

ハイパー核生成とチャネル結合

Production of Hypernuclei with coupled channels

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ハイパー核物理の課題

➤ 原子核深部を探る

— ハイペロンはパウリ排他律を受けないためプローブ(探針)となる

➤ Impurity Physics (不純物物理)

— “糊”としての役割

— 原子核構造(1粒子運動、殻構造、クラスター構造、集団運動)の変化

➤ Baryon-Baryon Interaction

— YN, YY Interaction based on $SU_f(3)$

— 核力の統一的理解・斥力芯の起源

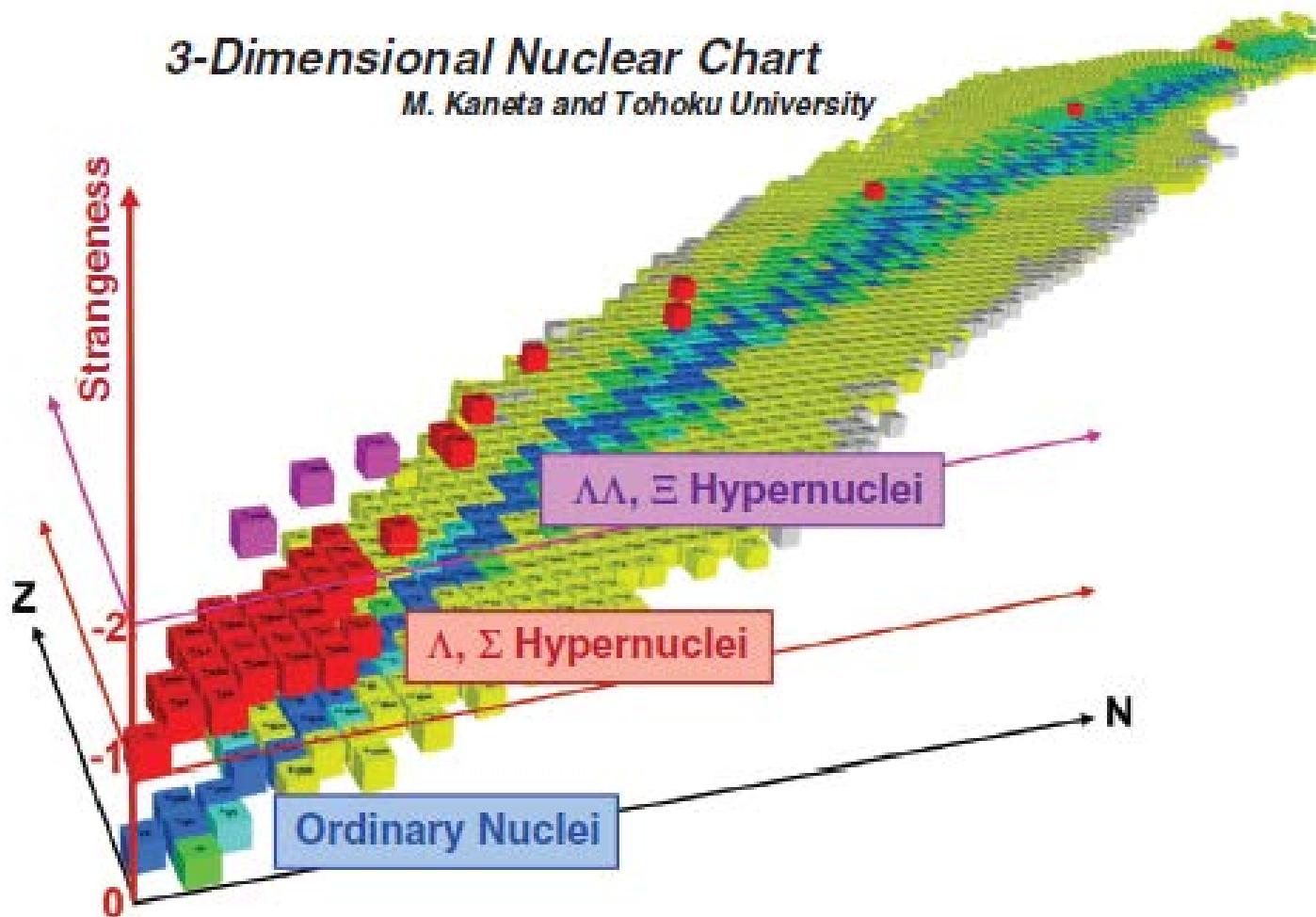
➤ “Exotic” Nuclear Physics

— ストレンジネスが拓く新しい原子核の面白さ

➤ Neutron Starの構造と進化

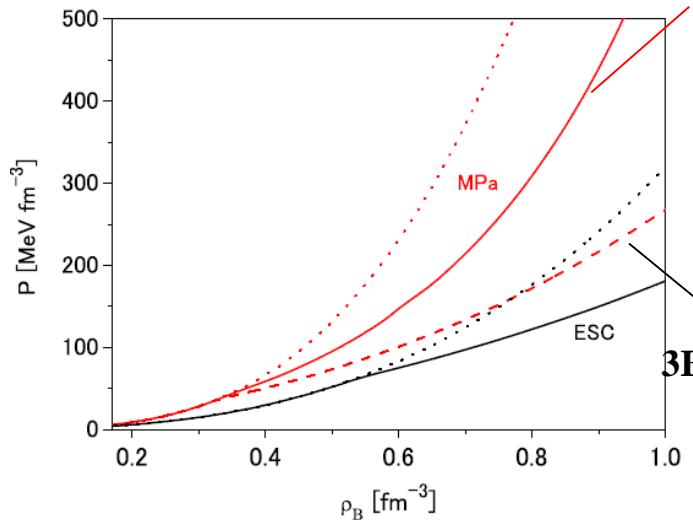
— 高密度核物質への戸口, EOS, 最大質量, 冷却, ...

3-Dimensional Nuclear Chart with Strangeness

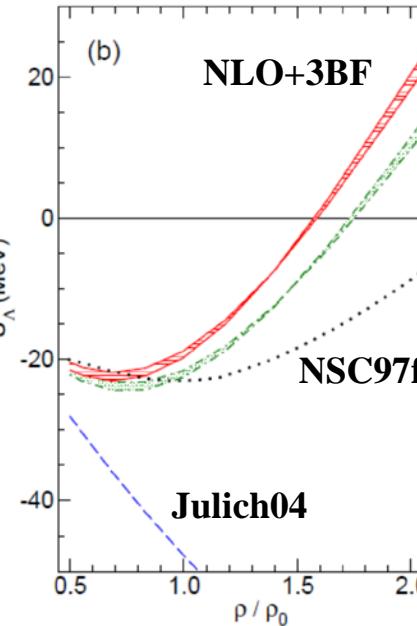
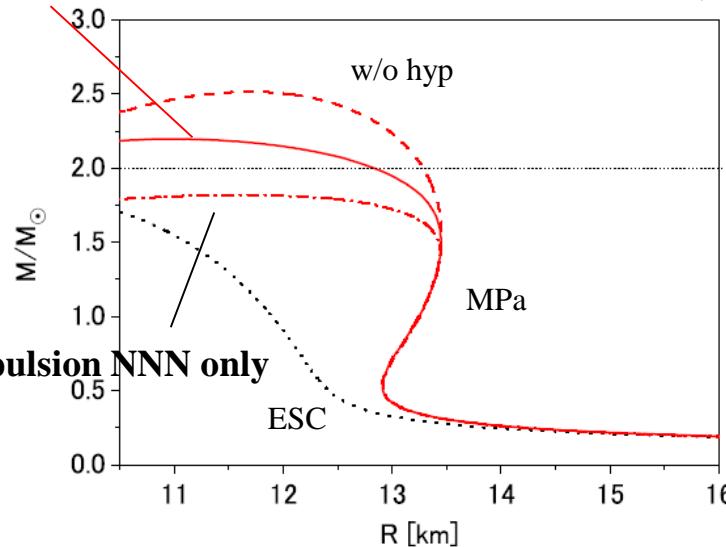


Repulsive MBF in “Hyperon Puzzle”

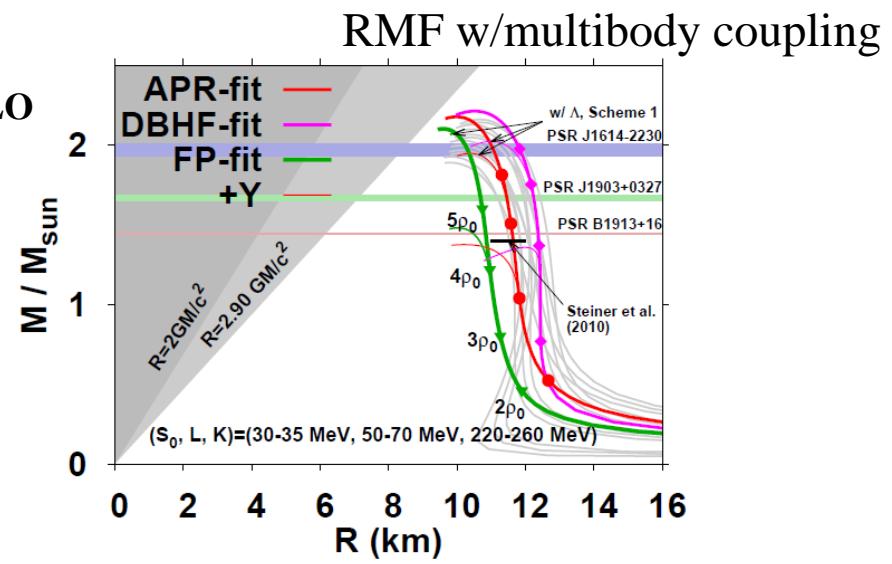
3B/4B repulsion NNN+YNN



Y. Yamamoto, et al., PRC90(2014)045805



Haidenbauer, et al
Eur. Phys. J.
A53(2017) 121.



Ohnishi, et al., SCHDM2017

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Coherent Λ - Σ coupling

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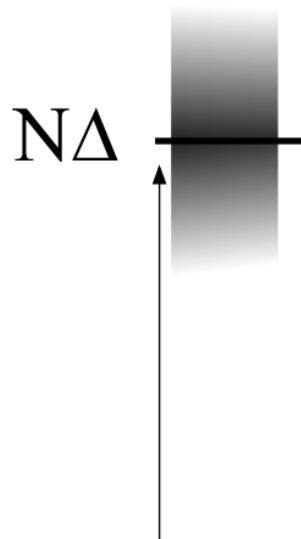
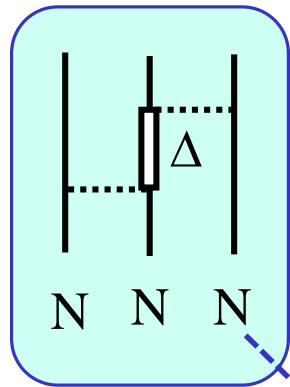


5. Summary

Dynamics in Hypernuclear Systems

Fujita-Miyazawa

3BF



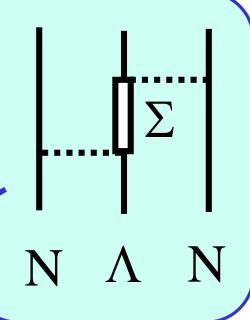
$N\Sigma$

$\sim 72 \text{ MeV}$

$N\Lambda$

$\Lambda N - \Sigma N$
coupling

ΛNN 3BF



$\sim 300 \text{ MeV}$

Nuclei

Hypernuclei

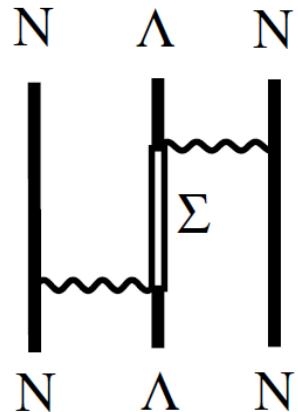
NN

$S = 0$

$S = -1$

- Various effects on the hyperon mixing
- Related to the 3BF in nuclei

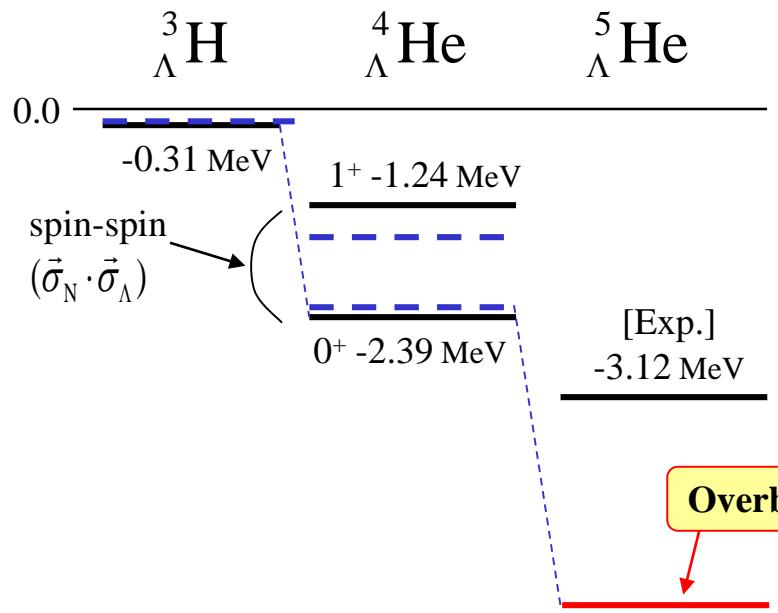
Coherent Λ - Σ coupling



Important role of
the Σ hyperon
in nuclei

Overbinding Problem on s-Shell Hypernuclei

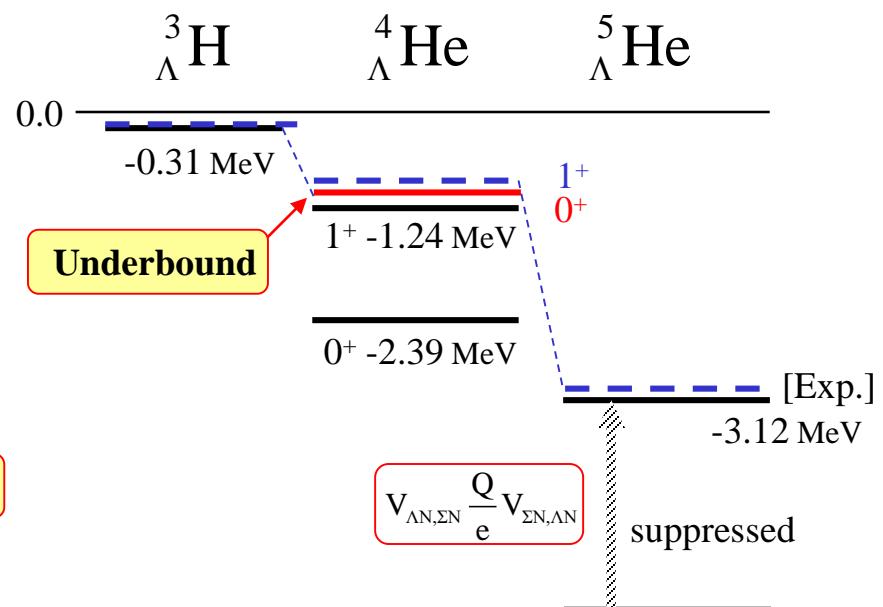
The Overbinding Problem



ΛN single-channel calc.

Dalitz et al., NP **B47** (1972) 109.

The Underbinding Problem



g-matrix calc. with $\Lambda\text{N}-\Sigma\text{N}(\text{D2})$

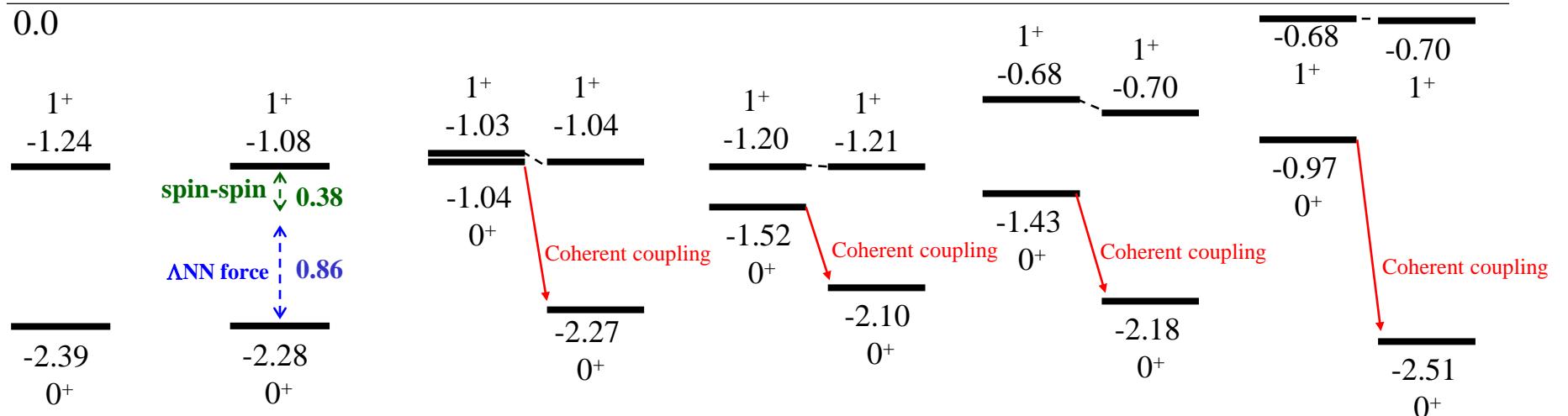
Akaishi et al., PRL **84** (2000) 3539.

		$^4_{\Lambda}H$	
S=1 pairs		1 ⁺	0 ⁺
$\Lambda p \Leftrightarrow -\sqrt{\frac{1}{3}} \Sigma^0 p + \sqrt{\frac{2}{3}} \Sigma^+ n$	$\begin{bmatrix} s_3 = 1 \\ s_3 = 0 \\ s_3 = -1 \end{bmatrix}$	-1/3 +1/3 +1/2	Cancel
$\Lambda n \Leftrightarrow \sqrt{\frac{1}{3}} \Sigma^0 n - \sqrt{\frac{2}{3}} \Sigma^- p$	$\begin{bmatrix} s_3 = 1 \\ s_3 = 0 \\ s_3 = -1 \end{bmatrix}$	+1/2 +1/2 +1/2	Coherently added
Contribution to $U_{\Sigma\Lambda}$		1/2	3/2
Λ - Σ coupling energy		1 : 9	

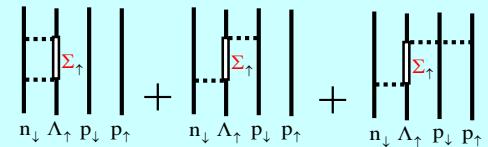
“The 0^+ - 1^+ difference is not a measure of ΛN spin-spin interaction.”

by B.F. Gibson

(unit in MeV) (${}^4_{\Lambda}\text{H}$)



ANN three-body force



${}^4_{\Lambda}\text{He}$

Exp.

phenomenological
 $V_{\text{AN}} + V_{\text{ANN}}$
 $\bar{V} = 6.20$

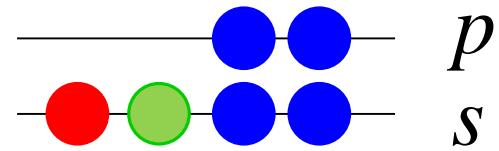
VMC

R. Sinha, Q.N.Usmani,
NPA684(2001)586c

Y. Akaishi, T.Harada, S.Shinmura, Khun Swe Myint,
PRL84(2000)3539

Breuckner-Hartree-Fock

Production of the neutron-rich Λ hypernucleus



(Σ) Λ p n

T. Harada, Y. Hirabayashi, PRC95 (2017) 044610.

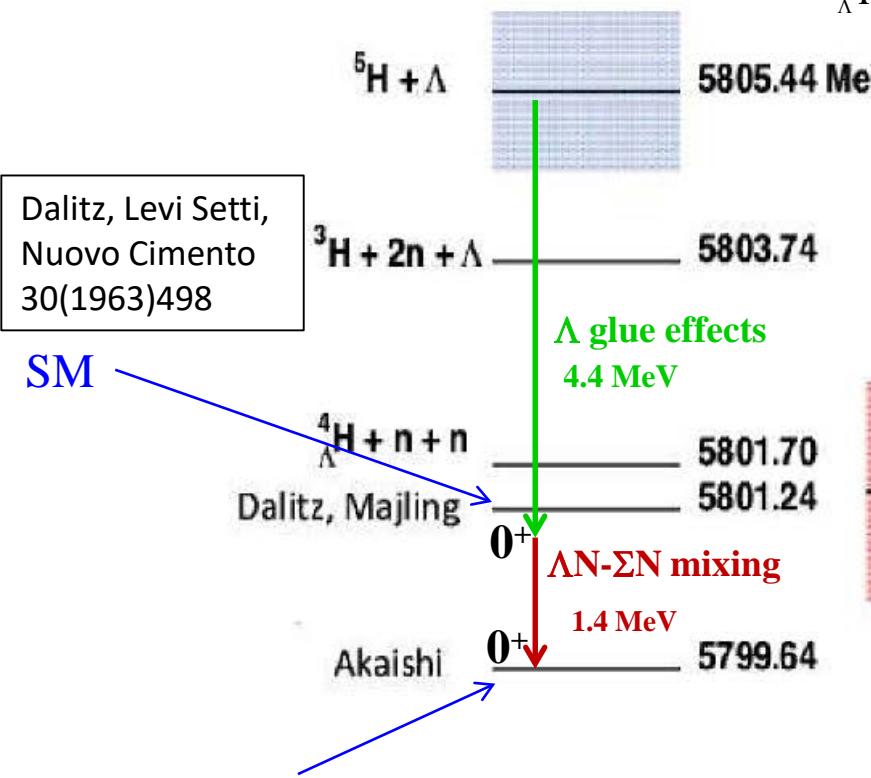
Introduction

- ${}^6_{\Lambda}\text{H}$ is one of the most interesting candidates to investigate neutron-rich hypernuclei; $B[{}^6_{\Lambda}\text{H}(0^+_{\text{g.s.}})] = 5.8 \text{ MeV}$ caused by the coherent $\Lambda\Sigma$ coupling.
Y. Akaishi, Khin Swe Myint, AIP Conf. Proc. 1011 (2008) 277.
- FINUDA collaboration reported a binding energy of $B({}^6_{\Lambda}\text{H}) = 4.5 \pm 1.2 \text{ MeV}$ in ${}^6\text{Li}(K^-_{\text{stop}}, \pi^+)$ reactions.
M. Agnello, et al., PRL. 108 (2012) 042501.
- No peak is observed around the ${}^4_{\Lambda}\text{H} + 2n$ threshold in the ${}^6\text{Li}(\pi^-, K^+) {}^6_{\Lambda}\text{H}$ reaction at $p_{\pi^-} = 1.2 \text{ GeV/c}$ by J-PARC E10 collaboration.
H. Sugimura, Phys. Lett. B729 (2014) 39.
R. Honda, Ph.D. thesis, Tohoku University (2014).

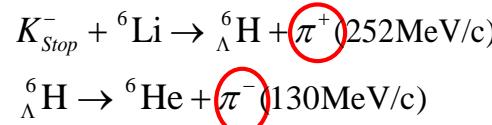
Production of neutron-rich ${}^6_{\Lambda}\text{H}$ hypernucleus

- Double charge-exchange (DCX) reaction
- Coherent $\Lambda\text{N}-\Sigma\text{N}$ mixing in neutron-rich environment

Status

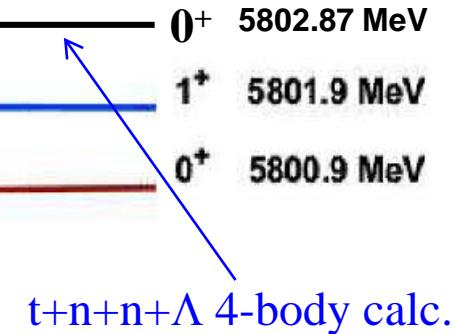
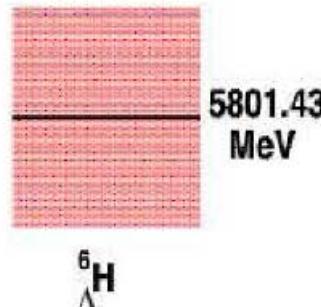


Khin Swe Myint, Akaishi, PTP Suppl.146(2002)599



Agnello et al.,
PRL108(2012)042501

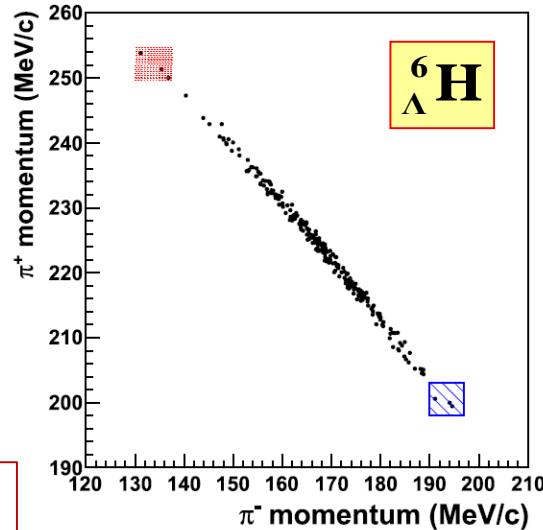
FINUDA Exp.



E. Hiyama et al., NPA908(2013)29

SM+Lambda-Sigma coupling

Gal, Millener, PLB725(2013)445

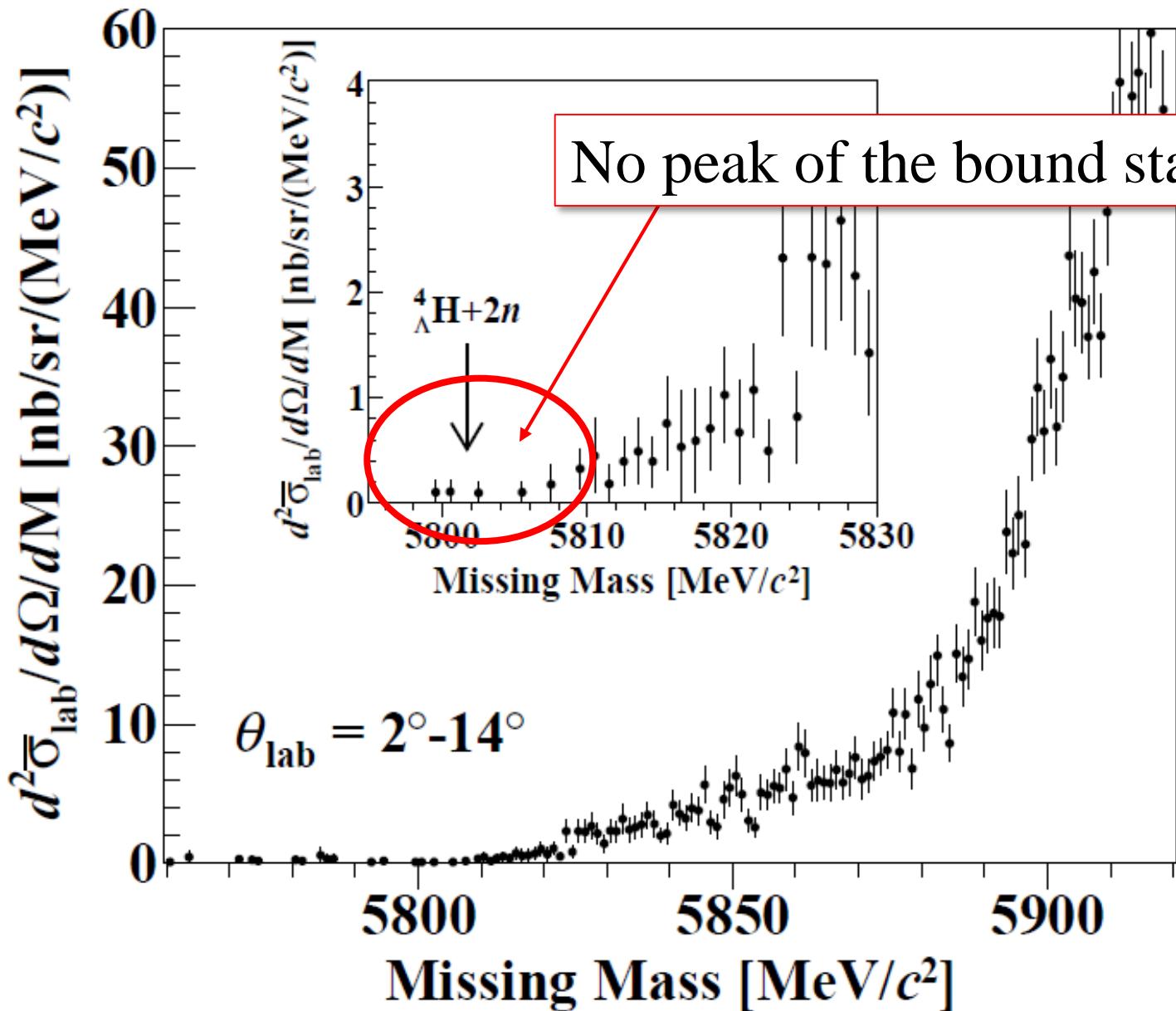


Our Purpose

- We theoretically demonstrate the inclusive spectra of the ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction within a distorted-wave impulse approximation, using a coupled $({}^5\text{H}-\Lambda)$ $+({}^5\text{He}-\Sigma^-)$ model with a spreading potential by the *one-step mechanism* via Σ^- doorways.

- (1) To study the $\Sigma\Lambda$ coupling effects related to the Σ -mixing and the strengths of the $\Lambda-{}^5\text{H}$ potential in ${}^6_{\Lambda}\text{H}(1^+_{\text{exc.}})$. [not ${}^6_{\Lambda}\text{H}(0^+_{\text{g.s.}})$] Λ regions
- (2) To extract valuable information on the Σ -nucleus potential for $\Sigma^- - {}^5\text{He}$ from the data of the J-PARC E10 experiments. Σ - regions

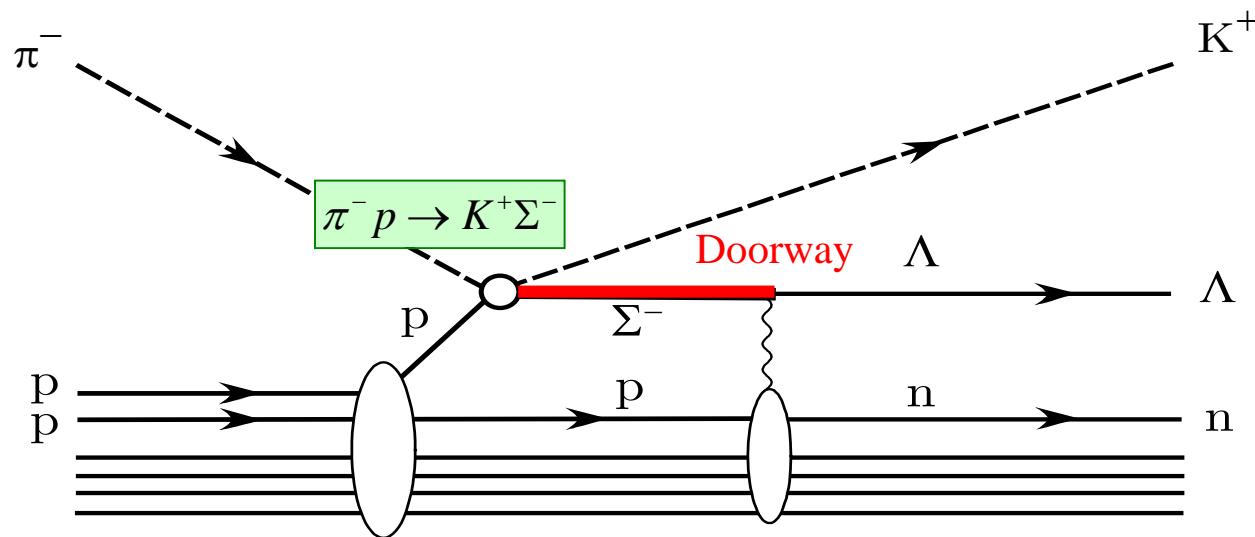
Search for the ${}^6_{\Lambda}\text{H}$ hypernucleus by ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions 1.2GeV/c@J-PARC E10



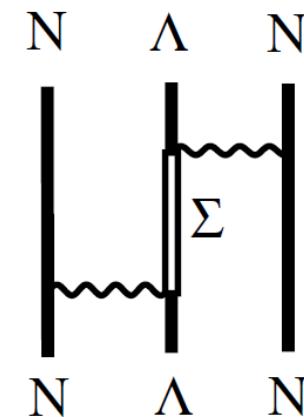
H.Sugimura et al.,
(J-PARC E10
Collaboration)
PLB 724 (2014)39.

R. Honda, et al.
(J-PARC E10
Collaboration),
PRC96 (2017) 014005

One-step process



via Σ^- doorways caused
by $\Lambda N - \Sigma N$ coupling



Model for final states of the hypernucleus

Single-particle shell model wf.

$$|\Psi_{J_B}({}_Y^6\text{H})\rangle = \sum_{JJ''j_nj_\Lambda} [\Phi_{J''}({}^5\text{H}), \varphi_{j_\Lambda}^{(\Lambda)}(r_\Lambda)]_{J_B} + \sum_{JJ'j_pj_\Sigma} [\Phi_{J'}({}^5\text{He}), \varphi_{j_\Sigma}^{(\Sigma^-)}(r_\Sigma)]_{J_B}$$

Σ^- mixing probability

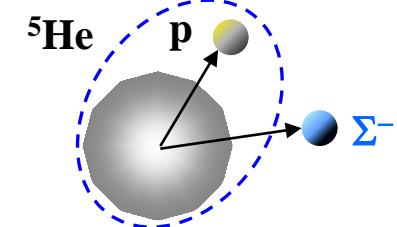
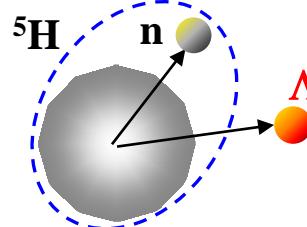
$$P_{\Sigma^-} = \sum_{j_2} \langle \varphi_{j_2}^{(\Sigma^-)} | \varphi_{j_2}^{(\Sigma^-)} \rangle$$

Hyperon-nucleus potentials

$$U_Y(r) = V_Y f(r, R, a) + i W_Y f(r, R', a')$$

$V_\Lambda = -19 \text{ MeV}$
is assumed

(V_Σ, W_Σ) determined
as fitting parameters



spreading potential for excited states

zero-range interaction:
Woods-Saxon form

$$f(r, R, a) = [1 + \exp((r - R)/a)]^{-1}$$

Coupling Λ - Σ folding potential

$$\begin{aligned} U_X(r) &= \left\langle [\Phi_{J'}({}^5\text{He}) \otimes \mathcal{Y}_{j'\ell's'}^{(\Sigma^-)}(\hat{r})]_{J_B} \mid \sum_i v_{\Sigma,\Lambda}(\mathbf{r}'_i, \mathbf{r}) \mid [\Phi_J({}^5\text{H}) \otimes \mathcal{Y}_{j\ell s}^{(\Lambda)}(\hat{r})]_{J_B} \right\rangle \\ &= \sum_{LSK} v_{\Sigma N, \Lambda N}^S C_{LSK}^{J_B}(J' J'') \mathcal{F}_{LSK}^{J' J''}(r) \end{aligned}$$

Shell-model w.f. with ($s^3 p^2$) configuration

zero-range interaction:

$$v_{\Lambda\Lambda-\Xi N} = v_{\Lambda\Lambda-\Xi N}^0 \delta(\mathbf{r} - \mathbf{r}')$$

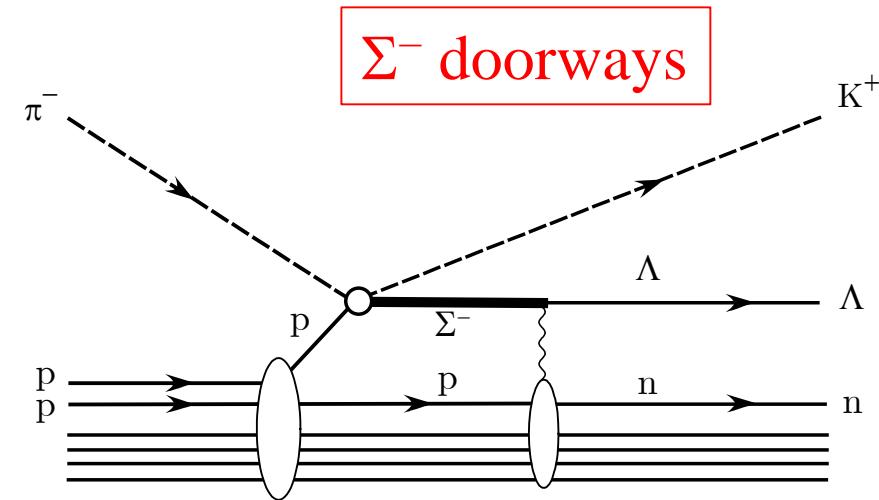
volume integral:

Coupled-channels DWIA calculation for one-step mechanism

Coupled-channel Green's function

$$\mathbf{G}(\omega) = \mathbf{G}^{(0)}(\omega) + \mathbf{G}^{(0)}(\omega) \mathbf{U} \mathbf{G}(\omega)$$

$$\mathbf{G}(\omega) = \begin{pmatrix} G_\Lambda(\omega) & G_X(\omega) \\ G_X(\omega) & G_\Sigma(\omega) \end{pmatrix}, \quad \mathbf{U} = \begin{pmatrix} U_\Lambda & U_X \\ U_X & U_\Sigma \end{pmatrix}$$



Inclusive cross sections

T. Harada, NPA672(2000)181

$$\left(\frac{d^2\sigma}{d\Omega_K dE_K} \right)_{\text{lab}} = \beta \frac{1}{[J_A]} \sum_{M_z} \sum_{\alpha' \alpha} \left(-\frac{1}{\pi} \right) \text{Im} \left[\int d\mathbf{r}' d\mathbf{r} F_\Sigma^{\alpha' \dagger}(\mathbf{r}') G_\Sigma^{\alpha' \alpha}(\omega, \mathbf{r}', \mathbf{r}) F_\Sigma^\alpha(\mathbf{r}) \right]$$

$$F_\Sigma^\alpha = \beta^{\frac{1}{2}} \underbrace{\overline{f}_{\pi^- p \rightarrow K^+ \Sigma^-}}_{\text{Fermi-averaged amplitudes}} \chi_{\mathbf{p}_K}^{(-)*} \chi_{\mathbf{p}_\pi}^{(+)} \langle \alpha | \hat{\psi}_p | \Psi_A \rangle$$

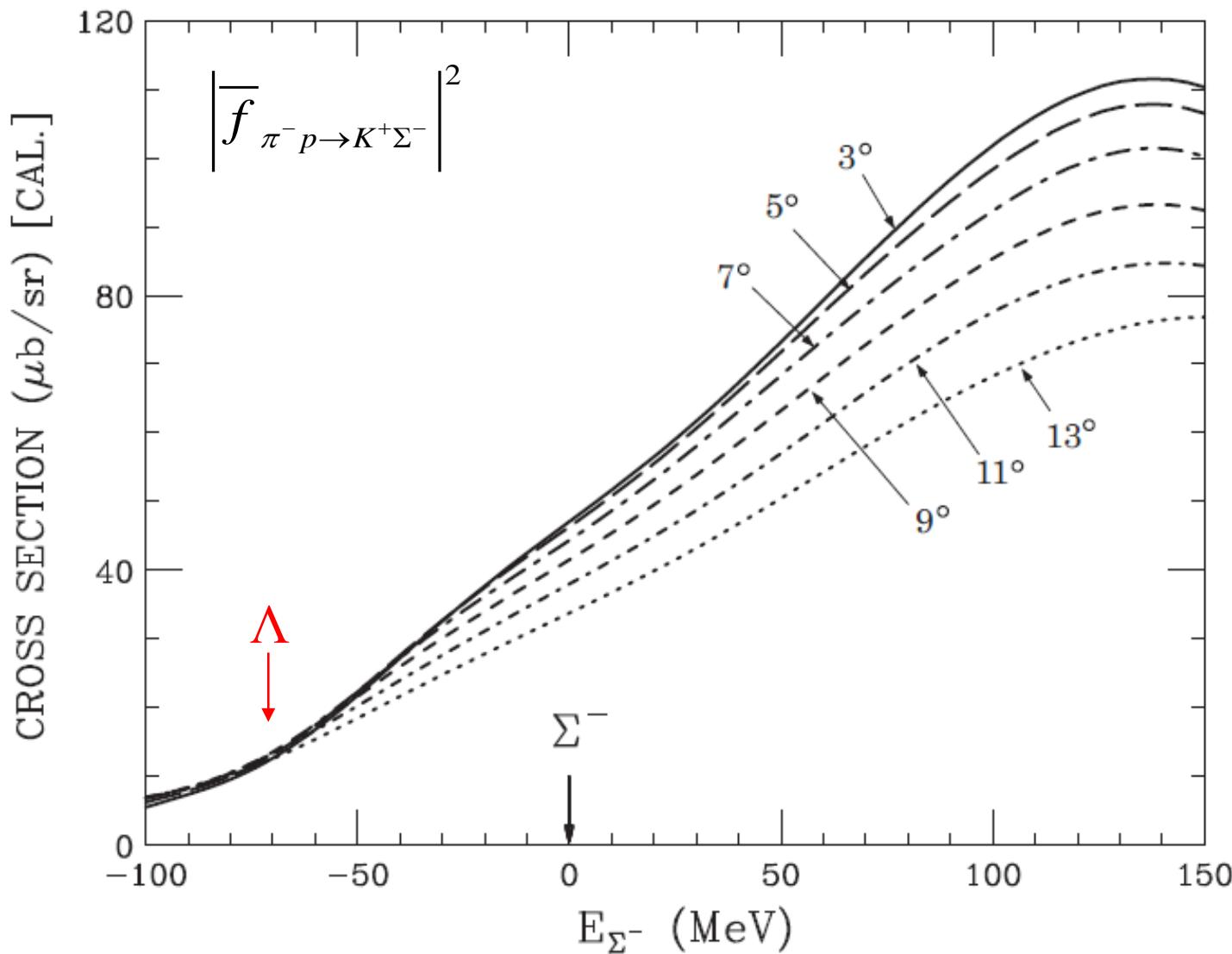
Fermi-averaged amplitudes

Decomposition of the inclusive spectrum into components

$$\text{Im } \hat{G}_\Sigma = \underbrace{\hat{\Omega}^{(-)\dagger} \{ \text{Im } \hat{G}_\Lambda^{(0)} \} \hat{\Omega}^{(-)}}_{\Lambda \text{ escape}} + \underbrace{\hat{\Omega}^{(-)\dagger} \{ \text{Im } \hat{G}_\Sigma^{(0)} \} \hat{\Omega}^{(-)}}_{\Sigma^- \text{ escape}} + \underbrace{\hat{G}^\dagger \{ W_{Y,T} \} \hat{G}}_{\text{Spreading (nuclear-core breakup)}}$$

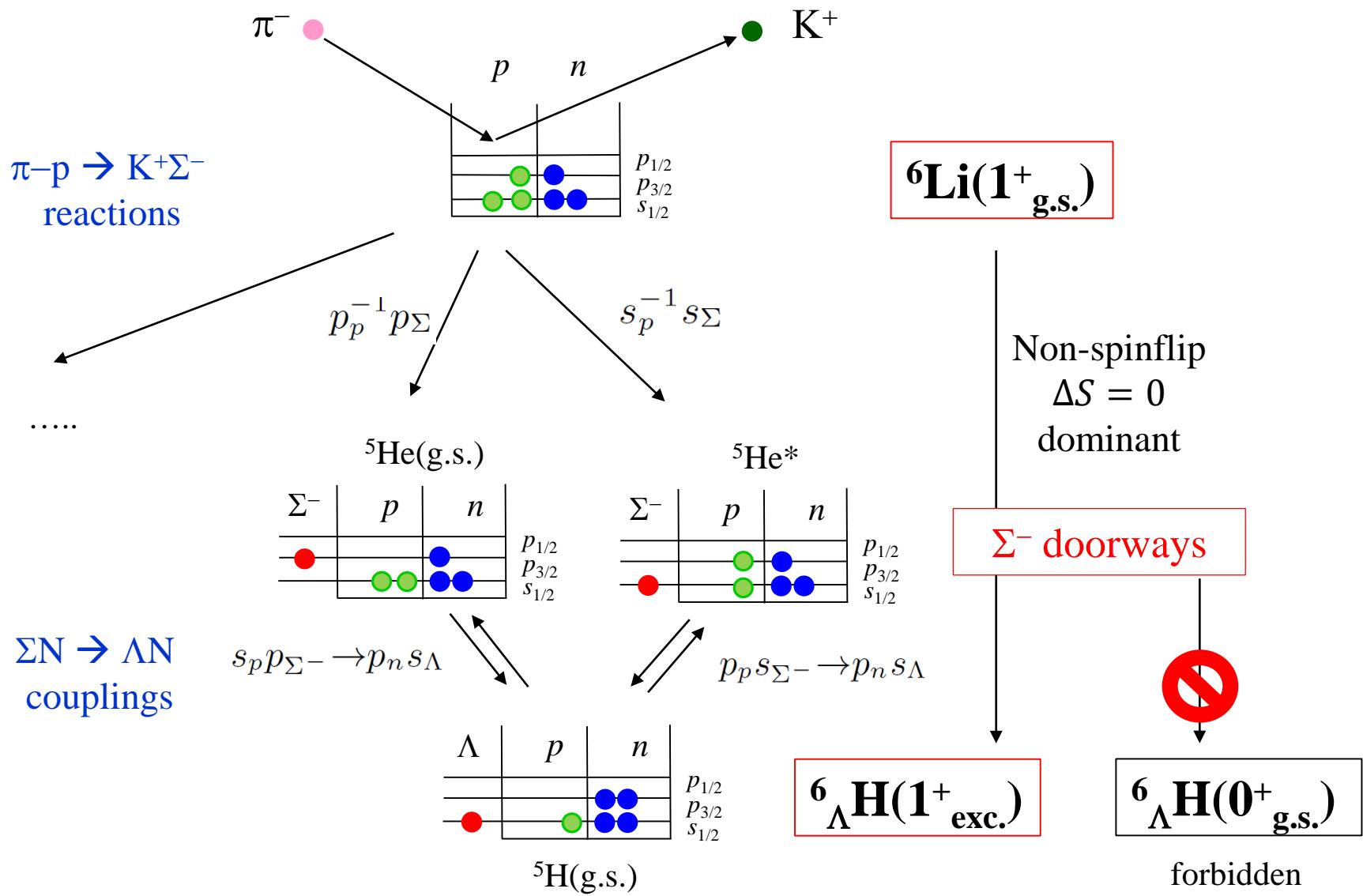
Angular dependence of the optimal Fermi-av. cross section

“ $\pi^- p \rightarrow K^+ \Sigma^-$ reactions” in the nucleus



- There exists a strong energy dependence in the amplitudes.

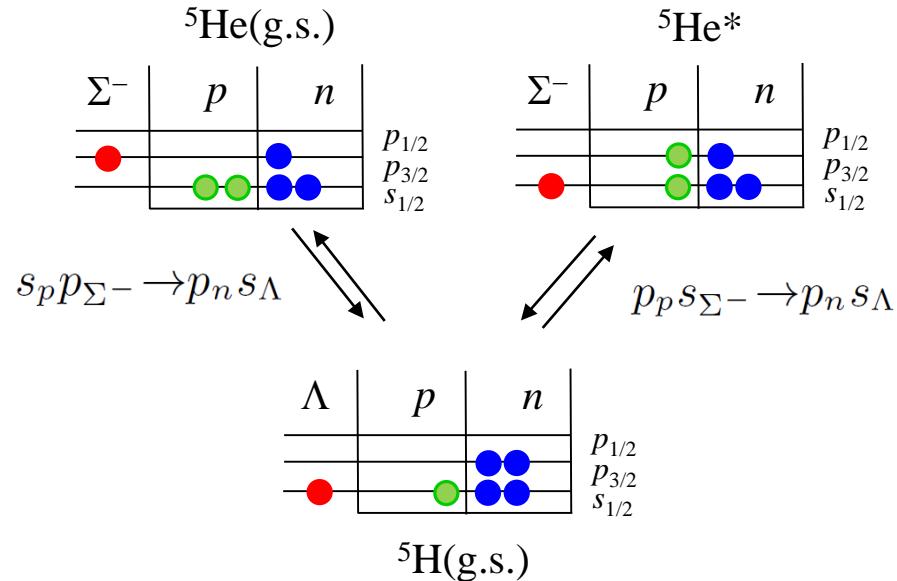
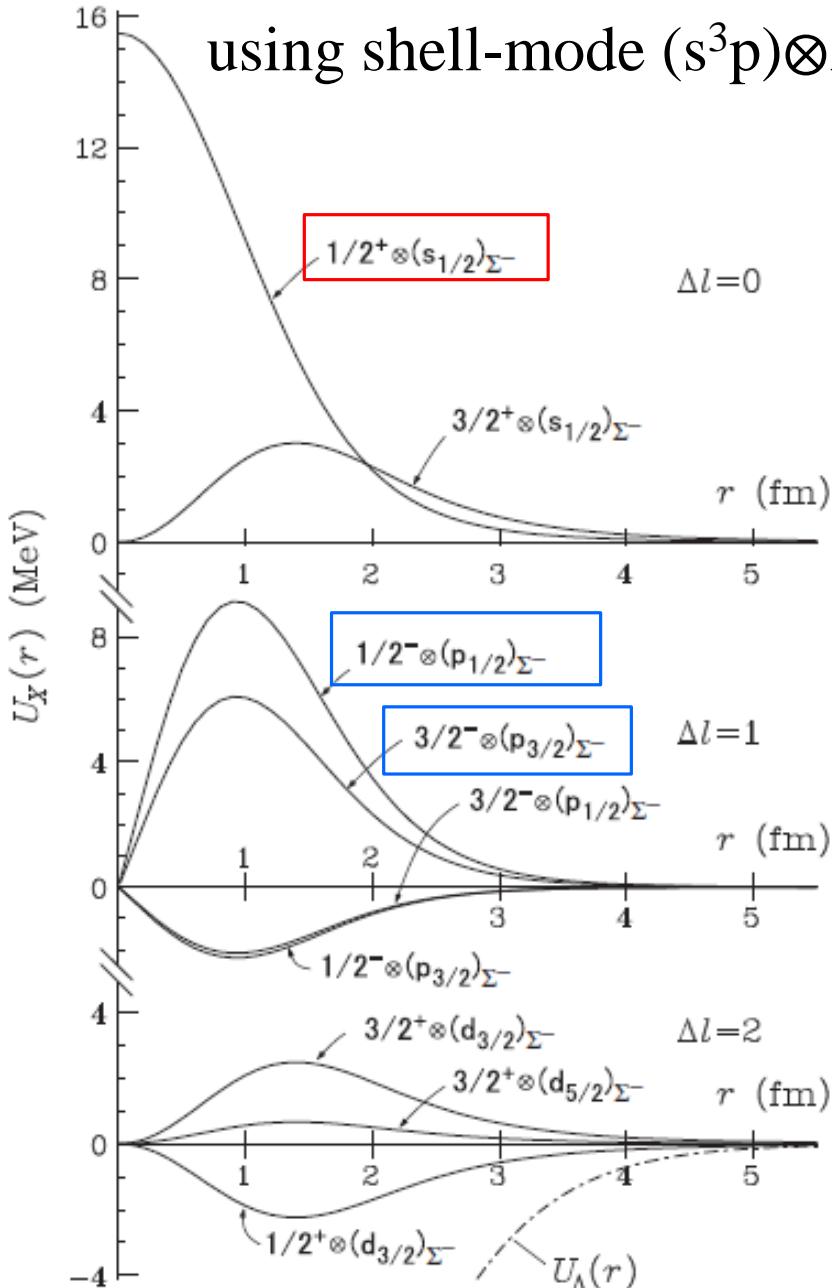
Schematic illustration of $^6\Lambda$ H production in the ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction



Calculated $\Sigma\Lambda$ coupling folding potentials in ${}^6_{\Lambda}\text{H}(1^+)$

using shell-mode ($s^3p \otimes L$) configurations for the core nucleus.

$$(v_{\Sigma N, \Lambda N}^1, v_{\Sigma N, \Lambda N}^0) = (-900 \text{ MeV} \cdot \text{fm}^3, 500 \text{ MeV} \cdot \text{fm}^3)$$

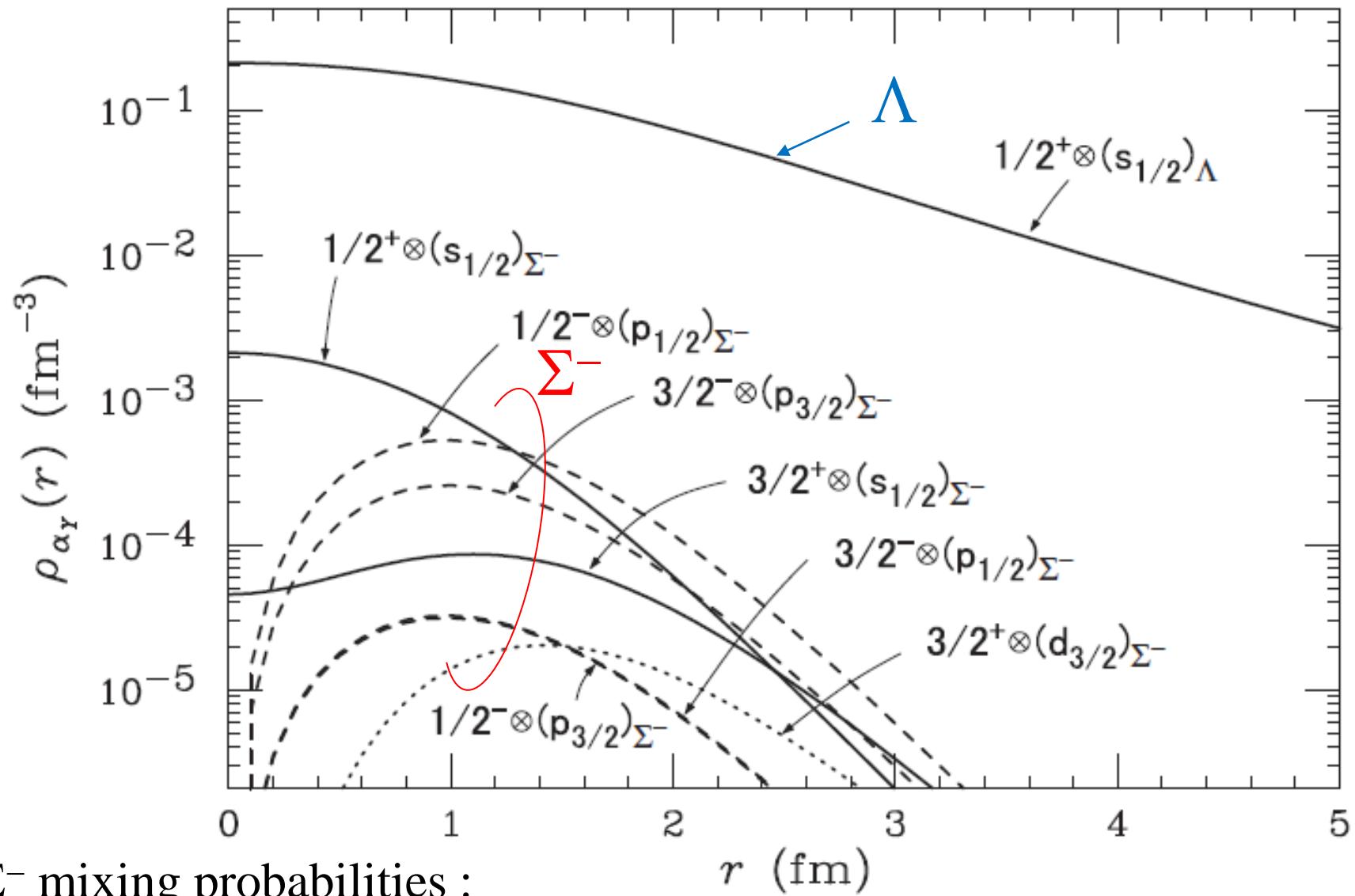


- Shell-model with *spsd* model space
- Central effective *YN* interaction (D2'g)

➤ The coupling strengths of $p_\Sigma \leftrightarrow s_\Lambda$ are so large, as well as $s_\Sigma \leftrightarrow s_\Lambda$.

Single-particle density distributions of Λ and Σ^- in ${}^6_{\Lambda}\text{H}(1^+)$

$$(v_{\Sigma N, \Lambda N}^1, v_{\Sigma N, \Lambda N}^0) = (-900 \text{ MeV} \cdot \text{fm}^3, 500 \text{ MeV} \cdot \text{fm}^3)$$



Σ^- mixing probabilities :

$$P_{\Sigma^-}(\text{tot}) = 0.32\% \quad [P_{\Sigma^-}(s_{\Sigma}) = 0.13\%, P_{\Sigma^-}(p_{\Sigma}) = 0.17\%]$$

Integrated cross section and Σ^- mixing probability

	$\tilde{v}_{\Sigma N, \Lambda N}^S$ (MeV)	$B_\Lambda(^6_\Lambda H)$	P_{Σ^-} (%)			${}^6_\Lambda H(1^+)$	
Case	$S = 1$	$S = 0$	(MeV)	s_Σ	p_Σ	d_Σ	good total agreement
D	0	0	1.492	0.00	0.00	0.00	0.00
C	-450	250	1.576	0.03	0.04	0.00	0.07
C	-900	500	1.841	0.13	0.17	0.02	0.32
B	-1350	750	2.328	0.34	0.41	0.04	0.79
A	-1800	1000	3.100	0.68	0.82	0.08	1.58

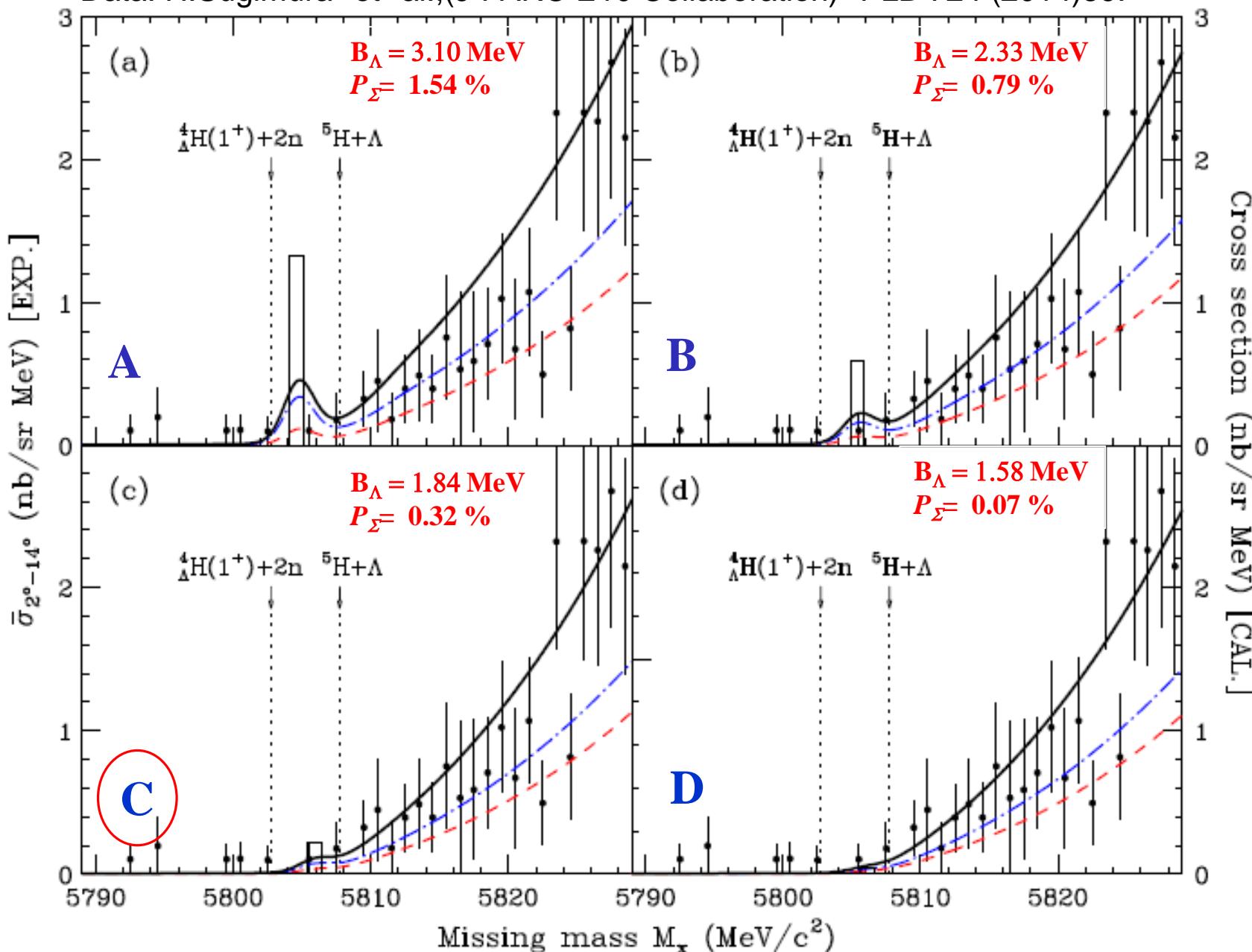
	$\tilde{v}_{\Sigma N, \Lambda N}^S$ (MeV)	$B_\Lambda(^6_\Lambda H)$	$d\sigma/d\Omega$ (nb/sr)			
Case	$S = 1$	$S = 0$	(MeV)	s_p^{-1}	p_p^{-1}	total
D	0	0	1.492	0.00	0.00	0.00
D	-450	250	1.576	0.03	0.01	0.04
C	-900	500	1.841	0.16	0.06	0.22
B	-1350	750	2.328	0.44	0.15	0.59
A	-1800	1000	3.100	1.00	0.32	1.32

→ Cross sections: $d\sigma/d\Omega = 0.22$ nb/sr Σ^- mixing probabilities:
 $P_{\Sigma^-}(\text{tot}) = 0.32\%$ [$P_{\Sigma^-}(s_\Sigma) = 0.13\%$, $P_{\Sigma^-}(p_\Sigma) = 0.17\%$]

Production cross section of ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

${}^6\Lambda\text{H}(1^+)$

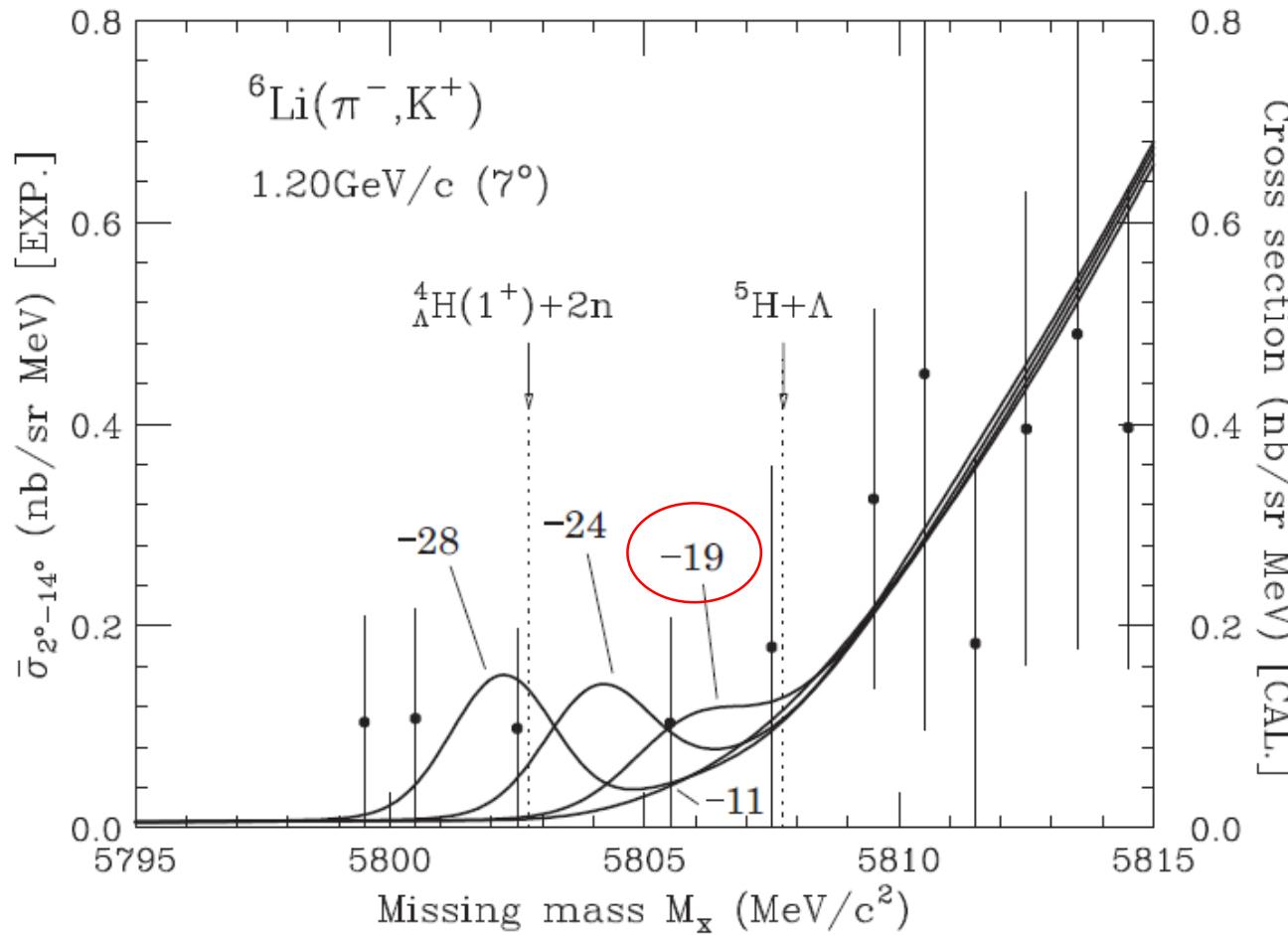
Data: H.Sugimura et al.,(J-PARC E10 Collaboration) PLB 724 (2014)39.



Dependence of the spectrum on V_Λ in the Λ - ${}^5\text{H}$ potential

- $V_\Lambda = -19, -24, -28 \text{ MeV}$ because the structure of ${}^5\text{H}$ is still uncertain experimentally.

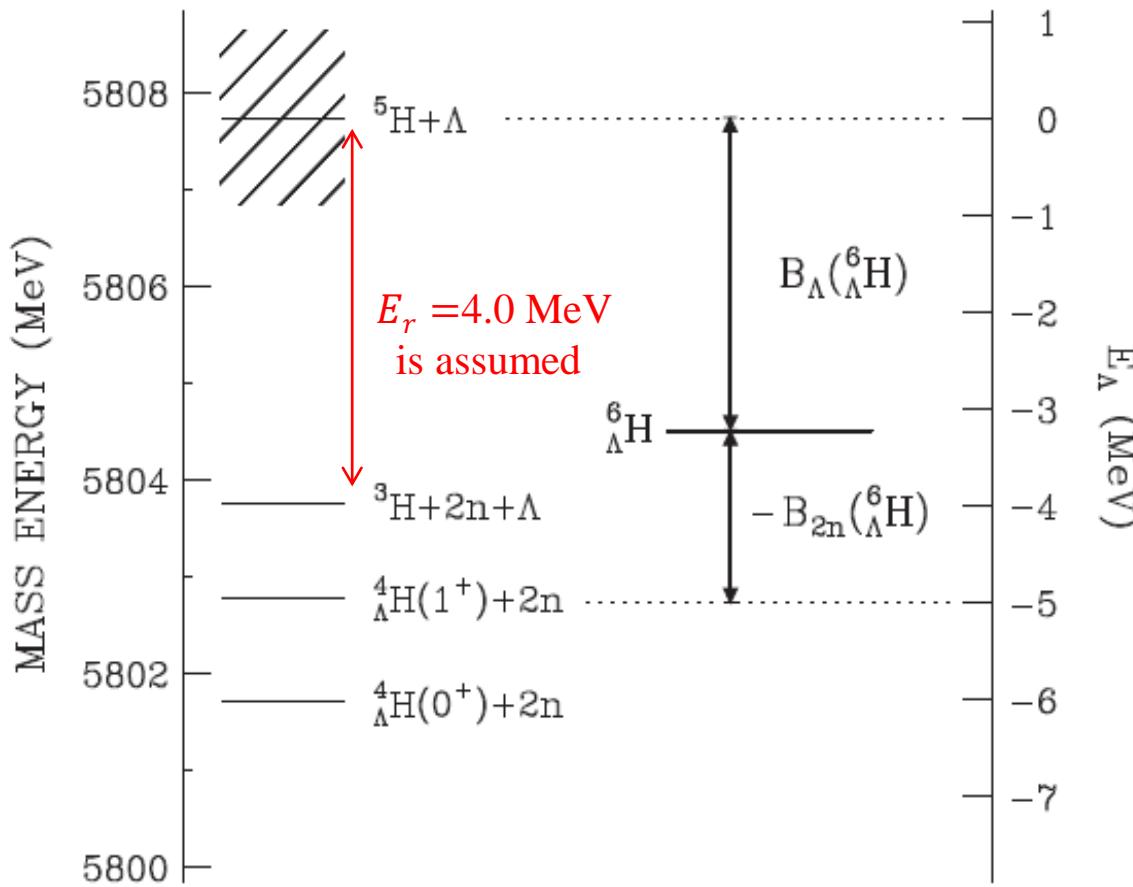
${}^6_\Lambda\text{H}(1^+)$



- The shallow potential $V_\Lambda = -19 \text{ MeV}$ is favored to be compared with the data.
- The shape of the spectrum is so sensitive to the structure of the ${}^5\text{H}$ resonance.

Energy spectrum and decay threshold of ${}^6\Lambda$ H

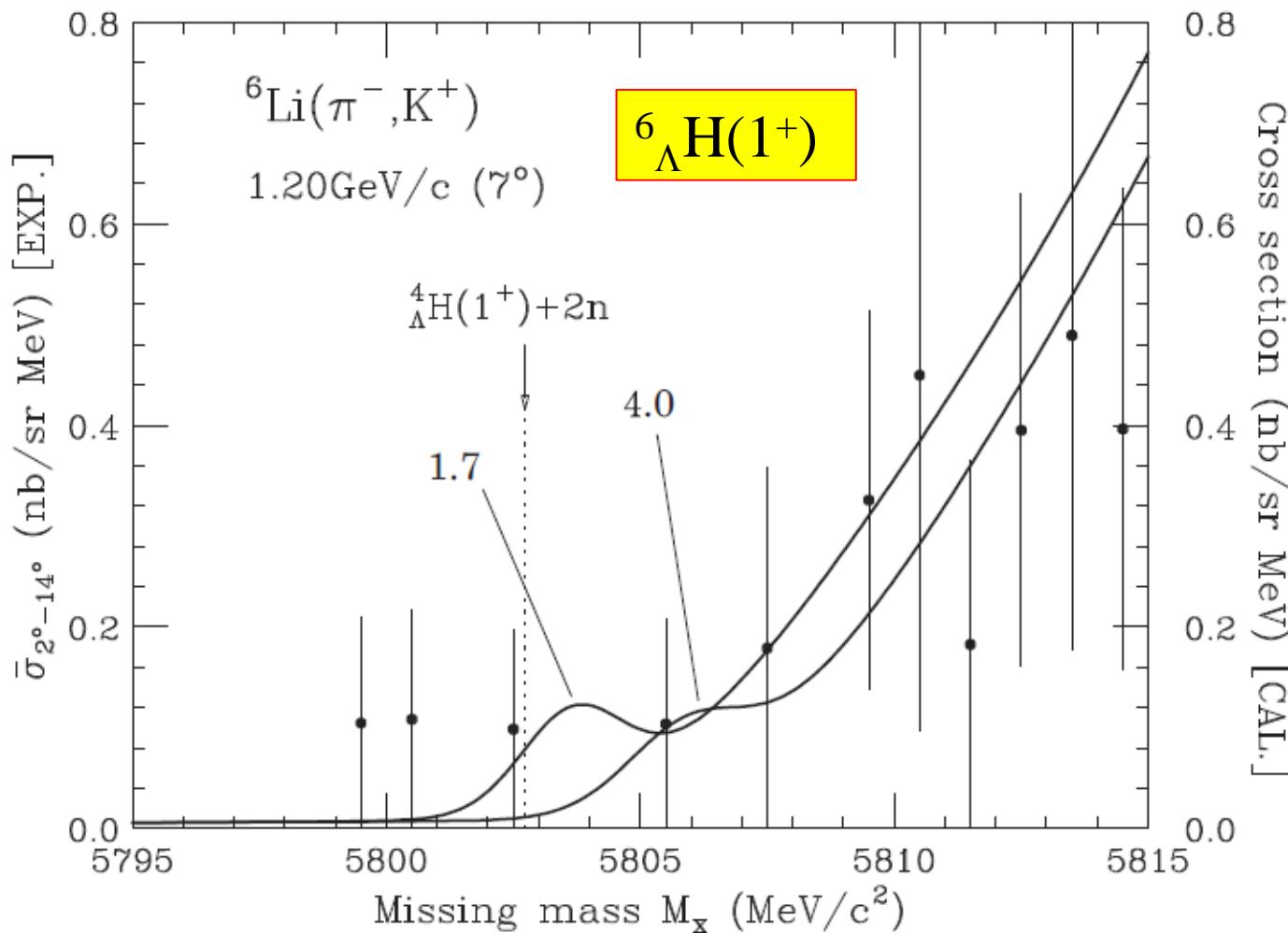
- We assume $E_r = M[{}^5\text{H}(1/2^+)] - M[{}^3\text{H} + 2\text{n}] = 4.0 \text{ MeV}$, rather than $E_r = 1.7 \text{ MeV}$ because the structure of ${}^5\text{H}$ is still uncertain experimentally.



E. Hiyama, et al., Nucl. Phys. A 908, 29 (2013); D. R. Tilley, et al., Nucl. Phys. A 708, 3 (2002);
J. Tanaka, Porposal for E428 experiments at RCNP (2014).

Dependence of the spectrum on E_r for the ${}^5\text{H}$ resonance

- $E_r = 4.0 \text{ MeV}, 1.7 \text{ MeV}$ in respect to the ${}^3\text{H} + 2\text{n}$ threshold.

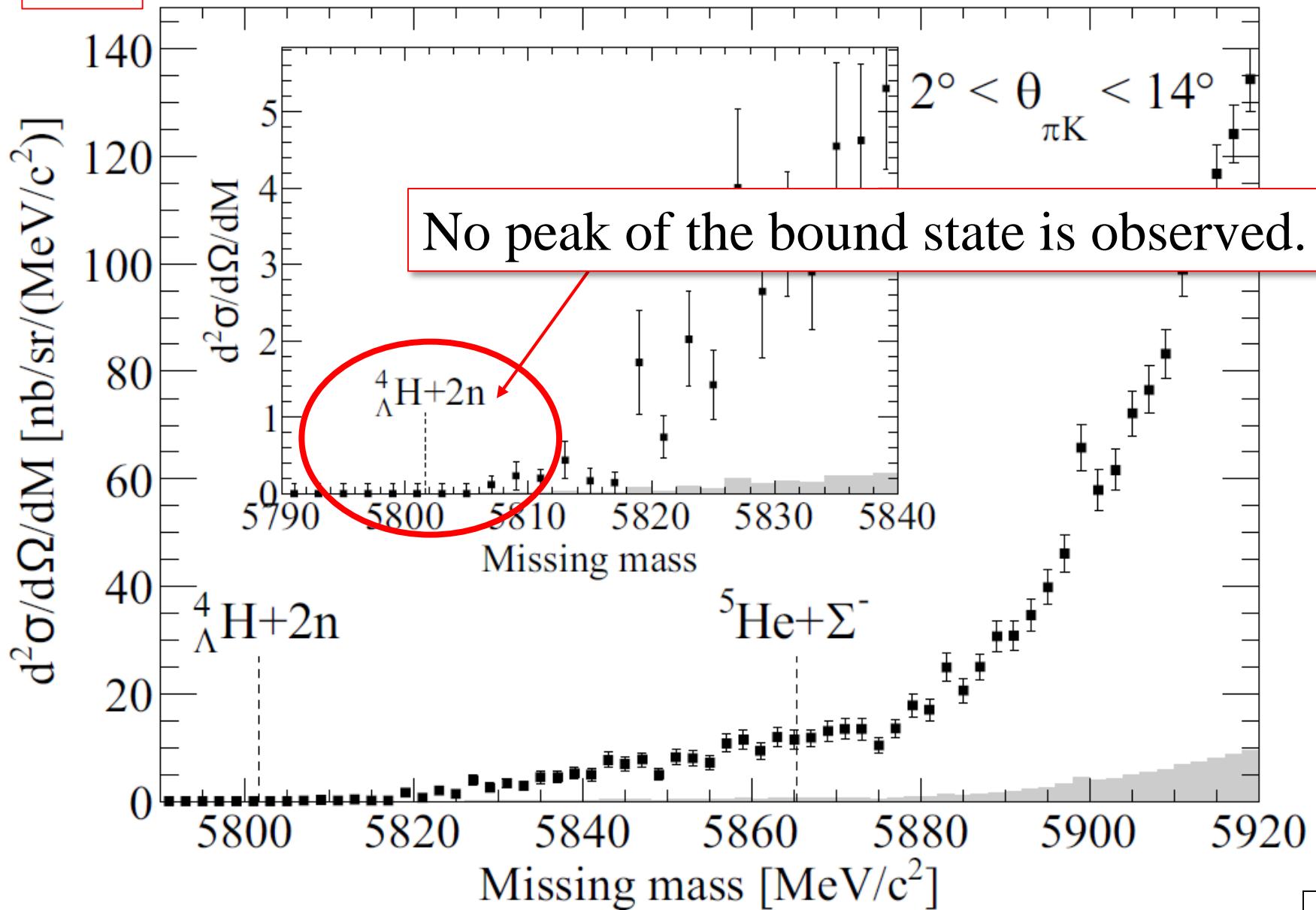


- The spectrum near the Λ threshold is very sensitive to the structure of the ${}^5\text{H}$ resonance (E_r, Γ_r).

Search for the ${}^6_{\Lambda}\text{H}$ hypernucleus by ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

E10

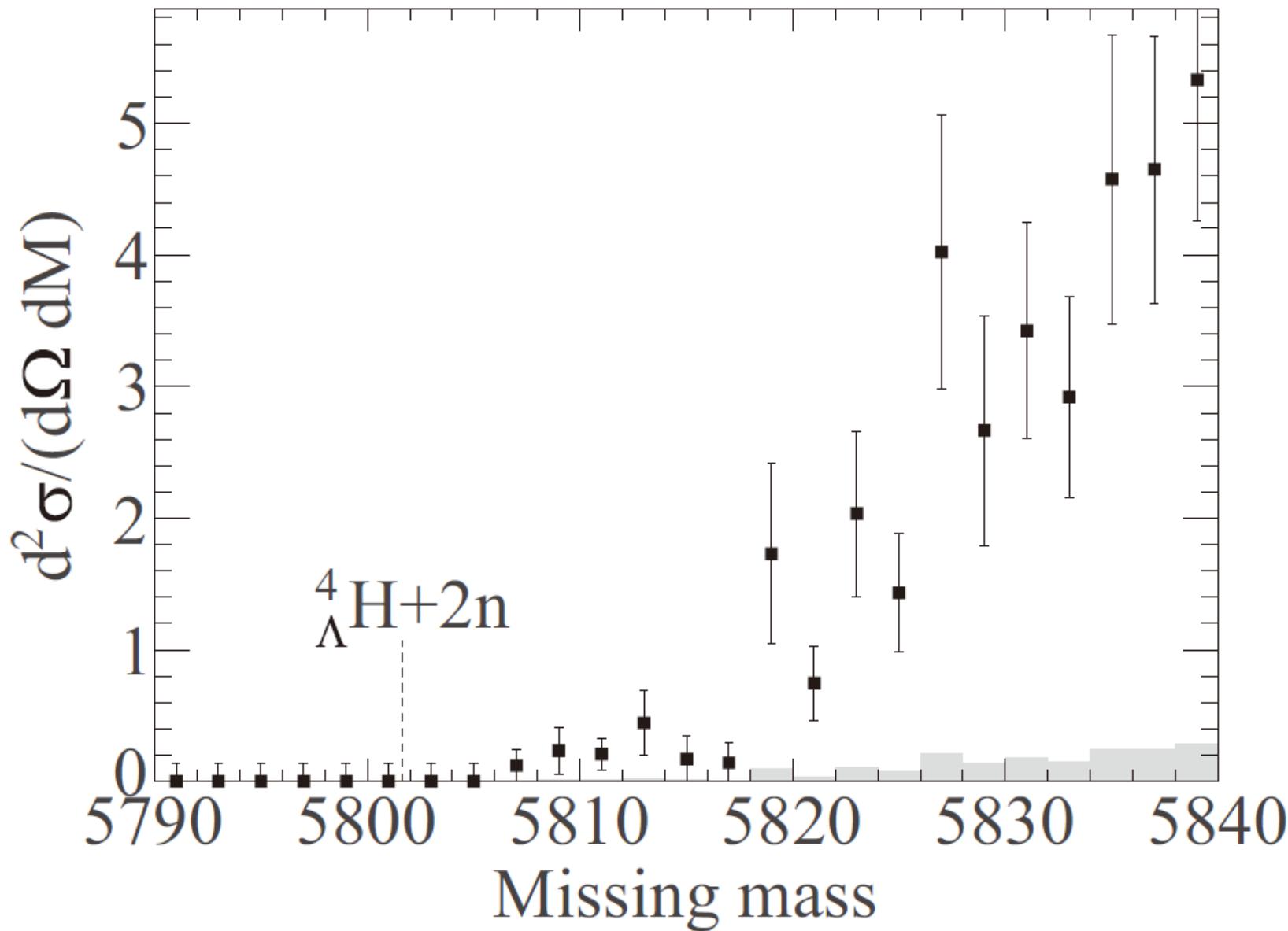
R. Honda et al. (J-PARC E10 Collaboration), PRC96, 014005 (2017)



Search for the ${}^6_{\Lambda}\text{H}$ hypernucleus by ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

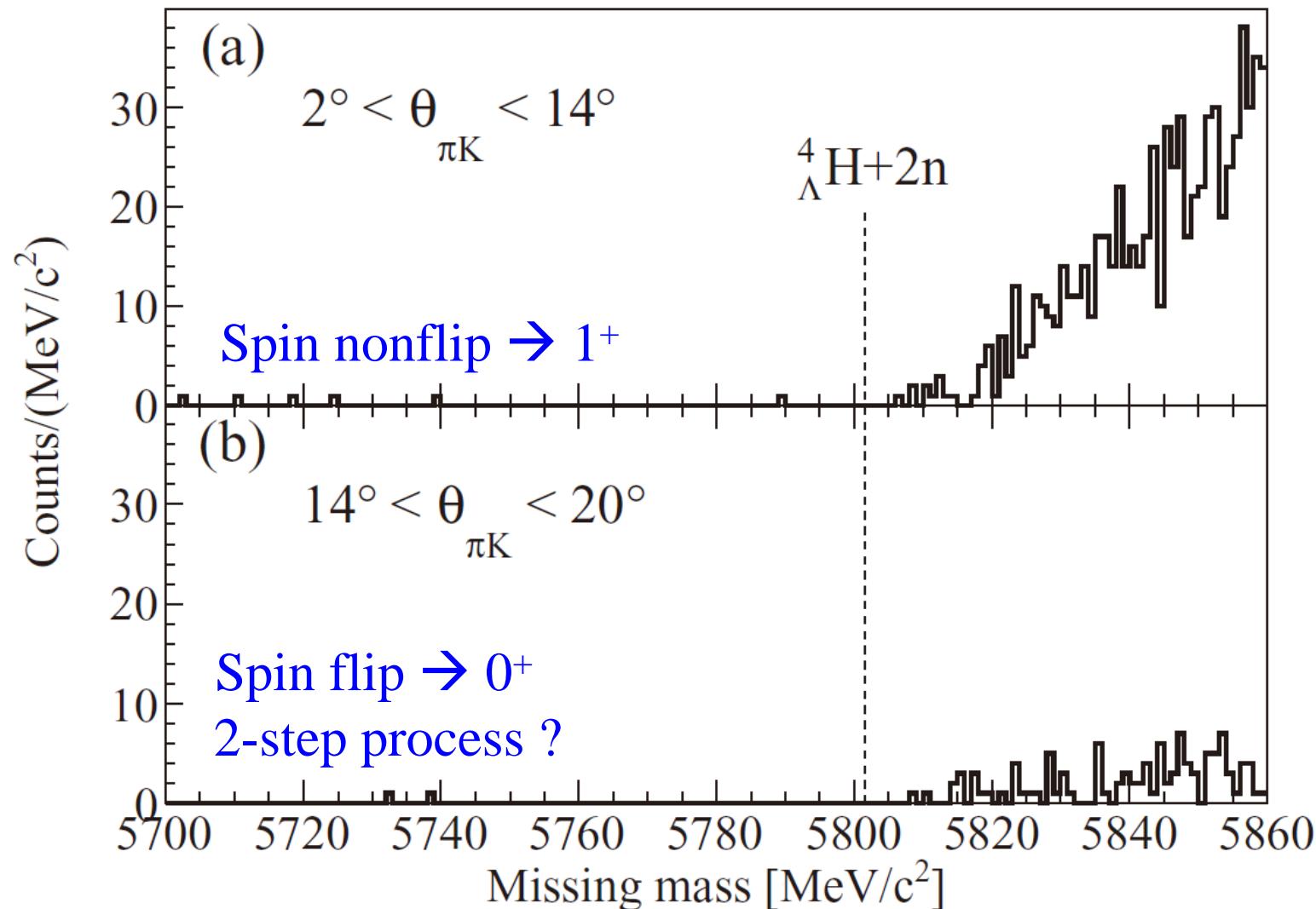
E10

R. Honda et al. (J-PARC E10 Collaboration), PRC96, 014005 (2017)



Production cross section of ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

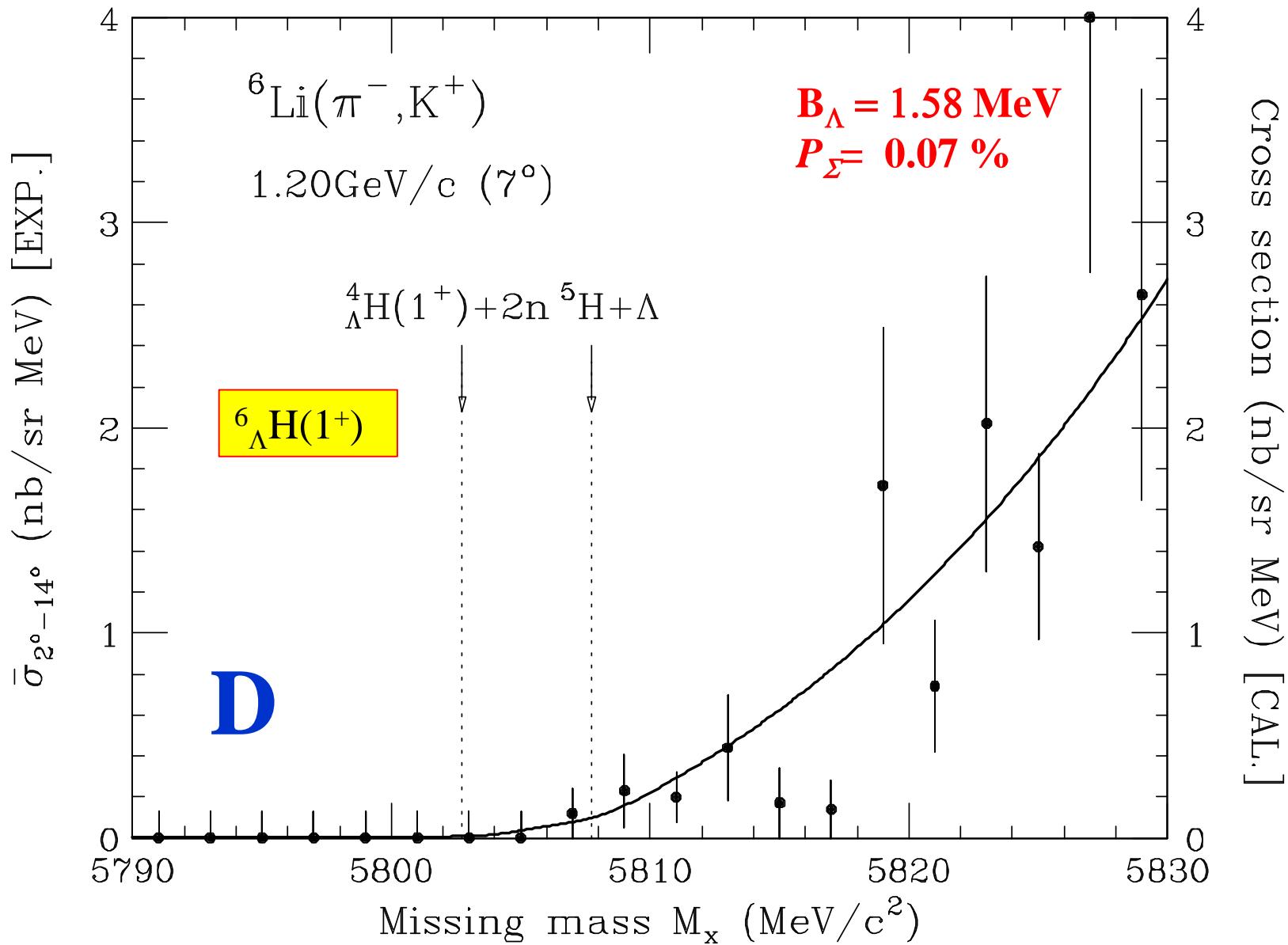
R. Honda et al. (J-PARC E10 Collaboration), PRC96, 014005 (2017)



Production cross section of ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

Hyperon-mixing

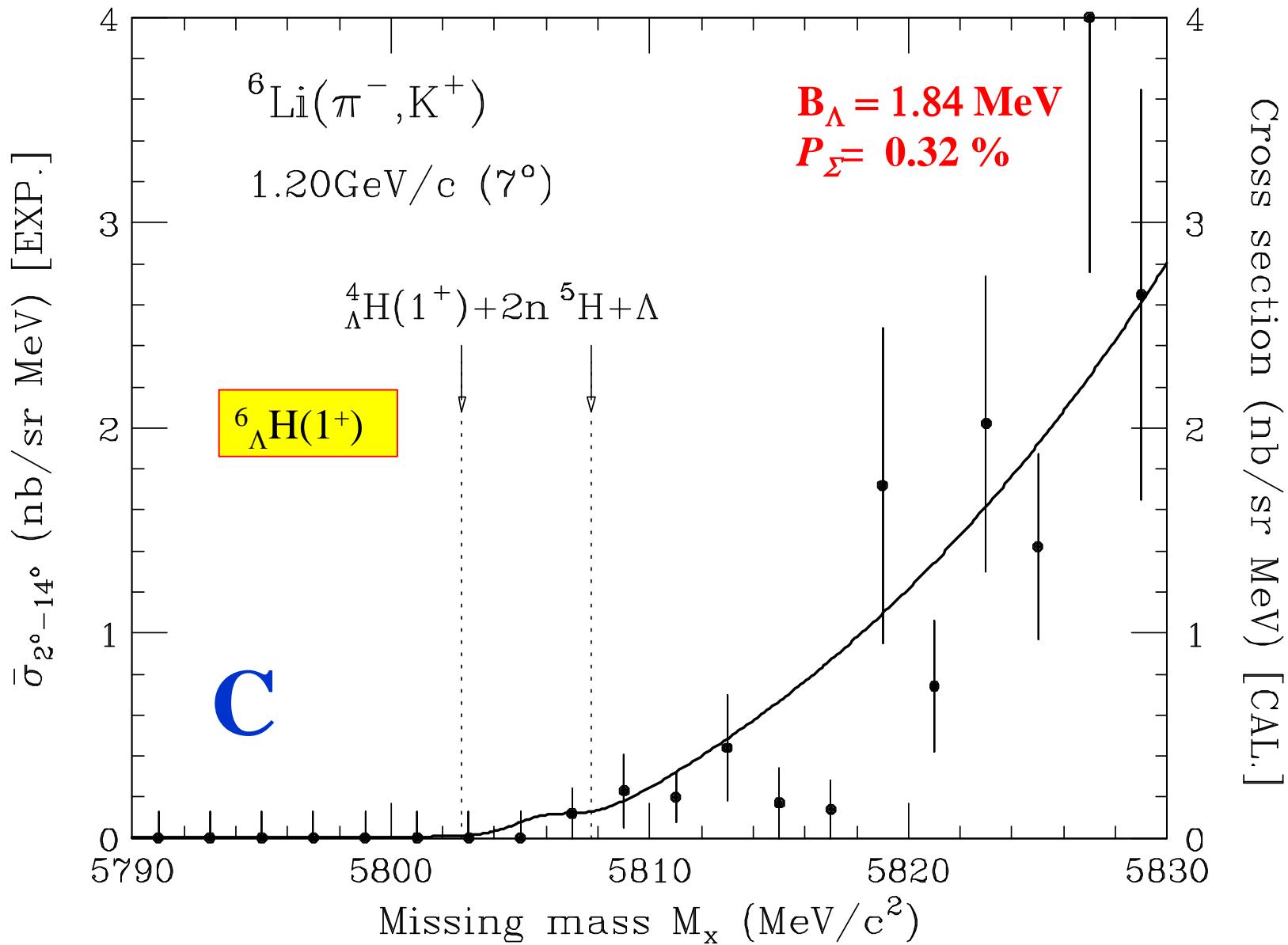
R. Honda et al. (J-PARC E10 Collaboration), PRC96, 014005 (2017)



Production cross section of ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

Hyperon-mixing

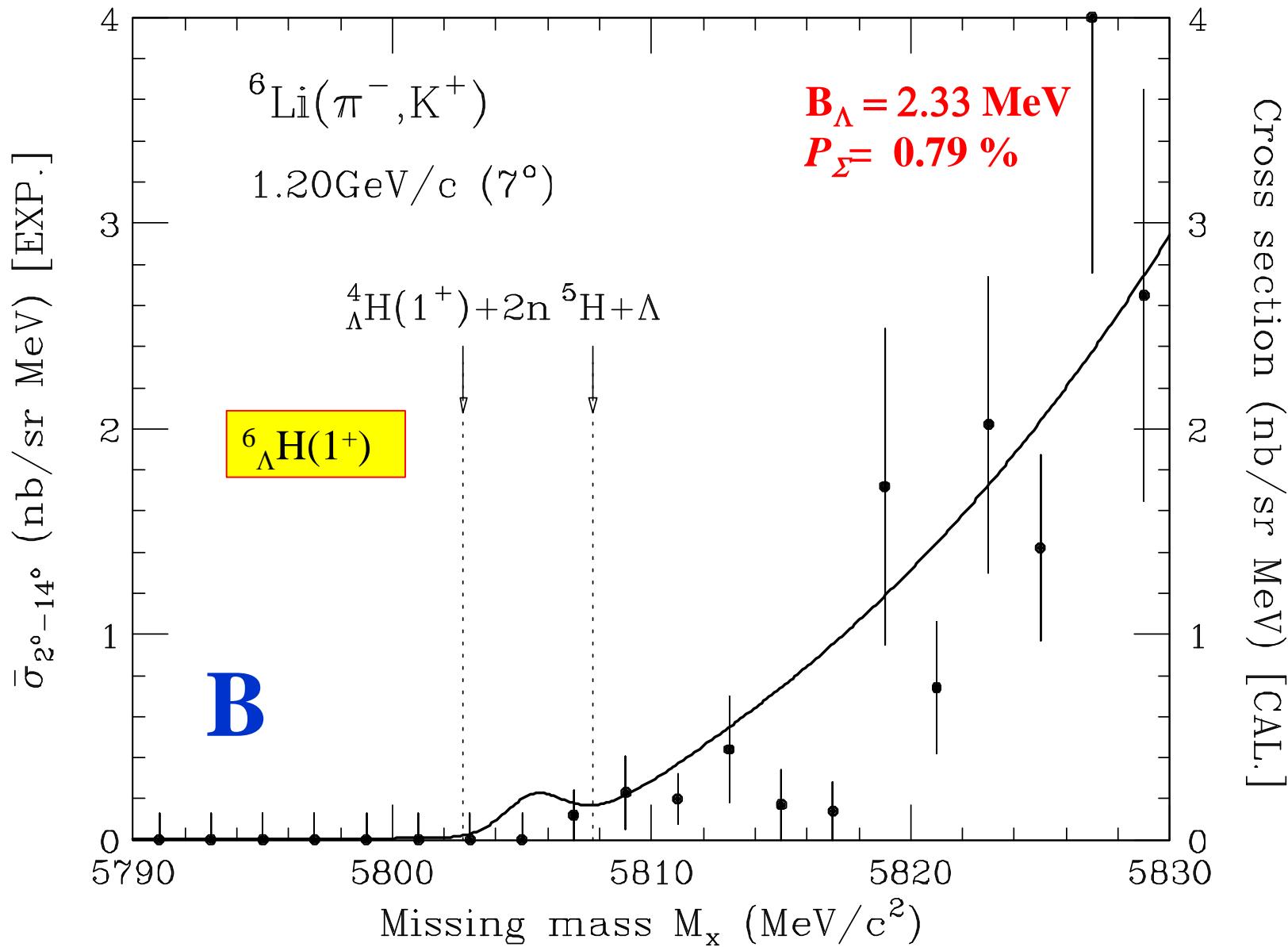
R. Honda et al. (J-PARC E10 Collaboration), PRC96, 014005 (2017)



Production cross section of ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

Hyperon-mixing

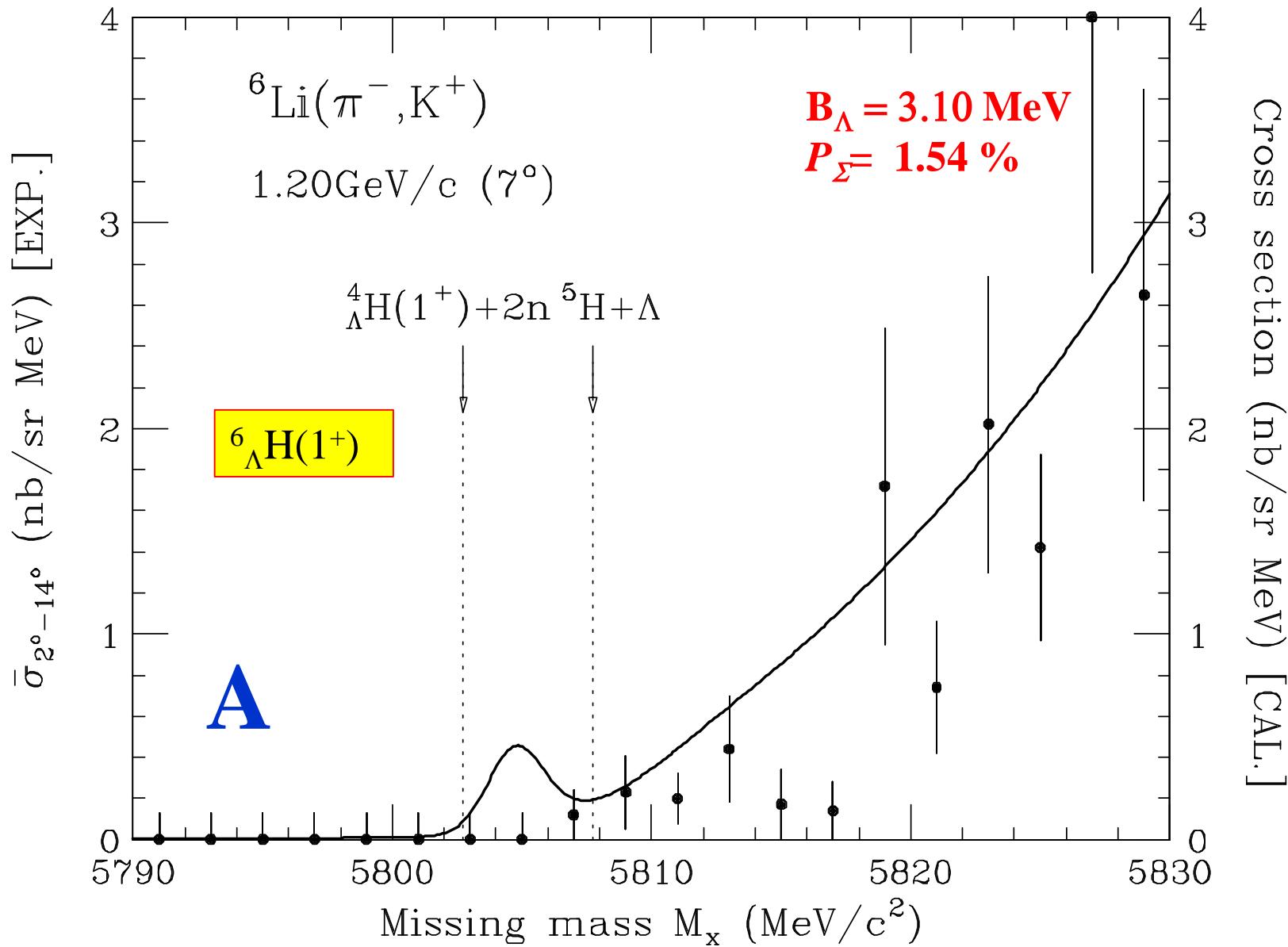
R. Honda et al. (J-PARC E10 Collaboration), PRC96, 014005 (2017)



Production cross section of ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

Hyperon-mixing

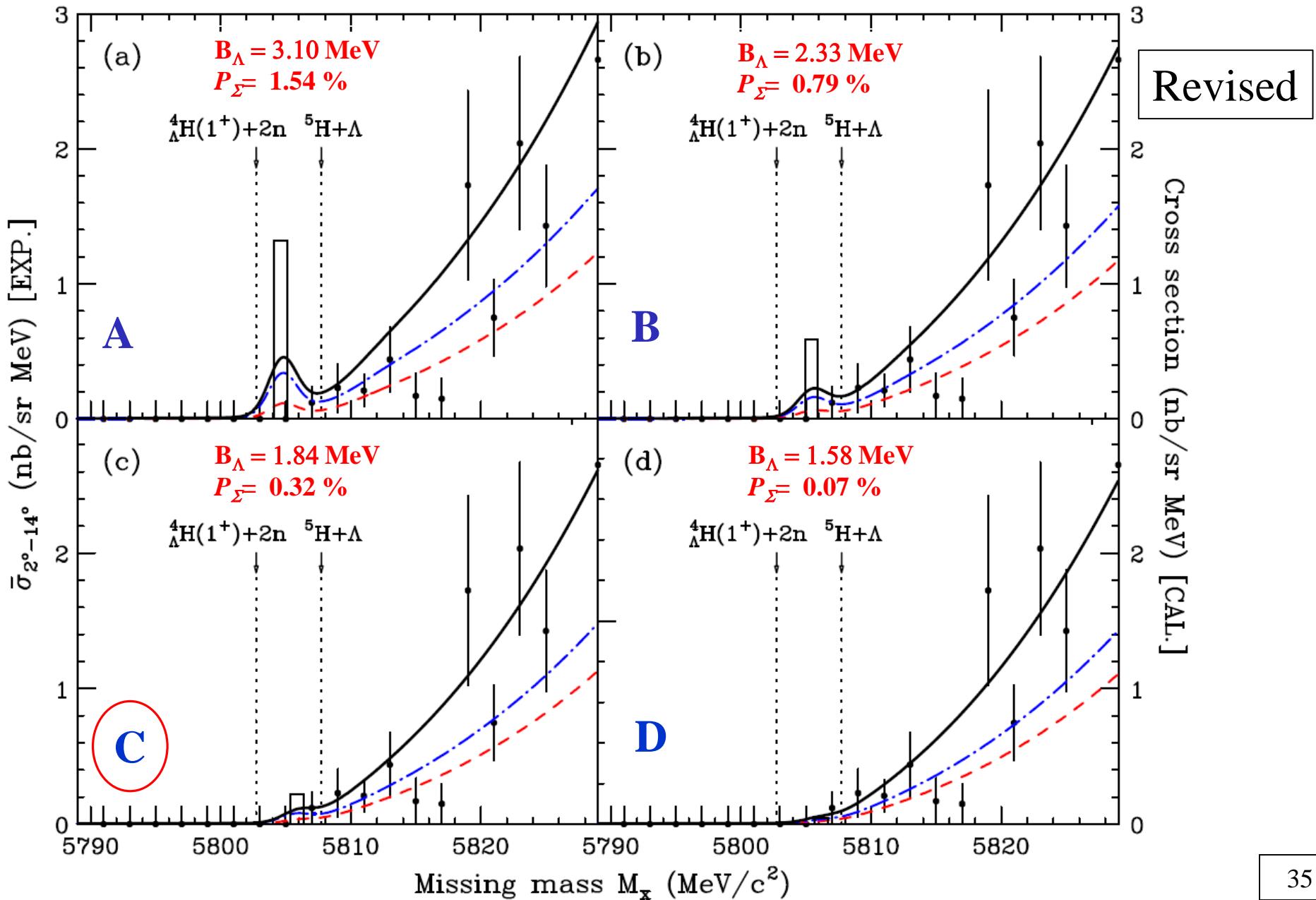
R. Honda et al. (J-PARC E10 Collaboration), PRC96, 014005 (2017)



Production cross section of ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

${}^6\Lambda\text{H}(1^+)$

Data: R.Honda et al.,(J-PARC E10 Collaboration), PRC96, 014005 (2017)



Remarks

Hyperon-mixing

- The calculated spectrum of the ${}^6_{\Lambda}\text{H}$ by the one-step mechanism via Σ^- doorways can explain the data of the DCX ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction at 1.20GeV/c .

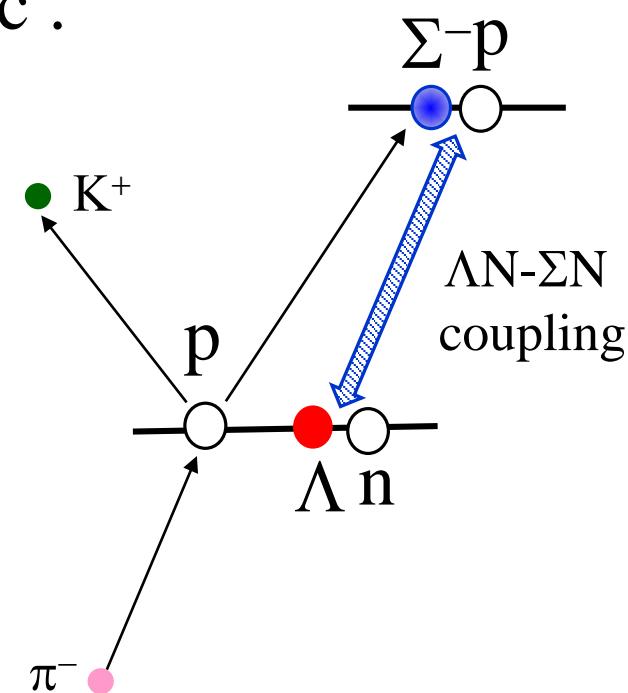
➤ $(V_\Sigma, W_\Sigma) = (+30 \text{ MeV}, -26 \text{ MeV})$
 ~~$(V_\Sigma, W_\Sigma) = (+20 \text{ MeV}, -20 \text{ MeV})$~~

- Σ^- mixing probability

$$P_\Sigma \sim 0.4 \% \text{ for } {}^6_{\Lambda}\text{H}(1^+_{\text{exc.}}).$$

$$[P_{\Sigma^-}(s_\Sigma) = 0.11\%, P_{\Sigma^-}(p_\Sigma) = 0.17\%]$$

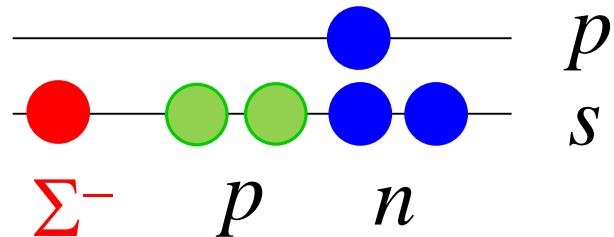
- Shallow Λ potential for ${}^5\text{H}_{\text{res}}$
 $(V_\Lambda \simeq -19 \text{ MeV})$ is favored.



- Our phenomenological calculations provide the ability to extract the production mechanism from the data.

Study of the Σ -nucleus potentials

Σ^- - ${}^5\text{He}$



T. Harada, R. Honda, Y. Hirabayashi, PRC 97 (2018) 024601.

Our Purpose

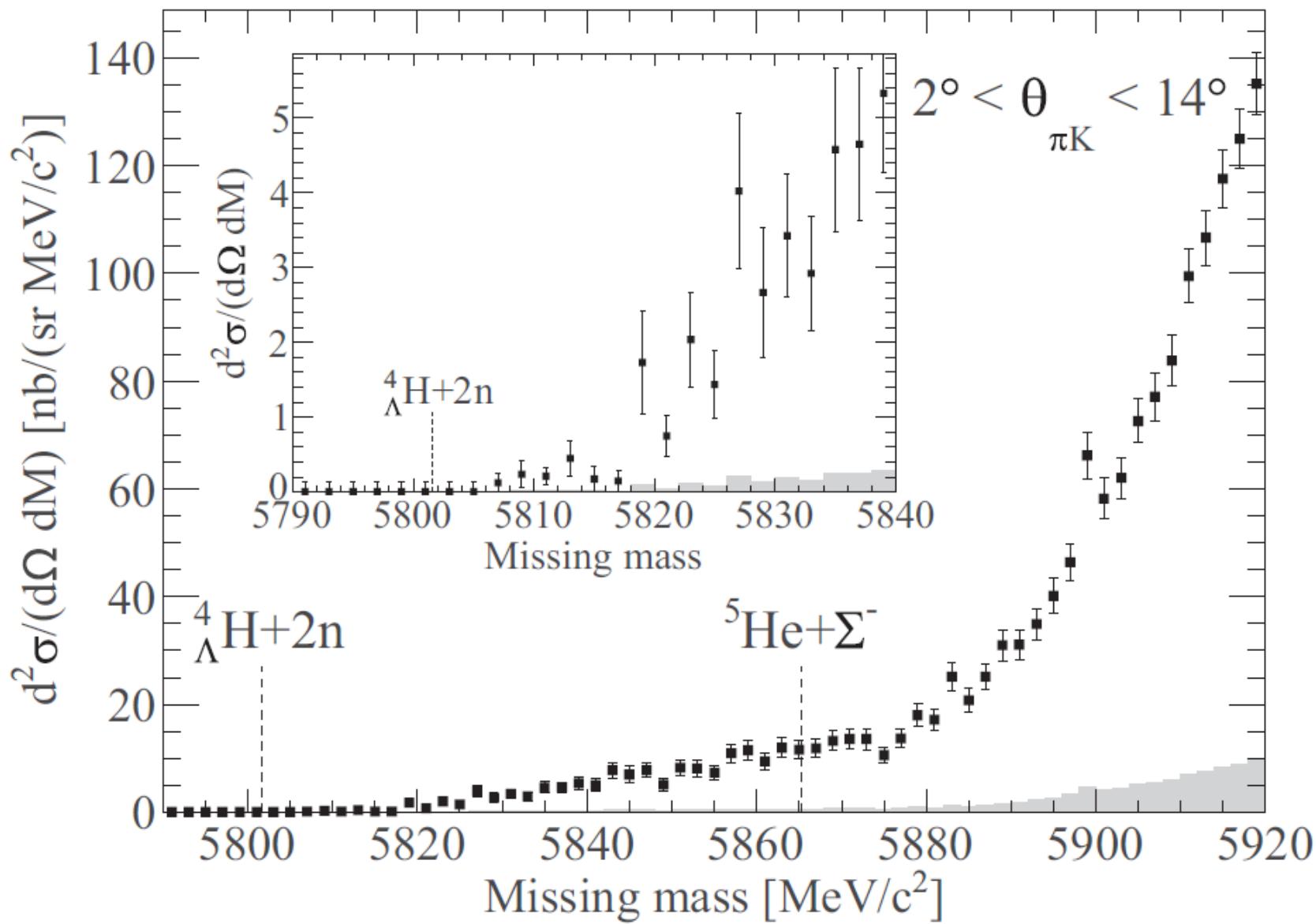
- We theoretically demonstrate the inclusive spectra of the ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction within a distorted-wave impulse approximation, using a coupled $({}^5\text{H}-\Lambda)$ $+({}^5\text{He}-\Sigma^-)$ model with a spreading potential by the *one-step mechanism* via Σ^- doorways.

- (1) To study the $\Sigma\Lambda$ coupling effects related to the Σ -mixing and the strengths of the $\Lambda-{}^5\text{H}$ potential in ${}^6_{\Lambda}\text{H}(1^+_{\text{exc.}})$. [not ${}^6_{\Lambda}\text{H}(0^+_{\text{g.s.}})$] Λ regions
- (2) To extract valuable information on the Σ -nucleus potential for $\Sigma^- - {}^5\text{He}$ from the data of the J-PARC E10 experiments. Σ^- regions

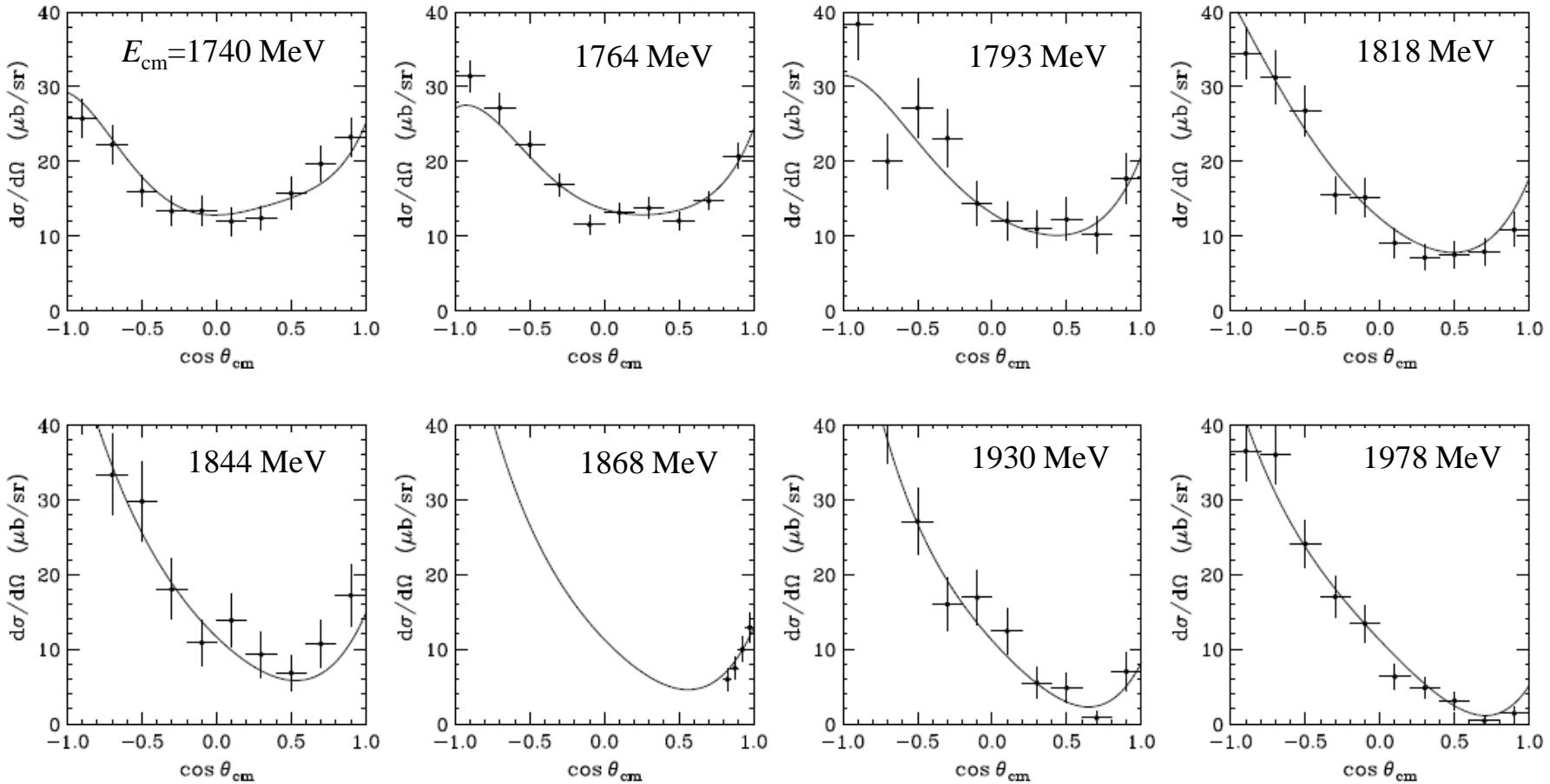
Search for the ${}^6_{\Lambda}\text{H}$ hypernucleus by ${}^6\text{Li}(\pi^-, \text{K}^+)$ reactions

E10

R. Honda, et al., (J-PARC E10 Collaboration), PRC96 (2017) 014005



Differential cross sections for the $\pi^- p \rightarrow K^+ \Sigma^-$ reactions



Exp. data

O.I. Dahl, et al., Phys. Rev. 163 (1967) 1430.

T.O. Binford, et al., Phys. Rev. 183 (1969) 1134.

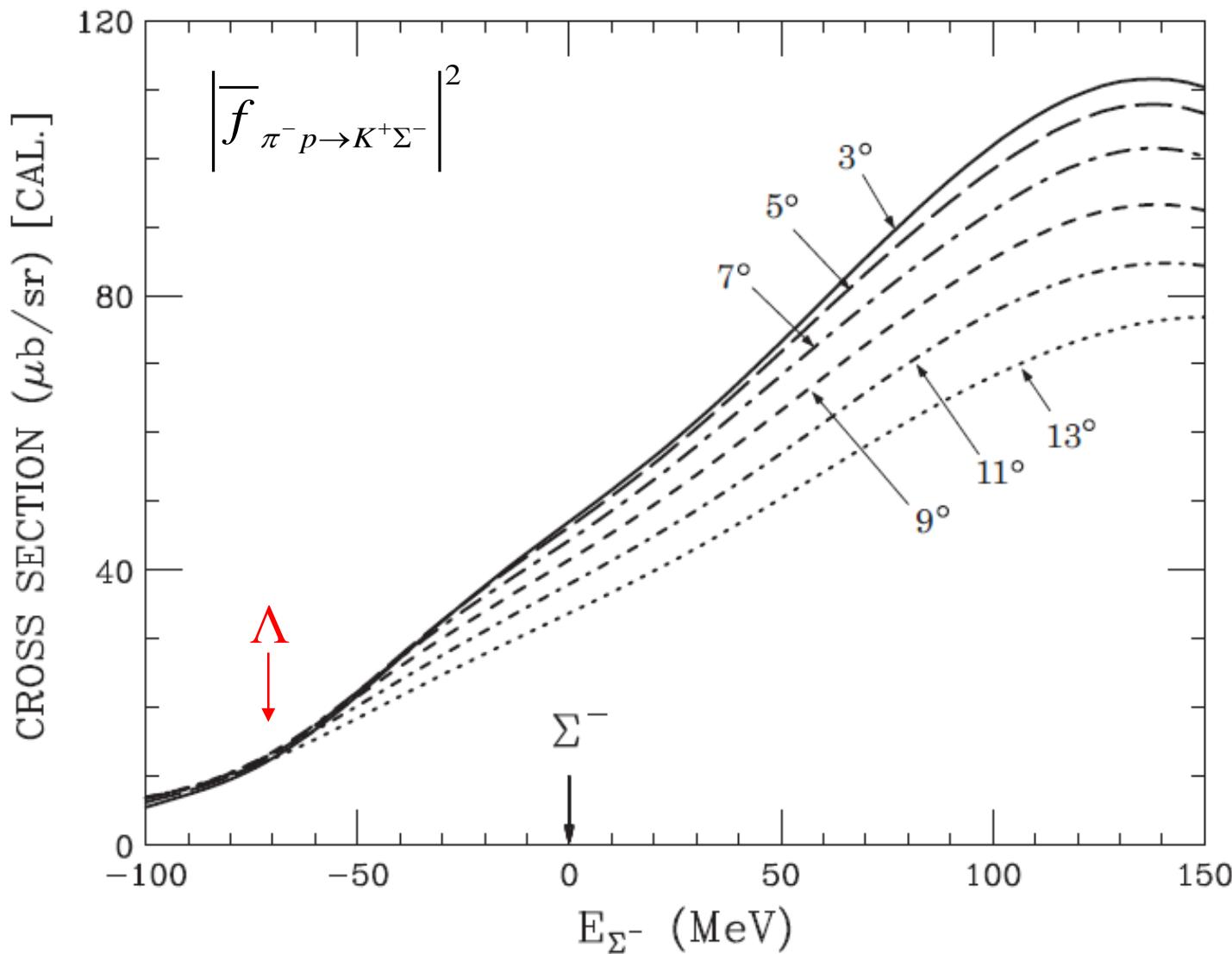
W. Langbein, F. Wagner, Nucl. Phys. B53 (1973) 251, and references therein.

R. Honda, Ph.D. thesis, Tohoku University (2014).

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{cm}}^{\text{elem}} = \lambda^2 \sum_{\ell=0}^{\ell_{\text{max}}} A_\ell(E_{\text{cm}}) P_\ell(\cos \theta_{\text{cm}})$$

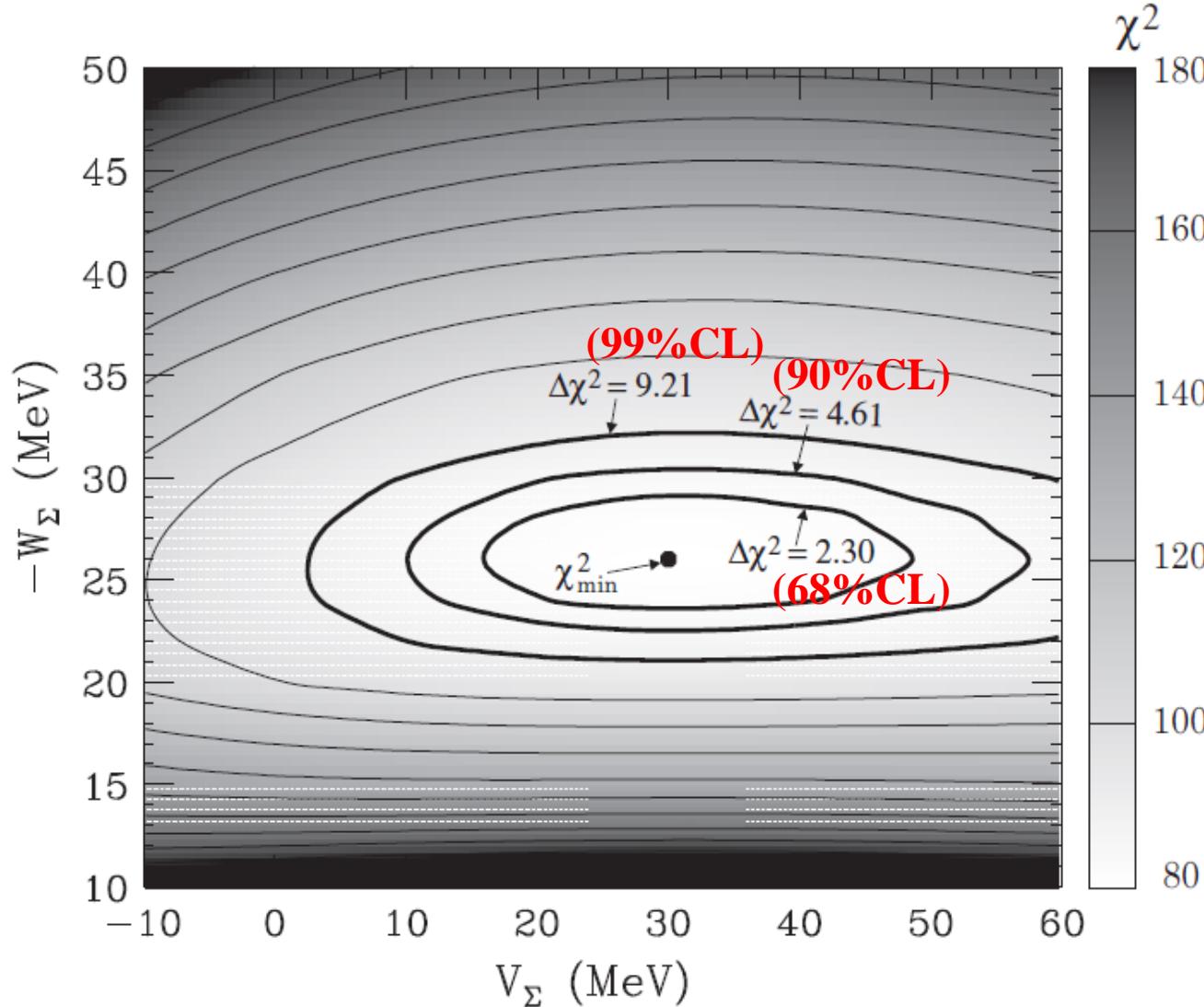
Angular dependence of the optimal Fermi-av. cross section

“ $\pi^- p \rightarrow K^+ \Sigma^-$ reactions” in the nucleus



- There exists a strong energy dependence in the amplitudes.

The χ^2 -value distribution in (V_Σ, W_Σ) plane



- **Fits to the spectrum by the WS potential**

$$U_\Sigma = (V_\Sigma + iW_\Sigma) / [1 + \exp((r - R) / a)]$$

$$R = r_0(A-1)^{1/3} \text{ fm}$$

$$r_0 = 0.835 \text{ fm}$$

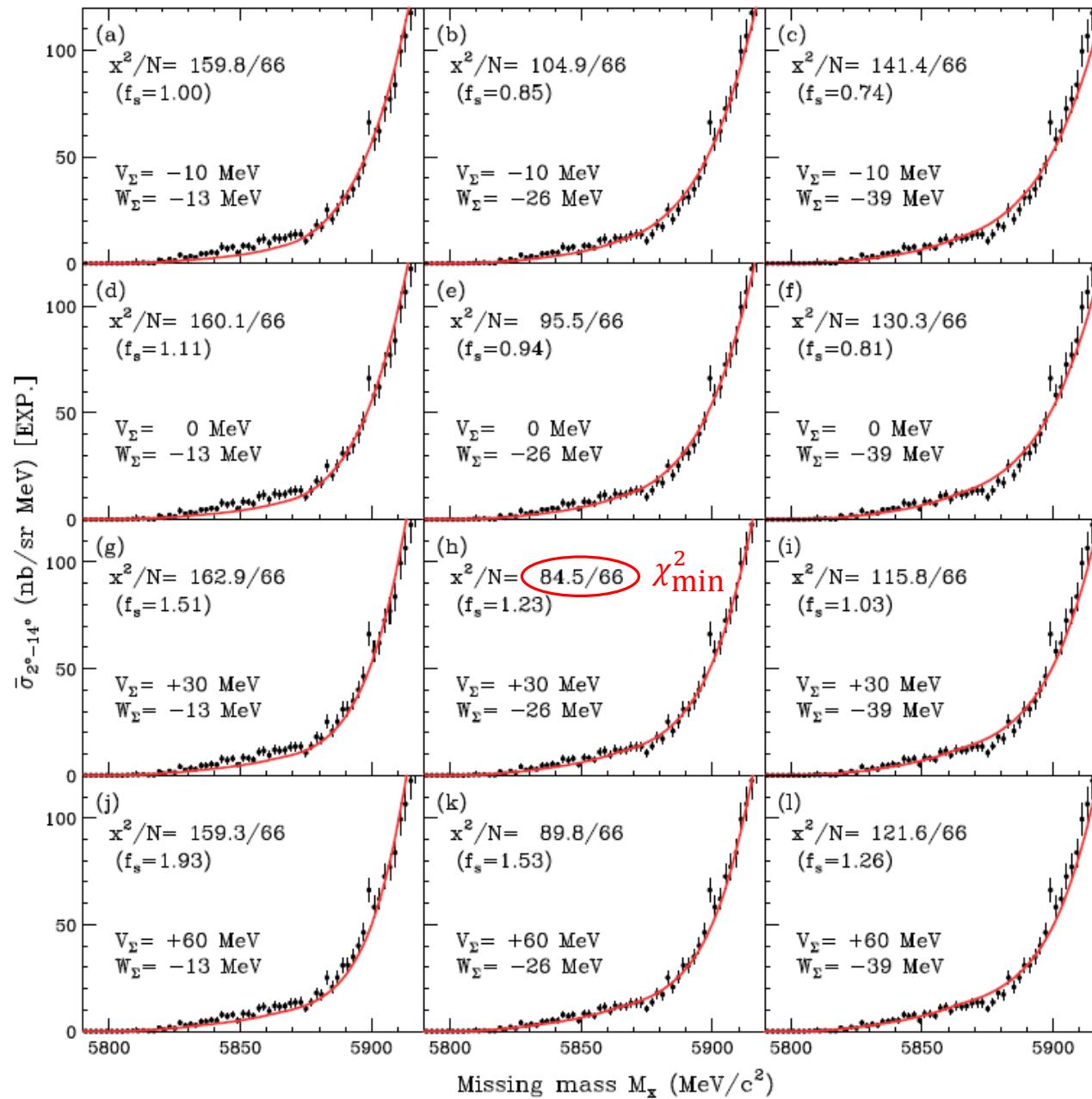
$$a = 0.706 \text{ fm}$$

Results

The χ^2 -fitting for various strength parameters V_Σ and W_Σ in the WS potential for Σ^- - ${}^5\text{He}$ systems.

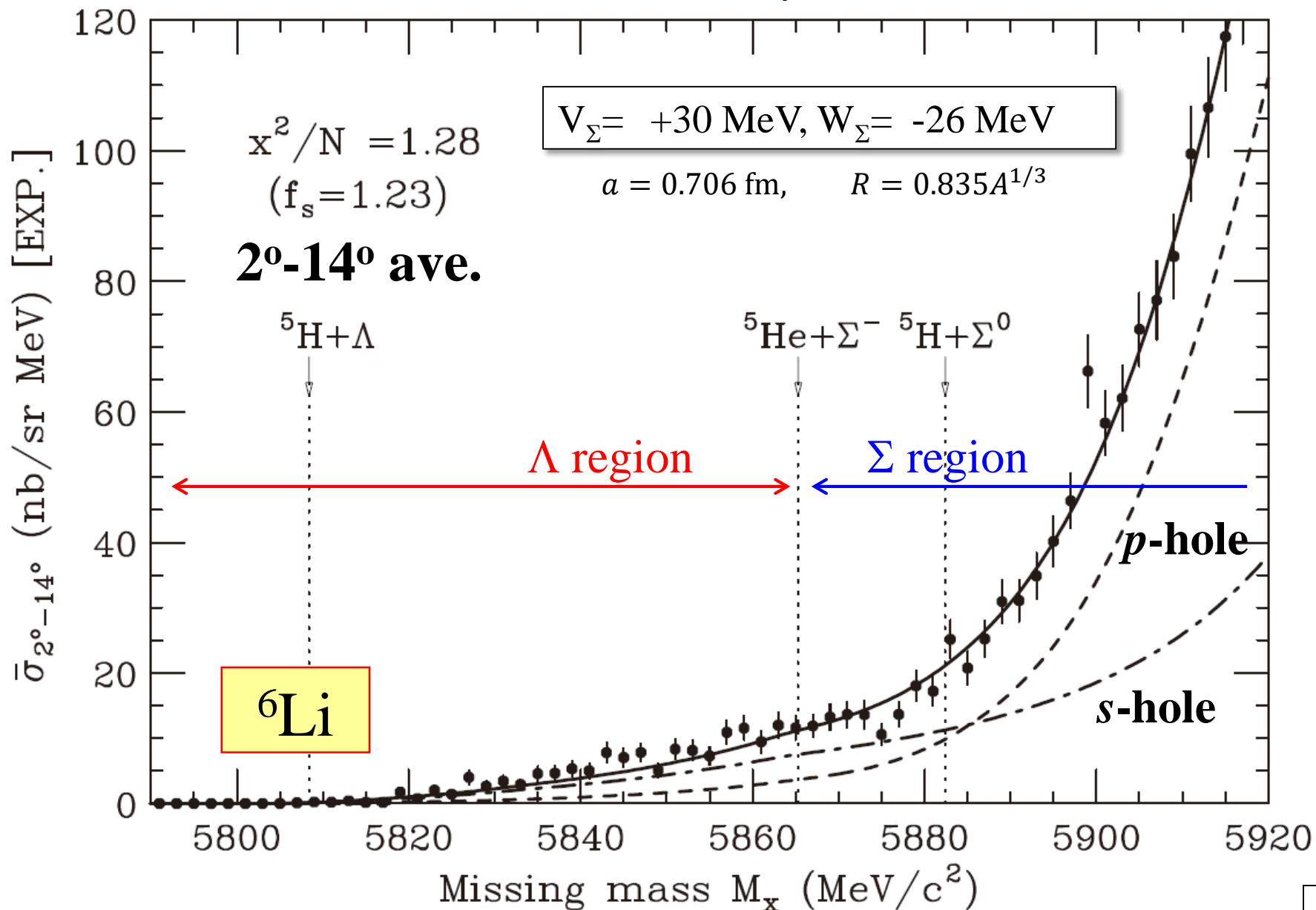
V_Σ (MeV)	W_Σ (MeV)	$\bar{\sigma}_{2^\circ-14^\circ}$	
		χ^2/N	f_s
χ^2_{\min}	-10	159.8/66	1.00
	0	160.1/66	1.11
	+30	162.9/66	1.51
	+60	159.3/66	1.93
	-10	104.9/66	0.85
	0	95.5/66	0.94
	+30	84.5/66	1.28
	+60	89.8/66	1.53
	-10	141.4/66	0.74
	0	130.3/66	0.81
	+30	115.8/66	1.03
	+60	121.6/66	1.26

Inclusive spectrum in ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction at 1.2GeV/c



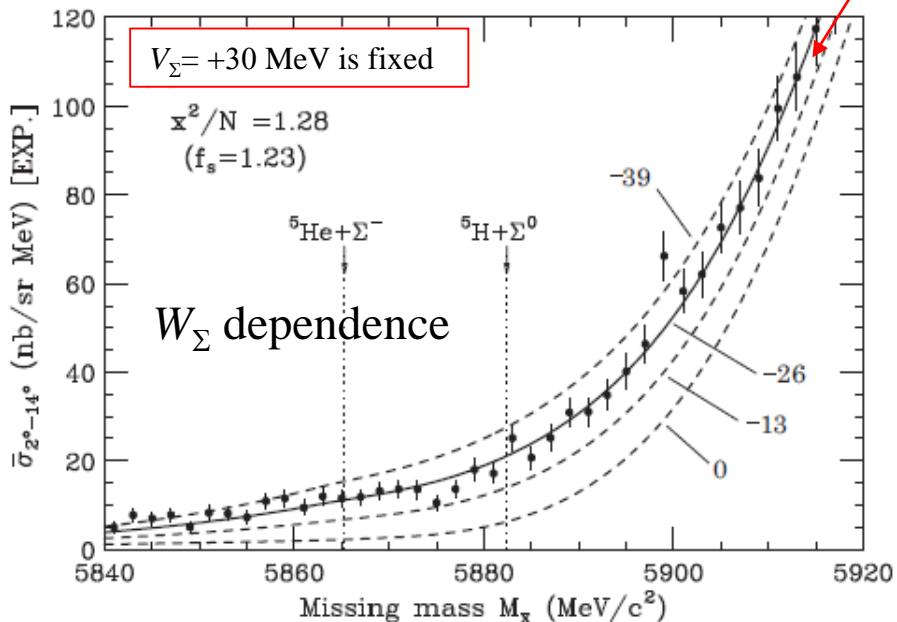
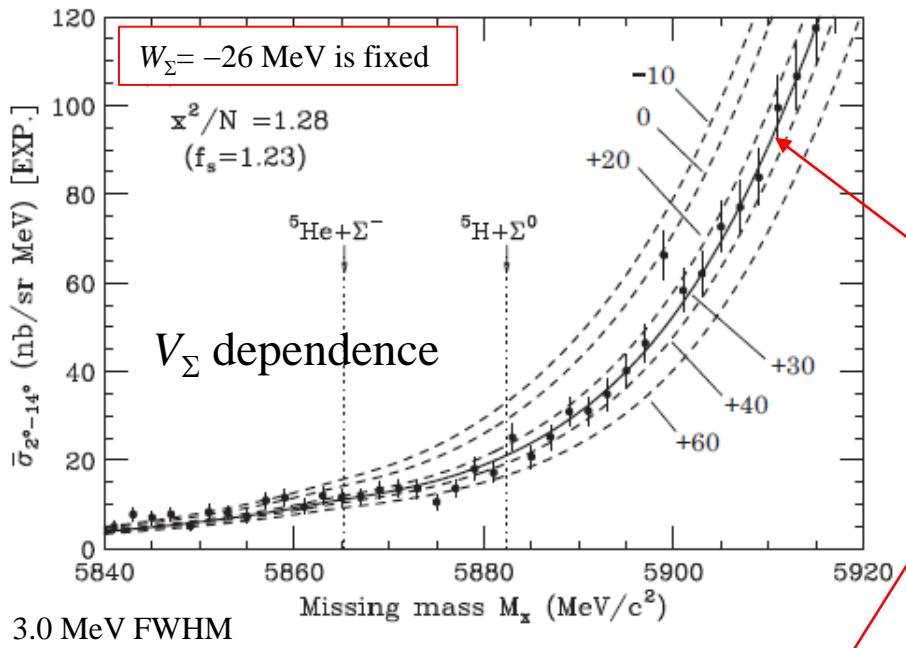
Inclusive spectrum in ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction at 1.2GeV/c

T. Harada, R. Honda, Y. Hirabayashi, PRC 97 (2018) 024601.



Dependence of the calculated spectra for the ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction

Data: R. Honda, et al., (J-PARC E10 Collaboration), PRC96 (2017) 014005



$$p_{\pi^-} = 1.2 \text{ GeV/c}$$

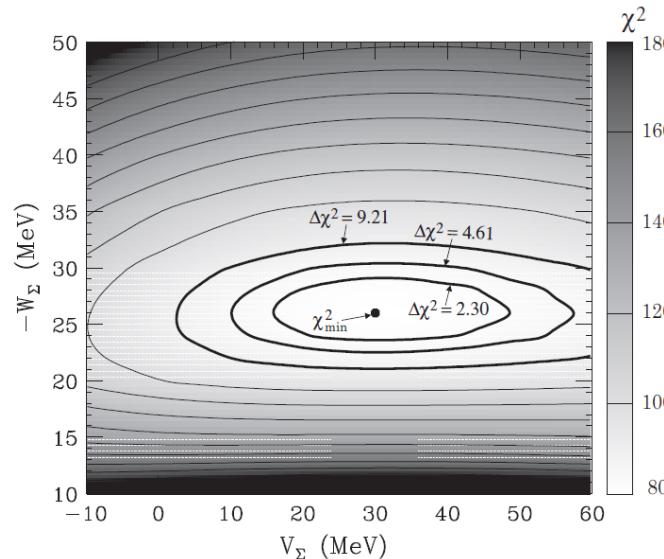
WS potential

The shape and magnitude of the spectrum are sensitive to the strengths of (V_Σ, W_Σ) .

$$(V_\Sigma, W_\Sigma) = (+30, -26) \text{ MeV}$$

$$\chi^2/N = 1.28 \text{ with } f_s \quad (N=66)$$

The χ^2 -value distribution in V_Σ, W_Σ



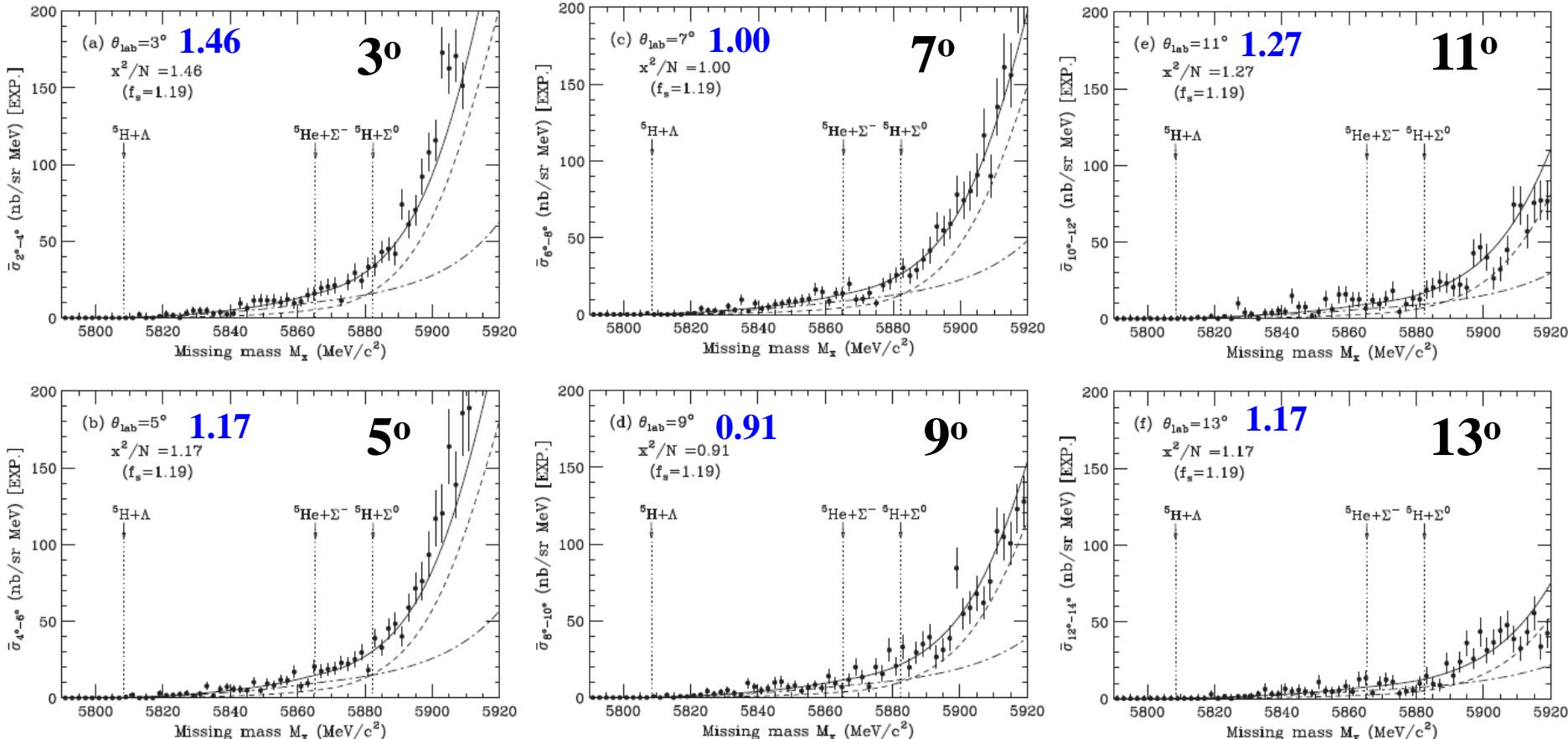
Inclusive spectrum in ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction at 1.2GeV/c

${}^6\text{Li}$

$V_\Sigma = +30 \text{ MeV}, W_\Sigma = -26 \text{ MeV}$

WS potential

$$a = 0.706 \text{ fm}, R = 0.835 A^{1/3}$$



$$\chi^2/N_{\text{all}} = 1.16 \text{ with } f_s = 1.19 \text{ (} N_{\text{all}} = 396 \text{)}$$

Σ -nucleus potentials fitted to the Σ -atomic data

DD-A'

Density-dependent (DD) potential C.J.Batty et al., Phys.Rep.287(1997)385

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

$\chi^2/N=20.1/23$

$\rho(r) = \rho_p(r) + \rho_n(r)$ $\delta\rho(r) = \rho_n(r) - \rho_p(r)$

RMF

Relativistic mean-field (RMF) potential J. Mares et al., NPA594(1995)311
 $\chi^2/N=18.1/23$

LDA-NF

Local density approximation (LDA) with YNG-NF

D. Halderson, Phys. Rev. C40(1989)2173

$\chi^2/N=20.4/23$

T.Yamada and Y.Yamamoto, PTP. Suppl. 117(1994)241

J. Dabrowski, Acta Phys. Pol. B31(2001)2179

Repulsive



LDA-S3

Local density approximation (LDA) with SAP3 (simulates ND)

T.Harada, in: Proceedings of the 23nd INS Symp. 1995, p.211

Attractive

WS-sh

Shallow Woods-Saxon potential: $(V_0, W_0) = (-10, -9)$ MeV

R.S.Hayano, NPA478(1988)113c

t_{eff} ρ

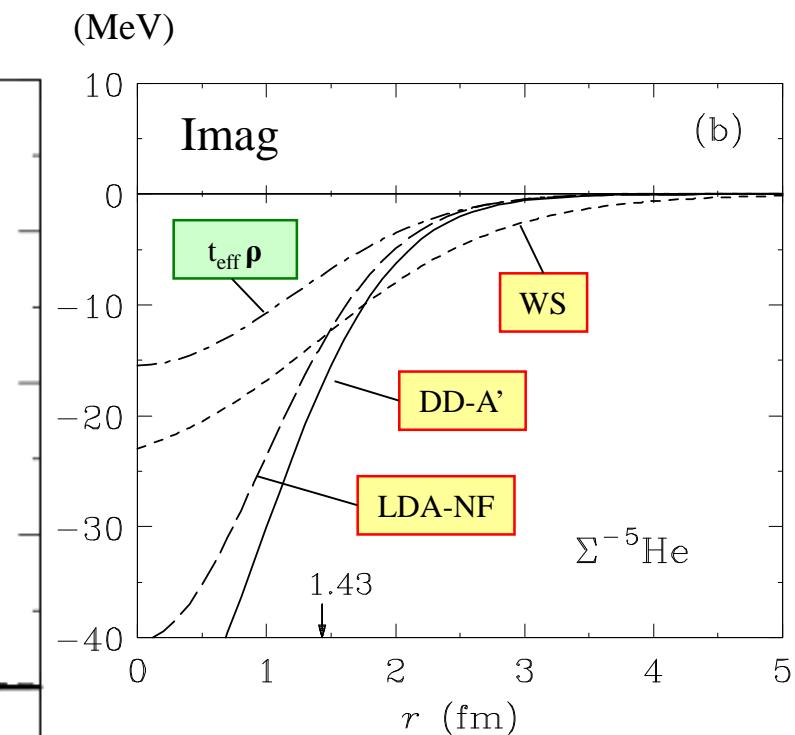
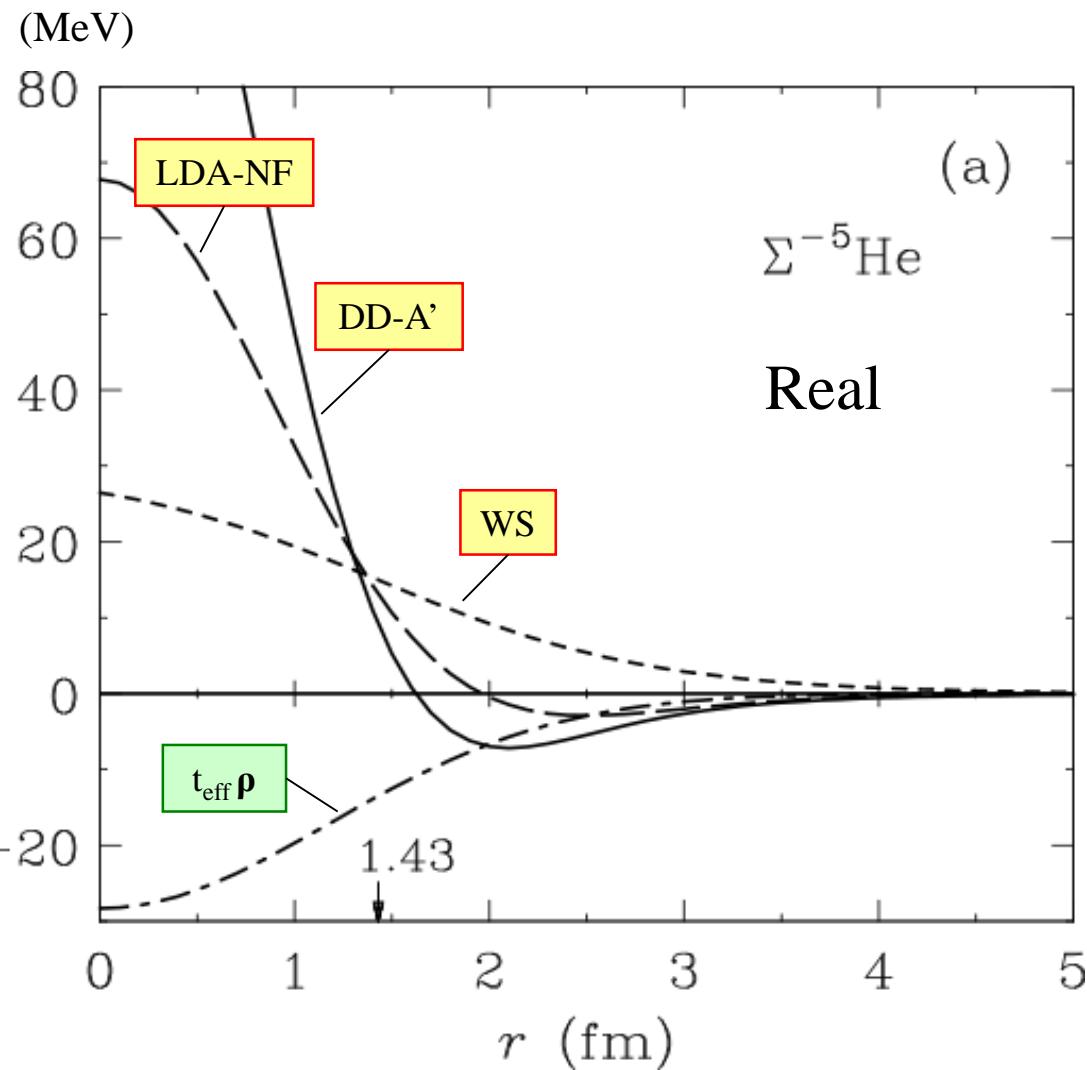
t_{eff} ρ -type potential ($B_0=B_1=0$): $a_0=0.36+i0.20$ fm

C.J.Batty, E.Friedman, A.Gal, PTP. Suppl. 117(1994)227

$\chi^2/N=23.1/23$

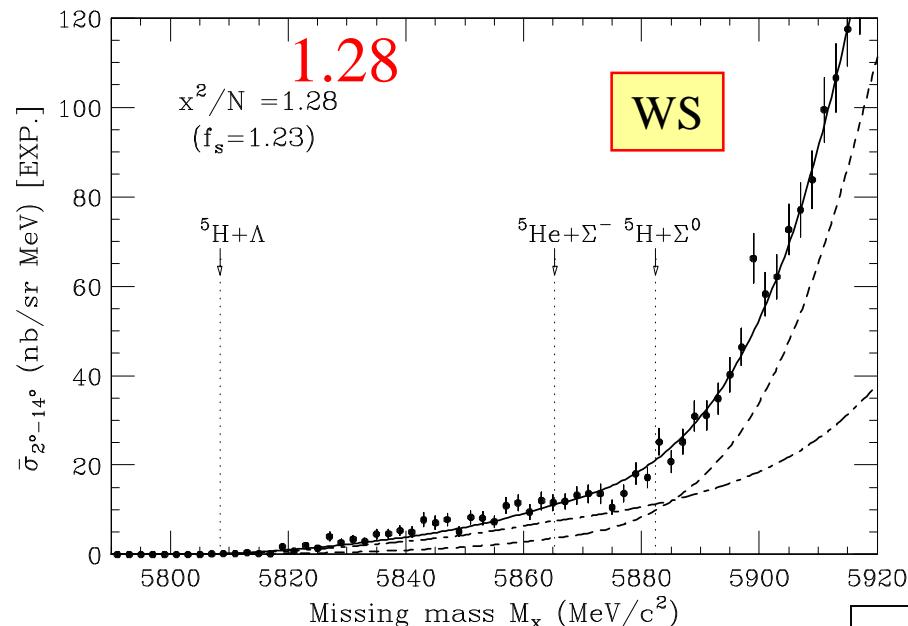
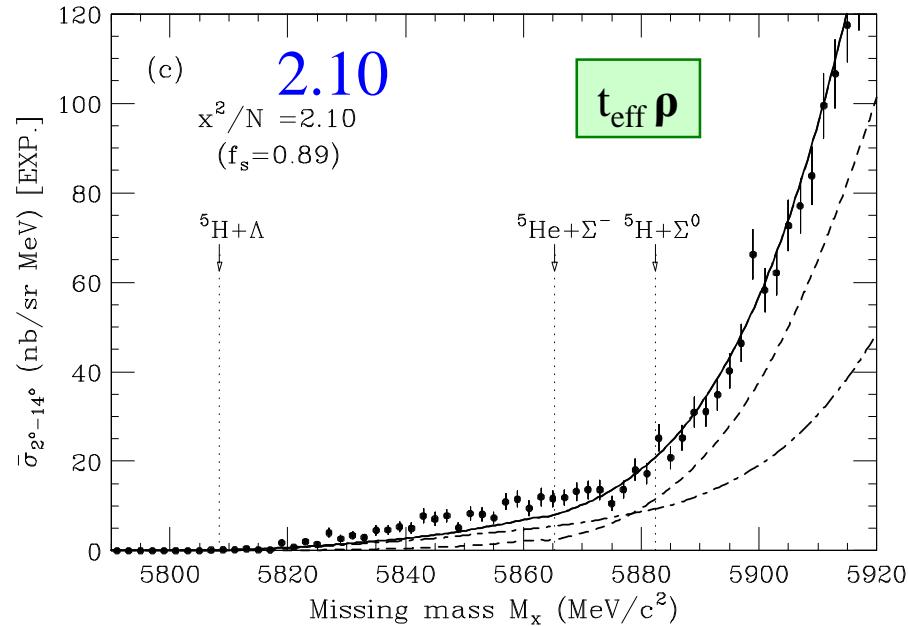
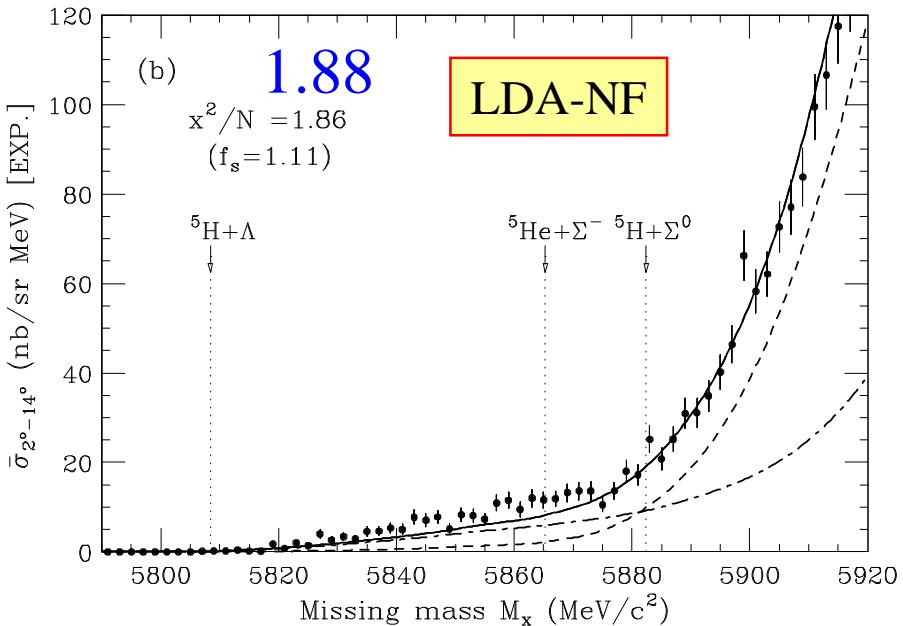
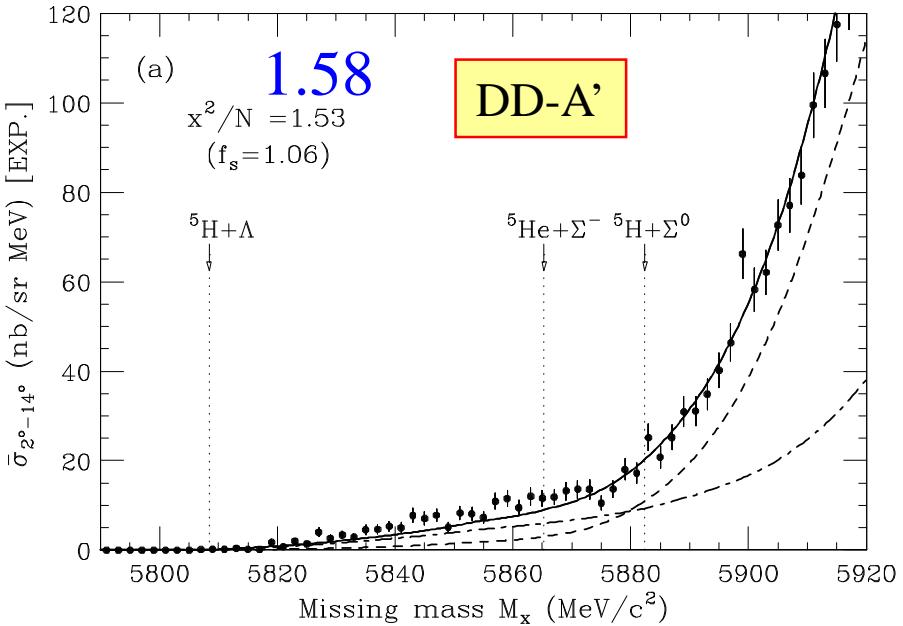
Σ^- -nucleus optical potentials in ${}^5\text{He} + \Sigma^-$

by using microscopic cluster wave functions



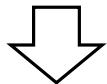
⇒ 励起状態に対する微視的な検討が必要(進行中)

Inclusive spectrum in ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction at 1.2GeV/c



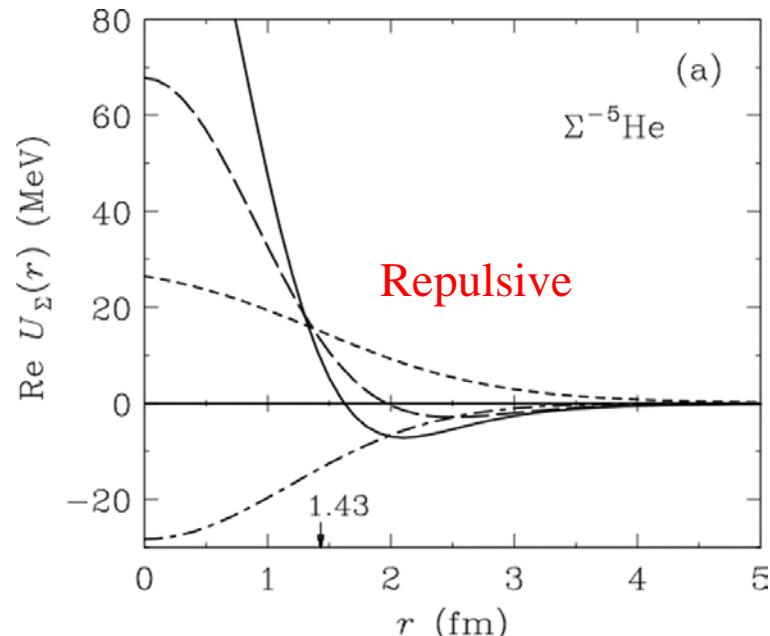
Remarks

- The calculated DWIA spectrum can fully explain the experimental data of the ${}^6\text{Li}(\pi^-, \text{K}^+)$ reaction at 1.2 GeV/c.
- The optimal Fermi-averaged t -matrix of $\pi^- p \rightarrow \text{K}^+ \Sigma^-$ reactions is essential to describe the energy and angular dependence of the data.
- The results show that the Σ^- - ${}^5\text{He}$ potential has the **repulsive** and **absorptive** components with $(V_\Sigma, W_\Sigma) = (+30 \text{ MeV}, -26 \text{ MeV})$ with the WS potential.



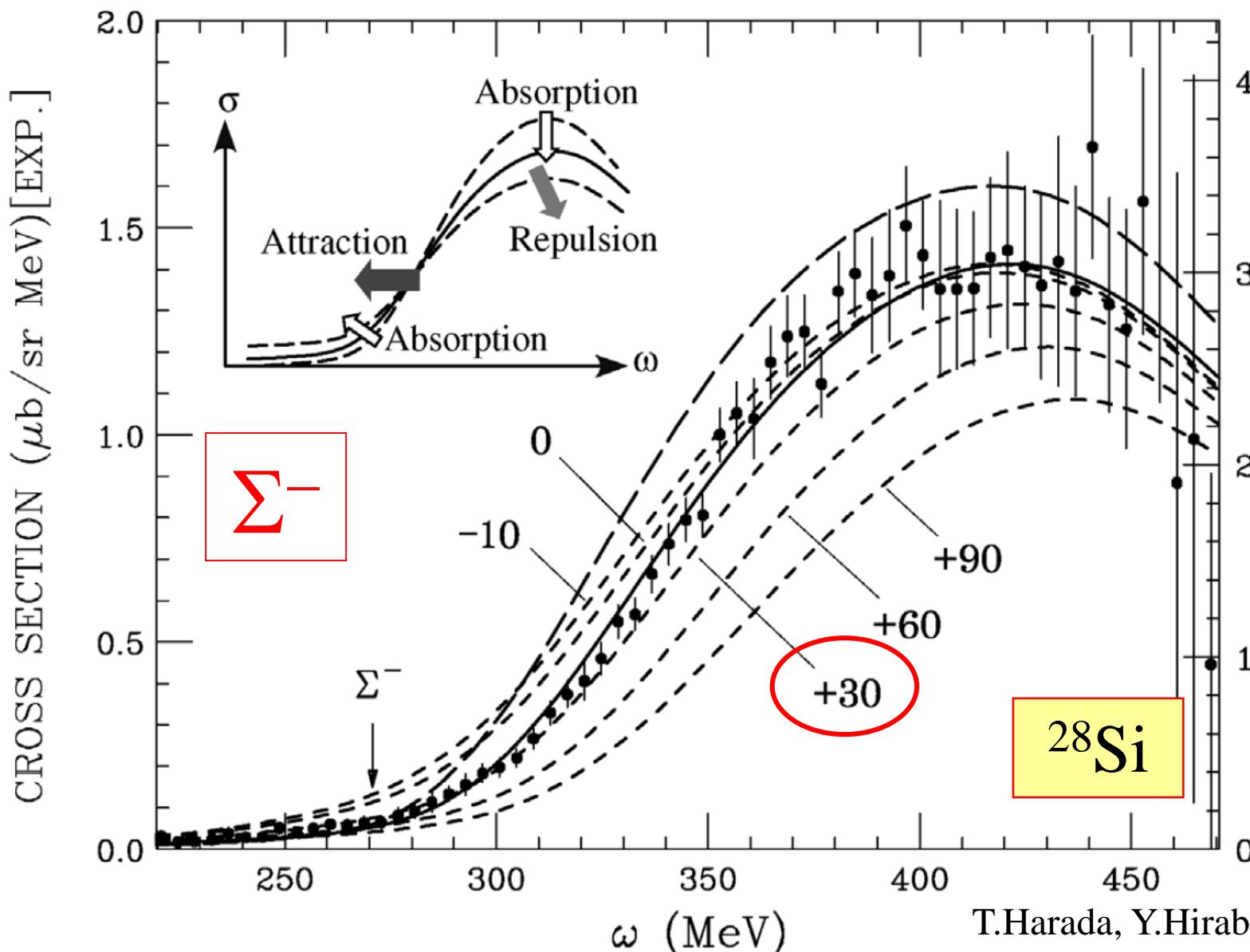
$(V_\Sigma, W_\Sigma) = (+48 \pm 16, -42 \pm 3) \text{ MeV}$
for N.M.

$(V_\Sigma, W_\Sigma) = (+30, -40) \text{ MeV}$ for ${}^{28}\text{Si}$
by Harada-Hirabayashi, NP759 (2005) 143



Inclusive spectrum in $^{28}\text{Si}(\pi^-, \text{K}^+)$ reaction at 1.2GeV/c

Exp. Data from P.K.Saha, H. Noumi, et al., PRC70(2004)044613

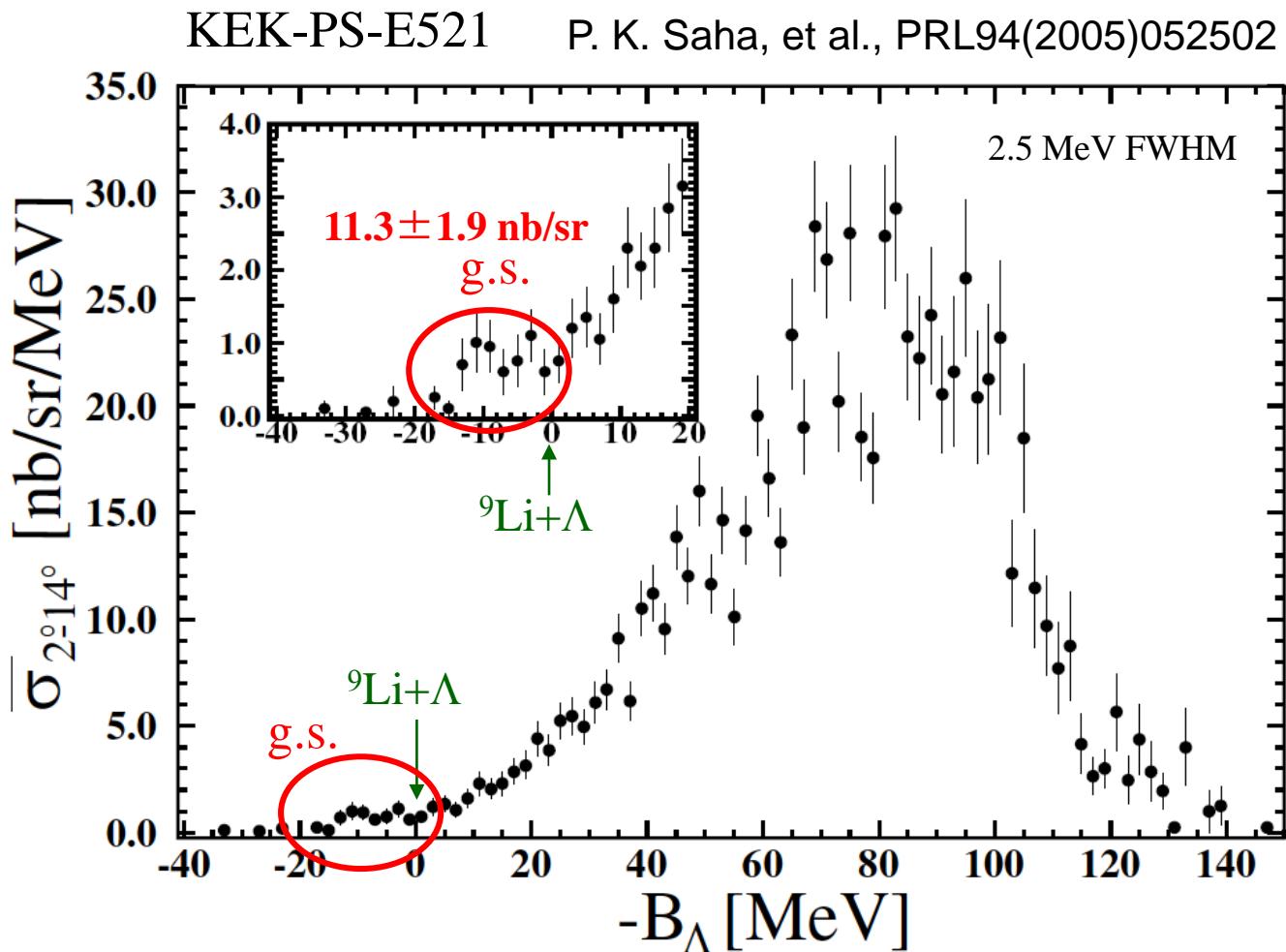


T.Harada, Y.Hirabayashi,
NPA759 (2005) 143

First production of neutron-rich Λ hypernuclei



Λ spectrum by DCX (π^- , K^+) reaction at 1.2GeV/c



Cross sections

- $p_\pi = 1.20 \text{ GeV/c}$
 $\frac{d\sigma}{d\Omega_L} \approx 11.3 \pm 1.9 \text{ nb/sr}$

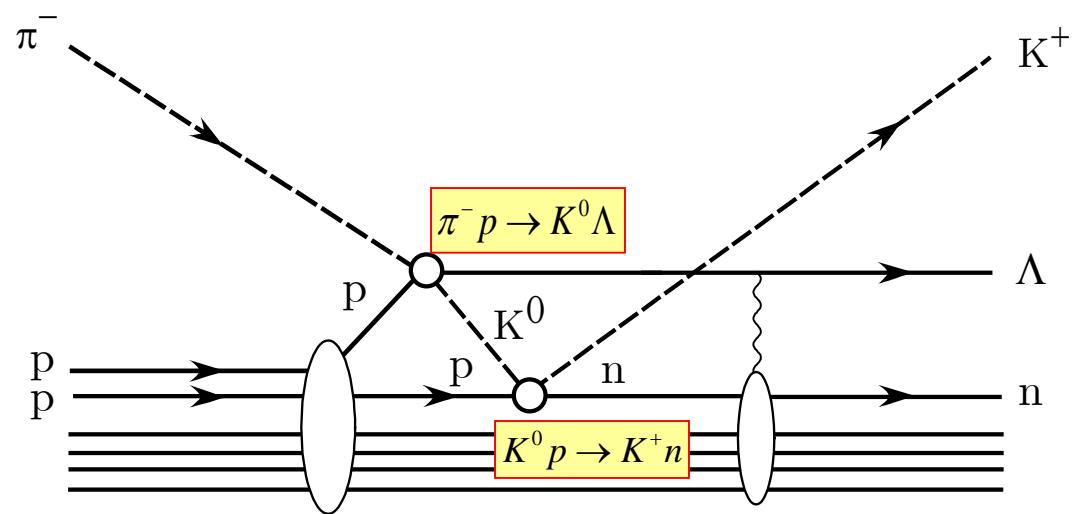
- $p_\pi = 1.05 \text{ GeV/c}$
 $\frac{d\sigma}{d\Omega_L} \approx 5.8 \pm 2.2 \text{ nb/sr}$

$\sim 1/1000$

${}^{12}\text{C}(\pi^+, K^+) {}_{\Lambda}^{12}\text{C}$ (1.2 GeV/c)
 $17.5 \pm 0.6 \mu\text{b/sr}$

$(\pi^-$, $K^+)$ – Double Charge Exchange (DCX) Reaction

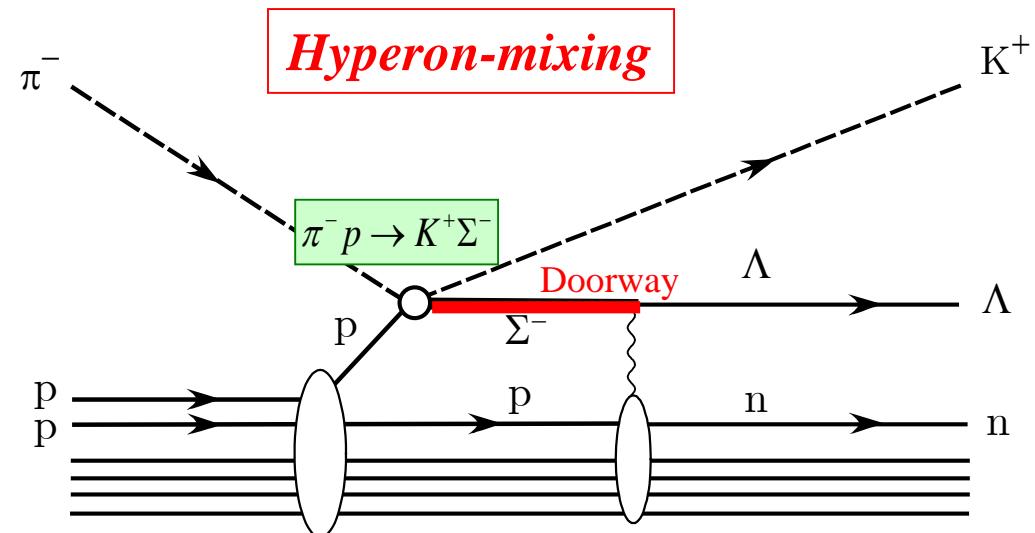
Two-step process:



One-step process:



via Σ^- doorways caused by ΛN - ΣN coupling



Λ spectrum by DCX (π^- , K^+) reactions at 1.2GeV/c

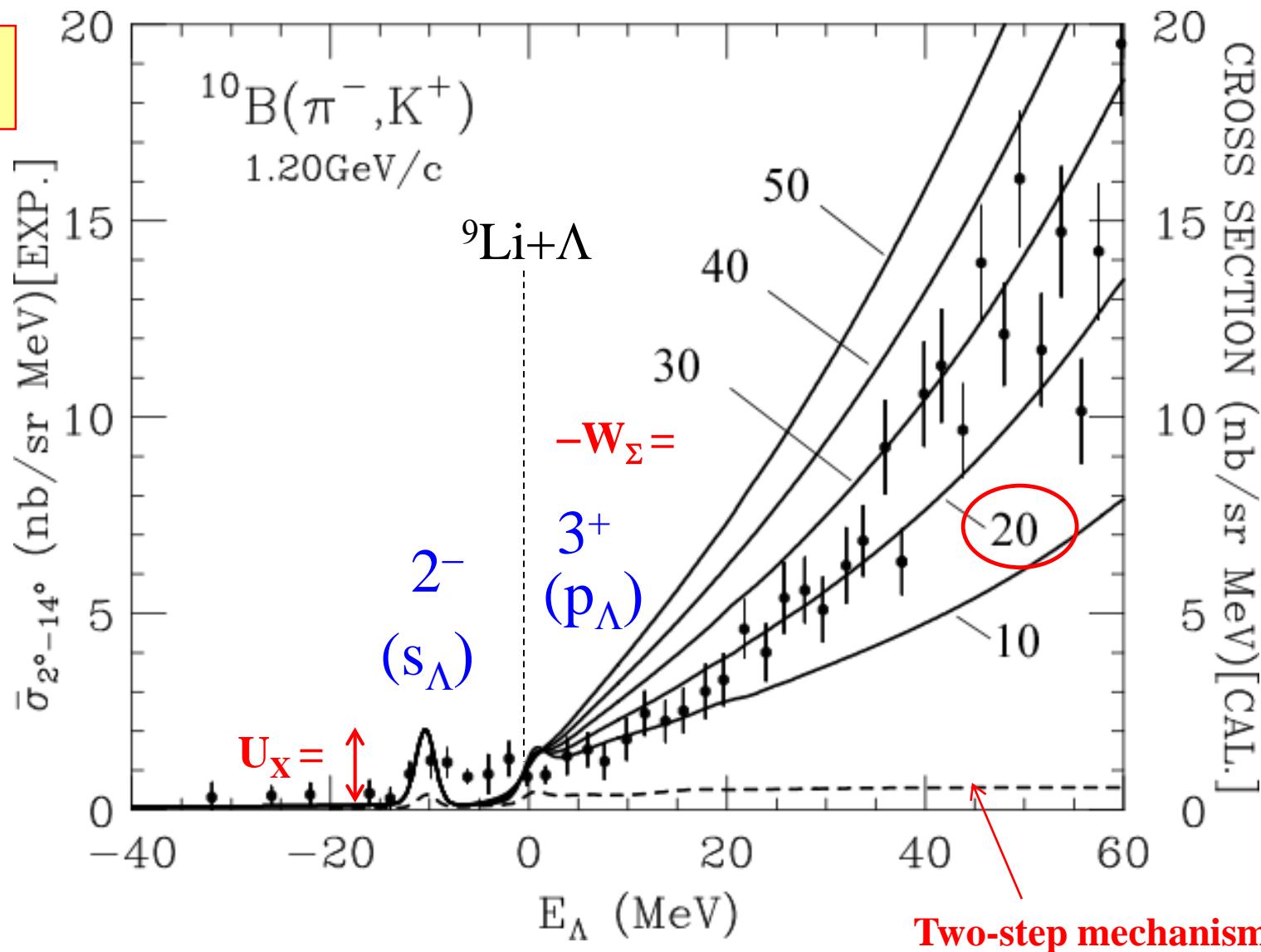
Harada, Umeya,Hirabayashi, PRC79(2009)014603

Spreading potential dep.

W_Σ

$U_X = 11$ MeV is fixed. $P_{\Sigma^-} = 0.57\%$

^{10}B



2017年度 J-PARC分室活動報告 (原田)

- 「ストレンジネス核物理」共同研究
6月10日(土)～ 6月13日(火) J-PARC分室@東海

J-PARC素粒子原子核セミナー

「Competing effects of nuclear deformation and hyperonic many-body force
on Lambda binding energy」 井坂 政裕(大阪大学核物理研究センター)

- 「ストレンジネス核物理」共同研究
7月 1日(土)～ 7月 3日(月) J-PARC分室@東海
- 「ストレンジネス核物理」共同研究
10月14日(土)～10月16日(月) J-PARC分室@東海

Summary

“DCX reactions via hyperon doorways”

- We have investigated production spectra of Λ , Σ and Ξ - $\Lambda\Lambda$ hypernuclear states in DCX reactions such as (π^-, K^+) and (K^-, K^+) reactions in terms of the *hyperon mixing* caused by the ΛN - ΣN (ΞN - $\Lambda\Lambda$) coupling.



“Coupled-channel calculations for hypernuclei ”

${}^{16}\text{O}(\text{K}^-, \text{K}^+) {}_{\Xi, \Lambda\Lambda}{}^{16}\text{C}$ / p -wave resonant state in ${}^4_{\Sigma}\text{He}$ /
 ΣNN quasibound state by ${}^3\text{He}(\text{K}^-, \pi^\mp)$ reactions /
 ${}^3\text{He}(\text{K}^-, \pi^-)\text{pp}\Lambda$ reactions + CDCC /

- *The channel coupling is important to give a description of the dynamics in hypernuclear physics.*

**Thank you very much
for your attention.**