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Production spectra of ^{3}He(π, K) reactions with continuum discretized coupled channels

T. Harada, Y. Hirabayashi†

Osaka Electro-Communication University, Neyaawa 572-8530, Japan
J-PARC Branch, KEK Theory Center, IPNS, KEK, Tokai, Ibaraki, 319-1106, Japan
† Information Initiative Center, Hokkaido University, Sapporo 060-0811, Japan

Outline

1. Introduction - ${}^{3}_{\Lambda}$H puzzle, *nn*Λ bound state?
2. Calculations
   - Continuum *pp*Λ states by the CDCC method
   - Microscopic (*pp*)-Λ folding-model potentials
   - Fermi-averaged amplitudes for πN-ΛK reactions
3. Results and Discussion
   - ^{3}He(π^{+}, K^{+})*pp*Λ at 1.20GeV/c
   - ^{3}He(π^{-}, K^{0})${}^{3}_{\Lambda}$H, *pn*Λ at 1.20GeV/c
4. Summary

1. Introduction

Lightest 3B Λ hypernucleus

■ The $^3_\Lambda$H lifetime puzzle

- Hypertriton ($^3_\Lambda$H) with B_Λ=130±50 keV is expected to have lifetime within a few % of the free Λ lifetime (τ_Λ =263.2±2.0 ps), which is supported by precise theoretical calculations.

- Recently, three heavy ion experiments found surprisingly short lifetime for $^3_\Lambda$H by STAR, HypHI and ALICE.

  $\tau(^3_\Lambda\mathrm{H})$ w.av = 185^{+28}_{-23} ps (–30% with reference to τ_Λ)

→ To solve the puzzle, experimental measurements of $^3_\Lambda$H lifetime are planned at J-PARC.

^{3}He(K$^-$,π^0) , ^{3}He(π^-, K^0) @J-PARC

■ Is there a nnΛ bound/resonant state ?

- The HypHI collaboration reported a bound nnΛ system.
- Theoretical calculations suggest that no $^3_\Lambda$n bound state exists.

^{3}H(e,e'K$^+$)nnΛ@JLAB, ^{3}He(K$^-$,π^+)nnΛ@J-PARC ← ^{3}He(π^+, K$^+$)ppΛ

In this talk,

We investigate theoretically the inclusive spectrum of the **^{3}He(π, K) reaction at 1.20 GeV/c** in the distorted-wave impulse approximation (DWIA), using the Continuum-Discretized Coupled-Channel (CDCC) method.

I will focus on

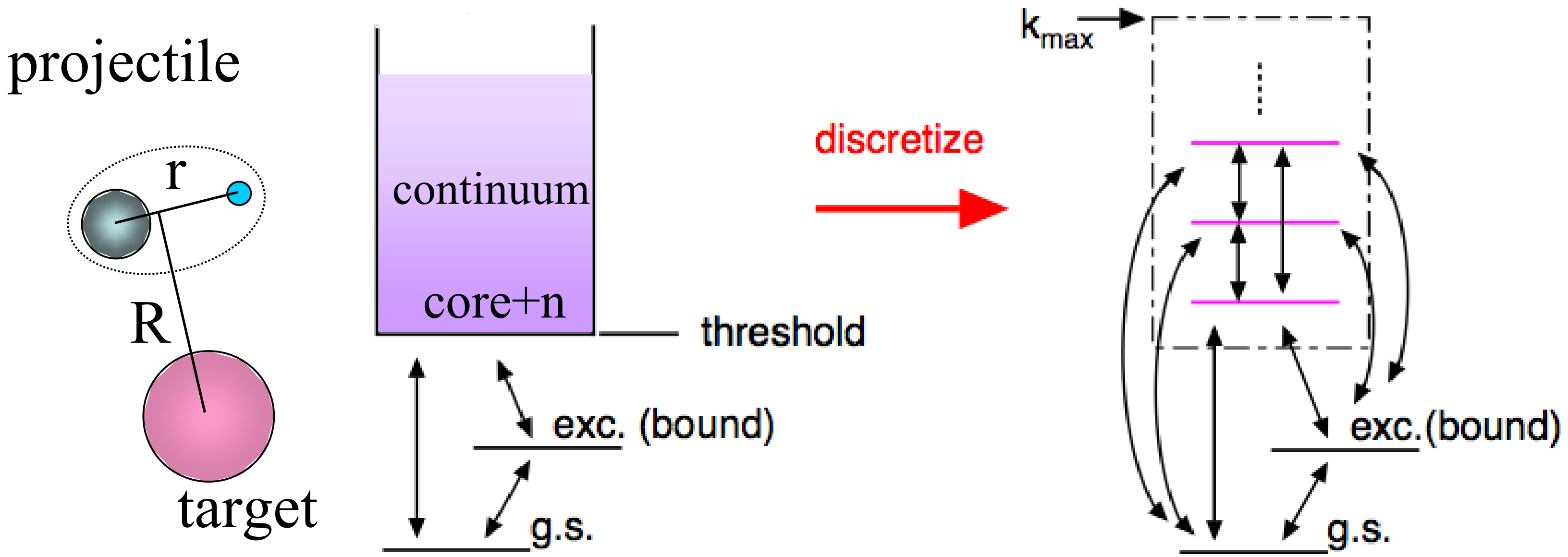
i. the Λ production spectra with CDCC in order to well describe the *pp* continuum states above the $p+p+\Lambda$ breakup threshold. **^{3}He(π^{+}, K^{+})ppΛ**

ii. the production cross section of the $^{3}_{\Lambda}$H$_{g.s.}$ (1/2^{+}) bound state and continuum states, considering the framework of the CDCC. **^{3}He(π^{-}, K^{0})pnΛ**

2. Calculations

Continuum-Discretized Coupled-Channel Method (CDCC)

M. Kamimura et al., Prog. Theor. Phys. Suppl. 89, 1 (1986)

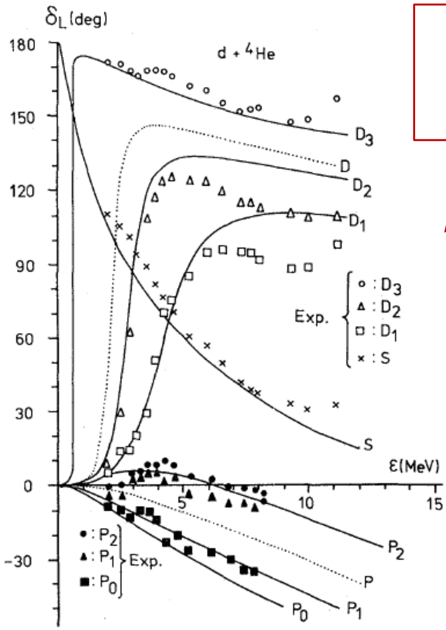


by Takashina

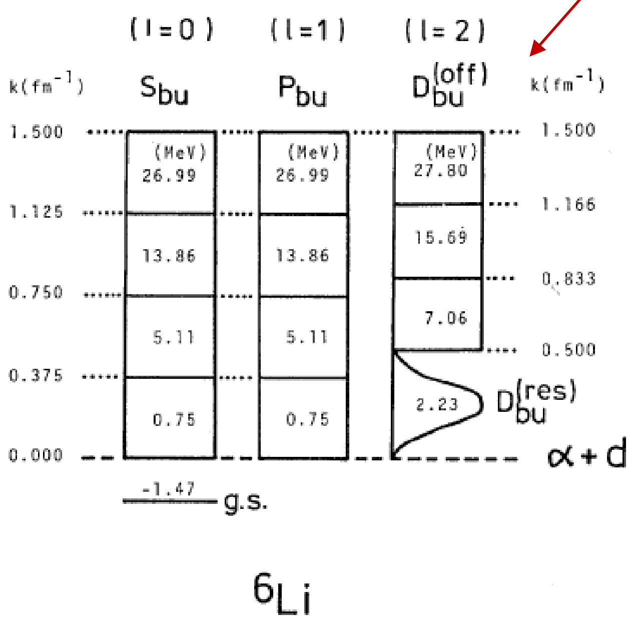
- We can describe the spectra and cross sections taking into account the continuum couplings together with the nuclear 3-body breakup processes.

CDCC calculations for ^{6}Li+^{58}Ni elastic scattering

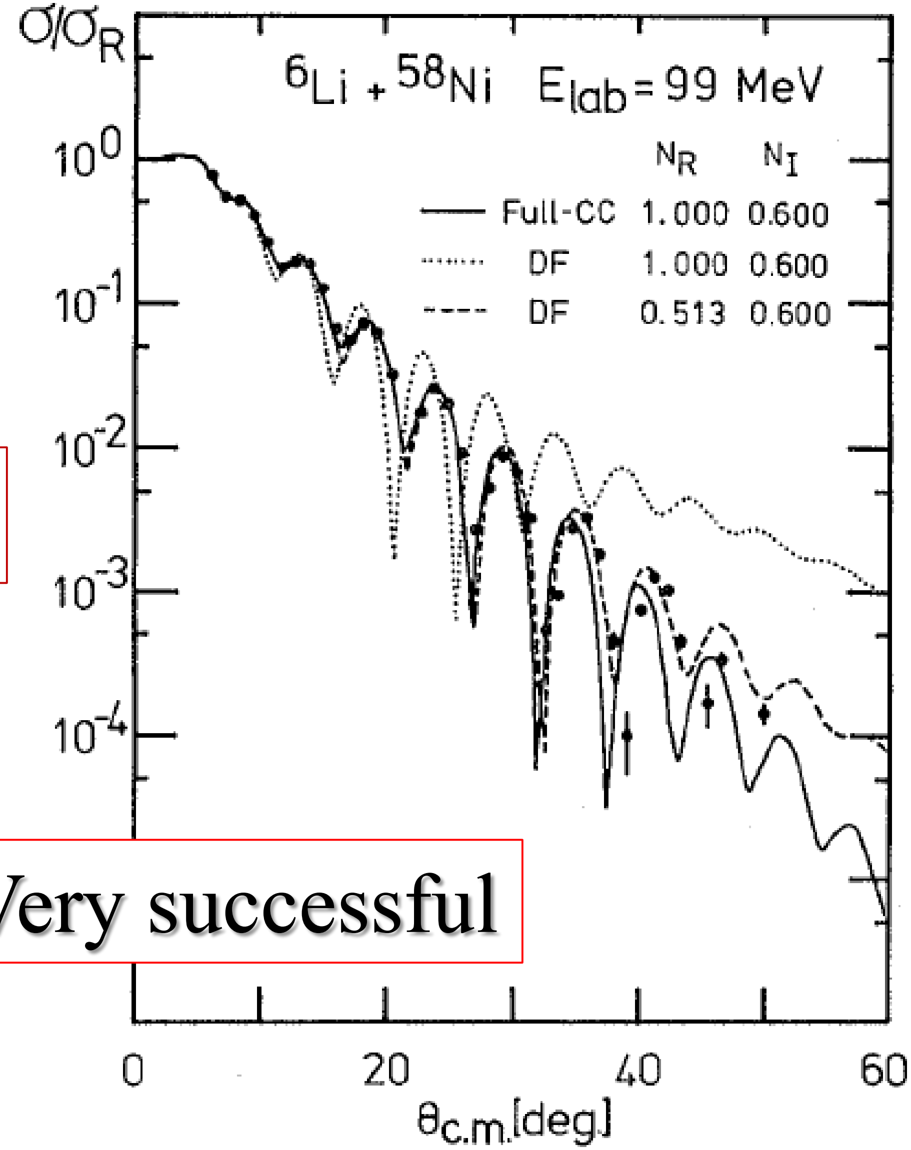
Y. Sakuragi et al., PTP. Suppl. 89, 136 (1986)



Phase shifts of d+α



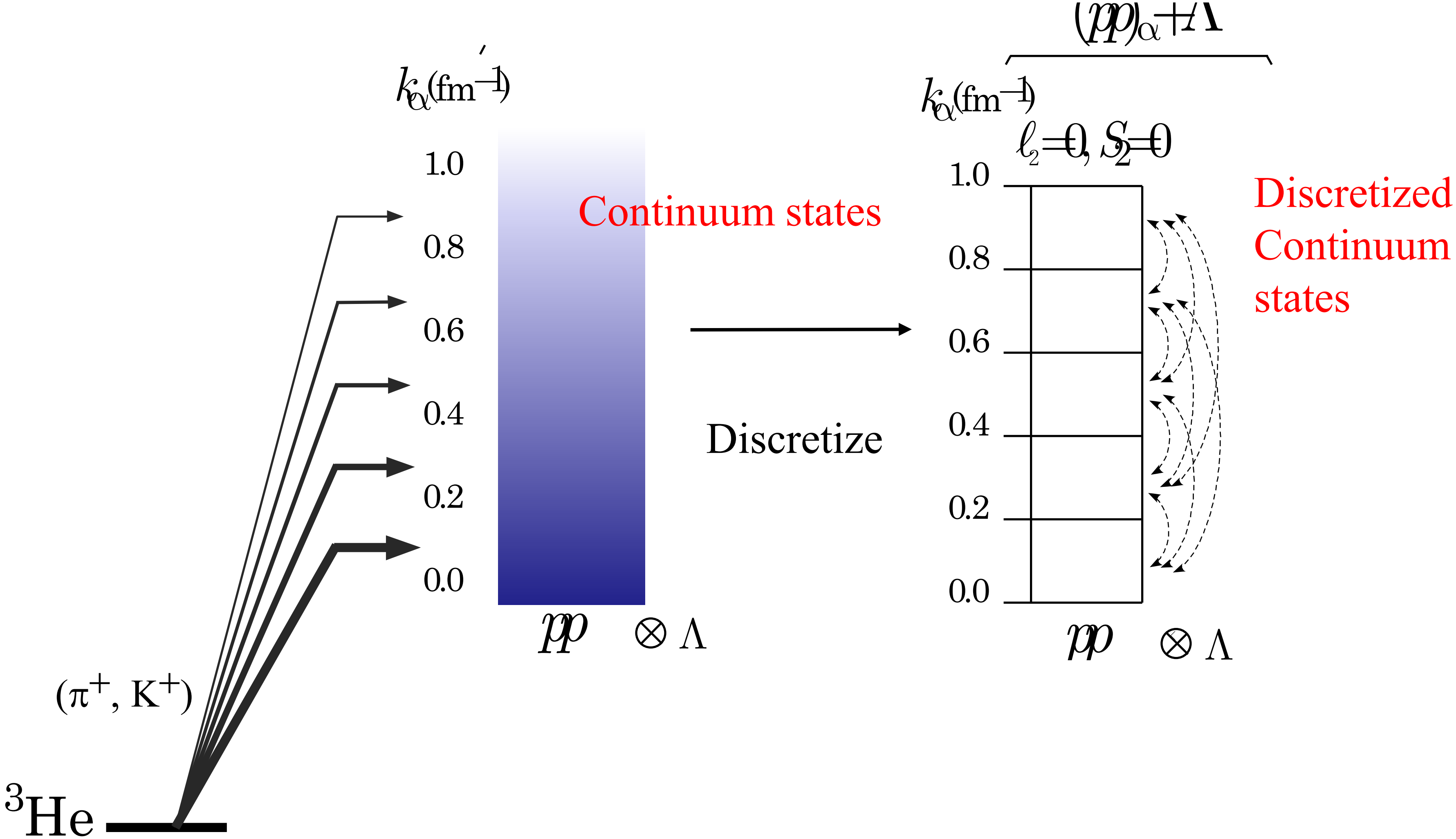
Model space of d+α



Very successful

Continuum-Discretized Coupled-Channel Method (CDCC)

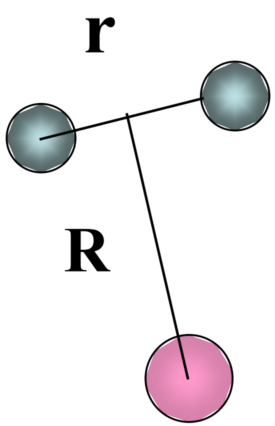
^{3}He (π^+, K$^+$) $pp\Lambda$



Wavefunction of the initial state for a 3He target nucleus

$$|\Psi_A\rangle = \hat{\mathcal{A}}\left[\left[\phi_0^{(2N)} \otimes \varphi_0^{(N)}\right]_{L_A} \otimes X^A_{T_A,S_A}\right]^{M_A}_{J_A},$$

$$X^A_{T_A,S_A} = \left[\chi^{(2N)}_{I_2,S_2} \otimes \chi^{(N)}_{1/2,1/2}\right]_{1/2,1/2},$$



Wavefunctions of final states for ppΛ

$$\Psi_B \simeq \Psi_B^{\rm CDCC}(\boldsymbol{r}, \boldsymbol{R})$$

$$= \sum_{\alpha=1}^{N_{\rm max}} \left[\left[\tilde{\phi}^{(2N)}_{\alpha,\ell_2}(\boldsymbol{r}) \otimes \varphi^{(\Lambda)}_{\alpha,\ell_\Lambda}(\boldsymbol{R})\right]_{L_B} \otimes X^B_{I_\alpha,S_\alpha}\right]^{M_B}_{J_B}$$

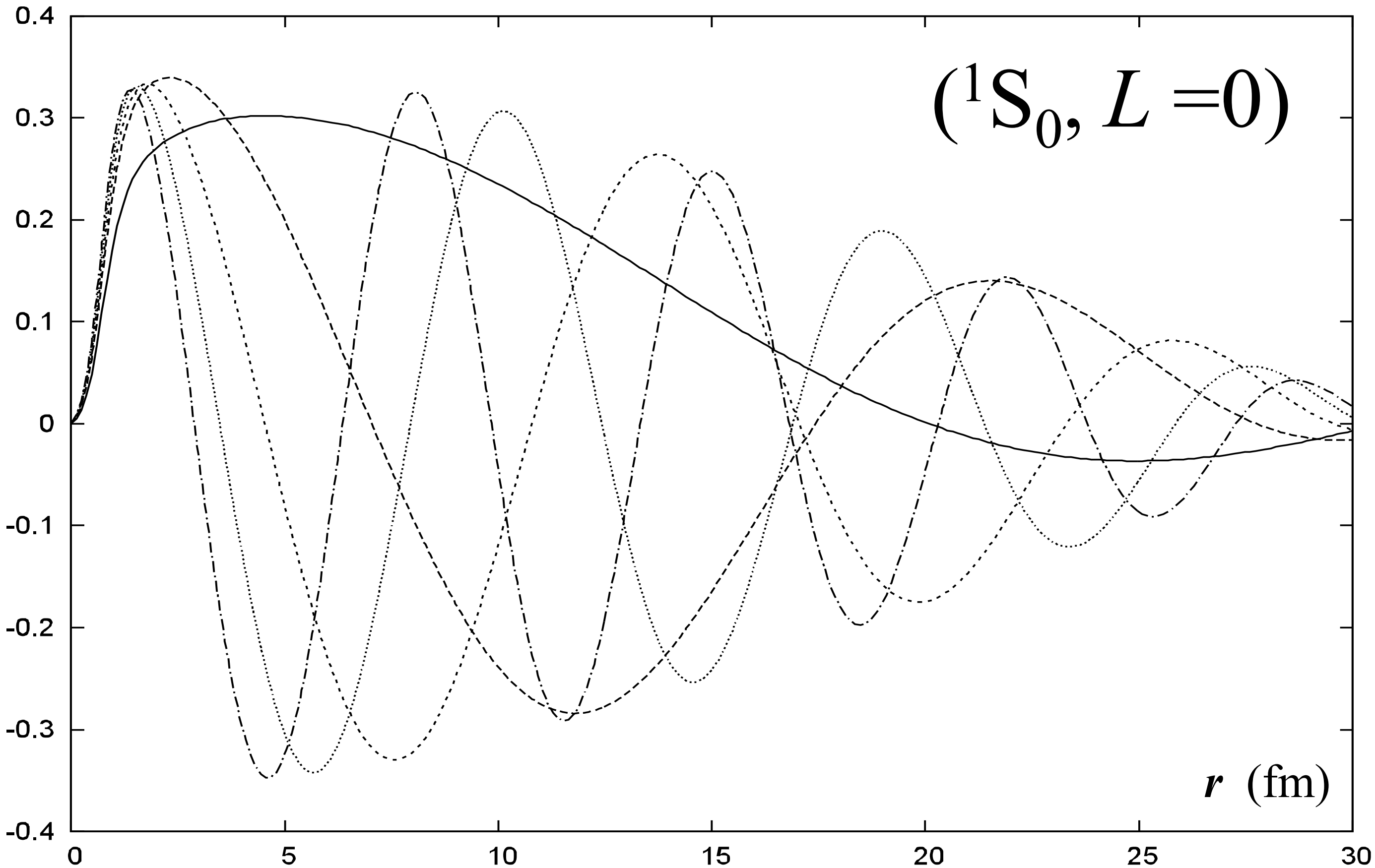
discretized w.f. for continuum pp states

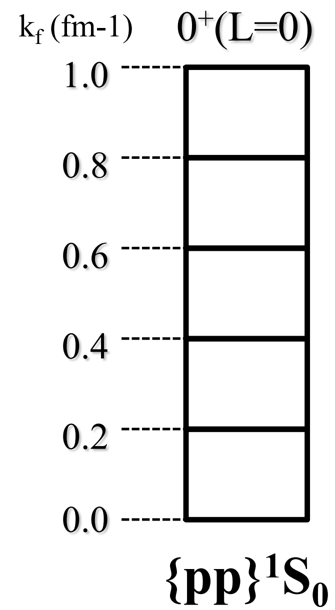
$$X^B_{I_\alpha,S_\alpha} = \left[\chi^{(2N)}_{I_2,S_2} \otimes \chi^{(\Lambda)}_{0,1/2}\right]_{I_\alpha,S_\alpha},$$

Method of momentum bins (discretized for the pp-systems)

$$\tilde{\phi}^{(2N)}_{\alpha,\ell_2}(\boldsymbol{r}) = \frac{1}{\sqrt{\Delta k}} \int_{k_\alpha}^{k_{\alpha+1}} \phi^{(2N)}_{\ell_2}(k,\boldsymbol{r})dk$$

$$\int d\boldsymbol{r}\, \tilde{\phi}^{(2N)}_{\alpha,\ell_2}(\boldsymbol{r})\tilde{\phi}^{(2N)}_{\alpha',\ell_2}(\boldsymbol{r}) = \delta_{\alpha\alpha'}$$





Coupled equations for the (pp)-Λ systems

$$\left[-\frac{1}{2\mu_\alpha}\nabla^2 + U_{\alpha\alpha}(\boldsymbol{R}) - (E - \bar{\varepsilon}_\alpha)\right]\varphi^{(\Lambda)}_{\alpha,\ell_\Lambda}(\boldsymbol{R})$$

$$= -\sum_{\alpha'\neq\alpha} U_{\alpha\alpha'}(\boldsymbol{R})\varphi^{(\Lambda)}_{\alpha',\ell_\Lambda}(\boldsymbol{R}), \qquad \bar{\varepsilon}_\alpha = \frac{\bar{k}^2_\alpha}{2\mu_\alpha} - \frac{1}{2}i\Gamma_\alpha$$

Microscopic (pp)-Λ folding-model potentials

$$U_{\alpha\alpha'}(\boldsymbol{R}) = \int \rho_{\alpha\alpha'}(\boldsymbol{r})\big(\overline{v}_{\Lambda N}(\boldsymbol{r}_1) + \overline{v}_{\Lambda N}(\boldsymbol{r}_2)\big)d\boldsymbol{r}$$

Nucleon or transition density

$$\rho_{\alpha\alpha'}(\boldsymbol{r}) = \langle\tilde{\phi}^{(2N)}_{\alpha,\ell_2}|\sum_i \delta(\boldsymbol{r} - \boldsymbol{r}_i)|\tilde{\phi}^{(2N)}_{\alpha',\ell_2}\rangle$$

Spin-averaged ΛN potentials

$$\overline{v}_{\Lambda N} = \frac{1}{4}v^s_{\Lambda N} + \frac{3}{4}v^t_{\Lambda N}$$

Simple Gaussian form

$$v^{s,t}_{\Lambda N}(r) = v^{(0)}_{s,t}\exp\left(-(r/b_{s,t})^2\right) \leftarrow$$

NSC97f	$a_{s,t}$,	$r^{\mathrm{eff}}_{s,t}$
Λn singlet	-2.51 fm	3.01 fm
Λn triplet	-1.75 fm	3.30 fm

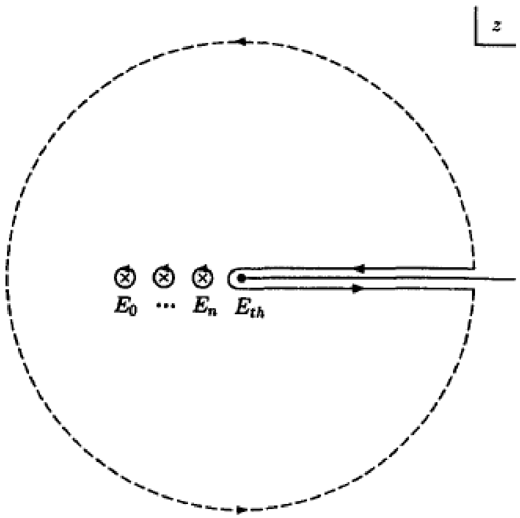
Coupled-channels DWIA calculation for Λ production

Coupled-channel Green's function

T.Harada, NPA672(2000)181

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

$$\hat{\mathbf{G}}^{(0)}(E_f) = \begin{bmatrix} G^{(0)}_{\Lambda_0} & & & \\ & G^{(0)}_{\Lambda_1} & & \\ & & \ddots & \\ & & & G^{(0)}_{\Lambda_N} \end{bmatrix} \quad \hat{\mathbf{U}} = \begin{bmatrix} U_{0,0} & U_{0,1} & \cdots & U_{0,N} \\ U_{1,0} & U_{1,1} & & \vdots \\ \vdots & & \ddots & \\ U_{N,0} & \cdots & & U_{N,N} \end{bmatrix}$$



Green's function method

$$\sum_B |\Psi_B\rangle\langle\Psi_B|\delta(E - E_B) = -\frac{1}{\pi}\mathrm{Im}\hat{G}(E)$$

Morimatsu, Yazaki, NPA483(1988)493

Strength function

$$S(E_B) = \sum_B |\langle\Psi_B|\hat{F}|\Psi_A\rangle|^2\delta(E_\pi + E_B - E_K - E_A)$$

$$= (-)\frac{1}{\pi}\mathrm{Im}\sum_{\alpha\alpha'}\int d\mathbf{R}d\mathbf{R}' F^\dagger_\alpha(\mathbf{R}) G_{\alpha\alpha'}(E_B;\mathbf{R},\mathbf{R}') F_{\alpha'}(\mathbf{R}')$$

Green's function

Double differential cross sections within the DWIA

$$\frac{d^2\sigma}{dE_K d\Omega_K} = \beta \frac{1}{[J_A]} \sum_{M_A} \sum_B |\langle \Psi_B | \hat{F} | \Psi_A \rangle|^2 \delta(E_K + E_B - E_\pi - E_A)$$

$$= S(E_B)$$

Production operators with zero-range interaction

$$\hat{F} = \int d\boldsymbol{r}\, \chi_\pi^{(-)*}(\boldsymbol{p}_K, \boldsymbol{r}) \chi_K^{(+)}(\boldsymbol{p}_\pi, \boldsymbol{r}) \sum_{j=1}^{A} \overline{f}_{\pi N \to \Lambda K}\, \delta(\boldsymbol{r} - \boldsymbol{r}_j) \hat{O}_j$$

$$\approx j_L^{(+)}\left(q \frac{M_C}{M_A} R\right)$$ distorted waves

Recoil factor

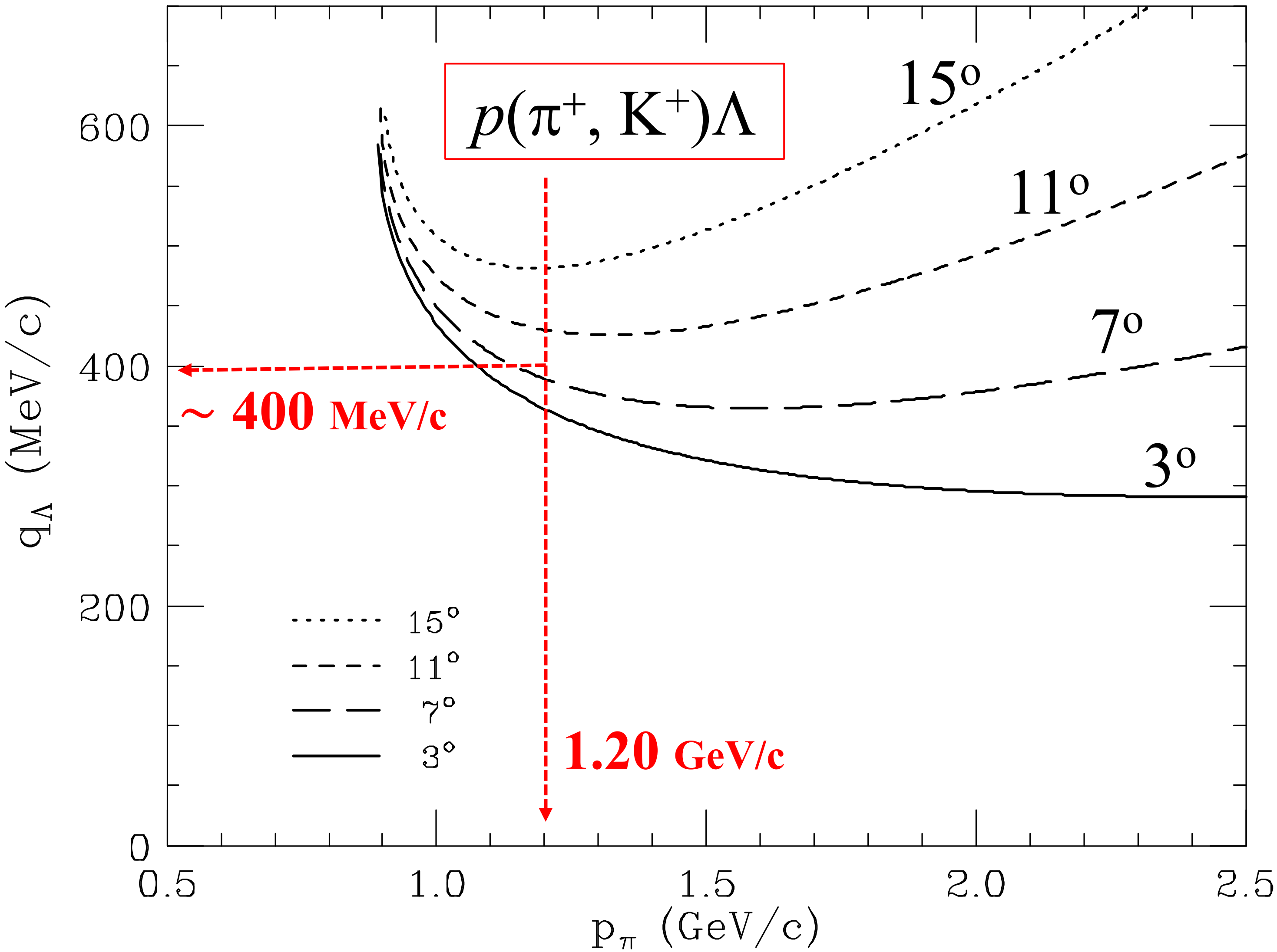
Momentum and energy transfer

$$\boldsymbol{q} = \boldsymbol{p}_\pi - \boldsymbol{p}_K, \qquad \omega = E_\pi - E_K$$

Optimal Fermi-averaged amplitude for πN-ΛK reactions

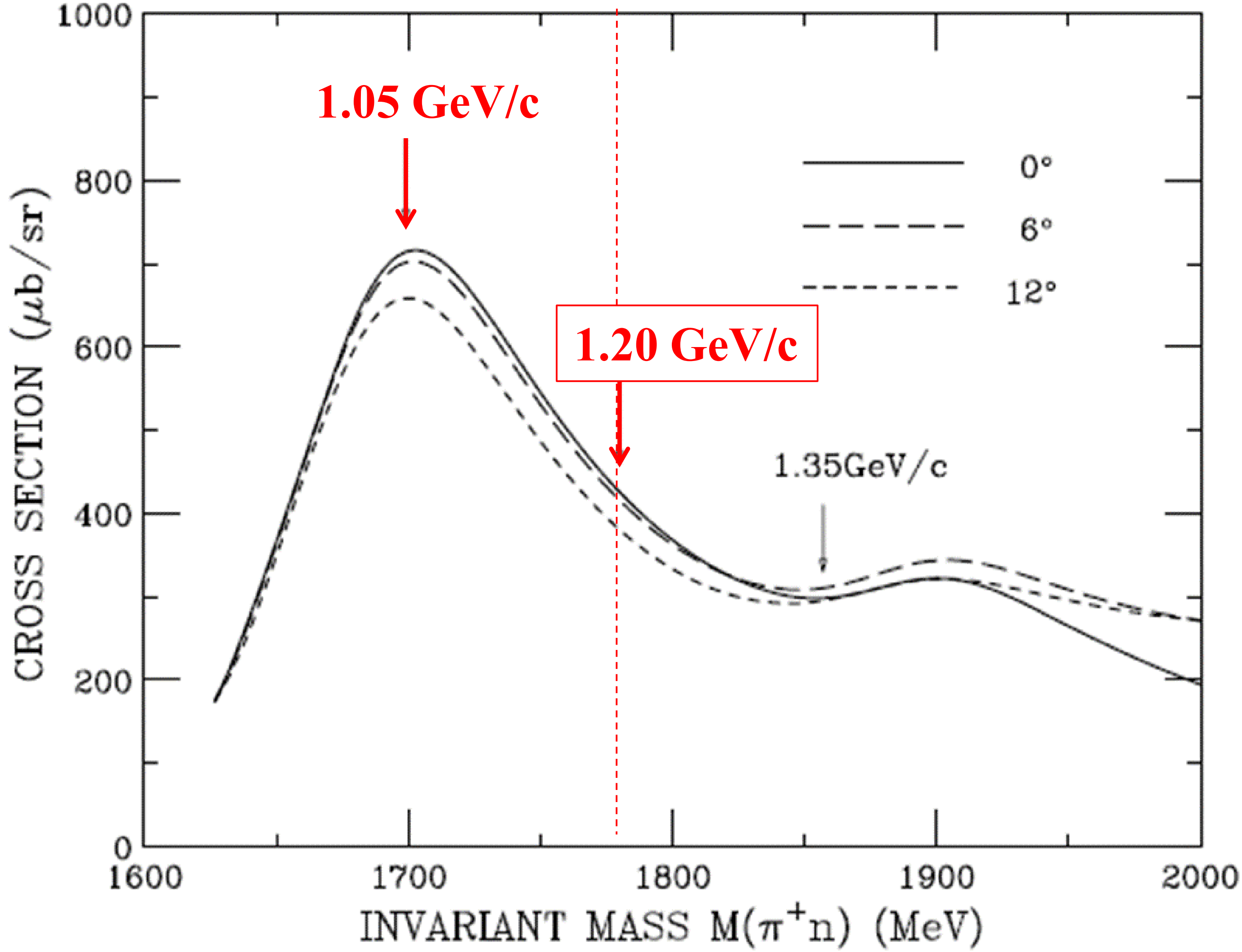
$$\overline{f}_{\pi N \to \Lambda K} = \frac{1}{2\pi} \sqrt{\frac{p_K E_K}{v_\pi \beta}} \langle t^{\rm opt}_{\pi N, K\Sigma}(p_\pi; \omega, \boldsymbol{q}) \rangle$$

Momentum transfer q_Λ for Λ production in (π^+, K^+) reactions



→ *The momentum transfer q_Λ becomes very large.*

Elementary cross section of the $\pi^+p \rightarrow K^+\Lambda$ reaction

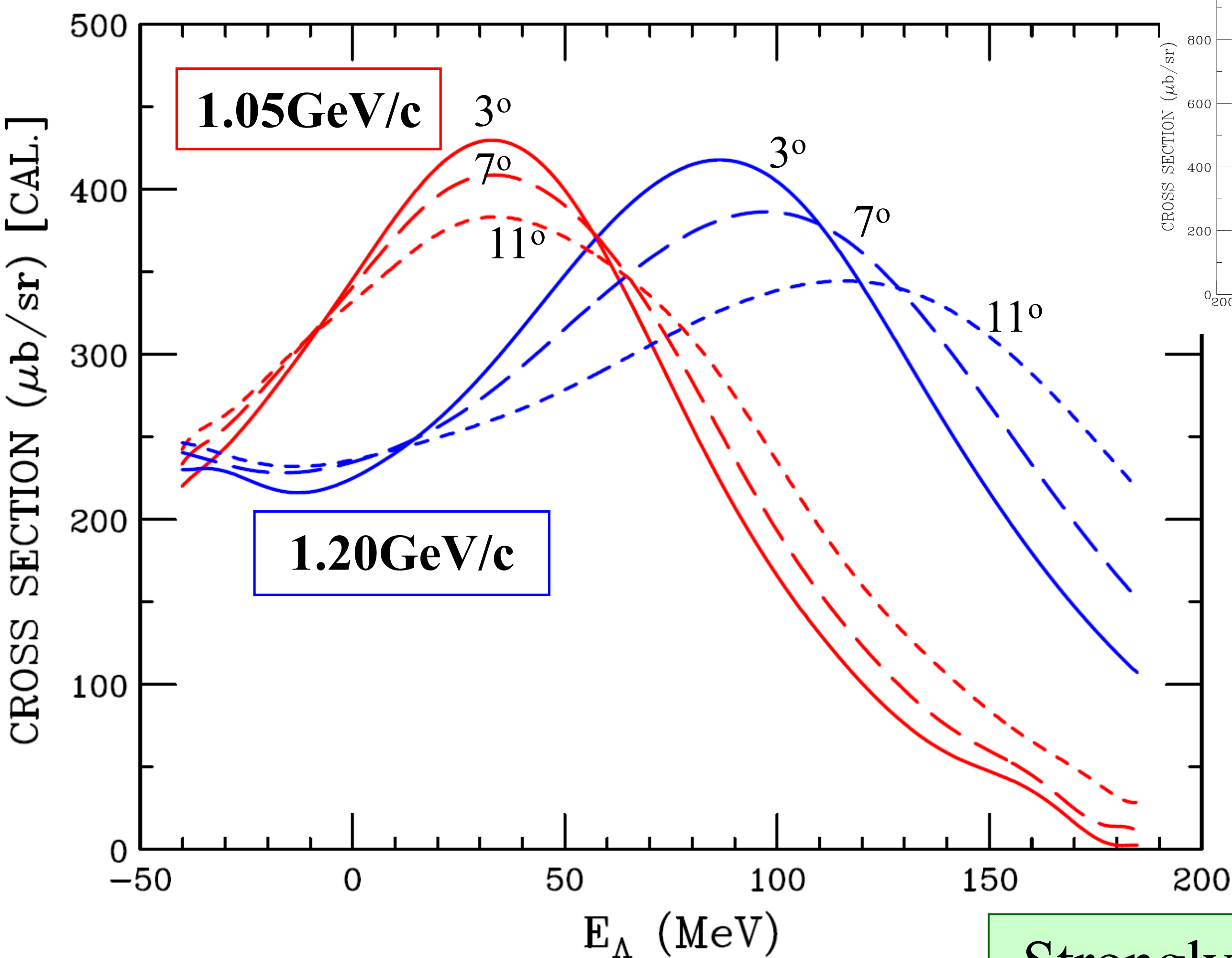


→ *The cross section σ_Λ has a strong incident momentum-dep.*

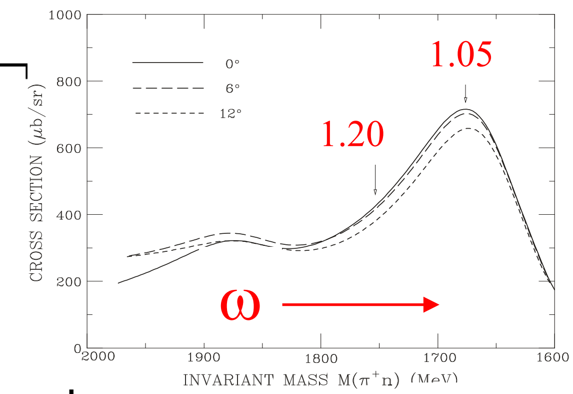
Fermi-averaged X-section of the $\pi^+ + n \rightarrow K^+ + \Lambda$ reaction on ^{3}He

$$\left(\frac{d\sigma}{d\Omega}\right)^{\rm opt} \equiv \beta |\overline{f}_{\pi N \to K\Lambda}|^2$$

T. Harada and Y.Hirabayashi, NPA744 (2004) 323.



$\pi^+ + n \rightarrow K^+ + \Lambda$ Cross Section



$M(\pi^+ n)$

Strongly E_Λ-dependent

3. Results and Discussion

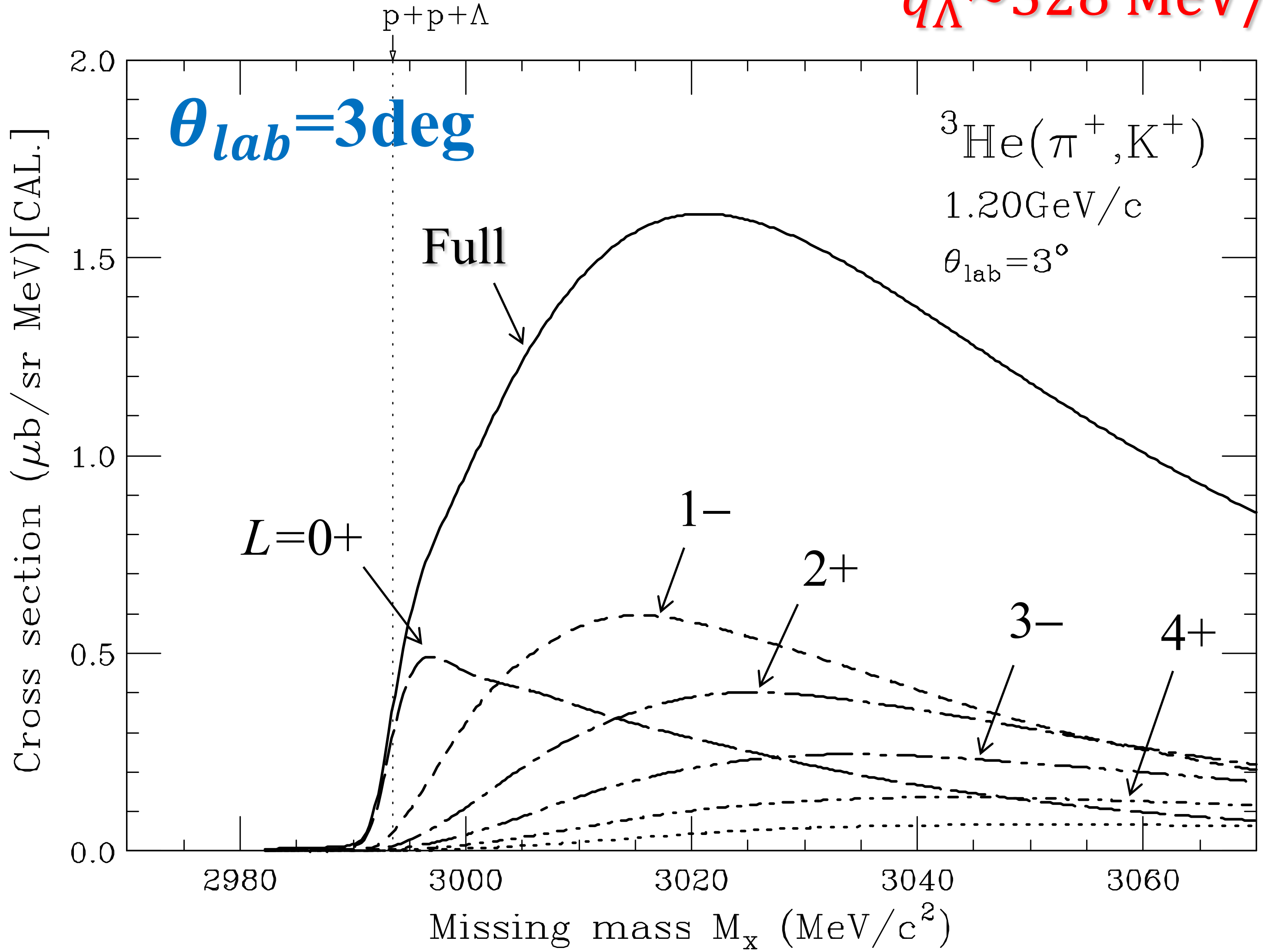
$^3He(\pi^+, K^+)\, pp\Lambda$

at 1.20GeV/c

Inclusive spectrum in ^{3}He(π^+,K$^+$)ppΛ at 1.20GeV/c

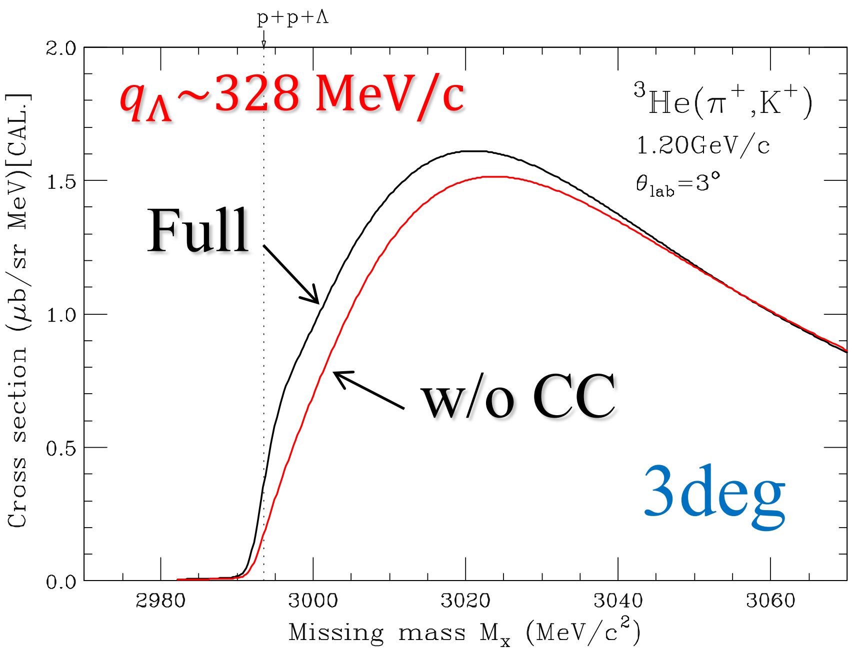
^{3}He (π^+, K$^+$) *pp*Λ

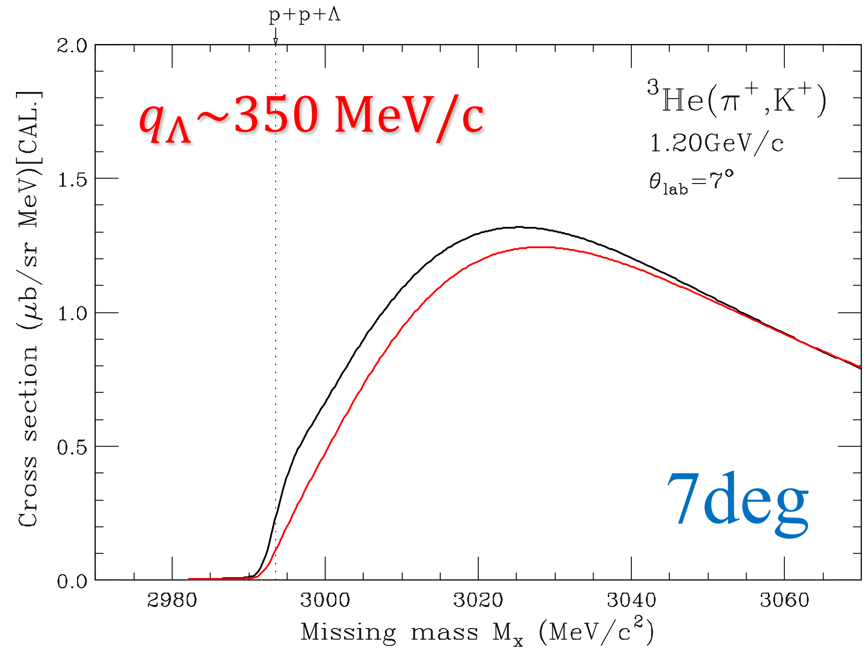
q_Λ~328 MeV/c

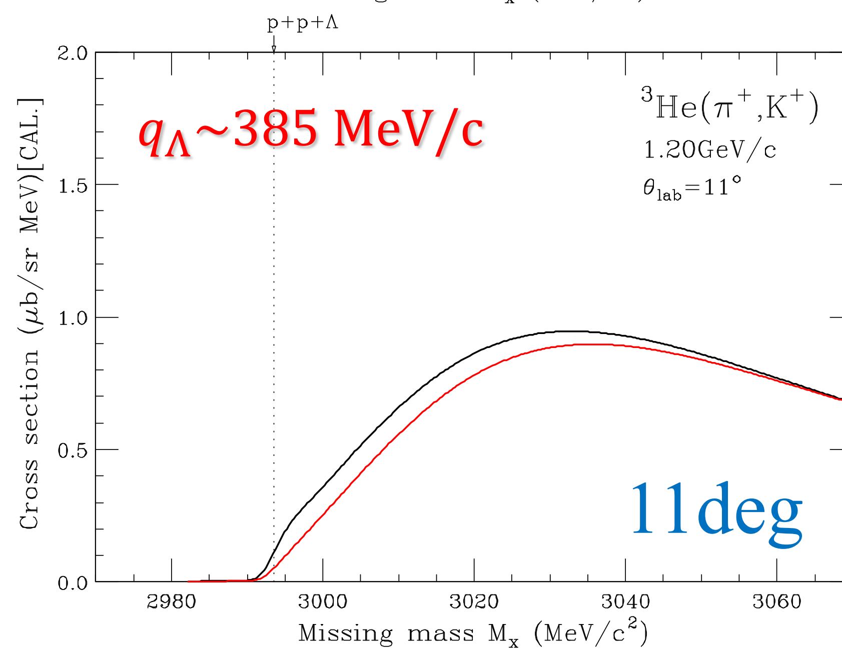


Effects of continuum couplings by the CDCC

^{3}He (π^{+}, K^{+}) $pp\Lambda$





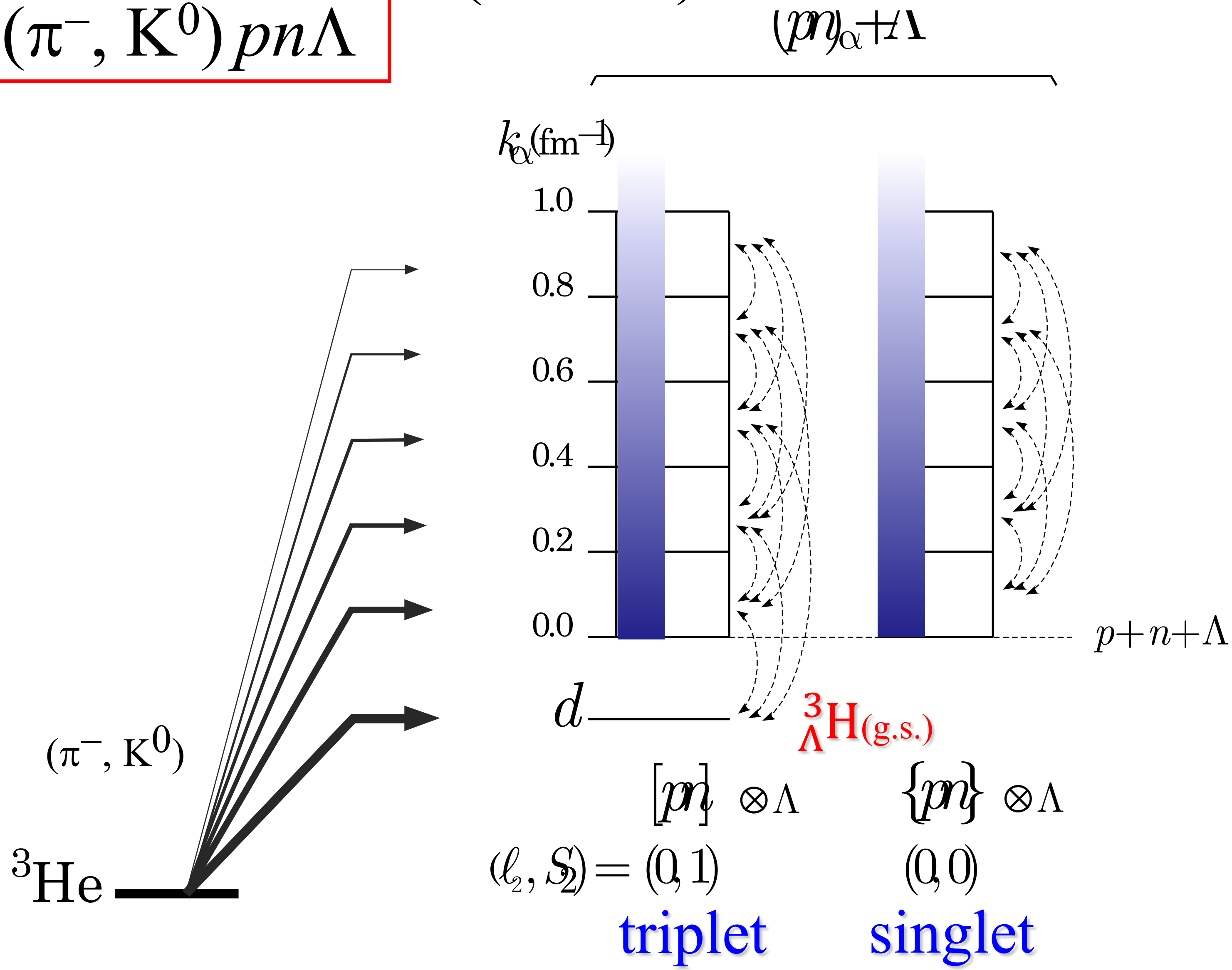


$^{3}He\ (\pi^{-}, K^{0})\ ^{3}_{\Lambda}H,\ pn\Lambda$

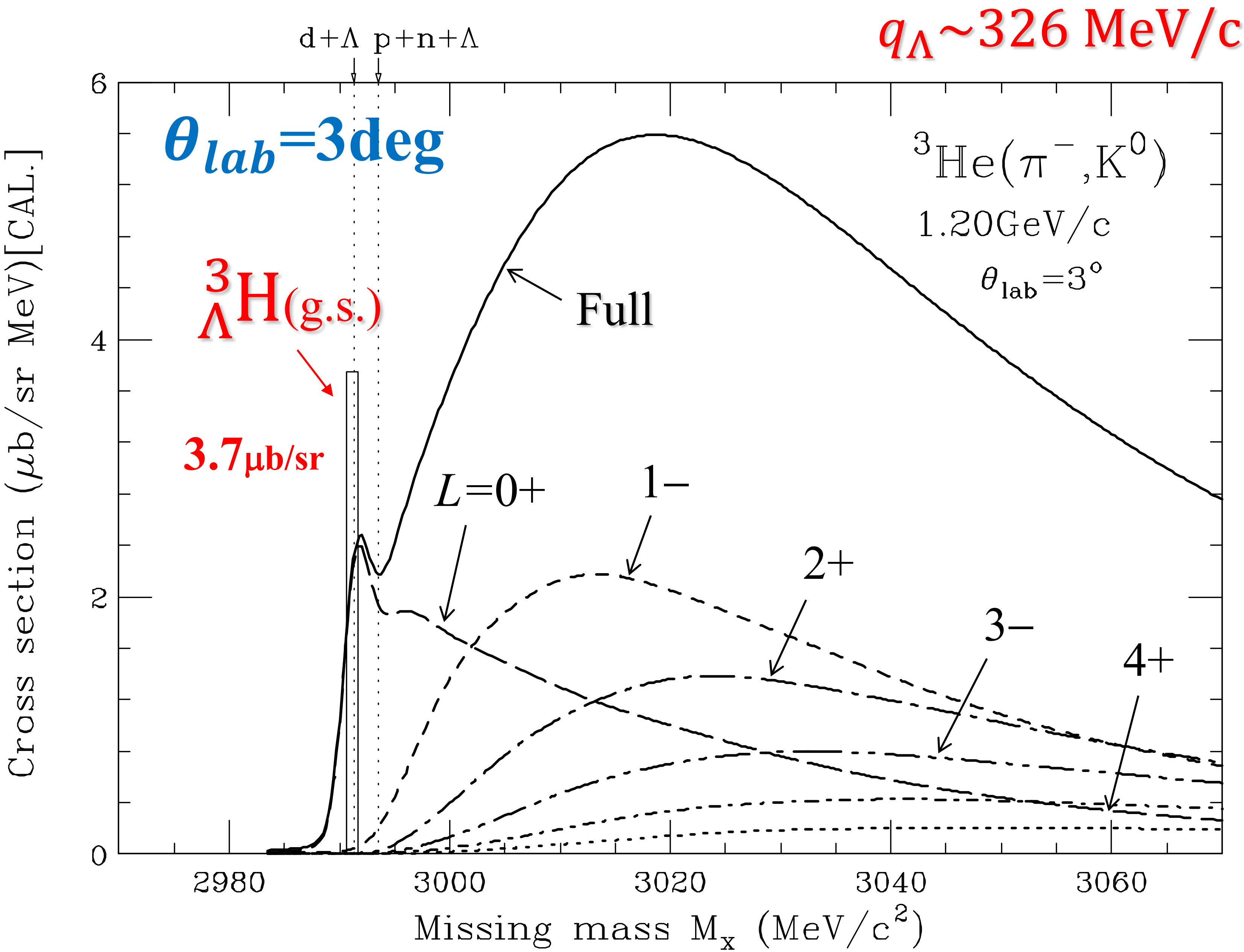
at 1.20GeV/c

Continuum-Discretized Coupled-Channel Method (CDCC)

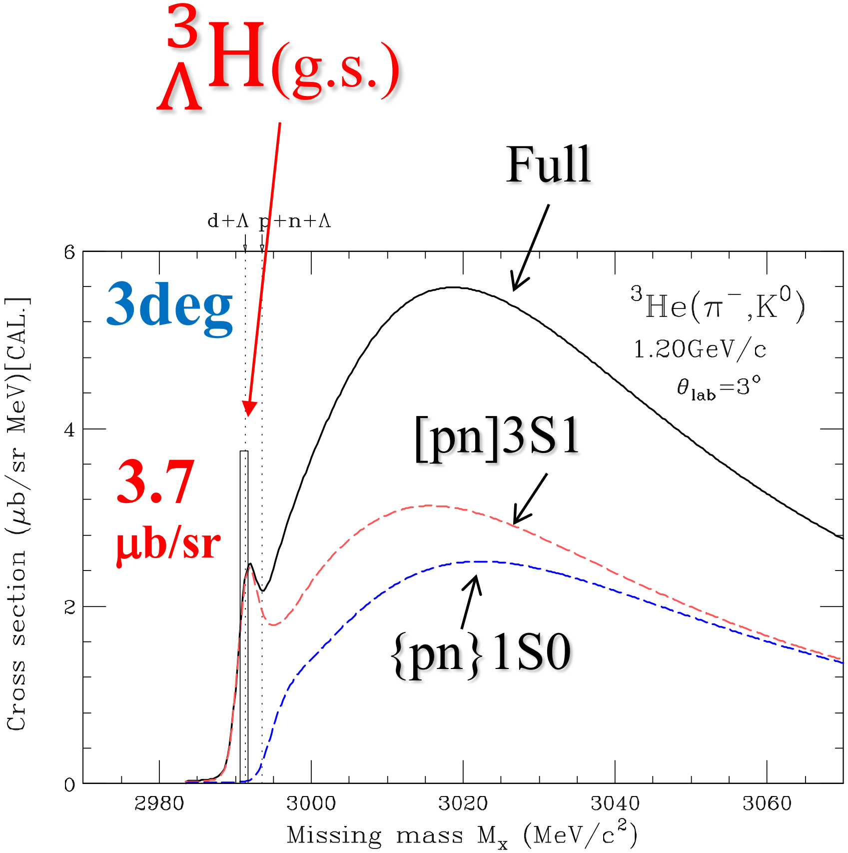
^{3}He (π^-, K^0) $pn\Lambda$

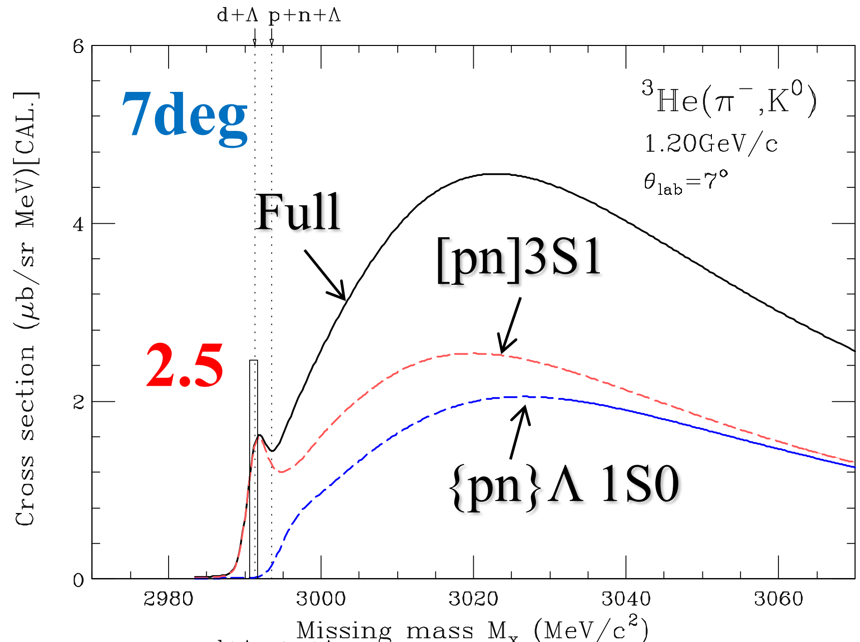


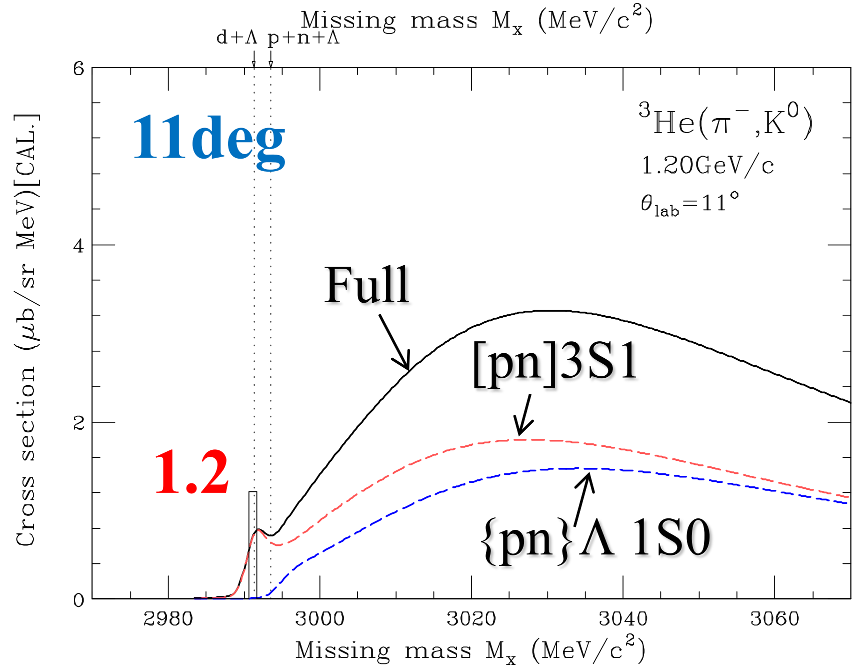
Inclusive spectrum in $^3He(\pi^-,K^0)pn\Lambda$ at 1.20GeV/c

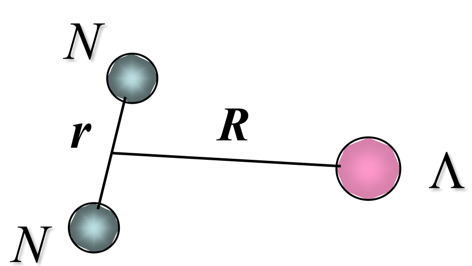


Components of the *NN*-core in *pn*Λ for the spectra

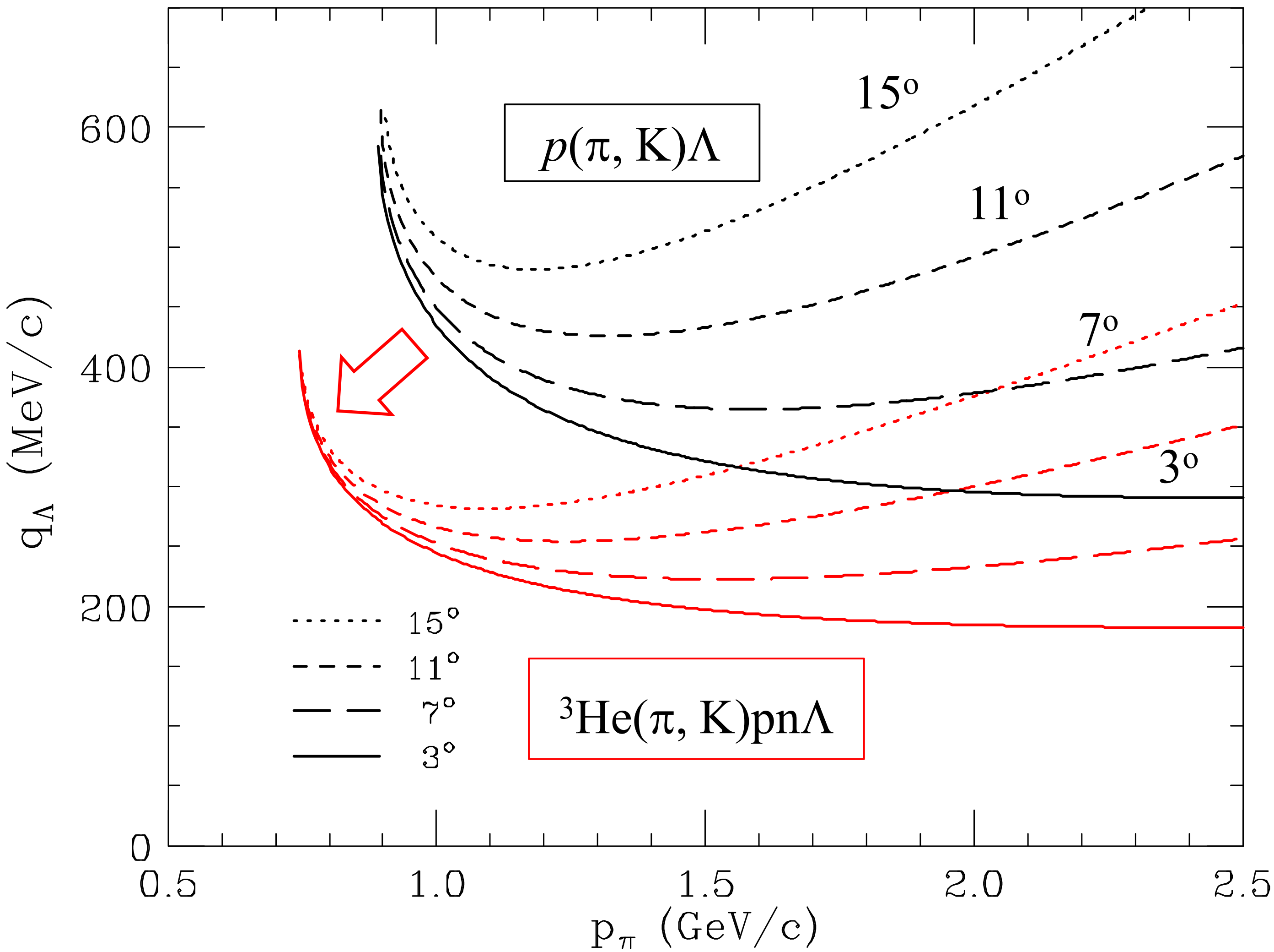








Effective recoil momentum q_Λ^{eff} for Λ production in ^{3}He

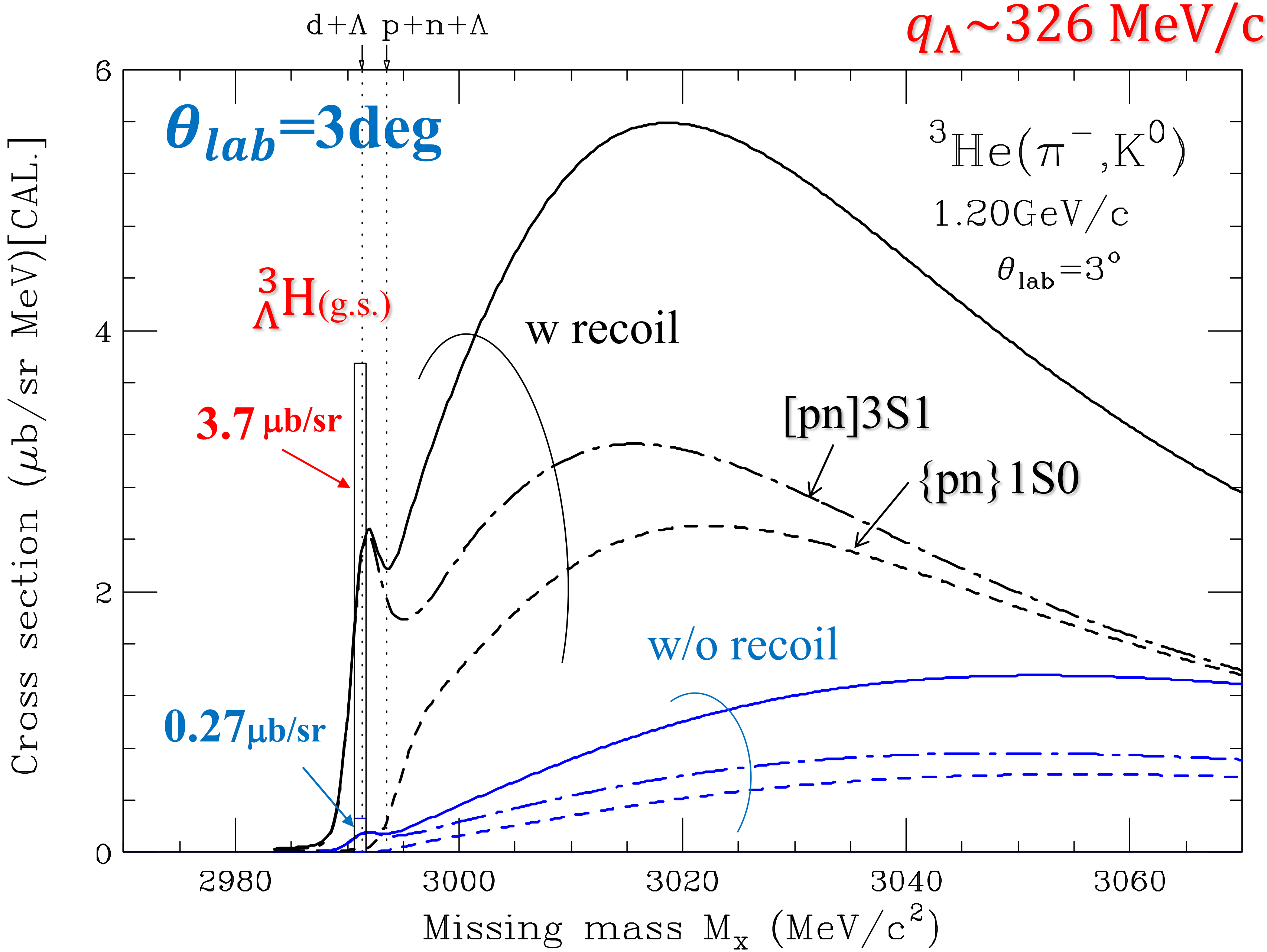


→ The effective recoil momentum becomes

$$q_\Lambda^{eff} \sim \frac{M_C}{M_A} q_\Lambda \approx \frac{2}{3} \times 400\ \mathrm{MeV/c} = 267\ \mathrm{MeV/c}$$

Recoil effects of the spectrum in ^{3}He(π^-,K^0)$pn\Lambda$

q_Λ~326 MeV/c



Summary

- Calculations of the coupled-channel Green's function with the CDCC provide the ability of describing continuum $NN\Lambda$ states including $N+N+\Lambda$ breakup processes.
- The production cross section of ${}^{3}_{\Lambda}$H($1/2^{+}$) accounts for 3.7 μb/sr at 1.2GeV/c (3^{o}) in the ^{3}He(π^{-},K^{0}) reaction.
- The recoil effects are very important to the production with a very light nuclear target as ^{3}He.

Future Subjects

- Convergence of the CDCC model space depending on (k_{max}, L_{max}) parameters should be checked.
- …

Thank you very much.