Λ, Σ, and Ξ hyperons in nuclear matter with NLO baryon-baryon interactions in chiral effective field theory

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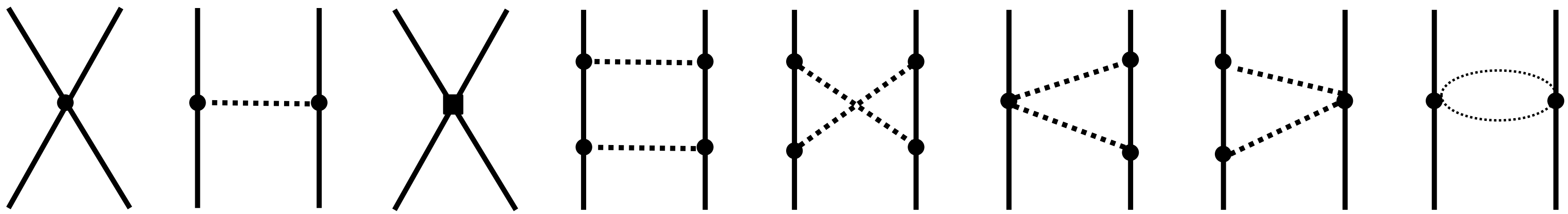
Baryon-baryon interactions in chiral effective field theory (ChEFT)

- S=0 (NN) sector: now standard for (low-energy) nuclear ab initio calculations (CCM, NCSM, GFMC, QMC, UMOA, …)
  - Systematic introduction of 3NFs which are decisively important in describing nuclei.
- S=−1 sector: reasonable description of Λ and Σ properties in the medium
  - Behavior of U_Λ in NS matter ⇨ possibility to resolve the hyperon puzzle
- S=−2 sector: scarce experimental data ⇨ large uncertainties in parameters
- It is important to explore Ξ properties in the medium described by the present NLO interactions, and compare them with forthcoming data.
- G-matrix calculations for Λ, Σ, and Ξ s.p. potentials in nuclear matter (NM)
  - $U_\Xi(k; k_F)$ in NM is translated to $U_\Xi(r; E)$ in ^{12}C by a simple LDA
  - Apply it to calculate (K^-,K^+) Ξ formation spectrum on ^{12}C

Hyperon-nucleon interactions in chiral effective field theory

- NLO diagrams（π, K, and η exchanges in SU(3)）

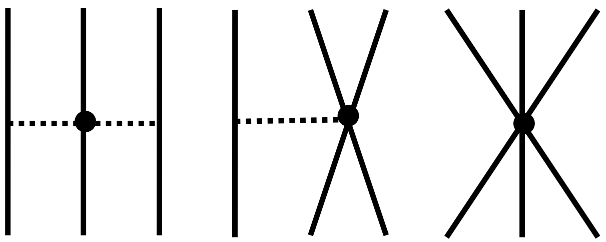
Haidenbauer, Petschauer, Kaiser, Meißner, Nogga, and Weise, Nucl. Phys. A915, 24 (2013)



- Leading three-baryon forces

Petschauer, Kaiser, Haidenbauer, Meißner, and Weise, Phys. Rev. C93, 014001 (2016)

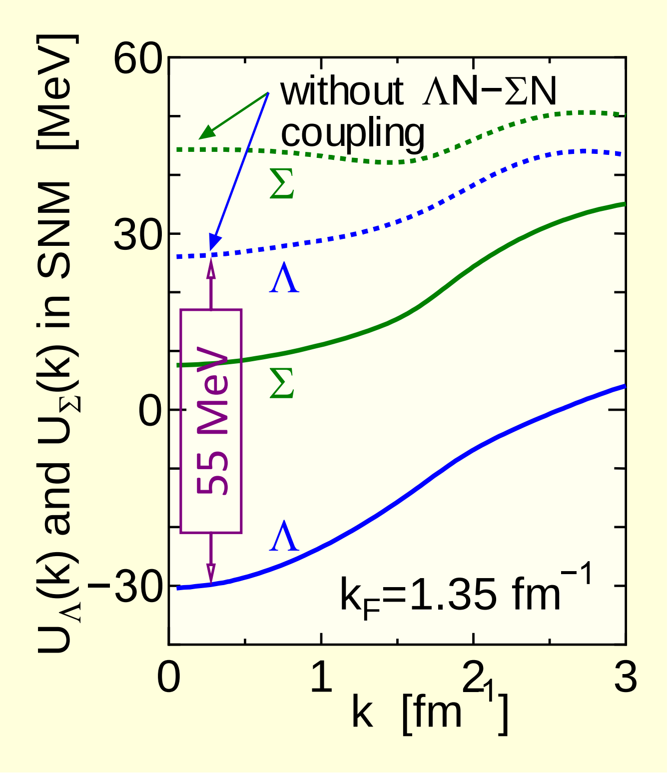
  - Assume decouplet dominance for 1π-exchange and contact LECs.
  - ΞNN is not considered in the present work.



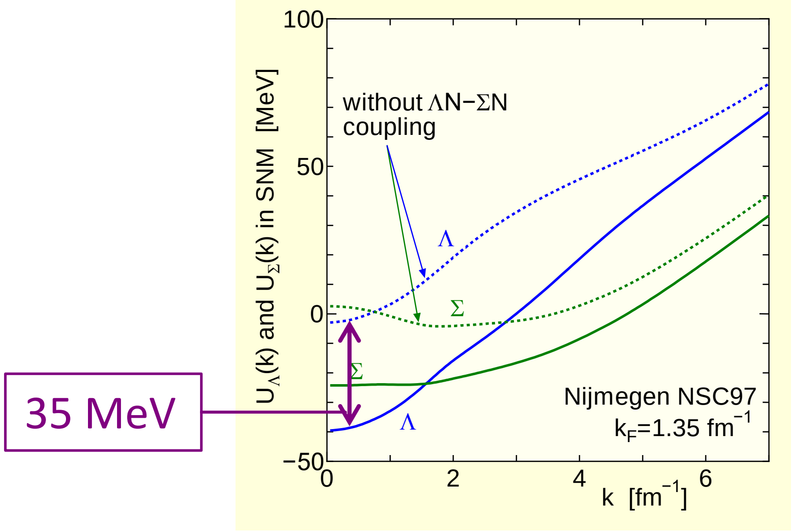
- The cutoff scale of ~ 600 MeV is not soft enough to use the interactions in a perturbative or HF method.
- High-momentum components are regularized by G-matrix equation with a continuous choice for intermediate spectra calculated self-consistently.

Λ and Σ s.p. potentials in SNM : NLO YN only

- ΛN attraction comes from ΛN -ΣN coupling, which is particularly large in Ch NLO.
  - If the coupling is switched off, the Λ s.p. potential is repulsive.
  - The depth of $U_\Lambda \cong 30$ MeV is consistent with experimental data.

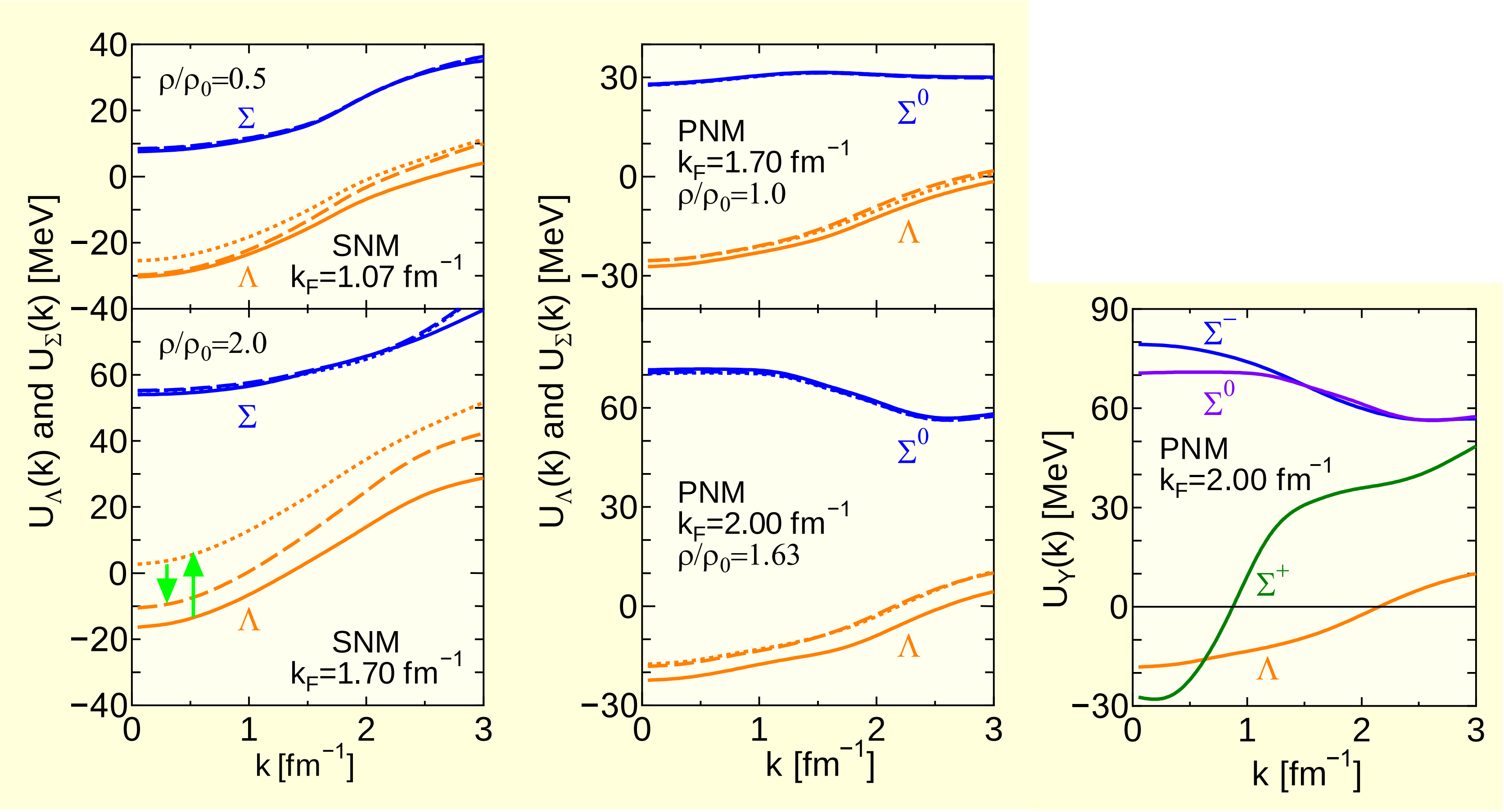


Cf. The case of Nijmegen NSC

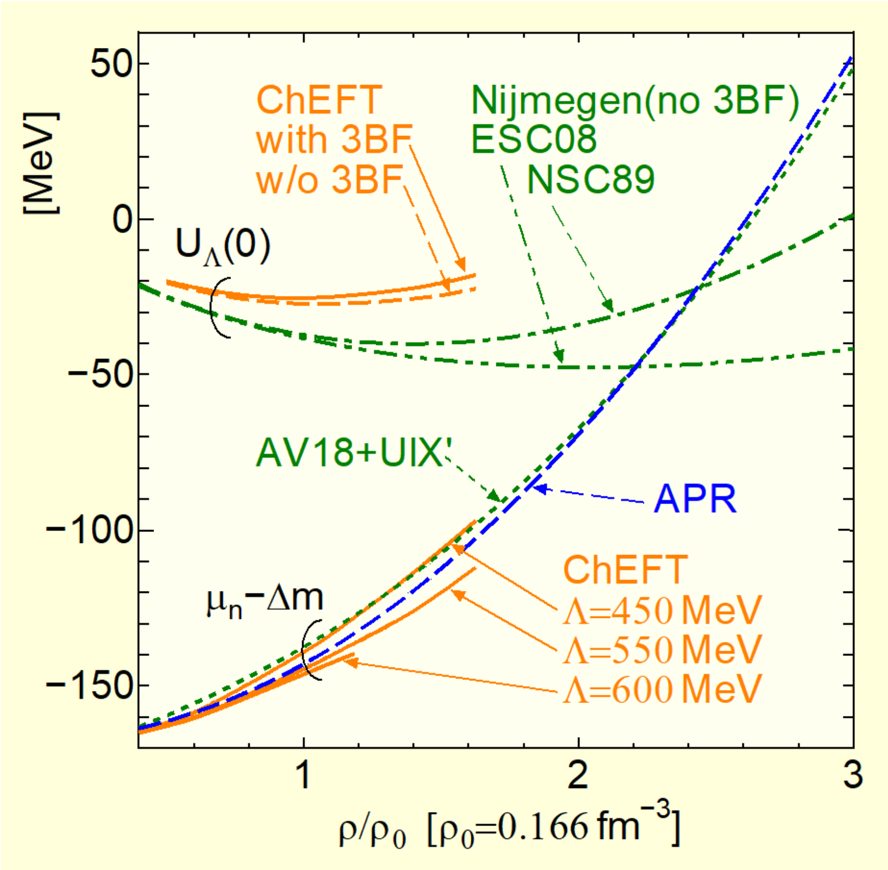


Λ and Σ s.p. potentials including 3BF in SNM and PNM

Solid: YN only, dotted: YN+ΛNN, dashed: YN+ΛNN+(ΛNN-ΣNN)



Density dependence of $U_\Lambda(k=0)$ in PNM



- The threshold of the Λ appearance, if any, is shifted to a higher density area.

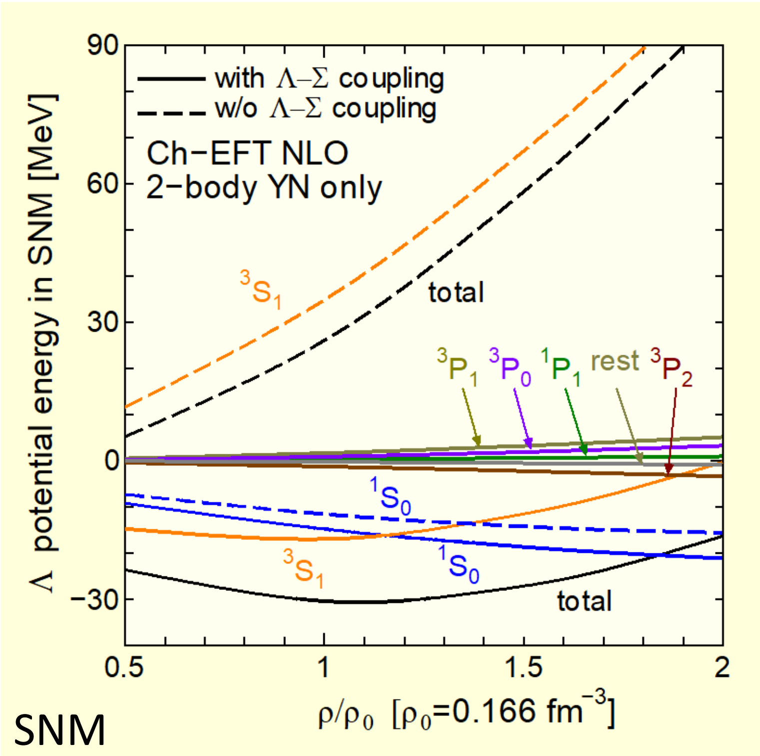
$$\mu_n = \frac{\hbar^2}{2m_n}(k_F^n)^2 + U(k_F^n)$$

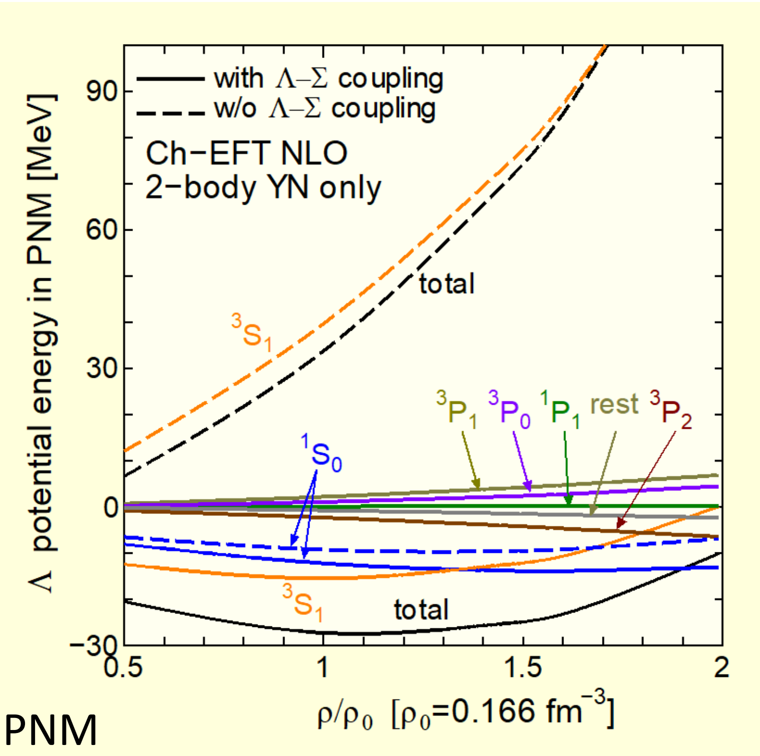
- Suggestive for resolving the hyperon puzzle.

  (NNLO is to be included in the future.)

Partial wave contributions to Λ potential in SNM and PNM

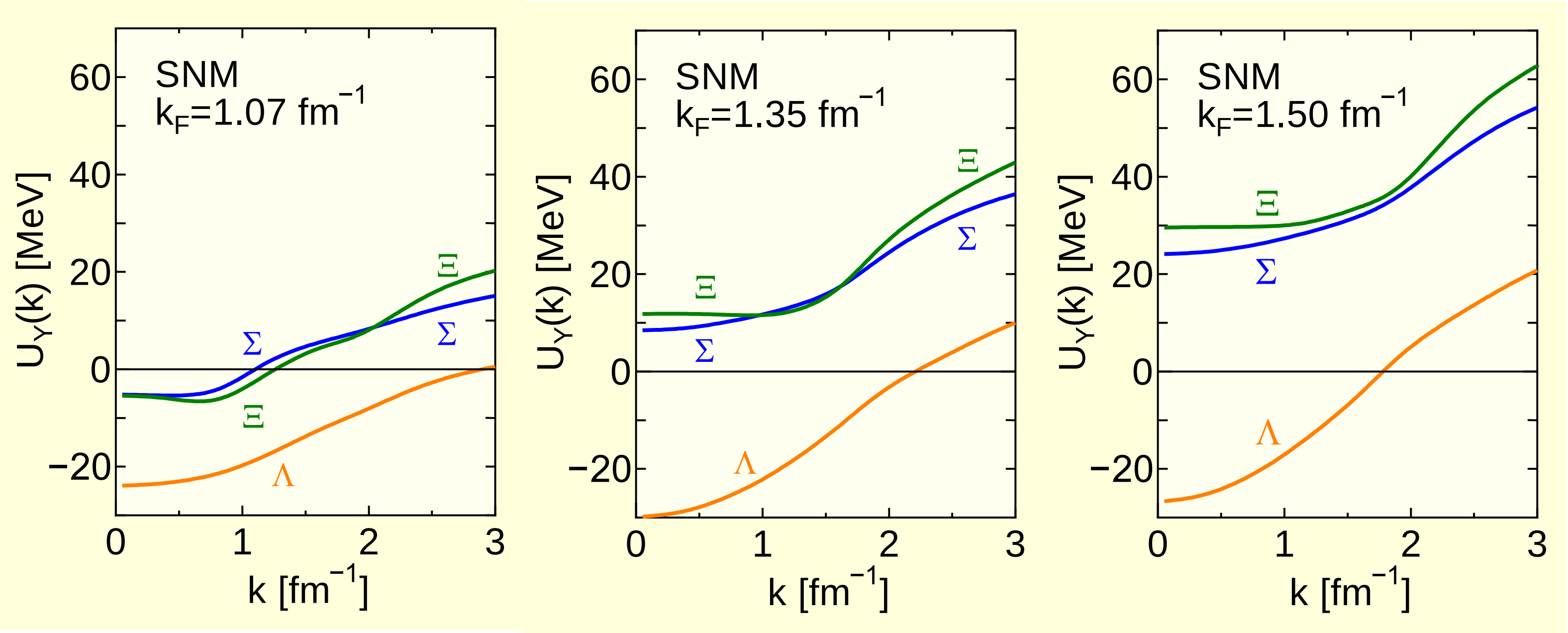
- The $^3S_1$ contribution before taking into account the ΛN-ΣN coupling is repulsive and strongly density dependent.
- Attractive ΛN-ΣN coupling effect is very large in the $^3S_1$ channel.
- The $^1S_0$ contribution is attractive.





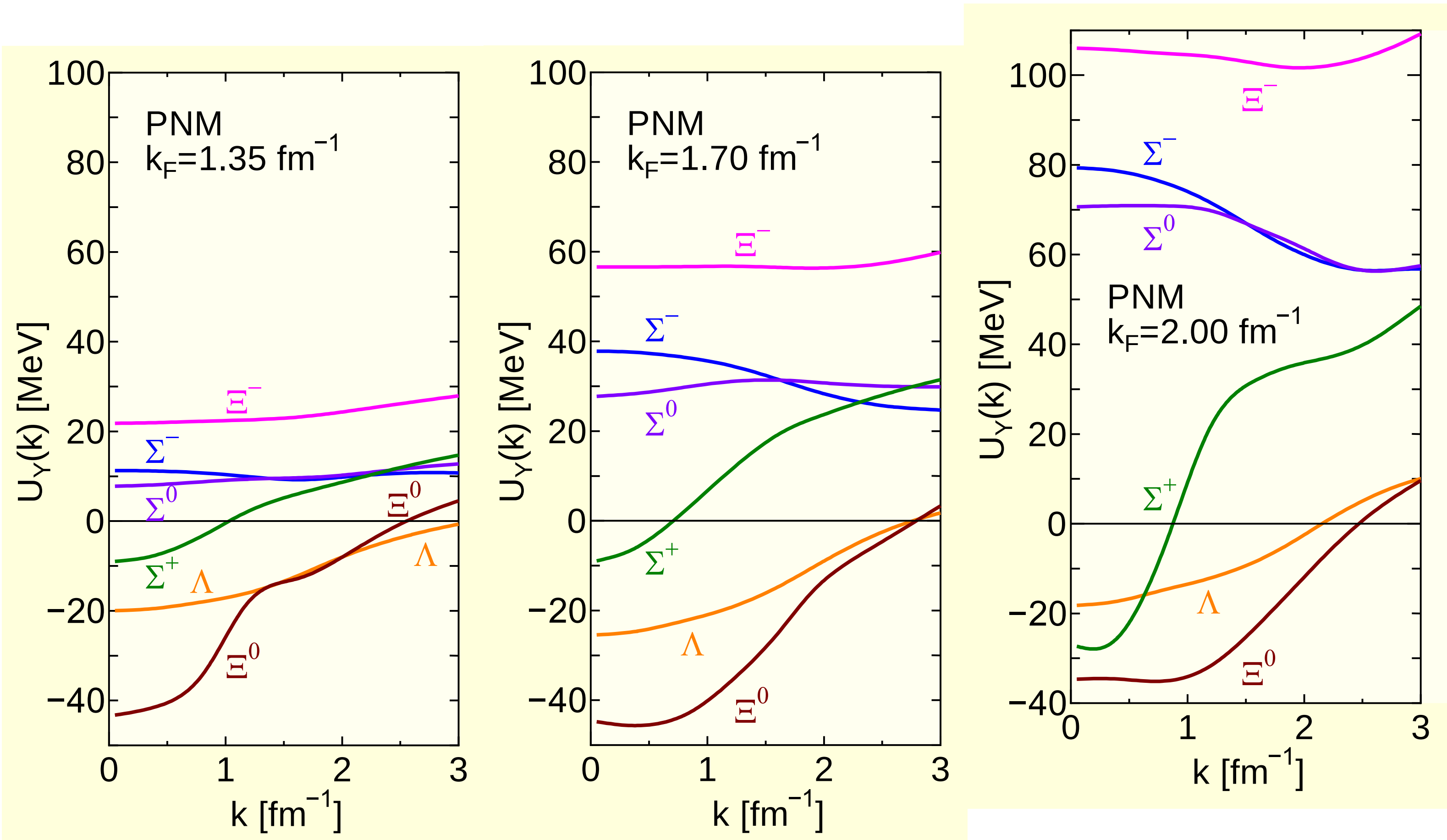
Ξ single-particle potential in symmetric nuclear matter

- On the basis of reasonable and promising results for the $S = -1$ sector, let us proceed forward to discuss the $S = -2$ sector.
  - The present parameterization naturally has uncertainties in $S = -2$.
- G-matrix calculations with a continuous choice of intermediate spectra.
  - N, Λ, and Σ s.p. potentials are those of ChEFT with 3BF effects.
- Ξ s.p. potential is attractive at low densities due to the T=0 $^3S_1$ attraction, but the T=1 $^3S_1$ repulsive contribution prevails in higher densities.



Ξ single-particle potential in pure neutron matter

- Strongly repulsive Ξ^- (and Σ^-) potential in PNM.

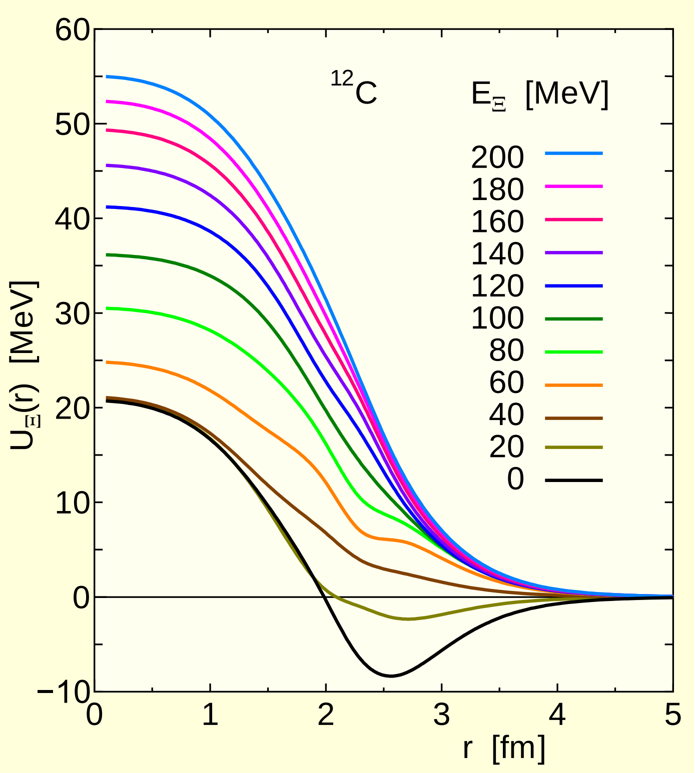


Ξ single-particle potential in ^{12}C

- Estimation of the Ξ potential in finite nuclei by a simple LDA.
  - Density distribution $\rho(r)$ ➡ local Fermi mom. $k_F(r) = \left(\frac{3\pi^2\rho(r)}{2}\right)^{1/3}$
  - $U_\Xi(k, k_F)$ in NM ➡ $U_\Xi(E, k_F)$ in NM ➡ $U_\Xi(\mathrm{r}) = U_\Xi(E, k_F(r))$ in ^{12}C

$$E = \frac{\hbar^2}{2m_\Xi}k^2 + U_\Xi(k, k_F)$$

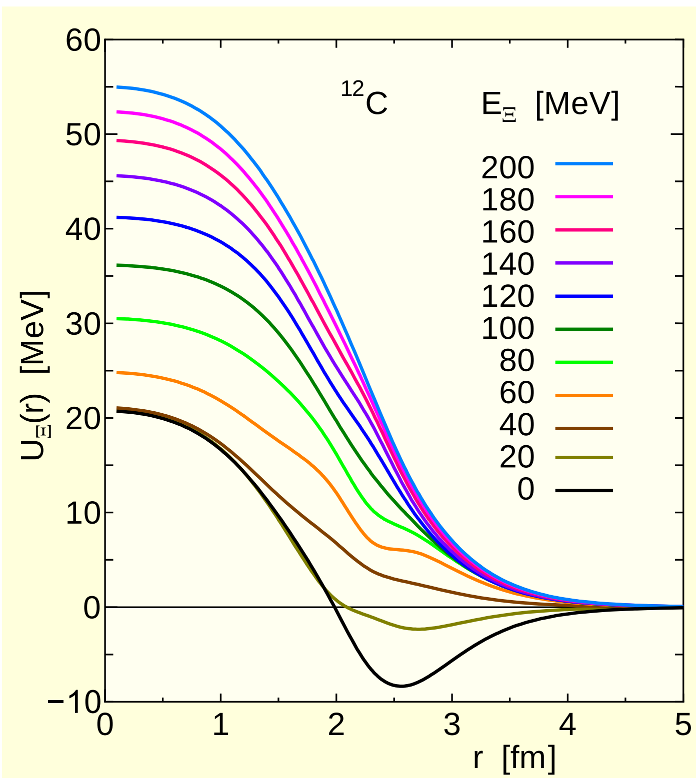
Results



- Attractive pocket in a surface region at low energies.
- Surface thickness is not well accounted for because of the lack of finite range effects.
  - The usefulness of the simple LDA can be checked by comparing the results with those of the explicit folding potential of the two-body interaction.

Parametrization of the calculated $U_\Xi(\mathrm{r})$ in a Woods-Saxon form

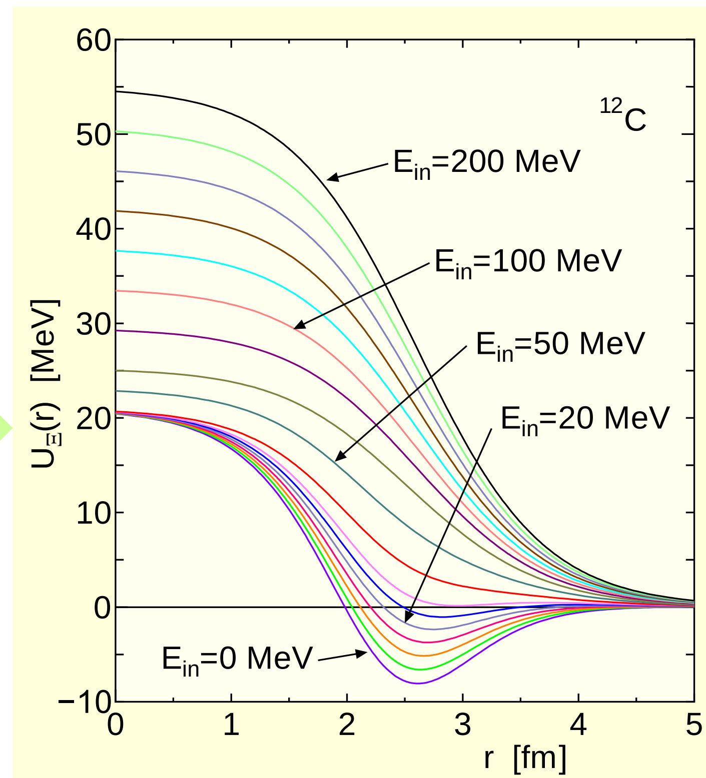
- $U_\Xi(\mathrm{r}) = V_1 \frac{1}{1+\exp((r-2.6)/0.55)} - V_2 \frac{\exp((r-2.4)/0.45)}{[1+\exp((r-2.4)/0.45)]^2}$
  - $V_1 = 21$ MeV for $E \leq 40$ MeV, $21 + \frac{34}{160}(E-40)$ MeV for $E \geq 40$ MeV.
  - $V_2 = 78$ MeV for $E \leq 0$ MeV, $\max\{78 - 1.25E, 0\}$ MeV for $E \geq 0$ MeV



Thickness is modified.

0.55 --> 0.65

0.45 --> 0.55

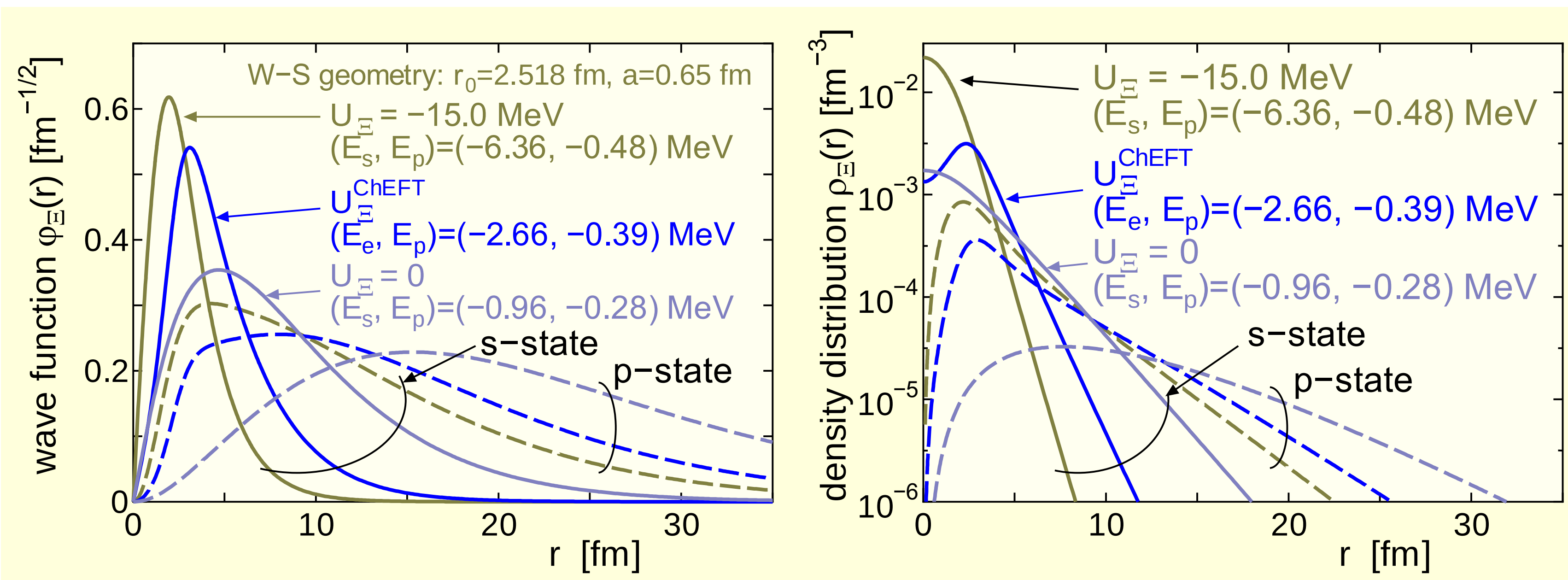


Ξ bound states in ^{12}C with $U_{\Xi}(\mathrm{r})$ of ChEFT

Bound states of $U_{\Xi}(\mathrm{r}; E = 0)$: Ξ^{-} Coulomb states are lowered.

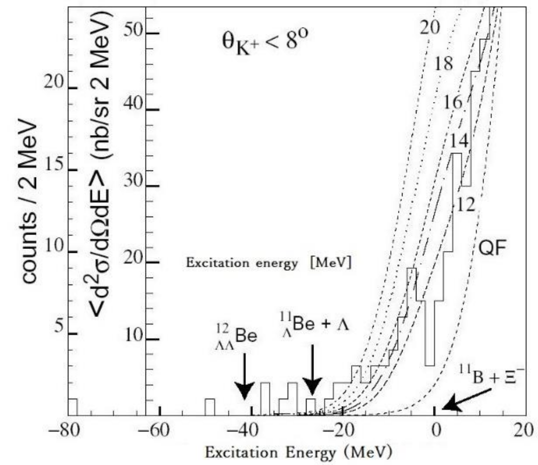
	$U_{coulomb}$ only		$U_{Coulomb}+U_{ChEFT}$	
state	E [MeV]	$\sqrt{\langle r^2 \rangle}$ [fm]	E [MeV]	$\sqrt{\langle r^2 \rangle}$ [fm]
l=0	-0.96	7.69	-2.66	4.37
l=1	-0.28	20.05	-0.39	13.55

$U_{Coulomb}$+WS(-15 MeV)		
state	E [MeV]	$\sqrt{\langle r^2 \rangle}$ [fm]
l=0	-6.36	2.71
l=1	-0.48	10.58



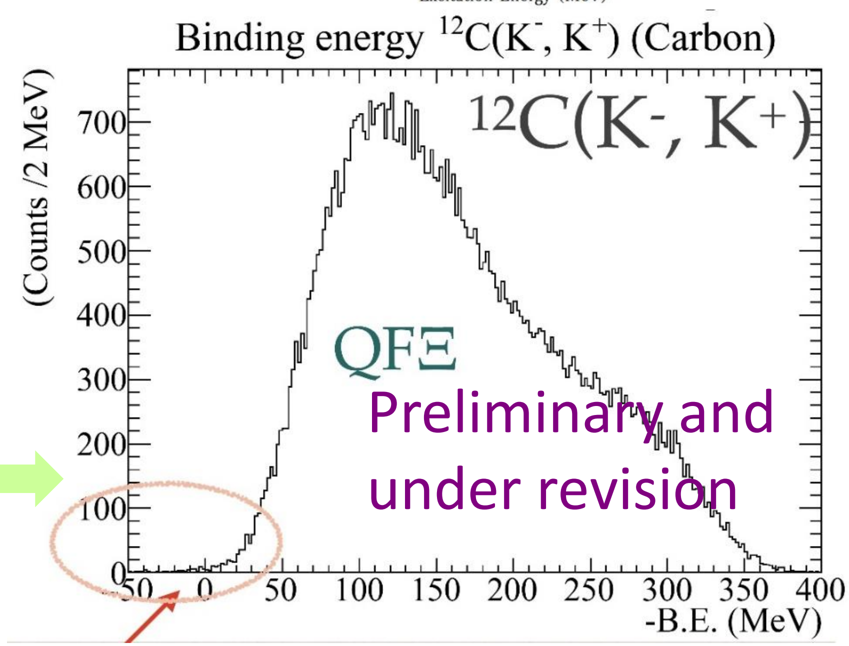
Experimental situation for the Ξ-nucleus interaction

- BNL E885: $^{12}C(K^-,K^+)$
  Khaustov *et al.*, Phys, Rev. C61, 054602 (2000)
  - No clear evidence of Ξ bound states (resolution is 14 MeV)



- Emulsion data (KEK373)
  Kiso event: Ξ-^{14}N
  $\Xi^- + {}^{14}N \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$
  B_{Ξ}=1.03±0.18 or 3.87±0.21 MeV
  (Coulomb binding is 0.17 MeV)

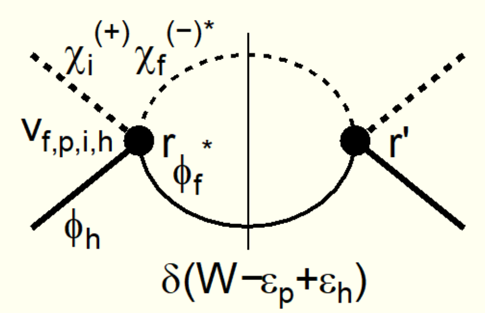
- J-PARC E05 run
  $^{12}C(K^-,K^+)$ Ξ formation spectrum at 1.8 GeV
  (mass resolution <2 MeV)
  Nagae, HYP2018



SCDW method for double differential cross section

- Double differential cross section for $K^- N \to K^+ \Xi \ (ih \to fp)$

$$\frac{d^2}{dW d\sigma} = \frac{\omega_i \omega_f}{(2\pi)^2} \frac{p_f}{p_i} \sum_{p,h} \frac{1}{4\omega_i \omega_f} \left| \left\langle \chi_f^{(-)} \phi_p \middle| v_{f,p,i,h} \middle| \chi_i^{(+)} \phi_h \right\rangle \right|^2 \delta(W - \epsilon_p + \epsilon_h)$$



  - Semi-classical distorted wave approximation

$$\chi^*(\boldsymbol{r}')\chi(\boldsymbol{r}) = |\chi(\boldsymbol{R})|^2 e^{i\boldsymbol{k}(\boldsymbol{R})\cdot(\boldsymbol{r}-\boldsymbol{r}')}$$

  - Wigner transformation of the density matrix

$$\sum_{m_h} \phi_h(\boldsymbol{r})\phi_h^*(\boldsymbol{r}') = \sum_{m_h} \phi_h(\boldsymbol{R} + \tfrac{1}{2}\boldsymbol{s})\phi_h^*(\boldsymbol{R} - \tfrac{1}{2}\boldsymbol{s}) = \int d\boldsymbol{K}\, \Phi_h(\boldsymbol{R}, \boldsymbol{K}) e^{i\,\boldsymbol{K}\cdot\boldsymbol{s}}$$

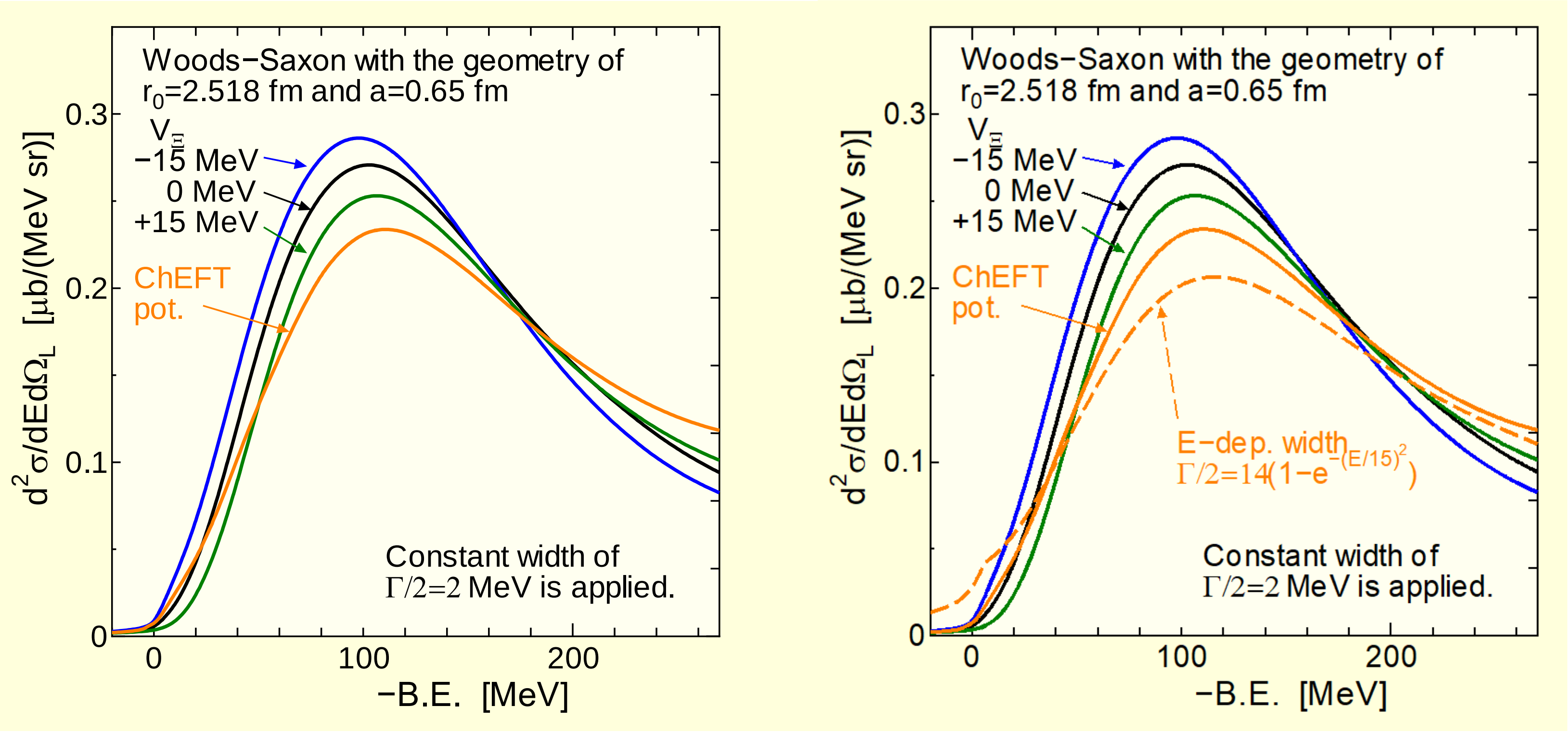
- SCDW expression of the double differential cross section

$$\frac{d^2}{dW d\sigma} = \frac{\omega_i \omega_f}{(2\pi)^2} \frac{p_f}{p_i} \xi^6 \iint d\boldsymbol{R} d\boldsymbol{K} \sum_p \frac{1}{4\omega_i \omega_f} \left|\chi_f^{(-)}(\boldsymbol{R})\right|^2 \left|\chi_i^{(+)}(\boldsymbol{R})\right|^2 \left|\chi_p^{(-)}(\xi\boldsymbol{R})\right|^2$$

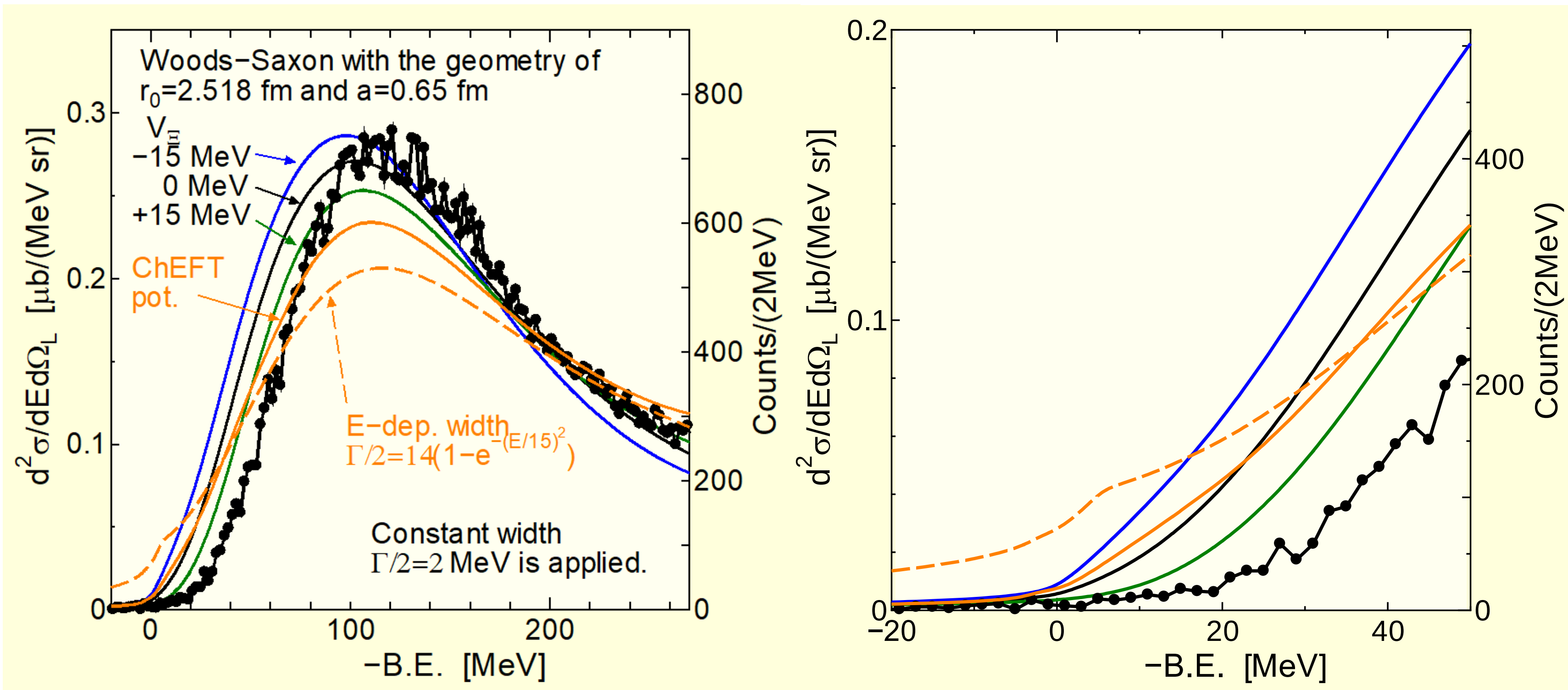
$$\times \left|v_{f,p,i,h}\right|^2 \frac{(2\pi)^3}{\xi^3} \sum_h \Phi_h\left(\xi\boldsymbol{R}, \frac{1}{\xi}\boldsymbol{K}\right) \delta(\boldsymbol{K} + \boldsymbol{k}_i(\boldsymbol{R}) - \boldsymbol{k}_f(\boldsymbol{R}) - \boldsymbol{k}_p(\boldsymbol{R}))\delta(W - \epsilon_p + \epsilon_h)$$

S. Hashimoto, M. Kohno, K. Ogata and M. Kawai, Prog. Theor. Phys. 119, 1005-1027 (2008)

Calculated $^{12}C(K^-,K^+)$ Ξ formation spectrum



Calculated $^{12}C(K^-,K^+)$ Ξ formation spectrum



Experimental data will change.

Cross section data is needed, instead of counts.

Summary

- Λ, Σ, and Ξ s.p. potentials are calculated in nuclear matter, using the present NLO YN interactions in chiral effective field theory
  - Λ hyperon: attraction decreases with increasing the density (due to the behavior of 3S1 contributions and Pauli blocking), which is suggestive for resolving the hyperon puzzle.
  - Σ hyperon: strongly repulsive Σ^- potential in neutron matter
- Ξ s.p. potential: attractive at low density and repulsive at high density
  - Ξ potential in finite nuclei is estimated by a simple LDA.
  - Attractive potential at a low-density surface region. ($E_{0s} = -2.66$ MeV)
  - With increasing the energy, the potential becomes repulsive.
  - $^{12}C(K^-,K^+)$ spectrum is calculated by the SCDW method, using the calculated Ξ potential. (Experimental data is under revision.)
- Ξ properties calculated using ChEFT baryon-baryon interactions are to be confronted with coming experimental data.
  - Possibility to reduce the uncertainties of the coupling and low-energy constants.