AFDMC calculations of homogeneous neutron matter in presence of hyperons

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Main collaborators:

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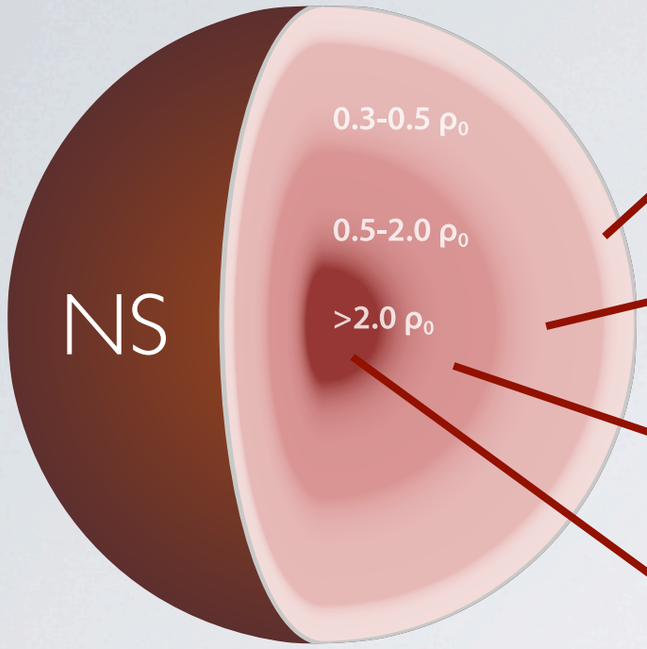
- S. Gandolfi (LANL, US-NM)

Otranto - May 31, 2013

Outline

- ✓ Motivations
- ✓ The Λ-nucleon interaction
- ✓ The idea of the project
- ✓ Results
- ✓ Conclusions

Motivations: theory & observations



$R \sim 10$ km

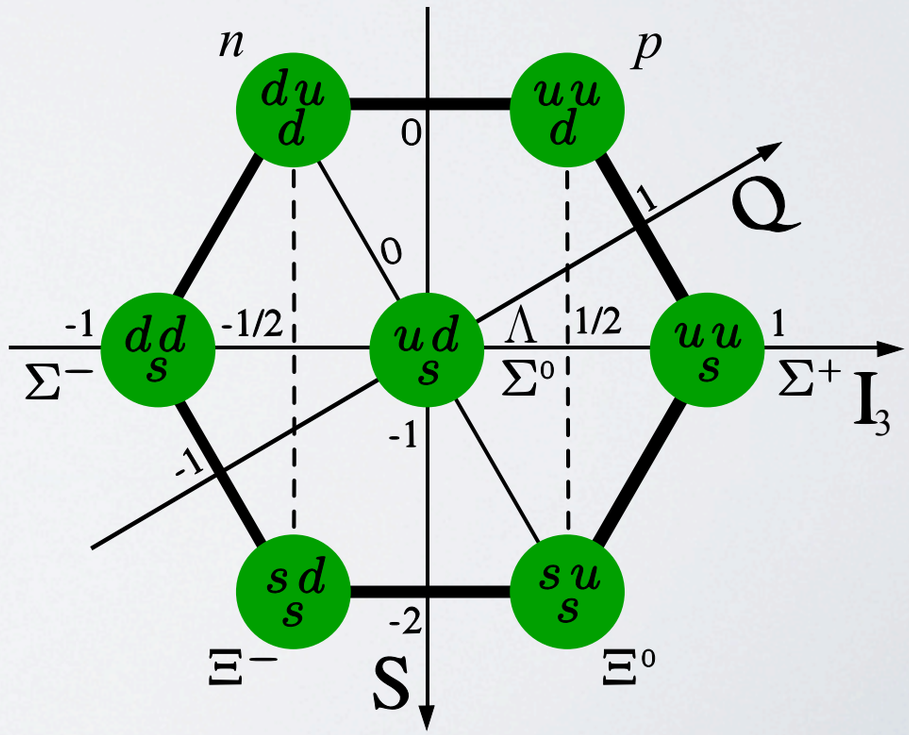
$M \sim 1.4\ M_\odot$

outer crust: $Z\ e$
$(0.3 \div 0.5$ km$)$

inner crust: $Z\ n\ e$
$(1 \div 2$ km$)$

outer core: $n\ p\ e\ \mu$
$(\sim 9$ km$)$

inner core: $n\ p\ e\ \mu\ \Lambda\ \Sigma\ \Xi\ \pi_c\ K_c\ q_p$?
$(0 \div 3$ km$)$



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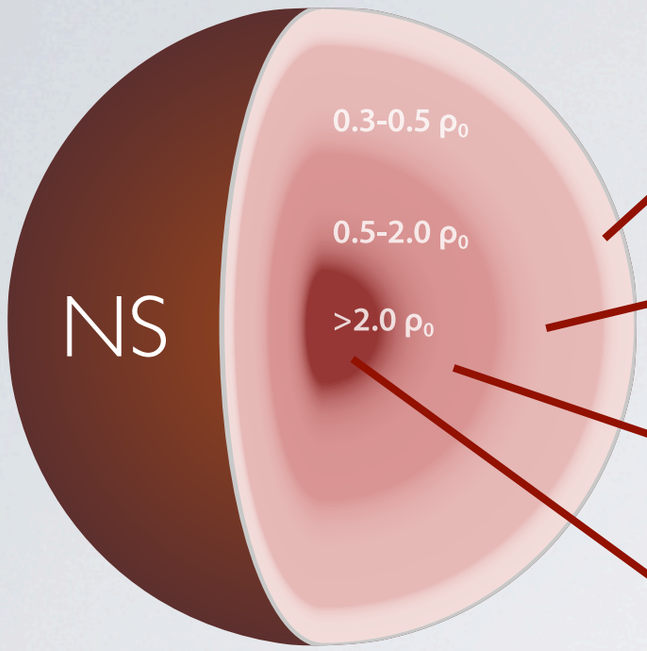

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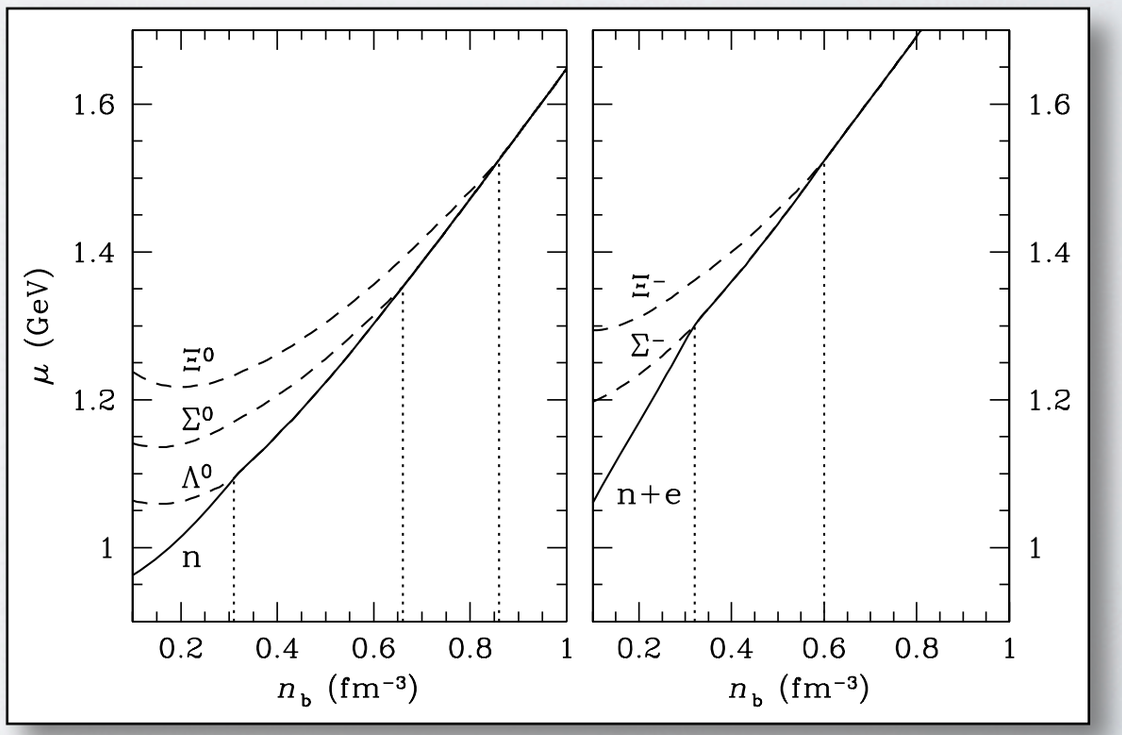
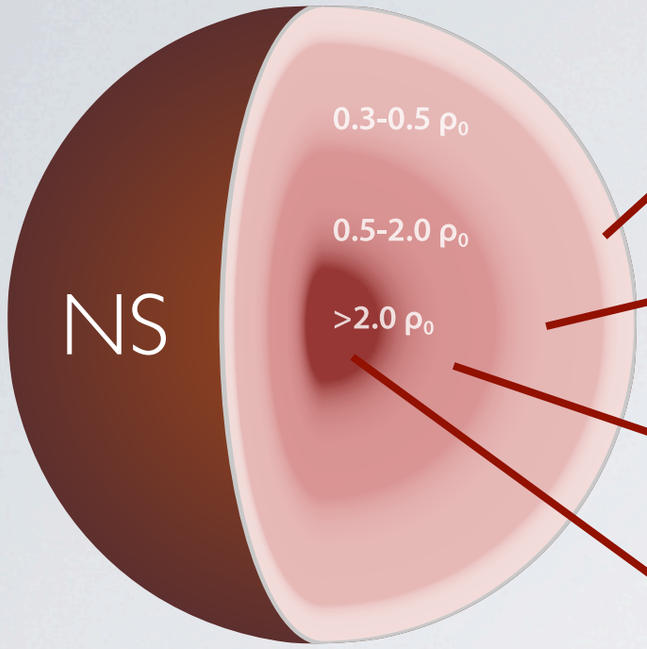
$(0 \div 3$ km$)$

$$Q = -1 : \mu_{b^-} = \mu_n + \mu_e$$
$$Q = \ \ 0 : \mu_{b^0} = \mu_n$$
$$Q = +1 : \mu_{b^+} = \mu_n - \mu_e$$



P. Haensel, A.Y. Potekhin, D.G. Yakovlev, Neutron Stars 1, Springer 2007

Motivations: theory & observations



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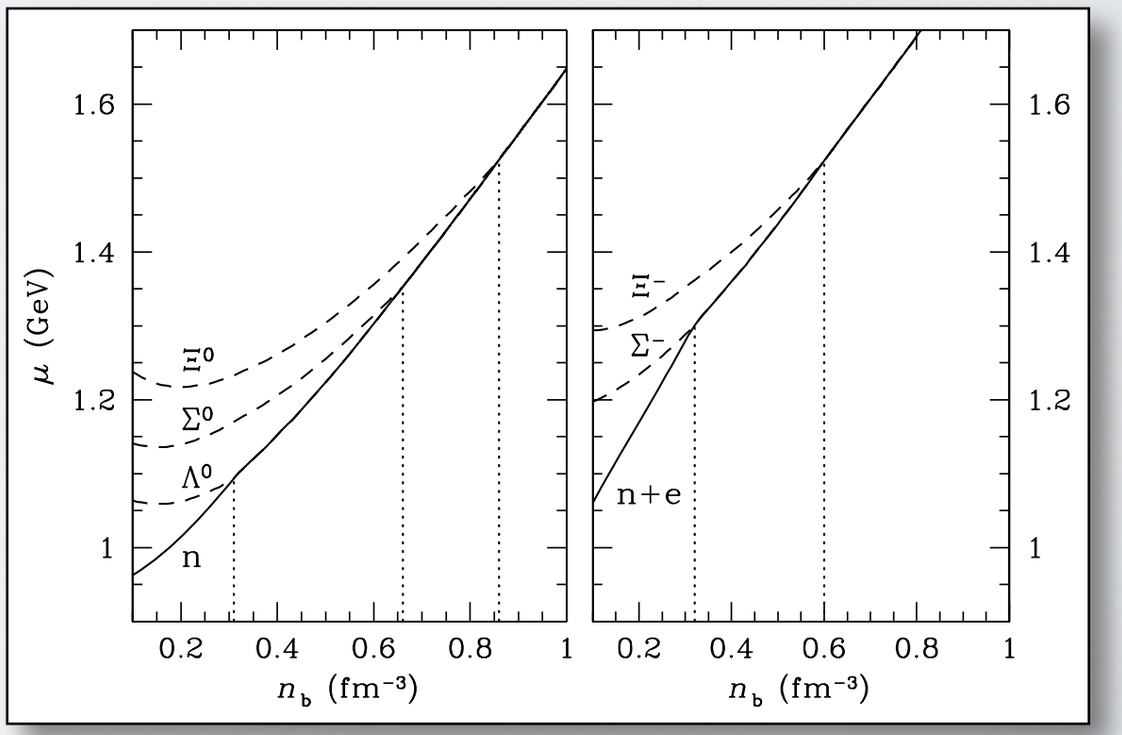
$(0 \div 3$ km$)$

composition strongly affects the properties of the neutron star

↓

EOS & M(R) relation



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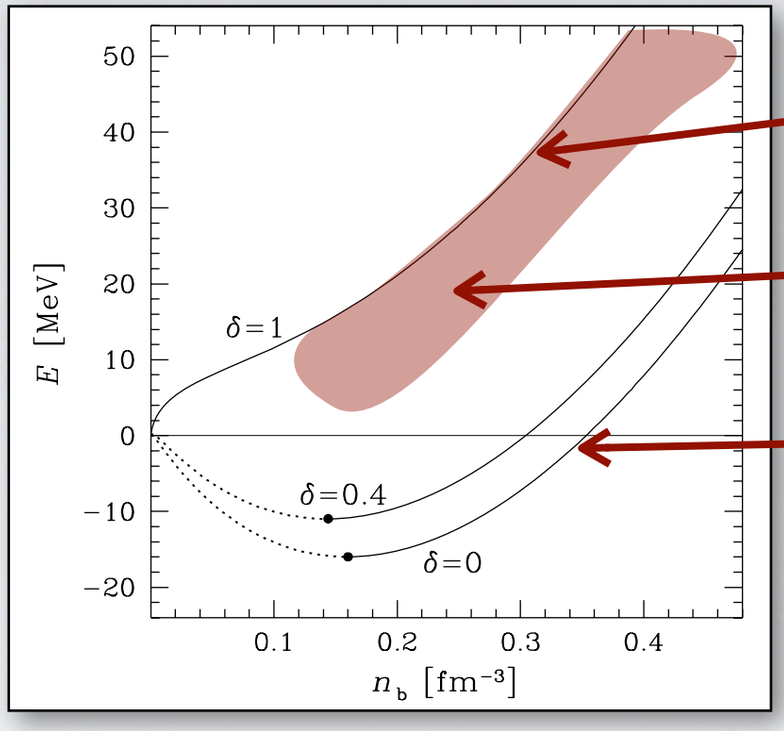
Motivations: theory & observations

$$\begin{cases} E \equiv E(n_b, \delta) \\ P = n_b^2 \dfrac{\partial E(n_b, \delta)}{\partial n_b} \end{cases}$$

$$n_b = n_p + n_n = A/V$$

$$\delta = \frac{n_n - n_p}{n_b}$$



pure n matter

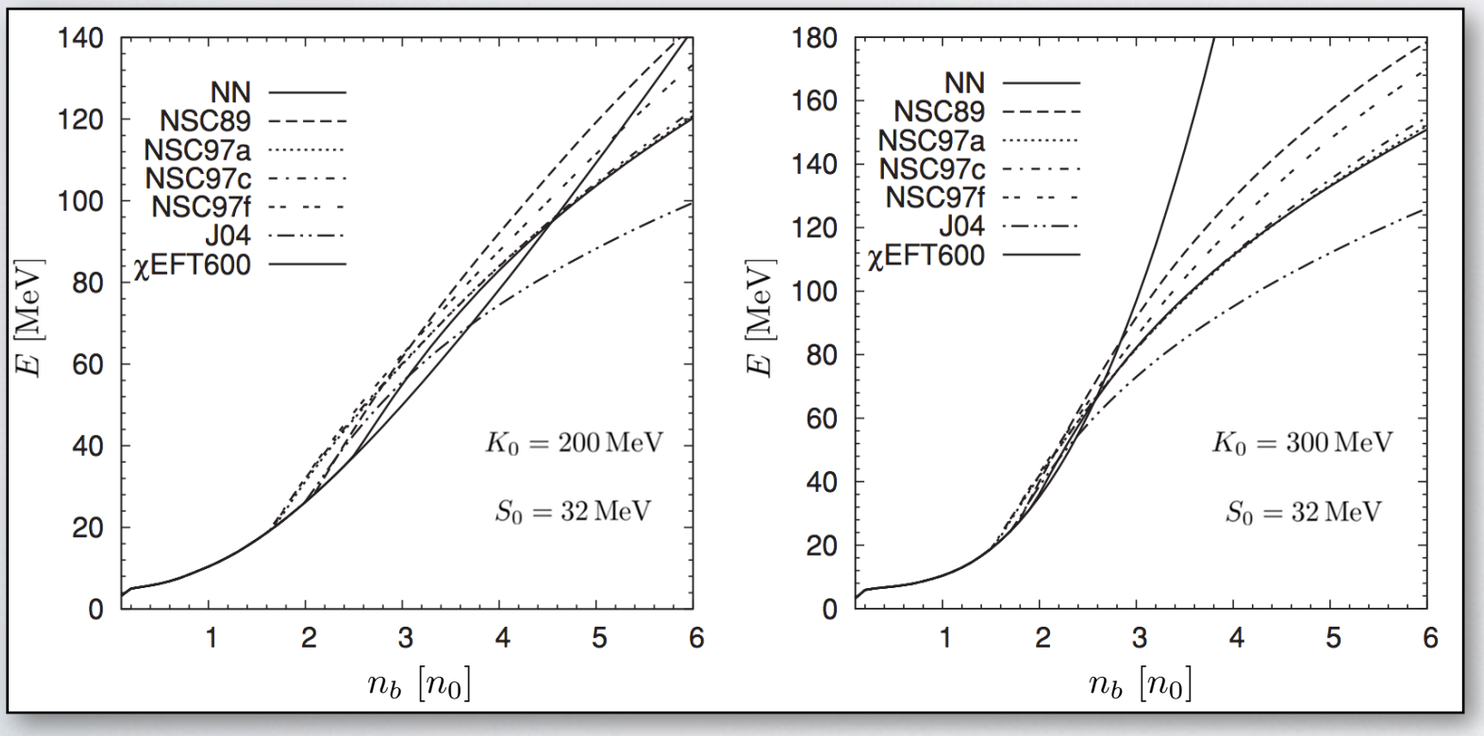
NS core

symmetric matter

$n_0 = 0.16 \text{ fm}^{-3}$

$E_0 = -16 \text{ MeV}$

P. Haensel, A.Y. Potekhin, D.G. Yakovlev, Neutron Stars 1, Springer 2007



H. Đapo, B.-J. Schaefer, and J. Wambach, Phys. Rev. C 81, 035803 (2010)

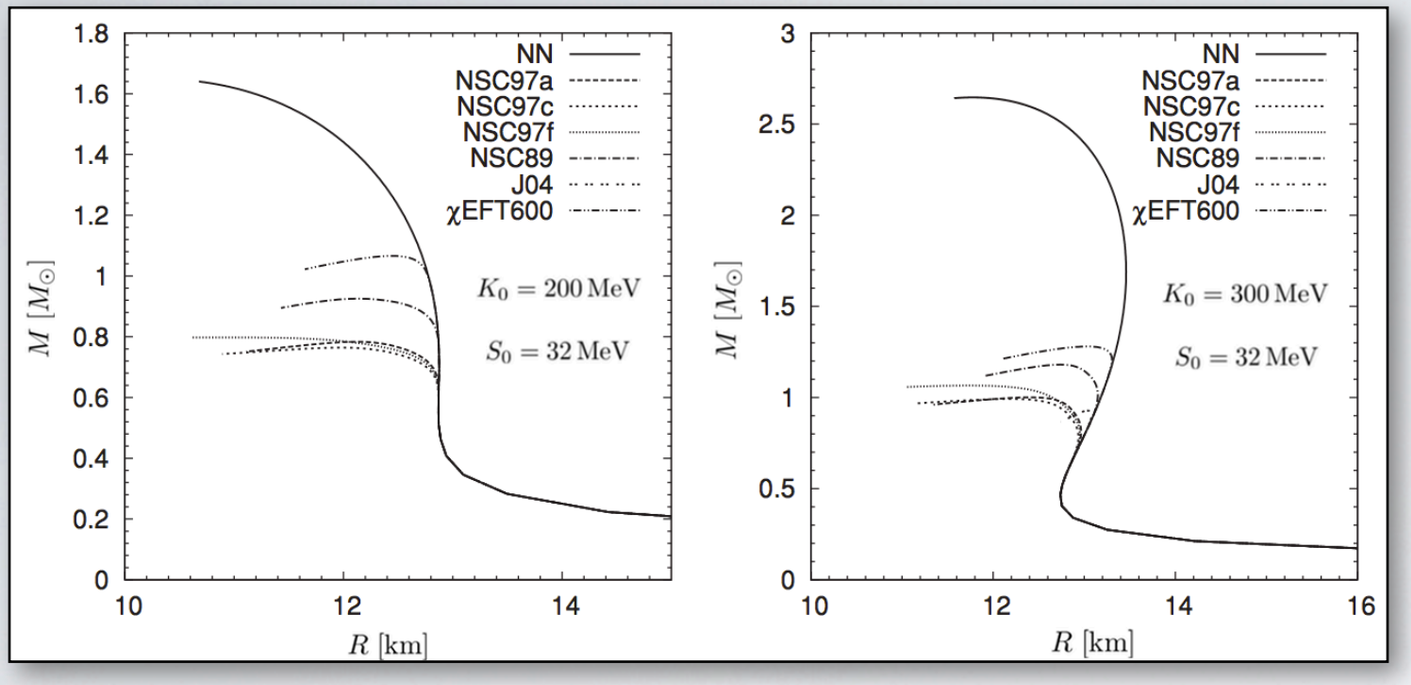
hyperons: softening of the EOS

↓

M(R) & Mmax (TOV)

model dependent

Motivations: theory & observations



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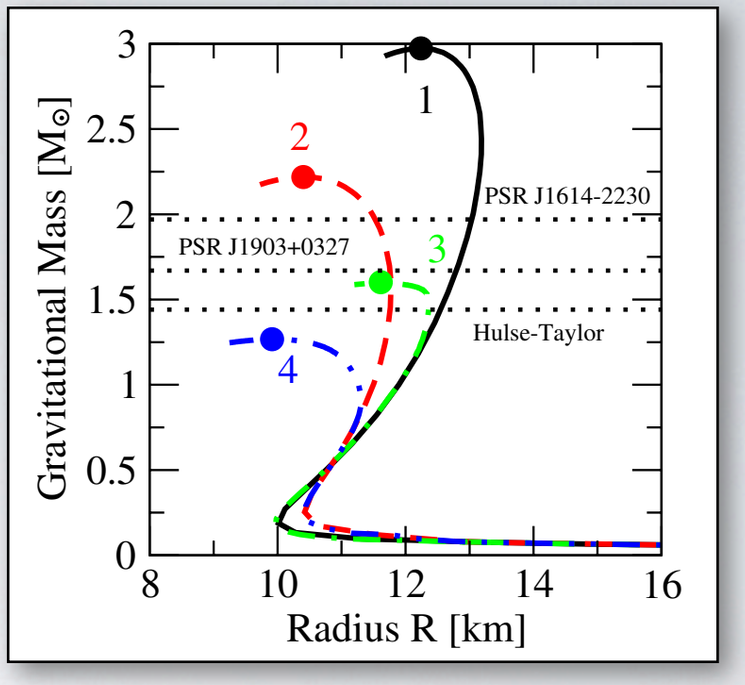
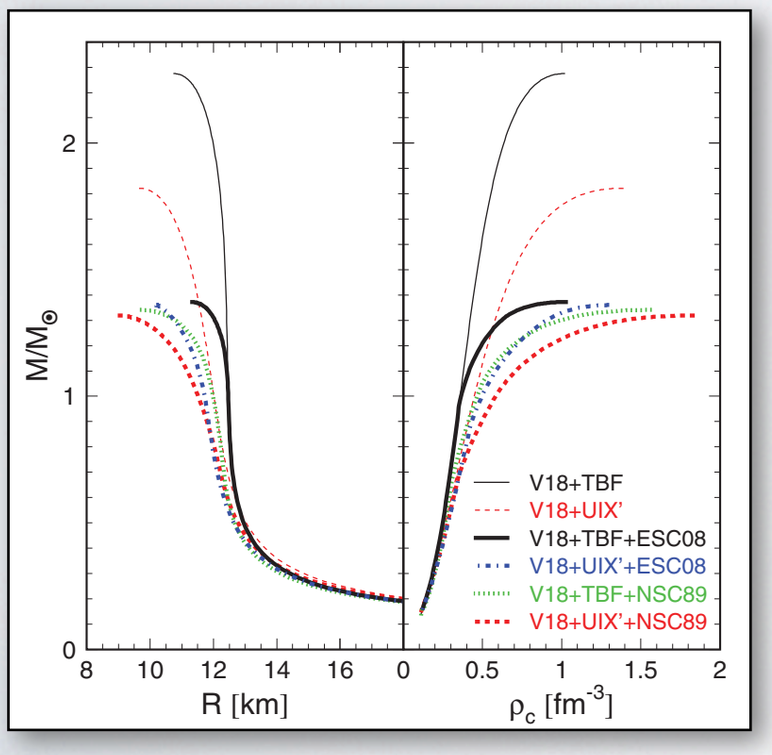
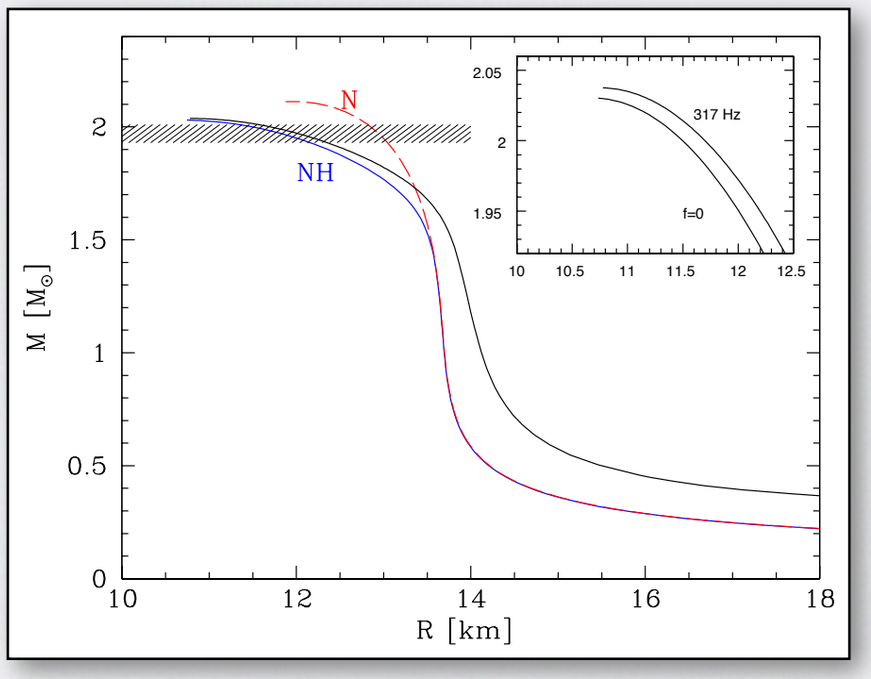


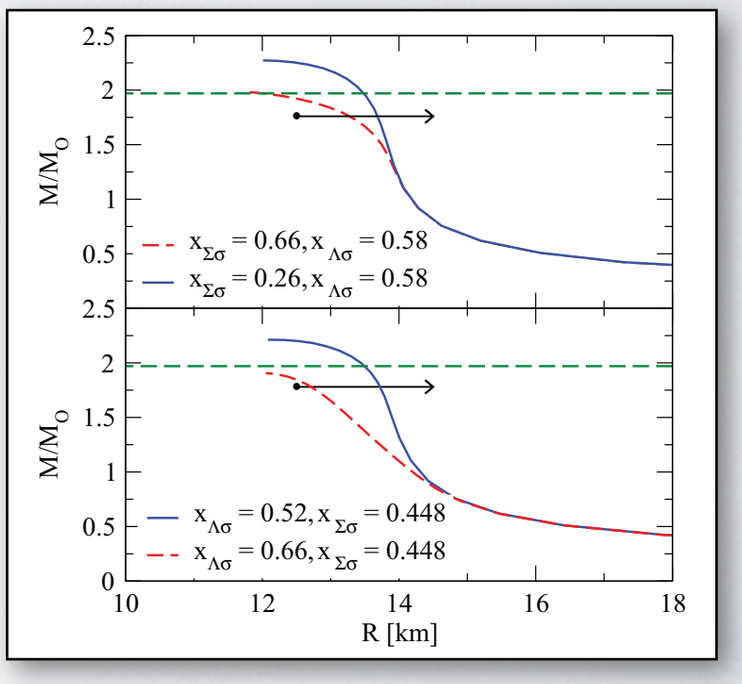
I. Vidaña, D. Logoteta, C. Providência, A. Polls, I. Bombaci, EPL 94, 11002 (2011)



H.-J. Schulze, T. Rijken, Phys. Rev. C 84, 035801 (2011)

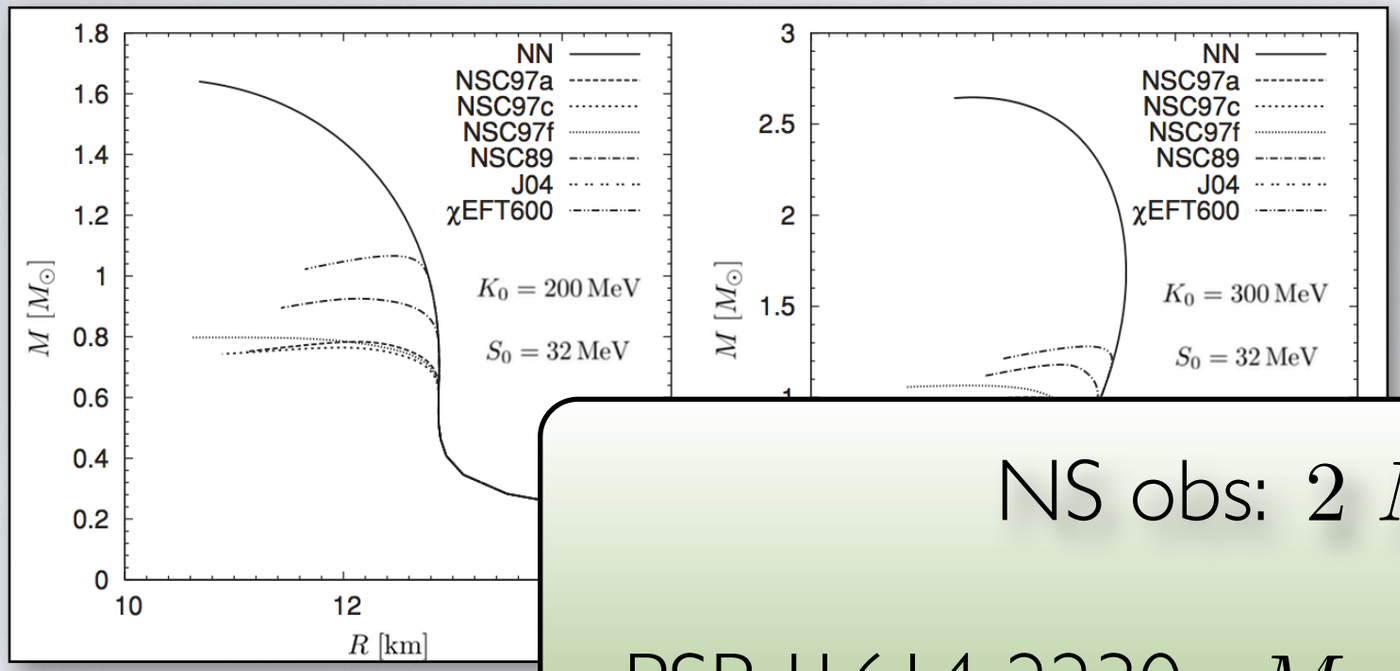


I. Bednarek, P. Haensel, J.~L. Zdunik, M. Bejger, R. Mańka, Astron. Astrophys. 543, A157 (2012)



G. Colucci, A. Sedrakian, Phys. Rev. C 87, 055806 (2013)

Motivations: theory & observations



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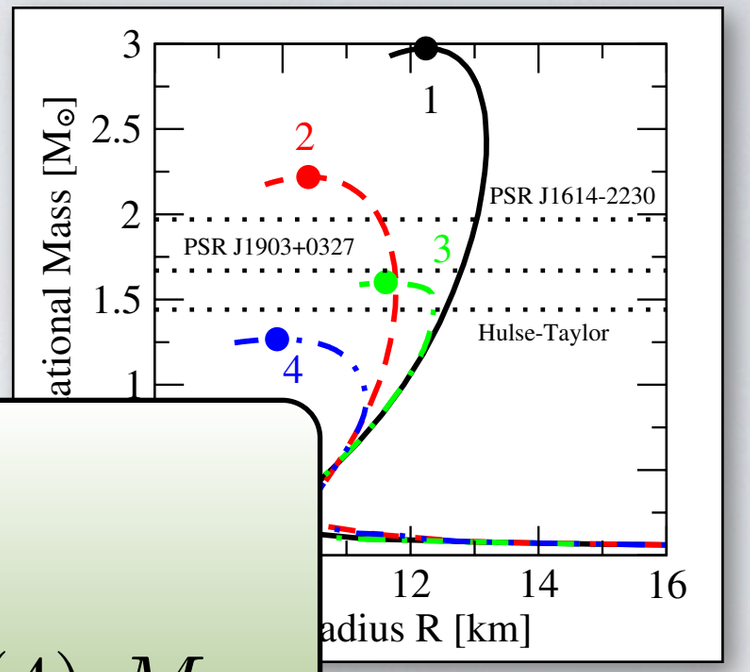


oteta, C. Providência,
, EPL 94, 11002 (2011)

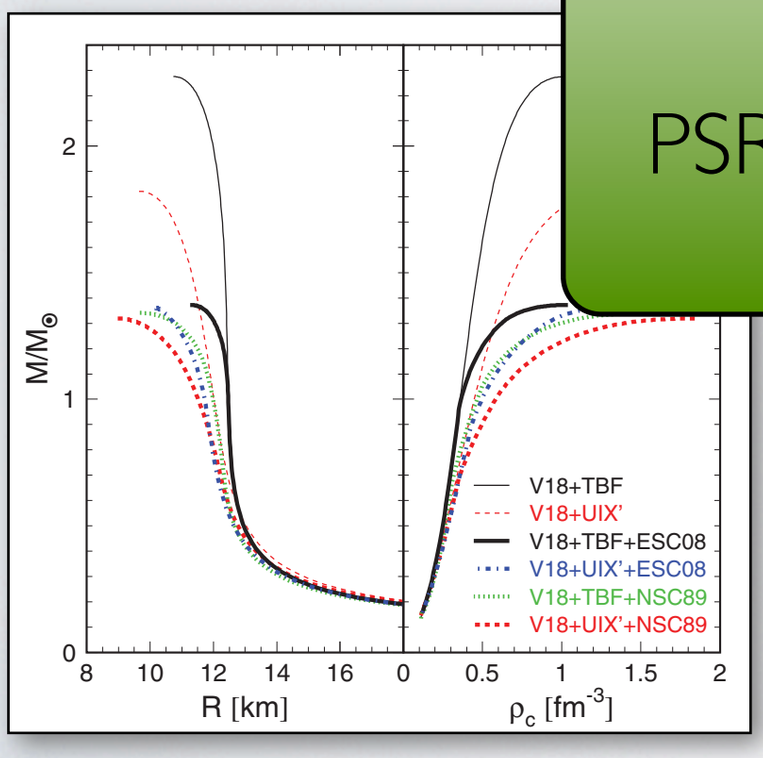
NS obs: $2\ M_\odot$

PSR J1614-2230: $M = 1.97(4)\ M_\odot$

P. B. Demorest et al. , Nature 467, 1081 (2010)

PSR J0348+0432: $M = 2.01(4)\ M_\odot$

J. Antoniadis et al. , Science 340, 1233232 (2013)



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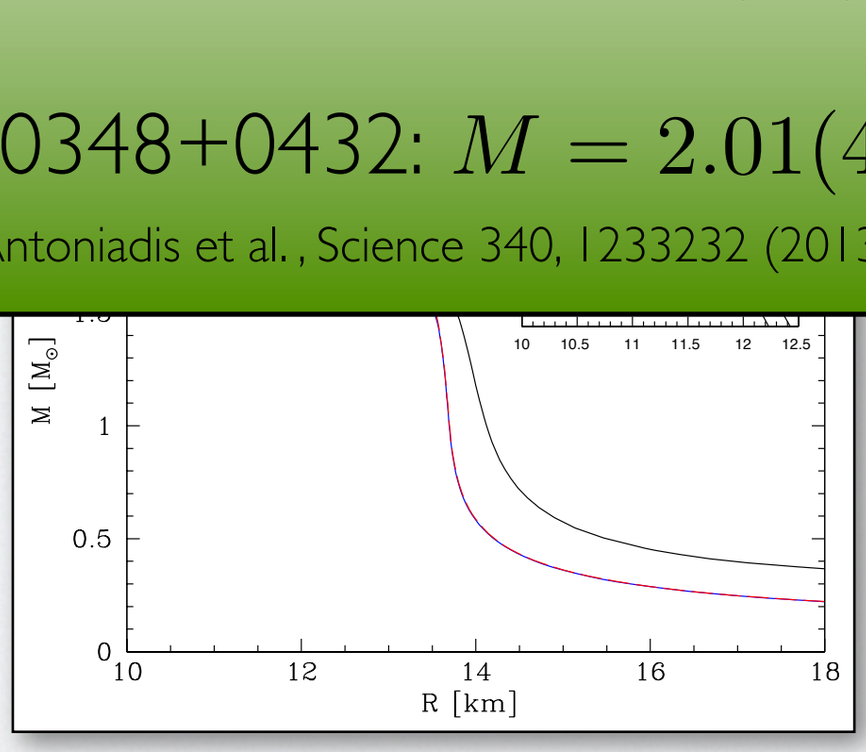

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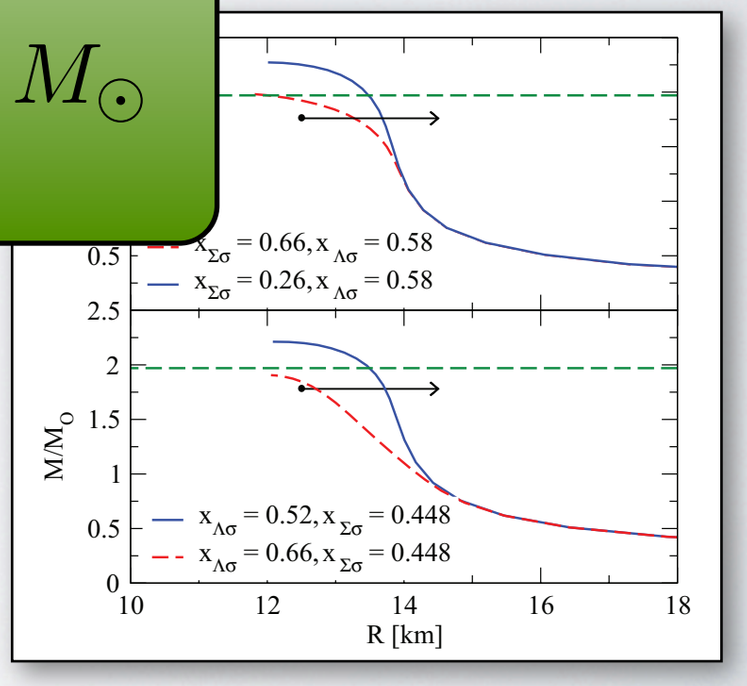

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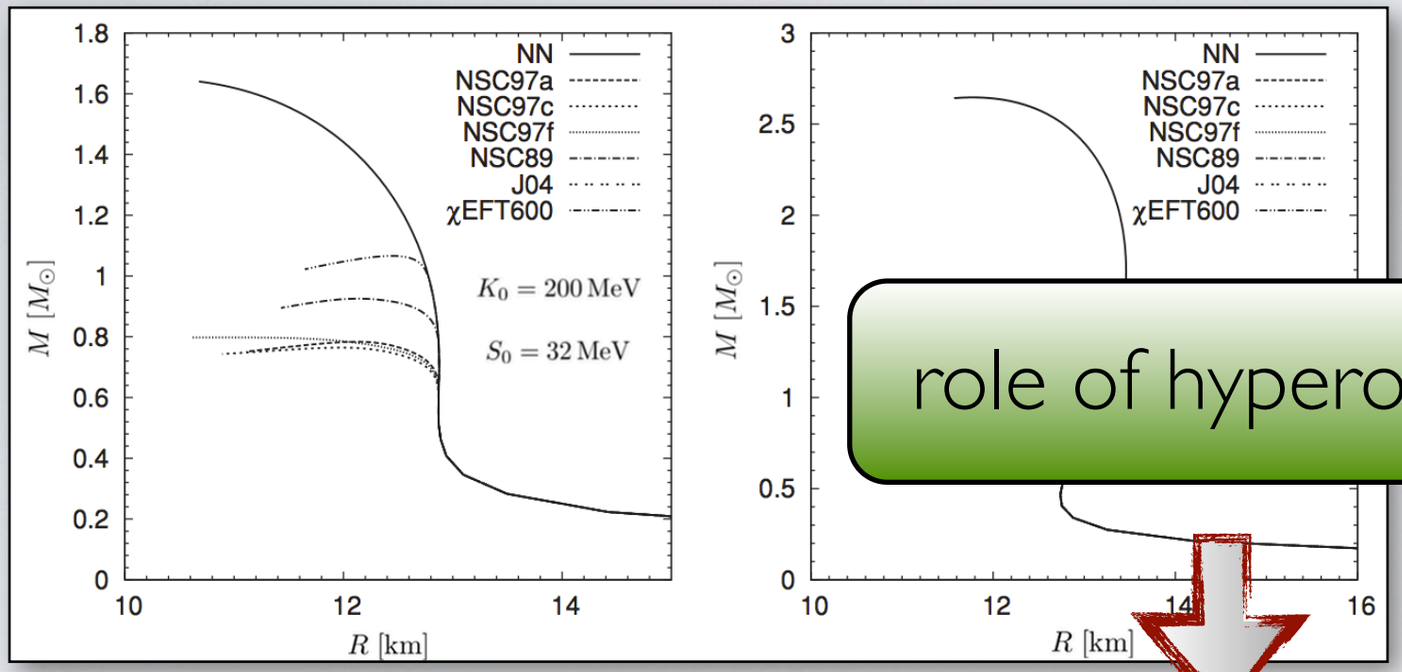

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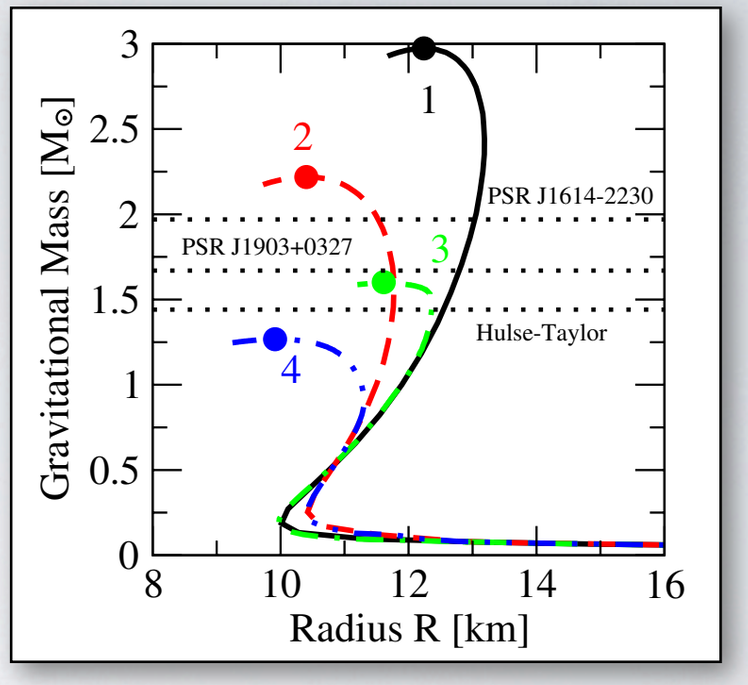
role of hyperons ?



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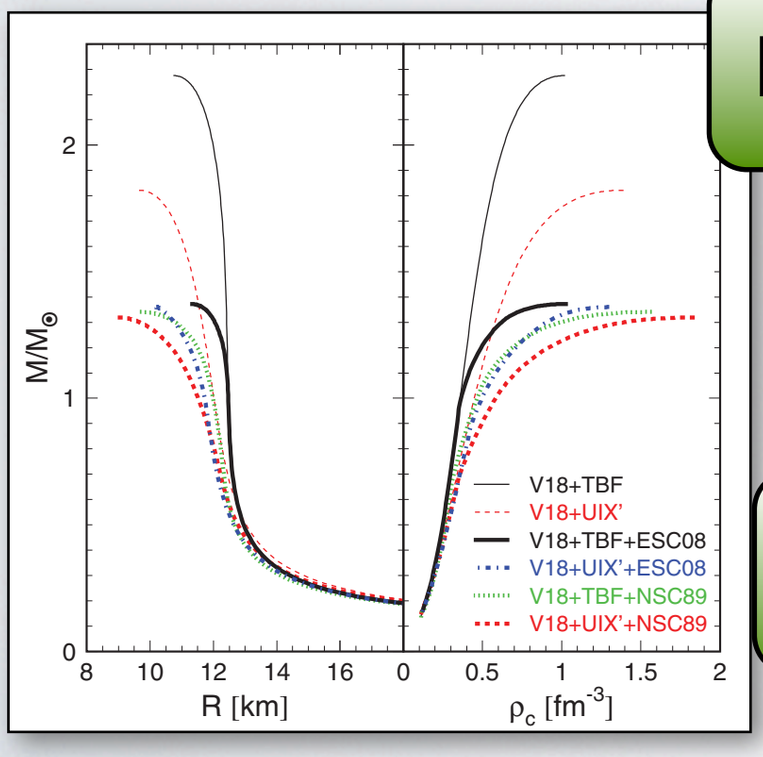
hyperon-nucleon interaction



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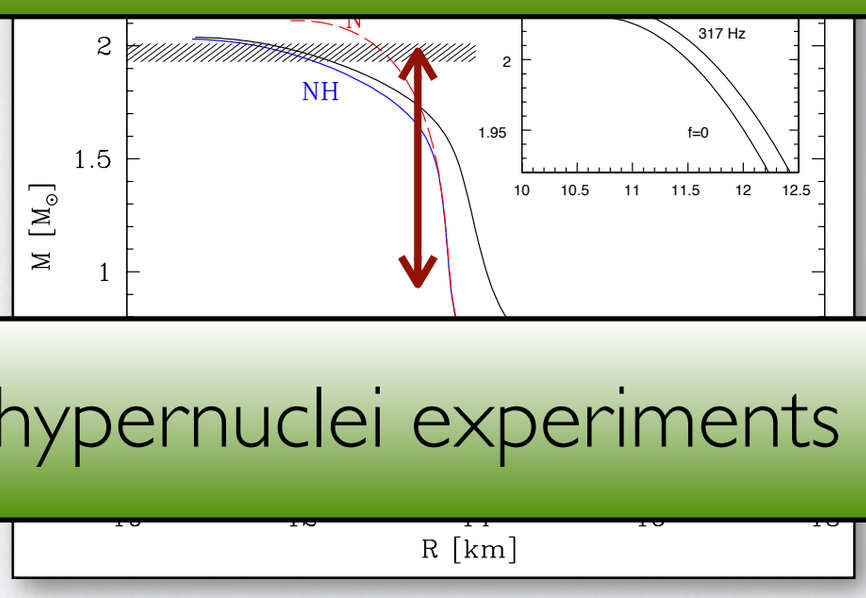

hypernuclei experiments

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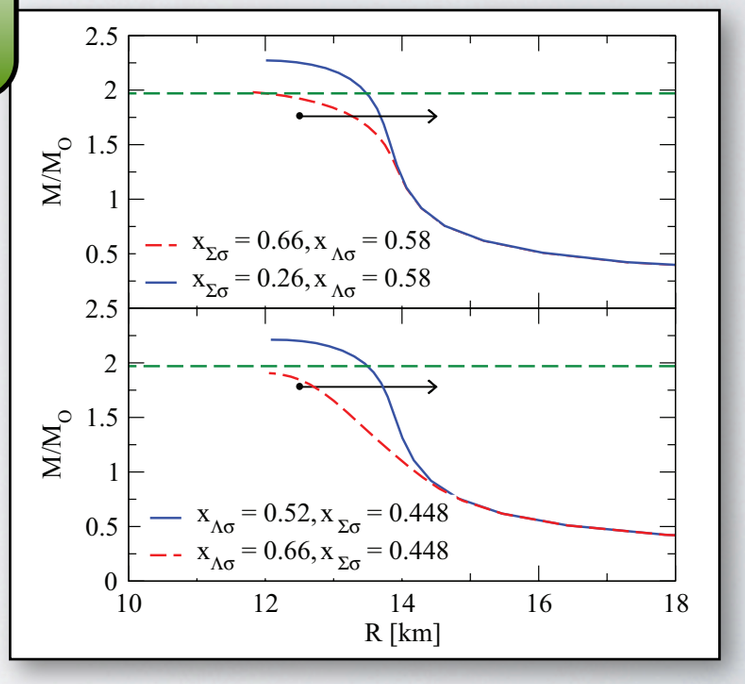
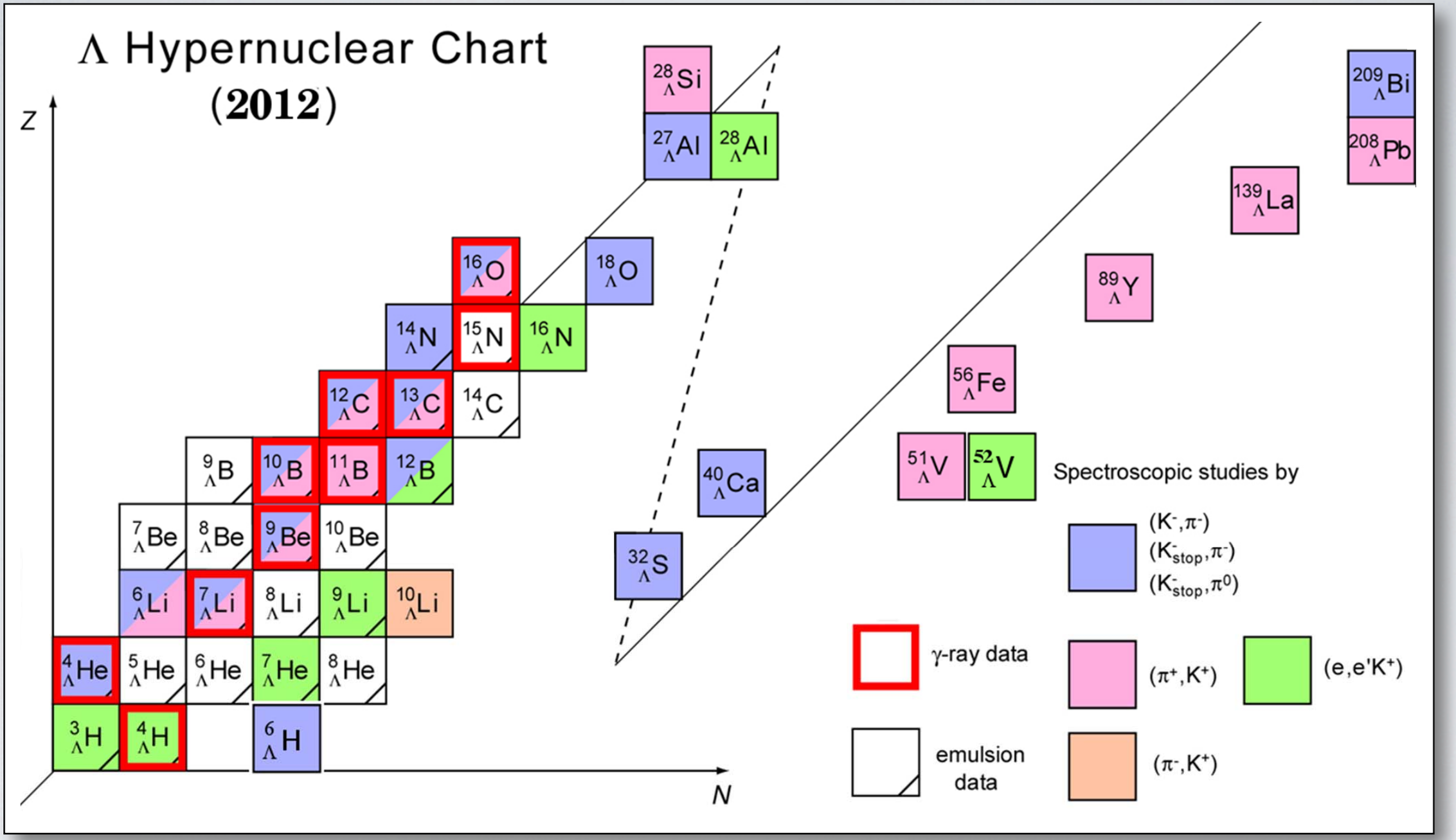


G. Colucci, A. Sedrakian, Phys. Rev. C 87, 055806 (2013)

Motivations: experimental status



Updated from: O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. 57, 564 (2006)

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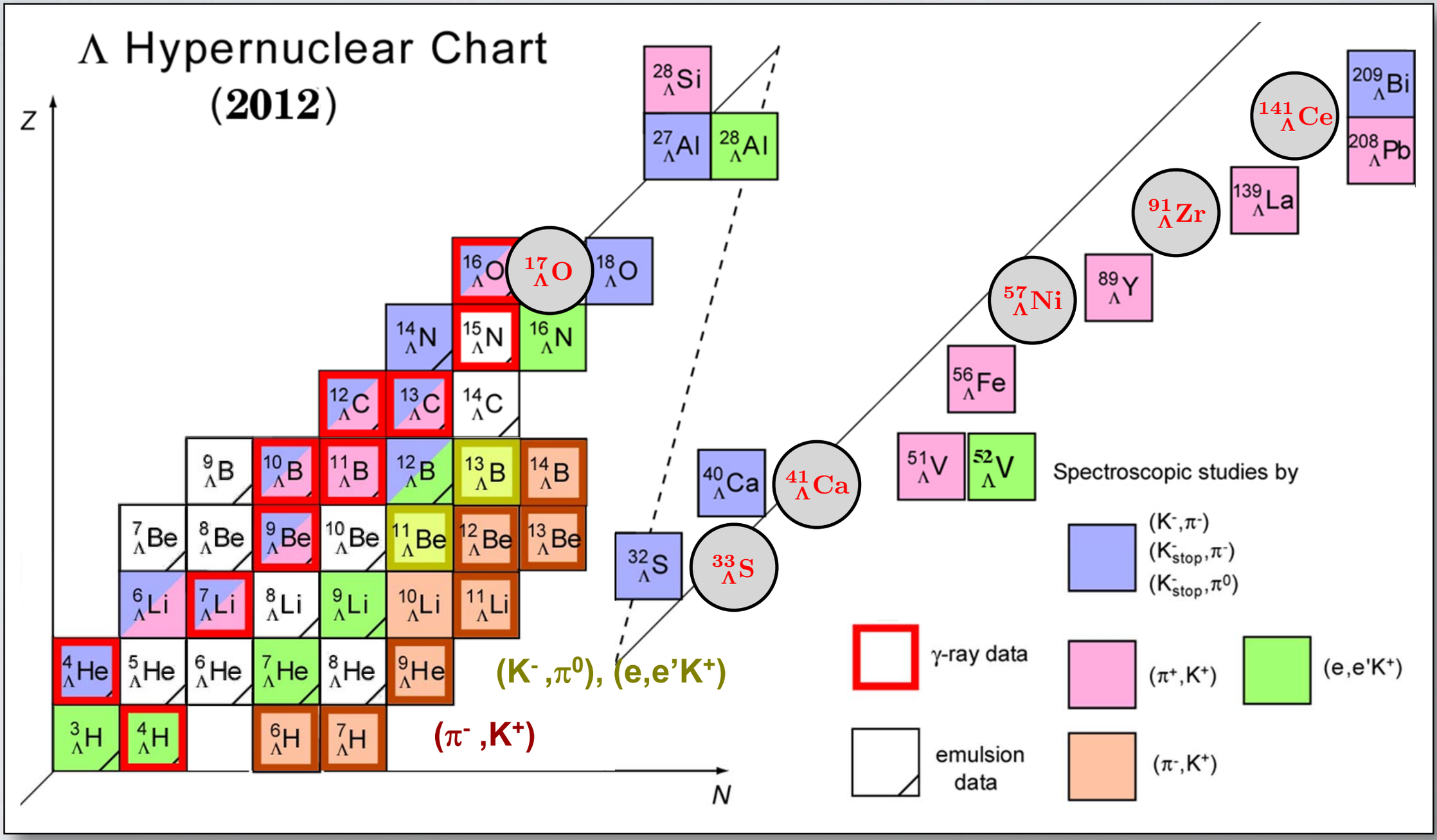

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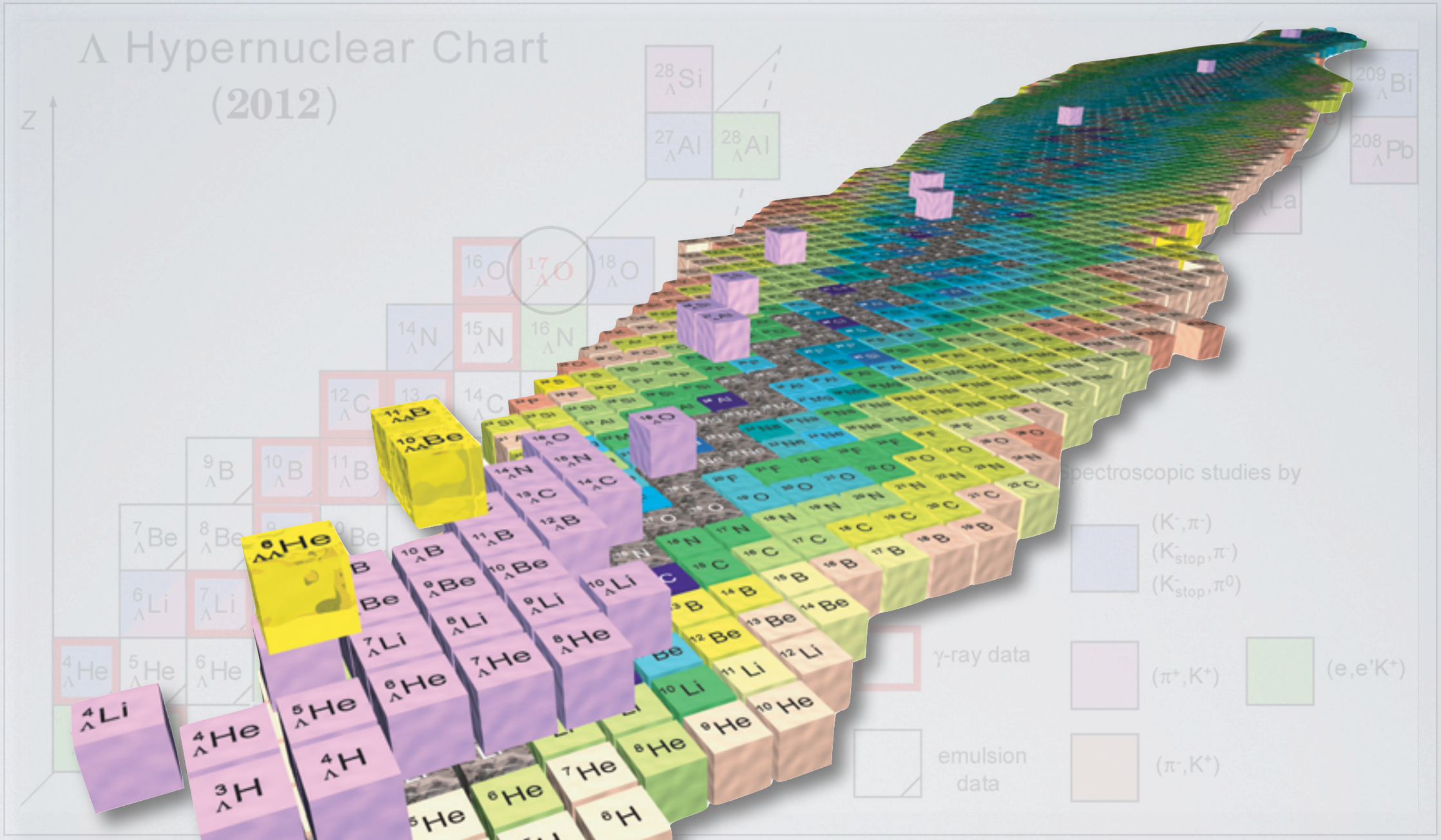
Λp scattering data

$$\begin{cases} \sim 600 & \text{low energy} \quad (p_{lab} = 200 \div 300 \text{ Mev/c}) \\ \sim 250 & \text{high energy} \quad (p_{lab} = 300 \div 1500 \text{ Mev/c}) \end{cases}$$

Motivations: experimental status



mura, Prog. Part. Nucl. Phys. 57, 564 (2006)

Λp sca[illegible]00 low energy $(p_{lab} = 200 \div 300$ Mev/c)

dat[illegible] ~ 250 high energy $(p_{lab} = 300 \div 1500$ Mev/c)

The Λ-nucleon interaction

Usmani et al. parametrization

- ✓ diagrammatic contributions due to pion exchange
- ✓ same structure of the nuclear Argonne potentials

  → implementation in QMC code (AFDMC)

- ✓ 2-body ΛN and 3-body ΛNN terms

A. Bodmer, Q. N. Usmani, J. Carlson, Phys. Rev. C 29, 684-687 (1984)

A. Bodmer, Q. N. Usmani, Nucl. Phys. A 477, 621-651 (1988)

A. A. Usmani, S. C. Pieper, Q. N. Usmani, Phys. Rev. C 51, 2347 (1995)

A. A. Usmani, Phys. Rev. C 52, 1773-1777 (1995)

A. A. Usmani, S. Murtaza, Phys. Rev. C 68, 024001 (2003)

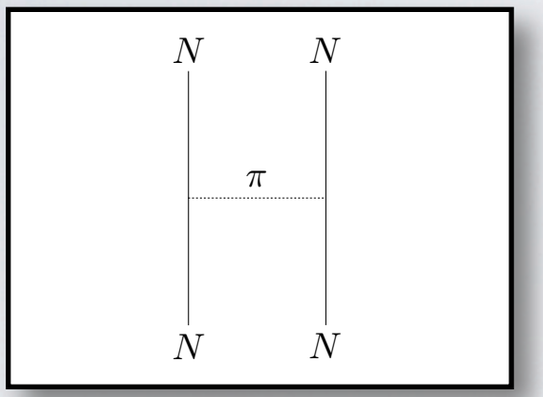
A. A. Usmani, Phys. Rev. C 73, 011302 (2006)

A. A. Usmani, F. C. Khanna, J. Phys. G: Nucl. Part. Phys. 35, 025105 (2008)

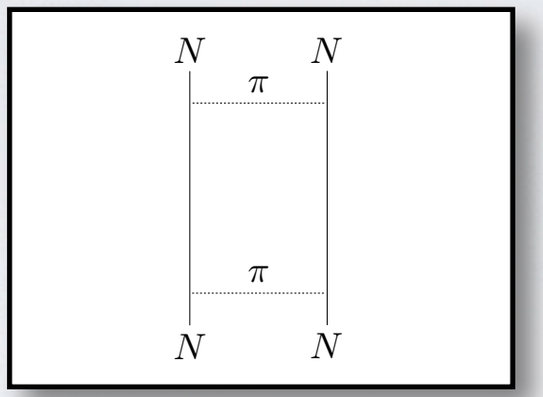
The Λ-nucleon interaction

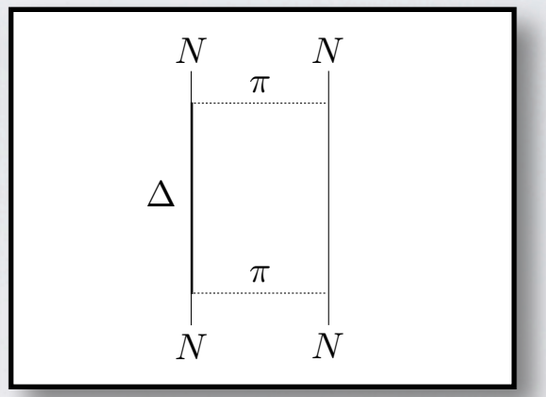
2-body

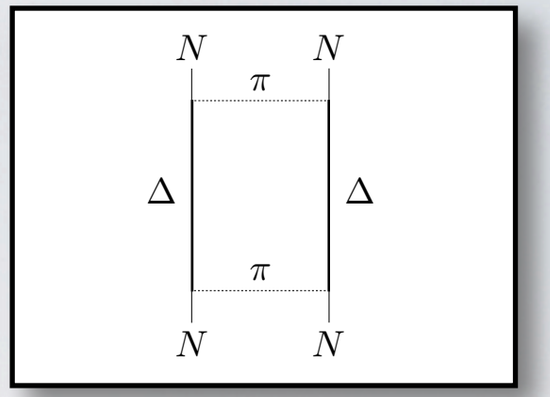
1π



2π

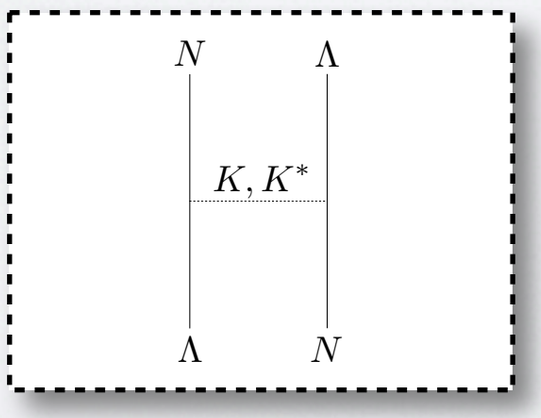


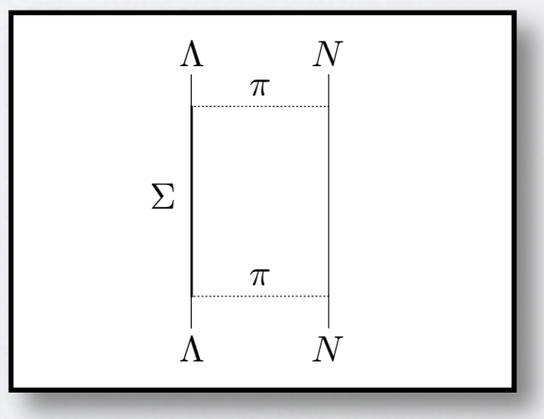


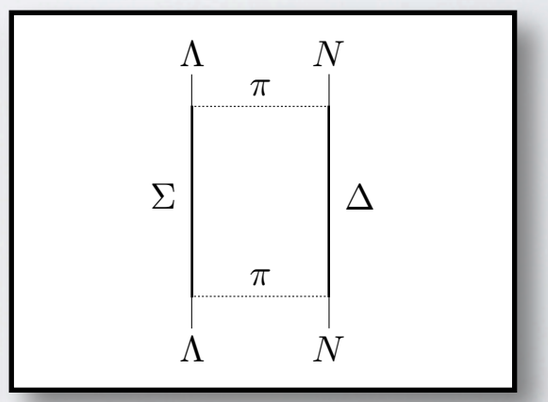


$\Lambda\pi\Sigma$ vertex

forbidden





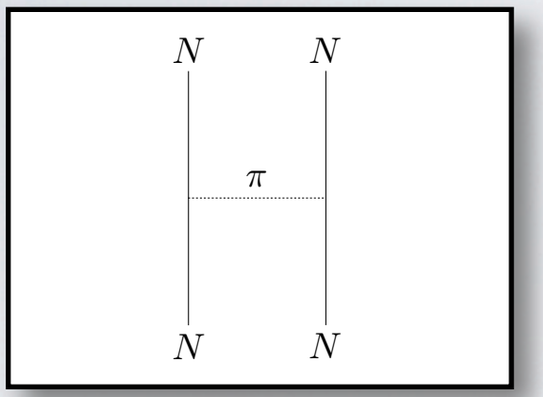


CSB $(A = 4)$

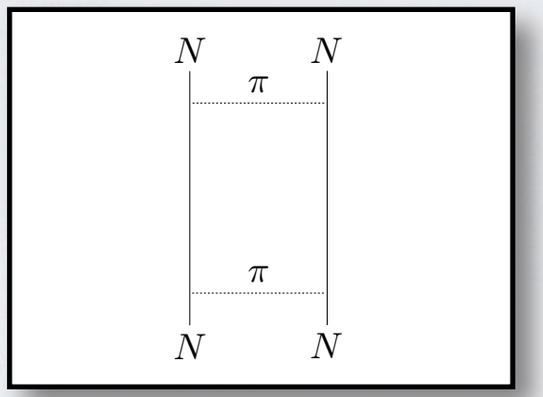
The Λ-nucleon interaction

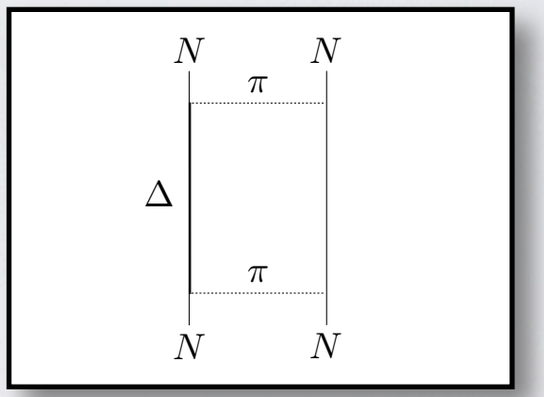
2-body

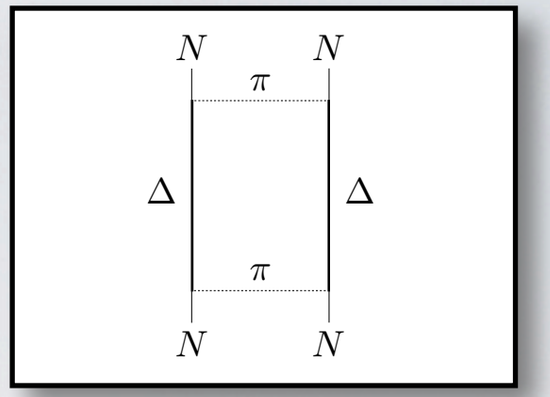
1π



2π



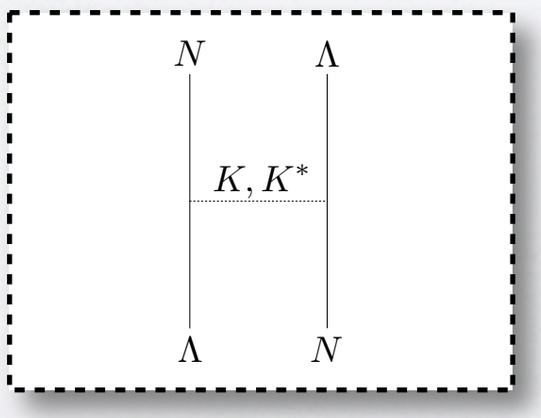


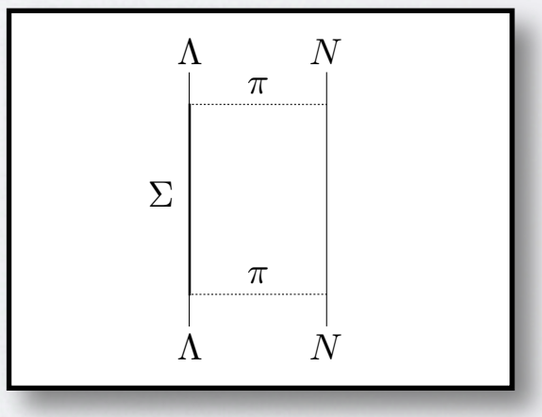


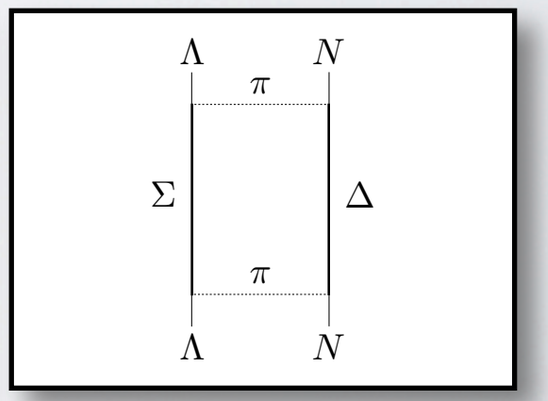
parameters fitted on $\Lambda\, p$ scattering data

$\Lambda\pi\Sigma$ vertex

forbidden





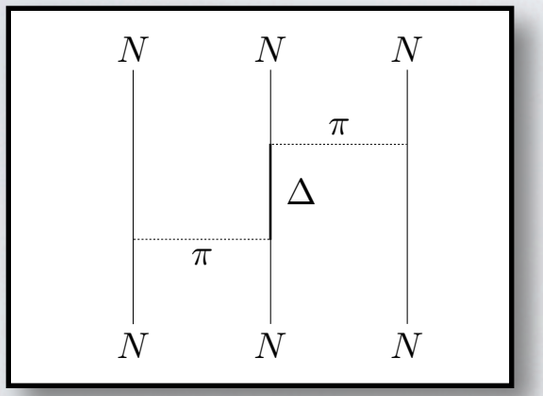


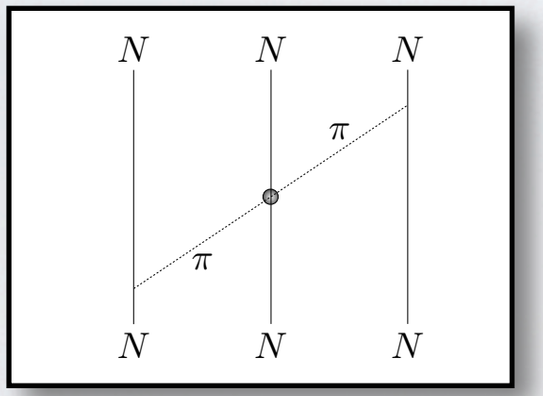
CSB $(A = 4)$

The Λ-nucleon interaction

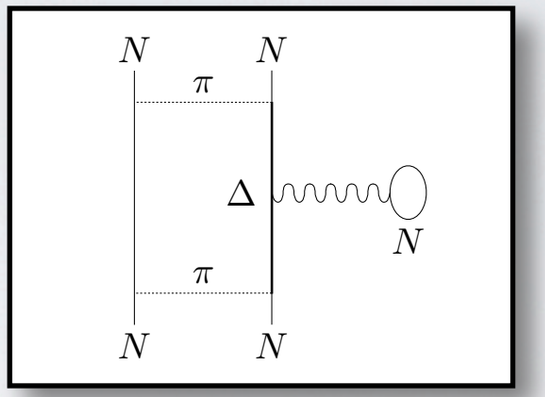
3-body

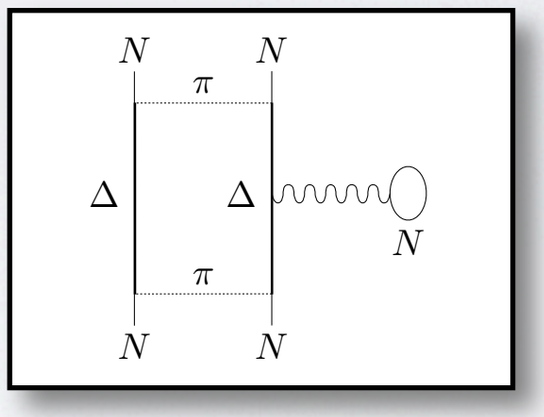
2π



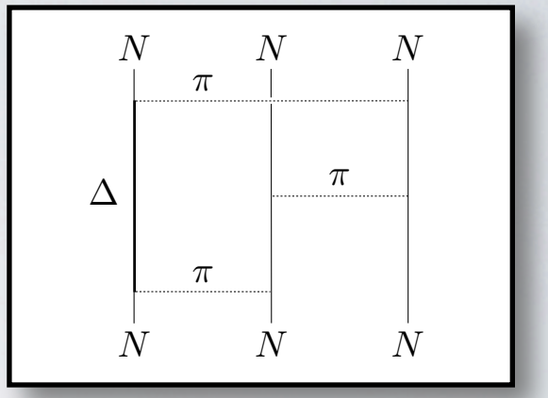


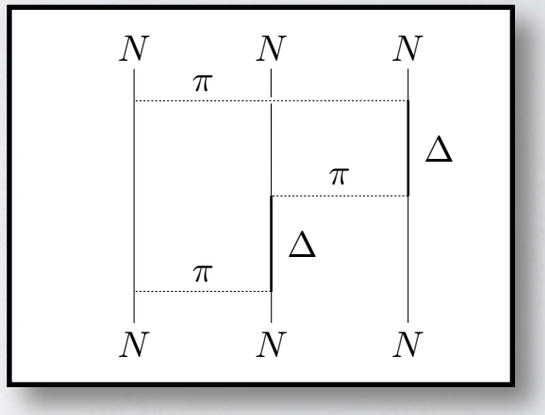
dispersive

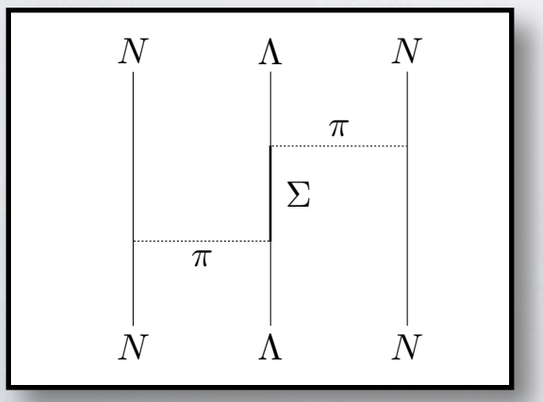


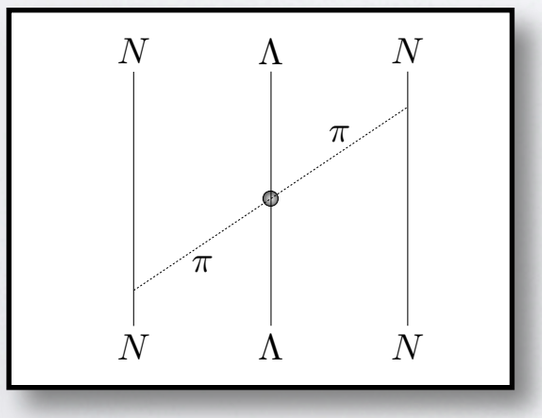


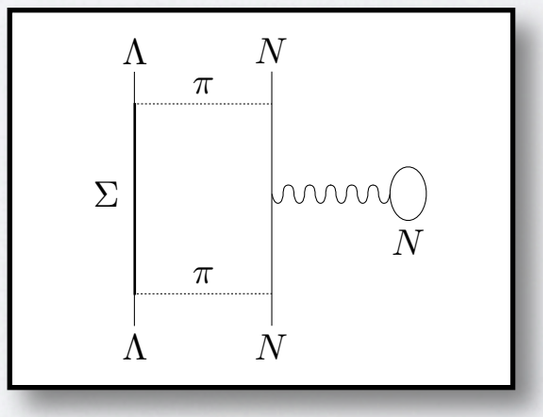
3π











forbidden

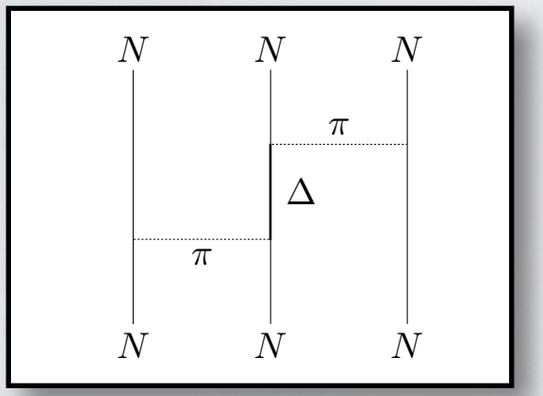
The Λ-nucleon interaction

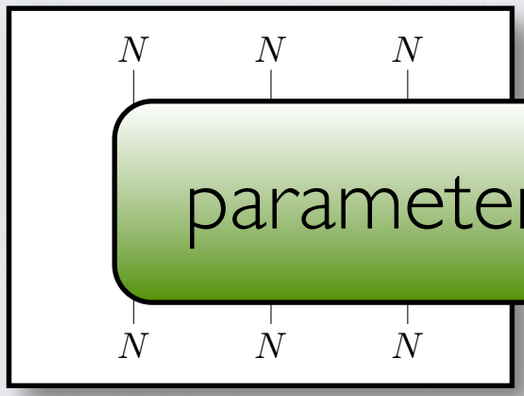
3-body

2π

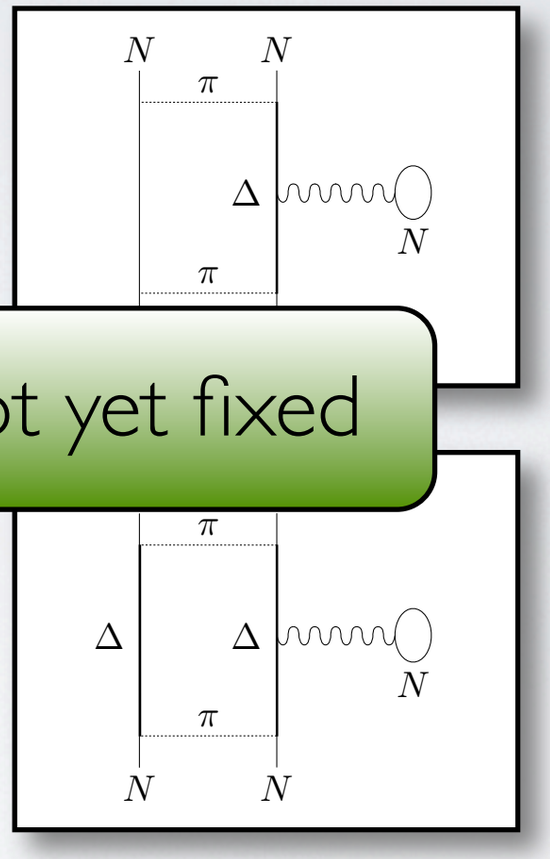
dispersive

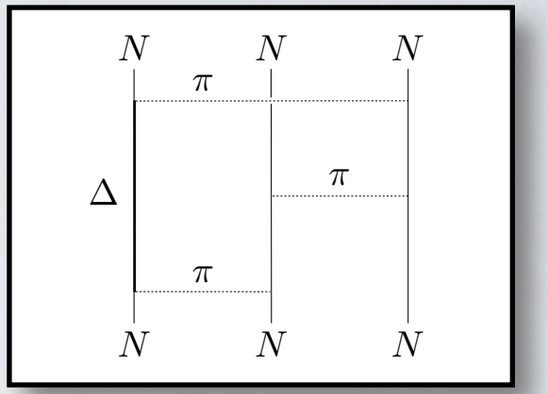
3π

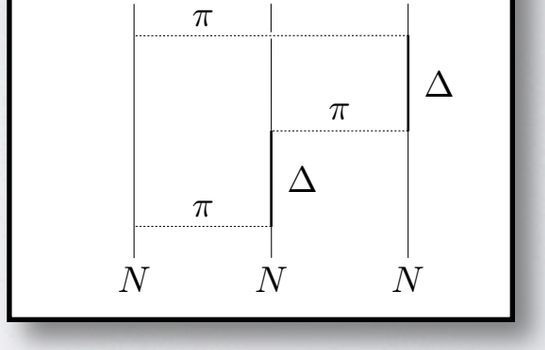




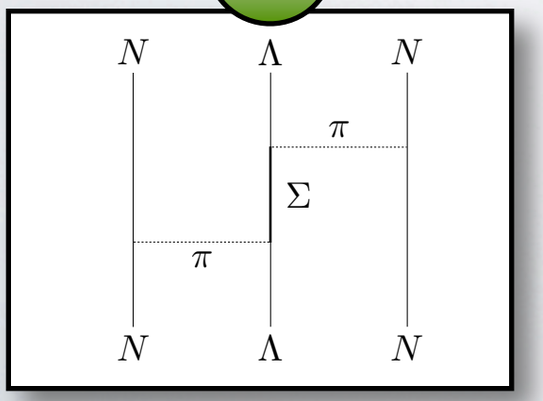
parameters not yet fixed



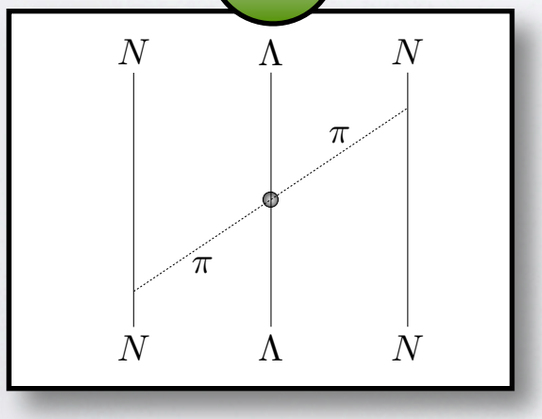




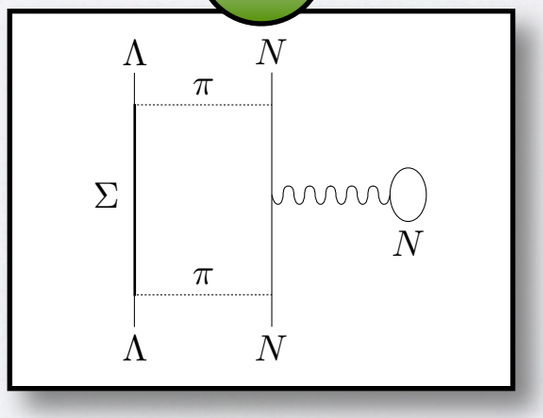
C^P



C^S



W^D



forbidden

The Λ-nucleon interaction

3-body

2π

dispersive

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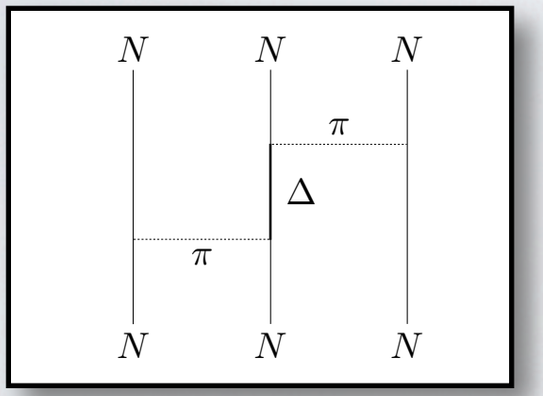
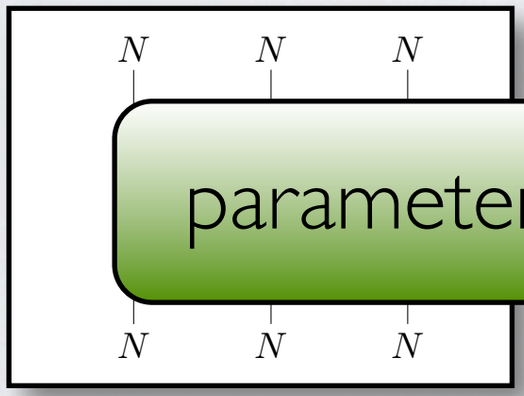
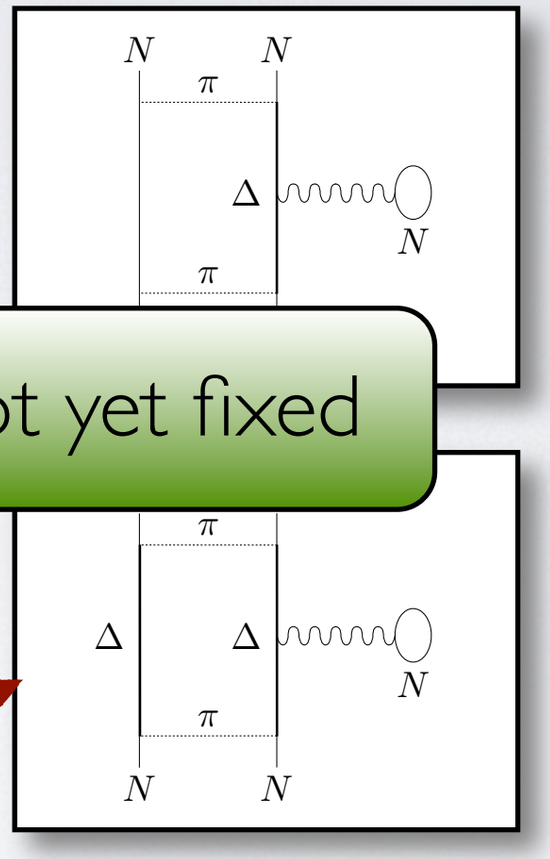
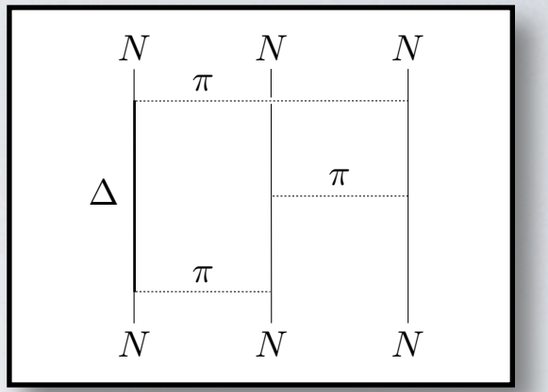
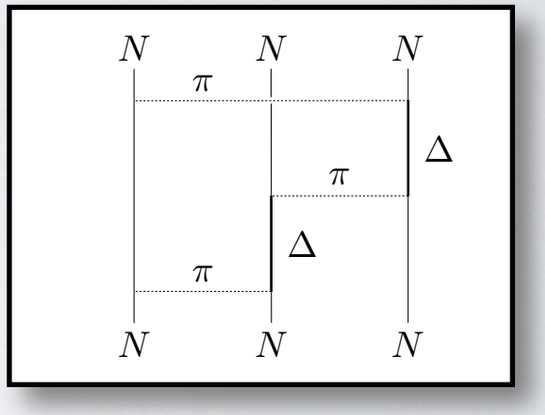




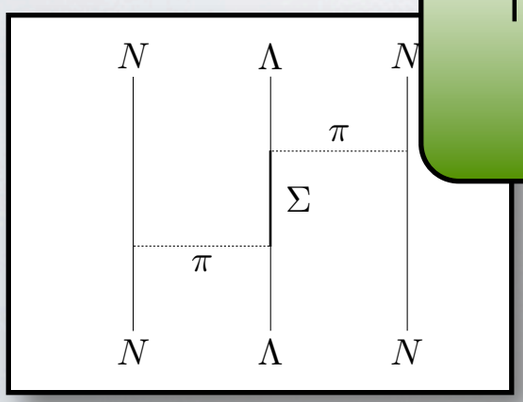


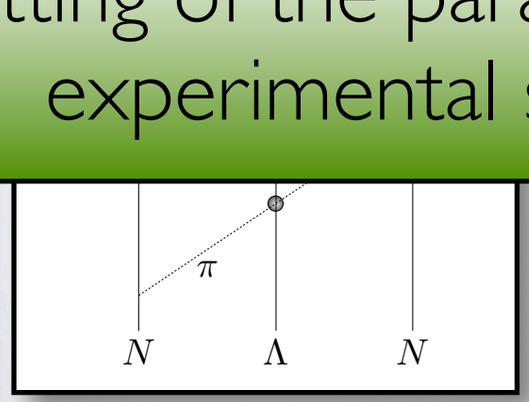


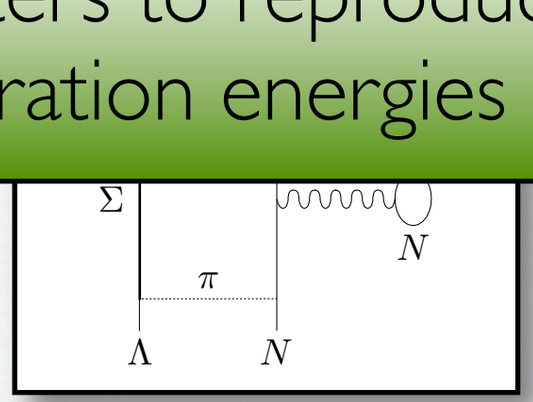


parameters not yet fixed

fitting of the parameters to reproduce experimental separation energies

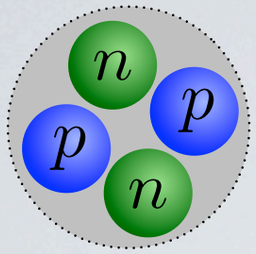






forbidden

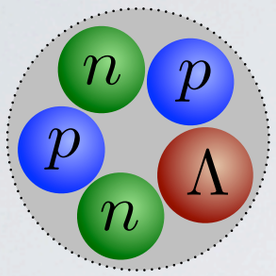
The idea of the project



nucleus $\longrightarrow$ $BE_{nuc} = \dfrac{\langle \psi_{nuc} | \mathcal{H}_{nuc} | \psi_{nuc} \rangle}{\langle \psi_{nuc} | \psi_{nuc} \rangle}$

$\mathcal{H}_{NN}$

ab-initio method : AFDMC



Λ-hypernucleus $\longrightarrow$ $BE_{hyp} = \dfrac{\langle \psi_{hyp} | \mathcal{H}_{hyp} | \psi_{hyp} \rangle}{\langle \psi_{hyp} | \psi_{hyp} \rangle}$

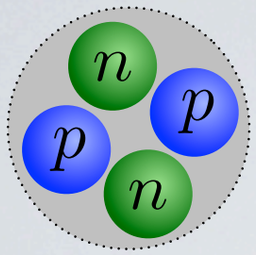
$\mathcal{H}_{NN} + \mathcal{H}_{\Lambda N(N)}$

$B_\Lambda = BE_{nuc} - BE_{hyp}$

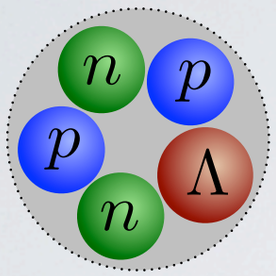
Hyp. : nuclear effects cancel at most

information about the hyperon-nucleon interaction

The idea of the project

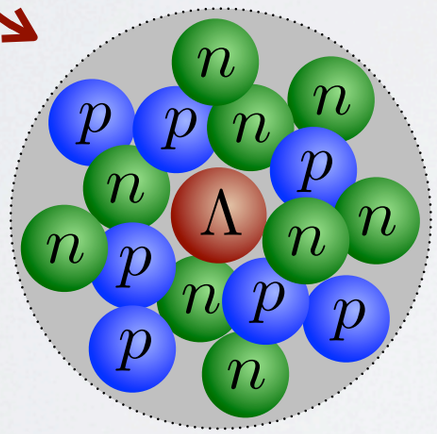


nucleus

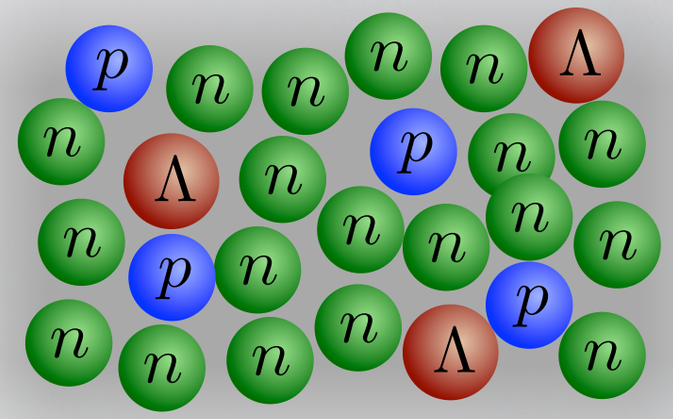


Λ-hypernucleus

comparison with experimental data in a wide mass range



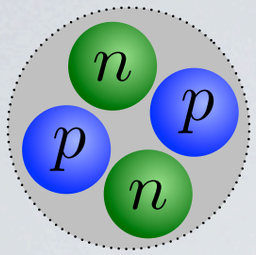
heavy Λ-hypernuclei



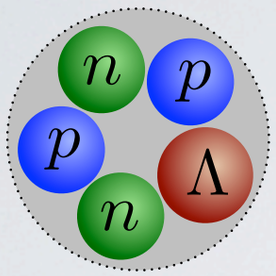
Λ-nuclear matter

extrapolation

The idea of the project



nucleus



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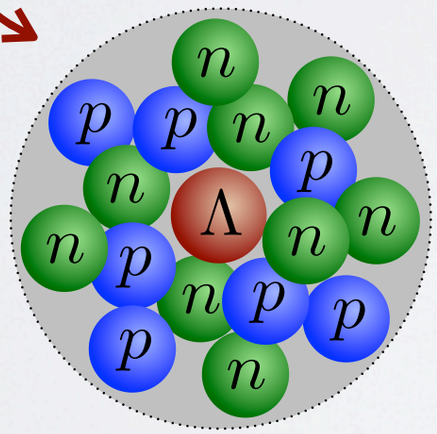

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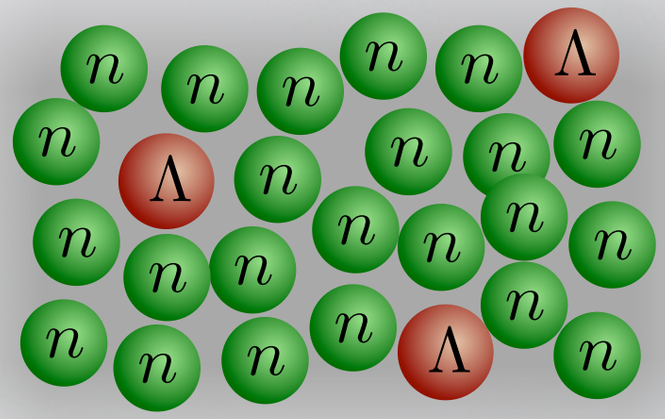
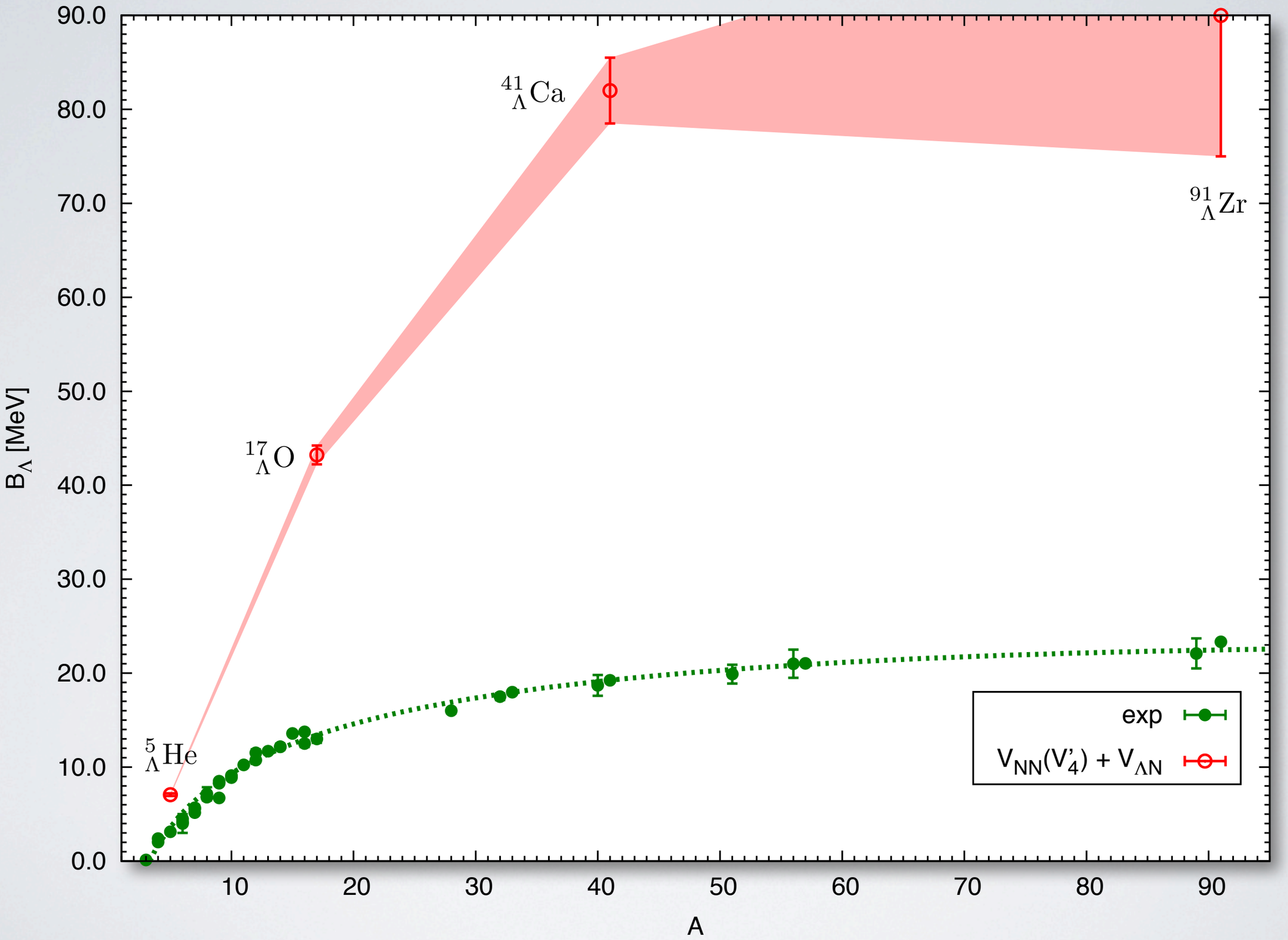
extrapolation



Λ-~~nuclear~~ matter

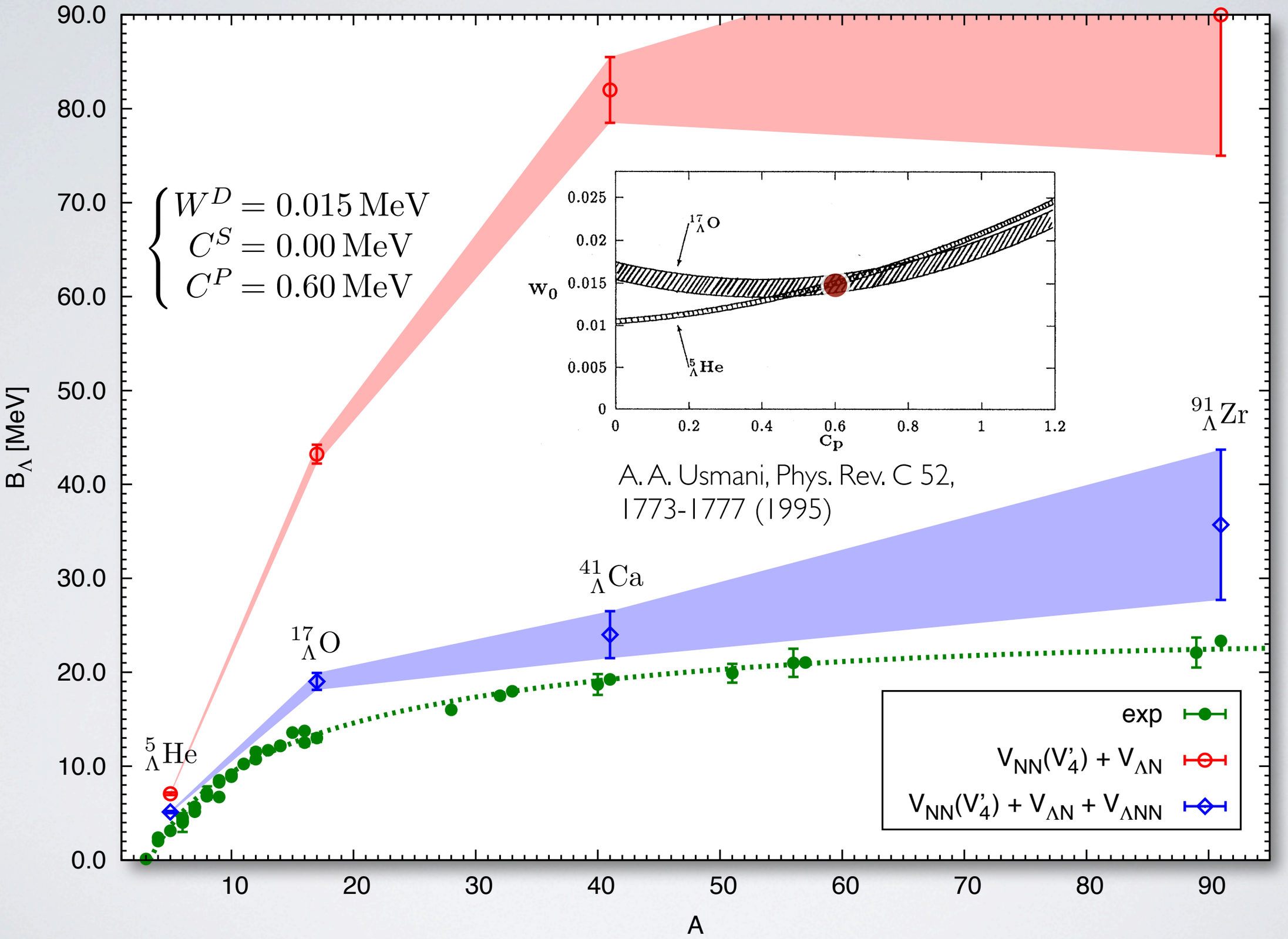
Λ-neutron matter

Results: Λ-hypernuclei



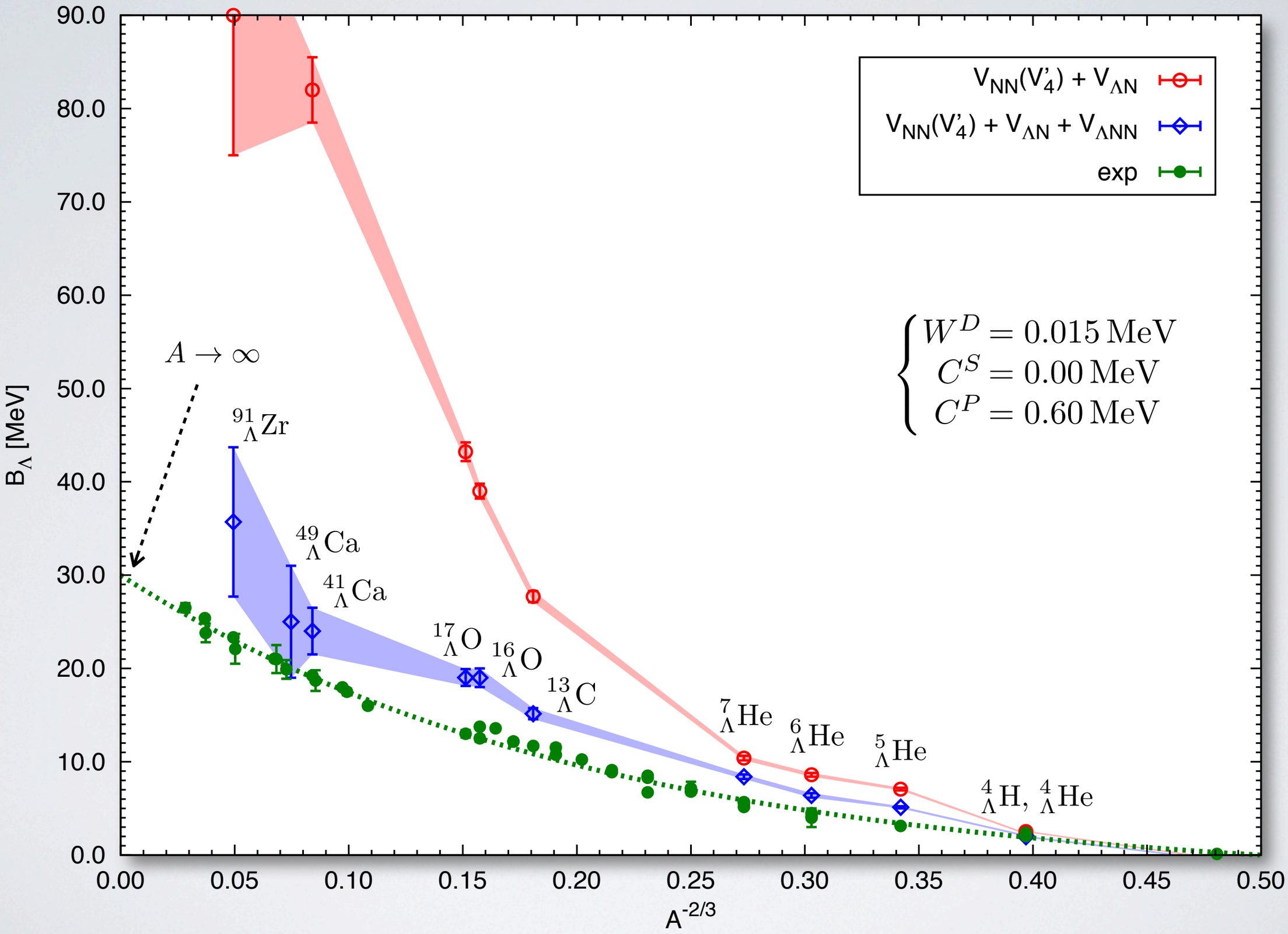
D. Lonardoni, S. Gandolfi, F. Pederiva, Phys. Rev. C 87, 041303(R) (2013)

Results: Λ-hypernuclei

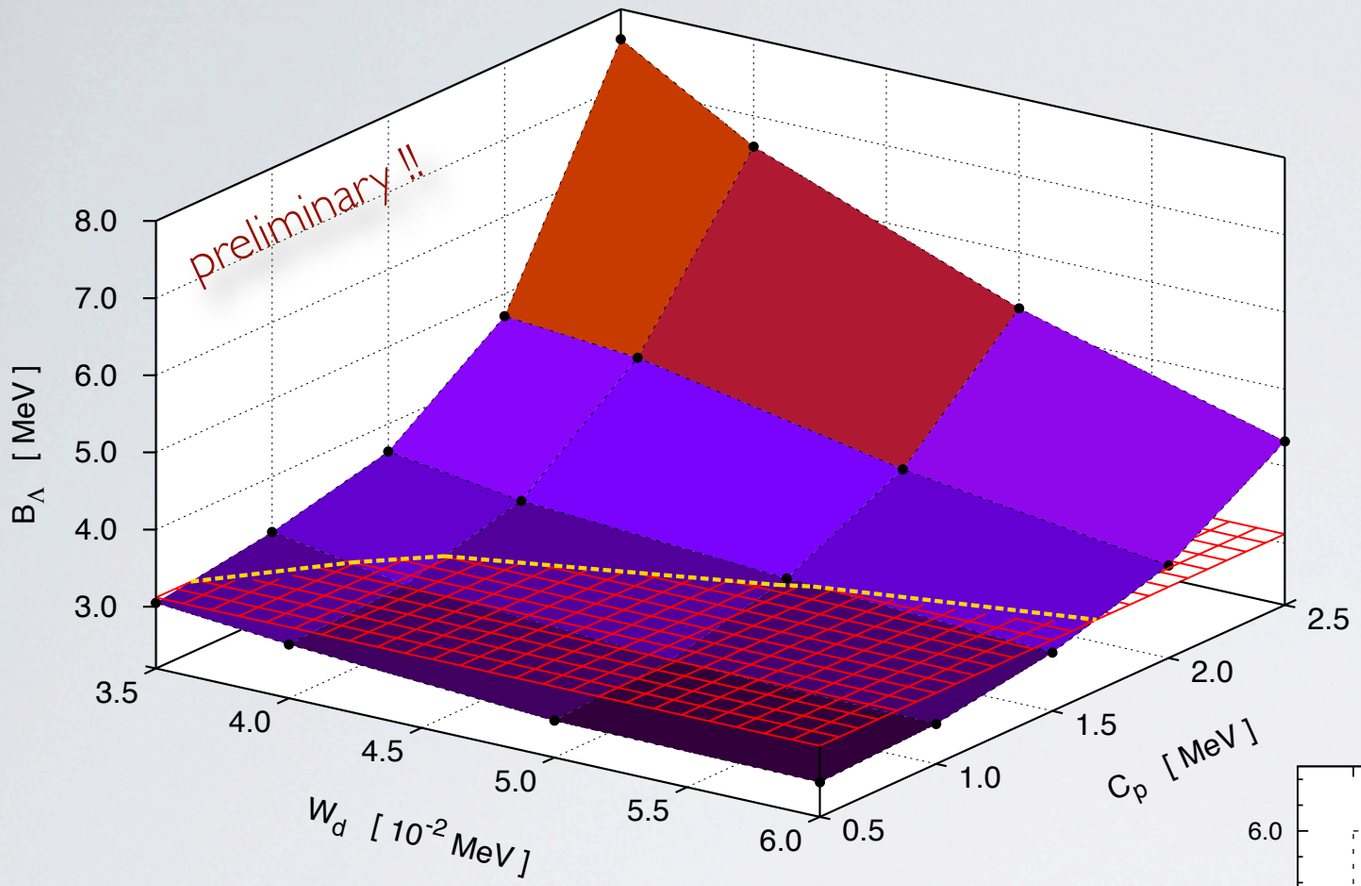


D. Lonardoni, S. Gandolfi, F. Pederiva, Phys. Rev. C 87, 041303(R) (2013)

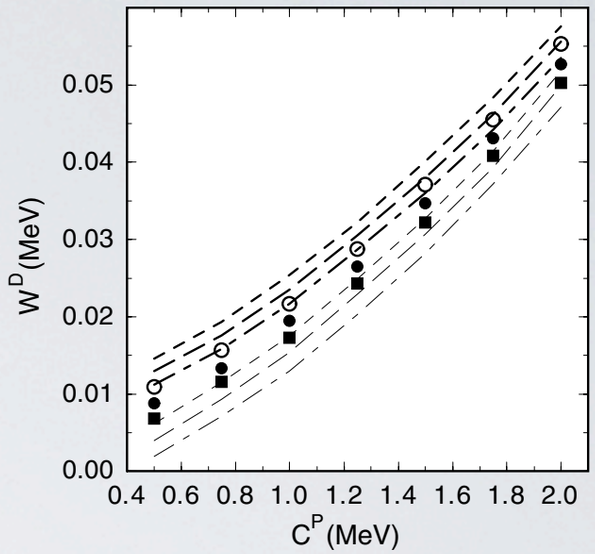
Results: Λ-hypernuclei



Results: Λ-hypernuclei



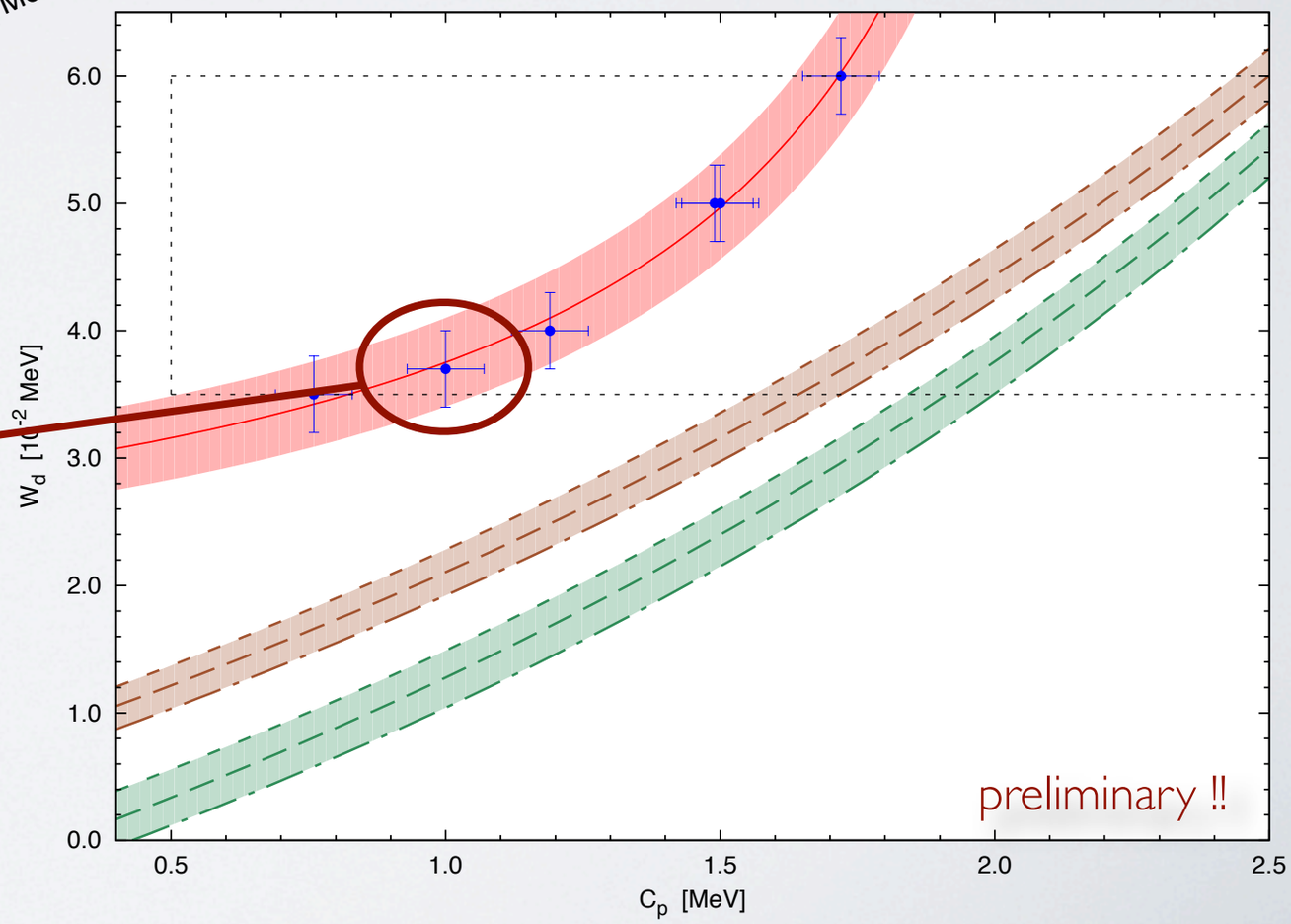
$^{5}_{\Lambda}\mathrm{He}$



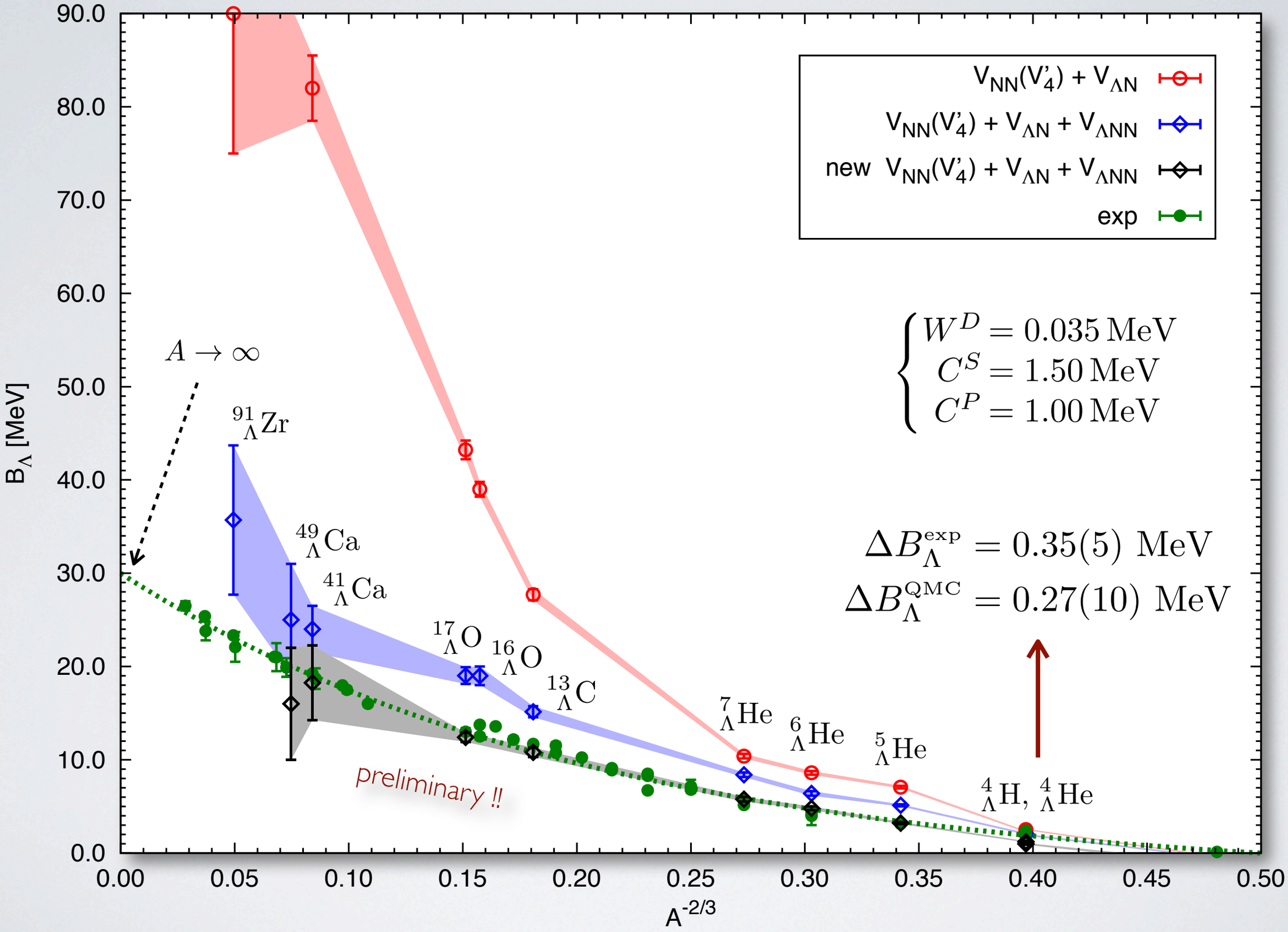
A. A. Usmani, F. C. Khanna,
J. Phys. G: Nucl. Part. Phys. 35, 025105 (2008)

$$\begin{cases} W^D = 0.035\,\mathrm{MeV} \\ C^S = 1.50\,\mathrm{MeV} \\ C^P = 1.00\,\mathrm{MeV} \end{cases}$$

good for $^{5}_{\Lambda}\mathrm{He}$ and $^{17}_{\Lambda}\mathrm{O}$



Results: Λ-hypernuclei



Results: Λ-neutron matter

neutron matter

$E(n_b)$

β eq.

nuclear matter

$E(n_b, x_p)$

$$x_p = \frac{n_p}{n_n + n_p}$$

Λ-neutron matter

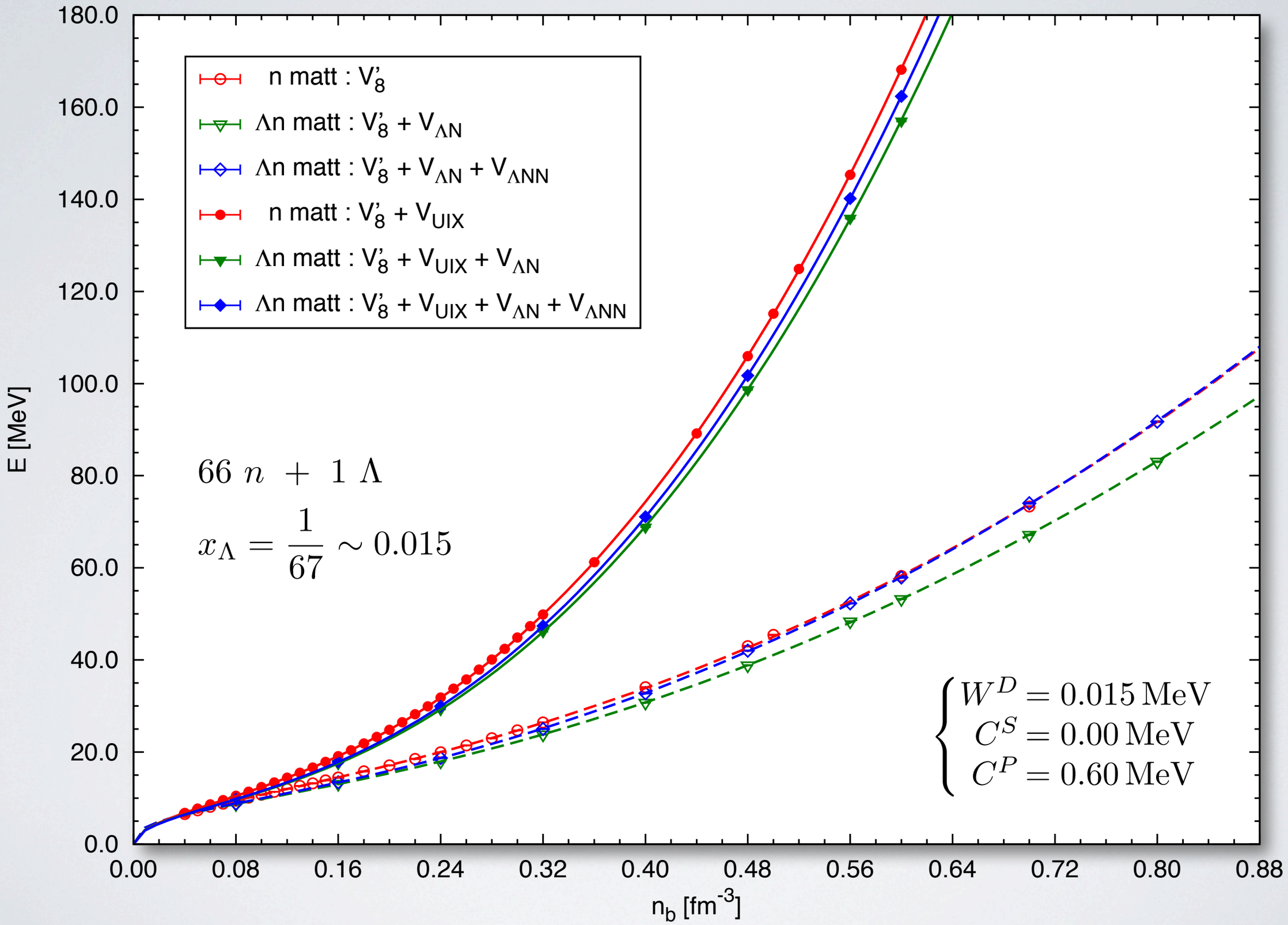
$E(n_b, x_\Lambda)$

$$x_\Lambda = \frac{n_\Lambda}{n_n + n_\Lambda}$$

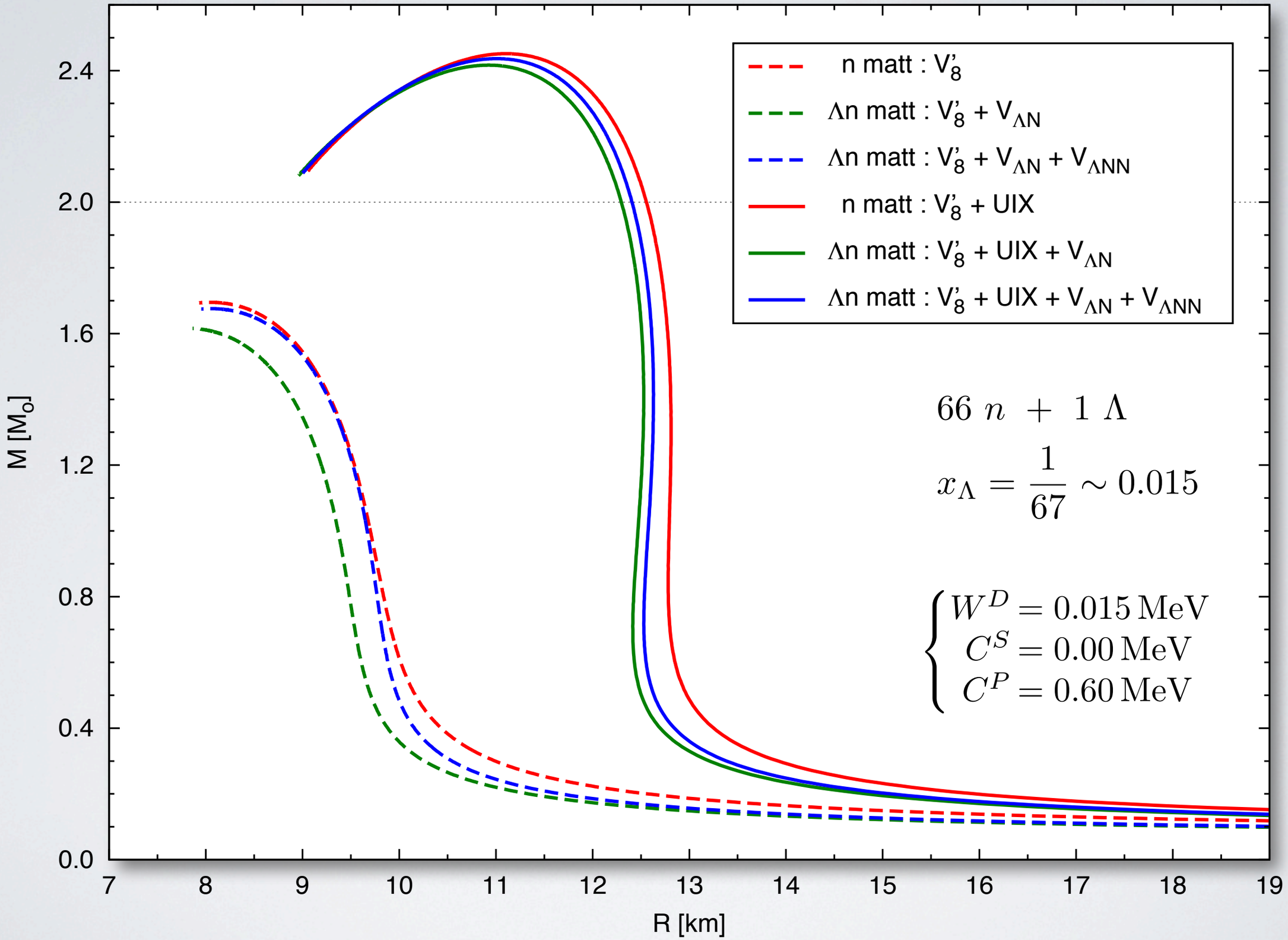
$$E(n_b, x_\Lambda) \begin{cases} E_n(n_b) \\ E_{n+\Lambda}(n_b) \\ x_\Lambda \ll 1 \end{cases} \longleftrightarrow \begin{cases} \varepsilon(n_b, x_\Lambda) \\ \mu_n(n_b, x_\Lambda) \\ \mu_\Lambda(n_b, x_\Lambda) \end{cases}$$

solve the TOV ⟶ M(R) & Mmax

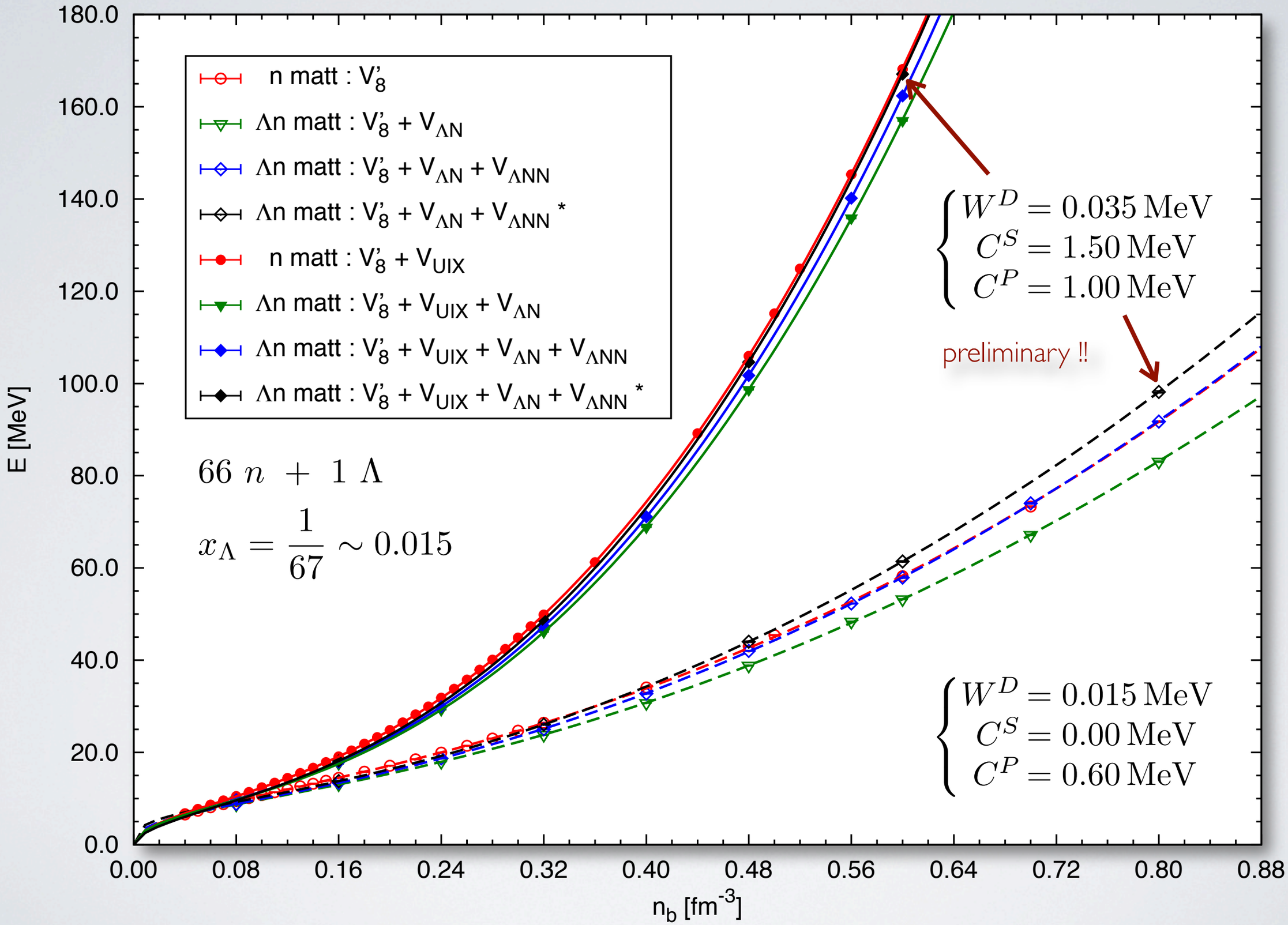
Results: Λ-neutron matter



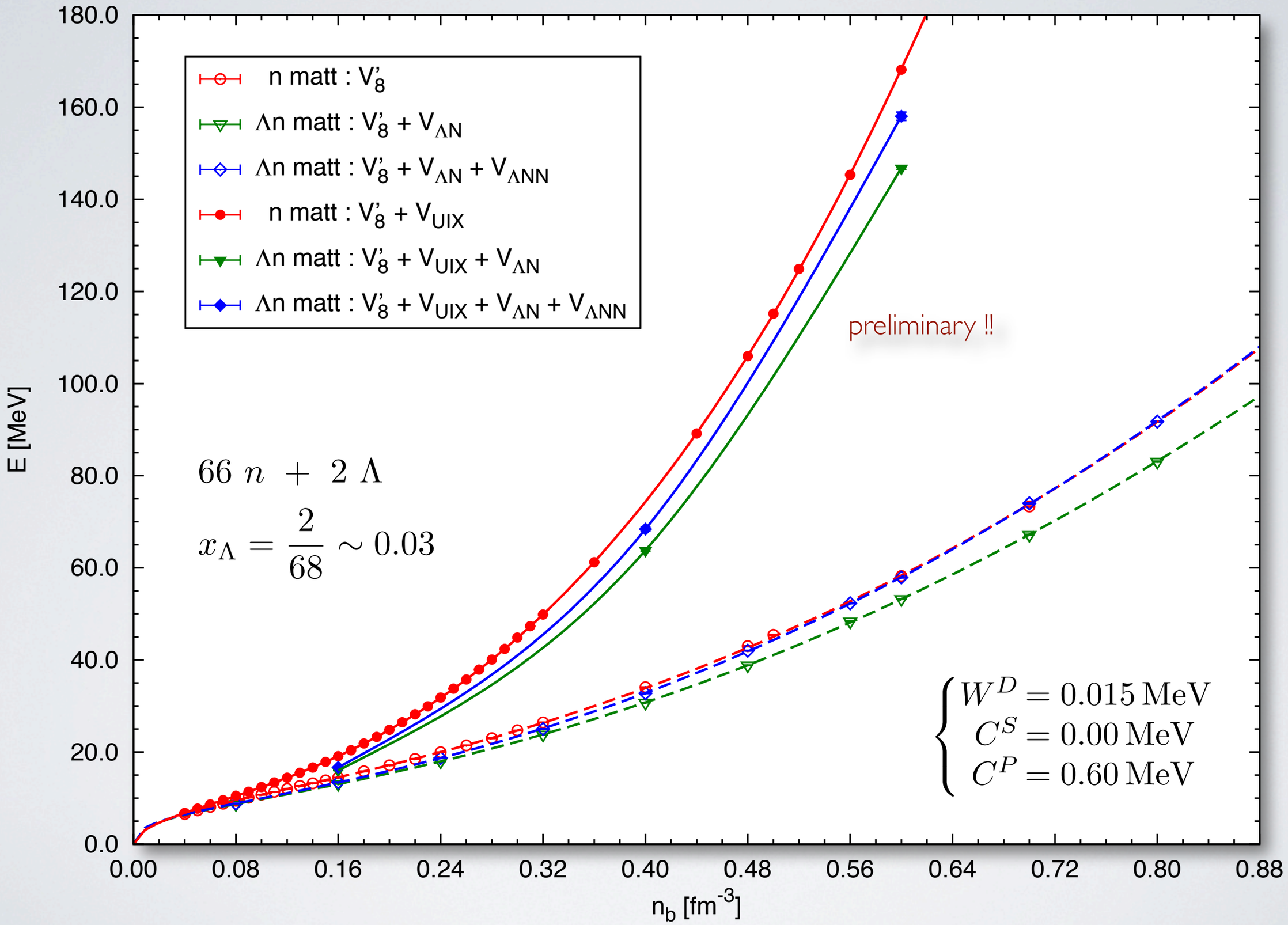
Results: Λ-neutron matter



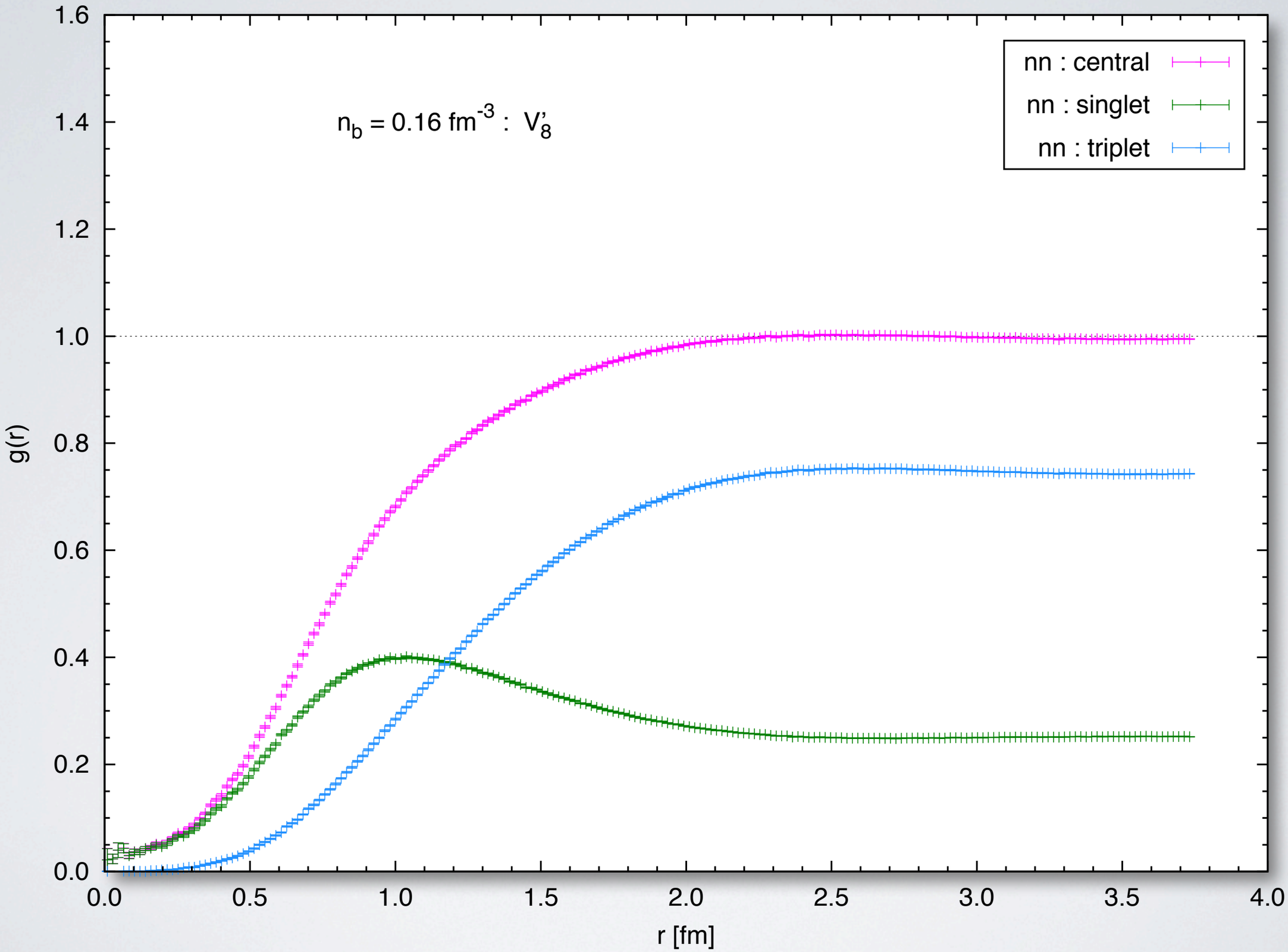
Results: Λ-neutron matter



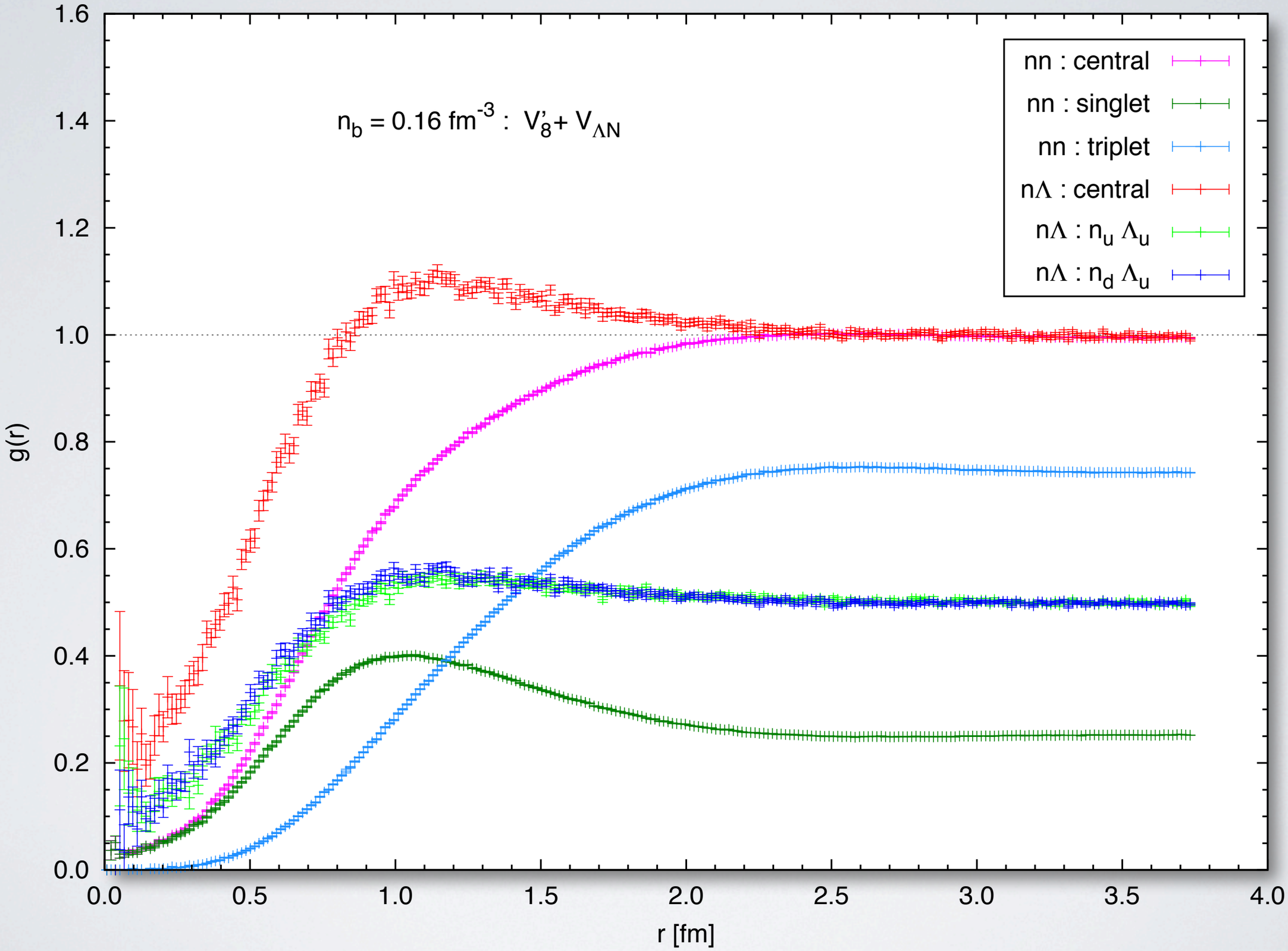
Results: Λ-neutron matter



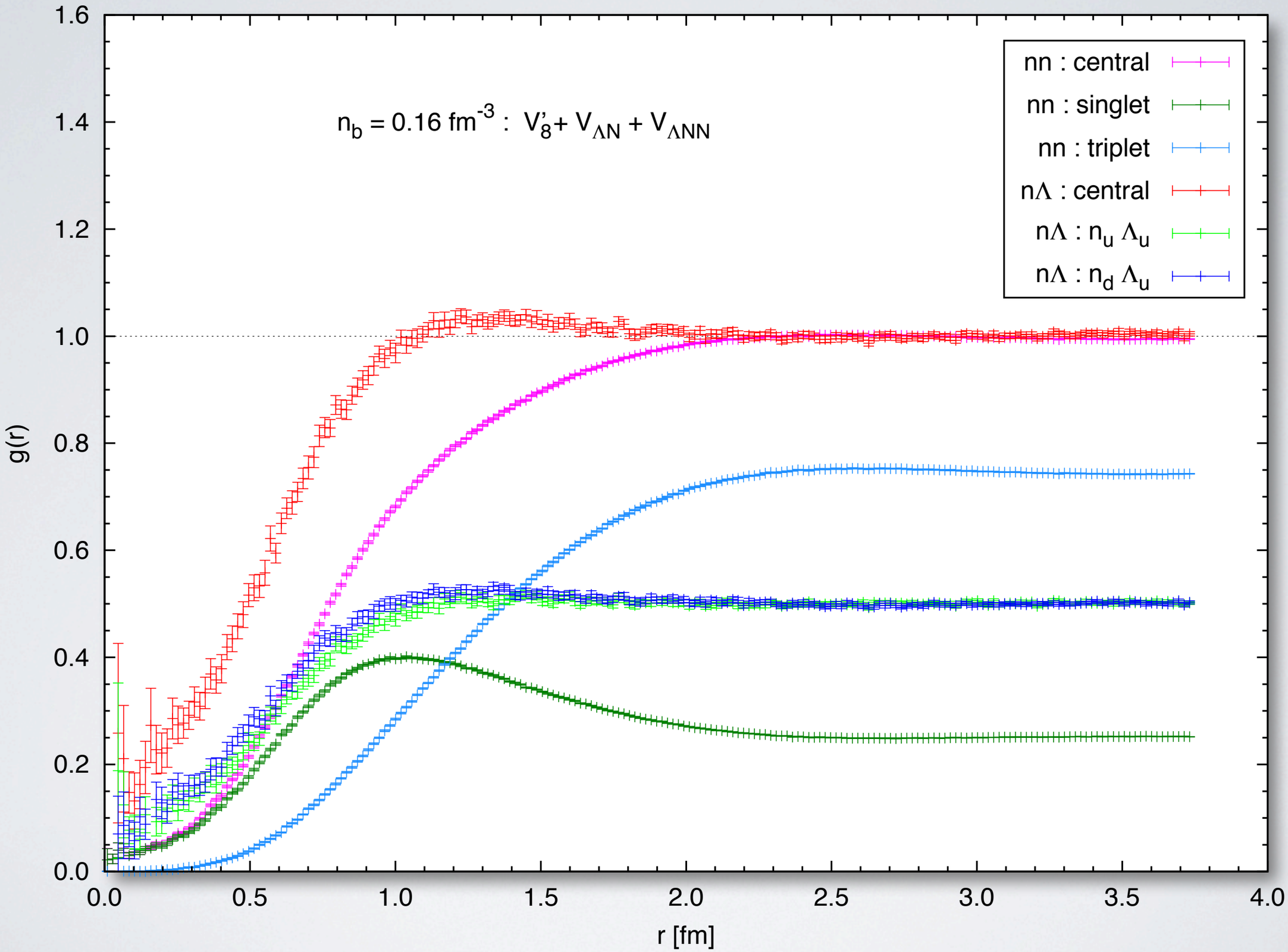
Results: Λ-neutron matter



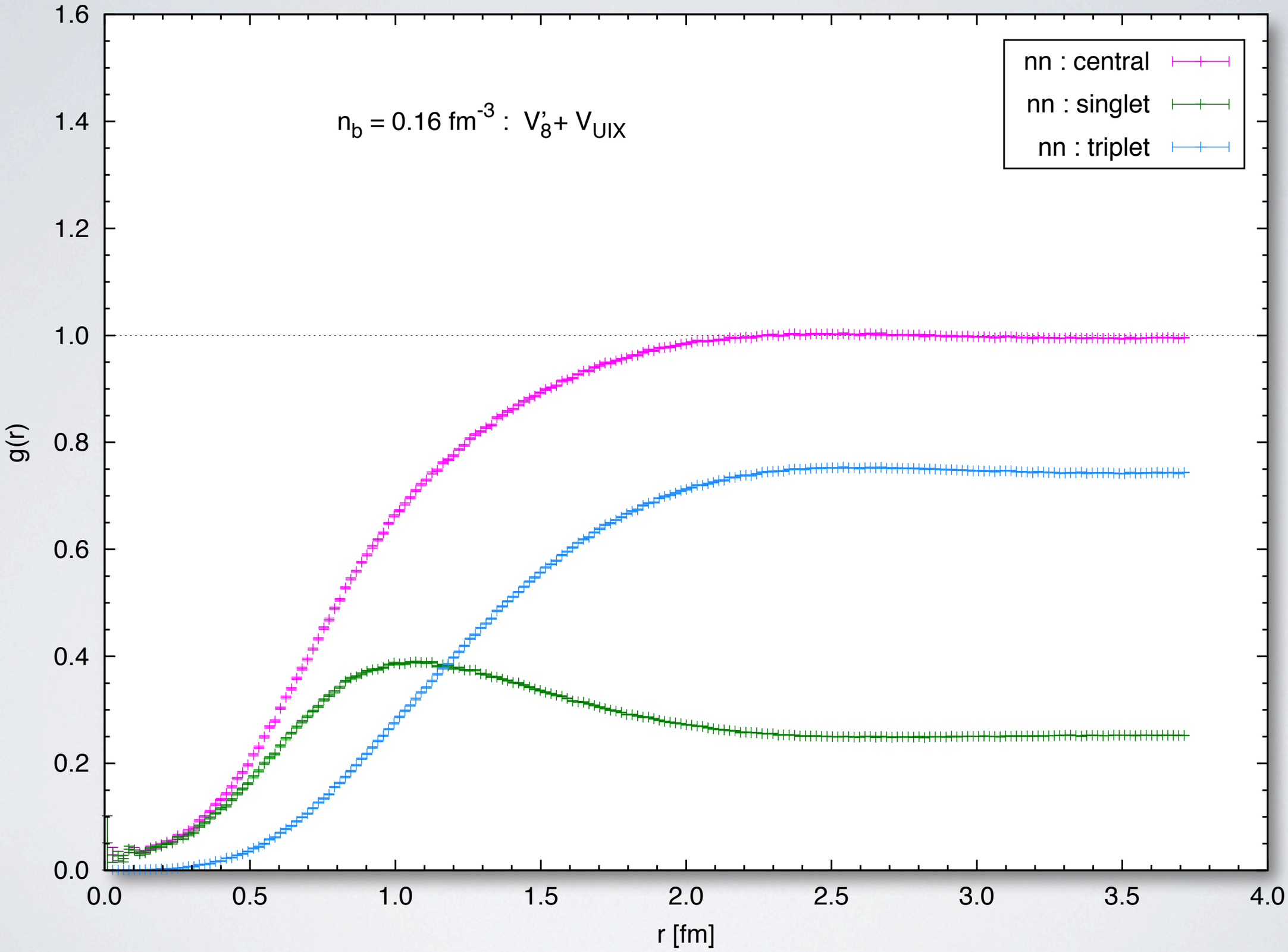
Results: Λ-neutron matter



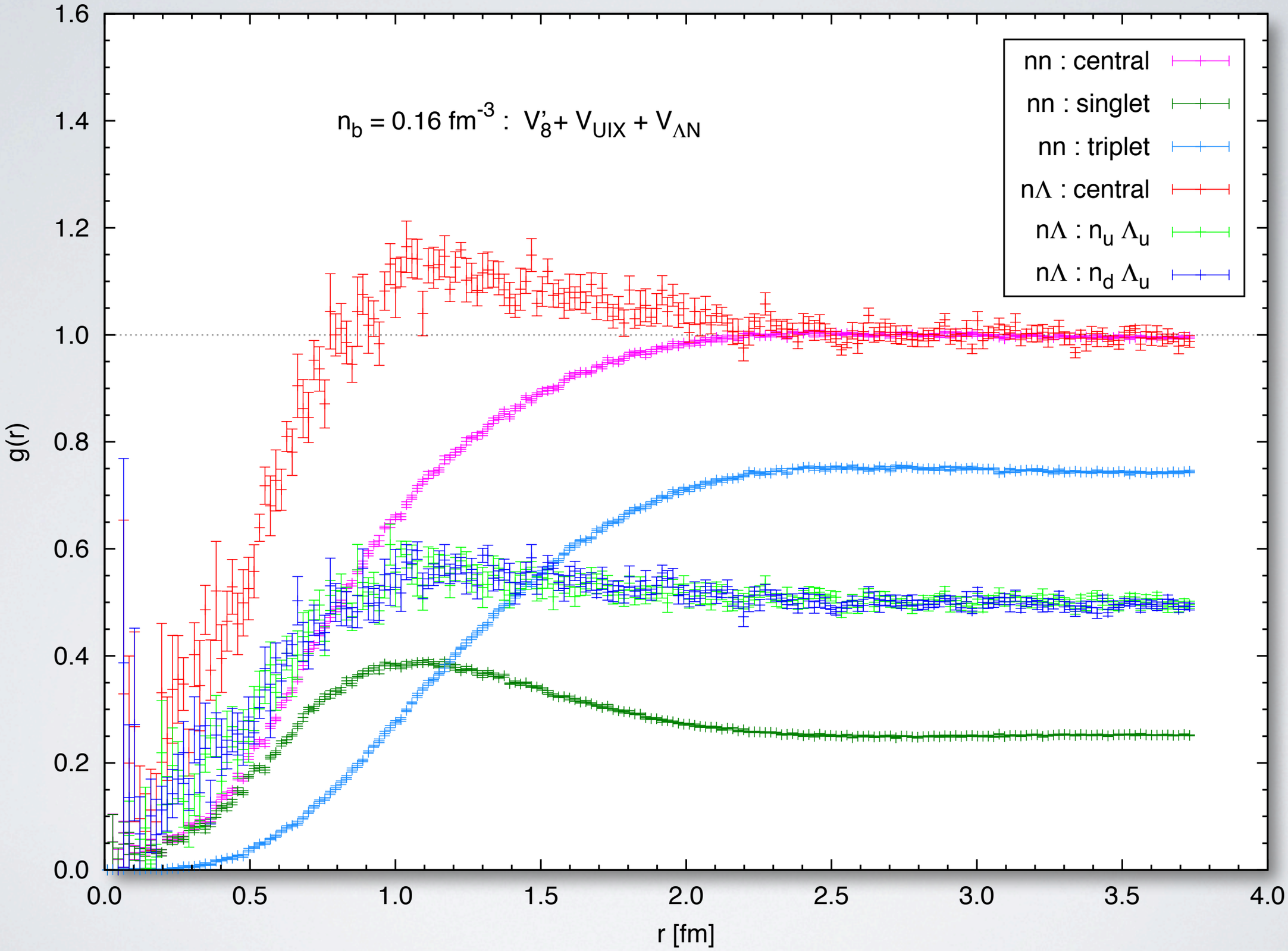
Results: Λ-neutron matter



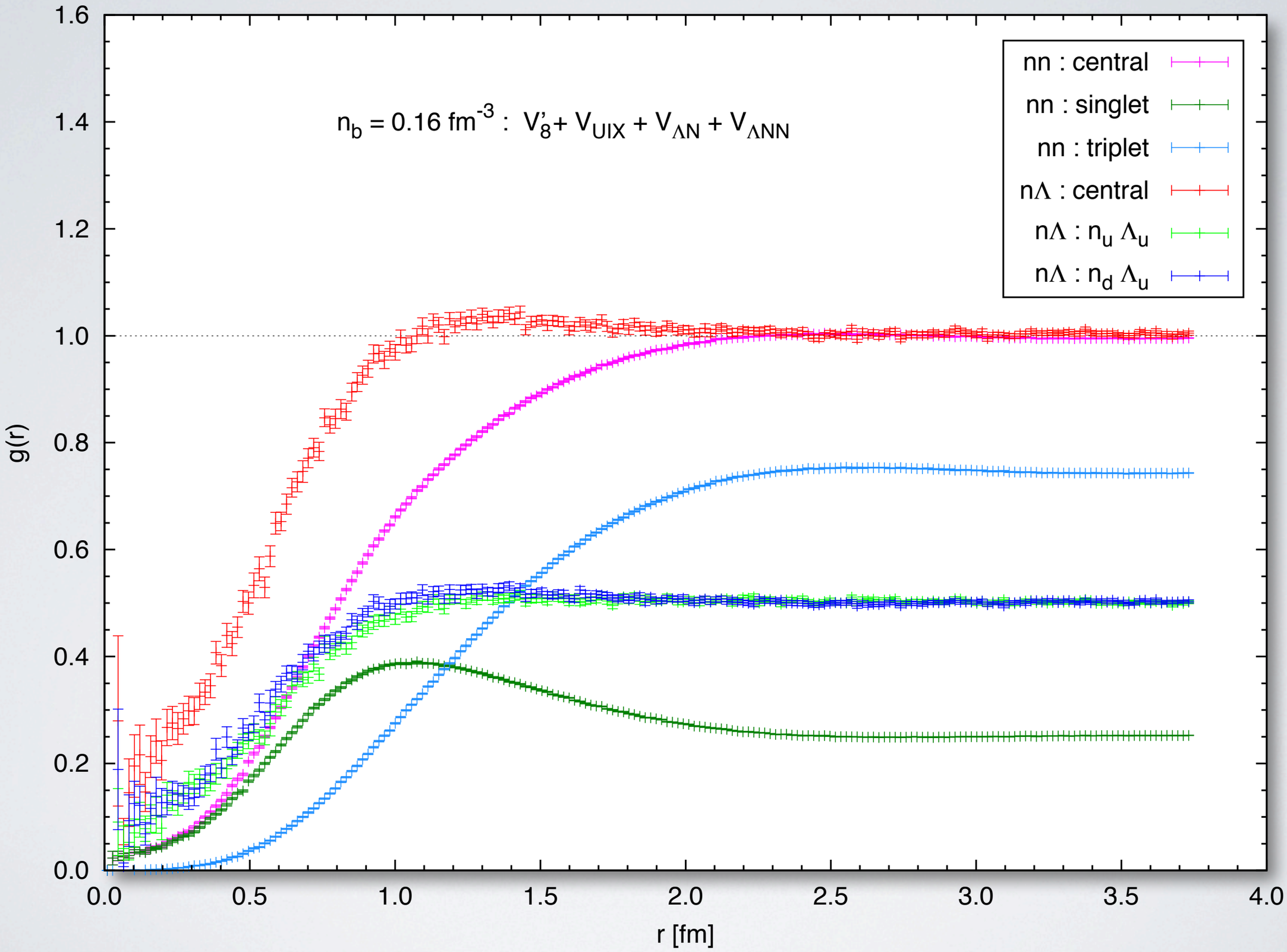
Results: Λ-neutron matter



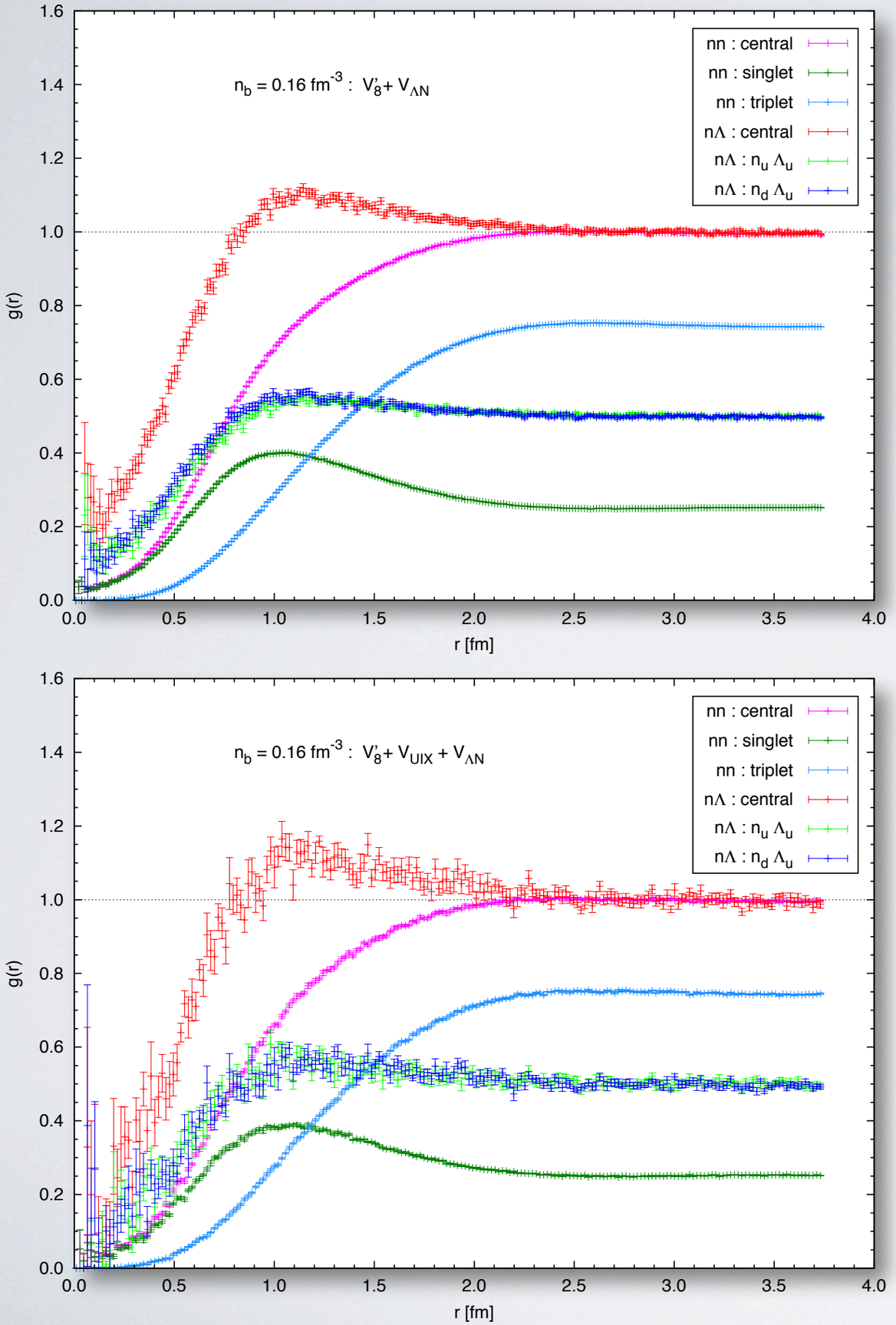
Results: Λ-neutron matter

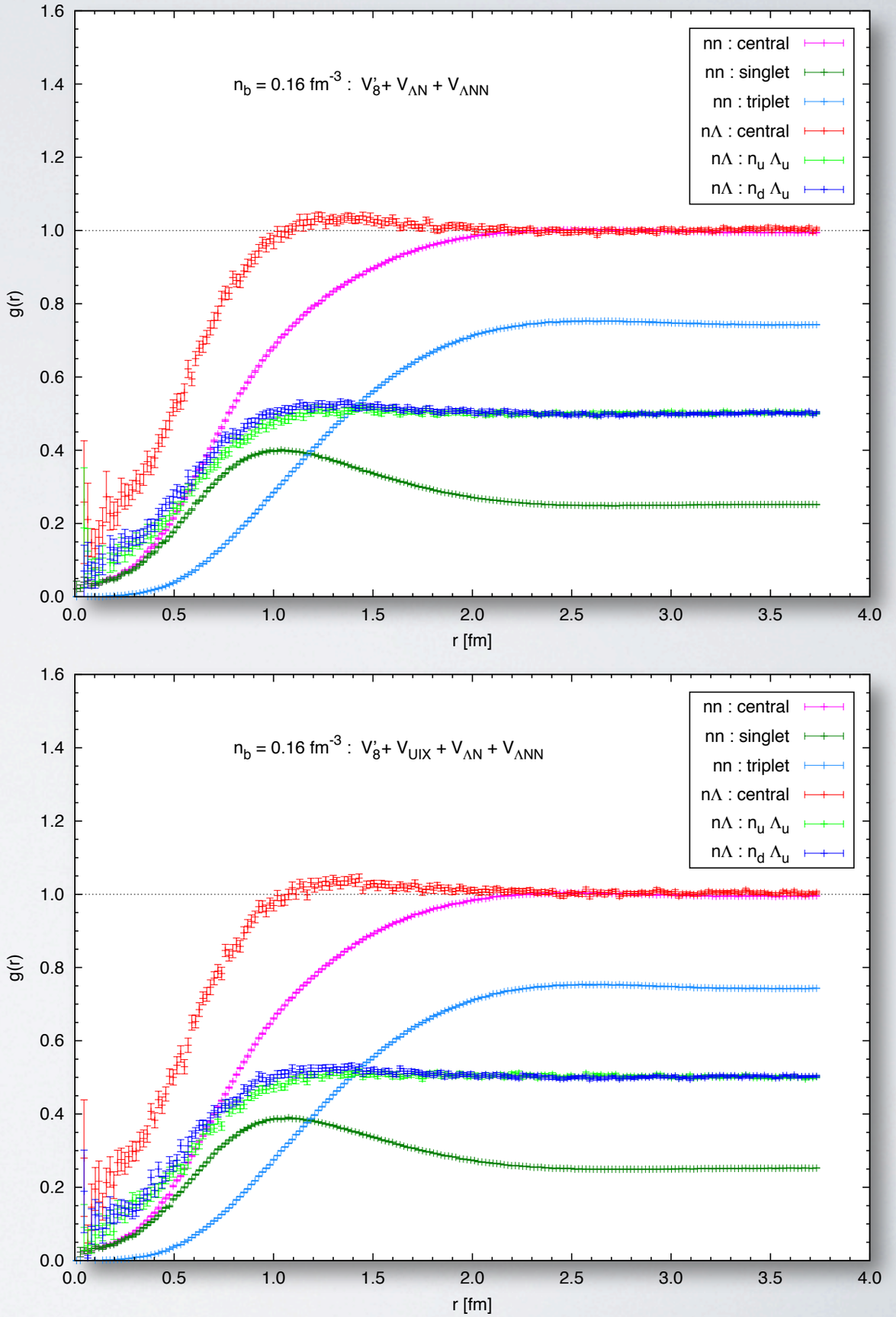


Results: Λ-neutron matter

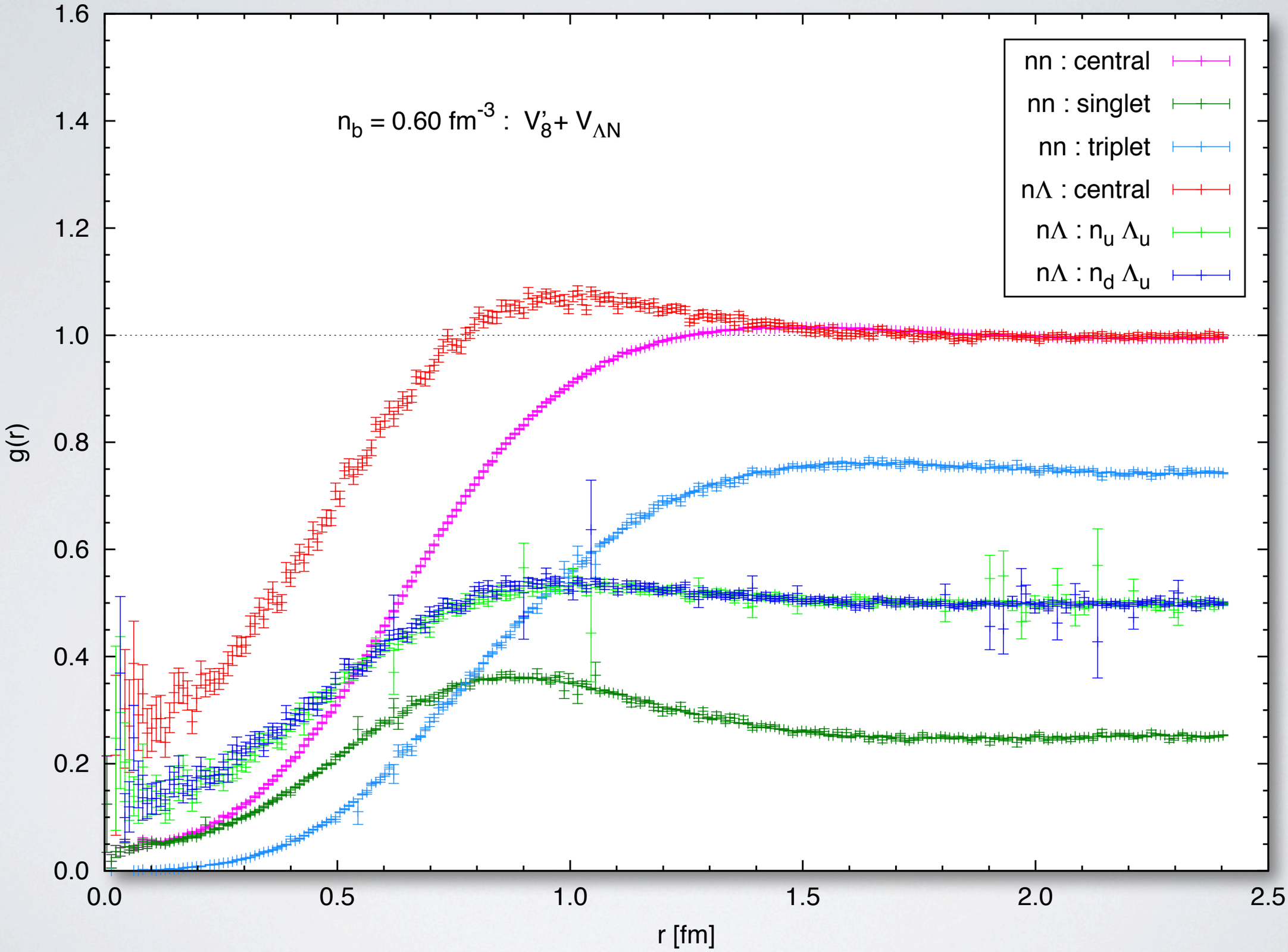


Results: Λ-neutron matter

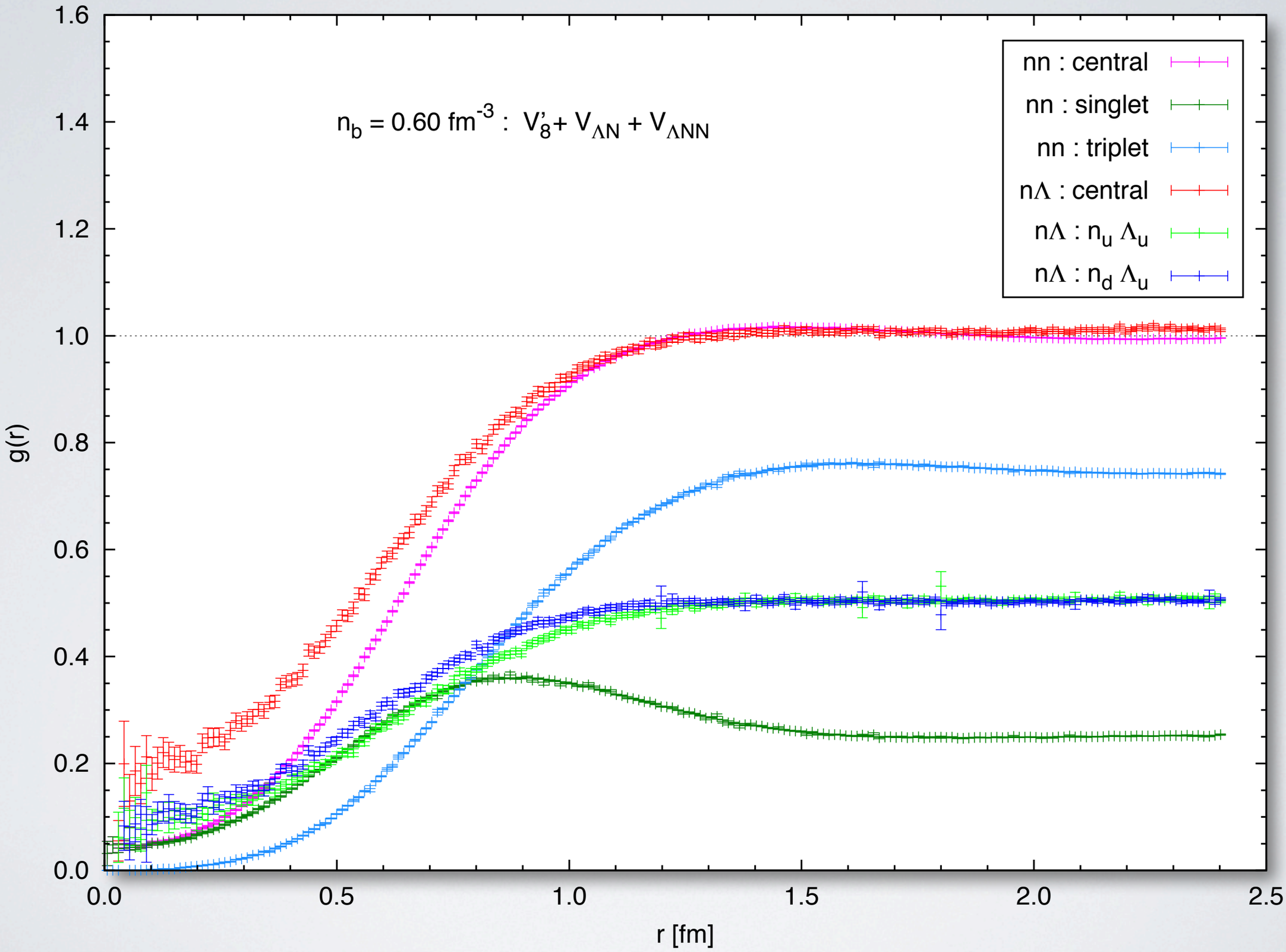




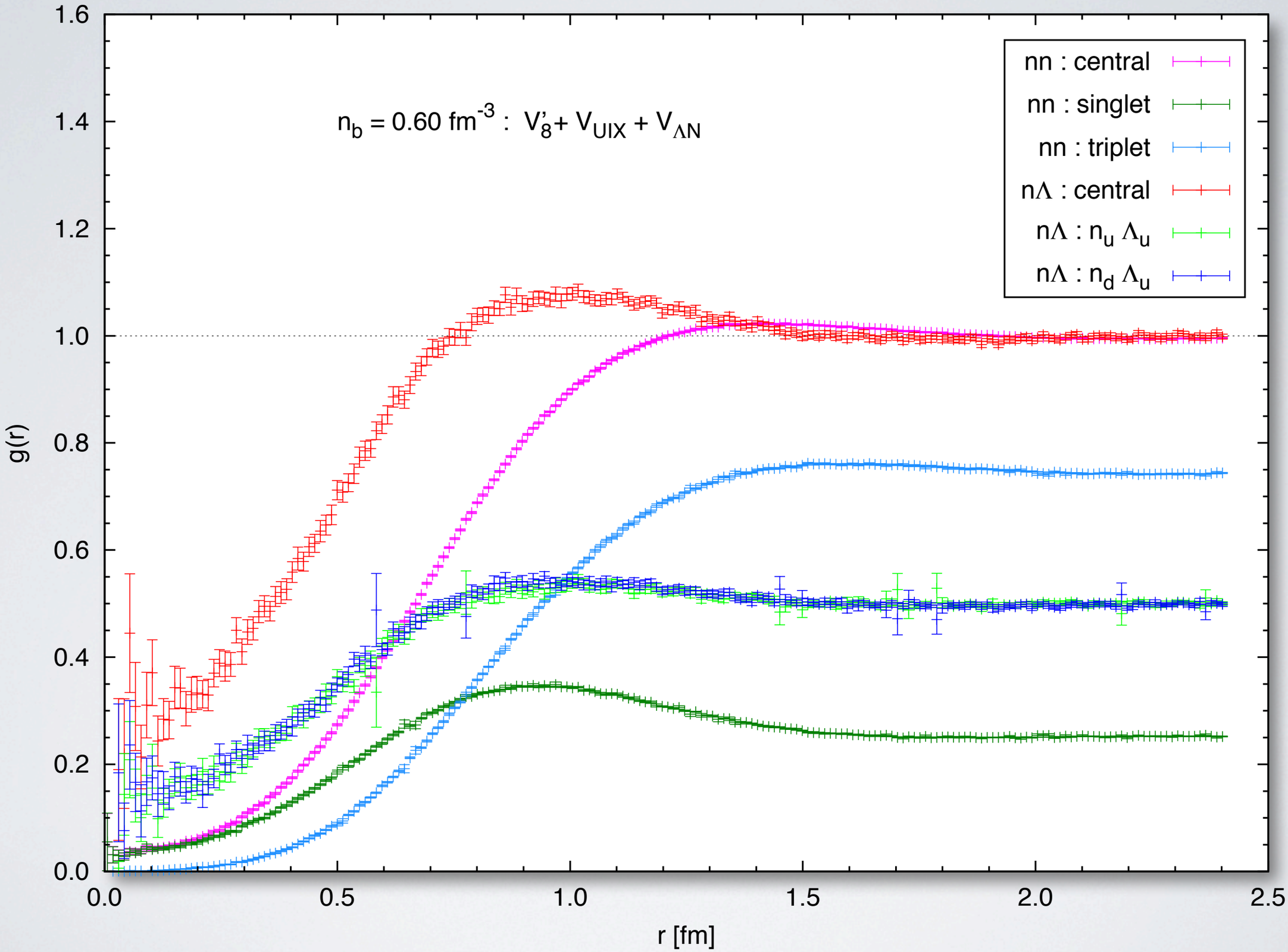
Results: Λ-neutron matter



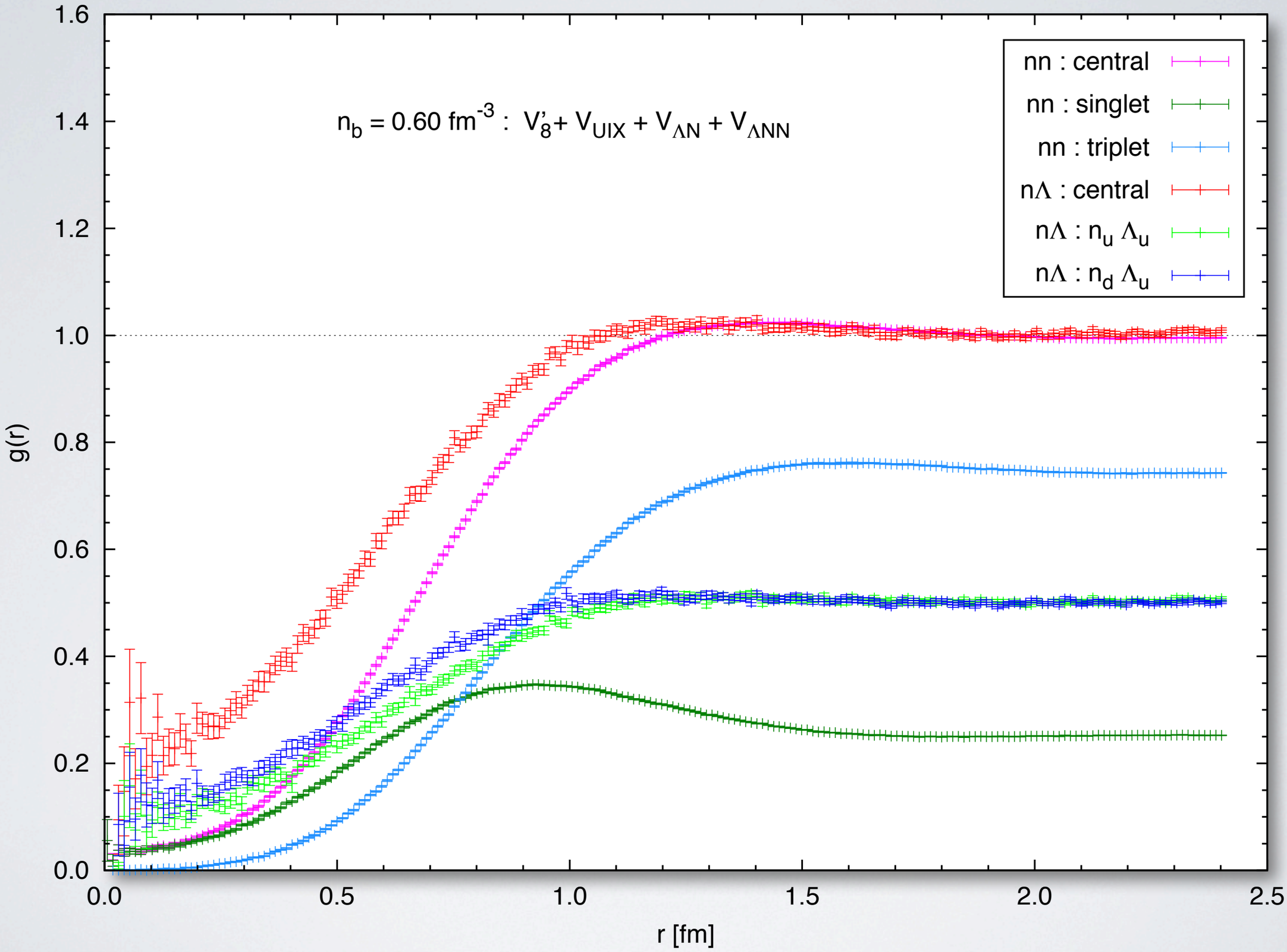
Results: Λ-neutron matter



Results: Λ-neutron matter



Results: Λ-neutron matter



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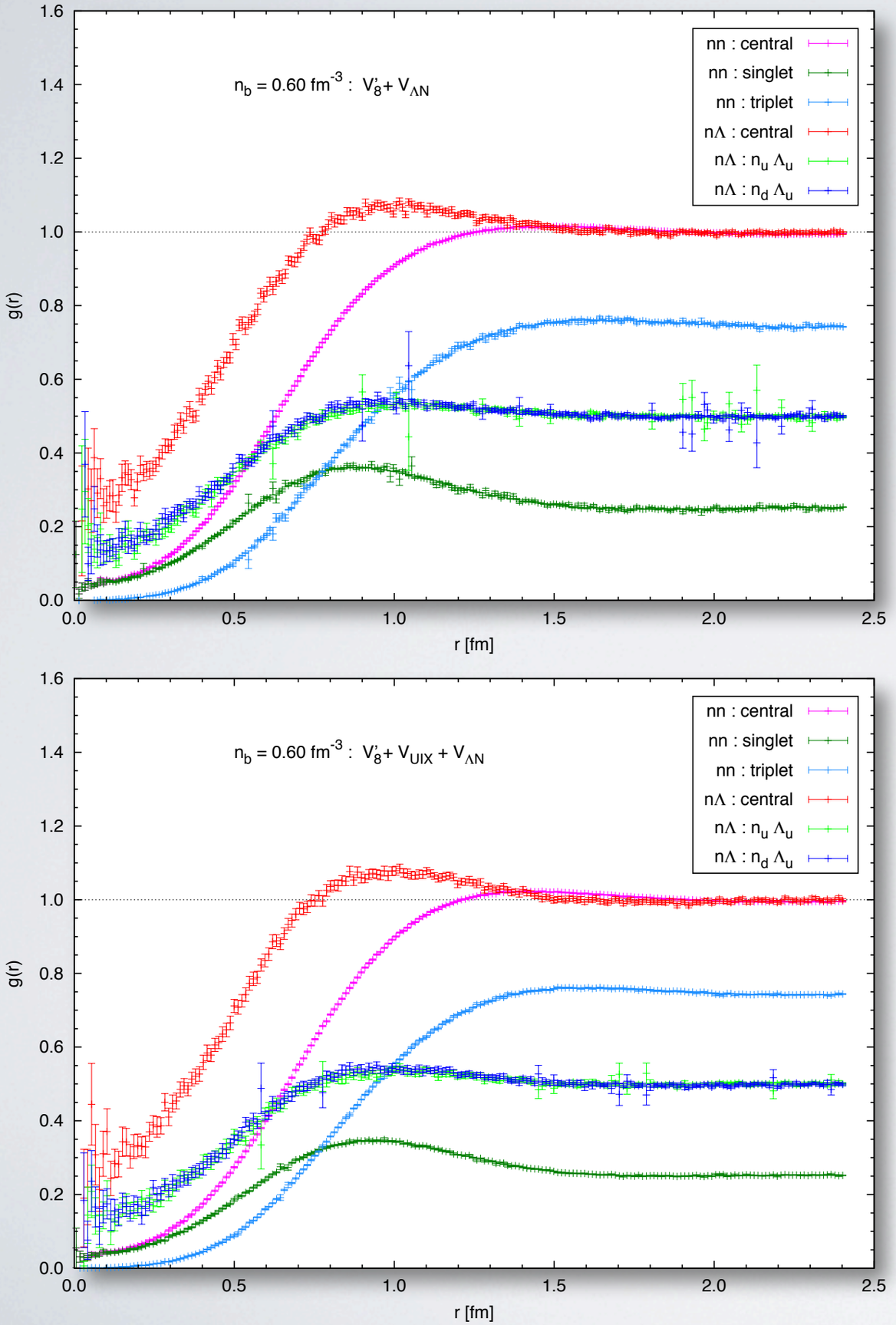

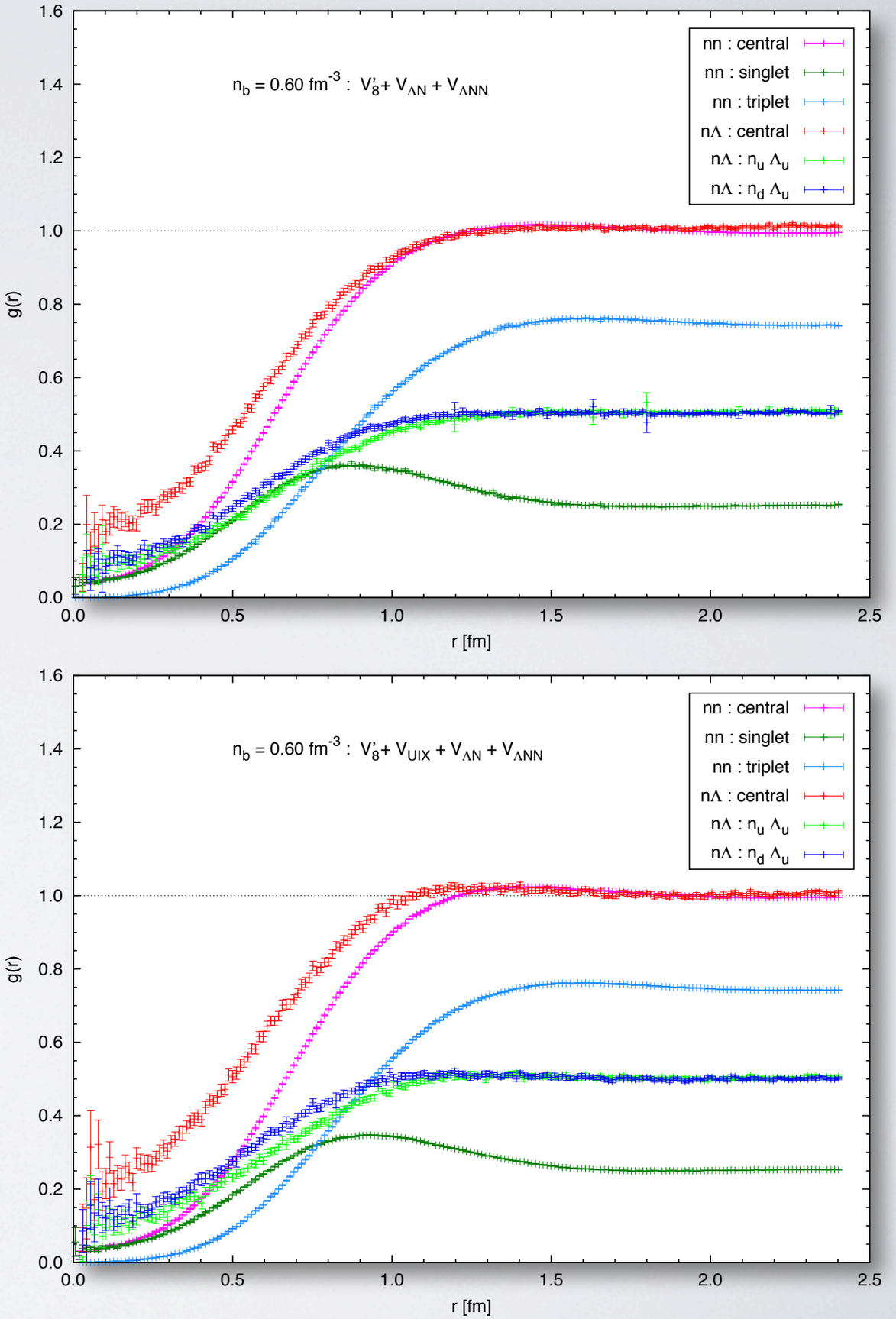

Conclusions

- AFDMC extension for finite and infinite hypernuclear systems (Λ)

study of the hyperon-nucleon interaction

- 3-body ΛNN repulsive interaction fundamental for the computation of the hyperon separation energy

fine tuning of the parameters

- equation of state for the Λ-neutron matter at a given Λ fraction

$E(n_b, x_\Lambda)$

M(R) & Mmax

work in progress

Thank you for
your attention !!