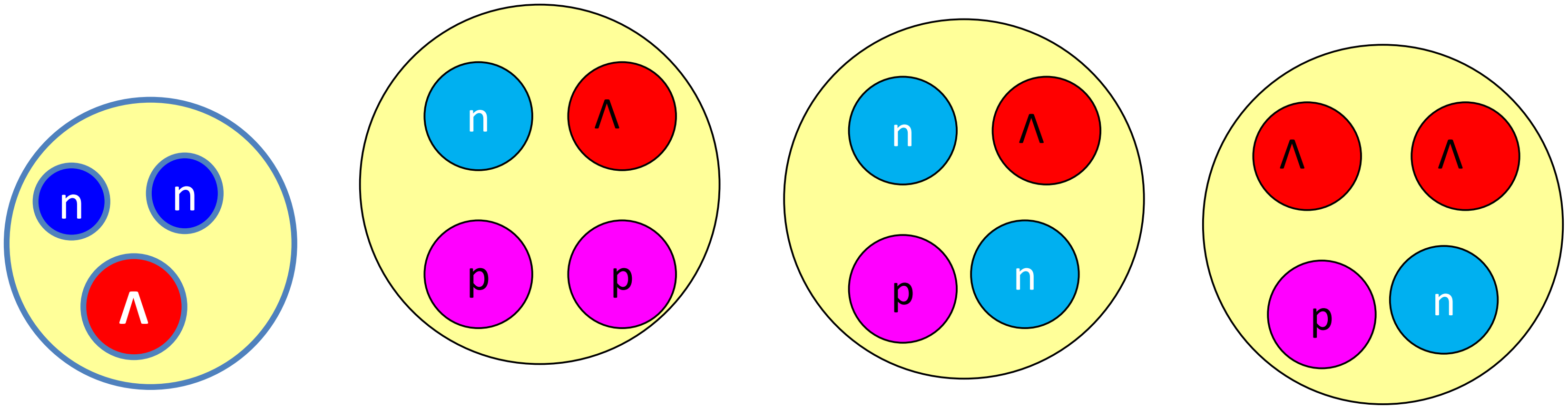
Few-body aspect of hypernuclei

E. Hiyama (RIKEN)

One of the important and interesting subjects : to study three- and four-baryon systems



${}^{3}_{\Lambda}n$ ${}^{4}_{\Lambda}He$ ${}^{4}_{\Lambda}H$ ${}^{4}_{\Lambda\Lambda}H$

C. Rappold et al., HypHI collaboration Phys. Rev. C 88, 041001 (R) (2013)

A. Esser, PRL114, 232501(2015)

(1) Why is it important to study these three-and four-body systems?

(2) What kind of new understandings do we obtain by solving these systems as three- and four-body problems?

Our few-body caluclational method

Gaussian Expansion Method (GEM) , since 1987 ,

▪A variational method using Gaussian basis functions

▪Take all the sets of Jacobi coordinates

Developed by Kyushu Univ. Group,
Kamimura and his collaborators.

Review article :
E. Hiyama, M. Kamimura and Y. Kino,
Prog. Part. Nucl. Phys. 51 (2003), 223.

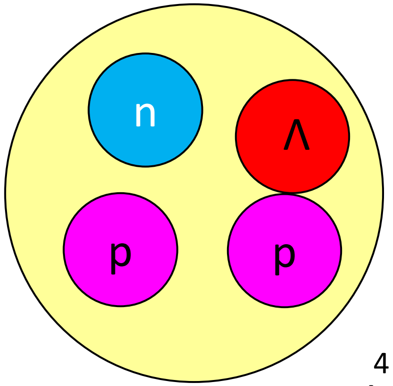
High-precision calculations of various 3- and 4-body systems:

Exsotic atoms / molecules , Light hypernuclei,
3- and 4-nucleon systems, 3-quark systems,
multi-cluster structure of light nuclei,

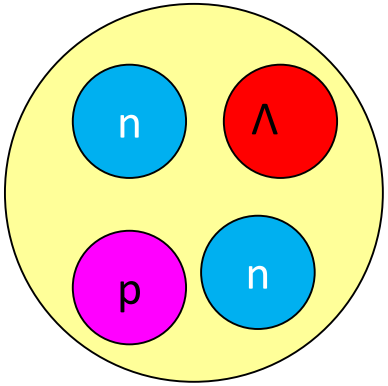
An example of the accuracy of the method:

Section 1

four-body calculation of $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He



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

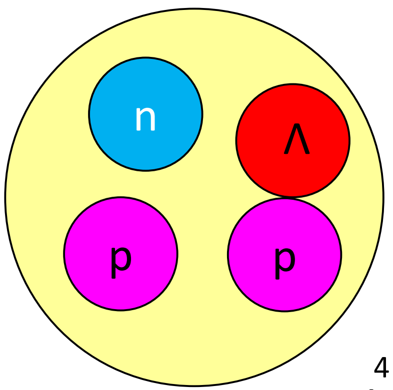


$^{4}_{\Lambda}$H

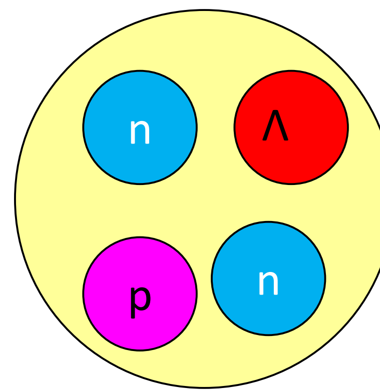
In S= -1 sector,
important subjects to extract information on YN interaction:

(1) Charge symmetry breaking

(2) ΛN－ΣN coupling

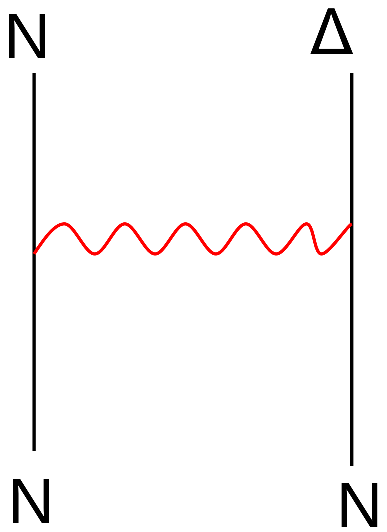


$^{4}_{\Lambda}He$



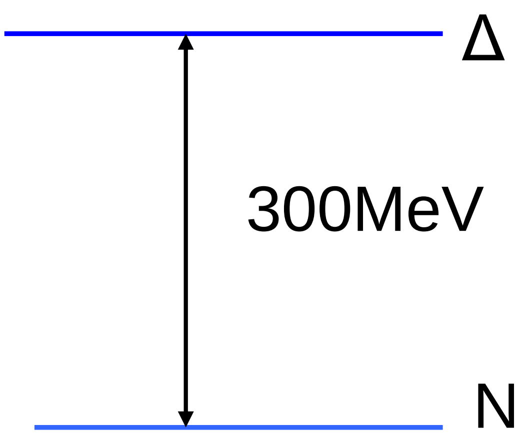
$^{4}_{\Lambda}H$

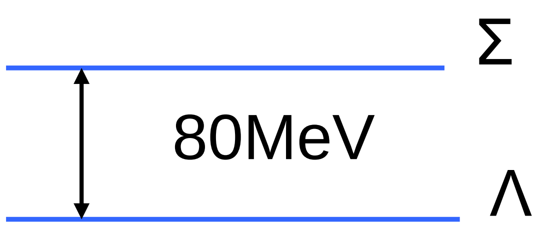
Non-strangeness nuclei

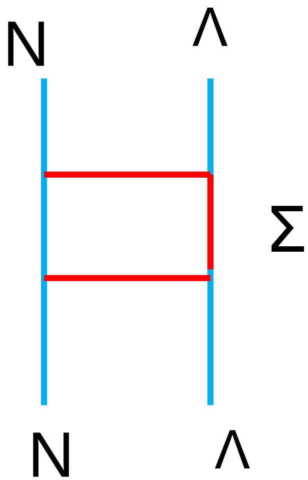


Nucleon can be converted into Δ.
However, since mass difference between nucleon and Δ is large, then probability of Δ in nucleus is not large.

On the other hand, the mass difference between Λ and Σ is much smaller, then Λ can be converted into Σ particle easily.



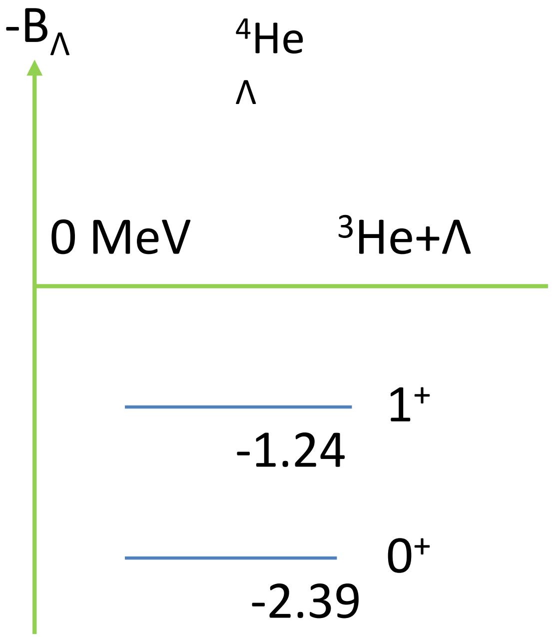




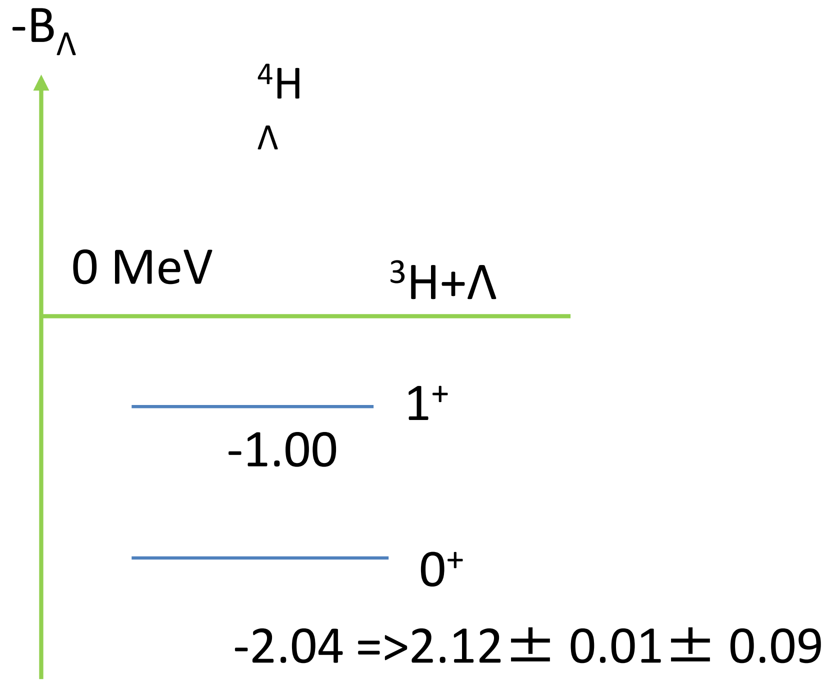
Interesting Issues for the ΛN-ΣN particle conversion in hypernuclei

(1) How large is the mixing probability of the Σ particle in the hypernuclei?

(2) How important is the ΛN—ΣN coupling in the binding energy of the Λ hypernuclei?

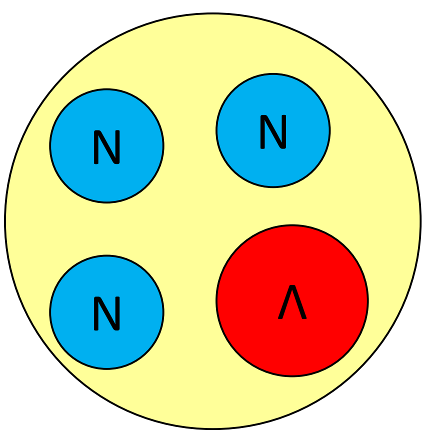


Exp.



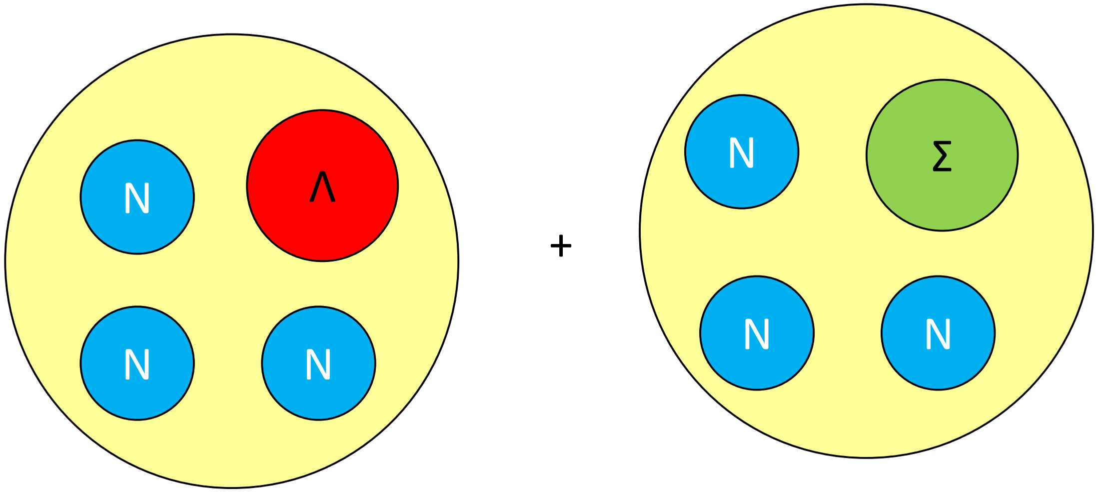
Exp.

A. Esser, PRL114, 232501(2015)



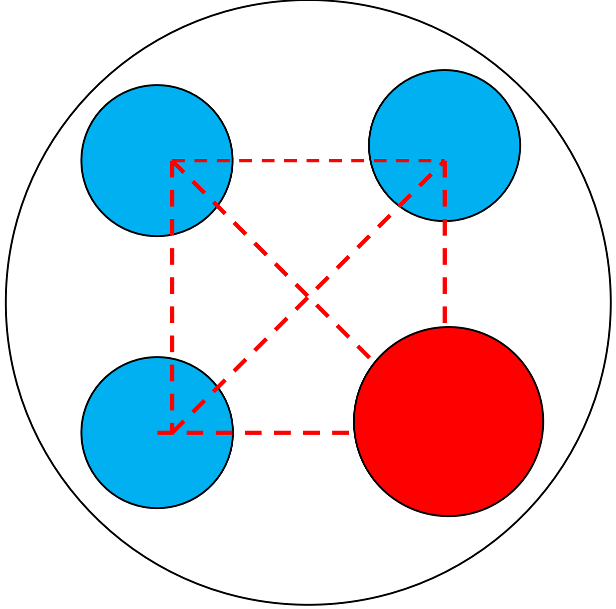
$^4_\Lambda He$

$^4_\Lambda H$



NNNΛ + NNNΣ

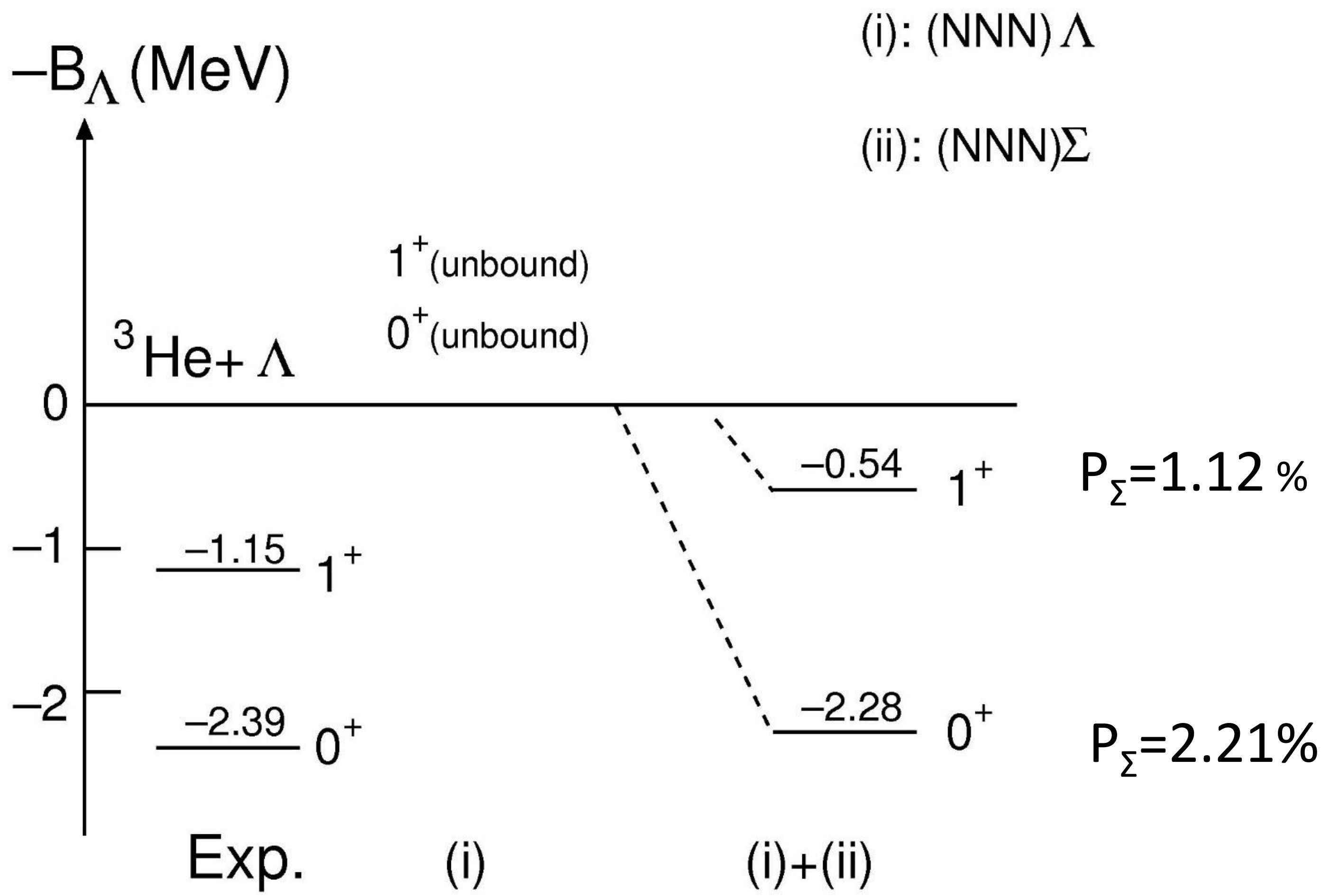
E. Hiyama et al., Phys. Rev. C65, 011301 (R) (2001).
H. Nemura et al., Phys. Rev. Lett. 89, 142502 (2002).
A. Nogga et al., Phys. Rev. Lett. 88, 172501 (2002).



${}^{4}_{\Lambda}\mathrm{He}$, ${}^{4}_{\Lambda}\mathrm{H}$

V_{NN} : AV8 potential

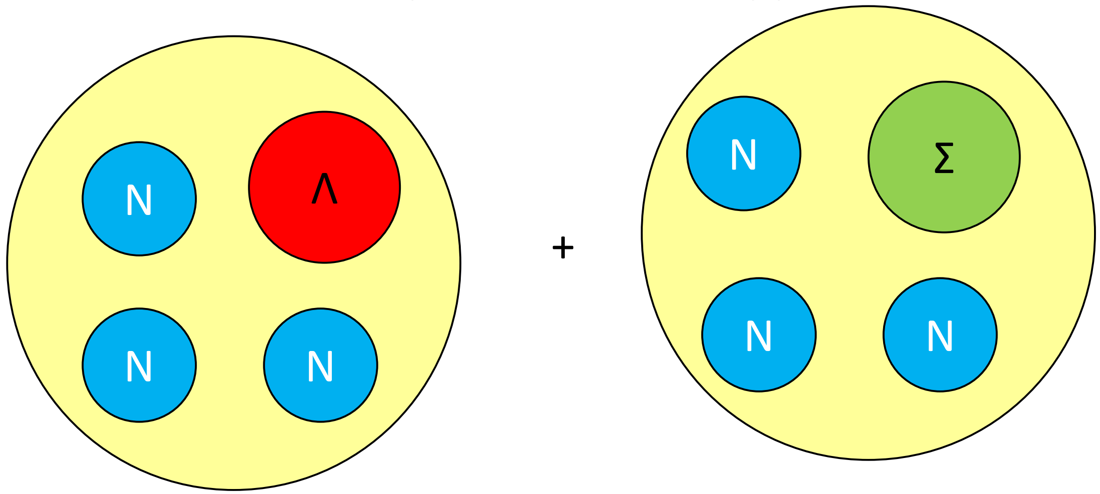
V_{YN} : Nijmegen soft-core '97f potential



(i): (NNN) Λ
(ii): (NNN)Σ
−B_Λ (MeV)
1+(unbound)
0+(unbound)
3He+ Λ
0
−1
−2
−1.15 1+
−2.39 0+
−0.54 1+
−2.28 0+
P_Σ=1.12 %
P_Σ=2.21%
Exp.
(i)
(i)+(ii)

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

To summarize the part of A=4 hypernuclei

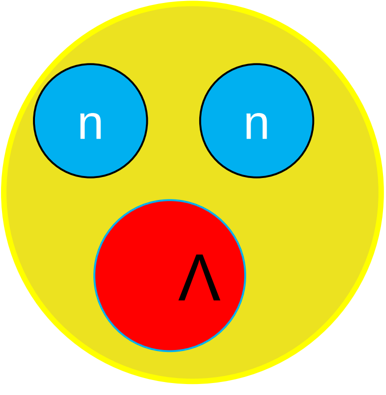


NNNΛ + NNNΣ

NNNΣ channel is essentially important to make A=4 hypernuclei.

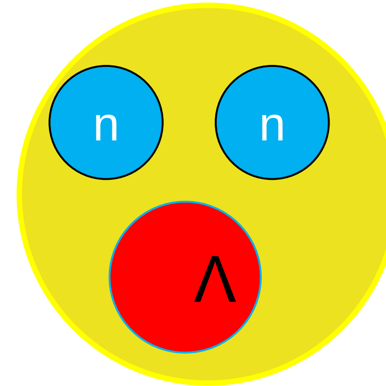
Section 2

three-body calculation of ${}^{3}_{\Lambda}n$



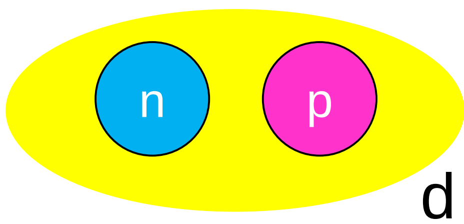
E. Hiyama, S. Ohnishi,
B.F. Gibson, and T. A. Rijken,
PRC89, 061302(R) (2014).

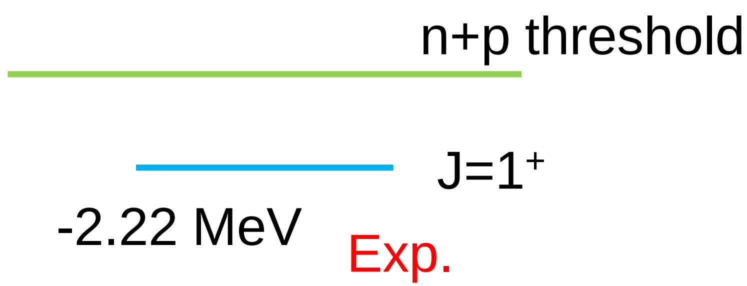
What is interesting to study nnΛ system?



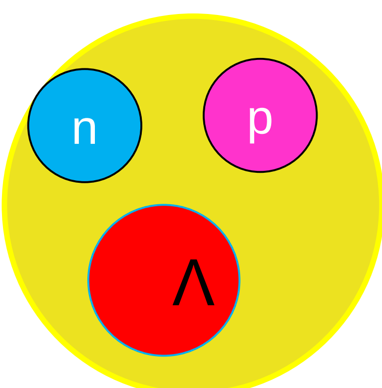
S=0

The lightest nucleus to have a bound state is deuteron.



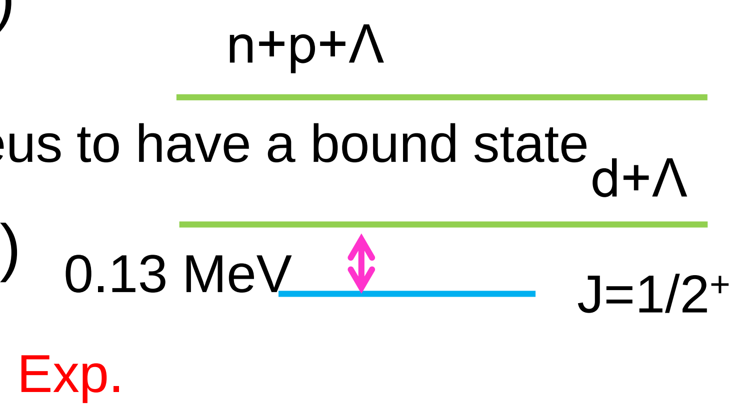


S=-1 (Λ hypernucear sector)



Lightest hypernucleus to have a bound state

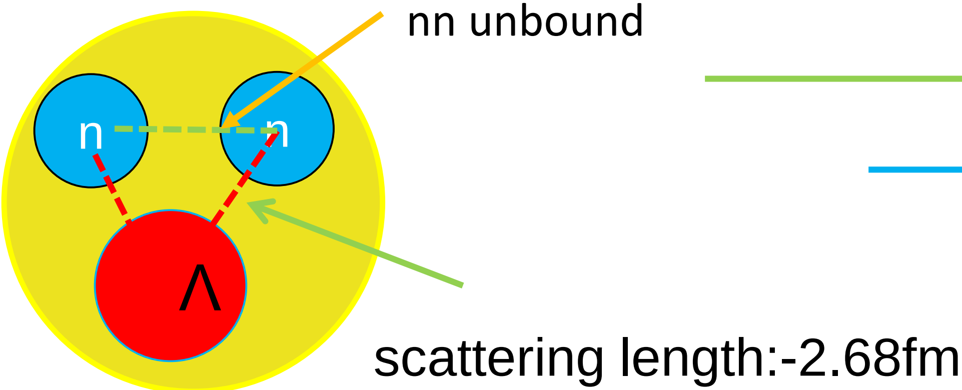
$^3_\Lambda$H (hyper-triton)

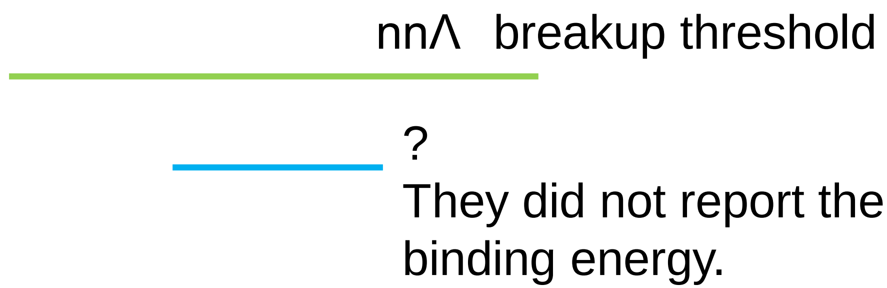


PHYSICAL REVIEW C 88, 041001(R) (2013)

Search for evidence of ${}^{3}_{\Lambda}n$ by observing $d + \pi^-$ and $t + \pi^-$ final states in the reaction of ${}^{6}\mathrm{Li} + {}^{12}\mathrm{C}$ at 2A GeV

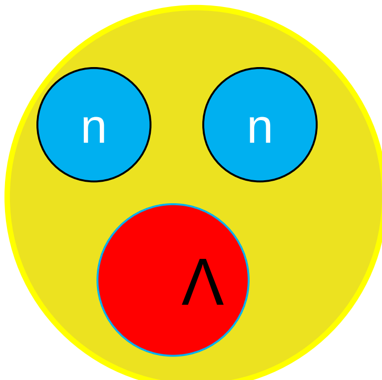
C. Rappold,[1,2,*] E. Kim,[1,3] T. R. Saito,[1,4,5,†] O. Bertini,[1,4] S. Bianchin,[1] V. Bozkurt,[1,6] M. Kavatsyuk,[7] Y. Ma,[1,4] F. Maas,[1,4,5] S. Minami,[1] D. Nakajima,[1,8] B. Özel-Tashenov,[1] K. Yoshida,[1,5,9] P. Achenbach,[4] S. Ajimura,[10] T. Aumann,[1,11] C. Ayerbe Gayoso,[4] H. C. Bhang,[3] C. Caesar,[1,11] S. Erturk,[6] T. Fukuda,[12] B. Göküzüm,[1,6] E. Guliev,[7] J. Hoffmann,[1] G. Ickert,[1] Z. S. Ketenci,[6] D. Khaneft,[1,4] M. Kim,[3] S. Kim,[3] K. Koch,[1] N. Kurz,[1] A. Le Fèvre,[1,13] Y. Mizoi,[12] L. Nungesser,[4] W. Ott,[1] J. Pochodzalla,[4] A. Sakaguchi,[9] C. J. Schmidt,[1] M. Sekimoto,[14] H. Simon,[1] T. Takahashi,[14] G. J. Tambave,[7] H. Tamura,[15] W. Trautmann,[1] S. Voltz,[1] and C. J. Yoon[3]
(HypHI Collaboration)

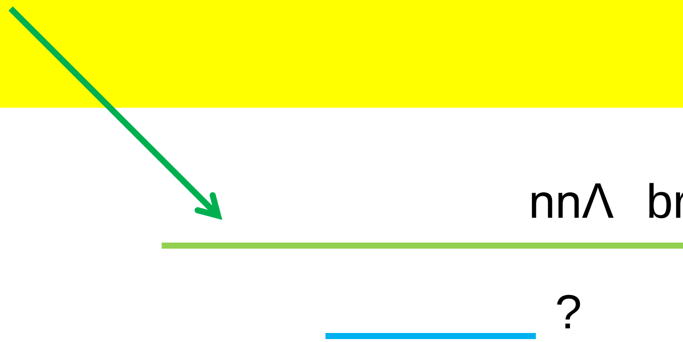




Observation of nnΛ system (2013)
Lightest hypernucleus to have a bound state
Any two-body systems are unbound.=>nnΛ system is bound.
Lightest Borromean system.

Theoretical important issue:
Do we have bound state for nnΛ system?
If we have a bound state for this system, how much is binding energy?



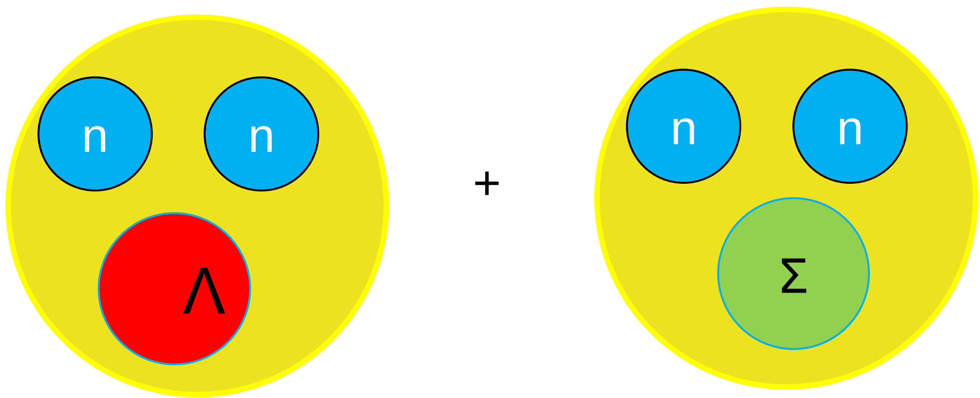


NN interaction : to reproduce the observed binding energies of ^{3}H and ^{3}He

NN: AV8 potential
We do not include 3-body force for nuclear sector.

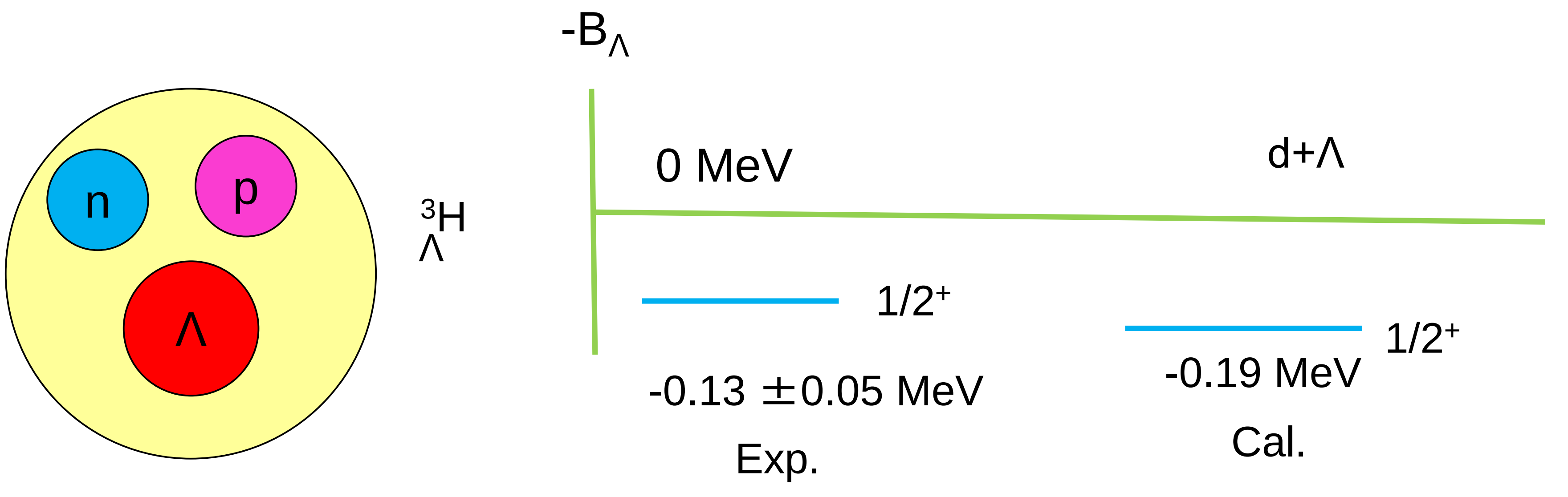
How about YN interaction?

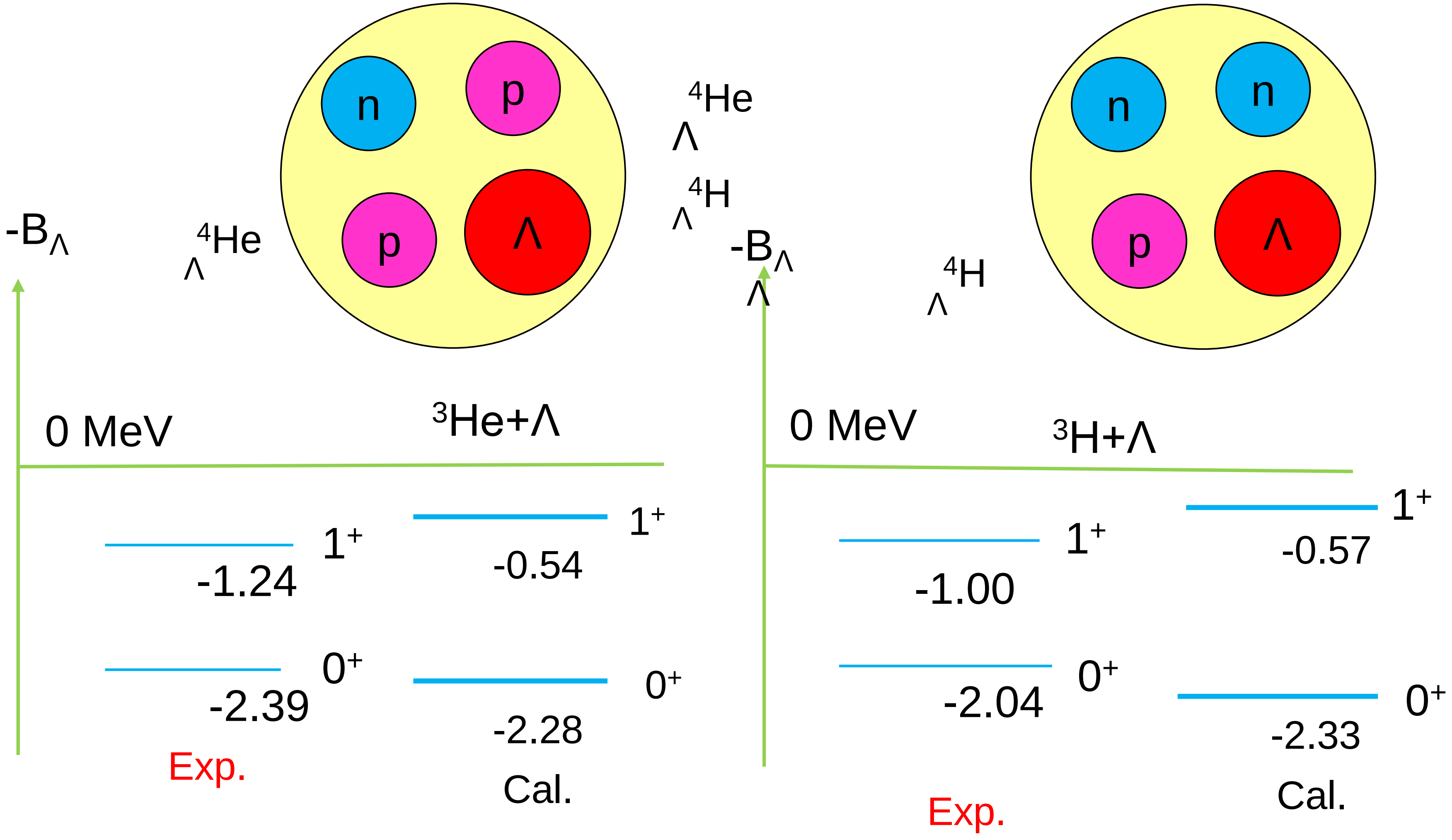
To take into account of Λ particle to be converted into Σ particle, we should perform below calculation using realistic hyperon(Y)-nucleon(N) interaction.



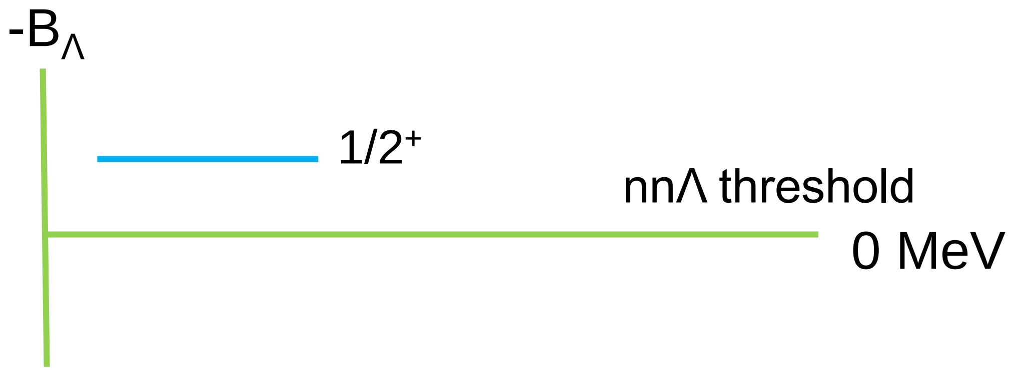
YN interaction: Nijmegen soft core '97f potential (NSC97f) proposed by Nijmegen group

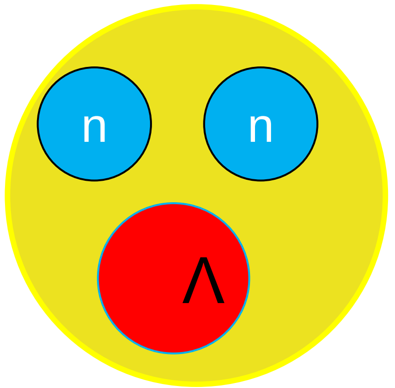
reproduce the observed binding energies of ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$


n
p
Λ
$^{3}_{\Lambda}H$
$-B_{\Lambda}$
0 MeV
d+Λ
1/2+
1/2+
-0.13 ±0.05 MeV
-0.19 MeV
Exp.
Cal.



What is binding energy of nnΛ?





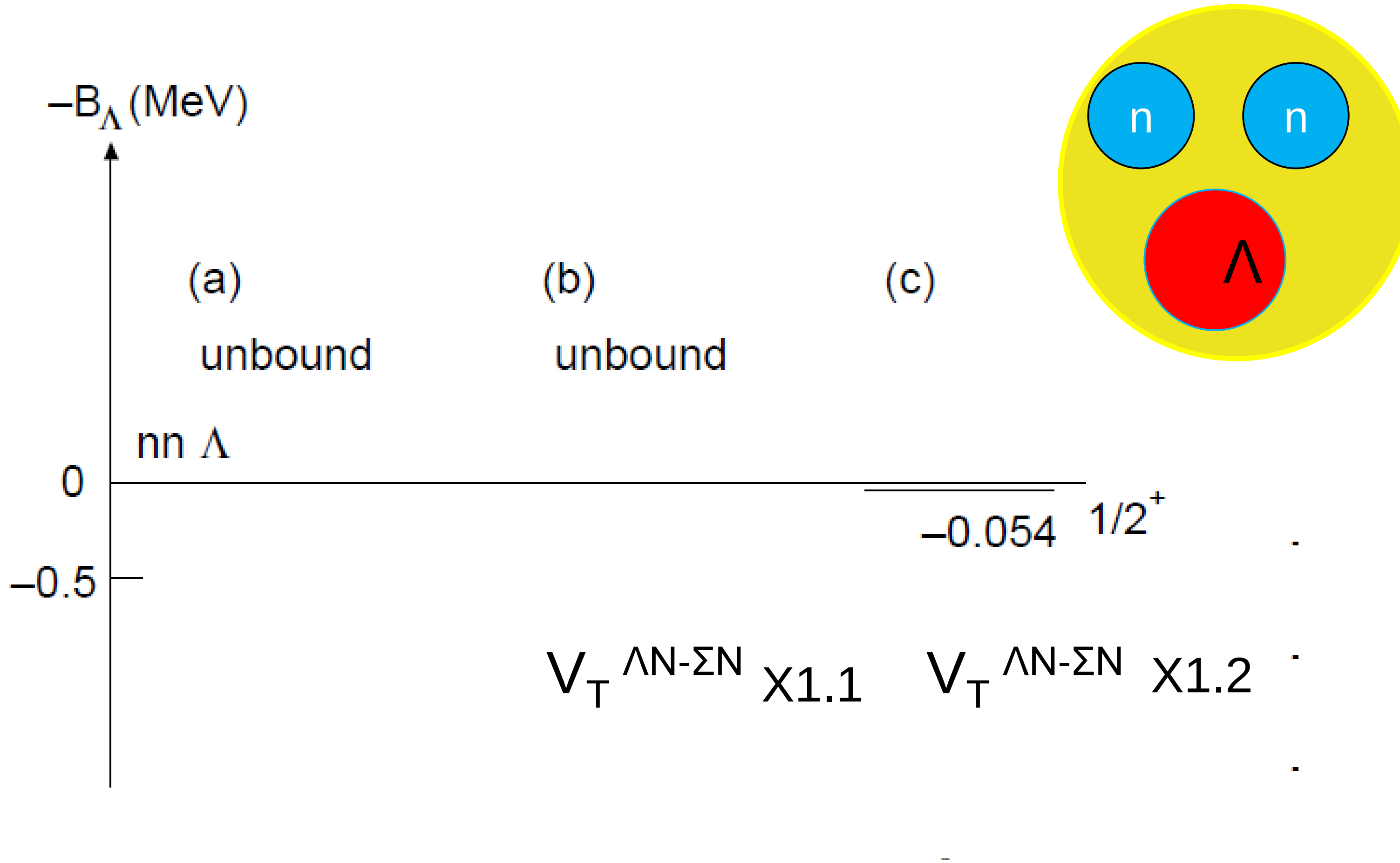
We have no bound state in nnΛ system.
This is inconsistent with the data.

Now, we have a question.

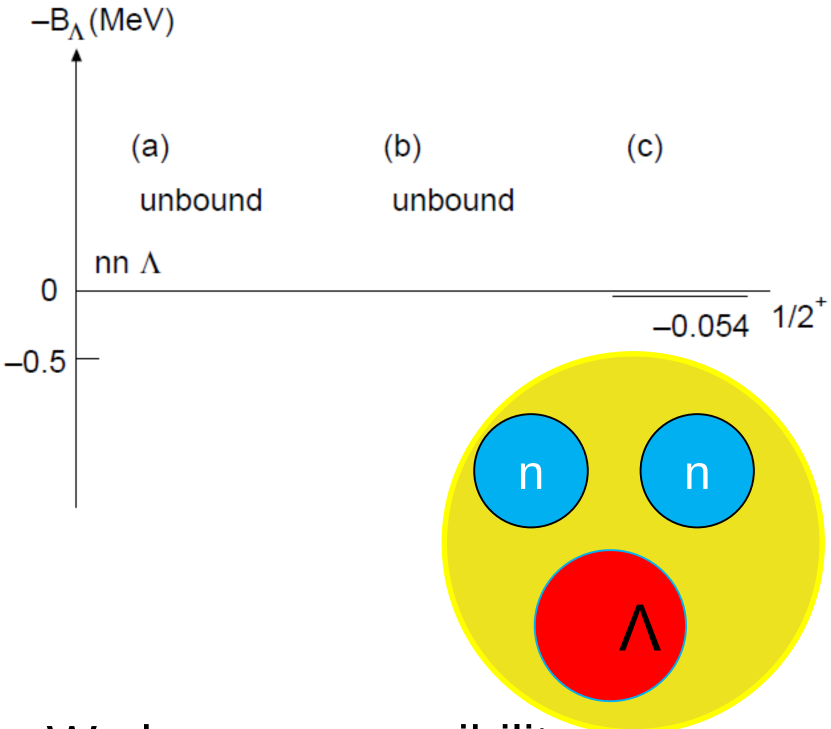
Do we have a possibility to have a bound state in nnΛ system tuning strength of YN potential ?

It should be noted to maintain consistency with the binding energies of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$.

$V_T^{\Lambda N-\Sigma N}$ X1.1, 1.2



When we have a bound state in nnΛ system, what are binding energies of ${}^{3}_{\Lambda}H$ and A=4 hypernuclei?



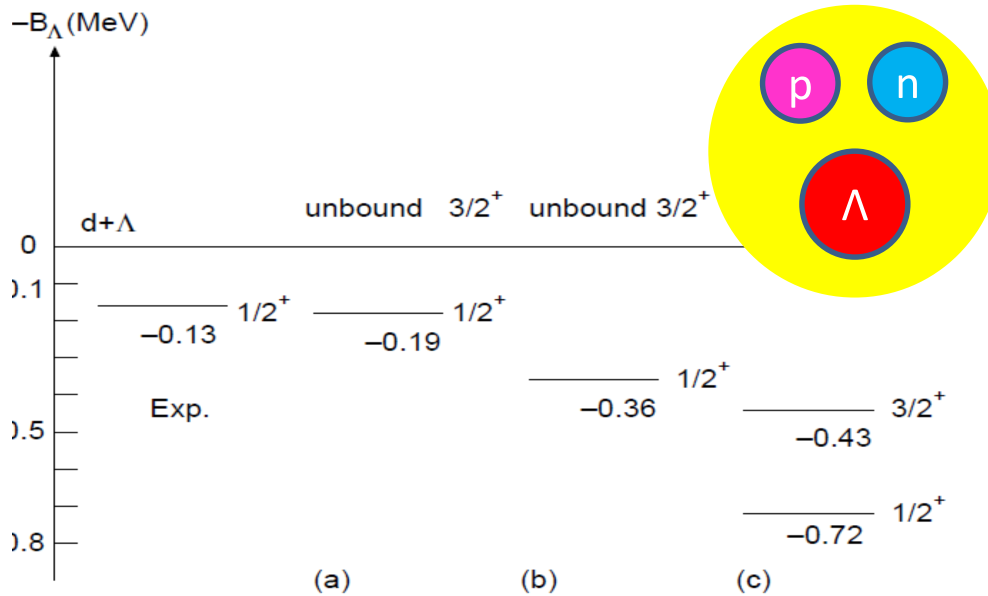
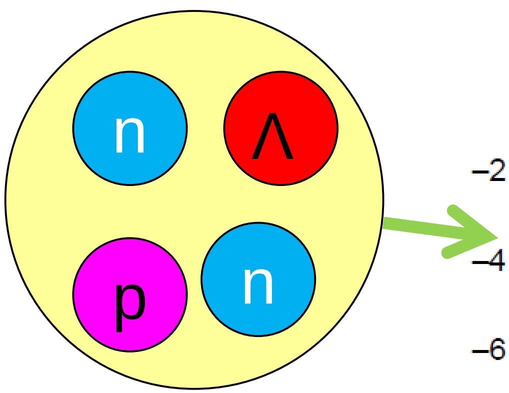
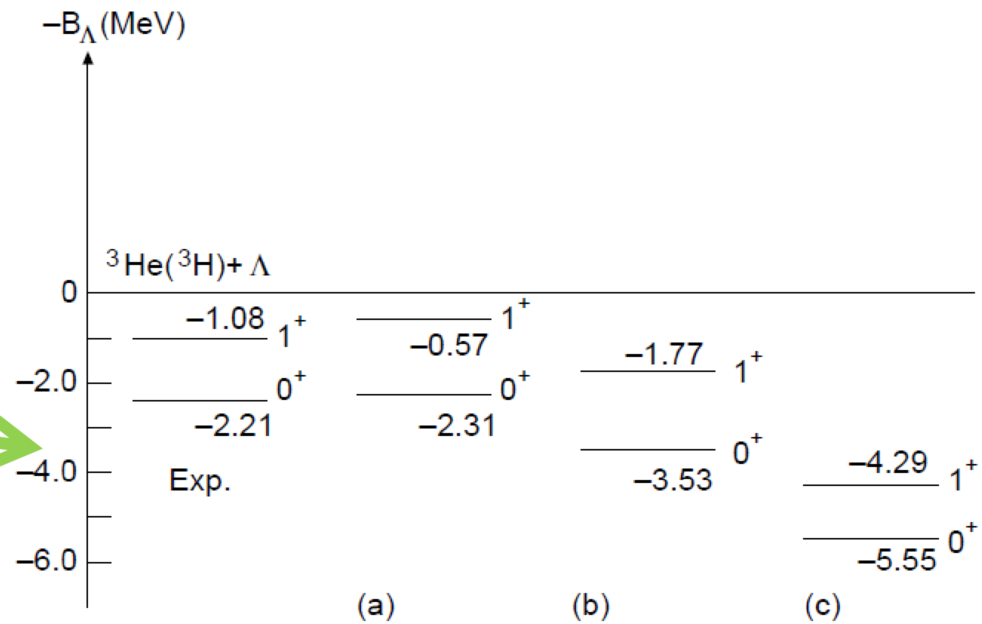


FIG. 3: Calculated Λ-separation energy for $^{3}_{\Lambda}$H with (a) $^{3}V^{T}_{N\Lambda-N\Sigma}$ × 1.00, (b) $^{3}V^{T}_{N\Lambda-N\Sigma}$ × 1.10, and (c) $^{3}V^{T}_{N\Lambda-N\Sigma}$ ×

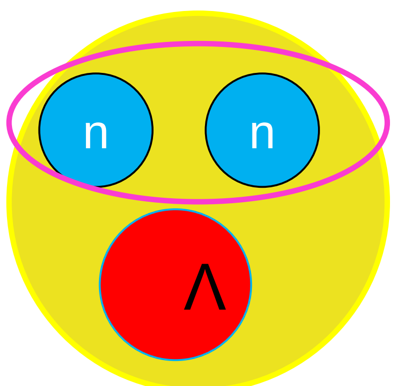
We have no possibility to have a bound state in nnΛ system.





Question: If we tune $^1S_0$ state of nn interaction,
Do we have a possibility to have a bound state in nnΛ?
In this case, the binding energies of ^{3}H and ^{3}He reproduce the observed data?

Some authors pointed out to have dineutron bound state in nn system. Ex. H. Witala and W. Gloeckle, Phys. Rev. C85, 064003 (2012).



T=1, $^1S_0$ state
I multiply component of $^1S_0$ state by 1.13 and 1.35. What is the binding energies of nnΛ?

PHYSICAL REVIEW C **85**, 064003 (2012)

Di-neutron and the three-nucleon continuum observables

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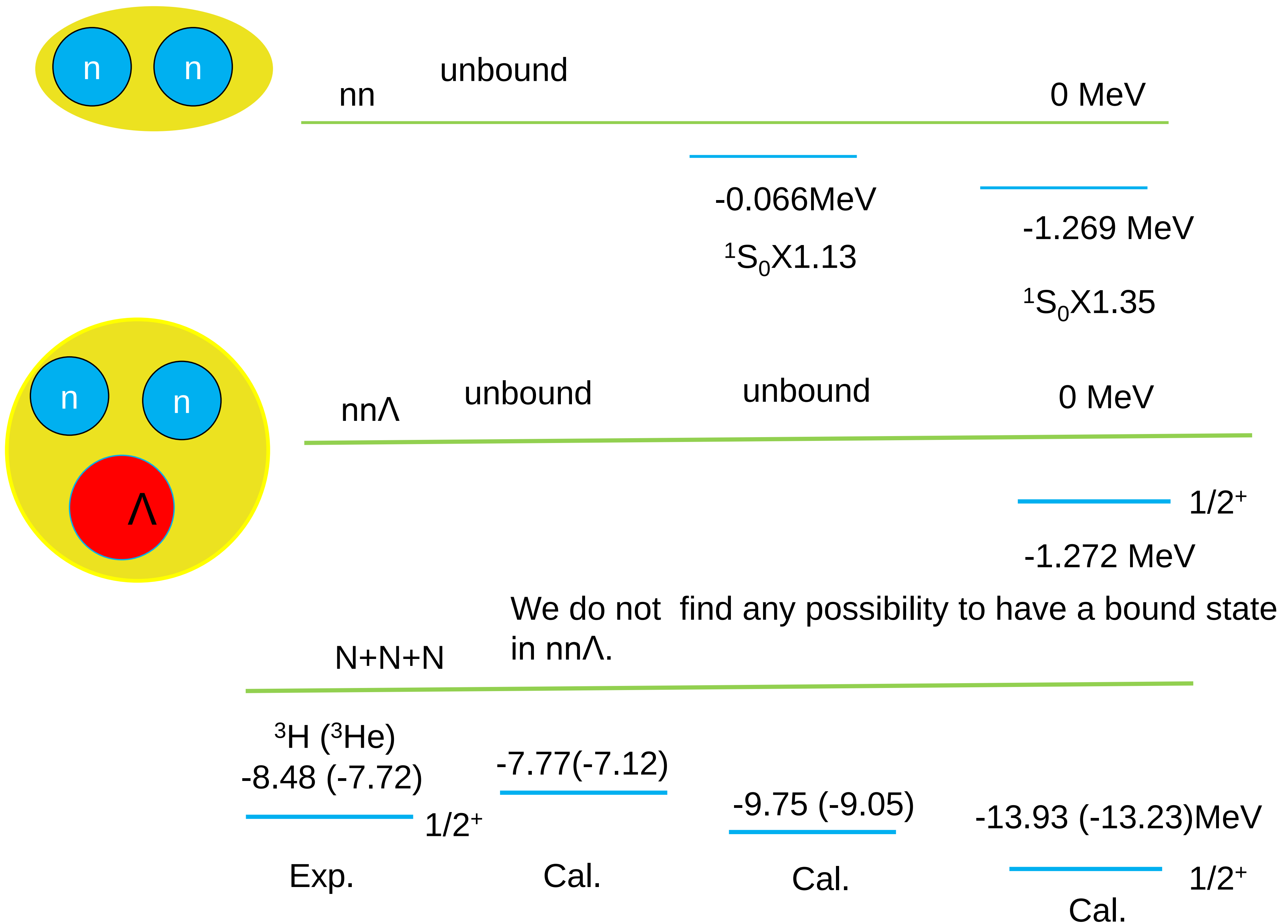
(Received 24 April 2012; published 25 June 2012)

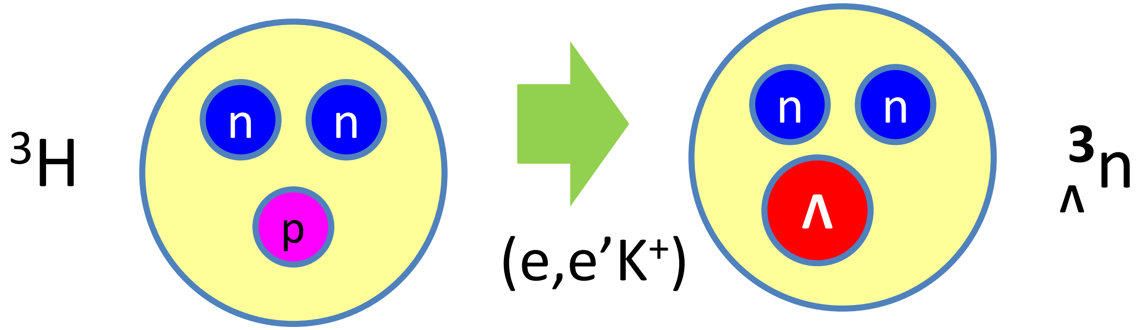
We investigate how strongly a hypothetical $^1S_0$ bound state of two neutrons would affect observables in neutron-deuteron reactions. To that aim we extend our momentum-space scheme of solving the three-nucleon Faddeev equations and incorporate in addition to the deuteron also a $^1S_0$ di-neutron bound state. We discuss effects induced by a di-neutron on the angular distributions of the neutron-deuteron elastic scattering and deuteron breakup cross sections. A comparison to the available data for the neutron-deuteron total cross section and elastic scattering angular distributions cannot decisively exclude the possibility that two neutrons can form a $^1S_0$ bound state. However, strong modifications of the final-state-interaction peaks in the neutron-deuteron breakup reaction seem to disallow the existence of a di-neutron.

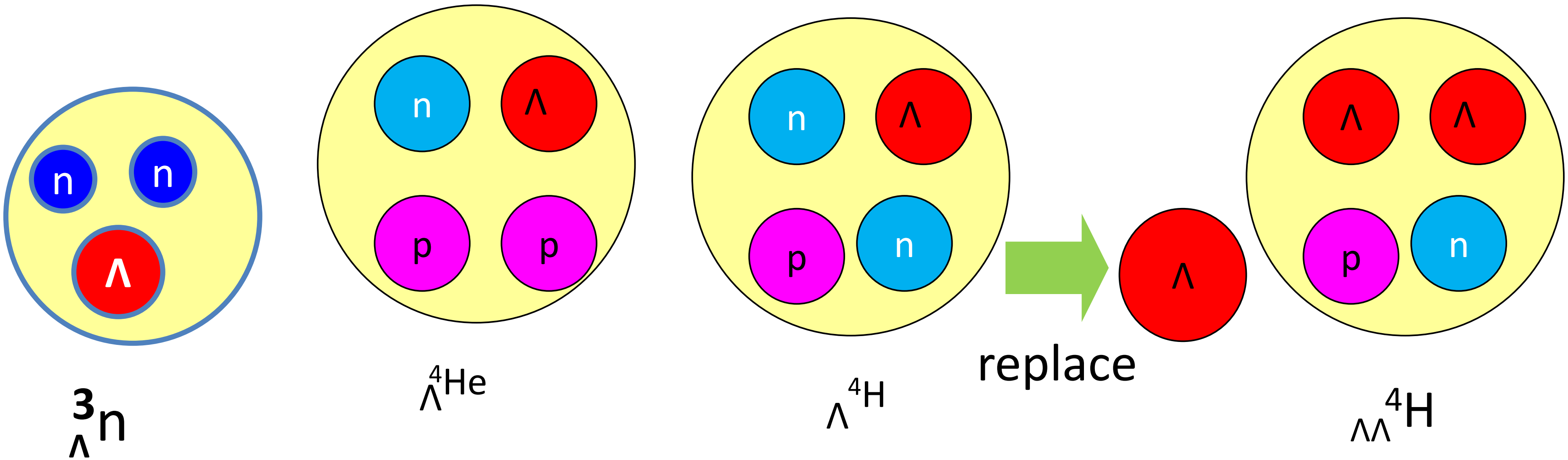

n
n
nn
unbound
0 MeV
-0.066MeV
1S0X1.13
-1.269 MeV
1S0X1.35
n
n
Λ
nnΛ
unbound
unbound
0 MeV
1/2+
-1.272 MeV
We do not find any possibility to have a bound state in nnΛ.
N+N+N
3H (3He)
-8.48 (-7.72)
1/2+
-7.77(-7.12)
-9.75 (-9.05)
-13.93 (-13.23)MeV
1/2+
Exp.
Cal.
Cal.
Cal.

Summary of nnΛ system:

Motivated by the reported observation of data suggesting a bound state nnΛ, we have calculated the binding energy of this hyperucleus taking into account ΛN-ΣN explicitly. We did not find any possibility to have a bound state in this system. However, the experimentally they reported evidence for a bound state. As long as we believe the data, we should consider additional missing elements in the present calculation. I need more data for nnΛ system. For this purpose, I am waiting for ALICE data.

It is planned to perform search experiment of nnΛ system at JLab to conclude whether or not the system exists as bound state experimentally. Also, it is planned to perform search experiment of nnΛ system at HypHI collaboration+Super FRS in 2018.



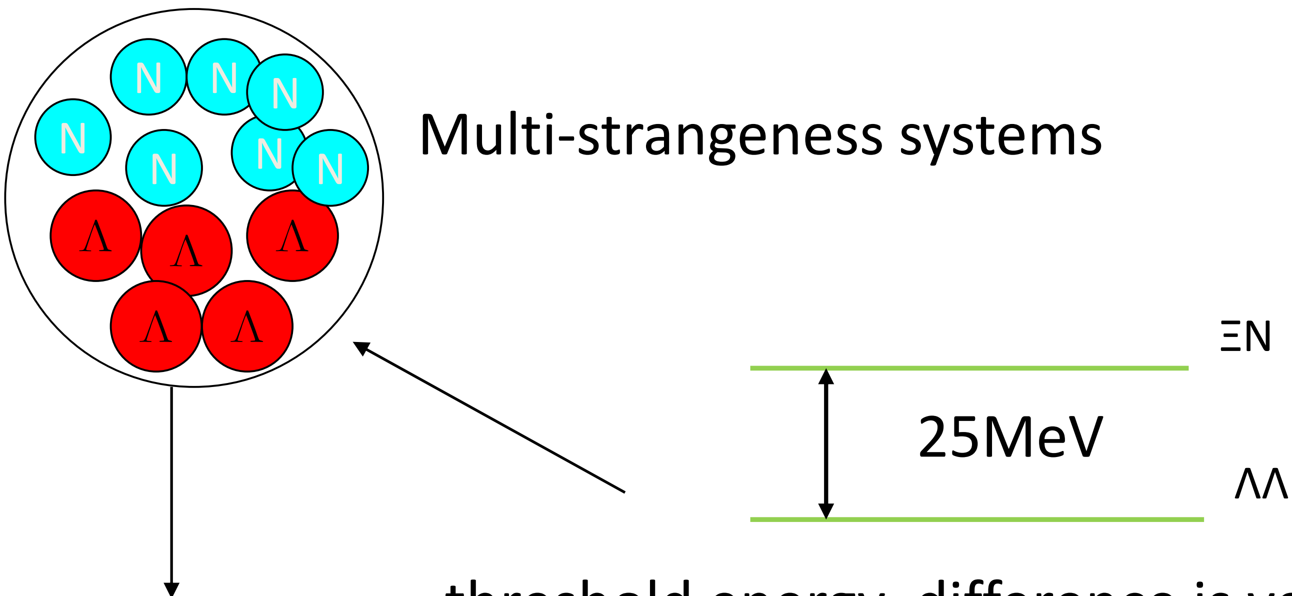


Interesting issue:

ΛΛ—ΞN coupling

ΛΛ-ΞN coupling

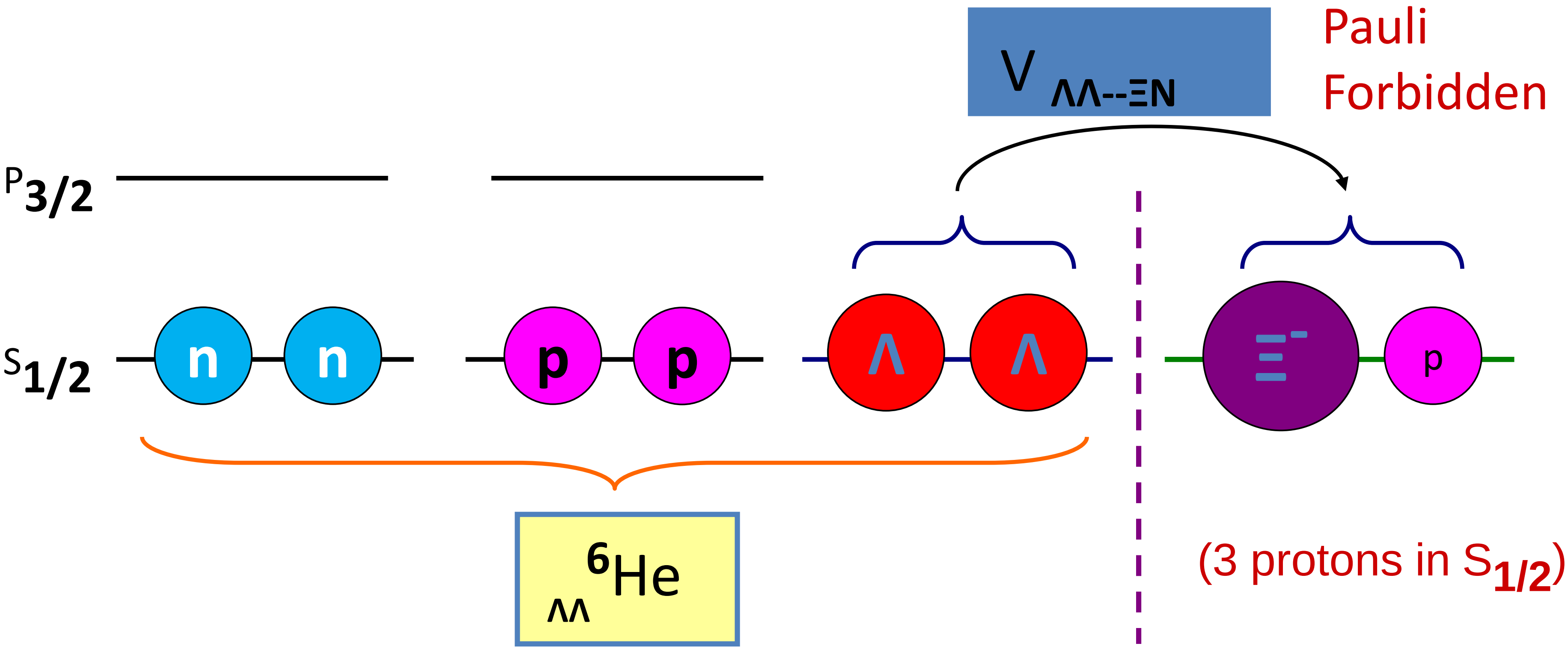
One of the major goals in hypernuclear physics
To study structure of multi-strangeness systems
(extreme limit : neutron star)



threshold energy difference is very small!

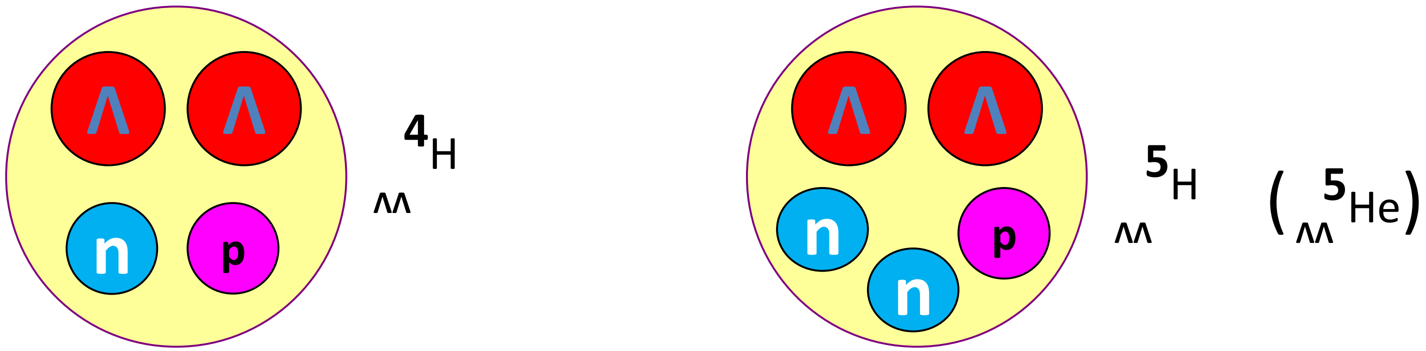
It is considered that
ΛΛ→ΞN particle conversion
is strong in multi-strangeness system.

Effect of **ΛΛ—ΞN** coupling is small in ${}_{\Lambda\Lambda}{}^{6}He$ which was observed as NAGARA event.

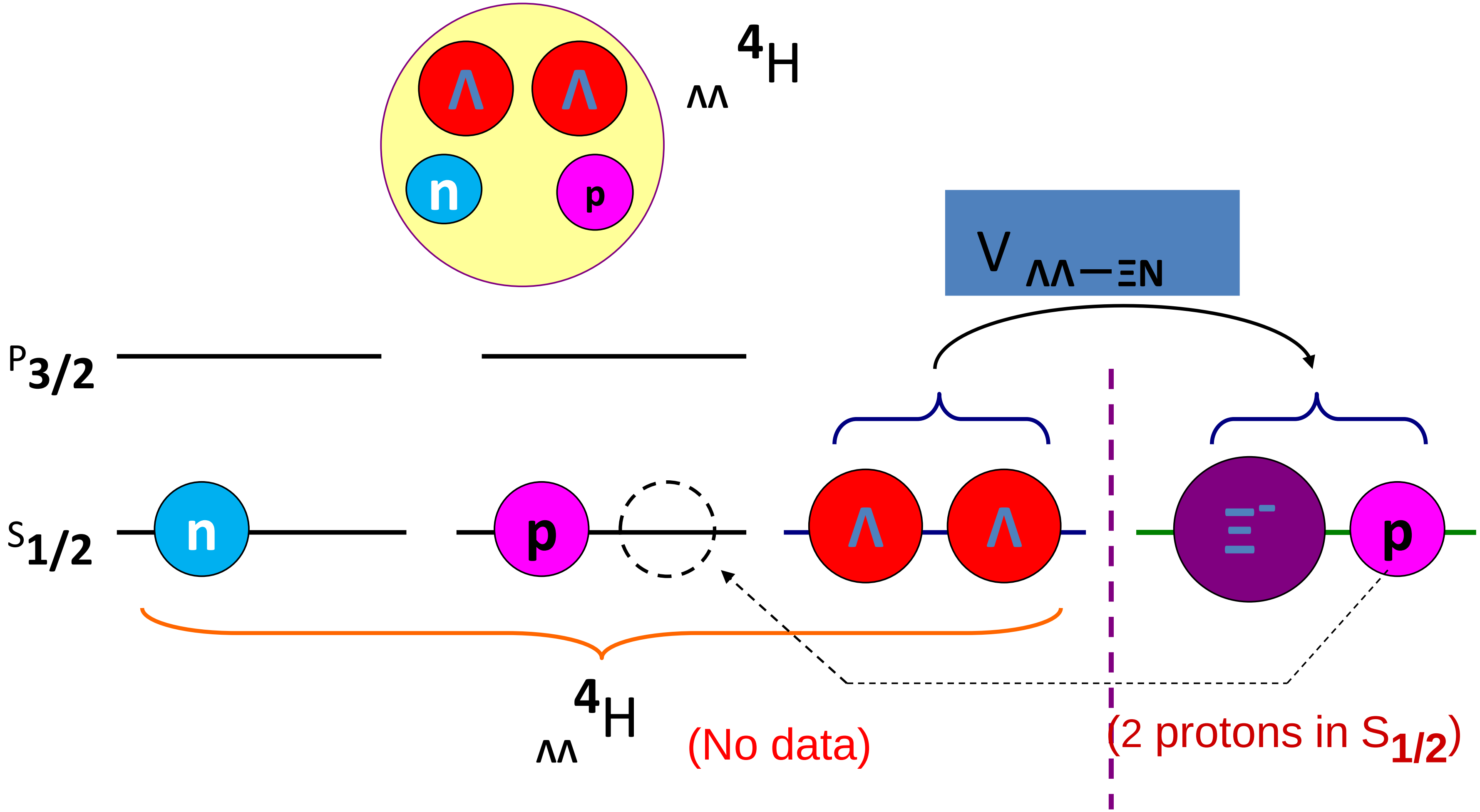


- I.R. Afnan and B.F. Gibson, Phys. Rev. C67, 017001 (2003).
- Khin Swe Myint, S. Shinmura and Y. Akaishi, nucl-th/029090.
- T. Yamada and C. Nakamoto, Phys. Rev.C62, 034319 (2000).

For the study of ΛΛ−ΞN coupling interaction, s-shell double Λ hypernuclei such as ${}^{4}_{\Lambda\Lambda}H$ and ${}^{5}_{\Lambda\Lambda}H$ (${}^{5}_{\Lambda\Lambda}He$) are very suitable.

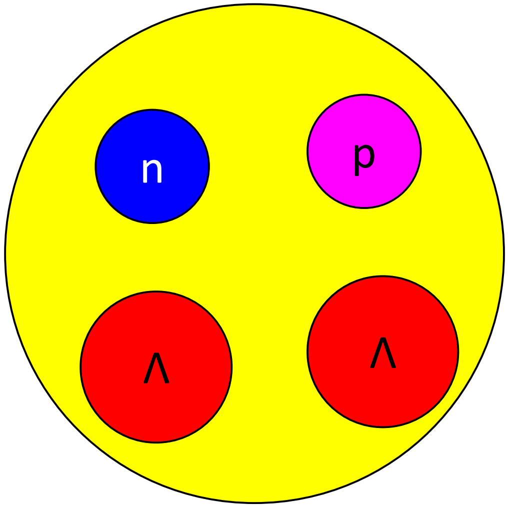


- I.N. Filikhin and A. Gal, Phys. Rev. Lett. 89, 172502 (2002)
- Khin Swe Myint, S. Shinmura and Y. Akaishi, Eur. Phys. J. A16, 21 (2003).
- D. E. Lanscoy and Y. Yamamoto, Phys. Rev. C69, 014303 (2004).
- H. Nemura, S. Shinmura, Y. Akaishi and Khin Swe Myint, Phys. Rev. Lett. 94, 202502 (2005).



Due to NO Pauli plocking, the ΛΛ—ΞN coupling can be large in $^{4}_{\Lambda\Lambda}H$

B.F. Gibson, I.R. Afnan, J.A.Carlson and D.R.Lehman, Prog. Theor. Phys. Suppl. 117, 339 (1994).



$^{4}_{\Lambda\Lambda}H$

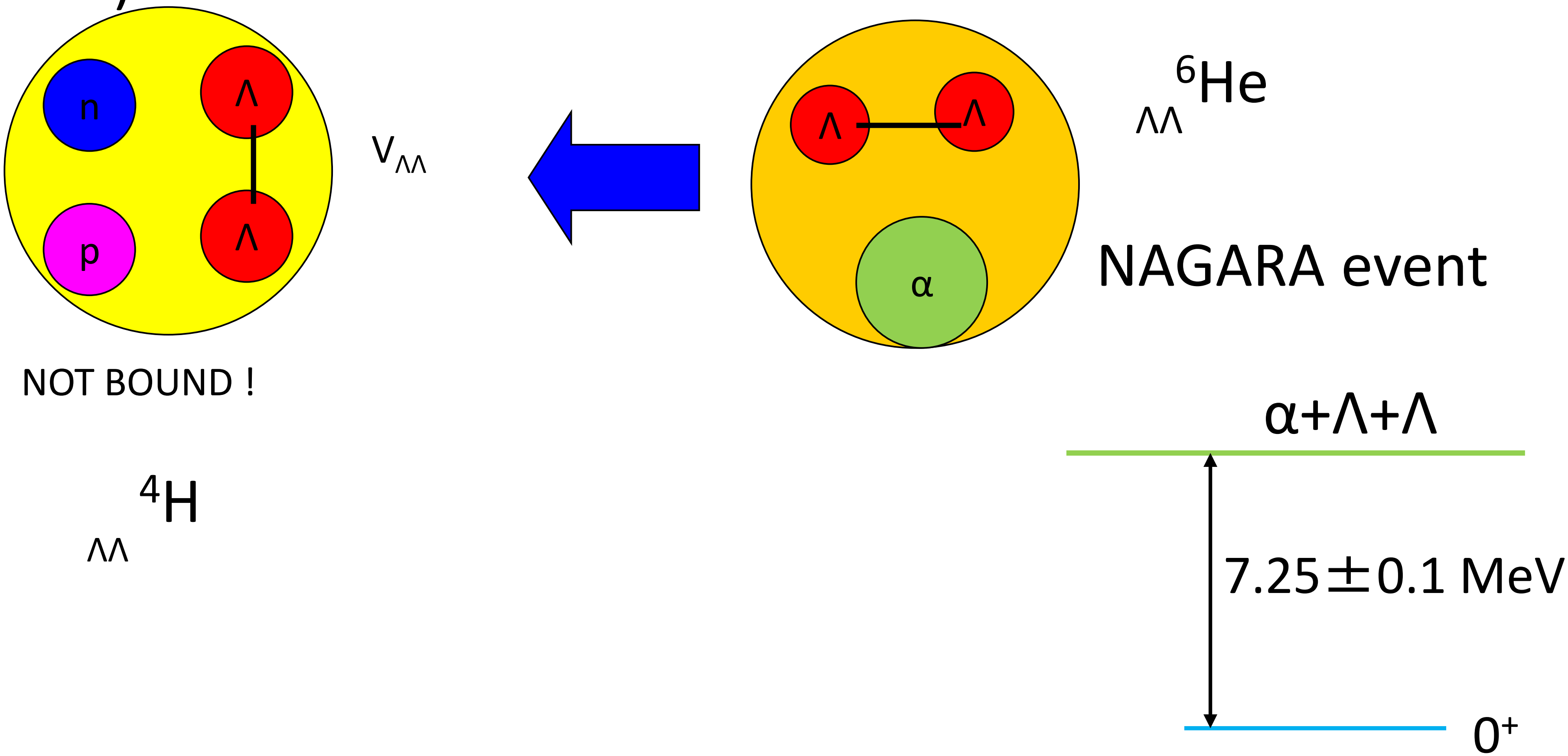
The important issue:

Does the YY interaction which designed to reproduce the binding energy of $^{6}_{\Lambda\Lambda}He$ make $^{4}_{\Lambda\Lambda}H$ bound?

And how does the effect of ΛΛ—ΞN coupling play important role in the binding energy of $^{6}_{\Lambda\Lambda}He$ and $^{4}_{\Lambda\Lambda}H$?

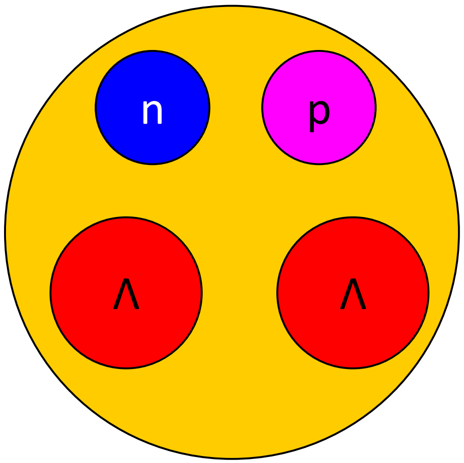
1)I.N. Filikhin and A. Gal, Phys. Rev. Lett. 89, 172502 (2002)

2)H. Nemura, Y. Akaishi et al., Phys. Rev. C67, 051001 (2002)



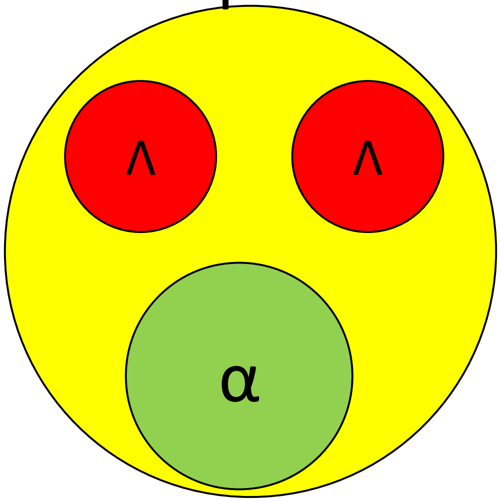
Did not include ΛΛ-ΞN coupling

ΛΛ-ΞN coupling => ▪ significant in $_{\Lambda\Lambda}{}^{4}H$

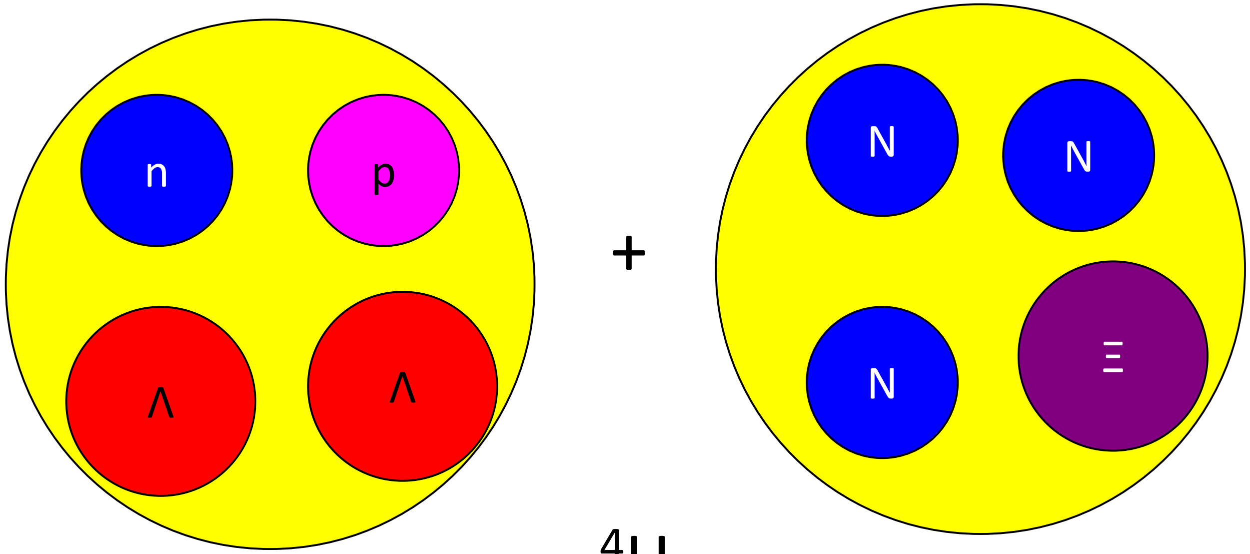


$_{\Lambda\Lambda}{}^{4}H$

▪ Not so important in $_{\Lambda\Lambda}{}^{6}He$

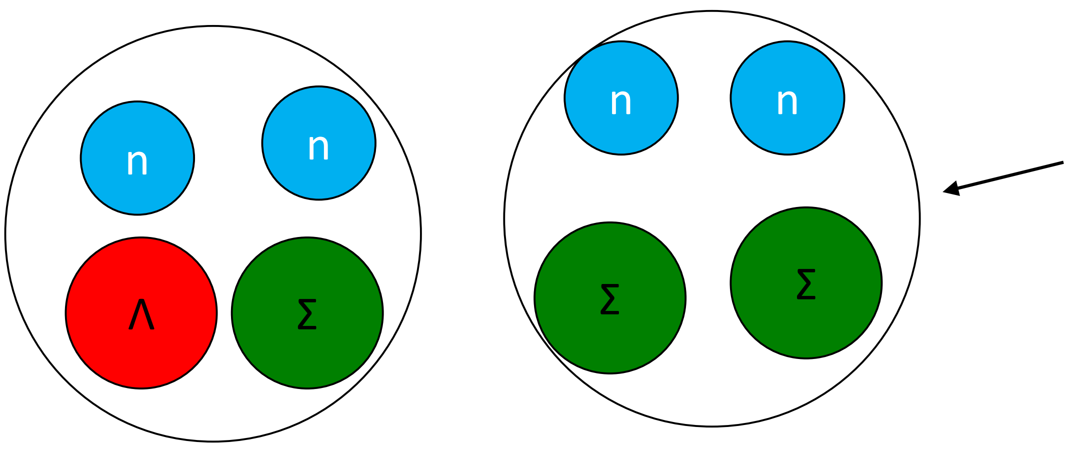


$_{\Lambda\Lambda}{}^{6}He$



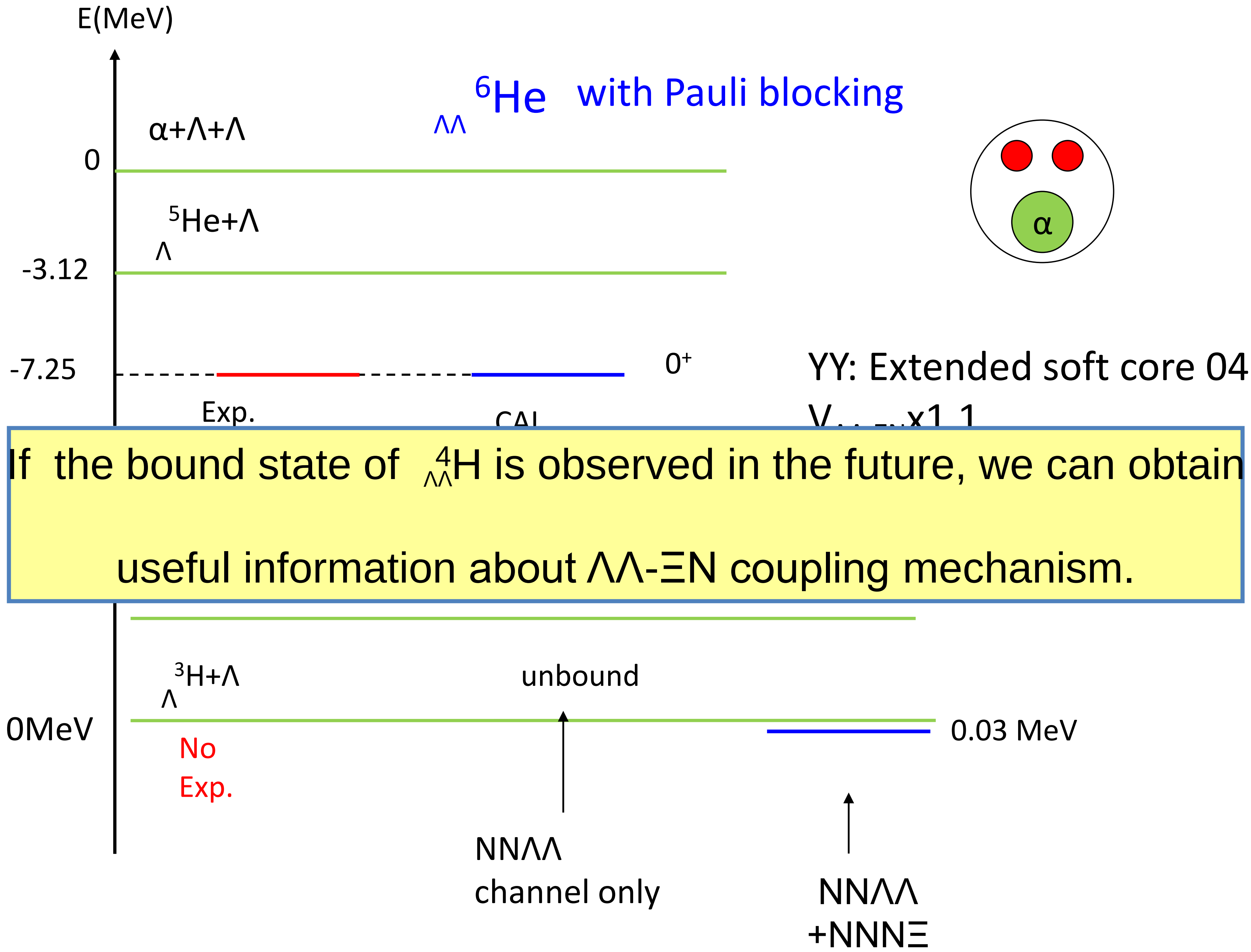
$^{4}_{\Lambda\Lambda}\mathrm{H}$

One of the most numerically difficult 4-body problem

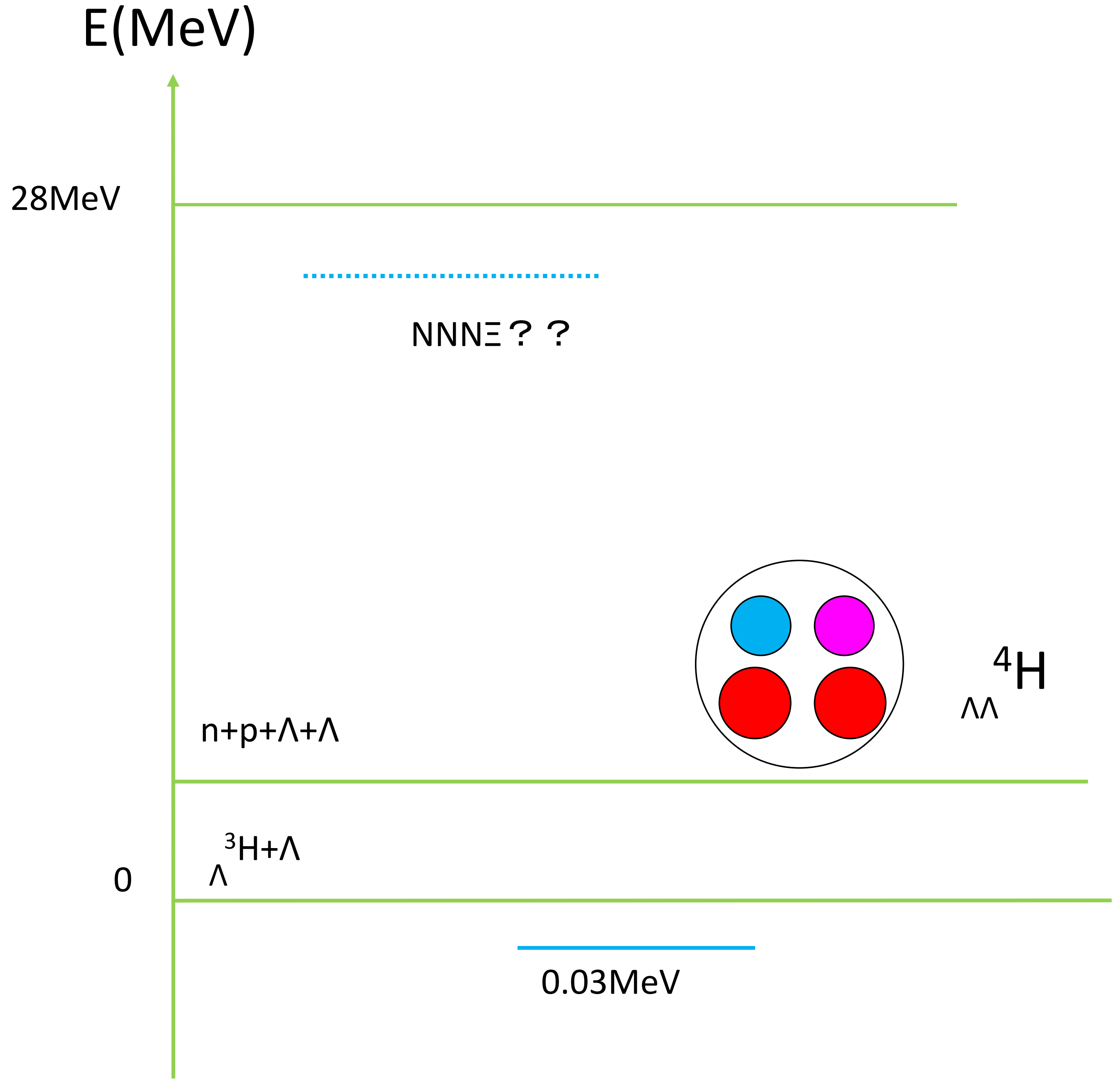


E. Hiyama

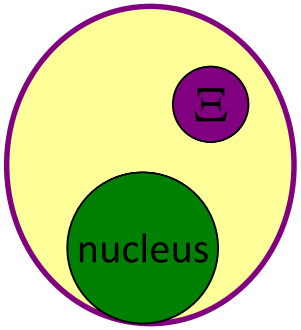
Dr. Nemura



If the bound state of $^{4}_{\Lambda\Lambda}$H is observed in the future, we can obtain useful information about ΛΛ-ΞN coupling mechanism.


E(MeV)
28MeV
NNNΞ？？
$^{4}_{\Lambda\Lambda}H$
n+p+Λ+Λ
$^{3}_{\Lambda}H$+Λ
0
0.03MeV

ΞN -ΞN interaction



Ξ hypernucleus

For the study of ΞN interaction, it is important to study the structure of Ξ hypernuclei.
Then, it is important to predict theoretically what kinds of Ξ hypernuclei will exist as bound states.

Important issue:

What kind of ΞN interaction should we employ?

Since there is no information about ΞN interaction, we cannot use phenomenological ΞN interaction.

We have realistic interactions although with large ambiguity.

- Nijmegen group
- Ehime group
- Kyoto-Niigata group

BNL-E885

PHYSICAL REVIEW C 61 054603

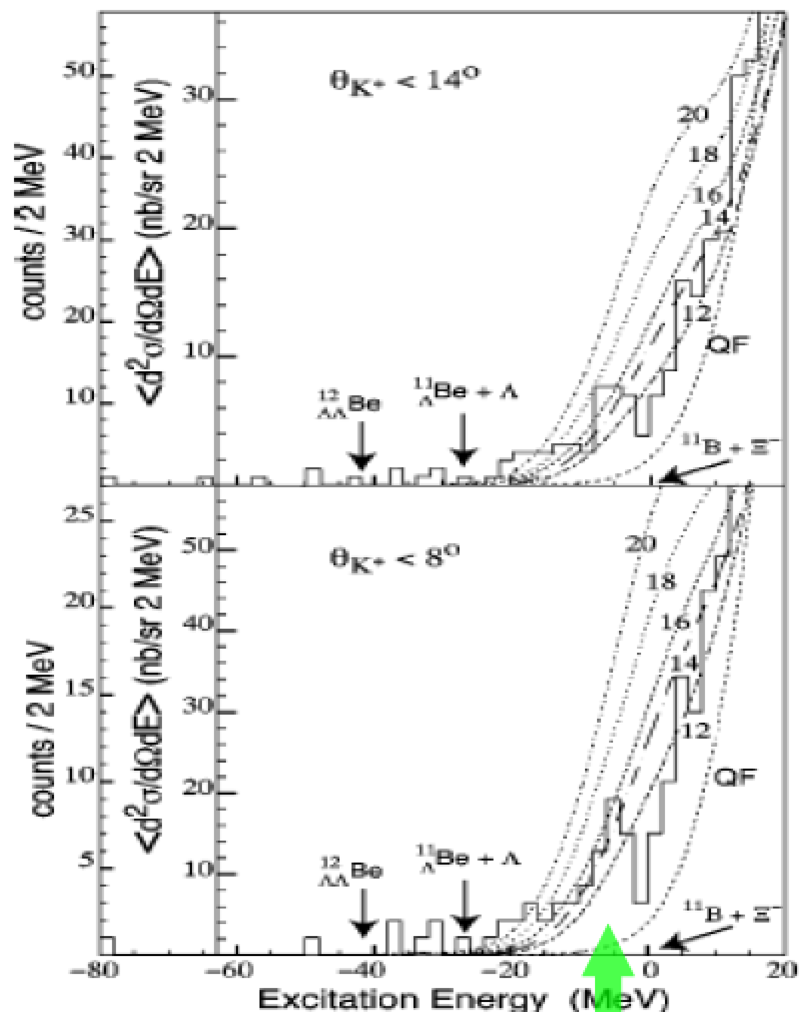
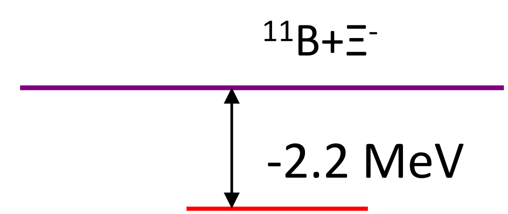


FIG. 6. Excitation-energy spectra from E885 for $^{12}C(K^-, K^+)X$

Only experimental data

By assuming a Ξ-nucleus Woods-Saxon potential with a depth of ～-14 MeV, we reproduce the experimental data.

This WS potential leads to be bound by -2.2 MeV in $^{12}_{\Xi^-}$Be when the Coulomb interaction is switched off.



We use this information.

The ΞN interaction to reproduce the data

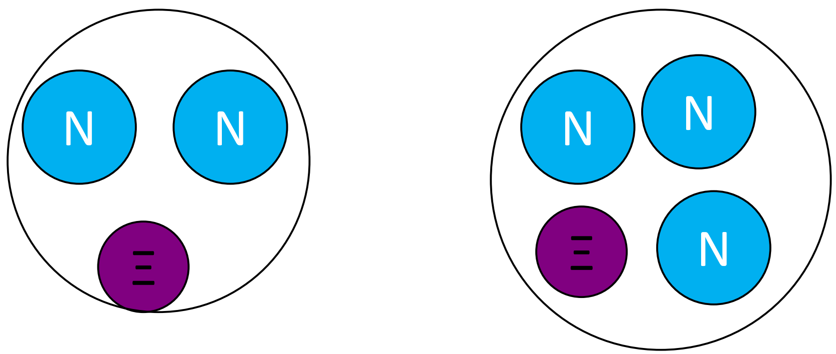
- Extended soft core 04d (ESC04d)

Th. A. Rijken, and Y. Yamamoto, Phys. Rev. C73, 044008(2006).

Extended soft core '08(ESC08)

Three- and four-body calculation using this potential is in progress.

ESC potential leads to give bound states in s-shell Ξ hypernuclei such as NNΞ and NNNΞ.



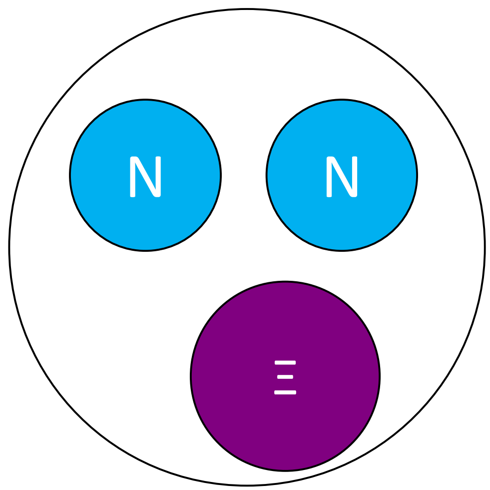
Results

ESC04

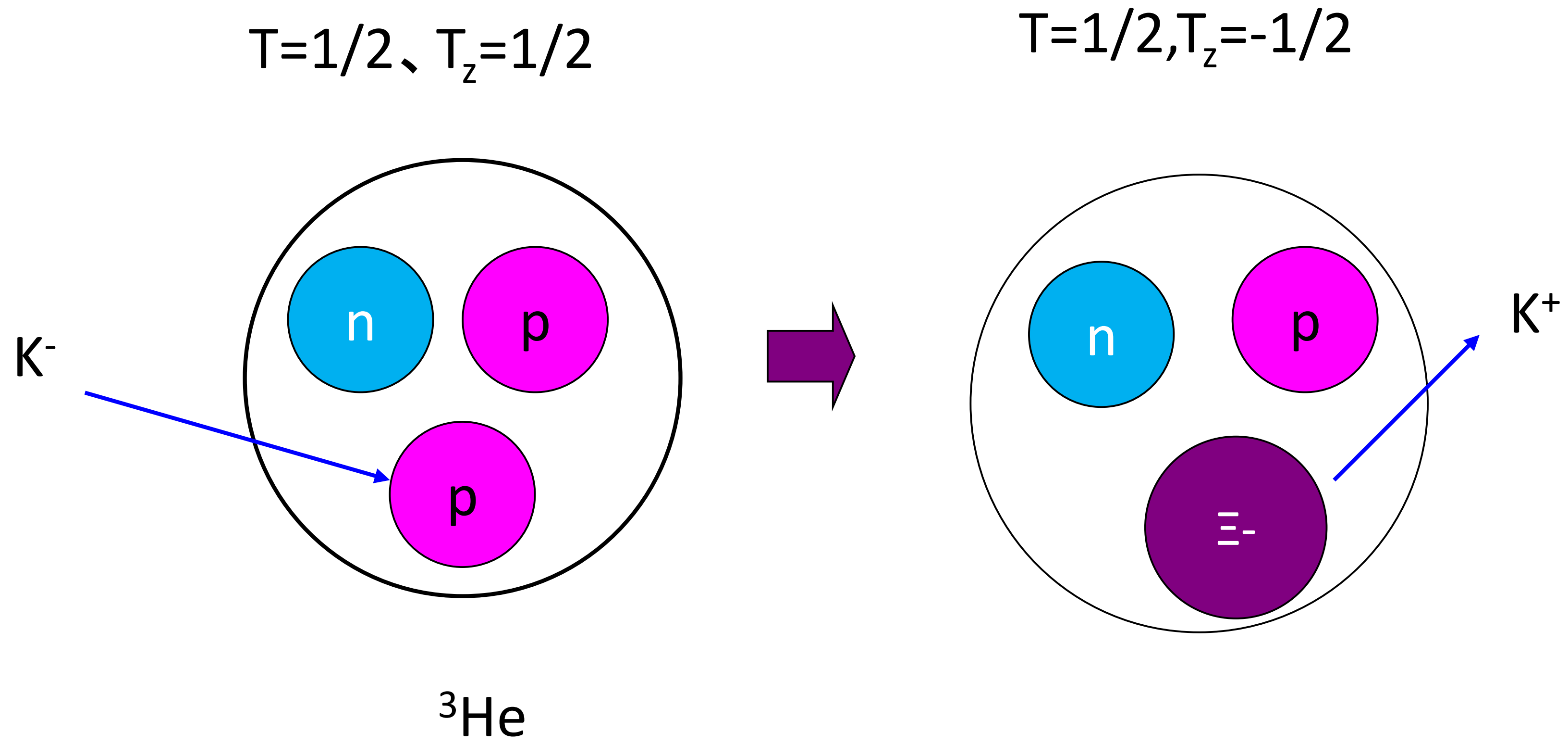
0 MeV (np)-Ξ

$1/2^{+}$

-0.15 MeV

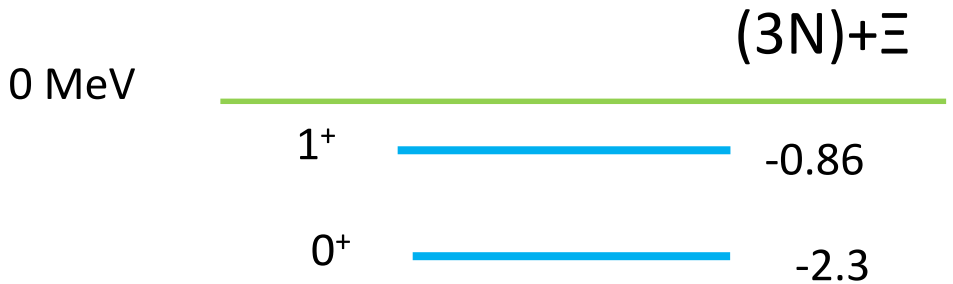


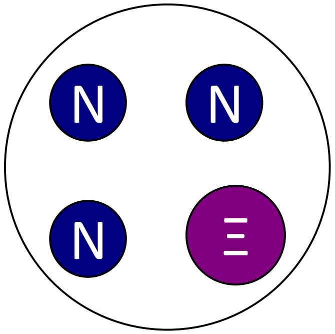
NNΞ



Using ^{3}He target, it might be produced this Ξ hypernucleus.
If this Ξ hypernucleus exist as bound state, what is isotope of this Ξ hypernucleus?

Results ESC04





T,S

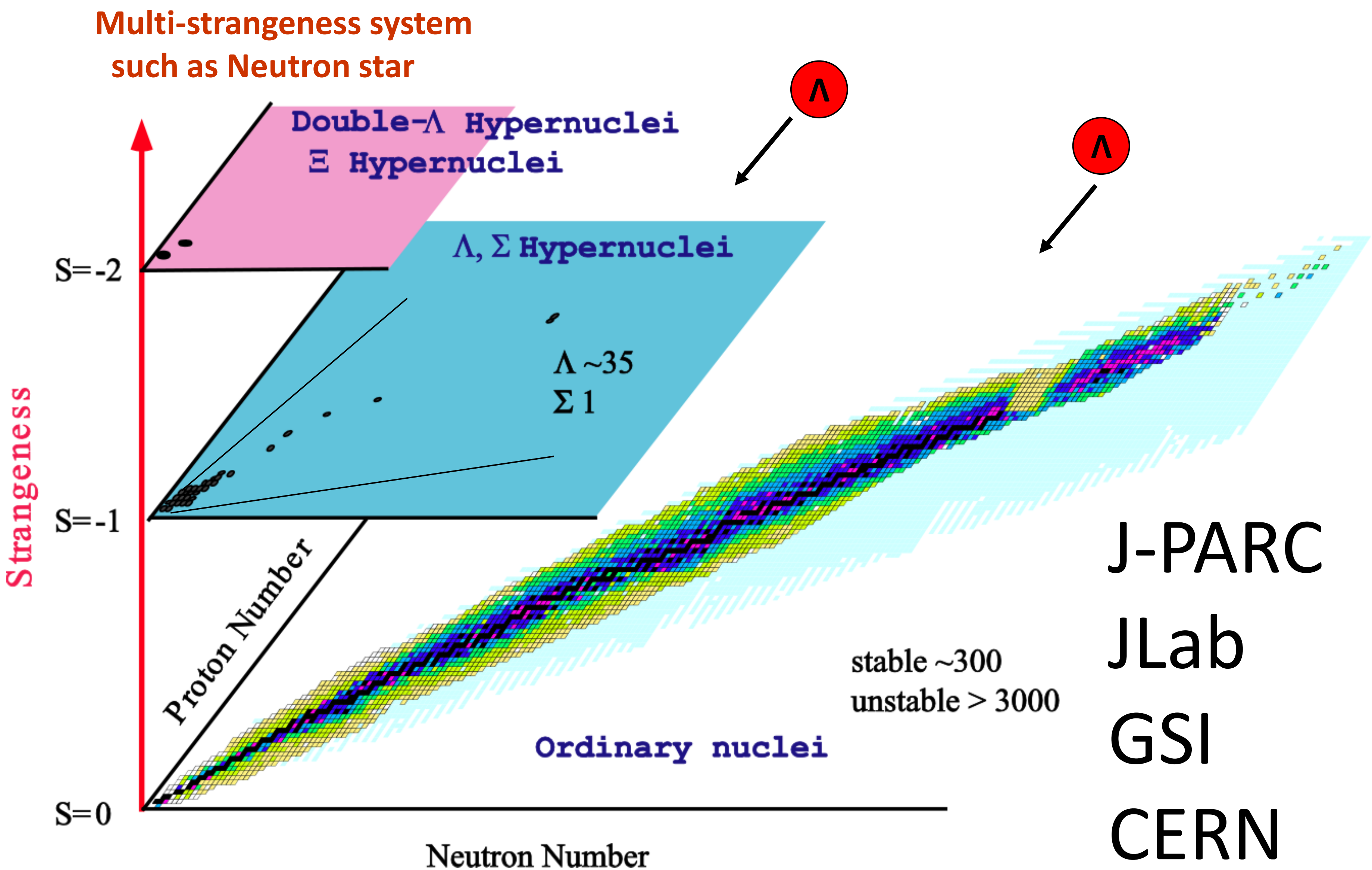
$$1^+: [12V(1,1)+V(1,0)+10V(0,1)+3V(0,0)]/26$$

$$0^+: [V(1,0)+V(0,1)]/2$$

1+ terms:
- V(1,0): repulsive
- V(0,1): strongly attractive
- V(0,0): repulsive

0+ terms:
- V(1,0): weakly repulsive
- V(0,1): strongly attractive

Nuclear chart with strangeness



J-PARC

JLab

GSI

CERN

Thank you!