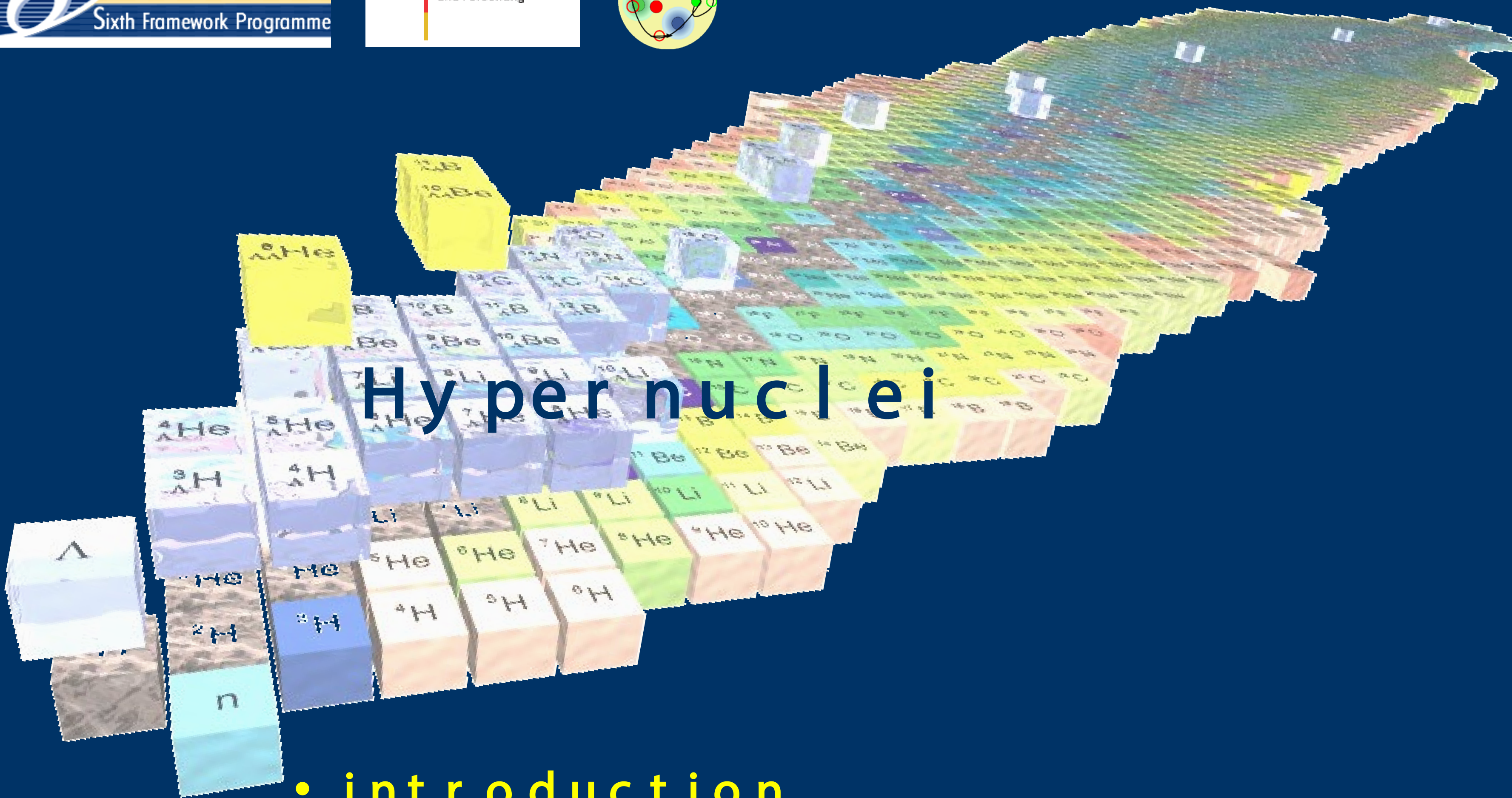
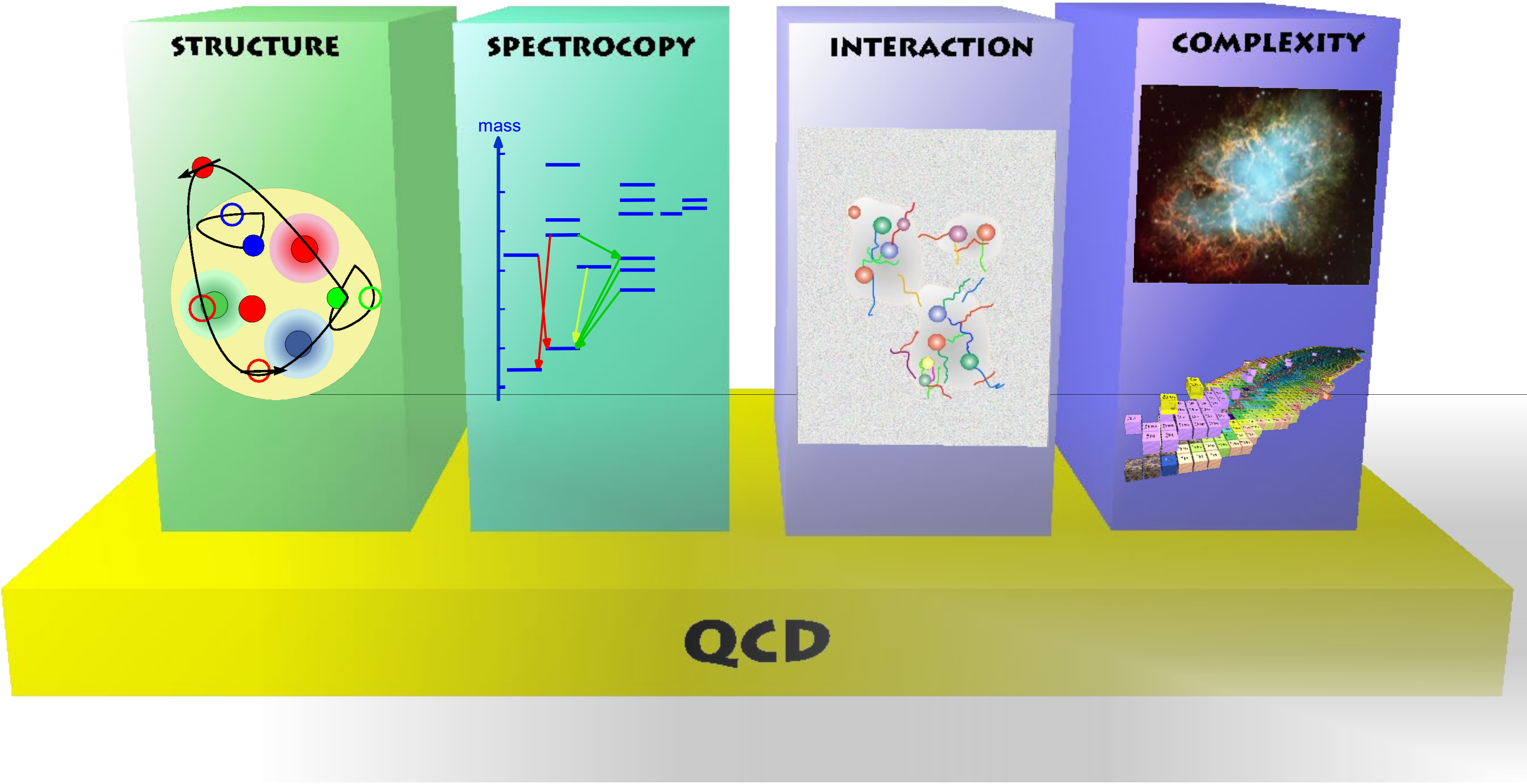
Hypernuclei



- introduction
- Shopping list of hypernuclei
- Production of Double hypernuclei
- DOUBLE HYPERNUCLEi AT PANDA

Pillars of QCD



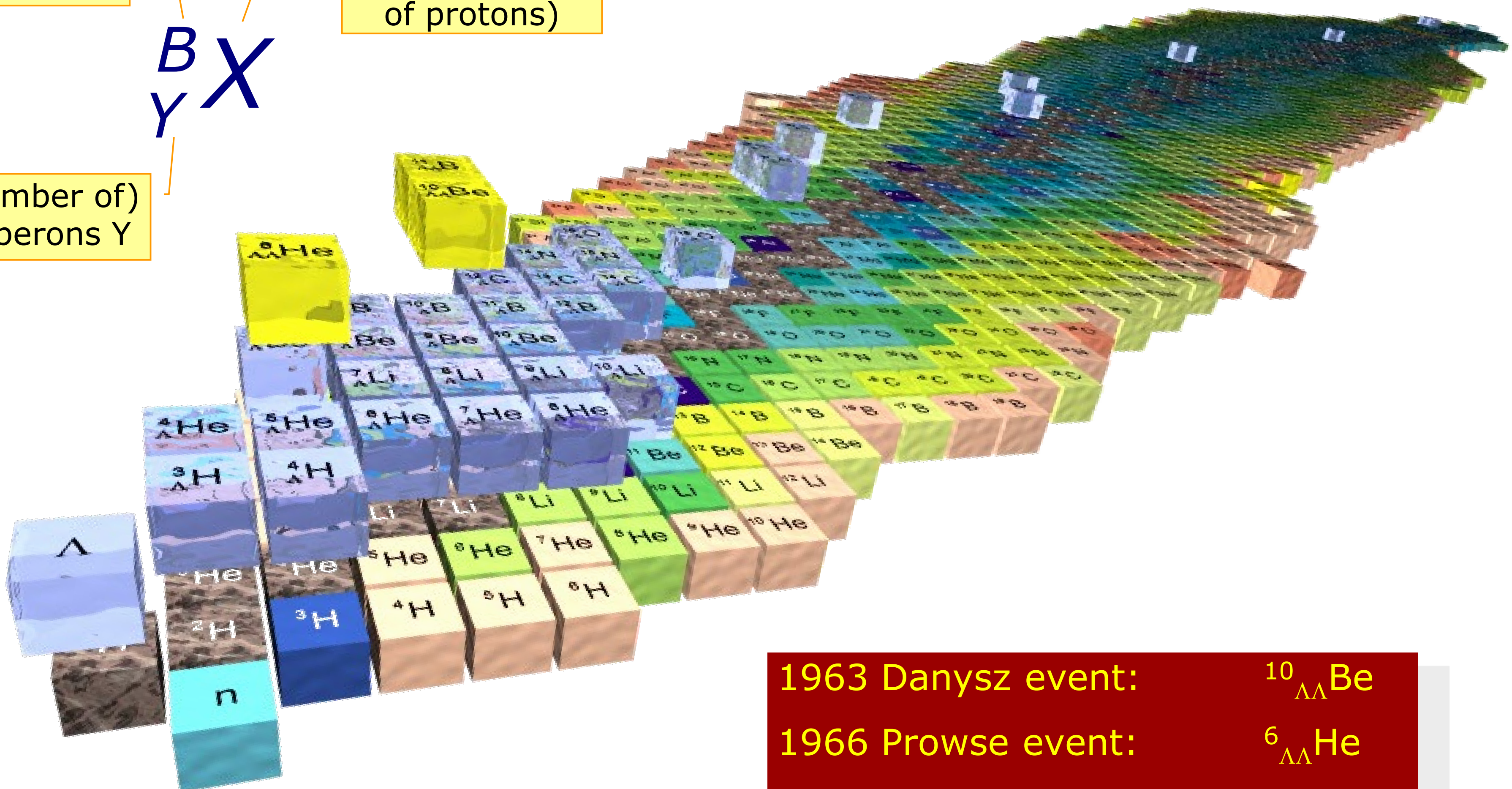
Hypernuclei – Present Situation

number of baryons N+Z+Y

element = total charge (not number of protons)

(number of) hyperons Y

$^{B}_{Y}X$



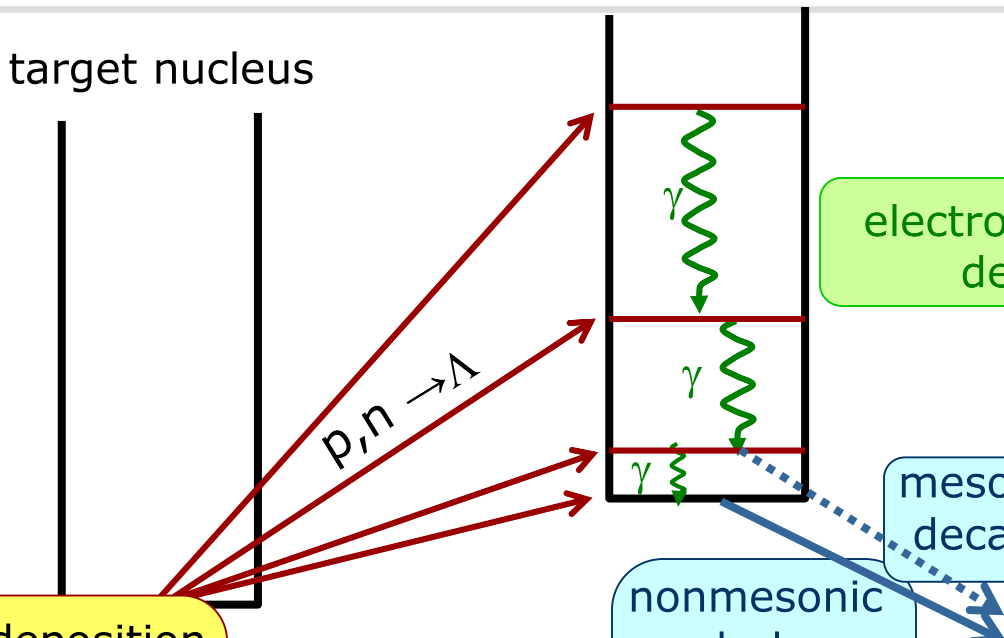
1963 Danysz event: $^{10}_{\Lambda\Lambda}Be$

1966 Prowse event: $^{6}_{\Lambda\Lambda}He$

1991 Aoki event: $^{13}_{\Lambda\Lambda}B$

2001 Nagara event: $^{6}_{\Lambda\Lambda}He$

Birth, Life and Death of a Hypernucleus



electromagnetic decays

mesonic decays $\Lambda \to p\pi^-$ $\Lambda \to n\pi^0$

nonmesonic weak decay
$\Lambda p \to np$
$\Lambda n \to nn$
$\Lambda\Lambda \to YN$

hadronic decay in emulsion

strangeness deposition
$e^+ + e^- \to \Phi \to K^+ + K^-$
$K^-_{stopped} + {}^A Z \to {}^A_\Lambda Z + \pi^-$
FINUDA

strangeness production
(π^+, K^+), (π^-, K^0)
BNL,KEK

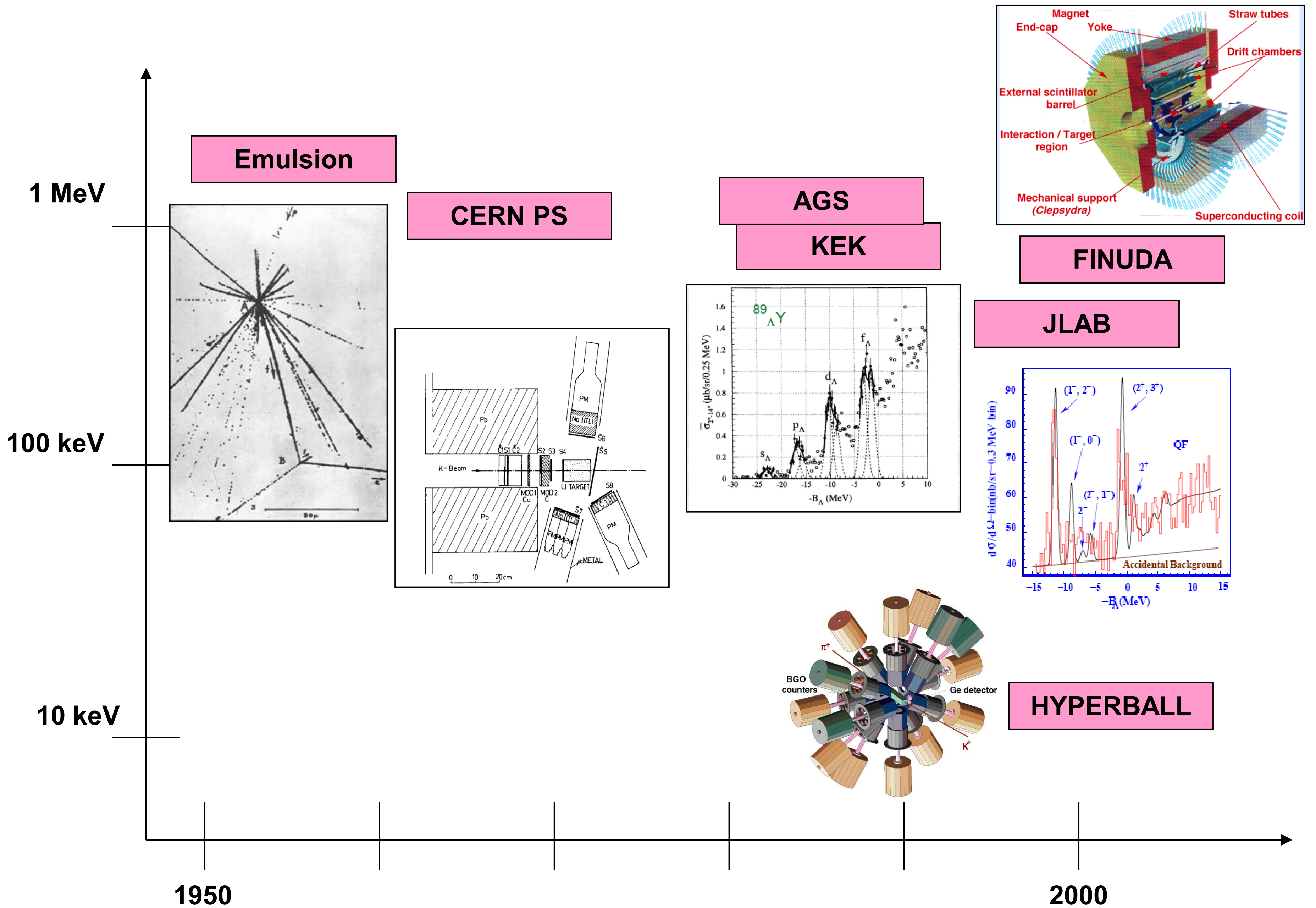
strangeness exchange
(K^-, π^-) , (K^-, π^0)
BNL,KEK,JPARC

electroproduction
$(e,e'K^+)$, (γ,K^+)
Jlab, MAMI-C

energy resolution

- K,π: 1-2 MeV
- $K_{stopped}$: 1 MeV
- e: 0.5 MeV
- γ-transitions: 5 keV

Past and Presence of Hypernuclei



Shopping list

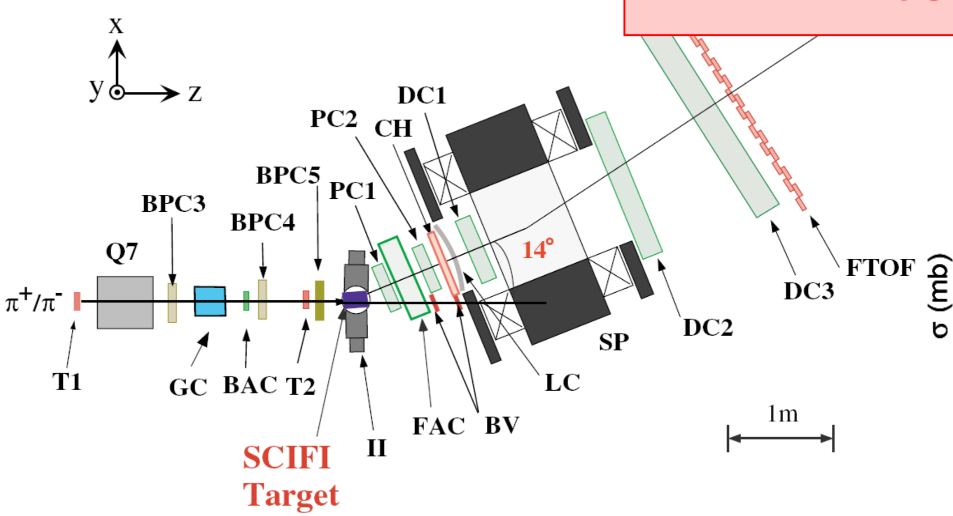
Physics of Hypernuclei

- the Y-N and Y-Y strong interactions in the $J^P = 1/2^+$ baryon octet
- the nuclear structure, e.g. the origin of the spin-orbit interaction
- specific aspects baryon-baryon weak interactions
- possible existence of dibaryon particles
- hyperons (Λ, Σ, Ξ) and meson properties in the nuclear medium
- the role played by quark degrees of freedom, flavour symmetry and chiral models in nuclear and hypernuclear phenomena

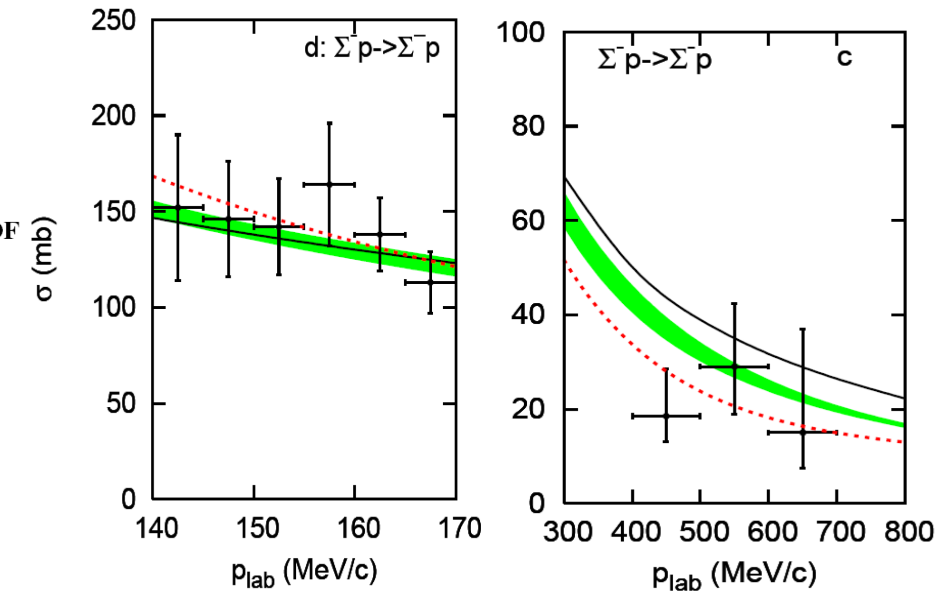
Exp. Approaches to Y-N interactions

- low energy baryon-baryon scattering
  - N-N: ~10^4 data points available
  - for hyperons only very few elastic data $\lesssim(\gtrsim)$300MeV/c
    - Λ-p→Λ-p: 12 (10) Σ^+-p→ Σ^+-p: 4 Σ^--p→ Σ^--p: 9 (3)
  - spin averaged → can not access LS or SS coupling
  - usually low statistics
    - Σ^-p: KEK-PS E289 (π^-,K$^+$) ⇒ 30 events
    - Σ^+p: KEK-PS 2 … 31 events each
    - Ξ^- p: (K$^-$,K$^+$) … 1 candidate

not practical for Y-Y interaction!



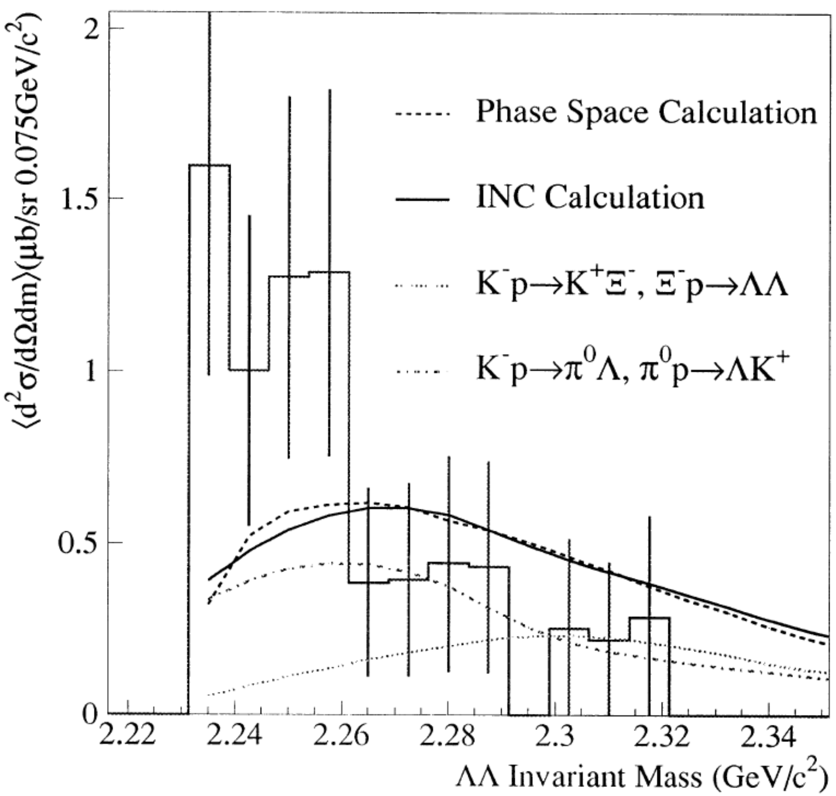
- JPARC: ~1000 events/day

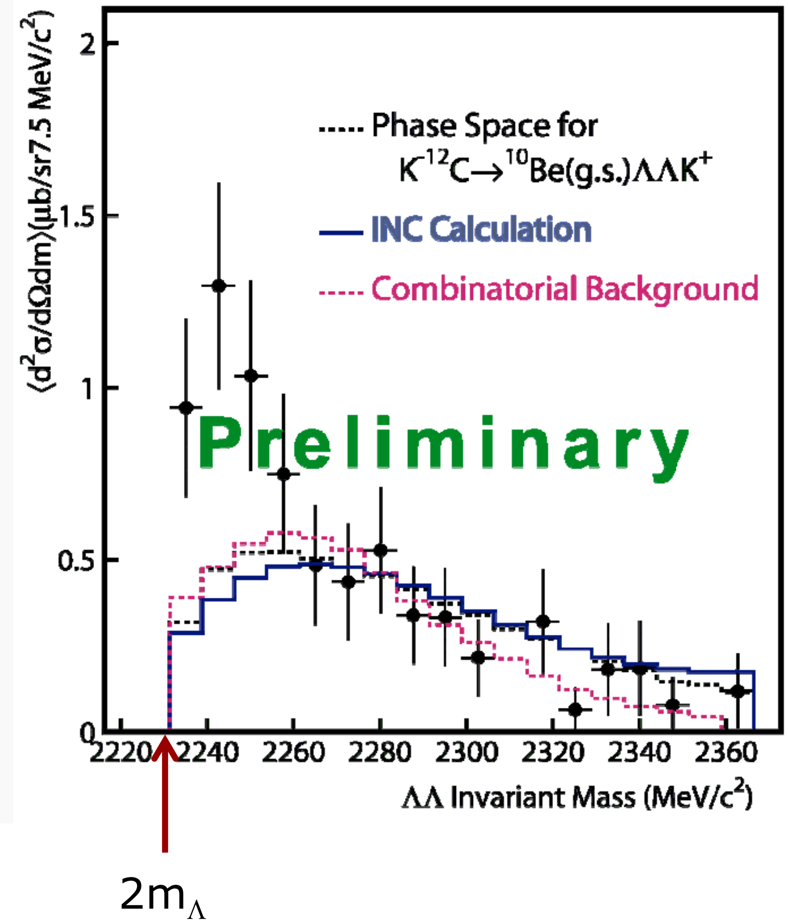


Polinder, Haidenbauer, Meißner 2006

Λ-Λ Final State Interaction

- hyperon-hyperon final state interaction via ΛΛ invariant mass
  - KEK-PS E224, Physics Letters B 444, 267 (1998)
  - KEK-PS E522: K.Nakazawa *PS-Review* (2004)

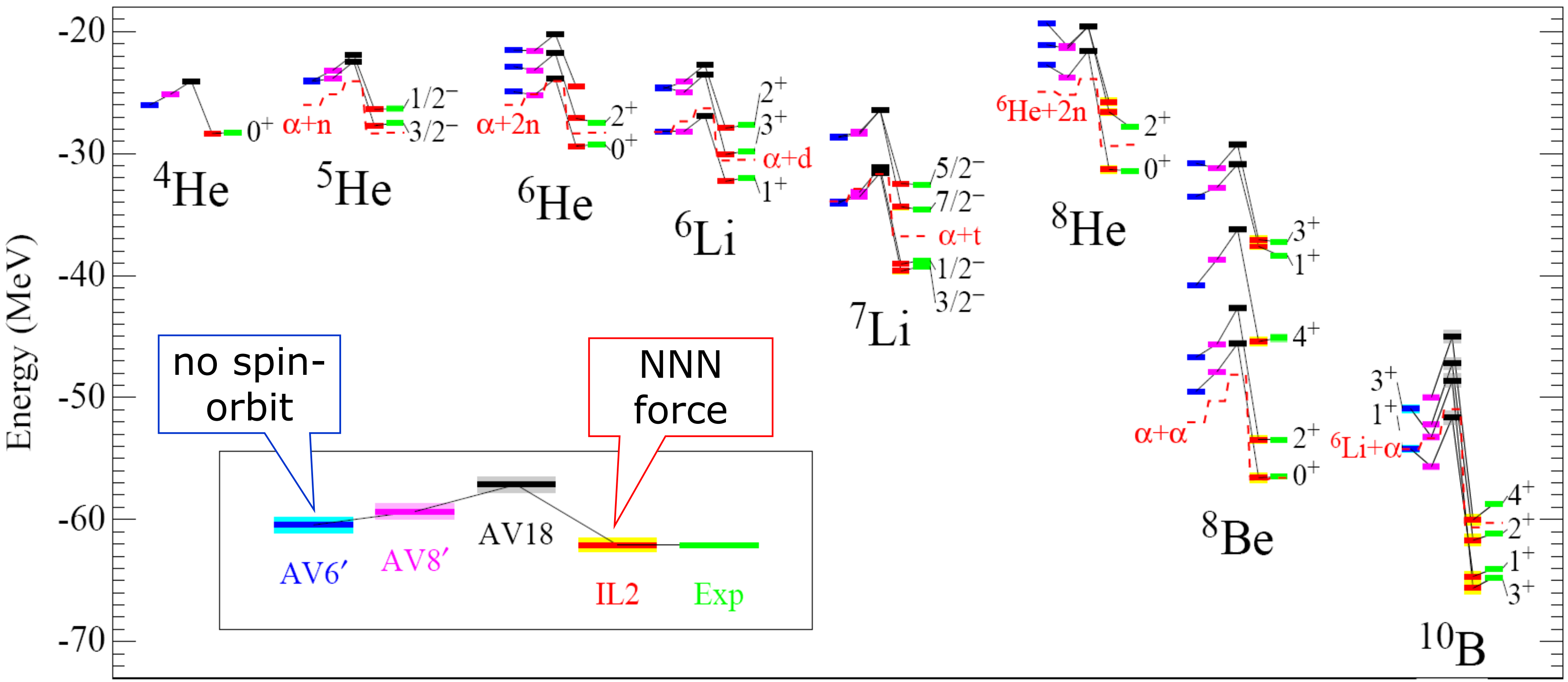




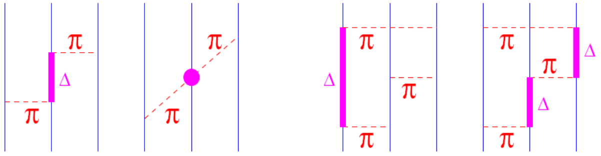
- feasible but difficult to interpret (rescattering, size,…)

Understanding Nuclear Structure

- Steven Stephen C. Pieper *et al.*, 2002
- potentials with increasing complexity

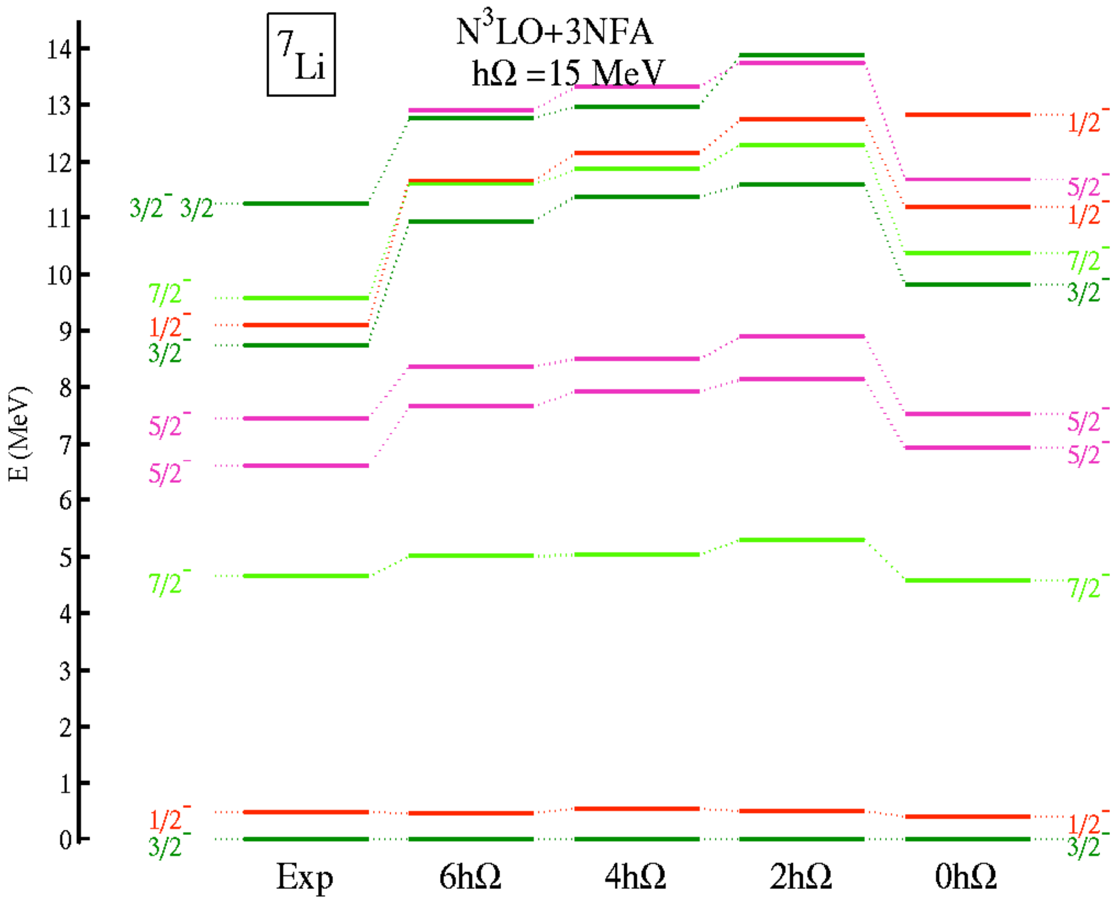


- spin-isospin and tensor forces present in long-range one-pion-exchange are essential
- multi-nucleon forces are vital
- sub-MeV precission (~3 parameters only)

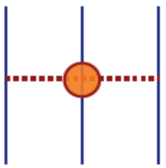


Nuclear Spectra in χEFT

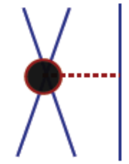
- great progress in recent years
  - e.g. Petr Navratil *et al.* (2005)
  - *consistent* (same cutoff parameter Λ) treatment of NN (N^3LO) and NNN force (N^2LO; from fit to ^3H and ^4He binding energies)



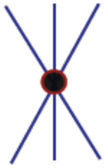
2-pion exchange term



one-pion +contact term



contact term



- no hypernuclei yet, but work in progress (N. Kaiser, Paolo Finelli…)

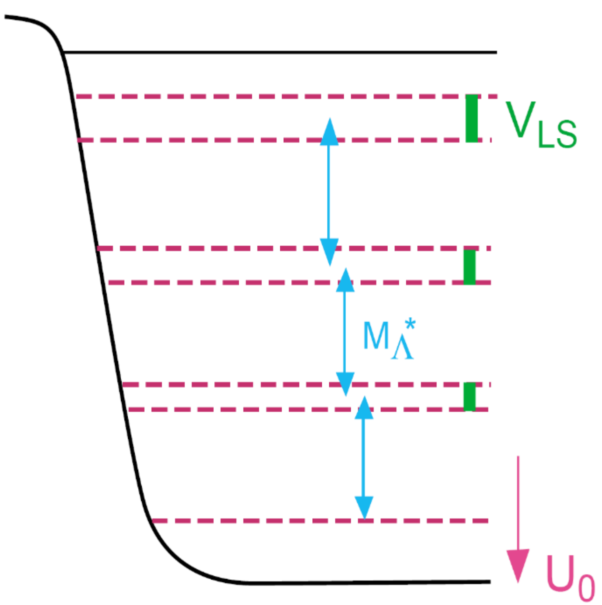
Physics of Hypernuclei

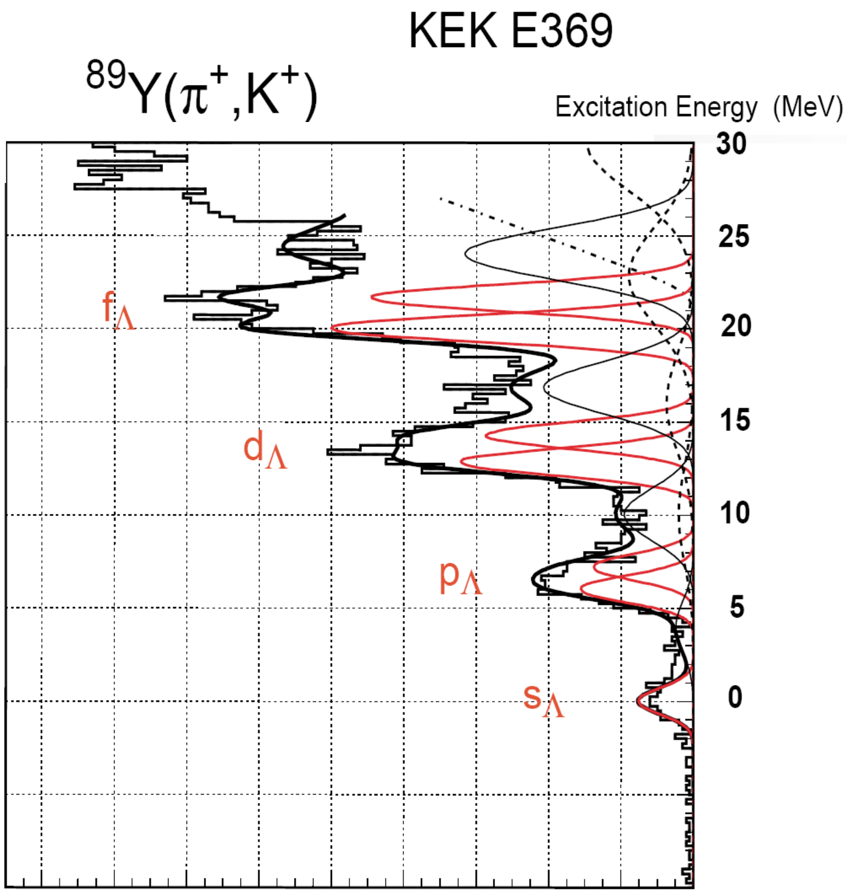
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

- the Y-N and Y-Y strong interactions in the $J^P = 1/2^+$ baryon octet
- the nuclear structure, e.g. the origin of the spin-orbit interaction
- specific aspects baryon-baryon weak interactions
- possible existence of dibaryon particles
- hyperons (Λ, Σ, Ξ) and meson properties in the nuclear medium
- the role played by quark degrees of freedom, flavour symmetry and chiral models in nuclear and hypernuclear phenomena

Λ Potential in Nuclei

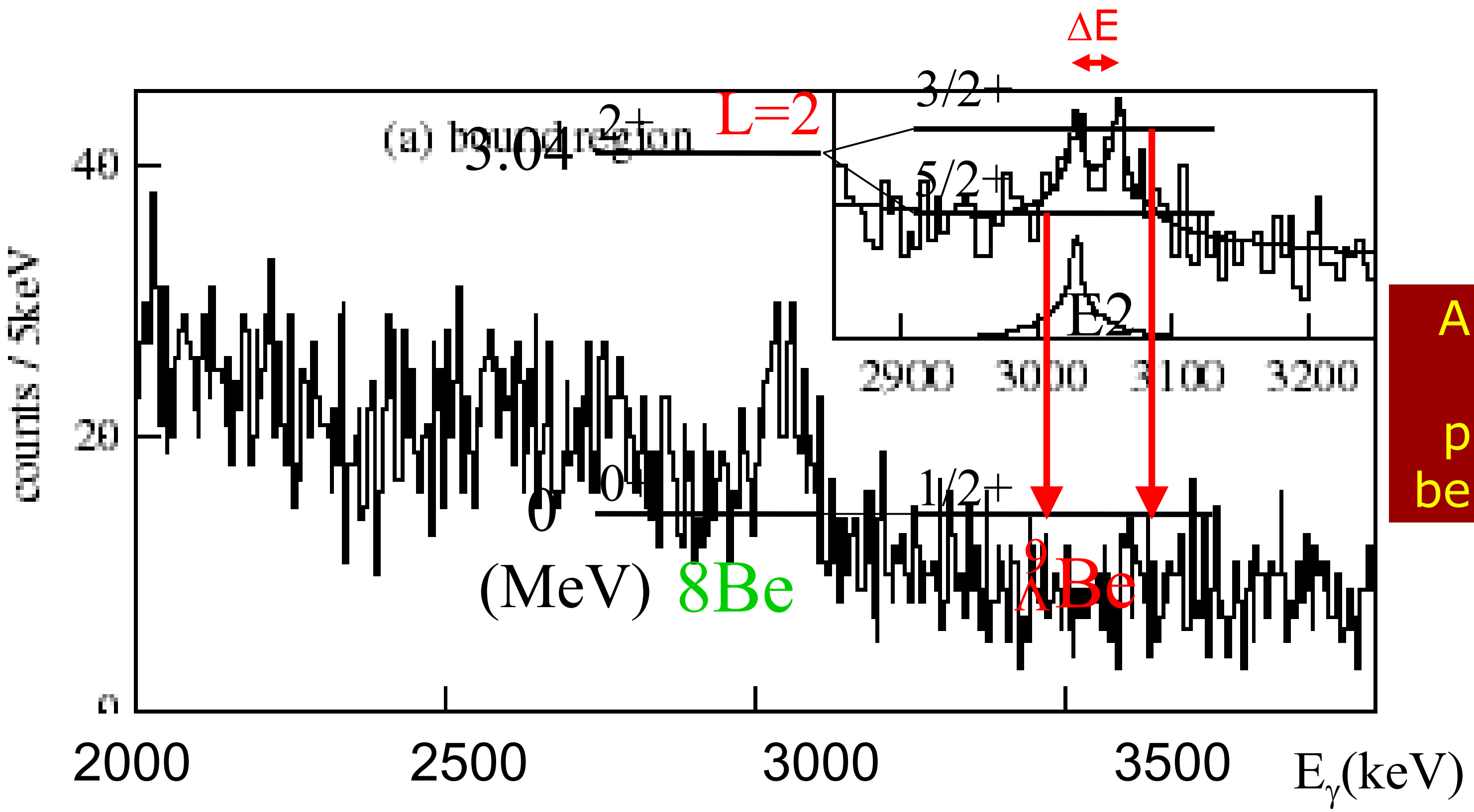
- in normal nuclei: strong spin-orbit interaction (~5MeV for light nuclei) needed to explain shell structure
  - Haxel, Jensen, Suess and Goeppert-Mayer (1949)
- origin still unclear
  - see e.g. N. Kaiser, Nucl. Phys. A709 (2002) 251





Spin-Orbit Force in Hypernuclei

- BNL AGS E930; H. Akikawa et al., PRL88(2002)082501
- γ ray from ${}^{9}_{\Lambda}\mathrm{Be}$ created by ${}^{9}\mathrm{Be}(K^{-},\pi^{-})$ reaction
- $\Delta E(5/2^{+},3/2^{+})$ $\Rightarrow$ ΛN spin-orbit force, LS (core structure: 2α rotating with L=2)



Also for multi-hypernuclei precission will be the key issue

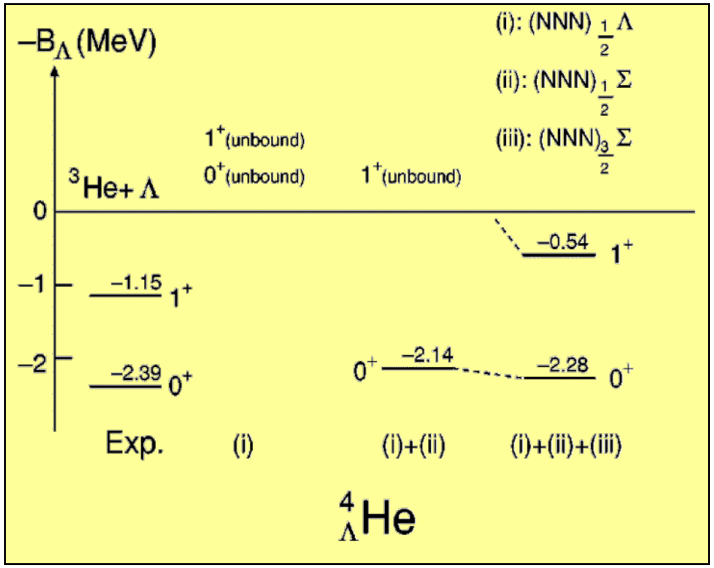
- $|\Delta E| = 31 \pm 3$ keV
- surprisingly small spin-orbit force (~few percent of NN case)

Y-N or Y-Y Interaction in Hypernuclei

- Mass difference between Σ and Λ in single hypernuclei and $\Lambda\Lambda$, ΞN, $\Lambda\Sigma$ in double hypernuclei are small
  - $m(\Xi^0 n)-m(\Lambda\Lambda)=23$MeV $m(\Sigma^0\Lambda)-m(\Lambda\Lambda)=77$MeV
- $\Rightarrow$ mixing important

  $\Rightarrow$ strong medium dependence

E. Hiyama *et al.*, Phys. Rev. C65, 011301R (2001)



- impact on spin-orbit force

  N. Kaiser, W.Weise, PRC 71, 015203 (2005)

- magnitude of mixing depends strongly on nuclei

  D. E. Lanskoy, Y. Yamamoto, Phys. Rev. C **69**, 014303 (2004)

  Nemura *et al.* (2005)

	${}^{4}_{\Lambda\Lambda}\mathrm{H}$ (${}^{3}_{\Lambda}\mathrm{H}$)	${}^{5}_{\Lambda\Lambda}\mathrm{H}$ (${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}^*$)	${}^{6}_{\Lambda\Lambda}\mathrm{He}$ (${}^{5}_{\Lambda}\mathrm{He}$)
$P_{N\Xi}$	0.12	4.34	0.27
$P_{\Lambda\Sigma}$ (P_{Σ})	0.35 (0.16)	2.52 (2.17, 0.36)	1.18 (0.55)
$P_{\Sigma\Sigma}$	0.01	0.05	0.04

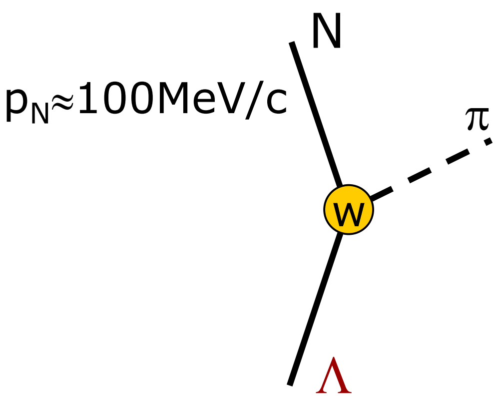
Physics of Hypernuclei

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

- the Y-N and Y-Y strong interactions in the $J^P = 1/2^+$ baryon octet
- the nuclear structure, e.g. the origin of the spin-orbit interaction
- specific aspects baryon-baryon weak interactions
- possible existence of dibaryon particles
- hyperons (Λ, Σ, Ξ) and meson properties in the nuclear medium
- the role played by quark degrees of freedom, flavour symmetry and chiral models in nuclear and hypernuclear phenomena

Weak Decay of Λ Hypernuclei

free Λ decay



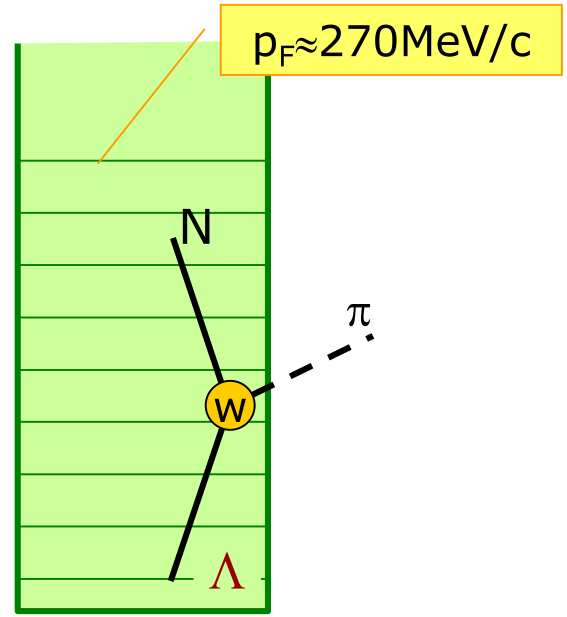
$\Lambda \rightarrow p\pi^- + 38\text{MeV}$ (64%)

$\Lambda \rightarrow n\pi^0 + 41\text{MeV}$ (36%)

$\tau_\Lambda = 263ps$

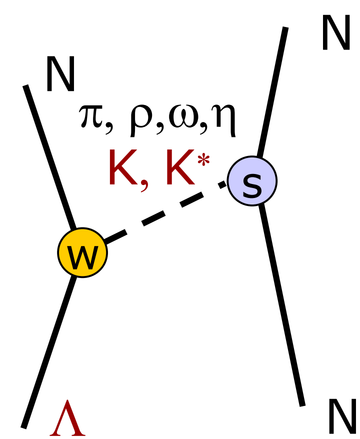
ΔI=1/2 rule

mesonic decay
of hypernuclei



suppresed by
Pauli blocking

non-mesonic
decay
of hypernuclei



$\Lambda p \rightarrow np + 176\text{MeV}$

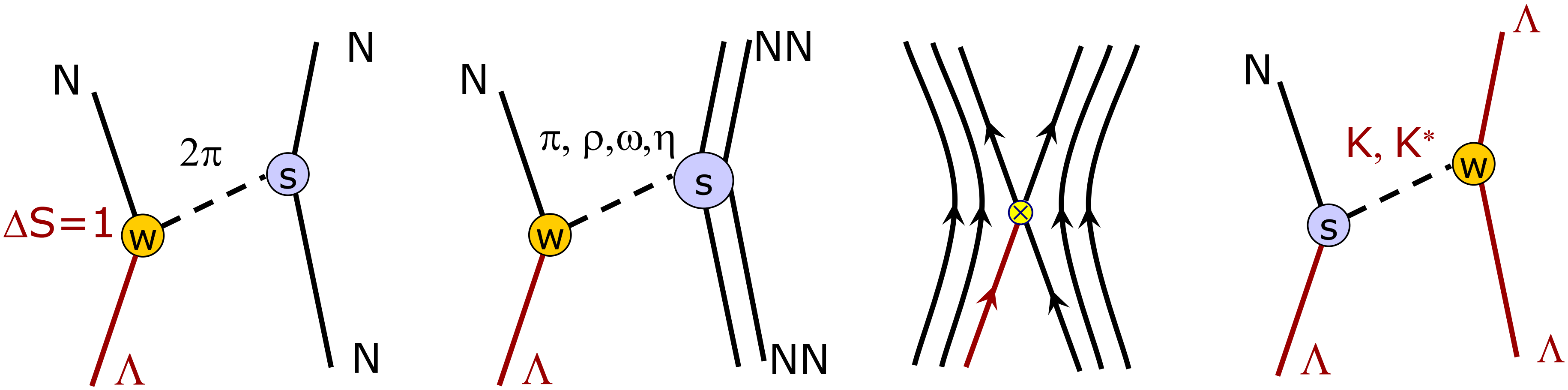
$\Lambda n \rightarrow nn + 176\text{MeV}$

dominant in all
but the lightest
hypernuclei

Weak Baryon-Baryon Interaction

$\Lambda N \to N N$

$\Lambda\Lambda \to Y N$

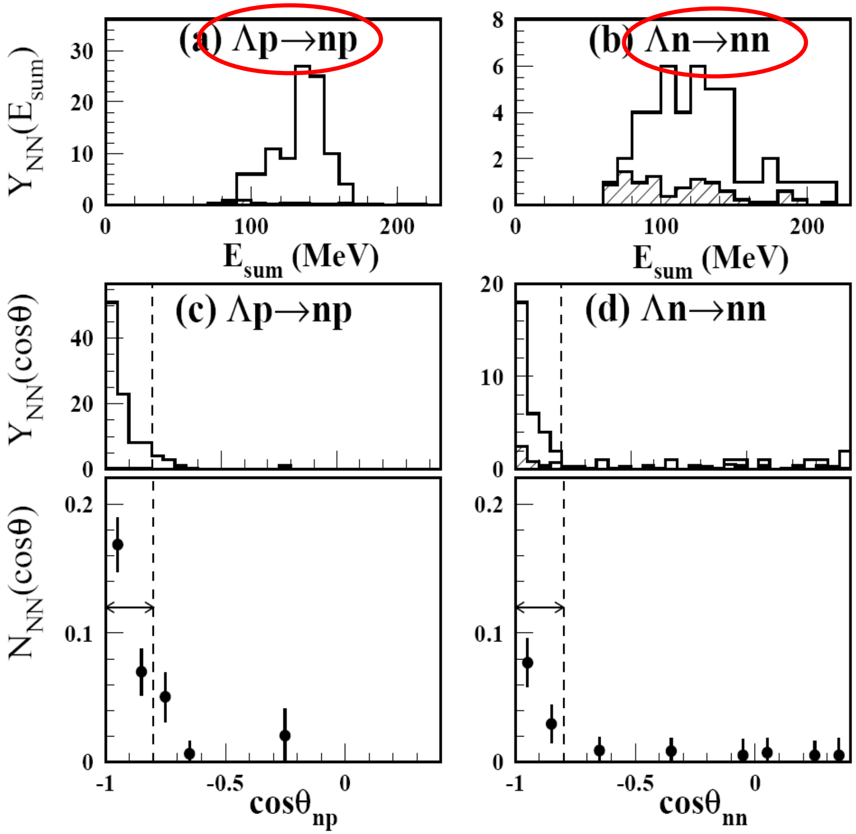


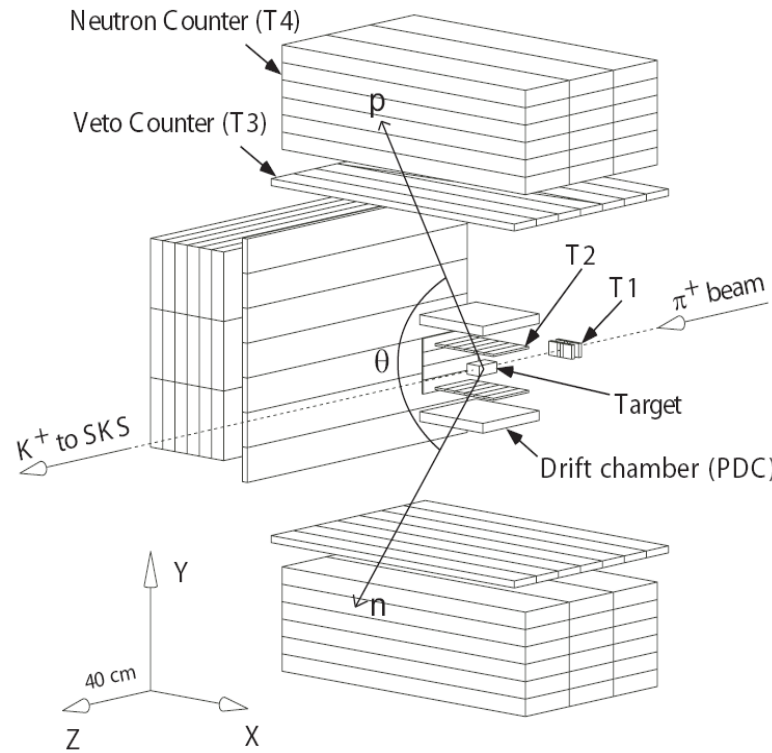
- two-pion exchange
- two-nucleon induced decays $\Lambda NN \to NNN$
- meson vs. direct quark process
- ${}_{\Lambda\Lambda}^{6}He$: $\Lambda\Lambda \to \Lambda n$ → access to weak $\Lambda\Lambda K$ vertex
  - A. Parreno, A. Ramos and C. Bennhold, Phys. Rev C **65**, 015205 : 3.6%
  - K. Sasaki, T. Inoue, and M. Oka, Nucl.Phys. A726 (2003) 349-355: 0.2%
  - K. Itonaga, T. Ueda, and T. Motoba, Nucl. Phys. A691 (2001) 197c: 2.5%

High statistics is another key issue

Example: Weak decay of $^5_\Lambda He$

- KEK–E462, B. H. Kang *et al.* Phys. Rev. Lett. 96. 062301 (2006)





$$\frac{\Gamma_n}{\Gamma_p} \approx \frac{N_{nn}}{N_{pn}} = 0.45 \pm 0.11_{stat} \pm 0.03_{sys}$$

- open issues
  - FSI
  - role of two nucleon induced decyas: ΛNN→NNN (→tripple coincidences ?)
- For ΛΛ→Λn: back-to back Λ-n coincidences

Physics of Hypernuclei

- the Y-N and Y-Y strong interactions in the $J^P = 1/2^+$ baryon octet
- the nuclear structure, e.g. the origin of the spin-orbit interaction
- specific aspects baryon-baryon weak interactions
- possible existence of dibaryon particles
- hyperons (Λ, Σ, Ξ) and meson properties in the nuclear medium
- the role played by quark degrees of freedom, flavour symmetry and chiral models in nuclear and hypernuclear phenomena

Physics of Hypernuclei

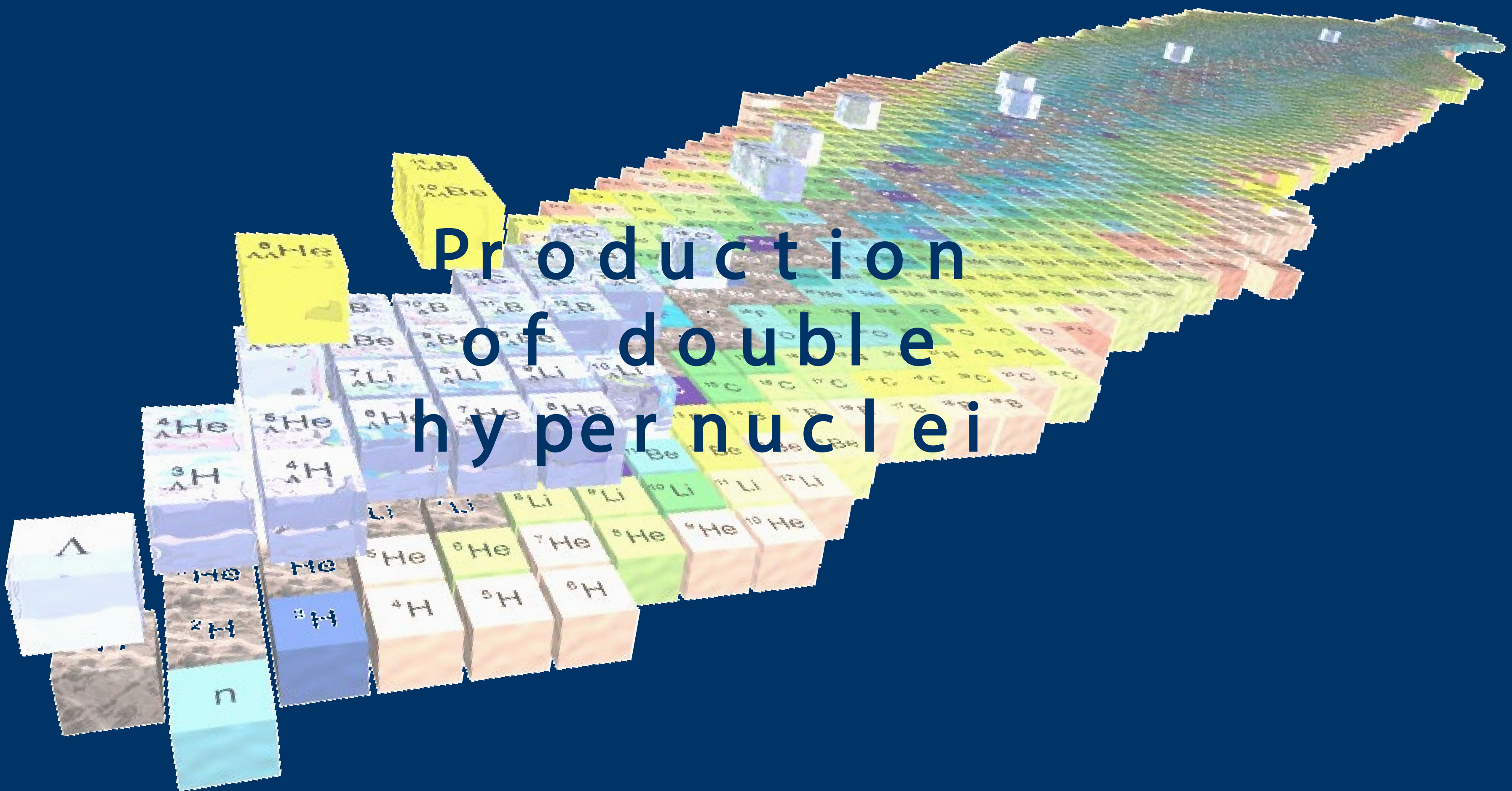
- the Y-N and Y-Y strong interactions in the $J^P = 1/2^+$ baryon octet
- the nuclear structure, e.g. the origin of the spin-orbit interaction
- specific aspects baryon-baryon weak interactions
- possible existence of dibaryon particles
- hyperons (Λ, Σ, Ξ) and meson properties in the nuclear medium
- the role played by quark degrees of freedom, flavour symmetry and chiral models in nuclear and hypernuclear phenomena

Physics of Hypernuclei

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

- the Y-N and Y-Y strong interactions in the $J^P = 1/2^+$ baryon octet
- the nuclear structure, e.g. the origin of the spin-orbit interaction
- specific aspects baryon-baryon weak interactions
- possible existence of dibaryon particles
- hyperons (Λ, Σ, Ξ) and meson properties in the nuclear medium
- the role played by quark degrees of freedom, flavour symmetry and chiral models in nuclear and hypernuclear phenomena

Production of double hypernuclei



Task

High resolution
γ-spectroscopy
and
weak decay studies
of double hypernuclei

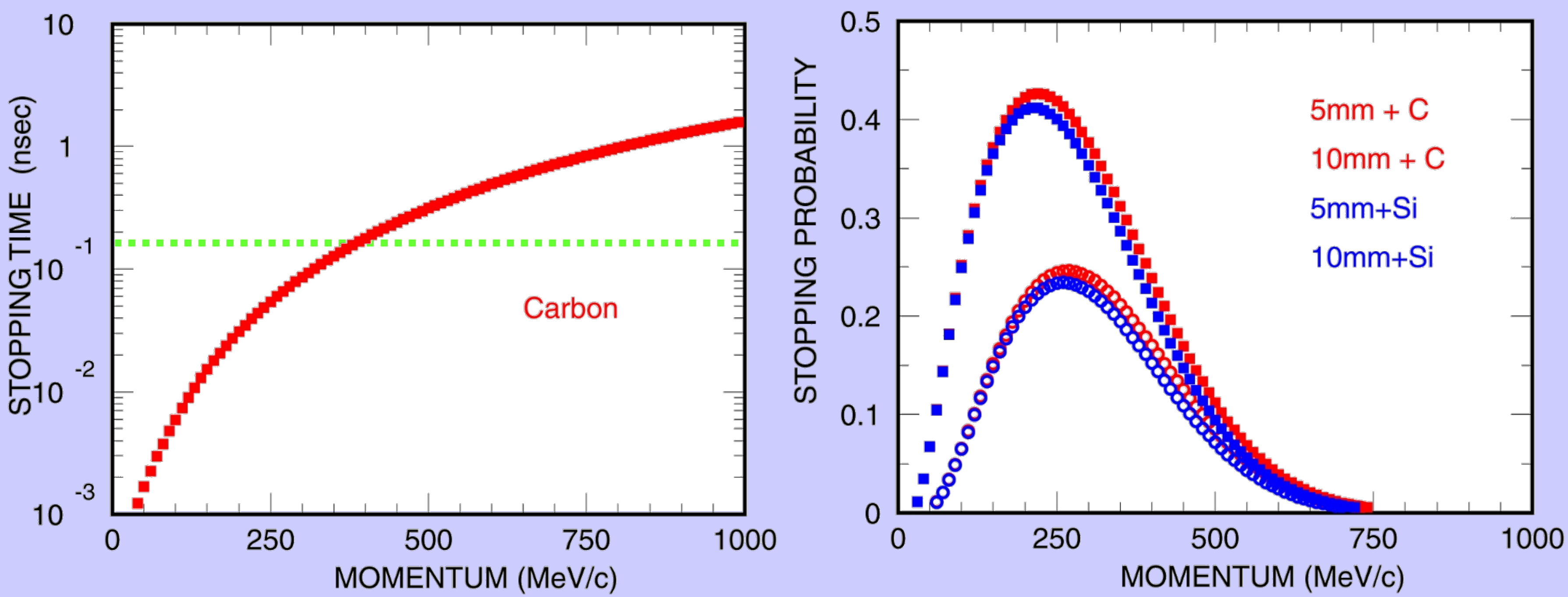
Production of $\Lambda\Lambda$–Hypernuclei

- simultaneous implantation of two Λ is not feasible
- reaction with lowest Q-value: $\Xi^- p \rightarrow \Lambda\Lambda$: 28MeV
  - large probability that two Λ's stick to same nucleus
- in most cases two-step process
  - production of Ξ^- in primary nucleus
  - slowing down and capture in a secondary target nucleus
- spectroscopic studies only possible via the decay products

- Production of Ξ^- by
  - strangeness exchange reaction $p(K^-,K^+)\Xi^-$
    - KEK (E176,E373), AGS (E906)
    - emulsion technique
  - antiproton capture and annihilation
    - FLAIR
  - direct implantation with energetic antiprotons
  - production with antiprotons and subsequent stopping and capture
    - PANDA

Ξ⁻ Properties

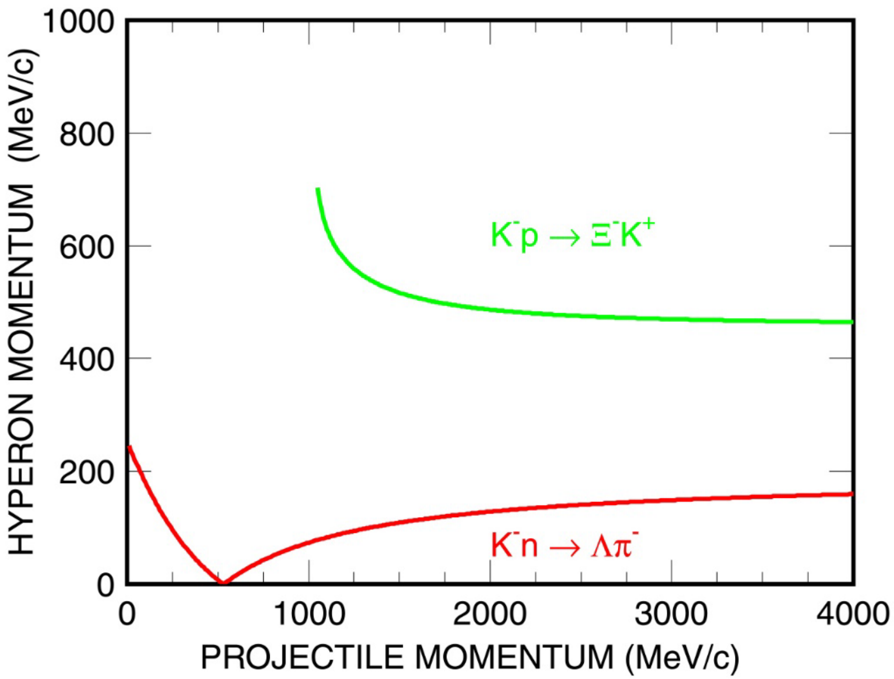
- Ξ⁻ mean lifetime 0.164 ns



- minimal distance production ⇔ capture
- initial momentum 100-500 MeV/c → range ~ few g/cm^2

Strangeness Exchange $p(K^-,K^+)\Xi^-$

- $p(K^-,K^+)\Xi^-$
  - needs K^- beam ($c\cdot\tau$=3.7cm)
  - recoil momentum >460 MeV/c
    ↪Ξ^- stopped in secondary target
- beams (e.g. JPARC)
  - p_K=1.8GeV
  - $1.4\cdot10^6$/spill
  - target thickness few g/cm^2

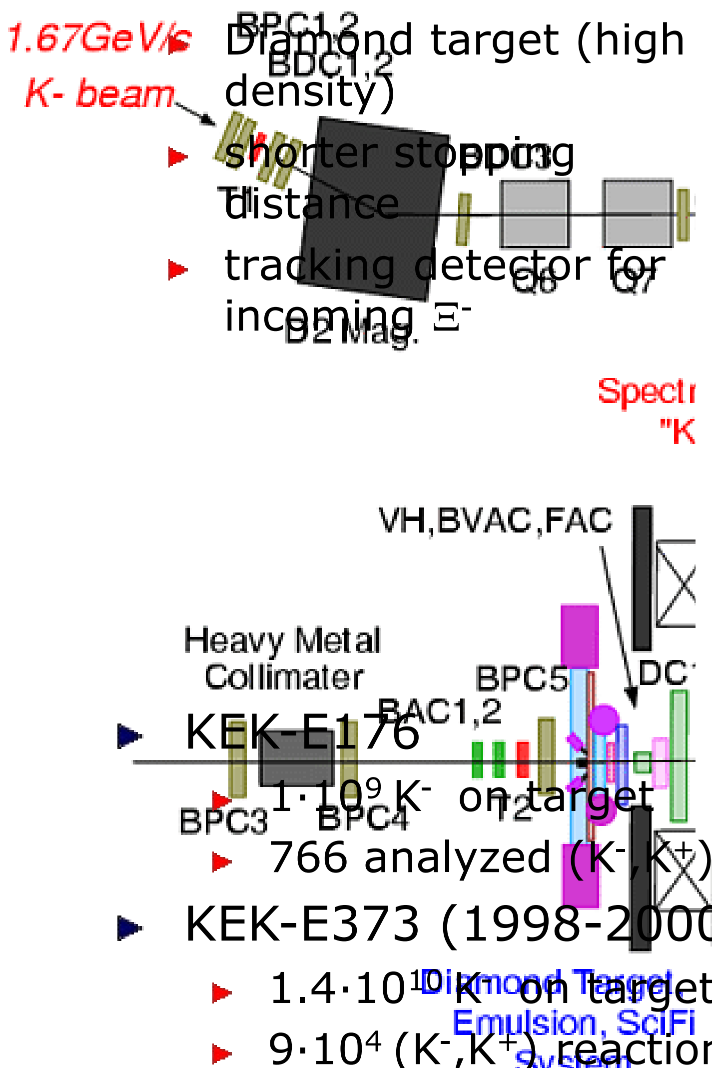


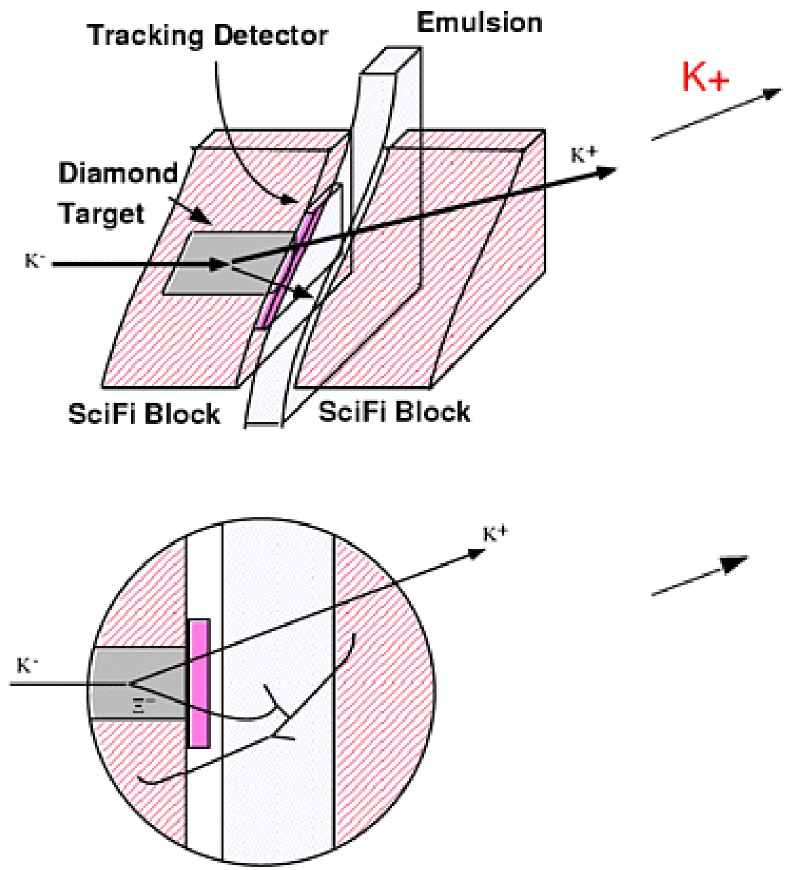
- Experiments
  - KEK-E176: 10^2 stopped Ξ
  - KEK- E373: 10^3 stopped Ξ
  - AGS-E885: 10^4 stopped Ξ

  } per week(s)

The KEK-E373 Experiment

- KEK proton synchrotron
- 1.66 GeV/c K$^-$ beam





- Diamond target (high density)
  - shorter stopping distance
  - tracking detector for incoming Ξ$^-$

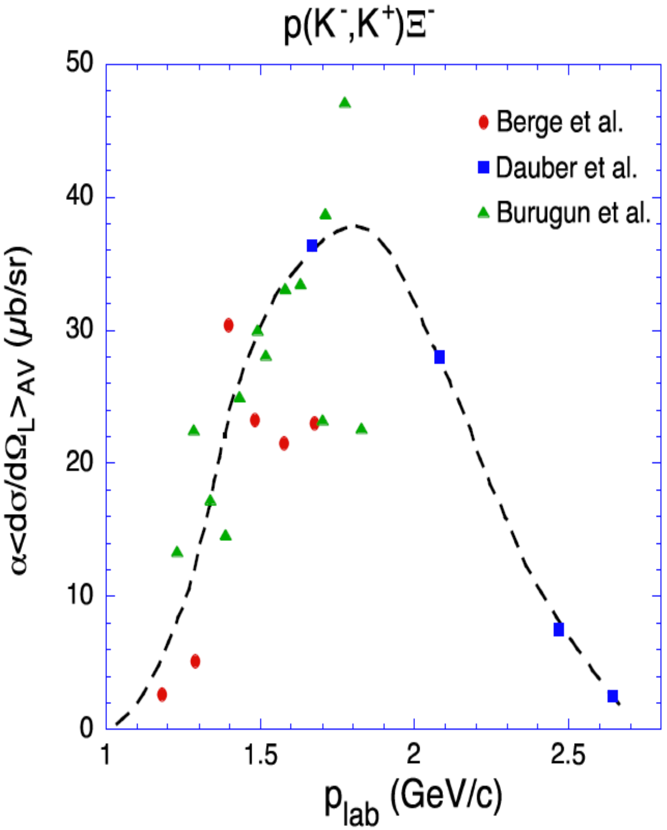
- KEK-E176
  - $1\cdot10^9$ K$^-$ on target
  - 766 analyzed (K$^-$,K$^+$) reactions, 497 Ξ$^-$ candidates
- KEK-E373 (1998-2000)
  - $1.4\cdot10^{10}$ K$^-$ on target, $1.3\cdot10^7$ trigger
  - $9\cdot10^4$ (K$^-$,K$^+$) reactions, 5096 Ξ$^-$ tracks in SciFi

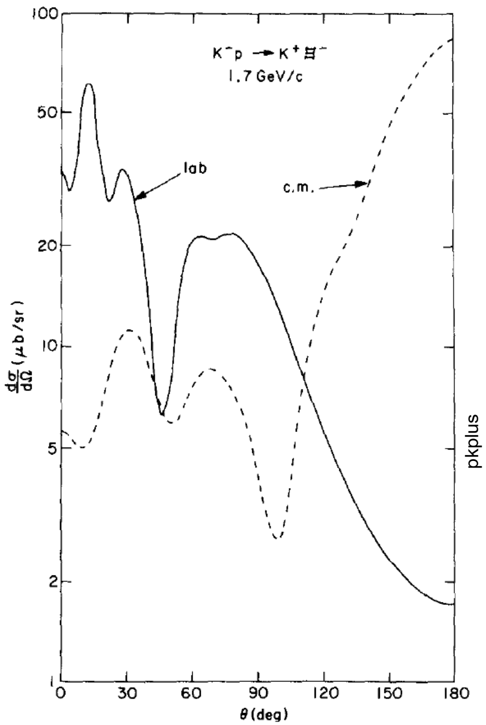
p(K⁻,K⁺)Ξ⁻ at JPARC

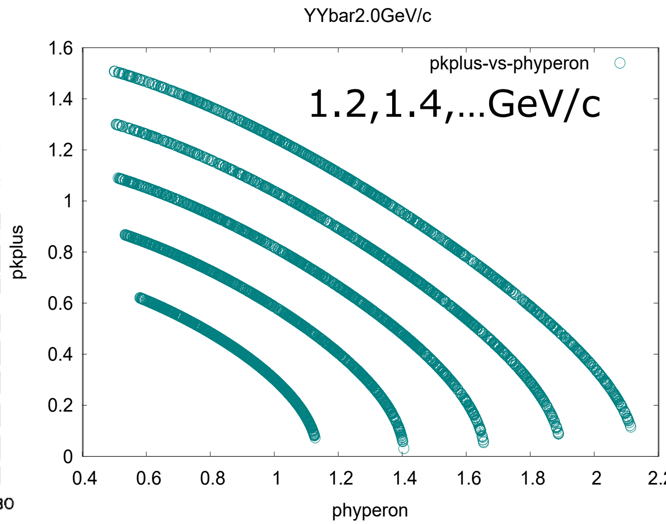
- maximum at p_{Lab}=1.8 GeV/c
- K⁺ angular distribution backward peaked
- decay losses

$$I_{Beam} \times d_{Target} \cdot N_A \times \sigma_{total} \times p_{stop}$$

$$10^7/s \times \left[\frac{10}{12} \cdot 6 \cdot 10^{23}\right] \times 80 \cdot 10^{-30} \times 10^{-3} = 0.4/s = 35000/day$$







ngular distributions for the $K^-p \to K^+\Xi^-$ reaction at 1.7 GeV/c in the center-of-mass dashed line) and lab (solid line) systems, from the data of Dauber *et al.* [14].

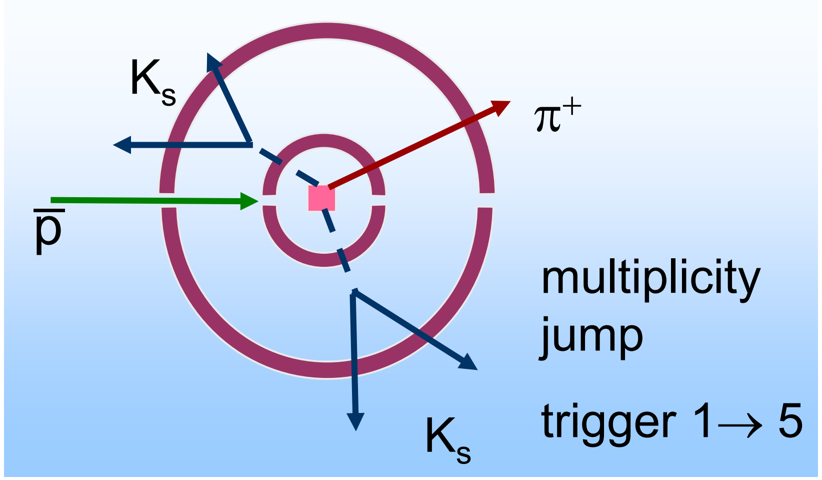
$\bar{p}$ – Annihilation at Rest

- K. Kilian (1987)

$p\bar{p} \rightarrow K^*\bar{K}^*$ $\quad p(K^*(892)) = 285$ MeV/c

$\hookrightarrow \bar{K}^*pn \rightarrow \pi^+ K H$

$p\,^3He \rightarrow KK\pi^+H$

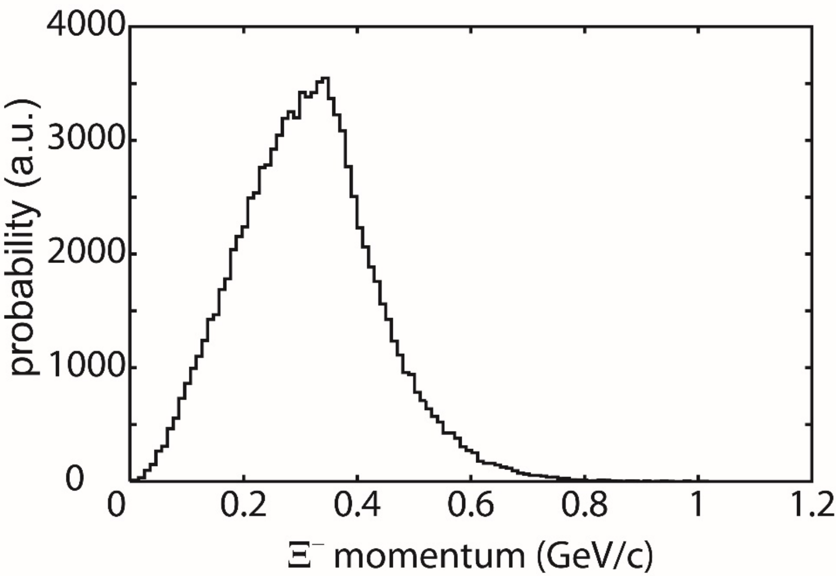


- ...FLAIR

$p\bar{p} \rightarrow K^*\bar{K}^*$ $\quad p(K^*) = 285$ MeV/c

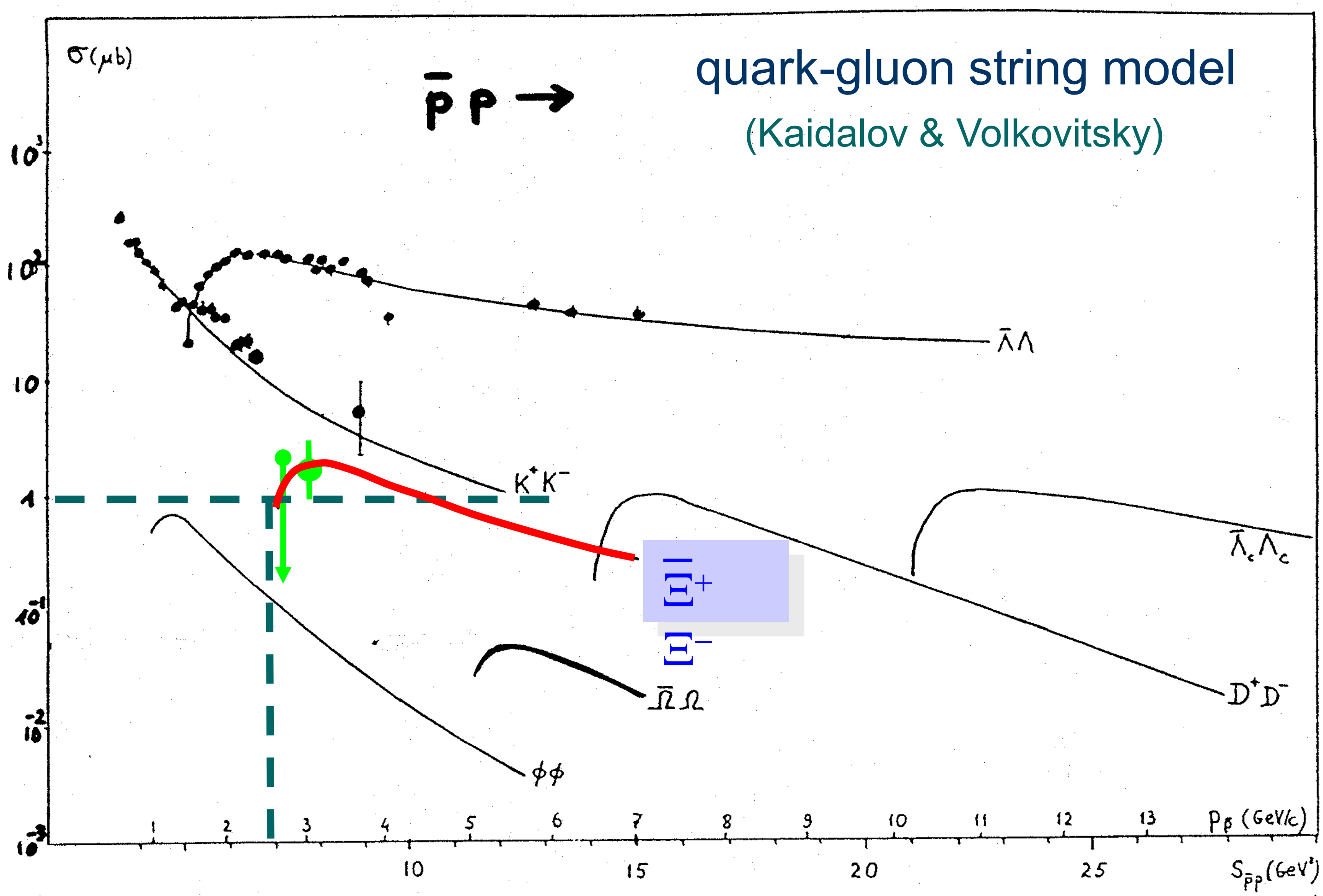
o $\bar{K}^*N \rightarrow K\,\Xi$

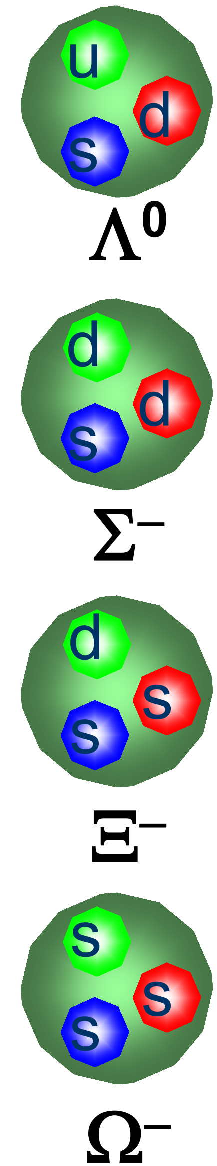
- count rate
  - $1.5 \cdot 10^{-3}$ probability for $\bar{p}p \rightarrow K^*\bar{K}^*$
  - 20% survival probability of K^* prior interaction
  - 10^{-3} probability for $\bar{K}^*N \rightarrow K^+\Xi^-$
  - stopping probability 20%
  - 10^6 antiprotons/s
  - ⇒ 5000 stopped Ξ^- per day



General Idea

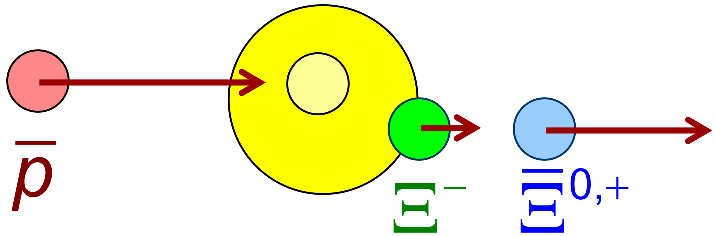
- Use $p\bar{p}$ Interaction to produce a hyperon "beam" ($\tau \sim 10^{-10}$ s) which is tagged by the antihyperon or its decay products
  - Data: B. Mugrave et al., Il Nuovo Cimento, Vol. XXXV, 735 (1965)



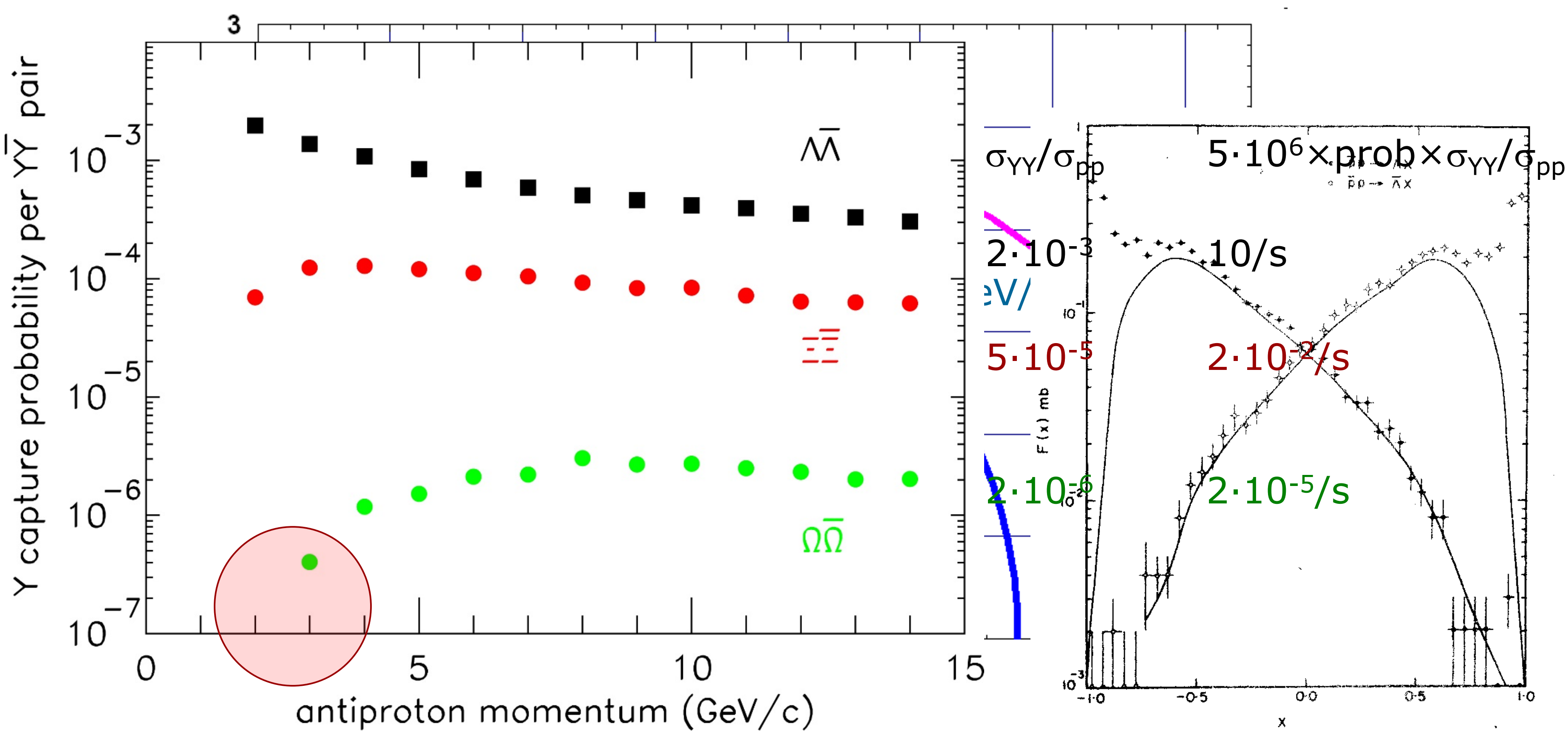


Direct Hyperon Implantation

- production of hyperons with small recoil



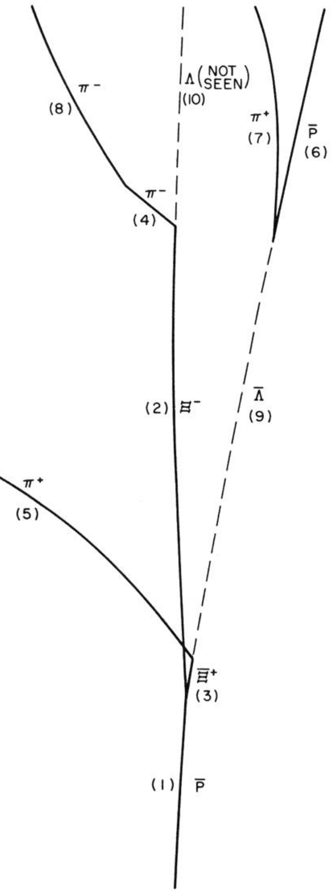
- minimum recoil momentum 500MeV/c (no Fermi motion!) $> p_F$

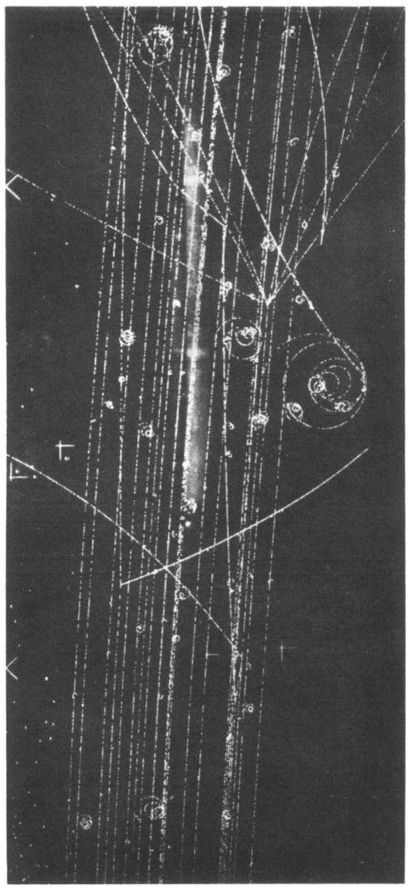


The Discovery of the Ξ

- discovered simultaneously at CERN and SLAC

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





VOLUME 8, NUMBER 6 PHYSICAL REVIEW LETTERS MARCH 15, 1962

OBSERVATION OF PRODUCTION OF A $\Xi^- + \bar{\Xi}^+$ PAIR*

H. N. Brown, B. B. Culwick, W. B. Fowler, M. Gailloud,† T. E. Kalogeropoulos, J. K. Kopp, R. M. Lea, R. I. Louttit, T. W. Morris, R. P. Shutt, A. M. Thorndike, and M. S. Webster
Brookhaven National Laboratory, Upton, New York
and
C. Baltay, E. C. Fowler, J. Sandweiss,‡ J. R. Sanford, and H. D. Taft
Yale University, New Haven, Connecticut
(Received February 19, 1962)

VOLUME 8, NUMBER 6 PHYSICAL REVIEW LETTERS MARCH 15, 1962

EXAMPLE OF ANTICASCADE ($\bar{\Xi}^+$) PARTICLE PRODUCTION IN $\bar{p}$-p INTERACTIONS AT 3.0 Gev/c

CERN, Geneva, Switzerland*
Laboratoire de Physique, Ecole Polytechnique, Paris, France
and
Centre d' Etudes Nucléaires, Département Saturne, Saclay, France
(Received February 19, 1962)

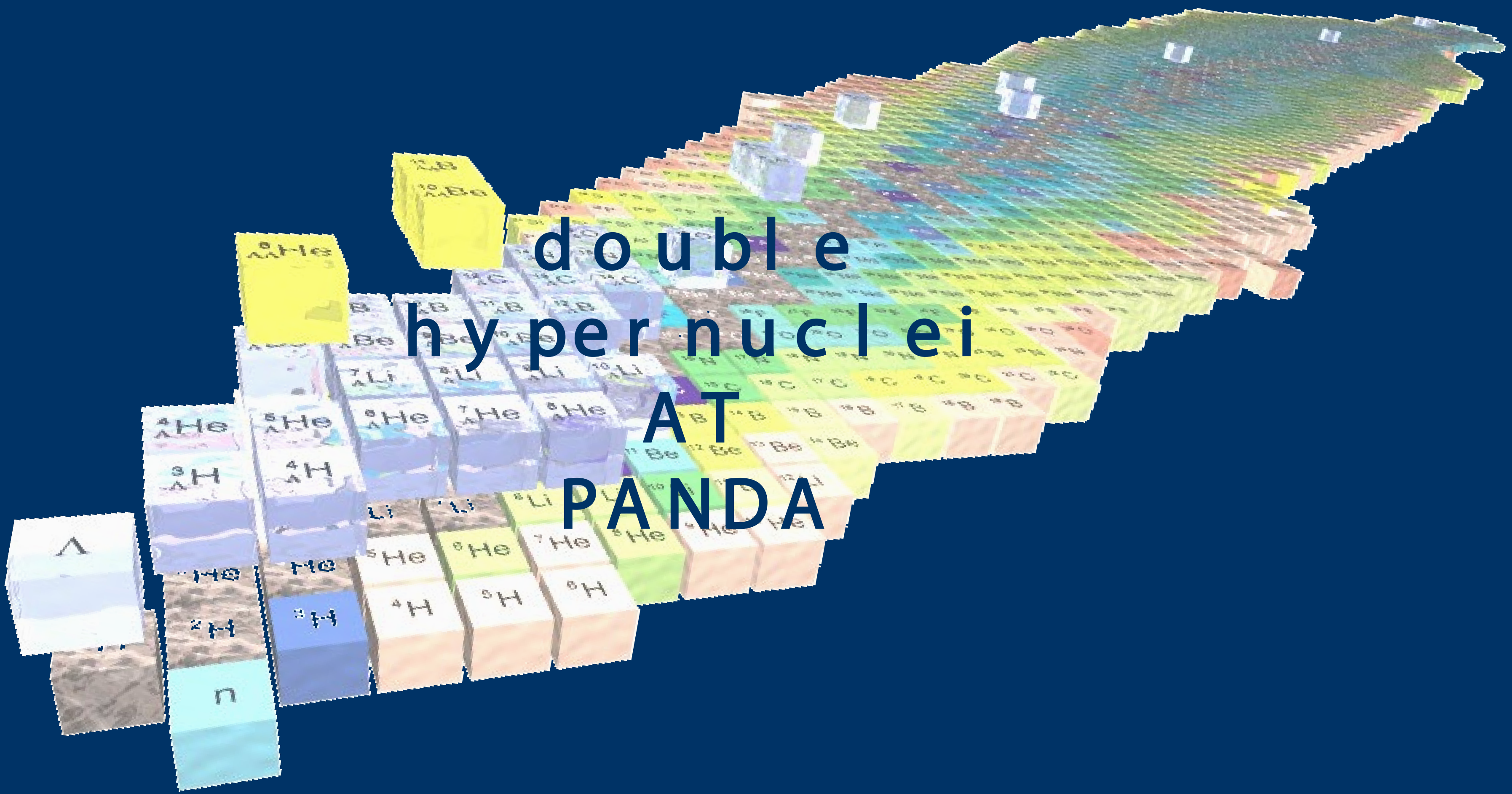
An experiment is in progress at the CERN proton synchrotron to study the interactions of fast antiprotons with protons. A high-energy separated beam[1] has been installed and optimized to provide, in the first instance, a high-purity beam of 3.0-Gev/c antiprotons. The interactions are being produced and observed in the Saclay 81-cm hydrogen bubble chamber.[2]

In the methodical scanning of the first ten thousand photographs (with an average of seven antiprotons per photograph) an event has been found showing the production of an anticascade particle ($\bar{\Xi}^+$). The object of this Letter is to present the data and the analysis leading to this conclusion.

One of the three views of the event is reproduced in Fig. 1. Briefly, the event is as follows: After travelling 20 cm in the chamber, a beam particle interacts at point A, producing two charged particles. The positive particle decays at point B (distant 6 cm from A) and the negative at point D (4 cm from A). Both decay secondaries are light particles, as we will see. At C—about 20 cm downstream from B—there appears a V^0, which will be identified later as the decay of a $\bar{\Lambda}^0$ particle. Near point B another two-prong interaction can be seen at point I: Stereoscopic reconstruction shows that there is no direct link between this interaction and the $\bar{\Lambda}^0$ decay.

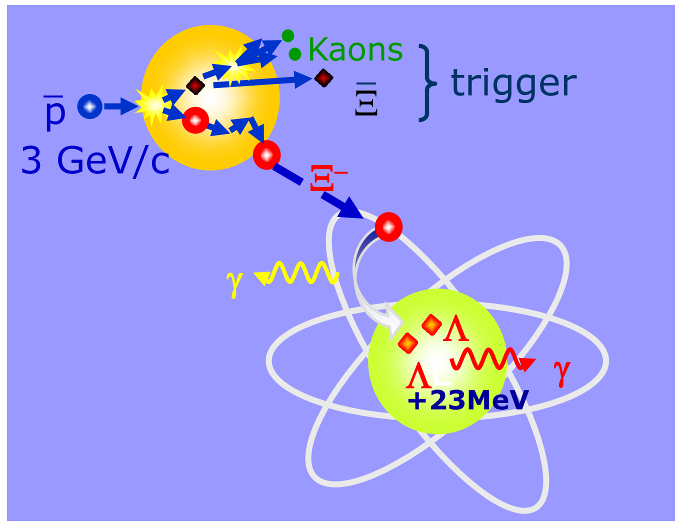
The event can be analyzed in several ways. We have chosen to proceed in two steps: We first analyze the event connected with the positive particle from apex A, and then with the improved knowledge thus derived we analyze the complete interaction at the same apex.

double hypernuclei AT PANDA



Production of Ξ^- at PANDA

- idea: make use of all (1-10^-4^≈1) *emitted* Ξ^-
- significant fraction of produced high momentum Ξ^- are degraded by elastic scattering in the primary nucleus to momenta in the range of 200-500MeV/c

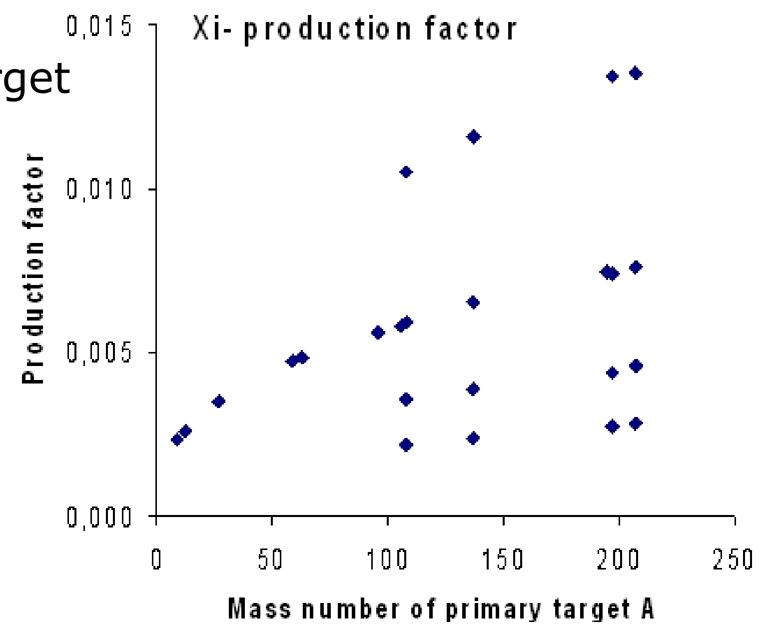


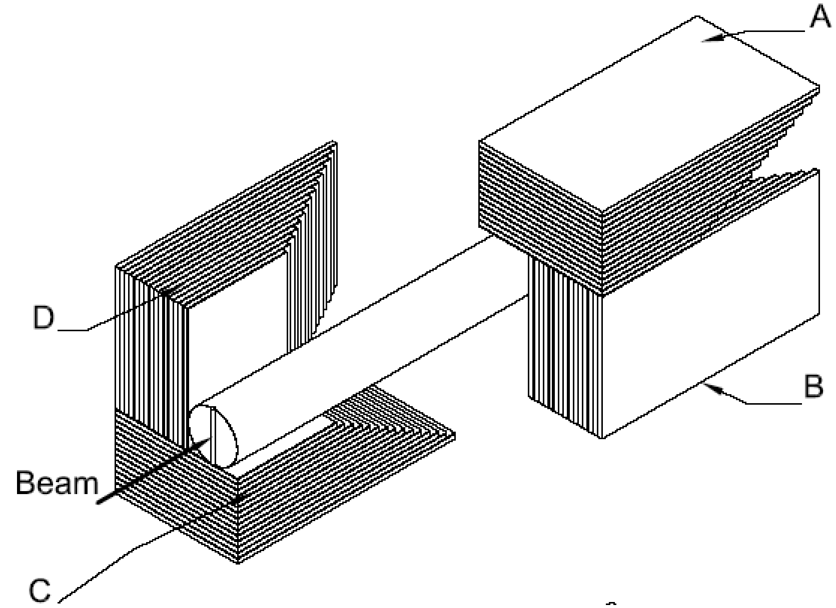
$$p + \bar{p} \rightarrow \Xi^- + \bar{\Xi}^+$$
$$p + \bar{p} \rightarrow \Omega^- + \bar{\Omega}^+$$

- capture of Ξ^- in secondary solid state target (short stopping time)
- secondary target only moderately excited (20-30MeV)
- antoproton momentum 3GeV/c
  - maximum Ξ production
  - low number of associated particles
  - particle background forward focused
- γ-ray detection at backward angles

Primary and Secondary Target

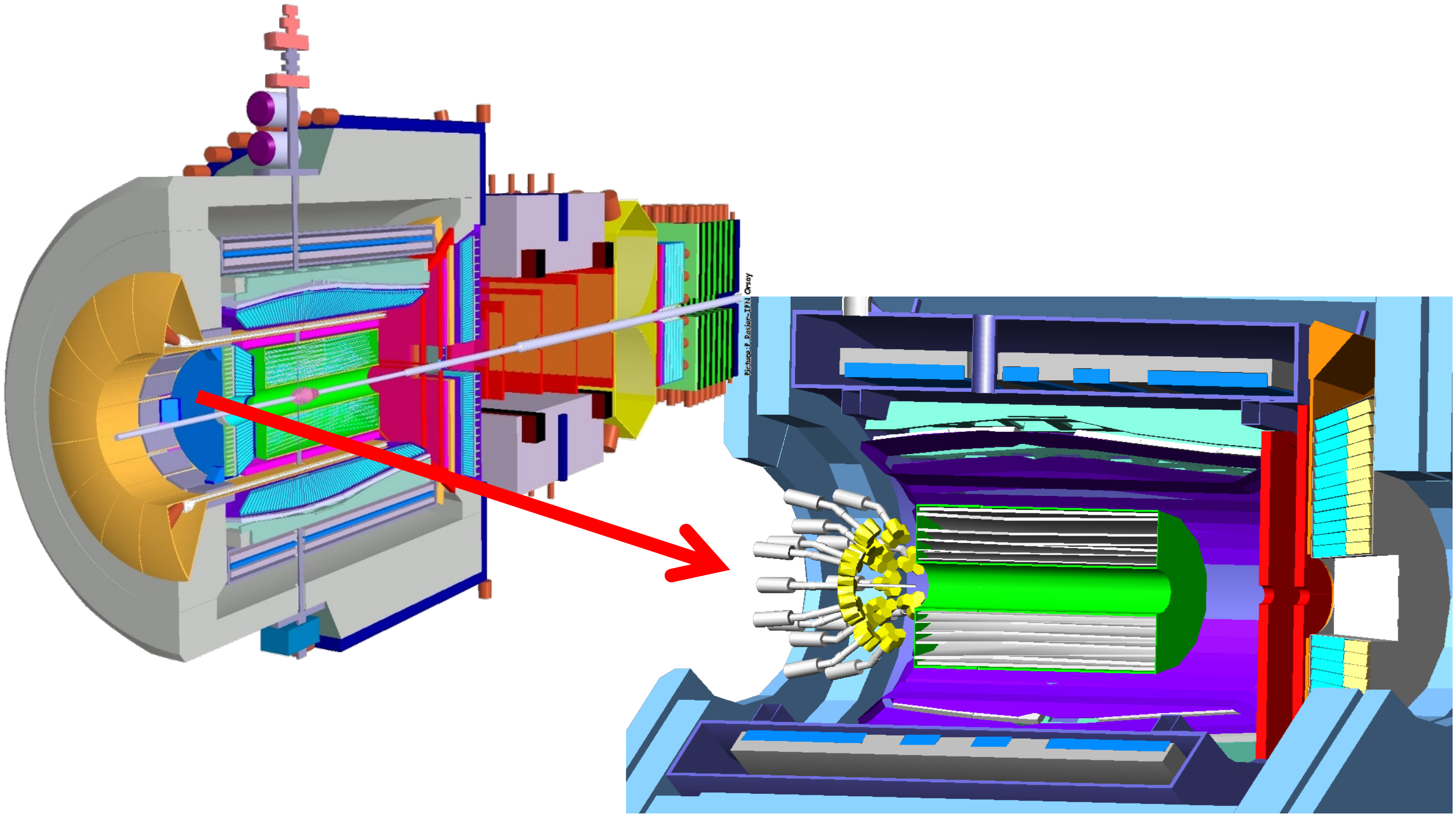
- primary reaction: Ξ-pair production
  - very limited space → nuclear wire target
  - Ξ production for given pbar rate → heavy target (not very critical)
  - beam scattering, neutrons → light target (crucial)
- secondary target
  - geometry defined by Ξ- range, angle distribution and lifetime
  - thickness ~5 gr/cm^2 (~2.5 cm)
- 4 sectors with 4 different targets (Li,Be, B, C)+Si-strip detectors
  - identification can rely on existing information on single hypernuclei
  - low γ-ray absorption
  - no x-ray background





PANDA Setup

- θ_{lab}< 45°: Ξ-bar, K trigger (PANDA)
- θ_{lab}= 45°-90°: Ξ-capture, hypernucleus formation
- θ_{lab}>90°: γ-detection Euroball at backward angles
  - neutron background (4000n $cm^{-2}s^{-1}$)



Count Rate Estimate

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

- technical proposal

$\overline{p}p$ interaction rate	$5 \cdot 10^6 s^{-1}$
$\overline{p}$ momentum	$3\,GeV/c$
internal target	$Z \approx 30$
detector	see Sec. 2
reactions of interest	$\overline{p}p \rightarrow \overline{\Xi}^+ \Xi^-$
	$\overline{p}n \rightarrow \overline{\Xi}^+ \Xi^0$
cross section ($\overline{p}N$)	$2\,\mu b$
rate	$200\,s^{-1}$
Ξ^- PF (see Sec. 4.6)	$6 \cdot 10^{-3}$
total stopped Ξ^-	104 000 per day
$\Xi^- p \rightarrow \Lambda\Lambda$ conversion probability	5 %
produced $\Lambda\Lambda$ hypernuclei	5 200 per day
probability of individual transition	10 %
target escape probability ($E_\gamma = 1\,MeV$)	70 %
full energy peak efficiency	3.5 %
trigger efficiency	40 %
detected individual transitions	150 per month

Z=6

50000/day

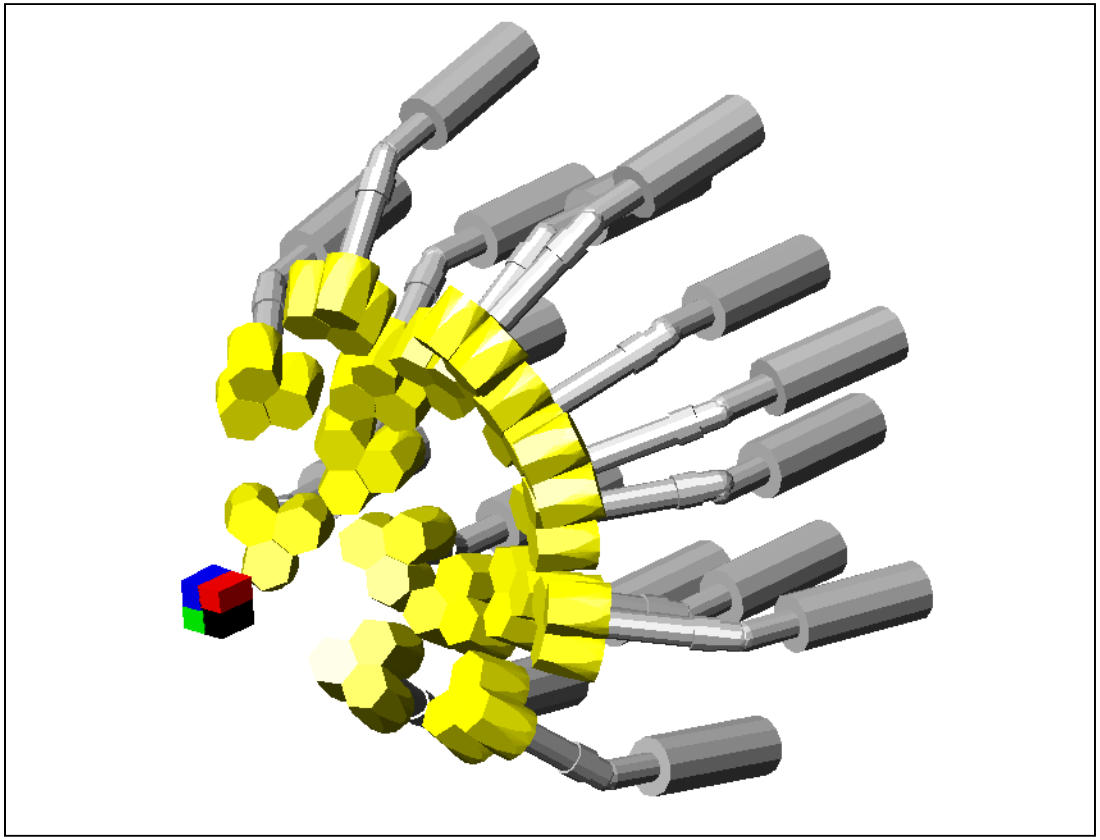
- In order to avoid beam losses due to Coulomb scattering ^{12}C as primary target ⇒ reduced rate by no more than factor 2 (may be recovered by optimized beam optics)

Future of S=-2 hypernuclei

Facility	reaction	device	Beam/ target	stopped Ξ^- /day
J-PARC	$(K^-,K^+)\Xi^-$ —	spectrometer hybrid detector	1.4 10^6 K/spill 5cm ^{12}C	1000
		γ-spectroscopy	10^7/s	35000
FLAIR	$pp_{stopped} \to K^*K^*$ — —	Vertex detector	10^6 stopped antiprotons per sec	5000
PANDA	$pp \to \Xi^-\Xi^+$	Vertex detector, Ge	^{12}C	50000

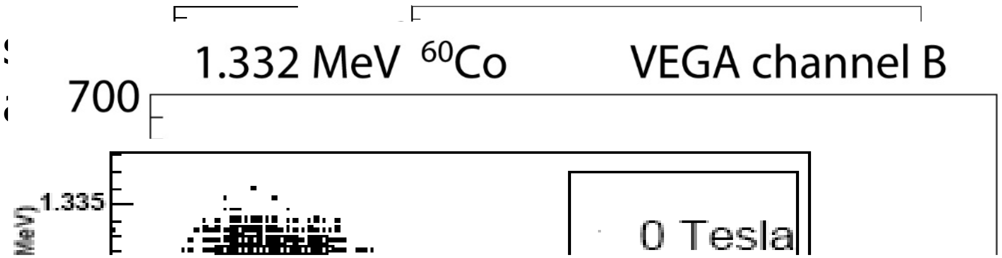
Challenges for Ge Detectors

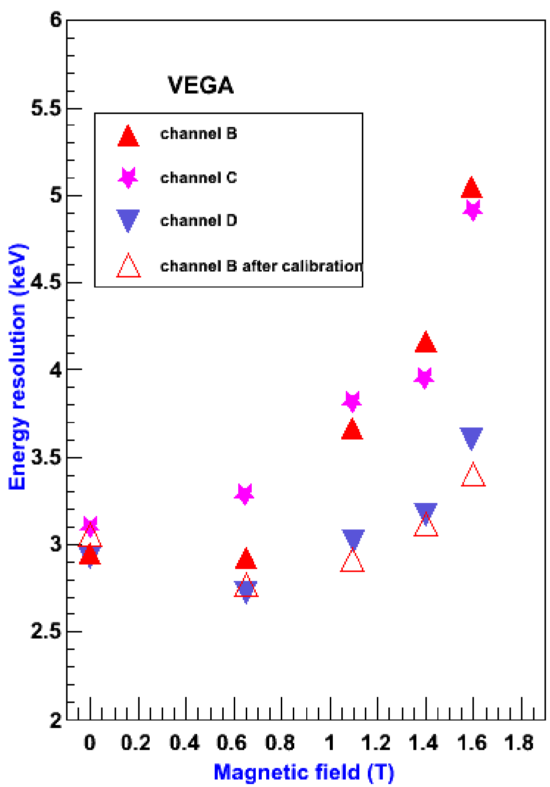
- Magnetic field ~ 1.2 T:
  - Change in the energy resolution and in the pulse shape.
- hadronic background and neutron damage
  - detector at backward angles
- Limited Space
  - need compact design of cooling system.

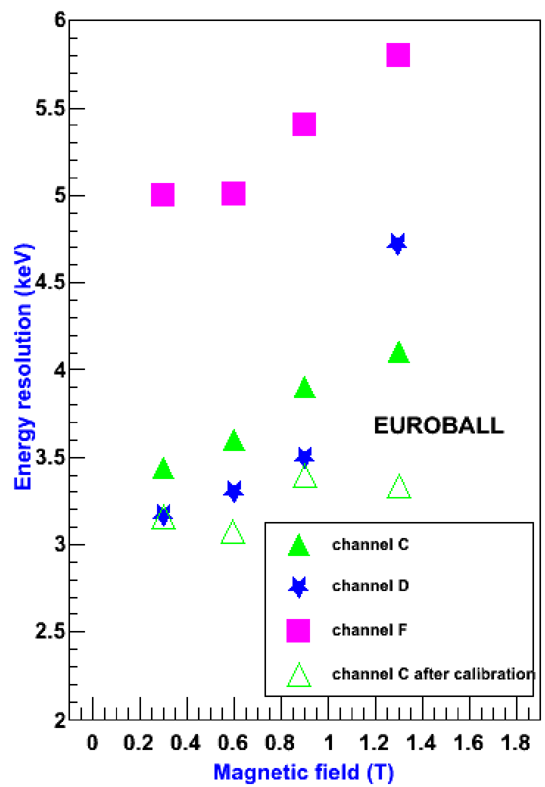


Ge Detectors in Magnetic Fields

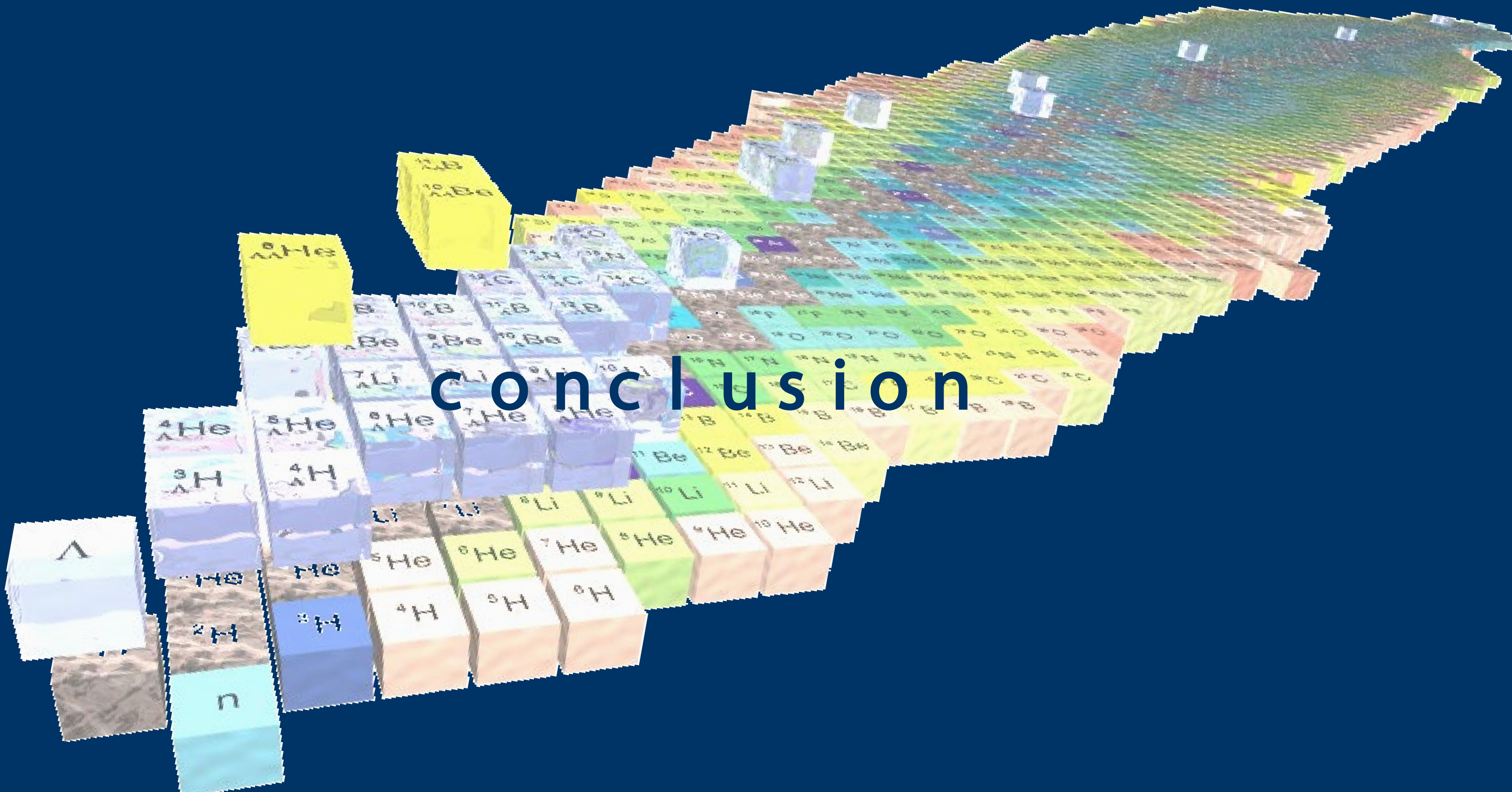
- distortion of puls shape in magnetic field
- increased signal risetime
- reduced ene
- ...
- ... e



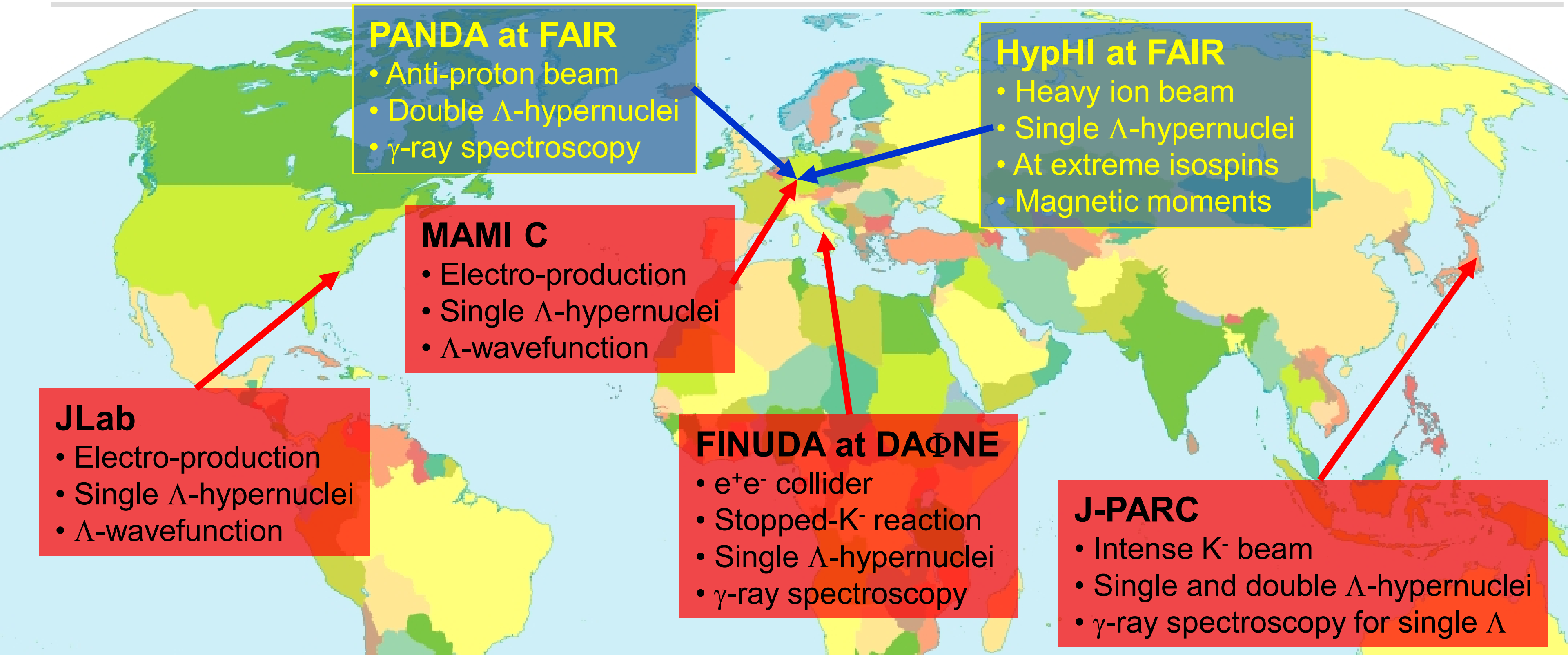




conclusion



International Hypernuclear Network



- Antiproton collisions with nuclei offer many opportunities to study strange baryons in *cold* nuclei
  - baryon-baryon interaction, weak decay, spectroscopy of baryonic atoms
- These studies are possible by a unique combination of experimental facilities at FAIR
  - γ-spectroscopy with Ge detectors ⊕ PANDA ⊕ antiproton beams
  - FLAIR
- Heavy Ions → HypHI