東京大学

Nov. 24-26, 2010

J-PARC における ストレンジネス核物理

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Outline - I

- 1st day
  - Historical Overview of Strengeness Nuclear Physics
  - Production of Hypernuclei
  - Hypernuclear structure and YN interaction
  - (π+,K+) Spectroscopy of Λ hypernuclei
- 2nd day
  - Hypernuclear gamma-ray spectroscopy
  - Σ hypernuclei
  - Weak decay of Hypernuclei

Outline -2

- 3rd day
  - J-PARC Facility
  - Kaonic Nuclei
  - Hypernuclear Spectroscopy of S= -2 systems

- 物理学教室コロキウム「ストレンジネスと原子核」

First day in UT

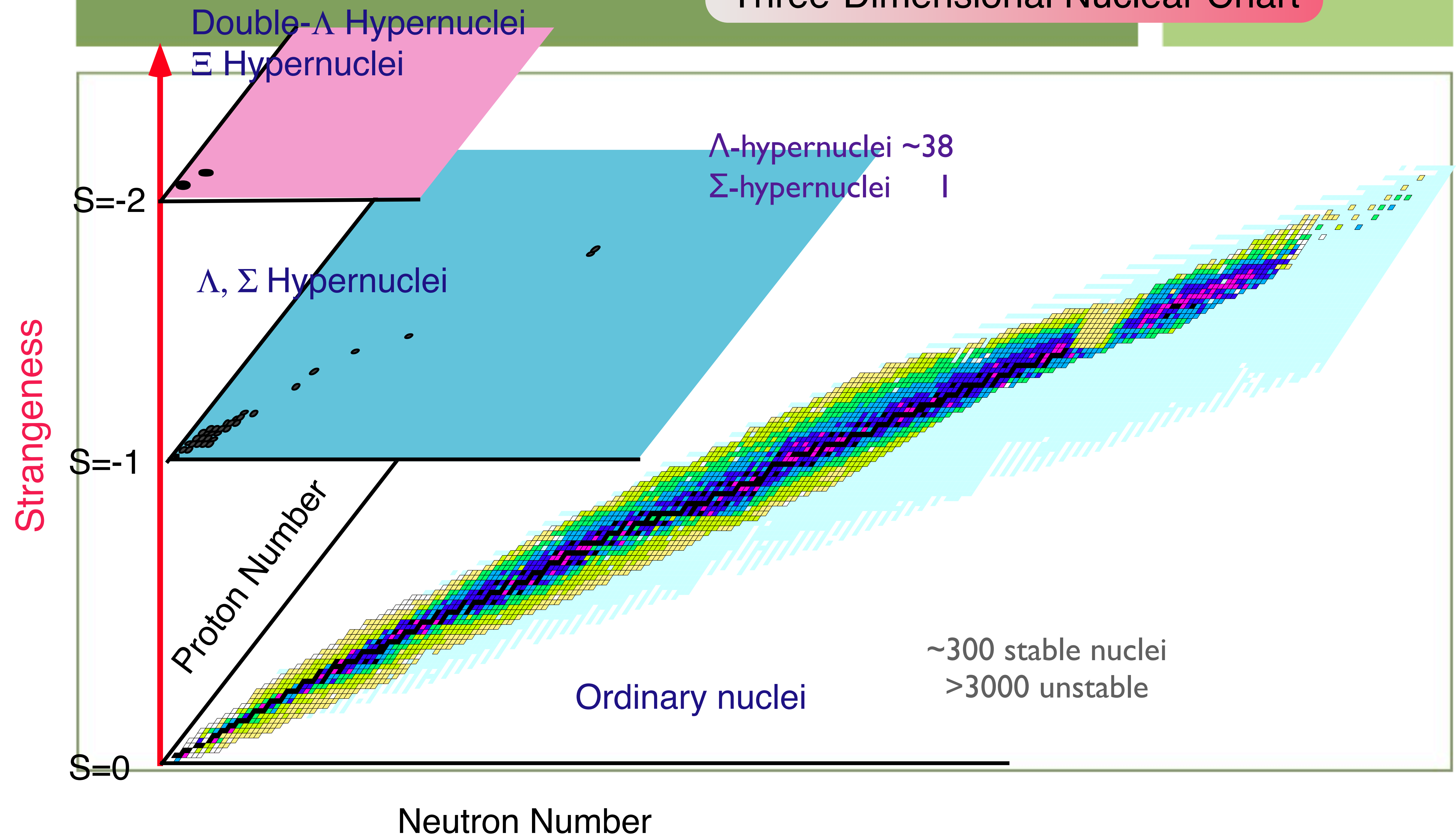
Hypernuclei

- A Nucleus with Hyperons

S		Lifetimes[s]	Main Decay channels	Mass [MeV/c^2]	Isospin
0	p: uud n: udd	Stable(?) 887	$pe^-\nu_e$(100%)	938.3 939.6	1/2
-1	Λ: uds	2.63×10^{-10}	$p\pi^-$(64%), $n\pi^0$(36%)	1115.7	0
-1	Σ^+: uus Σ^0: uds Σ^-: dds	0.8×10^{-10} 7.4×10^{-20} 1.48×10^{-10}	$p\pi^0$(52%), $n\pi^-$(48%) $\Lambda\gamma$ (~100%) $n\pi^-$(99.8%)	1189.4 1192.6 1197.4	1
-2	Ξ^0: uss Ξ^-: dss	2.9×10^{-10} 1.64×10^{-10}	$\Lambda\pi^0$(~100%) $\Lambda\pi^-$(~100%)	1315 1321	1/2

World of Strangeness Nuclear Physics

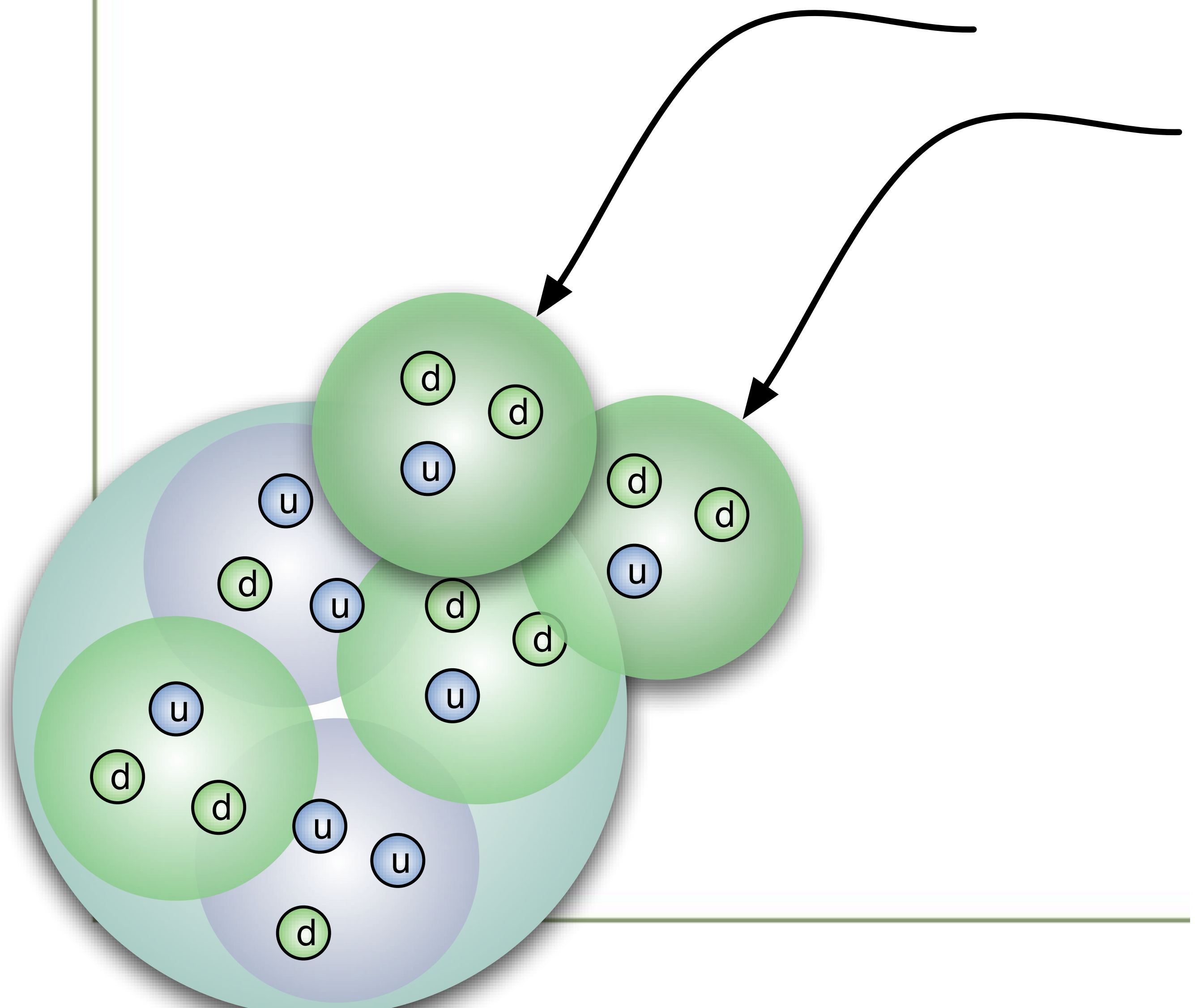
Three-Dimensional Nuclear Chart



Normal Nuclei

- Many-Body systems composed of proton(uud)& neutron(udd)
- Quark many-body systems with u & d quarks only

Fermions

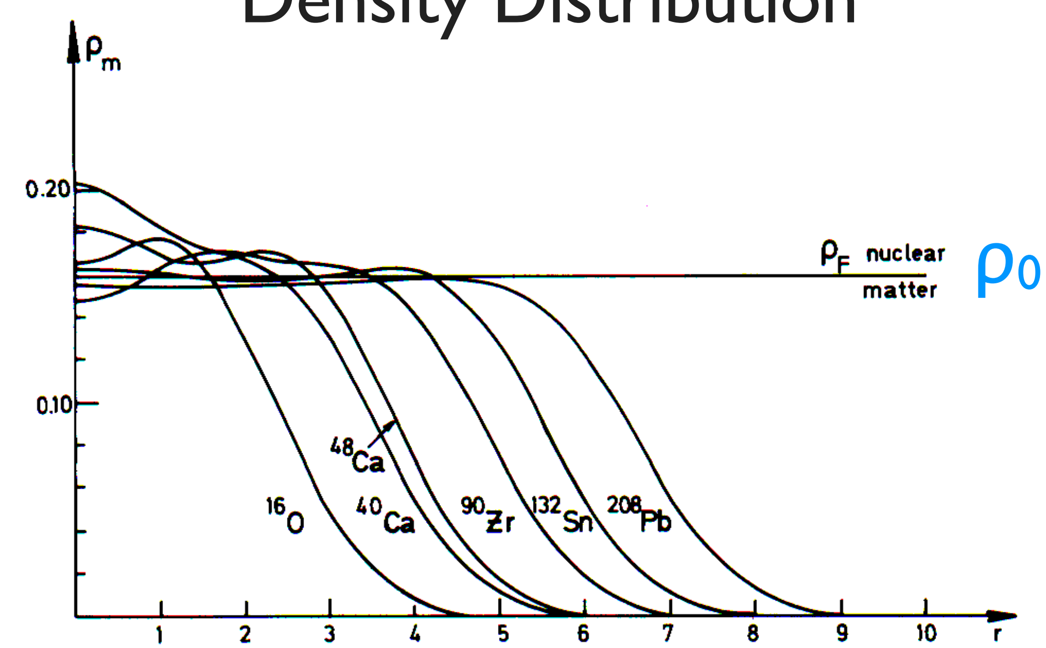


Saturation Density: $\rho_0 = 2.5 \times 10^{14}$ g/cm^3

Binding Energy: 8 MeV/nucleon

←Pauli Blocking, Repulsive core

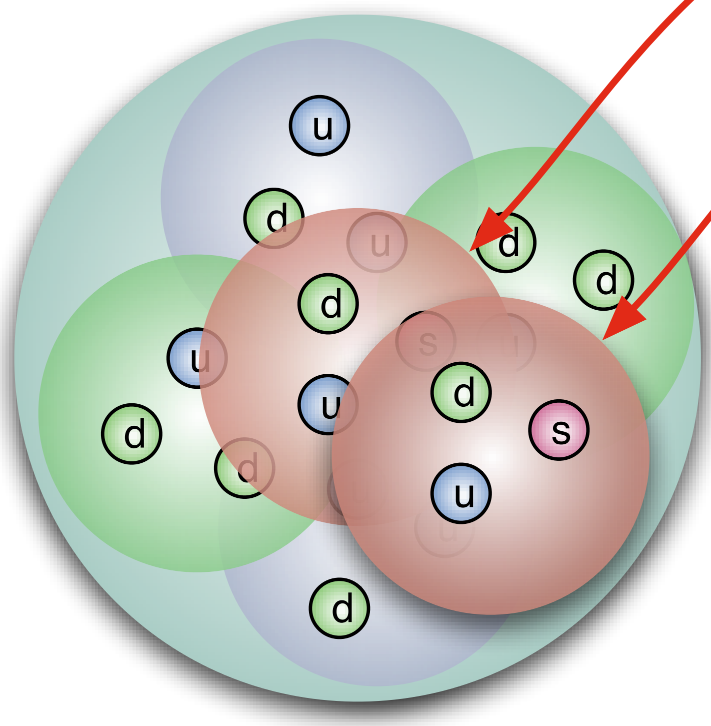
Density Distribution



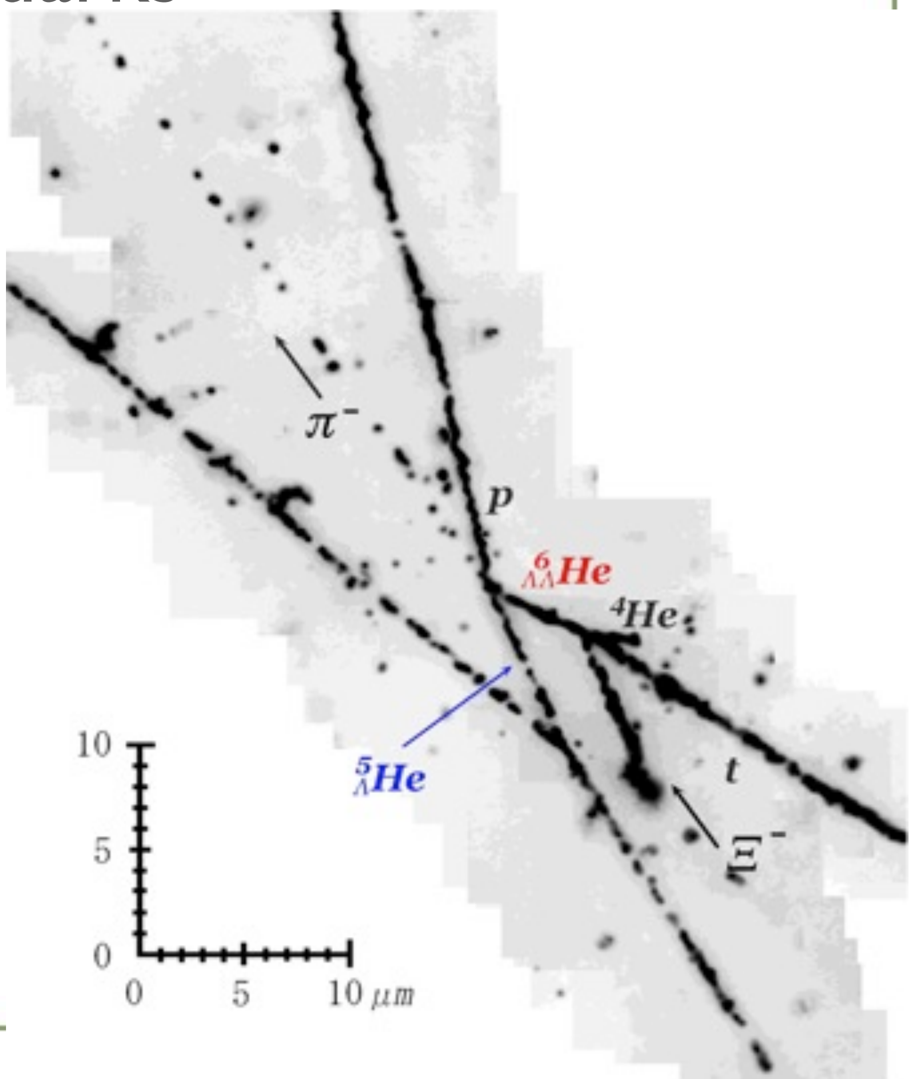
Hypernuclei

- Λ(uds)-Hypernuclei, Double-Λ Hypernuclei
- Quark many-body systems with u, d, & s quarks

No Pauli Blocking
→Higher Density

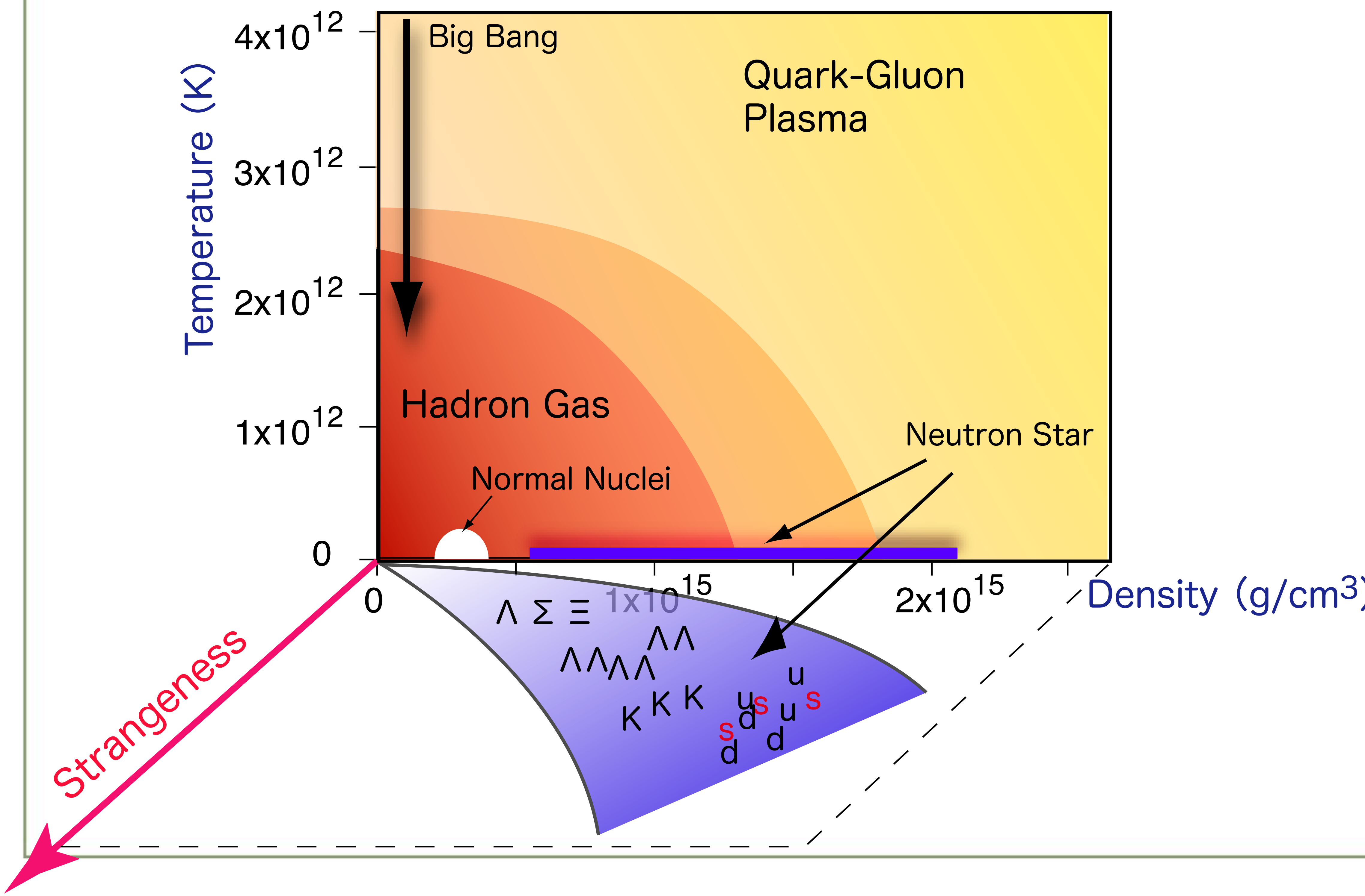


- Implant s quark(s) with u, d quarks



H.Takahashi et al., PRL 87, 212502(2001)

- Strangeness Degrees of Freedom
- → Something beyond the "standard" Nuclear Physics

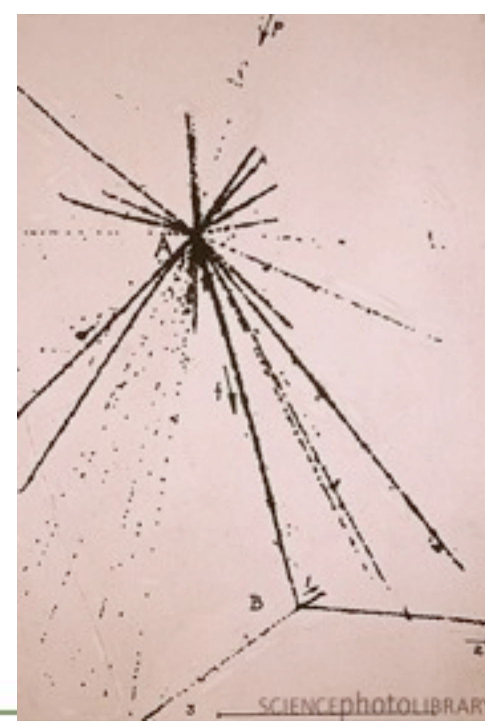


Brief history of Hypernuclear spectroscopy

- Discovery of Hyperfragments (1953) by M. Danysz and J. Pniewski
  - $\Lambda \sim p, n$

ACTA PHYSICA POLONICA B 35 (2004) 901-927.

  - Discovery of V particles (1947) by G. Rochester and C. Butler



Early days - 1950s~1960s

- Stopped K^- reactions in Nuclear emulsion and He bubble chamber
  - High efficiency for Hyperfragment formation
  - Identification of Light Hyperfragments
    - $^{3}_{\Lambda}H \sim {}^{15}_{\Lambda}N$
  - Binding energies of ground states
  - Spin assignments for several ground states

Stopped K$^-$ on ^{4}He

- Λ emission ~70%
- Σ emission ~30%

- Non-pionic ~17%

TABLE III. Branching ratios for K^- absorption at rest.

Reaction	Events/(stopping K^-) (%)
$K^-He^4 \rightarrow \Sigma^+\pi^-H^3$	9.3±2.3
$\rightarrow \Sigma^+\pi^- dn$	1.9±0.7
$\rightarrow \Sigma^+\pi^- pnn$	1.6±0.6
$\rightarrow \Sigma^+\pi^0\ nnn$	3.2±1.0
$\rightarrow \Sigma^+\ nnn$	1.0±0.4
Total $\Sigma^+ = (17.0\pm2.7)\%$	
$K^-He^4 \rightarrow \Sigma^-\pi^+H^3$	4.2±1.2
$\rightarrow \Sigma^-\pi^+ dn$	1.6±0.6
$\rightarrow \Sigma^-\pi^+ pnn$	1.4±0.5
$\rightarrow \Sigma^-\pi^0\ He^3$	1.0±0.5
$\rightarrow \Sigma^-\pi^0\ pd$	1.0±0.5
$\rightarrow \Sigma^-\pi^0\ ppn$	1.0±0.4
$\rightarrow \Sigma^-\ pd$	1.6±0.6
$\rightarrow \Sigma^-\ ppn$	2.0±0.7
Total $\Sigma^- = (13.8\pm1.8)\%$	
$K^-He^4 \rightarrow \pi^-\Lambda\ He^3$	11.2±2.7
$\rightarrow \pi^-\Lambda\ pd$	10.9±2.6
$\rightarrow \pi^-\Lambda\ ppn$	9.5±2.4
$\rightarrow \pi^-\Sigma^0\ He^3$	0.9±0.6
$\rightarrow \pi^-\Sigma^0\ (pd,ppn)$	0.3±0.3
$\rightarrow \pi^0\ \Lambda\ (\Sigma^0)\ (pnn)$	22.5±4.2
$\rightarrow \Lambda\ (\Sigma^0)\ (pnn)$	11.7±2.4
$\rightarrow \pi^+\Lambda\ (\Sigma^0) nnn$	2.1±0.7
Total $\Lambda\ (\Sigma^0) = (69.2\pm6.6)\%$	
Total $= \Lambda + \Sigma = (100_{-7}^{+0})\%$	

Hypernuclear Production by stopped K^-

- $o(10^{-3})$ per stopped K^- ; ... not so bad

TABLE IX. Calculated capture rates per stopped K^- (in units of 10^{-3}) for production of $1s_\Lambda$ states (1^- transition) and $1p_\Lambda$ states (0^+ and 2^+ transitions) and selected experimental rates.

Transition	Input	${}^{12}_{\Lambda}$B [3]	${}^{12}_{\Lambda}$C [2]	${}^{16}_{\Lambda}$O [2]
1^-	$[K_\chi]$	0.203	0.425	0.219
	$[K_{DD}]$	0.060	0.125	0.055
	Experimental rates	0.28 ± 0.08	0.98 ± 0.12	0.43 ± 0.06
0^+	$[K_\chi]$	0.096	0.216	0.134
	$[K_{DD}]$	0.011	0.021	0.020
2^+	$[K_\chi]$	0.547	1.052	0.872
	$[K_{DD}]$	0.192	0.410	0.330
$0^+ + 2^+$	$[K_\chi]$	0.643	1.268	1.006
	$[K_{DD}]$	0.203	0.431	0.350
	Experimental rates	0.35 ± 0.09	2.3 ± 0.3	1.68 ± 0.16

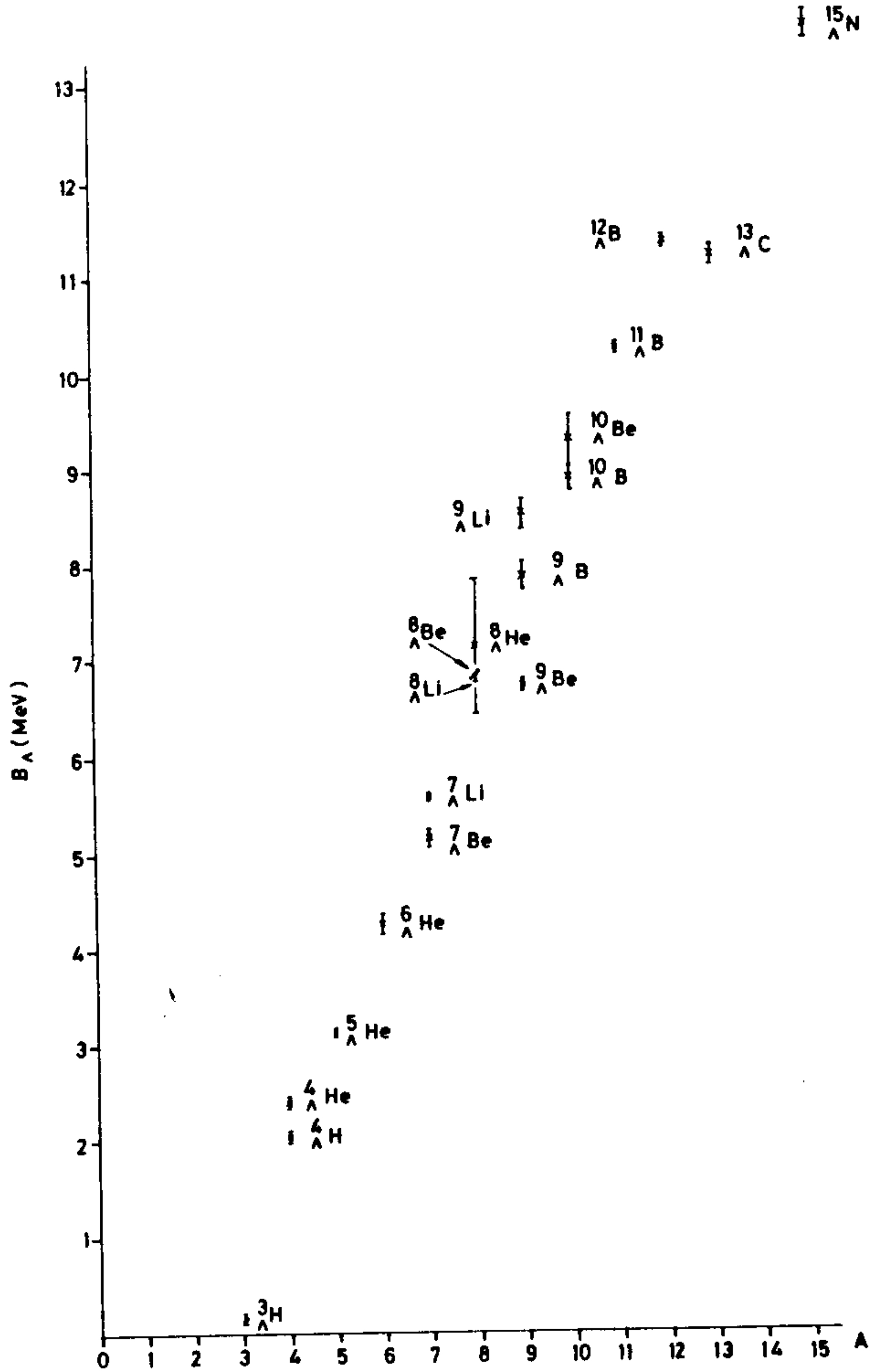
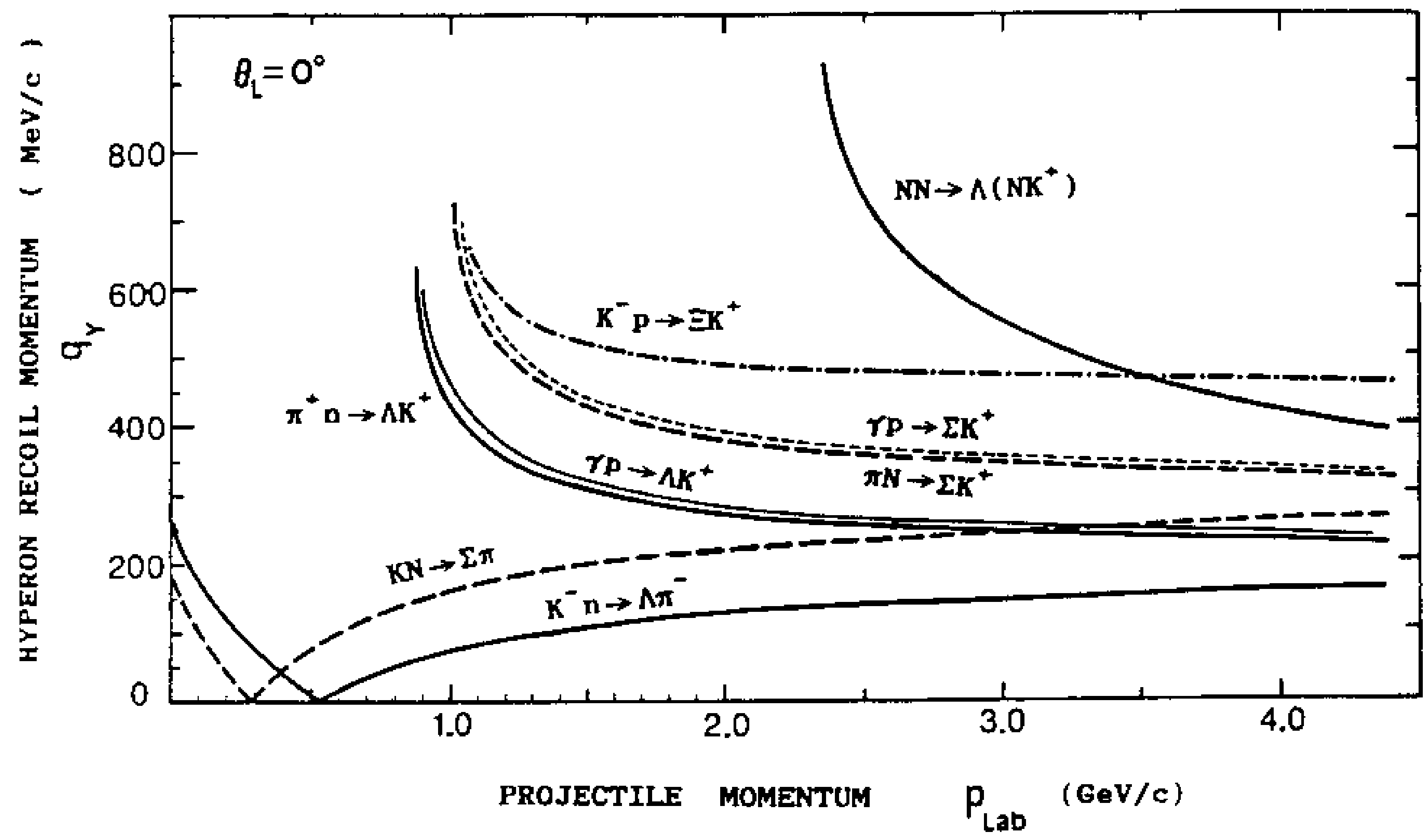


Fig. 10. Variation of the B_Λ values with the hypernuclear mass numbers.

In-flight (K^-,π^-) in 1970s

- Heidelberg-Saclay group
- "Magic momentum" - Recoilless condition
  - Population of Substitutional States: (p_n^{-1}, p_Λ)
  - Spectroscopic information on Excited states
    - Small Spin-Orbit splitting in Λ hypernuclei

Recoil Momentum of Hyperon



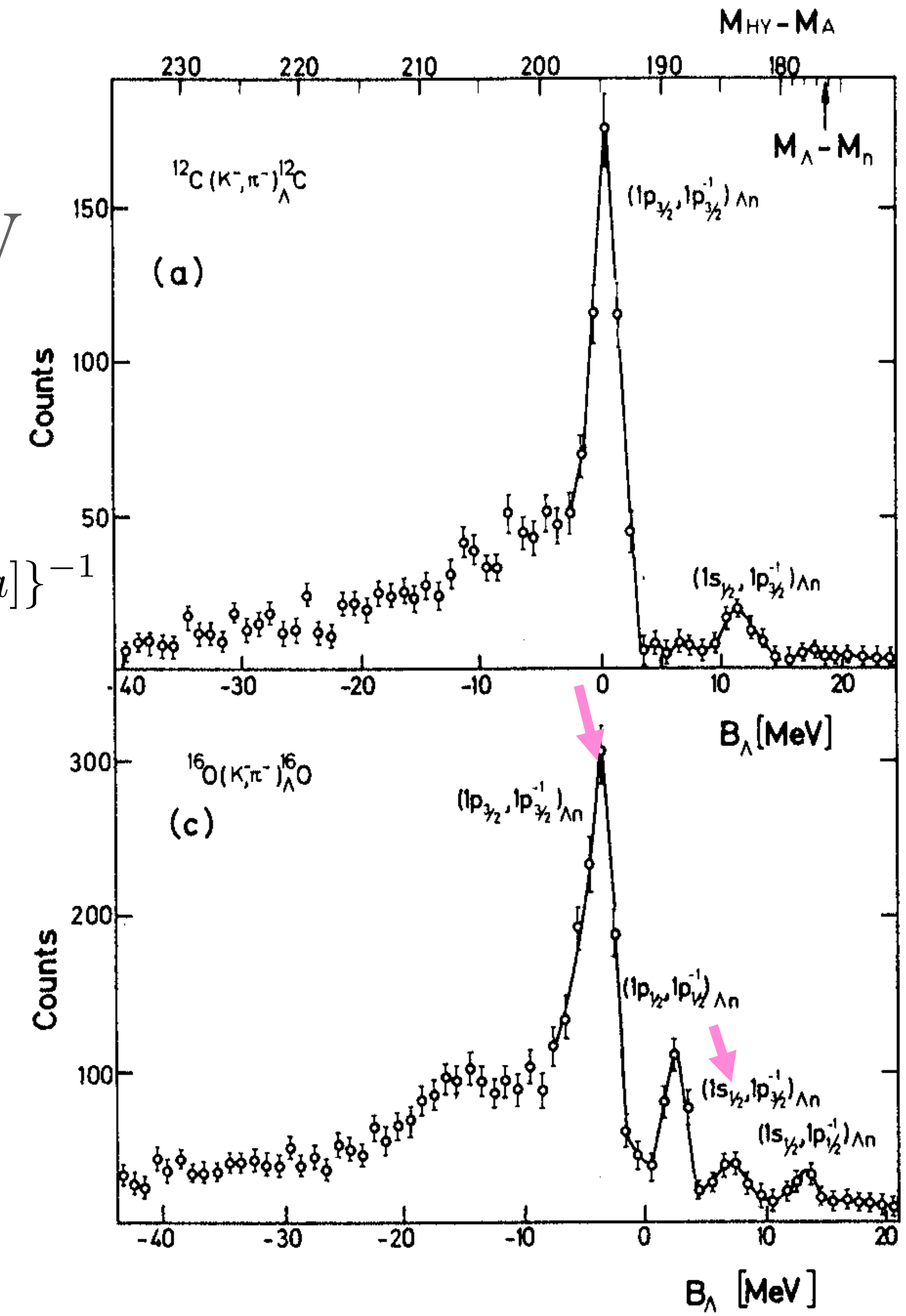
Data in the (K⁻,π⁻) reactions

- ${}^{16}_{\Lambda}O$
  - δ_p=0.8±0.7 MeV → V_{LS}=4±2 MeV
  - V_0=30 MeV

$$U_\Lambda = V_0^\Lambda f(r) + V_{LS}^\Lambda \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{df(r)}{rdr}\vec{\ell}\cdot\vec{s}, f(r) = \{1 + exp[(r-R)/a]\}^{-1}$$

For ordinary nuclei:

V_0~50 MeV,V_{LS}=20 MeV



BNL-AGS & KEK-PS in 1980s ~ 1990s

- Σ hypernuclei in (K^-, π^-)
  - narrow states → not reconfirmed
  - one bound state $^{4}_{\Sigma}\mathrm{He}$ → confirmed
- Success of (π^+, K^+) Spectroscopy
- Success of Hypernuclear γ Spectroscopy
- H-particle search, Double-Λ hypernuclei

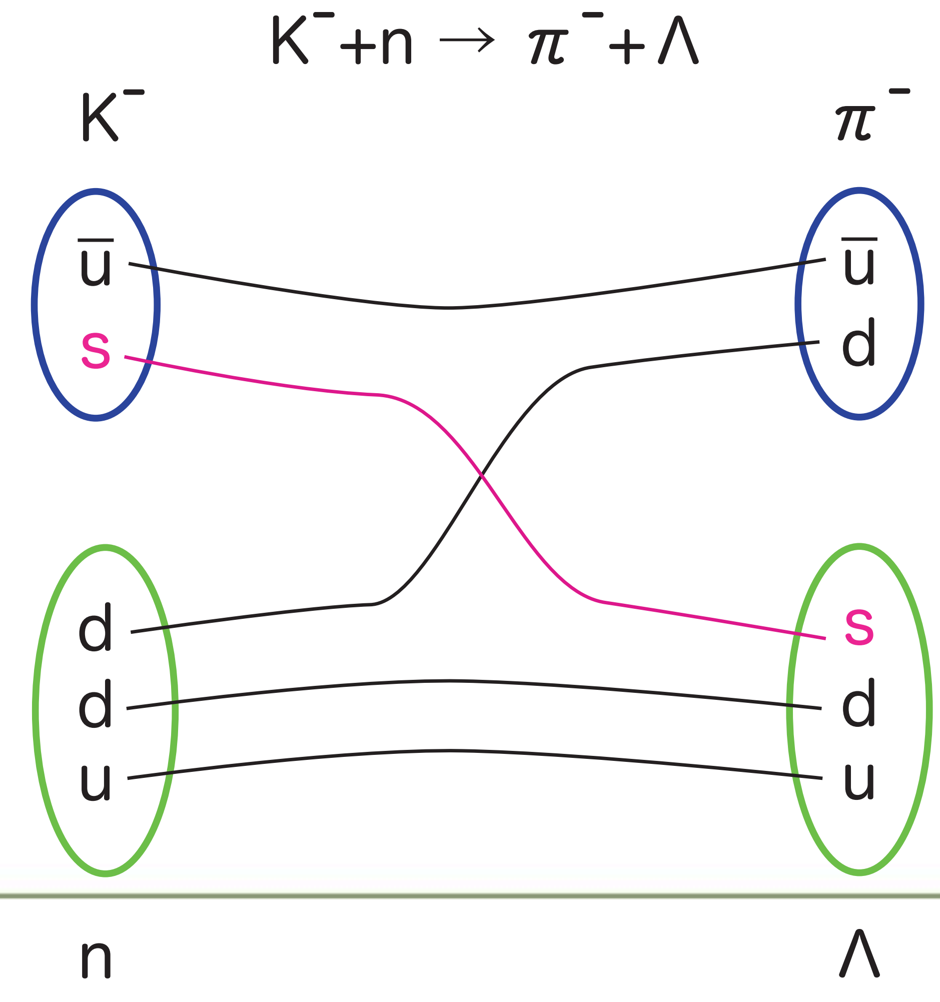
in the 21st century

- $(e,e'K^+)$ at JLab
  - $\Delta E \sim 0.9$ MeV → 0.3 MeV
- (K^-_{stop}, π^-) at DAFNE/FINUDA
  - $\Delta E \sim 0.7$ MeV
- J-PARC, GSI, Mainz, ...

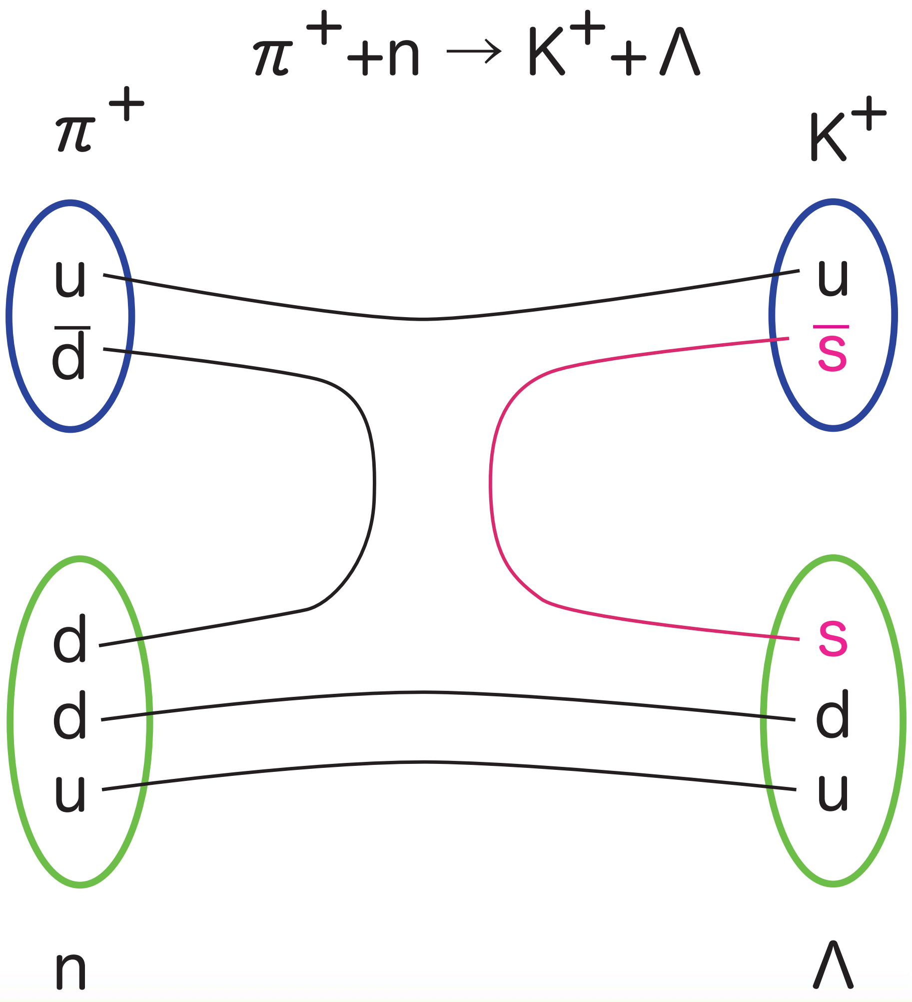
ハイパー一枚の作り方

How to produce hypernuclei ?

- Strangeness exchange reactions: (K^-, π^-)
  - Large cross section ~ mb/sr at 0 deg.
  - K^- intensity limited



- Associated production: (π^+, K^+), $(e,e'K^+)$
  - Smaller cross sections: ~10μb/sr, ~1nb/sr
  - High intensity beams: $>10^6\ \pi^+$, $>10^{13}\ e^-$

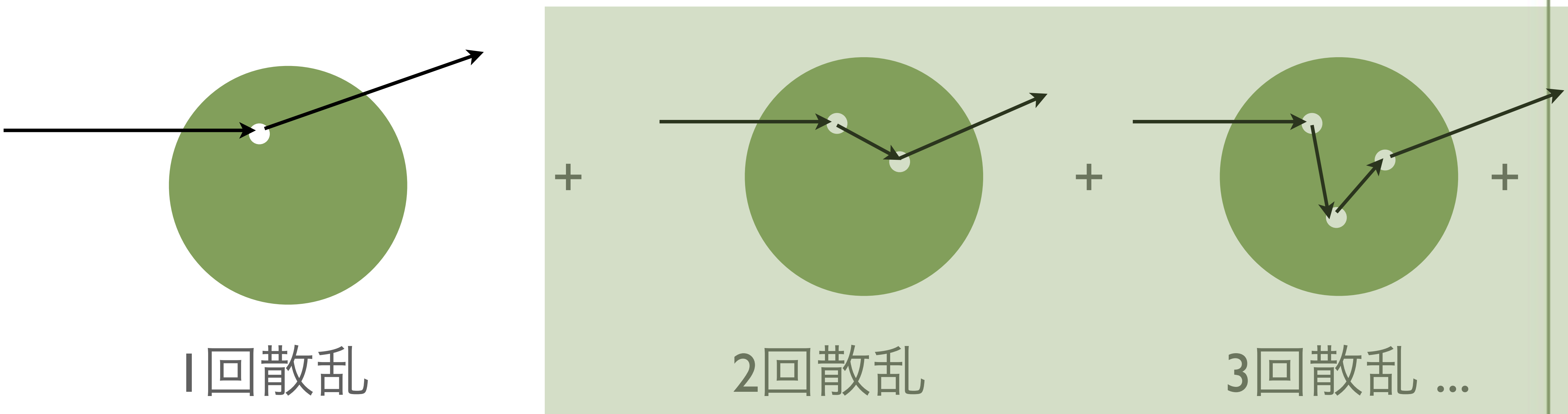


生成反応とその収量

	(K^-,π^-)	(π^+,K^+)	$(e,e'K^+)$
p_{BEAM} (GeV/c)	~0.7	1.05	1.8
$d\sigma/d\Omega$(μb/sr)	1000	10	10^{-3}
I_{BEAM} (s^{-1})	10^{+5}	10^{+6}	$>10^{+13}$
$\Delta\Omega$ (msr)	20	100	20
nx (g/cm^2)	3	3	0.1
ΔE (MeV)	3	2	0.2
Relative Yield	2	1	>3

反応機構

- DWIA (Distorted Wave Impulse Approximation)
  - Impulse Approx. : $p_{inc} \rightarrow$ high, $\lambda = h/p \rightarrow$ small $\ll$ 1fm



  - 核内での遷移振幅 ~ 自由散乱の遷移振幅

- 1 + “2” → 3 + “4”

$$\left(\frac{d^2\sigma_{fi}}{d\Omega_3 dE_3}\right)_{lab} = \frac{p_3 E_3}{(2\pi)^2 v_1} |T_{fi}|^2 \delta(\omega - E_1 + E_3)$$

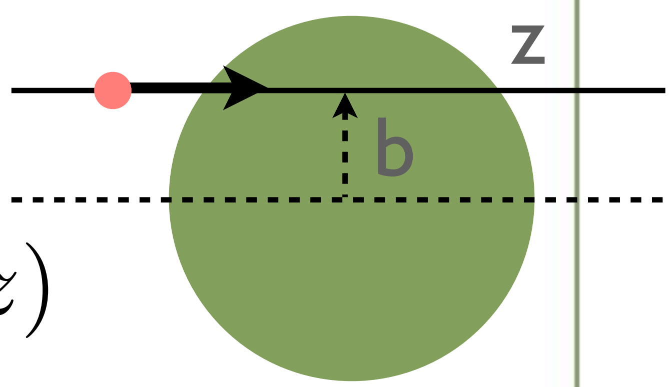
$$T_{fi} = \langle \chi_3^{(-)} | \langle f | \sum_j t_j | i \rangle | \chi_1^{(+)} \rangle$$

- t_j : 素過程反応
- $\chi_3^{(-)}$, $\chi_1^{(+)}$: 平面波(PWIA)、or 歪曲波(DWIA)

Distorted Wave

- Eikonal Approximation: E » U, pR » 1

$$\chi^{(+)}(b,z) = e^{ipz}\phi(b,z)$$



$$[-\nabla^2 + \mu^2 - \omega^2]\chi^{(+)}(b,z) = -2\omega U \chi^{(+)}(b,z)$$

$$\phi = \exp\{-iv^{-1}\int_{-\infty}^{z} U(b,z')dz'\}$$

$$2\omega U(b,z) = p\sigma^{tot}\rho(b,z)$$

$$\chi_3^{(-)*}(\boldsymbol{r})\chi_1^{(+)}(\boldsymbol{r}) = \exp\{i\boldsymbol{q}\cdot\boldsymbol{r} - \frac{1}{2}\sigma_{eff}\int_{-\infty}^{\infty}\rho(b,z')dz'\}$$

Mean free path = $1/\rho\sigma = 1/(4\ \mathrm{fm}^2)(0.15\ \mathrm{fm}^{-3}) = 1.6$ fm, $\sigma = 40$ mb

→核表面での反応が支配的

Effective nucleon number

- 素過程(1+2→3+4)での微分断面積を使う

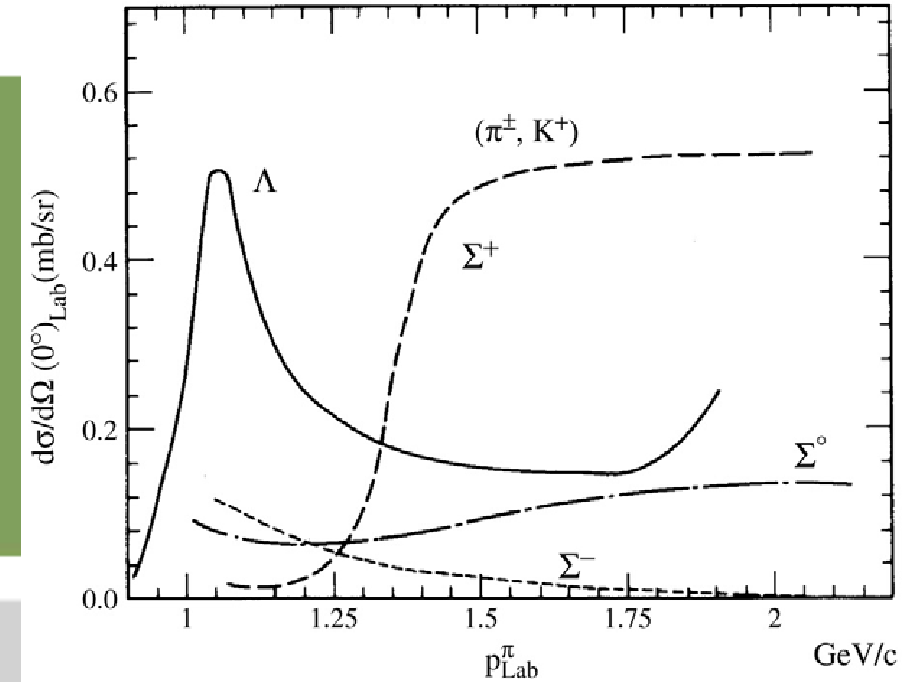
$$\left(\frac{d^2\sigma_{fi}}{d\Omega_3 dE_3}\right)_{lab} = \beta\left(\frac{d\sigma}{d\Omega_3}\right)_{lab} N_{eff}(\theta_{lab}; i \to f)\delta(\omega + E_3 - E_1)$$

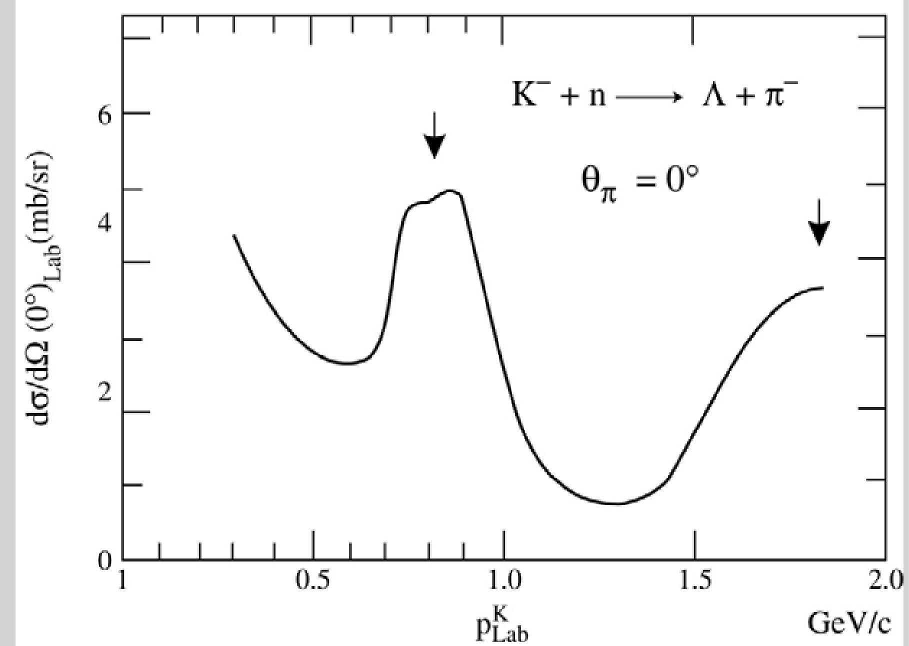
$$\beta = \left(1 + \frac{E_3^{(0)}}{E_4^{(0)}}\frac{p_3^{(0)} - p_1\cos\theta_{lab}}{p_3^{(0)}}\right)\frac{p_3 E_3}{p_3^{(0)} E_3^{(0)}}$$

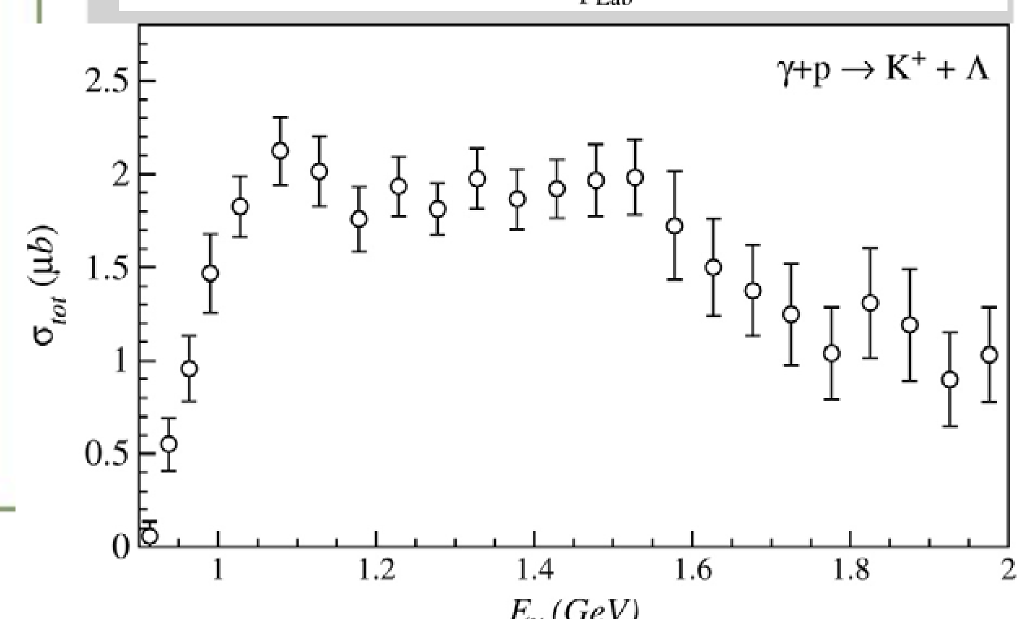
２体系((0))から多体系への運動学因子

入射エネルギー

- 1.05 GeV/c ; (π^+,K^+) for Λ
- 0.7-0.8 GeV/c ; (K^-,π^-) for Λ
- 1.2 - 1.8 GeV ; for (e,e'K^+) for Λ





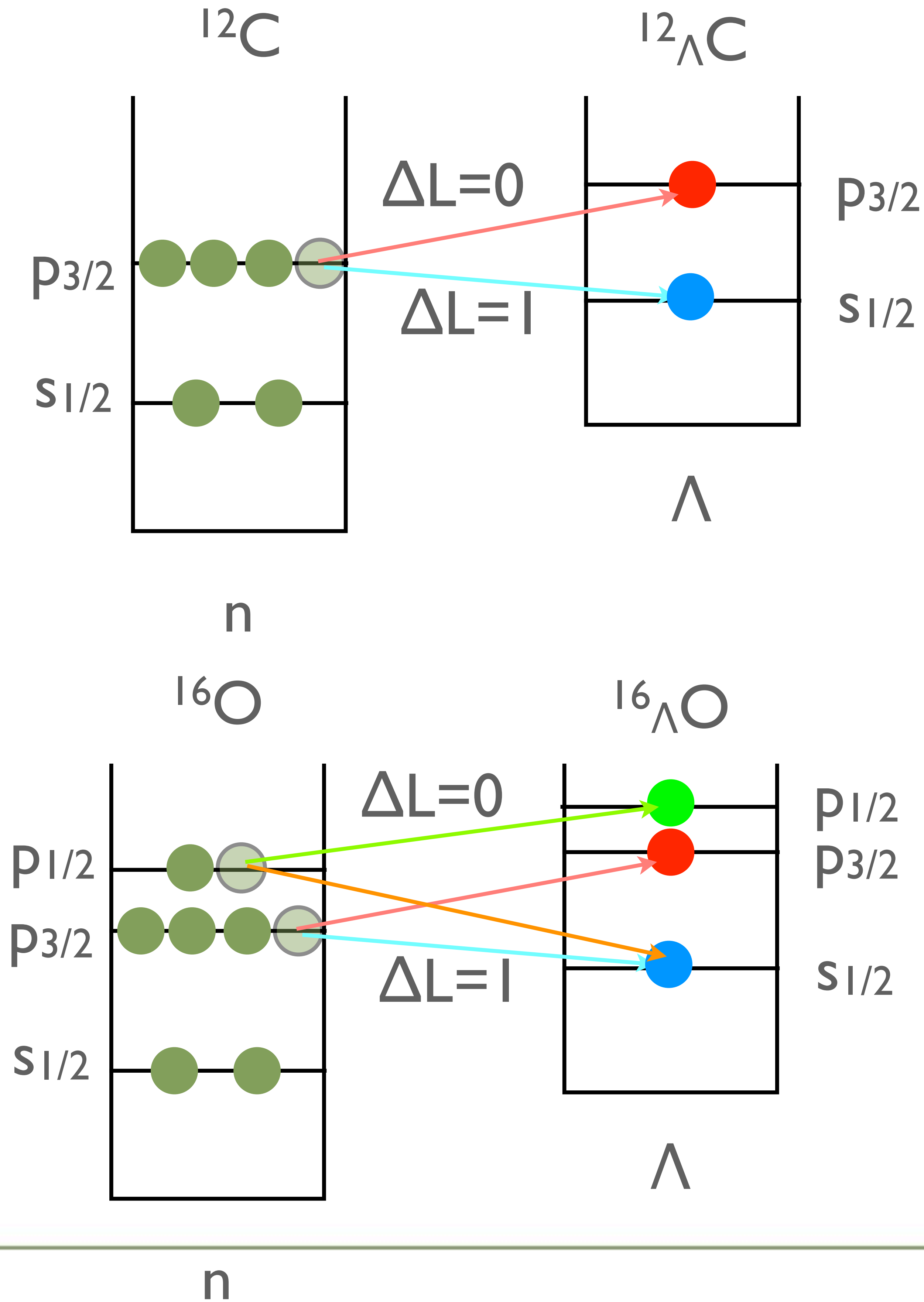


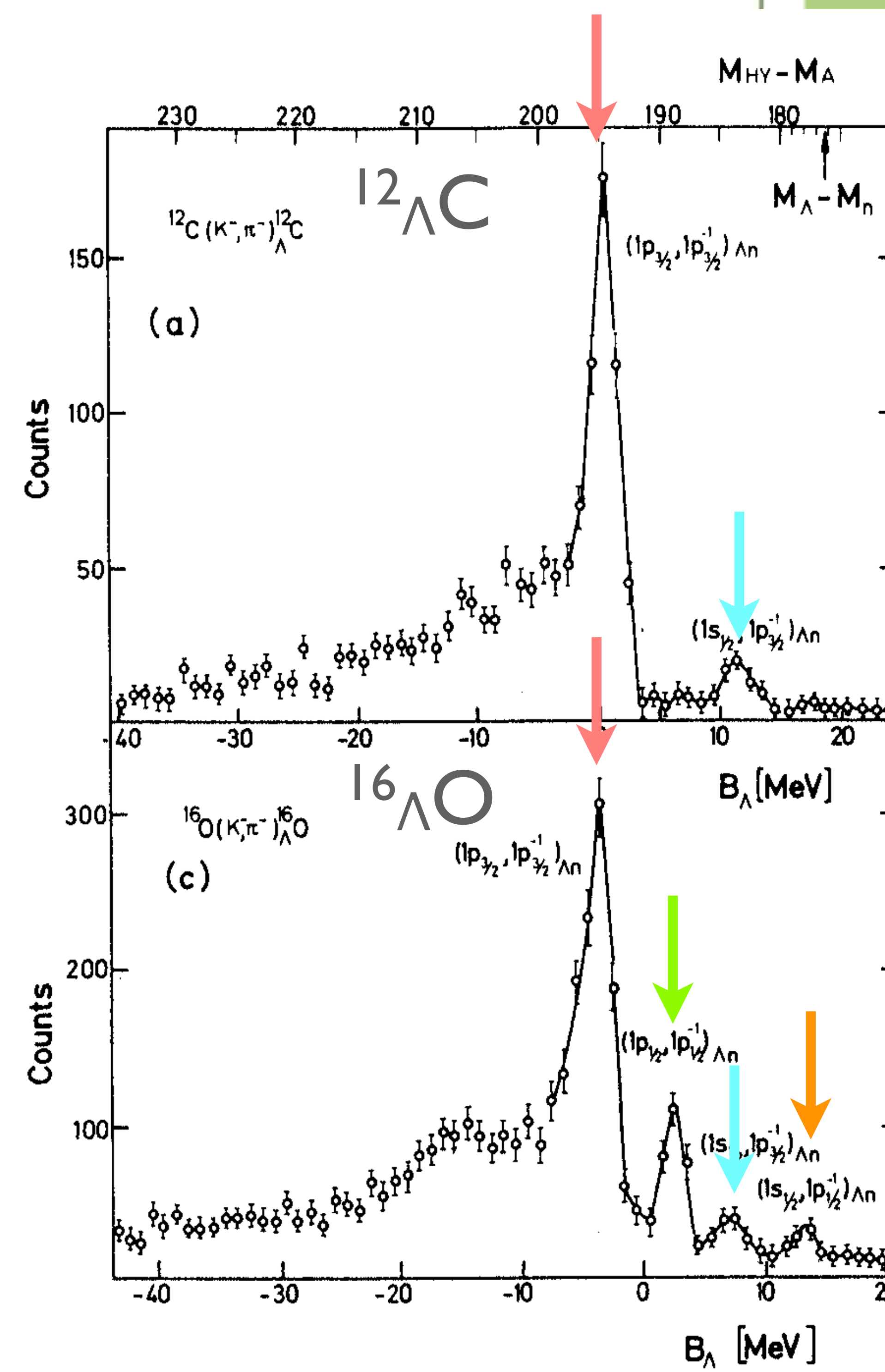
Hypernuclear Mass

- In-flight reactions: (π^+,K^+), (K^-,π^-)
  - $\pi^+ + A \rightarrow K^+ + HY$
    - $M_{HY}{}^2=(E_\pi+M_A-E_K)^2-(\boldsymbol{p}_\pi-\boldsymbol{p}_K)^2$; missing mass
    - $M_{HY} - M_A = B_n - B_\Lambda + M_\Lambda - M_n$
    - $-B_\Lambda = M_{HY} - (M_A + B_n - M_n + M_\Lambda)$
  - Need incident momentum & out-going momentum → Two Spectrometers

- Stopped K^- reaction: (K^-_{stop},π^-)
  - $K^- + A \rightarrow \pi^- + HY$
    - $M_{HY}{}^2 = (M_K + M_A - E_\pi)^2 - (\boldsymbol{p}_\pi)^2$; missing mass
    - $M_{HY} - M_A = B_n - B_\Lambda + M_\Lambda - M_n$
    - $-B_\Lambda = M_{HY} - (M_A + B_n - M_n + M_\Lambda)$
  - Need out-going π^- momentum only → One Spectrometer

(K^-,π^-) in-flight





Spectroscopic Information

- Mass→Binding Energy
  - Missing Mass measurement in in-flight reactions
  - Weak decays of Hyperfragments
- Spin Assignment
  - Weak Decay
  - Gamma Decay

$^{208}Pb(e,e'p)$

- $_{Z}A_{N}(e,e'p)\ _{Z-1}A'_{N}$: nucleon hole state
- Deep Hole States → Large Spreading Width > a few MeV

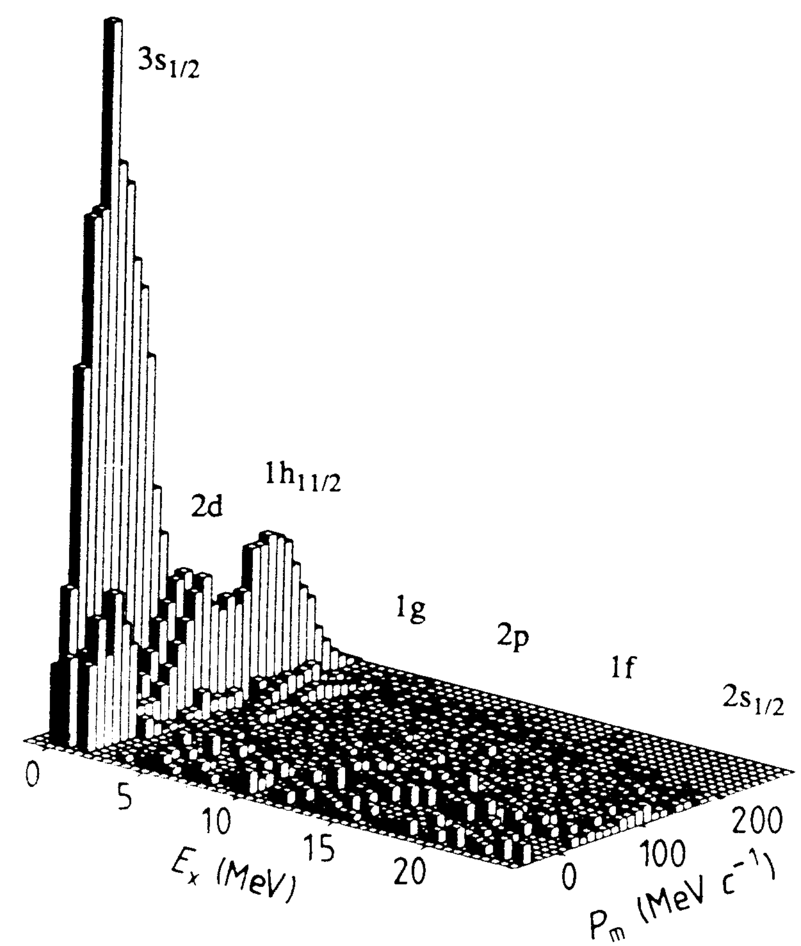
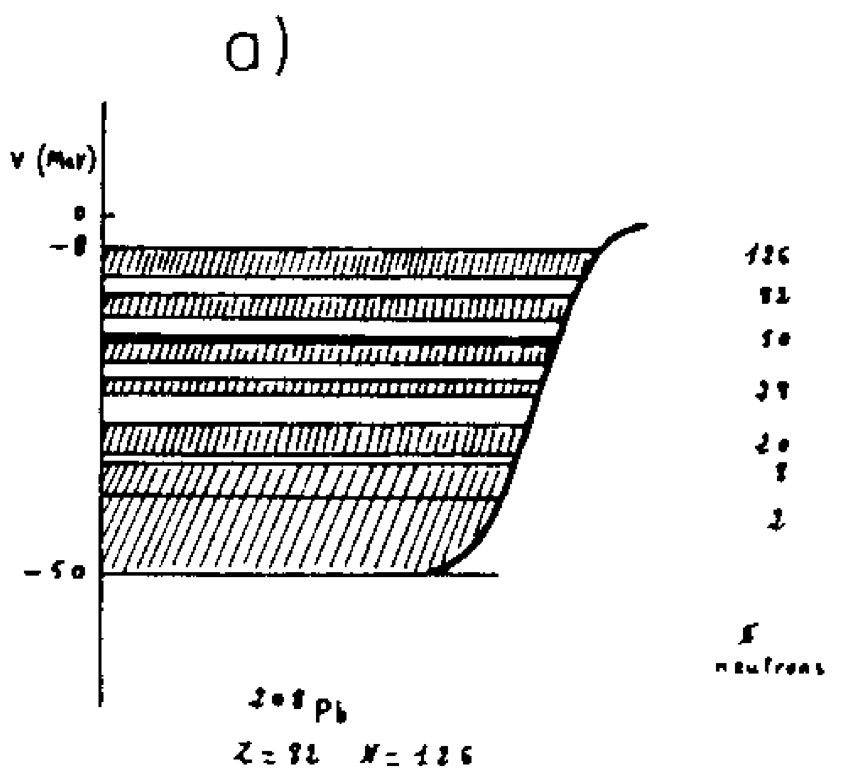
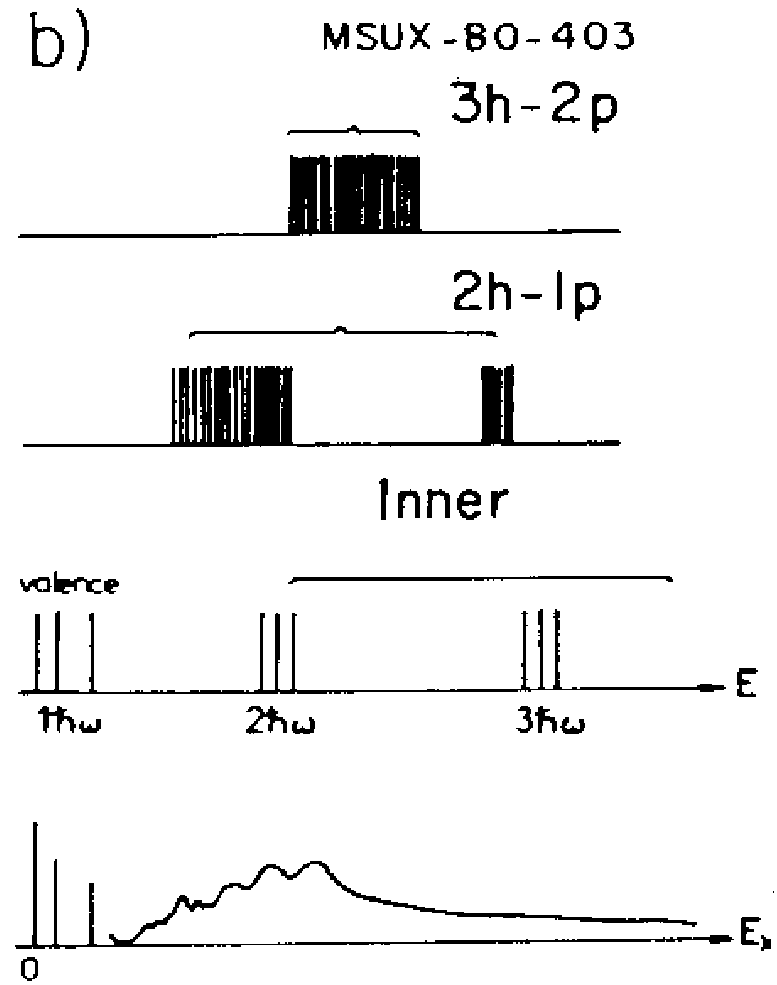
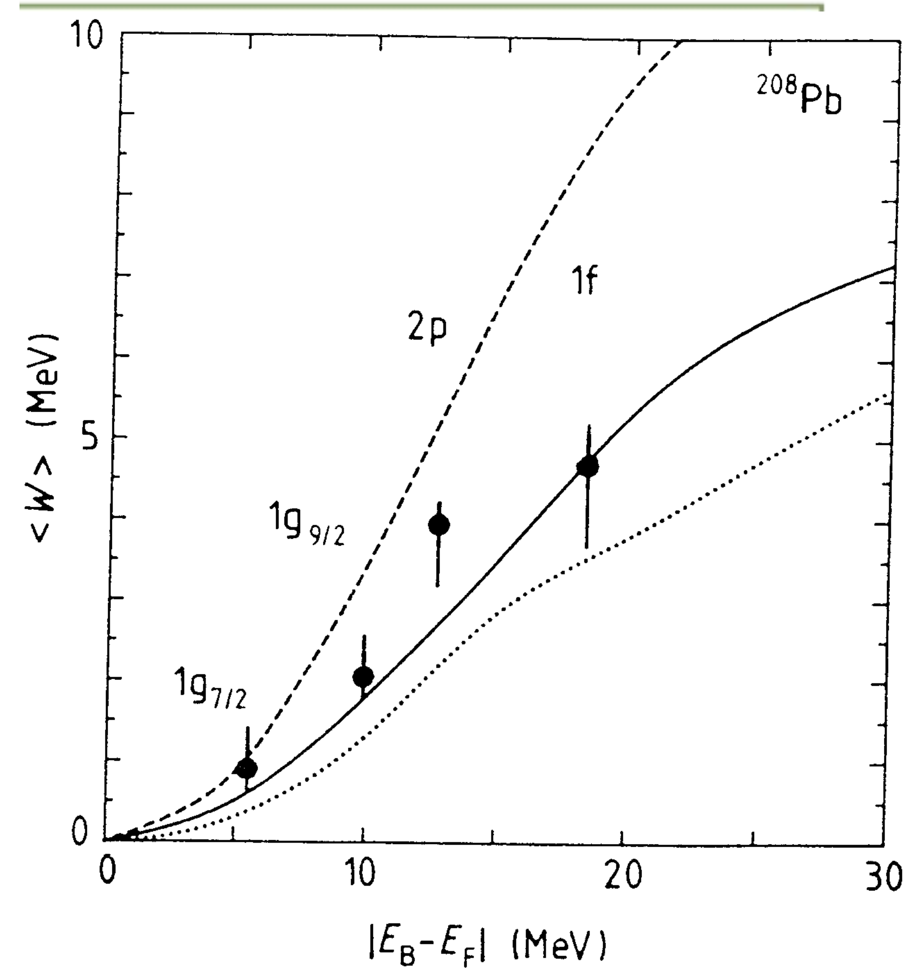


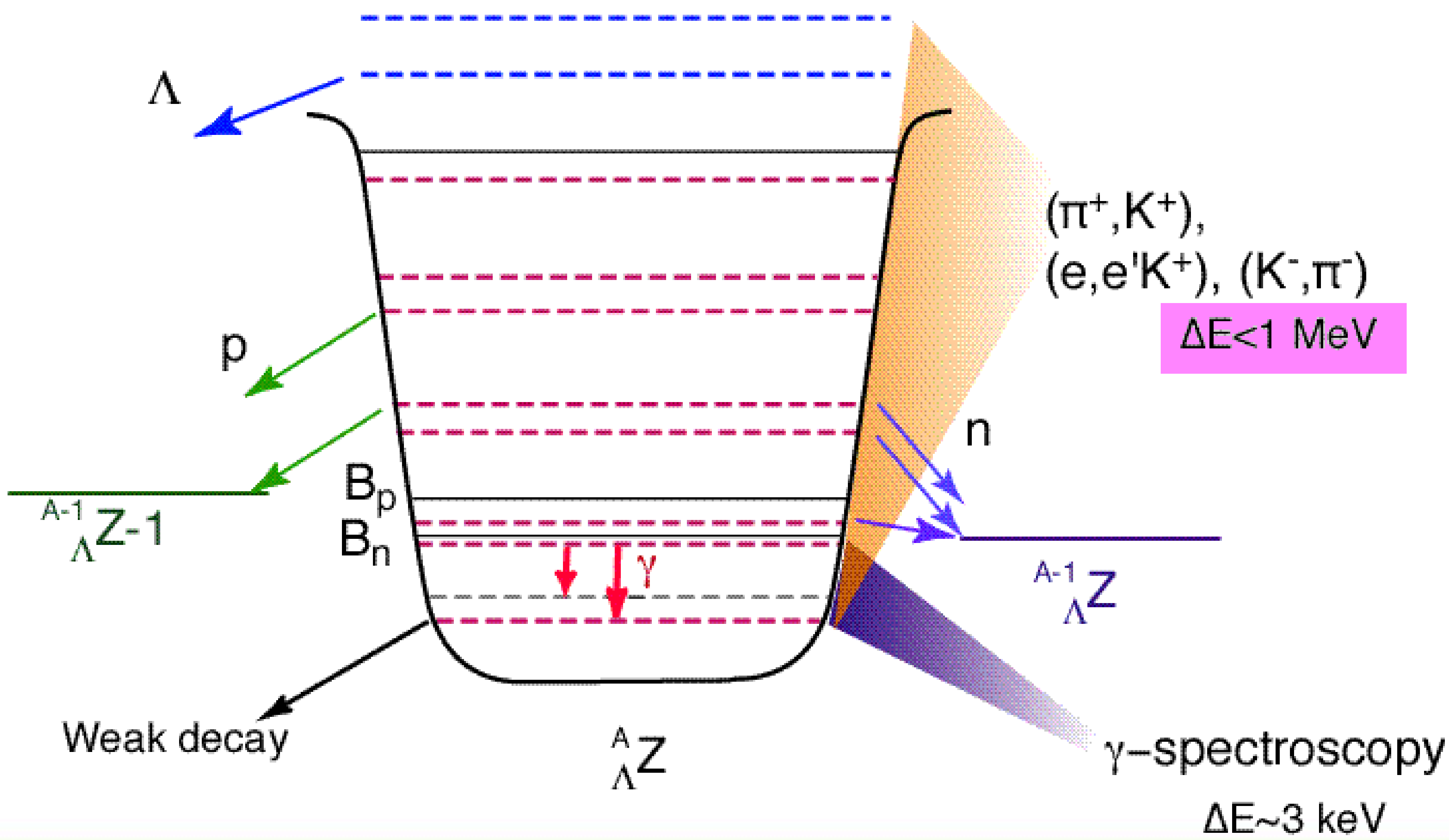
Figure 32. Experi
$^{208}Pb(e,e'p)^{207}Tl$.


a)


b)
MSUX-80-403
3h-2p
2h-1p
Inner
valence
E
1ħω
2ħω
3ħω
0
Eₓ


10
5
0
0
10
20
30
208Pb
2p
1f
1g9/2
1g7/2
<W> (MeV)
|EB-EF| (MeV)

Excited levels of Λ-hypernuclei



Monochromatic Peak

- Mesonic decay of Hyperfragments
  - $^4{}_\Lambda H$

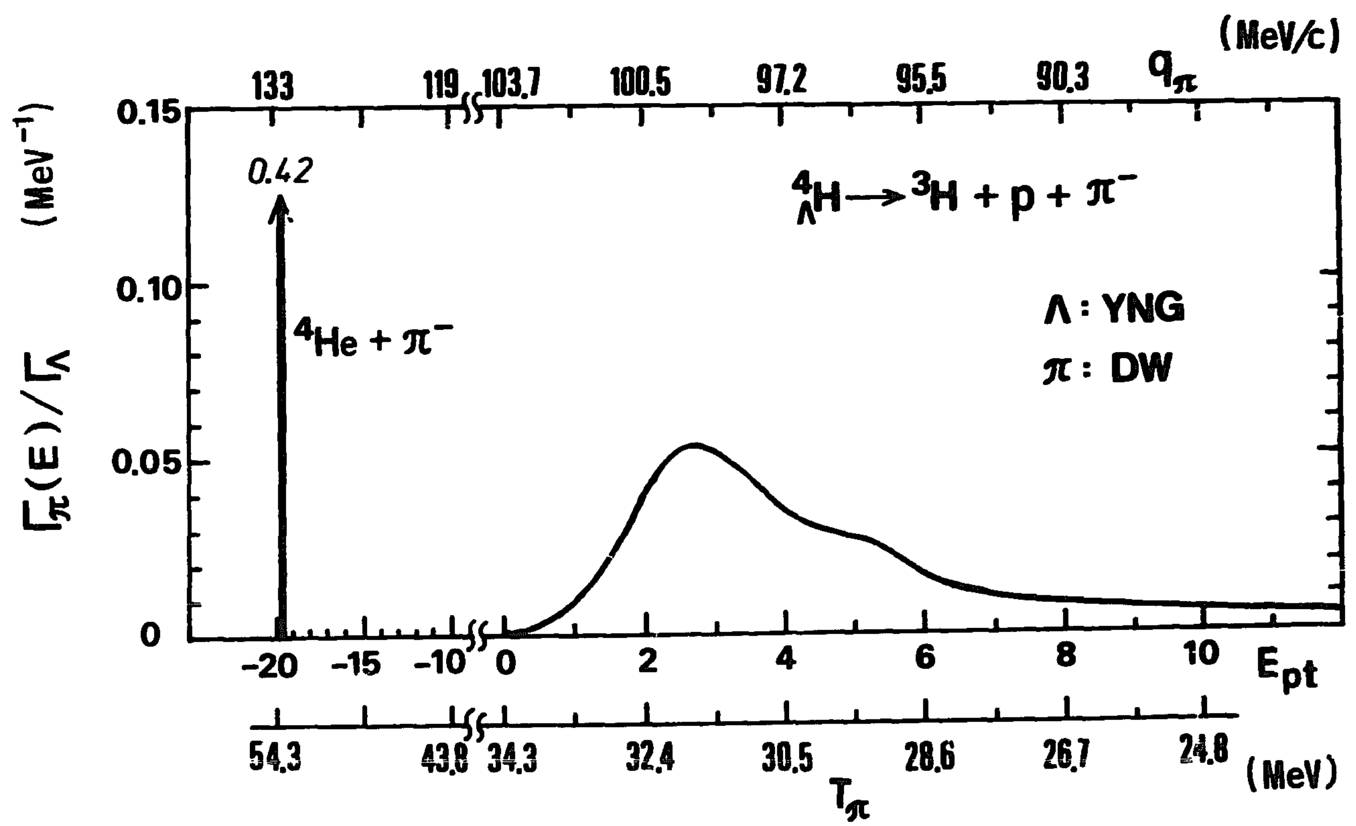


Fig. 9. The theoretical π^- decay spectrum $\Gamma_{\pi^-}(^4_\Lambda H)/\Gamma_\Lambda$ as a function of the proton-^3H relative energy E_{pt}.

Quasi-monochromatic

- ${}^{5}{}_{\Lambda}He \rightarrow \pi^{-} + p + {}^{4}He$; p_{π} = 99.9 MeV/c, $\Delta p \sim 1.4$ MeV/c

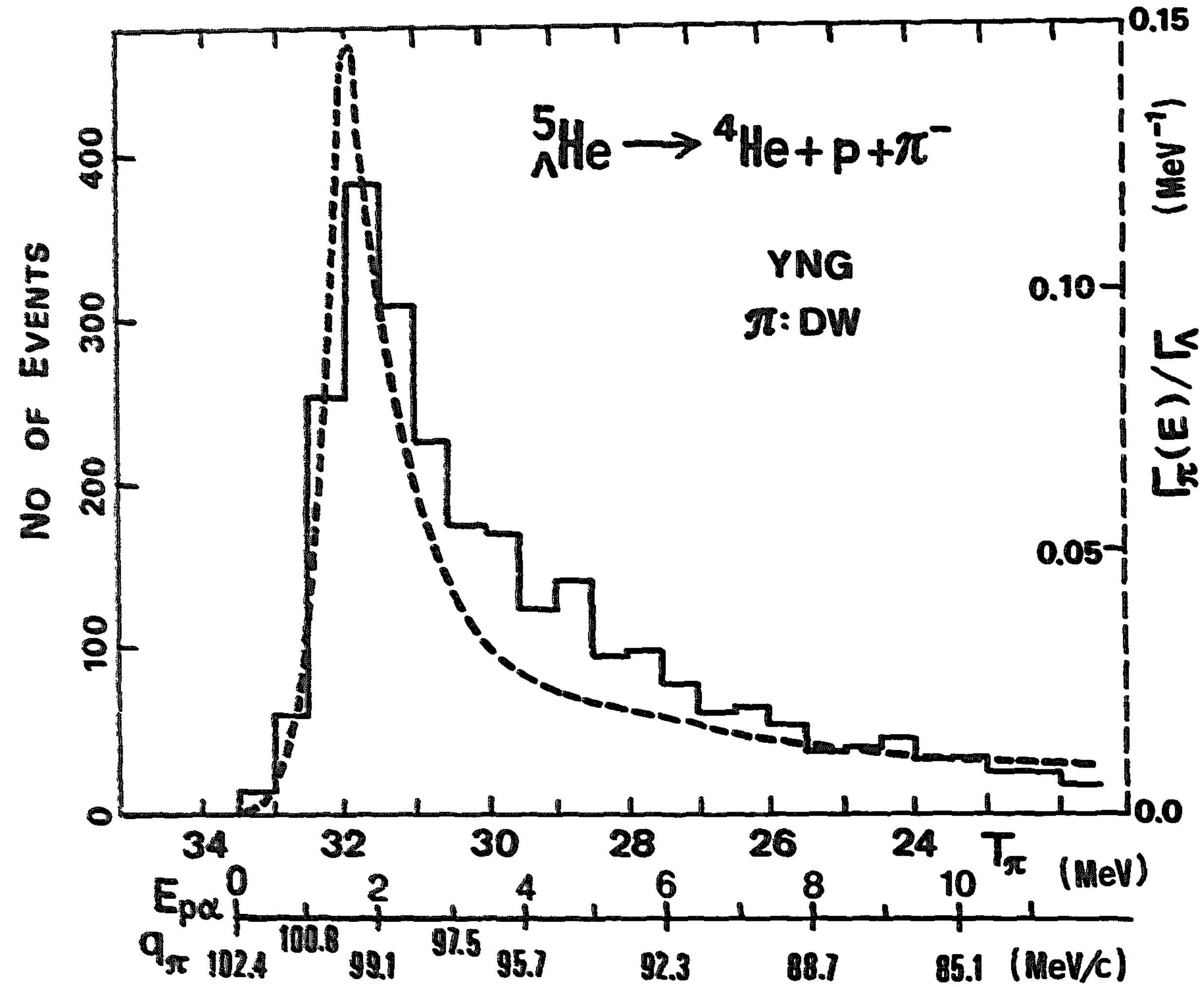


Fig. 4. The theoretical π^- decay spectrum $\Gamma_{\pi^-}({}^{5}_{\Lambda}He)/\Gamma_{\Lambda}$ with YNG drawn as a function of the $p\alpha$ relative energy $E_{p\alpha}$ is compared with the observed π^- decay spectrum taken in the emulsion experiment [18,33]. The calculated π^- decay rate is compared with the experimental values [12,20] in table 1 and fig. 5.

Mesonic Decay Rate

- $\Gamma_{\pi}/\Gamma_{\Lambda}$~0.4 - 0.6 for light fragments

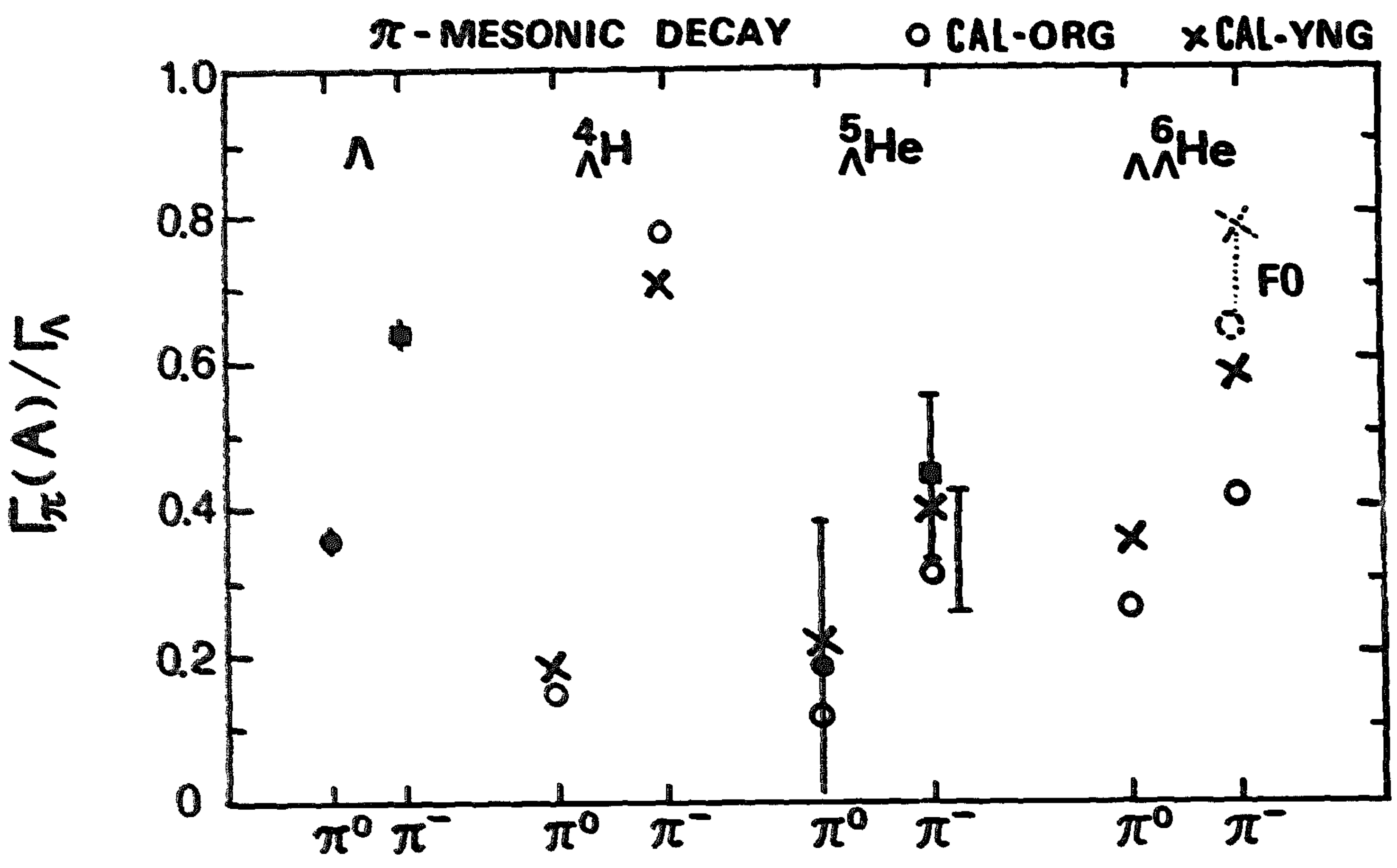
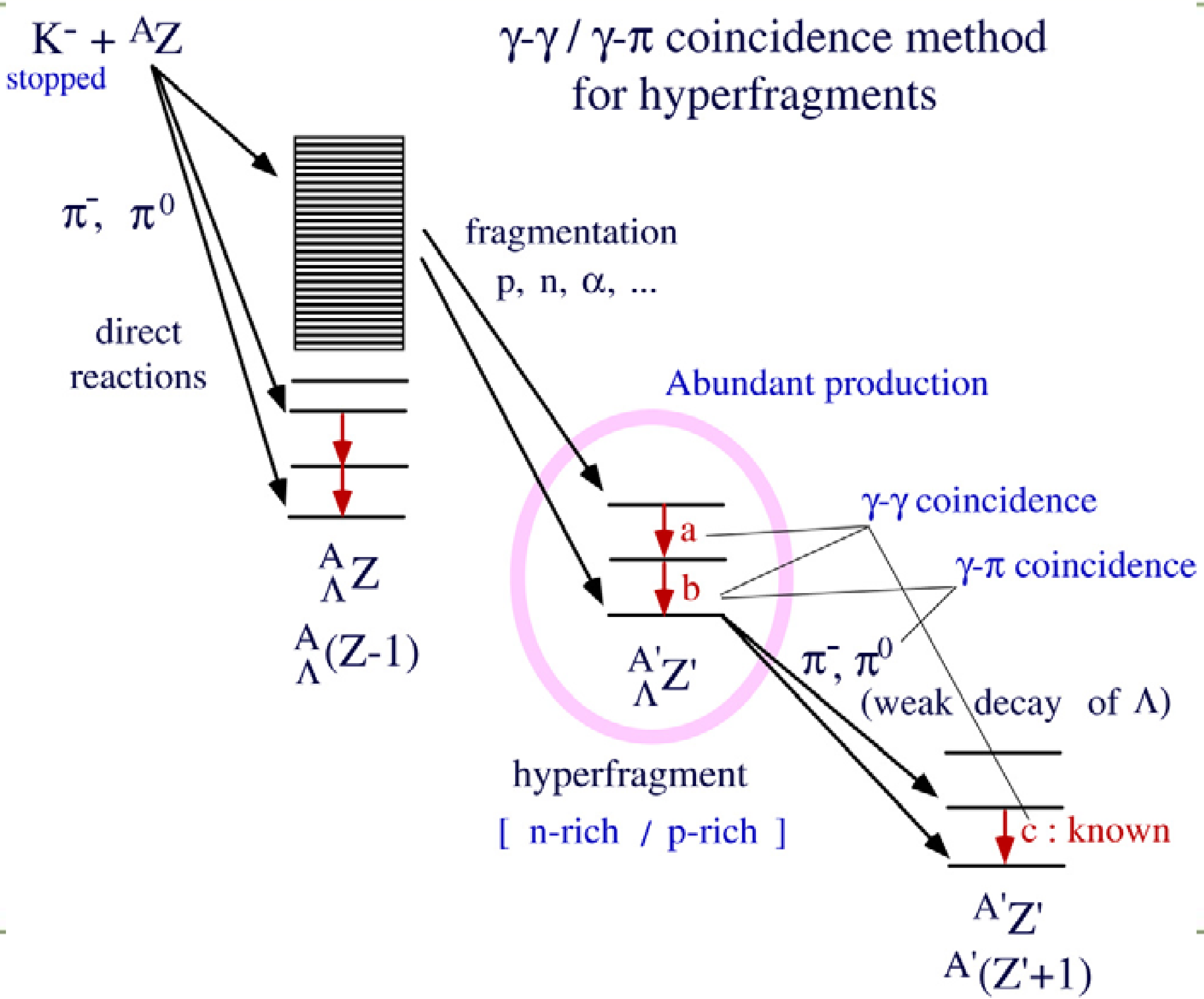


Fig. 5. Summary of the theoretical π-decay rates in units of Γ_{Λ}. The open circle and the cross correspond to ORG and YNG, respectively. The π^- decay rates of $^{6}_{\Lambda\Lambda}$He in the case of the F0 .1.1 interaction are also shown. The experimental values for $^{5}_{\Lambda}$He are taken from refs. [12,20]).

γ-ray spectroscopy

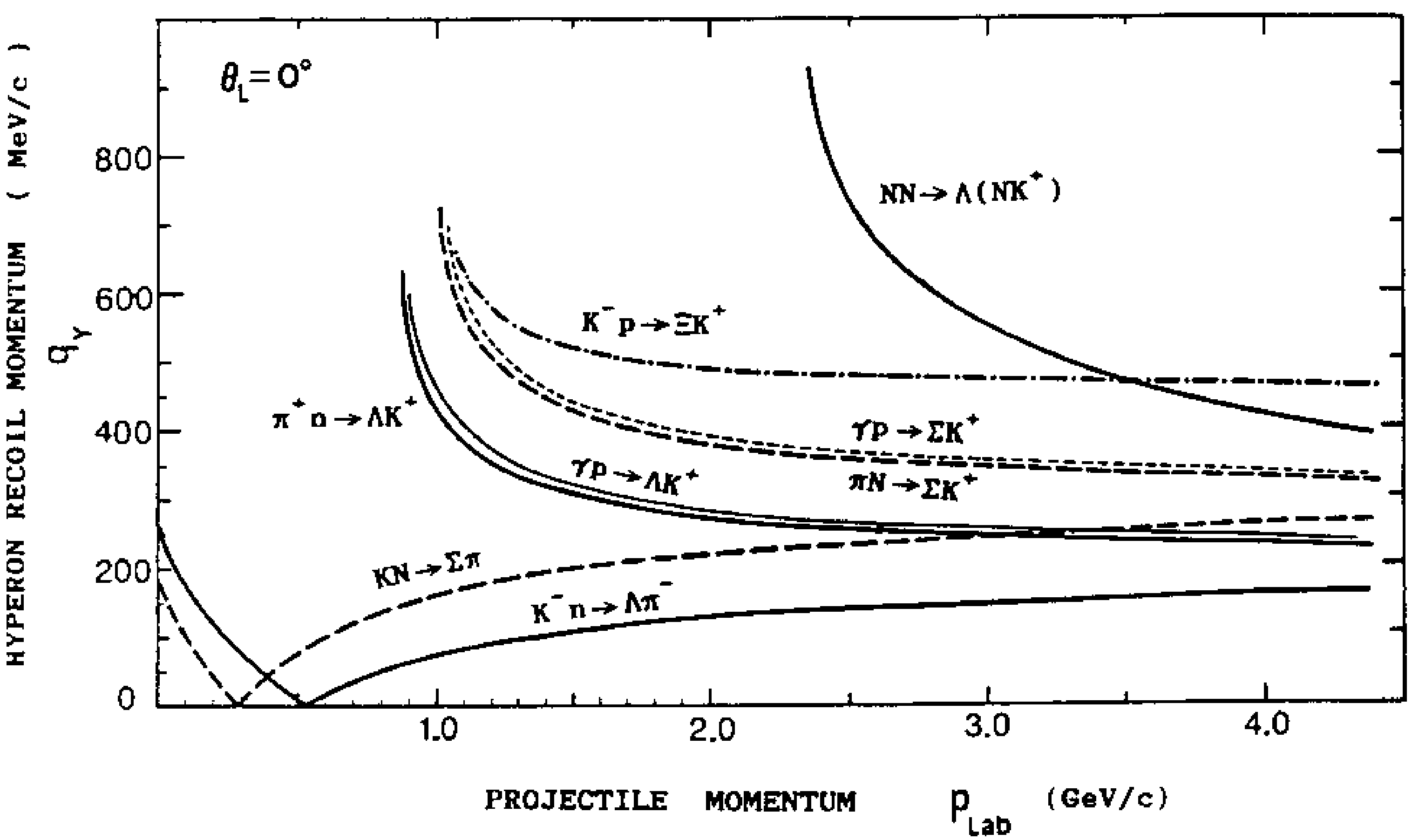


by H. Tamura

- Charged-particle Spectroscopy
  - magnetic spectrometer: $\Delta p/p > 10^{-4}$
  - $\Delta E = 0.3 \sim 2$ MeV
  - Absolute Energy Level
  - selectivity for produced states
- Gamma-ray Spectroscopy: Low detection efficiency
  - NaI(~100 keV), Ge(2-3 keV): Excellent Resolution
  - Energy level separation
  - Low-lying states below particle-emission threshold

Sticking probabilities

$$S_k(q; n_N l_N, n_Y l_Y) = \left|\langle \phi^{HO}_{n_Y l_Y}(r) \left| j_k(qr) \right| \phi^{HO}_{n_N l_N}(r) \rangle\right|^2$$



Production, Structure and Decay of Hypernuclei

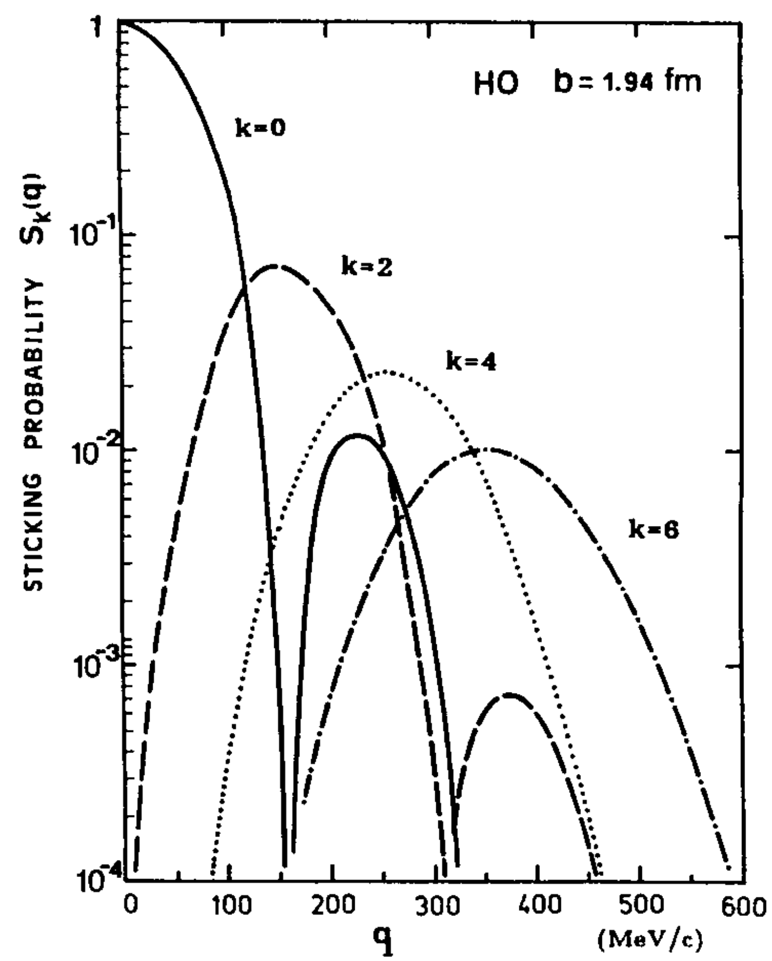


Fig. 2.4. The sticking probabilities $S_k(q; (0f)_N, (0f)_Y)$ of Eq. (2.2) as a function of q. The harmonic osci size parameter $b = 1.94$ fm is used.

- (K^-,π^-): q<100 MeV/c→$\Delta\ell$=0 dominant

Angular Distributions

- $\Delta\ell = 0$
  - $s_N \rightarrow s_\Lambda$
  - $p^{1/2}{}_N \rightarrow p^{1/2}{}_\Lambda$
- $\Delta\ell = 1$
  - $p^{3/2}{}_N \rightarrow s^{1/2}{}_\Lambda$
- $\Delta\ell = 2$
  - $p^{1/2}{}_N \rightarrow p^{3/2}{}_\Lambda$

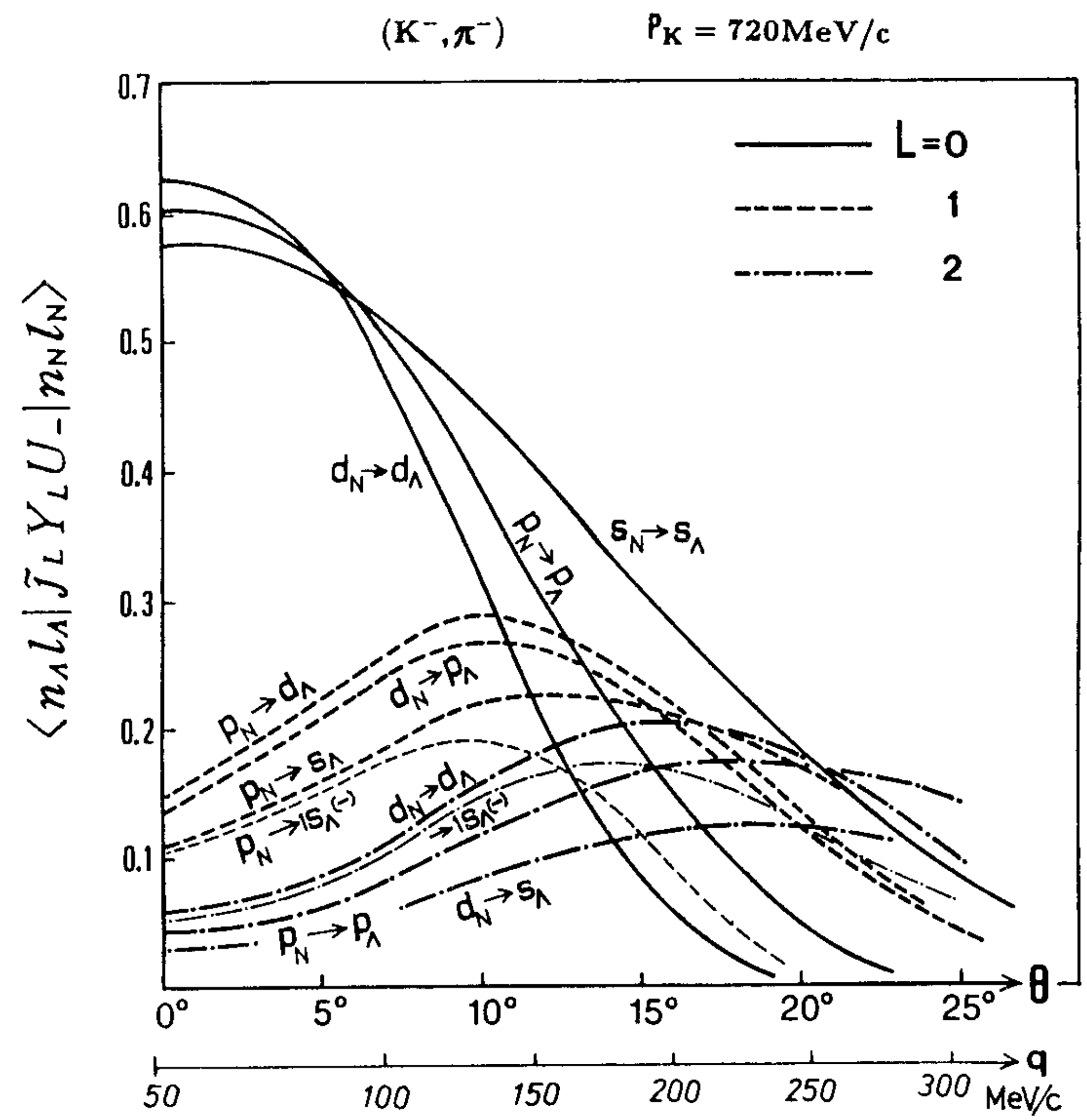
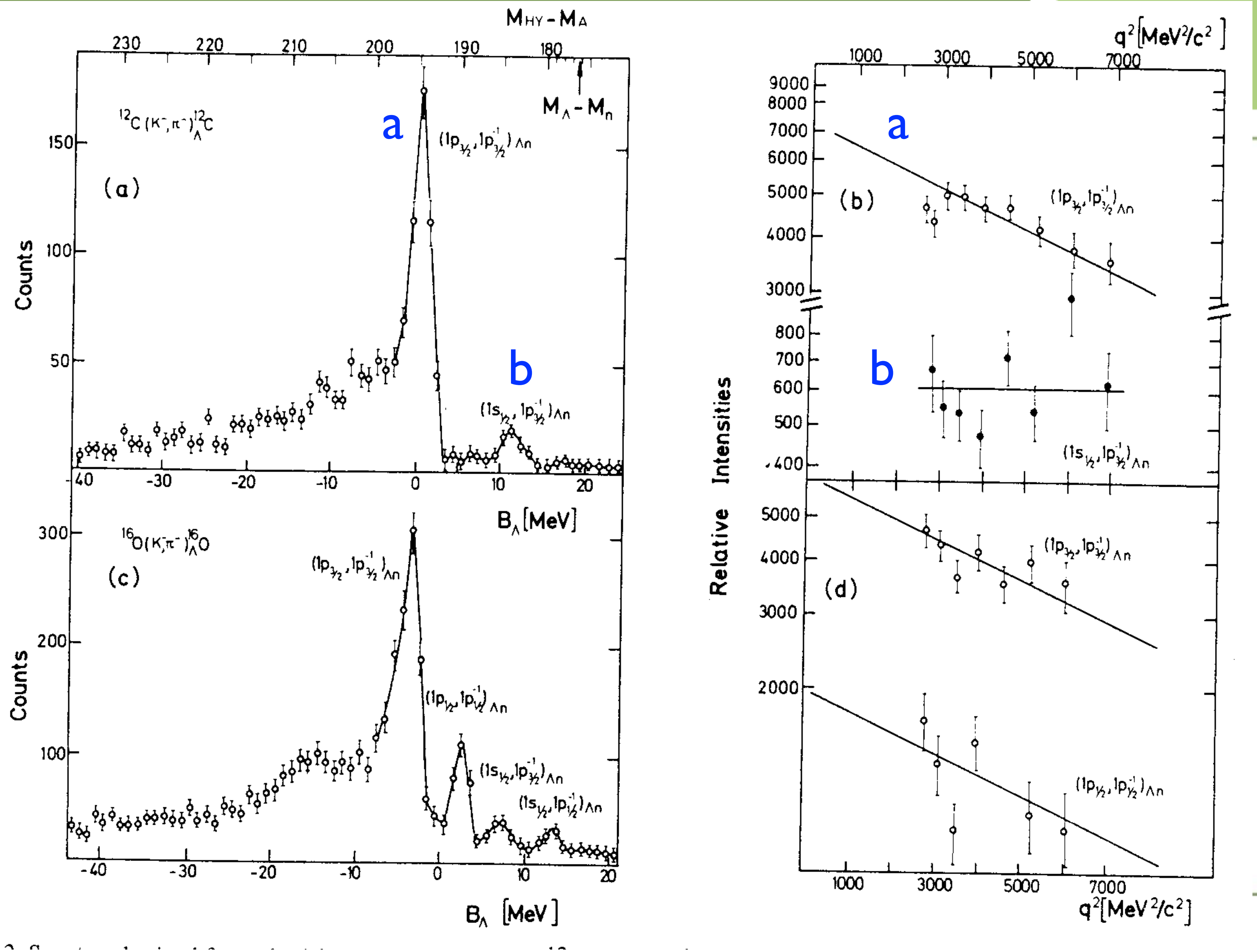


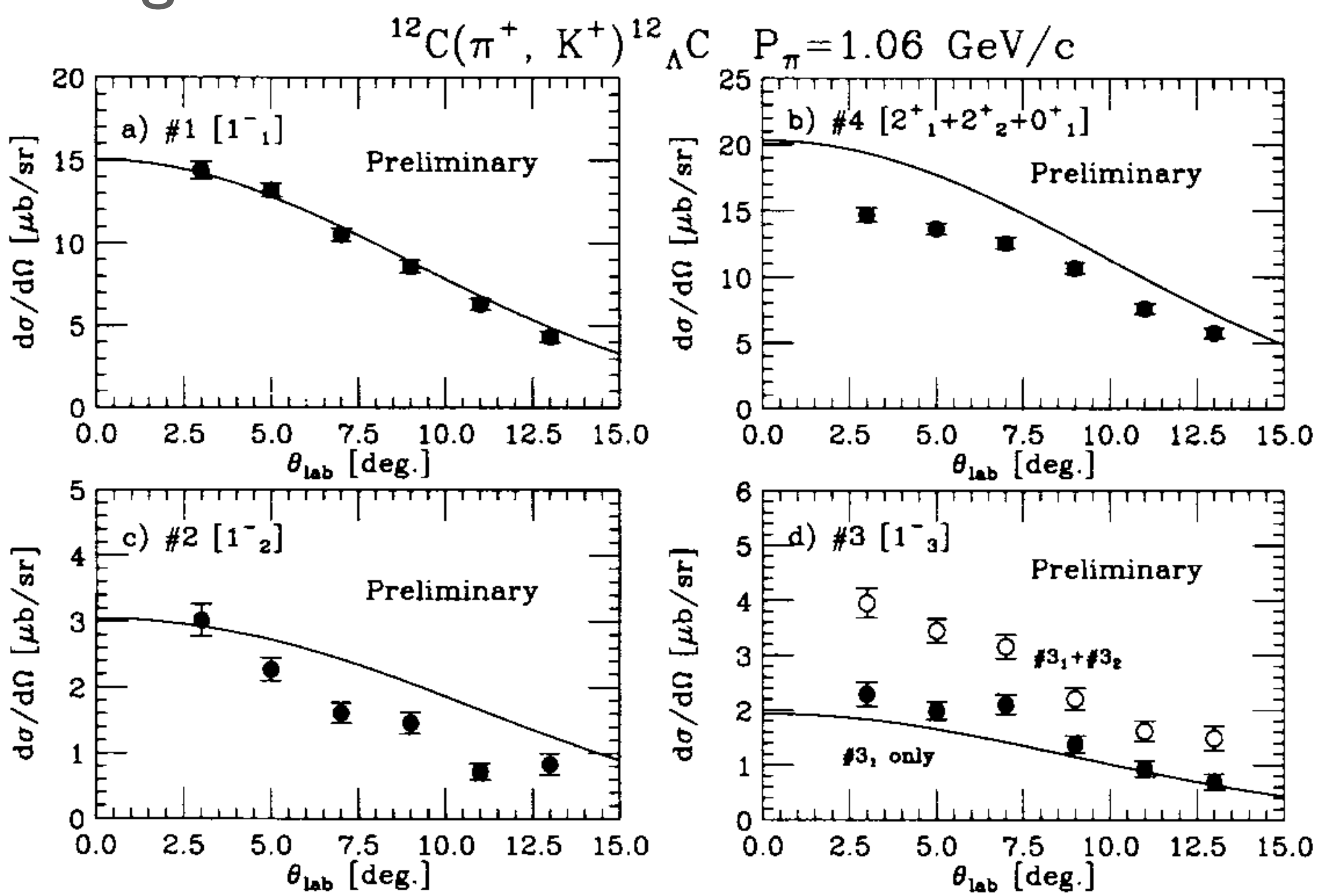
Fig. 4.1. θ-dependence of the single-particle transition matrix element $\langle n_\Lambda l_\Lambda | \tilde{j}_L Y_L U_- | n_N l_N \rangle$ calculated for the (K^-, π^-) reaction at $p_K = 720$ MeV/c.[255]

(K^-,π^-) on ^{12}C&^{16}O



Angular distribution in (π^+,K$^+$)

- Small change of q
- $^{12}{}_{\Lambda}$C: good agreement with a DWIA cal.



T.Takahashi et al., Nucl. Phys. A670 (2000) 265c.
Cal. by K.Itonaga et al., Phys. Rev. C49 (1994) 1045.

Spin of $^4_\Lambda$H (1)

- $^4_\Lambda$H=^{3}H(1/2)+Λ(1/2)
  - Initial State: J=0 or 1
  - Final State: π (0$^-$), ^{4}He(0$^+$)
    - s-wave(J=0) or p-wave(J=1)
    - isotropic or $\cos\Theta^2$

$$^4_\Lambda\mathrm{H} \rightarrow \pi^- + ^4\mathrm{He}$$

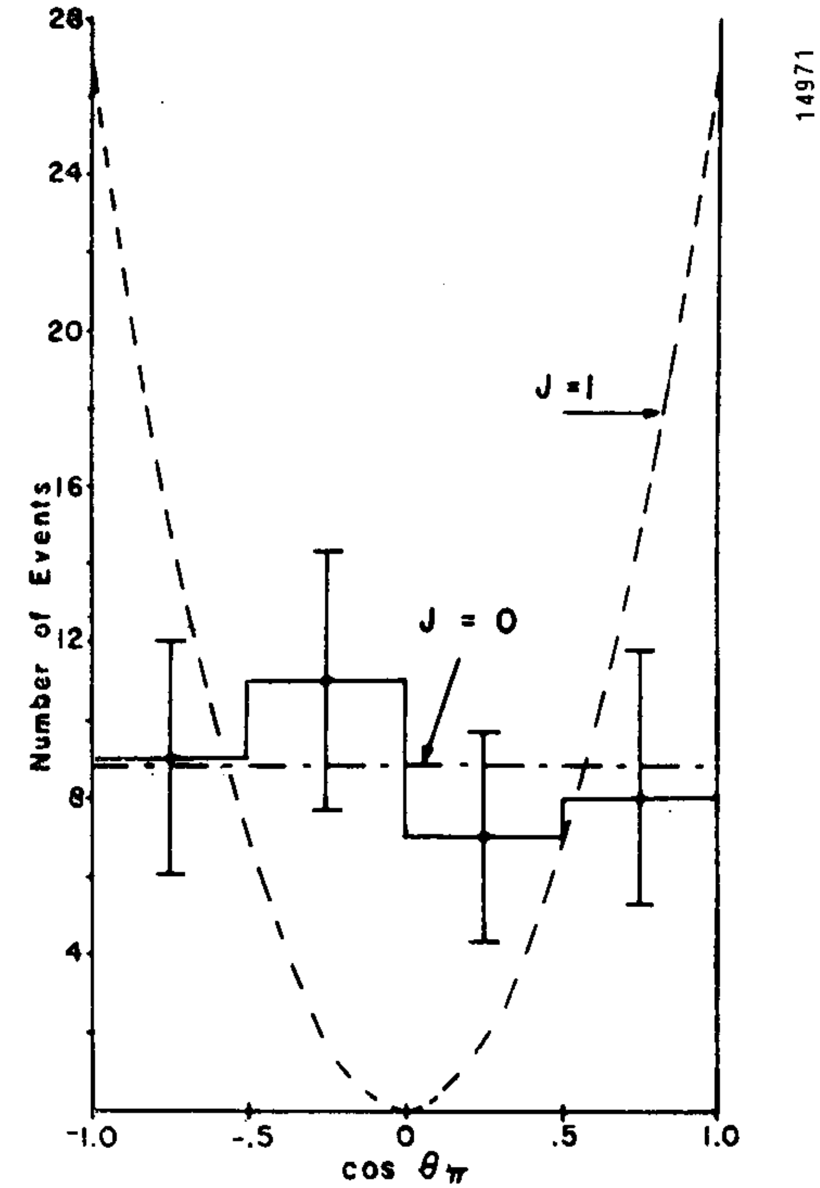
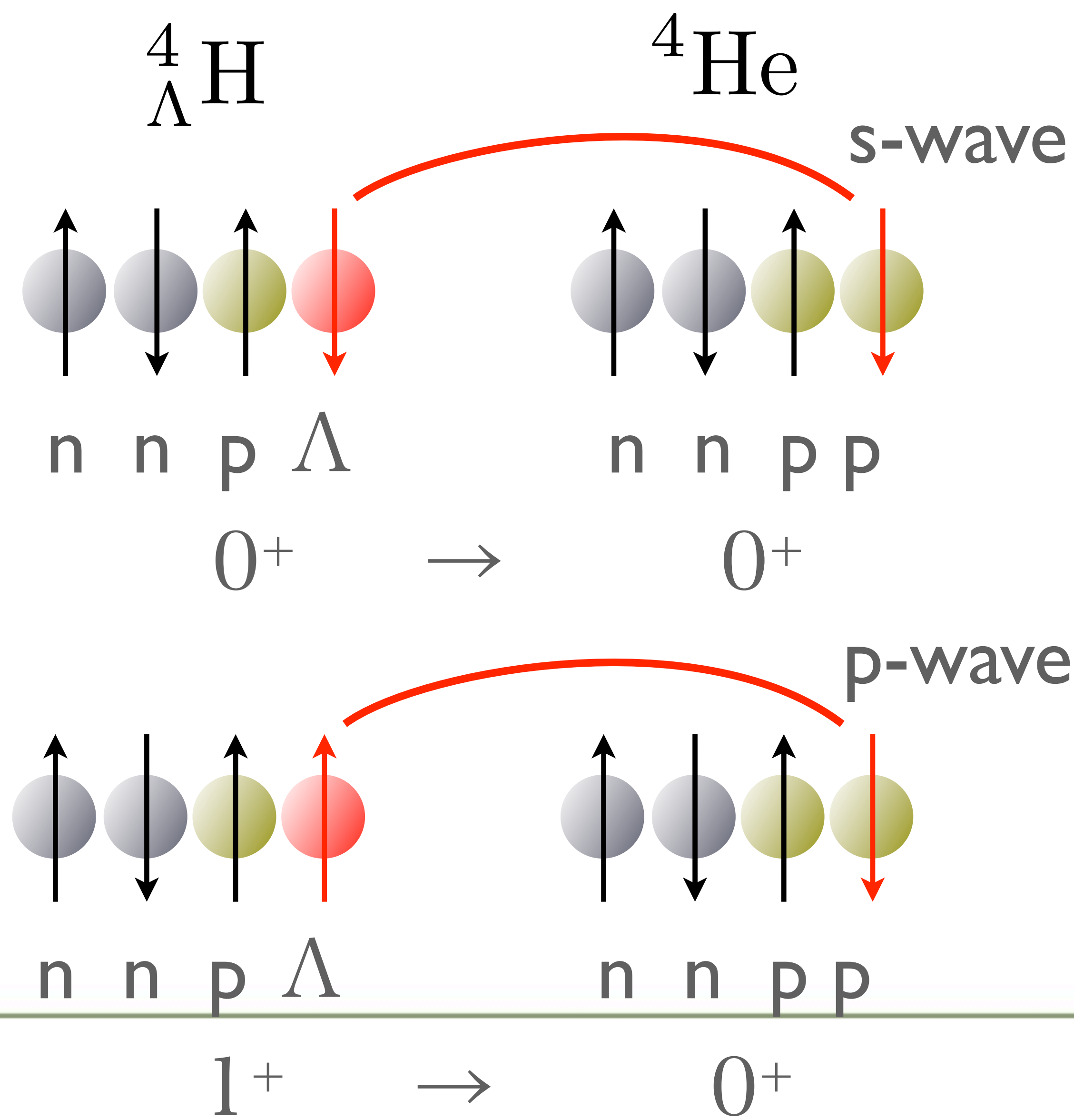


Fig. 1 The angular distribution of the π^- from the decay $_\Lambda H^4 \rightarrow \pi^- + He^4$, for hyperfragments produced in the capture reaction $K^- + He^4 \rightarrow {}_\Lambda H^4 + \pi^0$.

Spin of $^4_\Lambda H$ (2)

- $R_4 = (^4_\Lambda H \rightarrow \pi^- + ^4He)/(\text{all } \pi^- \text{ decays of } ^4_\Lambda H)$
- v.s. $p^2/(s^2+p^2)$



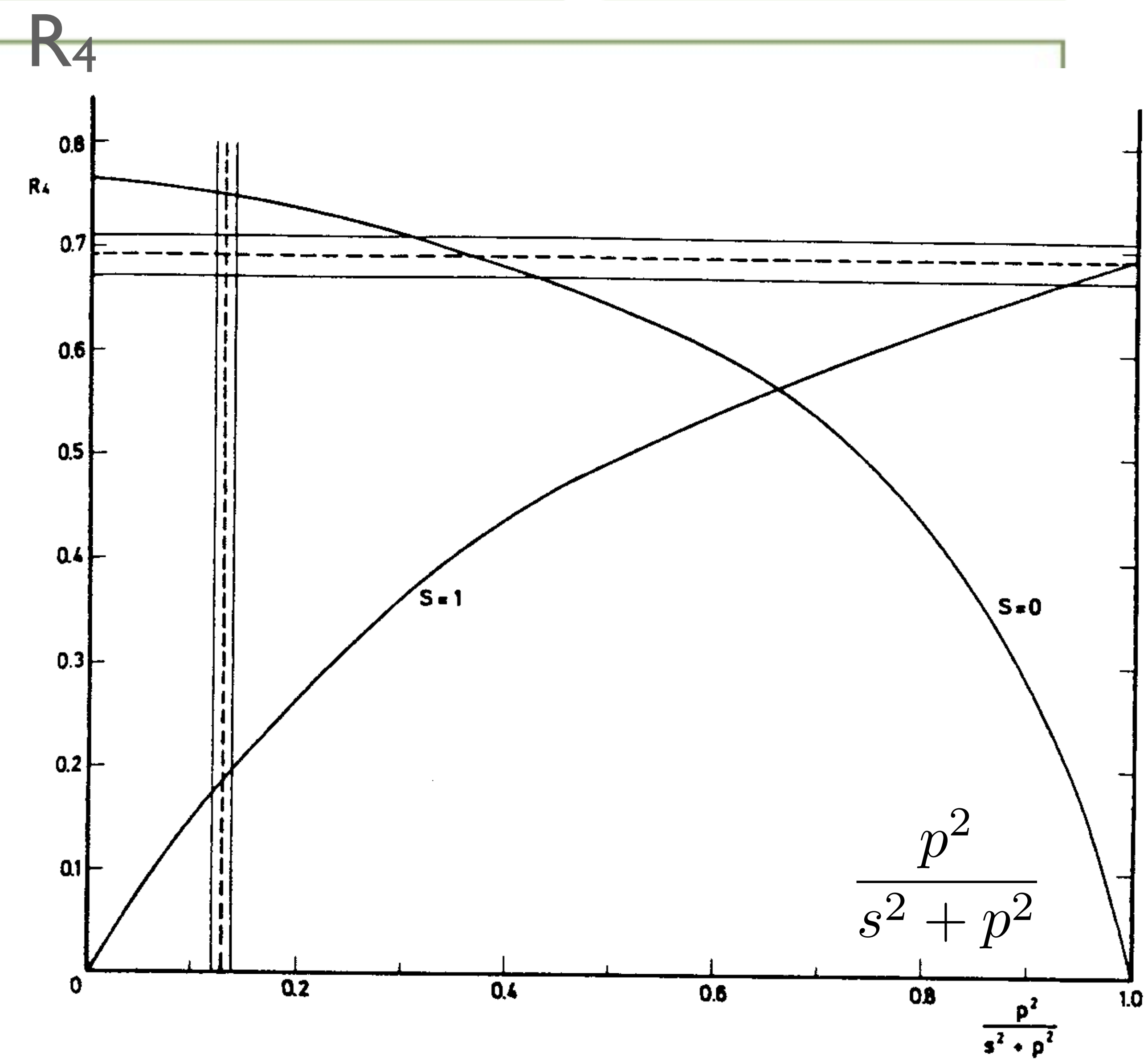


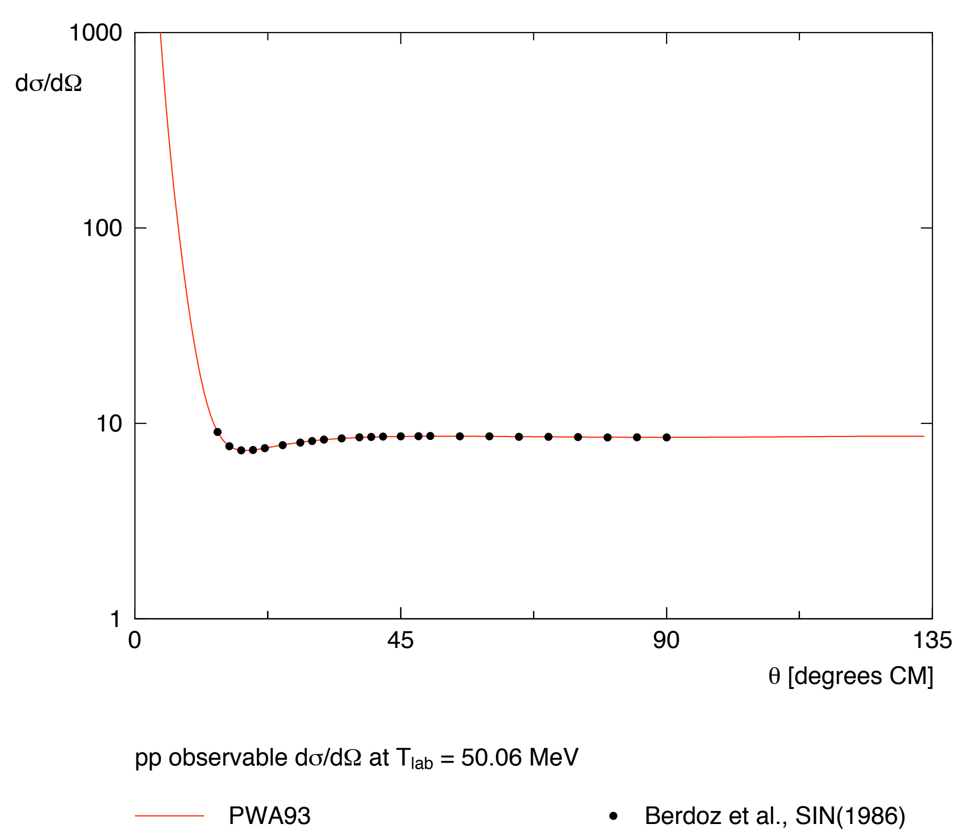
Fig. 3. The ratio $R_4 = (^4_\Lambda H \rightarrow \pi^- + ^4He)/(\text{all } \pi^- \text{ mesonic decays of } ^4_\Lambda H)$ as a function of $p^2/(p^2+s^2)$. The curves illustrate the results of the calculations made by Dalitz and Liu [4] for $J(^4_\Lambda H) = 0$ and 1.

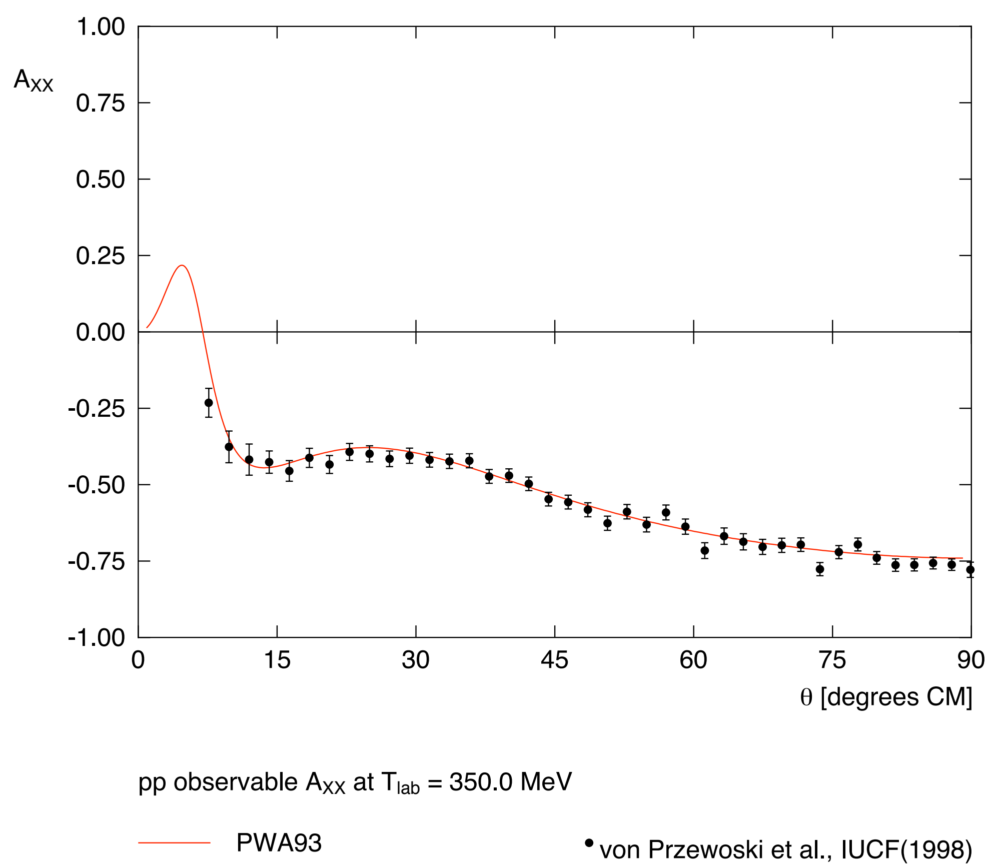
Motivations of Hypernuclear Spectroscopy

- Extract YN and YY interactions
  - difficulties in YN and YY scattering measurements
- Hyperon as an impurity
  - structure change, new symmetry, etc.
- Hyperon in nuclei
  - effective mass, magnetic moment, etc.

Realistic Nuclear Force

- Based on a lot of pp & pn scattering data:
  - ~5900 dσ/dΩ, >2000 Pol., +1700 data



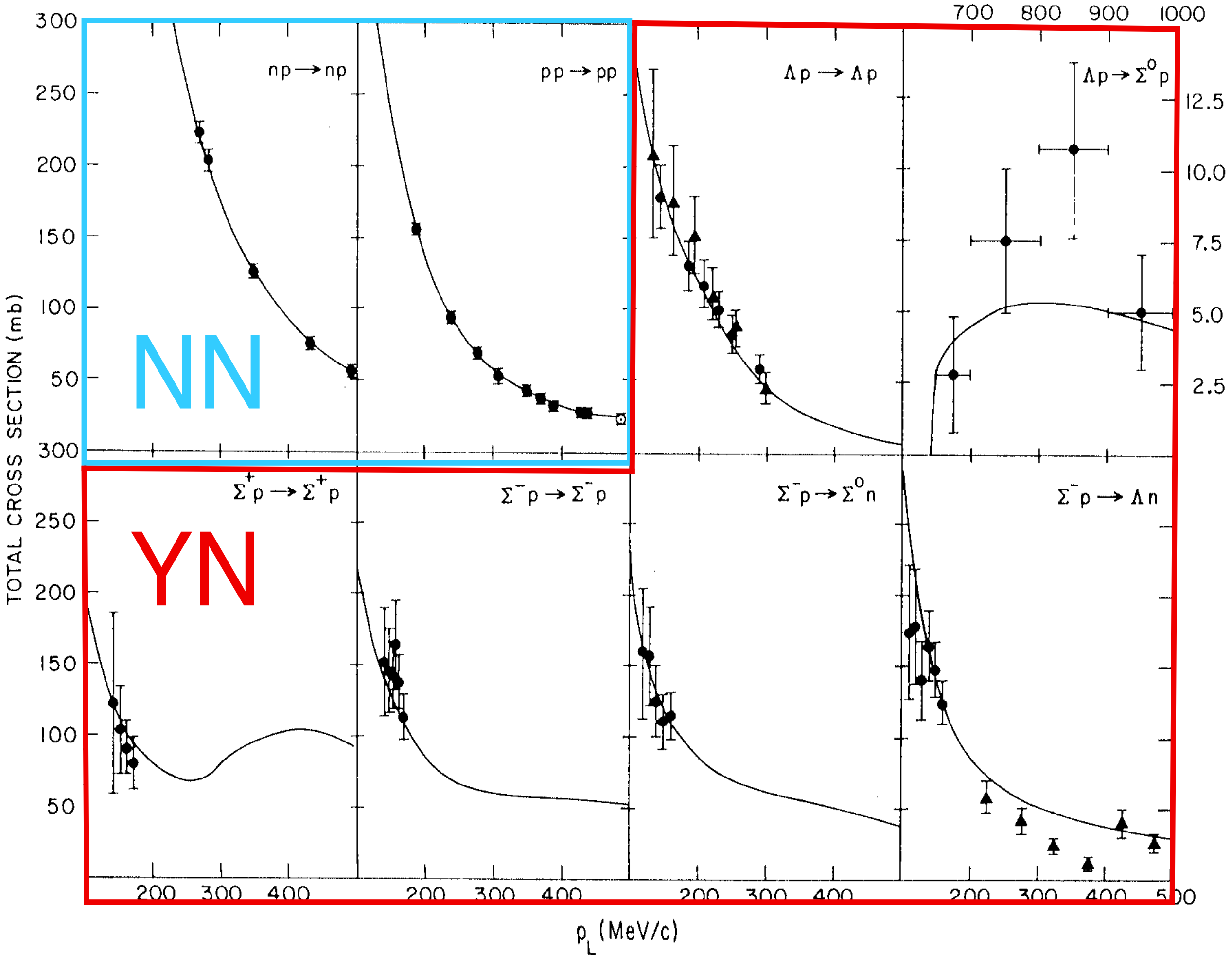


Hyperon-Nucleon Scattering

$\Sigma^{\pm}p$, Λp: only 38 data points

- $\Xi^{-}p$ elastic scattering and $\Xi^{-}p \to \Lambda\Lambda$ reaction
- Asymmmetry in Λp and $\Sigma^{+}p$ elastic scattering

Λ+p, Σ^{+}+p, Σ^{-}+p and Ξ^{-}+p scattering



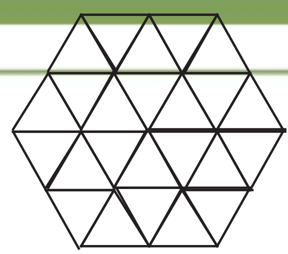
from Dover & Feshbach Ann.Phys.198(90)321

Need high quality data with high statistics

Baryon-Baryon Interaction

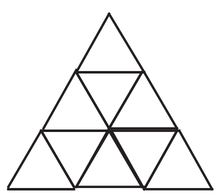
Baryon-Baryon Systems in SU(3)

27 s



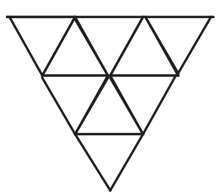
S=0 NN(T=1)
S=-1 ΣN(T=3/2)ΣN−ΛN(T=1/2)
S=-2 ΣΣ(T=2)ΞN−ΣΛ−ΣΣ(T=1)ΞN−ΣΣ−ΛΛ(T=0)
S=-3 ΞΣ(T=3/2)ΞΣ−ΞΛ(T=1/2)
S=-4 ΞΞ(T=1)

10 a



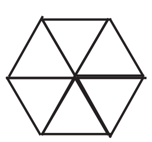
S=0 NN(T=0)
S=-1 ΣN−ΛN(T=1/2)
S=-2 ΞN−ΣΛ(T=1)
S=-3 ΞΣ(T=3/2)

10 a



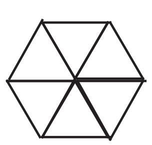
S=−1 ΣN(T=3/2)
S=-2 ΞN−ΣΛ−ΣΣ(T=1)
S=-3 ΞΣ−ΞΛ(T=1/2)
S=-4 ΞΞ(T=0)

8 s



S=−1 ΣN−ΛN(T=1/2)
S=-2 ΞN−ΣΛ(T=1)ΞN−ΣΣ−ΛΛ(T=0)
S=-3 ΞΣ−ΞΛ(T=1/2)

8 a



S=−1 ΣN−ΛN(T=1/2)
S=-2 ΞN−ΣΛ−ΣΣ(T=1)ΞN(T=0)
S=-3 ΞΣ−ΞΛ(T=1/2)

1 s

S=−2 ΞN−ΣΣ−ΛΛ(T=0)

H Dibaryon ?

- Understanding of the flavor SU(3) baryon-baryon interaction
  - Y-N, Y-Y < N-N ?
    Repulsive or Attractive ?
  - Repulsive cores in Y-N/Y-Y ?
    What's the origin ?
  - Spin-dependent forces in Y-N/Y-Y.
  - Dibaryons

Do we understand the Nuclear Force ?

Short-range forces (=repulsive core, LS force) determine the "basic properties of nucleus" (=saturation, magic number).

from textbook by Tamagaki

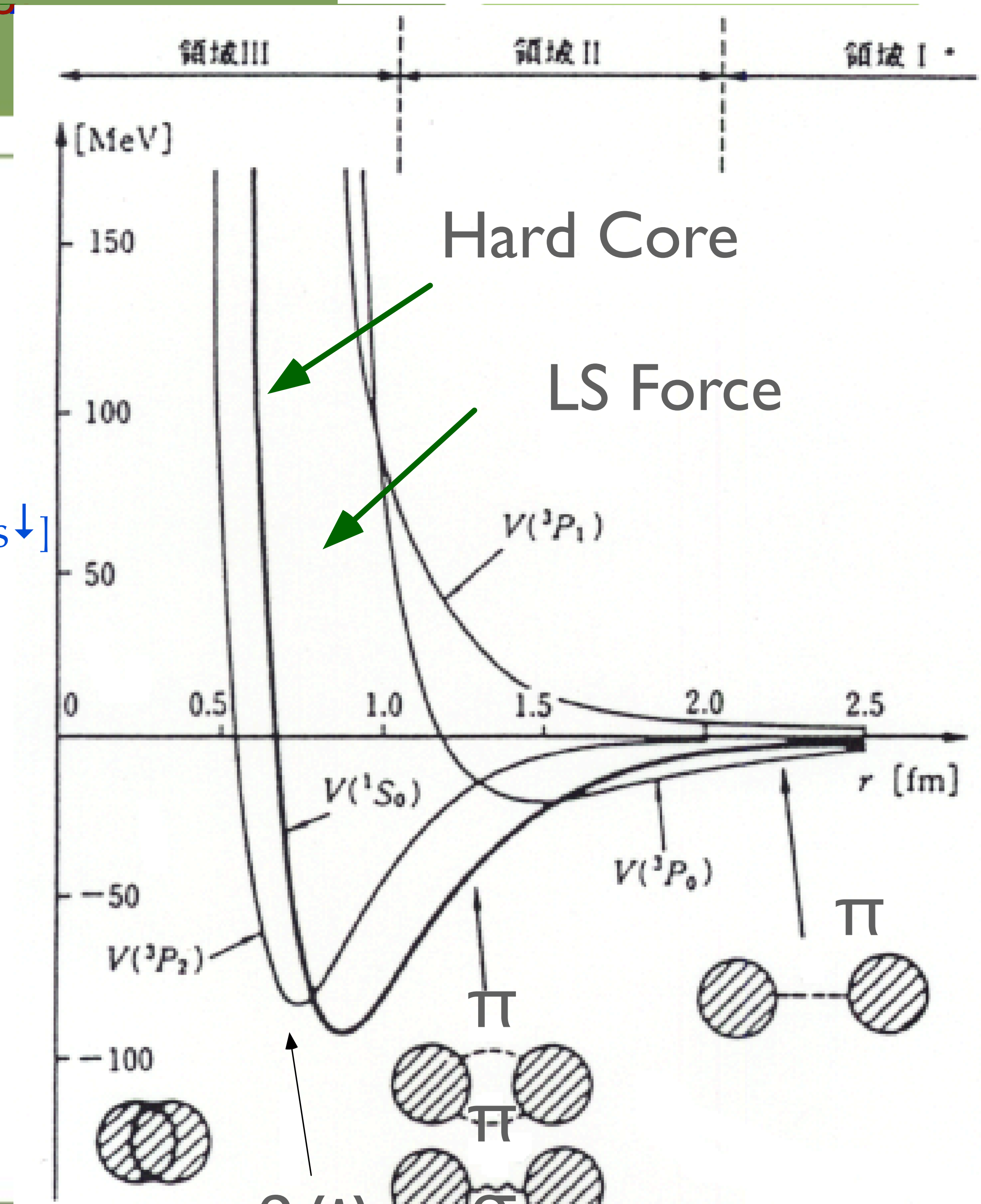
Quark Cluster Model

- NN repulsive core → color magnetic int.
  Δ-N mass difference

  ↓

  H dibaryon ($SU_f(3) \times SU_f(3)$ singlet) [$u^{\uparrow}u^{\downarrow}d^{\uparrow}d^{\downarrow}s^{\uparrow}s^{\downarrow}$]
  = Attractive core in ΛΛ-ΞN channel

- ΣN (I=3/2,S=1) strongly repulsive core
  ← quark Pauli blocking
- LS force → quark gluon exchange
  → Λ : very small
  Σ : as large as N



quark-gluon picture → ← meson exchange picture

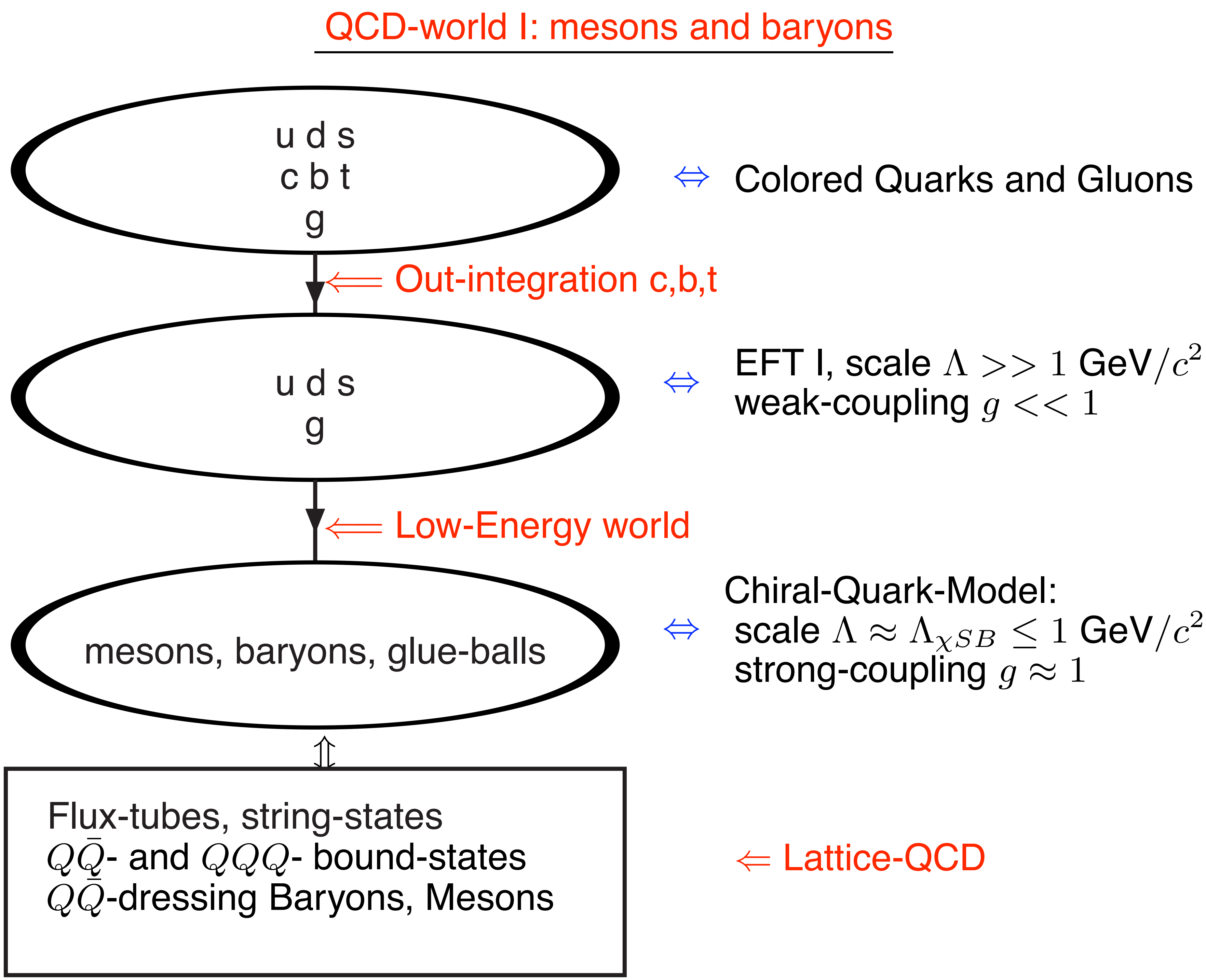
Theory Interest in Flavor Nuclear Physics

- Recent Model building:

1. Nijmegen models: OBE and ESC Soft-core (SC)
   Rijken, Phys.Rev. C73, 044007 (2006)
   Rijken & Yamamoto, Phys.Rev. C73, 044008 (2006)
   Rijken & Yamamoto, arXiv:nucl-th/060874 (2006)
2. Chiral-Unitary Approach model
   Sasaki, Oset, and Vacas, Phys.Rev. C74, 064002 (2006)
3. Jülich Meson-exchange models
   Haidenbauer, Meissner, Phys.Rev. C72, 044005 (2005)
4. Jülich Effective Field Theory models
   Polinder, Haidenbauer, Meissner, Nucl.Phys. A 779, 244 (2006)
5. Quark-Cluster-models: QGE + RGM
   Fujiwara et al, Progress in Part. & Nucl.Phys. 58, 439 (2007)
   Valcarce et al, Rep.Progr.Phys. 68, 965 (2005)

Th.A. Rijken

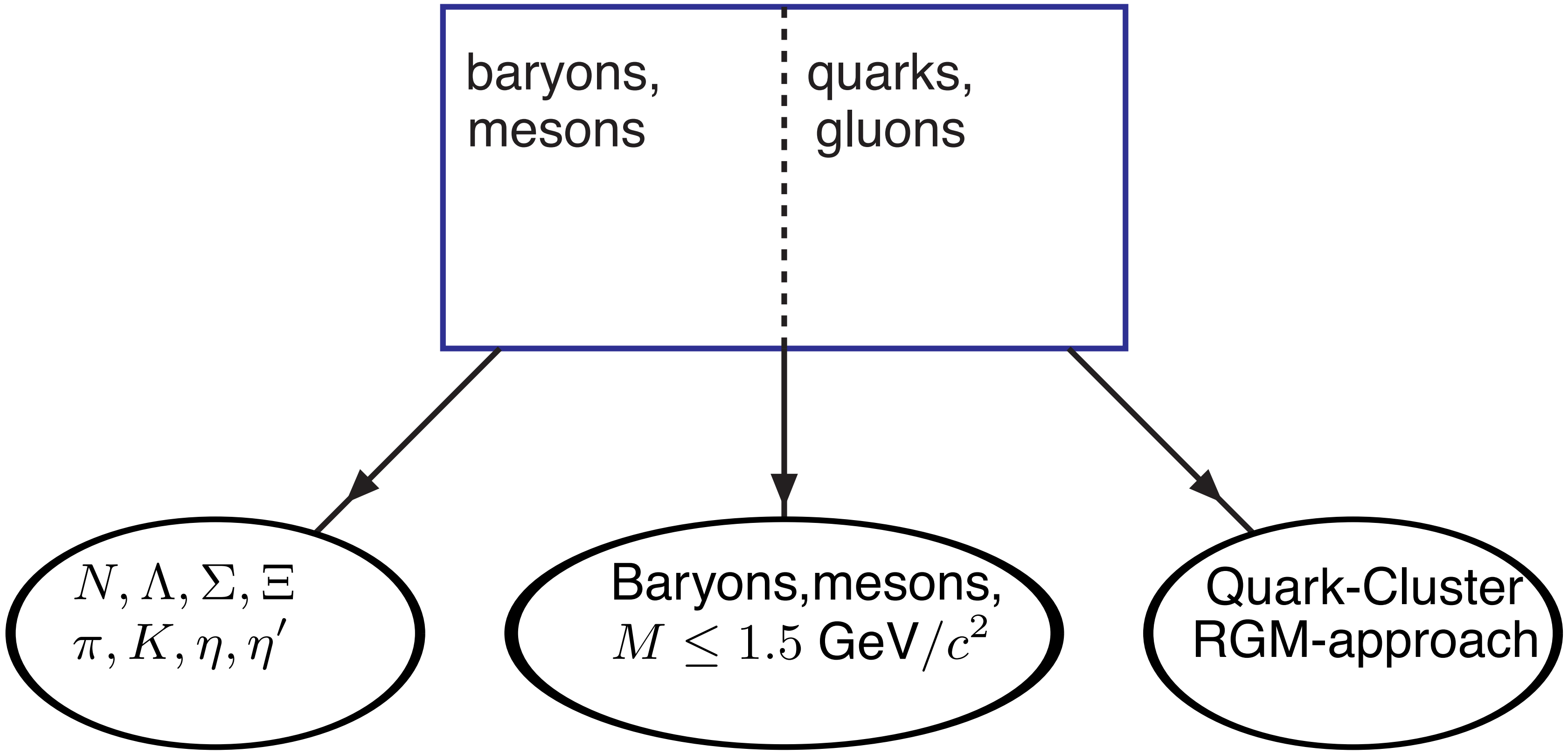
QCd-world I



Th.A. Rijken

QCD-world II

QCD-world II: Baryon/Meson-baryon Interactions



Goldstone-boson exch.
+ contact-terms
Chiral Pert. Models:
Van Kolck, Epelbaum,
Bonn-Jülich, Barcelona, etc.

Meson-exchange models
Nijmegen NSC97, ESC04,
Ehime, Jülich, etc.

Quark-Gluon-
+ OBE-exchange
Tokyo, Kyoto-Niagatta,
Tübingen, Salamanca,
Nanjing, etc.

Th.A. Rijken

Quark Pauli principle

- $(0s)^6$ is not allowed for [51]

$$[222]_c \times [51]_{sf} \times [6]_o \neq [1^6]$$

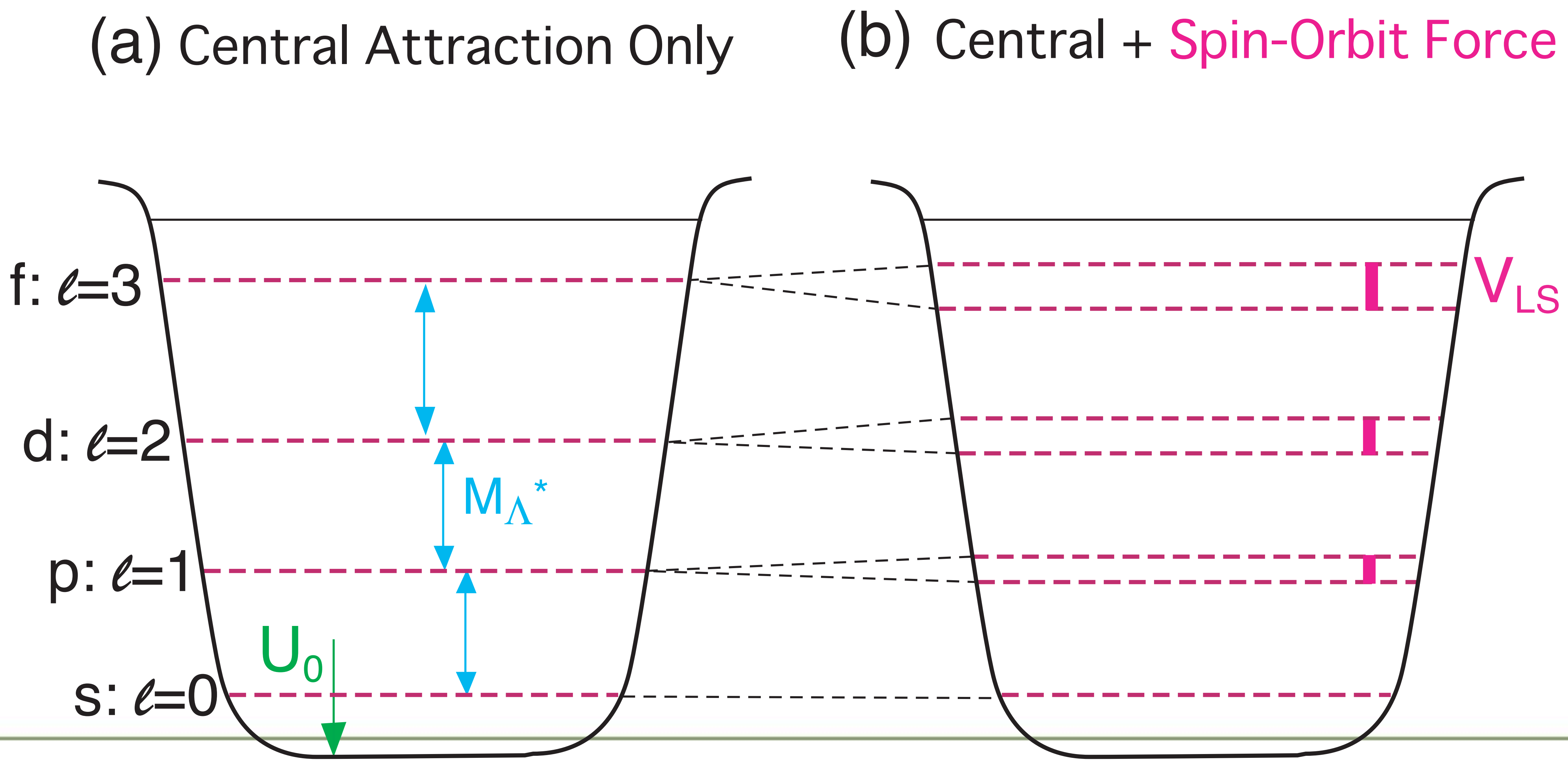
  - n: -|ddu>{2|++->-|+-+>-|-++>}/3$\sqrt{2}$
  - Σ⁻: |dds>{2|++->-|+-+>-|-++>} /3$\sqrt{2}$

$SU(6)_{fs}$-contents of the various potentials on the isospin,spin basis.

	(S,I)	$V = aV_{[51]} + bV_{[33]}$
$NN \to NN$	$(0,1)$	$V_{NN}(I=1) = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$NN \to NN$	$(1,0)$	$V_{NN} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$\Lambda N \to \Lambda N$	$(0,1/2)$	$V_{\Lambda\Lambda} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$\Lambda N \to \Lambda N$	$(1,1/2)$	$V_{\Lambda\Lambda} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$\Sigma N \to \Sigma N$	$(0,1/2)$	$V_{\Sigma\Sigma} = \frac{17}{18}V_{[51]} + \frac{1}{18}V_{[33]}$
$\Sigma N \to \Sigma N$	$(1,1/2)$	$V_{\Sigma\Sigma} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$\Sigma N \to \Sigma N$	$(0,3/2)$	$V_{\Sigma\Sigma} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$\Sigma N \to \Sigma N$	$(1,3/2)$	$V_{\Sigma\Sigma} = \frac{8}{9}V_{[51]} + \frac{1}{9}V_{[33]}$

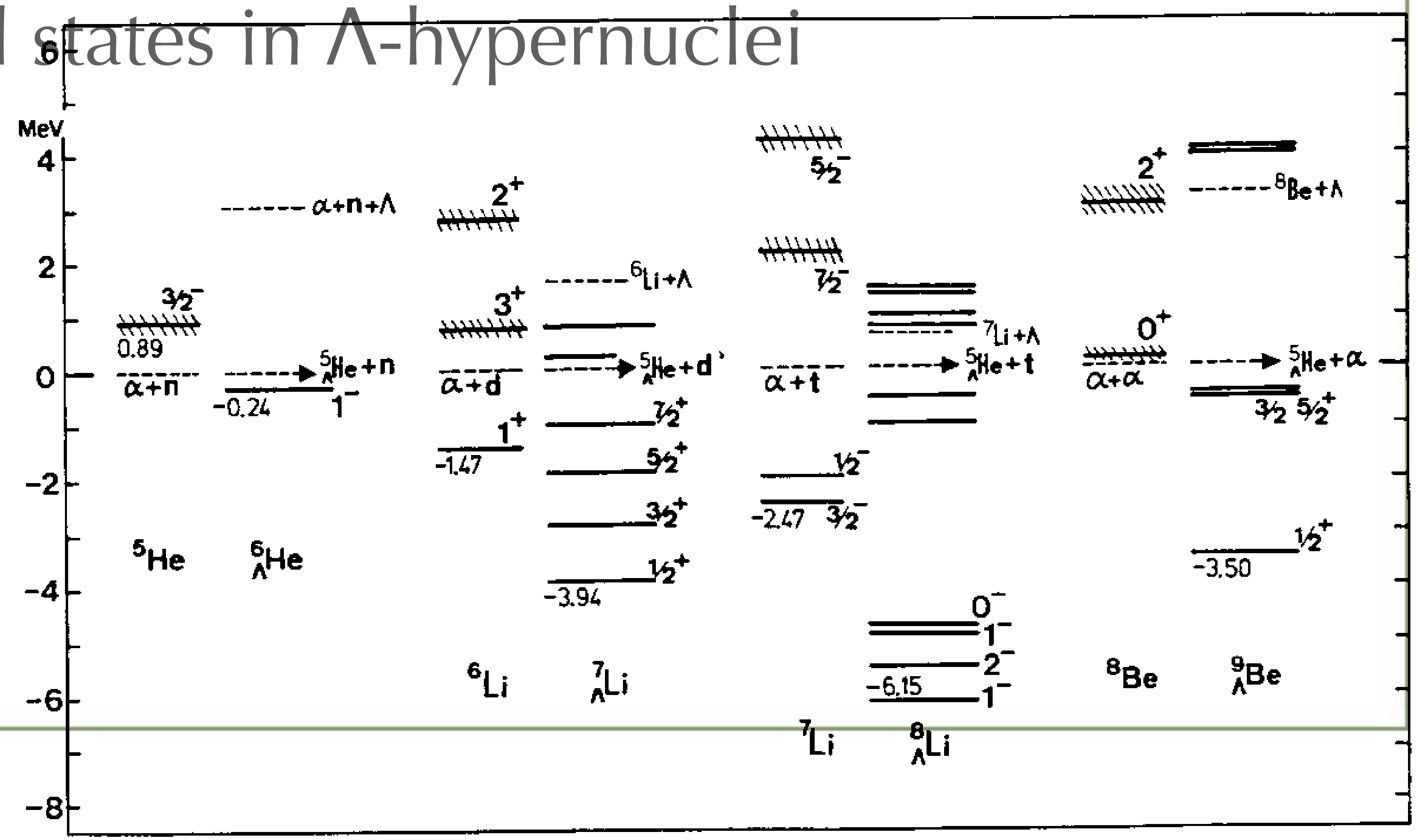
Hypernuclear structure and ΛN interaction

✓ $V_{\Lambda N} = U_O + V_S\, \sigma_N \cdot \sigma_\Lambda + V_\Lambda \ell_{N\Lambda} \cdot \sigma_\Lambda + V_N \ell_{N\Lambda} \cdot \sigma_N + V_T S_{12}$



Impurity Effect - I

- Glue-like role
  - Energetical stabilization
  - Resonant states in neutron-rich nuclei
    →Bound states in Λ-hypernuclei

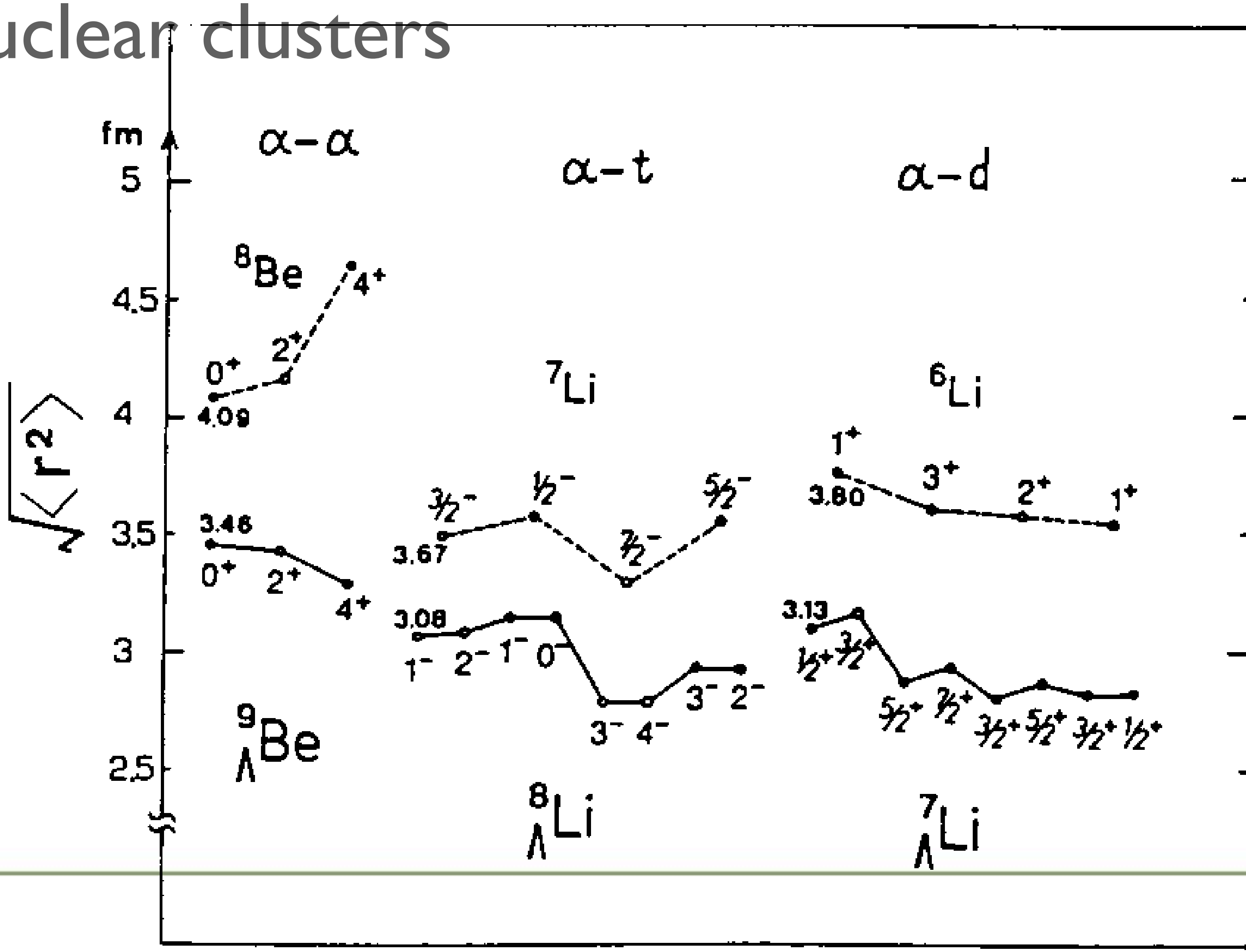


Impurity Effect -2

- Structure Change
  - Shrinkage of nuclear clusters

$B(E2) \propto |\langle f|\, e\, r^2 Y_2\, |i\rangle|^2$

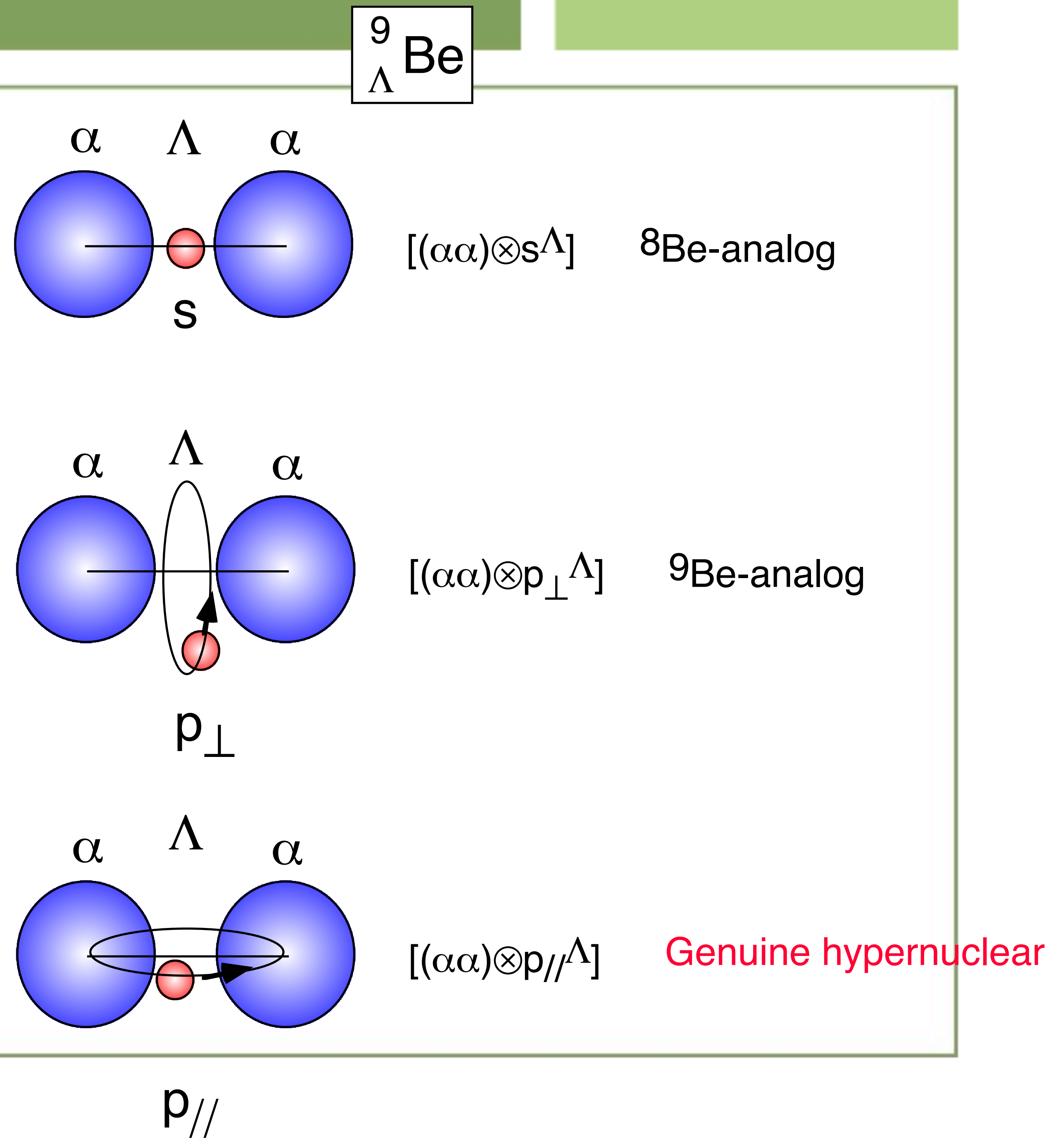
$\propto R^4$ or $(\beta \langle r^2\rangle)^2$



Impurity Effect -3

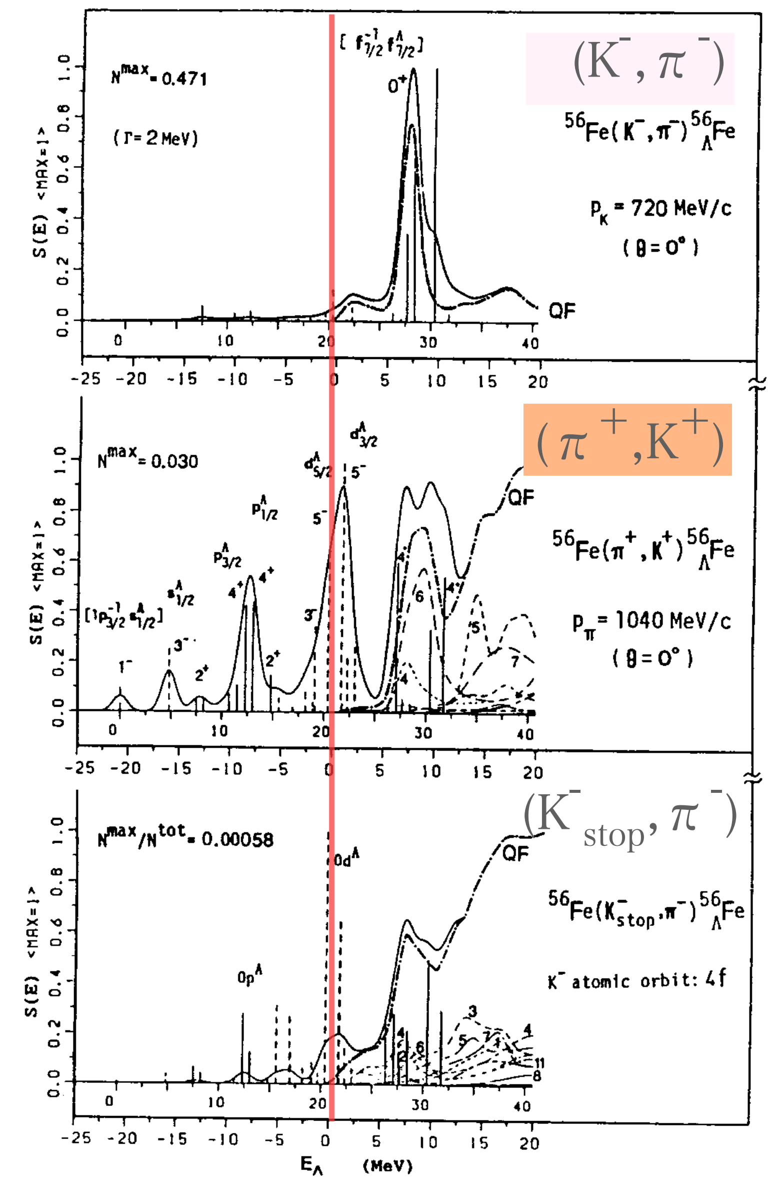
- **New symmetry:**
  - Supersymmetric state or
    Genuine hypernuclear state

$$^{9}Be(\pi^{+}, K^{+})^{9}_{\Lambda}Be$$



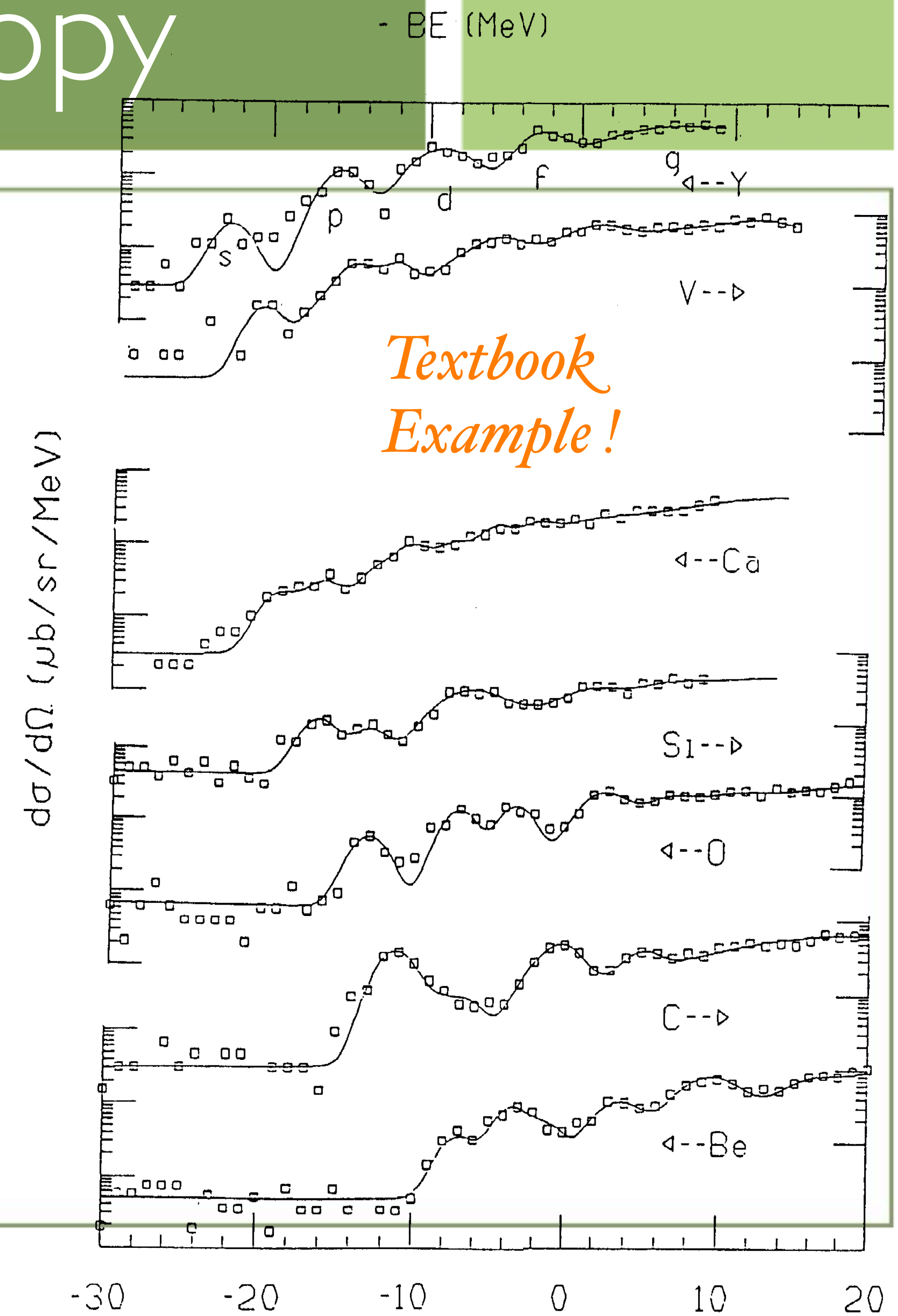
(π^+,K^+) Spectroscopy

- Merits
  - Large momentum transfer q~350 MeV/c
  - Efficiently produces deeply-bound states
  - Low backgrouds: γ , n
- Demerits
  - No difference in angular distributions

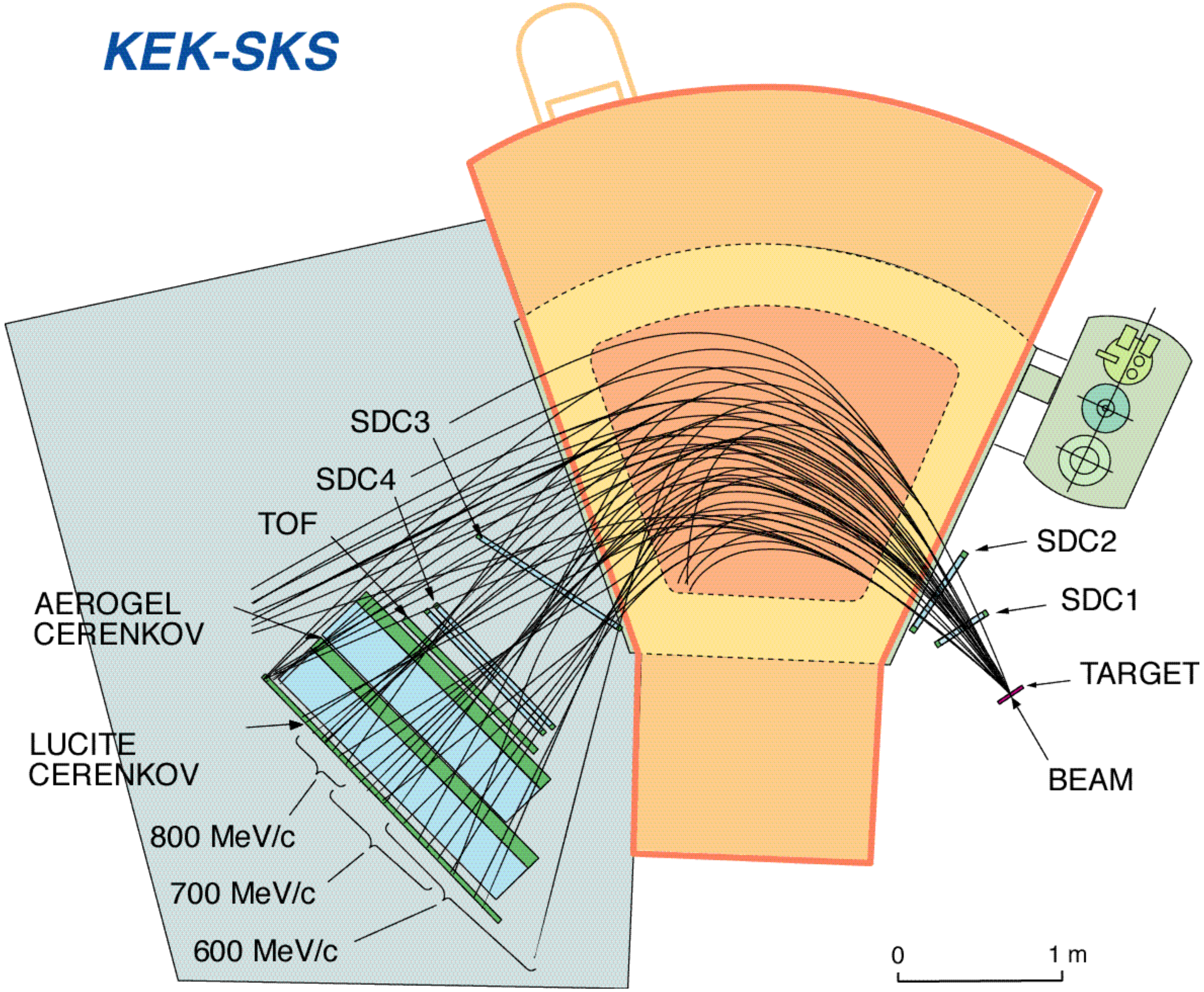


(π^+,K^+) Spectroscopy

- Reaction mechanism:
  - Dover, Ludeking, Walker, Phys. Rev. C22(1980) 2073.
- Success at BNL(1985, 1988)
  - ΔE~3 MeV
  - Up to $^{89}{}_{\Lambda}$Y
- q~350 MeV/c
  - natural-parity stretched states
  - $[(\ell_N j_N)^{-1}(\ell_\Lambda j_\Lambda)]$ with $J=\ell_N+\ell_\Lambda$



SKS spectrometer at KEK-PS



- Superconducting Kaon Spectrometer for the (π^+, K^+) reactions
- Constructed by INS, Univ. of Tokyo, from 1987 to 1990
- In operation since 1992

- B_{max}=3T(500A)
- Pole Gap=50 cm
- 10.6 MJ stored
- Cold Mass ~4.5 t
- ~280 tons

Design Specifications of the SKS

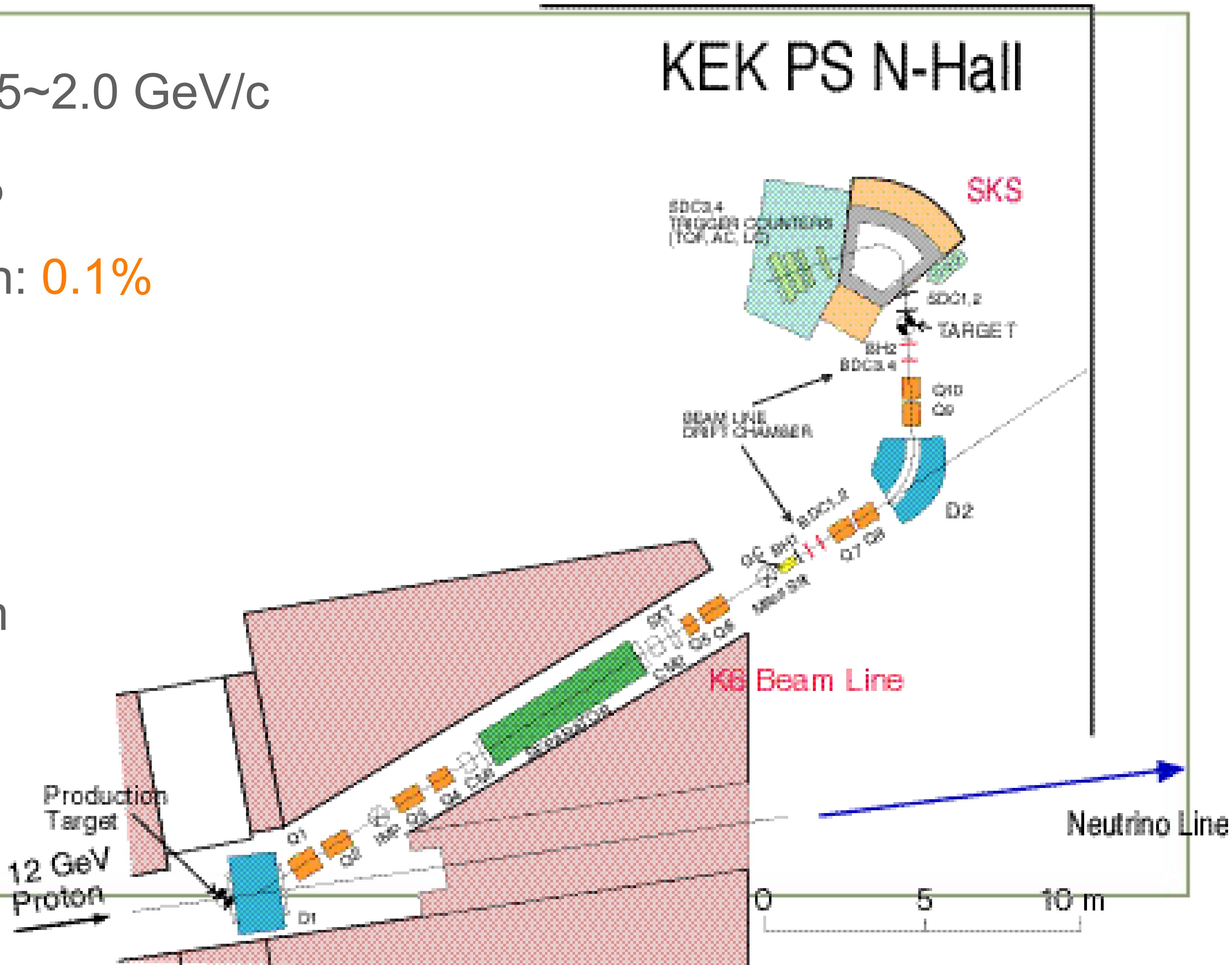
- Momentum resolution:
  0.1%(FWHM) at 720 MeV/c
- Solid angle: 100 msr
  - To get enough yields
- Short Flight Path: ~5 m
  - To reduce K^+ decays
- Initial Goal of Energy Resolution:
  2 MeV(FWHM)

K6 Beam Line for the SKS

- Momentum range: 0.5~2.0 GeV/c
- Momentum bite: ±3%
- Momentum resolution: 0.1% (FWHM)

  QQDQQ system
- Acceptance: 1.9 msr
- Channel length: 30 m
- ~2x10^6 π^+/spill

  at 1 GeV/c



Challenges in the SKS

- Good Energy Resolution: <2 MeV(FWHM)
- Magnetic Field Mapping: $\Delta B/B<10^{-3}$
  - Fully automated 3D positioning system
    - (120,000points x 7excitations) in 1.5 months
  - Very careful calibrations
- 3 T magnet with very low heat leak
- He transfer line with rotation capability

Momentum resolution

- K6 Beamline
  - Matrix representations for magnets
  - <x'| θ >~0
  - Resolution in 1st order

$$\vec{x}'_{out} = QQDQQ\vec{x}_{in}$$

$$\vec{x} = \left(x, y, \theta \equiv dx/dz, \varphi \equiv dy/dz, \delta \equiv (p - p_0)/p_0\right)$$

$$\frac{\langle x' | x \rangle \sigma_x}{\langle x' | \delta \rangle}$$

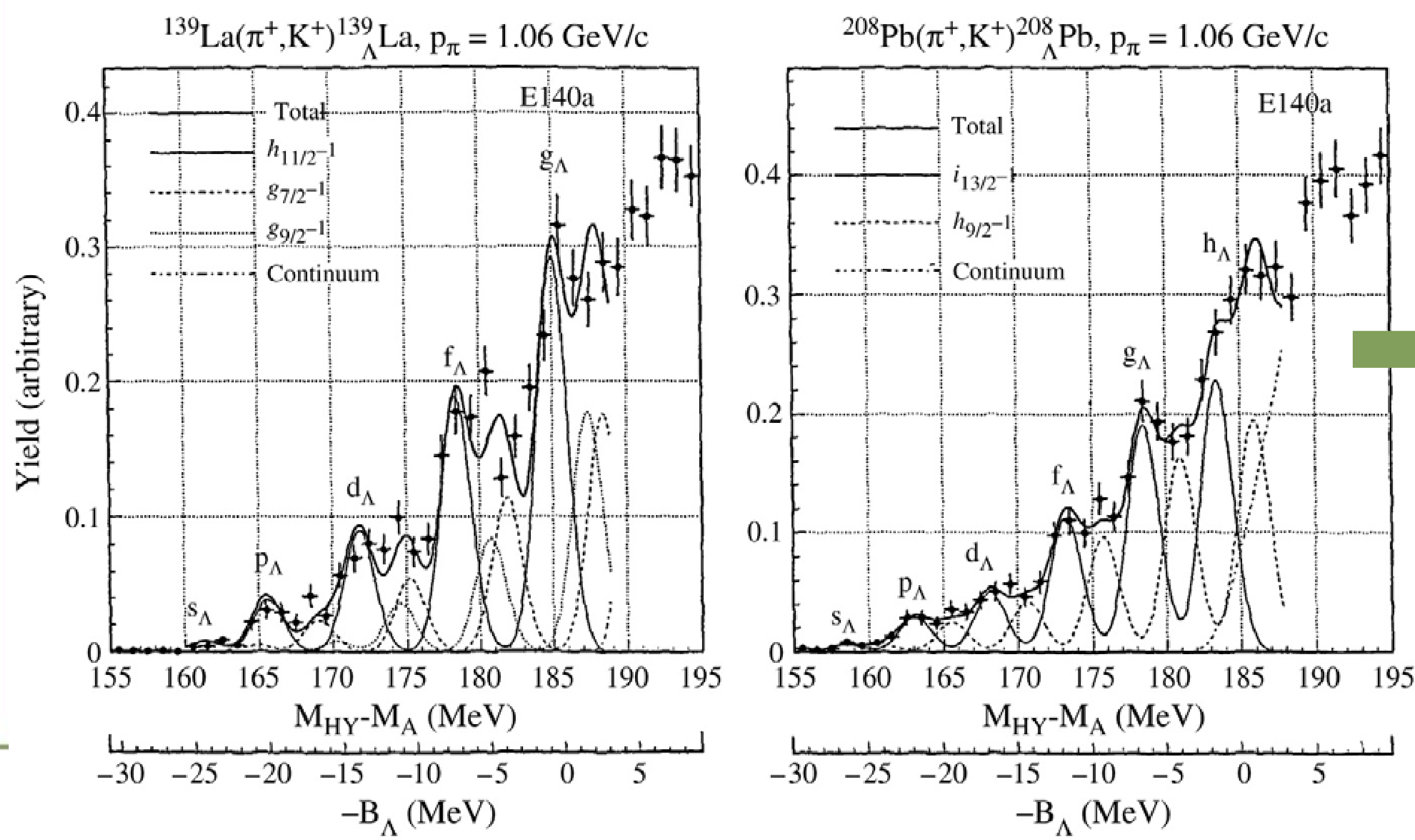
$$QQDQQ = \begin{pmatrix} \langle x'|x\rangle & \langle x'|y\rangle & \langle x'|\vartheta\rangle & \langle x'|\varphi\rangle & \langle x'|\delta\rangle \\ \langle y'|x\rangle & \langle y'|y\rangle & \langle y'|\vartheta\rangle & \langle y'|\varphi\rangle & \langle y'|\delta\rangle \\ \langle \vartheta'|x\rangle & \langle \vartheta'|y\rangle & \langle \vartheta'|\vartheta\rangle & \langle \vartheta'|\varphi\rangle & \langle \vartheta'|\delta\rangle \\ \langle \varphi'|x\rangle & \langle \varphi'|y\rangle & \langle \varphi'|\vartheta\rangle & \langle \varphi'|\varphi\rangle & \langle \varphi'|\delta\rangle \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

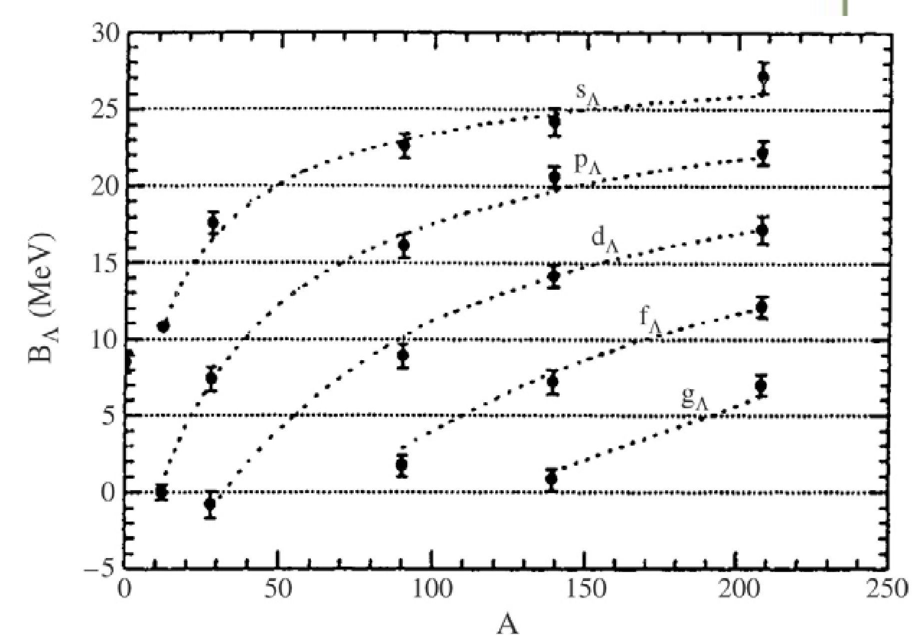
(π,K^{+}) experiments with SKS

- E140a: ^{10}B, ^{12}C, ^{28}Si, ^{89}Y, ^{139}La, ^{208}Pb
  - Phys. Rev. C 53 (1996) 1210.
- E336: ^{7}Li, ^{9}Be, ^{13}C, ^{16}O
  - Nucl. Phys. A 639 (1998) 93c, Nucl. Phys. A 691 (2001) 123c.
- E369: ^{89}Y, ^{51}V, ^{12}C in high-resolution
  - Phys. Rev. C 64 (2001) 044302.
- E521: $^{10}B(\pi^{-}, K^{+})$
  - Phys. Rev. Lett. 94 (2005) 052502.

E140a: First (π^+,K^+) exp. with the SKS

- Targets: ^{10}B, ^{12}C, ^{28}Si, ^{89}Y, ^{139}La, ^{208}Pb
  - $^{12}{}_{\Lambda}$C: First observation of core-excited states
  - Confirmed Λ Shell Structures up to $^{208}{}_{\Lambda}$Pb



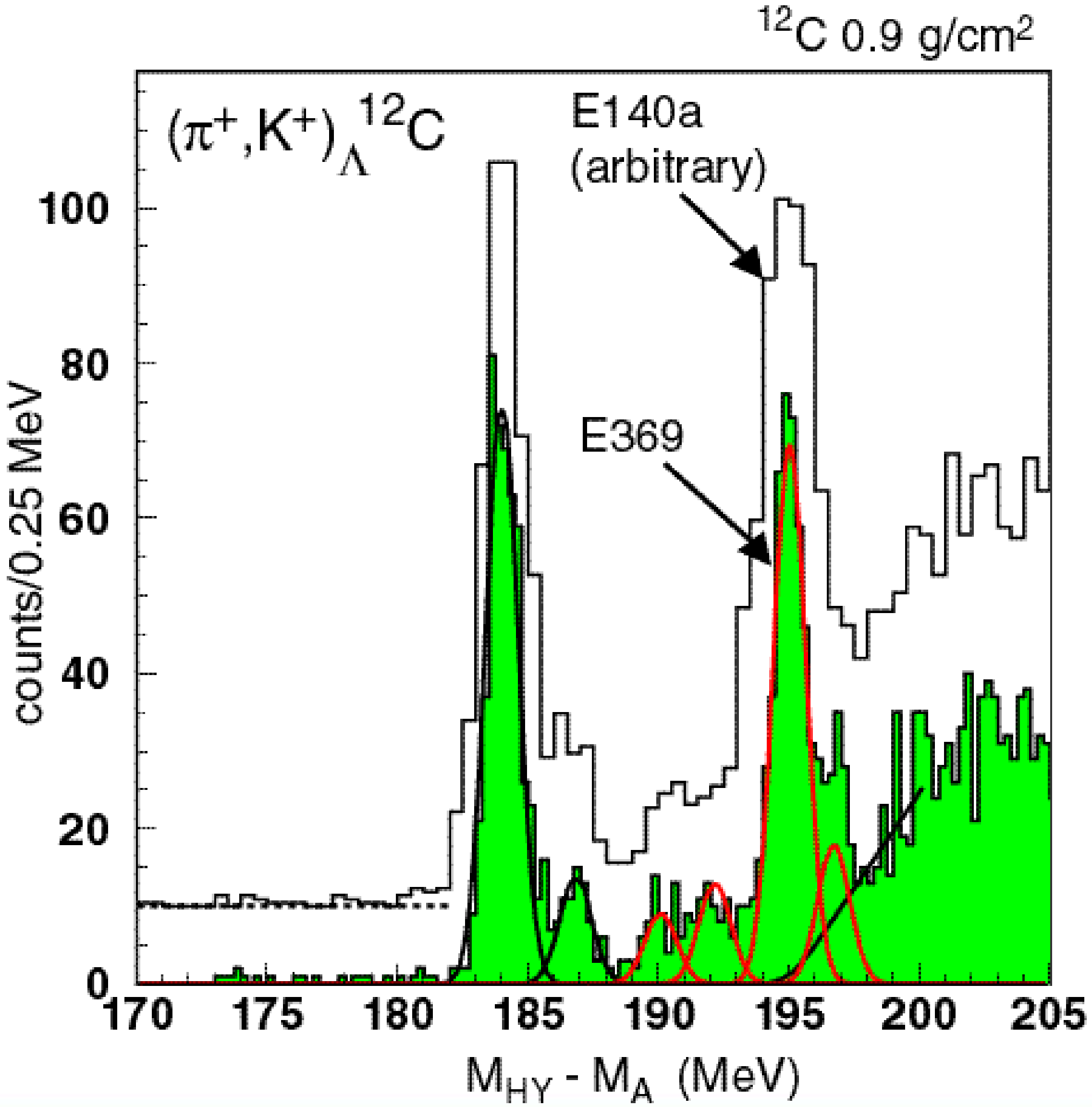


T.Hasegawa et al., Phys. Rev. C53 (1996) 1210

E369: $_{\Lambda}{}^{12}C$

- Best energy resolution
- ΔE(FWHM) =1.45 MeV

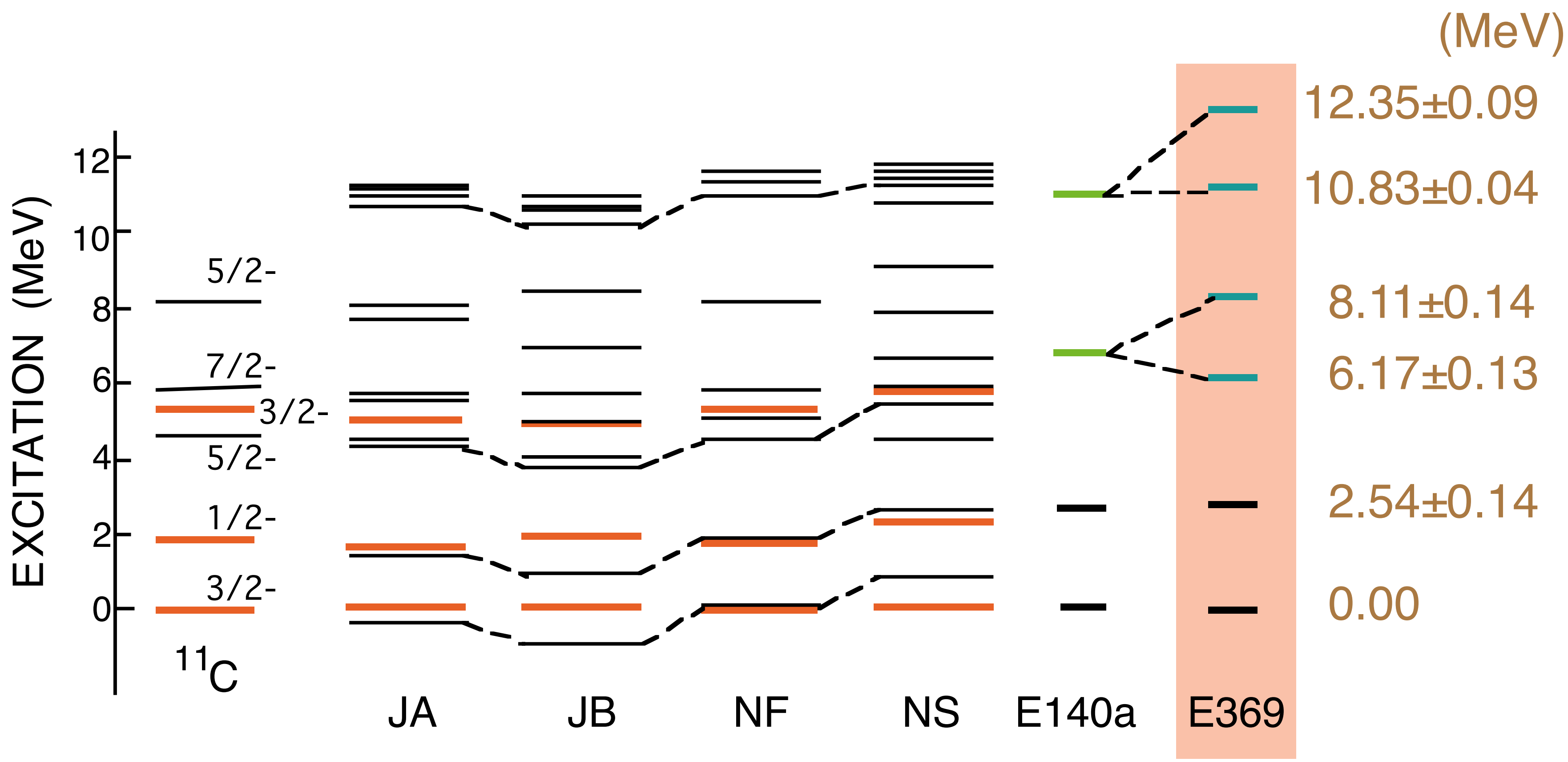
2.0 MeV



Core-excited states of $_{\Lambda}^{12}C$

- New states are resolved.

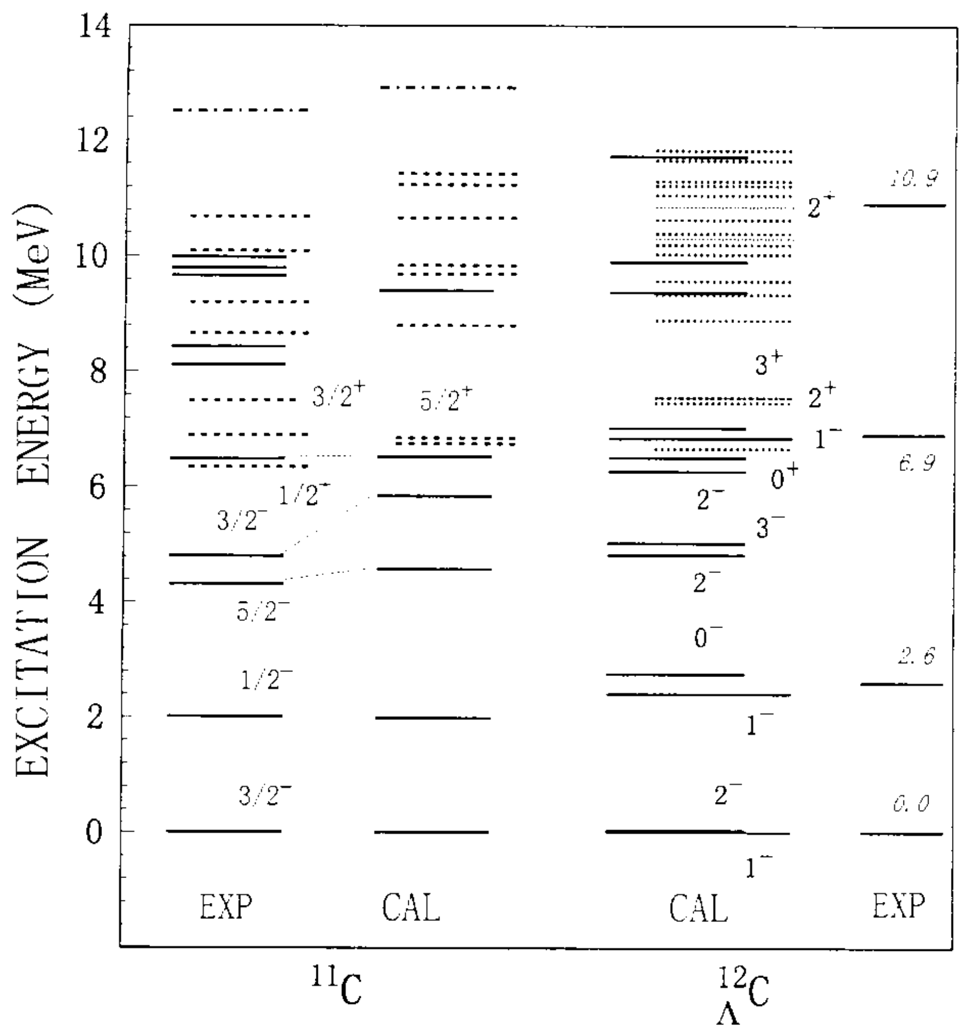
Effects of ΛN spin-dependent forces



Parity-mixing intershell coupling

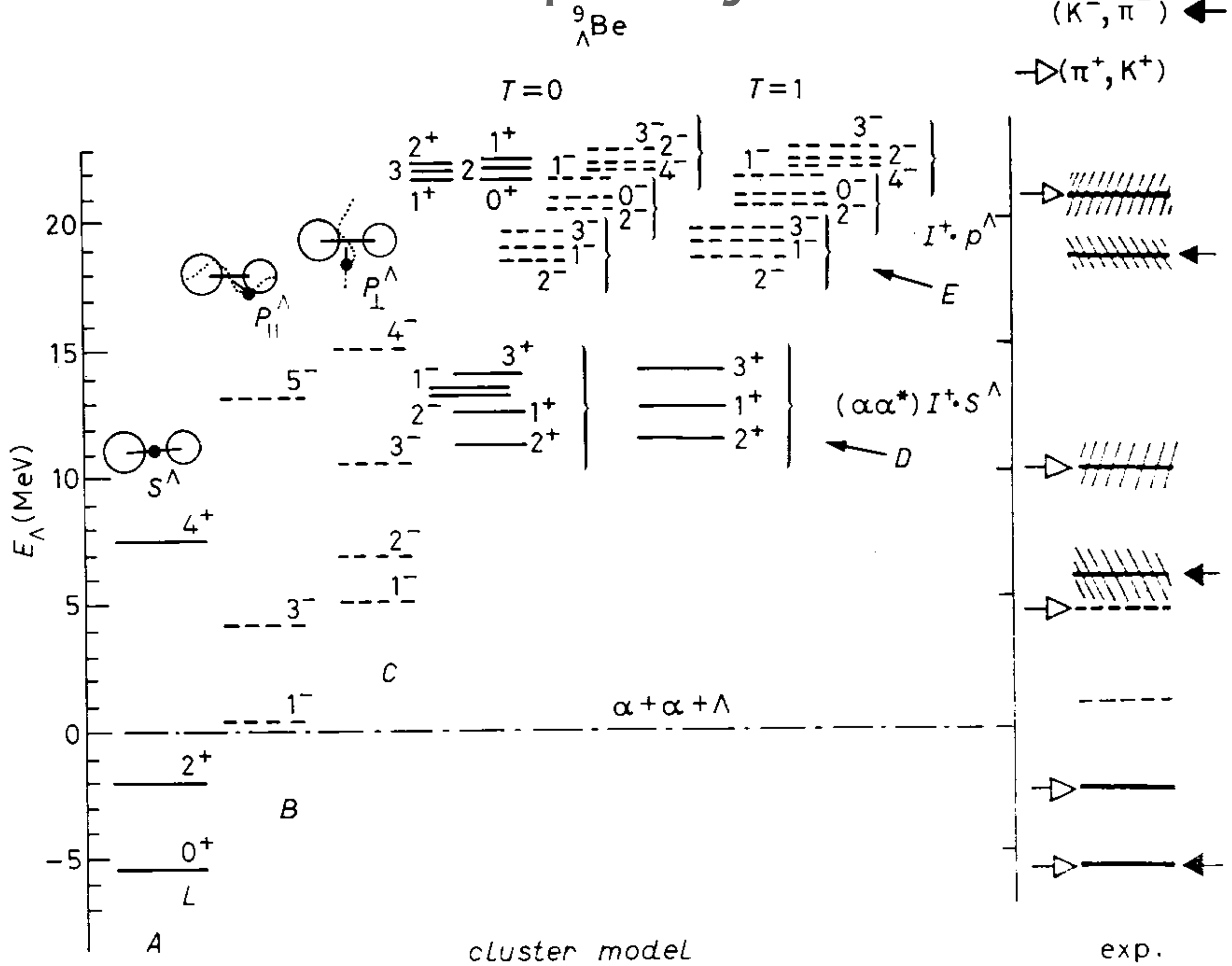
- T. Motoba, in HYP97(Nucl. Phys. A 639 (1998) 135c.)

$$\left|{}^{12}_{\Lambda}C;J^{+}\right\rangle = \left[s^4p^7\right]_- \otimes 1p^{\Lambda} + \left\{\left[s^4p^6(sd)^1\right]_+ + \left[s^3p^8\right]_+\right\} \otimes 1s^{\Lambda}$$

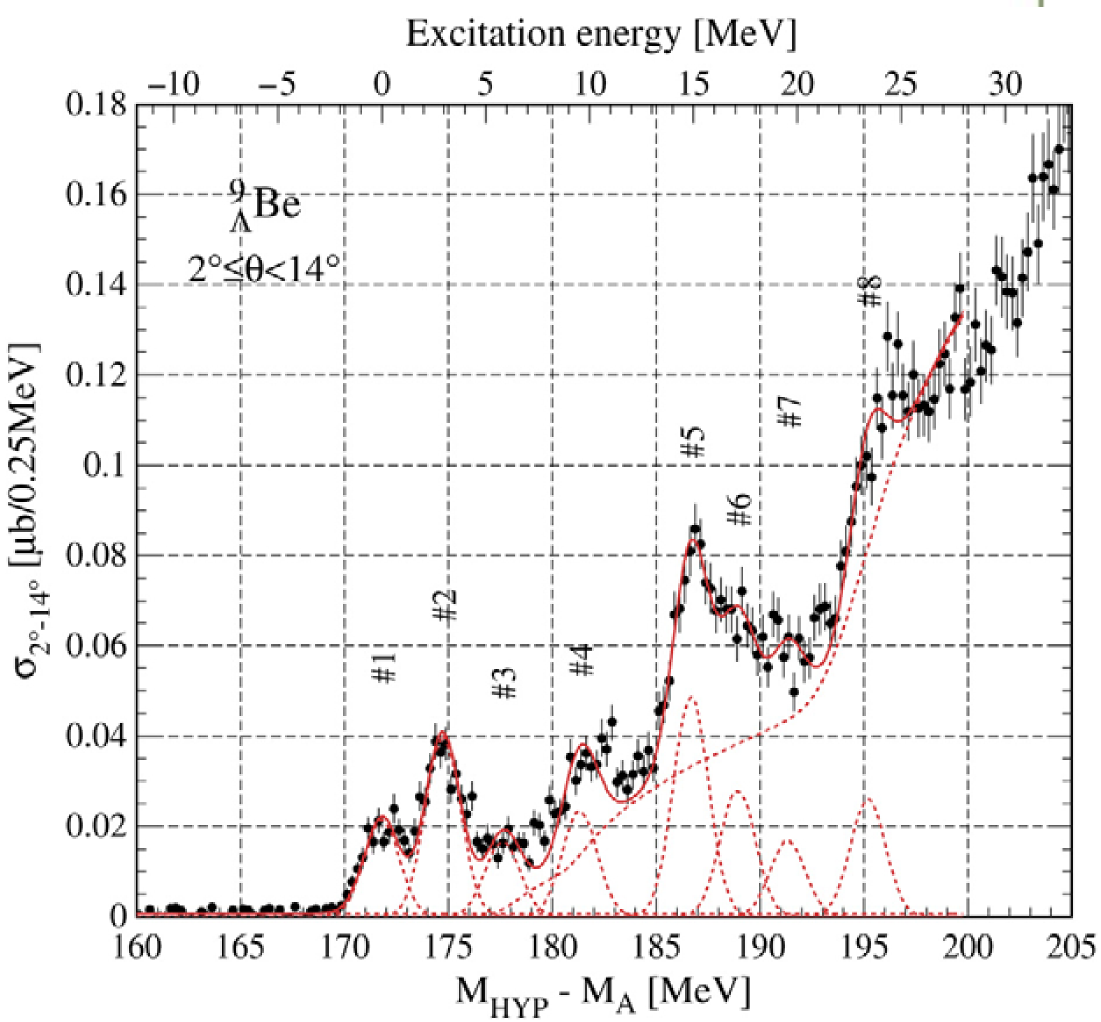


E336: $^{9}_{\Lambda}$Be

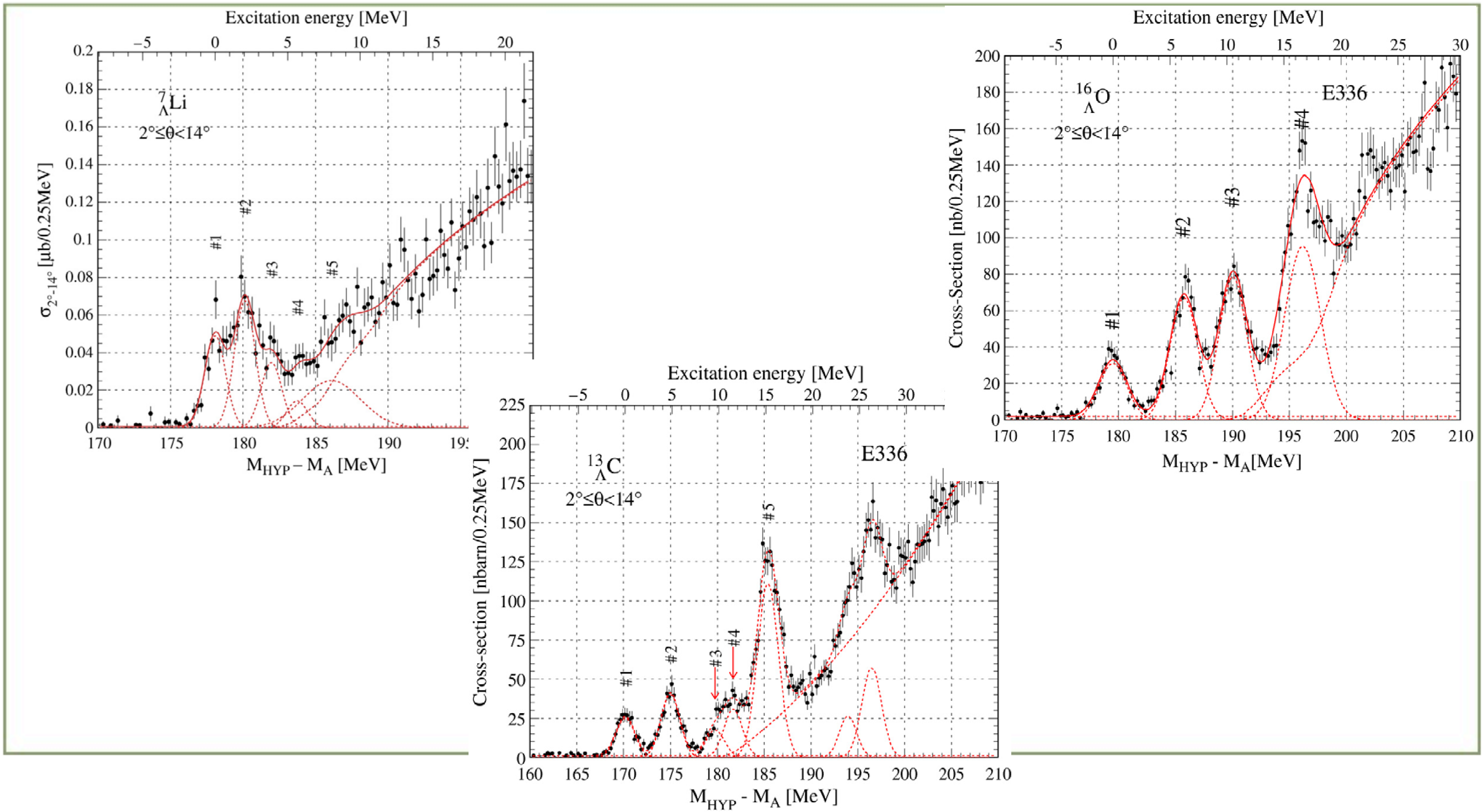
- Observation of “genuine” hypernuclear states or “Supersymmetric” states



T.Motoba, Il Nuovo Cim. 102A (1989) 345.

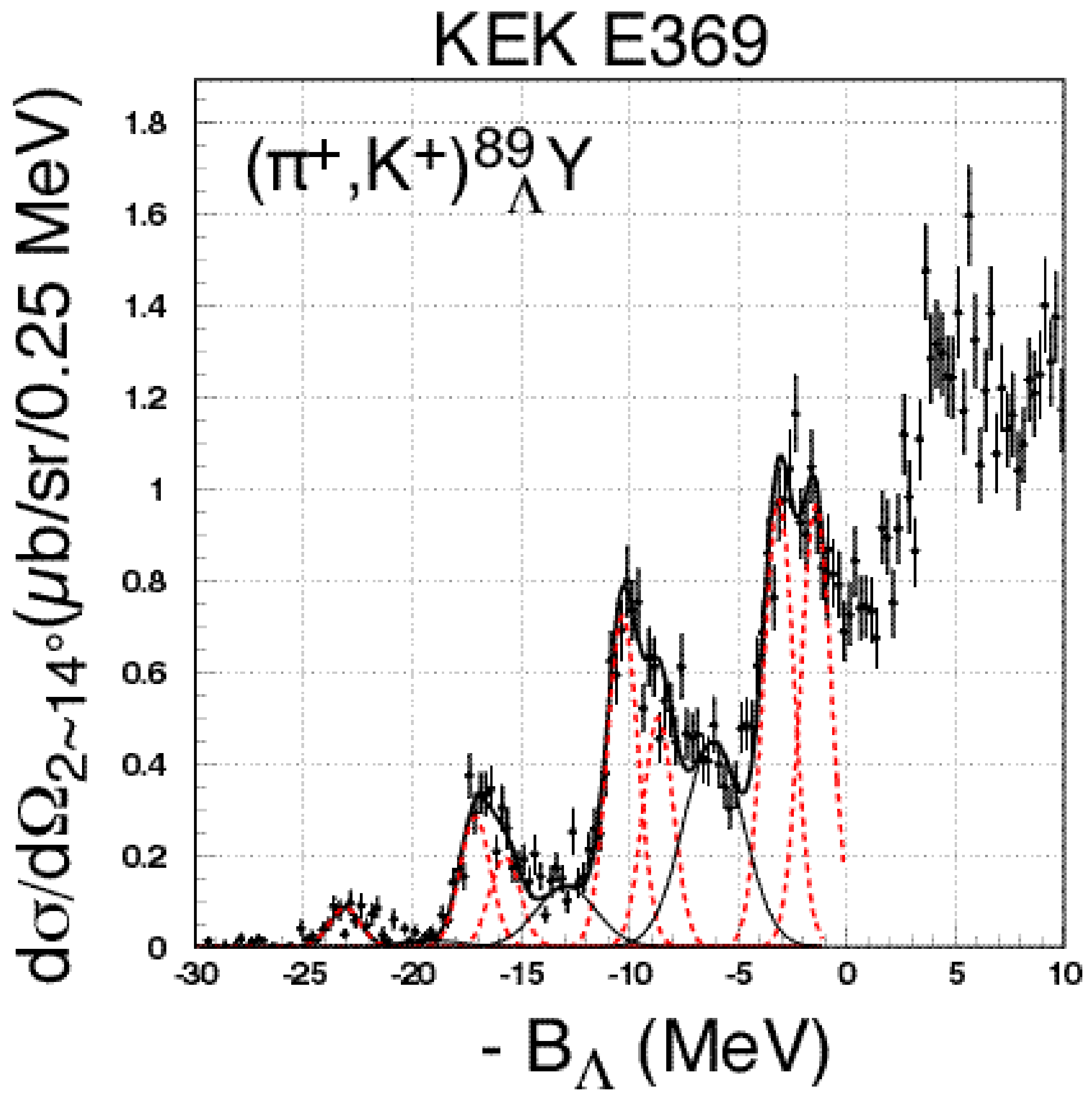


E336: $_{\Lambda}^{7}Li$, $_{\Lambda}^{13}C$, $_{\Lambda}^{16}O$



E369: $_\Lambda^{89}Y$

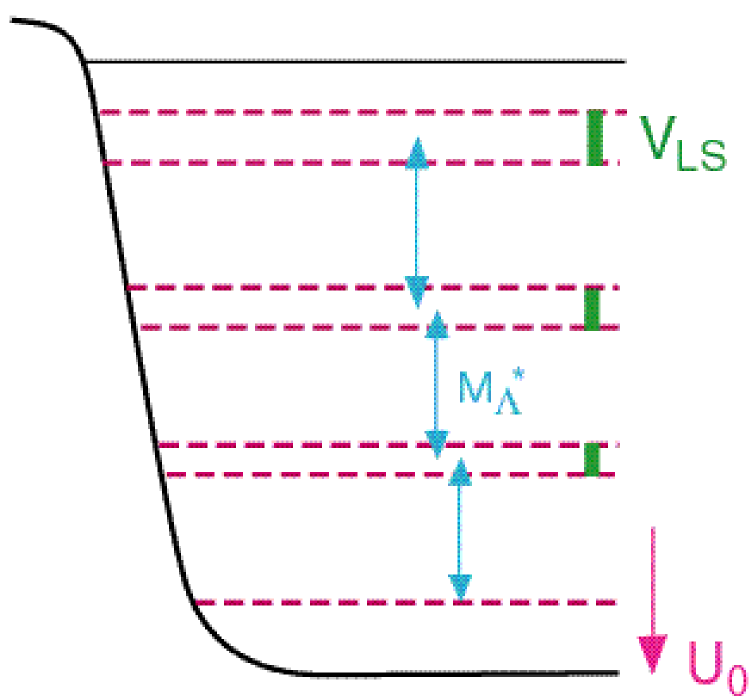
- $B_{\Lambda s}$=23.1±0.1 MeV
- Energy Splitting
  - ΔE_f=1.70±0.10 MeV
  - ΔE_d=1.63±0.14 MeV
  - ΔE_p=1.37±0.20 MeV
- Peak Ratio
  - R/L_f=0.99±0.07
  - R/L_d=0.69±0.06
- Extra n-hole at +4.1±0.1 MeV, width=3.2±0.2 MeV



Single-particle motion of Λ in heavy hypernuclei

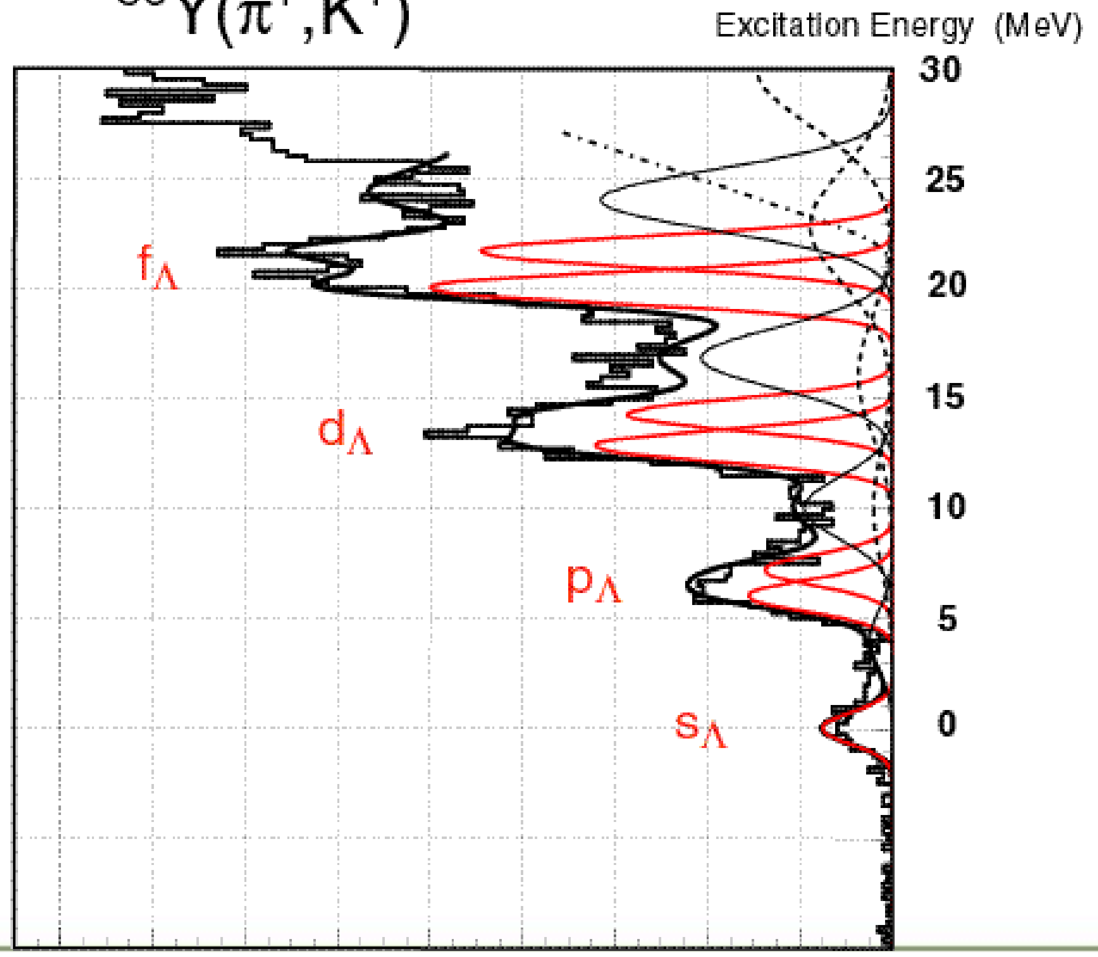
- U_0=-30.5 MeV
- M_Λ^*=0.7~0.8xM_Λ

by Y.Yamamoto



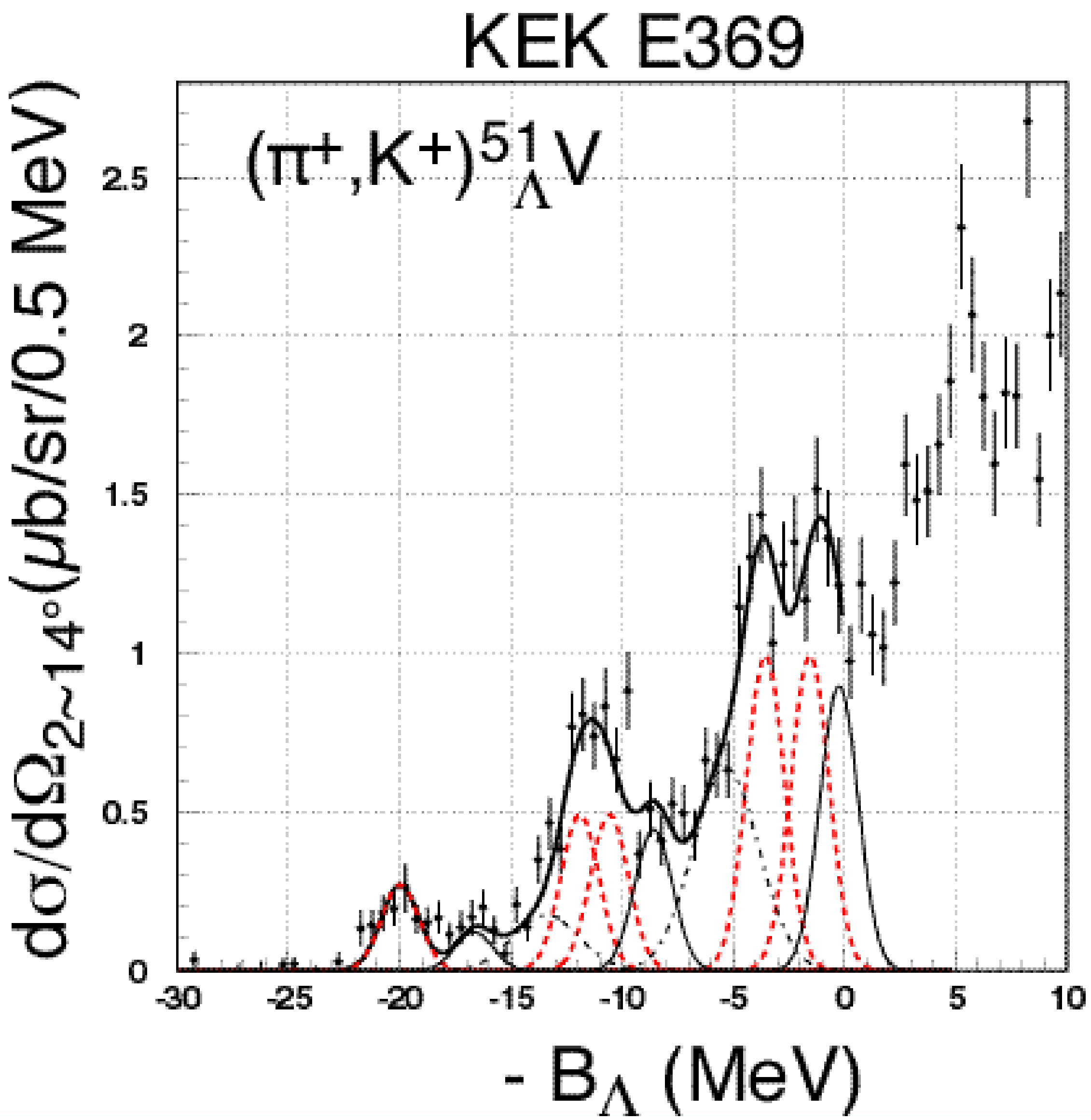
KEK E369

$^{89}Y(\pi^+,K^+)$



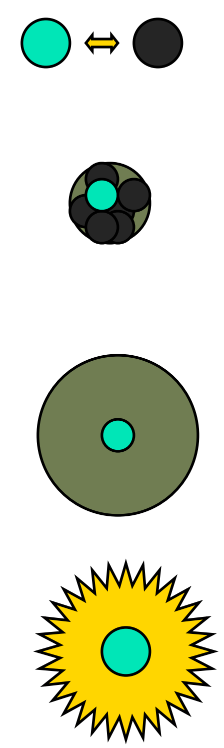
E369: $_{\Lambda}^{51}V$

- Splitting in d-(and p-) orbit(s)
- $B_{\Lambda s}$=(20±0.13)+0.56 MeV
- Width=1.95 MeV
- Peak Ratio=1(fixed)
  - Extra n-holes
    - At +3.3±0.2 MeV, width=1.95 MeV
    - At +6.6±0.2 MeV, width=3.46 MeV



Heavy Λ-Hypernuclei

- *A bridge to strange matter*
  - 2-body Y-N interaction
    - Baryon-baryon interactions in $SU(3)_f$
    - Short range part: meson picture or quark picture ?
  - Light hypernuclei (A<~20)
    - Fine structure ⟷ Spin-dependent interactions
    - Cluster structure
  - Heavy hypernuclei (A>~80)
    - Single-particle potential: $U_0(r)$, $m_\Lambda^*(r)$, $V_{\Lambda NN}$, ...
  - Neutron star (A~10^{57}): $\rho > 5\ \rho_0$
    - Hyperonization → Softening of E.O.S.
    - Superfluidity

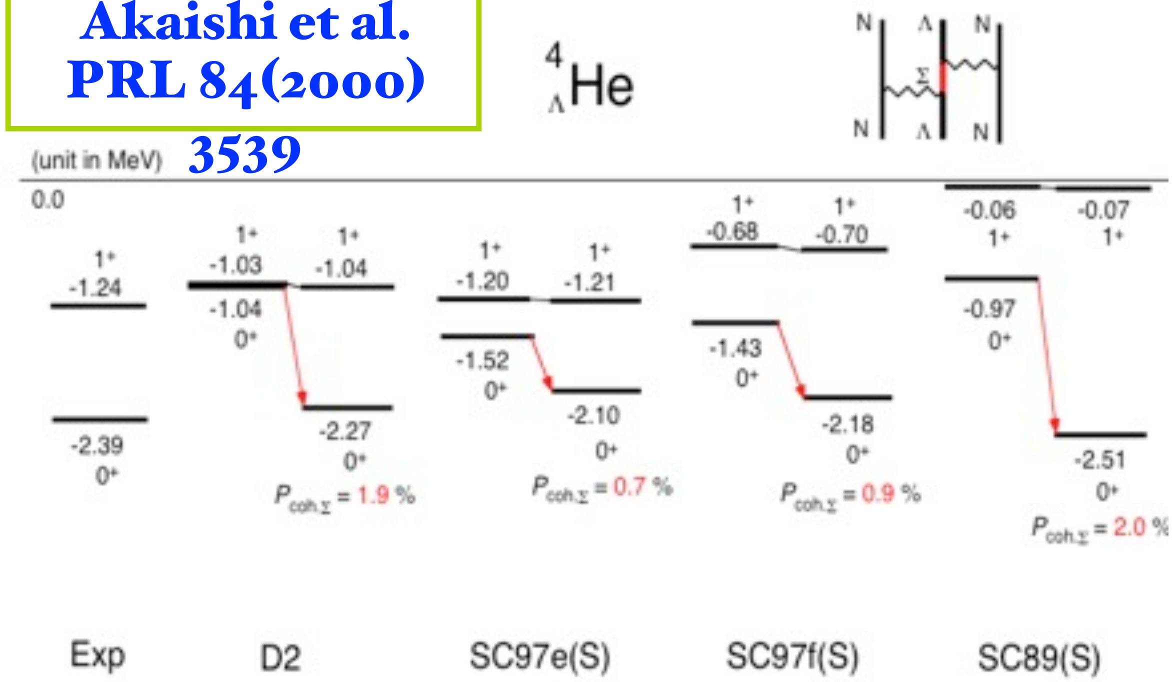


E521: Production of neutron-rich Λ hypernuclei by the (π^-, K^+) double-charge-exchange reaction

A pilot experiment for spectroscopic studies of the neutron-rich Λ hypernuclei via the (π^-, K^+) reaction

Production cross section/ Background (sensitivity)
⇒ Understanding of the Reaction Mechanism

Akaishi et al. PRL 84(2000) 3539



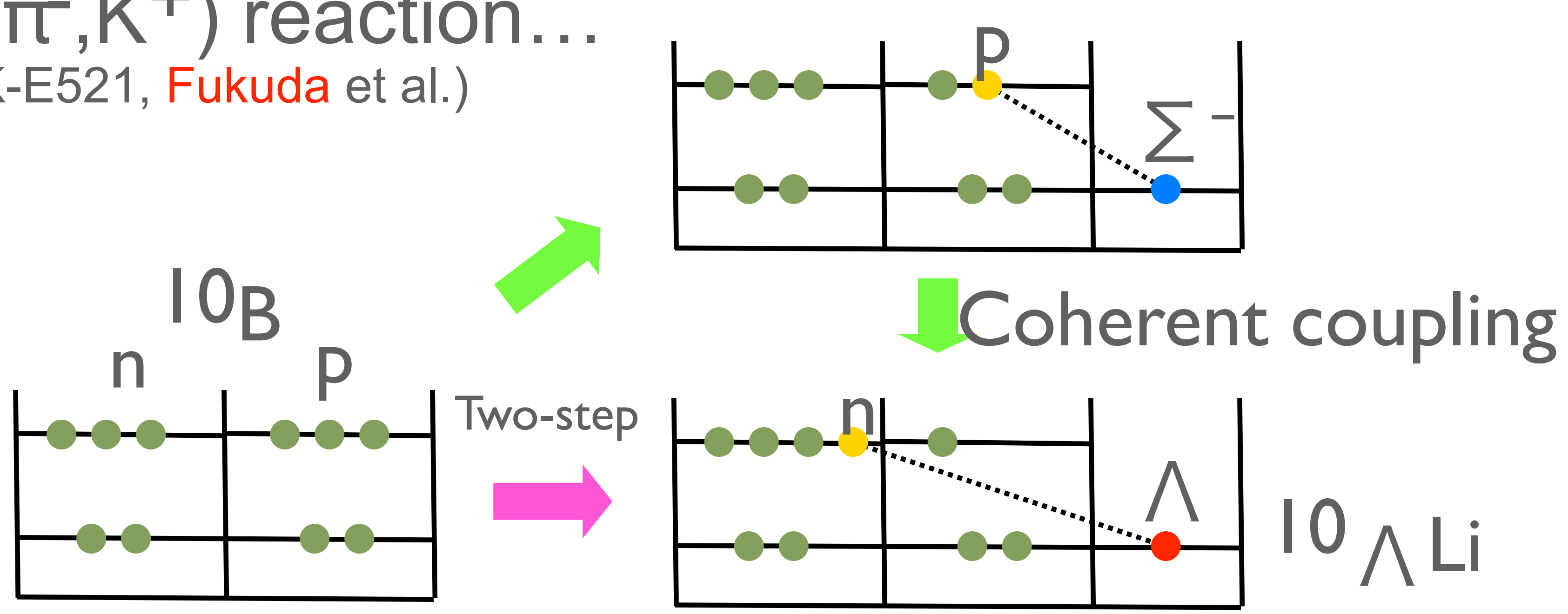
Λ - Σ coherent coupling in A=4 hypernuclei

…solved an underbinding problem,
known as an overbinding problem in
$^{5}_{\Lambda}$He

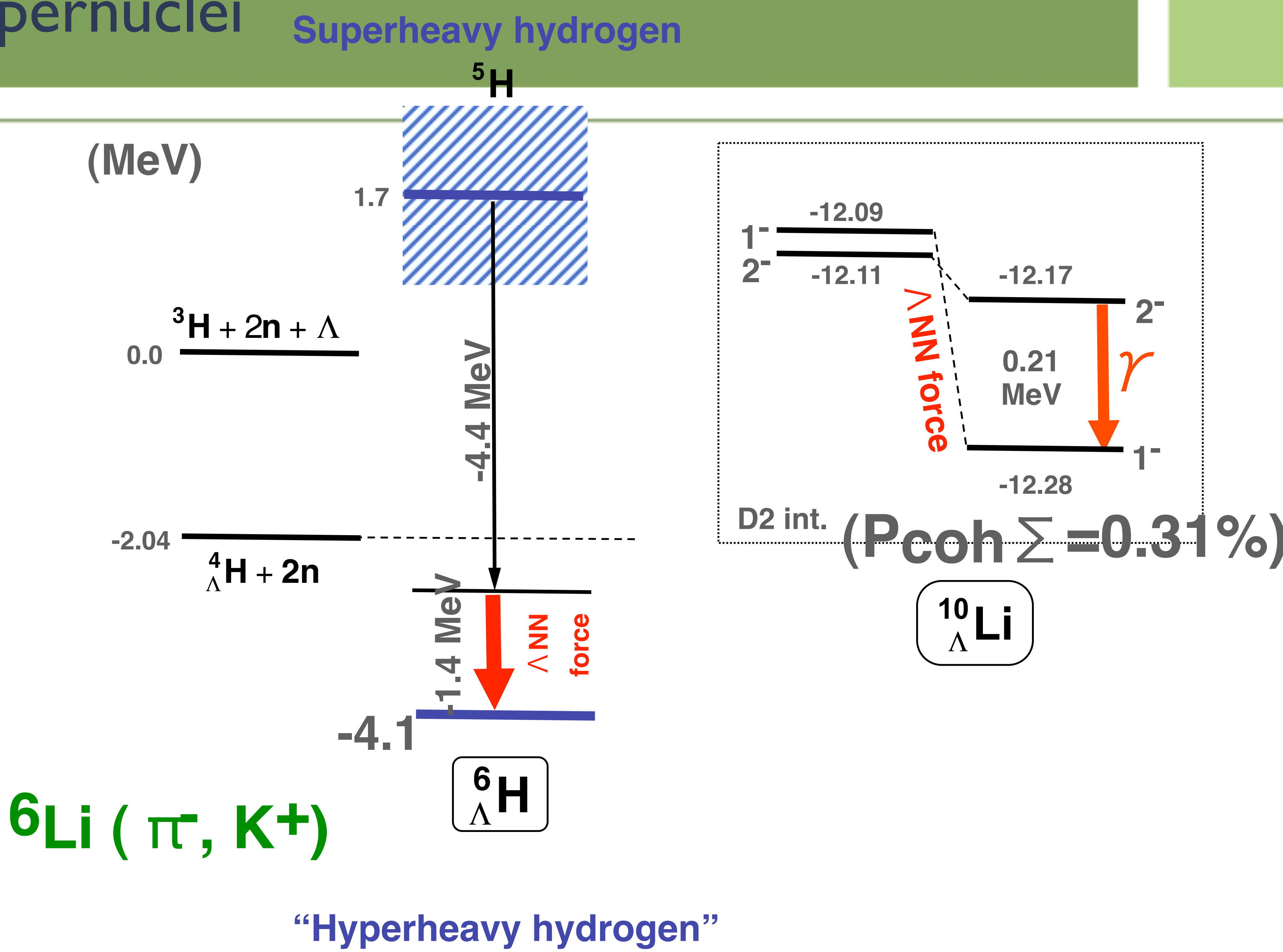
Y.Akaishi *et al.*, PRL84(2000)3539

To be confirmed/examined in other examples

In the (π^-,K^+) reaction…
(KEK-E521, Fukuda et al.)



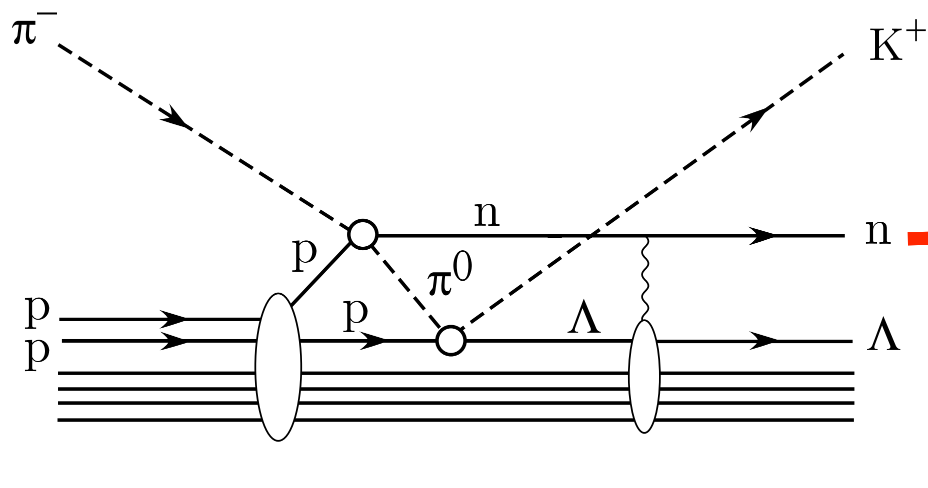
Effect of Coherent Σ mixing in n-rich hypernuclei

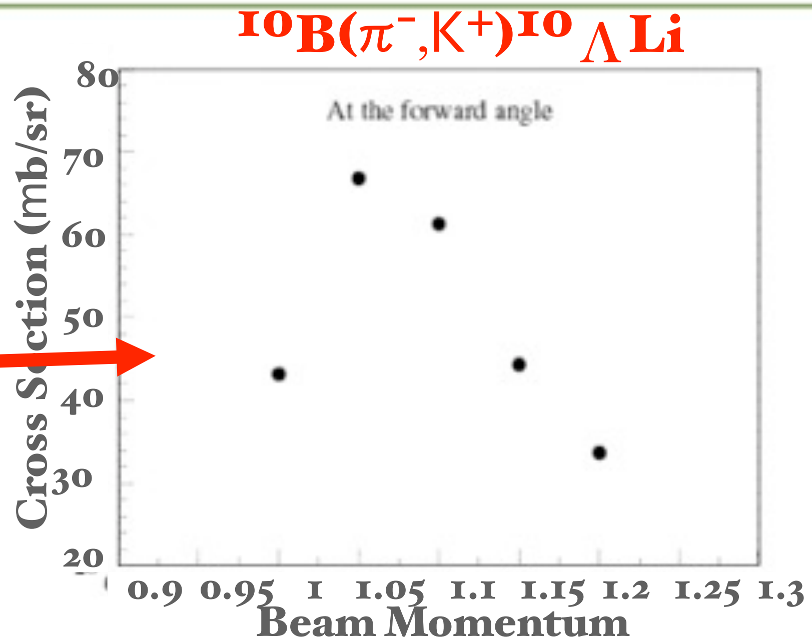


Reaction mechanism

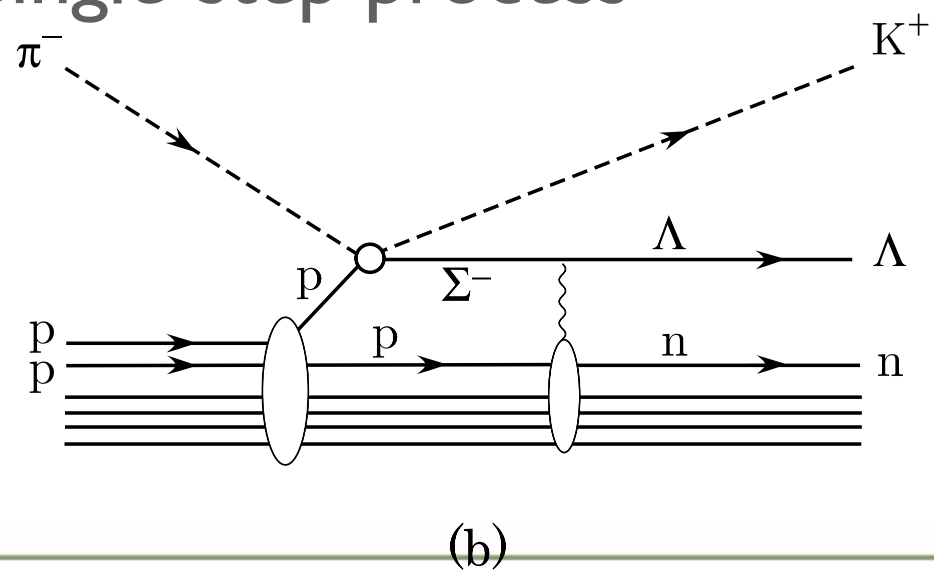
Tretyakova, Akaishi et al.

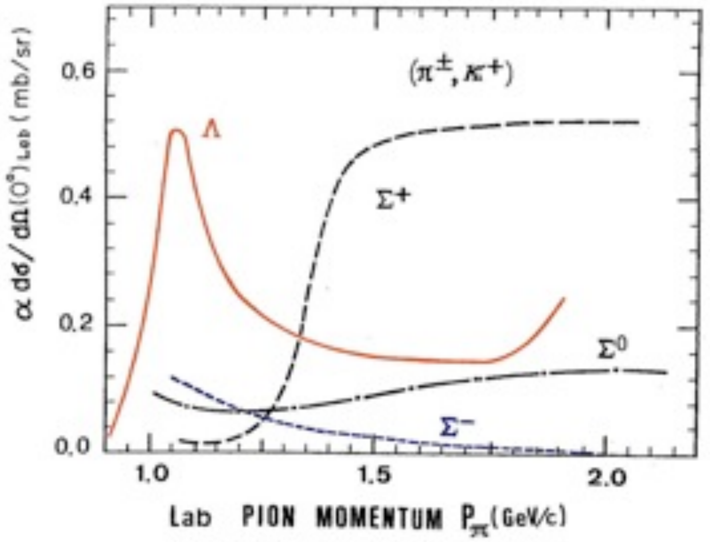
- Two-step process:





- Single-step process





Experiemntal Results

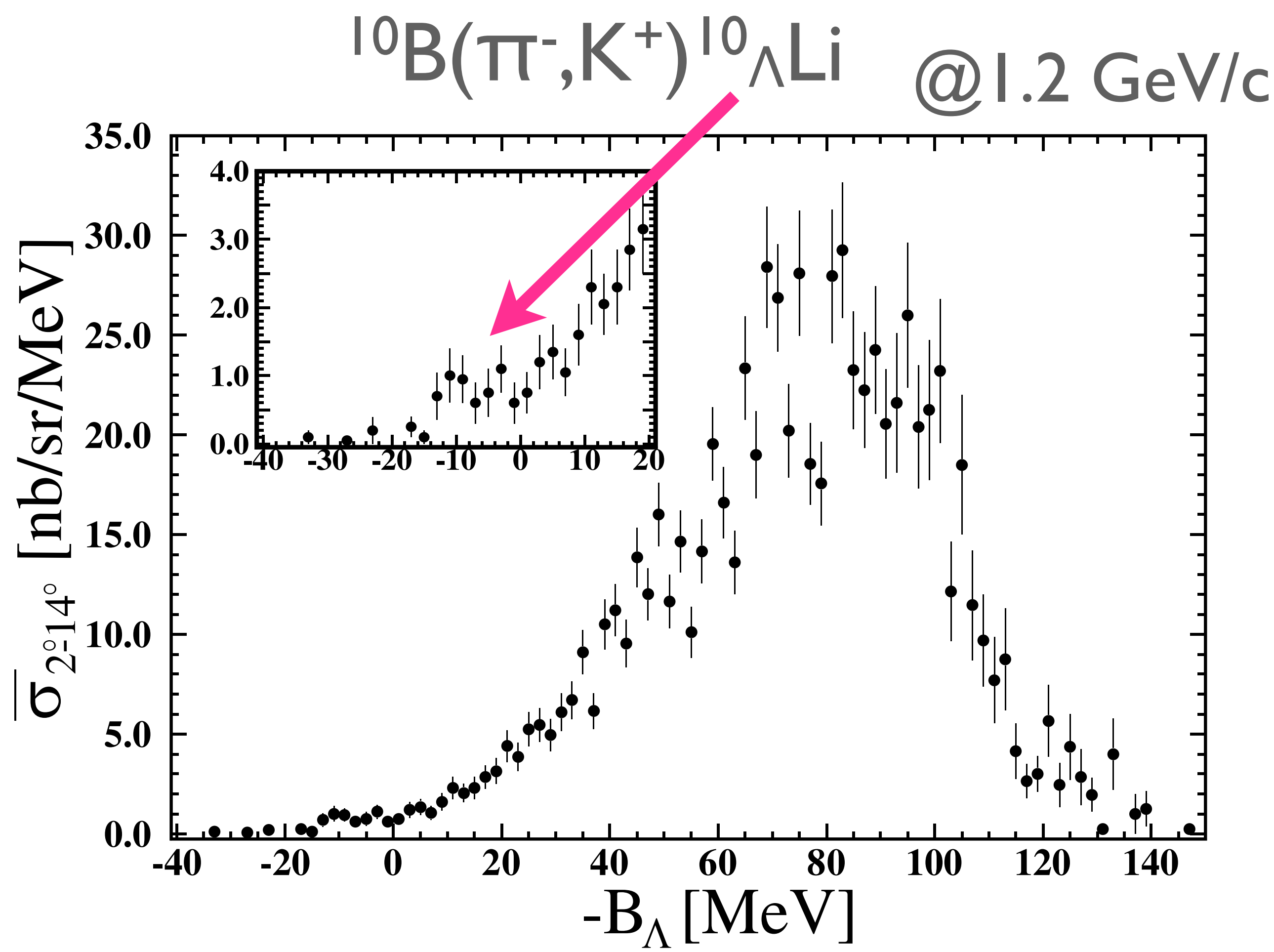


FIG. 3. Missing-mass spectrum of the (π^-, K^+) reaction on a ^{10}B target at 1.2 GeV/c. The horizontal and vertical axes are the same as Fig. 2. An expanded view near the Λ bound region is shown in the inset.

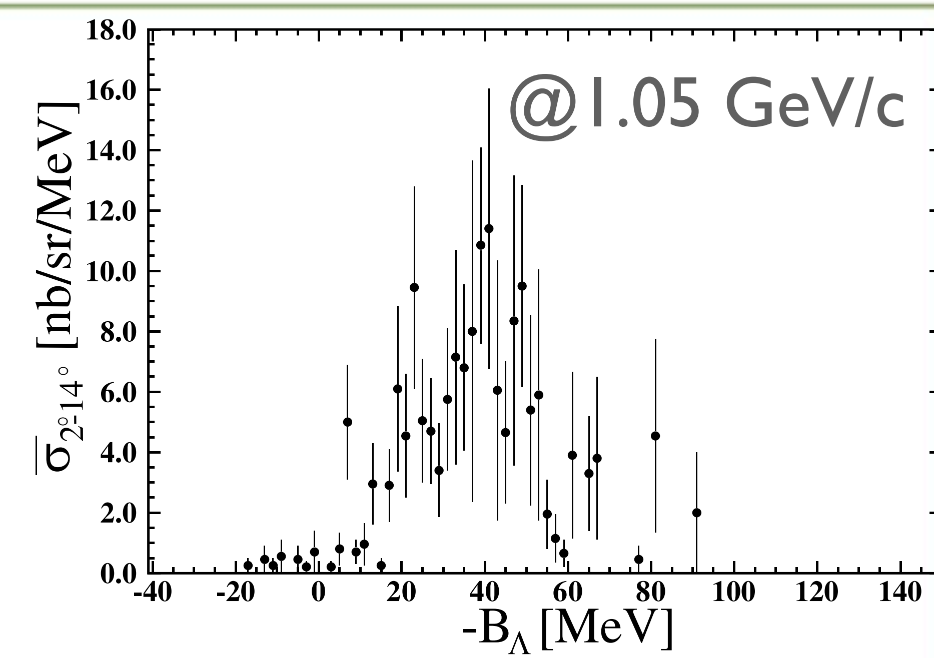


FIG. 2. Missing-mass spectrum of the (π^-, K^+) reaction on a ^{10}B target at 1.05 GeV/c. The horizontal axis shows the binding energy of a Λ, whereas the vertical axis shows the cross section in terms of nb/sr/MeV.

P.K. Saha et al., PRL 94 (2005) 052502.

Ratio of the Λ production cross section (π^-,K^+) to (π^+,K^+)

TABLE I. Hypernuclear production cross sections for the bound region averaged over the scattering angle from 2° to 14°. The cross section with an asterisk shows a lower limit by extrapolating the quasifree components linearly. The quoted errors are statistical.

Reaction	Cross Section 1.05 GeV/c	Cross Section 1.2 GeV/c
$^{12}C(\pi^+, K^+)^{12}_{\Lambda}C$	18.0 ± 0.7 μb/sr	17.5 ± 0.6 μb/sr
$^{10}B(\pi^+, K^+)^{10}_{\Lambda}B$	7.8 ± 0.3 μb/sr	
$^{10}B(\pi^-, K^+)^{10}_{\Lambda}Li$	5.8 ± 2.2 nb/sr	11.3 ± 1.9 nb/sr $9.6 \pm 2.0^*$ nb/sr

Σ mixing ?

- T. Harada et al., PRC 79 (2009) 014603.

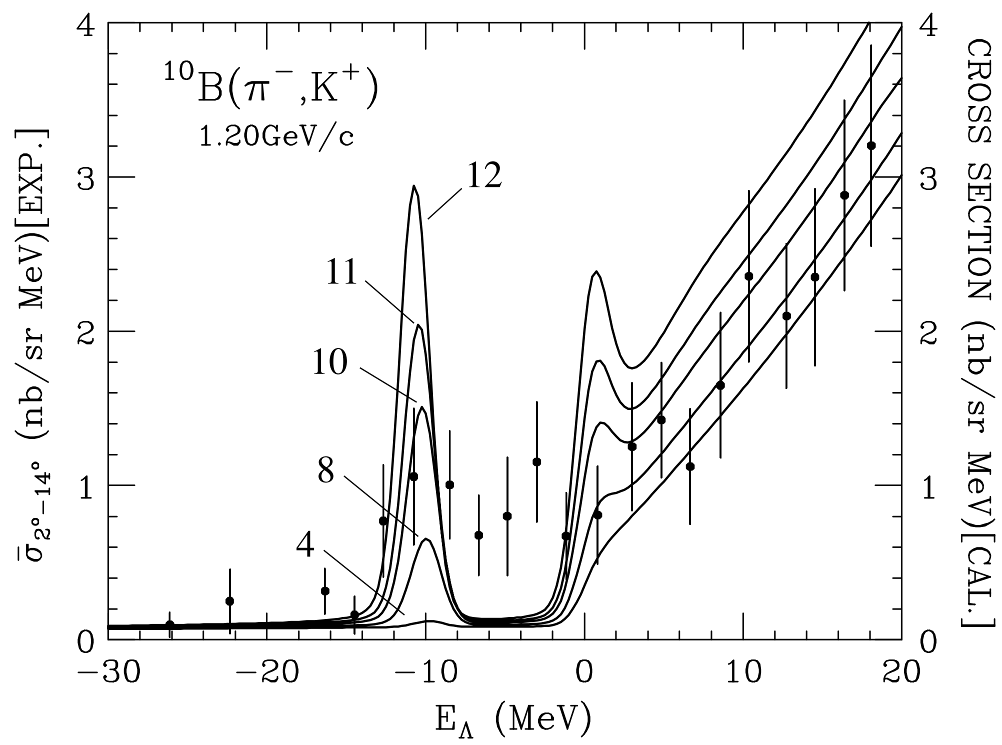
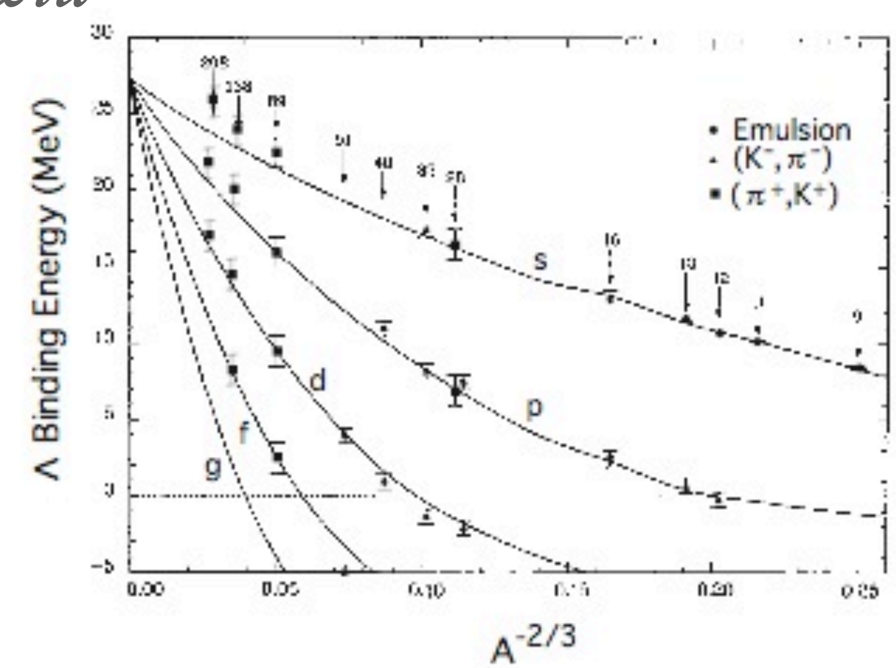


FIG. 3. Calculated inclusive Λ spectra obtained by the one-step mechanism near the Λ threshold in the $^{10}B(\pi^-, K^+)$ reaction at 1.20 GeV/c (6°), by changing $V_{\Sigma\Lambda}$ for the Λ-Σ coupling potential. The experimental data are taken from Ref. [12]. The solid curves denote $V_{\Sigma\Lambda} = 4, 8, 10, 11$, and 12 MeV when $-W_\Sigma = 20$ MeV, with a detector resolution of 2.5 MeV FWHM.

$P_\Sigma \sim 0.47 - 0.68\%$

Summary on (π ,K) spectroscopy

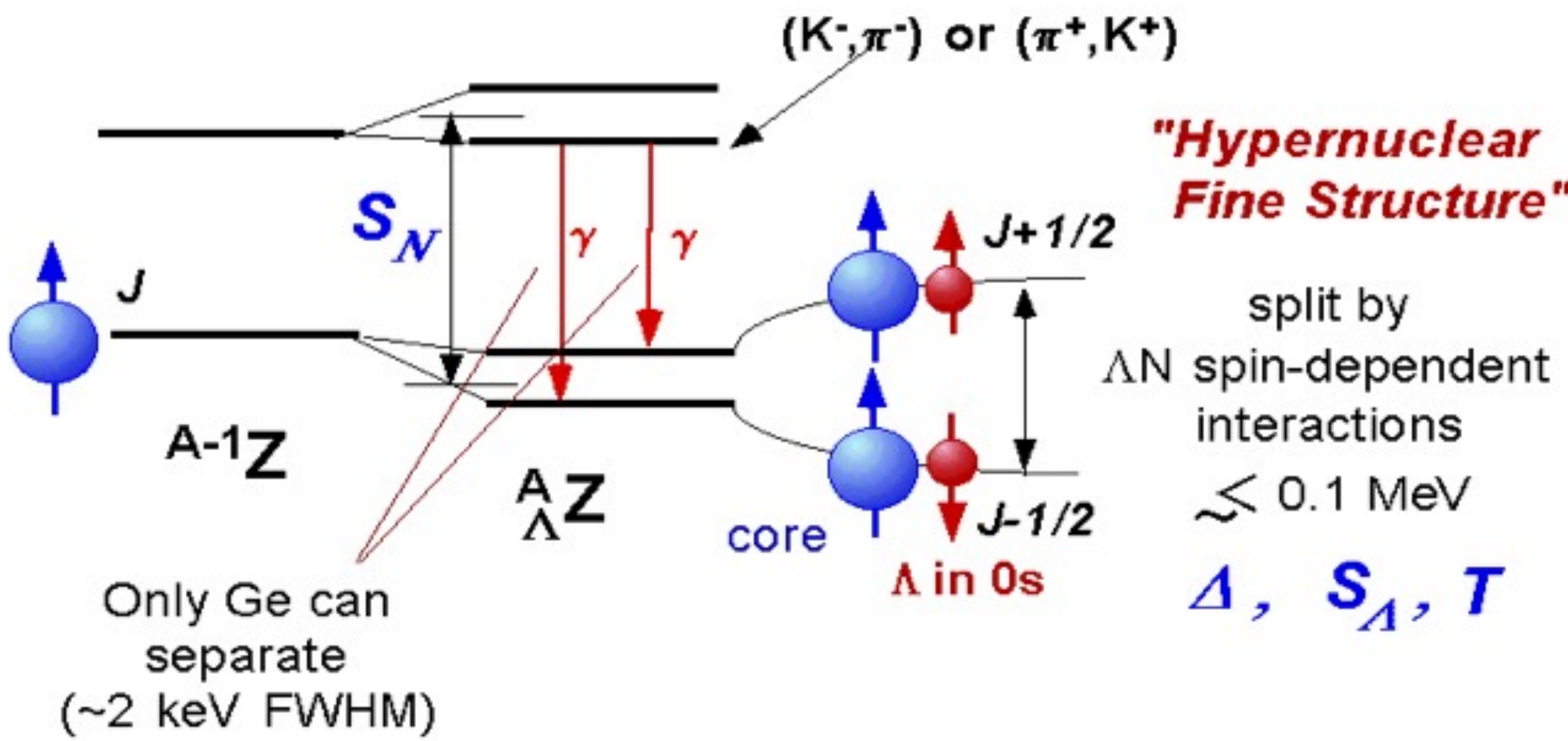
- The (π,K) Spectroscopy has been successful.
  - Gross feature of Single-particle levels of Λ
  - Effective for Heavy Λ hypernuclei
    - *High-resolution spectroscopy (ΔE~0.2 MeV) will be interesting*
  - Possibility to study neutron-rich hypernuclei with (π^-,K^+)



Second day in UT

γ spectroscopy

- Low-lying levels of Λ hypernucleus



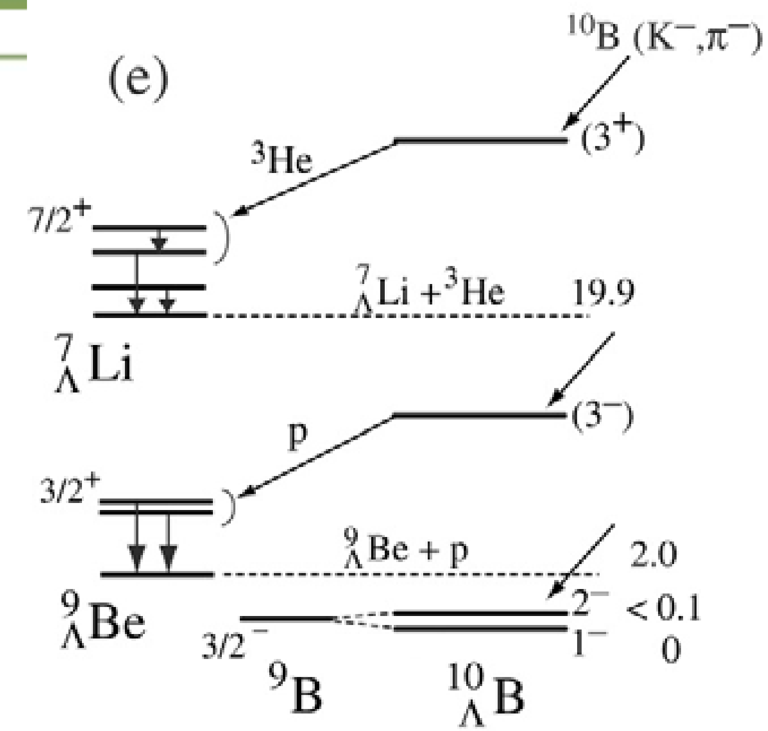
- 2-body ΛN effective interaction

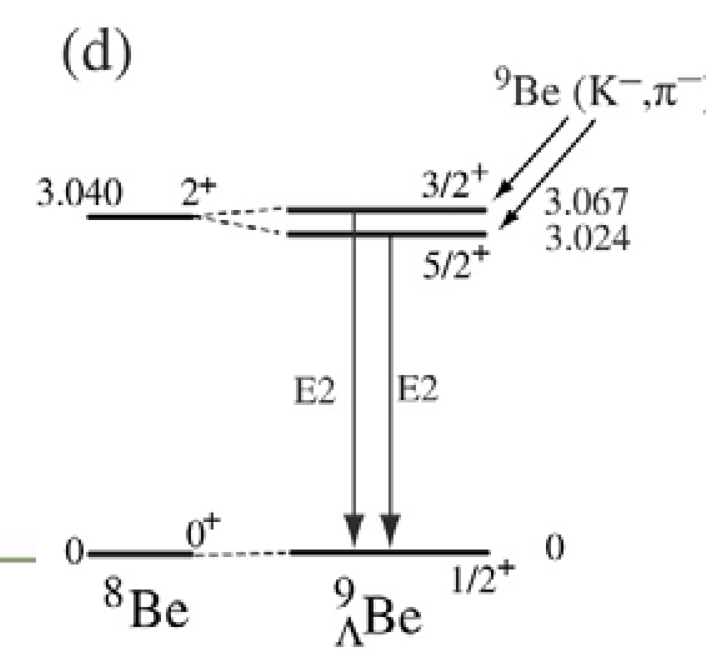
$$V^{eff}_{\Lambda N} = V_0(r) + \underbrace{V_\sigma(r)\,\vec{s}_\Lambda \vec{s}_N}_{\Delta} + \underbrace{V_\Lambda(r)\,\vec{l}_{\Lambda N} \vec{s}_\Lambda}_{S_\Lambda} + \underbrace{V_N(r)\,\vec{l}_{\Lambda N} \vec{s}_N}_{S_N} + \underbrace{V_T(r)\,S_{12}}_{T}$$

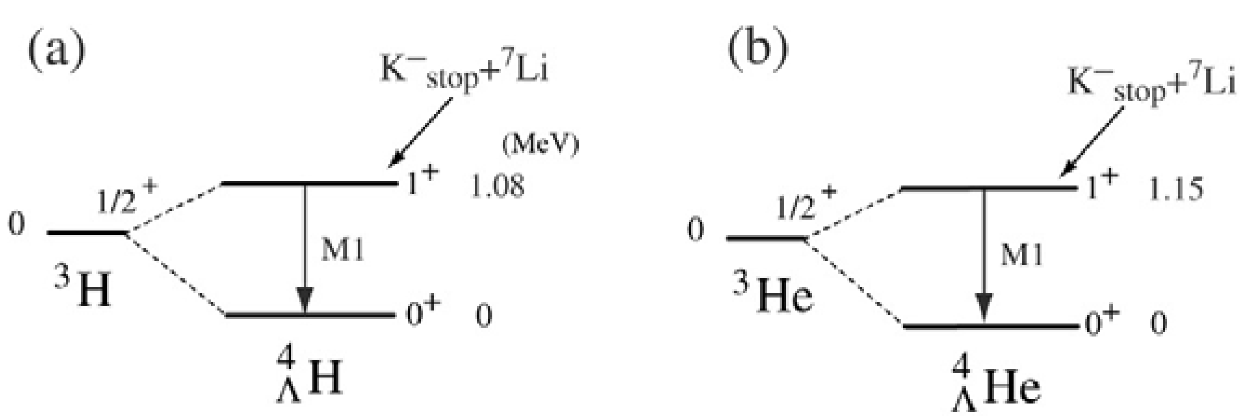
p-shell : 4 radial integrals for $p_N s_\Lambda$ w.f.

Hypernuclear γ -rays before Hyperball

${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He	1.10±0.04 MeV	NaI
${}^{7}_{\Lambda}$Li	2.034±0.023 MeV	NaI
${}^{9}_{\Lambda}$Be	3.079±0.04 MeV	NaI
${}^{10}_{\Lambda}$B	not observed	Ge







Hyperball

(Tohoku/ Kyoto/ KEK, 1998)

- Large acceptance for small hypernuclear γ yields

  Ge (r.e. 60%) x 14

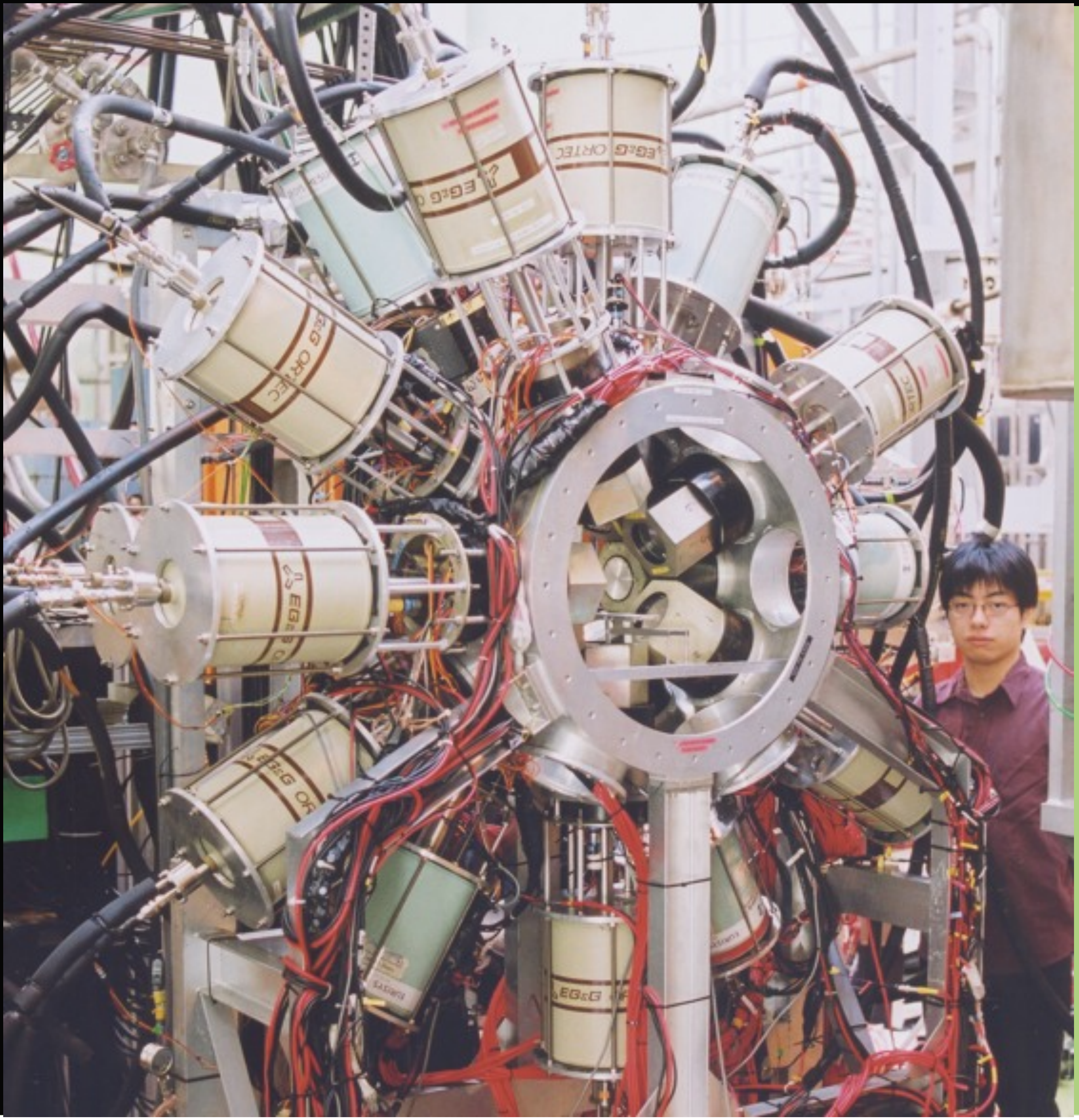
  $\Delta\Omega$ ~ 15%

  η_{peak}~ 3% at 1 MeV

- High-rate electronics for huge background

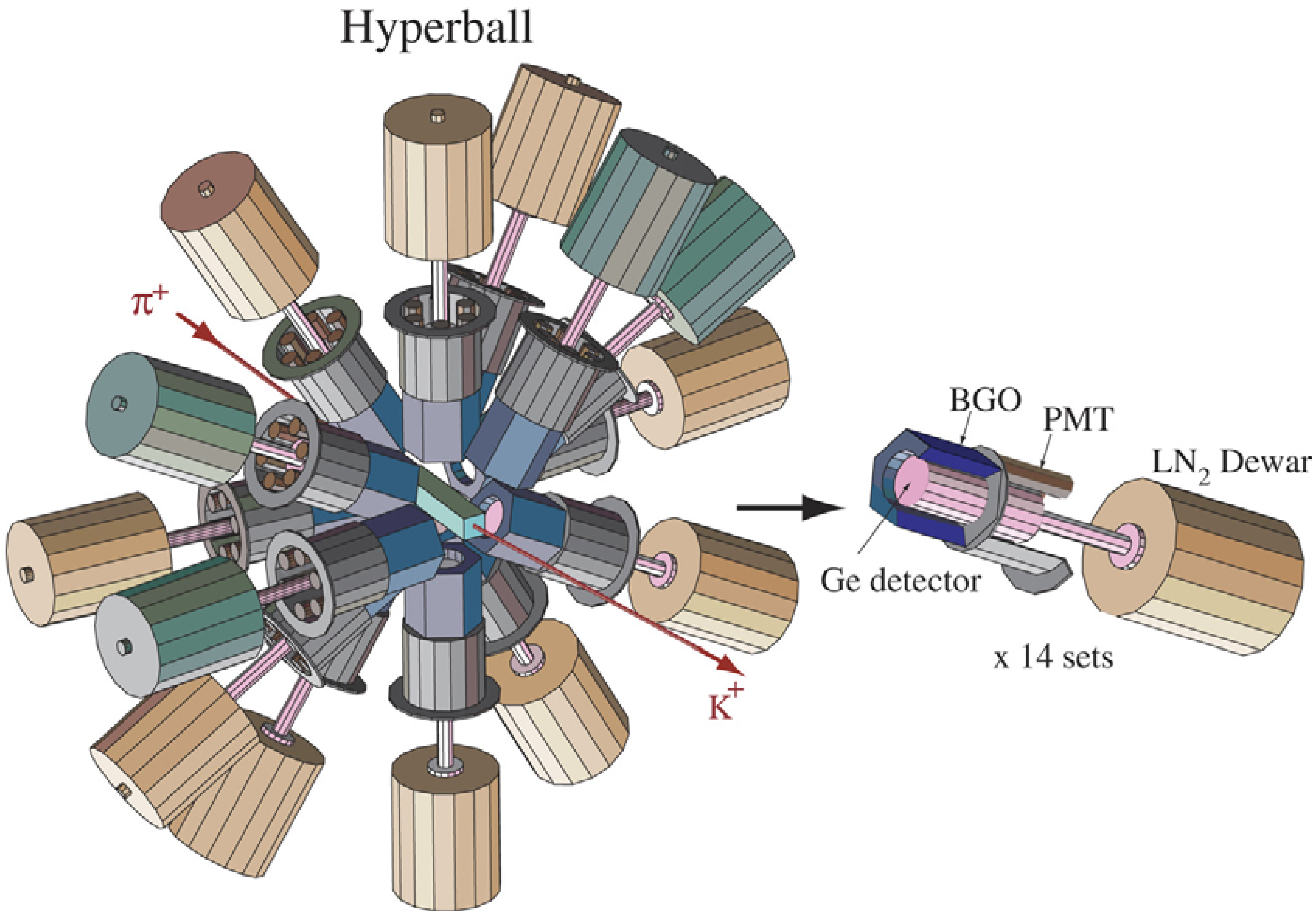
  1 TeV/sec, 100 kHz

- BGO counters for π^0 and Compton suppression



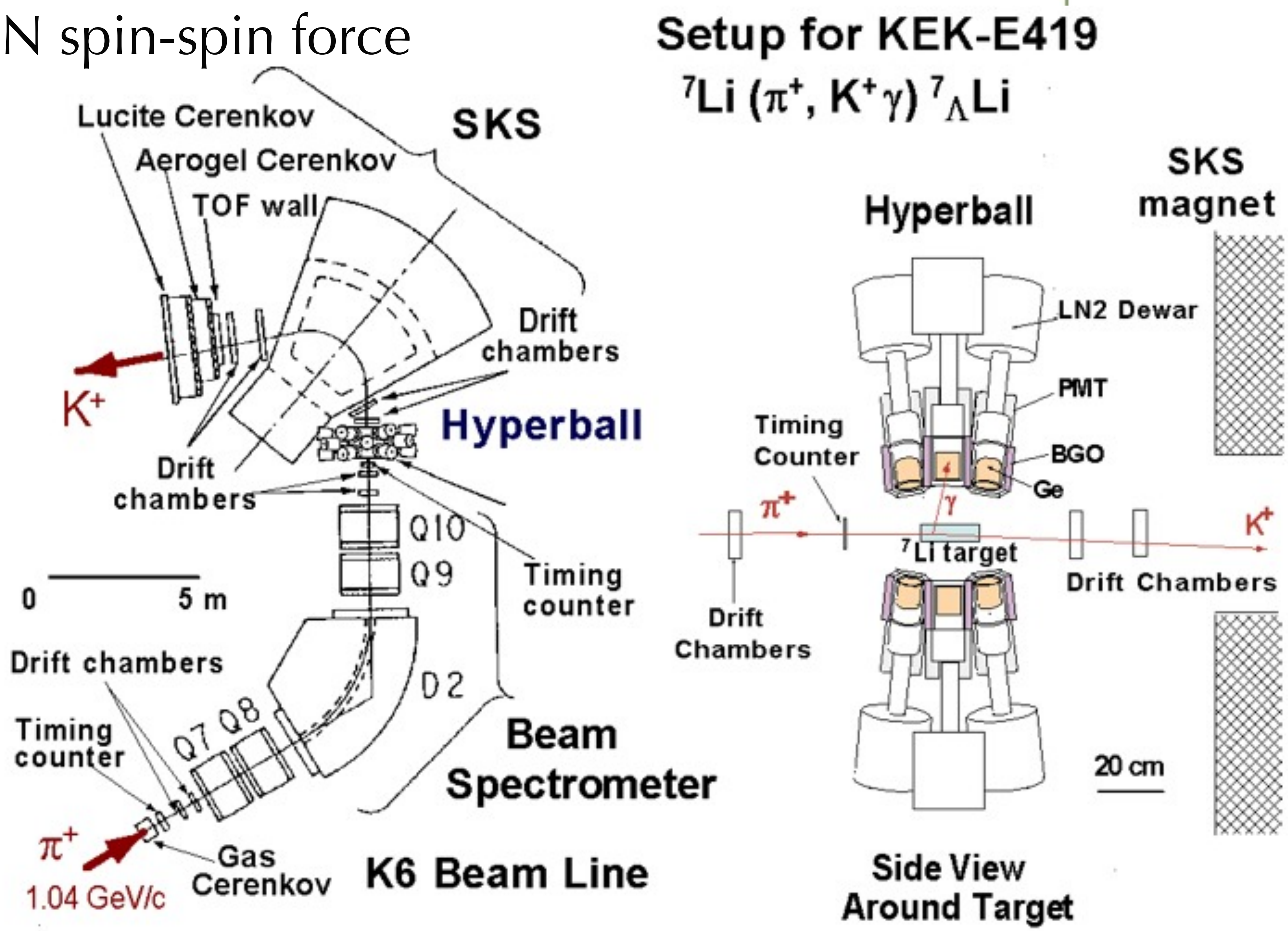
Resolution of hypernuclear spectroscopy

1 MeV $\rightarrow$ 2 keV FWHM

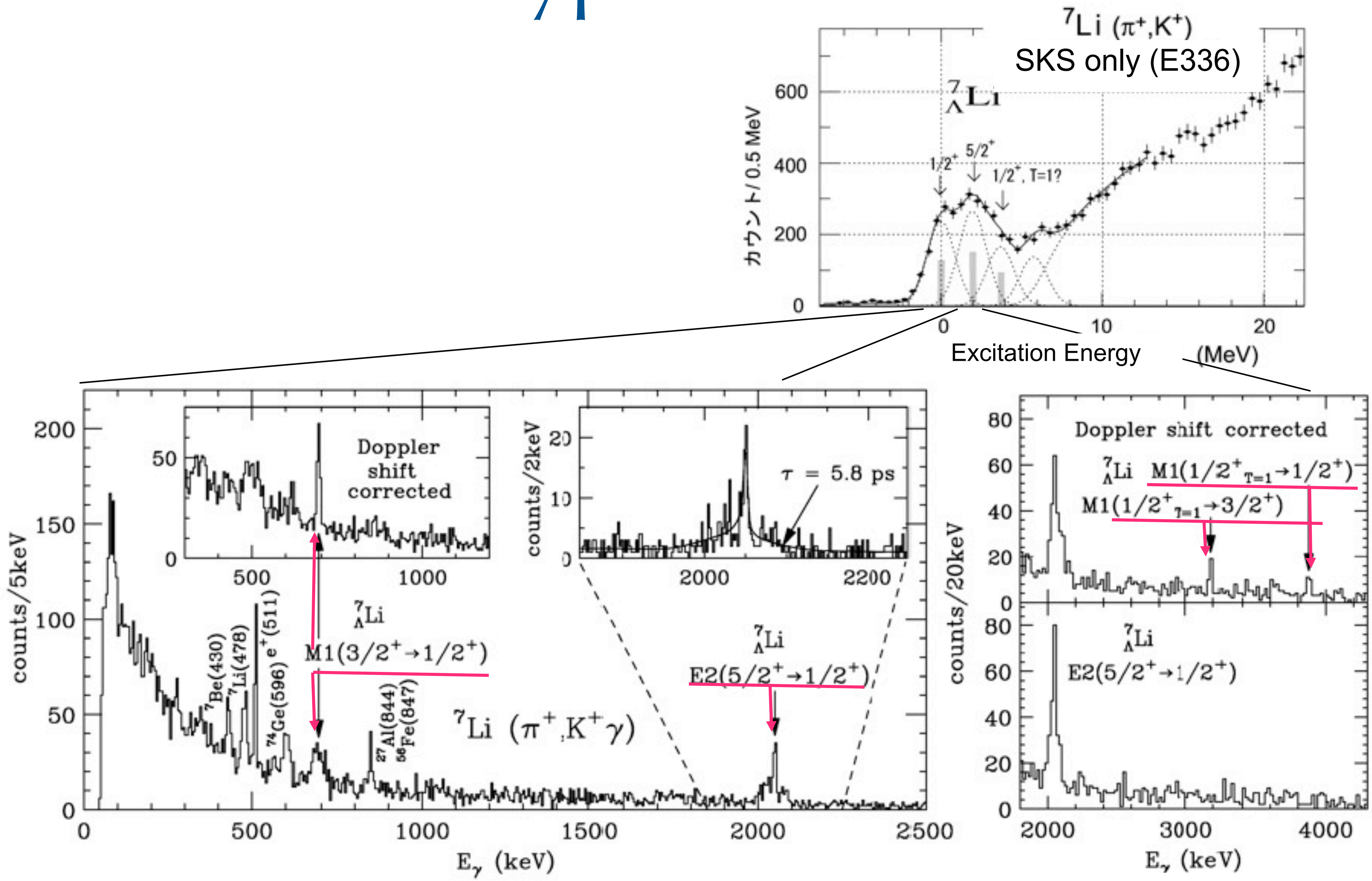

Hyperball
π+
K+
BGO
PMT
LN2 Dewar
Ge detector
x 14 sets

E419: γ spectroscopy of $^{7}_{\Lambda}$Li

- First exp. with Hyperball
- B(E2) → shrinking effect
- Spin-flip M1 → ΛN spin-spin force

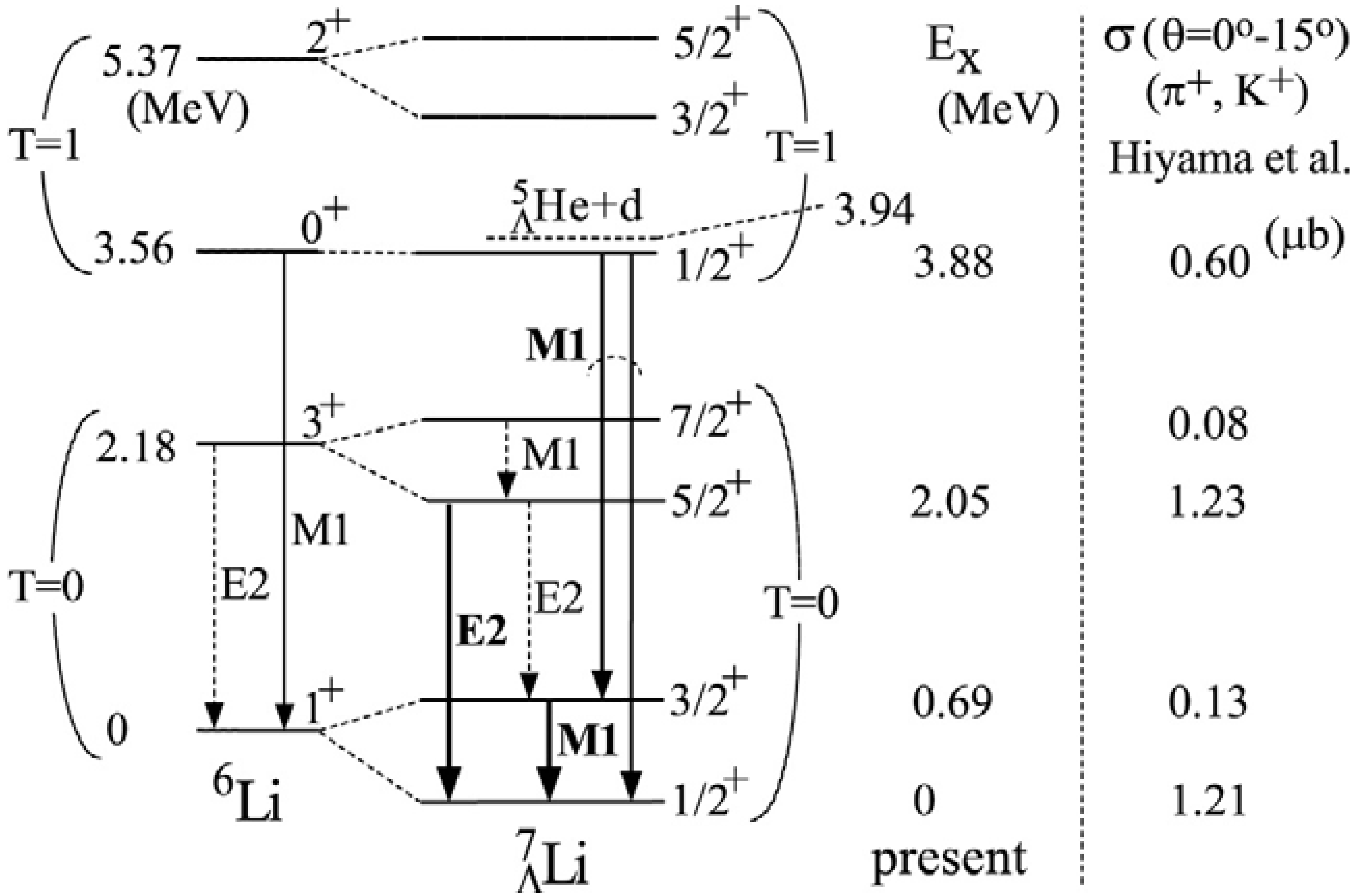


E419: SKS+Hyperball



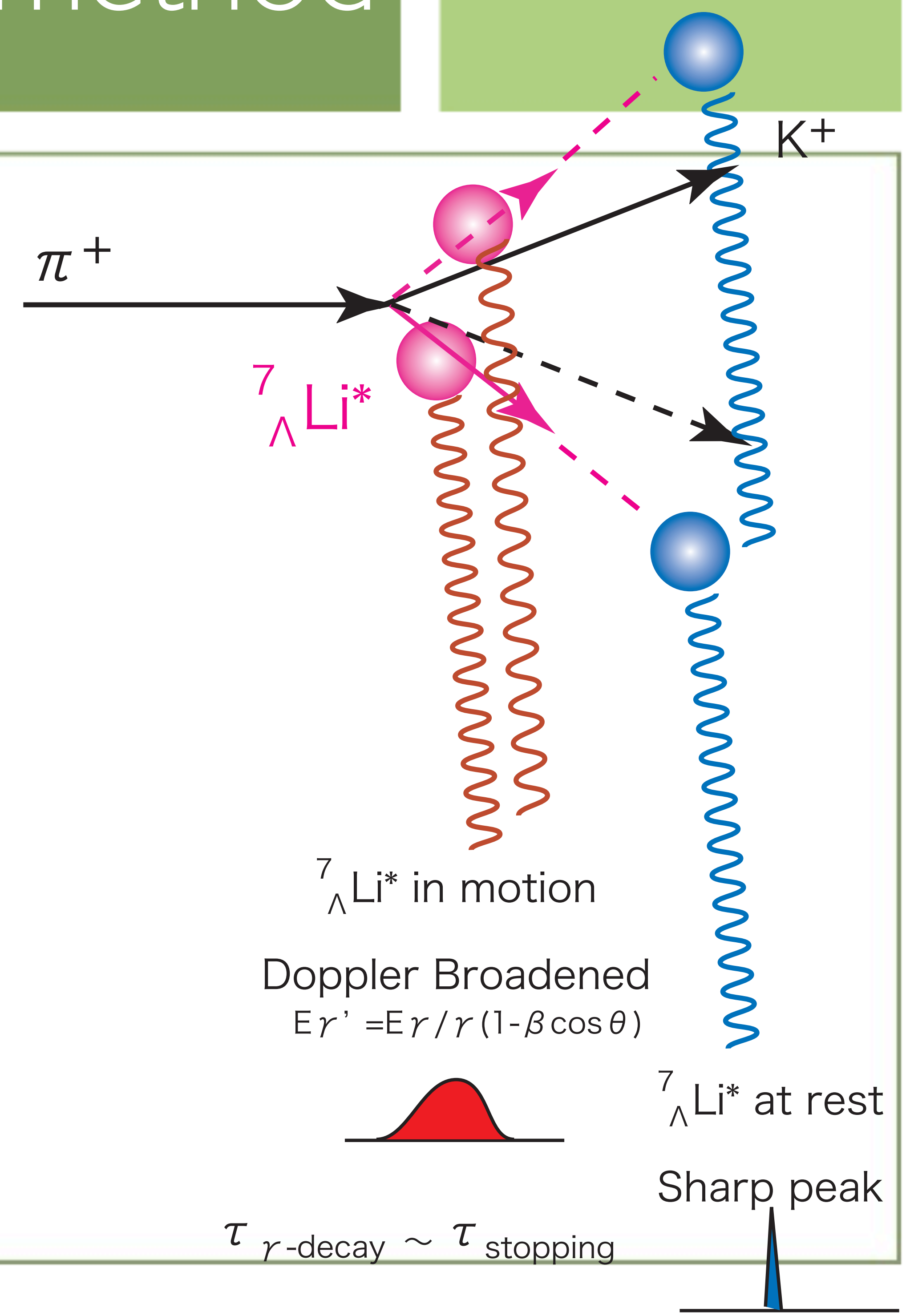
Tamura et al., PRL 94(2000) 5963

First observation of well-identified hypernuclear γ rays with Ge.


5.37
(MeV)
2+
T=1
3.56
0+
5/2+
3/2+
T=1
5ΛHe+d
3.94
1/2+
Ex
(MeV)
σ (θ=0°-15°)
(π+, K+)
Hiyama et al.
3.88
0.60 (μb)
M1
2.18
3+
7/2+
M1
5/2+
0.08
2.05
1.23
T=0
E2
M1
E2
E2
T=0
0
1+
3/2+
M1
1/2+
0.69
0.13
0
1.21
6Li
7ΛLi
present

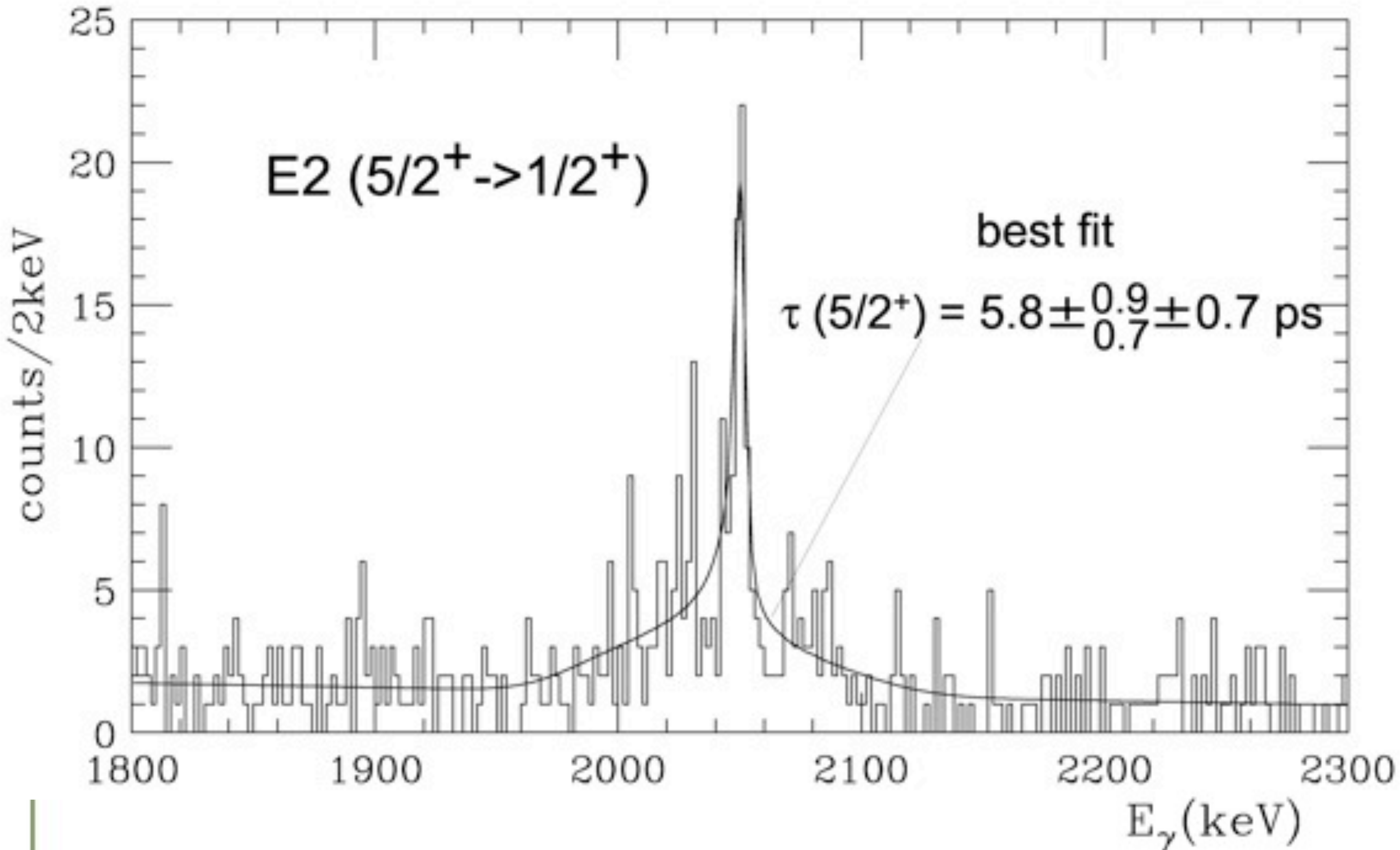
Doppler shift attenuation method

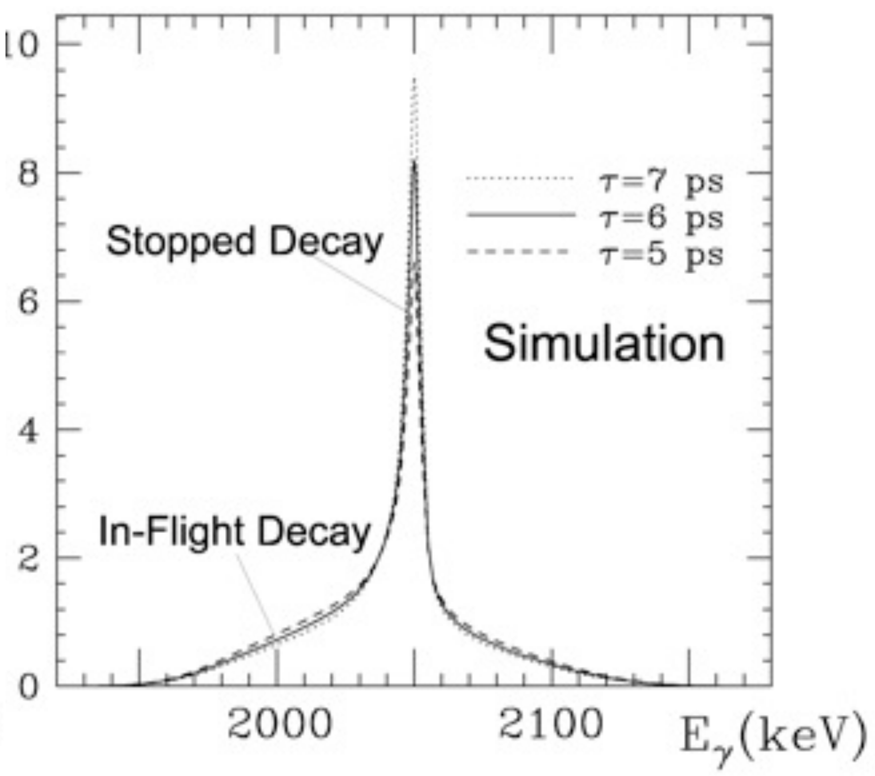
- $\tau_{\gamma\text{-decay}} \sim \tau_{\text{stopping}}$
- 5.8 ps 13 ps
  - mixture of a sharp peak and a broad peak



Lifetime and B(E2)

Lifetime Measurement
using Dopper Shift Attenuation Method





$\Gamma(E2; 5/2^+ \rightarrow 1/2^+) = BR / \tau(5/2^+) = 1.22 \times 10^9 E^5 B(E2)$

$BR = 93.6 \pm 3.8$ %

[weak decay $(230 \pm 40 \text{ ps})^{-1}$, $BR(5/2^+ \rightarrow 3/2^+) = 3.8 \pm^{0.5}_{3.8}$%]

=> $B(E2) = 3.6 \pm 0.5 \pm^{0.5}_{0.4}\ e^2 fm^4$

B(E2)

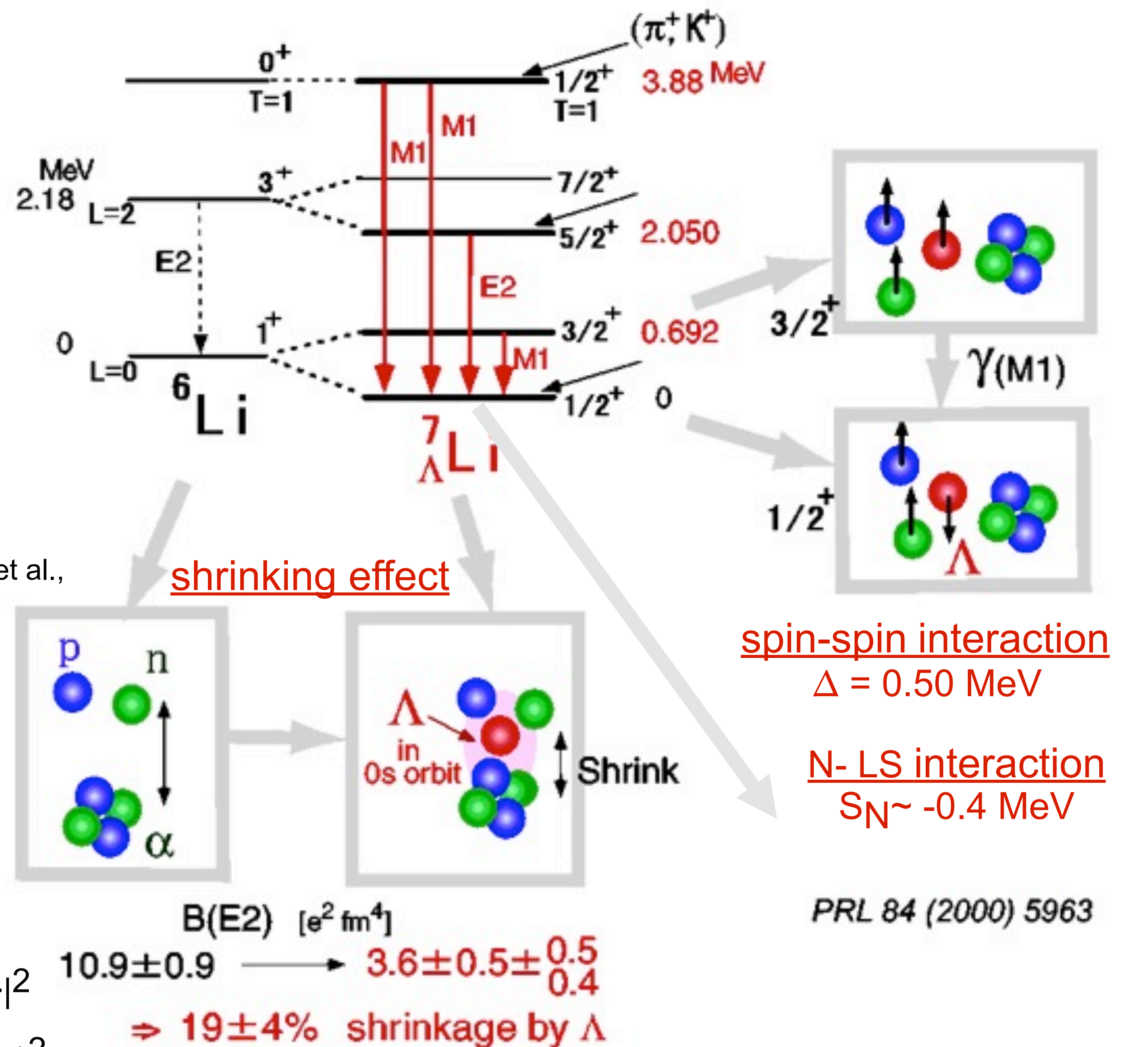
$$\Gamma(E(M)\lambda : I_i \rightarrow I_f) = \frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\frac{1}{\hbar}(\frac{\omega}{c})^{2\lambda+1}B(E(M)\lambda; I_i \rightarrow I_f)$$

$$\begin{aligned} B(E(M)\lambda; I_i \rightarrow I_f) &= \sum_{\mu M_f} |\langle I_f M_f|\mathcal{M}(E(M)\lambda,\mu)|I_i M_i\rangle|^2 \\ &= \frac{1}{2I_i+1}|\langle I_f||\mathcal{M}(E(M)\lambda)||I_i\rangle|^2 \end{aligned}$$

$$\begin{aligned} \mathcal{M}(E\lambda,\mu) &= \int \rho(\vec{r})r^\lambda Y_{\lambda\mu}(\hat{r})d\tau \\ \mathcal{M}(M\lambda,\mu) &= \frac{-1}{c(\lambda+1)}\int \vec{j}(\vec{r})\cdot(\vec{r}\times\nabla)r^\lambda Y_{\lambda\mu}(\hat{r})d\tau \end{aligned}$$

$$\begin{aligned} \Gamma(E1) &= 1.59\times 10^{15}(E)^3 B(E1) \\ \Gamma(E2) &= 1.22\times 10^{9}(E)^5 B(E2) \qquad in \;\; e^2(fm)^{2\lambda} \end{aligned}$$

Summary on $^{7}_{\Lambda}$Li



Predicted by Motoba et al.,
Prog.Theor.Phys.
70 (1983) 189.

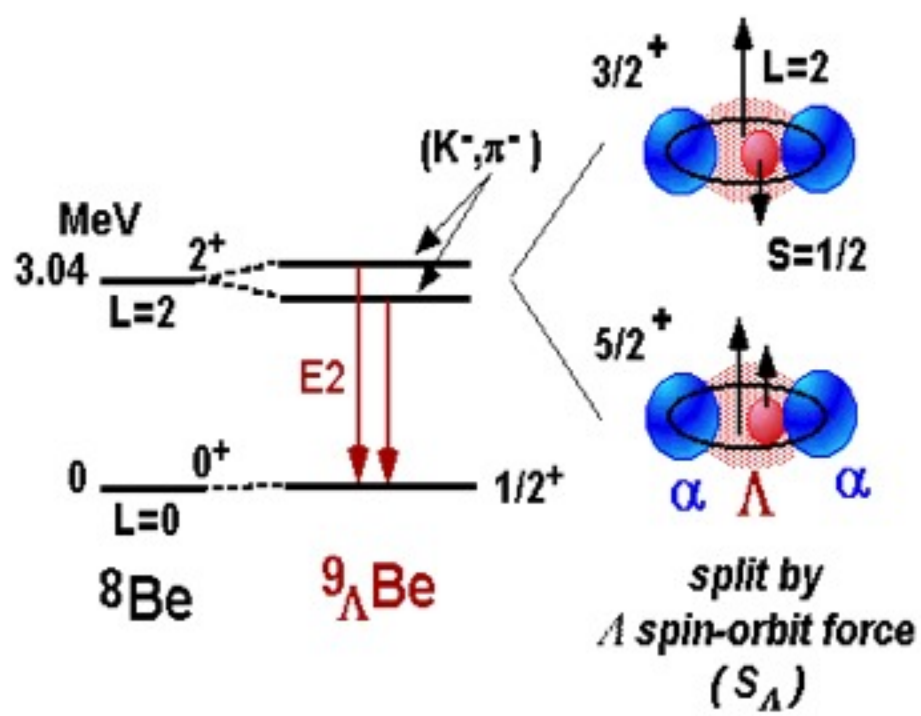
$B(E2) \propto |\langle f|\, e\, r^2\, Y_2\, |i\rangle|^2$

$\propto R^4$ or $(\beta \langle r^2 \rangle)^2$

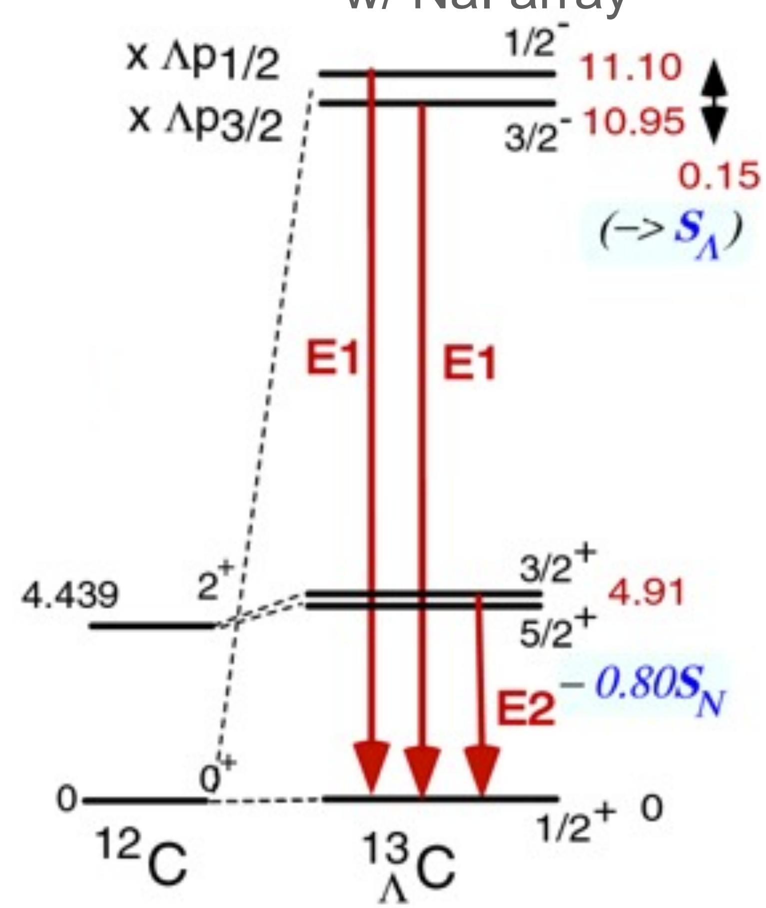
Tanida et al., PRL 86(2001) 1982

ΛN spin-orbit force

$^{9}Be\ (K^-, \pi^-\ \gamma)\ ^{9}_{\Lambda}Be$
BNL E930-1



$^{13}C\ (K^-, \pi^-\ \gamma)$ BNL E929
w/ NaI array



Ajimura et al., PRL 86 (2001) 4255

$^{13}{}_{\Lambda}C$

$p_{1/2}$, $p_{3/2}$ single-particle level splitting

E(1/2⁻)-E(3/2⁻) =152±54±36 keV

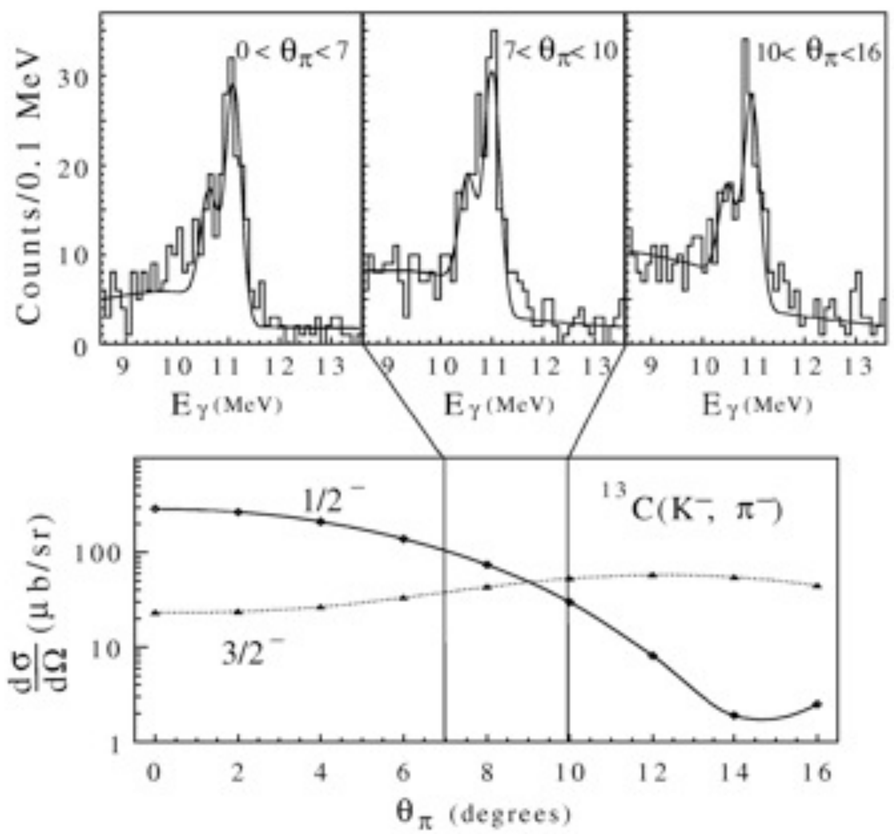


FIG. 2. γ ray spectra taken in coincidence with scattered π⁻'s (upper panel) and differential cross section of 1/2⁻ and 3/2⁻ states calculated by Motoba [18] (lower panel) are shown.

-forward

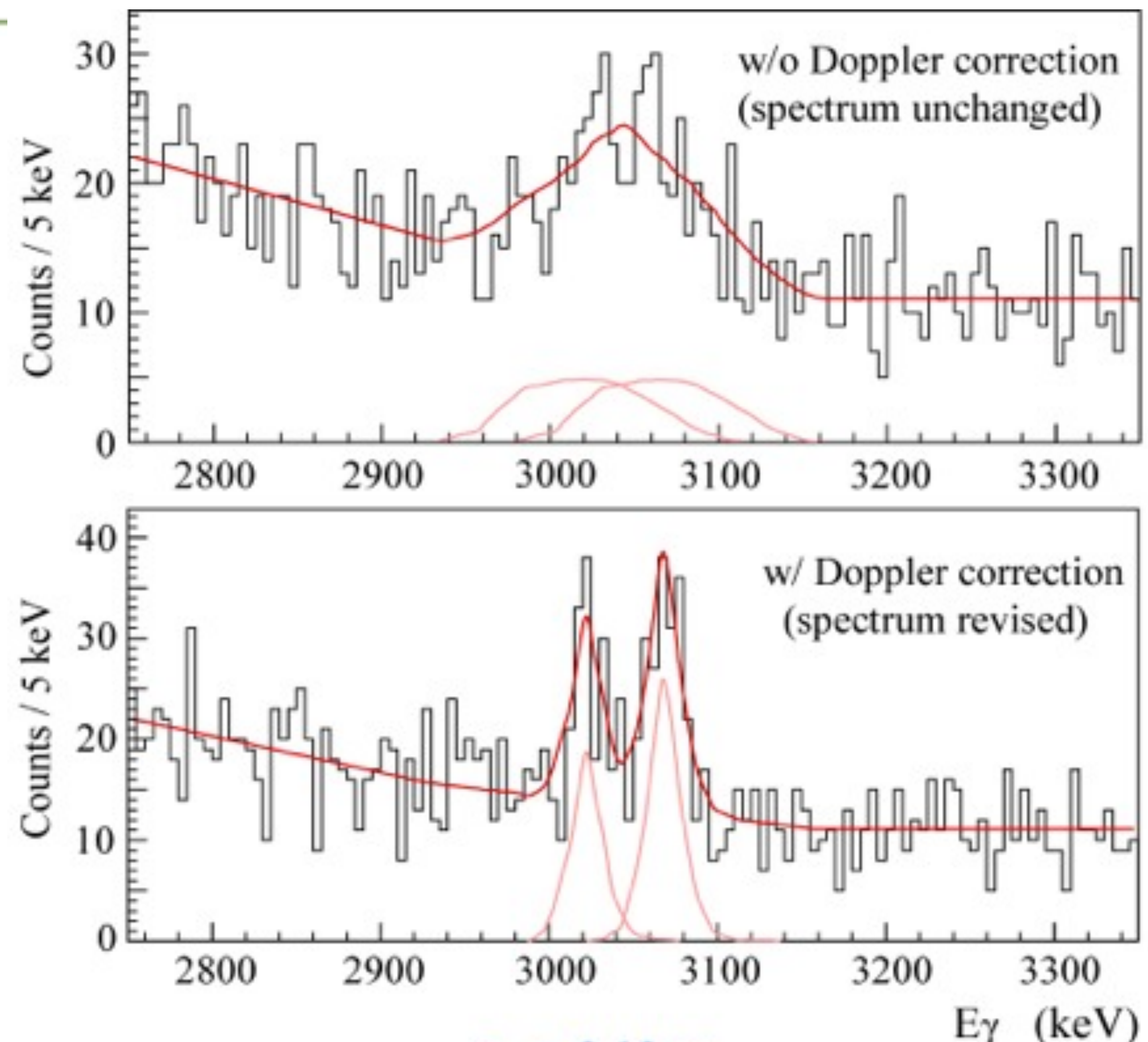
$(p_{1/2,n}{}^{-1}, p_{1/2,\Lambda})$ $\Delta L=0$

-backward

$(p_{1/2,n}{}^{-1}, p_{3/2,\Lambda})$ $\Delta L=2$

$^{9}_{\Lambda}$Be

Revised



Revised Results

$\tau < 0.10$ ps

$\Delta E = 43 \pm 5$ keV

$E = 3024 \pm 3 \pm 1,\ 3067 \pm 3 \pm 1$ keV

χ^2 /dof = 1.22

Hiyama et al: PRL 85 (2000) 270

E(3/2$^+$)-E(5/2$^+$)

Meson exch. 0.08 - 0.20 MeV

quark 0.035 - 0.040 MeV

・Millener:

E(3/2$^+$)-E(5/2$^+$)

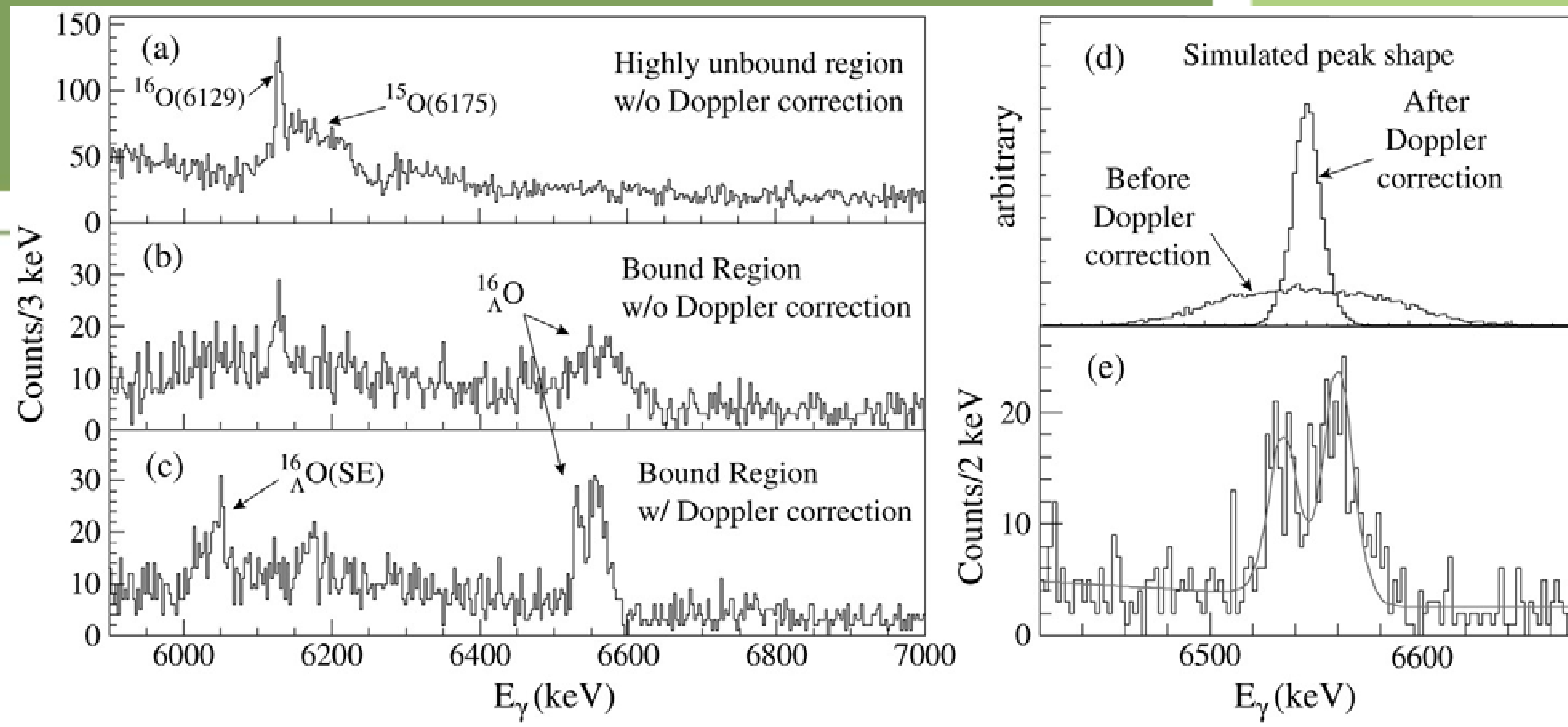
= -0.035 Δ - 2.465S_Λ + 0.936T

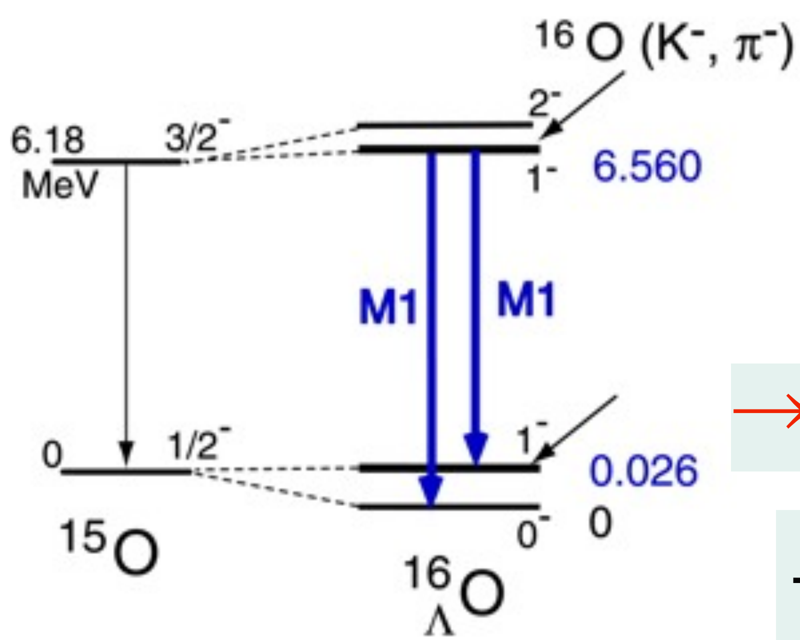
S_Λ = -0.02 MeV

Consistent with

very small LS splitting in $^{13}_{\Lambda}$C

$^{16}_{\Lambda}O$





$\Delta E = 26.1 \pm 1.4 \pm 0.6$ keV

$E(1^-)-E(0^-) = -0.39\,\Delta + 1.4\,S_\Lambda - 0.005\,S_N + 7.8\,T + LS$

(Millener, 2001)

<- $\Delta = 0.46$ MeV, $S_\Lambda = -0.01$ MeV

→ **T = 26 -32 keV** First info. on T

	ND	NF	NSC89	NSC97f	
T	18	33	36	54	(keV)

Some of
Meson Exchange model
predictions agree

Summary of p-shell levels

- Δ=0.48 MeV, S_Λ=-0.01 MeV, S_N=-0.43 MeV, T=0.03 MeV

Table 18
Energies of the four hypernuclear level spacings that are described in terms of the spin-dependent ΛN interaction parameters obtained by Millener's shell model calculations [101]

Hypernuclear levels		Shell model calculation by Millener	$\Lambda\Sigma$ (MeV)	Exp. (MeV)
${}^{7}_{\Lambda}$Li	$E(3/2^+) - E(1/2^+)$	$1.444\Delta + 0.054S_\Lambda + 0.016S_N - 0.271T$	+0.071	0.692
${}^{7}_{\Lambda}$Li	$\overline{E(7/2^+, 5/2^+)}$	$-0.05\Delta + 0.07S_\Lambda + 0.70S_N - 0.08T$		1.858
	$-\overline{E(3/2^+, 1/2^+)}$[a]	$+\Delta E_{core}$[b]		
${}^{9}_{\Lambda}$Be	$E(3/2^+) - E(5/2^+)$	$-0.037\Delta - 2.464S_\Lambda + 0.003S_N + 0.994T$	−0.008	0.043
${}^{16}_{\Lambda}$O	$E(1^-) - E(0^-)$	$-0.382\Delta + 1.378S_\Lambda - 0.004S_N + 7.850T$	−0.014[c]	0.026

Experimental energies obtained by the Hyperball experiments are also shown. The effect of the Λ–Σ coupling estimated by Millener is listed as $\Lambda\Sigma$.

[a] $\overline{E(J_1, J_2)} = [(2J_1+1)E(J_1) + (2J_2+1)E(J_2)]/(2J_1+2J_2+2)$ denotes the center of gravity energy for the doublet (J_1, J_2).

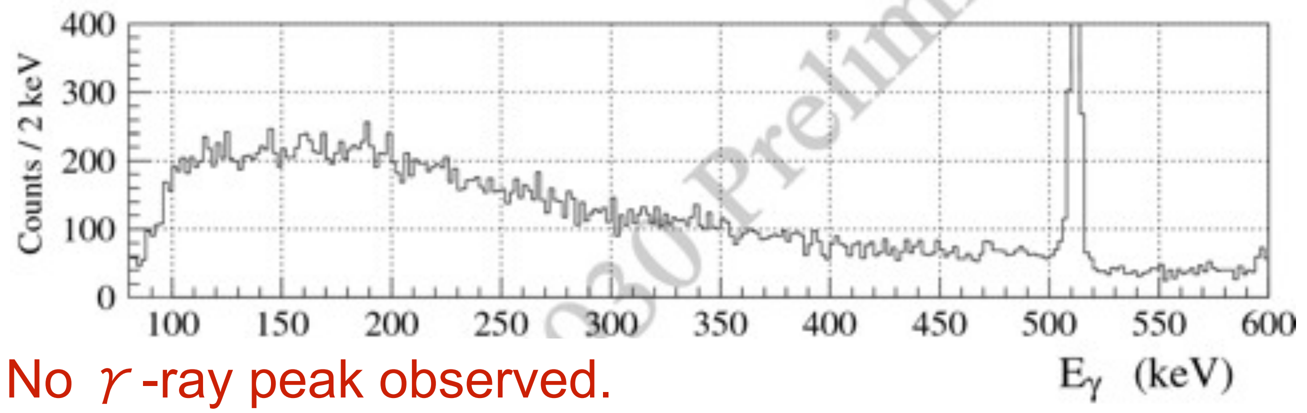
[b] $\Delta E_{core} = E({}^6\text{Li}; 3^+) - E({}^6\text{Li}; 1^+) = 2.186$ MeV.

[c] A small 1^- mixing effect of 0.016 MeV is added to a Λ–Σ coupling effect of −0.030 MeV.

γ spectrum of $^{10}{}_{\Lambda}B$ (E930-2)

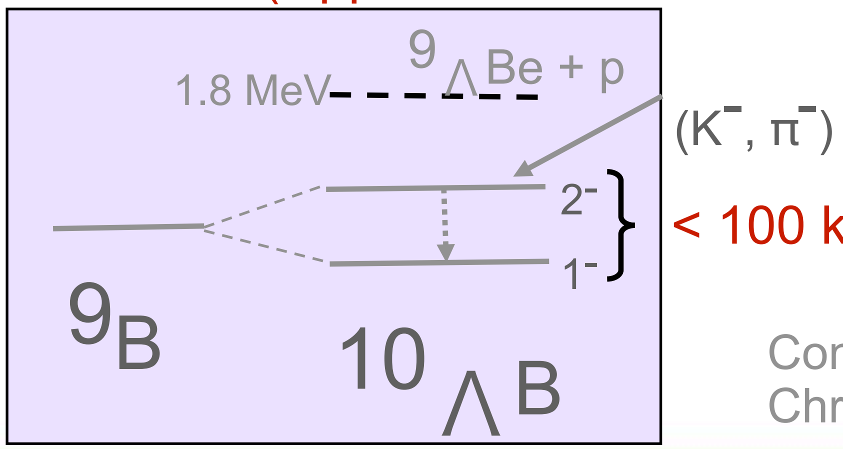
$^{10}B\ (K^-, \pi^-)\ ^{10}{}_{\Lambda}B$

$-40 < -B_{\Lambda}^* < -10$ MeV *uncalibrated
(5 MeV lower than the $^{9}{}_{\Lambda}Be$ gate)



No γ-ray peak observed.

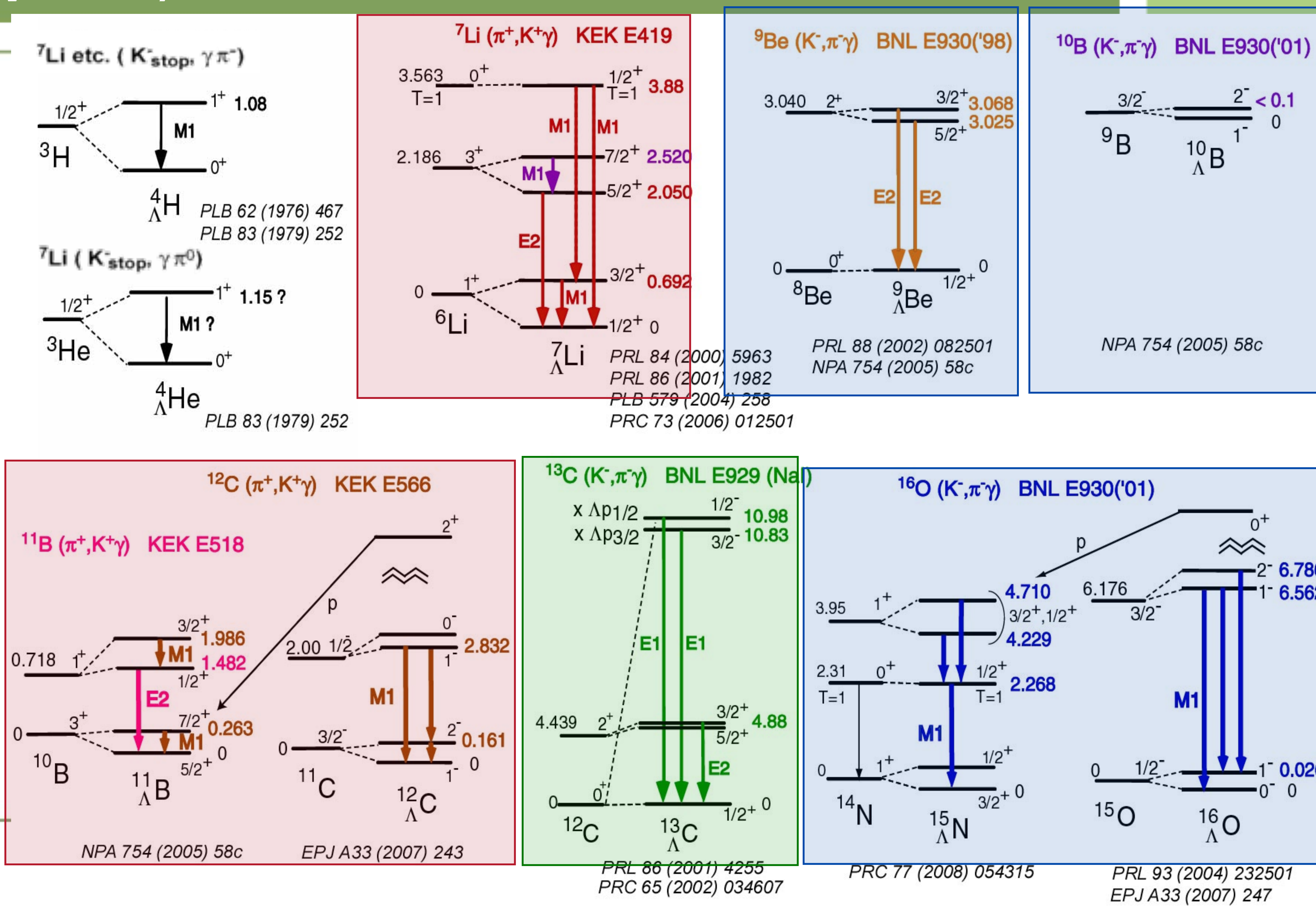
(Upper limit to be determined.)



< 100 keV δ ~ 200 keV from Δ = 0.5 MeV

Confirmed
Chrien et al., Phys. Rev. C 41 (1990) 1062.

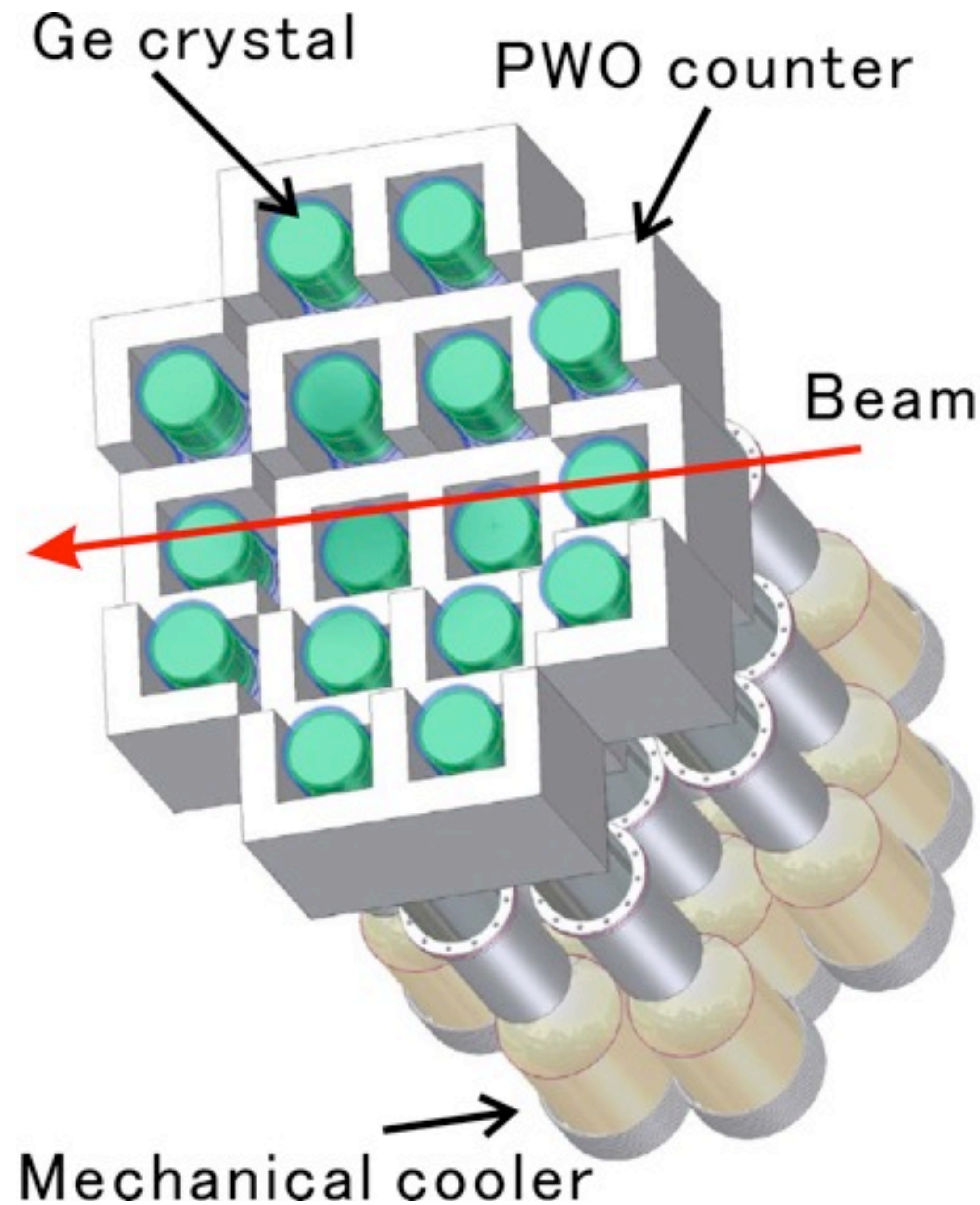
Summary of Hypernuclear γ rays



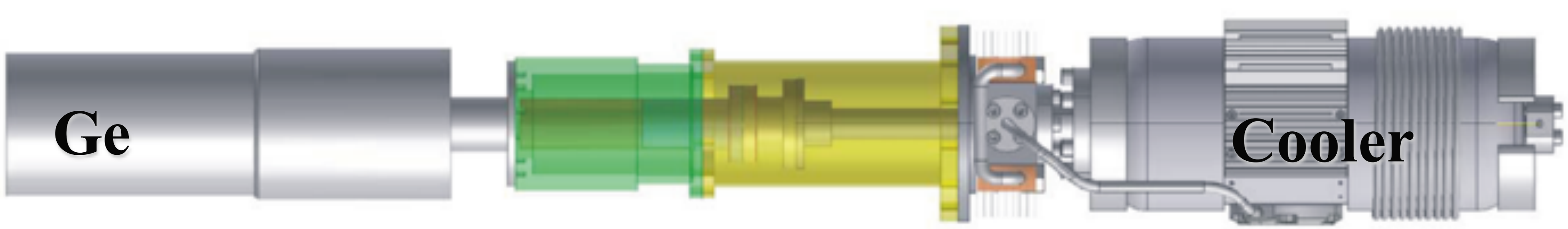
by H.Tamura

Hyperball-J

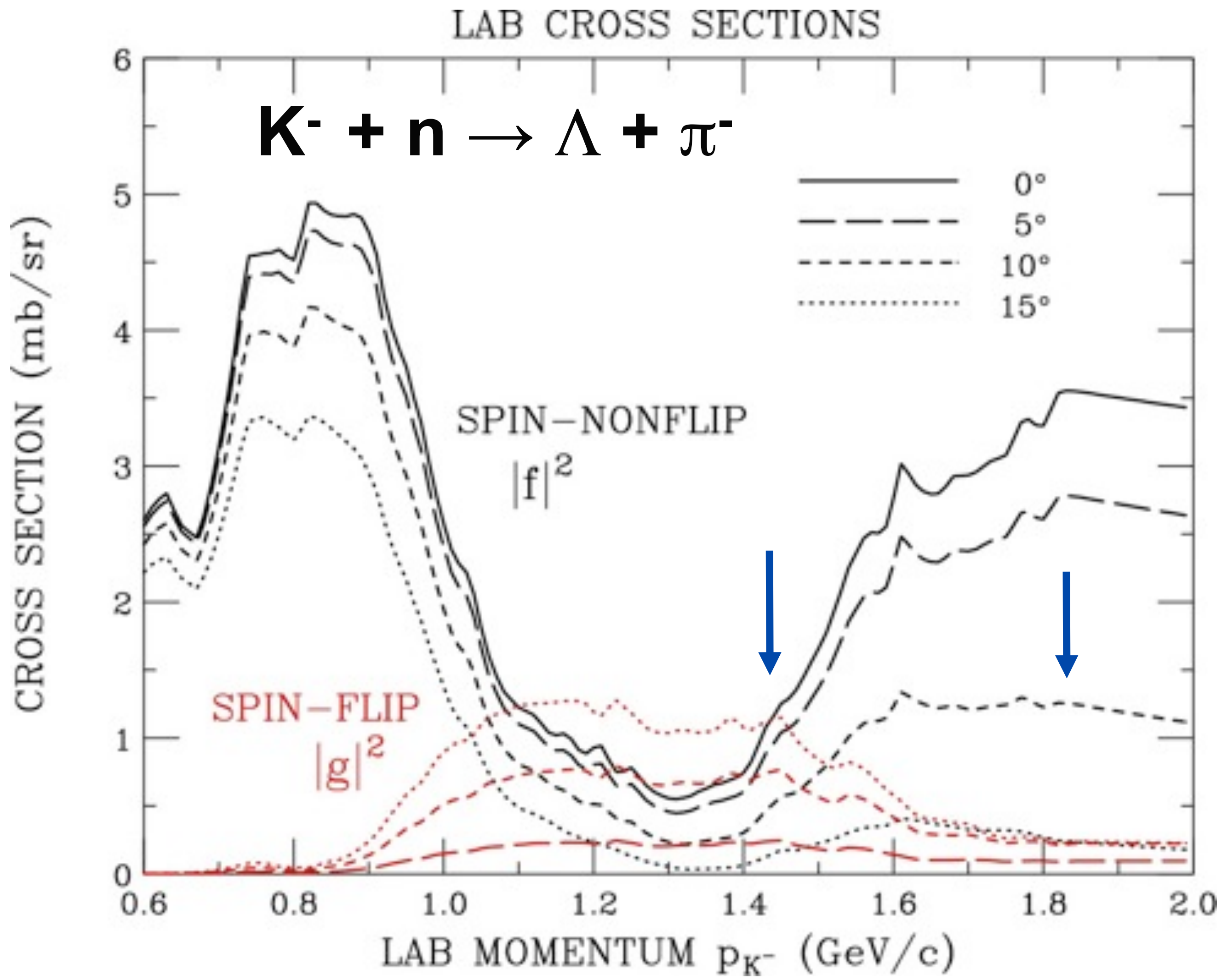
- Ge (single, r.e.~60%) x ~32
  → peak efficiency ~6% at 1 MeV
  (x ~3 of Hyperball)
- Mechanical cooling
  -- Lower temp. for less radiation damage
  -- Save space for flexible arrangement
- PWO background suppression counters replaced from BGO for higher rate
- Waveform readout (under development)
  => Rate limit ~2x10^{7} particles /s
  (x5 of Hyperball)



Lower half



Best K^- beam momentum



Both spin-flip and nonflip states should be produced.

→ p_K = 1.1 or 1.5 GeV/c

p_K = 1.1 GeV/c : K1.1 + "SKS" (ideal)
p_K = 1.5 GeV/c : K1.8 + SKS (realistic)

High K/π ratio to minimize radiation damage to Ge detectors
→ Double-stage separation. K1.8BR is not good.

Beam and Setup

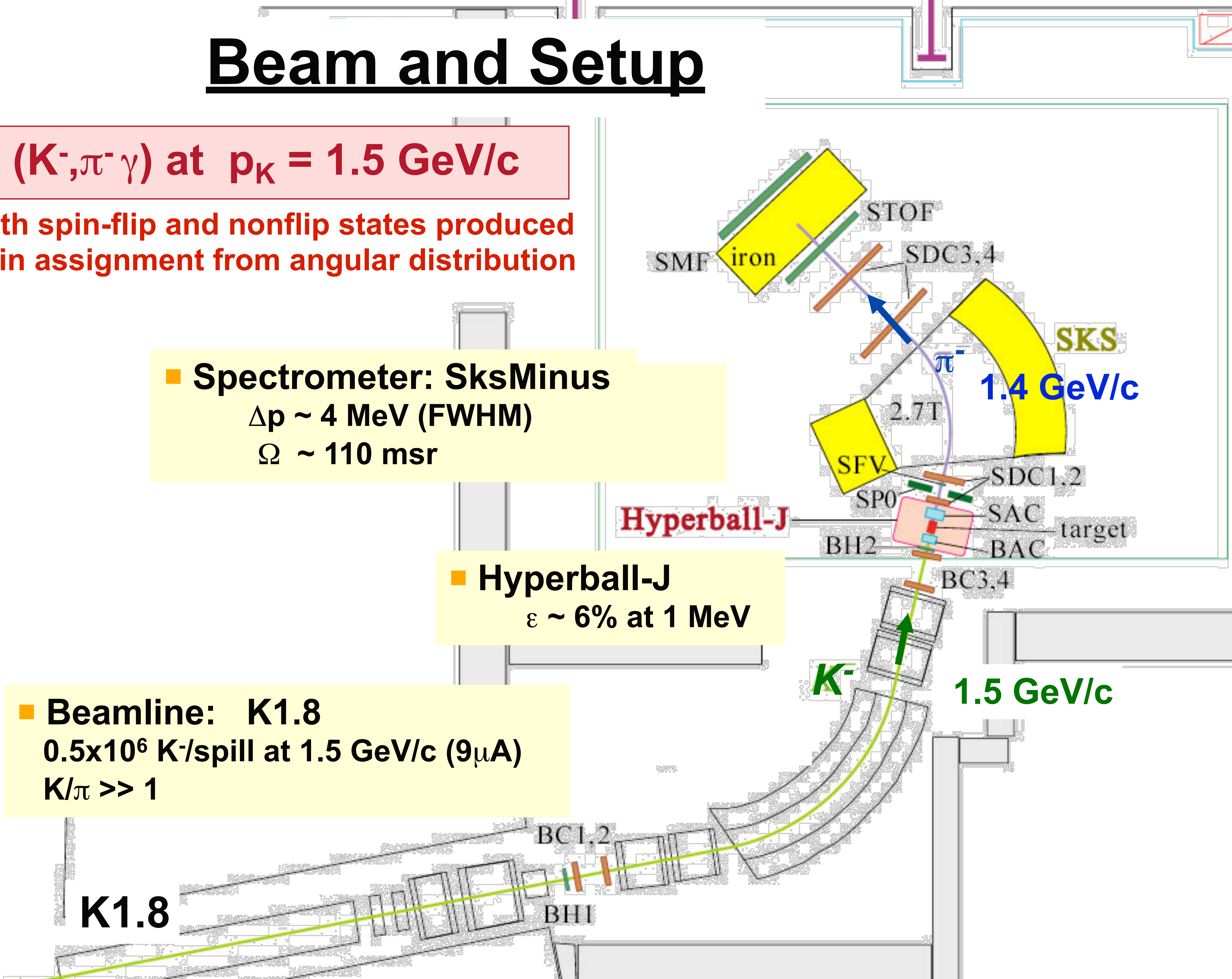
$(K^-,\pi^-\gamma)$ at $p_K = 1.5$ GeV/c

Both spin-flip and nonflip states produced
Spin assignment from angular distribution

- **Spectrometer: SksMinus**
  $\Delta p \sim 4$ MeV (FWHM)
  $\Omega \sim 110$ msr

- **Hyperball-J**
  $\varepsilon \sim 6\%$ at 1 MeV

- **Beamline: K1.8**
  0.5×10^6 K^-/spill at 1.5 GeV/c (9μA)
  $K/\pi >> 1$



g factor of Λ in nucleus

- **Motivation**

  μ_Λ in nucleus -> medium effect of baryons

  Can be investigated using a Λ in 0s orbit

- **B(M1) of Λ-spin-flip M1 transition -> g_Λ**

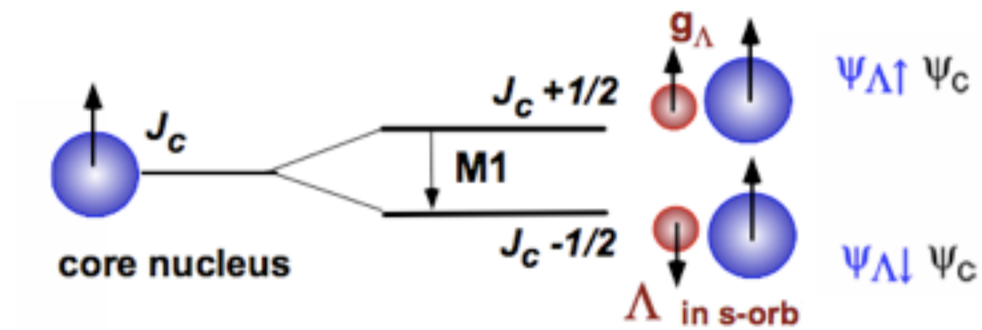
Reduction of constituent q mass? Swelling?

$$B(M1) = (2J_{up}+1)^{-1} |\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$

$$= (2J_{up}+1)^{-1} |\langle \psi_{\Lambda\downarrow} \psi_c \| \mu \| \psi_{\Lambda\uparrow} \psi_c \rangle|^2$$

$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c) J_\Lambda$$

$$= \frac{3}{8\pi} \frac{2J_{low}+1}{2J_c+1} (g_\Lambda - g_c)^2 \quad [\mu_N^2]$$



- **How to measure**

  Doppler-shift attenuation method :

  $$\Gamma = BR / \tau = \frac{16\pi}{9} E_\gamma^3 \, B(M1)$$

  applied to "hypernuclear shrinkage" in $^7_\Lambda$Li ($5/2^+$->$1/2^+$) from B(E2)

  PRL 86 ('01)1982

- **Preliminary data (statistical error only) from $^7_\Lambda$Li ($3/2^+$->$1/2^+$) (BNL E930)**

$$g_\Lambda = -1.1 \, ^{+0.6}_{-0.4} \, \mu_N \Leftrightarrow g_\Lambda(\text{free}) = -1.226 \, \mu_N$$

-> < 5% accuracy at J-APRC

Proposed B(M1) measurement

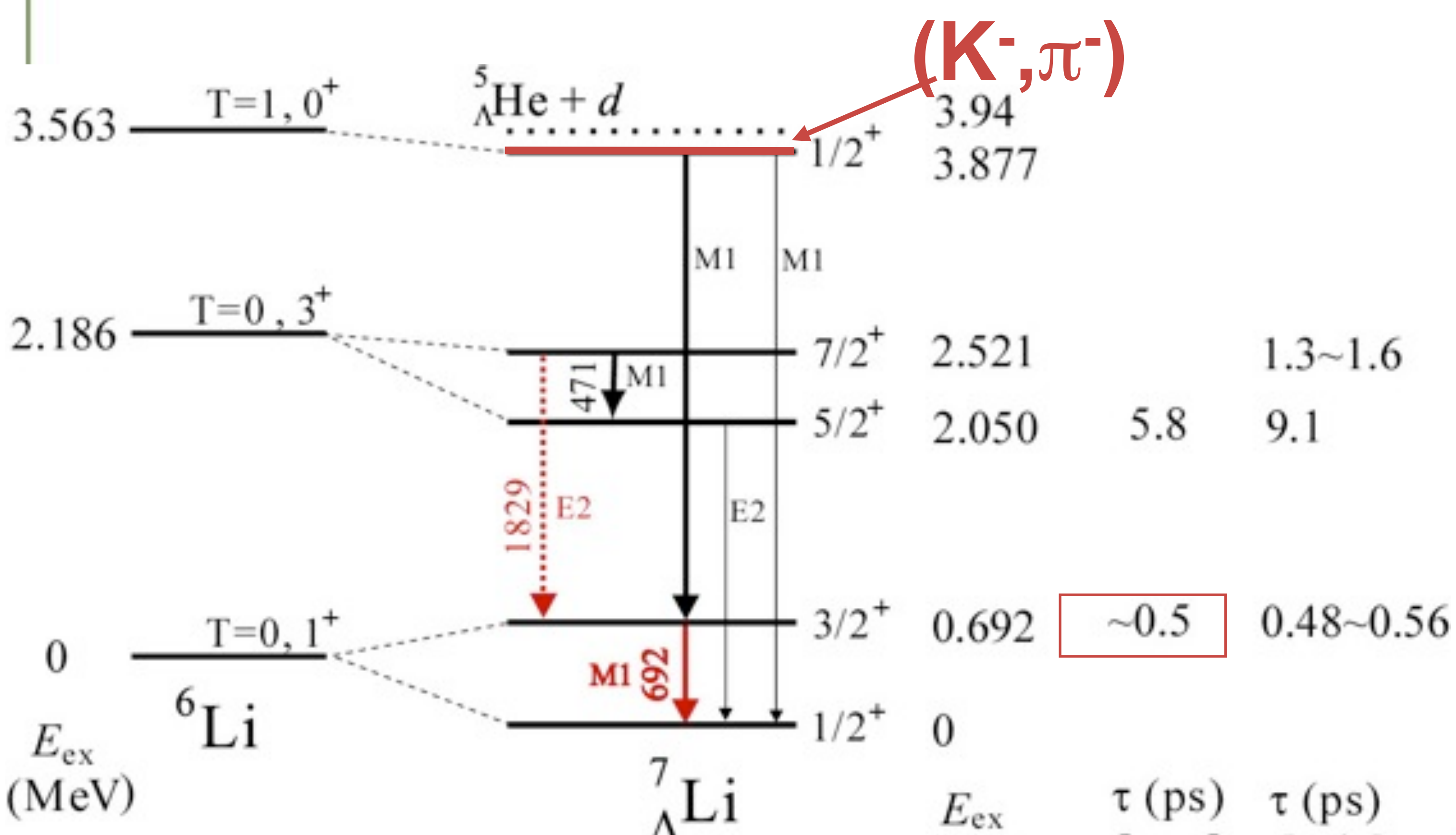
Difficulties in B(M1) measurement

- Doppler Shift Attenuation Method works only when $\tau \lesssim t_{stop}$
- τ is very sensitive to E_γ because $B(M1) \propto 1/\tau \propto E_\gamma^3$. But E_γ is unknown.
- Cross sections and background cannot be accurately estimated.

Previous attempts: ${}^{10}_{\Lambda}B$, ${}^{11}_{\Lambda}B$ (E_γ too small → τ >> t_{stop}), ${}^{7}_{\Lambda}Li$ (by product: indirect population)

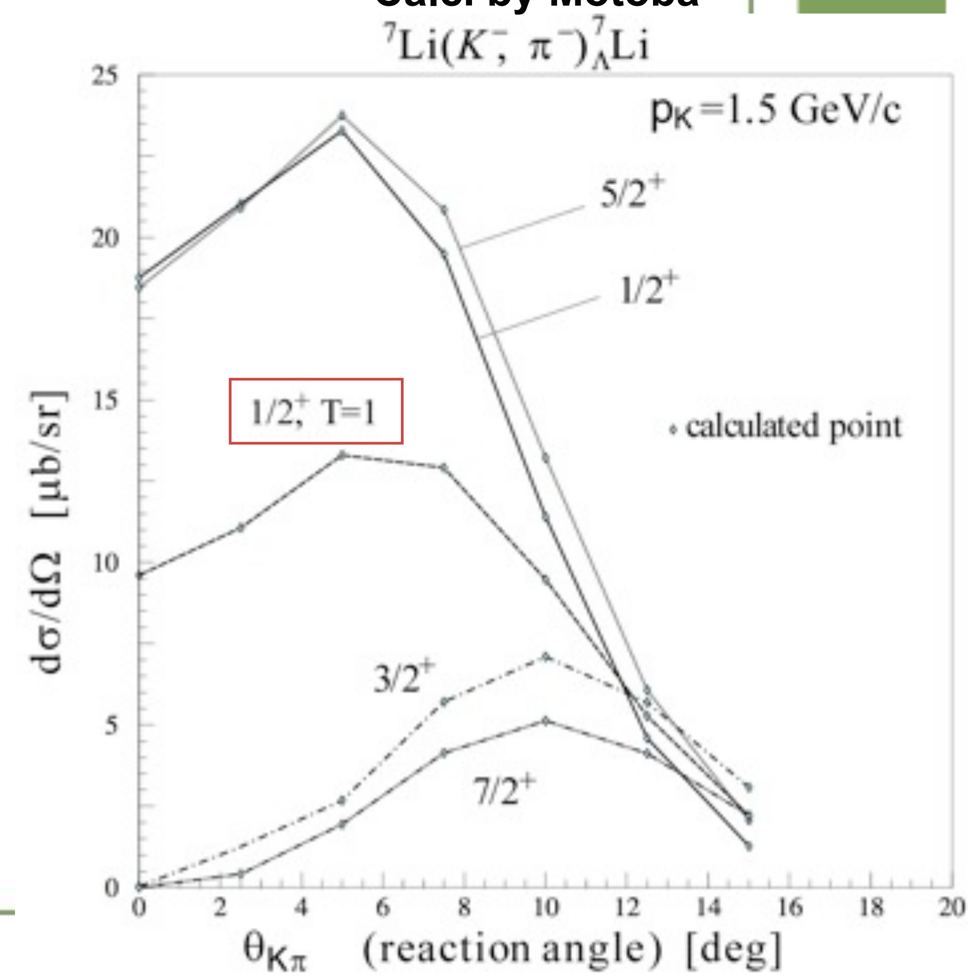
To avoid ambiguities, we use the best-known hypernucleus, ${}^{7}_{\Lambda}Li$.

- Energies of all the bound states and B(E2) were measured,
- γ-ray background level was measured,
- cross sections are reliably calculated.
- τ = 0.5ps, t_{stop} = 2-3 ps for 1.5 GeV/c (K^-,π^-) and Li_2O target



PRL 84 (2000) 5963
PRC 73 (2006) 012501

Calc. by Motoba



Expected yield and sensitivity

Yield estimate

$N_K = 0.5 \times 10^6$ /spill

Target (^{7}Li in Li_2O) = 20cm x 2.0g/cm^3 x 14/30 x 0.934 / 7 x 6.02×10^{23}

$\int d\sigma/d\Omega(1/2;1)\ \Delta\Omega$ x BR($1/2^+;1\rightarrow3/2^+$) = 0.84 μb x 0.5

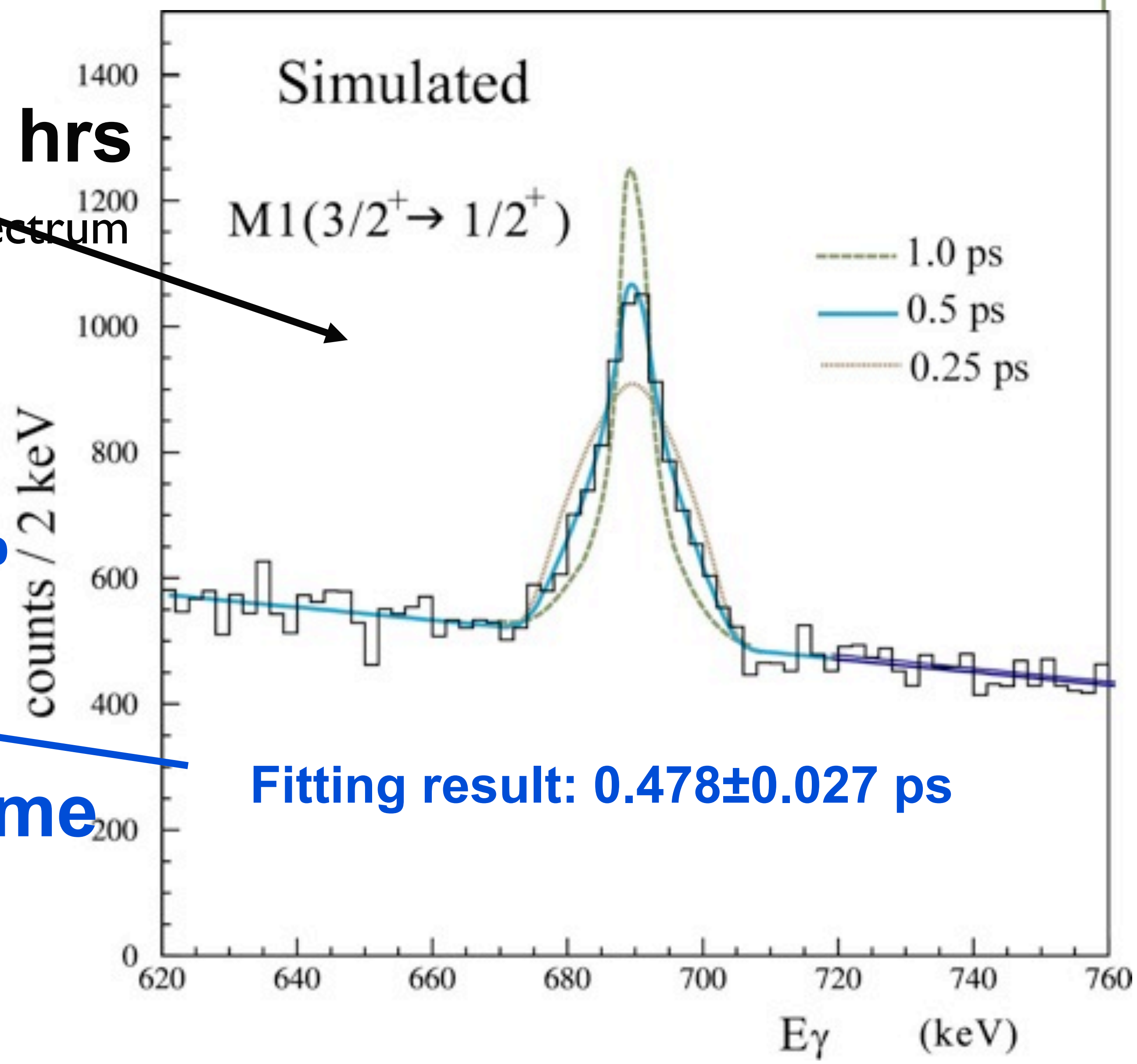
ε(Ge) x ε (tracking) = 0.7 x 0.6

→

Yield ($3/2^+\rightarrow1/2^+$) = 7.3 /hr(1000 spill)

= 3600 / 500 hrs

Background estimated from E419 $^7_\Lambda$Li spectrum



Fitting result: 0.478±0.027 ps

- **Stat. error $\Delta\tau/\tau$ = 5.4%**

→ $\dfrac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|}$ **~ 3%**

- **Syst. error < 5%**
mainly from stopping time

Σ Hypernuclei

History of Σ Hypernuclei

- ✓ Σ^- atom X-ray：Level shifts, widths
  - CERN('75), RAL('78), BNL('93)
  - $^{12}C \sim ^{208}Pb$, 23 data points
  - $V_{opt}(r) = t_{eff} \bullet \rho(r)$ (C.J.Batty, Nucl. Phys. A372 (81) 433)
    - $-\mathrm{Re}\, V_{opt}(0) \sim$ 25-30 MeV, Attractive
    - $-\mathrm{Im}\, V_{opt}(0) \sim$ 10-15 MeV, Absorptive
      - $\Sigma N \rightarrow \Lambda N$ conversion (strong interaction)
  - Σ hypernuclei may exist, but the widths are broad
  - No Spectroscopy $\Gamma \sim 2\mathrm{Im}V$

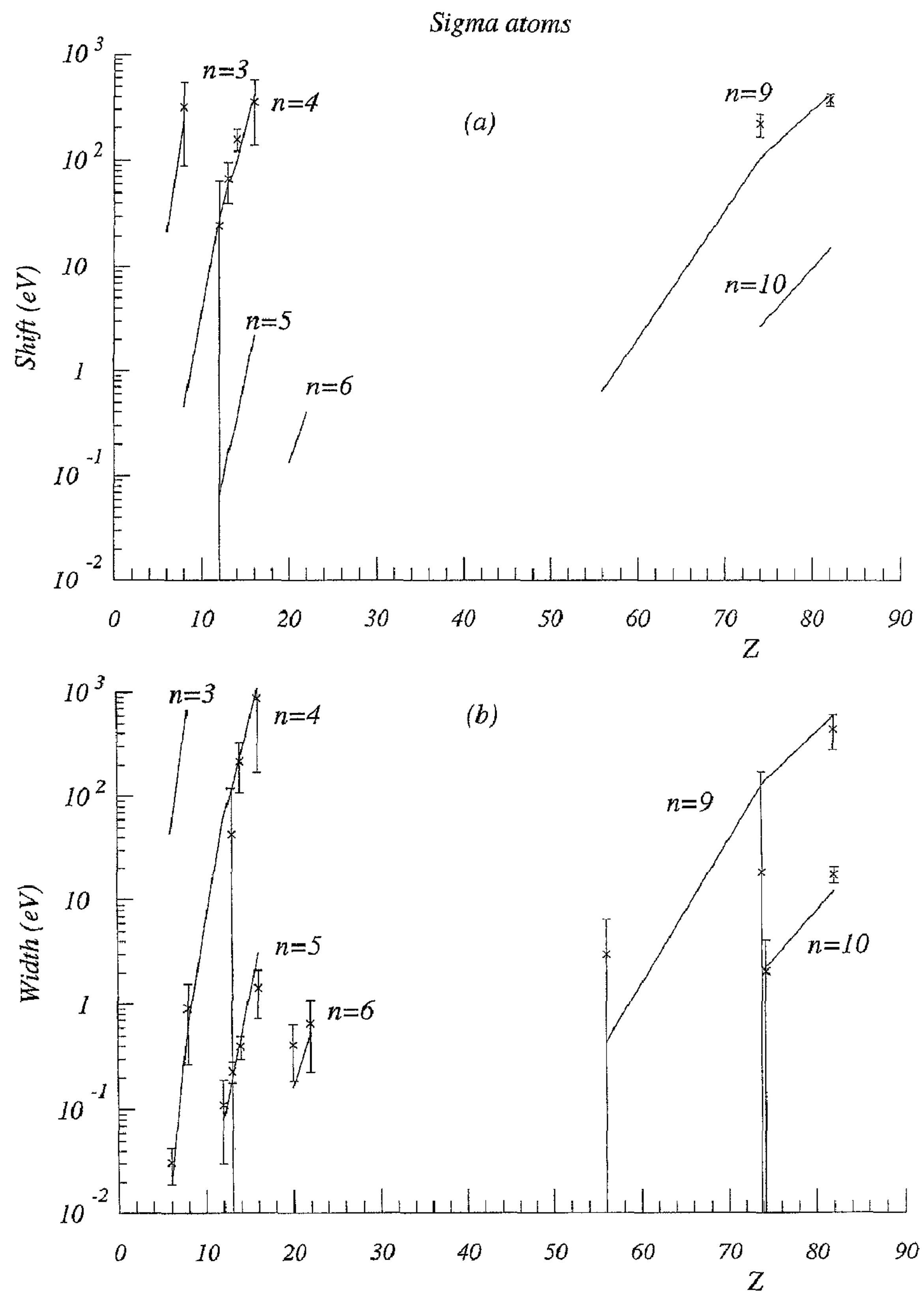


Fig. 9. Shift and width values for sigma atoms. The continuous lines join points calculated with the best-fit optical potential discussed in Section 6.2.

Σ-Nucleus potential

- Σ-atom X-ray

C.J.Batty et al., NP A372(81)433.

$$V(r) + iW(r) = -\left(\frac{4\pi\hbar^2}{2\mu}\right)\left(1 + \frac{\mu}{M_N}\right)\bar{a}\rho(r)$$
$$= -(28 + i15)MeV\rho(r)/\rho_0$$

$\bar{a} = 0.35 + i0.19 : scattering - length,$

$\mu : reduced - mass$

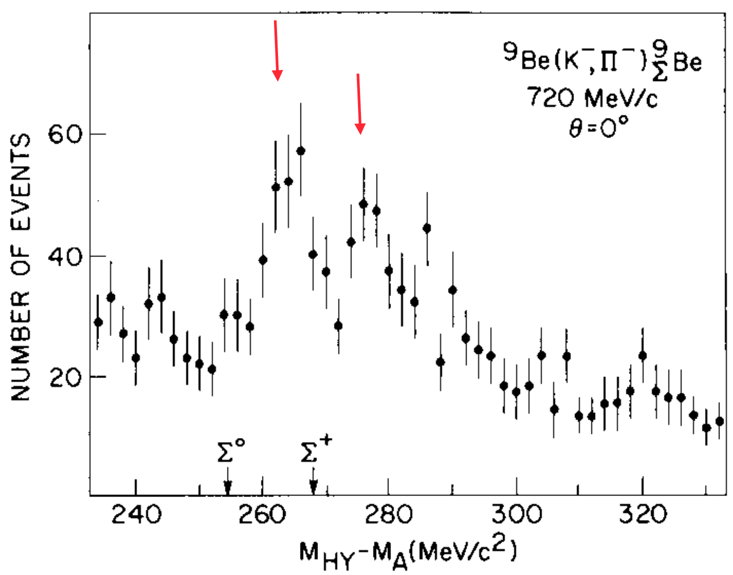
- DWIA analysis: Green Function method

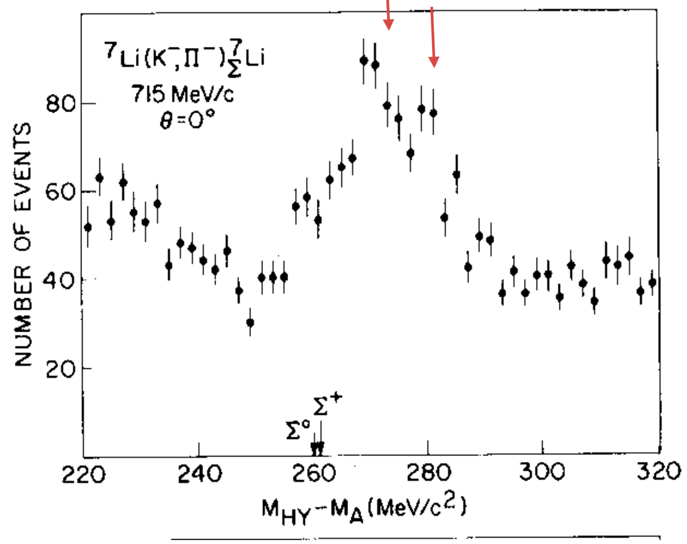
Morimatsu and Yazaki, NP A483(88)493,
R.S.Hayano, NP A478(88)113c.

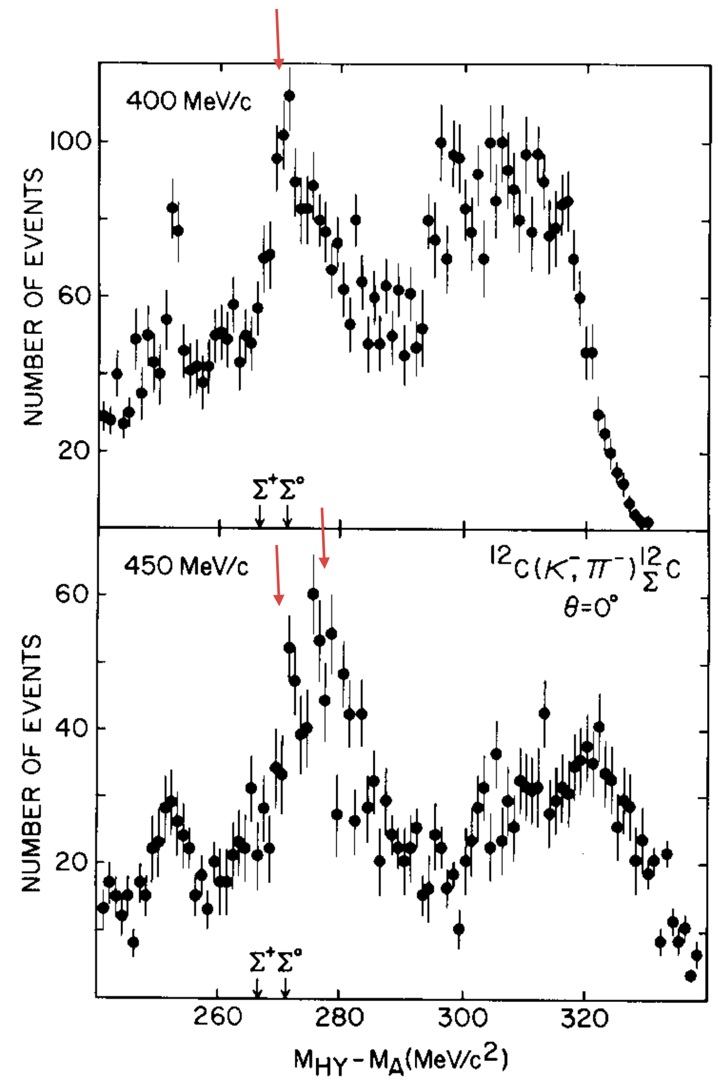
V_0<12 MeV, W_0>6 MeV for ^{12}C

Narrow width problem in 1980s

- ✓ ^{9}Be(K$^-$,π$^-$) at CERN(1980)
  - Narrow peak(~7 MeV) in unbound region
  - – BNL, KEK



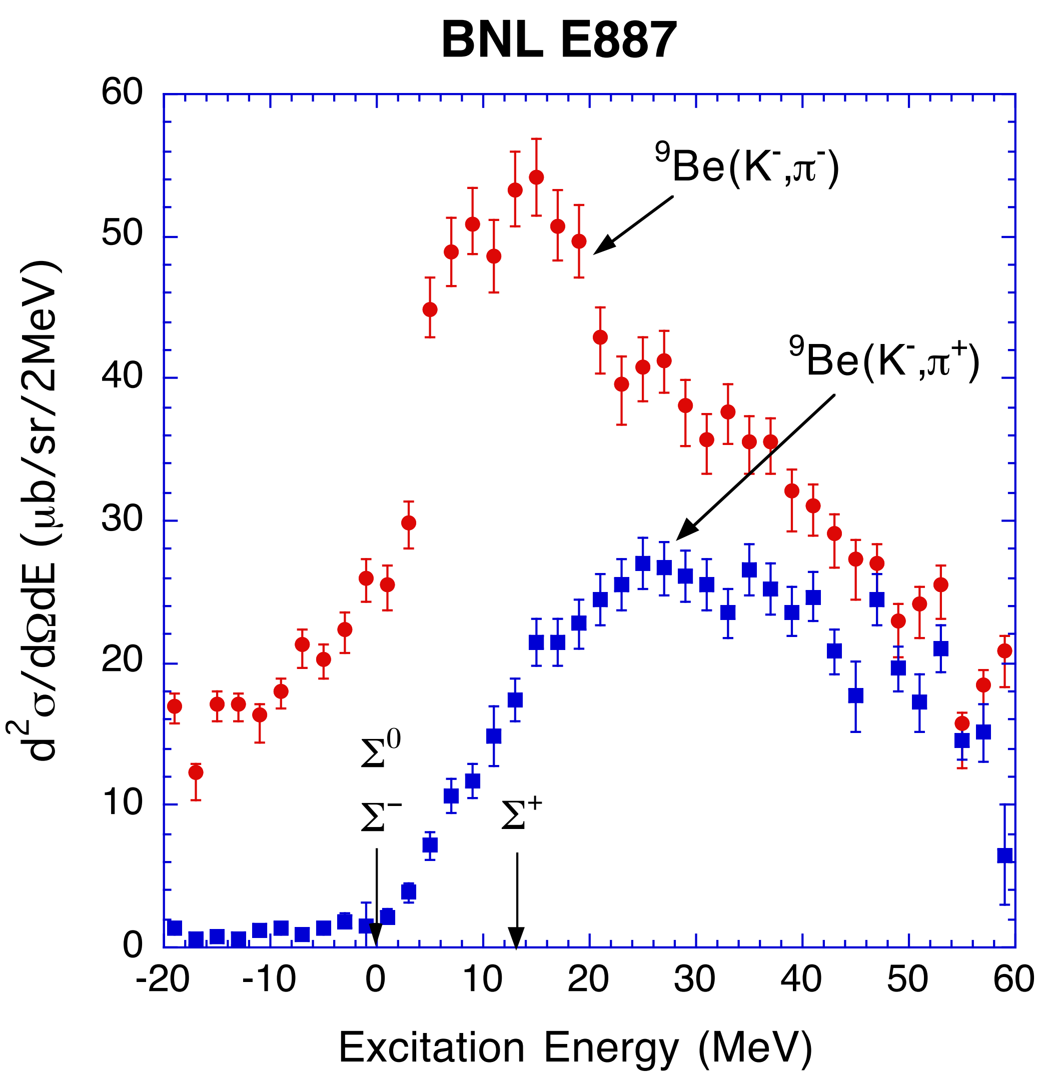




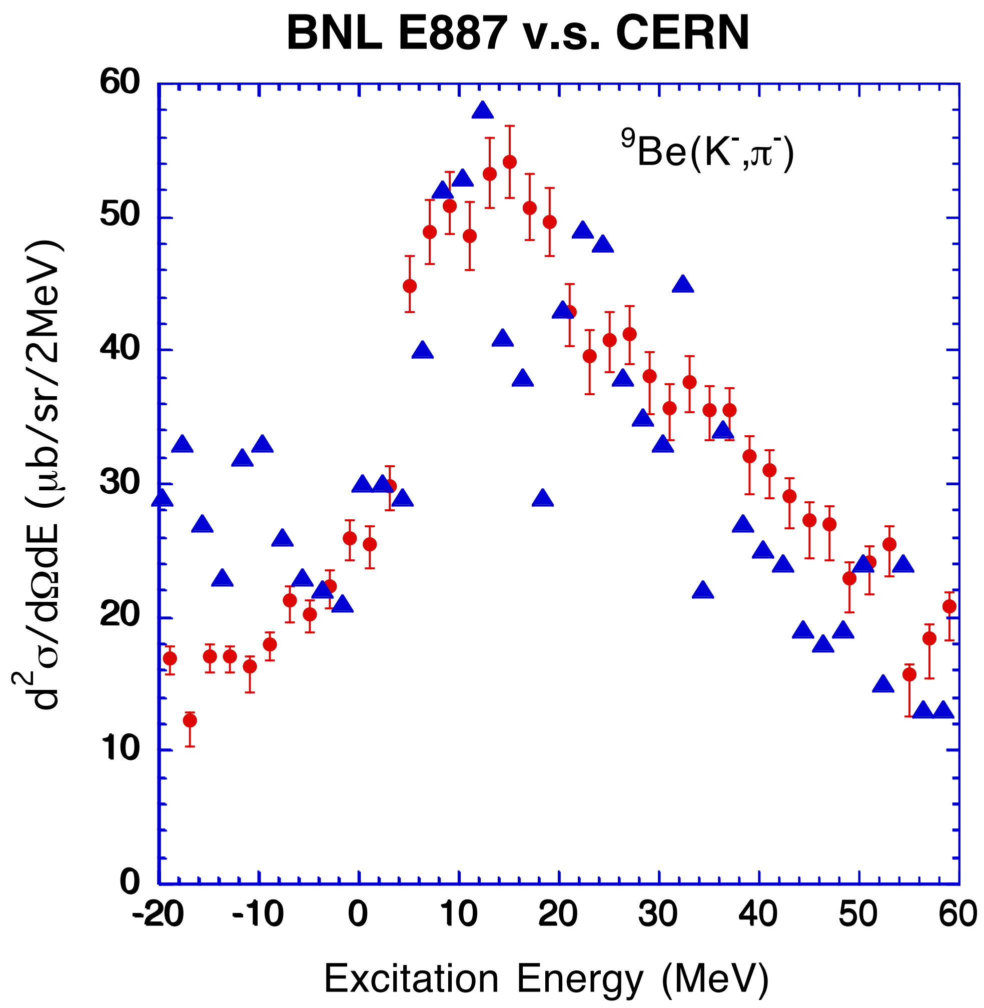
BNL E887

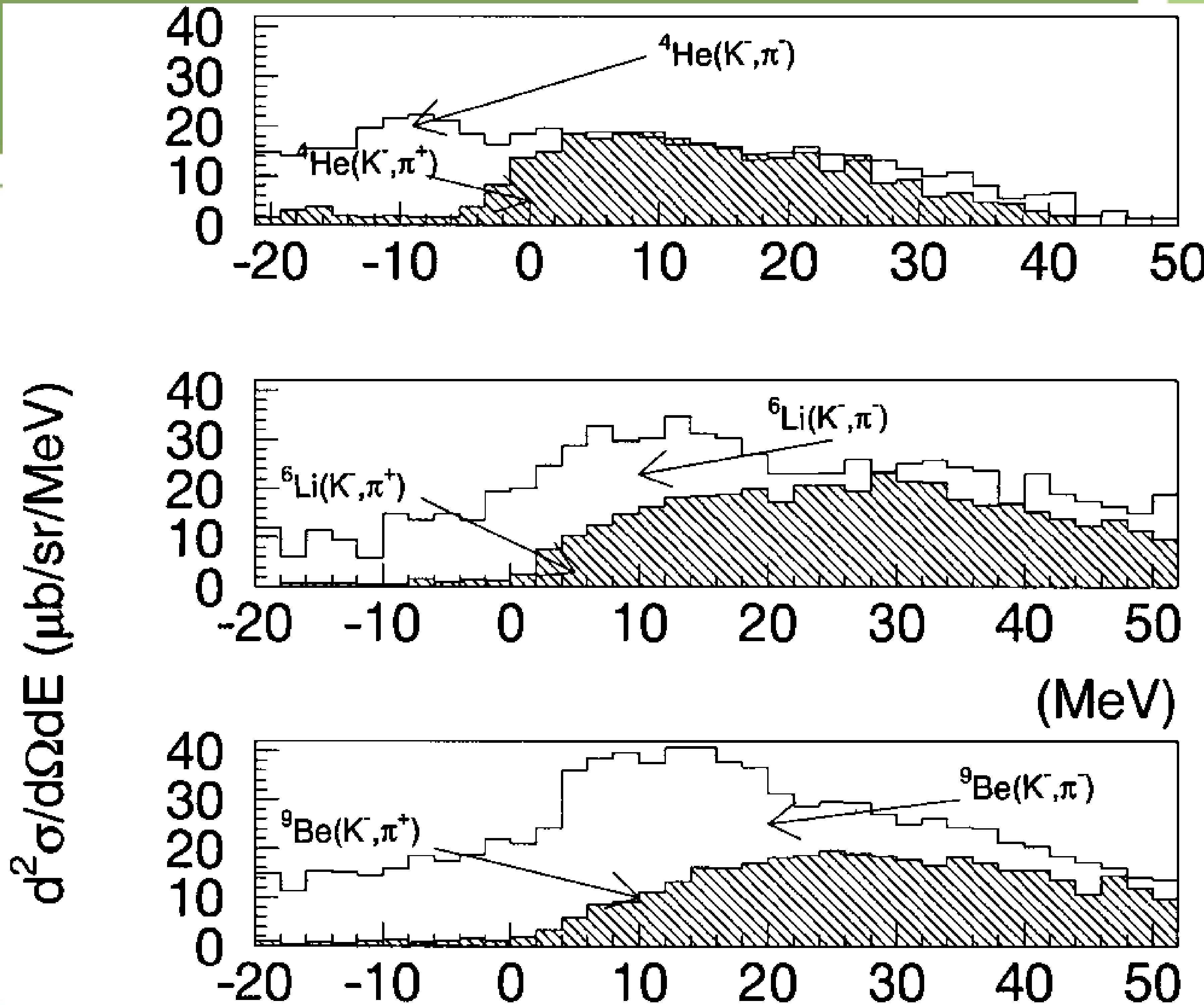
- ✓ 600 MeV/c
- ✓ 4 degrees

- ✓ No Peaks !!



E887 vs. CERN Data





S. Bart et al., PRL 83 (1999) 5238.

束縛状態の問題

- ポテンシャルの実部の深さ？
  - Σ原子のX線データの密度依存型ポテンシャルによる再解析
    - 弱い引力：原子核外部の長距離
    - 強い斥力：原子核内部

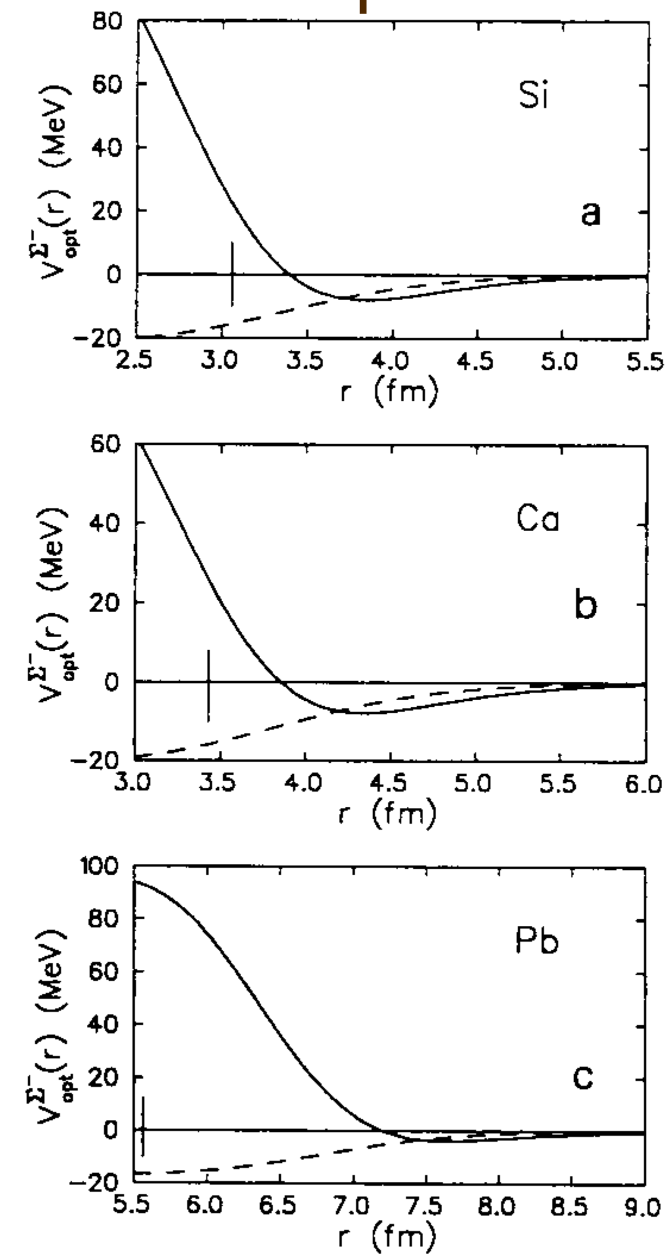
$$2\mu V_{opt}(r) = -4\pi\left(1+\frac{\mu}{m_n}\right)\left\{\left[b_0 + B_0\left(\frac{\rho(r)}{\rho(0)}\right)^{\alpha}\right]\rho(r) + \left[b_1 + B_1\left(\frac{\rho(r)}{\rho(0)}\right)^{\alpha}\right]\delta\rho(r)\right\}$$

    - 軽い核を除いて、束縛状態は存在しない!?

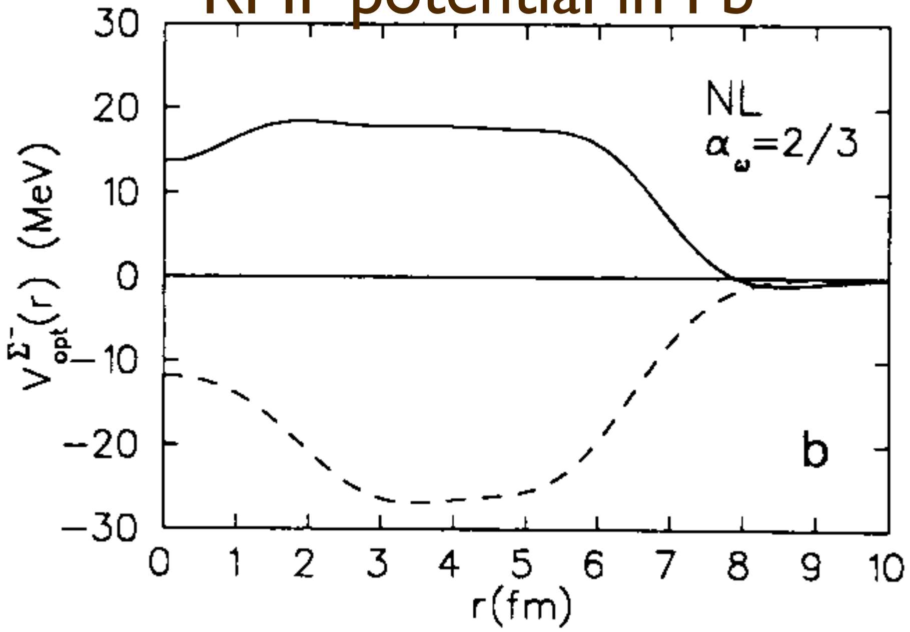
Repulsive ??

- C.J.Batty,E.Friedman,A.Gal, Phys.Lett.B335(94)273; PTP Suppl.117(94)227.
- J.Mares et al., NP A594(95)311.

DD potential

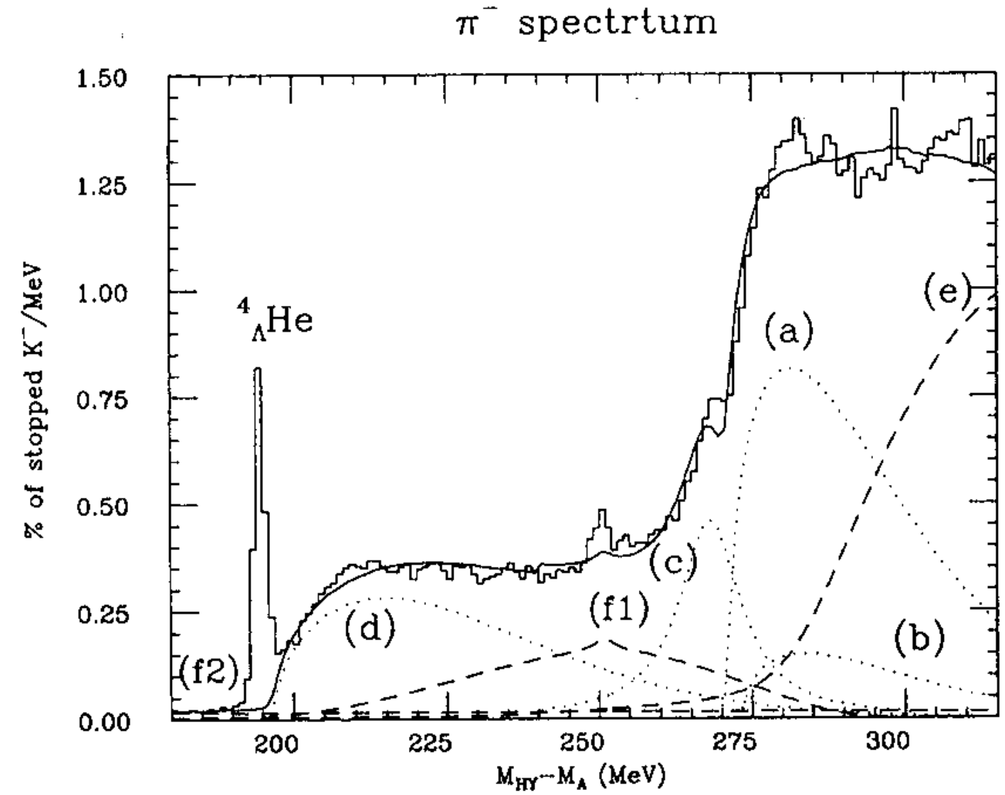


RMF potential in Pb



Existence of any bound states ?

- ✓ Only candidate
  - $^4He(K^-_{stop},\pi^-)$: R.S.Hayano et al.
  - predicted by Harada and Akaishi
- ✓ Definitive evidence ?
  - Large bakcground
  - K^- orbit
    - *S or P ?*



B_Σ=2.8±0.7 MeV

Γ_Σ=12.1±1.2 MeV

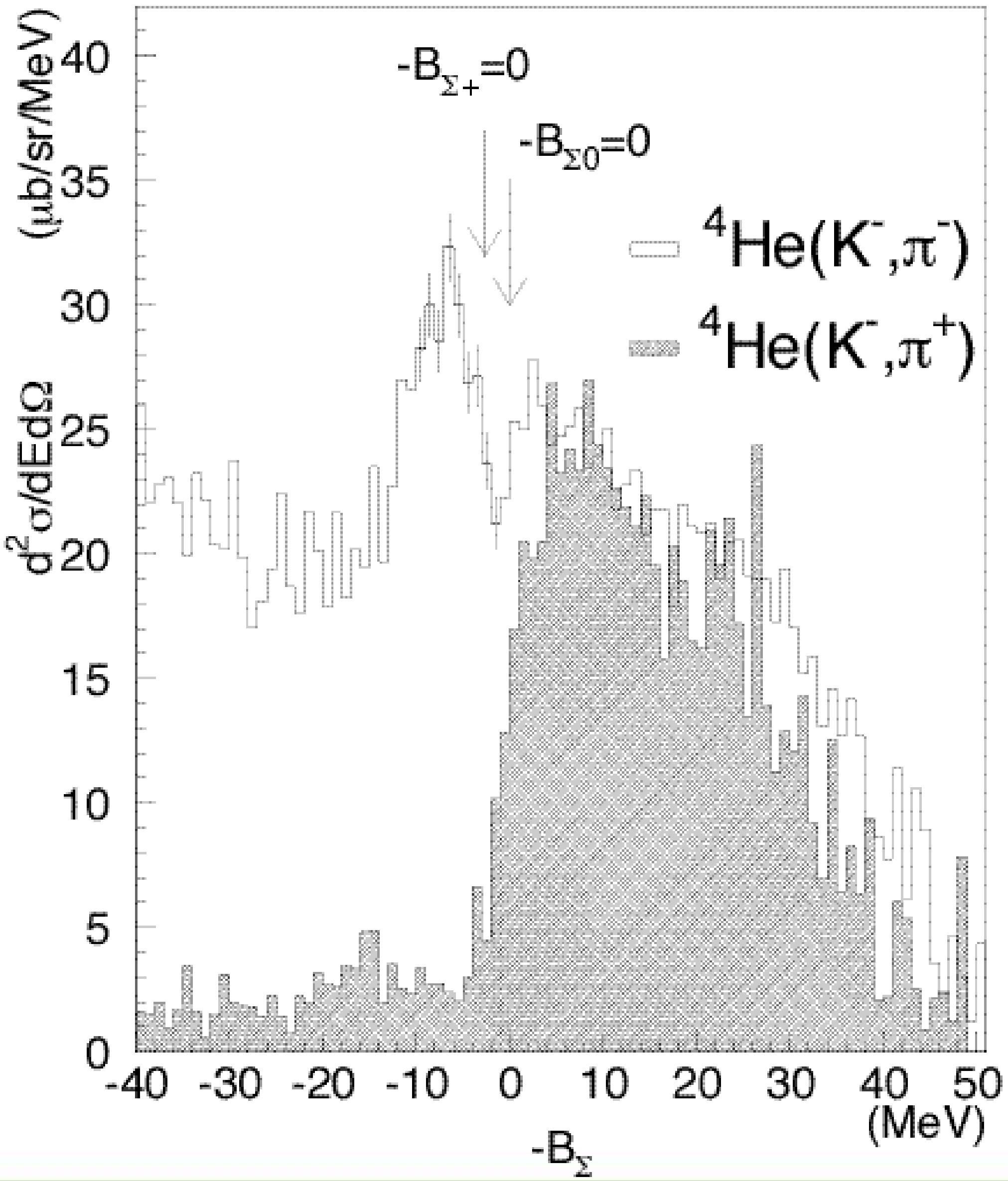
R.S. Hayano et al., PL B231 (1989).

H.Outa et al., Prog. Theor. Phys. Suppl. 117 (1994) 177.

BNL E905: In-flight (K^-,π^-)

T. Nagae et al., PRL 80 (1998) 1605.

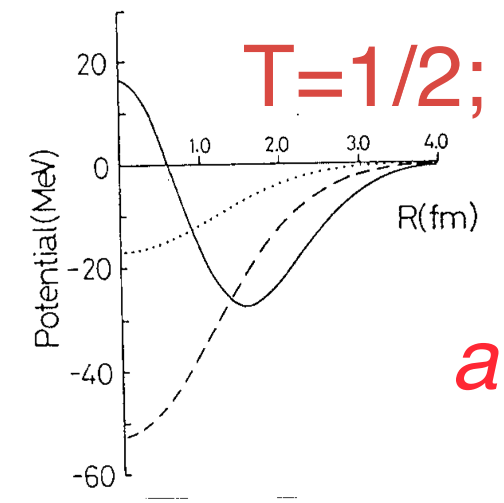
- ✓ 600 MeV/c, 4 deg.
- ✓ Simple analysis: DWIA
- ✓ Established the existence of a bound state
  - B_Σ : 4.4±0.3±1 MeV
  - Width : 7±0.7+1.2/-0.0 MeV (FWHM)



Harada and Akaishi

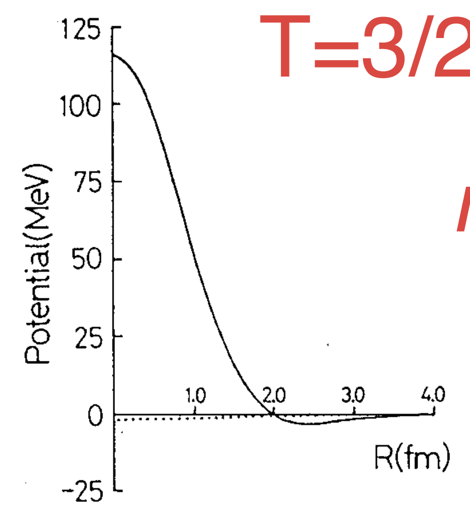
- ✓ Strong Isospin dependence
  - Lane term
  - $U_{C\Sigma} = U^0 + U^t T_C \cdot t_\Sigma / A$

- T. Harada et al., Nucl. Phys. A507(1990) 715.
- T. Harada, PRL 81 (1998) 5287.



T=1/2; $U^0 - U^t$

attractive



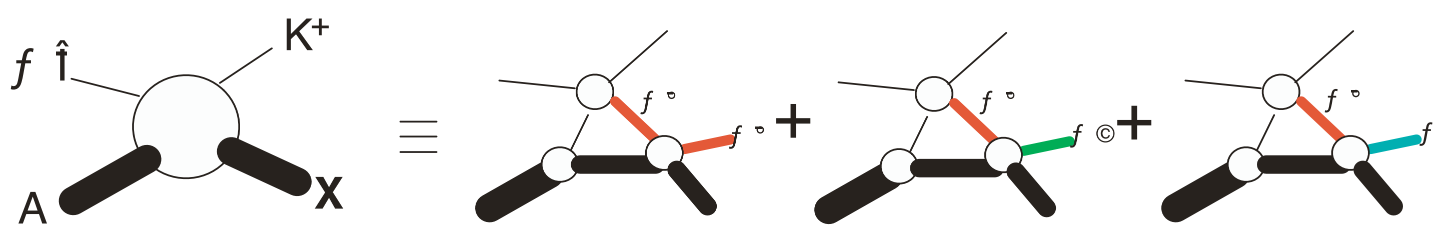
T=3/2; $U^0 + 1/2U^t$

repulsive

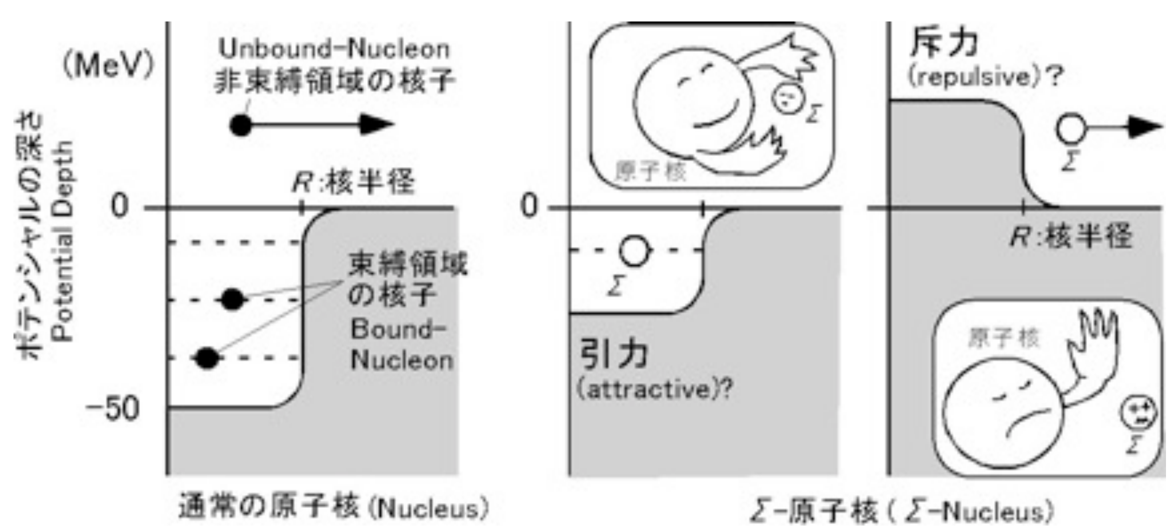
E438: Study of Σ-nucleus potential by the (π^-,K^+) reaction on heavy nuclei

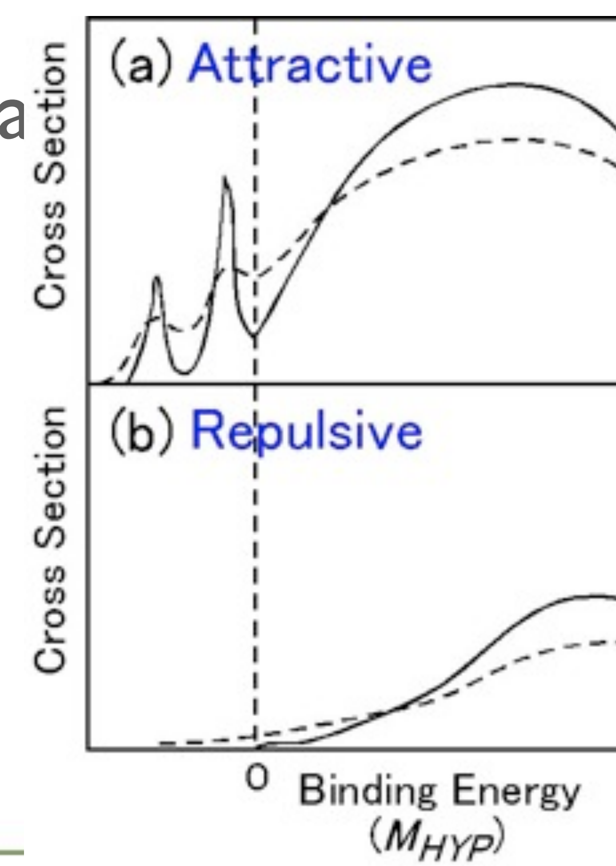
$U_\Sigma = V_\Sigma + i W_\Sigma$

No Σ-hypernuclear bound states, but $^4_\Sigma$He



Inclusive spectrum tells the Σ potential

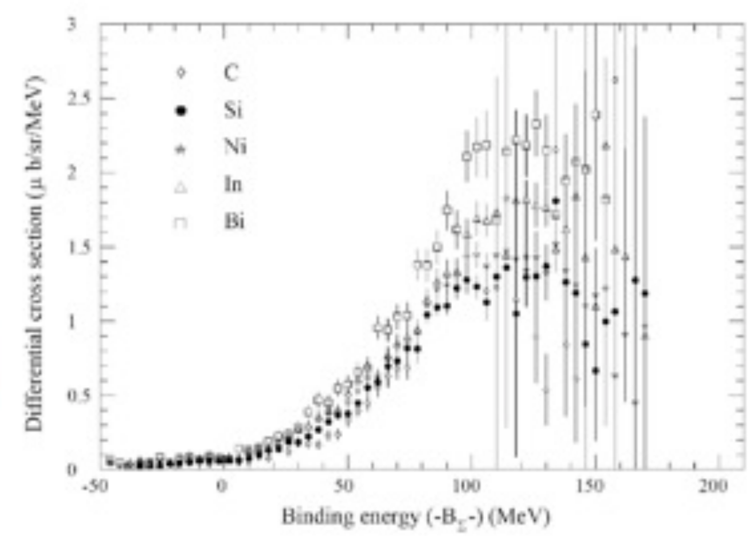


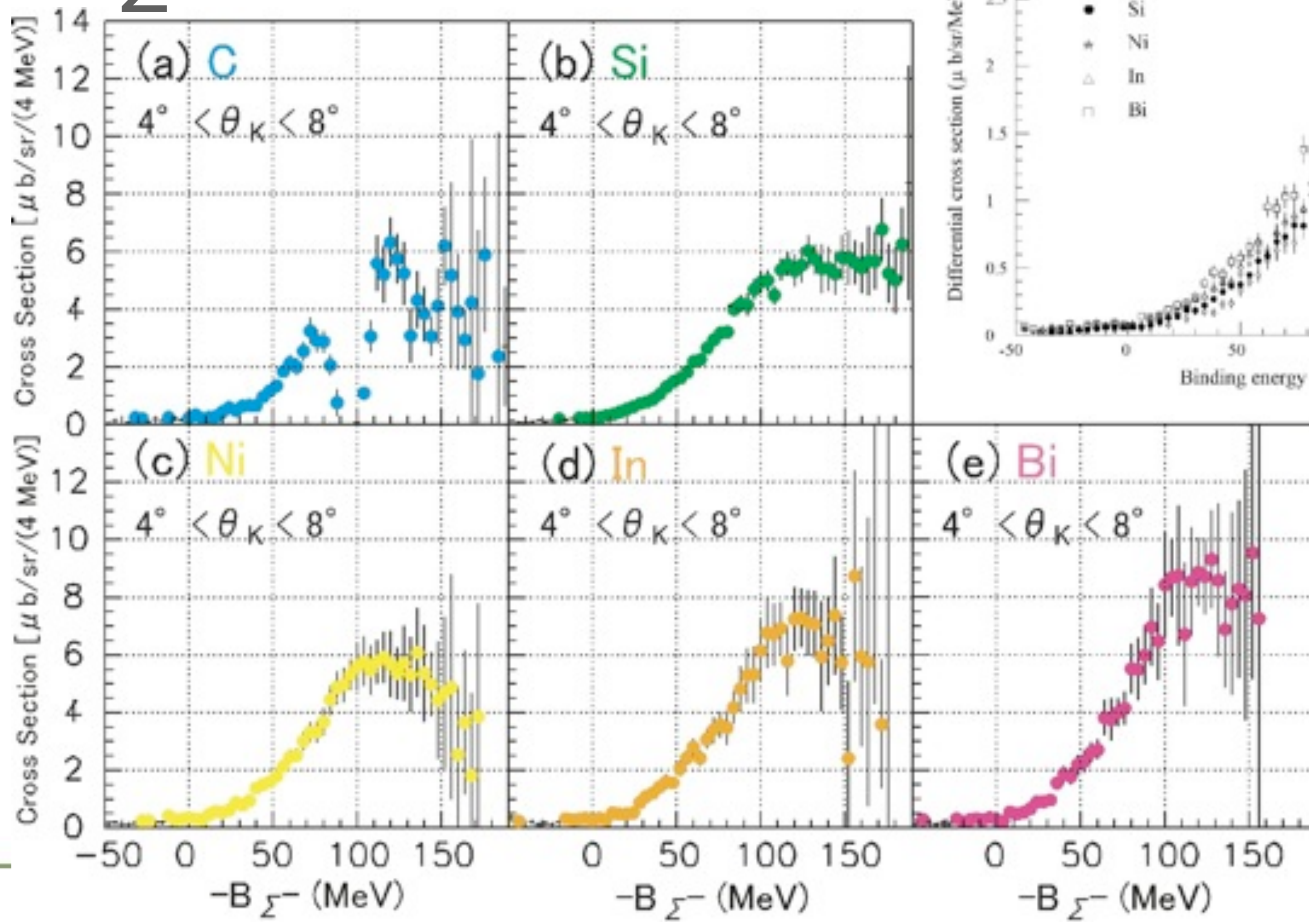


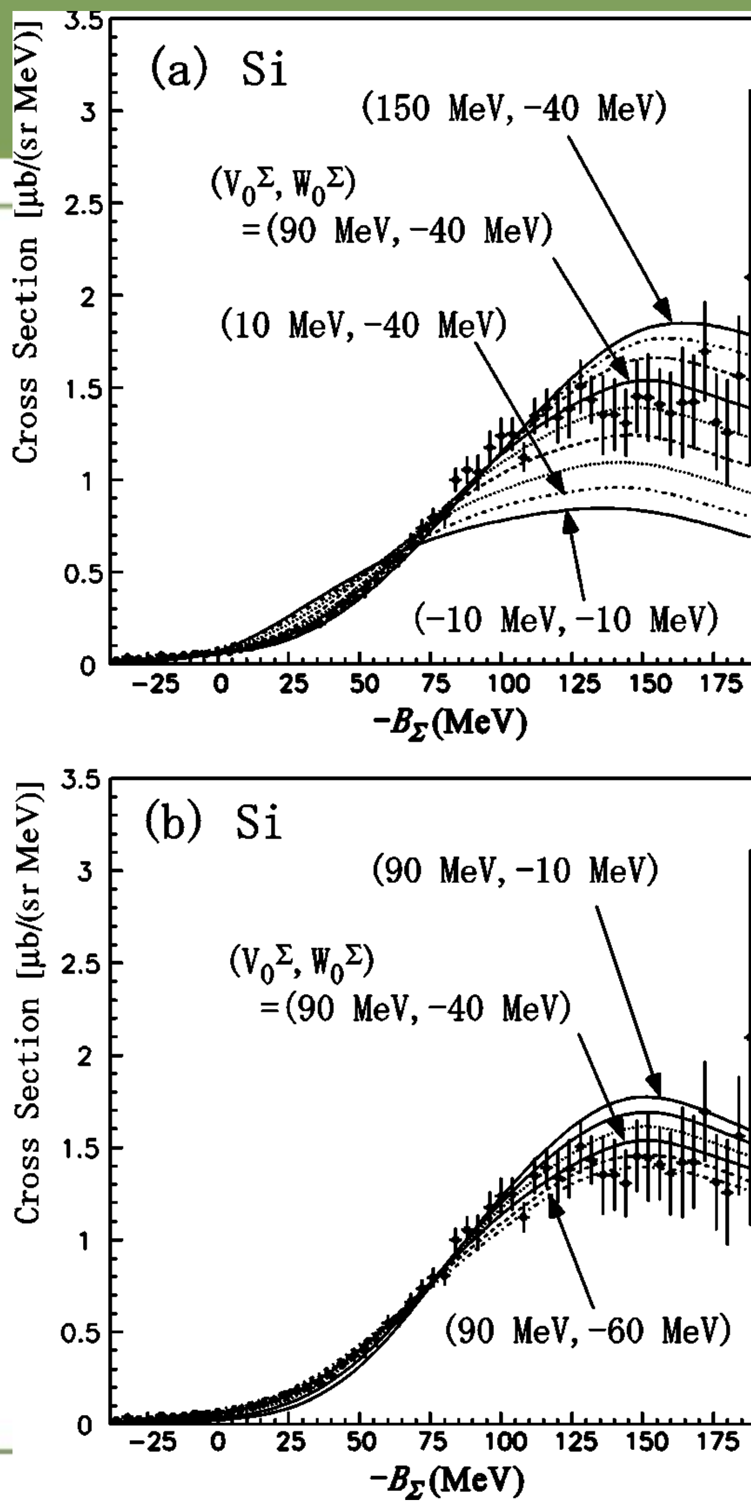
Measured Inclusive (π^-,K^+) Spectra on C, Si, Ni, In, & Bi

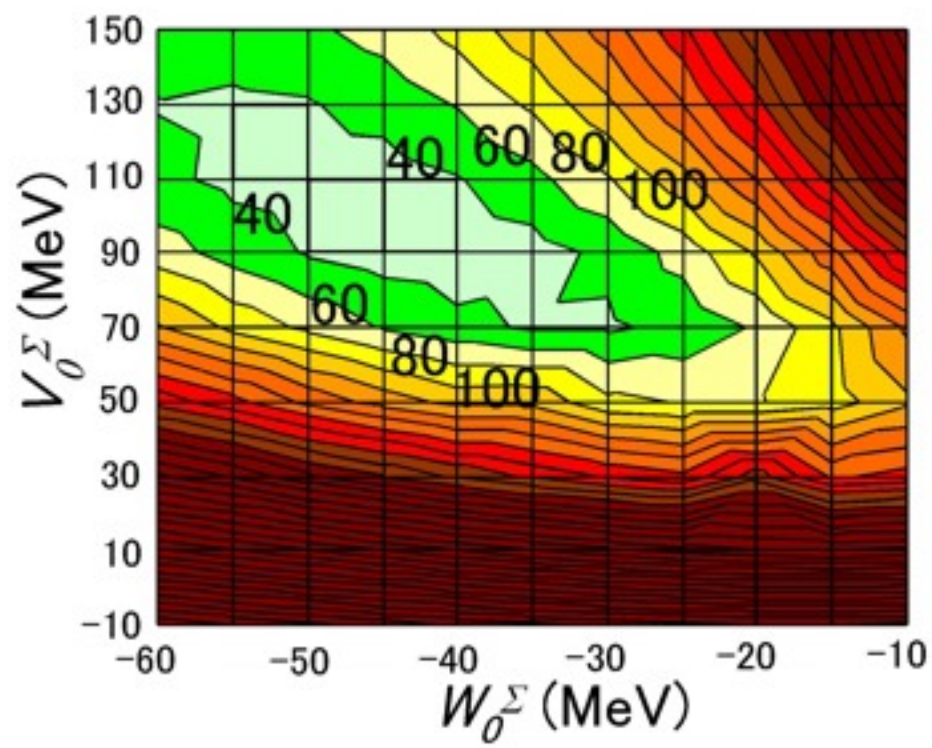
- Similar Shape
- No peak in $-B_{\Sigma^-} < 0$ MeV
- Maximum @ $-B_{\Sigma^-} > 120$ MeV

P.K. Saha et al., Phys. Rev. C 70 (2004) 044613.







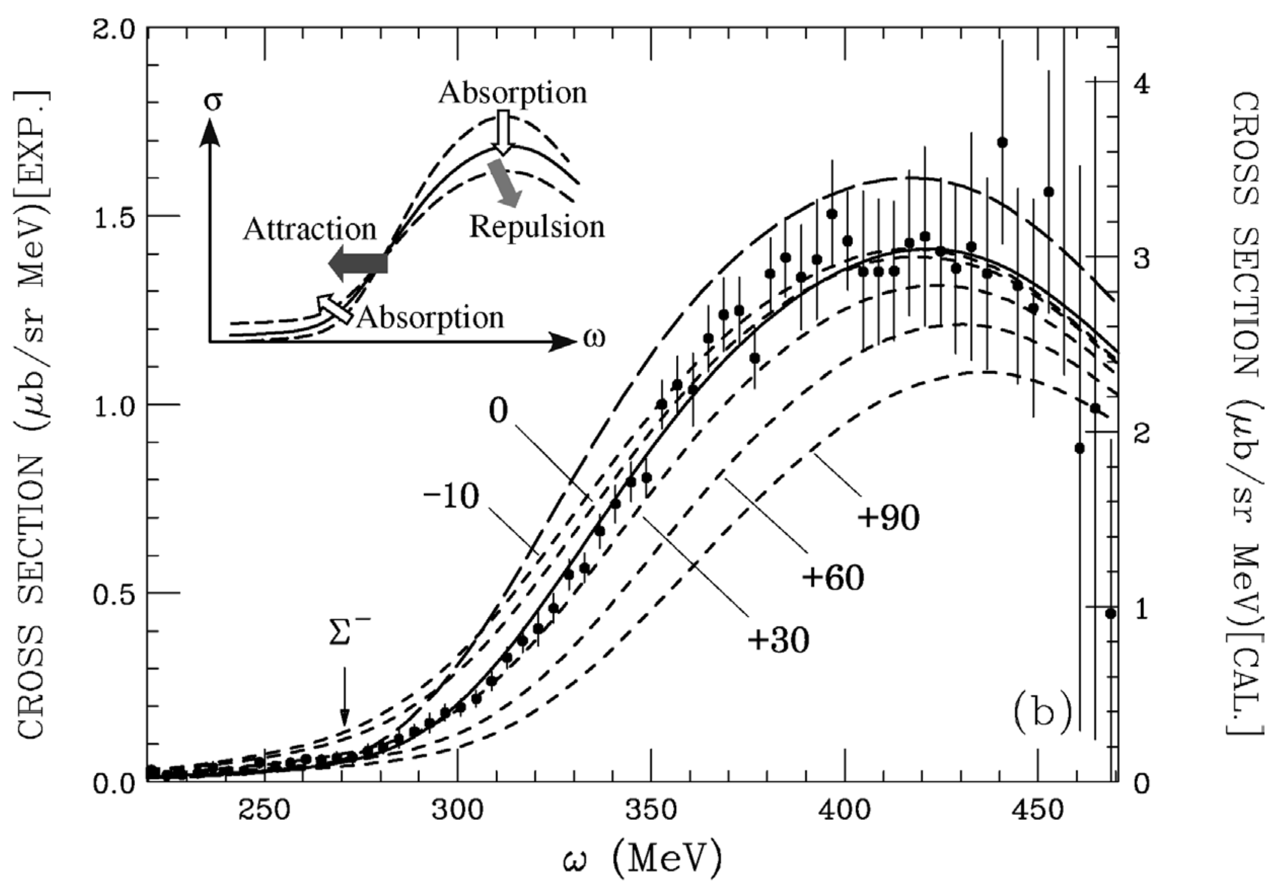


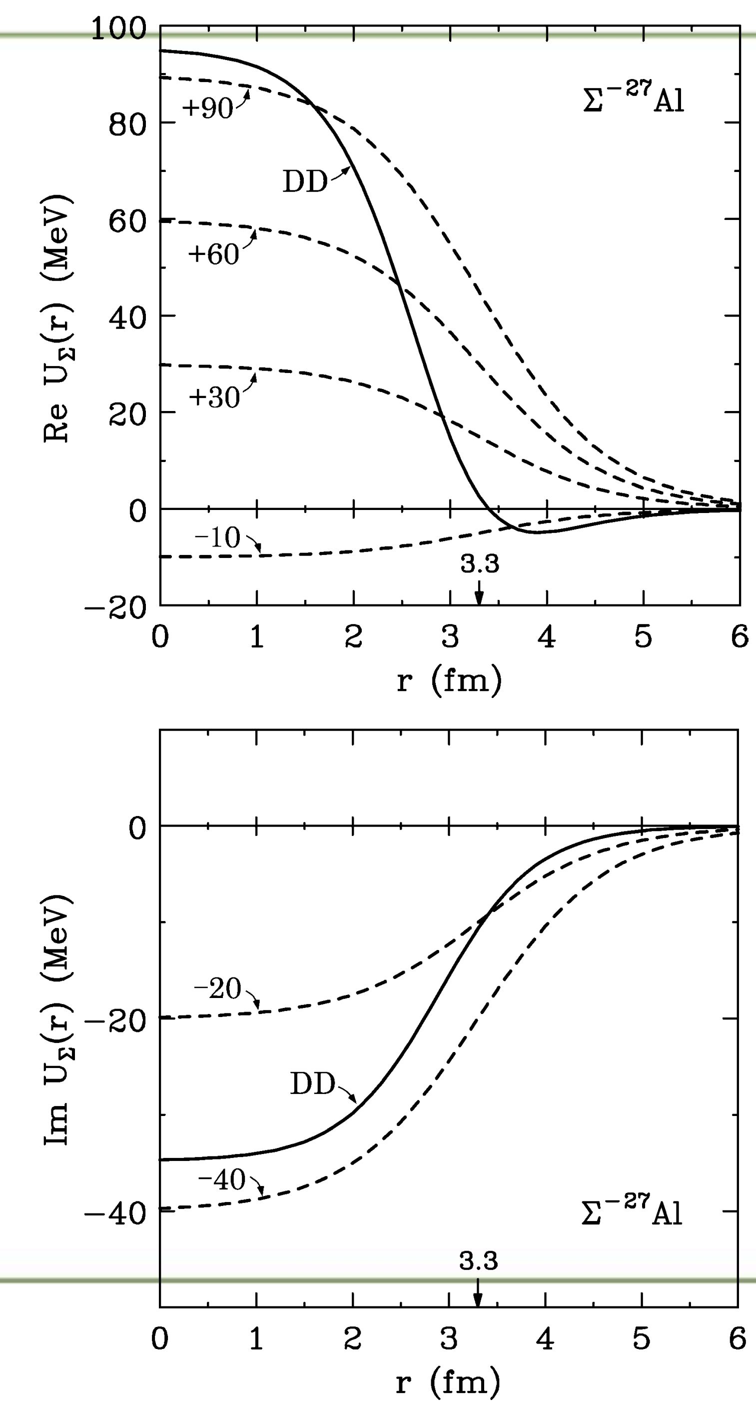
V_0=+90 MeV, W_0=-40 MeV

Theoretical analysis by Harada & Hirabayashi

T. Harada, Y. Hirabayashi / Nuclear Physics A 759 (2005) 143–169

- V_0=+30 MeV, W_0=-40 MeV





Summary on Σ hypernuclei

- No narrow states in unbound region
- One bound state in ${}^{4}_{\Sigma}\mathrm{He}$
  - ${}^{7}_{\Sigma}\mathrm{Li}$? Nucl. Phys. A 547 (1992) 175c.
- Σ-Nucleus potential is repulsive in medium-heavy system.

Weak decay of Hypernuclei

W. M. Alberico and G. G., Phys. Rep. **369**, 1 (2002);
Hadron Physics, IOS Press, Amsterdam, 2005, p. 125 [nucl-th/0410059].
E. Oset and A. Ramos, Prog. Part. Nucl. Phys. 41, 191 (1998).

Λの崩壊

$$\begin{aligned}\Lambda \quad \to \quad & \pi^- p \qquad (\text{B.R.} = 63.9 \times 10^{-2}) \\ & \pi^0 n \qquad (\text{B.R.} = 35.8 \times 10^{-2})\end{aligned}$$

with a lifetime $\tau_\Lambda^{\text{free}} \equiv \hbar/\Gamma_\Lambda^{\text{free}} = 2.632 \times 10^{-10}$ sec.

$$\begin{aligned}\Lambda \quad \to \quad & n\gamma \qquad (\text{B.R.} = 1.75 \times 10^{-3}) \\ & p\pi^-\gamma \qquad (\text{B.R.} = 8.4 \times 10^{-4}) \\ & pe^-\overline{\nu}_e \qquad (\text{B.R.} = 8.32 \times 10^{-4}) \\ & p\mu^-\overline{\nu}_\mu \qquad (\text{B.R.} = 1.57 \times 10^{-4})\end{aligned}$$

ΔI＝1/2則

$$|\pi^- p\rangle = \sqrt{\frac{1}{3}}\left|\frac{3}{2},-\frac{1}{2}\right\rangle - \sqrt{\frac{2}{3}}\left|\frac{1}{2},-\frac{1}{2}\right\rangle,$$

$$|\pi^0 n\rangle = \sqrt{\frac{2}{3}}\left|\frac{3}{2},-\frac{1}{2}\right\rangle + \sqrt{\frac{1}{3}}\left|\frac{1}{2},-\frac{1}{2}\right\rangle.$$

Hence the ratio of amplitudes for $\Delta I = 1/2$ transitions yields:

$$\frac{\Gamma^{\text{free}}_{\Lambda\to\pi^- p}}{\Gamma^{\text{free}}_{\Lambda\to\pi^0 n}} \simeq \frac{\left|\langle\pi^- p|T_{1/2,-1/2}|\Lambda\rangle\right|^2}{\left|\langle\pi^0 n|T_{1/2,-1/2}|\Lambda\rangle\right|^2} = \left|\frac{\sqrt{2/3}}{\sqrt{1/3}}\right|^2 = 2,$$

$$\left\{\frac{\Gamma^{\text{free}}_{\Lambda\to\pi^- p}}{\Gamma^{\text{free}}_{\Lambda\to\pi^0 n}}\right\}^{\text{Exp}} \simeq 1.78,$$

while a $\Delta I = 3/2$ process should give:

$$\frac{\Gamma^{\text{free}}_{\Lambda\to\pi^- p}}{\Gamma^{\text{free}}_{\Lambda\to\pi^0 n}} \simeq \frac{\left|\langle\pi^- p|T_{3/2,-1/2}|\Lambda\rangle\right|^2}{\left|\langle\pi^0 n|T_{3/2,-1/2}|\Lambda\rangle\right|^2} = \left|\frac{\sqrt{1/3}}{\sqrt{2/3}}\right|^2 = \frac{1}{2}.$$

$$\left|\frac{A_{1/2}}{A_{3/2}}\right| \simeq 30.$$

ハイパー核の弱崩壊

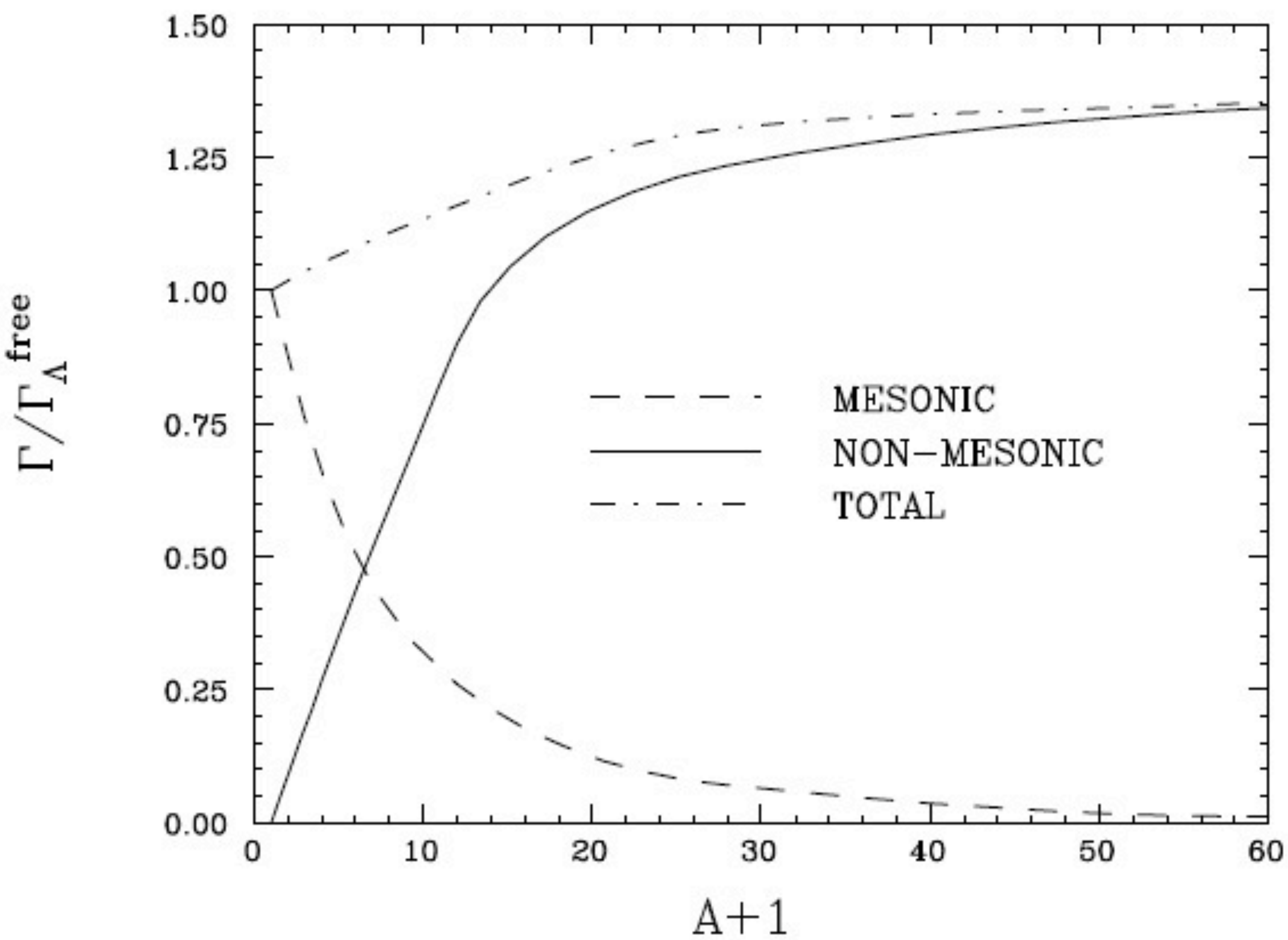
- 中間子崩壊モード
  - $\Lambda \rightarrow \pi N$ (Q~37 MeV) ➡ p_N(90 MeV/c) < p_F

Pauli Suppressed

- 非中間子崩壊モード
  - $\Lambda N \rightarrow NN$ (Q~176 MeV) ➡ p_N (400 MeV/c) > p_F

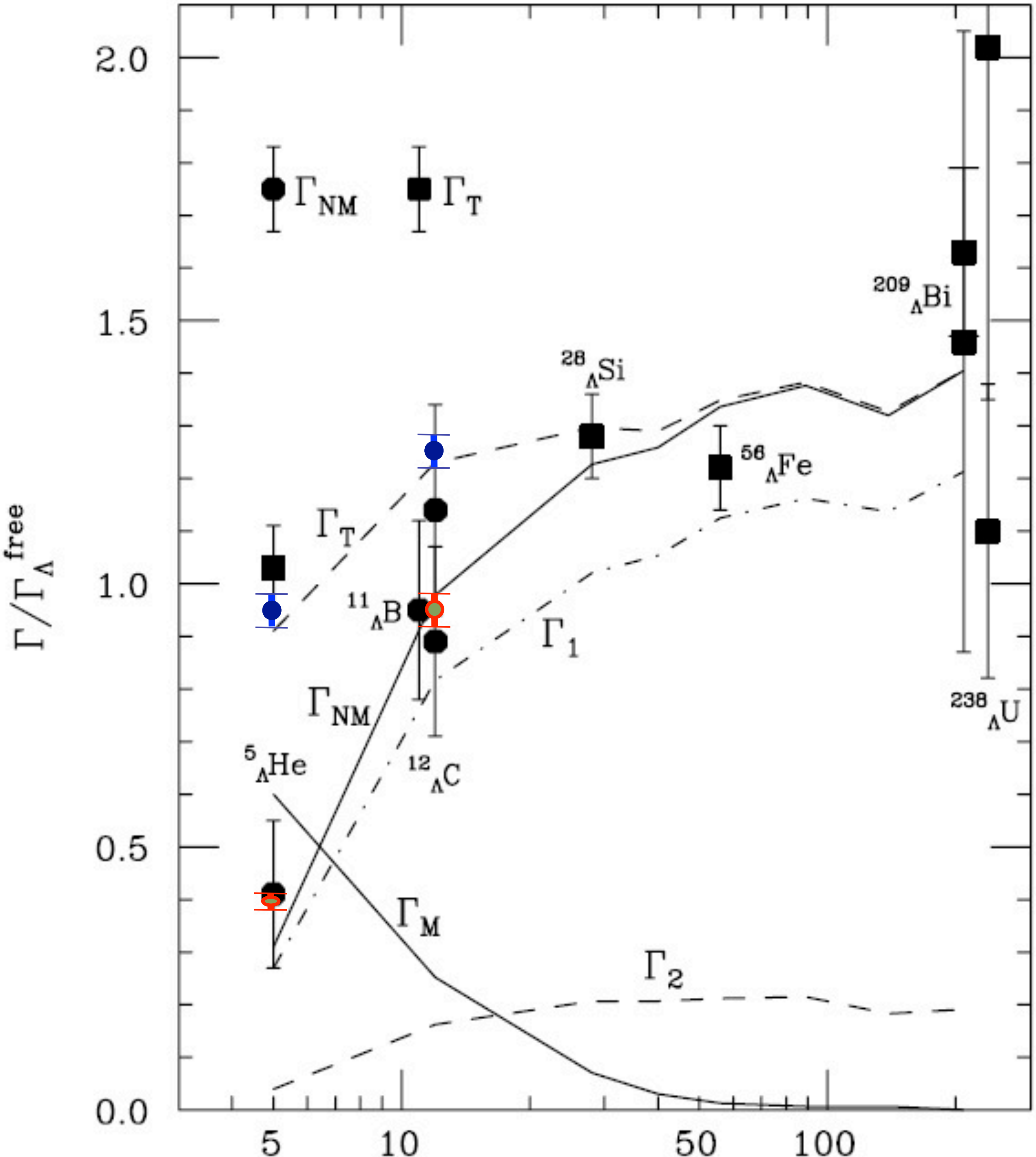
$$\Gamma_T = \Gamma_M + \Gamma_{NM},$$

$$\Gamma_M = \Gamma_{\pi^-} + \Gamma_{\pi^0}, \quad \Gamma_{NM} = \Gamma_1 + \Gamma_2, \quad \Gamma_1 = \Gamma_n + \Gamma_p,$$



$$\Gamma_1(A) \propto \int d\vec{r}\,|\psi_\Lambda(\vec{r})|^2 \rho_A(\vec{r}),$$

Mass number dependence of Γ_{NM}



NON–MESONIC WEAK DECAY OF HYPERNUCLEI

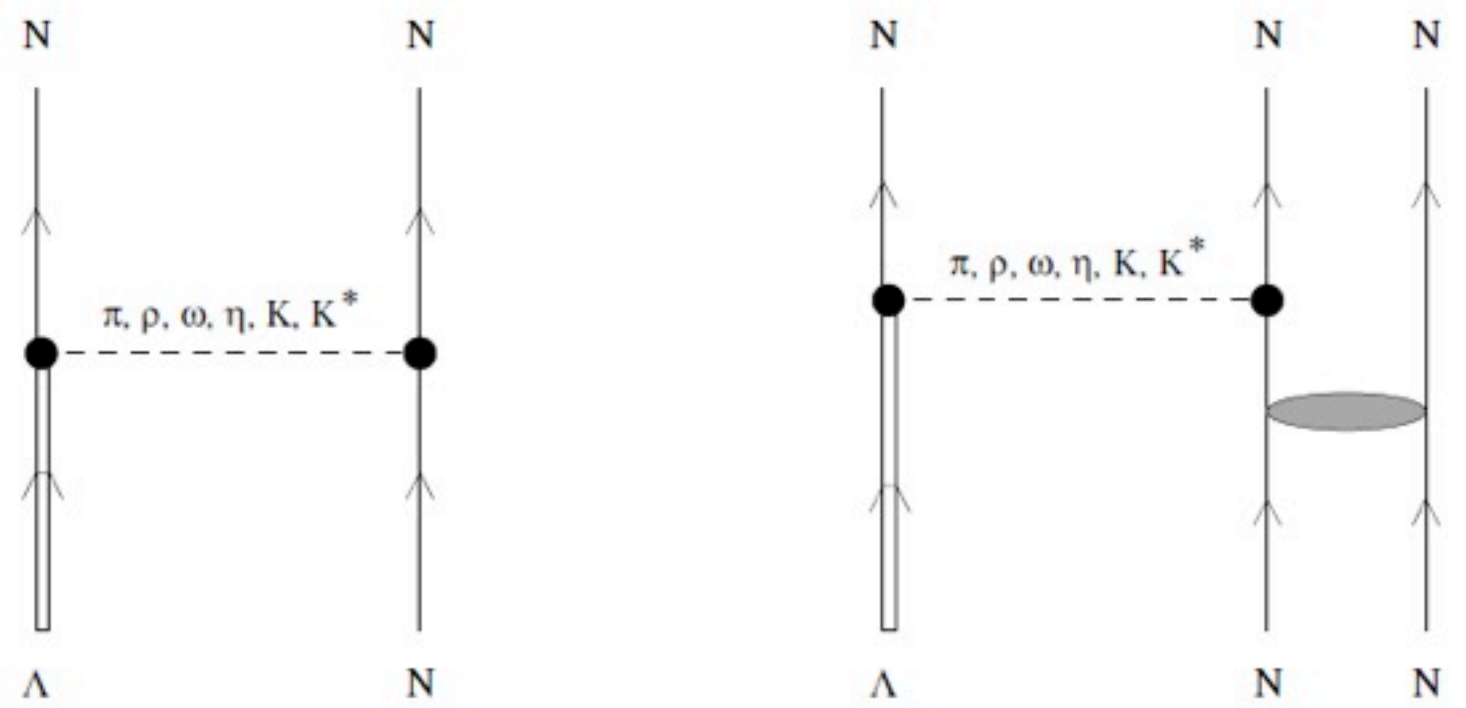
One–nucleon induced

$$\Lambda n \rightarrow nn \qquad \Gamma_n$$

$$\Lambda p \rightarrow np \qquad \Gamma_p$$

Two–nucleon induced

$$\Lambda NN \rightarrow nNN \qquad \Gamma_2$$

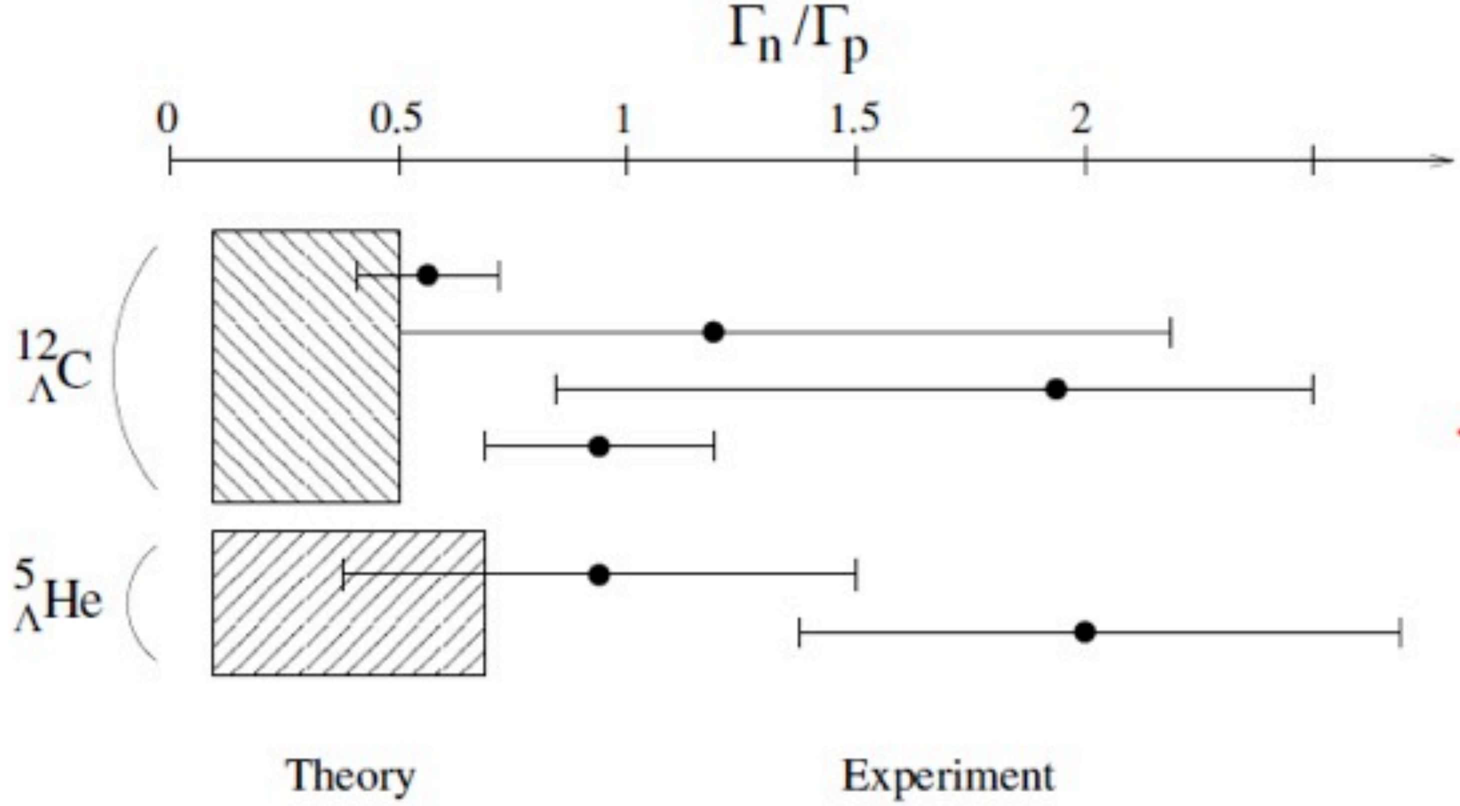


$$\Gamma_T = \Gamma_M + \Gamma_{NM} = \Gamma_{\pi^0} + \Gamma_{\pi^-} + \Gamma_n + \Gamma_p + \Gamma_2$$

Γ_n/Γ_pパズル

THE RATIO Γ_n/Γ_p

For many years, a sound theoretical explanation of the large experimental values of $\frac{\Gamma_n}{\Gamma_p} \equiv \frac{\Gamma(\Lambda n \to nn)}{\Gamma(\Lambda p \to np)}$ has been missing



< year 2003

Theory strongly underestimated Experiment!

[W. M. Alberico and G. G., Phys. Rep. 369, 1 (2002)]
[E. Oset and A. Ramos, Prog. Part. Nucl. Phys. 41, 191 (1998)]

Experiment

✦ Large uncertainties in the extraction of Γ_n/Γ_p from "old" data (< year 2002)

– only Single–Proton Spectra measured

– very indirect determination of the decay rates, probable overestimation of

$$\frac{\Gamma_n}{\Gamma_p} = \frac{\Gamma_{\rm T} - \Gamma_{\rm M} - \Gamma_2 - \Gamma_p}{\Gamma_p} \Longleftarrow \Gamma_p \text{ underestimated}, \ \Gamma_2 \text{ neglected}$$

$$\left(\Gamma_2 = 0\,, \Gamma_p = 0.8[\Gamma_p]^{\rm th} : \frac{\Gamma_n}{\Gamma_p} = 1 \iff \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm th} = 0.3 \right)$$

✦ KEK–E462/E508: simultaneous measurement of Single–Proton and Single–Neutron Spectra (year 2003) [1]

– improved determination of $\frac{\Gamma_n}{\Gamma_p}$ from $\frac{N_n}{N_p}$ ratio

✦ KEK–E462/E508: Nucleon–Nucleon Coincidence Spectra (years 2003–2006) [2]

– more direct determination of $\frac{\Gamma_n}{\Gamma_p}$ from $\frac{N_{nn}}{N_{np}}$ ratio

✦ First data from FINUDA@DAΦNE, experiments planned at J–PARC and HypHI@GSI

[1] S. Okada et al., PLB 597, 249 (2004)
[2] B. H. Kang et a., PRL 96, 062301 (2006); M. J. Kim et al., PLB 641, 28 (2006)

Theory

- The One–Pion–Exchange (OPE) model predicts very small ratios:

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm OPE}({}^5_\Lambda{\rm He},\, {}^{12}_\Lambda{\rm C}) = 0.1 \div 0.2$$

[$\Delta I = 1/2$ rule + strong tensor component $\Lambda N(^3S_1) \rightarrow nN(^3D_1)$ requiring $I_{nN} = 0 \Longleftrightarrow N = p$]

- but the OPE reproduces the observed total non–mesonic rates, $\Gamma_{\rm NM} = \Gamma_n + \Gamma_p (+\Gamma_2)$.

Other interaction mechanisms beyond the OPE should then be responsible for the overestimation of Γ_p and the underestimation of Γ_n

- Heavier Mesons (ρ, K, K^*, ω, η, 2π, $2\pi/\rho$, $2\pi/\sigma$) [Parreño et al., Itonaga et al., Jido et al.]
- Direct Quark Mechanism [Oka et al.]
- Two–Nucleon Induced Mechanism [Alberico et al., Ramos et al.]
- Nucleon Final State Interactions [Ramos et al., Garbarino et al.]

History of hypernuclear weak decay experiments…

Merit/ Demerit

Year	Method	Merit/Demerit
		＊Clean decay identification → ground state spin assignment ＊ Low energy threshold for p
～1960	Emulsion and Bubble chamber	＊Hypernuclear formation is not identified ＊Blind for neutral particles ＊No timing information
1985	Counter experiment start @BNL/KEK w/ (K,π)	＊Hypernuclear formation tagged → branching ratio ! ＊Direct lifetime meas. w/TOF counter
		＊Still hard to see neutral particles ＊High energy threshold for p (Ep>30～40MeV)
1995	SKS experiments w/ (π,K) reaction	
2000～2002	n+p/n+n coincidence	＊Heavy Λ hypernuclear production ＊Neutral particle detection ＊Asymmetry of p from NMWD ＊Improved statistics → n+p/n+n double coincidence
2004～	New era started! → FINUDA@DAFNE / J-PARC	

$$1/\tau_{HY} = \Gamma_{tot} = \begin{cases} \Gamma_m \begin{cases} \Gamma_{\pi^-} \ (\Lambda \to p + \pi^-) \\ \Gamma_{\pi^0} \ (\Lambda \to n + \pi^0) \end{cases} \\ \Gamma_{nm} \begin{cases} \Gamma_p \ (\Lambda + \text{“}p\text{”} \to n + p) \\ \Gamma_n \ (\Lambda + \text{“}n\text{”} \to n + n) \end{cases} \end{cases}$$

Γ_n / Γ_p *ratio*

: The most important observable used to study the **isospin structure of the NMWD**.

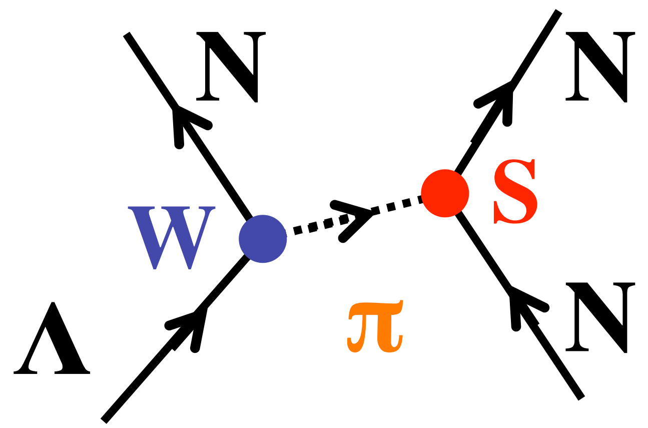
Simple theoretical model

Γ_p (Λ+"p"→ n + p)
Γ_n (Λ+"n"→ n + n)

⇨ $\Gamma_n / \Gamma_p \sim 0.1$

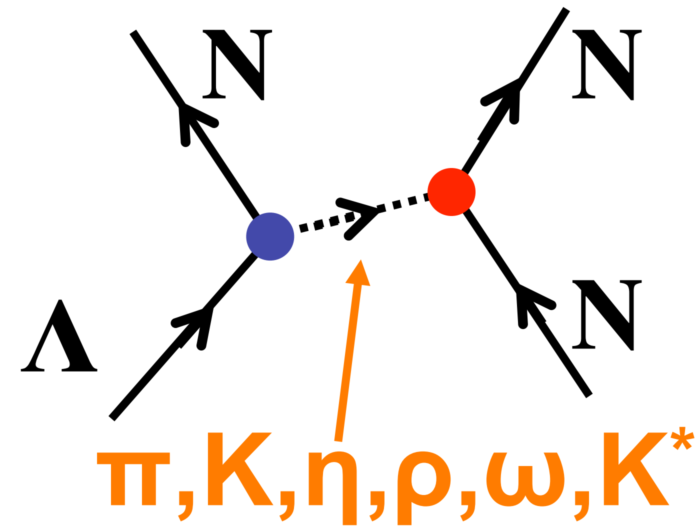
Theoretical

One Pion Exchange (OPE)

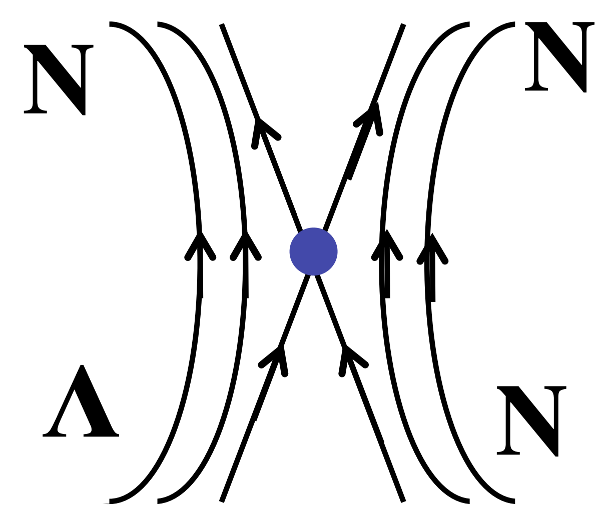


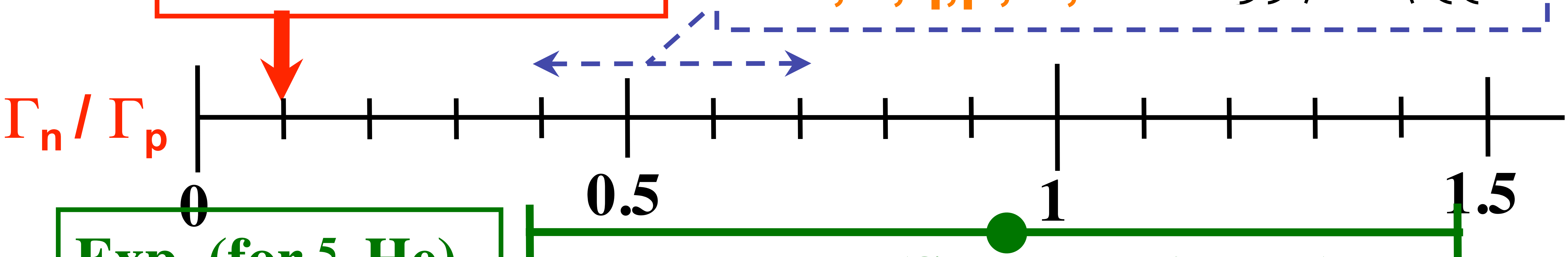
Tensor-dominant
→ requires the final Nn pair to have isospin 0.

Meson Exchange mechanism



Direct Quark mechanism





Exp. (for $^5_\Lambda$He)

0.93±0.55 (Szymanski et al.)

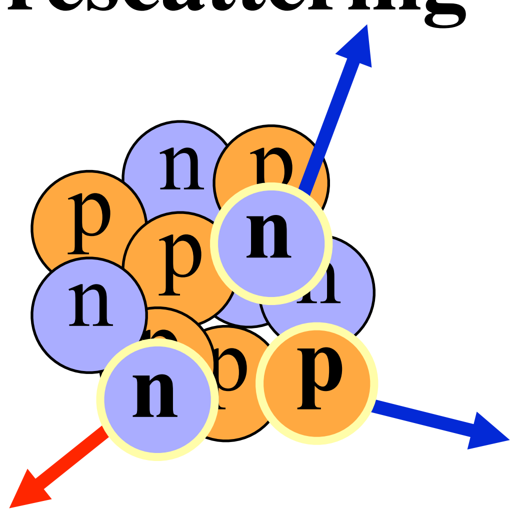
Γ_n / Γ_p ***ratio puzzle***

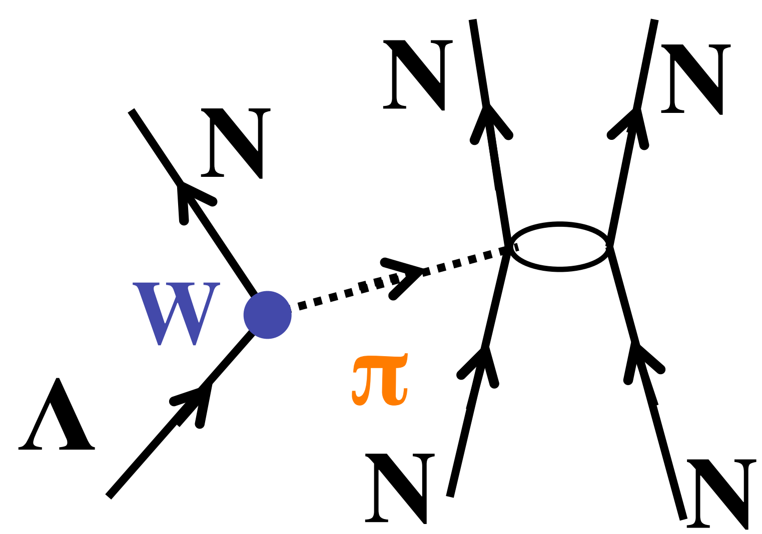
Experimental difficulties in single nucleon measurement

- ✓ **Difficulty in detecting neutrons.**
  → **There is no experiment to observe both of the protons and neutrons simultaneously with high statistics.**
- ✓ **Final state interaction (FSI) effect**
  → **not well established**
- ✓ **Distinguish between the FSI and "ΛNN→nNN" process**

Final state interaction (FSI) effect	**ΛNN→NNN (2N-induced process)**

rescattering



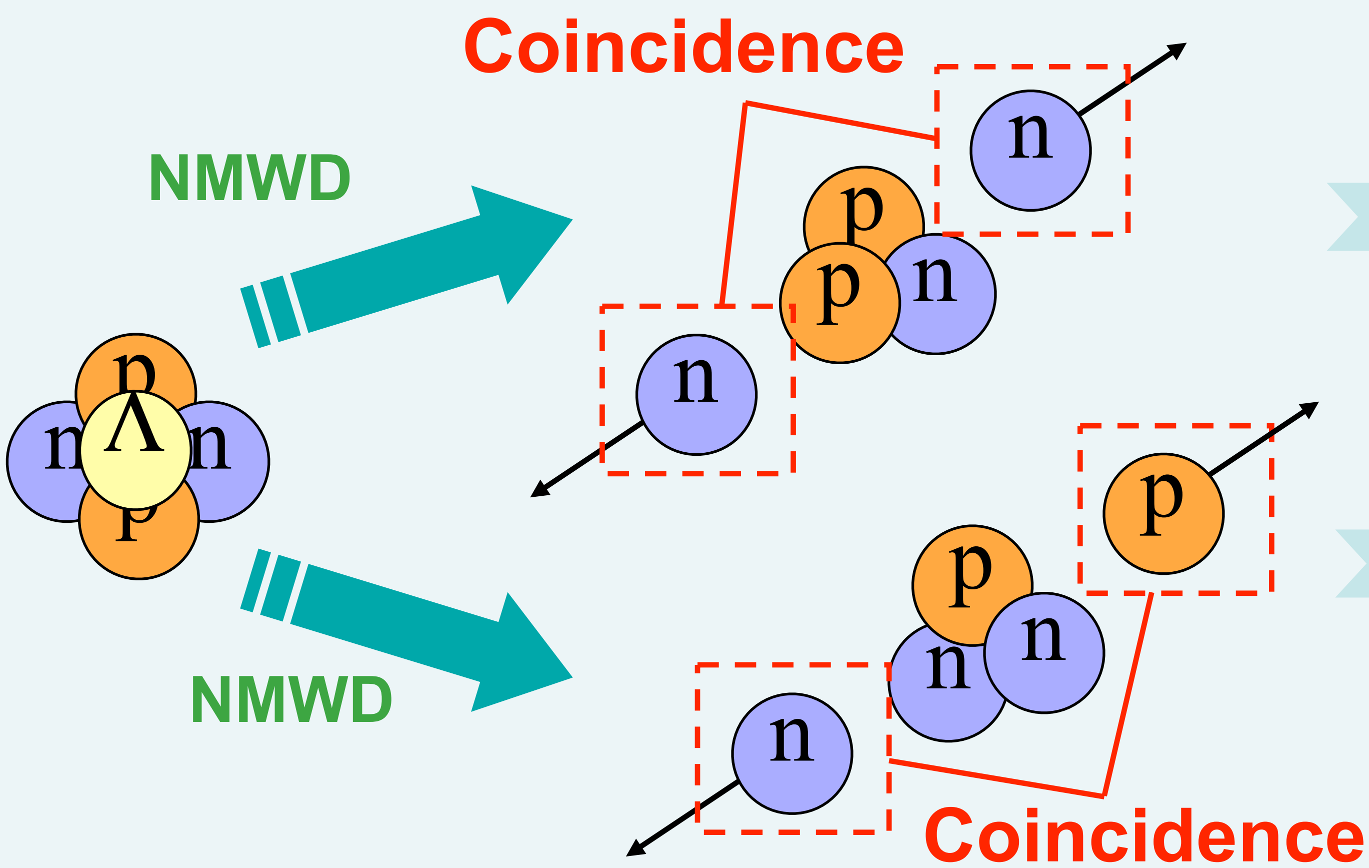


(One of the theoretical model)

The present experiment

KEK-PS E462/E508

NMWD : $\Lambda N \to NN$



1) **Angular correlation**
(back-to-back, $\cos\theta < -0.8$)
2) **Energy correlation**
($Q \sim E(N1)+E(N2) \sim$ 152MeV)

Direct measurement of the Γ_n / Γ_p ratio

⇨ *Select $\Lambda N \to NN$ events w/o FSI effect & $\Lambda NN \to NNN$.*

$$N(\Lambda n \to nn) \times (\Omega_n \times \Omega_n)_{av.} \times \varepsilon_n^2 \times (1 - R_{FSI})$$

$$N(\Lambda p \to np) \times (\Omega_n \times \Omega_p)_{av.} \times \varepsilon_n \times \varepsilon_p \times (1 - R_{FSI})$$

* $\cos\theta < -0.8$
* E(N1)+E(N2) cut

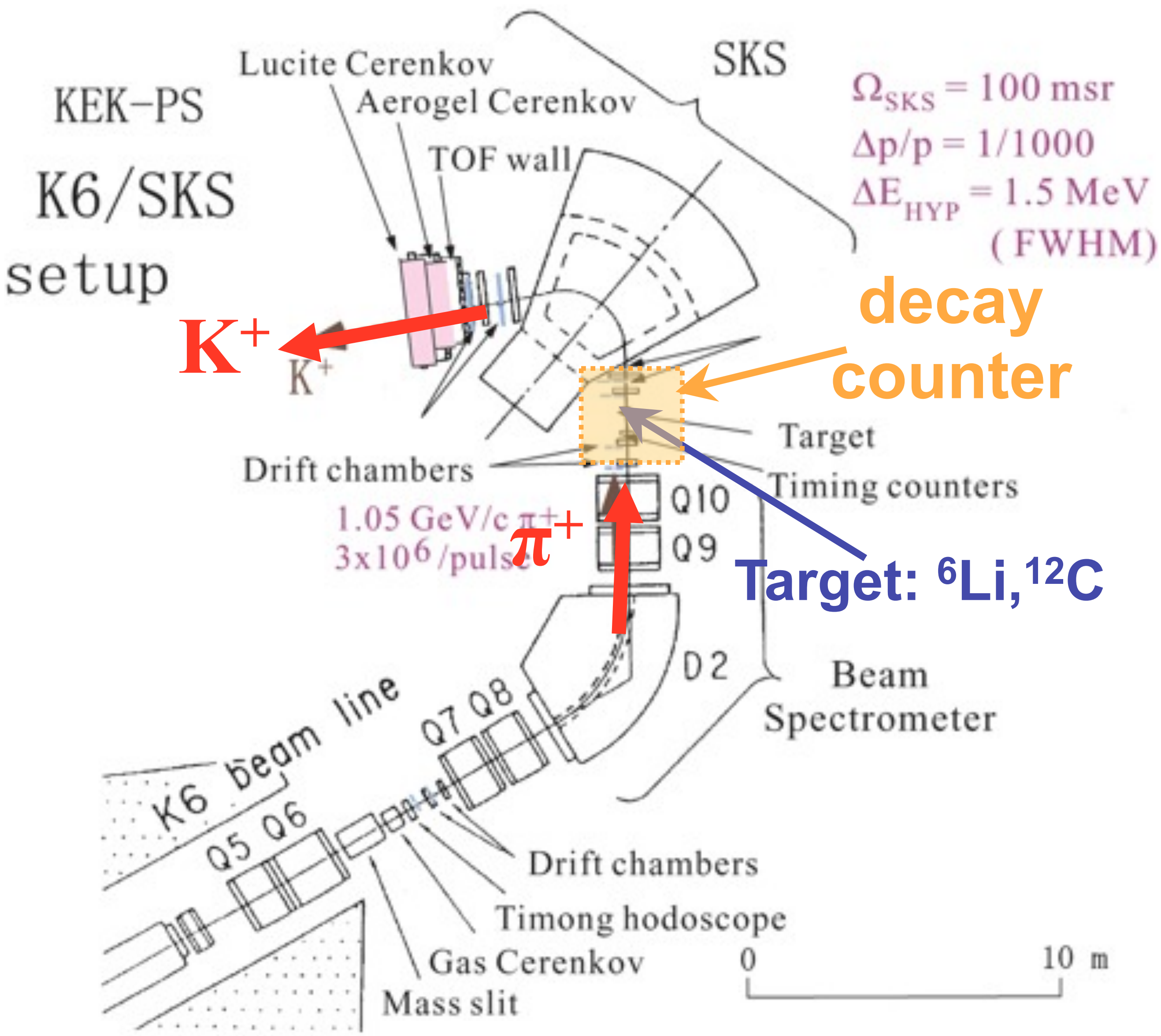
$$\frac{\Gamma_n}{\Gamma_p} = \frac{N(nn - \text{pair coin})}{N(np - \text{pair coin})} \times \frac{\varepsilon_p}{\varepsilon_n}$$

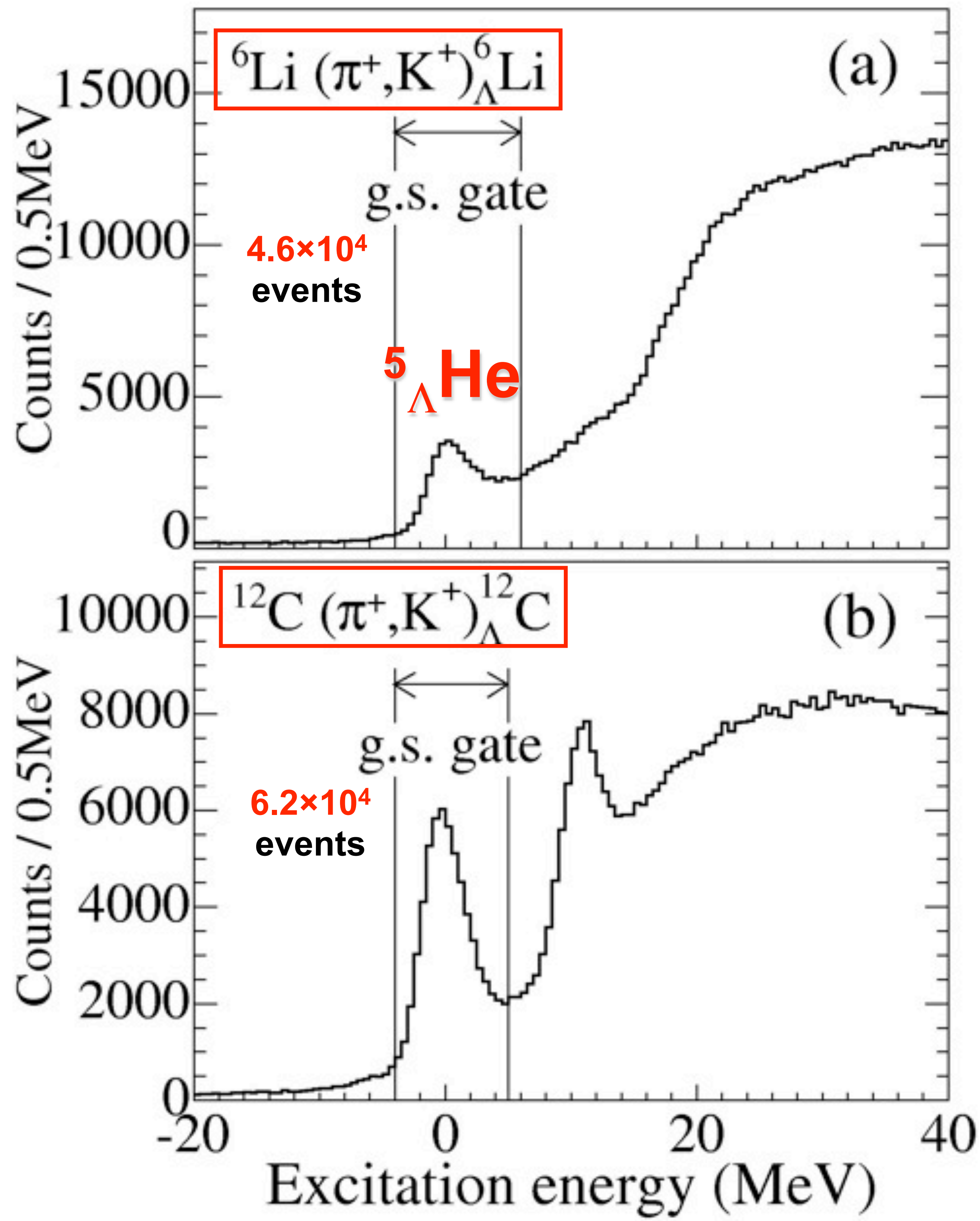
Select light hypernuclei to minimize FSI effect, $^{5}_{\Lambda}He$ and $^{12}_{\Lambda}C$

Excitation-energy spectra for $^{6}_{\Lambda}$Li and $^{12}_{\Lambda}$C

The ground state of $^{6}_{\Lambda}$Li is above the threshold of $^{5}_{\Lambda}$He + p.

$$^{6}_{\Lambda}\mathrm{Li}_{\,(g.s.)} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p$$

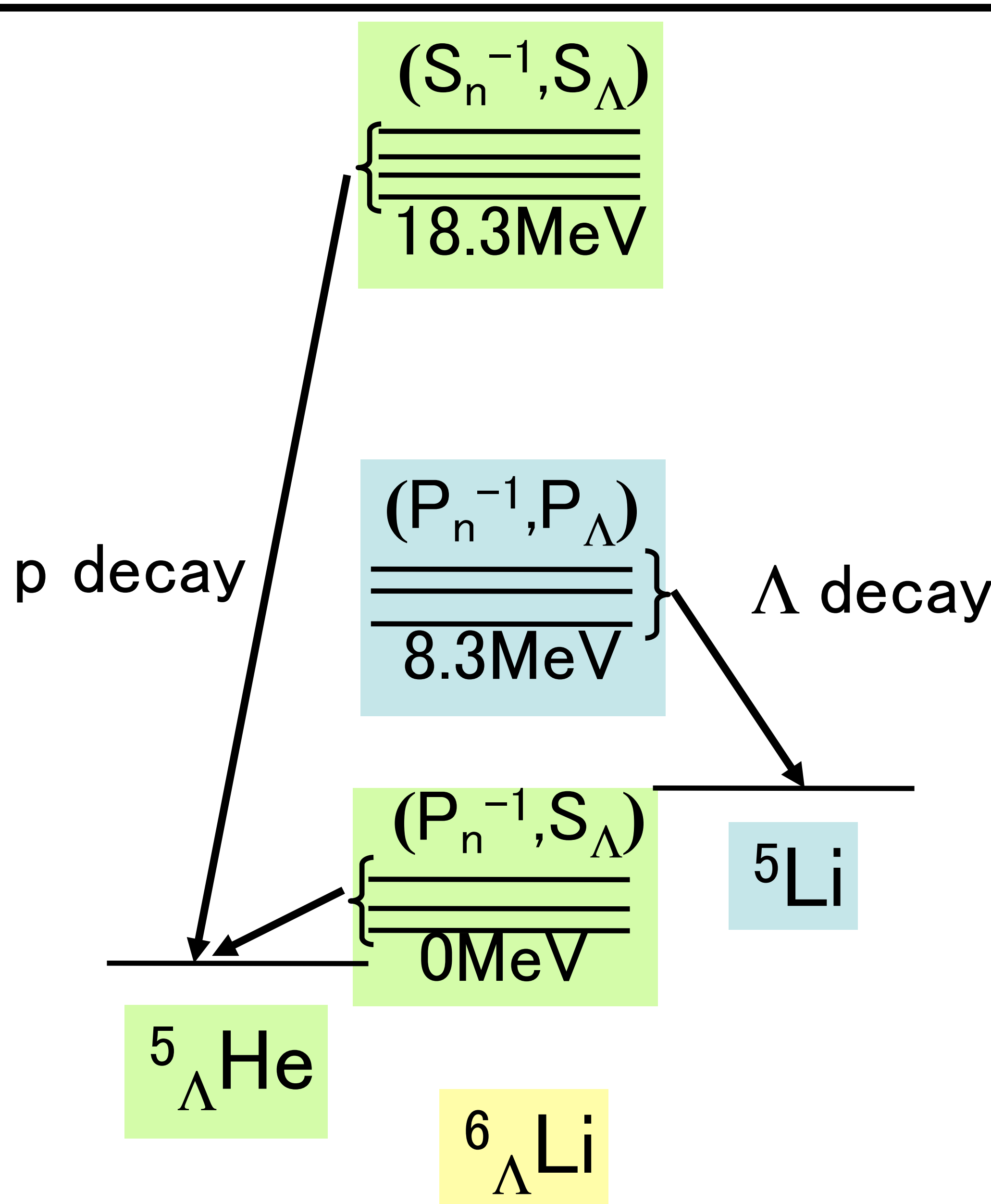


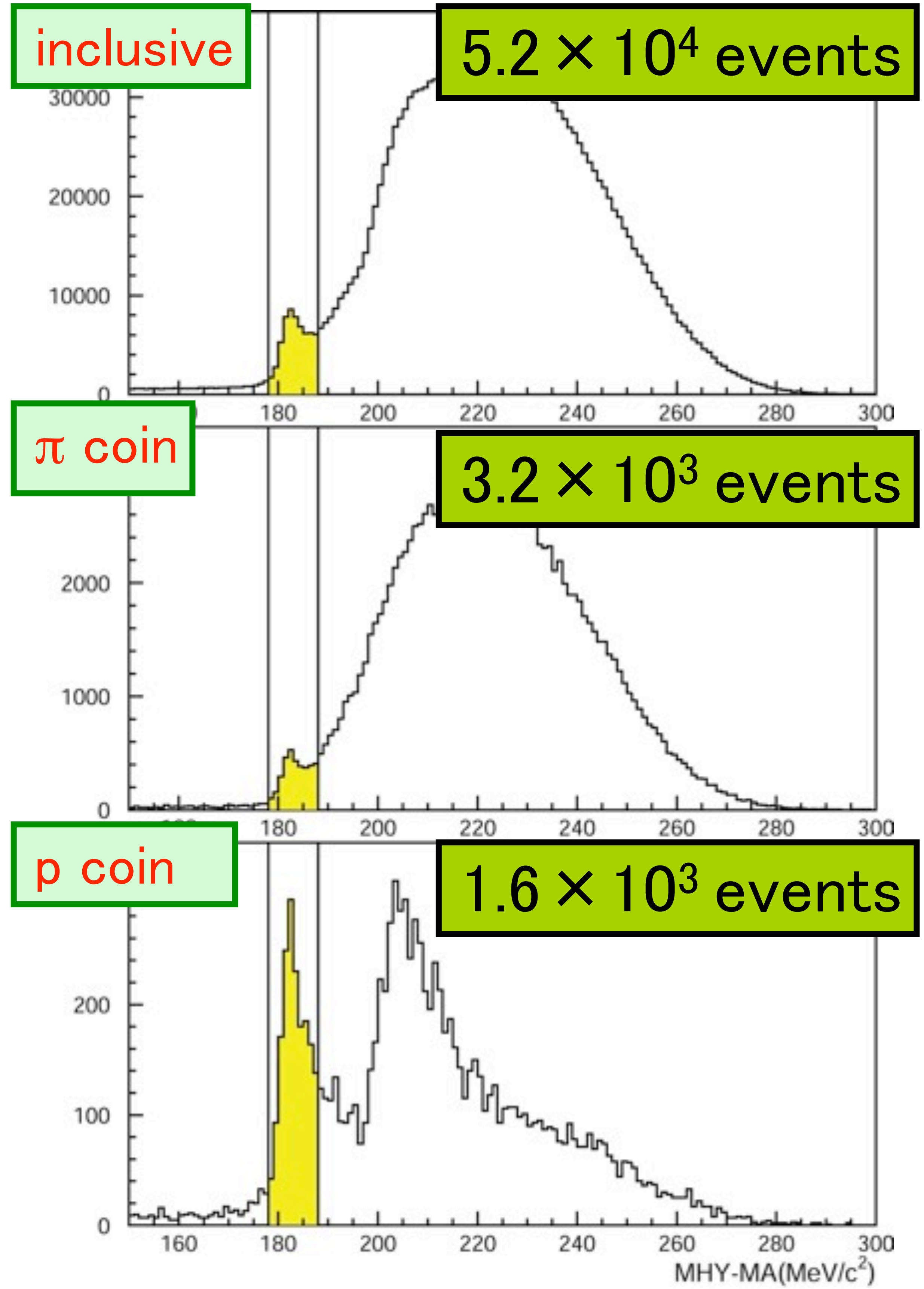


${}^{6}_{\Lambda}$Li Hypernuclear mass spectra

$$^{6}\mathrm{Li} + \pi^{+} \rightarrow {}^{6}_{\Lambda}\mathrm{Li} + K^{+}$$

$${}^{6}_{\Lambda}\mathrm{Li} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p$$



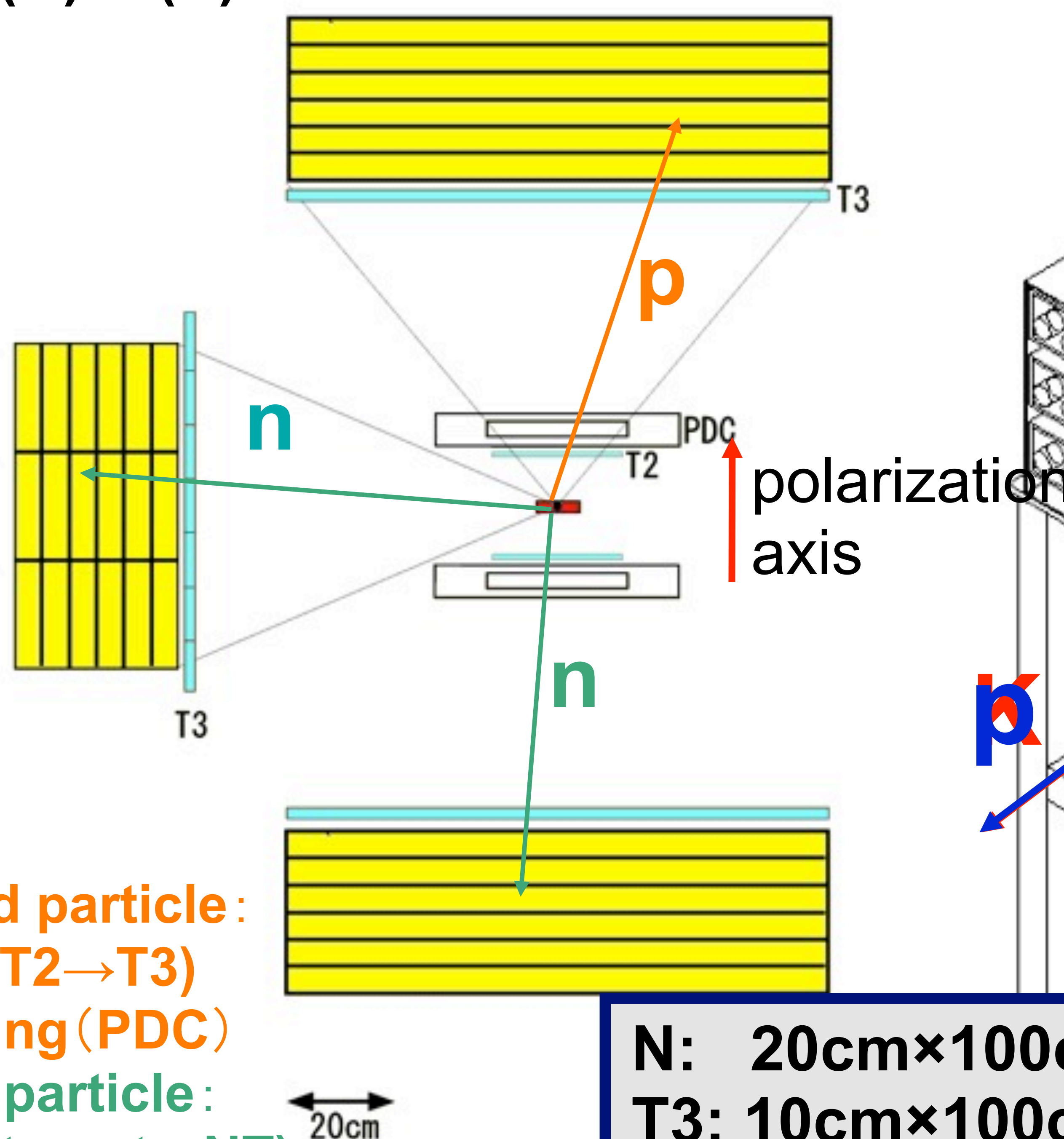


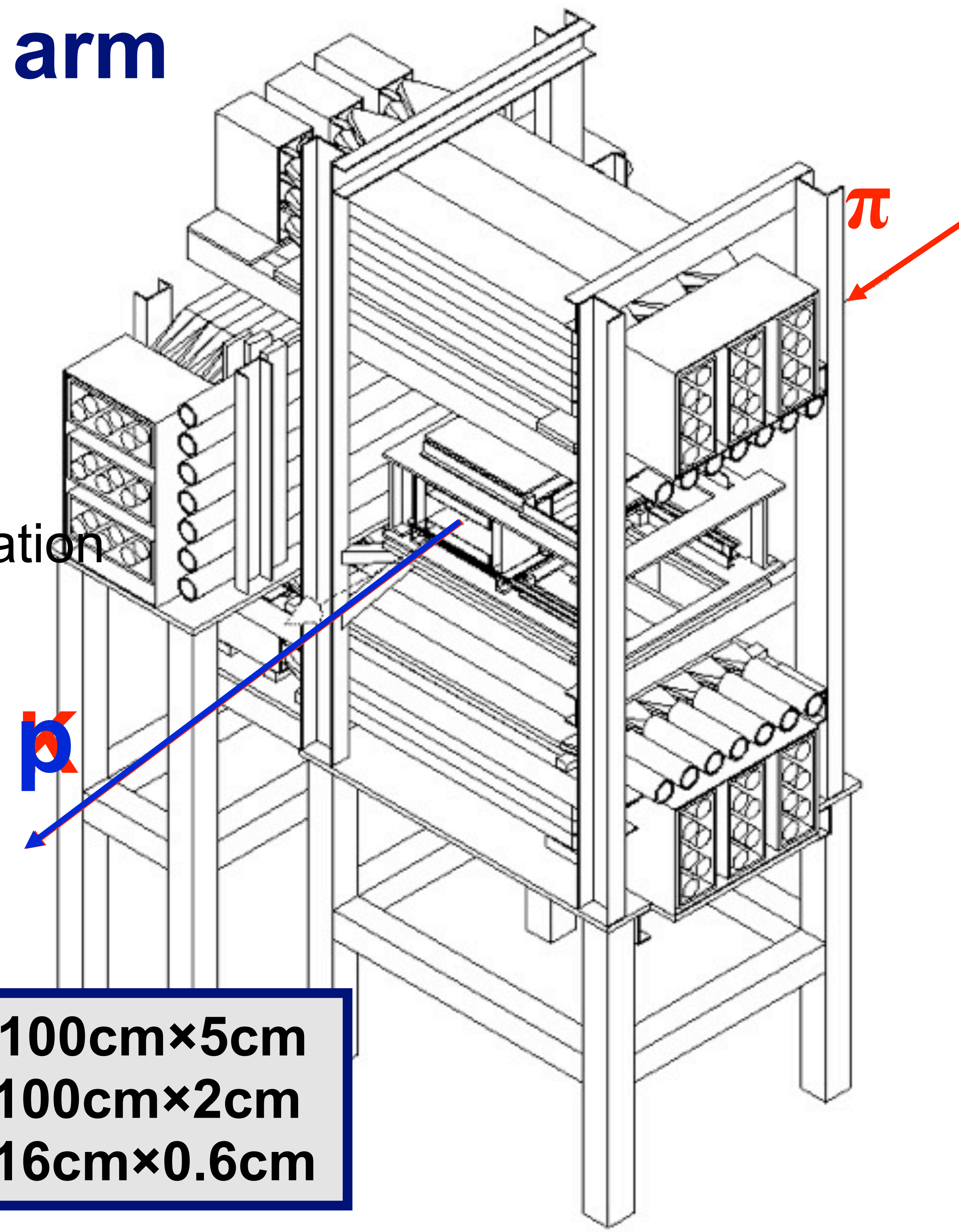
Decay counter Setup

(KEK-PS K6 & SKS)

Solid angle: 26%
9(T)+9(B)+8(S)%

Decay arm



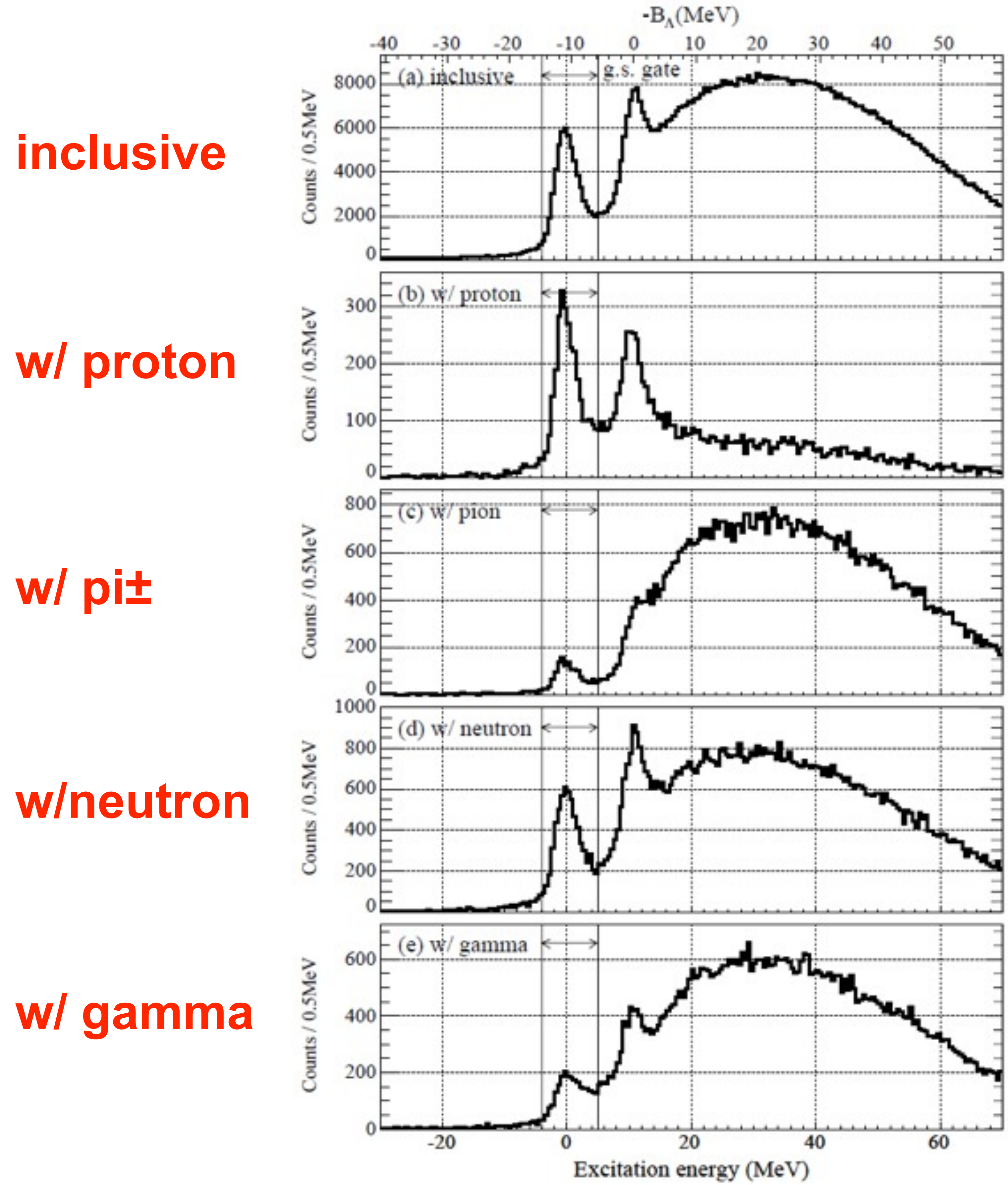


Charged particle:
- TOF (T2→T3)
- tracking (PDC)

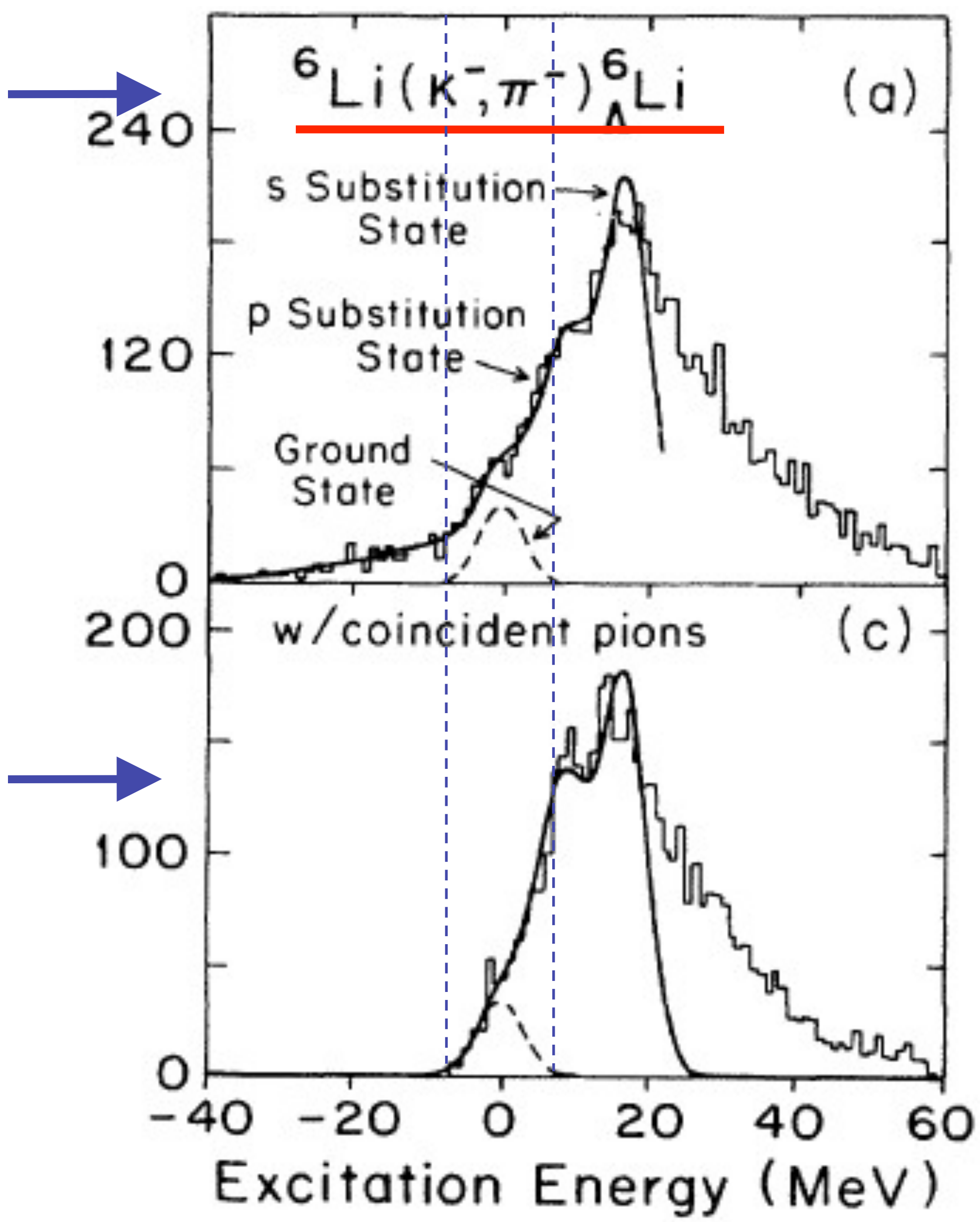
Neutral particle:
- TOF (target→NT)
- T3 VETO

N: 20cm×100cm×5cm
T3: 10cm×100cm×2cm
T2: 4cm×16cm×0.6cm

Excitation spectra w/ coincident decay particles for $^{12}_{\Lambda}C$



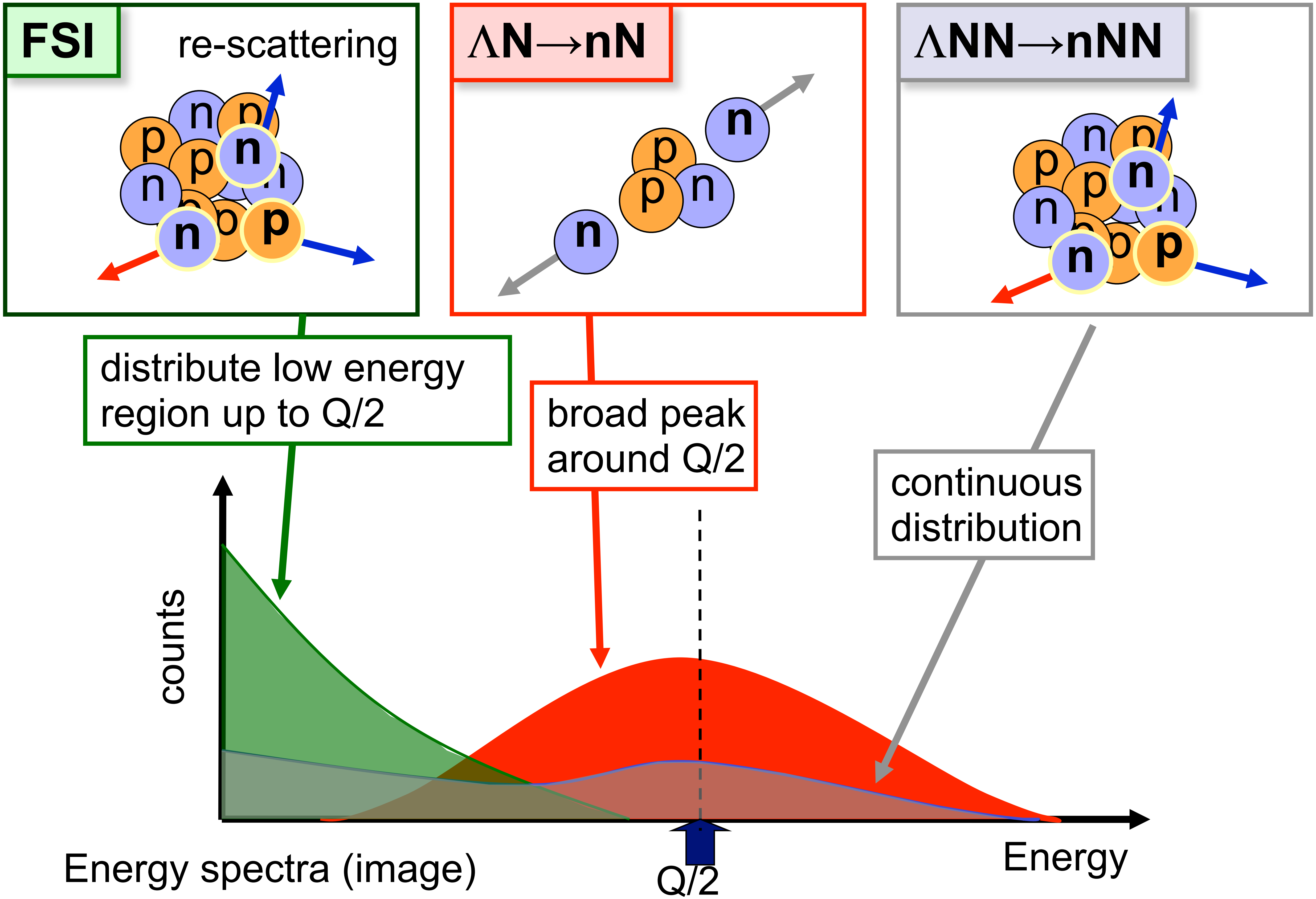
previous experiment at BNL



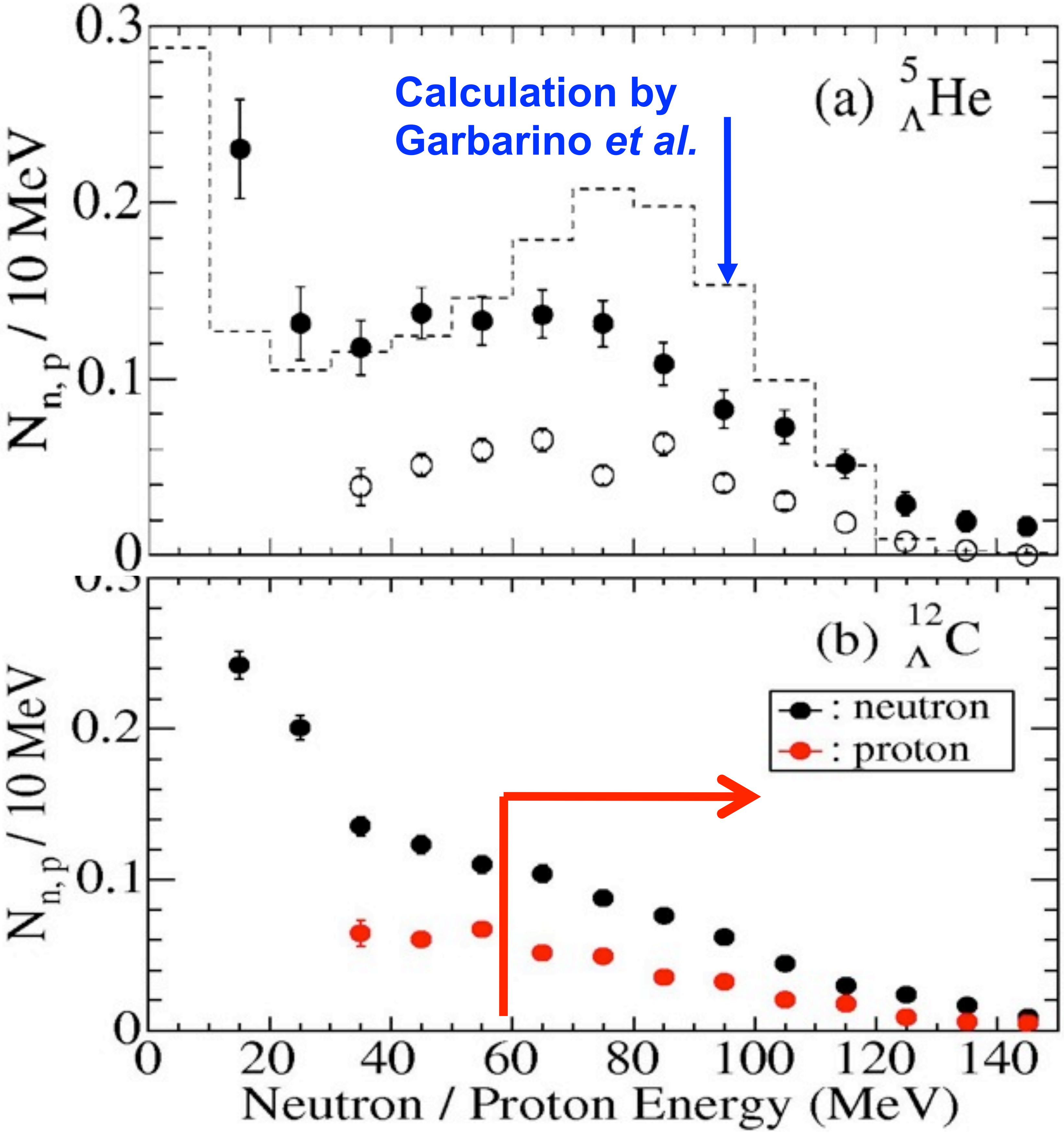
The **g.s. peak is clearly seen** in all spectra with coincident decay particles.

. Kameoka *et al.* **Nucl. Phys. A754 (2005) 173c**
. Okada *et al.* **Nucl. Phys. A754 (2005) 178c**

Expected Spectrum



Single proton/neutron spectra from $^{5}_{\Lambda}$He and $^{12}_{\Lambda}$C



$N_n \sim 2N_p$

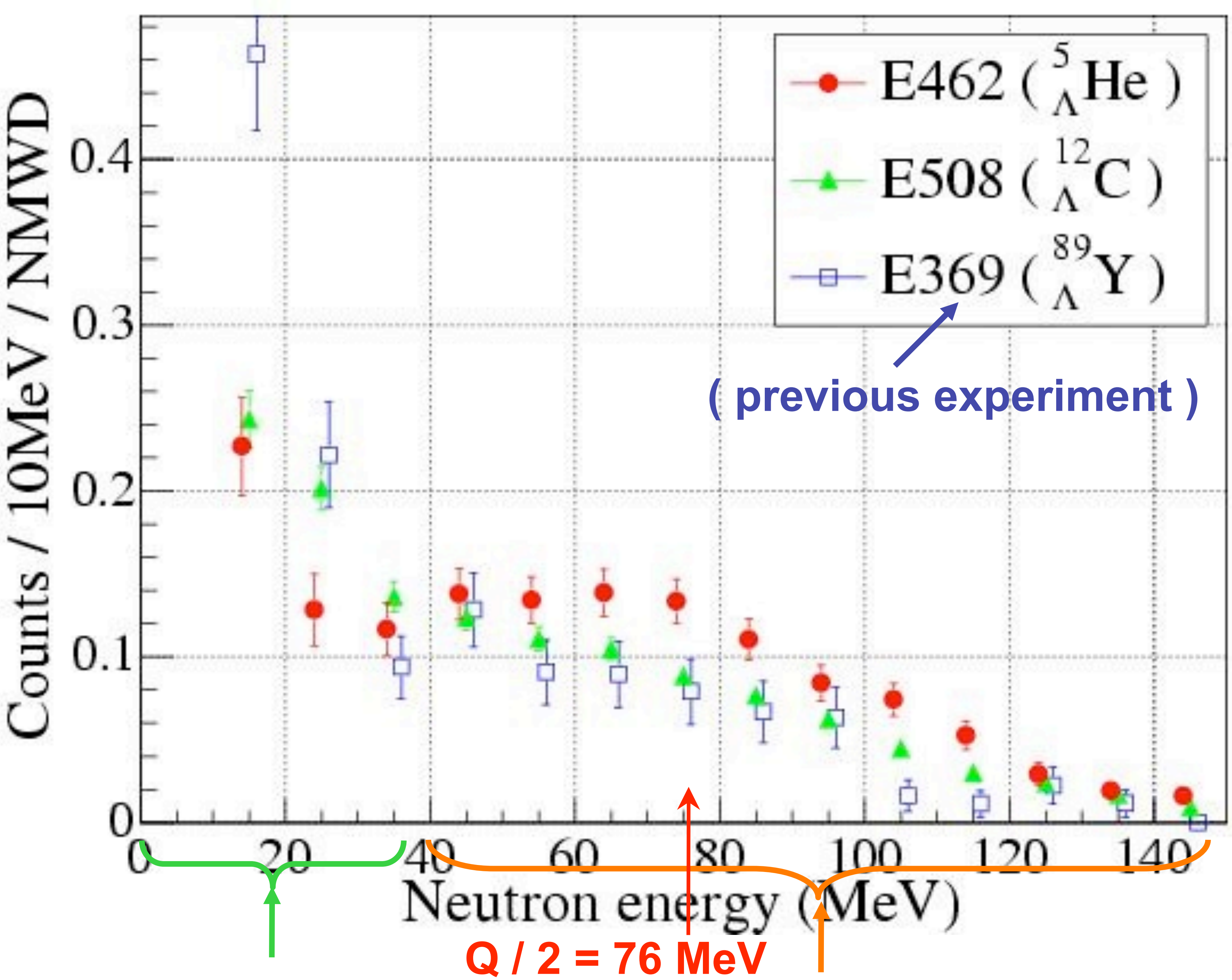
$$N_n/N_p \cong 2 \times (\Gamma_n/\Gamma_p) + 1.$$

$$N_n/N_p({}^{5}_{\Lambda}\mathrm{He}) = 2.17 \pm 0.15(\mathrm{stat}) \pm 0.16(\mathrm{sys})$$
$(60 < E < 110\ \mathrm{MeV})$,

$$N_n/N_p({}^{12}_{\Lambda}\mathrm{C}) = 2.00 \pm 0.09(\mathrm{stat}) \pm 0.14(\mathrm{sys})$$
$(E > 60\ \mathrm{MeV})$,

S.Okada et al., PLB 597 (2004) 249

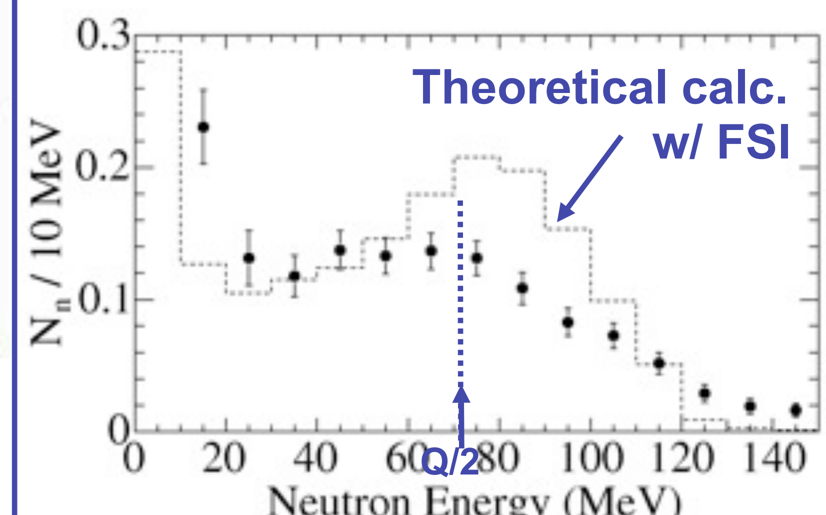
Mass number dependence of neutron energy spectra (A=5,12,89)



$^{5}_{\Lambda}$He

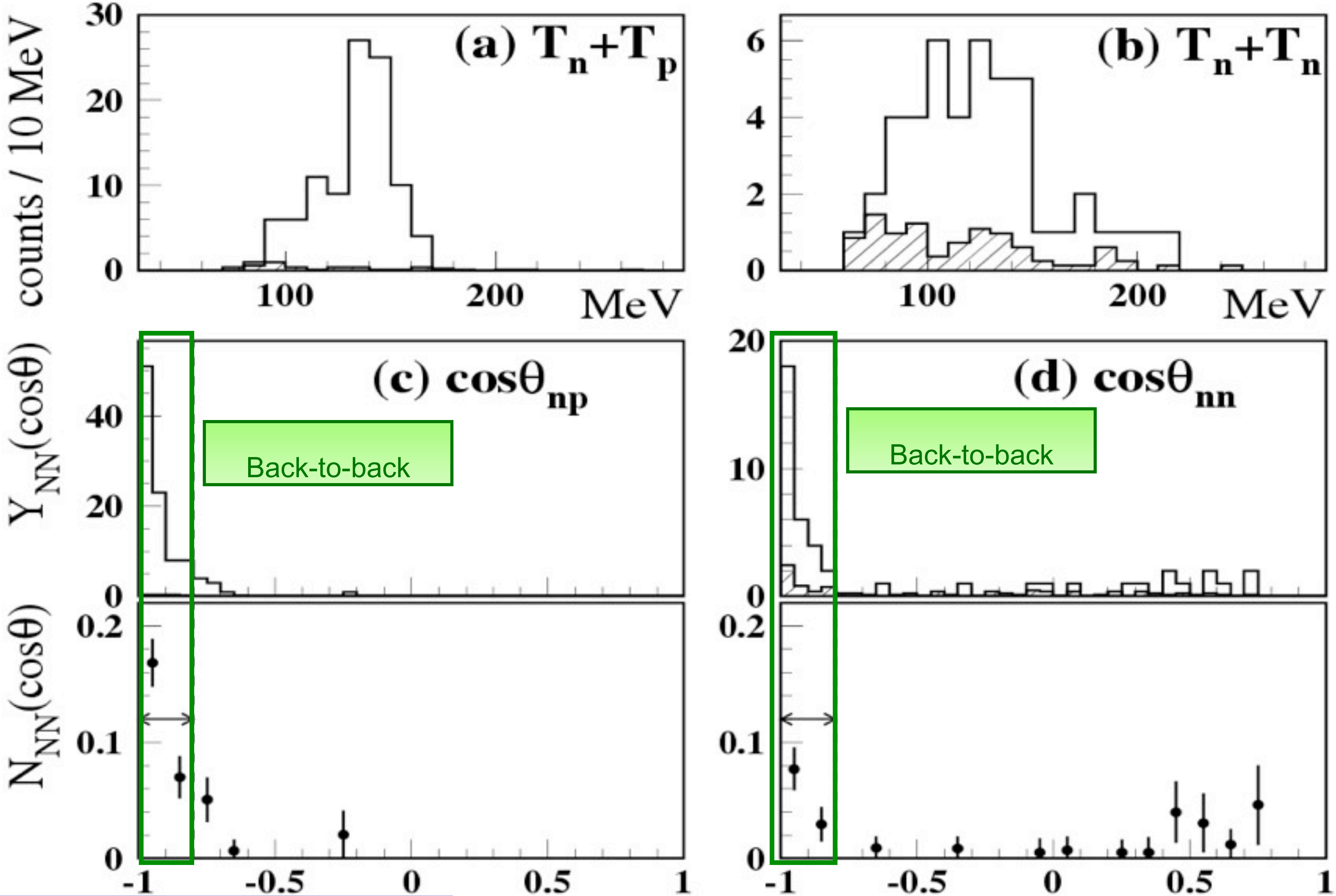
No peaking at Q / 2 (76MeV) even $^{5}_{\Lambda}$He

⇨ **suggested larger contribution of ΛNN→NNN or FSI than theoretical prediction.**



As the mass number become lager, the number of neutron become lager in the low energy part, and smaller in the high energy part.

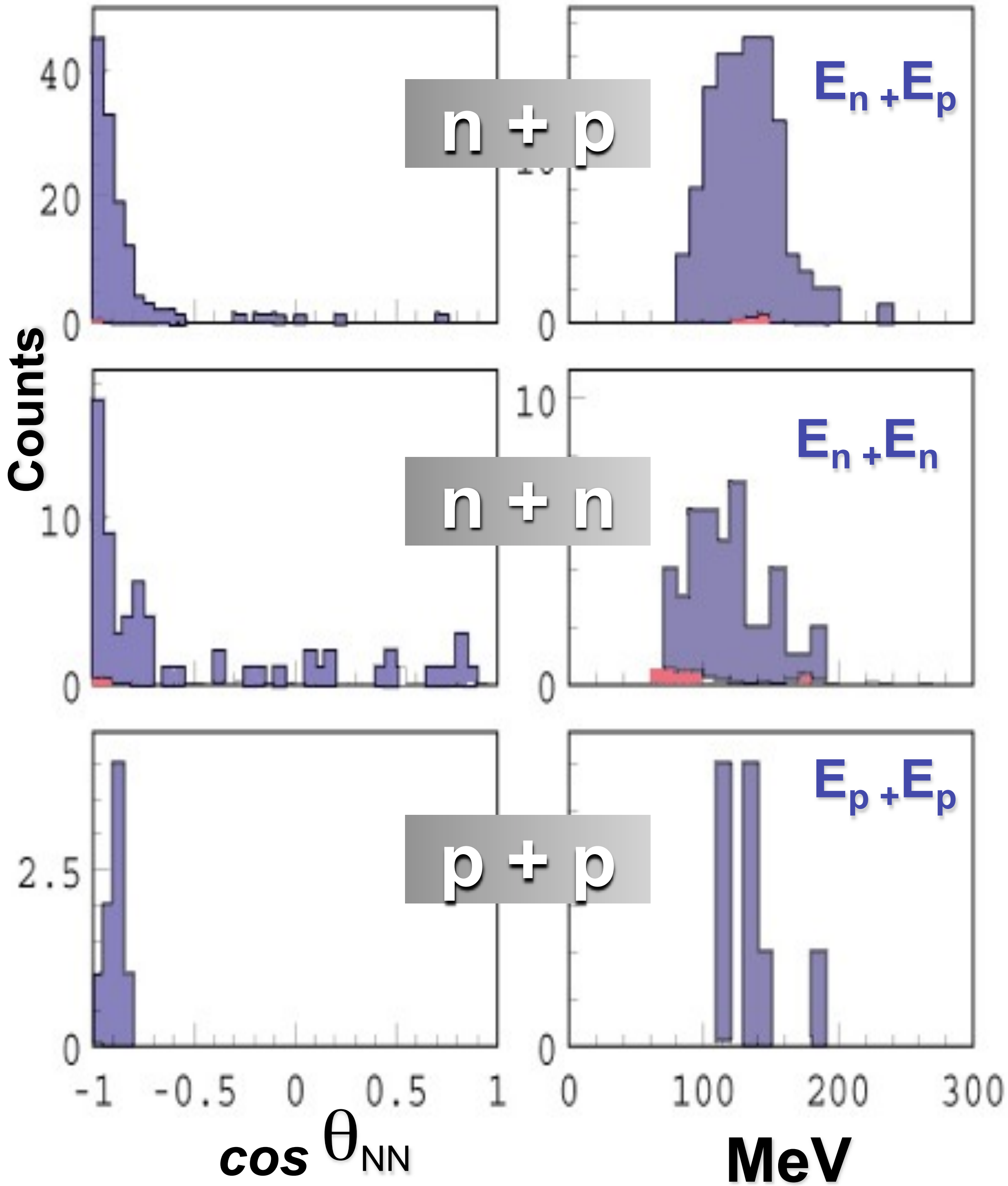
np- & nn- angular distribution ($^5_\Lambda He$)

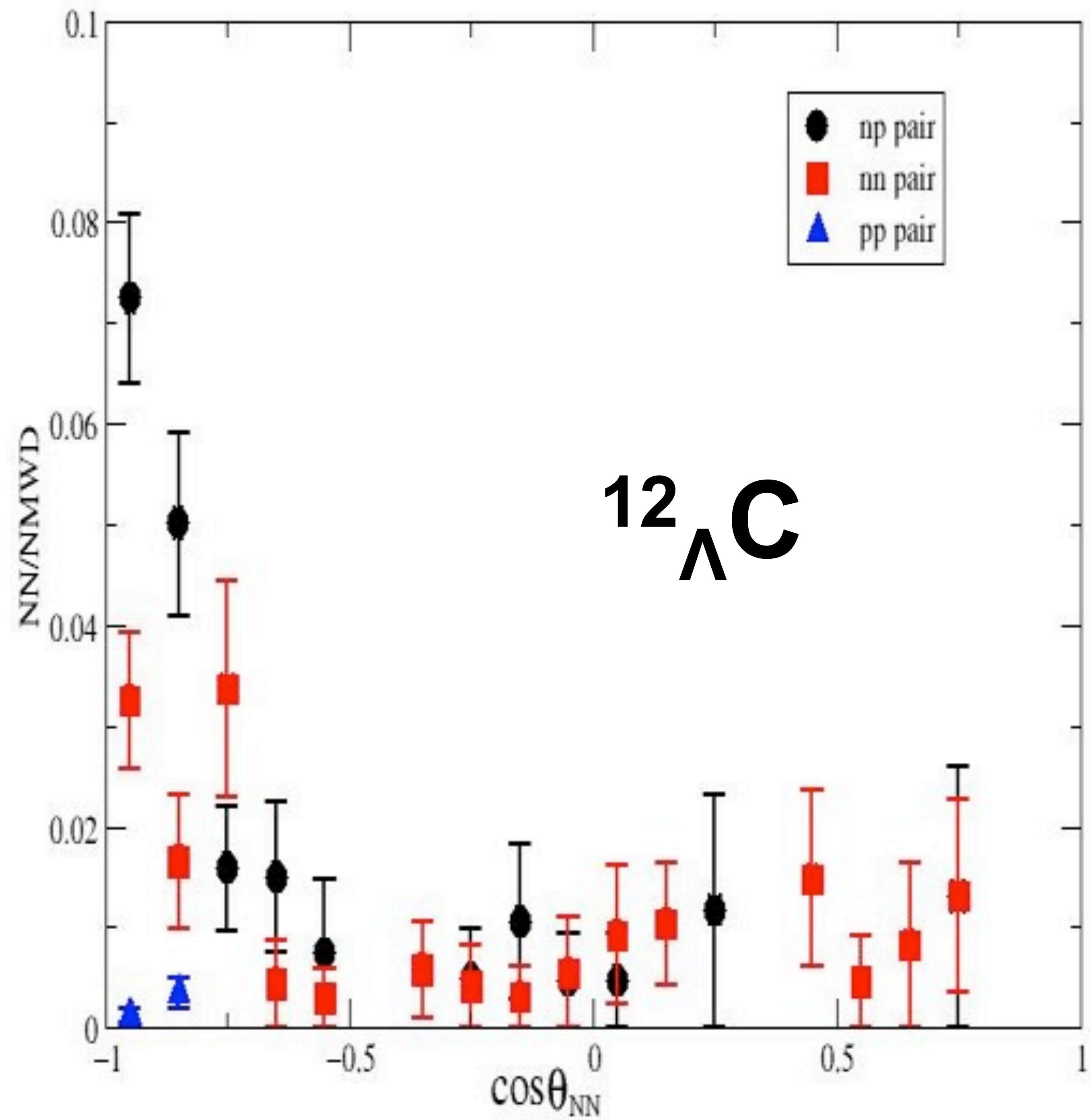


$\Gamma_n/\Gamma_p \sim N_{nn} / N_{np} =$ **0.45±0.11±0.03**

systematic error is mainly come from efficiency for neutron (6%) + acceptance(3%)

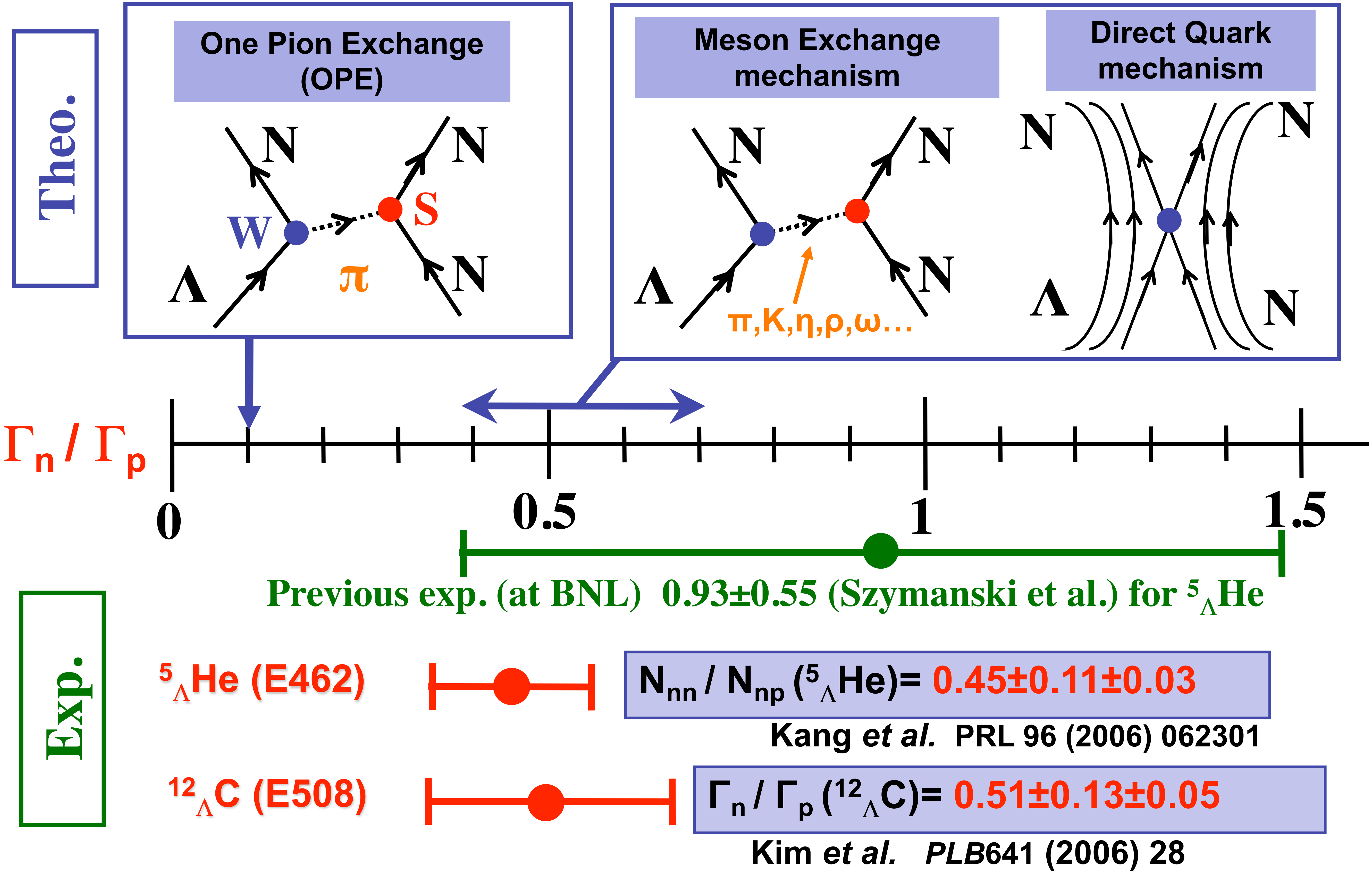
Coincidence Measurement (A=12)





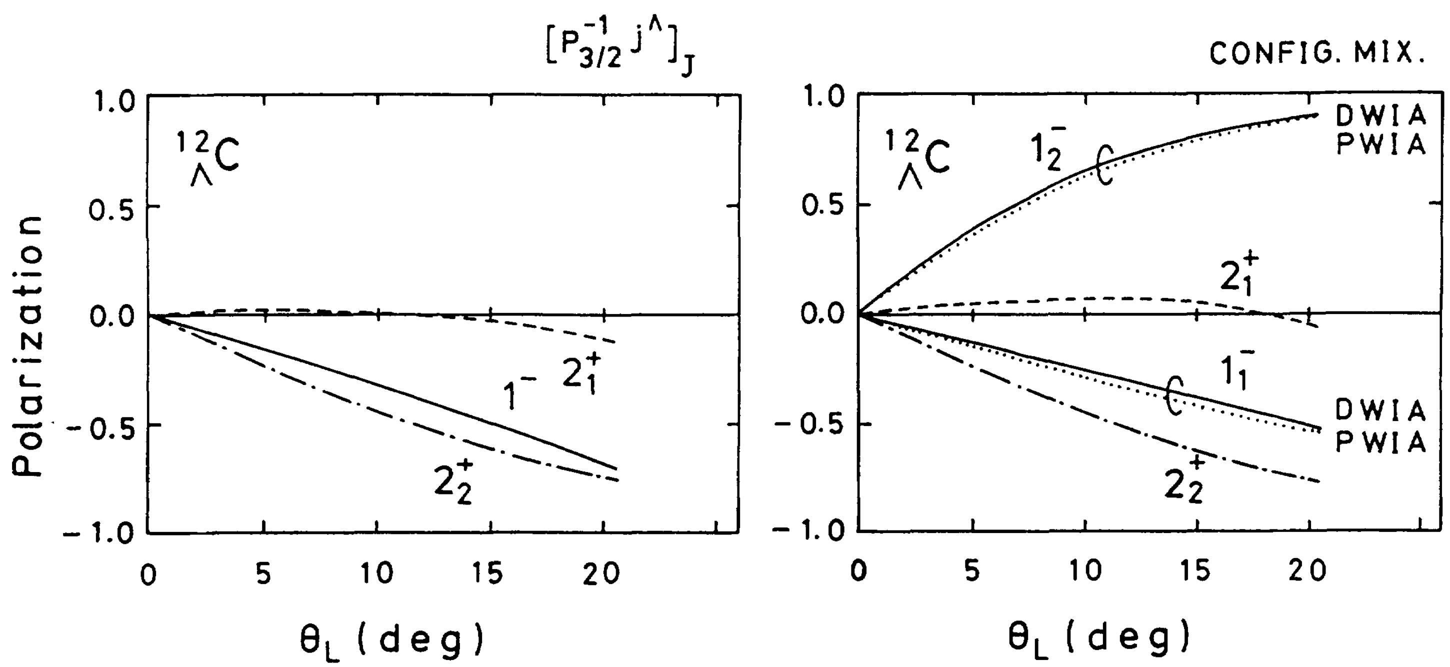
$\Gamma_n/\Gamma_p \sim N_{nn} / N_{np}$ =
0.51±0.13±0.05

Γ_n / Γ_p ratio



偏極と非対称度

偏極ハイパー核の生成



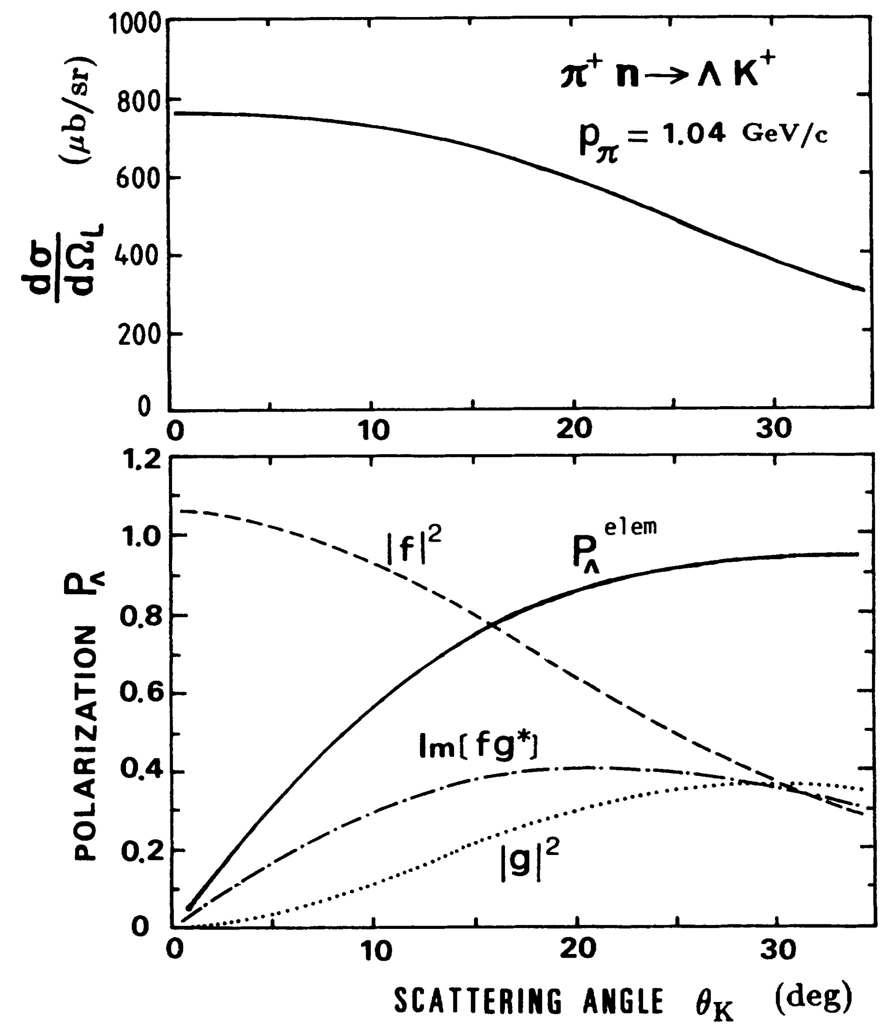


FIG. 8. The spin-nonflip amplitude (f), spin-flip one (g), differential cross section, and polarization calculated as a function of the laboratory scattering angle for $\pi^+ n \to \Lambda K^+$ at $p_\pi = 1.04$ GeV/c. See Eq. (1) for the definition of the amplitudes and Eq. (11) for the Λ polarization in the free space. The two-body laboratory cross section is given by $d\sigma/d\Omega = C(|f|^2 + |g|^2)$ where C is a proportionality coefficient [7].

Asymmetry measurement of decay proton

Asymmetry : Volume of the asymmetric emission from NMWD

$$N(\theta) = N_0(1 + \underline{A}\cos\theta)$$

Asymmetry

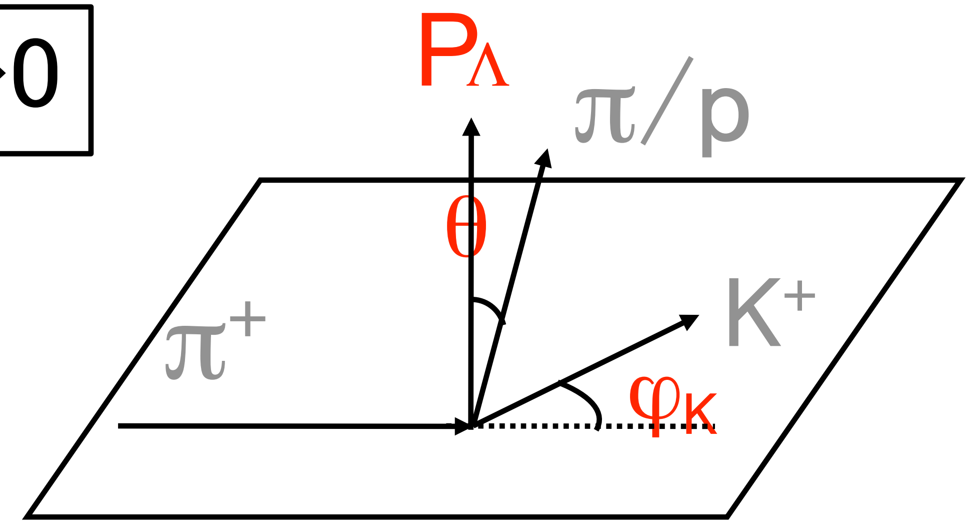
$$= N_0(1 + \underline{\alpha} P_{\Lambda} \cos\theta)$$

Asymmetry parameter

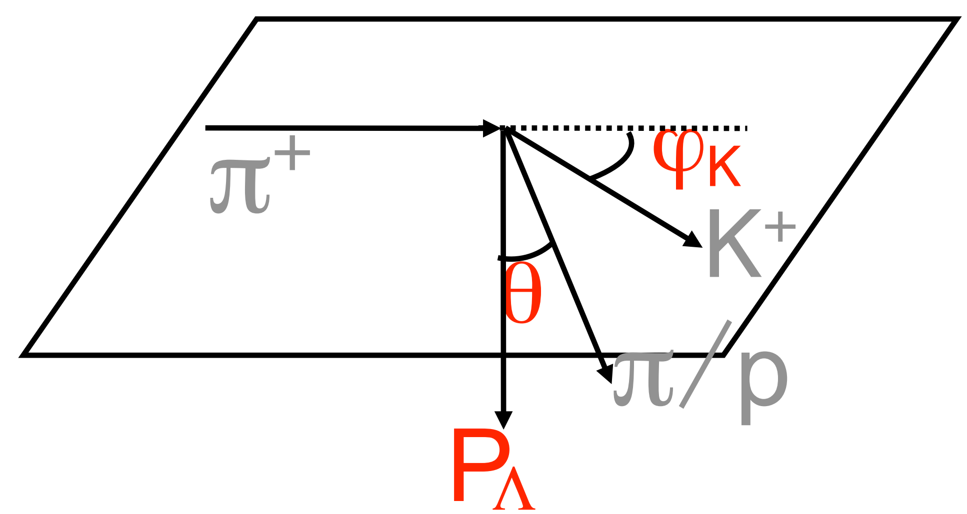
$$A = \frac{(R+1)}{(R-1)}, \quad R = \frac{N(\theta^+)}{N(\theta^-)}$$

$$R = \left\{ \frac{N(\theta^+(+\varphi)) \times N(\theta^-(-\varphi))}{N(\theta^+(-\varphi)) \times N(\theta^-(+\varphi))} \right\}^{1/2}$$

$\varphi_K > 0$



$\varphi_K < 0$



Difference of acceptance & efficiency → canceled out !!

Importance of α_{nm} measurement

If assuming initial S state

Initial state	**Final state**	Amplitude	**Isospin**	Parity
$^1S_0$	$^1S_0$	a	1	No
	$^3P_0$	b	1	Yes
$^3S_1$	$^3S_1$	c	0	No
	$^3D_1$	d	0	No
	$^1P_1$	e	0	Yes
	$^3P_1$	f	1	Yes

$$\alpha_p^{NM} = \frac{\sqrt{3}/2\left[-ae + b(c - \sqrt{2}d)/\sqrt{3} + \underline{(\sqrt{2}c + d)f}\right]}{1/4\left\{a^2 + b^2 + 3(c^2 + d^2 + e^2 + f^2)\right\}}$$

➡ **We can know the interference between states with different Isospin and Parity .**

$$\Gamma_n/\Gamma_p = \frac{2(a^2 + b^2 + f^2)}{a^2 + b^2 + c^2 + d^2 + e^2 + f^2}$$ (Applying ΔI=1/2 rule)

α_{NM} for ${}^{5}_{\Lambda}He$ NMWD

- Polarization of Λ ➡ Estimated from mesonic decay

$$A_{\pi}=\alpha_{\pi}P_{\Lambda}\varepsilon$$

A_{π}: Asymmetry of Pion

α_{π}: Asymmetry Parameter of Pion ($=-0.642\pm0.013$)

P_{Λ}: Polarization of Lambda

ε : Attenuation factor

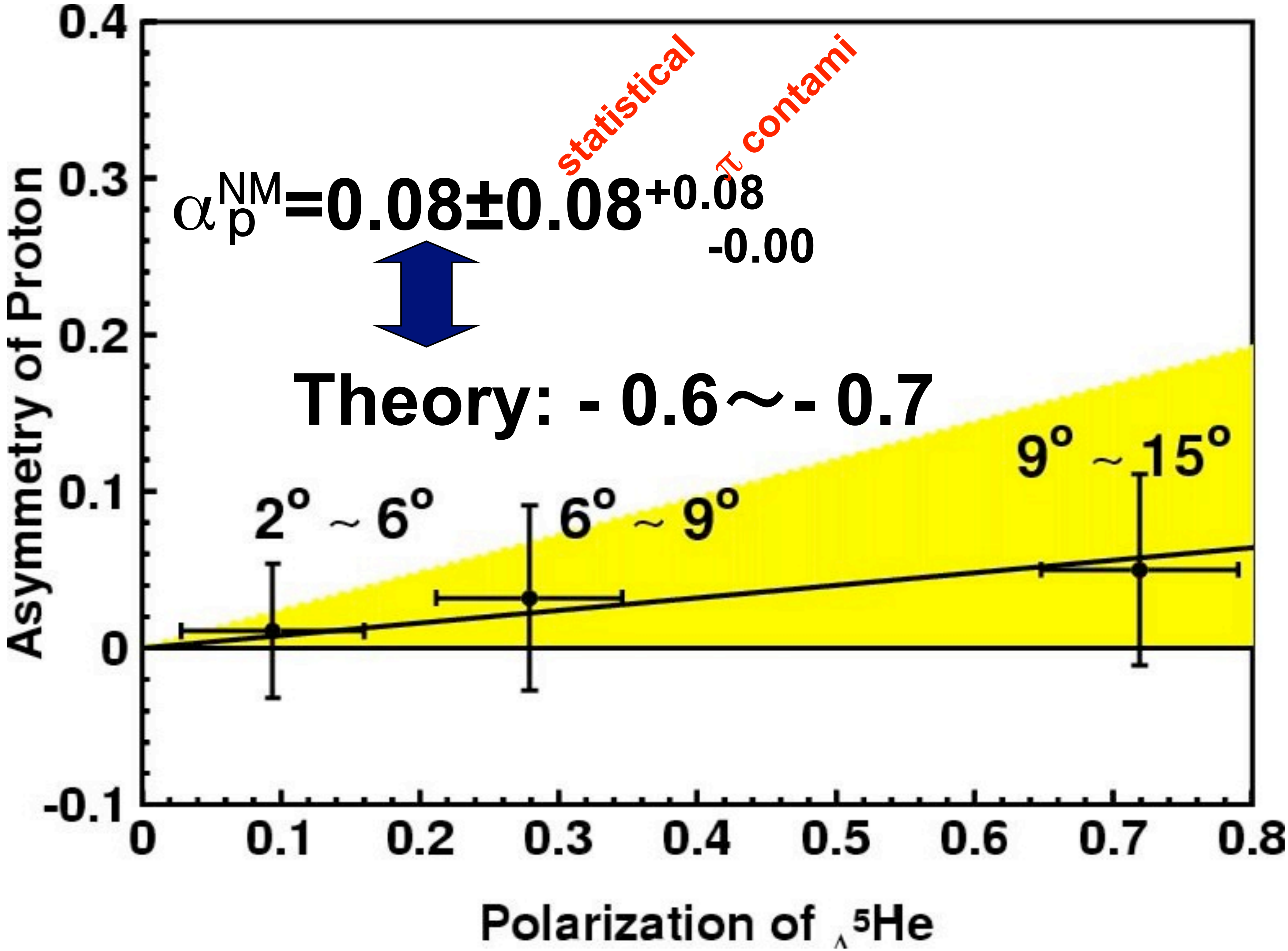
- Asymmetry Parameter of Proton

$$A_{p}=\alpha^{NM}_{p}P_{\Lambda}\varepsilon$$

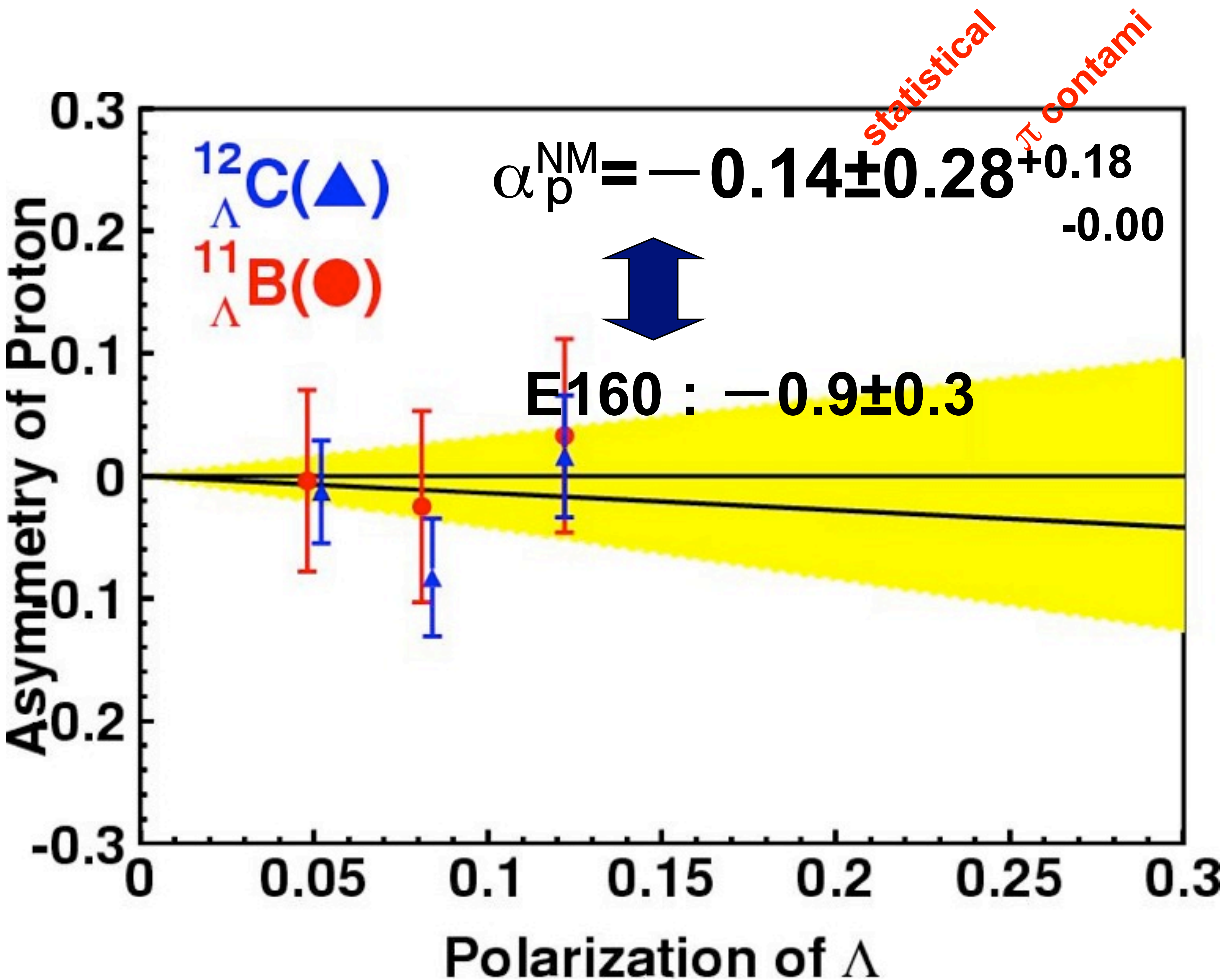
We can calculate α^{NM}_{p} without theoretical help !

Asymmetry parameter of $^{5}_{\Lambda}He$

Nucl.Phys.A754 (2005) 168c
nucl-ex/050916

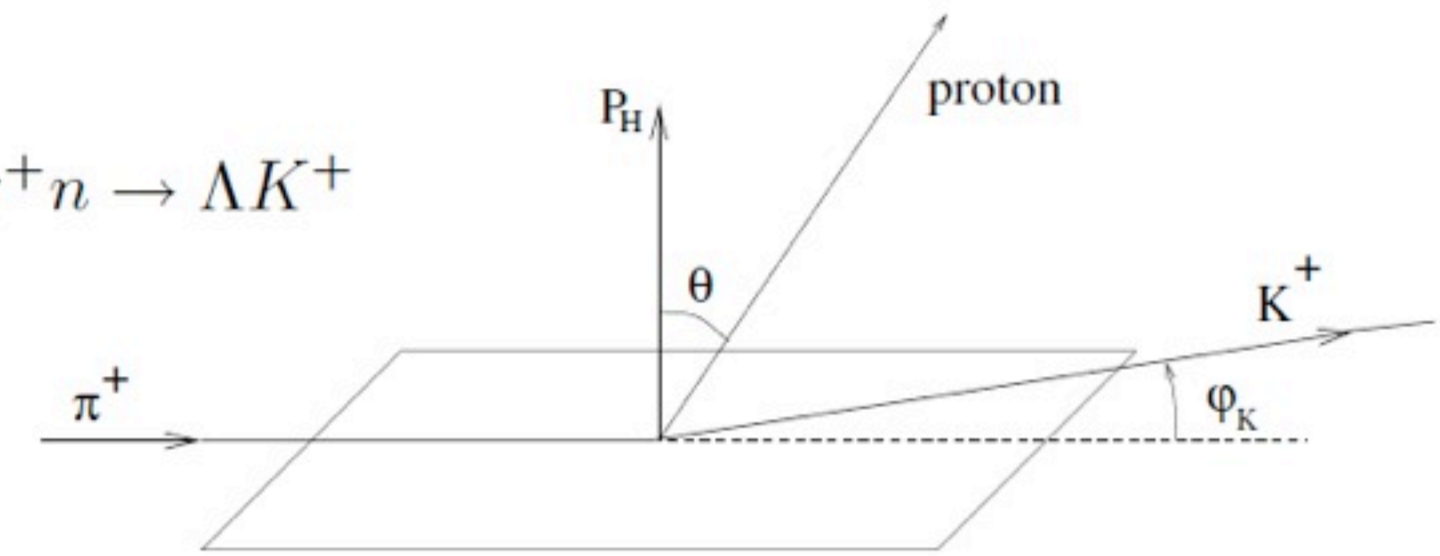


Asymmetry parameter of ${}^{12}_{\Lambda}C$, ${}^{11}_{\Lambda}B$



POLARIZED HYPERNUCLEI: THE DECAY ASYMMETRY

$\pi^+ n \to \Lambda K^+$



✦ Weak decay proton intensity from $\vec{\Lambda} p \to np$: $I(\theta) = I_0 \left[1 + p_\Lambda \, a_\Lambda \cos\theta\right]$

$$p_\Lambda = \Lambda \text{ polarization}$$

$$a_\Lambda = \text{intrinsic } \Lambda \text{ asymmetry parameter}$$

$a_\Lambda \iff$ interference among PC and PV $\vec{\Lambda} p \to np$ channels

$\Longrightarrow$ information on strengths and relative phases of the decay amplitudes

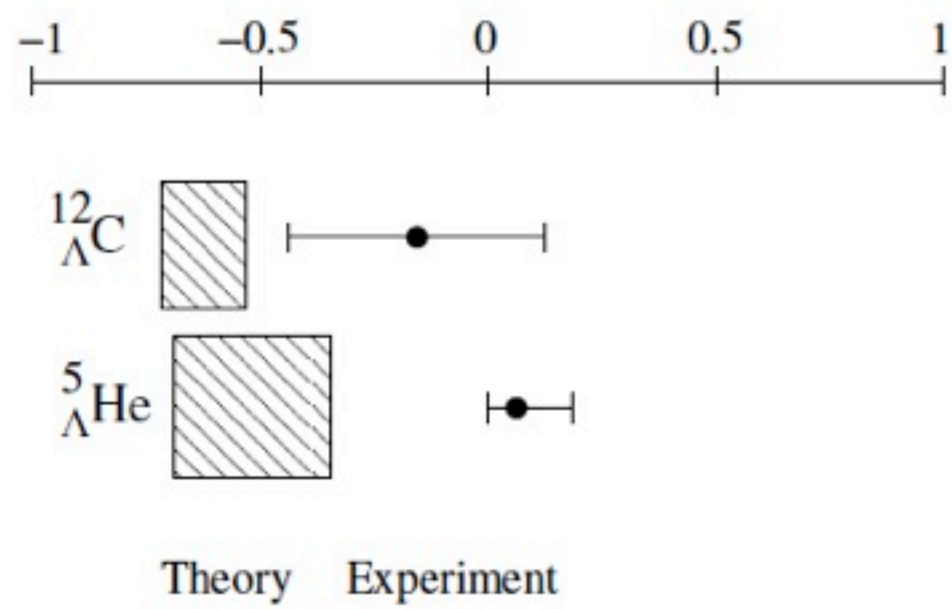
✦ Nucleon FSI modify the weak decay proton intensity $I(\theta)$

Experimentally one measures $I^{\mathrm{M}}(\theta) = I_0^{\mathrm{M}} \left[1 + p_\Lambda \, a_\Lambda^{\mathrm{M}} \cos\theta\right]$

$\Longrightarrow$ *observable* Λ asymmetry parameter $a_\Lambda^{\mathrm{M}} = \dfrac{1}{p_\Lambda} \dfrac{I^{\mathrm{M}}(0^\circ) - I^{\mathrm{M}}(180^\circ)}{I^{\mathrm{M}}(0^\circ) + I^{\mathrm{M}}(180^\circ)}$

		${}^{5}_{\Lambda}\mathrm{He}$	${}^{12}_{\Lambda}\mathrm{C}$
Sasaki et al.	a_Λ		
$\pi + K + \mathrm{DQ}$		-0.68	
Parreño et al.			
$\pi + \rho + K + K^* + \omega + \eta$		-0.68	-0.73
Itonaga et al.			
$\pi + K + \omega + 2\pi/\rho + 2\pi/\sigma$		-0.33	
Barbero et al.			
$\pi + \rho + K + K^* + \omega + \eta$		-0.54	-0.53
KEK–E508	a_Λ^{M}		$-0.16 \pm 0.28^{+0.18}_{-0.00}$
KEK–E462		$+0.07 \pm 0.08^{+0.08}_{-0.00}$	

KEK–E508/E462: T. Maruta et al., EPJA 33, 255 (2007)



FSI prevent establishing direct comparisons between a_Λ and a_Λ^{M}

$\Longrightarrow$ a theoretical evaluation of a_Λ^{M} is required

OME + Nucleon FSI

[W. M. Alberico, G.G., A. Parreño and A. Ramos, PRL 94, 082501 (2005)]

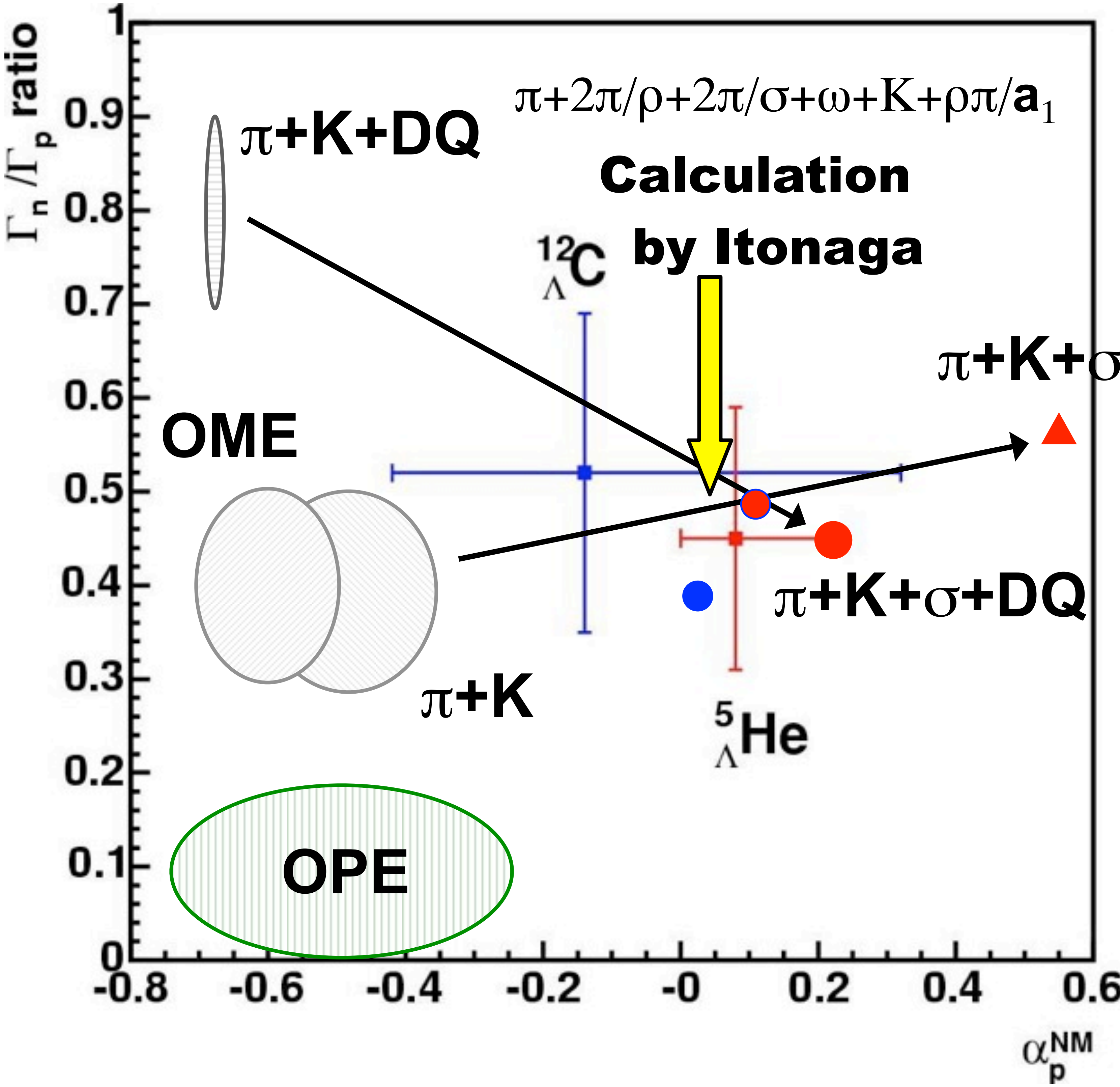
$$\mathrm{OME} = \pi + \rho + K + K^* + \eta + \omega$$

$$I(\theta) = I_0\,[1 + p_\Lambda\, a_\Lambda \cos\theta] \qquad I^{\mathrm{M}}(\theta) = I_0^{\mathrm{M}}\,[1 + p_\Lambda\, a_\Lambda^{\mathrm{M}} \cos\theta]$$

	${}^{5}_{\Lambda}\mathrm{He}$	${}^{11}_{\Lambda}\mathrm{B}$	${}^{12}_{\Lambda}\mathrm{C}$
a_Λ	-0.68	-0.81	-0.73
$a_\Lambda^{\mathrm{M}}\,(T_p \geq 30$ MeV$)$	-0.46	-0.39	-0.37
$a_\Lambda^{\mathrm{M}}\,(T_p \geq 50$ MeV$)$	-0.52	-0.55	-0.51
$a_\Lambda^{\mathrm{M}}\,(T_p \geq 70$ MeV$)$	-0.55	-0.70	-0.65
KEK–E462	$0.07 \pm 0.08^{+0.08}_{-0.00}$		
KEK–E508		$-0.16 \pm 0.28^{+0.18}_{-0.00}$	

Data from [T. Maruta et al., EPJA 33, 255 (2007)]

Comparison with recent calculations



π+K,OME can reproduce Γ_n/Γ_p ratio but predict large negative α^{NM}

Γ_n/Γ_p and α^{NM} can be reproduced by π+K+σ+DQ model

Sasaki *et al.*
PRC71 (2005)035502

(1) Large $b(^1S_0 \rightarrow {}^3P_0)$ and $f(^3S_0 \rightarrow {}^3P_1)$ amplitude

(2) Violation of $\Delta I=1/2$ rule considered

$$\frac{\sqrt{3}/2[-ae+b(c-\sqrt{2}d)/\sqrt{3}+(\sqrt{2}c+d)f]}{1/4\{a^2+b^2+3(c^2+d^2+e^2+f^2)\}}$$

- **Effective Field Theory: $\pi + K +$ Leading–Order Contact Interactions**

  [A. Parreño, C. Bennhold and B. R. Holstein, PRC 70, 051601 (2004)]

  - LOCI coefficients fixed to reproduce experimental $\Gamma_{\rm NM}$ and Γ_n/Γ_p for ${}^5_\Lambda$He, ${}^{11}_\Lambda$B and ${}^{12}_\Lambda$C and $a_\Lambda({}^5_\Lambda\text{He})$
  - Predicted a dominating central, spin– and isospin–independent contact term

- **$\pi + K + \sigma$ + Direct Quark**

  [K. Sasaki, M. Izaki, M. Oka, PRC 71, 035502 (2005)]

  - Decay data for s-shell hypernuclei fitted to obtain the weak couplings of the scalar–isoscalar σ–meson, $\mathcal{H}^{\rm W}_{\Lambda\sigma N} = g_W \bar{\psi}_N (A_\sigma + B_\sigma \gamma_5)\phi_\sigma \psi_\Lambda$
  - All ${}^5_\Lambda$He decay observables reasonably reproduced. No calculation for ${}^{12}_\Lambda$C

- **OME + σ**, OME$= \pi + \rho + K + K^* + \eta + \omega$

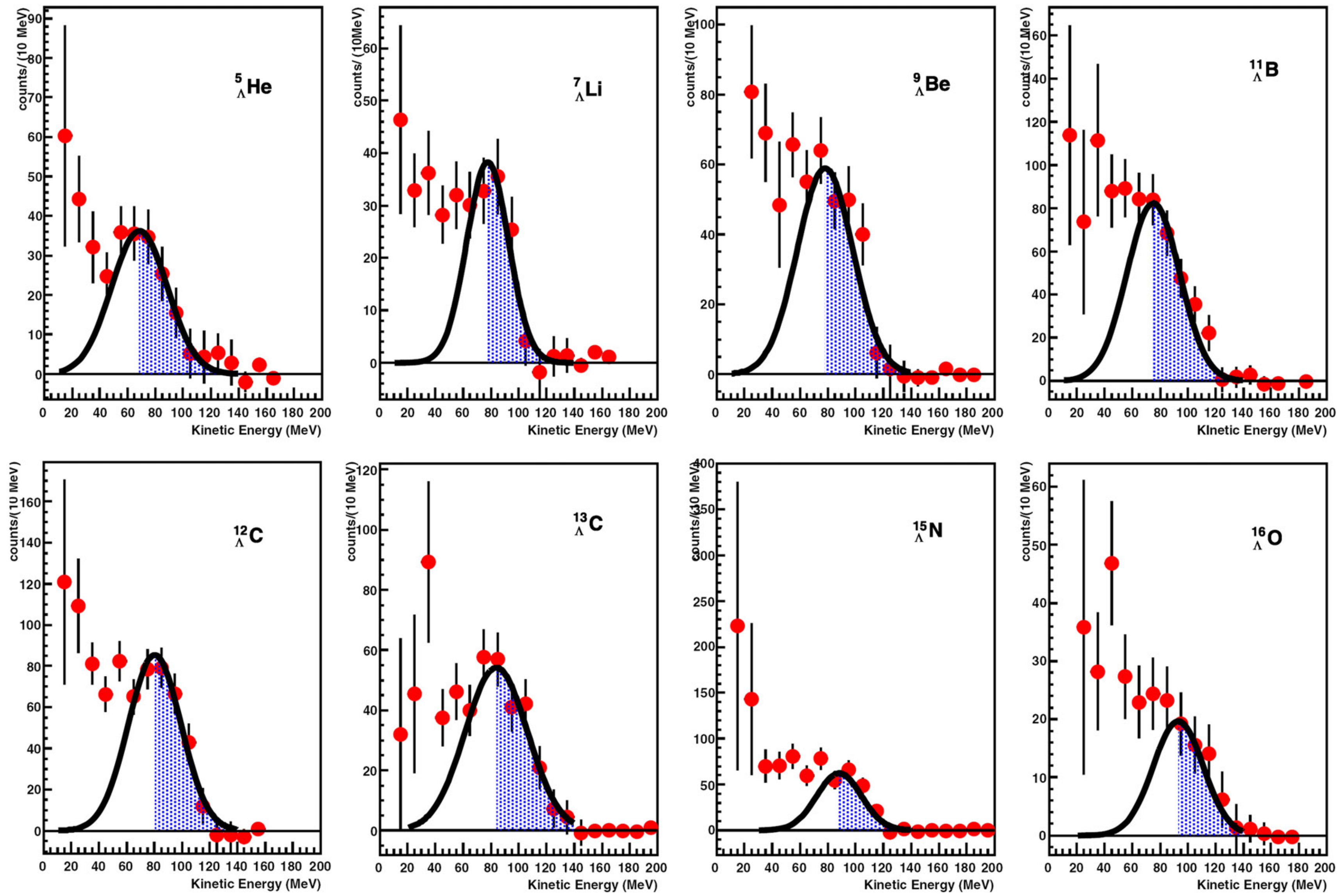
  [C. Barbero and A. Mariano, PRC 73, 024309 (2006)]

  - Unknown σ couplings fixed to reproduce measured $\Gamma_{\rm NM}({}^5_\Lambda\text{He})$ and $\Gamma_n/\Gamma_p({}^5_\Lambda\text{He})$
  - Improved overall agreement with experiment for ${}^{12}_\Lambda$C and ${}^5_\Lambda$He but data for $a_\Lambda({}^5_\Lambda\text{He})$ could not be reproduced

- $\Longrightarrow$ **Importance of the Scalar–Isoscalar channel in Asymmetry calculations**

Γ_{2N} ?

- FINUDA



$^{5}_{\Lambda}$He
$^{7}_{\Lambda}$Li
$^{9}_{\Lambda}$Be
$^{11}_{\Lambda}$B
$^{12}_{\Lambda}$C
$^{13}_{\Lambda}$C
$^{15}_{\Lambda}$N
$^{16}_{\Lambda}$O
counts/(10 MeV)
Kinetic Energy (MeV)

$$R(A) = \frac{0.5 + \frac{\Gamma_2}{\Gamma_p}}{1 + \frac{\Gamma_2}{\Gamma_p}} + bA.$$

$$\frac{\Gamma_2}{\Gamma_{\mathrm{NMWD}}} = \frac{\Gamma_2/\Gamma_p}{(\Gamma_n/\Gamma_p) + 1 + (\Gamma_2/\Gamma_p)}.$$

$$\frac{\Gamma_2}{\Gamma_{\mathrm{NMWD}}} = 0.24 \pm 0.10.$$

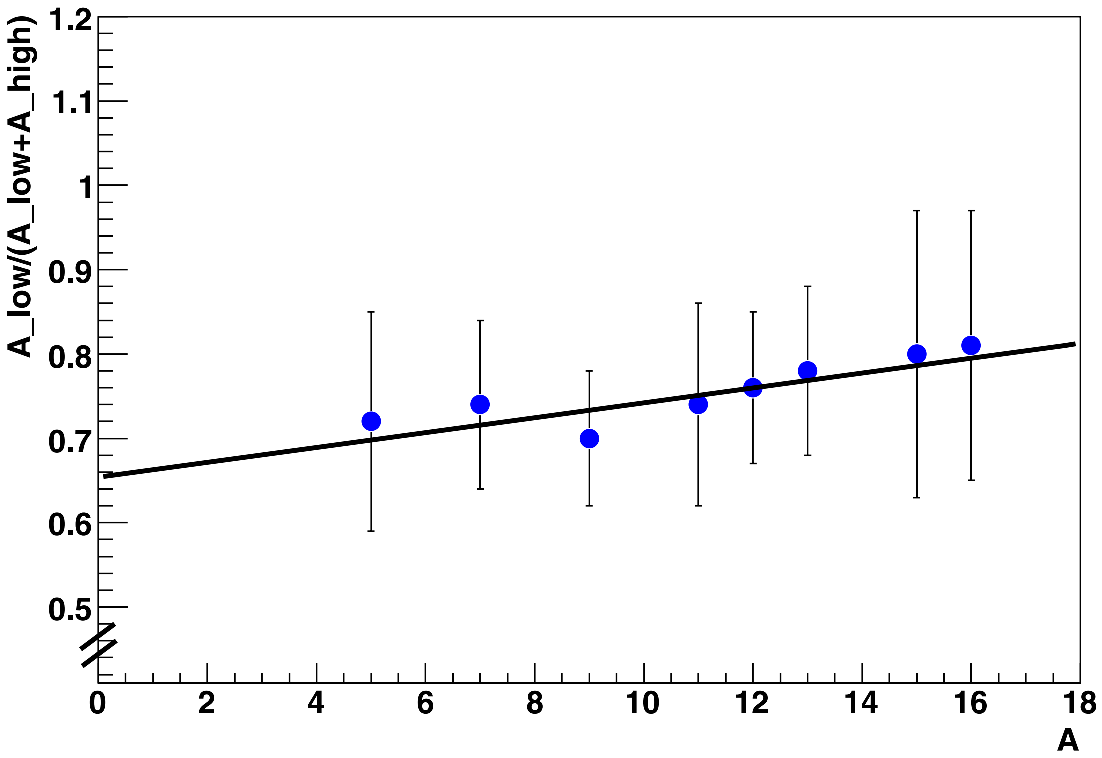


Fig. 2. The ratio $A_{\mathrm{low}}/(A_{\mathrm{low}} + A_{\mathrm{high}})$ as a function of the hypernuclear mass number.

- KEK E502: PRL 103(2009) 182502.
  - Γ_{2N}/Γ_{NM}=0.29±0.13

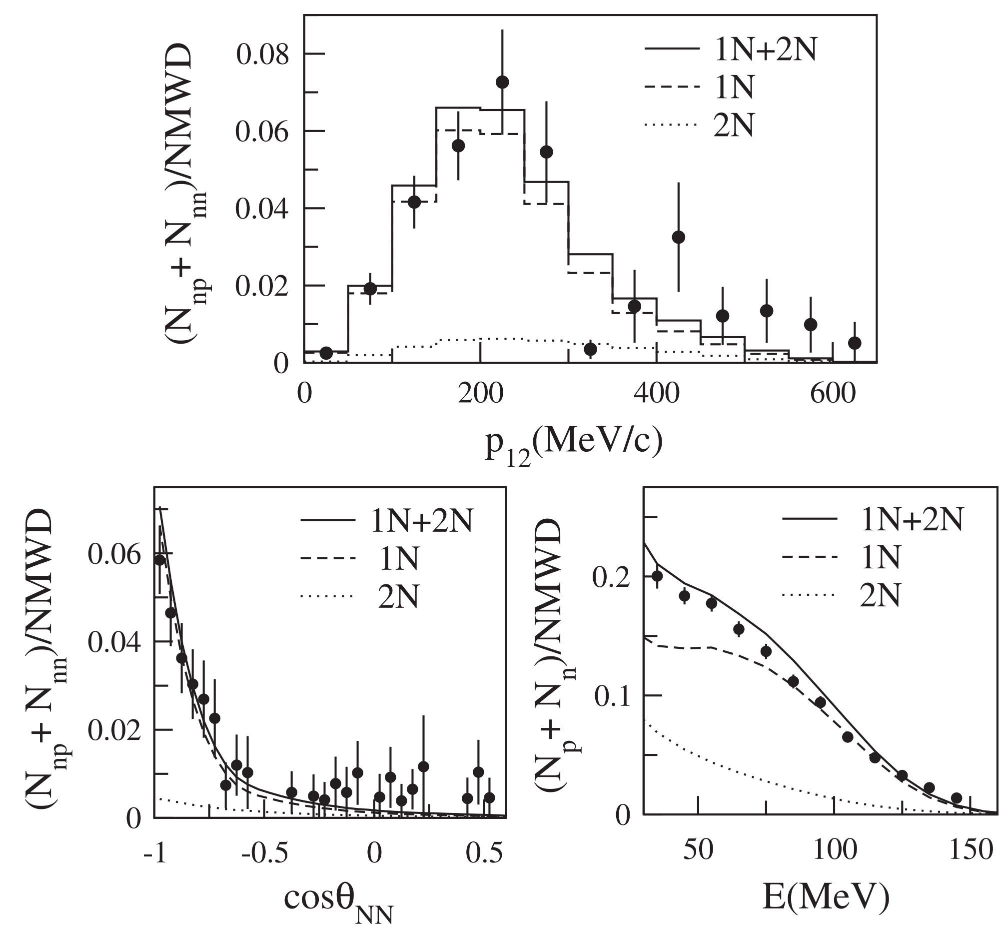


FIG. 4. The momentum sum (upper) and the angular (lower left) correlation of the pair sum $N_{np}+N_{nn}$ and the normalized nucleon yields $N_N(E)$ are compared with those of INC($1N+2N$) (solid lines) with $b_{2N}=0.29$. The decomposed $1N$- (dashed lines) and $2N$-NMWD (dotted lines) contribution also are shown.

ΔI＝1/2則の検証

s–shell Hypernuclei $\Longleftrightarrow$ $\Delta I = 1/2$ Rule

- Block–Dalitz Phenomenological Model $\Longrightarrow$ Spin–Isospin structure of $\Lambda N \to nN$

- Introducing the rates R_{NJ} for the spin–singlet (R_{n0}, R_{p0}) and spin–triplet (R_{n1}, R_{p1}) elementary $\Lambda N \to nN$ interactions:

$$\begin{aligned}
\Gamma_{\rm NM}({}^{3}_{\Lambda}\mathrm{H}) &= (3R_{n0} + R_{n1} + 3R_{p0} + R_{p1})\,\frac{\rho_2}{8} \\
\Gamma_{\rm NM}({}^{4}_{\Lambda}\mathrm{H}) &= (R_{n0} + 3R_{n1} + 2R_{p0})\,\frac{\rho_3}{6} \\
\Gamma_{\rm NM}({}^{4}_{\Lambda}\mathrm{He}) &= (2R_{n0} + R_{p0} + 3R_{p1})\,\frac{\rho_3}{6} \\
\Gamma_{\rm NM}({}^{5}_{\Lambda}\mathrm{He}) &= (R_{n0} + 3R_{n1} + R_{p0} + 3R_{p1})\,\frac{\rho_4}{8}
\end{aligned}$$

- Relations which test the $\Delta I = 1/2$ Rule

$$\frac{\Gamma_n({}^{4}_{\Lambda}\mathrm{He})}{\Gamma_p({}^{4}_{\Lambda}\mathrm{H})} = \frac{\frac{\Gamma_n}{\Gamma_p}({}^{4}_{\Lambda}\mathrm{H})\frac{\Gamma_n}{\Gamma_p}({}^{4}_{\Lambda}\mathrm{He})}{\frac{\Gamma_n}{\Gamma_p}({}^{5}_{\Lambda}\mathrm{He})} = \frac{R_{n0}}{R_{p0}} \quad \Longleftrightarrow \quad \Delta I = 1/2 \text{ Rule:} \quad \frac{R_{n1}}{R_{p1}} \leq \frac{R_{n0}}{R_{p0}} = 2$$

TABLE XI. – *Experimental data for the non–mesonic weak decay of s–shell hypernuclei.*

	$\Gamma_n/\Gamma_\Lambda^{\rm free}$	$\Gamma_p/\Gamma_\Lambda^{\rm free}$	$\Gamma_{\rm NM}/\Gamma_\Lambda^{\rm free}$	Γ_n/Γ_p	Ref.
${}^4_\Lambda$H			0.22 ± 0.09		reference value
			0.17 ± 0.11		KEK [11]
			0.29 ± 0.14		[73]
${}^4_\Lambda$He	0.04 ± 0.02	0.16 ± 0.02	0.20 ± 0.03	0.25 ± 0.13	BNL [74]
${}^5_\Lambda$He	0.20 ± 0.11	0.21 ± 0.07	0.41 ± 0.14	0.93 ± 0.55	BNL [37]

- ΔI=1/2

$$R_n(^1S_0) = 2R_p(^1S_0), \quad R_n(^3P_0) = 2R_p(^3P_0), \quad R_n(^3P_1) = 2R_p(^3P_1).$$

$$\frac{R_{n1}}{R_{p1}} \leq \frac{R_{n0}}{R_{p0}} = 2.$$

$$\frac{R_{n0}}{R_{p0}} = \frac{4r^2 - 4r + 1}{2r^2 + 4r + 2}$$

$$r = \frac{\langle I_f = 1||A_{1/2}||I_i = 1/2\rangle}{\langle I_f = 1||A_{3/2}||I_i = 1/2\rangle}$$

To J-PARC

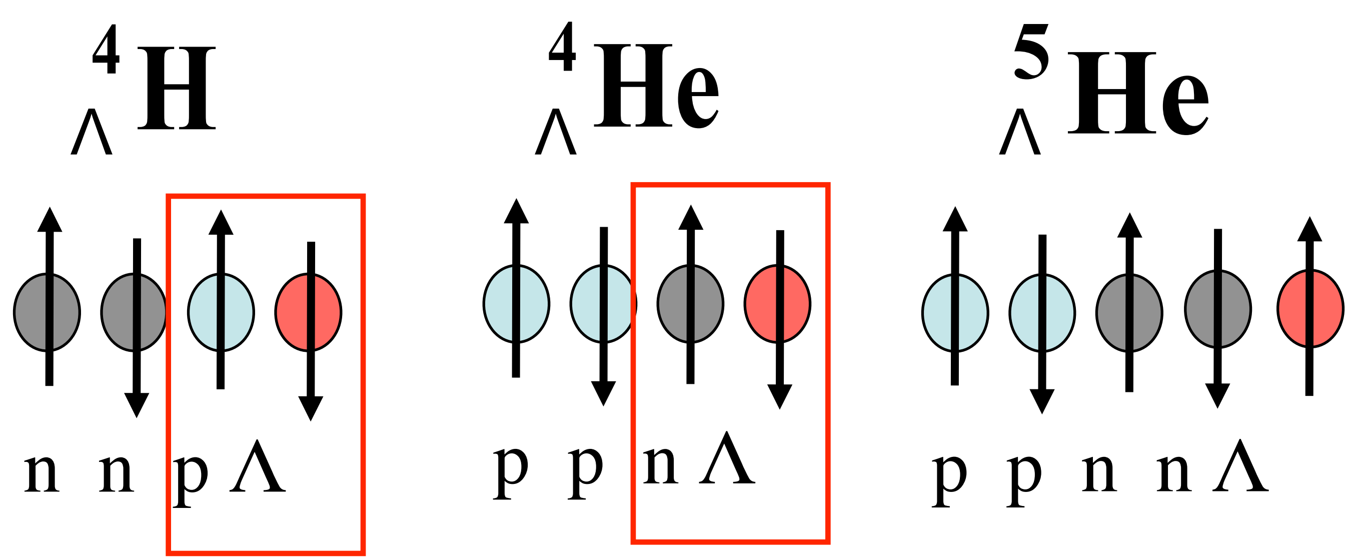
Non-mesonic weak decay of $^4_\Lambda$He and $^4_\Lambda$H

see S.Ajimura : J-PARC LOI 21

Spin / isospin dependence

$$\Gamma_{nm}(^4_\Lambda H) = (3R_{n1} + R_{n0} + 2R_{p0}) \times \rho_4 / 6$$
$$\Gamma_{nm}(^4_\Lambda He) = (2R_{n0} + 3R_{p1} + R_{p0}) \times \rho_4 / 6$$
$$\Gamma_{nm}(^5_\Lambda He) = (3R_{n1} + R_{n0} + 3R_{p1} + R_{p0}) \times \rho_5 / 8$$

R_{NS} … N : Λn→nn, Λp→np
S : spin = 0 or 1



^{4}He (K^-,π^-) $^4_\Lambda$He or
^{4}He (π^+,K^+) $^4_\Lambda$He
→ n+n back-to-back

^{4}He (K^-,π^0) $^4_\Lambda$H
→ p+n back-to-back
(π^0 spectrometer)

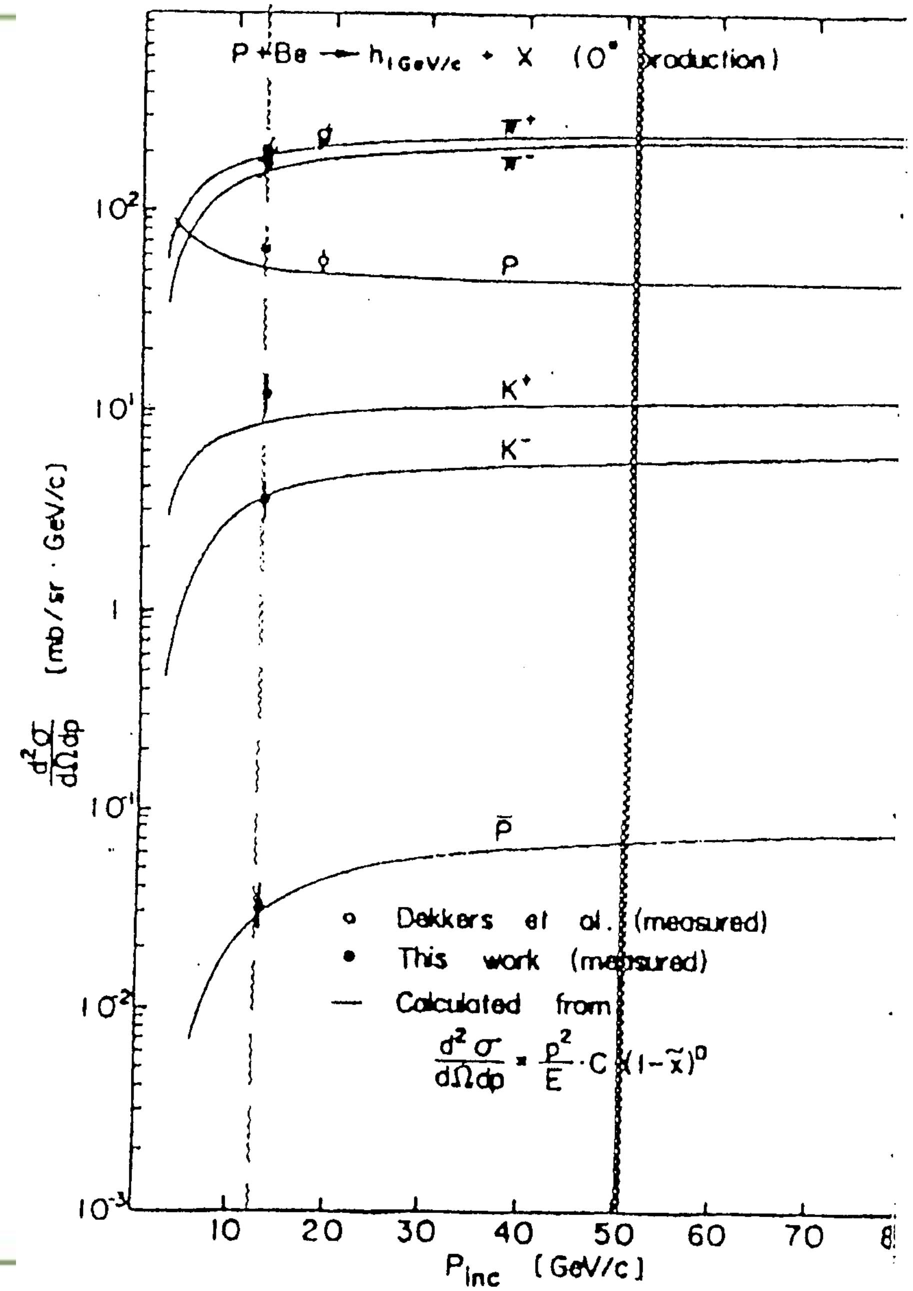
→ *Need one-order higher statistics.* → *J-PARC*

Third day in UT

Production of Secondary Meson Beams

- p+A→π, K, + X at forward angles
  - $E_{cm} = (m_1{}^2+m_2{}^2+2E_1{}^{lab}m_2)^{1/2}$
    $\sim(2E_1{}^{lab}m_2)^{1/2}$
  - $\pi^+ > \pi^-$ ←charge conservation
  - $K^+ > K^-$ ←threshold difference
  - π > K >> anti-p

$s\bar{s}$: $K^+\Lambda$(500+175), K^-K^+ (500+500)



p+C→π⁻, K⁻, anti-p

18 GeV

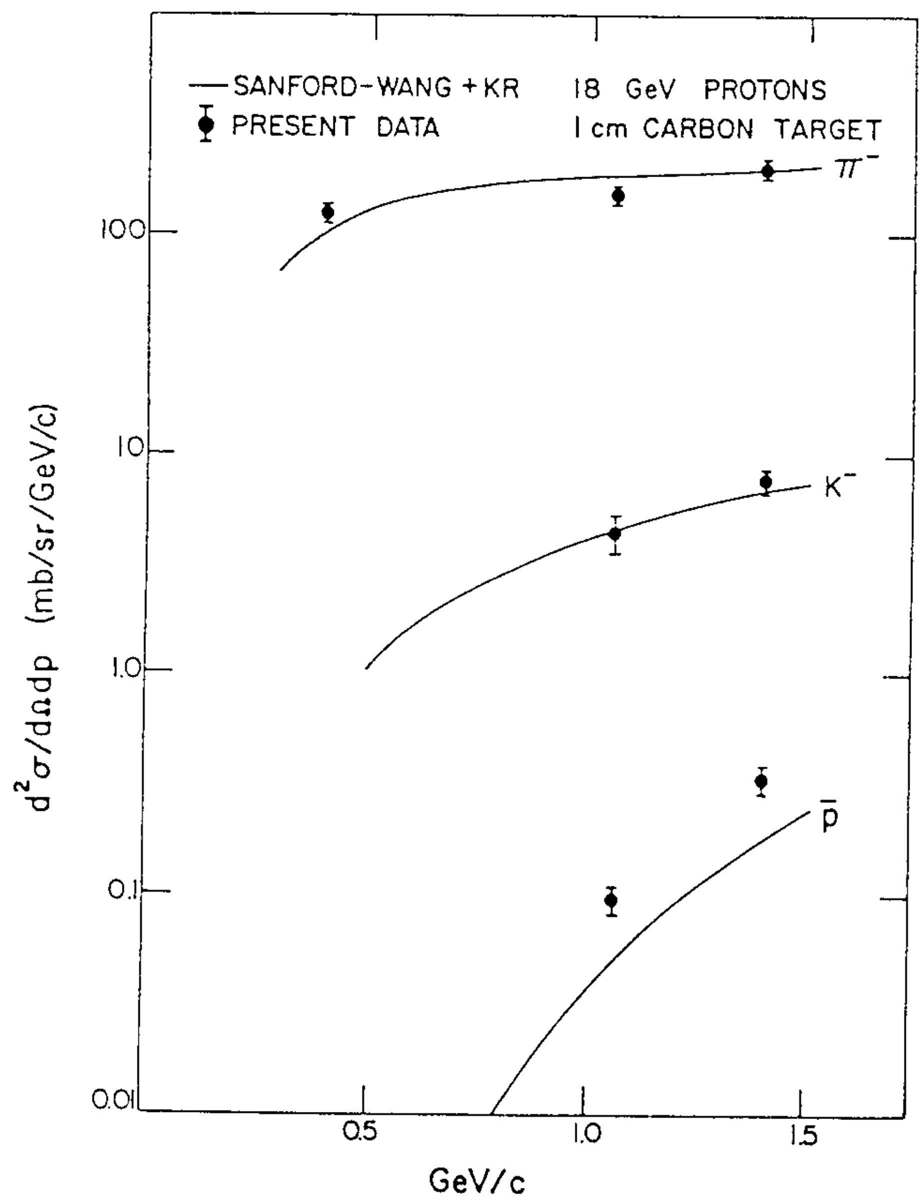


Fig. 5. 18-GeV production cross sections on 1-cm carbon target.

24 GeV

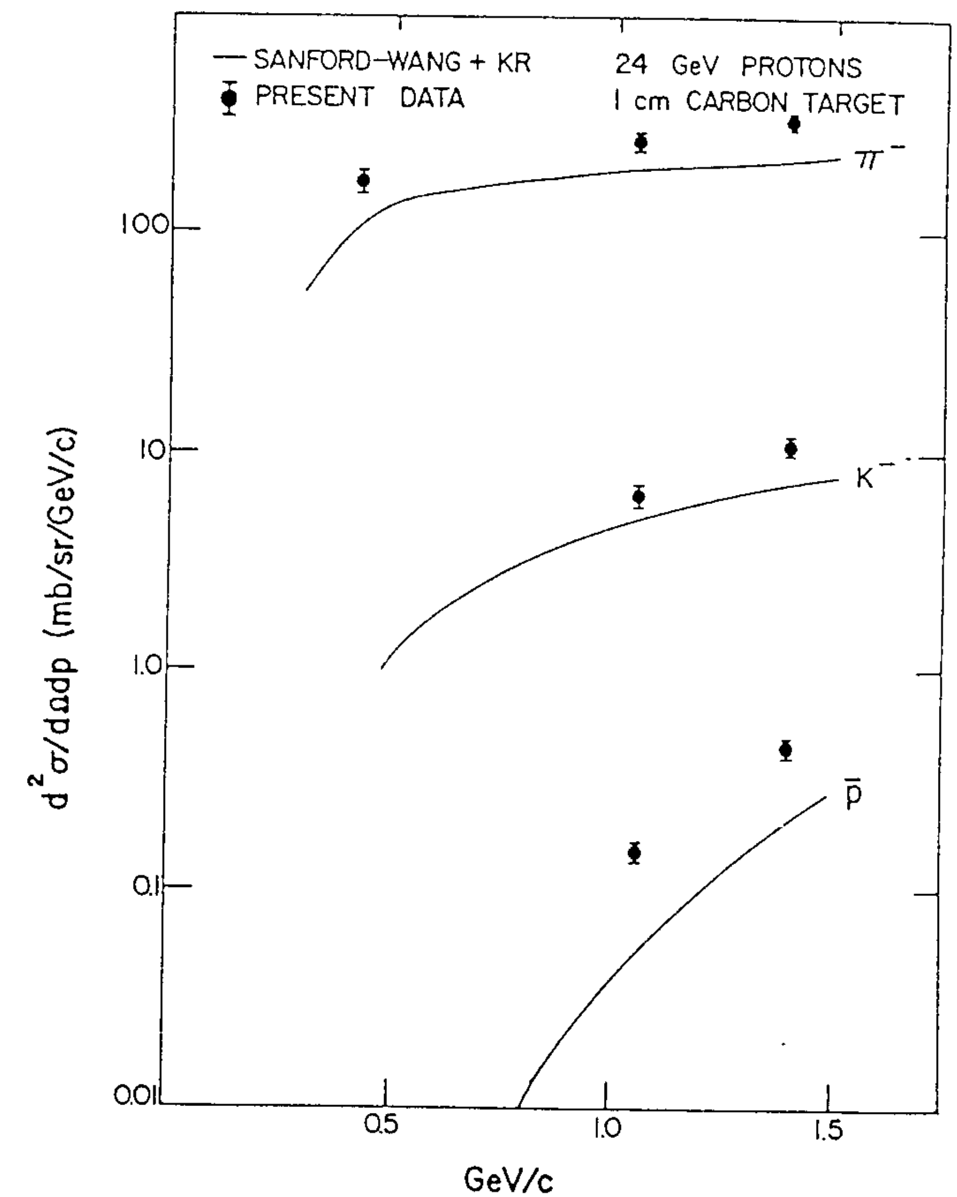
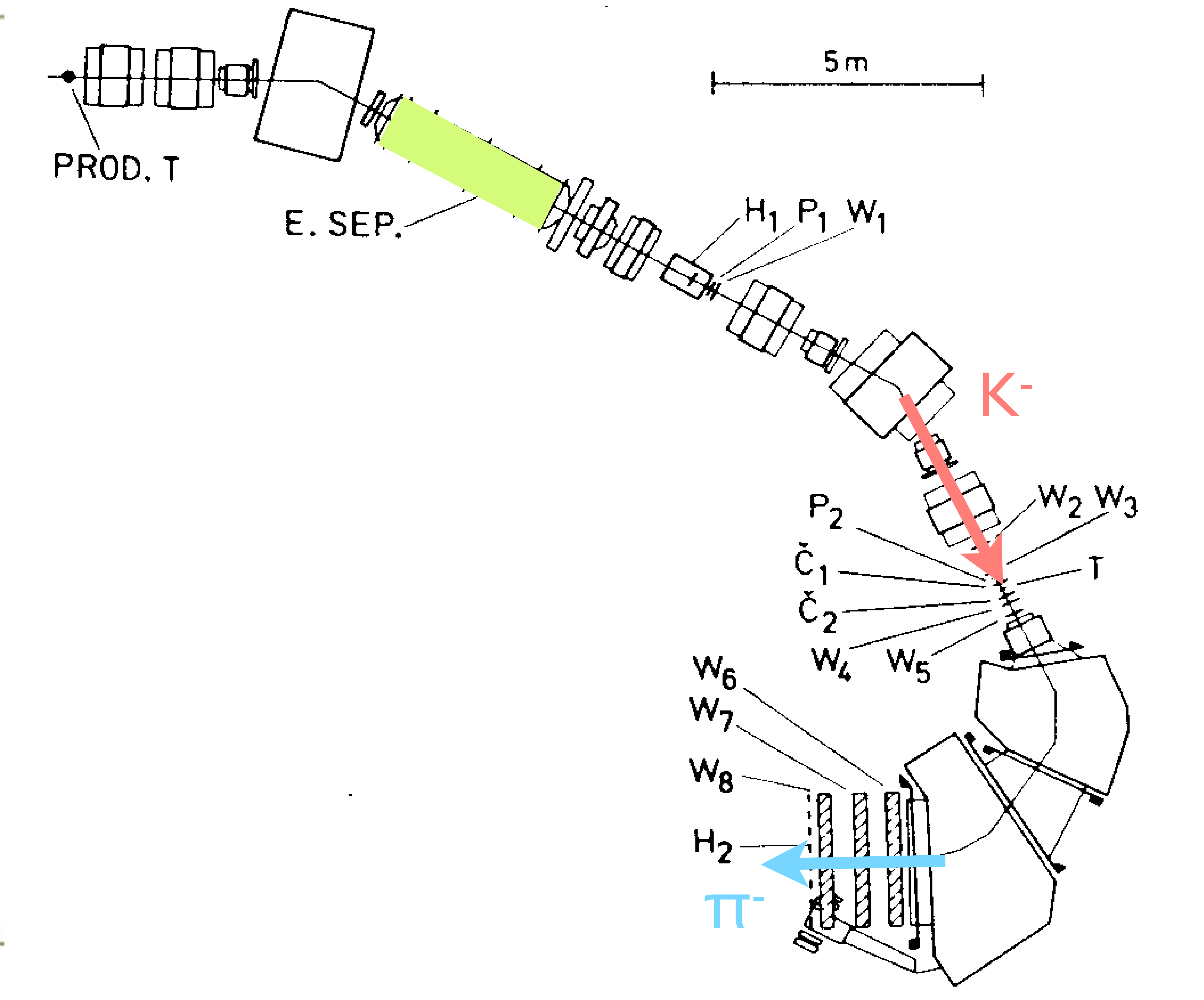
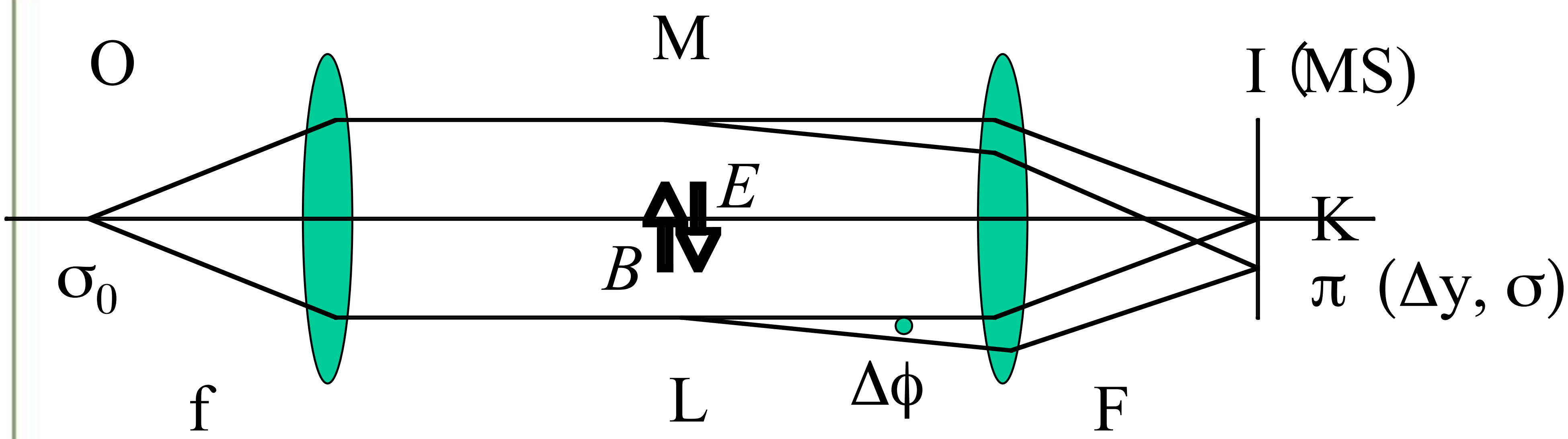


Fig. 6. 24-GeV production cross sections on 1-cm carbon target.

SPES II for (K⁻,π⁻)

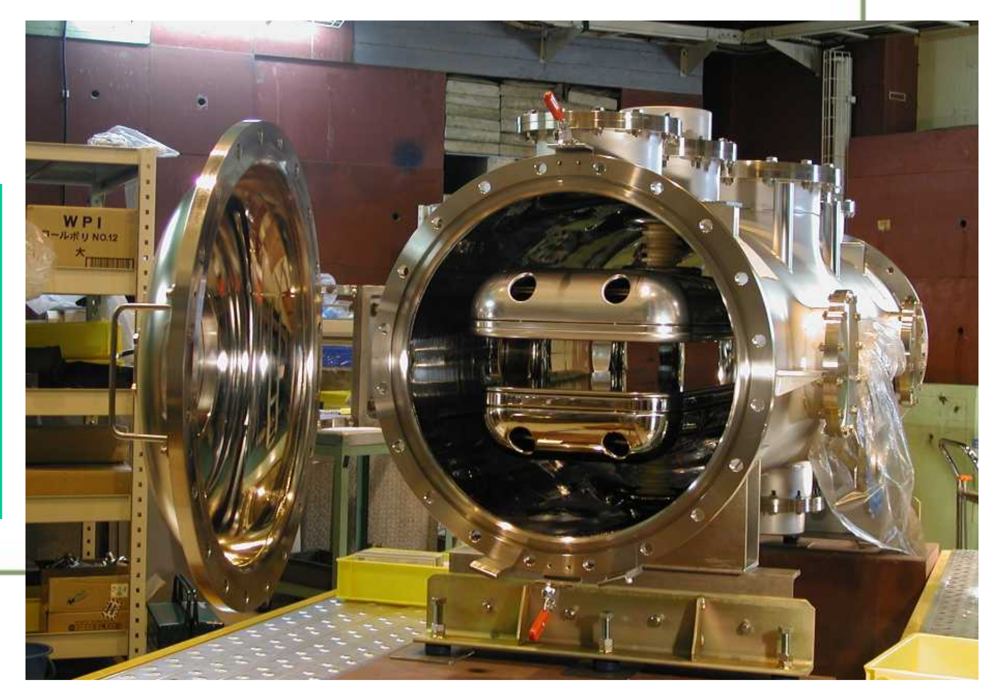


Electro-Static Mass Separator



+/-400 kV

$$\Delta\phi = eEL\,(\beta_K^{-1} - \beta_\pi^{-1})\,/(pc)$$



$\Delta y = -F\Delta\phi$

$\sigma = -(F/f)\sigma_0$

$S = \Delta y/\sigma = \Delta\phi\sigma_0/f$

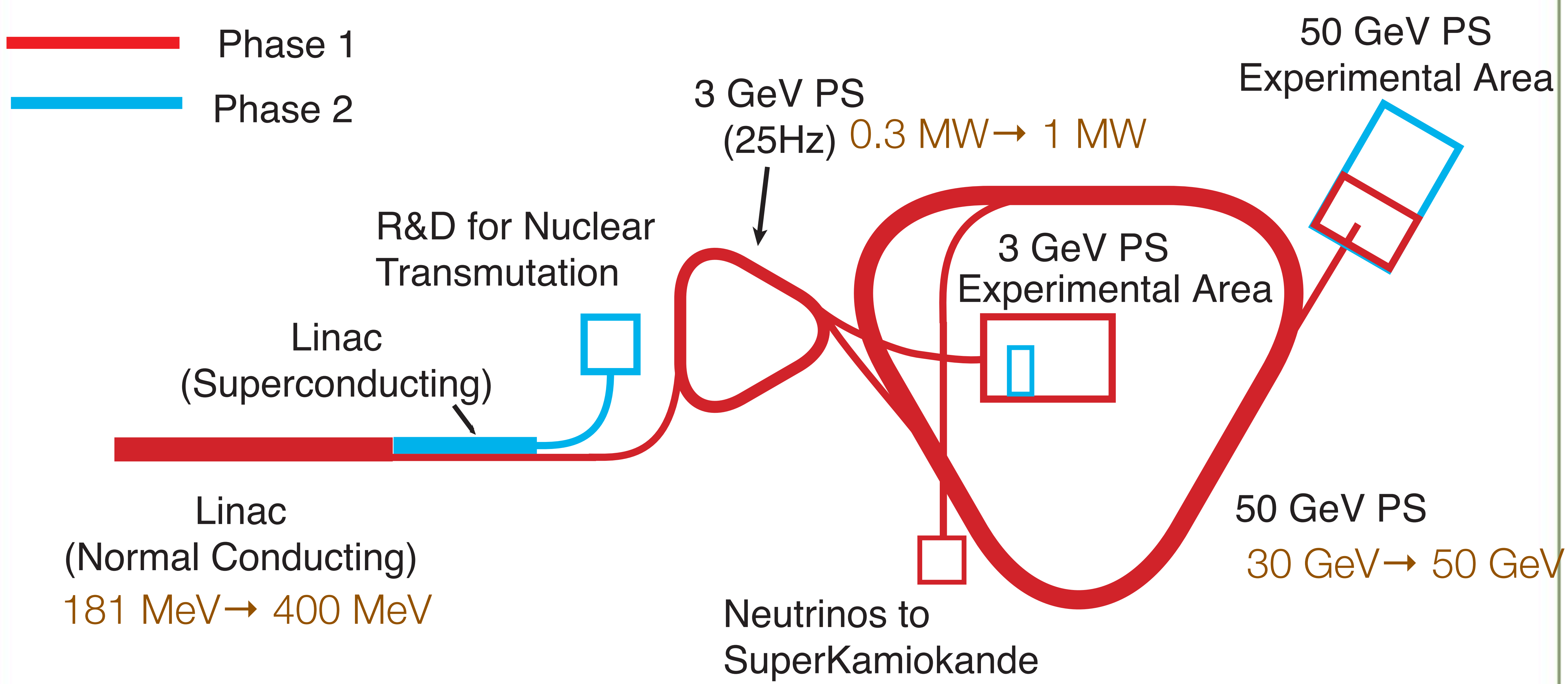
Decay of Meson Beams

- Lifetime ($c\tau$): π^+(7.8045 m), K^-(3.713 m)
- Decay Length= $\beta\gamma c\tau = p/m \cdot c\tau$
  - K^-@1 GeV/c : 1000/500•$c\tau$=7.4 m
    5m line: Decay rate=1-exp(-5m/7.4m)~49%
  - π^-@1 GeV/c: 1000/140•$c\tau$=55.7 m
    15m line: Decay rate=1-exp(-15m/55.7m)~23%

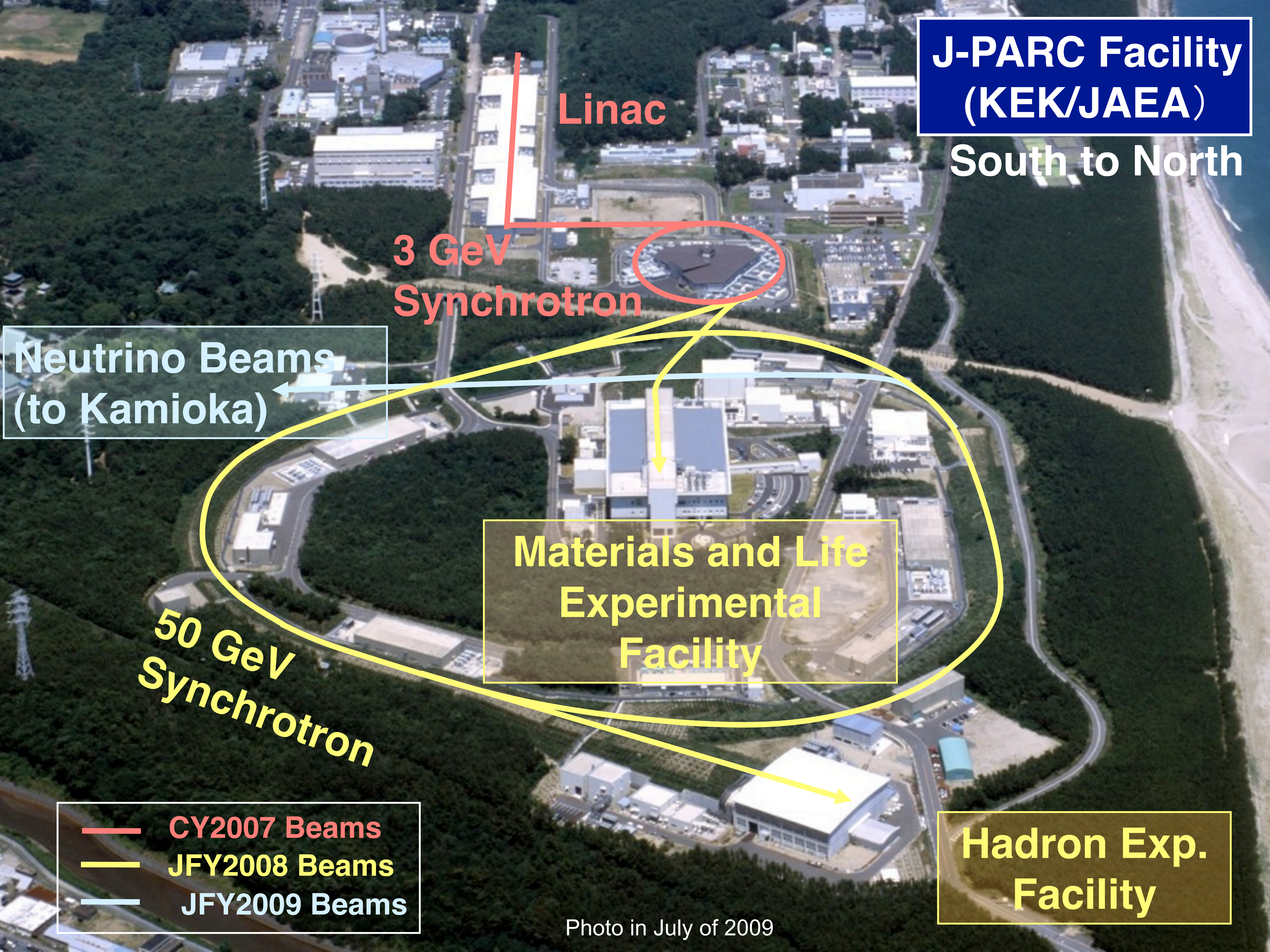
Introduction to J-PARC

- Japan Proton Accelerator Research Complex
- Three high-intensity proton beams at 400 MeV (LINAC), 3 GeV (RCS), and 50 GeV(MR).
- To produce various secondary beams in high-intensity: K, π, anti-p, ν, neutron, μ, etc.
- Construction: 2001 - 2008
- Joint Project between KEK and JAEA

Phase 1&2

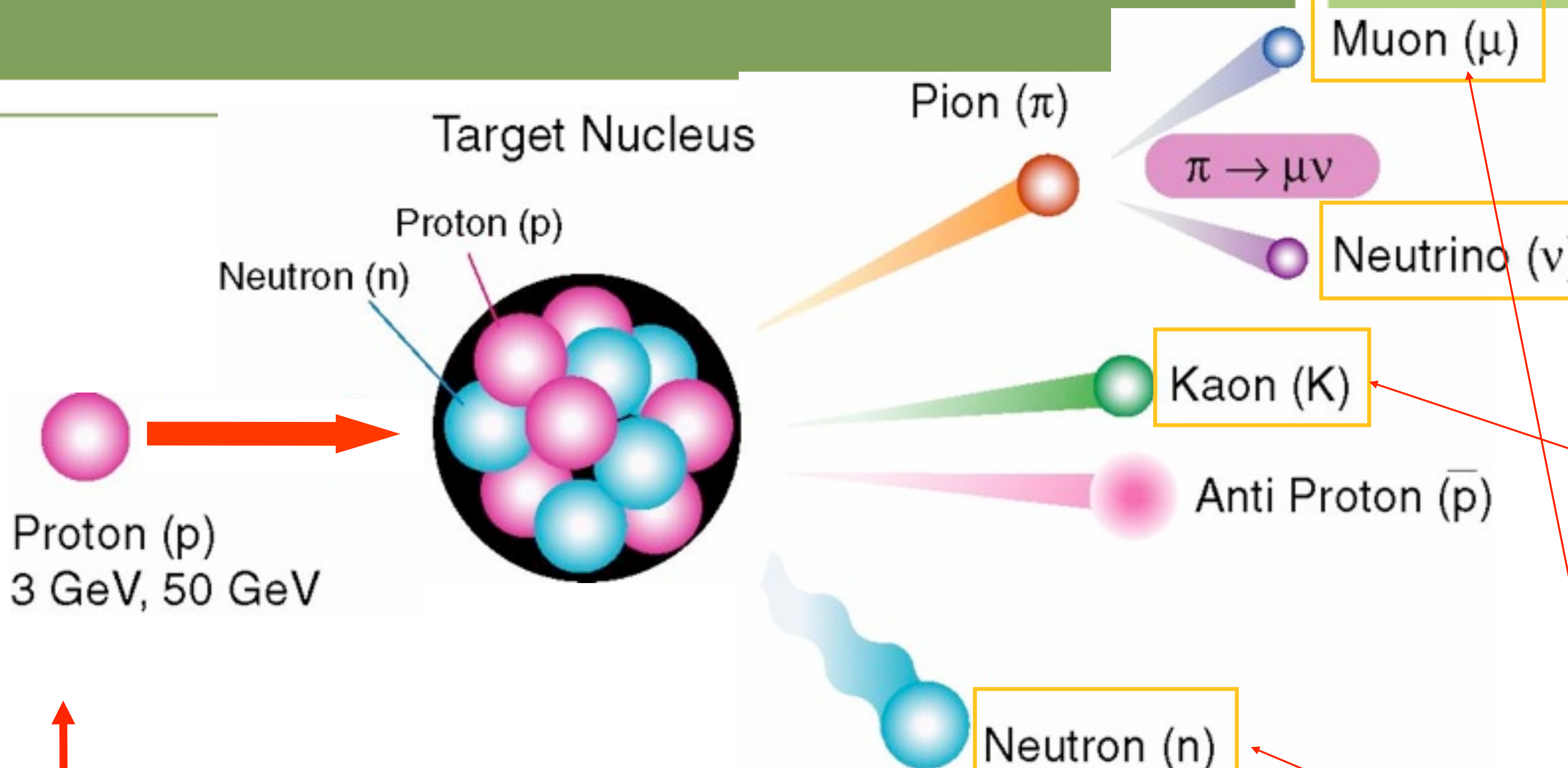


Phase 1:→ Total 1,500 Oku-Yen (56% JAEA, 44% KEK)!



J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Photo in July of 2009

Goals at J-PARC

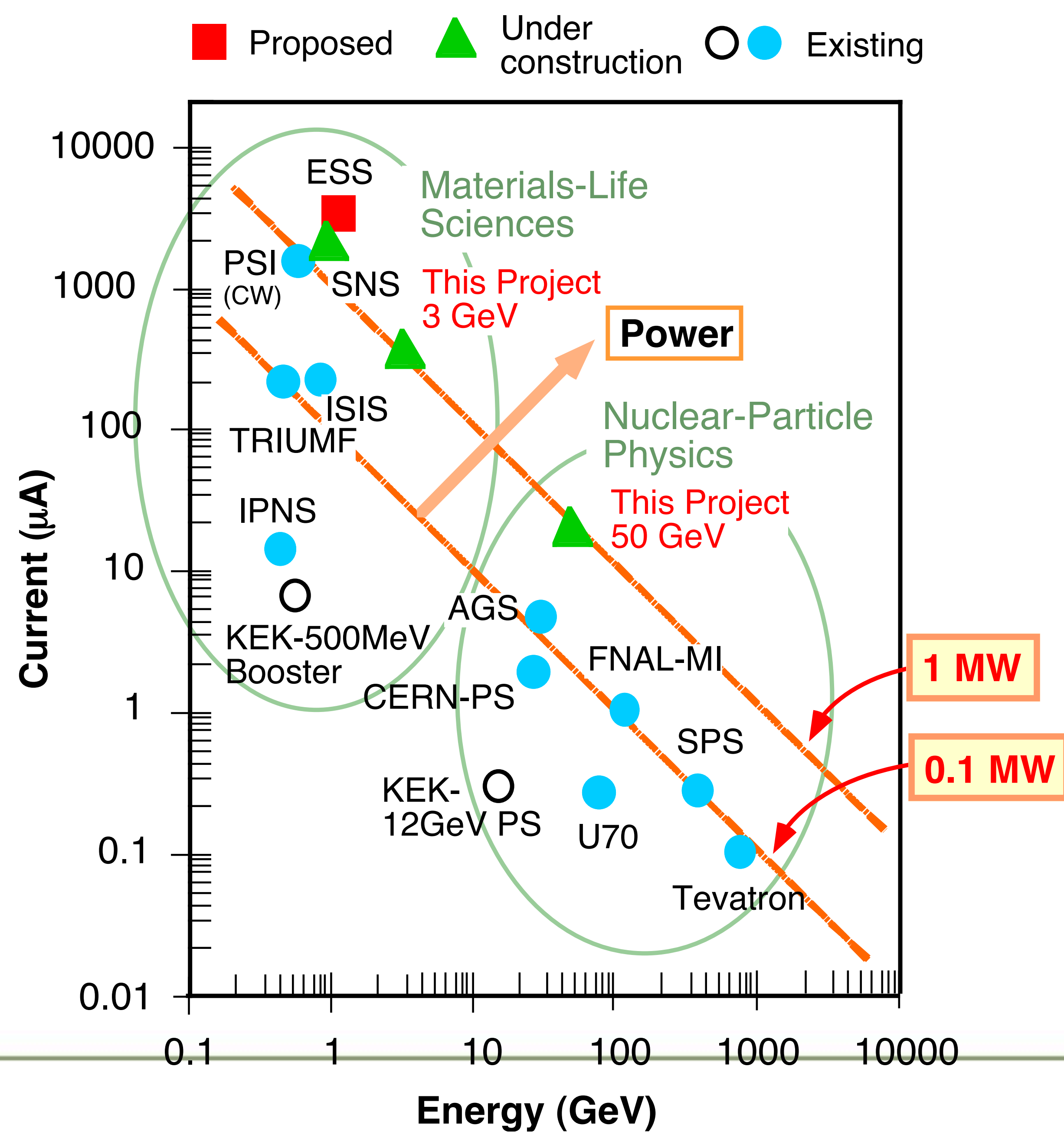


Need to have high-power proton beams

→ MW-class proton accelerator
(current frontier is about 0.1 MW)

Materials & Life Sciences at 3 GeV
Nuclear & Particle Physics at 50 GeV
R&D toward Transmutation at 0.6 GeV

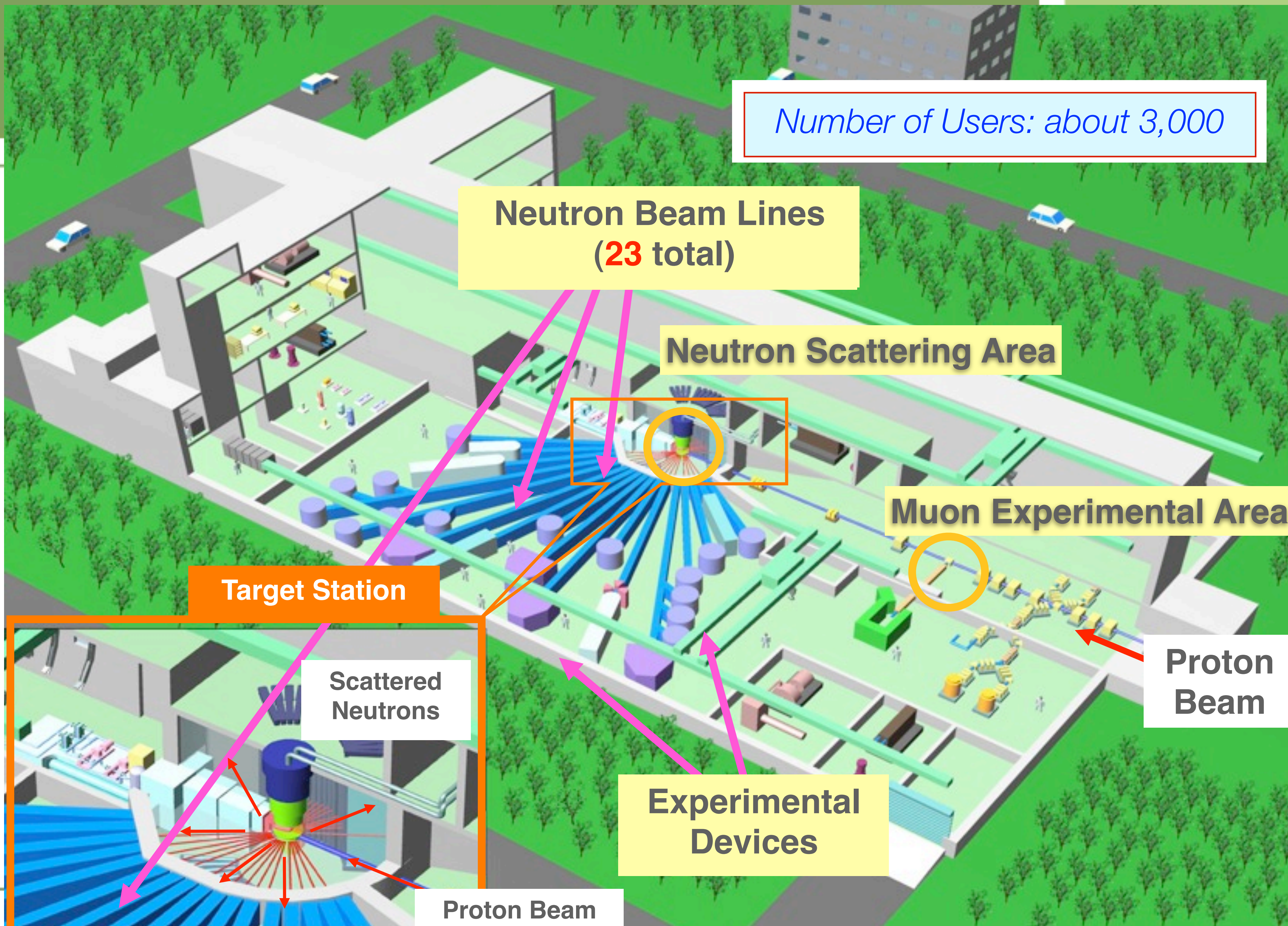
Beam Power Frontier



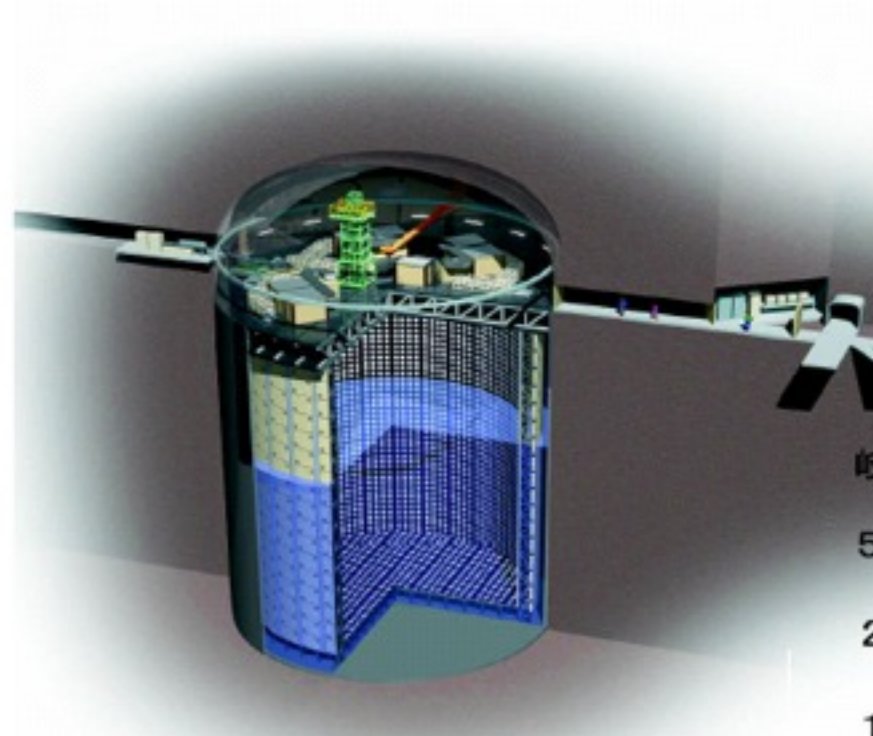
Materials and Life Science Experimental Facility

Facility similar to SNS in the US and to ISIS in the UK

Materials & Life Science Experimental Facility



Super Kamiokande



岐阜県神岡町地下1000m

50000トン水チェレンコフ

20インチPMT約12000本

1996〜

Neutrino Experimental Facility

↑

Number of Users: about 400

(about 1/4 from Japan)

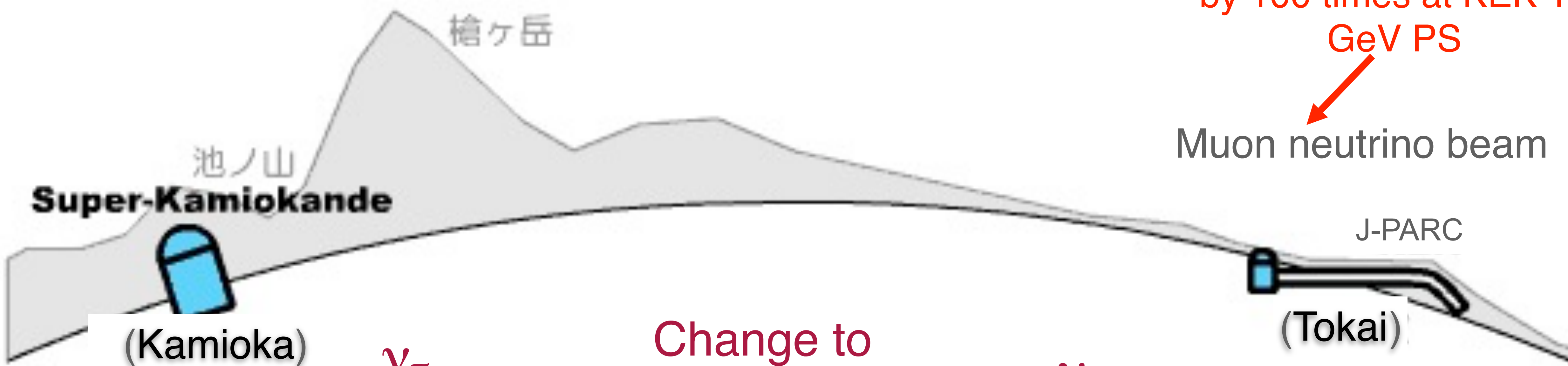
Experiments with Intense Neutrino Beams

T2K Experiment

T2K = Tokai to Kamioka

Intense neutrino beam by 100 times at KEK 12 GeV PS

Muon neutrino beam



ν_τ ← Change to ← ν_μ

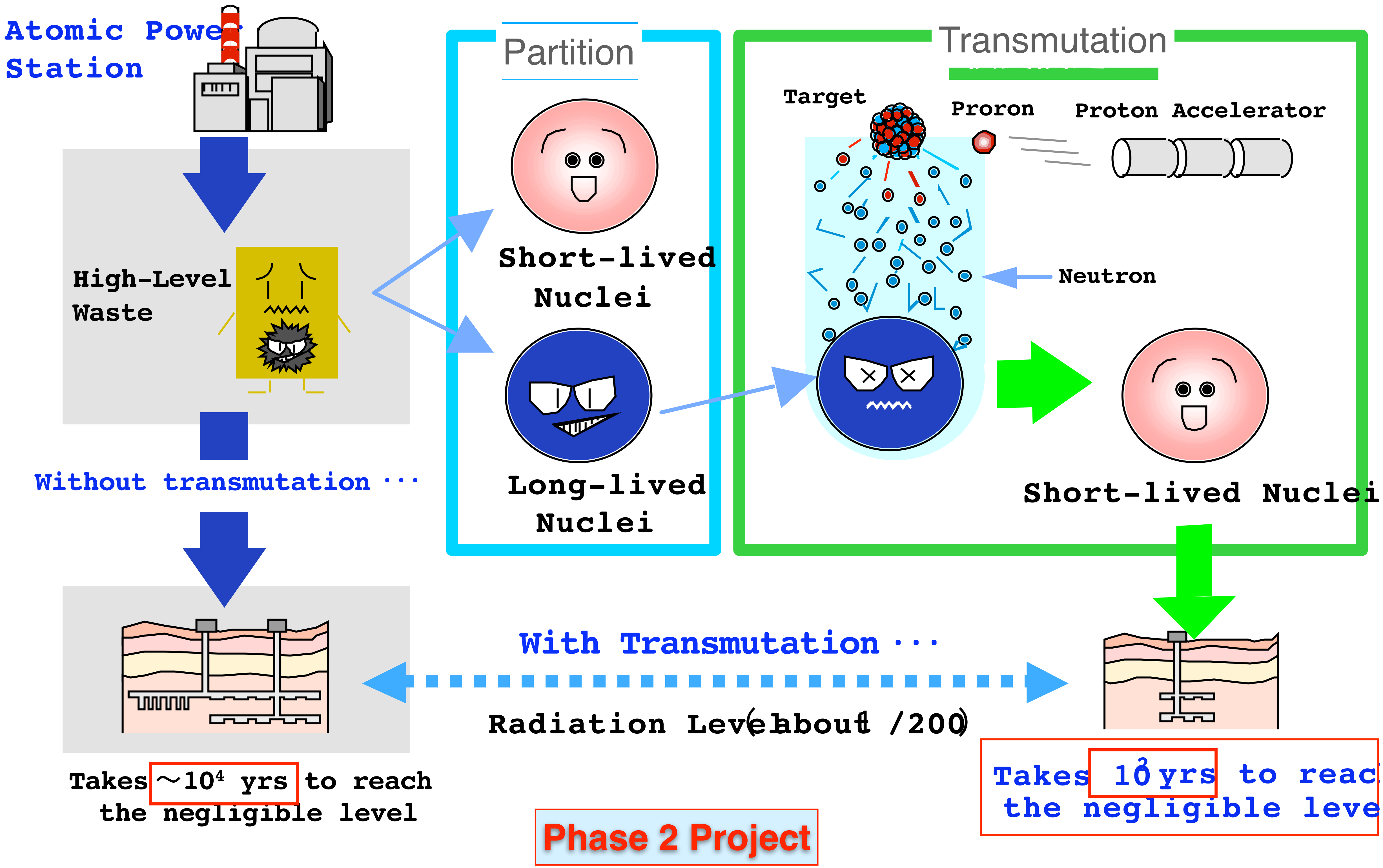
ν_e ← Change to ← ν_μ

Disappearance of ν_μ ↔ High Statistics T2K

(Five year data at KEK-PS can be measured within a few weeks at J-PARC)

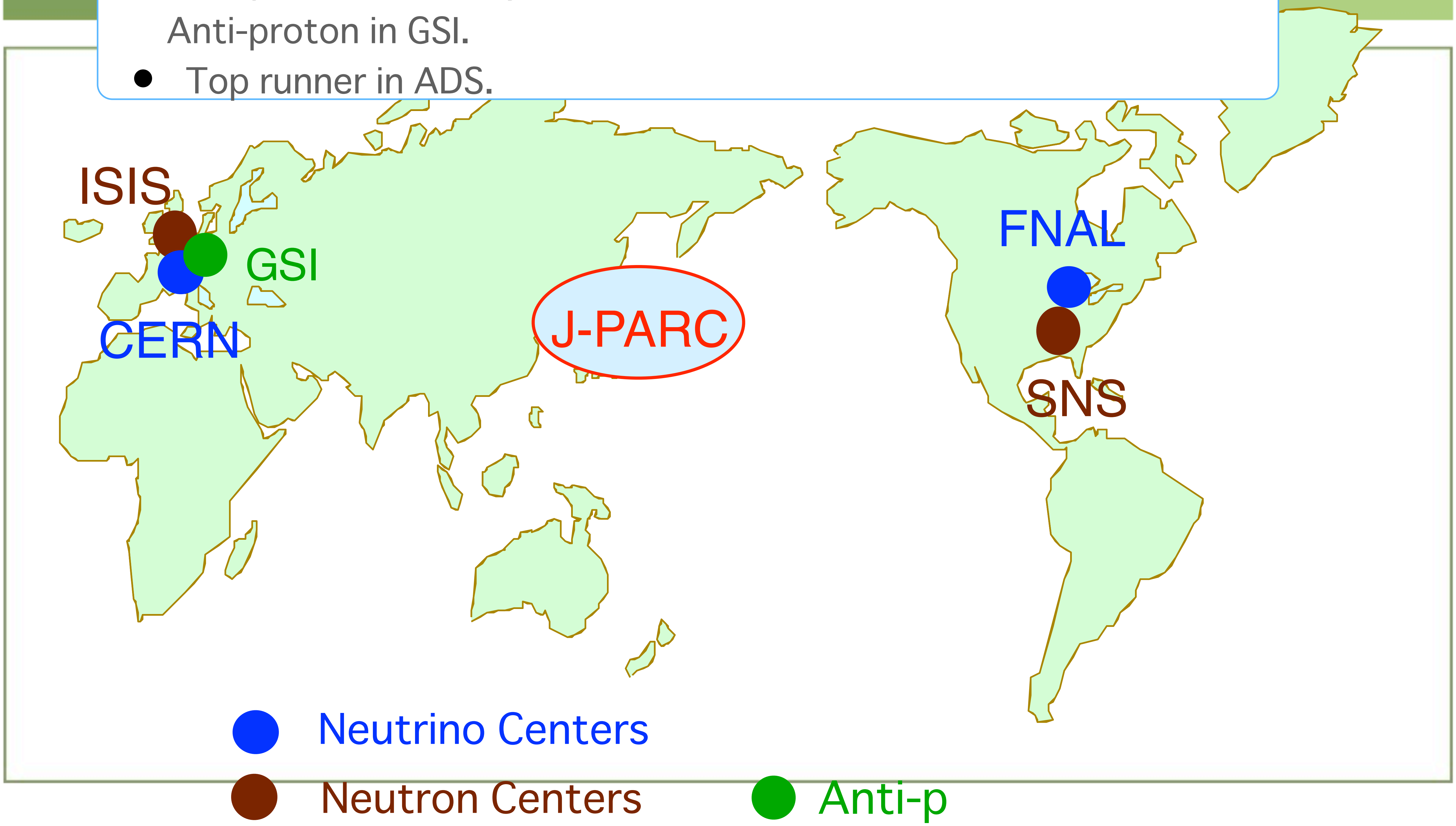
Detection of ν_e at Super Kamiokande ↔ Totally new experiment

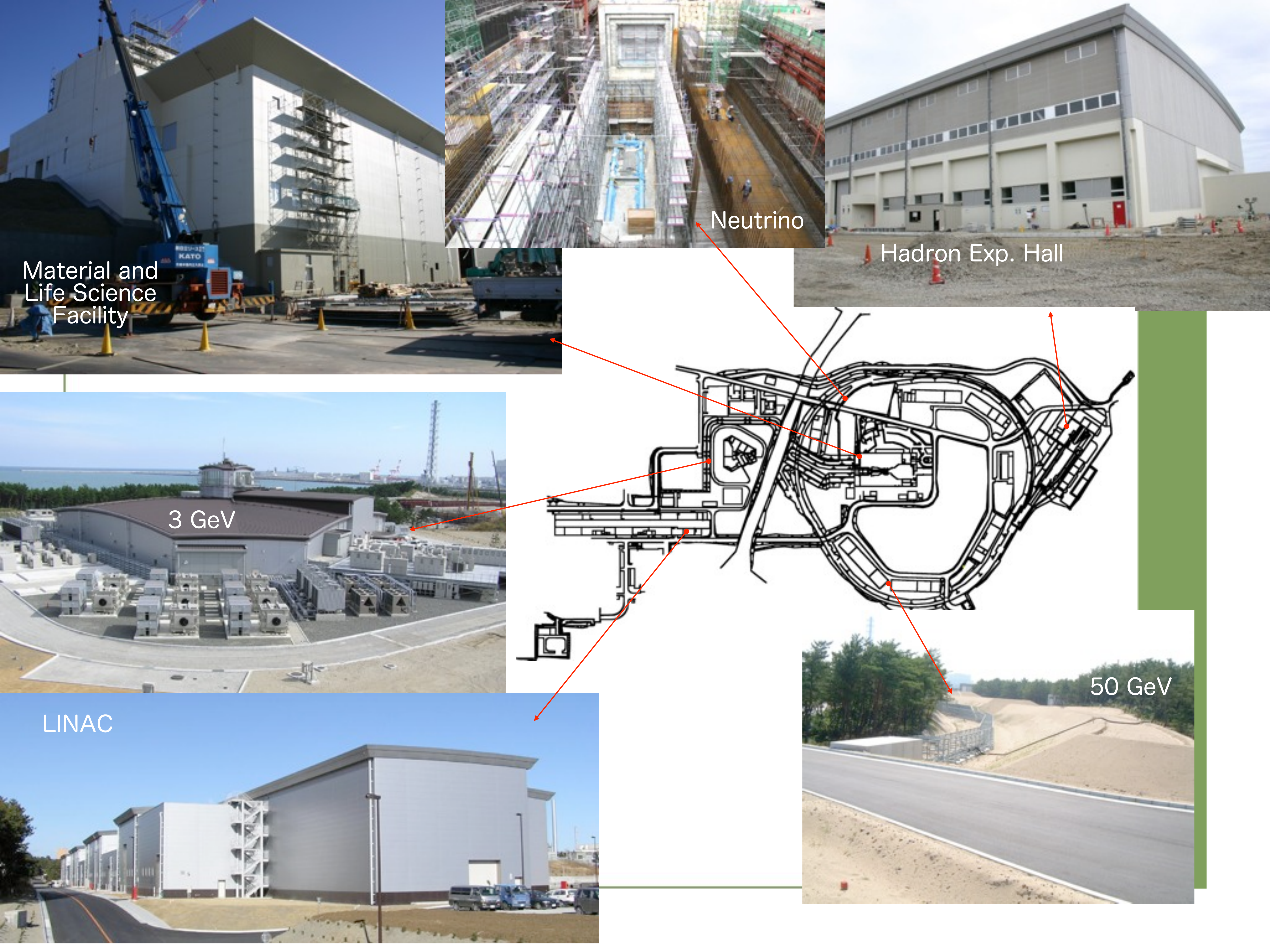
Accelerator-Driven Transmutation (ADS)

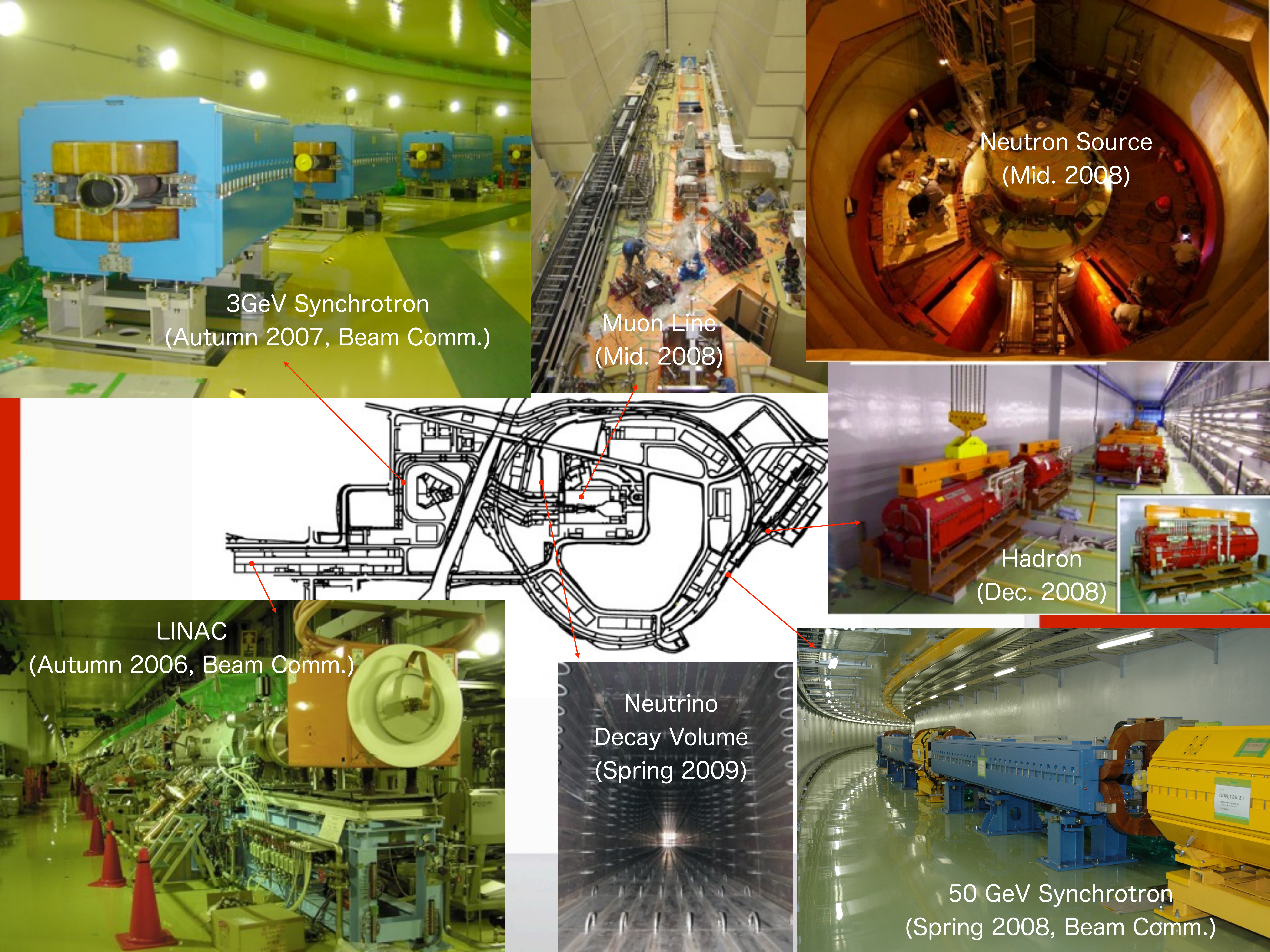


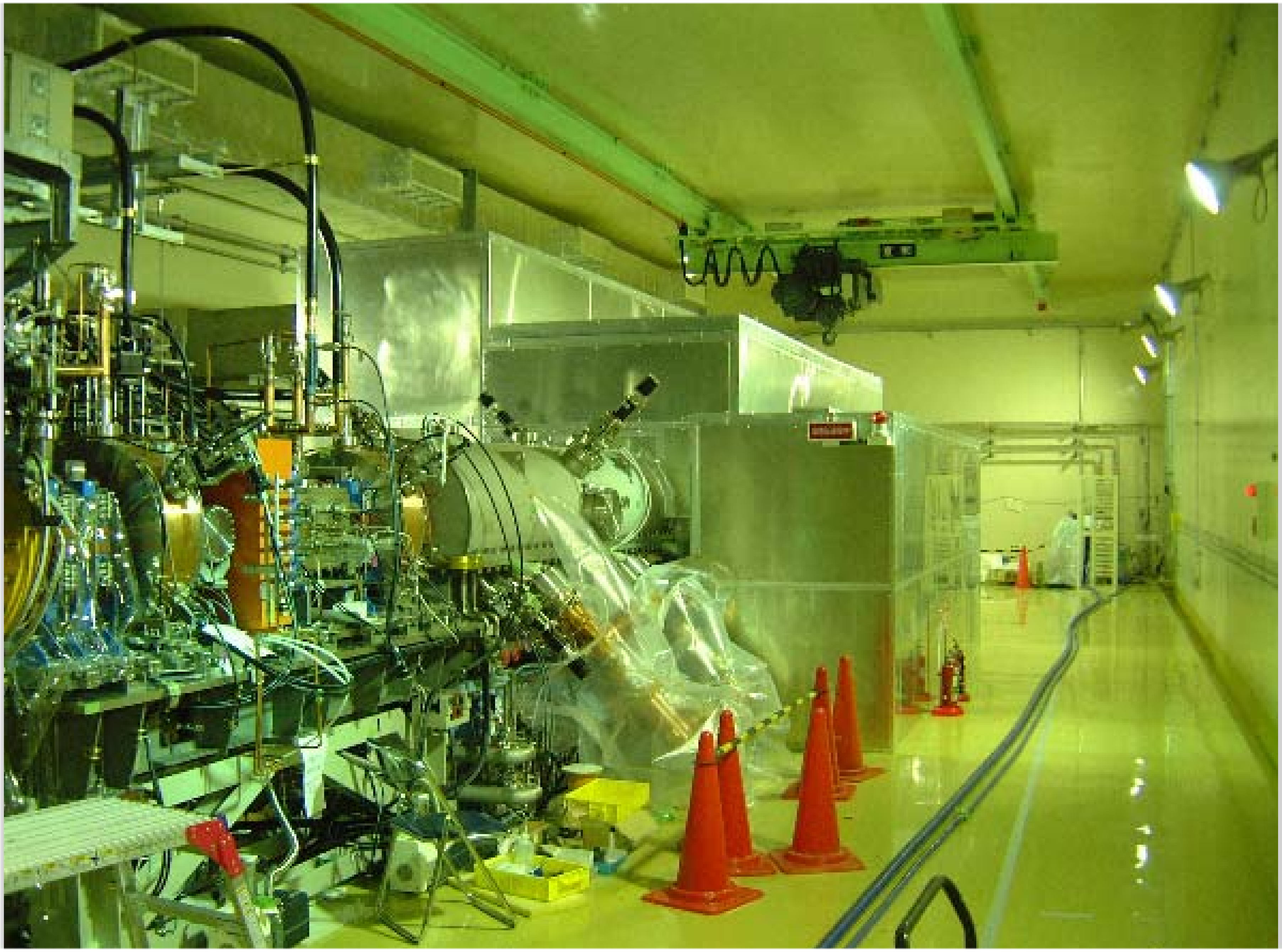
International Research Center

- One of Three major Neutron Sources in Material and Life Science
- Unique Kaon Factory, and One of Three Neutrino beam lines.
  Anti-proton in GSI.
- Top runner in ADS.



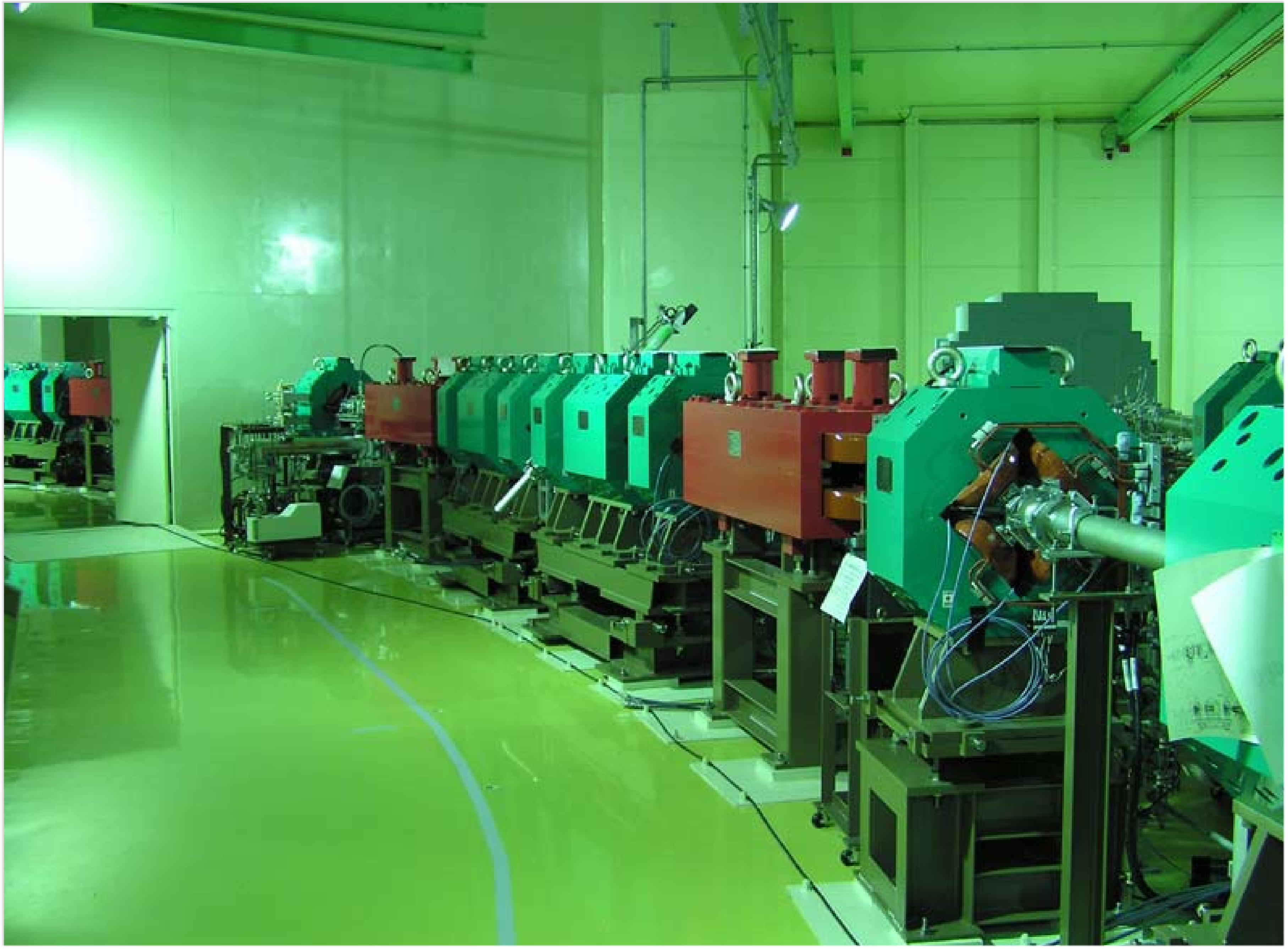

Material and Life Science Facility
Neutrino
Hadron Exp. Hall
3 GeV
LINAC
50 GeV


3GeV Synchrotron
(Autumn 2007, Beam Comm.)
Muon Line
(Mid. 2008)
Neutron Source
(Mid. 2008)
Hadron
(Dec. 2008)
LINAC
(Autumn 2006, Beam Comm.)
Neutrino
Decay Volume
(Spring 2009)
50 GeV Synchrotron
(Spring 2008, Beam Comm.)



H^- Ion Source, RFQ

SDTL



LINAC → 3GeV

3GeV Ring

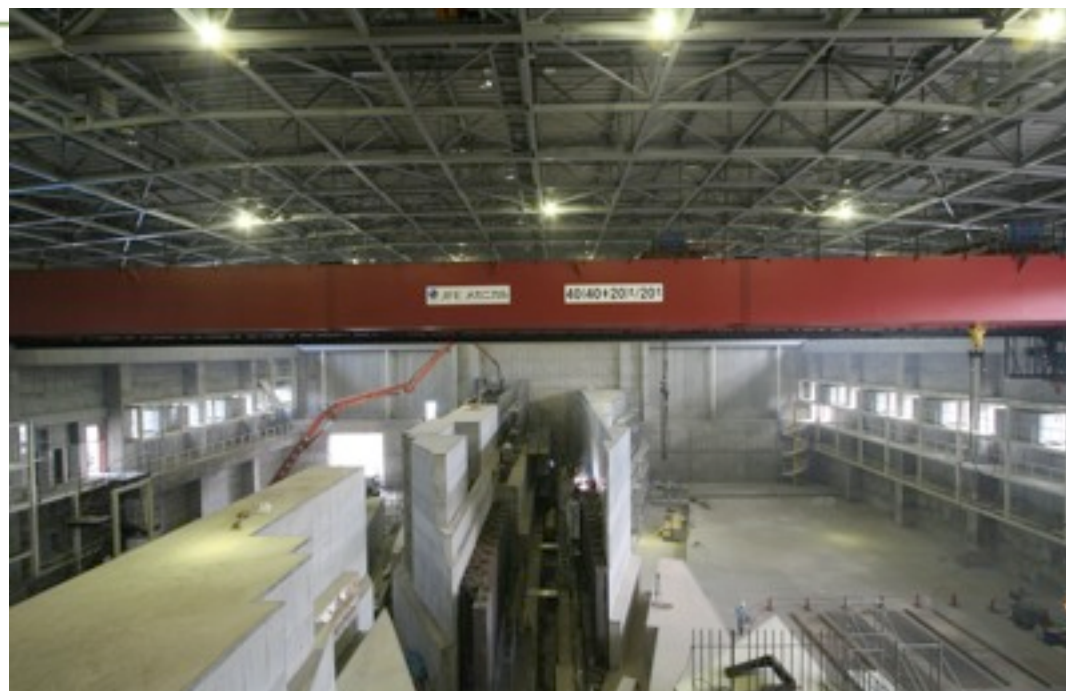
50 GeV Ring

LINAC beam at 181 MeV: Jan.24,07

RCS acceleration at 3 GeV;
Oct. 31, 2007

Hadron Exp. Hall

60m x 56m
Compl. in July, 2007

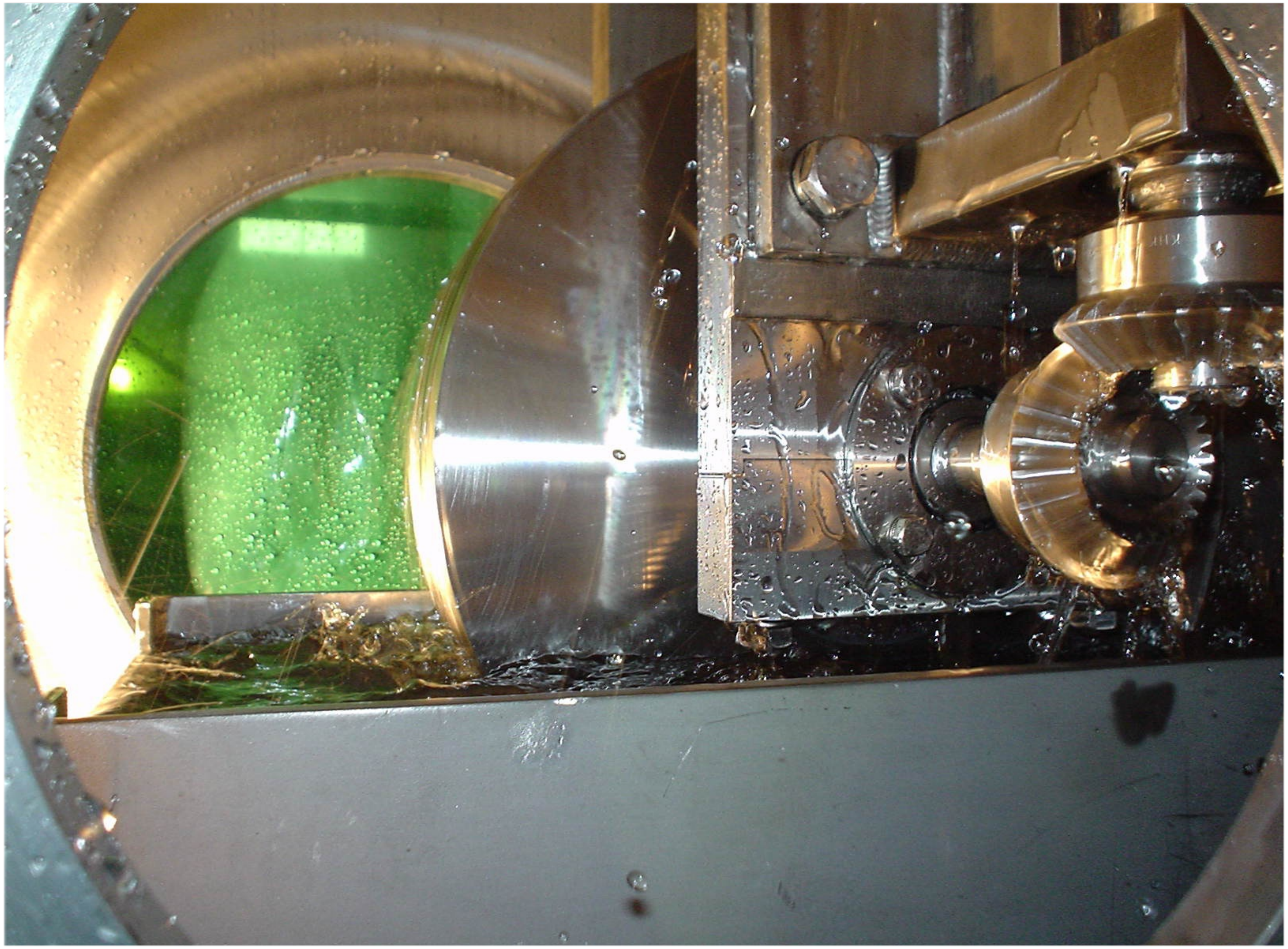


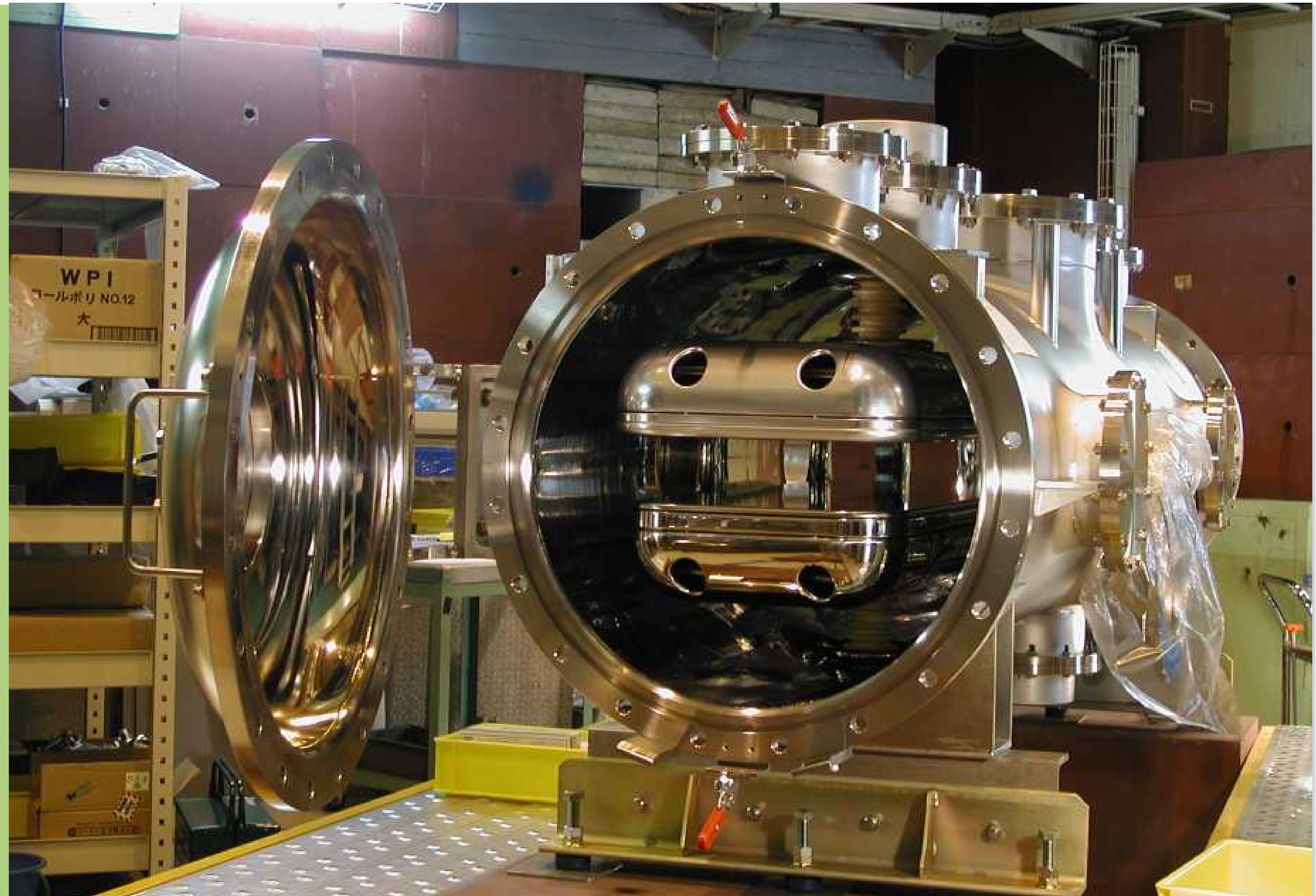
160 m long
Test starts
in Jan., 2007

Slow-extraction Line

Production Target T1

12 kW
Ni rotator
water cooled





3 m long
+/-400 kV
in 10cm gap

Electro-Static Separator

Mineral Insulator Coil

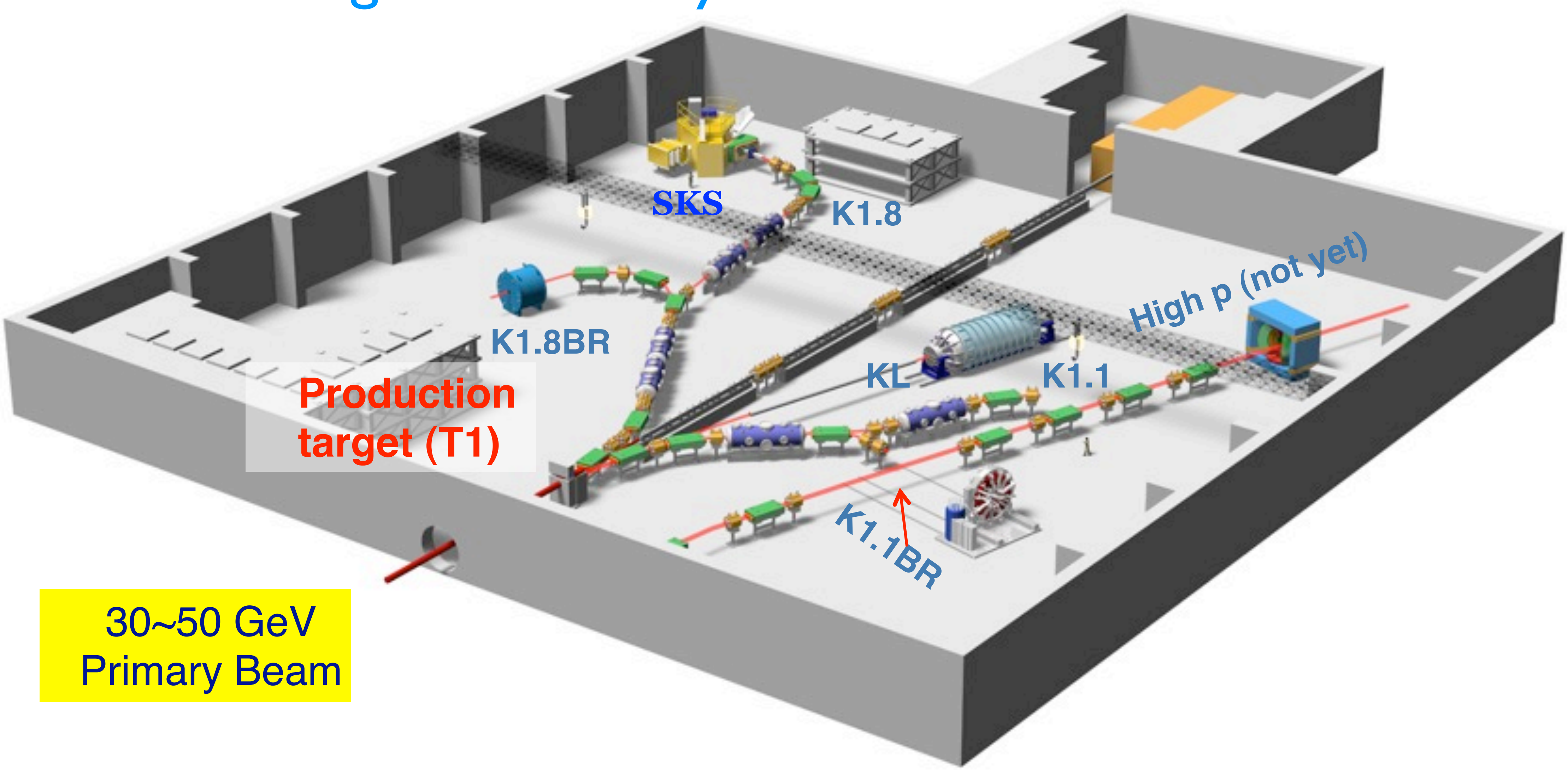
K1.8 D1 coil

Hadron Experimental Hall

First beam in Feb. 2009

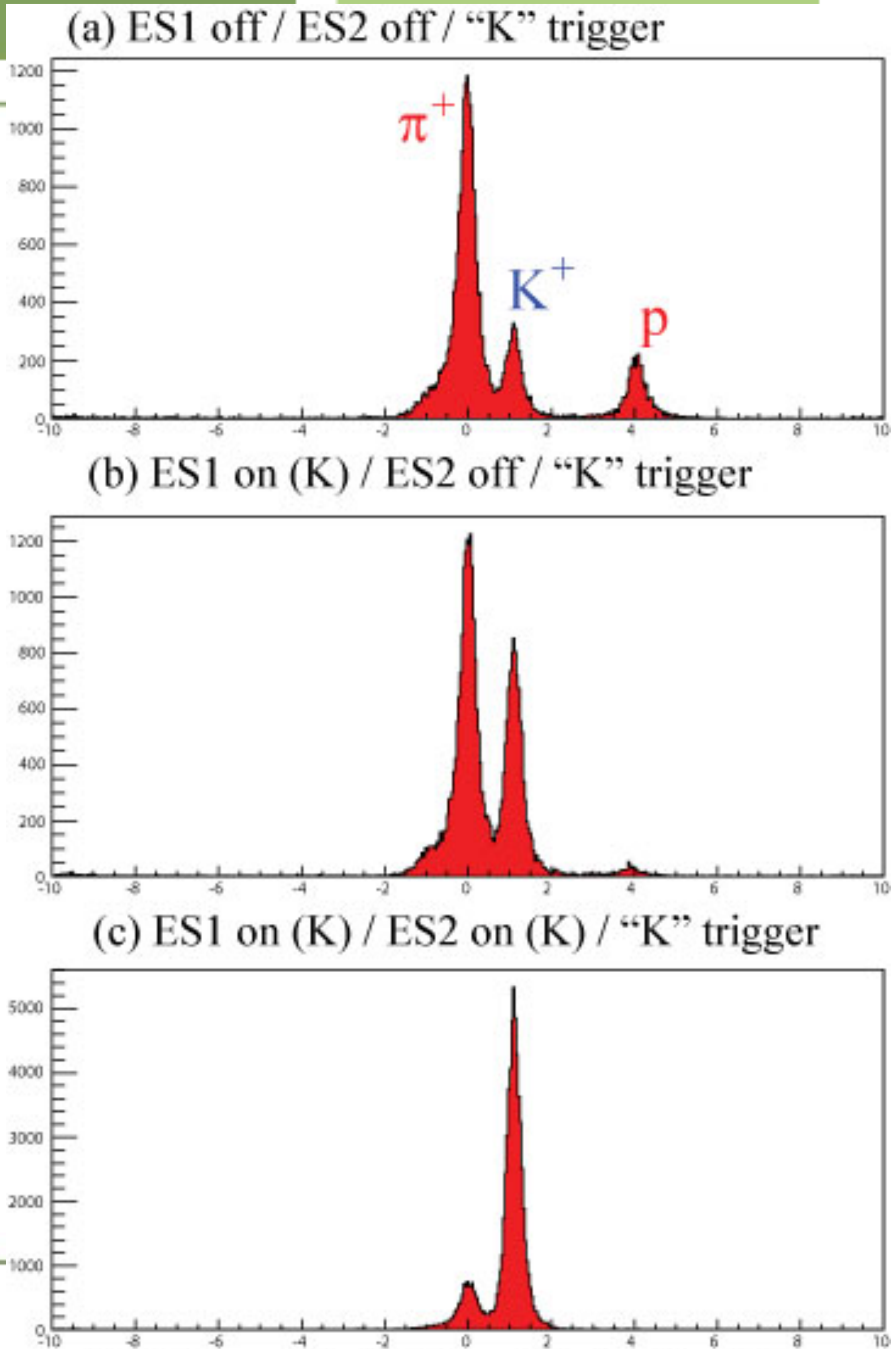
60m x 56m

World highest intensity Kaon beams !



Recent beam status At Hadron Hall

- Double-stage electro-static separator works very well
  - Good K/π ratio !
  - Intensity & Time structure should be improved.

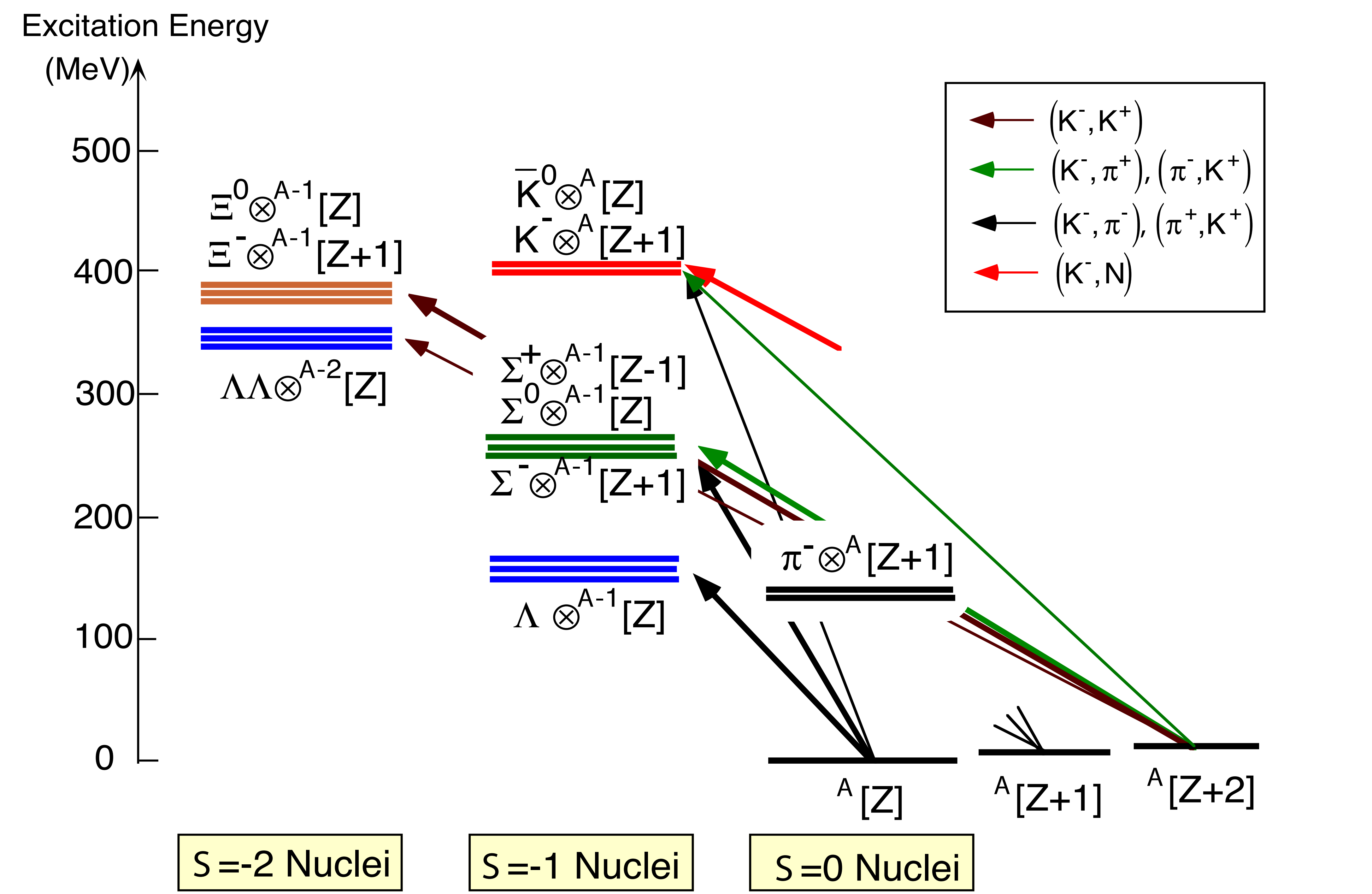


Proposals at J-PARC

- Proposal Call : Nov., 2005 - Apr., 2006
- 20 proposals including 4 LoIs
  - 13 proposals in Nuclear Physics
- Five Day-1 Experiments
  - E05: Ξ hypernuclei Spectroscopy (Nagae) [1st priority]
  - E13: Hypernuclear γ -ray Spectroscopy (Tamura) [2nd priority]

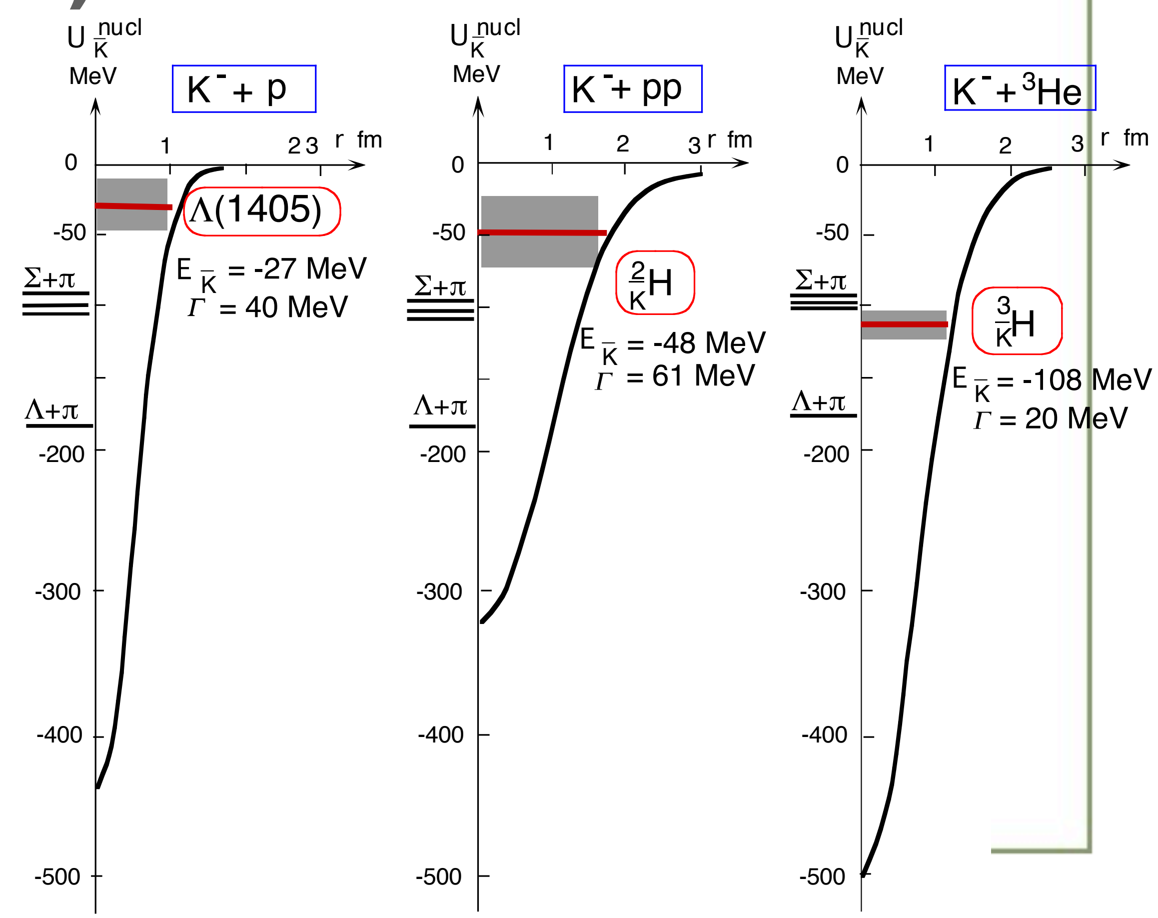
- E15: Search for K^-pp bound state (Iwasaki, Nagae)
- E17: Kaonic ^3He 3d→2p X-ray (Hayano, Outa)
- E19: Search for Penta-quark in $\pi^-p \rightarrow K^-X$ reaction (Naruki)
  - ↑ Day-1 experiments --
- E07: Hybrid-Emulsion for Double-Λ (Imai, Nakazawa, Tamura)
- E03: Ξ-atom X rays (Tanida)
- E10: Production of neutron-rich Λ-hypernuclei with the double-charge-exchange reaction (A. Sakaguchi and T. Fukuda)
- and more ...

Kaonic Nuclei

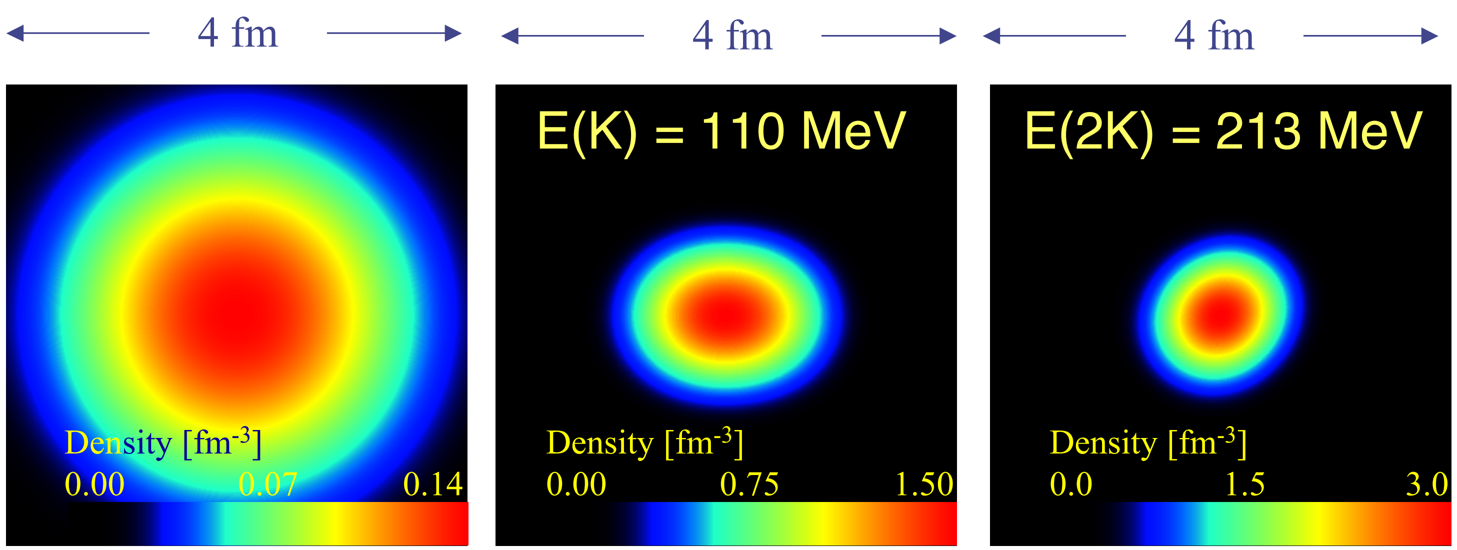


$\bar{K}N$ Bound States

- Prediction by Akaishi and Yamazaki
  - **$\bar{K}N$ scattering lengths**
  - **K^-p atomic shift(KEK E228)**
  - **Mass & width of $\Lambda(1405)$**
  - **Strong attraction in I=0 $\bar{K}N$ interaction**
  - **K^-pp, K^-ppp, K^-pppn, ...**



Formation of High Density State

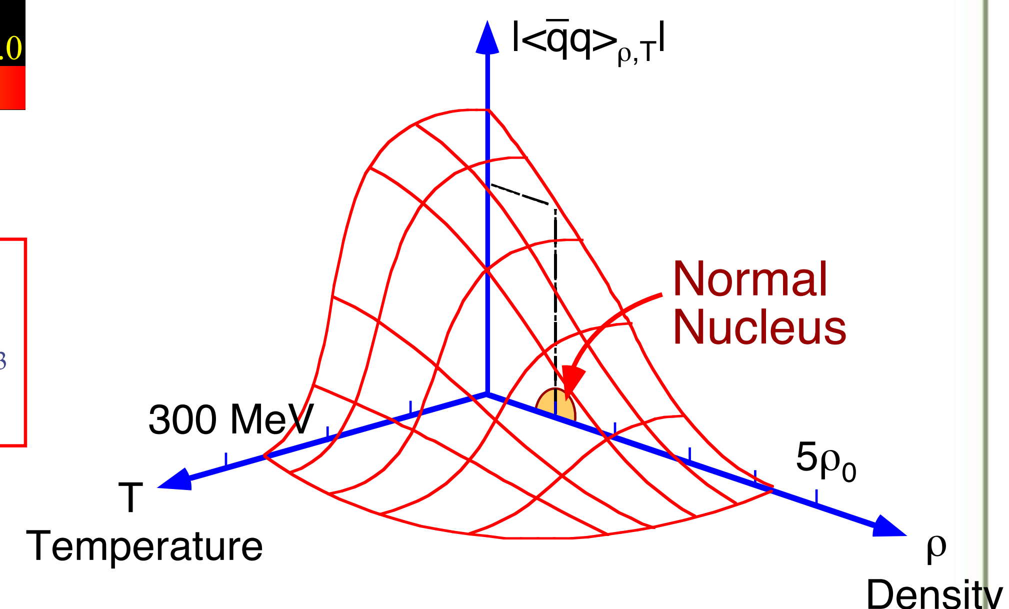


ppn	ppnK$^-$	ppnK$^-$K$^-$
total B.E. = 6.0 MeV	total B.E. = 118 MeV	total B.E. = 221 MeV
central density = 0.14 fm^{-3}	central density = 1.50 fm^{-3}	central density = 3.01 fm^{-3}
R_{rms} = 1.59 fm	R_{rms} = 0.72 fm	R_{rms} = 0.69 fm

$\rho > \rho_0 \times 10$!?

Dote et al.

- Formation of Cold(T=0) and Dense($\rho > 5\ \rho_0$) nuclear matter
- Chiral symmetry restoration
- Kaon condensation



T. Hatsuda and T. Kunihiro, Phys. Rev. Lett. **55** (1985) 158.
W. Weise, Nucl. Phys. **A443** (1993) 59c.

$\bar{K}$ interaction

- $\bar{K}N$ interaction
  → strongly attractive in the isospin I=0 term
  (A. D. Martin, kaonic hydrogen X-ray @ KpX)

- How about $\bar{K}$-Nucleus interaction ?
  - Very deep attractive ? (150—200MeV)
  - Shallow attractive ? (50—75MeV)
    - *Ambiguity remains with kaonic atom data ($\rho << \rho_0$)*

Hadronic Atoms

E. Friedman, A. Gal / Physics Reports 452 (2007) 89–153

- Klein-Gordon equation

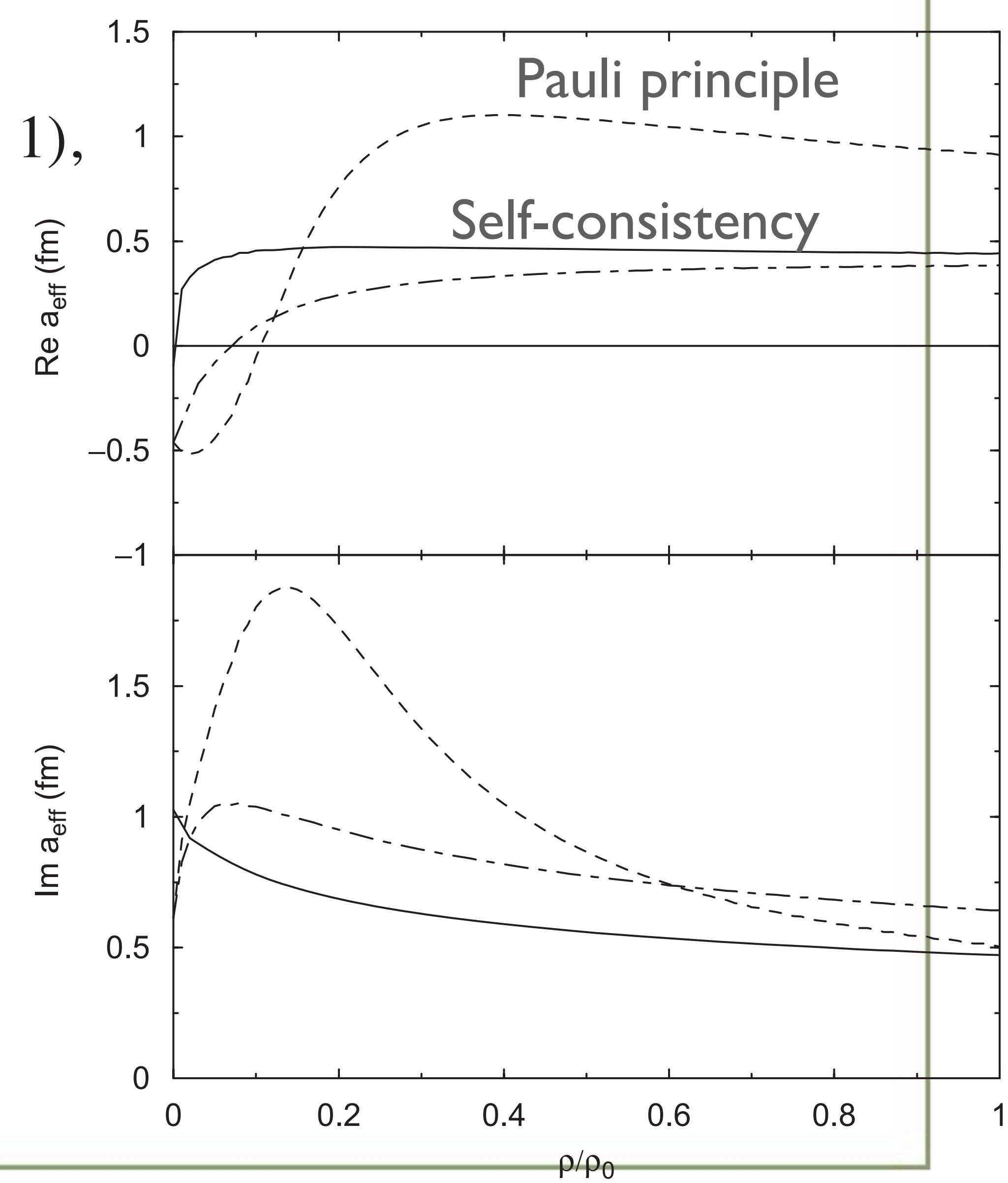
$$[\nabla^2 - 2\mu(B + V_{\rm opt} + V_c) + (V_c + B)^2]\psi = 0 \quad (\hbar = c = 1),$$

$$2\mu V_{\rm opt}(r) = -4\pi\left(1 + \frac{A-1}{A}\frac{\mu}{M}\right)\{b_0[\rho_n(r) + \rho_p(r)] + \tau_z b_1[\rho_n(r) - \rho_p(r)]\}.$$

$$2\mu V_{\rm opt}(r) = -4\pi\left(1 + \frac{\mu}{M}\right)[a_{K^-p}(\rho)\rho_p(r) + a_{K^-n}(\rho)\rho_n(r)],$$

where

$$a_{K^-p} = b_0 - b_1, \quad a_{K^-n} = b_0 + b_1$$



K^-p interaction near threshold

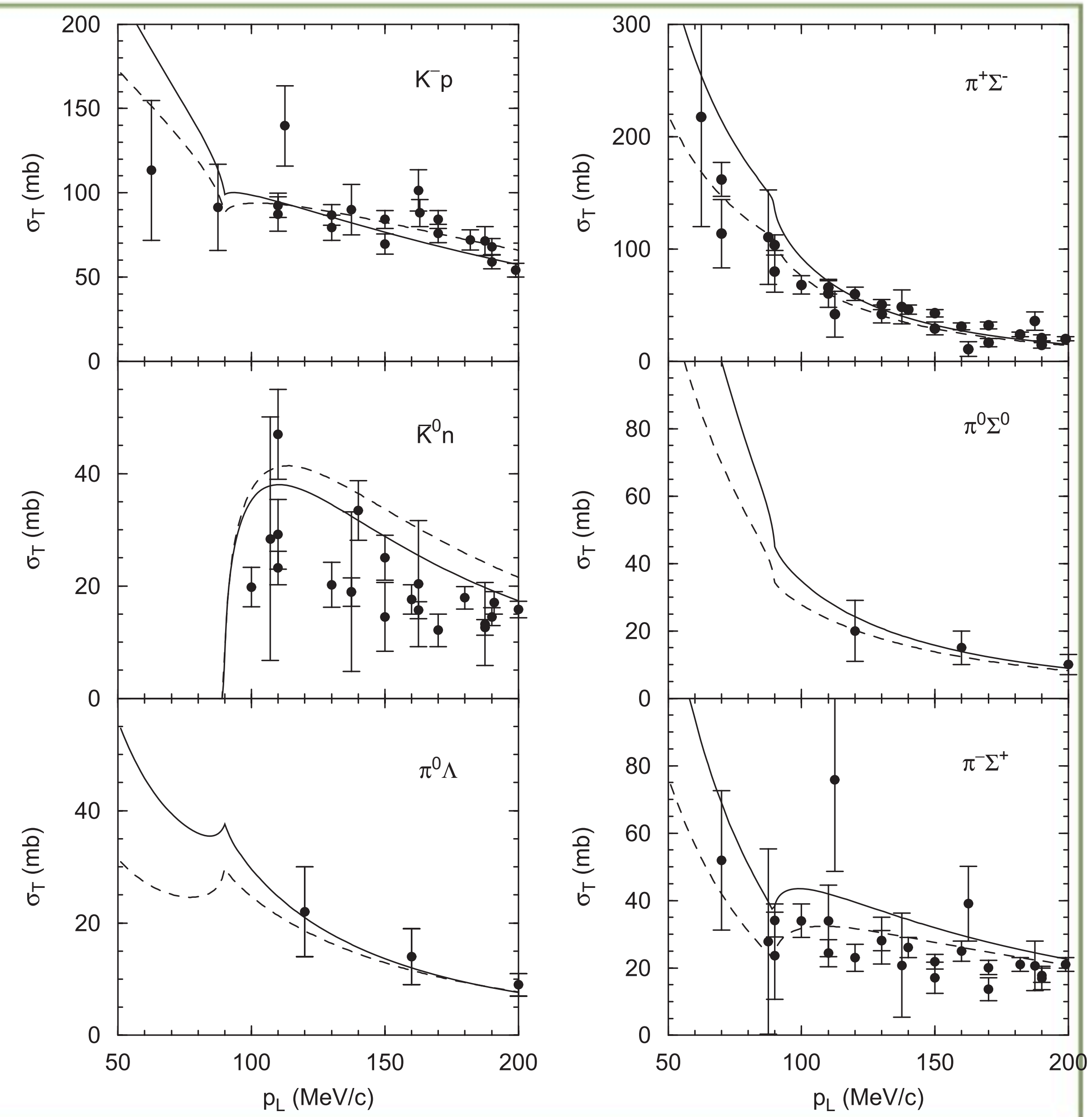
- Threshold branching ratios

$$\gamma = \frac{\Gamma(K^-p \to \pi^+\Sigma^-)}{\Gamma(K^-p \to \pi^-\Sigma^+)} = 2.36 \pm 0.04,$$

$$R_c = \frac{\Gamma(K^-p \to \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^-p \to \text{all inelastic channels})} = 0.664 \pm 0.011,$$

$$R_n = \frac{\Gamma(K^-p \to \pi^0\Lambda)}{\Gamma(K^-p \to \pi^0\Lambda, \pi^0\Sigma^0)} = 0.189 \pm 0.015.$$

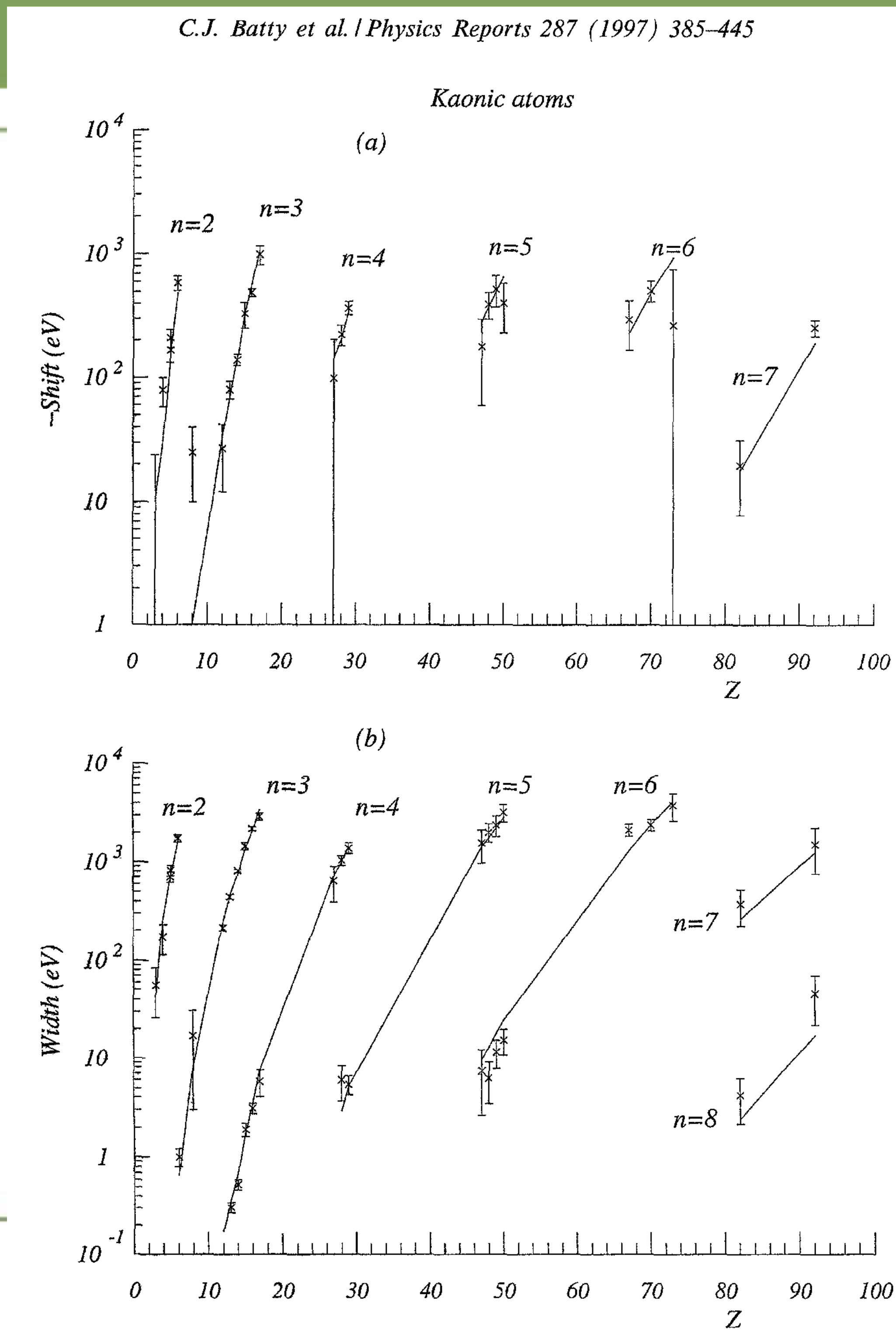
- K^-p Scattering data
- Kaonic hydrogen

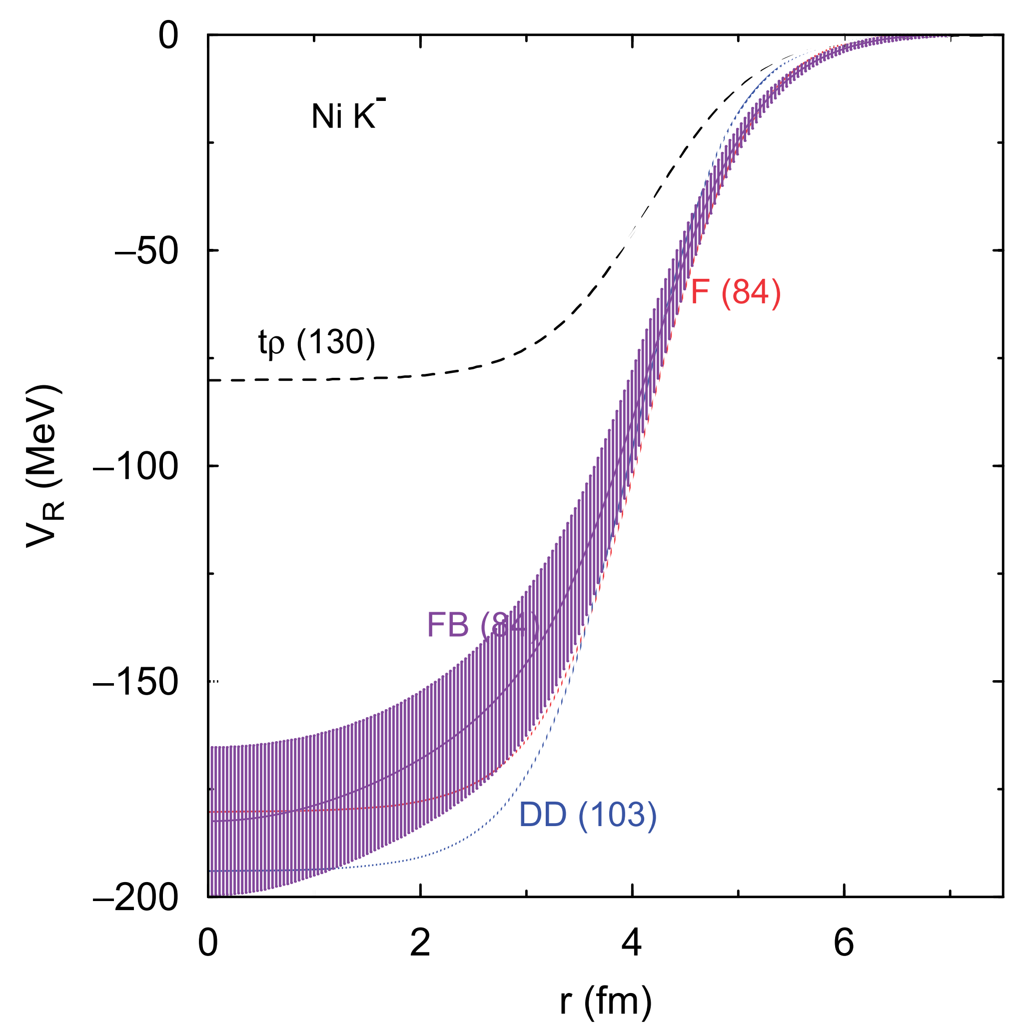


$$\epsilon_{1s} - \mathrm{i}\frac{\Gamma_{1s}}{2} \approx -2\alpha^3\mu^2_{K^-p}a_{K^-p}(1 - 2\alpha\mu_{K^-p}(\ln\alpha - 1)a_{K^-p})$$

$a(K^-p)=(-0.78\pm0.15\pm0.03)+(0.49\pm0.25\pm0.12)i$ fm

Kaonic Atoms





Antikaon in nuclear medium

- Theory
  - Kaon condensation in neutron stars
  - Mass modification in a high density matter
- Experiment
  - Heavy ion collision (high T)
  - Nuclear $\overline{K}$ bound state (T=0)
    - could exist when the potential is very deep
    - predicted by Akaishi and Yamazaki

Importance of $\bar{K}NN$ Systems

- ***K^-p***:
  - $\Lambda(1405)$ is such a bound state or a 3-quark state ?
- ***K^-pp, K^-pn, (K^-nn)***:
  - *modification of $\bar{K}N$ interaction, isospin dependence*
- ***K^-ppn*** and/or ***K^-pnn, K^-ppp***:
  - modification of $\bar{K}N$ interaction ?, Isospin dependence ?
  - nuclear contraction effects
  - many-body effect, relativistic effect, ...

Detection Methods (1)

- **Missing-mass spectroscopy**
  - (K^-_{stop}, n or p) … KEK-PS E471/E549, **FINUDA**
    - $^4He(K^-_{stop}, n)S^+(3140)$ …K^-ppn ?
    - $^4He(K^-_{stop}, p)S^0(3115)$ …K^-pnn ?
  - (K^-, n or p) … BNL-AGS E930 / KEK-PS E548
    - $^{16}O(K^-, n)^{15}OK^-$ … B_K= 130, 90, (50) MeV
  - (K^-, π^-), (π^+, K^+) … J-PARC

Detection Methods (2)

- **Invariant-mass spectroscopy**
  - Heavy-ion collision … GSI-FOPI
  - K^- absorption at rest in a nucleus … **FINUDA**

$$K^- pp \rightarrow \Lambda + p, \quad \Lambda \rightarrow p + \pi^-$$

three final particles to be detected

$$K^- pn \rightarrow \Lambda + n \;,\; \Sigma^- + p$$

$$K^- ppn \rightarrow \Lambda + d$$

Decay Modes

- Mesonic decay

$$K^- + N \to \Sigma + \pi$$

closed if the state is deep enough

$$K^- + N \to \Lambda + \pi$$

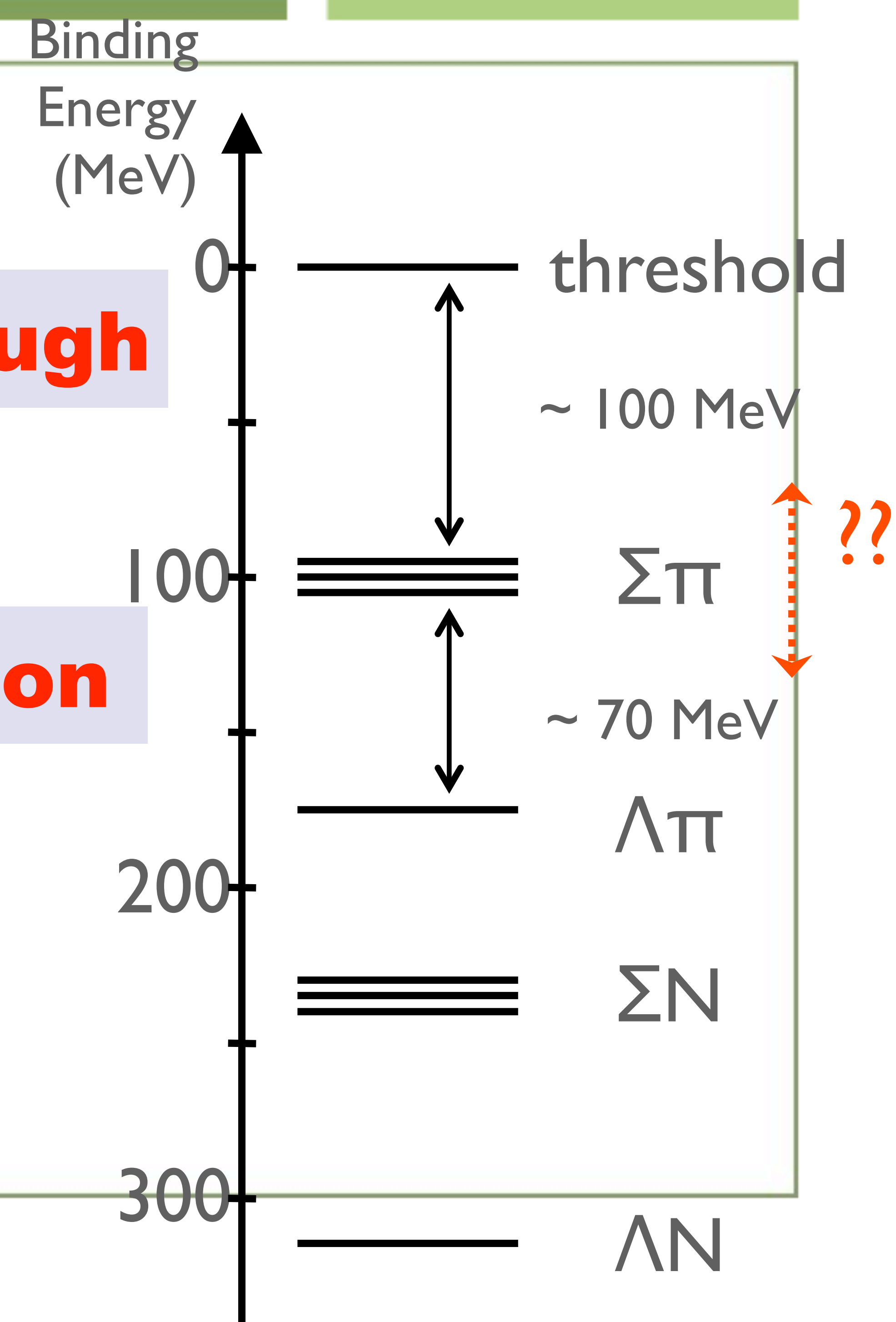
suppressed by the I=0 attraction

- Non-mesonic decay

$$K^- + NN \to \Sigma + N$$

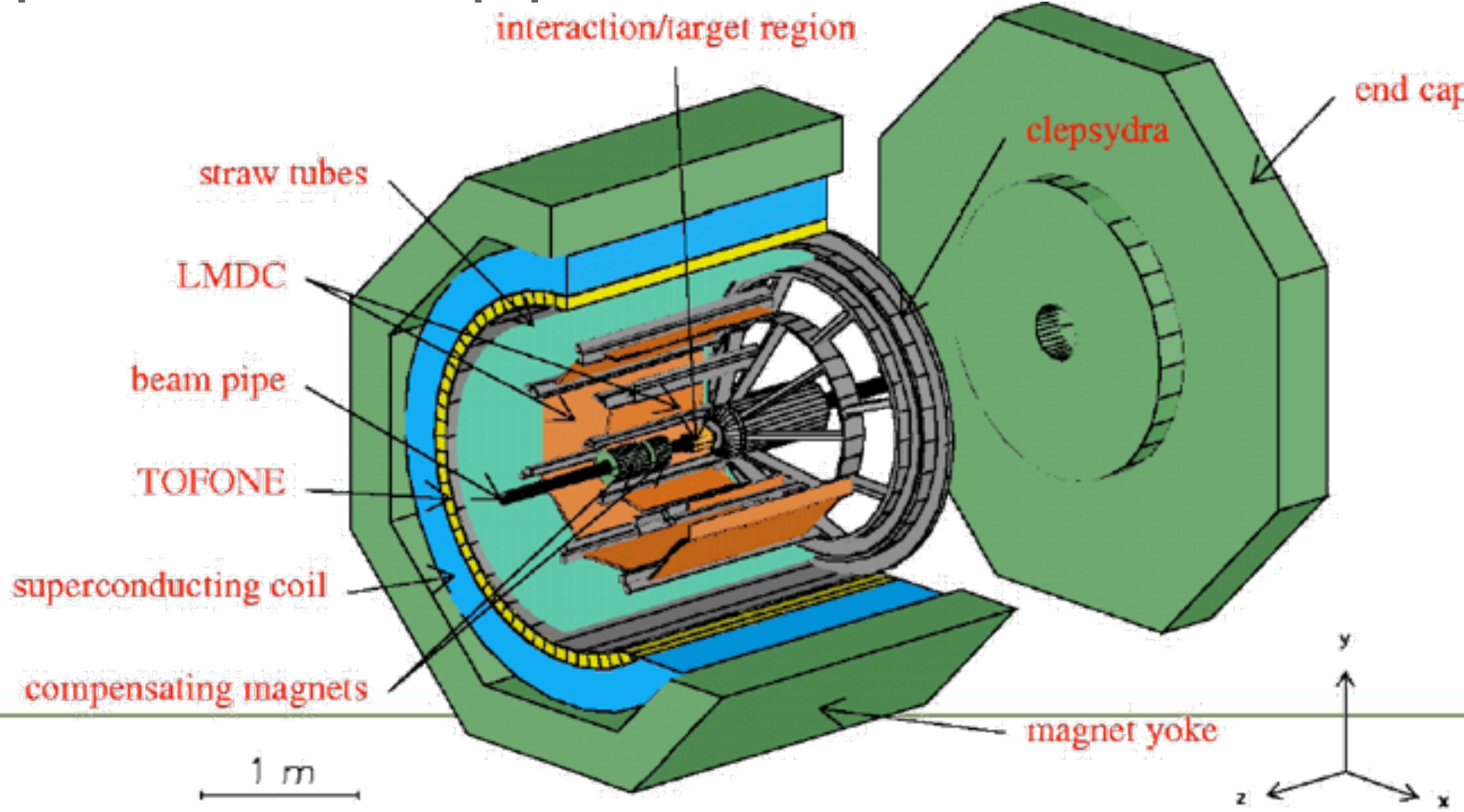
$$\to \Lambda + N$$

should exist



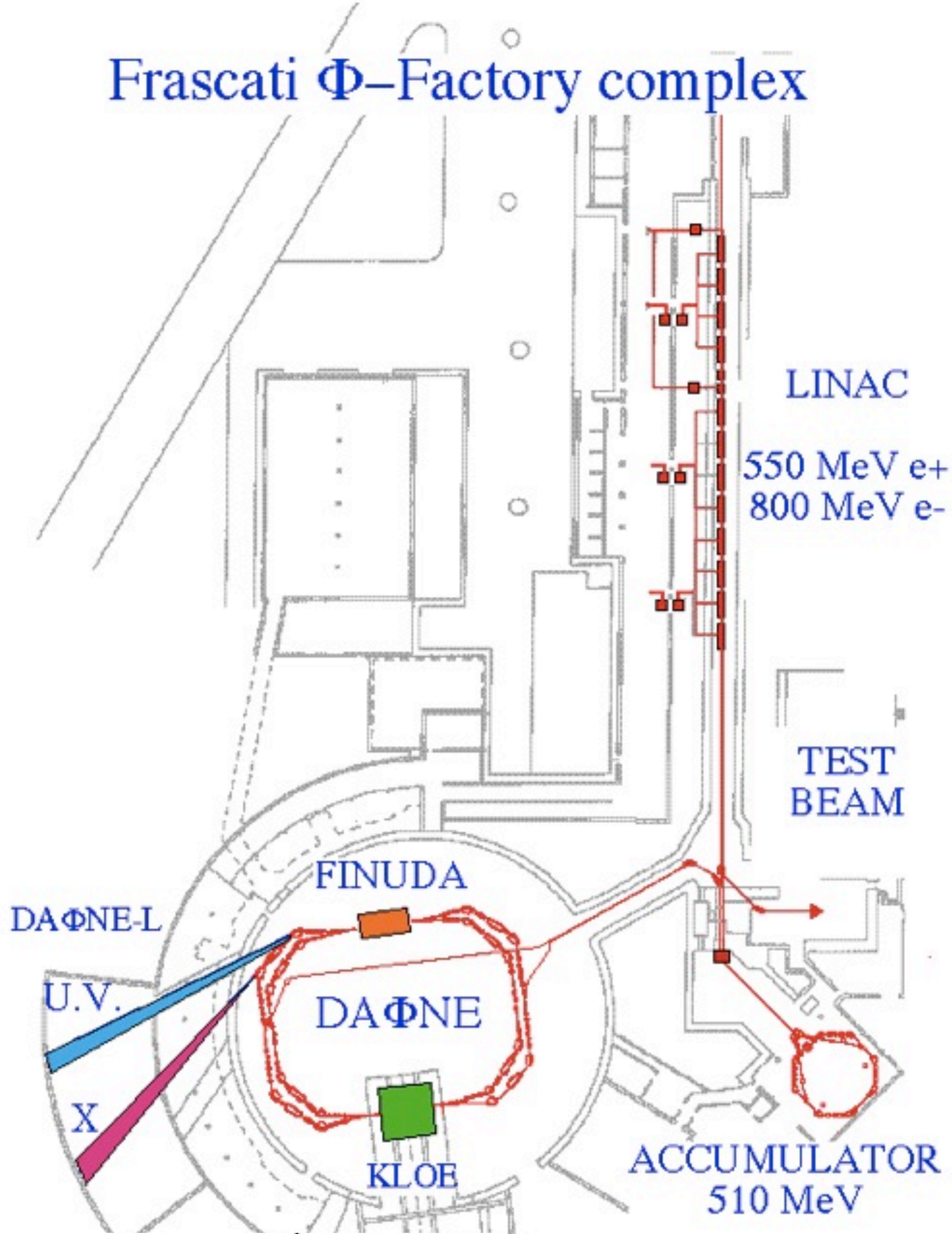
FINUDA experiment

- Λ-hypernuclear spectroscopy with the (K^-_{stop}, π^-) reaction
- B=1.0T, acceptance ~70%, $\Delta p/p$~0.35%



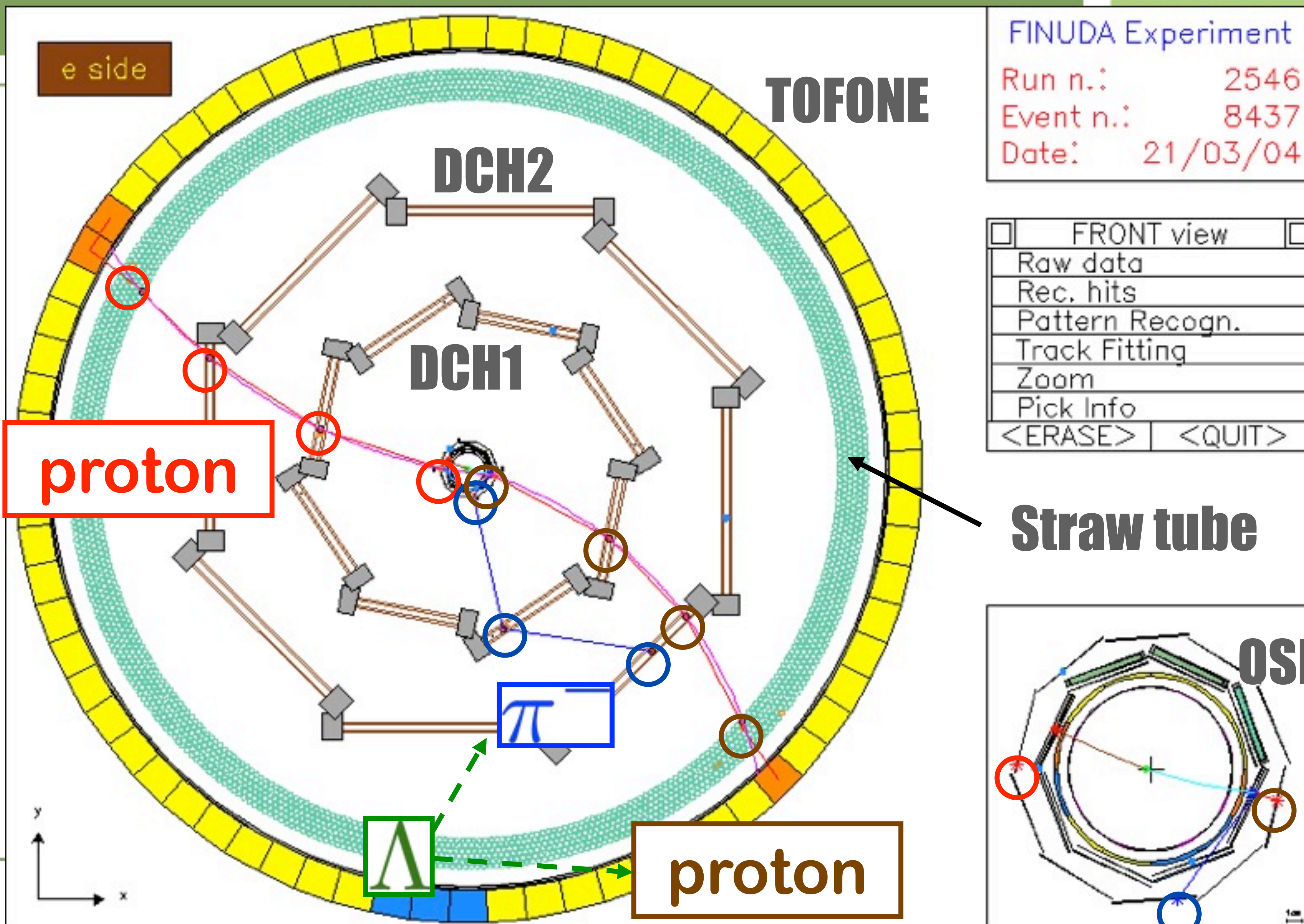
DAΦNE φ-factory

- Beam energy 510 MeV
- Luminosity <5×10^{32}/cm^2/s
  - (10^{32}/cm^2/s = 216 $K^{\pm}$/s)
- Crossing angle 12.5 mrad

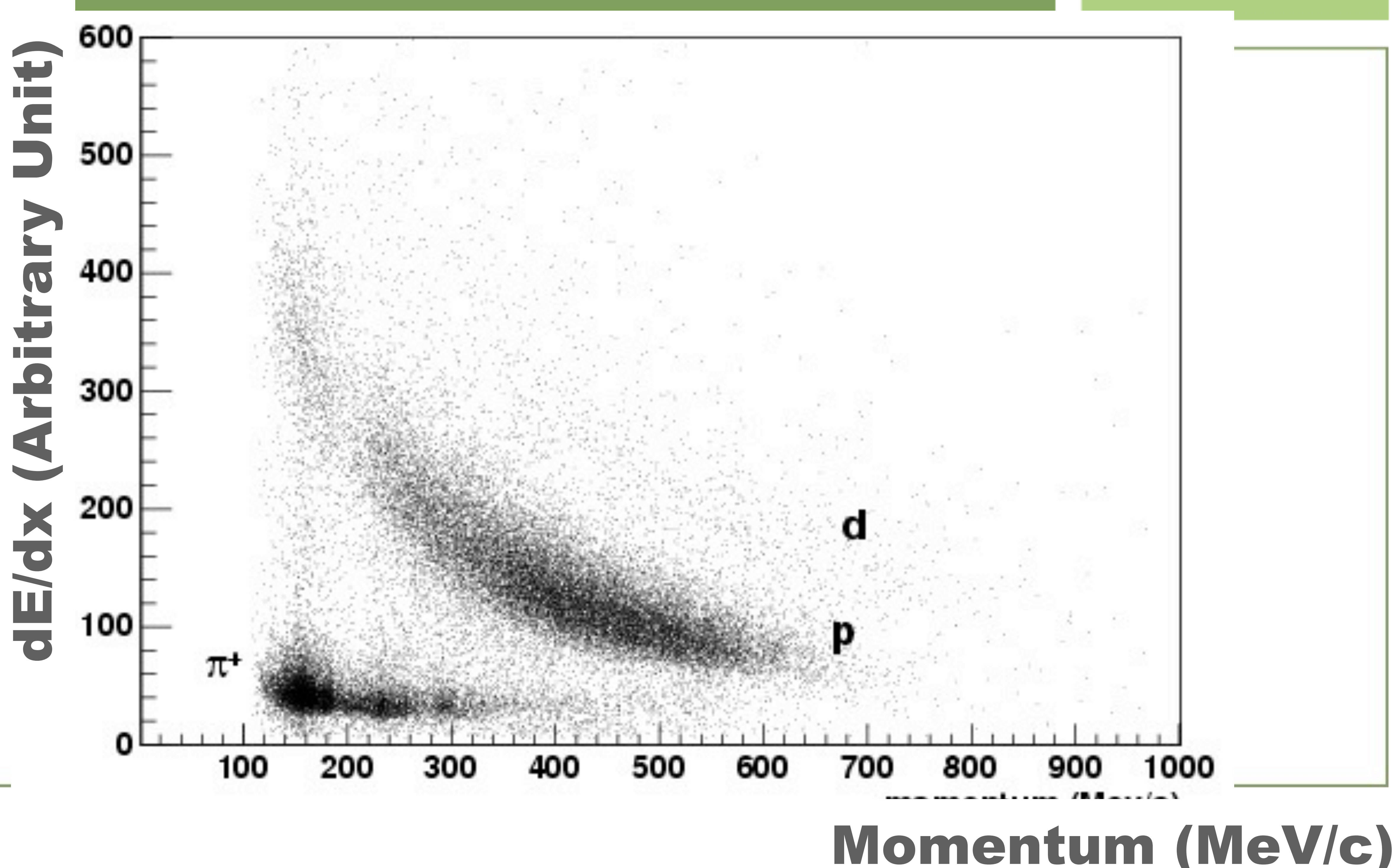


$$e^+e^- \rightarrow \phi(1020) \rightarrow K^+K^-$$ (T_K=16 MeV)

Event display ($K^-pp \rightarrow \Lambda + p$)



PID by dE/dx in OSIM



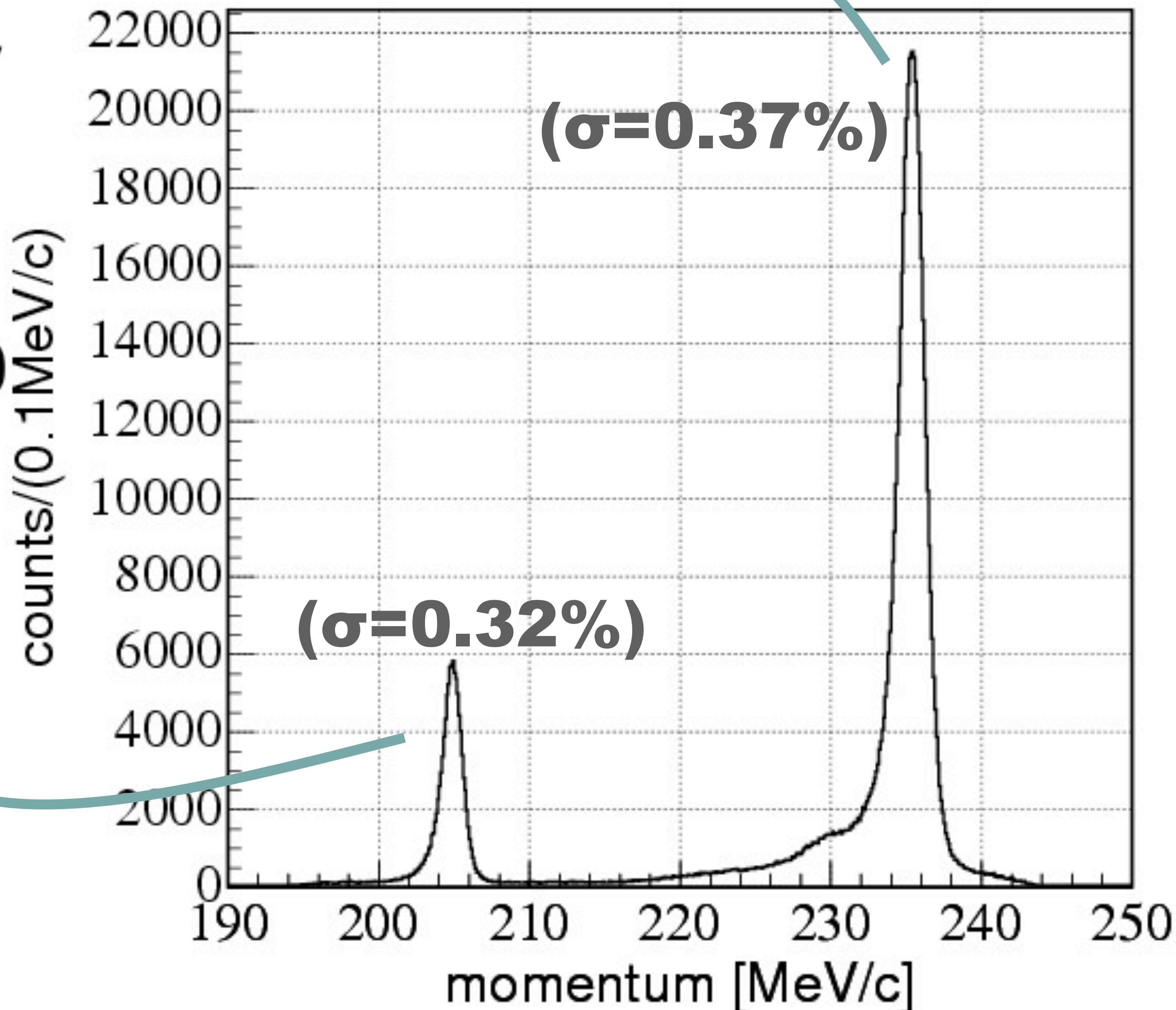
Momentum calibration

$$K^+ \rightarrow \mu^+ \nu_\mu$$

b.r. 63.4%
236 MeV/c

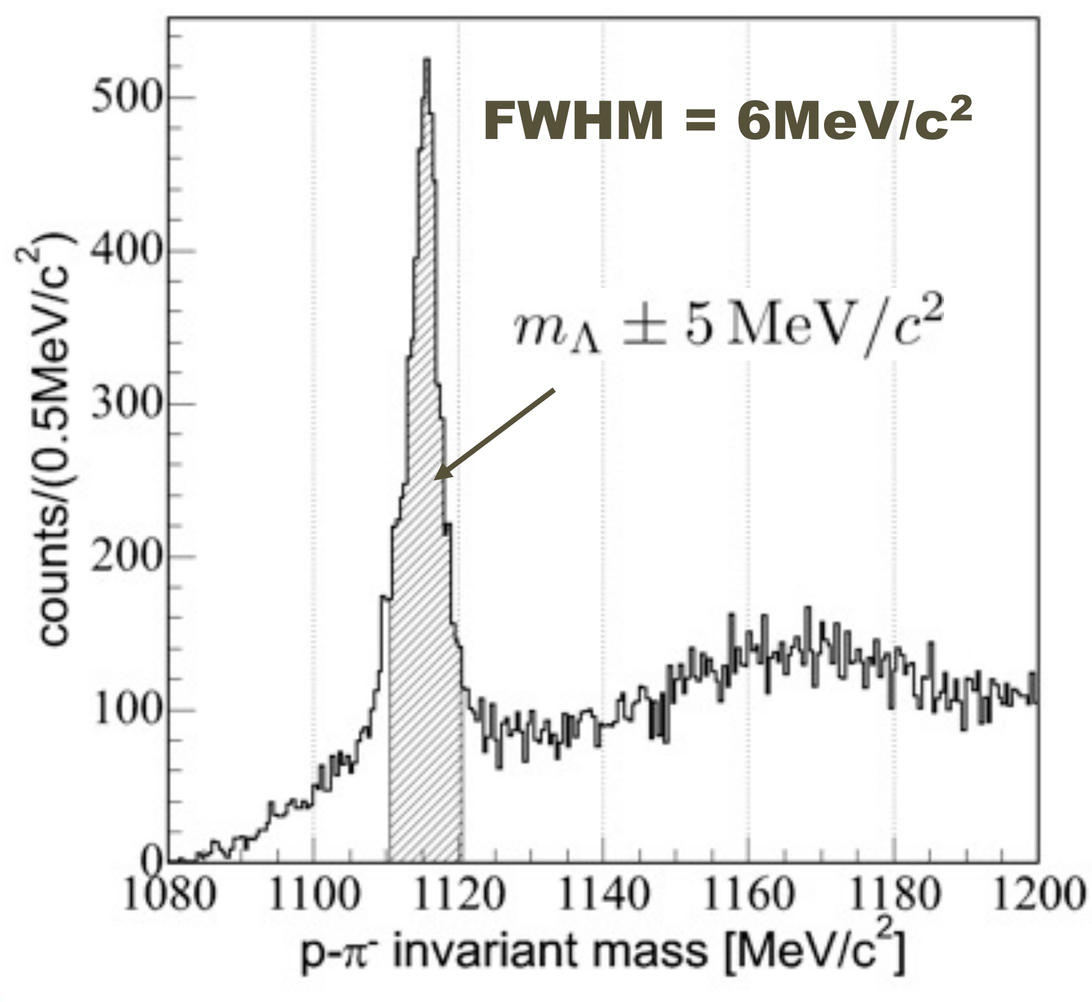
$$K^+ \rightarrow \pi^+ \pi^0$$

b.r. 21.1%
205 MeV/c



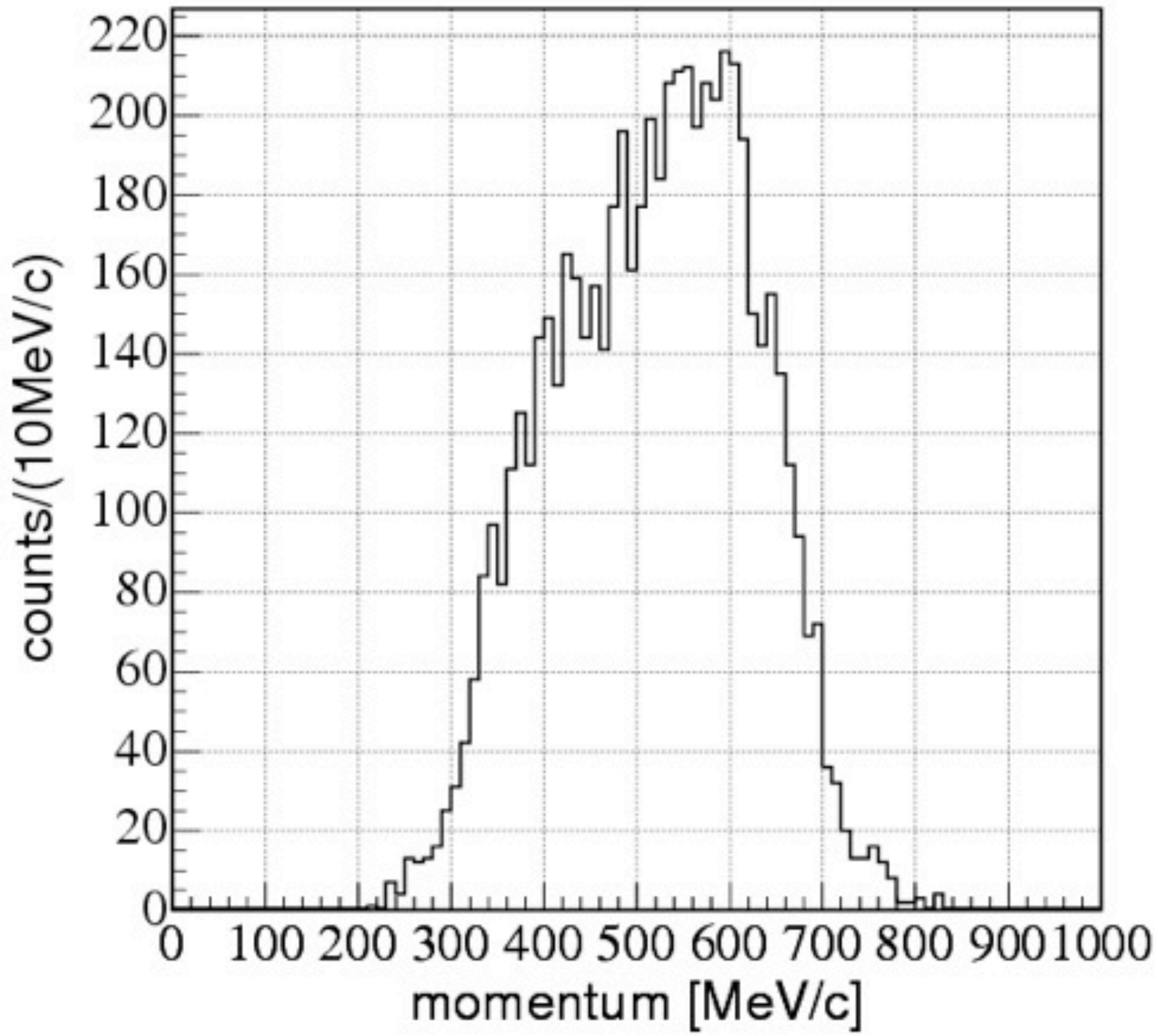
Detection of a Λ hyperon

Invariant mass of a proton and a π^-



Λ momentum distribution

(acceptance uncorrected)



Λ in Kaon absorption

- **quasi-free process (80–85%)**

$$K^- + \text{"}N\text{"} \to \Lambda + \pi \ , \ \Sigma + \pi$$

$$p_\Lambda \lesssim 400\,\mathrm{MeV}/c$$

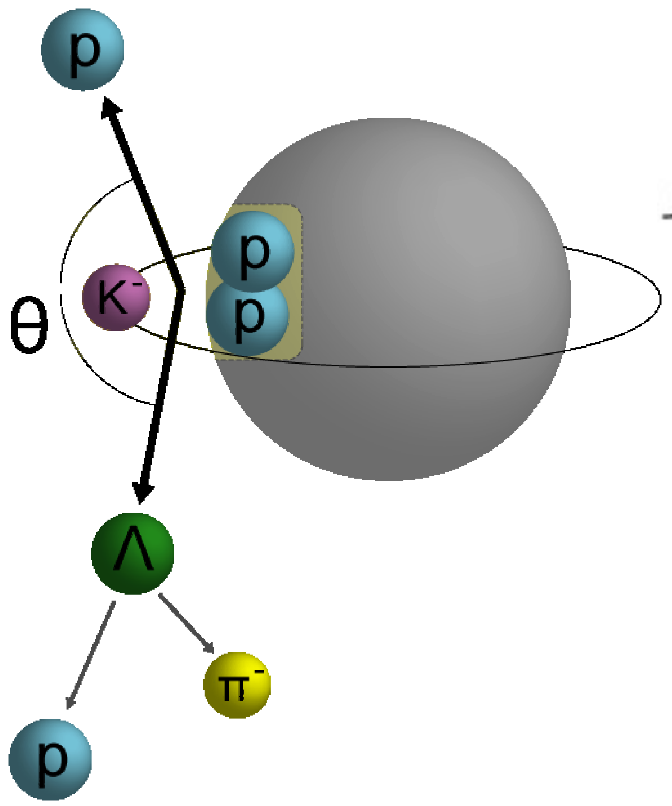
- **two-nucleon absorption (15–20%)**

$$K^- + \text{"}NN\text{"} \to \Lambda + N \ , \ \Sigma + N$$

$$p_\Lambda : \ 400 - 700\,\mathrm{MeV}/c$$

Λ-p coincidence events

- About 5% of the Λ events are associated with a proton.

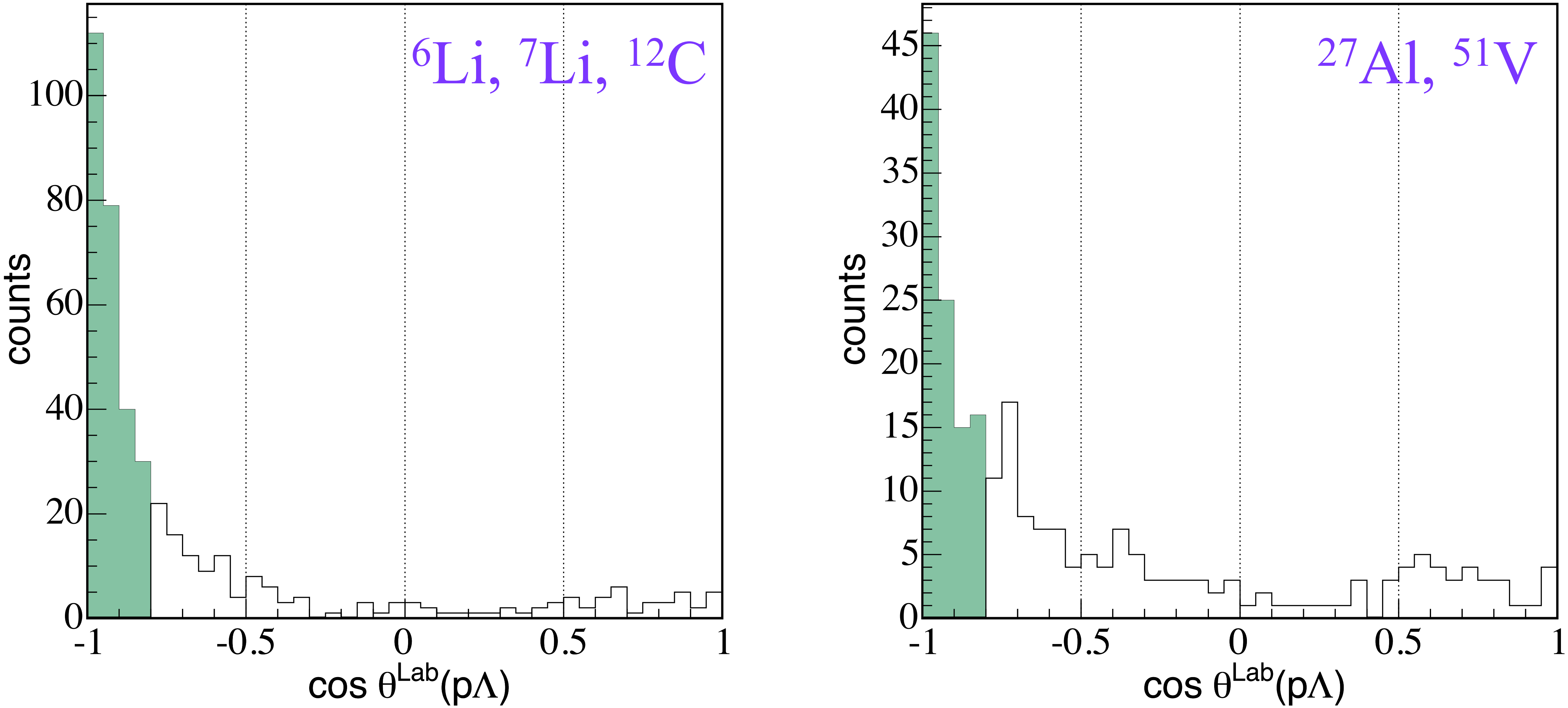


Two-proton absorption ?

$$K^- + \text{“}pp\text{”} \rightarrow \underbrace{\Lambda + p}$$

Back-to-back correlation
is expected.

Angular correlation of Λ-p

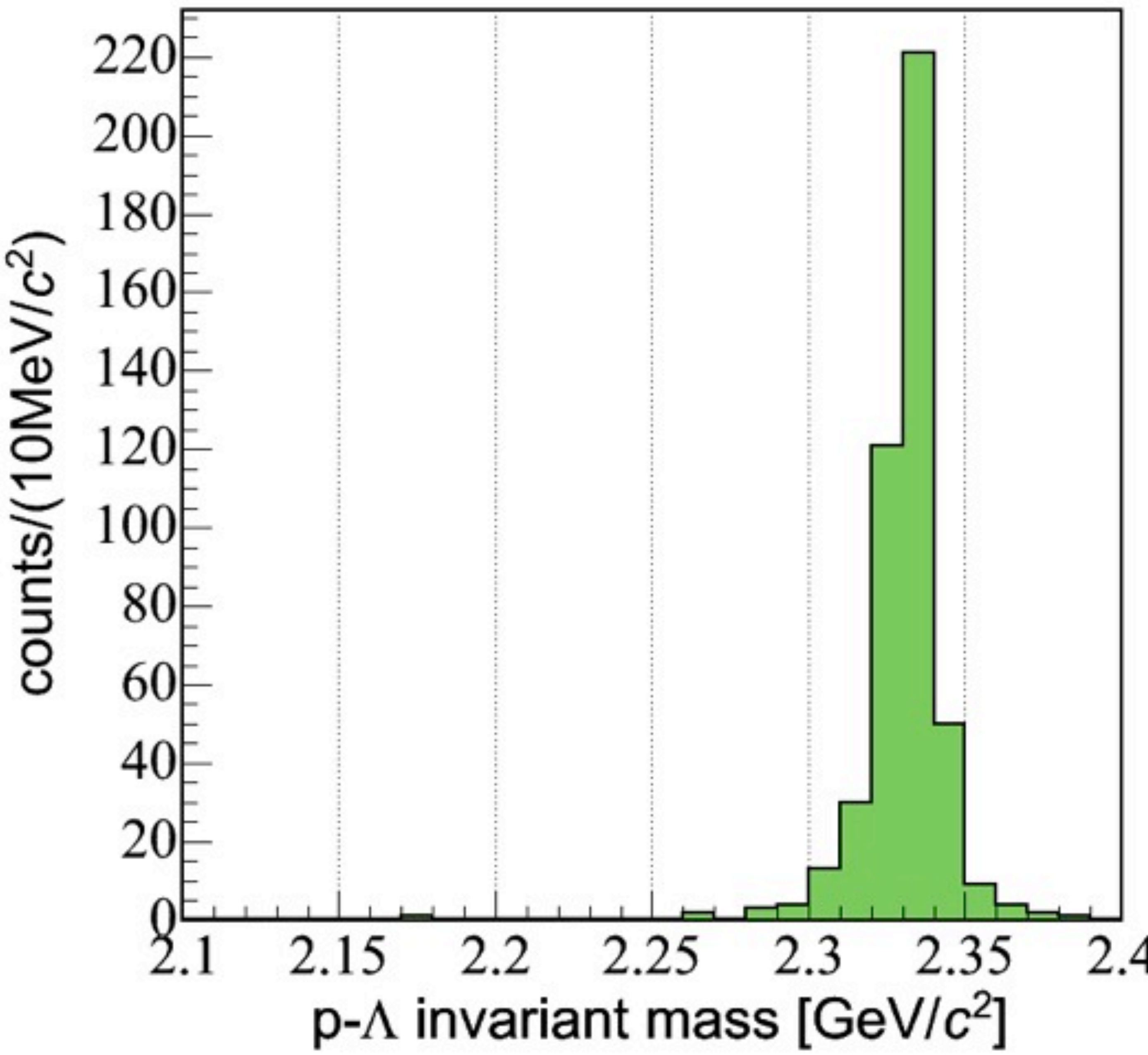


Naive expectation of invariant mass distribution

- Peak around

$$m_{K^-} + 2m_p = 2.37\,\mathrm{GeV/c^2}$$

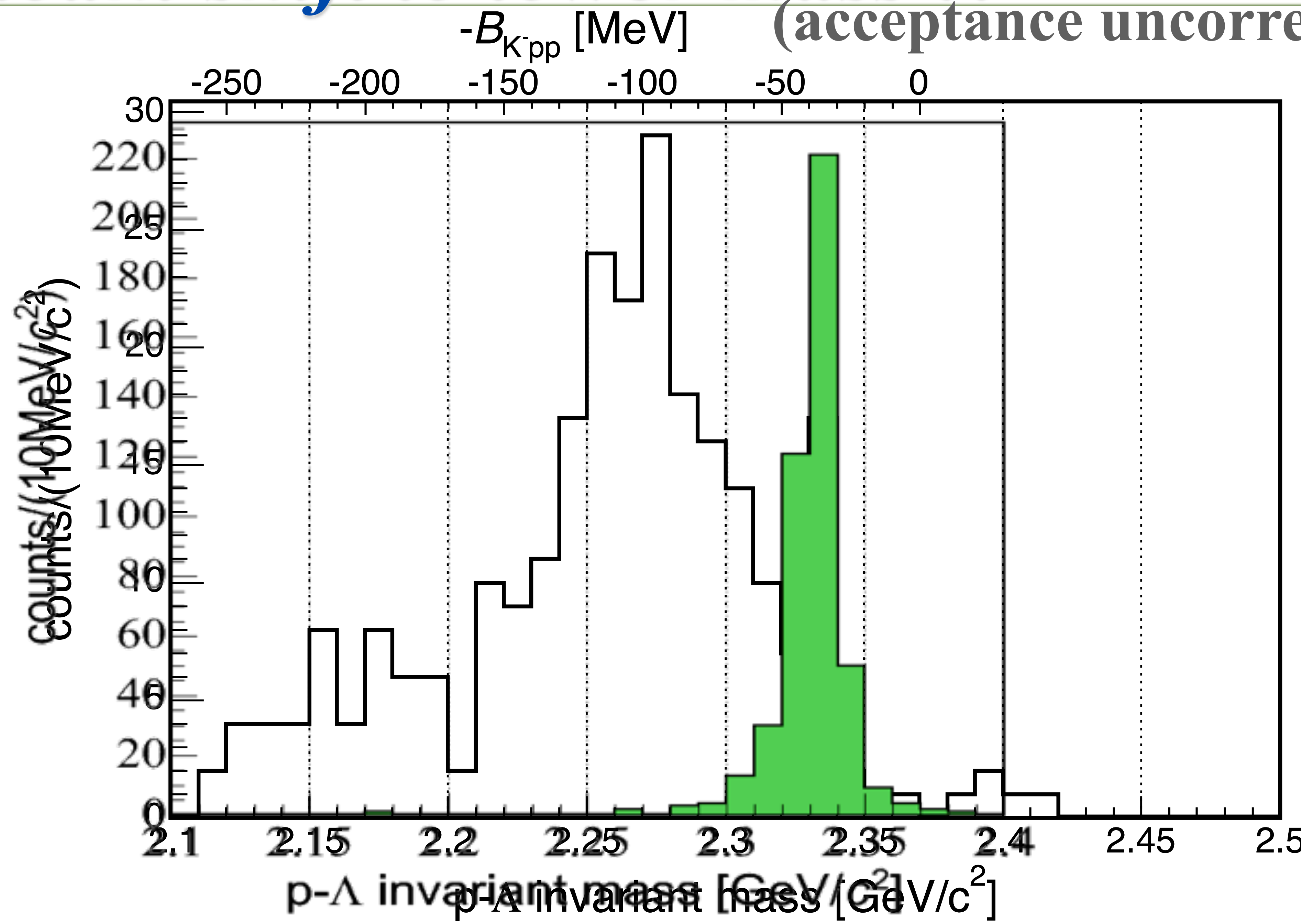
- Shift due to
  - separation energy of two protons
  - kinetic energy of the system

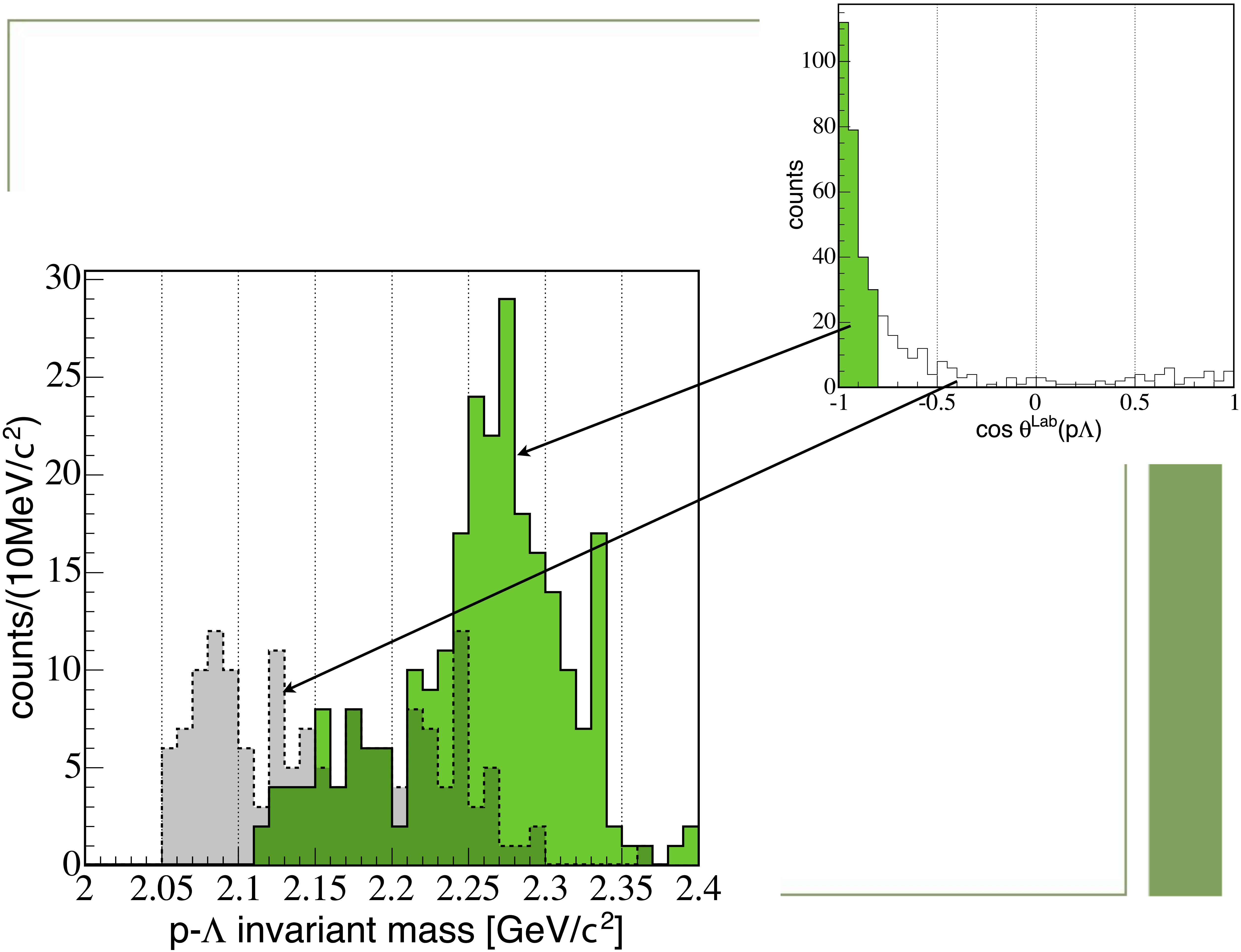


Invariant-mass distribution

Significant shift to lower mass !!

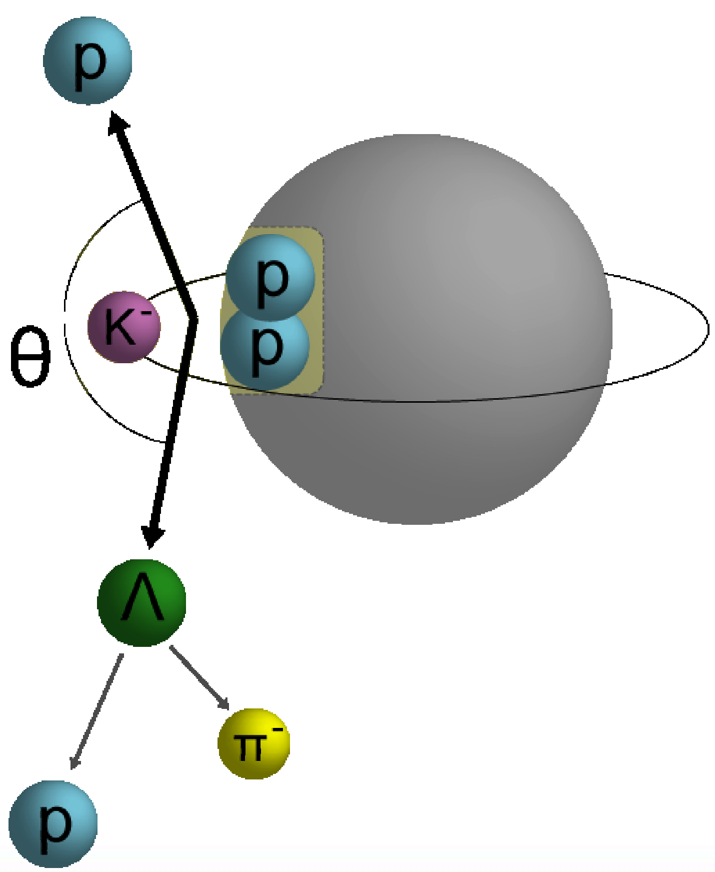
(acceptance uncorrected)

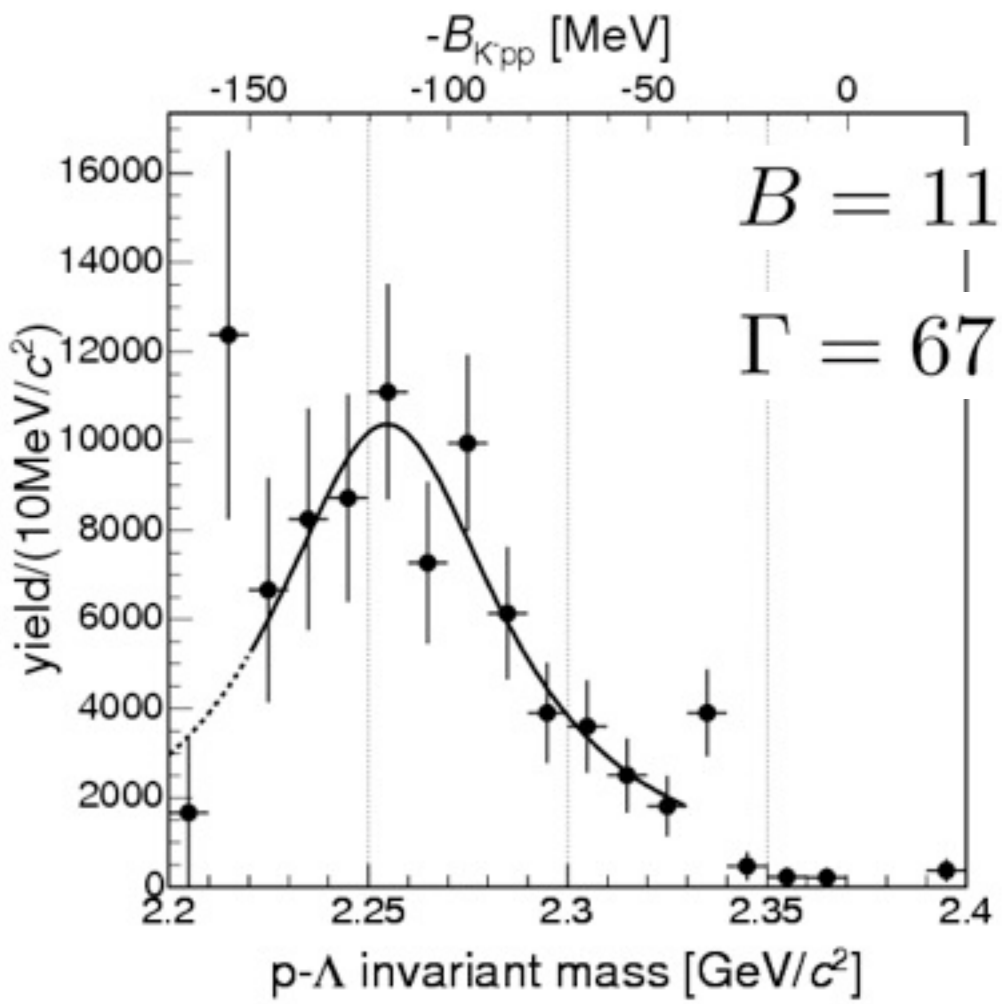



counts
cos θ^Lab(pΛ)
counts/(10MeV/c²)
p-Λ invariant mass [GeV/c²]

Evidence for K^-pp in FINUDA

K- Absorption on ^{6,7}Li, ^{12}C
Back-to-back Λ+p pair





$$B = 115\,^{+6}_{-5}\,^{+3}_{-4}\ \mathrm{MeV}$$

$$\Gamma = 67\,^{+14}_{-11}\,^{+2}_{-3}\ \mathrm{MeV}$$

M. Agnello et al., PRL 94(2005) 212303.

Few-body calculations on $K^{-}pp$

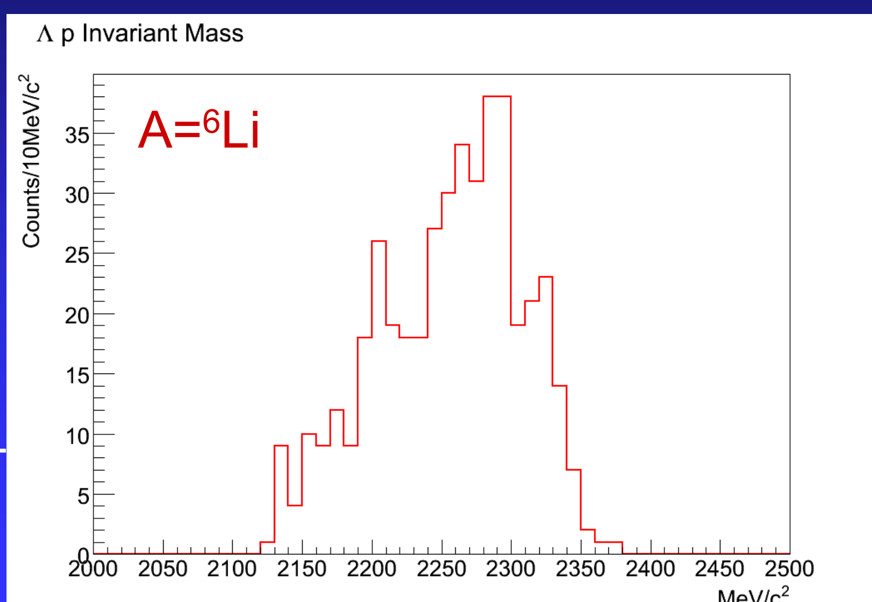
- K-pp does exist !!
  ... but maybe broad.

(MeV)	ATMS Yamazaki & Akaishi, PLB535 (2002) 70.	Variational Dote, Hyodo, Weise, PRC79 (2009) 014003.	Faddeev Shevchenko, Gal, Mares, PRL98 (2007) 082301.	Faddeev Ikeda & Sato, PRC79 (2009) 035201.	Variational Wycech & Green, PRC79 (2009) 014001.
B	48	17-23	50-70	60-95	40-80
Γ	61	40-70	90-110	45-80	40-85

New FINUDA data

- K^-pp confirmed for ^{6}Li only, with better statistics

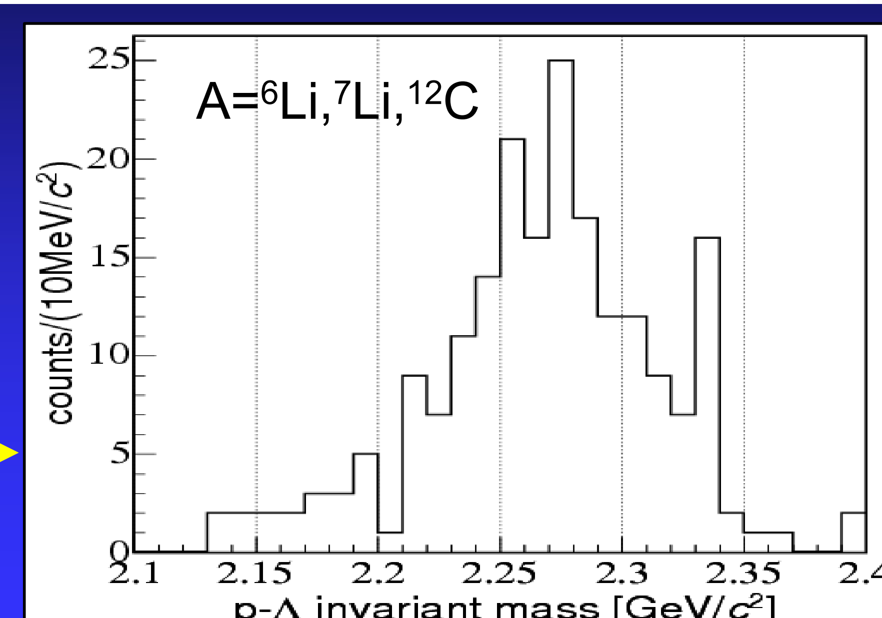
no acceptance corrected



New
inv mass spectra
compatible with
published one

New data ⟷ Old data

Same cuts applied



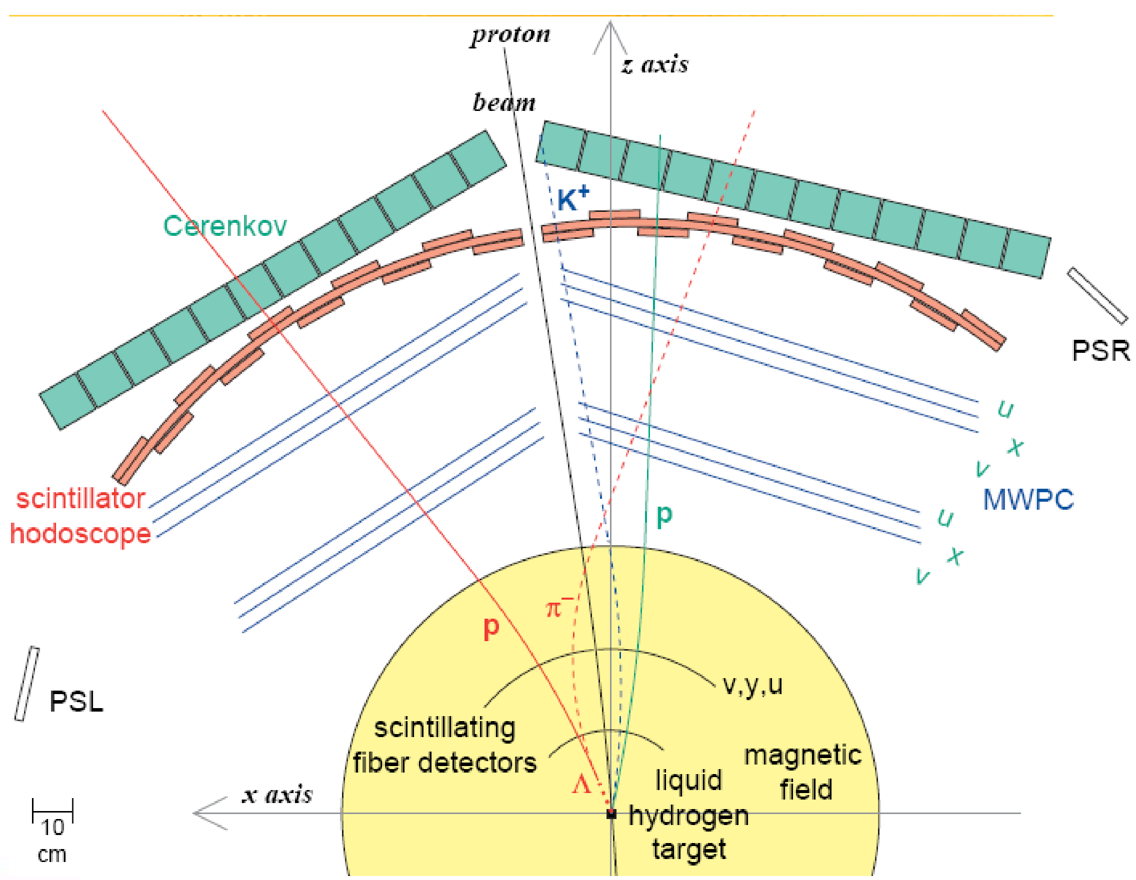
FINUDA Coll., PRL 94(2005)212303

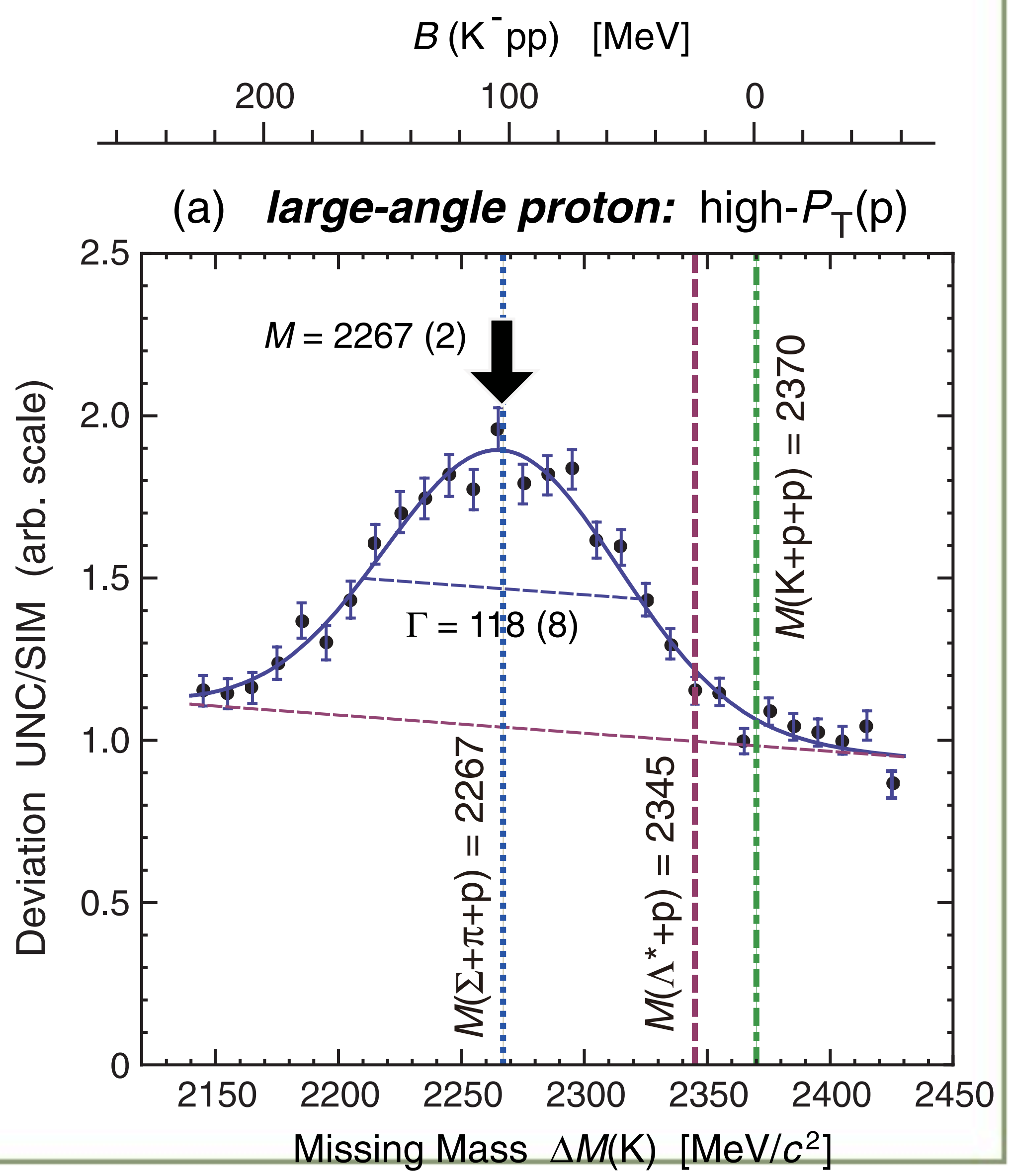
no acceptance corrected

DISTO data on $K^{-}pp$

- $p+p \rightarrow K^{-}pp + K^{+}$ at 2.85 GeV
  - $M=2267\pm3\pm5$ MeV/c^2
  - $\Gamma= 118\pm8\pm10$ MeV

T. Yamazaki et al., PRL 104 (2010) 132502.



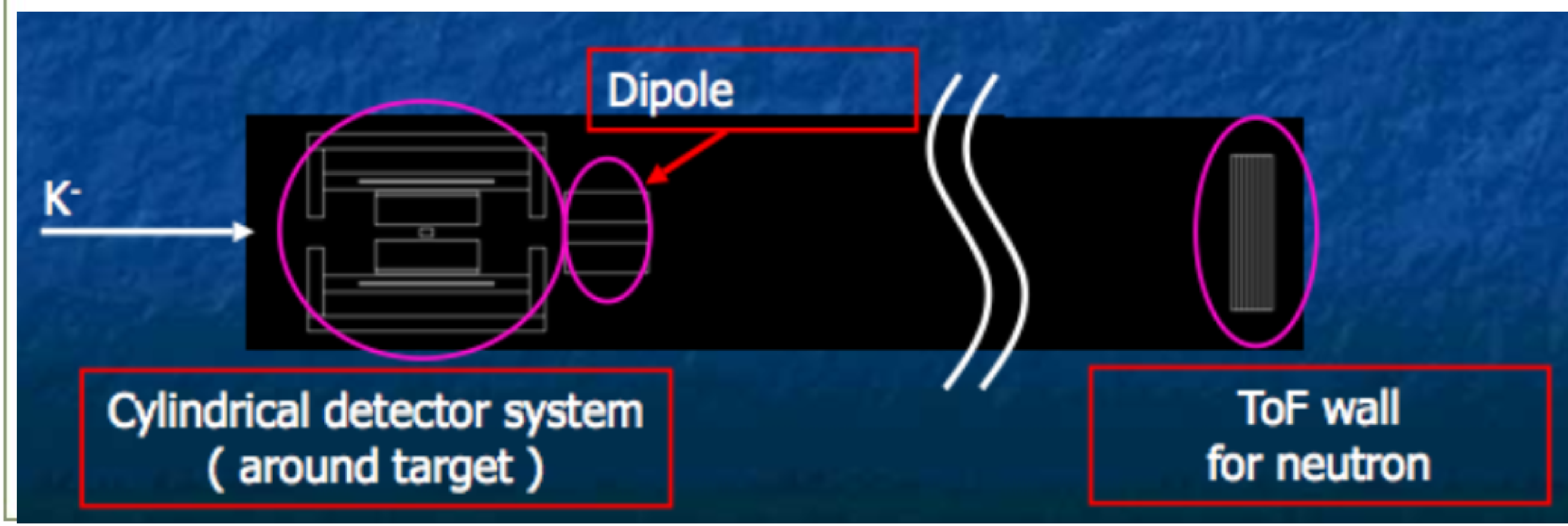


A Search for deeply-bound kaonic nuclear states by in-flight ^{3}He(K$^-$,n) reaction

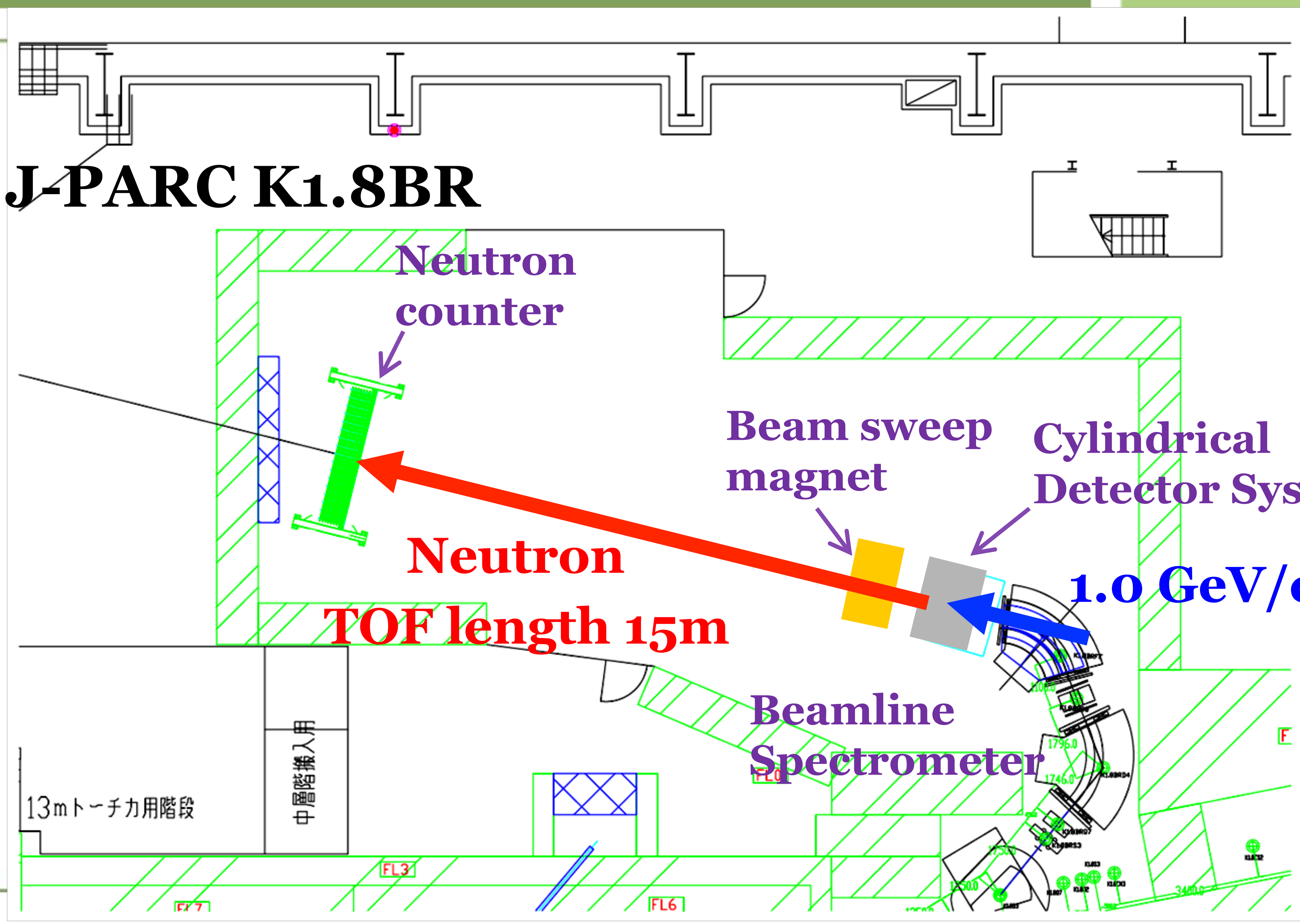
E15
M. Iwasaki et al.

$$K^- + {}^3\text{He} \rightarrow \langle K^- pp \rangle + \boxed{n} \qquad \text{TOF}$$

$$\langle K^- pp \rangle \rightarrow \Lambda + p \rightarrow \boxed{p\pi^- + p} \qquad \text{CDC}$$

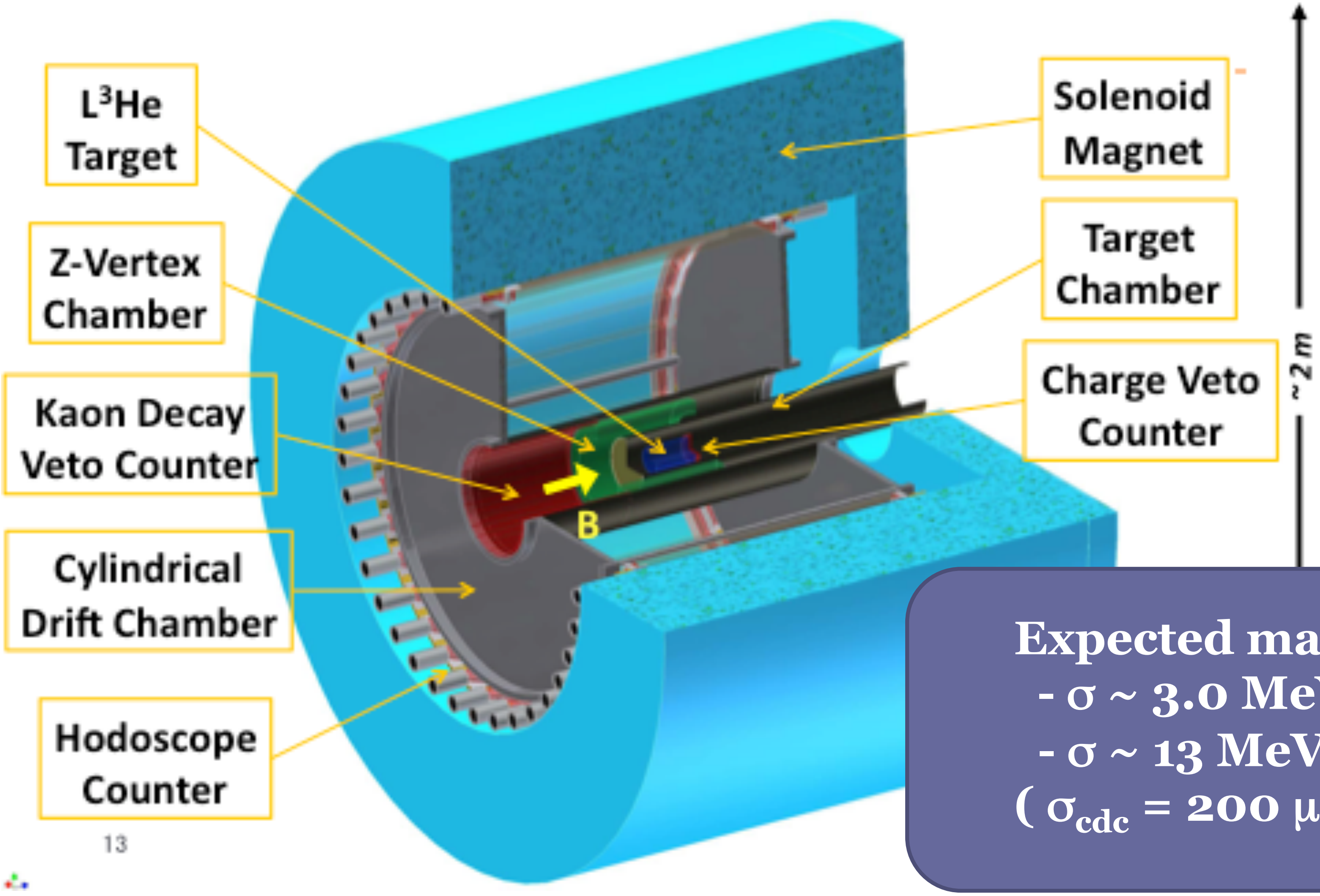


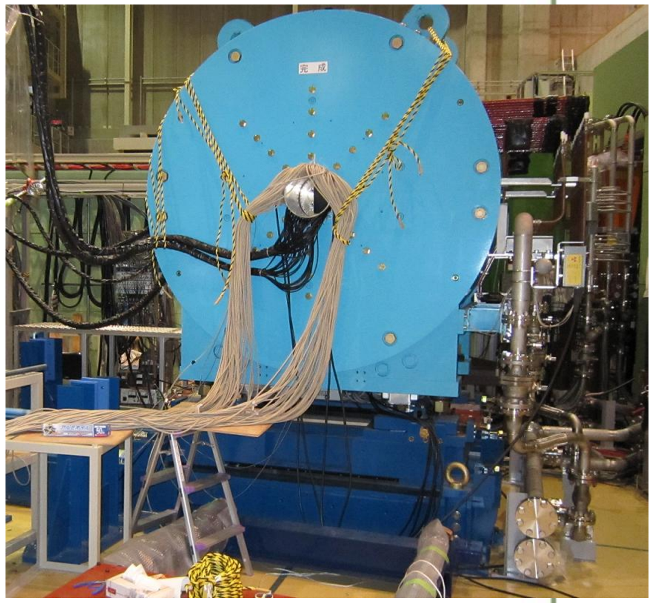
Experimental Setup



Cylindrical Detector System

- **A newly developed system for invariant mass study**



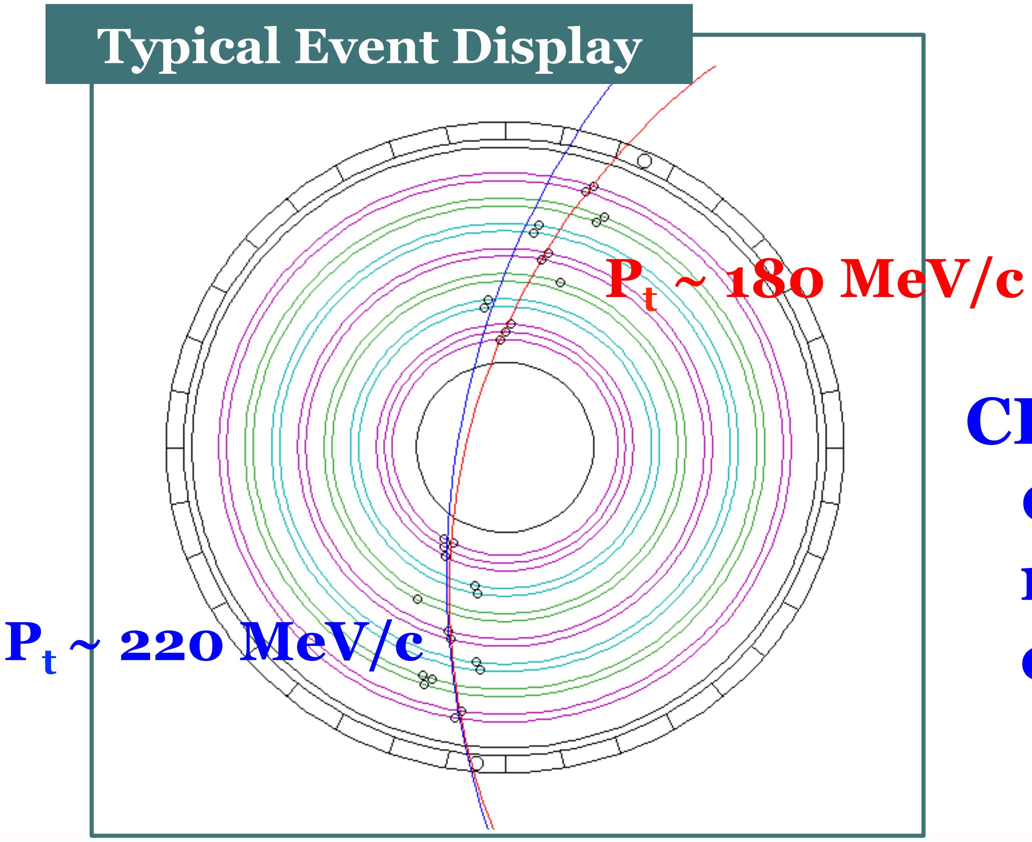


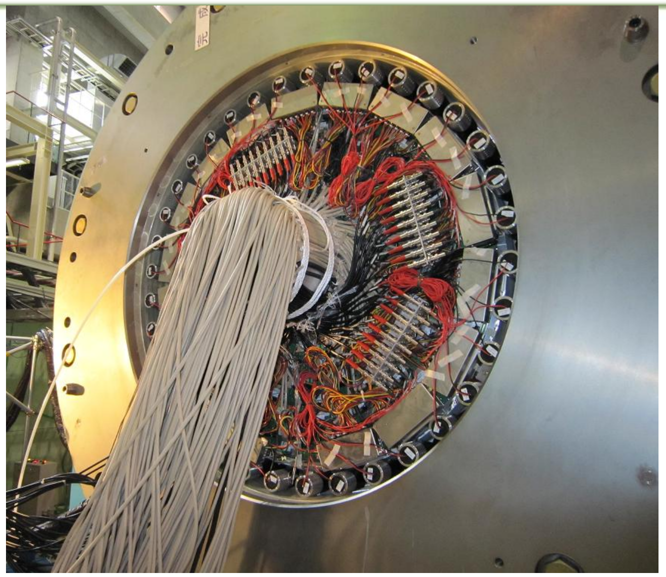
Expected mass resolution :
- **$\sigma \sim 3.0$ MeV/c^2 for Λ**
- **$\sigma \sim 13$ MeV/c^2 for K^-pp**

(σ_{cdc} = 200 μm / Field : 0.5 T)

Status of CDS

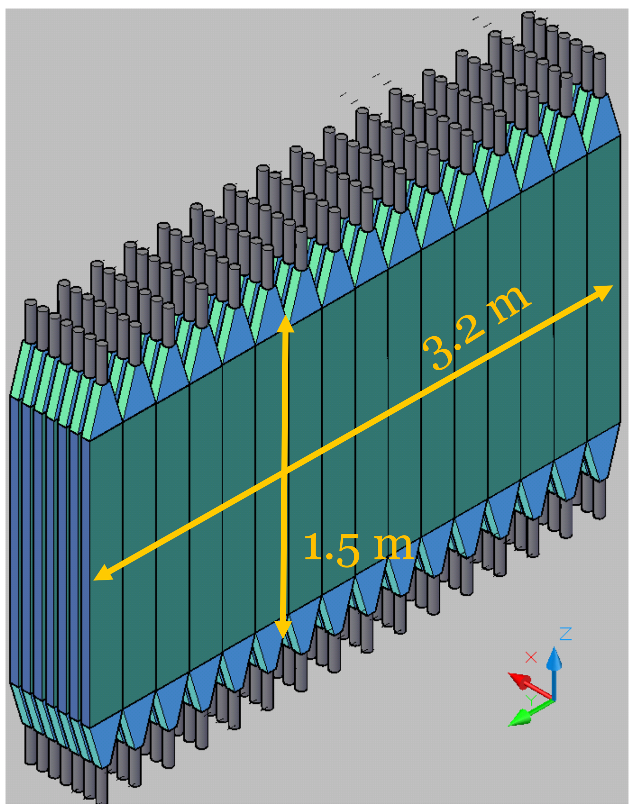
- All of the components(CDC, CDH) have been installed into the solenoid magnet.





CDS commissioning with 0.5 T magnetic field is now under way using cosmic ray.

Neutron counter

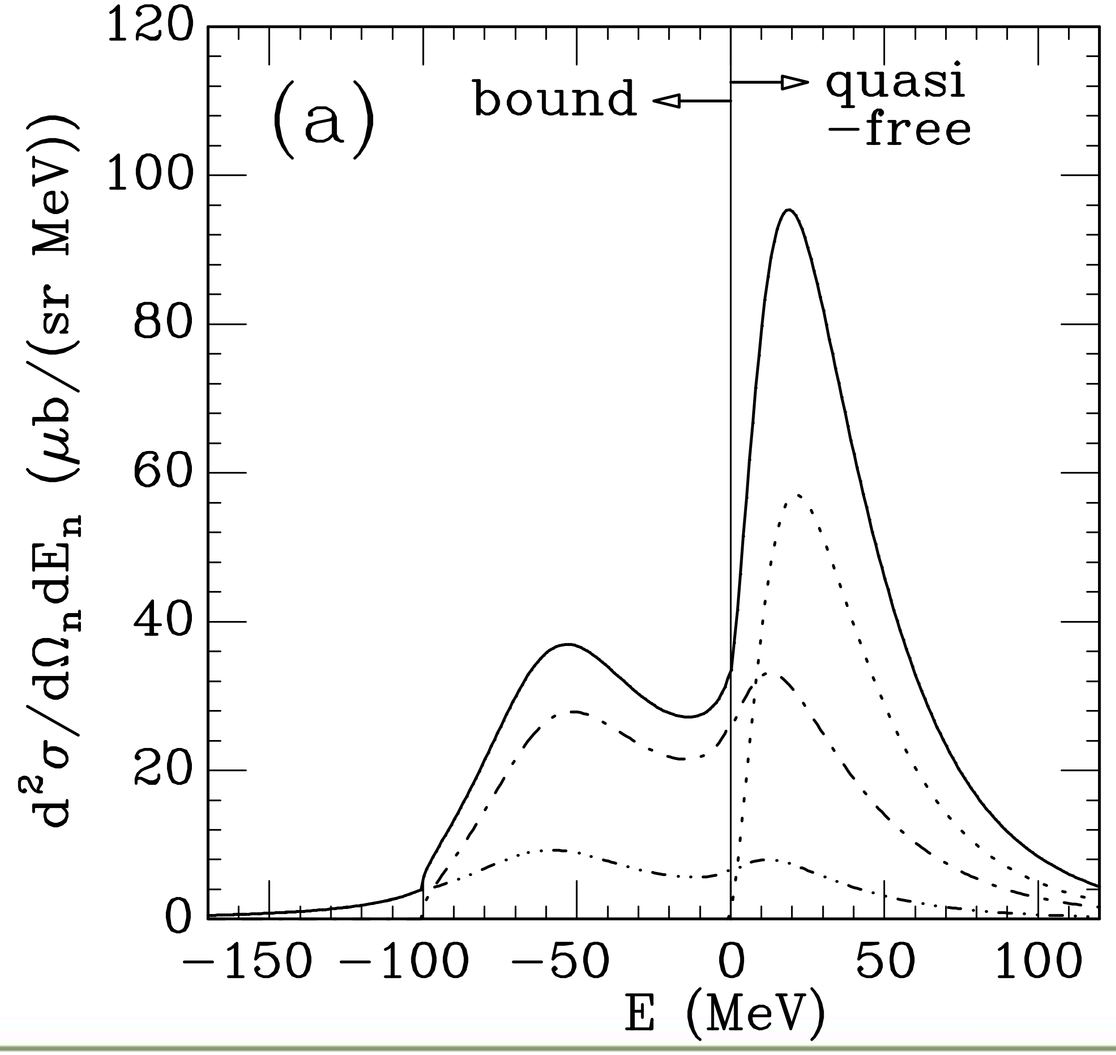


rearrange

- $20 \times 5 \times 150\ cm^3$ Plastic Scintillator
- Configuration : 16 (wide) x 7 (depth)
- Surface area : 3.2m x 1.5m
- missing mass resolution for K^-pp
  $\sigma = 9.2\ MeV/c^2$ (P_n=1.3 GeV/c, σ_{TOF}=150 ps)

Neutron spectrum

- (V_0, W_0)=(-300 MeV, -93 MeV)→B=51 MeV, Γ= 67 MeV

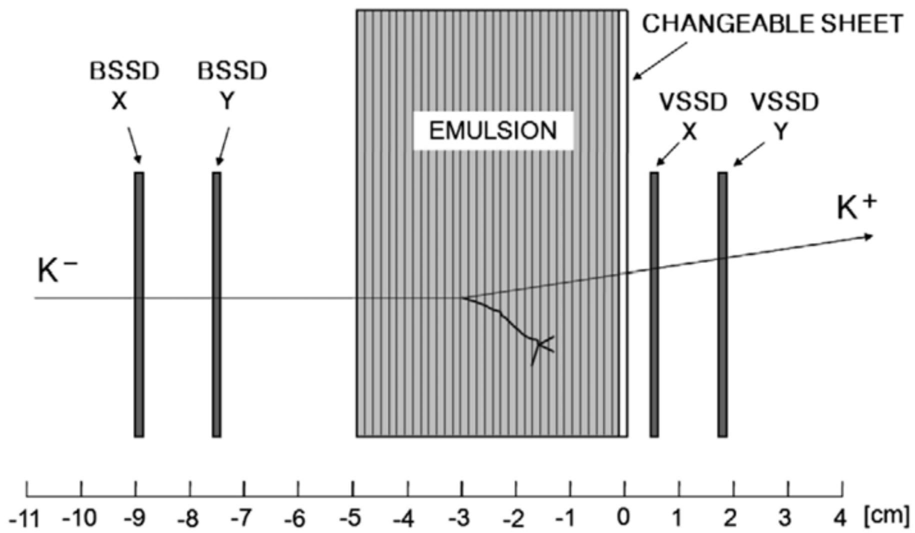


S=-2 Systems

Hybrid Emulsion Experiments

by K. Nakazawa

KEK E176



<u>Introduction of experimental method</u>

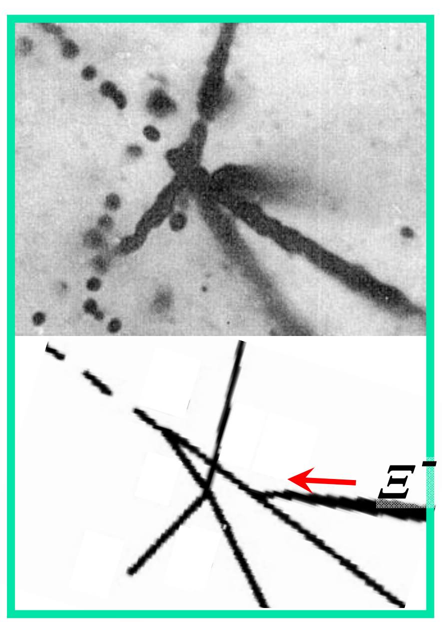
1. select Q.F. (K-,K+) reaction & reconstruct K^+.
2. following up K^+ meson in emulsion.
3. following down Ξ^- cand. track.
4. check seq. topology of DHY at end point.

$\Rightarrow$ Ξ^- stops : 77.6 +/- 5.1 events

captured by

light elem. (C,N,O) : $42.3^{+4.5}_{-9.6}$ %

heavy elem. (Ag, Br): $57.7^{+6.1}_{-9.6}$ %



<u>most probable case</u>

$^{14}N + \Xi^- \Rightarrow {}^{13}_{\Lambda\Lambda}B + p + n$

${}^{13}_{\Lambda\Lambda}B \Rightarrow {}^{13}_{\Lambda}C^* + \pi^-$: ***Ex* = 4.9 MeV**

${}^{13}_{\Lambda\Lambda}B$

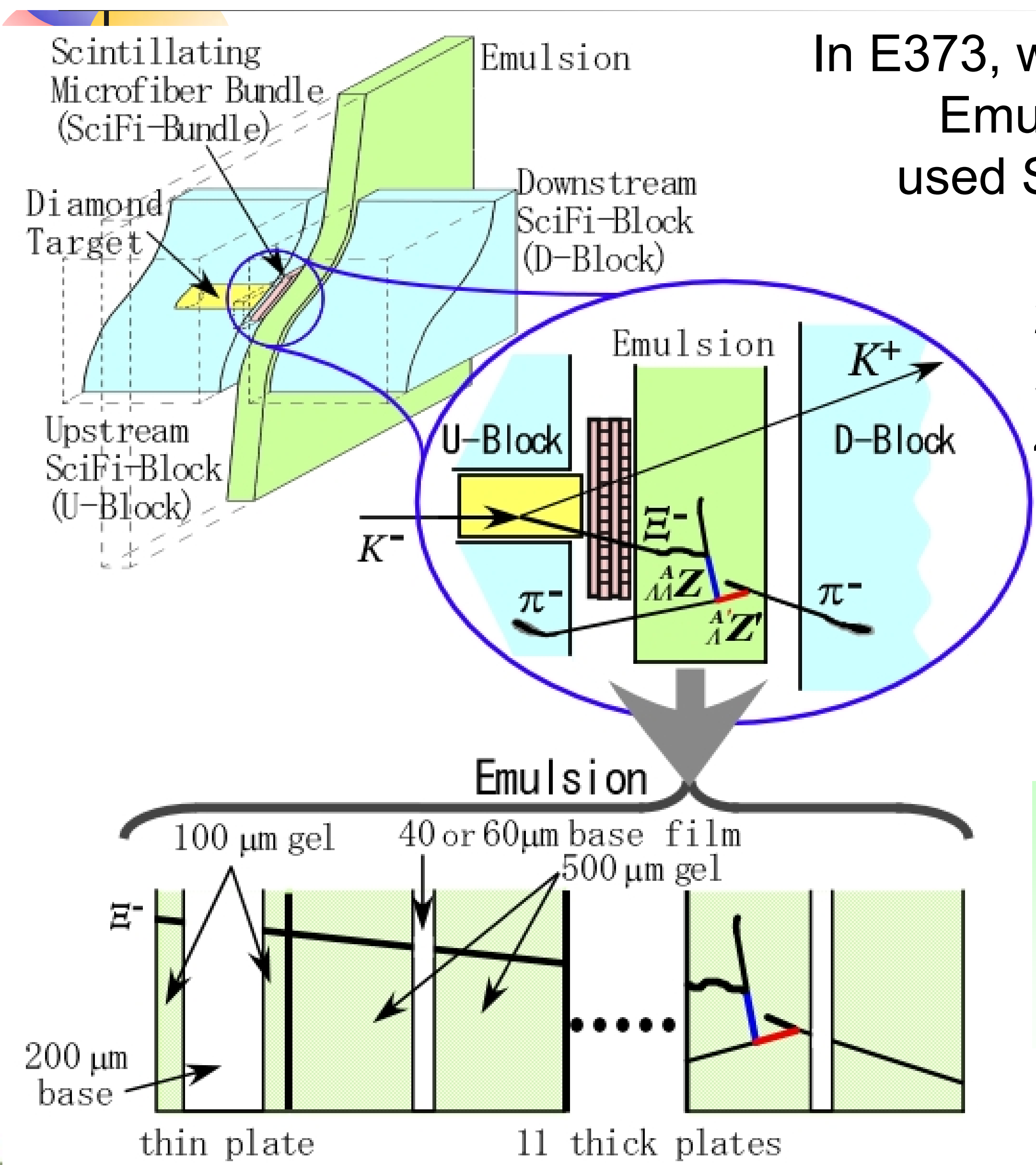
$B_{\Lambda\Lambda}$ = 23.3 +/- 0.7 MeV

$\Delta B_{\Lambda\Lambda}$ = 0.6 +/- 0.8 MeV

[Assumption]
B_{Ξ^-} = 0.17 MeV (atomic **3D** in ^{14}N-Ξ^-)

S. Aoki et al, NP A 828 (2009) 191.

KEK E373



In E373, we changed the target
Emuslion (E176) ==> Diamond,
used SciFi-Blcok and -Bundle.

1. select Q.F. (K-,K+) reaction,
2. reconstruct Ξ^- cand. track,
3. following down Ξ^- cand. track,
4. careful analysis of the vertex.

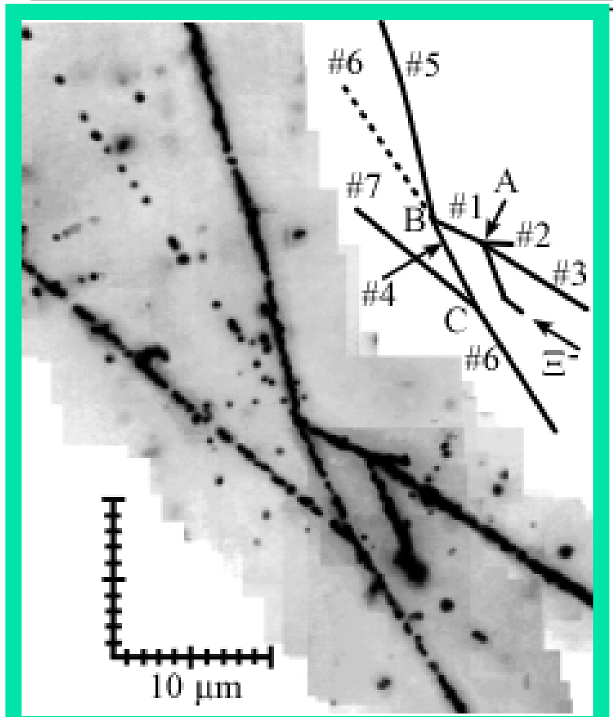
==> ~10^3 Ξ^- stops

" the most significant result of the past 5 years in hypernuclear physics. "

Final Report of the 2004 KEK PS External Review Committee (August 30, 2004),p5.

for NAGARA event

- Nagara Event



Unique assignment

$$^{12}\mathrm{C} + \Xi^- \rightarrow {}_{\Lambda\Lambda}^{6}\mathrm{He} + {}^{4}\mathrm{He} + t$$
$$\hookrightarrow {}_{\Lambda}^{5}\mathrm{He} + p + \pi^-.$$

1. From Consistency in A & B : $B_{\Xi^-} < 1.86$ MeV
2. By kinematical fitting : $B_{\Lambda\Lambda} = 6.79 + 0.91\ B_{\Xi^-}$ (+/- 0.16) MeV
   $\Delta B_{\Lambda\Lambda} = 0.55 + 0.91\ B_{\Xi^-}$ (+/- 0.17) MeV

if we take into account $B_{\Xi^-} = 0.13$ **MeV** [atomic $3D$: ^{12}C- Ξ^-]

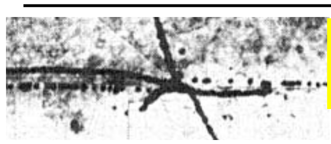
$_{\Lambda\Lambda}^{6}\mathrm{He}$ $B_{\Lambda\Lambda}$ = 6.91 +/- 0.16 MeV, $\Delta B_{\Lambda\Lambda}$ = 0.67 +/- 0.17 MeV

cf. **in the paper PRL(2001)** $B_{\Lambda\Lambda}$ **= 7.25 +/- 0.19 MeV,** $\Delta B_{\Lambda\Lambda}$ **= 1.01 +/- 0.20 MeV**

This discrepancy was come from the mass change of Xi- hyperon in PDG.

H. Takahashi et al., PRL 87 (2001) 212502.

Summary of Emulsion events

	$^{A}_{\Lambda\Lambda}Z$	Ξ^- Captured	$B_{\Lambda\Lambda}$ - B_{Ξ^-} [MeV]	$\Delta B_{\Lambda\Lambda}$ - B_{Ξ^-} [MeV]	Assumed level	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
NAGARA	$^{6}_{\Lambda\Lambda}$He	^{12}C	$B_{\Lambda\Lambda}$ = 6.79 + 0.91 B_{Ξ^-} (+/- 0.16) $\Delta B_{\Lambda\Lambda}$ = 0.55 + 0.91 B_{Ξ^-} (+/- 0.17) B_{Ξ^-} < 1.86		3D	6.91 +/- 0.16	0.67 +/- 0.17
MIKAGE	$^{6}_{\Lambda\Lambda}$He	^{12}C	9.93 +/- 1.72	3.69 +/- 1.72	3D	10.06 +/- 1.72	3.82 +/- 1.72
DEMACHI-YANAGI	$^{10}_{\Lambda\Lambda}$Be*	^{12}C	11.77 +/- 0.13	-1.65 +/- 0.15 *cf.* *Ex* = 3.0	3D	11.90 +/- 0.13	-1.52 +/- 0.15 *cf.* *Ex* = 3.0
HIDA	$^{11}_{\Lambda\Lambda}$Be	^{16}O	20.26 +/- 1.15	2.04 +/- 1.23	3D	20.49 +/- 1.15	2.27 +/- 1.23
	$^{12}_{\Lambda\Lambda}$Be	^{14}N	22.06 +/- 1.15	-------	3D	22.23 +/- 1.15	-------
E176	$^{13}_{\Lambda\Lambda}$B -> $^{13}_{\Lambda}$C*		------- *Ex* = 4.9	--------	3D	23.3 +/- 0.7	0.6 +/- 0.8
	$^{10}_{\Lambda\Lambda}$Be -> $^{9}_{\Lambda}$Be*		------- *Ex* = 3.0	--------	not checked, yet.	14.7 +/- 0.4	1.3 +/- 0.4

M.Danysz et al., PRL.11(1963)29;
R.H.Dalitz et al., Proc. R.S.Lond.A436(1989)1

Search for Double-Λ with Sequential Weak Decay

- Large Branch of Mesonic Weak Decay in Light hyperfragments
- Characterisitc π^- emission

$^{5}_{\Lambda\Lambda}H \rightarrow {}^{5}_{\Lambda}He + \pi^-$

P $_{\pi-}$~130 MeV/c

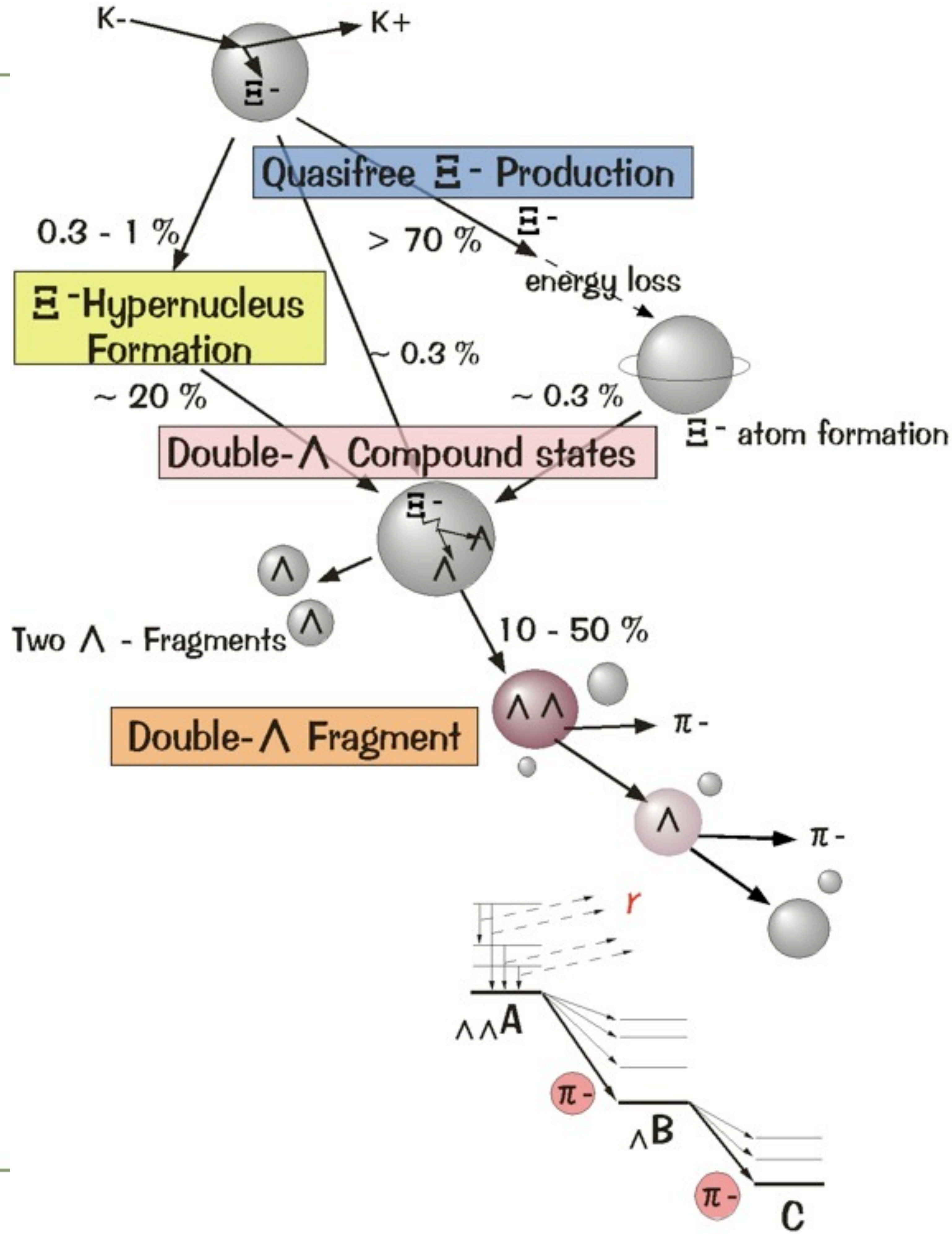
Γ_π/Γ_{tot} ~0.21

$\rightarrow {}^{4}He + p + \pi^-$

P $_{\pi-}$=99.2 MeV/c

Width =1 MeV/c

$\Gamma_{\pi-}/\Gamma_{tot}$ ~0.39



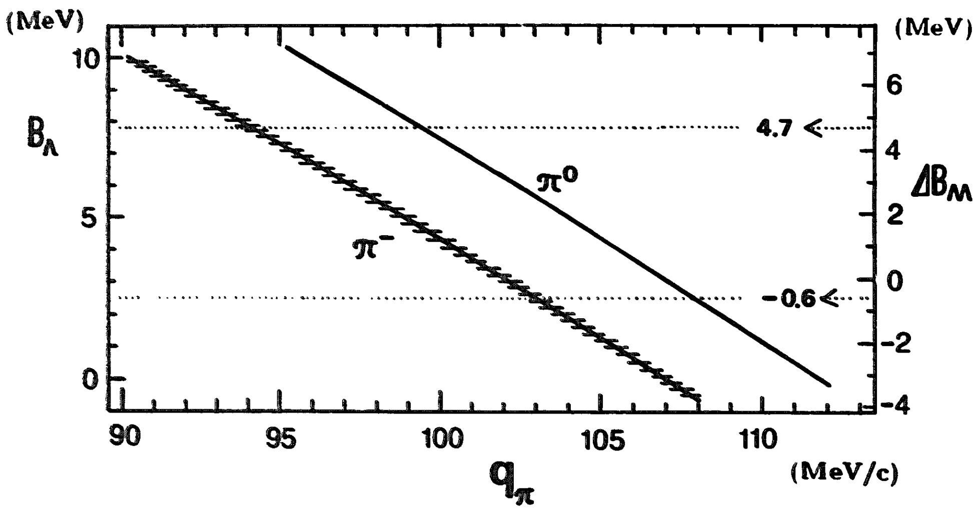


Fig. 8. The Λ-binding energy $B_\Lambda({}^5_\Lambda He)$ is plotted as a function of the weak decay pion momentum q_π. The corresponding $\Lambda\Lambda$ interaction matrix element $\Delta B_{\Lambda\Lambda}$ is also shown on the right scale. The hatch for the π^- decay indicates the predicted pion momentum width $\Delta q = 0.45$ MeV/c.

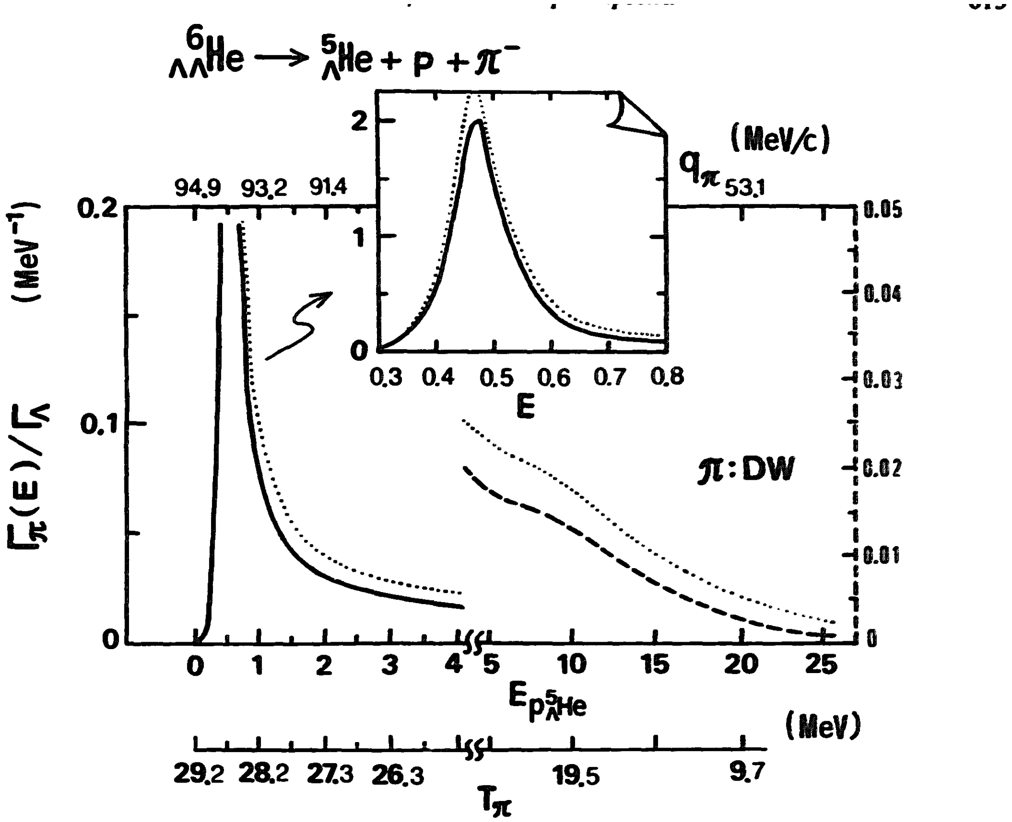
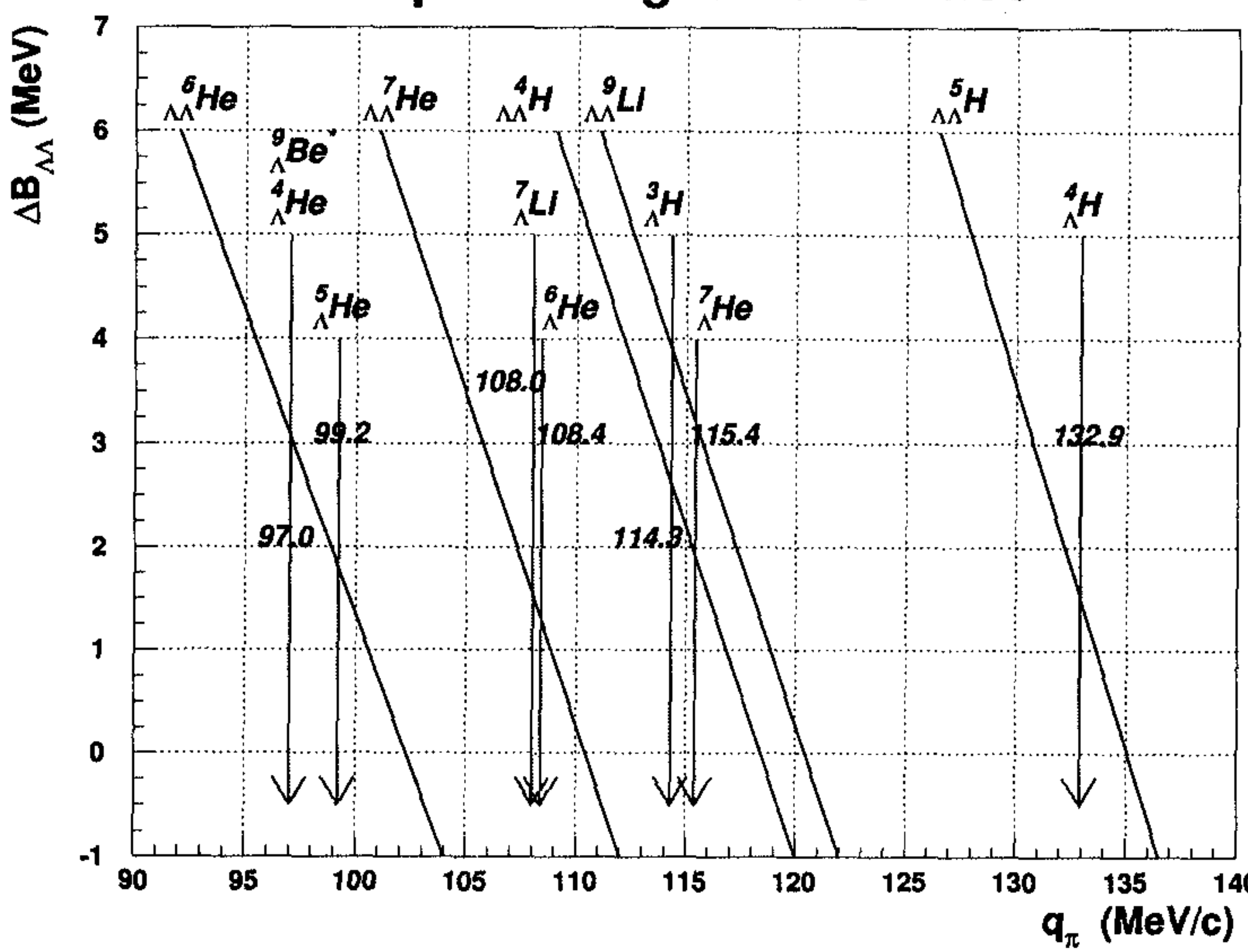


Fig. 7. The theoretical π^- decay spectrum $\Gamma_{\pi^-}({}^6_{\Lambda\Lambda}He)/\Gamma_\Lambda$ with YNG is drawn by solid line as a function of the proton-${}^5_\Lambda$He relative energy $E \equiv E_{p{}^5_\Lambda He}$. The shallow Λ-binding energy case described in sect. 4.2 results in the dotted curve in which case the pion momentum and energy should be shifted (cf. fig. 8).

Expected Signals and Lines

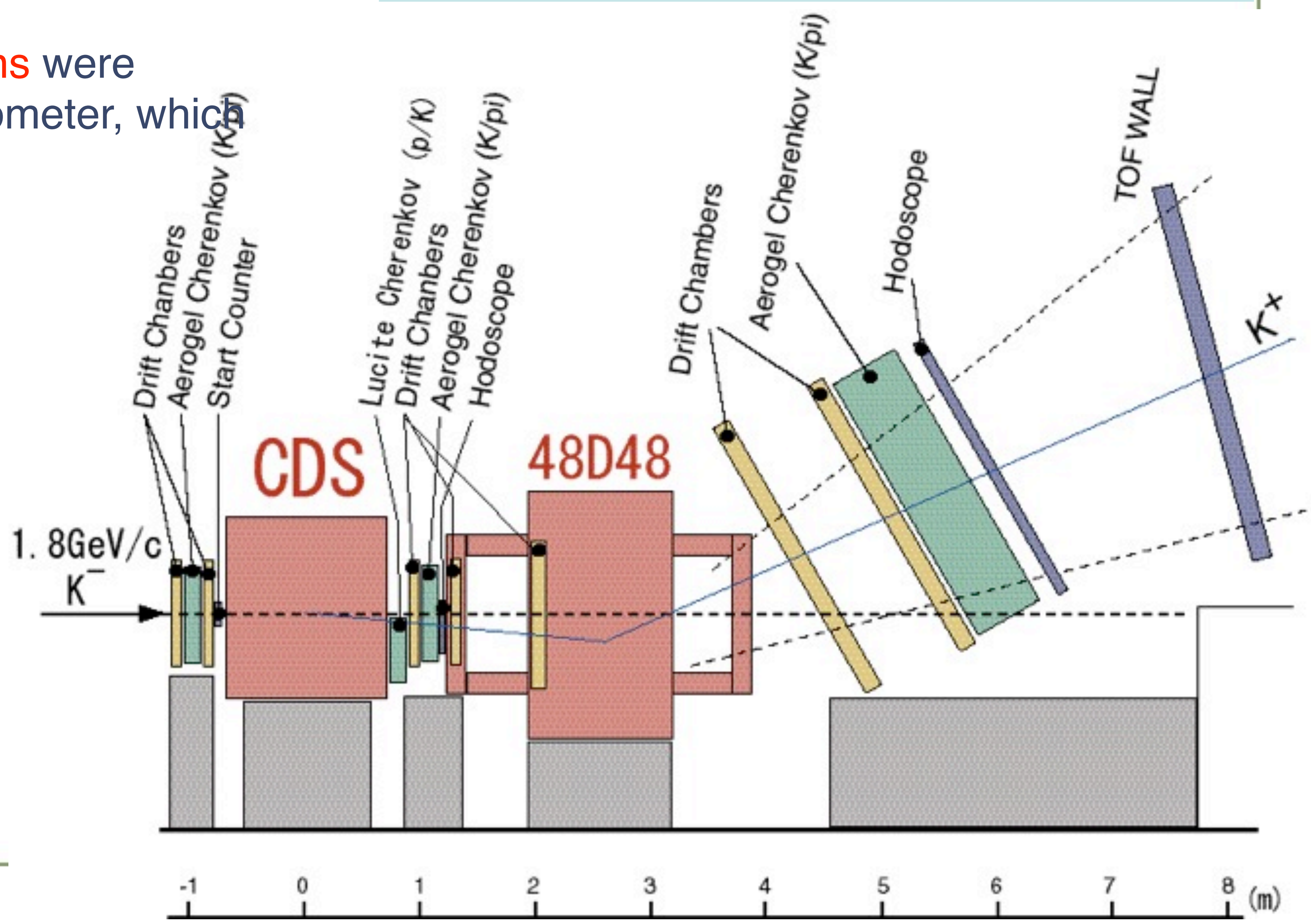


BNL E906

- 1998 Run Summary
  - 0.9 x 10^{12} K^- (1.8 GeV/c) was irradiated
  - Target was a ^{9}Be plate (6"x 2"x1/2" high)

48D48 spectrometer system and CDS

- 1.1x10^5 (K^-,K^+) reactions were identified by 48D48 spectrometer, which covers 2-10 deg.



Cylindrical Detector System

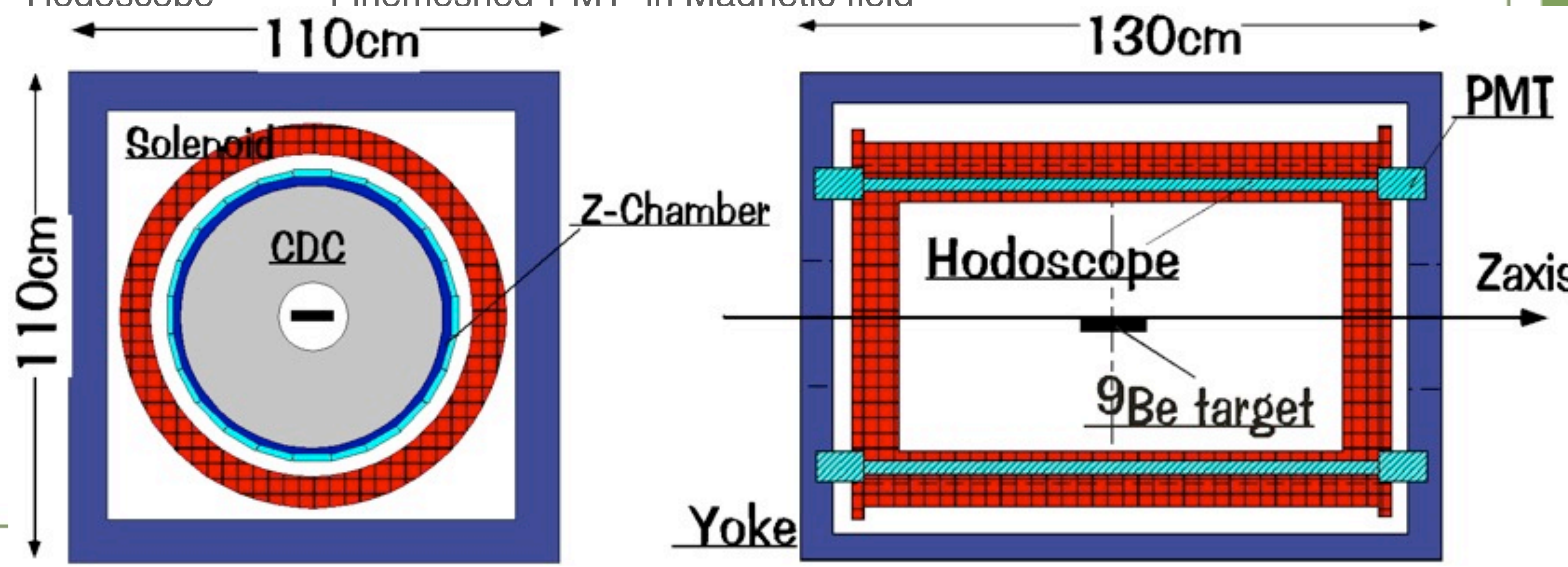
- Large solid angle 72% of 4π
- Momentum resolution for 100MeV/c π 9-10MeV/c(FWHM)

– Solenoid magnet Uniform field variation less than 0.5%

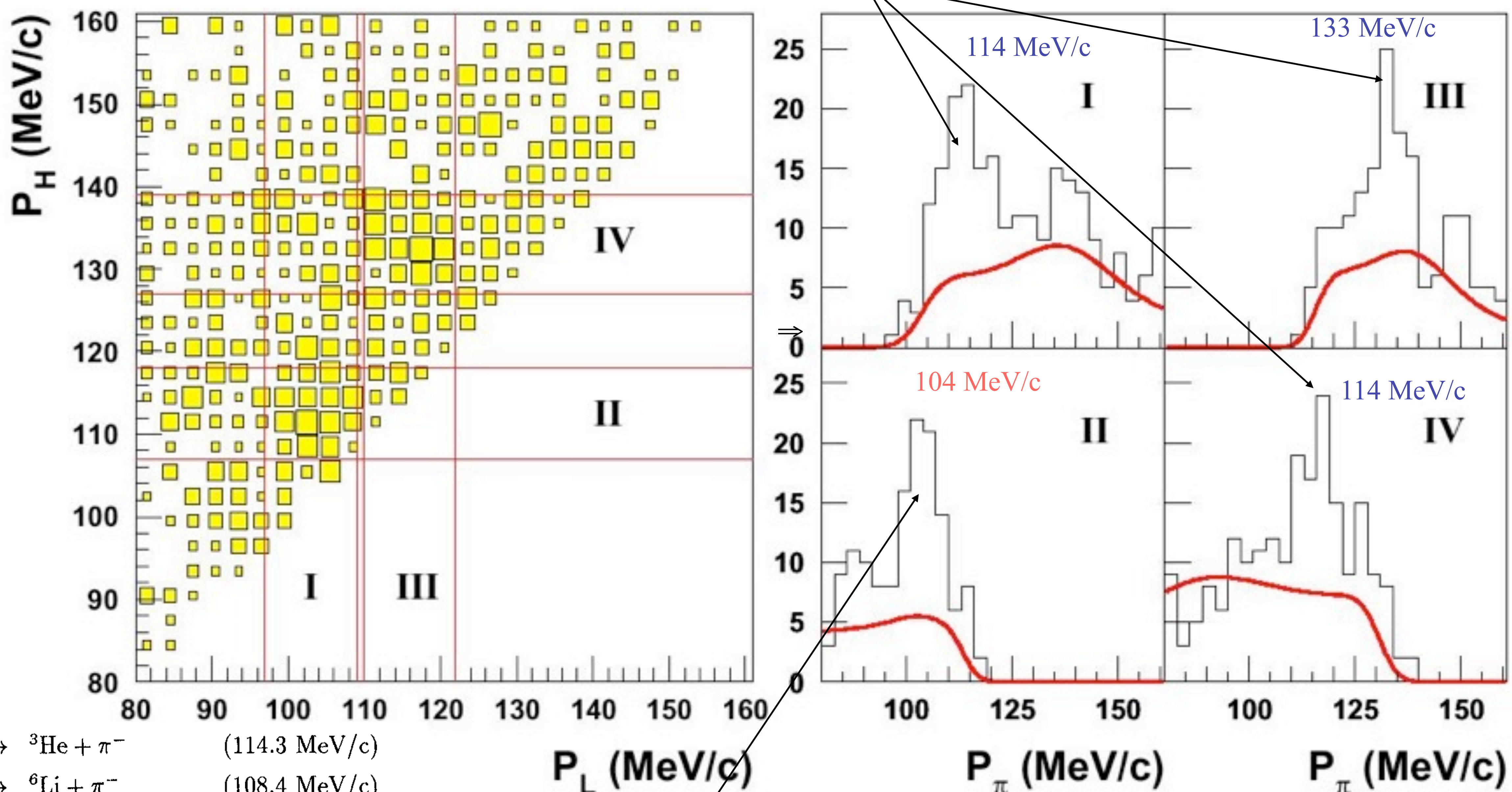
– Cylindrical Drift Chamber (CDC)
  Low Z materials
  gas ; He:C_2H_6=50%:50%
  field-wire ; gold plated aluminium
  12 layers ; 6 stereo layers, 6 axial layers, 576 cells

– Z-Chamber 5.5mm pitch Cathode strip readout-MWPC

– Hodoscope Finemeshed-PMT in Magnetic field



Consistent with known single Λ hypernuclei $^{3}_{\Lambda}\mathrm{H} + {}^{4}_{\Lambda}\mathrm{H}$



(i) $\begin{cases} {}^{3}_{\Lambda}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \pi^- & (114.3\ \mathrm{MeV/c}) \\ {}^{6}_{\Lambda}\mathrm{He} \longrightarrow {}^{6}\mathrm{Li} + \pi^- & (108.4\ \mathrm{MeV/c}) \end{cases}$

(ii) $\begin{cases} {}^{3}_{\Lambda}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \pi^- & (114.3\ \mathrm{MeV/c}) \\ {}^{4}_{\Lambda}\mathrm{H} \longrightarrow {}^{3}\mathrm{H} + \mathrm{p} + \pi^- & (\sim 98\ \mathrm{MeV/c}) \end{cases}$

(iii) $\begin{cases} {}^{4}_{\Lambda\Lambda}\mathrm{H} \longrightarrow {}^{4}_{\Lambda}\mathrm{He} + \pi^- & (\sim 116\ \mathrm{MeV/c}) \\ \qquad\qquad \downarrow & \\ \qquad\qquad {}^{3}\mathrm{He} + \mathrm{p} + \pi^- & (\sim 97\ \mathrm{MeV/c}) \end{cases}$

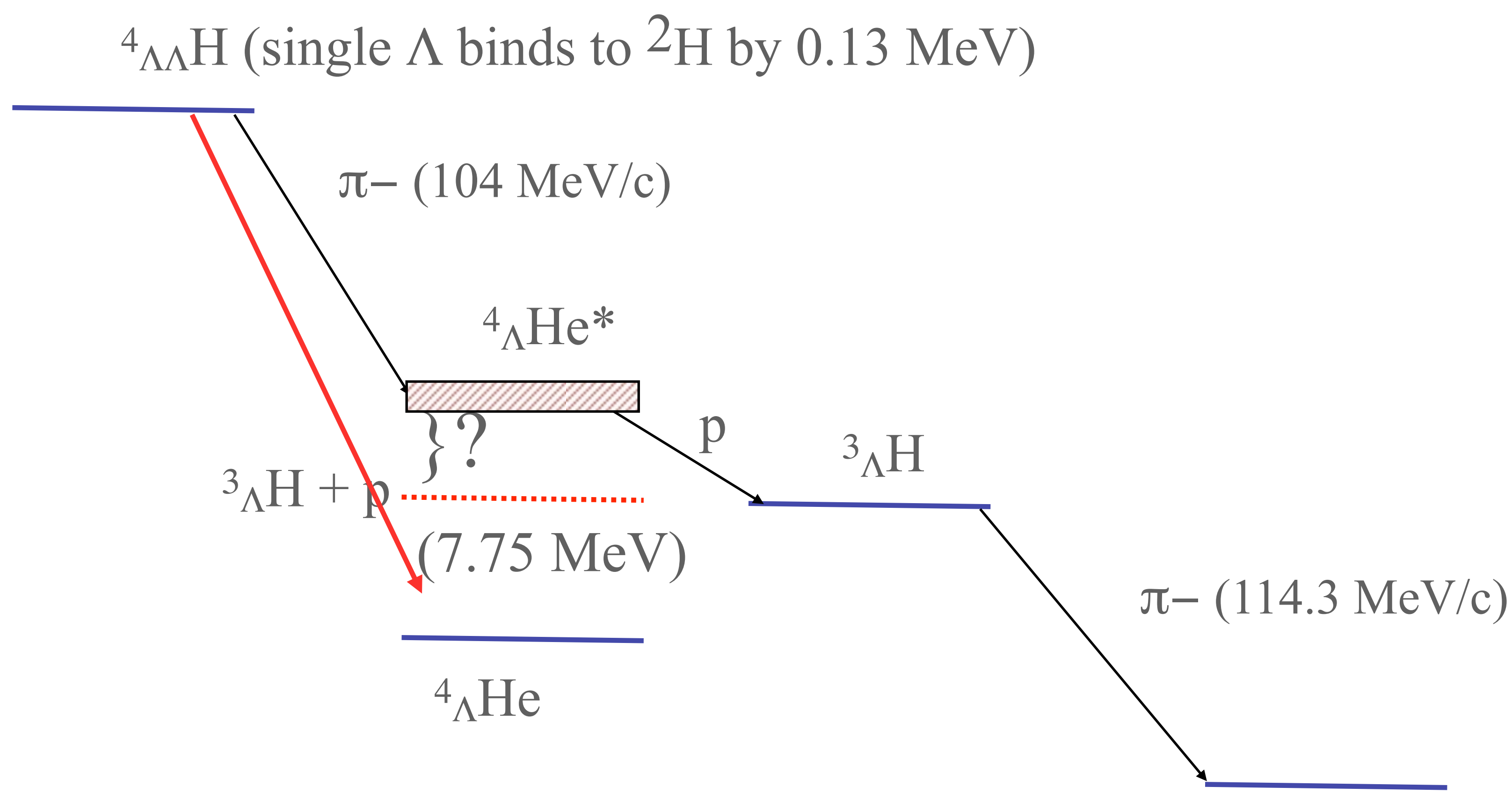
(iv) $\begin{cases} {}^{4}_{\Lambda\Lambda}\mathrm{H} \longrightarrow {}^{4}_{\Lambda}\mathrm{He}^* + \pi^- & (\sim 103\ \mathrm{MeV/c}) \\ \qquad\qquad \downarrow & \\ \qquad\qquad {}^{3}_{\Lambda}\mathrm{H} + \mathrm{p} & \\ \qquad\qquad \downarrow & \\ \qquad\qquad {}^{3}\mathrm{He} + \pi^- & (114.3\ \mathrm{MeV/c}) \end{cases}$

Phys. Rev. Lett. 87, 132504 (2001)

Candidate for ΛΛ hypernucleus decay

new interpretation by S. Randeniya: $^{7}_{\Lambda\Lambda}\mathrm{He}$

Suggested decay mode of $^4{}_{\Lambda\Lambda}H$ and limits on $\Delta B_{\Lambda\Lambda}$



$^4{}_{\Lambda}$He excitation(MeV)	$\Delta B_{\Lambda\Lambda}$(MeV)
7.75	1.8

Search for two body decay mode $^4{}_{\Lambda\Lambda}H \rightarrow {}^4{}_{\Lambda}He(1^+) + \pi^-$

Spectroscopic Study of Ξ-Hypernucleus, $^{12}_{\Xi}Be$, via the $^{12}C(K^-,K^+)$ Reaction

E05

T. Nagae et al.

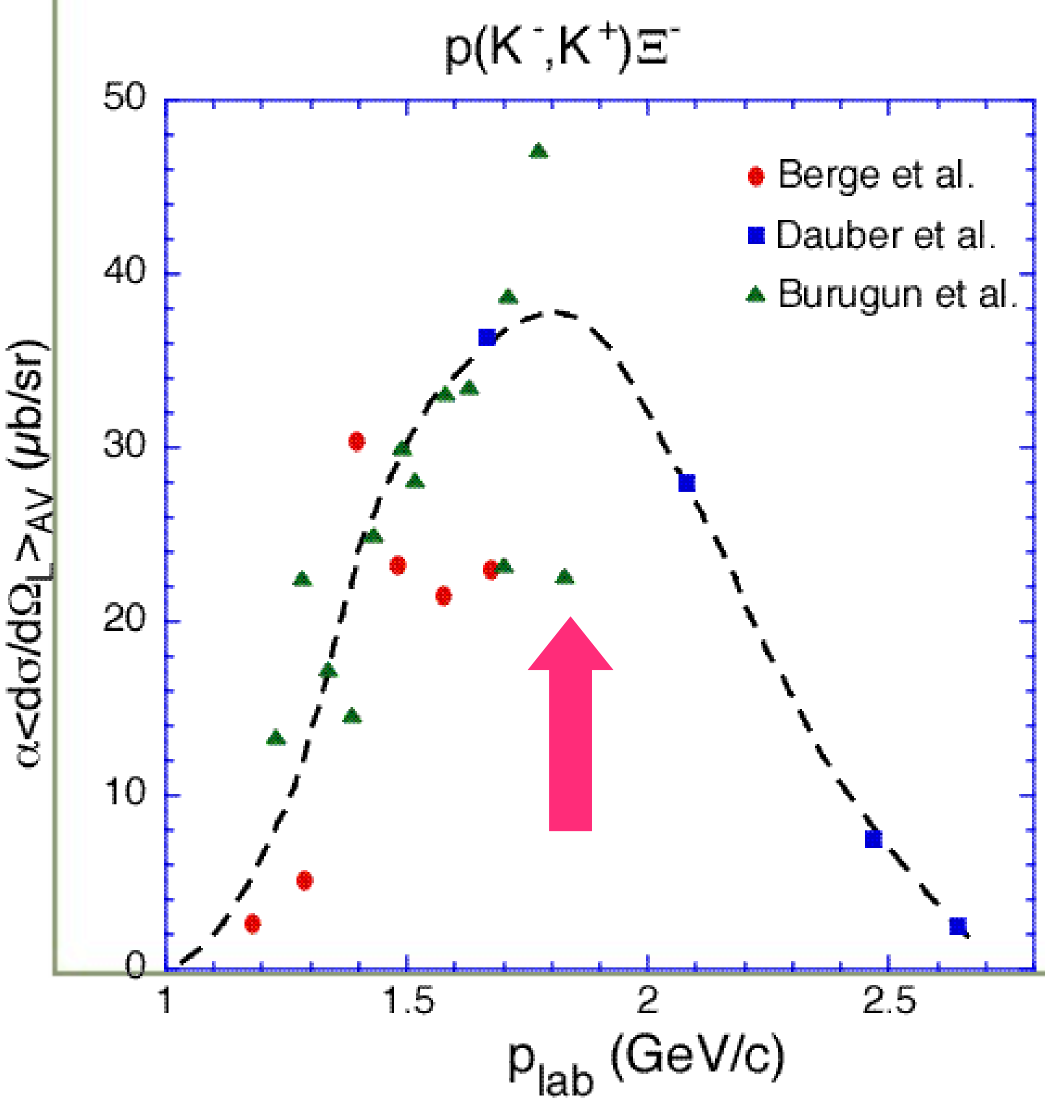
- Discovery of Ξ-hypernuclei
- Measurement of Ξ-nucleus potential depth and width of $^{12}_{\Xi}Be$
- Beam: K^- @ 1.8 GeV/c, 1.4×10^6/spill
- CH_2 ~2 g/cm^2 : 2 weeks for tuning and calibrations
- ^{12}C 5.4 g/cm^2 : 4 weeks
- Setup:K1.8 & SKS+

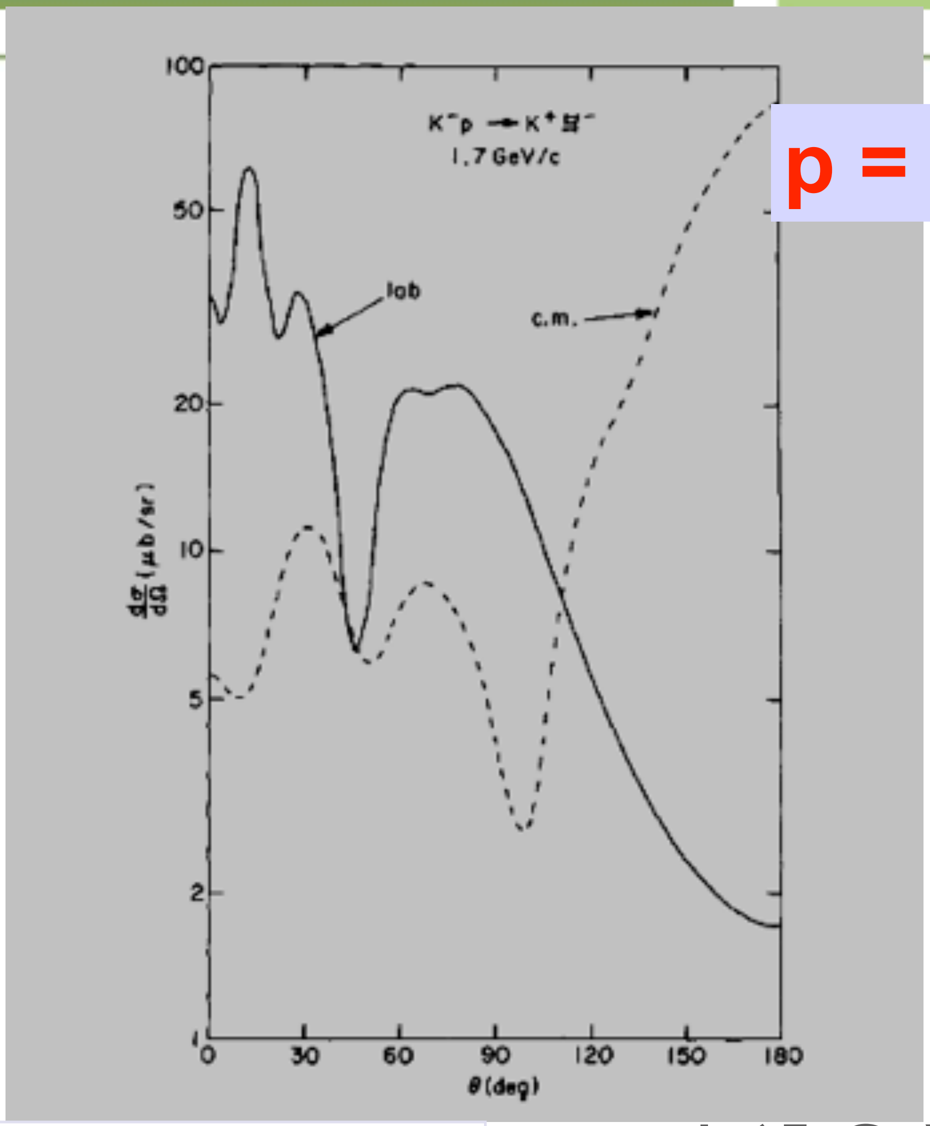
Unique experiment at J-PARC :

No other place can do this experiment !

K- p → K+ Ξ- Cross Section

C.B.Dover & A.Gal
Ann. of Phys. 146(1983)309





p = 1.7GeV/c

T.Iijima et al.
NPA546(1992)588

p = 1.65 GeV/c
$1.7° < \theta_{lab} < 13.6°$
35±4 μb/sr

Purpose of the experiment

- First Spectroscopic Study of S=-2 systems in (K^-,K^+) reaction
  - Ξ-hypernuclei → double-Λ hypernuclei
  - Ξp-ΛΛ mixing
  - First step for multi-strangeness baryon systems
- ΞN Interactions: almost no information
  - Attractive or repulsive ? → potential depth
  - Ξp→ΛΛ conversion ? → conversion width
  - Isospin dependence ? → Lane term($\tau_\Xi \bullet \tau_C / A$)

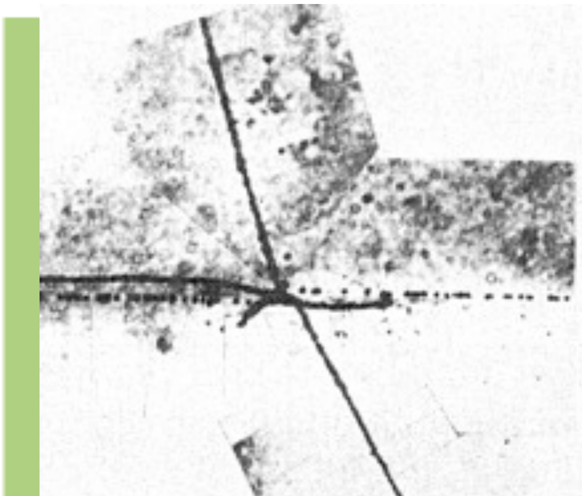
Information on S=-2

- Double Λ hypernuclei
  - Two old emulsion events(1963,1966)
  - One recent event in KEK E176(1991)
  - Nagara event in KEK E373(2001)
    - Binding energy of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ $\Delta B_{\Lambda\Lambda}$ =0.67±0.17 MeV
    - m_H>2223.7 MeV/c^2

H.Takahashi et al., PRL 87 (2001) 212502

- Ξ hypernuclei ?

M.Danysz et al., PRL.11(1963)29;



$\Delta B_{\Lambda\Lambda}$ = 4.3±0.4 MeV

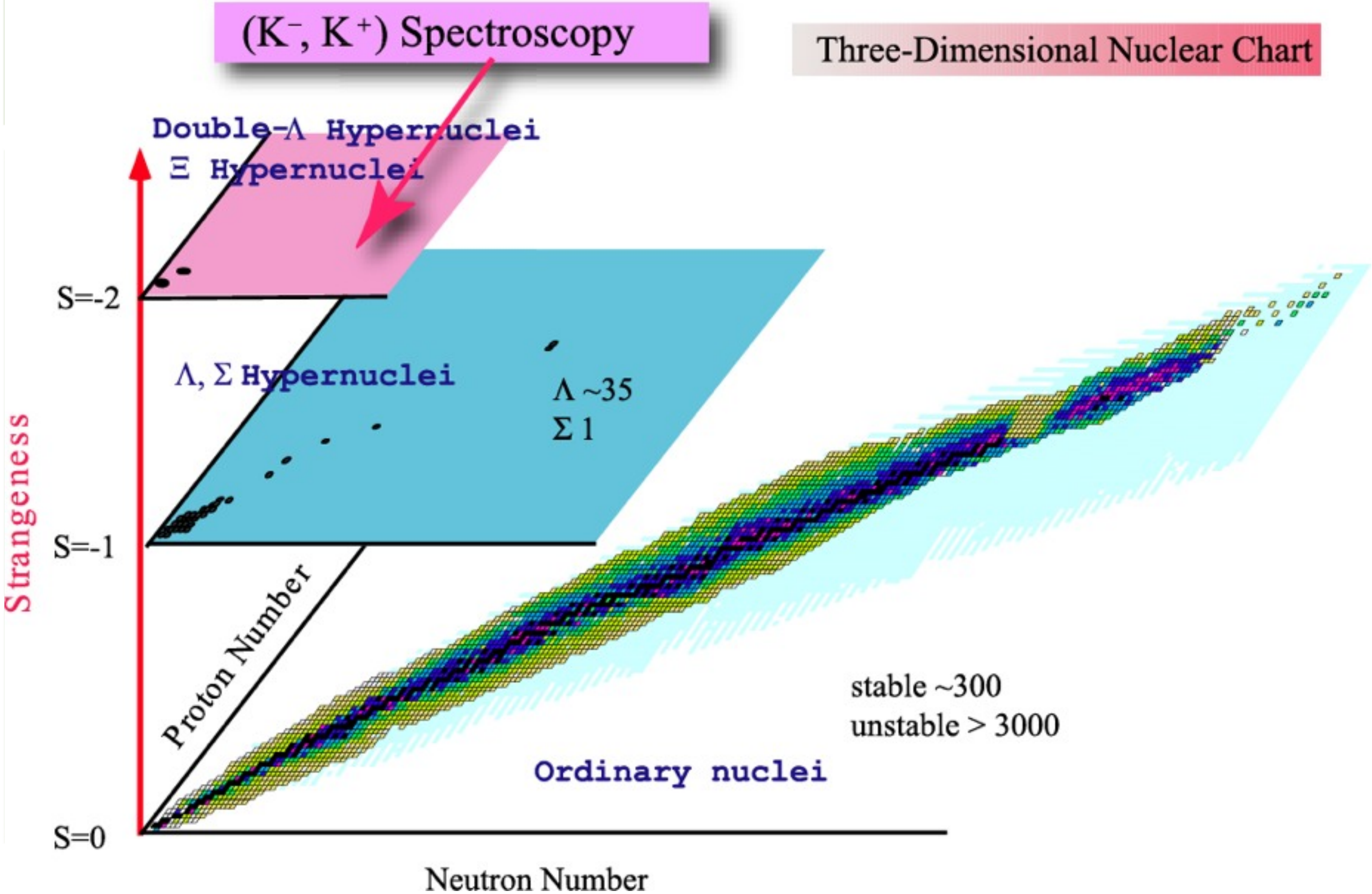
D.J.Prowse, PRL.17(1966)782

$\Delta B_{\Lambda\Lambda}$ = 4.6±0.5 MeV

S.Aoki et al, PTP.85(1991)1287

$\Delta B_{\Lambda\Lambda} = 4.9 \pm^{0.7}_{0.8}$ MeV

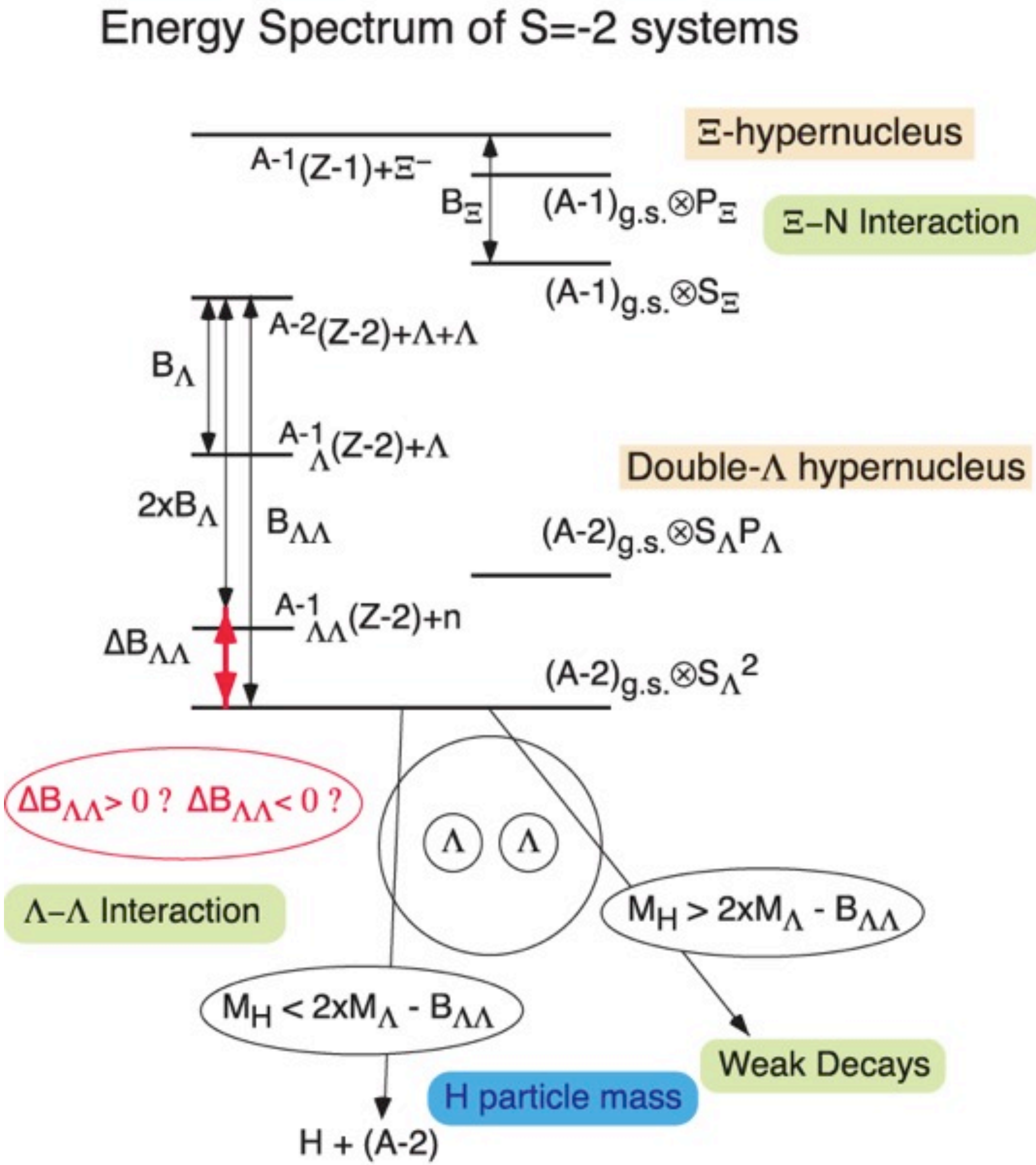
Strangeness Nuclear Physics

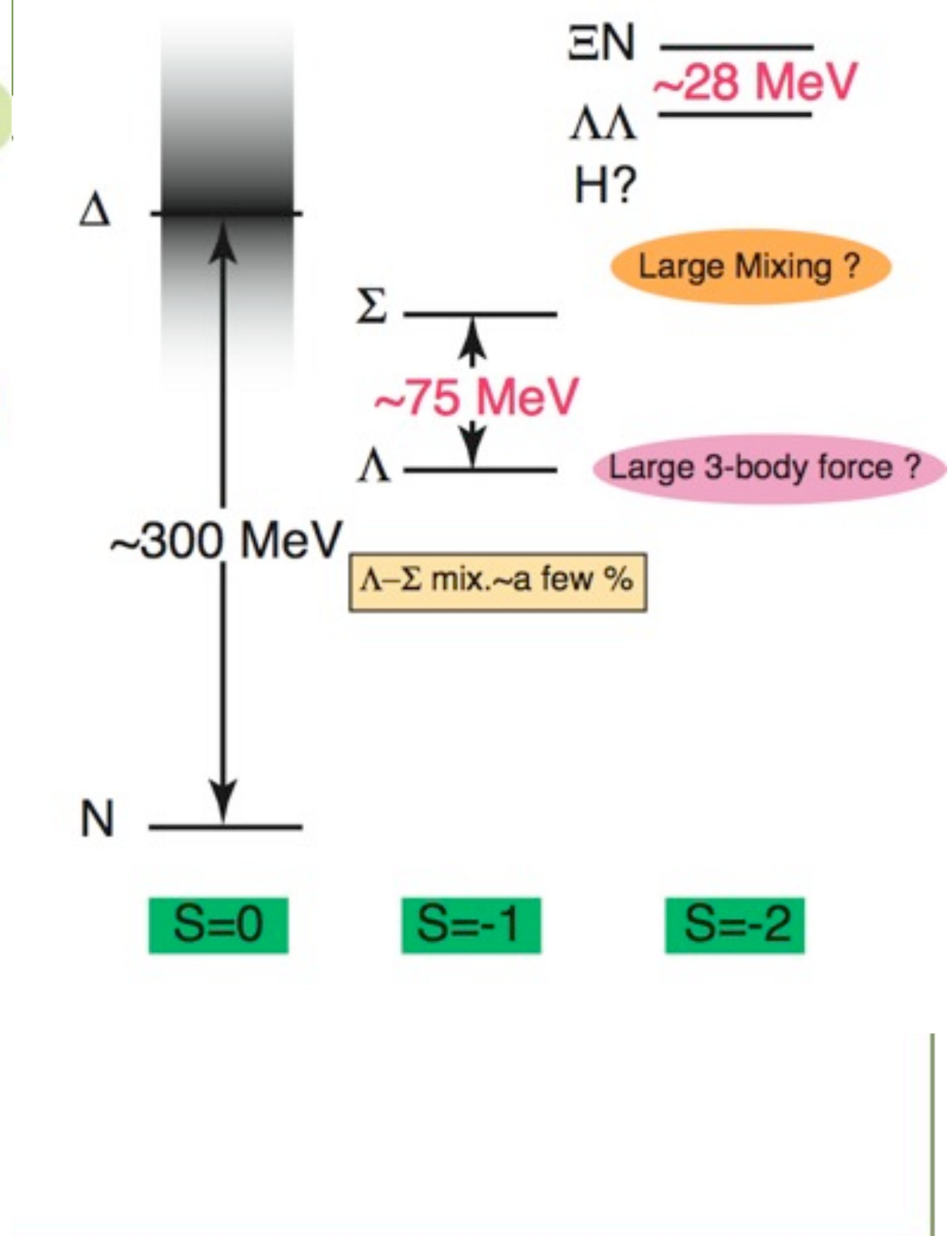


Purpose of the experiment - cont.

- First Spectroscopic Study of S=-2 systems in (K^-,K^+) reaction
  - Ξ-hypernuclei → double-Λ hypernuclei
  - Ξp-ΛΛ mixing
  - First step for multi-strangeness baryon systems
- ΞN Interactions: almost no information
  - Attractive or repulsive ? → potential depth
  - Ξp→ΛΛ conversion ? → conversion width
  - Isospin dependence ? → Lane term($\tau_\Xi \cdot \tau_C / A$)

S=-2 Baryon Systems





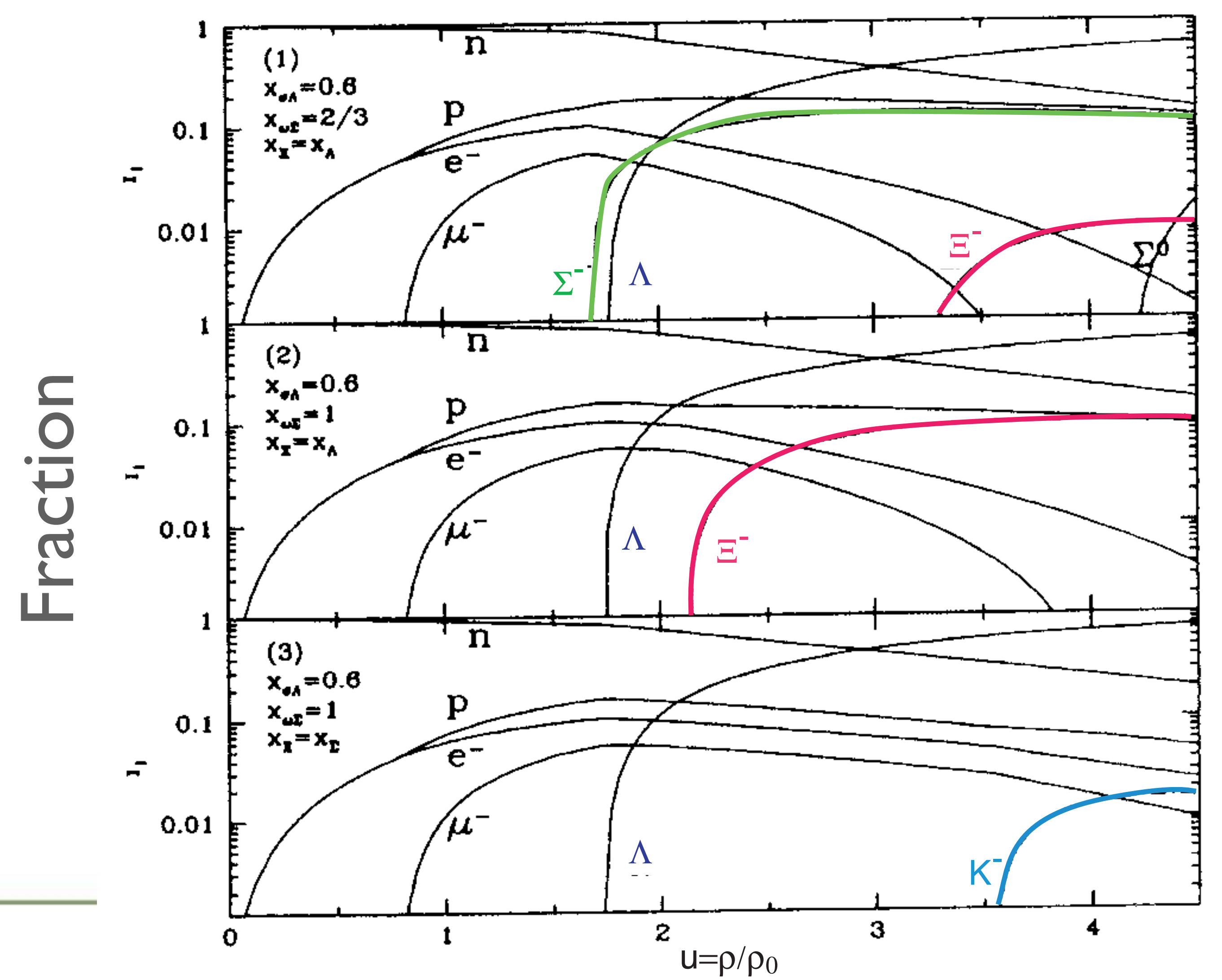
Purpose of the experiment - cont.

- First Spectroscopic Study of S=-2 systems in (K^-,K^+) reaction
  - Ξ-hypernuclei → double-Λ hypernuclei
  - Ξp-ΛΛ mixing
  - First step for multi-strangeness baryon systems
- ΞN Interactions: almost no information
  - Attractive or repulsive ? → potential depth
  - Ξp→ΛΛ conversion ? → conversion width
  - Isospin dependence ? → Lane term($\tau_\Xi \bullet \tau_C / A$)

Ξ hypernuclei potential ?

- Λ, Σ^-, Ξ^-, K^- in Neutron Star Core ?

- Chemical Potential: $$\mu_B = m_B + \frac{k_F^2}{2m_B} + U(k_F)$$



$U_\Sigma < 0$, $U_\Xi < 0$

$U_\Sigma > 0$, $U_\Xi < 0$

$U_\Sigma > 0$, $U_\Xi > 0$

Purpose of the experiment - cont.

- First Spectroscopic Study of S=-2 systems in (K^-,K^+) reaction
  - Ξ-hypernuclei → double-Λ hypernuclei
  - Ξp-ΛΛ mixing
  - First step for multi-strangeness baryon systems
- ΞN Interactions: almost no information
  - Attractive or repulsive ? → potential depth
  - Ξp→ΛΛ conversion ? → conversion width
  - Isospin dependence ? → Lane term$(\tau_\Xi \bullet \tau_C / A)$

U_Ξ and Partial Wave Contributions in Nuclear Matter

Model	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ_Ξ
NHC-D	0 1	−2.6 −3.2	0.1 −2.3	−2.1 −3.0	−0.2 −0.0	−0.7 −3.1	−1.9 −6.3	−25.2	0.9
Ehime	0 1	−0.9 −1.3	−0.5 −8.6	−1.0 −0.8	0.3 −0.4	−2.4 −1.7	−0.7 −4.2	−22.3	0.5
ESC04d*	0 1	6.3 7.2	−18.4 −1.7	1.2 −0.8	1.5 −0.5	−1.3 −1.2	−1.9 −2.8	−12.1	12.7

- OBE (NHC-D, Ehime)
  - odd-state attraction
  - strong A-dependence of V_Ξ
- ESC04d*
  - strong attraction of $^3S_1$(T=0)

Hyperon-Nucleus Potentials

	Central	Spin-Orbit	Imaginary
ΛN	$V^{\Lambda} \sim 2/3 \times V^{N}$ ~30 MeV	very small	—
ΛΛ	weak attraction $\Delta B_{\Lambda\Lambda} \sim 1$ MeV		
ΣN	Strongly Repulsive, Large Isospin-dep.	$Vso^{\Sigma} \sim Vso^{N}$	Large
ΞN	Weakly Attractive, Isospin-dep.: Large or Small ??	$Vso^{\Xi} \ll -Vso^{N}$??	Small or Large ??

Previous Measurements on $^{12}C(K^-,K^+)$ BNL-AGS E885

P_K=1.8 GeV/c

ΔM=9.9 MeV/c^2 (FWHM) for $p(K^-,K^+)\Xi^-$

P.Khaustov et al, PRC61(2000)0546

$-20 < E_\Xi < 0$ MeV

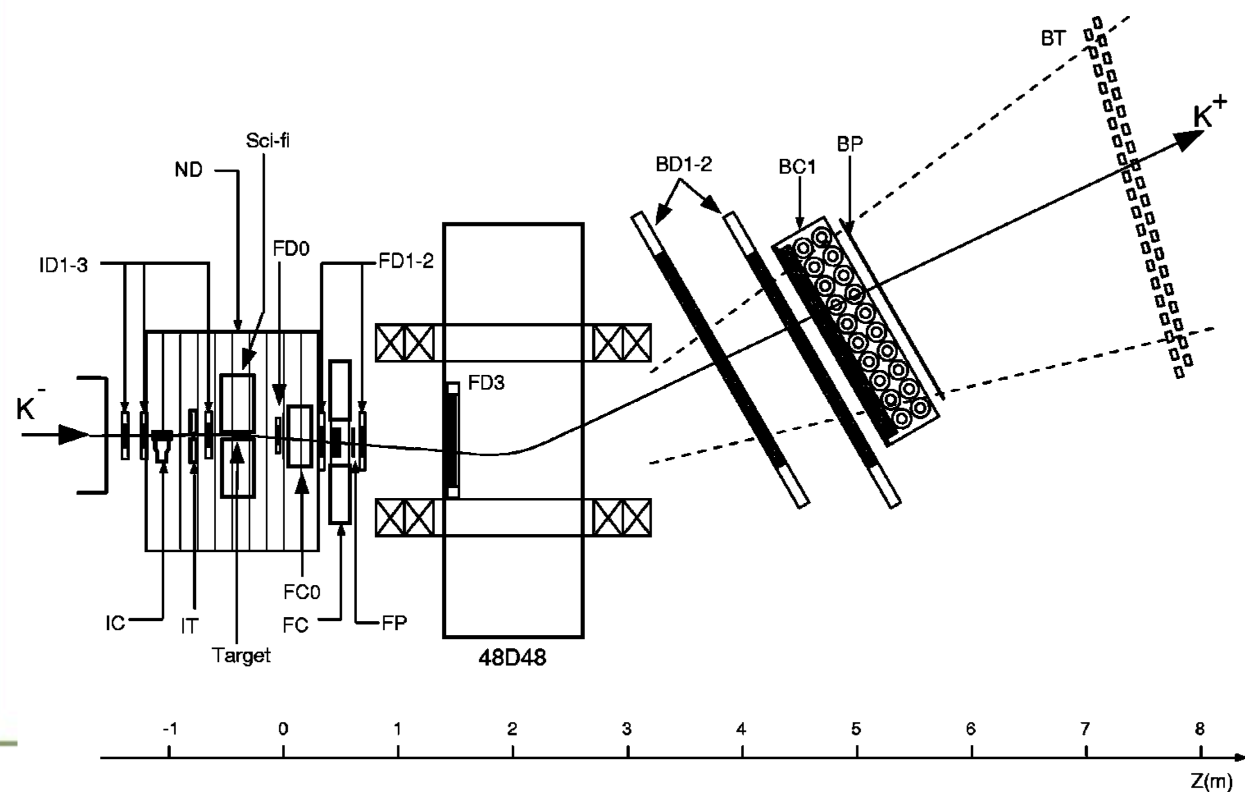
89±14 nb/sr $\theta < 8°$

42± 5 nb/sr $\theta < 14°$

PHYSICAL REVIEW C **61** 054603

Evidence !? V_Ξ = -14 MeV

P. KHAUSTOV *et al.*



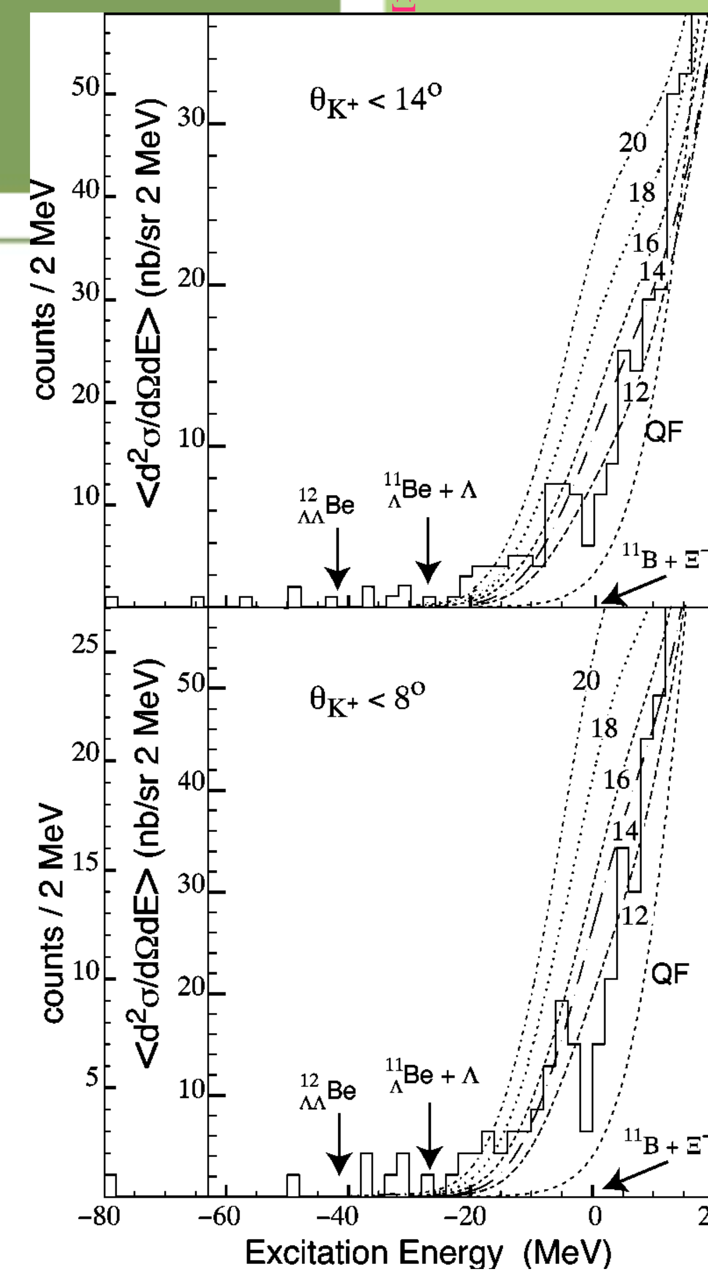
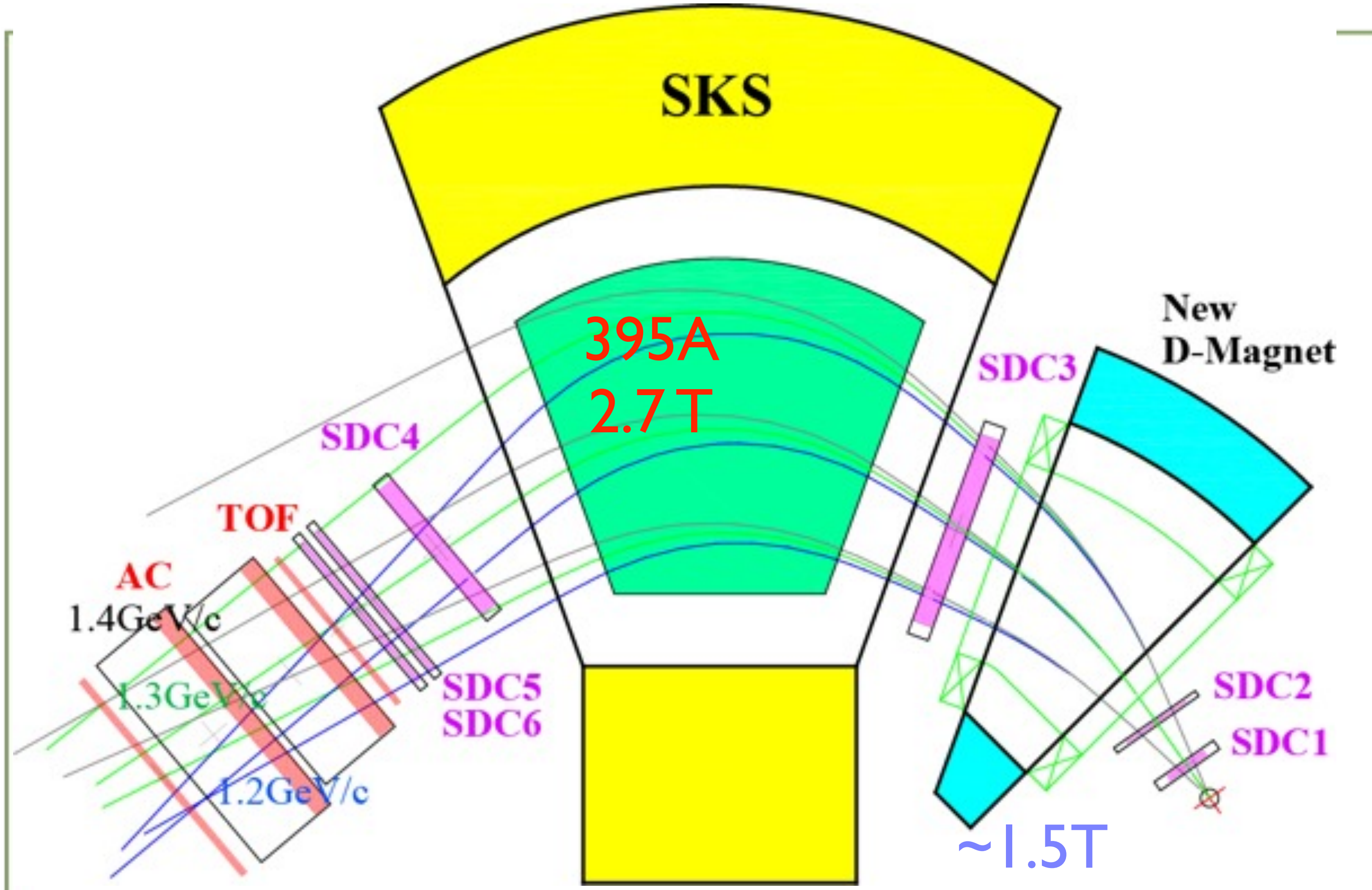


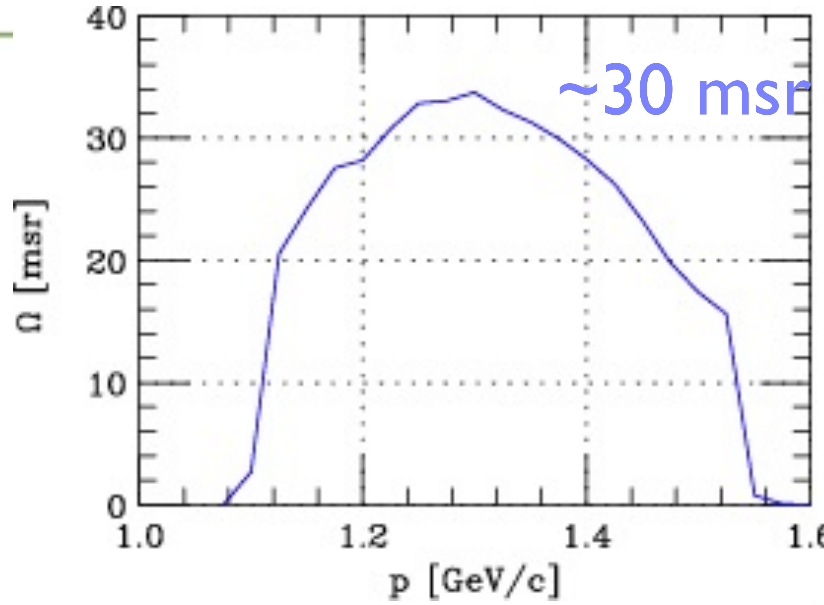
FIG. 6. Excitation-energy spectra from E885 for $^{12}C(K^-,K^+)X$ for $\theta_{K^+}<14°$ (top figure) and $\theta_{K^+}<8°$ (bottom figure) along with $^{12}_{\Xi}$Be production theoretical curves for $V_{0\Xi}$ equal to 20, 18, 16, 14, and 12 MeV. The results of a quasifree Ξ production calculation are also shown (curve QF). The expected location of the ground state of $^{12}_{\Lambda\Lambda}$Be and the thresholds for $^{11}_{\Lambda}$Be+Λ and ^{11}B+Ξ^- production are indicated with arrows.

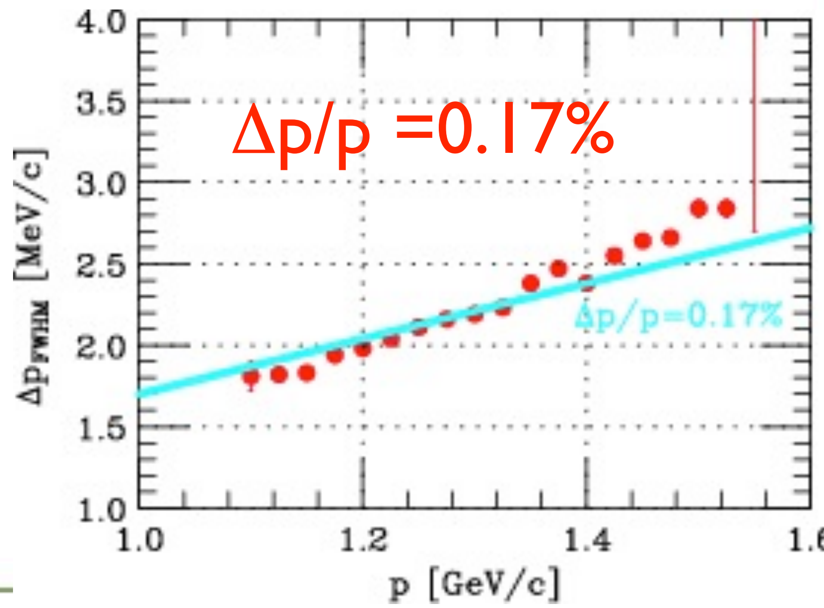
Experimental Setup

- K1.8 beam line
  - Double Electro-static Separators→$K^-/\pi^-=6.9$
  - High Intensity: 1.4×10^6 K^-/spill @ 30 GeV(9μA)
  - Beam Spectrometer (QQDQQ): $\Delta p/p=3.3\times10^{-4}$ (FWHM)
- SKS+ spectrometer
  - A new dipole magnet in front of SKS
  - Acceptance: 30 msr
  - Momentum Resolution: $\Delta p/p=1.7\times10^{-3}$(FWHM)
  - New simple cryogenics system

SKS+ Spectrometer

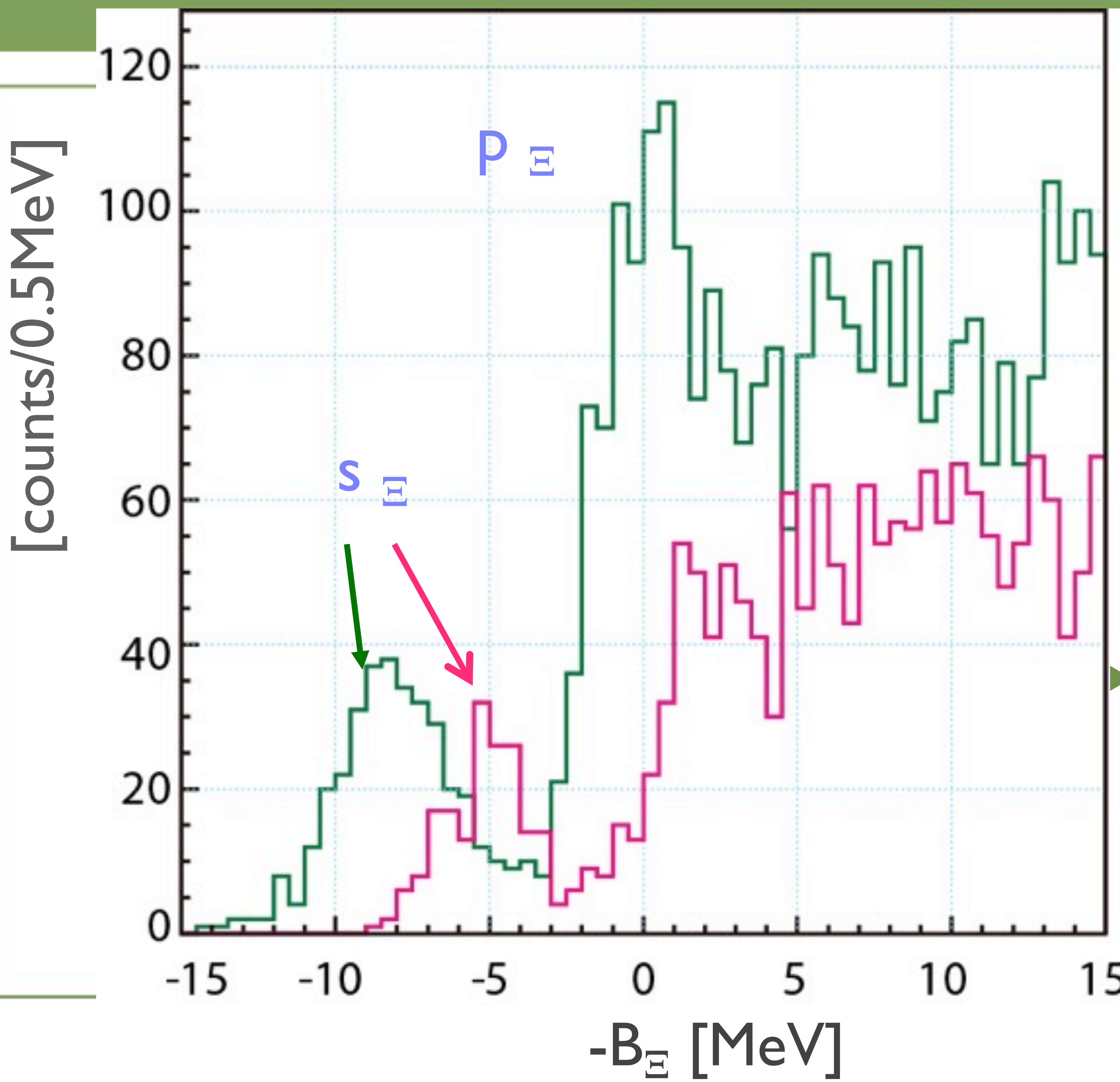






- 95°total bend
- ~7m flight path
- Δx=0.3 mm (RMS)

Expected $^{12}{}_{\Xi}$Be Spectrum



$\Delta E_{meas.} < 3$ MeV_{FWHM}

V_{Ξ}= -20MeV

V_{Ξ}= -14MeV

- Precision:
  - Peak Position: 0.1 - 0.3 MeV
  - Width: 0.2 - 1 MeV

Summary

- J-PARC Construction: 2001 ~ 2009
  - Beam commissioning: LINAC(Oct., 06), RCS (Sep., 07), MR(May, 08)
  - Beam from MR: Jan., 09
- Day-1 Experiments in preparation
  - Ξ hypernuclei
  - Deeply-bound Kaonic nuclei
  - Hypernuclear gamma-ray spectroscopy
  - etc.