Search for kaonic nuclei at DAΦNE 2: the AMADEUS project

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111 Scientists from 33 Institutes
of 13 Countries
have signed the
AMADEUS LOI

AMADEUS

Antikaon
Matter
At
DAΦNE:
Experiments with
Unraveling
Spectroscopy

Eine kleine Nachtmusik

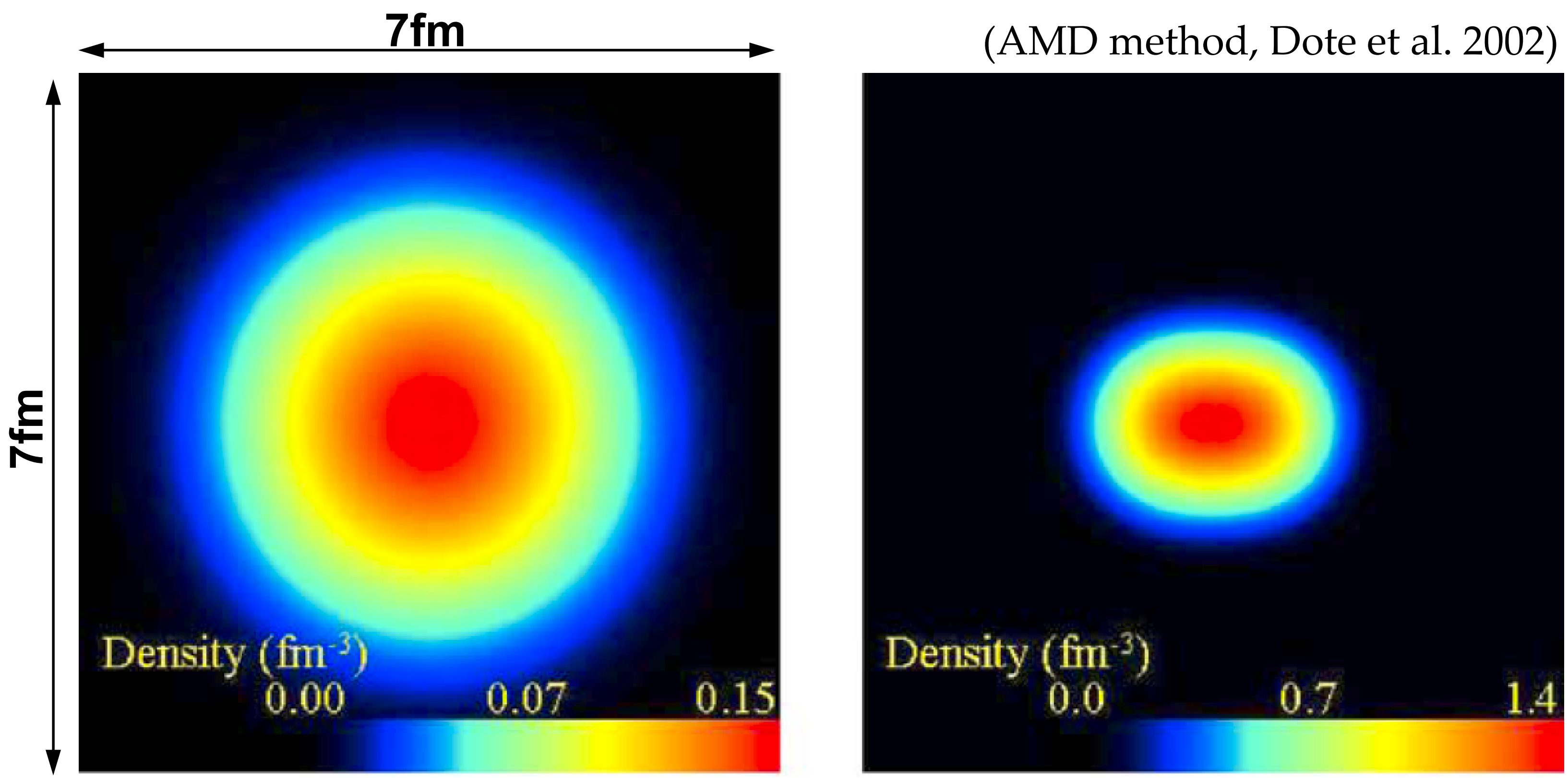
Outline

- Physics motivation
- Formation of antikaon bound nuclear states
- DAΦNE 2
- AMADEUS - the experimental program
  - the KLOE detector
  - design studies
- Conclusions

Antikaon-mediated bound nuclear cluster

^3He $\xrightarrow{\text{shrinkage}}$ $^3HeK^-$

(AMD method, Dote et al. 2002)



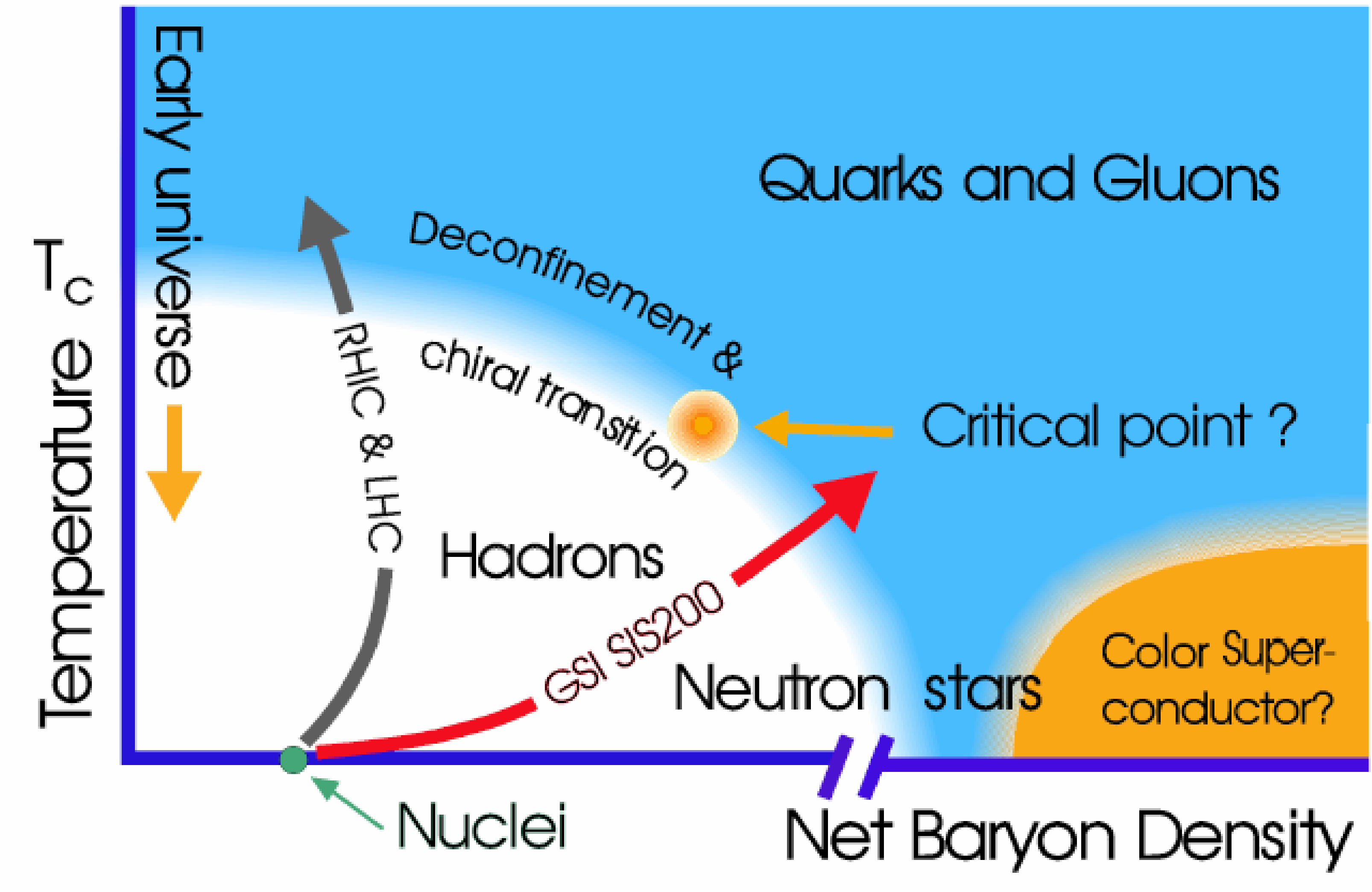
Explore cold and dense nuclear → $\rho_{KNC} \sim 4 - 10 \times \rho_0$

Impact to fundamental physics

- information on the modification of the kaon mass and on $\bar{K}N$ interaction in a nuclear medium, important for the 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
  $\rightarrow$ implication on astrophysics: neutron stars, strange stars
- nuclear dynamics under extreme conditions could be investigated (e.g. nuclear compressibility)

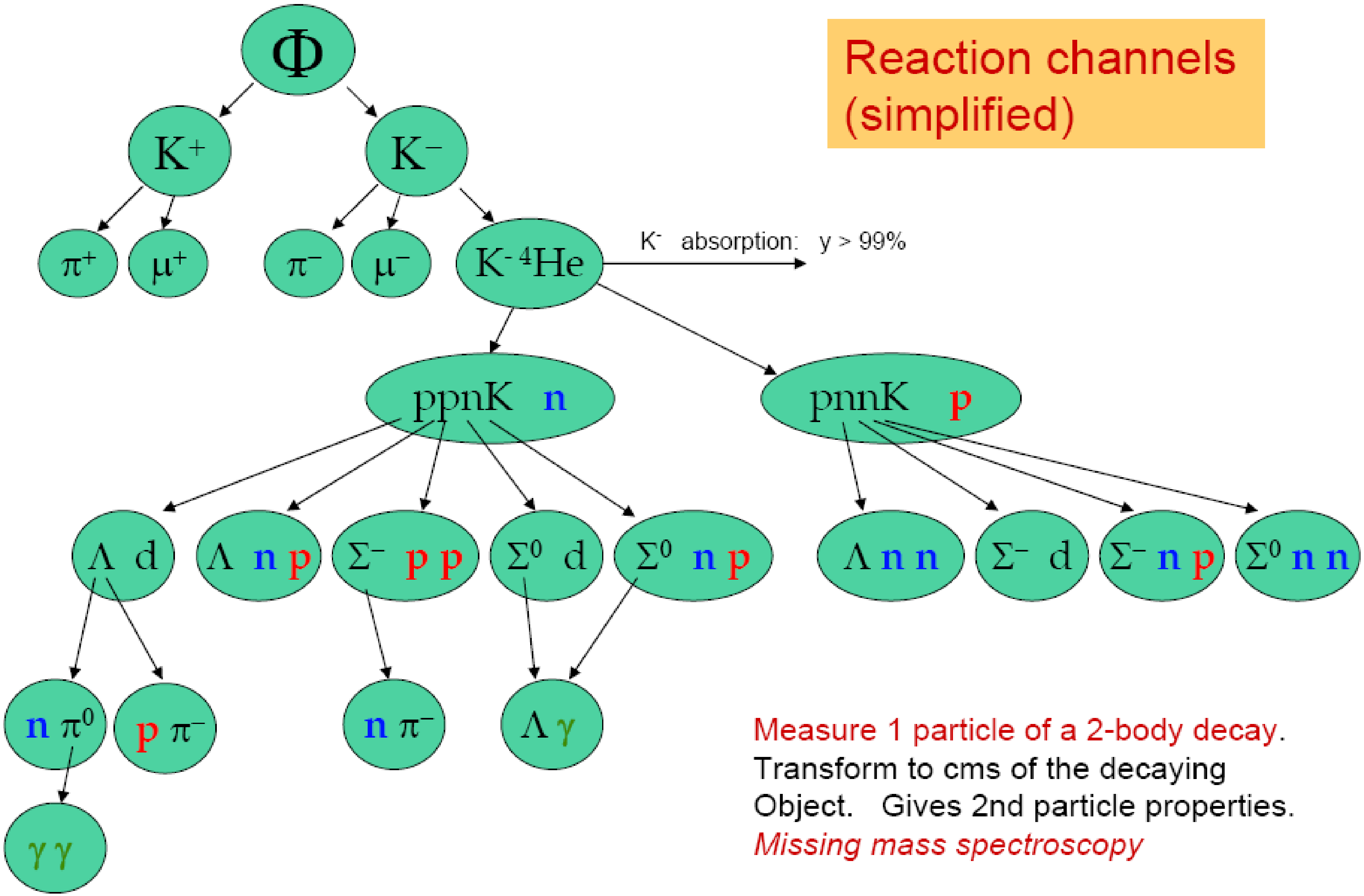
Exploring dense nuclear states

→ with K^- bound states at $T \sim 0$



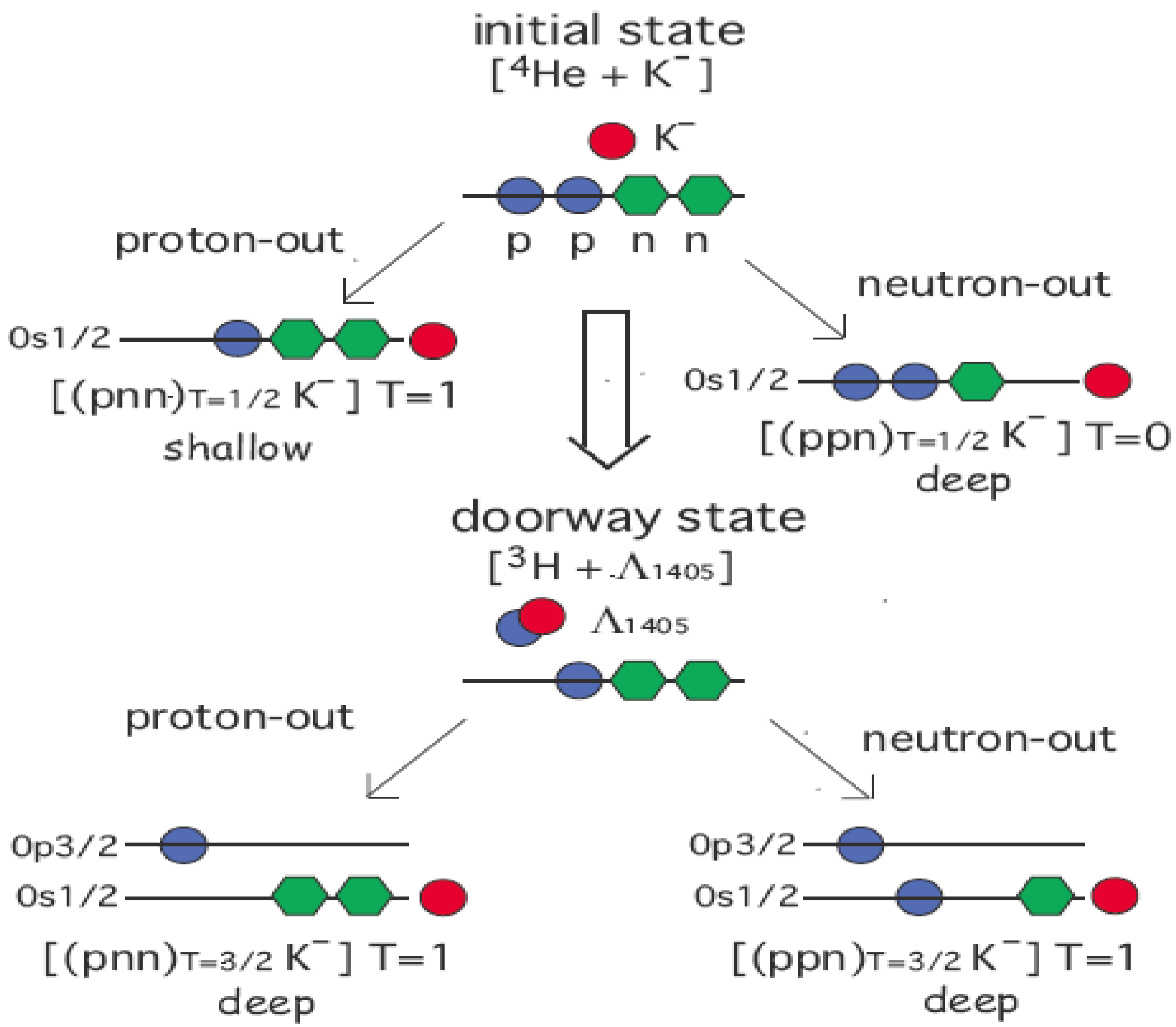
Formation of KNC

Reaction channels (simplified)



Measure 1 particle of a 2-body decay.
Transform to cms of the decaying Object. Gives 2nd particle properties.
Missing mass spectroscopy

Λ(1405) a doorway to antikaon nuclei



Production mechanism of KNC

- stopped K^- reactions on light nuclei
- in-flight K^- reactions
- protons on N
- heavy ion collisions

→ identification and study of antikaon nuclear cluster

formation - missing mass
decay - invariant mass

Evidence for antikaon-mediated bound nuclear systems

- PS-E471 at KEK
  PS-E570 at KEK
- FOPI at GSI
- FINUDA at LNF

DAΦNE 2 for AMADEUS

- the future experiments in Japan J-PARC will produce kaonic nuclear states only with K^--induced reactions in-flight

- alternative approaches followed at GSI with FOPI using proton-nucleus collisions at beam energies close to the strangeness production threshold and with nucleus-nucleus collisions

- a dedicated facility – AMADEUS at DAΦNE2 can become the scientific pole to study antikaon-mediated bound nuclear systems with K^- induced reaction at rest

DAΦNE 2 for AMADEUS

The main features of DAΦNE 2 are:

- low-momentum (127 MeV/c) charged kaons
  ~ 1200/s at $L \approx 10^{33}$ $cm^{-2}s^{-1}$
- low momentum spread (< 0.1%)
- K-pair production in back-to-back topology
- hadronic background intrinsically low
  (different for extracted beams)

AMADEUS Experimental Program

- study of the most fundamental 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**

AMADEUS – experimental setup

The formation process:

- $K^- + {}^4He \rightarrow p + (pnnK^-)$ $p \sim 550$ MeV/c
- $K^- + {}^4He \rightarrow n + (pnnK^-)$ $n \sim 510$ MeV/c

exotic nuclear states in light nuclei produced with (K^-, N) reactions at rest will be observed using missing mass – by the energy distribution of the ejected protons and neutrons

➢ therefore, the setup should be capable to measure:

outgoing protons up to 600 MeV/c

outgoing neutrons up to 600 MeV/c

preferable, in a 4π acceptance detector with good efficiency and resoltion

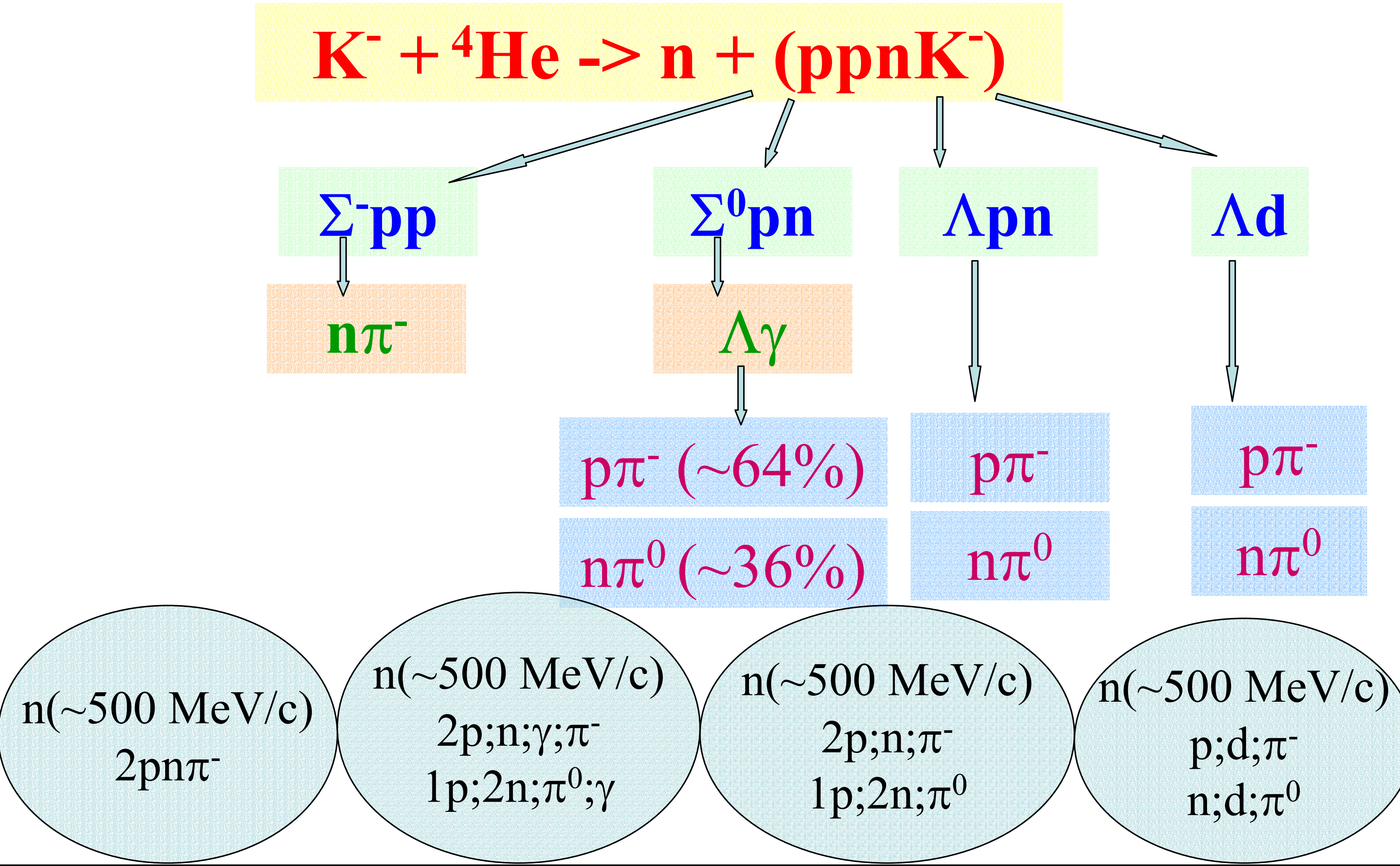
AMADEUS – experimental setup

The decay process:

the exotic states are expected to predominantly decay into final states containing Λ and Σ hyperons and protons, neutrons, deuterons or larger systems of nucleons

- therefore, the most important feature of a detector is the reconstruction capability for Λ and Σ hyperons from the invariant mass of their decay into protons and pions and/or gammas

The ppnK$^-$ decay process



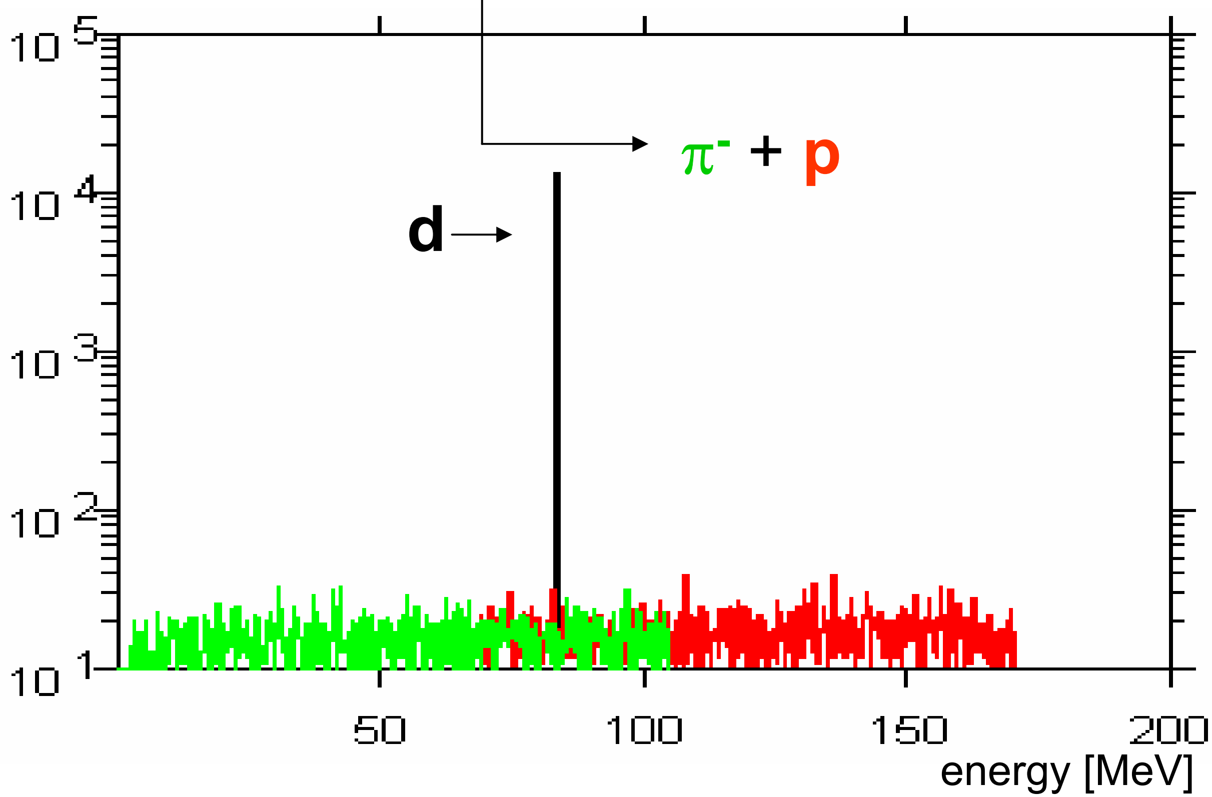
The ppnK$^-$ decay process

^{4}He (K$^-_{stopped}$, n) ppnK$^-$ Q~72 MeV (B.E.=100 MeV)

^{4}He + K$^-$ → ppnK$^-$ + n → (p~325 MeV/c, E_{kin}~55 MeV)

ppnK$^-$ → Λ° + d → (p~565 MeV/c, E_{kin}~85 MeV)

Λ° → π^- + p



Features of the experimental setup

The complete study of the characteristic features of the antikaon bound nuclear system requires knowledge of:
binding energy, level width and partial widths, angular momenta, isospin, sizes, densities, etc.

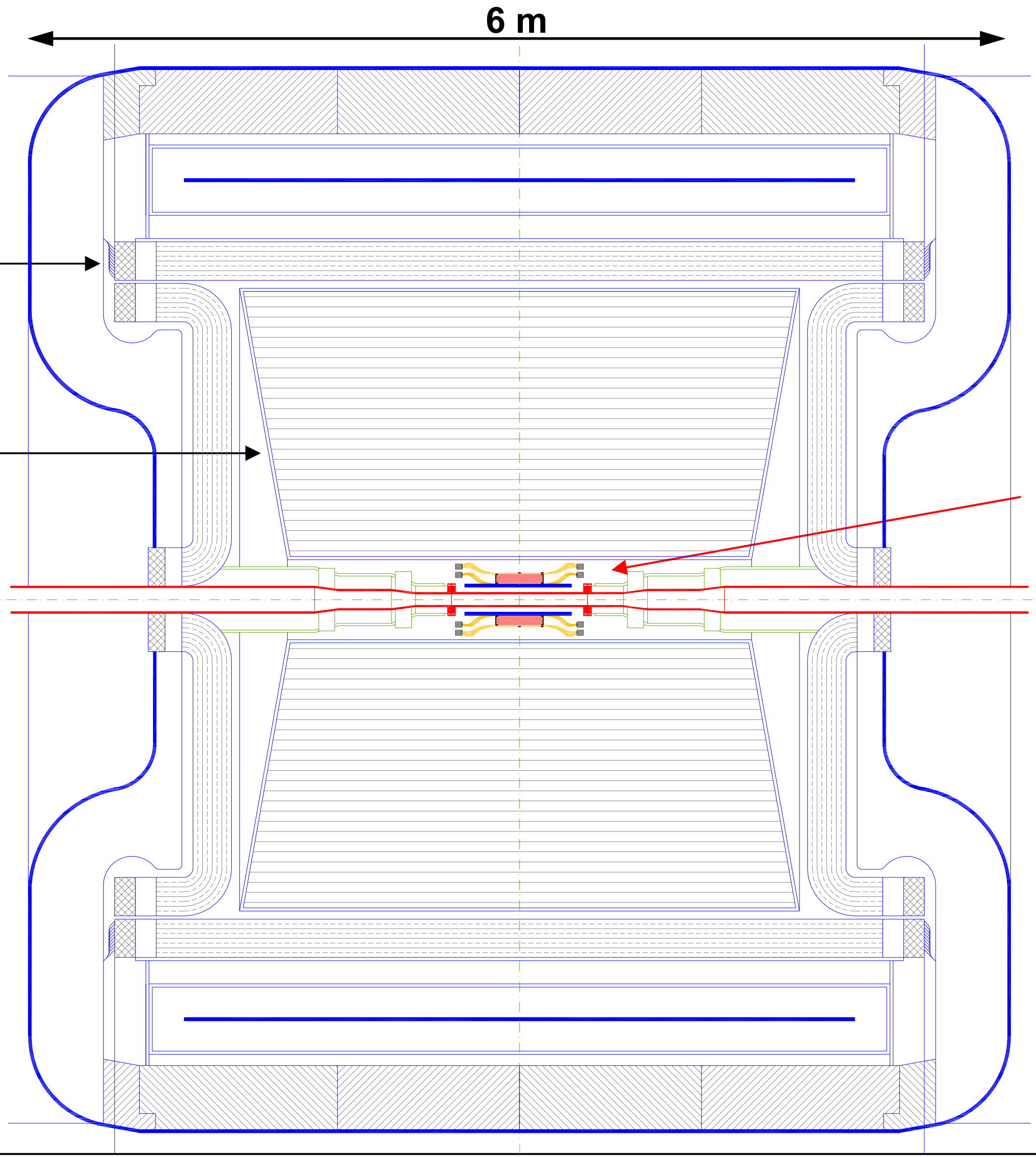
→ this can be done by simultaneously observing the production stage of the K^--clusters and all the decay products of the formed cluster - their momentum correlations contain information on the internal structure of this exotic system

→ it is therefore necessary to use a 4π dedicated detector capable of detecting charged and neutral particles, created in both, the formation and decay of the KNC

AMADEUS within KLOE

KLOE – EMC

KLOE – Drift Chamber



Possible setup for AMADEUS within KLOE:

Cryogenic target
Inner tracker
Kaon trigger

The KLOE detector

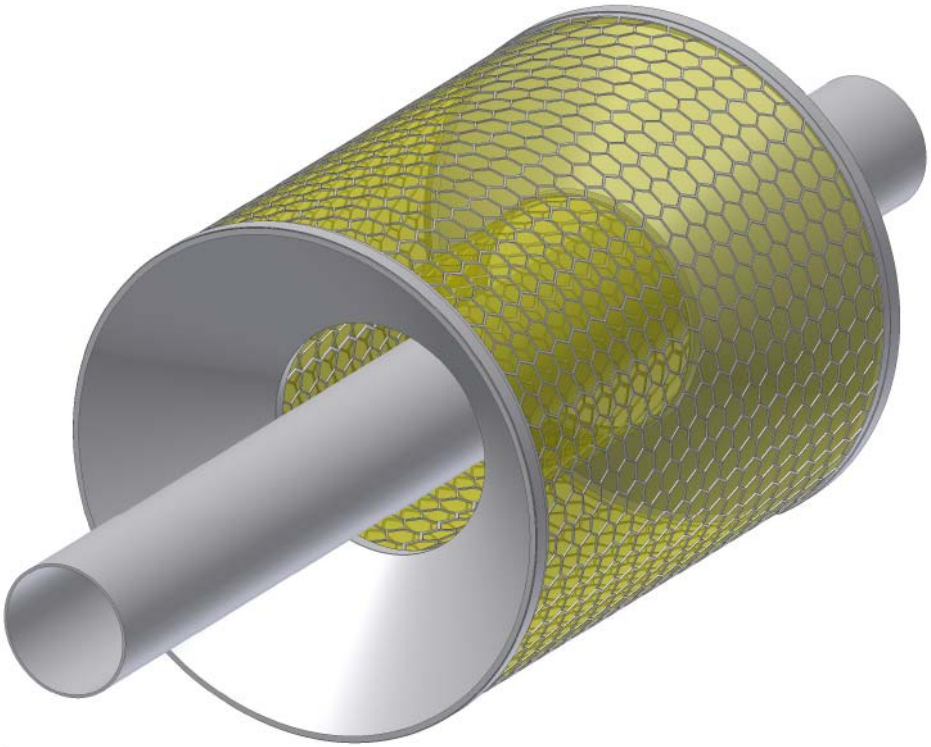
Performance of the KLOE 4π detector:

- fully checked and exploited in numerous measurements done by KLOE collaboration
- studies of processes with BR of $< 10^{-3}$ (10^{-6})
- acceptance 96%
- spatial resolution of vertices in DC: 3 mm
- dE/dx capacity for particle ID implemented
- EMC $dE/E_g \sim 5.7\%/E^{1/2}$
- $\sigma_{t=} (54/E^{1/2} + 50)$ ps
- $K_s \rightarrow \pi^+\pi^-$ at 0.8 MeV/c^2
- π^0 mass reconstructed, resolution ~ 2-3 %
- neutron detection!

AMADEUS cryogenic target cell

working temperature: 5 -10 K
working pressure: < 0.5 MPa

thin-walled design: 75μm Kapton,
with aluminum grid reinforcement (grid transmission > 85 %)

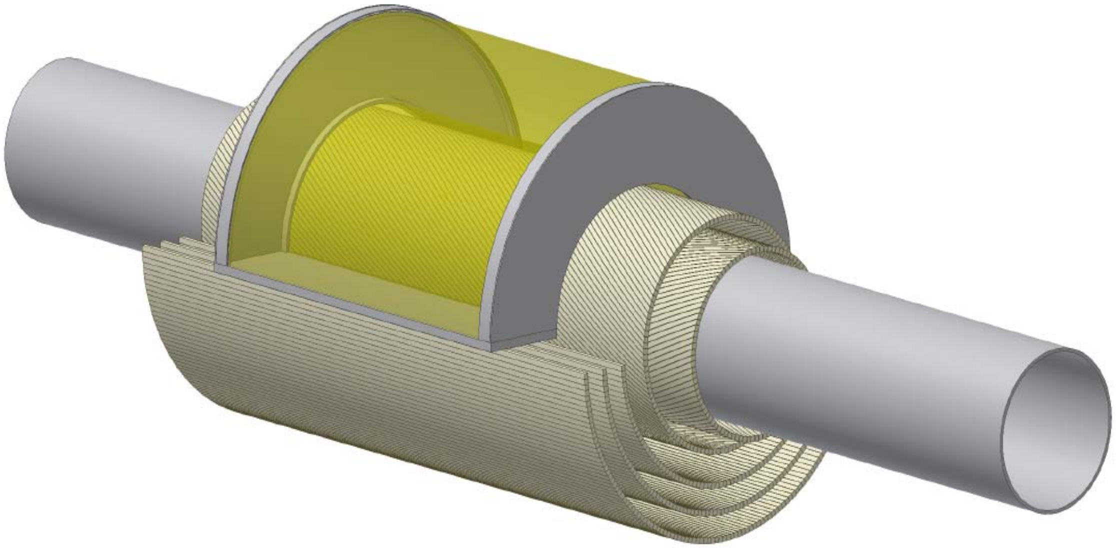


inner diameter: 110 mm
outer diameter: 210 mm
inner length: 120 mm
outer length: 200 mm

Kaon trigger for AMADEUS

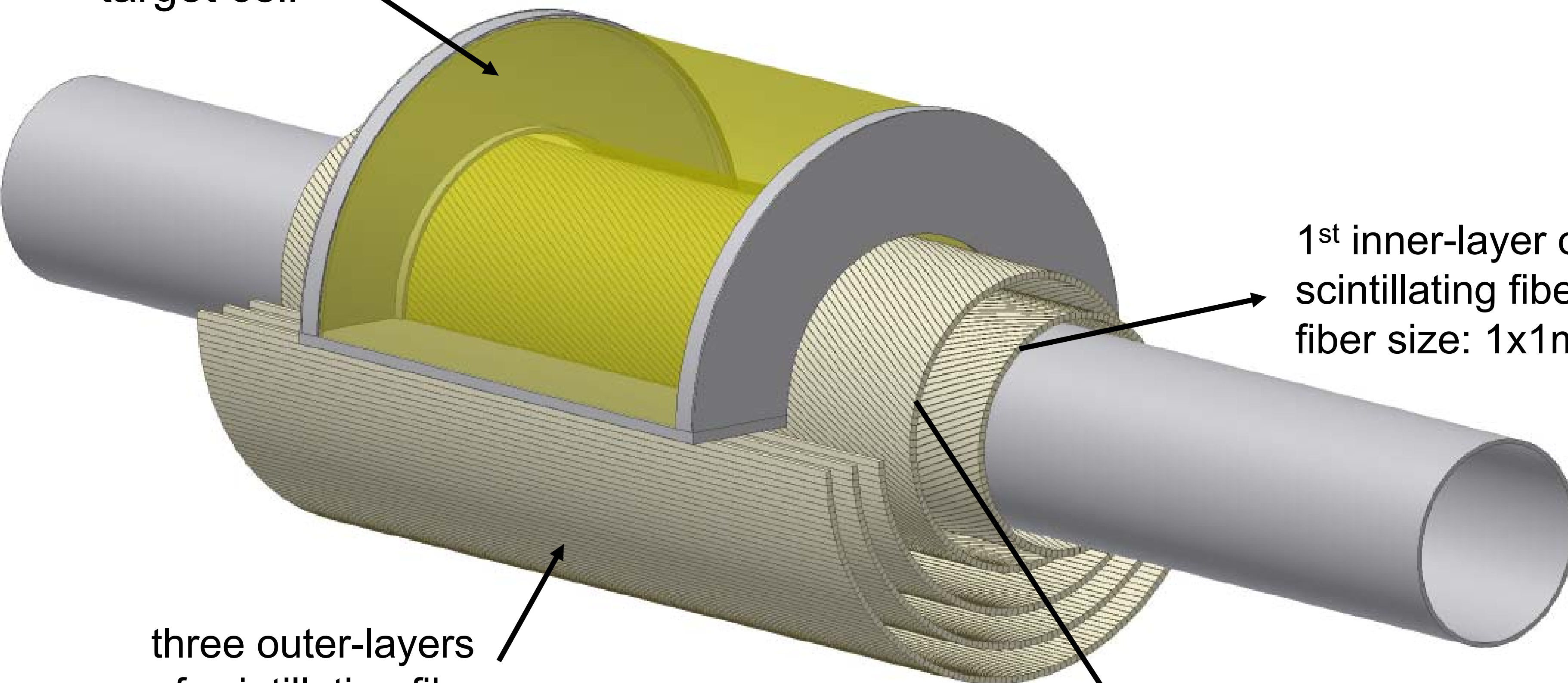
- optimal solution for a kaon trigger system, consisting of:

two cylindrical inner-layer of scintillating fibers:
x-y position of ± 1mm → determination of K^- stopping region

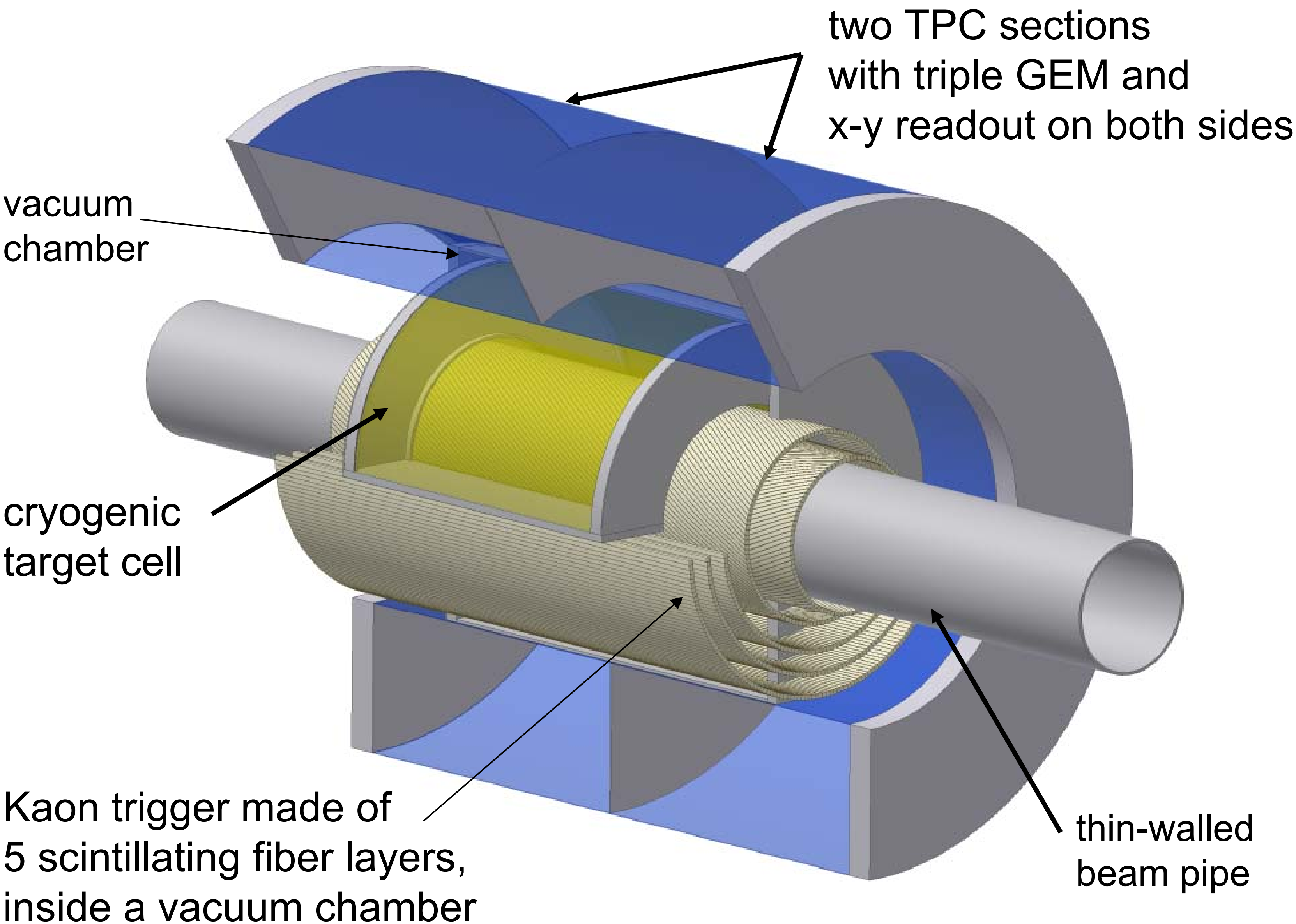


three half cylindrical outer-layer of scintillating fibers:
with inner and outer scintillating fibers a track reconstruction possible, therefore K^+ and K^- distinguishable

Kaon trigger for AMADEUS



AMADEUS within KLOE

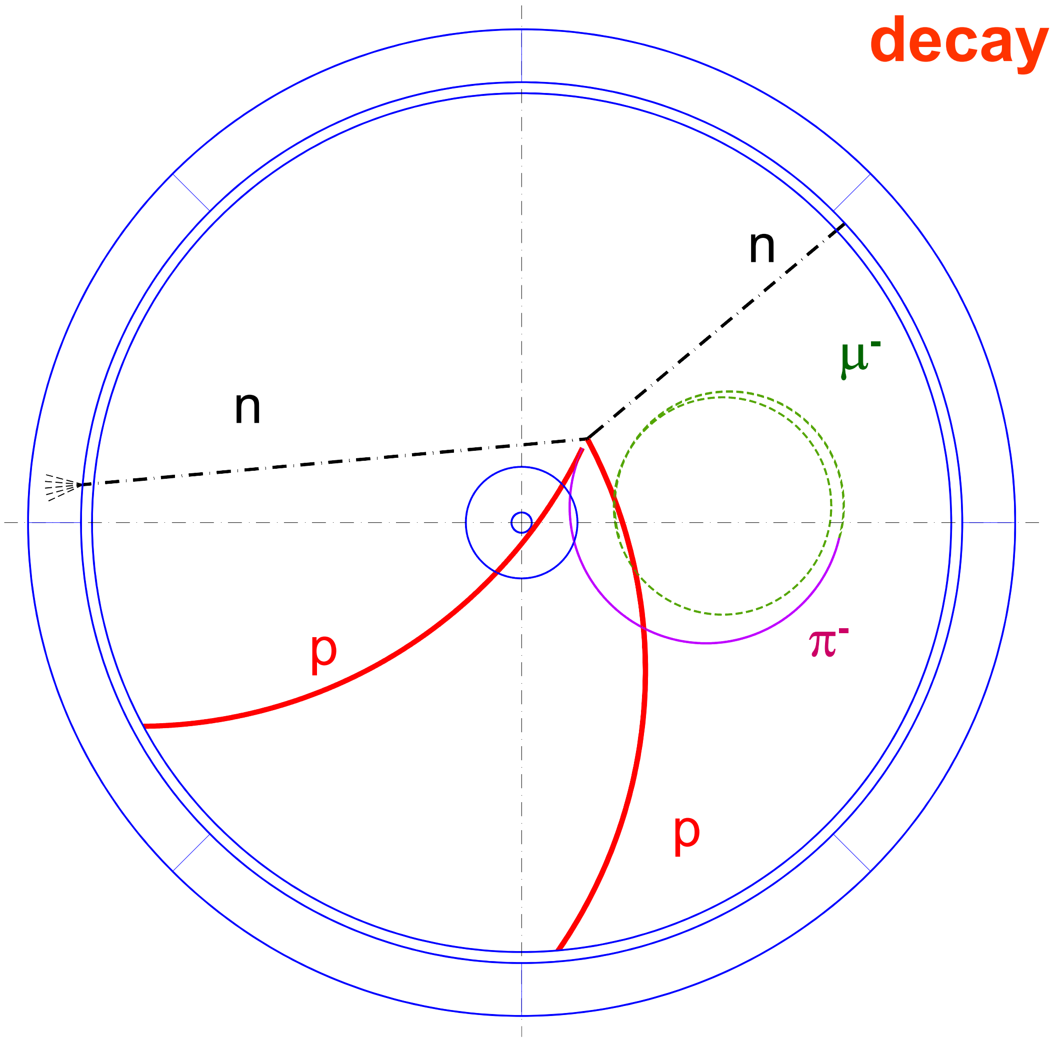


"Sign" of ppnK⁻ cluster

$^4He + K^- \rightarrow ppnK^- + n$

decay: ppnK⁻ → Λ° + **p + n**

Λ° → **p + π^-**



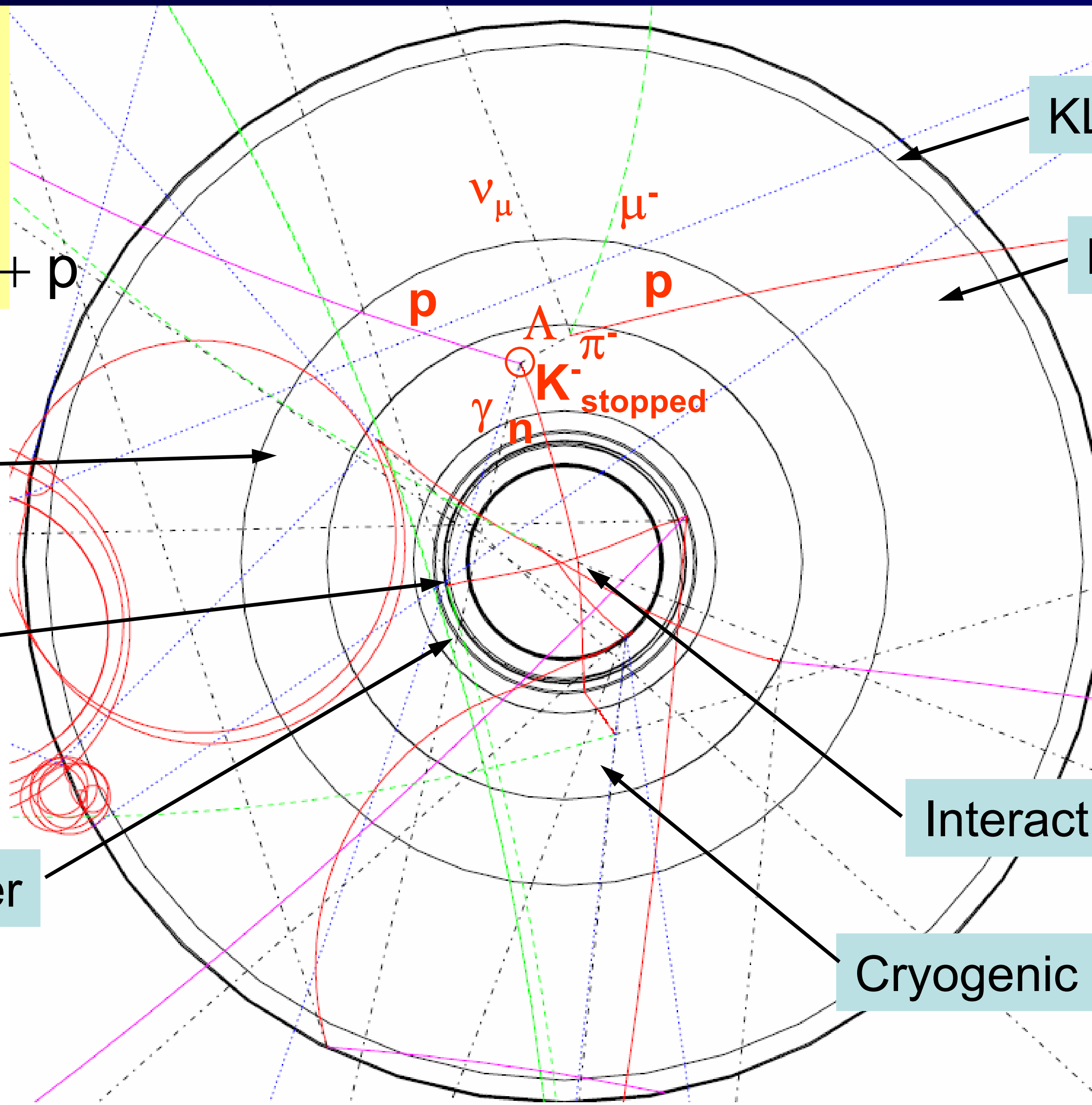
Event display for ppnK$^-$

ppnK$^-$ $\rightarrow$

$\Sigma^0 + n + p$

$\rightarrow \gamma + \Lambda$

$\rightarrow \pi^- + p$



Rate estimation

Production rate of charged kaon pairs:

$$R = L \cdot \sigma \cdot b = 600\ s^{-1}$$

L … mean luminosity	$4.10^{32}\ cm^{-2}s^{-1}$
σ … Φ production cross section	$3.10^{30}\ cm^{2}$
b … branching ratio for $K^{\pm}$	0.49

→ produced $K^{\pm}$ per month (80% duty cyle): ~ 1.10^{9}

→ stopped K^{-} in the cryogenic He gas target: ~ 4.10^{8}
(K⁻He systems produced)

~ 4.10^{5} antikaon nuclear clusters produced
(production efficiency 10^{-3})

First action towards AMADEUS

Pre-experiment

a preliminary Monte Carlo simulation shows that with an integrated luminosity of 2 fb^{-1} due to stopped K^- in the He gas of the DC one might have collected already:

> 1500 events of

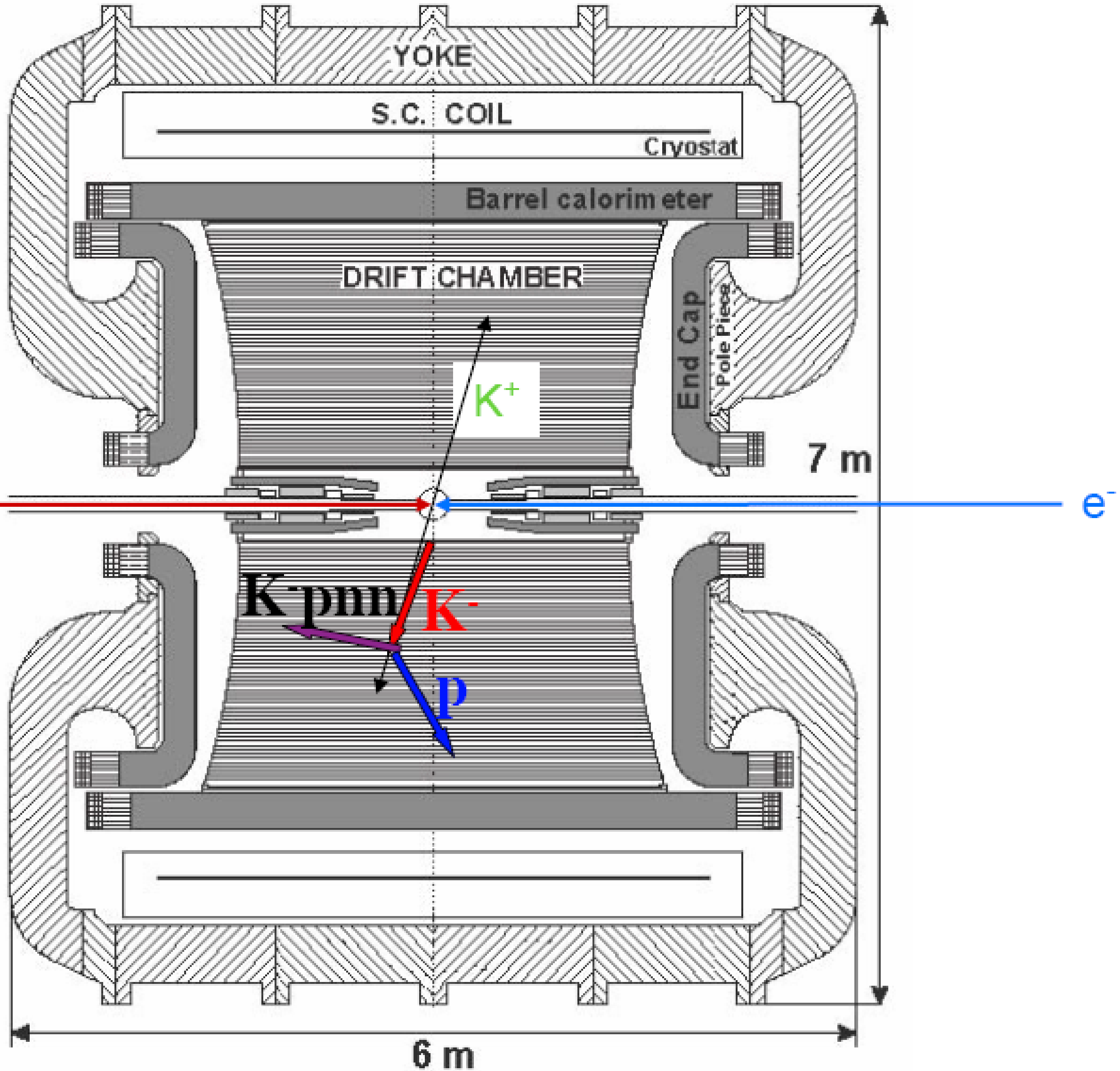
$$K^- + {}^4He \rightarrow p + (pnnK^-)$$

> 500 events of

$$K^- + {}^4He \rightarrow n + (ppnK^-)$$

First action towards AMADEUS

Schematic
side view of
the KLOE detector



The drift chamber is filled with He + isobutane at atmospheric pressure;
He as active volume

First action towards AMADEUS

KLOE calorimeter efficiency for neutrons

a) Monte Carlo GEANT simulation
   $\rightarrow$ neutron efficiency $_{500MeV/c}$ > 20% (~30%)

b) KLOE+SIDDHARTA tests on KLOE calorimeter prototype on neutron beam

Future (expected) progress

- **Kaonic hydrogen and deuterium with SIDDHARTA** shift and width ~ eV → determination of I=0 and I=1 KN scattering lengths
- **Kaonic helium with SIDDHARTA at LNF** and **J-PARC**
- **Low-energy scattering data:** precision measurements on $K^{\pm}$ scattering on nucleons/nuclei at DAΦNE 2 might become possible
- **Λ(1405):** precise KN measurements at threshold with SIDDHARTA (and low-energy scattering data) will improve the knowledge of the sub-threshold KN dynamics and clarify the nature of Λ(1405); additional information due to the measurement of the two-body branching ratio in K^{-} absorption at rest with AMADEUS

Conclusions

The scientific case of the study of deeply bound kaonic nuclear states deals with one of the most important - yet unsolved problems - in hadron physics:
how the hadron masses and hadron interaction change in the nuclear medium and what is the structure of cold dense hadronic matter

With AMADEUS at DAΦNE2 we plan to study the K^- induced processes at rest, which will be – if antikaon-mediated bound nuclear systems exists - a direct way to investigate hadron interaction in nuclear matter.

LNF - INFN   GSI – FAIR   J-PARC