Scientific plans of the DIRAC experiment beyond 2010

Leonid Nemenov

New Opportunities in the Physics Landscape at CERN
11 May 2009

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 collaboration

CERN
Geneva, Switzerland

Czech Technical University
Prague, Czech Republic

Institute of Physics ASCR
Prague, Czech Republic

Nuclear Physics Institute ASCR
Rez, Czech Republic

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

SINP of Moscow State University
Moscow, Russia

IHEP
Protvino, Russia

Santiago de Compostela University
Santiago de Compostela, Spain

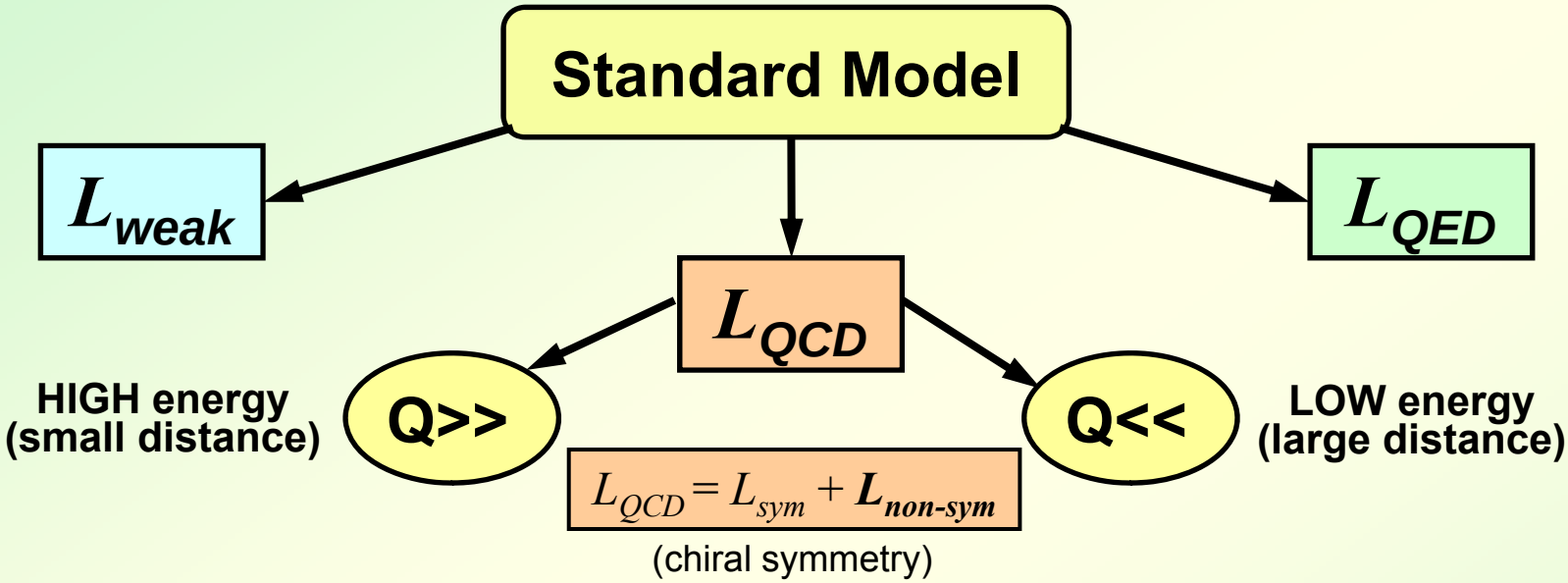
Bern University
Bern, Switzerland

Zurich University
Zurich, Switzerland

Outline

- *Low-energy QCD precise predictions*
- *Method of ππ and πK atoms lifetime measurement*
- *DIRAC setup*
- *Results on the ππ scattering lengths measurement*
- *Evidence for πK atoms*
- *Request of 2010 run for observation of the long-lived states of ππ atoms. Prospects for the Lamb-shift measurement.*
- *New prospects of DIRAC at SPS CERN*

Theoretical motivation



perturbative QCD:
L_{QCD} (q,g)
Interaction → „weak“ (asympt. freedom): expansion in coupling.

Check only L_{sym} (m_q<<)

chiral sym. & breaking:
L_{eff} (GB: π,K,η)
Interaction → „strong“ (confinement) - **but**: expansion in mom. & mass.

Check L_{sym} as well as

$L_{non\text{-}sym}$

spontaneously broken symmetry — quark-condensate

Theoretical status

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

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

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

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

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.

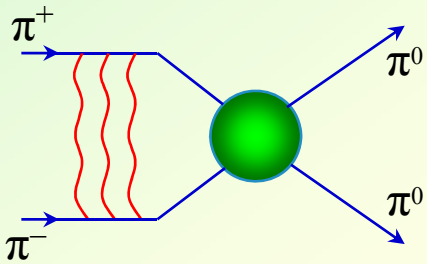
Because l_3 and l_4 are sensitive to the quark condensate,
precision measurements of a_0, a_2 are a way
to study the **structure** of the QCD vacuum.

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 $\pi^0\pi^0$:



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

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

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

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

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

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

$L^{(2)}, L^{(4)}$ *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

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

II. Roy-Steiner equations:

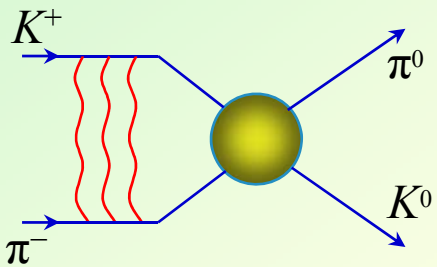
$$a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015$$

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), $\tau=1/\Gamma$ 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

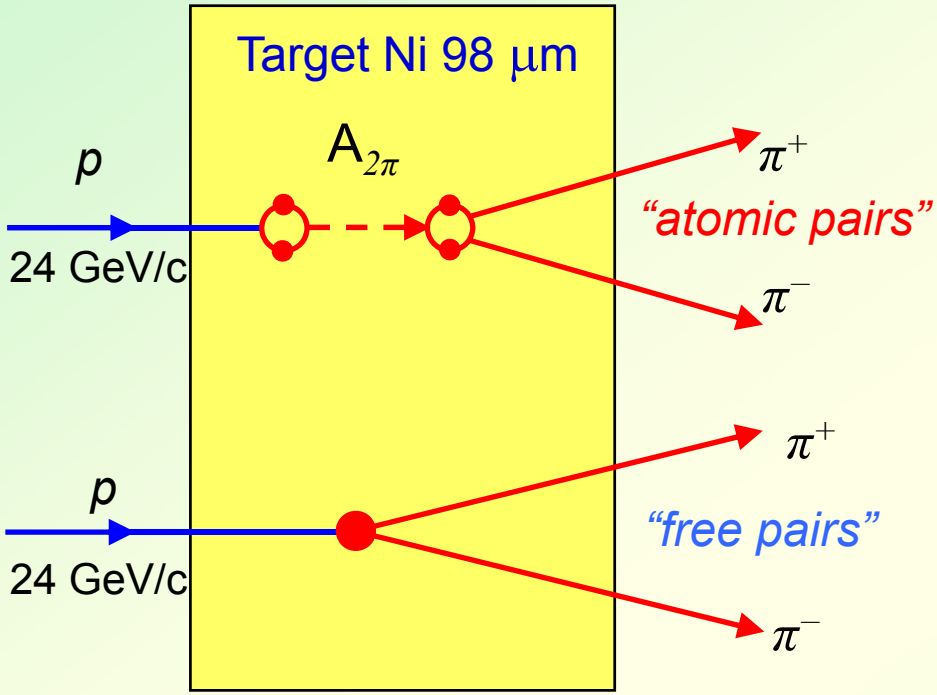
What new will be known if πK scattering length will be measured?

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

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

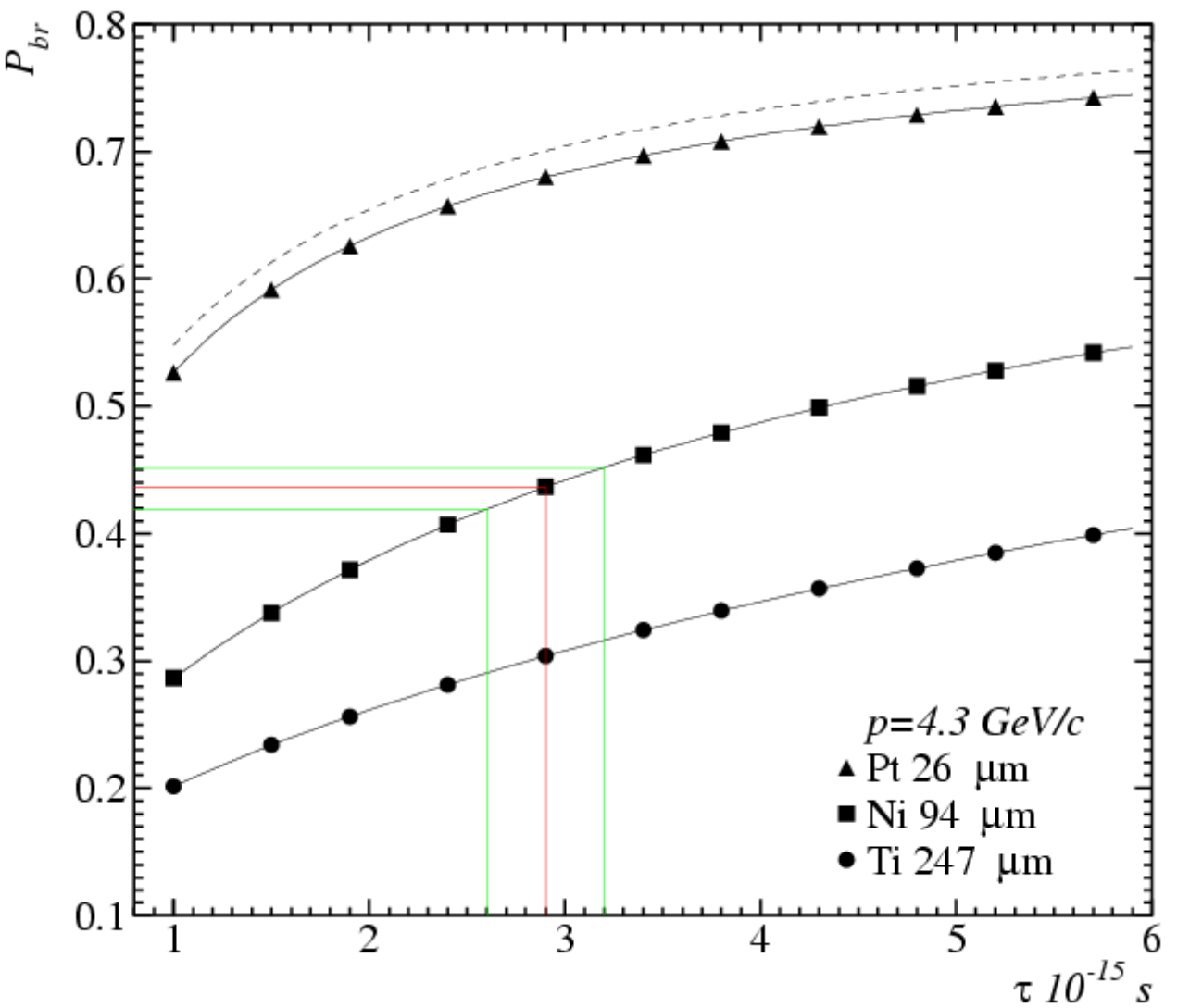
Resolution on Q: $Q_x \approx Q_y \approx 0.3$ Mev/c, $Q_L \approx 0.5$ MeV/c

The same method for $A_{\pi K}$

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

Break-up probability

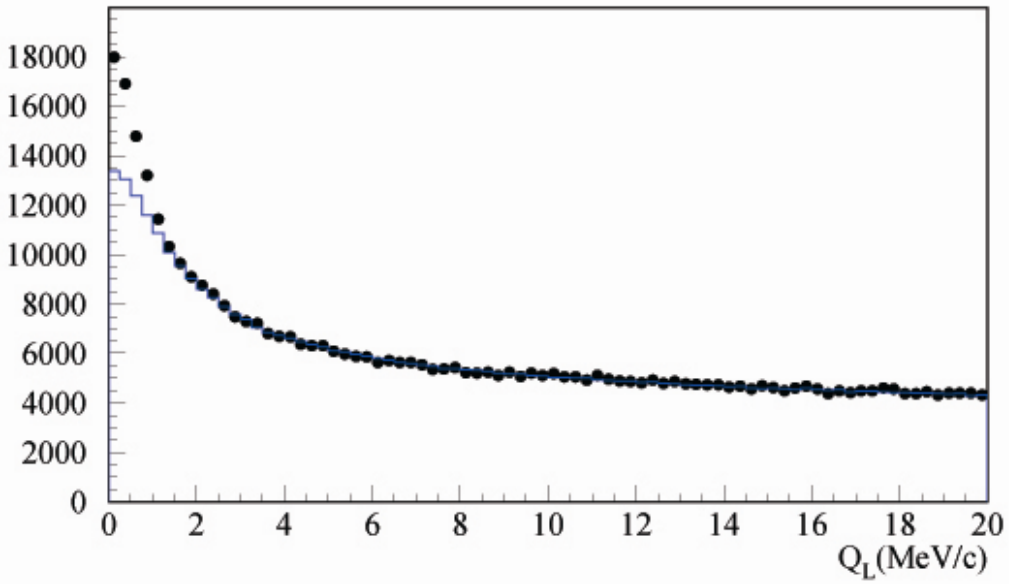
Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on pionium lifetime τ



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

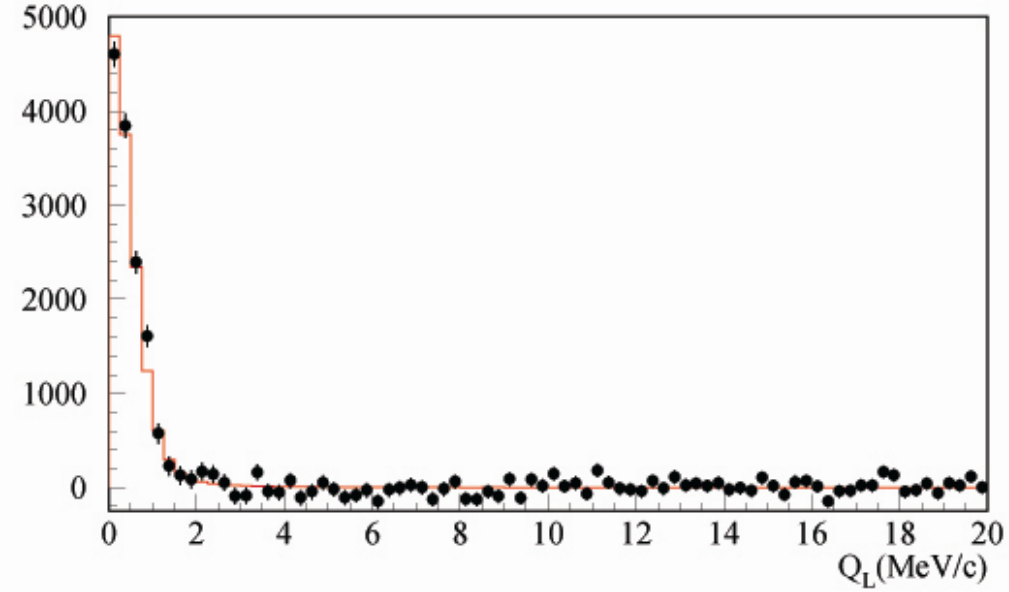
There is an optimal target material for a given lifetime

DIRAC preliminary results with GEM/MSGC



Q_L distribution

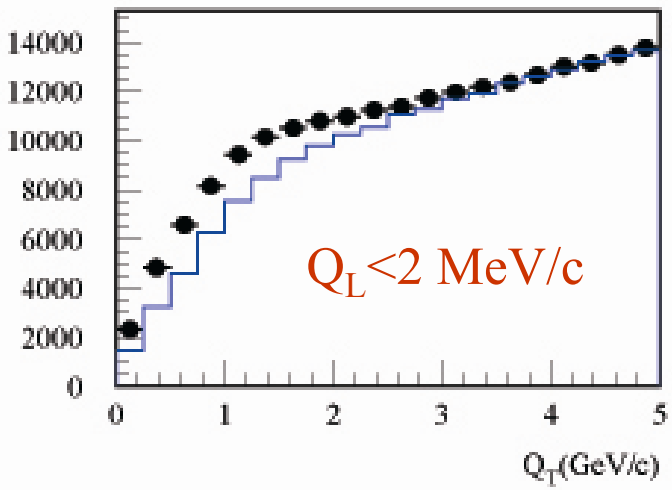
←All events

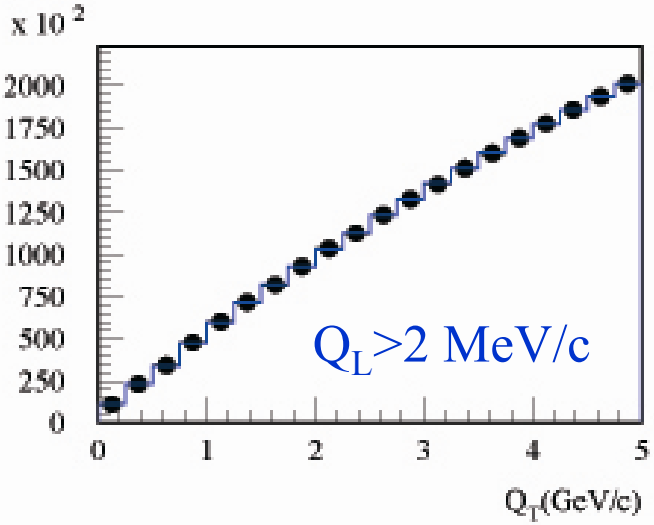


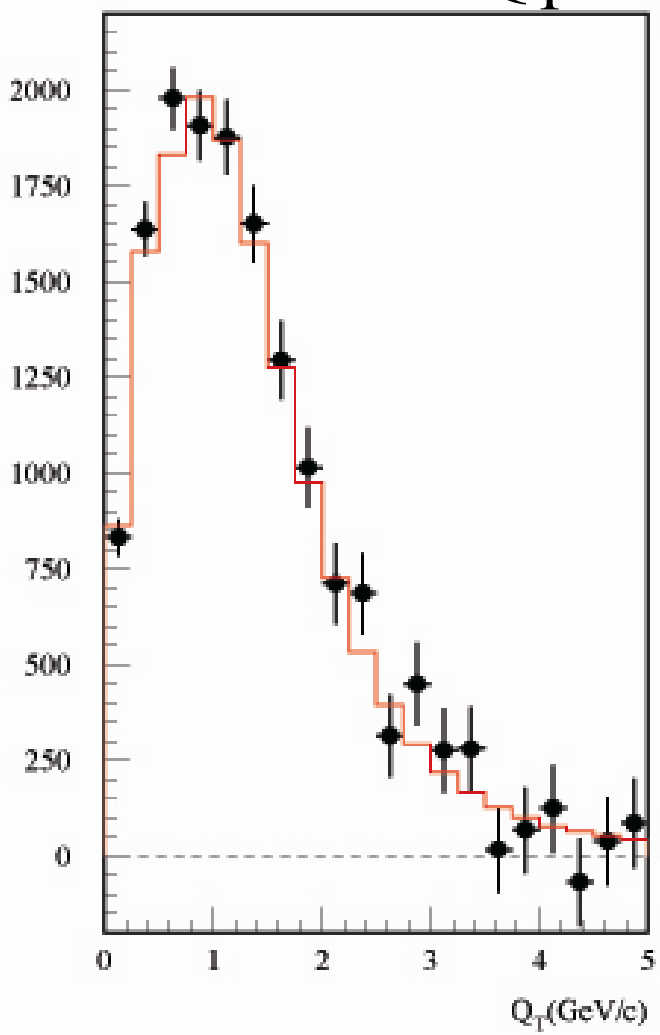
←After background subtraction

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

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

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

Including GEM/MicroStripGasChambers => number of reconstructed events is 17000 => the statistical error in $|a_0\text{-}a_2|$ 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:

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

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

...without constraint (a_2 free):

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

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

...with ChPT constraint between a_0 and a_2:

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

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):

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

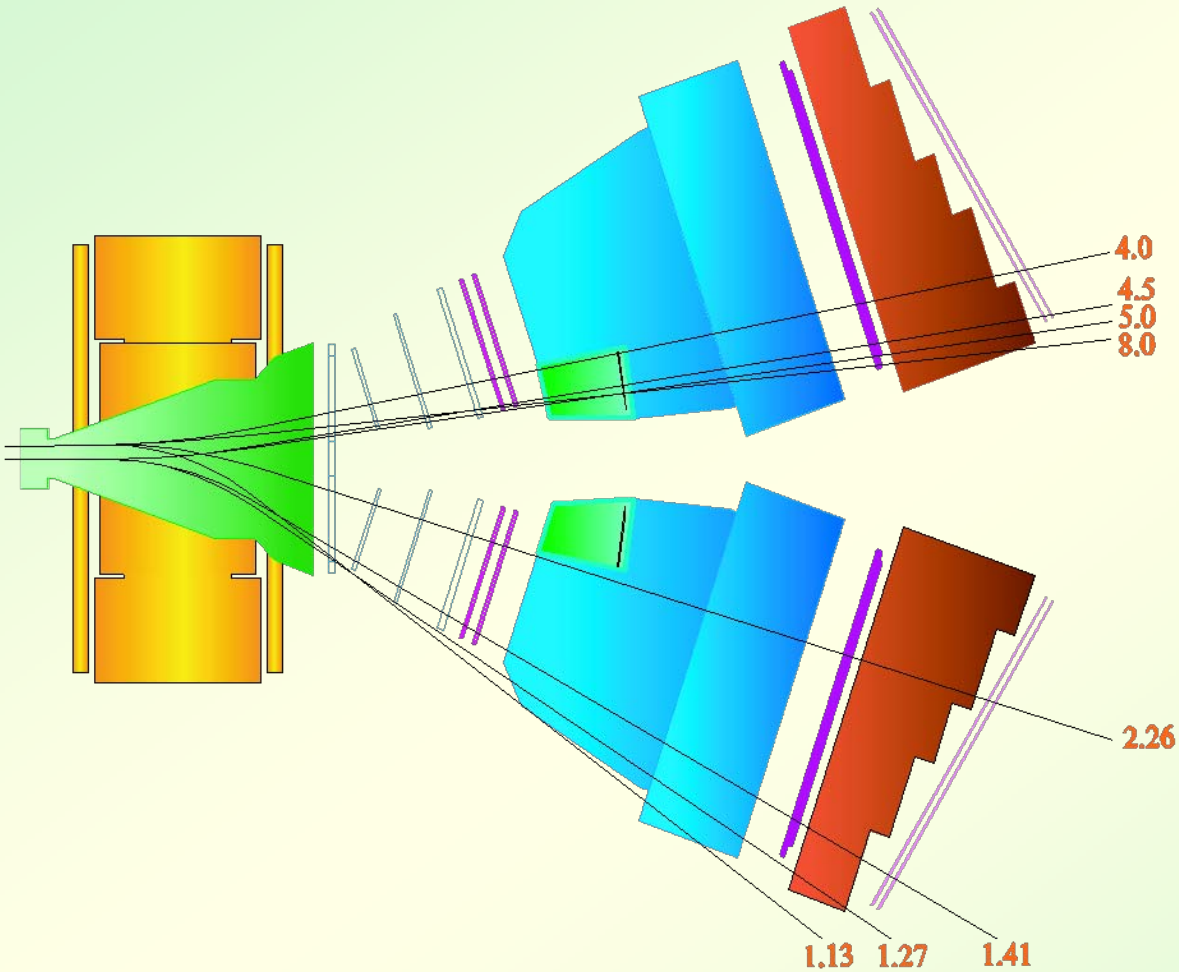
$$\Rightarrow a_2 = -0.0432 \pm 20\%\big|_{stat} \pm 7.9\%\big|_{syst} \pm 6.5\%\big|_{th} = \ldots \pm 22\%\big|_{tot}$$

...with ChPT constraint between a_0 and a_2:

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

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

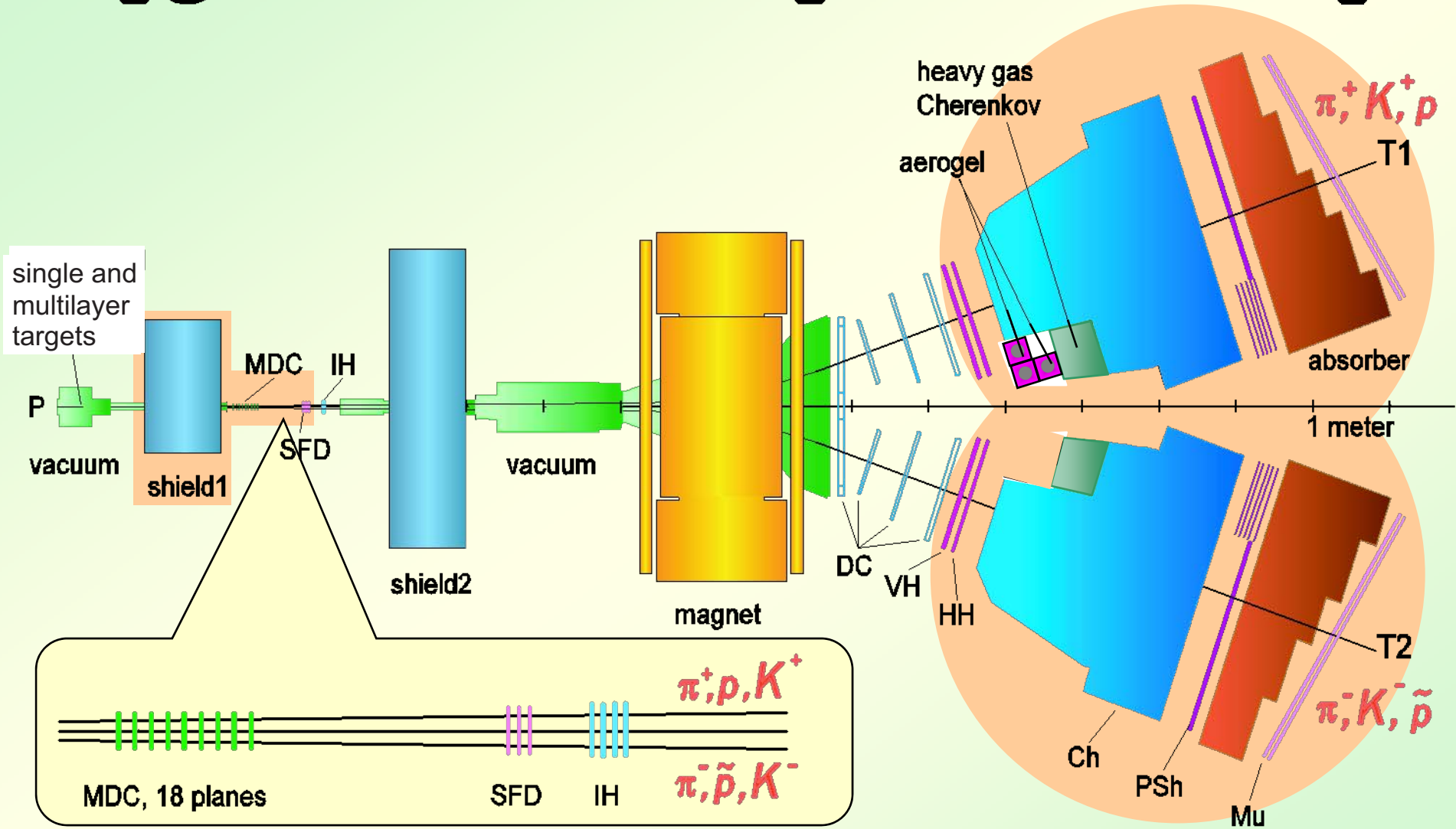
The numbers to the right of the tracks lines are the π^- and K^+ momenta in GeV/c



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

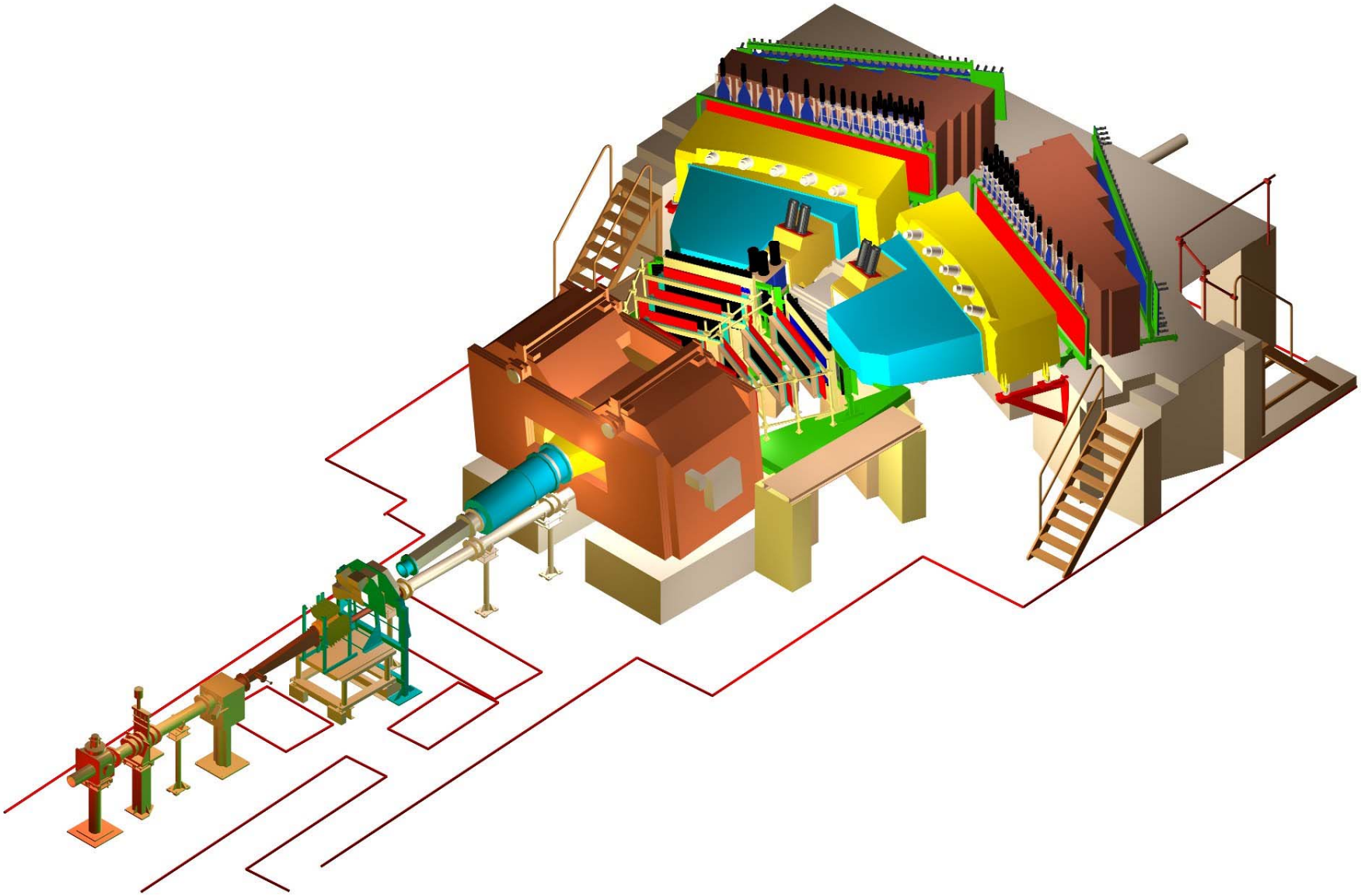
P_{atom} (GeV/c)	P_{π} (GeV/c)	P_K (GeV/c)
5.13	1.13	4.0
5.77	1.27	4.5
6.41	1.41	5.0
10.26	2.26	8.0

Upgraded DIRAC experimental setup



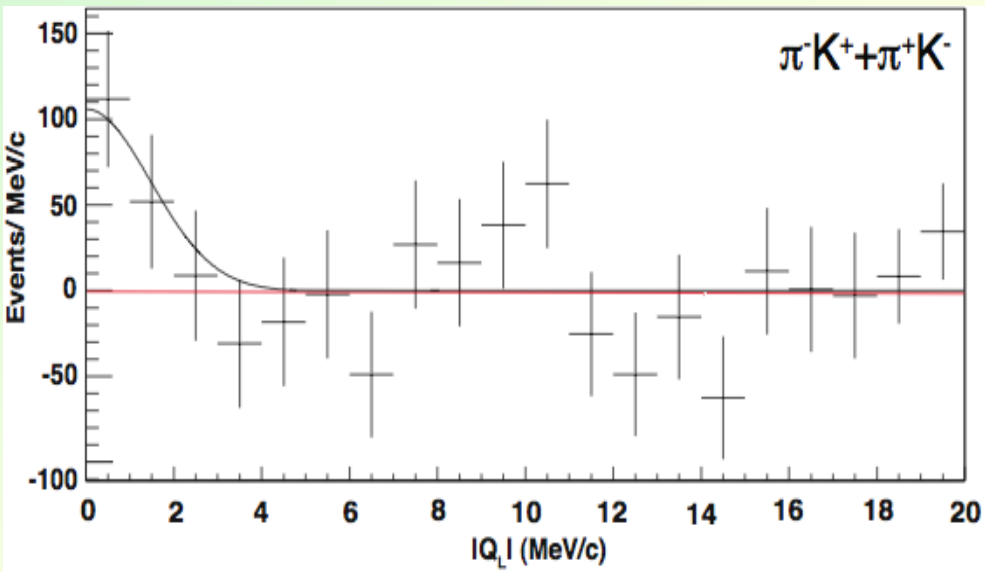
Modifided parts

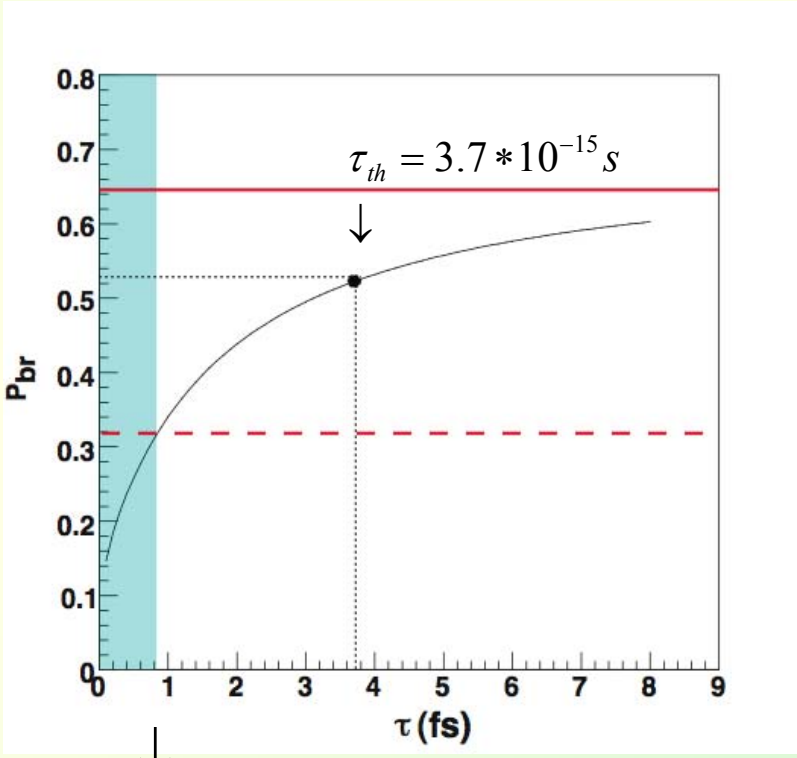
Upgraded DIRAC experimental setup



Downstream detectors

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





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

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

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

Beam request 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.

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 $n = 2$

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

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

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

(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.*
(2004) J. Schweizer, EPJ C36 483

(1999) A. Gashi *et al.*
(2000) D. Eiras and J. Soto
(2000) D. Eiras and J. Soto
A. Rusetsky, *priv. comm.*

Metastable Atoms

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

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

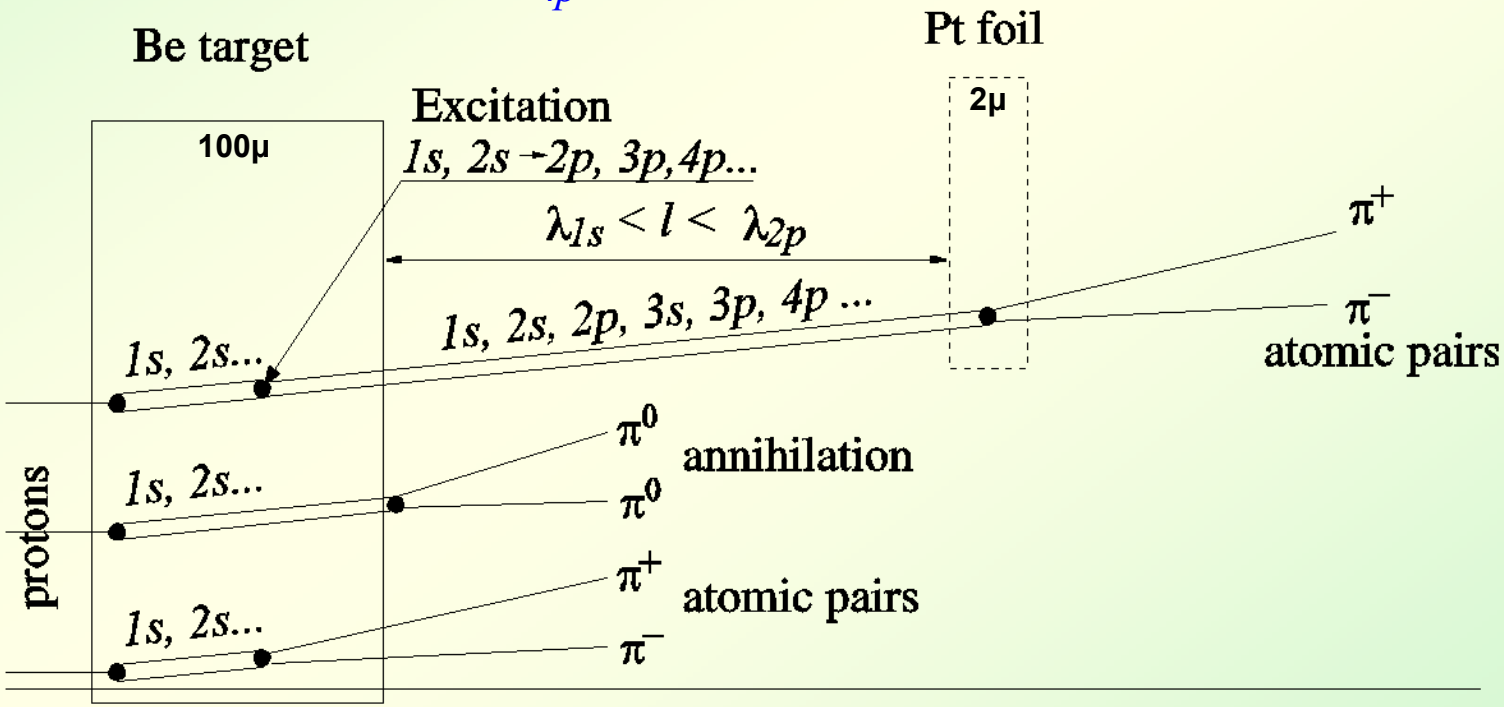


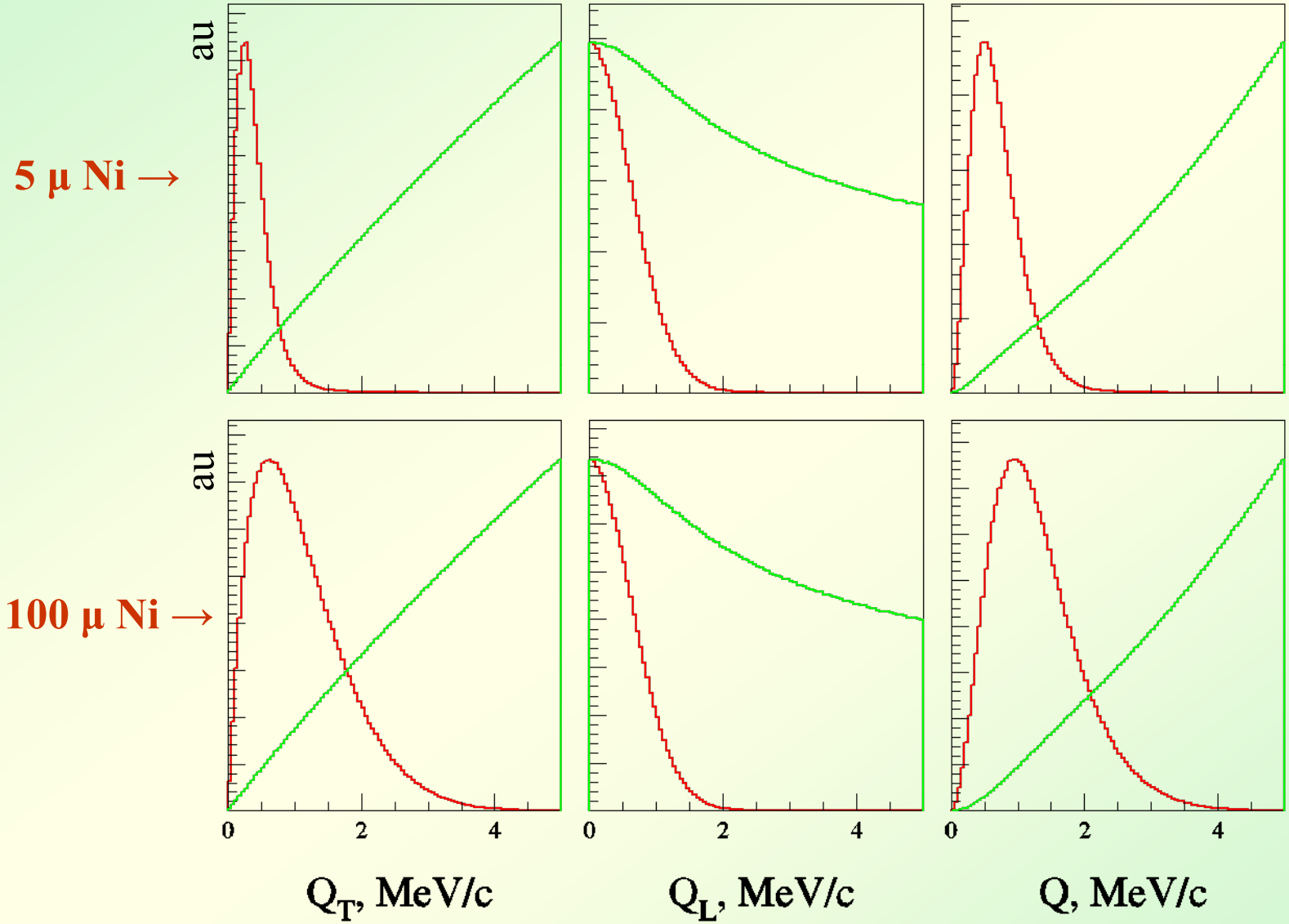
Illustration for observation of the $A_{2\pi}$ long-lived states with breaking foil.

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%

Metastable Atoms - Backgrounds



Atomic pairs

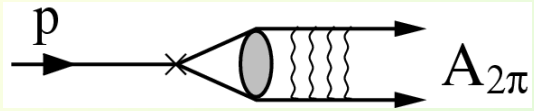
Coulomb background

$A_{2\pi}$ and $A_{\pi K}$ production

$$\frac{d\sigma^{A}_{nlm}}{d\vec{P}} = (2\pi)^3 \frac{E}{M} \left|\psi^{(C)}_{nlm}(0)\right|^2 \frac{d\sigma^{0}_{s}}{dp_1 dp_2} \square \frac{d\sigma}{dp_1} \cdot \frac{d\sigma}{dp_2}$$

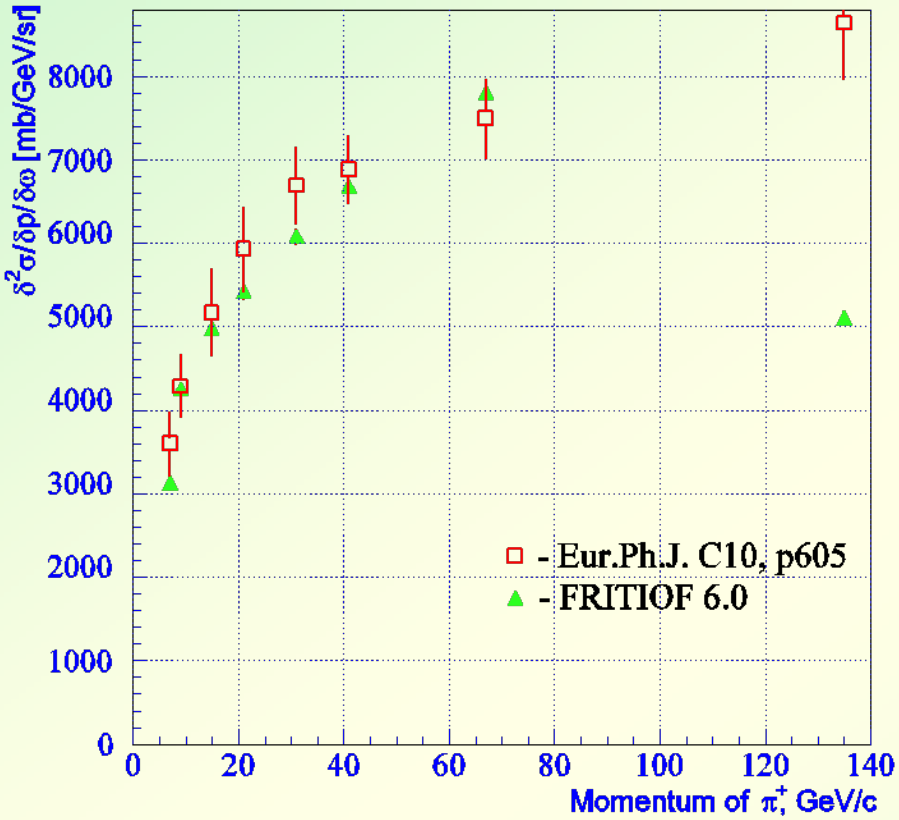
for atoms $\vec{v}_1 = \vec{v}_2$ *where* $\vec{v}_1, \vec{v}_2$ *– velocities of particles in the L.S. for all types of atoms*

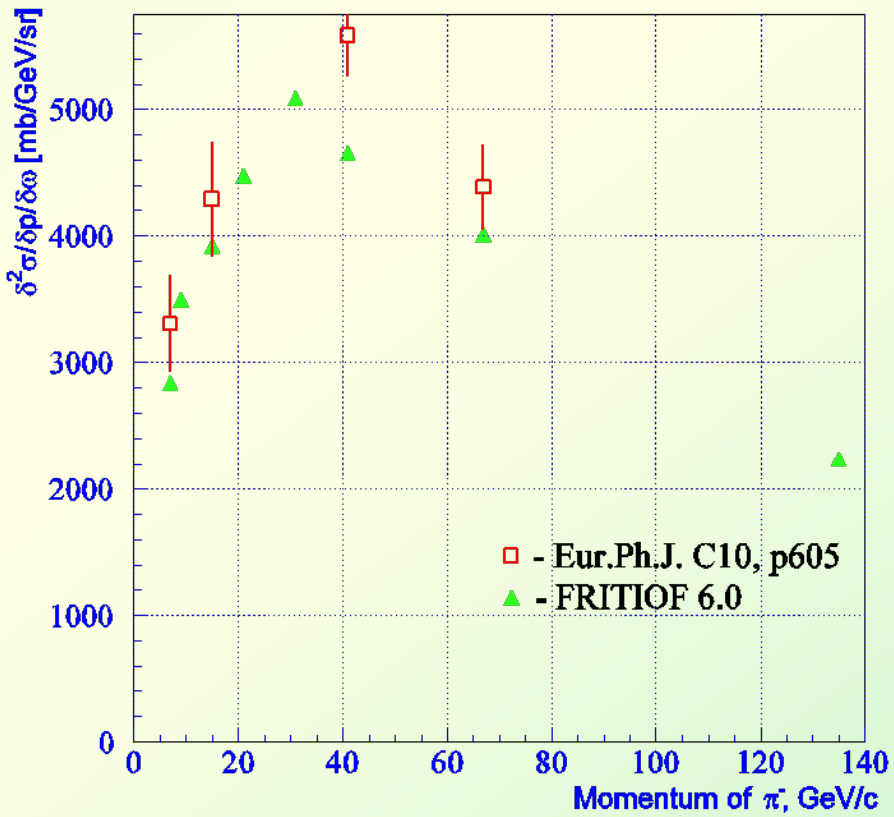
for $A_{2\pi}$ *production* $\vec{p}_1 = \vec{p}_2$



for $A_{\pi K}$ *production* $\vec{p}_\pi = \frac{m_\pi}{m_K} \vec{p}_K$

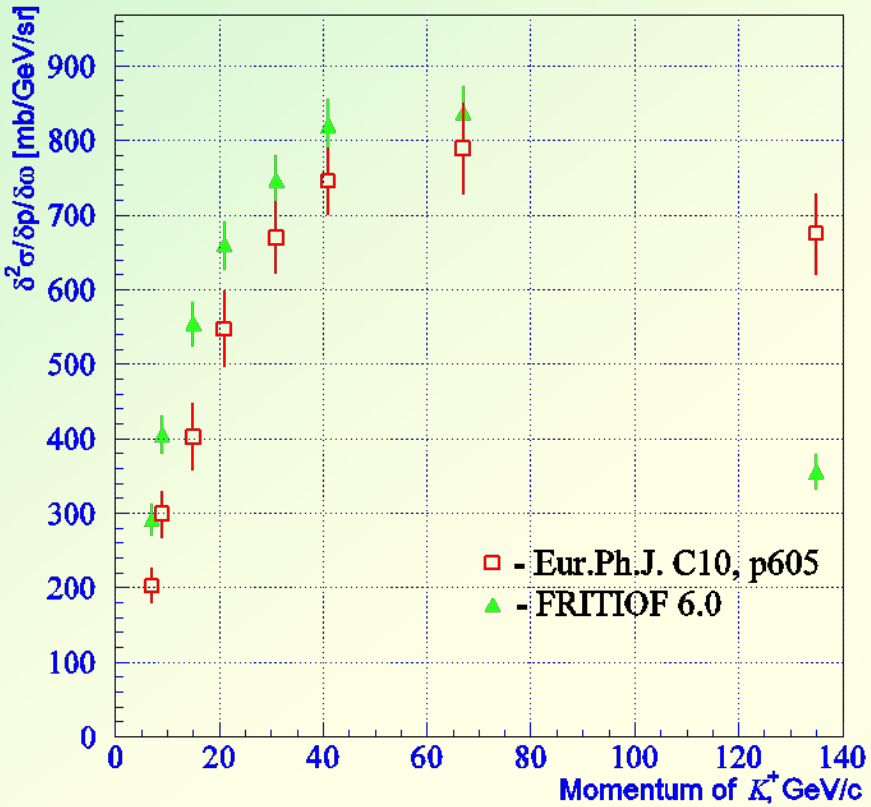
Inclusive cross-sections for π+, π– - mesons generation

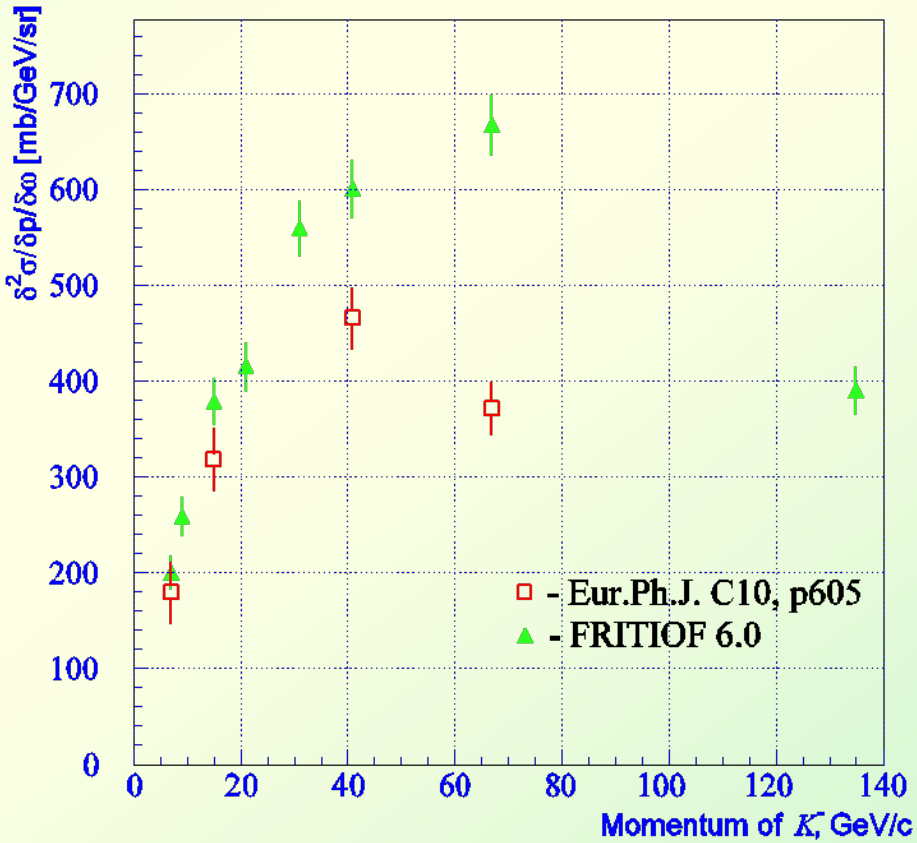




$$E_p = 450 GeV \quad \theta_L = 0°$$

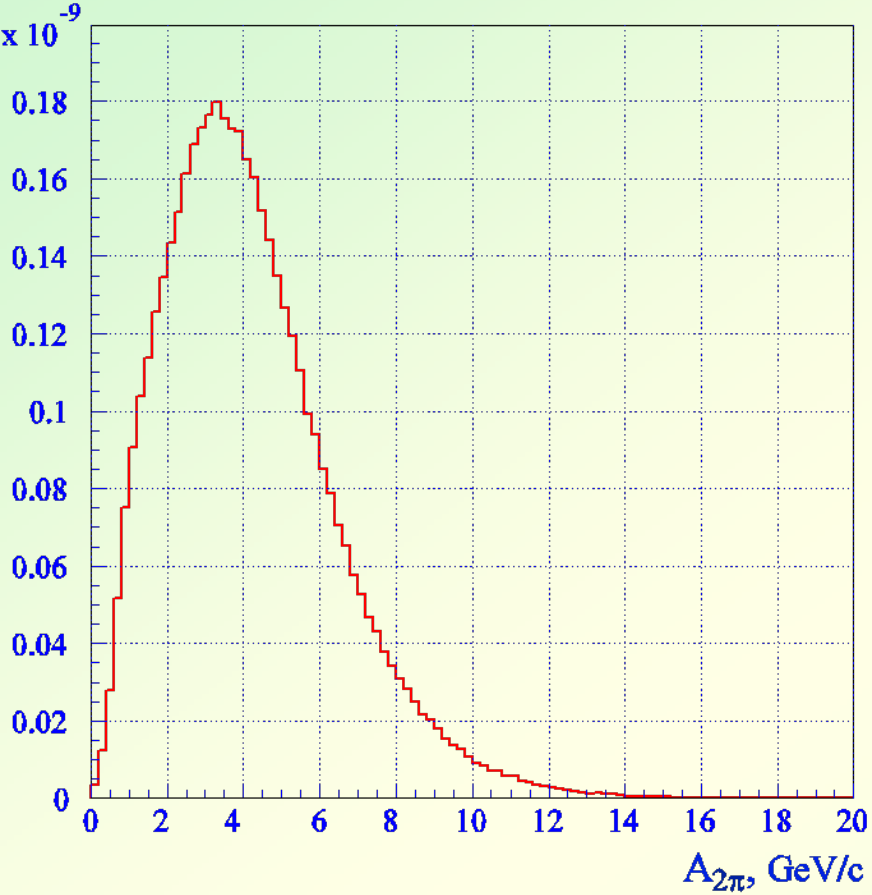
Inclusive cross-sections for K^+, K^- - mesons generation

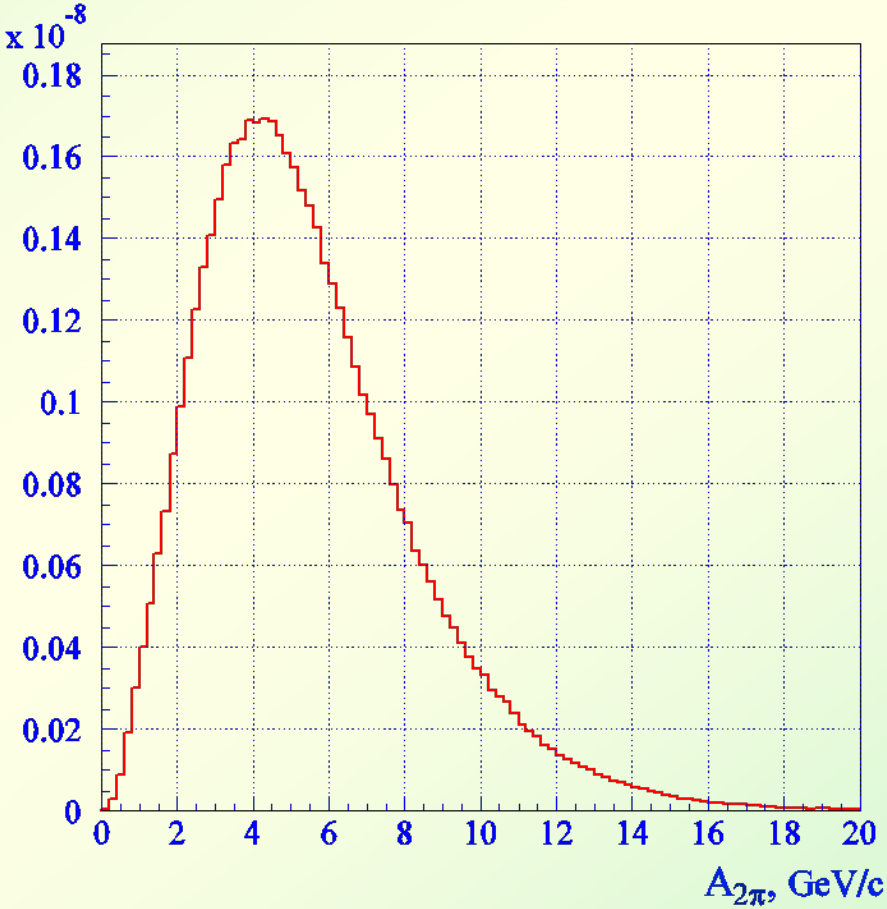




$$E_p = 450 GeV \quad \theta_L = 0°$$

$A_{2\pi}$ momentum distributions (5.7°)

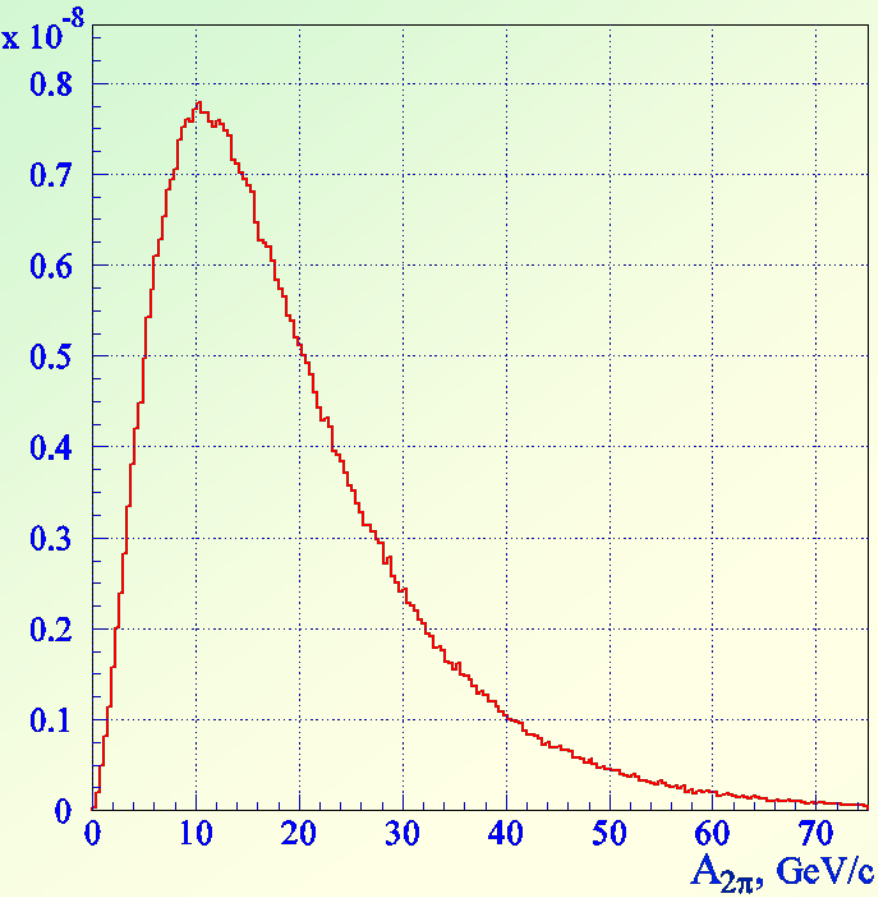


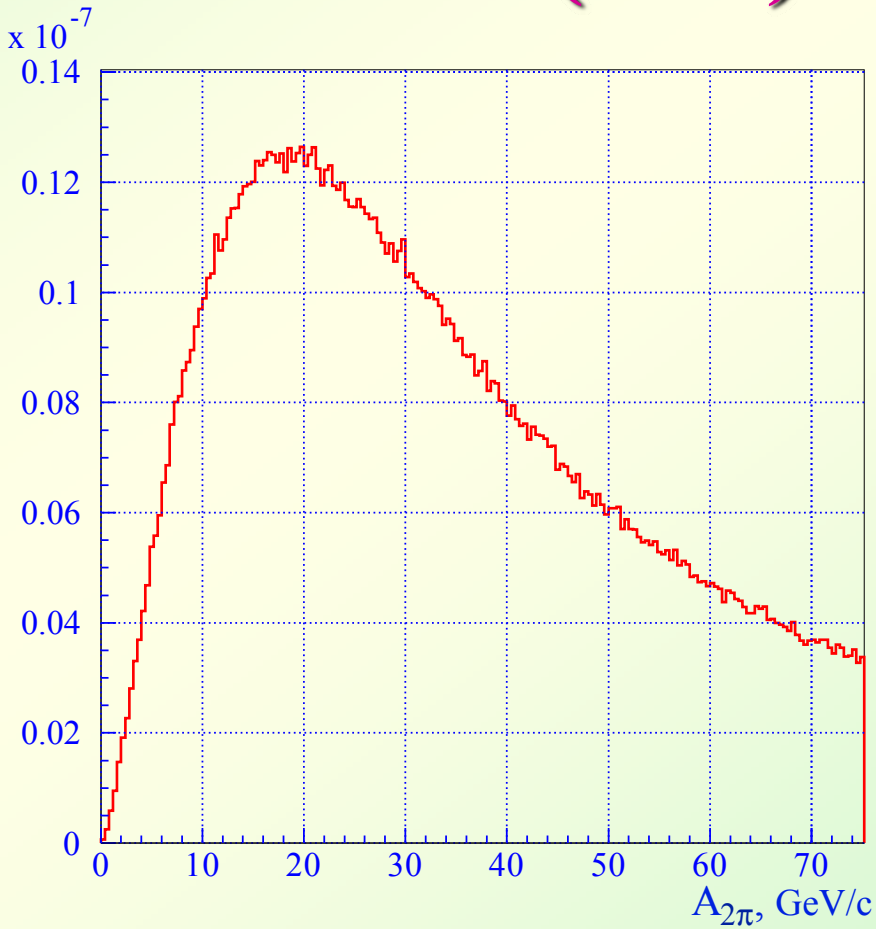


$\theta_L = 5.7° \pm 1.3° \;\; E_p = 24 GeV$

$\theta_L = 5.7° \pm 1.3° \;\; E_p = 450 GeV$

$A_{2\pi}$ momentum distributions (0-2°)

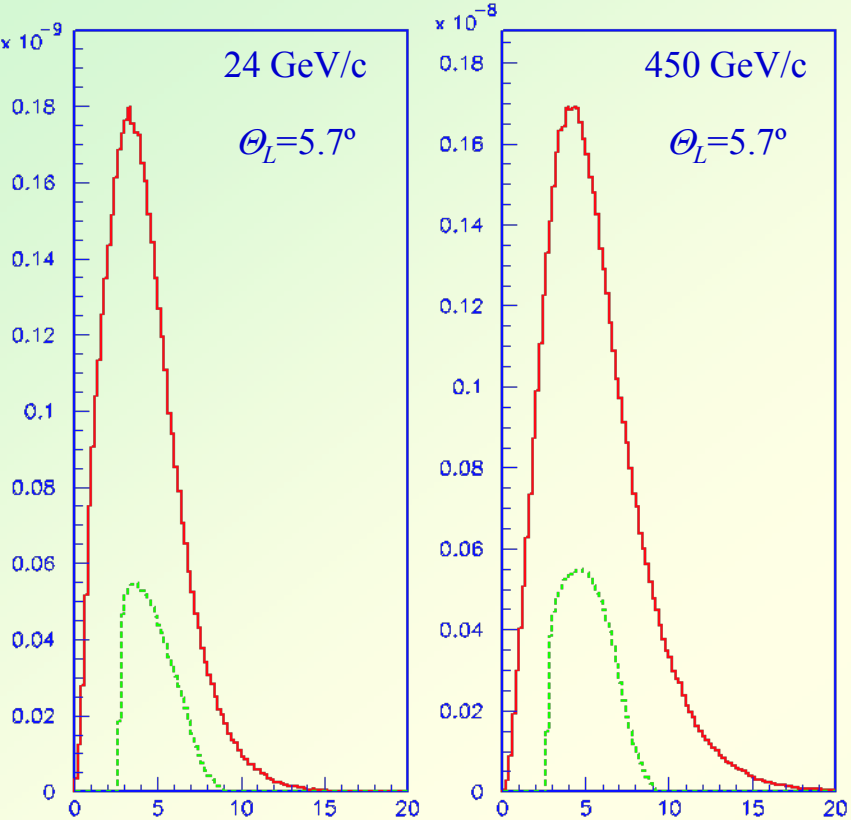




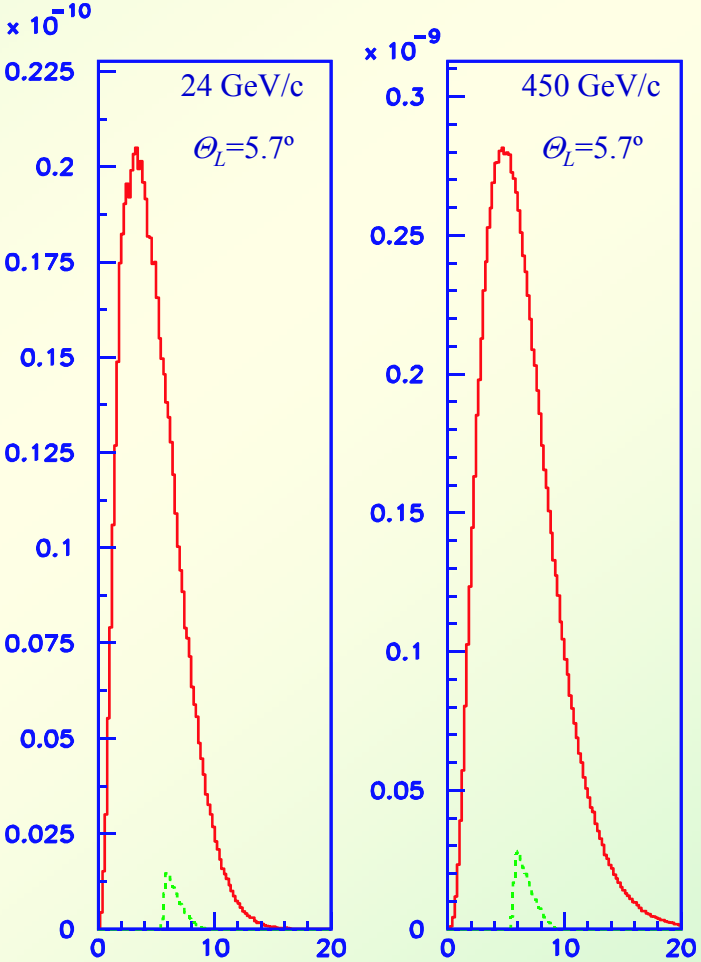
$\theta_L = 2° \pm 1.3°$ $E_p = 450 GeV$

$\theta_L = 0° \pm 1.3°$ $E_p = 450 GeV$

$A_{2\pi}$ and $A_{\pi K}$ momentum distributions



Momentum of $A_{2\pi}$, *GeV / c*



Momentum of $A_{\pi^+K^-}$, *GeV / c*

— - red curve atom spectra in channel the aperture

- green curve atom spectra registered by the set-up

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

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

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

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

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

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

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

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

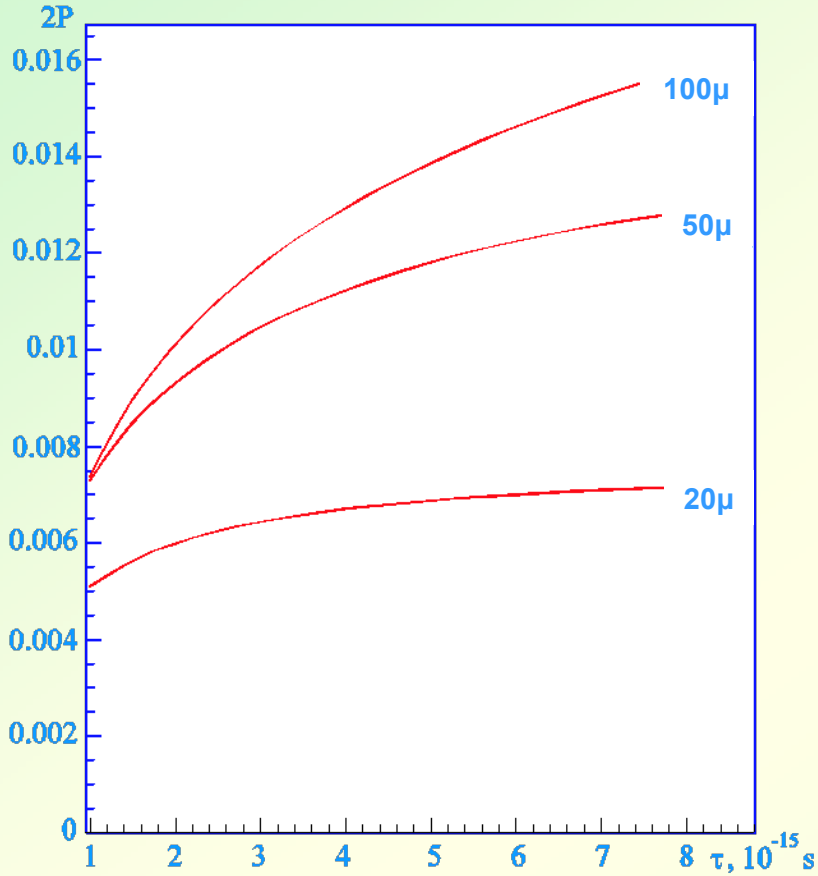
$$(E_{np} - E_{ns})_{\pi\pi} \rightarrow \delta(2a_0 + a_2)$$

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

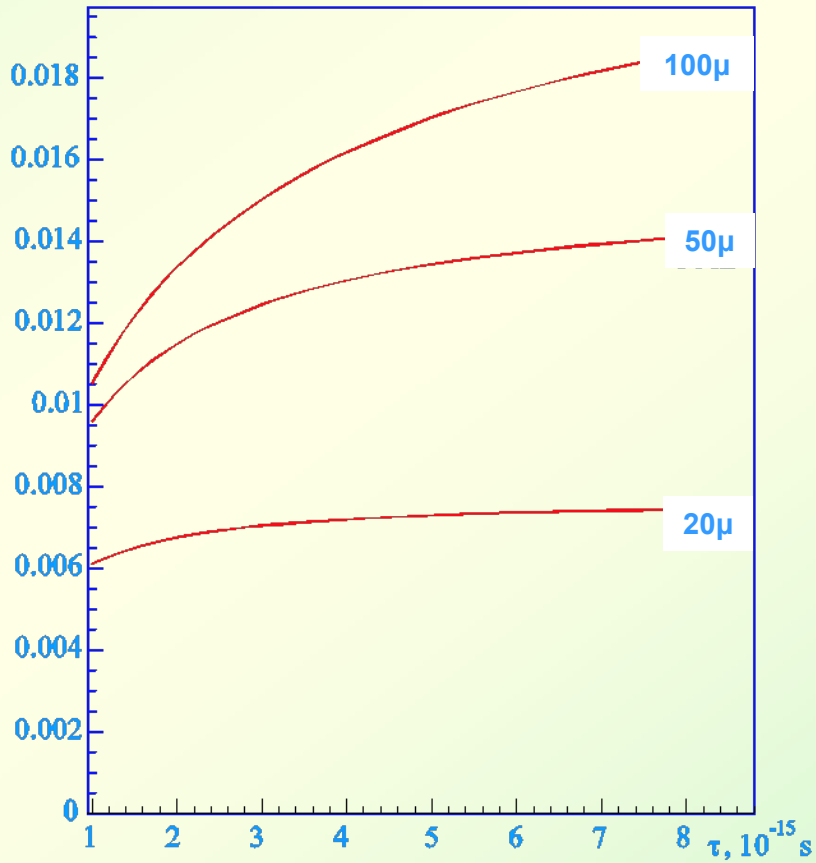
$$(E_{np} - E_{ns})_{\pi K} \rightarrow \delta(2a_{1/2} + a_{3/2})$$

Thank you for your attention

Metastable Atoms – Lifetime dependence



$p(A_{2\pi}) = 4.5 GeV / c$

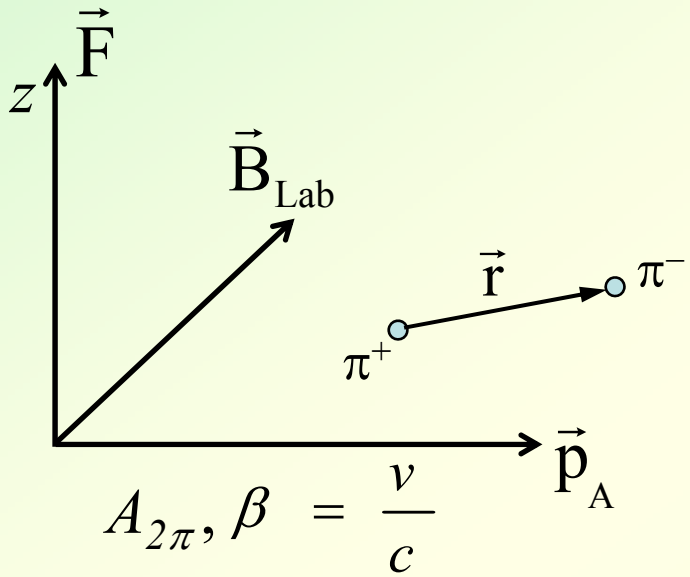


$p(A_{2\pi}) = 10 GeV / c$

Yields of the long-lived states $2p$ ($m = 0$) as a function of the $A_{2\pi}$ lifetime for Beryllium targets ($Z = 04$). Target thicknesses are given in microns on the right side of the picture.

External magnetic and electric fields

Atoms in a beam are influenced by external magnetic field and the relativistic Lorentz factor



$\vec{r}$ ≡ relative distance between π^+ and π^- mesons in $A_{2\pi}$ atom

$\vec{B}_{Lab}$ ≡ laboratory magnetic field

$\vec{F}$ ≡ electric field in the CM system of an $A_{2\pi}$ atom

$$F = \beta\gamma B_{Lab} \approx \gamma B_{Lab}$$

The dependence of $A_{2\pi}$ life time in 2p-states τ_{eff} from a strength of the electric field F

$$\tau_{eff} = \frac{\tau_{2p}}{1 + \frac{|\xi|^2}{4}\frac{\tau_{2p}}{\tau_{2s}}} = \frac{\tau_{2p}}{1 + 120|\xi|^2}$$

where: $$|\xi|^2 \approx \frac{F^2}{\left(E_{2p} - E_{2s}\right)^2}$$

$B_{Lab} = 4$ Tesla

$$\begin{cases} \gamma = 20 \ , & |\xi| = 0.1 \quad \Rightarrow \quad \tau_{eff} = \dfrac{\tau_{2p}}{2.2} \\ \gamma = 40 \ , & |\xi| = 0.2 \quad \Rightarrow \quad \tau_{eff} = \dfrac{\tau_{2p}}{6} \end{cases}$$