Three-Baryon Interactions in HyperMatter

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Agenda

- **Views on Three-Body Interactions**
- **GI-(D)BHF Theory: SU(3) Approach to In-medium Interactions**
- **Nuclear Matter, Hypermatter, and Hypernuclei**
- **Λ and Σ 3-body Self-Energies from the Nuclear Isovector Mean-Field**
- **Summary**

H. Lenske, M. Dhar, *Lect.Notes Phys. 948 (2018) 161*

H. Lenske, M. Dhar, Th. Gaitanos, Xu Cao, *Prog.Part.Nucl.Phys.* 98 (2018) 119

Briefs on „Three-Nucleon“ Interactions

3-Nucleon Interactions

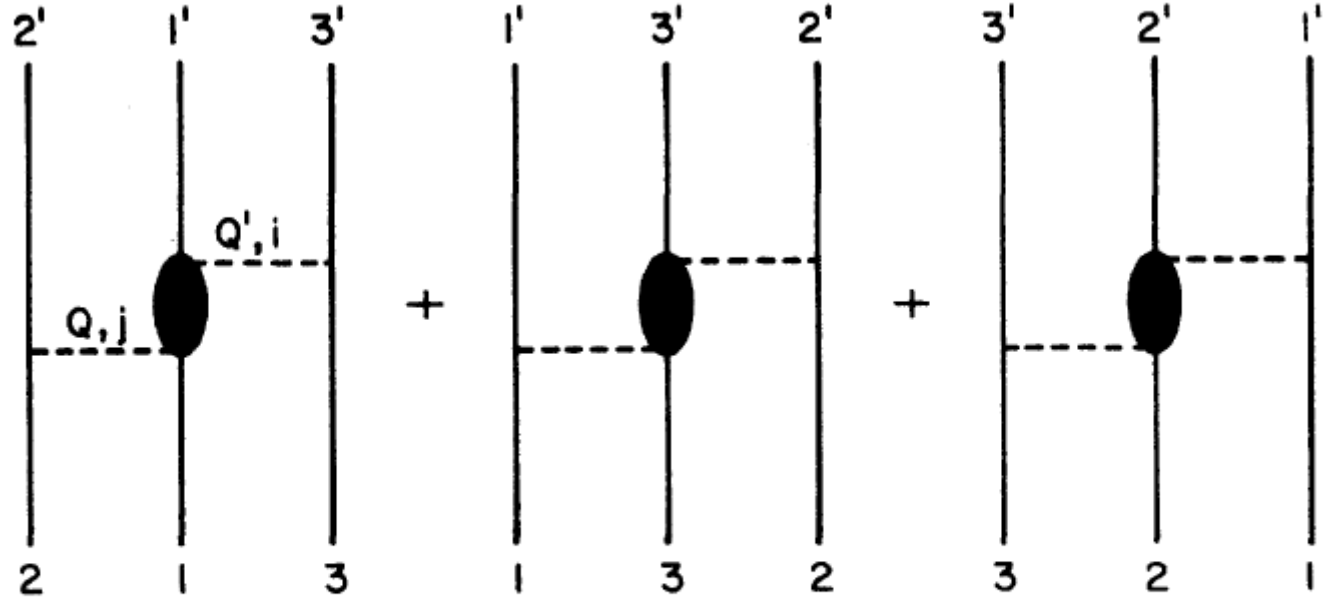
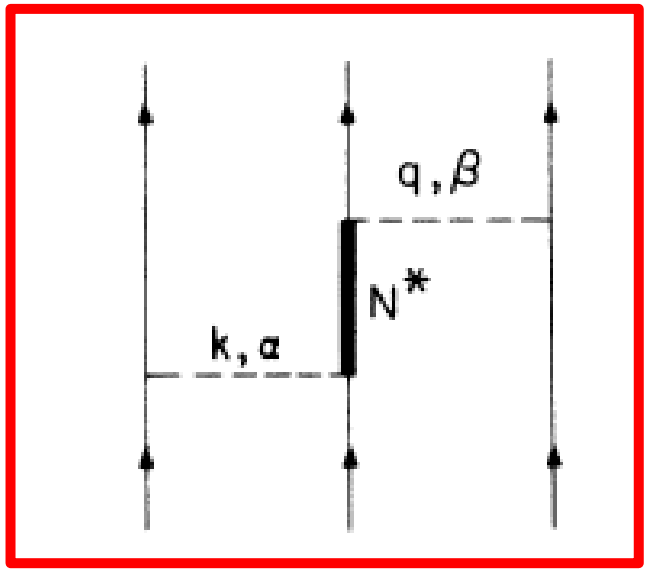


FIG. 1. The Feynman diagrams for the two-pion exchange three-nucleon potential. The shaded oval represents anything except a forward propagating nucleon state.

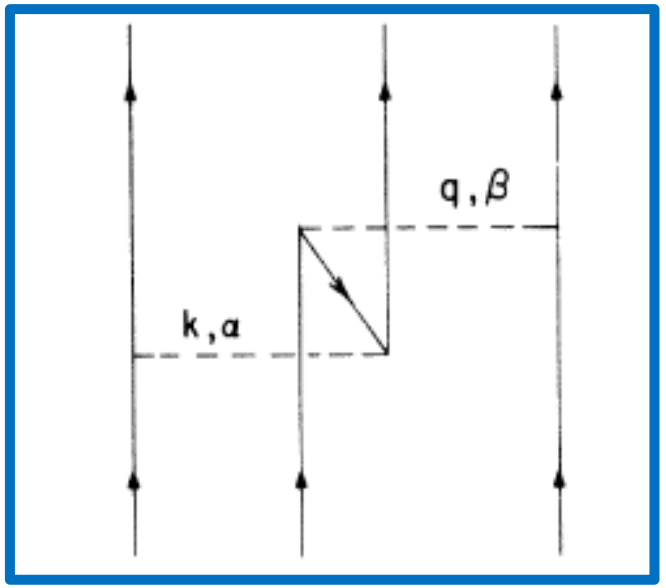
From: Coon and Glöckle, PRC 23 (1981) 1790

Origin of 2-(pion)-Meson Exchange 3-Nucleon Interactions
…or the meaning of „anything“



One nucleon scattered into a resonance state

+



Three-body force arising from a virtual nucleon-antinucleon pair.

N* = Δ_{33}(1232) → attractive Fujita-Miyazawa TNI

J. Fujita and H. Miyazawa, Prog. Theor. Phys. **17**, 360 (1957).

Non-relativistically suppressed
but strong in covariant approaches

Conclusion by the mid-1990ies
from the Fujita-Miyazawa (FM) and the Tucson-Melbourne TNI

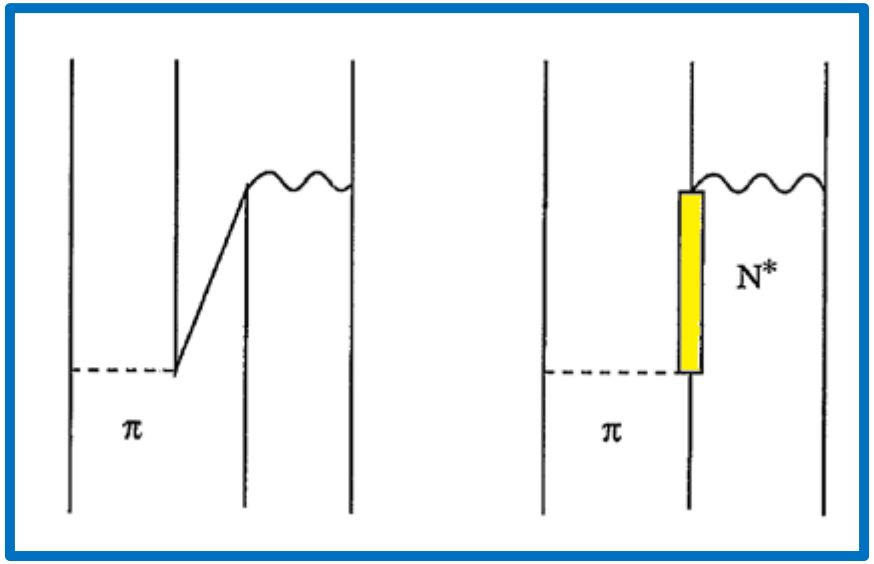
- **Overbinding of ^{3}H and ^{3}He by a few hundred keV**
- **Overbinding of the α-particle by 2-4 MeV**
- **Missing spin-independent 3-nucleon repulsion**
- **→ Urbana model: FM-attraction and phenomenological 3-body repulsion**

  (Pandharipande, Wiringa…)

Repulsive short-range three-nucleon interaction

S. A. Coon, M. T. Peña, and D. O. Riska

(PRC 52 (1995) 2925)

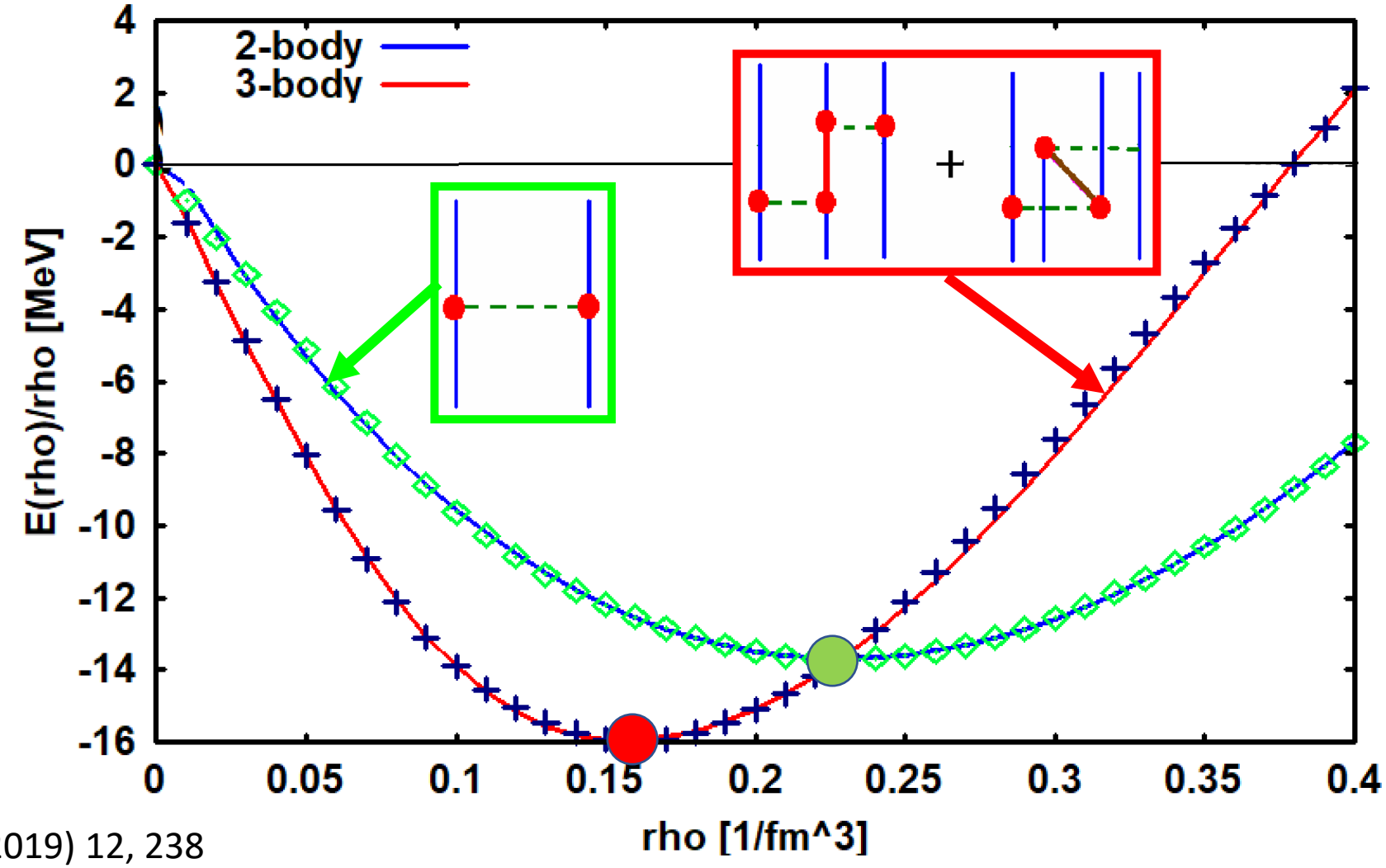


= scalar (σ,a_0) and vector mesons (ω,ρ)

= pions

= $\Delta_{33}(1232)$ and $N_{11}(1440)$ „Roper“

Two- and Three-Body Interactions and the EoS of SNM
GI-EDF G-Matrix plus „Urbana“-type TNI



- *Eur.Phys.J.A* 55 (2019) 12, 238
- *Eur.Phys.J.A* 57 (2021) 3, 89

Open Questions on the Nature of 3-body Interactions

- **Urbana approach: NN-sector is coupled to sub-nucleonic degrees of freedom**

  → virtual N* configurations

- **Phenomenological EDF approach: parametrize TNI by effective conctact interactions**

  → introduce terms $\sim \rho^{\alpha}$

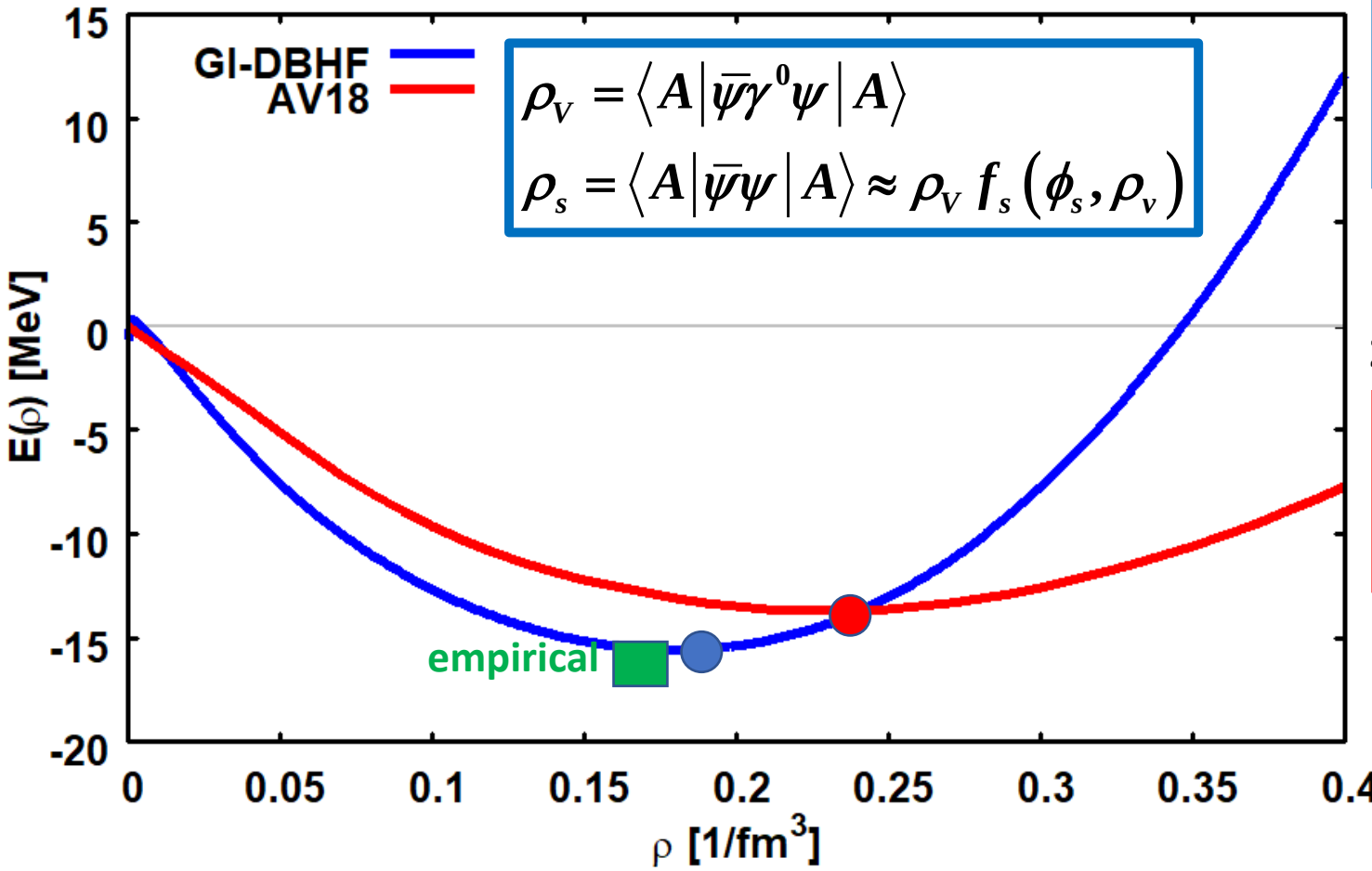
- **EFT approach: derive TNI in a systematic order-by-order expansion**

  → appearing in N^2LO

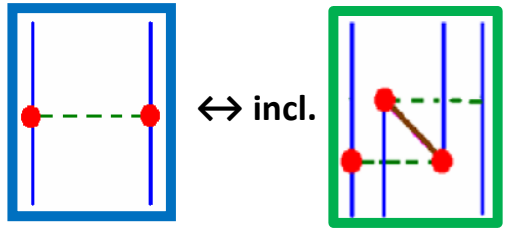
- **Covariant DHBF/EDF approach: 2-body methods essentially describe EoS and B(A)**

  → polarization by coupling to negative energy states

2-Body Covariant vs. 2-Body Non-Relativistic Nucleonic EoS

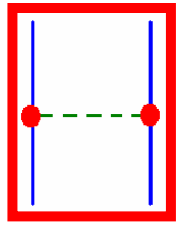


2-body covariant



??

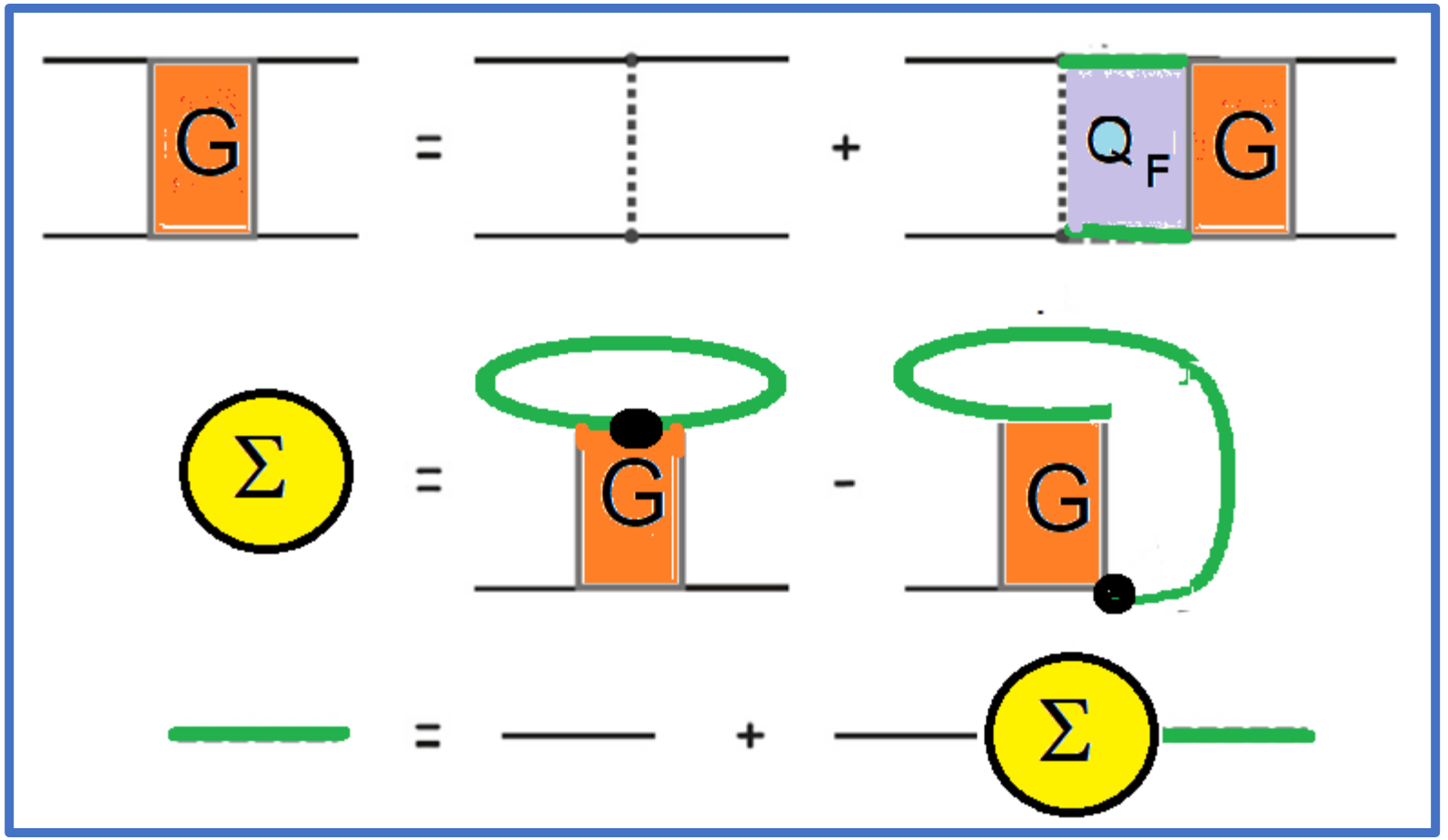
2-body non-relat.



„Covariant repulsion“ → suppresion of scalar attraction with density

Covariant GI-DBHF Description of In-Medium Interactions

Dirac-Brueckner Hartree-Fock Theory
Self-Consistent Approach to In-Medium Interactions



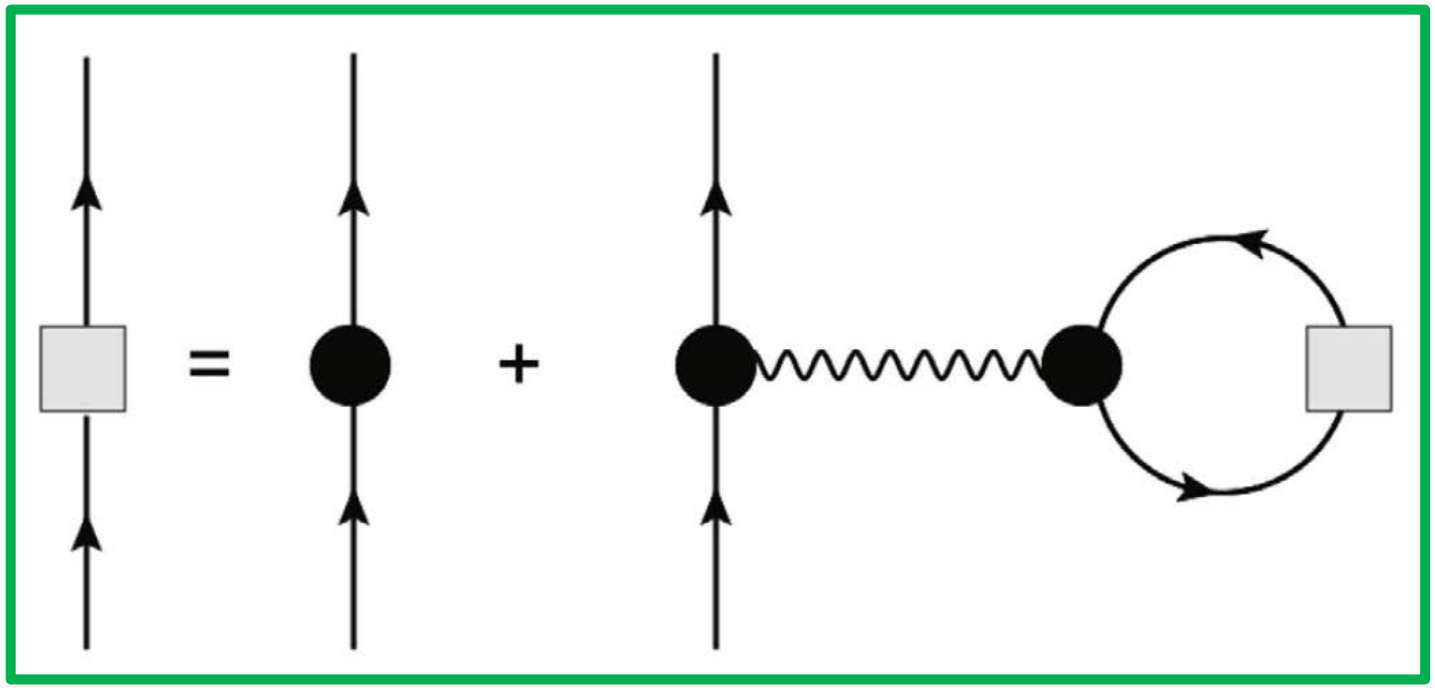
G-matrix

Baryon Self-energies

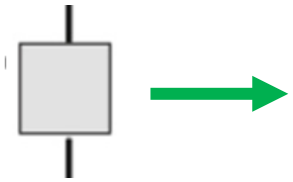
In-medium propagators

H.L., C. Fuchs, Phys.Lett.B 345 (1995) 355; Phys.Rev.C 52 (1995)
F. Dejong, H.L., Phys.Rev.C 57 (1998) 3099; H. L., Lecture Notes in Phys. 641 (2004) 147

Integral Equation for the Dressed In-Medium Vertices



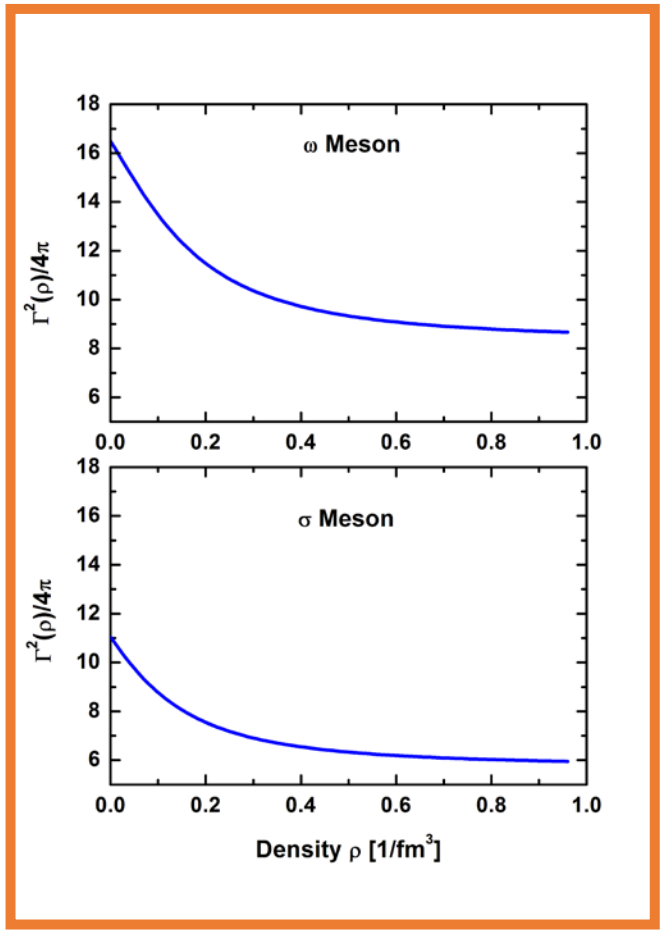
…in-medium (D)BHF vertices dressed by a density dependent form factor:



$$\Gamma_{\mathcal{B}\mathcal{B}'a}(q_s, k_F) \simeq \frac{1}{1 - \int dq' V_a \mathcal{G}^* Q_F \,|_{\mathcal{B}\mathcal{B}'}} \; g_{\mathcal{B}\mathcal{B}'a}.$$

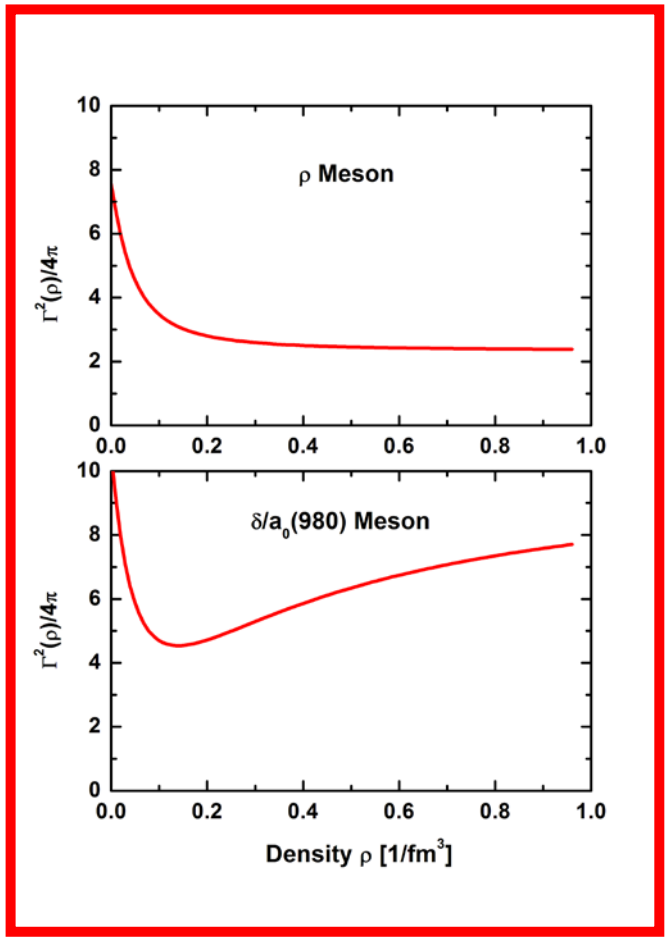
(a=σ,ω,ρ…)

Nuclear Matter DBHF Mean-Field NN-Vertices



$$\frac{\Gamma^2_{NNa}(\rho)}{4\pi}$$

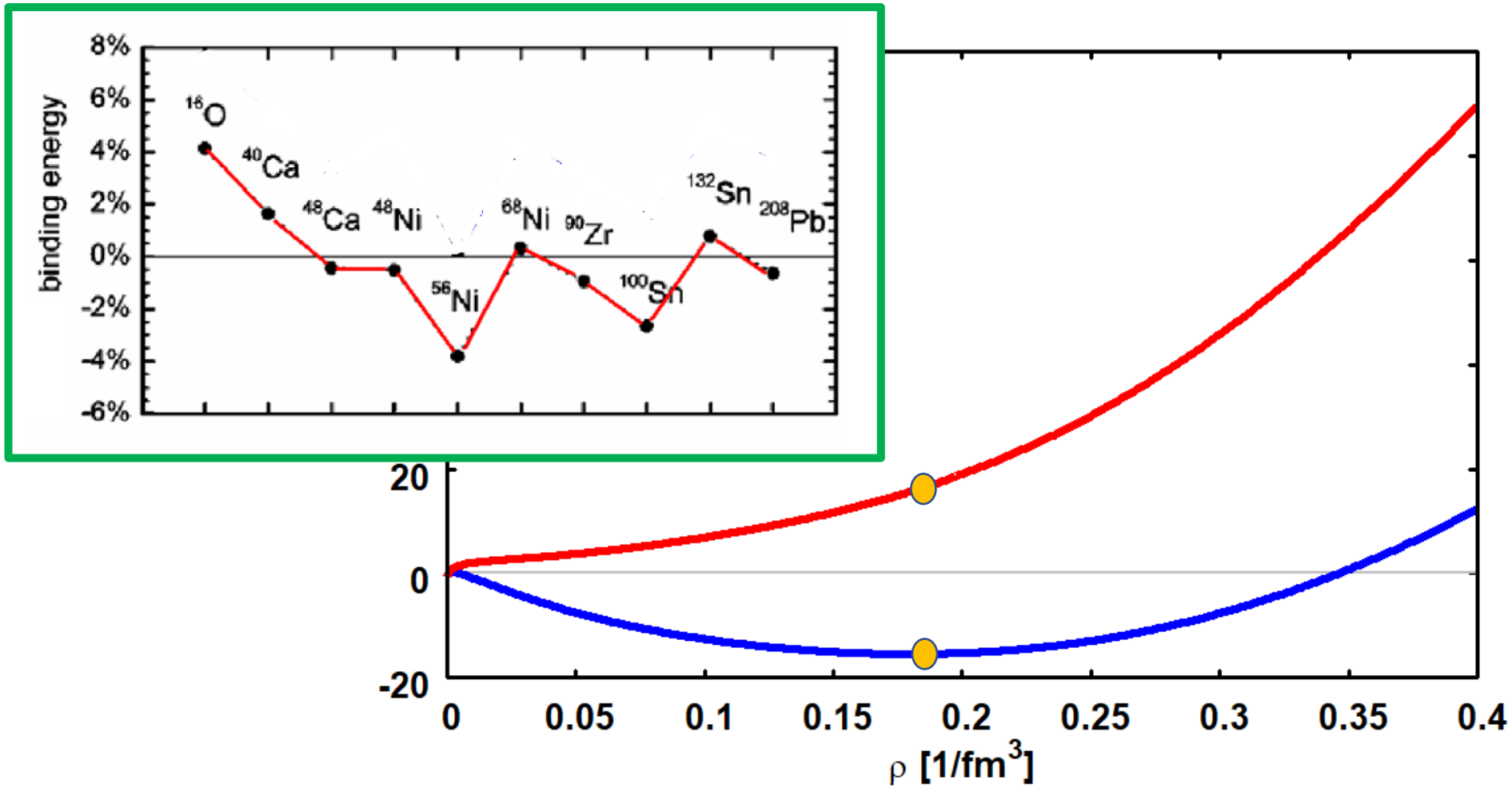
$$\Gamma^2_{BB'a} \approx g^2_{BB'a}\left(1 - f_{BB'a}(\rho)\right)$$



Isoscalar Vertices

Isovector Vertices

GI-DBHF 2-body Results for Infinite Nuclear Matter

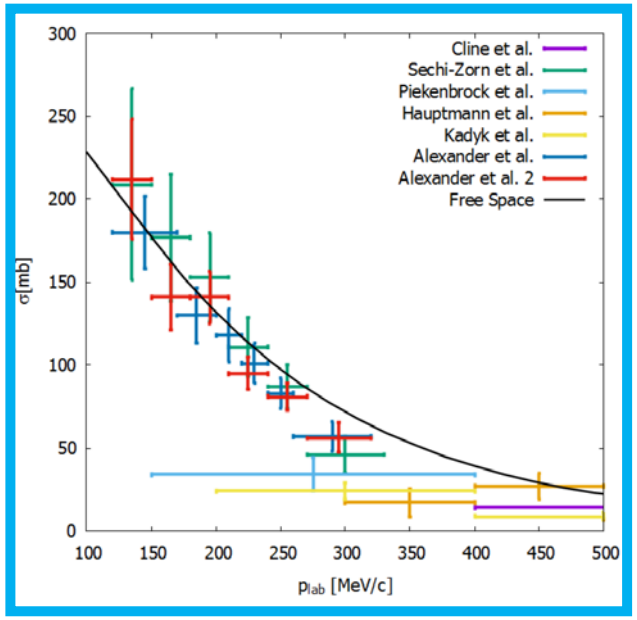


- *Hofmann, Keil, Lenske, Phys.Rev.C* 64 (2001) 034314

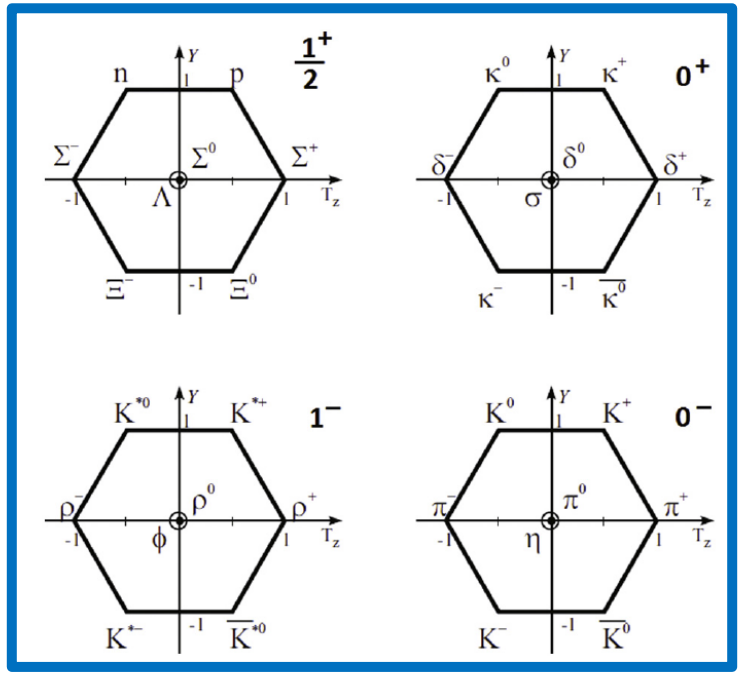
SU(3) Meson-Baryon Octet Interactions

Baryon and Meson $SU_f(3)$ –Multiplets and OBE Interactions

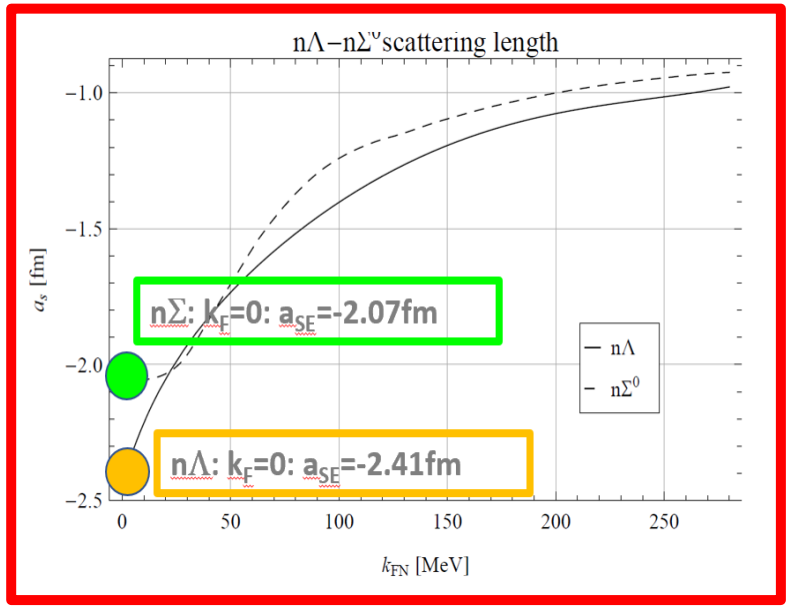
Nijmegen, Jülich, Giessen…



GI-OBE Free Space Results
M. Dhar, JLU Thesis



$$\mathcal{L} = \mathcal{L}_{\mathcal{B}} + \mathcal{L}_{\mathcal{M}} + \mathcal{L}_{int}$$



GI-OBE In-Medium Results
M. Dhar, JLU Thesis

NN-Interactions and the fundamental SU(3) Octet Coupling Constants

$$g_{NN\pi} = g_D^{(ps)} + g_F^{(ps)} \quad ; \quad g_{NN\eta} = \frac{1}{\sqrt{3}}\left(-g_D^{(ps)} + 3g_F^{(ps)}\right)$$

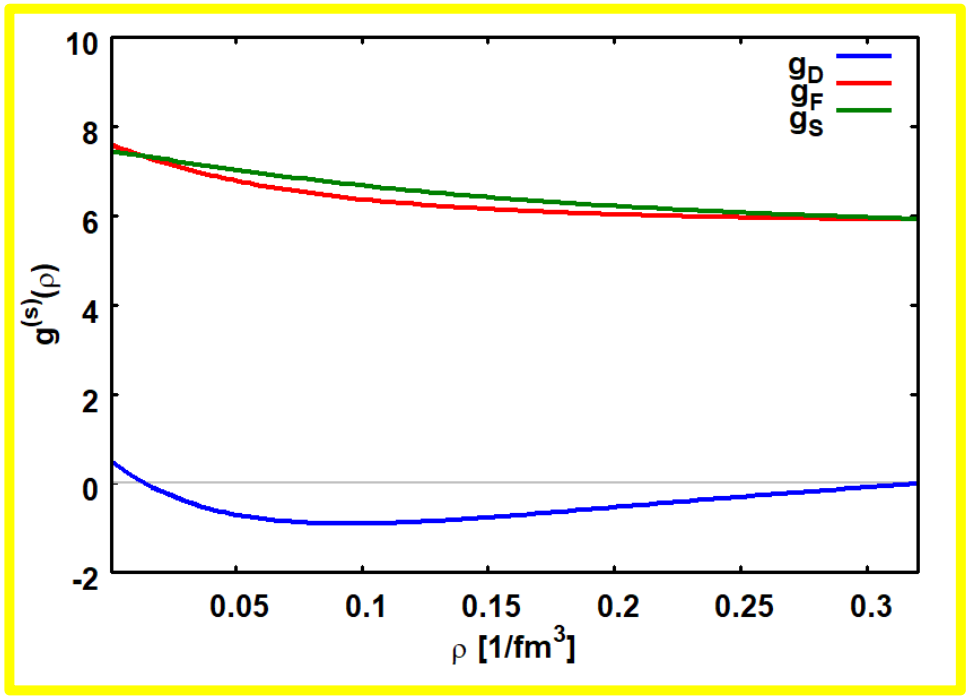
$$g_D^{(ps)} = \frac{1}{4}\left(3g_{NN\pi} - \sqrt{3}g_{NN\eta}\right) \quad ; \quad g_F^{(ps)} = \frac{1}{4}\left(g_{NN\pi} + \sqrt{3}g_{NN\eta}\right)$$

and accordingly for the scalar and vector couplings, also including octet-singlet mixing; corresponding relations for hyperons

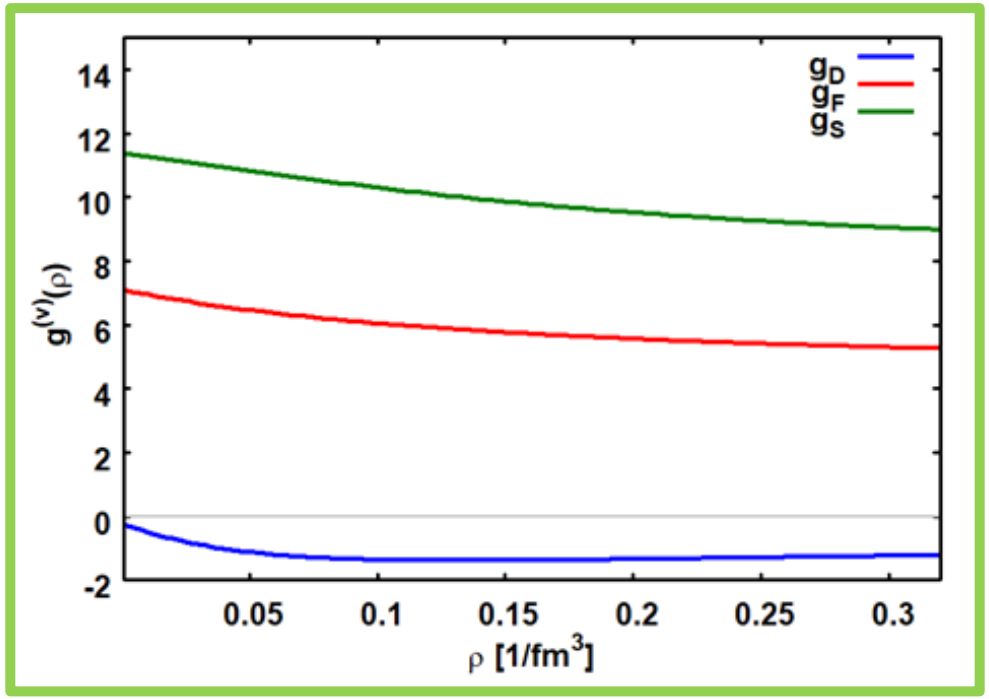
...there is symmetry breaking!

Derived In-Medium Fundamental SU(3)-Vertices

$$g_D^{(m)} = \frac{1}{4}\left(3g_{NNa} - \sqrt{3}g_{NNf}\right) \quad ; \quad g_F^{(m)} = \frac{1}{4}\left(g_{NNa} + \sqrt{3}g_{NNf}\right)$$
$$\left(a = \pi, \rho, a_0 \;\; ; \;\; f = \eta, \omega, \sigma\right)$$



Scalar



Vector

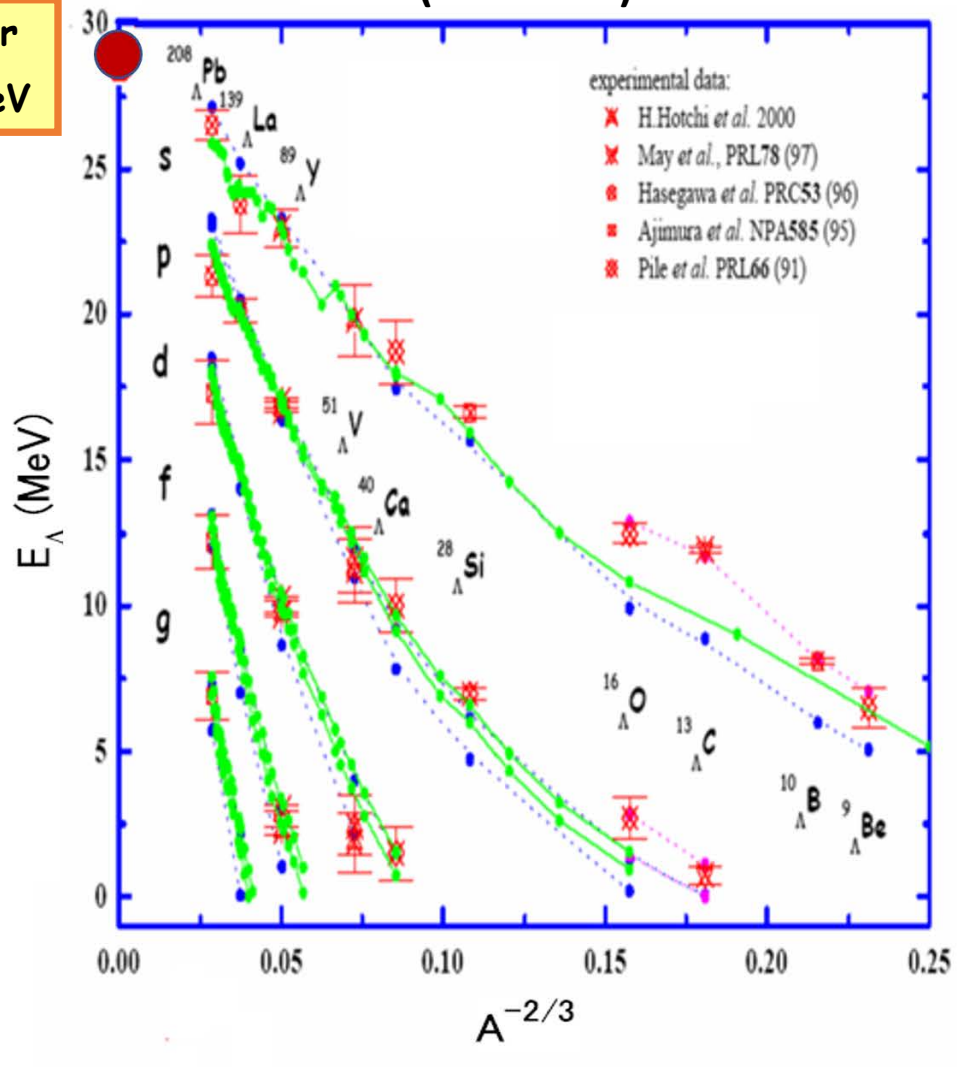
H.L., M. Dhar, Lect.Notes Phys. 948 (2018) 161
H.L., M. Dhar et al, Prog.Part.Nucl.Phys. 98 (2018) 119

Hypernuclei

Nuclear Matter

S_Λ = 28…30 MeV

Giessen DBHF
(covariant)

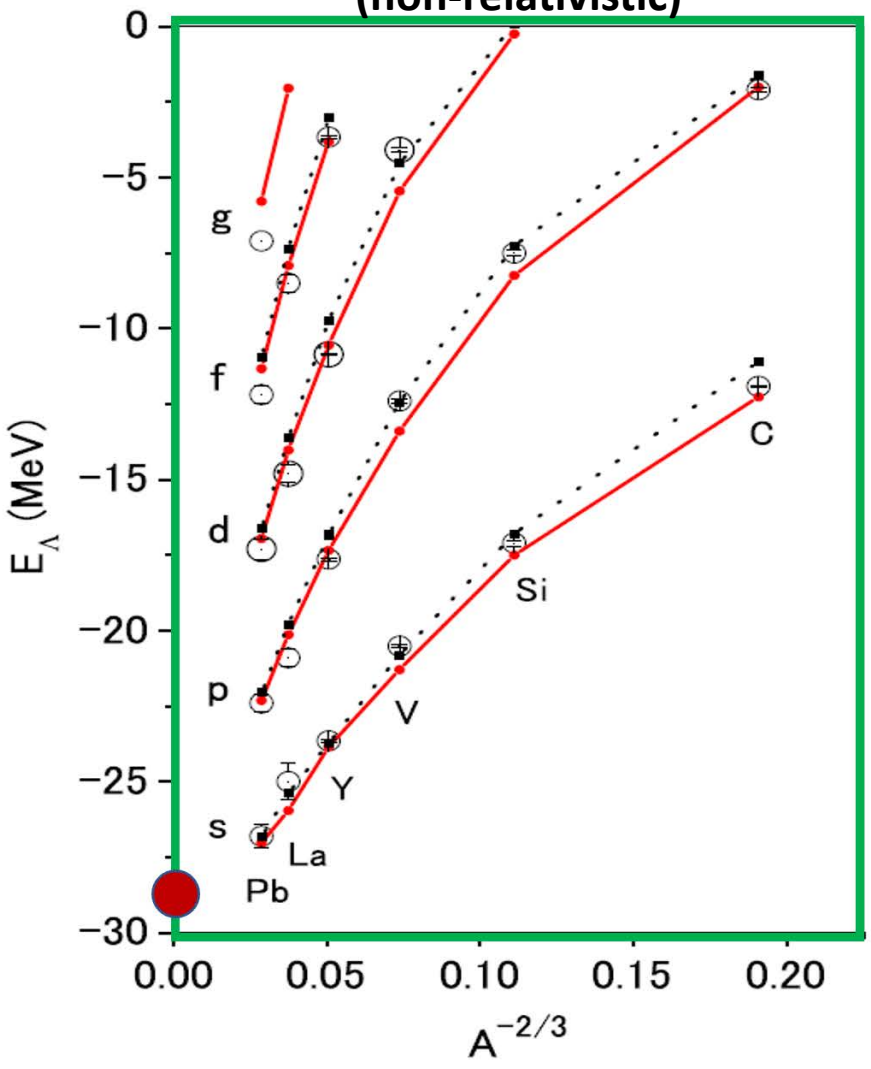


Keil, Hofmann, H.L., Phys.Rev.C 61 (2000) 064309

Covariant EDF – without TBI

GI-DBHF Vertex Functionals

ESC08+MPP
(non-relativistic)

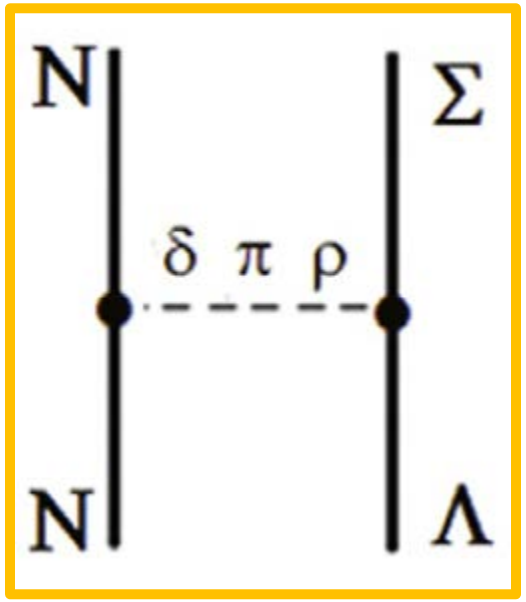


Yamamoto et al., Phys. Rev. C 90 (2014) 045805

G-matrix Folding Approach

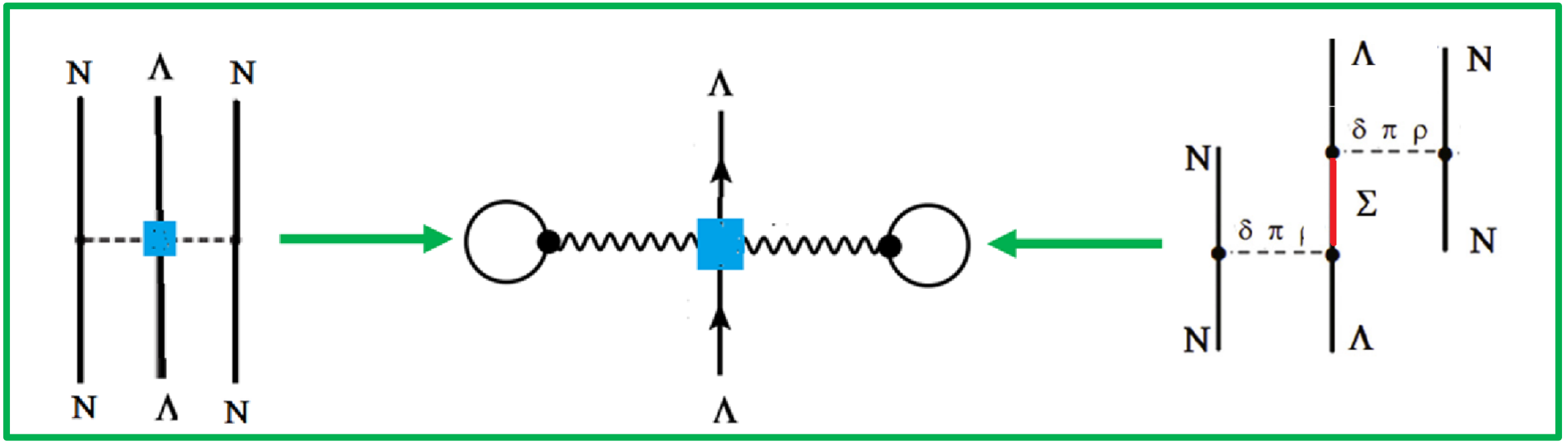
Empirical NNN + YNN Multi-Pomeron Forces

Λ-Σ Mixing by Isovector Interactions and Induced „3-Body“ Self-Energies



$$L = -g_{\Lambda\Sigma s}\,\overline{\Psi}_{\Sigma}\,\vec{\tau}\Psi_{\Lambda}\bullet\vec{\phi} + g_{\Lambda\Sigma v}\,\overline{\Psi}_{\Sigma}\,\vec{\tau}\gamma_{\mu}\Psi_{\Lambda}\bullet\vec{V}^{\mu}$$

Effective YNN 3-Body Interactions and the Nuclear Mean-Field



N²LO χEFT

$$\sim (\rho_n + \rho_p)^2$$

contracted over Fermi-Sea

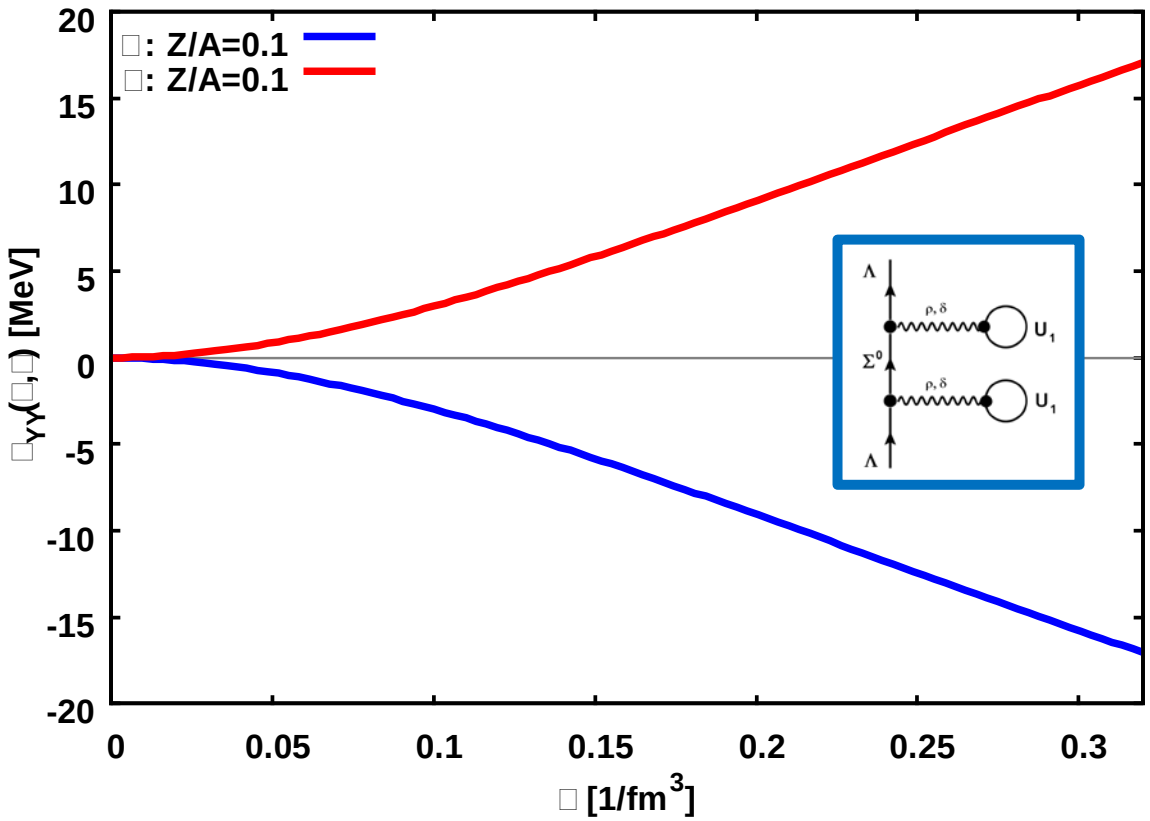
$$U_{\Lambda}^{(2)}(\rho_B, \omega) = U_1^{\Lambda\Sigma}(\rho_B) G_{\Sigma}(\omega) U_1^{\Sigma\Lambda}(\rho_B) \langle \Lambda | \tau_0 | \Sigma^0 \rangle^2$$

Second Order Λ Self-Energy

Isovector Mixing

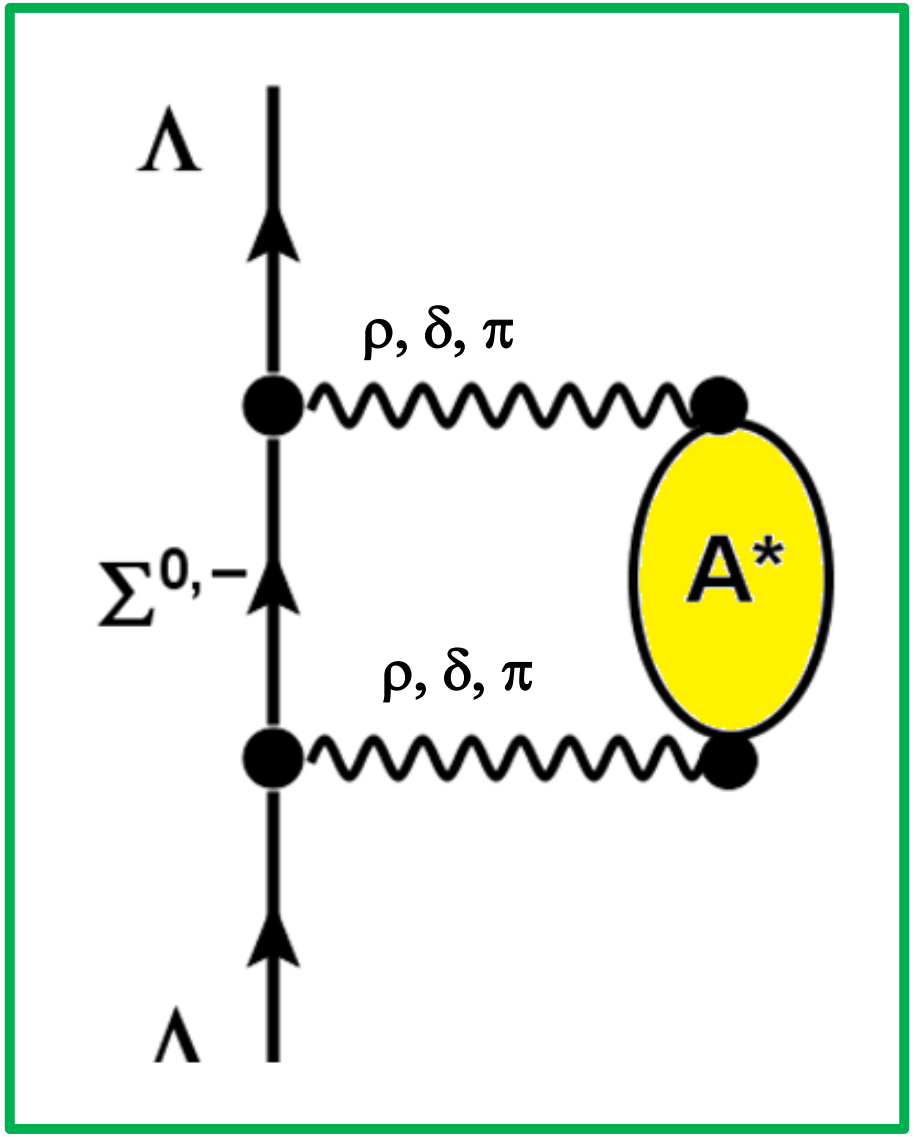
$$\sim (\rho_n - \rho_p)^2$$

Λ and Σ Induced Self-Energies from the Nuclear Isovector Mean-Field



$$\sim \frac{\left(N-Z\right)^2}{M_\Sigma^* - M_\Lambda^*}\left\langle V_\tau \right\rangle^2 \sim 2...3(N-Z)^2$$

Induced Λ Dynamical Polarization Self-Energy by Isovector Λ-Σ Mixing



Fermi- and Gamov-Teller Modes

Summary

- **Views on three-nucleon interactions, their origins, and their interpretation**
- **Covariant In-medium BB-interaction by DBHF theory: GI-DHBF**
- **SU(3) relations connecting NN, NY, and YY interactions**
- **Hypermatter and hypernuclei**
- **Isovector Mean-field Λ-Σ mixing and induced YNN self-energies**

Recent reviews:

***H.L., M. Dhar, Lect.Notes Phys.* 948 (2018) 161**

***H.L., M. Dhar, Th. Gaitanos, Xu Cao, Prog.Part.Nucl.Phys.* 98 (2018) 119**