Precise predictions of low-energy QCD and their check by the DIRAC experiment

DImeson
Relativistic
Atomic
Complexes

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25 May 2006

Outline

- High-energy and low-energy QCD
- Precise predictions of low-energy QCD
- Experimental check of low-energy QCD predictions
- First lifetime measurement of the $\pi^+\pi^-$-atom
- The new experiment on the investigation of $\pi^+\pi^-$-atom and observation of πK-atoms at PS CERN
- Potentials of the DIRAC setup at SPS CERN, GSI CERN and J-PARC

DIRAC collaboration

75 Physicists from 18 Institutes

CERN
Geneva, Switzerland

Czech Technical University
Prague, Czech Republic

Institute of Physics ASCR
Prague, Czech Republic

Ioannina University
Ioannina, Greece

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

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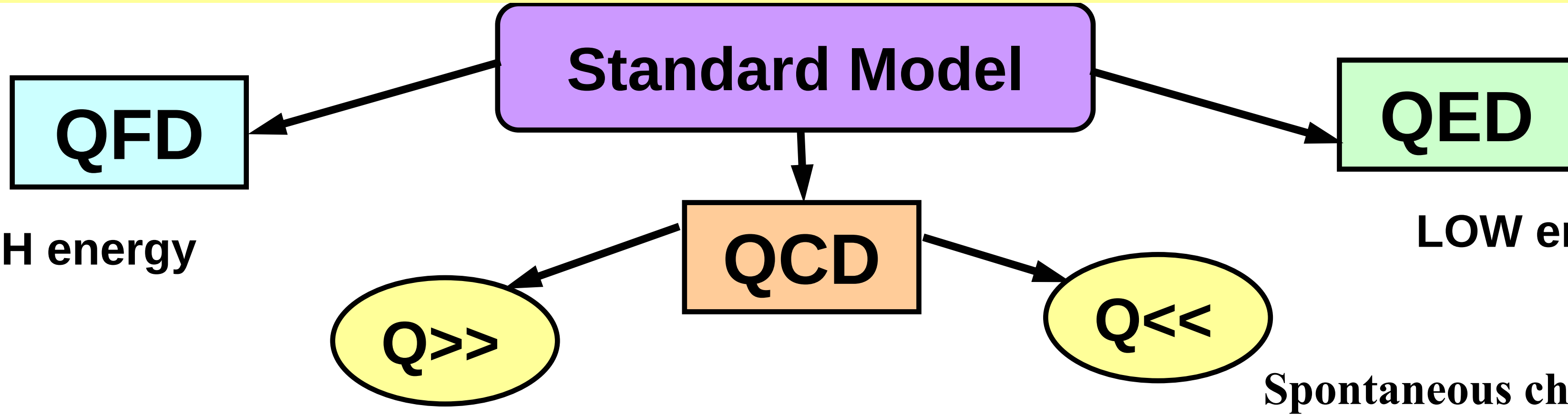
Theoretical motivation



HIGH energy

LOW energy

perturbative QCD

Spontaneous chiral symmetry breaking
(1967 – Weinberg)

QCD Lagrangian in presence of quark masses:

$$\mathcal{L}_{QCD(q,g)} = \mathcal{L}_{sym} + \mathcal{L}_{break\text{-}sym}$$

- high energy (small distance)
- “weak” interaction (asymptotic freedom)
- expansion in coupling

M, for large Q, depends only on: $\mathcal{L}_{sym}$

- low energy (large distance)
- strong interaction (confinement)
- expansion in momentum & mass

$$\mathcal{L}_{eff}(\pi,K,\eta) = \mathcal{L}_{sym} + \mathcal{L}_{break\text{-}sym}$$

M, for small Q, depends on both: $\mathcal{L}_{sym}$ and $\mathcal{L}_{break\text{-}sym}$ and q-condensate

At low energies, QCD is replaced by an effective quantum field theory (ChPT) formulated in terms of asymptotically observable fields like π, K, η

1979 – Weinberg 1984 – Gasser & Leutwyler

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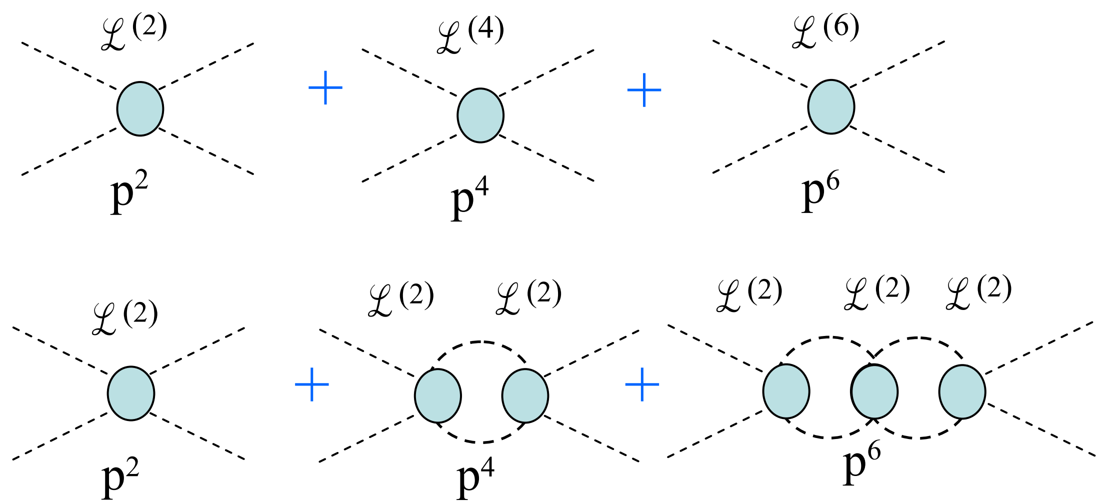
ChPT predictions for $\Delta = |a_0^0 - a_0^2|$

In ChPT effective Lagrangian $\mathcal{L}_{eff}$ is constructed as an expansion in powers of external momenta and of quark masses

$$\mathcal{L}_{\mathbf{eff}} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \mathcal{L}^{(6)} + \ldots$$



Tree | One loop | Two loops

1966 Weinberg (tree):	$\mathcal{L}^{(2)}$	$a_0 - a_2 = 0.20$	$a_0 = 0.159$ $a_2 = -0.045$
1984 Gasser-Leutwyler (1-loop):	$\mathcal{L}^{(4)}$	$a_0 - a_2 = 0.25 \pm 0.01$	$a_0 = 0.203$ $a_2 = -0.043$
1995 Knecht *et al.* (2-loop):	$\mathcal{L}^{(6)}$	Generalized ChPT	
1996 Bijnens *et al.* (2-loop):	$\mathcal{L}^{(6)}$	$a_0 - a_2 = 0.258 \pm (<3\%)$	$a_0 = 0.217$ $a_2 = -0.042$
2001 Colangelo *et al.* (& Roy):	$\mathcal{L}^{(6)}$	$a_0 - a_2 = 0.265 \pm 0.004$ (1.5%)	$a_0 = 0.220$ $a_2 = -0.044$

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ππ scattering lengths

Present low energy QCD predictions:

$$a_0 = 0.220 \pm 0.005\,(2.3\%)$$
$$a_2 = -0.0444 \pm 0.0010\,(2.3\%)$$
$$a_0 - a_2 = 0.265 \pm 0.004\,(1.5\%)$$

First result:

L. Rosselet *et al.*,
Phys. Rev. D15 (1977) 574

$a_0 = 0.28 \pm 0.05\,(18\%)$ using Roy eqs.

Results from E865/BNL: $K \to \pi^+\pi^- e^+\nu_e (K_{e4})$

S.Pislak *et al.*, Phys. Rev. Lett. 87 (2001) 221801
using Roy eqs.

$$a_0 = 0.203 \pm 0.033\,(16\%)$$
$$a_2 = -0.055 \pm 0.023\,(42\%)$$

using Roy eqs. and ChPT constraints $a_2 = f_{ChPT}(a_0)$

$$a_0 = 0.216 \pm 0.013\,(stat) \pm 0.004(syst) \pm 0.002\,(theor)$$
$$\delta a_0 = \pm 6\%\,(stat) \pm 2\%(syst) \pm 1\%\,(theor)$$

Results from NA48/2: $K^+ \to \pi^0\pi^0\pi^+$

$$(a_0 - a_2)m_\pi = 0.268 \pm 0.010\,(stat) \pm 0.004\,(syst)$$
$$\delta(a_0 - a_2) = \pm 3.7\%(stat) \pm 1.5\%(syst) \pm 5\%(theor)$$

DIRAC current results, 2001data

$$(a_0 - a_2)m_\pi = 0.264 \pm 7.5\%\,(stat)\,{}^{+3\%}_{-8\%}\,(syst)$$

DIRAC expected results, 2001–2003 data

$$\delta(a_0 - a_2) = \pm 5\%\,(stat)\,{}^{+3\%}_{-8\%}\,(syst)$$

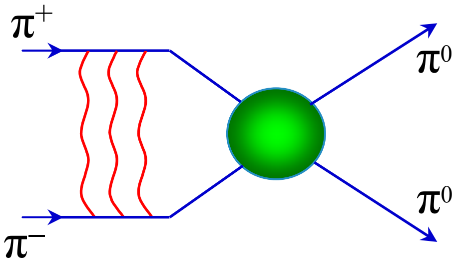
Upgraded DIRAC

$$\delta(a_0 - a_2) = \pm 2\%(stat) \pm 1\%(syst) \pm 1\%(theor)$$

Theoretical limits

1. $A_{2\pi}$ time of life

$$A_{2\pi} \to \pi^0 \pi^0 \qquad \Gamma(\pi^0\pi^0) = R_\pi (a_0 - a_2)^2 (1 + \delta_\pi)$$



H. Jalloul, H.Sazdjian 1998

M.A. Ivanov et al. 1998

A. Gashi et al. 2002

J. Gasser et al. 2001 $\rightarrow \delta_\pi = (5.8 \pm 1.2) \cdot 10^{-2}$

Current limit for accuracy in scattering lengths measurement from the $A_{2\pi}$ lifetime $\frac{\Delta |a_0 - a_2|}{|a_0 - a_2|} = 0.6\%$

2. $A_{2\pi}$ interaction with matter

L.Afanasyev, G.Baur, T.Heim, K.Hencken, Z.Halabuka, A.Kotsinyan, S.Mrowczynski, C.Santamarina, M.Schumann, A.Tarasov, D.Trautmann, O.Voskresenskaya from Basel, JINR and CERN

Current limit for accuracy in scattering lengths measurements due to accuracy in $P_{br}(\tau)$ $\frac{\Delta |a_0 - a_2|}{|a_0 - a_2|} = 1.2\%$

This value will be reduced by a factor of 2

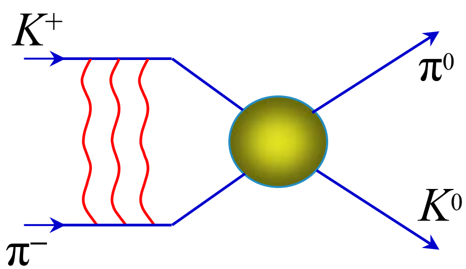
Theoretical limits

$A_{K^+\pi^-}$ and $A_{K^+\pi^-}$ time of life

$$A_{K^+\pi^-} \to \pi^0 K^0$$

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

$$\Gamma(\pi K) = R_K \, |a_{1/2} - a_{3/2}|^2 \, (1 + \delta_K)$$



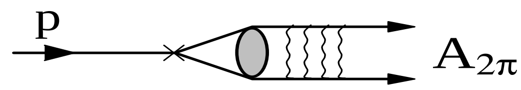
$$\delta_K = (4.0 \pm 2.2) \cdot 10^{-2} \qquad \frac{\Delta |a_{1/2} - a_{3/2}|}{|a_{1/2} - a_{3/2}|} = 1.1\%$$

J. Schweizer (2004)

Production of pionium

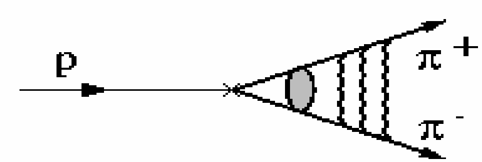
Atoms are Coulomb bound state of two pions produced in one proton-nucleus collision

$$\frac{d\sigma_{nlm}^{A}}{d\vec{P}} = (2\pi)^3 \frac{E_A}{M_A} \left|\psi_{nlm}^{(C)}(0)\right|^2 \frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}\bigg|_{\vec{p}_+=\vec{p}_-}$$



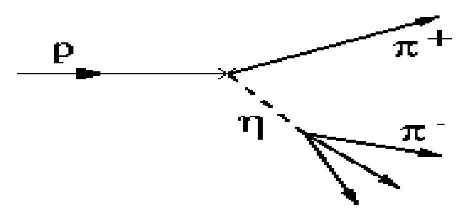
Background processes:

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

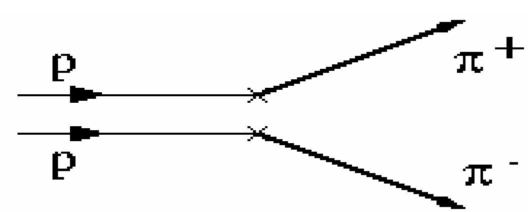


$$\frac{d^2\sigma_C}{d\vec{p}_+ d\vec{p}_-} = A_C(q) \frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}, \qquad A_C(q) = \frac{2\pi m_\pi \alpha / q}{1 - \exp(-2\pi m_\pi \alpha / q)}$$

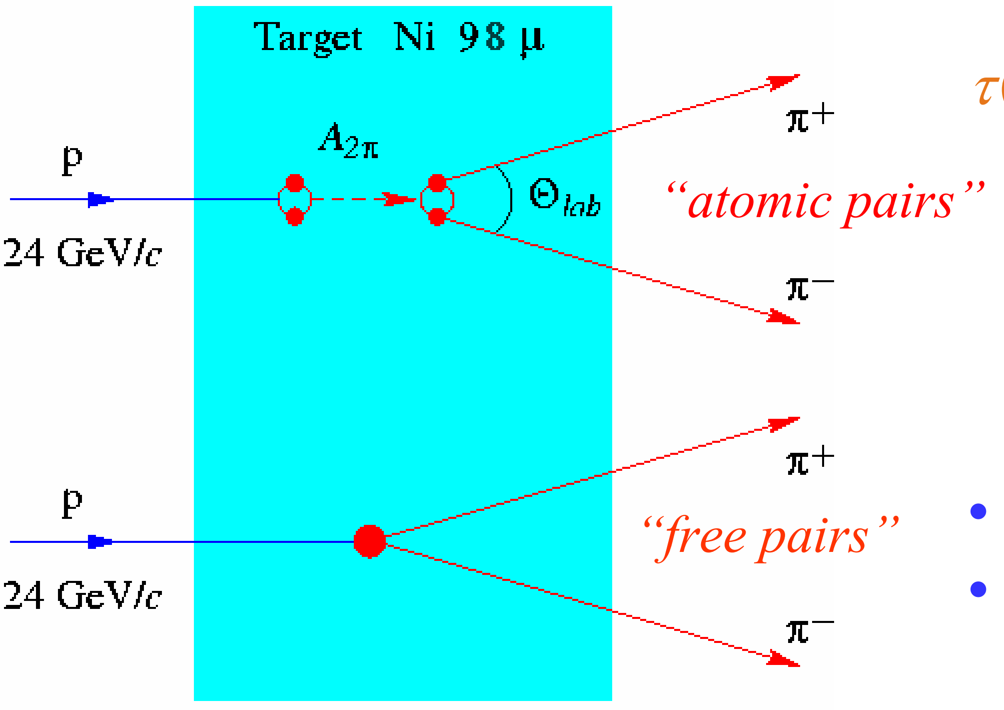
Non-Coulomb pairs. They are produced in one proton nucleus collision. At least one pion originates from a long lived resonance. No Coulomb interaction in the final state



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



Method of $A_{2\pi}$ observation and lifetime measurement



L. Nemenov, Sov. J. Nucl. Phys. (1985)

$\tau(A_{2\pi})$ too small to be measured directly

e.m. interaction of $A_{2\pi}$ in the target

$A_{2\pi} \rightarrow \pi^+\pi^-$

$Q < 3MeV/c \quad E_+ \approx E_- \quad \Theta_{lab} < 2.5\ mrad$

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

First observation of $A_{2\pi}$ have been done by the group from JINR, SINP MSU and IHEP at U-70 Protvino Afanasyev L.G. et al., Phys.Lett.B, 1993.

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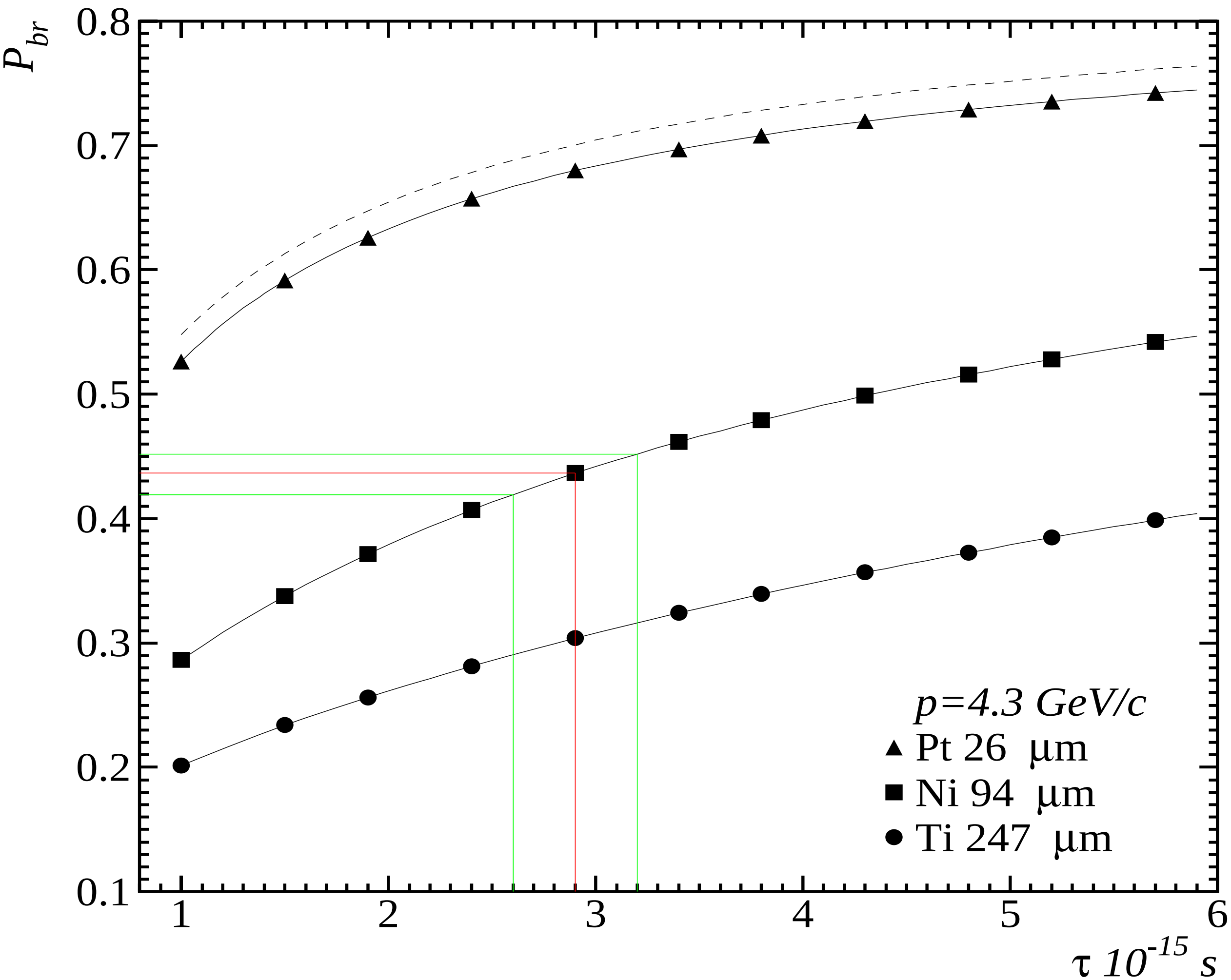
Break-up probability

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

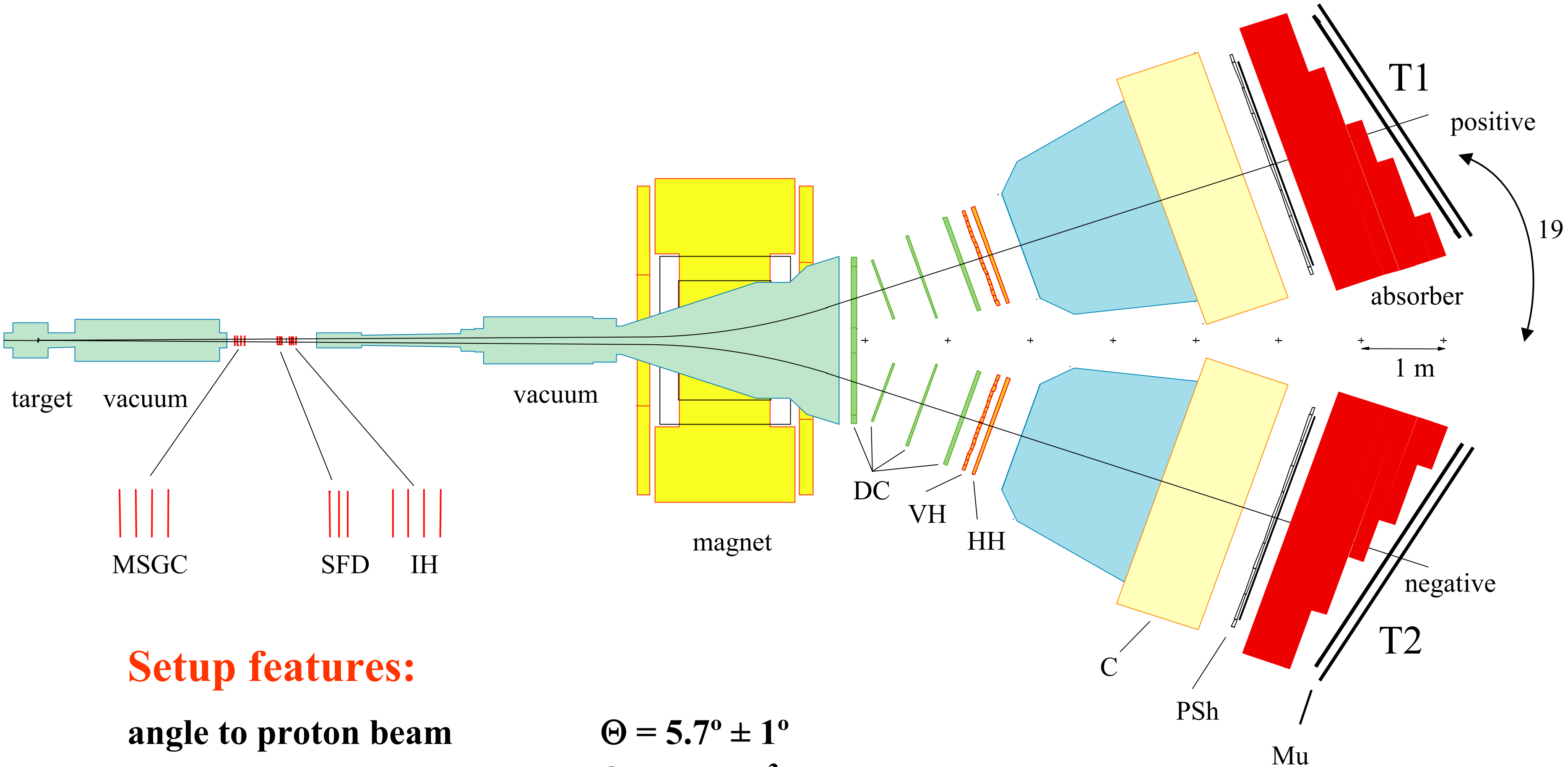


All targets have the same thickness in radiation lengths $6.7*10^{-3}$ X_0

There is an optimal target material for a given lifetime

The detailed knowledge of the cross sections (Afanasyev&Tarasov; Trautmann et al) (Born and Glauber approach) together with the accurate description of atom interaction dynamics (including density matrix formalism) permits us to know the curves within 1%.

DIRAC set-up



Setup features:

angle to proton beam $\Theta = 5.7^{o} \pm 1^{o}$

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

dipole magnet B = 1.65 T, BL = 2.2 Tm

momentum range $1.2 \leq p_{\pi} \leq 8$ GeV/c

momentum resolution $\Delta p/p \approx 3 \cdot 10^{-3}$

resolution on relative momentum

$\sigma Q_x \approx \sigma Q_y \leq 0.5$ MeV/c,

and $\sigma Q_L \approx 0.5$ MeV/c

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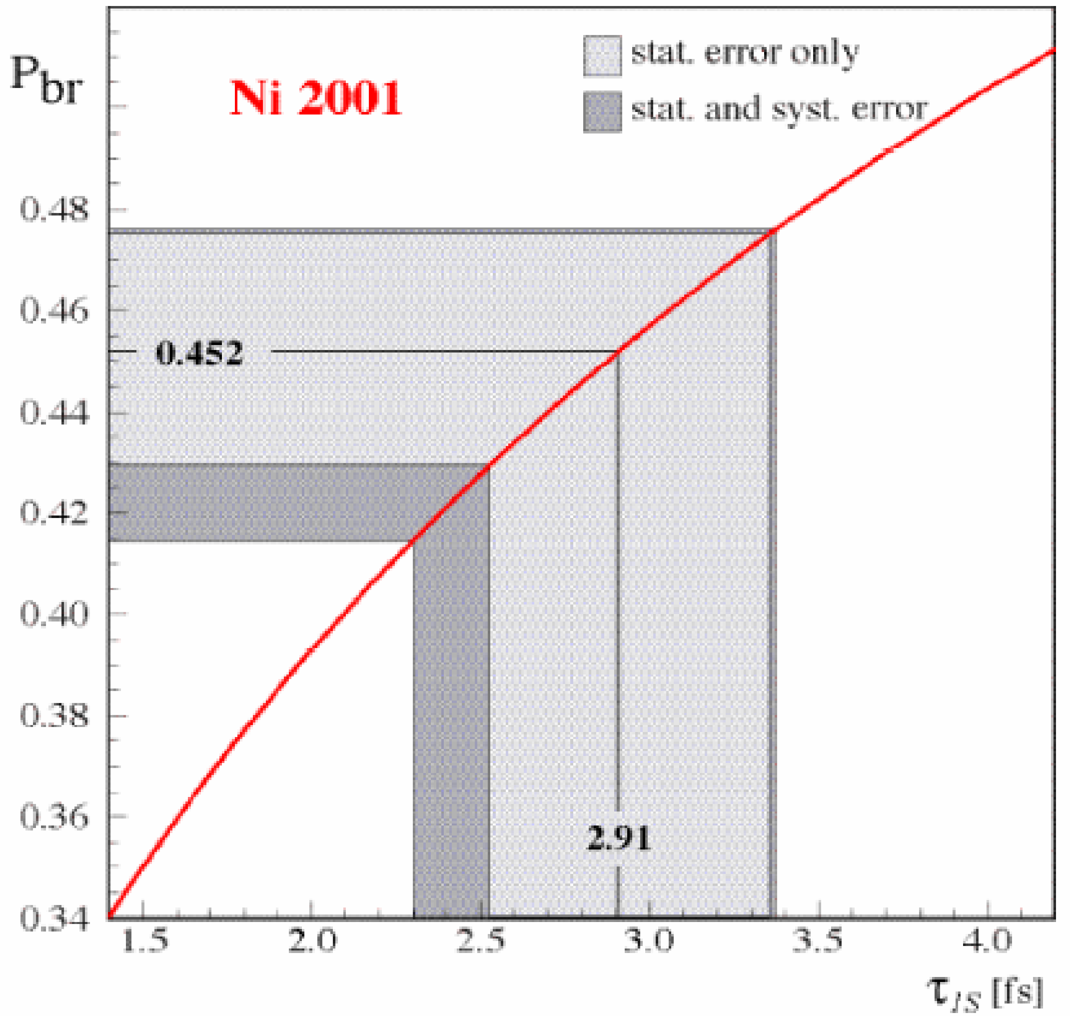
Lifetime of Pionium



Result from DIRAC:

$$\tau = \left(2.91 \begin{matrix} +0.45 \\ -0.38 \end{matrix}\Big\}_{stat} \begin{matrix} +0.19 \\ -0.49 \end{matrix}\Big\}_{syst}\right) \times 10^{-15}\,\mathrm{s}$$

$$|a_0 - a_2| = 0.264^{+0.033}_{-0.020}\, m_\pi^{-1}$$

ChPT prediction:

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

$$a_0 - a_2 = 0.265 \pm 0.004$$

DIRAC analysis

Results for the lifetime: $\tau_{1S} = 2.91 \begin{matrix}+0.45\\-0.38\end{matrix}\Big\}_{stat} \begin{matrix}+0.19\\-0.49\end{matrix}\Big\}_{syst} = 2.91 \begin{matrix}+0.49\\-0.62\end{matrix} \ [fs]$ $\tau_{1S}^{ChPT} = 2.9 \pm 0.1 \ [fs]$

Result for scattering lengths: $|a_0 - a_2| = 0.264 \begin{matrix}+0.033\\-0.020\end{matrix} \ [m_\pi^{-1}]$ $|a_0 - a_2|_{ChPT} = 0.265 \pm 0.004 \ [m_\pi^{-1}]$

Improvements with full statistics

Number of Atomic pairs (approx.)									
	Pt1999 24 GeV	Ni2000 24 GeV	Ti2000 24 GeV	Ti2001 24 GeV	Ni2001 24 GeV	Ni2002 20 GeV	Ni2002 24 GeV	Ni2003 20 GeV	Sum
Sharp selection	280	1300	900	1500	**6500**	3000	4500	1400	**19400**
Downstream only									**27000**

$$\left.\frac{\sigma_{P_{br}}}{P_{br}}\right|_{stat}^{now} = 0.051 \Rightarrow \left.\frac{\sigma_{P_{br}}}{P_{br}}\right|_{stat}^{full\ statistics} = 0.03 \Rightarrow \left.\frac{\delta\,|a_0 - a_2|}{a_0 - a_2}\right|_{stat} = 5\%$$

as in the project

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

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

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

πK scattering

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

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

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

A. Rossel. – 1999

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

J. Bijnens, P. Talaver. – April 2004

II. Roy-Steiner equations:

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

III. $A_{\pi K}$ lifetime:

$$A_{\pi^+ K^-} \to \pi^0 \bar{K}^0 \quad (A_{K^+ \pi^-} \to \pi^0 K^0)$$

$$\Gamma(\pi^0 \bar{K}^0) \sim |a_0^{1/2} - a_0^{3/2}|^2$$

precision~1%

J. Schweizer. – 2004

$$\tau = (3.7 \pm 0.4) \cdot 10^{-15}\ \text{s}$$

Main goals and time scale for the $A_{2\pi}$ and $A_{\pi K}$ experiments

Manufacture of all new detectors and electronics: 18 months
Installation of new detectors: 3 months

2006
Test of the Upgraded setup and calibration: 4 months
Observation $A_{2\pi}$ in the long-lived states.

2007 and 2008
Measurement of $A_{2\pi}$ lifetime: 12 months

In this time 86000 $\pi\pi$ atomic pairs will be collected to estimate $A_{2\pi}$ lifetime with precision of:

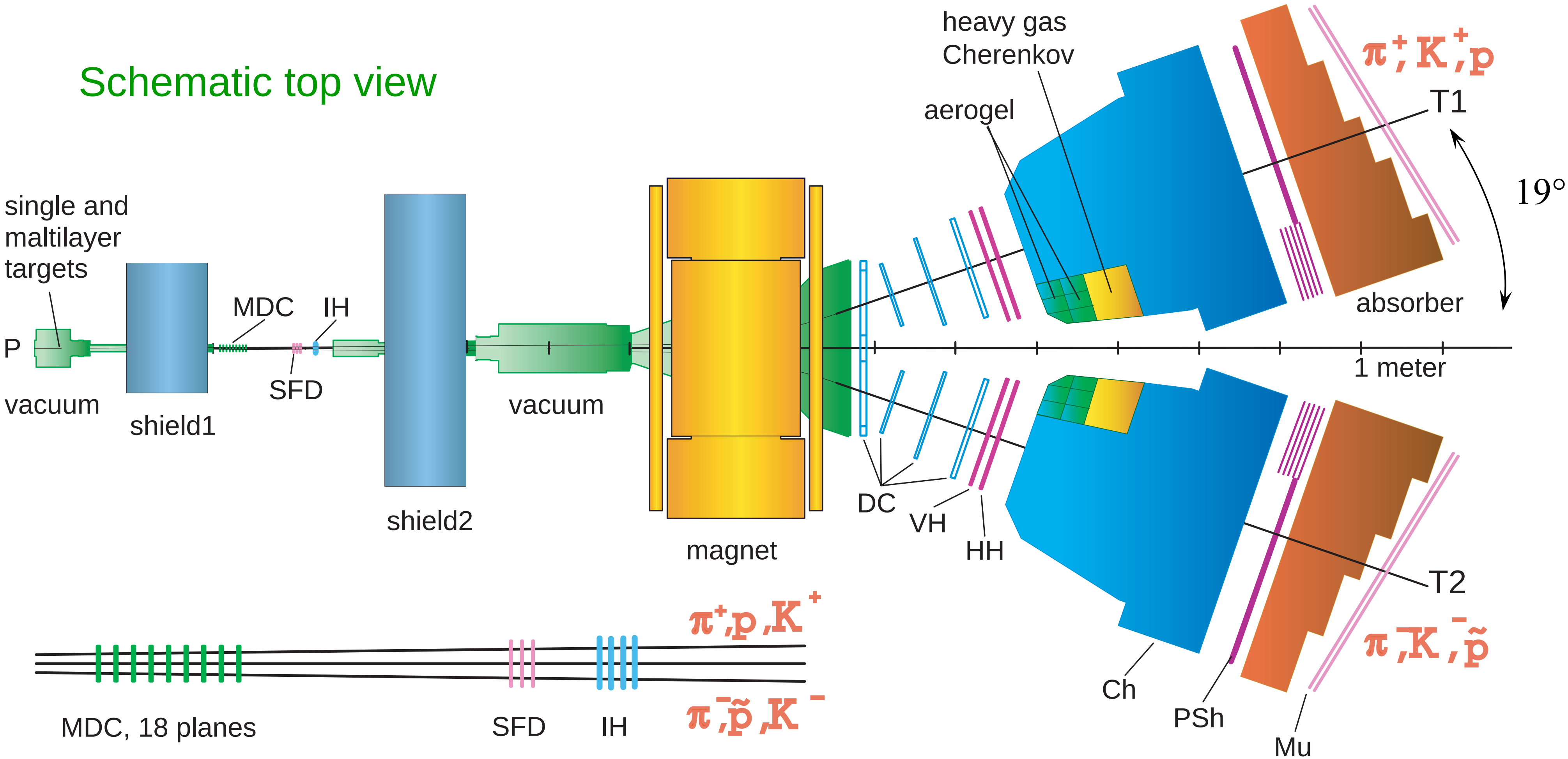
$$\frac{\sigma_\tau}{\tau} = 6\%, \qquad \frac{\sigma(a_0 - a_2)}{a_0 - a_2} = 3\%$$

At the same time we also plan
to observe $A_{\pi K}$ and $A_{K\pi}$;
to detect 5000 πK atomic pairs to estimate $A_{\pi K}$ lifetime with precision of:

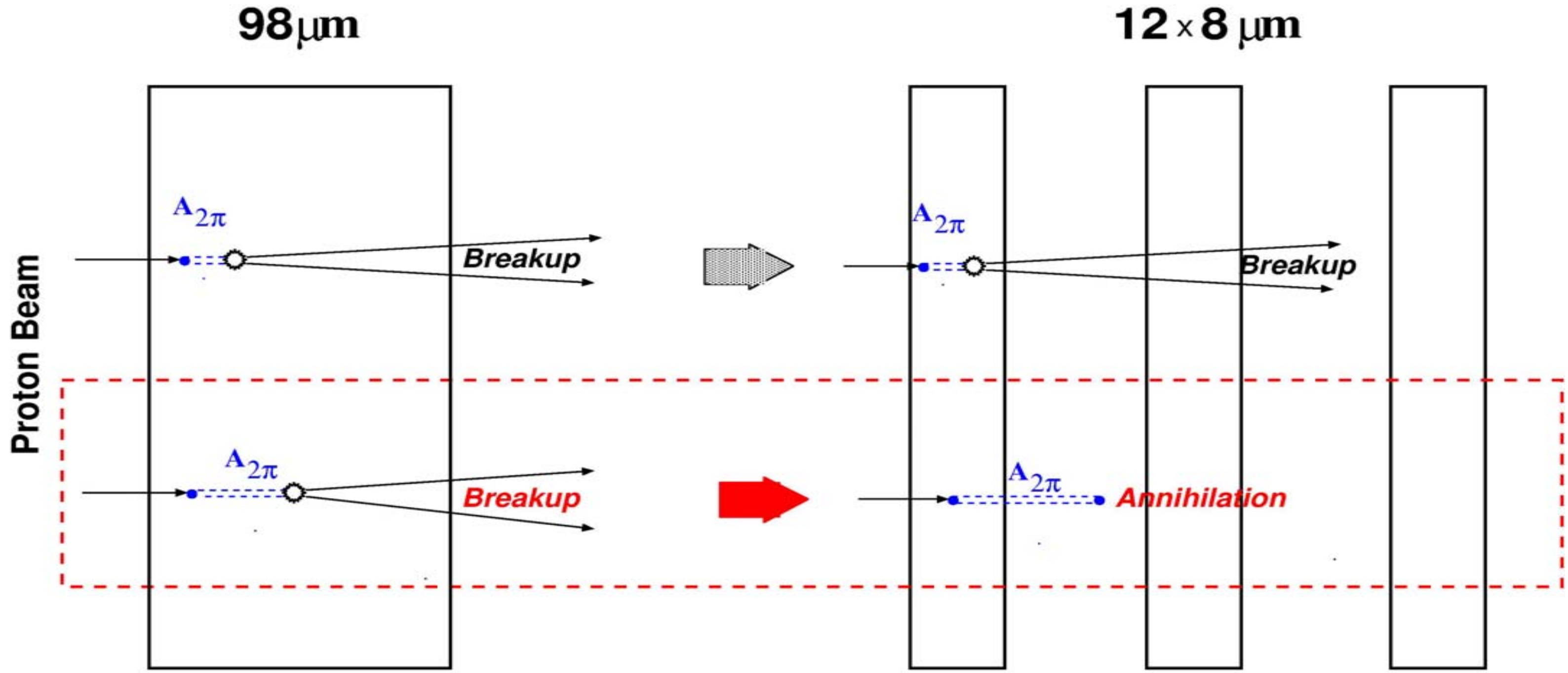
$$\frac{\sigma_\tau}{\tau} = 20\%, \qquad \frac{\sigma(a_{1/2} - a_{3/2})}{a_{1/2} - a_{3/2}} = 10\%$$

This estimation of the beam time is based on the $A_{2\pi}$ statistics collected in 2001 and on the assumption of having 2.5 spills per supercycle during 20 hours per day.

Upgrade DIRAC experimental set-up description



Dual Target Method



- Single/Multilayer target comparison:
  - Same amount of multiple scattering
  - Same background (CC, NC, ACC)
  - Same number of produced $A_{2\pi}$, but lower number of dissociated pairs

Conclusions

Present low-energy ***QCD*** predictions for ***ππ*** and ***πK*** scattering lengths

$\pi\pi \quad \delta a_0 = 2.3\% \qquad \delta a_2 = 2.3\% \qquad \delta(a_0 - a_2) = 1.5\%$

$\pi K \quad \delta(a_{1/2} - a_{3/2}) \approx 10\%$

Expected results of DIRAC ADDENDUM at PS CERN

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

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

Observation of metastable $A_{2\pi}$

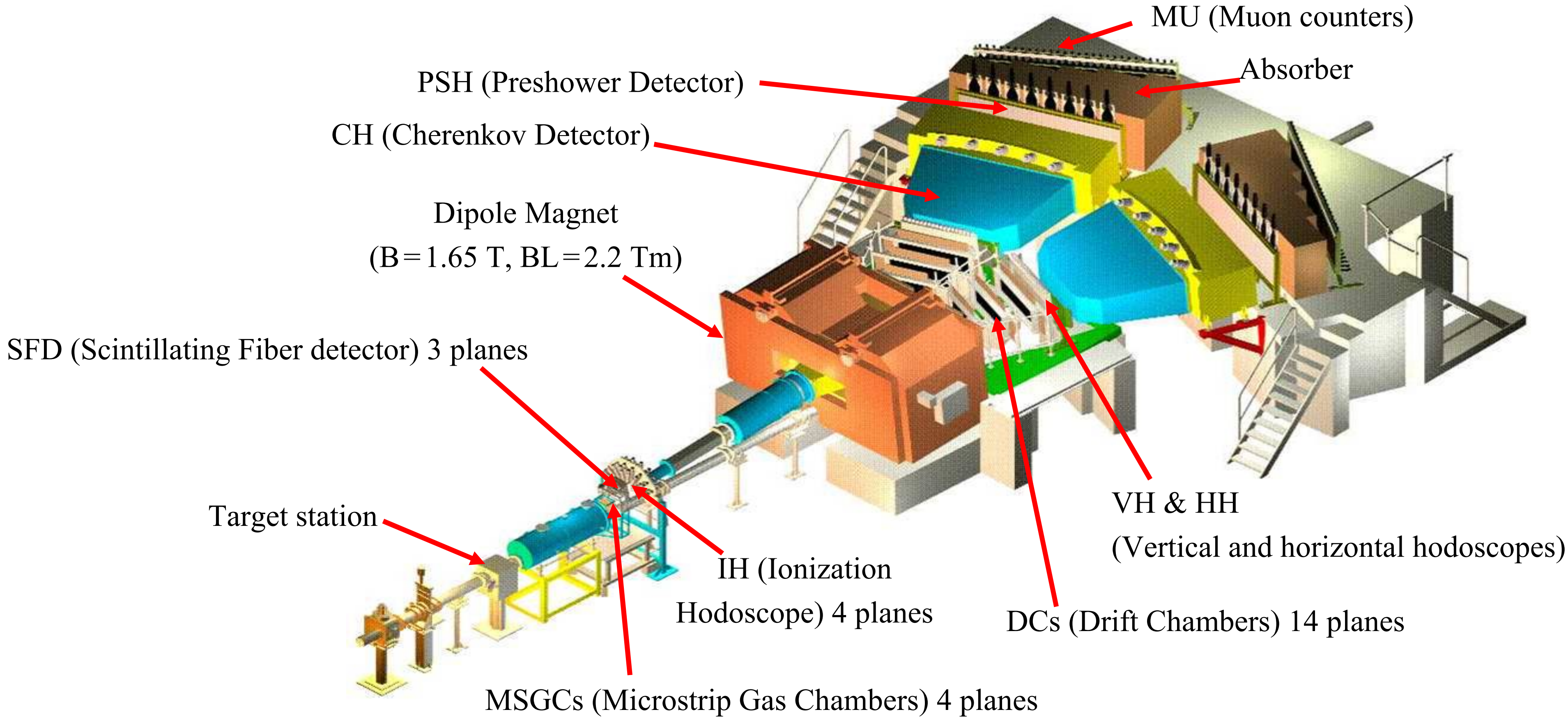
DIRAC at SPS CERN

$$\tau(A_{2\pi}) \to \delta(a_0 - a_2) = \pm 0.5\%(stat) \pm 1\%(syst) \pm 1\%(theor)$$

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

Possibility of the observation of $(\pi^{\pm}\mu^{\mp})$ – atoms and of (K^+K^-) – atoms will be studied

DIRAC isometric view



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

momentum range $1.2 \leq p_{\pi} \leq 8$ GeV/c

momentum resolution $\Delta p/p \approx 3 \cdot 10^{-3}$

resolution on relative momentum

$\sigma Q_x \approx \sigma Q_y \leq 0.5$ MeV/c,

and $\sigma Q_L \approx 0.5$ MeV/c

Upstream:

MSGC, SFD,IH

Downstream:

DC, VH, HH, Ch, PSh, Mu

Experimental status on πK

In the 60's and 70's, set of experiments were performed to measure πK scattering amplitudes. Most of them were done studying the inelastic scattering of kaons on protonsor neutrons, and later also on deuterons.

The kaon beams used in these experiments had energies ranging from 2 to 13 GeV.

The main idea of those experiments was to determine the contribution of the One Pion Exchange (OPE) mechanism. This allows to obtain the πK scattering amplitude.

Analysis of experiments gave the phases of πK-scattering in the region of $0.7 \leq m(\pi K) \leq 2.5$ GeV.

The most reliable data on the phases belong to the region $1 \leq m(\pi K) \leq 2.5$ GeV.