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Antikaon bound states and meson spectroscopy with stopped antiprotons

Johann Zmeskal, SMI Vienna

FLAIR Meeting
Cockcroft Institute
February 21, 2011

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FLAIR Meeting

Outline

- Physics motivation
- Search for antikaon nuclear bound systems
- Antiproton annihilation to produce strangeness
- Experimental setup

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Physics motivation

Physics Motivation

- information on the modification of the kaon mass and antiK-N interaction in a nuclear medium, important for further understanding of spontaneous and explicit symmetry breaking of QCD

- gain information on the transition from the hadronic phase to a quark-gluon phase
  $\rightarrow$ changes of vacuum properties of QCD and the quark condensate

- kaon condensation in a nuclear medium

- nuclear dynamics under extreme conditions could be investigated (e.g. nuclear compressibility)

Low-energy QCD

• The low-energy interactions of the lightest pseudoscalar mesons (pions and kaons) with nuclear systems are largely dictated by the spontaneously broken chiral symmetry of QCD.

• In the limit of mass-less up, down and strange quarks, pions and kaons would emerge as mass-less Goldstone bosons. The explicit symmetry breaking induced by the small *u− and d−quarks masses* ($m_{u,d}$ < 10 MeV), moves the pion mass to its empirical (small) value.

• The strange quark mass, $m_s \sim 0.1$ *GeV*, can still (with caution) be considered small compared to the spontaneous chiral symmetry breaking scale and therefore deeply bound states of kaons in the strong fields of a nucleus represent ideal conditions for investigating the way in which the spontaneous and explicit chiral symmetry breaking pattern of low-energy QCD changes in a nuclear environment.

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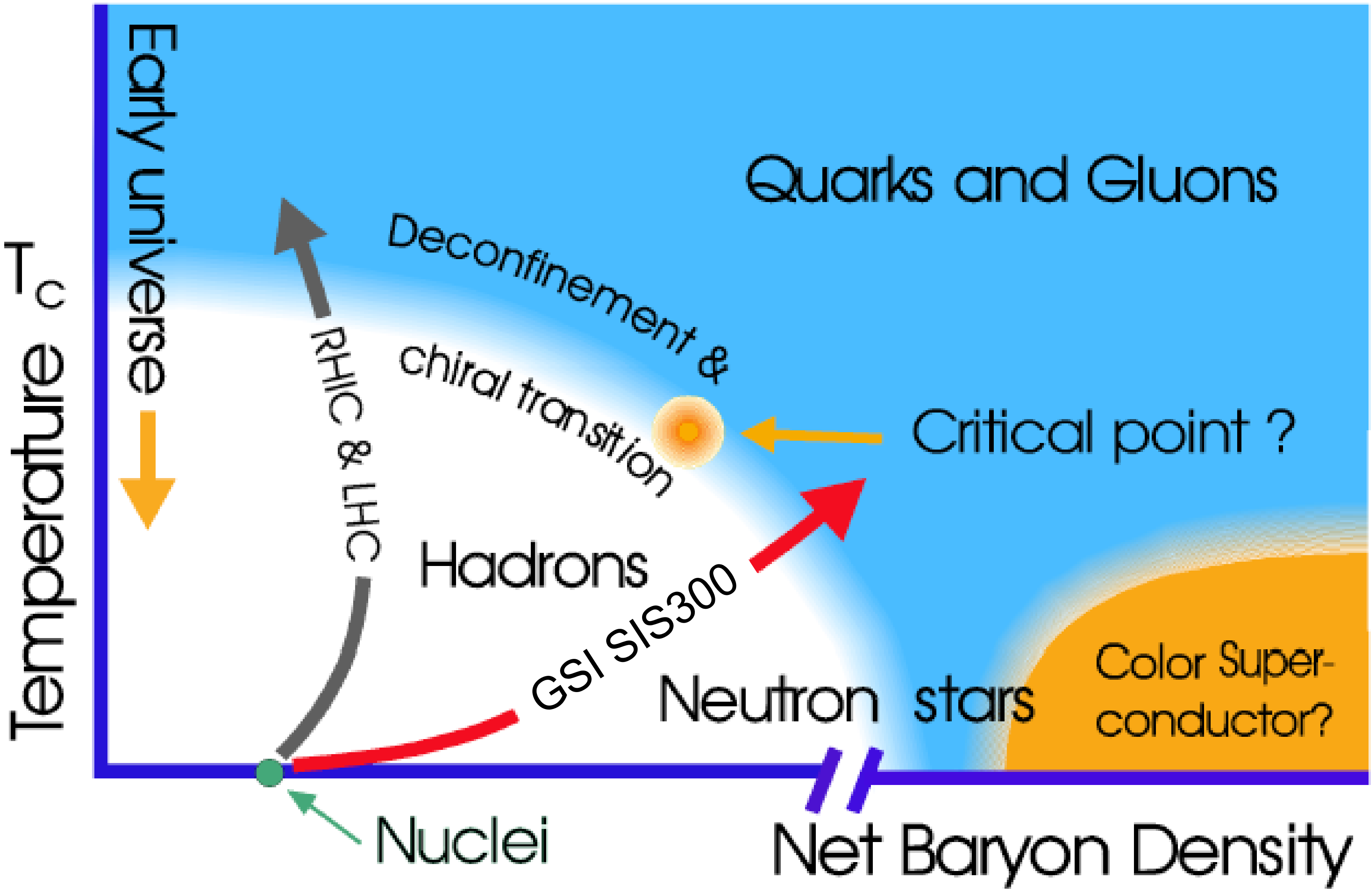
Exploring dense nuclei with K^- bound states



Antikaon-mediated deeply bound nuclear states

Physics Motivation

- **Deeply bound kaonic nuclear states** in presence of a strong antiK-N attractive potential were firstly suggested by Wycech (*Nucl. Phys. A450 (1986)).*

- A further important step in strangeness nuclear physics can be considered the work by Y.Akaishi, T.Yamazaki (*Phys. Rev.* ***C65*** *(2002) 044005)* and by P. Kienle and W. Weise

→ *Strong attractive I=0 antiK-N interaction favors discrete nuclear states bound to ~ 100 MeV with (narrow) width of 30-70 MeV (still under discussion!).*

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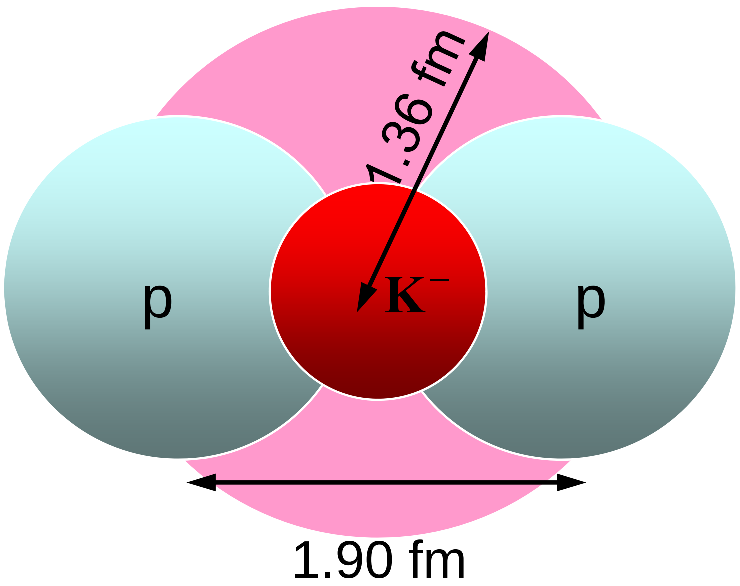
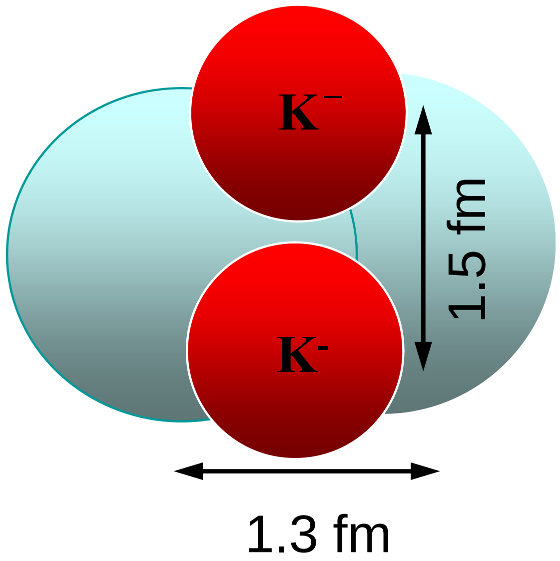
Antikaon bound nuclear cluster

ppK^-



Strange deuteron?

$ppK^- K^-$



$\bar{u}s$

uud   uud

$\bar{u}s$

uuddss

Jaffe's H* di-baryon?

Antikaon bound nuclear cluster

Production of KNC

- stopped K^- reactions on light nuclei
- in-flight K^- reactions
- protons on N
- heavy ion collisions
- stopped antiproton annihilation at rest

→ identification and study of antikaon nuclear cluster by performing an exclusive measurement

formation - missing mass

decay - invariant mass

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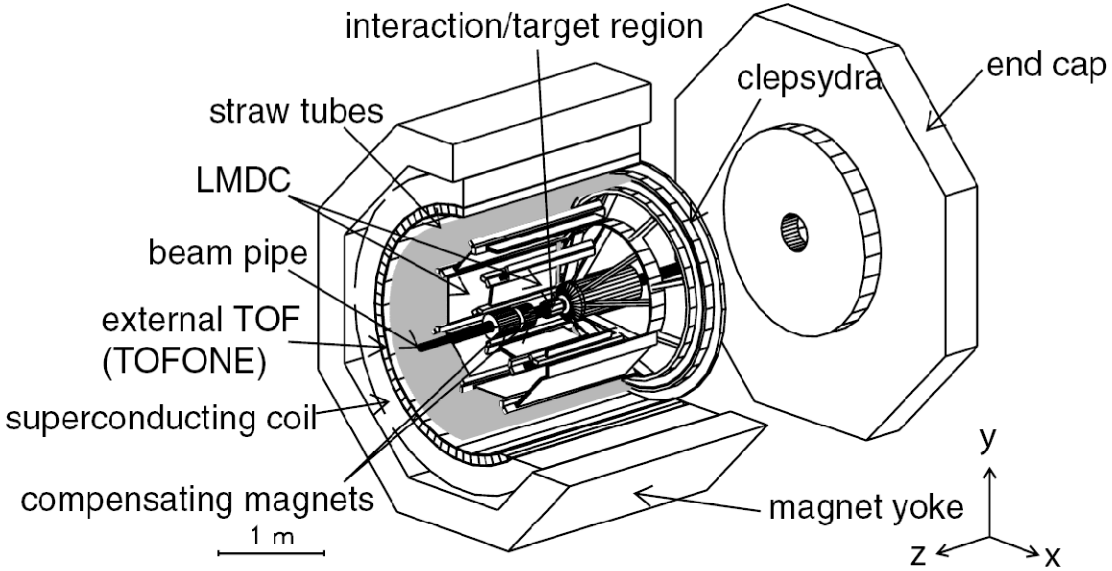
Antikaon bound nuclear cluster

FINUD data analysis

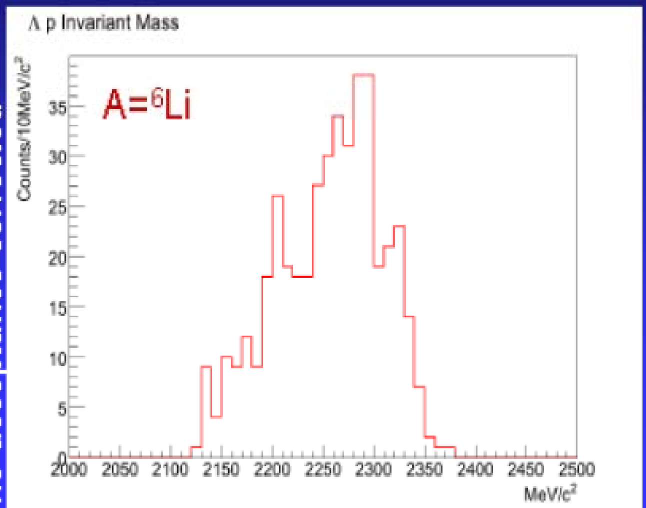
(LN Frascati)



2006-07 data

2003-04 data

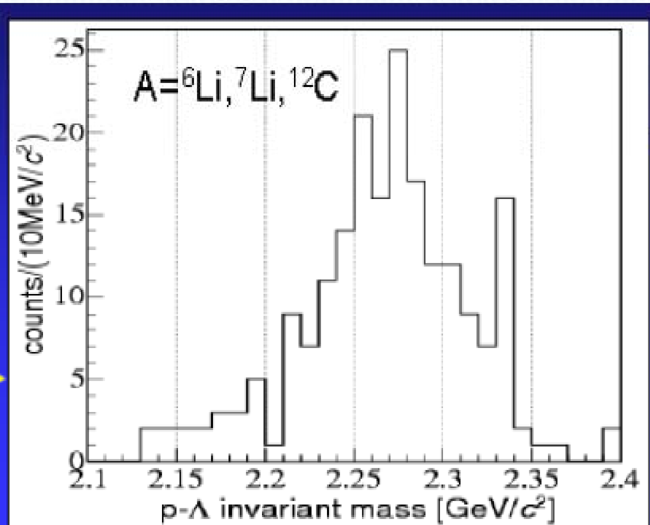
no acceptance corrected



New
inv mass spectra
compatible with
published one

New data ⟷ Old data

Same cuts applied



no acceptance corrected

FINUDA Coll., PRL 94(2005)212303

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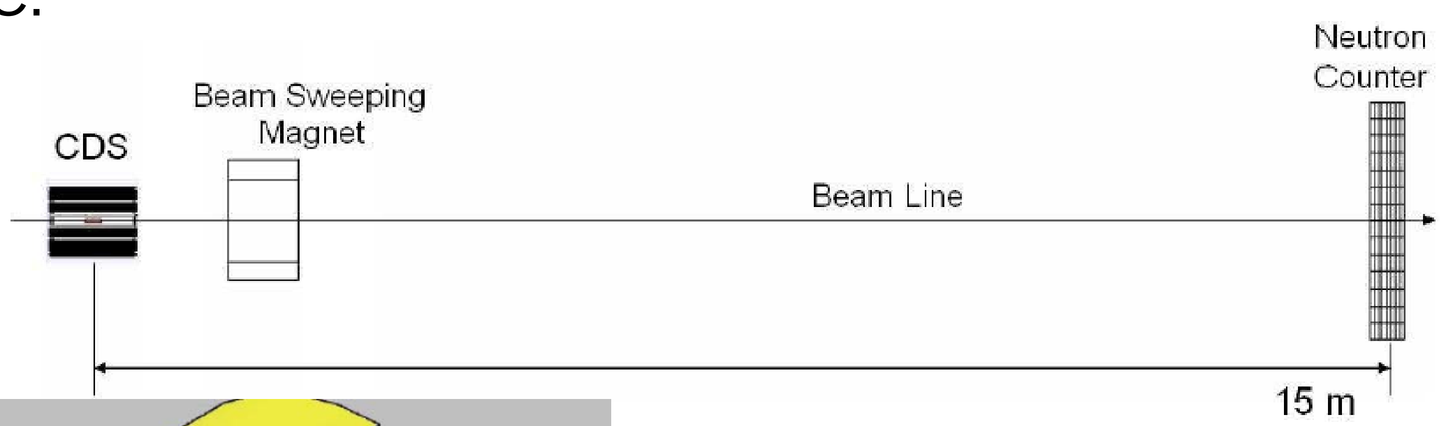
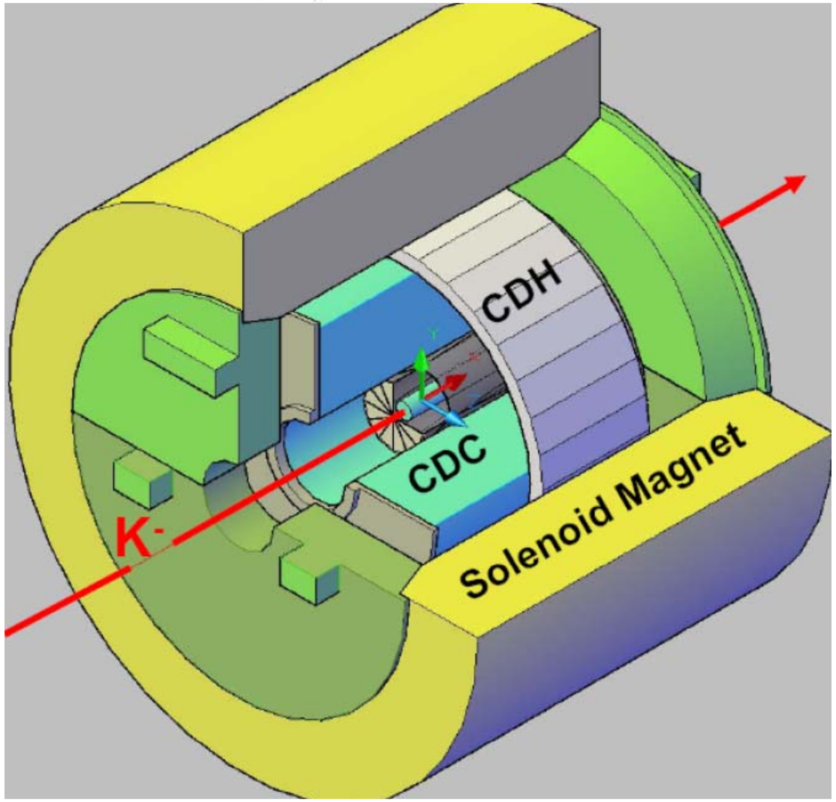
J-PARC E15

Search for ppK$^-$ at the K1.8 (K$^-$ momentum 1.8 GeV/c) beam line at J-PARC.





$$K^- + {}^3He \rightarrow ppK^- + n$$

$$ppK^- \rightarrow \Lambda^0 + p \rightarrow p + \pi^- + p$$

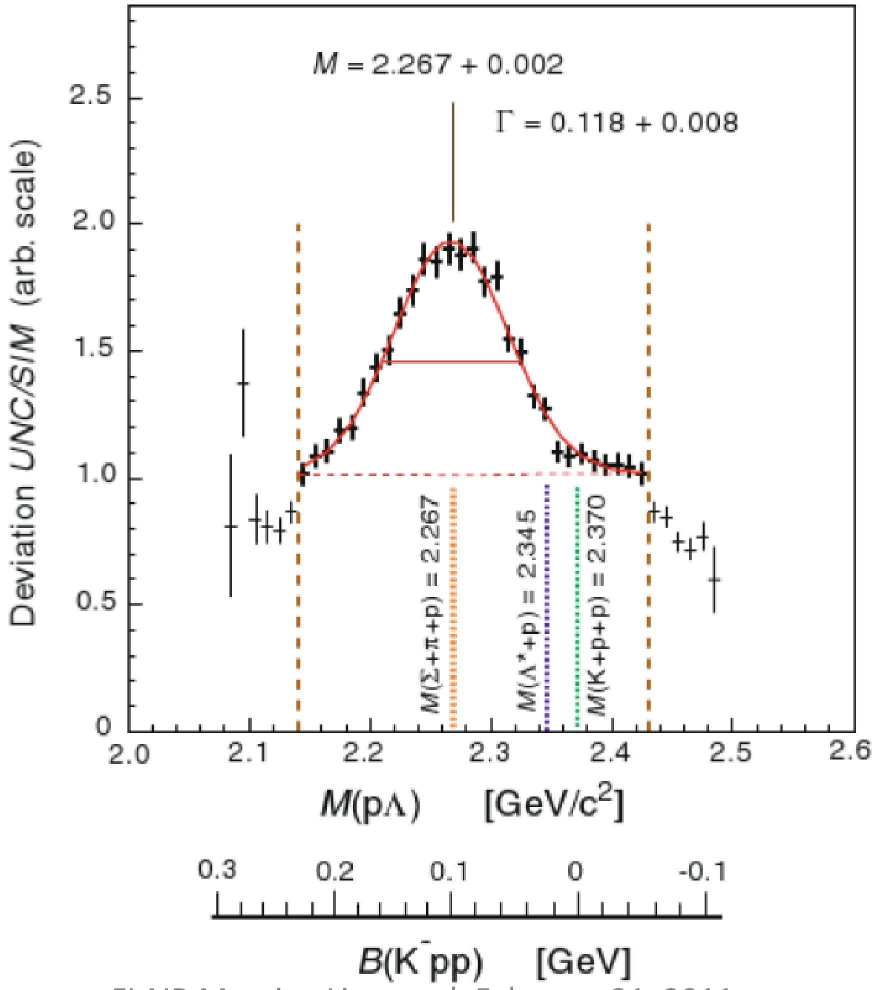
Search for deeply bound KNC

DISTO data analysis
(SATURNE, Saclay)

PRL 104, 132502 (2010) PHYSICAL REVIEW LETTERS week ending 2 APRIL 2010

Indication of a Deeply Bound and Compact K⁻ pp State Formed in the pp • p• K⁺ Reaction at 2.85 GeV

T. Yamazaki,[1,2] M. Maggiora,[3] P. Kienle,[4,5] K. Suzuki,[4] A. Amoroso,[3] M. Alexeev,[3] F. Balestra,[3] Y. Bedfer,[6] R. Bertini,[3,6]
L. C. Bland,[7] A. Bren ... oni,[3] R. Dressler,[9] M. Dzemidzic,[7]
J.-Cl. Faivre,[6] L. Ferre ... Grasso,[3] S. Heinz,[3,6] W. W. Jacobs,[7]
W. Kühn,[8] A. Maggic ... Ritman,[8] P. Salabura,[10] S. Sosio,[3]



Search for ppK$^-$ with FOPI

Search for deeply bound KNC

Search for the most fundamental KNC, namely K$^-$pp, by using the following reaction:

$$p + p \rightarrow K^+ + X$$

where *X* undergoes a successive decay:

$$X = K^-pp \rightarrow \Lambda + p \rightarrow [p + \pi-] + p$$

in this two-body reaction one can obtain information on *X* from both the missing mass and invariant mass:

$$M_X = MM(pp - K^+)$$
$$M_X = Minv(\Lambda - p)$$

→ **experiment performed at GSI 2009**

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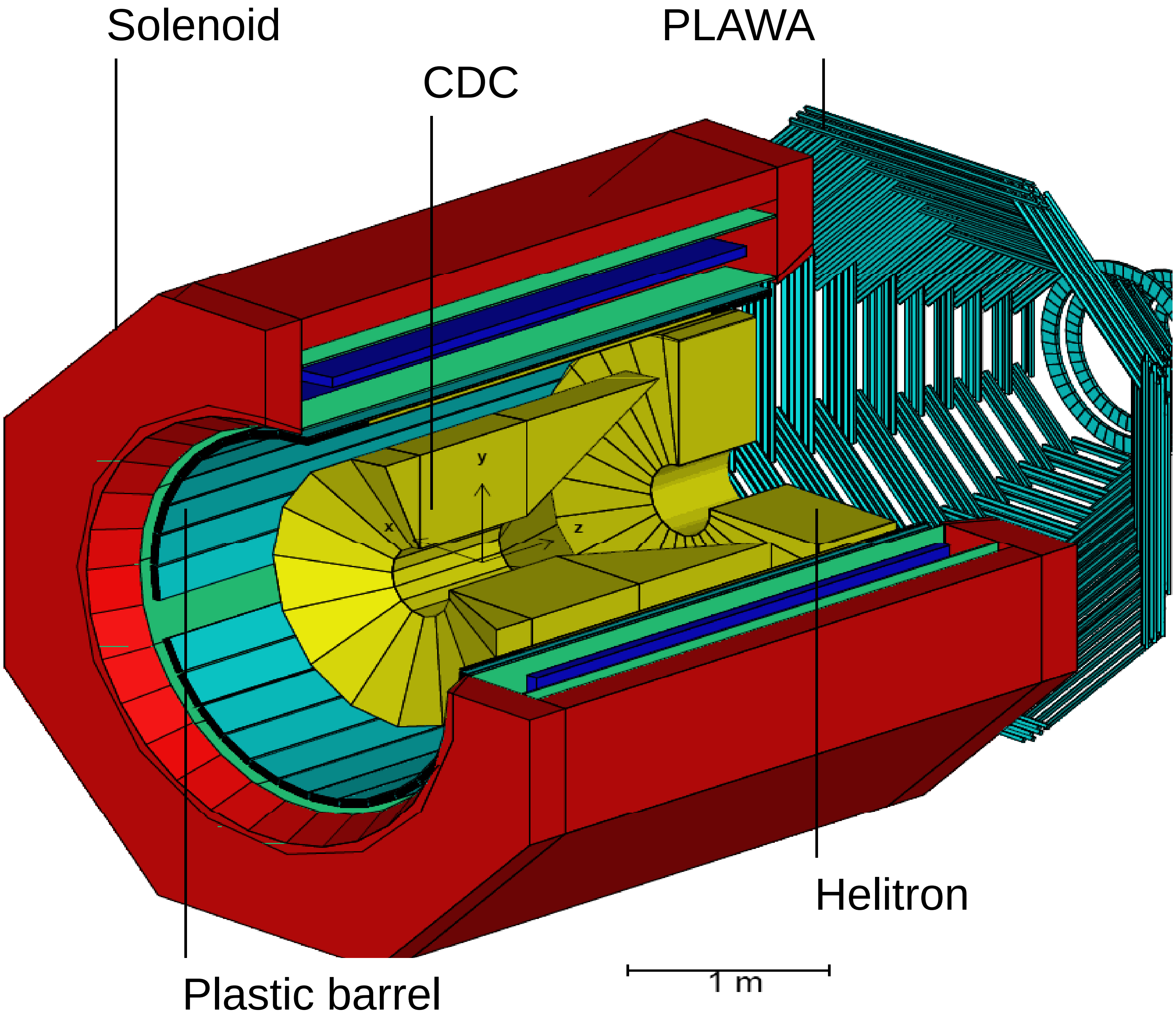
Search for ppK^{-} with FOPI



Search for deeply bound KNC

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Experimental programme of AMADEUS

- study of the most fundamental antikaon deeply bound nuclear systems, the **kaonic dibaryon states: ppK⁻ and (pnK⁻)** produced in a ^{3}He gas target

- as next step, the **kaonic 3-baryon states: ppnK⁻ and pnnK⁻** produced in a ^{4}He gas target

- in addition, we plan to extend these studies systematically over a broad range of nuclear targets, like **Li, B and Be**

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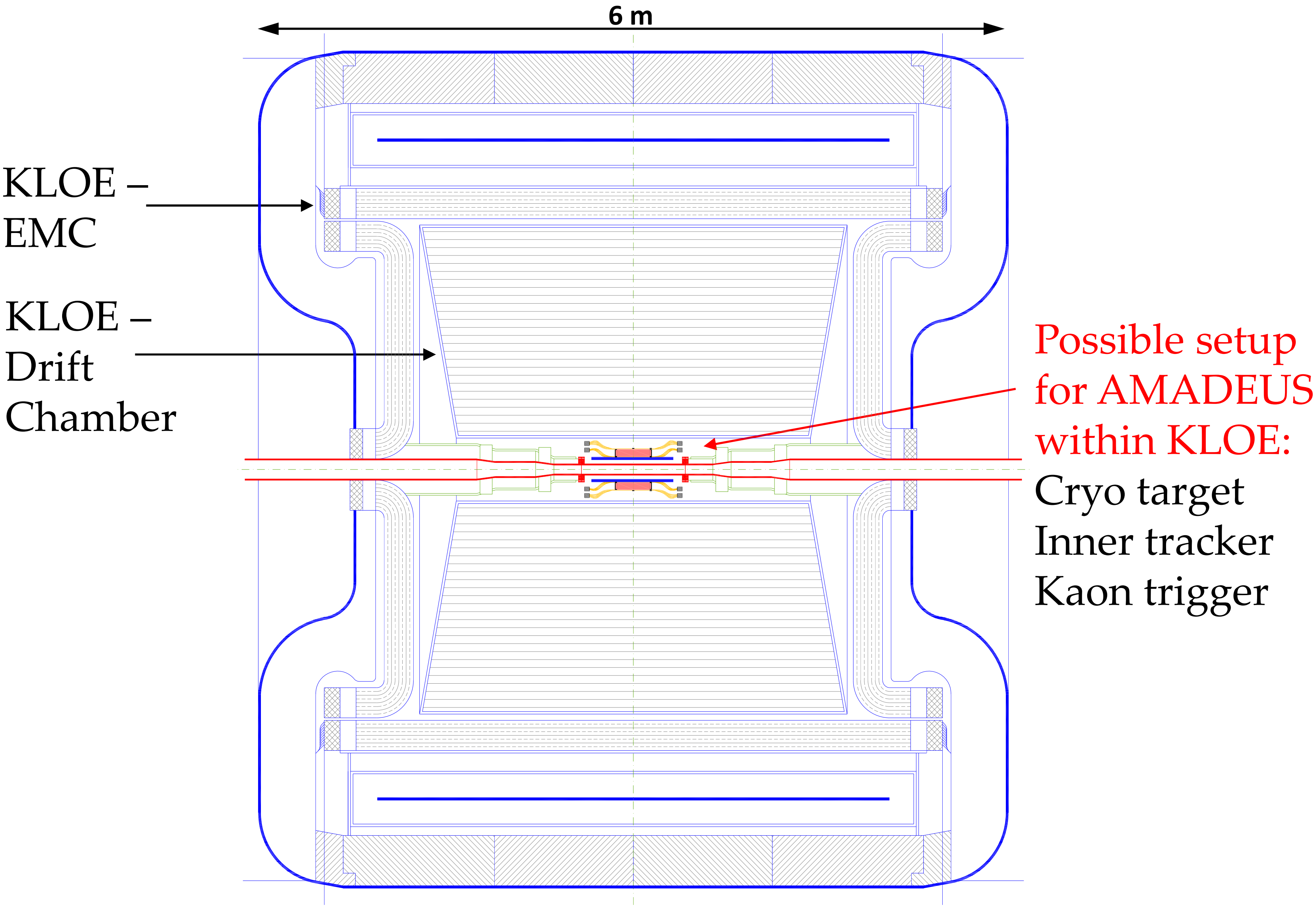
Antikaon bound nuclear cluster

AMADEUS within KLOE



OBELIX ('86~'96) [Nucl. Phys., **A797**, 109 (2007).]

- p^{bar4}He annihilation
- stopped p^{bar} @ CERN/LEAR
- gas target (^{4}He@NTP, H_2@3atm)
- **cylindrical spectrometer**
- spiral projection chamber, scintillator barrels, jet-drift chambers
- $2.4x10^5/4.7x10^4$ events of 4/5-prong in ^{4}He
- **p_{min} = 100/150/300MeV/c for π/K/p**

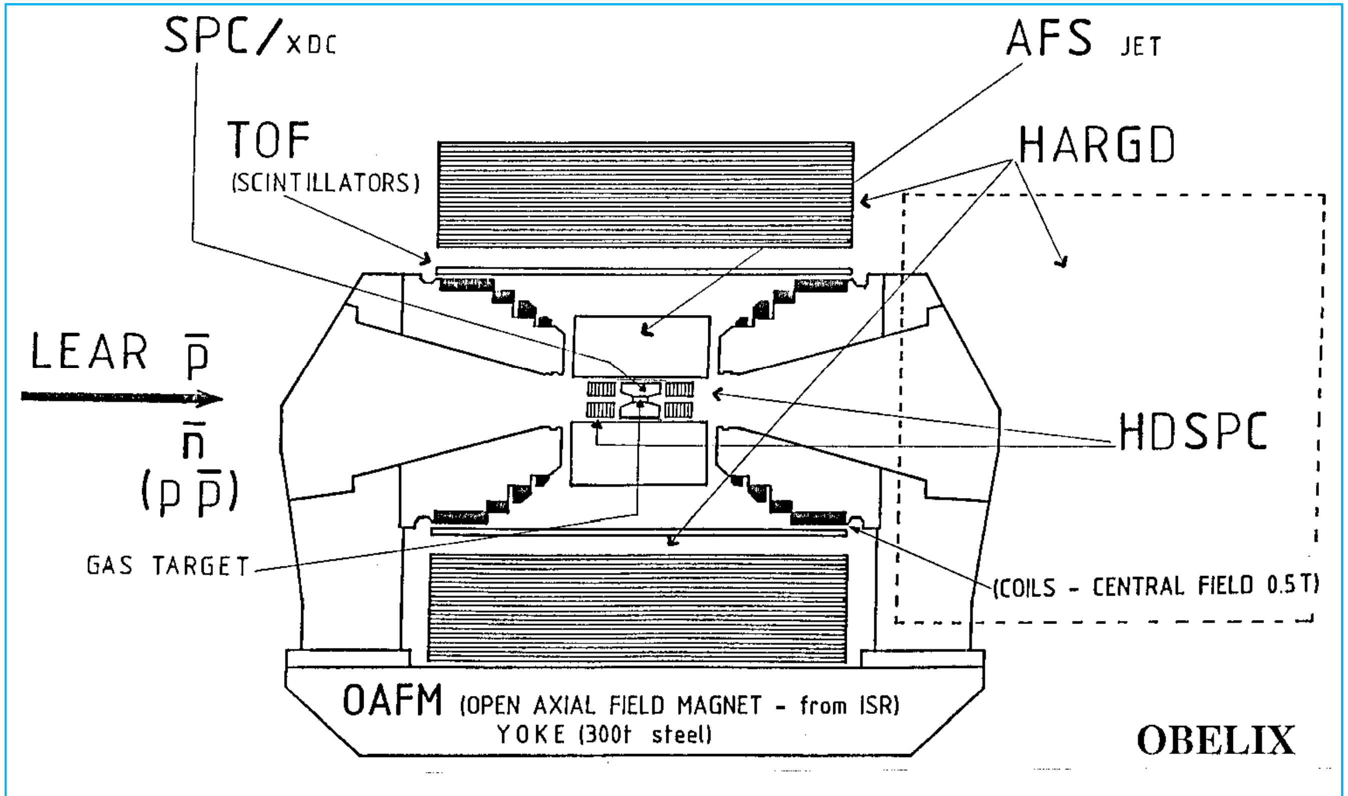


Fig. 1.1 OBELIX detector: schematic view

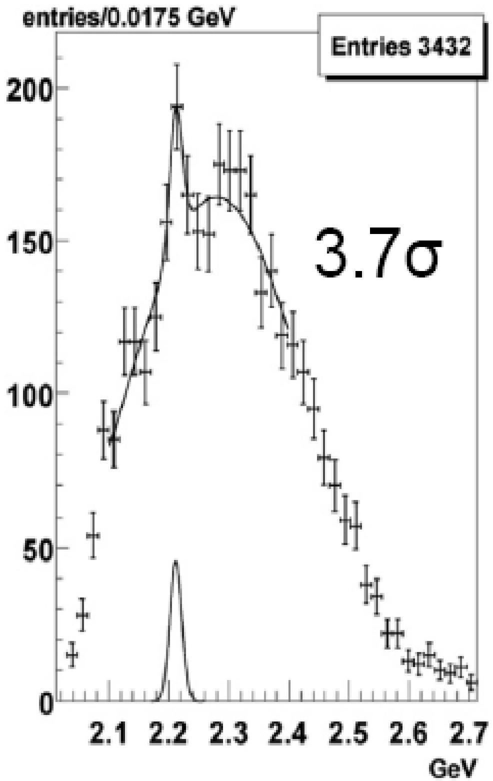
Signal of bound states ?

OBELIX data

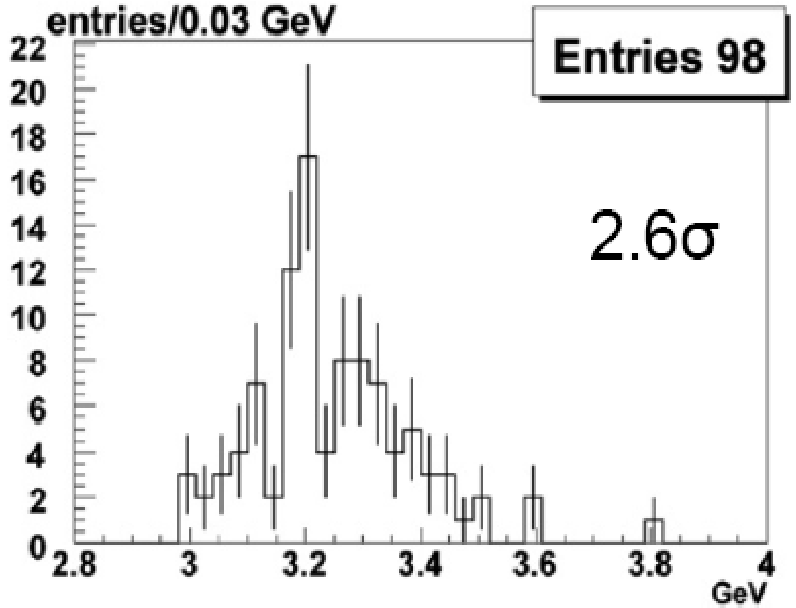
$$\bar{p} + {}^4He \rightarrow ppnK^- + K^0$$

$$ppnK^- + K^0 \rightarrow \Lambda^0 + d + K^0$$

Λp invariant mass



Λd invariant mass



G. Bendiscioli, et al., Nuclear Phys. A 789 (2007) 222

m = (2212.1±4.9) MeV
B.E. = −(160.9±4.9) MeV
Γ < (24.4±8.0) MeV $1.5 \cdot 10^{-4}$

m = (3190±15) MeV
B.E. = −(121±15) MeV
Γ < 60 MeV $0.4 \cdot 10^{-4}$

Antiproton annihilation

Kaon production in pbar-He

Bendiscioliet al., NPA 797(2007)109; Bendiscioliet al., NPA 815(2009)67

	Charge	Number of detected fast p and/or d	Final states		Number of involved nucleons ^{3}He	^{4}He	Annihilation type	
1	−1	0	$K^{\pm}\pi^{\mp}\pi^{-}2p_s(n)$	$K^{+}K^{-}\pi^{-}2p_s(n)$	1	1–2	$\bar{p}n$	
2	−1	1	$pK^{-}\pi^{-}2p_s$		–	2	$\bar{p}n$	
3	0	0	$K^{\pm}\pi^{\mp}p_s n(n)$	$K^{+}K^{-}p_s n(n)$	1–2	1–3		$\bar{p}p$
4	0	1	$pK^{\pm}\pi^{\mp}\pi^{-}p_s(n)$	$pK^{+}K^{-}\pi^{-}p_s(n)$	2	2–3	$\bar{p}n$	
5	0	1	$dK^{\pm}\pi^{\mp}\pi^{-}p_s$	$dK^{+}K^{-}\pi^{-}p_s$	–	3	$\bar{p}n$	
6	0	2	$2pK^{-}\pi^{-}p_s$		–	3	$\bar{p}n$	
7	0	2	$2pK^{\pm}\pi^{\mp}2\pi^{-}p_s$	$2pK^{+}K^{-}2\pi^{-}p_s$	–	3	$\bar{p}n$	
8	1	0	$K^{\pm}\pi^{\mp}\pi^{+}2n(n)$	$K^{+}K^{-}\pi^{+}2n(n)$	2–3	2–4		$\bar{p}p$
9	1	1	$pK^{\pm}\pi^{\mp}n(n)$	$pK^{+}K^{-}n(n)$	2–3	2–4		$\bar{p}p$
10	1	1	$dK^{\pm}\pi^{\mp}(n)$	$dK^{+}K^{-}(n)$	3	3–4		$\bar{p}p$
11	1	2	$2pK^{-}(n)$		3	3–4	$\bar{p}n$	
12	1	2	$2pK^{\pm}\pi^{\mp}\pi^{-}(n)$	$2pK^{+}K^{-}\pi^{-}(n)$	3	3–4	$\bar{p}n$	
13	1	2	pdK^{-}		–	4	$\bar{p}n$	
14	1	2	$pdK^{\pm}\pi^{\mp}\pi^{-}$	$pdK^{+}K^{-}\pi^{-}$	–	4	$\bar{p}n$	
15	1	3	$3pK^{-}\pi^{-}$		–	4	$\bar{p}n$	
16	1	3	$3pK^{\pm}\pi^{\mp}2\pi^{-}$	$3pK^{+}K^{-}2\pi^{-}$	–	4	$\bar{p}n$	

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

Production enhanced compared to pbar-p production by a factor 13, 22 respectively!

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Strangeness S=-2 production yields

$$K^+ + K^+ + p + \Sigma^- + \Sigma^- \Rightarrow (0.17 \pm 0.04) \cdot 10^{-4}$$
$$K^+ + K^+ + n + \pi^- + \Sigma^- + \Sigma^+ \Rightarrow (2.71 \pm 0.47) \cdot 10^{-4}$$
$$K^+ + K^+ + n + \Lambda^0 + \Sigma^- \Rightarrow (1.21 \pm 0.29) \cdot 10^{-4}$$
$$K^+ + K^+ + n + n + K^- + \Lambda^0 \Rightarrow (0.28 \pm 0.14) \cdot 10^{-4}$$

G. Bendiscioli, et al.,
Nuclear Phys. A 789 (2007) 107

Antiproton annihilation

Antiproton annihilation

14 October 1999

ELSEVIER

PHYSICS LETTERS B

Physics Letters B 464 (1999) 323–330

Double strangeness production in $\bar{p}Xe$ annihilation at low energy

DIANA Collaboration

V.V. Barmin [a], V.G. Barylov [a], V.S. Borisov [a], G.V. Davidenko [a], A.G. Dolgolenko [a], C. Guaraldo [b], V.A. Matveev [a], G.S. Mirosidi [a], K. Myklebost [c], M. Olsen [c], C. Petrascu [b,1], V.A. Shebanov [a], N.N. Shishov [a], A.A. Sibirtsev [d], L.I. Sokolov [a], B.S. Volkov [a], N.K. Zombkovskaya [a]

[a] *Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia*
[b] *Laboratori Nazionali di Frascati dell' INFN, C.P. 13, I-00044 Frascati, Italy*
[c] *Physics Department, University of Bergen, N-5007 Bergen, Norway*
[d] *Institut für Theoretische Physik, Universität Giessen, D-35392 Giessen, Germany*

33 double kaon events were found
yield ~ 10^{-4}

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Strangeness S=-2 production

Antiproton annihilation

We propose to use the antiproton annihilation reaction on light nuclei to produce and study double-strange nuclei in reactions such as:

$$\bar{p} + p \rightarrow K^- + K^- + K^+ + K^+$$

➡ energetically forbidden at rest (-98 MeV)

$$\bar{p} + A \rightarrow K^+ + K^+ + [K^- K^- pp(A-3)]$$

➡ bound state formation → E_B ~ 100 MeV

➡ 2 K^+ indicate a strong binding of the K^- pair in the nucleus

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The double-strangeness production yield of ~10^{-4} makes it possible to explore the exotic systems.

First experimental approach at J-PARC

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Letter of Intent for J-PARC

Double Anti-kaon Production in Nuclei by Stopped Anti-proton Annihilation

dated on 17 / 06 / 2009

M. Iwasaki[1], P. Kienle[2,3], H. Ohnishi[1], F. Sakuma[1*], and J. Zmeskal[2]
[1] *RIKEN, Japan*
[2] *Stefan Meyer Institut für subatomare Physik, Austria*
[3] *Technische Universitat Munchen, Germany*

Abstract

We propose to search for double strangeness production by $\bar{p}$ annihilation on helium nuclei at rest. The proposed experiment will provide significant information on double strangeness production and double strangeness cluster states.

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How to Measure?

we focus the reaction:

$$\bar{p} + {}^3He \rightarrow K^+ + K^0 + X \quad (X = K^- K^- pp)$$

(although K^-K^-pp decay modes are not known at all,)

we assume the most energetic favored decay mode:

$$K^- K^- pp \rightarrow \Lambda + \Lambda$$

final state = $K^+K^0\Lambda\Lambda$

We can measure the K^-K^-pp signal **exclusively**

by detection of all particles, $K^+K^0\Lambda\Lambda$, using $K^0 \rightarrow \pi^+\pi^-$ mode

We need

wide-acceptance detectors.

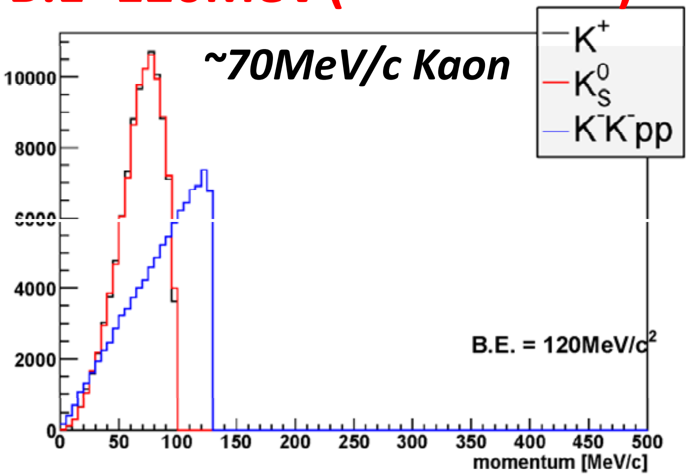
Expected Kinematics

K⁺K⁰X momentum spectra

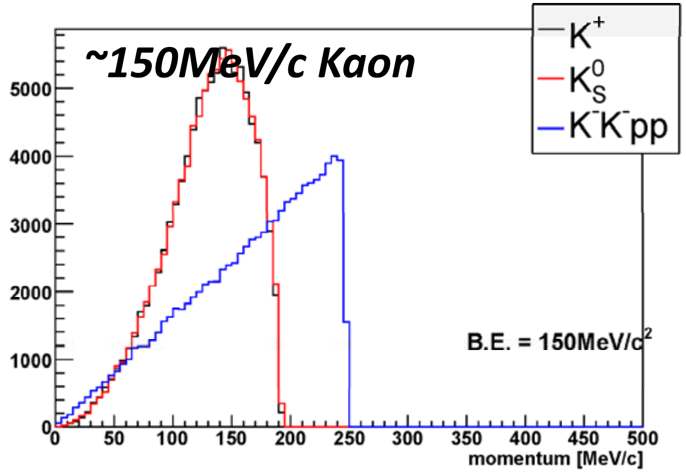
$$\bar{p} + {}^{3}He \rightarrow K^{+} + K^{0}_{S} + K^{-}K^{-}pp$$

assumptions:
- ✓ widths of K^-K^-pp = 0
- ✓ isotropic decay

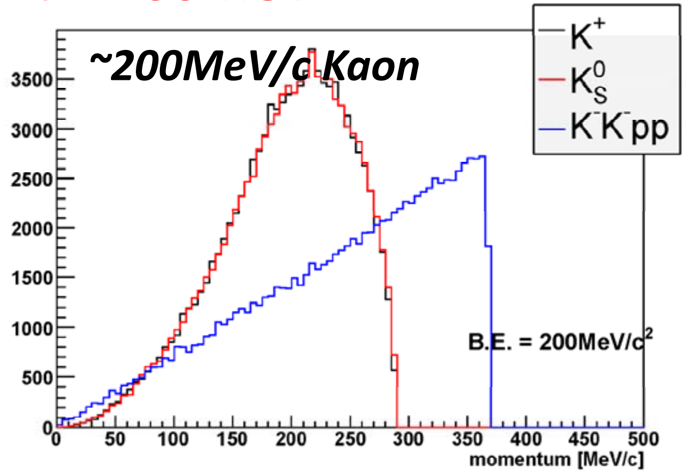
B.E=120MeV (th.+11MeV)



B.E=150MeV



B.E=200MeV



In the K^-K^-pp production channel, the kaons have very small momentum of up to 300MeV/c, even if B.E.=200MeV.

We have to construct low mass material detectors.

~200MeV/c π from K^0_S, ~800MeV/c Λ, ~700MeV/c p from Λ, ~150MeV/c π from Λ

Antiproton annihilation at FLAIR

Experimental studies of strangeness production at FLAIR@FAIR

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Search for antikaon bound systems

performing an "exclusive" measurement

formation process:

$$\bar{p} + {}^{4}He \rightarrow \boxed{K^{+} + K^{+}} + [pnnK^{-}K^{-}]$$

decay processes:

$$[pnnK^{-}K^{-}] \rightarrow p + \Sigma^{-} + \Sigma^{-}$$

$$\rightarrow p + (n + \pi^{-}) + (n + \pi^{-})$$

$$[pnnK^{-}K^{-}] \rightarrow n + \Lambda^{0} + \Sigma^{-}$$

$$\rightarrow n + (p + \pi^{-}) + (n + \pi^{-})$$

$$\rightarrow \boxed{p + 2\pi^{-} + 2n}$$

Future efforts to search for double-bound antikaon nuclear cluster

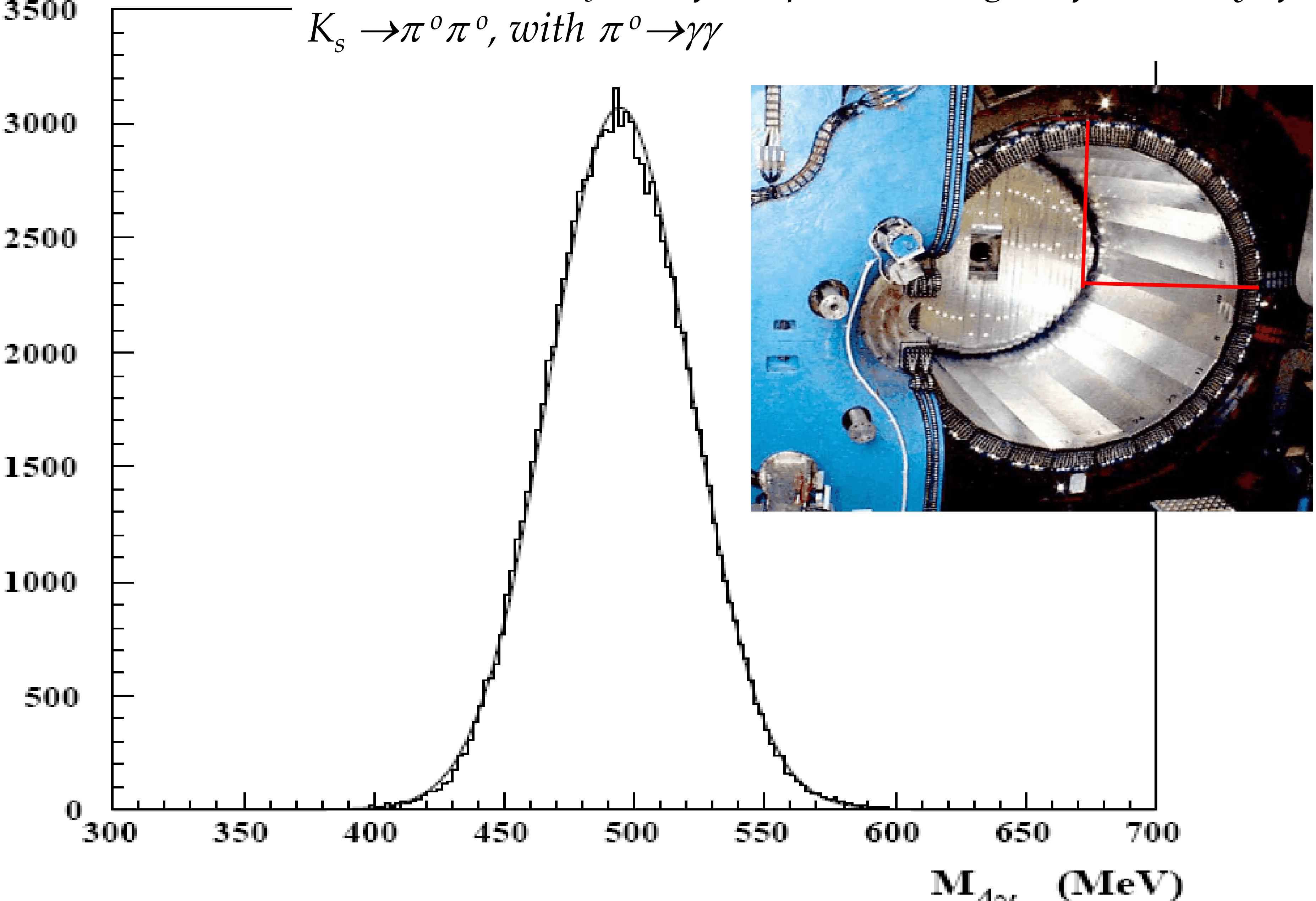
using antiproton annihilation at rest with a new dedicated setup at FLAIR (CERN-AD?)

➢ New detector concept for FLAIR

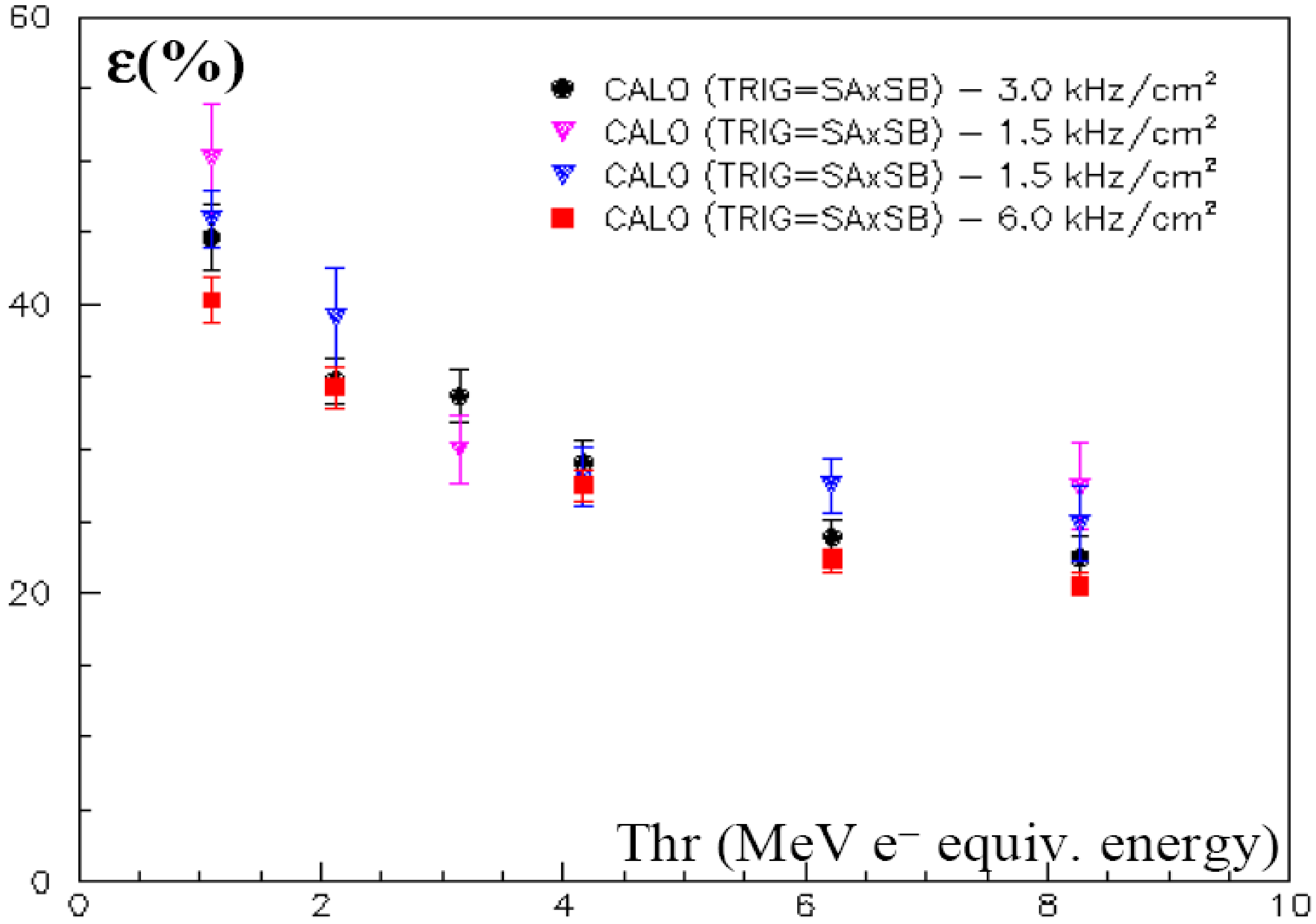
- Start counter – scintillating fibres with Geiger Mode - APD readout
- PID – with a TPC - GEM (similar as proposed for PANDA)
- For neutral particle detection - a Calorimeter with alternating scintillating fibres – lead layers (KLOE-type)

KLOE electromagnetic calorimeter

Reconstructed K_s mass from photon energies of the decay of $K_s \rightarrow \pi^0 \pi^0$, with $\pi^0 \rightarrow \gamma\gamma$



Calorimeter efficiency for neutrons



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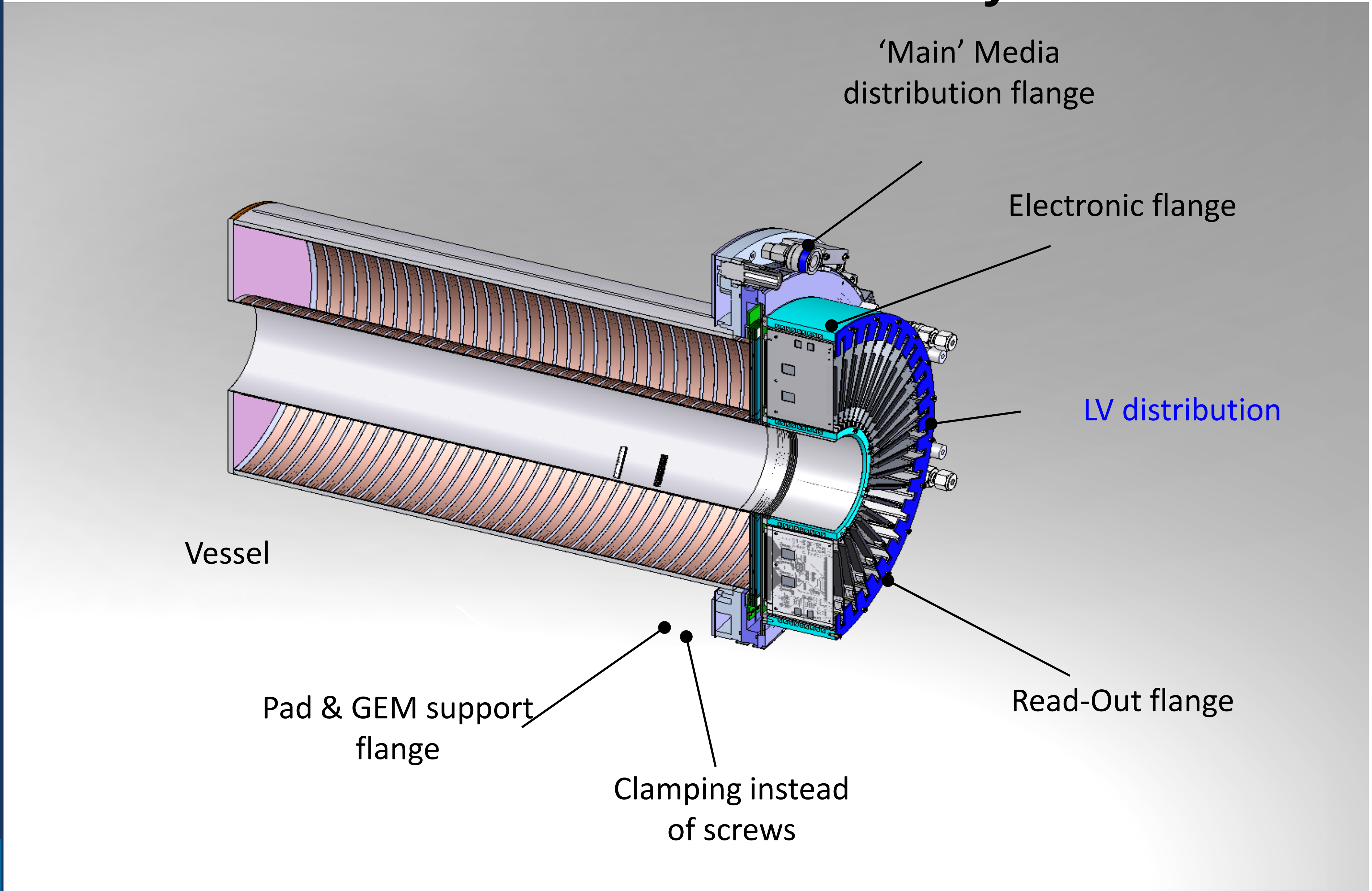
PANDA TPC prototype

work within EU-FP7 HadronPhysics2



Antiproton annihilation at FLAIR

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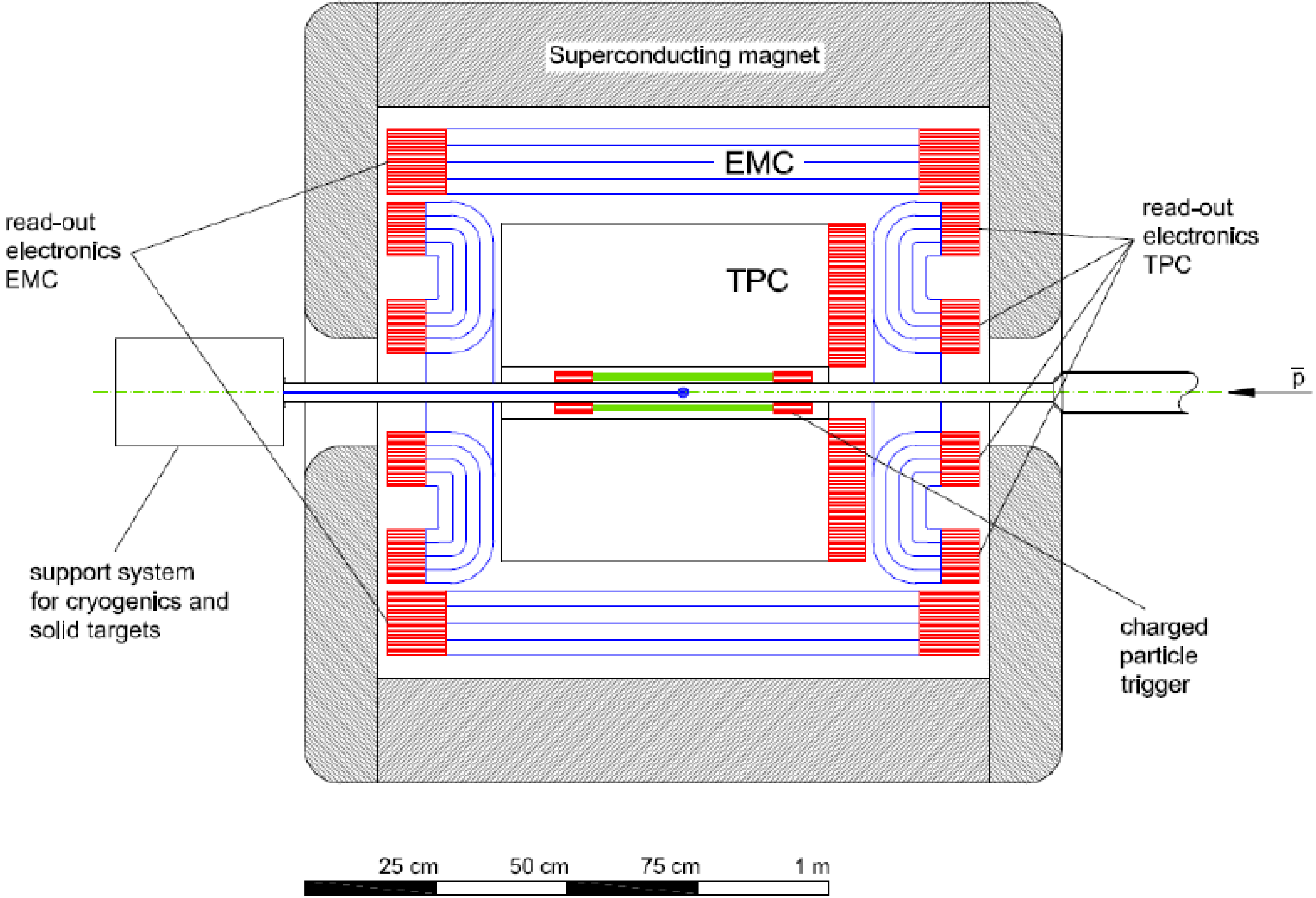
Antiproton annihilation setup



Antiproton annihilation on ^{4}He at rest

$\bar{p}^4\text{He} \to 4665.9$ MeV		$2K^+(2K^-, 3N) \to 4$ prongs	E_s (MeV)
	1	$2K^+\Lambda\Lambda 2\pi^- p_s \to 2K^+(n\pi^0)(n\pi^0)2\pi^-$ (ps) $\to 2K^+ 2\pi^-(2np_s 2\pi^0)$	4436.4
	2	$2K^+\Sigma^-\Sigma^- p_s \to 2K^+(n\pi^-)(n\pi^-)p_s \to 2K^+ 2\pi^-(2np_s)$	4320.3
$\bar{p}^4\text{He} \to 4665.9$ MeV		$2K^+(2K^-, 3N) \to 5$ prongs	
	3	$2K^+K^0\Lambda 2n\pi^- \to 2K^+(p\pi^-)2n\pi^- K^0 \to 2K^+ p 2\pi^-(2nK^0)$	4619.4
	4	$2K^+\Lambda\Lambda n\pi^- \to 2K^+(n\pi^0)(p\pi^-)n\pi^- \to 2K^+ p 2\pi^-(2n\pi^0)$	4297.8
	5	$2K^+\Lambda\Lambda n 2\pi^-\pi^+ \to 2K^+(n\pi^0)(n\pi^0)n\pi^- \to 2K^+ p 2\pi^-(2n\pi^0)$	4437.4
	6	$2K^+\Sigma^-\Sigma^+ n\pi^- \to 2K^+(n\pi^-)(n\pi^+)n\pi^- \to 2K^+ 2\pi^-\pi^+(3n)$	4461.3
	7	$2K^+\Sigma^-\Lambda n \to 2K^+(n\pi^-)(p\pi^-)n\pi^- \to 2K^+ p 2\pi^-(2n)$	4240.0
	8	$2K^+K^-\Lambda 2n \to 2K^+K^-(p\pi^-)2n \to 2K^+K^- p\pi^-(2n)$	4475.8

Three nucleon absorption: *pbar-^{4}He annihilation reactions into four and five prongs with production of **two K$^+$** admitted by the energy conservation,* i.e., with threshold energy *less than the pbar-^{4}He mass (4664 MeV).*

Crude rate estimate

- using the OBELIX result for:

$$K^+ + K^+ + p + \Sigma^- + \Sigma^- \qquad \Rightarrow \quad (0.17 \pm 0.04) \cdot 10^{-4}$$

$$K^+ + K^+ + n + \Lambda^0 + \Sigma^- \qquad \Rightarrow \quad (1.21 \pm 0.29) \cdot 10^{-4}$$

- with a pbar rate ~ 10^4 s^{-1}
- stopped pbars ~ 30%
- efficiency for correlated events ~ 0.5 %

~ 20 K^+K^+-pairs produced per day!

~ 150 K^+K^+-pairs produced per day!

Antiproton annihilation at FLAIR

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Antiproton annihilation at FLAIR

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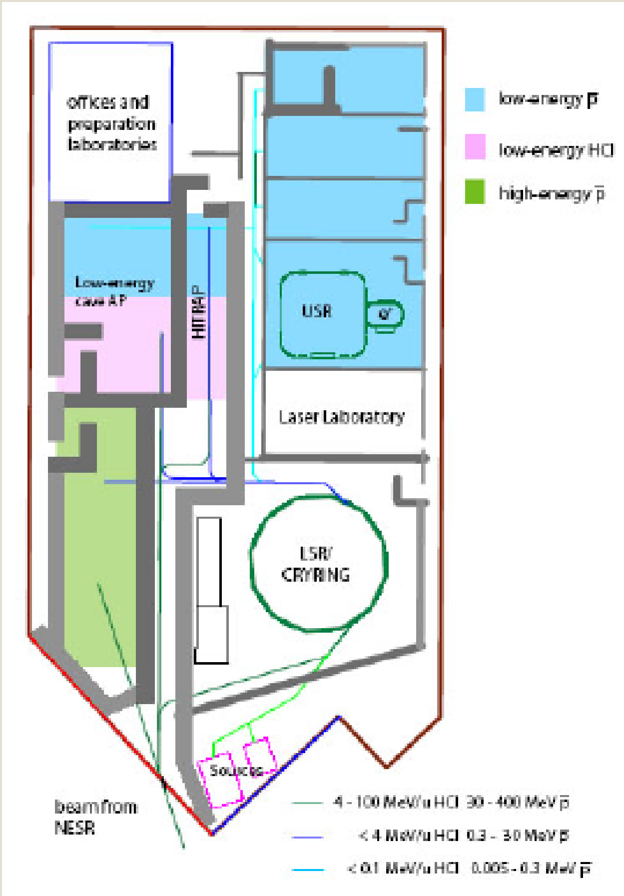

Only at FLAIR studies can be performed systematically

- continous beam
- variety of targets

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Summary

- Using the OBELIX results, it seems very promising to perform the outlined experiment at **FLAIR to study "strangeness production"**
  - more detailed studies necessary

➢ Work started on the development of a TPC-GEM detector, SiPM - within the EU 7th – Framework Programme: HadronPhysics2 (new proposal for HadronPhysics3 -> active target)

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SMI

$K^{-}pp$ System

self consistent AMD calculation

- Energy decomposition:

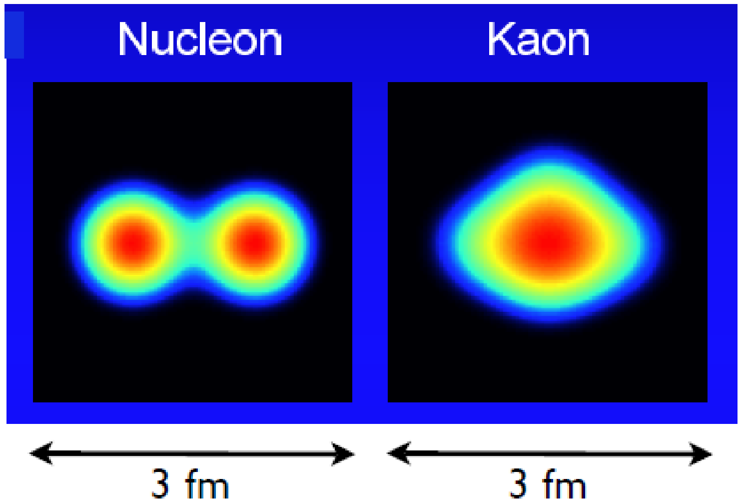
$$E = \langle \Psi(K^{-}pp) | T_{kin} + V_{NN} + V_{\bar{K}N} + V_{coul} | \Psi(K^{-}pp) \rangle$$

range a [fm]	0.67	0.7	0.8
E_{tot} [MeV]	-53	-34	-22
$\langle T_{kin} \rangle$ [MeV]	470	382	270
$\langle V^{s-wave}_{\bar{K}N} \rangle$ [MeV]	-405	-341	-255
$\langle V^{p-wave}_{\bar{K}N} \rangle$ [MeV]	-131	-89	-49
$\langle V_{NN} \rangle$ [MeV]	15	16	14
$\langle V_{coul} \rangle$ [MeV]	-2	-2	-2

A. Doté
W.W.

- Typical configuration:

nucleons well separated (R ~ 1.5 fm)



kaon field in the center

Symmetry and symmetry breaking

Physics Motivation

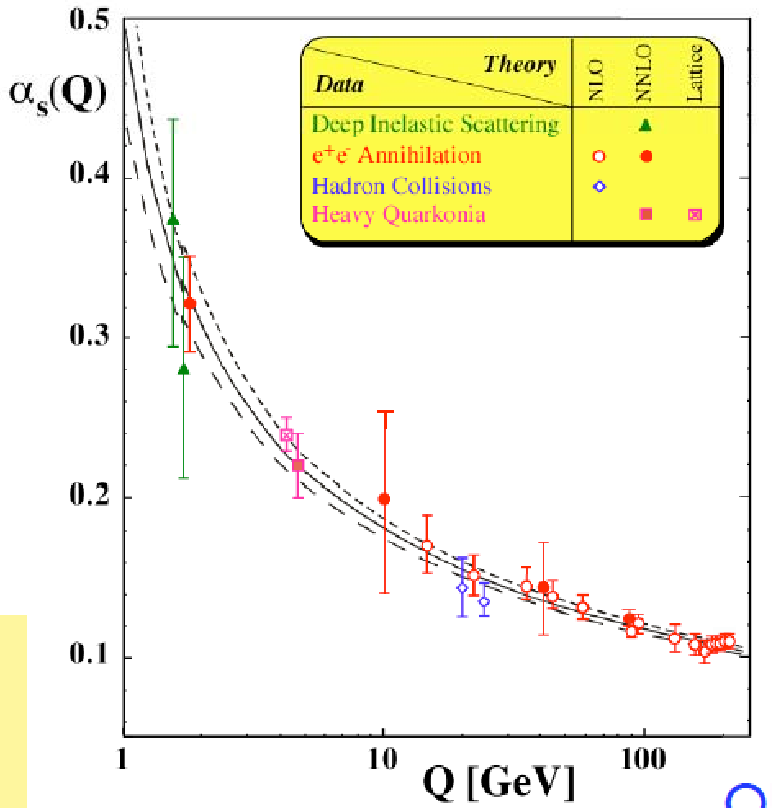
QCD $$\mathcal{L}_{QCD} = \bar{\psi}\,(i\gamma_\mu \mathcal{D}^\mu - \mathrm{m})\,\psi - \frac{1}{4}\mathrm{G}_{\mu\nu}\mathrm{G}^{\mu\nu}$$

BASIC CONCEPTS and **STRATEGIES**

"LOW - Q"
(<< 1 GeV)
↕
LONG DISTANCE
(~ 1 fm)

↓

SPONTANEOUS
(CHIRAL)
SYMMETRY BREAKING



"HIGH - Q"
(>several GeV)
↕
SHORT DISTANCE
(< 0.1 fm)

↓

Theory of
WEAKLY
INTERACTING
QUARKS and GLUONS

→ Effective Field Theory of WEAKLY INTERACTING
NAMBU-GOLDSTONE BOSONS

ÖAW Österreichische Akademie der Wissenschaften

Technische Universität München

Low-Energy QCD : CHIRAL SYMMETRY

- **QCD** with (almost) **MASSLESS u-** and **d-QUARKS** (N_f = 2)

$\psi = (\mathrm{u}, \mathrm{d})^T$

$SU(2)_L \times SU(2)_R$

pseudoscalar isovector

$\pi^a \leftrightarrow \bar{\psi}\gamma_5 \mathbf{t}^a \psi$

$J^\pi = 0^- \quad I = 1$

PION

scalar isoscalar

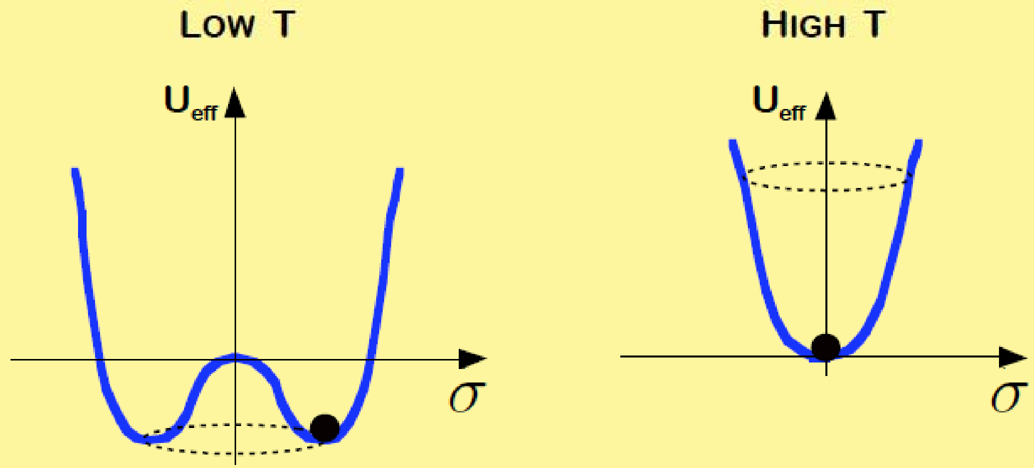
$\sigma \leftrightarrow \bar{\psi}\psi$

$J^\pi = 0^+ \quad I = 0$

invariant:

$\sigma^2 + \pi^2 = f^2$

- **SPONTANEOUS SYMMETRY BREAKING**
  (Nambu - Goldstone)



- **CHIRAL** (QUARK) **CONDENSATE**

$\langle \bar{q}q \rangle \neq 0$ $\qquad$ $\langle \bar{q}q \rangle = 0$

Annihilation in hadron physics

Stefan-Meyer-Institut

- Annihilation is a fascinating process, one of the most interesting in low-energy hadron physics, in which matter undergoes a transition from its baryon structure to one consisting solely of mesons.

- The quark model offers a new way to describe the so-called "annihilation" (not only the actual annihilation of all incoming quarks and antiquarks), namely due to a simple re-arrangement into quark–antiquark pairs.
(If quark re-arrangement will be the leading mechanism, NN annihilation would be better considered by analogy with rearrangement collisions in atomic or molecular physics.)

- Intermediate scenarios are however conceivable, where some of the incoming quarks and antiquarks annihilate, and new quark–antiquark pairs are created.

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