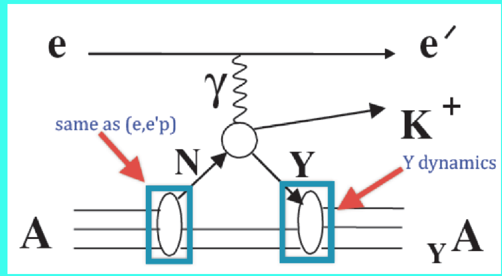
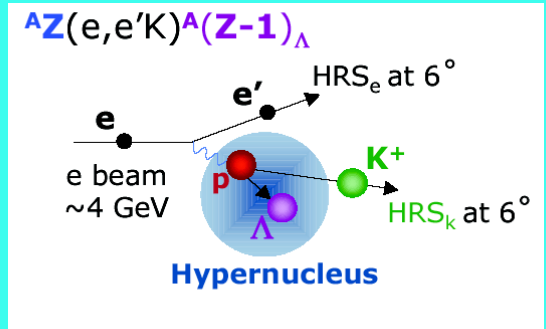
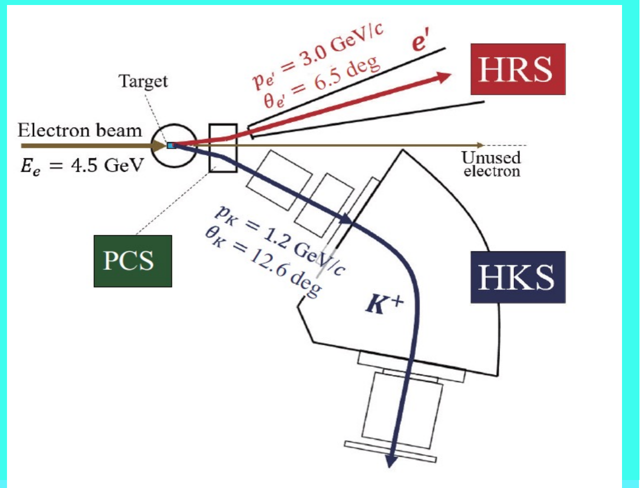
Studying Λ interactions in nuclear matter with the $^{208}Pb(e,e'K^+)^{208}_{\Lambda}Tl$

F. Garibaldi - Jlab - 03-03-2023

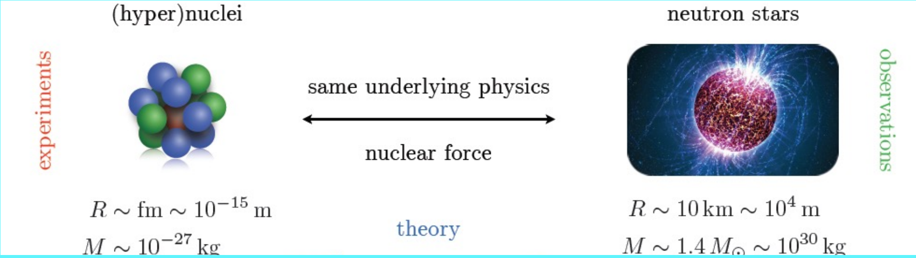
- The physics
- Why $^{208}\mathrm{Pb}(\mathrm{e},\mathrm{e}'\mathrm{K}^+)^{208}_{\Lambda}\mathrm{Tl}$?
  - Theory framework
  - The experiment
- Summary and conclusions







The hyperon dynamics

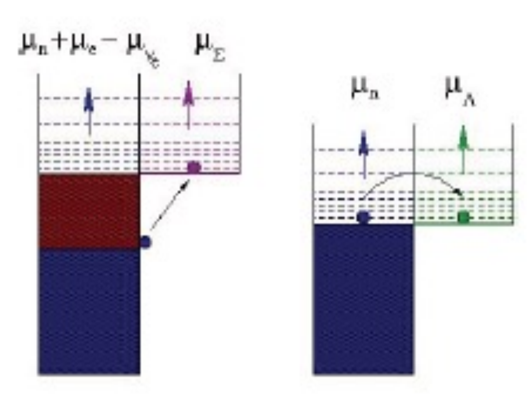


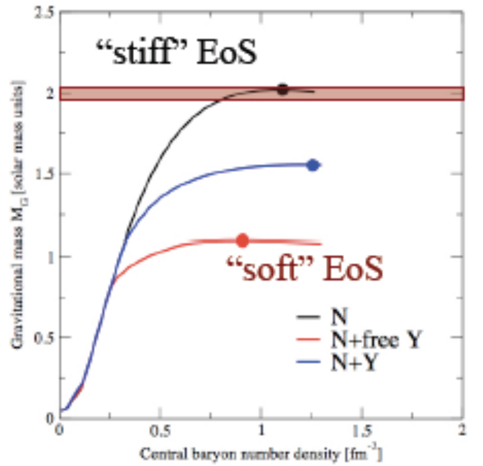
Neutron stars are remnants of the gravitational collapse of massive stars having masses of (1-2 Mo ~ 2 x 10^{33} Kg)

They are excellent observatories to test fundamental properties of nuclear matter under extreme conditions and offer interesting interplay between nuclear processes and astrophysical observables

Hyperons are expected to appear in their core at $\rho \sim (2\text{-}3)\rho_0$ when μ_N is large enough to make conversion of N to Y energetically favorable

but





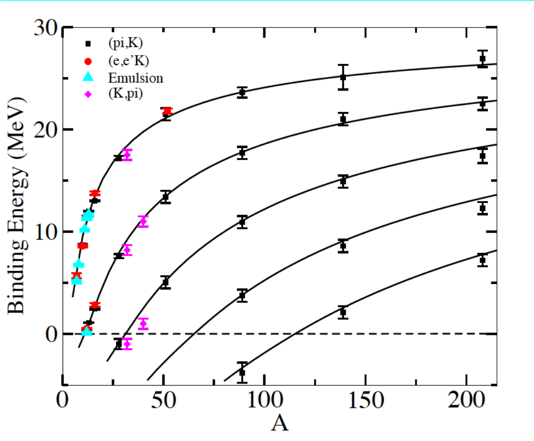
The relief of the Fermi pressure due to its appearance → EoS stiffer → reduction of the mass to values incompatible with observation (~ 2 Mo that requires much stiffer EoS)

Strong softening of the EoS of dense matter due to the appearance of hyperons which leads to maximum masses of compact stars that are not compatible with the observations.

The present understanding of the nuclear interactions involving hyperons is far from being complete. The reason is in a combination of an incomplete knowledge of the forces governing the system (in the hypernuclear case both two- and three-body forces), and in the concurrent use of approximated theoretical many-body techniques.

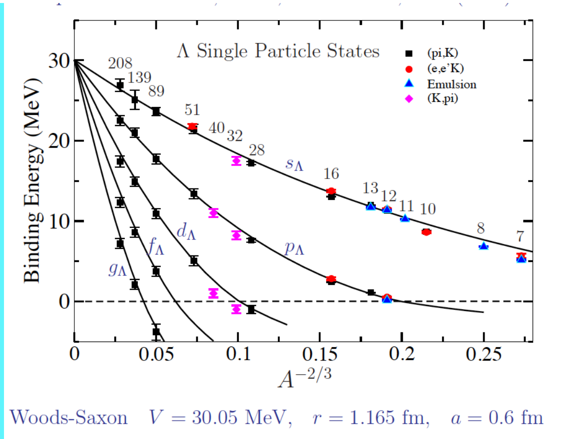
The use of the Pb target will allow us to investigate hypernuclear dynamics in a new environment, in which three-body interactions are expected to play an important role. This will allow us, in the framework of a more general approach, to study the hyperon puzzle in a complementary way with respect to the approved proposal ${}^{40}_{\Lambda}K$ and ${}^{48}_{\Lambda}K$ on isospin dependence of ΛNN

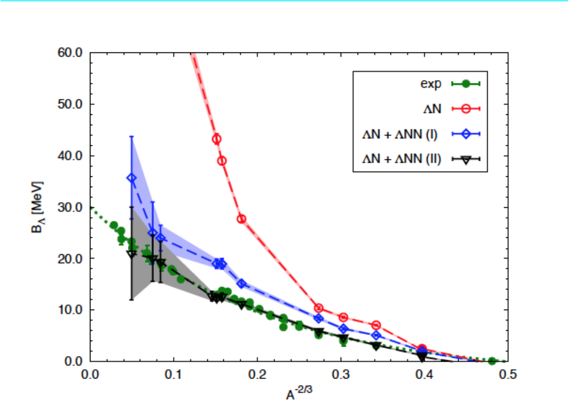
In fact it has been suggested that three body forces could provide additional repulsion making the EOS stiffer enough to help solving the hyperon puzzle



Millener

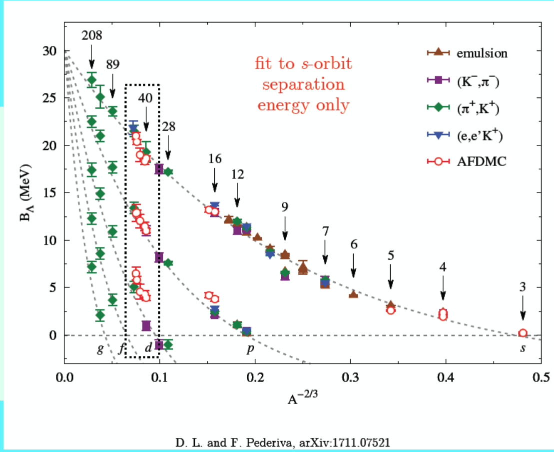
the spacings of the single-particle energies as a function put more constraints on the theoretical fits. Skyrme includes 3-body





Lonardoni

the effect of including the ΛNN termin in the Hamiltonian is very strong. It provides the repulsion necessary to realistically reproduce the limiting value of B_Λ



Vidana

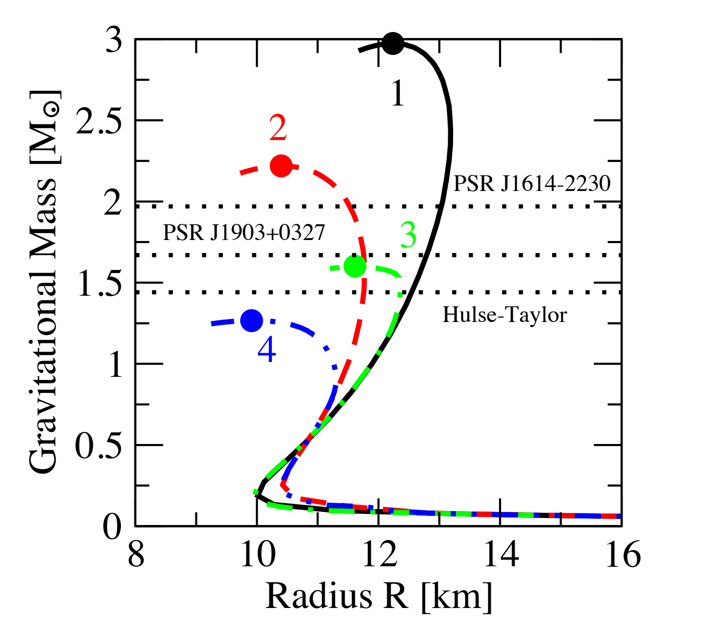
Effect of NNΛ interaction on hypernuclei

Λ separation energy in $^{41}_{\Lambda}$Ca, $^{91}_{\Lambda}$Zr & $^{209}_{\Lambda}$Pb

	$^{41}_{\Lambda}$Ca	$^{91}_{\Lambda}$Zr	$^{209}_{\Lambda}$Pb
NSC97a	23.0	31.3	38.8
NSC97a+NNΛ$_1$	14.9	21.1	26.8
NSC97a+NNΛ$_2$	13.3	19.3	24.7
NSC97e	24.2	32.3	39.5
NSC97e+NNΛ$_1$	16.1	22.3	27.9
NSC97e+NNΛ$_2$	14.7	20.7	26.1
Exp.	18.7(1.1)*	23.6(5)	26.9(8)

Only hypernuclei described as a closed shell nuclear core + a Λ sitting in a s.p. state are considered. Comparison with the closest hypernucleus for which exp. data is available

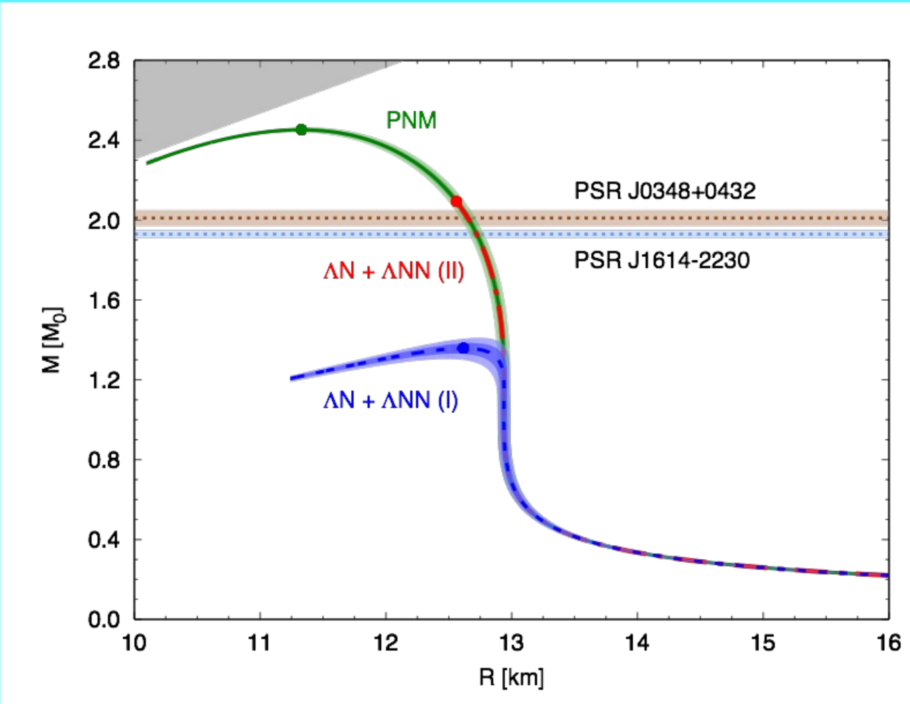
Inclusion of ΛNN improves the agreement with data for $^{91}\Lambda$Zr & $^{209}\Lambda$Pb.



It clearly appears that the inclusion of YNN forces (curve 3) leads to a large increase of the maximum mass, although the resulting value is still below the two solar mass line.

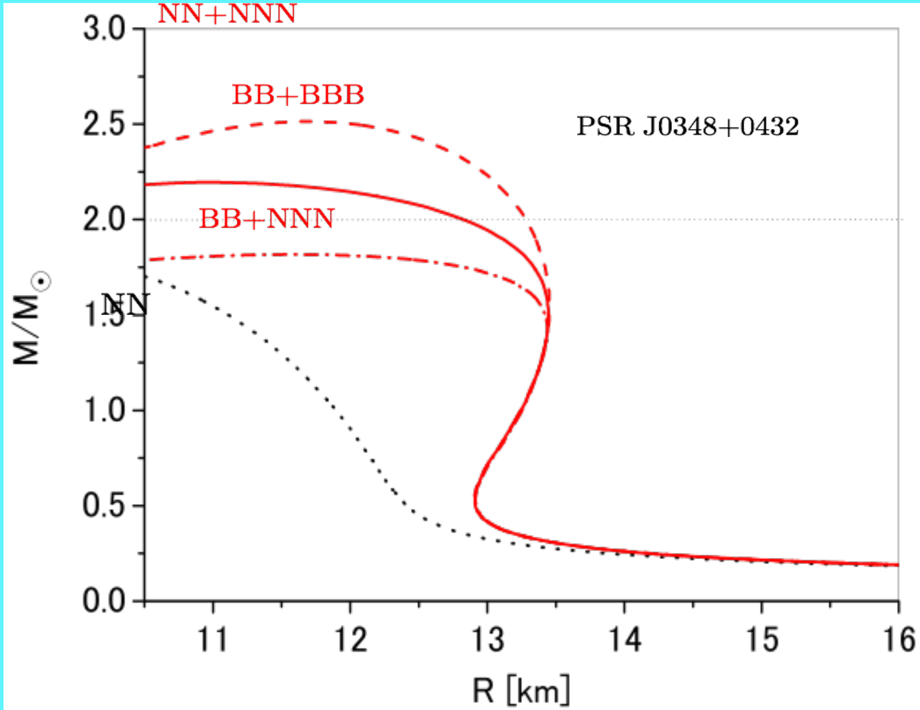
1. Nucleons without 3 body forces
2. Nucleons with 3 body forces
3. Λ and N with 3 body forces(ΛNN)
4. Λ and N without 3 body force

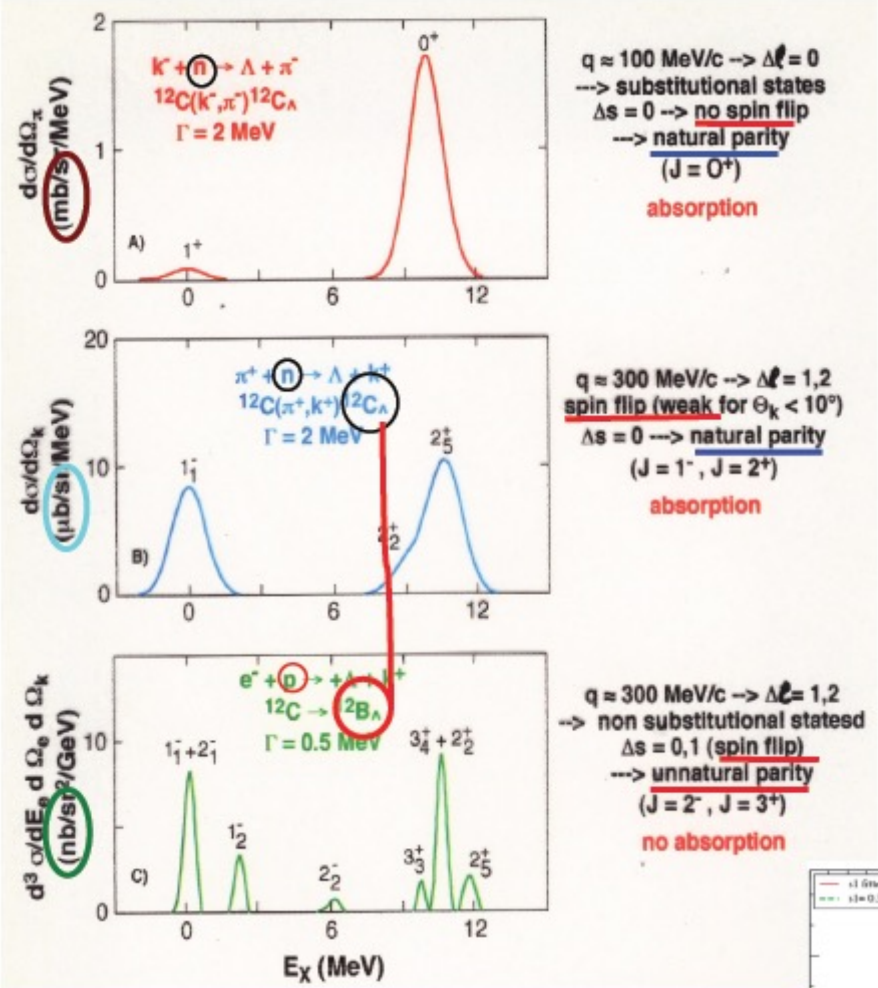
D.Lonardoni *et al.*, Phys. Rev. Lett. 114, 092301 (2015) (AFDMC)

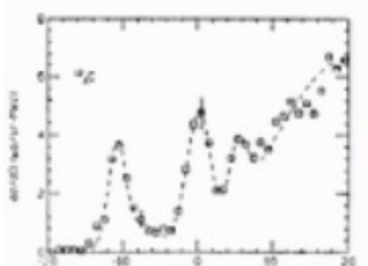


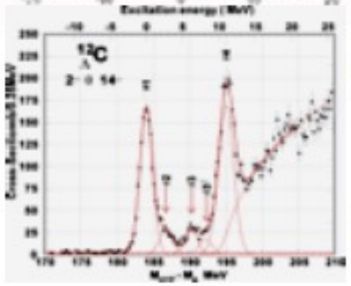
Y. Yamamoto *et al.*, Phys. Rev. C 90, 045805 (2014)

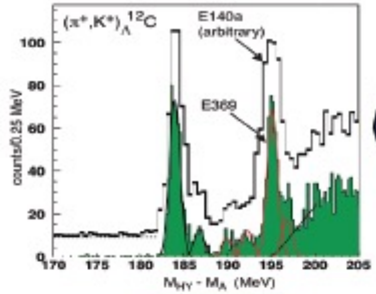
G-Matrix: ESC08 + MPa

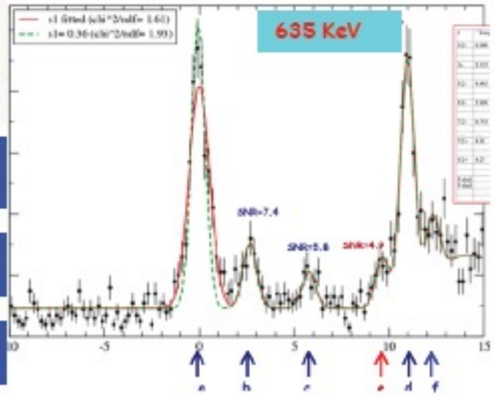












BNL 3 MeV

KEK336 2 MeV

Improving energy resolution

~ 1.5 MeV

and

using electromagnetic probe

High resolution, high yield, and systematic study is essential

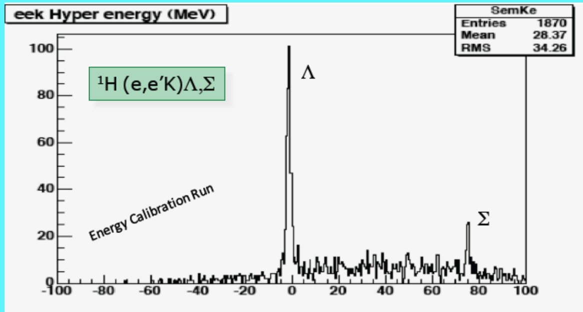
new aspects of hyernuclear structure

production of mirror hypernuclei

energy resolution ~ 500 KeV

(e,e'K+) hypernuclear spectroscopy provides information on the cross section as well as on the binding energy. These information are complementary to the information obtained by decay product studies such as gamma and decay-pion spectroscopies

Hypernuclear spectroscopy is the only method that can measure the absolute binding energy for ground and excited states with an high accuracy (~ 70 KeV)



Energy calibration IS important !

We are proposing to extend the experimental study of kaon electroproduction to the ^{208}Pb(e,e′K$^+$)$^{208}{}_{\Lambda}$Tl reaction.

It is a complementary (to the $^{40}{}_{\Lambda}$K and $^{48}{}_{\Lambda}$K experiment that was approved by PAC 45) way to address the same problem ("hyperon puzzle").

In fact E12-15-008 will allow us to extract isospin dependence of the 3-body ΛNN force

Three-body ΛNN forces are known to be strongly A-dependent, making the ^{208}Pb target uniquely suited to study Λ interaction in a uniform nuclear medium with large neutron excess

The contribution of three-nucleon forces, which is known to be large and repulsive in nuclear matter at equilibrium density, is believed to be much smaller and attractive in ^{40}Ca

Theoretical framework

Exploiting K^+ electroproduction data to constrain the models of hyperon dynamics requires a quantitative understanding of the nucleon sector

A framework has been developed (O.Benhar*, P. Bydzowsky**, I.Vidana***) to carry out calculations of the nuclear $(e,e'K^+)$ cross section within the formalism of nuclear many-body theory, which has been extensively and successfully employed to study the proton knockout, $(e,e'p)$ reaction. In fact, the clear connection between $(e,e'p)$ and $(e,e'K^+)$ processes that naturally emerges from the proposed analysis, shows that the missing energy spectra measured in $(e,e'p)$ experiments provide the baseline for a model-independent determination of the hyperon binding energies

** New Elementary calculations have been performed

*** Microscopic calculations of the Λ spectral function in a variety of nuclei, ranging from ^{5}He to ^{208}Pb, have been recently carried out (Vidana)

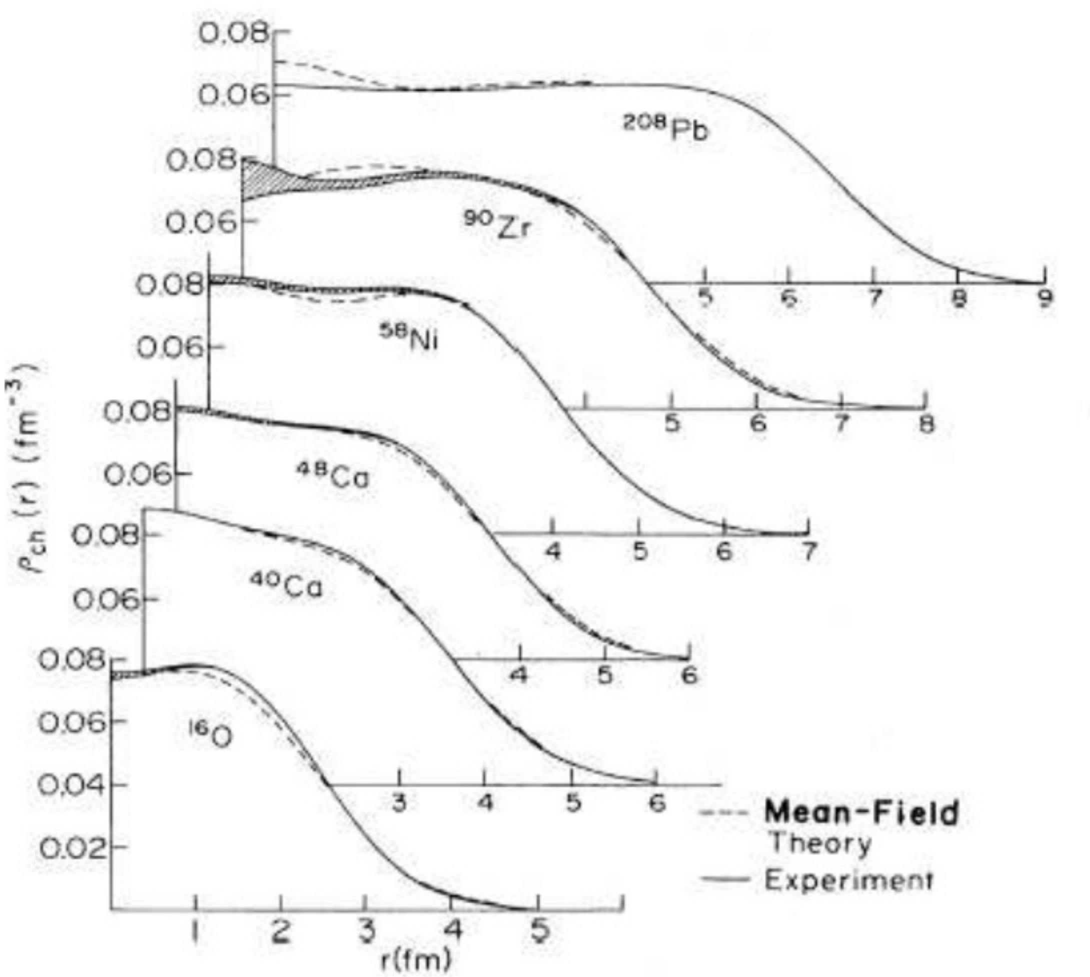
**** Cross sections for the new kinematics have been calculated by T. Motoba

***** and J. Millener

******* Calculations by Millener, Vidana, Lonardoni et al for A dependence

******** G-matrix calulations by Y. Yamamoto *et al.*

B. Frois and C.N. Papanicolas, Ann. Rev. Nucl. Part. Sci. 37, 133 (1987)

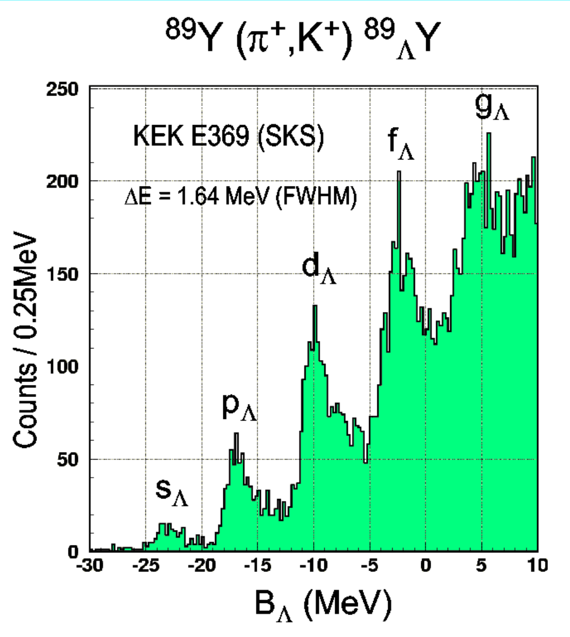


The measured charge density distribution of ^{208}Pb clearly shows that the region of nearly constant density accounts for a very large fraction (~70 %) of the nuclear volume, thus suggesting that its properties largely reflect those of uniform nuclear matter in the neutron star

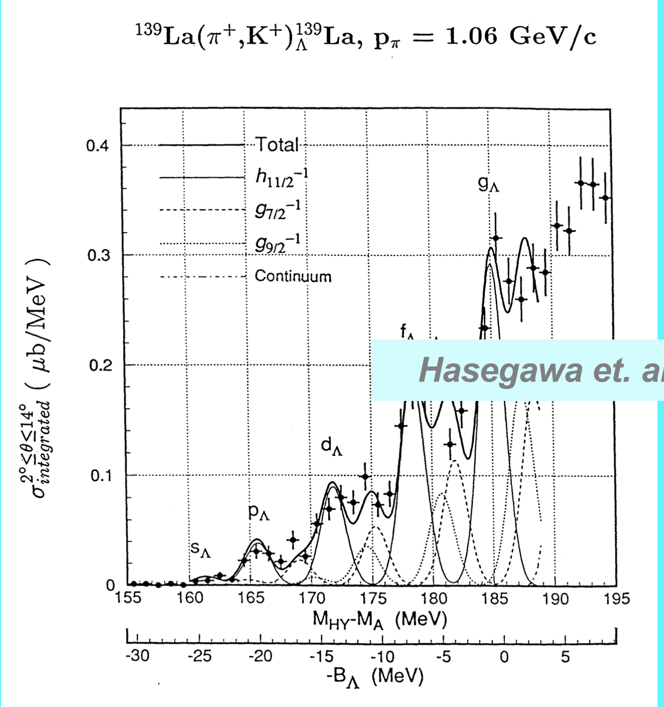
The validity of this conjecture has been long established by a comparison between the results of theoretical calculations and the data extracted from the ^{208}Pb(e,e´p)^{207}Tl cross sections measured at NIKHEF in the 1990s

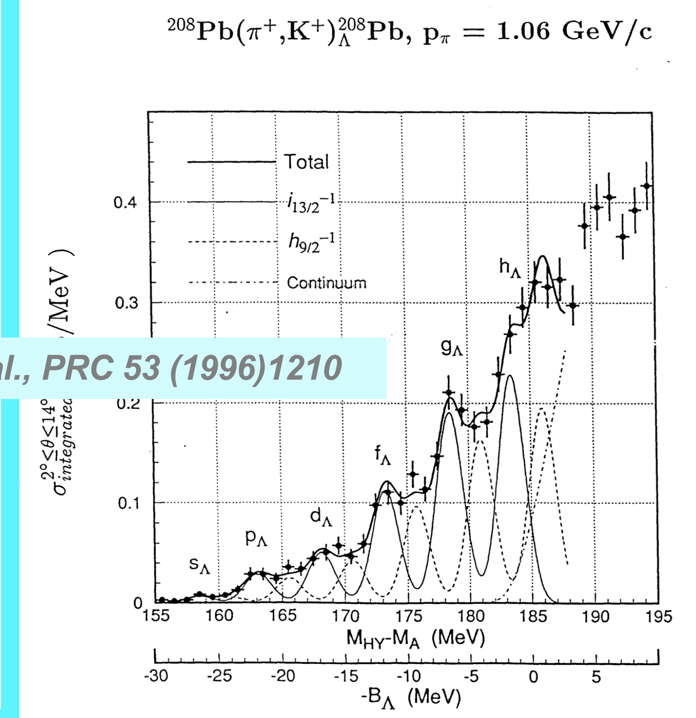
Hyperon in heavy nuclei – ^{208}(e,e'K+)$^{208}{}_{\Lambda}$Ti

✓ Mass spectroscopy to its extreme



Hotchi et al., PRC 64 (2001) 044302





Hasegawa et. al., PRC 53 (1996)1210

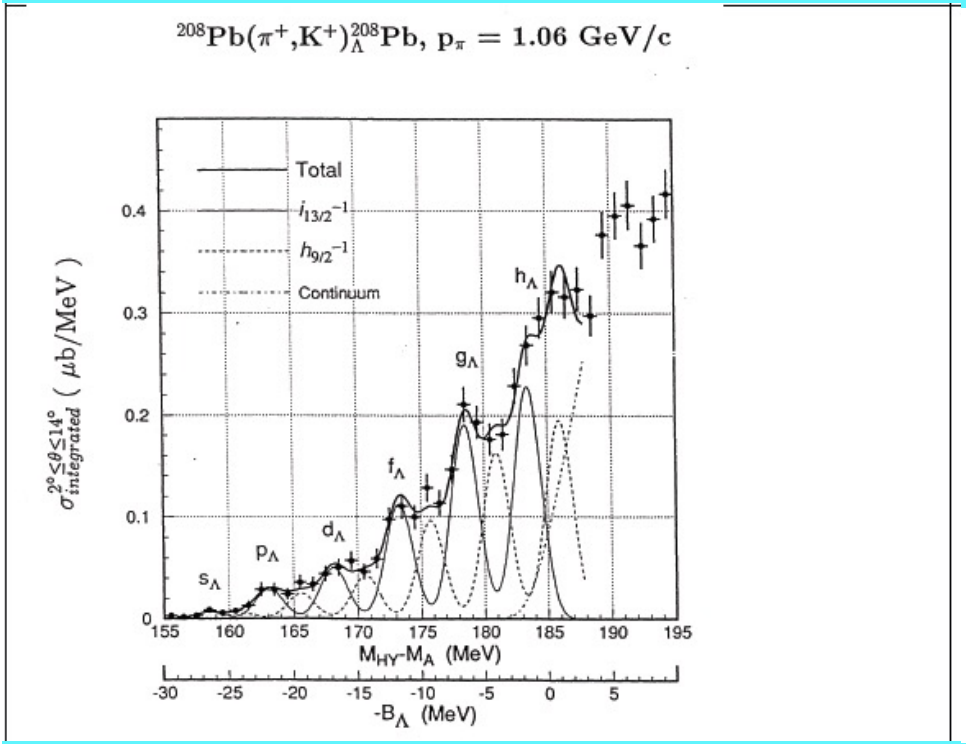
"Up to now these data are the best proof ever of quasi particle motion in a strongly interacting system" (Review paper by Hashimoto and Tamura)

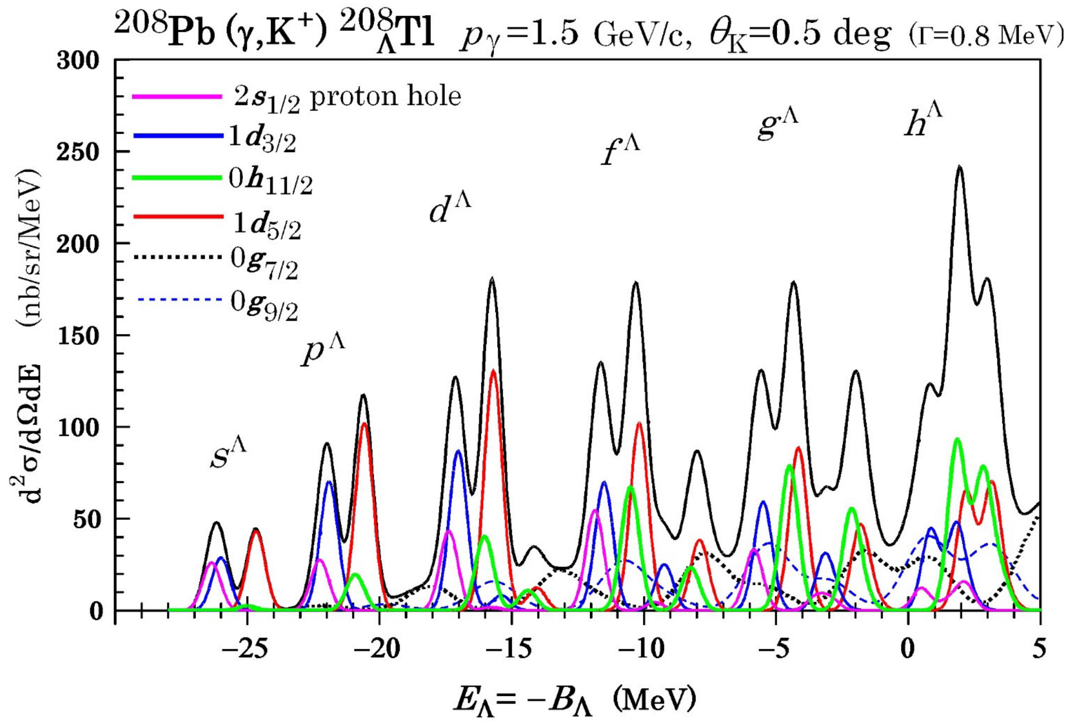
✓ (π,k) reaction, levels barely visible for Pb

(e,e'K) reaction can do better

Better energy resolution (*and calibration*)

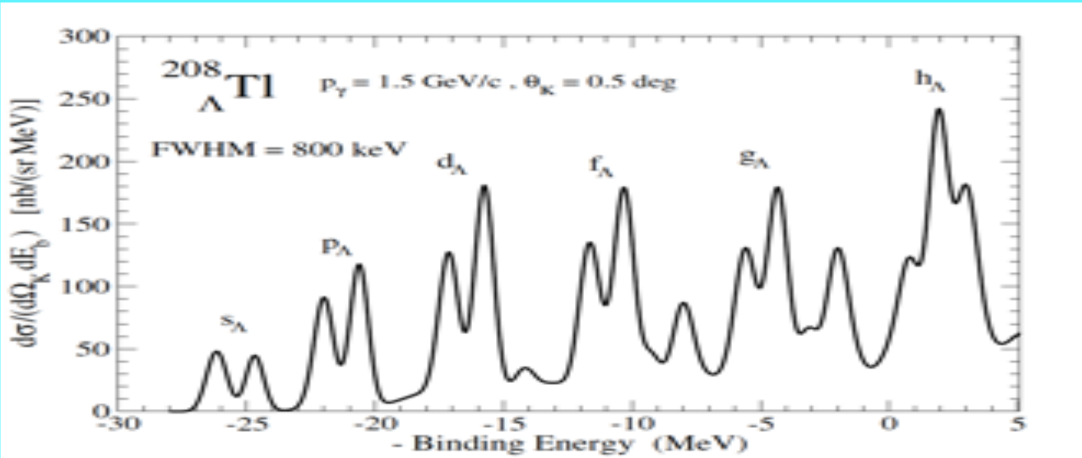
→ more precise Λ single particle energies.

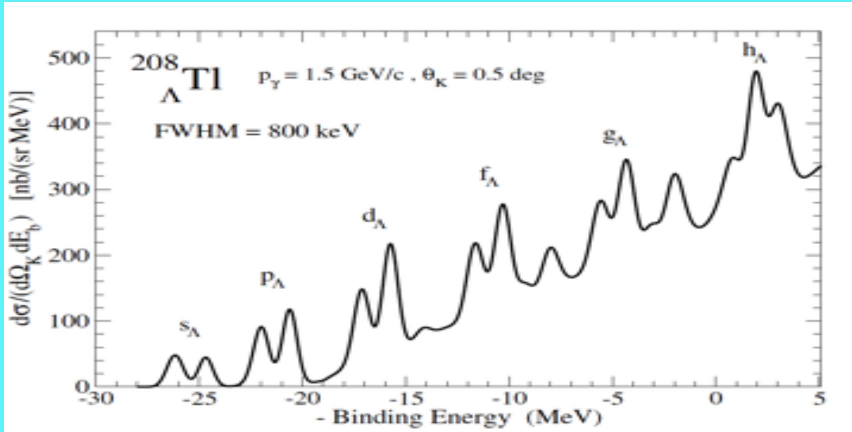


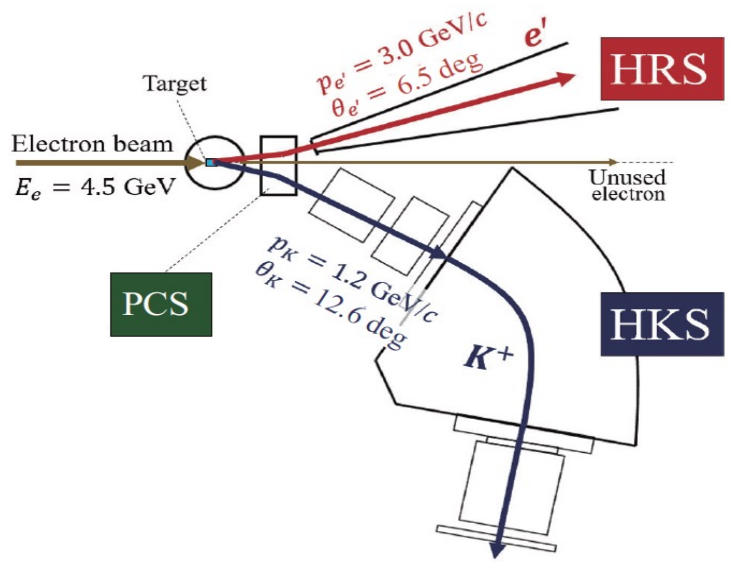


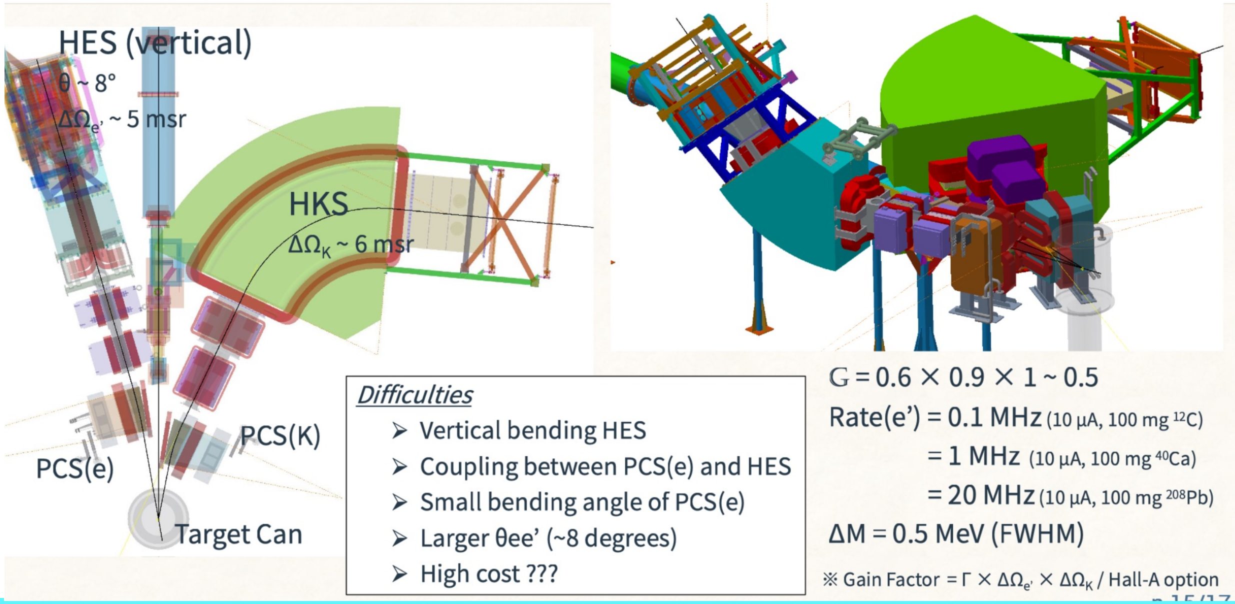
Millener-Motoba calculations

- Particle hole calculation, weak-coupling of the Λ hyperon to the hole states of the core (i.e. no residual Λ-N interaction). One can extract Λ single-particle energies from each of the observed peaks. **Each peak does correspond to several levels** based on two closely-spaced proton-hole states



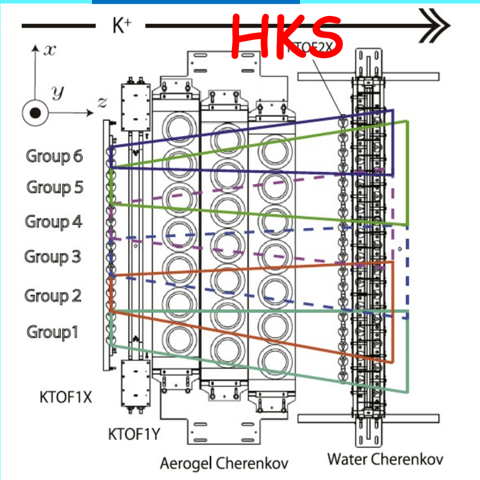






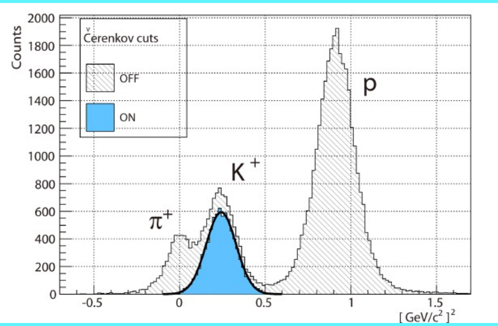
Target	Beam Current (μA)	Target thickness (mg/cm^2)	Assumed cross section (Nb/Sr)	Expected yield (/hour)	Number of events	Rquested beam time (hours)	B.G. Rate (MeV/h)	S/N
^{208}Pb	25	100	80 (g.s.)	0.24	115	480	0.084	18.5

PID



3 TOF, 2 water Cherenkov, three aerogel Cerenkov

pK=1.2 GeV/c)



(π/k rejection ratio: 4.7 x 10^{-4})

(T. Gogami et al, NIM (2018) 69-83)

Challenges?

Target

The target comes from the expertise gained with the PREX one (Silviu Covrig)

- A water cooled target at room temperature could sustain a beam current in the range of 10 microA with a beam spot at least 16 mm^2 in area.

- If the target is cooled down to at least 15 K, then the beam current can be increased by a factor of at least 2x compared with RT cooling (minimum beam spot/raster area of 9 mm^2), in the range of 20 microA.

If the target is cooled down to 15 K and also rotated (or oscillated in one direction), then the beam current can be increased another factor of 2x, in the range of at least 40 microA.

So, for PR12-20-013, cryo-cooling the target is enough to achieve its goals. No rotation of the target would be needed for beam currents less than 30 microA

For PR12-20-013 we need 25 microA

We might add up the RICH detector

An e-mail from Silviu Covrig (March 2 2023)

Dear Franco
As much as I would have liked to attend the workshop, unfortunately I will be out of town tomorrow and won't be able to attend both in person and on zoom as I will be traveling tomorrow for most of the day.
Feel free to mention any of the following:
CFD thermal simulations of solid foils have been benchmarked for the PREX2/CREX1 targets. PREX2 used 0.5 mm thick 208Pb foils, sandwiched between artificial diamond foils, C-208Pb-C which have been operated, during PREX2, up to 80 uA e- beam current.
Your experiment plans to use 0.1 mm bare 208Pb up to 25 uA, and CFD simulations estimate that these foils will do fine if cryogenically cooled (just like the PREX2/CREX1 targets were, we have the design of the target ladders with the cooling circuit, the target frame has been engineered, manufactured and operated during PREX2 and we will plan to use a similar design in your experiment). The CFD techniques have also been benchmarked for the APEX target W foils. In case someone thinks it necessary (typically this may come out of the ERR) we could do something similar with what we did for the APEX target: compare CFD simulations with measurements from laser heating Pb foils. The laser heating apparatus is being brought back to operations to test target foils for the positron source. This is part of jlab's effort to develop a local positron source/target. I am involved with this effort and we plan to have the apparatus operational within a few months. If anyone would think it necessary, we could also test Pb foils going forward.
Please let me know if there are questions/comments about the target's performance. I would be happy to address them.Sorry that I cannot attend and I hope you'll have fruitful discussions

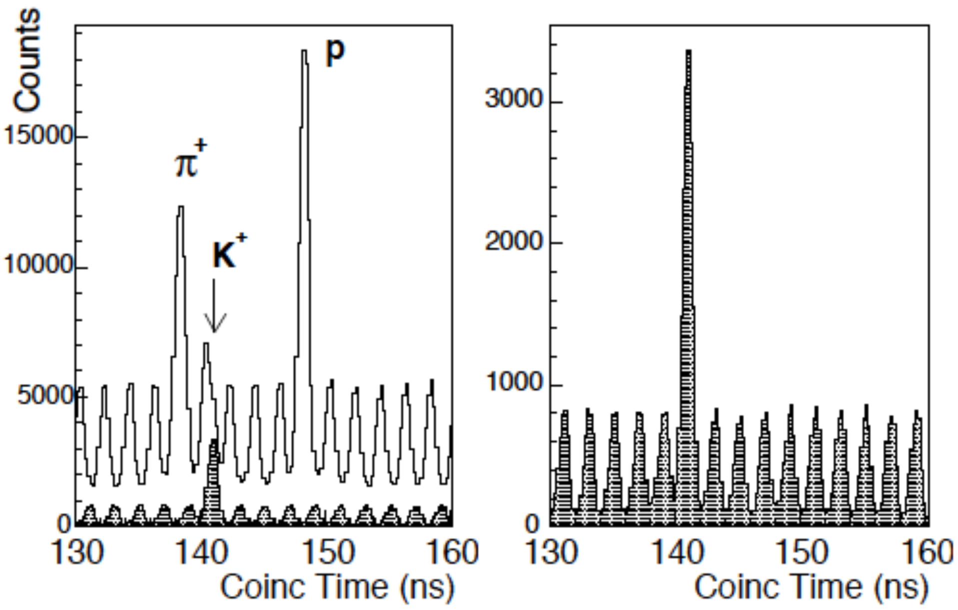


FIG. 10. Hadron plus electron arm coincidence time spectra. Left panel: the unfilled histogram is obtained by selecting kaons with only the threshold aerogel Cherenkov detectors. The filled histogram (expanded in the right panel) also includes the RICH kaon selection. The remaining contamination is due to accidental $(e, e') \otimes (e, K^+)$ coincidences. The π and p contamination is clearly reduced to a negligible contribution.

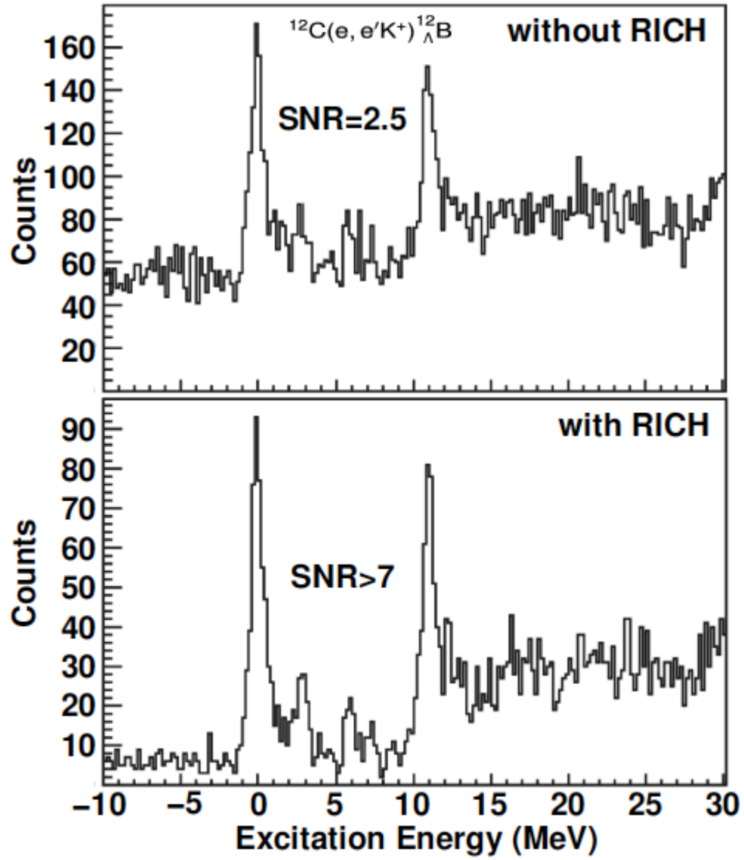


FIG. 11. Excitation energy spectra of $^{12}_{\Lambda}$B using, for kaon identification, only the aerogel (upper plot) or also the RICH (lower plot). The counts are for 200 keV bins.

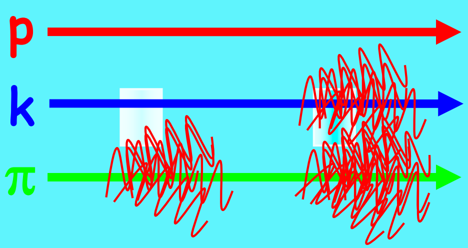
The PID Challenge

Very forward angle ---> high background of π and p

-TOF and 2 aerogel in not sufficient for unambiguous K identification !

Kaon Identification through Aerogels

p_h = 1.7 : 2.5 GeV/c



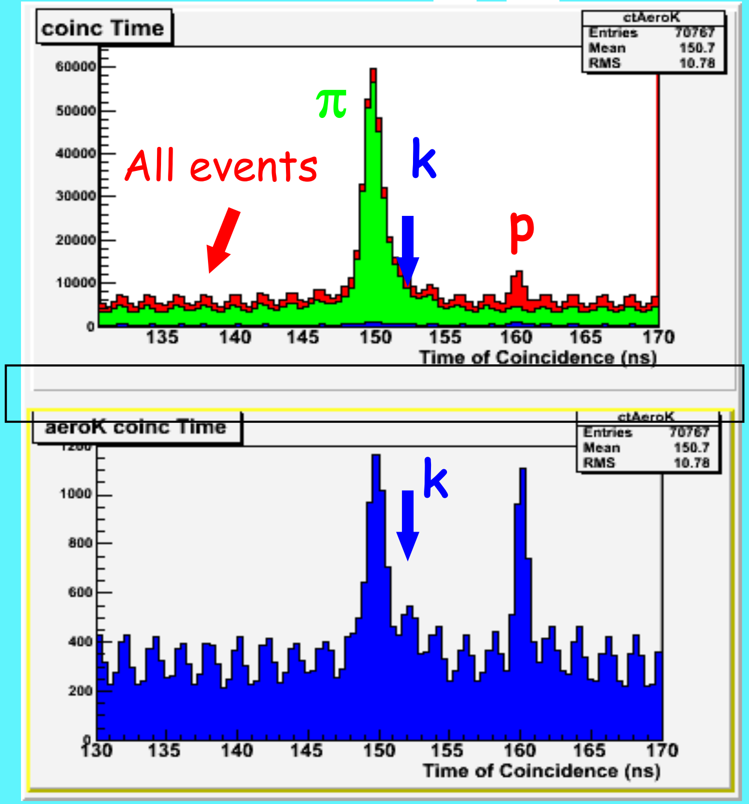
AERO1 AERO2

n=1.015 n=1.055

Pions = A1•A2

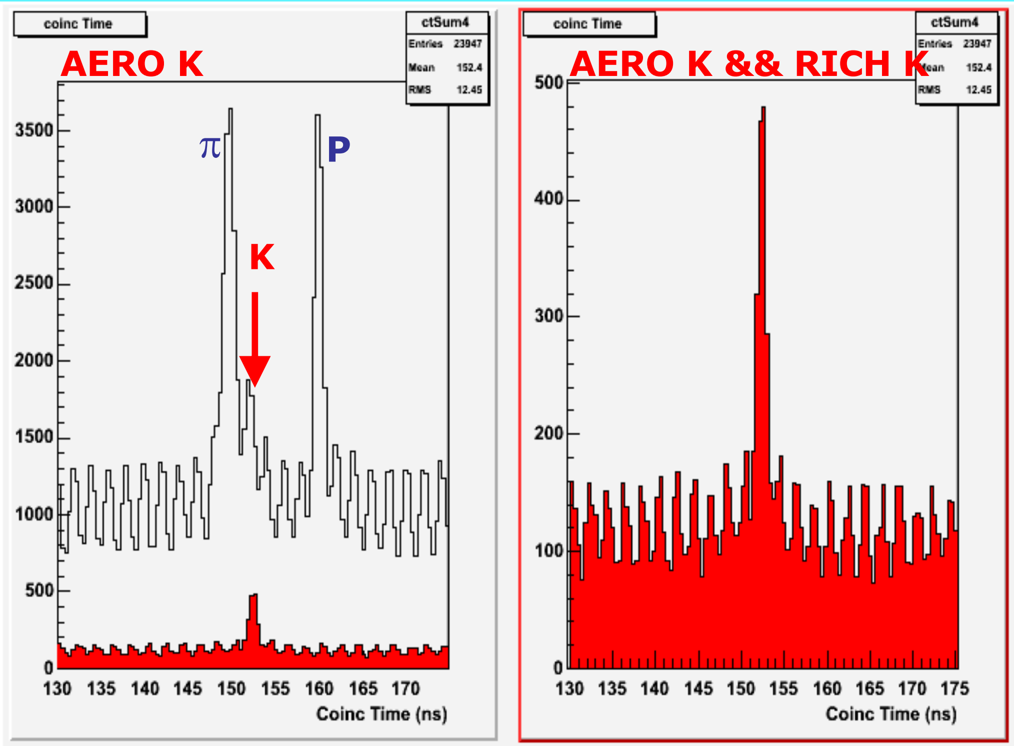
Kaons = $\overline{\text{A1}}$•A2

Protons = $\overline{\text{A1}}$•$\overline{\text{A2}}$



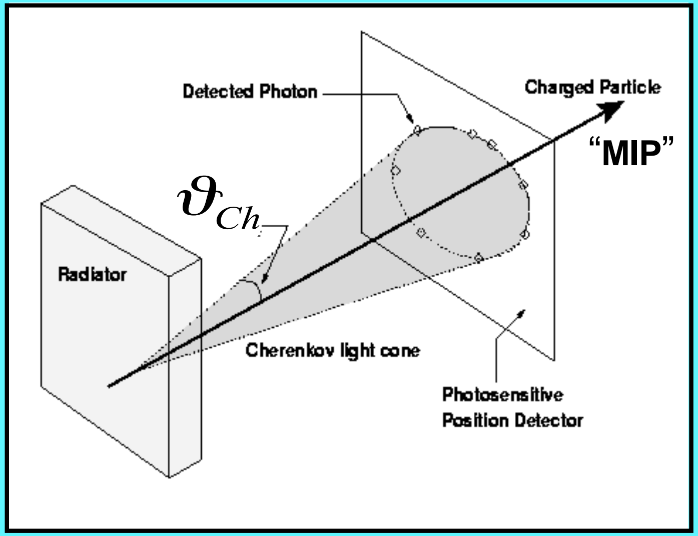
RICH - PID - Effect of kaon selection

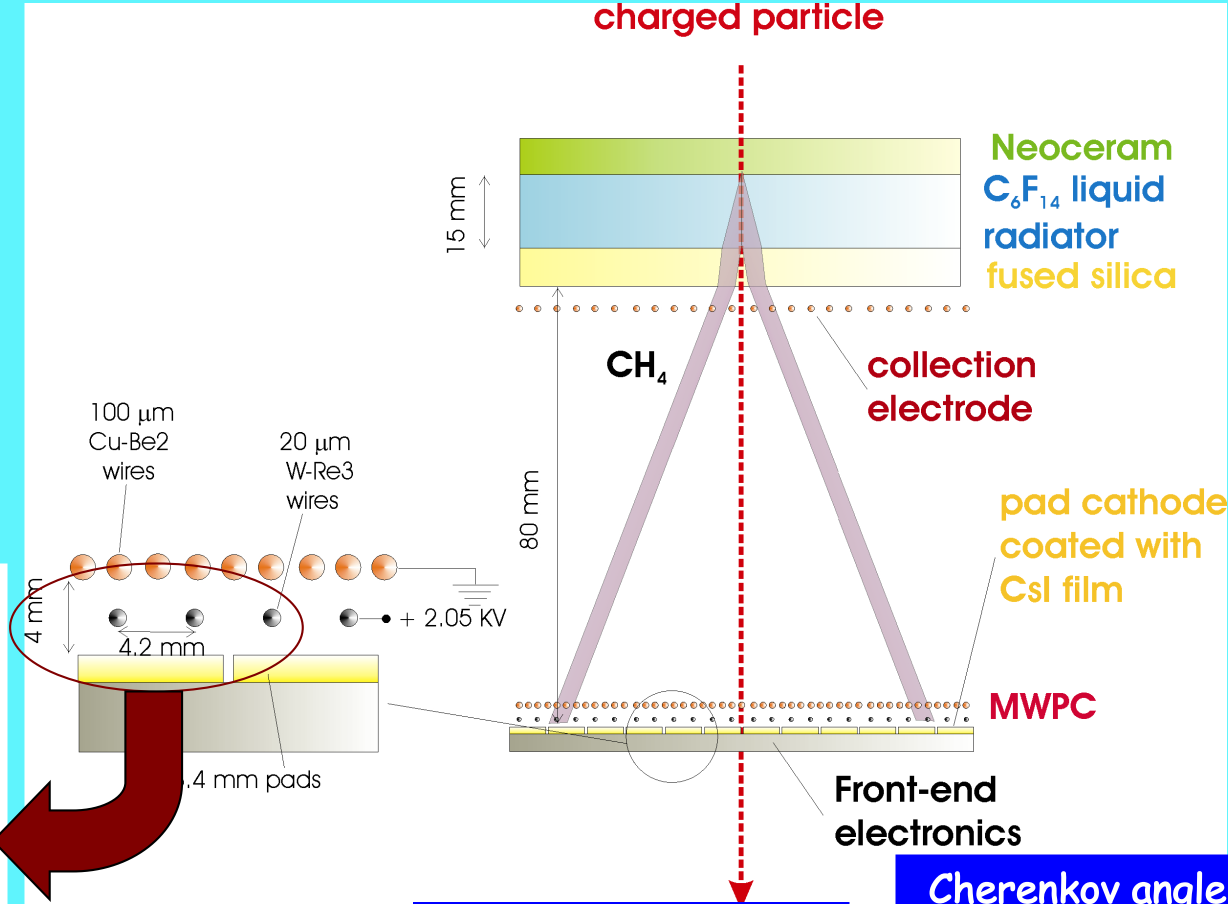
Coincidence Time selecting kaons on Aerogels and on RICH

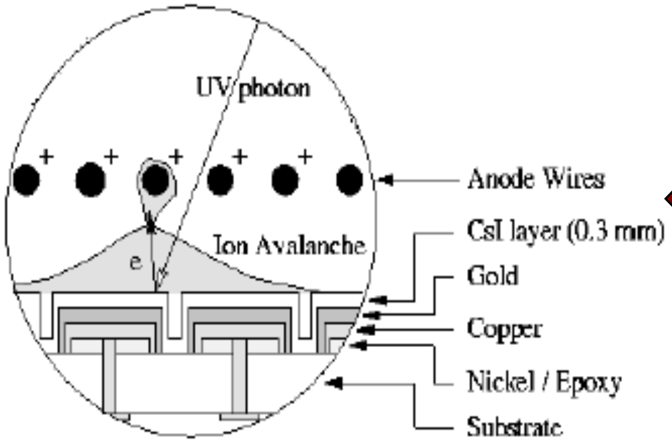


Pion rejection factor ~ 1000

RICH detector -C_6F_{14}/CsI proximity focusing RICH







$$n_\sigma \sim \sqrt{\frac{m_A^2 - m_B^2}{2\tan\theta_c\, p\, \sigma_\theta^r}}$$

Separation Power

$$\vartheta_2 - \vartheta_1 = n_\sigma \sigma_{\vartheta_c}$$

Cherenkov angle resolution

$$\sigma_{\vartheta_c} = \frac{\sigma_\vartheta^{p.e.}}{\sqrt{N_{p.e}}}$$

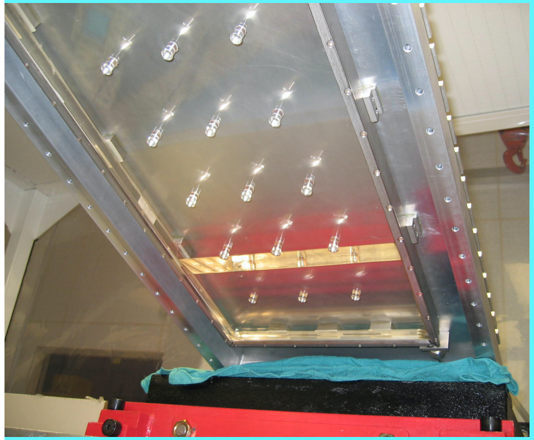
N. of detected photoelectrons

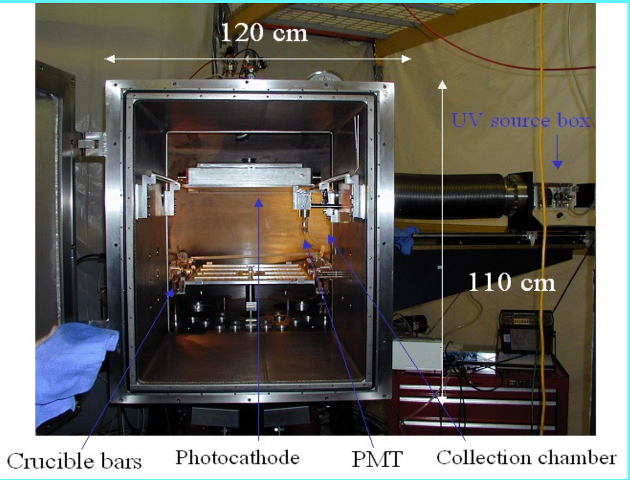
$$N_{p.e.} = 370 L \sin^2 \vartheta_c \prod_i \varepsilon_i \Delta E \approx 20 - 50$$

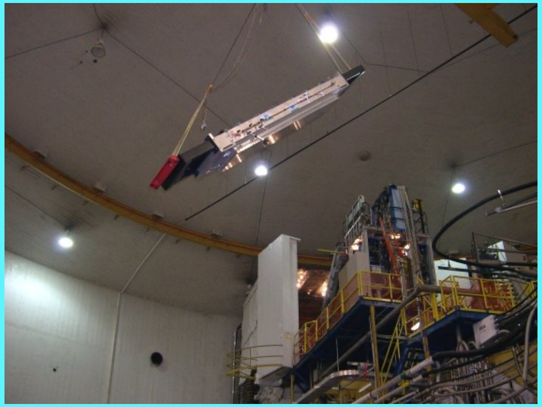
Performances

- $N_{p.e.}$ # of detected photons(p.e.) ← maximize
- and σ_θ (angular resolution) ← minimize

The RICH detector at Jefferson Lab



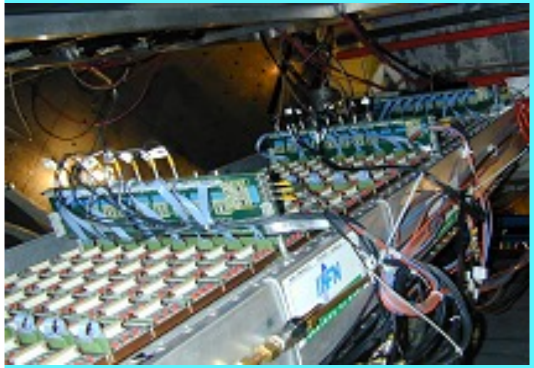




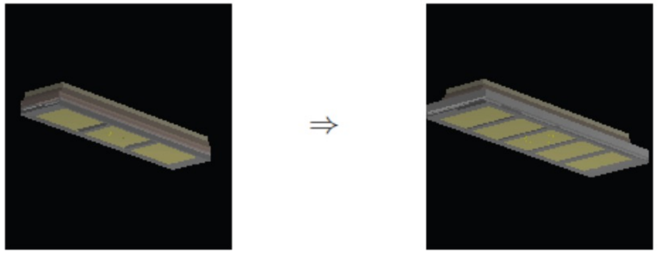
RICH flying to hunt kaons

into the detector hut

RICH Detector



The RICH detector has been upgraded for the neutron Transversity experiment. Easy calculation show that the new layout would allow us to get a pion/kon rejection factor of 10^{12}



Radiator	15 mm thick Liquid Freon (C_6F_{14}, n=1.28)
Proximity Gap	100→ 175 mm, filled with Methane at STP
Photon converter	300 nm CsI film coated on Pad Planes
Position Detector	3→ 5 × pad planes = 1940 × 403→ 2015 × 646 mm^2
	Multi Wire/Pad Proportional Chamber, HV= 1050 ÷ 1100 V
Pad Plane	403.2 × 640 mm^2 (single pad: 8.4 × 8 mm^2)
FE Electronics	11520→ 19200 analog chs. multiplexed S&H

Fig. A1. Old and new upgrated RICH layout

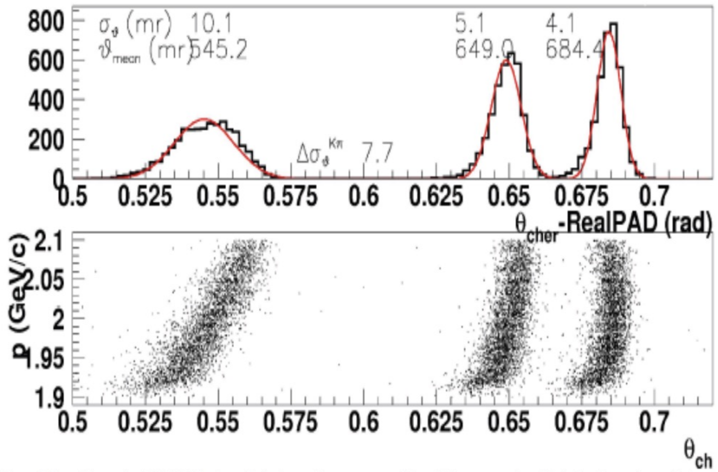


Fig. A3. Upgrated RICH simulated performance. Pion/Kaon angle distribution (equal hadrons populations) at 2 GeV/c momentum, in the HRS acceptance. The Mcarlo is tuned on Hall A hypernuclear experimental data.

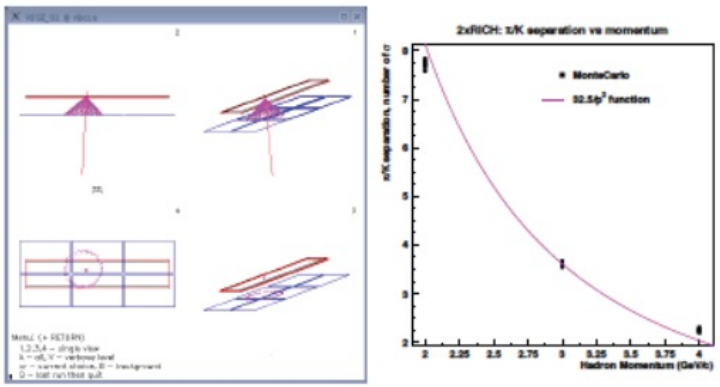


Fig. A2 Upgraded RICH simulation events (left panel) and expected performance (right panel): pion-kaon separation (number of sigmas) at different hadron momenta. The simulation is tuned to the E-94-107 hypernuclear experimental data.

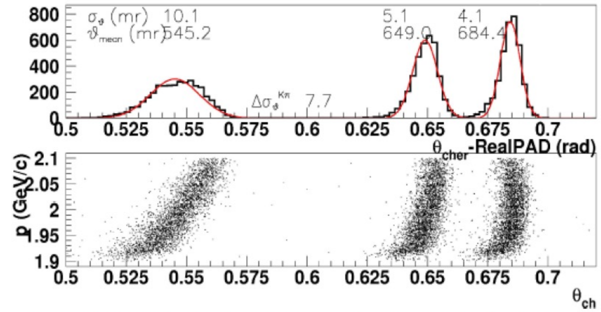


Fig. 11. Upgrated RICH simulated performance. Pion/Kaon angle distribution (equal hadrons populations) at 2 GeV/c momentum, in the HRS acceptance. The Mcarlo is tuned on Hall A hypernuclear experimental data.

In Fig. 9 we show the old and new (upgrated) layout. The photon detection plane was doubled (3 more pad panels added). This would have allowed the detectors to separate kaons, in the E-94-107 kinematical conditions (at a kaon momentum ~ 2 GeV/c) with a higher rejection ratio, an additional ~ 1.5 sigma (Fig.10,11) corresponding to a pion:kaon rejection better than 1:10000 at 2.0 GeV/c, with improved efficiency.

In our experiment the central momentum of the detected kaons will be 1.2 GeV/c. For this reason even better performances to separate kaons from pions will be obtained. Easy calculation [37] bring to ~ 7.8 sigma the pion – kaon separation angle. Adding, conservatively 1.5 sigma, we would obtain a separation ~ 9.3 sigma. This would correspond, assuming a factor ~ 100 for pion-kaon particle population, to a ~ 10^6 power rejection

Convoluting the threshold Cherenkov and the RICH power rejection we would have a pion-kaon power rejection ~ 10^{12}

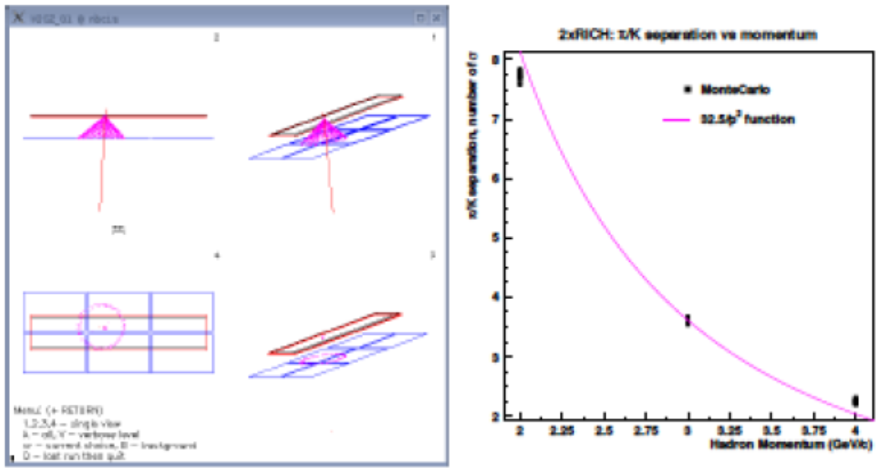


Fig. 10 Upgraded RICH simulation events (left panel) and expected performance (right panel): pion-kaon separation (number of sigmas) at different hadron momenta. The simulation is tuned to the E-94-107 hypernuclear experimental data.

Summary and conclusions

We propose to extend the experimental study of kaon electroproduction to the ^{208}Pb(e,e'K)$^{208}{}_{\Lambda}$Tl reaction to study the hyperon puzzle in a complementary way with respect to the approved proposal $^{40}{}_{\Lambda}$K and $^{48}{}_{\Lambda}$K on isospin dependence of ΛNN

ΛNN could provide additional repulsion making the EOS stiffer enough to help solving the hyperon puzzle. Moreover they rapidly increase with A, making the ^{208}Pb target uniquely suited to study Λ interaction in a uniform nuclear medium with large neutron excess

In fact, the contribution of three-nucleon forces, which is known to be large and repulsive in nuclear matter at equilibrium density, is believed to be much smaller and attractive in ^{40}Ca

The availability of accurate ^{208}Pb(e,e'p)^{207}Tl data may be exploited to achieve a largely model-independent analysis of the measured cross section, based on the well established formalism of nuclear many-body theory

In conclusion, even if the typical baryon density inside a neutron star is much higher than in a hypernucleus a precise knowledge of the ^{208}Pb level structure can, by constraining the hyperon-nucleon potential, contribute to more reliable predictions regarding the internal structure of neutrons stars, and in particular their maximum mass

"Therefore is of vital importance to perform precision spectroscopy of heavy Λ hypenuclei with mass resolution comparable to or better than the energy differences of core excited states, in order to further investigate the structure of the Λ hyperon deeply bound states in heavier nuclei.

→ (e,e'K) spectroscopy is a promising approach to this problem

We know that there are plans at KEK to produce high resolution pion beams

This is very good because of the complementarity of the two approaches