Последние результаты коллаборации DIRAC в CERN по изучению $\pi^+\pi^-$ и πK атомов

Л.Афанасьев ОИЯИ от коллаборации ДИРАК

Workshop on Precision Physics and Fundamental Physical Constants

Всероссийское совещание по прецизионной физике и фундаментальным физическим константам

Дубна, 6-9 декабря 2011

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

Trieste University and INFN-Trieste
Trieste, Italy

University of Messina
Messina, Italy

KEK
Tsukuba, Japan

Kyoto Sangyou University
Kyoto, Japan

Tokyo Metropolitan University
Tokyo, Japan

IFIN-HH
Bucharest, Romania

JINR
Dubna, Russia

IHEP
Protvino, Russia

SINP of Moscow State University
Moscow, Russia

Santiago de Compostela University
Santiago de Compostela, Spain

Bern University
Bern, Switzerland

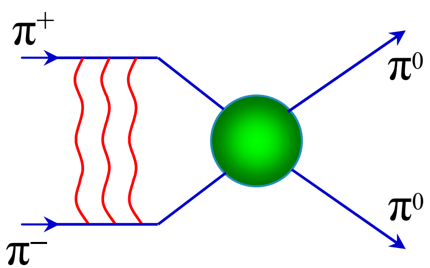
Zurich University
Zurich, Switzerland

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≈0.5 MeV

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



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

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

Uretsky 1961; Bilenkiy 1969

* Gasser et al (2001)

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

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

$$\frac{\Delta\tau}{\tau} = 10\% \;\Rightarrow\; \frac{\Delta\,|a_0 - a_2|}{|a_0 - a_2|} = 5\%$$

Theoretical Status

In ChPT the effective Lagrangian which describes the ππ interaction is an expansion in (even) terms: $$L_{eff} = \underbrace{L^{(2)}}_{\text{(tree)}} + \underbrace{L^{(4)}}_{\text{(1-loop)}} + \underbrace{L^{(6)}}_{\text{(2-loop)}} + \cdots$$

1966 Weinberg (tree): $L^{(2)}$ $a_0 - a_2 = 0.20$

1984 Gasser-Leutwyler (1-loop): $L^{(4)}$ $a_0 - a_2 = 0.25 \pm 0.01$

1995 Knecht et al. (2-loop): $L^{(6)}$ gChPT

1996 Bijnens et al. (2-loop): $L^{(6)}$ $a_0 - a_2 = 0.258 \pm (< 3\%)$

2001 Colangelo et al. (& Roy): $L^{(6)}$ $a_0 - a_2 = 0.265 \pm 0.004 (1.5\%)$

And the theoretical results for the scattering lengths up to 2-loops are:

	Tree (Weinberg)	1-loop (Gass.&Leut.)	2-loop (Bijnens et al.)	2loop+Roy (Colangelo et al.)
a_0	0.16	0.203	0.219	0.220 ± 2.3%
a_2	-0.045	-0.043	-0.042	-0.044 ± 2.3%

These results (precision) depend on the low-energy constants (LEC) l_3 and l_4.

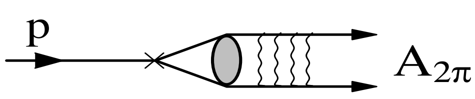
Because *l3* and *l4* are sensitive to the quark condensate, precise measurements of a_0, a_2 are a way to study the **structure** of the QCD vacuum.

Lattice gauge calculations from **2006** provided values for these l_3 and l_4.

Production of pionium

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

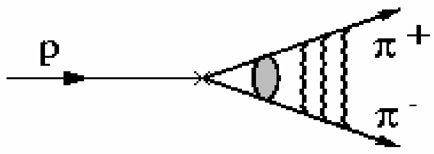
$$\frac{d\sigma_{nlm}^{A}}{d\vec{P}} = (2\pi)^3 \frac{E_A}{M_A} \left|\psi_{nlm}^{(C)}(0)\right|^2 \left.\frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}\right|_{\vec{p}_+=\vec{p}_-} \qquad \sigma_A = k\sigma_C(Q<Q_0)$$



Nemenov 1985

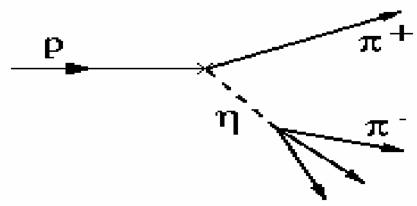
Background processes:

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

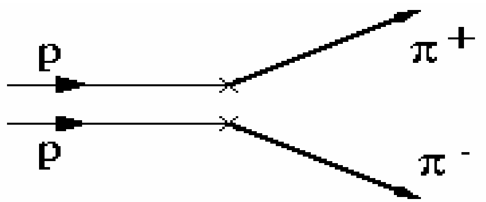


$$\frac{d^2\sigma_C}{d\vec{p}_+ d\vec{p}_-} = A_C(q)\frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}, \qquad A_C(q) = \frac{2\pi m_\pi \alpha / q}{1-\exp(-2\pi m_\pi \alpha / q)}$$

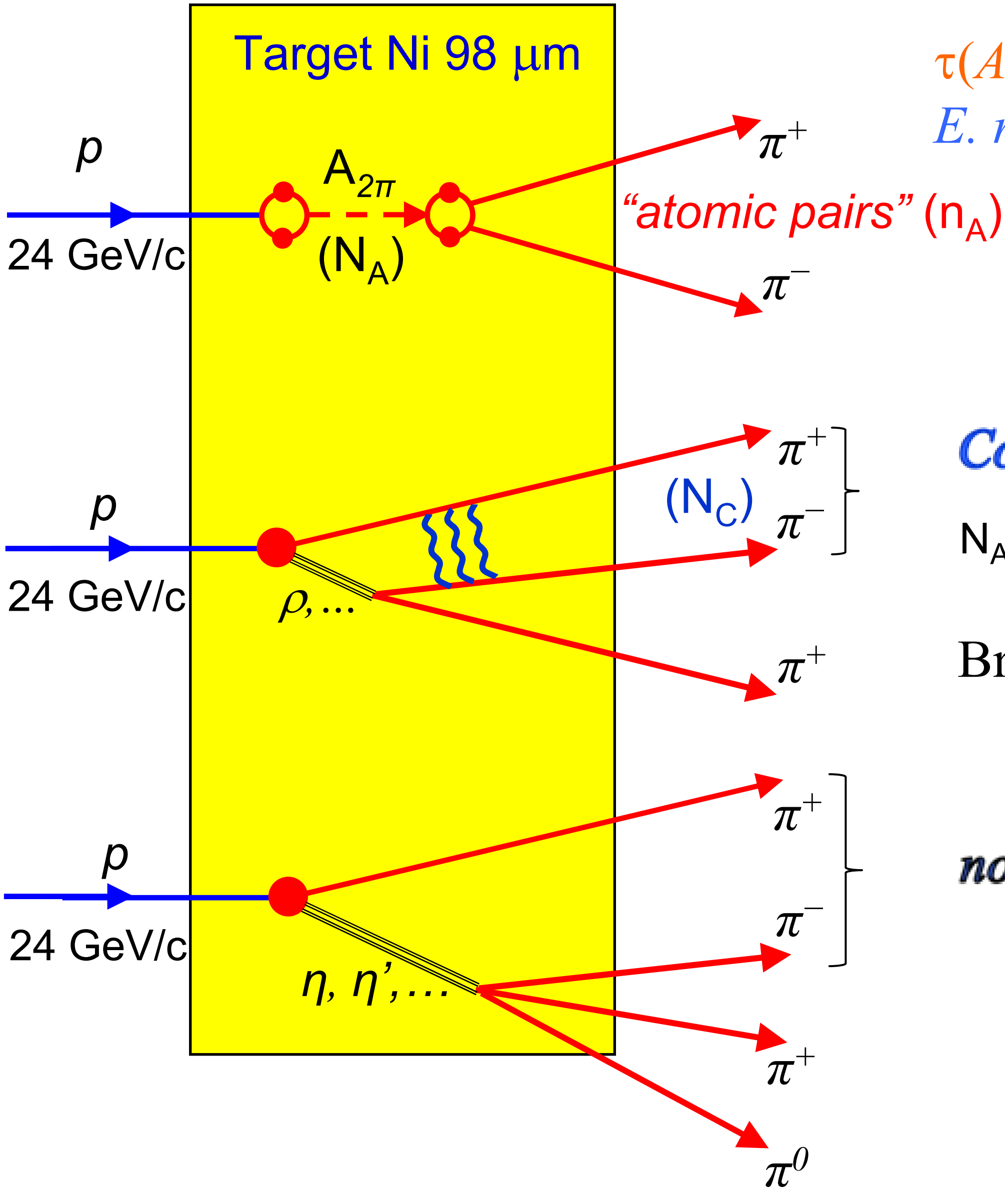
Non-Coulomb pairs. They are produced in one proton nucleus collision. At least one pion originates from a long lived resonance. No Coulomb interaction in the final state



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



Method of $A_{2\pi}$ 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*

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:

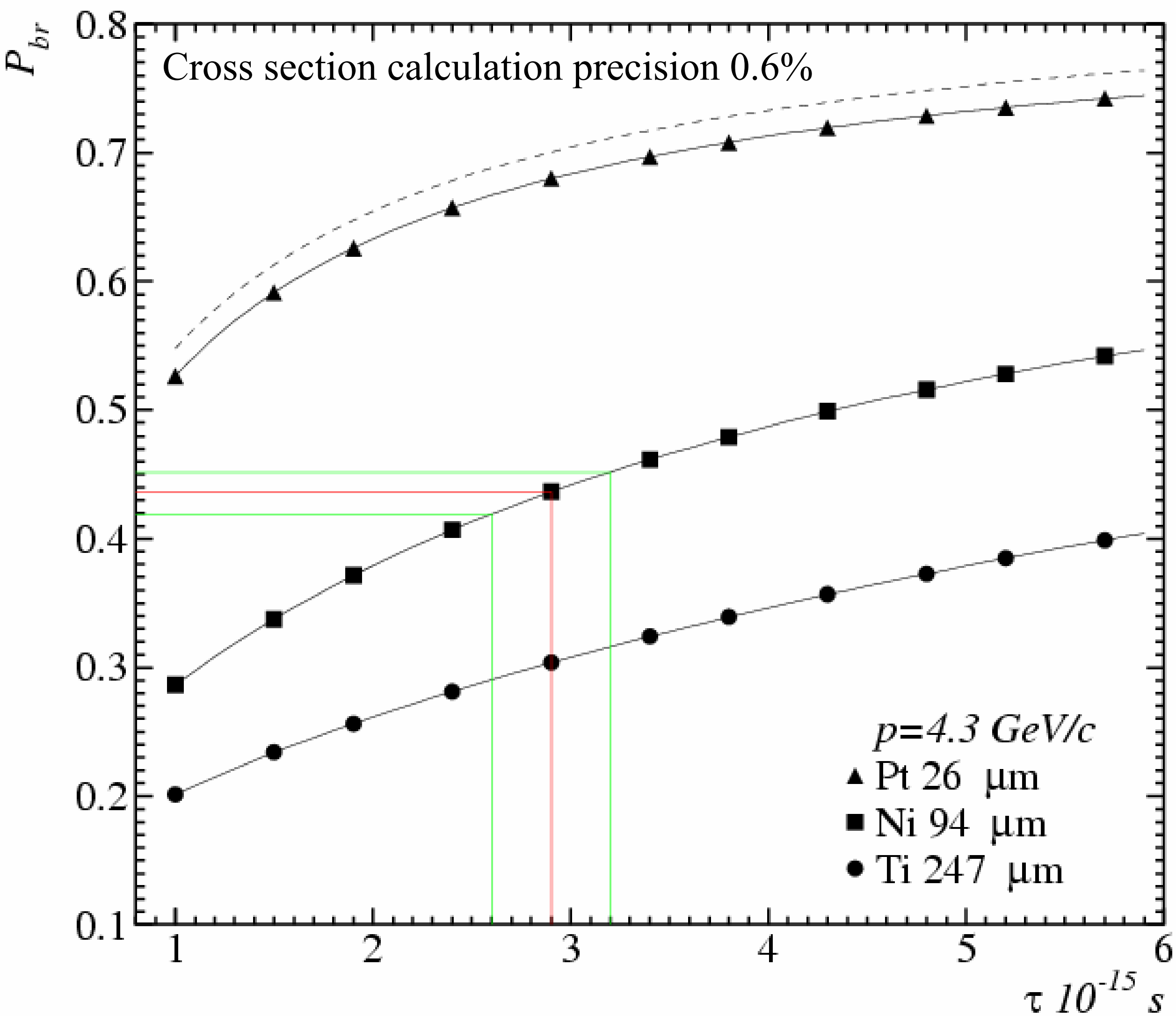
$$a_{nlm}^{n'l'm'} = \frac{\sigma_{nlm}^{n'l'm'} \rho N_0}{A} \quad \text{if } nlm \neq n'l'm', \qquad a_{nlm}^{nlm} = -\frac{\sigma_{nlm}^{tot} \rho N_0}{A} - \begin{cases} 2M_\pi / Pc\tau_n & l=0. \\ 0 & l \neq 0. \end{cases}$$

$\sigma_{nlm}{}^{n'l'm'}$ 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

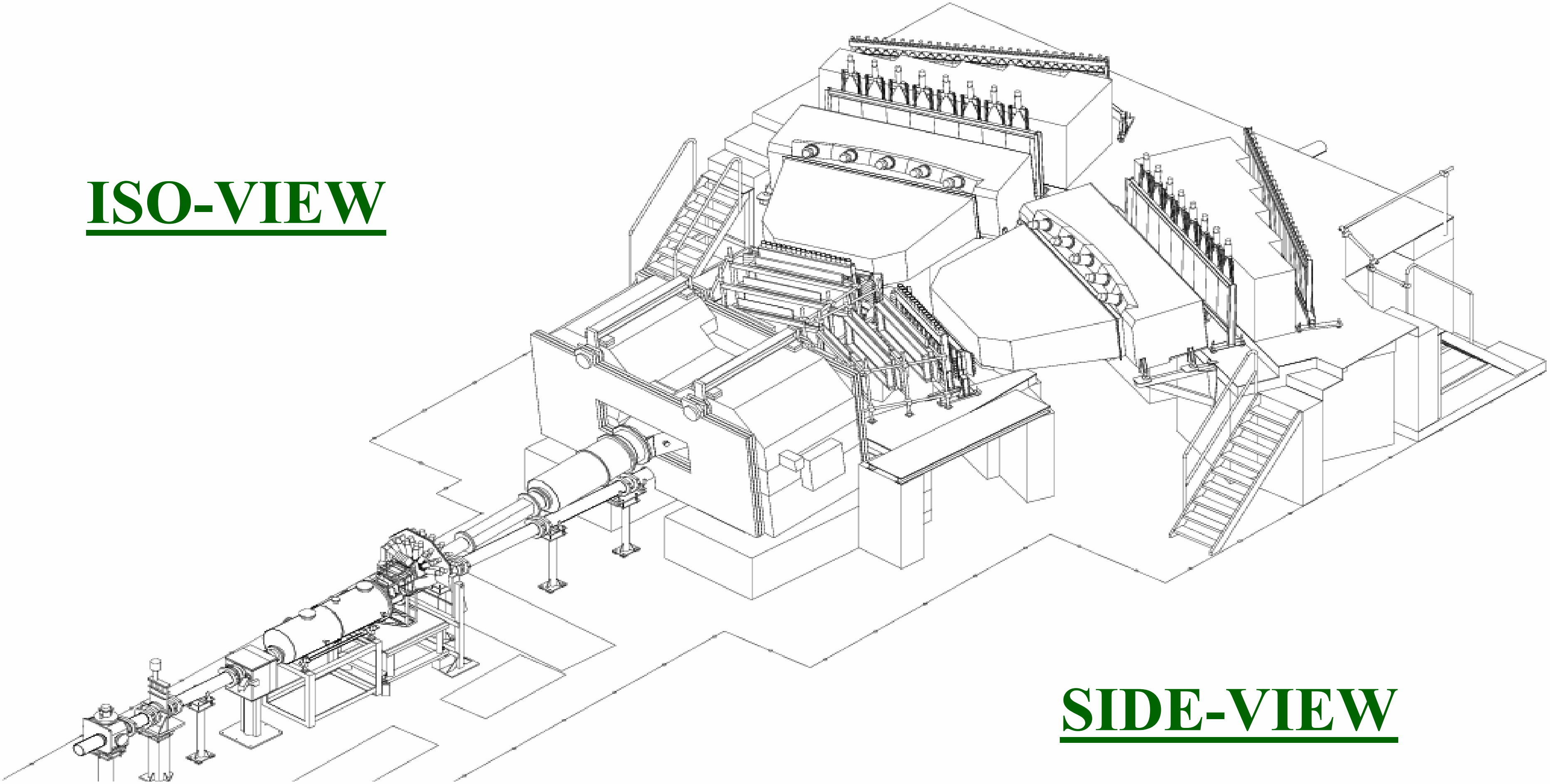


$\delta\tau = 10\% \rightarrow \delta Pbr = 4\%$

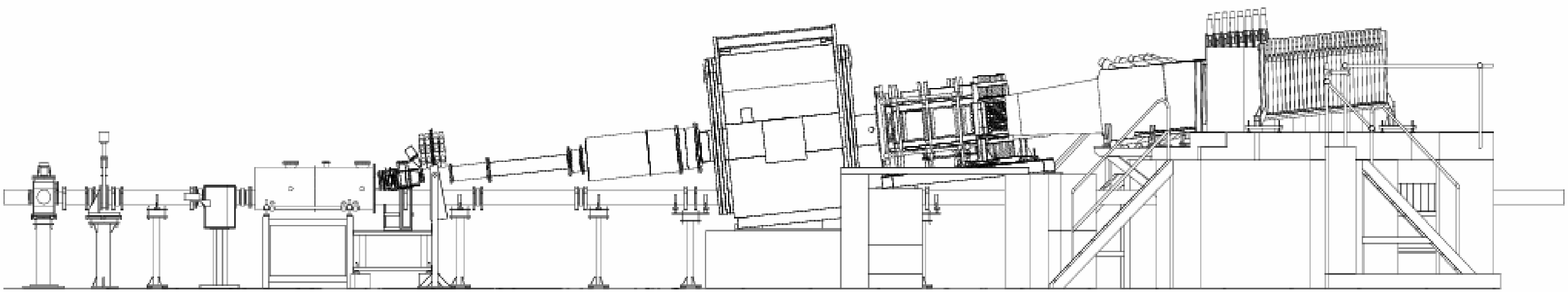
All targets have the same thickness in radiation lengths $6.7*10^{-3}$ X_0

There is an optimal target material for a given lifetime

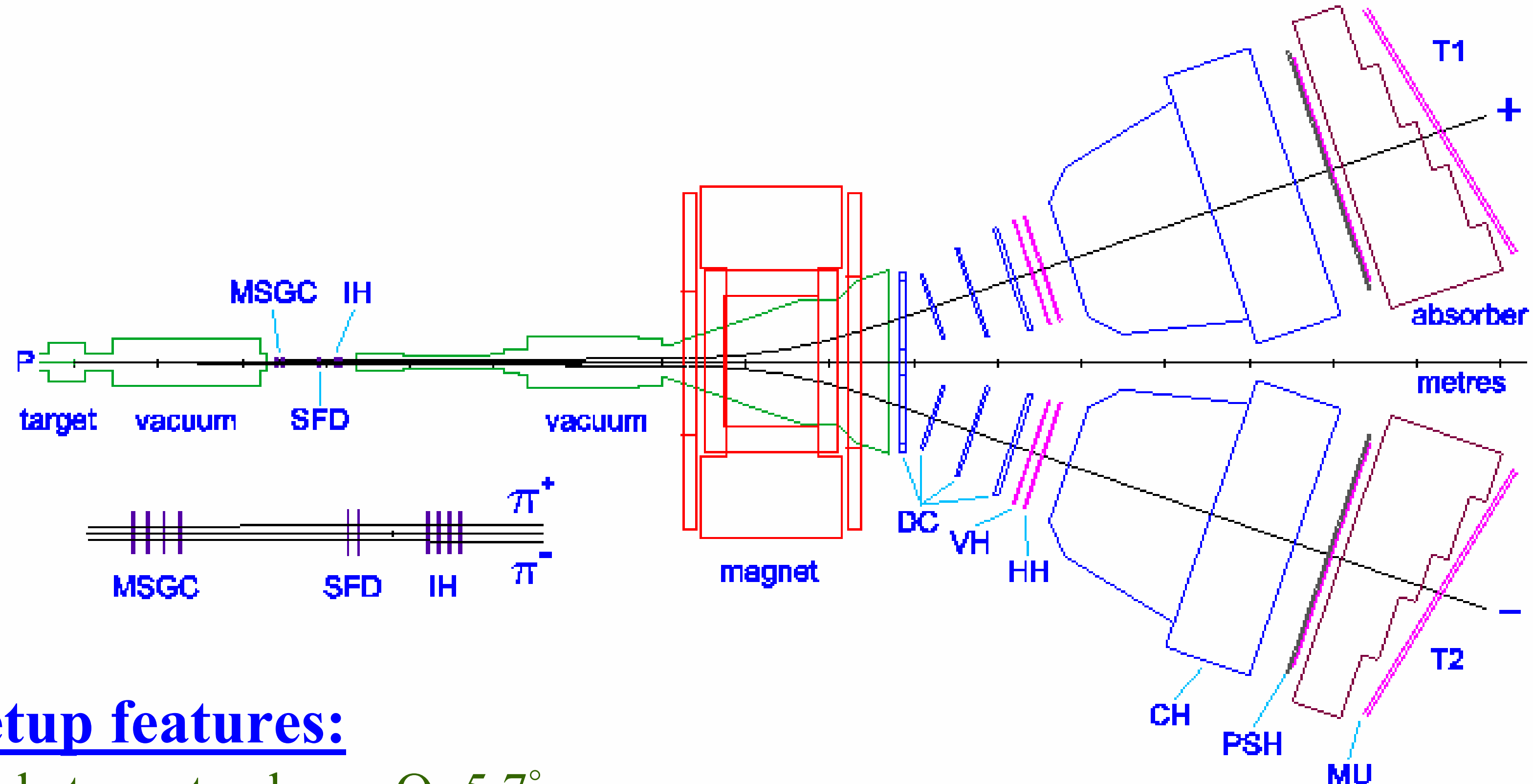
ISO-VIEW



SIDE-VIEW



DIRAC Spectrometer



Setup features:

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

channel aperture $\Omega = 1.2 \cdot 10^{-3}$ sr

magnet 2.3 T·m

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

Thin targets: ~ 7 ×10–3 X_0, Nuclear efficiency: 3×10^{-4}

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

Proton beam ~ 10^{11} proton/spill

Analysis based on MC

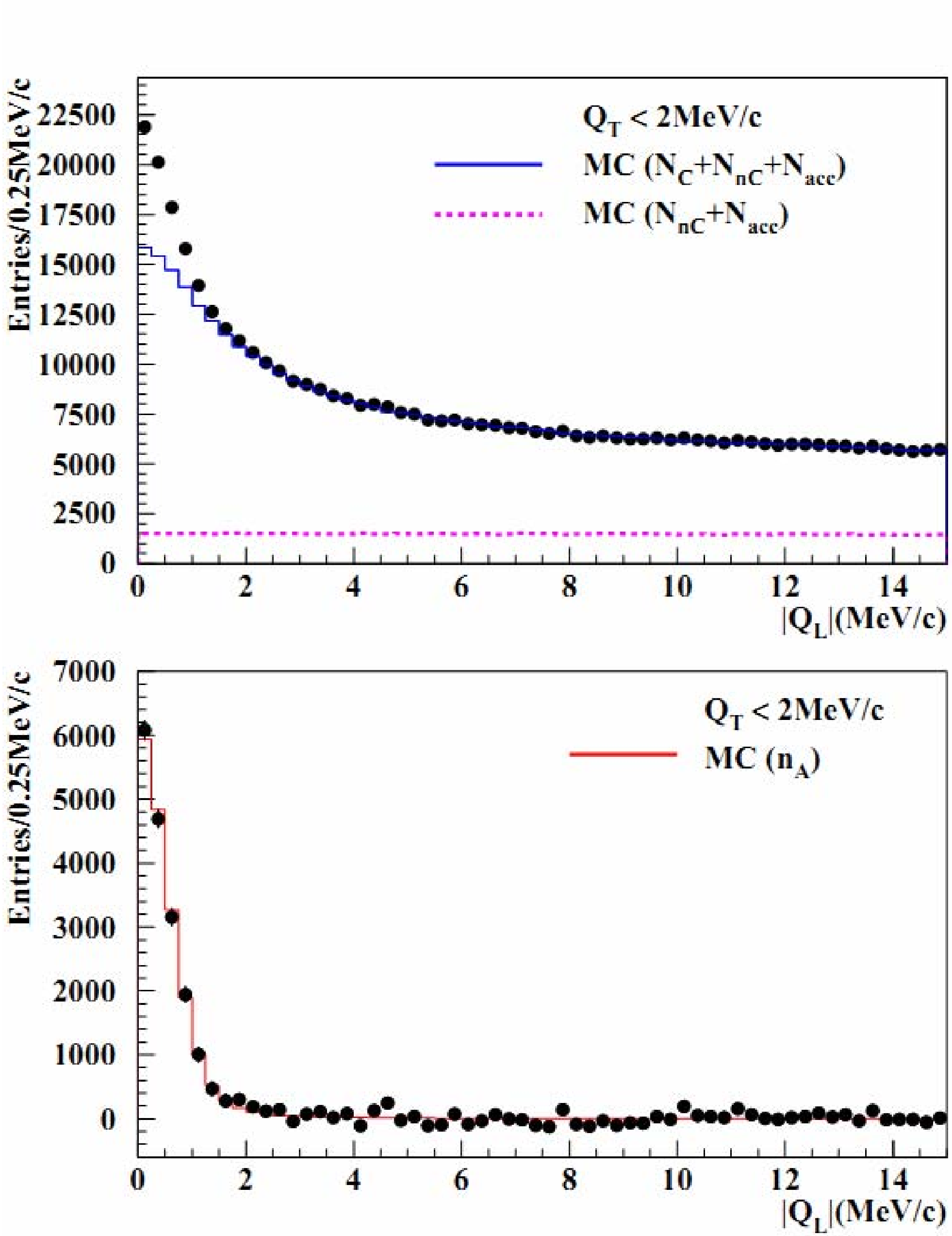
Atoms are generated in **nS states** using measured momentum distribution for **short-lived** sources. The atomic pairs are generated according to the evolution of the atom while propagating through the target

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.

DIRAC results

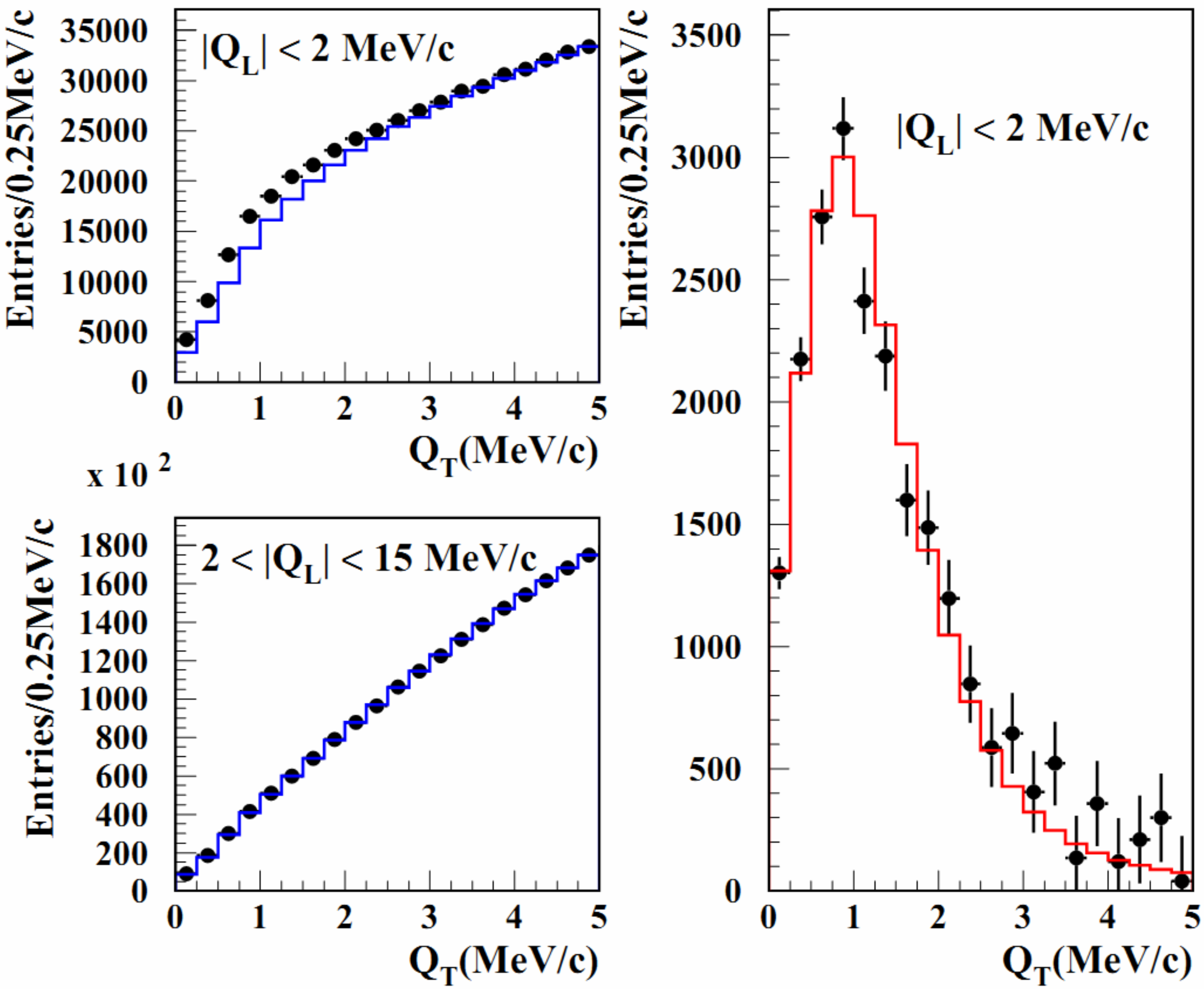


Q_L distribution

←All events

←After background subtraction

DIRAC results

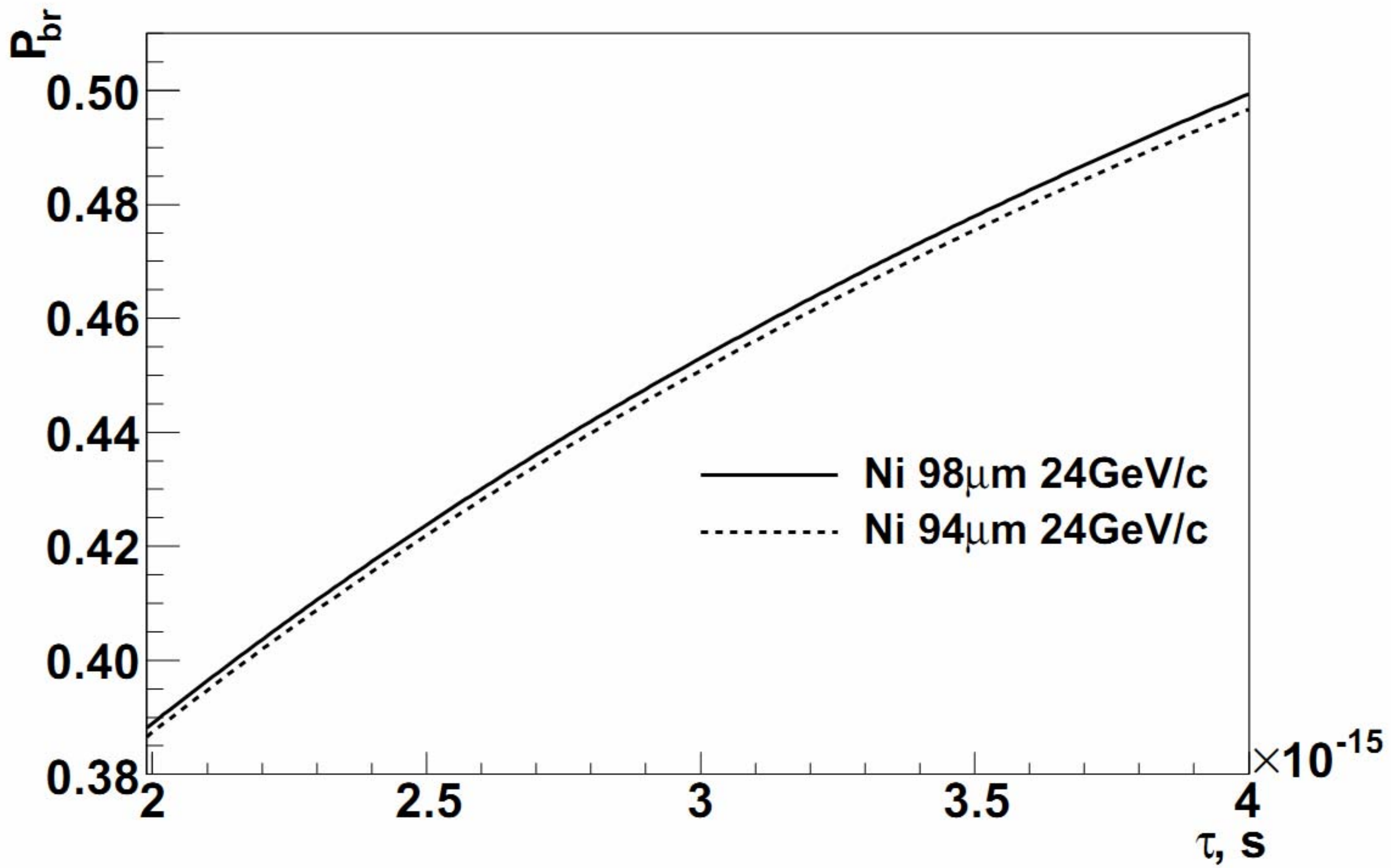


Q_T distribution

←After background subtraction for Q_L<2MeV/c

Results

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	



Systematic Errors

Systematic errors on P_{br}

source	σ
multiple scattering	± 0.0077
momentum smearing	± 0.0026
double-track resolution	± 0.0014
K^+K^- and $p\bar{p}$	± 0.0011
trigger simulation	± 0.0004
background hits	± 0.0001
target impurity	± 0.0013
finite size	± 0.0011
calculation of $P_{br}(\tau)$	± 0.0042
Overall error	± 0.0094

Results: lifetime & scattering length

DIRAC data	τ_{1s} $(10^{-15}s)$ value	stat	syst	theo*	tot	$\lvert a_0 - a_2 \rvert$ value	stat	syst	theo*	tot	Reference
2001	2.91	$^{+0.45}_{-0.38}$	$^{+0.19}_{-0.49}$		$[21\%]$	0.264	$^{+0.017}_{-0.020}$	$^{+0.022}_{-0.009}$		$[12\%]$	PL B 619 (2005) 50
2001-03	3.15	$^{+0.20}_{-0.19}$	$^{+0.20}_{-0.18}$		$[9\%]$	0.2533	$^{+0.0080}_{-0.0078}$	$^{+0.0078}_{-0.0073}$		$[4\%]$	PL B 704 (2011) 24

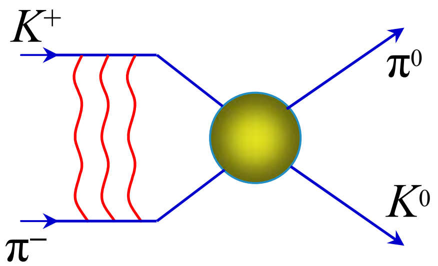
* theoretical uncertainty included in systematic error

NA48	K-decay	$a_0 - a_2$ value	stat	syst	theo	tot	Reference
2009	$K_{3\pi}$	0.2571	± 0.0048	± 0.0029	0.0088		EPJ C64 (2009) 589
2010	K_{e4} & $K_{3\pi}$	0.2639	± 0.0020	± 0.0015			EPJ C70 (2010) 635

$K^+\pi^-$ 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), $\tau=1/\Gamma$ 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 $\dfrac{\Delta\Gamma}{\Gamma} = 20\,\% \quad \Rightarrow \quad \dfrac{\Delta\left|a_{1/2} - a_{3/2}\right|}{\left|a_{1/2} - a_{3/2}\right|} = 10\,\%$

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

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

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

A. Rossel. – 1999

J. Bijnens, P. Talaver. – April 2004

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

II. Roy-Steiner equations:

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

P.Büttiker et al. – 2004

πK scattering

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

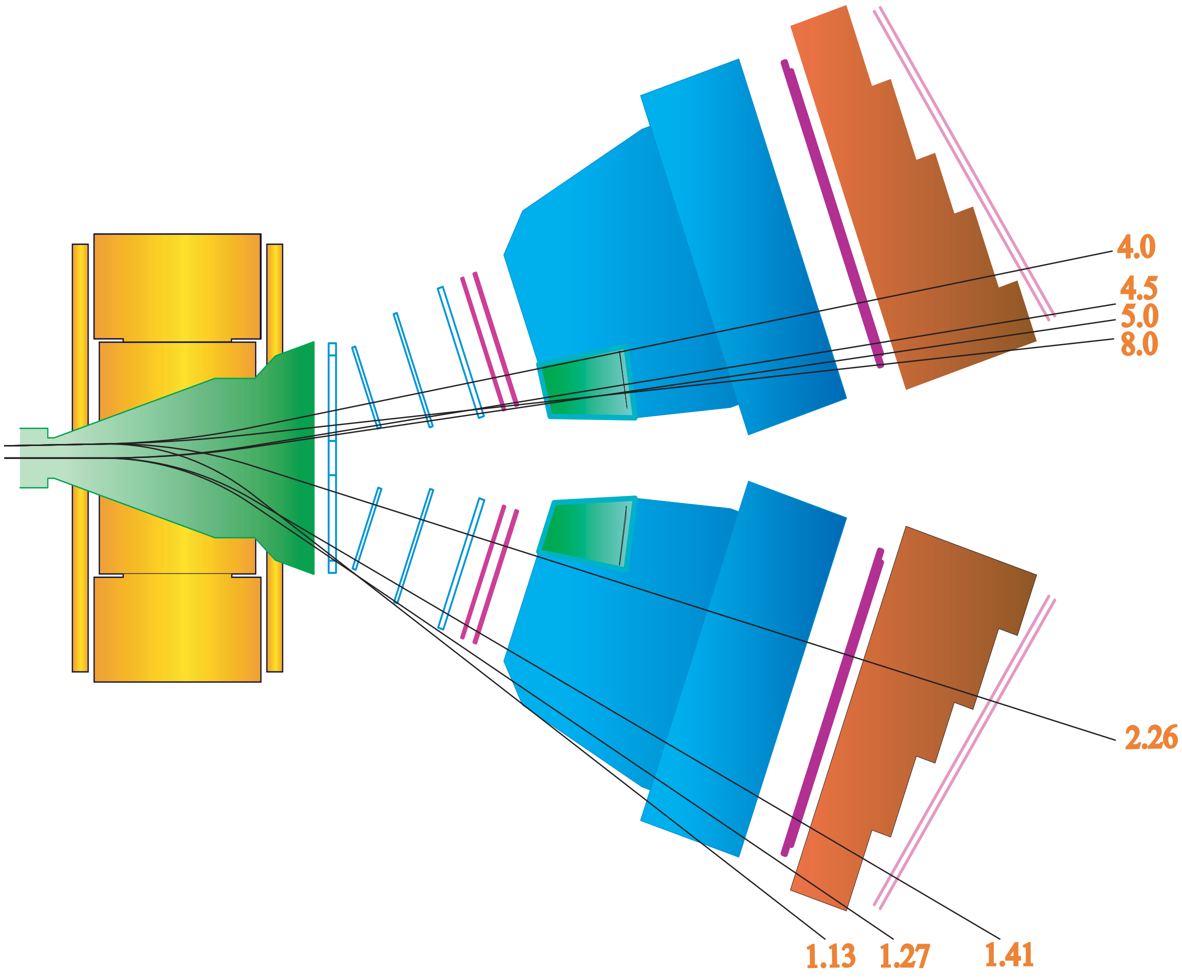
The measurement of the s-wave πK scattering lengths would test our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD (u, d and s quarks), while the measurement of $\pi\pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking (u, d quarks).

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

Experimental data on the πK low-energy phases are absent

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

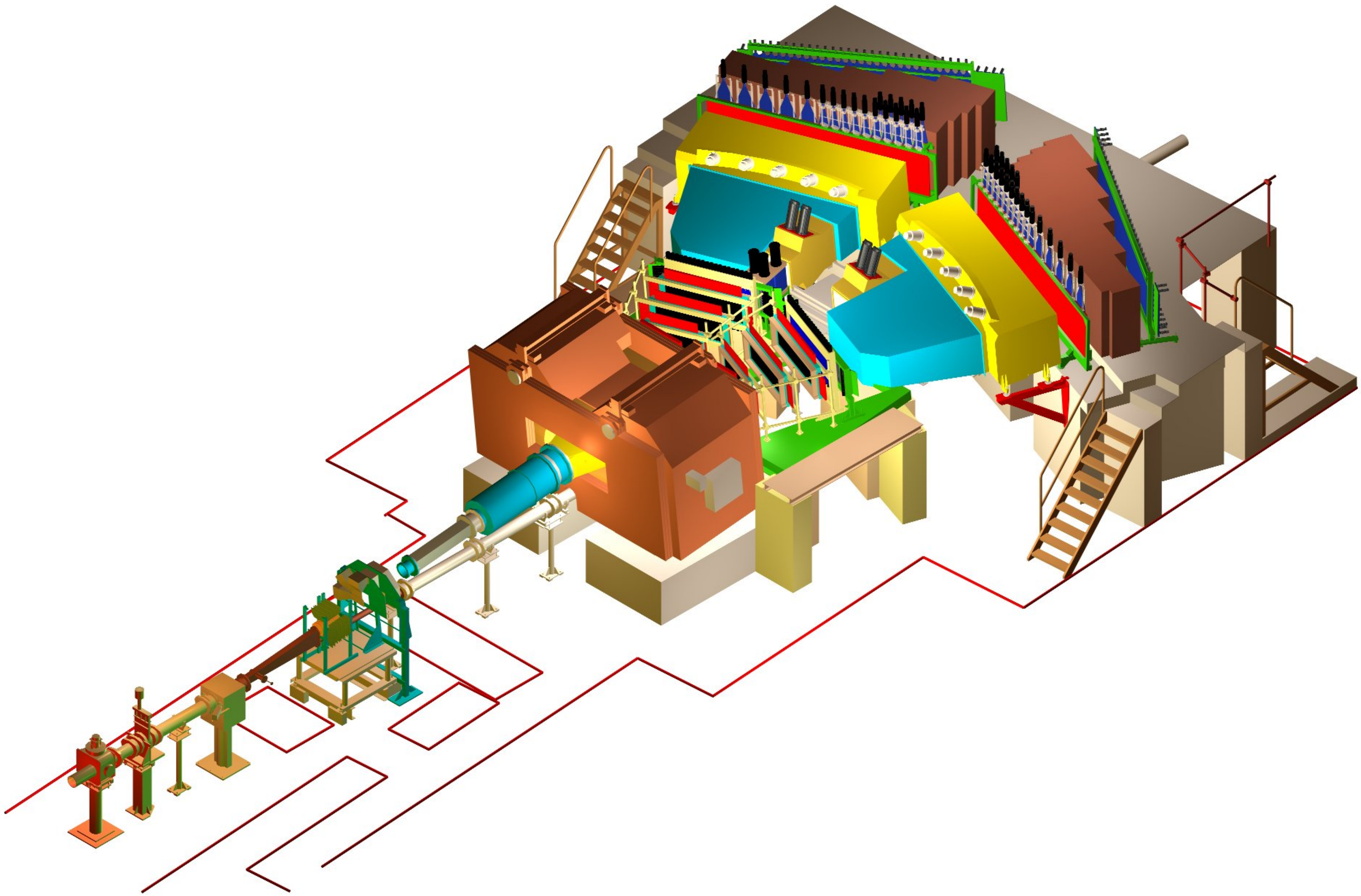
The numbers to the right of the tracks lines are the π^- and K^+ momenta in GeV/c



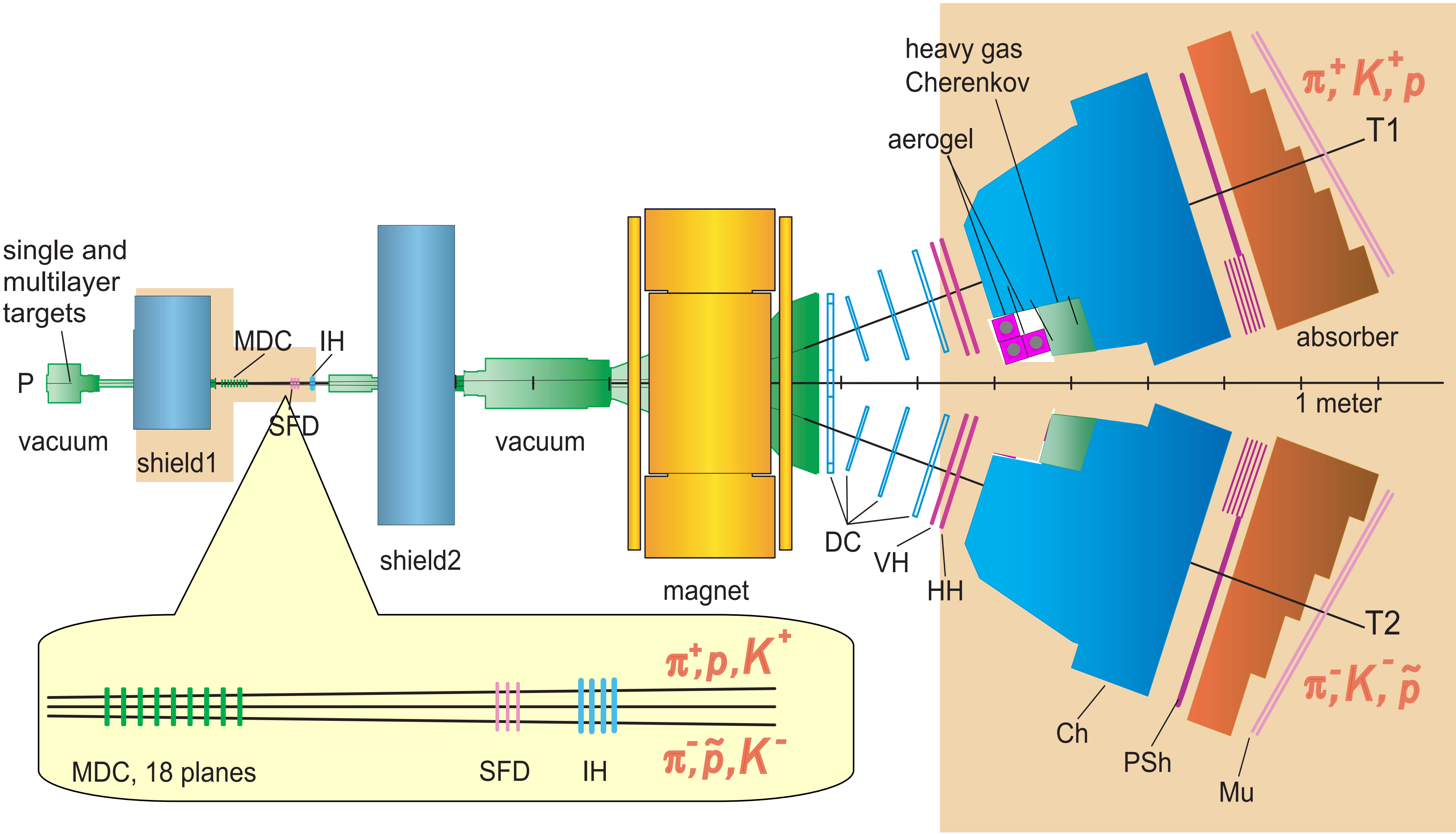
The $A_{K\pi}$, π^- and K^+ momenta are shown in the following table:

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 2007

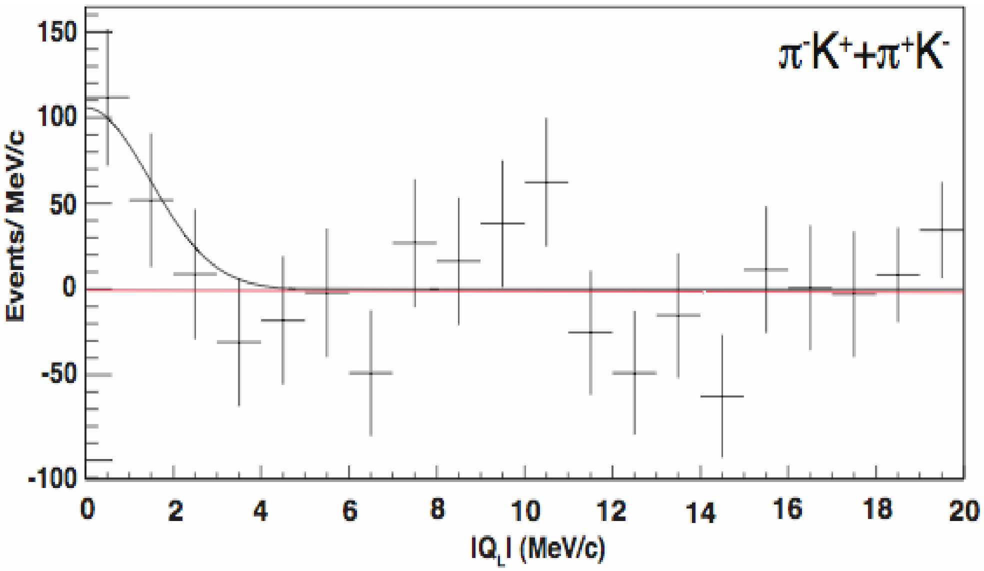


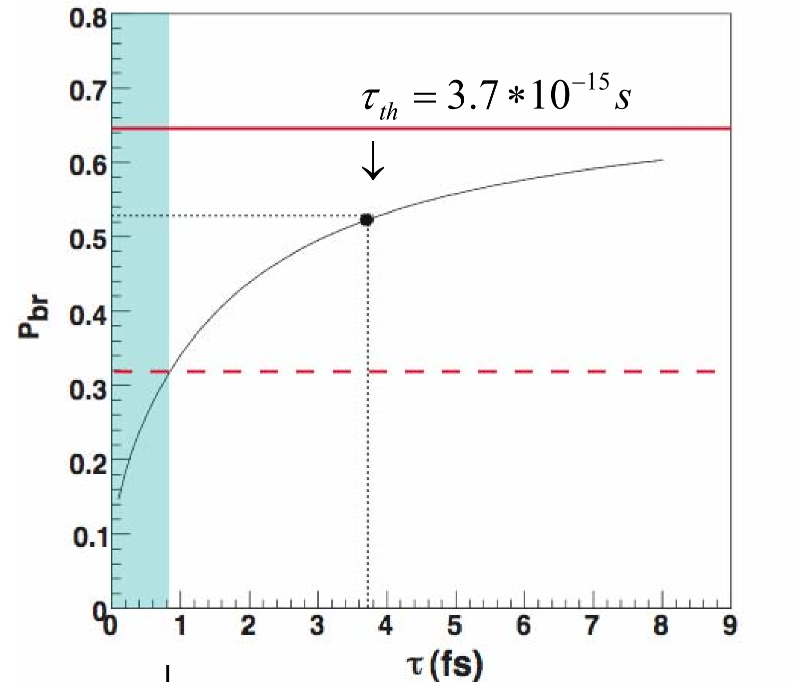
Upgraded DIRAC experimental setup



Modified parts

$\pi^- K^+$ and $\pi^+ K^-$ atom signal (2007 data)





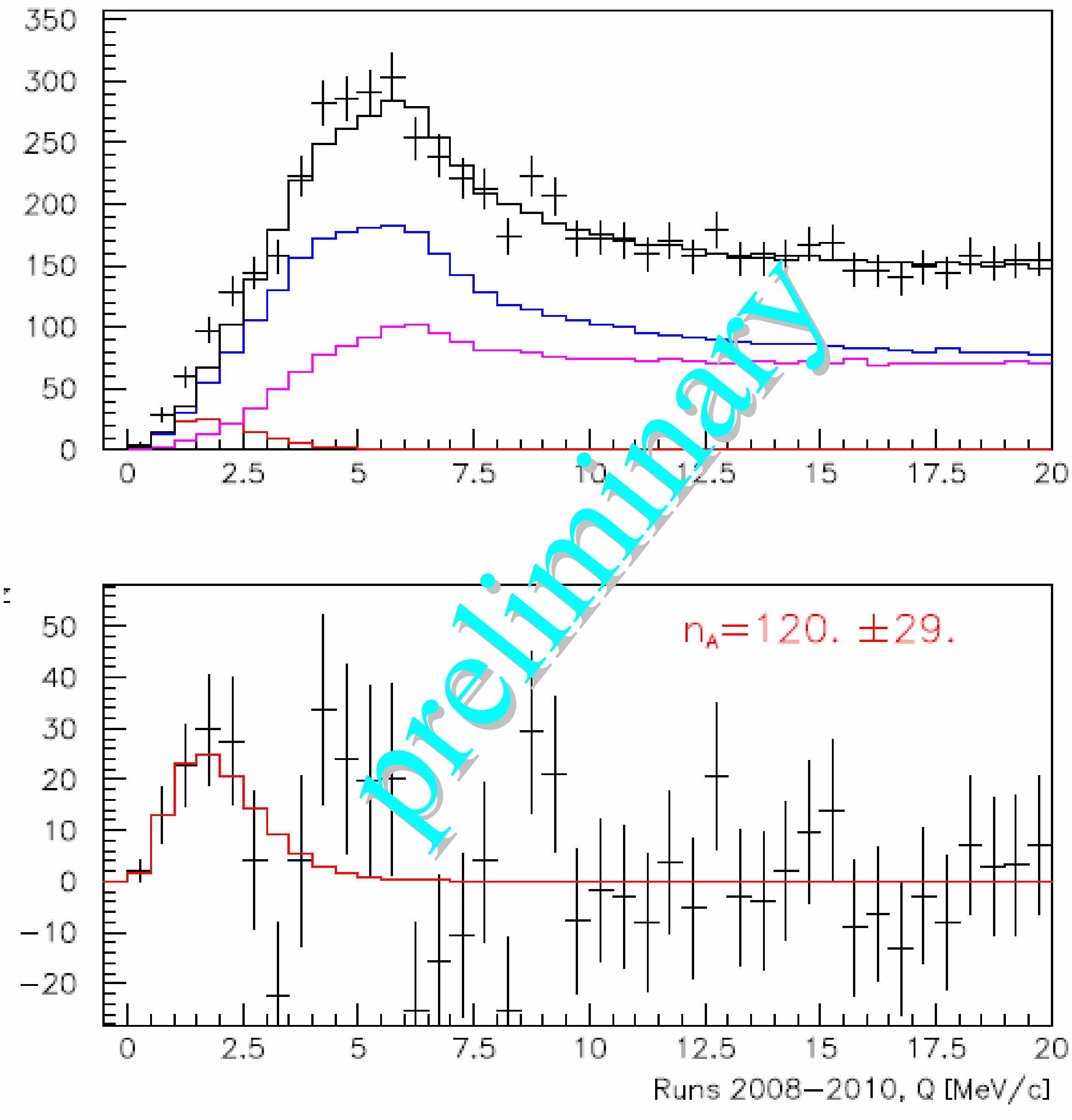
In total:
173±54 πK-atomic pairs are observed
with a significance of 3.2σ.

$\downarrow$

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

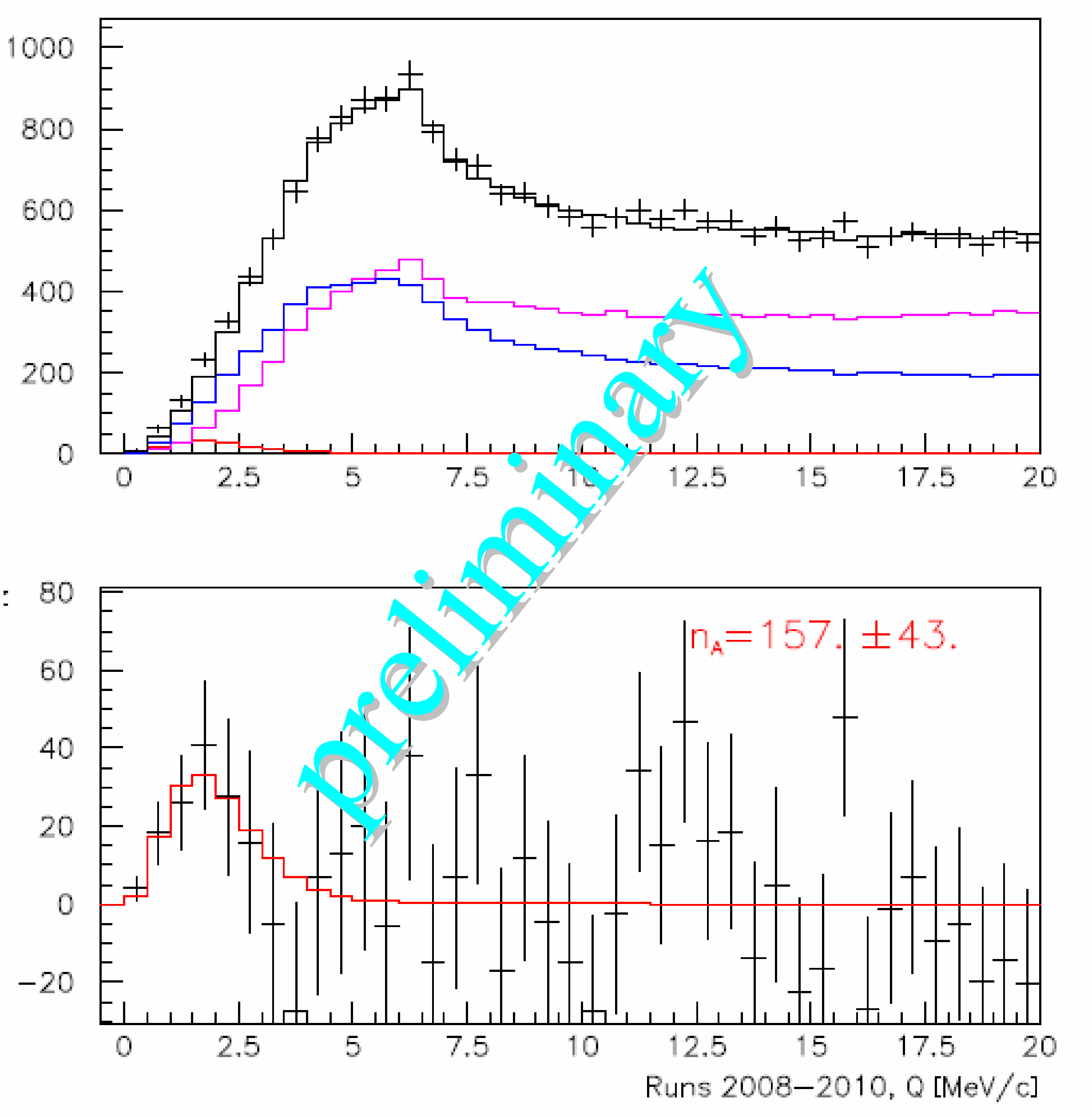
B. Adeva et al.,"Evidence for πK-atoms with DIRAC", Physics Letters B 674 (2009) 11
Y. Allkofer, PhD Thesis, Universität Zürich, 2008.

π^+K^- -atoms 2008-2010 data



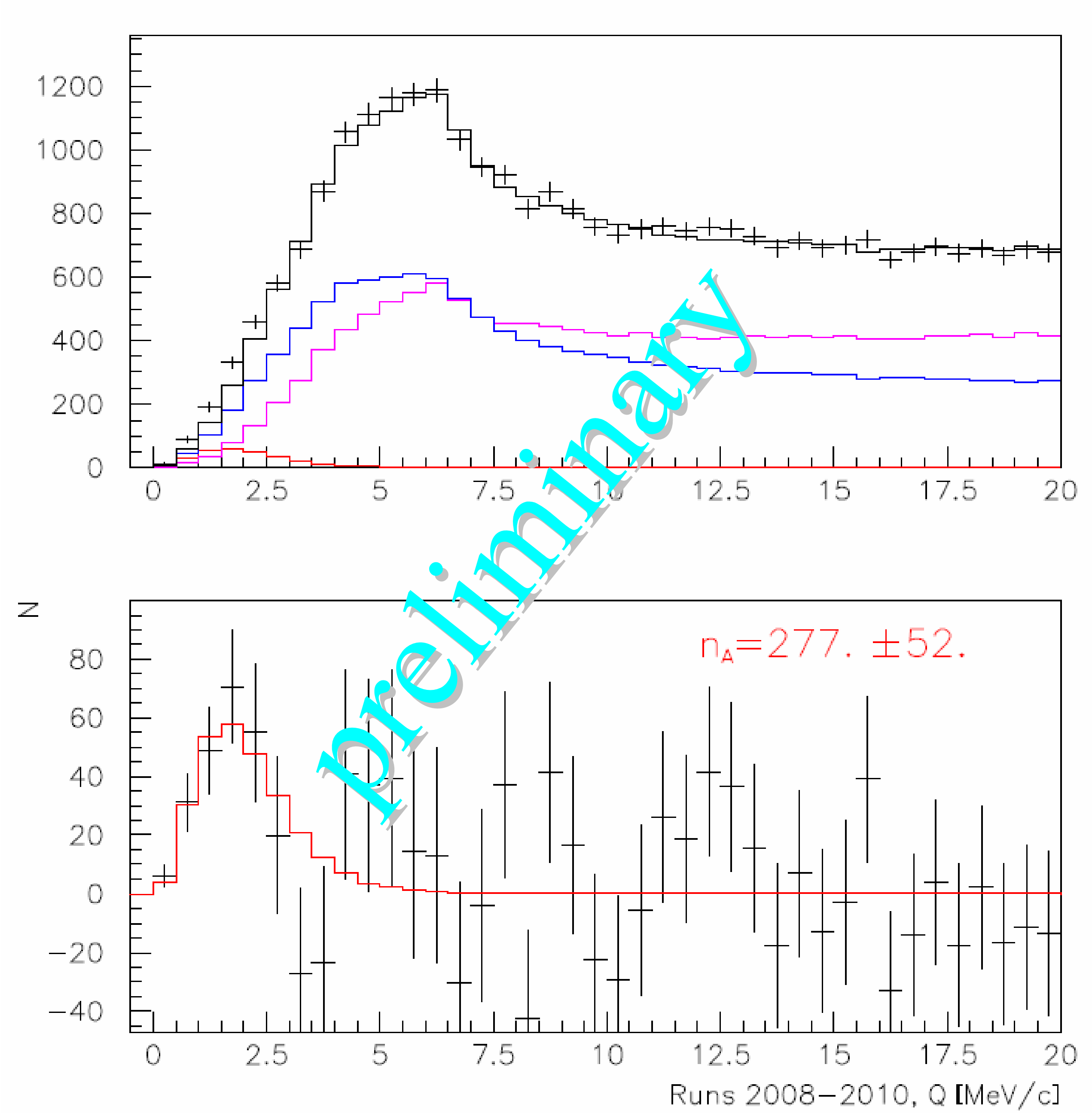
Q – relative momentum in the πK c.m.s.

$\pi^- K^+$ -atoms 2008-2010 data



Q – relative momentum in the πK c.m.s.

$\pi^- K^+$ and $\pi^+ K^-$ atoms 2008-2010 data



Q – relative momentum in the πK c.m.s.

Long-lived $\pi^+\pi^-$ atoms, physics motivation

$A_{2\pi}$ decay dominated by annihilation process:

$$\longrightarrow \pi^+ + \pi^- \rightarrow \pi^0 + \pi^0$$

$A_{2\pi}$ lifetime depends on the $\pi\pi$ scattering length difference $|a_0 - a_2|$

$$\longrightarrow \frac{1}{\tau} \approx W_{\pi^0\pi^0} = R\left|a_0 - a_2\right|^2$$

Energy shift contributions

$$\longrightarrow \Delta E_{nl} = \Delta E_{nl}^{em} + \Delta E_{nl}^{vac} + \Delta E_{nl}^{str}$$

Strong interaction contribution

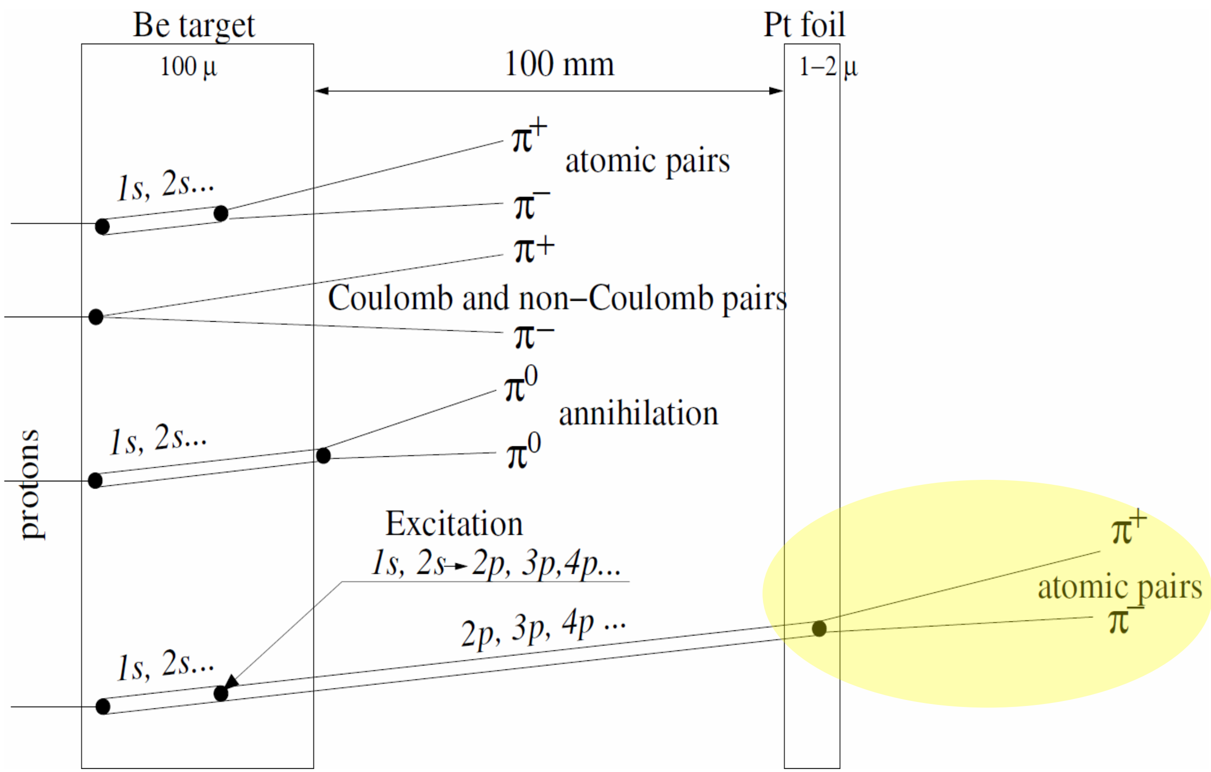
$$\longrightarrow \Delta E_{n0}^{str} = A_n\left(2a_0 + a_2\right)$$

$$\Delta E^{2s-2p} = \Delta E_{20}^{str} + \Delta E_{20}^{em} - \Delta E_{21}^{em} + \Delta E_{20}^{vac} - \Delta E_{21}^{vac} = -0.59 \pm 0.01 eV$$

$$\Delta E_{20}^{str} = -0.447 eV$$

Observation method

The $A_{2\pi}$ decay in the *p*-state is forbidden by angular momentum conservation. So the lifetime of the $A_{2\pi}$ atom in the 2*p* state (τ_{2p}=1.17 ·10^{-11} s) is determined by the 2*p*–1*s* radiative transition with a subsequent annihilation in 1*s* state (τ_{1s}=3 ·10^{-15} s): $\pi^+ + \pi^- \rightarrow \pi^0 + \pi^0$



The lifetime of the *np*-states is about 10^3 larger than the *ns*-states, so it is possible to measure the **energy difference of these levels** by exerting an **electric field** (Stark effect) on the atom and tracking the field dependence of the decay probability.

The influence of an **magnetic field** on the $A_{2\pi}$ atom lifetime opens the possibility to measure the **splitting between 2*s* and 2*p* levels.**

For p_A = 4.5 GeV/c (γ = 16.1)

$$\begin{cases} \tau_{1s} = 2.9 \times 10^{-15}\ \text{s}, & \lambda_{1s} = 1.4 \times 10^{-3}\ \text{cm} \\ \tau_{2s} = 2.3 \times 10^{-14}\ \text{s}, & \lambda_{2s} = 1.1 \times 10^{-2}\ \text{cm} \\ \tau_{2p} = 1.17 \times 10^{-11}\ \text{s}, & \lambda_{2p} = 5.7\ \text{cm},\ \lambda_{3p} \approx 19\ \text{cm}, \\ & \qquad\qquad\qquad \lambda_{4p} \approx 43\ \text{cm} \end{cases}$$

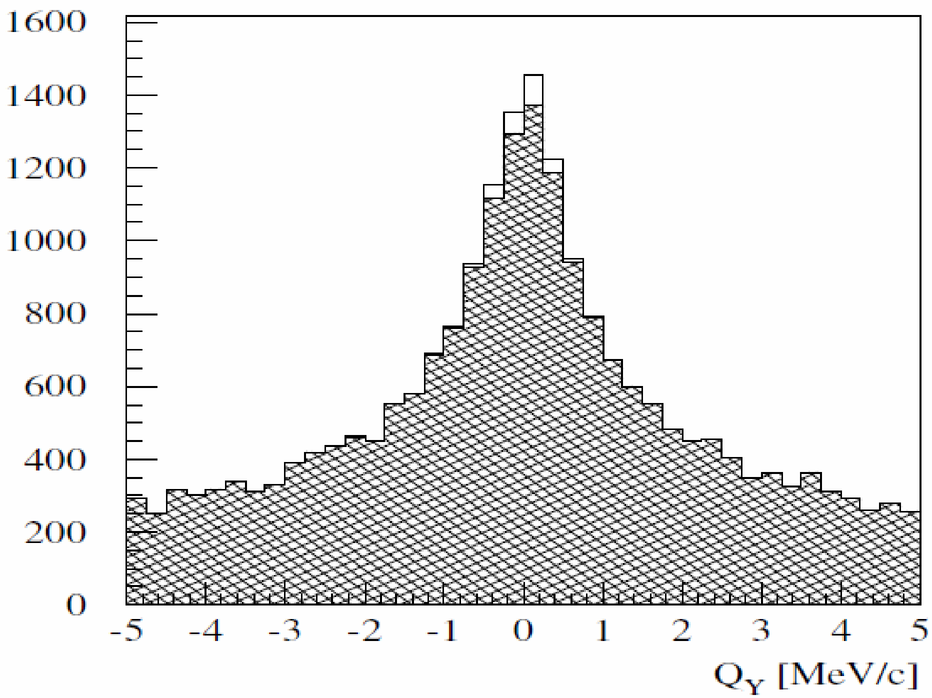
Production yields of $A_{2\pi}$ long-lived states

Target material characteristics for production of long-lived atomic states

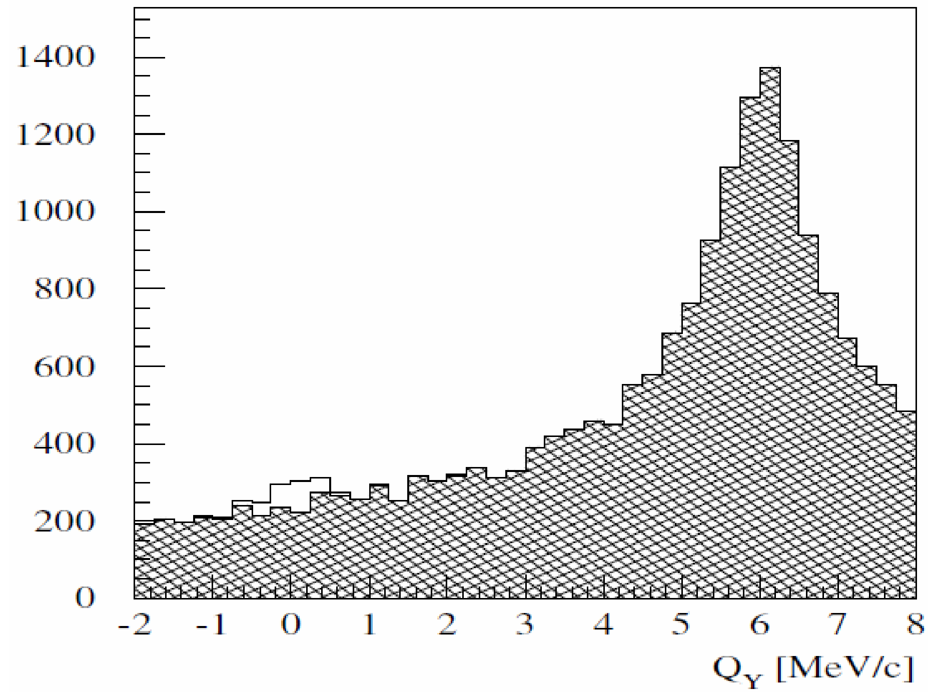
- ***target thickness****, chosen to provide maximum production yield of long-lived states*
- $A_{2\pi}$ ***breakup*** *probability*
- **Σ ($l \geq 1$):** *total yield of long-lived states including states with $n \leq 7$*
- **$2p_0$, $3p_0$, $4p_0$**, *production yield of p-states with magnetic quantum number $m = 0$*
- **Σ (l =1, m = 0):** *sum of the p-states up to $n = 7$*

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%

Simulation of long-lived $A_{2\pi}$ observation



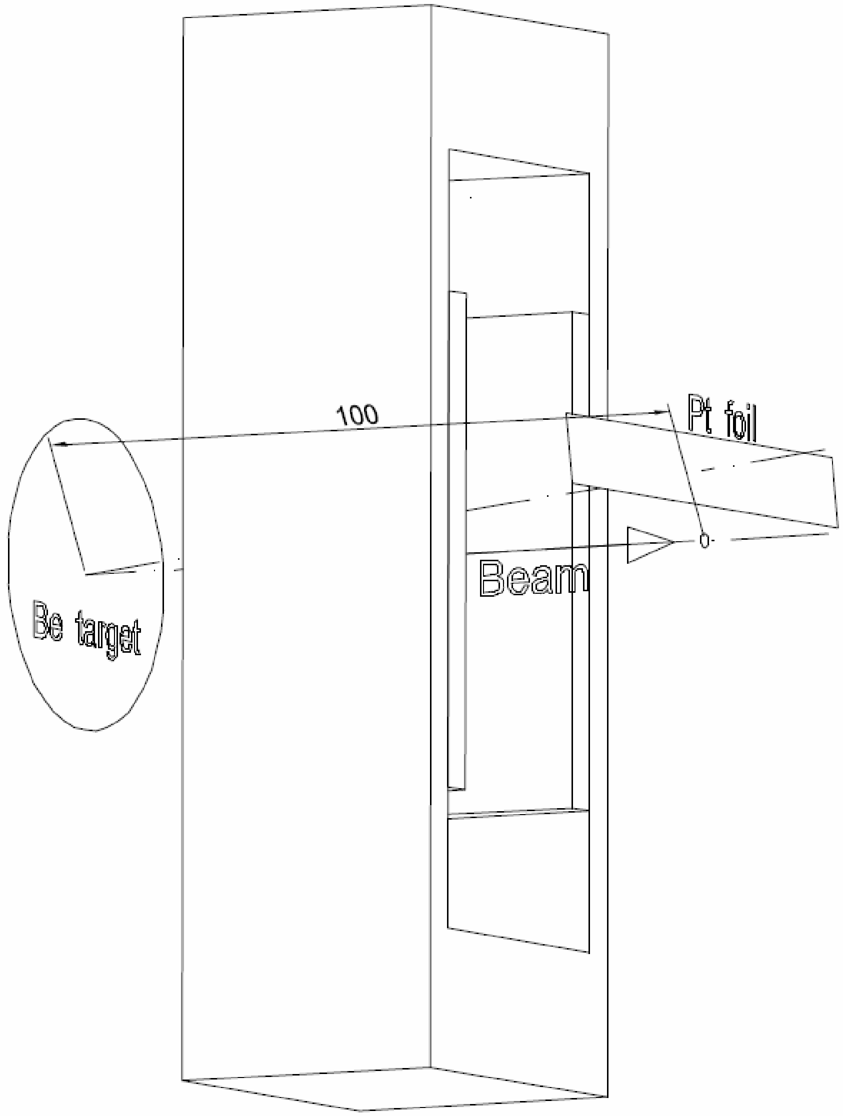
Without magnet



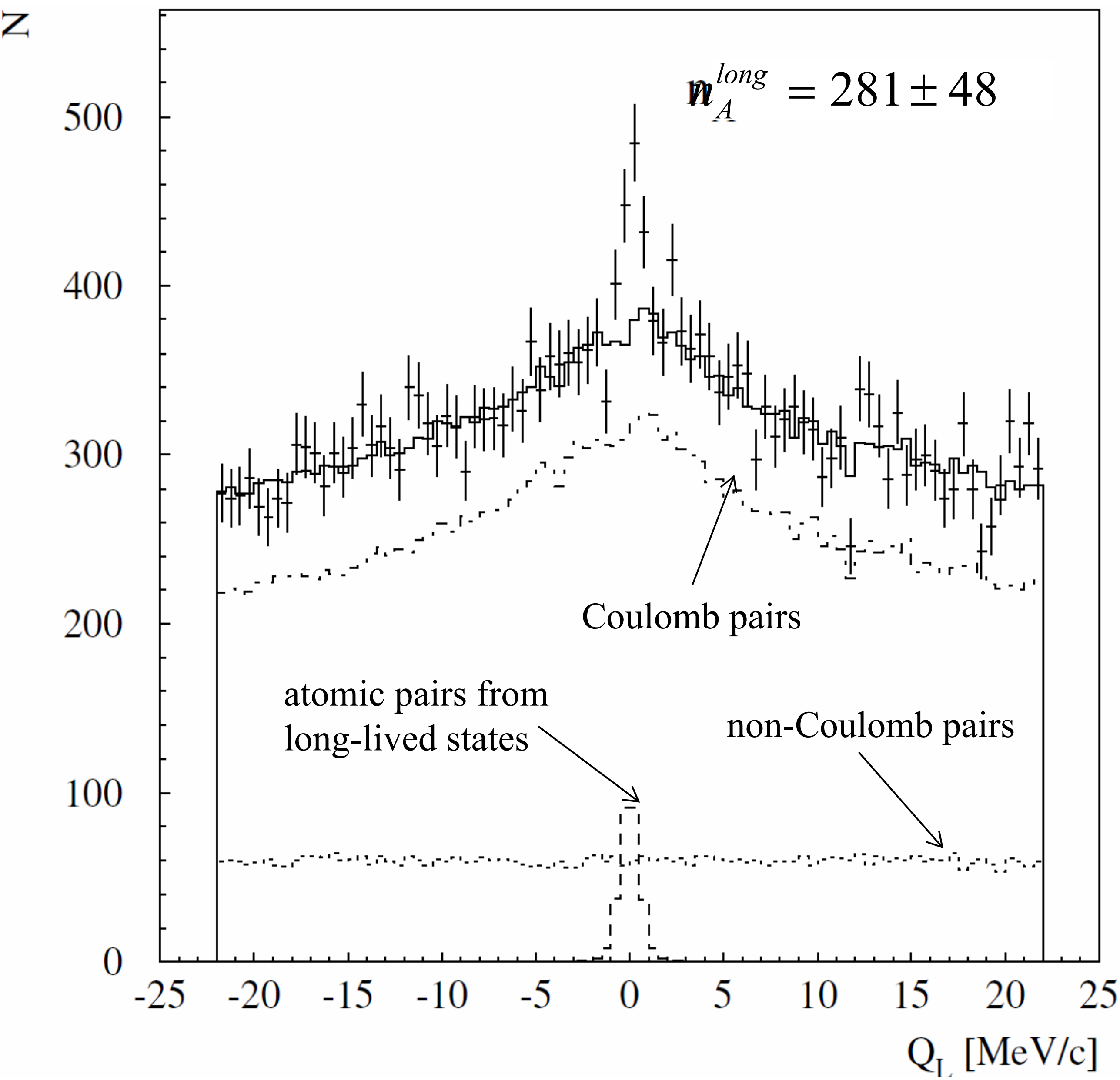
With magnet after Be target

Simulated distribution of $\pi^+\pi^-$ pairs over Q_Y with criteria: $|Q_X| < 1$ MeV/c, $|Q_L| < 1$ MeV/c. "Atomic pairs" from long-lived atoms (light area) above background (hatched area) produced in Beryllium target.

Arrangement of Beryllium target, permanent magnet and Platinum foil.



Simulation of long-lived $A_{2\pi}$ observation

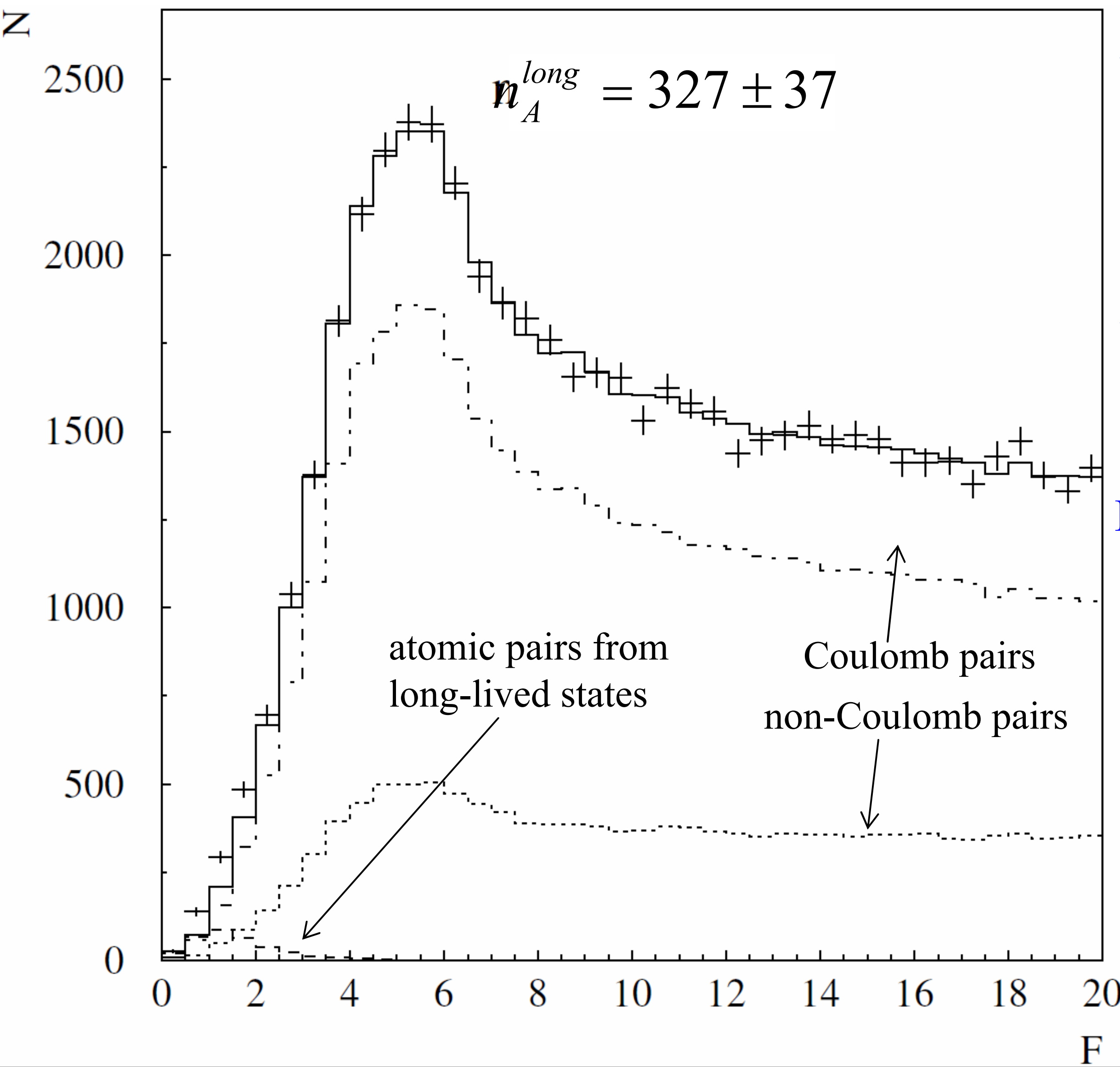


Simulated distribution of $\pi^+\pi^-$ pairs over Q_L, with criterion $Q_T < 1$ MeV/c. "Experimental" data (points with error bars) are fitted by a sum of "atomic pairs" from long-lived states, "Coulomb pairs" and "non-Coulomb pairs".
The background sum is shown by the solid line.

The number of atomic pairs are found to be

$$n_A^{long} = 281 \pm 48$$

Simulation of long-lived $A_{2\pi}$ observation



Simulated distribution of $\pi^+\pi^-$ pairs over F, with criterion $Q_T < 2$ MeV/c. "Experimental" data (points with error bars) are fitted by a sum of "atomic pairs" from long-lived states, "Coulomb pairs", "non-Coulomb pairs". The background sum is shown by the solid line.

$$F = \sqrt{\left(\frac{Q_X}{0.50}\right)^2 + \left(\frac{Q_Y}{0.32}\right)^2 + \left(\frac{Q_L}{0.56}\right)^2}$$

where 0.50, 0.32 and 0.56 Mev/c are RMS's of the atomic pairs distribution over corresponding components of the relative momentum Q. Now,

$$n_A^{long} = 327 \pm 37\ ;\ \frac{n_A}{\sigma_{n_A}} = 8.8$$

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=5.7º						
	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 $\pi\pi$ 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

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

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

2011-2012 Observation of metastable $\pi^+\pi^-$ atoms and study of a possibility to measure its Lamb shift.

DIRAC at SPS CERN beyond 2012

$$\tau(A_{2\pi}) \to \delta(a_0 - a_2) = \pm 0.5\%(stat)$$

$$(E_{np} - E_{ns})_{\pi\pi} \to \delta(2a_0 + a_2)$$

$$\tau(A_{\pi K}) \to \delta(a_{1/2} - a_{3/2}) = \pm 2.5\%(stat)$$

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

Thank you for your attention