DIRAC experiment (PS212)

A.Benelli

JINR, Zurich University

MESON 2012 Conference, Krakov, June, 2012.

DIRAC collaboration

- CERN
- Czech Technical University
- Institute of Physics ASCR
- Nuclear Physics Institute ASCR
- INFN-Laboratori Nazionali di Frascati
- University of Messina
- KEK
- Kyoto University
- Kyoto Sangyou University
- Tokyo Metropolitan University
- IFIN-HH
- JINR
- SINP of Moscow State University
- IHEP
- Santiago de Compostela University
- Bern University
- Zurich University

ChPT predicts s-wave scattering lengths:

ππ :

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

$a_0 - a_2 = 0.265 \pm 0.004$

G. Colangelo et al.,
Nucl. Phys. B 603 (2001) 125

$\tau = (2.9 + 0.1)$ fs

Kπ :

1-loop approx.
$a_{1/2} = 0.19 \pm 0.2$ $a_{3/2} = -0.05 \pm 0.02$

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

$a_{1/2} - a_{3/2} = 0.24$ ($\pm$8%)

2-loop approx. J. Bijnens, P.P. Donthe, P.Talavera 2004
$a_{1/2} - a_{3/2} = 0.267$ ($\pm$ <8%)

Roy-Steiner equations :

P. Buttiker et al 2004

$a_{1/2} - a_{3/2} = 0.269 + 0.015$

$\tau = (3.7 + 0.4)$ fs

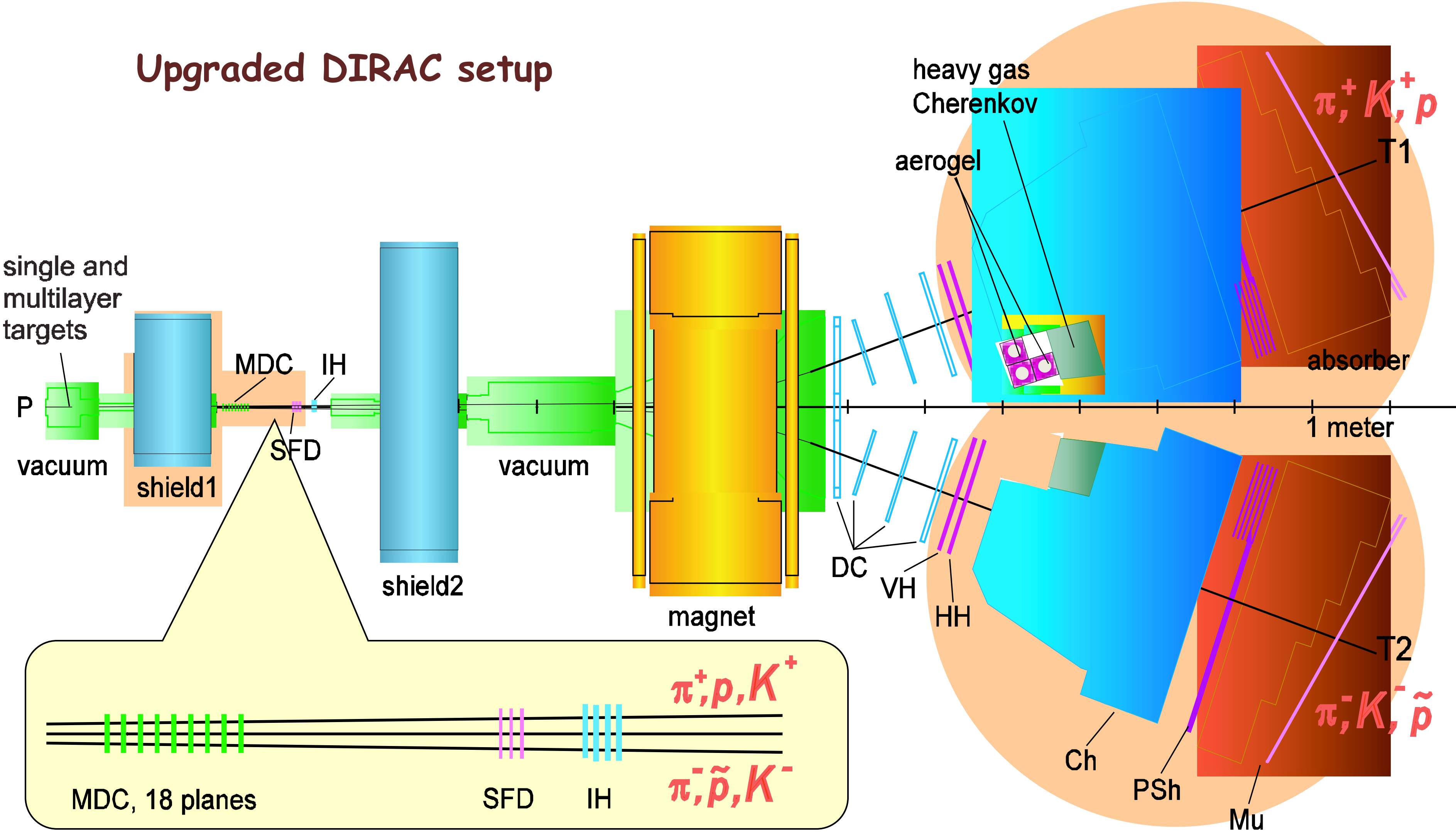
The main DIRAC aim is the accurate measurement of $\pi\pi$ scattering lenghts and the first measurement of πk scattering lenghts

- $A\pi\pi$ lifetime measurement

- observation of $K\pi$ atoms and their lifetime measurement

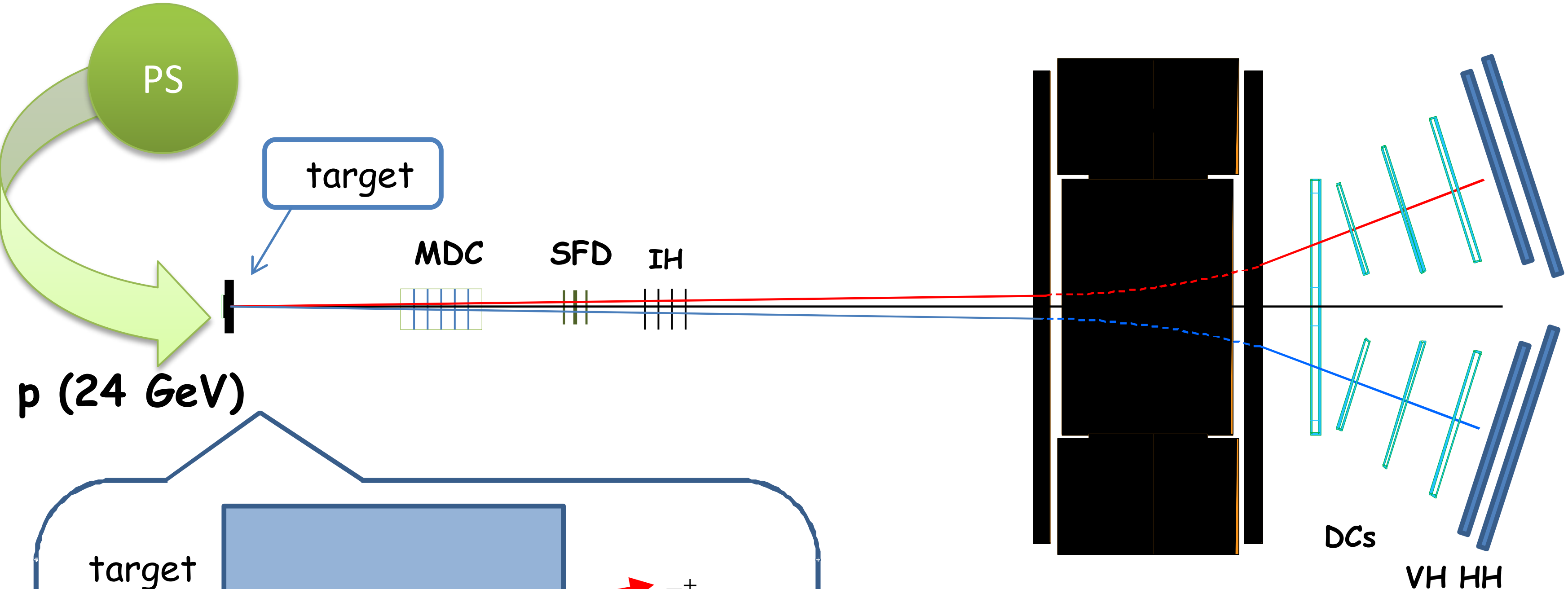
- long lived atoms observation

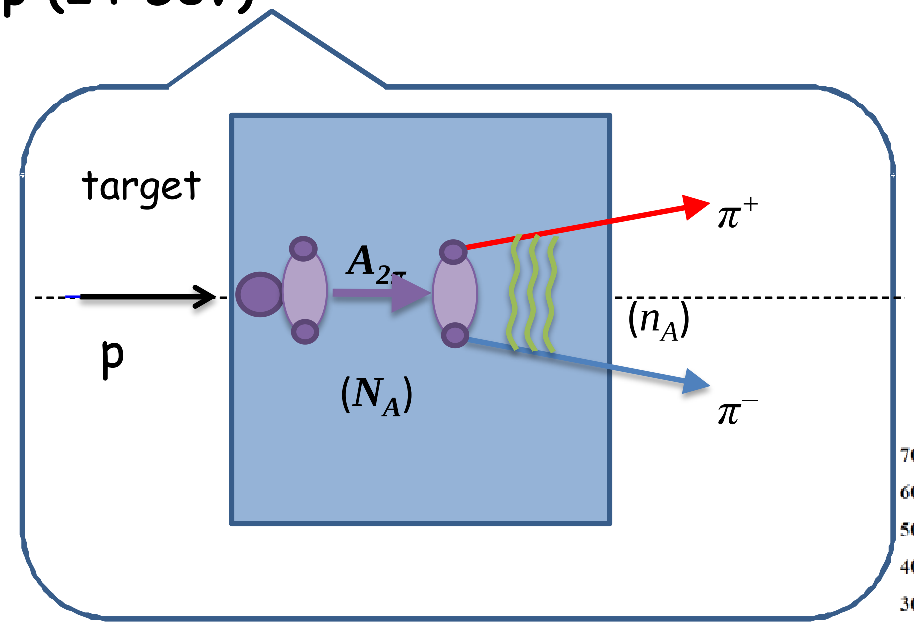
DIRAC setup

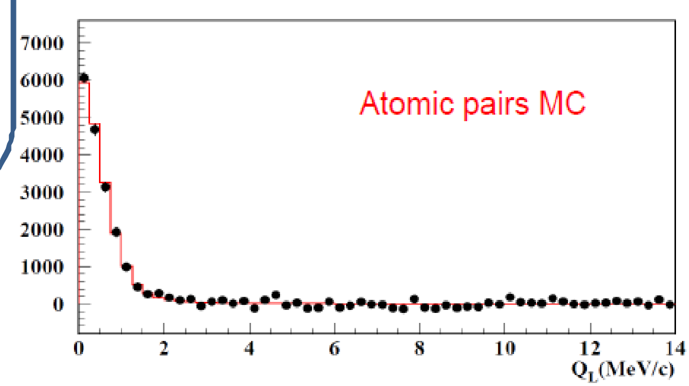


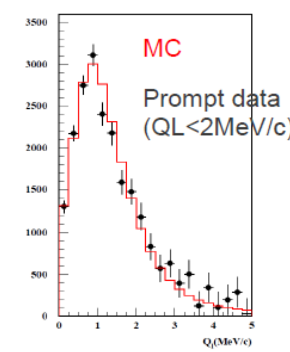
Modifided parts

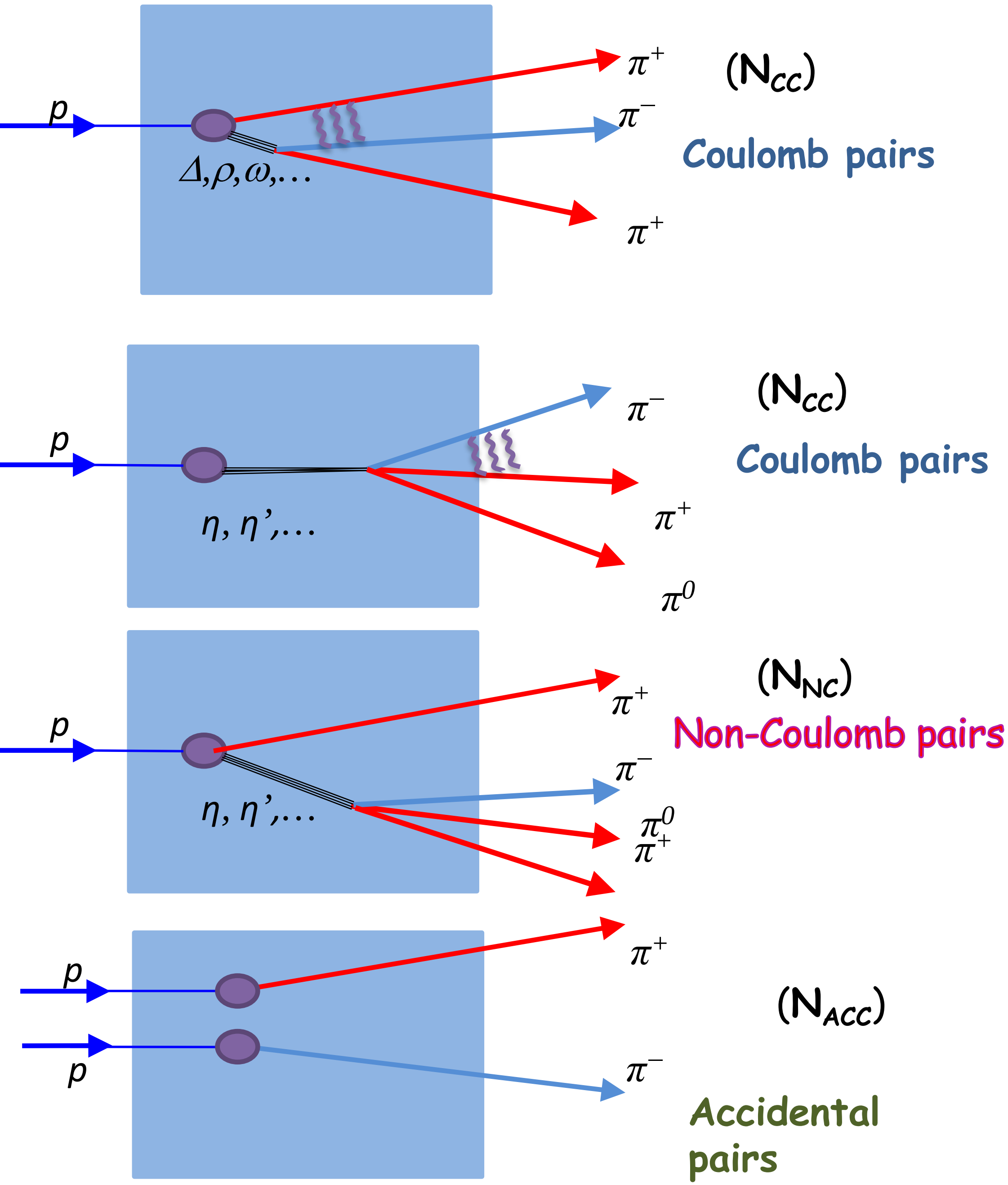
MDC - *microdrift gas chambers*, **SFD** - *scintillating fiber detector*, **IH** – *ionization hodoscope*. **DC** - *drift chambers* , **VH** – *vertical hodoscopes*, **HH** – *horizontal hodoscopes*, **Ch** – *nitrogen Cherenkov* , **PSh** - *preshower detectors* , **Mu** - *muon detectors*

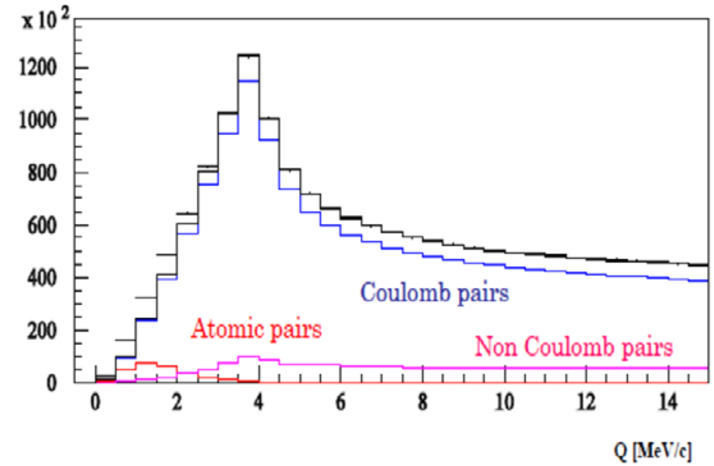

PS
target
MDC
SFD
IH
p (24 GeV)
DCs
VH HH

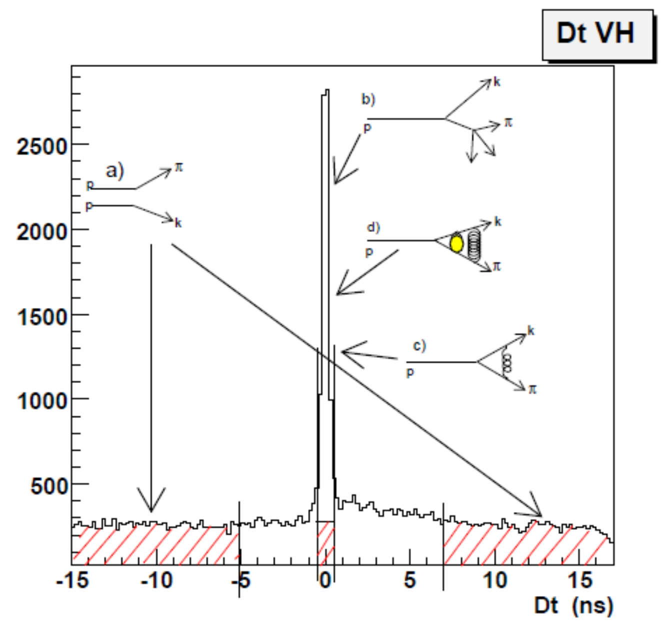

target
p
$A_{2\pi}$
(N_A)
(n_A)
π^+
π^-


Atomic pairs MC
7000
6000
5000
4000
3000
2000
1000
0
0
2
4
6
8
10
12
14
Q_L(MeV/c)


MC
Prompt data
(QL<2MeV/c)


p
Δ,ρ,ω,…
π+
π−
π+
(NCC)
Coulomb pairs
p
η, η’,…
π−
π+
π0
(NCC)
Coulomb pairs
p
η, η’,…
π+
π−
π0
π+
(NNC)
Non-Coulomb pairs
p
p
π+
π−
(NACC)
Accidental pairs

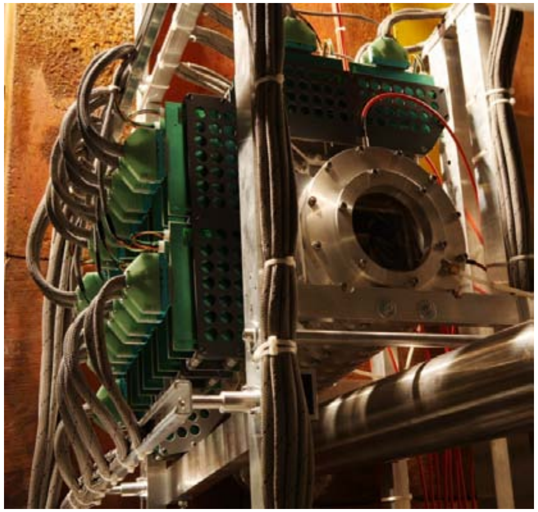

x 10 2
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
Coulomb pairs
Atomic pairs
Non Coulomb pairs
Q [MeV/c]


Dt VH
2500
2000
1500
1000
500
-15
-10
-5
0
5
10
15
Dt (ns)
a)
b)
c)
d)

(2003: GEM-MSGC)

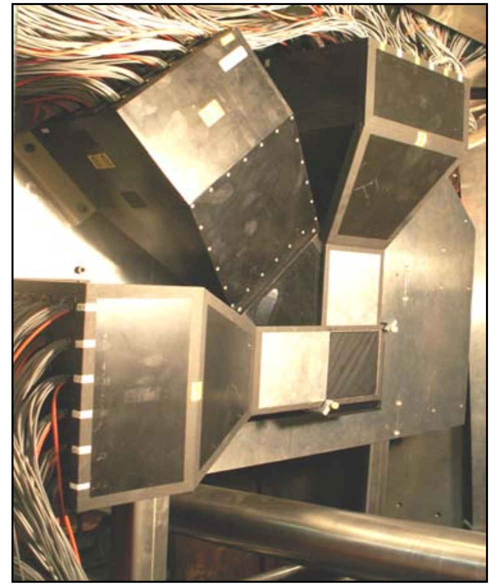
TRACKING

Micro Drift Chambers



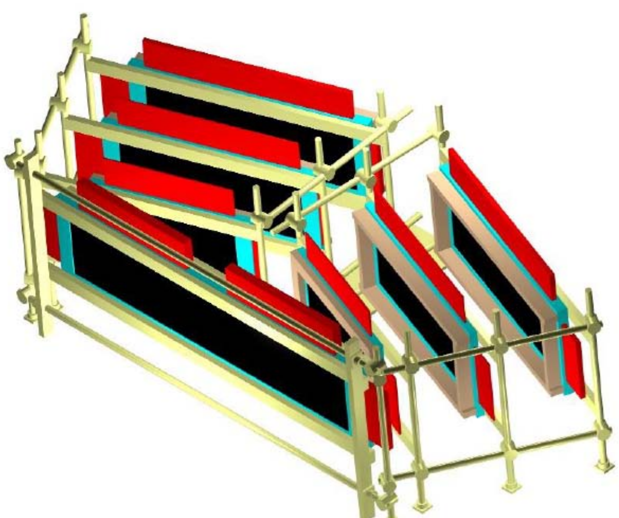
18 planes: X, Y, U
Area: 80x80 mm
Gas mixture: Ar(0.33)+
iC4H10(0.66)+H2O(0.01)
Anode pitch 2.5 mm
32 wires in a plane
Sell size: 2.5x2 mm
Drift time: 26 ns
Time resolution: <1 ns
Space. resol. <80 mkm
2 track resol. <200 mkm
Readout time: <3 mks

Scintillation fibres detector



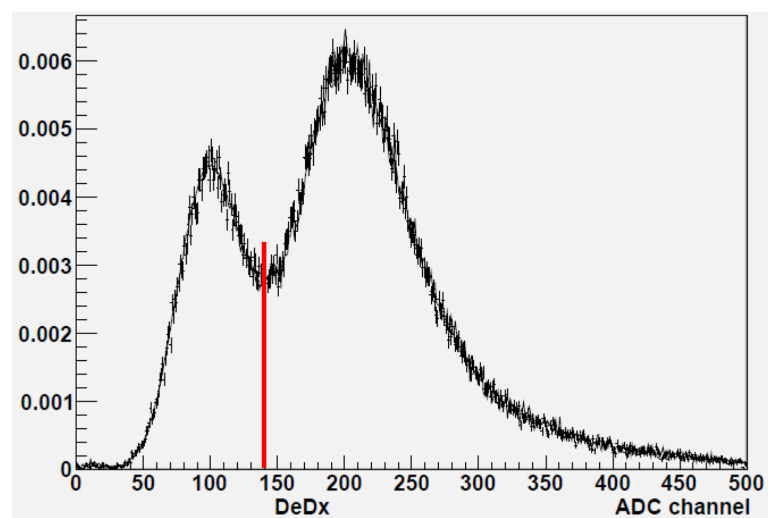
Plane X (Y) (2006)
Area 98.5×107 mm
Thickn. (one plane) 3.1 mm
480 columns
8 fibres in a column
Fibre diameter 0.5 mm
Column pitch 0.205 mm
30 16 ch H6568 per plane
Light output 11 p.e.
Time resolution 0.46 ns
Space resol. $\sigma \approx 60\ \mu m$
New electronics
ADC-TDC for 960 channels
Plane U (2002)

Drift chambers

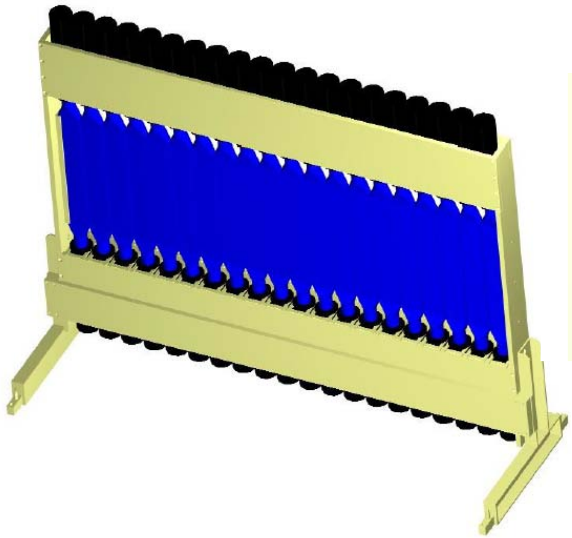


DC1: 2x80x40 cm
X,Y,W,X,Y,W. 800 ch
DC2: X,Y, 80x40 cm
DC3: X,Y, 112x40 cm
DC4: X,Y,X,Y,
128x40 cm
Both arms: 1216 ch
Anode pitch: 10 mm
Cell: 10x10 mm
Cathode: 20 mkm
carbon-coated mylar
Anode wires: 50 mkm
copper-beryllium alloy
Drift velocity: 50 mkm
Amplitude: 1 mA
Pulse width: 20 ns
Resolution 90 mkm

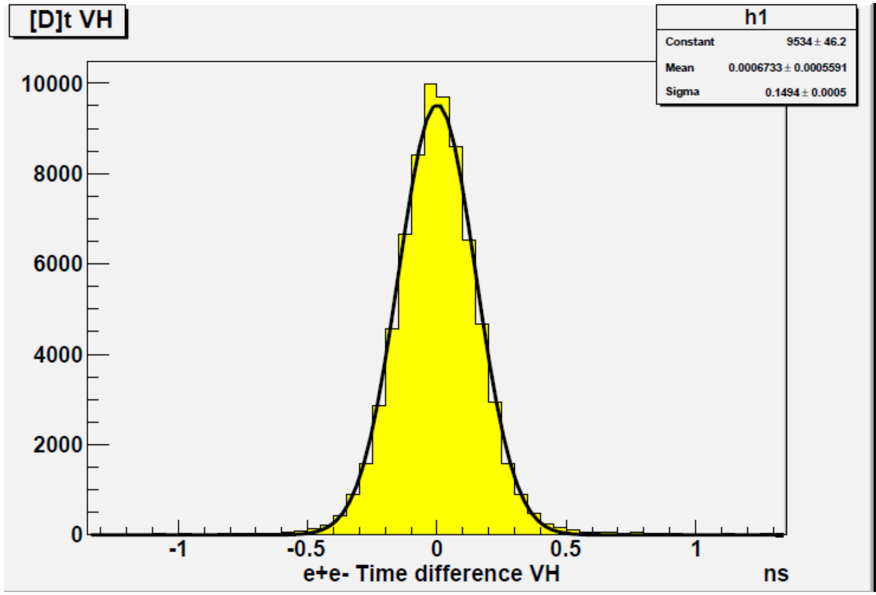
Ionisation Hodoscope



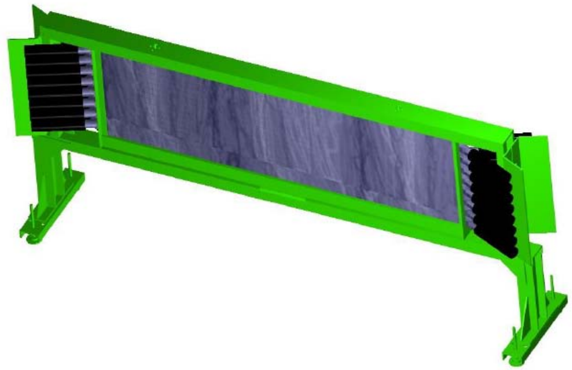
Vertical Hodoscope



Area 144x40 cm
20 slabs 40x7x2.2 cm
BICRON BC420
Two Hamamatsu
R1828-01



Horizontal Hodoscope



Area 150x40 cm
16 slabs
150x2.5x2.5 cm
Philips XP2008
Time resolution
330 ps (2)
Time resolution
233 ps (1)

Trigger requests tracks coplanarity

Physics Letters B 704 (2011) 24–29

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Physics Letters B

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Determination of $\pi\pi$ scattering lengths from measurement of $\pi^+\pi^-$ atom lifetime

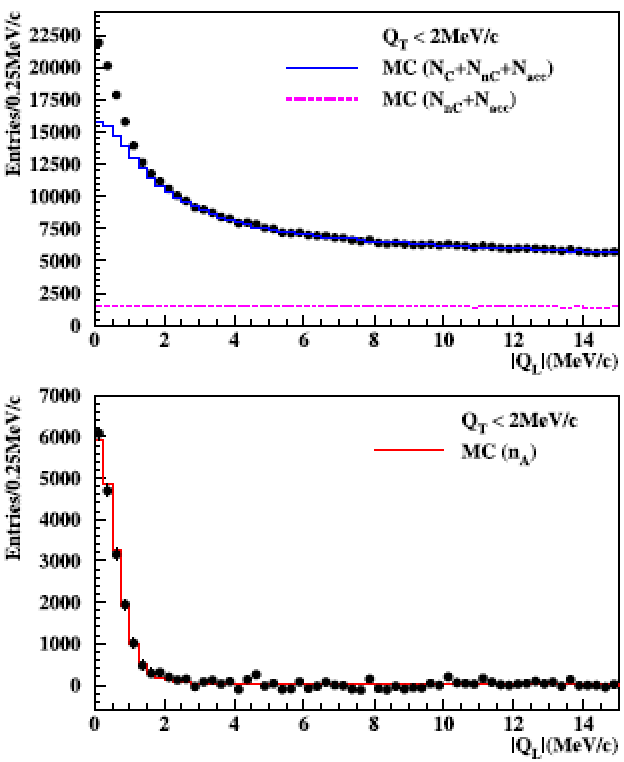


Fig. 1. $|Q_L|$ fit projections of the $\pi^+\pi^-$ spectrum from data (dots) and simulation (MC lines). The top plot shows the experimental spectrum compared with the simulated background components (no pionium signal), with (solid line) and without (dotted line) Coulomb pairs (N_C). The bottom plot shows the experimental $|Q_L|$ spectrum after background subtraction and the simulated pionium spectrum.

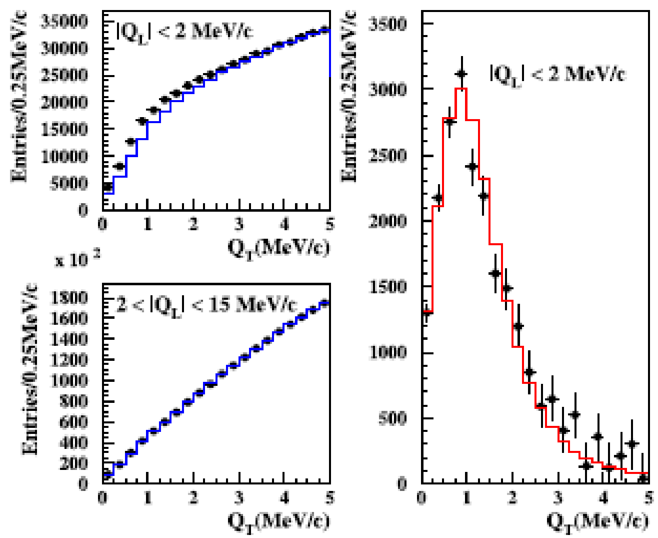


Fig. 2. Q_T fit projections of the $\pi^+\pi^-$ spectrum from data (dots) and simulation (line). The left plots show the comparison between the experimental spectra and the full simulated background. The plots correspond to different Q_L regions: top left plot in the $A_{2\pi}$ signal region (low $|Q_L|$) and bottom left plot away from it (higher $|Q_L|$). The right plot shows the Q_T spectrum after background subtraction and the simulated pionium spectrum.

$$n_A = 21227 \pm 407$$

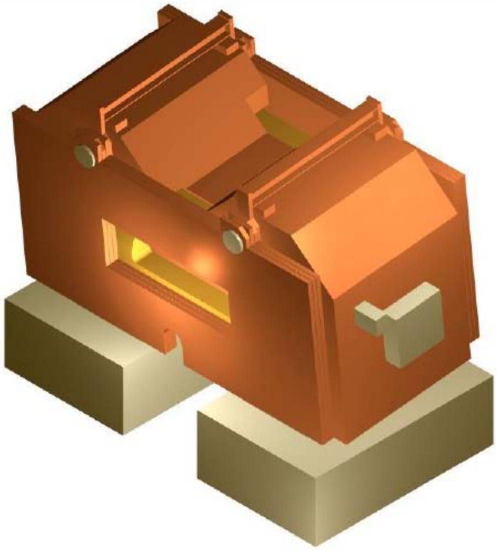
Published results on $\pi\pi$ atom: lifetime & scattering length

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	$^{+0.45}_{-0.38}$	$^{+0.19}_{-0.49}$		$\left[^{+0.49}_{-0.62}\right]$	0.264	$^{+0.017}_{-0.020}$	$^{+0.022}_{-0.009}$		$\left[^{+0.033}_{-0.020}\right]$	PL B 619 (2005) 50
2001-03	3.15	$^{+0.20}_{-0.19}$	$^{+0.20}_{-0.18}$		$\left[^{+0.28}_{-0.26}\right]$	0.2533	$^{+0.0078}_{-0.0080}$	$^{+0.0072}_{-0.0077}$		$\left[^{+0.0106}_{-0.0111}\right]$	PL B 704 (2011) 24

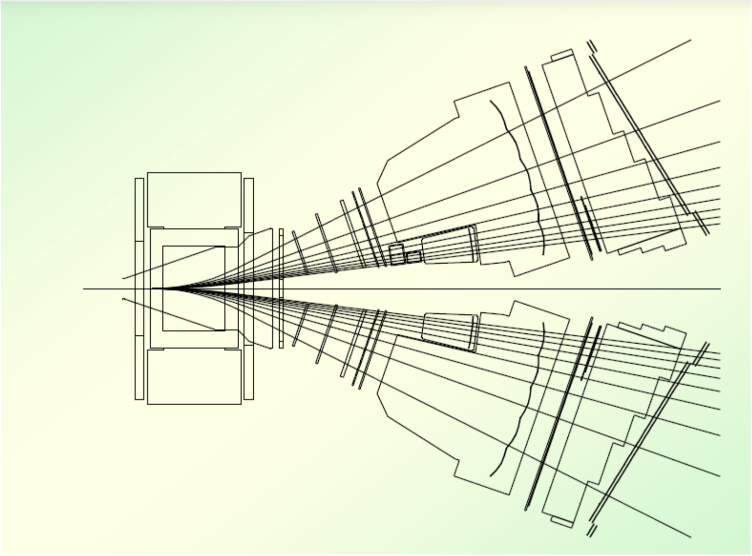
* theoretical uncertainty included in systematic error

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

ππ and kπ geometrical acceptance

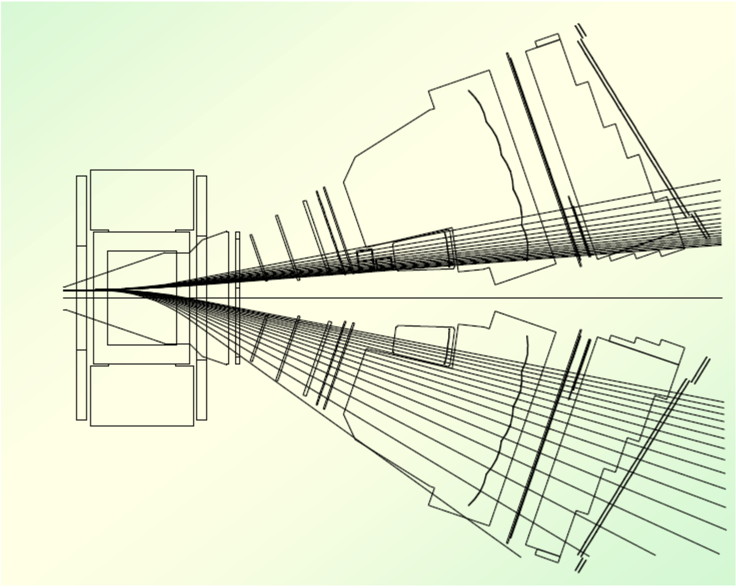


MNP21/3
B = 1.65 T
BL= 2.2 Tm
Current 2500 A
Power 1.43 MW
Weight 120 ton
Dim. 4.2x2.5x2.0 m
Gap 1.5x0.5x1.1 m
Screens
400x200x15 cm
Coils 2x165 turns
Coils 18x18 mm
Water 23 kg/cm2
Water 540 l/min



π

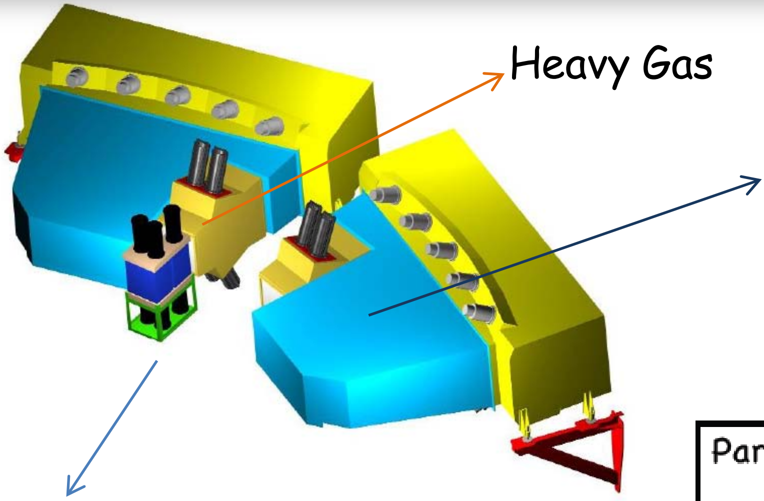
π



K

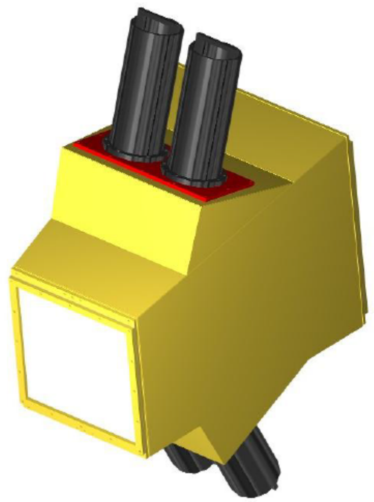
π

Cherenkov detectors



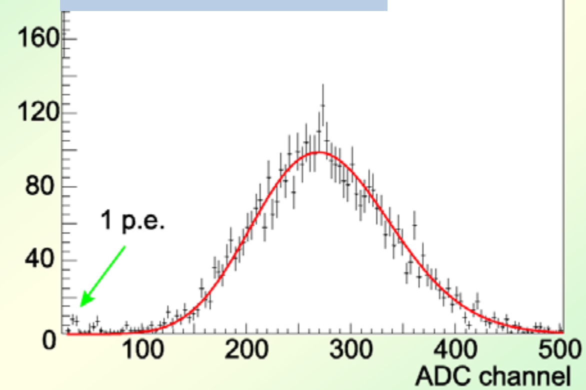
Particle type	Heavy Gas	Aerogel	Nitrogen
pion	✪ p>2.7GeV	✪ (1.008)p>0.9GeV (1.015) p>1.1GeV	✪p>5.5GeV
proton	✖	✪ (1.008)p>7.5GeV (1.015)p>5.3GeV	✖
kaon	✖	✪ (1.008)p>3.9GeV (1.015)p>2.9GeV	✖
electron	✪	✪	✪

Heavy Gas Cerenkov detector

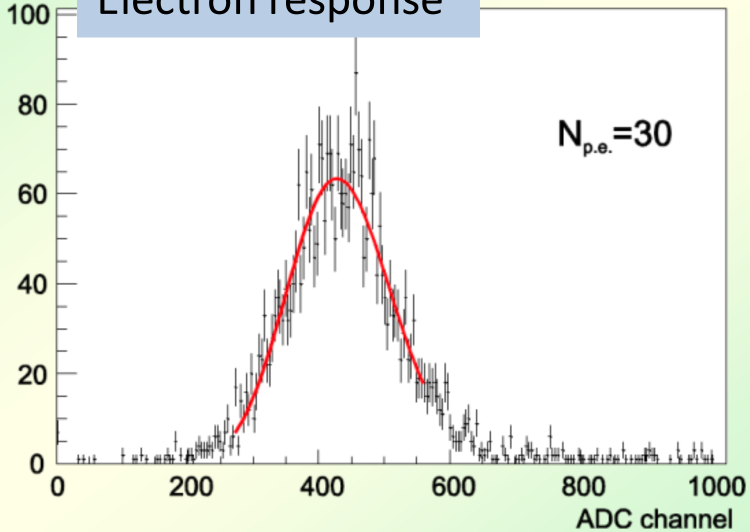


C4F10, perfluorocarbon
Transparency up to 190 nm
n=1.00135
Max. Cherenkov angle 3.03 deg
For pion detection 4-8 GeV/c
Threshold for pions 2.7 GeV/c
Window 42x44 cm
Radiator thickness 85 cm
Volume 0.4 m3 per detector
4 spherical mirrors 293x286 mm
R=1194 mm
4 flat mirrors 185x185 mm
4 PMs: HAMAMATSU 6528
5 inch with UV-glass
Nphe=30 for electrons
Quality factor *N0*= 125 cm-1
Efficiency for pions with
p >4 Gev/c >99.5%

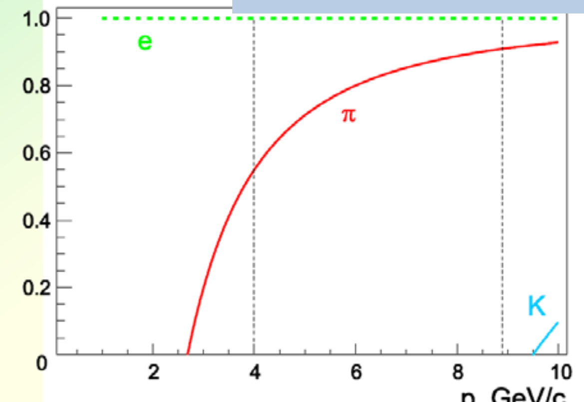
Pion response



Electron response

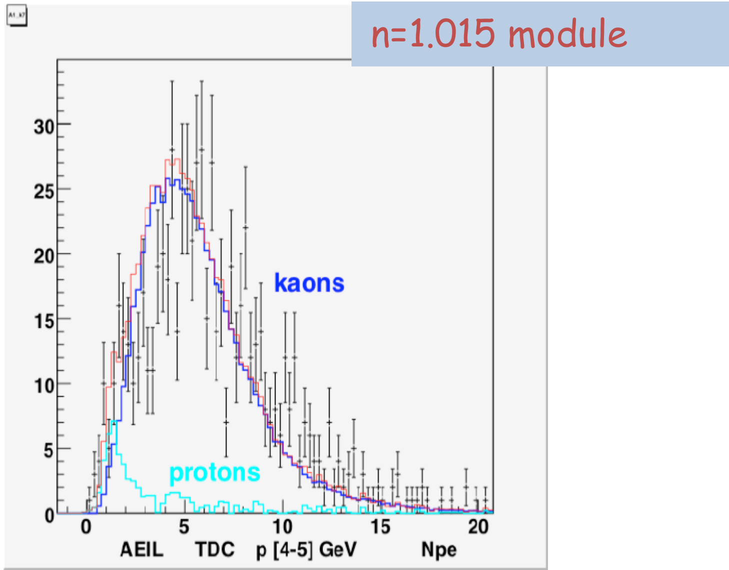


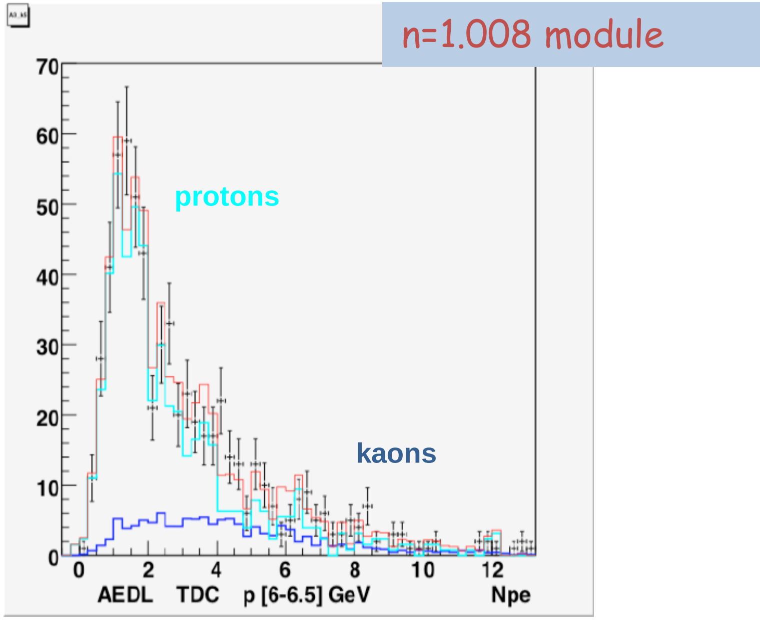
Light vs momentum

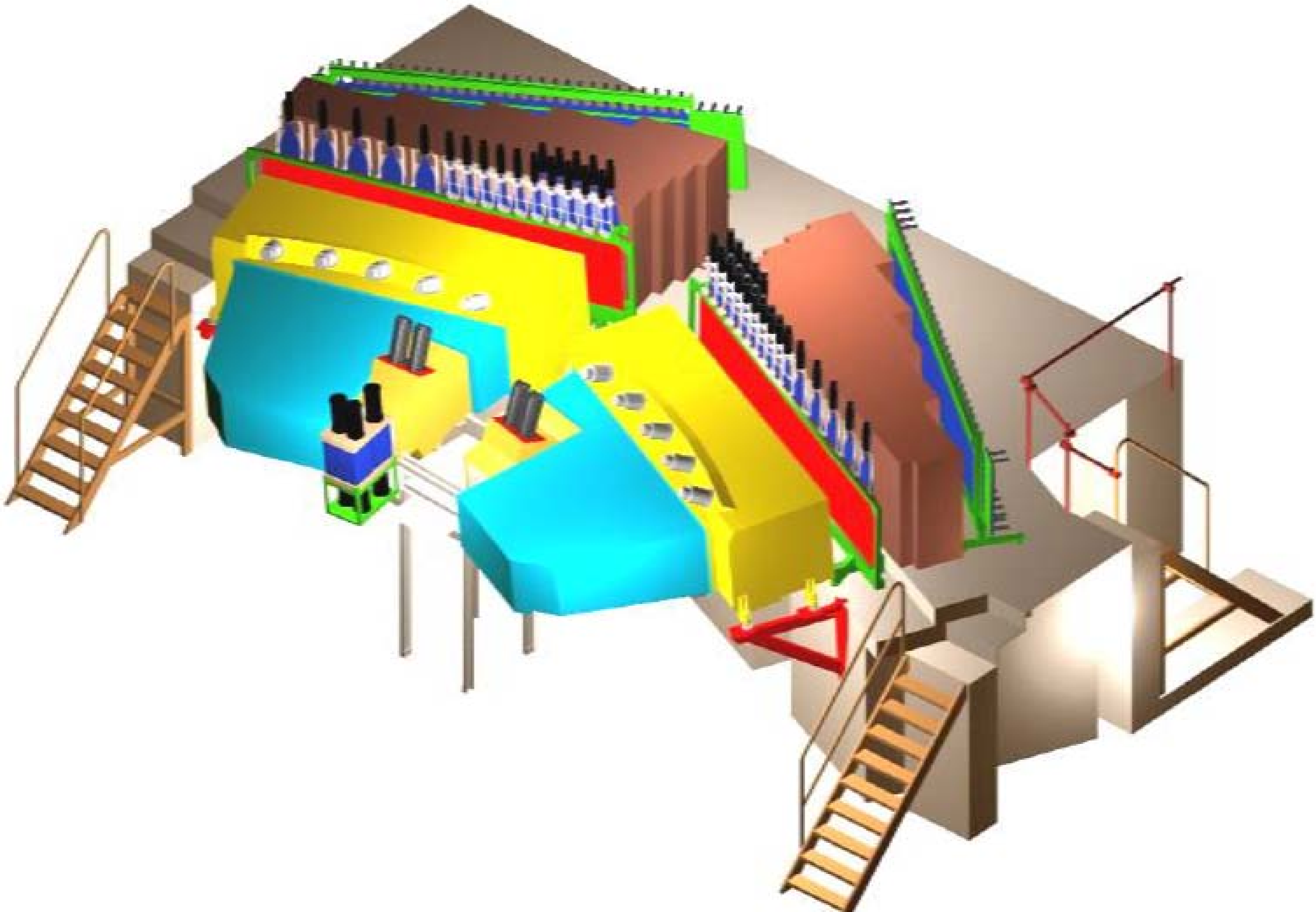


Aerogel Cerenkov detector

Three modules
Novosibirsk
n=1.015: for 4-5.5 GeV/c
33x42 cm, L=11-23 cm
Japan
n=1.008: for 5.5-8 GeV/c
16x42 cm, L=16-23 cm
Pyramidal shape
Wavelength shifter
p-terphenyl on
tetratex reflector foils
50% increase in light
PMTs Photonis XP4570/B
5-inch. UV-glass
Nphe: 6.9 and 3.9 for
heavy and light modules
Efficiency for K+: 85-95%







Physics Letters B 674 (2009) 11–16

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Physics Letters B

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Evidence for πK-atoms with DIRAC

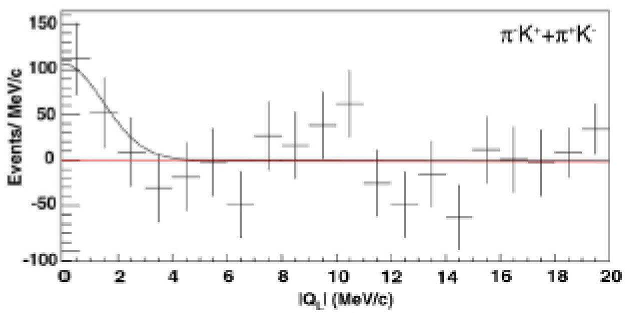


Fig. 6. Residuals between data and the fitted background for $\pi^- K^+$ and $\pi^+ K^-$. A Gaussian fit has been applied (solid line) to illustrate the distribution of atomic-pairs.

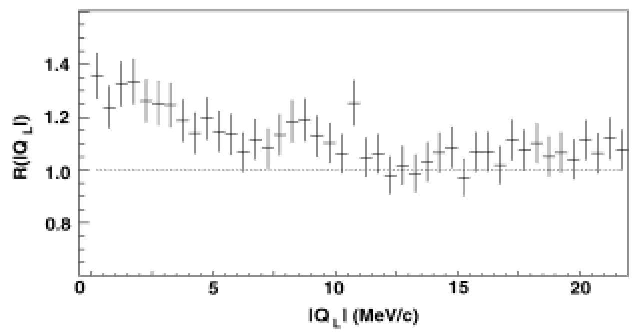


Fig. 7. Correlation function R as a function of $|Q_L|$ for $\pi^- K^+$-pairs. The deviation from the horizontal dotted line proves the existence of Coulomb correlated $\pi^- K^+$-pairs.

$n_{A_{\pi k}}$ = 173±54 3.2 σ

τ > 0.8 fs

90% CL

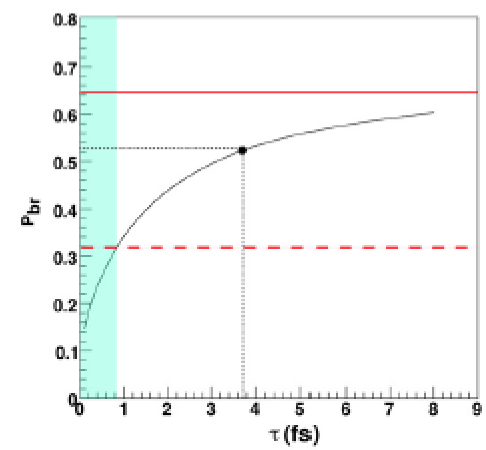
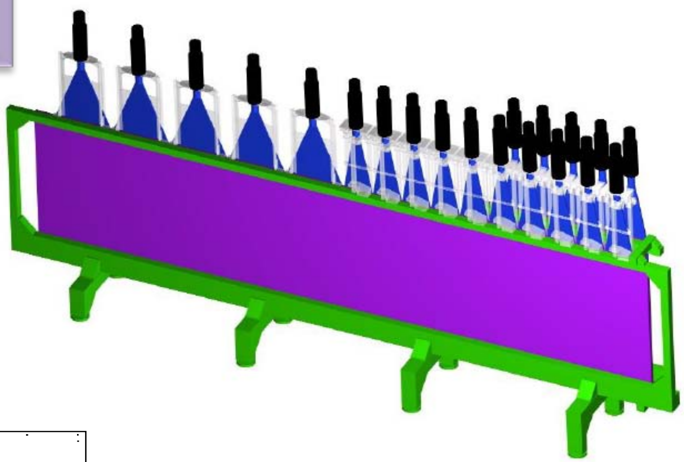
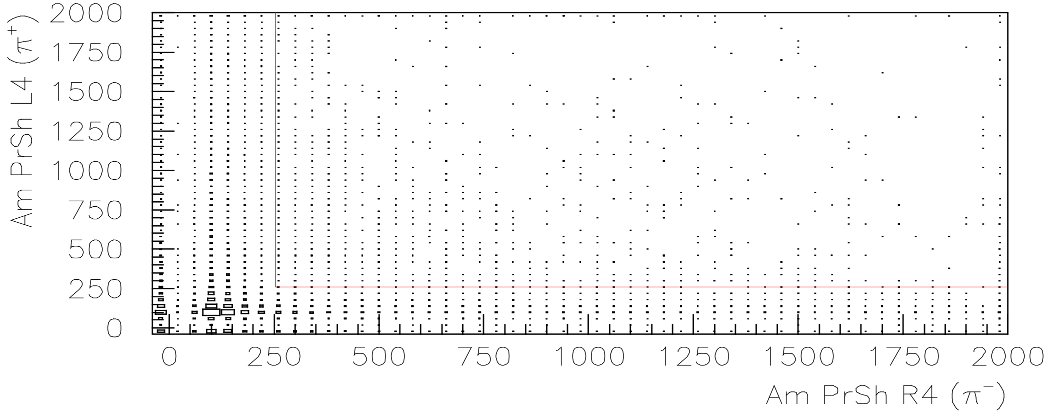


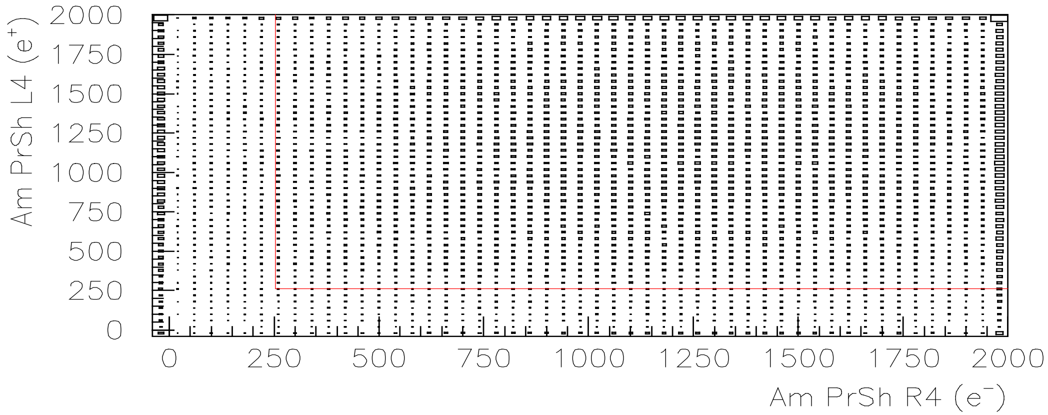
Fig. 8. Breakup probability P_{br} for the 26 μm Pt-target as a function of mean life of πK-atoms in the 1S-state. The horizontal solid line is the measured breakup probability and the horizontal dashed line the 1.28σ lower bound corresponding to a lower limit of 0.8 fs for the mean life. The excluded area (90% confidence level) is shown in turquoise. The horizontal dotted line gives the theoretical prediction [8].

Preshower detector



Area:
350x75 cm
First layer:
Area 1:
175x75 cm
5 counters
35x75x1 cm
Area 2:
175x75 cm
10 counters
17.5x75x1 cm
Second layer:
Area:
87.5x75 cm
5 counters
17.5x75x1 cm

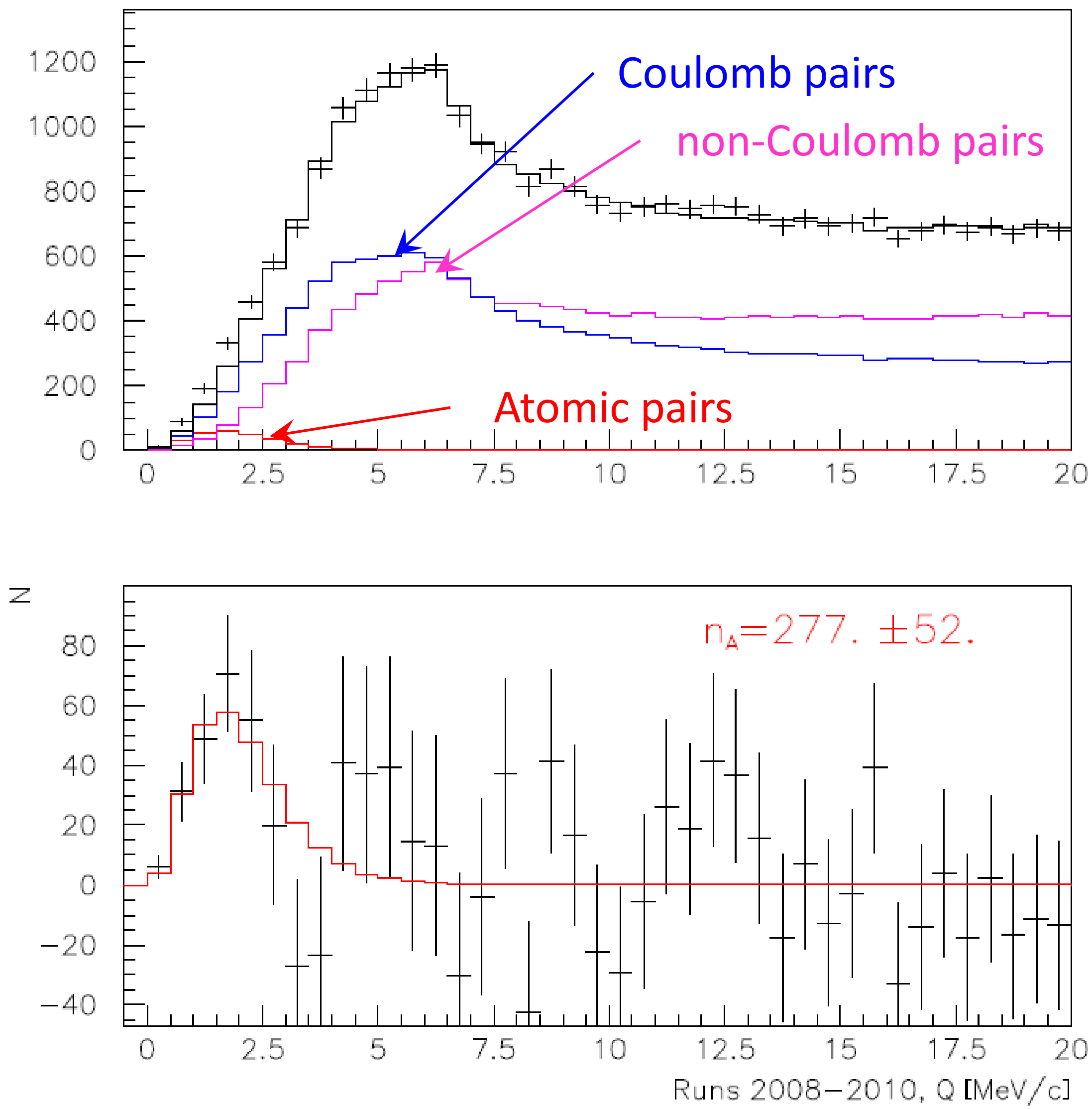




Cut efficiency :
12.5% e^+e^-
97.5% $\pi\pi$

e^+e^- subtraction
97.8% $\pi\pi$

π^-K^+ and π^+K^- prompt pairs

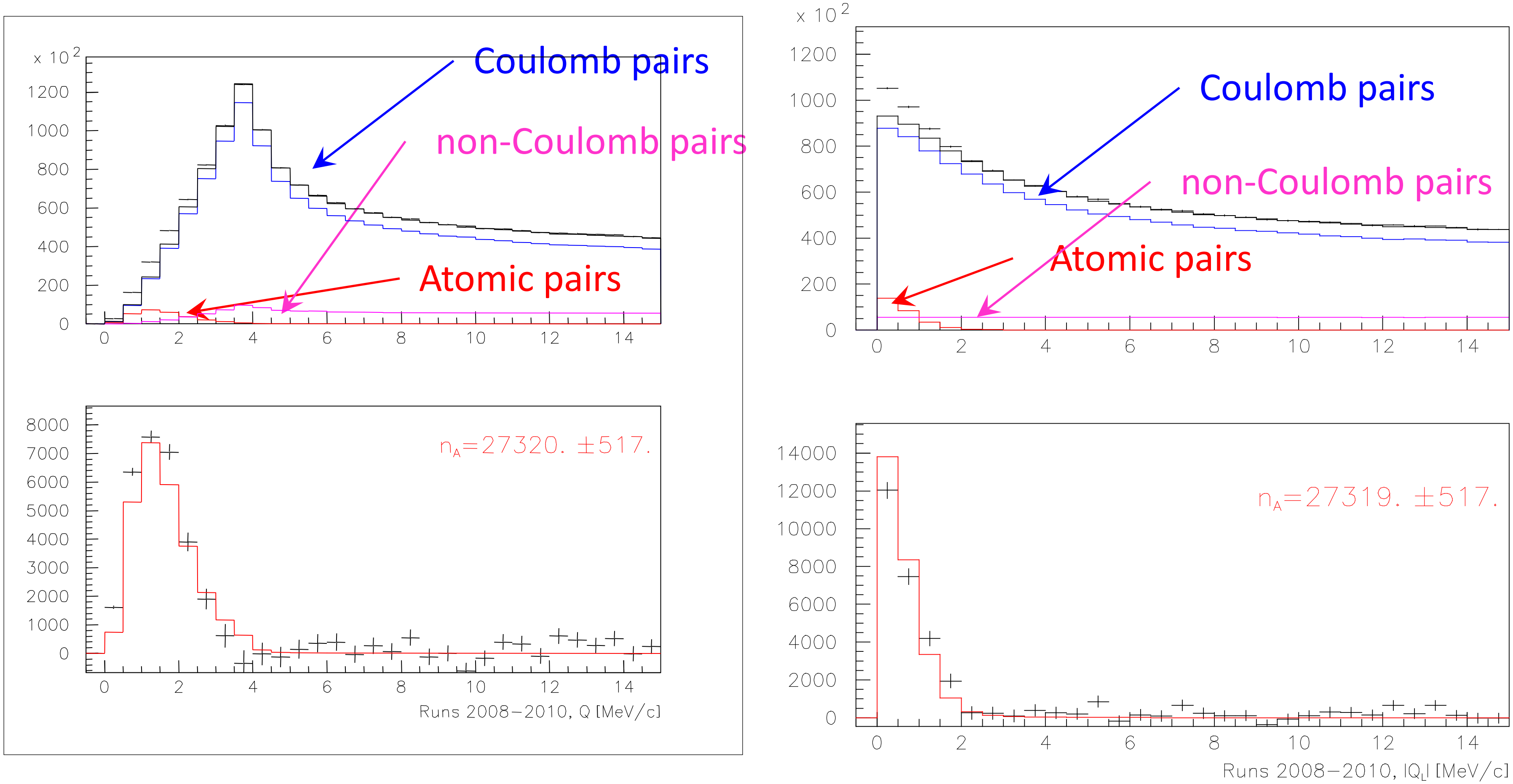


Run 2008-2010, statistics with low and medium background (⅔ of all statistics). Point-like production of all particles. The e^+e^- background was not subtracted.

5.3 σ

26% relative error on $|a_{1/3}-a_{2/3}|$

$\pi^+\pi^-$ prompt pairs

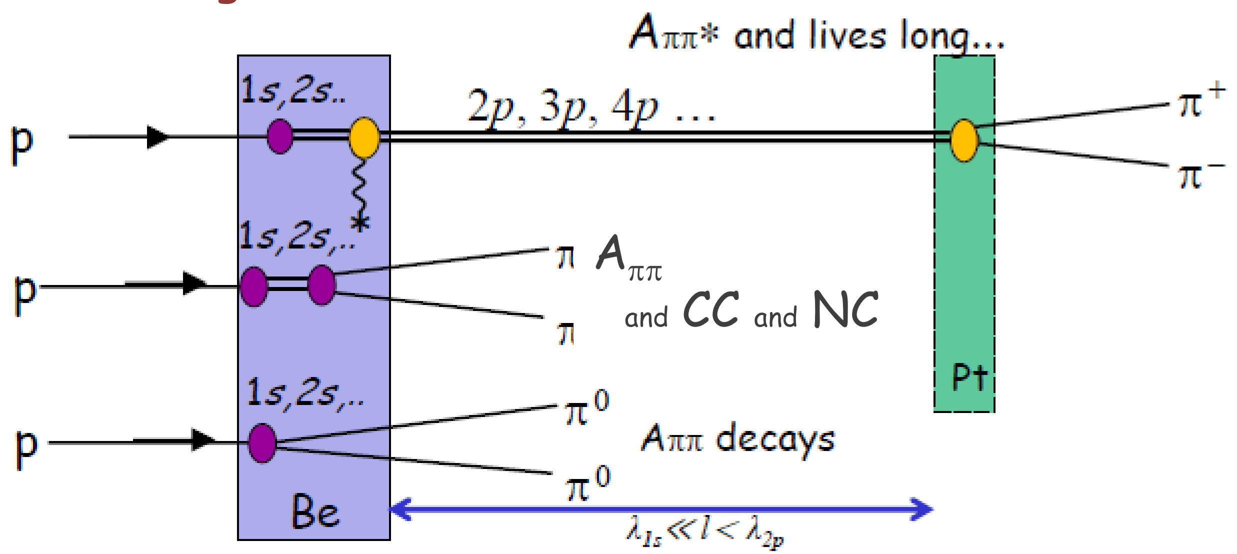


Run 2008-2010, statistics with low and medium background (⅔ of all statistics). Point-like production of all particles. The e^+e^- background was not subtracted.

Long lived atoms

In order to measure an other combination of scattering length : $2a_0+a_2$

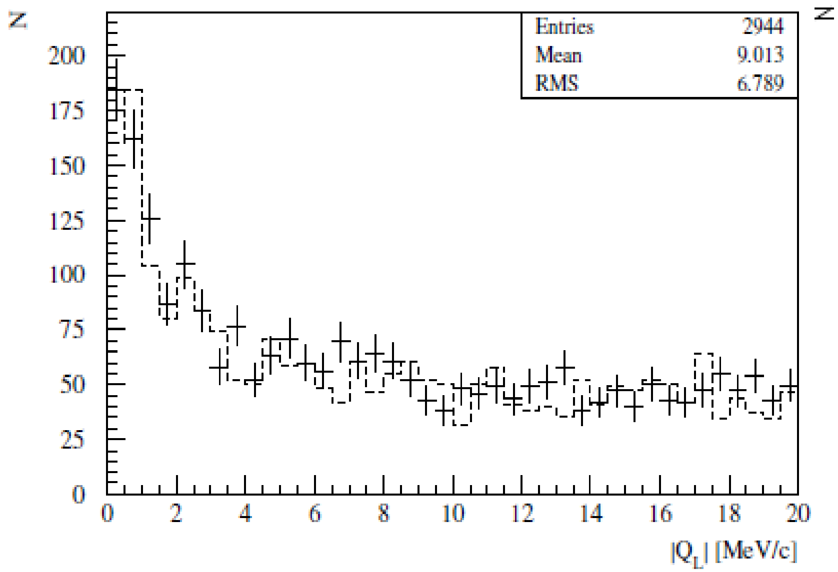
2011-2012 data taking



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

2010-2011 : Production of $A_{2\pi}$ in Beryllium target

Distribution over $|Q_L|$ of $\pi^+\pi^-$ pairs collected in 2010-2011 with Beryllium target with the cut Q_T<1 MeV/c. Experimental data (points with errors) have been fitted by a sum of simulated *CC* and NC pairs (dashed line).

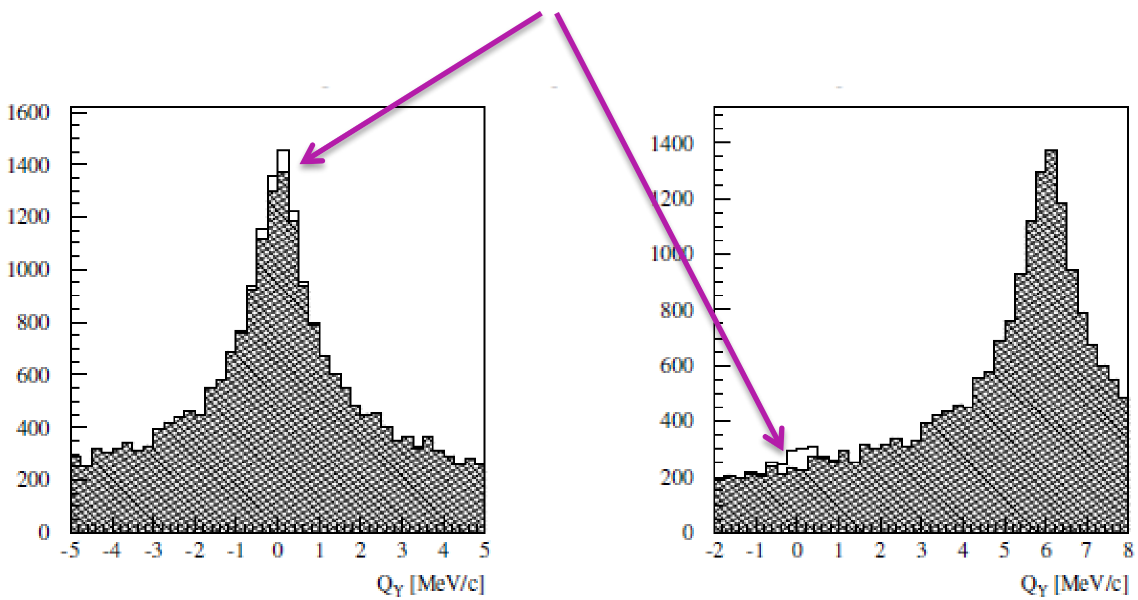


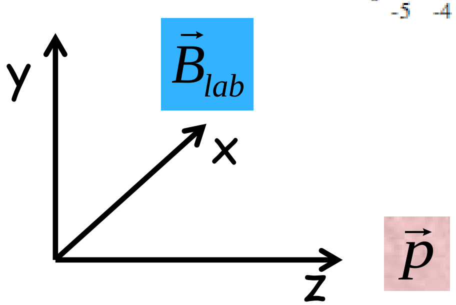
Produced atoms normalized on the proton flux : $N_{A_{2\pi}}$ = (5.1 ± 0.5) x 10 $^{-14}$

Simulation of the permanent magnet at the target

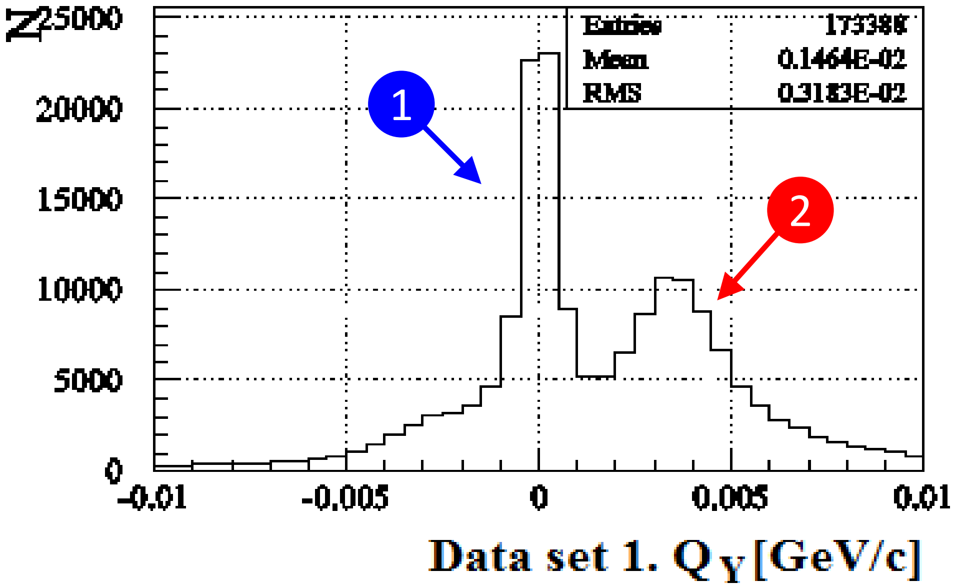
Simulated atomic pairs from long lived atoms(light area) over Q_Y above the background of pp pairs produced in the Beryllium target with cuts $|Q_X, Q_L|$<1MeV/c (hatched area). On the left side without the magnet and on the right with the magnet used during 2011.

Atomic pairs from long lived atoms





2011 data : Experimental distribution of e^+e^- over Q_Y

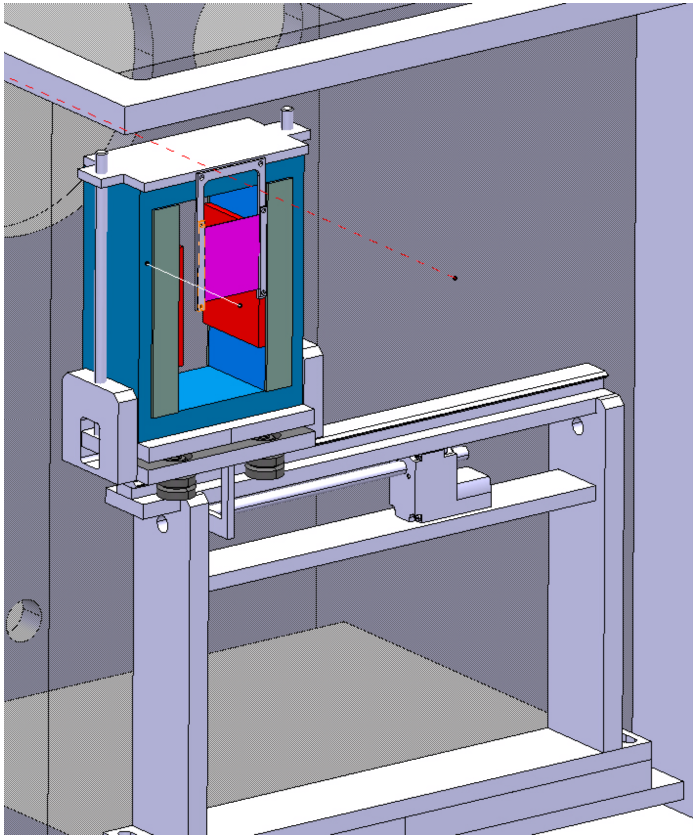


2 Pairs generated on Be target before magnet

1 Pairs generated after magnet

Magnet for 2012 run

- 2 new magnets: Sm_2Co_{17}, high resistivity against radiation, B=0.26T, expected signal > 9 sigma.
- New retracting device allows to replace magnet fast.



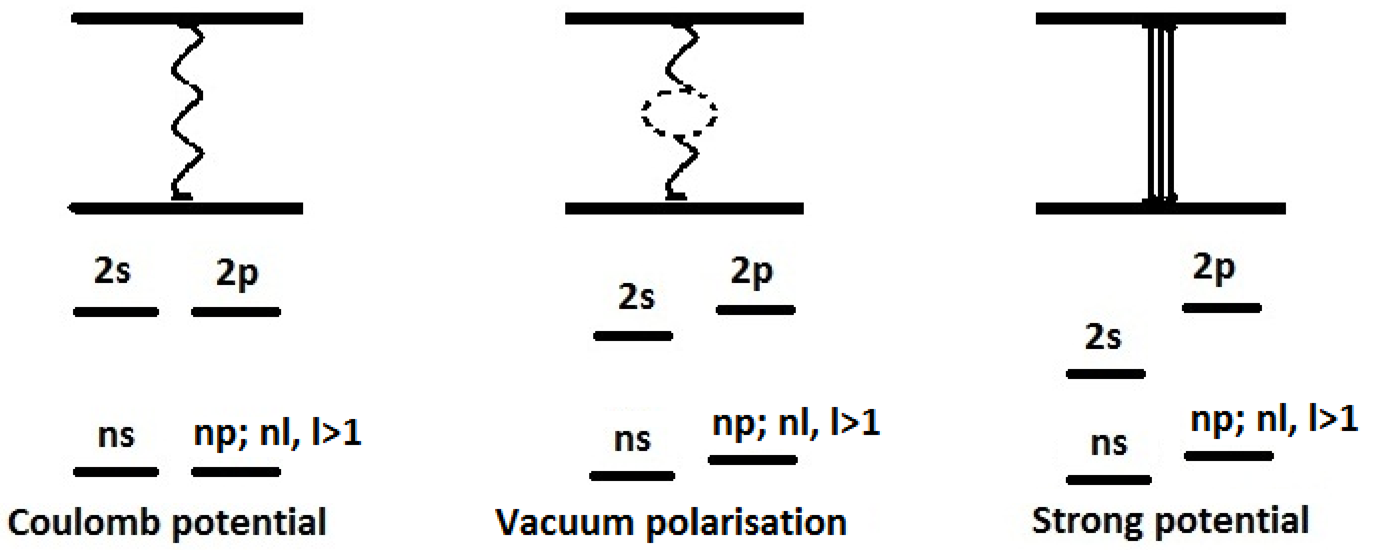
BLUE … magnet yoke

GREY … magnet poles

RED … magnet shimming

PURPLE … Pt foil

Energy splitting in theory



$$\mathbf{E_{2s} - E_{2p} = \Delta_{2s-2p}} \qquad \mathbf{\Delta^{vac}_{2s-2p} = -0.107\ eV} \qquad \mathbf{\Delta^{str}_{2s-2p} = -0.47\ eV}$$

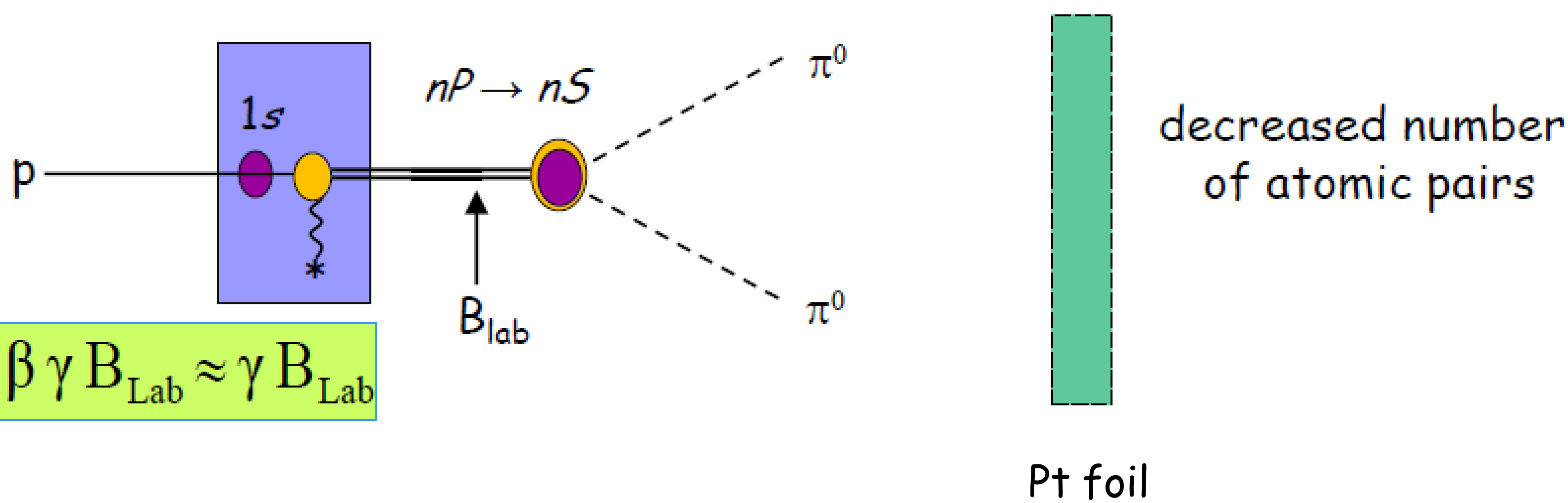
$$\mathbf{\Delta^{str}_{2s-2p} = -\frac{\alpha^3 m_\pi}{8}\frac{1}{6}(2a_0 + a_2) + \cdots} \qquad \mathbf{\Delta^{tot}_{2s-2p} = -0.59 \pm 0.01\ eV}$$

The observation of $\pi\pi$ atom long-lived states opens the future possibility to measure the energy difference between *ns* and *np* states *ΔE(ns-np)* and the value of $\pi\pi$ scattering lengths $|2a_0+a_2|$.

ΔE in practice .. observation method

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**.

Magnetic field → Electric field → mixing $2p_0$-$2s$,...



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

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

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

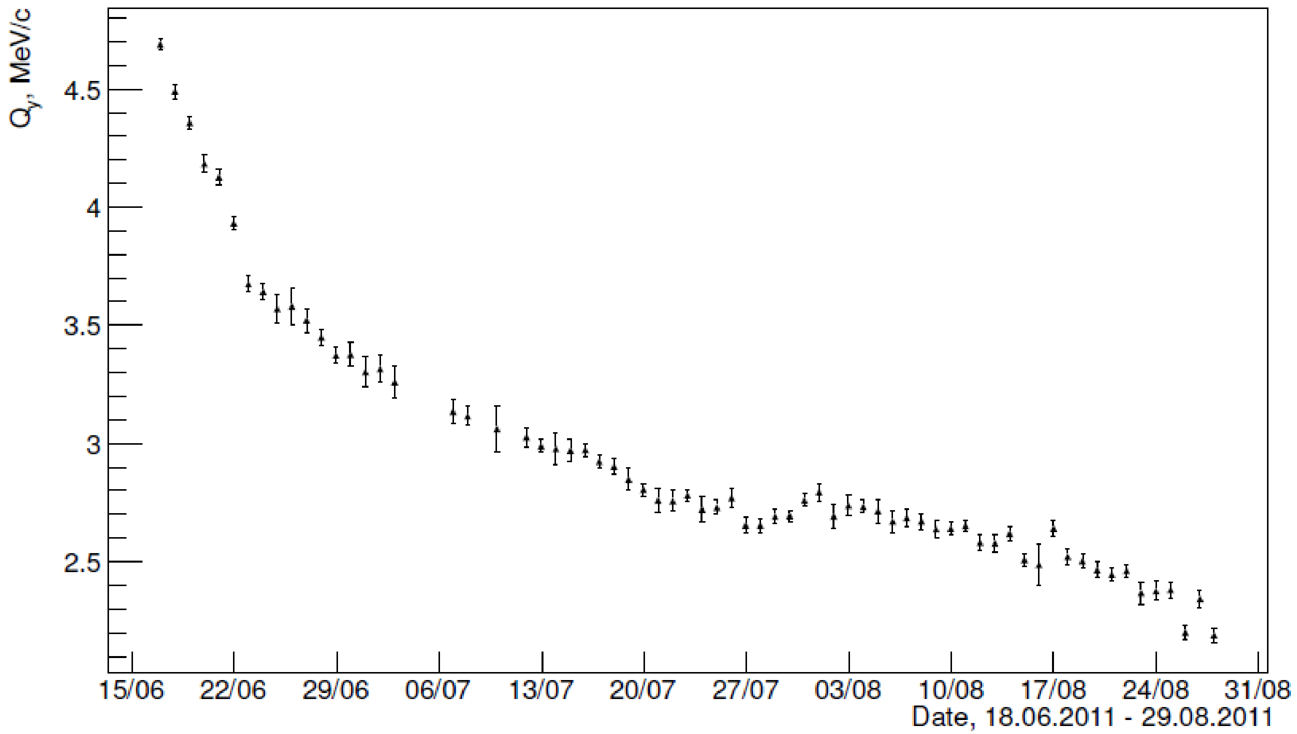
where: $$|\xi|^2 \approx \frac{F^2}{(E_{2p} - E_{2s})^2}$$

$$B_{\text{Lab}} = 4\ \text{Tesla} \quad \begin{cases} \gamma = 20\ , & |\xi| = 0.1 \quad \Longrightarrow \quad \tau_{\text{eff}} = \dfrac{\tau_{2p}}{2.2} \\ \gamma = 40\ , & |\xi| = 0.2 \quad \Longrightarrow \quad \tau_{\text{eff}} = \dfrac{\tau_{2p}}{6} \end{cases}$$

SPS (450 GeV) : yield of $A_{2\pi}$ and $A_{k\pi}$ will increase of a factor 20 per proton-nucleus interaction.

Thank you for your attention

Degradation of the permanent magnet in June - August 2011



The position of second peak in Q_Y distributions of e^+e^- pairs versus dates.