi^+\pi^-$ atoms is dominated by the annihilation process into $\pi^0\pi^0$:

$$\Gamma = \frac{1}{\tau} = \Gamma_{2\pi_0} + \Gamma_{2\gamma} \text{ with } \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi_0}} \approx 4\times 10^{-3}$$

$$\Gamma_{1S,2\pi^0} = R\,|a_0 - a_2|^2 \quad \text{with} \quad \frac{\Delta R}{R} \approx 1.2\%^{*}$$

* Gasser et al (2001)

$$\tau = (2.9 \pm 0.1)\times 10^{-15}\, s$$

a_0 and a_2 are the ππ S-wave scattering lengths for isospin I=0 and I=2.

If $$\frac{\Delta\tau}{\tau} = 4\% \quad \Rightarrow \quad \frac{\Delta|a_0 - a_2|}{|a_0 - a_2|} = 2\%$$

πK scattering lengths

I. ChPT predicts s-wave scattering lengths:

$$a_0^{1/2} = 0.19 \pm 0.2 \qquad a_0^{3/2} = -0.05 \pm 0.02$$

V. Bernard, N. Kaiser, U. Meissner. – 1991

$\mathscr{L}^{(2)}, \mathscr{L}^{(4)}$ *and* $1-loop$

$$a_0^{1/2} - a_0^{3/2} = 0.23 \pm 0.01$$

A. Rossel. – 1999

J. Bijnens, P. Talaver. – April 2004

$\mathscr{L}^{(2)}, \mathscr{L}^{(4)}, \mathscr{L}^{(6)}$ *and* $2\text{-}loop$

II. Roy-Steiner equations:

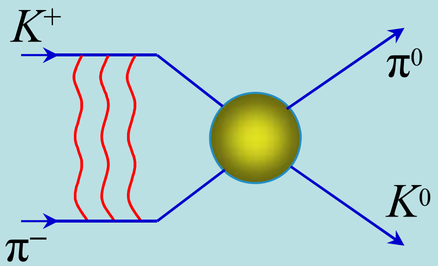
$$a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015$$

P.Büttiker et al. – 2004

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

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

$E_B = -2.9$ keV $r_B = 248$ fm $p_B \approx 0.8$ MeV



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

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

$$\Gamma_{1S,K^0\pi^0} = R_K \left|a_{1/2} - a_{3/2}\right|^2 \quad \text{with} \quad \frac{\Delta R_K}{R_K} \approx 2\%^*$$

* J. Schweizer (2004)

From Roy-Steiner equations: $a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015$

$$\downarrow$$

$$\tau = (3.7 \pm 0.4) \cdot 10^{-15}\ s$$

If $$\frac{\Delta\Gamma}{\Gamma} = 20\,\% \quad \Rightarrow \quad \frac{\Delta\left|a_{1/2} - a_{3/2}\right|}{\left|a_{1/2} - a_{3/2}\right|} = 10\,\%$$

πK scattering

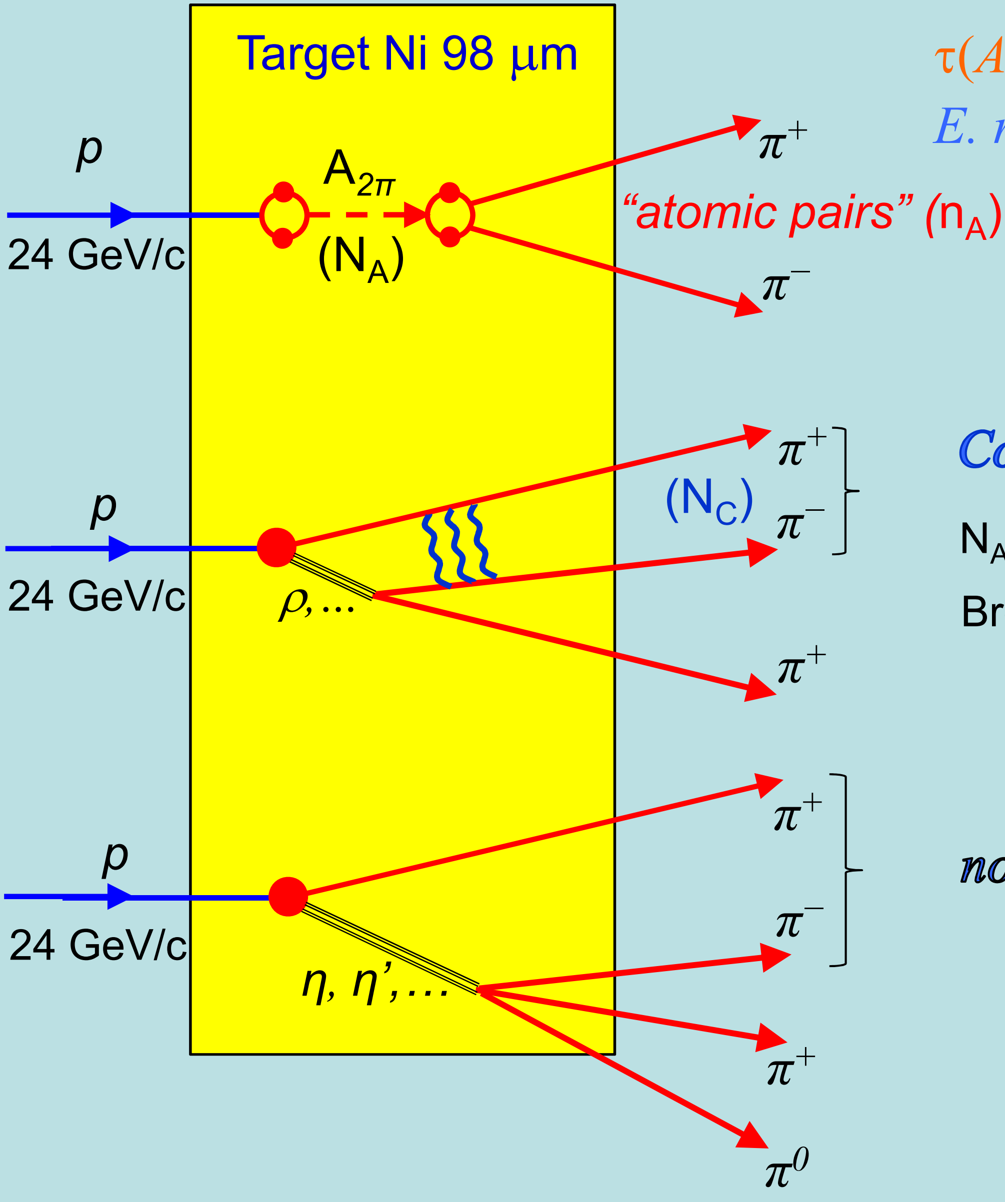
What new will be known if πK scattering length will be measured?

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

Method of $A_{2\pi}$ observation and lifetime measurement



$\tau(A_{2\pi})$ is too small to be measured directly.

E. m. interaction of $A_{2\pi}$ in the target:

$$A_{2\pi} \rightarrow \pi^+\pi^-$$

$$Q < 3 MeV/c,\ \Theta_{lab} < 3\ mrad$$

***Coulomb** from short-lived sources*

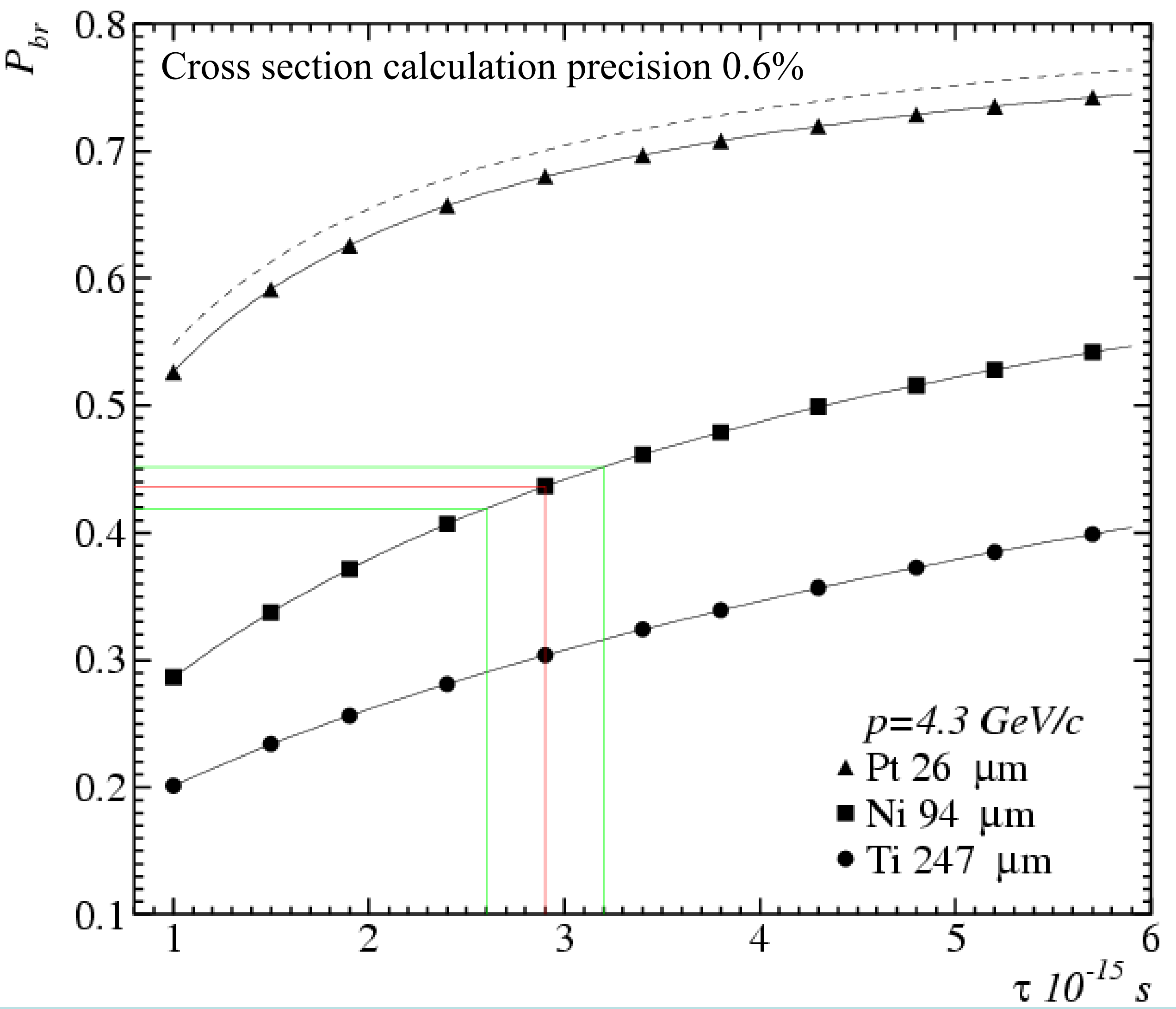
$N_A = K(Q_0)\ N_C(Q<Q_0)$ with known $K(Q_0)$

Breakup probability: $P_{br}=n_A/N_A$

***non-Coulomb** from long-lived sources*

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



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

Method of $A_{2\pi}$ observation and lifetime measurement

Main features of the DIRAC set-up

Thin targets: $\sim 7 \times 10^{-3}\, X_0$
Nuclear efficiency: 3×10^{-4}
Vacuum magnetic spectrometer
Proton beam $\sim 10^{11}$ proton/spill
Momentum of secondaries 1.3 – 7 GeV/c
Resolution on Q:

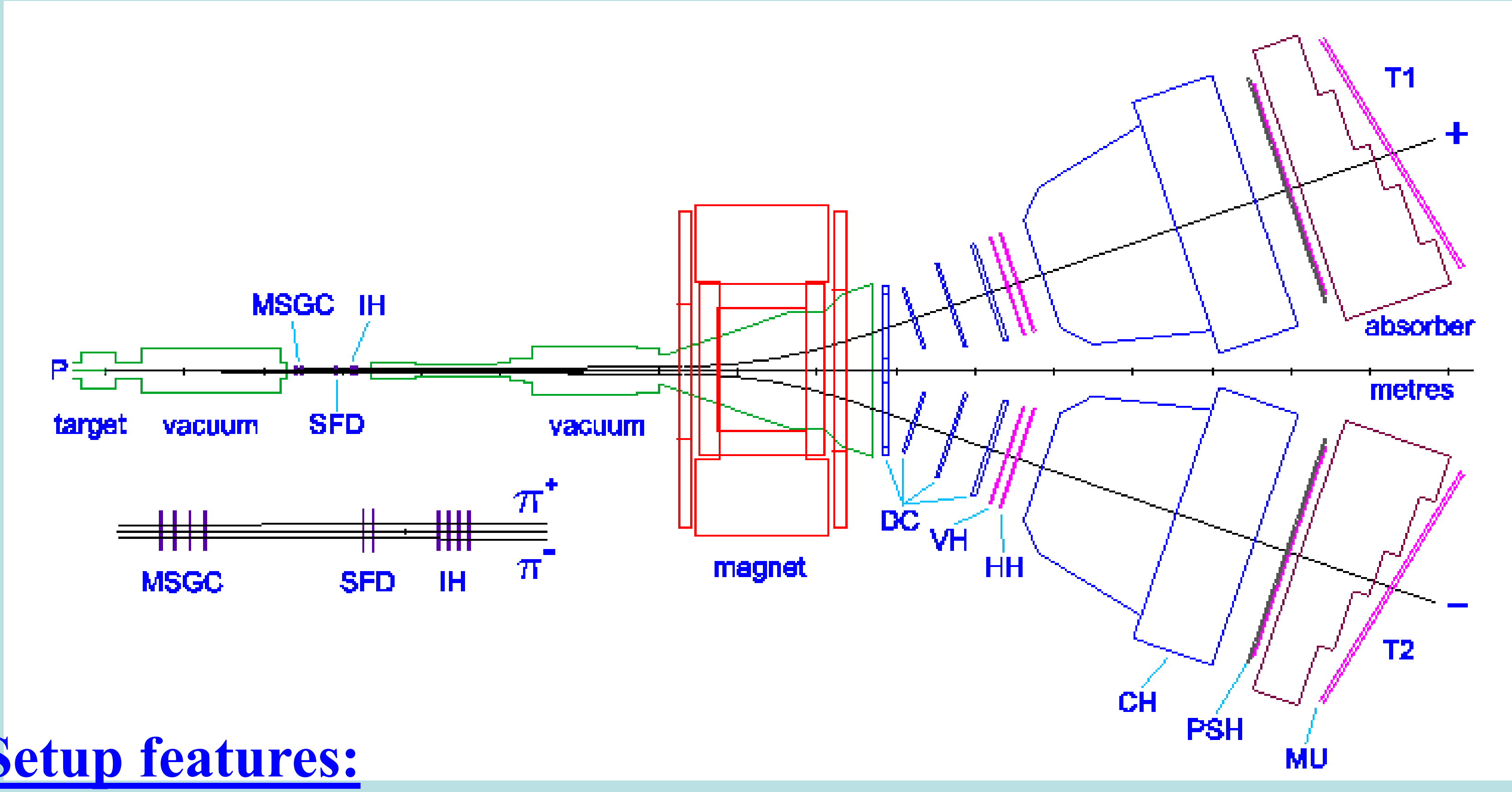
$Q_x \approx Q_y \approx 0.3$ Mev/c,

$Q_L \approx 0.5$ MeV/c

The same method is applied to $A_{\pi K}$,

$$p_K = \frac{m_K}{m_\pi} p_\pi$$

DIRAC Spectrometer



Setup features:

angle to proton beam $\Theta=5.7^\circ$

channel aperture $\Omega=1.2\cdot10^{-3}$ sr

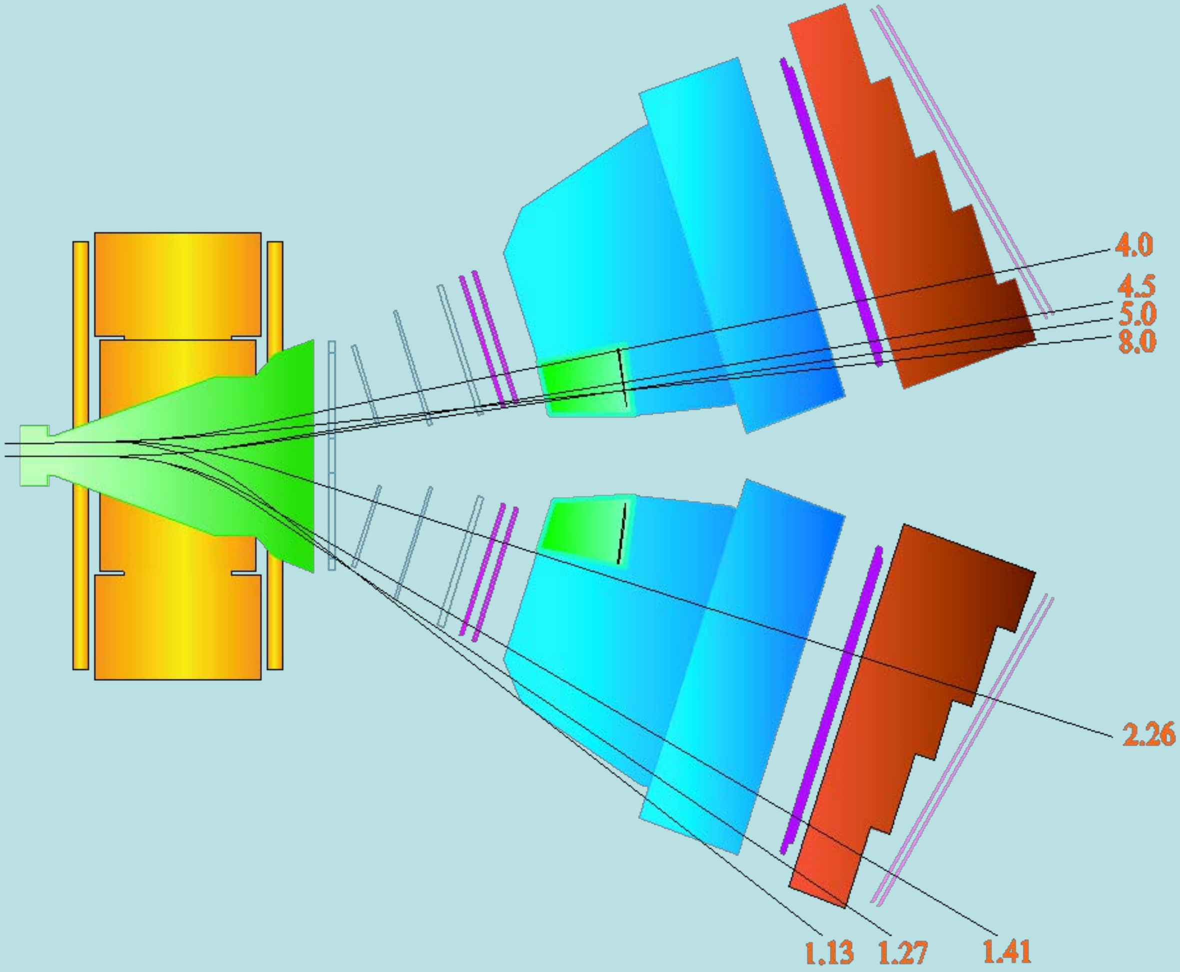
magnet 2.3 T·m

momentum range $1.2\leq p_\pi\leq 7$ GeV/*c*

resolution on relative momentum $\sigma_{QX}\approx\sigma_{QY}\leq 0.5$ MeV/*c*, $\sigma_{QL}\approx 0.5$ MeV/*c*

Trajectories of π^- and K^+ from the $A_{K\pi}$ break-up

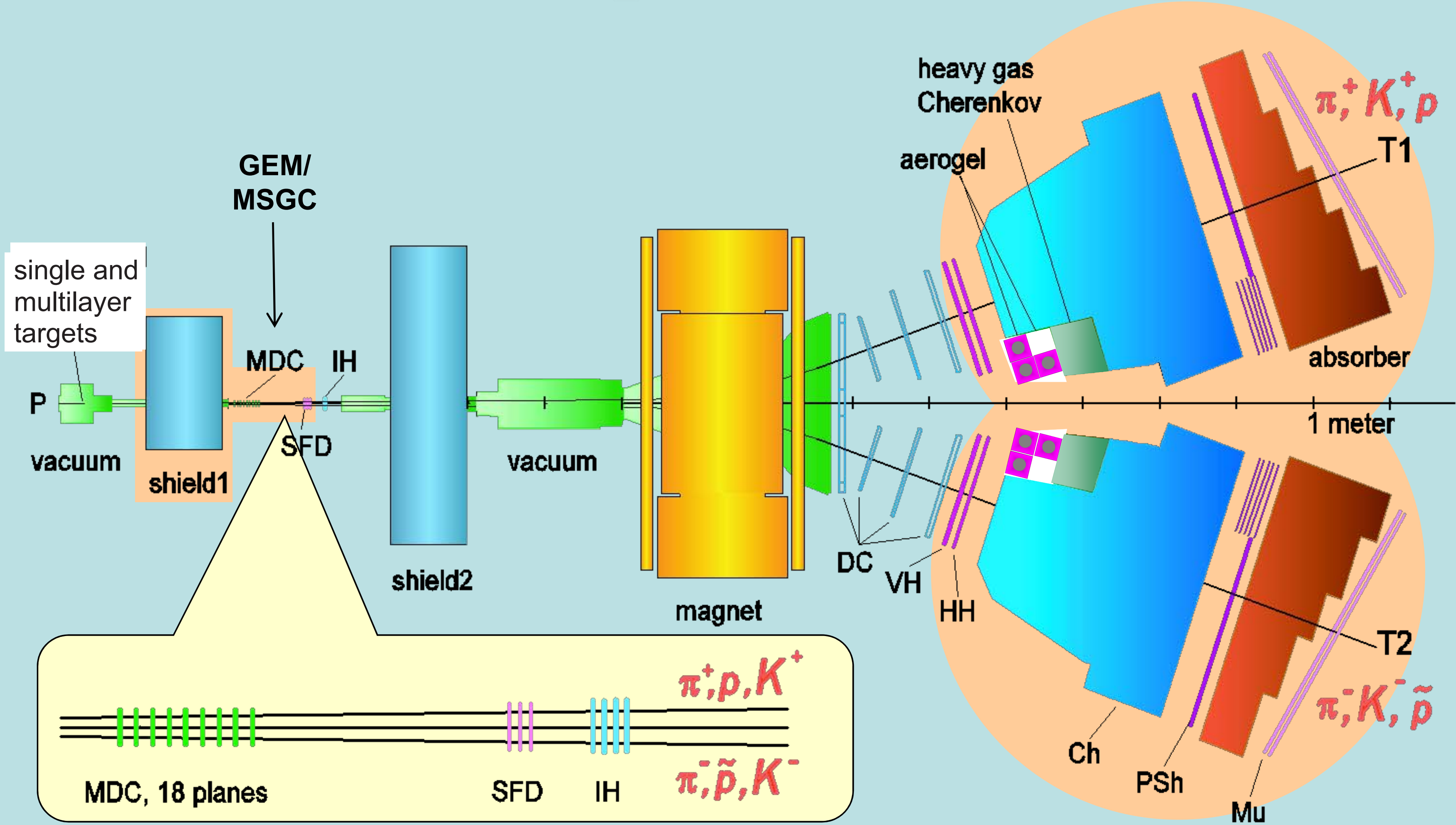
The numbers to the right of the tracks lines are the π^- and K^+ momenta in GeV/c



The $A_{K\pi}$, π^- and K^+ momenta are shown in the following table:

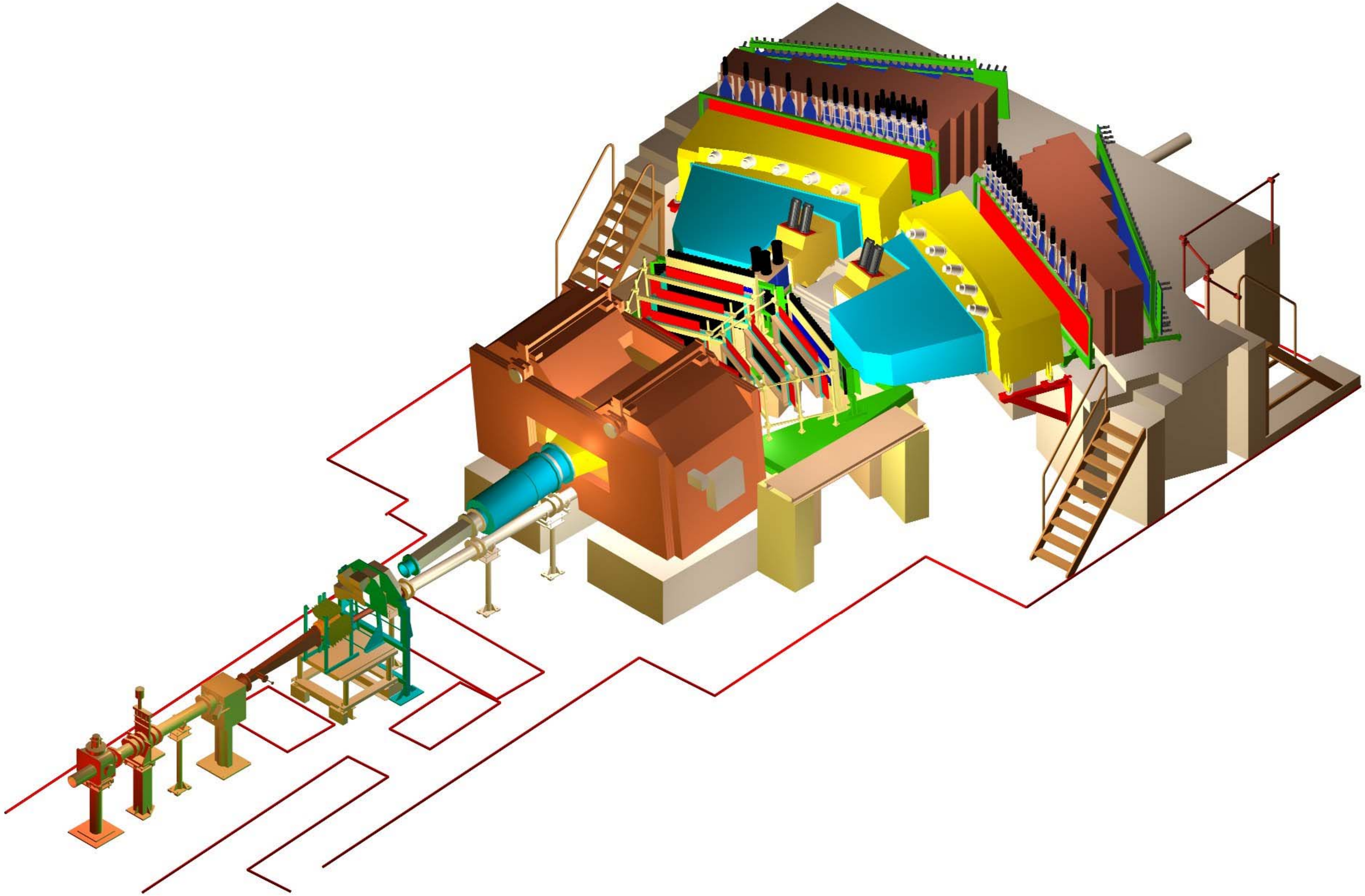
P_{atom} (GeV/c)	P_π (GeV/c)	P_K (GeV/c)
5.13	1.13	4.0
5.77	1.27	4.5
6.41	1.41	5.0
10.26	2.26	8.0

DIRAC experimental setup



Modifided parts

Upgraded DIRAC experimental setup



Analysis based on MC

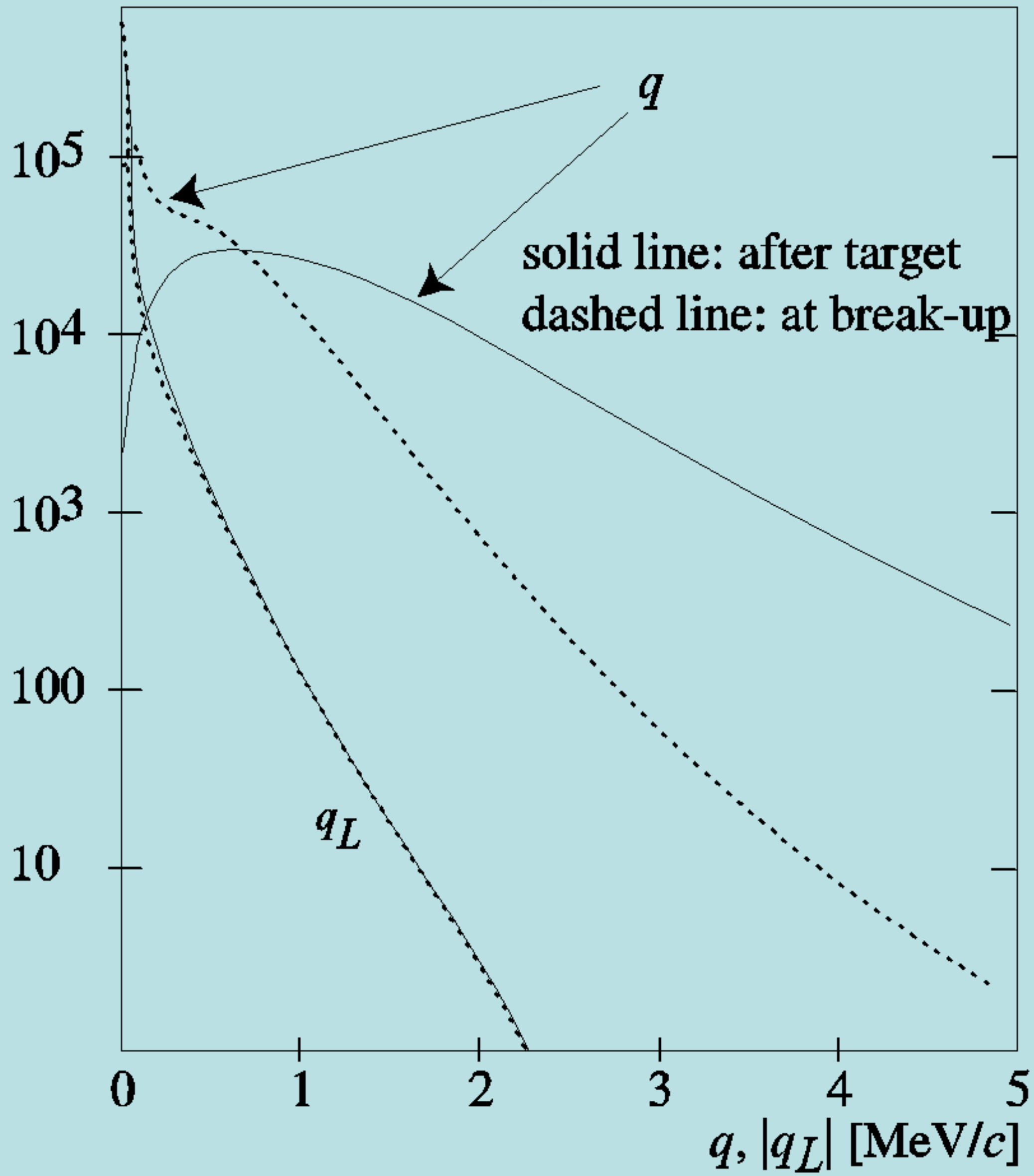
Atoms are generated in **nS states** using measured momentum distribution for **short-lived** sources. The atomic pairs are generated according to the evolution of the atom while propagating through the target

Background processes:

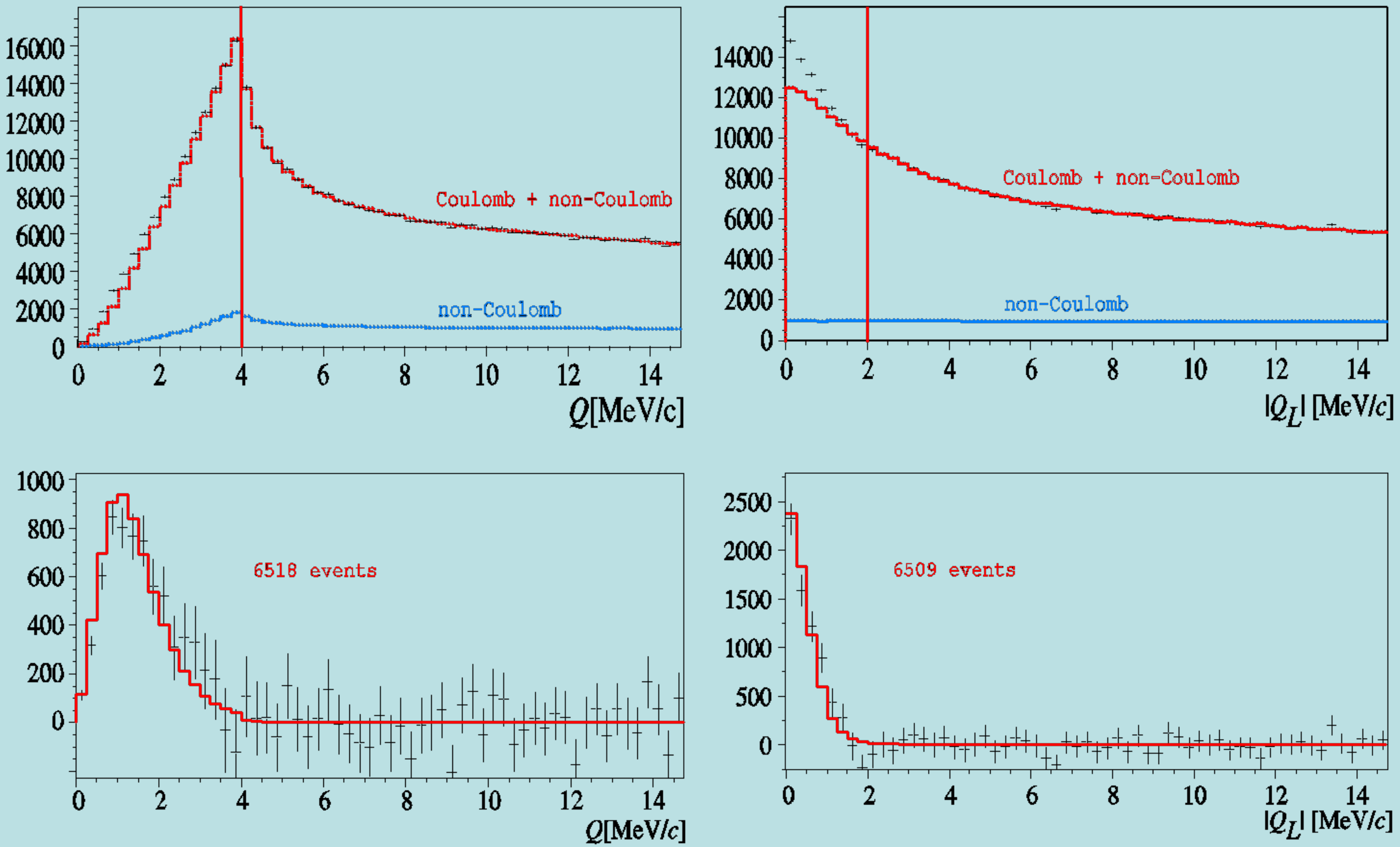
Coulomb pairs are generated according to $A_C(Q)Q^2$ using measured momentum distribution for **short-lived** sources.

Non-Coulomb pairs are generated according to Q^2 using measured momentum distribution for **long-lived** sources.

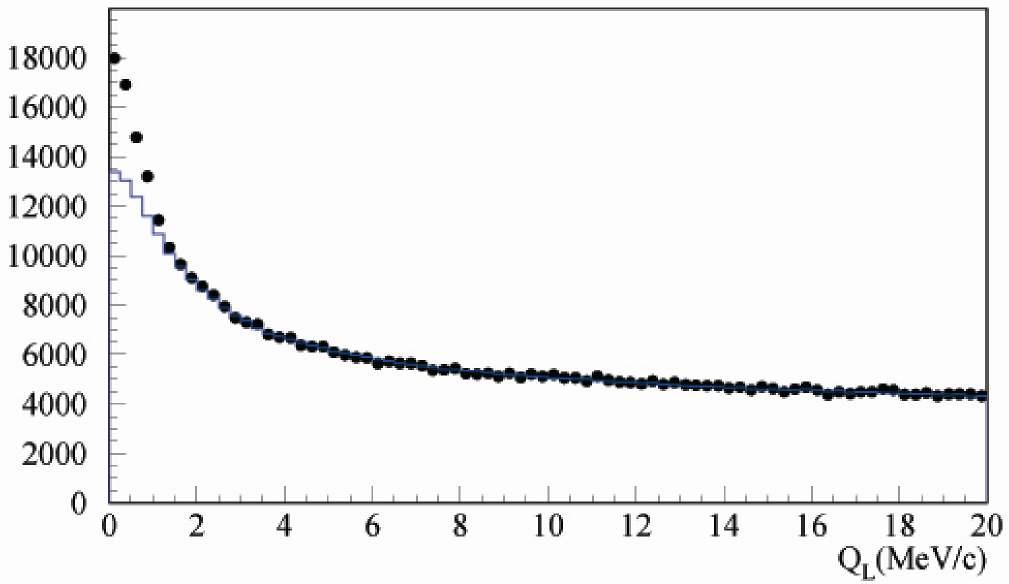
Atomic pairs MC

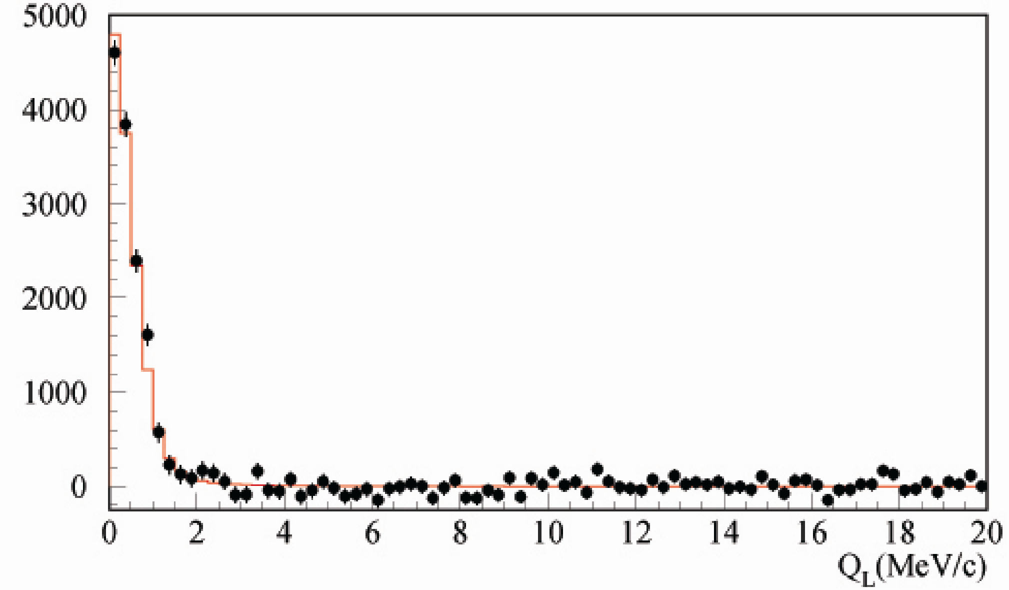


Atomic pairs (2001)



DIRAC preliminary results with GEM/MSGC





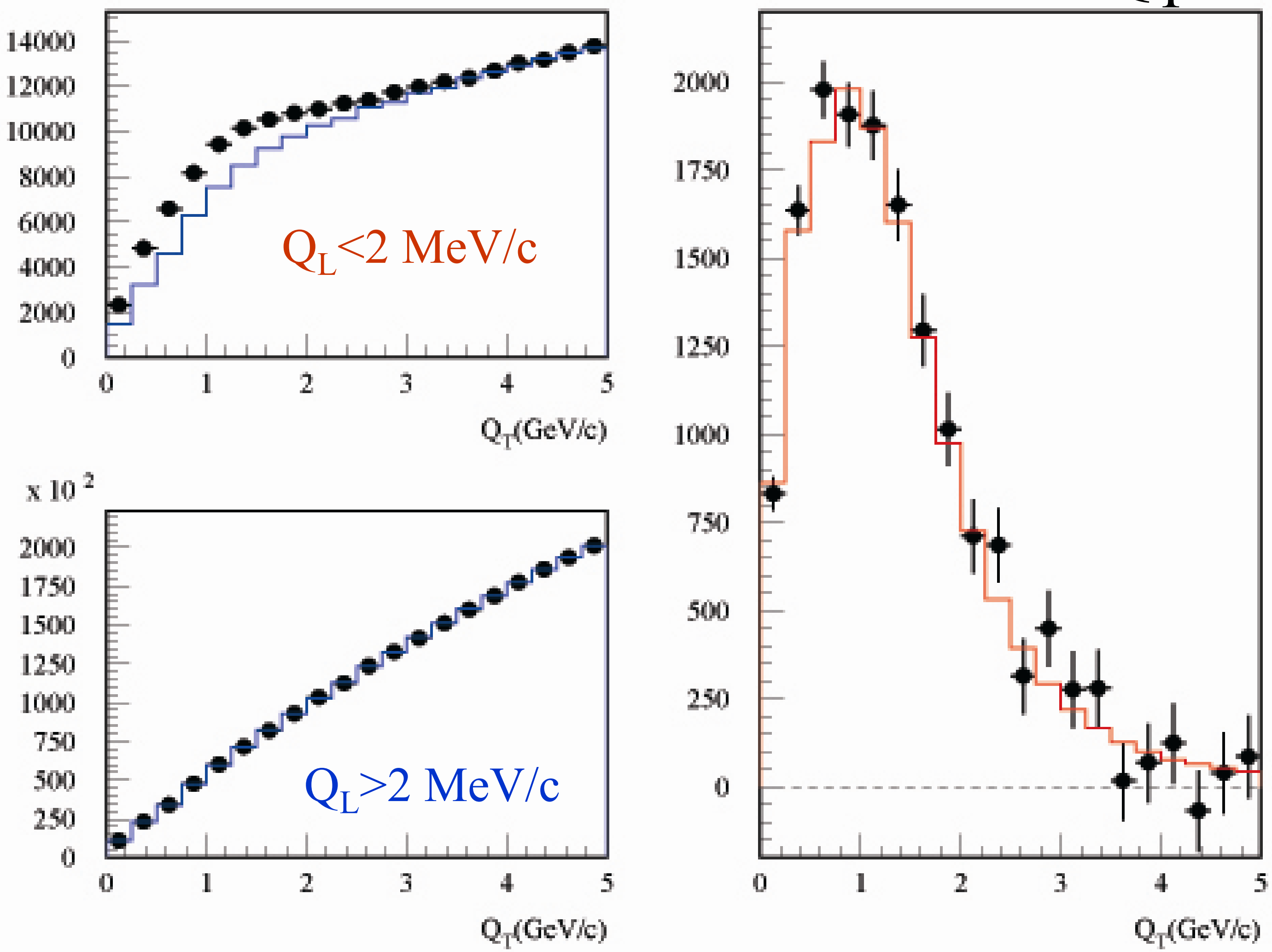
Q_L distribution

←All events

←After background subtraction

DIRAC preliminary results with GEM/MSGC

Q_T distribution



←After background subtraction for Q_L<2MeV/c

DIRAC Experimental results

$A_{2\pi}$ lifetime

2005 **DIRAC** (PL B619, 50)

$$\tau = \left(2.91 \,{}^{+0.45}_{-0.38}\Big|_{stat} \;{}^{+0.19}_{-0.49}\Big|_{syst}\right) \text{fs} = \left(\ldots {}^{+0.49}_{-0.62}\Big|_{tot}\right) \text{fs}$$

...based on 2001 data (6530 observed atoms)

$$\Rightarrow |a_0 - a_2| = 0.264 \pm 7.2\%\Big|_{stat} \pm {}^{10}_{3}\%\Big|_{syst} = \ldots \boxed{\pm {}^{13}_{8}\%\Big|_{tot}}$$

2008 **DIRAC** (SPSC 22/04/08)

$$\tau = \left(2.82 \,{}^{+0.25}_{-0.23}\Big|_{stat} \pm 0.19\Big|_{syst}\right) \text{fs} = \left(\ldots {}^{+0.31}_{-0.30}\Big|_{tot}\right) \text{fs}$$

...major part 2001-03 data (13300 observed atoms)

$$\Rightarrow |a_0 - a_2| = 0.268 \pm 4.4\%\Big|_{stat} \pm 3.7\%\Big|_{syst} = \ldots \boxed{\pm 5.5\%\Big|_{tot}}$$

Including GEM/MicroStripGasChambers => number of reconstructed events is 17000
=> the statistical error in $|a_0$-$a_2|$ is 3%, and the expected full error is <5%.

Comparison with other experimental results

$K\to 3\pi$:

2006 **NA48/2** (PL B633, 173)

...with ChPT constraint between a_0 and a_2:

$$\Rightarrow a_0 - a_2 = 0.264 \pm 2.3\%|_{stat} \pm 1.5\%|_{syst} \pm 4.9\%|_{ext} = \ldots \pm 5.6\%|_{tot}$$

2009 **NA48/2** (seminar at CERN)

...without constraint (a_2 free):

$$\Rightarrow a_0 - a_2 = 0.257 \pm 1.9\%|_{stat} \pm 0.8\%|_{syst} \pm 0.4\%|_{ext} \pm 3.5\%|_{th} = \ldots \pm 4.1\%|_{tot}$$

$$\Rightarrow a_2 = -0.024 \pm 54\%|_{stat} \pm 38\%|_{syst} \pm 8.3\%|_{ext} \pm 63\%|_{th} = \ldots \pm 92\%|_{tot}$$

...with ChPT constraint between a_0 and a_2:

$$\Rightarrow a_0 - a_2 = 0.263 \pm 0.8\%|_{stat} \pm 0.4\%|_{syst} \pm 0.8\%|_{ext} \pm 1.9\%|_{th} = \ldots \pm 2.2\%|_{tot}$$

Comparison with other experimental results

Ke4:

2008 **NA48/2** (EPJ C54, 411)

...without constraint (a_2 free):

$$\Rightarrow a_0 = 0.233 \pm 6.9\%\big|_{stat} \pm 3.0\%\big|_{syst} = \ldots \pm 7.5\%\big|_{tot}$$

$$\Rightarrow a_2 = -0.0471 \pm 23\%\big|_{stat} \pm 8.5\%\big|_{syst} = \ldots \pm 25\%\big|_{tot}$$

2009 **NA48/2** (seminar at CERN)

...without constraint (a_2 free):

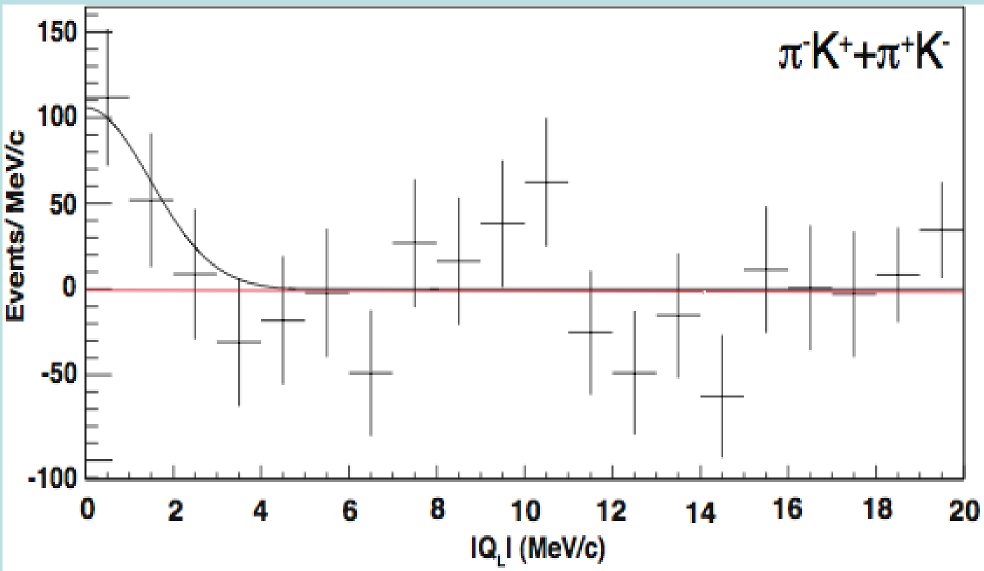
$$\Rightarrow a_0 = 0.2220 \pm 5.8\%\big|_{stat} \pm 2.3\%\big|_{syst} \pm 1.7\%\big|_{th} = \ldots \pm 6.5\%\big|_{tot}$$

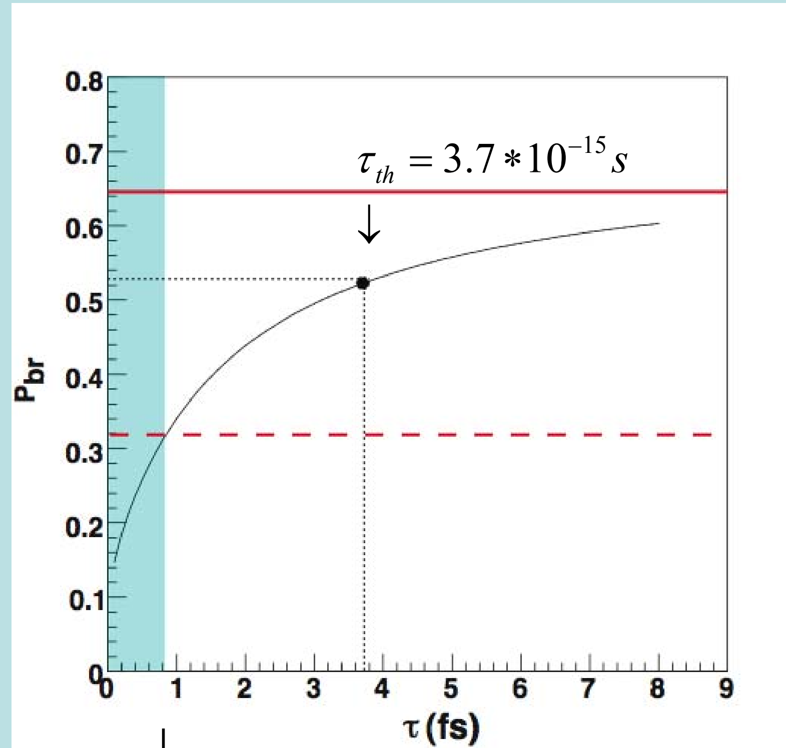
$$\Rightarrow a_2 = -0.0432 \pm 20\%\big|_{stat} \pm 7.9\%\big|_{syst} \pm 6.5\%\big|_{th} = \ldots \pm 22\%\big|_{tot}$$

...with ChPT constraint between a_0 and a_2:

$$\Rightarrow a_0 = 0.2206 \pm 2.2\%\big|_{stat} \pm 0.8\%\big|_{syst} \pm 2.9\%\big|_{th} = \ldots \pm 3.7\%\big|_{tot}$$

$\pi^- K^+$ and $\pi^+ K^-$ atom signal





$\downarrow$

In total:
173±54 πK-atomic pairs are observed
with a significance of 3.2σ.

$\tau > 0.8 * 10^{-15} s$ at 90%CL

B. Adeva et al.,“Evidence for πK-atoms with DIRAC”, Physics Letters B 674 (2009) 11
Y. Allkofer, PhD Thesis, Universität Zürich, 2008.

Plans for 2010

Observation of the long-lived states of $A_{2\pi}$ is opening a possibility to measure the Lamb shift and to determine the new combination of $\pi\pi$ scattering lengths $2a_0 + a_2$.

For this observation, which was planed in our addendum, we need the run in 2010 during around 5 months in the same conditions as in 2009.

Metastable Atoms

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

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

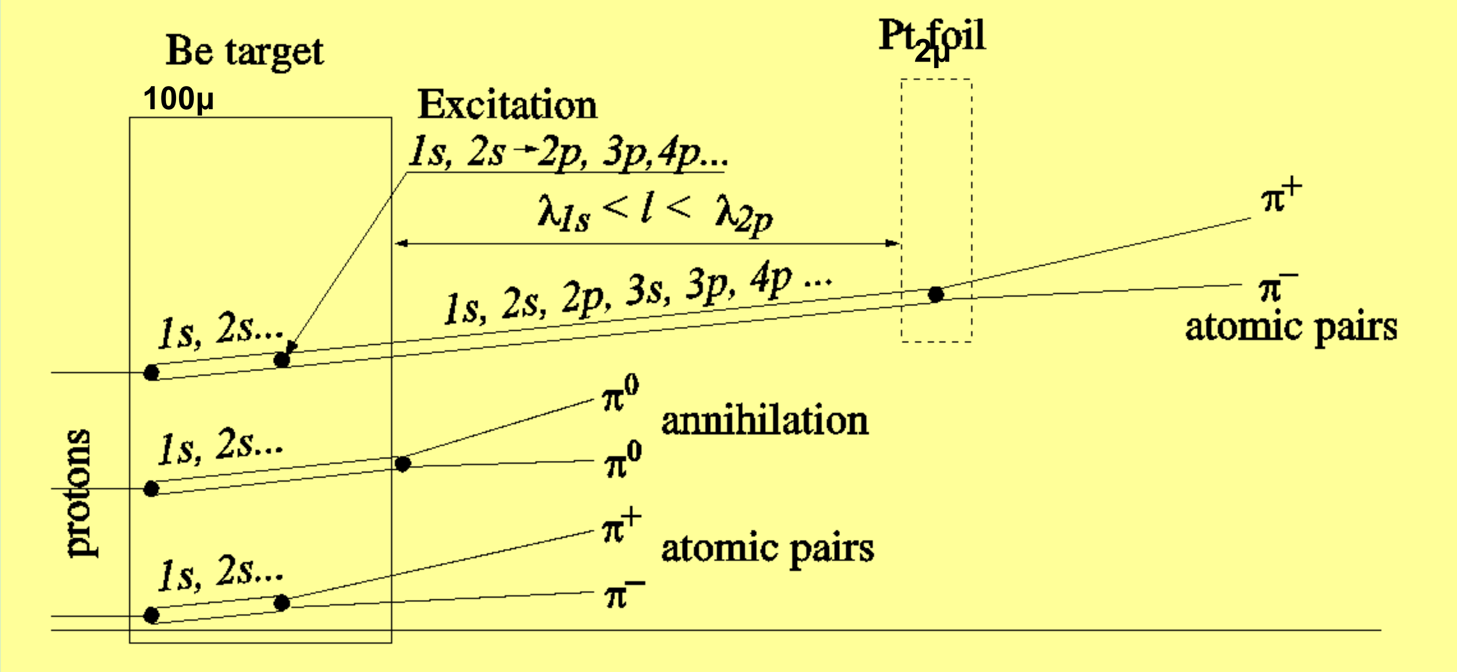


Illustration for observation of the $A_{2\pi}$ long-lived states with breaking foil.

Metastable Atoms

Probabilities of the $A_{2\pi}$ breakup (Br) and yields of the long-lived states for different targets provided the maximum yield of summed population of the long-lived states: **$\Sigma(l \geq 1)$**

Target Z	Thickness μ	Br	Σ ($l \geq 1$)	$2p_0$	$3p_0$	$4p_0$	Σ ($l = 1$, $m = 0$)
04	100	4.45%	5.86%	1.05%	0.46%	0.15%	1.90%
06	50	5.00%	6.92%	1.46%	0.51%	0.16%	2.52%
13	20	5.28%	7.84%	1.75%	0.57%	0.18%	2.63%
28	5	9.42%	9.69%	2.40%	0.58%	0.18%	3.29%
78	2	18.8%	10.5%	2.70%	0.54%	0.16%	3.53%

Energy splitting between np - ns states in $\pi^+\pi^-$ atom

$$\Delta E_n \equiv E_{ns} - E_{np}$$

$$\Delta E_n \approx \Delta E_n^{vac} + \Delta E_n^{s} \qquad \Delta E_n^s \sim 2a_0 + a_2$$

For $n = 2$

$$\Delta E_2^{vac} = -0.107\ eV \quad from\ QED\ calculations$$

$$\Delta E_2^{s} \approx -0.45\ eV \quad numerical\ estimated\ value\ from\ ChPT$$

$$a_0 = 0.220 \pm 0.005$$
$$a_2 = -0.0444 \pm 0.0010$$

(2001) *G. Colangelo, J. Gasser and H. Leutwyler*

$$\Rightarrow \boxed{\Delta E_2 \approx -0.56\ \text{eV}}$$

(1979) A. Karimkhodzhaev and R. Faustov
(1983) G. Austen and J. de Swart
(1986) G. Efimov *et al.*
(1999) A. Gashi *et al.*
(2000) D. Eiras and J. Soto
(2004) J. Schweizer, EPJ C36 483
A. Rusetsky, *priv. comm.*

Prospects of DIRAC

Creation of an intense source of $\pi\pi$, πK and other exotic atoms at SPS proton beam and using them for accurate measurements of all S-wave $\pi\pi$ and πK scattering length to check the precise low energy QCD predictions

DIRAC prospects at SPS CERN

Yields of atoms at PS and SPS

Yield of dimeson atoms per one proton-Ni interaction, detectable by DIRAC upgrade setup at Θ_L=5.7°						
	24 GeV			450 GeV		
E_p	$A_{2\pi}$	$A_{K^+\pi^-}$	$A_{\pi^+K^-}$	$A_{2\pi}$	$A_{K^+\pi^-}$	$A_{\pi^+K^-}$
W_A	$1.1\cdot10^{-9}$	$0.52\cdot10^{-10}$	$0.29\cdot10^{-10}$	$0.13\cdot10^{-7}$	$0.10\cdot10^{-8}$	$0.71\cdot10^{-9}$
W_A^N	1.	1.	1.	12.	19.	24.
W_A/W_π	$3.4\cdot10^{-8}$	$16.\cdot10^{-10}$	$9.\cdot10^{-10}$	$1.3\cdot10^{-7}$	$1.\cdot10^{-8}$	$7.1\cdot10^{-9}$
W_A^N/W_π^N	1.	1.	1.	3.8	6.2	8.
				A multiplier due to different spill duration ~4		
Total gain	**1.**	**1.**	**1.**	**15.**	**25.**	**32.**

DIRAC prospects at SPS CERN

Present low-energy ***QCD*** predictions for ***ππ*** and ***πK*** scattering lengths

$\pi\pi \quad \delta a_0 = 2.3\% \quad \delta a_2 = 2.3\% \quad \delta(a_0 - a_2) = 1.5\%$ …will be improved by *Lattice* calculations

$\pi K \quad \underbrace{\delta a_{1/2} = 11\% \quad \delta a_{3/2} = 40\%}_{ChPT} \quad \underbrace{\delta a_{1/2} = 10\% \quad \delta a_{3/2} = 17\%}_{Roy\text{-}Steiner}$ …will be significantly improved by *ChPT*

Planned results of DIRAC ADDENDUM at PS CERN after 2008-2009

$$\tau(A_{2\pi}) \rightarrow \delta(a_0 - a_2) = \pm 2\%(stat) \pm 1\%\ (syst) \pm 1\%\ (theor)$$

$$\tau(A_{\pi K}) \rightarrow \delta(a_{1/2} - a_{3/2}) = \pm 10\%(stat) \pm ....\pm 1.5\%\,(theor)$$

2010-2011 Observation of metastable $\pi^+\pi^-$ atoms and study of a possibility to measure its Lamb shift.
Study of the possibility to observe K^+K^- and $\pi^\pm\mu^\mp$ atoms using 2008-2009 data.

DIRAC at SPS CERN beyond 2011

$$\tau(A_{2\pi}) \rightarrow \delta(a_0 - a_2) = \pm 0.5\%(stat) \qquad \tau(A_{\pi K}) \rightarrow \delta(a_{1/2} - a_{3/2}) = \pm 2.5\%(stat)$$

$$(E_{np} - E_{ns})_{\pi\pi} \rightarrow \delta(2a_0 + a_2) \qquad (E_{np} - E_{ns})_{\pi K} \rightarrow \delta(2a_{1/2} + a_{3/2})$$

Thank you for your attention

Estimation of relative errors for break-up probability measurement

	Q	Q_L	Q_L,Q_T
Statistical	0.031	0.044	0.031
Multiple scattering	0.018	0.008	0.014
Heavy particles admixture	0.001	0.008	0.001
Finit size effects	0./ -0.006	0./ -0.004	0./ -0.005/
Double track resolution	0.009	0.001	0.003
Background particles	0.002	0.003	0.002
Trigger simulation	0.002	0.002	0.003
All systematic	+0.021/ -0.022	0.012	+0.015/ -0.016

Estimation of relative errors for lifetime

Statistical	**0.0[illegible]7 - 0.122**
Systematic	0.033 - 0.060