Results and scientific plans of the DIRAC experiment at CERN

Leonid Nemenov

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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

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

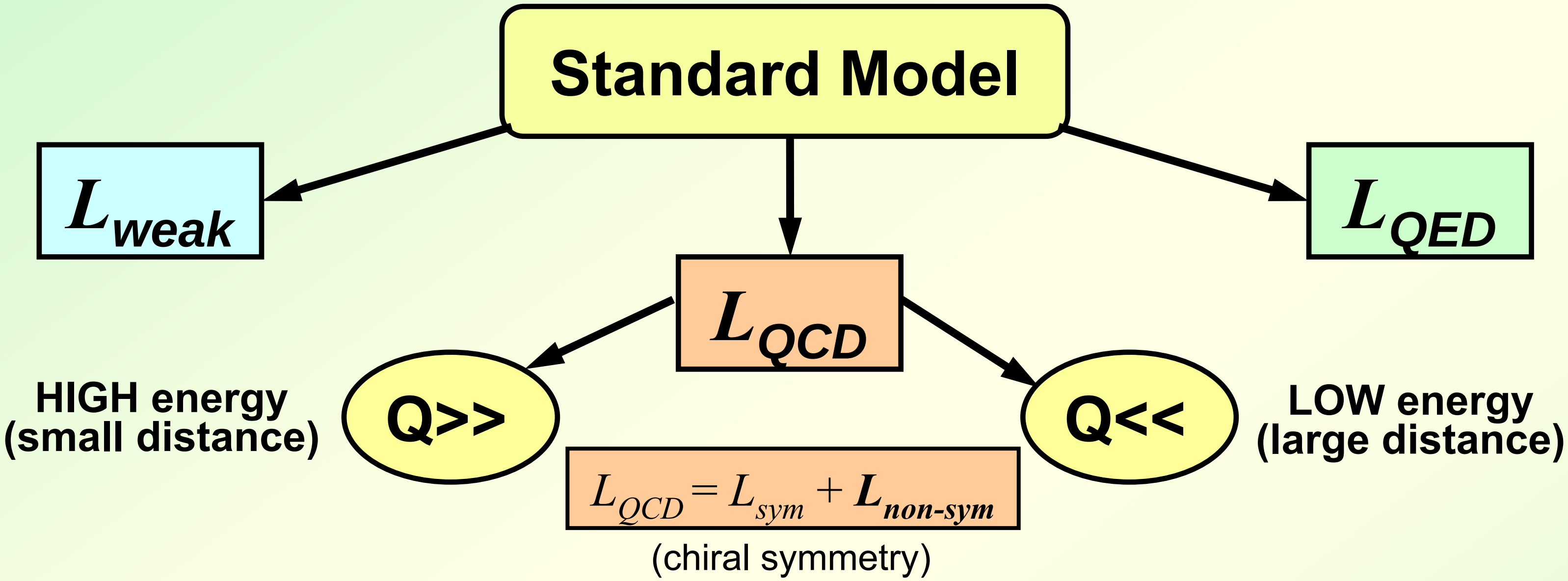
Bern University
Bern, Switzerland

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*
- *Plan 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

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

→ 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:

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

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.

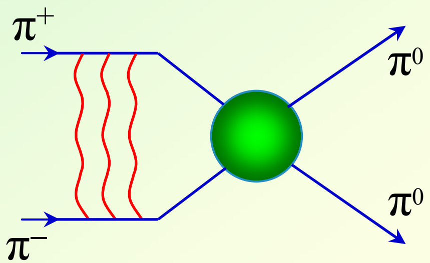
Because l_3 and l_4 are sensitive to the quark condensate,
precision measurements of a_0, a_2 are a way
to study the **structure** of the QCD vacuum.

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 $\pi^0\pi^0$:



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

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

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

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:

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

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

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

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

A. Rossel. – 1999

$$a_0^{1/2} - a_0^{3/2} = (0.220 - (-0.047)) = 0.267$$

J. Bijnens,P. P. Donthe
P. Talavera. – 2004

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

II. Roy-Steiner equations:

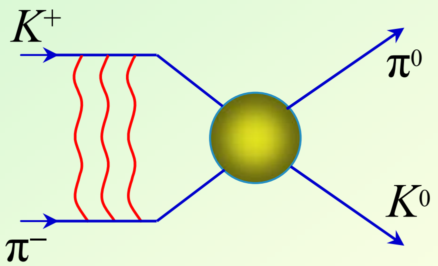
$$a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015$$

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 $K^0\pi^0$:

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

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

(**) 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

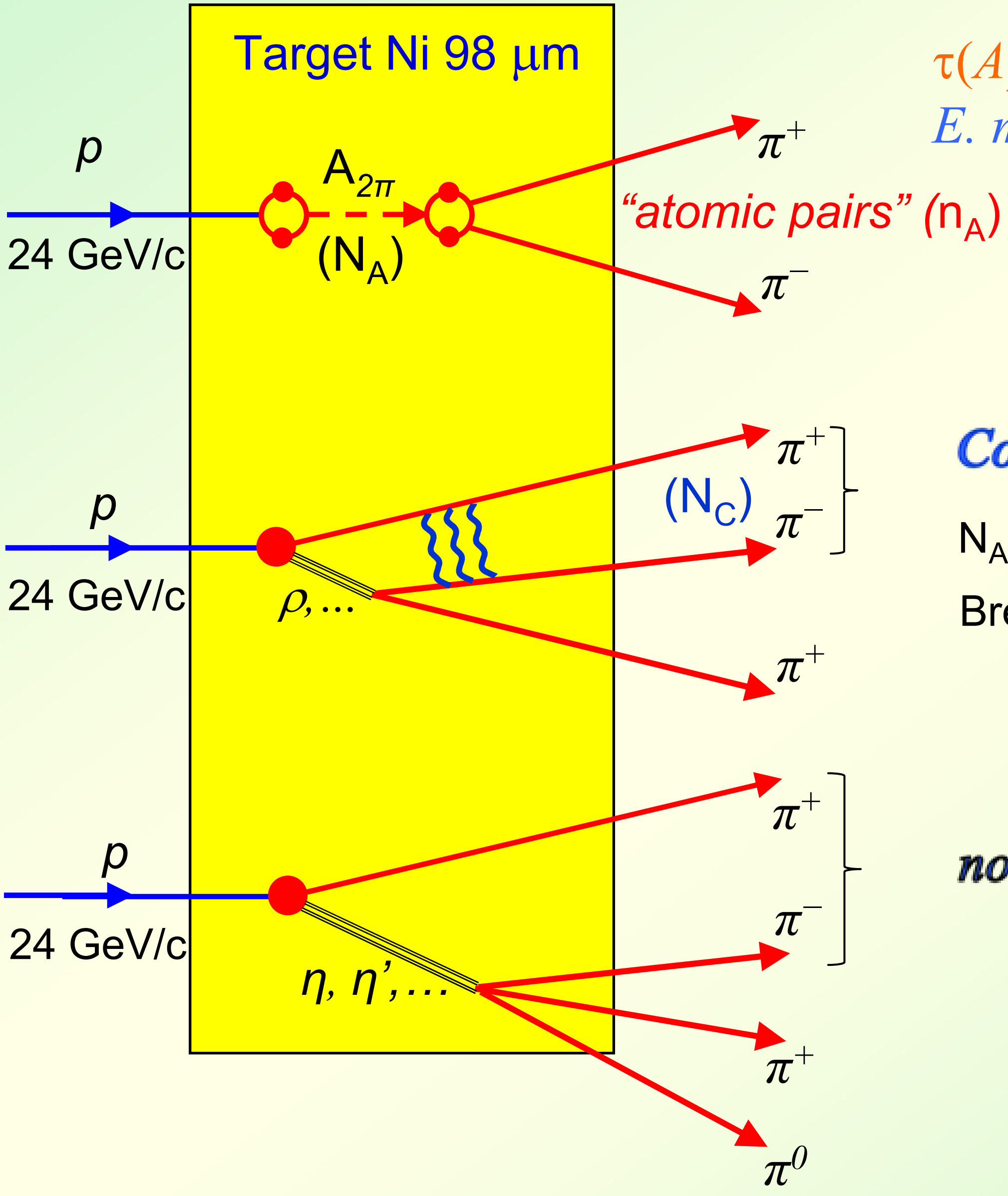
What new will be known if πK scattering length will be measured?

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*

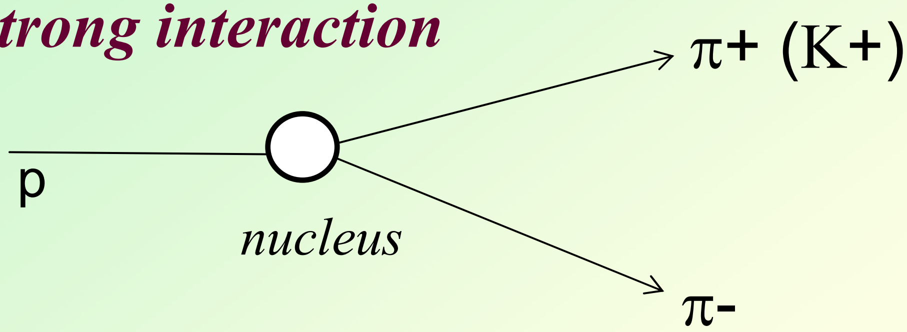
$N_A = K(Q_0)\ N_C(Q<Q_0)$ with known $K(Q_0)$

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

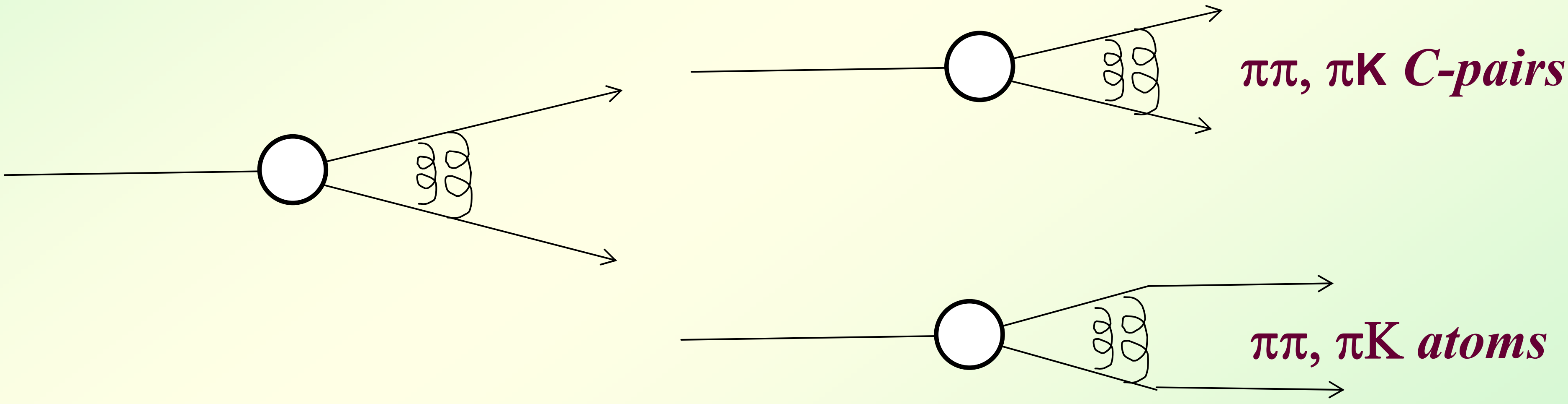
non-Coulomb *from long-lived sources*

Coulomb pairs and atoms

Strong interaction



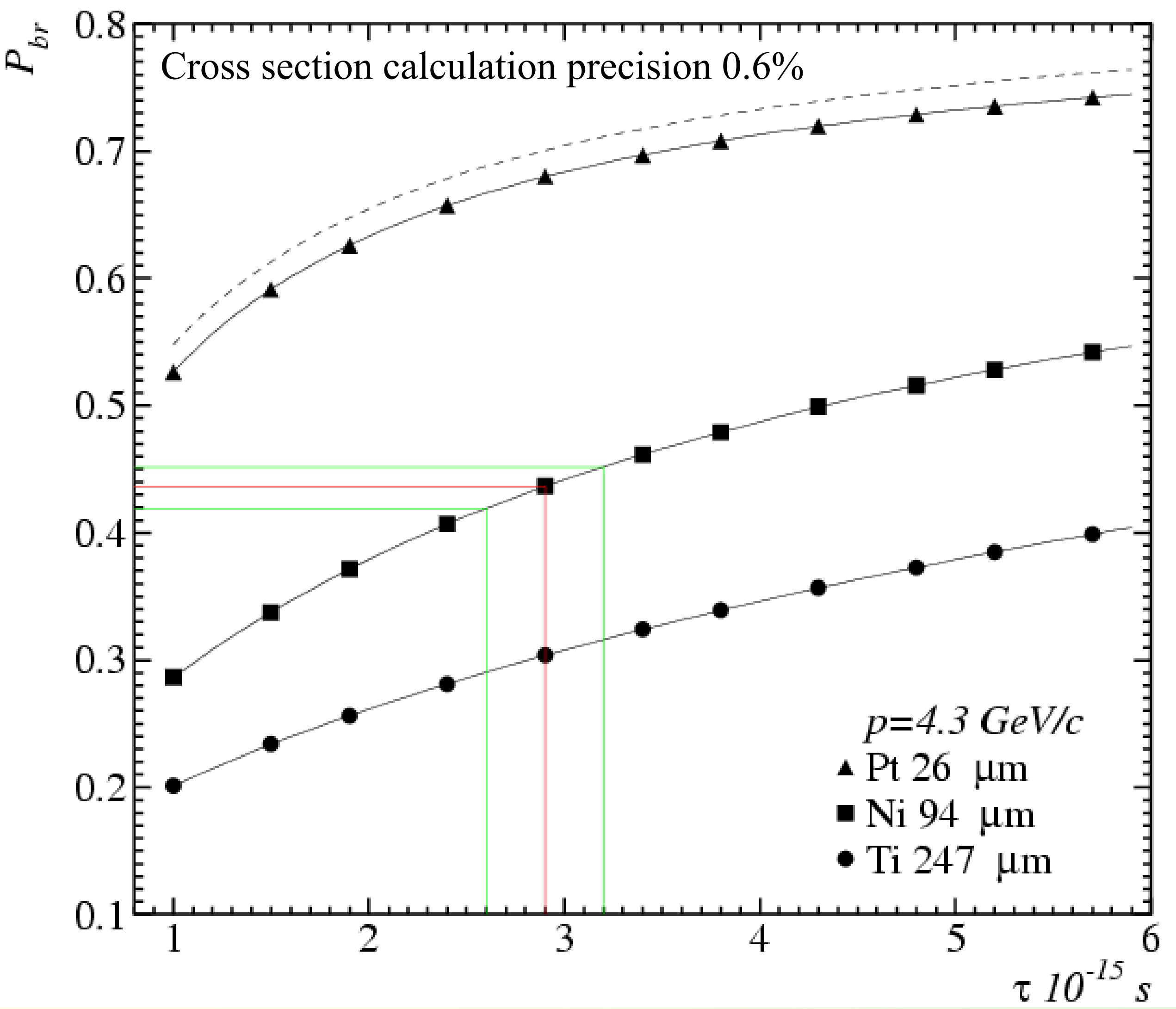
For small Q there are Coulomb pairs :



The yield strongly increases with Q decreasing.

Break-up probability

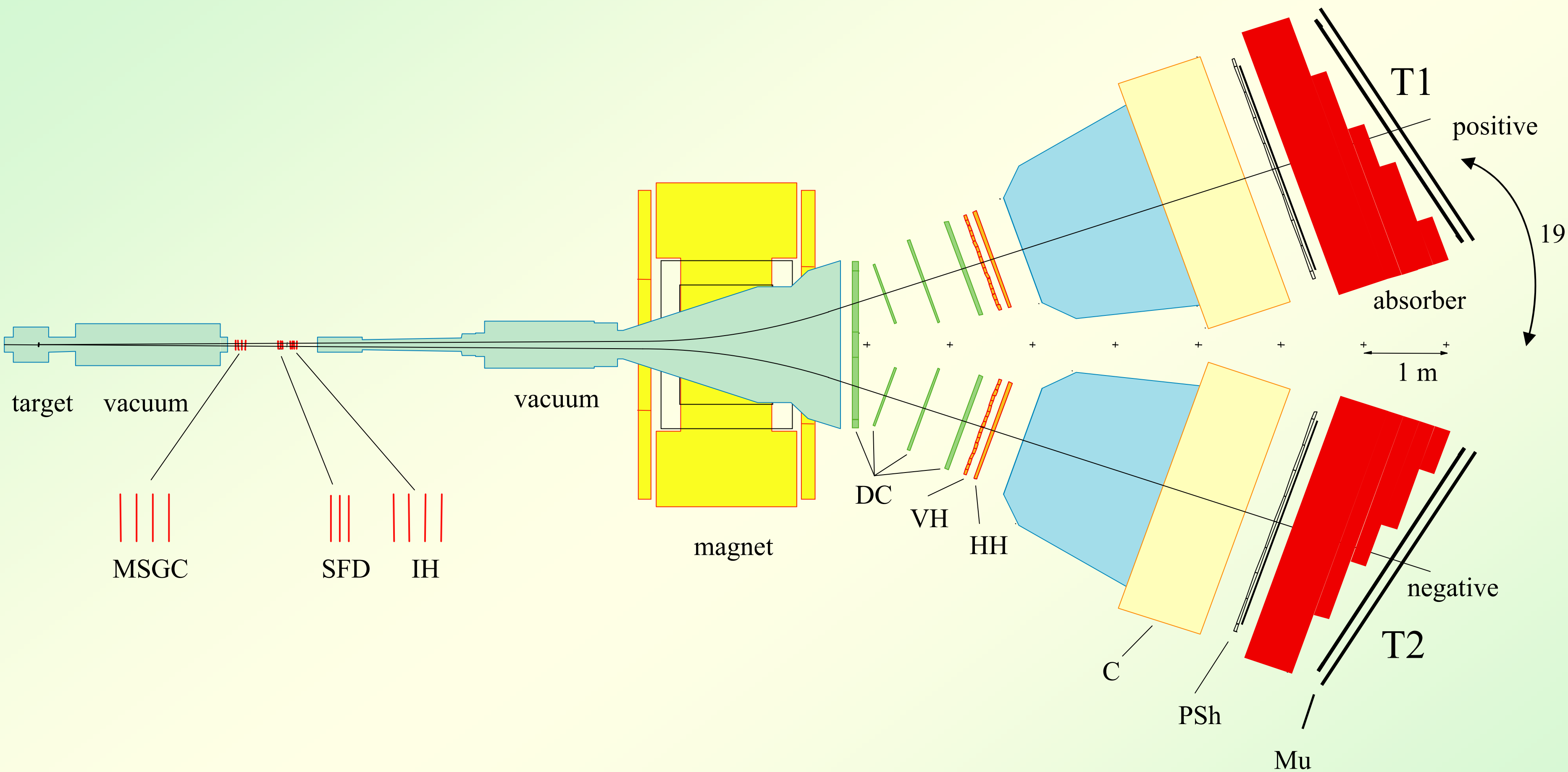
Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on pionium lifetime τ



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

There is an optimal target material for a given lifetime

DIRAC First Setup



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
Resolution on $\frac{\delta P_{Lab}}{P_{Lab}} \sim 3.5 \cdot 10^{-3}$
Resolution on Q:

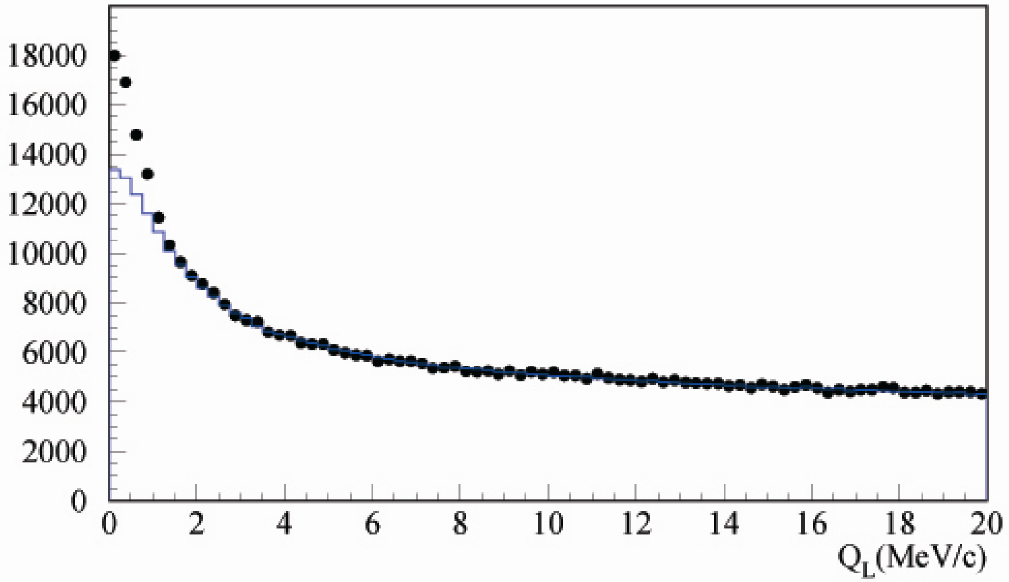
$Q_x \approx Q_y \approx$ 0.1 Mev/c,

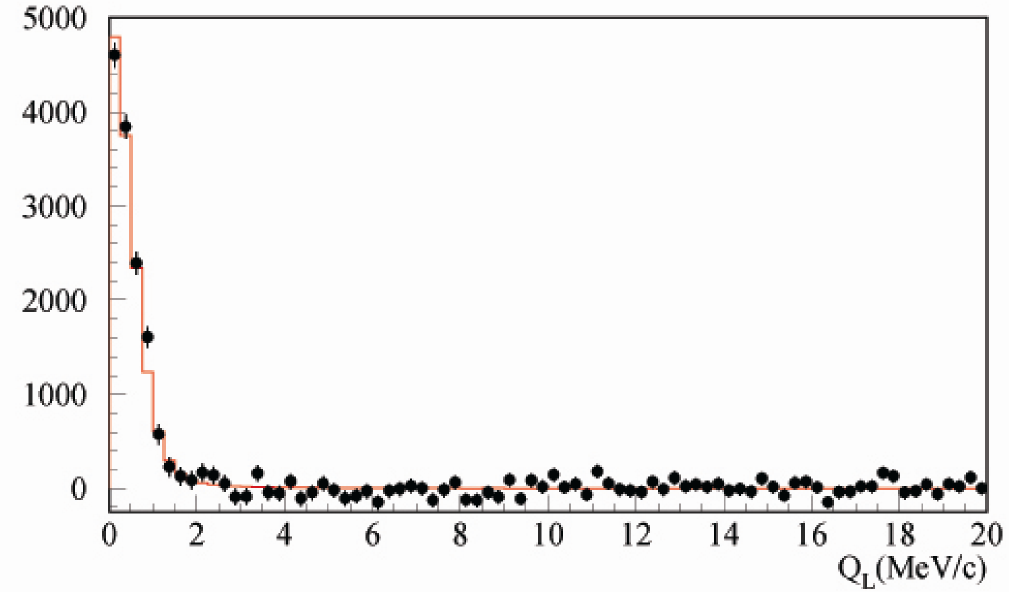
$Q_L \approx$ 0.5 MeV/c

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

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

DIRAC preliminary results with GEM/MSGC





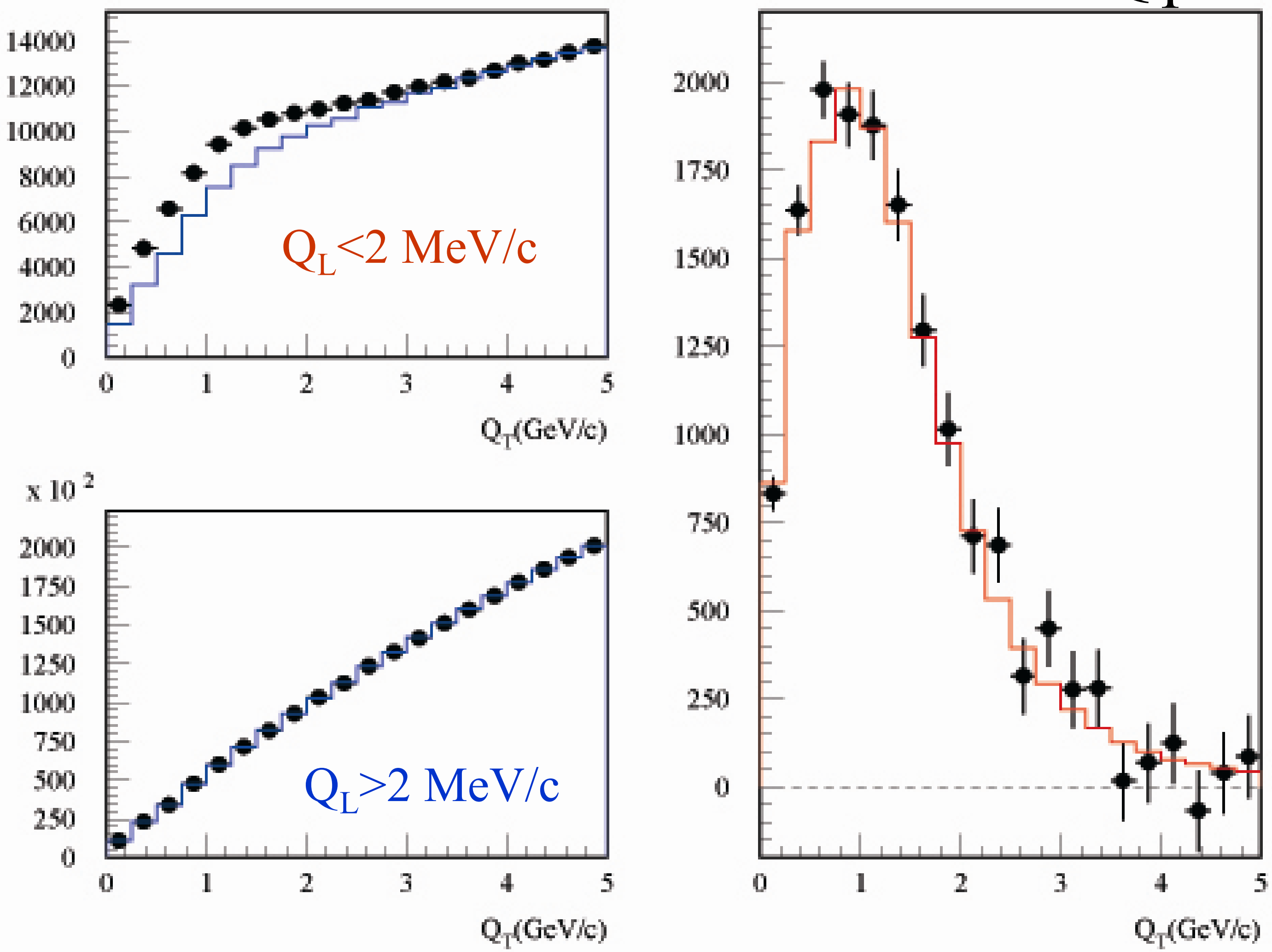
Q_L distribution

←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 20000 => the statistical error in $|a_0$-$a_2|$ is 3%, and the expected full error is <5%.

Comparition with other experimental results

$K \to 3\pi$:

2009 **NA48/2** (EPJ C64, 589)

...without constraint between a_0 and a_2:

$$\Rightarrow a_0 - a_2 = 0.2571 \pm 1.9\%\big|_{stat} \pm 1.0\%\big|_{syst} \pm 0.5\%\big|_{ext} = \ldots \pm 2.2\%$$

and 3.4% theory uncertainty

...with ChPT constraint between a_0 and a_2:

$$\Rightarrow a_0 - a_2 = 0.2633 \pm 0.9\%\big|_{stat} \pm 0.5\%\big|_{syst} \pm 0.7\%\big|_{ext} = \ldots \pm 1.3\%$$

and 2% theory uncertainty

Ke4:

2009 **NA48/2** (CD09, Bern)

...without constraint between a_0 and a_2:

$$\Rightarrow a_0 = 0.2220 \pm 5.8\%\big|_{stat} \pm 2.3\%\big|_{syst} \pm 1.7\%\big|_{theo} = \ldots \pm 6.4\%$$

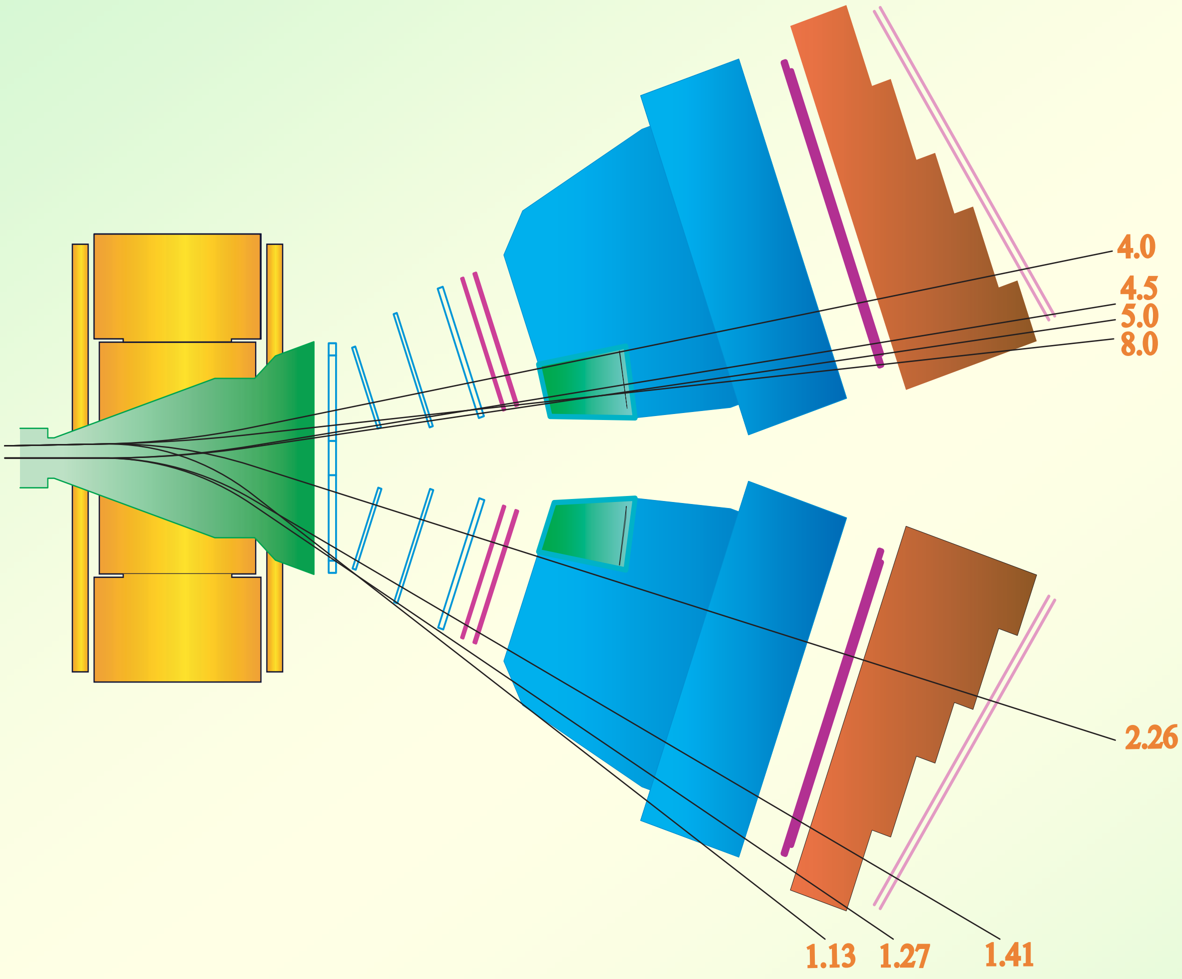
$$\Rightarrow a_2 = -0.0432 \pm 20\%\big|_{stat} \pm 7.9\%\big|_{syst} \pm 6.5\%\big|_{theo} = \ldots \pm 22\%$$

...with ChPT constraint between a_0 and a_2:

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

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

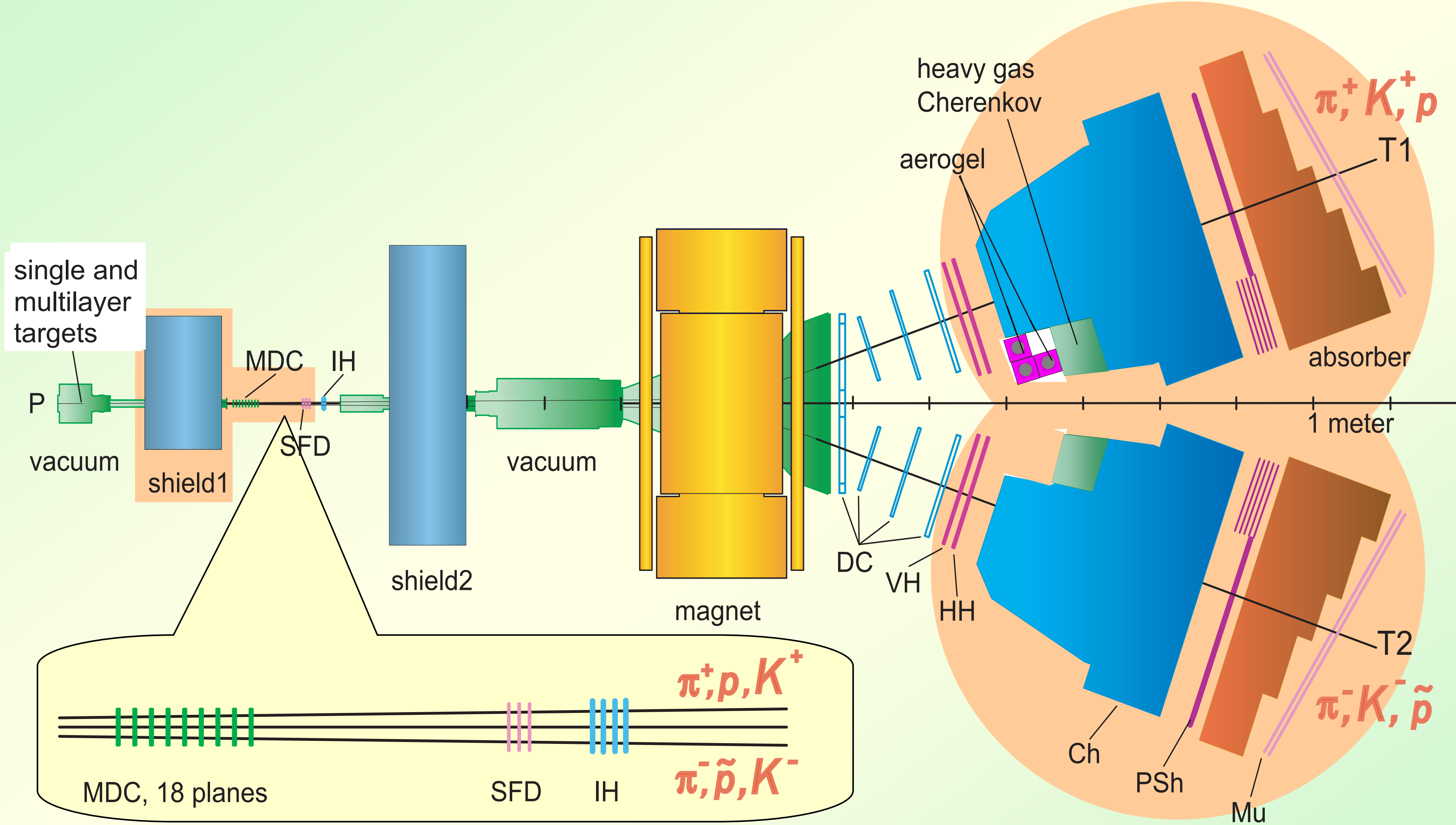
The numbers to the right of the tracks lines are the π^- and K^+ momenta in GeV/c



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

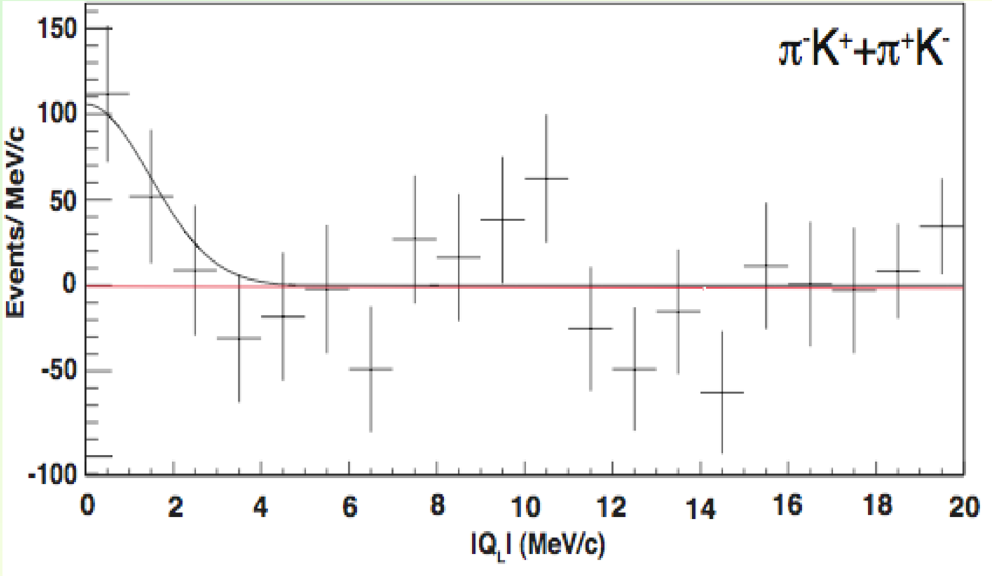
P_{atom} (GeV/c)	P_π (GeV/c)	P_K (GeV/c)
5.13	1.13	4.0
5.77	1.27	4.5
6.41	1.41	5.0
10.26	2.26	8.0

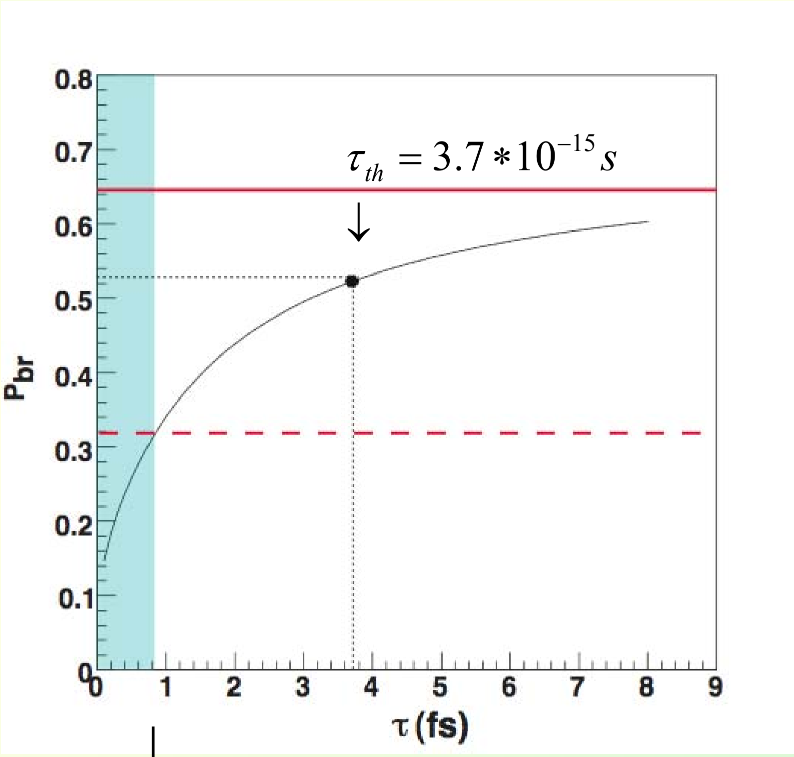
Upgraded DIRAC experimental setup



Modifided parts

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





↓

In total:

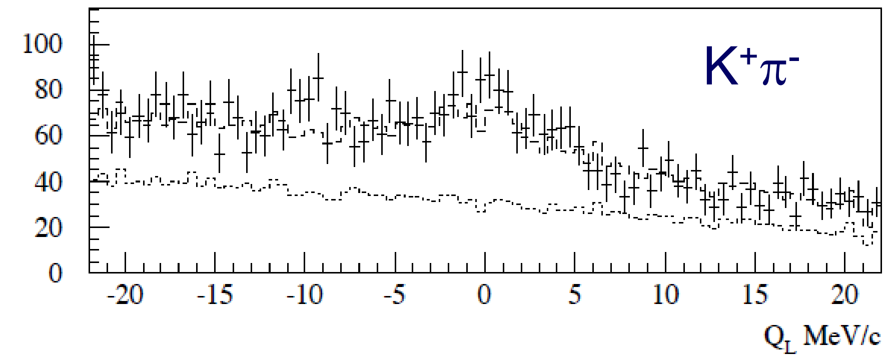
173±54 πK-atomic pairs are observed with a significance of 3.2σ.

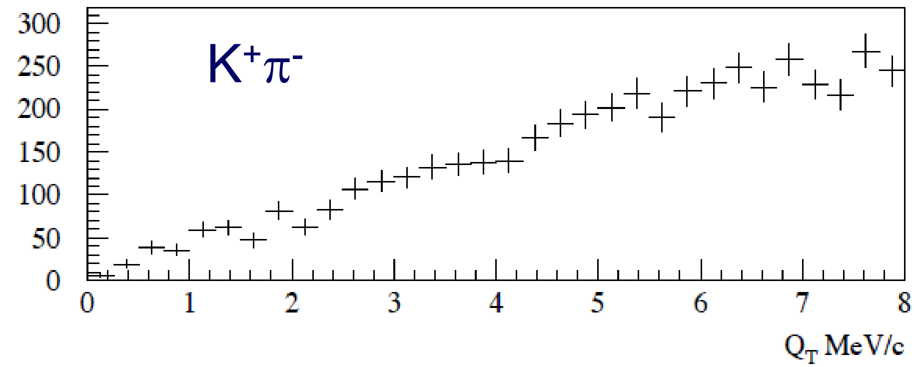
$\tau > 0.8 * 10^{-15} s$ at 90%CL

B. Adeva et al.,"Evidence for πK-atoms with DIRAC", Physics Letters B 674 (2009) 11

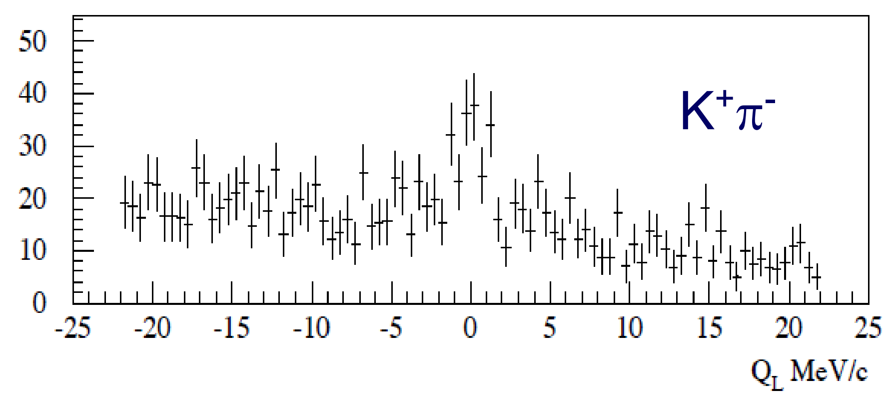
Y. Allkofer, PhD Thesis, Universität Zürich, 2008.

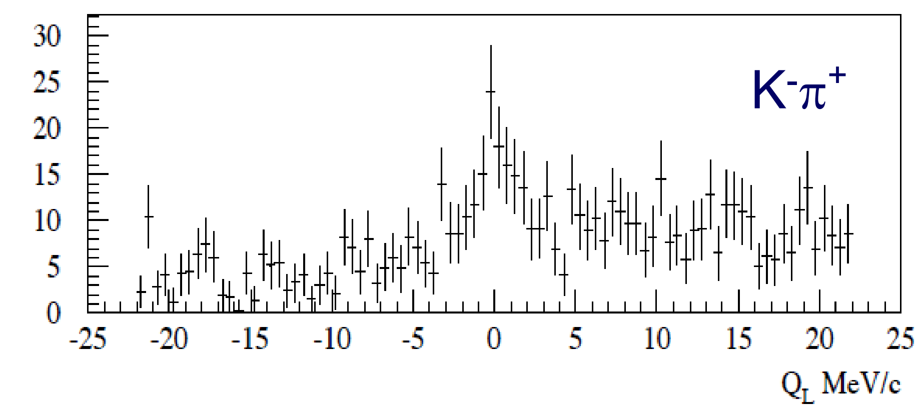
Q_L distributions from 2008 data





Q_T distribution of $K^+\pi^-$ pairs from 2007 data





Q_L distribution for $K^-\pi^+$ and $K^+\pi^-$ pairs from 2008 data

Predictions

Table 3: Predictions for πK pairs of both signs with the Nickel target

	2008 + 2009			2008 + 2009+2010
reconstruction efficiency	N_A	n_A	$n_A/Error$	$n_A/Error$
42%	255	79	3.06 ± 0.37	3.79 ± 0.46
63%	442	137	4.07 ± 0.49	5.15 ± 0.62
80%	561	174	4.54 ± 0.55	5.74 ± 0.70

Table 4: Prediction for πK pairs of both signs with the Platinum target (2007) and Nickel target (2008+2009)

	2007 + 2008 + 2009
reconstruction efficiency	$n_A/Error$
42%	3.82 ± 0.35
63%	4.67 ± 0.45
80%	5.08 ± 0.51

Accuracy of $|a_{1/2}-a_{3/2}|$ measurement

Accuracy of the measurement	5σ (20%)	6σ (17%)	6.5σ (15%)
τ (s)	$(3.7^{+60\%}_{-43\%})\cdot 10^{-15}$	$(3.7^{+51\%}_{-38\%})\cdot 10^{-15}$	$(3.7^{+46\%}_{-32\%})\cdot 10^{-15}$
$\delta_{avreage}\lvert a_{1/2}-a_{3/2}\rvert$	26 %	23 %	20 %

Scientific plan for 2011

To performe in 2011 the data taking for observation of the long-lived states of $A_{2\pi}$. This observation is opening a possibility to measure the Lamb shift and to determine the new combination of $\pi\pi$ scattering lengths $2a_0 + a_2$.

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 $n = 2$

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

$\Delta E_2^{s} \approx -0.45\ eV$ *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*

$\Rightarrow$ $\Delta E_2 \approx -0.56$ 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.*

Metastable Atoms

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

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

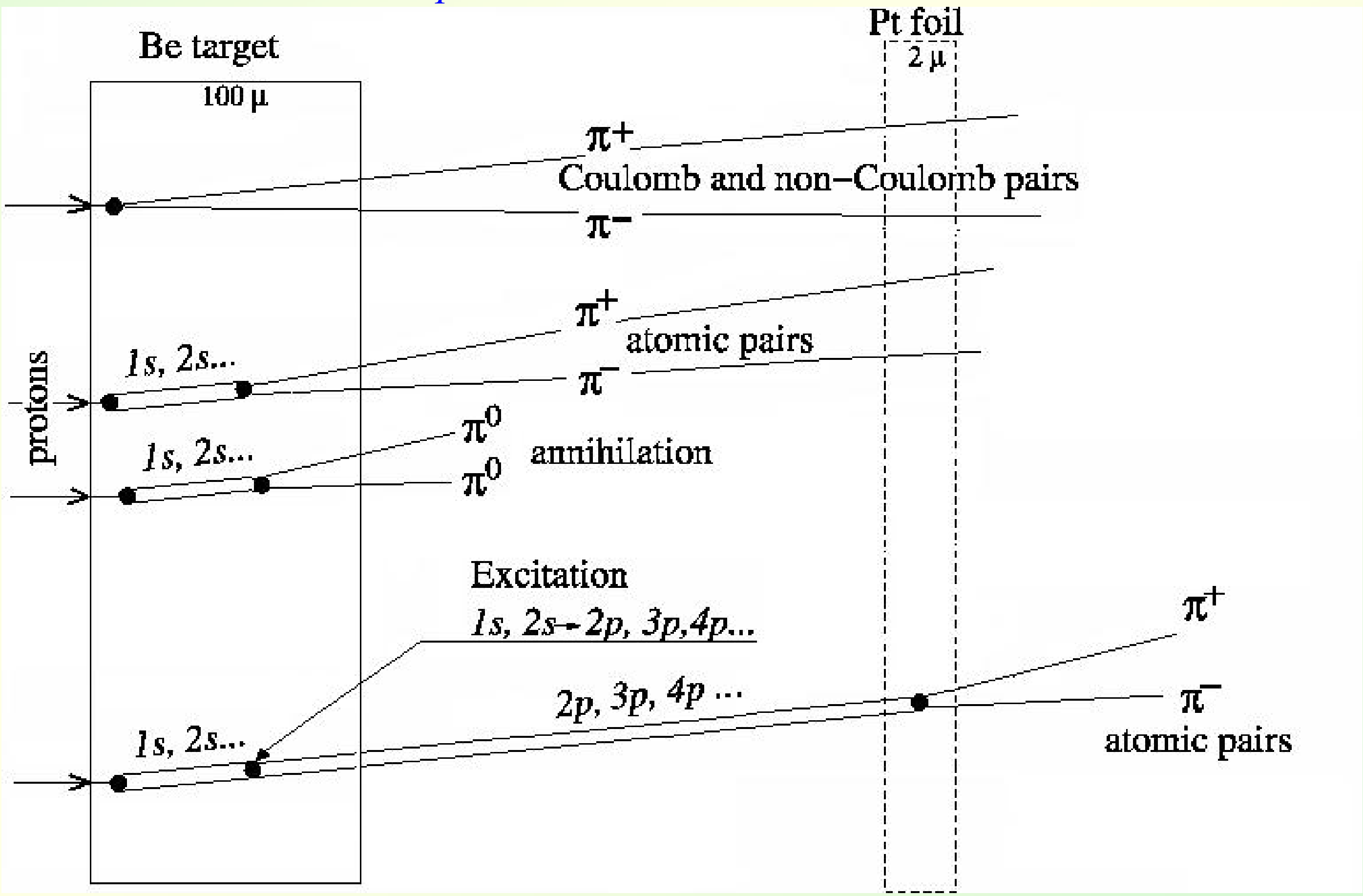


Illustration for observation of the $A_{2\pi}$ long-lived states with breaking foil.

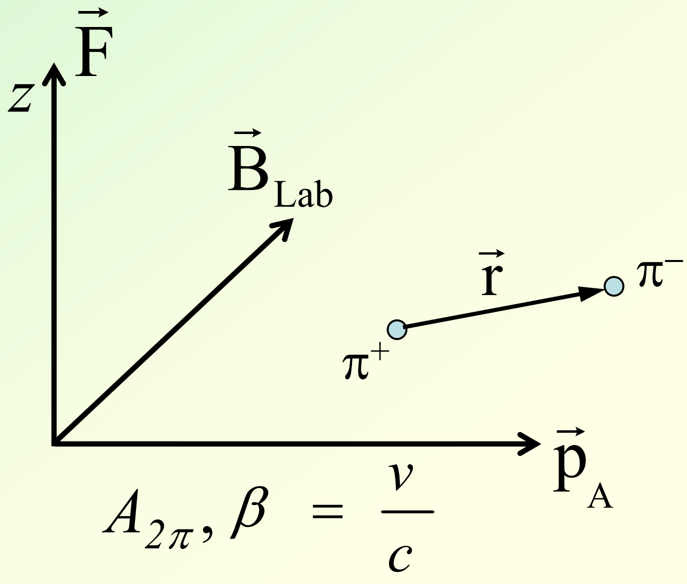
Metastable Atoms

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%

External magnetic and electric fields

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



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

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

$\vec{F} \equiv$ 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

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

Prospects of DIRAC

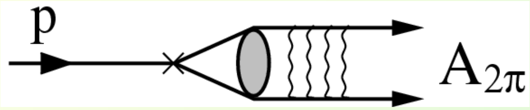
Creation of an intense source of $\pi\pi$, πK and other exotic atoms at SPS proton beam and using them for accurate measurements of all S-wave $\pi\pi$ and πK scattering length to check the precise low energy QCD predictions

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

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

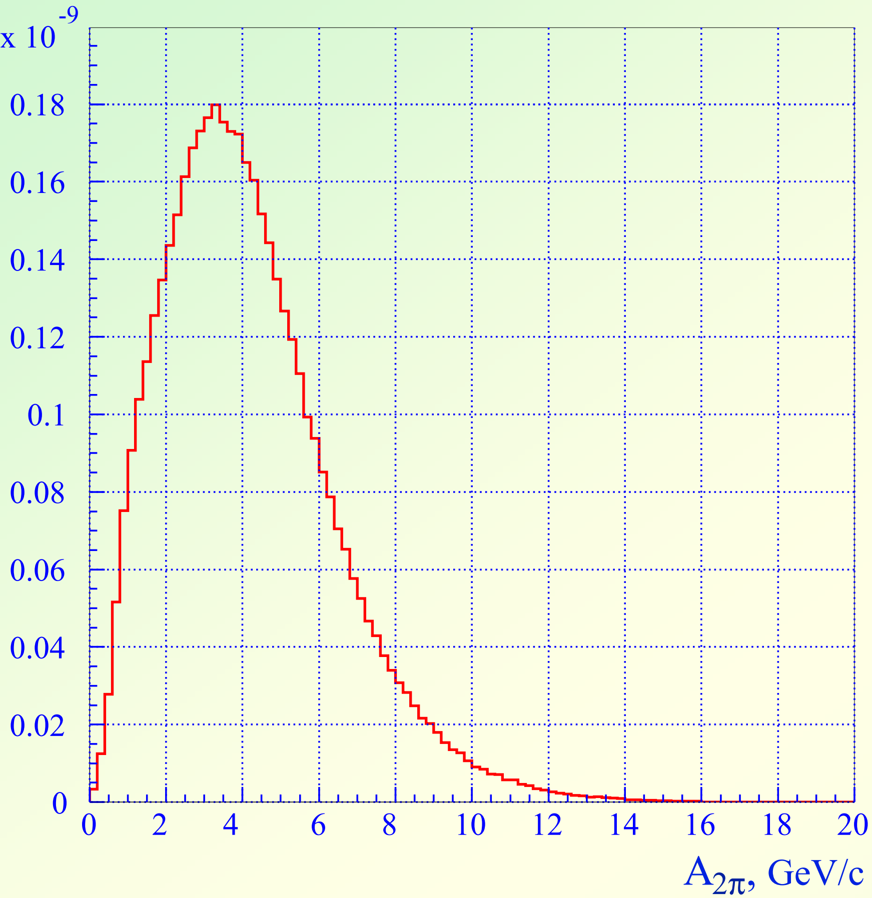
for atoms $\vec{v}_1 = \vec{v}_2$ *where* $\vec{v}_1, \vec{v}_2$ *– velocities of particles in the L.S. for all types of atoms*

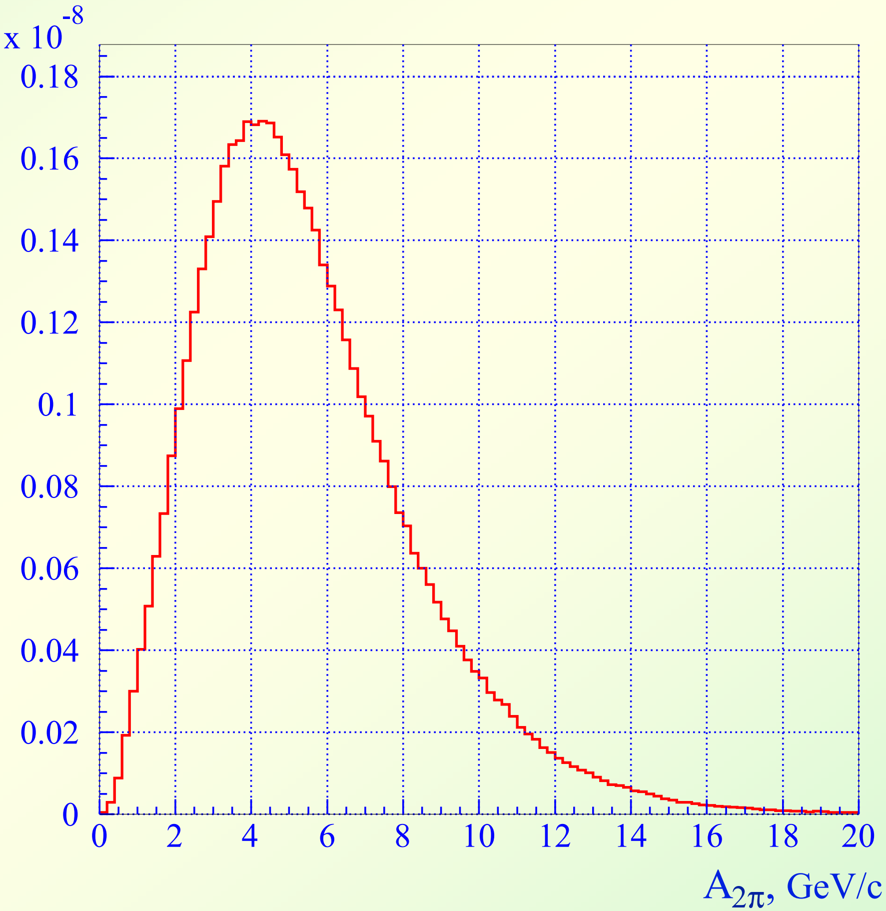
for $A_{2\pi}$ *production* $\vec{p}_1 = \vec{p}_2$



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

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

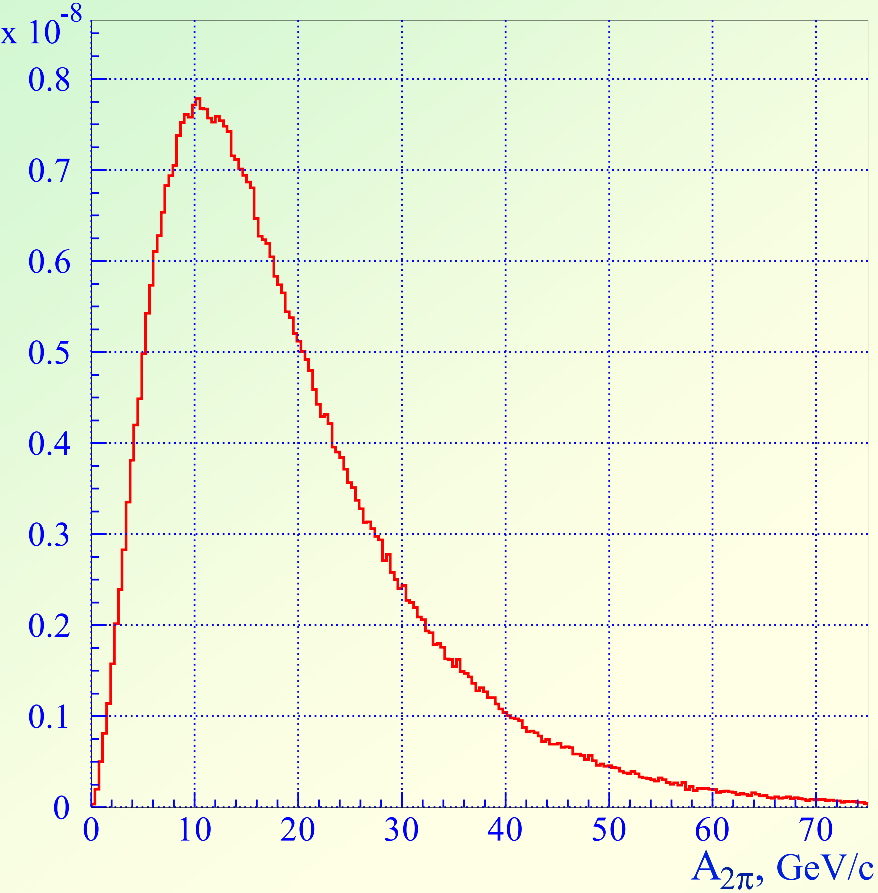


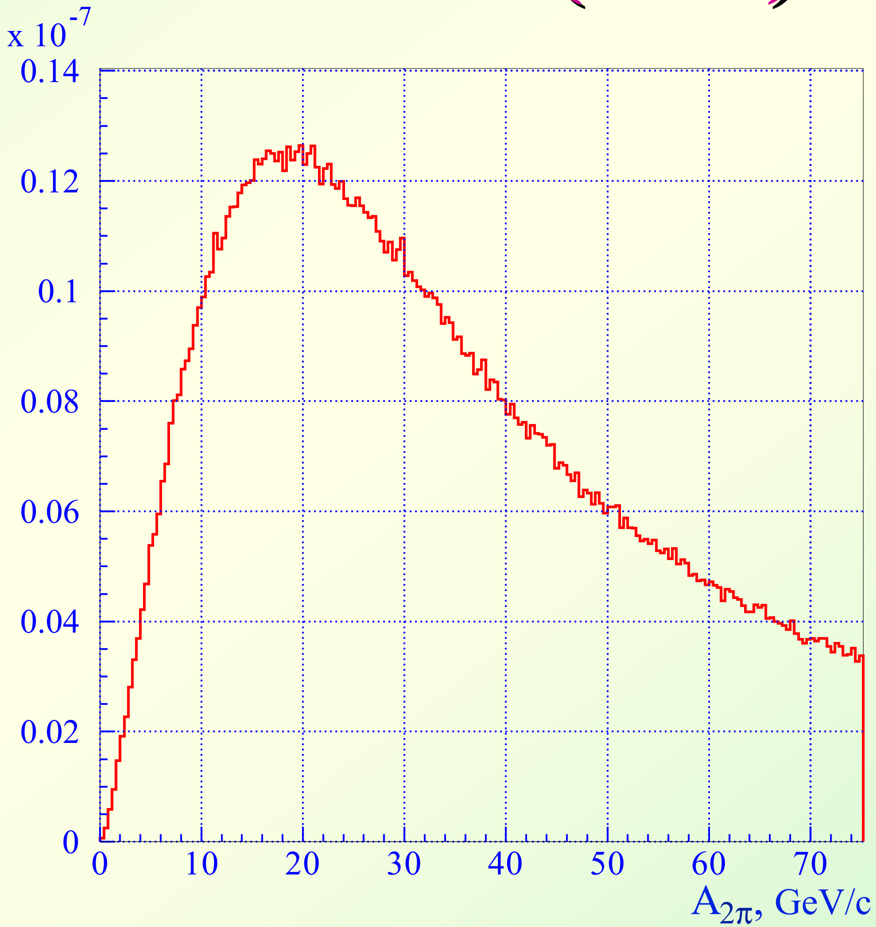


$\theta_L = 5.7° \pm 1.3° \;\; E_p = 24 GeV$

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

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





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

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

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 $\pi\pi$ 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*

Expected results of DIRAC ADDENDUM at PS CERN after 2008-2010

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

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

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 2008-2010 data.

DIRAC at SPS CERN beyond 2011

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

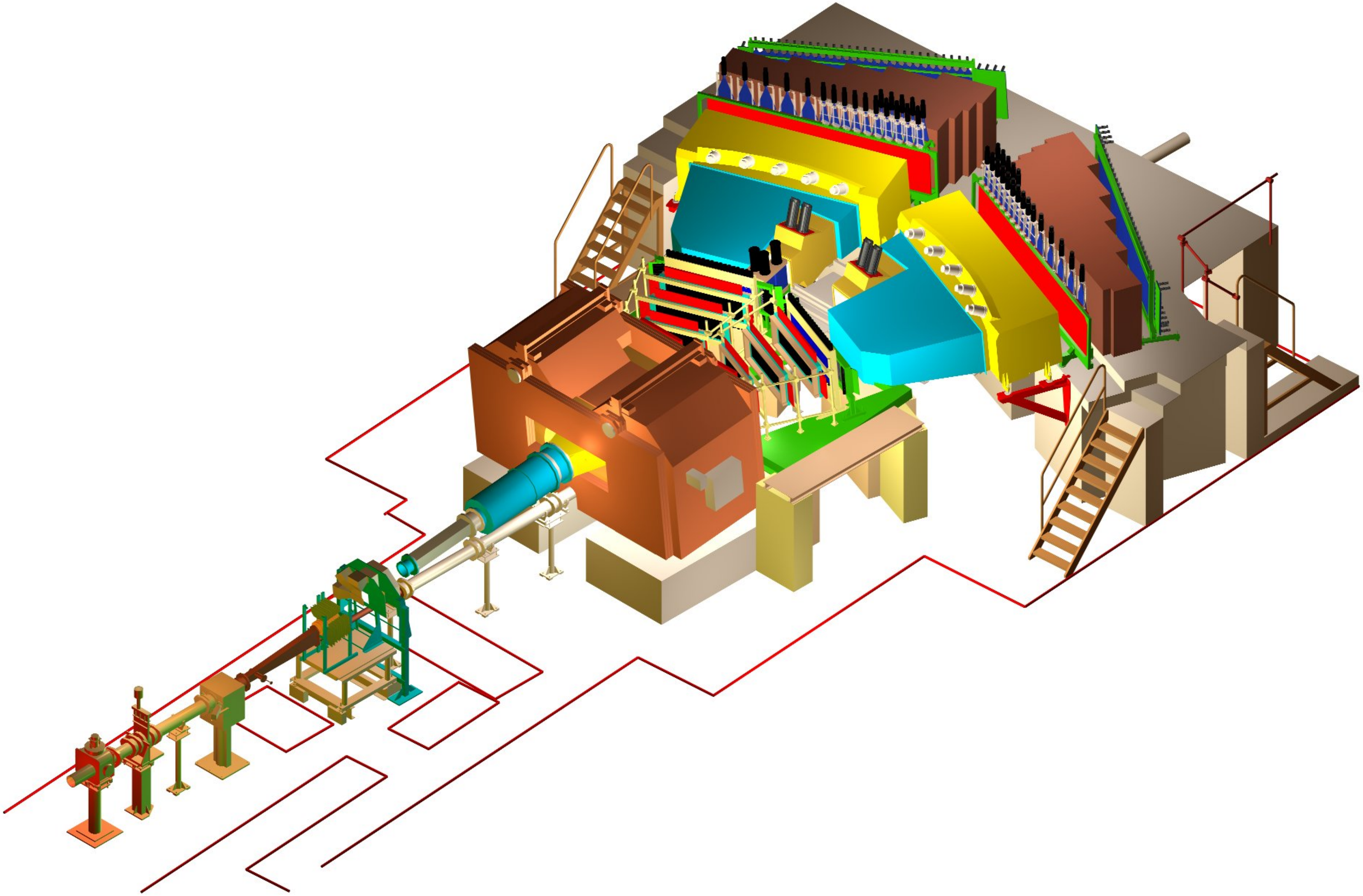
$$(E_{np} - E_{ns})_{\pi\pi} \rightarrow \delta(2a_0 + a_2)$$

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

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

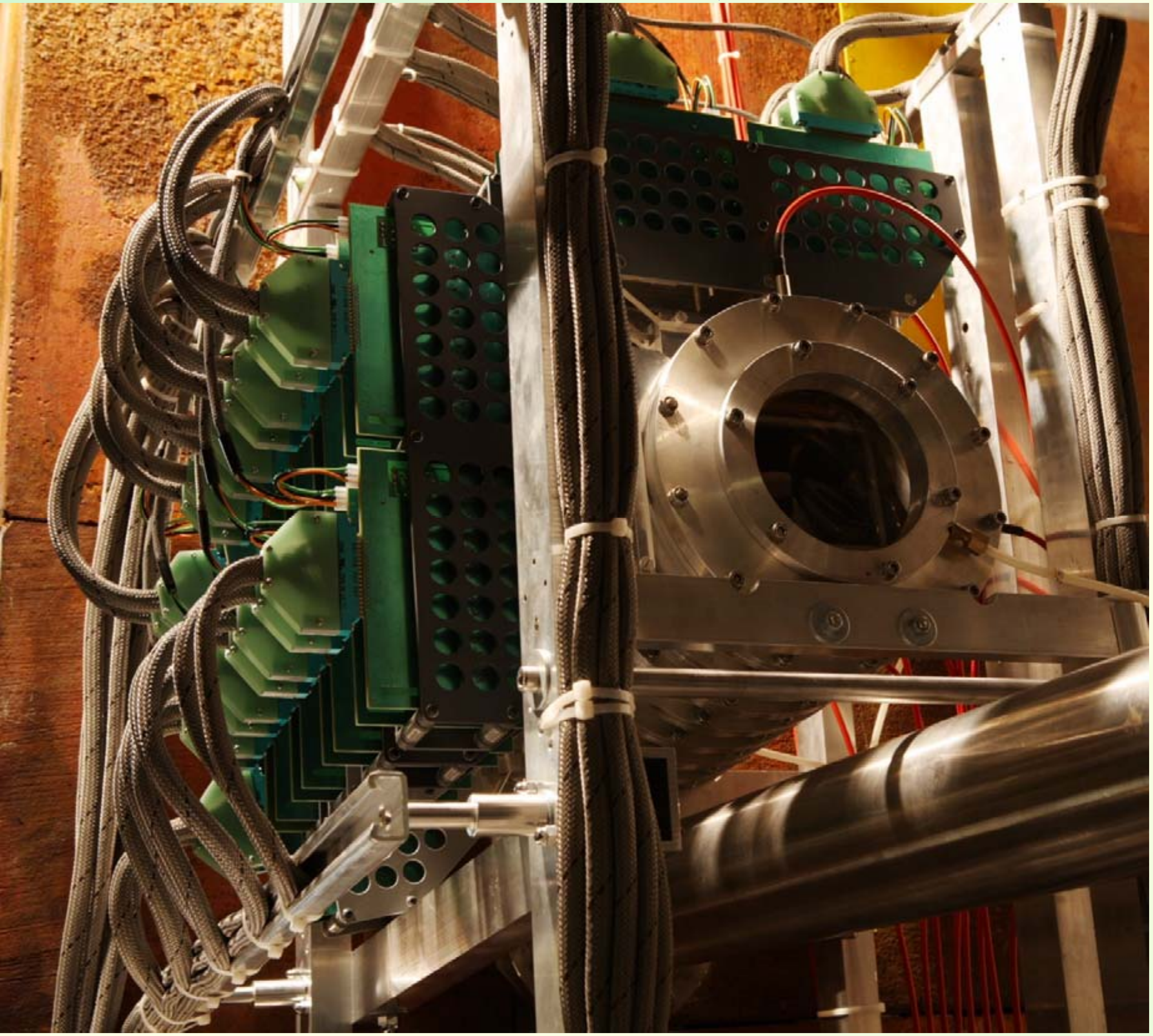
Thank you for your attention

Upgraded DIRAC experimental setup



Micro Drift Chambers I

Responsibility: **JINR (*Dubna*, Russia), Basel University (*Basel*, Switzerland)**

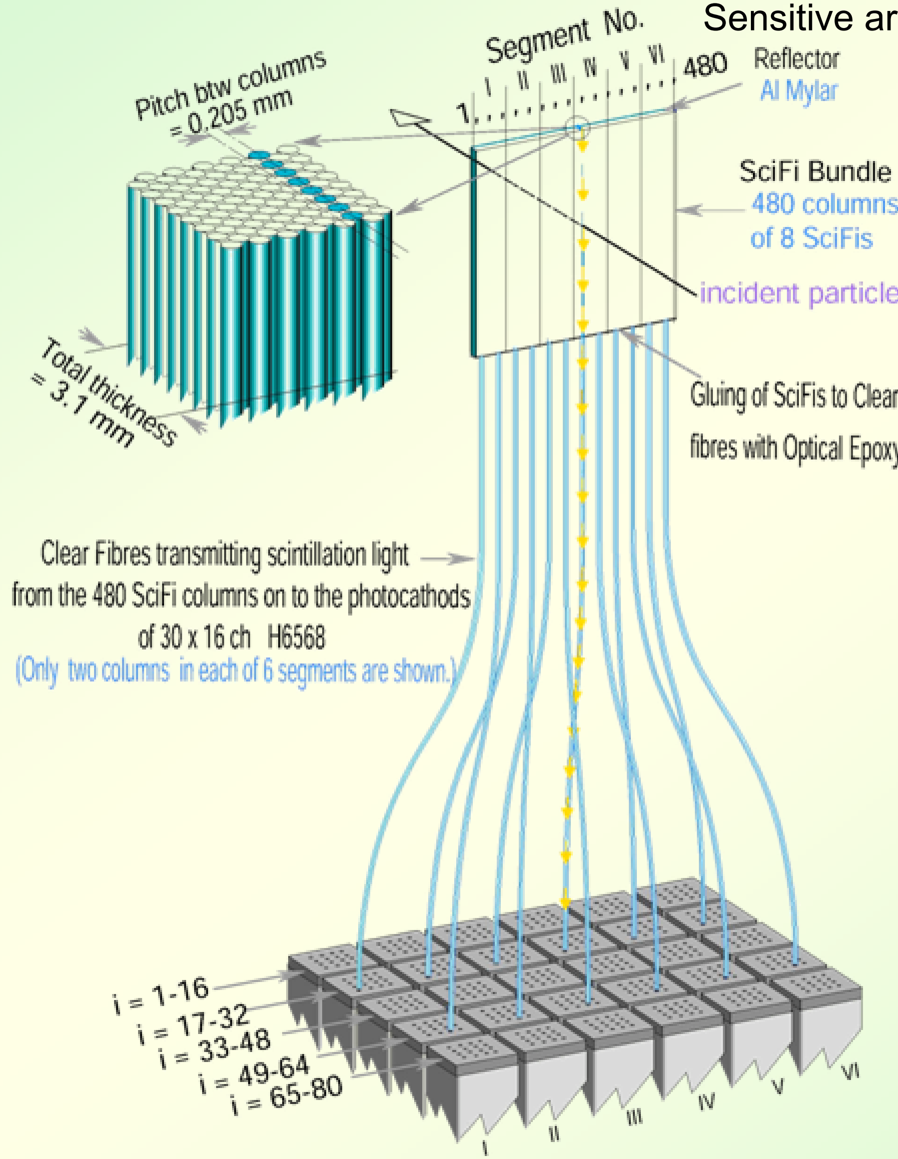


Main features:

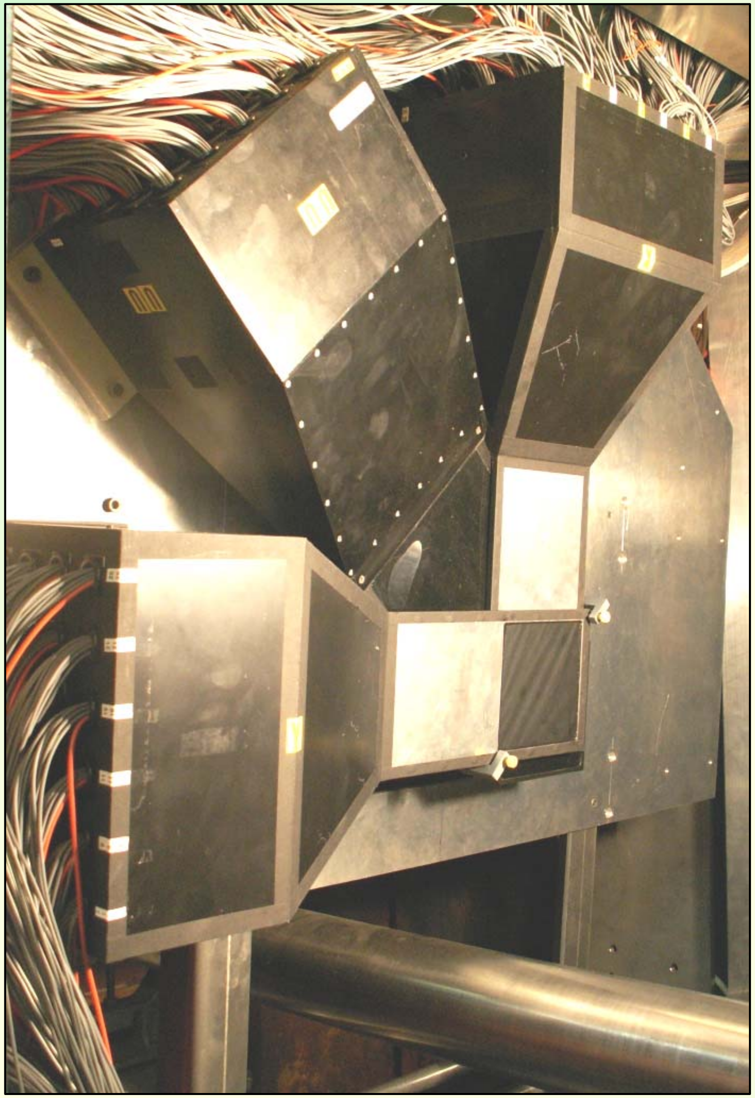
- High spatial accuracy $\sigma < 30\ \mu m$ (2004 result);
- Distinguish two close tracks with distance **< 200 μm**;
- Efficiency **> 98%** at $I = 2\times10^{11}$ protons/spill;
- total detector thickness $<5\times10^{-3}\ X_0$;
- time resolution < **1** ***ns***;
- readout time < **3** ***μs***.

Scintillation Fiber Detector I

Sensitive area = 98.5 x 107 mm^2



Scintillation Fiber Detector



Characteristics:

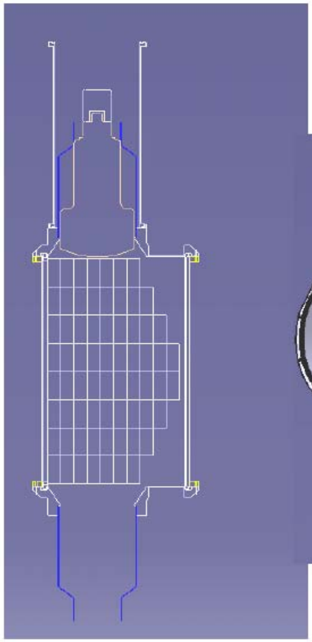
- Size of the plane — $100 \times 100\ mm^2$
- Thickness of the material for one plane — $3\ mm$ (1% X_0)
- Mean light output: — ≈ 11 *p.e.*
- Mean Detector Efficiency: — ≈ 98 %
- Time Resolution without coordinate and amplitude corrections — ≈ 0.46 *ns*
- Space resolution — $\sigma \approx 60\ \mu m$
- New electronics (*ADC-TDC for each channel*) — 960 *channels*

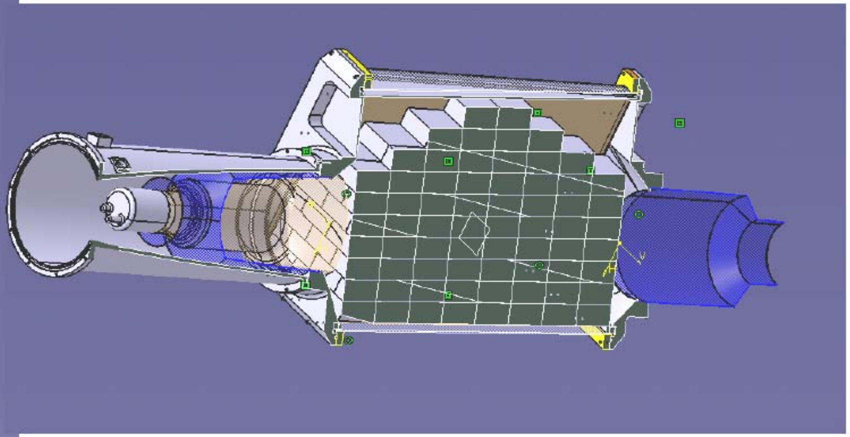
Aerogel Cherenkov detector

Responsibility:

Zurich University (*Zurich*, Switzerland)

The n=1.008 counter

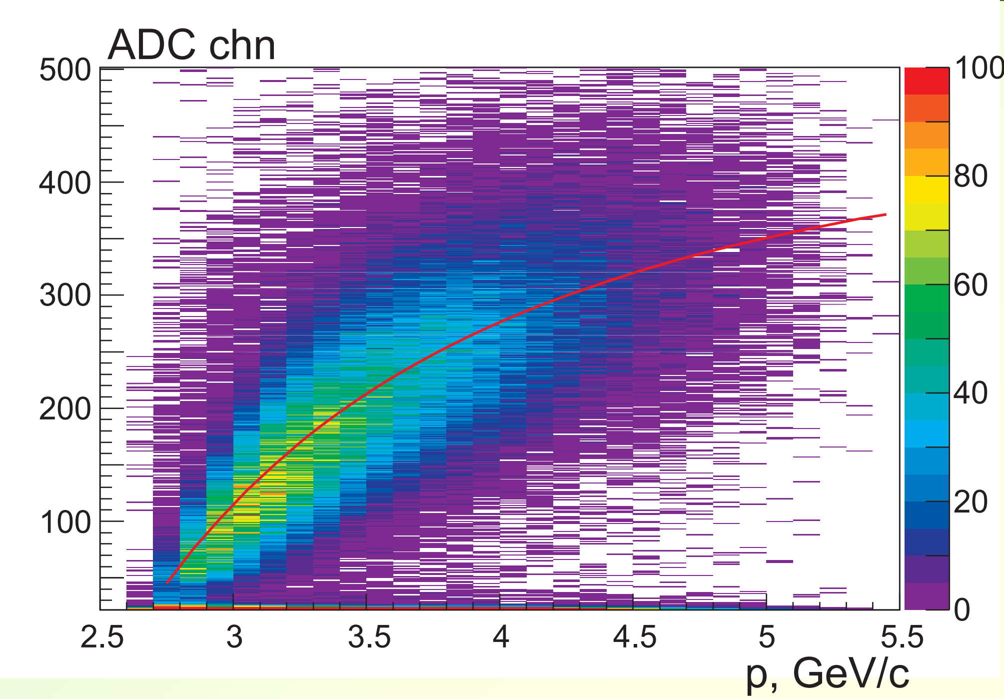


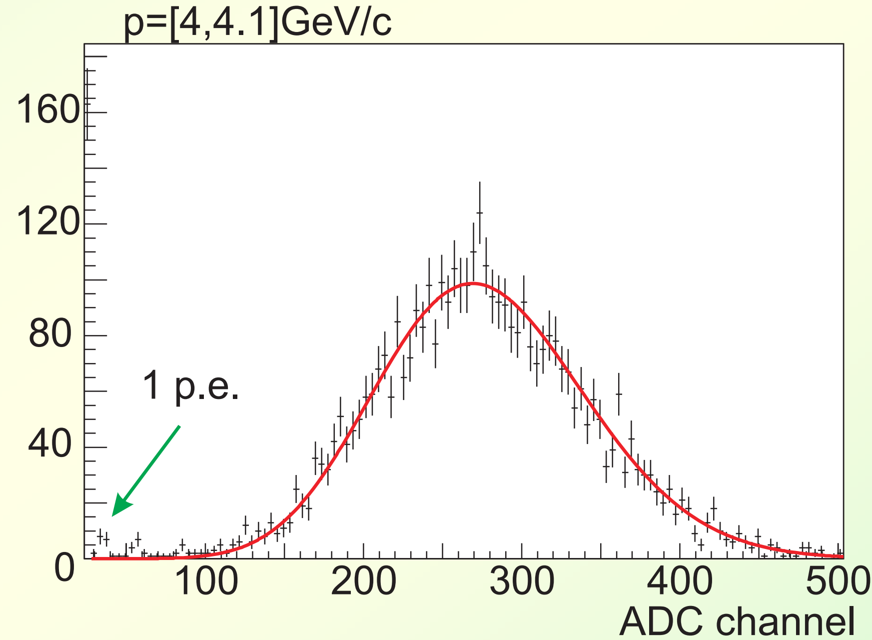


Status:

Aerogel detectors were installed on the setup

Cherenkov detector C_4F_{10}





$$N_{p.e} = LN_0\left(1-\frac{1}{\beta^2 n^2}\right) = LN_0 \sin^2\Theta_C$$

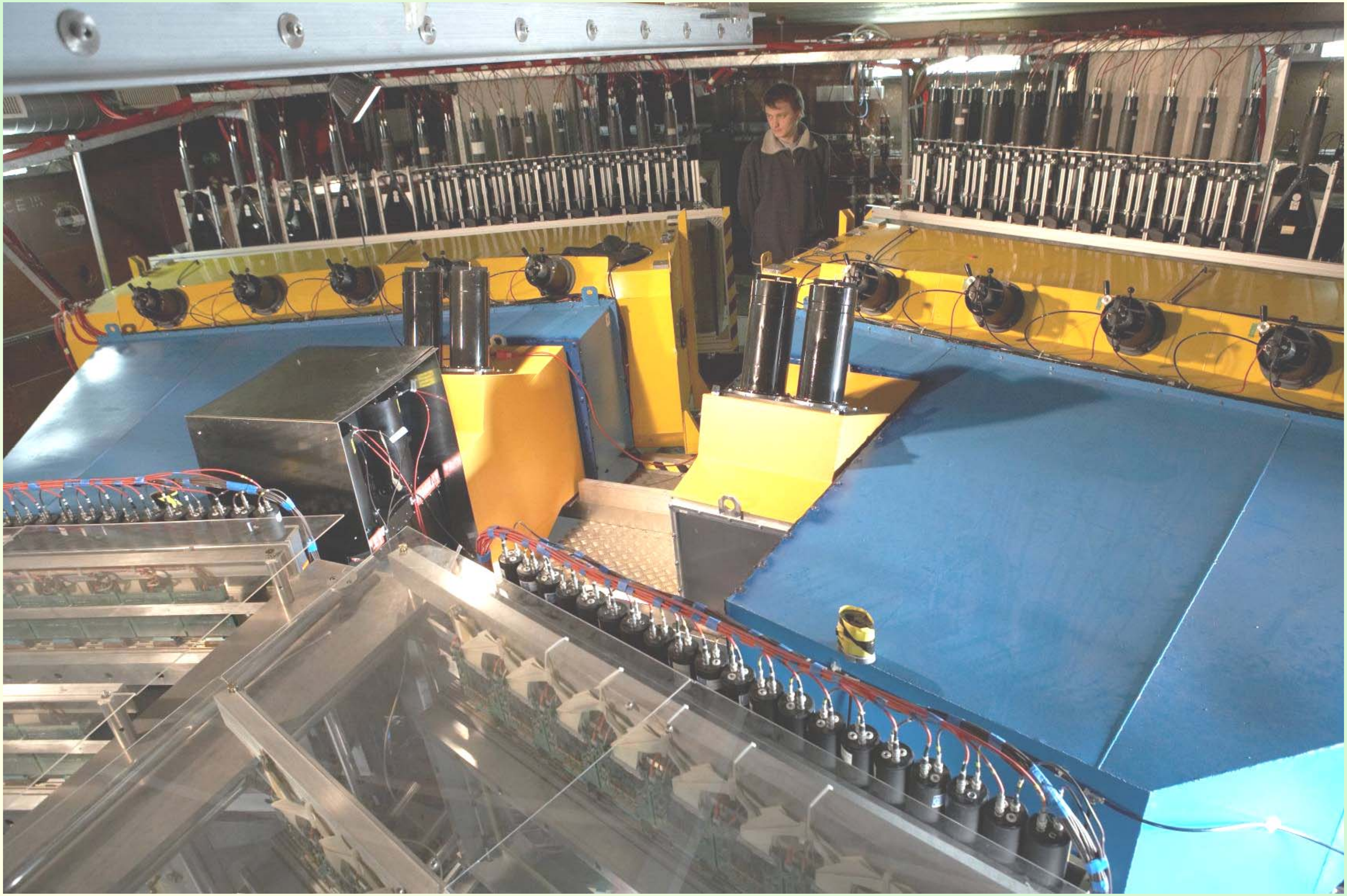
Cherenkov detector quality factor $N_0 = 125\ \mathrm{cm}^{-1}$

$$\langle n(C_4F_{10})\rangle = 1.00135$$

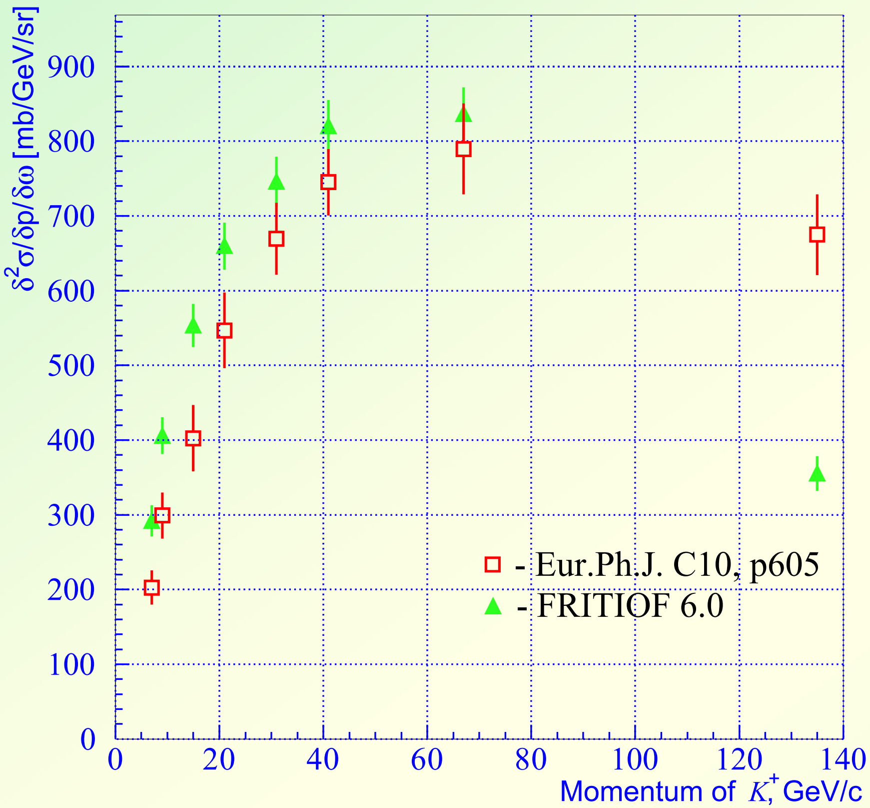
Efficiency to detect pions with momenta >4GeV is >99.5%

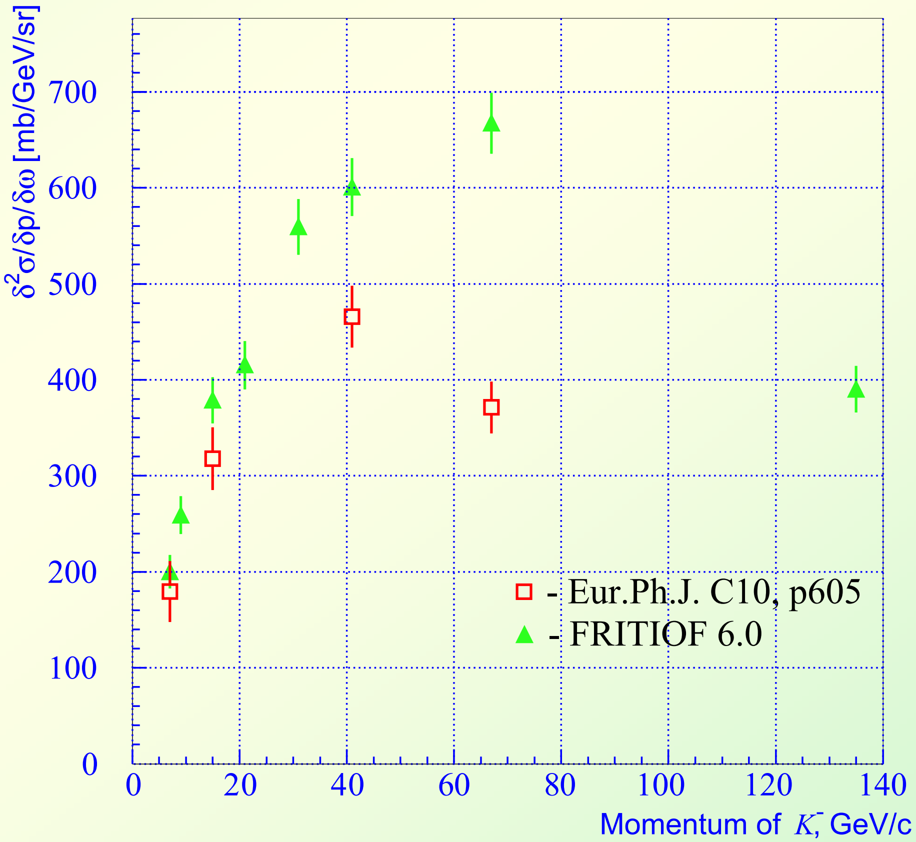
$$N_{p.e.}(\beta=1) \approx 30\text{p.e.}$$

Downstream detectors



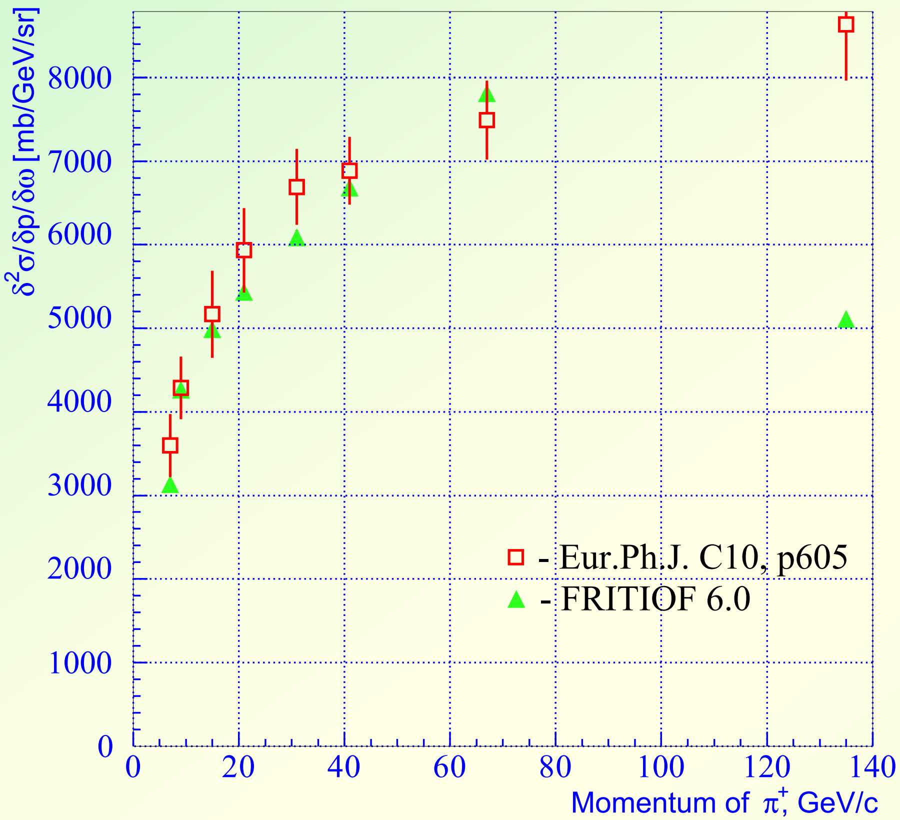
Inclusive cross-sections for K^+, K^- - mesons generation

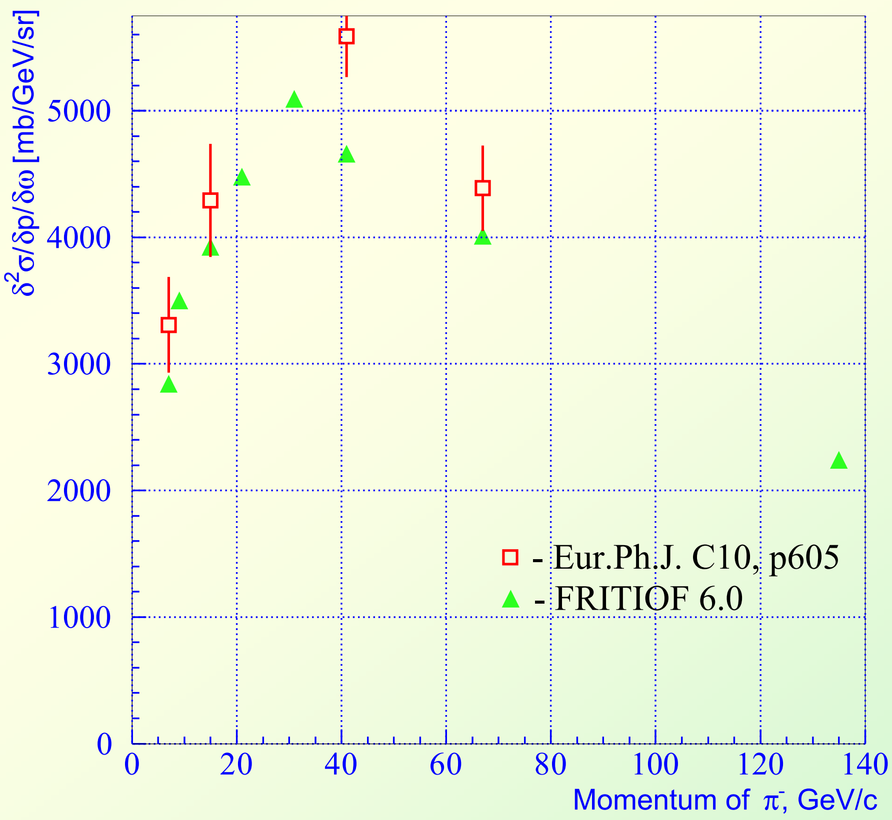




$$E_p = 450 GeV \quad \theta_L = 0°$$

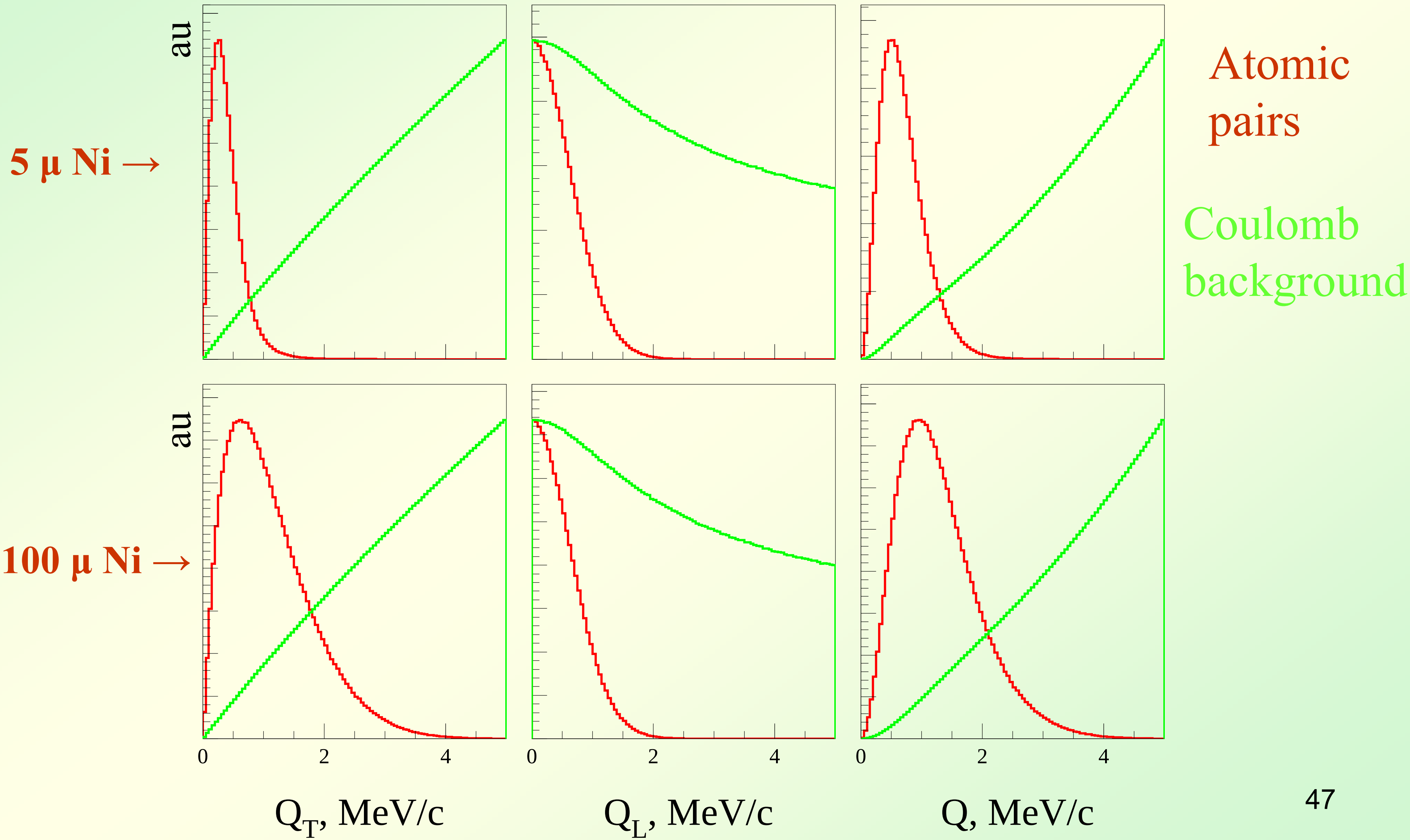
Inclusive cross-sections for π+, π– - mesons generation



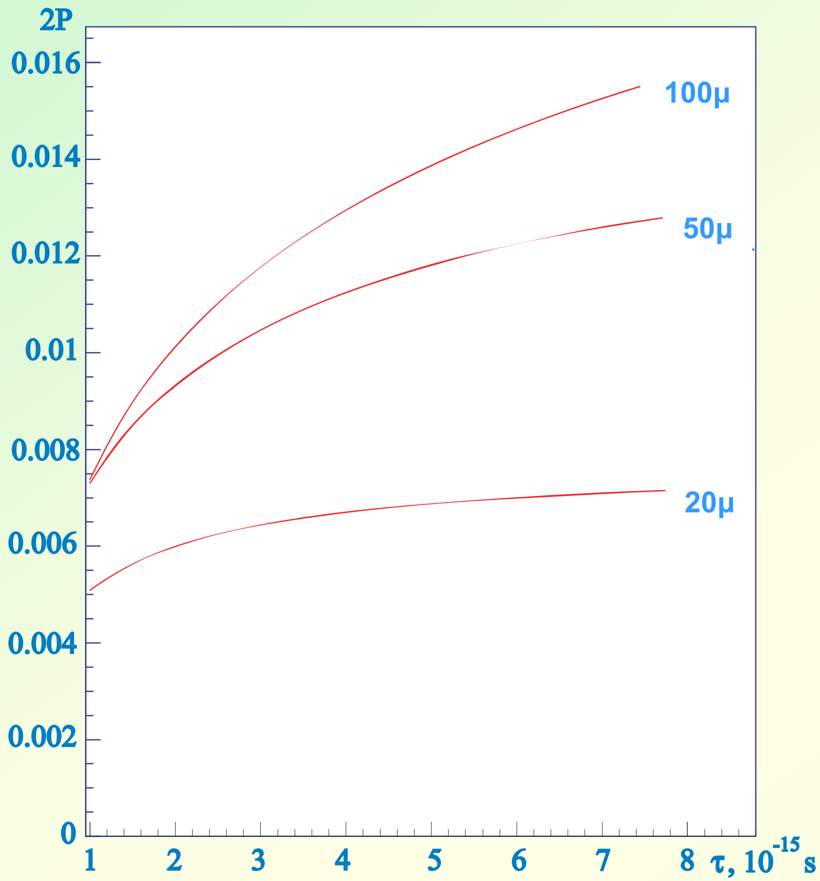


$$E_p = 450 GeV \quad \theta_L = 0°$$

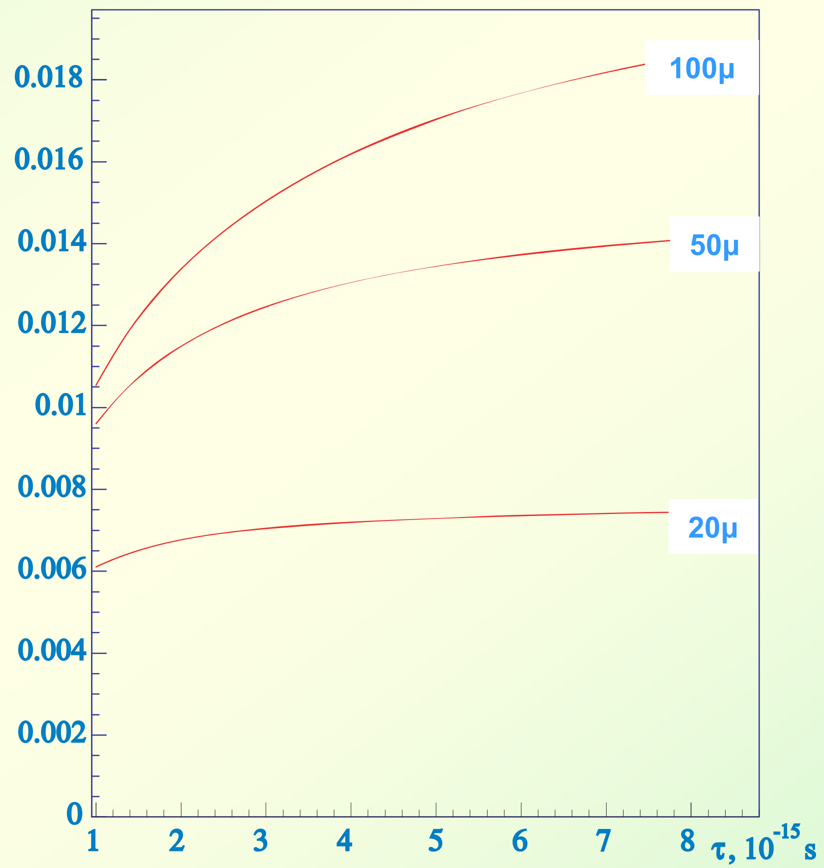
Metastable Atoms - Backgrounds



Metastable Atoms – Lifetime dependence



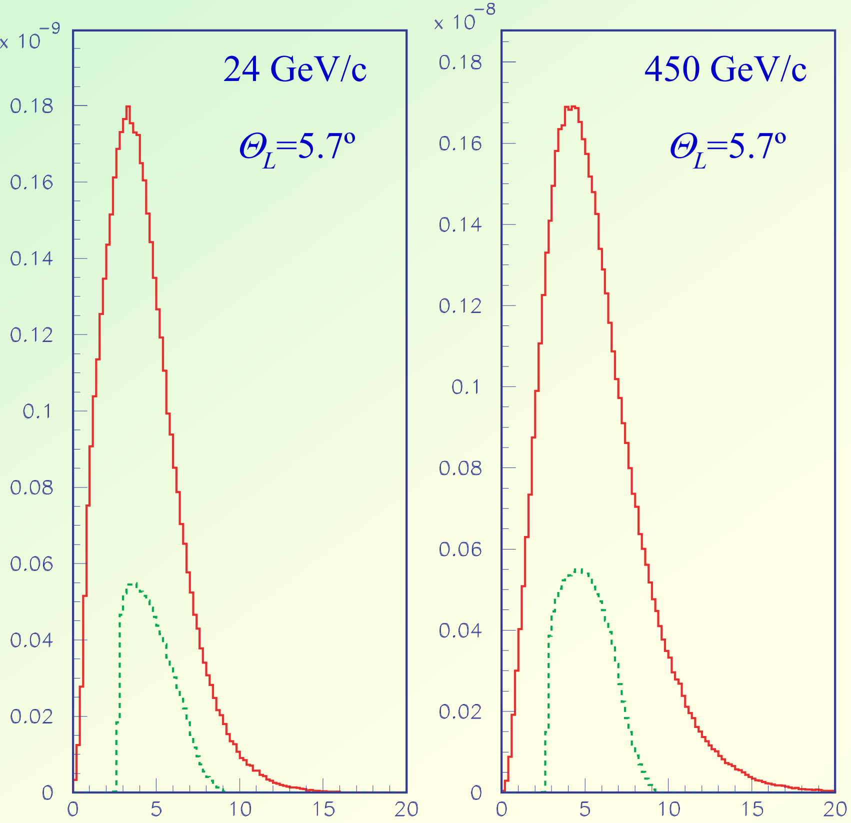
$p(A_{2\pi}) = 4.5 GeV/c$



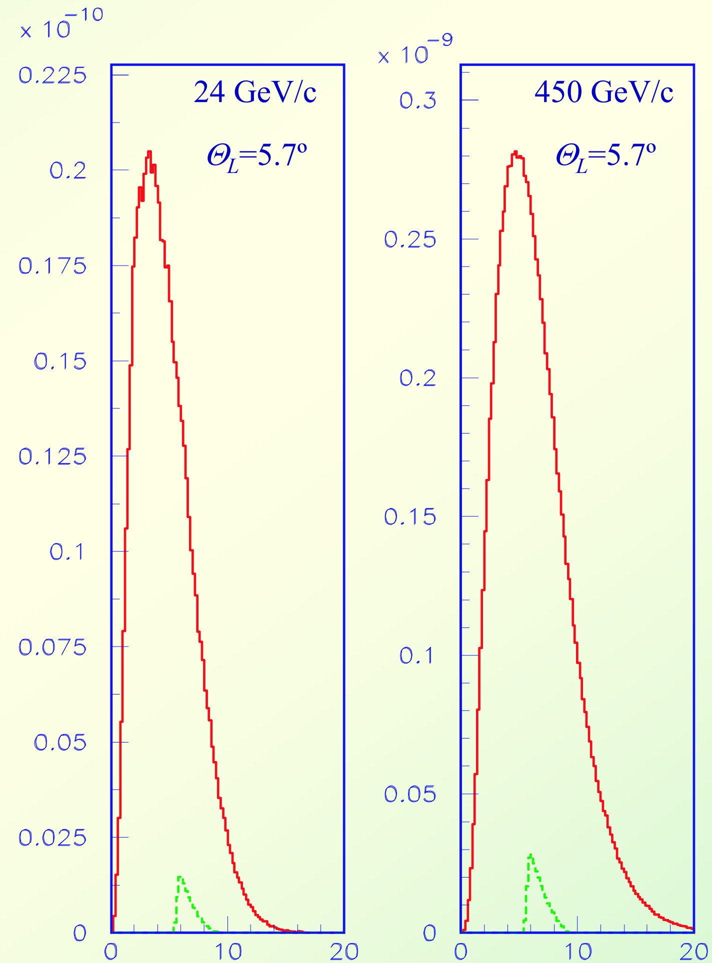
$p(A_{2\pi}) = 10 GeV/c$

Yields of the long-lived states 2*p* (*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.

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



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

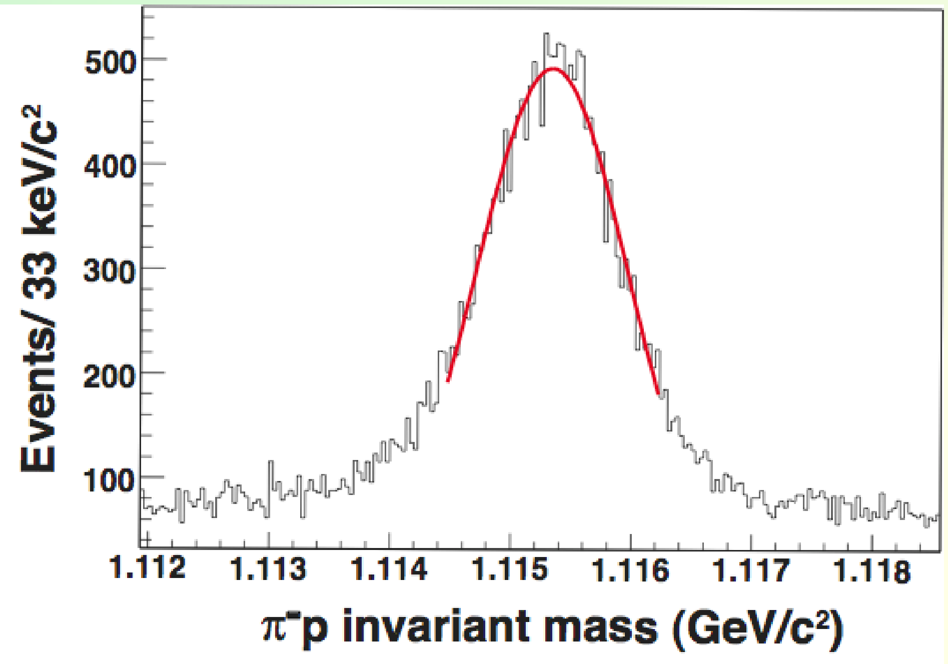


$Momentum\ of\ \ A_{\pi^+K^-}, GeV\,/\,c$

— - red curve atom spectra in channel the aperture

- green curve atom spectra registered by the set-up

π−p mass & π+π− signal in 2007



Setup calibration with Λ decays

Observation of $\pi^+\pi^-$ atoms with the Platinum target