クォークと原子核

クォークとレプトン　点状粒子

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

物質を構成するのは、u, d, e, (ν_e)

低質量ハドロン

- バリオン
  - ハイペロン（Λ、Σ、Ξ）
    - ストレンジネス量子数を持つバリオン

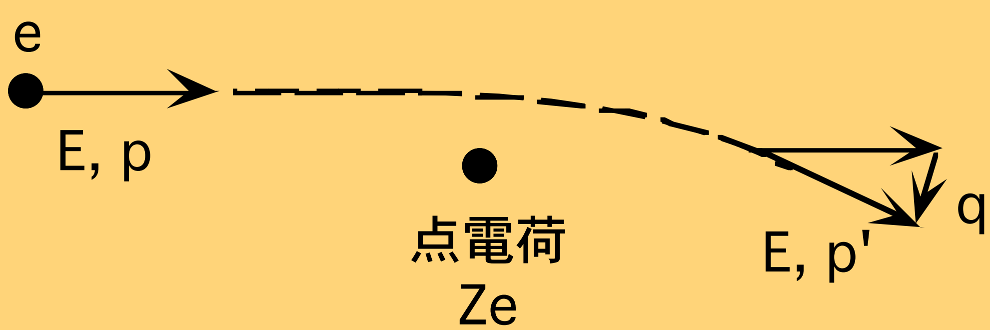
S		Lifetims[s]	Main Decay channels	Mass [MeV/c^2]
0	P n	Stable? 887	$pe^-\nu_e$(100%)	938.3 939.6
−1	Λ	$2.63\cdot10^{-10}$	$p\pi^-$(64%),$n\pi$(36%)	1115.7
−1	$\Sigma^\pm$ Σ^0 Σ^-	$0.8\cdot10^{-10}$ $7.4\cdot10^{-20}$ $1.48\cdot10^{-10}$	$p\pi^0$(52%),$n\pi^+$(48%) $\Lambda\gamma$(~100%) $n\pi^-$(99.8%)	1189.4 1192.6 1197.4
−2	Ξ^0 Ξ^-	$2.9\cdot10^{-10}$ $1.64\cdot10^{-10}$	$\Lambda\pi^0$(~100%) $\Lambda\pi^-$(~100%)	1315 1321

- メソン（擬スカラ、ベクトル）

	Lifetims[s]	Main Decay channels	Mass [MeV/c^2]
$\pi^\pm$ π^0	$2.6\cdot10^{-8}$ $8.4\cdot10^{-17}$	$\mu^\pm\nu_\mu$(~100%) $e^\pm\nu_e$(1.2x10^{-4})	139.6 135.0
$K^\pm$ K_S K_L	$1.2\cdot10^{-8}$ $8.9\cdot10^{-11}$ $5.2\cdot10^{-8}$	$\mu^\pm\nu_\mu$(64%) 2π(~100%) 3π(34%)	493.6 497.7 497.7
η η'	$5.5\cdot10^{-19}$ $3.3\cdot10^{-21}$	3π(56%),2γ(39%) ππη(65%),ργ(30%)	547.4 957.8

	Lifetims[s]	Main Decay channels	Mass [MeV/c^2]
ρ	$4.3\cdot10^{-24}$	2π(~100%)	769.9
$K^\pm$	$1.3\cdot10^{-24}$	Kπ(~100%)	896.1(0) 891.6(-)
ω	$7.8\cdot10^{-23}$	3π(89%)	781.9
ϕ	$1.5\cdot10^{-22}$	2K(84%),ρπ(13%)	1014.9

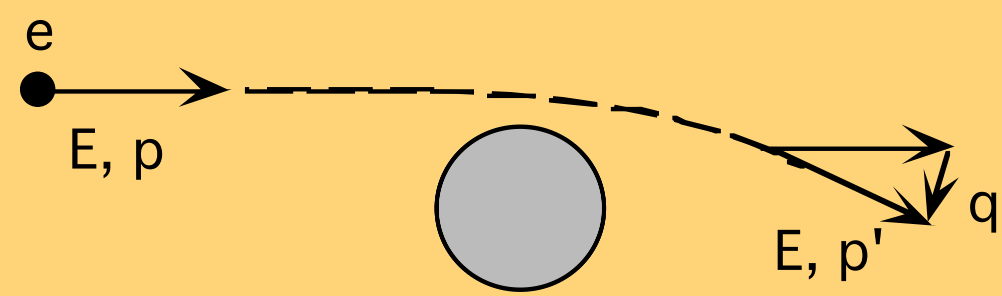
電子散乱の実験



$$\frac{d\sigma}{d\Omega} = \frac{4(Ze^2)^2E^2}{q^4}\left(1 - \frac{q^2}{4E^2}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}$$

Rutherford

Effect of electron helicity



拡がりのある電荷

Ze

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \left|F(q)\right|^2$$

$$F(q) = \int e^{iqr}\ \rho(r)dr$$

$\rho(r)$: 電荷分布

電子と陽子の散乱

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left|F\left(q^2\right)\right|^2$$

ローゼンブルースの公式

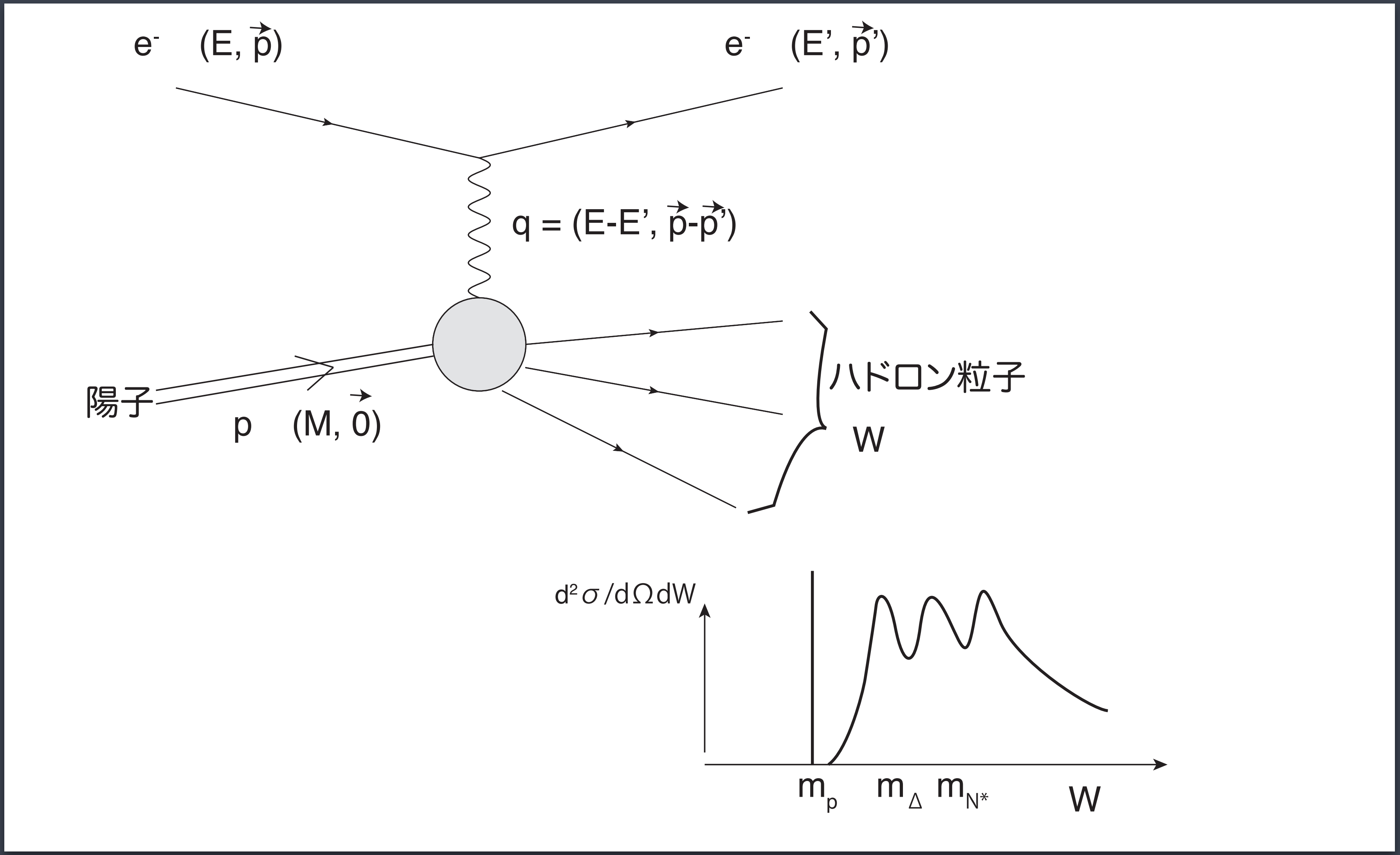
$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left[\frac{G_E{}^2(q^2)+\tau G_M{}^2(q^2)}{1+\tau} + 2\tau G_M{}^2(q^2)tan^2\frac{\theta}{2}\right], \tau = \frac{q^2}{4Mc^2}$$

$$G_E\left(q^2\right) = \frac{G_M\left(q^2\right)}{2.79} = \left(1+\frac{q^2}{0.71(GeV/c)^2}\right)^{-2}$$

電気構造因子
磁気構造因子

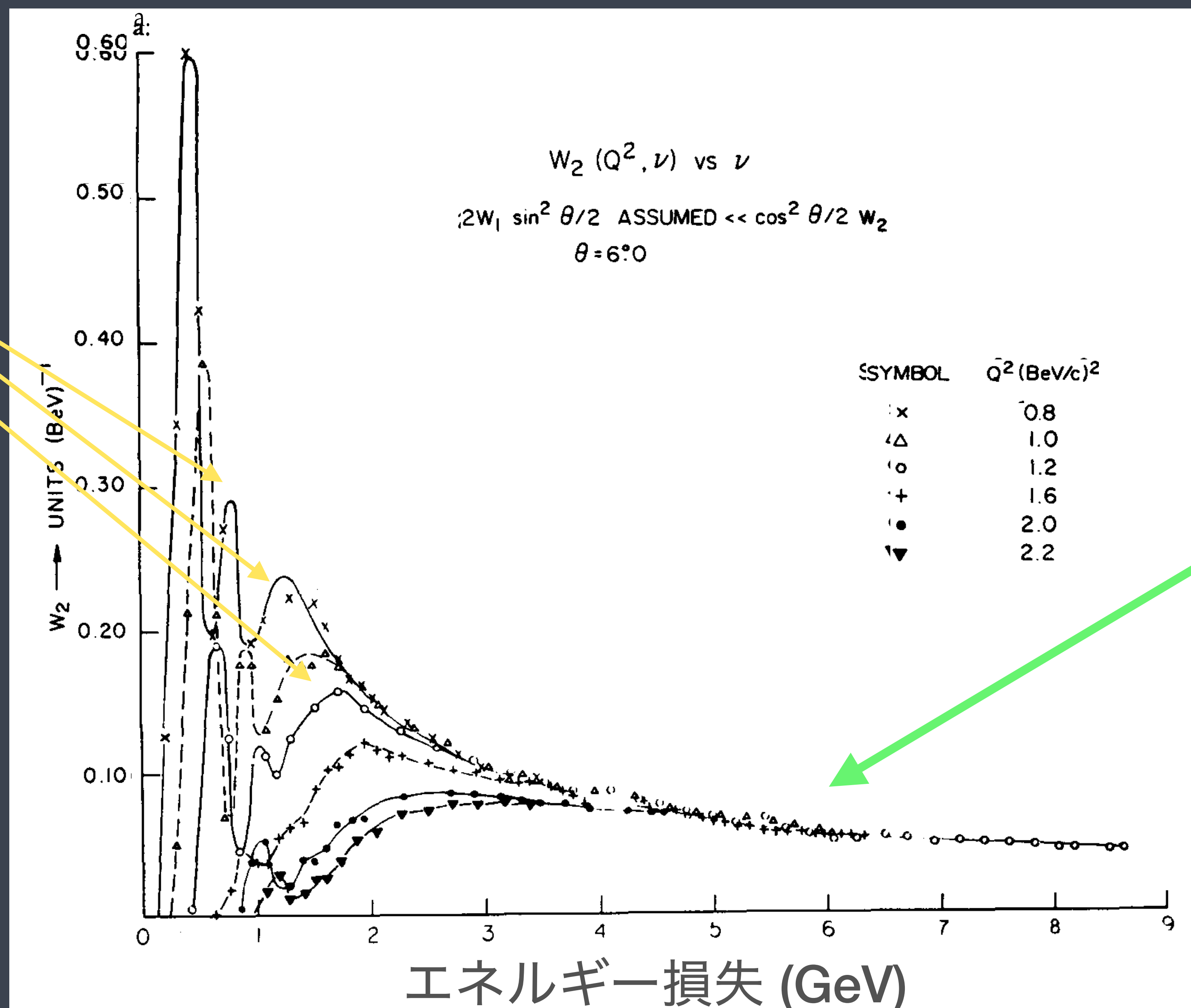
陽子の平均２乗半径=0.81 fm

非弾性散乱の運動学



電子散乱のデータ: 高エネルギー

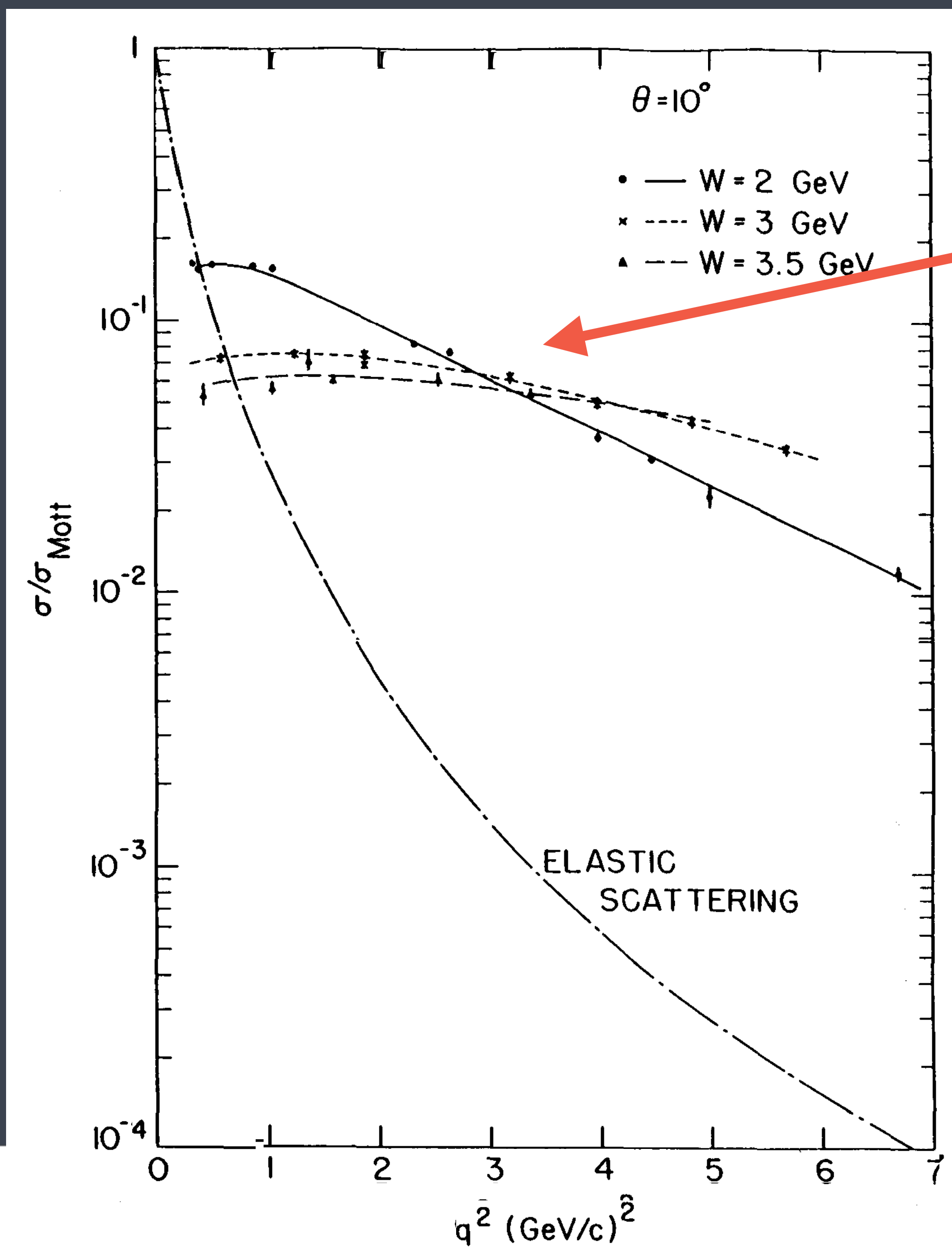
核子の
励起状態
Δ, N*

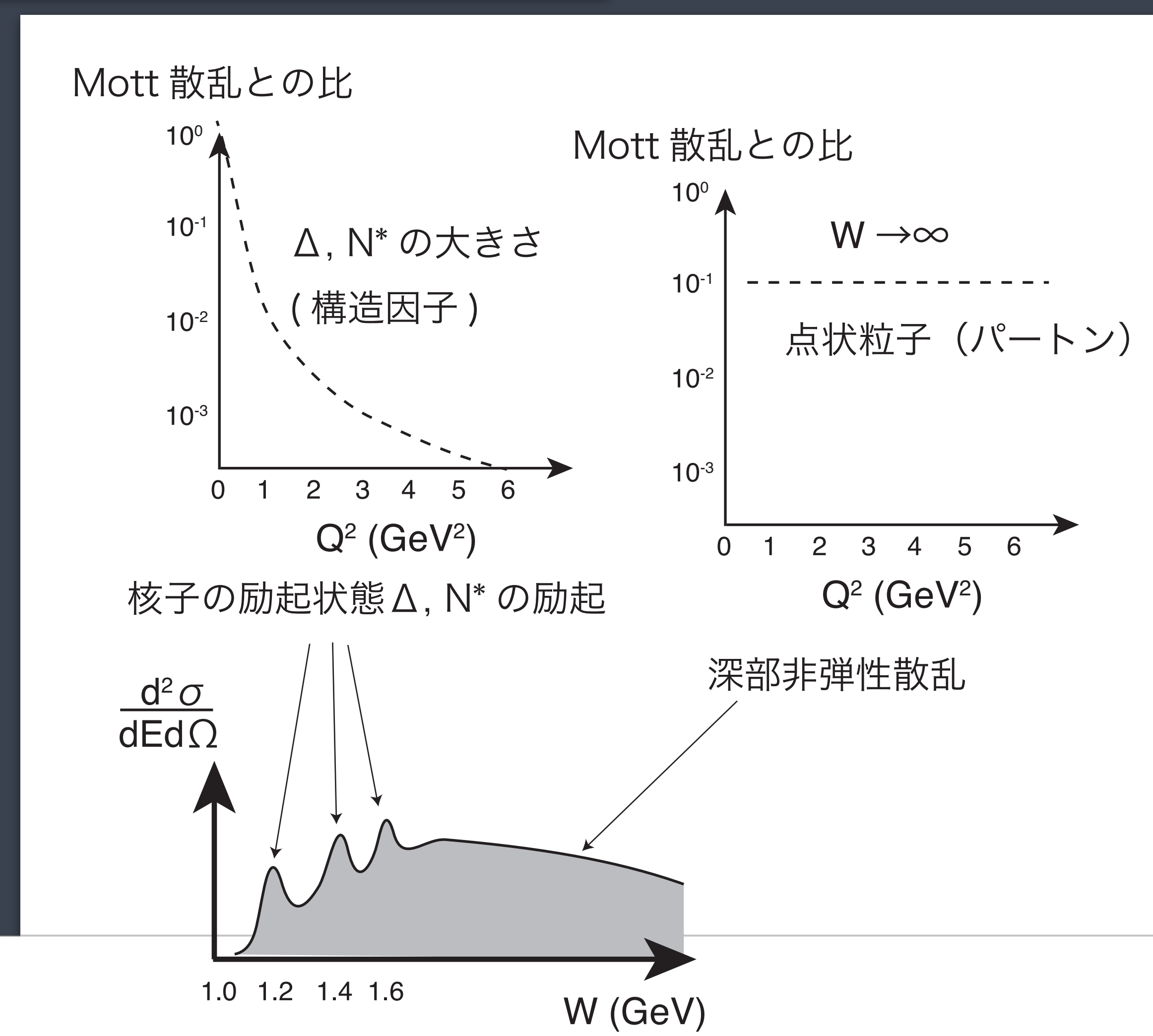


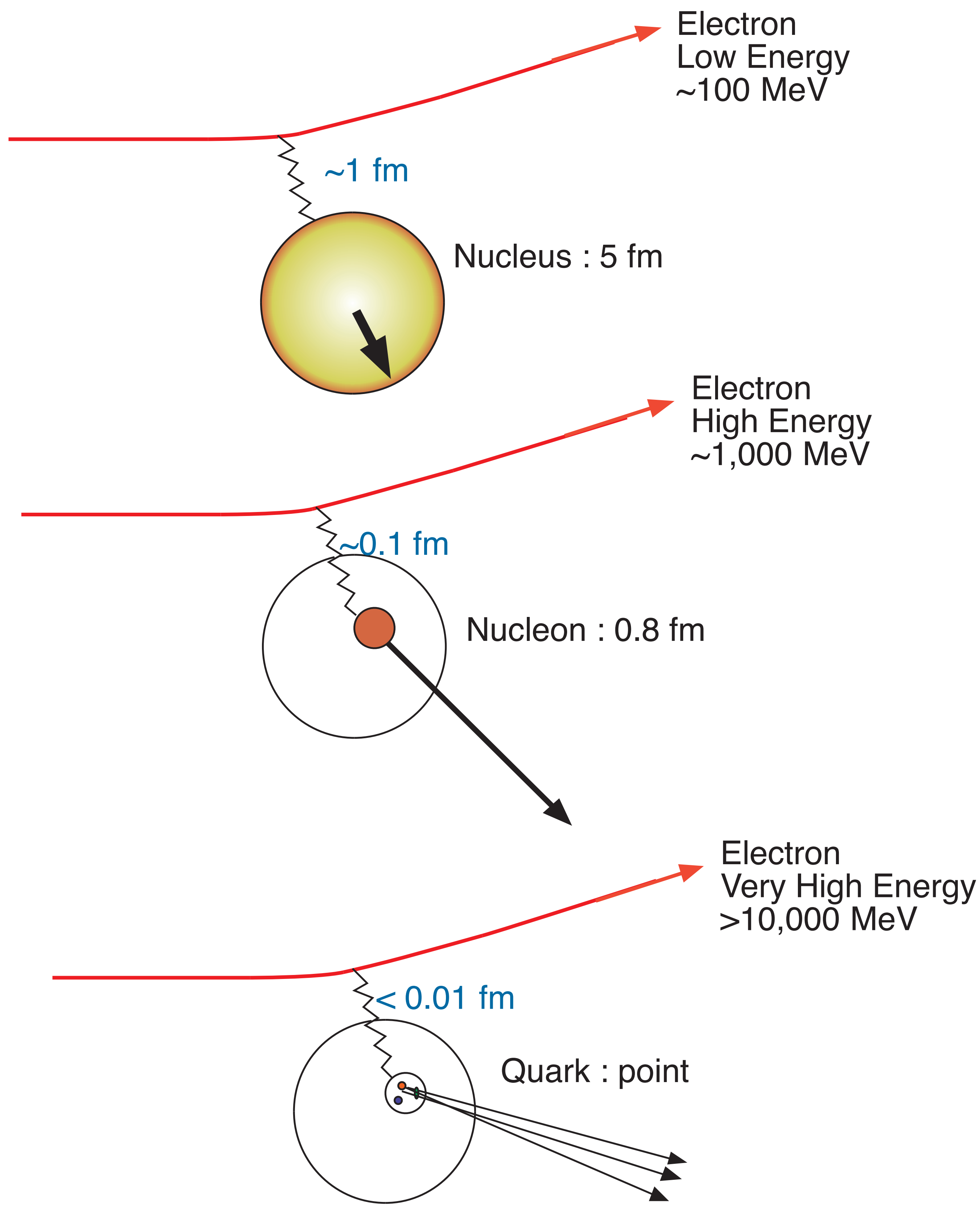
Deep
Inelastic
Sattering
(深部非弾性
散乱)

電子散乱のデータ (つづき)

点電荷との散乱
(パートンの発見)

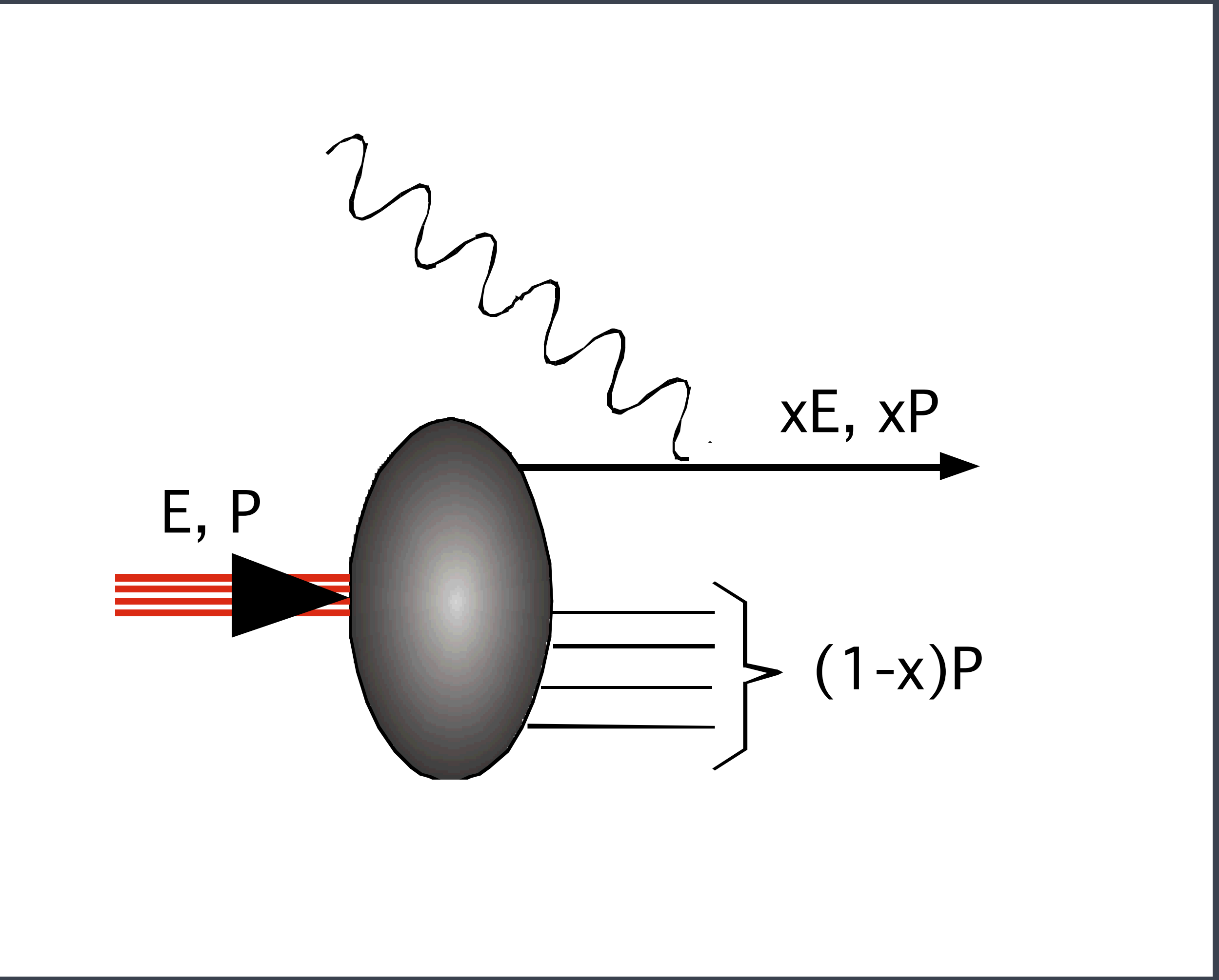


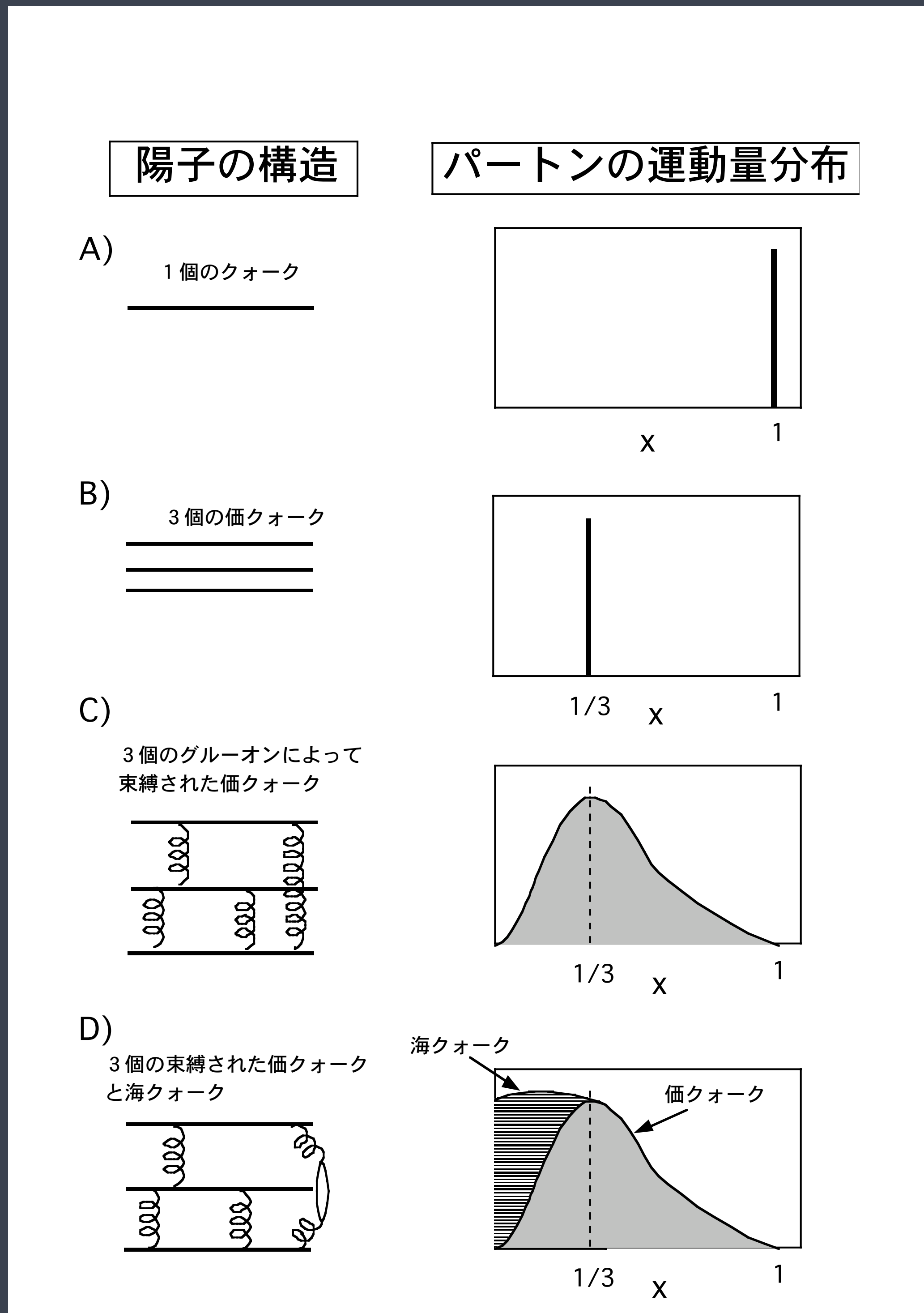



Electron
Low Energy
~100 MeV
~1 fm
Nucleus : 5 fm
Electron
High Energy
~1,000 MeV
~0.1 fm
Nucleon : 0.8 fm
Electron
Very High Energy
>10,000 MeV
< 0.01 fm
Quark : point

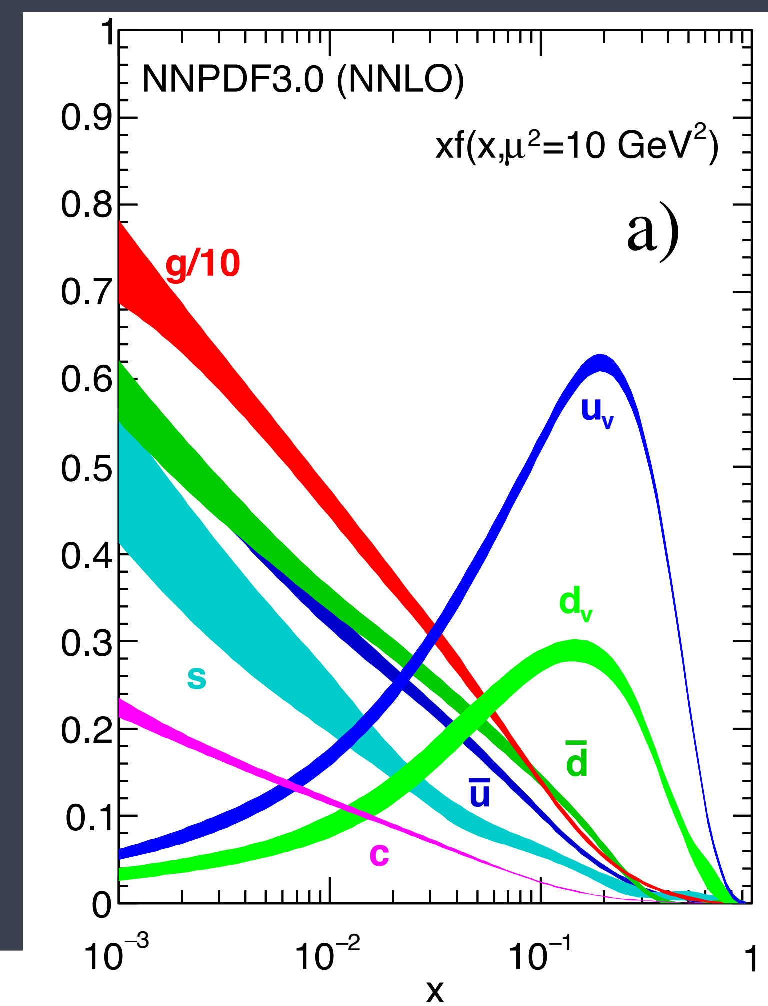
パートンモデル

	陽子	パートン
エネルギー	E	xE
運動量	p_L	xp_L
	$p_T=0$	$p_T=0$
質量	M	xM





全クォークが担う運動量〜半分
残りの半分はグルーオンが担う



パートン=クォーク？

- スピン1/2 : Callan-Gross関係式

  $2xF_1=F_2$

$$K_0 = F_2/(xF_1) - 1$$

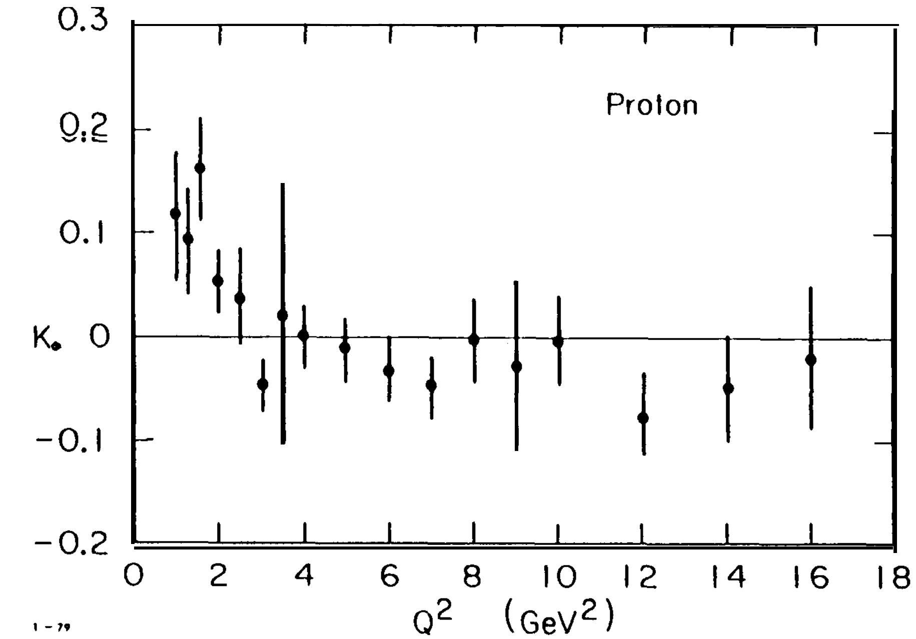


Fig. 18. The Callan-Gross relation: K_0 vs q^2, where K_0 is defined in the text. These results established the spin of the partons as 1/2.

- 分数電荷: -1/3e, +2/3e

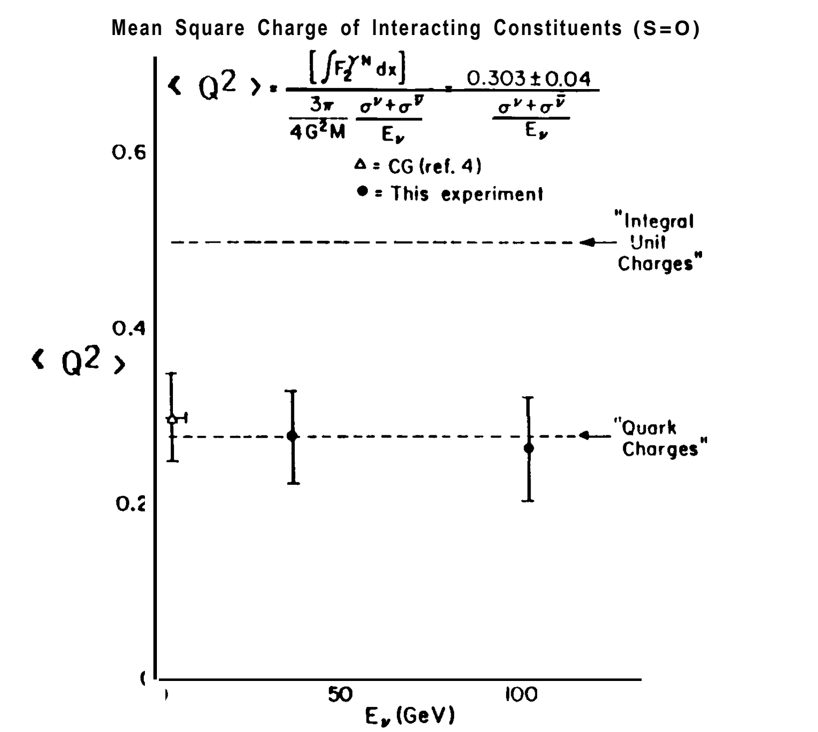
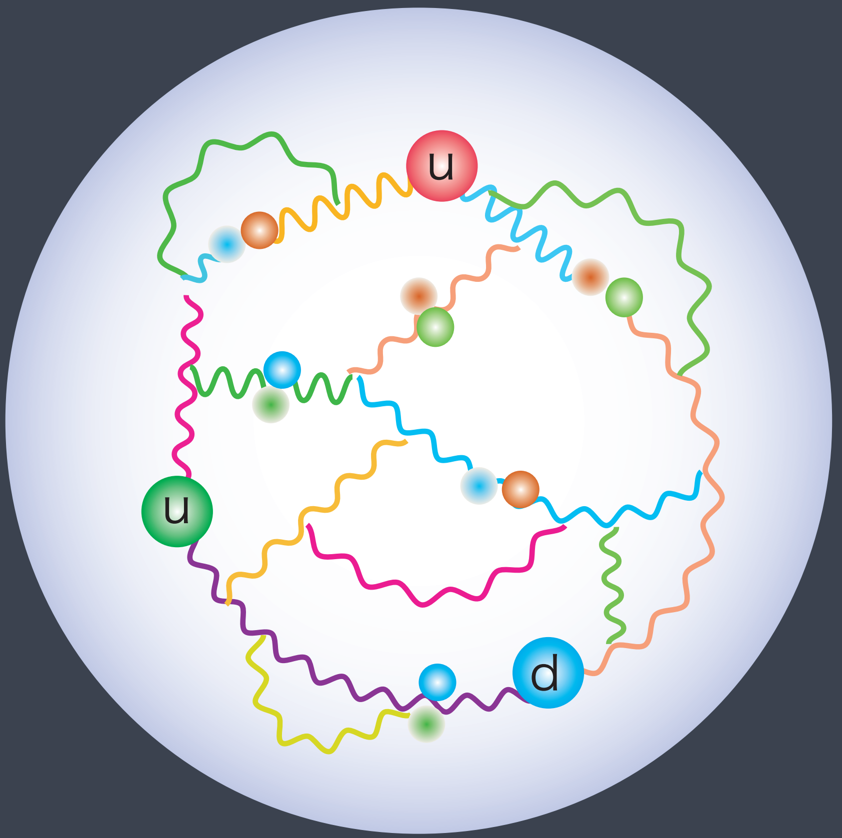


Fig. 11: Comparison of the ratio of integrated electron-nucleon and neutrino-nucleon structure functions to the value 5/ 18 expected from quark charges. The open triangle data point is from Gargamelle and the tilled-in circles are from the CIT-NAL Group. From Ref. [45]. The quantity Q^2) is the mean square charge of the quarks in a target consisting of an equal number of protons and neutrons.

陽子の内部構造

- 2個のuクォーク＋1個のdクォーク
  - グルーオン〜50%
  - 海クォーク$(q\bar{q})$
- “色”がひしめき合う世界
- →外部は”白”

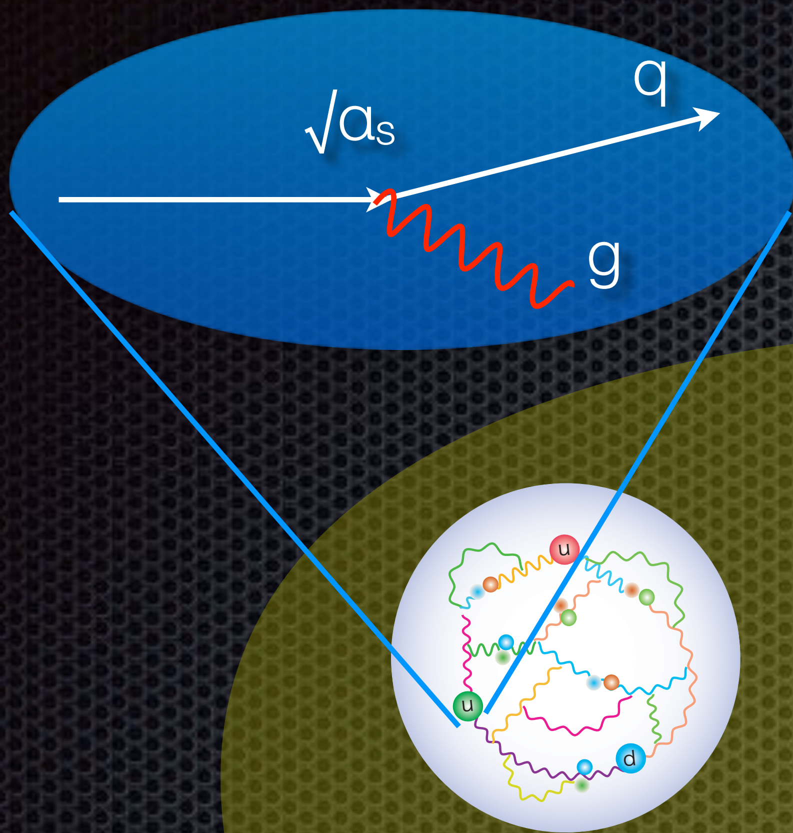


原子核のクォークによる記述は可能か？

- 原子核は、Z個の陽子とN個の中性子から構成される(A=Z+N)。
- 原子核は、3A個のクォークから構成される。

これまでのところ、そうでなければ説明できない現象は見つかっていない。

QCDの諸様相



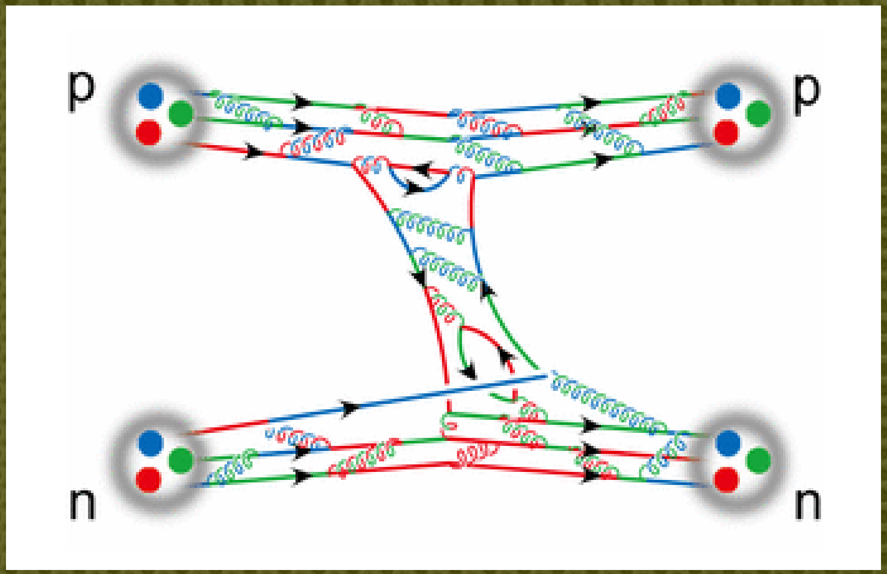
クォーク・グルーオンの力学

摂動論的QCD←漸近的自由性

A=1
クォーク閉じ込め

クォーク多体系の世界

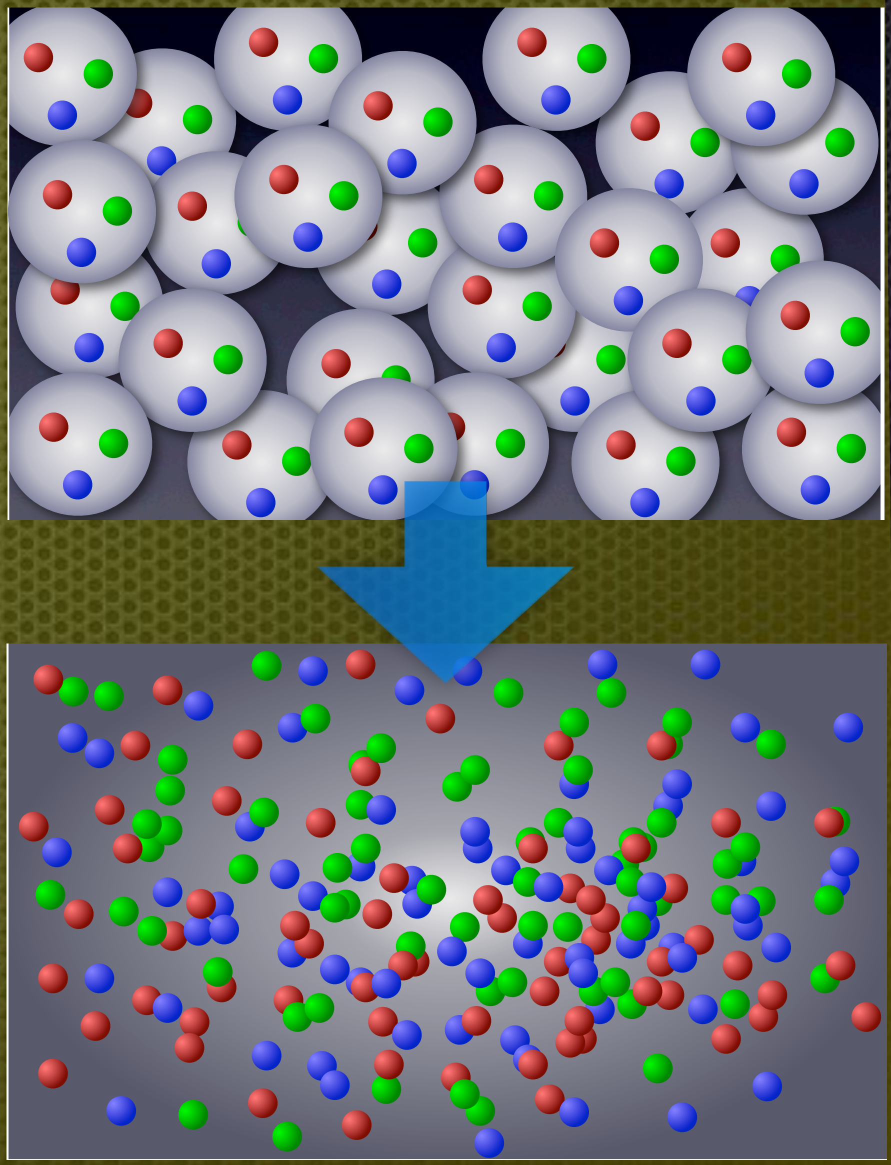
非摂動論的QCD



A=2
バリオン間相互作用（核力）

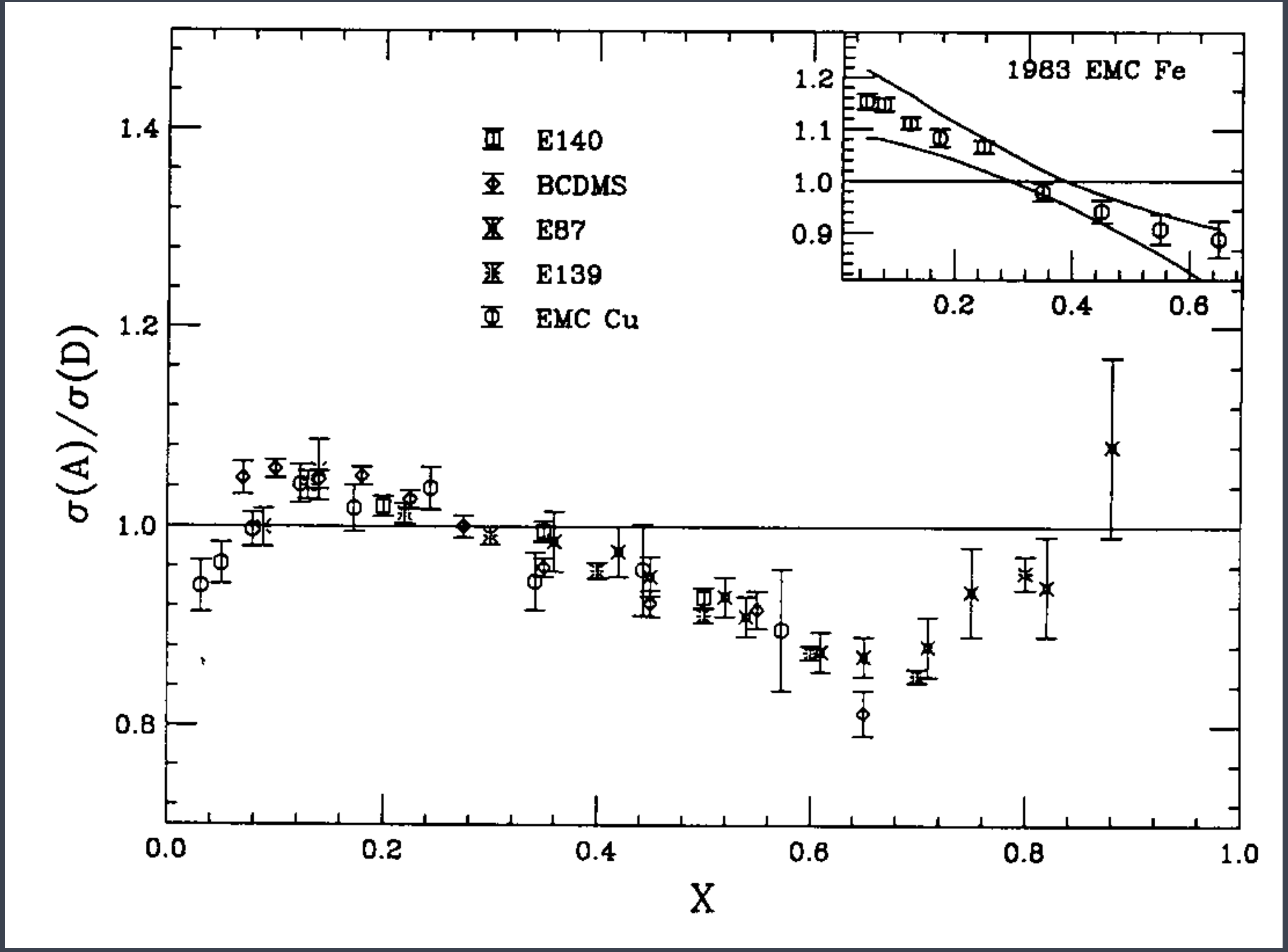
SU(3)$_F$への拡張

A=∞
高密度核物質：QCD相転移



マルチ・ストレンジネスの世界

EMC効果



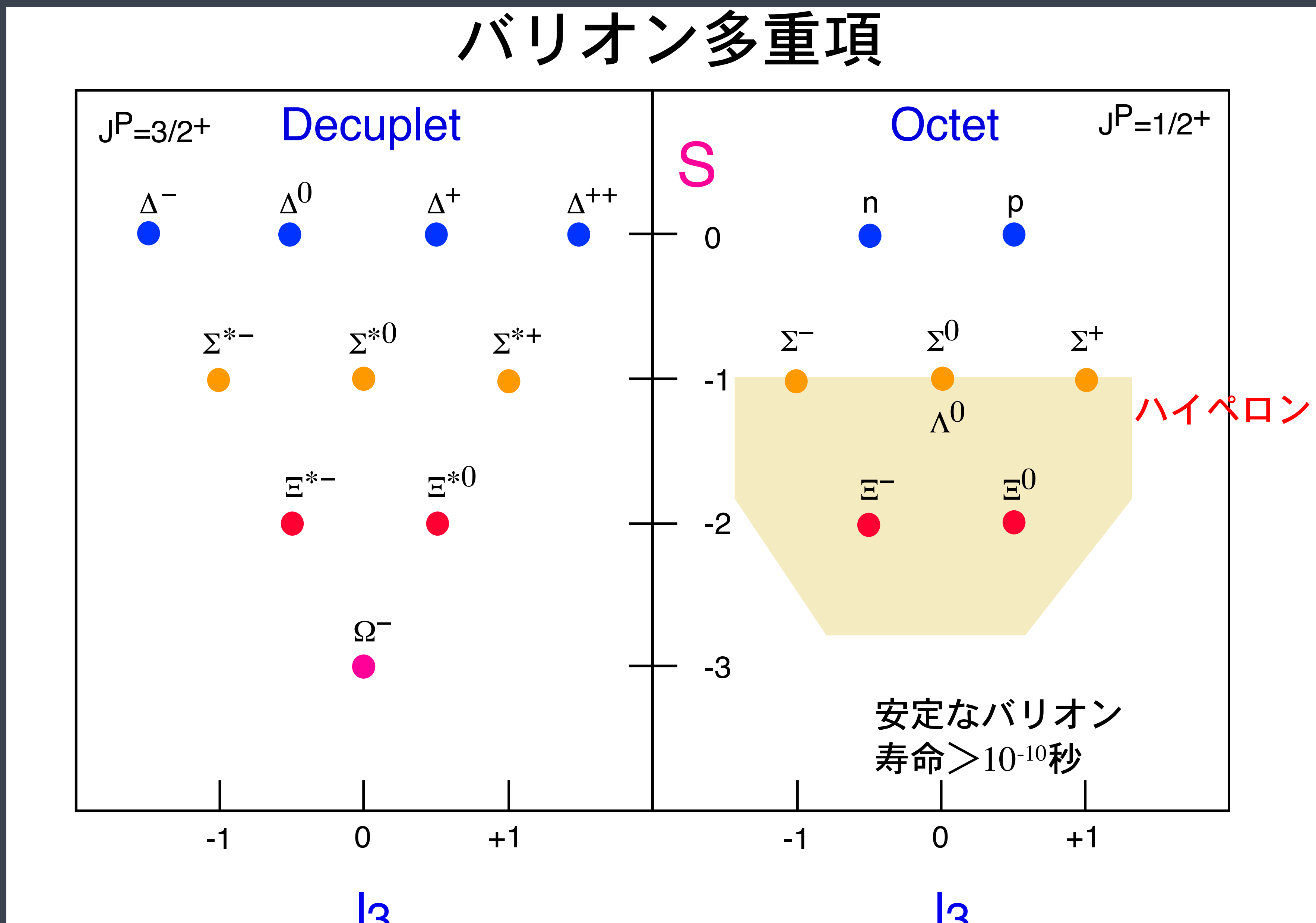
原子核に束縛された陽子の
運動量分布は真空中と同じか？

1994年

European Muon Collaboration

ハドロンと原子核

バリオン族



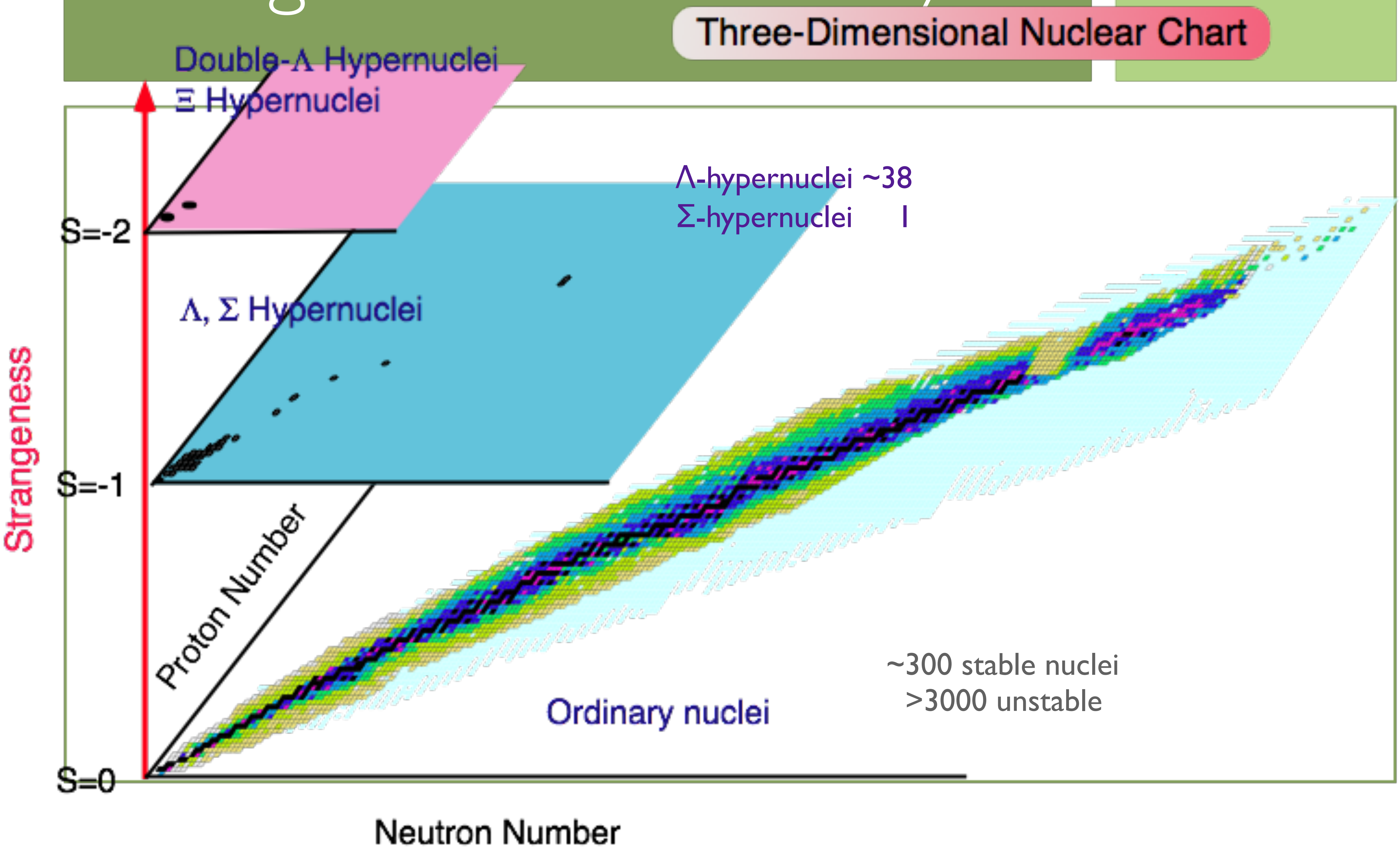
qqq: $3 \times 3 \times 3 = 10_S + 8_M + 8_M + 1_A$

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

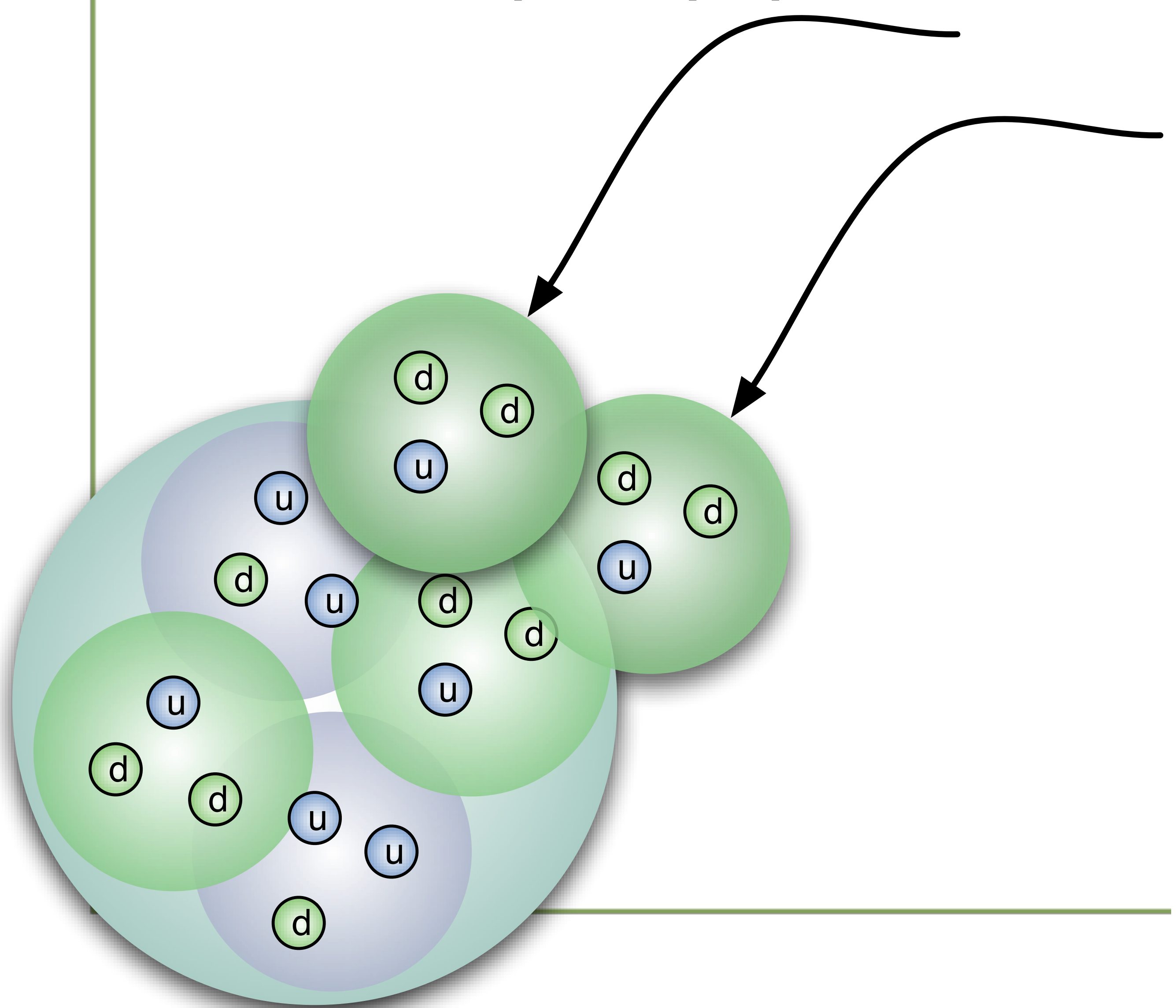
World of Strangeness Nuclear Physics



Normal Nuclei

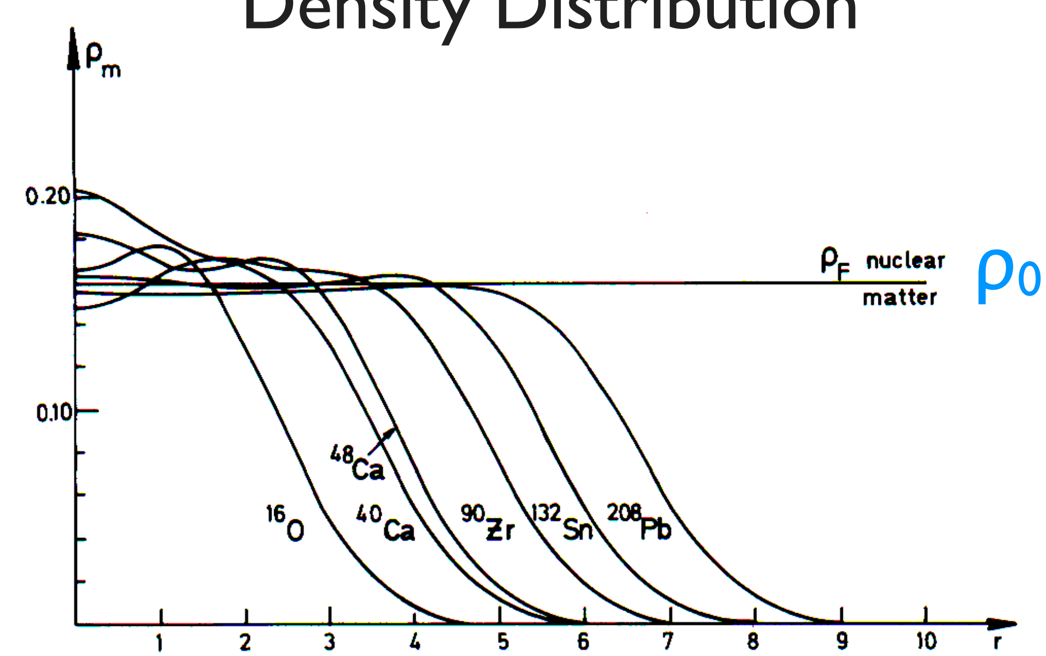
- Many-Body systems composed of proton(uud)& neutron(udd)
- Quark many-body systems with u & d quarks only

Fermions



Saturation Density: $\rho_0 = 2.5 \times 10^{14}$ g/cm^3
Binding Energy: 8 MeV/nucleon
←Pauli Blocking, Repulsive core

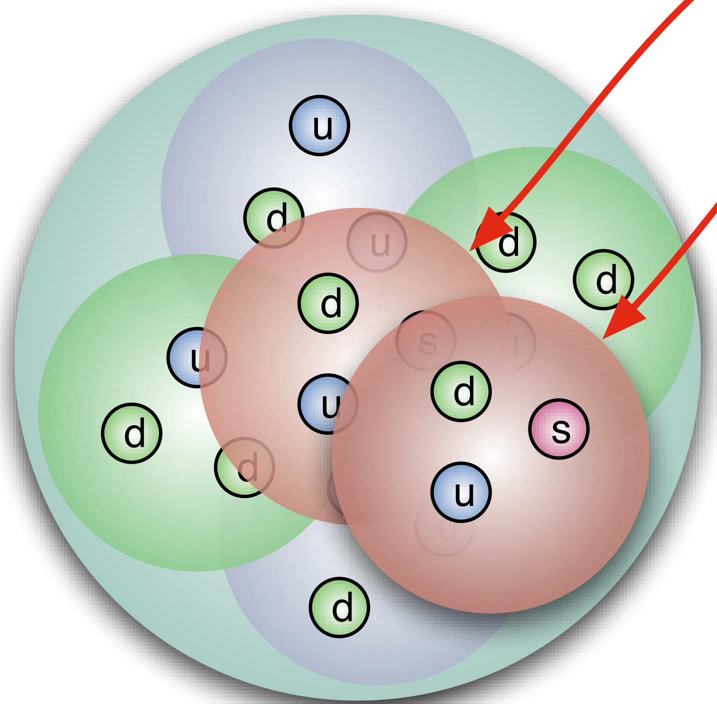
Density Distribution



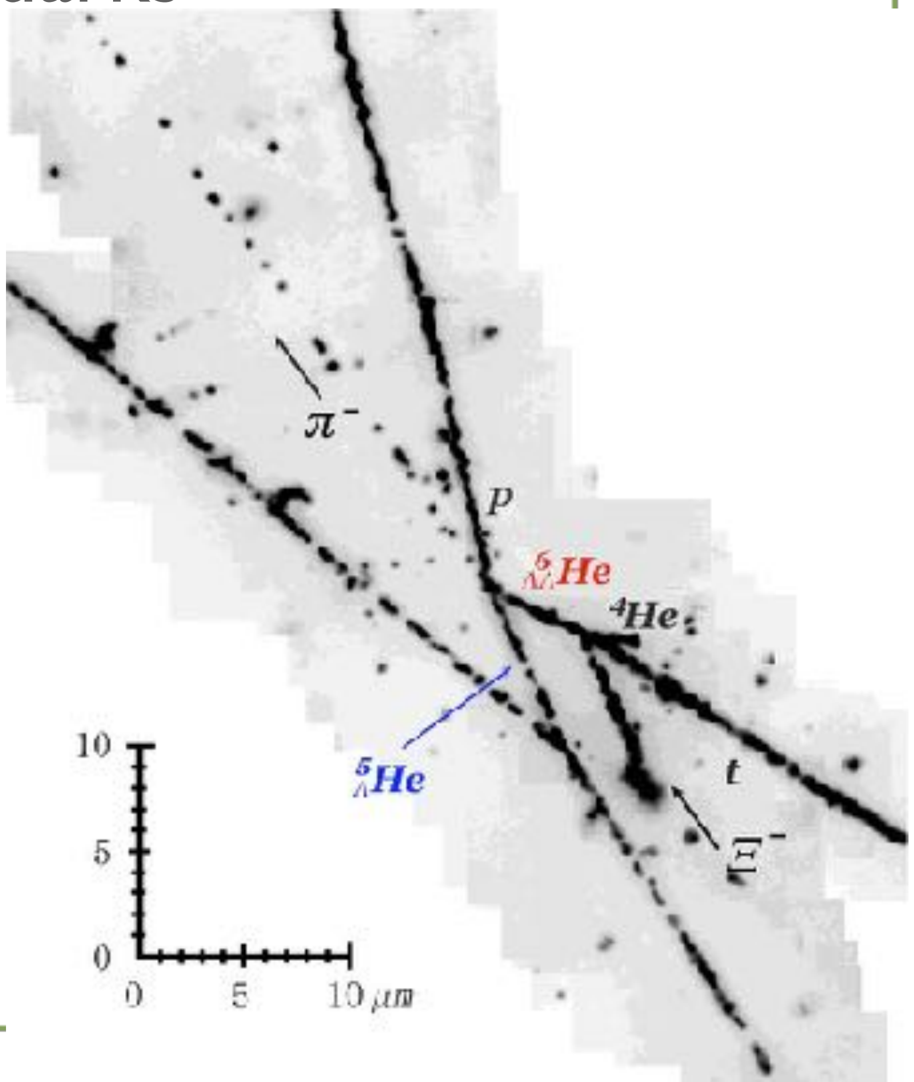
Hypernuclei

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

No Pauli Blocking
→Higher Density

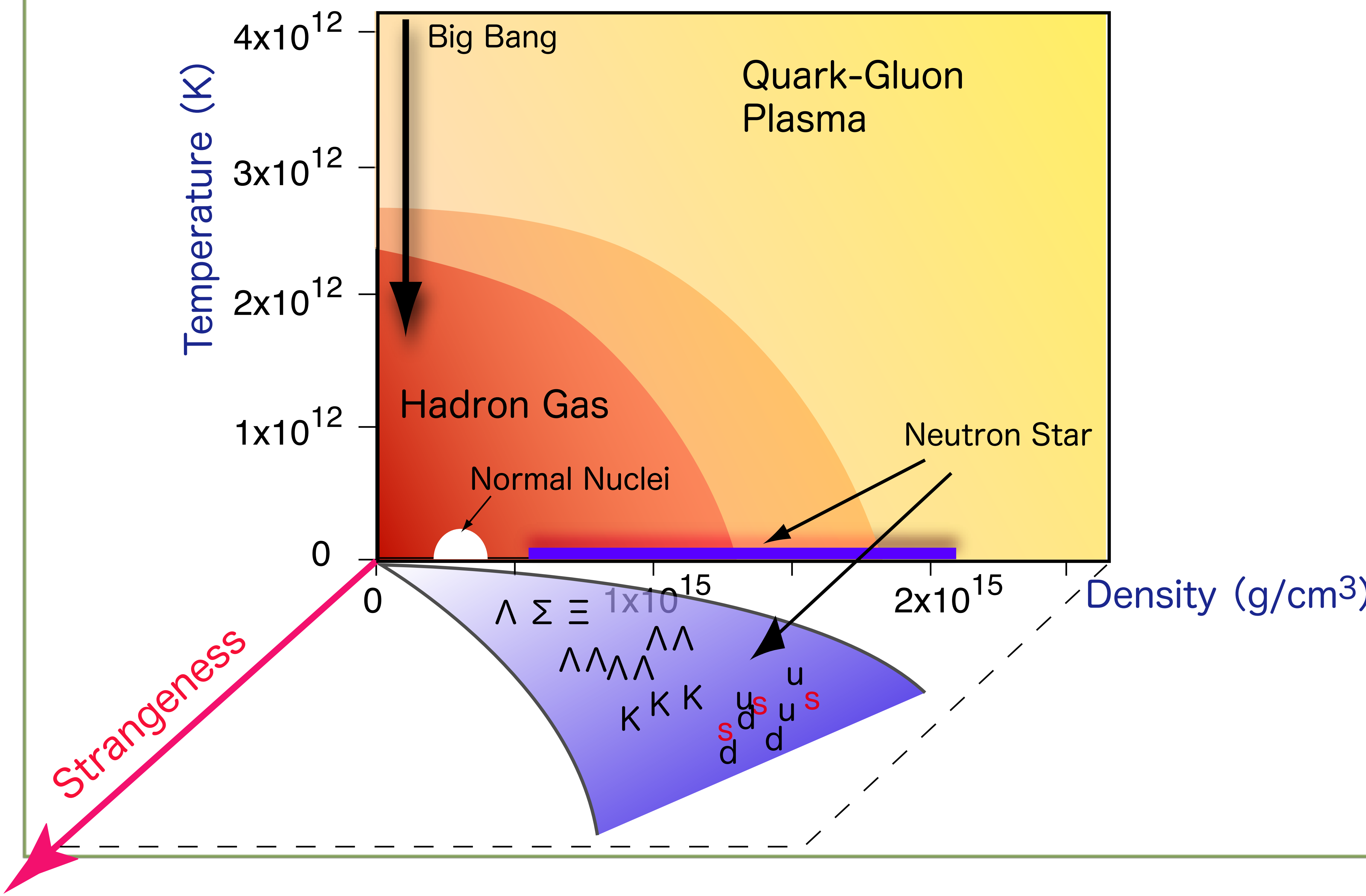


- Implant s quark(s) with u, d quarks

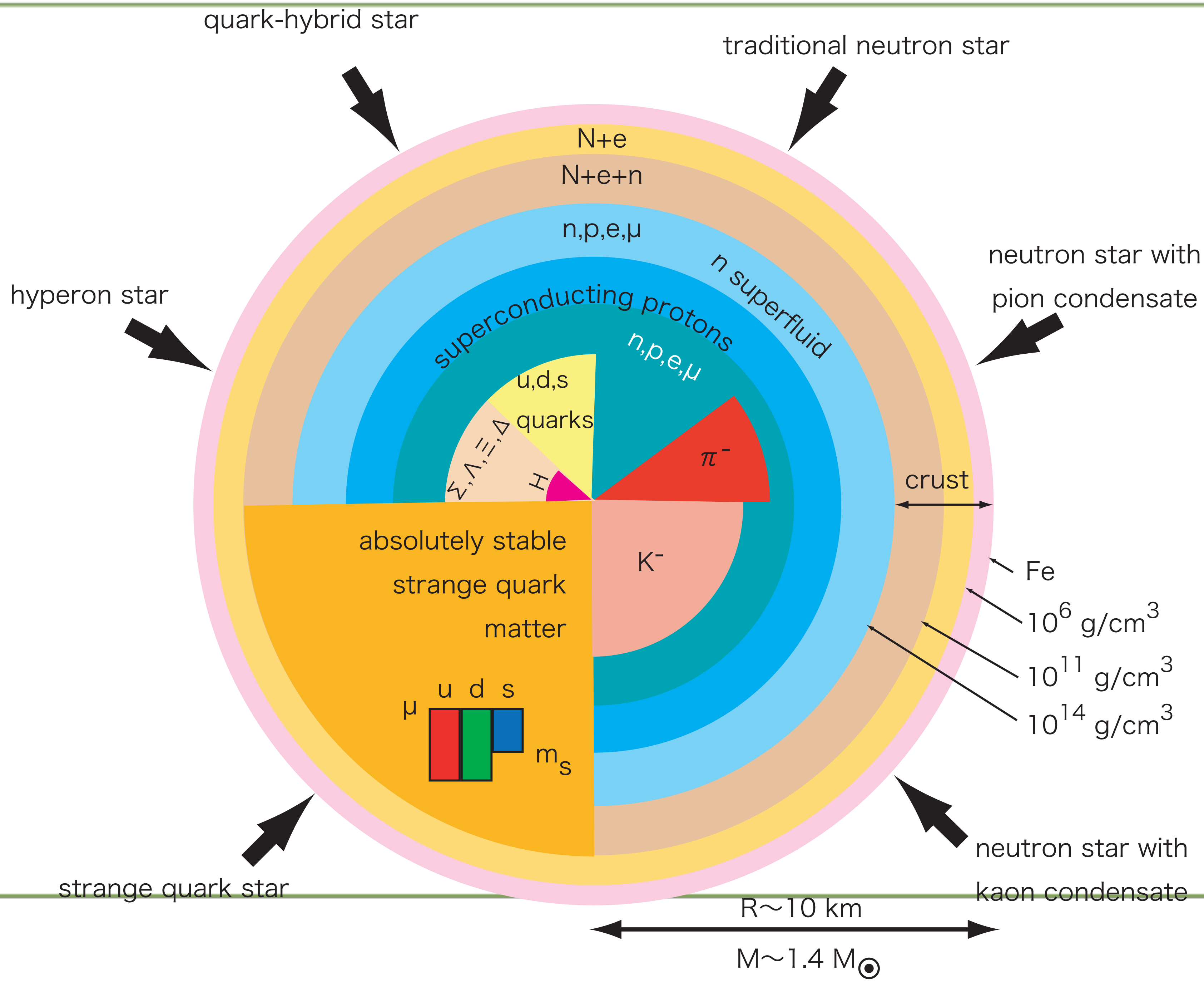


H.Takahashi et al., PRL 87, 212502(2001)

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



Neutron Star core ?

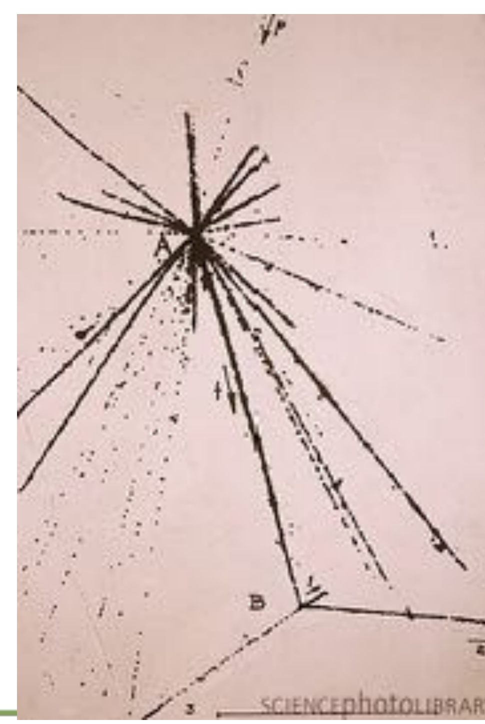


Brief history of Hypernuclear spectroscopy

- Discovery of Hyperfragments (1953) by M. Danysz and J. Pniewski

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

  - $\Lambda \sim p, n$
  - 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^-) (%)
$K^-He^4 \to \Sigma^+\pi^- H^3$	9.3 ± 2.3
$\to \Sigma^+\pi^- dn$	1.9 ± 0.7
$\to \Sigma^+\pi^- pnn$	1.6 ± 0.6
$\to \Sigma^+\pi^0\ nnn$	3.2 ± 1.0
$\to \Sigma^+\ \ nnn$	1.0 ± 0.4
Total $\Sigma^+ = (17.0\pm2.7)\%$	
$K^-He^4 \to \Sigma^-\pi^+ H^3$	4.2 ± 1.2
$\to \Sigma^-\pi^+ dn$	1.6 ± 0.6
$\to \Sigma^-\pi^+ pnn$	1.4 ± 0.5
$\to \Sigma^-\pi^0\ He^3$	1.0 ± 0.5
$\to \Sigma^-\pi^0\ pd$	1.0 ± 0.5
$\to \Sigma^-\pi^0\ ppn$	1.0 ± 0.4
$\to \Sigma^-\ \ pd$	1.6 ± 0.6
$\to \Sigma^-\ \ ppn$	2.0 ± 0.7
Total $\Sigma^- = (13.8\pm1.8)\%$	
$K^-He^4 \to \pi^-\Lambda\ He^3$	11.2 ± 2.7
$\to \pi^-\Lambda\ pd$	10.9 ± 2.6
$\to \pi^-\Lambda\ ppn$	9.5 ± 2.4
$\to \pi^-\Sigma^0\ He^3$	0.9 ± 0.6
$\to \pi^-\Sigma^0\ (pd,ppn)$	0.3 ± 0.3
$\to \pi^0\ \Lambda\ (\Sigma^0)\ (pnn)$	22.5 ± 4.2
$\to \Lambda\ (\Sigma^0)\ \ (pnn)$	11.7 ± 2.4
$\to \pi^+\Lambda\ (\Sigma^0) nnn$	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
	$[K_{\mathrm{DD}}]$	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
	$[K_{\mathrm{DD}}]$	0.011	0.021	0.020
2^+	$[K_\chi]$	0.547	1.052	0.872
	$[K_{\mathrm{DD}}]$	0.192	0.410	0.330
$0^+ + 2^+$	$[K_\chi]$	0.643	1.268	1.006
	$[K_{\mathrm{DD}}]$	0.203	0.431	0.350
	Experimental rates	0.35 ± 0.09	2.3 ± 0.3	1.68 ± 0.16

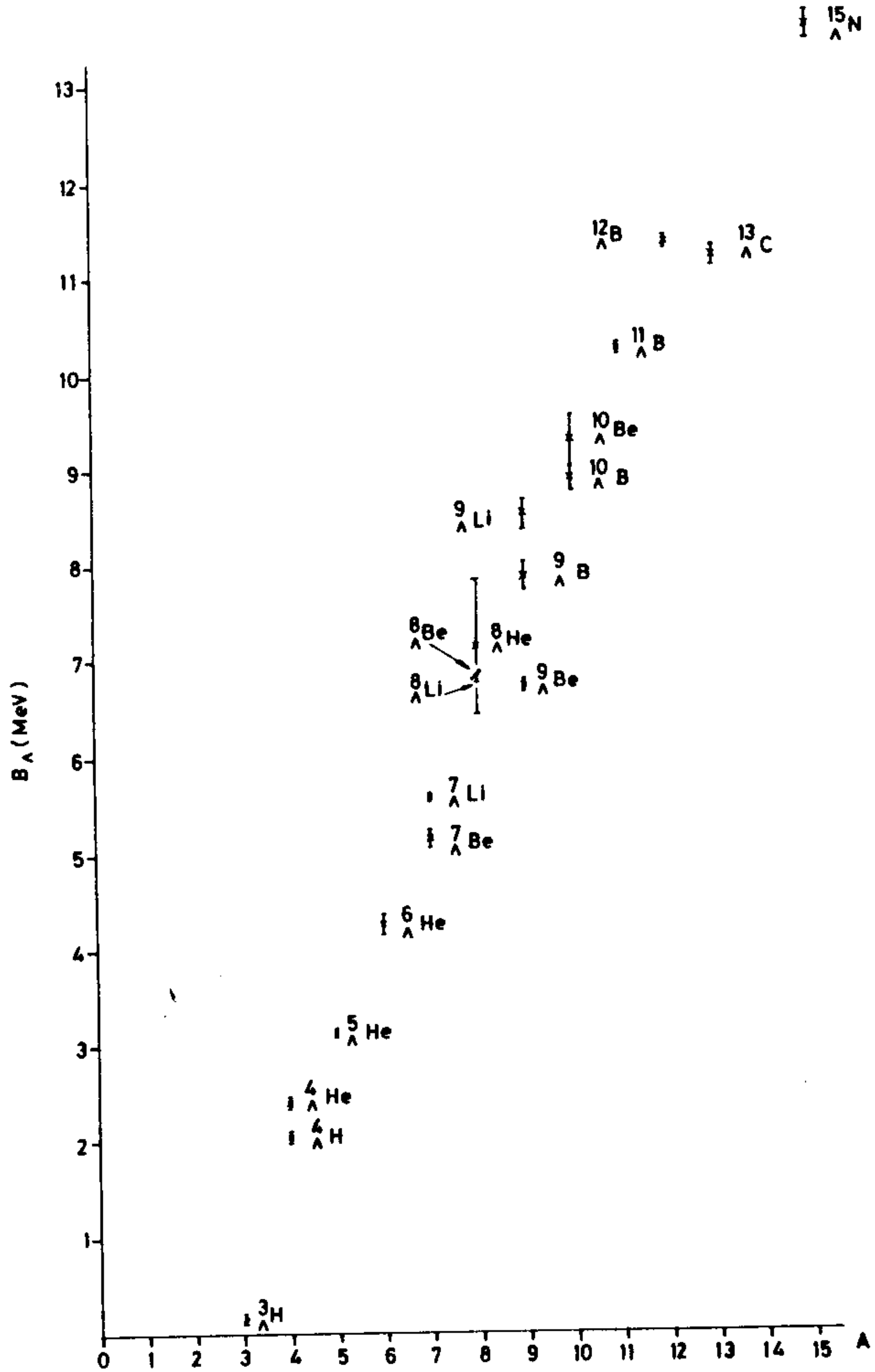
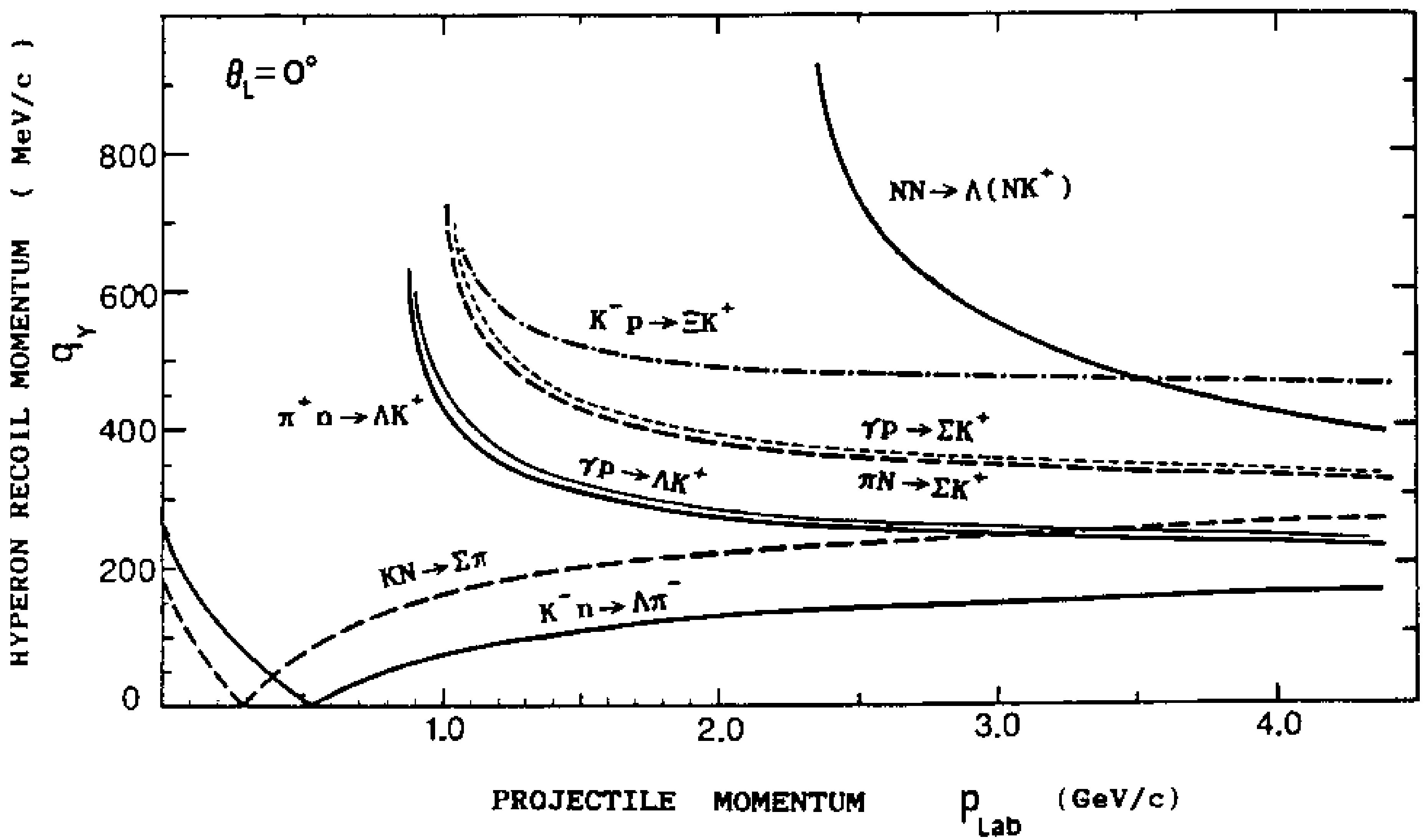


Fig. 10. Variation of the B_Λ values with the hypernuclear mass numbers.

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



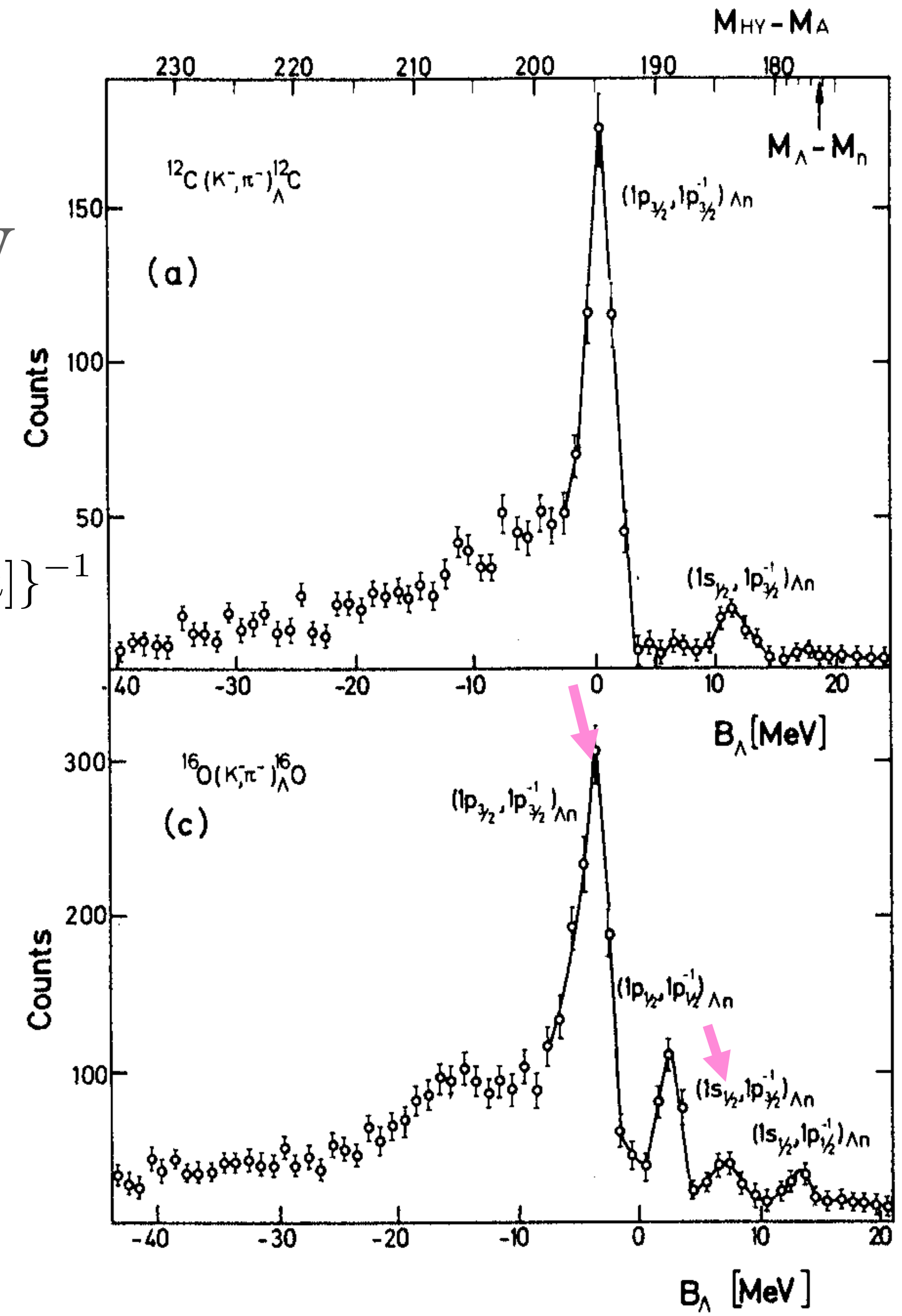
Data in the (K⁻,π⁻) reactions

- $^{16}{}_{\Lambda}O$
  - 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 $^4_\Sigma$He → confirmed
- Success of (π^+, K^+) Spectroscopy
- Success of Hypernuclear γ Spectroscopy
- H-particle search, Double-Λ hypernuclei

in the 21st century

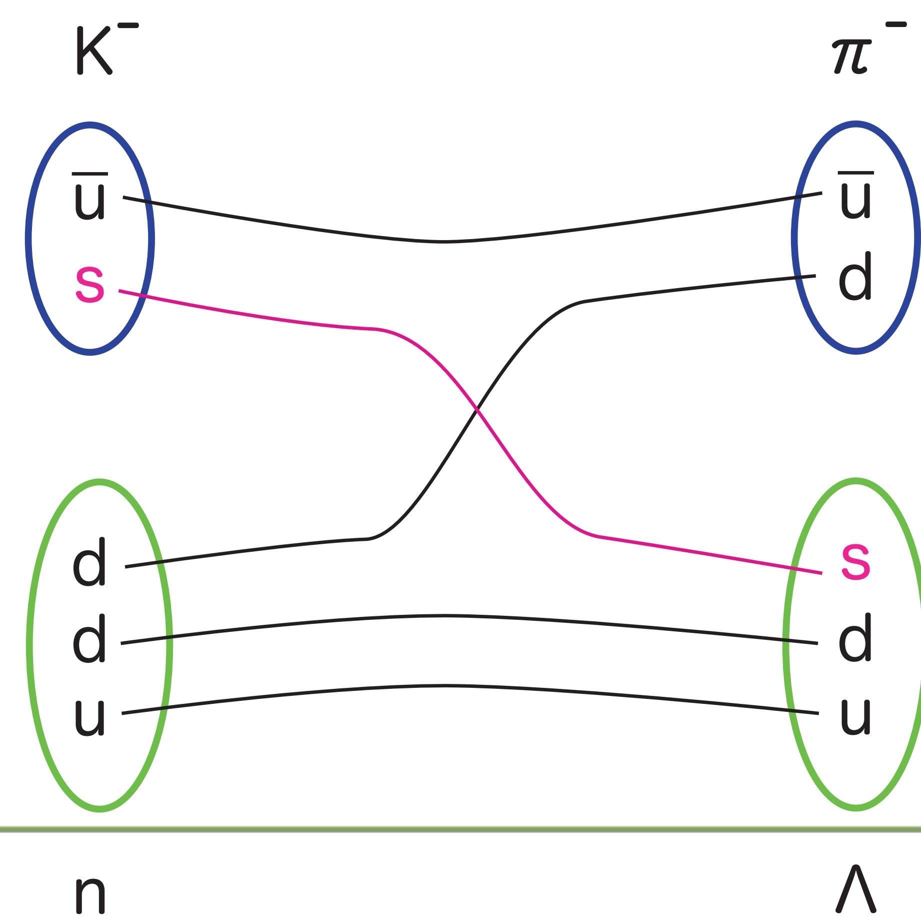
- $(e,e'K^+)$ at JLab
  - $\Delta E \sim 0.9$ MeV → 0.3 MeV
- (K^-_{stop}, π^-) at DAFNE/FINUDA
  - $\Delta E \sim 0.7$ MeV
- J-PARC, GSI, Mainz, ...

ハイパー一校の作り方

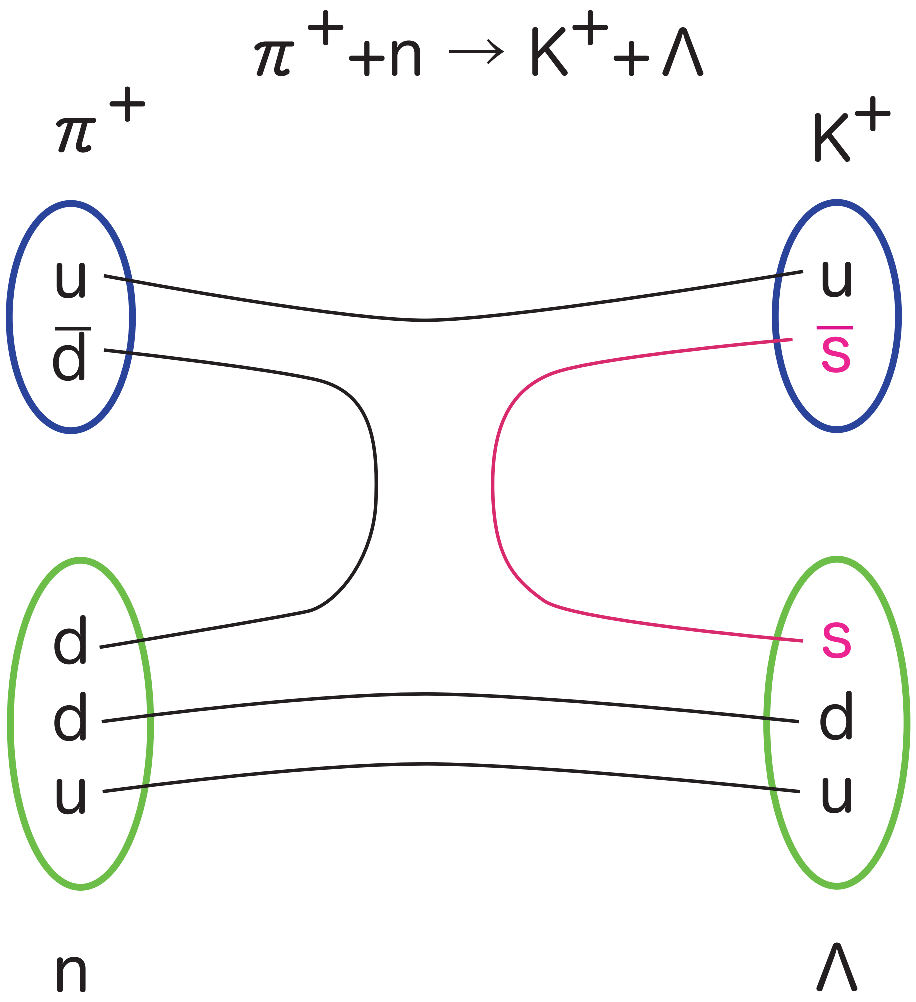
How to produce hypernuclei ?

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

$K^- + n \rightarrow \pi^- + \Lambda$



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

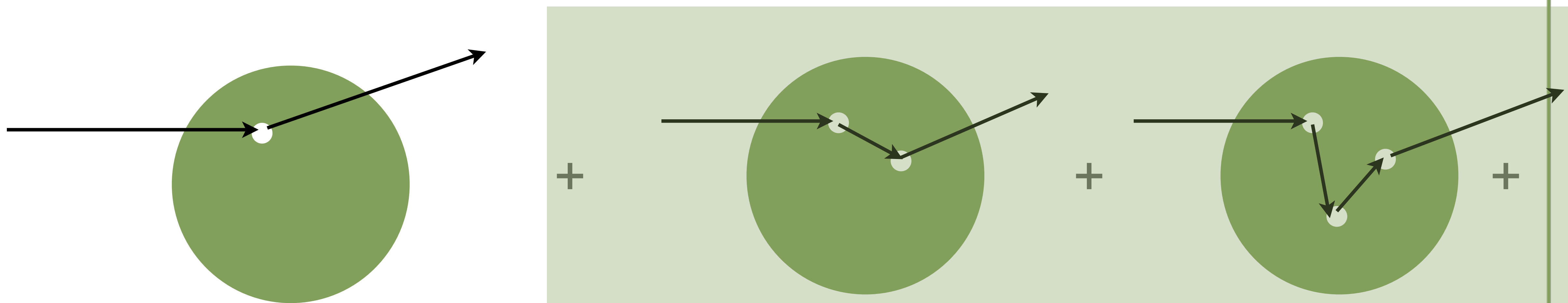


生成反応とその収量

	(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 « 1fm



1回散乱 + 2回散乱 + 3回散乱 ... +

  - 核内での遷移振幅 ~ 自由散乱の遷移振幅

- 1 + “2” → 3 + “4”

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

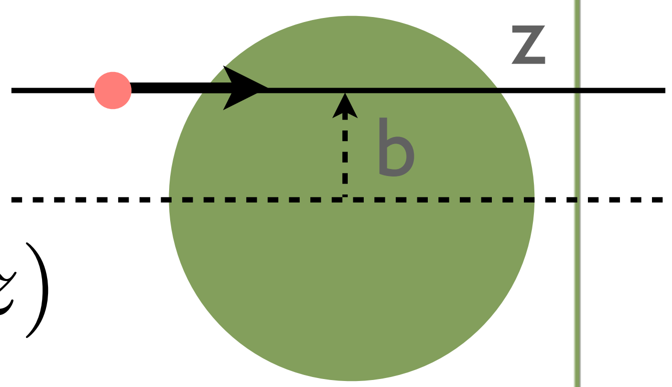
$$T_{fi} = \langle\chi_3^{(-)}|\langle f|\sum_j t_j|i\rangle|\chi_1^{(+)}\rangle$$

- 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

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

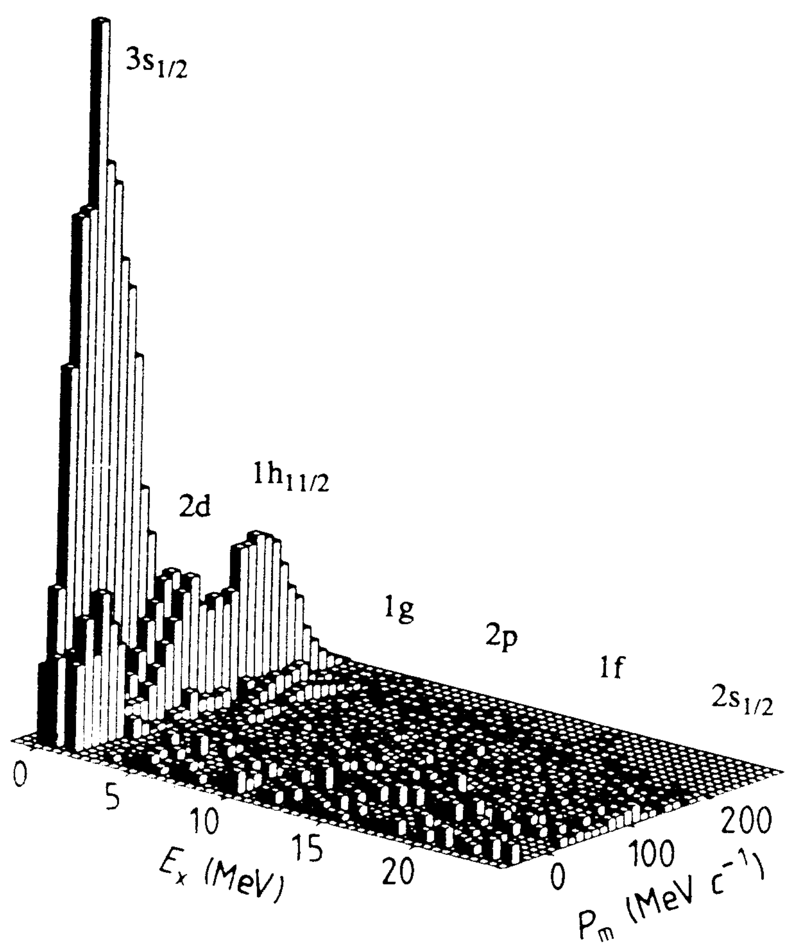
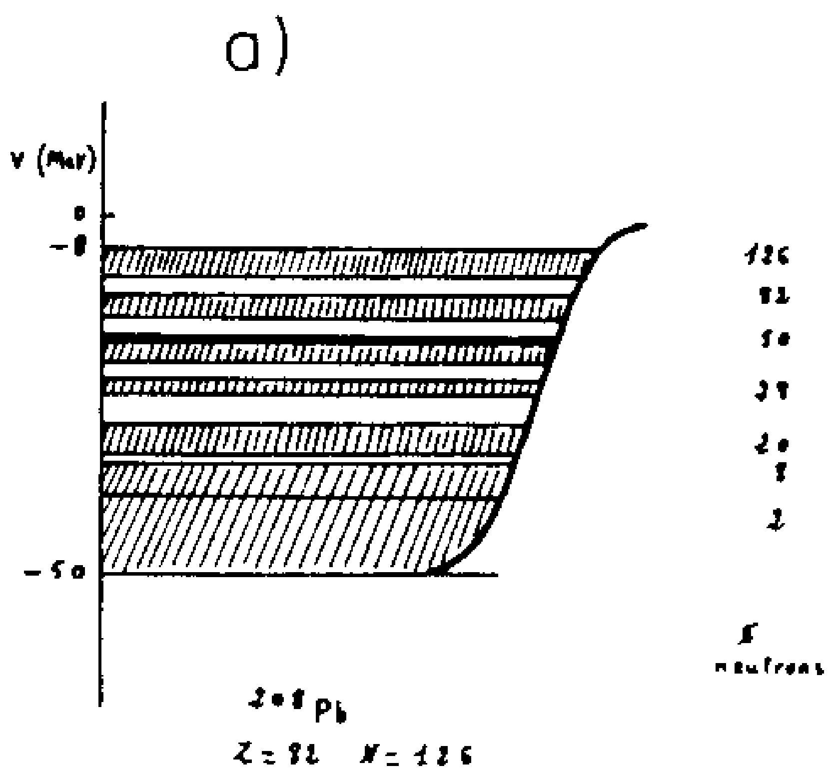
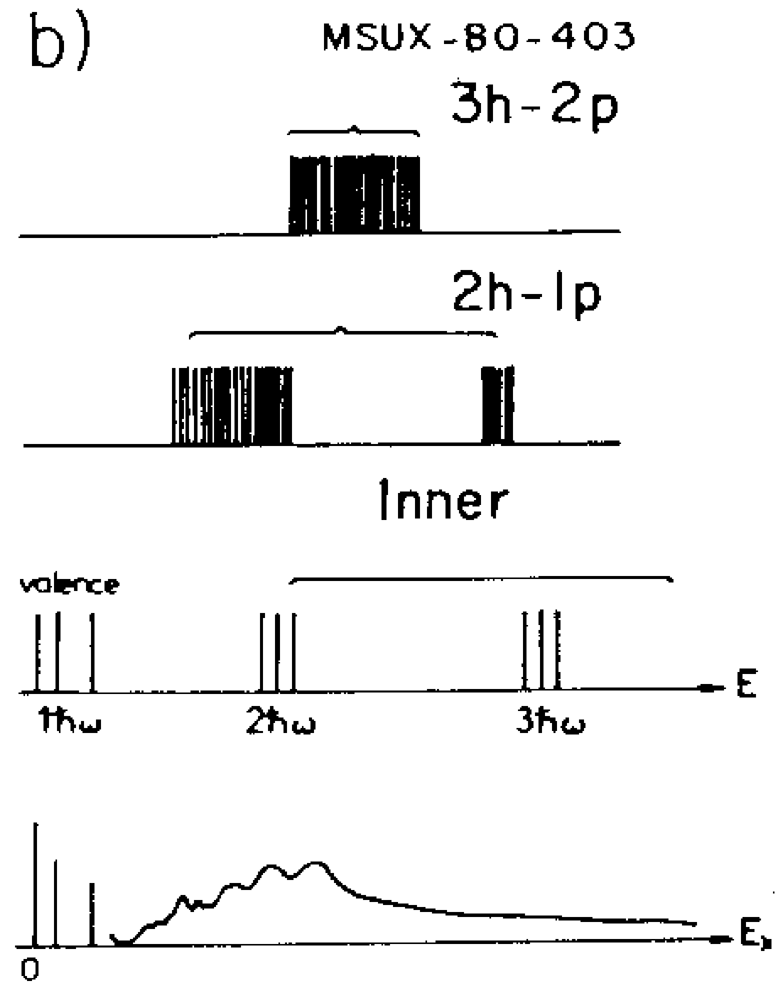
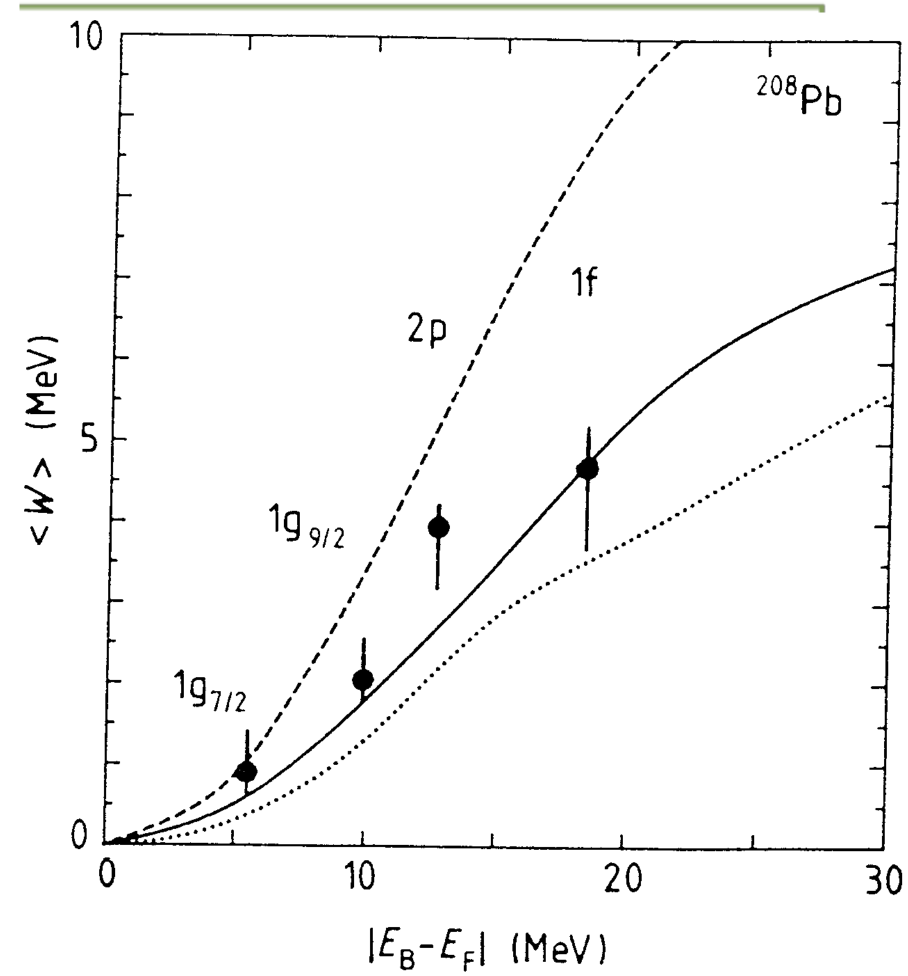


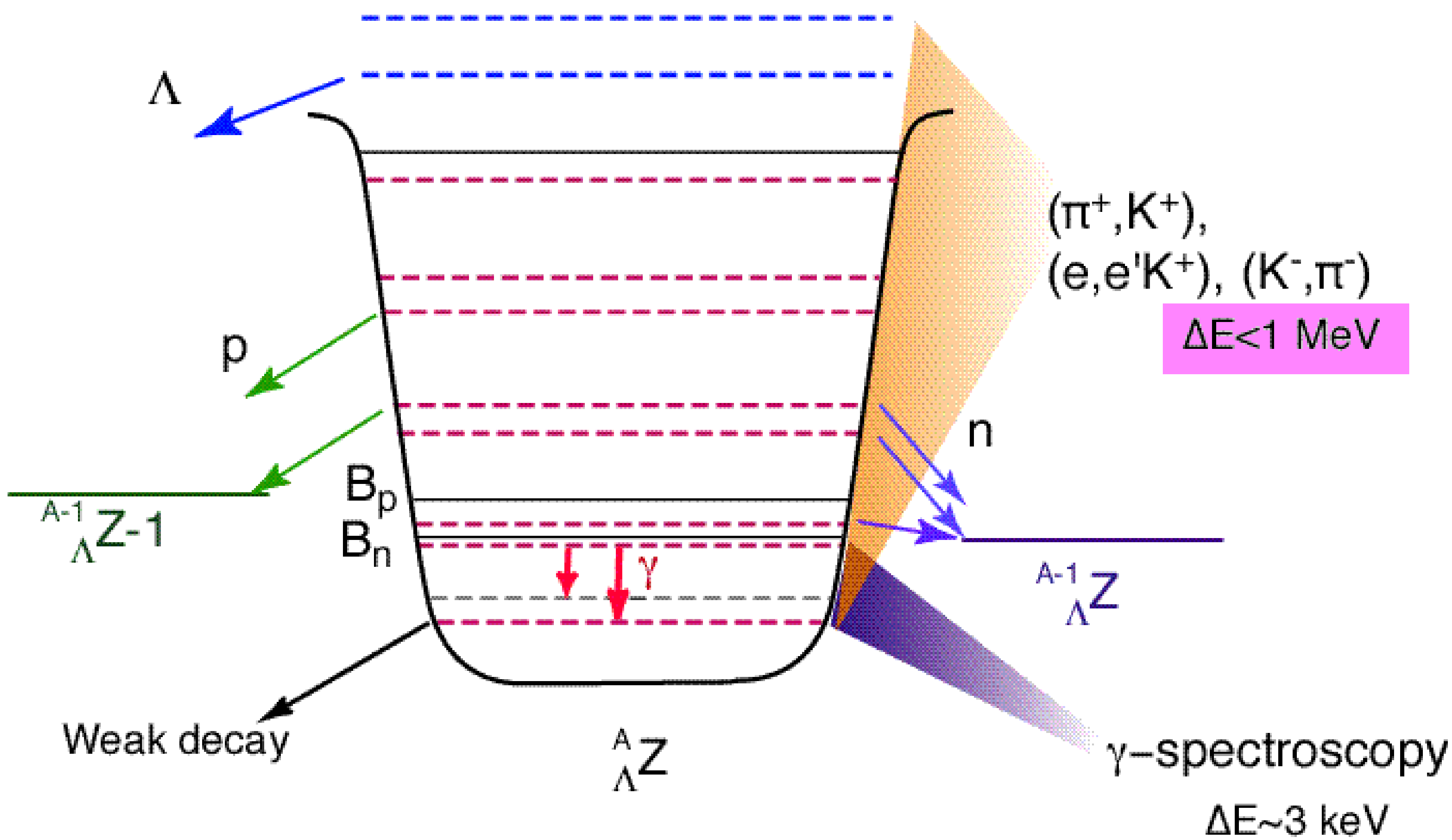
Figure 32. Experi
$^{208}Pb(e,e'p)^{207}Tl$.


a)
V (MeV)
0
-8
-50
126
82
50
28
20
8
2
neutrons
208Pb
Z = 82 N = 126


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


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

Excited levels of Λ-hypernuclei



Monochromatic Peak

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

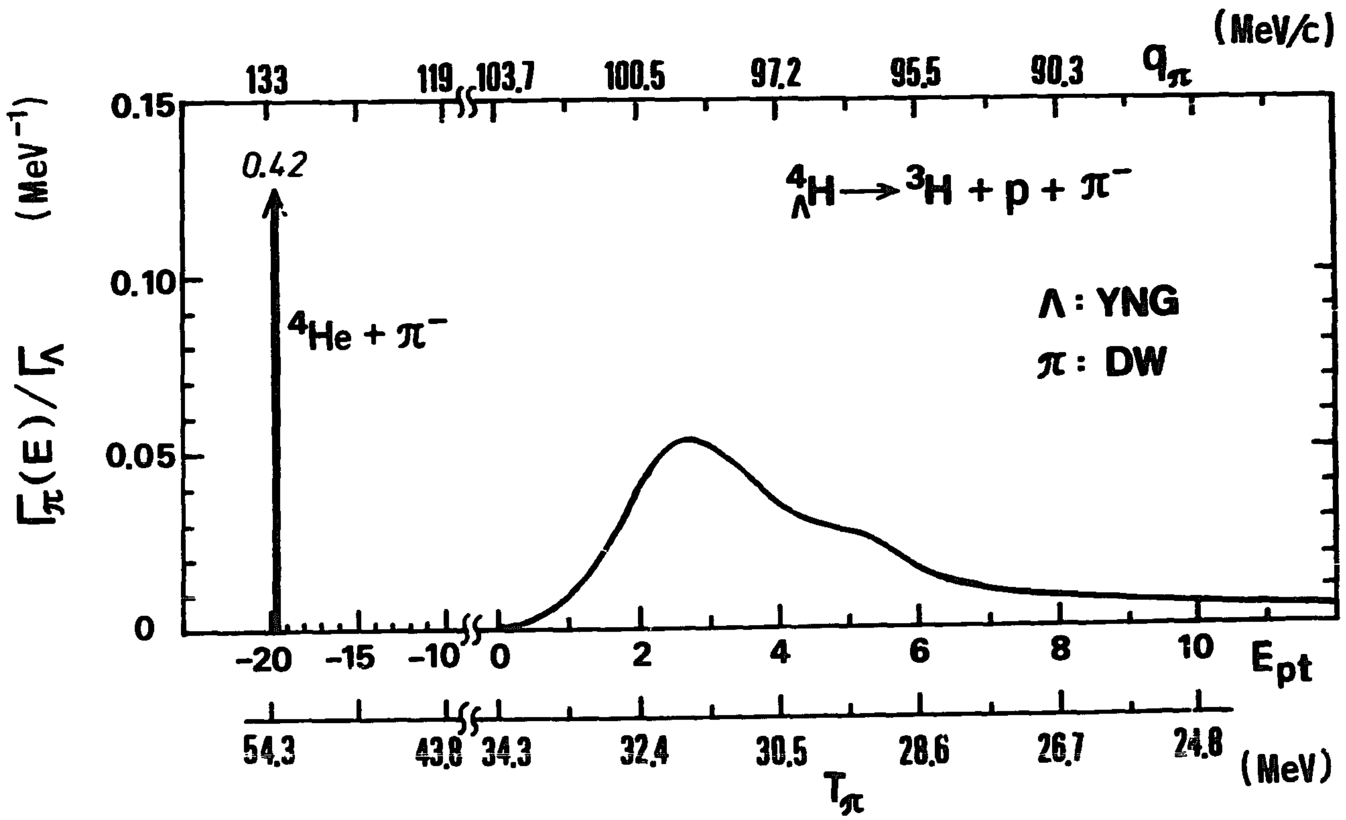


Fig. 9. The theoretical π^- decay spectrum $\Gamma_{\pi^-}(^4_\Lambda H)/\Gamma_\Lambda$ as a function of the proton-^{3}H relative energy E_{pt}.

Quasi-monochromatic

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

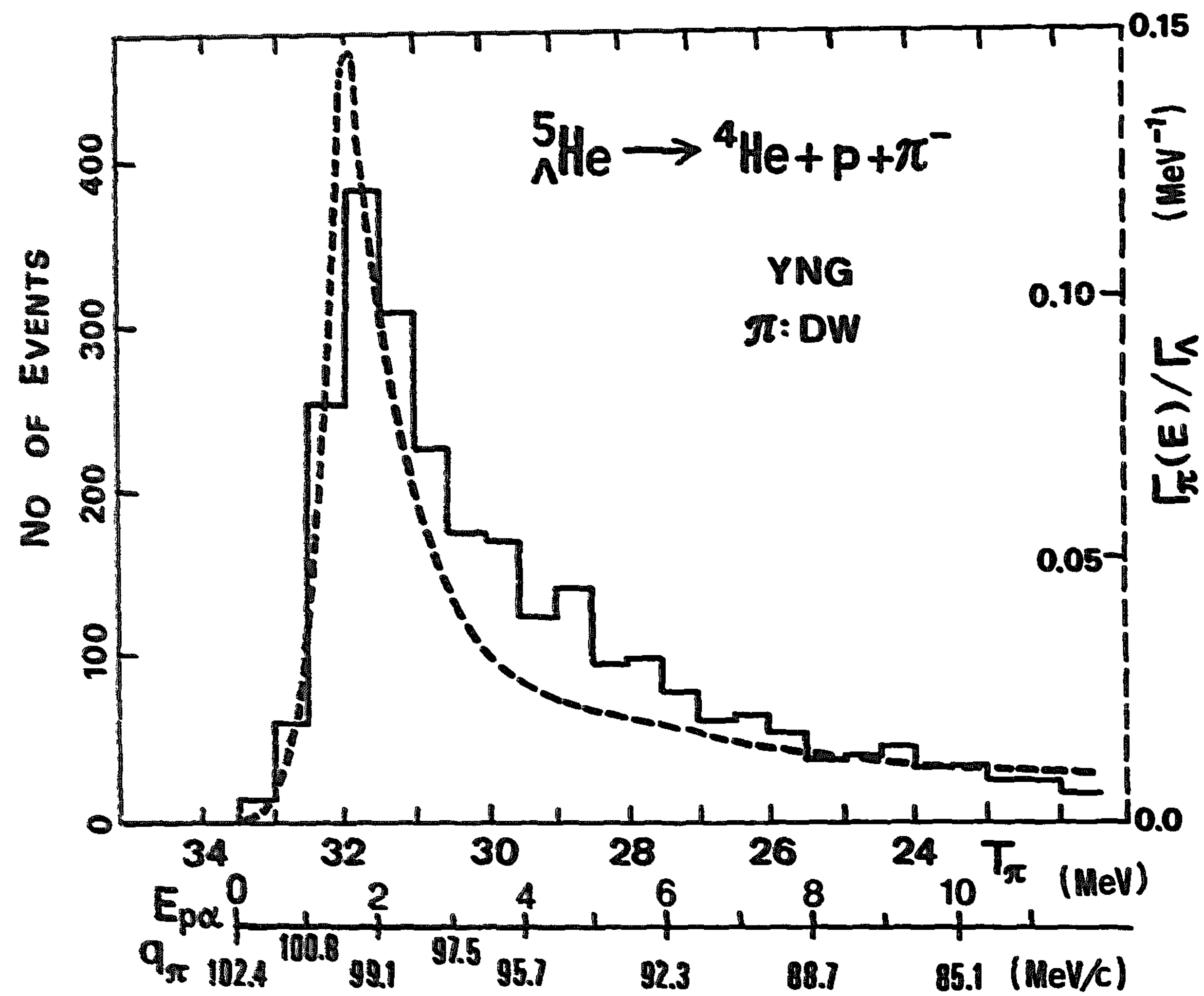


Fig. 4. The theoretical π^- decay spectrum $\Gamma_{\pi^-}({}^{5}_{\Lambda}He)/\Gamma_\Lambda$ with YNG drawn as a function of the pα relative energy $E_{p\alpha}$ is compared with the observed π^- decay spectrum taken in the emulsion experiment [18,33]). The calculated π^- decay rate is compared with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

Mesonic Decay Rate

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

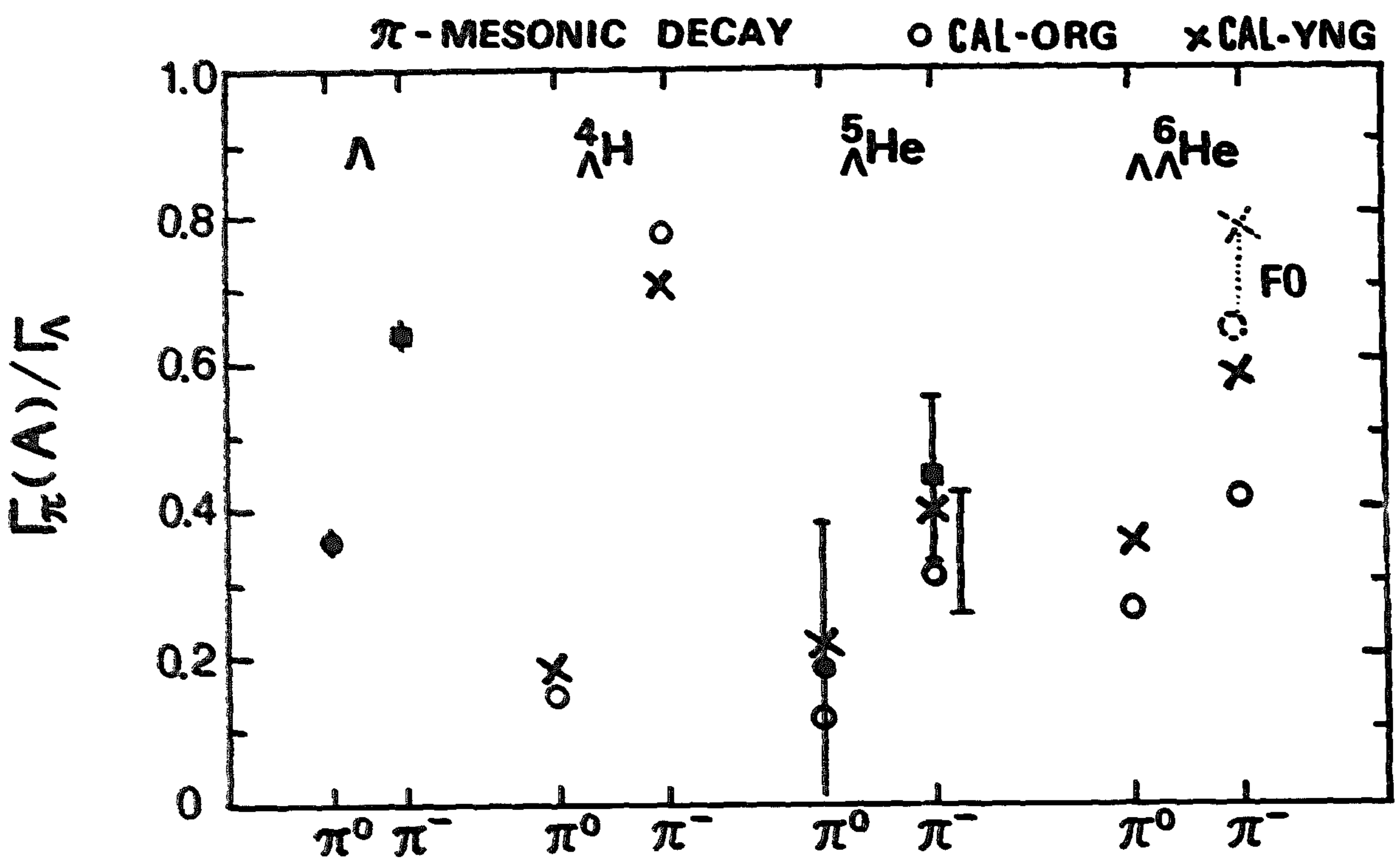
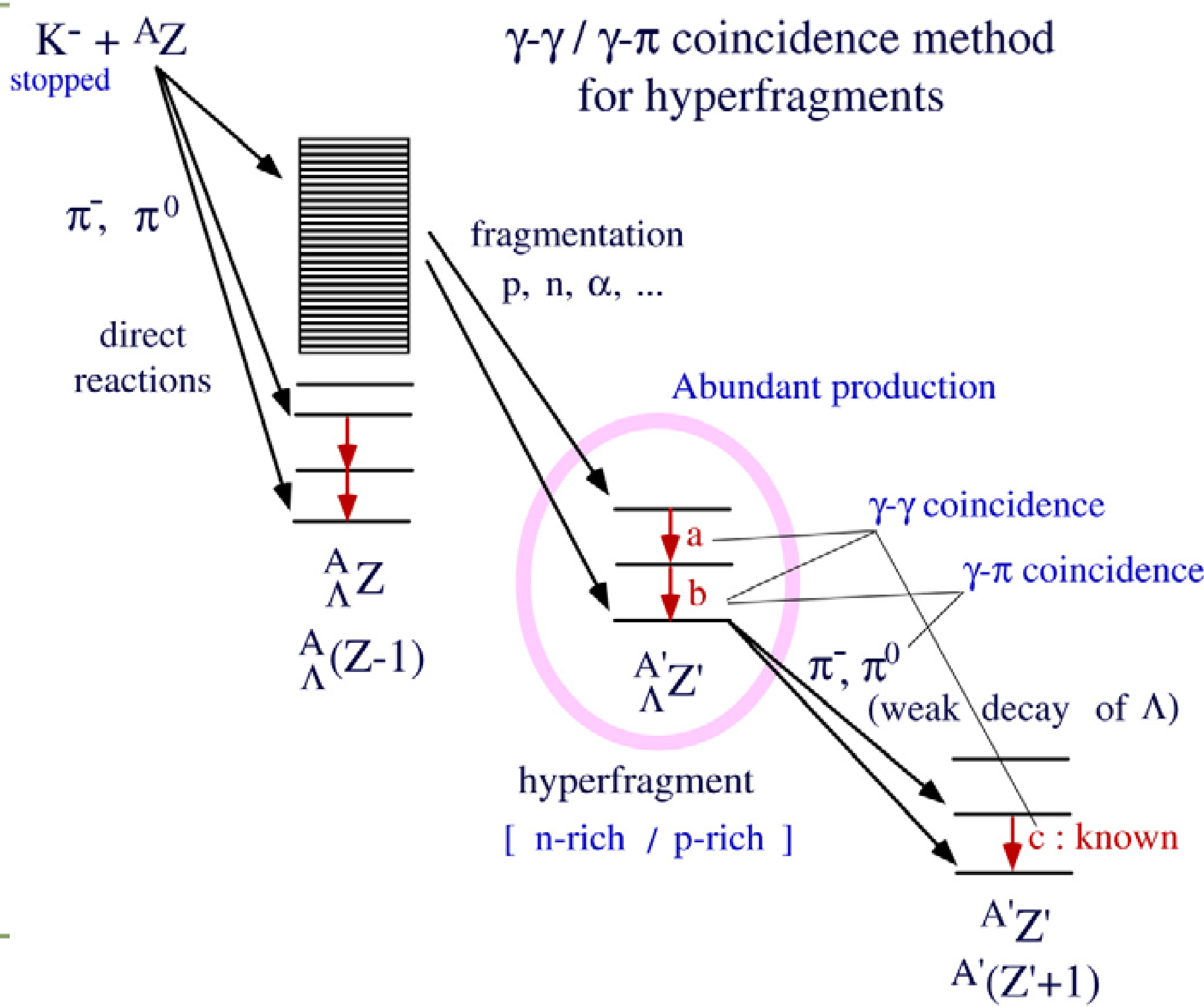


Fig. 5. Summary of the theoretical π-decay rates in units of Γ_{Λ}. The open circle and the cross correspond to ORG and YNG, respectively. The π^- decay rates of ${}^{6}_{\Lambda\Lambda}$He in the case of the F0 .1.1 interaction are also shown. The experimental values for ${}^{5}_{\Lambda}$He are taken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

γ-ray spectroscopy

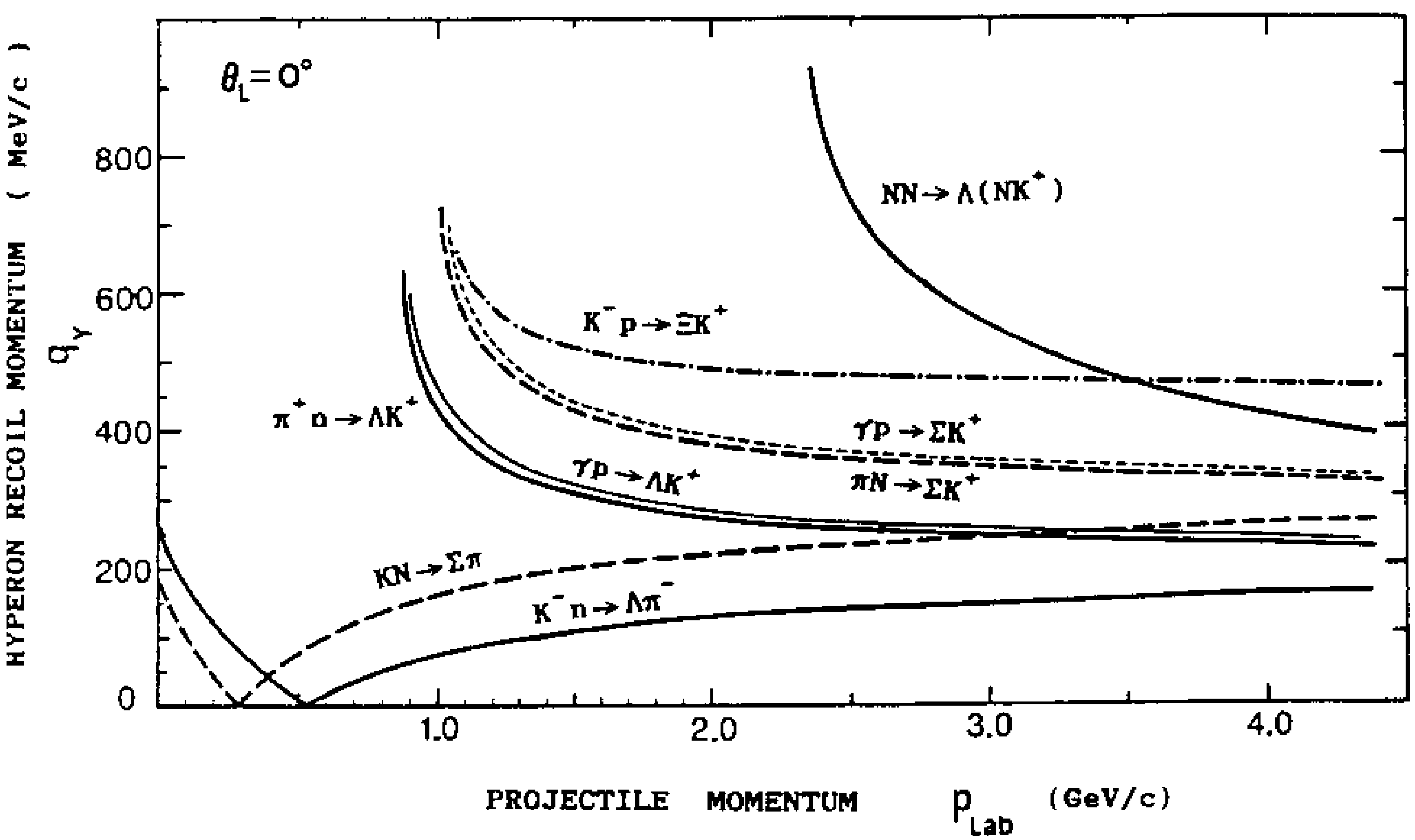


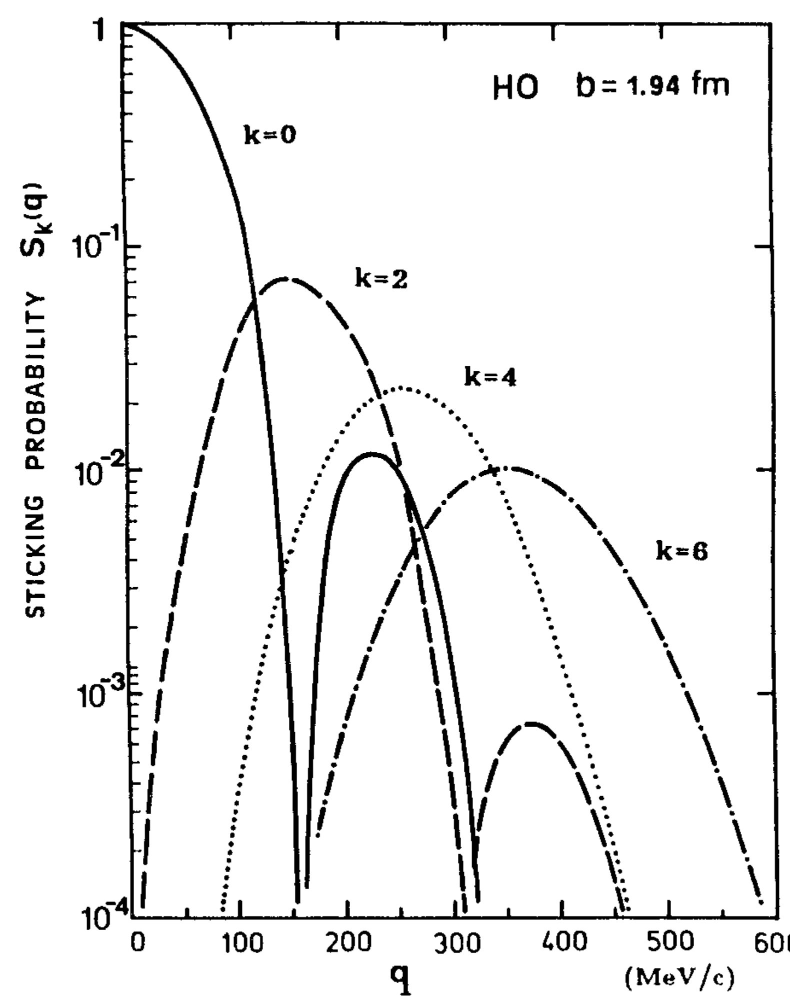
by H. Tamura

- 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

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





- (K^-,π^-): q<100 MeV/c→Δℓ=0 dominant

Angular Distributions

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

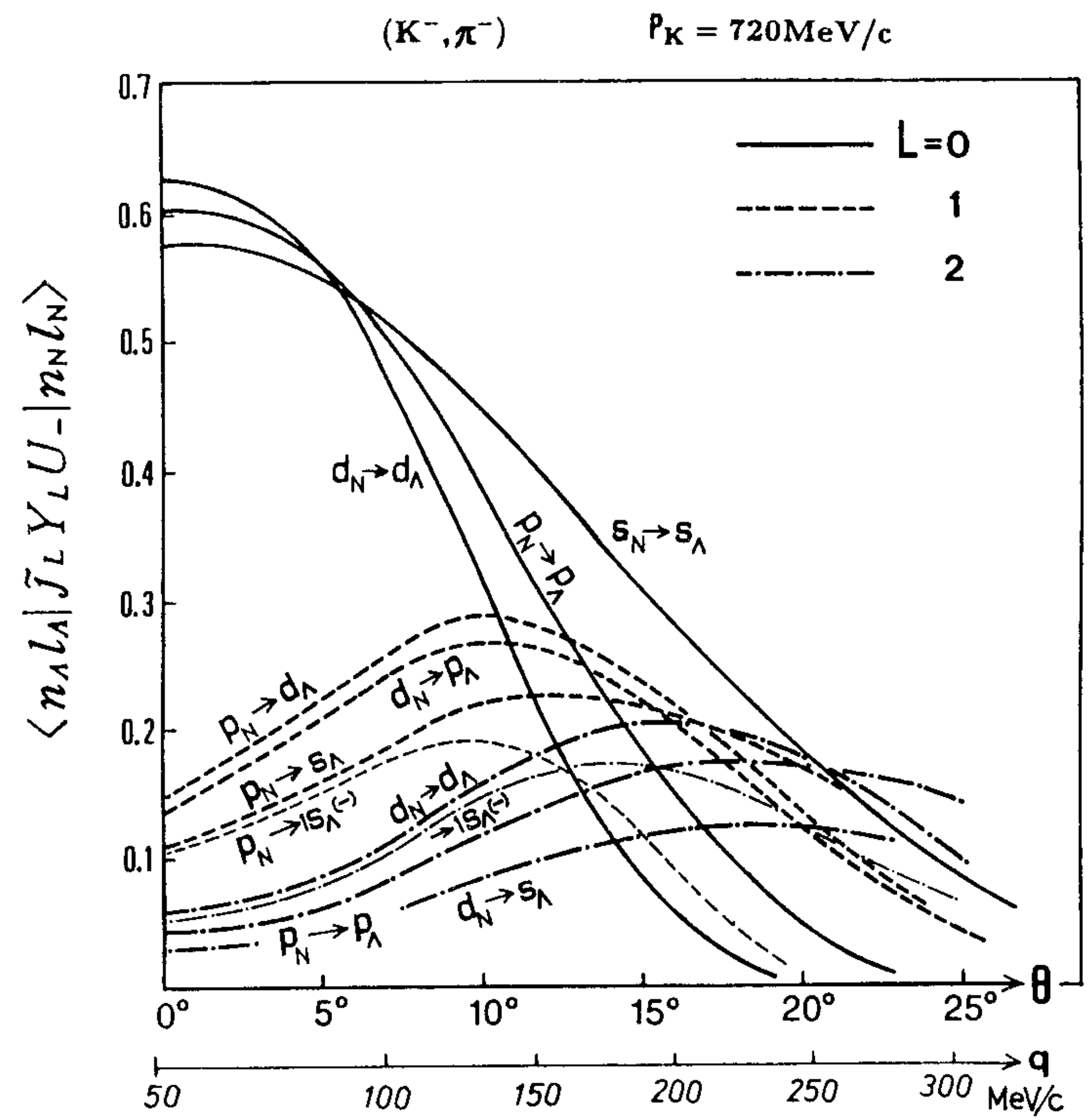
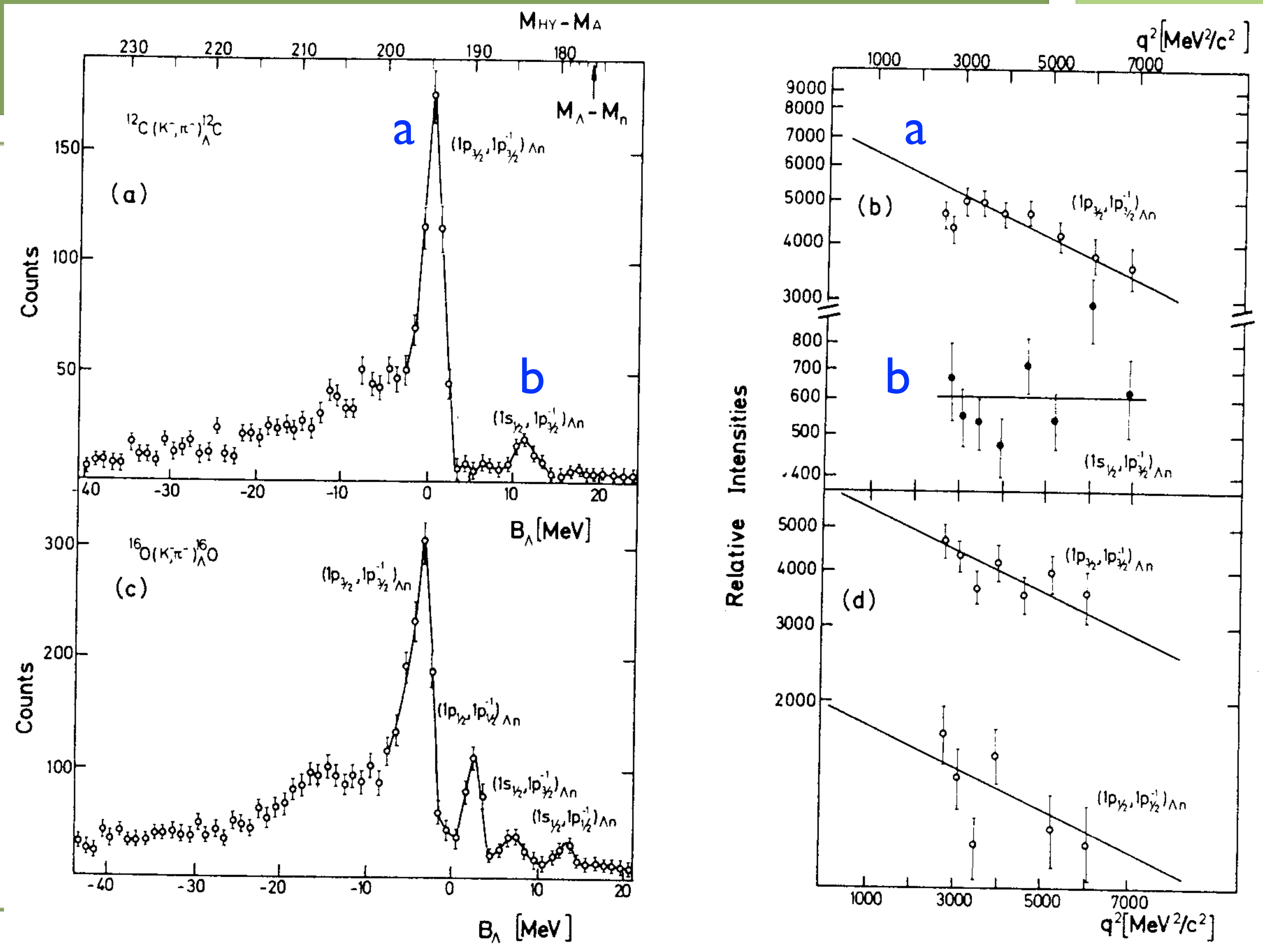


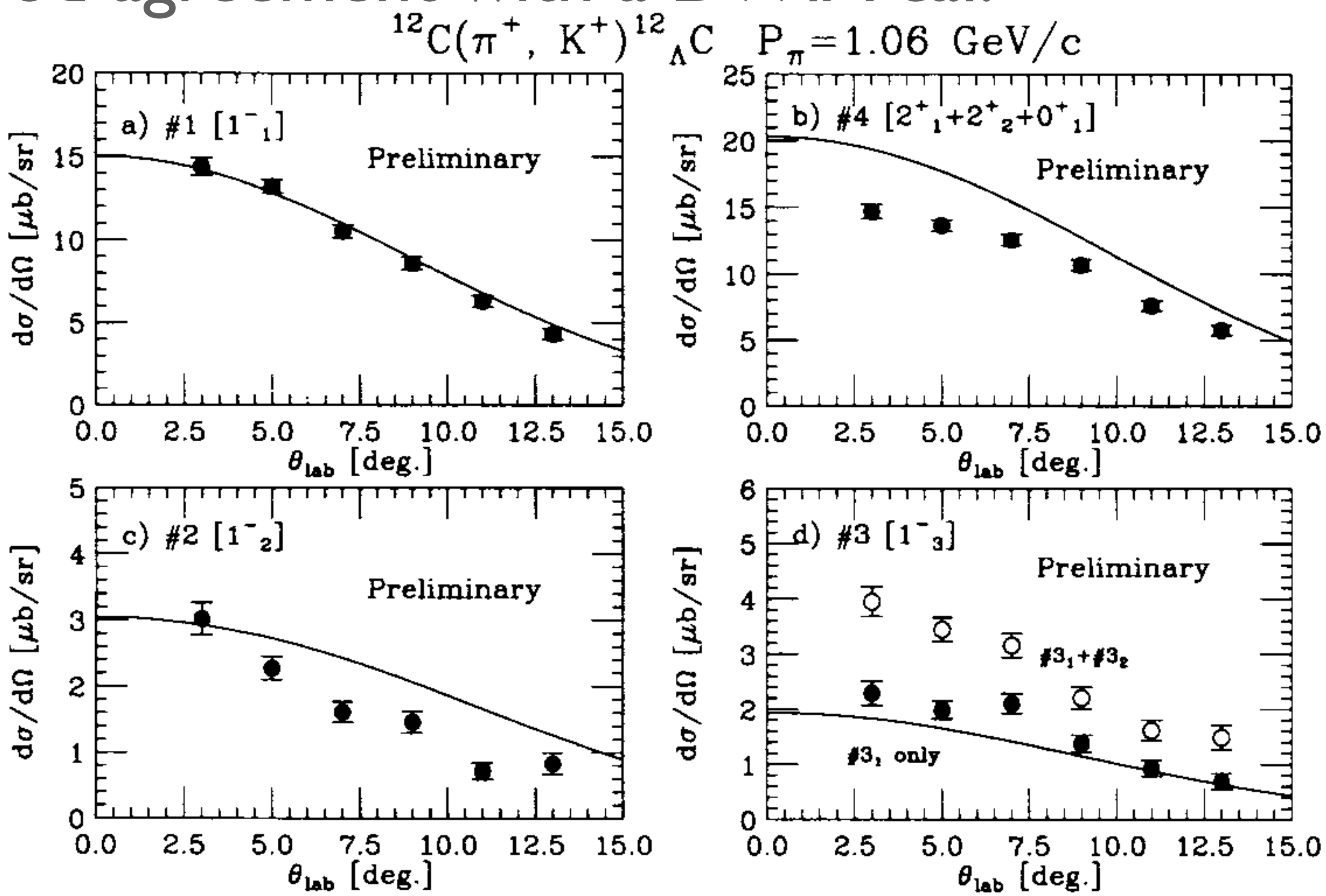
Fig. 4.1. θ-dependence of the single-particle transition matrix element $\langle n_\Lambda l_\Lambda | \tilde{j}_L Y_L U_- | n_N l_N \rangle$ calculated for the (K^-, π^-) reaction at $p_K = 720$ MeV/c.[255]

(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)

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

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

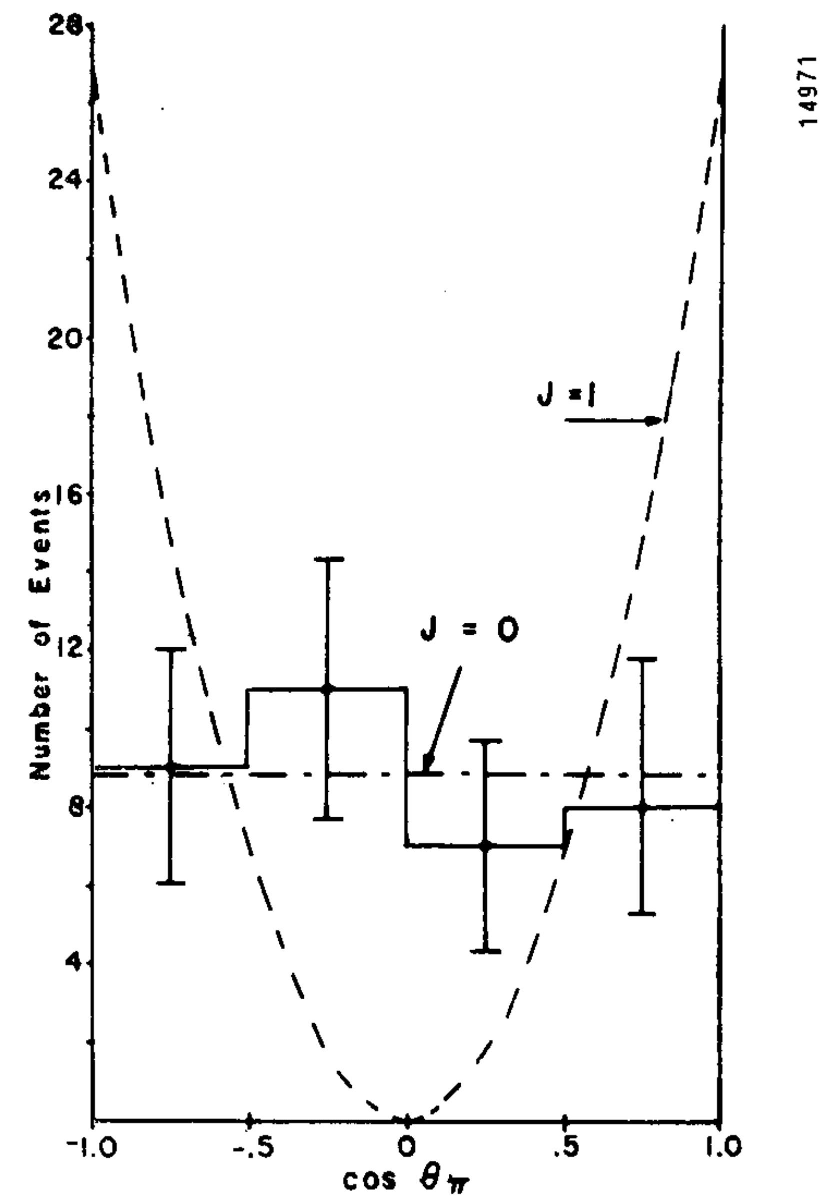
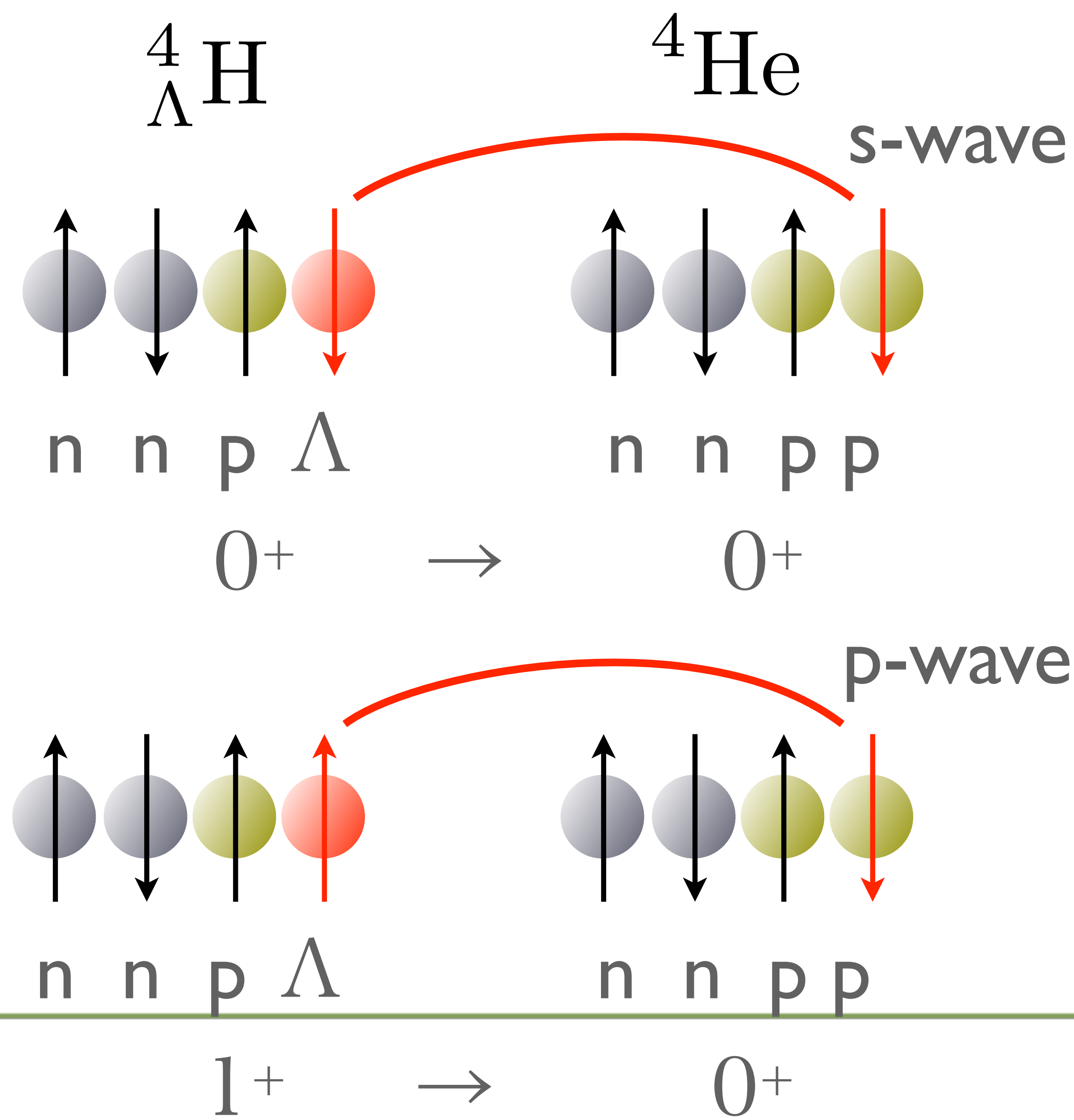


Fig. 1 The angular distribution of the π^- from the decay $_\Lambda H^4 \rightarrow \pi^- + He^4$, for hyperfragments produced in the capture reaction $K^- + He^4 \rightarrow {}_\Lambda H^4 + \pi^0$.

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. $p^2/(s^2+p^2)$



R4

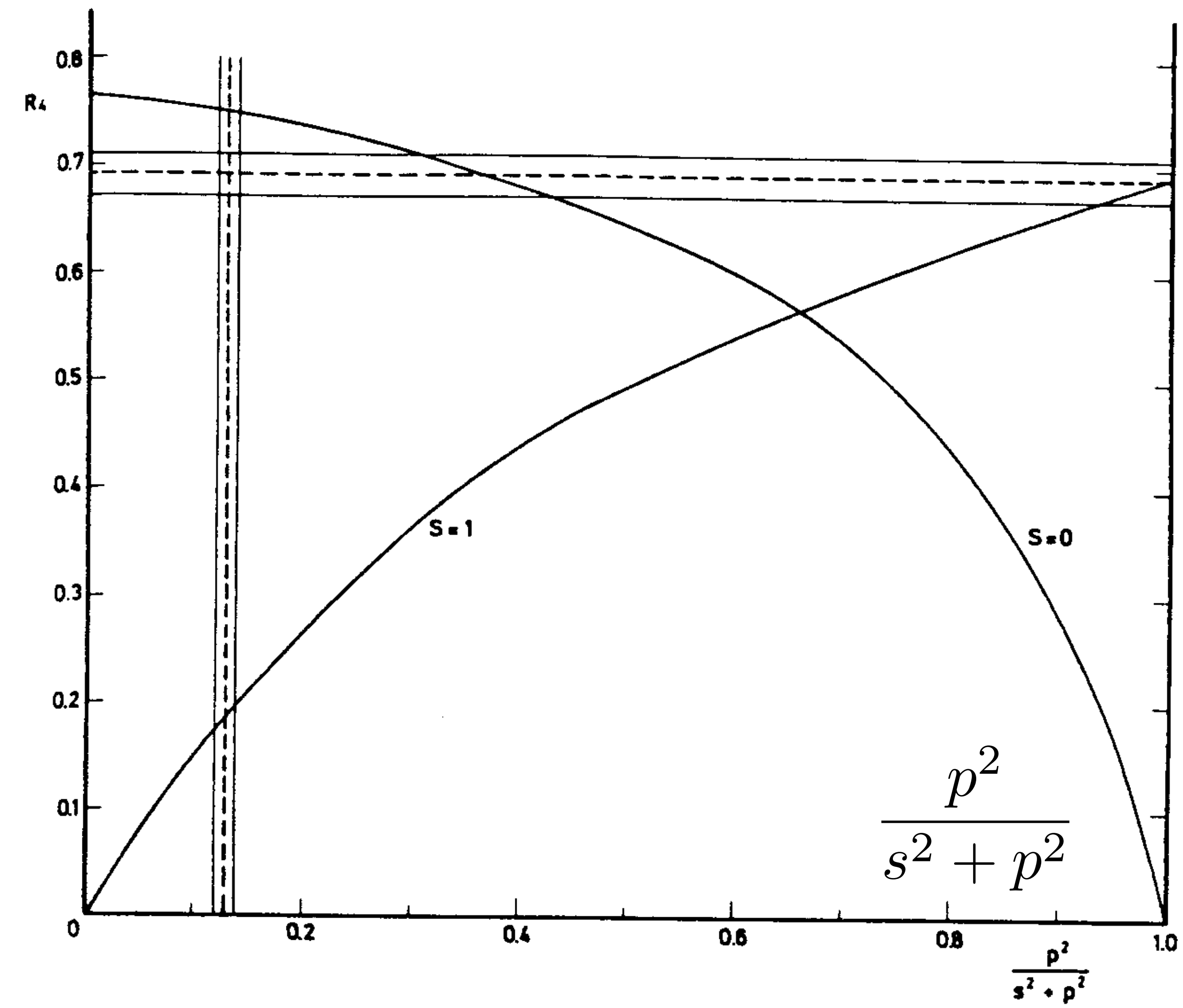


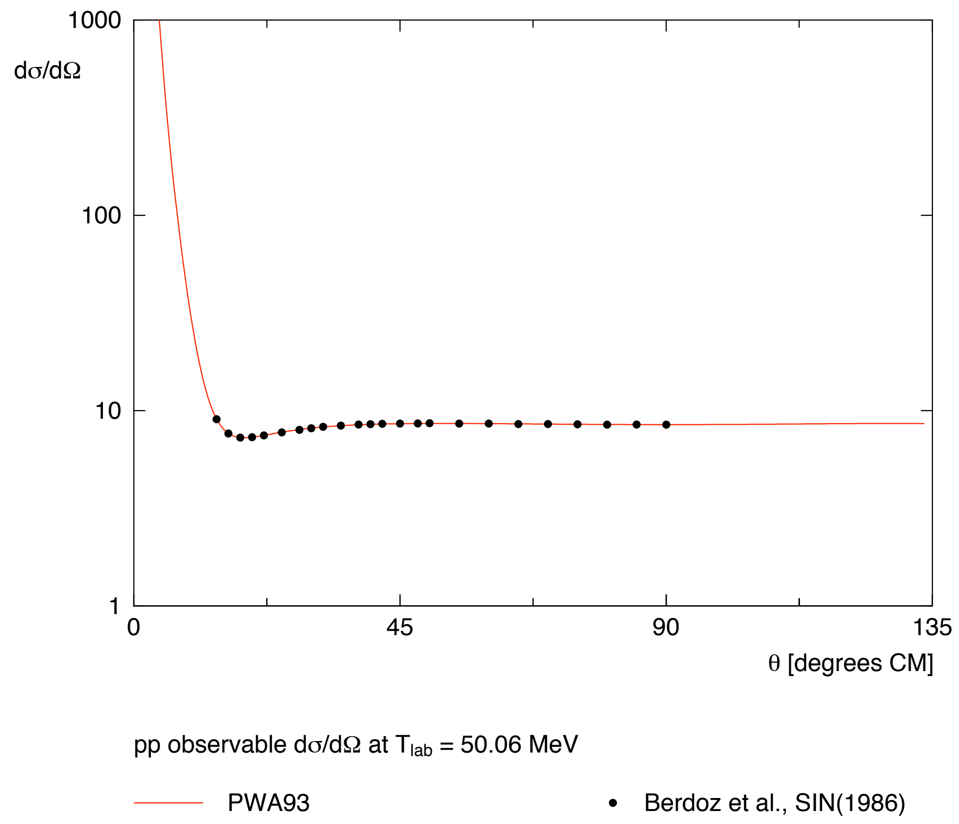
Fig. 3. The ratio $R_4 = (^4_\Lambda H \rightarrow \pi^- + {}^4He)/(\text{all } \pi^- \text{ mesonic decays of } {}^4_\Lambda H)$ as a function of $p^2/(p^2+s^2)$. The curves illustrate the results of the calculations made by Dalitz and Liu [4] for $J(^4_\Lambda H) = 0$ and 1.

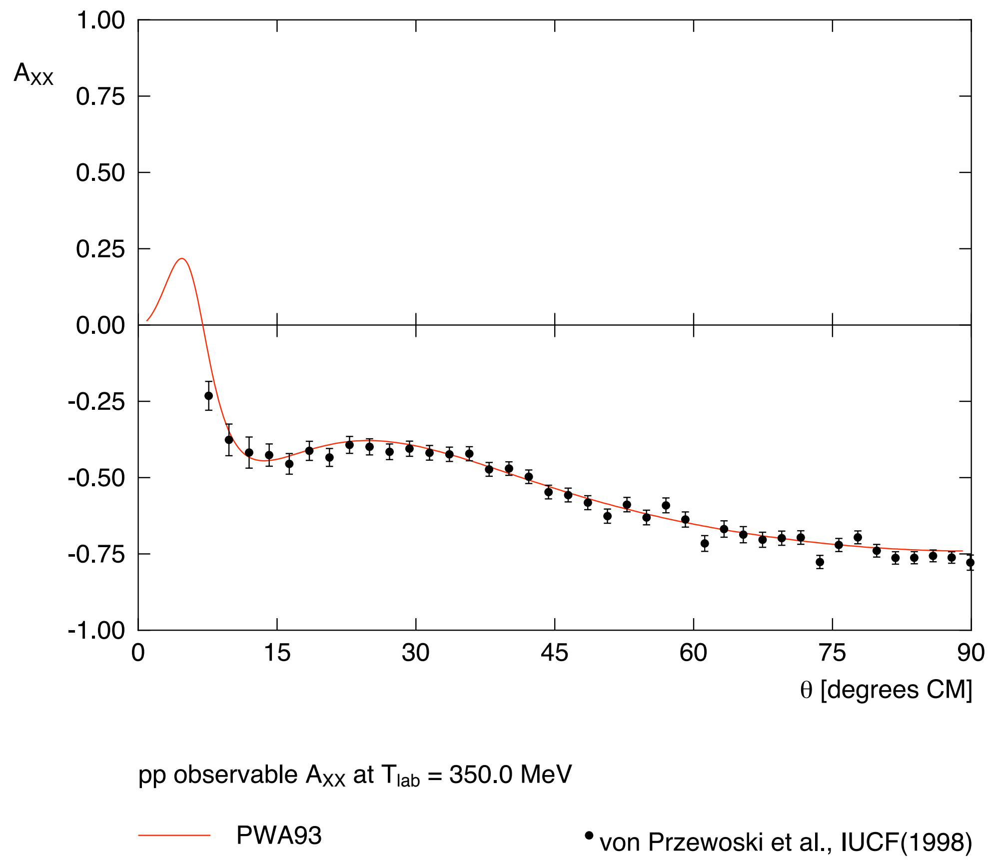
Motivations of Hypernuclear Spectroscopy

- 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 $d\sigma/d\Omega$, >2000 Pol., +1700 data



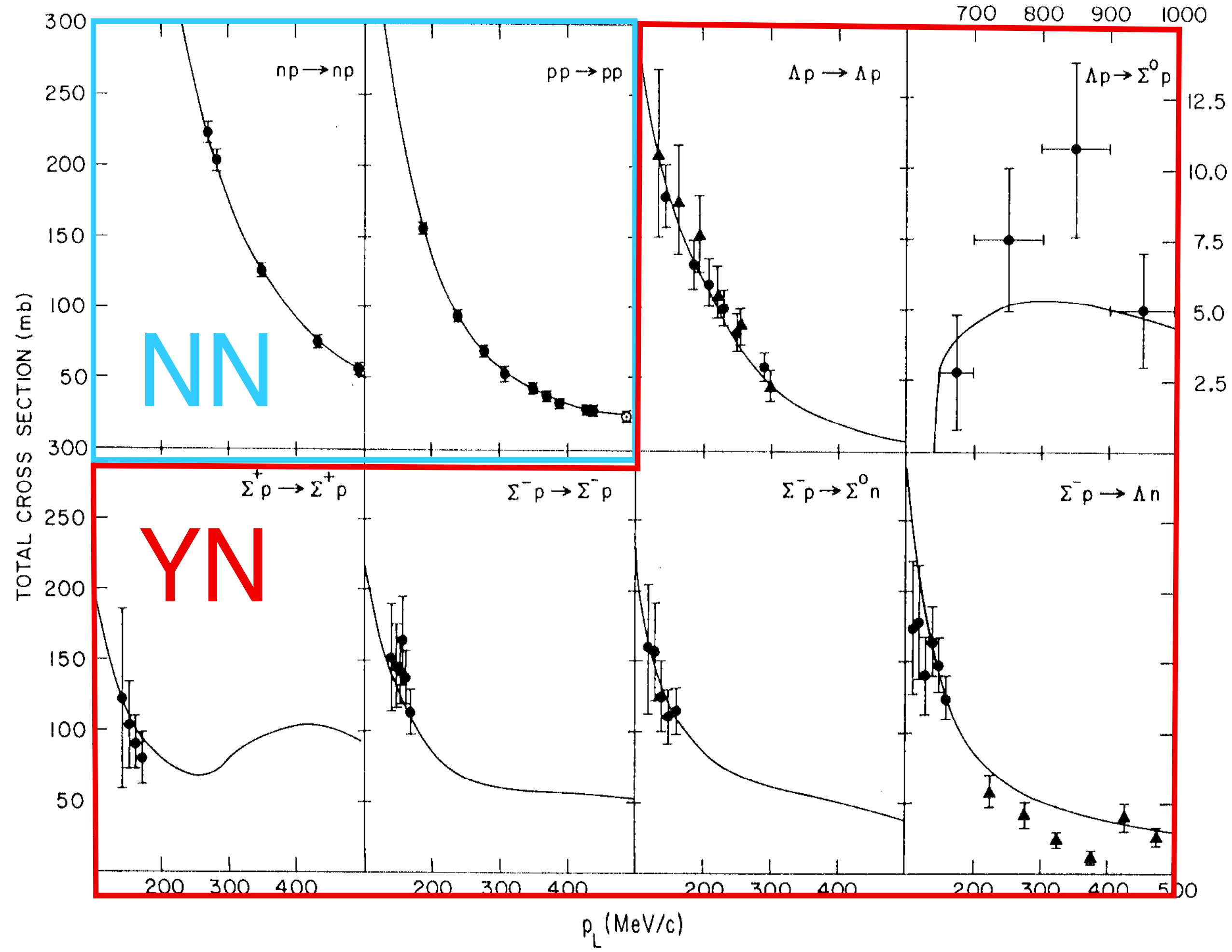


Hyperon-Nucleon Scattering

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

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

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



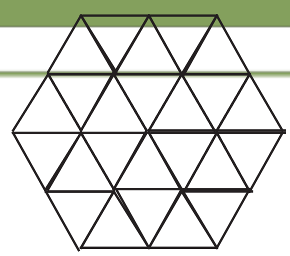
from Dover & Feshbach Ann.Phys.198(90)321

Need high quality data with high statistics

Baryon-Baryon Interaction

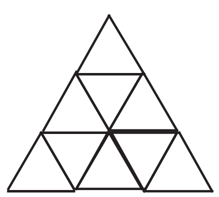
Baryon-Baryon Systems in SU(3)

27 s



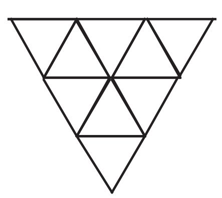
S=0 NN(T=1)
S=-1 ΣN(T=3/2)ΣN–ΛN(T=1/2)
S=-2 ΣΣ(T=2)ΞN–ΣΛ–ΣΣ(T=1)ΞN–ΣΣ–ΛΛ(T=0)
S=-3 ΞΣ(T=3/2)ΞΣ–ΞΛ(T=1/2)
S=-4 ΞΞ(T=1)

10 a



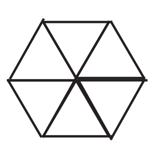
S=0 NN(T=0)
S=-1 ΣN–ΛN(T=1/2)
S=-2 ΞN–ΣΛ(T=1)
S=-3 ΞΣ(T=3/2)

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)

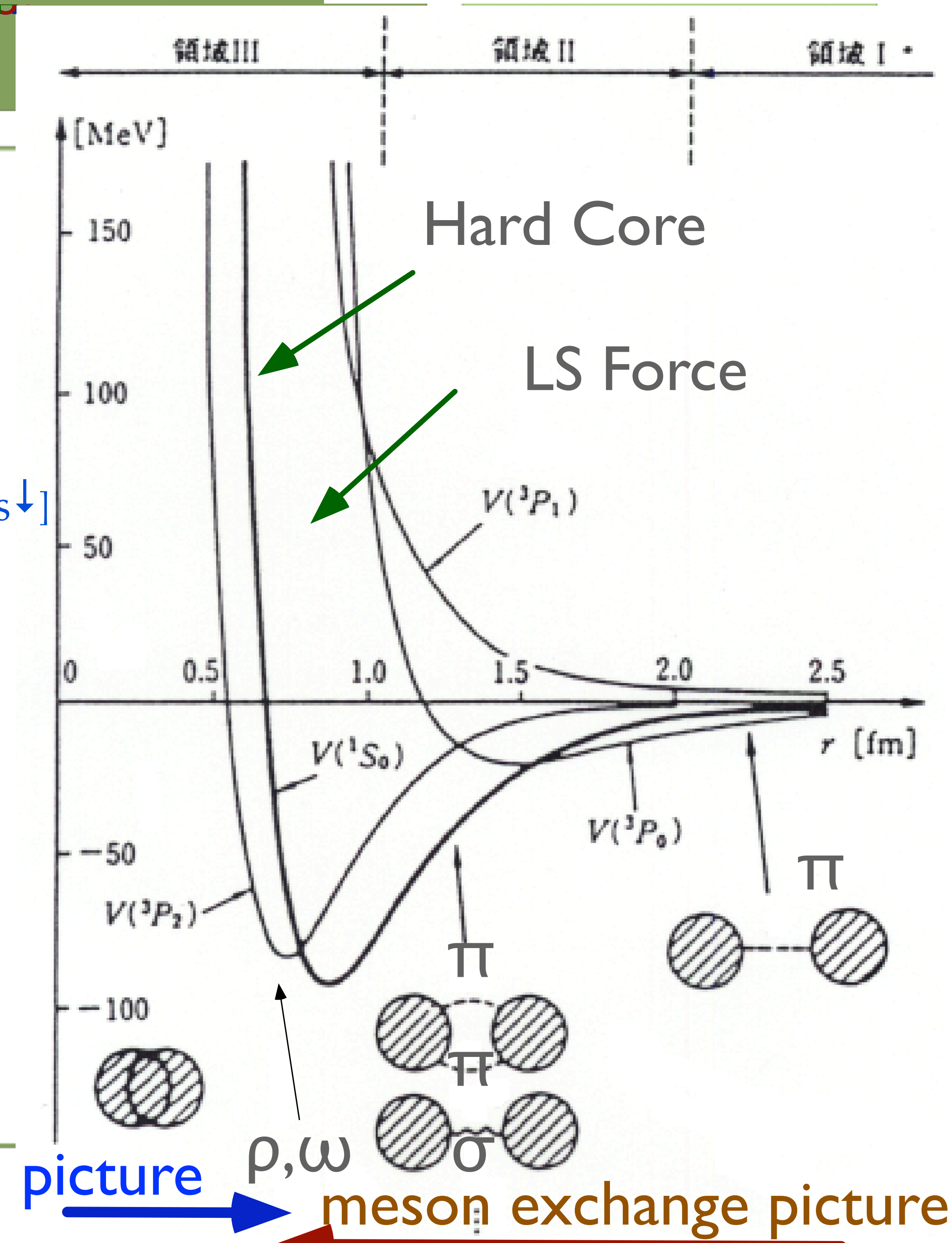
H Dibaryon ?

- 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 $\Lambda\Lambda$-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

Theory Interest in Flavor Nuclear Physics

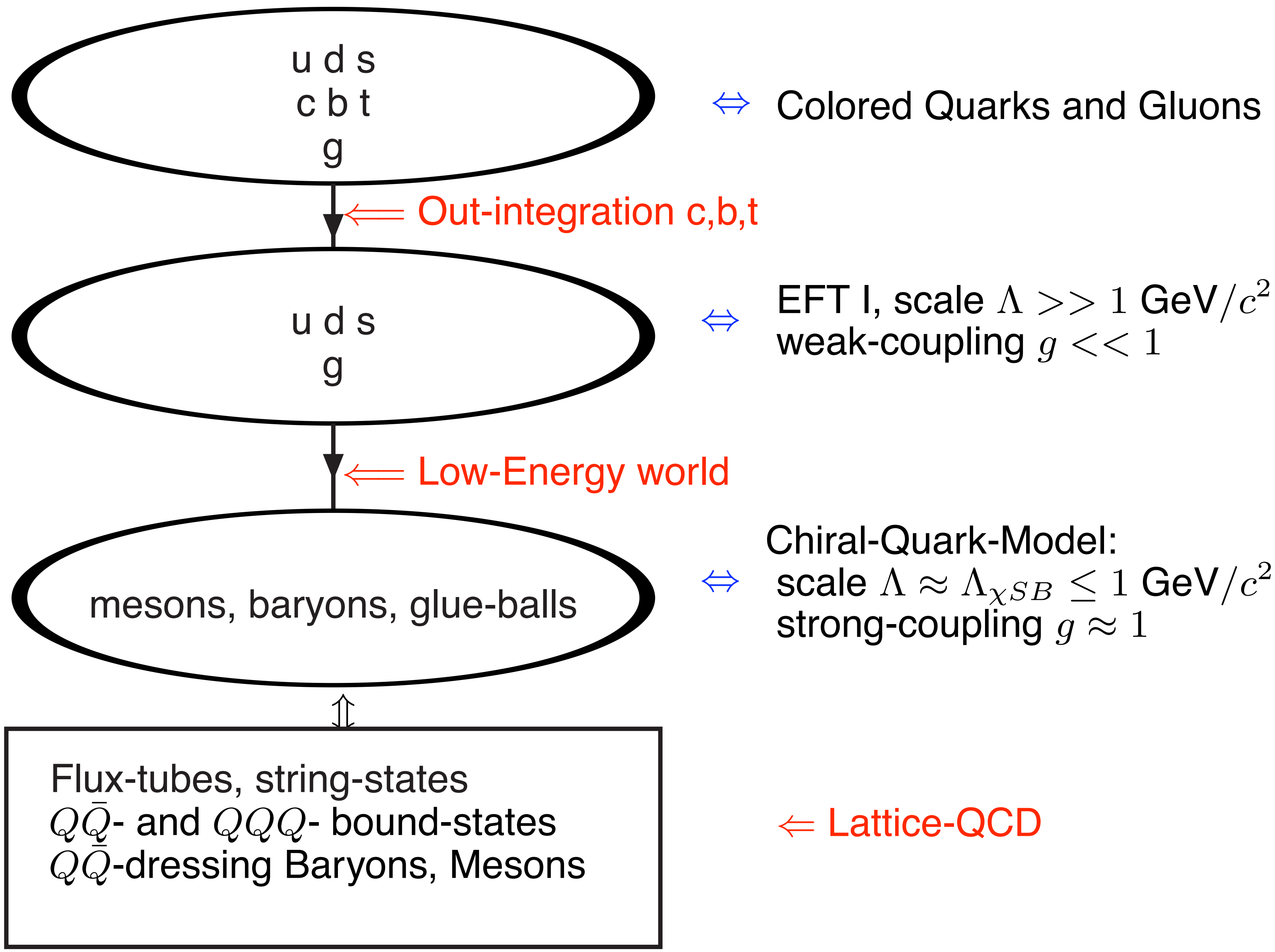
- Recent Model building:

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

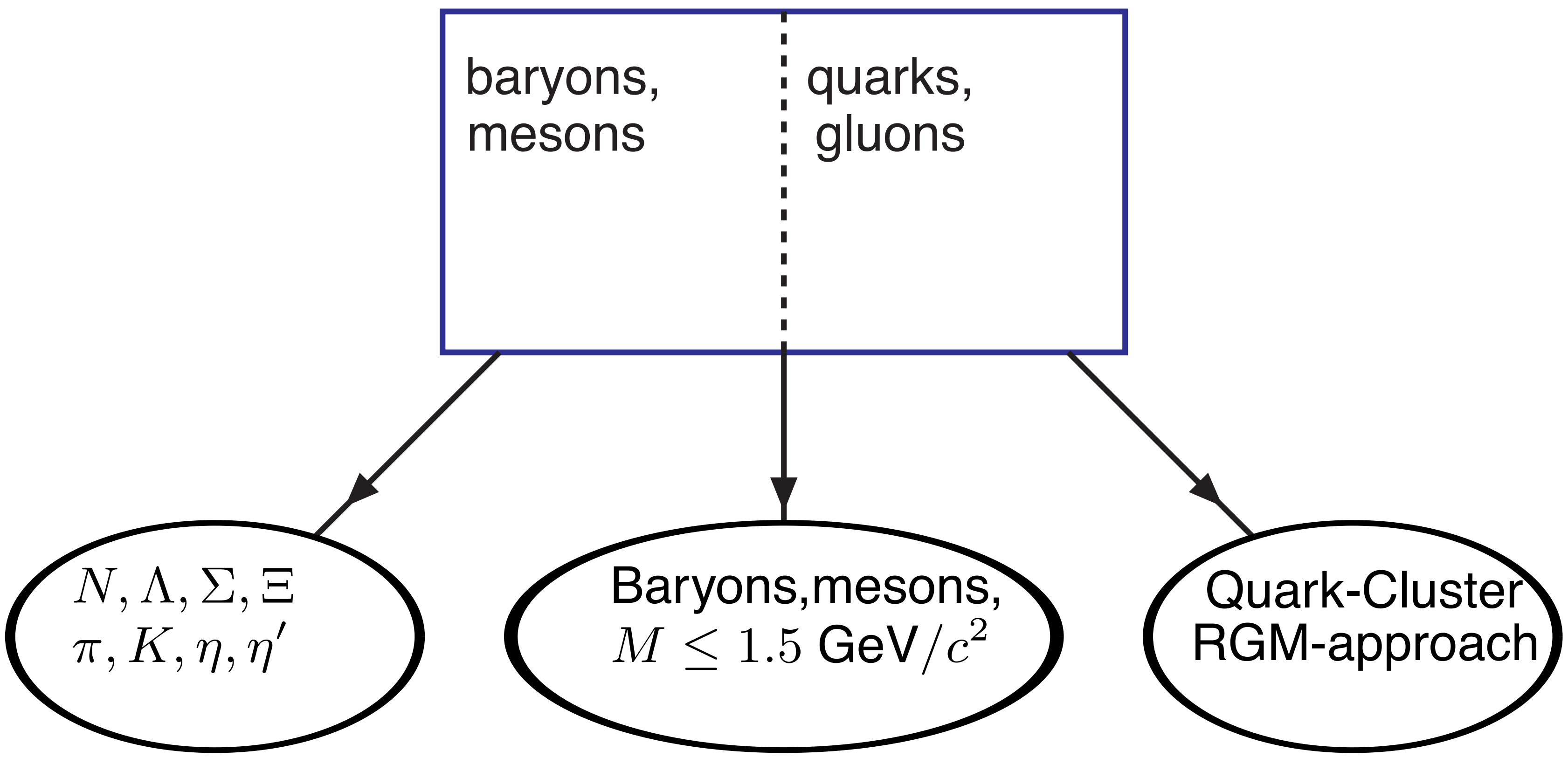
QCD-world I: mesons and baryons



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]

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

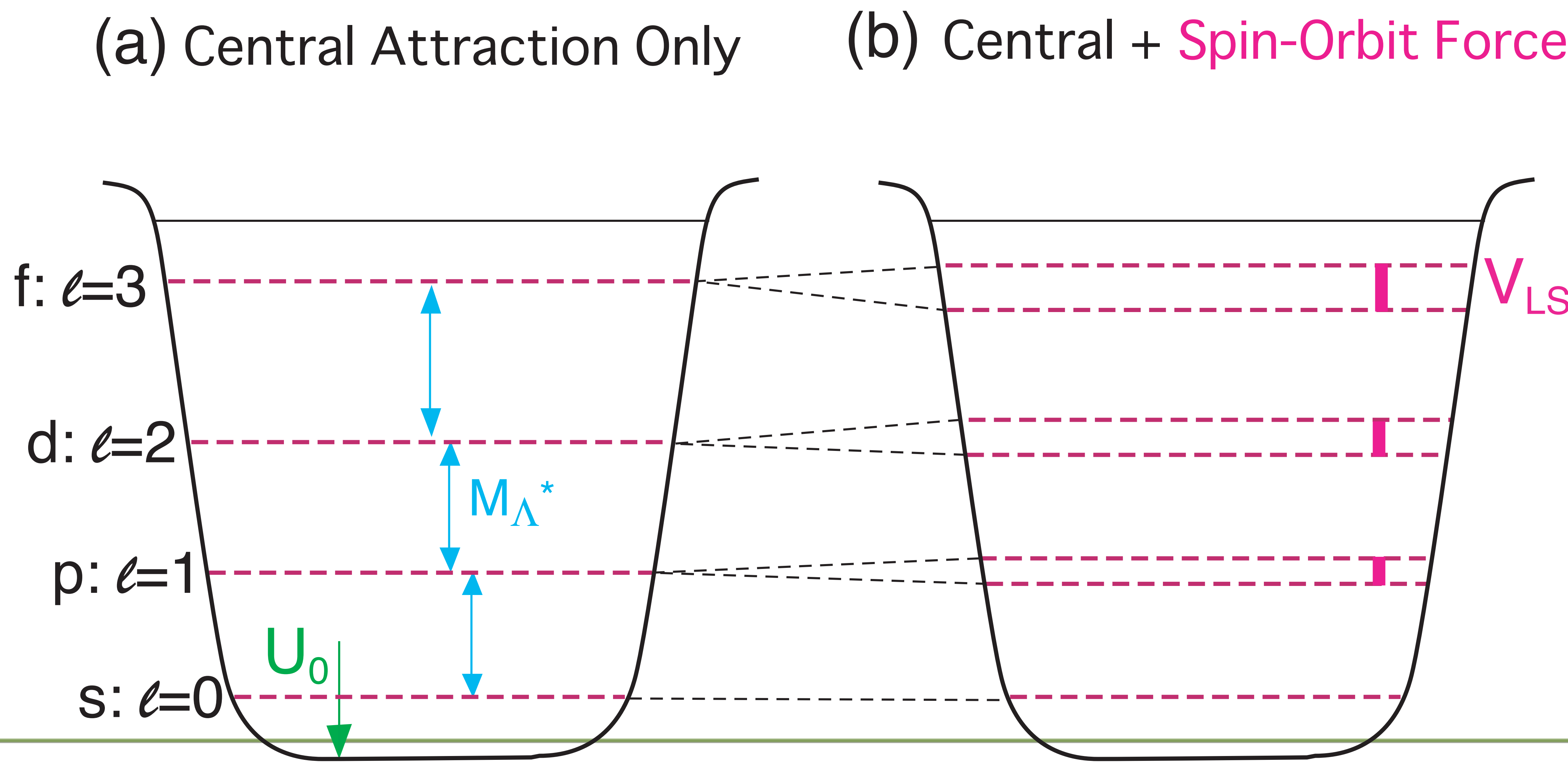
  - n: -|ddu>{2|++->-|+-+>-|-++>}/3$\sqrt{2}$
  - Σ⁻: |dds>{2|++->-|+-+>-|-++>} /3$\sqrt{2}$

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

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

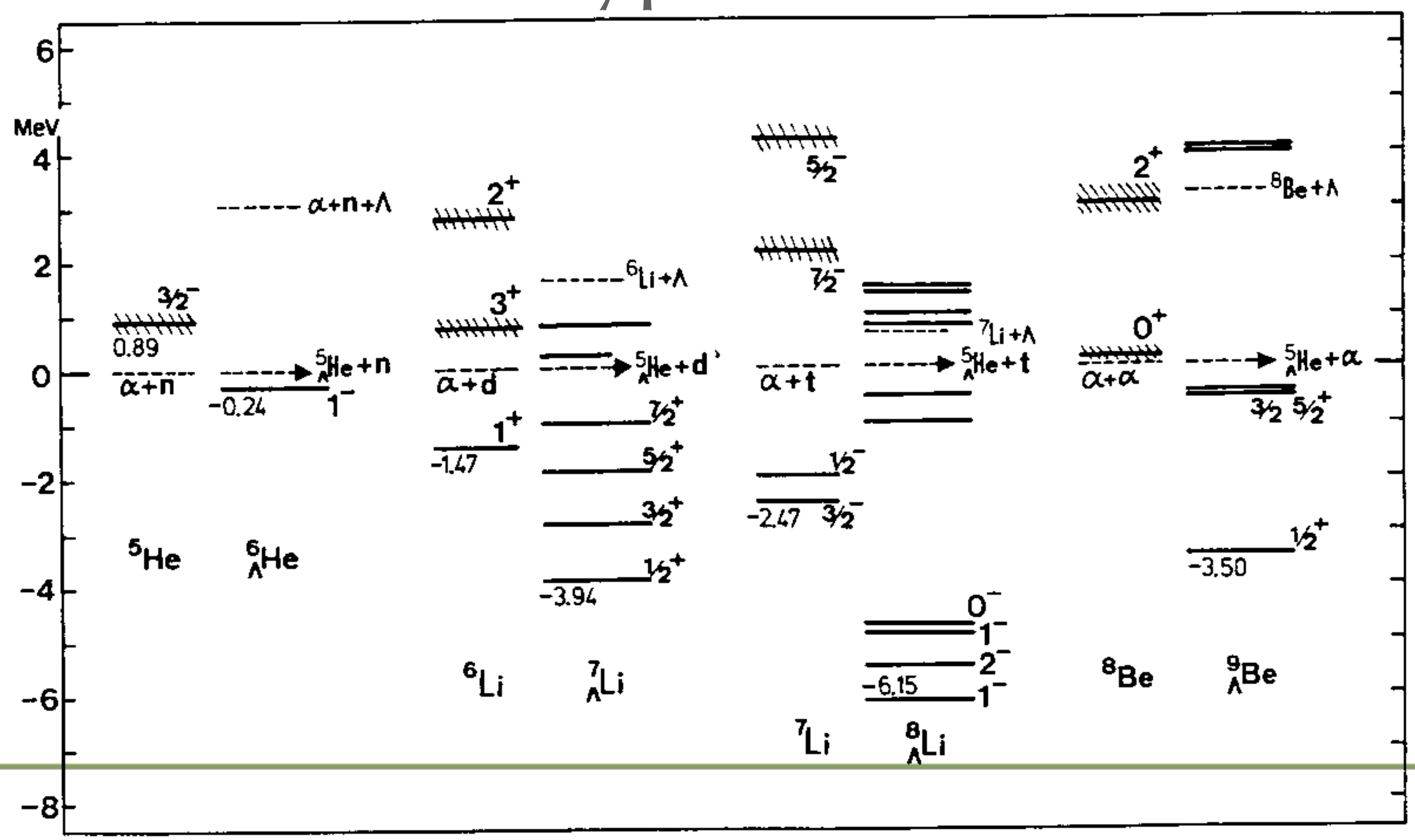
Hypernuclear structure and ΛN interaction

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



Impurity Effect - I

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

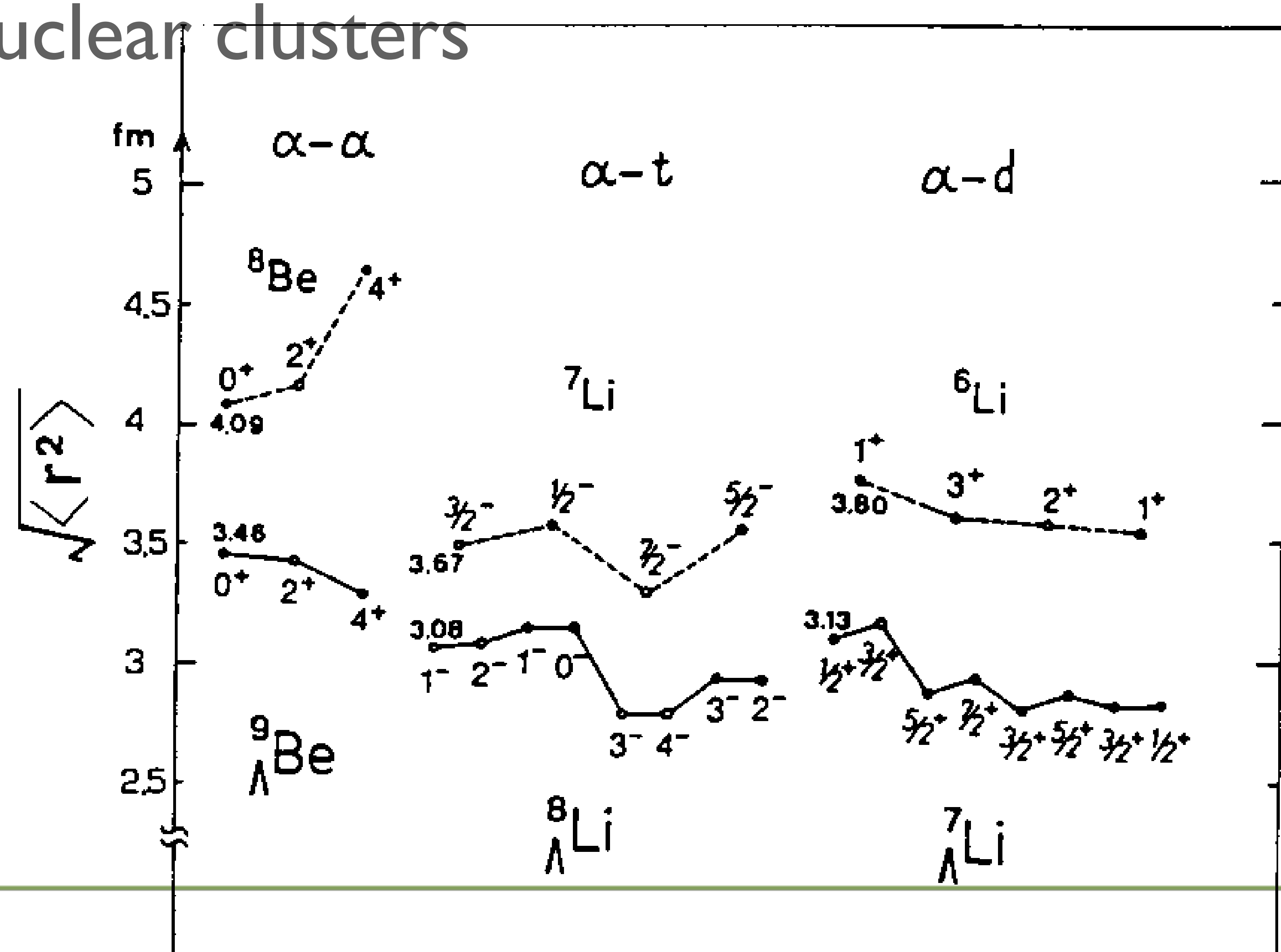


Impurity Effect -2

- Structure Change
  - Shrinkage of nuclear clusters

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

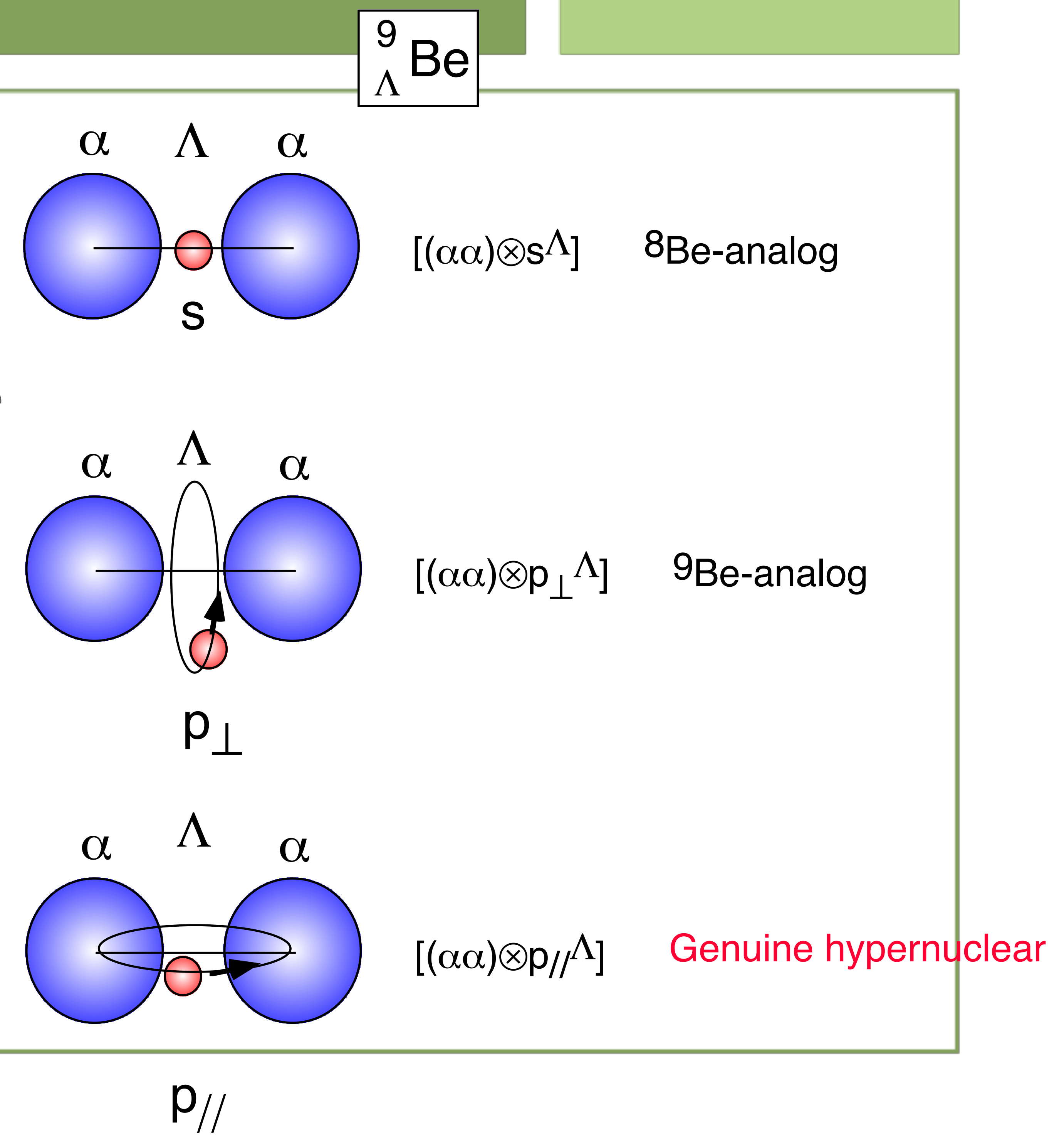
$\propto R^4$ or $(\beta \langle r^2 \rangle)^2$



Impurity Effect -3

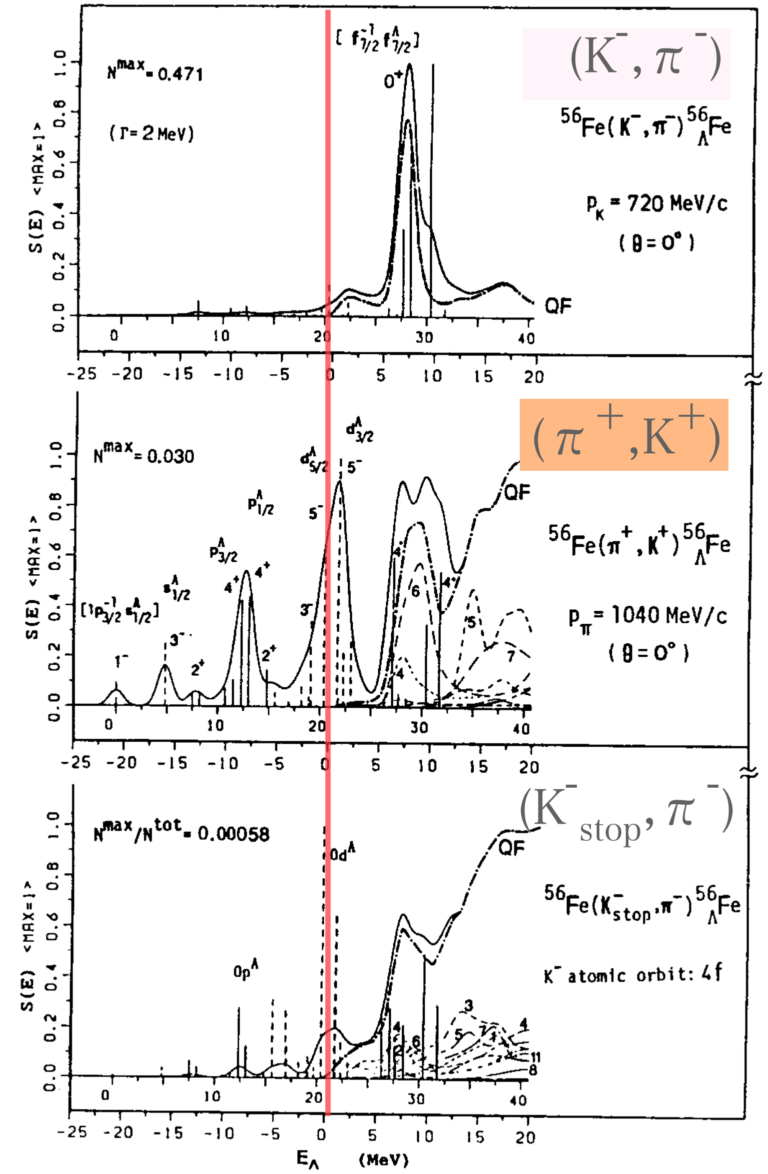
- New symmetry:
  - Supersymmetric state or Genuine hypernuclear state

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



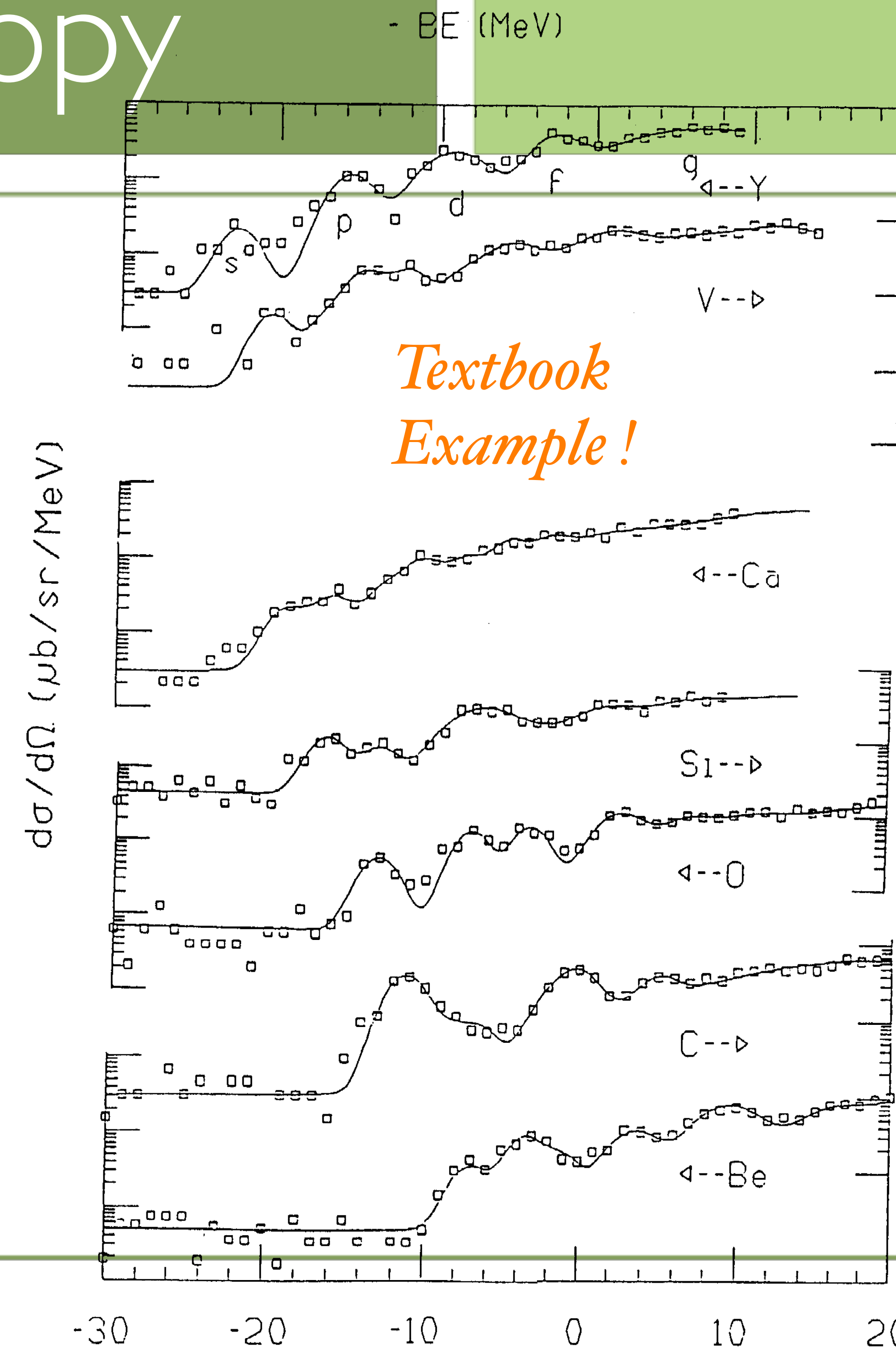
(π^+, K^+) Spectroscopy

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

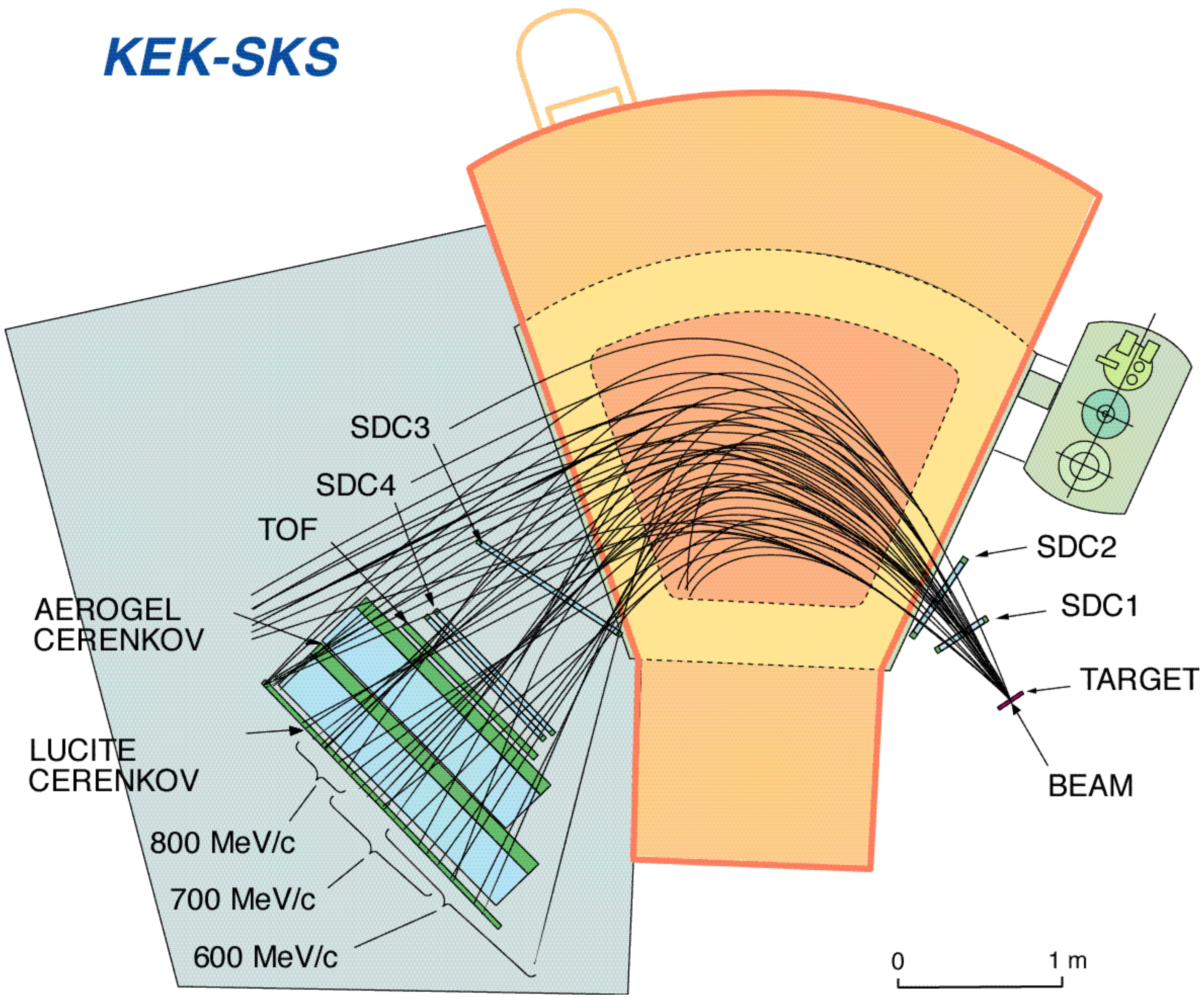


(π^+,K^+) Spectroscopy

- Reaction mechanism:
  - Dover, Ludeking, Walker, Phys. Rev. C22(1980) 2073.
- Success at BNL(1985, 1988)
  - $\Delta E \sim 3$ 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

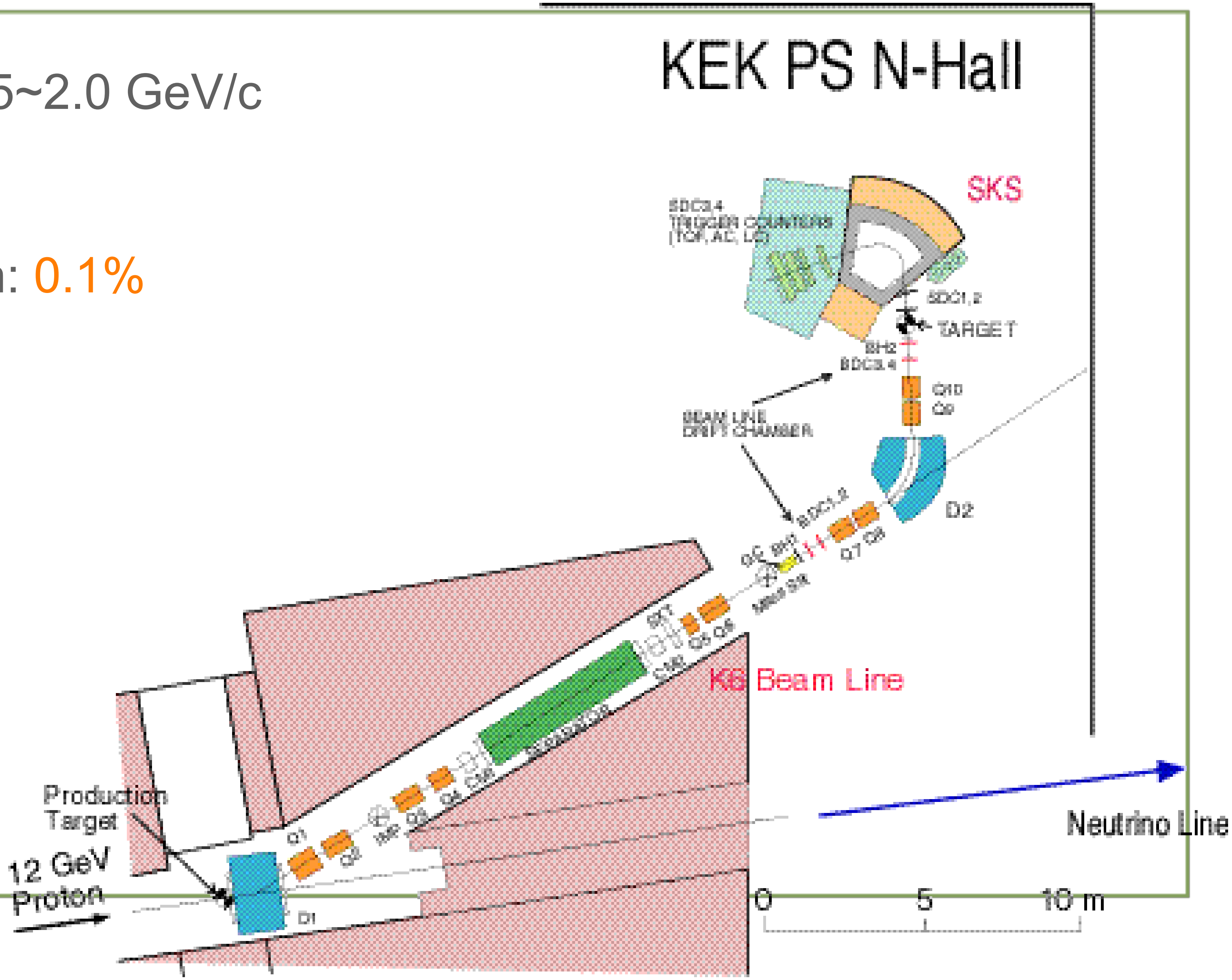
- Momentum resolution:
  0.1%(FWHM) at 720 MeV/c
- Solid angle: 100 msr
  - To get enough yields
- Short Flight Path: ~5 m
  - To reduce K^+ decays
- Initial Goal of Energy Resolution:
  2 MeV(FWHM)

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
- ~$2 \times 10^6\ \pi^+$/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

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

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

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

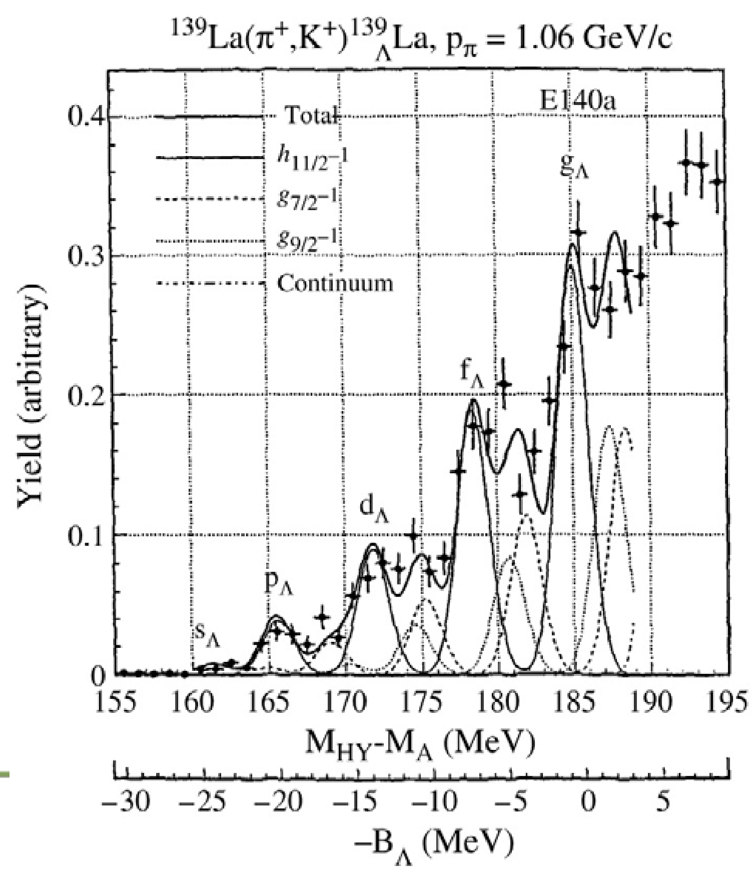
$$\frac{\langle x'|x\rangle \sigma_x}{\langle x'|\delta\rangle}$$

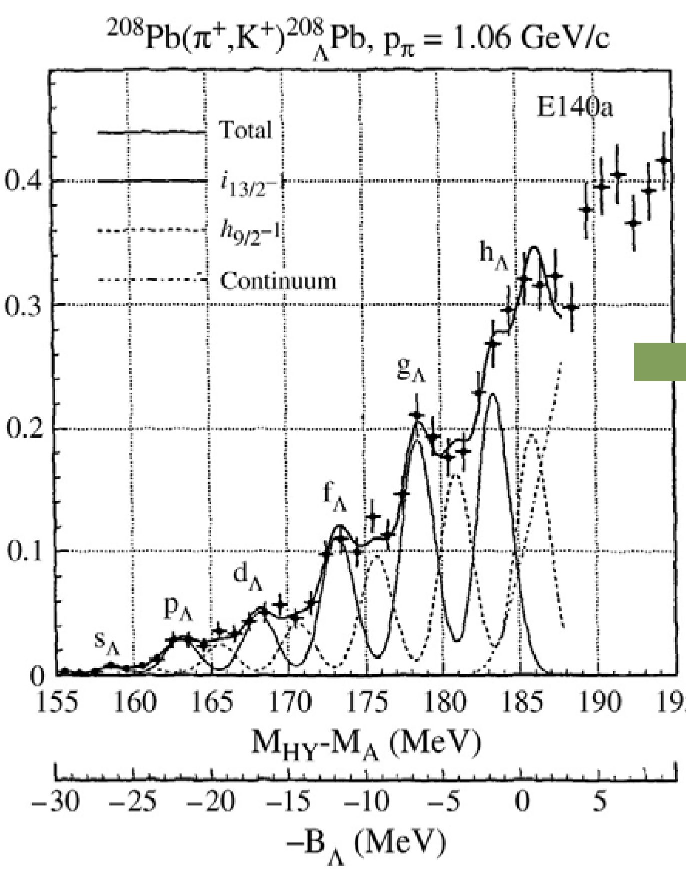
(π,K^+) experiments with SKS

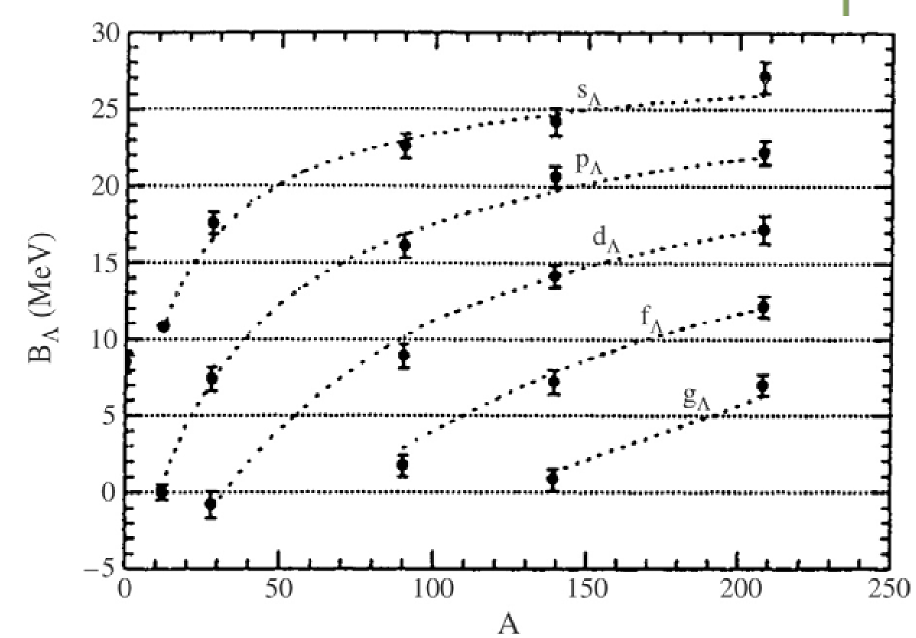
- E140a: ^{10}B, ^{12}C, ^{28}Si, ^{89}Y, ^{139}La, ^{208}Pb
  - Phys. Rev. C 53 (1996) 1210.
- E336: ^{7}Li, ^{9}Be, ^{13}C, ^{16}O
  - Nucl. Phys. A 639 (1998) 93c, Nucl. Phys. A 691 (2001) 123c.
- E369: ^{89}Y, ^{51}V, ^{12}C in high-resolution
  - Phys. Rev. C 64 (2001) 044302.
- E521: $^{10}B(\pi^-,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



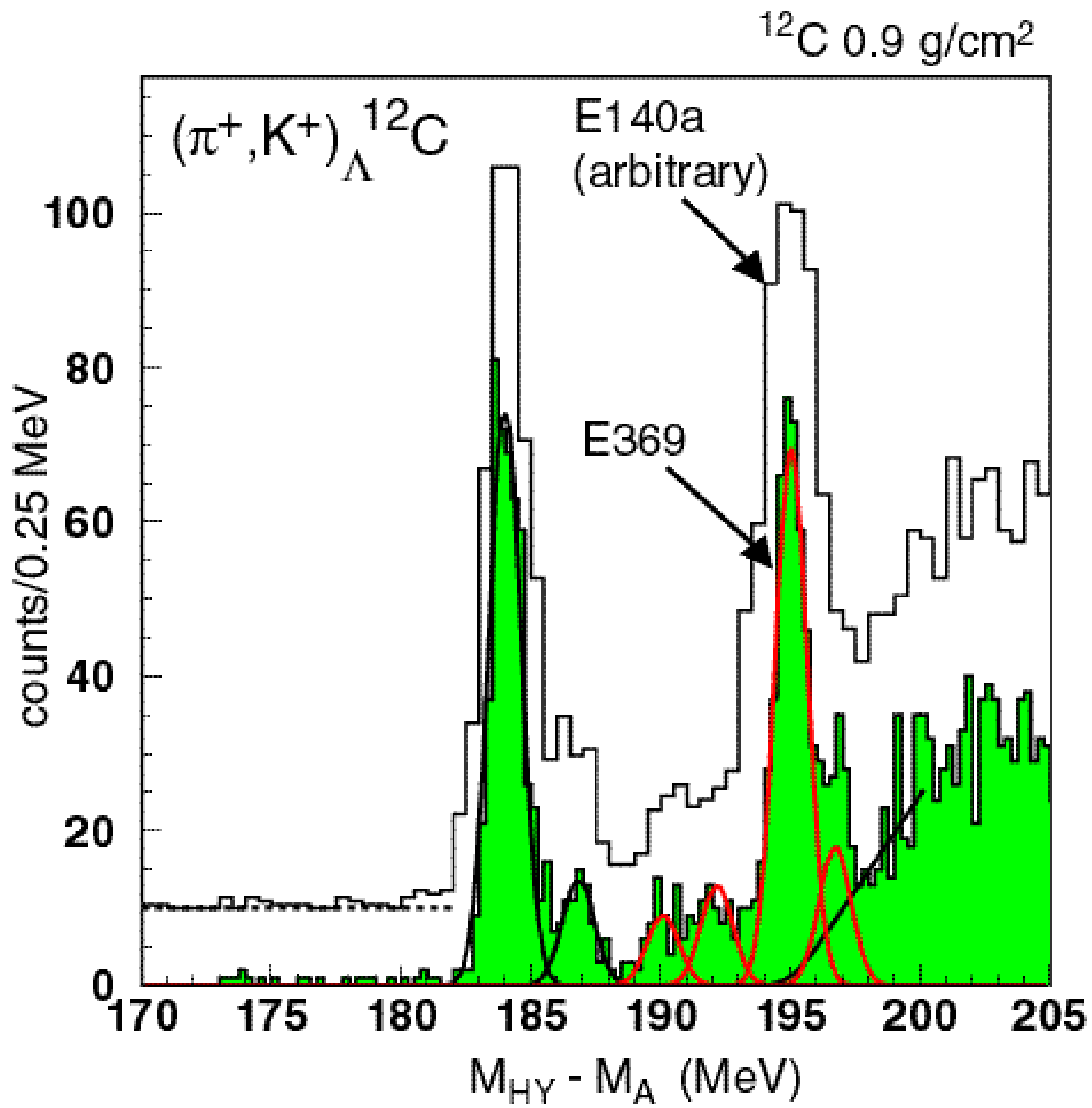




T.Hasegawa et al., Phys. Rev. C53 (1996) 1210

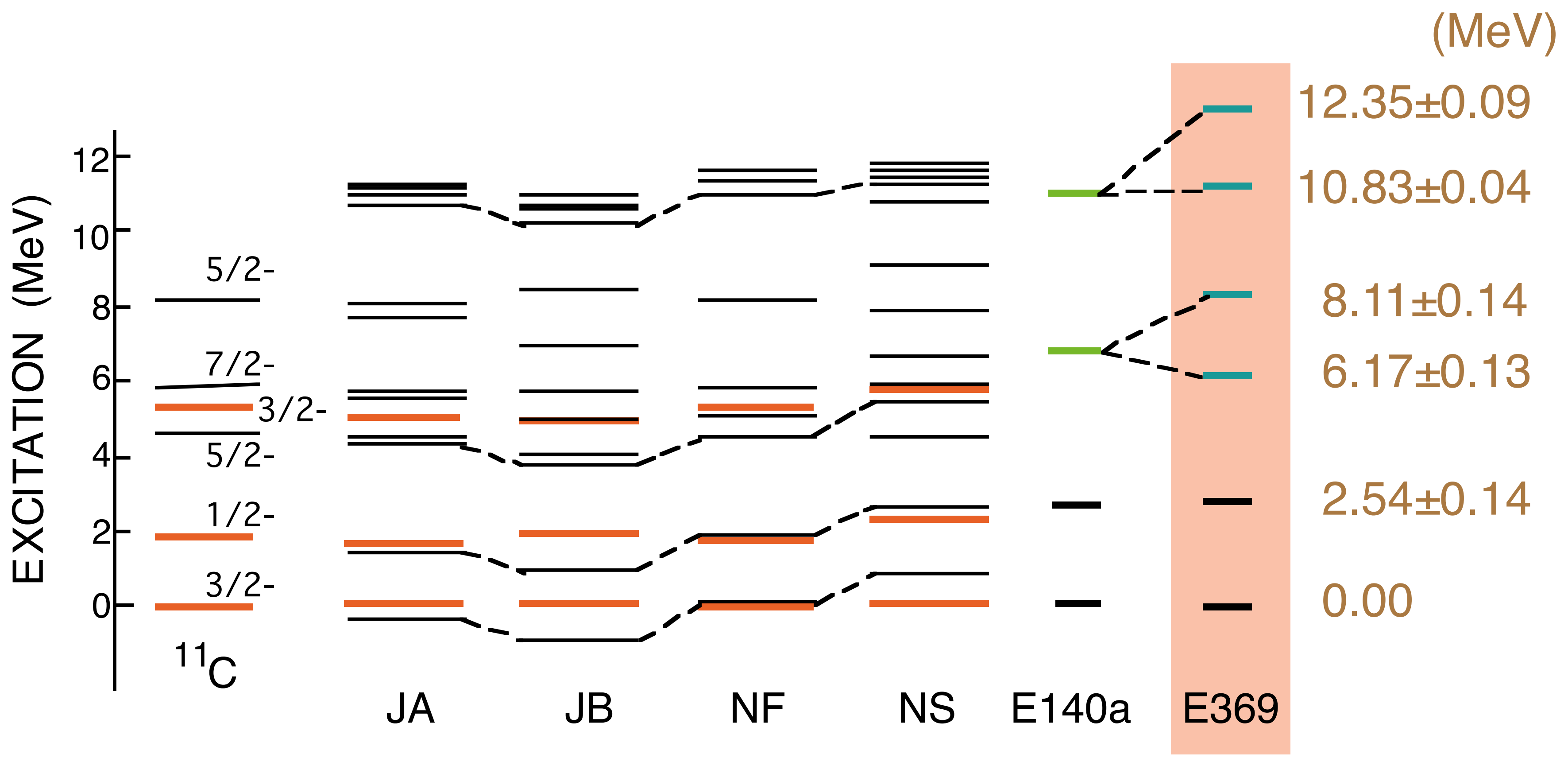
E369: $_{\Lambda}^{12}C$

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



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

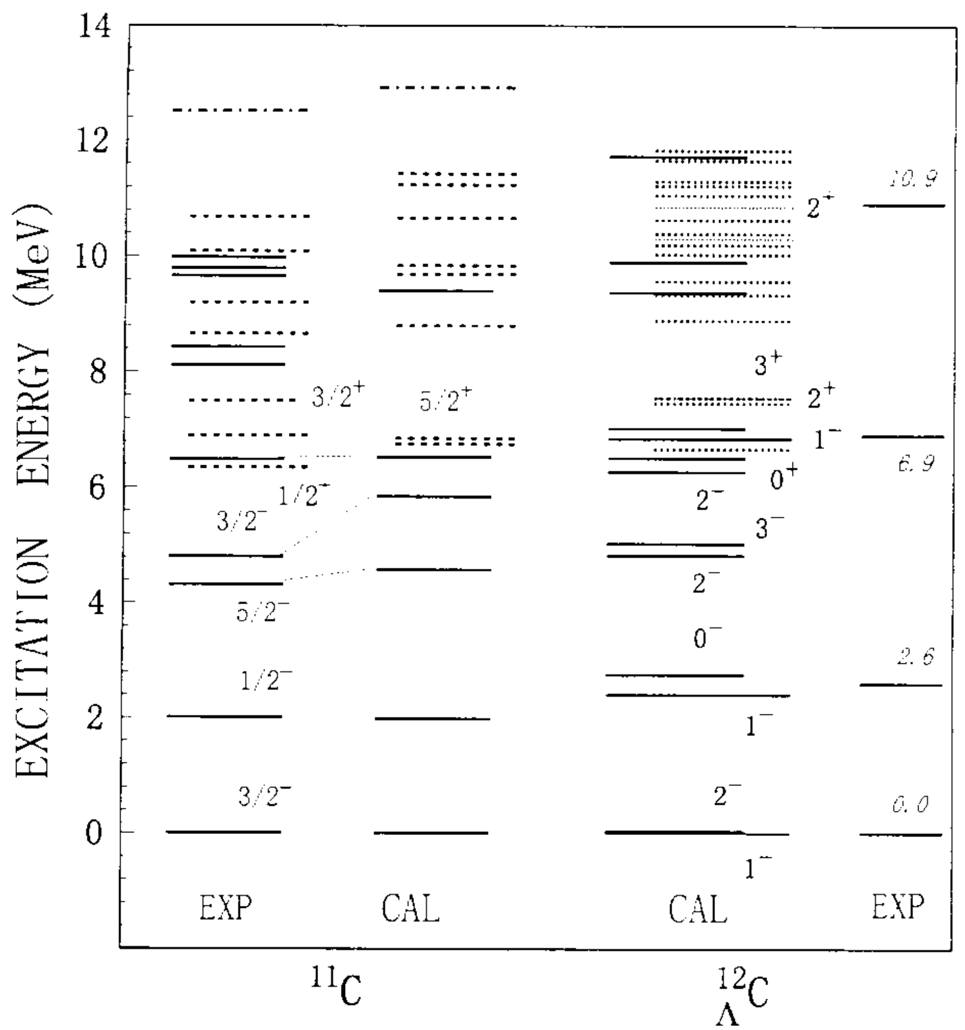
- New states are resolved.
  Effects of ΛN spin-dependent forces



Parity-mixing intershell coupling

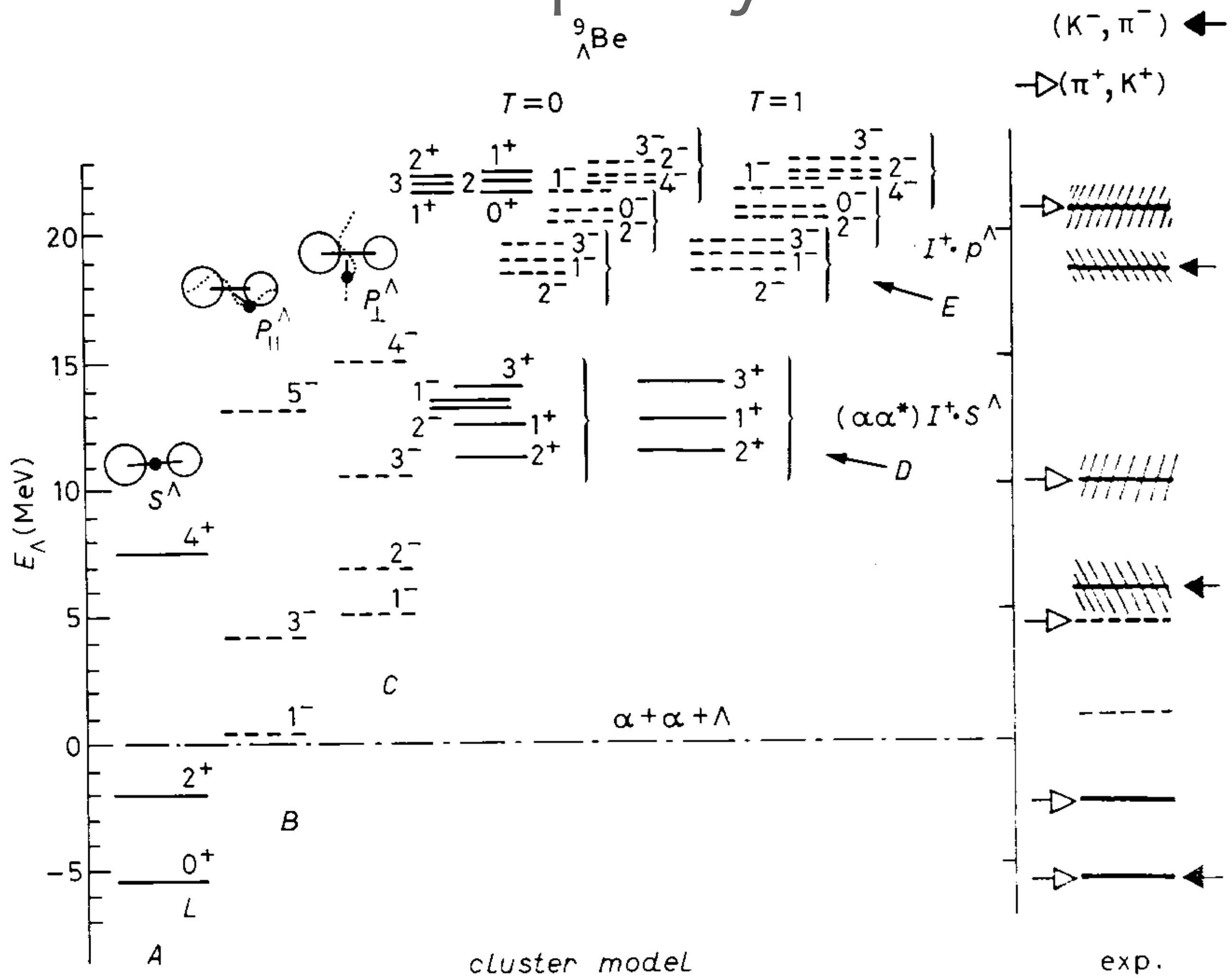
- T. Motoba, in HYP97(Nucl. Phys. A 639 (1998) 135c.)

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

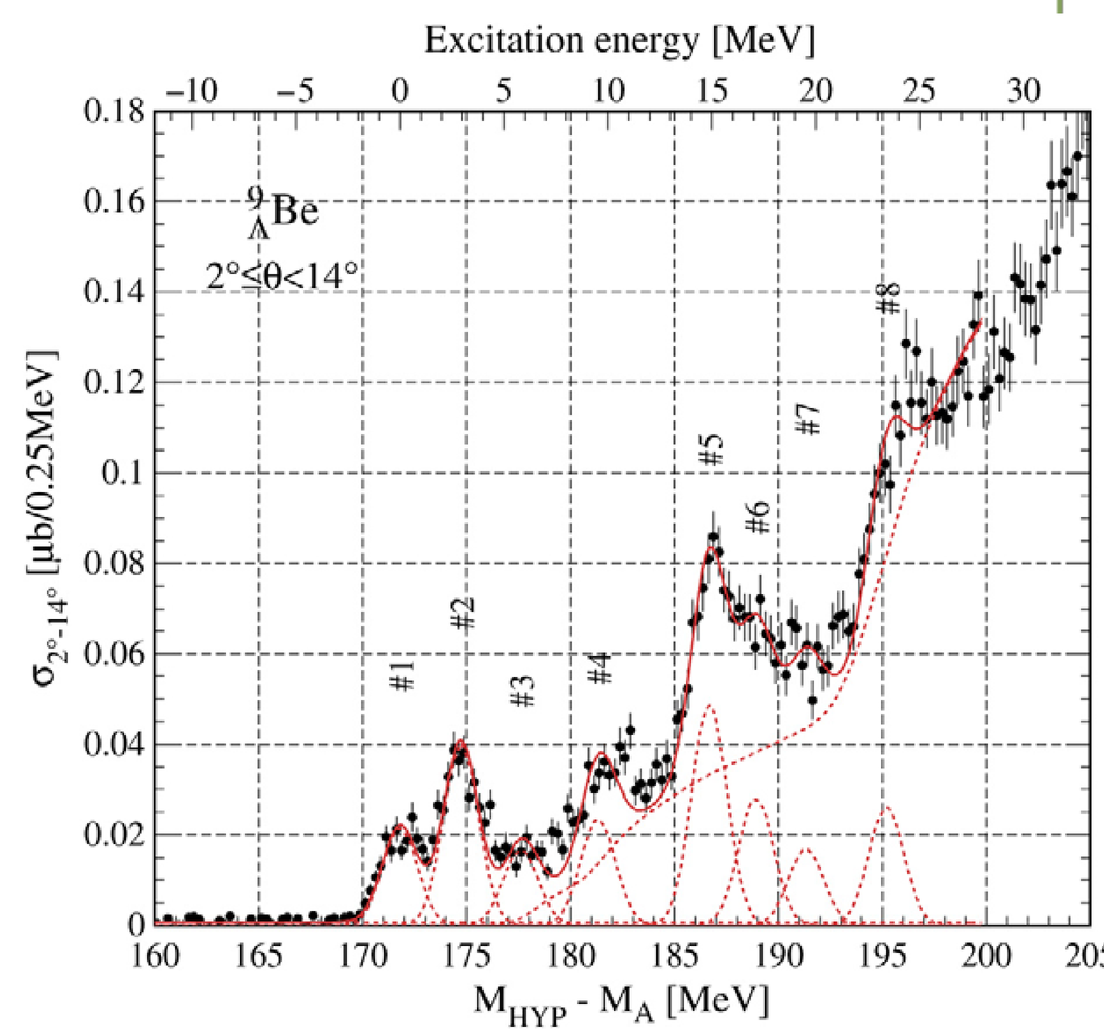


E336: $^{9}_{\Lambda}\mathrm{Be}$

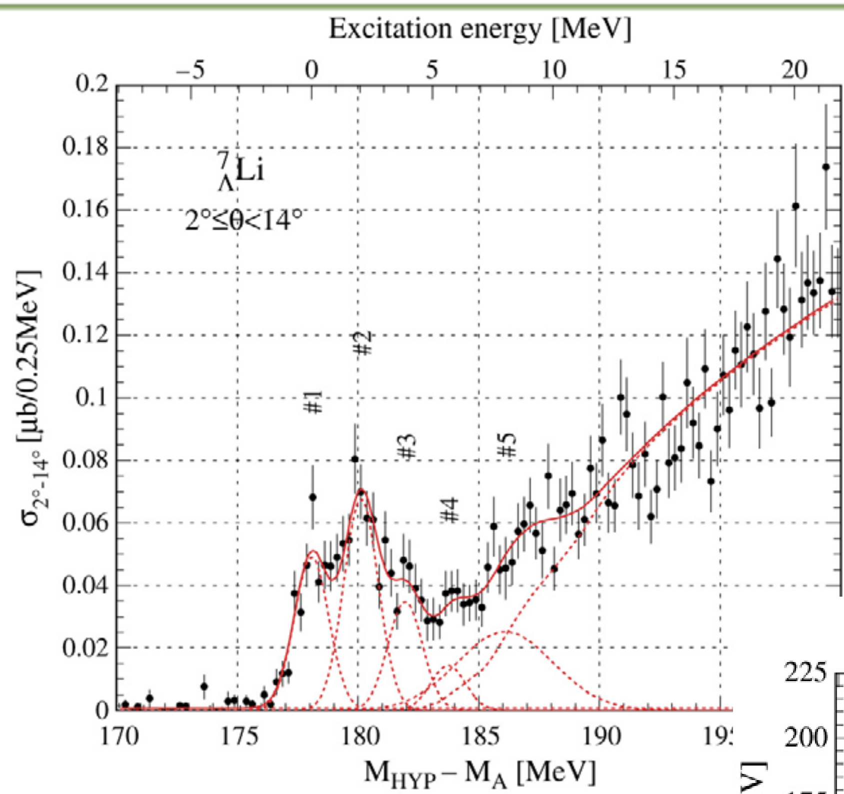
- Observation of "genuine" hypernuclear states or "Supersymmetric" states

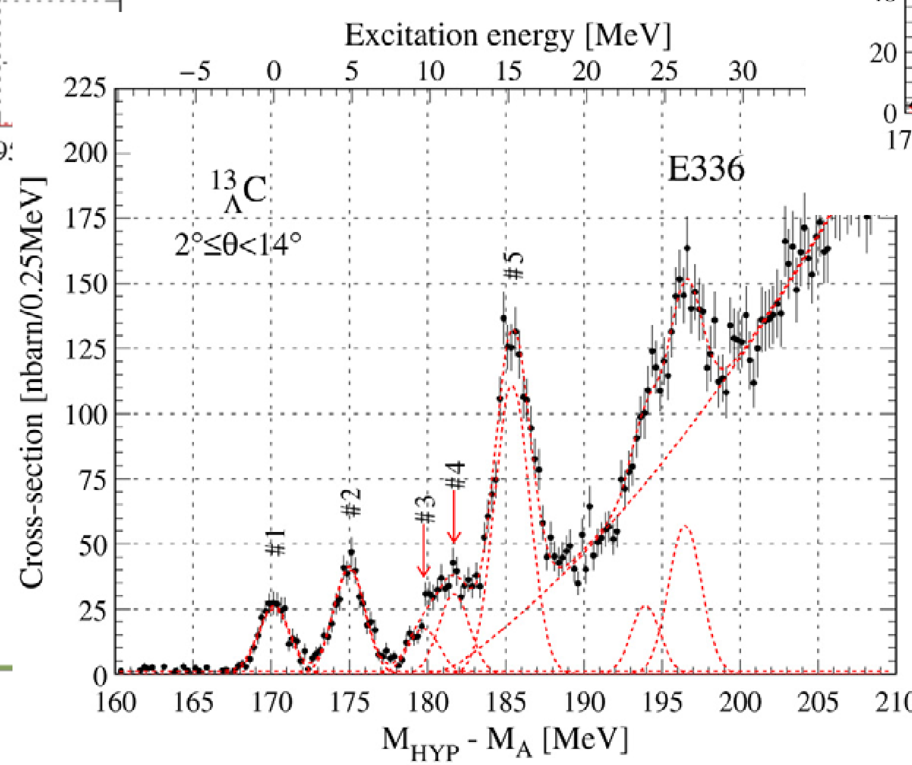


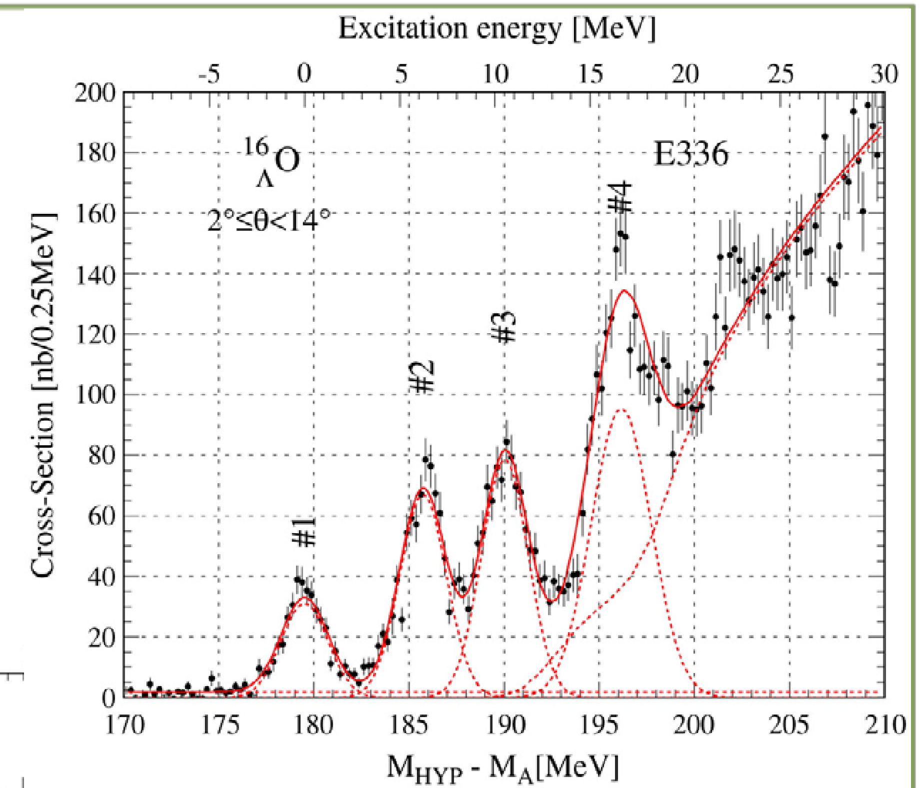
T.Motoba, Il Nuovo Cim. 102A (1989) 345.



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

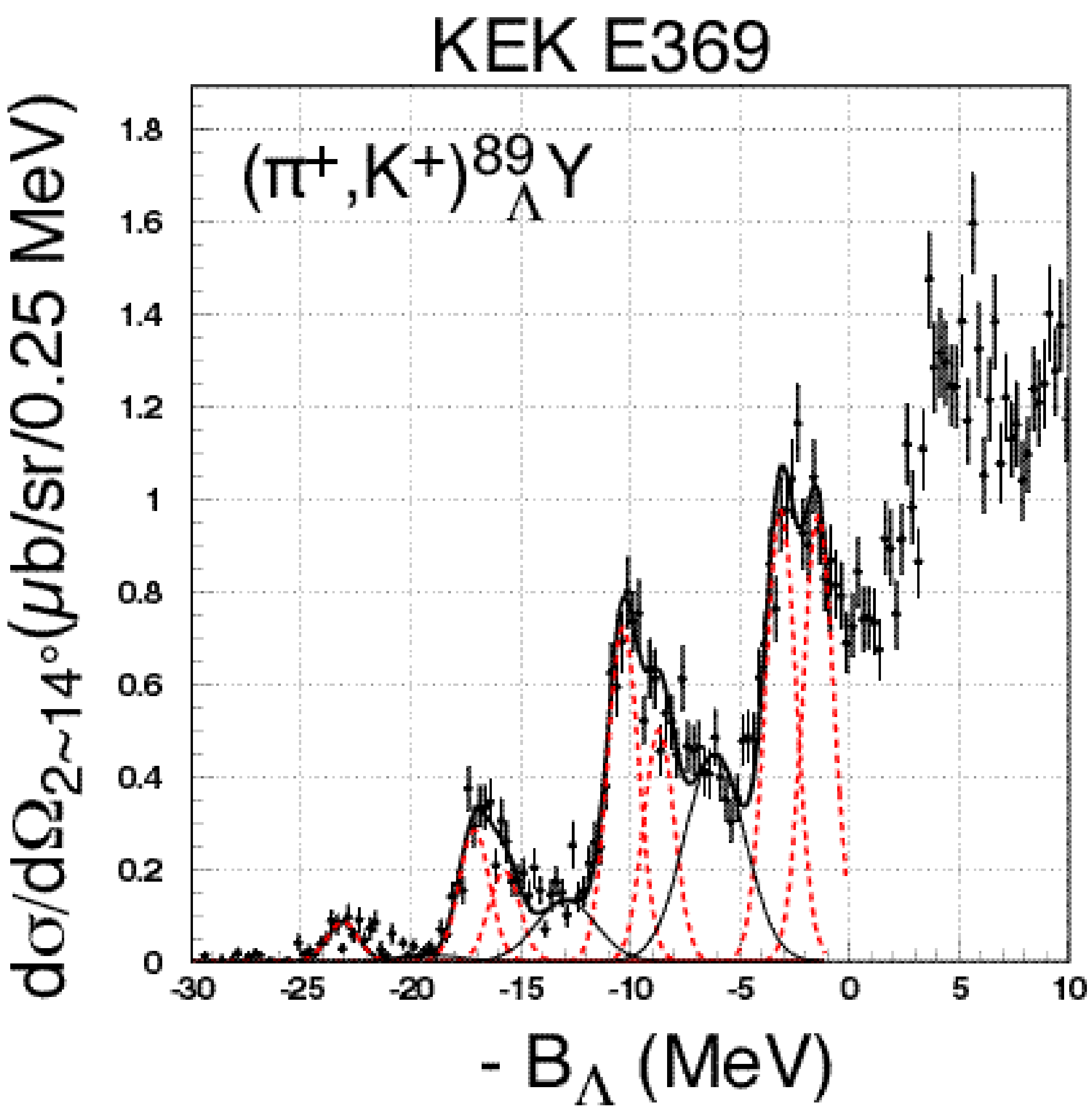






E369: $_{\Lambda}^{89}Y$

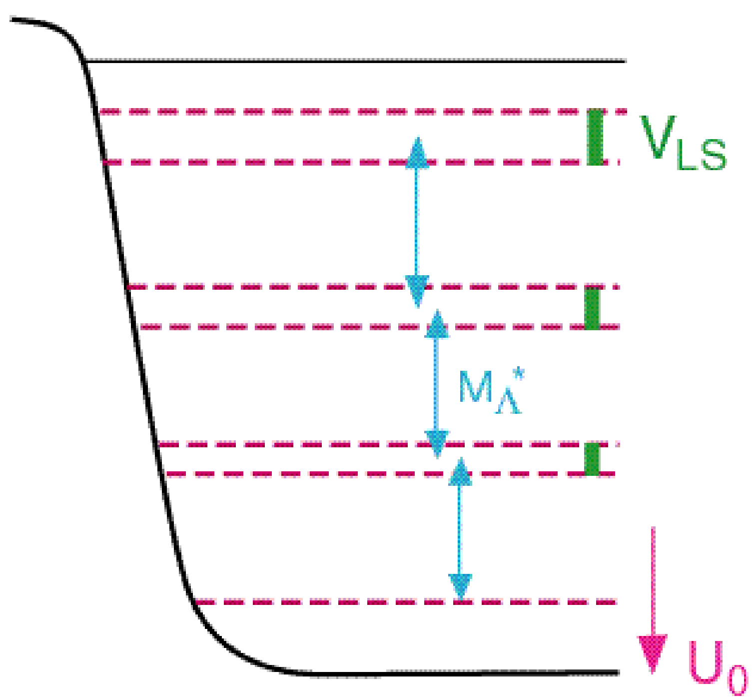
- $B_{\Lambda s}$=23.1±0.1 MeV
- Energy Splitting
  - ΔE_f=1.70±0.10 MeV
  - ΔE_d=1.63±0.14 MeV
  - ΔE_p=1.37±0.20 MeV
- Peak Ratio
  - R/L_f=0.99±0.07
  - R/L_d=0.69±0.06
- Extra n-hole at +4.1±0.1 MeV, width=3.2±0.2 MeV



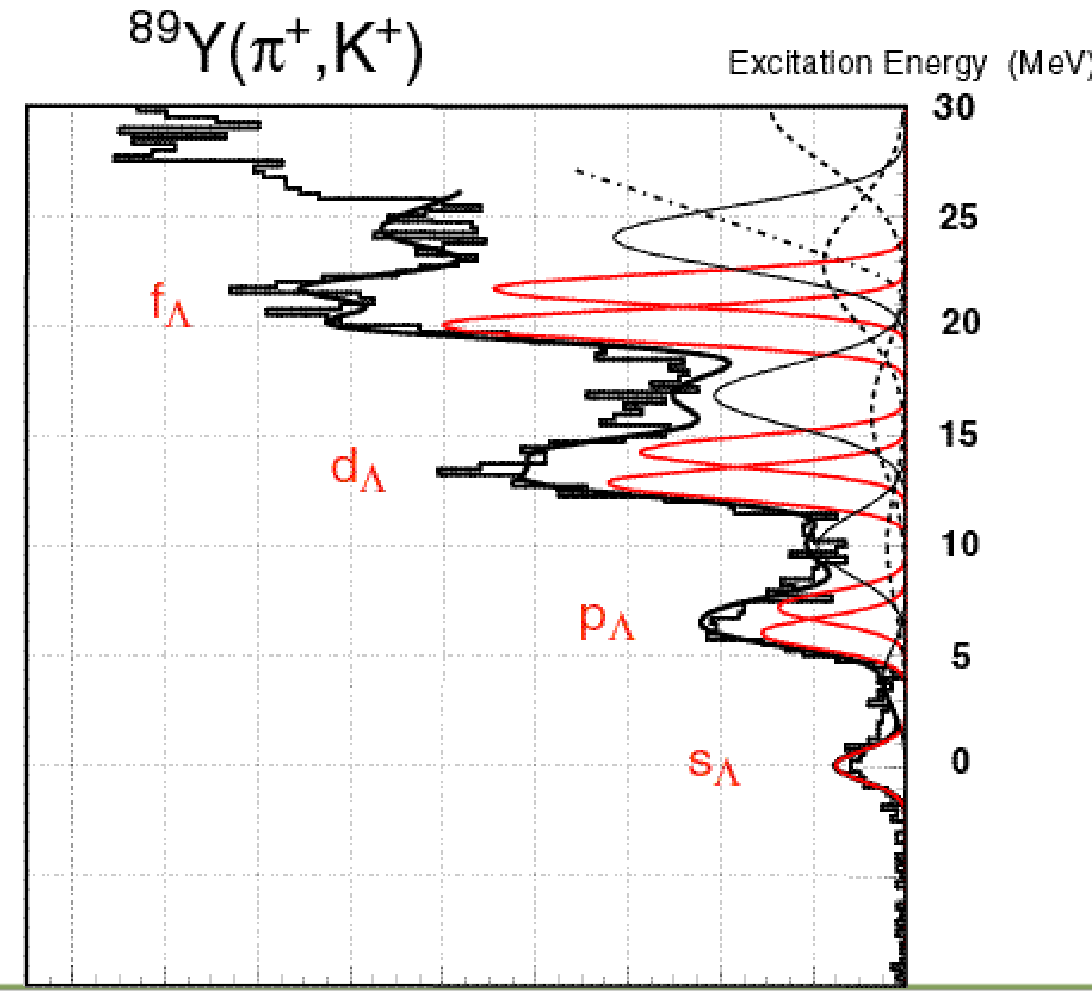
Single-particle motion of Λ in heavy hypernuclei

- U_0=-30.5 MeV
- M_Λ^*=0.7~0.8xM_Λ

by Y.Yamamoto

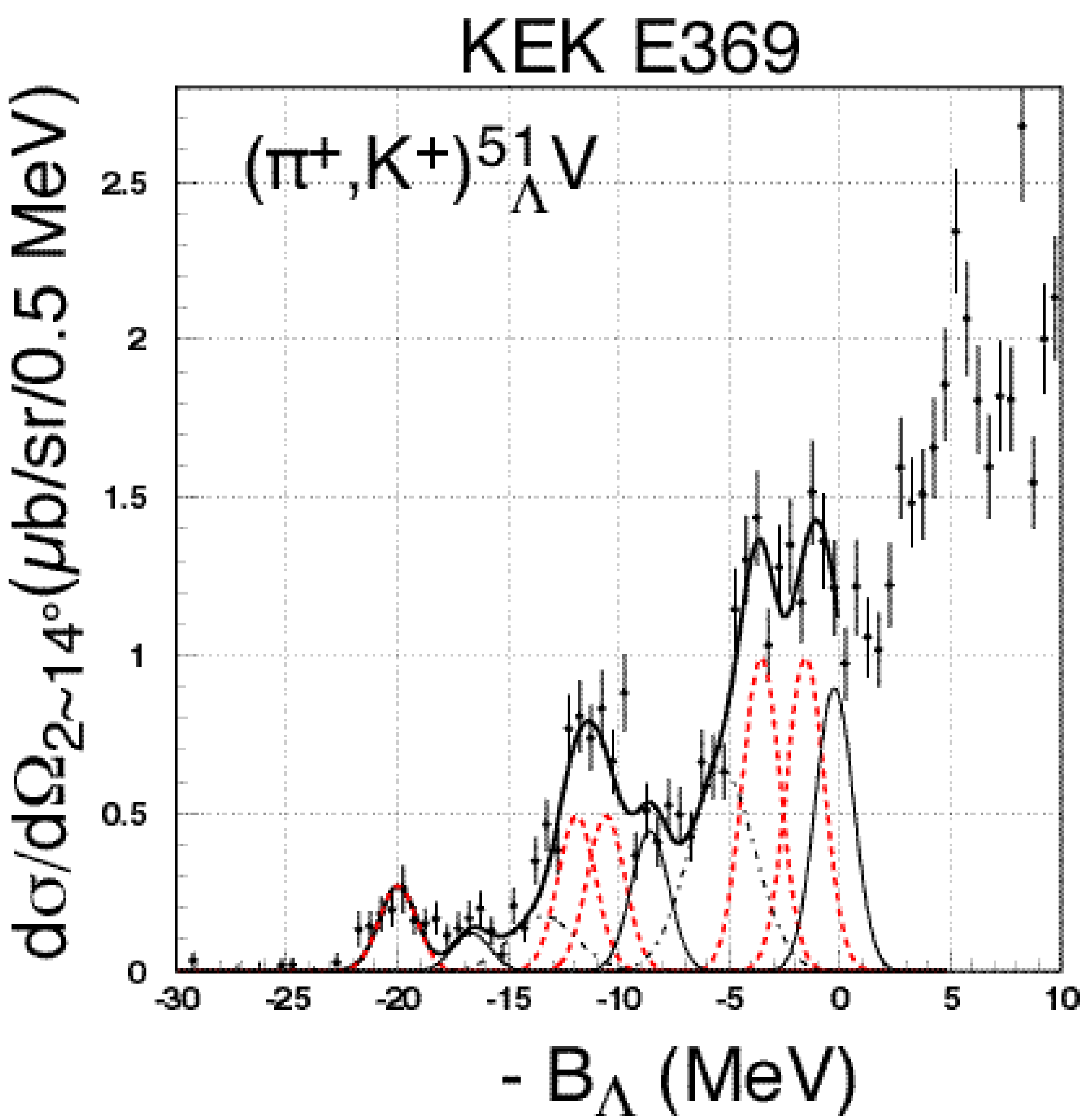


KEK E369



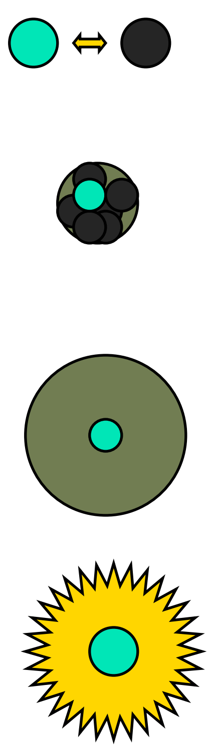
E369: ${}^{51}_{\Lambda}V$

- 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



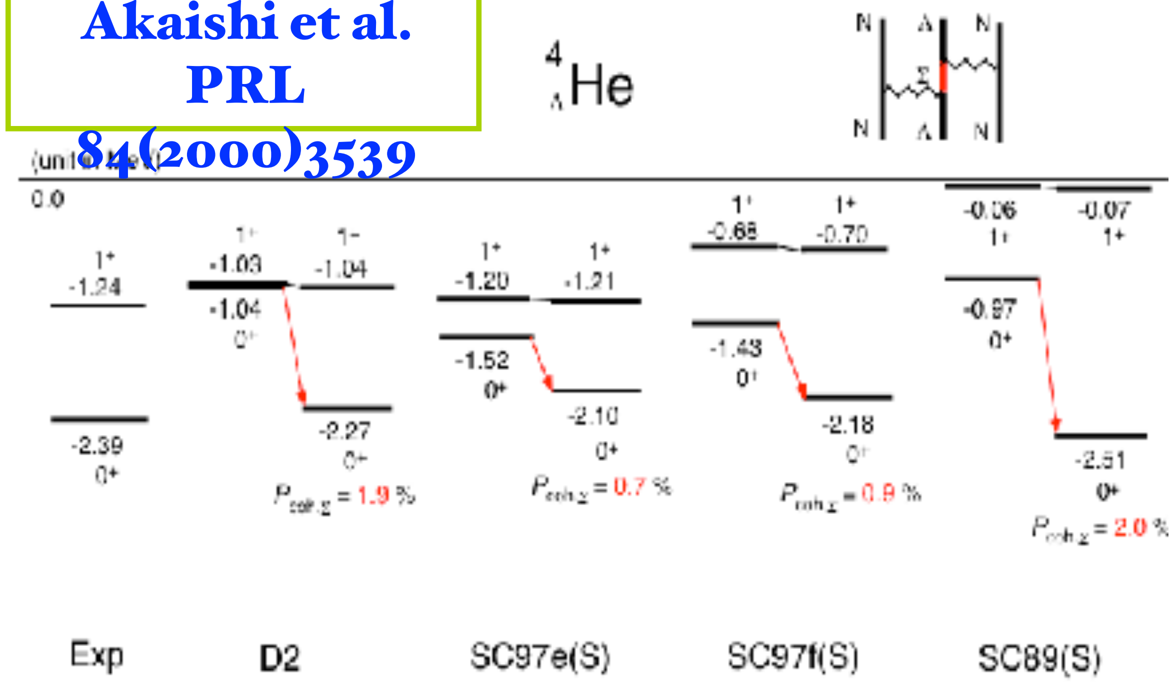
E521: Production of neutron-rich Λ hypernuclei by the (π^-,K$^+$) double-charge-exchange reaction

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

Production cross section/ Background (sensitivity)

$\Rightarrow$ Understanding of the Reaction Mechanism

Akaishi et al. PRL 84(2000)3539



Λ-Σ coherent coupling in A=4 hypernuclei

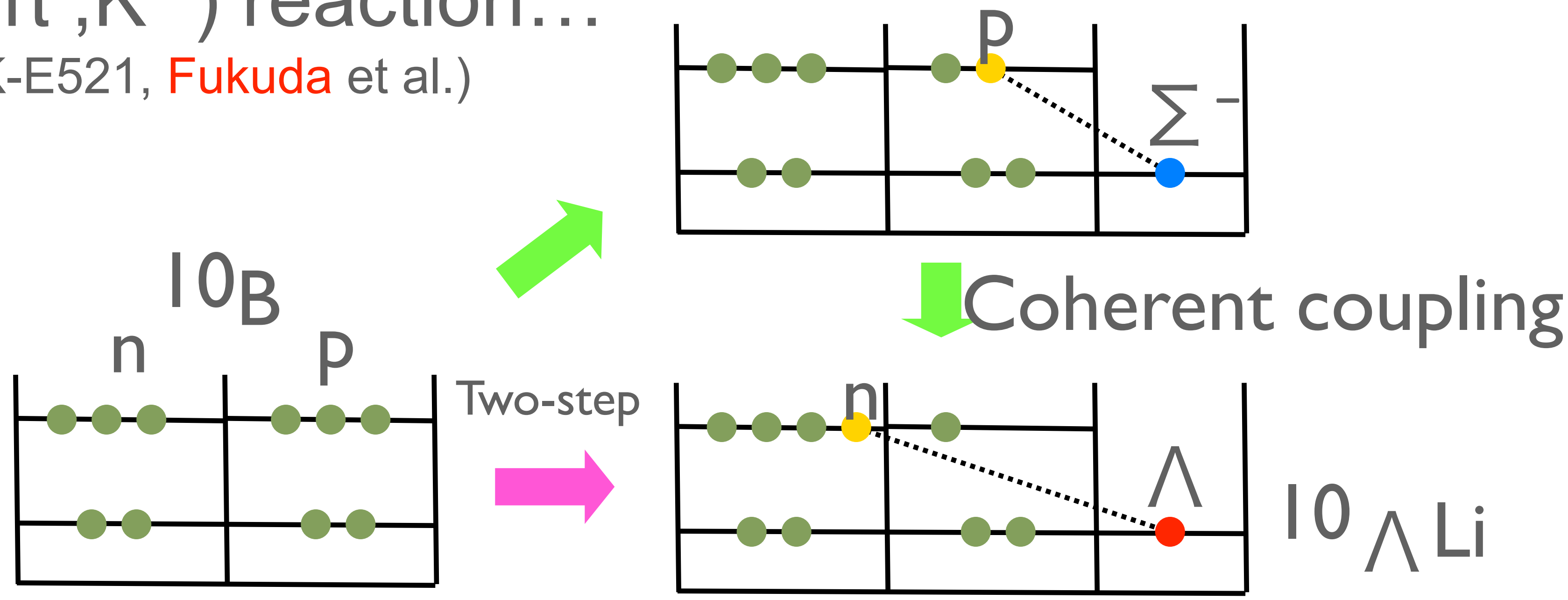
…solved an underbinding problem,
known as an overbinding problem in

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

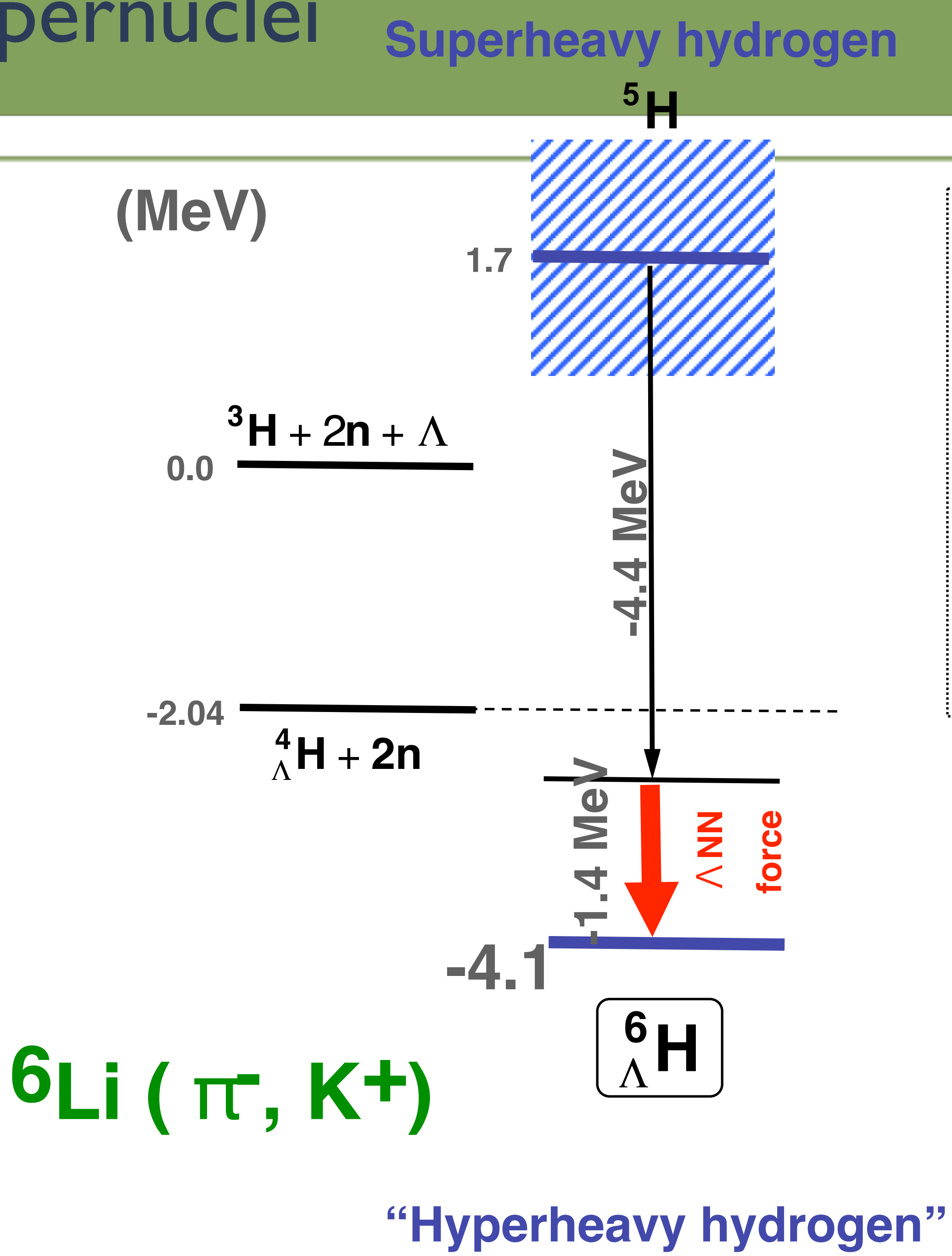
Y.Akaishi *et al.*, PRL84(2000)3539

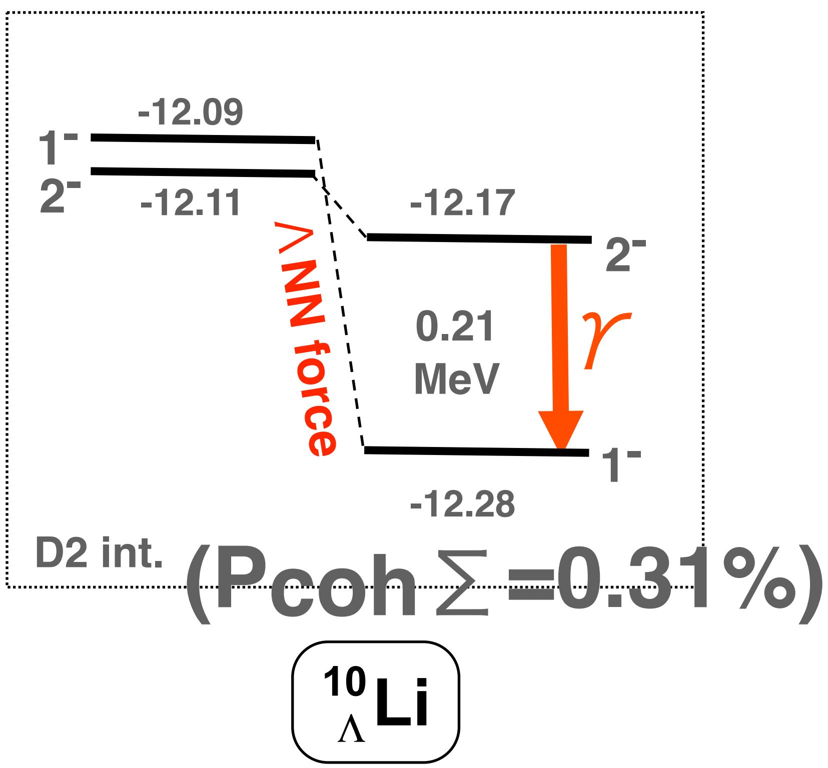
To be confirmed/examined in other examples

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



Effect of Coherent Σ mixing in n-rich hypernuclei

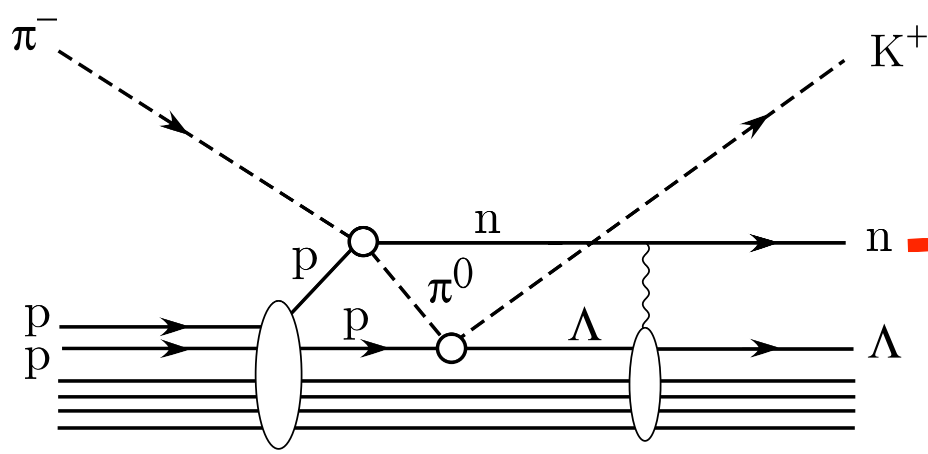




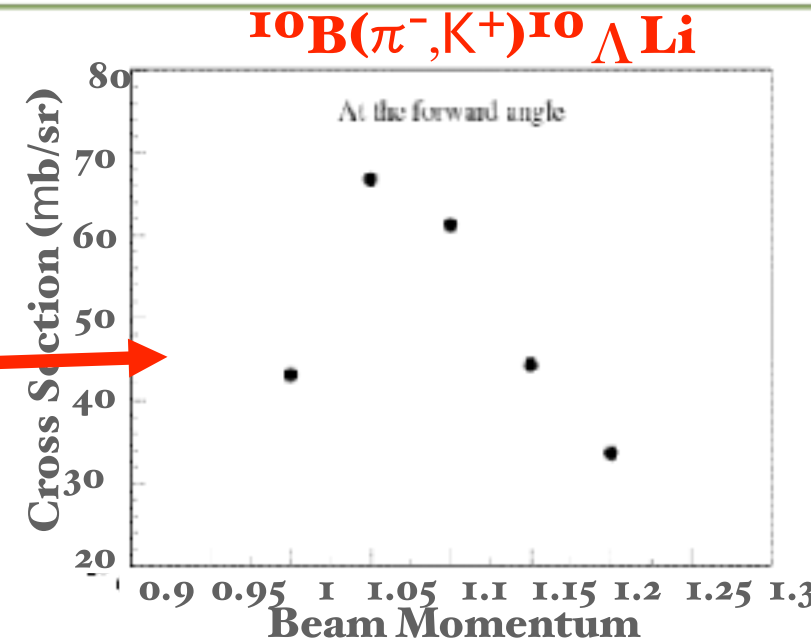
Reaction mechanism

Tretyakova, Akaishi et al.

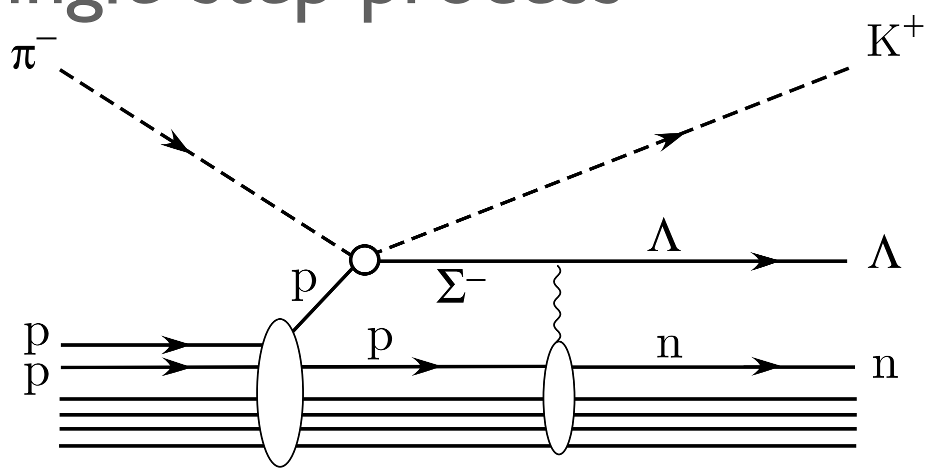
- Two-step process:



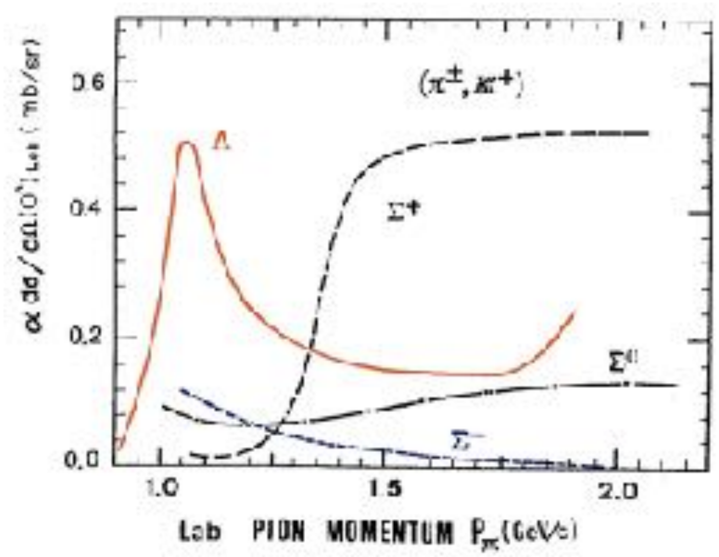
(a)



- Single-step process



(b)



Experiemntal Results

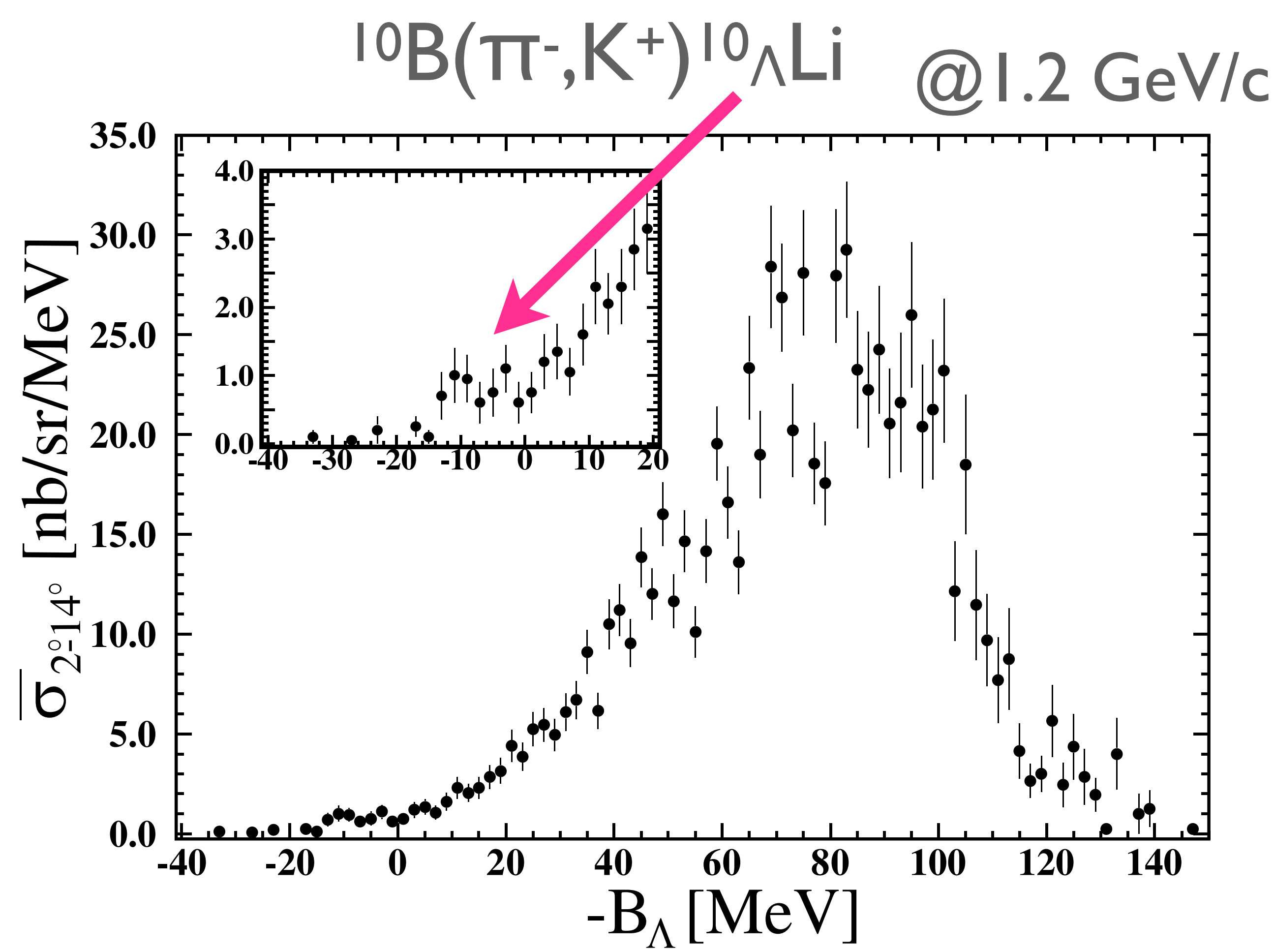


FIG. 3. Missing-mass spectrum of the (π^-, K^+) reaction on a ^{10}B target at 1.2 GeV/c. The horizontal and vertical axes are the same as Fig. 2. An expanded view near the Λ bound region is shown in the inset.

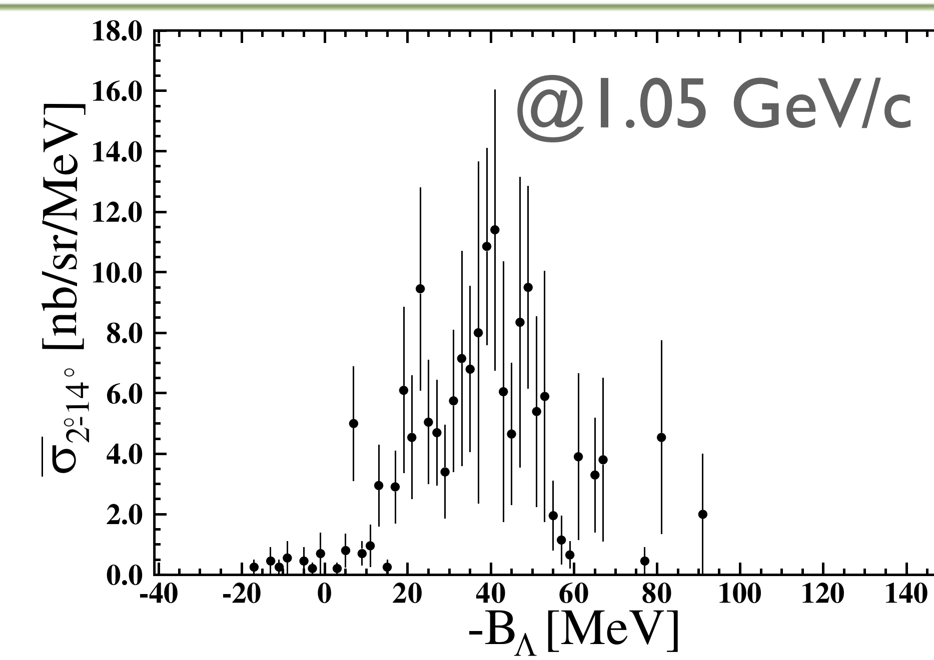


FIG. 2. Missing-mass spectrum of the (π^-, K^+) reaction on a ^{10}B target at 1.05 GeV/c. The horizontal axis shows the binding energy of a Λ, whereas the vertical axis shows the cross section in terms of nb/sr/MeV.

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
$^{12}\mathrm{C}(\pi^+, K^+)^{12}_{\Lambda}\mathrm{C}$	$18.0 \pm 0.7\ \mu\mathrm{b/sr}$	$17.5 \pm 0.6\ \mu\mathrm{b/sr}$
$^{10}\mathrm{B}(\pi^+, K^+)^{10}_{\Lambda}\mathrm{B}$	$7.8 \pm 0.3\ \mu\mathrm{b/sr}$	
$^{10}\mathrm{B}(\pi^-, K^+)^{10}_{\Lambda}\mathrm{Li}$	$5.8 \pm 2.2\ \mathrm{nb/sr}$	$11.3 \pm 1.9\ \mathrm{nb/sr}$ $9.6 \pm 2.0^*\ \mathrm{nb/sr}$

Σ mixing ?

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

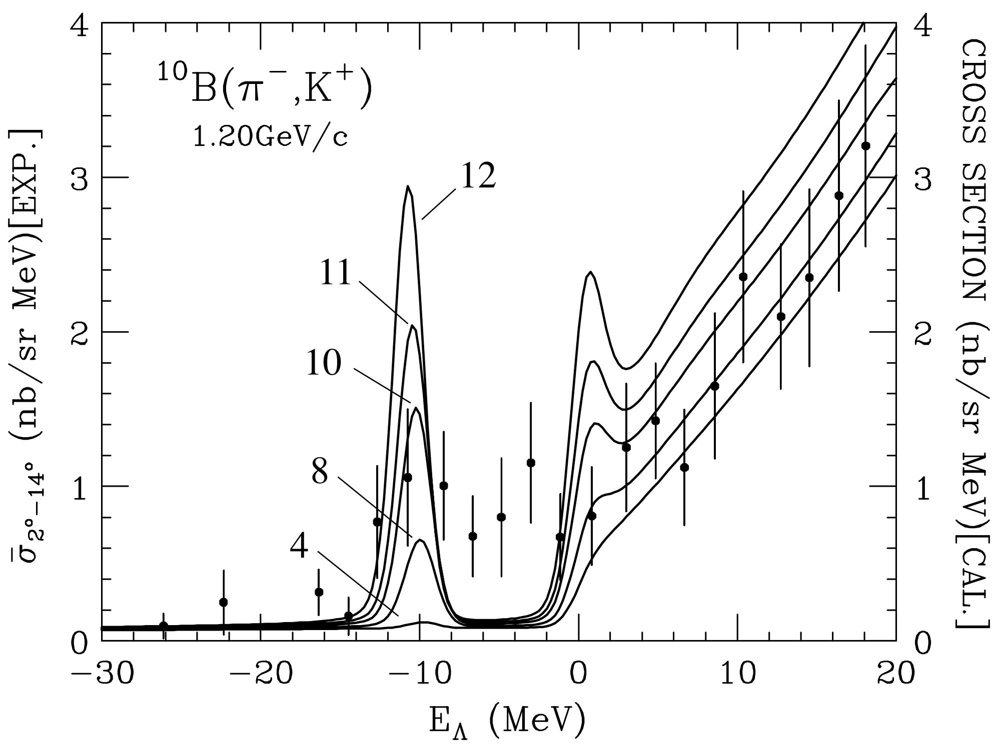
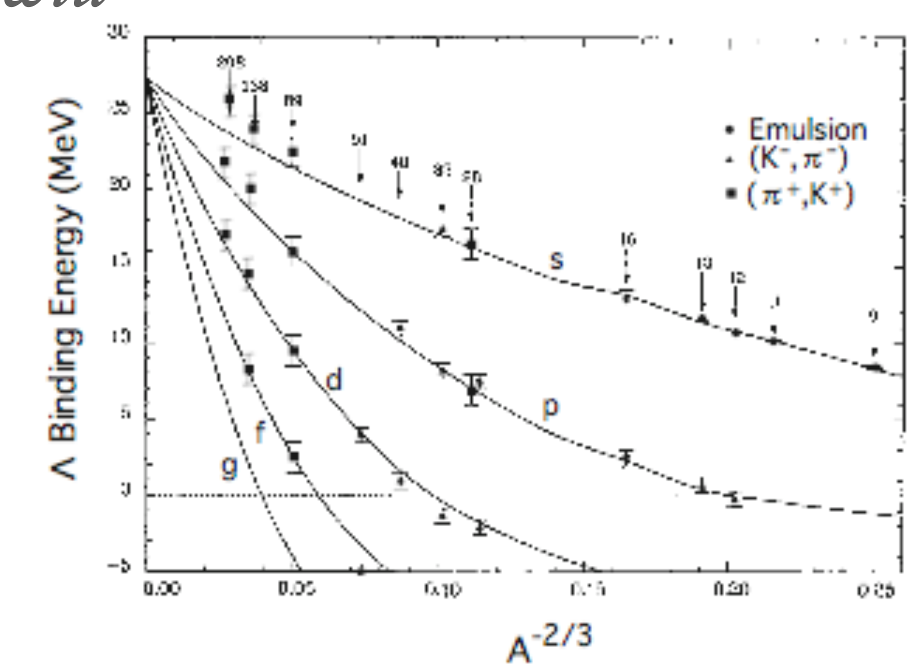


FIG. 3. Calculated inclusive Λ spectra obtained by the one-step mechanism near the Λ threshold in the $^{10}B(\pi^-, K^+)$ reaction at 1.20 GeV/c (6°), by changing $V_{\Sigma\Lambda}$ for the Λ-Σ coupling potential. The experimental data are taken from Ref. [12]. The solid curves denote $V_{\Sigma\Lambda}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

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

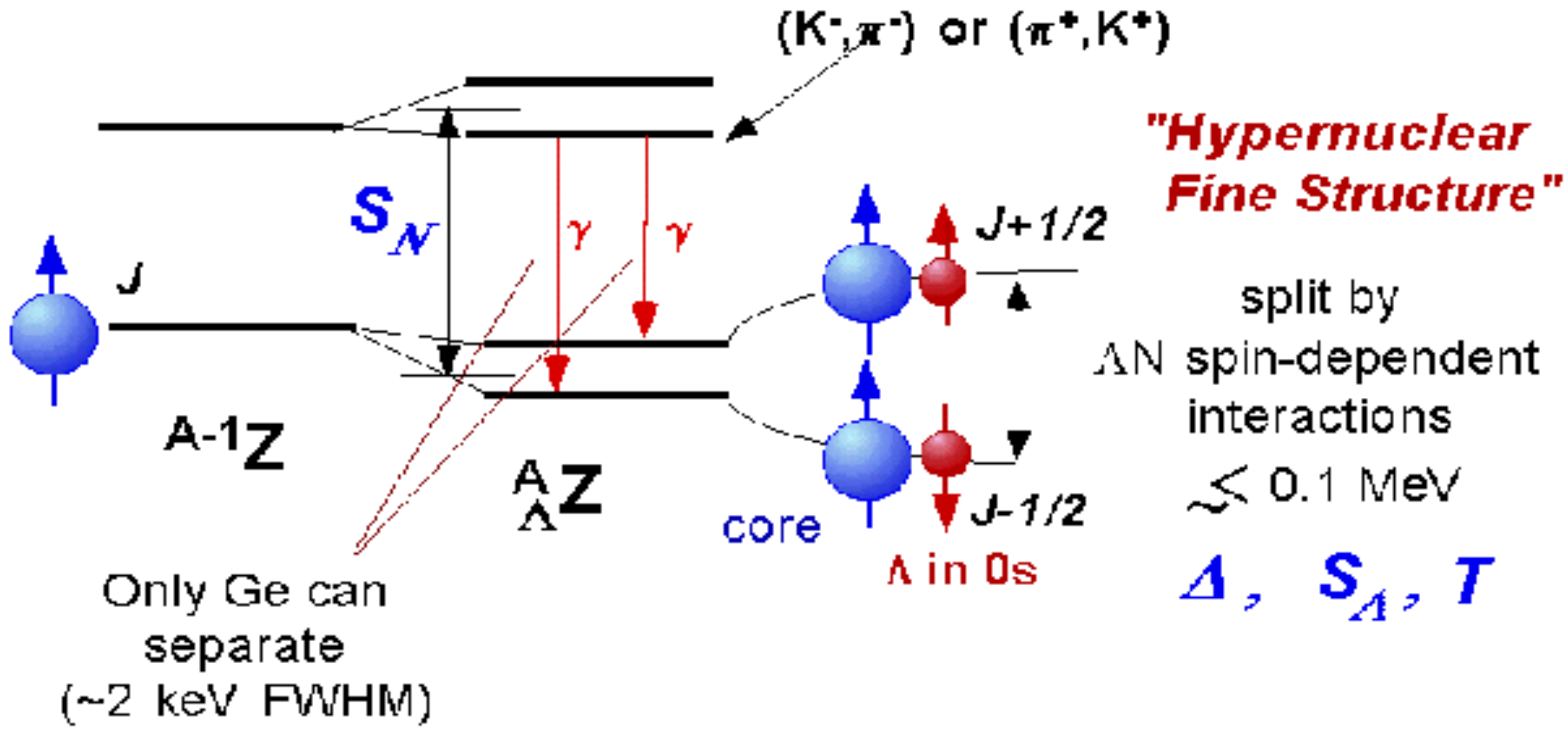
Summary on (π ,K) spectroscopy

- 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^+)



γ spectroscopy

- Low-lying levels of Λ hypernucleus



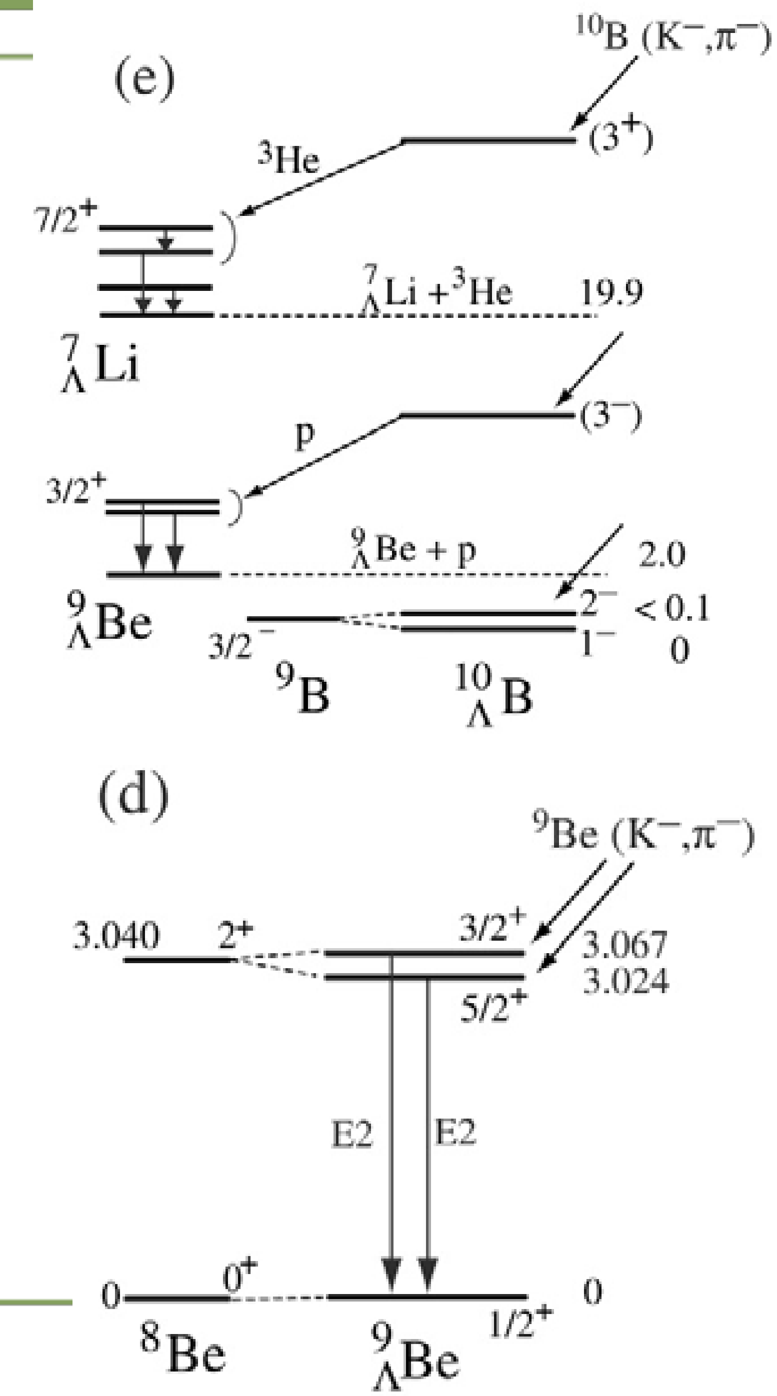
- 2-body ΛN effective interaction

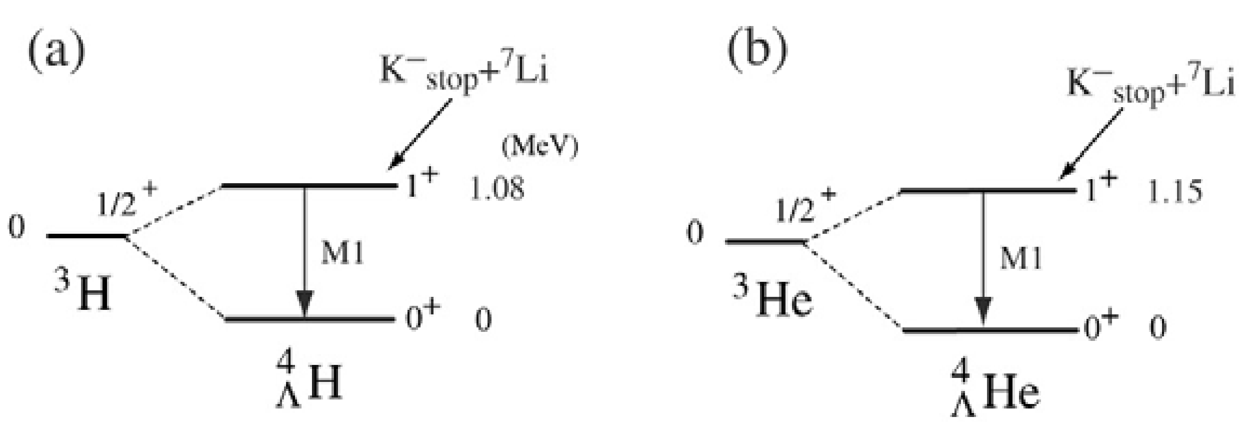
$$V_{\Lambda N}^{\mathrm{eff}} = V_0(r) + \underbrace{V_\sigma(r)\, \vec{s}_\Lambda \vec{s}_N}_{\Delta} + \underbrace{V_\Lambda(r)\, \vec{l}_{\Lambda N} \vec{s}_\Lambda}_{S_\Lambda} + \underbrace{V_N(r)\, \vec{l}_{\Lambda N} \vec{s}_N}_{S_N} + \underbrace{V_T(r)\, S_{12}}_{T}$$

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

Hypernuclear γ -rays before Hyperball

$^{4}_{\Lambda}\mathrm{H}$, $^{4}_{\Lambda}\mathrm{He}$	1.10±0.04 MeV	NaI
$^{7}_{\Lambda}\mathrm{Li}$	2.034±0.023 MeV	NaI
$^{9}_{\Lambda}\mathrm{Be}$	3.079±0.04 MeV	NaI
$^{10}_{\Lambda}\mathrm{B}$	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

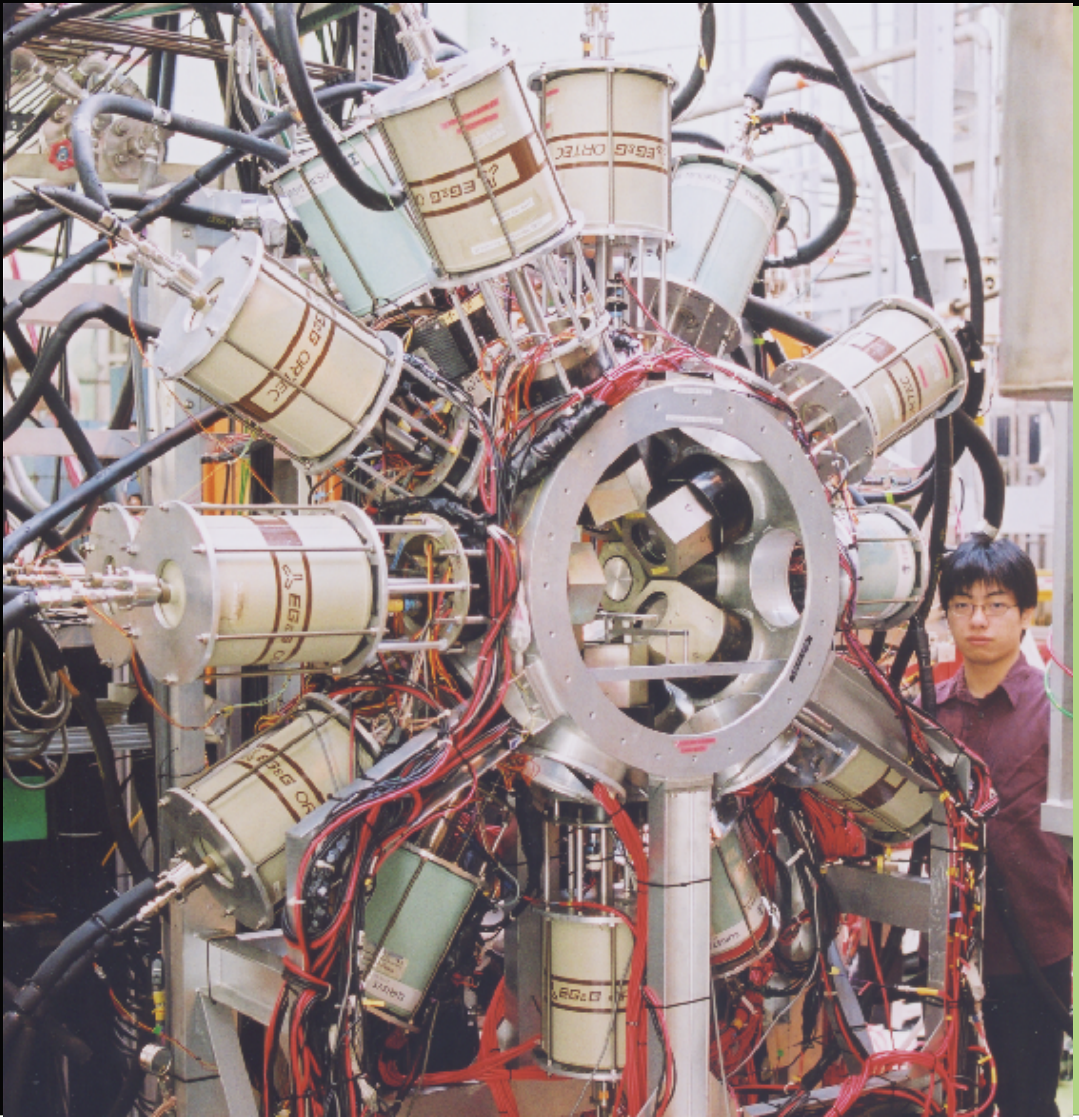
- High-rate electronics for huge background

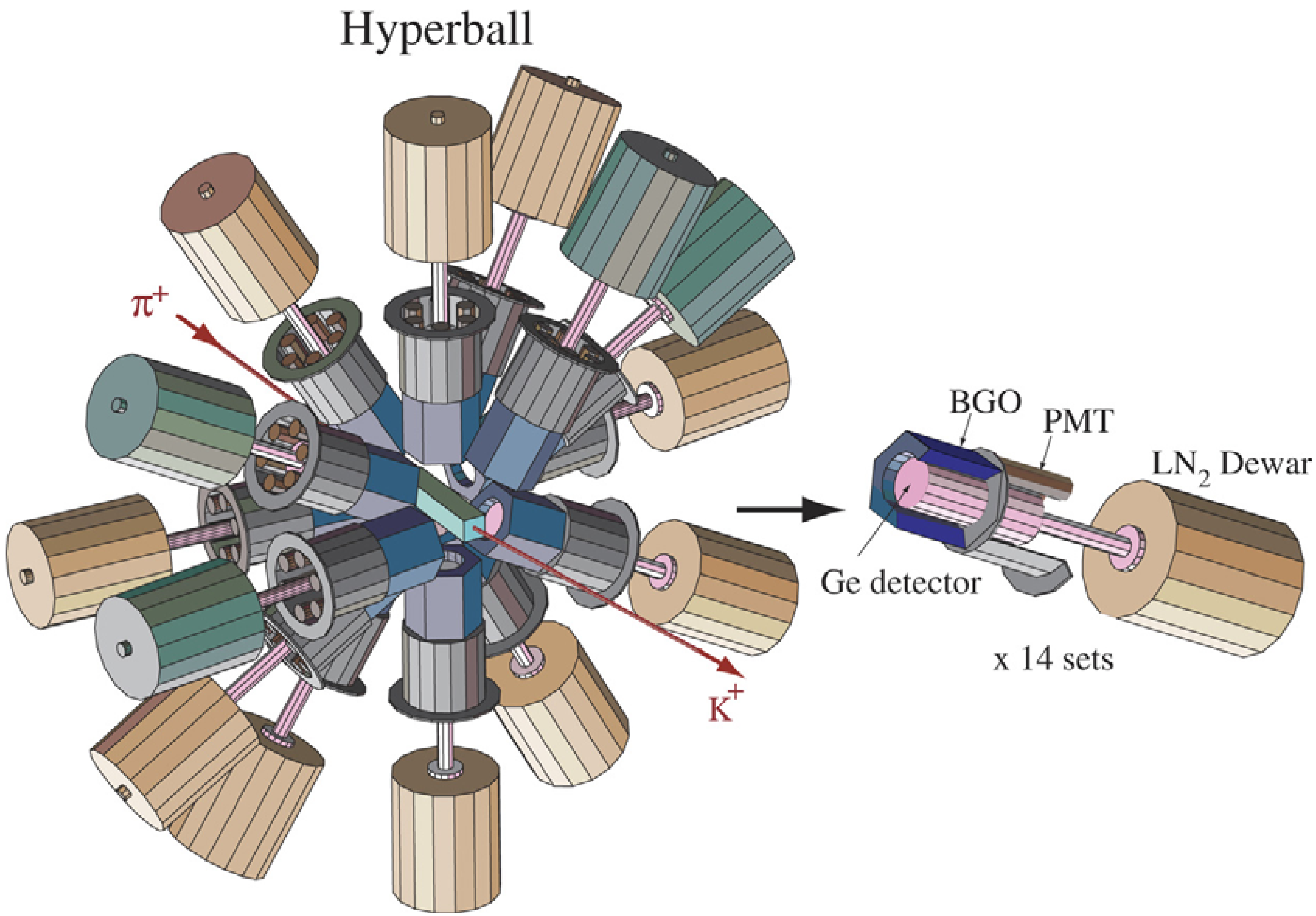
  1 TeV/sec, 100 kHz

- BGO counters for π^0 and Compton suppression

Resolution of hypernuclear spectroscopy

1 MeV → 2 keV FWHM

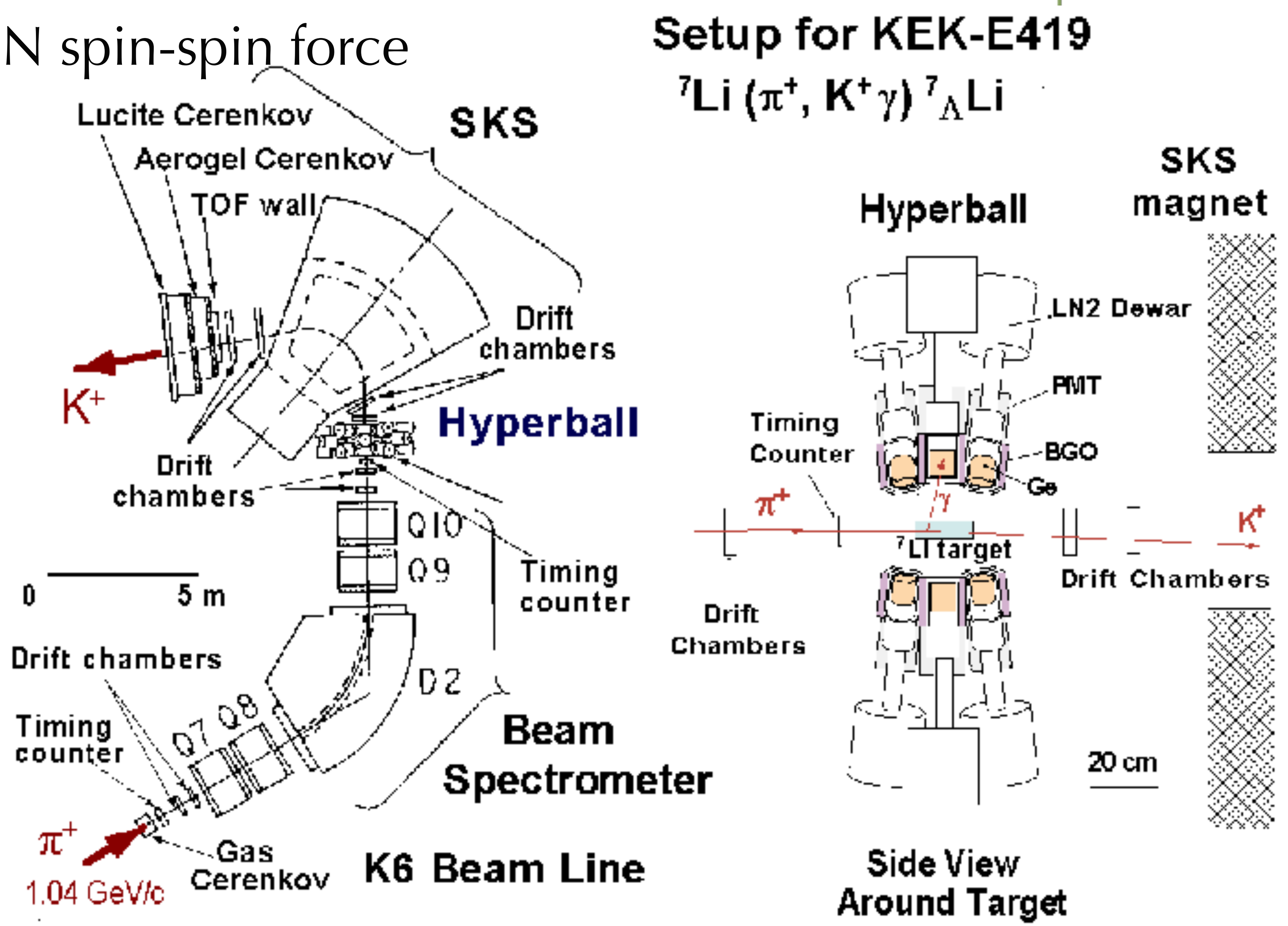




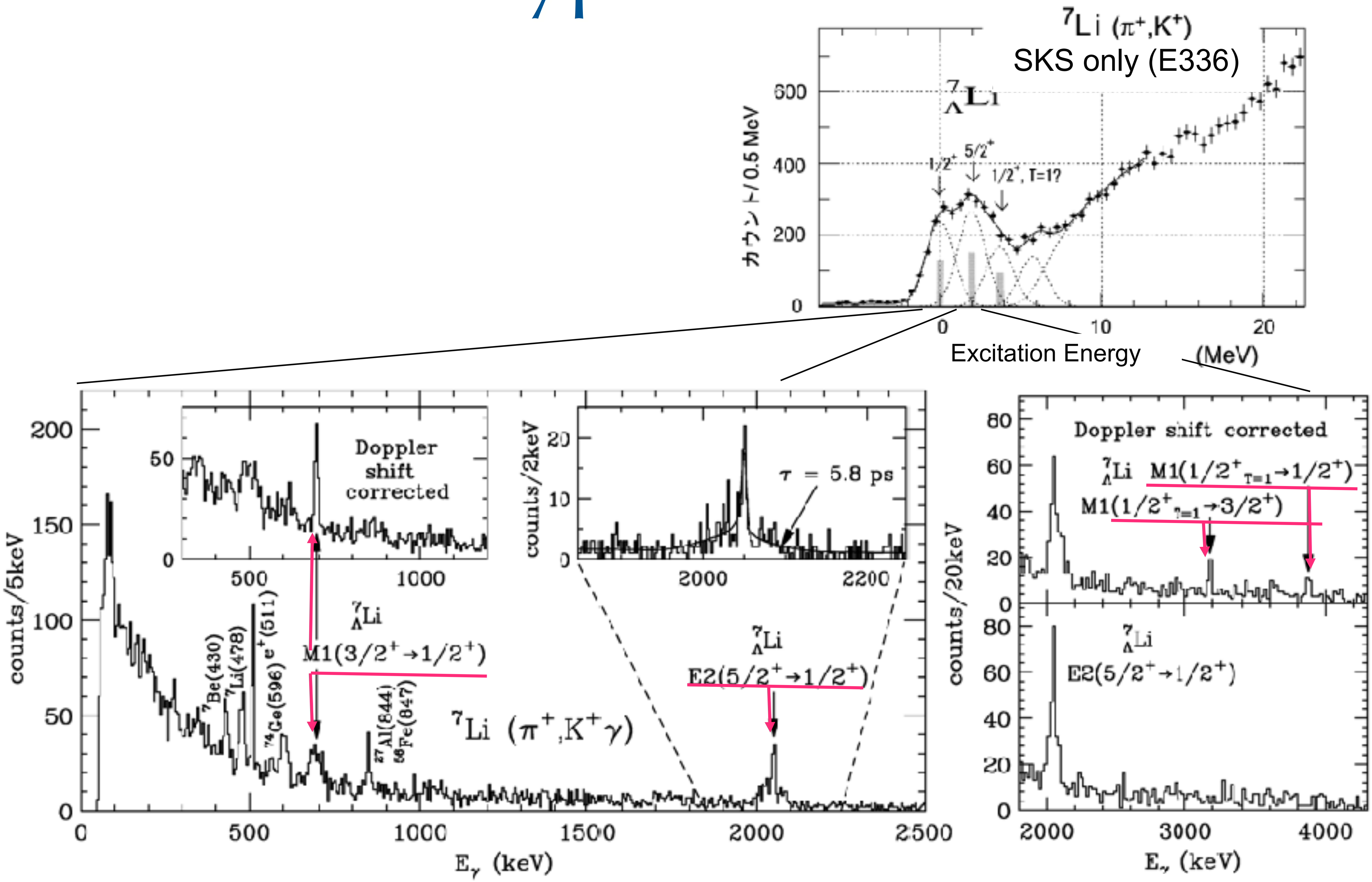
Hyperball
π+
K+
BGO
PMT
LN2 Dewar
Ge detector
x 14 sets

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

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

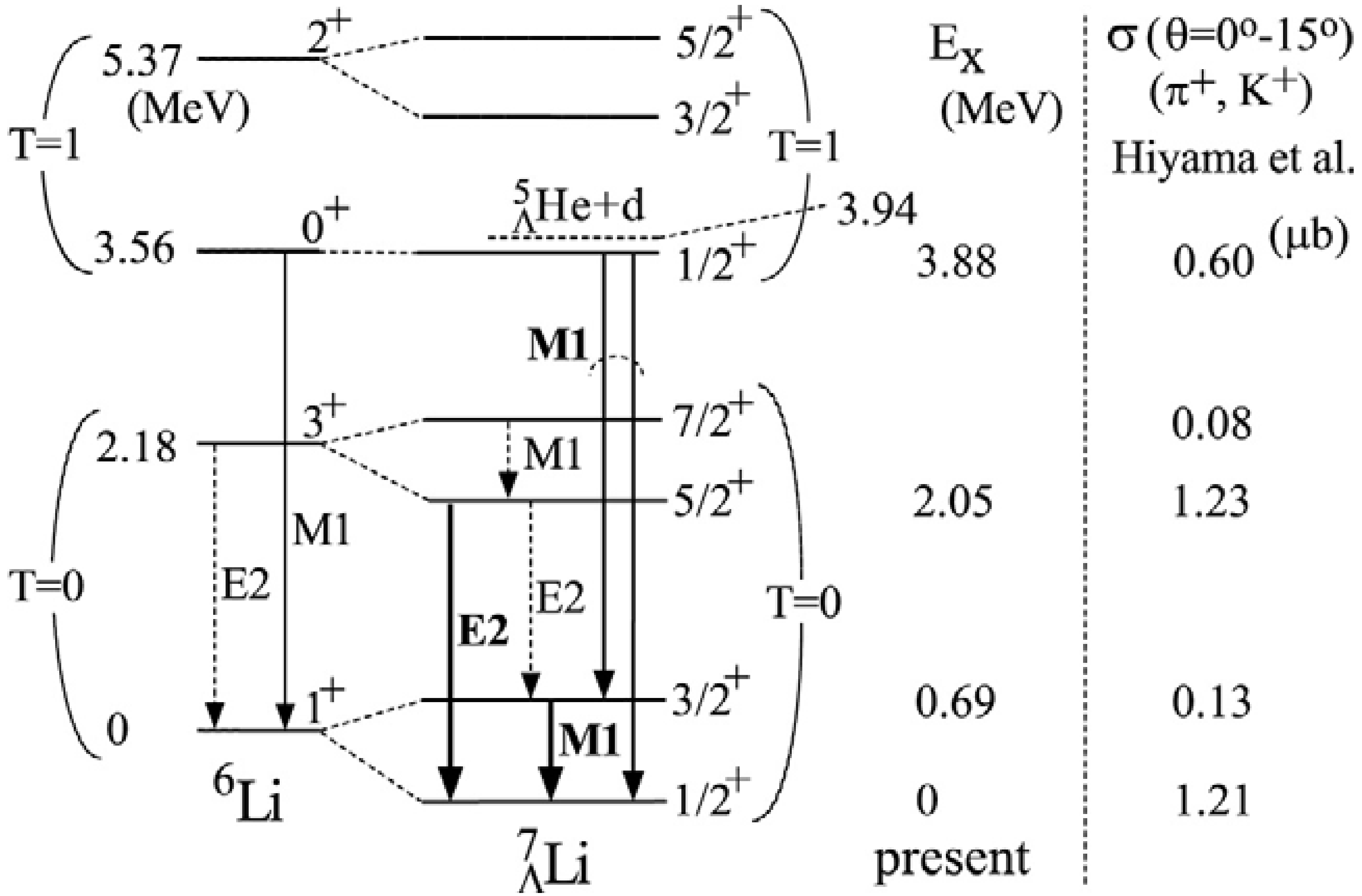


E419: SKS+Hyperball



Tamura et al., PRL 94(2000) 5963

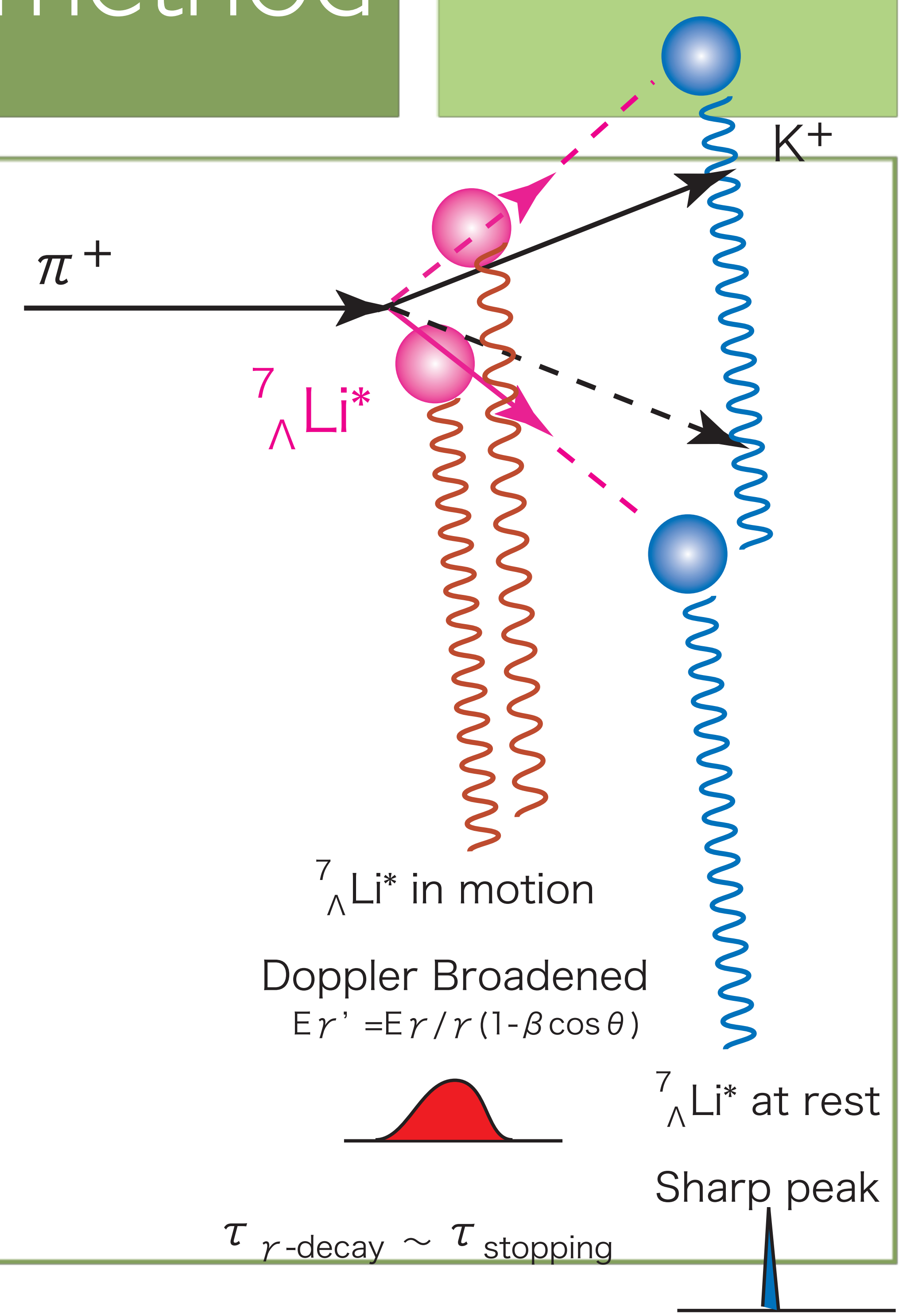
First observation of well-identified hypernuclear γ rays with Ge.



5.37
(MeV)
2^+
$5/2^+$
$3/2^+$
T=1
T=1
E_x
(MeV)
σ (θ=0°-15°)
(π^+, K^+)
Hiyama et al.
$^{5}_{\Lambda}$He+d
3.94
3.56
0^+
$1/2^+$
3.88
0.60 (μb)
M1
2.18
3^+
$7/2^+$
0.08
M1
$5/2^+$
2.05
1.23
T=0
E2
M1
E2
E2
T=0
0
1^+
$3/2^+$
0.69
0.13
M1
$1/2^+$
0
1.21
^{6}Li
$^{7}_{\Lambda}$Li
present

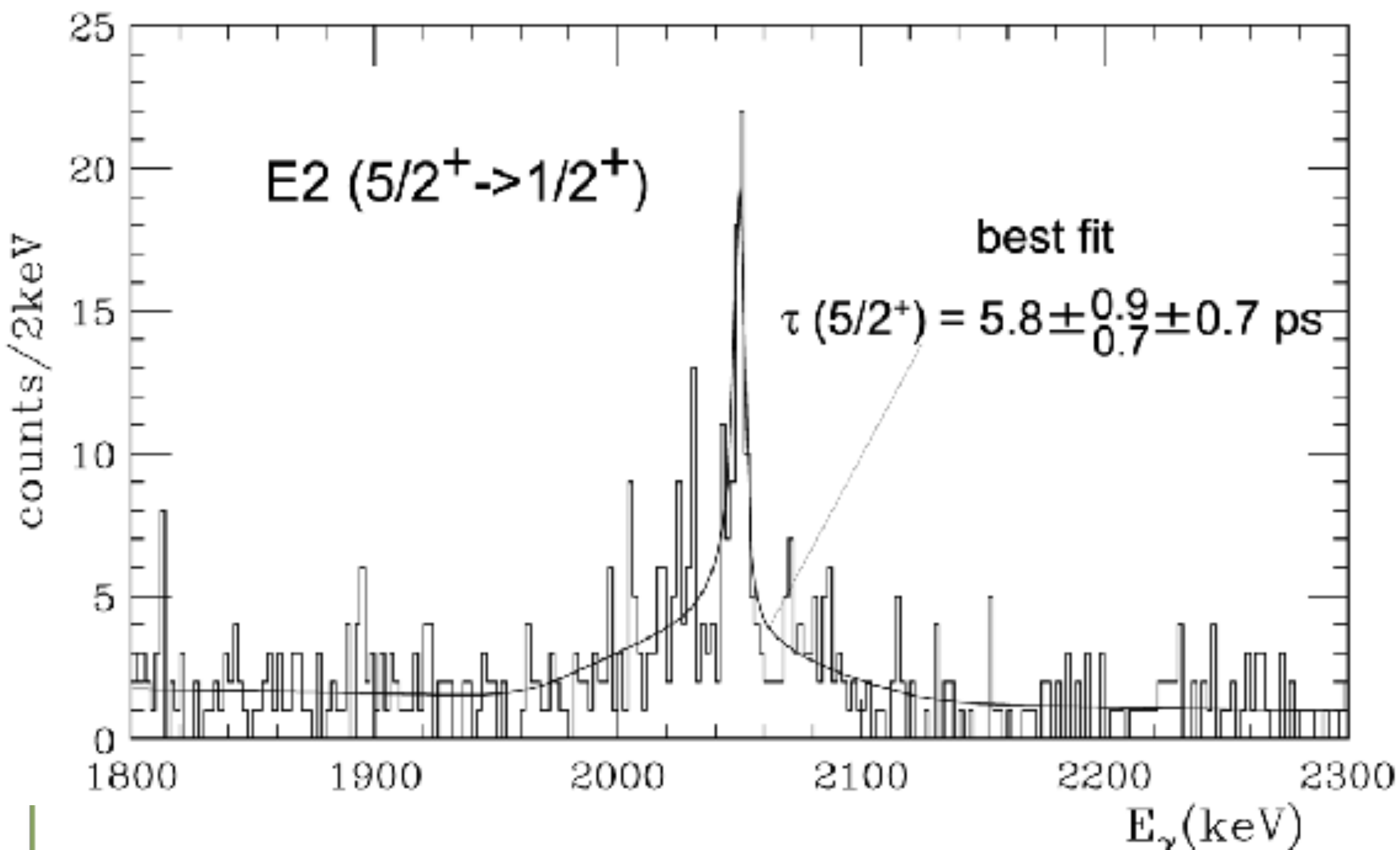
Doppler shift attenuation method

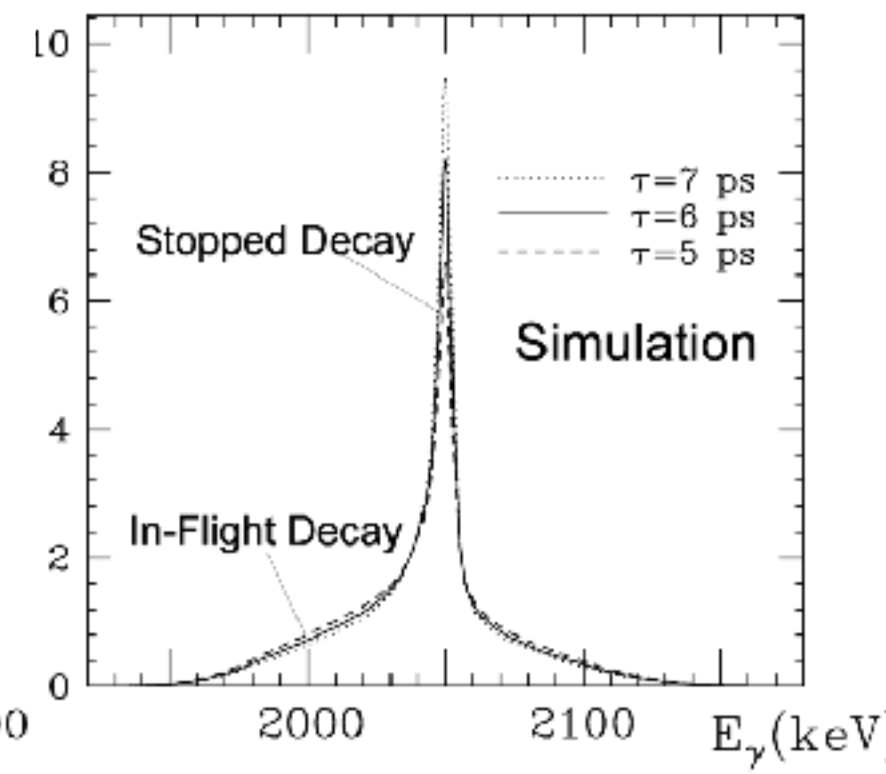
- $\tau_{\gamma\text{-decay}} \sim \tau_{\text{stopping}}$
- 5.8 ps 13 ps
  - mixture of a sharp peak and a broad peak



Lifetime and B(E2)

Lifetime Measurement
using Dopper Shift Attenuation Method





Γ(E2; $5/2^+ \to 1/2^+$) = BR / τ ($5/2^+$) = 1.22 x 10^9 E^5 B(E2)

BR = 93.6±3.8 %

[weak decay $(230\pm40 \text{ ps})^{-1}$, BR($5/2^+ \to 3/2^+$)=$3.8\pm^{0.5}_{3.8}$%]

=> B(E2)=$3.6\pm0.5\pm^{0.5}_{0.4}$ e^2fm^4

B(E2)

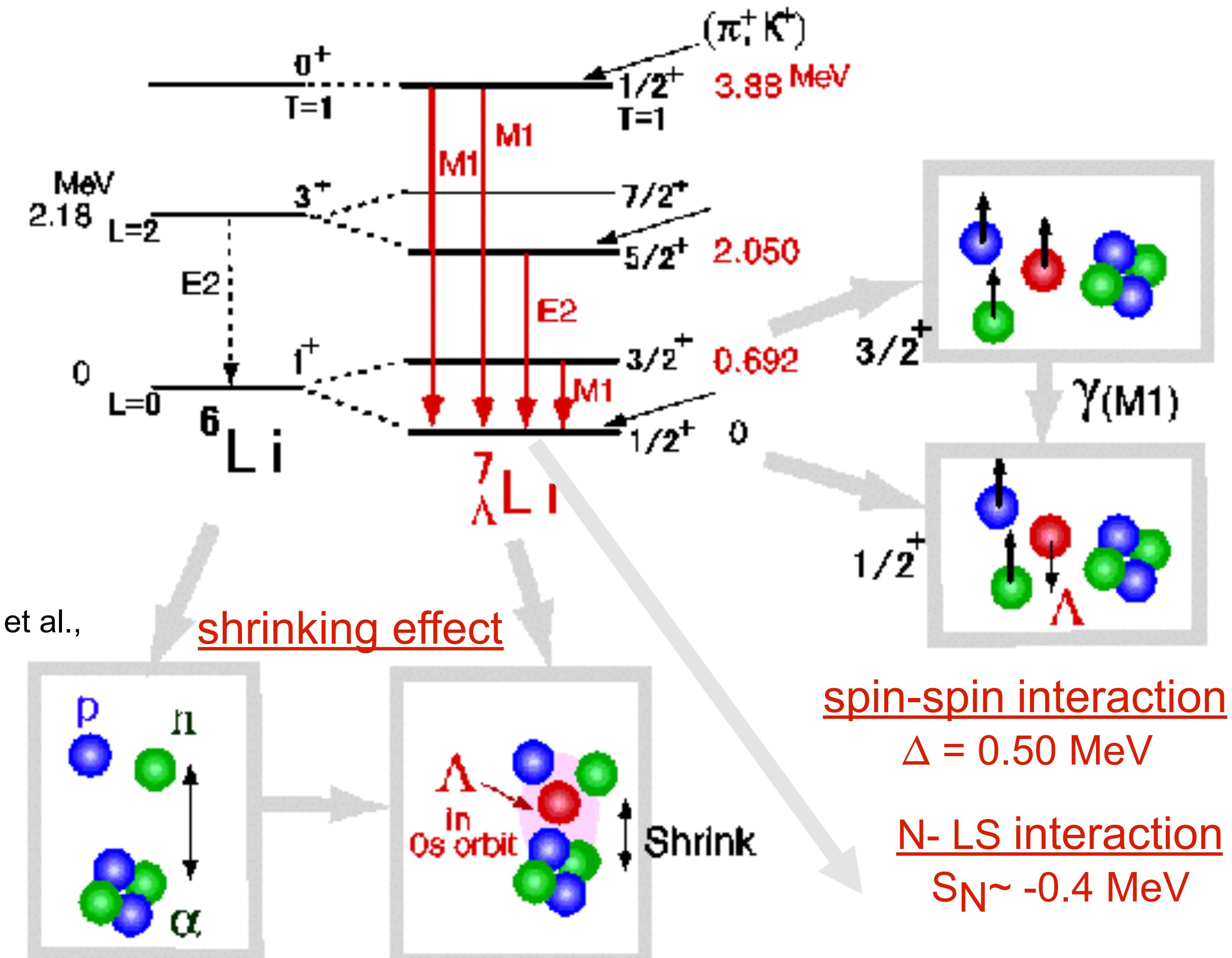
$$\Gamma(E(M)\lambda : I_i \rightarrow I_f) = \frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\frac{1}{\hbar}(\frac{\omega}{c})^{2\lambda+1}B(E(M)\lambda; I_i \rightarrow I_f)$$

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

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

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

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



spin-spin interaction
Δ = 0.50 MeV

N- LS interaction
S_N~ -0.4 MeV

PRL 84 (2000) 5963

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

shrinking effect

B(E2) [$e^2 fm^4$]

$10.9\pm0.9 \longrightarrow 3.6\pm0.5\pm^{0.5}_{0.4}$

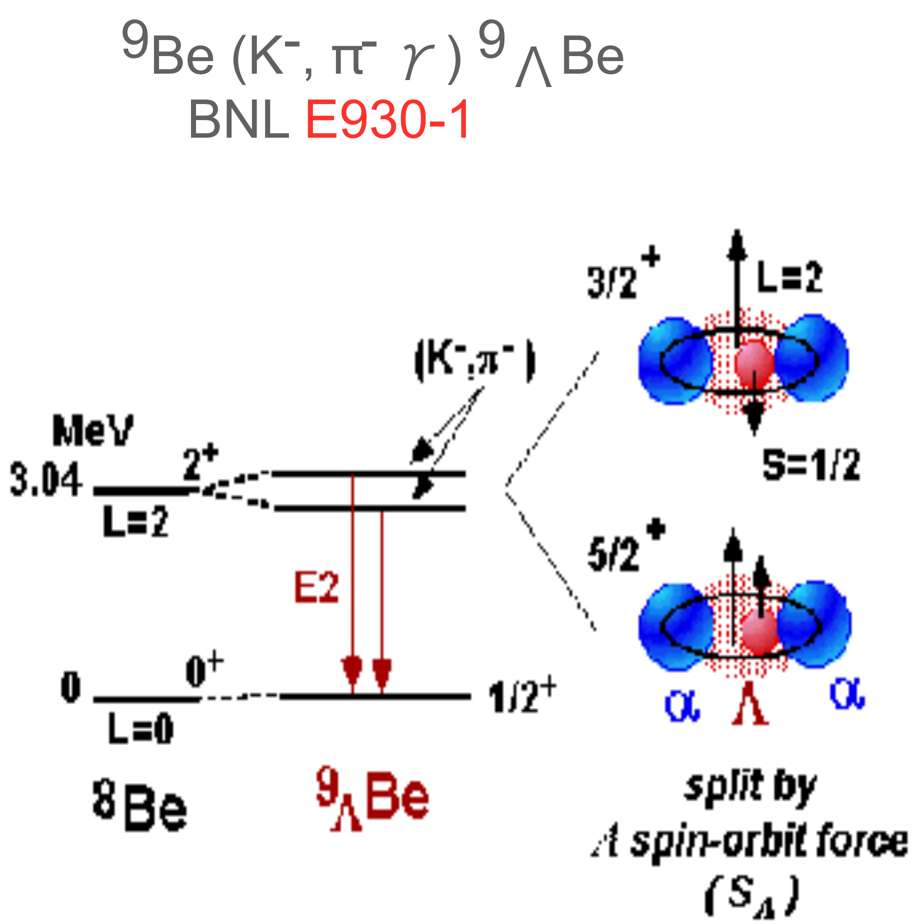
$\Rightarrow$ 19±4% shrinkage by Λ

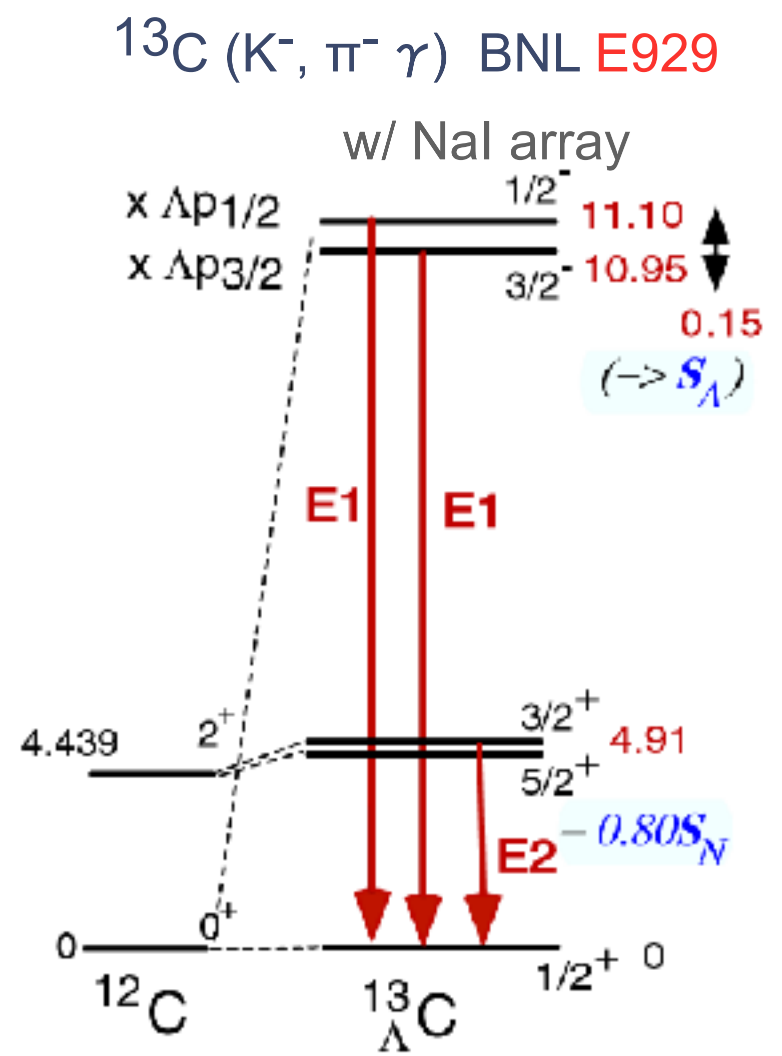
B(E2) $\propto |\langle f|\, e\, r^2\, Y_2\, |i\rangle|^2$

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

Tanida et al., PRL 86(2001) 1982

ΛN spin-orbit force





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

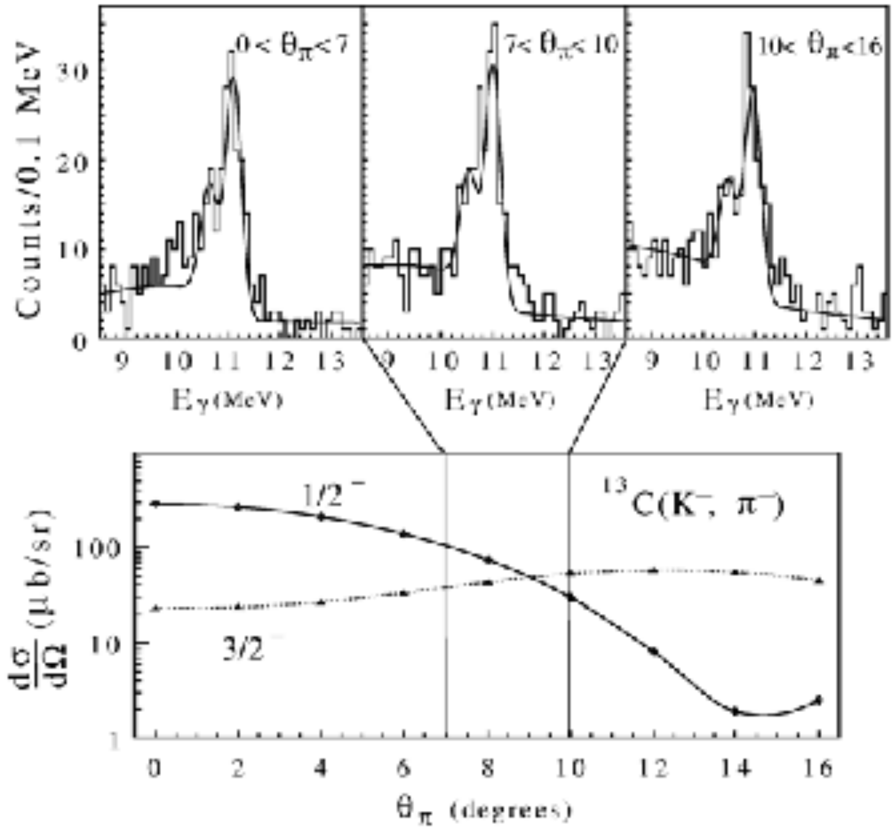


FIG. 2. γ ray spectra taken in coincidence with scattered π⁻'s (upper panel) and differential cross section of 1/2⁻ and 3/2⁻ states calculated by Motoba [18] (lower panel) are shown.

-forward

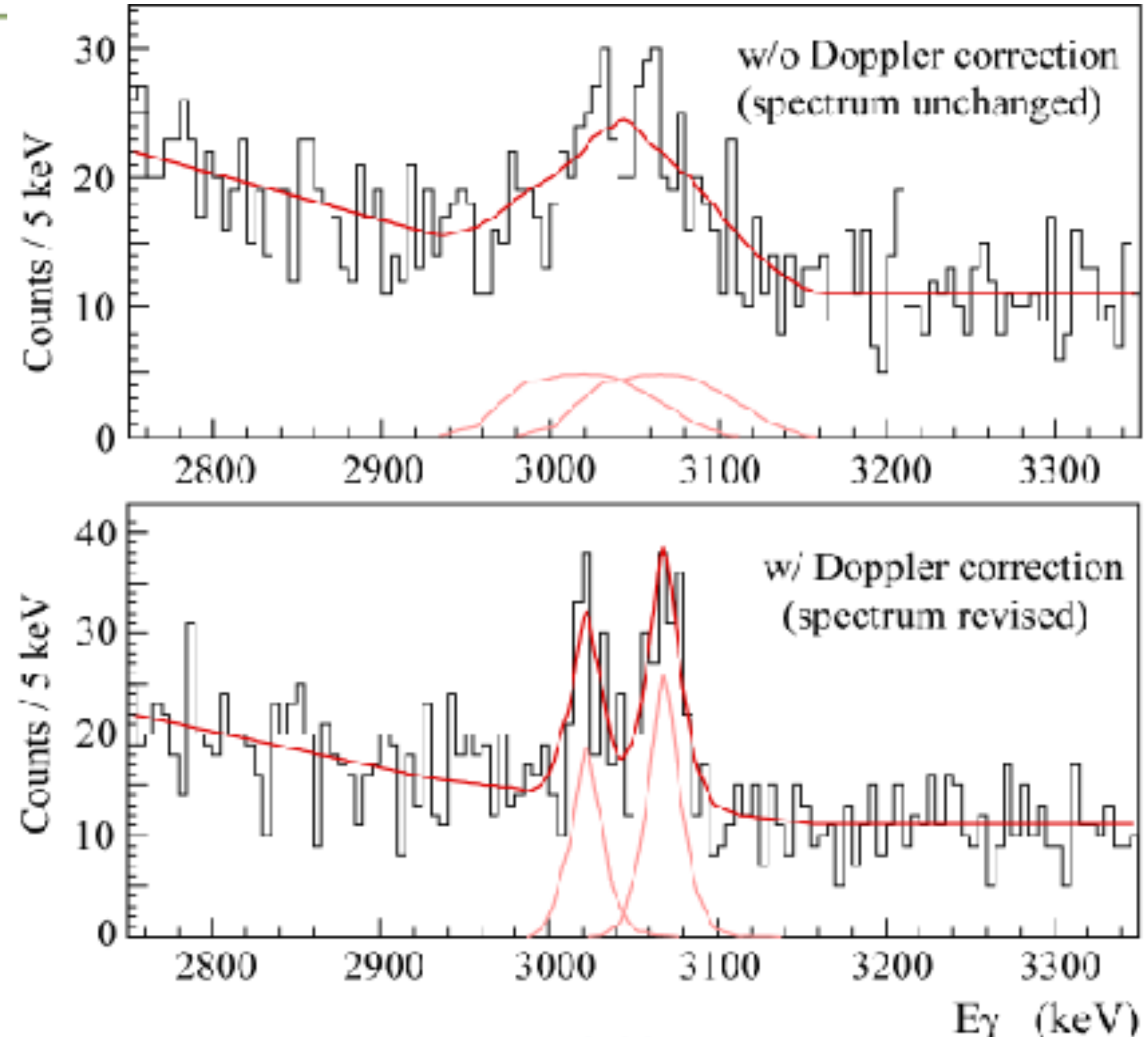
$(p_{1/2,n}^{-1}, p_{1/2,\Lambda})$ $\Delta L=0$

-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:

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

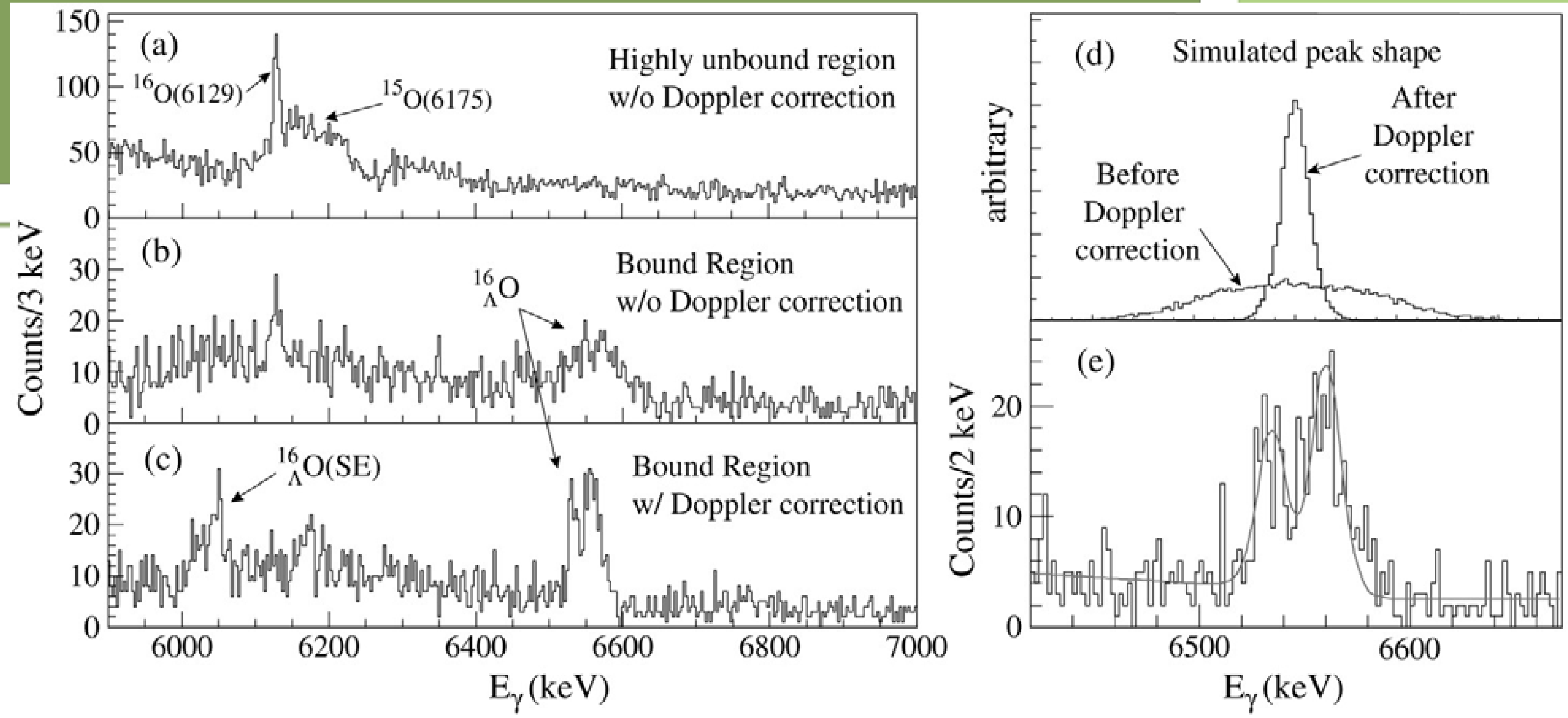
$= -0.035\,\Delta - 2.465 S_\Lambda + 0.936 T$

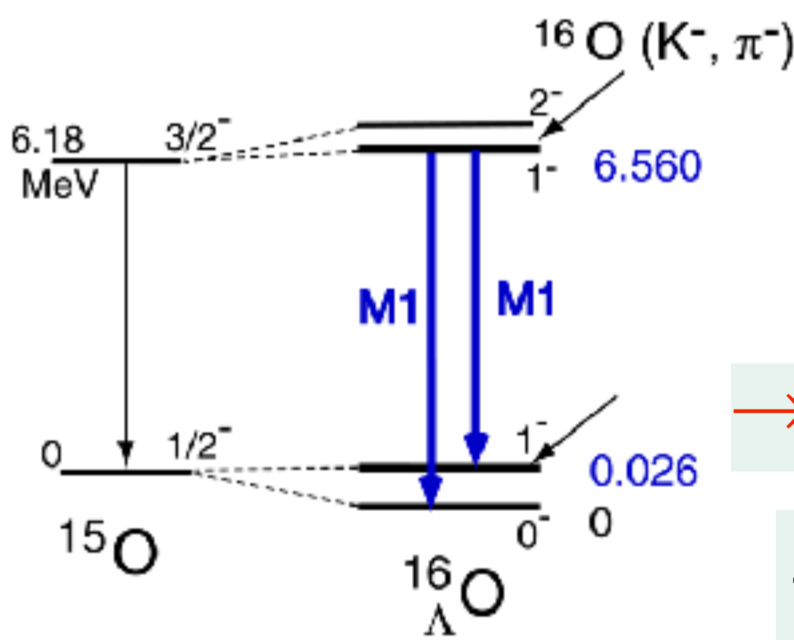
$S_\Lambda = -0.02$ MeV

Consistent with

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

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





ΔE = 26.1±1.4±0.6 keV

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

(Millener, 2001)

<- Δ = 0.46 MeV, S_Λ = -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 $\Lambda\Sigma$.

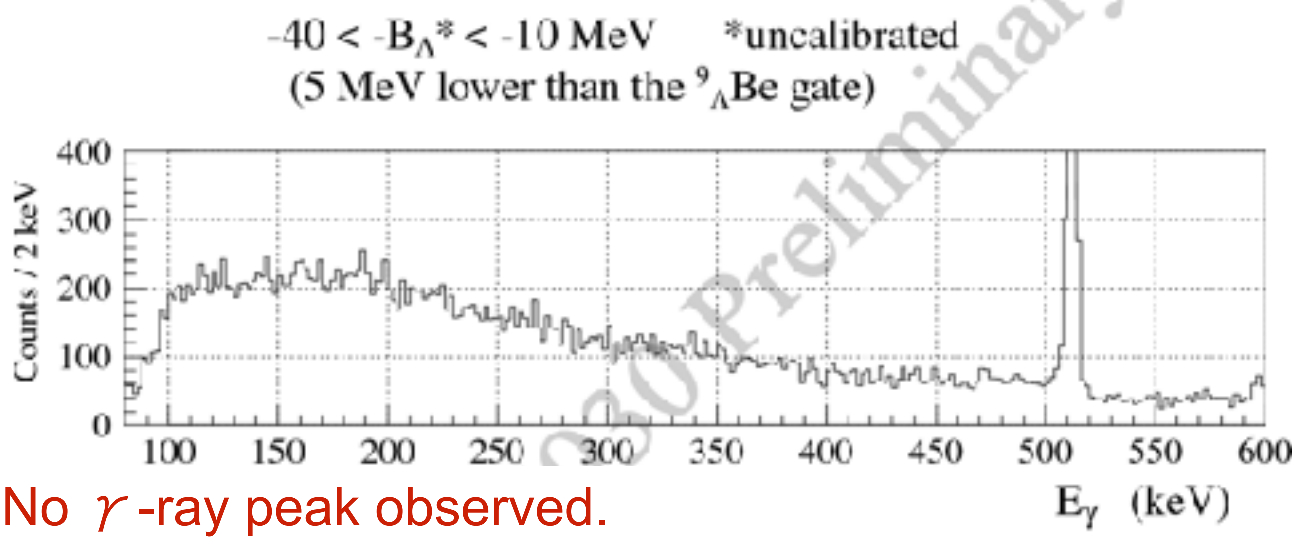
[a] $\overline{E(J_1, J_2)} = [(2J_1 + 1)E(J_1) + (2J_2 + 1)E(J_2)]/(2J_1 + 2J_2 + 2)$ denotes the center of gravity energy for the doublet (J_1, J_2).

[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.

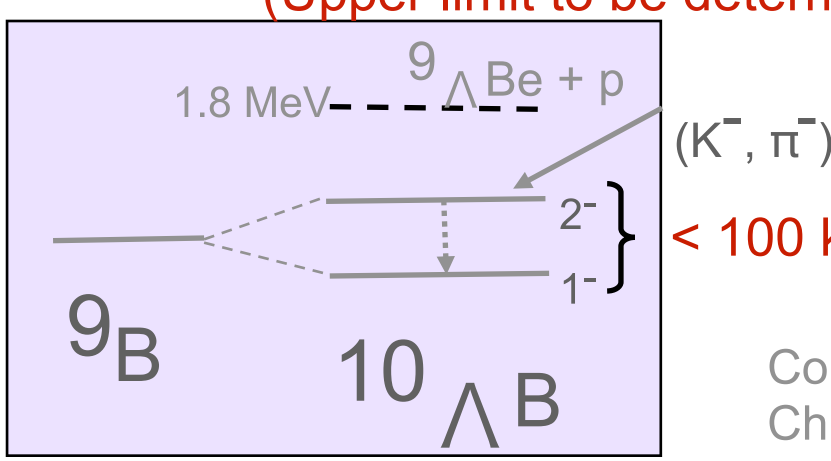
γ spectrum of ${}^{10}_{\Lambda}B$ (E930-2)

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



No γ-ray peak observed.

(Upper limit to be determined.)

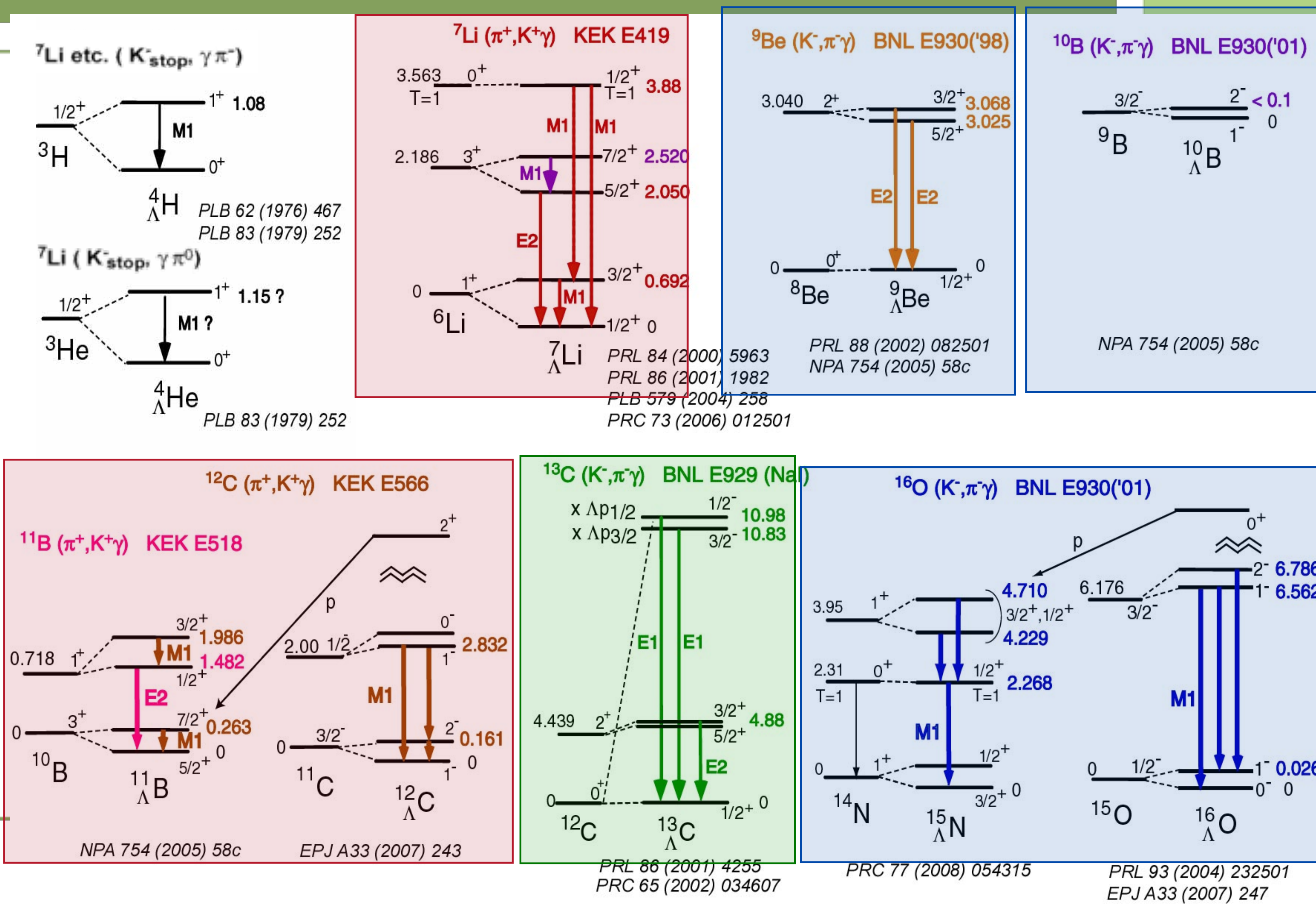


< 100 keV $\delta \sim 200$ keV from $\Delta = 0.5$ MeV

Confirmed

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

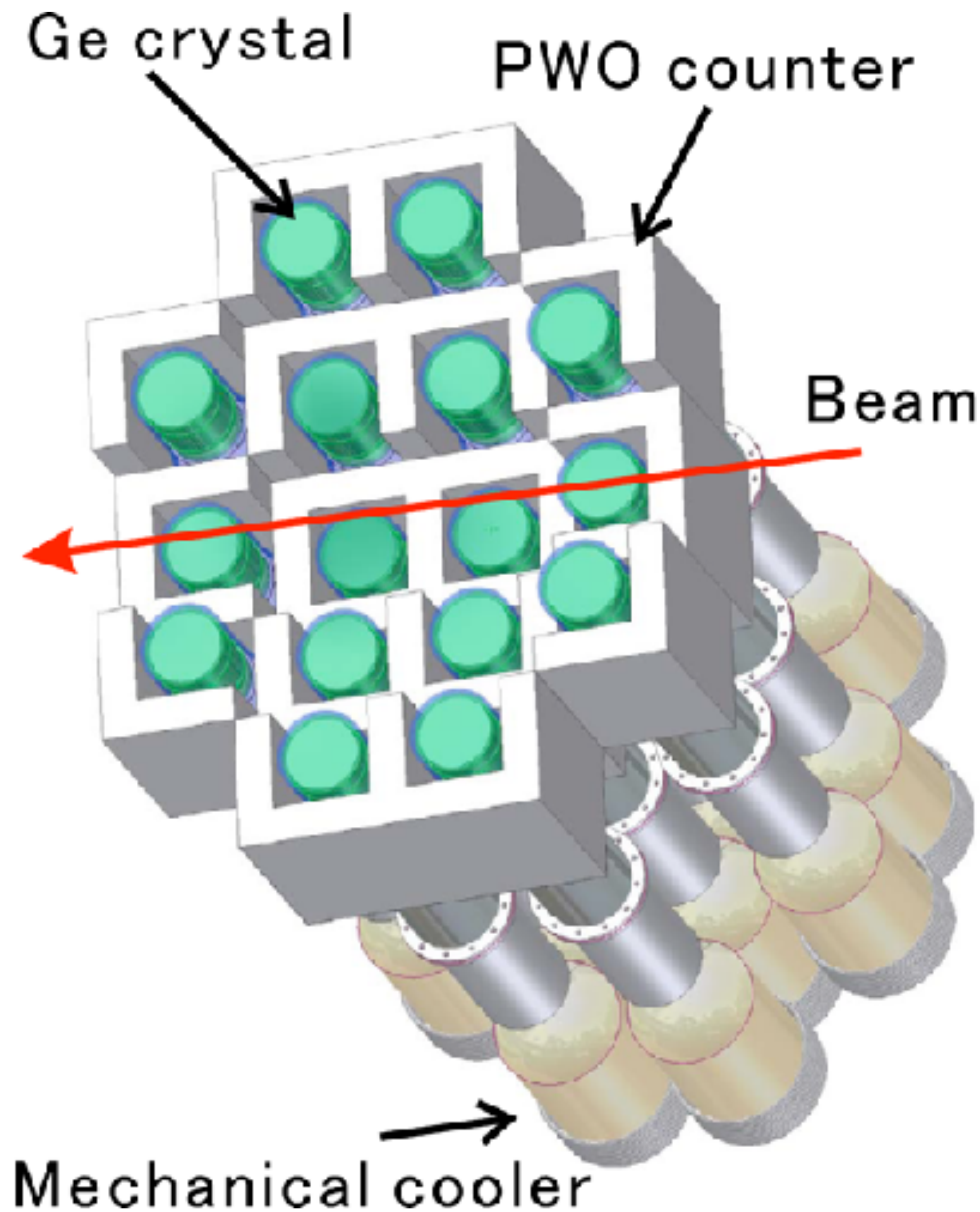
Summary of Hypernuclear γ rays



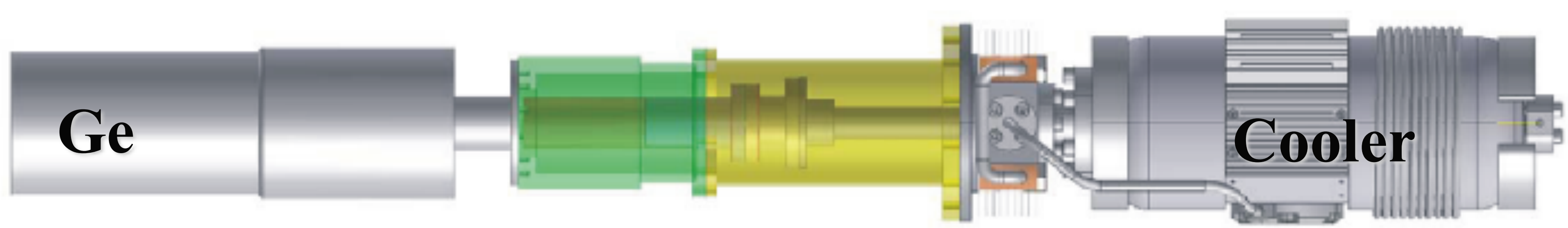
by H.Tamura

Hyperball-J

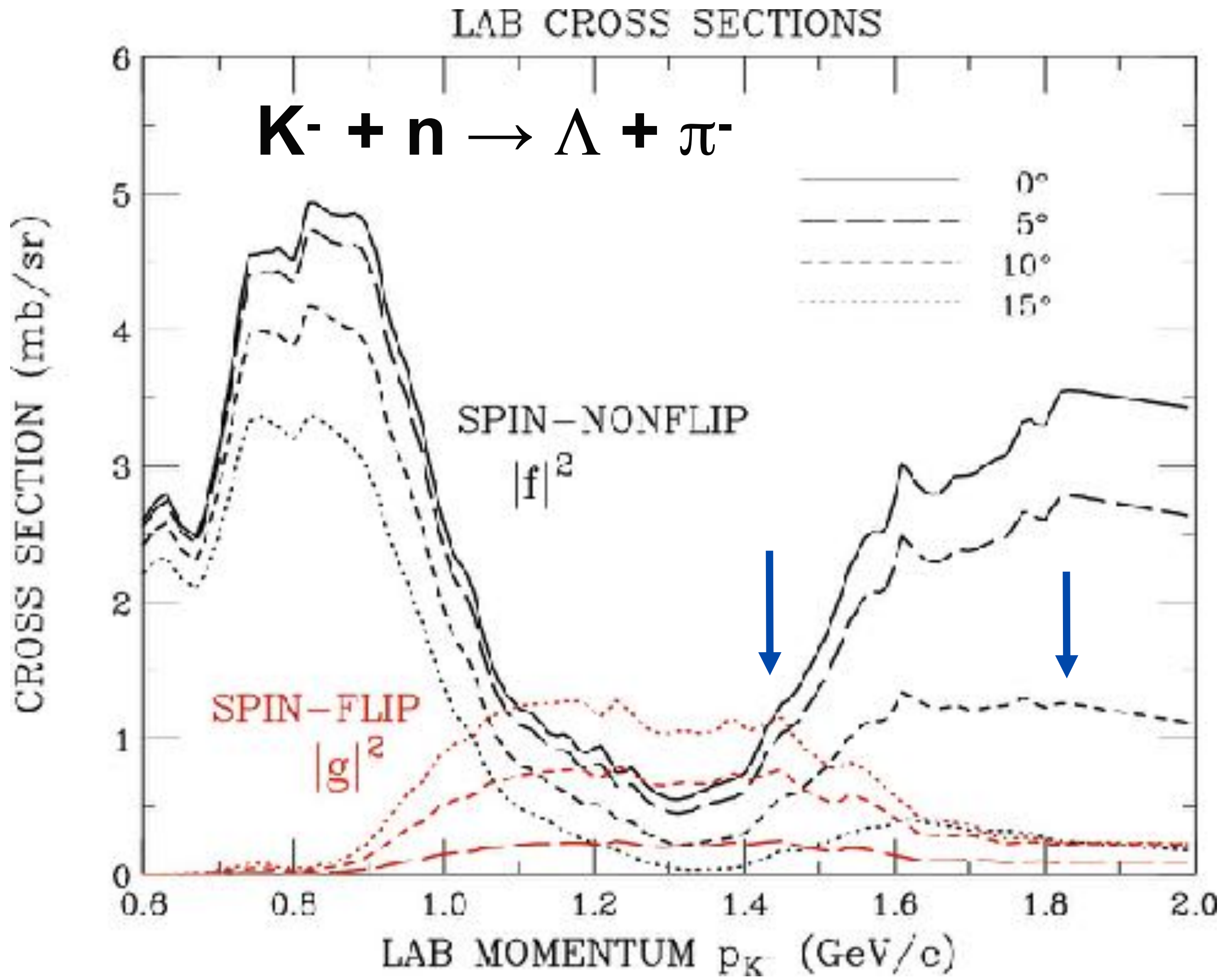
- Ge (single, r.e.~60%) x ~32
  → peak efficiency ~6% at 1 MeV
  (x ~3 of Hyperball)
- Mechanical cooling
  -- Lower temp. for less radiation damage
  -- Save space for flexible arrangement
- PWO background suppression counters replaced from BGO for higher rate
- Waveform readout (under development)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



Lower half



Best K$^-$ beam momentum



Both spin-flip and nonflip states should be produced.

$\rightarrow$ 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)

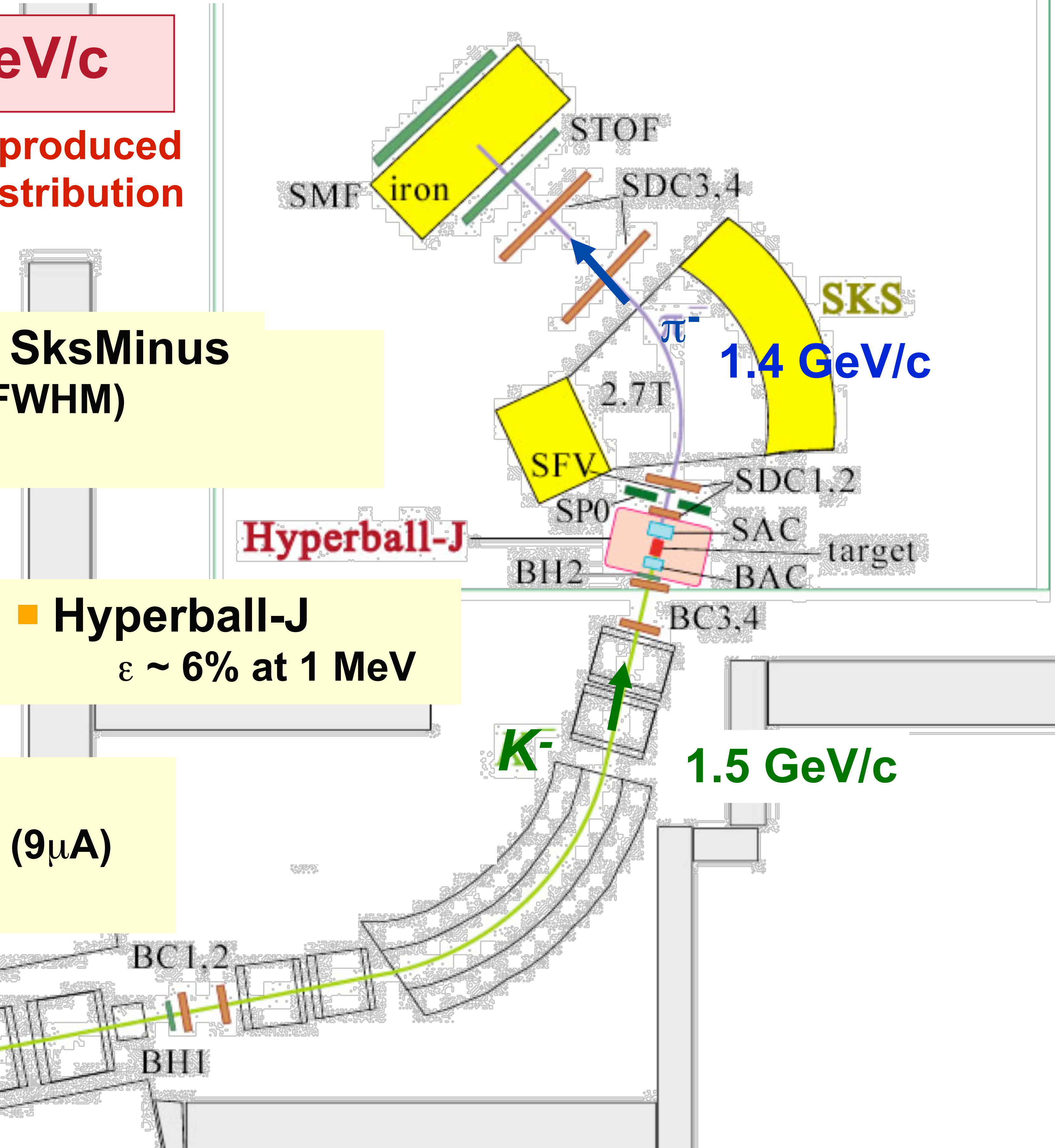
High K/π ratio to minimize radiation damage to Ge detectors
$\rightarrow$ Double-stage separation. K1.8BR is not good.

Beam and Setup

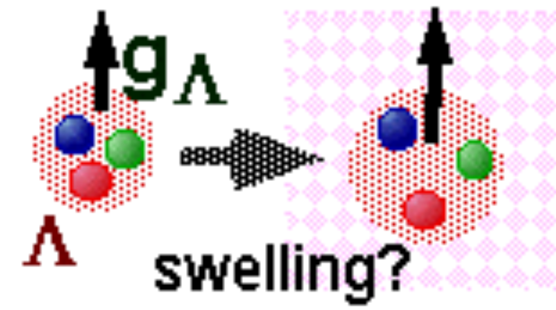
(K^-,$\pi^-\gamma$) at p_K = 1.5 GeV/c

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

- **Spectrometer: SksMinus**
  - Δp ~ 4 MeV (FWHM)
  - Ω ~ 110 msr
- **Hyperball-J**
  - ε ~ 6% at 1 MeV
- **Beamline: K1.8**
  - 0.5×10^6 K^-/spill at 1.5 GeV/c (9μA)
  - K/π >> 1



g factor of Λ in nucleus



- **Motivation**

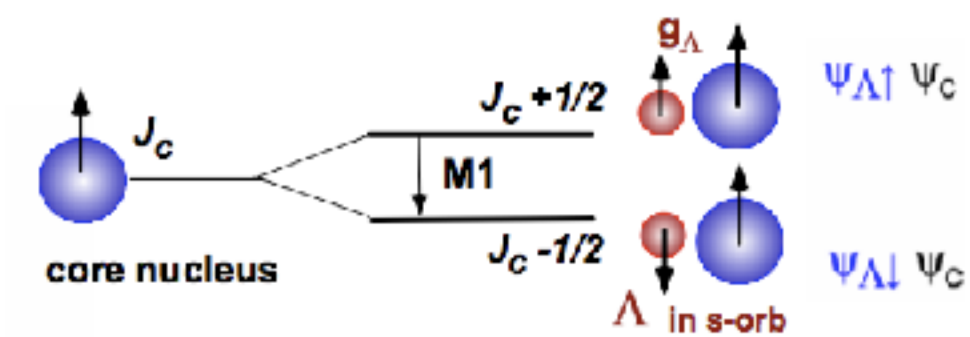
  μ_Λ in nucleus -> medium effect of baryons

  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 ($5/2^+ \to 1/2^+$) from B(E2)
PRL 86 ('01)1982

- **Preliminary data (statistical error only)**
  from $^7{}_\Lambda$Li ($3/2^+ \to 1/2^+$) (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

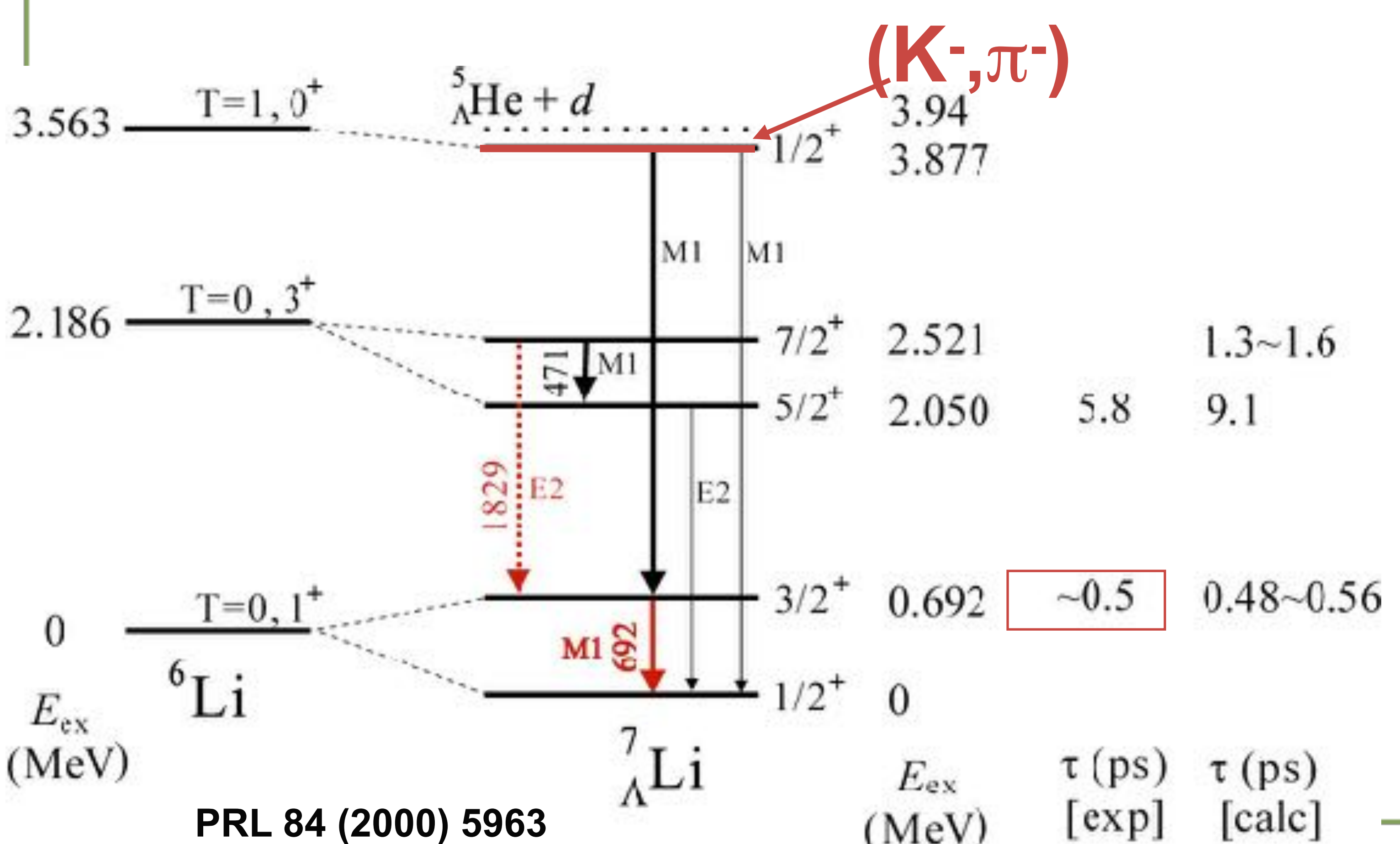
Difficulties in B(M1) measurement

- 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 $\rightarrow \tau \gg t_{stop}$), $^{7}_{\Lambda}$Li (by product: indirect population)

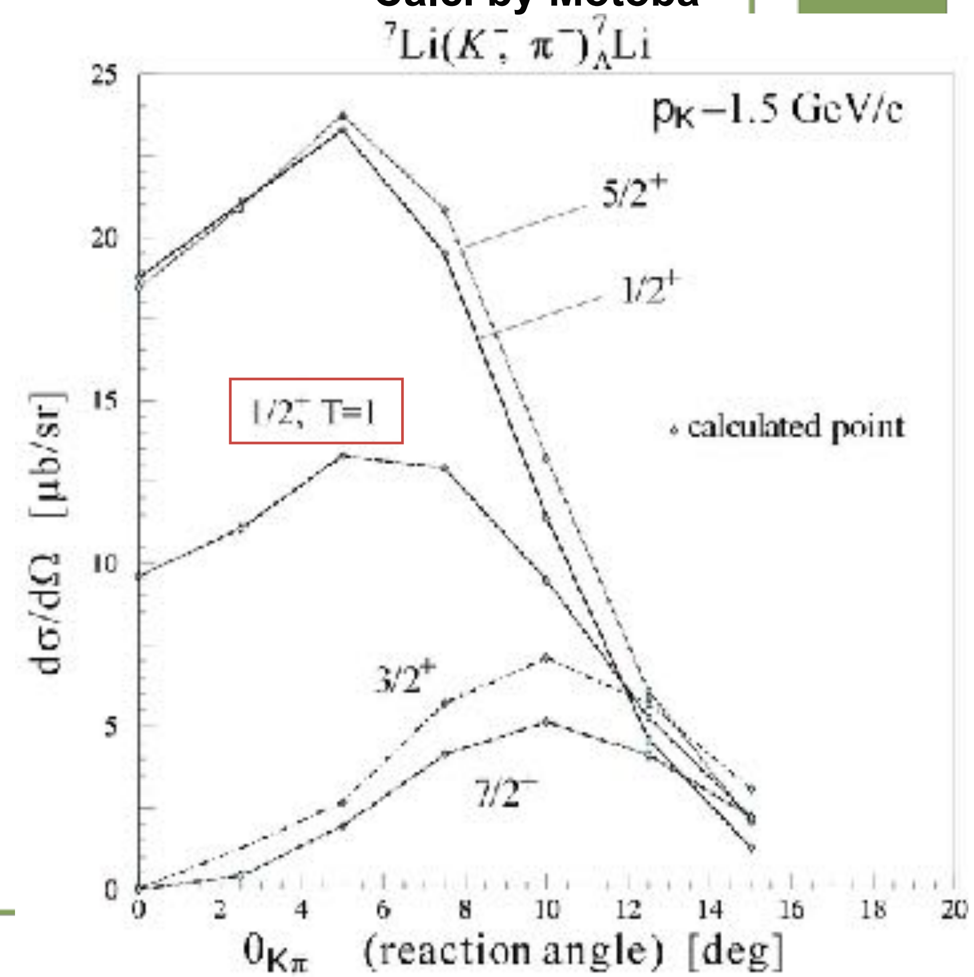
To avoid ambiguities, we use the best-known hypernucleus, $^{7}_{\Lambda}$Li.

- 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 x 10^6 /spill

Target (^{7}Li in Li_2O) = 20cm x 2.0g/cm^3 x 14/30 x 0.934 / 7 x 6.02x10^{23}

$\int d\sigma/d\Omega(1/2;1)\,\Delta\Omega$ x BR($1/2^+;1 \rightarrow 3/2^+$) = 0.84 μb x 0.5

ε(Ge) x ε (tracking) = 0.7 x 0.6

→

Yield ($3/2^+ \rightarrow 1/2^+$) = 7.3 /hr(1000 spill)

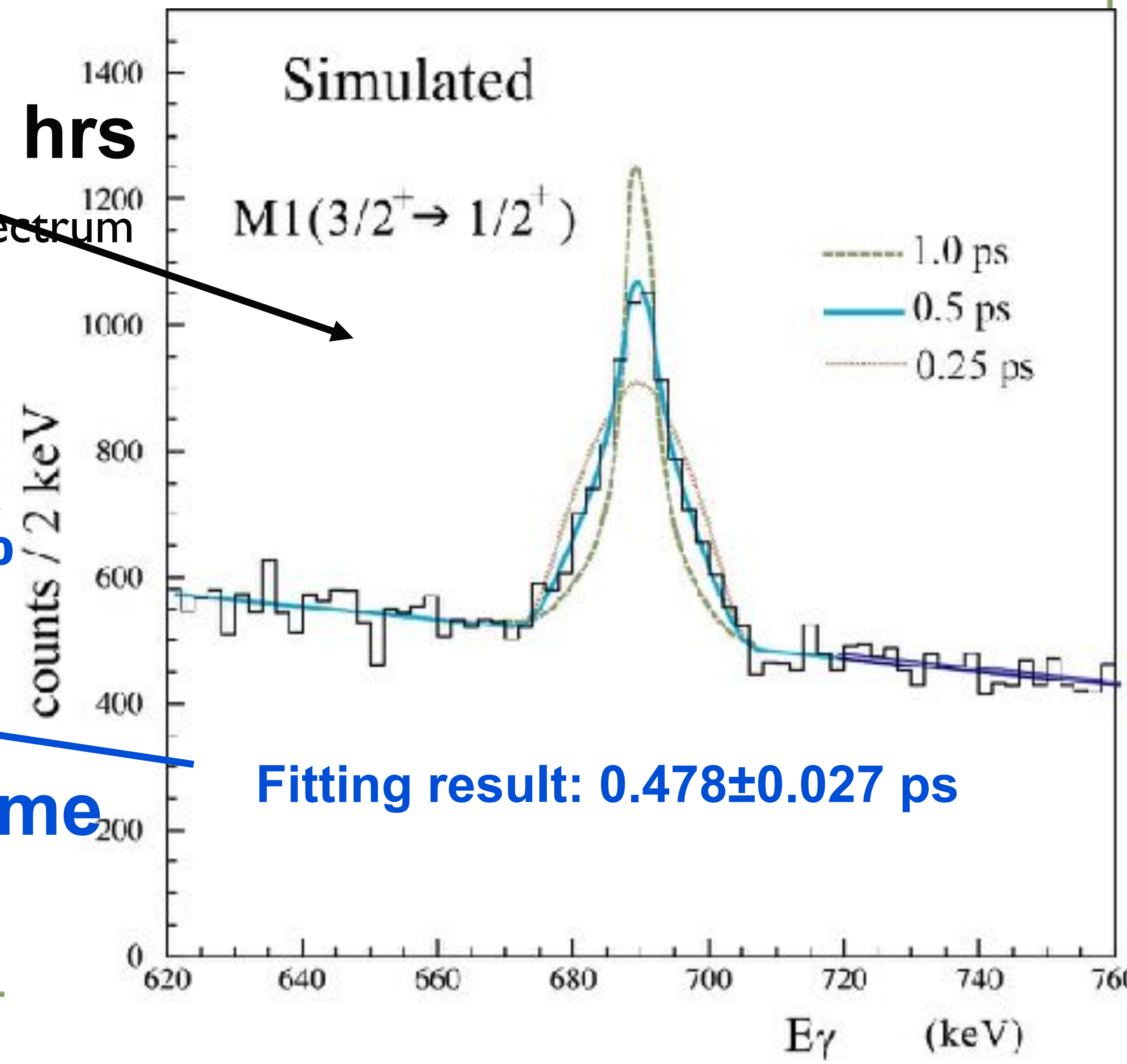
= 3600 / 500 hrs

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

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

$$\rightarrow \frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|} \sim 3\%$$

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



Fitting result: 0.478±0.027 ps

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)
    - $-\mathrm{Re}\ V_{opt}(0) \sim 25\text{-}30$ MeV, Attractive
    - $-\mathrm{Im}\ V_{opt}(0) \sim 10\text{-}15$ MeV, Absorptive
      - $\Sigma N \rightarrow \Lambda N$ conversion (strong interaction)
  - Σ hypernuclei may exist, but the widths are broad
  - No Spectroscopy $\Gamma \sim 2\mathrm{Im}V$

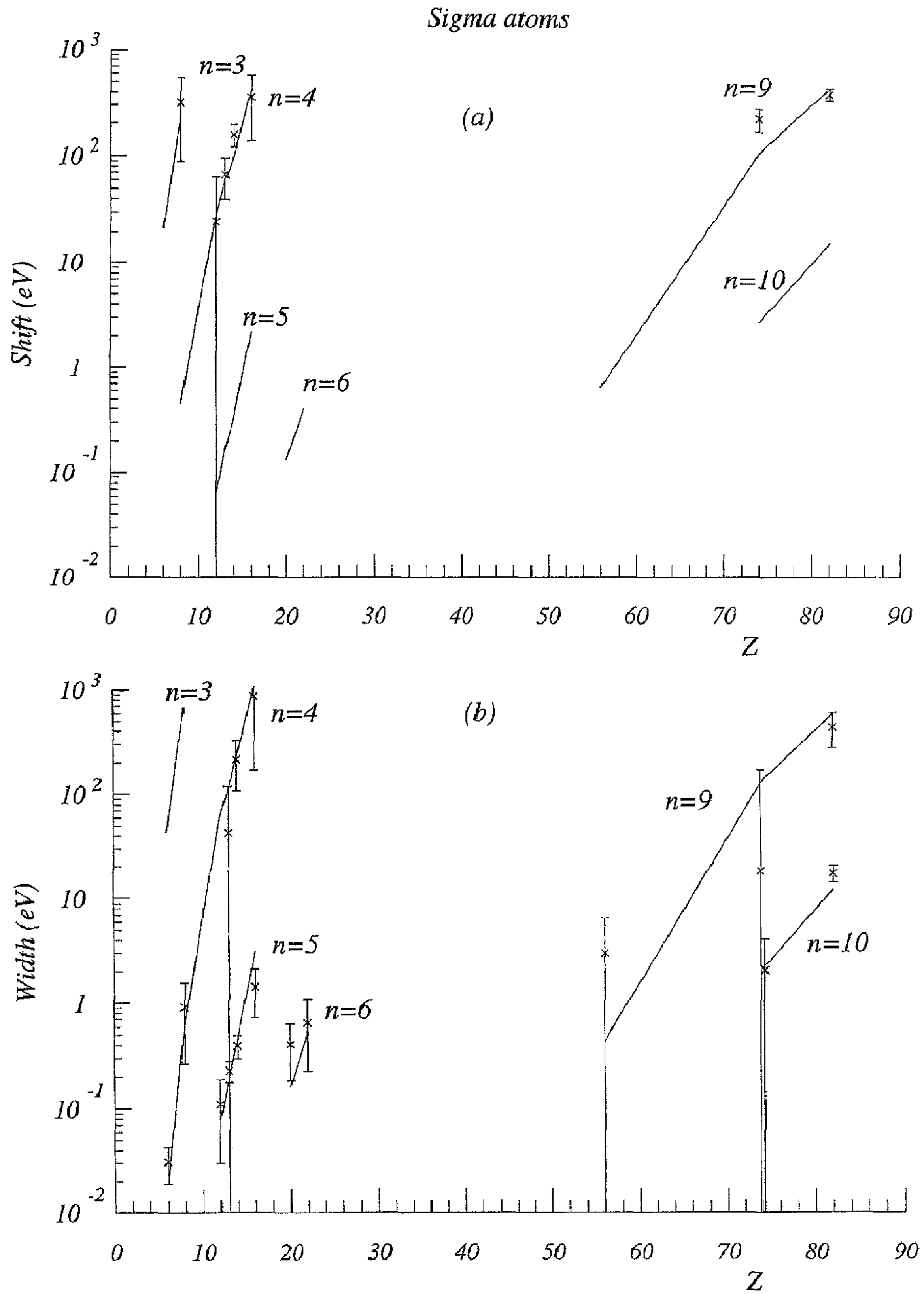


Fig. 9. Shift and width values for sigma atoms. The continuous lines join points calculated with the best-fit optical potential discussed in Section 6.2.

Σ-Nucleus potential

- Σ-atom X-ray

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

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

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

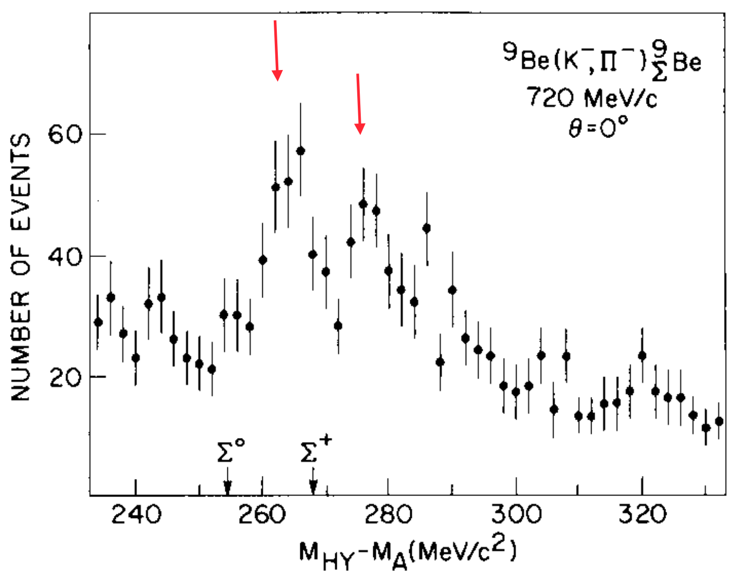
$\mu : reduced - mass$

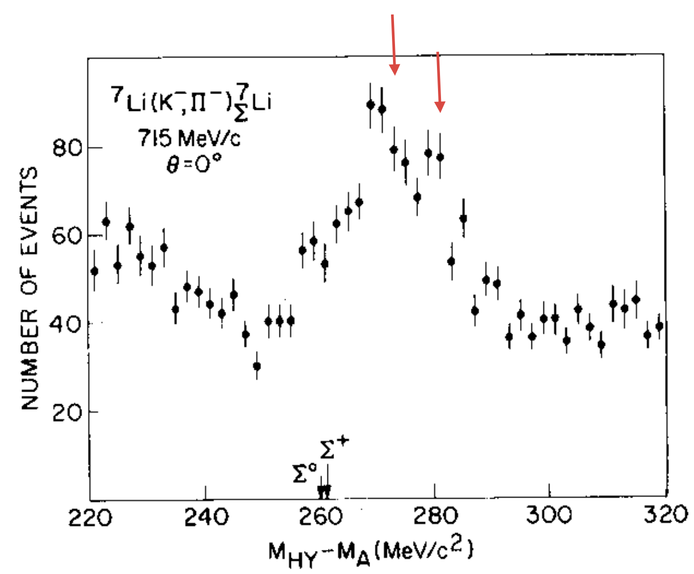
- DWIA analysis: Green Function method

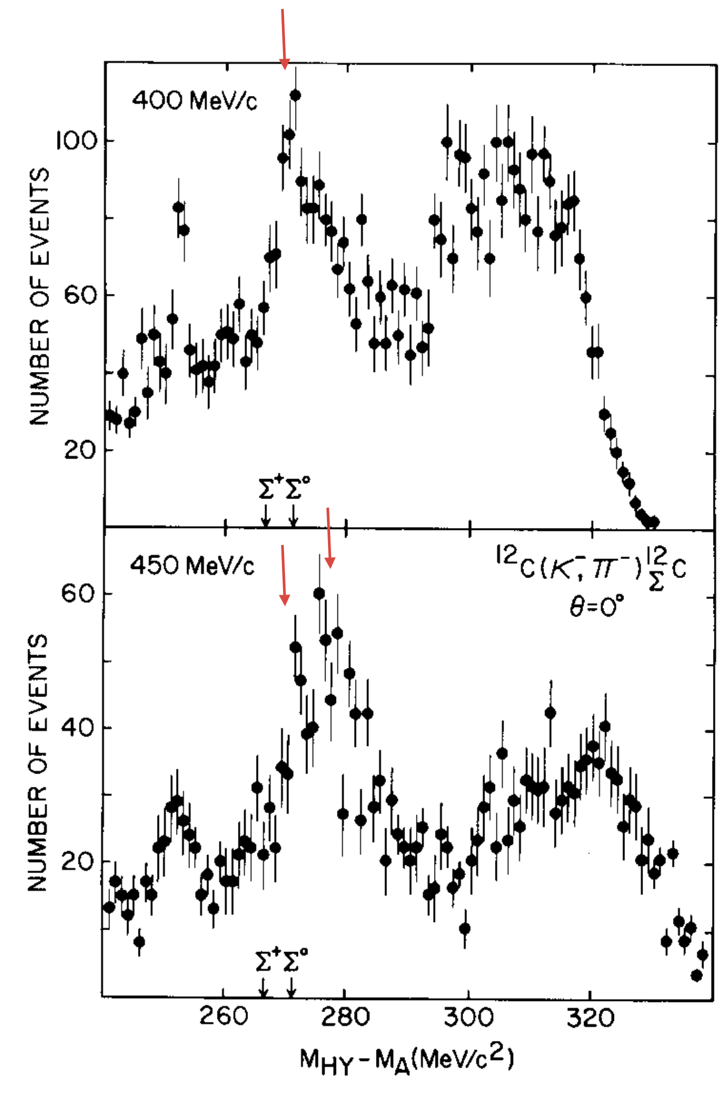
Morimatsu and Yazaki, NP A483(88)493,
R.S.Hayano, NP A478(88)113c.

Narrow width problem in 1980s

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



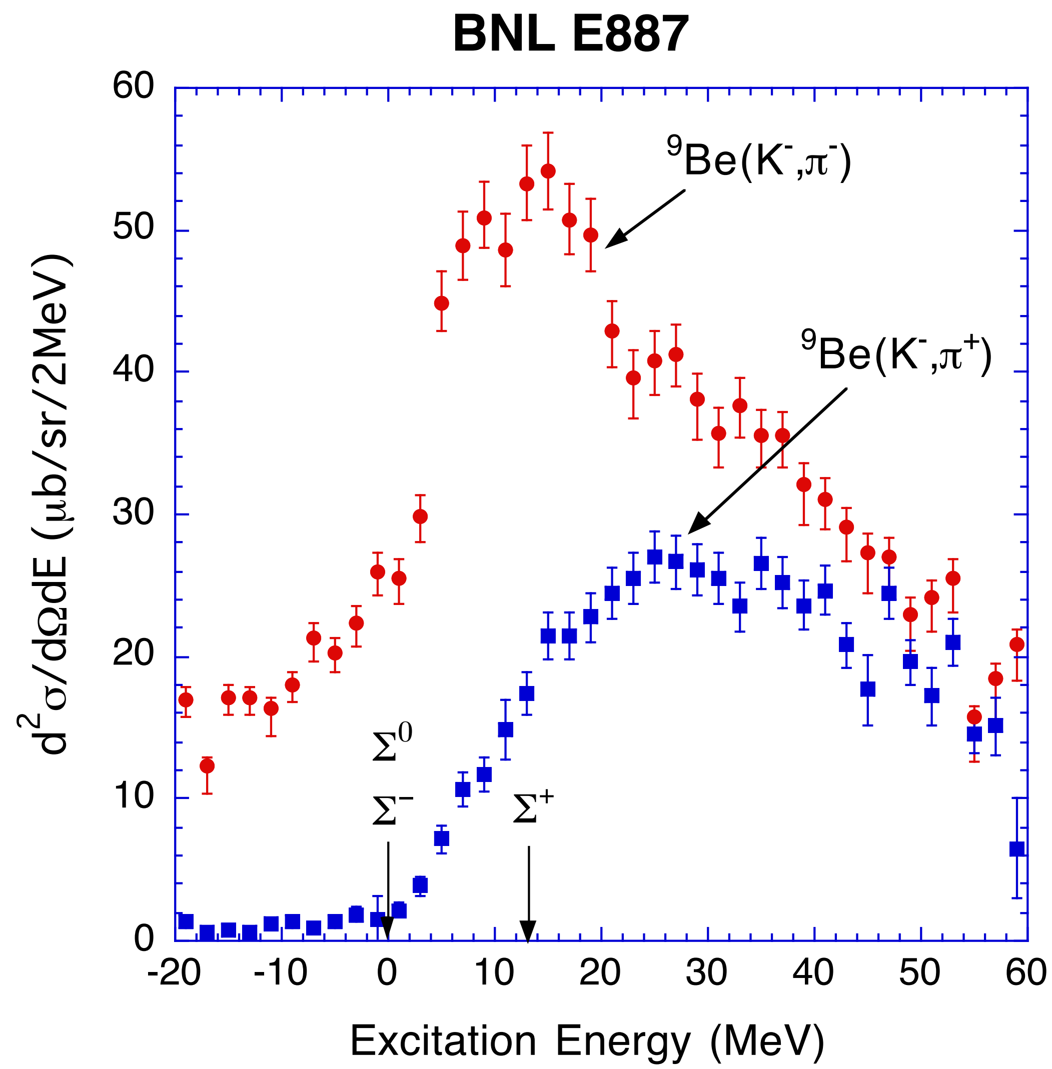




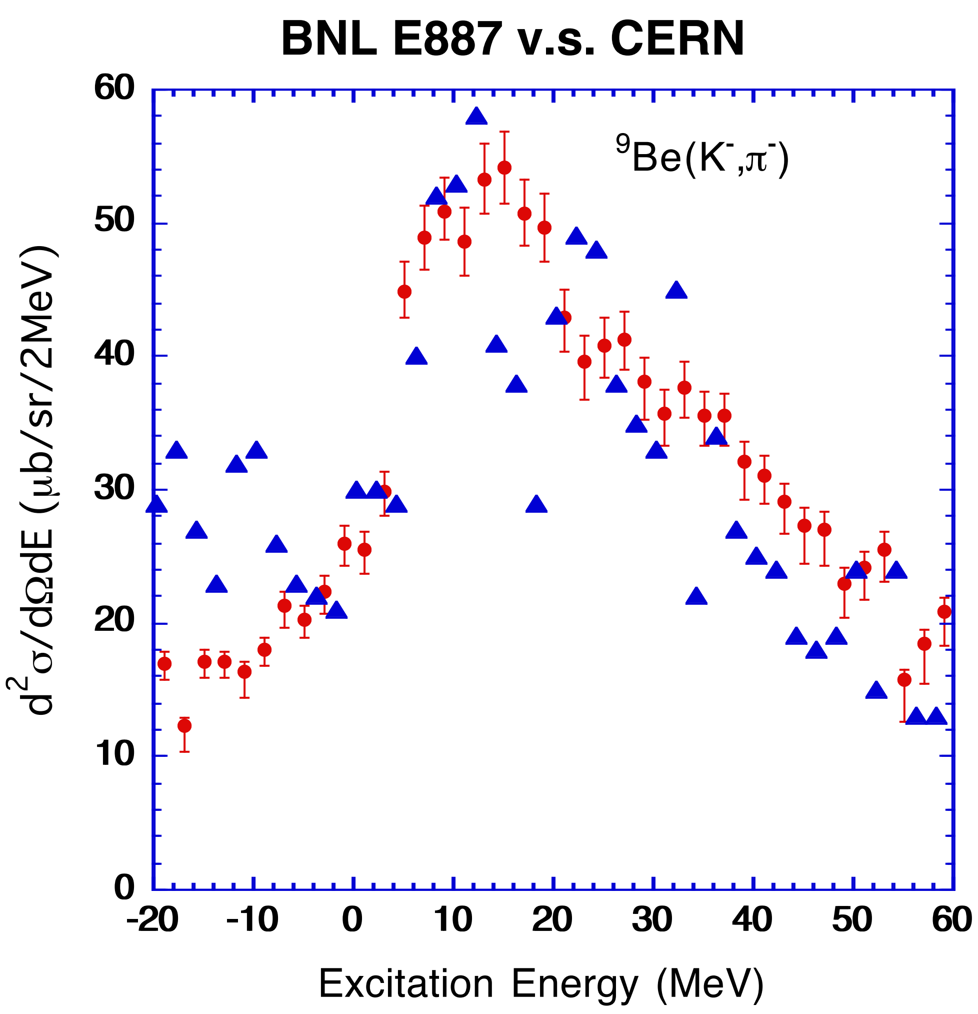
BNL E887

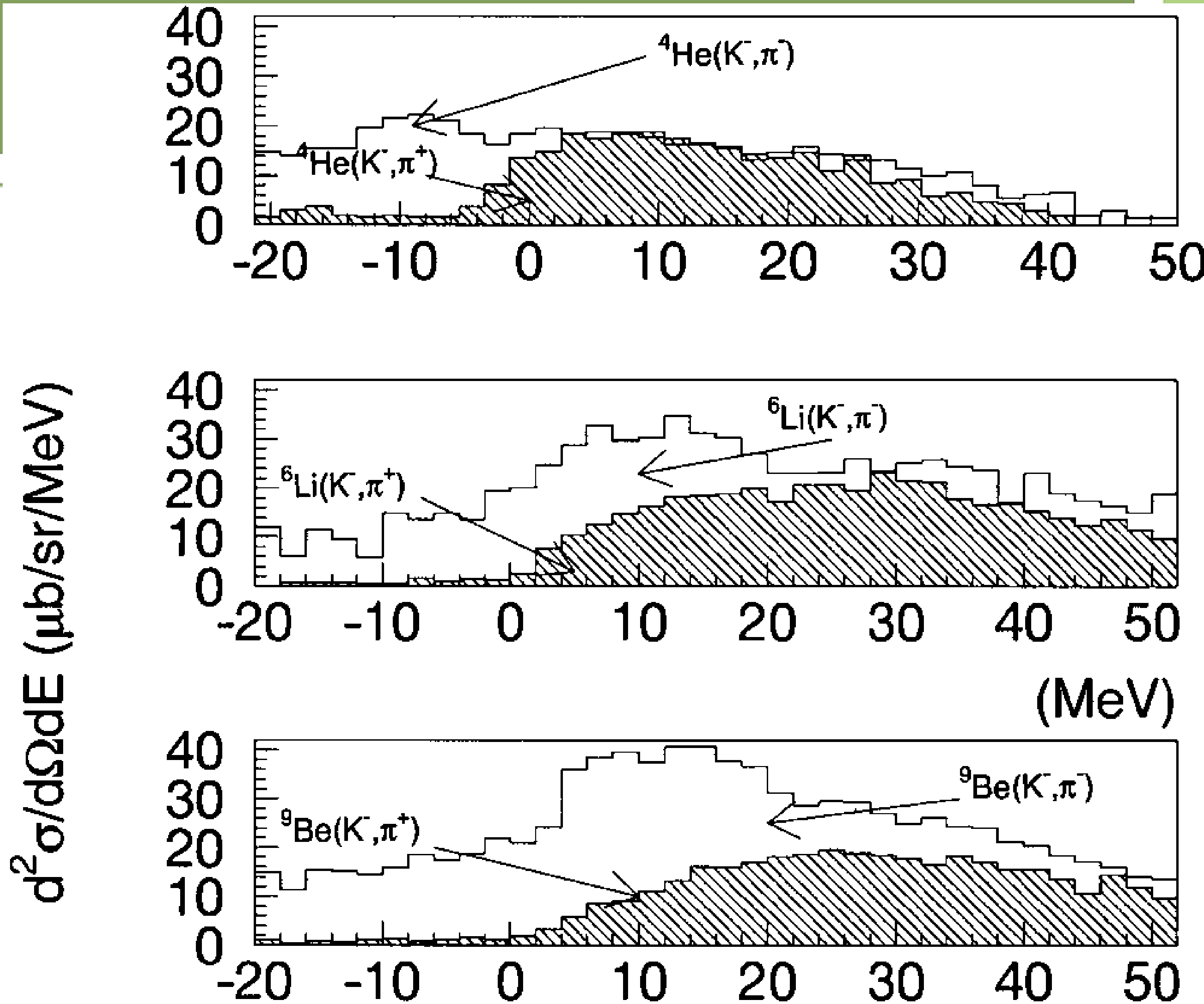
- 600 MeV/c
- 4 degrees

- 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

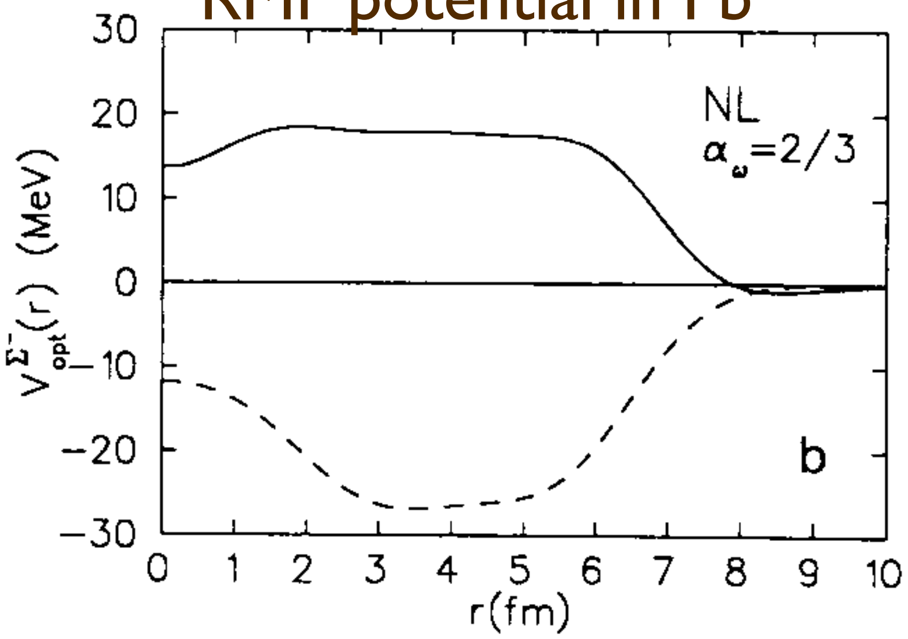
$$2\mu V_{opt}(r) = -4\pi\left(1+\frac{\mu}{m_n}\right)\left\{\left[b_0 + B_0\left(\frac{\rho(r)}{\rho(0)}\right)^{\alpha}\right]\rho(r) + \left[b_1 + B_1\left(\frac{\rho(r)}{\rho(0)}\right)^{\alpha}\right]\delta\rho(r)\right\}$$

    - 軽い核を除いて、束縛状態は存在しない!?

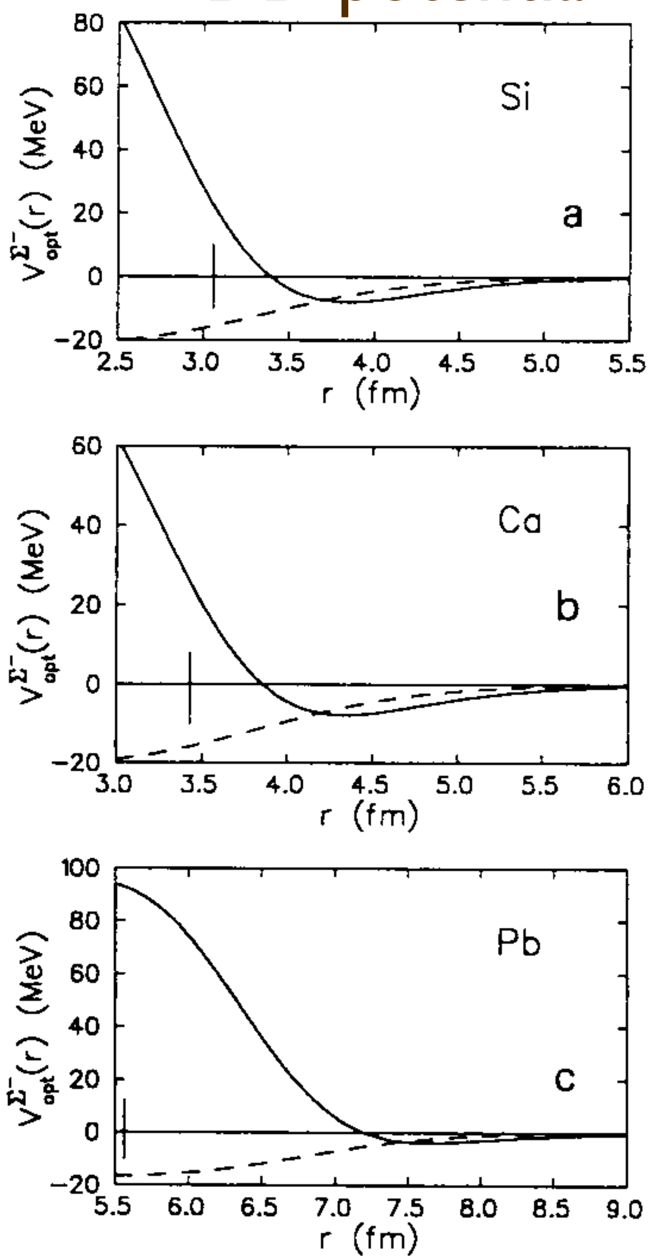
Repulsive ??

- 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.

RMF potential in Pb

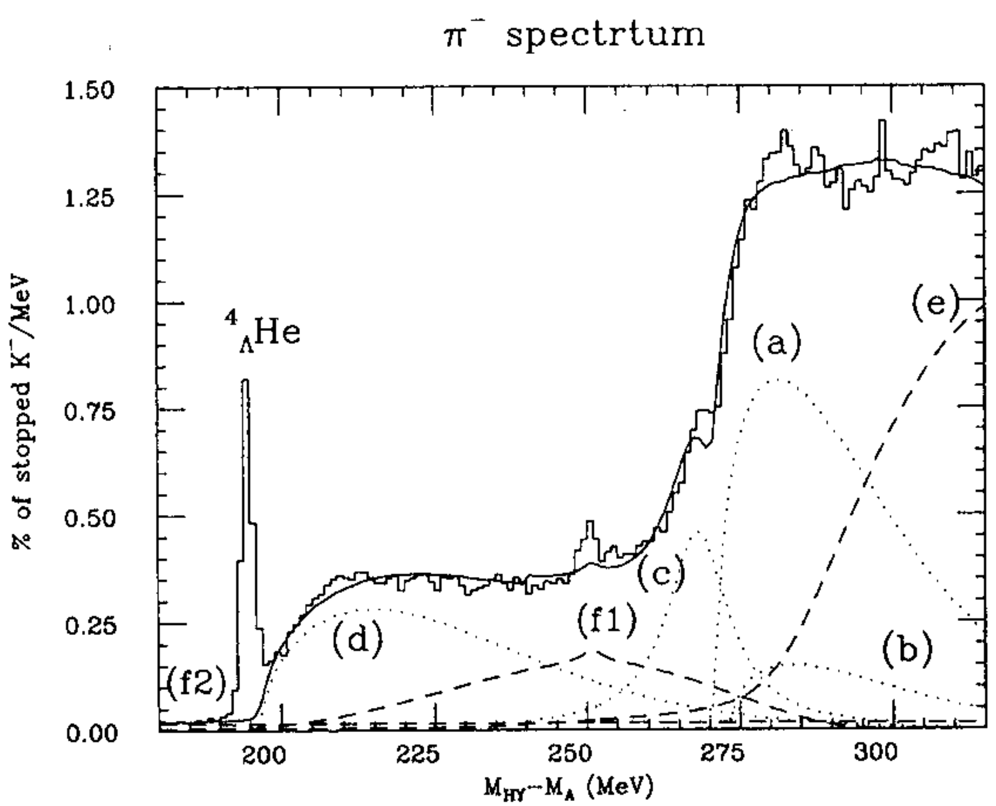


DD potential



Existence of any bound states ?

- Only candidate
  - ^{4}He(K^-_{stop},π^-) : 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

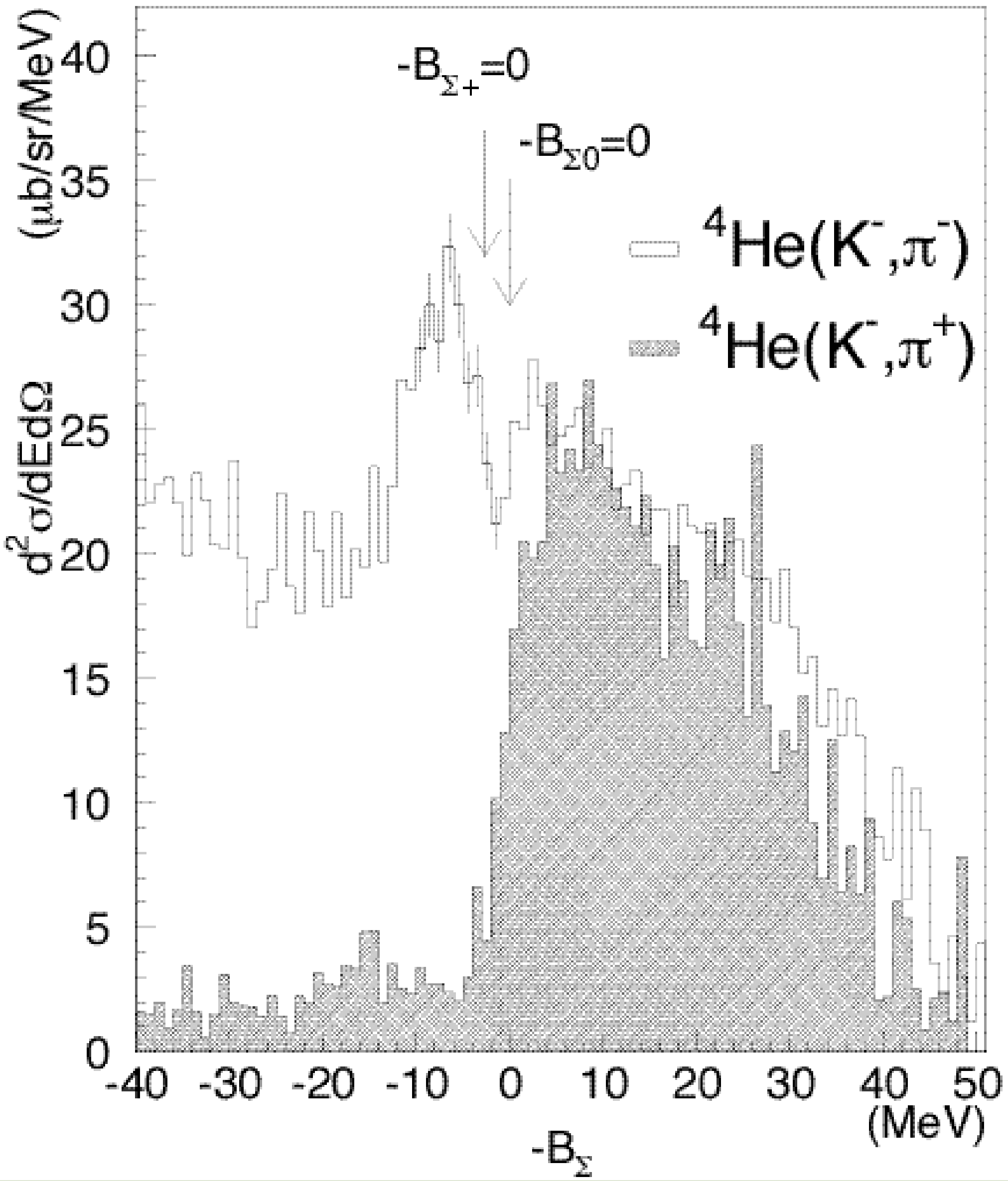
R.S. Hayano et al., PL B231 (1989).

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

BNL E905: In-flight (K^-,π^-)

- 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)

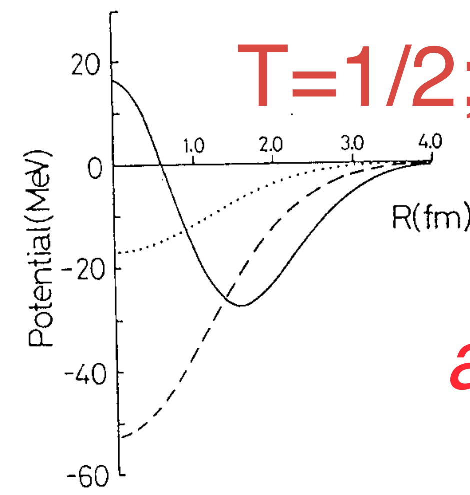
T. Nagae et al., PRL 80 (1998) 1605.



Harada and Akaishi

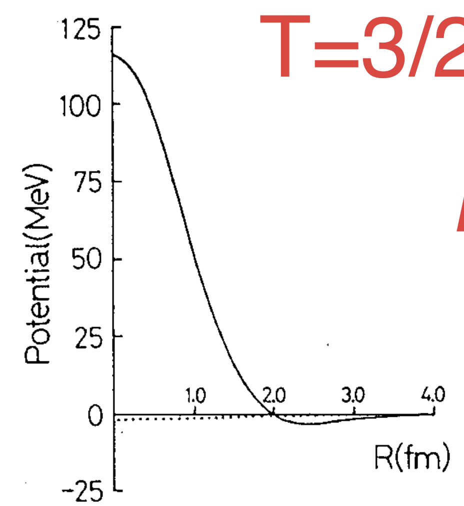
- Strong Isospin dependence
  - Lane term
  - $U_{C\Sigma} = U^0 + U^t T_C \cdot t_\Sigma / A$

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



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

attractive



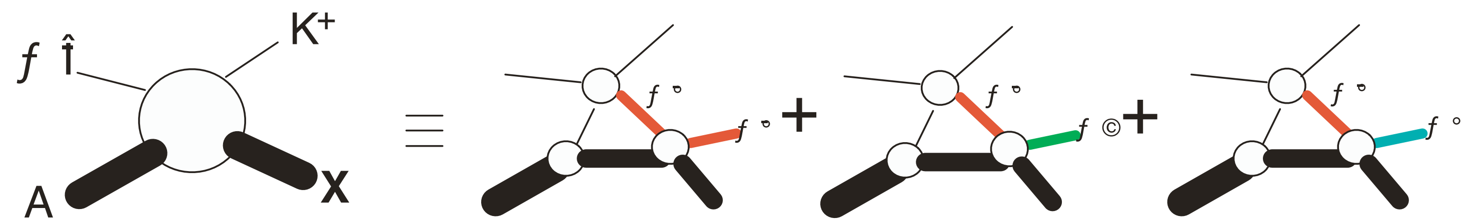
$T=3/2;\ U^0 + 1/2U^t$

repulsive

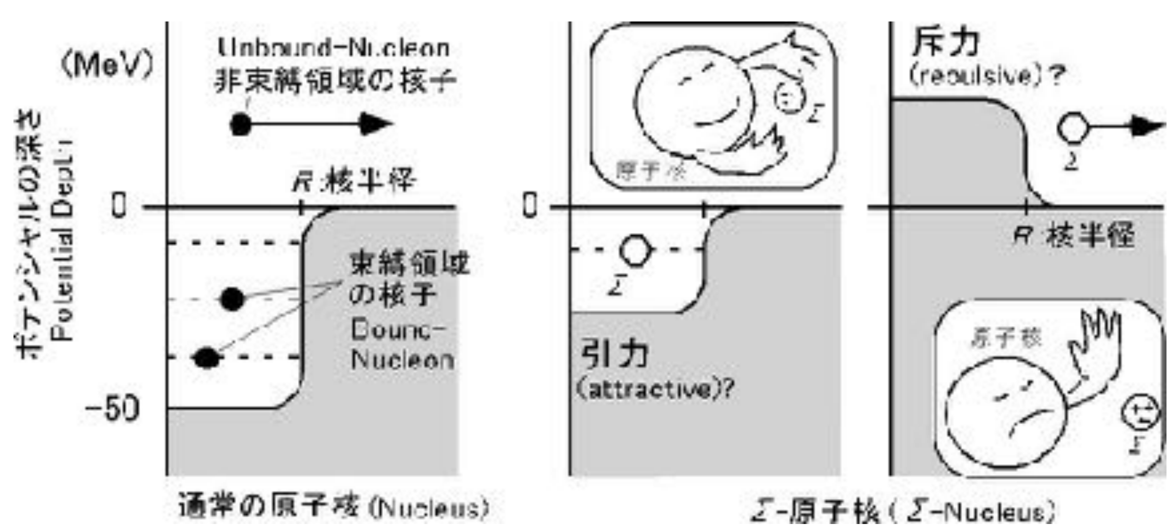
E438: Study of Σ-nucleus potential by the (π^-,K^+) reaction on heavy nuclei

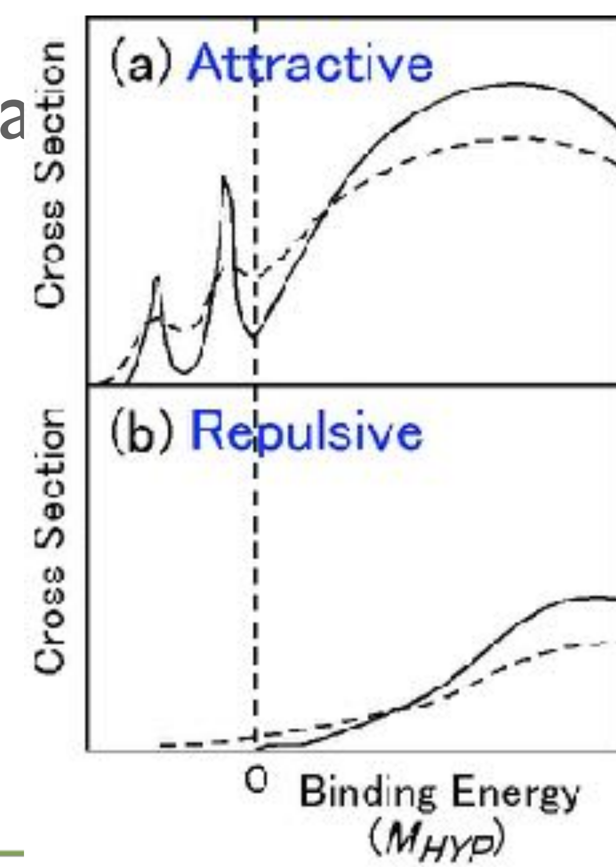
$U_\Sigma = V_\Sigma + i\,W_\Sigma$

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



Inclusive spectrum tells the Σ potential

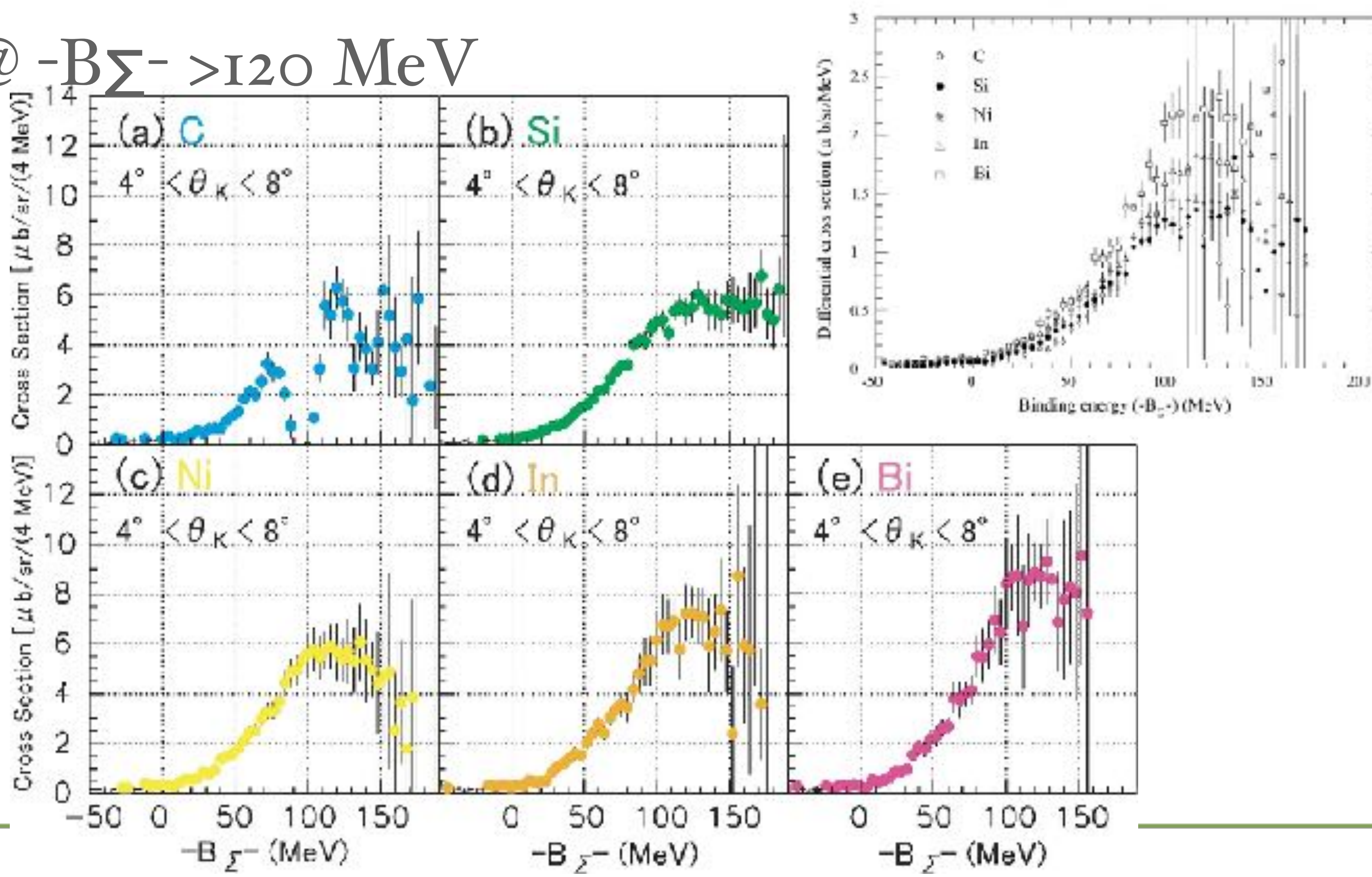


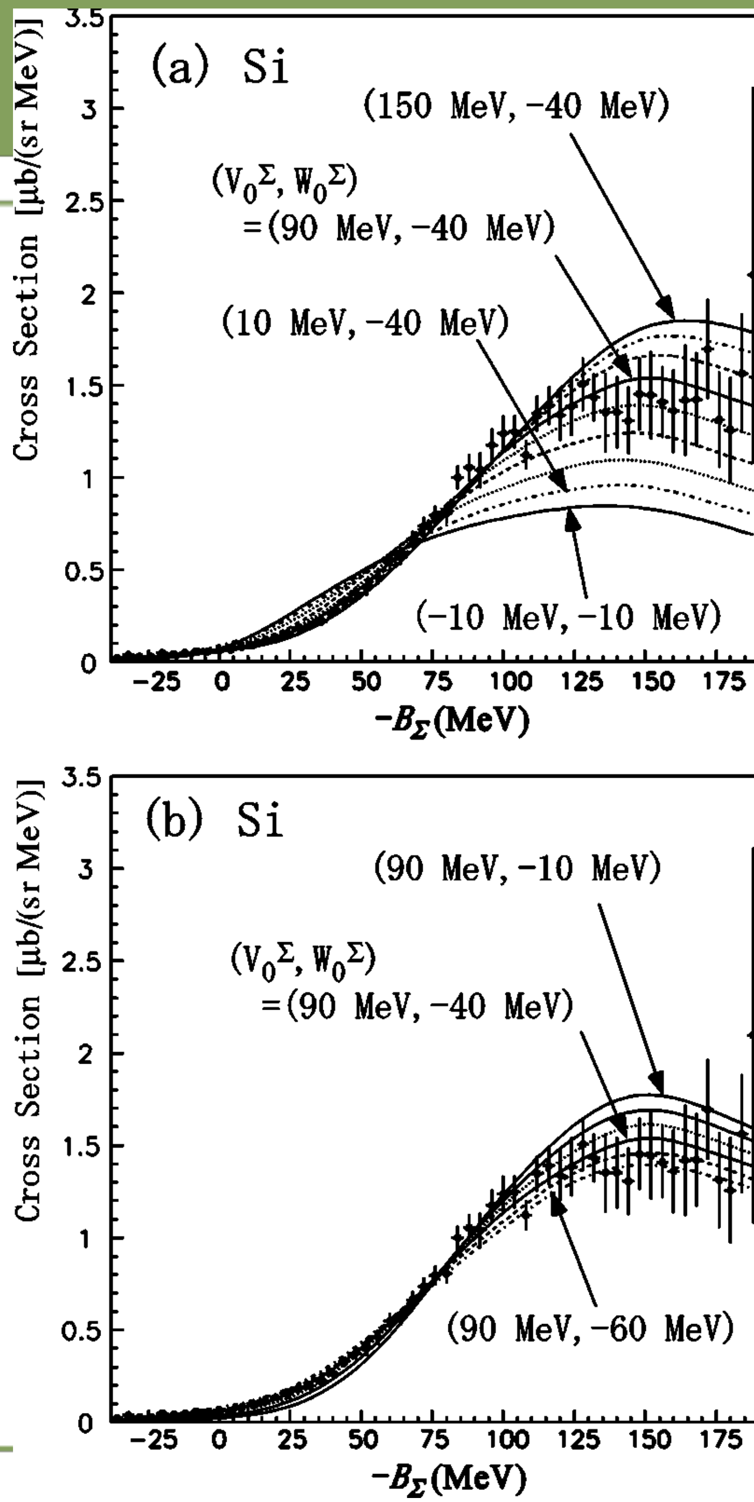


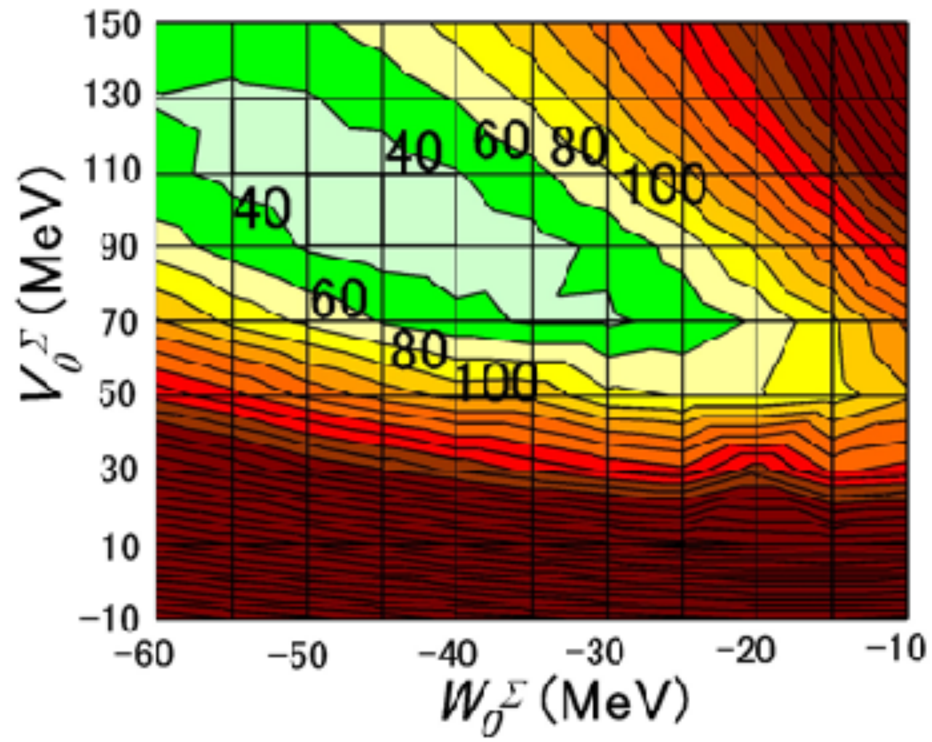
Measured Inclusive (π^-,K^+) Spectra on C, Si, Ni, In, & Bi

- 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.





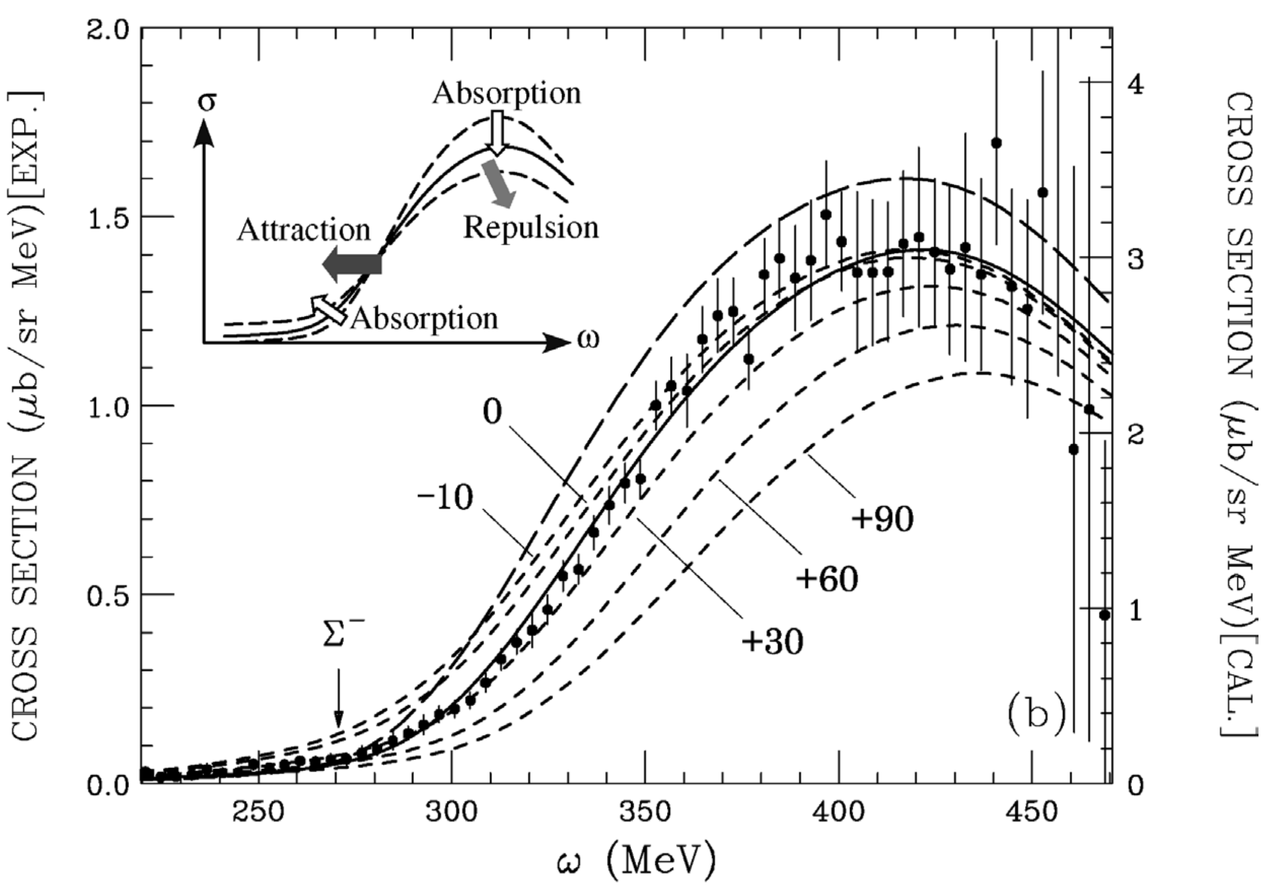


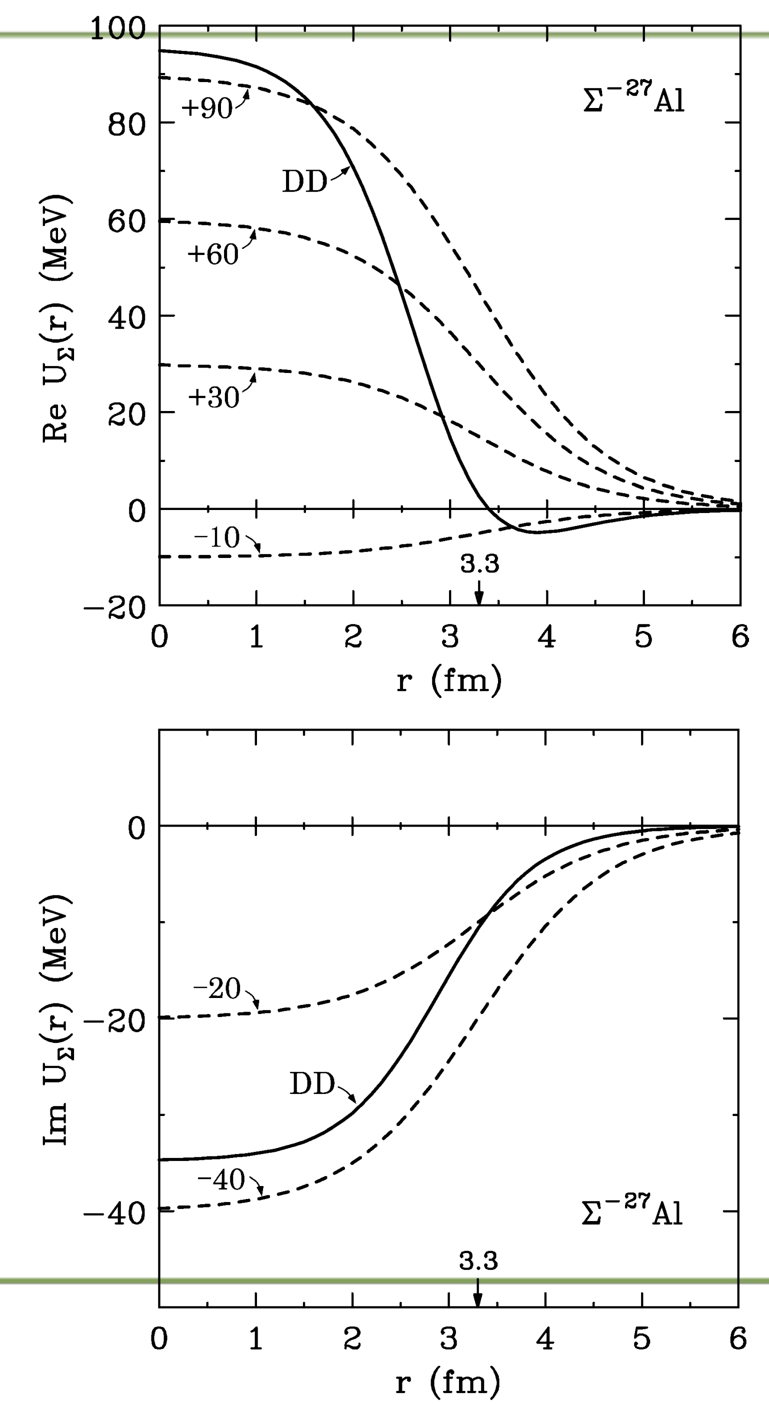
V_0=+90 MeV, W_0=-40 MeV

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

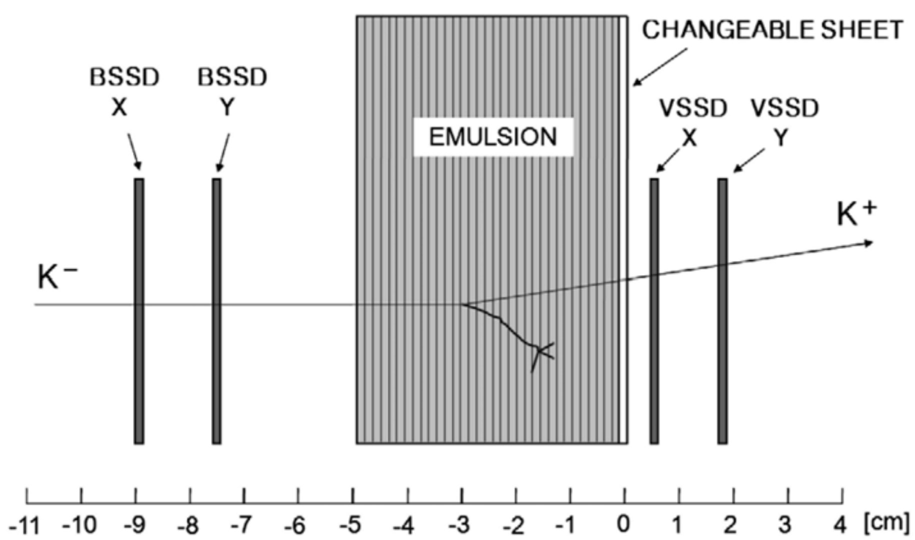
- No narrow states in unbound region
- One bound state in $^{4}_{\Sigma}\mathrm{He}$
  - $^{7}_{\Sigma}\mathrm{Li}$? Nucl. Phys. A 547 (1992) 175c.
- Σ -Nucleus potential is repulsive in medium-heavy system.

S=-2 Systems

Hybrid Emulsion Experiments

by K. Nakazawa

KEK E176



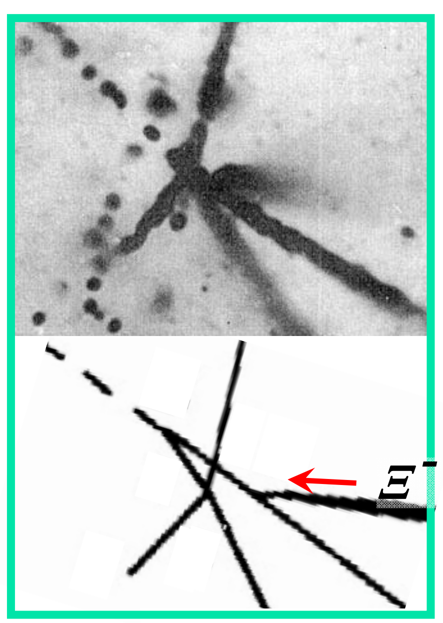
Introduction of experimental method

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): $57.7^{+6.1}_{-9.6}$ %



most probable case

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

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

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

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

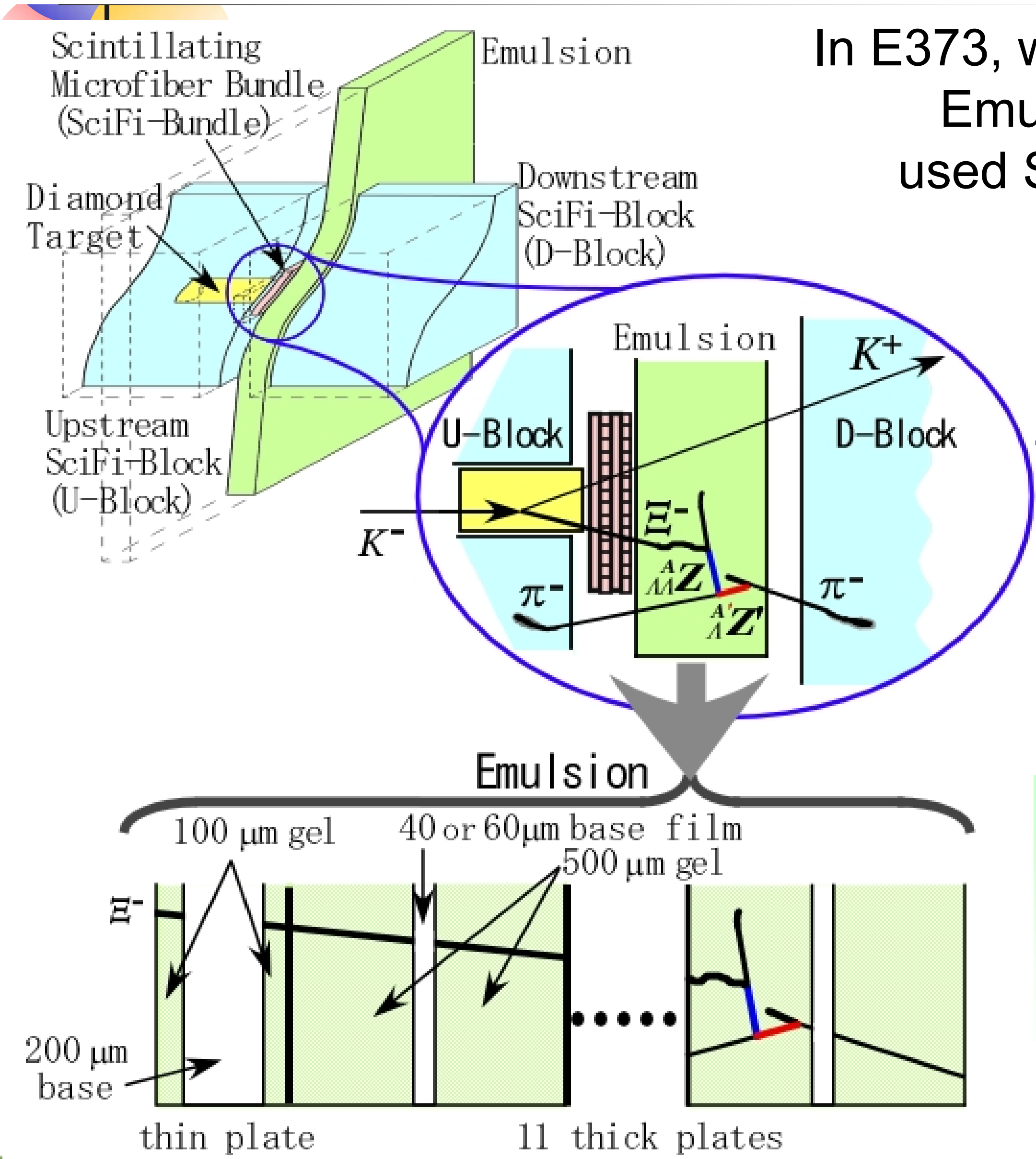
$\Delta B_{\Lambda\Lambda}$ = 0.6 +/- 0.8 MeV

[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.

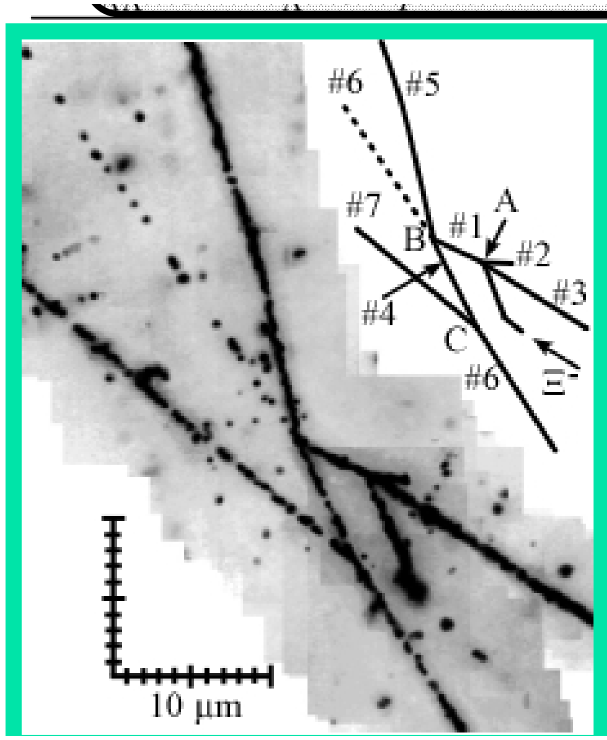
==> ~10^3 Ξ^- stops

“ 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

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

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 3*D* : ^{12}C- Ξ^-]

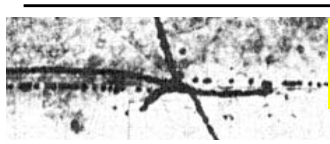
$^{6}_{\Lambda\Lambda}$**He** $B_{\Lambda\Lambda}$ = 6.91 +/- 0.16 MeV, $\Delta B_{\Lambda\Lambda}$ = 0.67 +/- 0.17 MeV

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.

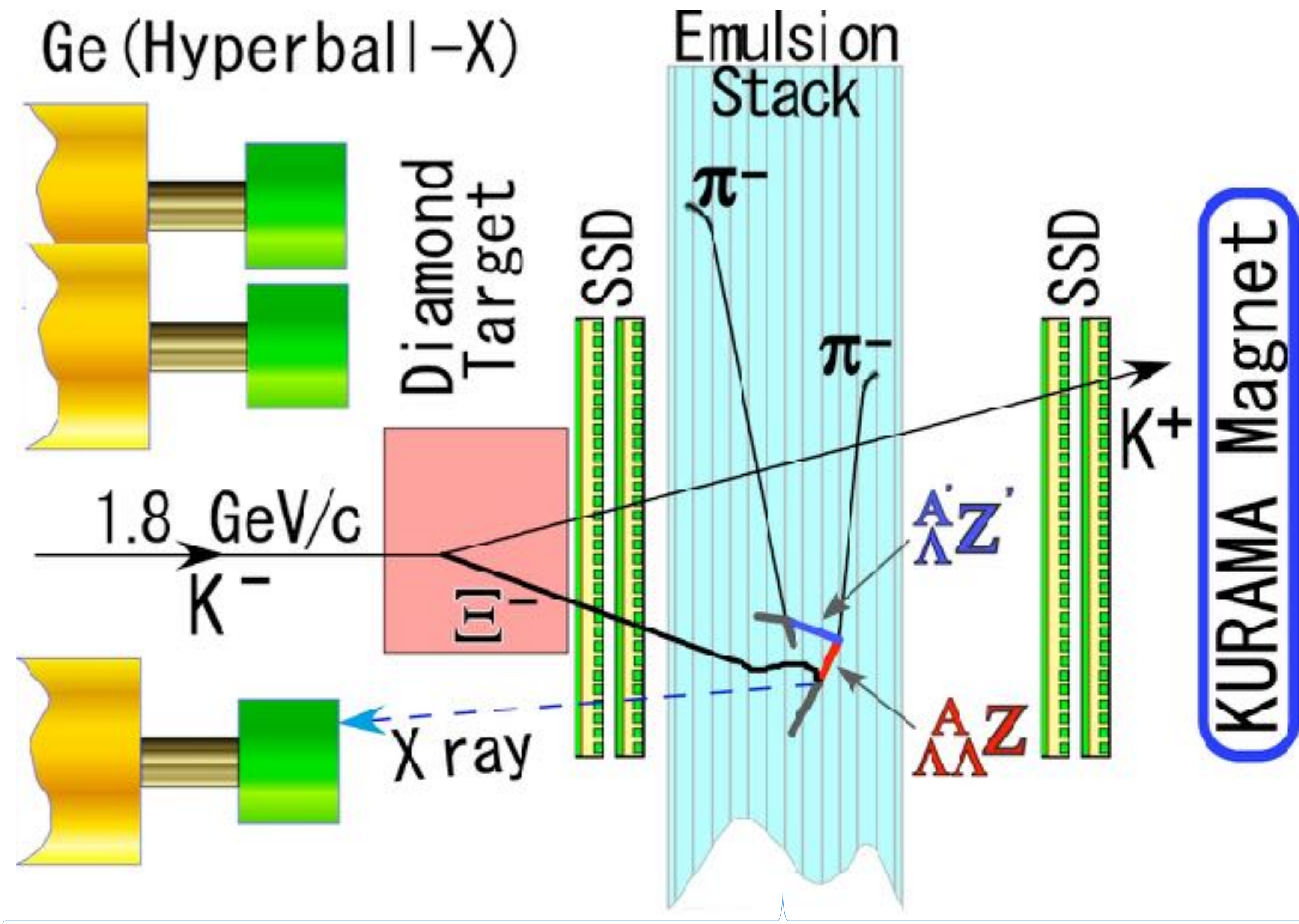
Summary of Emulsion events

	$^{A}_{\Lambda\Lambda}Z$	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

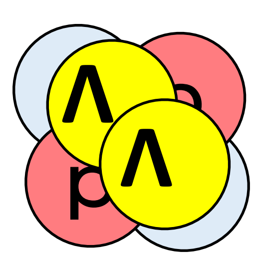
M.Danysz et al., PRL.11(1963)29;
R.H.Dalitz et al., Proc. R.S.Lond.A436(1989)1

J-PARC E07

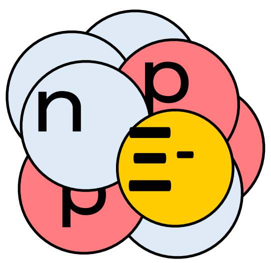
Systematic study of double strangeness nuclei with Hybrid emulsion method



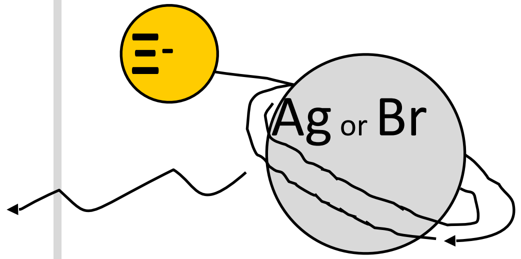
$\Lambda\Lambda$ hypernucleus



Ξ hypernucleus



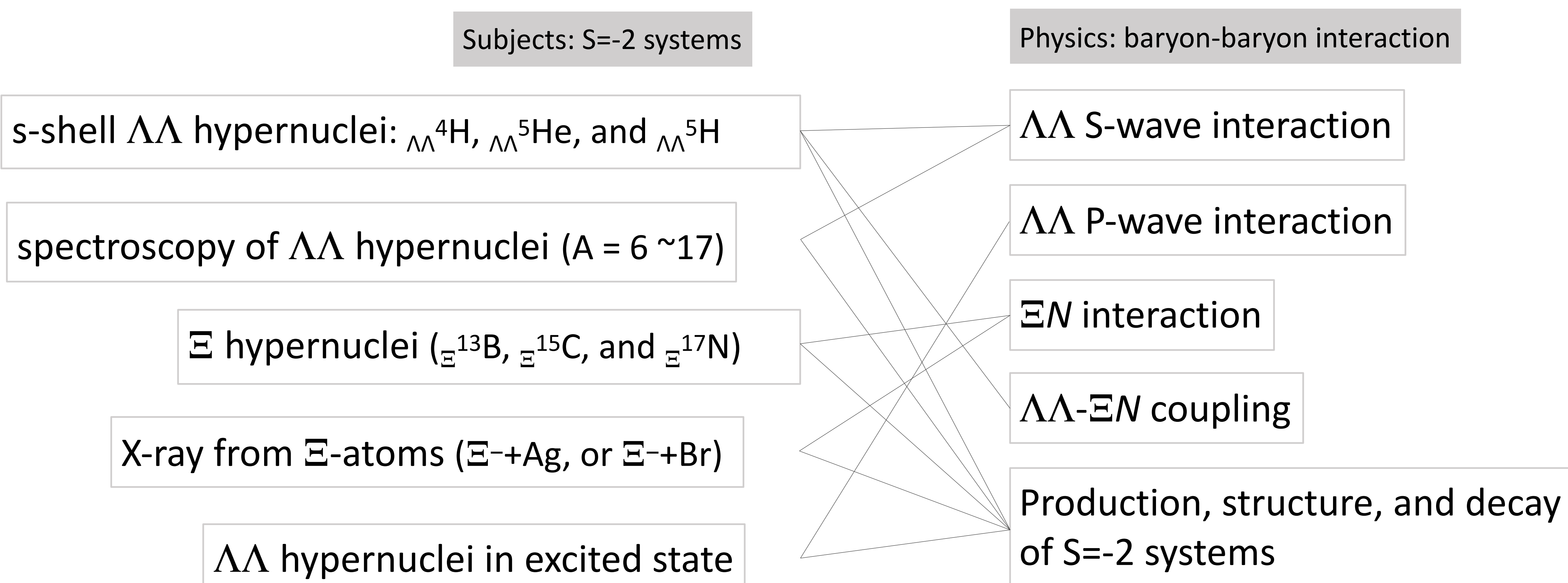
X-ray from Ξ^- atom



Concept: 10k Ξ^- stop events, which is 10 times statistics more than that of KEK-PS E373

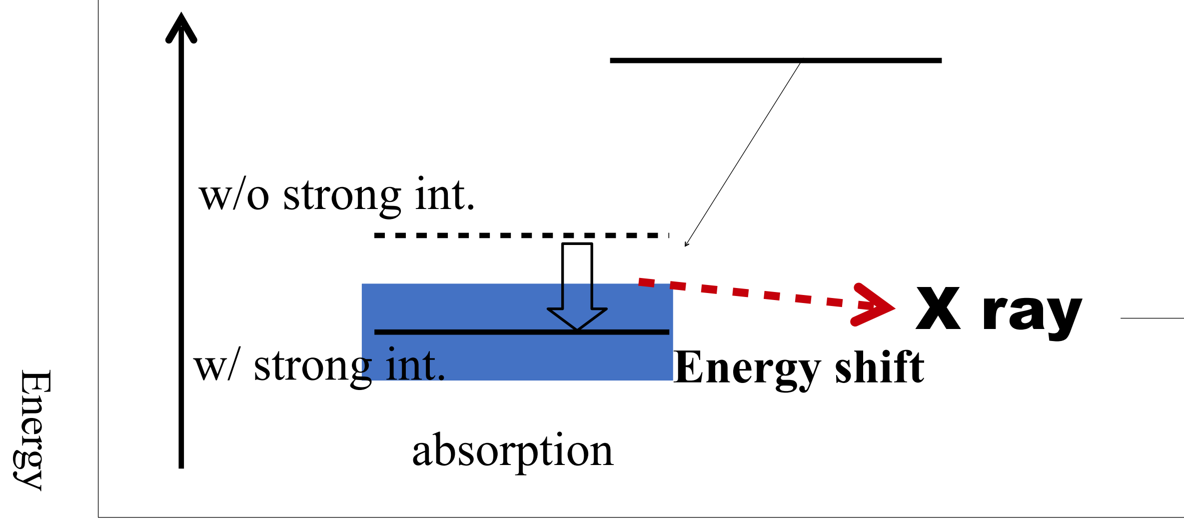
	KEK-PS E373	J-PARC E07 (in proposal)
Emulsion gel	0.8 tons	2.1 tons
Purity of K^- beam	25%	~85%
Ξ^- stop yield	~650	10k
S=-2 hypernuclei	9	~10^2

Physics motivations



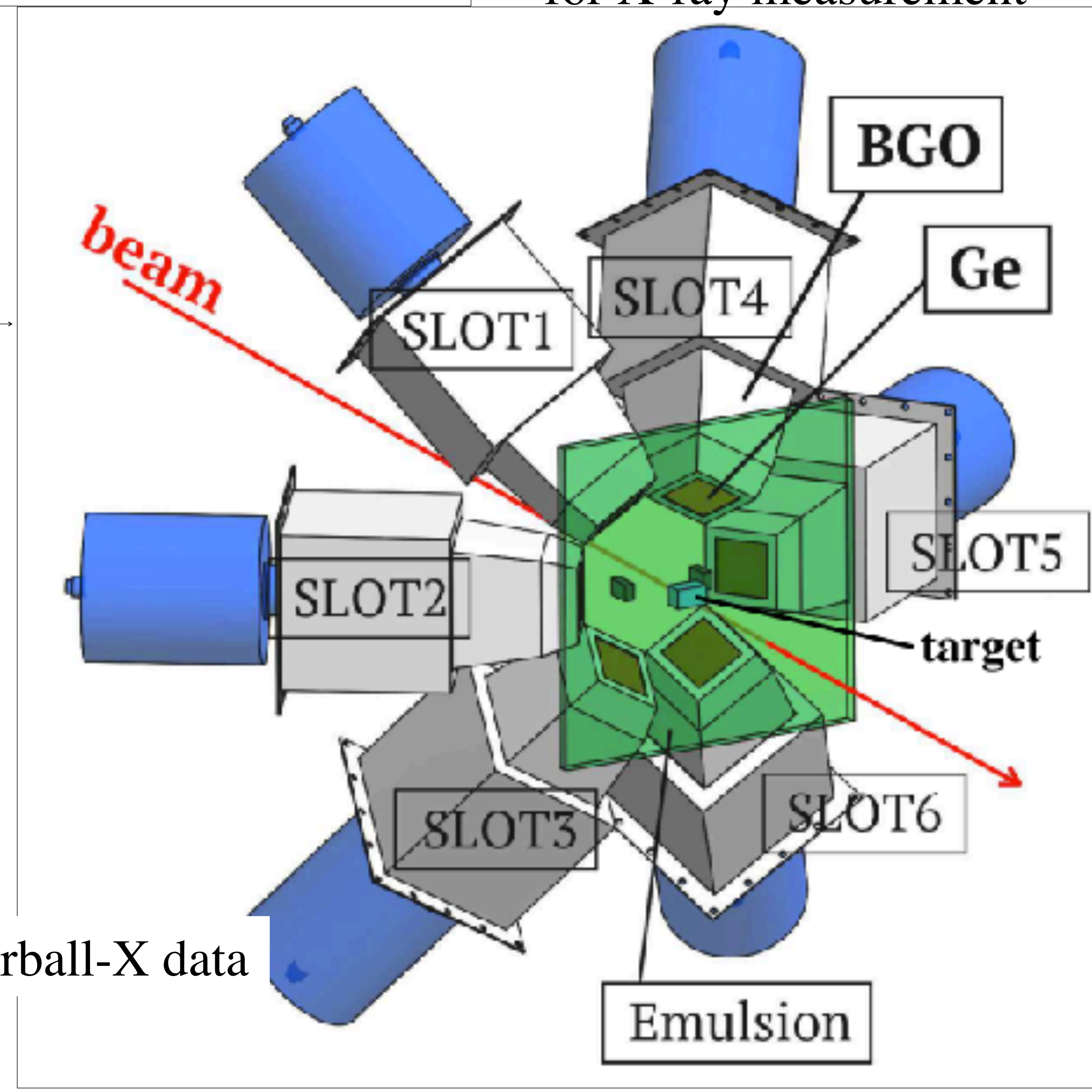
Ξ^- atom X-ray spectroscopy at J-PARC (E07)

Level scheme of Ξ^- atom



Hyperball-X

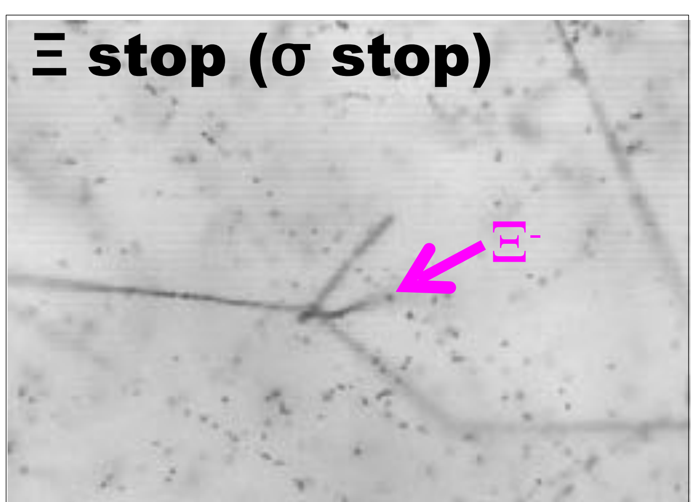
Ge detector array for X-ray measurement



Hybrid emulsion method

Select (K^-, K^+) reaction by spectrometers

Select Ξ^- stop event by emulsion image



Coincidence with Hyperball-X data

Analysis status

Ξ^- Ag atom , Ξ^- Br atom data (from the emulsion)

→ 20% coincidence analysis is finished

Ξ^- C atom data (from the diamond target)

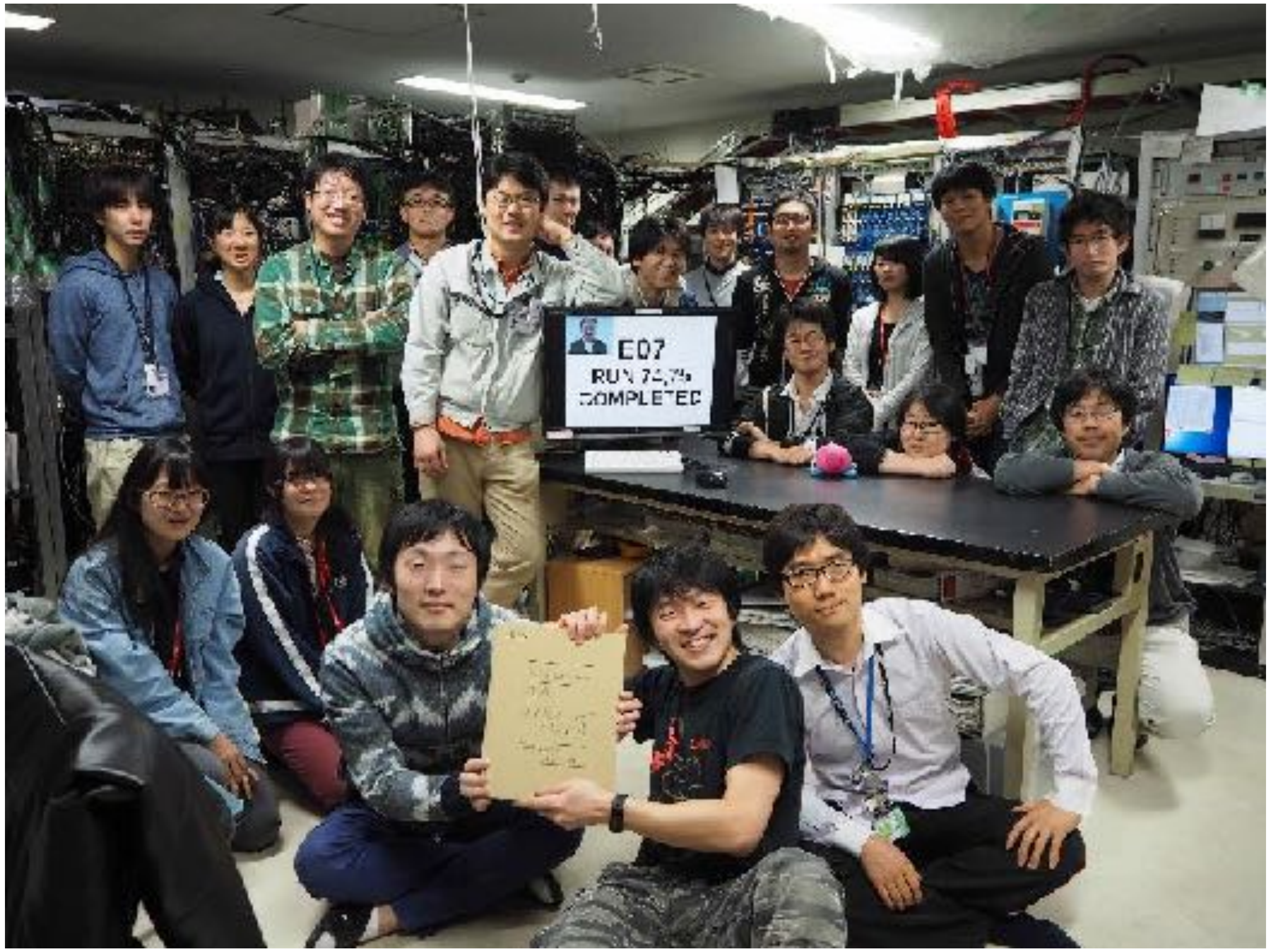
→ On going

Beam exposure

May-Jun. 2016
 KURAMA Commissioning : 5.0 days
 Physics : 4.9 days

4/15 - 4/19, 2017 (44kW)
 Emulsion exposure : 50 h
 calibration : 19 h

5/25 - 6/29, 2017 (10 - 37.5kW)
 Emulsion exposure : 23.4 days
 calibration : 8.5 h



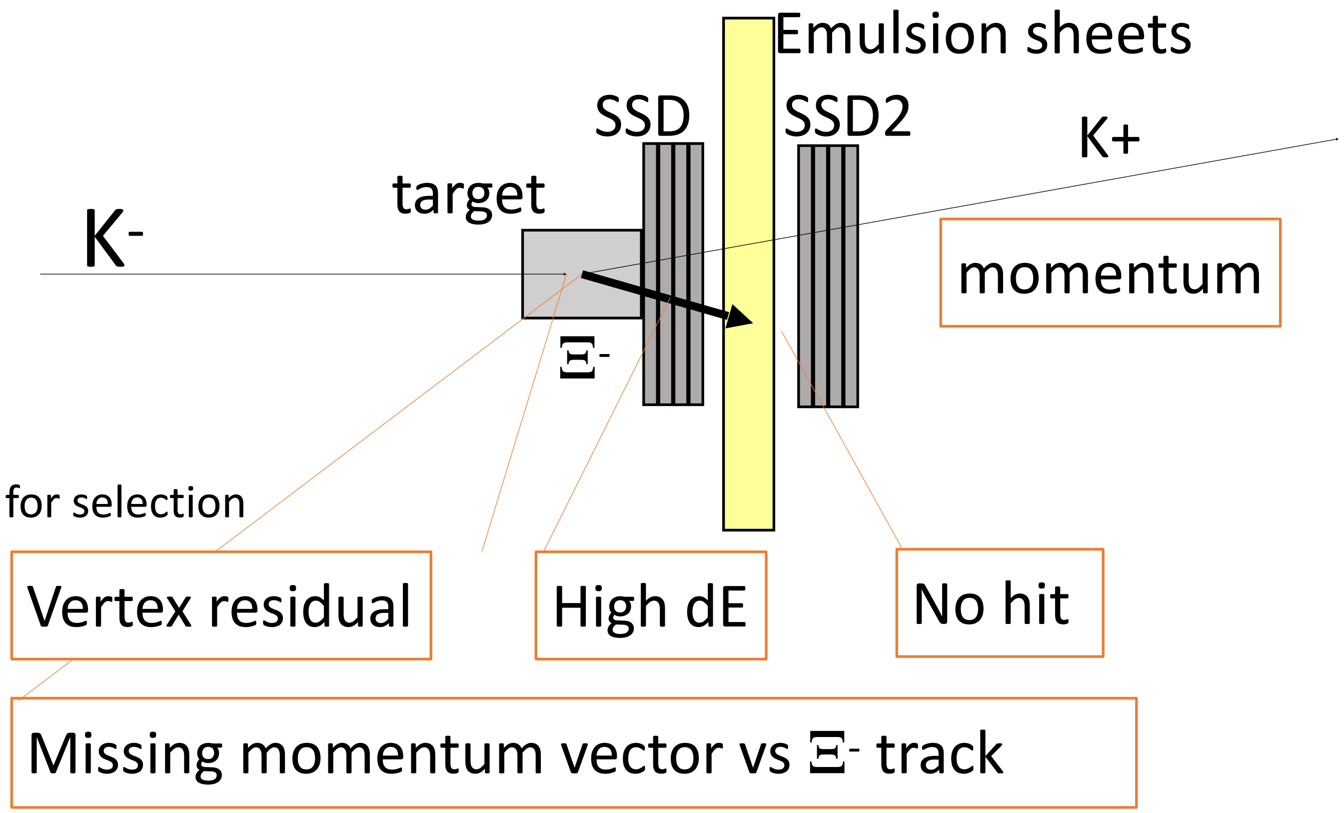
Jul. 1st 2017, Run end photo @K1.8 counting room

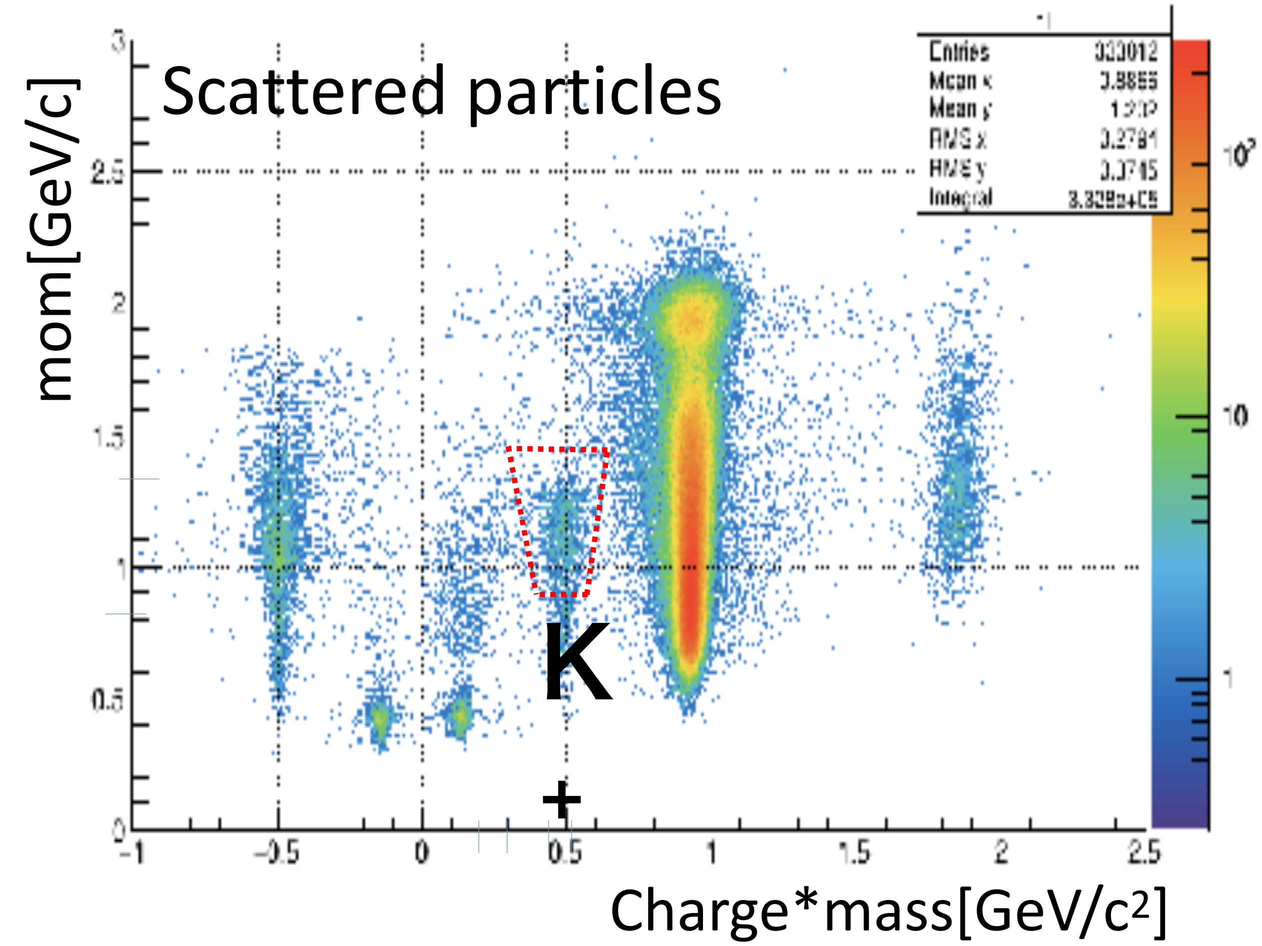
Year	Beam power [kW]	K^- intensity [/spill]	K^- purity	Time [h/mod.]
2016	42	260k	81%	6.5
2017	44	310k	83%	5.6
2017	37.5	280k	82%	6.0
2017	10 - 35	120k – 270k	50% - 82%	6.5 – 9.0

118 emulsion modules

Photographic processing: completed in Feb. 2018 in Gifu-U.

Ξ- selection from the (K-, K+) reaction by off-line analysis





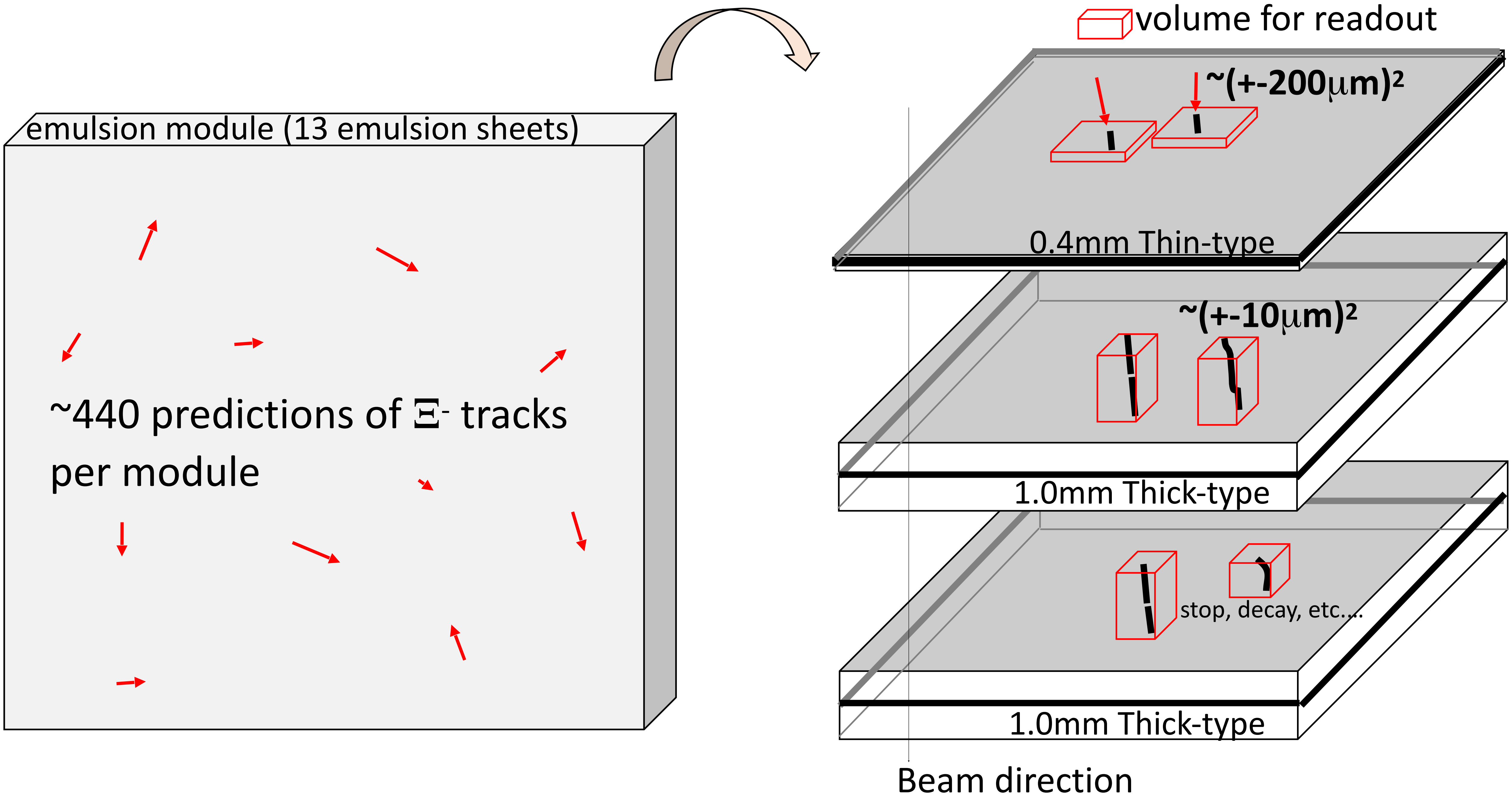
Criteria for Ξ- track selection

by simulation for 118 modules

Level	Ξ- stop	prediction/mod.		
1	9k	~440	High S/N & stop ratio	1st priority
2	1k	~850	Realistic selection	
3	1k	6.2k	All Ξ- stop	
4	negligible	16k	All combination	

Track following for Ξ⁻ stop event

* Disassembling
* Photographic developing



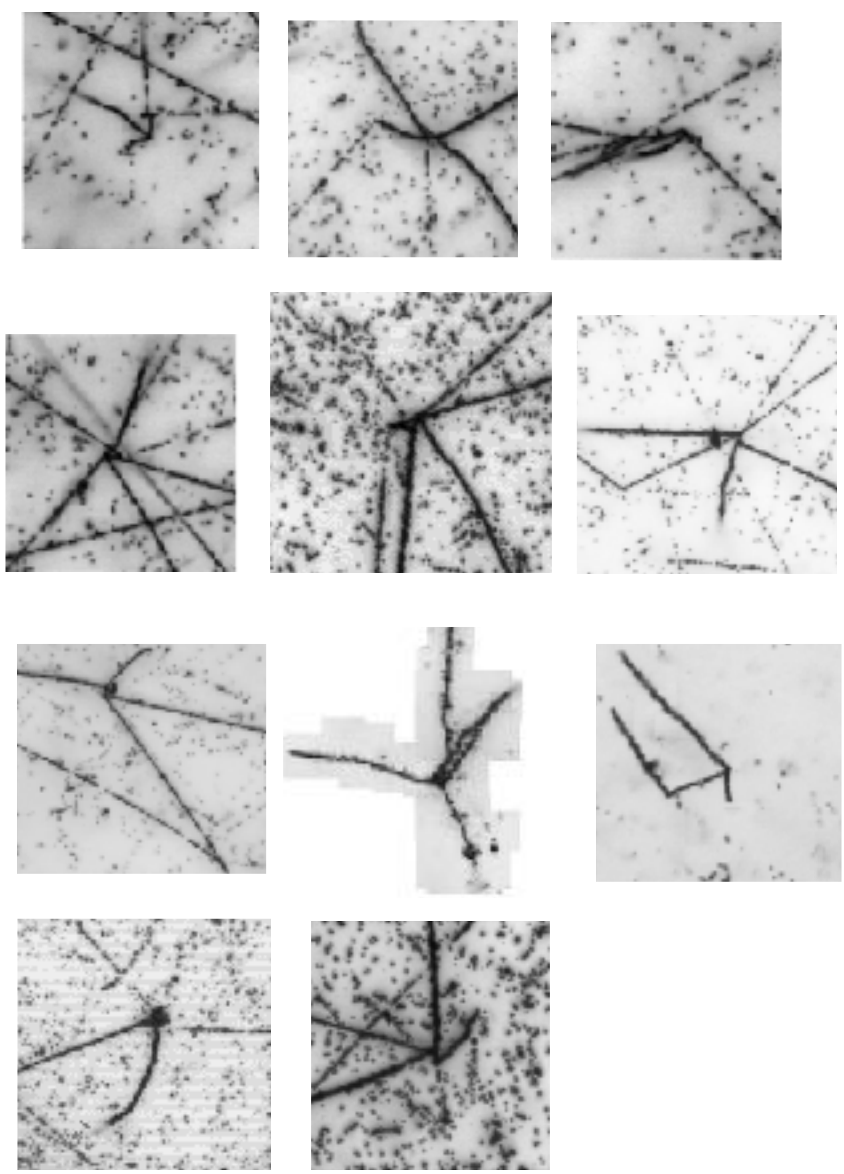
Automated Track Following (Sample Movie)
https://youtu.be/3fiWI5tDx2U

2019 May

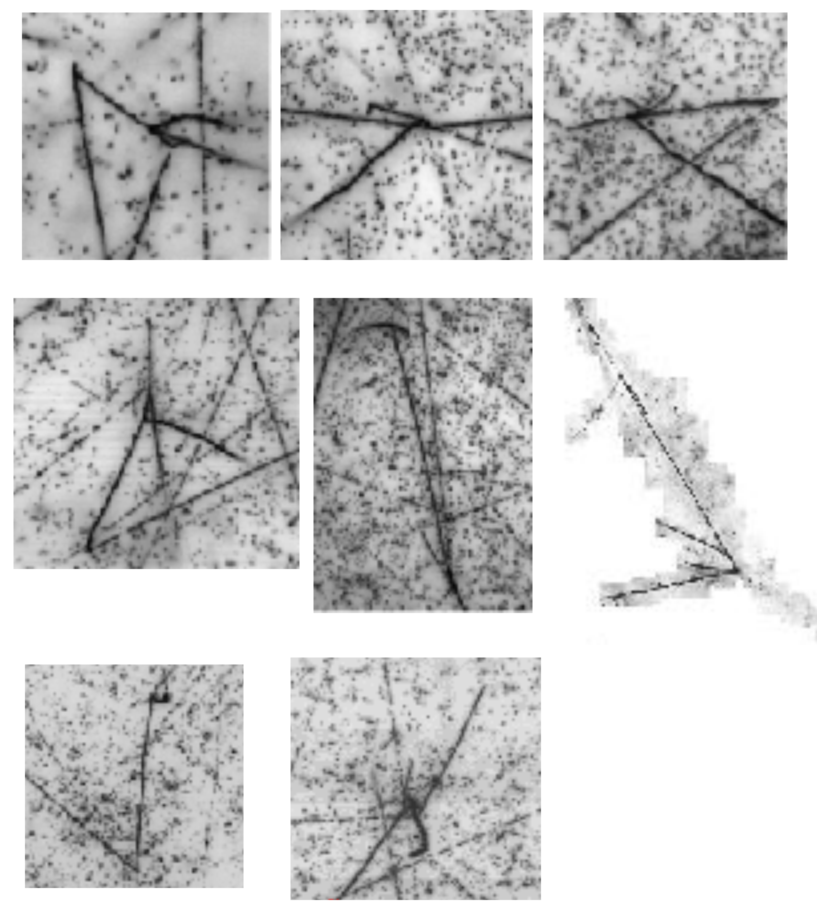
So far, 70% of emulsion sheets has been scanned at least once.

	KEK-PS E373	E07 (current)
Ξ^- stop with nuclear fragment	430	1.6k (1.6k/430 = 3.8)
S=-2 system	9	26

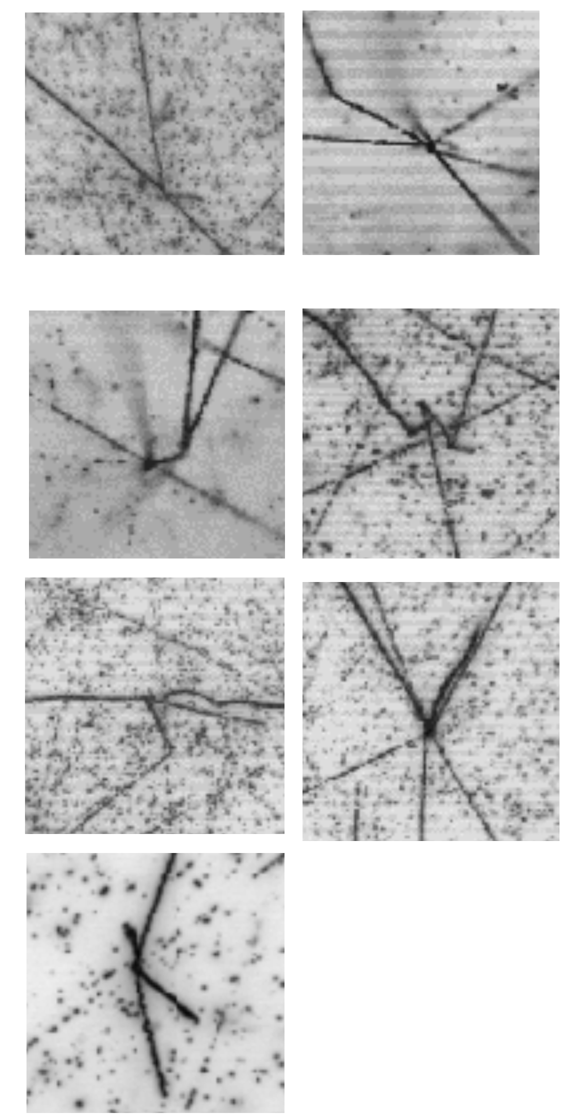
11 double Lambda events



8 twin events



7 others

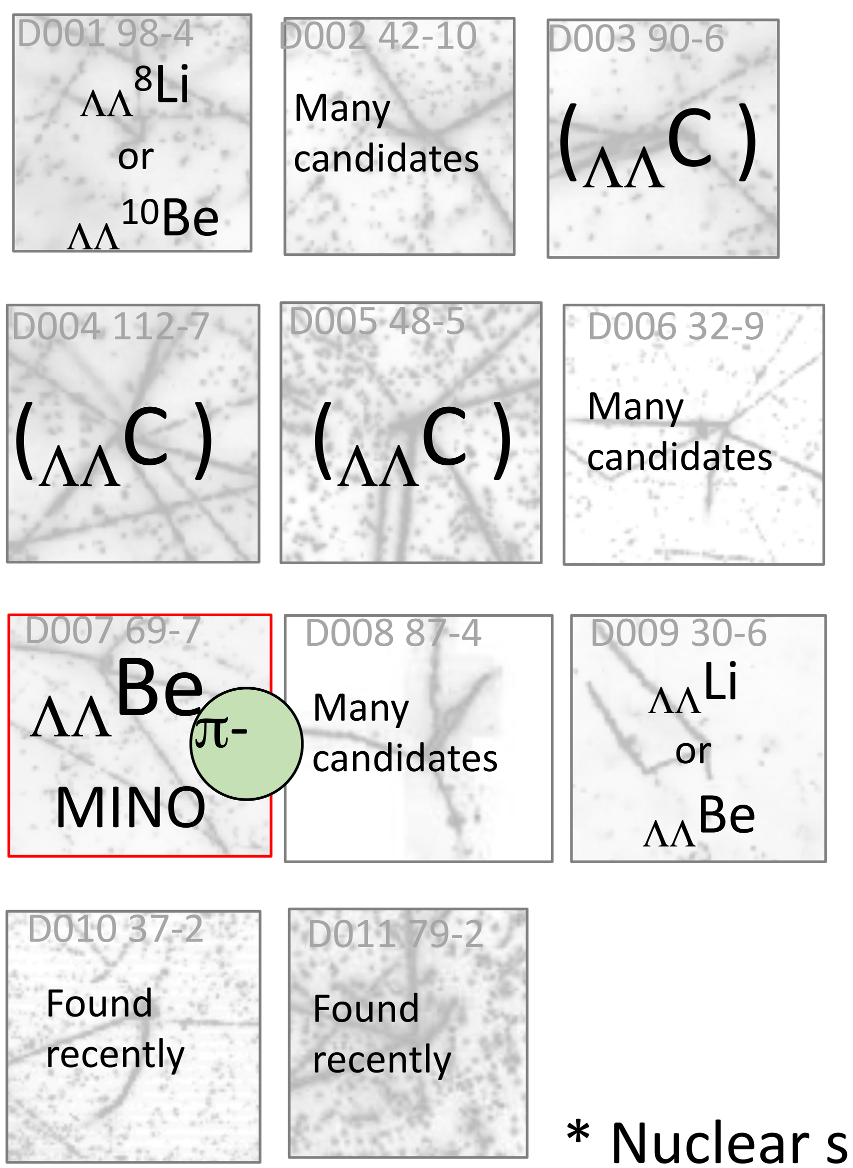


2019 May

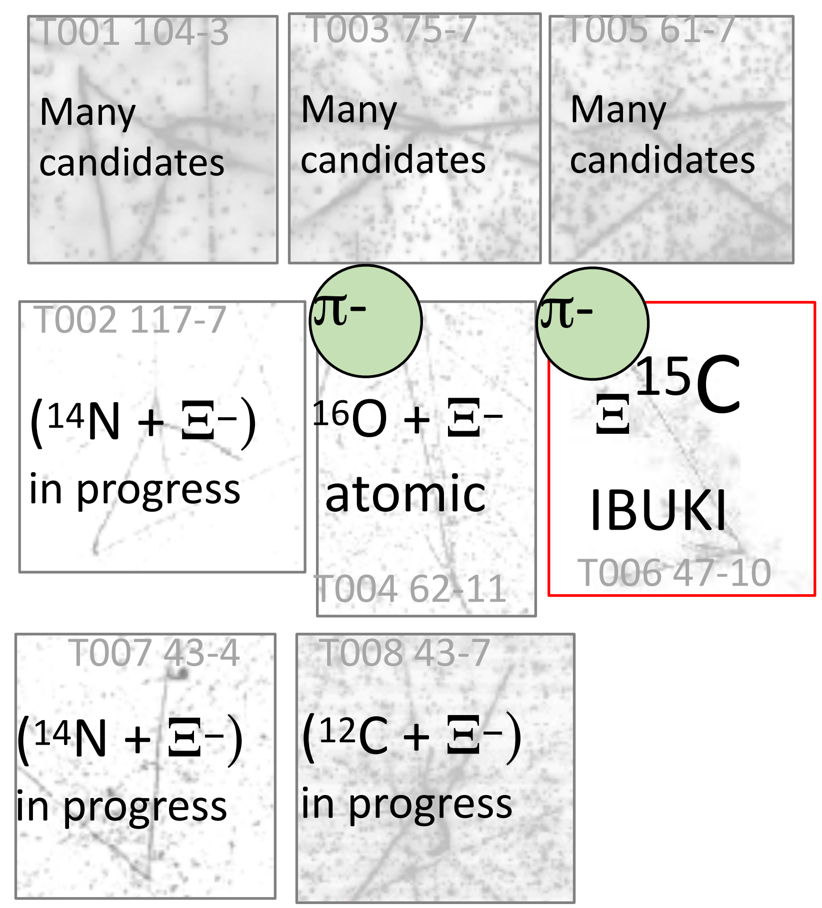
So far, 70% of emulsion sheets has been scanned at least once.

	KEK-PS E373	E07 (current)	
Ξ^- stop with nuclear fragment	430	1.6k	(1.6k/430 = 3.8)
S=-2 system	9	26	

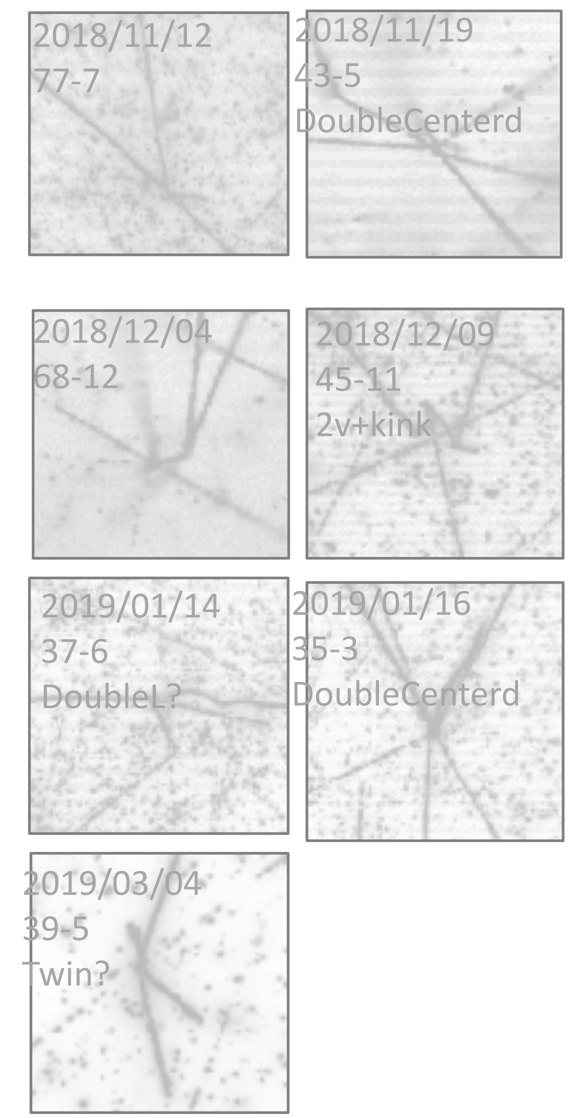
11 double Lambda events



8 twin events



7 others

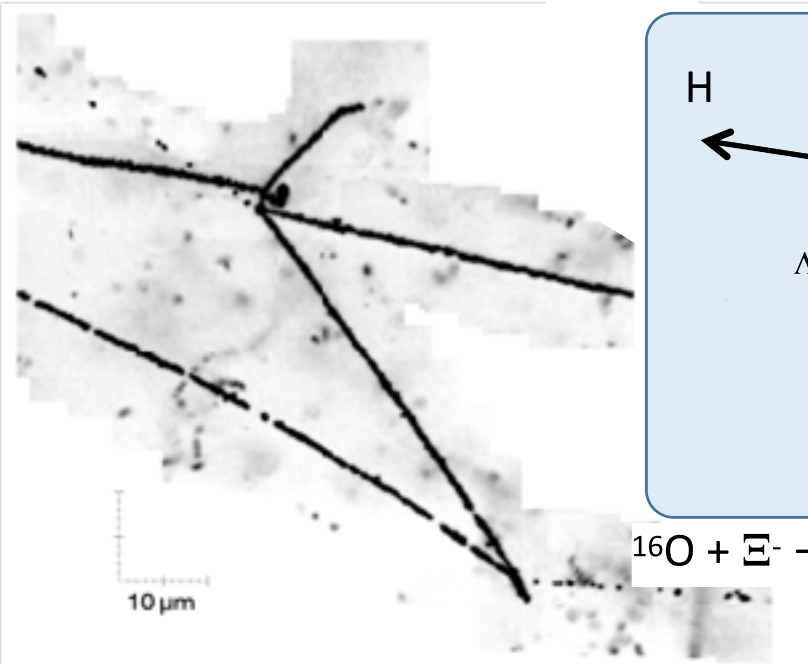


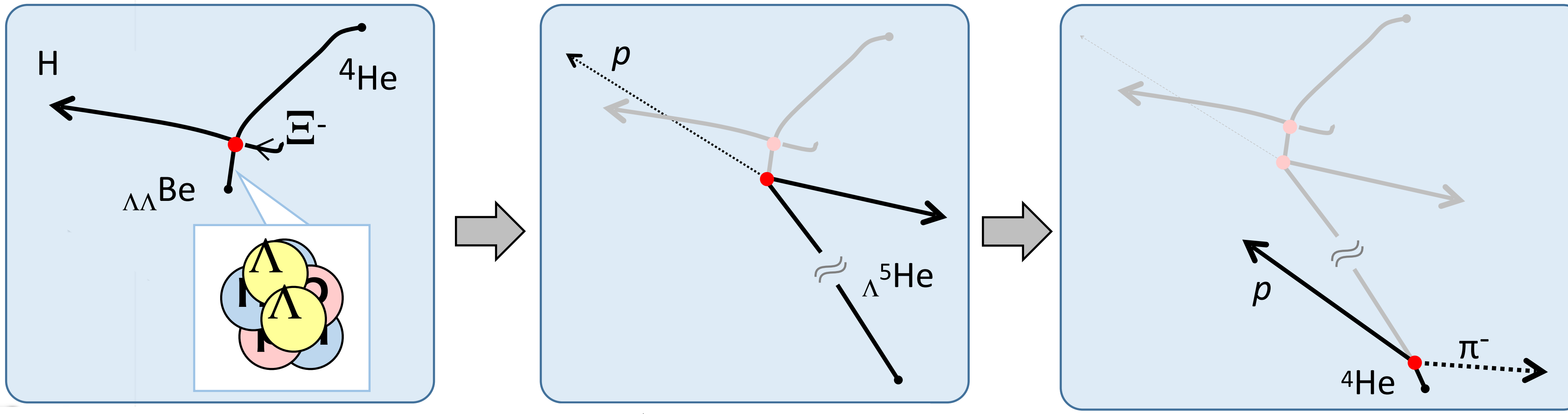
* Nuclear species of some event are identified.

* B_{Ξ^-} or $\Delta B_{\Lambda\Lambda}$ are measured quantitatively in several events (red framed).

Double-Λ Hypernucleus MINO event

H. Ekawa et al.,Prog. Theor. Exp. Phys. 2019, 021D02



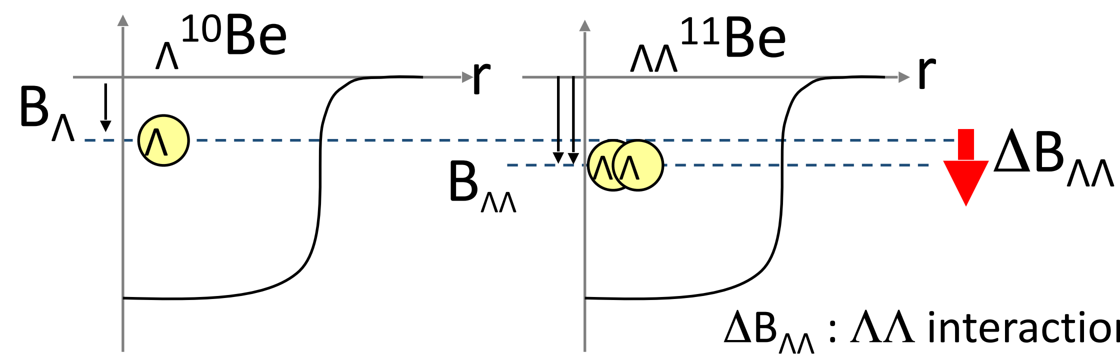


^{16}O + Ξ^- → $_{\Lambda\Lambda}$Be + ^{4}He + H

$_{\Lambda\Lambda}$Be → $_\Lambda{}^5$He + H + *p* + x*n*

$_\Lambda{}^5$He → ^{4}He + p + π^-

$$^{16}\mathrm{O} + \Xi^- \to ({}^{10}_{\Lambda\Lambda}\mathrm{Be},\ {}^{11}_{\Lambda\Lambda}\mathrm{Be},\ {}^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_\Lambda\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$



$\Delta B_{\Lambda\Lambda}$: ΛΛ interaction energy

M(^{9}Be) + M_Λ - B_Λ

M(^{9}Be) + 2M_Λ - $B_{\Lambda\Lambda}$

Possible interpretations	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]	kinematic fitting χ^2	p-value[%]
Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{10}$Be + ^{4}He + t	15.05 +- 0.11	1.63 +- 0.14	11.5	0.9
Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{11}$Be + ^{4}He + d	19.07 +- 0.11	1.87 +- 0.37	7.3	6.4
Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{12}$Be* + ^{4}He + p	13.68 +- 0.11 + E_{ex}	-2.7 +- 1.0 + E_{ex}	11.3	1.0

$_{\Lambda\Lambda}{}^{11}$Be is most probable by kinematic fittng χ^2 (DOF=3)

where, B_{Ξ^-} = 0.23 MeV, 3D orbit of ^{16}O

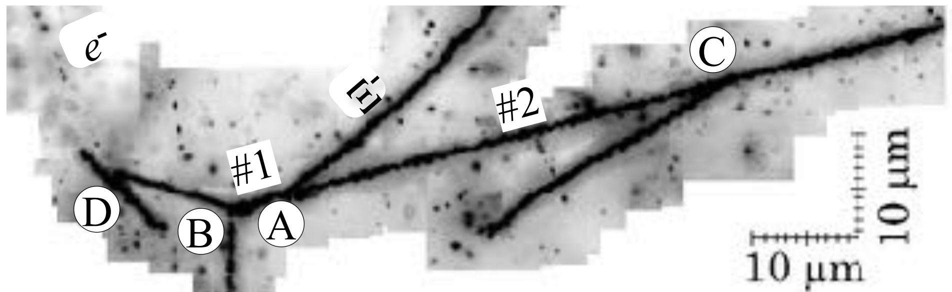
In a new nuclide event of $_{\Lambda\Lambda}$Be, a $\Delta B_{\Lambda\Lambda}$, ΛΛ interaction energy, has been obtained successfully.

Deeply bound Ξ^--^{14}N systems

0.174 MeV:3D atomic state

Prog. Theor. Phys. 105 (2001) 627.

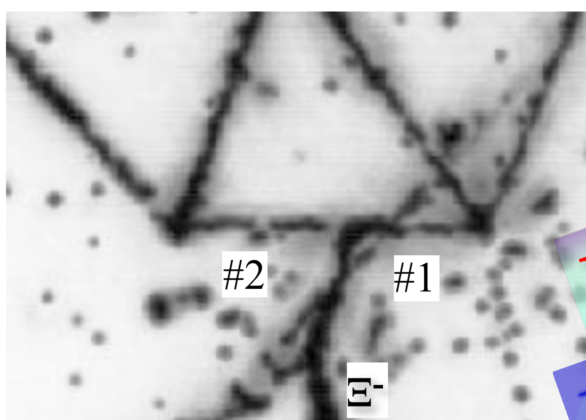
KISO event
(KEK-E373)



E.Hiyama, K. Nakazawa, Annu. Rev. Nucl. Part. Sci. 2018.68.131

B_{Ξ^-} 1.03 ± 0.18 (MeV) or 3.87 ± 0.21

KINKA event
(KEK-E373)

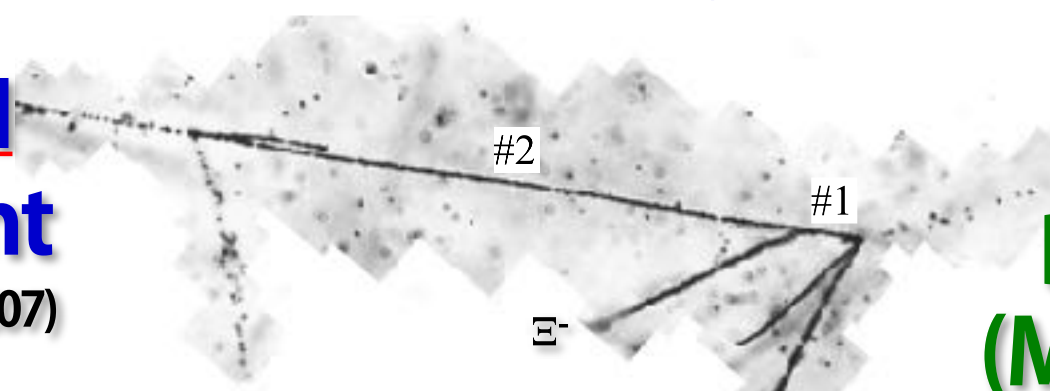


B_{Ξ^-} (MeV) 5 or 8

Preliminary

Preliminary

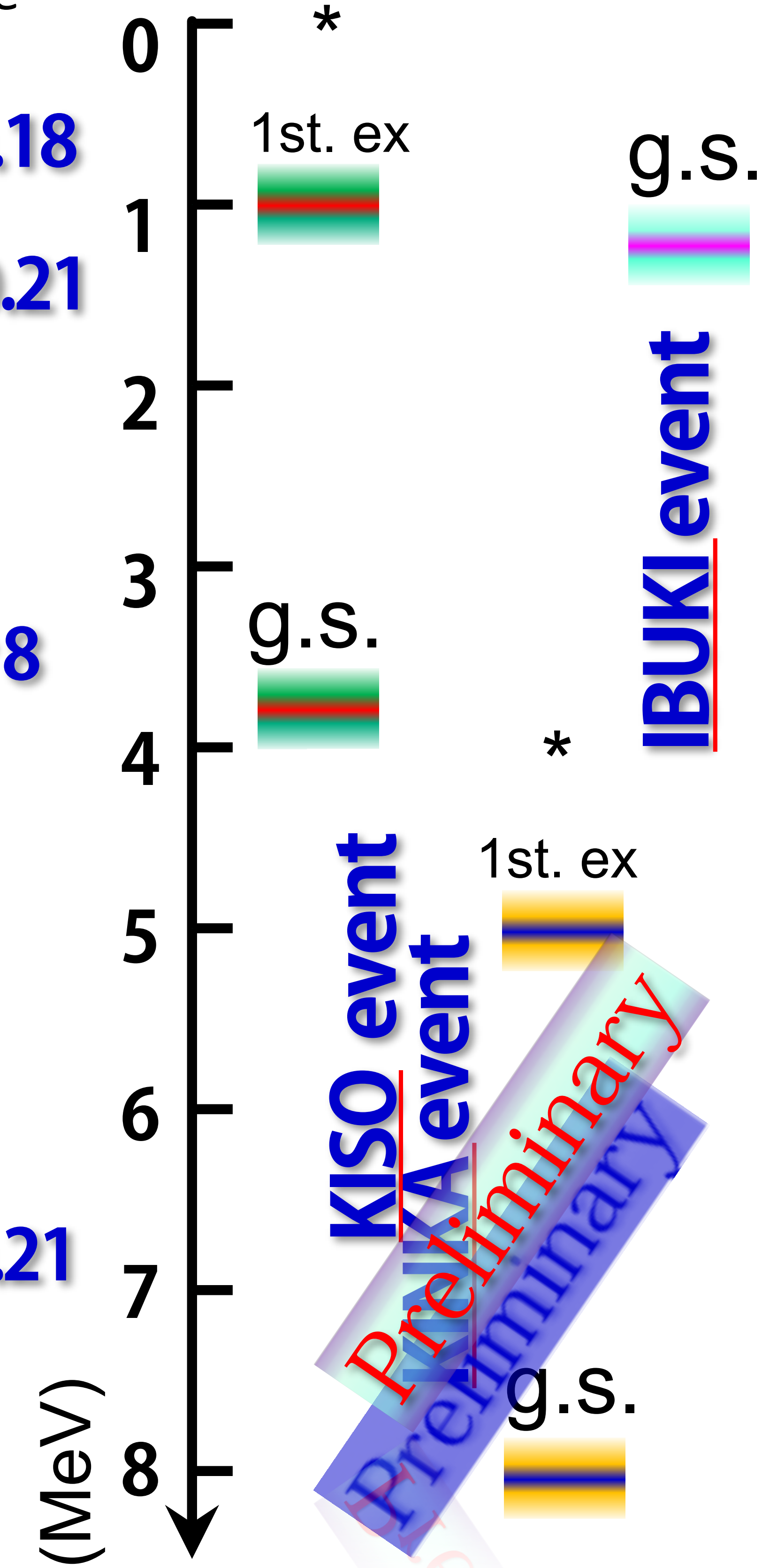
IBUKI event
(J-PARC E07)



S. Hayakawa, PhD thesis (2019) Osaka Univ., Unpublished

B_{Ξ} 1.27 ± 0.21 (MeV)

$B_{\Xi^-}(\Xi^- + ^{14}N)$



* Multiple candidates of Ξ hypernucleus with B_{Ξ^-} beyond 3D atomic level in Ξ^--^{14}N systems

* We expect more examples through further analysis in E07.

Search for Double-Λ with Sequential Weak Decay

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

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

$P_{\pi^-} \sim 130$ MeV/c

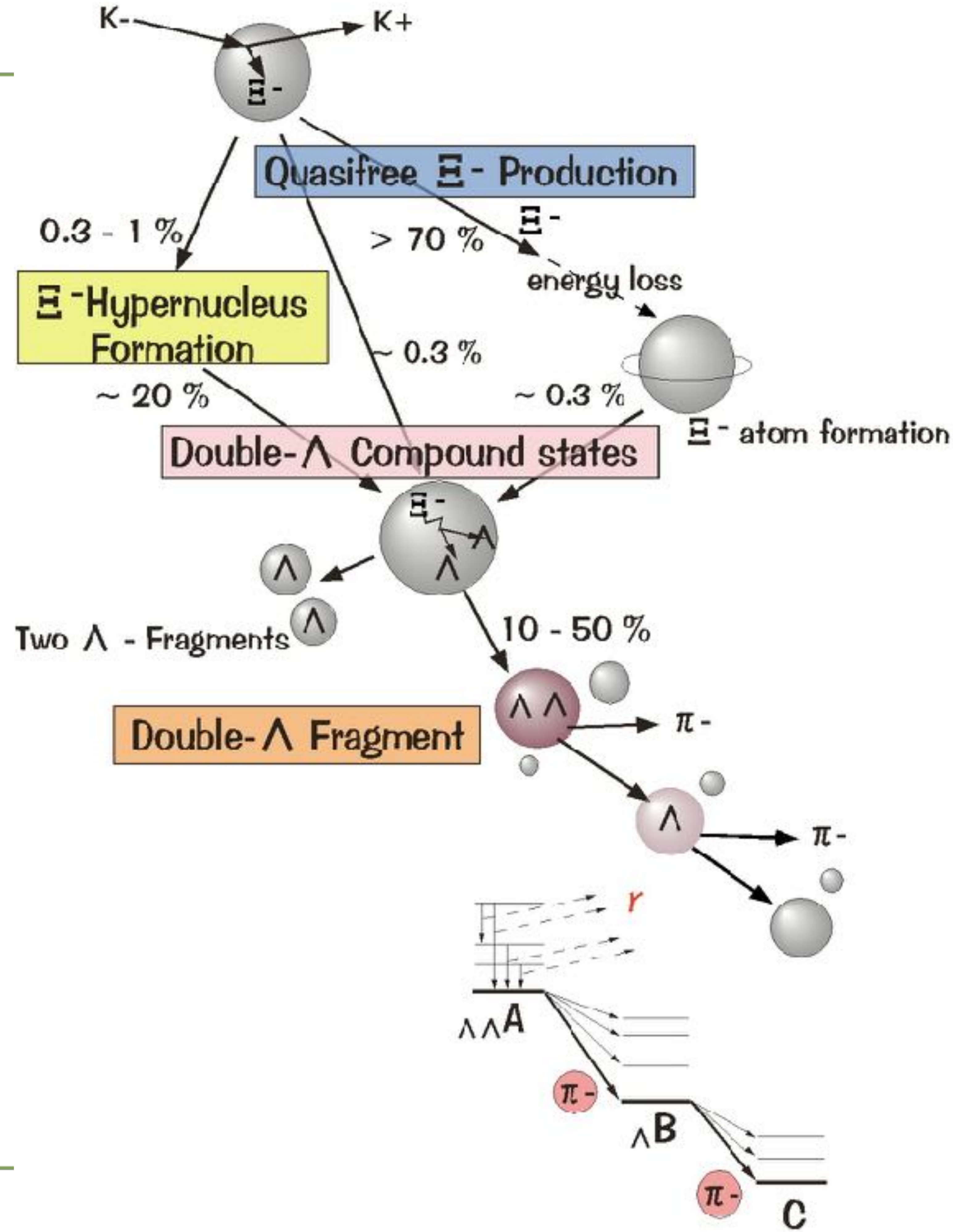
$\Gamma_{\pi}/\Gamma_{tot}$ ~0.21

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

$P_{\pi^-} = 99.2$ MeV/c

Width =1 MeV/c

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



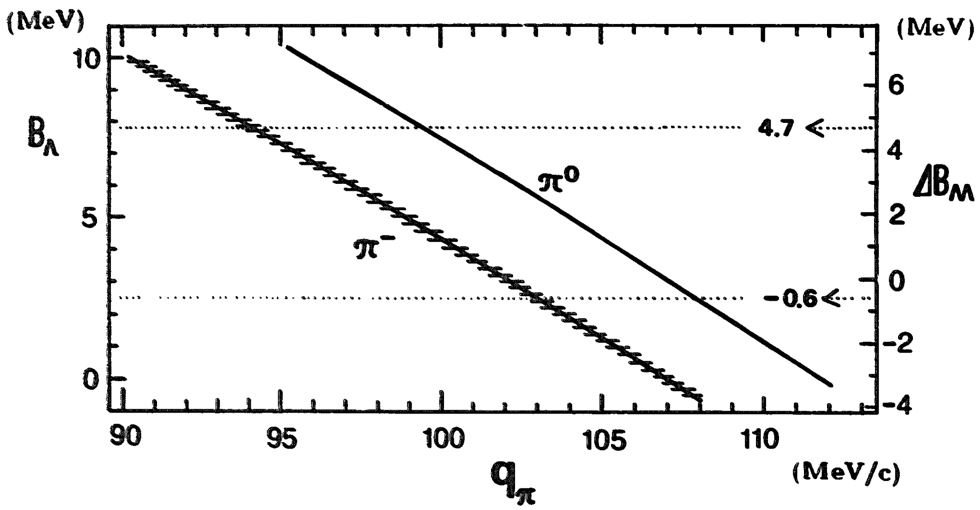


Fig. 8. The Λ-binding energy $B_\Lambda({}^5_\Lambda He)$ is plotted as a function of the weak decay pion momentum q_π. The corresponding $\Lambda\Lambda$ interaction matrix element $\Delta B_{\Lambda\Lambda}$ is also shown on the right scale. The hatch for the π^- decay indicates the predicted pion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

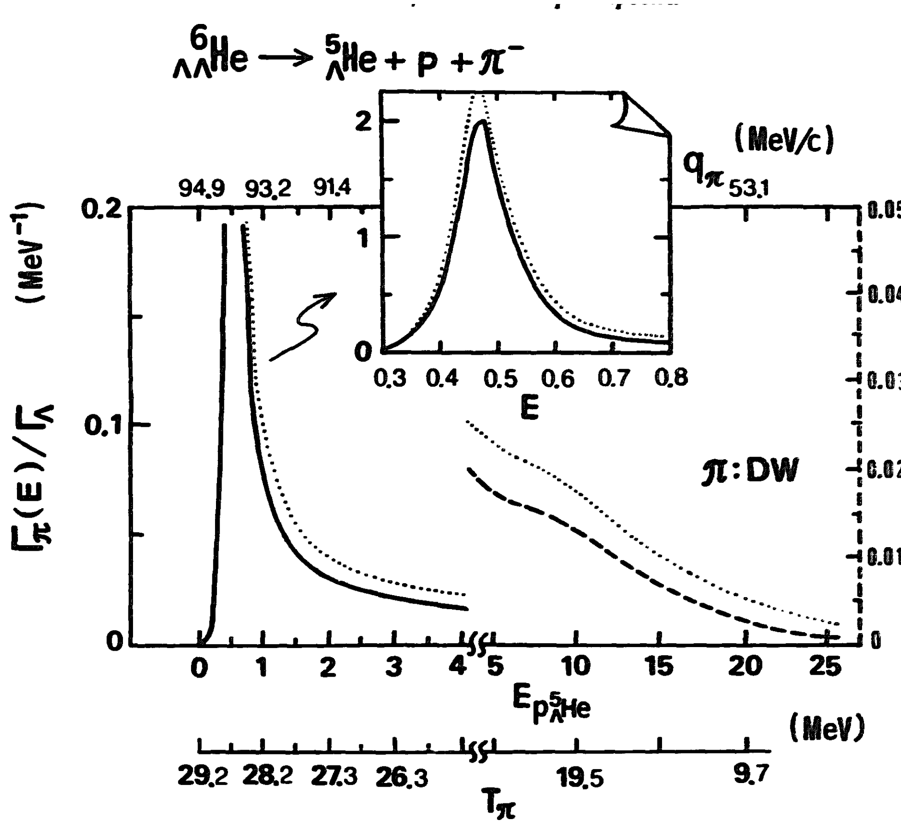
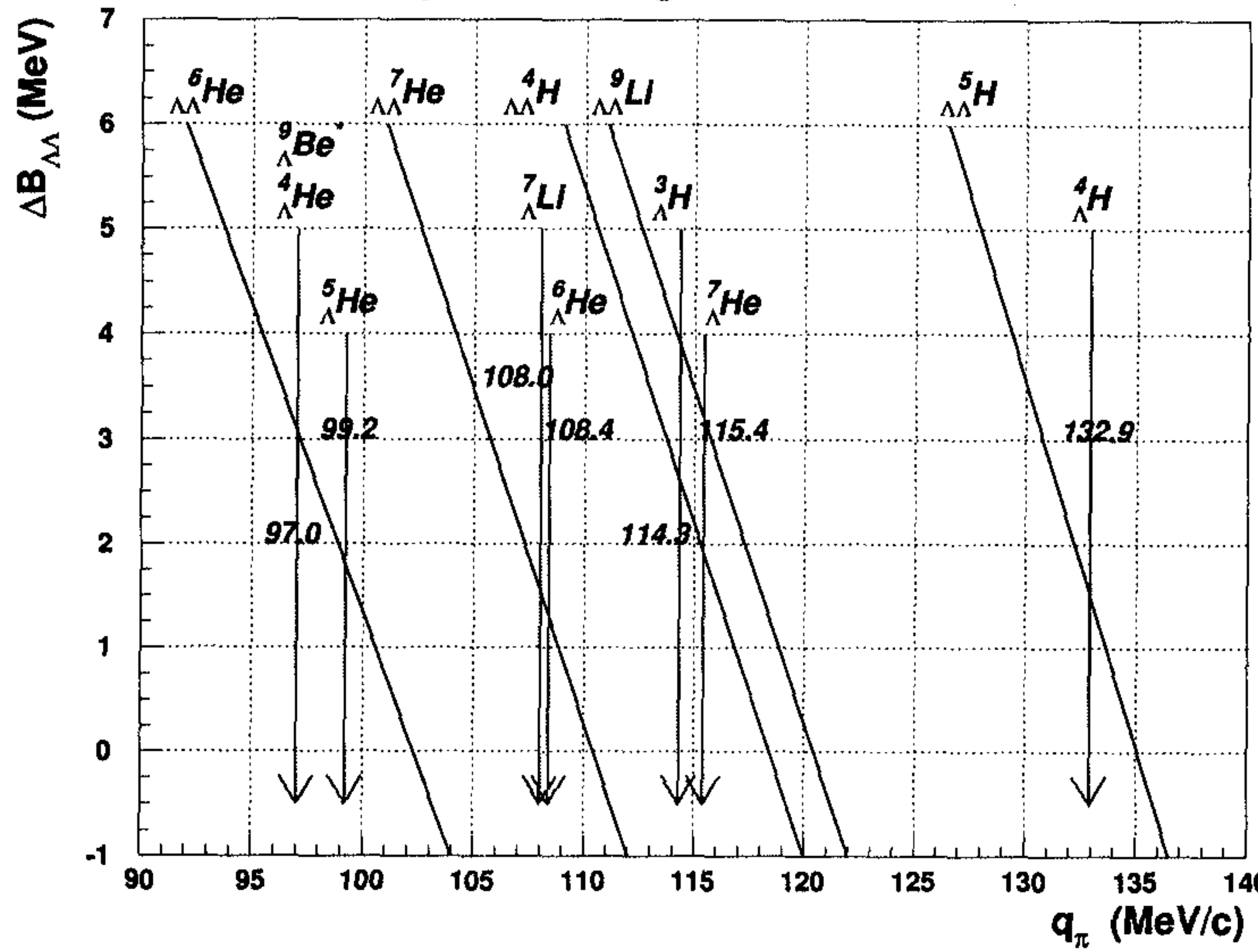


Fig. 7. The theoretical π^- decay spectrum $\Gamma_{\pi^-}({}^6_{\Lambda\Lambda}He)/\Gamma_\Lambda$ with YNG is drawn by solid line as a function of the proton-${}^5_\Lambda He$ relative energy $E \equiv E_{p{}^5_\Lambda He}$. The shallow Λ-binding energy case described in sect. 4.2 results in the dotted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

Expected Signals and Lines

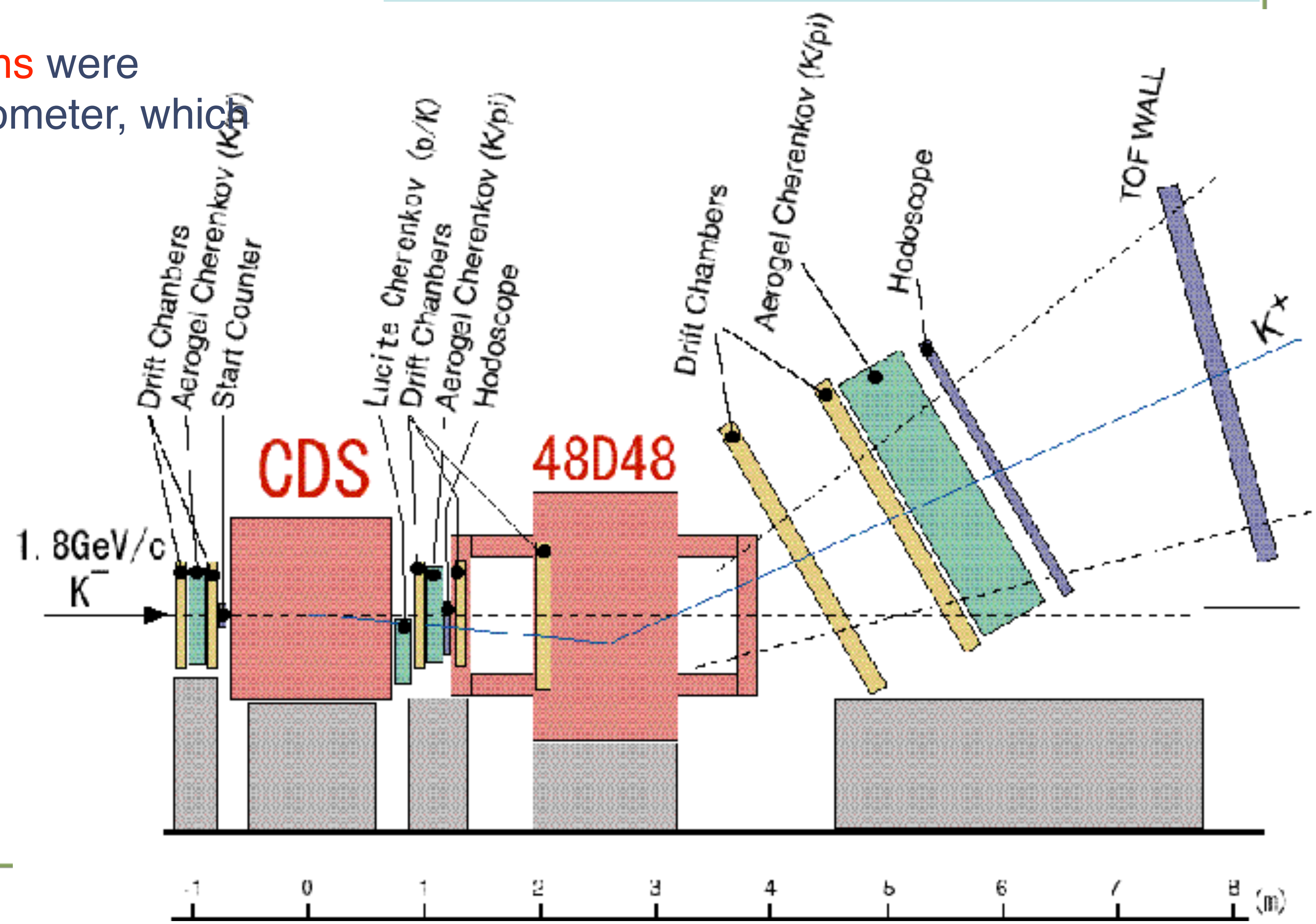


BNL E906

- 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

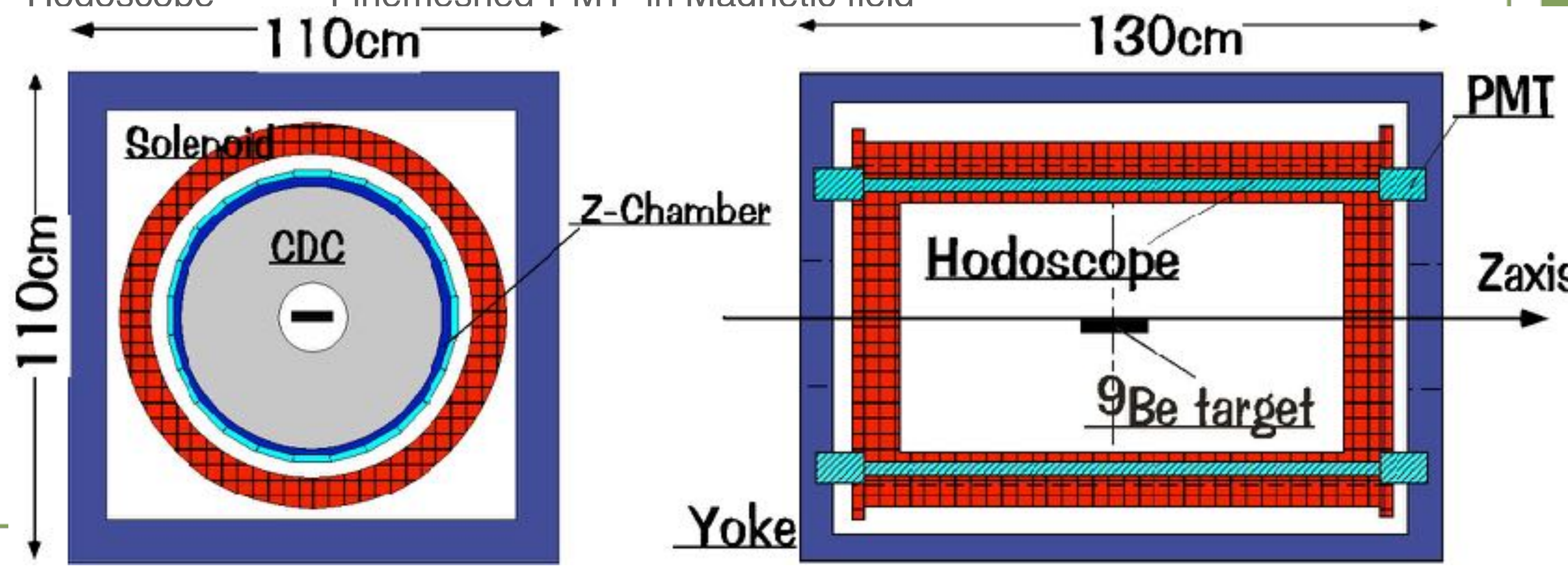
- 1.1x10^5 (K^-,K^+) reactions were identified by 48D48 spectrometer, which covers 2-10 deg.



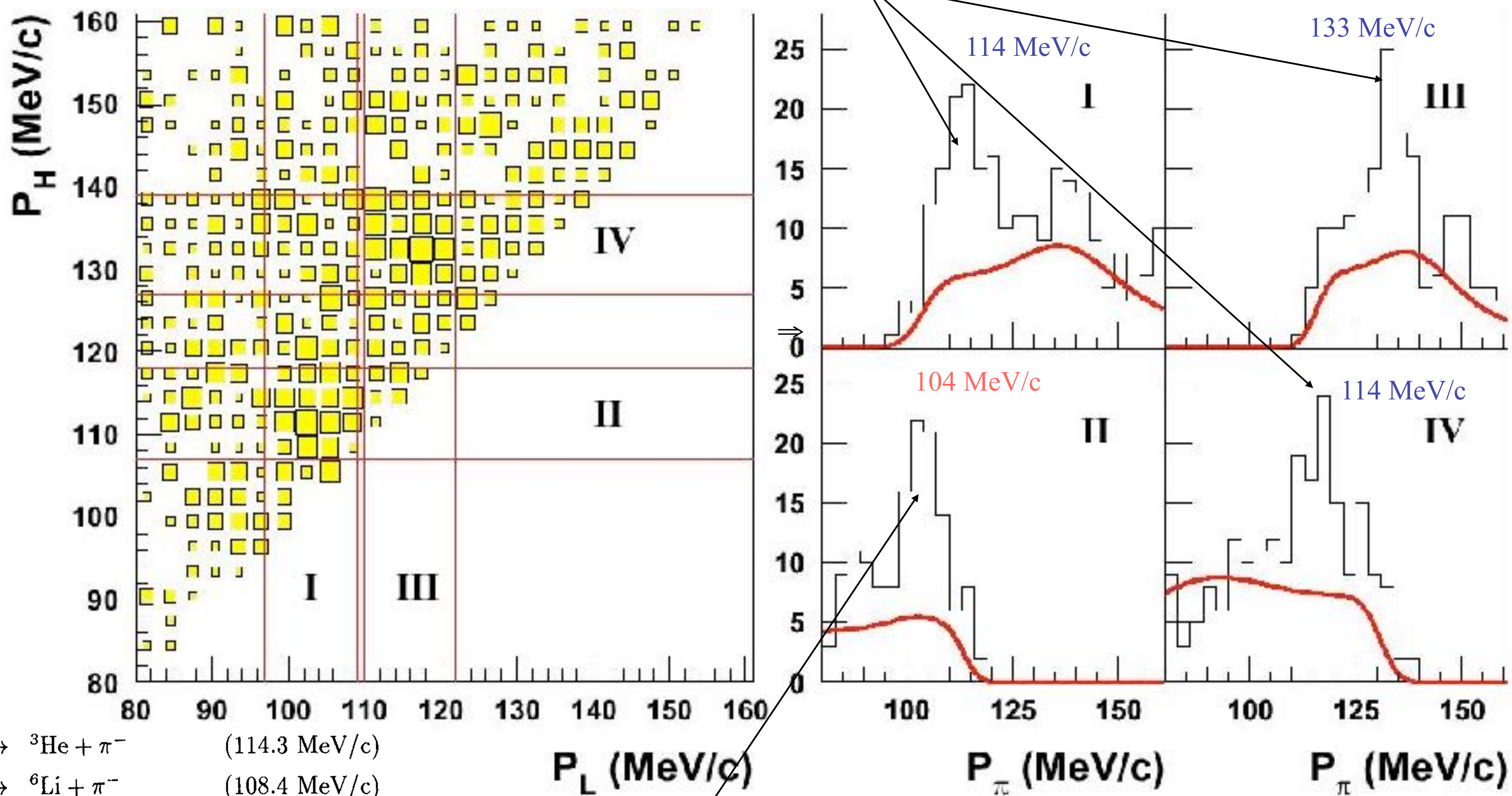
Cylindrical Detector System

- 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 $^{3}_{\Lambda}\mathrm{H} + {}^{4}_{\Lambda}\mathrm{H}$



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

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

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

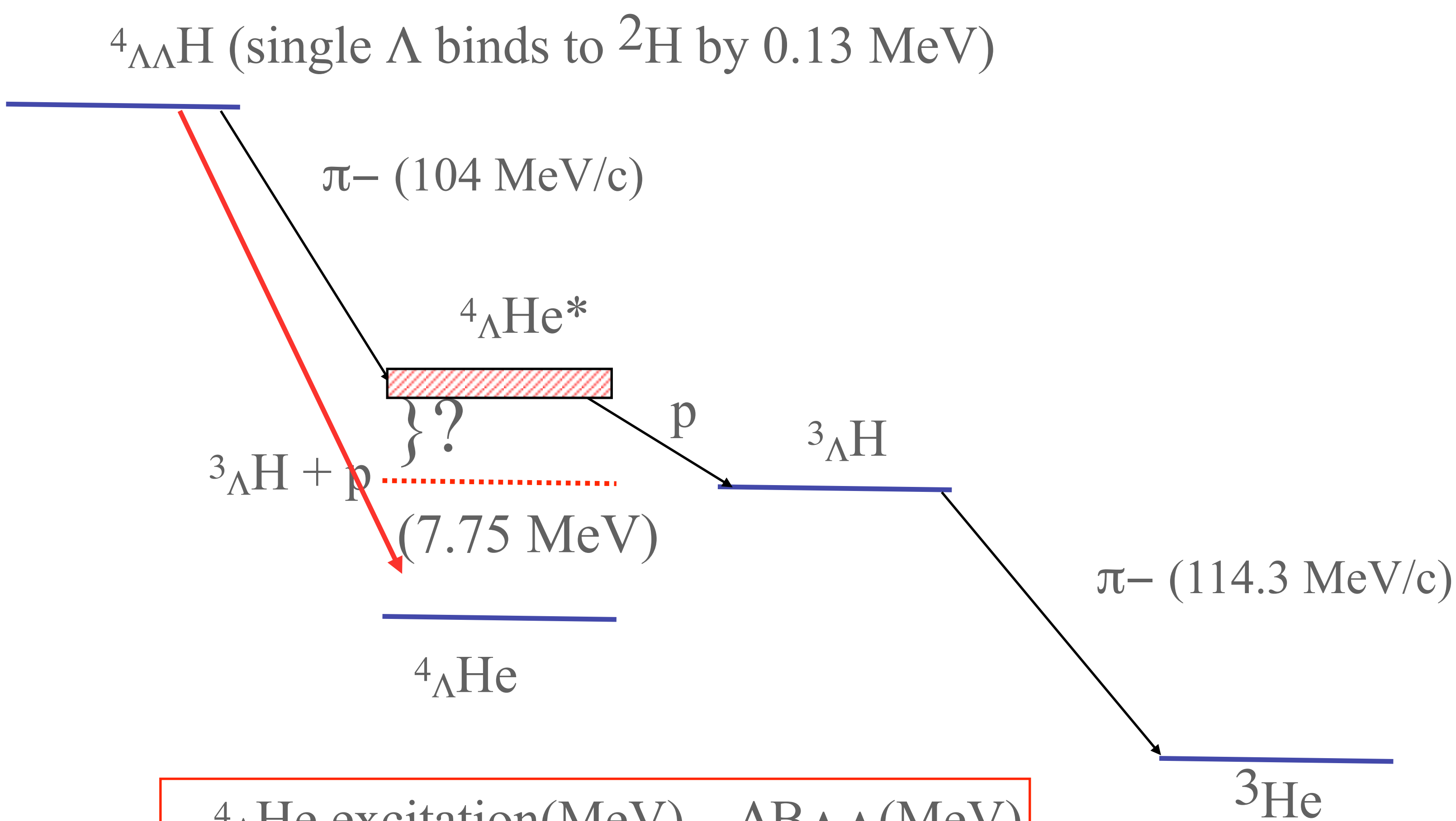
$$(iv)\quad \begin{cases} {}^{\ 4}_{\Lambda\Lambda}\mathrm{H} \longrightarrow {}^{4}_{\Lambda}\mathrm{He}^* + \pi^- & (\sim 103\ \mathrm{MeV/c}) \\ \qquad\qquad \downarrow & \\ \qquad\qquad {}^{3}_{\Lambda}\mathrm{H} + \mathrm{p} & \\ \qquad\qquad \downarrow & \\ \qquad\qquad {}^{3}\mathrm{He} + \pi^-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

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 $^{4}_{\Lambda\Lambda}H \rightarrow {}^{4}_{\Lambda}He(1^{+}) + \pi^{-}$

K中間子原子核

Contents

- Past measurements on *"K^-pp"*
  - FINUDA, E549 : $K^-_{stop}A$ reactions (K^-pp)→Λp
  - DISTO：pp→ΛpK^+
  - HADES, LEPS, E15 $^3He(K^-,n)$
- Recent measurements on *"K^-pp"*
  - J-PARC E27： $d(\pi^+,K^+pp)X$
  - J-PARC E15： $^3He(K^-, \Lambda p)n$ in the first data taking in 2013
- Discussion：Role of Λ(1405) as a doorway
- Summary

Recent high-statistics data by T. Yamaga

AY02

PHYSICAL REVIEW C, VOLUME 65, 044005

Nuclear $\bar{K}$ bound states in light nuclei

Yoshinori Akaishi[1] and Toshimitsu Yamazaki[2]
[1]*Institute of Particle and Nuclear Studies, KEK, Tsukuba 305-0801, Japan*
[2]*RI Beam Science Laboratory, RIKEN, Wako 351-0198, Japan*
(Received 21 August 2001; published 1 April 2002)

The possible existence of deeply bound nuclear $\bar{K}$ states is investigated theoretically for few-body systems. The nuclear ground states of a K^- in ^{3}He, ^{4}He, and ^{8}Be are predicted to be discrete states with binding energies of 108, 86, and 113 MeV and widths of 20, 34, and 38 MeV, respectively. The smallness of the widths arises from their energy-level locations below the $\Sigma\pi$ emission threshold. It is found that a substantial contraction of the surrounding nucleus is induced due to the strong attraction of the $I=0$ $\bar{K}N$ pair, thus forming an unusually dense nuclear medium. Formation of the $T=0$ $K^-\otimes{}^3\mathrm{He}+\bar{K}^0\otimes{}^3\mathrm{H}$ state in the ^{4}He (stopped K^-, n) reaction is proposed, with a calculated branching ratio of about 2%.

DOI: 10.1103/PhysRevC.65.044005 PACS number(s): 13.75.Jz, 21.10.Dr, 21.45.+v, 21.80.+a

YA02

ELSEVIER

Physics Letters B 535 (2002) 70–76

PHYSICS LETTERS B

www.elsevier.com/locate/npe

(K^-, π^-) production of nuclear $\overline{K}$ bound states in proton-rich systems via Λ^* doorways

Toshimitsu Yamazaki [a], Yoshinori Akaishi [b]

[a] *RI Beam Science Laboratory, RIKEN, Wako, Saitama-ken, 351-0198 Japan*
[b] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki-ken, 305-0801 Japan*

Received 2 January 2002; received in revised form 13 February 2002; accepted 13 February 2002

Editor: J.P. Schiffer

Abstract

We propose to use the (K^-, π^-) and (π^+, K^+) reactions to produce deeply bound nuclear $\overline{K}$ states in proton-rich systems, in which an elementary formation of $\Lambda(1405)$ and $\Lambda(1520)$ plays the role of a doorway state. Exotic discrete $\overline{K}$ bound systems on unbound nuclei, such as K^-pp, K^-ppp and K^-pppn, are predicted to be produced, where a high-density nuclear medium is formed as a result of nuclear contraction due to the strong K^-–p attraction.

YDA 04

Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Physics Letters B 587 (2004) 167–174
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Invariant-mass spectroscopy for condensed single- and double-$\bar{K}$ nuclear clusters to be formed as residues in relativistic heavy-ion collisions

Toshimitsu Yamazaki [a], Akinobu Doté [b], Yoshinori Akaishi [b]

[a] RI Beam Science Laboratory, RIKEN, Wako, Saitama 351-0198, Japan
[b] Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan

Received 26 September 2003; received in revised form 9 January 2004; accepted 9 January 2004

Editor: J.P. Schiffer

Abstract

Using a phenomenological $\bar{K}N$ interaction, we predict that few-body double-$\bar{K}$ nuclei, such as ppK^-K^- and $ppnK^-K^-$, as well as single-$\bar{K}$ nuclei, are tightly bound compact systems with large binding energies and ultra-high nucleon densities. We point out that these $\bar{K}$ nuclear clusters can be produced as residual fragments in relativistic heavy-ion collisions, and that their invariant masses can be reconstructed from their decay particles.

The unique signature for $\bar{K}$ cluster formation is a clear peak to be revealed in the invariant-mass spectra of its decay particles, if all of the decay particles with their energies and momenta are correctly identified. This method applies to limited cases, where $\bar{K}$ clusters can decay to trackable particles, such as

(i) $$ppK^- \to \Lambda + p, \quad (12)$$

(ii) $$ppnK^- \to \Lambda + d, \quad (13)$$

Bound States of Baryon number=2

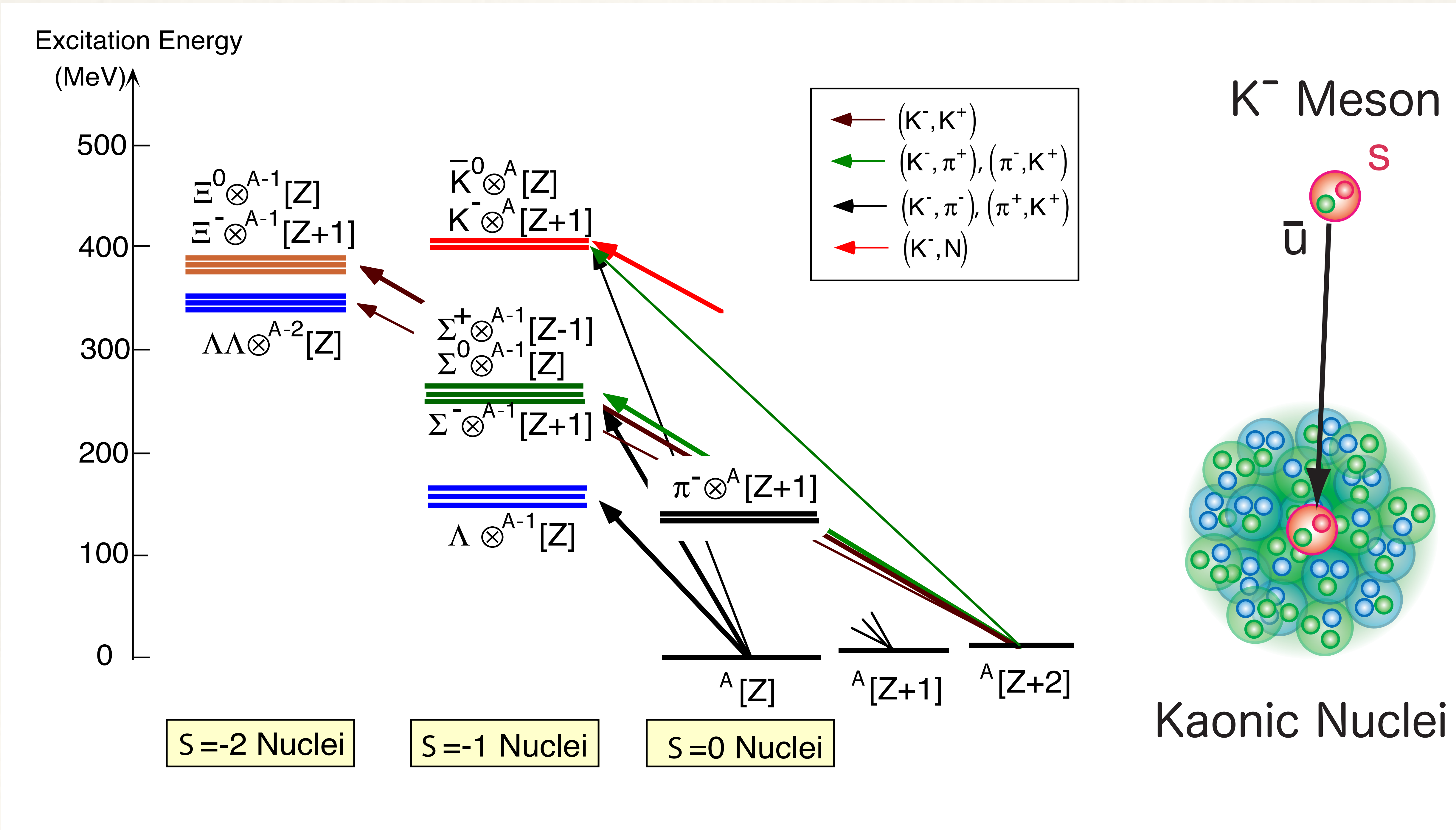
- S=0 : One bound state
  - deuteron = p+n with T=0, $J^P=1^+$ *$\Delta\Delta$, T=0, $J^P=3^+$*
- S=-1: No bound states ?
  - Λ hypernuclei : A≥3 ($^3{}_\Lambda$H)
  - Σ hypernuclei : A≥4 ($^4{}_\Sigma$He)

K^-pp

- S=-2: ??
  - $\Lambda\Lambda$-H dibaryon, ΞN

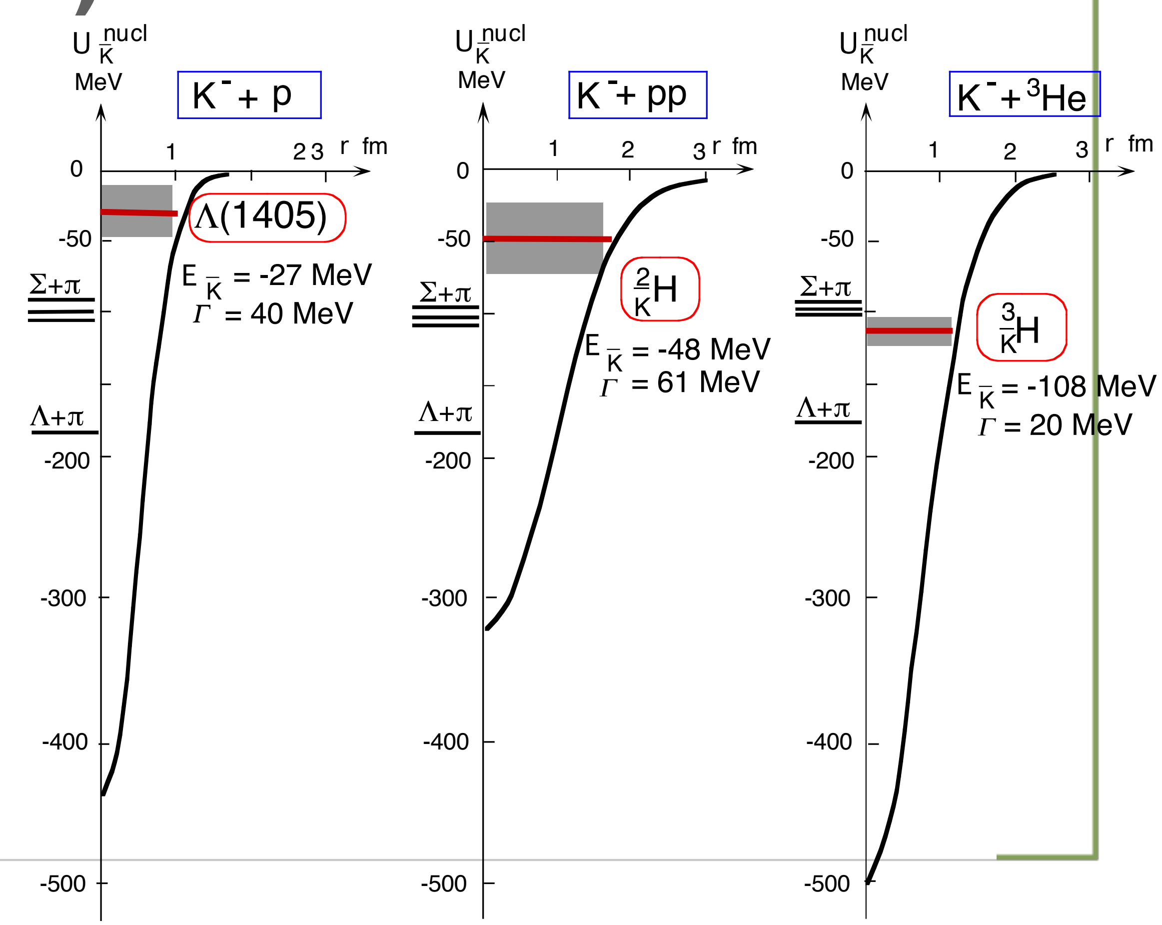
New type of Strange matter

- Strange meson (K^-, K^{bar}) in Nuclei.

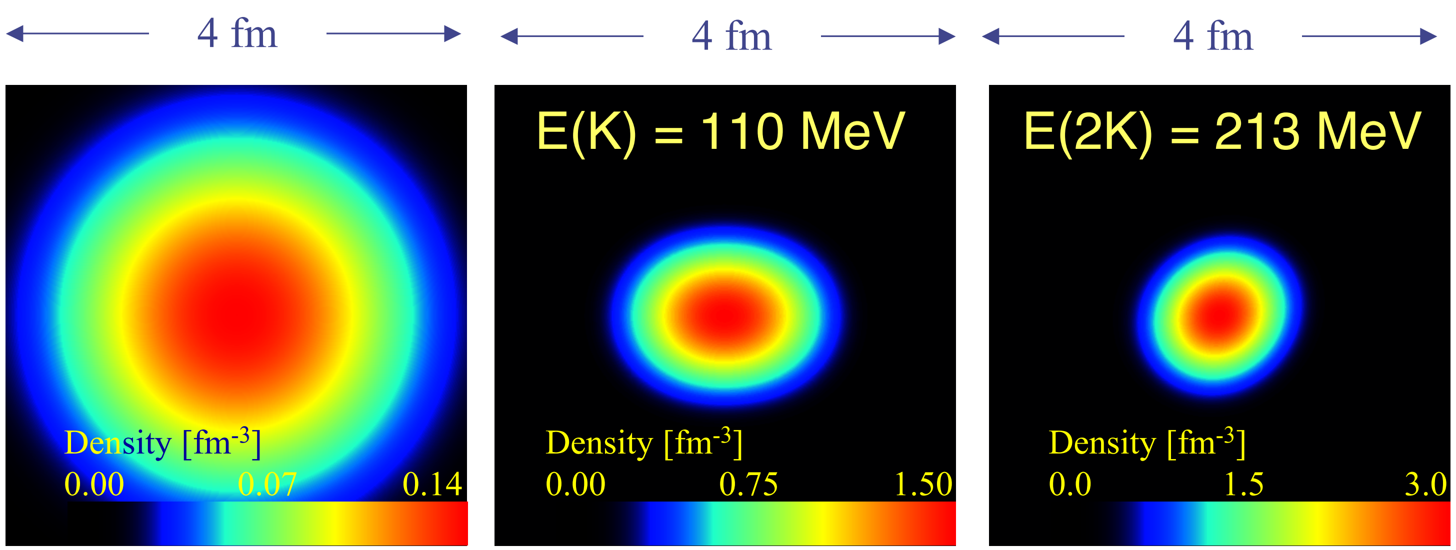


$\bar{K}N$ Bound States

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



Formation of High Density State

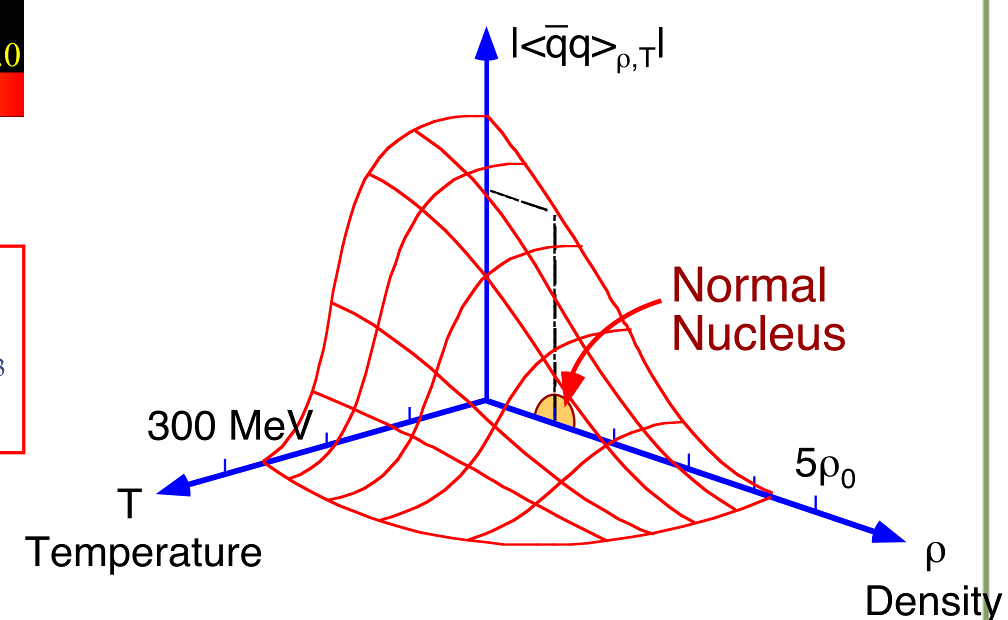


ppn	ppnK$^-$	ppnK$^-$K$^-$
total B.E. = 6.0 MeV	total B.E. = 118 MeV	total B.E. = 221 MeV
central density = 0.14 fm^{-3}	central density = 1.50 fm^{-3}	central density = 3.01 fm^{-3}
R_{rms} = 1.59 fm	R_{rms} = 0.72 fm	R_{rms} = 0.69 fm

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

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 ($\rho \ll \rho_0$)*

Hadronic Atoms

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

- Klein-Gordon equation

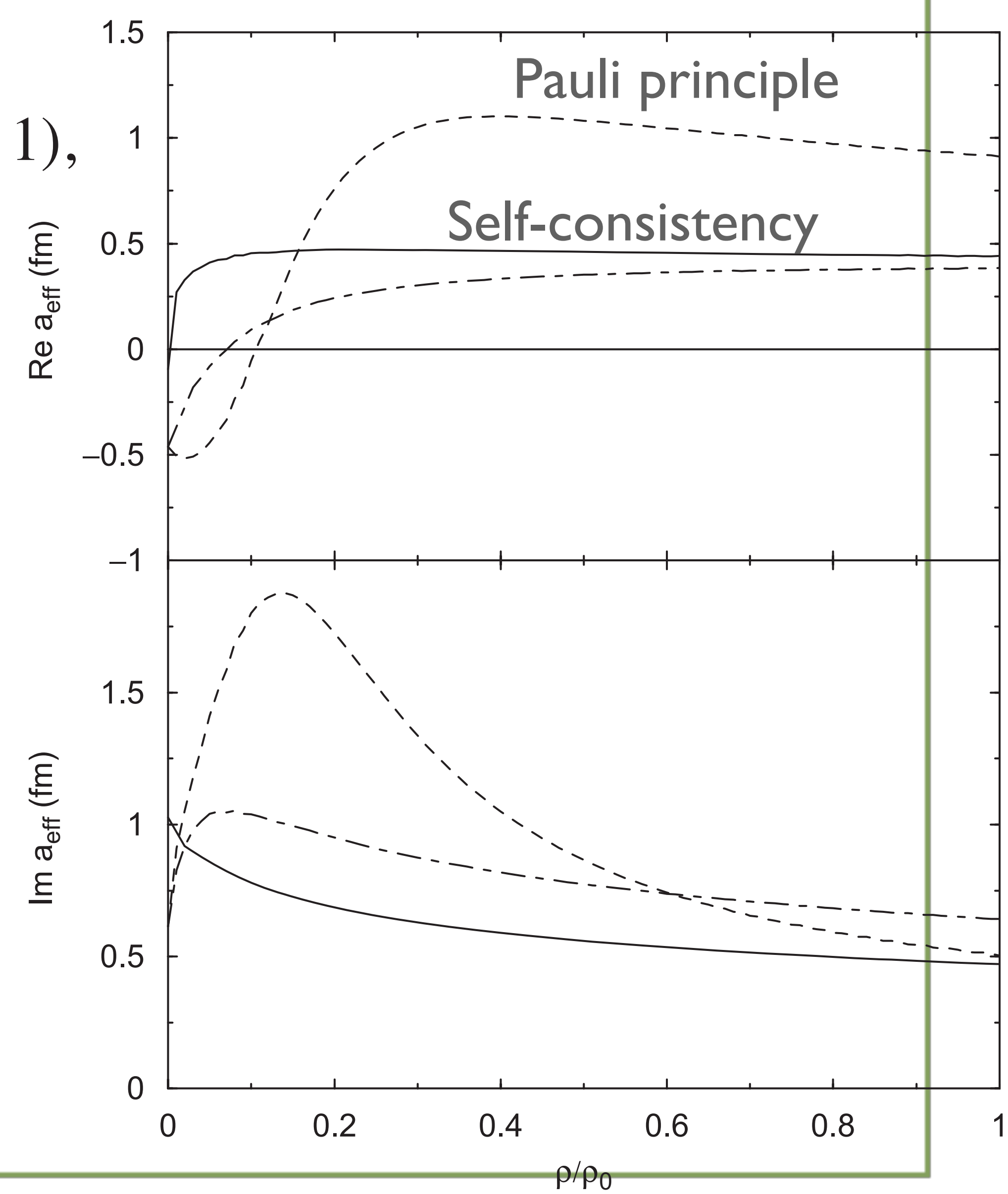
$$[\nabla^2 - 2\mu(B + V_{\rm opt} + V_c) + (V_c + B)^2]\psi = 0 \quad (\hbar = c = 1),$$

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

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

where

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



K-p interaction near threshold

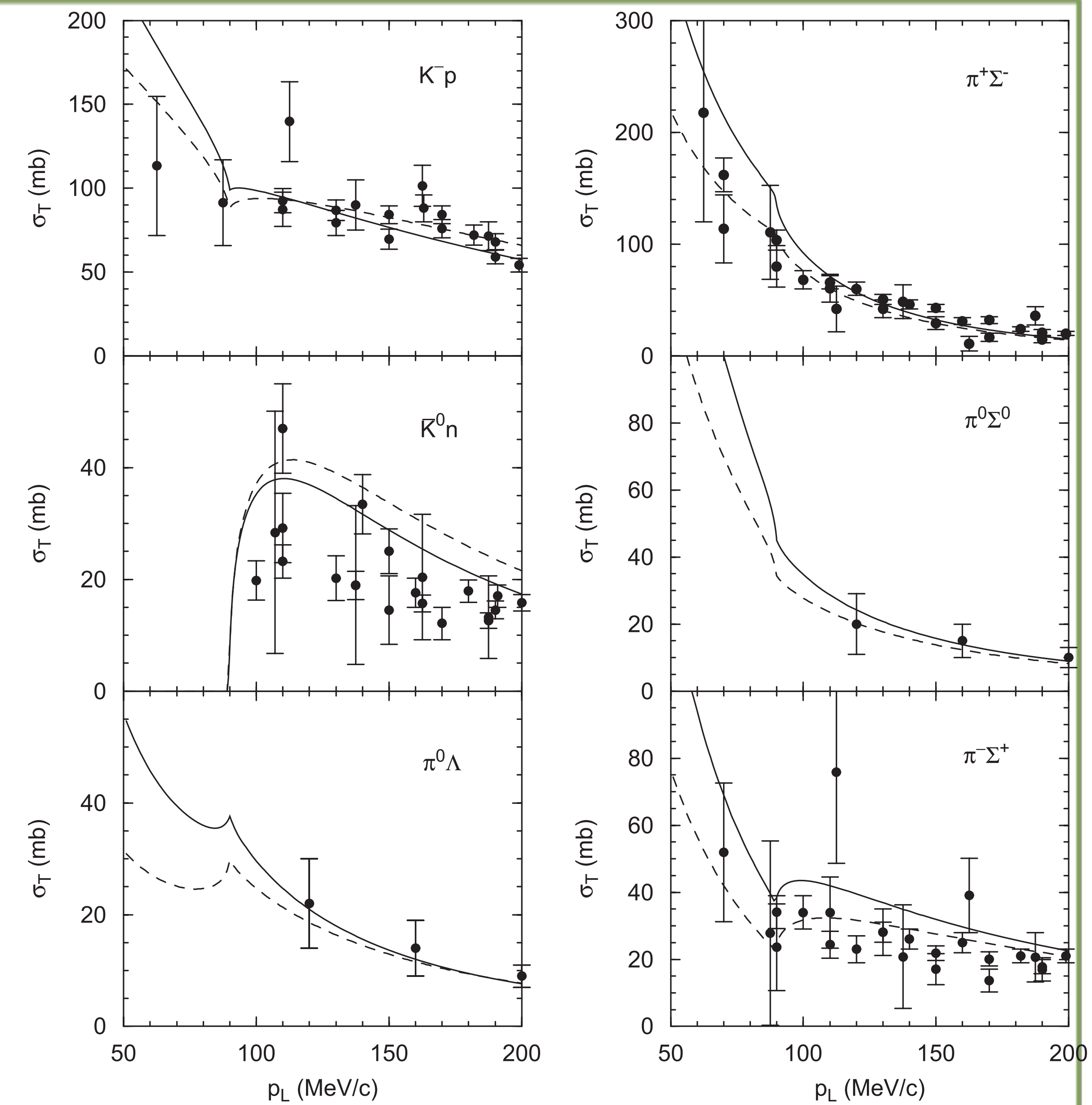
- Threshold branching ratios

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

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

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

- K-p Scattering data

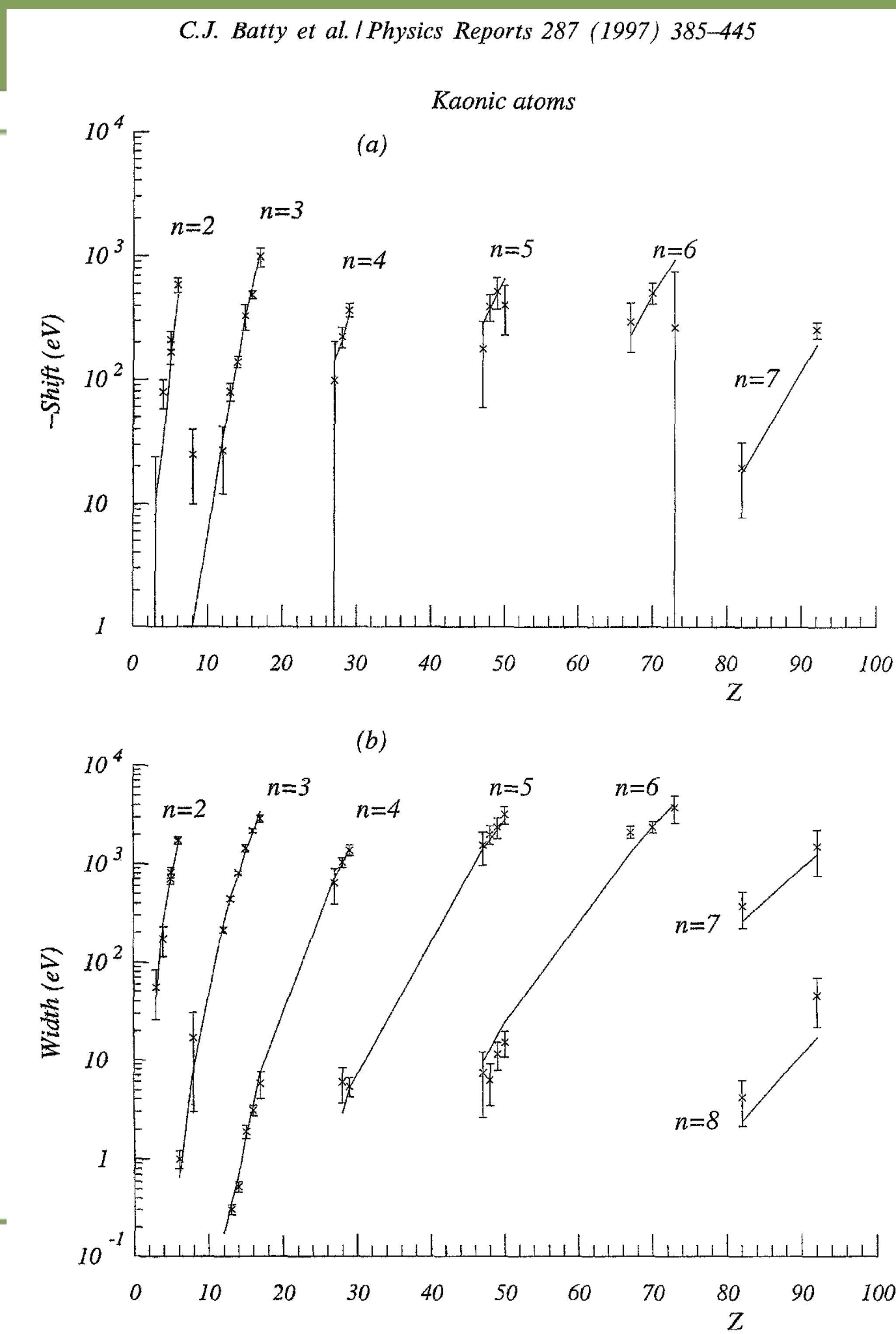


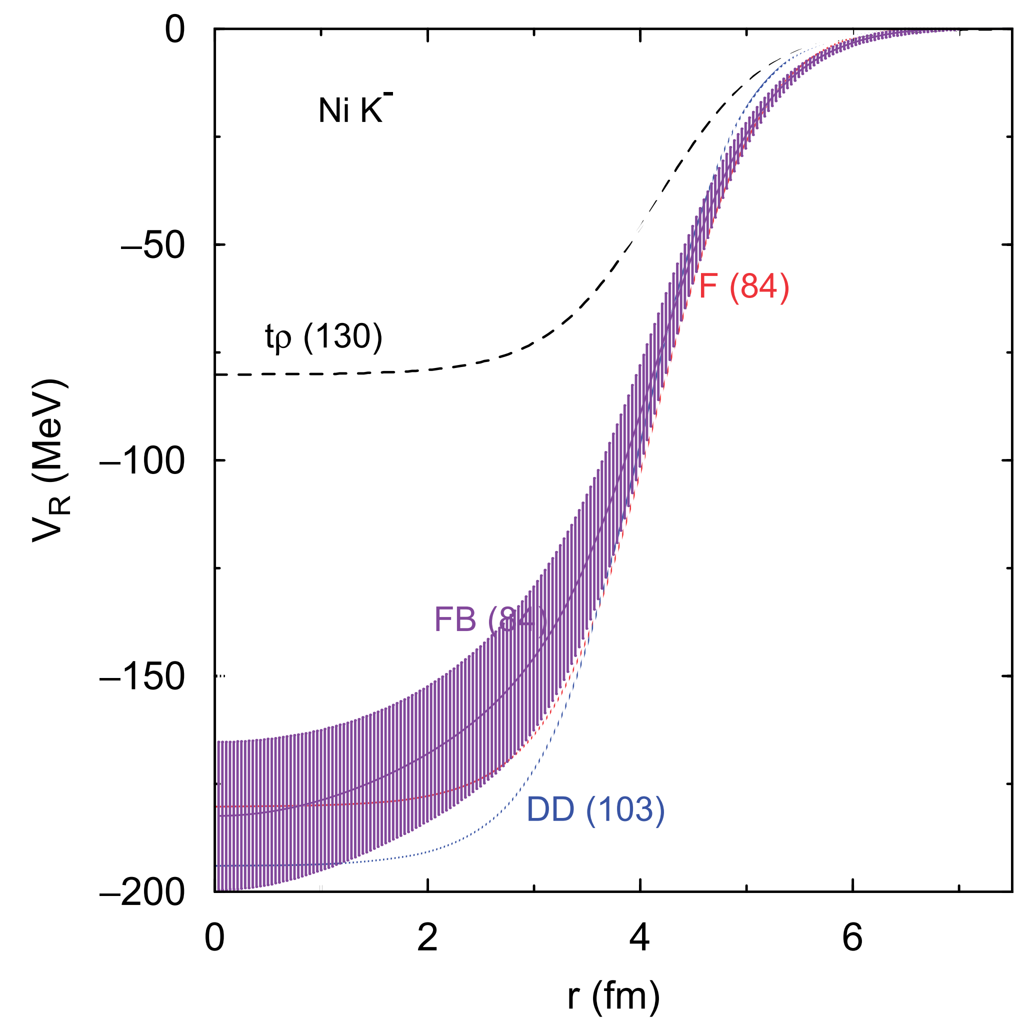
- Kaonic hydrogen

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

a(K-p)=(-0.78±0.15±0.03)+(0.49±0.25±0.12)*i* fm

Kaonic Atoms

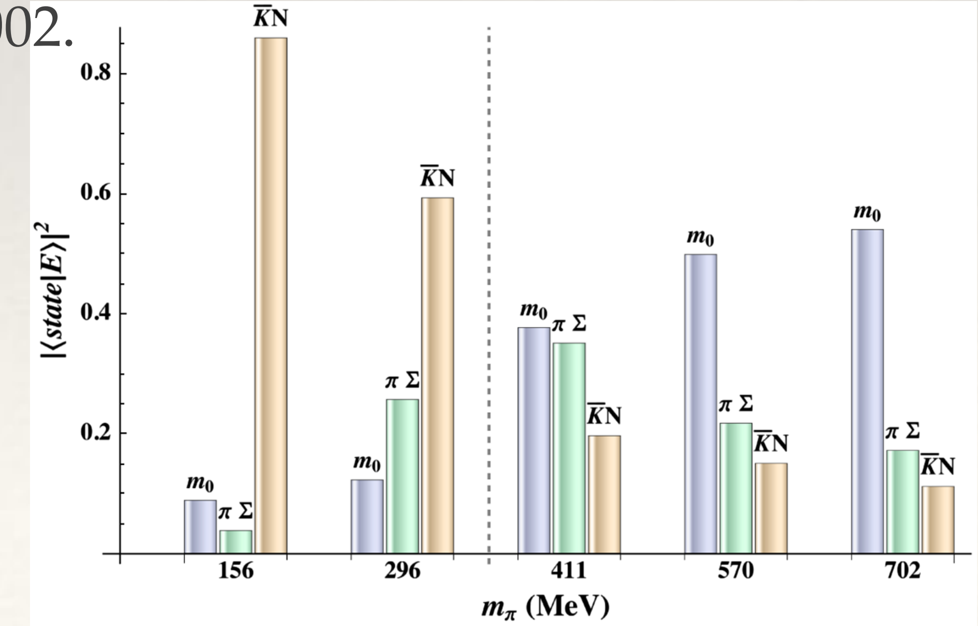




K^-pp

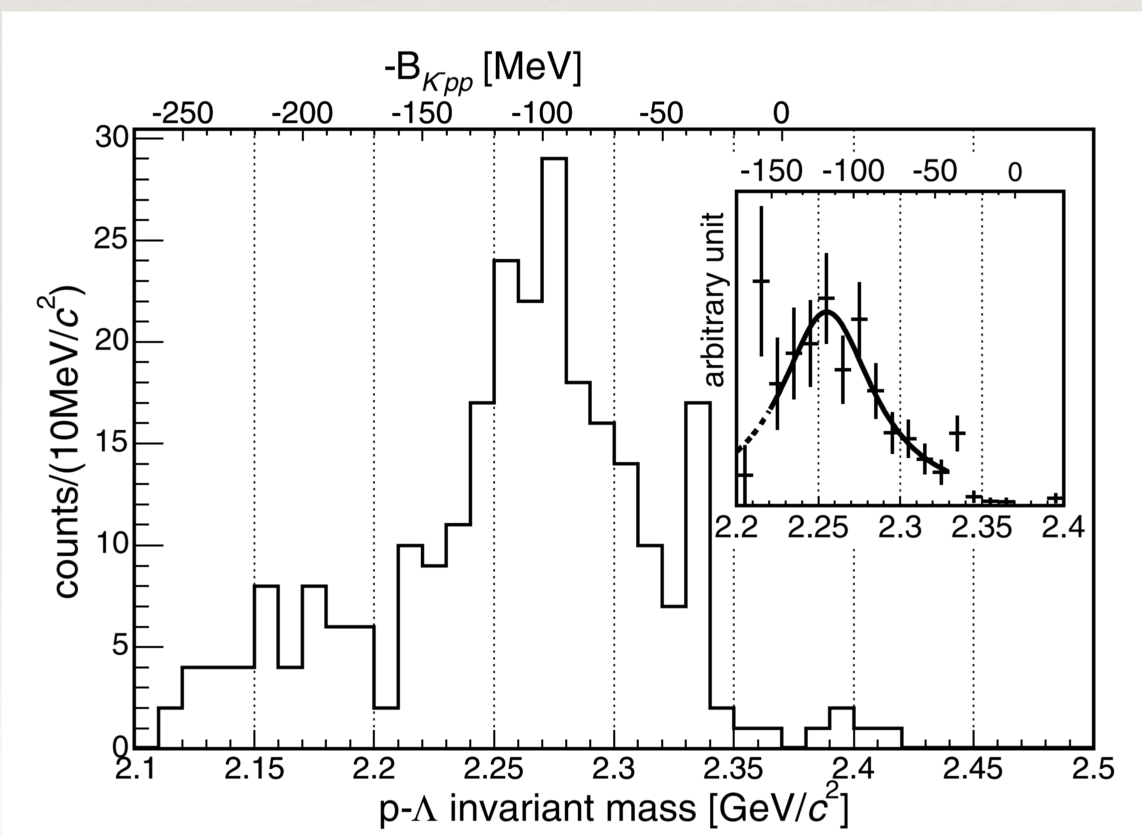
- $\overline{\mathrm{K}}$N : attraction in Isospin=0
  - Kaonic hydrogen X-ray ; SIDDHARTA
    M. Bazzi et al., NPA 881 (2012) 88-97.
  - Low-energy scattering measurements + Branching ratios at threshold
  - Λ(1405) below the K^-p threshold
    - $J^{\pi}=1/2^-$; Moriya et al., Phys. Rev. Lett. 112 (2014) 082004.
    - Antikaon-Nucleon Molecule from Lattice QCD
      ; J.M.M. Hall et al., Phys. Rev. Lett. 114 (2015) 132002.

- Possible existence of "K^-pp" : Y=1, I=1/2, $J^{\pi}=0^-$

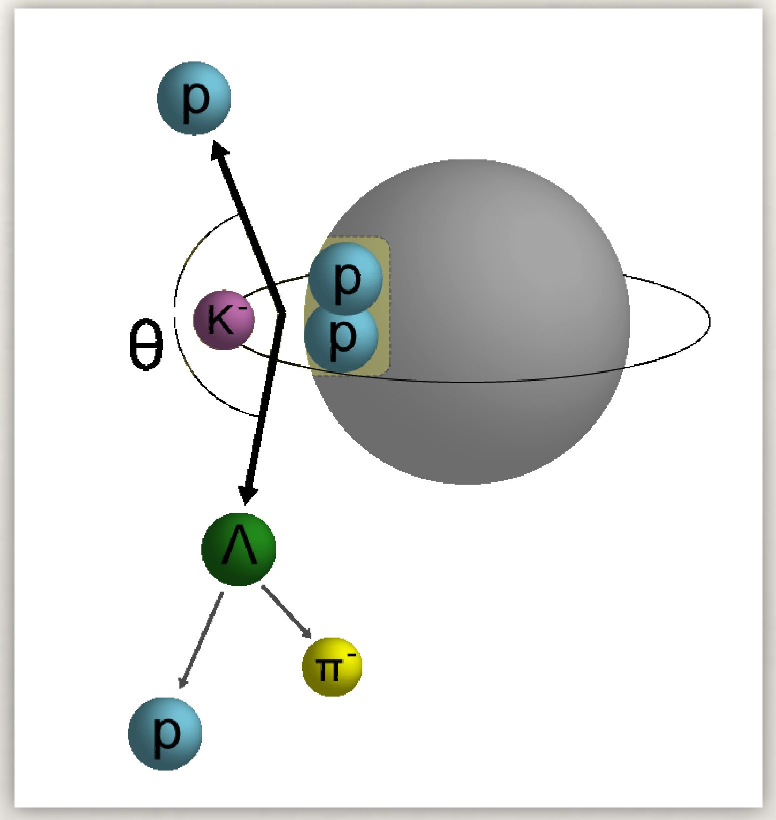


Past Measurements on *K⁻pp* #1

- First evidence of $K^{-}pp$ with ^{6}Li+^{7}Li+^{12}C by FINUDA
  - A lot of back-to-back Λp pairs with small invariant mass



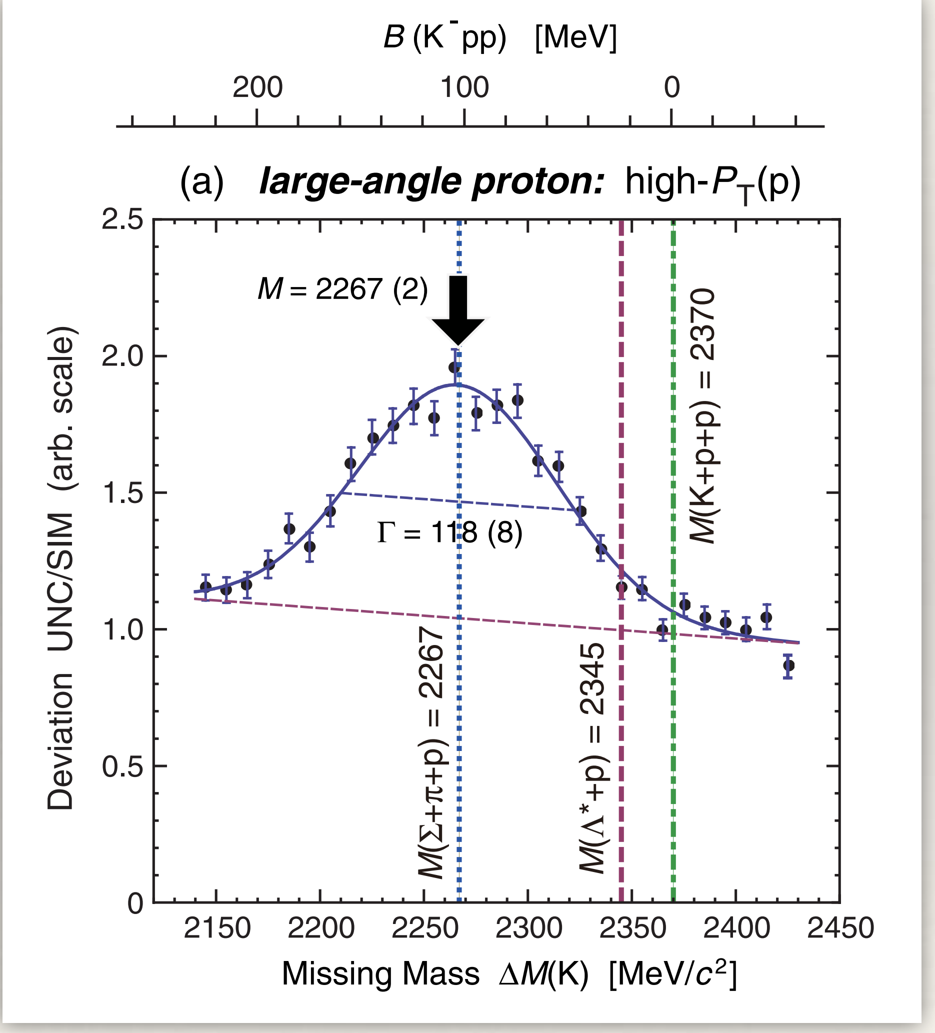
M. Agnello et al., PRL94, (2005) 212303



B=115+6/-5+3/-4 MeV
Γ= 67+14/-11+2/-3 MeV

Past Experiments on $K^{-}pp$ #2

- DISTO data: $p+p \rightarrow p\Lambda(K^{-}pp) + K^{+}$ at 2.85 GeV
  - $M = 2267 \pm 3 \pm 5$ MeV / c^2
  - $\Gamma = 118 \pm 8 \pm 10$ MeV
- Not observed at 2.5 GeV
  - small Λ^* production cross section



T. Yamazaki et al., PRL 104 (2010) 132502.
P. Kienle et al., Eur. Phys. J. A 48 (2012) 183.

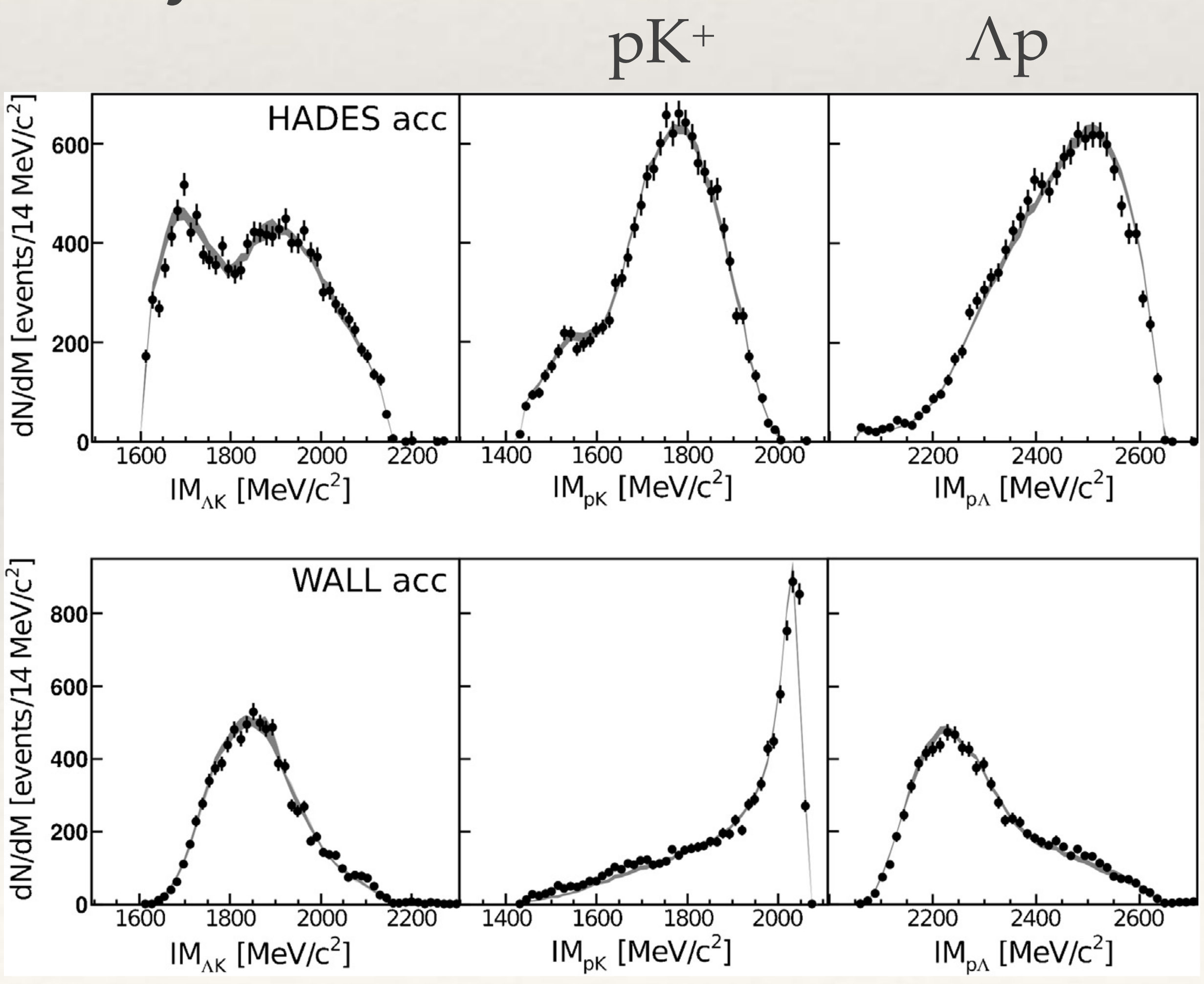
Past Measurements on *K⁻pp* #3

- HADES G. Agakishiev et al., Phys. Lett. B 742 (2015) 242-248.
  - $p+p \rightarrow K^+ p \Lambda$ @3.5 GeV; S/N<<1
  - Bonn-Gatchina Partial Wave Analysis well reproduces the data
  - *$K^- pp$* production upper limit ~4 μb for Γ=70 MeV (2.22-2.37 GeV/c²)

    ⇅

    Λ(1405) production ~10μb

Sensitivity ?

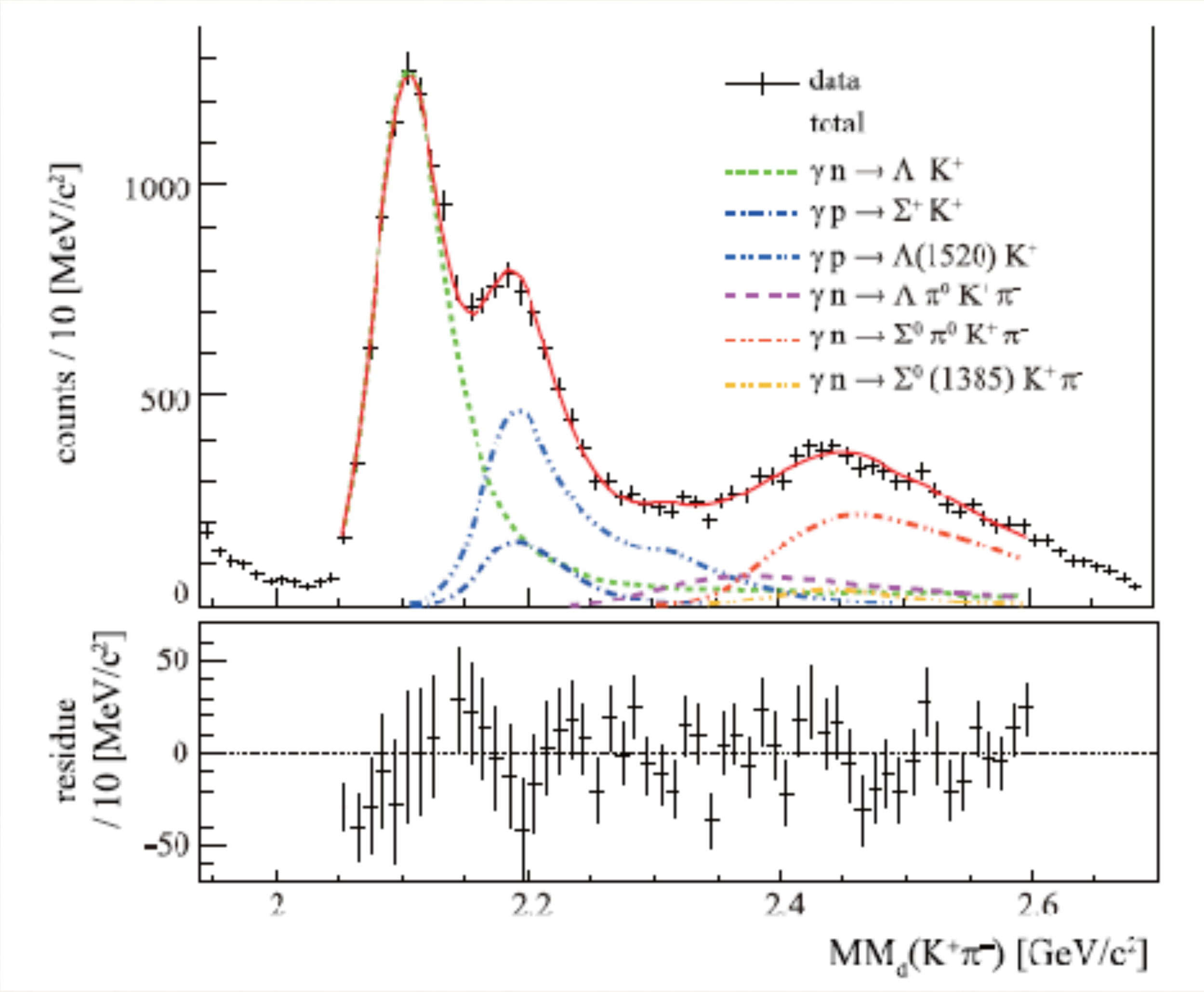


Past Measurements on $K^{-}pp$ #4

- LEPS/SPring-8

A.O. Tokiyasu et al., Phys. Lett. B 728 (2014) 616-621.

  - $d(\gamma, K^{+}\pi^{-})$ reaction (E_{γ}=1.5-2.4 GeV)
  - Inclusive missing-mass
    σ_{m}~10 MeV
    - Background
      $K^{+}\Lambda(1520)$, $K^{+}\pi^{-}\pi Y$
  - Upper limits:2.22-2.36 GeV/c²
    < 1.1-2.9 μb for Γ=100 MeV,
    9.9-26% of KπY productions

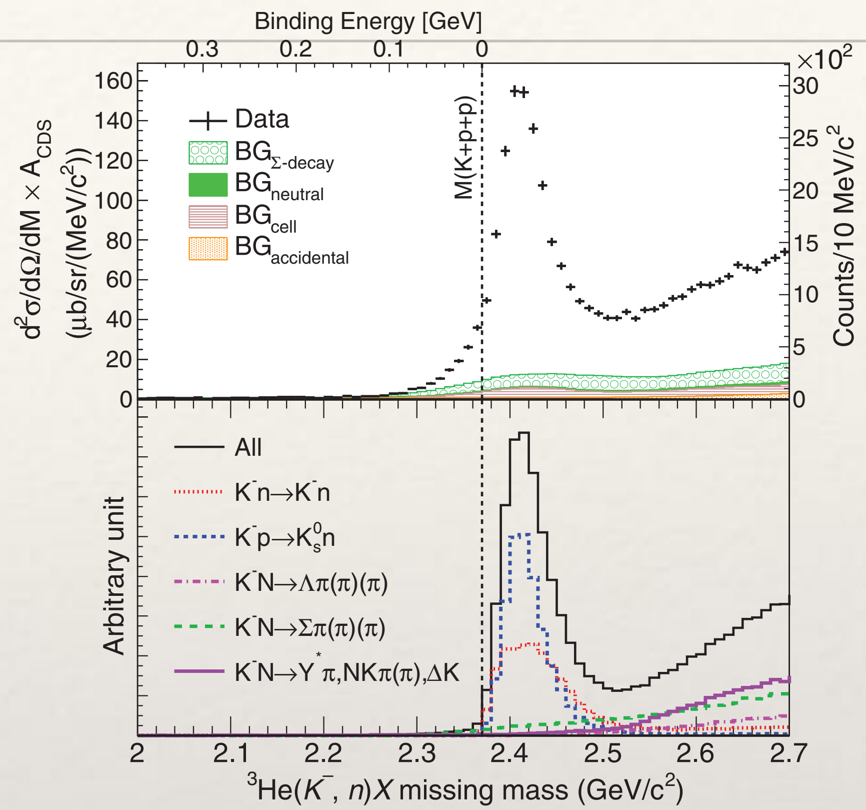


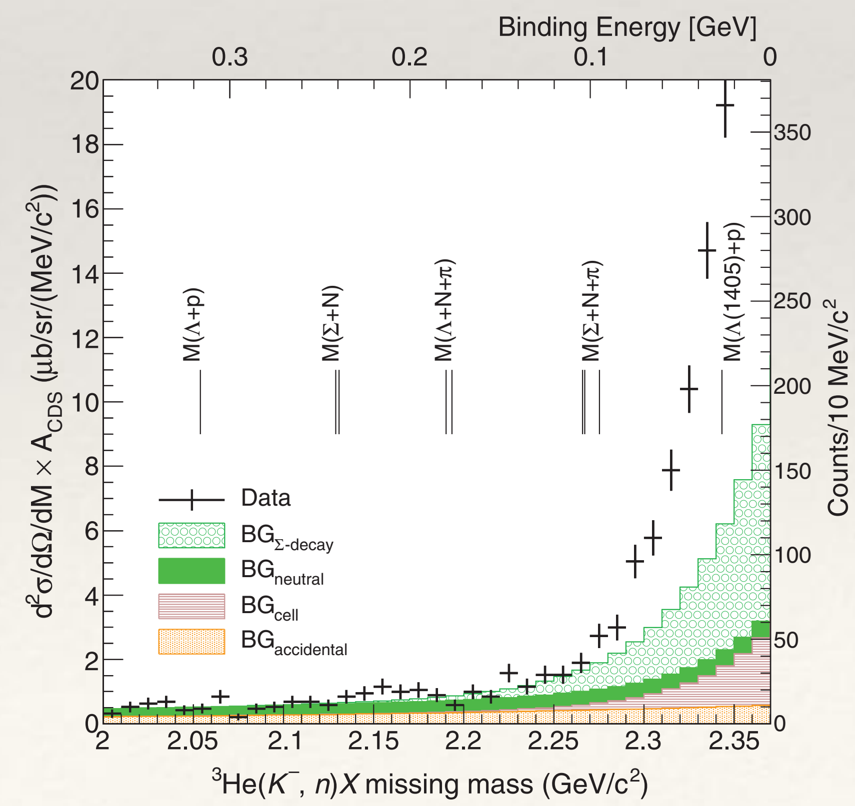
Sensitivity ?

Past Measurements on *K⁻pp* #5

- J-PARC E15
  T. Hashimoto et al., PTEP (2015) 061D01.
  - ^{3}He(K$^-$,n) reaction @ 1 GeV/*c*
  - Semi-inclusive missing-mass
    σ_m:5-15 MeV
  - *K⁻pp* production upper limit
    100-270 μb/sr for Γ=100 MeV
    (~5% of QF *K⁻n* elastic)

Sensitivity ?





Theoretical calculations on $K^{-}pp$

- Methods : Variational vs. Faddeev
  → Almost same results by using the same interaction model

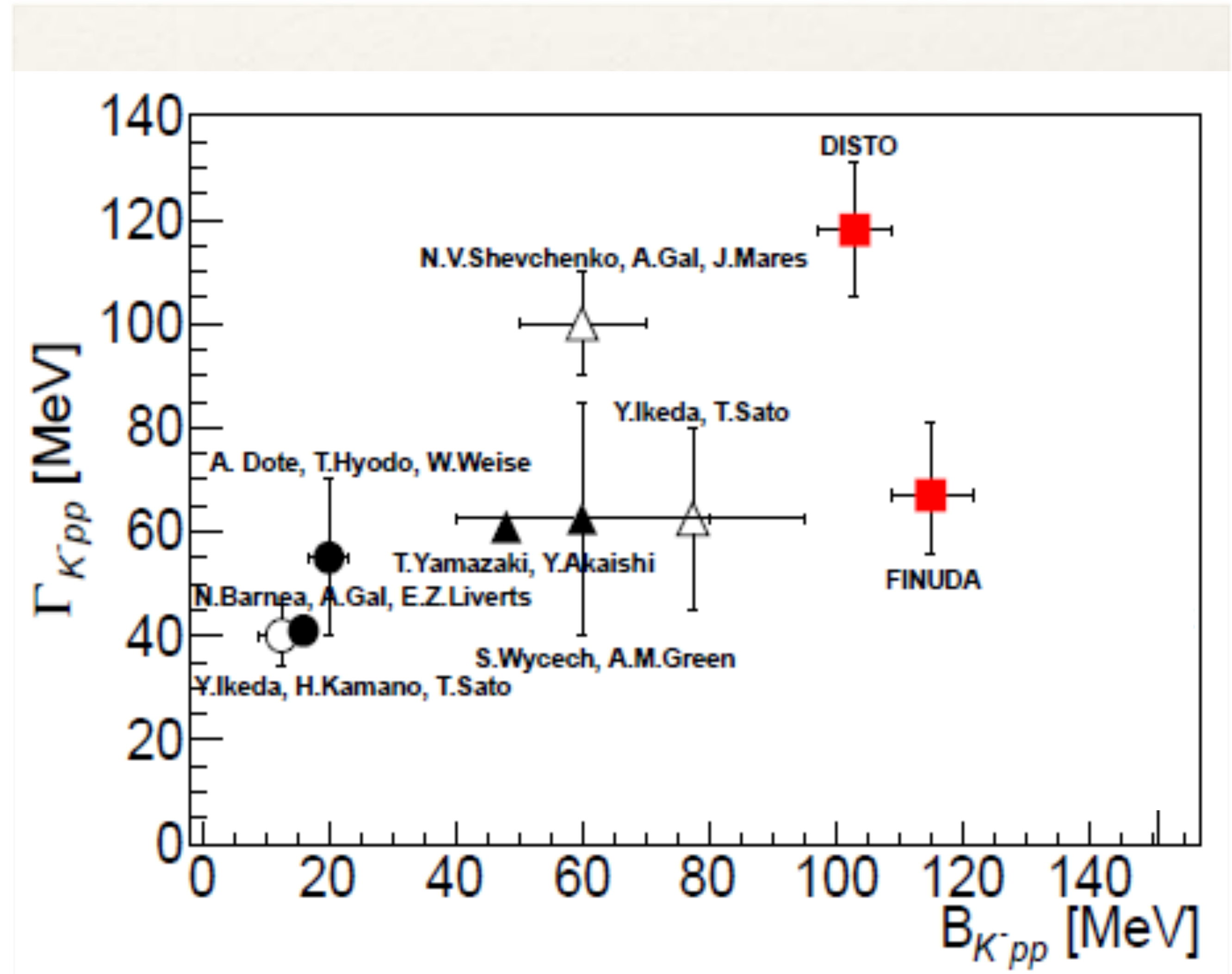
- $\overline{K}N$ Interaction Models :
  Chiral SU(3)-based (Energy dependent) → Shallow~20 MeV
  Phenomenological (Energy independent) → Deep~40-70 MeV

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

FSI effects ? (V.K. Magas et al.), Λ*N bound state (T. Uchino et al.)

Comparison between Theory and Exps.

- Binding energy
  - Shallow case: B~20 MeV
  - Deep case: B~40-70 MeV
  - Observations: B~100 MeV
- Width
  - agreement: Γ~30-100 MeV



By Y. Ichikawa

Lessons

- It looks hard to observe the $K^{-}pp$ signal in inclusive measurements. (LEPS, J-PARC E15 fwd “n”)
  - Small and Broad signature ; ~1
    two-step reaction (two nucleons be involved)
  - Large and Widely distributed QF background ; >10~100
    single-step reaction

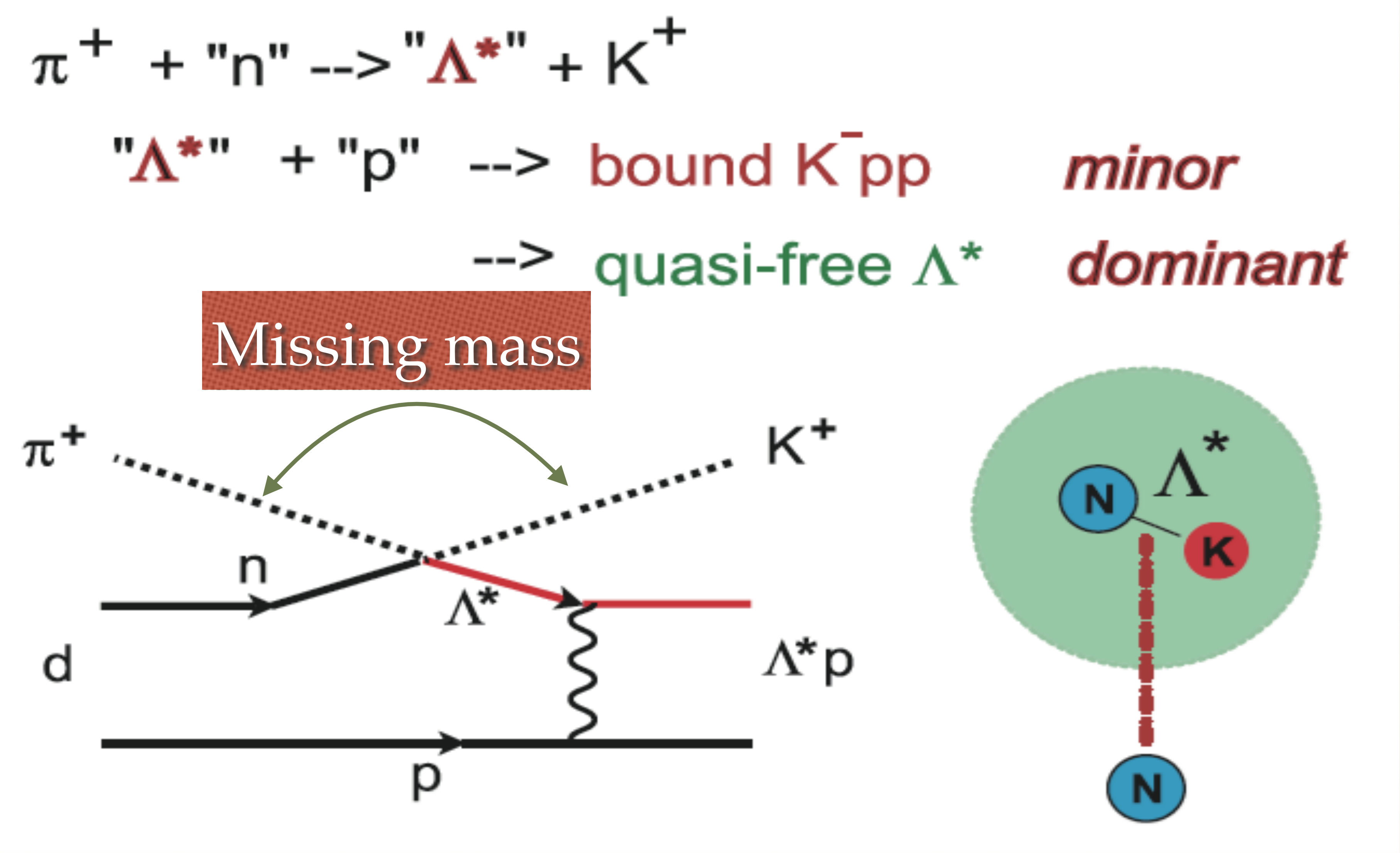
Recent Measurements on *K^-pp*

- ⭐ J-PARC E27： $d(\pi^+, K^+pp)X$
- ⭐ J-PARC E15： $^3He(K^-, \Lambda p)n$

J-PARC E27

Y. Ichikawa et al., PTEP (2014) 101D03.
Y. Ichikawa et al., PTEP (2015) 021D01.

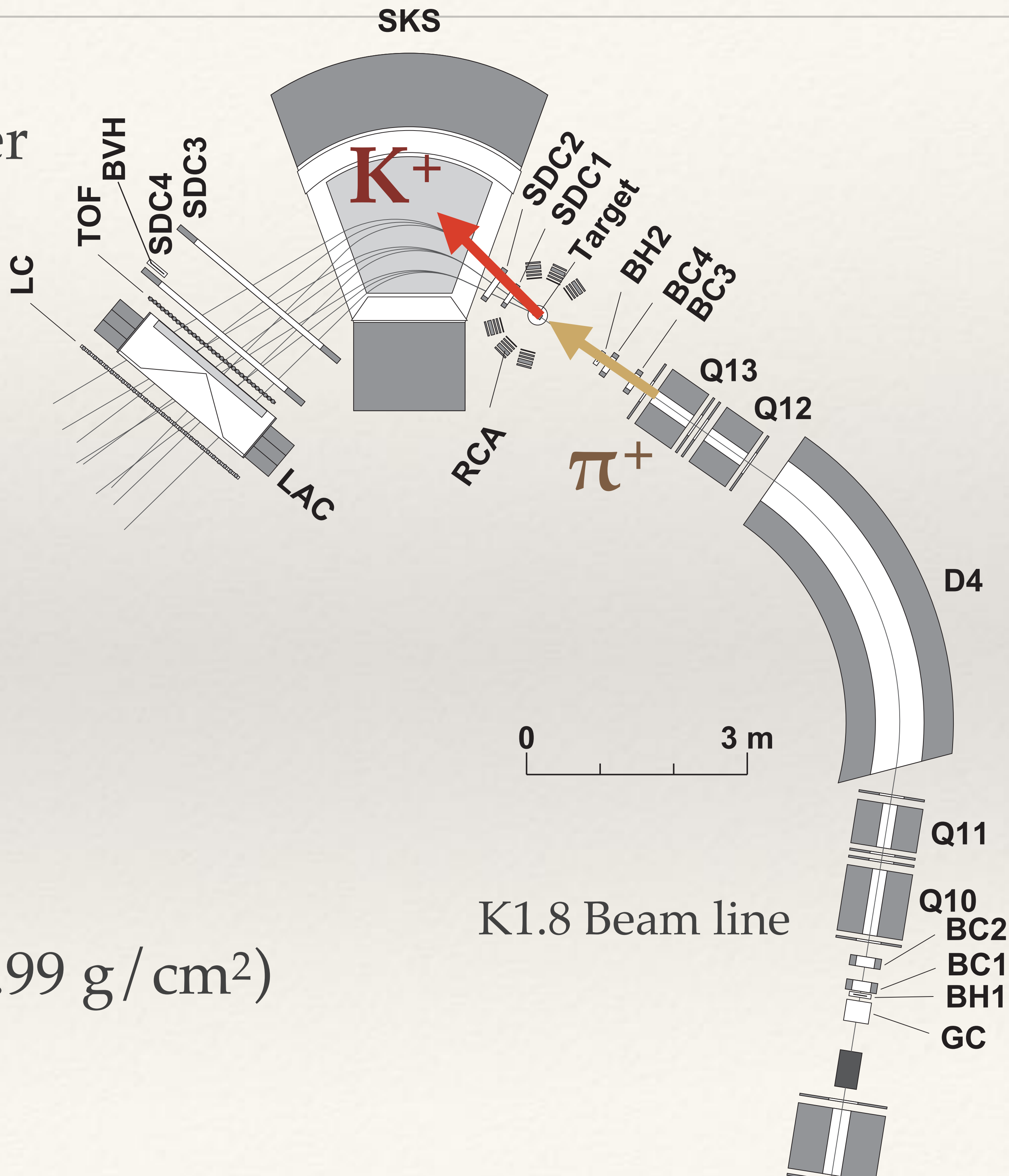
- d(π^+, K$^+$) reaction @1.69 GeV / c



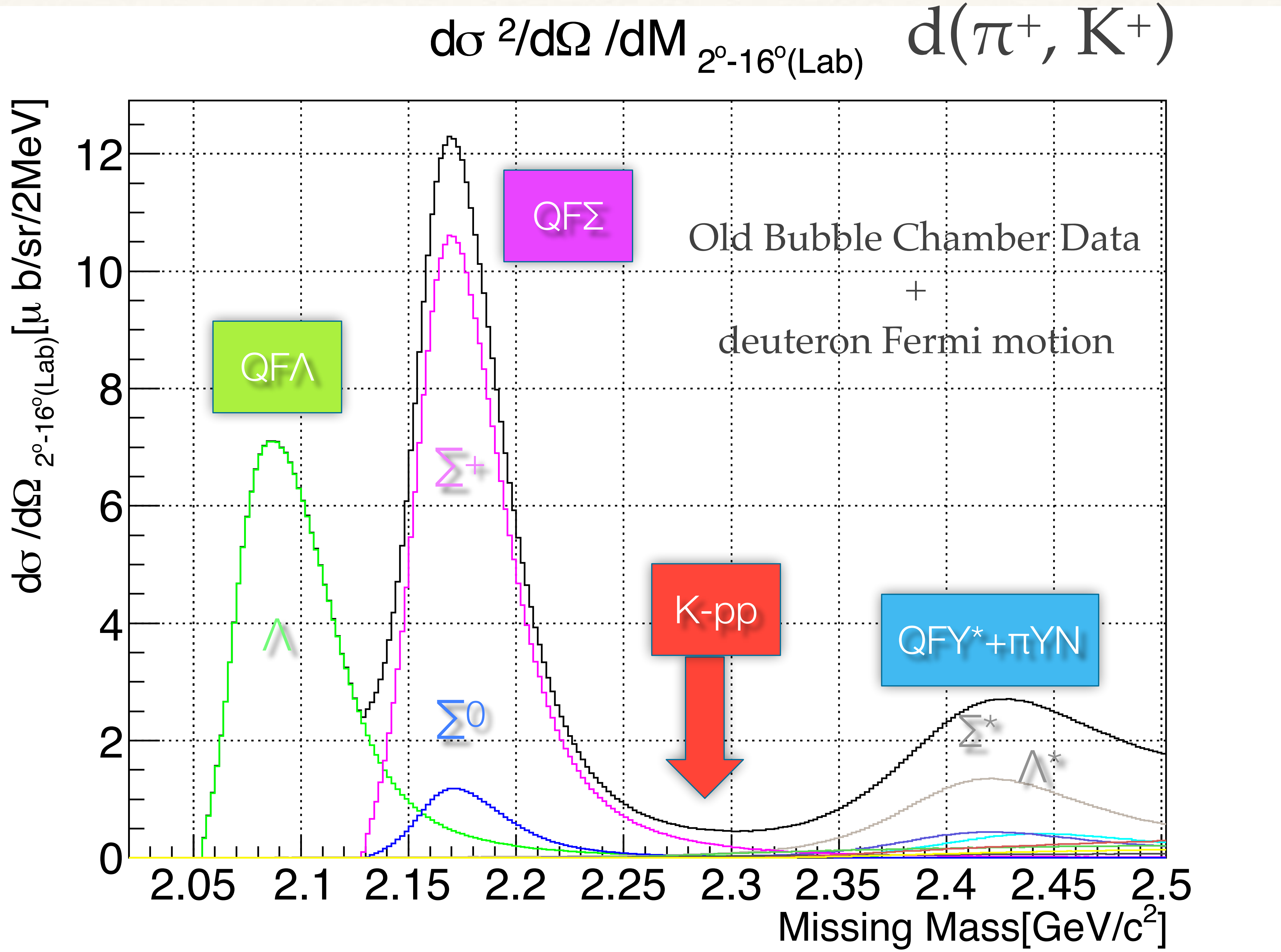
Yamazaki & Akaishi, Phys. Rev. C 76 (2007) 045201.

Experimental Setup

- K1.8 beam line spectrometer
  - 1.69 GeV/*c* π^+
  - $\Delta p/p \sim 2\text{x}10^{-3}$
- SKS spectrometer
  - 0.8-1.3 GeV/*c* K^+
  - $\Delta p/p \sim 2\text{x}10^{-3}$
  - $\Delta\Omega \sim 100$ msr
- Target : liquid deuterium(1.99 g/cm^2)

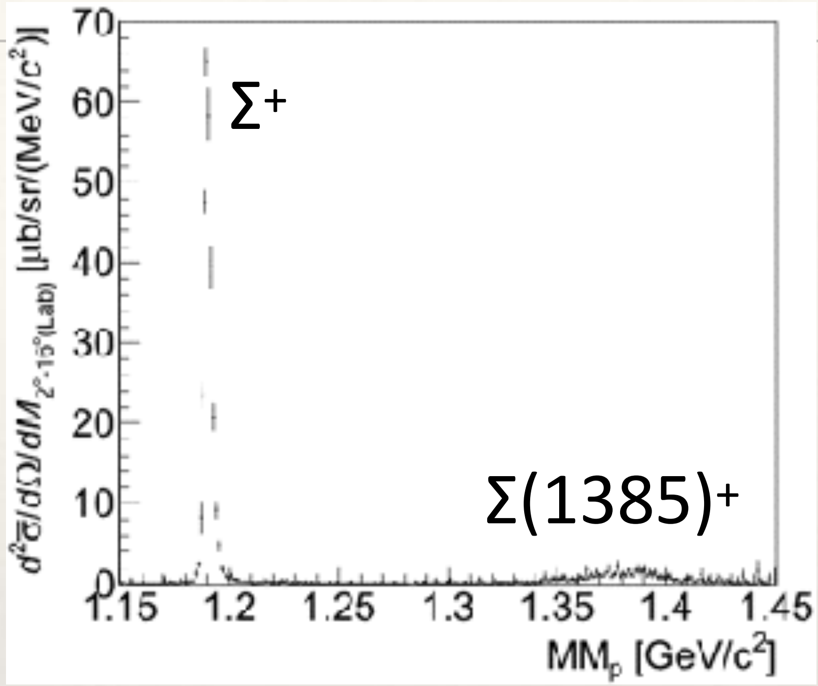


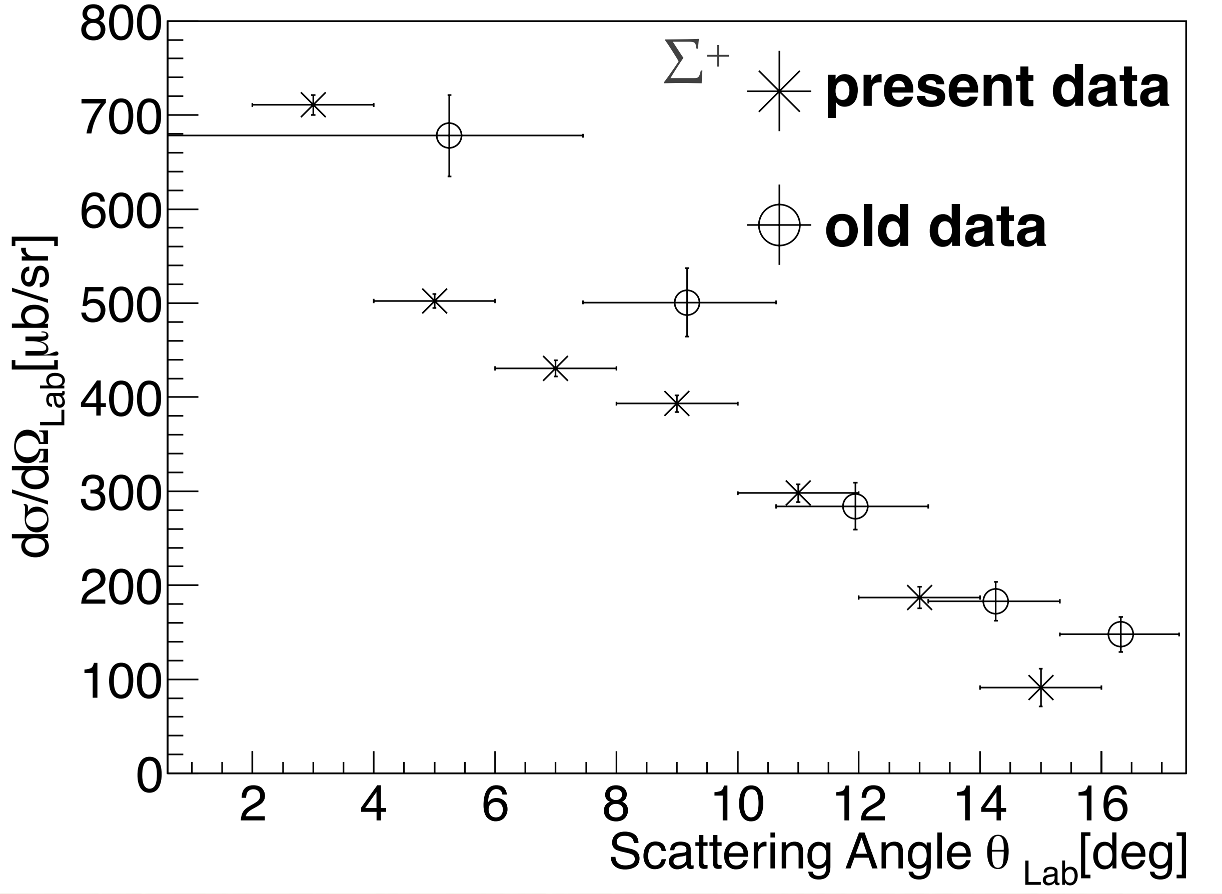
Expected Inclusive Spectrum

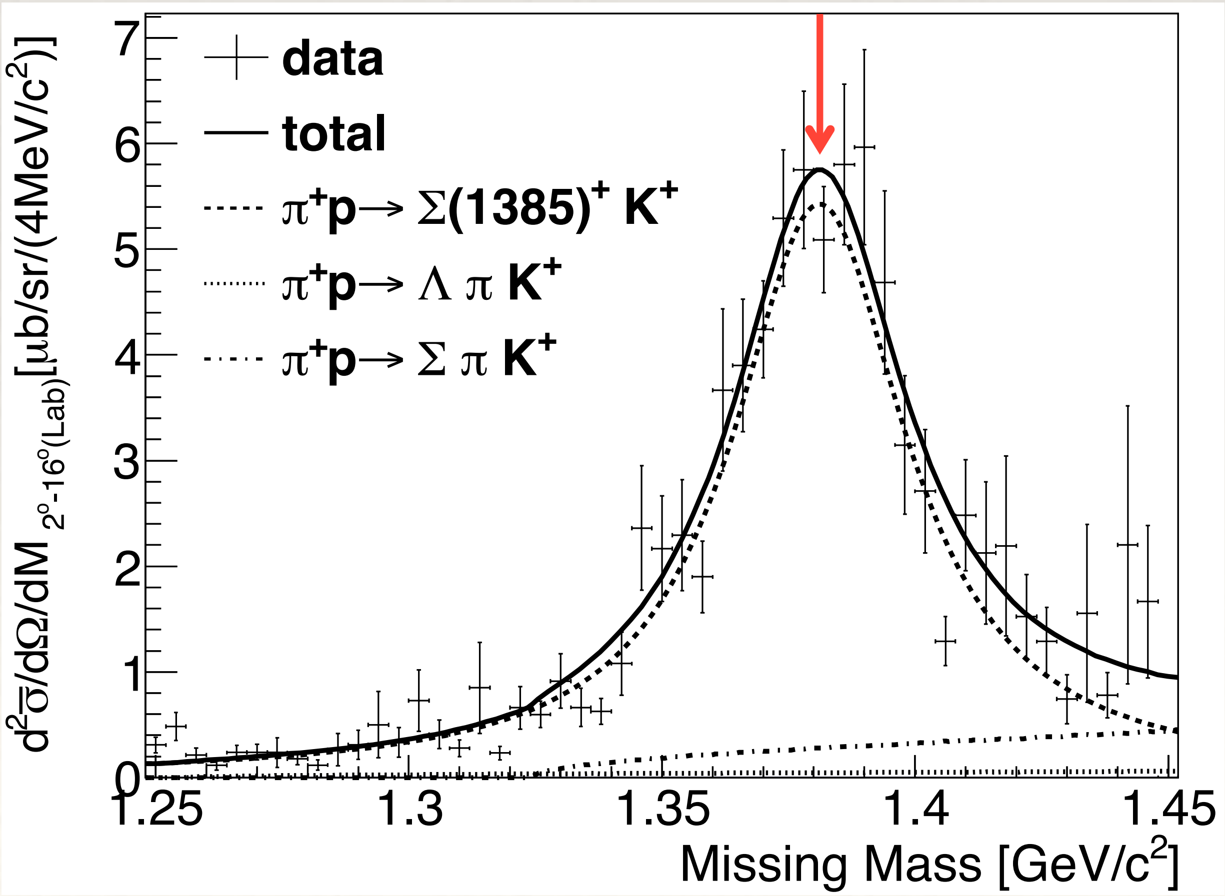


p(π^+,K$^+$)Σ^+/Σ^* @1.69 GeV/c

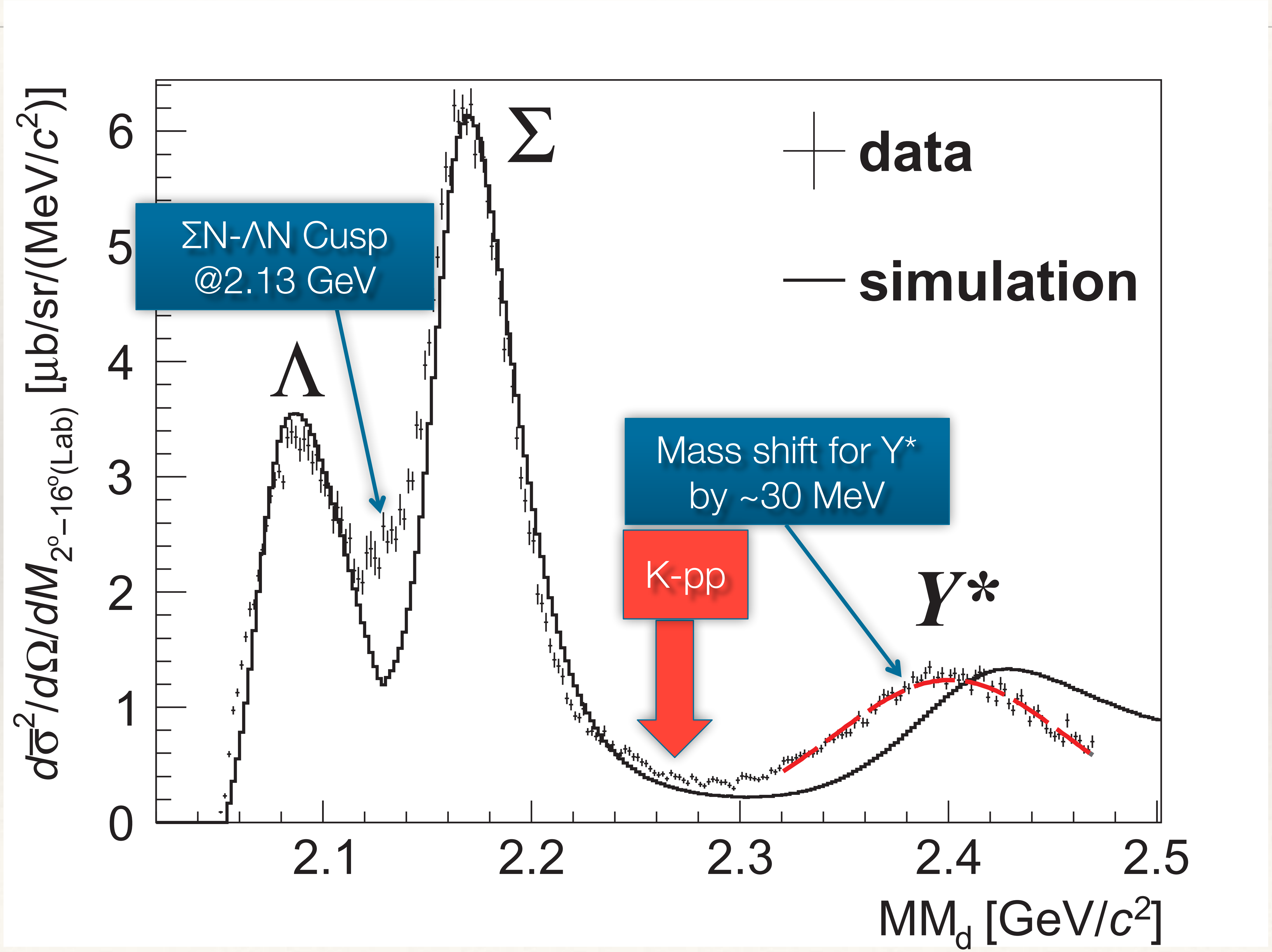
- Σ^+ and $\Sigma^+(1385)$: mass & width are consistent with PDG
  - Δm_{FWHM}=2.8±0.1 MeV / c^2



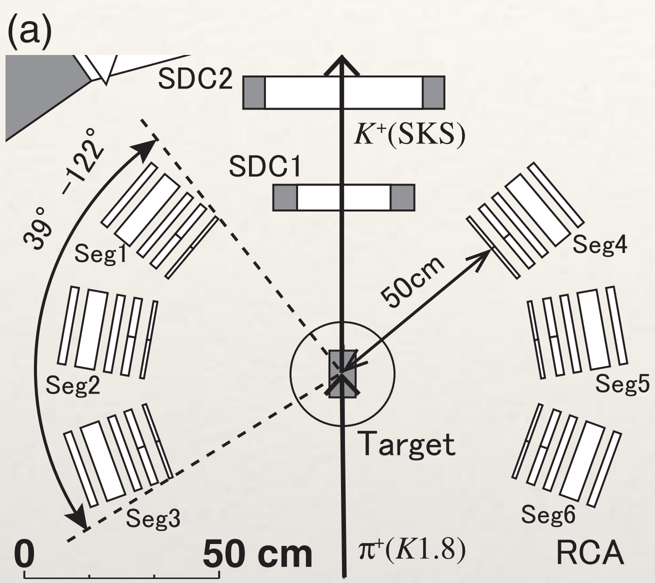


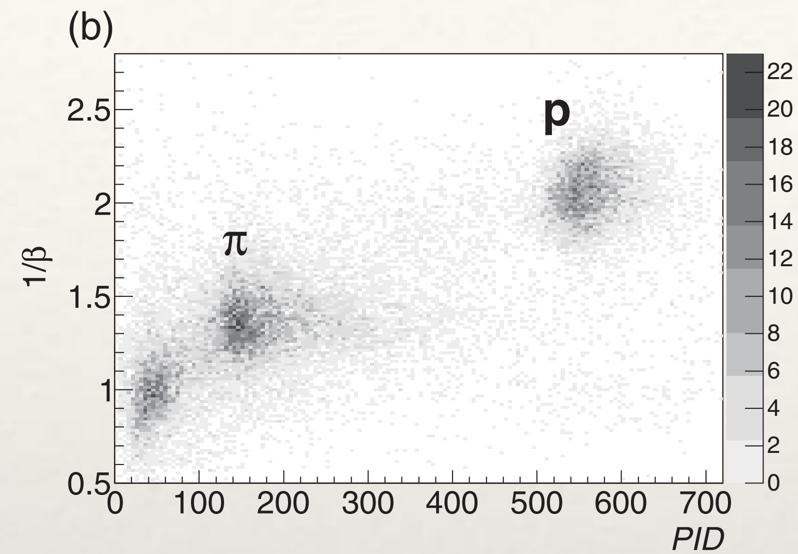


Measured d(π^+,K$^+$)X spectrum



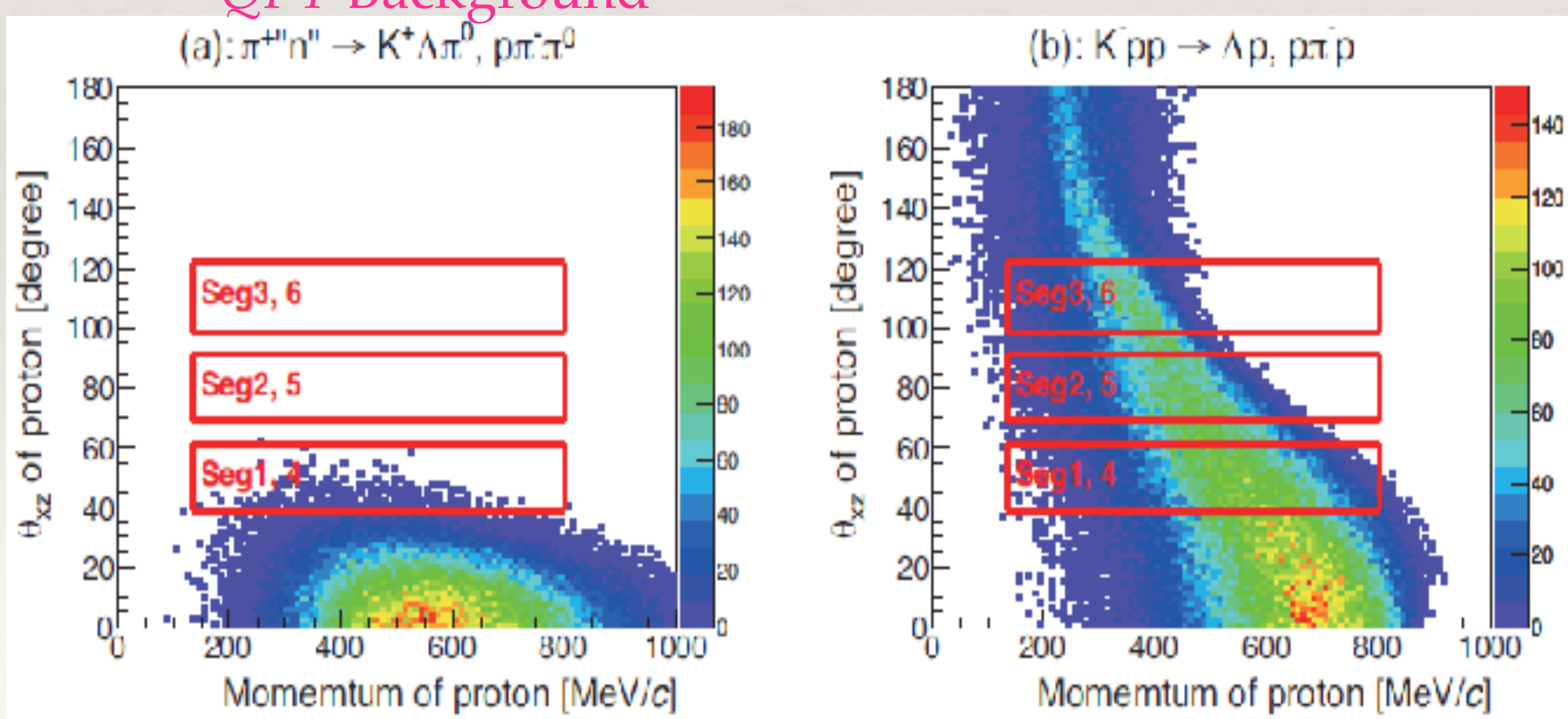
Range counter for Proton tagging





- Range Counter Arrays (RCA)
  - 5 layers(1+2+2+5+2 cm) of Plastic scinti.
  - 39-122 deg. (L+R)
  - 50 cm TOF → β_p

QFY Background

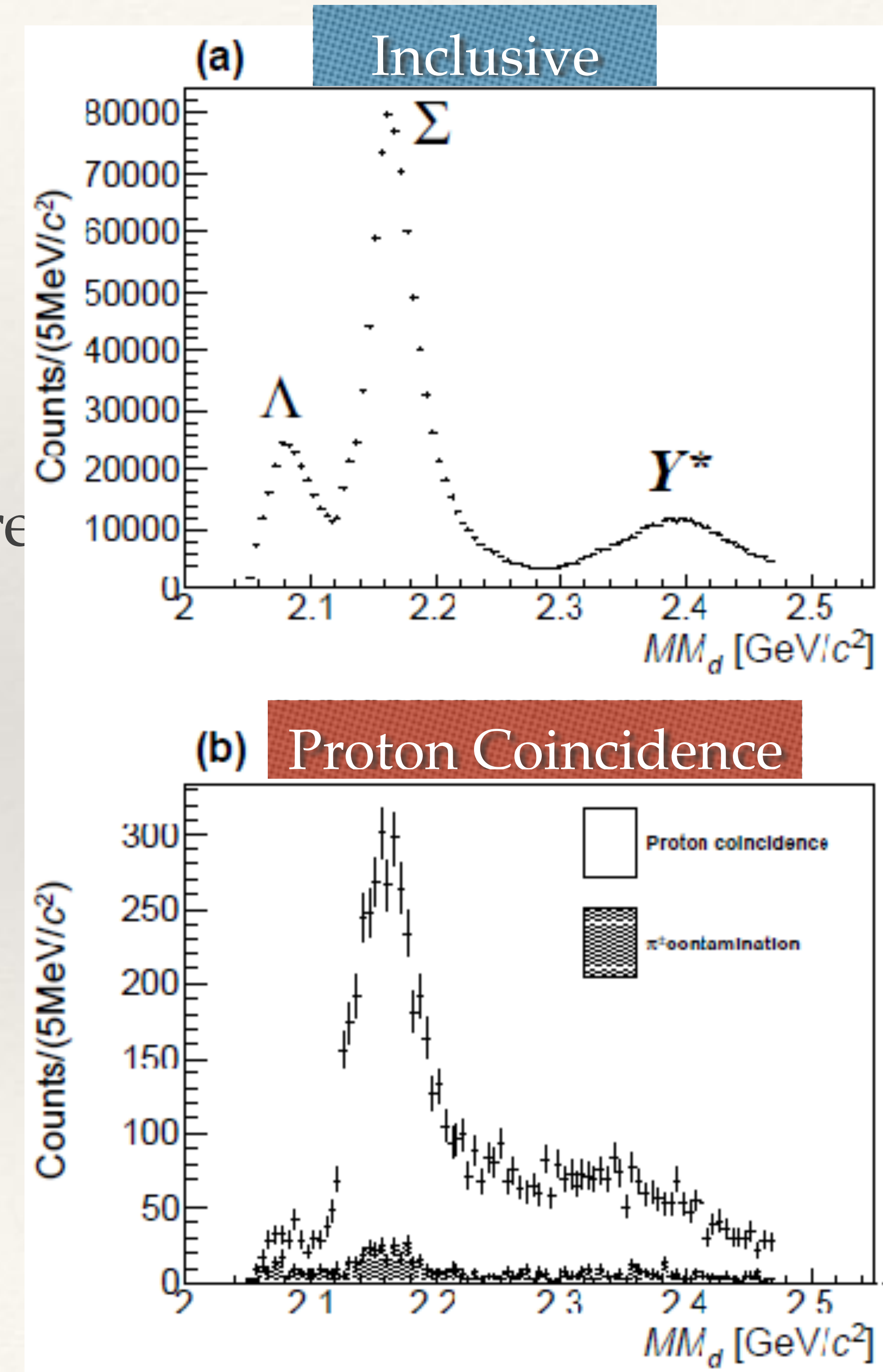


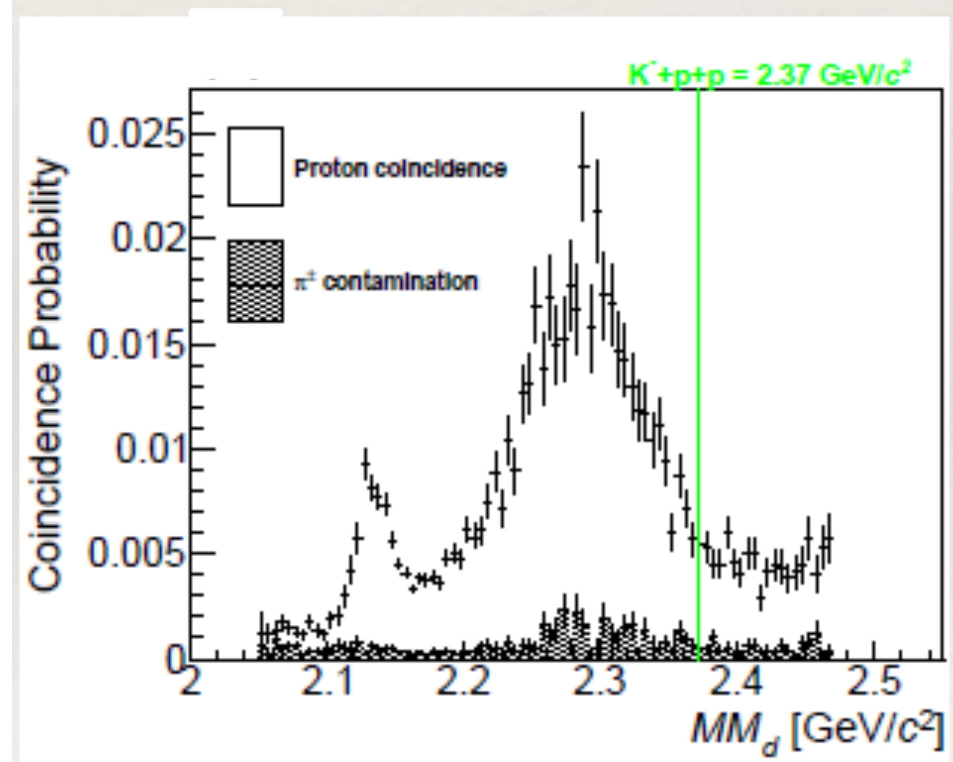
K-pp Signal

Coincidence Study

Proton mom. ≥250 MeV/*c*

- QFΛ, QFΣ, QFY*s are suppressed as expected !!

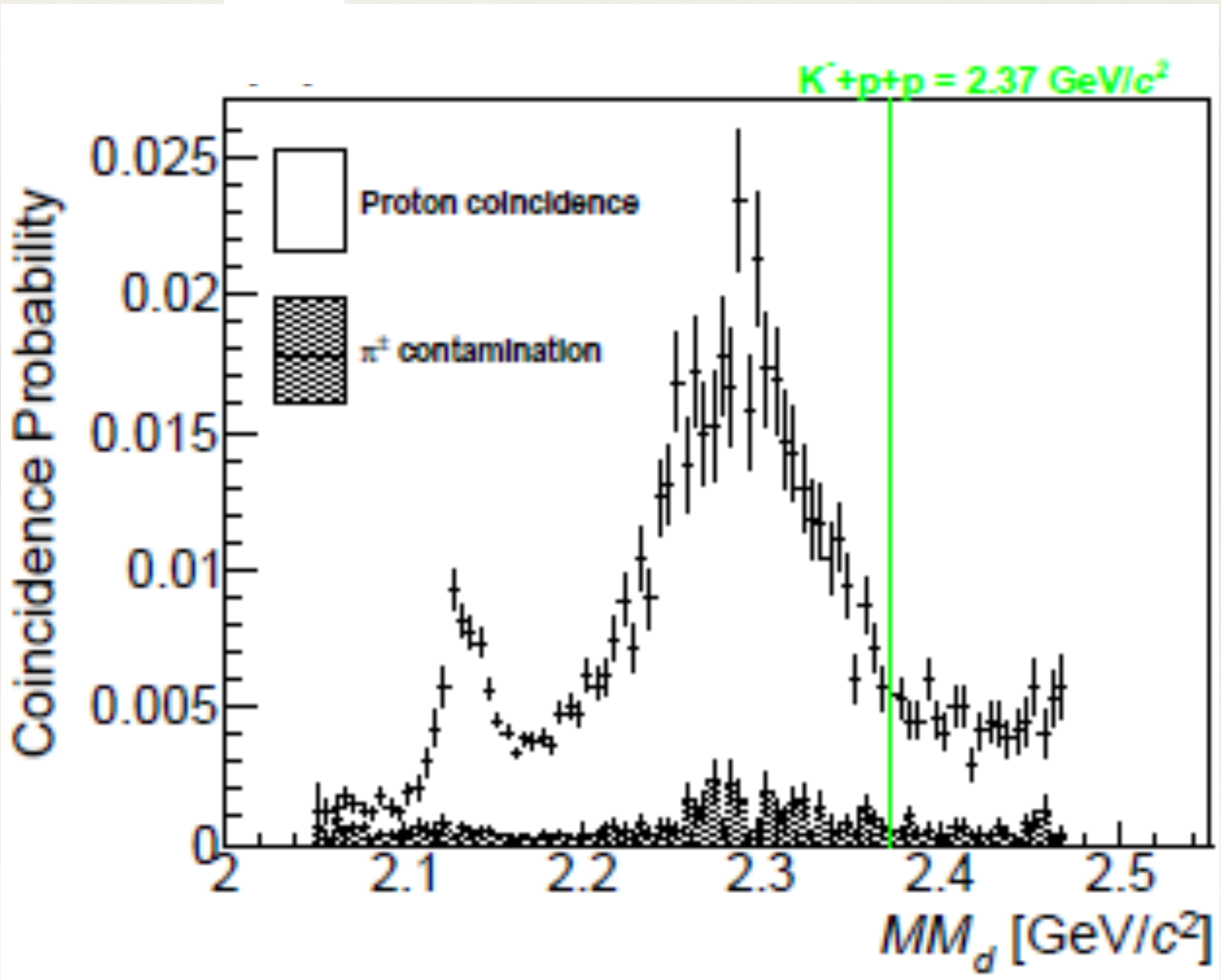




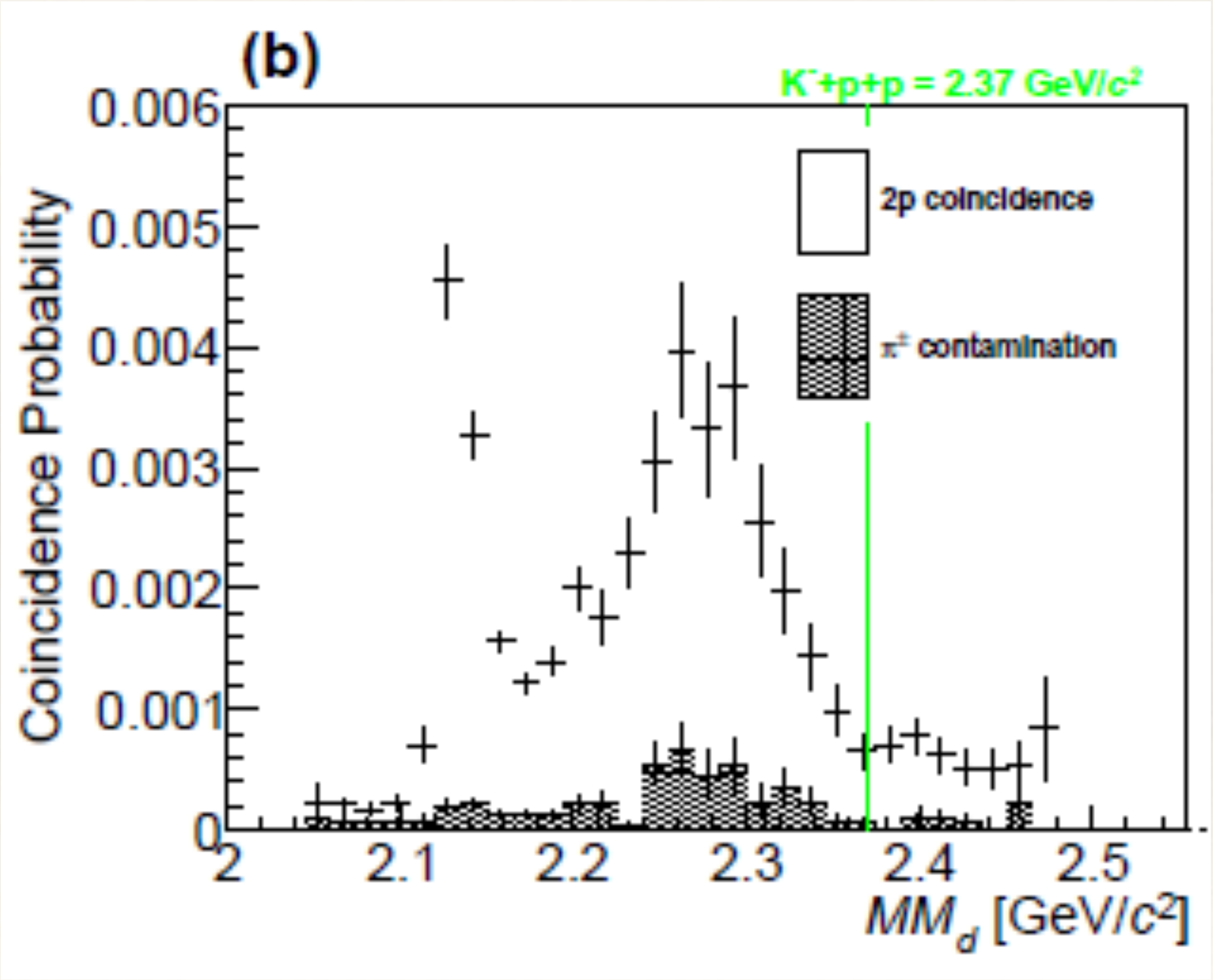
- What's left ?
  - Y, Y* +N→p+X

One-proton coincidence

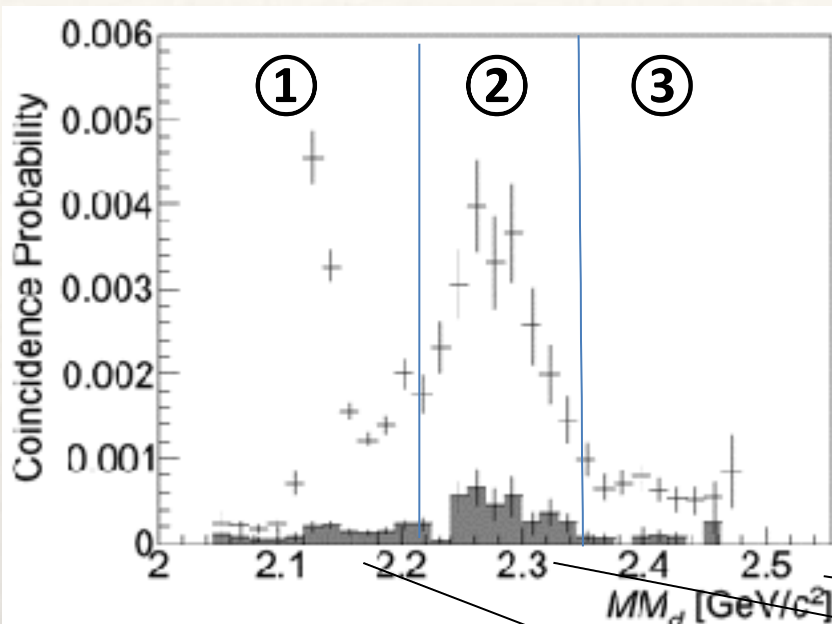
- Coincidence Probability(MM)
  = One-proton coincidence(MM) / Inclusive(MM)
  - Enhancement near the ΣN threshold (2.13 GeV / c^2)
  - Broad bump at ~2.28 GeV / c^2



Two-proton coincidence

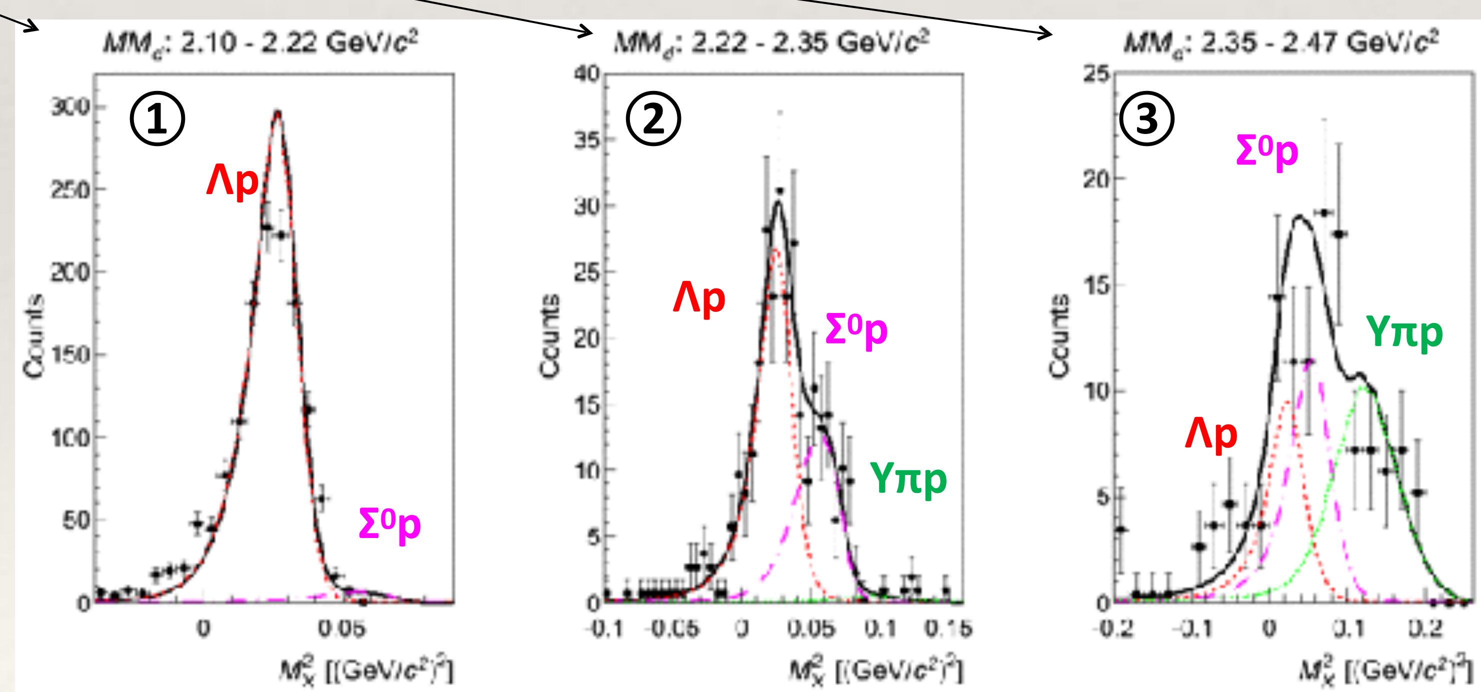


Two-proton coin. & Decay mode



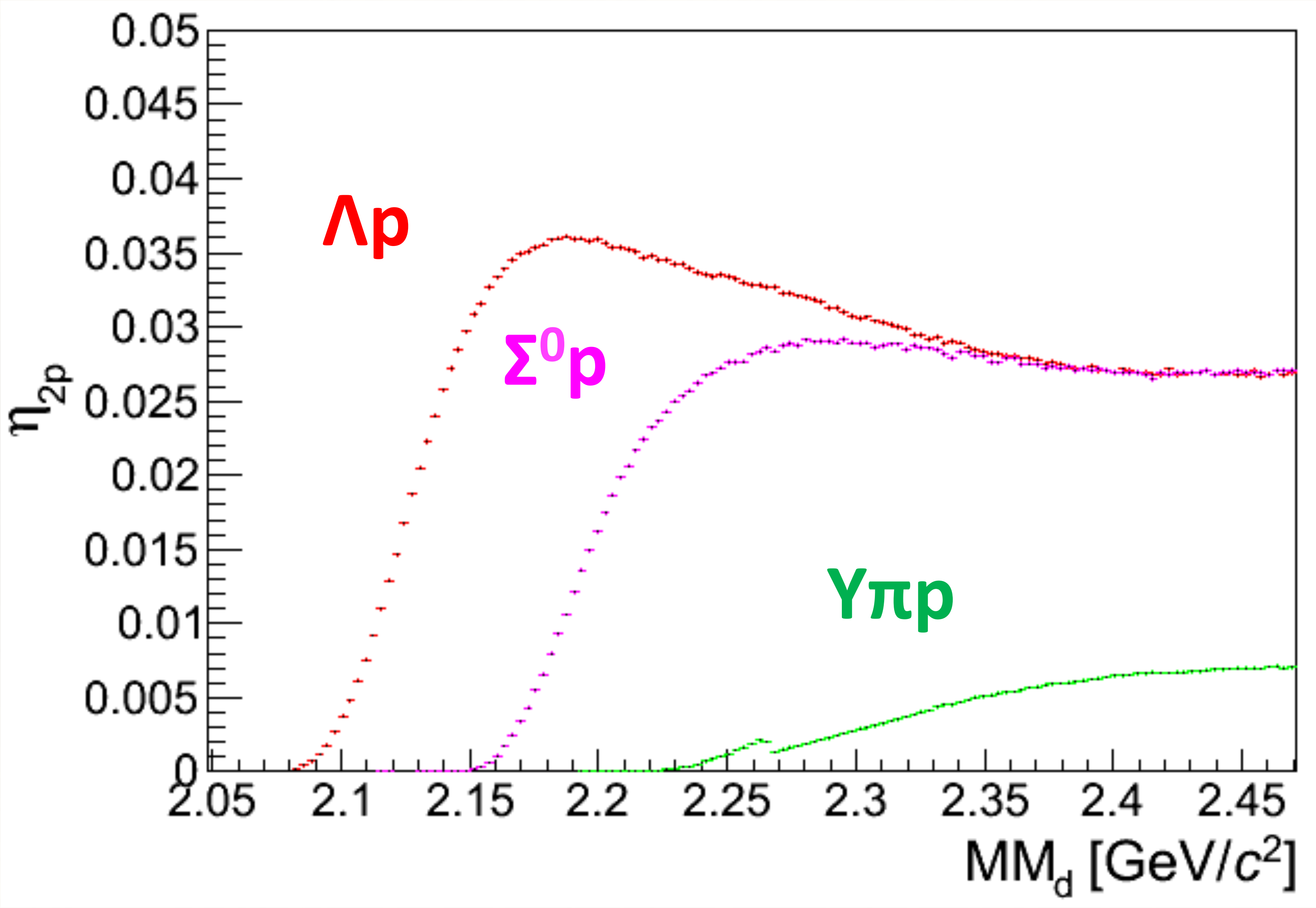
- Two-protons in the final state :
  $K^-pp \rightarrow$ Λp, Σ^0p, $Y\pi$p
  ppπ, pp$\pi\gamma$, pp$\pi\pi(\gamma)$
- d(π^+,K$^+$pp)X

+ Data
— X = π (FS: Λp)
— X = $\pi\gamma$ (FS: Σ^0p)
— X = 2$\pi(\gamma)$ (FS: $Y\pi$p)
— Sum



Kinematically almost-complete measurement !

Mass-acceptance for each decay mode

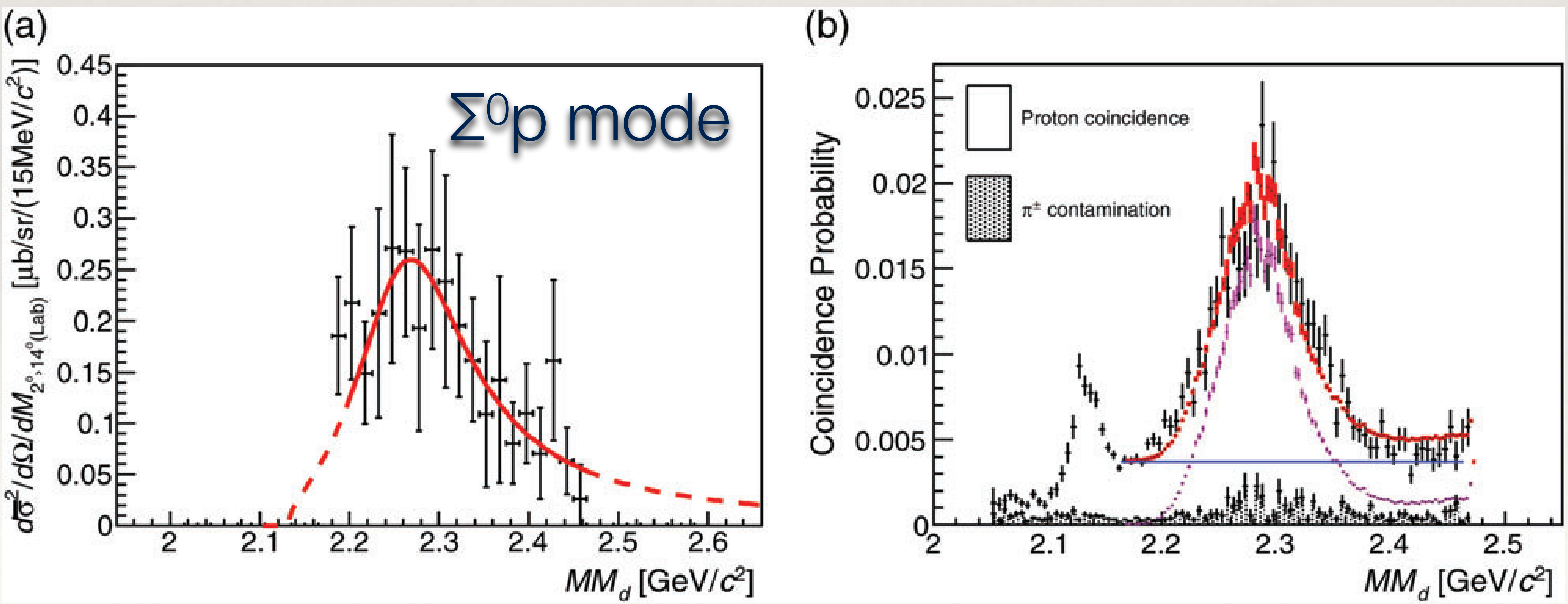


$K^{-}pp$-like Structure

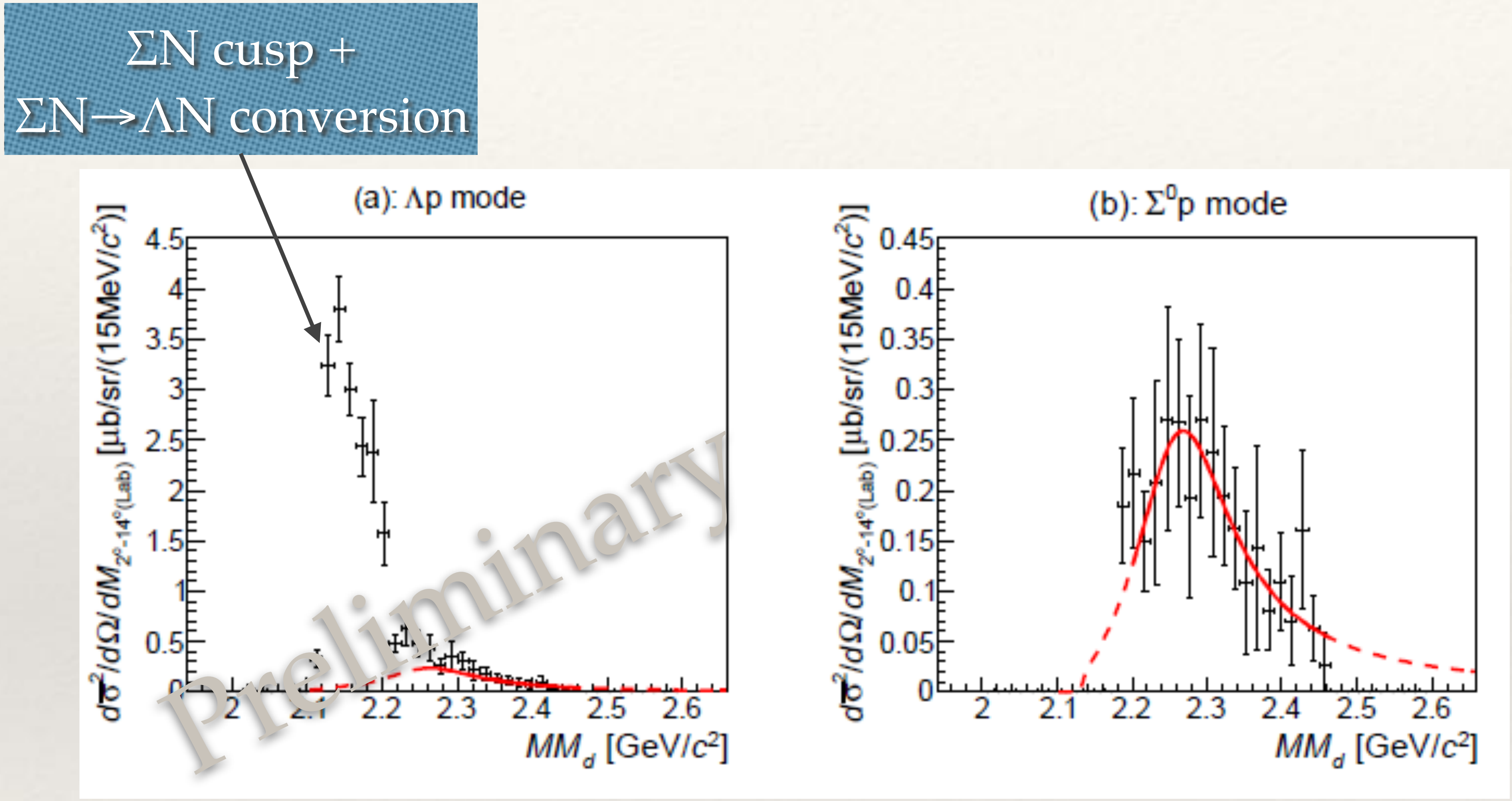
- Mass : $2275^{+17}_{-18}(\text{stat.})^{+21}_{-30}(\text{syst.})\ \text{MeV}/c^2$
- Width : $162^{+87}_{-45}(\text{stat.})^{+66}_{-78}(\text{syst.})\ \text{MeV}$

Relativistic Breit-Wigner

- Binding Energy $95\ ^{+18}_{-17}\ (\text{stat.})\ ^{+30}_{-21}\ (\text{syst.})\ \text{MeV}$



Λp/Σ⁰p Branching Fraction



$$\frac{\Gamma_{\Lambda p}}{\Gamma_{\Sigma^0 p}} = 0.92^{+0.16}_{-0.14}(stat)^{+0.60}_{-0.42}(syst)$$

$$\frac{d\sigma}{d\Omega}_{K^- pp \to \Sigma^0 p} = 3.0 \pm 0.3(\mathrm{stat})^{+0.7}_{-1.1}(\mathrm{syst})\mu\mathrm{b/sr}$$

$$\frac{d\sigma}{d\Omega}_{\Lambda(1405)} = 36.9\ \mu\mathrm{b/sr}$$

$$\frac{d\sigma}{d\Omega}_{K^- pp \to \Lambda p/\Sigma^0 p} \Big/ \frac{d\sigma}{d\Omega}_{\Lambda(1405)} \approx 15.7\%$$

E15: ^{3}He(K$^-$, pΛ)n

Y. Sada et al., PTEP 2016, 051D01.

- Λp(ppπ$^-$) in CDS.
  $\sigma_{\Lambda p}$~10 MeV
- "n" in missing-mass
  σ_n~40 MeV

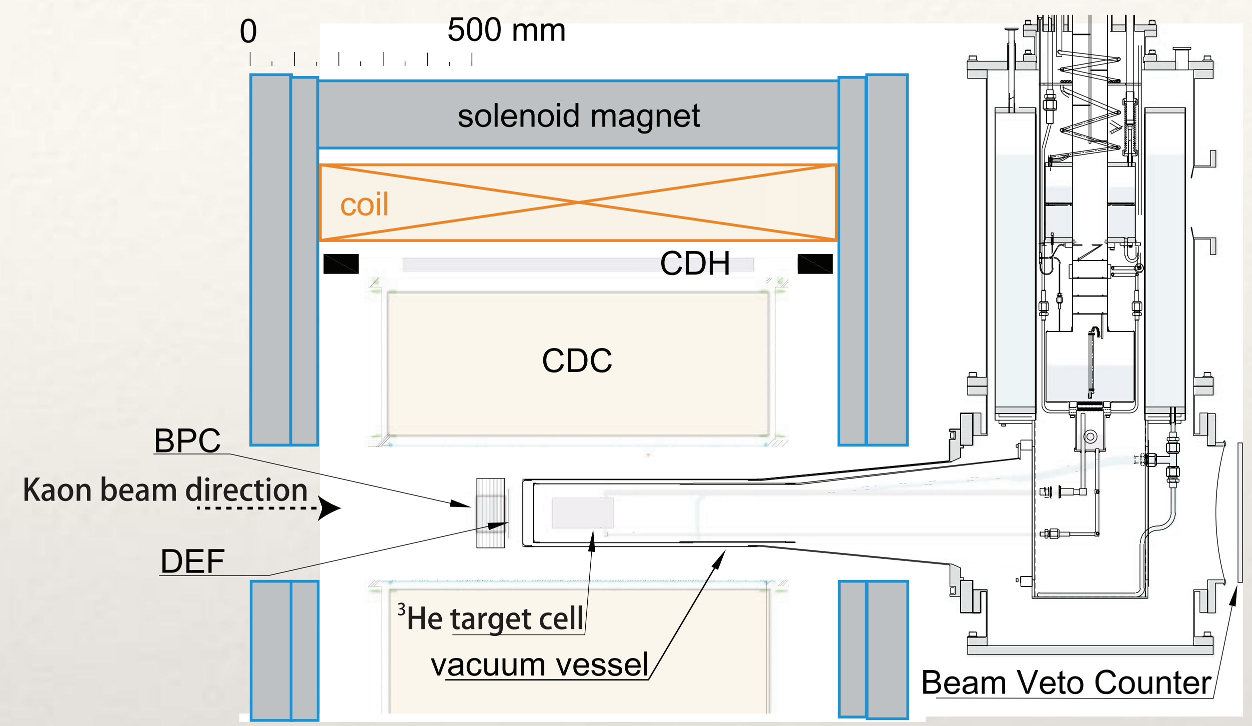
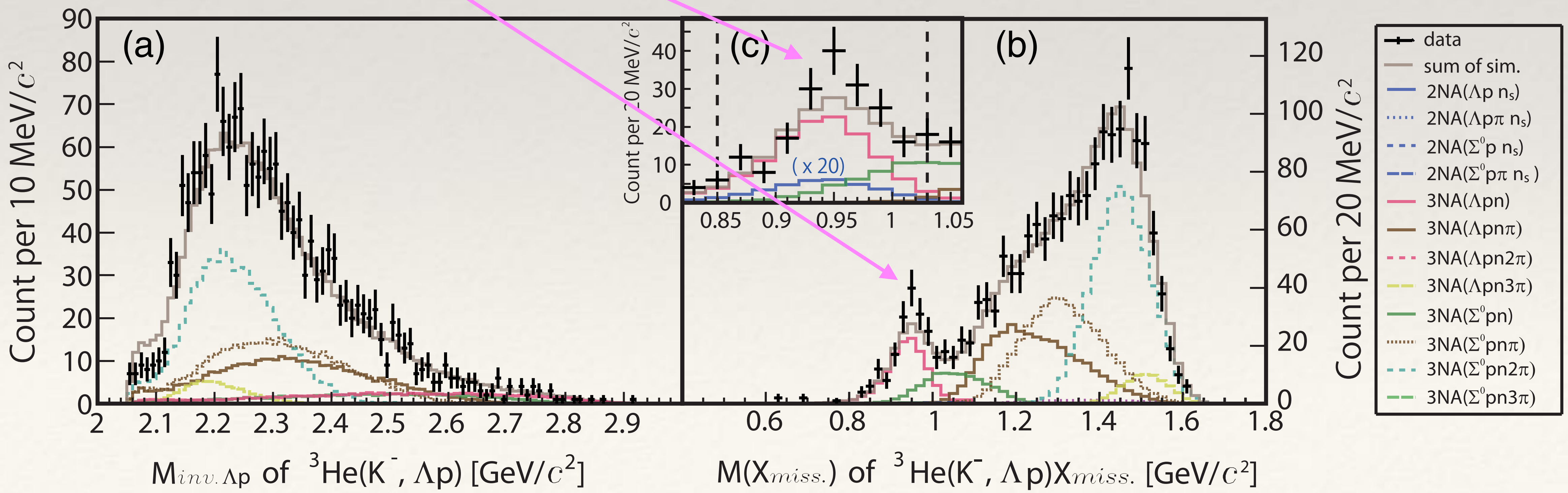
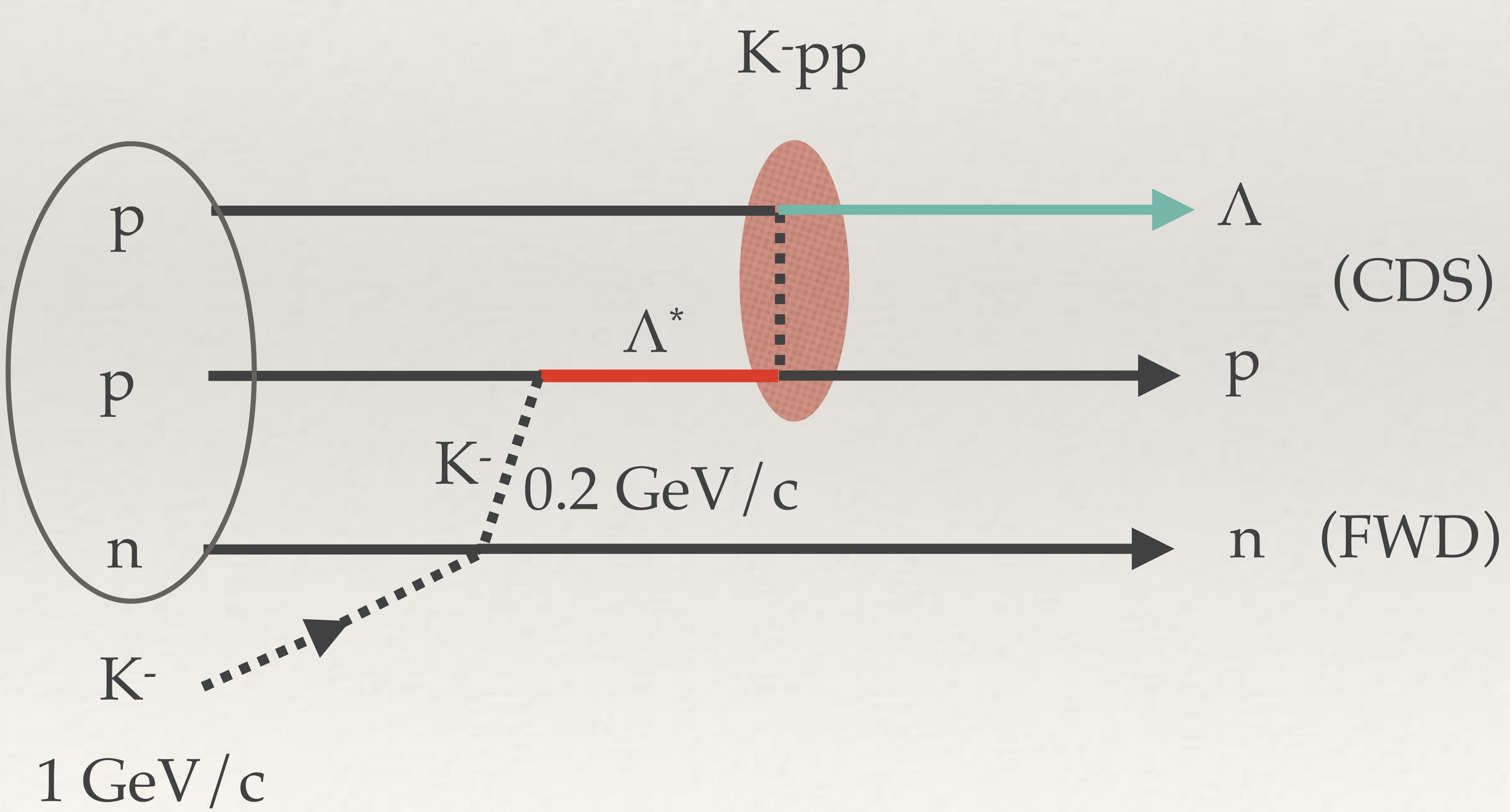


Fig. 1. Schematic diagram of detectors in the CDS and of the target system [22].



$K^{-}pp$ Production through Λ^*

- $K^{-}+n \rightarrow n+K^{-}$; $1 GeV/c \rightarrow 0.2$ GeV/c
- $K^{-}+p \rightarrow \Lambda^*$, $\Lambda^*+p \rightarrow (K^{-}pp) \rightarrow \Lambda+p$

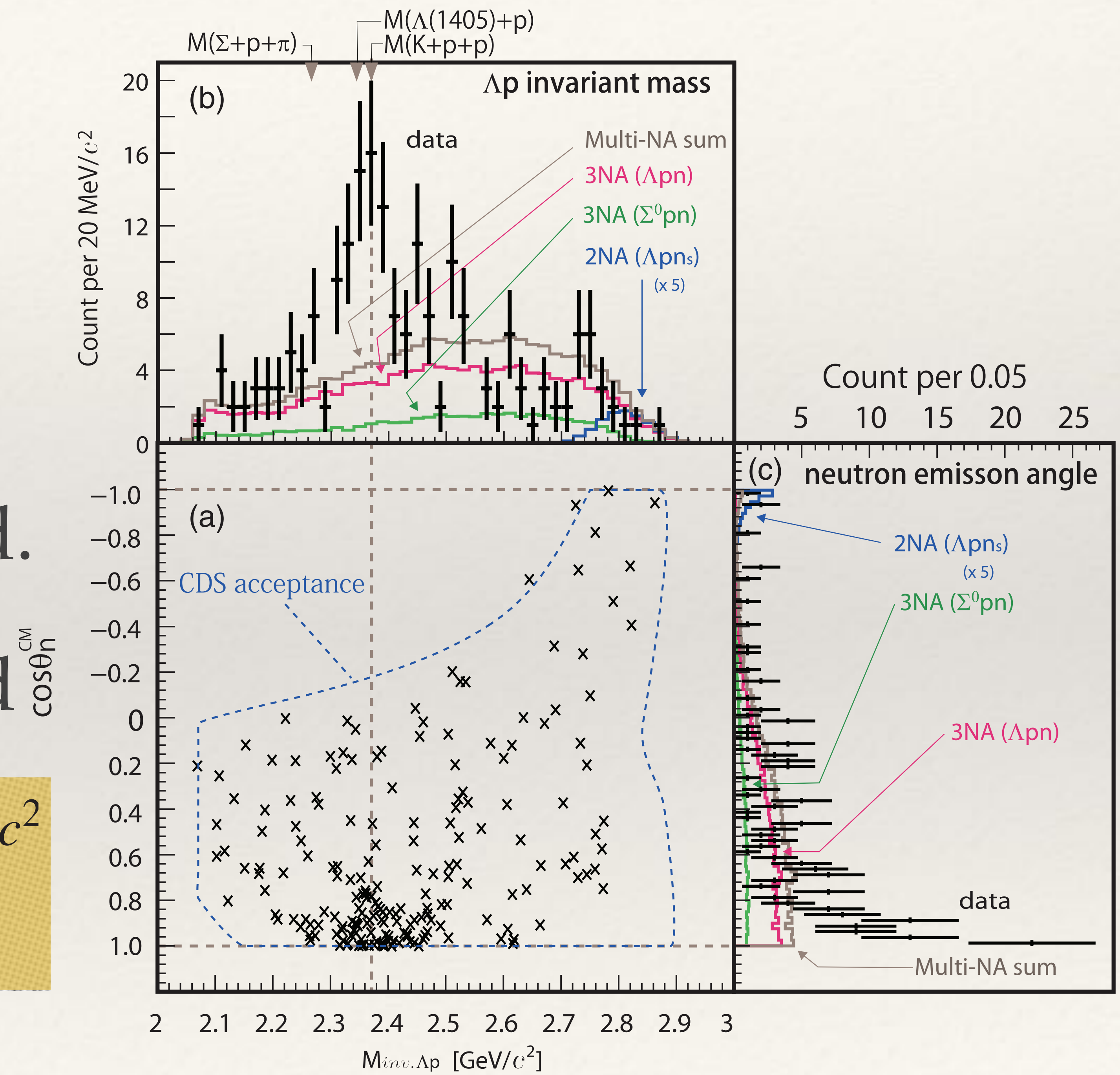


pΛ vs. "n"

- A uniform distribution in 3-body phase space ?!

  +

- A structure near the K+p+p threshold.
  - "n" in the very forward



$$M_X = 2355^{+6}_{-8}\ (\text{stat.}) \pm 12\ (\text{syst.})\,\text{MeV}/c^2$$

$$\Gamma_X = 110^{+19}_{-17}\ (\text{stat.}) \pm 27\ (\text{syst.})\,\text{MeV}/c^2$$

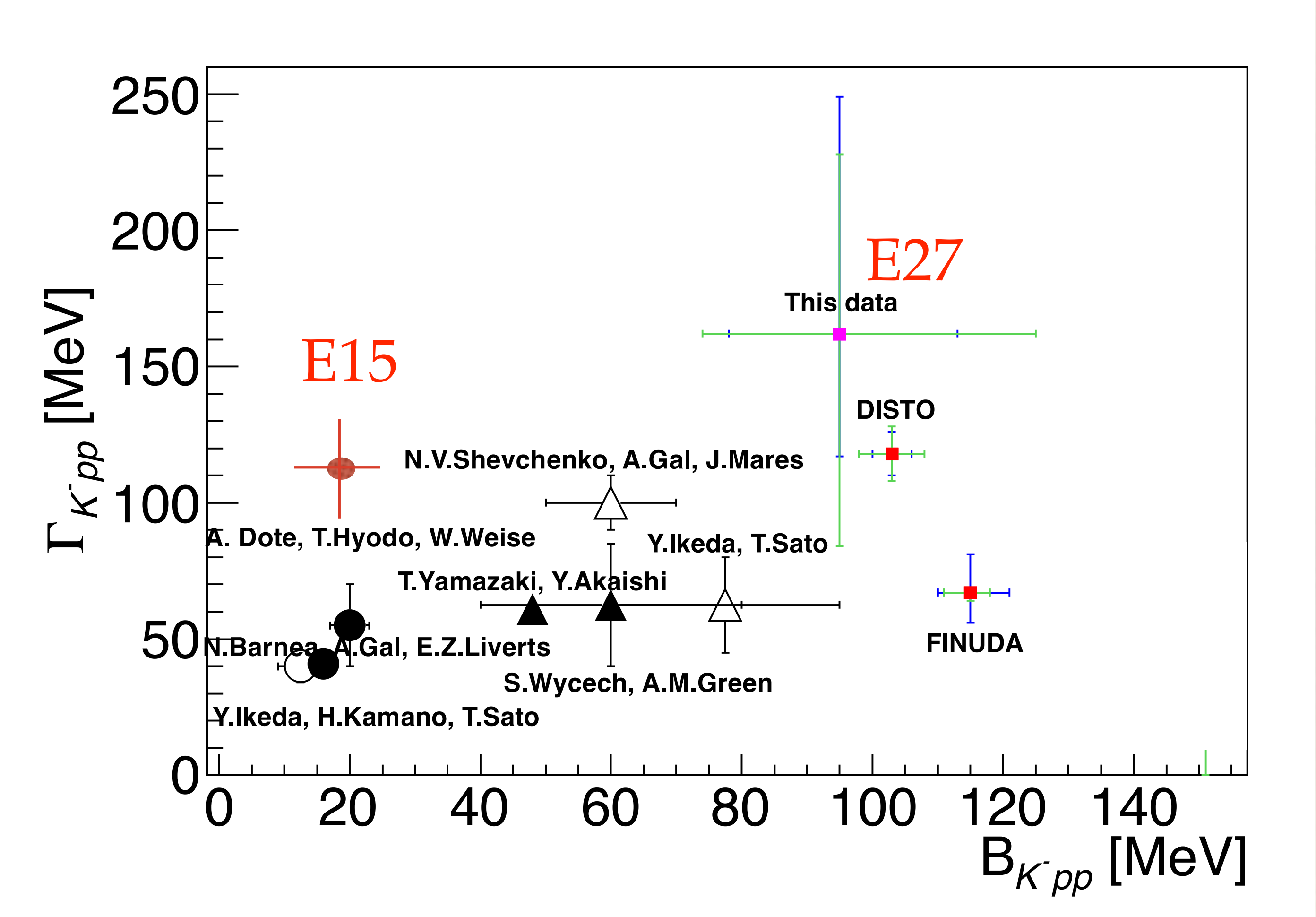
$$\frac{d^2\sigma_X}{dM_{\text{inv.}\Lambda p}\,dq_{\Lambda p}} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{\text{inv.}\Lambda p} - M_X)^2 + (\Gamma_X/2)^2} \times \left|\exp\left(-q_{\Lambda p}^2/2Q_X^2\right)\right|^2$$

Remarks

- $\Lambda(1405)$ production seems to be necessary,
  - (OK for DISTO, HADES, J-PARC E27; △ for FINUDA, ? for E15)
    - but, not enough !
- Need to understand the $\Lambda^*(E)p \rightarrow K^-pp$ dynamics
    - $\rightarrow$sensitivity of the measurements
      7% of $\Lambda(1405)$ in E27 $\Leftrightarrow$ < 40% in HADES

Discussion on "*K⁻pp*"

- B(FINUDA)>B(DISTO)~B(E27) » B(E15)
  115 100 95 15
  - We have two states ?
- Width is broad(> 70 MeV)
  - $\Gamma_{Mesonic}$~50 MeV
  - $\Gamma_{Non\text{-}Mesonic} > \Gamma_{Mesonic}$?



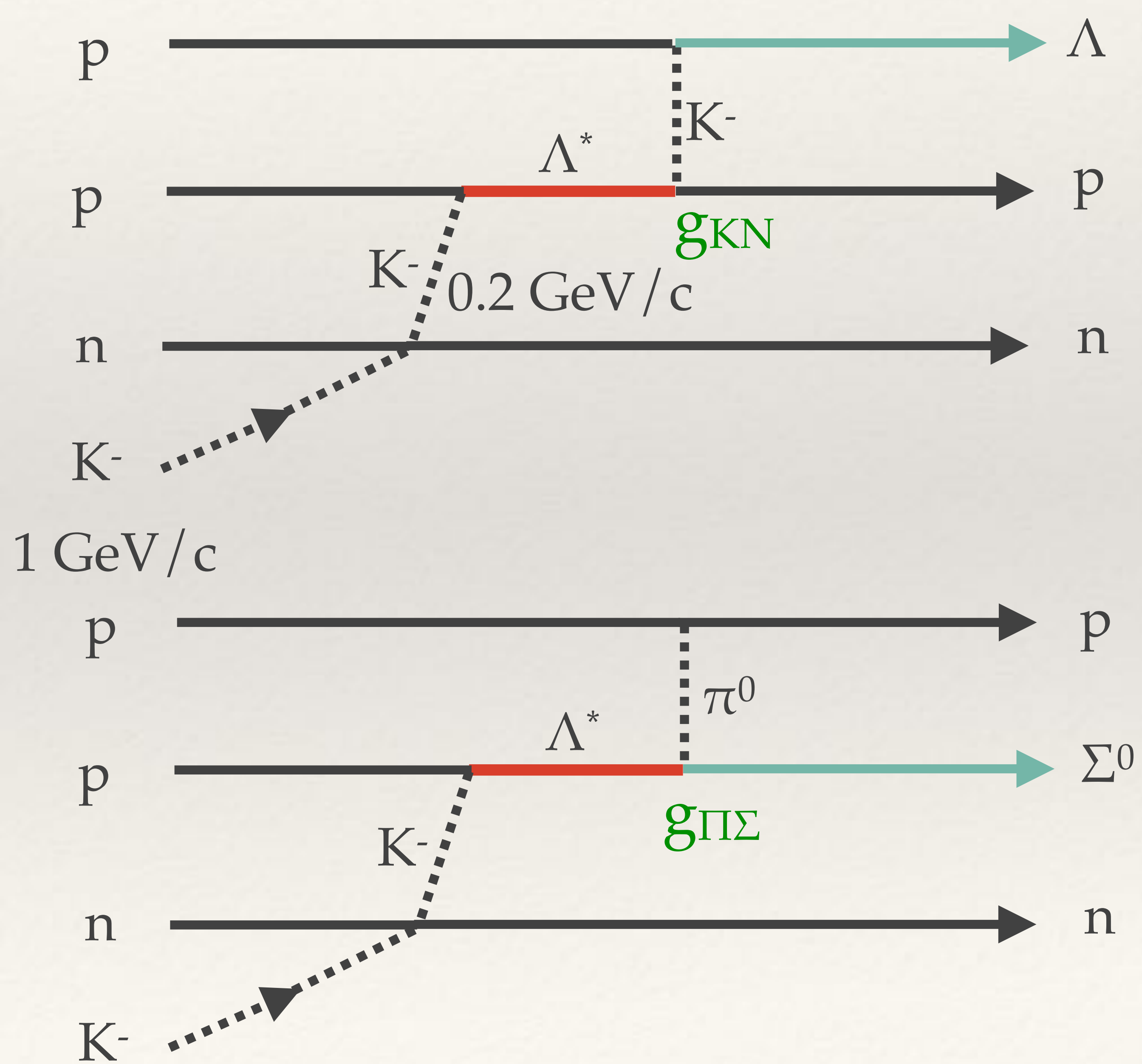
Mysteries of *K^-pp*

- Main decay mode is theoretically expected to be $\Sigma\pi N$ channel.
    - *if B>100 MeV, $\Sigma\pi N$ mode is closed.*
- *However …*
    - No observations in $\Sigma\pi N$ channel.
    - Signals are in non-mesonic (Λp, $\Sigma^0 p$).
- Binding energies:
    - Two states ? Shallow(E15) and Deep(E27, DISTO).
    - Momentum Transfer ~0.2 GeV/c ~0.6 GeV/c

Role of $\Lambda(1405)$ as a doorway

- $\Gamma_{\Lambda p}/\Gamma_{\Sigma p}$ ~0.92 (E27),
  =1.2 (ChUA)
  - depends on $g_{KN}/g_{\pi\Sigma}$ »1.
  - $\Gamma_{Mesonic} : \Gamma_{Non\text{-}Meso.}$~7 : 3.
- $\Lambda^* \rightarrow \Sigma^*$
  - $\Gamma_{\Lambda p}/\Gamma_{\Sigma p}$ »1
  - $\Gamma_{Mesonic} : \Gamma_{Non\text{-}Meso.}$~1 : 1.

T. Sekihara et al., PRC 86 (2012) 065205.
PRC 79 (2009) 062201(R).



Other possibilities

- Dibaryon as $\pi\Lambda N$-$\pi\Sigma N$ bound states

  H. Garcilazo, A. Gal, NPA 897 (2013) 167-178.

  $Y=1, I=3/2, J^{\pi}=2^{+}$

- $\Lambda(1405)N$ bound state T. Uchino et al., NPA868 (2011) 53.

  $I=1/2, J^{\pi}=0^{-}$; not so large binding

- A lower $\pi\Sigma N$ pole of "$K^{-}pp$"

  a broad resonance near the $\pi\Sigma N$ threshold

  A. Dote, T. Inoue, T. Myo, PTEP (2015) 043D02.

- Enhanced $\bar{K}N$ interaction due to

  Partial restoration of Chiral symmetry;

  S. Maeda, Y. Akaishi, T. Yamazaki, Proc. Jpn. Acad., B 89 (2013) 418-437.

Summary

- Two measurements suggest two bound states: Shallow(~20 MeV) and Deep(~100 MeV).
  - At least, there exists a $K^{-}pp$ bound state.
  - Whether both states co-exist ?
    - Deep : $K^{-}pp_{gs}$, and Shallow : $K^{-}pp_{excited}$?
    - or
    - Shallow : $K^{-}pp_{gs}$, and Deep : $\pi\Sigma N$ bound state ?
- Measure the Spin-Parity and Isospin of $K^{-}pp$!