# Antikaon Interactions with Nucleons and Nuclei – AMADEUS at DAΦNE

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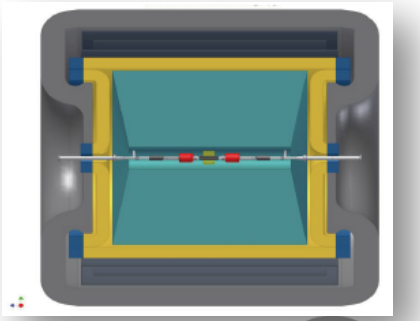


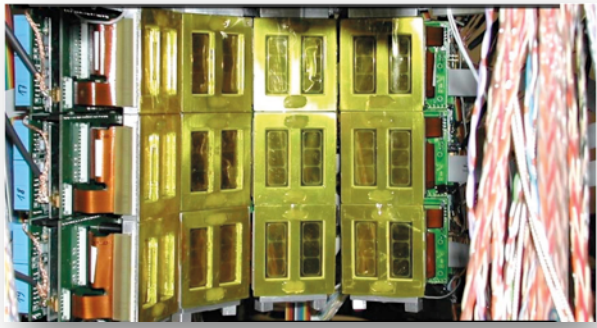
# Motivation

- Antikaon interaction with nucleons and nuclei represents an interplay between explicit and spontaneous chiral symmetry breaking
- Character of the antikaon-nucleon/nuclei interaction at low energy – attractive and absorptive
- Exotics in the strangeness sector, e.g. Λ(1405)
- Existence of (dense) baryonic matter, bound strong interaction with strangeness?
- Role of strangeness in compact stars (neutron stars)

# Some solved/open problems in $K_{bar}N$ interaction

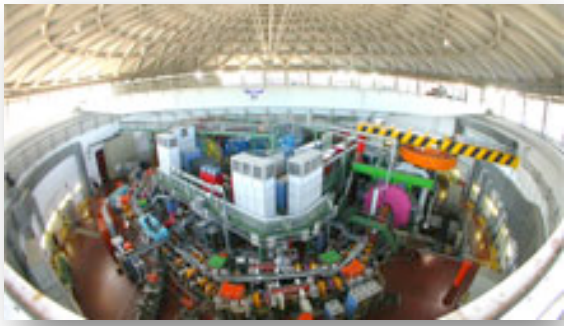
Solved problems:

- Kaonic hydrogen/deuterium: 1s state shift/width
  → essential input for theory by SIDDHARTA
  see talk by J. Zmeskal at INPC2016
- Kaonic helium: 2p state shift puzzle solved



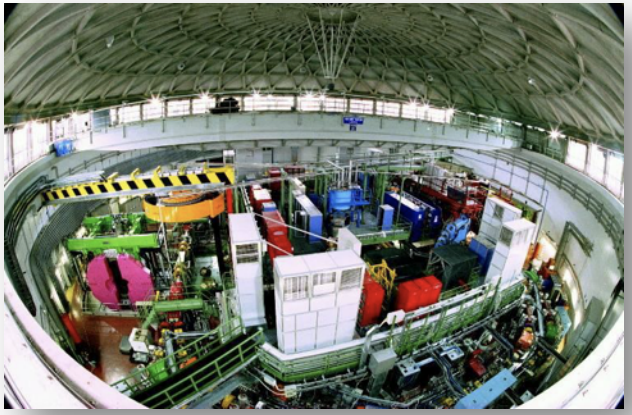
Open issues:

- $K_{bar}N$ interaction attractive and absorptive ($K_{bar}N$ potential attractive and absorptive according to theory confirmed by kaonic atoms) – but how strong?
- Bound states, Λ(1405), kaonic nuclei like $K^-pp$
- Absorption of $K_{bar}$ in nuclei
- Role of strangeness in compact stars
- Kaonic deuterium shift, width - $K^-n$ interaction

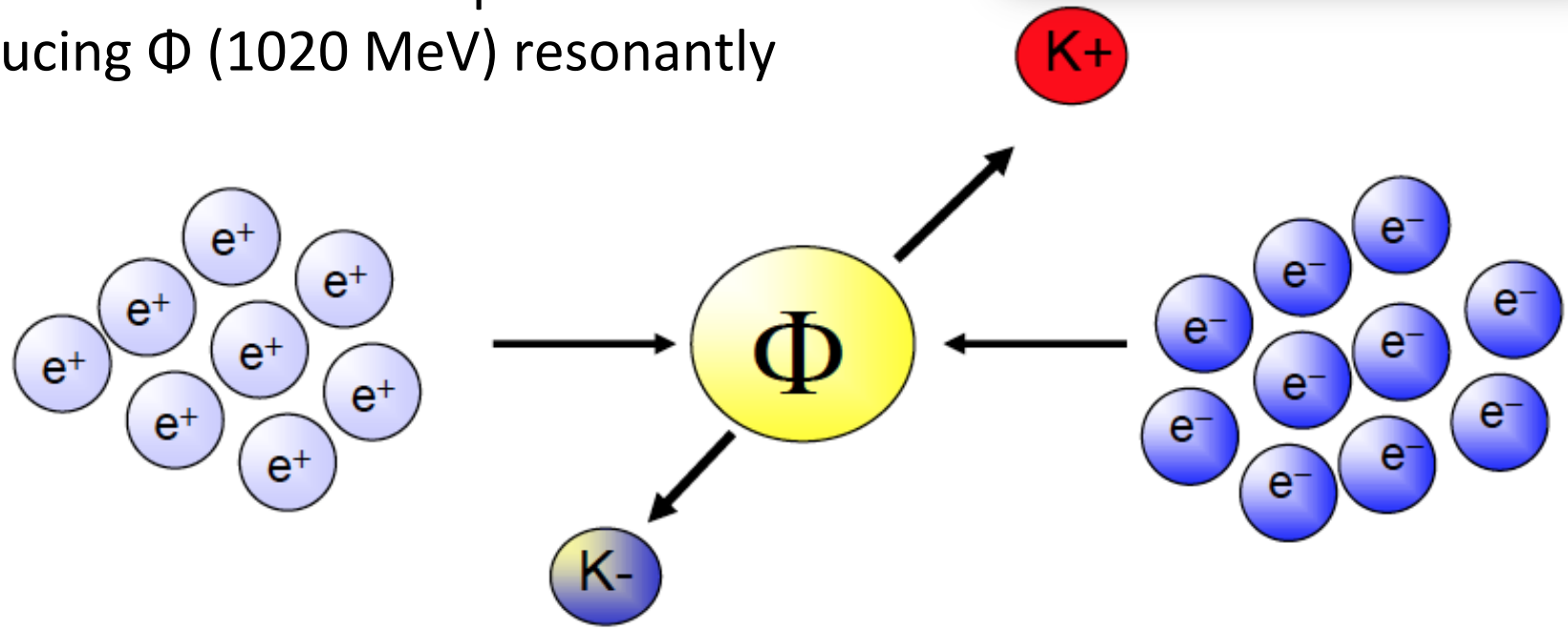


# DAΦNE:

# Φ Factory of LNF-INFN



Double anular electron-positron collider producing Φ (1020 MeV) resonantly

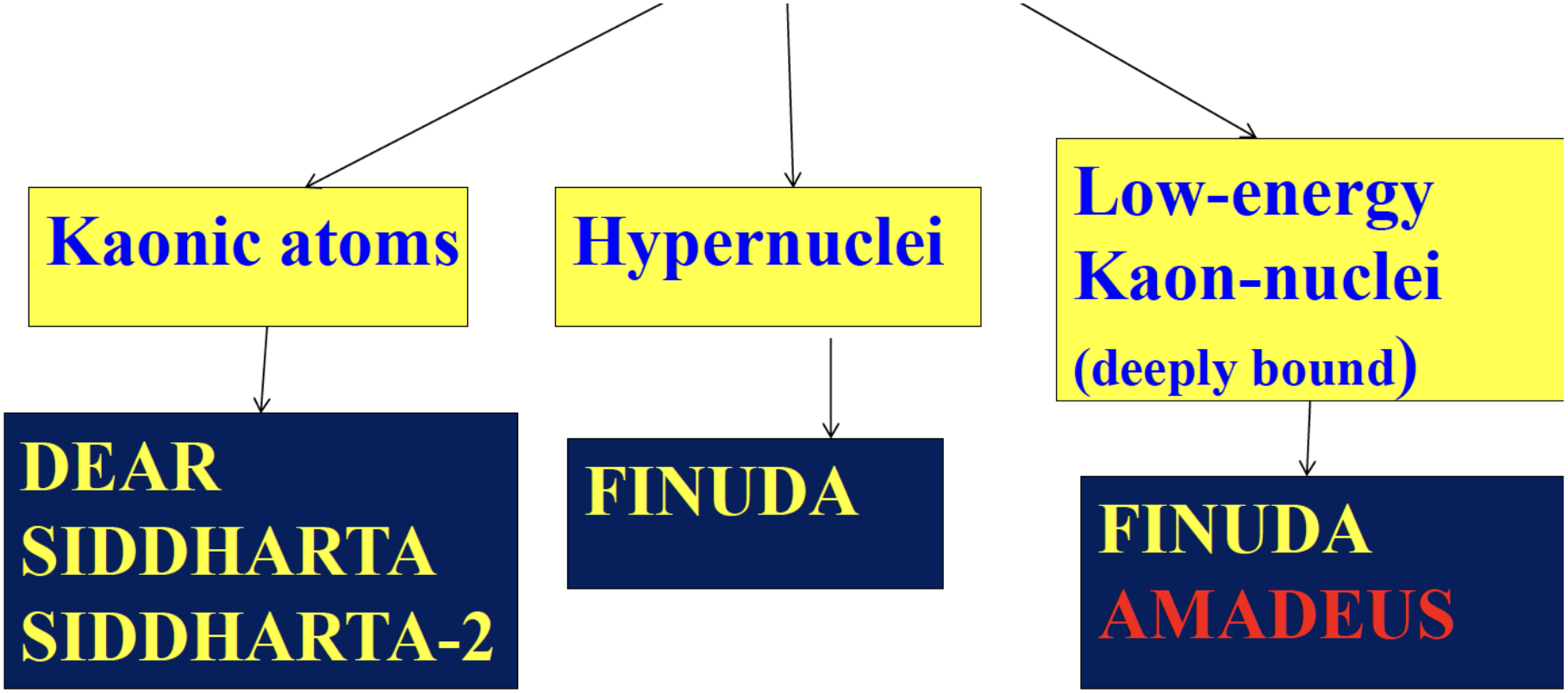



Flux of produced kaons: about 1000/second

# DAΦNE: Unique source of antikaons

- Antikaons (kaons) from the Φ vector meson decay – nearly mono-energetic $K^-$ (127MeV/c≈16 MeV)
- ≈50% branching of the two-body decay $\Phi \rightarrow K^+K^-$
- Low hadronic background kaon source
- Ideal for experiments on kaonic atoms and low-energy antikaon interactions on nuclei (AMADEUS)

# DAFNE collider: Strangeness nuclear physics research



# AMADEUS

**A**ntikaon

**M**atter

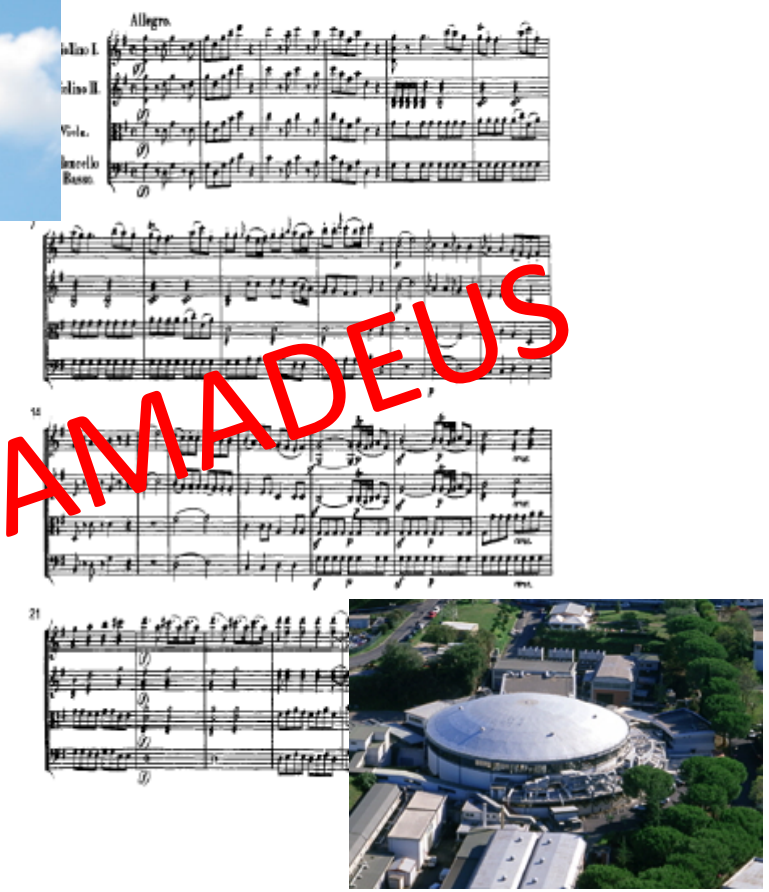
**A**t

**D**AΦNE:

**E**xperiments with

**U**nraveling

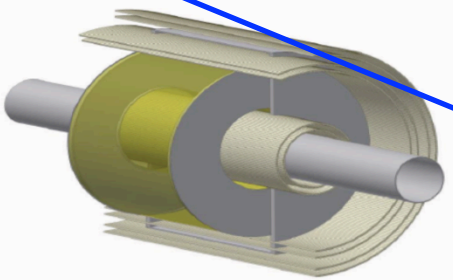
**S**pectroscopy

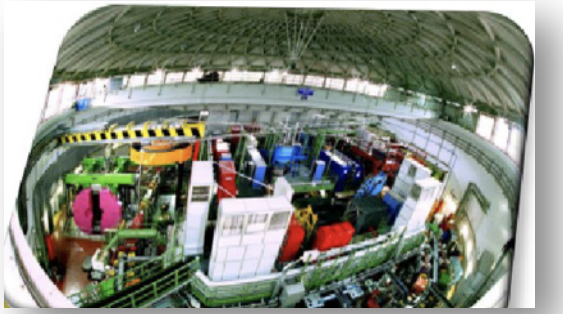


Letter of Intent

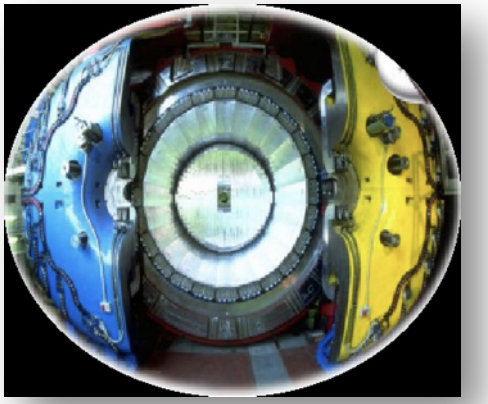
**Study of deeply bound kaonic nuclear states at DAΦNE2**

AMADEUS Collaboration





DAΦNE kaon source + KLOE



Powerful combination of DAFNE with the detector system of KLOE (96% acceptance)
Very good performance for the detection of **charged and neutral** particle in the relevant energy range

# AMADEUS

*Antikaon Matter At DAΦNE: Experiments with Unraveling Spectroscopy*

AMADEUS collaboration
116 scientists from 14 Countries and 34 Institutes

lnf.infn.it/esperimenti/siddharta
and
LNF-07/24(IR) Report on lnf.infn.it web-page (Library)

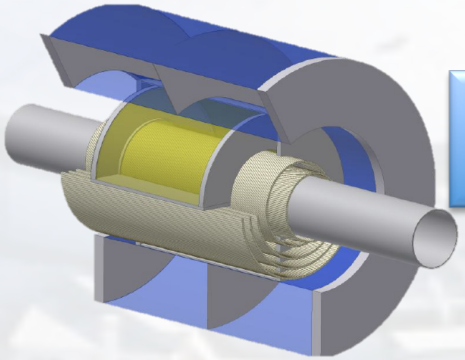
AMADEUS started in 2005 and
was presented and discussed in all the LNF Scientific Committees

EU Fundings FP7 – HP2 and HP3:
Network WP9 – LEANNIS;
WP24 (SiPM JRA);
WP28 (GEM JRA)


Kaon scattering

Subthreshold resonances

Antikaon nuclear absorption



AMADEUS- a laboratory for low-energy kaon physics

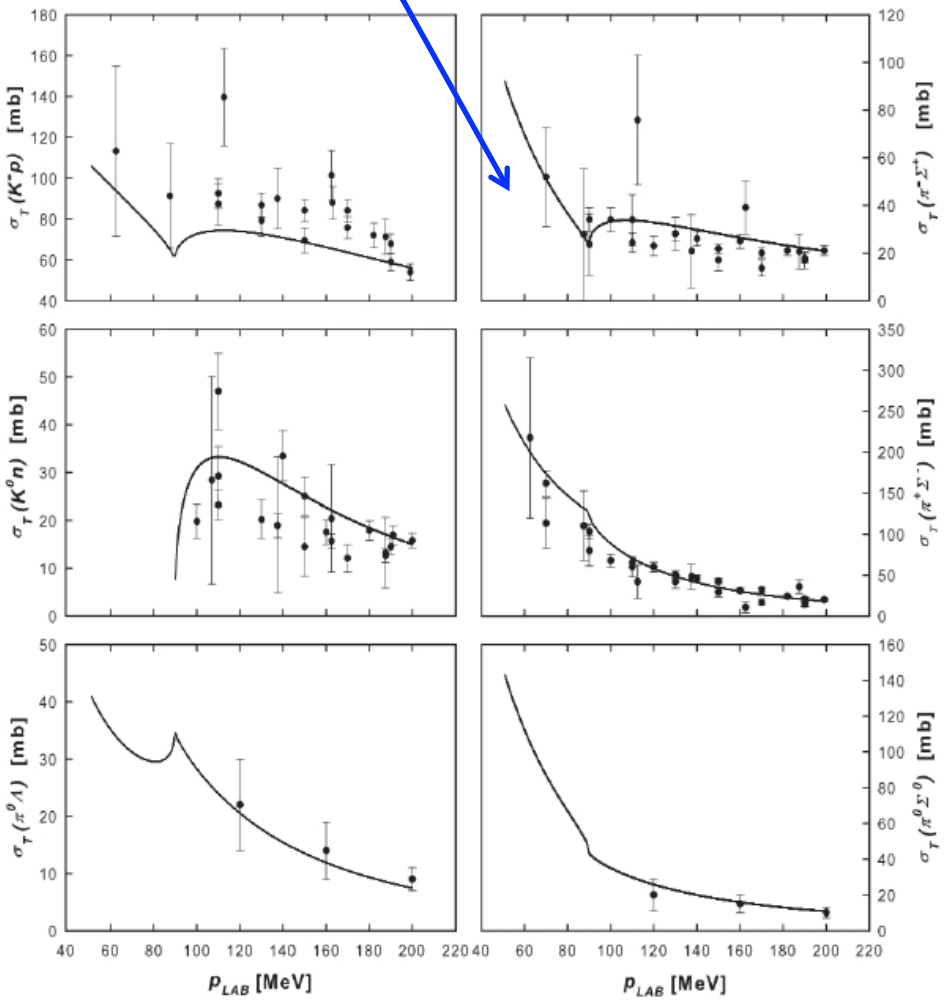
Antikaon bound states

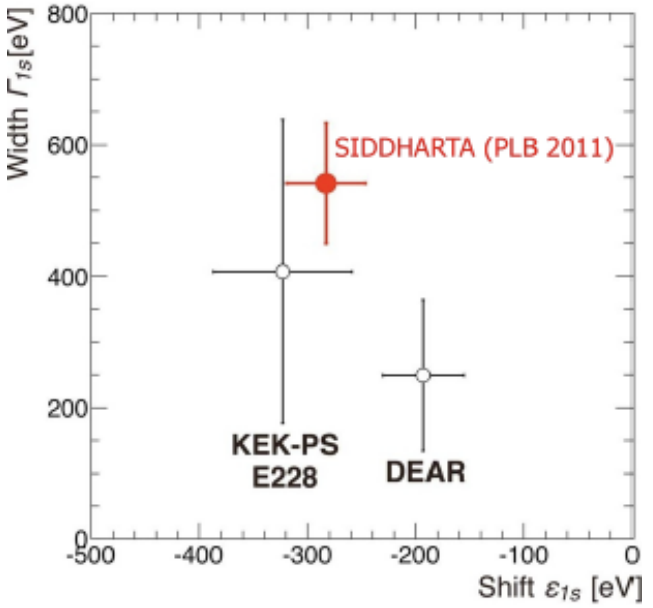
Hypernuclear physics

Consequences of strangeness for dense baryonic matter (neutron stars)?

# Kaon/antikaon scattering

Data at low momenta (<100 MeV/c) missing




Threshold data from kaonic hydrogen → SIDDHARTA

The region between threshold and ≈100 MeV → terra incognita

# Properties of hadronic resonances

PDG, Phys. Rev. D86 (2012)

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) (URL: http://pdg.lbl.gov)

## $\Lambda(1405)\ 1/2^-$

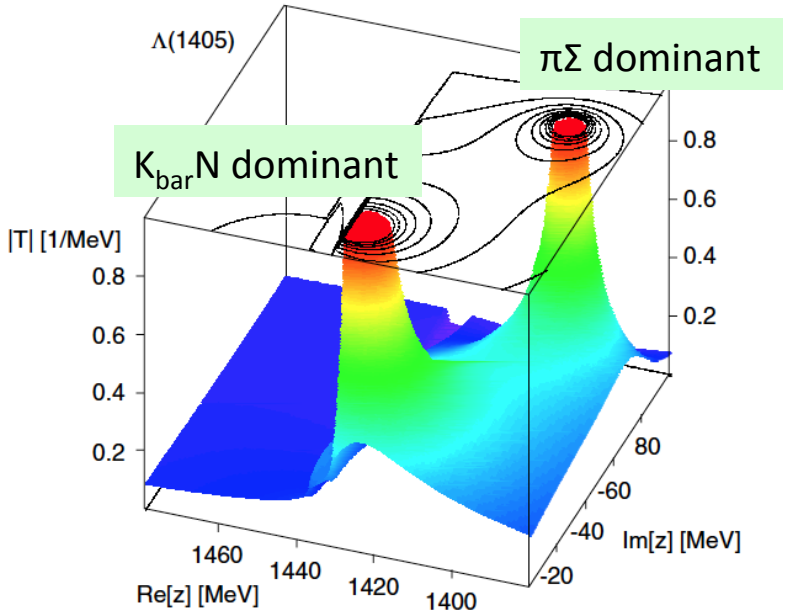
$I(J^P) = 0(\frac{1}{2}^-)$ Status: ****

### $\Lambda(1405)$ MASS

**PRODUCTION EXPERIMENTS**

| VALUE (MeV) | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$1405.1^{+1.3}_{-1.0}$ OUR AVERAGE** | | | | | |
| $1405\ ^{+1.4}_{-1.0}$ | | ESMAILI | 10 | RVUE | $^4$He $K^-$ → $\Sigma^\pm\pi^\mp X$ at rest |
| $1406.5 \pm 4.0$ | | [1] DALITZ | 91 | | M-matrix fit |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $1391 \pm 1$ | 700 | [1] HEMINGWAY | 85 | HBC | $K^- p$ 4.2 GeV/$c$ |
| ~ 1405 | 400 | [2] THOMAS | 73 | HBC | $\pi^- p$ 1.69 GeV/$c$ |
| 1405 | 120 | BARBARO-... | 68B | DBC | $K^- d$ 2.1–2.7 GeV/$c$ |
| $1400 \pm 5$ | 67 | BIRMINGHAM | 66 | HBC | $K^- p$ 3.5 GeV/$c$ |
| $1382 \pm 8$ | | ENGLER | 65 | HDBC | $\pi^- p$, $\pi^+ d$ 1.68 GeV/$c$ |
| $1400 \pm 24$ | | MUSGRAVE | 65 | HBC | $\bar{p}p$ 3–4 GeV/$c$ |
| 1410 | | ALEXANDER | 62 | HBC | $\pi^- p$ 2.1 GeV/$c$ |
| 1405 | | ALSTON | 62 | HBC | $K^- p$ 1.2–0.5 GeV/$c$ |
| 1405 | | ALSTON | 61B | HBC | $K^- p$ 1.15 GeV/$c$ |

## $\Lambda(1405)$ one- or two-pole object??




T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67 (2012) 55-98

# Antikaon absorption in nuclei

1) $K^-$ Y π CORRELATION

'p' , 'n' BOUND nucleons

- $K^-$ 'n' → Λπ⁻ (direct formation) → Σ(1385) I=1

- $K^-$ 'p' → $\Sigma^0\pi^0$ → Λ(1405) I=0
- $K^-$ 'p' → $\Sigma^+\pi^-$ → $\Lambda^* + \Sigma^*$

To measure the amount of resonant capture → position of the resonance

2) Y N CORRELATION

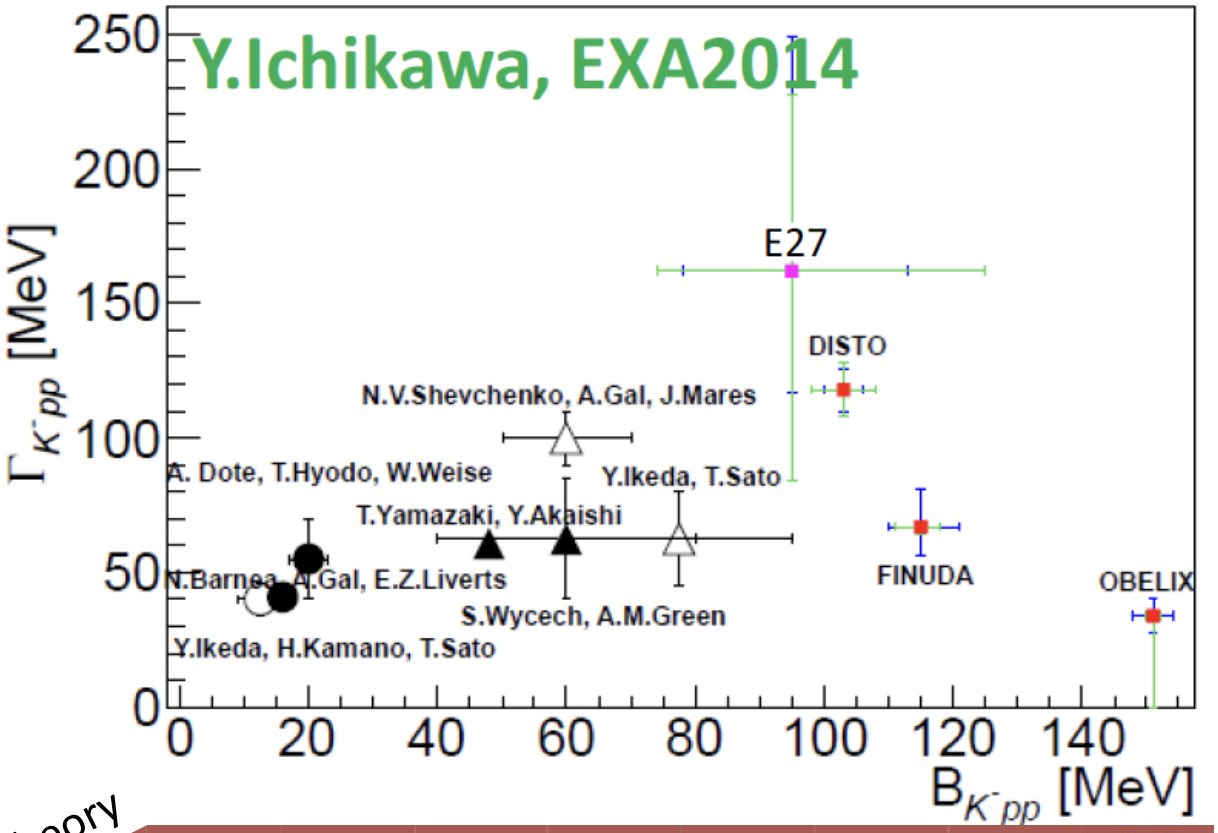
- $K^-$ 'pp' → $\Lambda/\Sigma^0$ p (without YN scattering) → $(K^-\text{ 'pp'})^{B.S.}$
- $K^-$ 'ppn' → Λ d (without YN scattering) → $(K^-\text{ 'ppn'})^{B.S.}$
- $K^-$ 'ppnn' → Λ t → rare 4NA

search for possible bound states

- with YN scattering → to get information on $U_{YN}$

# Quasi-bound kaonic nuclei ?

Decay widths and binding energies from experiment and theory:




Theory

| | Dote,Hyodo, Weise | Akaishi, Yamazaki | Barnea, Gal, Liverts | Ikeda, Sato | Ikeda, Kamano,Sato | Schevchenko ,Gal, Mares | Revai, Schevchenko | Maeda, Akaishi, Yamazaki |
|---|---|---|---|---|---|---|---|---|
| B (MeV) | 17-23 | 48 | 16 | 60-95 | 9-16 | 50-70 | 32 | 51.5 |
| Γ(MeV) | 40-70 | 61 | 41 | 45-80 | 34-46 | 90-110 | 49 | 61 |

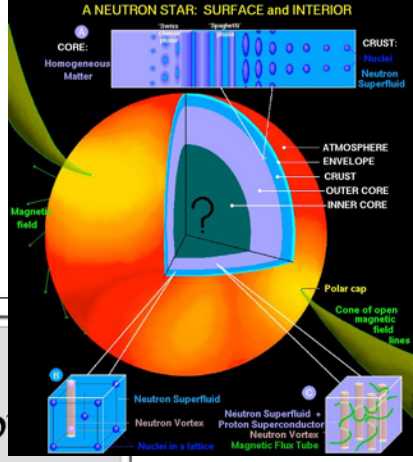
The present knowledge from experiment and theory is still insufficient to make a clear statement about quasi-bound kaonic nuclear systems

- Experiments so far:

FINUDA
KEK
DISTO
FOPI
HADES
OBELIX
J-PARC E15, E27

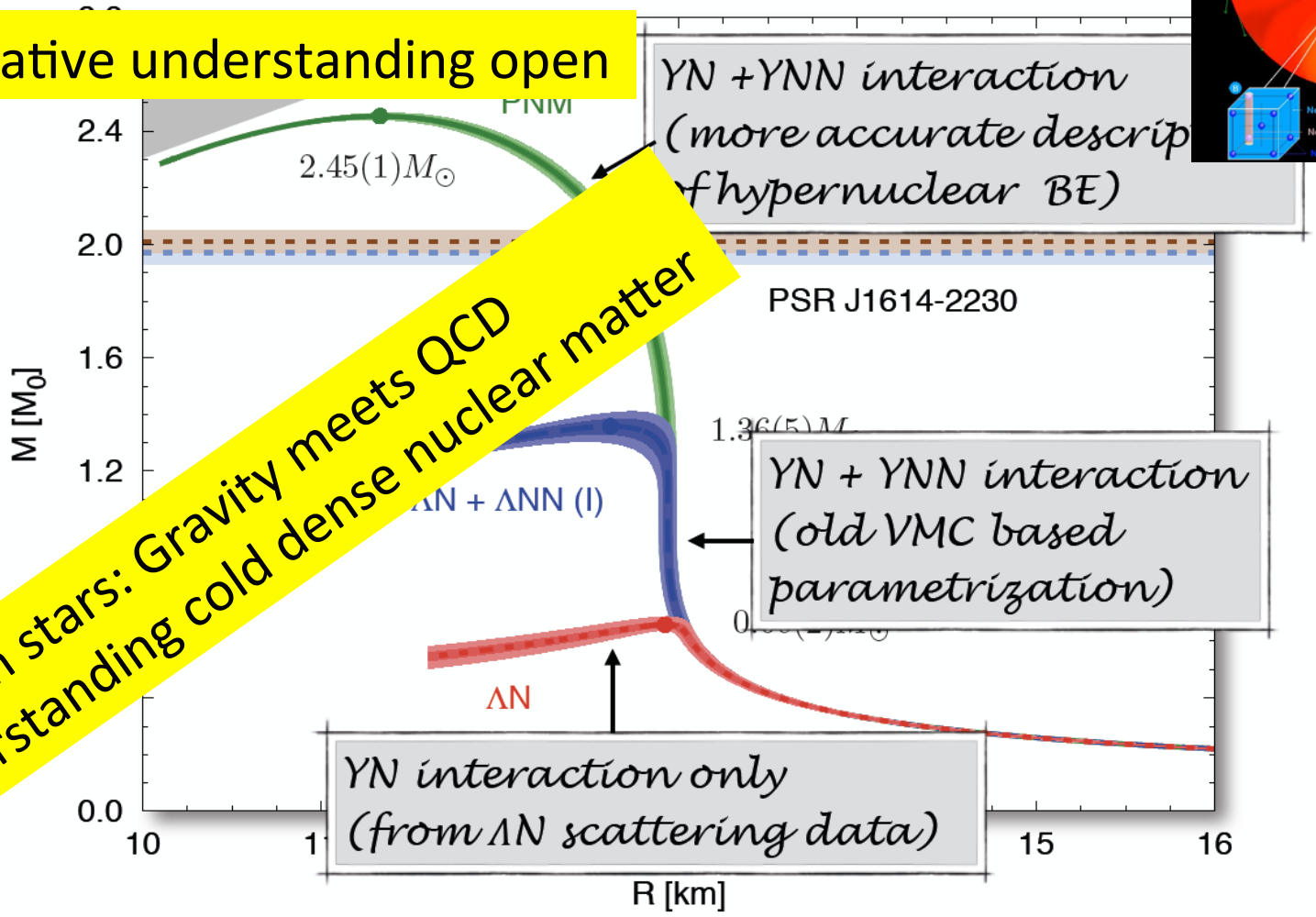
- Future: AMADEUS

# Strangeness in Neutron Stars?




Quantative understanding open

Neutron stars: Gravity meets QCD
Understanding cold dense nuclear matter




YN +YNN interaction
(more accurate descrip
f hypernuclear BE)

YN + YNN interaction
(old VMC based
parametrization)

YN interaction only
(from ΛN scattering data)

Diego Lonardoni, Alessandro Lovato, Stefano Gandolfi, and Francesco Pederiva, Phys. Rev. Lett. **114** (2015), 092301

# Hypernuclear studies: Neutron-rich hypernuclei

- Neutron-rich hypernuclei produced by stopped $K^-$
- Studies of mesonic and non-mesonic decays
  → detection of charged and neutral particles
  (e.g. $\pi^0$ spectroscopy)

Examples

- Direct production (yield $10^{-3} - 10^{-4}$ /$K_{stop}$)
  ($K^-$, $\pi^0$) process

$K^-_{stop}\ {}^{6}Li \rightarrow {}^{6}_{\Lambda}He\ \pi^0$ Never observed

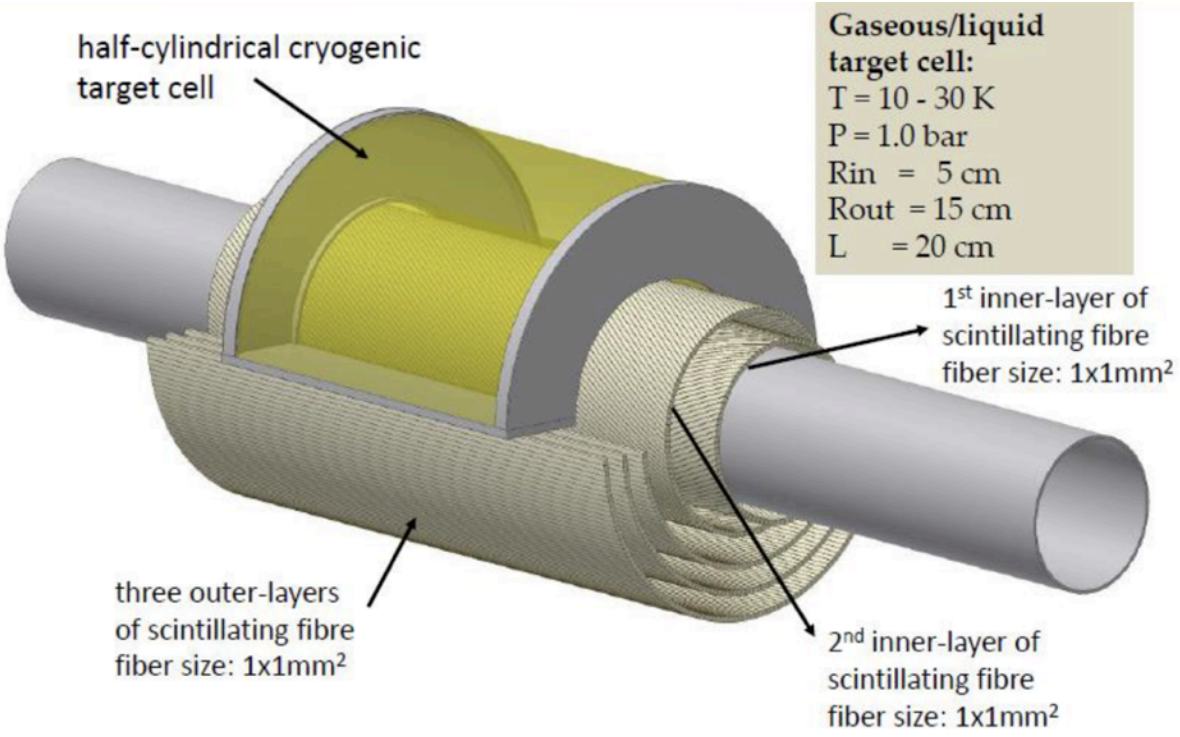
$K^-_{stop}\ {}^{7}Li \rightarrow {}^{7}_{\Lambda}He\ \pi^0$ Claimed at JLAB, confirmation required

- 2-step process (yield $10^{-5} - 10^{-6}$ /$K_{stop}$)
  ($K^-$, $\pi^+$) process

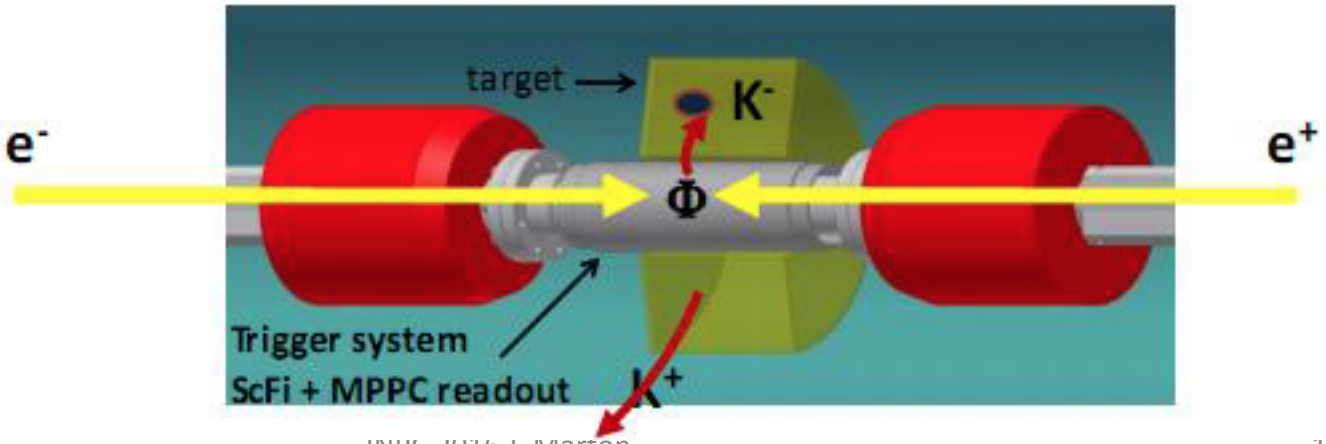
$K^-_{stop}\ {}^{6}Li \rightarrow {}^{6}_{\Lambda}H\ \pi^+$ 3 events seen in FINUDA, comfirmation open

$K^-_{stop}\ {}^{7}Li \rightarrow {}^{7}_{\Lambda}H\ \pi^+$ Never observed

# Possible AMADEUS Setup




Axial magnetic field: 0.5T



# Calorimeter

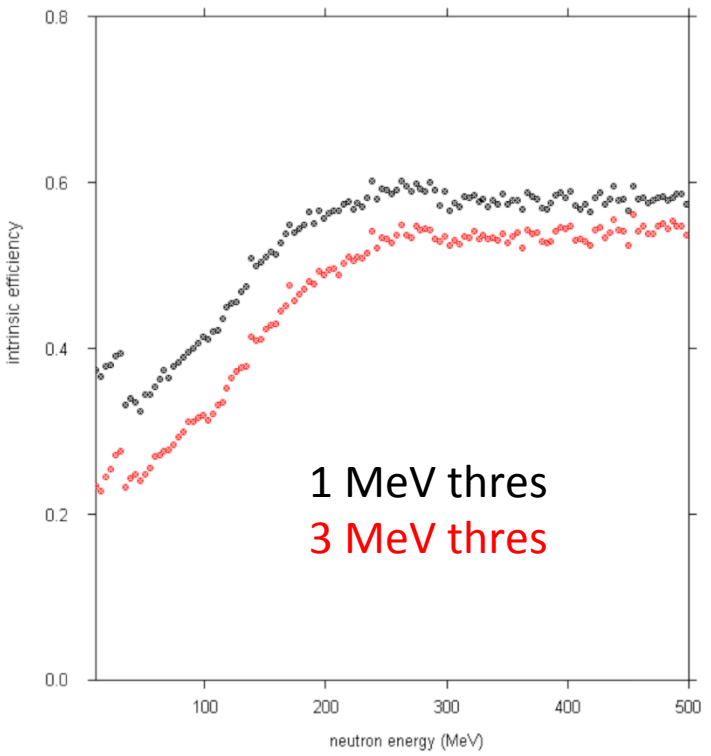
Nuclear Instruments and Methods in Physics Research A 598 (2009) 244–247

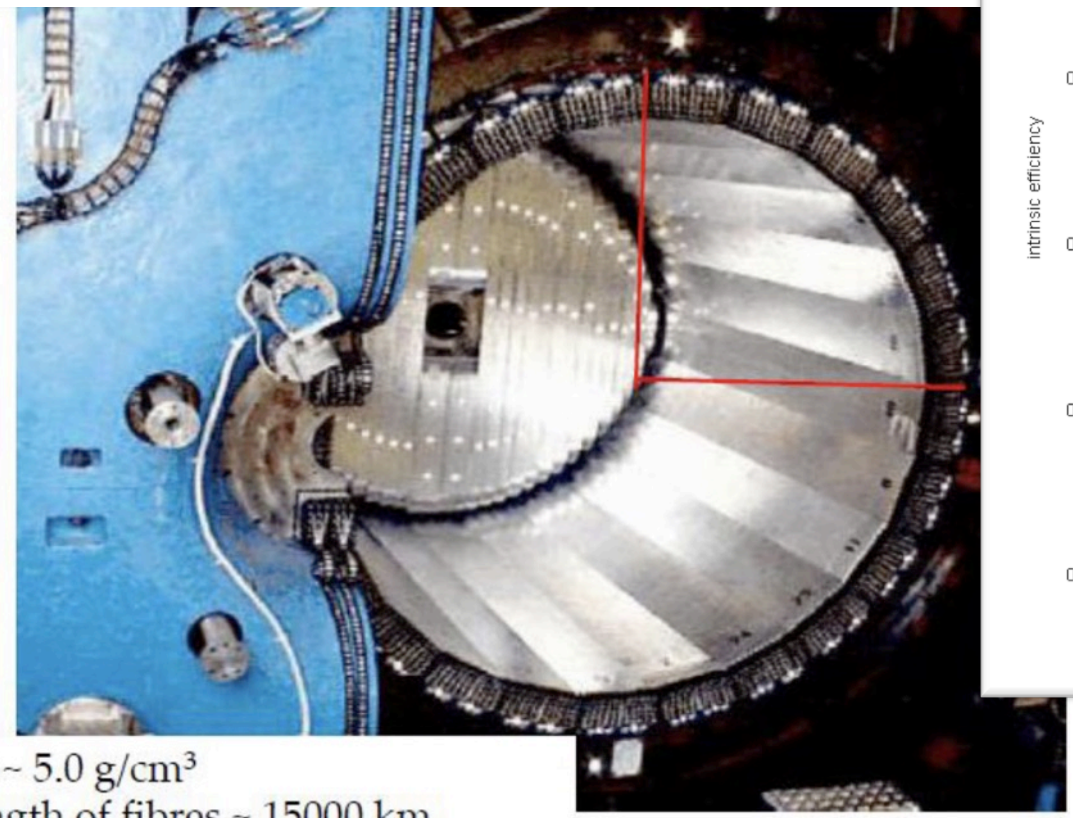
Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Measurement of the detection efficiency of the KLOE calorimeter for neutrons between 22 and 174 MeV



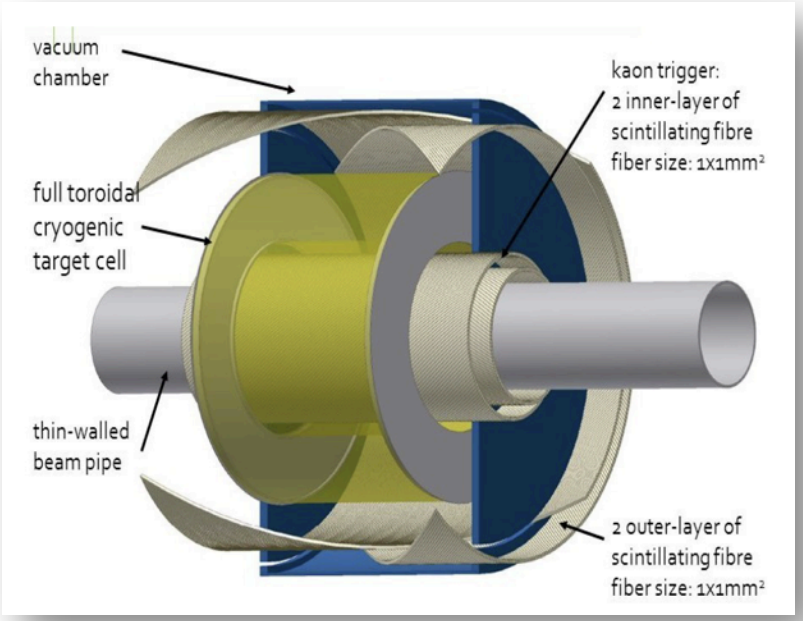



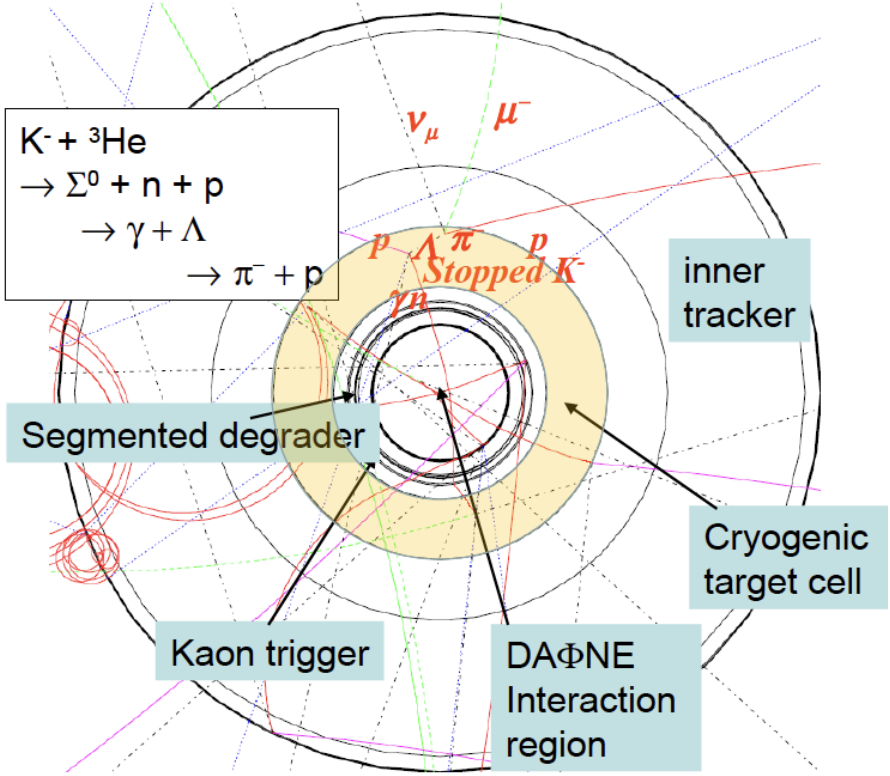
density ~ 5.0 g/cm³
total length of fibres ~ 15000 km
read out by ~ 5000 mesh PM

$\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$

98 % solid angle coverage

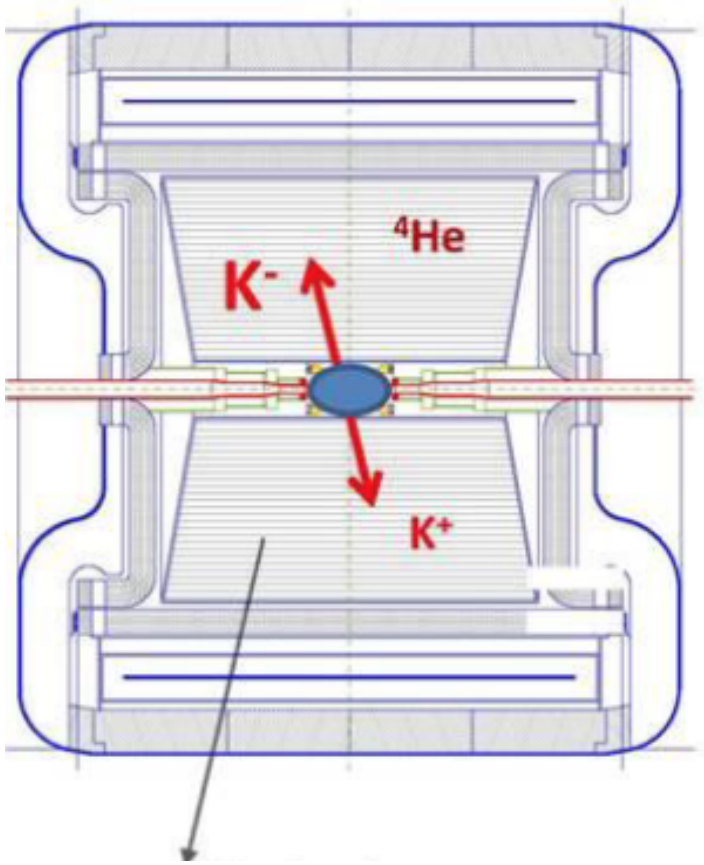
# AMADEUS setup: Example $K^-$ absorption on $^3He$




MC simulation of tracks in
A dedicated AMADEUS setup
With a $^3He$ cryogenic target.
Tracks after $K^-$ reaction on $^3He$.

# Pre-AMADEUS studies with KLOE data

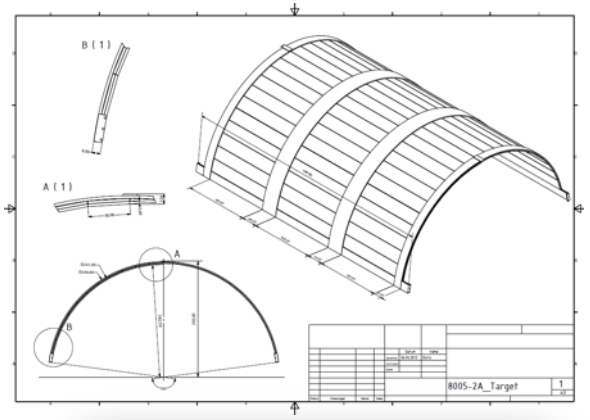


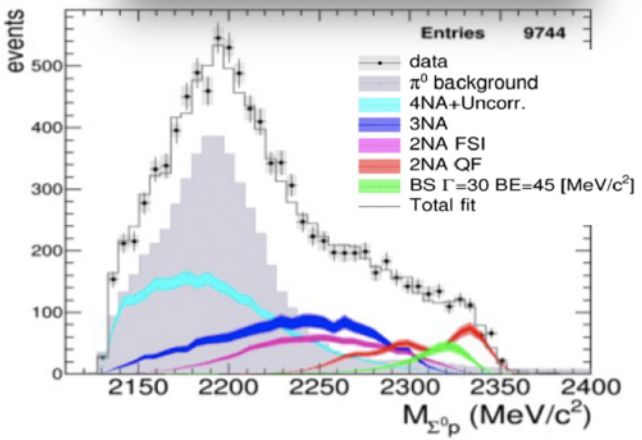

KLOE Drift Chamber (DC)

- Study of antikaon interaction in nuclear matter following $K^-$ absorption in the DC gas (or structure materials)
- KLOE drift chamber (DC) gas: mainly $^4$He (90% $^4$He, 10% isobutane $C_4H_{10}$)
- 0.1% $K^-$ stop in the DC gas (Monte Carlo, data analysis)
- Enables the study of $K^-$ absorption and searches for bound states (e.g. with 2 $fb^{-1}$ hundreds of kaonic clusters) – analysis of $\Lambda/\Sigma$ – p,d, t correlations
- However: Analysis complicated due to material mix

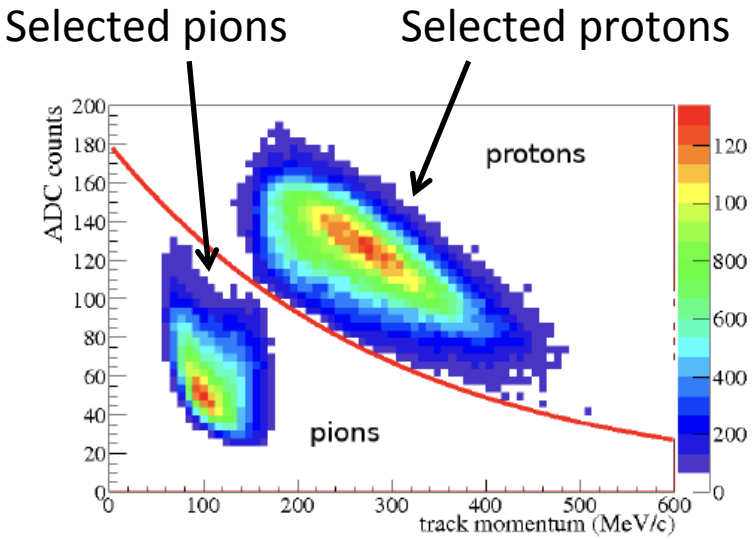
# Pre-AMADEUS

- Analyses of KLOE data collected 2004 – 2005
- Special setup with a pure carbon “target” inserted into KLOE (2012) – gain in statistics (90 $pb^{-1}$), K- absorption in carbon at rest)
- Investigation of topics:
  - Λp, $\Sigma^0$p from 1NA or 2NA (single/double nucleon absorption), search for $K^-$pp
  - Λ-d nuclear absorption and search for $K^-$ppn, Λ-t
  - Λ(1405) → $\Sigma^0\pi^0$ and Λ(1405) → $\Sigma^+\pi^-$
  - ΣN/ΛN internal conversion rates
- R&D for optimized setup

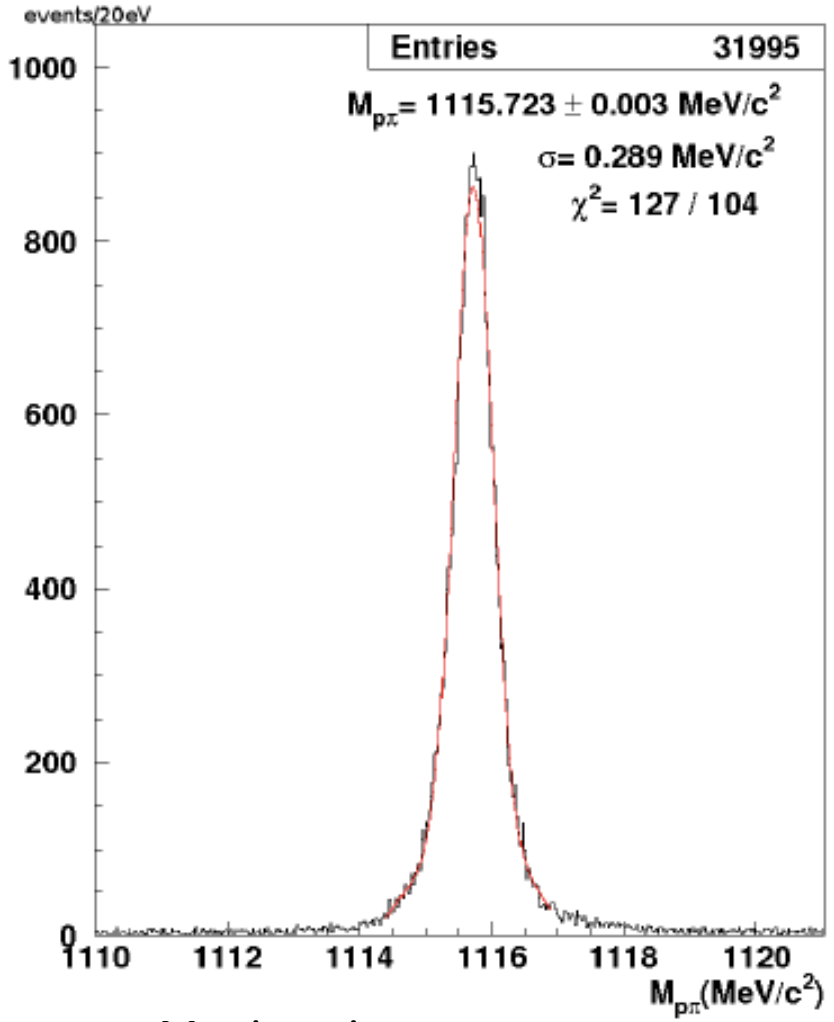


# Data analysis: Λ(1116) selection




dE/dx (ADC counts) - momentum

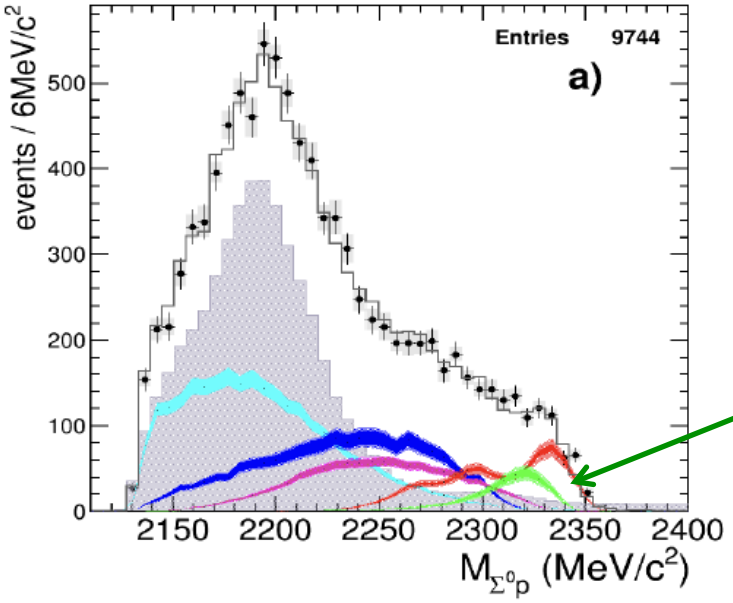



$M_{p\pi^-}$ invariant mass spectrum

# Recent results from Pre-AMADEUS

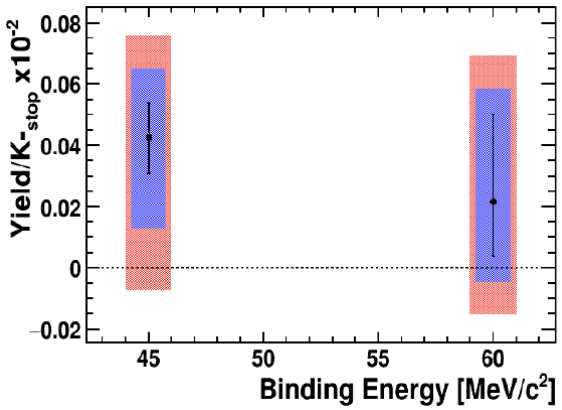
**K⁻ absorption on two nucleons and ppK⁻ bound state search in the $\Sigma^0$p final stat**

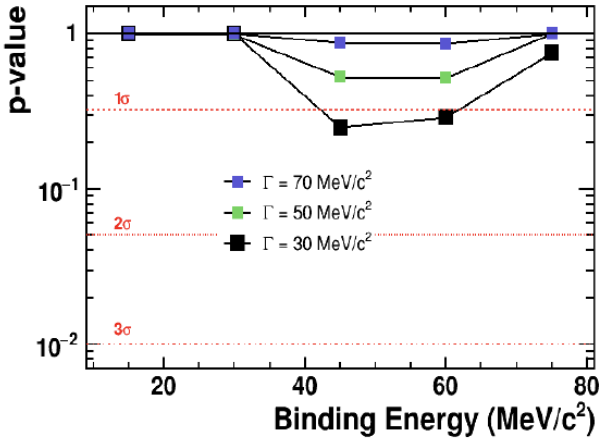
O. Vázquez Doce[1,2], L. Fabbietti[1,2], M. Cargnelli[3], C. Curceanu[4], J. Marton[3], K. Piscicchia[4,5], A. Scordo[4], D. Sirghi[4], I. Tucakovic[4], S. Wycech[6], J. Zmeskal[3], A. Anastasi[4,7], F. Curciarello[7,8,9], E. Czerwinski[10], W. Krzemien[6], G. Mandaglio[7,11], M. Martini[4,12], P. Moskal[10], V. Patera[13,14], E. Pérez del Rio[4] and M. Silarsk




$L_{int}$= 1.74 fb$^{-1}$
$K^-_{stop}$ = 3.25 $10^8$

K-pp ?



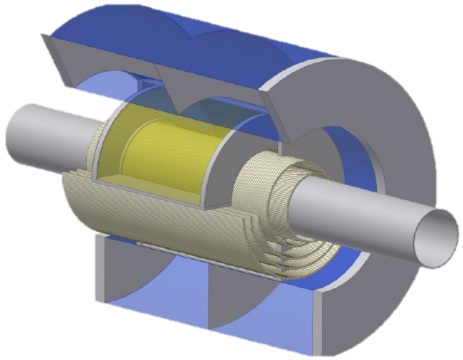

ppK⁻/K−stop=(0.044±0.009stat+0.004−0.005syst)·10⁻²

Significance 1σ – not sufficient to claim ppK⁻ observation

Physics Letters B, Volume 758, 10 July 2016, Pages 134-139

# Summary

The Pre-AMADEUS program demonstrated already the enormous potential of the KLOE detector for strangeness nuclear physics.



The dedicated AMADEUS setup will provide a powerful laboratory for experimental studies of antikaon induced reactions employing low-energy or stopped kaons reacting in targets (feasibility of active targets, TPC).

*Thank you for your attention*