EMMI Workshop: Anti-matter, hyper-matter and exotica production at the LHC

20-22 July 2015
CERN
Europe/Berlin timezone

Hypernuclei – Hyperon-hyperon interactions

Hypernuclei

Few-body Λ hypernuclei

Exact calculations possible

C. Rappold et al. PLB 728 (2014) 543

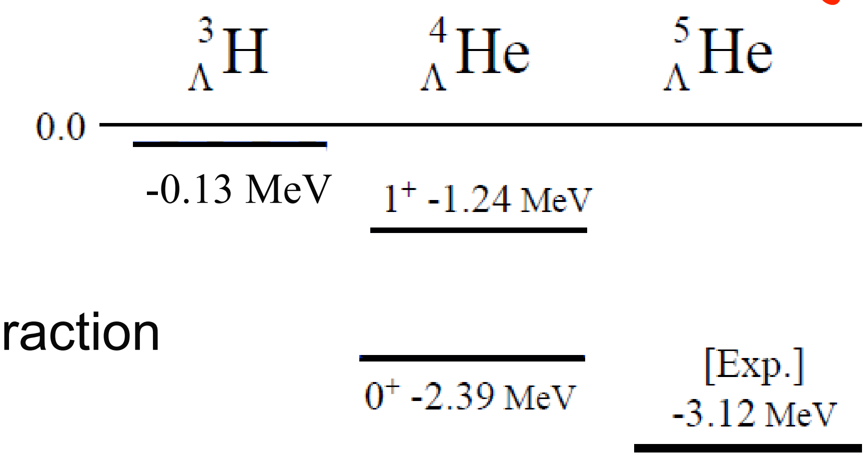
A=3 ${}^{3}_{\Lambda}H$ B_{Λ} =130 keV => stringent test for ΛN interaction

$\tau < 200$ ps (by HIC): why so short??

Weak decay branches not measured well

nnΛ bound ?

pnΛ(T=1) ?



A=4 ${}^{4}_{\Lambda}H$/ ${}^{4}_{\Lambda}He$

0+/1+ ΛN spin-spin, $\Lambda N-\Sigma N$ interaction

Charge symmetry breaking ?

A=5 ${}^{5}_{\Lambda}He$

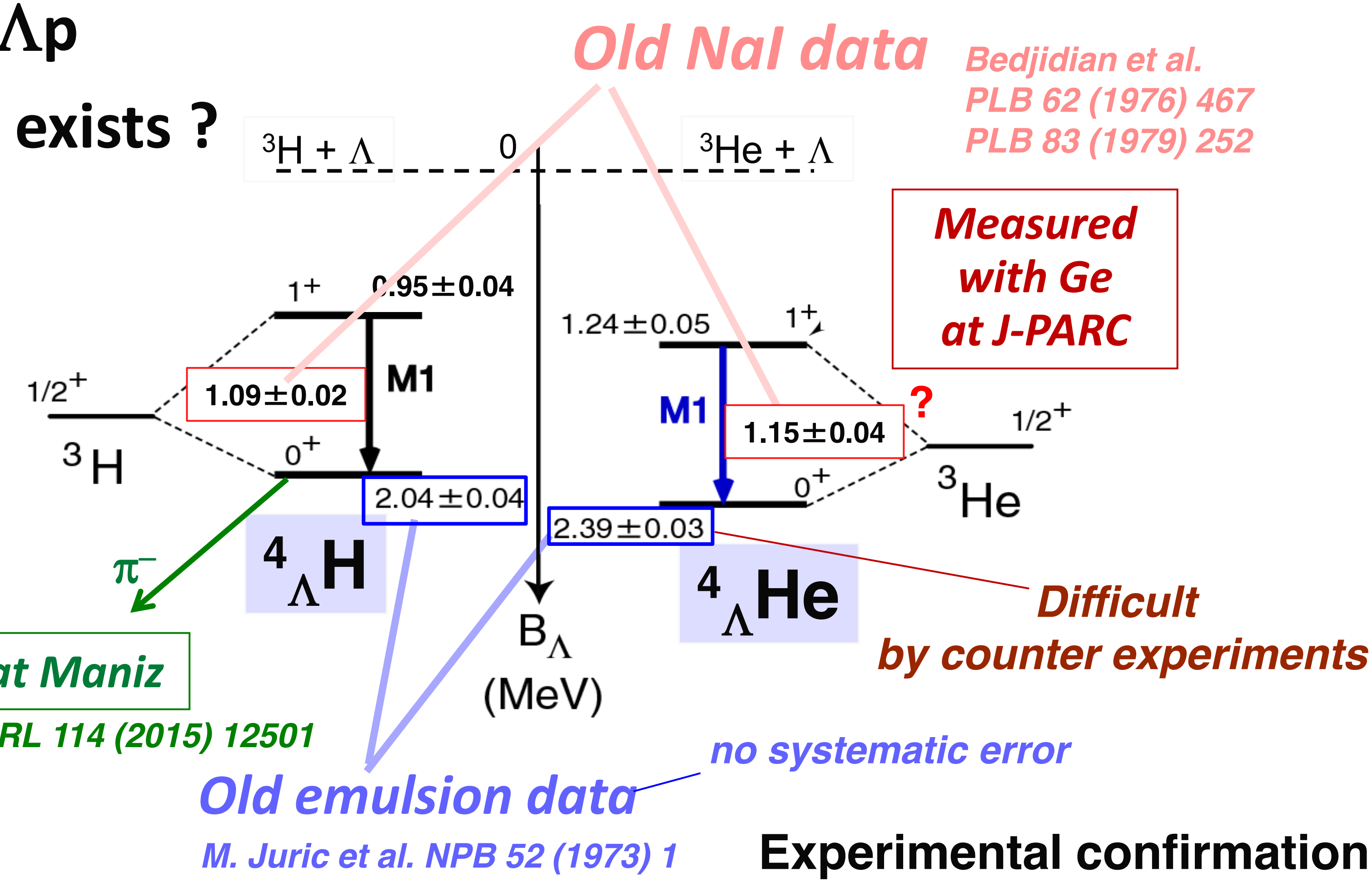
Overbinding problem

=> B_{Λ}(A=3,4,5) explained well with $\Lambda N-\Sigma N$ interaction

Charge Symmetry Breaking puzzle in A=4

$\Lambda n \neq \Lambda p$

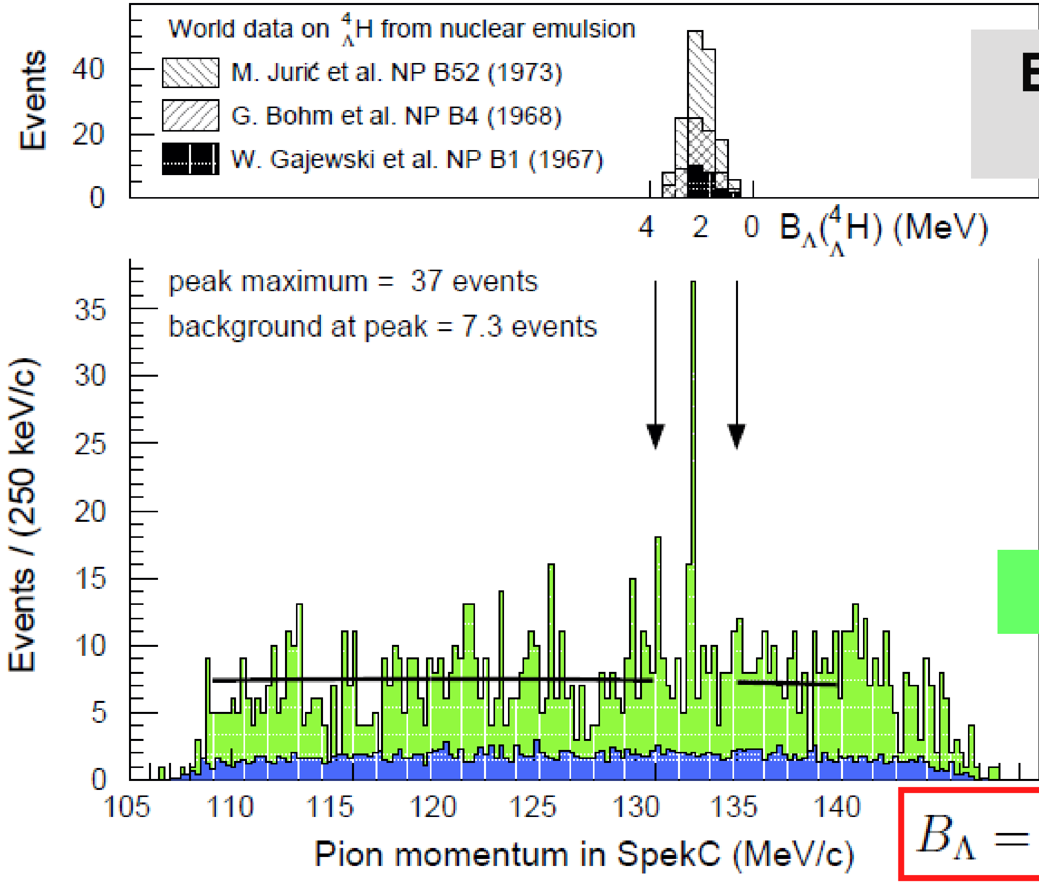
a large CSB exists ?



Experimental confirmation of CSB also necessary

Origin is unkown.
ΛN-ΣN coupling? But 4-body calc's with Λ–Σ mixing using Nijmegen interactions give ΔB < 100keV
=> Long standing puzzle

MAMI Result

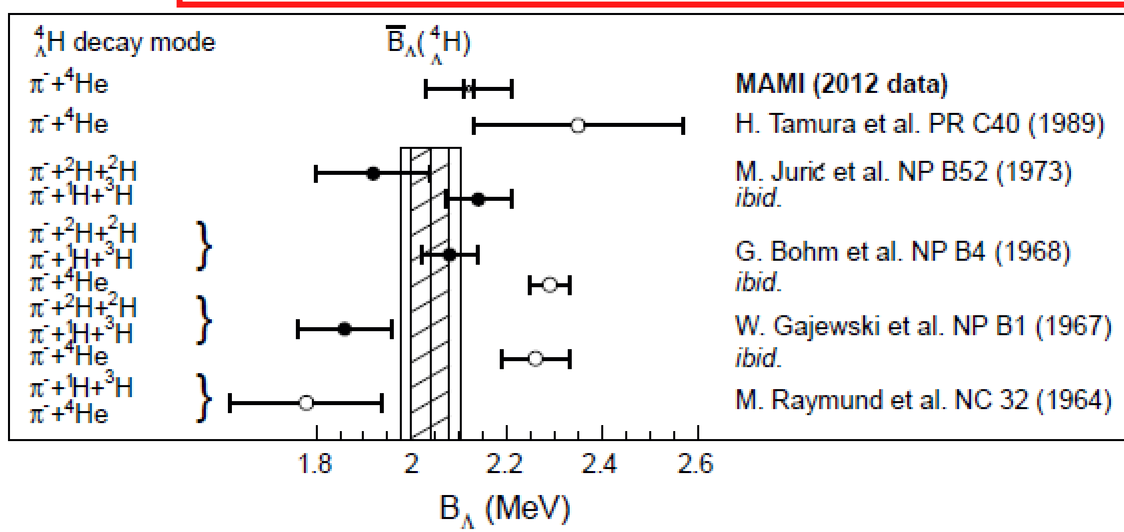


Emulsion data

electroproduction

MAMI data

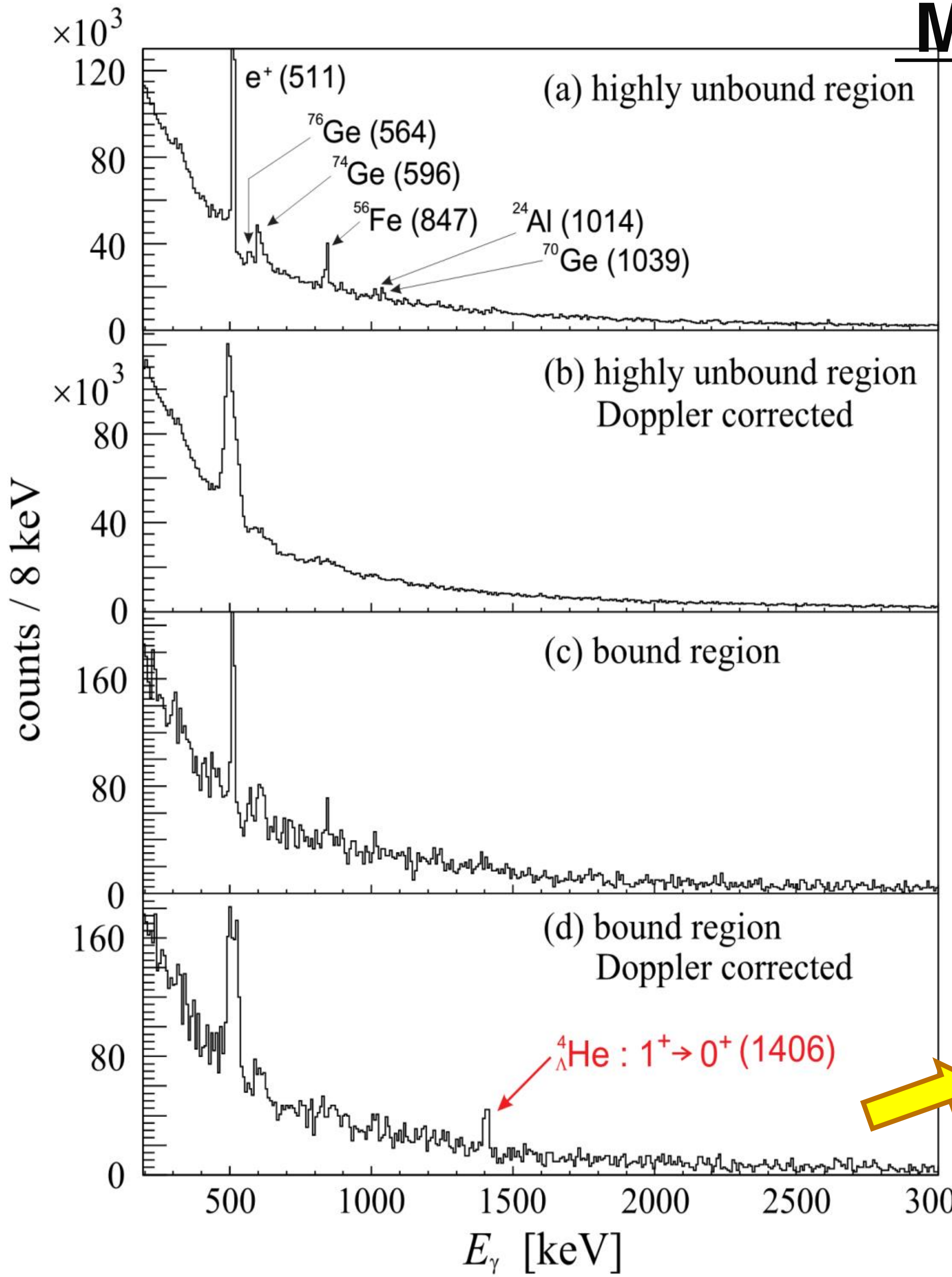
$$B_\Lambda = 2.12 \pm 0.01 \text{ (stat.)} \pm 0.09 \text{ (syst.) MeV}$$



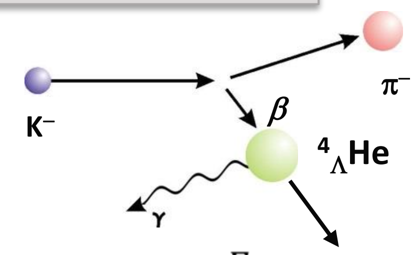
A. Esser et al., PRL 114 (2015) 12501

A1 Collaboration

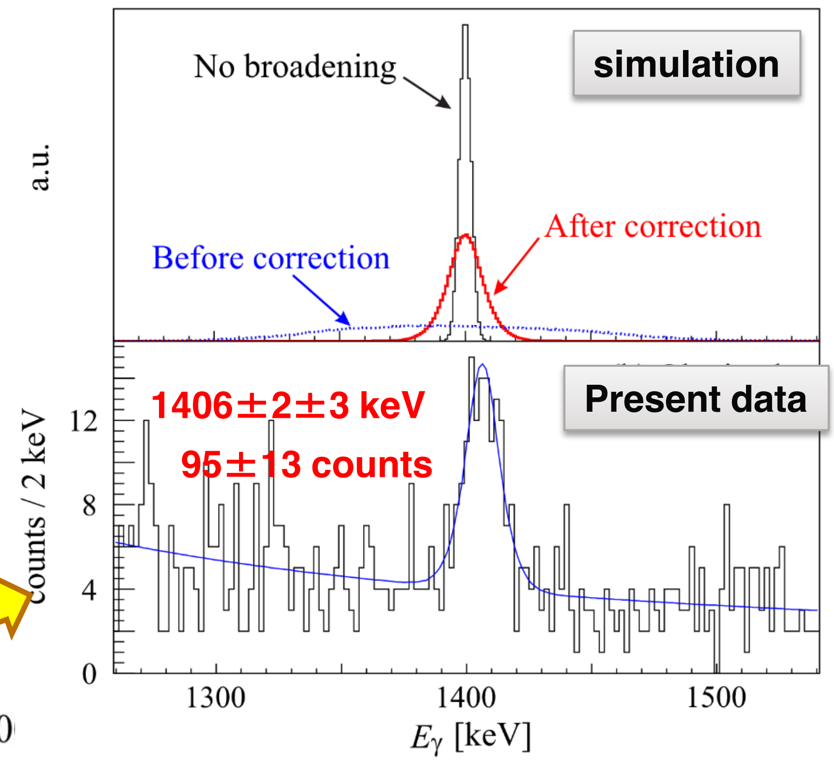
Mass-gated γ spectrum



Doppler shift correction

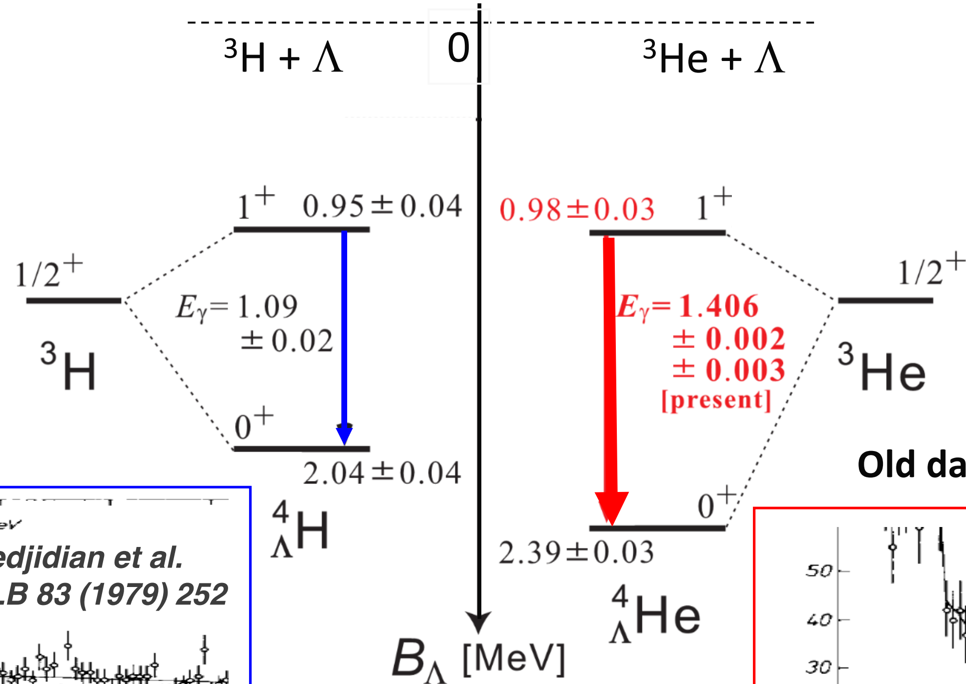


$$E_{corrected} = \frac{E_{measured}}{\gamma(1 + \beta cos\theta_\gamma)}$$

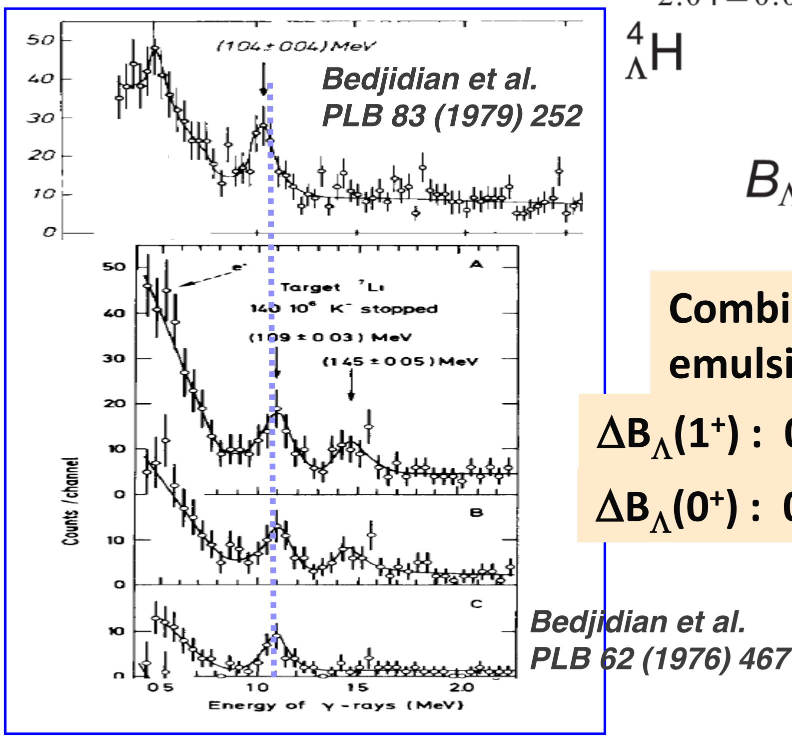


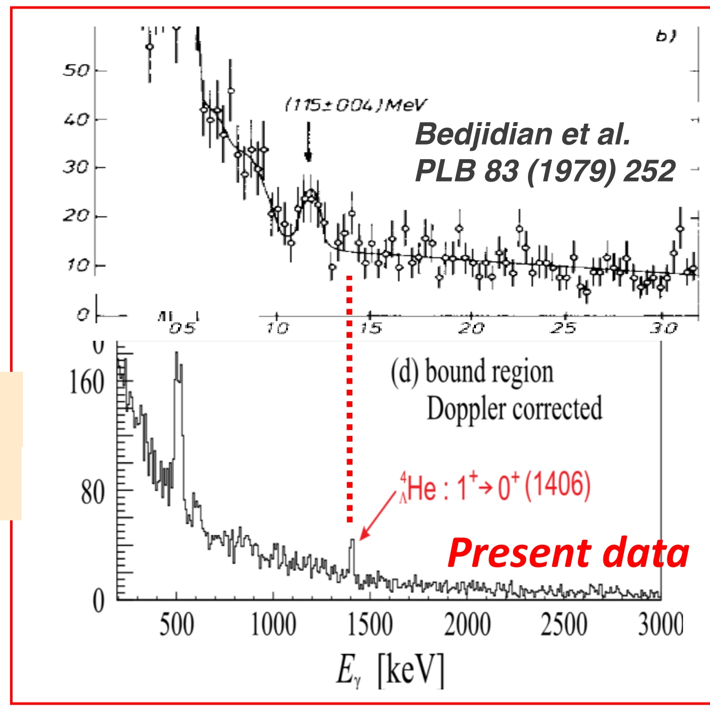
1⁺ cross section seems lower by 1/2-1/3

Results



Old data (1.15 MeV) was denied.





Combining with emulsion data,

$\Delta B_\Lambda(1^+)$: 0.03±0.05 MeV

$\Delta B_\Lambda(0^+)$: 0.35±0.05 MeV

- **Existence of CSB confirmed only by γ-ray data**
- **Large spin dependence in CSB found by combining with emulsion data**

- New data on CSB in A=4 hypernuclei:

  B_Λ of ${}^4_\Lambda H(0^+)$ measured via pion decay spectroscopy

  ---- Consistent with old emulsion data

  ${}^4_\Lambda He(1^+ \rightarrow 0^+)$ γ-ray measured to be 1.406 MeV

  ⇔1.09 MeV for ${}^4_\Lambda H$

  -- A large CSB effect in ΛN interaction confirmed.

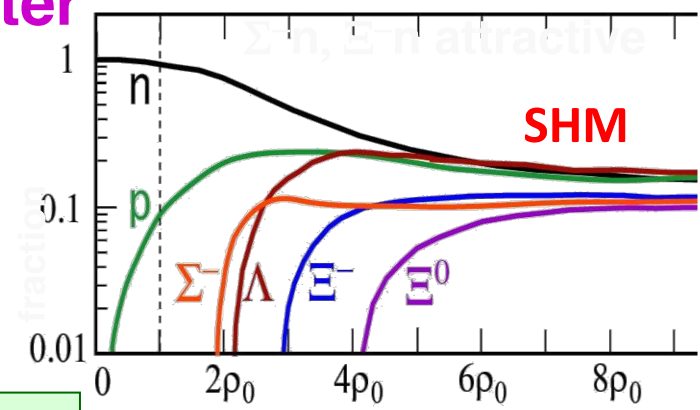
  --CSB has a spin dependence

- Ξ nuclear bound system (Kiso event) was observed for the first time -> Ξ potential is attractive

Under preparation
(Partly) took data

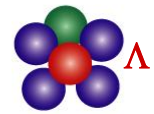
Status of Strangeness NP @J-PARC

toward neutron star matter

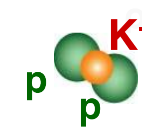


------- S=-1 --------

- n-rich Λ hypernuclei by (π^-,K^+) **E10**



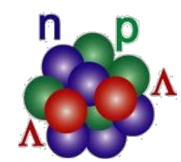
- γ spectroscopy of Λ hypernuclei **E13**
  - -> ΛN, ΛN-ΣN (ΛNN) int.
  - => Fraction of Λ in n-rich matter
- K^-pp by ^{3}He(K^-,n) **E15**
- K^-pp by d(π^+,K^+) **E27**
  - -> $K^{bar}N$ int. in matter => K condensation in n star?
  - Property of high density nuclear systems



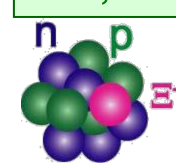
- $\Sigma^{\pm}p$ scattering **E40**
  - -> Σ^-n (= Σ^+p) (Quark Pauli effect) , Σ^-p->ΛN int. => Σ^- exists in n-star?

------- S=-2 --------

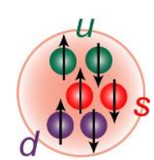
- ΛΛ hypernuclei **E07**
  - -> ΛΛ interaction , ΛΛ correlation?
  - => Λ fraction in Strange Hadronic Matter



- Ξ hypernuclear spectroscopy **E05**
- Ξ atomic X rays **E03, E07**
  - -> ΞN interaction => Ξ^- exists in n-star?



- H dibaryon search from H-> ΛΛ, $\Lambda p\pi^-$ **E42**
  - -> Short-range BB force (Color magnetic int.)



First observation of a Ξ-nuclear bound state

KEK E373 “Kiso event”

K. Nakazawa et al. PTEP 2015, 033D02

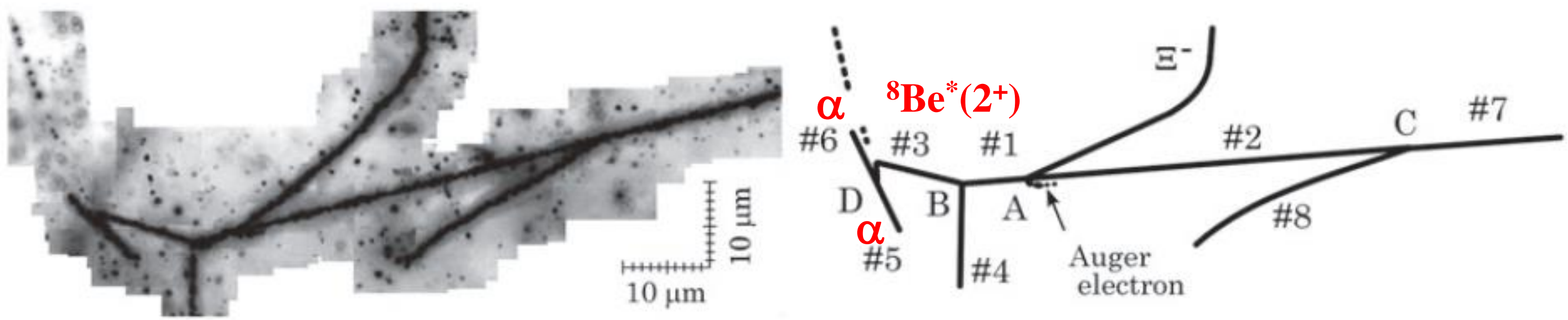


Fig. 1. A superimposed image from photographs and a schematic drawing of the KISO event.

$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$$

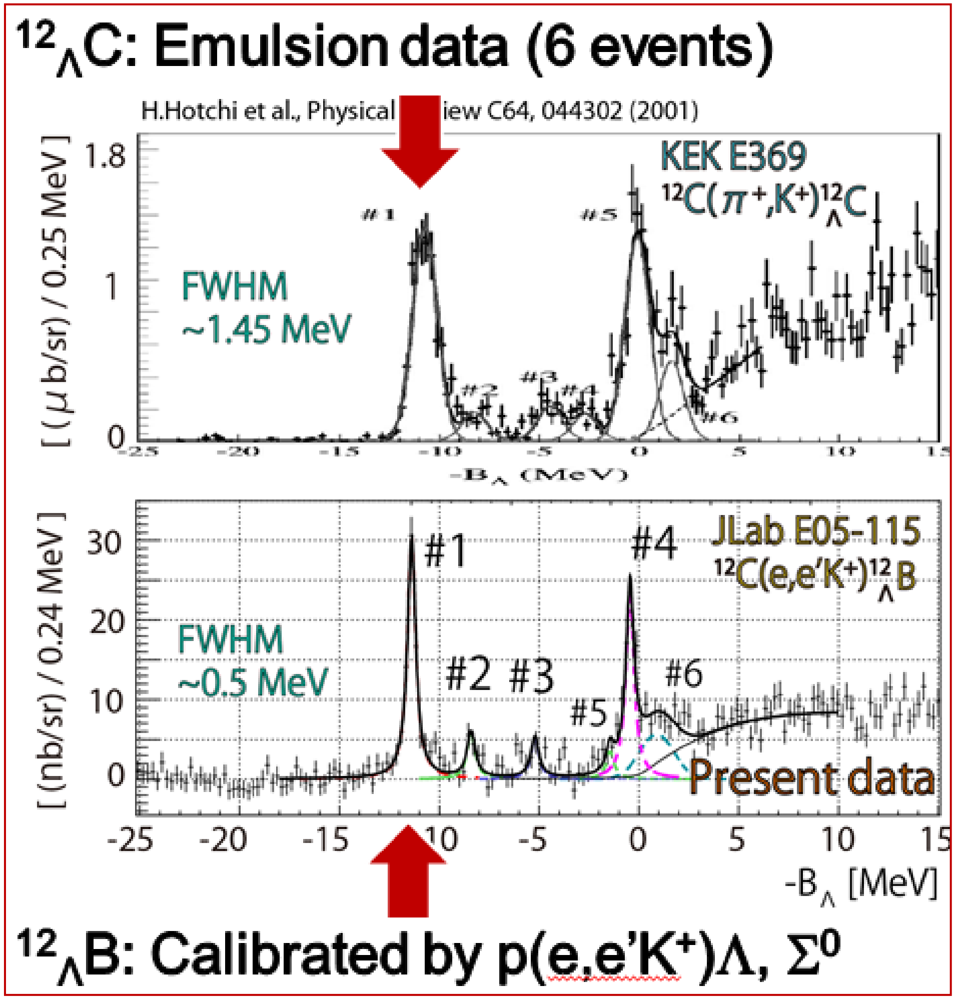
$$B_{\Xi^-} = \boxed{4.38 \pm 0.25\ \mathrm{MeV}} - \boxed{1.11 \pm 0.25\ \mathrm{MeV}} \quad >> \mathrm{E(3D)} = 0.17\ \mathrm{MeV}$$

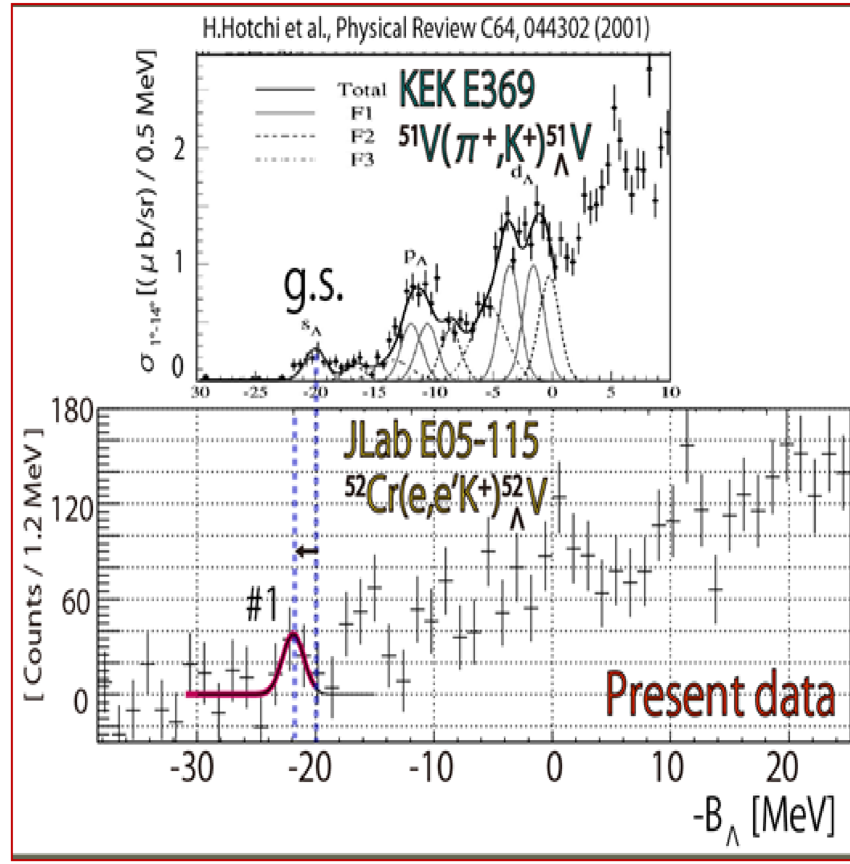
${}^{10}_{\Lambda}\mathrm{Be}$ in g.s. ${}^{10}_{\Lambda}\mathrm{Be}$ in highest excited state

(Ehime pot.) $U_{\Xi} \sim 20$ MeV => B_{Ξ}(2p state) = 1.1 MeV

(e,e'K⁺) data at JLab

Slide by Nakamura





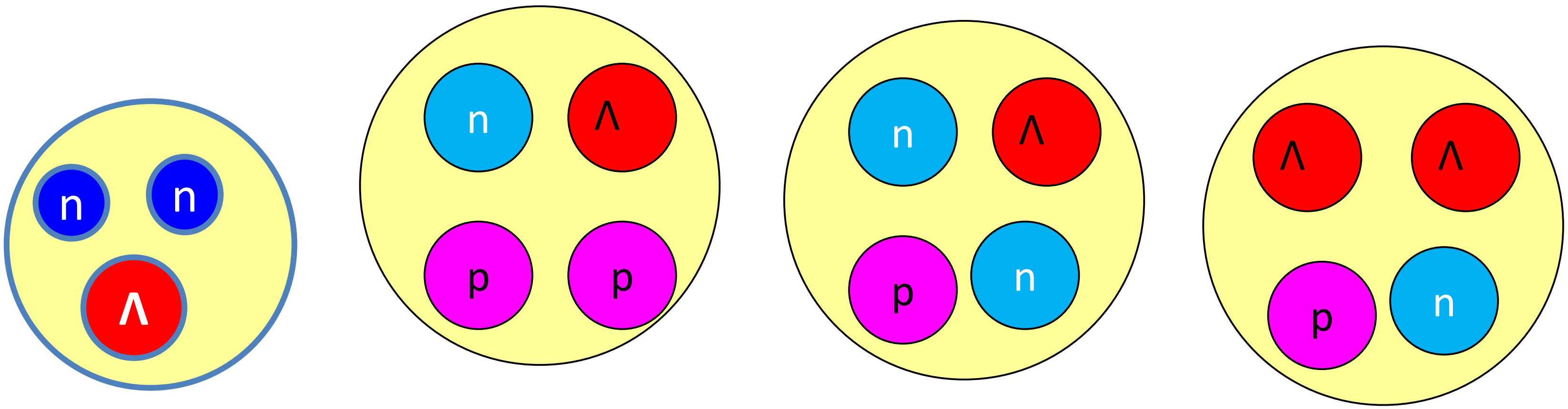
Going to heavier hypernuclei

Resolution ~0.5 MeV (FWHM)
Absolute accurary ~0.1 keV

^{40}Ca/ ^{48}Ca target runs conditionally approved

Experiment – theory

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

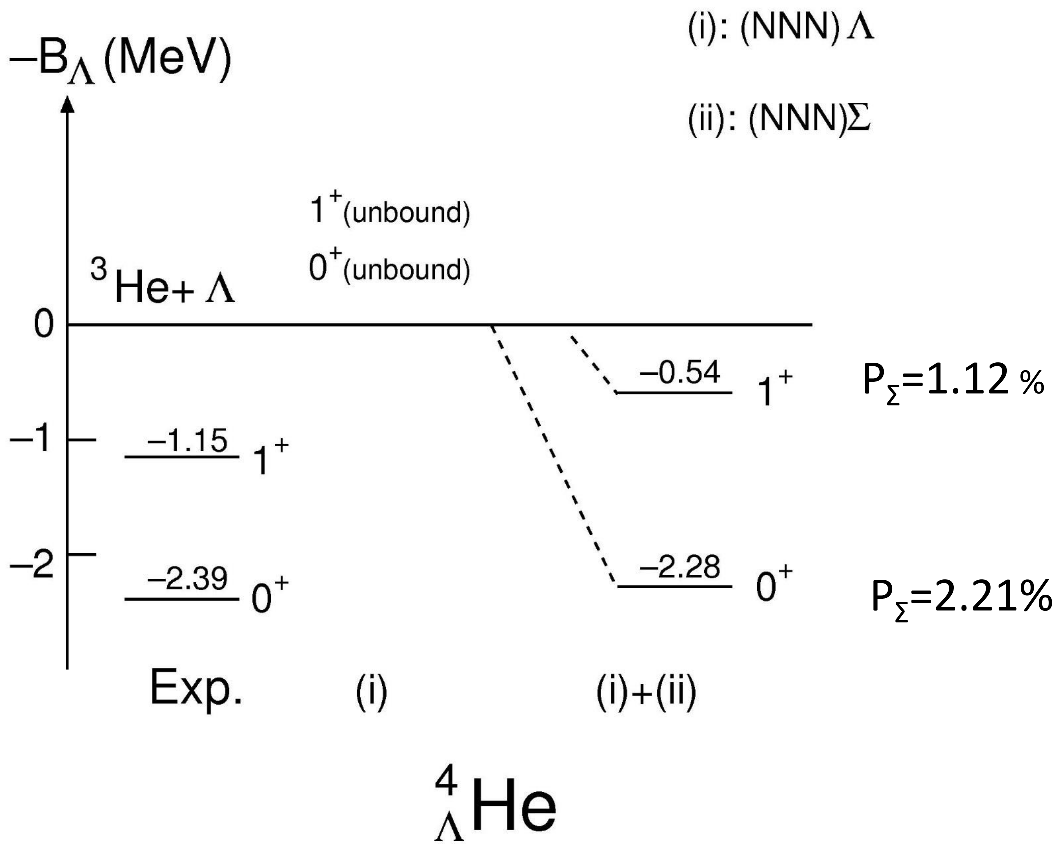


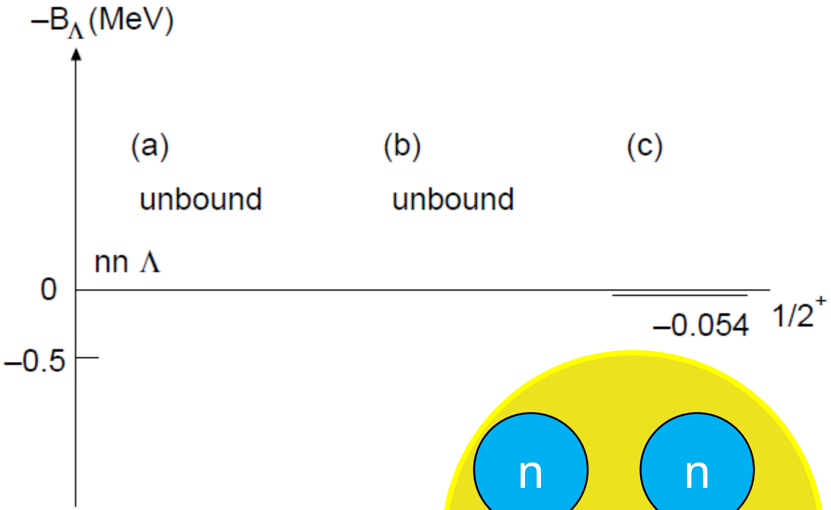
$^{3}_{\Lambda}n$ $^{4}_{\Lambda}He$ $^{4}_{\Lambda}H$ $^{4}_{\Lambda\Lambda}H$

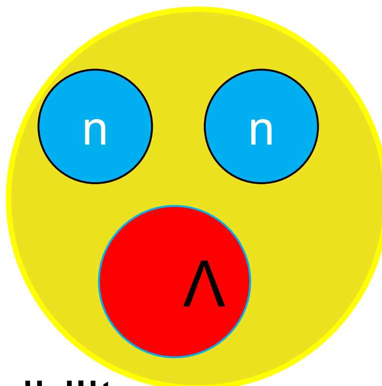
C. Rappold et al., HypHI collaboration Phys. Rev. C 88, 041001 (R) (2013)

A. Esser, PRL114, 232501(2015)

Emiko Hiyama


(i): (NNN) Λ
(ii): (NNN)Σ
−BΛ (MeV)
1+(unbound)
0+(unbound)
3He+ Λ
0
−1
−2
−1.15 1+
−2.39 0+
−0.54 1+
−2.28 0+
PΣ=1.12 %
PΣ=2.21%
Exp.
(i)
(i)+(ii)
4ΛHe





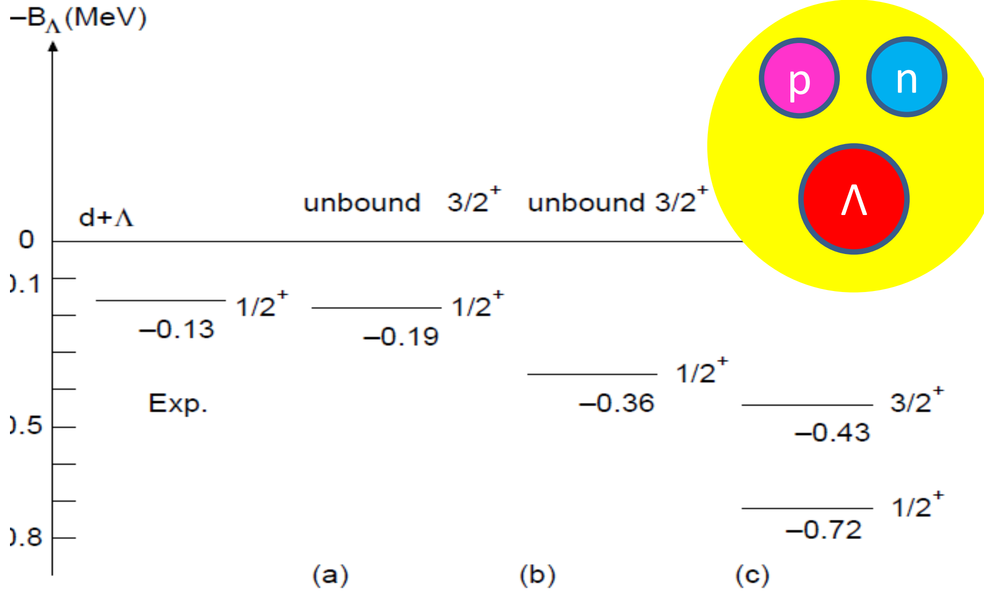
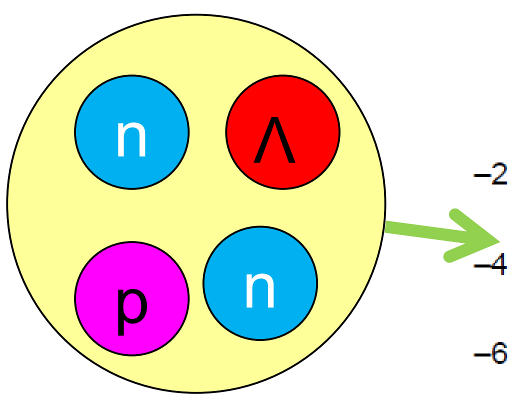
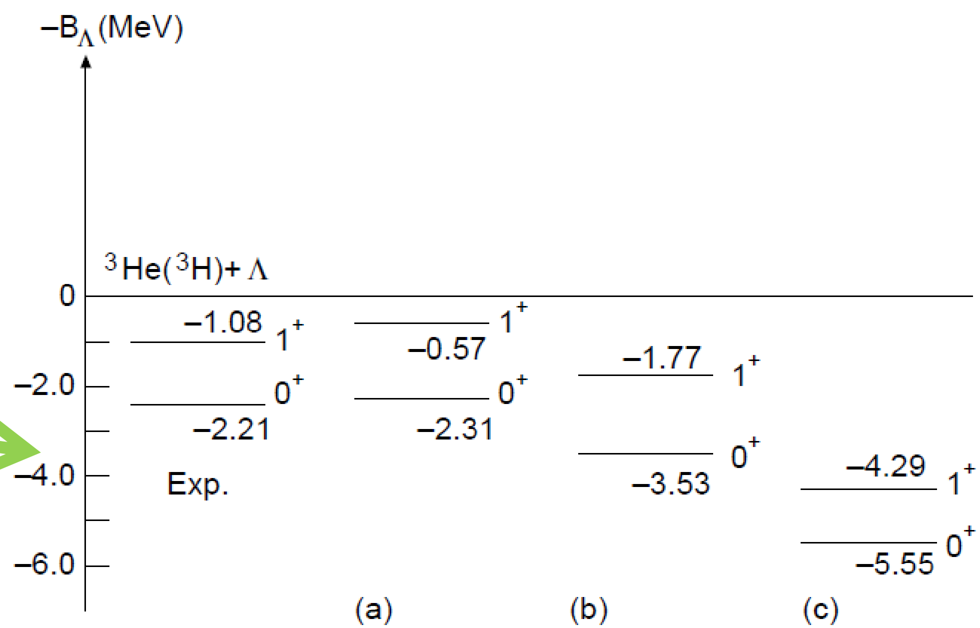


FIG. 3: Calculated Λ-separation energy for $^3_\Lambda$H with (a) $^3V^T_{N\Lambda-N\Sigma}\times 1.00$, (b) $^3V^T_{N\Lambda-N\Sigma}\times 1.10$, and (c) $^3V^T_{N\Lambda-N\Sigma}\times$

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





$$\boldsymbol{H} = \boldsymbol{\Delta M} + \boldsymbol{T}_{\text{int}} + \boldsymbol{V}_{\text{NN}} + \boldsymbol{V}_{\text{3N}} + \boldsymbol{V}_{\text{YN}}$$

- NN: chiral N^3LO

  Entem & Machleidt

  Phys. Rev. C **68**, 041001(R) (2003)

  $\Lambda_{\text{NN}} = 500\,\text{MeV}$

- 3N: chiral N^2LO

  Navrátil

  Few-Body Syst. **41**, 117 (2007)

  $\Lambda_{\text{3N}} = 500\,\text{MeV}$

- YN: chiral LO

  Polinder, Haidenbauer & Meißner

  Nucl. Phys. A **779**, 244 (2006)

  $\Lambda_{\text{YN}} = 600\,\text{MeV}, 700\,\text{MeV}$

  OR Jülich'04

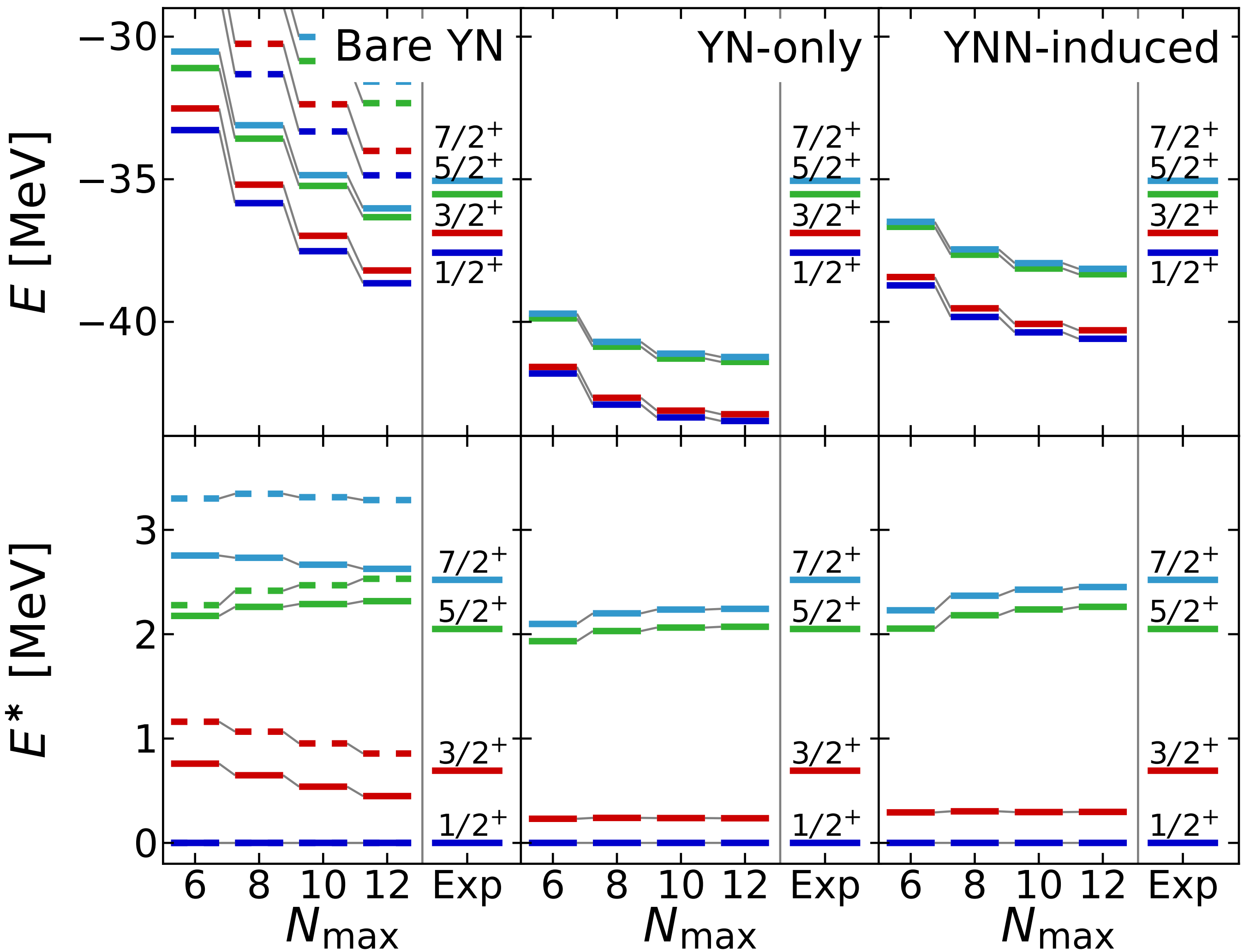
  Haidenbauer & Meißner

  Phys. Rev. C **72**, 044005 (2005)

  meson-exchange

NN+3N yields quantitative description of *p*-shell nuclei

${}^{7}_{\Lambda}$Li — Effect of Induced YNN



Chiral LO

— $\Lambda = 600\,\text{MeV}$

- - $\Lambda = 700\,\text{MeV}$

$\alpha_N = 0.08\,\text{fm}^4$

$\alpha_Y = 0.08\,\text{fm}^4$

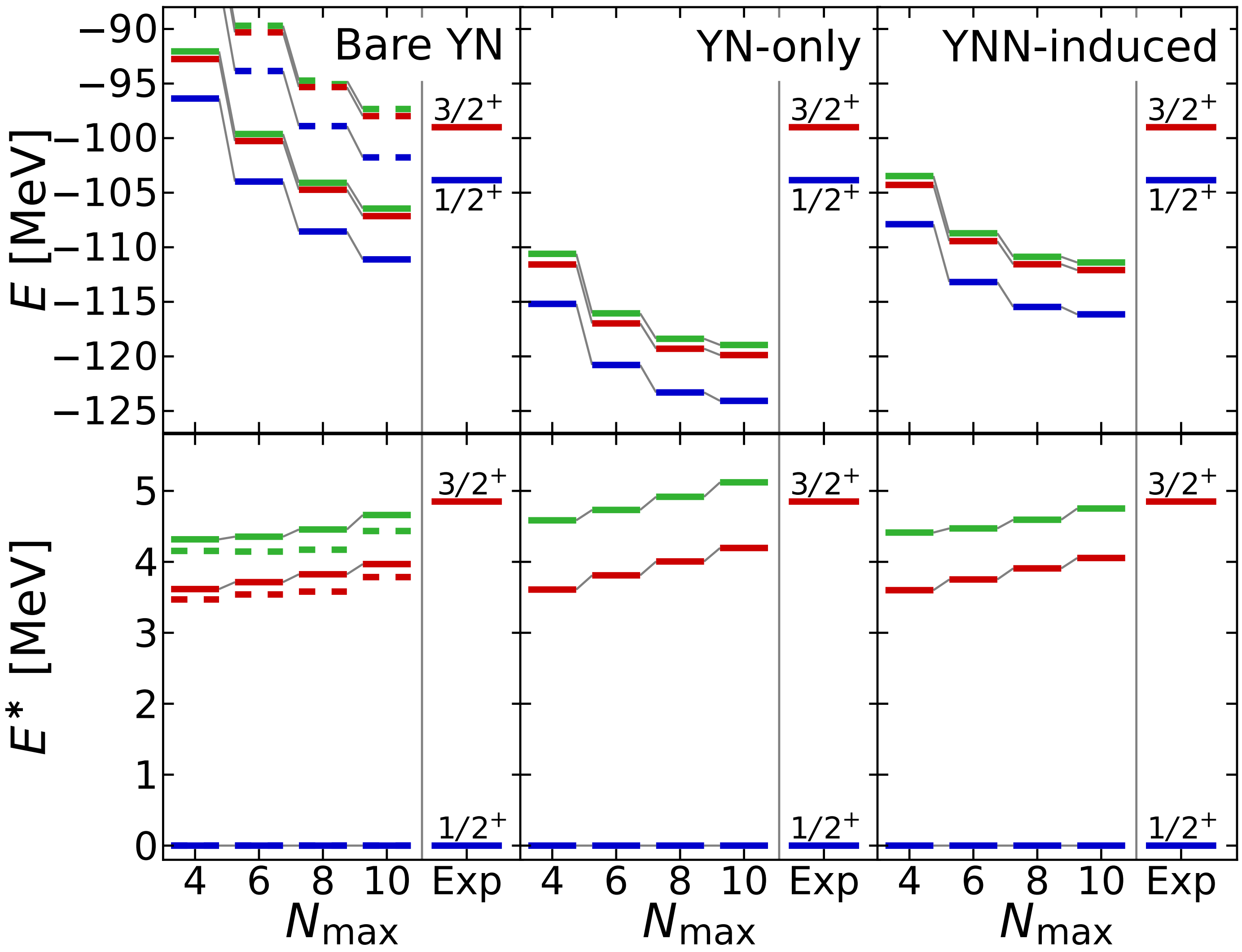
$\hbar\Omega = 20\,\text{MeV}$

YN-only overbinds

Induced YNN reduces overbinding

Splittings too small, within cutoff uncertainties

${}^{13}_{\Lambda}$C — Effect of Induced YNN



Chiral LO

— $\Lambda = 600\,\text{MeV}$

- - $\Lambda = 700\,\text{MeV}$

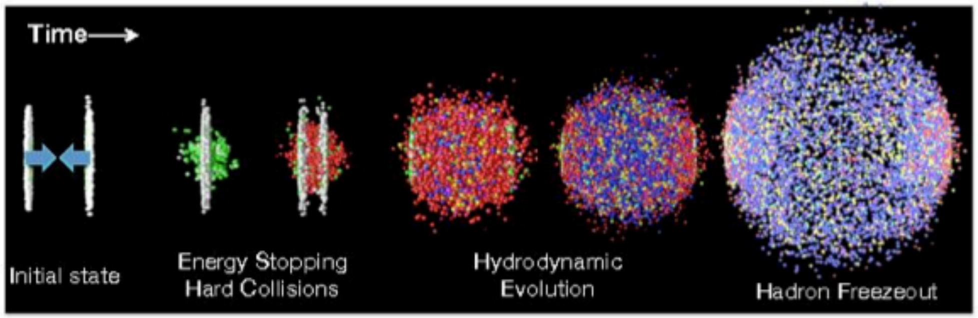
$\alpha_N = 0.08\,\text{fm}^4$
$\alpha_Y = 0.08\,\text{fm}^4$
$\hbar\Omega = 20\,\text{MeV}$

Overbinding partially due to neglected 4N

Induced YNN have slight effect on spectra

Hyperon-hyperon interaction

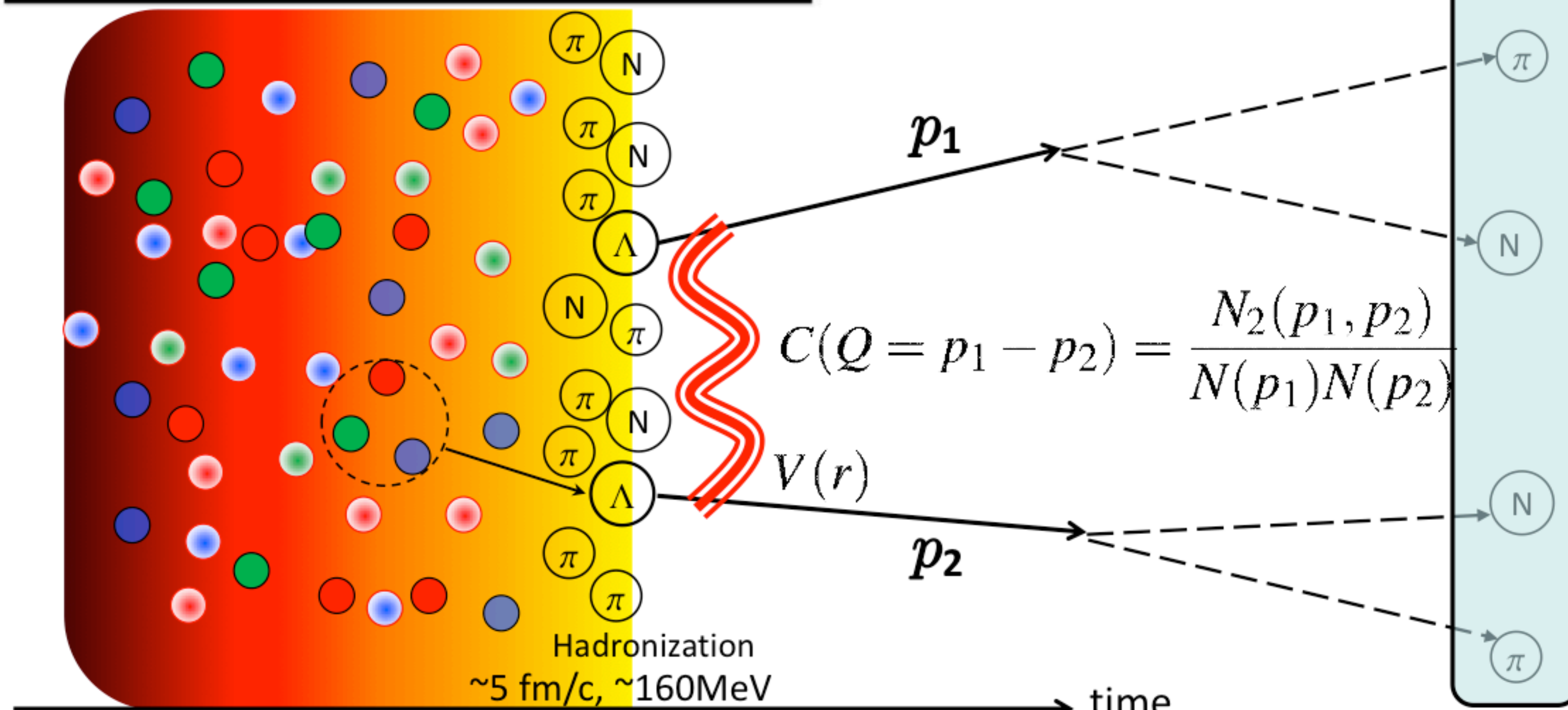
RHIC Can Tell Us about ΛΛ interaction



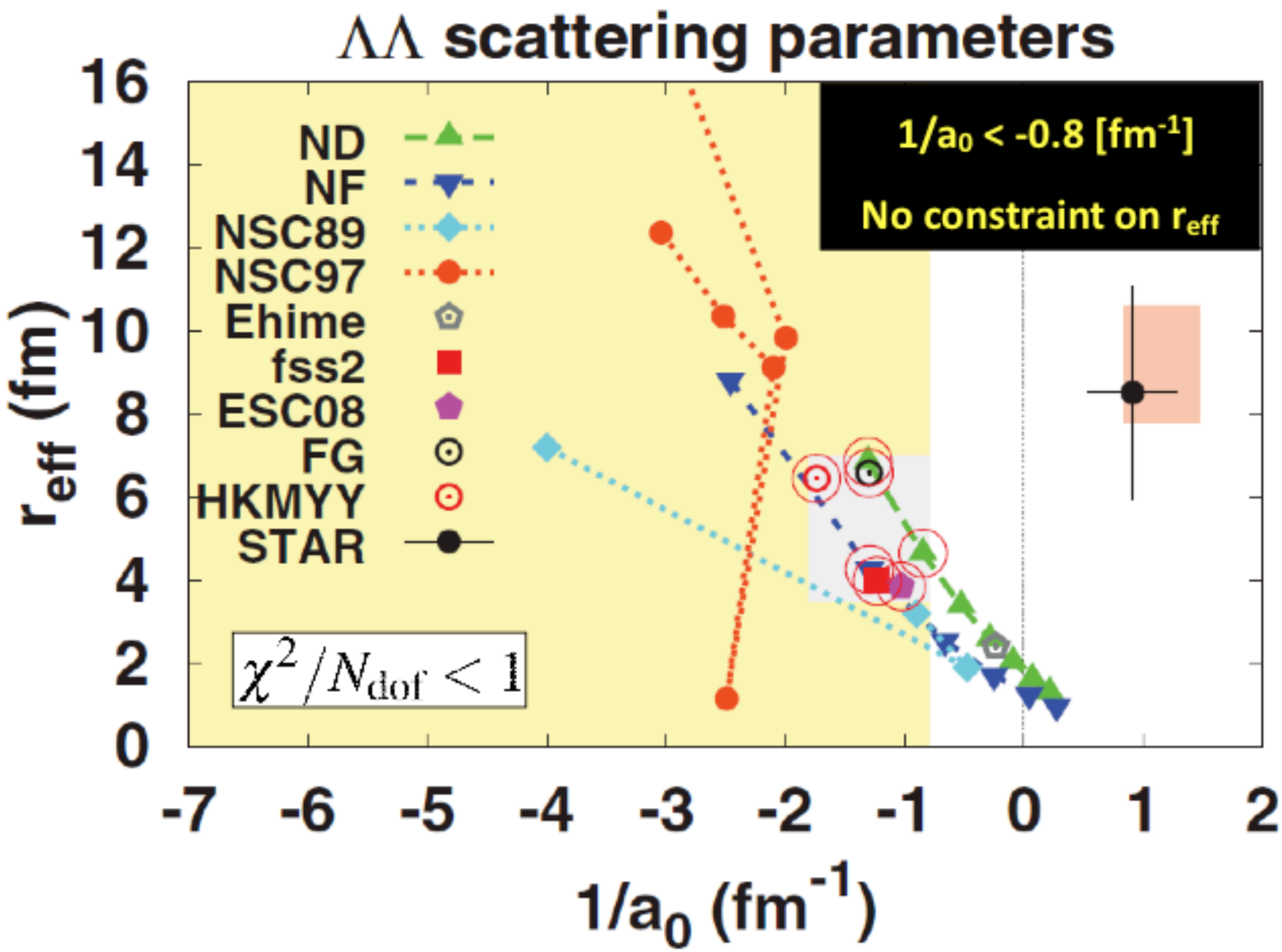
Au+Au 200AGeV

$$\frac{dN_\Lambda}{dy} \simeq 0.6 - 13 \qquad \times 10^8 \text{ events}$$

(60-80%) (0-5%)



Constraints on a_o and r_{eff}



Interests of S=-2 multi-baryon system

H-dibaryon

- The flavor singlet state with J=0 predicted by R.L. Jaffe.
  - Strongly attractive color magnetic interaction.
  - No quark Pauli principle for flavor singlet state.

Double-Λ hypernucleus

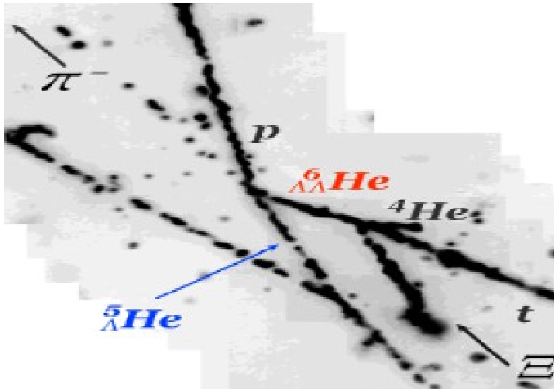
- Conclusions of the "NAGARA Event"

K.Nakazawa and KEK-E176 & E373 Collaborators

Λ–N attraction

Λ–Λ weak attraction

$m_H \geq 2m_\Lambda$ - 6.9MeV

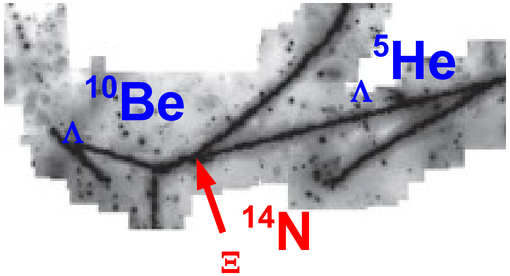


Ξ hypernucleus

- Conclusions of the "KISO Event"

K.Nakazawa and KEK-E373 Collaborators

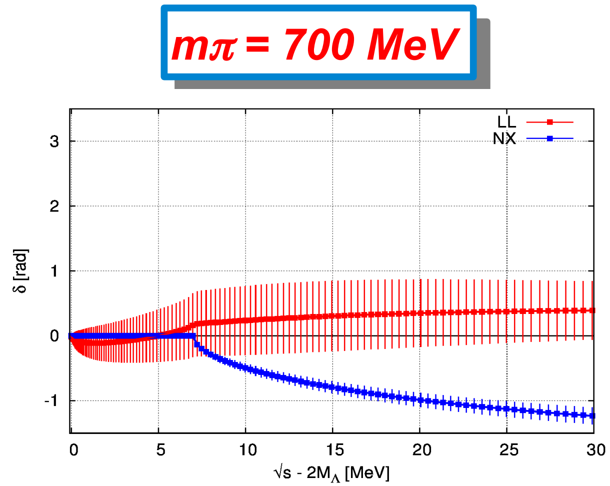
Ξ–N attraction

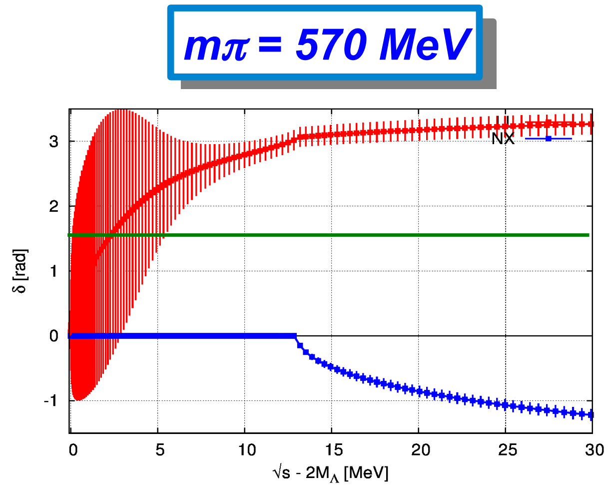


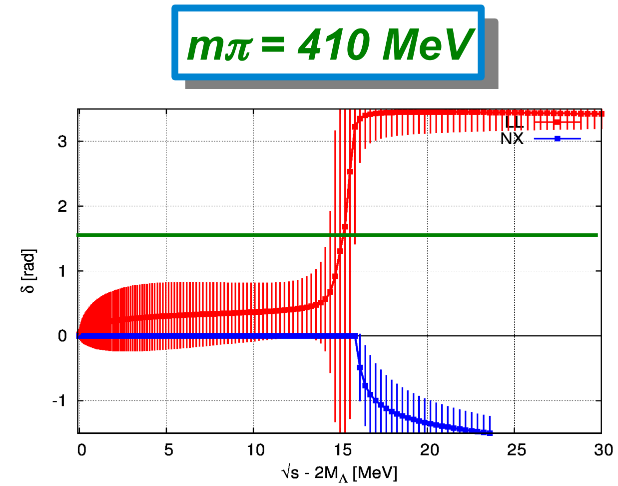
$\Lambda\Lambda$ and $N\Xi$ phase shifts

▶ N_f = 2+1 full QCD with L = 2.9fm

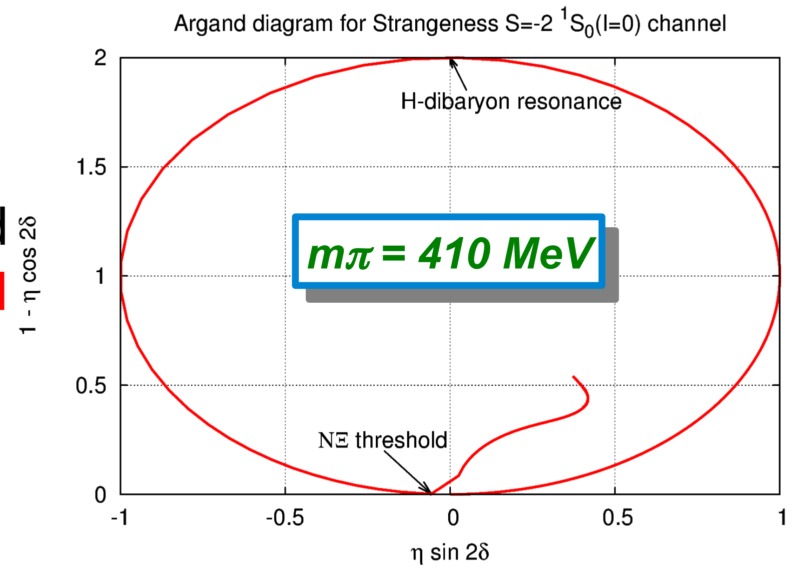
Preliminary!







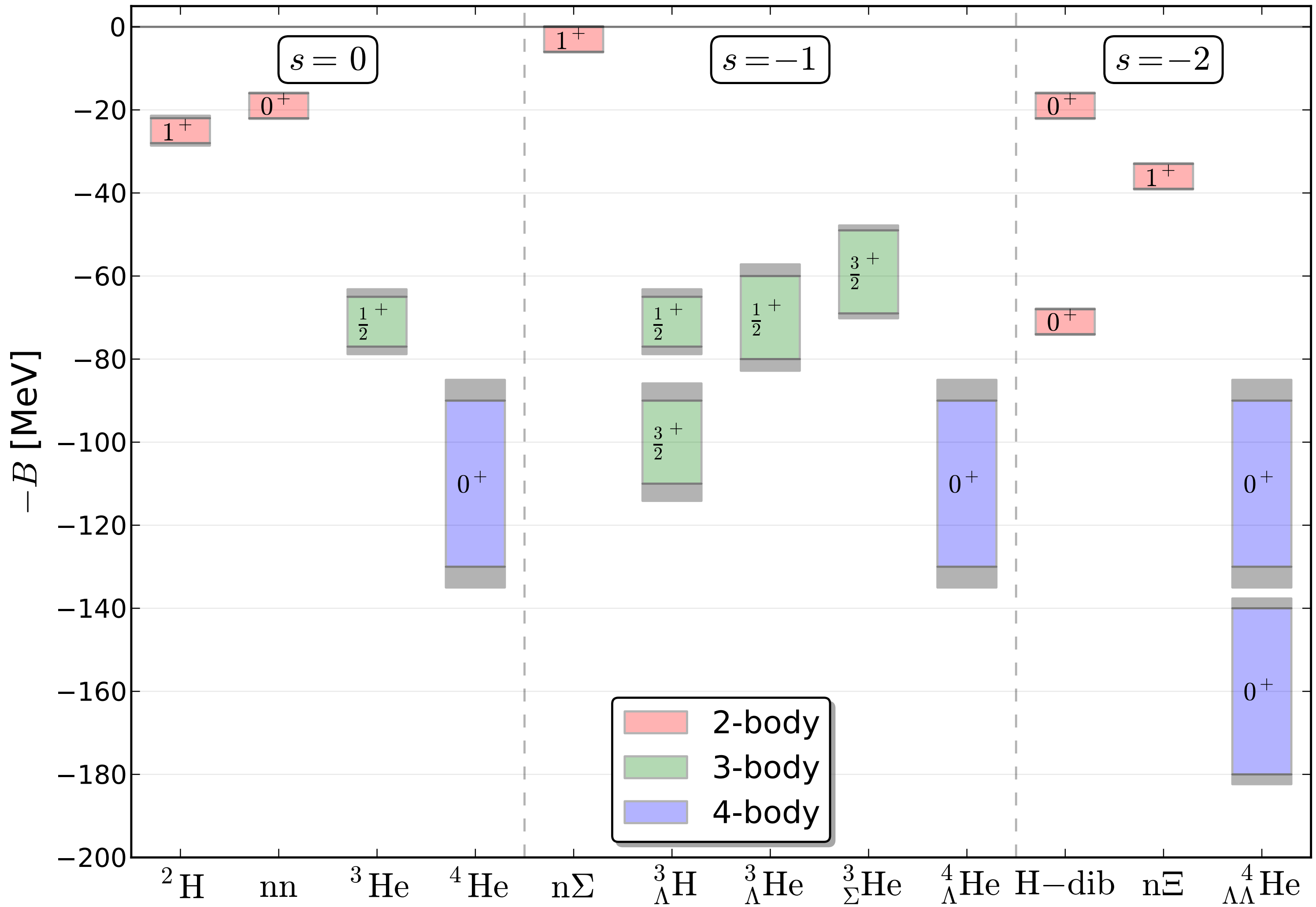
- m_π = 700 MeV : bound state
- m_π = 570 MeV : resonance near $\Lambda\Lambda$ threshold
- m_π = 410 MeV : resonance near $N\Xi$ threshold



H-dibaryon is unlikely bound state

NPLQCD Phys. Rev. D87 (2013) 3, 034506

$SU(3)_f$



no e.m. interactions

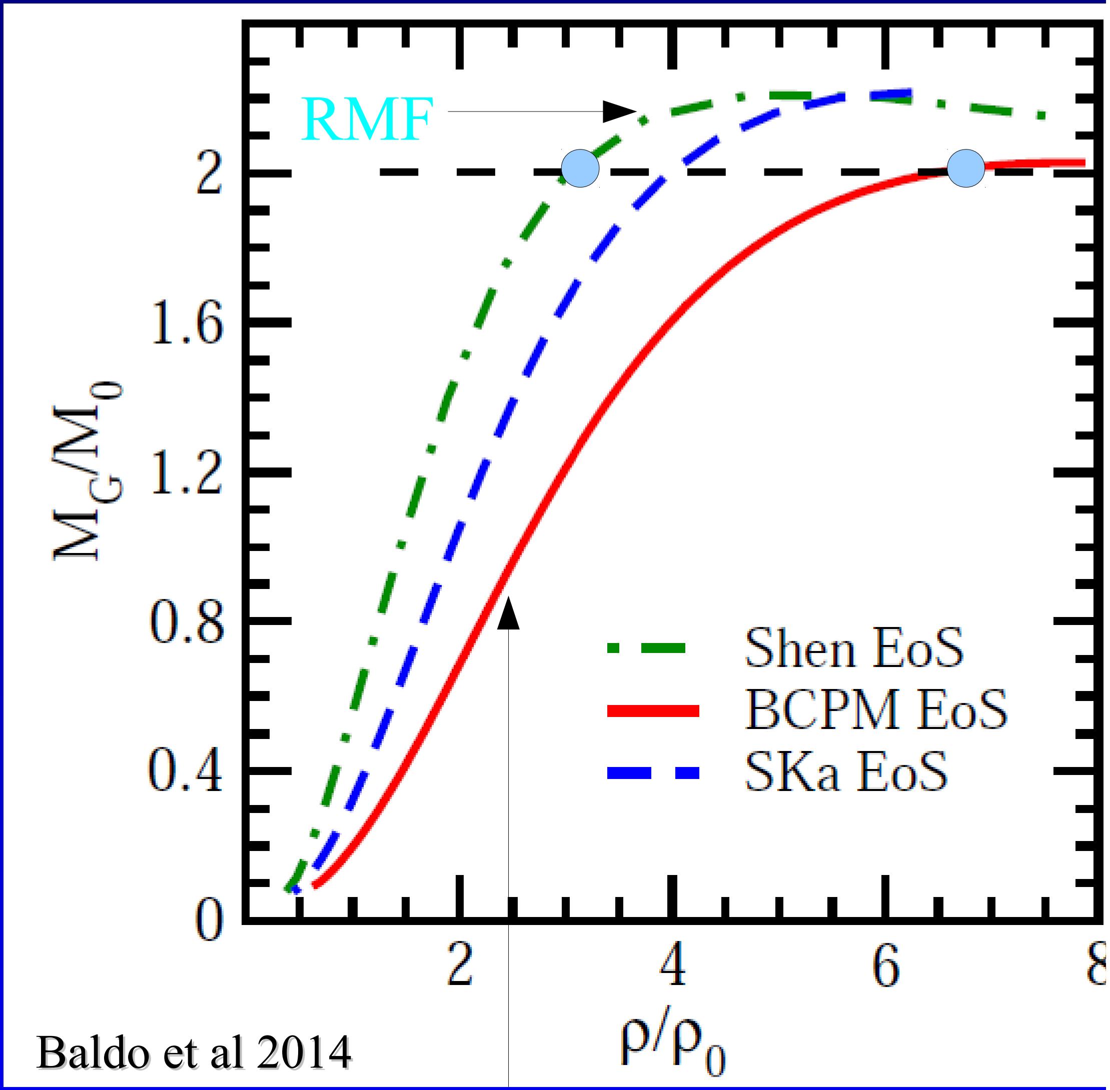
$(\pi,\ J^2, J_z, s, A, I^2, I_z)$

What does a $2M_{sun}$ star mean?

"Standard" neutron stars, just nucleons and electrons.

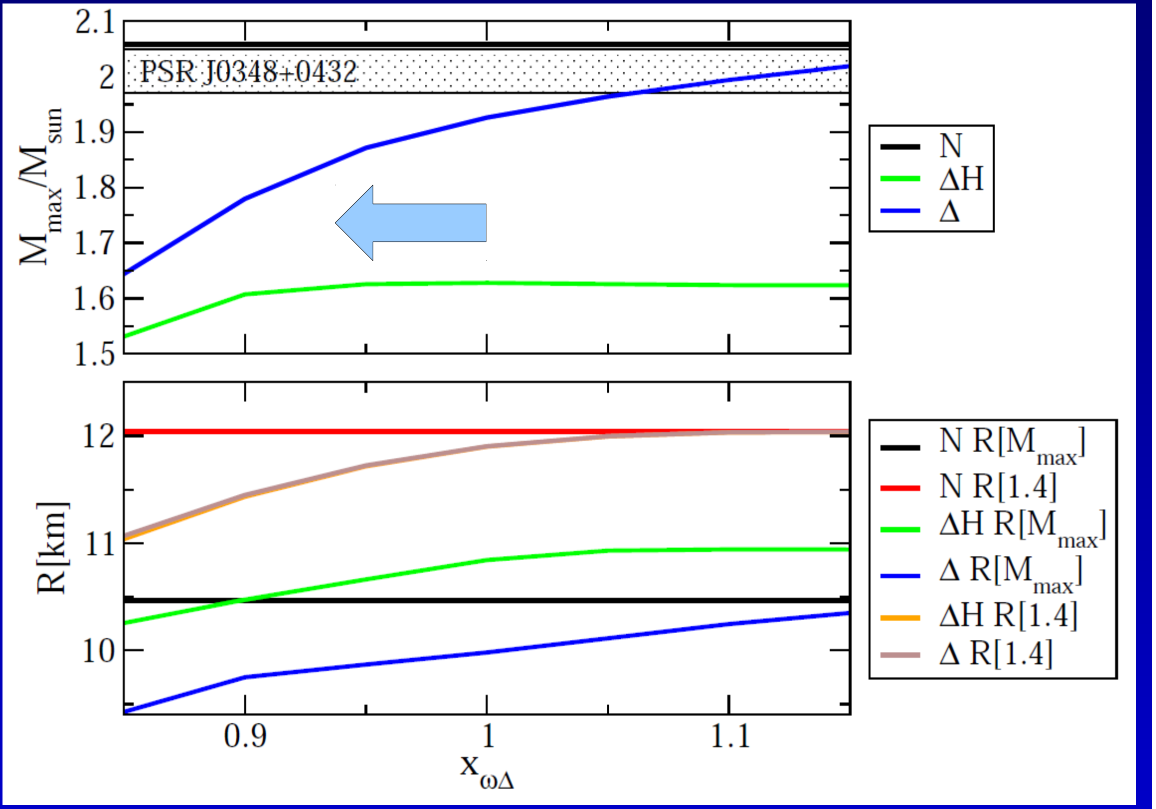
Central baryon densities of a $2M_{sun}$ star 3-7 times nuclear saturation density. Are there really just nucleons? Hyperons & Δ ?

Pagliara talk

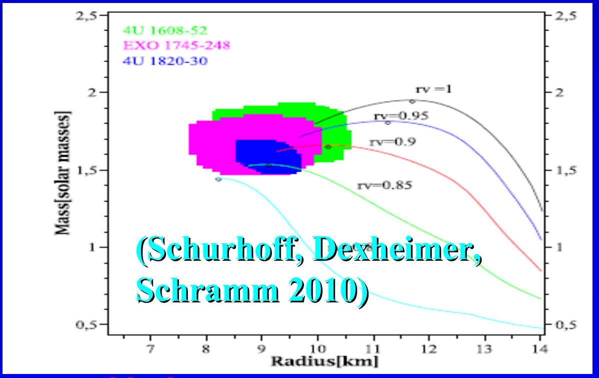


Microscopic calculation: nucleon nucleon potential and three body forces

Maximum mass and radii: the maximum mass is significantly smaller than the measured ones. Also, very compact stellar configurations are possible.



See also:



Punchline2: beside the "hyperon puzzle" is there also a "delta isobars puzzle"?

-) New masses and radii measurements challenge nuclear physics: tension between high mass and small radii. 2.4 Msun candidates already exist.

-) Hyperons and delta puzzles

-) NICER mission, with a precision of 1km in radii measurements, could hopefully solve the problem

-) Possible existence of two families of compact stars (high mass – quark stars, low mass – hadronic stars). Rich phenomenolgy: frequency and mass distributions, explosive events, strangelets

Hyperon puzzle in Neutron Stars

Massive $2M_\odot$ neutron stars:

2010 PSR J1614-2230 (1.97 $\pm$ 0.04) $M_\odot$
2013 PSR J0348-0432 (2.01 $\pm$ 0.04) $M_\odot$

- Problem: Softening EoS by hyperon mixing (e.g. Schulze et al)
- Conclusion: [Yamamoto et al PRC88 (2014), EPJA (2015)]

The puzzle can be solved by a
Universal Three-Baryon Repulsion
on the basis of heavy-ion data

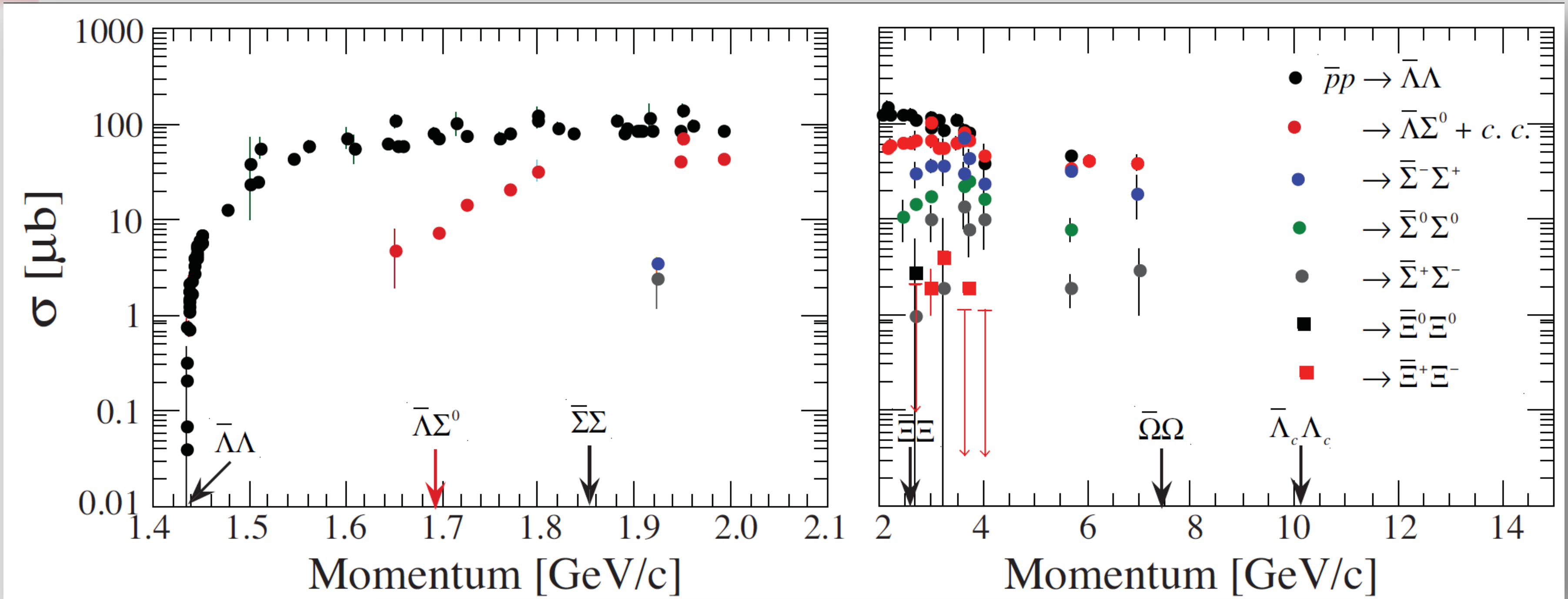
Collaborators: Y. Yamamoto, T. Furumoto, N. Yasutake,
H.-J. Schulze, and M.M. Nagels.

1. High-quality Simultaneous Fit/Description $NN \oplus YN$,
   OBE, TME, MPE meson-exchange dynamics.
   $SU_f(3)$-symmetry, (Non-linear) chiral-symmetry.
2. Scalar-meson nonet structure $\Leftrightarrow$ Nagara $\Delta B_{\Lambda\Lambda}$ values.
3. NO S=-1 Bound-States, NO $\Lambda\Lambda$-Bound-State,
4. Prediction: $D_{\Xi N} = \Xi N(I=1,{}^3S_1)$ B.S.!, $D_{\Xi\Xi} = \Xi\Xi(I=1,{}^1S_0)$ B.S. ??!
5. Similar role tensor-force in ${}^3S_1$ NN-, $\Lambda/\Sigma N$-, ΞN-, and $\Lambda/\Sigma\Xi$-channels.

G-matrix and EOS of the ESC YN/YY-interactions:

a. ESC08: Excellent G-matrix predictions for the $U_\Lambda, U_\Sigma, U_\Xi$ well-depth's,
   ΛN spin-spin and spin-orbit, and Nagara-event okay.
b. Neutron Star mass $M/M_\odot = 1.44 - 2.10 \Leftrightarrow$ Universal Multi-Pomeron
   Repulsion, including Λ, Σ, Ξ

Stored $\bar{p}$ – a Factory for strange *and* charmed $Y\bar{Y}$-Pairs



P̄ANDA

Production Rates (1-2 (fb)$^{-1}$/y)

Final State	cross section	# reconstr. events/y
Meson resonance + anything	100μb	10^{10}
$\Lambda\bar{\Lambda}$	50μb	10^{10}
$\Xi\bar{\Xi}$ ($\to_{\Lambda\Lambda}$ A)	2μb	10^8 (10^5)
$D\bar{D}$	250nb	10^7
J/ψ ($\to e^+e^-, \mu^+\mu^-$)	630nb	10^9
χ_2 ($\to J/\psi + \gamma$)	3.7nb	10^7
$\Lambda_c\bar{\Lambda}_c$	20nb	10^7
$\Omega_c\bar{\Omega}_c$	0.1nb	10^5

Perspectives: Hypernuclei

J-PARC
MAINZ
CERN
BNL
JLab

FAIR (?)