Status Report of DIRAC

LIFETIME MEASUREMENT OF $\pi^+\pi^-$ AND $\pi^\pm K^\mp$ ATOMS TO TEST LOW-ENERGY *QCD*

DIRAC collaboration

75 Physicists from 19 Institutes

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

SINP of Moscow State University
Moscow, Russia

IHEP
Protvino, Russia

Santiago de Compostela University
Santiago de Compostela, Spain

Basel University
Basel, Switzerland

Bern University
Bern, Switzerland

Zurich University
Zurich, Switzerland

Outline

- ***Introduction***
- ***Results on the ππ atom lifetime measurement using data 2001-2003.***
- ***Result of 2007 run: evidence for πK atoms.***
- ***Results of 2008 run and plans for 2009***
- ***Request of 2010 run for observation of the long-lived states of ππ atoms.***

Main goals of DIRAC in 2005-2009 and beyond

- *Lifetime measurement of $A_{2\pi}$ atoms with precision better than 6%,which gives a precision for $|a_0 - a_2|$ better than 3%.*
- *Observation of $A_{\pi K}$ and $A_{K\pi}$ atoms.*
- *The measurement of their lifetime and difference of πK scattering lengths $|a_{1/2} - a_{3/2}|$ with accuracy about 10%.*
- *Observation of the long-lived states of $A_{2\pi}$, with prospect to measure the Lamb shift and of determining the value of $2a_0 + a_2$ in a model-independent way.*

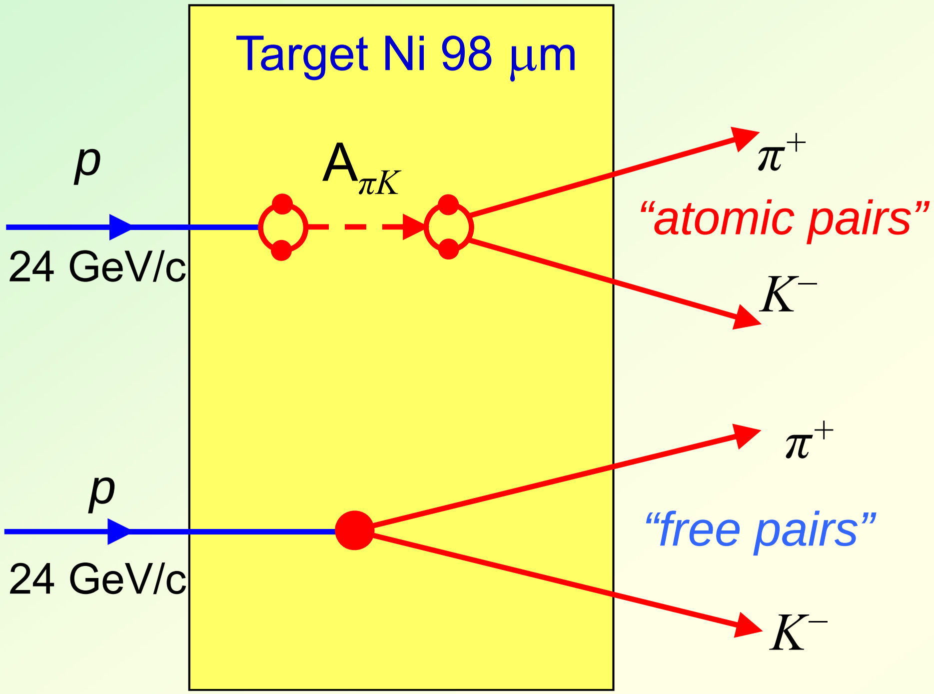
πK scattering

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!

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



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

e. m. interaction of $A_{\pi K}$ in the target

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

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

$$Q < 3 MeV/c,\ p_K = \frac{m_K}{m_\pi} p_\pi,\ \Theta_{lab} < 3\ mrad$$

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

Main features of the DIRAC set-up

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

Magnetic spectrometer

Proton beam ~ 10^{11} proton/spill

Resolution on Q: $Q_x \approx Q_y \approx 0.5$ Mev/c, $Q_L \approx 1.0$ MeV/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)

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

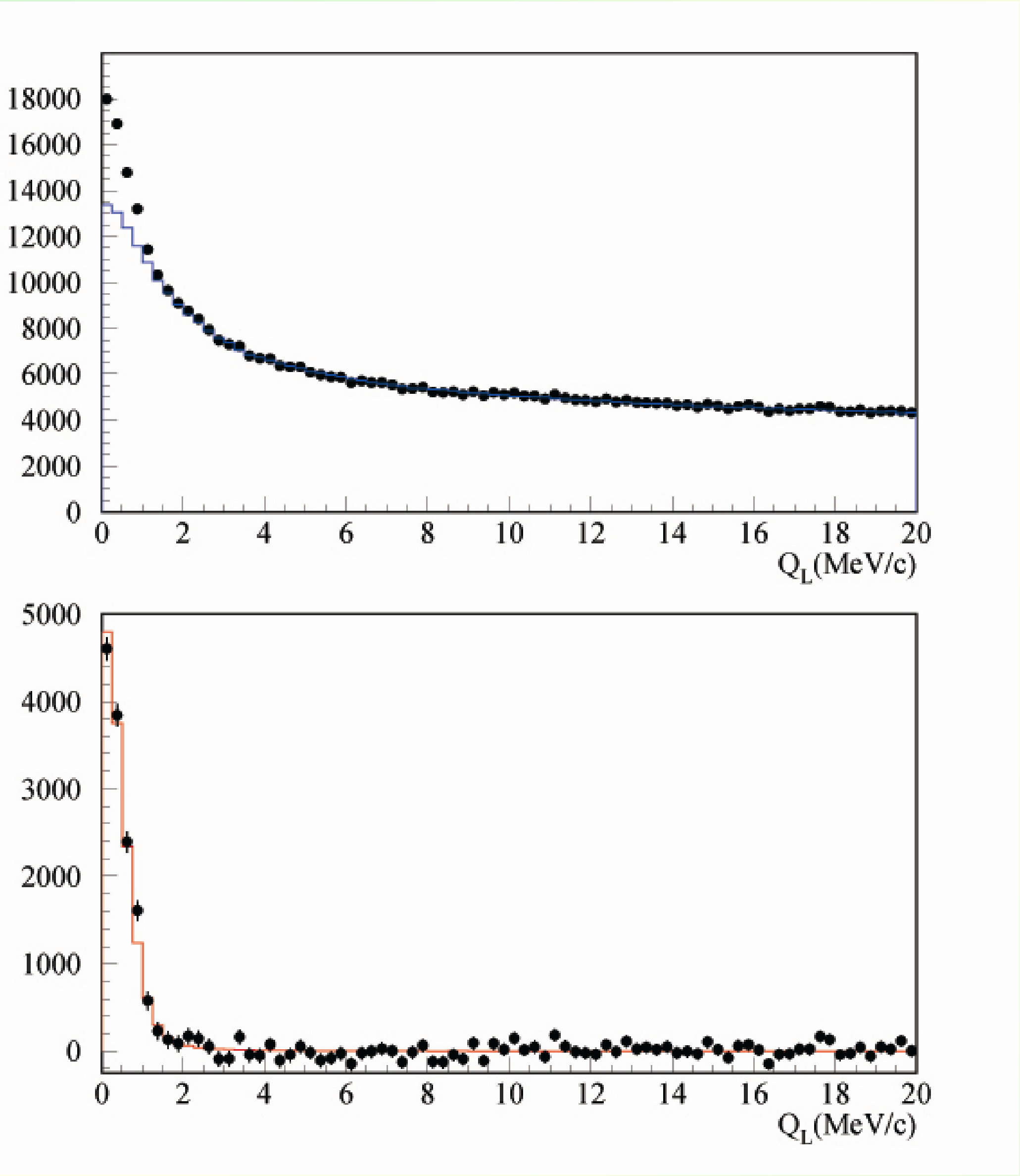
2008 **DIRAC** (SPSC 22/04/08) $\tau = \left(2.82\,{}^{+0.25}_{-0.23}\Big|_{stat} \pm 0.19\big|_{syst}\right)\text{fs} = \left(\ldots{}^{+0.31}_{-0.30}\Big|_{tot}\right)\text{fs}$

...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%.

DIRAC preliminary results with GEM/MSGC



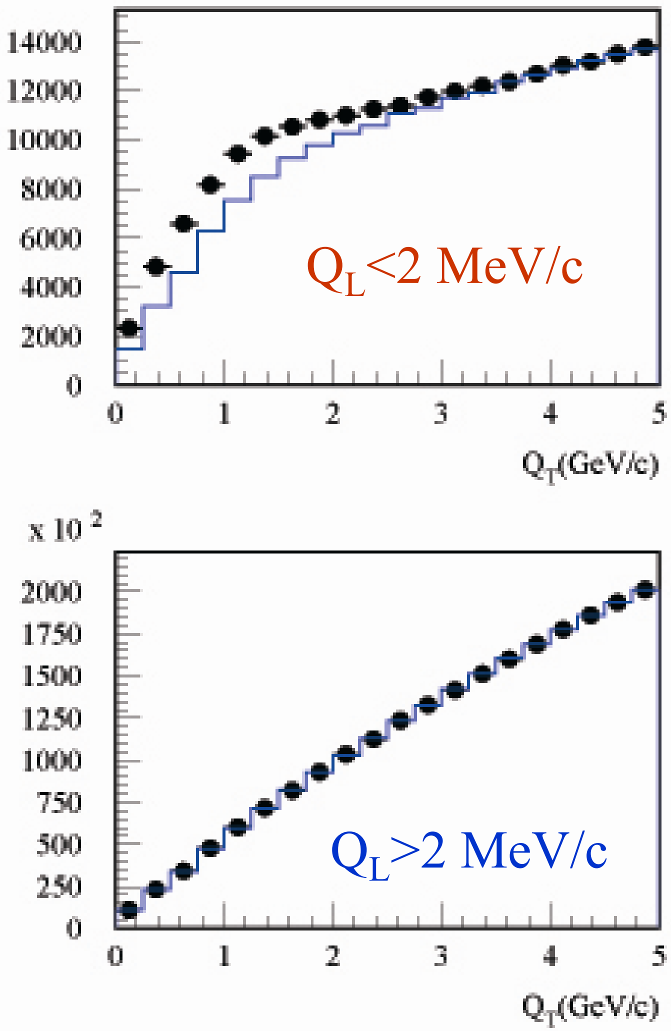
Q_L distribution

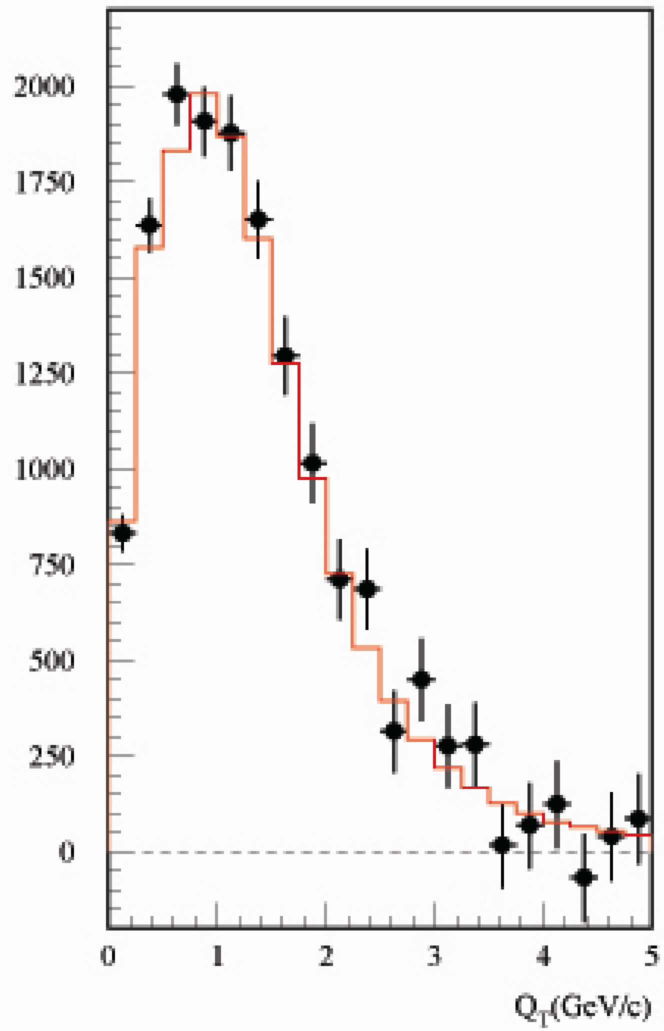
←All events

←After background subtraction

DIRAC preliminary results with GEM/MSGC

Q_T distribution





←After background subtraction for Q_L<2MeV/c

Comparition with other experimental results

$K \to 3\pi$:

2006 **NA48/2** (PL B633, 173) ...with ChPT constraint between a_0 and a_2:

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

2008 **NA48/2** (Confinement8, Mainz) ...with ChPT constraint between a_0 and a_2:

$$\Rightarrow a_0 - a_2 = 0.266 \pm 1.1\%\big|_{stat} \pm 0.8\%\big|_{syst} \pm 0.4\%\big|_{ext} \pm \ldots\%\big|_{th}$$

Ke4:

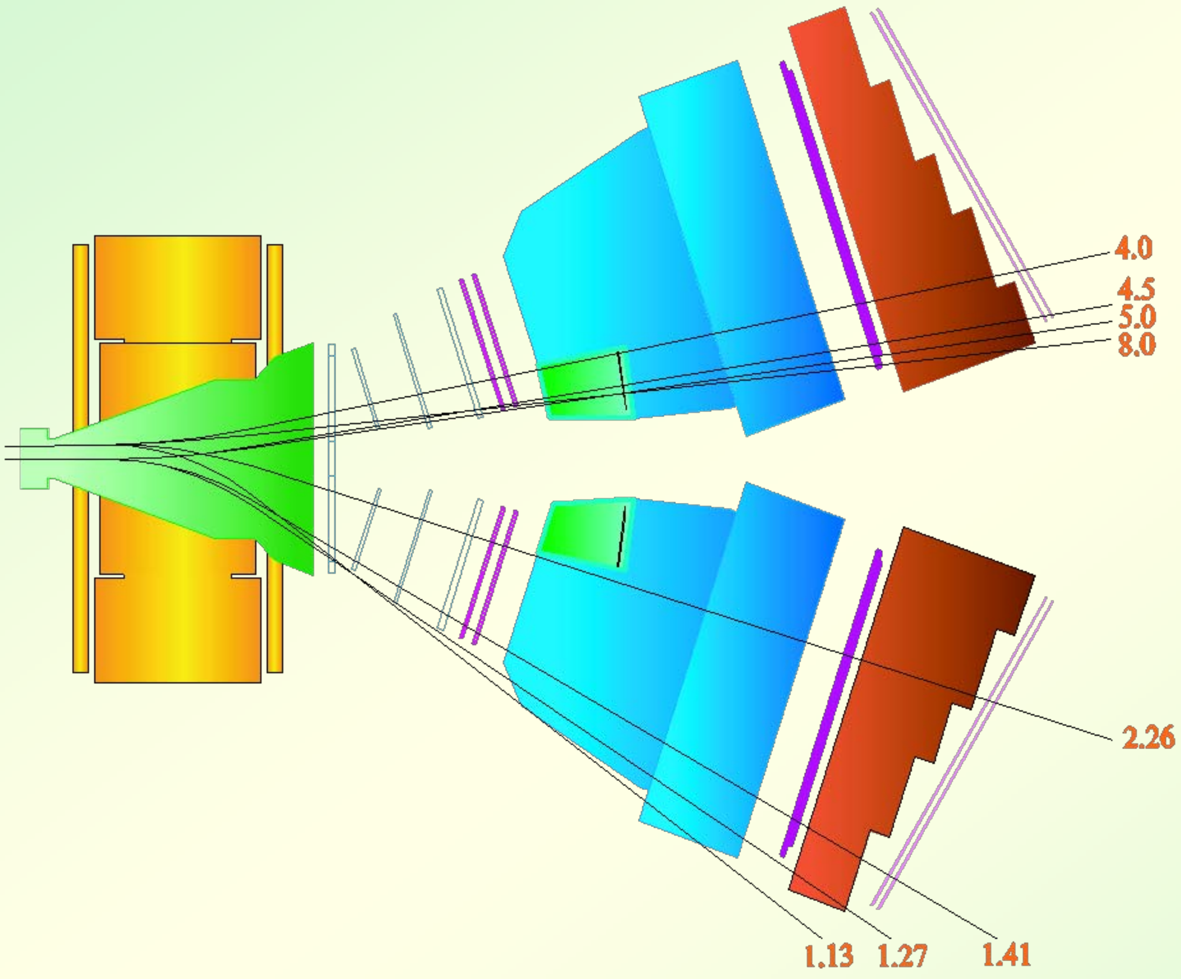
2008 **NA48/2** (EPJ C54, 411)

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

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

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

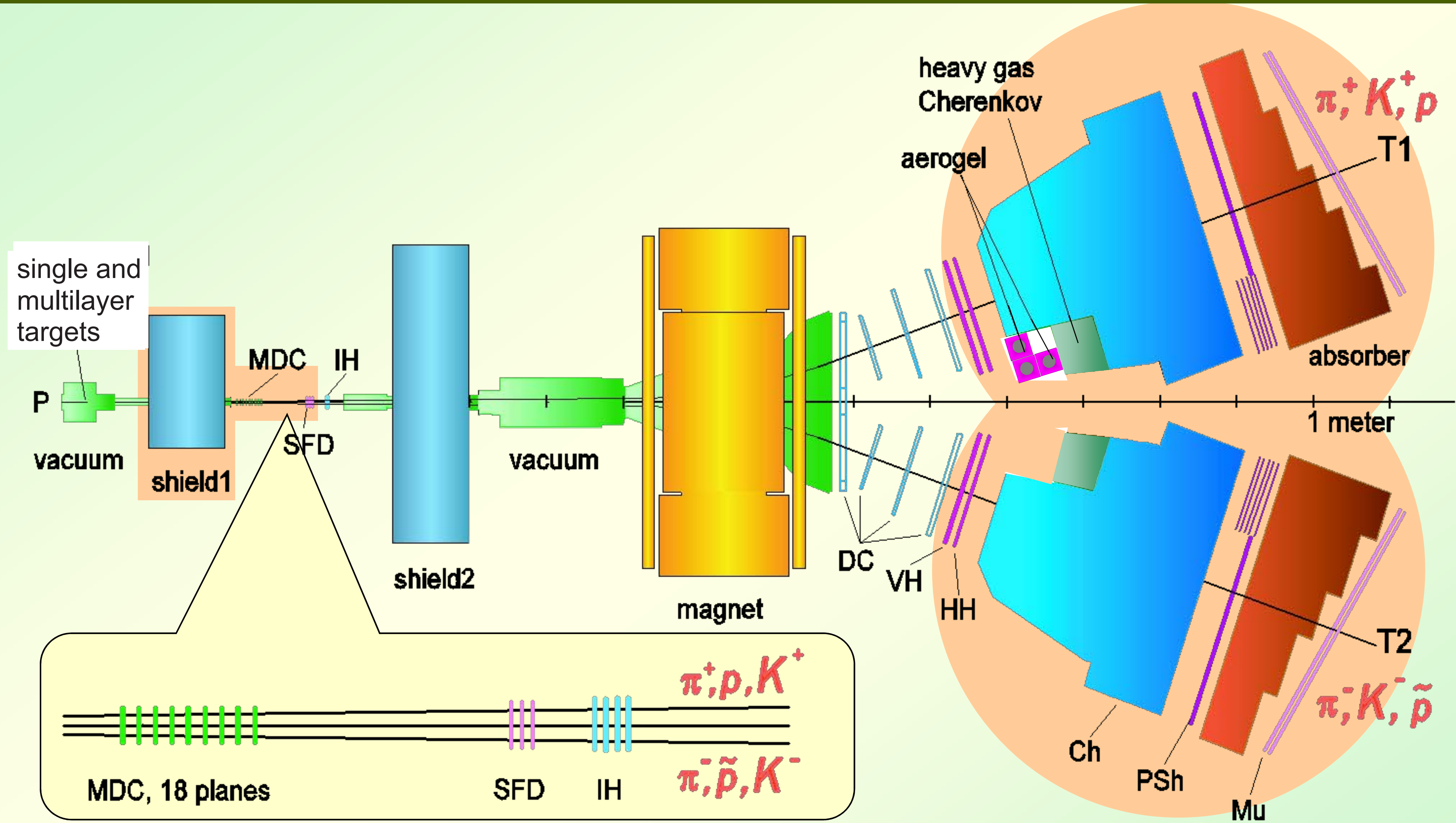
The numbers to the right of the tracks lines are the π^- and K^+ momenta in GeV/c



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

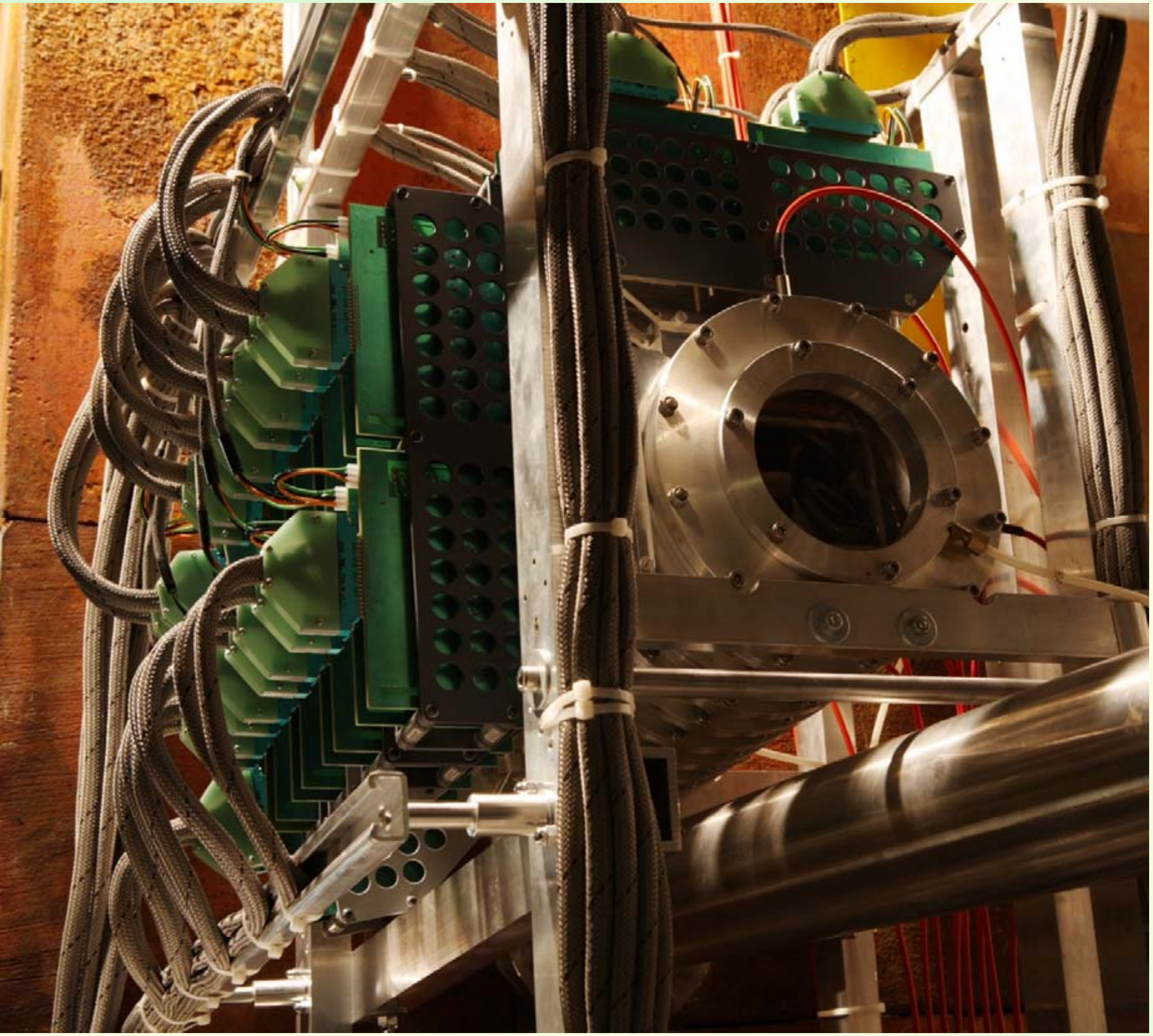
P_{atom} (GeV/c)	P_π (GeV/c)	P_K (GeV/c)
5.13	1.13	4.0
5.77	1.27	4.5
6.41	1.41	5.0
10.26	2.26	8.0

Upgraded DIRAC experimental setup



Modifided parts

Micro Drift Chambers

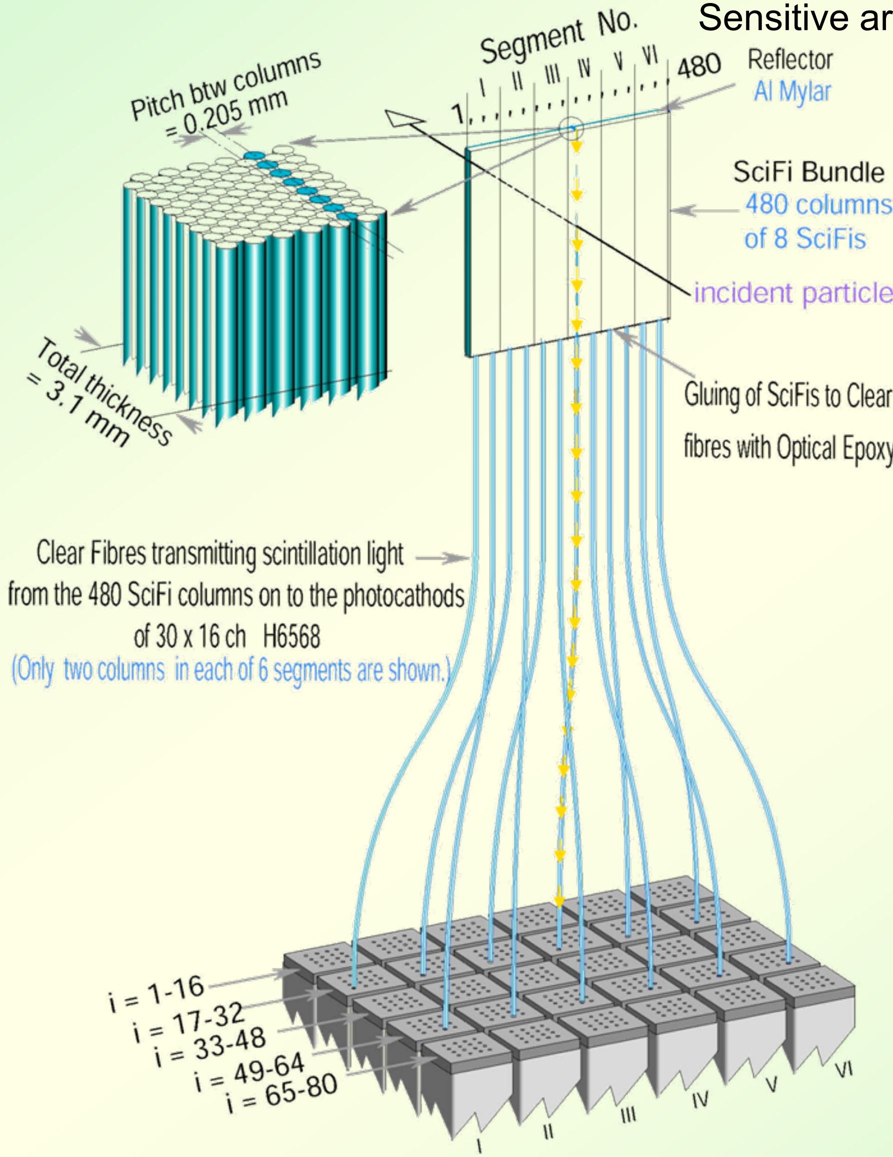


Main features:

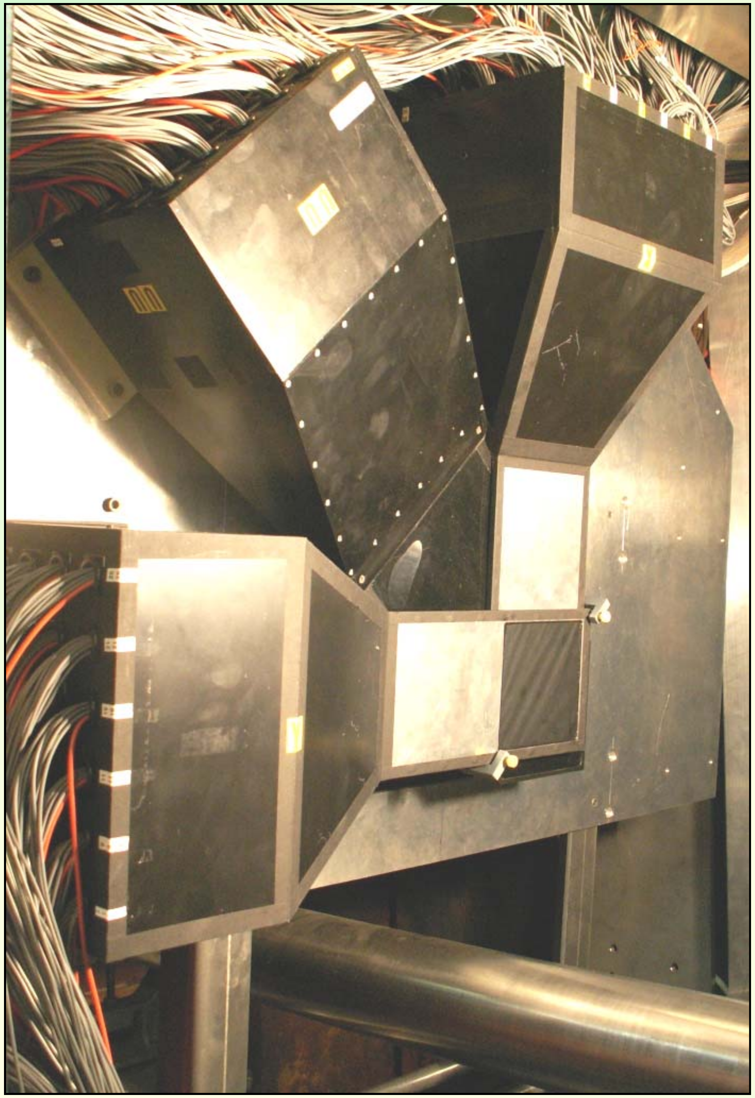
- High spatial accuracy **$\sigma \leq 80$ μm**;
- Efficiency > **98%** at **I = 2×10^{11}** protons/spill;
- total detector thickness **$<5\times10^{-3}$** X_0;
- drift time < **23** ***ns***;
- time resolution < **1** ***ns***;
- readout time < **3** ***μs***.

Scintillation Fiber Detector

Sensitive area = 98.5 x 107 mm^2



Scintillation Fiber Detector



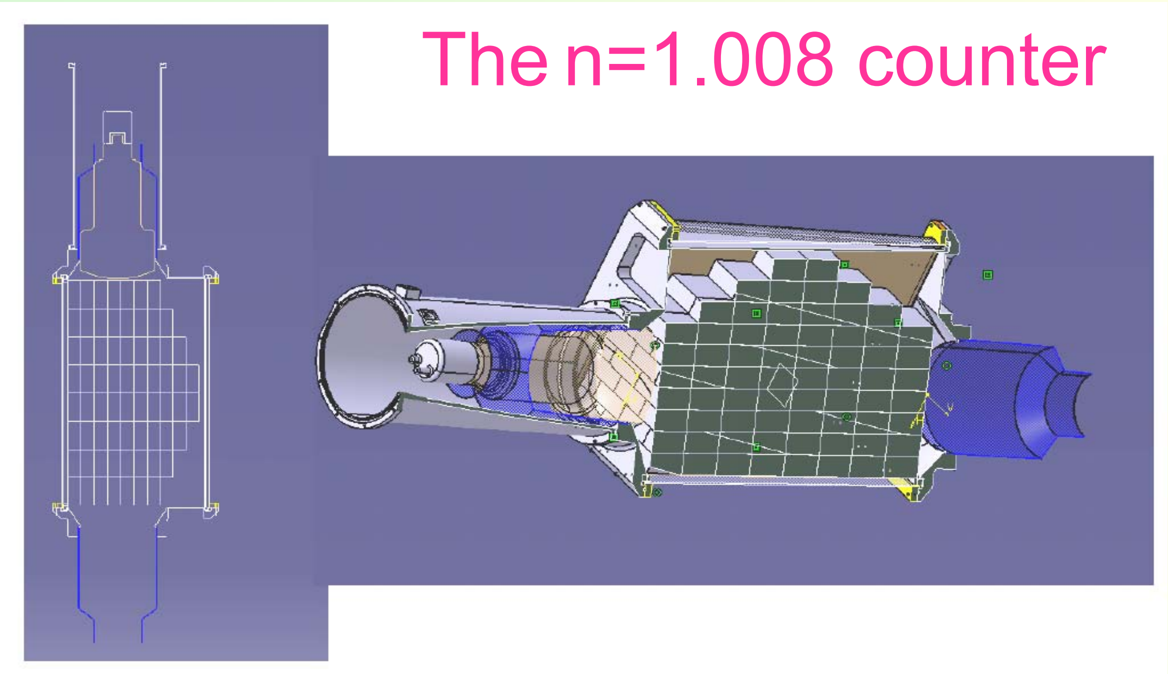
Characteristics:

- Size of the plane — 100 100 *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 — σ ≈ 60 *μm*
- New electronics (*ADC-TDC for each channel*) — 960 *channels*

Aerogel Cherenkov detector

Responsibility:

Zurich University (*Zurich*, Switzerland)



Status:

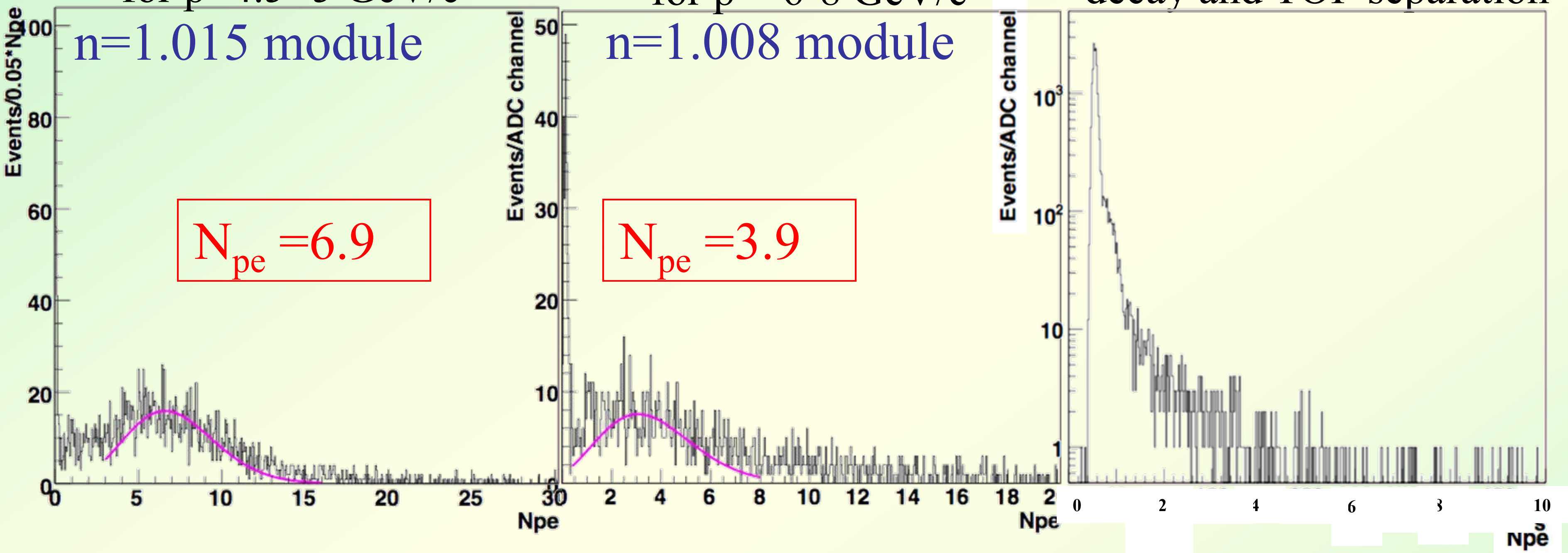
Aerogel detectors were installed on the setup

Aerogel: Kaon and proton signal

Negative kaon spectrum for p=4.5 -5 GeV/c

Negative kaon spectrum for p = 6-8 GeV/c

Pure proton signal from Λ decay and TOF separation



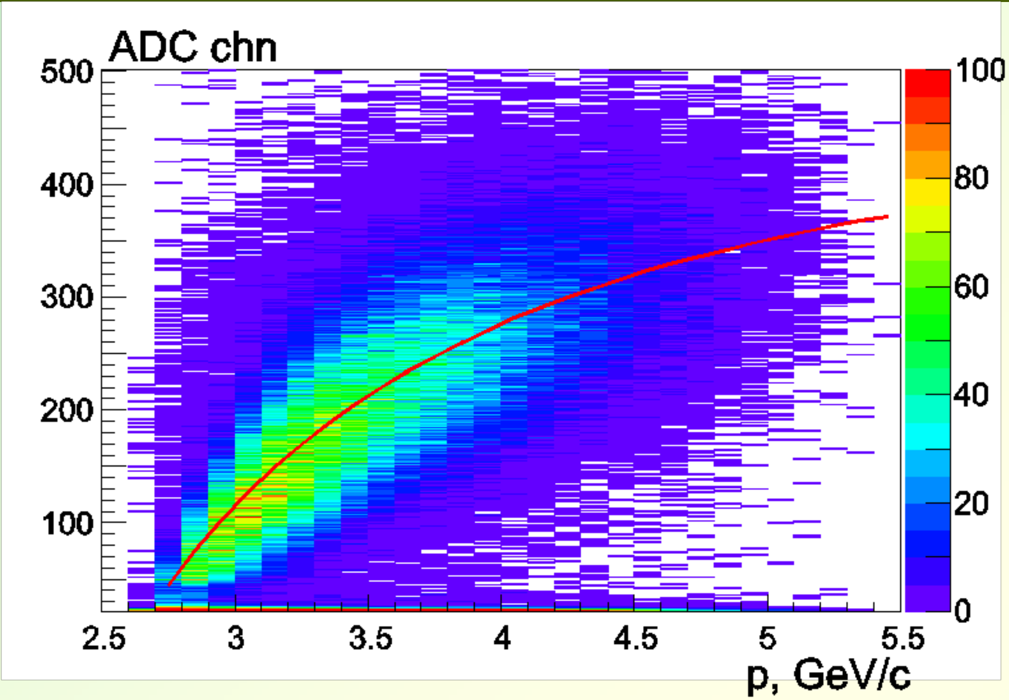
Proton rejection efficiency for a cut in the ADC 20 channels above pedestal:

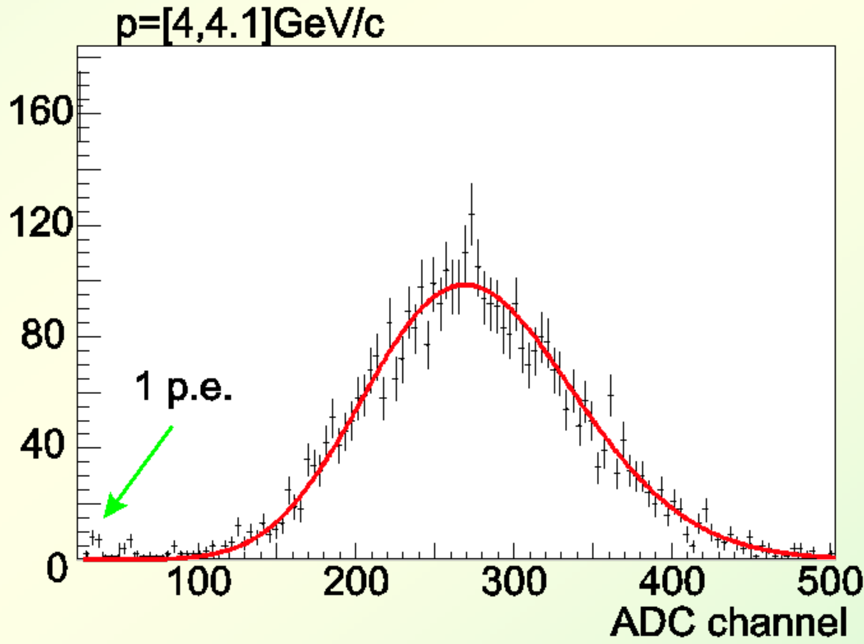
- 94.2 % for the heavy aerogel @p= 4.5-5 GeV/c
- 89.3 % for the light aerogel @p = 6-8 GeV/c

Kaon detection efficiency for the same cut:

- 95.6 % for the heavy aerogel @p= 4.5-5 GeV/c
- 92.4 % for the light aerogel @p= 6-8 GeV/c

Cherenkov detector C_4F_{10}





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

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

$$\langle n(\text{C}_4\text{F}_{10})\rangle = 1.00135$$

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

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

All Cherenkov detectors

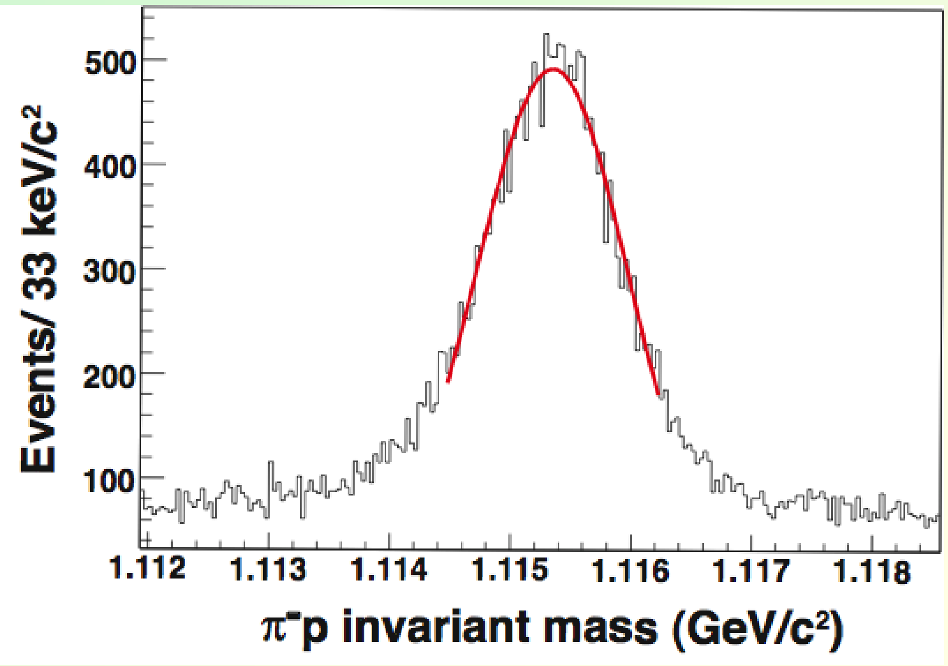
Experimental results

Run 2006 was lost because of the broken magnets in the beam-line.

Run 2007

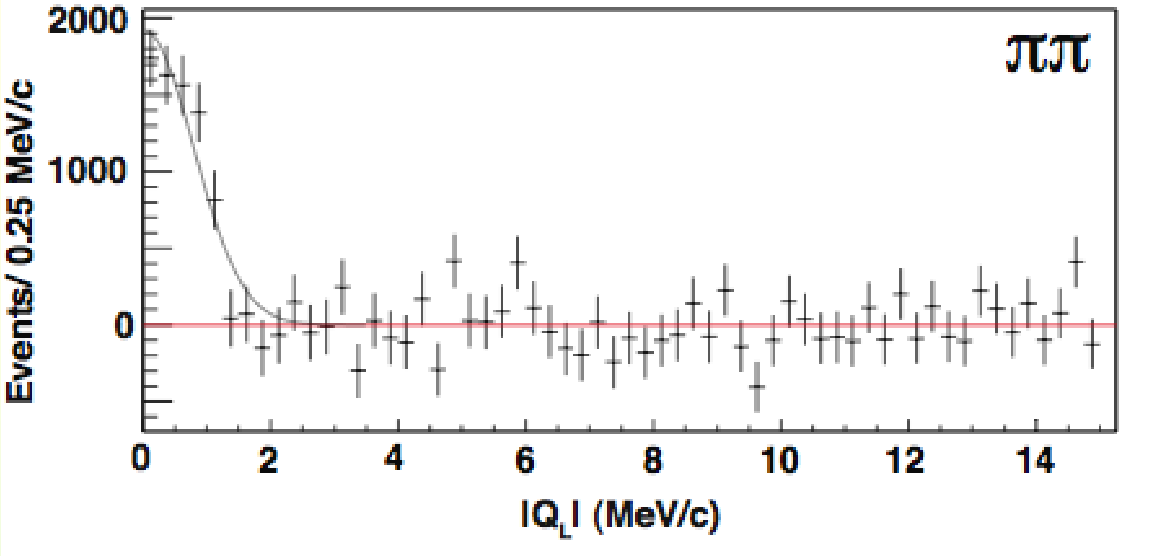
- Improvement of the proton beam time structure and the beam intensity distribution at spills.
- Beam intensity about 1.9×10^{11} proton/spill
  1st level triggers numbers
  $3200(\pi^+\pi^-)+2100(K^+\pi^-)+1000(\pi^+K^-)=6300$ 1/spill
- Number of recorded events 2000 per spill is near to the hardware limit of DAQ
- Full number of $\pi^+\pi^-$ and πK events recorded during 2 months of data taking is 1.6×10^9

π–p mass & π+π– signal in 2007

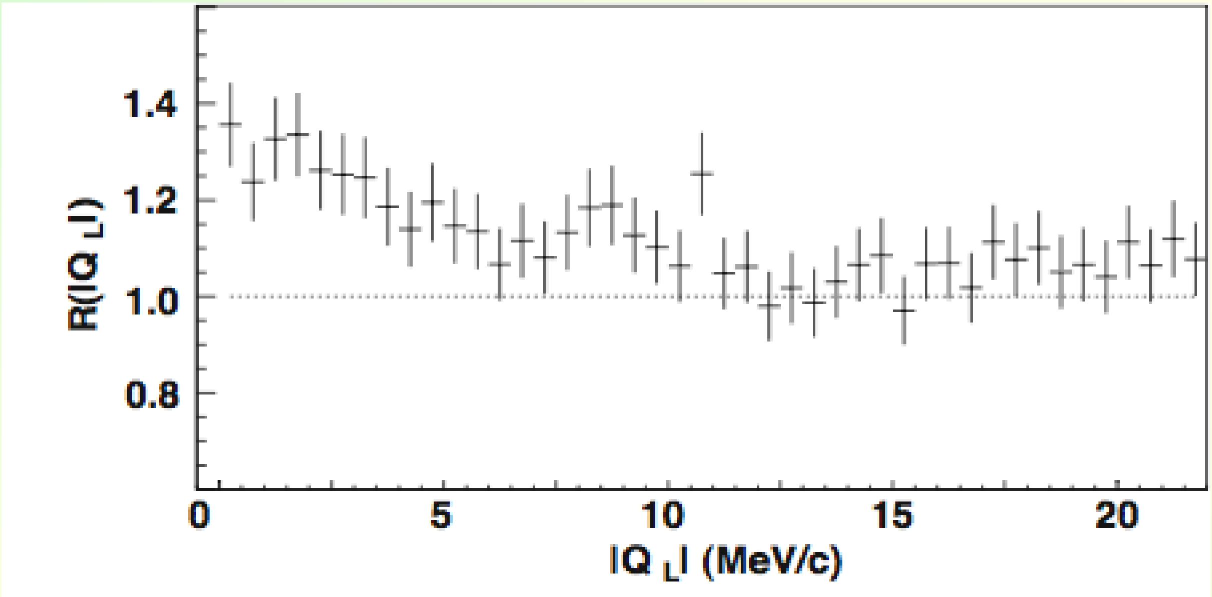


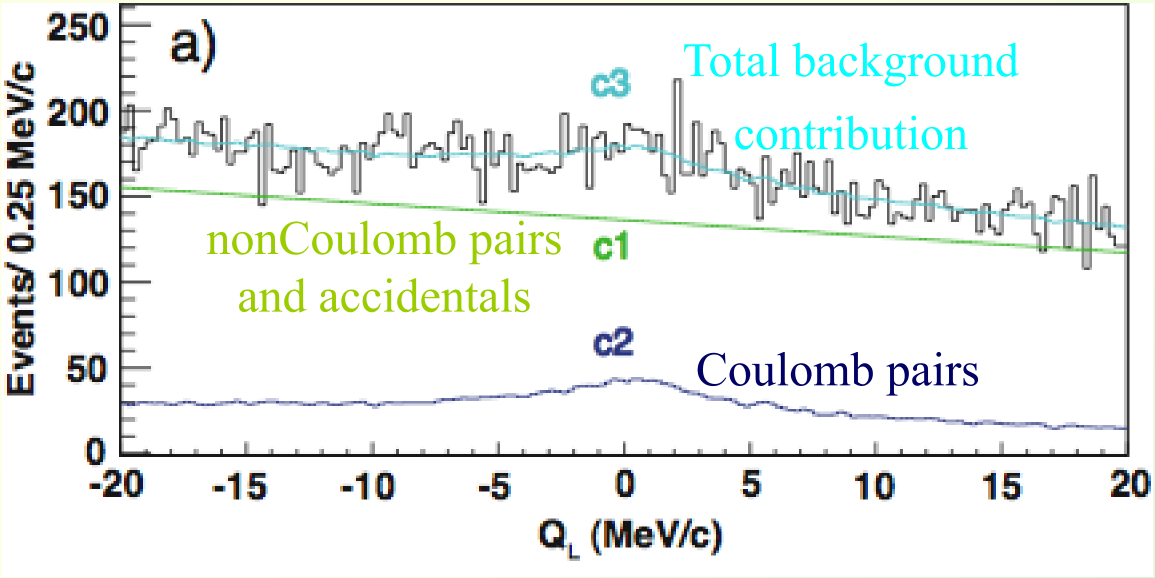
Setup calibration with Λ decays

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

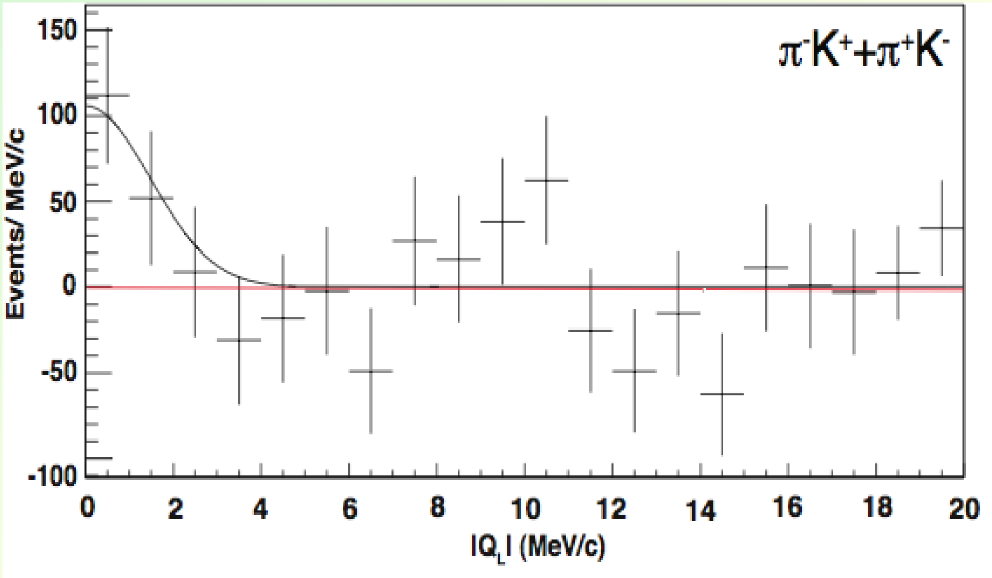


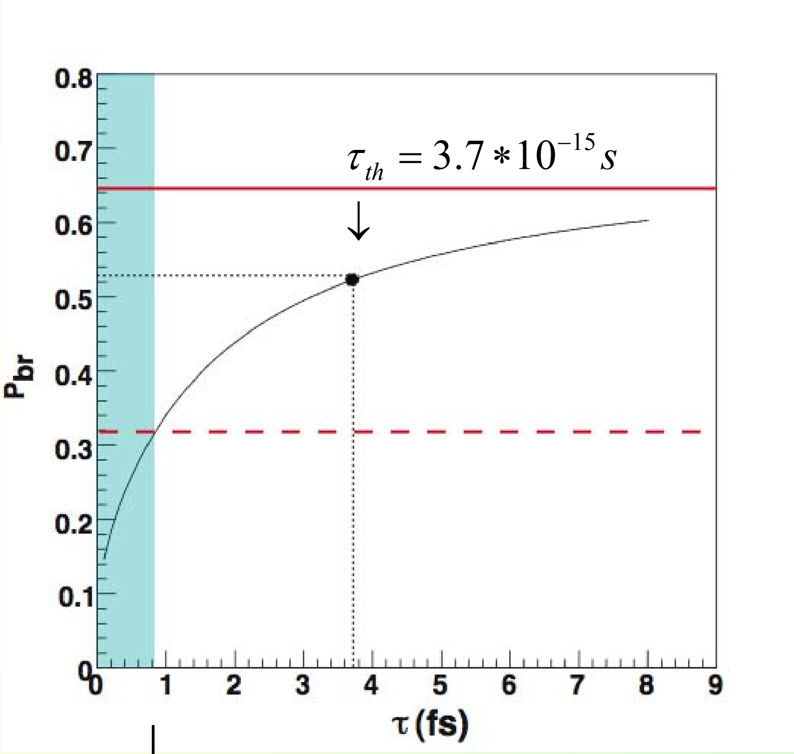
Coulomb correlation in $\pi^- K^+$ pairs





π^-K^+ and π^+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.

RUN 2008

- The upgraded DIRAC setup with the new front-end electronics, readout system and DAQ was fully tuned.
- Data taking for the lifetime measurement of $A_{2\pi}$, observation of $A_{K\pi}$ and $A_{\pi K}$ and their lifetime measurement have been performed during 2.5 months and 1.6×10^{9} events were collected.
- The full set of events collected in 2008 was processed in so-called preselection mode, which includes the full events reconstruction and some very safe cuts on the relative momentum of pairs. The background level at the reconstructed events is expected to be by factor 4 less in respect to 2007 data due to the vertices detectors implementation.

Run 2009

Run 2009 will increase the statistics of $A_{2\pi}$, $A_{\pi K}$ and $A_{K\pi}$ on factor 2.5. For that, after 3-4 weeks of tuning, we need 5-6 spill per supercycle (about 40 seconds) till the end of PS physics this year.

Energy Splitting between np - ns states in (π^+ - π^-) 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*

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

(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.*

Metastable Atoms

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

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

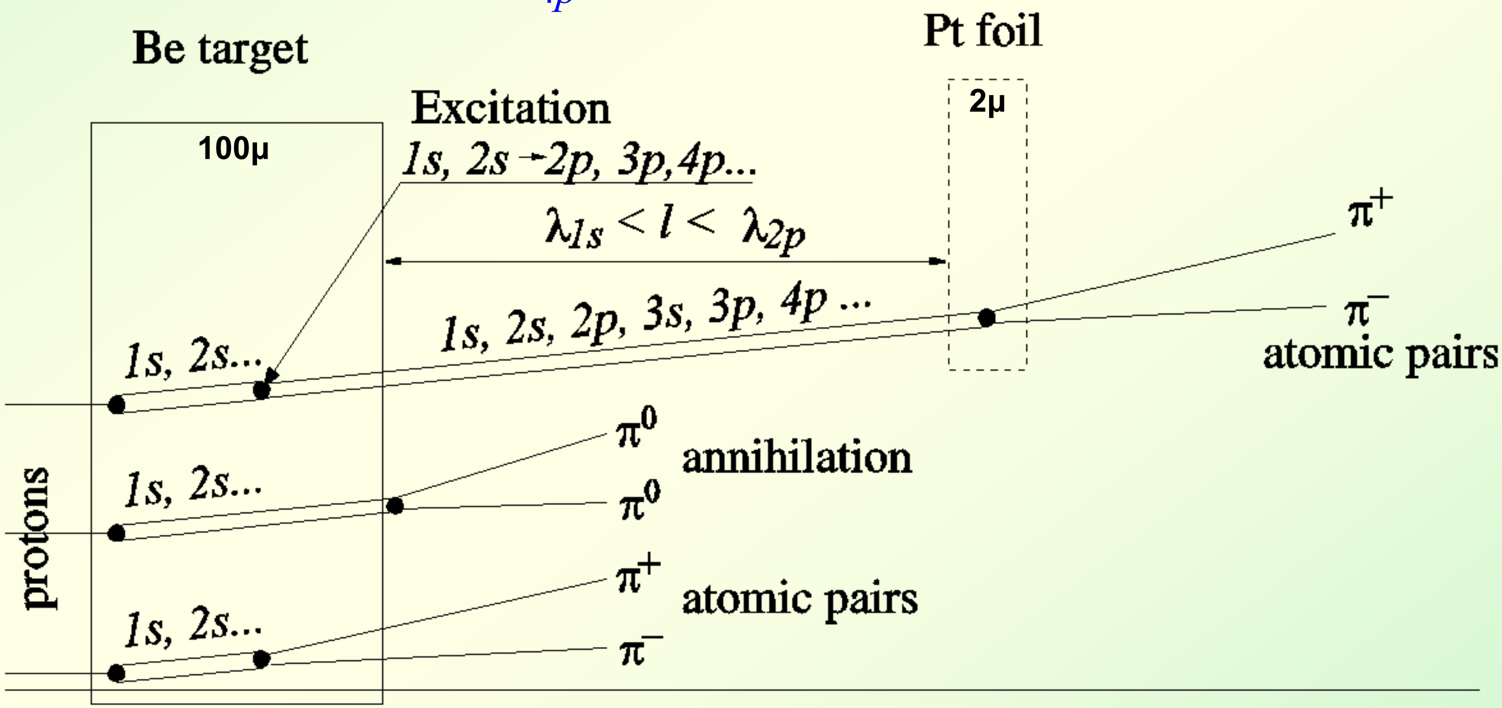


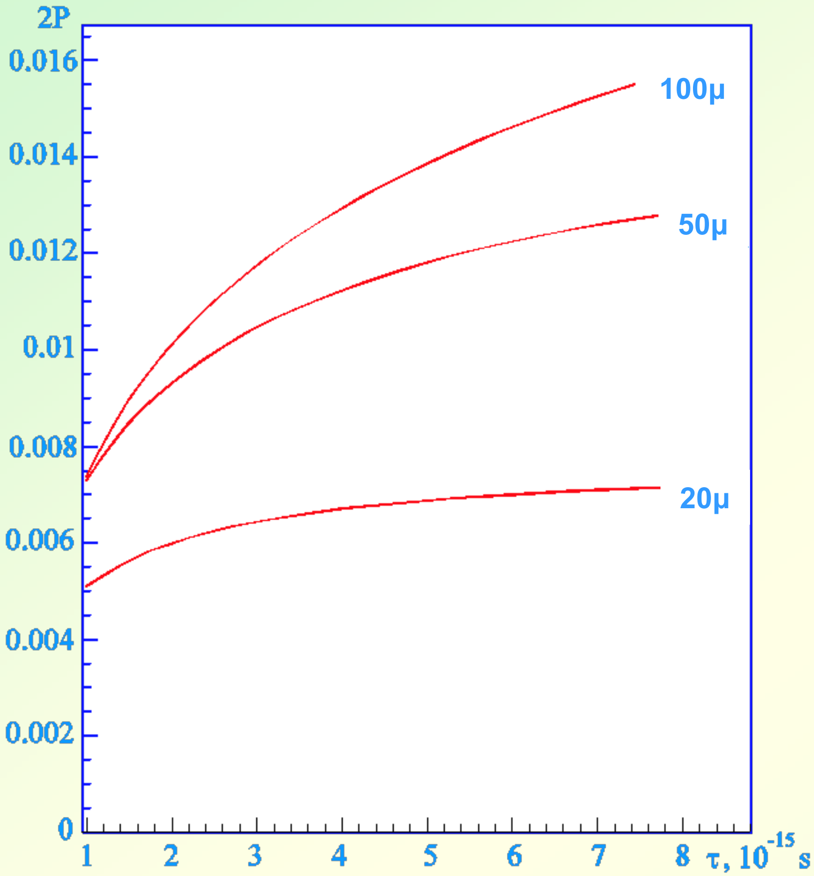
Illustration for observation of the $A_{2\pi}$ long-lived states with breaking foil.

Metastable Atoms

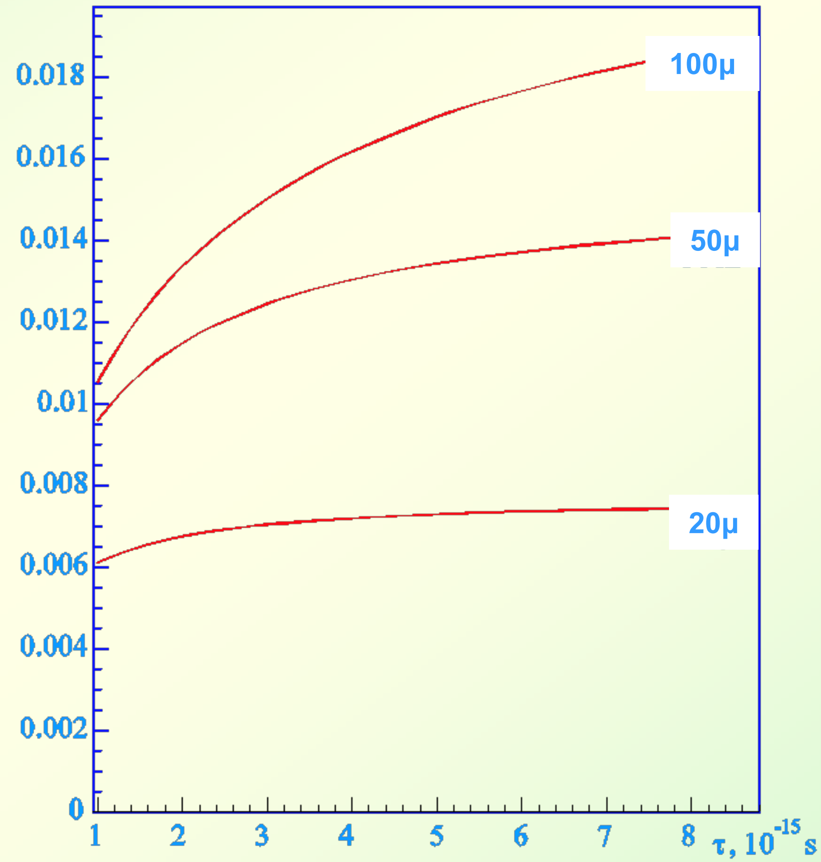
Probabilities of the $A_{2\pi}$ breakup (Br) and yields of the long-lived states for different targets provided the maximum yield of summed population of the long-lived states: **$\Sigma(l \geq 1)$**

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 – Lifetime dependence



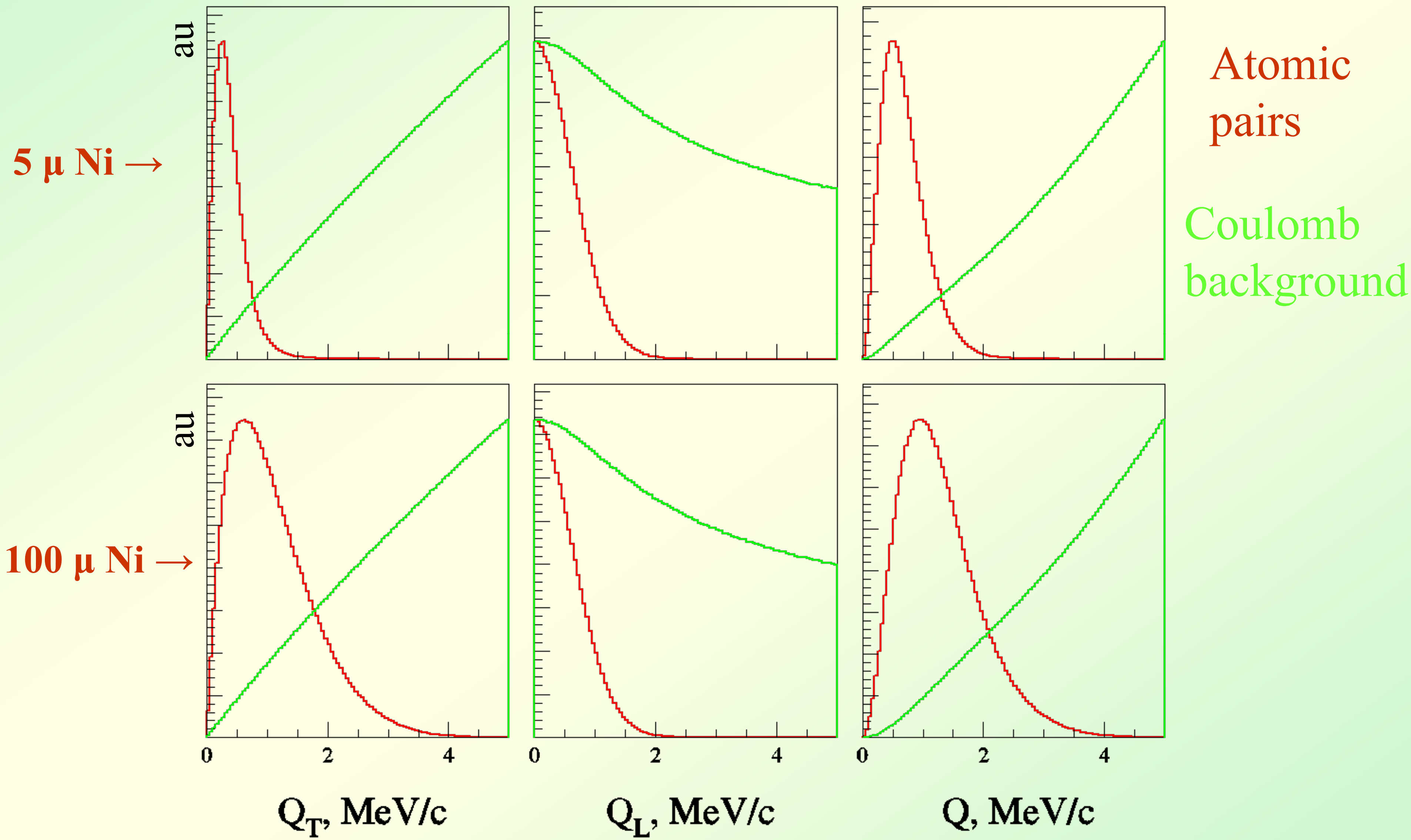
$p(A_{2\pi}) = 4.5 GeV/c$



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

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.

Metastable Atoms - Backgrounds



Beam request for 2010

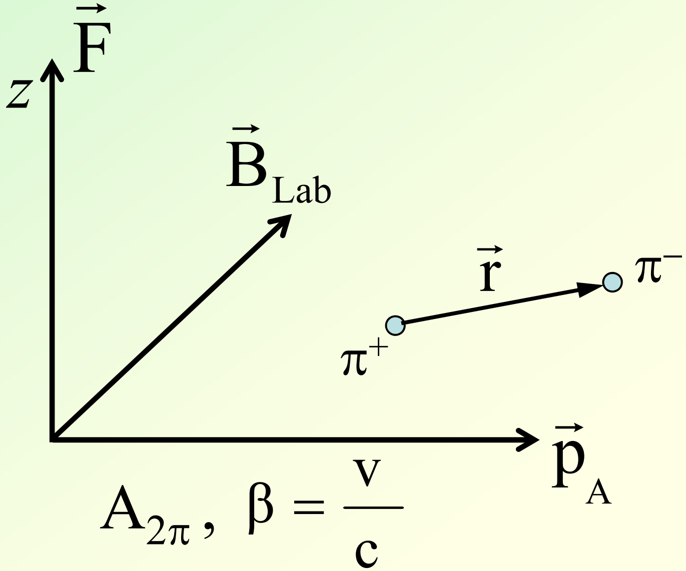
Observation of the long-lived states of $A_{2\pi}$ is opening a possibility to measure the Lamb shift and to determine the new combination of $\pi\pi$ scattering lengths $2a_0 + a_2$.

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.

Thank you for your attention

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

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

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

$$B_{\text{Lab}} = 4 \text{ Tesla}$$

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

DIRAC before & beyond 2011

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 before & beyond 2011

Present low-energy *QCD* predictions for **ππ** 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 $\underbrace{\delta a_{1/2} = 11\% \;\; \delta a_{3/2} = 40\%}_{\text{ChPT}}$ $\underbrace{\delta a_{1/2} = 10\% \;\; \delta a_{3/2} = 17\%}_{\text{Roy-Steiner}}$ …will be significantly improved by *ChPT*

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

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

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

2010-2011 Observation of metastable $\pi^+\pi^-$ atoms and estimation its Lamb shift

Study of the possibility to observe K^+K^- and $\pi^\pm\mu^\mp$ atoms using 2008-2009 data.

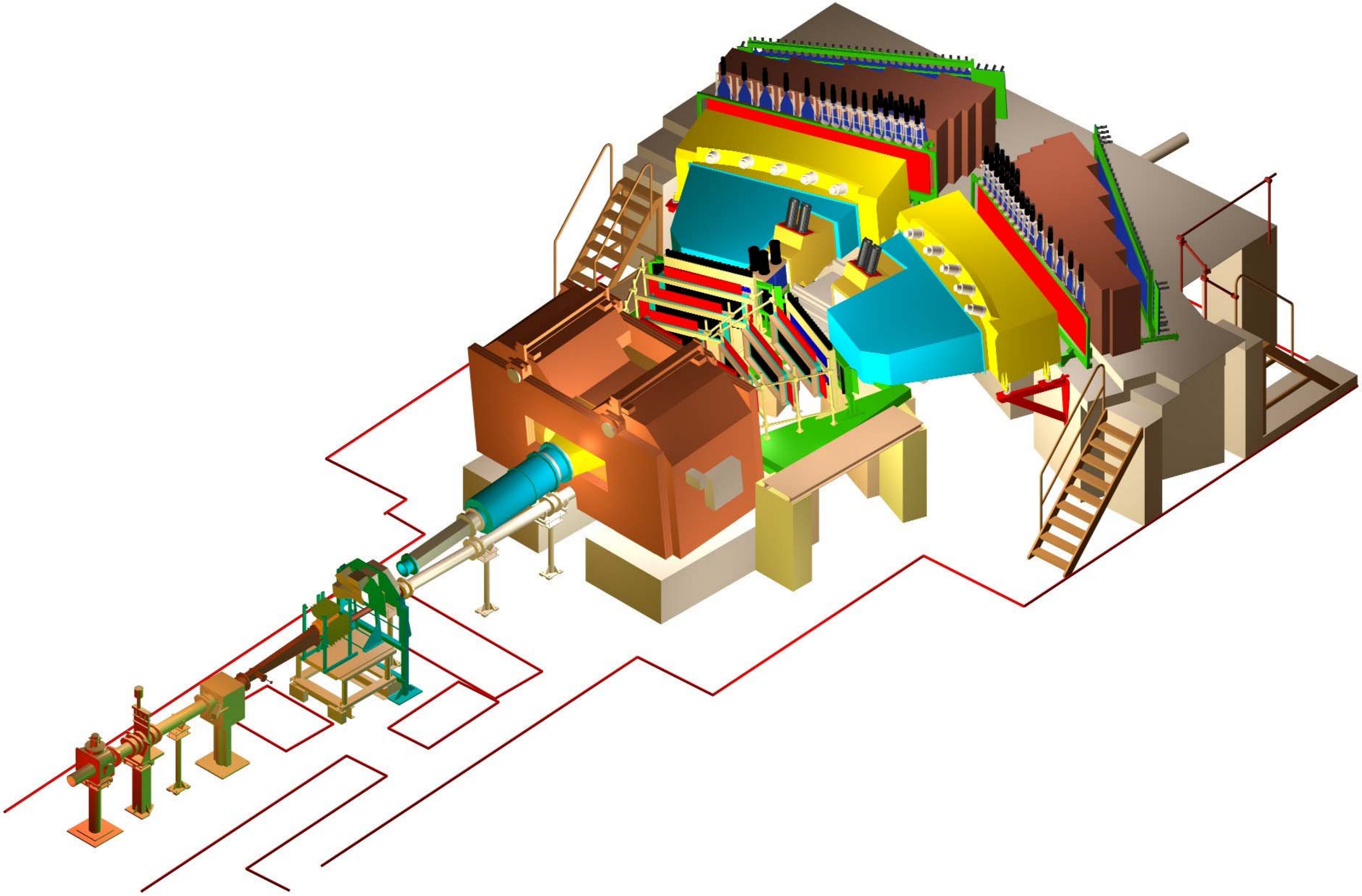
DIRAC at SPS CERN beyond 2011

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

$$(E_{np} - E_{ns})_{\pi\pi} \rightarrow \delta(2a_0 + a_2) \approx \pm 2.5\%(stat) \qquad (E_{np} - E_{ns})_{\pi K} \rightarrow \delta(2a_{1/2} + a_{3/2})$$

DIRAC at PS2 CERN beyond 2011 - under investigation

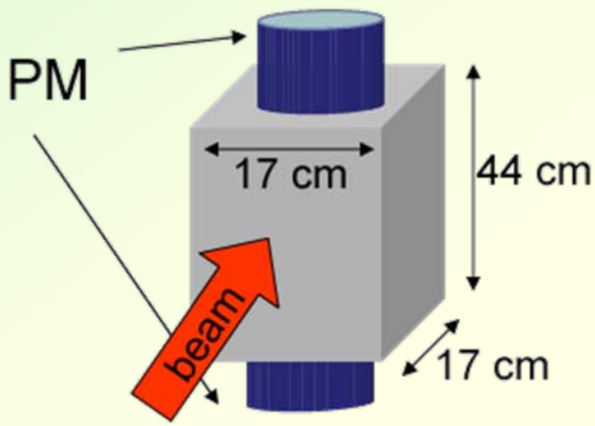
Upgraded DIRAC experimental setup

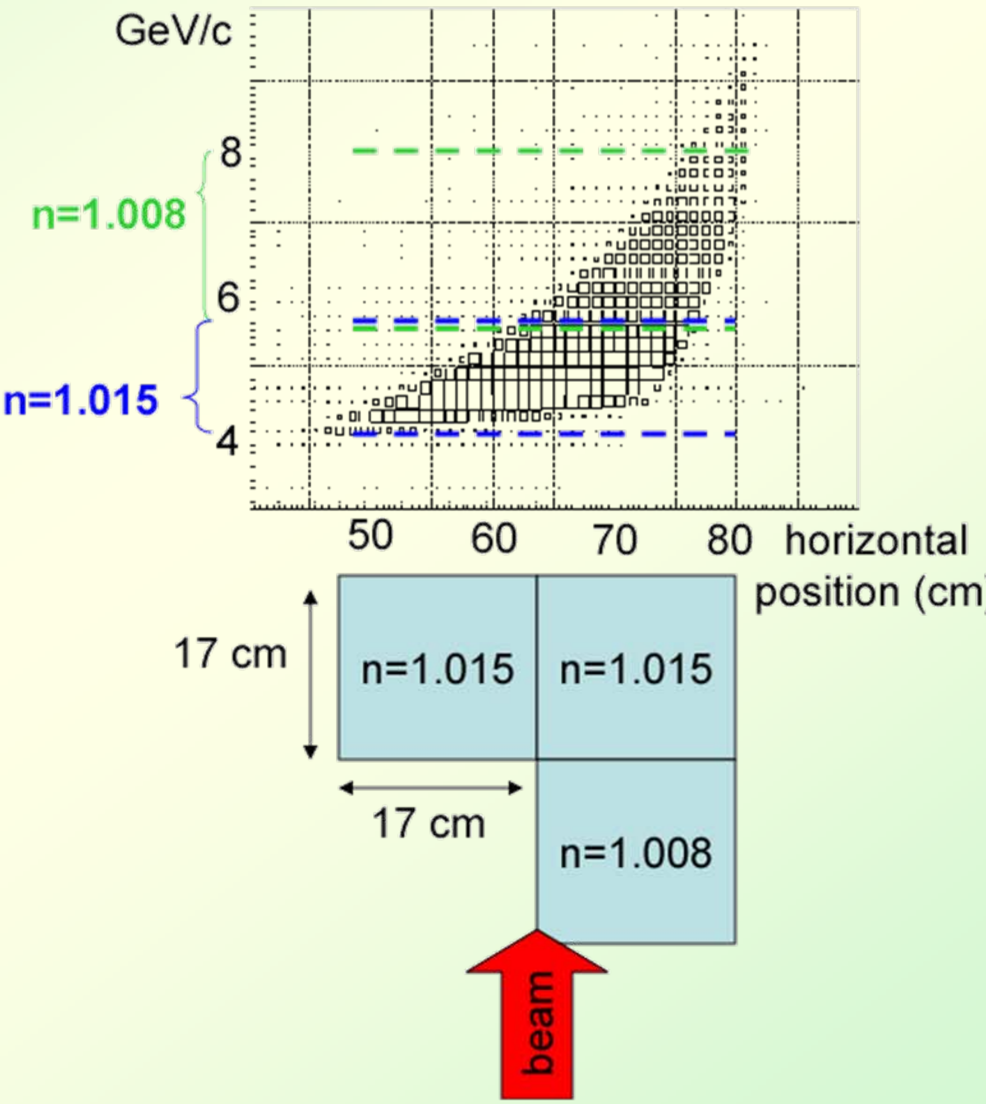


Aerogel Cherenkov detector I

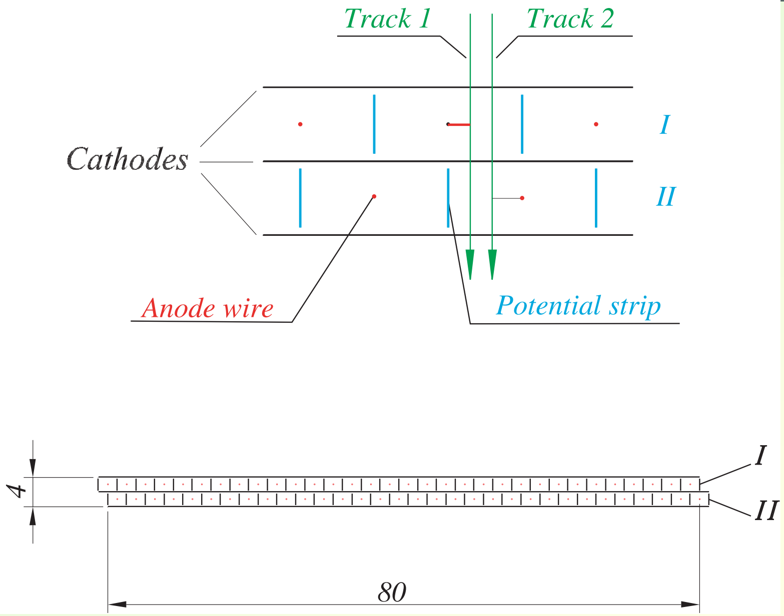
Responsibility:

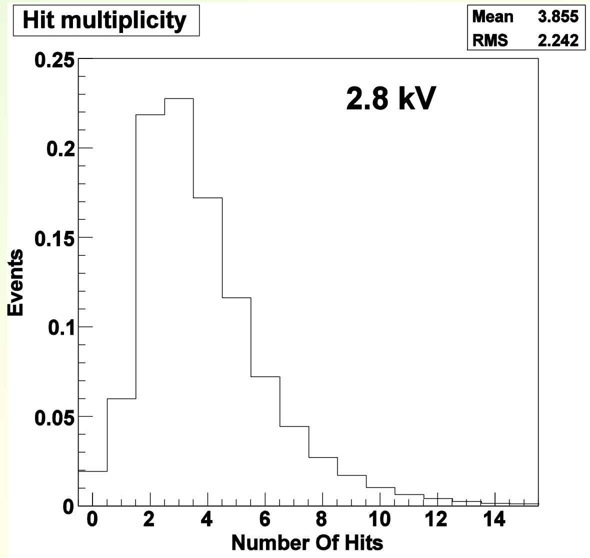
Zurich University (*Zurich*, Switzerland)





Micro Drift Chambers II

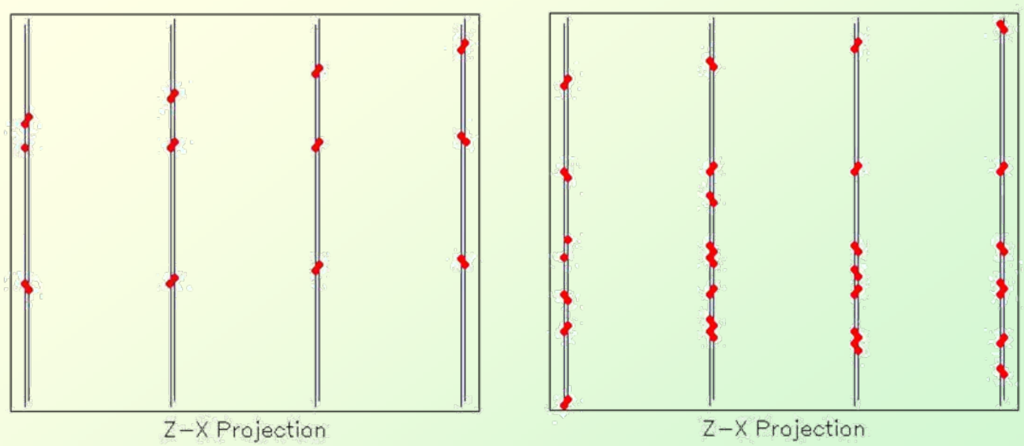




Online data 2007

Target: Pt (28μm)
Intensity: 2x10^{11}

Examples of event



Status

During 2007 run Micro Drift Chambers with the new electrodes and all electronics were finally implemented into the DIRAC setup and DAQ system.

Data with different MDC working condition were collected.