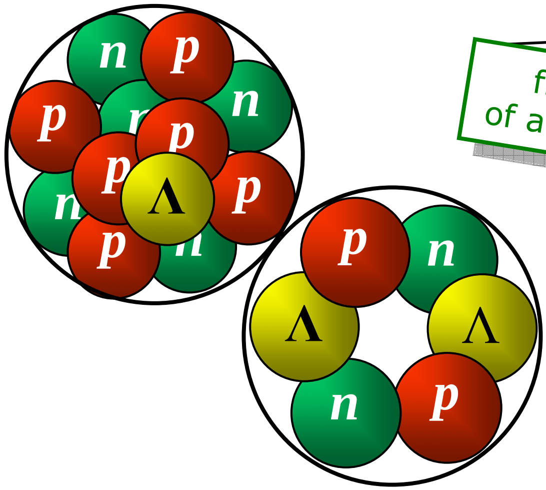
Perspectives on the physics of hypernuclei

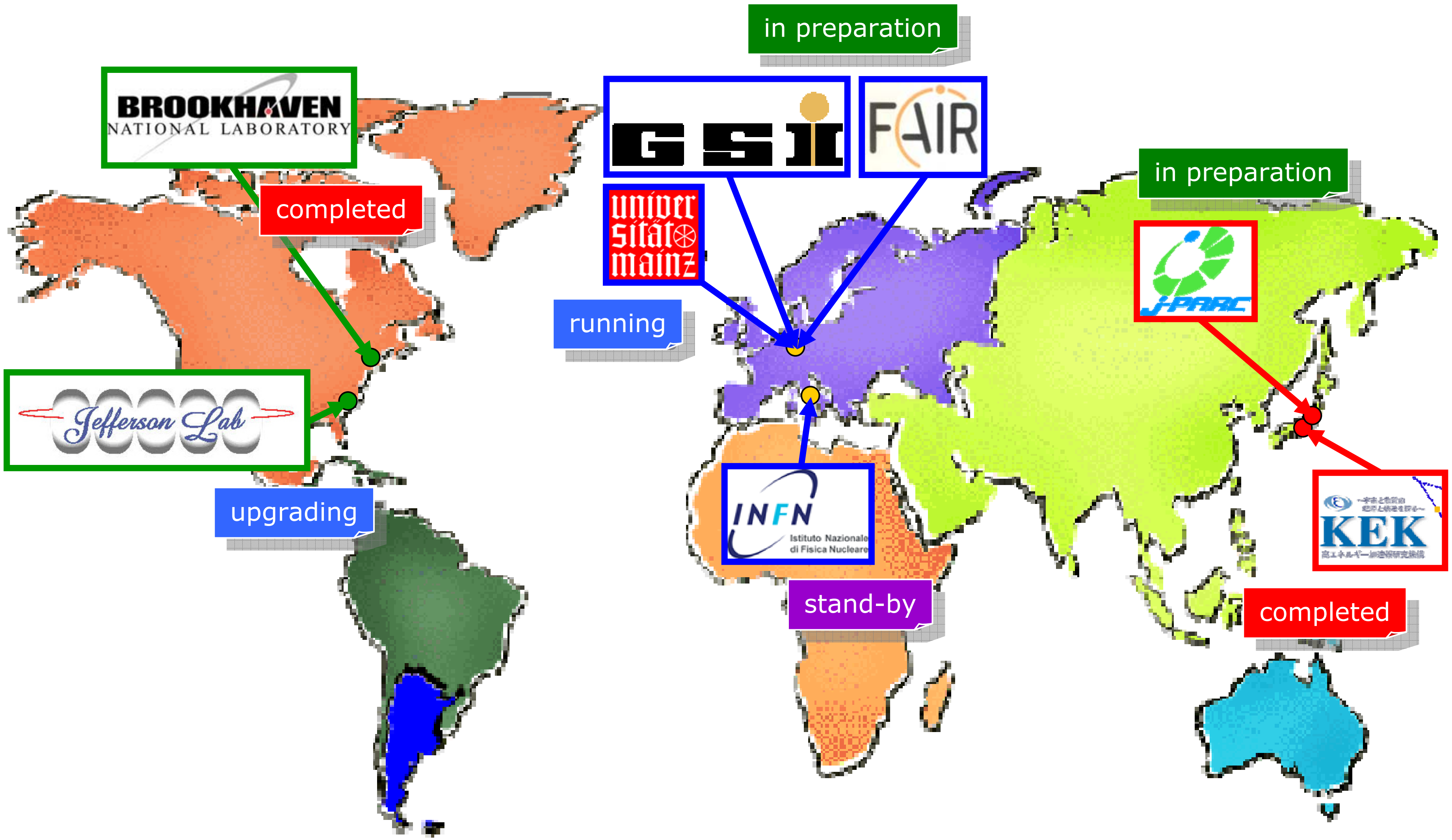


from the point of view of an Italian experimentalist

Alessandro Feliciello

I.N.F.N. - Sezione di Torino

Outline



in preparation
BROOKHAVEN
NATIONAL LABORATORY
completed
Jefferson Lab
upgrading
GSI
FAIR
universität mainz
running
INFN
Istituto Nazionale di Fisica Nucleare
stand-by
in preparation
J-PARC
KEK
completed

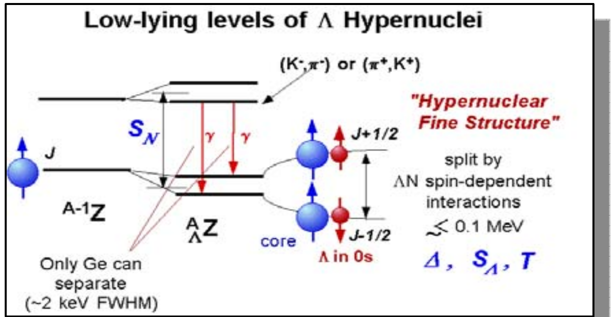
Open questions

- (low-energy) *YN* interaction
  - detailed knowledge of the hypernuclear fine structure
    → evaluation of the spin dependent terms of the *ΛN* interaction
  - measurement of angular distribution of γ–rays
    → determination of spin and parity of each observed level

Spin-dependent forces

The simple structure of light hypernuclear system can be described in the frame of the shell model

$$V_{\Lambda-N}(r) = V_0(r) + \overbrace{V_\sigma(r)\vec{s}_N\cdot\vec{s}_\Lambda}^{\Delta} + \overbrace{V_\Lambda(r)\vec{l}_{N\Lambda}\cdot\vec{s}_\Lambda}^{S_\Lambda} + \overbrace{V_N(r)\vec{l}_{N\Lambda}\cdot\vec{s}_N}^{S_N}$$
$$\underbrace{+V_T(r)[3(\vec{\sigma}_N\cdot\vec{r})(\vec{\sigma}_\Lambda\cdot\vec{r}-\vec{\sigma}_N\cdot\vec{\sigma}_\Lambda)]}_{T}$$

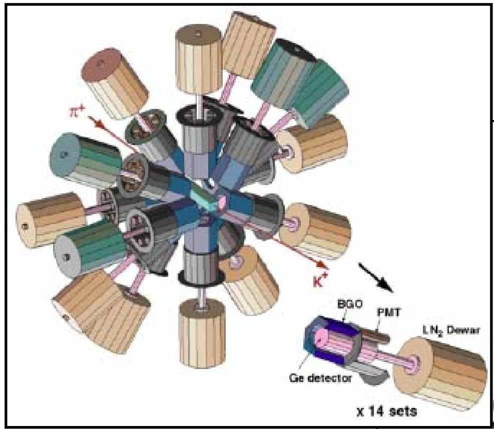


Each of the 4 terms (Δ, S_Λ, S_N, T) correspond to a radial integral that can be phenomelogically determined from the low-lying level structure of *p*-shell hypernuclei

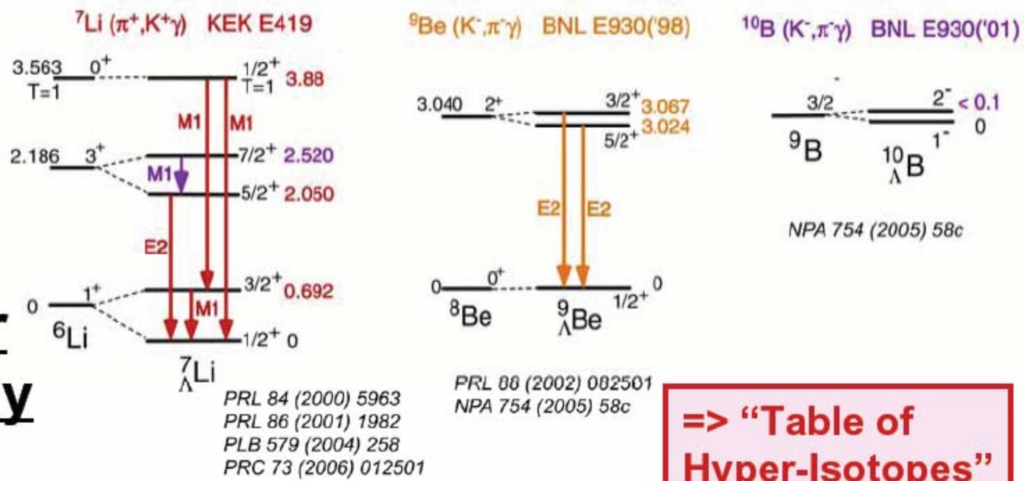
The knowledge of these characteristics of the ΛN interaction allows to improve baryon-baryon interaction description

A. Feliciello / 6th Japan-Italy Symposium on Heavy-Ion Physics "Perspectives in Nuclear Physics", Tokai, Japan, November 11-15, 2008.

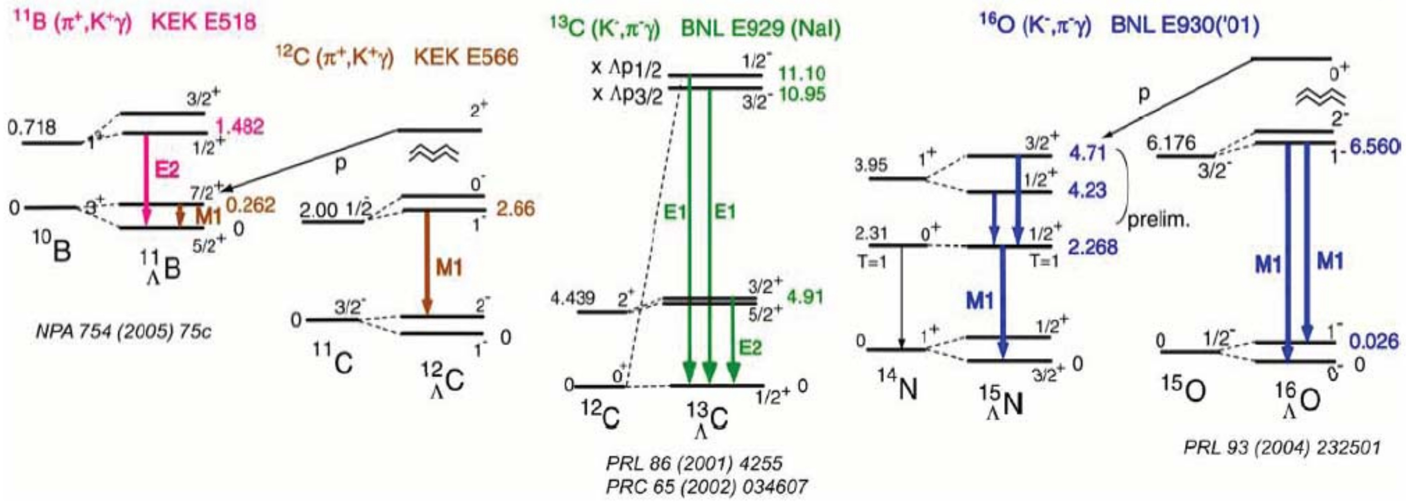
Where do we stand?



Status of hypernuclear γ spectroscopy

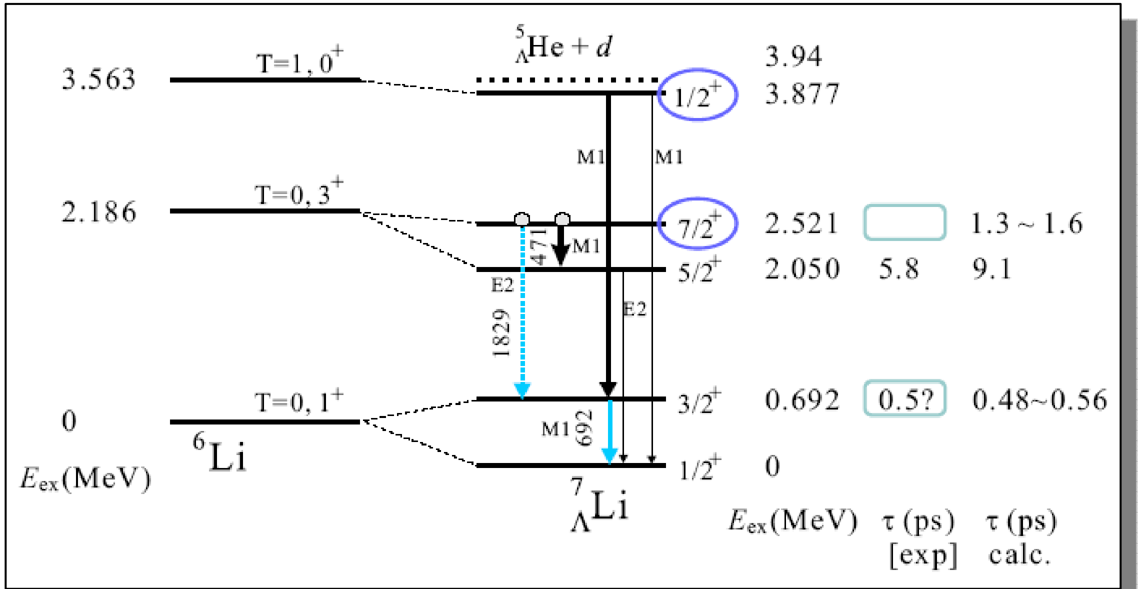


=> "Table of Hyper-Isotopes"



H. Tamura

Where do we stand?



HYPERBALL

KEK E419: (π^+, K^+)

BNL E930: (K^-, π^-)

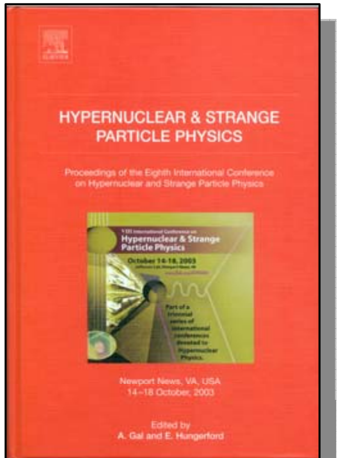
KEK E509: (K^-, π^-)

$\Delta = 0.48$

$S_\Lambda = -0.01$

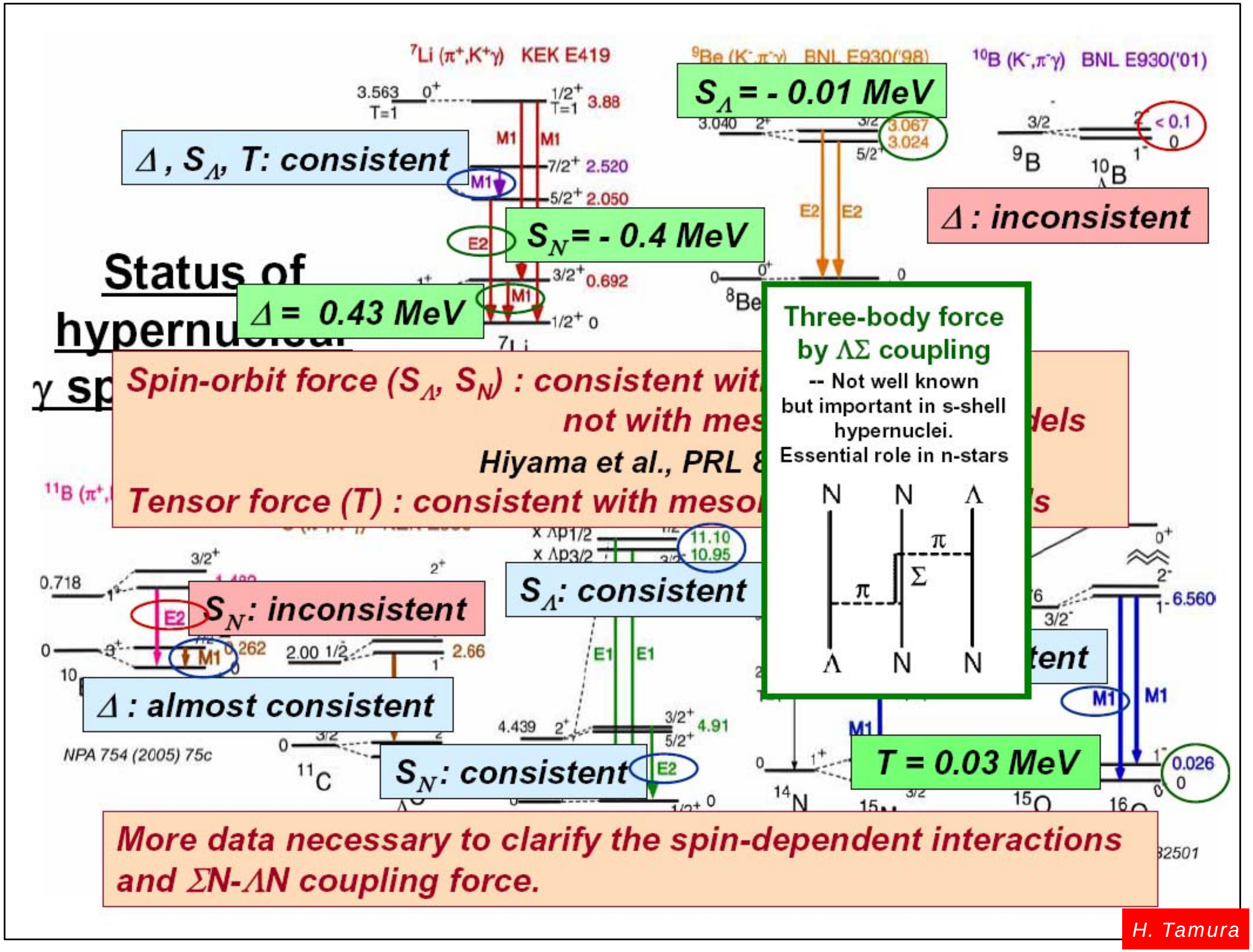
$S_N = -0.40$

$T = 0.03$



D.J. Millener, *Nucl. Phys. A* 754 (2005) 48c

Where do we stand?



What do we learnt?

- the determined set of parameters is not universal
- γ-ray spectroscopy is the new frontier for hypernuclear physics

The crucial benchmark

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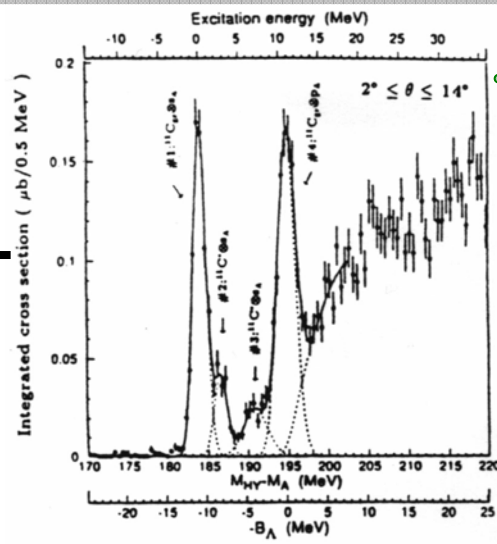
1996

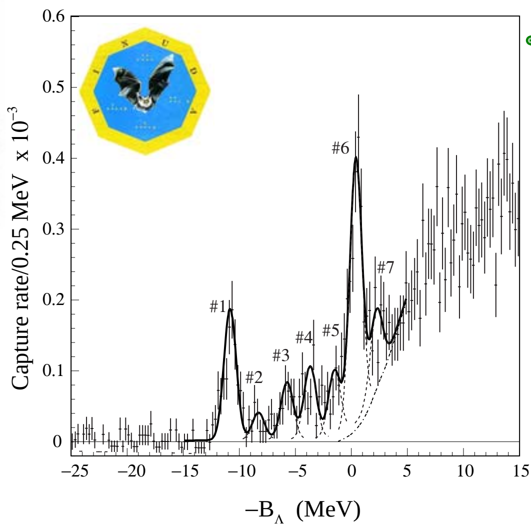


$^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$

T. Hasegawa *et al.*, Phys. Rev. C 53 (1996) 1210

ΔE ~ 1.9 MeV FWHM

2005

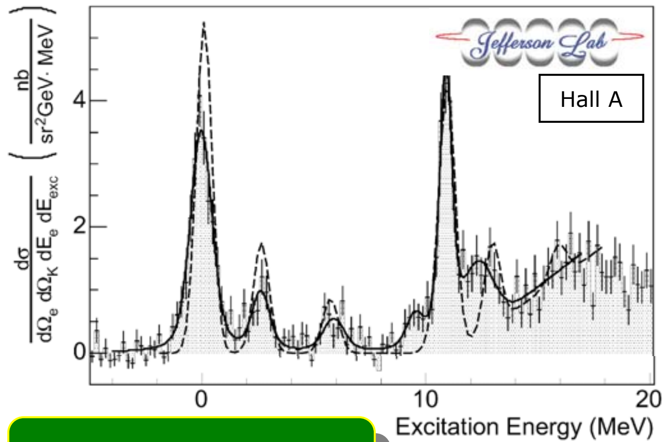


$^{12}C(K^-_{stop},\pi^-)^{12}_{\Lambda}C$

M. Agnello *et al.*, Phys. Lett. B 622 (2005) 35

ΔE ~ 1.3 MeV FWHM

2008



$^{12}C(e,e',K^+)^{12}_{\Lambda}B$

G.M. Urciuoli *et al.*, Nucl. Phys. A 805 (2008) 170

ΔE ~ 0.67 MeV FWHM

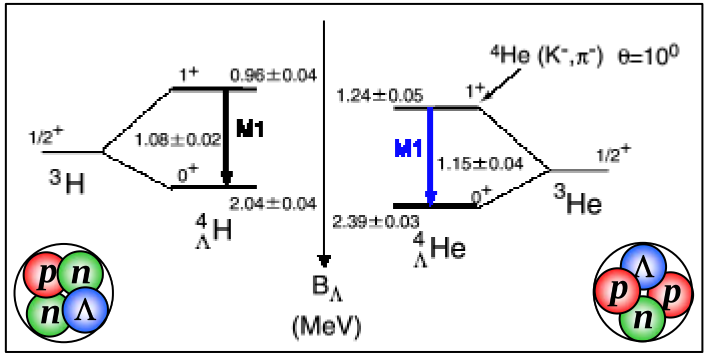
t

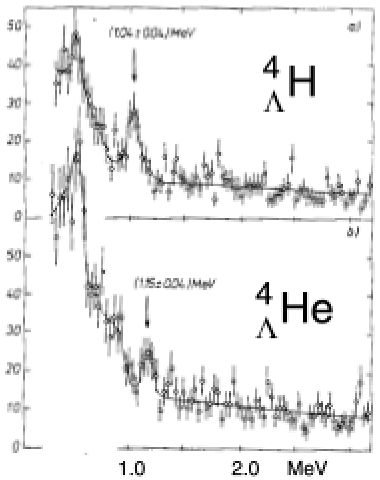
A. Feliciello / 6th Japan-Italy Symposium on Heavy-Ion Physics "Perspectives in Nuclear Physics", Tokai, Japan, November 11-15, 2008.

Charge symmetry breaking

$$\Lambda \begin{cases} I = 0 \\ q = 0 \end{cases} \Rightarrow \Lambda p = \Lambda n$$

if the charge symmetry holds exactly





$$B_\Lambda({}^4_\Lambda H) \neq B_\Lambda({}^4_\Lambda He)$$

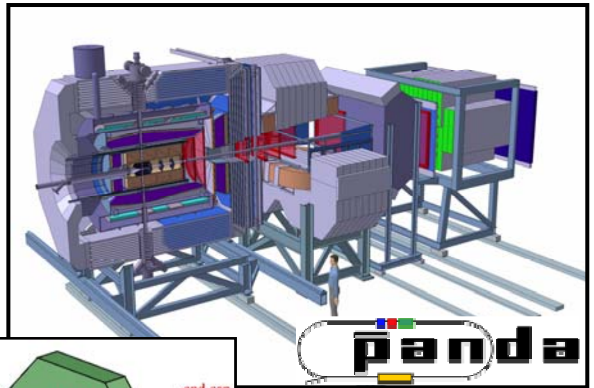
Λp more attractive than Λn

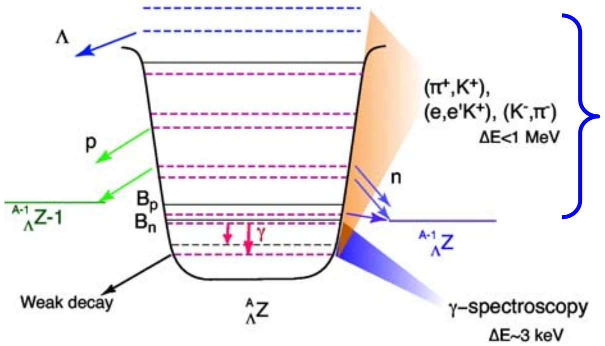
A.R. Bodmer *et al.*, *Phys. Rev.* C 31 (4) (1985) 1400

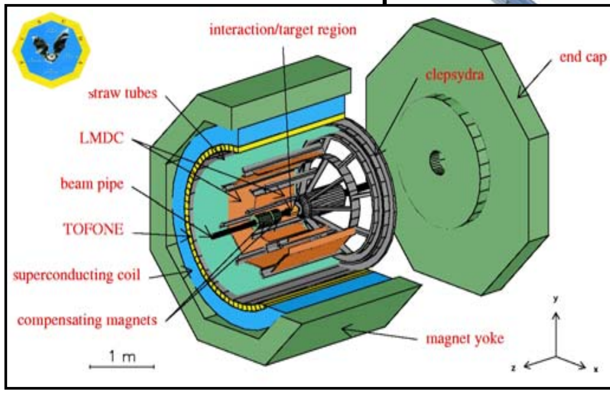
possible explanations:
- $\Lambda\Sigma^0$ mixing
- $\Lambda N - \Sigma N$ coupling

Which role for magnetic spectrometer?

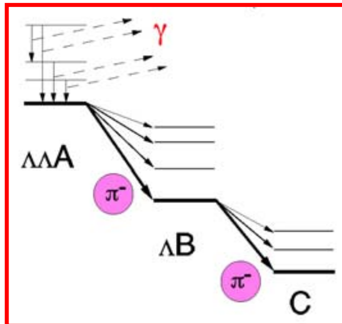
the region of high excitation energy
in heavy Λ-hypernuclei
cannot be explored
with γ-spectroscopy







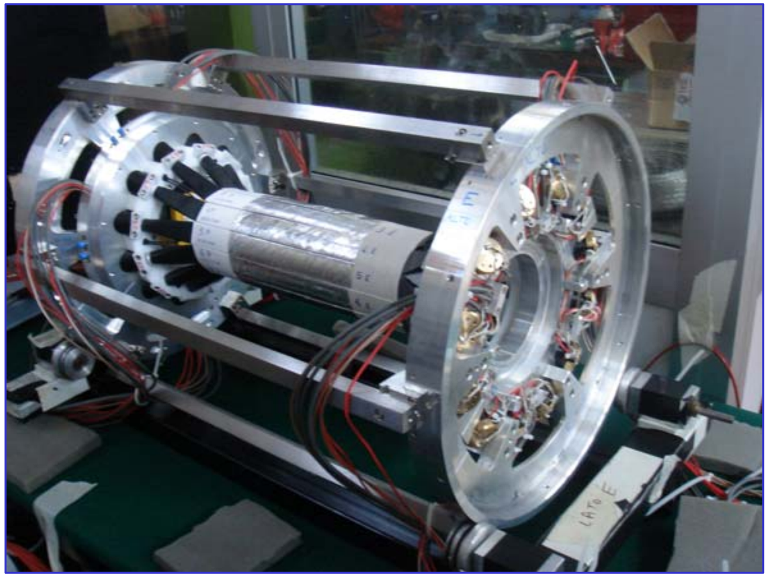
unambiguous identification of the S = -2 hypernuclei
usually relies on the observation of
the double sequential (pionic) weak decay



the next generation apparatuses should be a smart combination
of magnetic spectrometer and γ-ray detector arrays

A paradigmatic example of collaboration

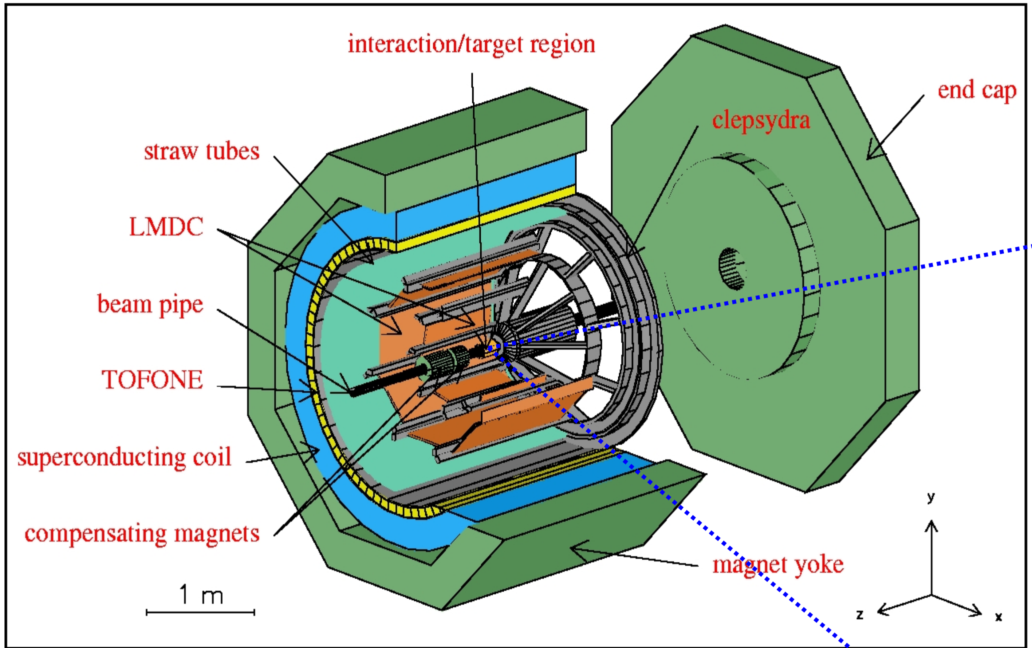
FINUDA



FINUDA

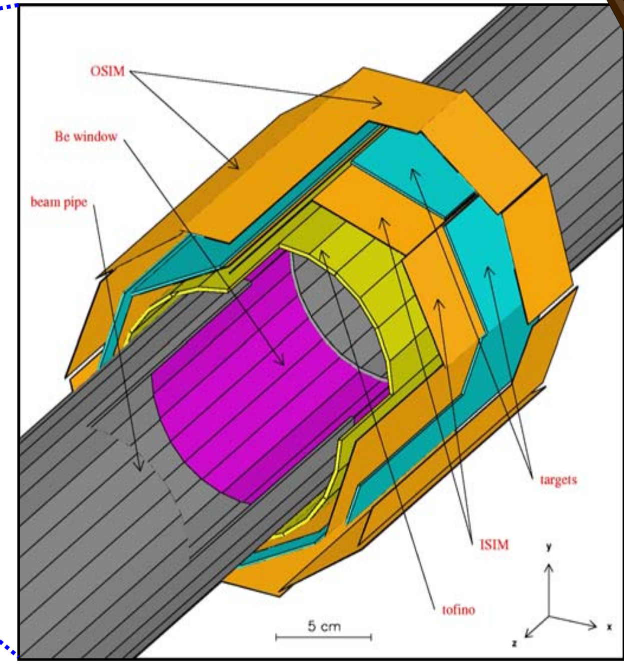
JAPAN

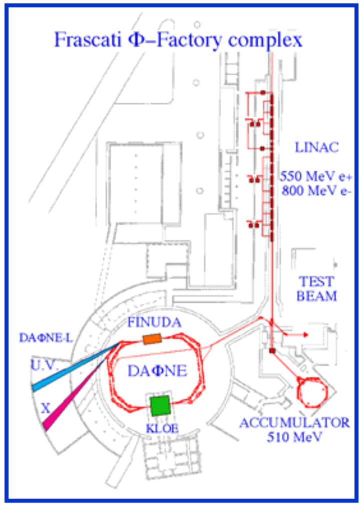
FINUDA @ DAΦNE

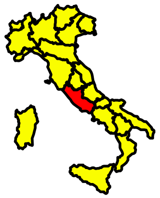


$$e^- + e^+ \rightarrow \phi \rightarrow K^- K^+$$

$$K^-_{stop} + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$







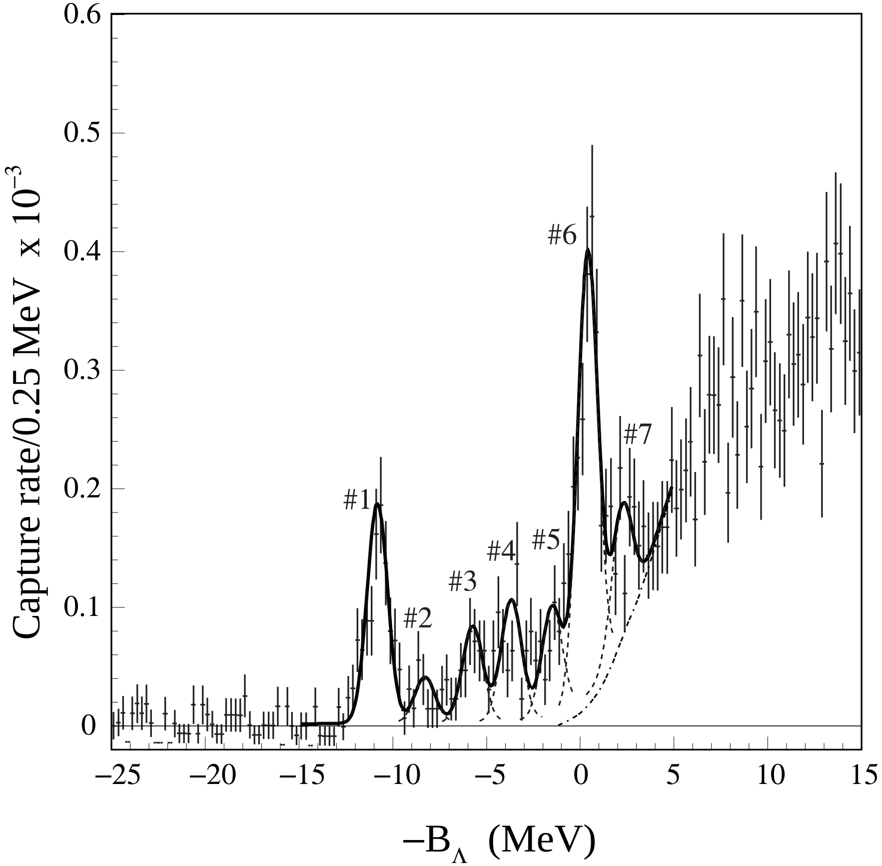
energy	510 MeV
luminosity	5 10^{32} cm^{-2} s^{-1}
σ_x (rms)	2.11 mm
σ_y (rms)	0.021 mm
σ_z (rms)	35 mm
bunch length	30 mm
crossing angle	12.5 mrad
frequency (max)	368.25 MHz
bunch/ring	up to 120
part./bunch	8.9 10^{10}
current/ring	5.2 A (max)

$${}^A_\Lambda Z \rightarrow \begin{cases} {}^A(Z+1) + \pi^- \\ {}^{(A-2)}(Z-1) + p + n \\ {}^{(A-2)}Z + n + n \end{cases}$$

FINUDA @ DAΦNE

$^{12}C(K^-_{stop},\pi^-)^{12}_{\Lambda}C$

ΔE ~ 1.3 MeV FWHM



Peak number	$-B_\Lambda$ (MeV)	Capture rate/(stopped K^-)[$\times 10^{-3}$]
1	-10.94 ± 0.06	$1.01 \pm 0.11_{stat} \pm 0.10_{syst}$
2	-8.4 ± 0.2	0.21 ± 0.05
3	-5.9 ± 0.1	0.44 ± 0.07
4	-3.8 ± 0.1	0.56 ± 0.08
5	-1.6 ± 0.2	0.50 ± 0.08
6	0.27 ± 0.06	2.01 ± 0.17
7	2.1 ± 0.2	0.58 ± 0.18

M. Agnello *et al.*, Phys. Lett. B 622 (2005) 35

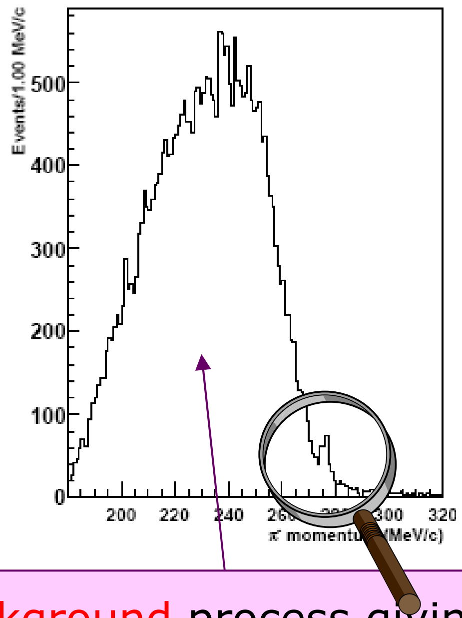
A. Feliciello / 6th Japan-Italy Symposium on Heavy-Ion Physics "Perspectives in Nuclear Physics", Tokai, Japan, November 11-15, 2008.

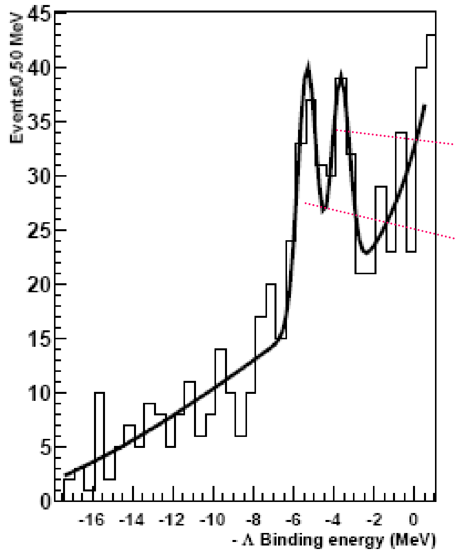
FINUDA @ DAΦNE

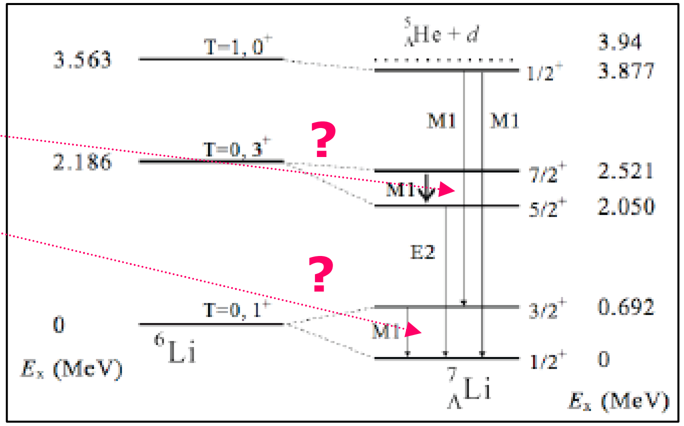
$^{7}Li(K^{-}_{stop},\pi^{-})^{7}_{\Lambda}Li$

ΔE ~ 1.1 MeV FWHM

M. Ukai *et al.*, Phys. Rev. C 73 (2006) 012501







$$B_{\Lambda}^{g.s.} = 5.58 \pm 0.03 \text{ MeV}$$

M. Jurić *et al.*, Nucl. Phys. Rev. B 52 (1973) 1

background process giving π^{-} following K^{-} absorption on ^{7}Li

$K^{-}(\mathcal{NN}) \rightarrow \Sigma^{-}\mathcal{N}$

$\Sigma^{-} \rightarrow n\pi^{-}$

$K^{-}n \rightarrow \Lambda\pi^{-}$

$K^{-} \rightarrow \mu^{-}\nu_{\mu}$ in flight

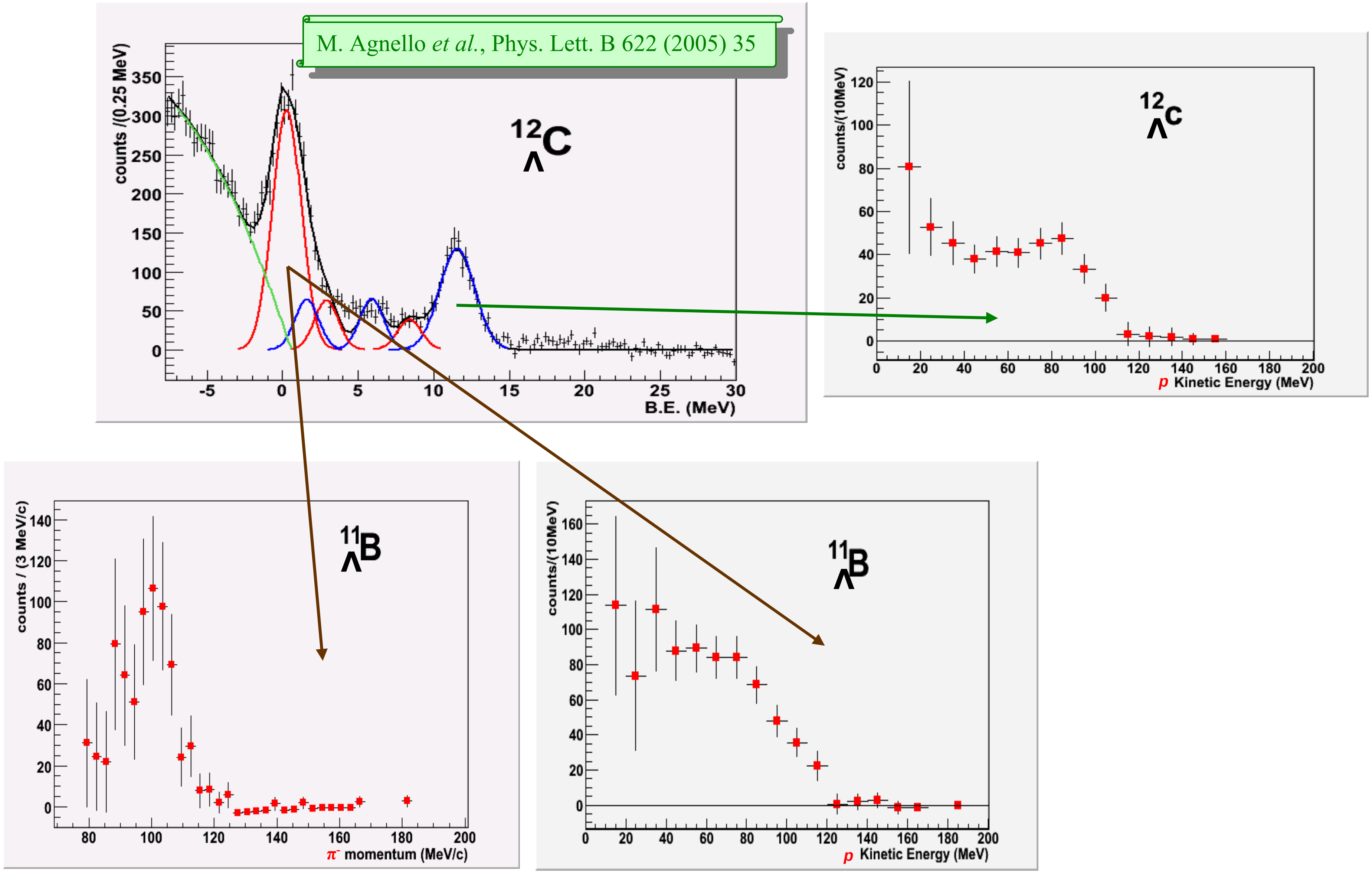
	$-B_{\Lambda} \pm stat. \pm syst.$ (MeV)	Yield (events)	Production rate (per K^{-} stop)
1	$-5.33 \pm 0.13 \pm 0.18$	52 ± 11	$0.47 \pm 0.12 \pm 0.11$‰
2	$-3.68 \pm 0.15 \pm 0.18$	44 ± 10	$0.39 \pm 0.11 \pm 0.11$‰

spin-flip amplitude ≈ 0 ⇒

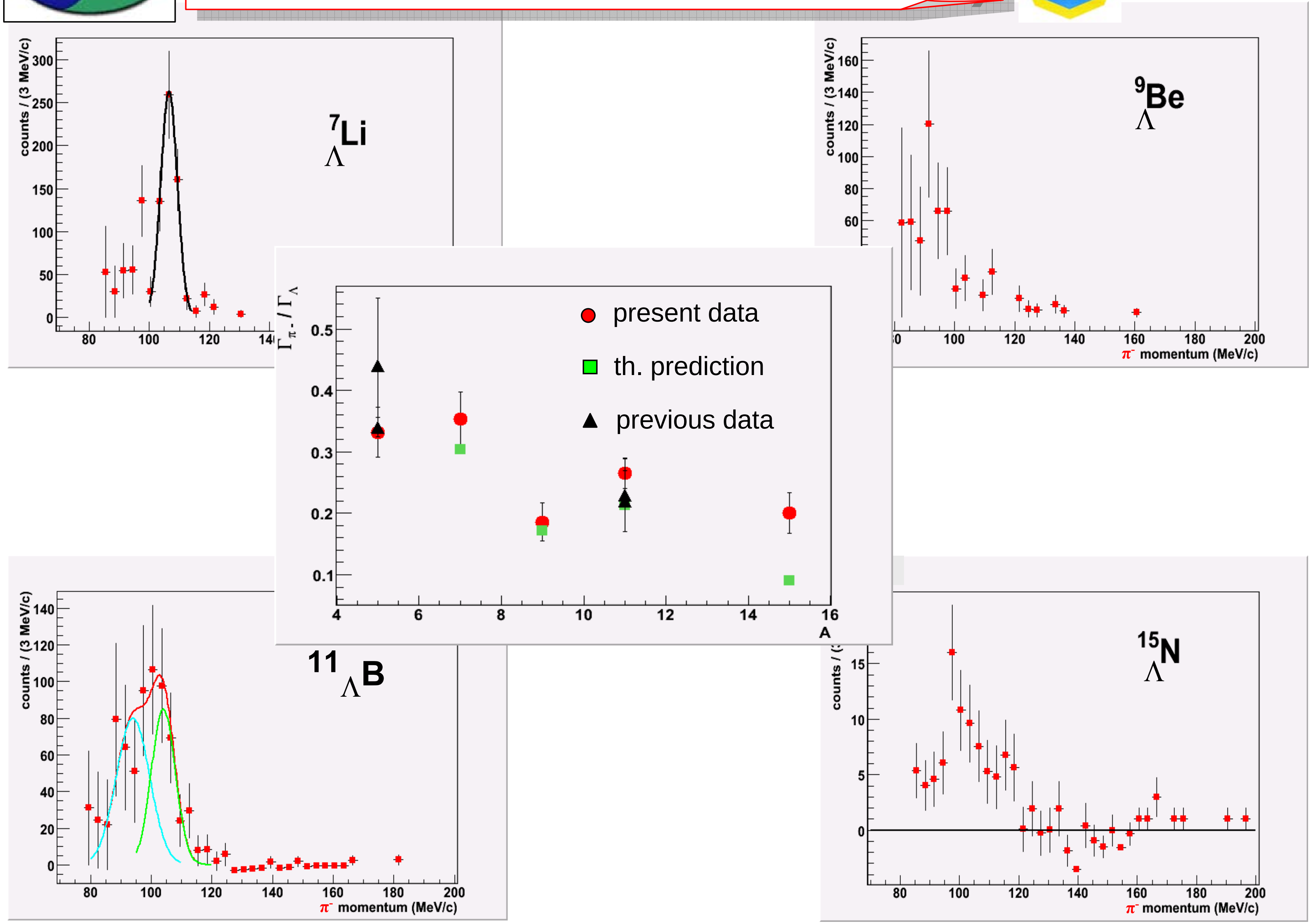
❶ ≡ $1/2^{+}$

❷ ≡ $5/2^{+}$

Λ-hypernucleus decay

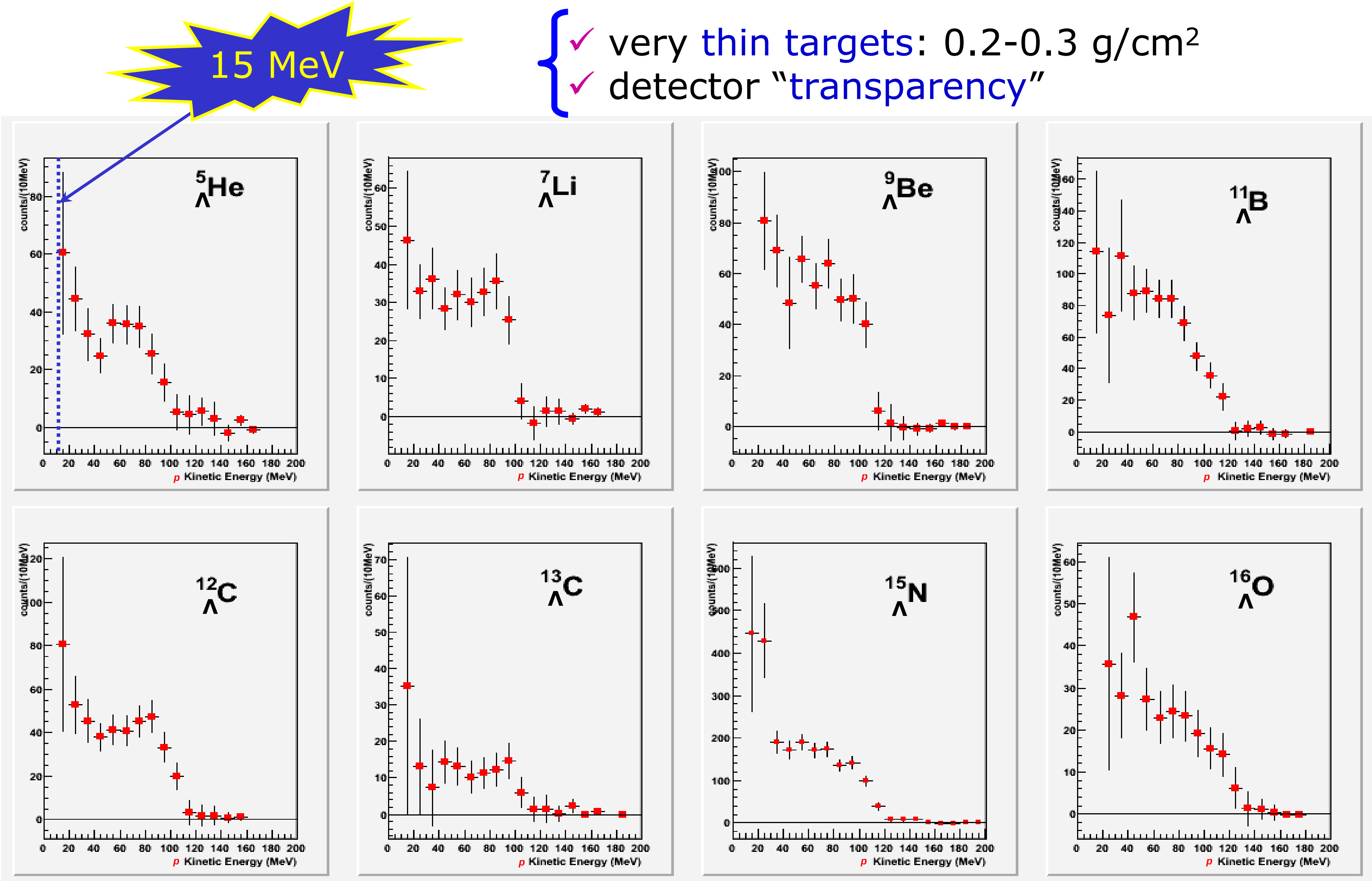


Λ-hypernucleus mesonic decay

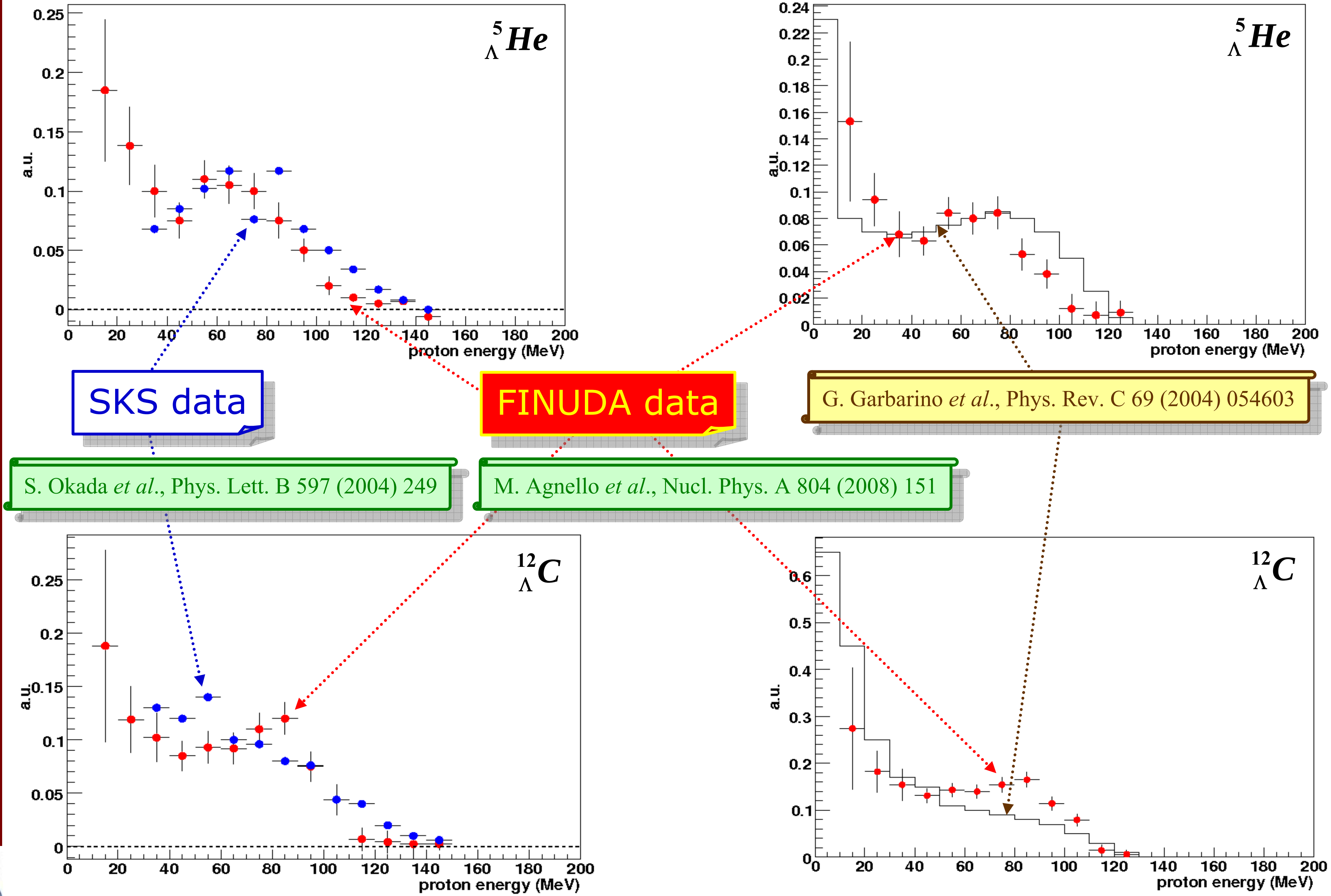


Λ-hypernucleus non-mesonic decay

- ✓ very thin targets: 0.2-0.3 g/cm²
- ✓ detector "transparency"



Λ-hypernucleus non-mesonic decay



Open questions

- (low-energy) YN interaction
  - detailed knowledge of the hypernuclear fine structure
    → evaluation of the spin dependent terms of the ΛN interaction
  - measurement of angular distribution of γ–rays
    → determination of spin and parity of each observed level

- Impurity nuclear physics
  - measurement of transition probability B(E2)
    → information on the size and deformation of hypernuclei
    → measurement of nucleus core shrinking → glue-like role of Λ

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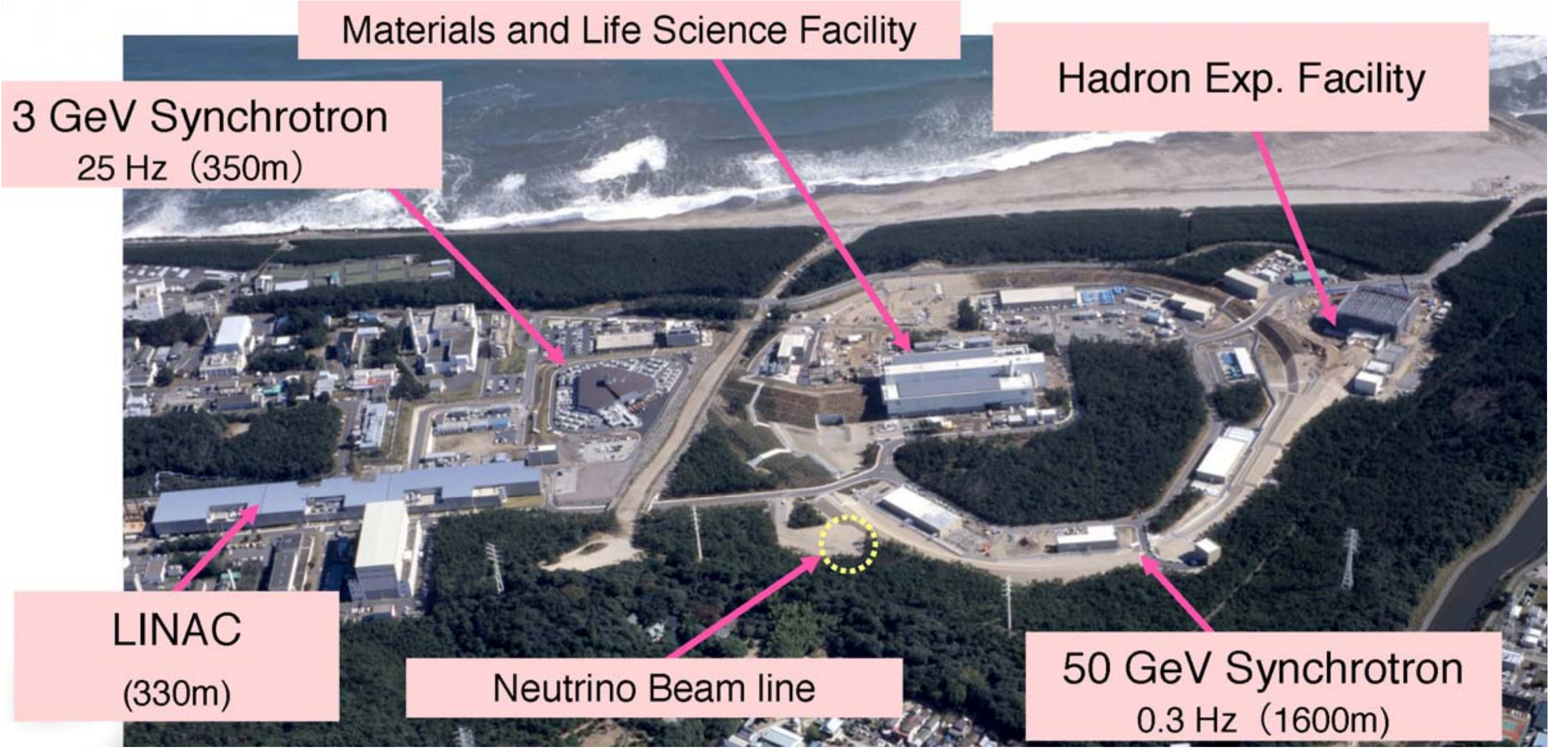
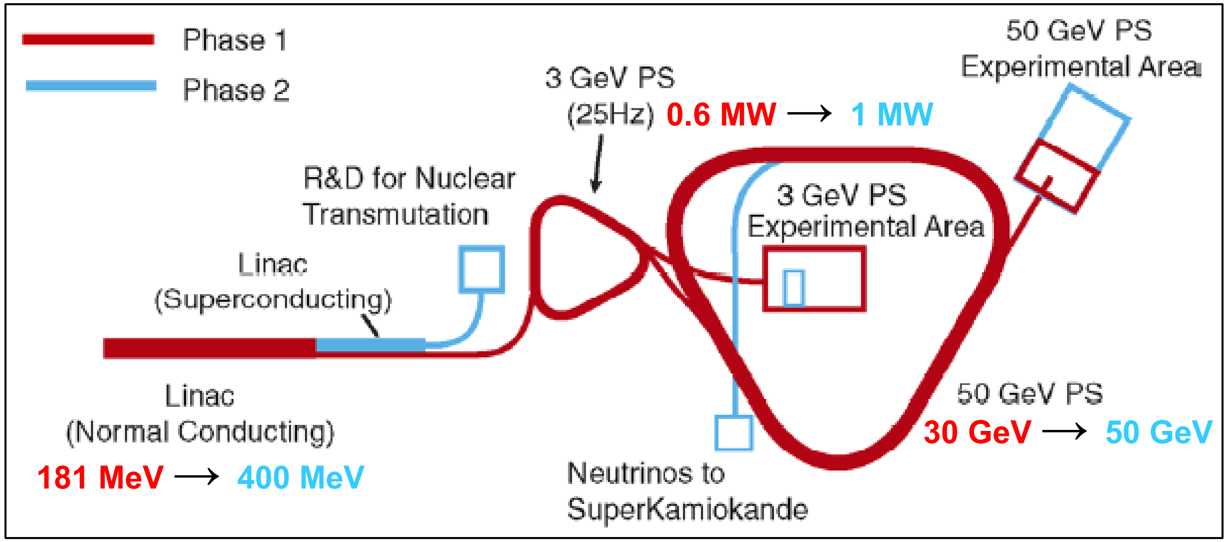
Open questions

- (low-energy) Y*N* interaction
  - detailed knowledge of the hypernuclear fine structure
    → evaluation of the spin dependent terms of the *ΛN* interaction
  - measurement of angular distribution of γ−rays
    → determination of spin and parity of each observed level
- Impurity nuclear physics
  - measurement of transition probability B(E2)
    → information on the size and deformation of hypernuclei
    → measurement of nucleus core shrinking → glue role of Λ
- Properties of hyperons in nuclear matter (medium effect)
  - measurement of transition probability B(M1)
    → g-factor value for Λ in nuclear matter

Japan Proton Accelerator Research Complex



Phase 1: Total 1500 Oku-Yen (56% JAEA, 44% KEK)



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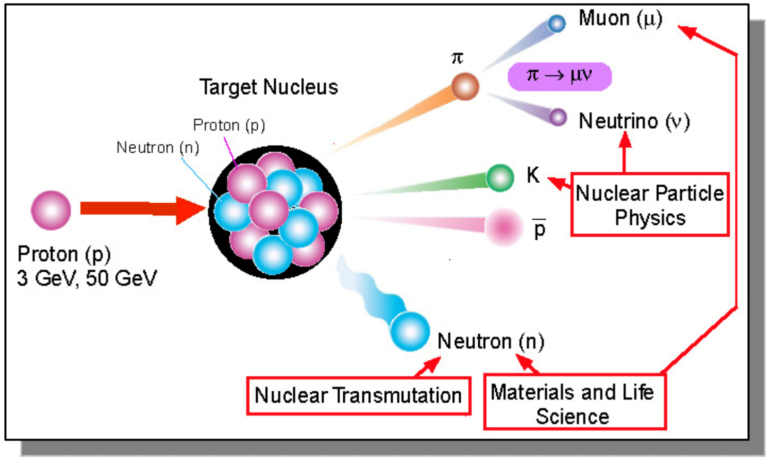
J-PARC physics program



Strangeness Nuclear Physics approved experiments

day-1

- E05: Ξ hypernuclei spectroscopy (1st priority)
- E13: hypernuclear γ–ray spectroscopy (2nd priority)

- E15: search for $K^{-}pp$ bound state
- E17: kaonic ^{3}He 3d → 2p X-ray
- E19: search for penta-quark in $\pi^{-}p \rightarrow K^{-}X$ reaction

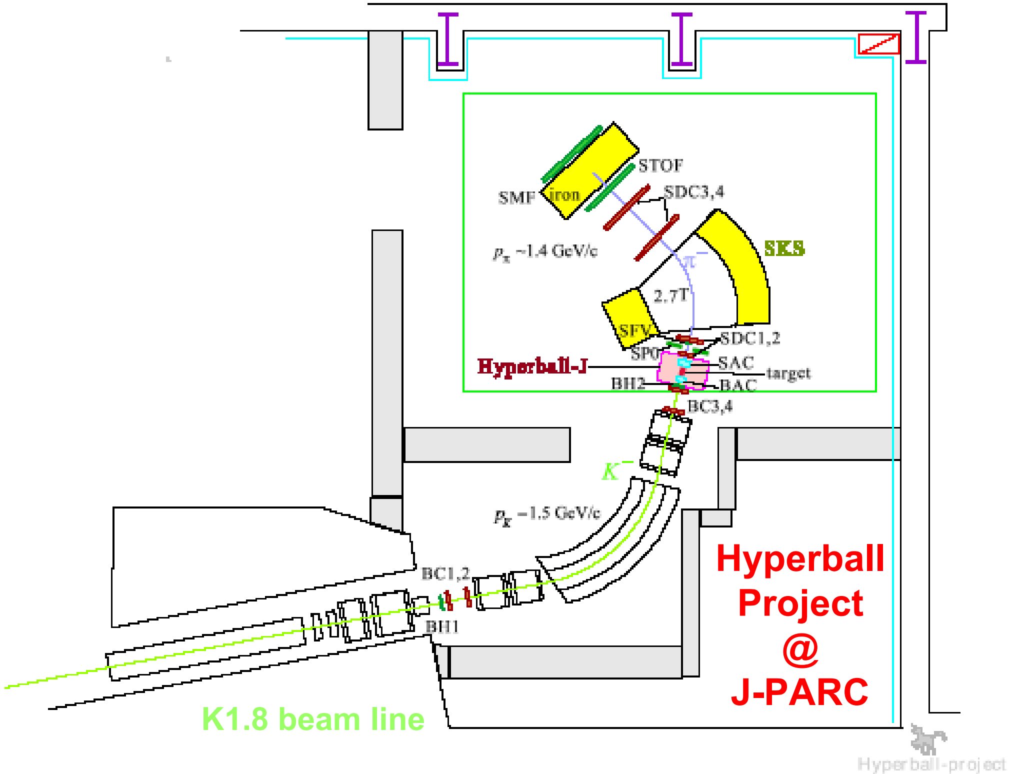
- E07: hybrid emulsion for double Λ hypernuclei
- E03: Ξ-atom X-rays

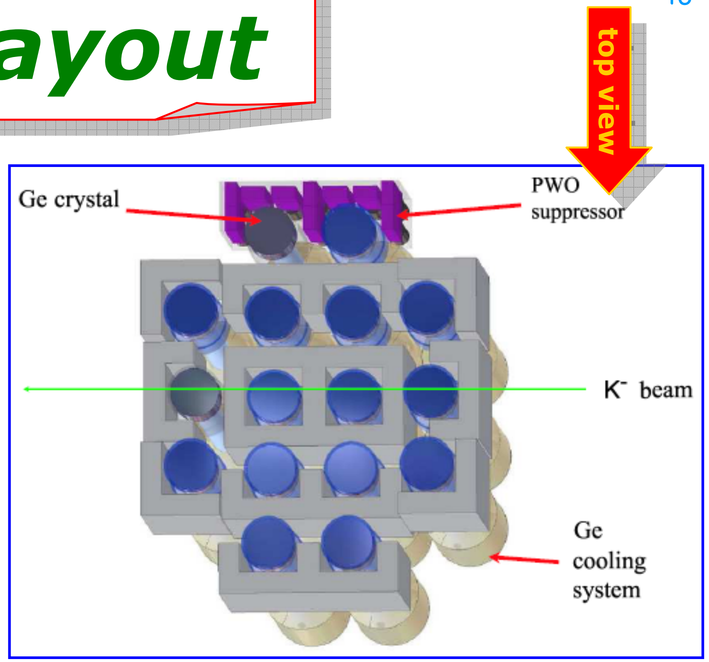
- ...

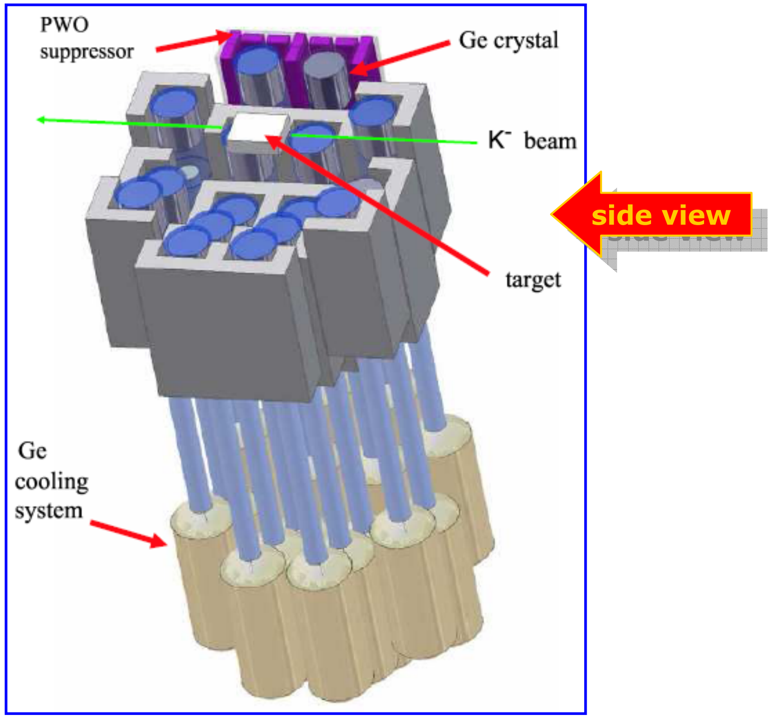
E13 experimental layout

γ-ray spectroscopy of hypernuclei

- further study of ΛN interaction: $_\Lambda^4$He, $_\Lambda^{10}$B, $_\Lambda^{11}$B, $_\Lambda^{19}$F
  - ΛN-ΣN coupling and 3-body force
  - charge symmetry breaking (Λn ≠ Λp?)
  - radial dependence (interaction range)
- g_Λ in a nucleus from spin-flip B(M1): $_\Lambda^7$Li



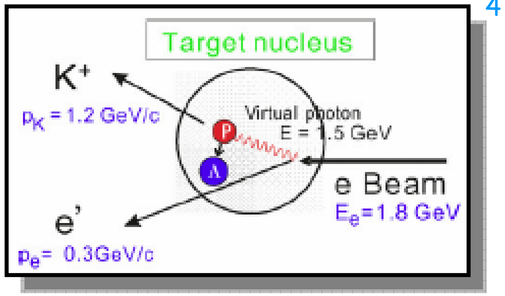




Jefferson Lab

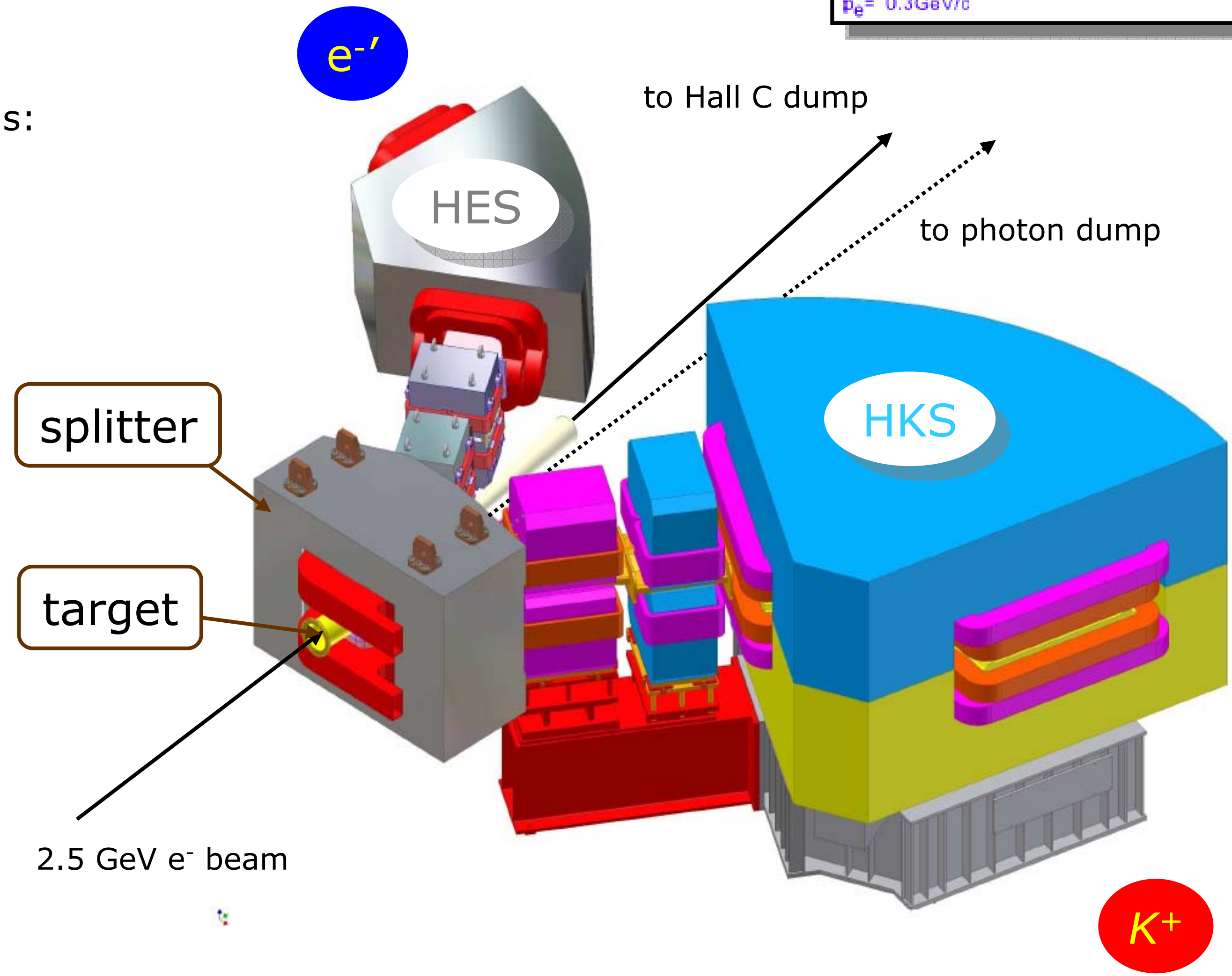
Hall C

JLab12



- angular distributions:

$$^{16}O(e,e'K^{+})^{16}_{\Lambda}N$$



O. Hashimoto *et al.*, *Nucl. Phys. A* 804 (2008) 125

S=-2 systems

S = -2 systems study is not just a simple extension of what has been done for S = -1 system

- new physics items:
  - a detailed and consistent understanding of the quark aspect of the baryon-baryon forces in the SU(3) space will not be possible as long as experimental information on the *YY* channel is not available
  - search for *H* particle
  - existence of S = -2 (deeply) bound $\bar{K}$ states

- experimental challenges:
  - (abundant) production of ΛΛ- and Ξ^--hypernuclei is really difficult
  - identification of produced hyperfragments is problematic
  - γ-ray measurement in coincidence

The status of the art

single event analysis

reference (year)	hyper nucleus	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]	notes
M. Danysz *et al.*, *Nucl. Phys.* 49 (1963) 121	${}^{10}_{\Lambda\Lambda}Be$	17.7 ± 0.4	4.3 ± 0.4	emulsion exp.; Dalitz' reanalysis
D. Prowse *et al.*, *Phys. Rev. Lett.* 17 (1966) 782	${}^{6}_{\Lambda\Lambda}He$	10.9 ± 0.5	4.6 ± 0.5	emulsion exp.; Dalitz' criticism
S. Aoki *et al.*, *Prog. Theor. Phys.* 85 (1991) 951	${}^{13}_{\Lambda\Lambda}B$	27.6 ± 0.7	4.8 ± 0.7	KEK-E176 emulsion-counter hybrid exp. (*) — same event
S. Aoki *et al.*, *Prog. Theor. Phys.* 85 (1991) 1287	${}^{10}_{\Lambda\Lambda}Be$	8.5 ± 0.7	-4.9 ± 0.7	
J.K. Ahn *et al.*, *Phys. Rev. Lett.* 87 (2001) 132504	${}^{4}_{\Lambda\Lambda}H$	---	---	BNL-E906 "mass production"
H. Takahashi *et al.*, *Phys. Rev. Lett.* 87 (2001) 212501	${}^{6}_{\Lambda\Lambda}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$	KEK-E373 emulsion-counter hybrid exp.
H. Takahashi *et al.*, *Nucl. Phys.* A 721 (2003) 951c	${}^{10}_{\Lambda\Lambda}Be$	$12.33^{+0.35}_{-0.21}$	---	KEK-E373 emulsion-counter hybrid exp.

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

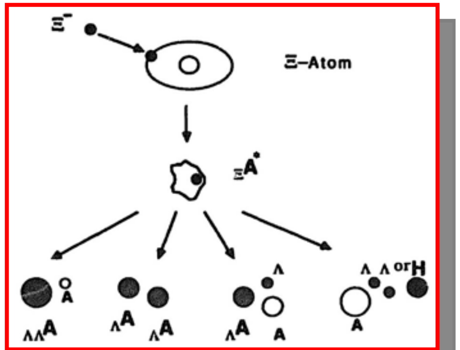
(*) see:
C.B. Dover, D.J. Millener, A. Gal and D.H. Davis, *Phys. Rev.* C 44 (1991) 1905

ΛΛ- and Ξ-hypernucleus production

Ξ^- atomic capture reaction at rest
is one of the most effective way to look for double Λ-hypernuclei

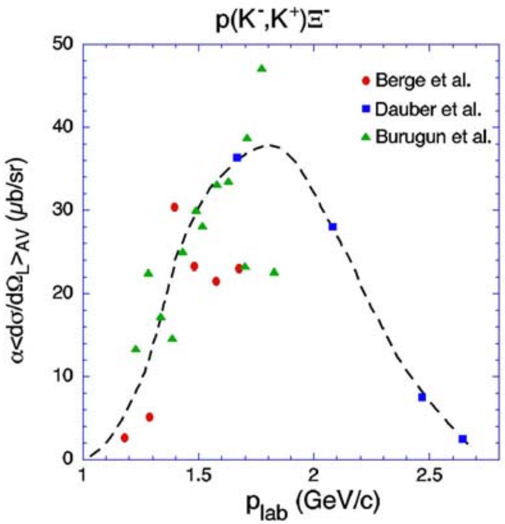
- compound double Λ state: $\Xi^- + {}^{A}Z \rightarrow {}^{(A-1)}(Z-1) \oplus \Lambda \oplus \Lambda$

$\Xi^- + p \rightarrow \Lambda + \Lambda + 28\ \mathrm{MeV}$



- quasi deuteron model: $\Xi^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda\Lambda}(Z-1) + n$ ← high energy

$\Xi^- + \text{"d"} \rightarrow \text{"}\Lambda\Lambda\text{"} + n$ ← high energy



$K^- + p \rightarrow \Xi^- + K^+$ q.f.

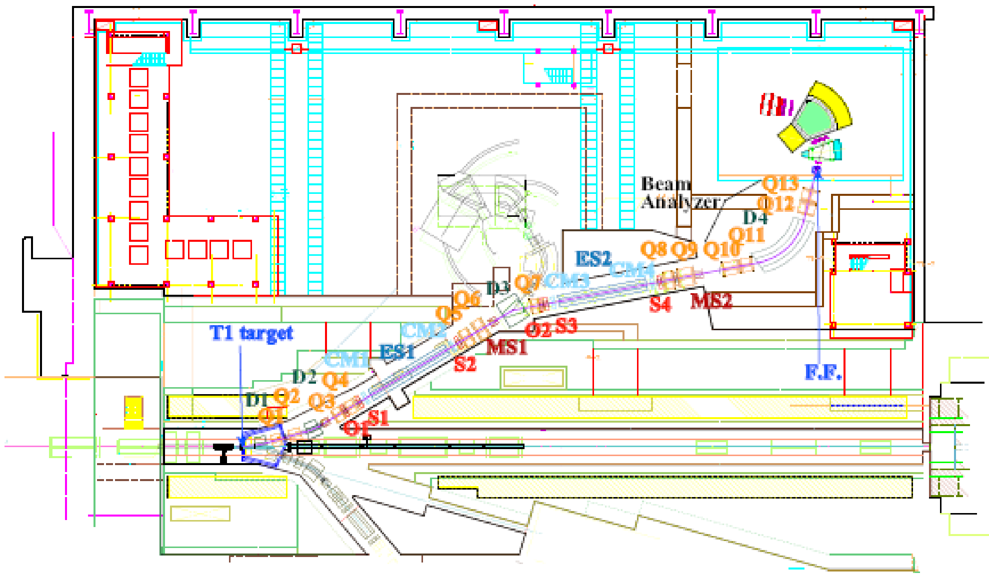
$K^- + {}^{A}Z \rightarrow {}^{A}_{\Xi}(Z-1) + K^+$

K⁻ beams:

@ BNL 1.88 GeV/c
@ KEK 1.66 GeV/c
@ J-PARC 1.80 GeV/c

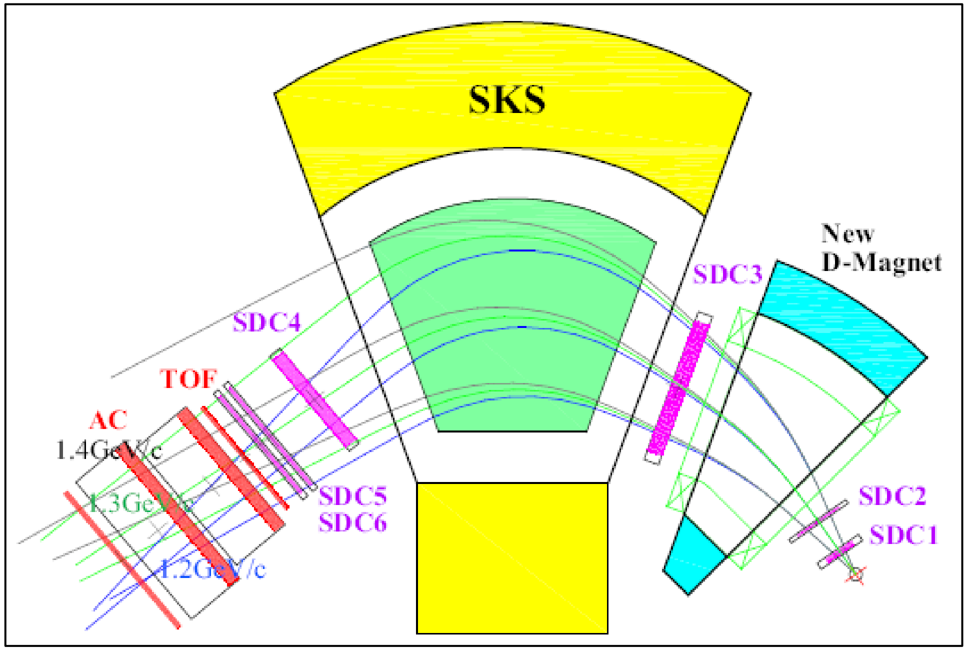
A. Feliciello / 6th Japan-Italy Symposium on Heavy-Ion Physics "Perspectives in Nuclear Physics", Tokai, Japan, November 11-15, 2008.

E05 experimental layout



Spectroscopic study of Ξ-hypernucleus, $^{12}Be_{\Xi}$, via the $^{12}C(K^-,K^+)$ reaction

- first spectroscopic study of S = -2 systems in (K^-,K^+) reaction
- Ξ*N* interaction
  - ? attractive or repulsive
  - ? depth of Ξ-nuclear potential
  - ? isospin dependence
  - ? Ξ*N*-ΛΛ *coupling force*



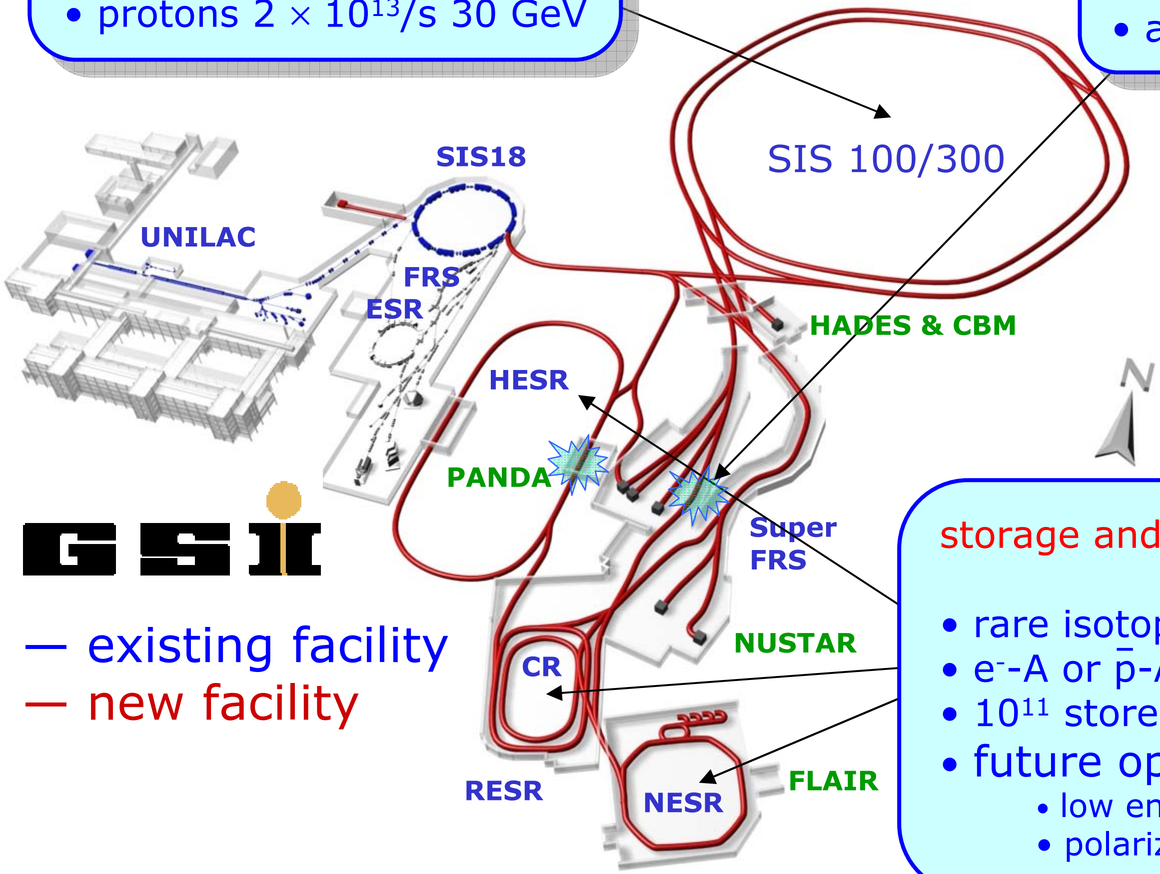
Facility for Antiproton and Ion Research

primary beams

- $^{238}U^{28+}$ 10^{12}/s @ 2.7 AGeV
- $^{238}U^{92+}$ 10^{10}/s @ 35 AGeV
- protons 2×10^{13}/s 30 GeV

secondary beams

- radioactive ion beams @ 2 AGeV
- antiprotons 0 → 15 GeV/c



— existing facility
— new facility

storage and cooler rings

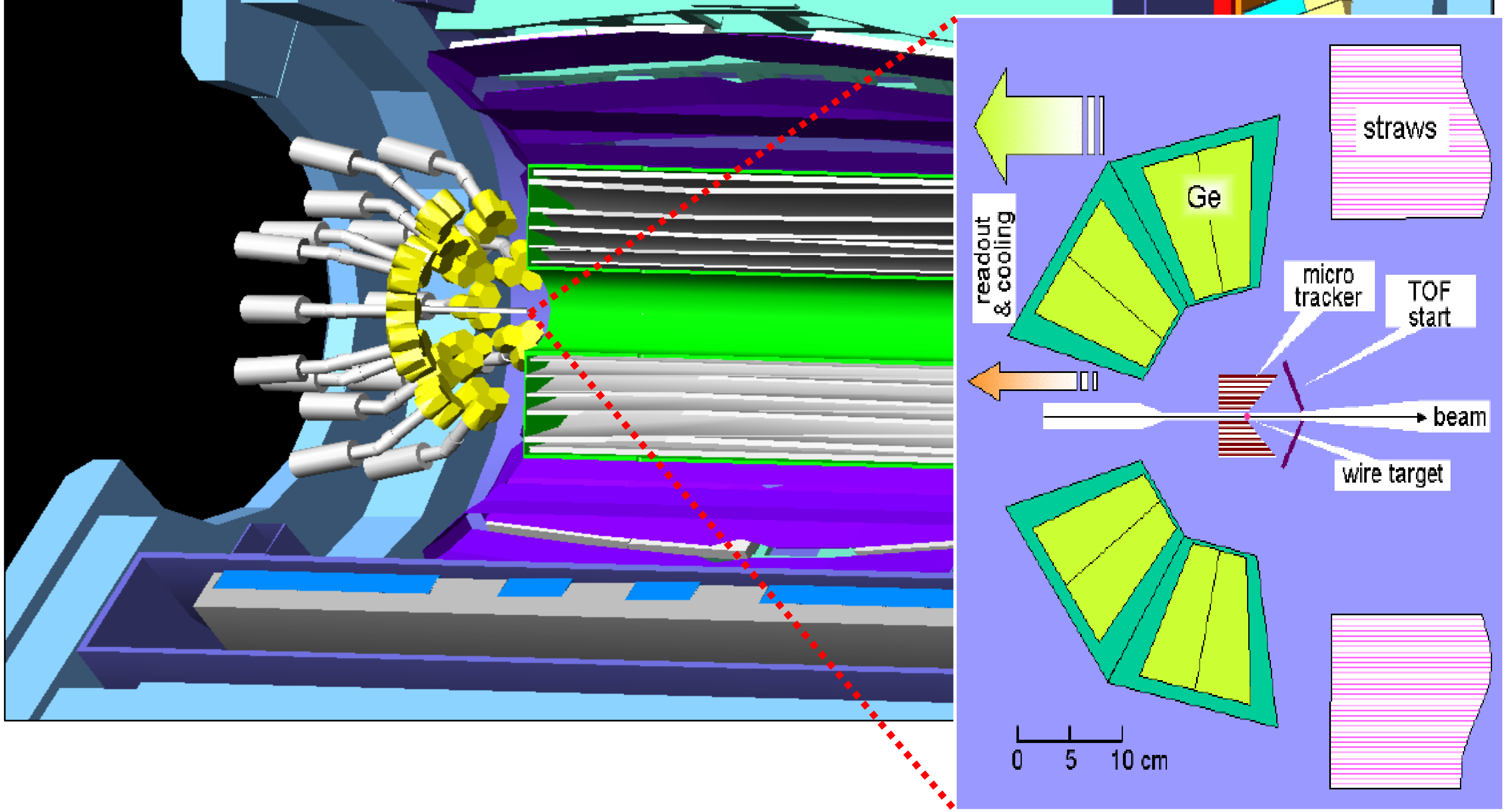
- rare isotope and stable ion beams
- e^--A or $\bar{p}$-A collider
- 10^{11} stored and cooled $\bar{p}$ 0.8 → 15 GeV/c
- future options:
  - low energy $\bar{p}$ for $\bar{H}$ beyond 2015
  - polarized $\bar{p}$ (?)

cost:	1.2 G€
commissioning:	2015

A look to the future

$$\bar{p} + p \rightarrow \Xi^- + \bar{\Xi}^+ \; (@ \sim 3\ \mathrm{GeV/c})$$

$$\Xi^- + {}^{A}Z \rightarrow {}^{(A-1)}(Z-1) \oplus \Lambda \oplus \Lambda$$



Summary

☑ Hypernuclear physics is a challenging research field and has a great discovery potential

- number of exp. physicist involved is growing
- main item in several future physics program at new facilities
- dedicated beams and apparatus
- significant theoretical effort well tuned on exp. data

☛ The synergic exploitation of the progress in detection techniques and of the improvement of the quality of the available beams is the premise for a significant step forward in our understanding of the baryon-baryon interaction.

Thank you!

どうも　ありがとう