KAON - and HYPERON - NUCLEAR INTERACTIONS from CHIRAL SU(3) EFFECTIVE FIELD THEORY

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PHYSIK DEPARTMENT

- Kaon and antikaon interactions with nucleons and nuclei
  - Chiral SU(3) coupled-channels dynamics and the $\Lambda(1405)$
  - Constraints from kaonic hydrogen and $\mathrm{K^-p}$ scattering
  - $\mathrm{K^+N}$ interaction update
- Hyperon-nucleon interactions from chiral SU(3) EFT
  - Hyperon-nuclear potential and hyperon-NN three-body forces
  - Strangeness in cold & dense baryonic matter ?
    "Hyperon puzzle" in neutron stars

Part I.

Antikaon and Kaon Interactions with Nucleons and Nuclei

Historical Reminder:

Kaons and Antikaons in Nuclear Matter

In-medium Chiral SU(3) Dynamics with Coupled Channels

- **Kaon spectrum** in **baryonic matter** determined by:

$$\omega^2 - \vec{q}^2 - m_K^2 - \Pi_K(\omega, \vec{q}; \rho) = 0$$

$$\Pi_{K^-} = 2\omega U_{K^-} = -4\pi \left[f_{K^- p}\,\rho_p + f_{K^- n}\,\rho_n\right] + \ldots +$$

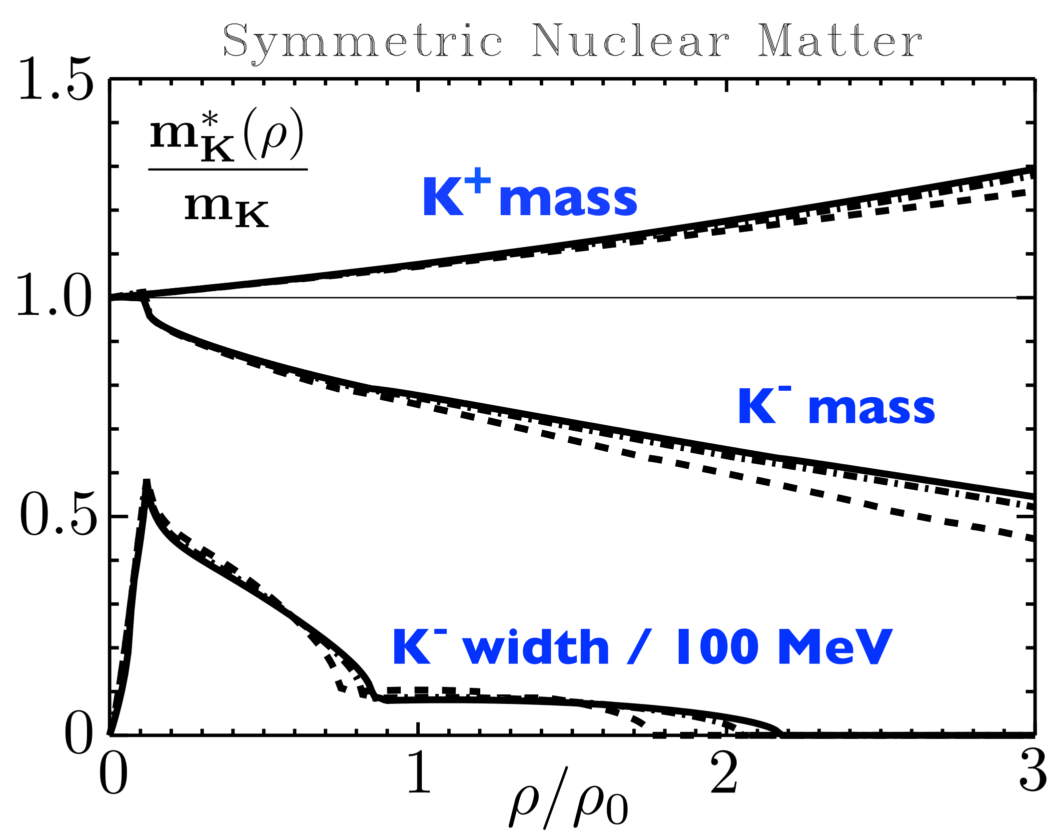
Pauli blocking, Fermi motion, 2N correlations

V. Koch
Phys. Lett. B 337 (1994) 7

M. Lutz
Phys. Lett. B 426 (1998) 12

A. Ramos, E. Oset
Nucl. Phys. A 671 (2000) 481

M. Lutz, C.L. Korpa, M. Möller
Nucl. Phys. A 808 (2008) 124



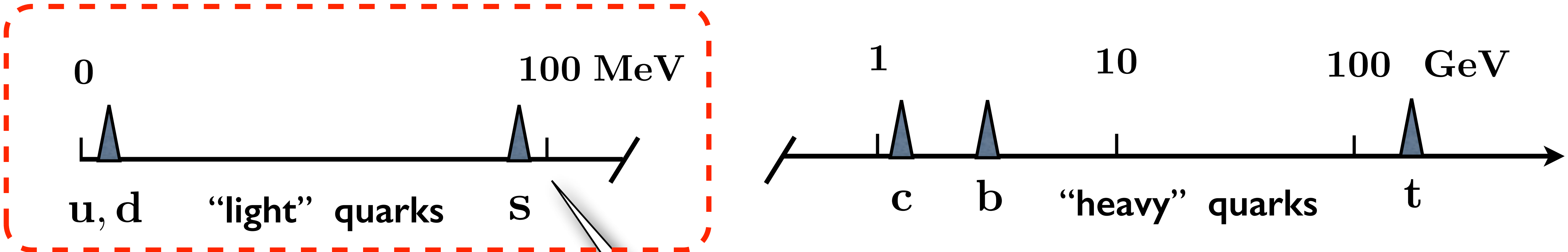
T. Waas, N. Kaiser, W.W.:
Phys. Lett. B 379 (1996) 34

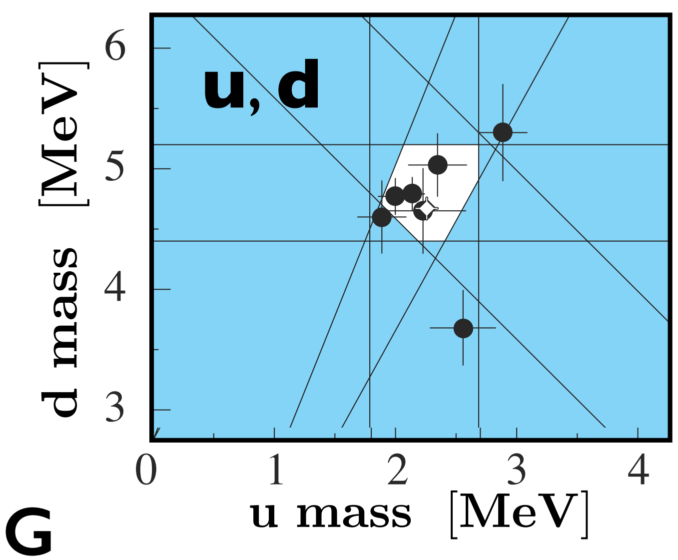
T. Waas, W.W.:
Nucl. Phys. A 625 (1997) 287

- **Kaon condensation** in dense baryonic matter ?

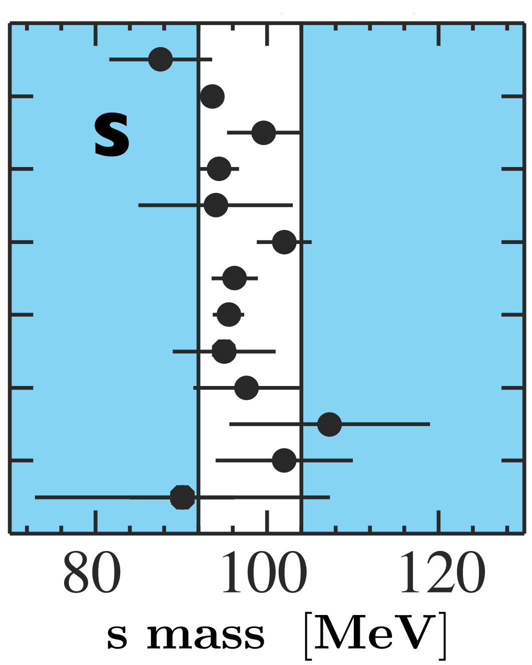
… first suggested by D. Kaplan, A. Nelson (1985), but: ruled out by neutron star constraints

Low-Energy QCD
Hierarchy of Quark Masses





PDG 2018



$(\mu = 2\ \text{GeV})$

$$m_u = 2.2 \pm 0.5\ \text{MeV} \qquad m_d = 4.7 \pm 0.5\ \text{MeV}$$

$$m_s = 95^{+9}_{-3}\ \text{MeV}$$

Chiral Symmetry

$$SU(3)_L \times SU(3)_R$$

Spontaneously broken (QCD dynamics)

Explicitly broken by non-zero quark masses

Spontaneously Broken
CHIRAL $\mathbf{SU(3)_L \times SU(3)_R}$ SYMMETRY

- **NAMBU - GOLDSTONE BOSONS**:

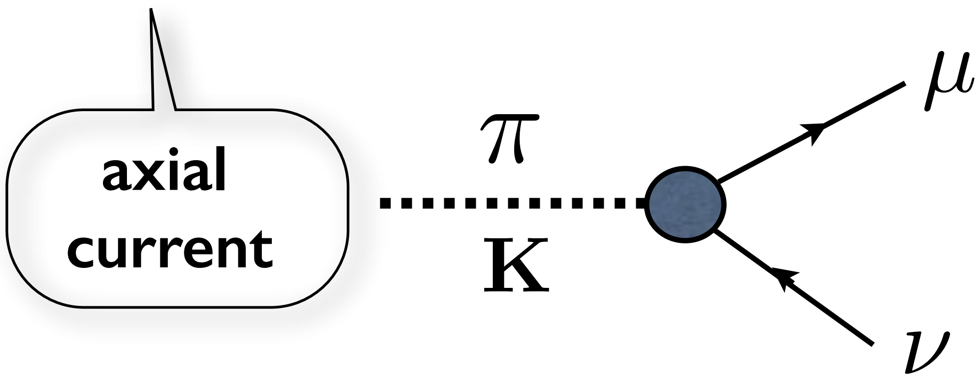
Pseudoscalar SU(3) meson octet $\{\phi_a\} = \{\pi, \mathbf{K}, \bar{\mathbf{K}}, \eta_8\}$

- **DECAY CONSTANTS**:

Chiral limit: $\mathbf{f} = \mathbf{86.2\ MeV}$

$$\langle 0|\mathbf{A}_a^\mu(0)|\phi_b(p)\rangle = i\delta_{ab}\, p^\mu\, \mathbf{f}_b$$

Order parameter : $4\pi\,\mathbf{f} \sim \mathbf{1\ GeV}$



$$\mathbf{f}_\pi = \mathbf{92.3 \pm 0.1\ MeV}$$
$$\mathbf{f_K} = \mathbf{110.8 \pm 0.3\ \ MeV}$$

- **G**ell-Mann, **O**akes, **R**enner relations

$$\mathbf{m}_\pi^2\, \mathbf{f}_\pi^2 = -\frac{\mathbf{m_u + m_d}}{\mathbf{2}}\langle \bar{\mathbf{u}}\mathbf{u} + \bar{\mathbf{d}}\mathbf{d}\rangle$$

$$\mathbf{m_K^2\, f_K^2} = -\frac{\mathbf{m_u + m_s}}{\mathbf{2}}\langle \bar{\mathbf{u}}\mathbf{u} + \bar{\mathbf{s}}\mathbf{s}\rangle$$

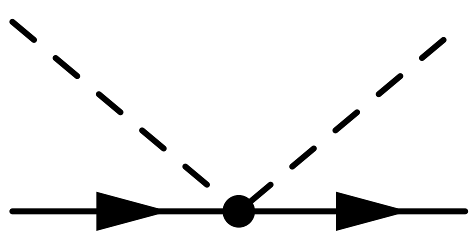
+ higher order corrections

Spontaneously Broken CHIRAL SYMMETRY

- **GOLDSTONE's Theorem:**

Massless **Nambu-Goldstone bosons do not interact** in the limit of zero momentum (long-wavelength limit)

- **S-wave interactions of NG bosons**



scattering amplitude $\mathbf{T \sim \frac{E}{f^2}}$

$\mathbf{E = \sqrt{m^2 + k^2}}$
explicit
chiral symmetry breaking

meson decay constant
order parameter of
spontaneous
chiral symmetry breaking

Tomozawa - Weinberg
low-energy theorem

CHIRAL SU(3) EFFECTIVE FIELD THEORY

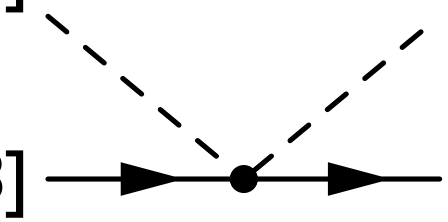
ordered hierarchy of driving interactions

- **Leading order terms**
  (Tomozawa & Weinberg)

  dominate up to $\mathbf{p_{lab} \sim 0.5}$ GeV

pseudoscalar meson octet [8]

baryon octet [8]



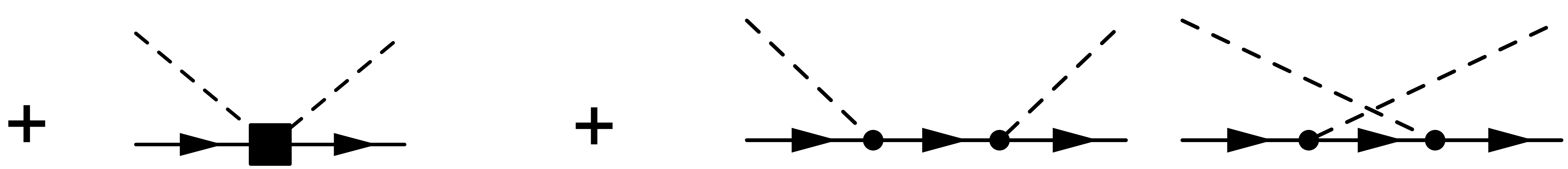
- LO $\bar{\mathrm{K}}\mathrm{N}$ (S = -1) and KN (S = +1) **threshold (s wave) amplitudes :**

$$\mathbf{T(K^+p)_{thr} = 2\,T(K^+n)_{thr} = -\frac{m_K}{f^2}}$$ **repulsive**

$$\mathbf{T(K^-p)_{thr} = 2\,T(K^-n)_{thr} = \frac{m_K}{f^2}}$$ **attractive**

Potentials:

$$\mathbf{V(r)} = -\frac{\mathbf{T}}{2E}\,\delta^{\mathbf{3}}(\mathbf{r})$$



next-to-leading order (NLO) $\mathcal{O}(p^2)$

input: several low-energy constants

Chiral $\mathbf{SU(3)_L \times SU(3)_R}$ Effective Field Theory

- Starting point: **Meson-Baryon Lagrangian** (chiral limit)

$$\mathcal{L}_{MB} = \mathrm{tr}\left(\bar{B}\left(i\gamma^\mu D_\mu - M_0\right)B\right) - \frac{D}{2}\,\mathrm{tr}\left(\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}\right) - \frac{F}{2}\,\mathrm{tr}\left(\bar{B}\gamma^\mu\gamma_5[u_\mu, B]\right)$$

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ -\Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix} \qquad P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

- **Chiral covariant derivative:** $D_\mu B = \partial_\mu B + [\Gamma_\mu, B]$

$$\Gamma_\mu = \frac{1}{2}(u^\dagger\partial_\mu u + u\partial_\mu u^\dagger) \qquad u_\mu = i(u^\dagger\partial_\mu u - u\partial_\mu u^\dagger)$$

- **Chiral (pseudoscalar Nambu-Goldstone boson) field :**

$$\boldsymbol{U}(x) = \boldsymbol{u}^2(x) = \exp\left(i\frac{\sqrt{2}P(x)}{f}\right)$$

transforms as

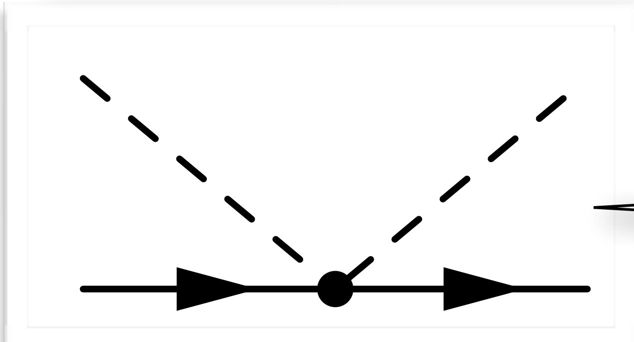
$$\boldsymbol{U} \to \boldsymbol{R\,U\,L}^\dagger \qquad \boldsymbol{R} \in \boldsymbol{SU(3)}_R \quad \boldsymbol{L} \in \boldsymbol{SU(3)}_L$$

- **Input :** $F = 0.46 \quad D = 0.81 \quad (g_A = F + D = 1.27) \quad f = 0.09\,GeV$

- **Physical meson and baryon masses [SU(3) breaking]**

CHIRAL SU(3) EFFECTIVE FIELD THEORY COUPLED CHANNELS DYNAMICS:

- NLO hierarchy of driving terms -



$$\mathcal{L}_{WT} = \frac{1}{2}\mathrm{Tr}(\bar{B}\gamma^\mu \Gamma_\mu B)$$

leading order (Tomozawa-**W**einberg) terms

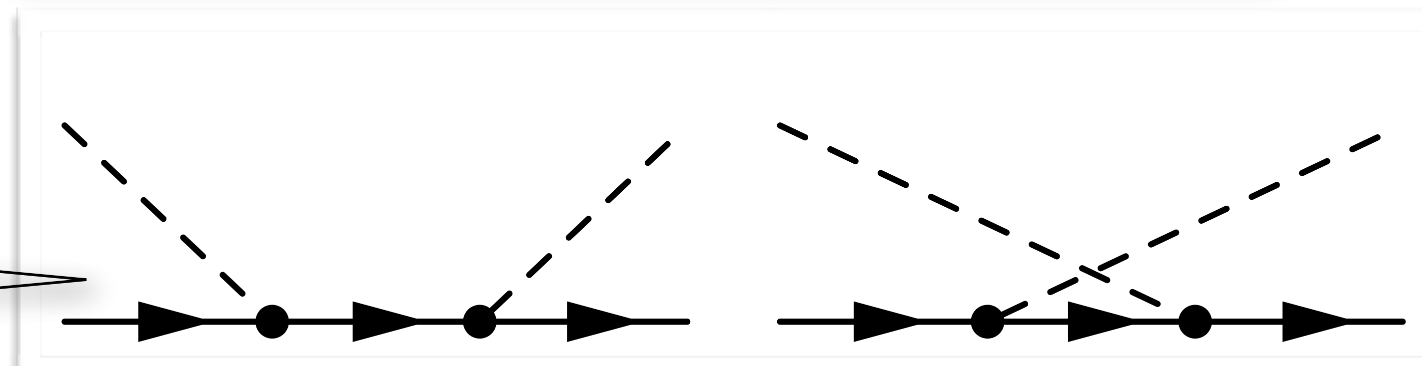
input: physical pion and kaon decay constants

direct and crossed **Born terms**

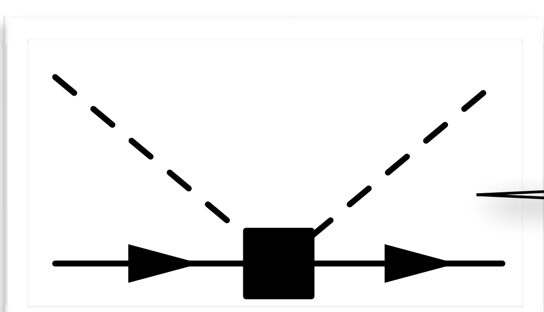
input: axial vector constants

D and F from hyperon beta decays

$$g_A = D + F = 1.27$$



$$\mathcal{L}_1^{MB} = \mathrm{Tr}\left(\frac{D}{2}(\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}) + \frac{F}{2}(\bar{B}\gamma^\mu\gamma_5[u_\mu, B])\right)$$



next-to-leading order (NLO) $\mathcal{O}(p^2)$

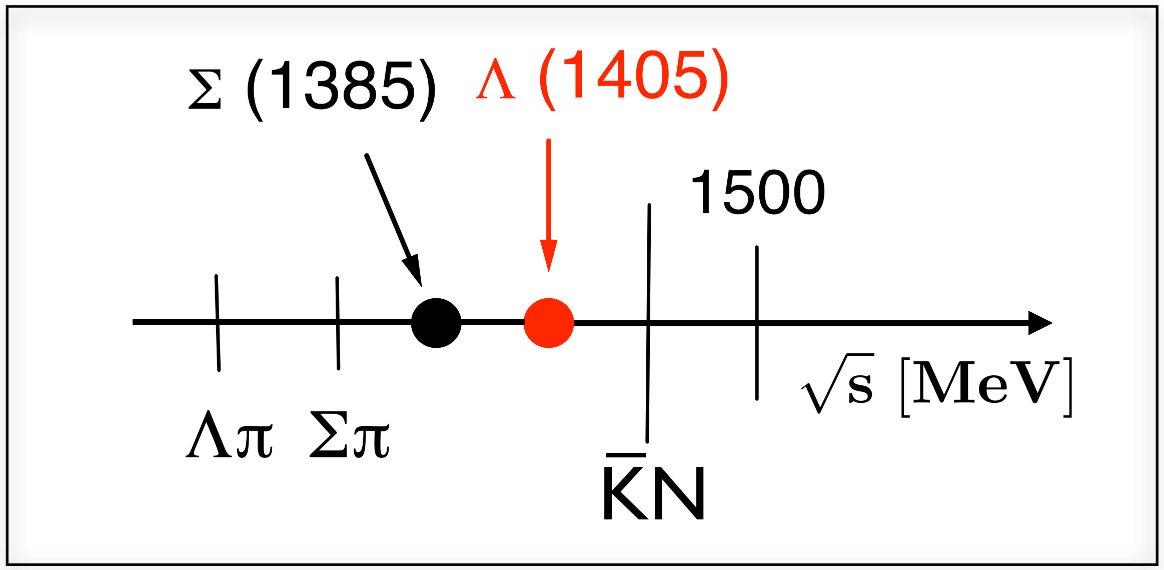
input: several low-energy constants

$$\begin{aligned}\mathcal{L}_2^{MB} =& b_D \mathrm{Tr}\big(\bar{B}\{\chi_+, B\}\big) + b_F \mathrm{Tr}\big(\bar{B}[\chi_+, B]\big) + b_0 \mathrm{Tr}(\bar{B}B)\mathrm{Tr}(\chi_+) \\ &+ d_1 \mathrm{Tr}\big(\bar{B}\{u^\mu, [u_\mu, B]\}\big) + d_2 \mathrm{Tr}\big(\bar{B}[u^\mu, [u_\mu, B]]\big) \\ &+ d_3 \mathrm{Tr}(\bar{B}u_\mu)\mathrm{Tr}(u^\mu B) + d_4 \mathrm{Tr}(\bar{B}B)\mathrm{Tr}(u^\mu u_\mu),\end{aligned}$$

Low-Energy $\bar{K}N$ Interactions

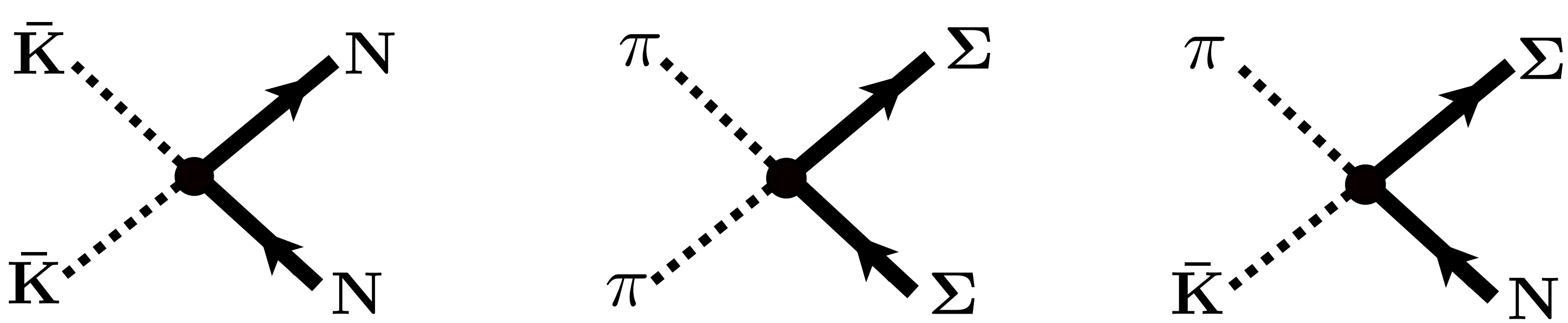
- Framework: **Chiral SU(3) Effective Field Theory** ... but :
- Chiral Perturbation Theory **NOT** applicable:
  $\Lambda(1405)$ resonance 27 MeV below $K^- p$ threshold

N. Kaiser, P. Siegel, W.W. (1995)
E. Oset, A. Ramos (1998)

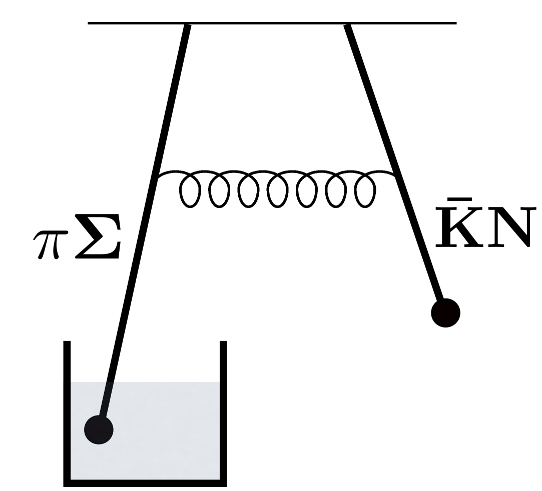


Non-perturbative
Coupled Channels
approach based on
Chiral SU(3) Dynamics

- Leading s-wave I = 0 meson-baryon interactions (Weinberg-Tomozawa)



channel coupling

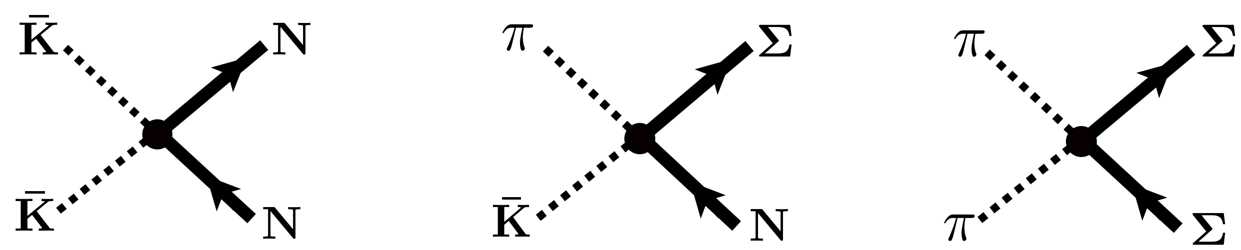


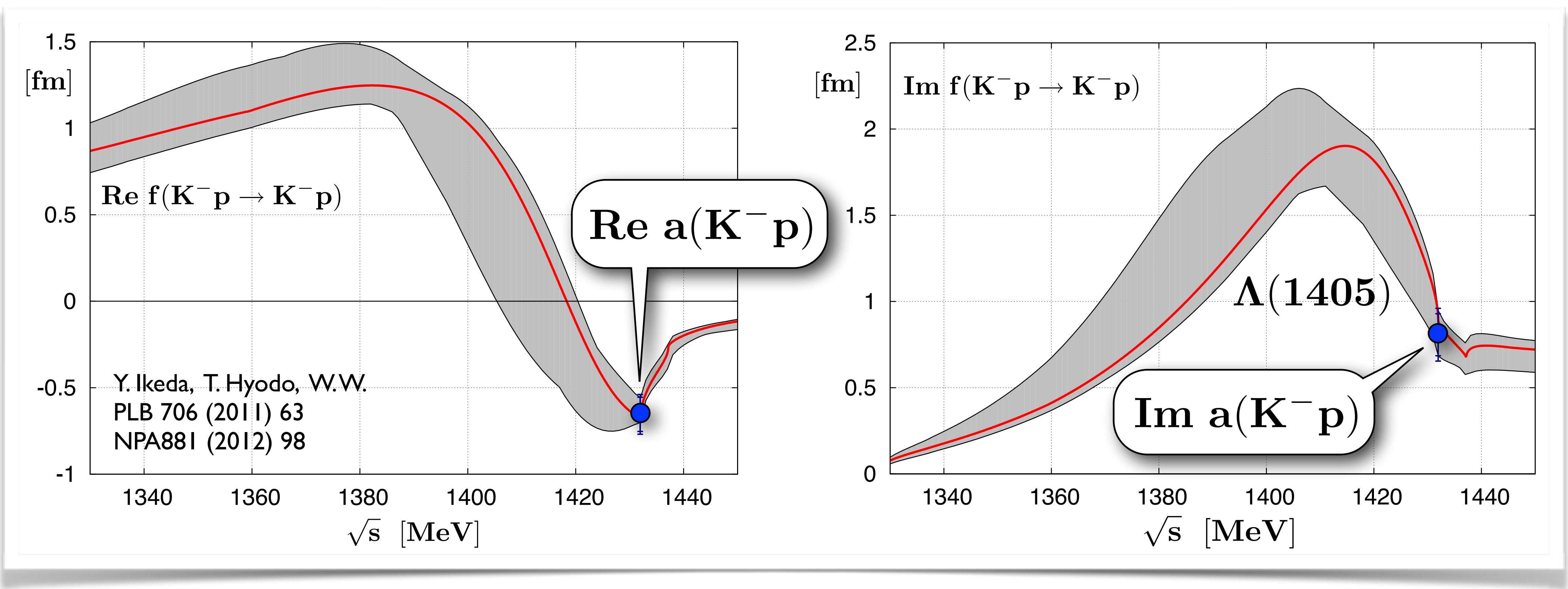
Review:
T. Hyodo, D. Jido
Prog. Part. Nucl. Phys. 67 (2012) 55

Low-Energy $\overline{\mathrm{K}}\mathrm{N}$ Interactions

Framework:
Non-perturbative **Coupled Channels** approach based on
Chiral SU(3) Effective Field Theory
Review: T. Hyodo, D. Jido : Prog. Part. Nucl. Phys. 67 (2012) 55

- **Coupled-Channels Bethe-Salpeter equation** $\mathbf{T} = \mathbf{V} + \mathbf{V} \cdot \mathbf{G} \cdot \mathbf{T}$

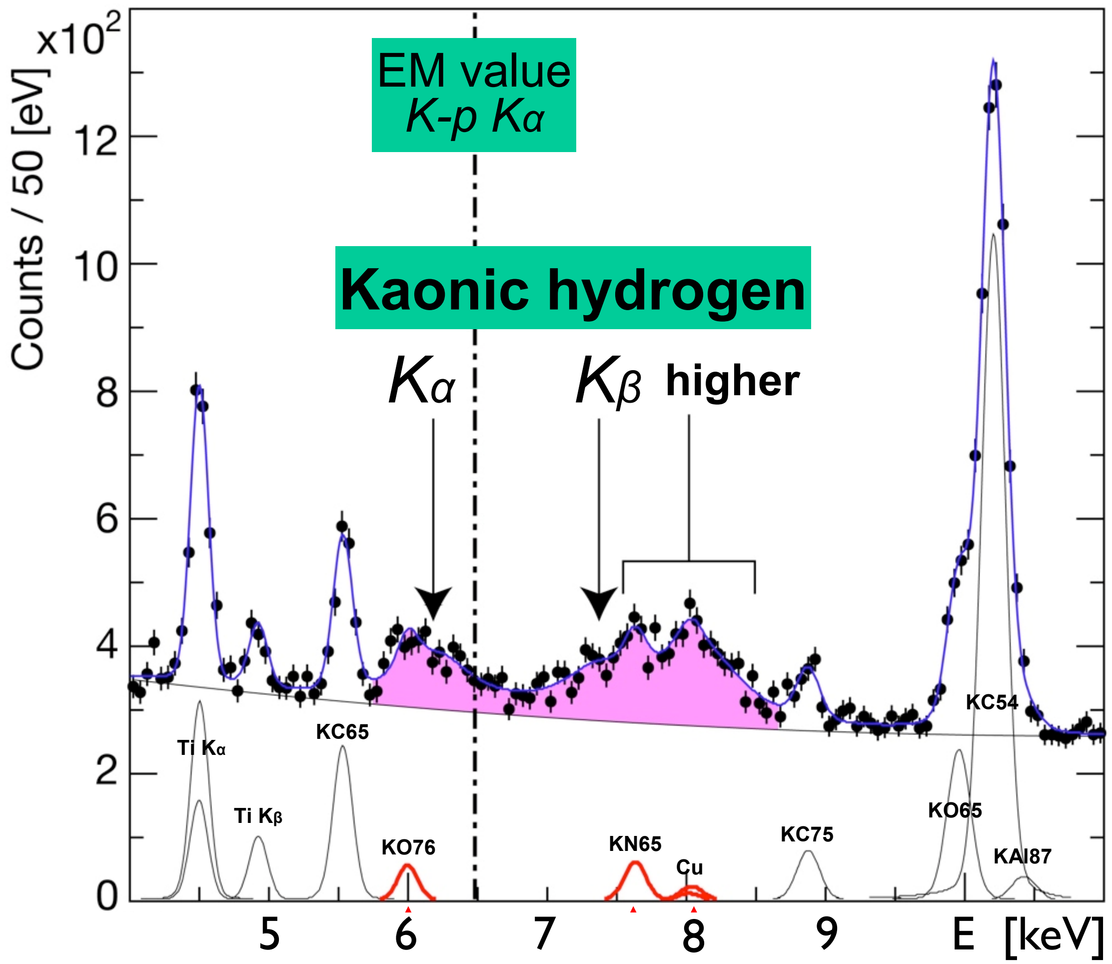




- **Scattering length** constraints from **SIDDHARTA kaonic hydrogen** measurements

CONSTRAINTS from KAONIC HYDROGEN

- SIDDHARTA

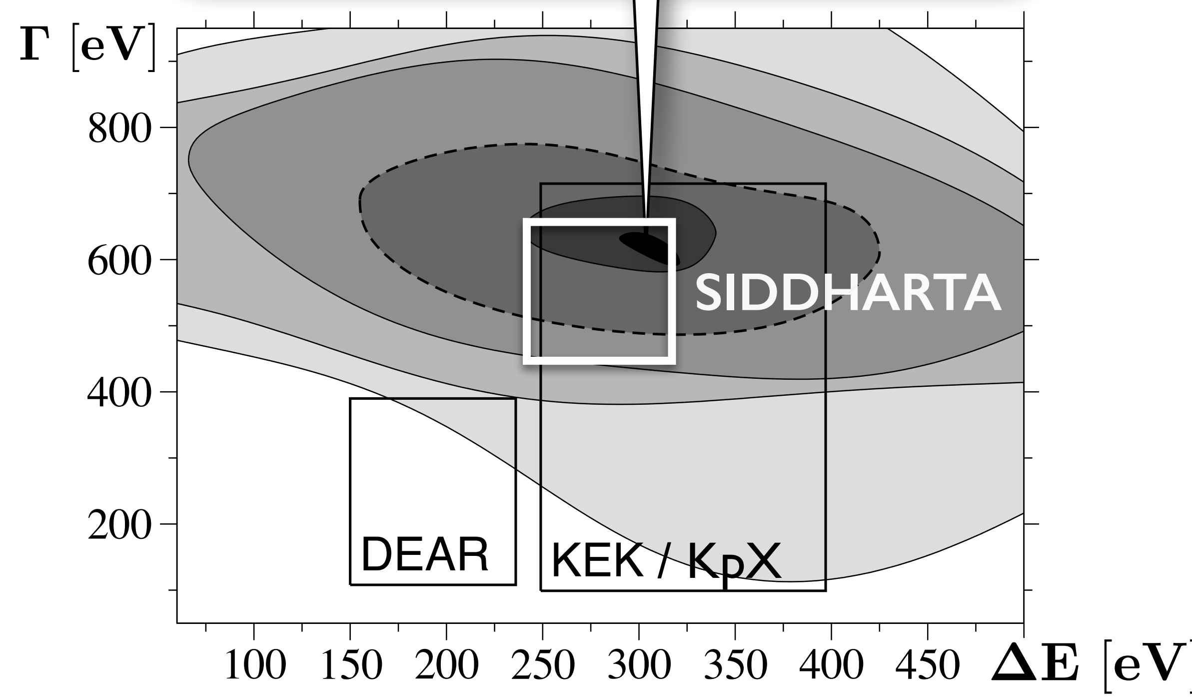


M. Bazzi et al. (SIDDHARTA collaboration)
Phys. Lett. B 704 (2011) 113
Nucl. Phys. A 881 (2012) 88

- **Strong interaction**

1s energy shift and width

Leading order (Tomozawa-Weinberg)
Chiral SU(3) Dynamics



B. Borasoy, R. Nissler, W.W.
Phys. Rev. Lett. 94 (2005) 213401

R. Nissler
Thesis 2008

$$-\varepsilon_{1s} = \Delta E = 283 \pm 36\,(stat) \pm 6\,(syst) \quad eV$$

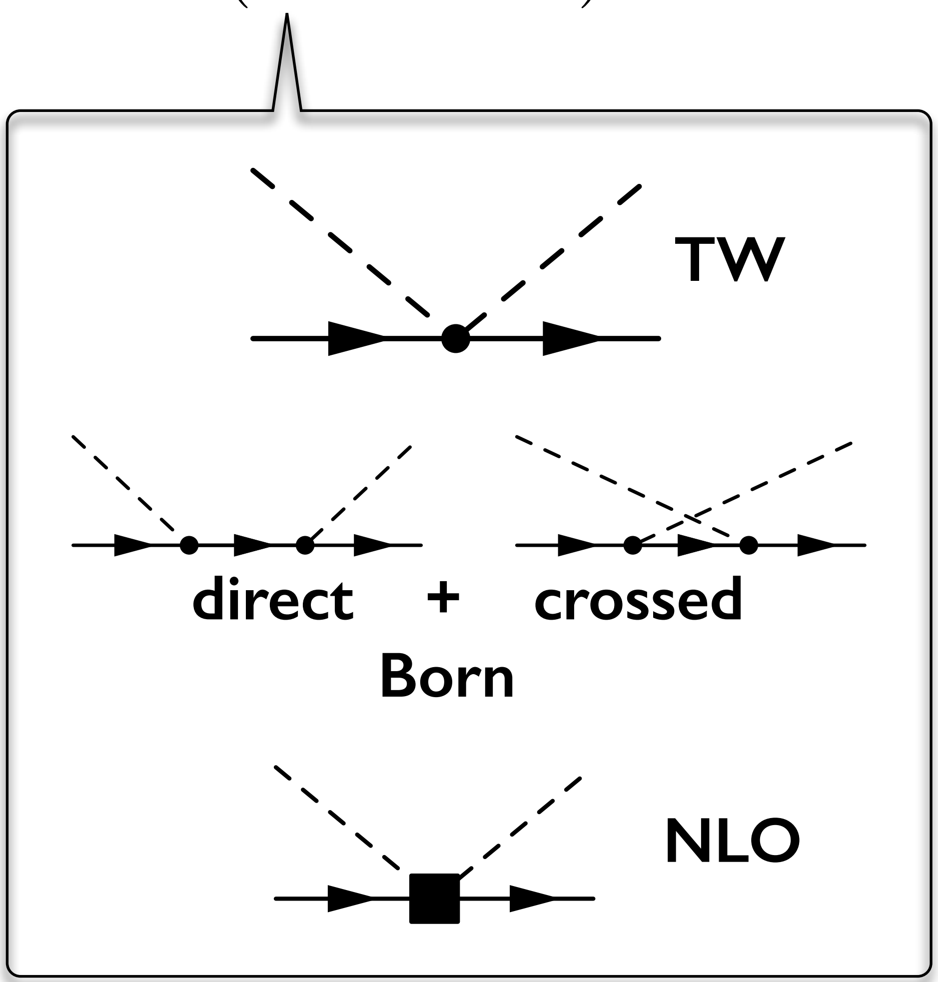
$$\Gamma = 541 \pm 89\,(stat) \pm 22\,(syst) \quad eV$$

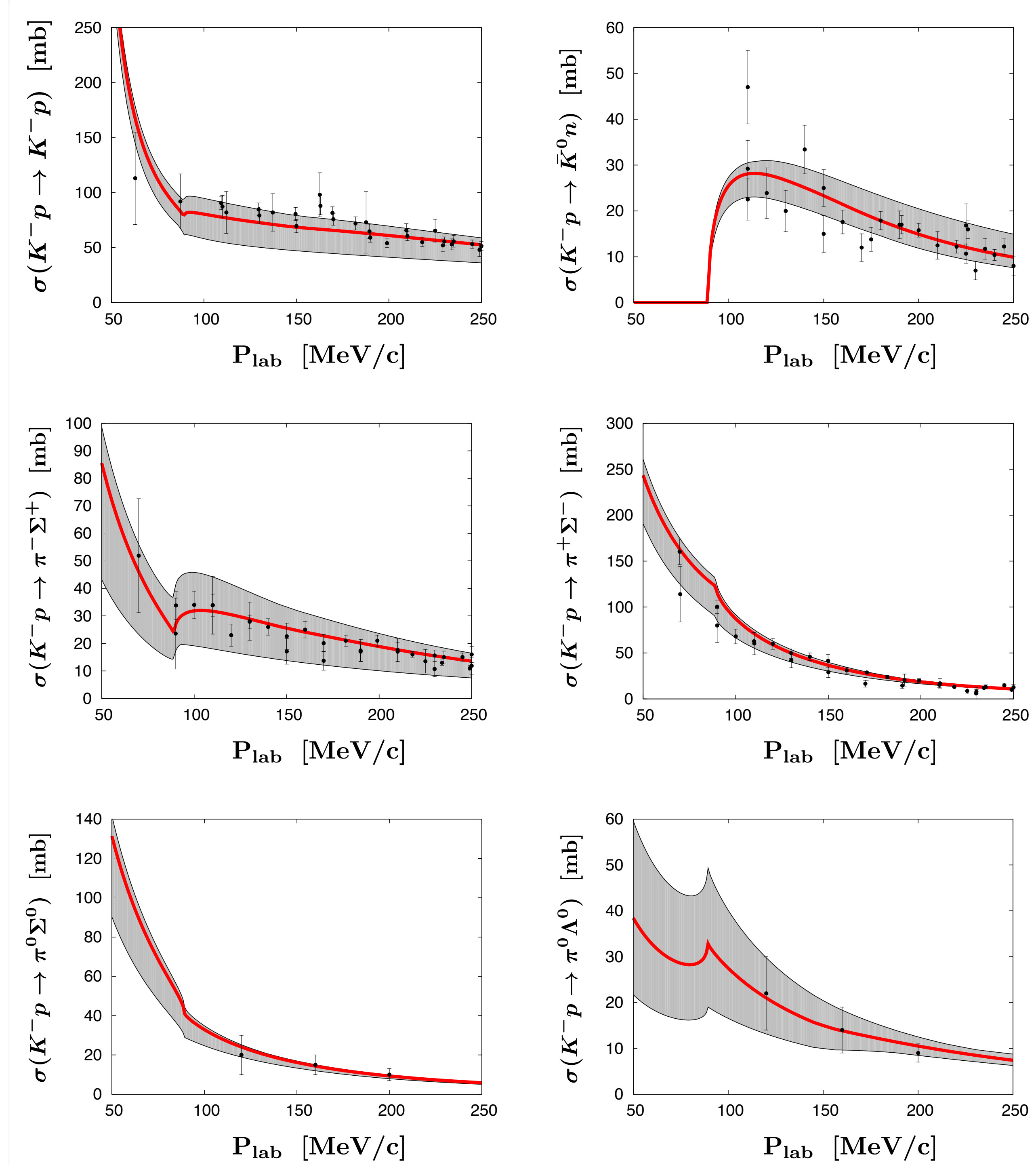
CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

Y. Ikeda, T. Hyodo, W.W.: Nucl. Phys. A 881 (2012) 98

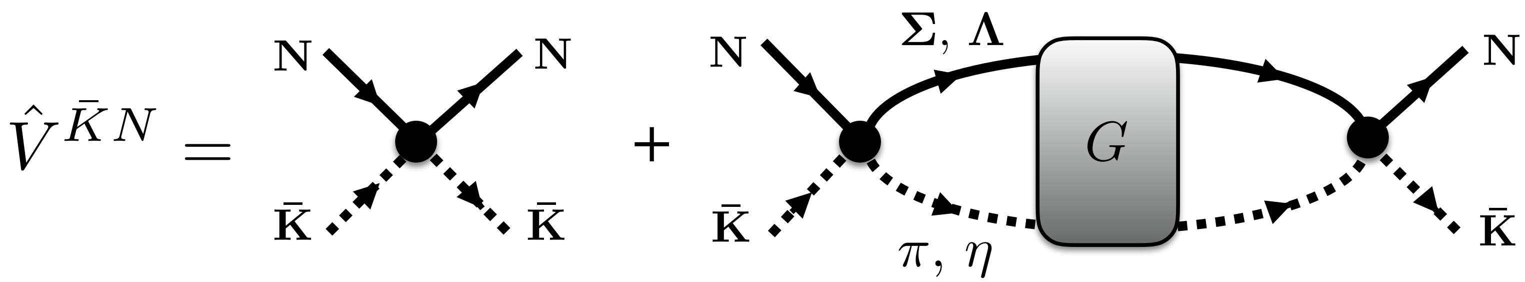
- **Coupled-Channels Bethe-Salpeter eqn.**

$$\mathbf{T} = \mathbf{V} + \mathbf{V} \cdot \mathbf{G} \cdot \mathbf{T}$$
$$= (\mathbf{V}^{-1} - \mathbf{G})^{-1}$$



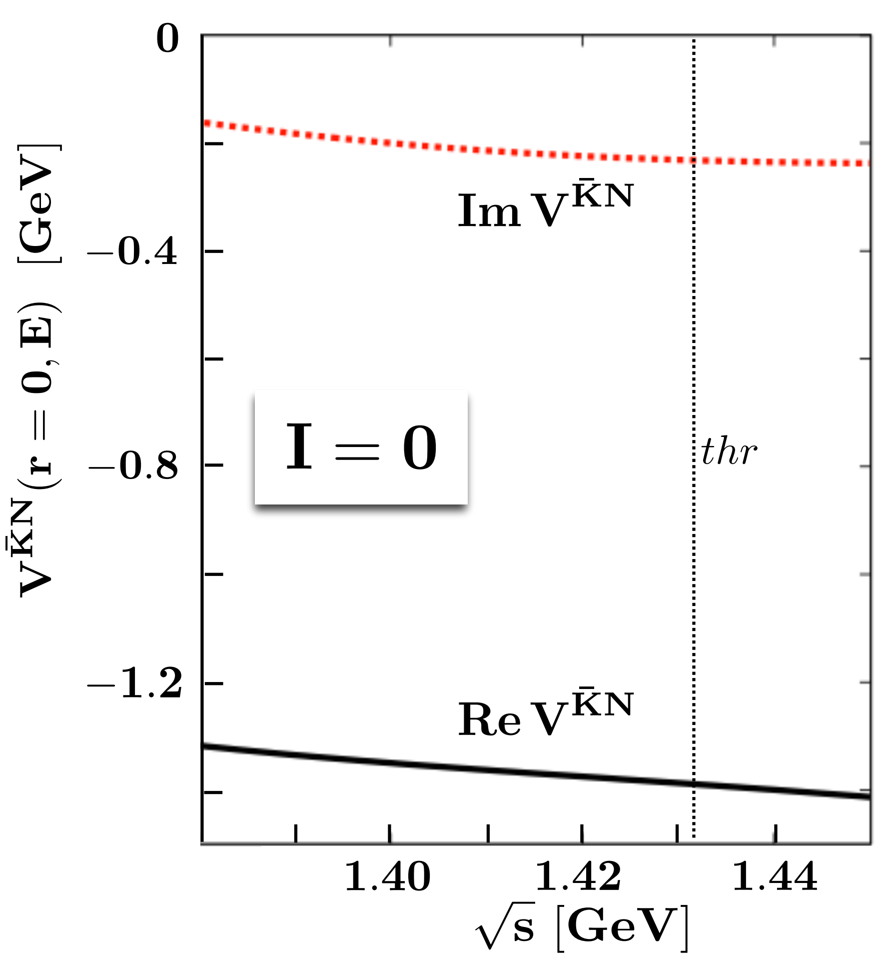


$\overline{\mathrm{K}}\mathrm{N}$ equivalent local POTENTIAL



Input e.g. for antikaon-nuclear few-body calculations - designed to reproduce :

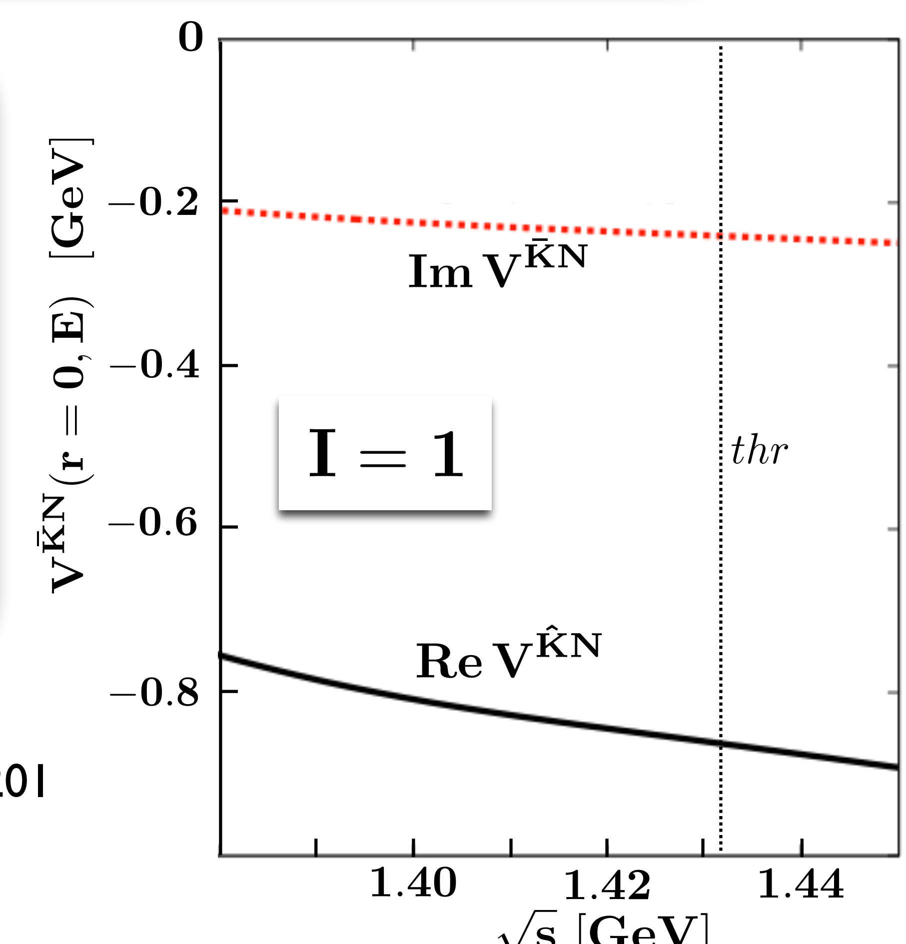
- **Two-body scattering data and threshold branching ratios**
- **Kaonic hydrogen (SIDDHARTA) data**
- $\mathbf{\Lambda(1405)}$ **and** $\pi\Sigma$ **mass spectra (coupled channels)**



$$V^{\bar{K}N}(r,E) = \frac{e^{-r^2/b^2}}{\pi^{3/2}\,b^3}\,U(E)$$

$$b \simeq 0.4\,\mathrm{fm}$$

K. Miyahara, T. Hyodo
Phys. Rev. C93 (2016) 015201

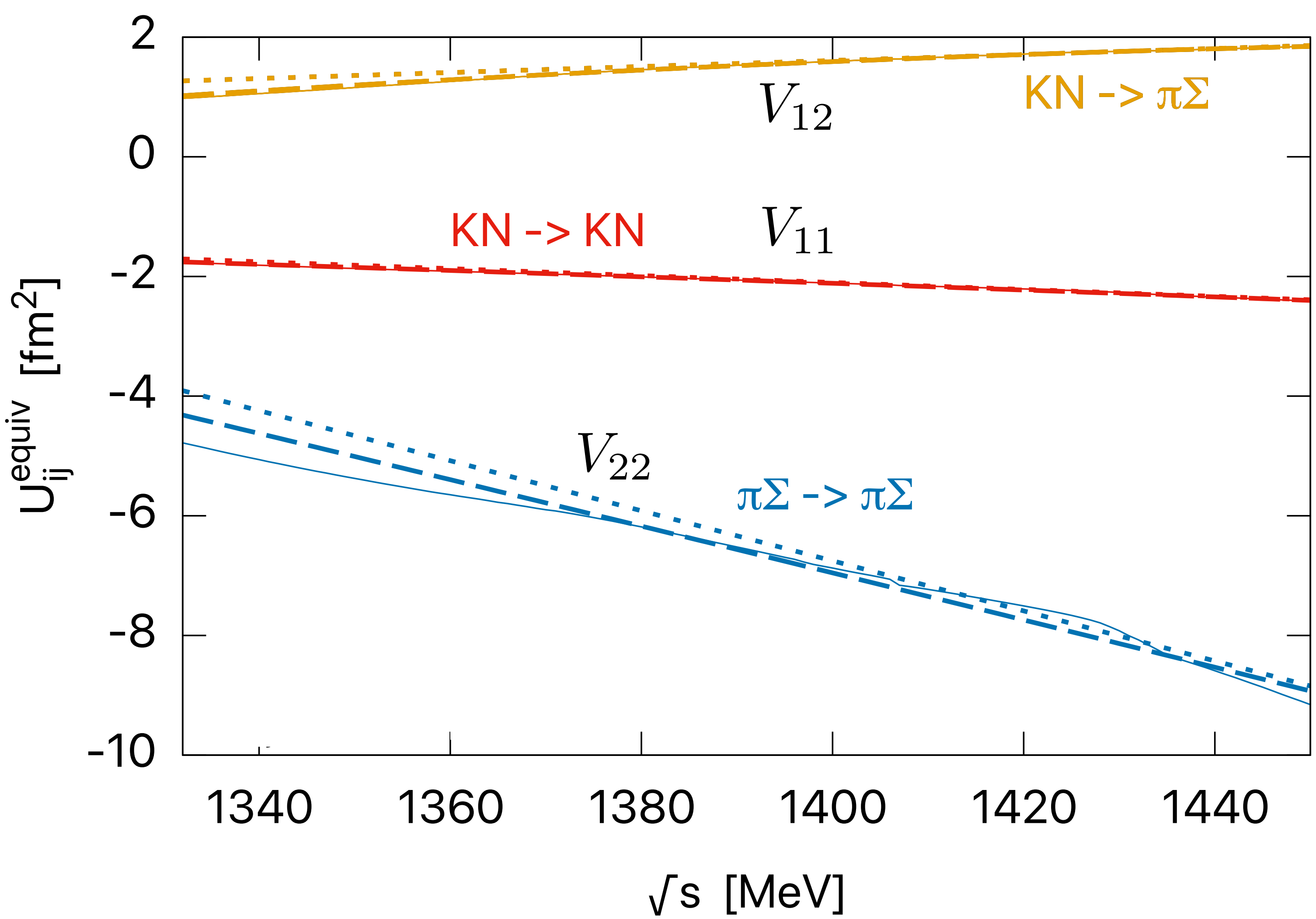


PHYSICAL REVIEW C **98**, 025201 (2018)

Construction of a local $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential and composition of the $\Lambda(1405)$

Kenta Miyahara,[1,*] Tetsuo Hyodo,[2] and Wolfram Weise[3]
[1]*Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*
[2]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[3]*Physik-Department, Technische Universität München, 85748 Garching, Germany*

Local and energy-dependent potentials $\mathbf{V_{ij}(r,\sqrt{s}) = U_{ij}(\sqrt{s})\,g_{ij}(r)}$



… useful for extrapolations to higher energies

… reproduce T-matrix when solving coupled-channels Schrödinger equation

PTEP

Prog. Theor. Exp. Phys. 2019, 013D01 (23 pages)
DOI: 10.1093/ptep/pty130

KN scattering amplitude revisited in a chiral unitary approach and a possible broad resonance in $S = +1$ channel

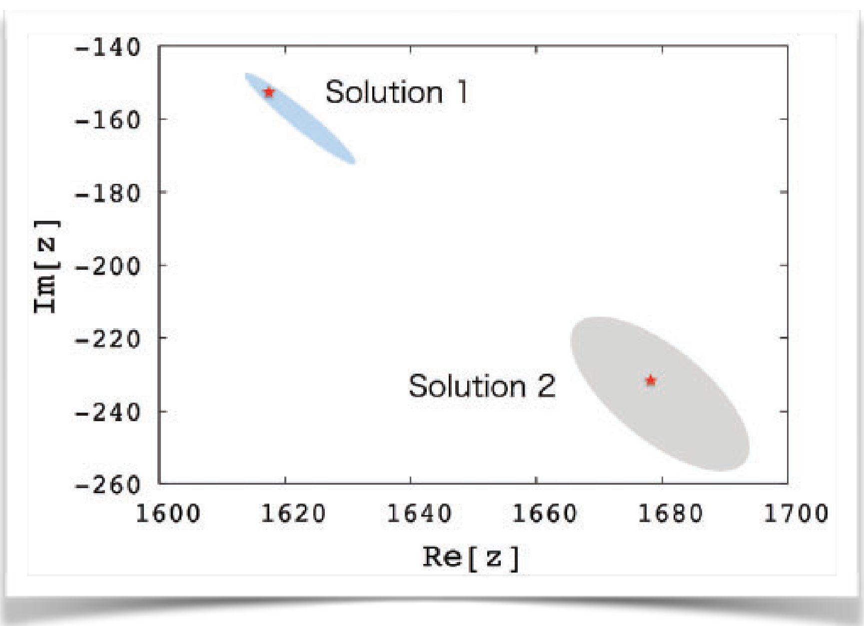
Kenji Aoki[1,2,*] and Daisuke Jido[2,1]

[1] *Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan*
[2] *Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Megro, Tokyo 152-8551, Japan*

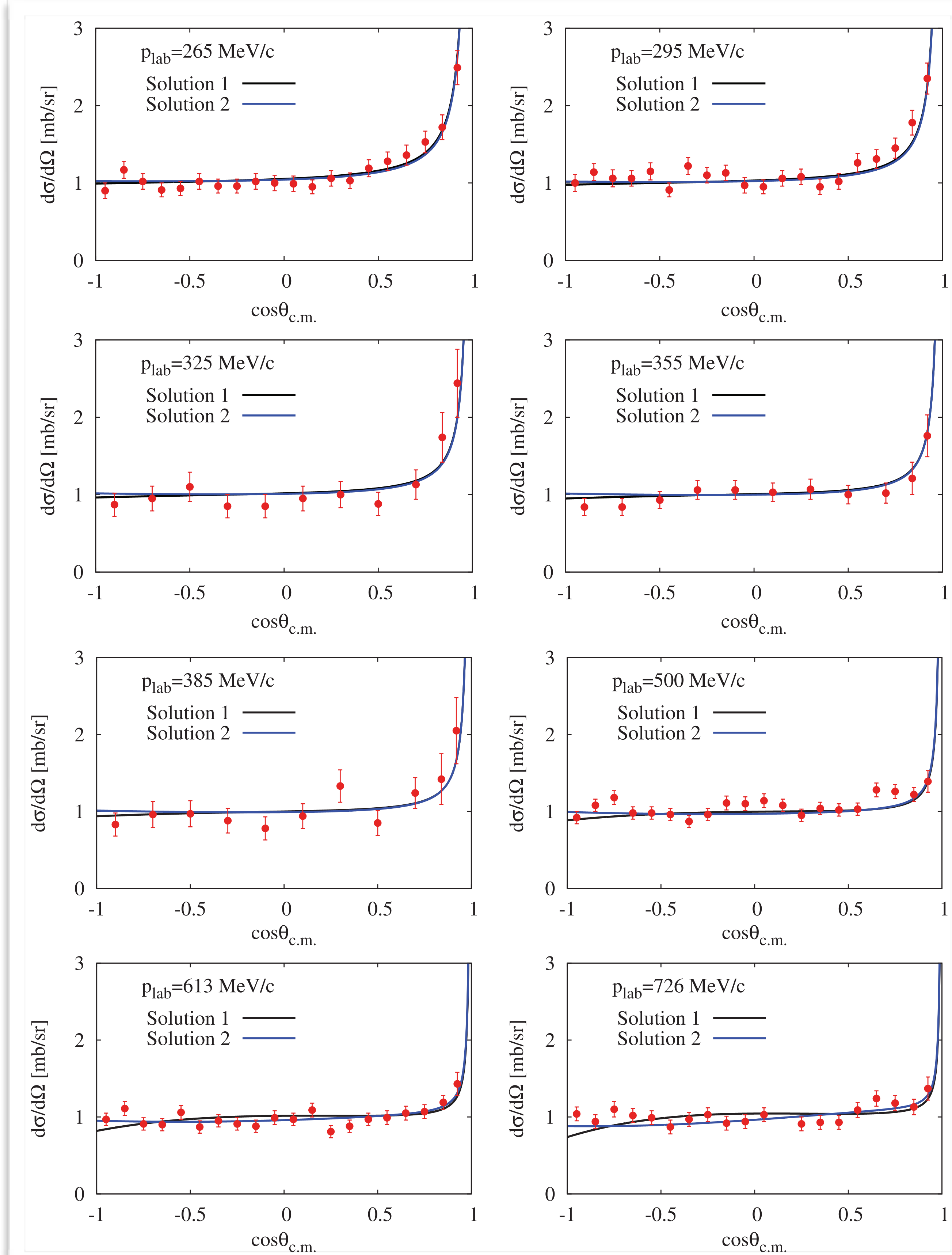
- Chiral SU(3) NLO calculations of K^+p and K^+n scattering
- Broad resonances in I = 0 KN

Table 3. The resonance states of Solutions 1 and 2.

amplitude (J^P)	mass [MeV]	width [MeV]
Solution 1 $P_{01}\left(\frac{1}{2}^+\right)$	1617	305
Solution 2 $P_{03}\left(\frac{3}{2}^+\right)$	1678	463



K^+p differential cross sections

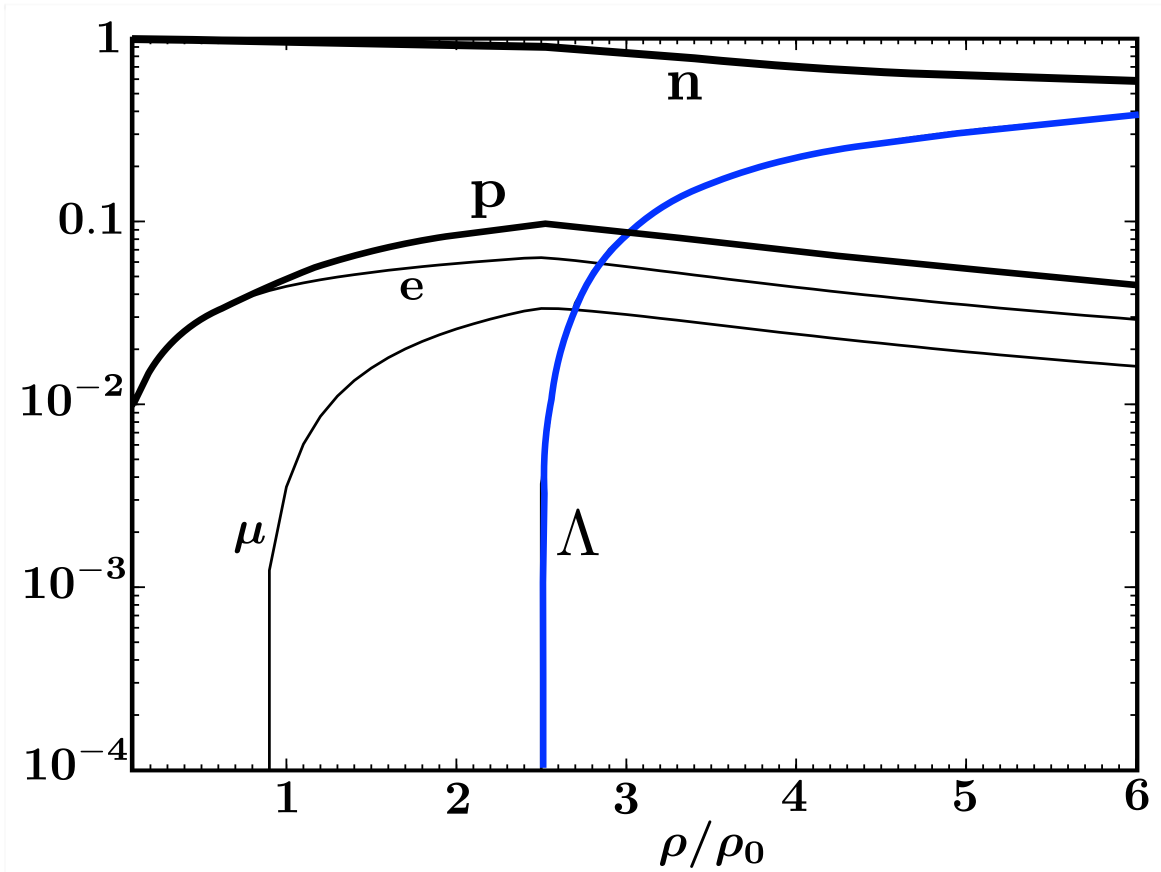


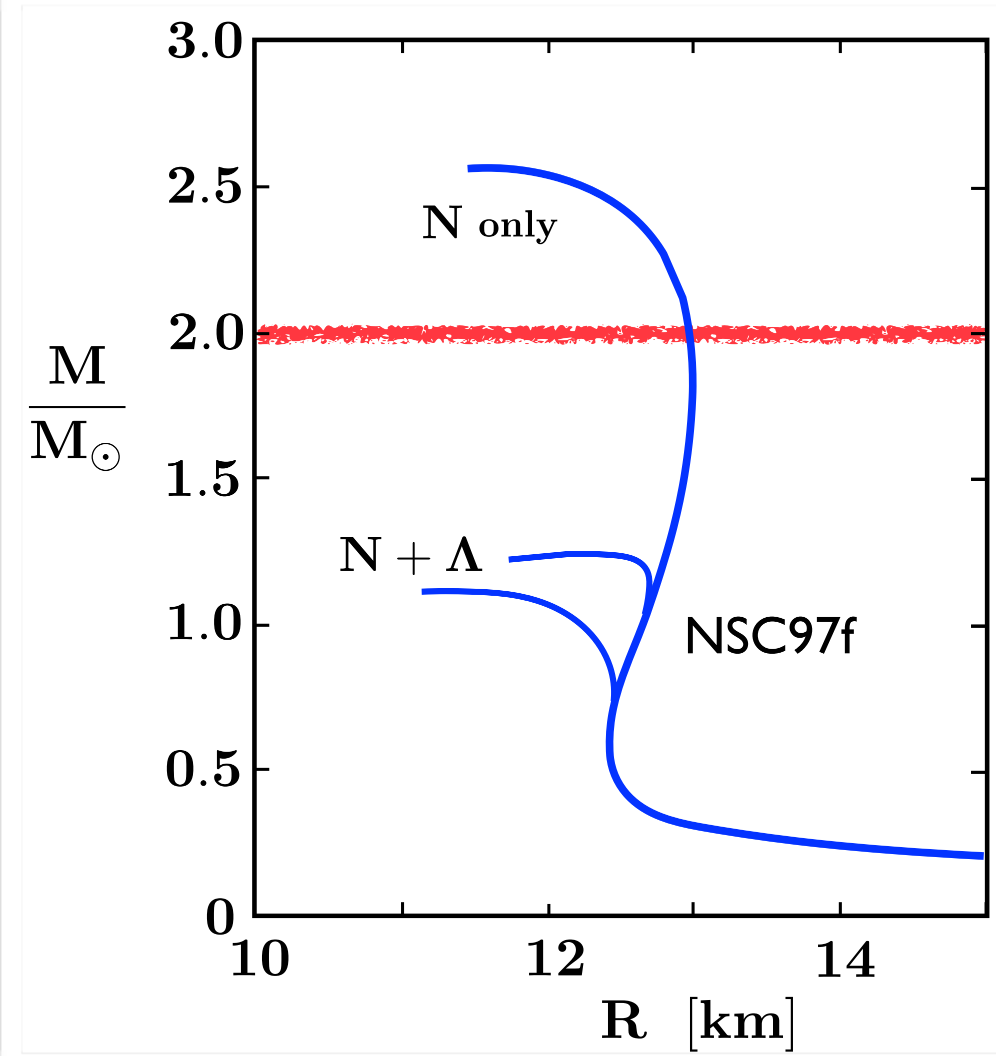
Part II.
Hyperon-Nuclear Interactions and Strangeness in Dense Matter

- **Chiral SU(3) Effective Field Theory of Hyperon-Nucleon Interactions**
- **Two- and Three-Body Forces**
- **"Hyperon Puzzle" in Neutron Stars**

NEUTRON STAR MATTER including HYPERONS

H. Djapo, B.-J. Schaefer, J. Wambach
Phys. Rev. C81 (2010) 035803





- Adding hyperons ⟶ Equation of State far too soft

"Hyperon Puzzle"

NEUTRON STAR MATTER including HYPERONS

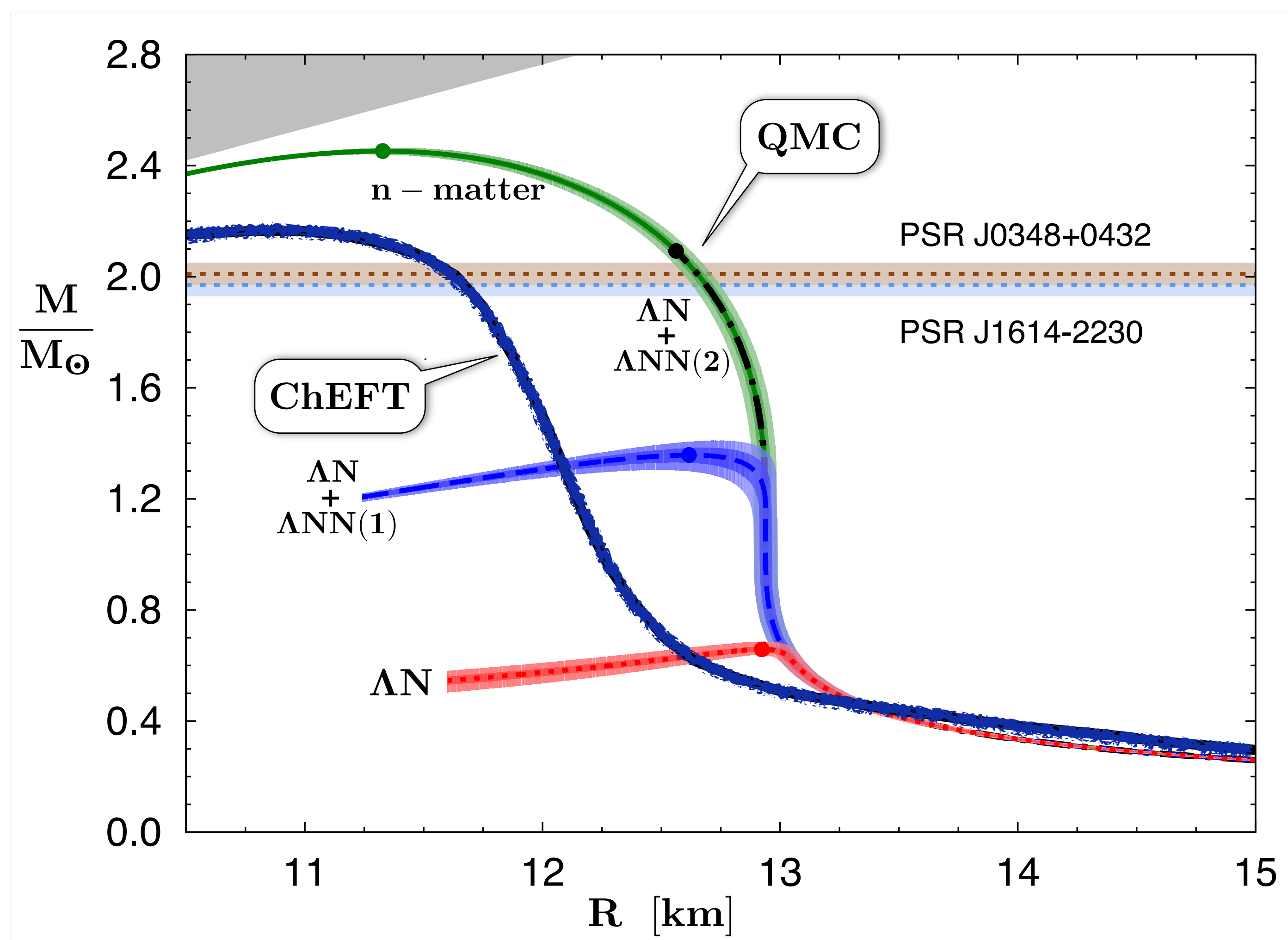
Quantum Monte Carlo **calculations** using phenomenological hyperon-nucleon and hyperon-NN **three-body** interactions constrained by **hypernuclei**

ChEFT calculations "conventional" n-star matter

T. Hell, W.W.
PR C90 (2014) 045801

ChEFT + FRG

M. Drews, W.W.
Prog. Part. Nucl. Phys. 93 (2017) 69
PR C91 (2015) 035802



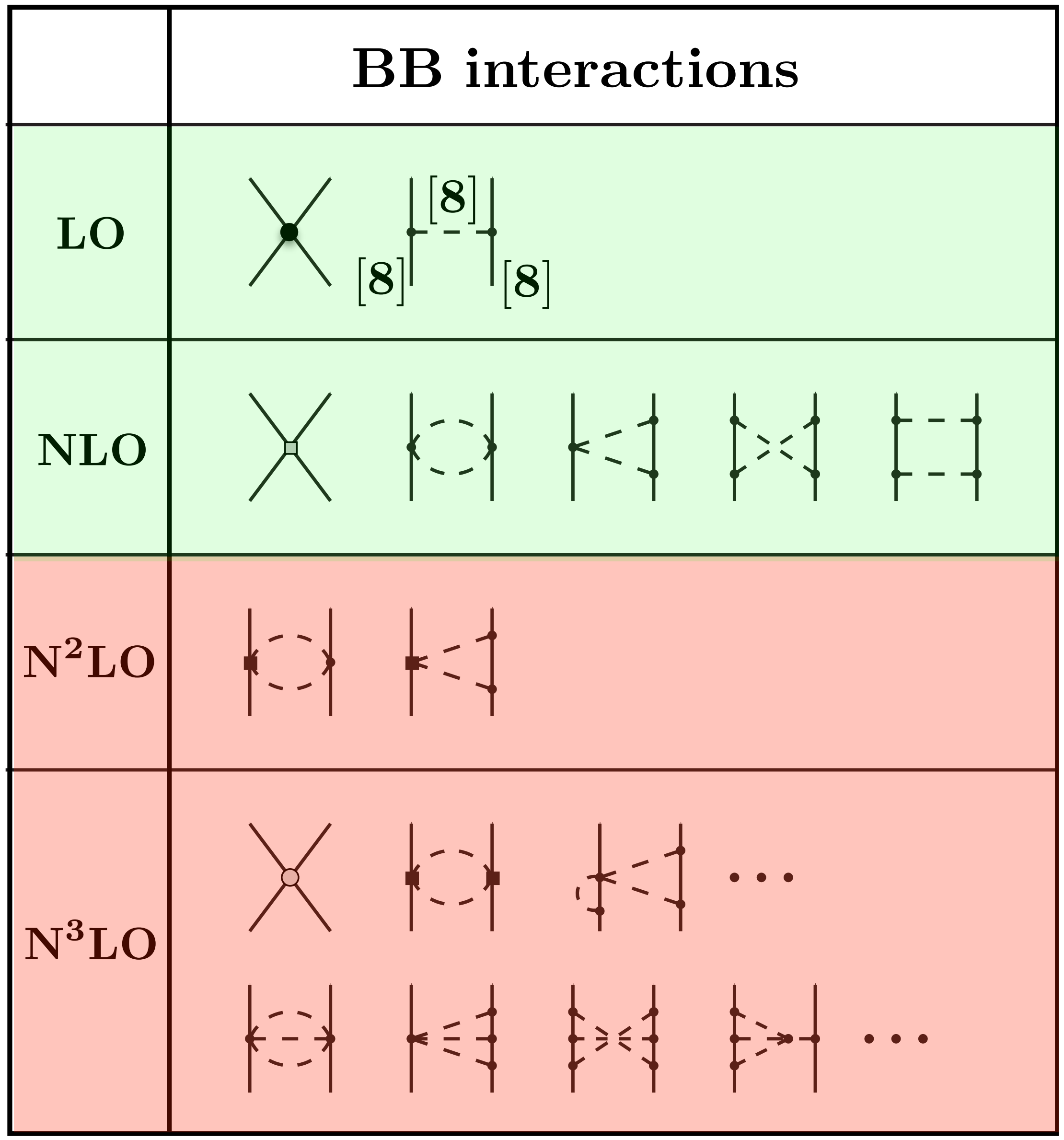
QMC computations (hyper-neutron matter)

D. Lonardoni,
A. Lovato,
S. Gandolfi,
F. Pederiva

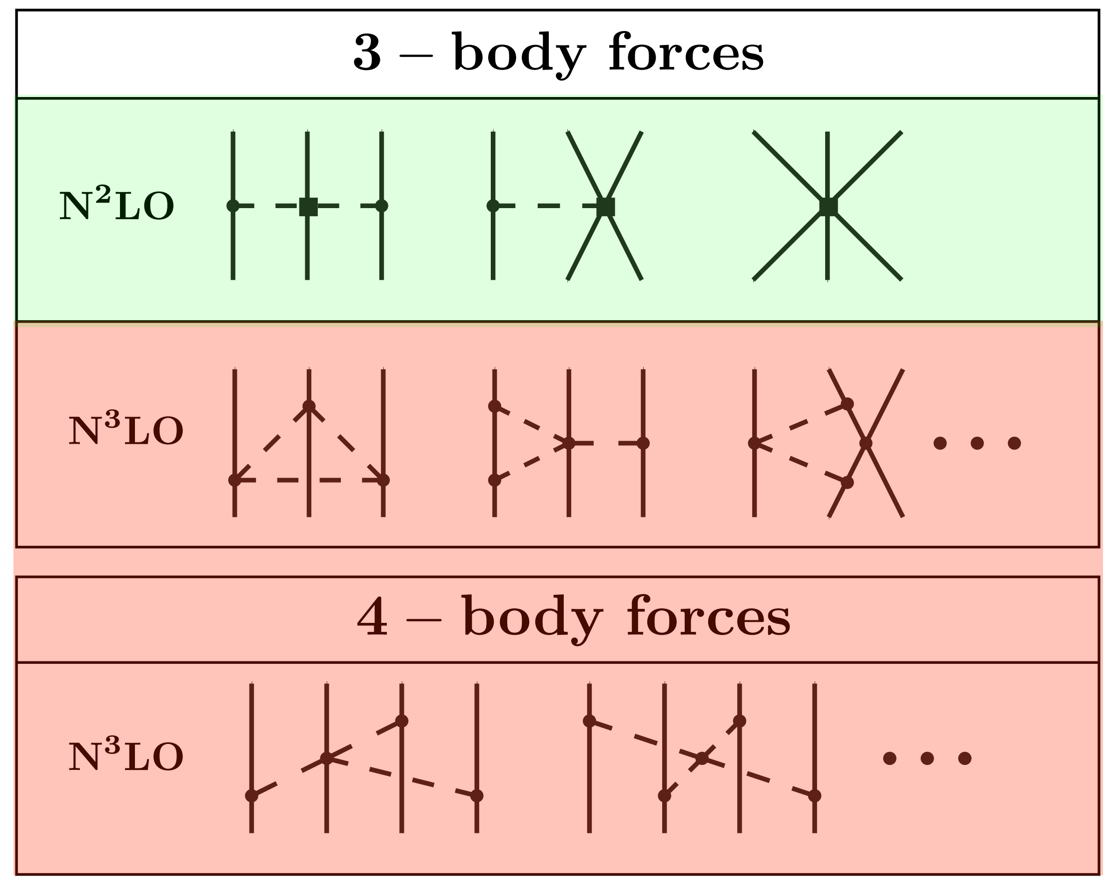
Phys. Rev. Lett. 114 (2015) 092301

Inclusion of **hyperons**: EoS **too soft** to support 2-solar-mass n-stars unless: **strong repulsion** in **YN** and **YNN** … interactions

BARYON-BARYON INTERACTIONS from **CHIRAL SU(3) EFFECTIVE FIELD THEORY**



- Systematically organized hierarchy in powers of $\frac{Q}{\Lambda}$
  (Q: momentum, energy, pion mass)



- **NN interaction :** has reached $\mathrm{N^4LO}$ level
- **YN interaction :** so far very limited empirical data base
  ⟶ **restriction** to NLO plus **YNN three-body forces**

Chiral SU(3) Effective Field Theory and Hyperon-Nucleon Interactions

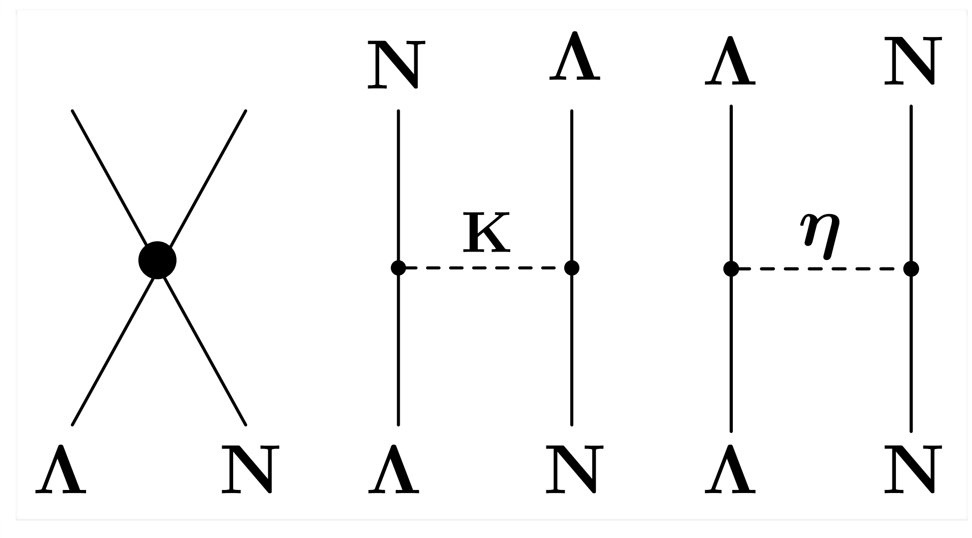
J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W.: Nucl. Phys. A 915 (2013) 24

Example:

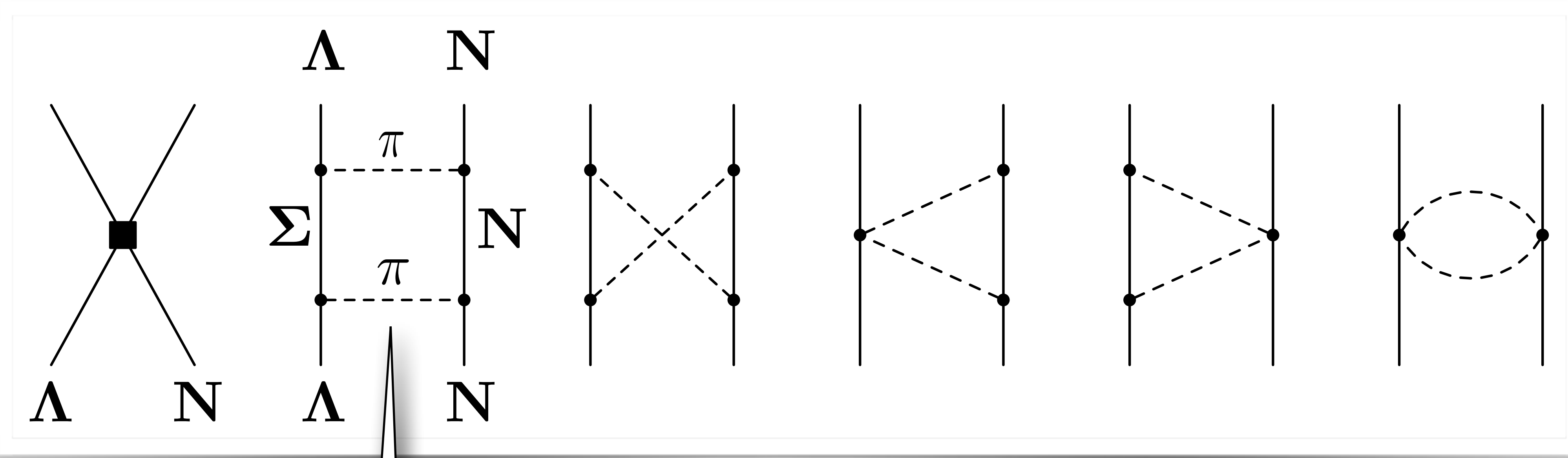
Λ N

interaction

- **Leading order (LO)**

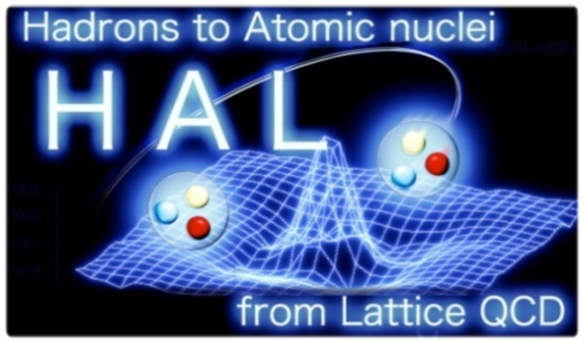


- **Next-to-leading order (NLO)**



2nd order tensor force

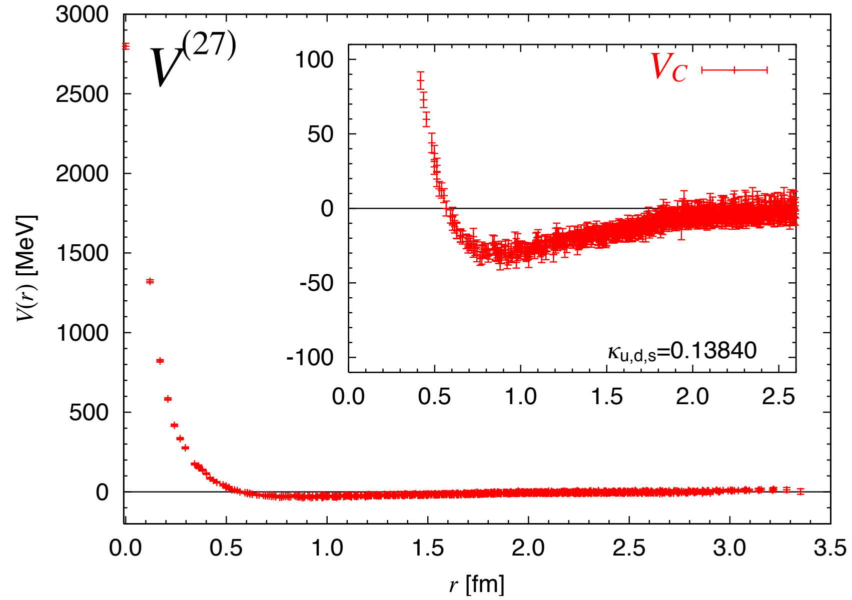
Hyperon - Nucleon Interactions from **Lattice QCD**

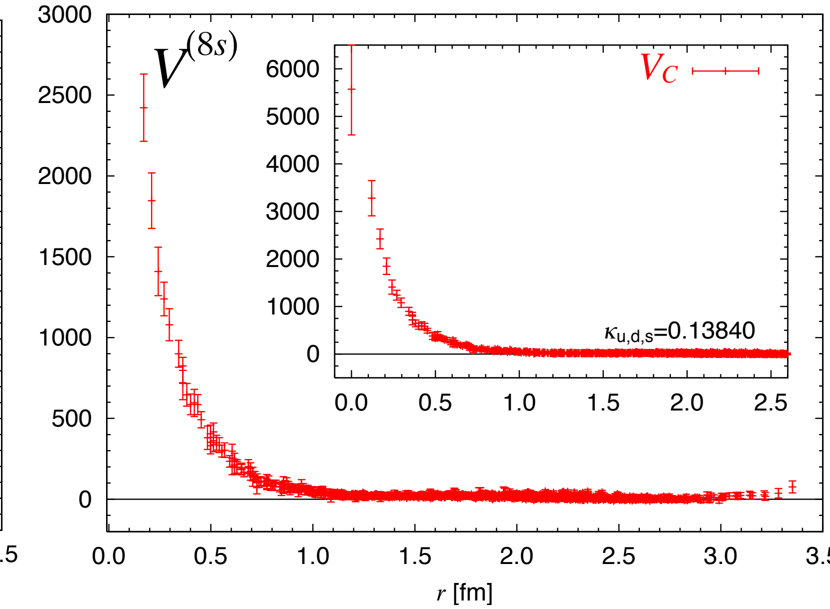


$$\mathbf{m_{ps}} = \mathbf{0.47\,GeV}$$

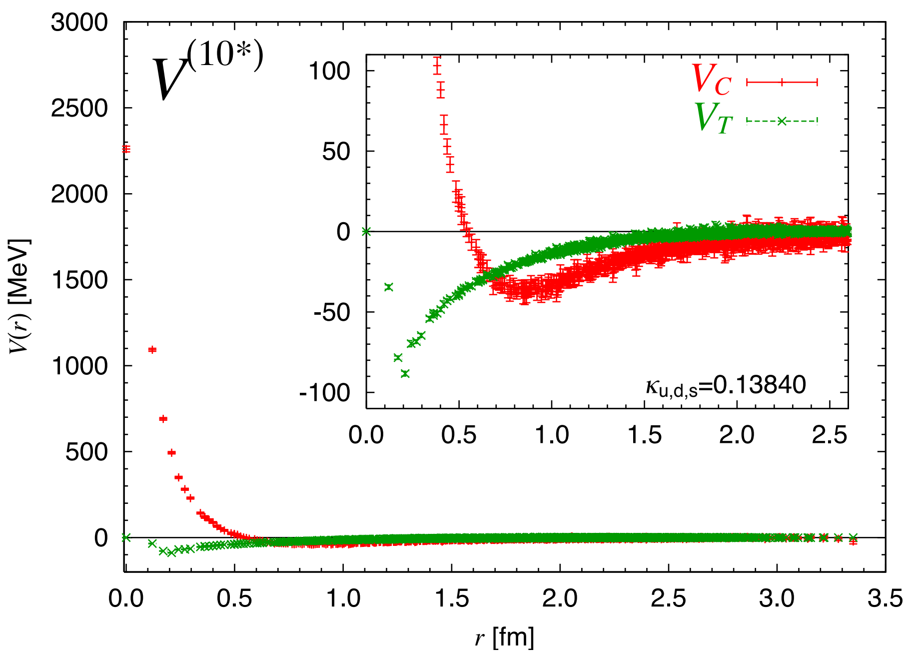
T. Inoue et al.
PTP 124 (2010) 591
Nucl. Phys. A881 (2012) 28

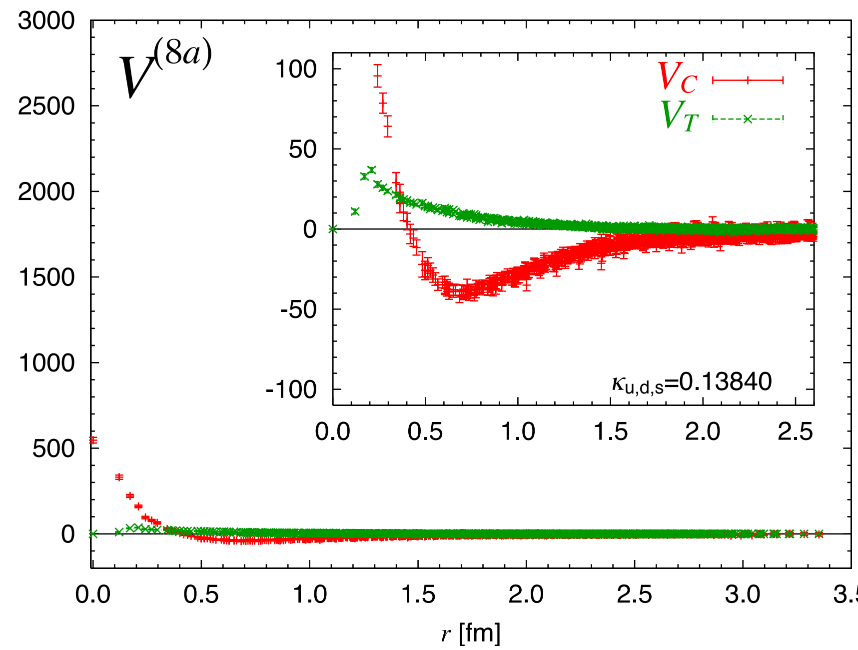
$$\Lambda\mathbf{N}(^1\mathbf{S_0}) = \frac{9}{10}[\mathbf{27}] + \frac{1}{10}[\mathbf{8_s}]$$





$$\Lambda\mathbf{N}(^3\mathbf{S_1}) = \frac{1}{2}[\mathbf{10^*}] + \frac{1}{2}[\mathbf{8_a}]$$



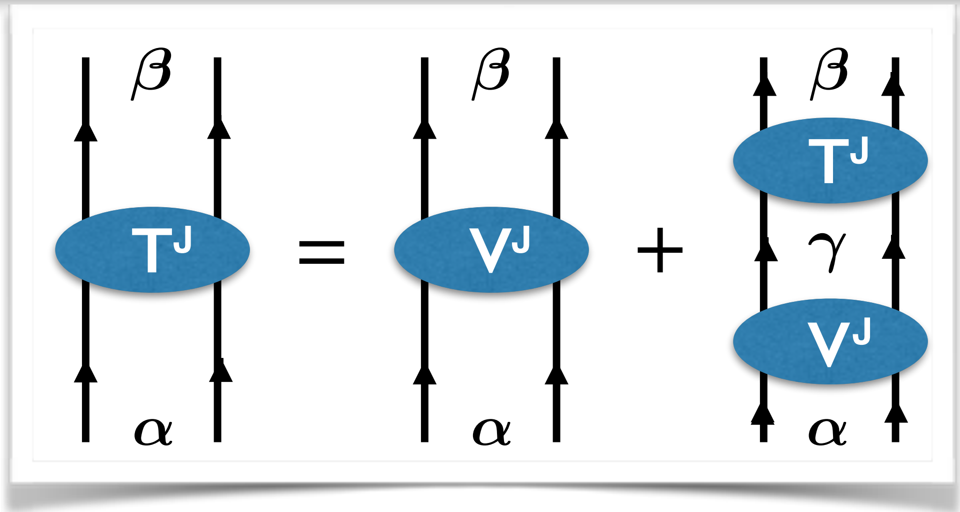


- new recent developments:

  towards physical quark masses

- **Strong short-distance repulsive interaction in all channels**

Coupled-Channels Lippmann-Schwinger Equation



- Partial waves (LS)J , baryon-baryon channels α, β

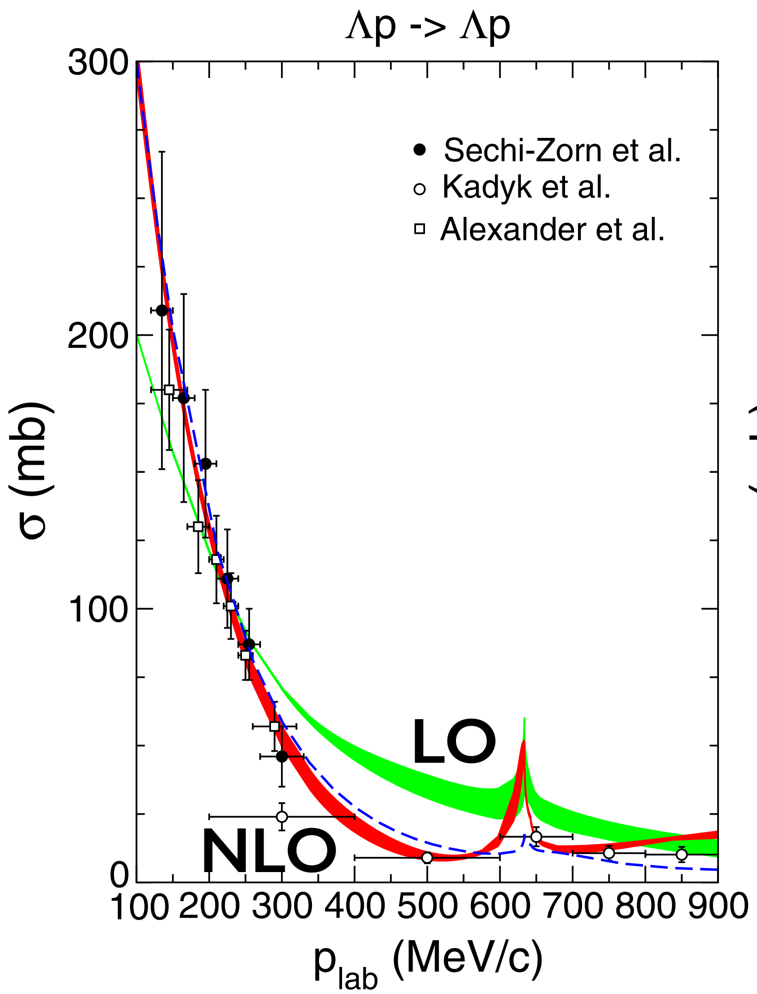
$$\mathbf{T}^J_{\beta\alpha}(p_f, p_i; \sqrt{s}) = \mathbf{V}^J_{\beta\alpha}(p_f, p_i) + \sum_\gamma \int_0^\infty \frac{dp\, p^2}{(2\pi)^3} \mathbf{V}^J_{\beta\gamma}(p_f, p) \frac{2\mu_\gamma}{p_\gamma^2 - p^2 + i\varepsilon} \mathbf{T}^J_{\gamma\alpha}(p, p_i; \sqrt{s})$$

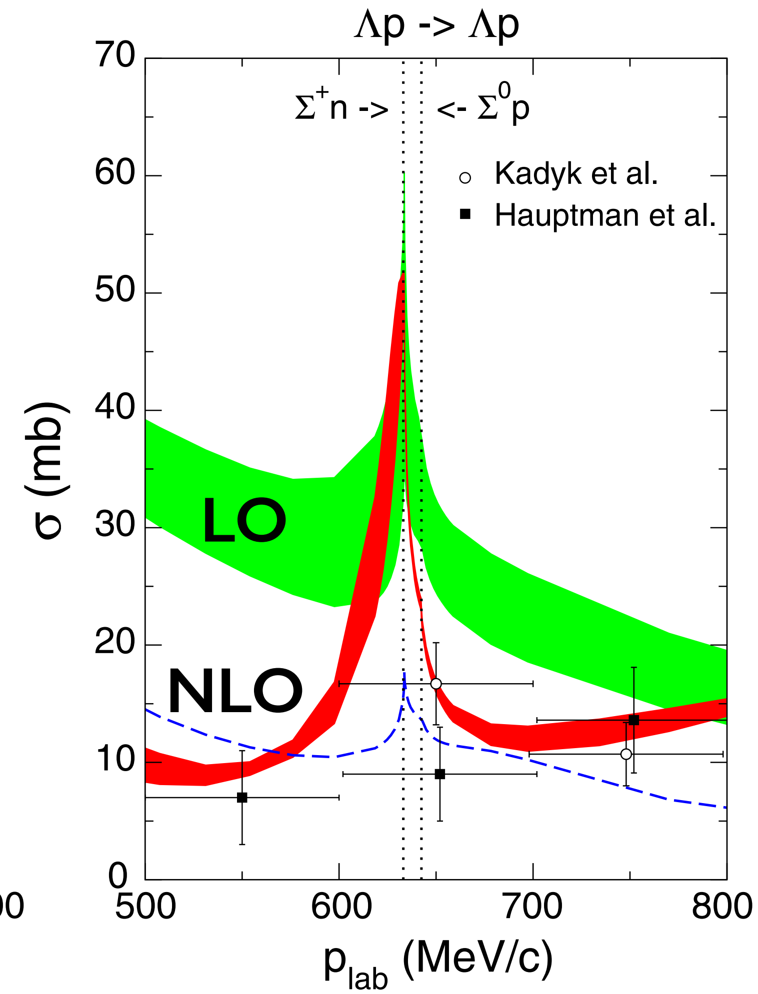
- On-shell momentum of intermediate channel γ determined by :

$$\sqrt{s} = \sqrt{M^2_{\gamma,1} + p^2_\gamma} + \sqrt{M^2_{\gamma,2} + p^2_\gamma}$$

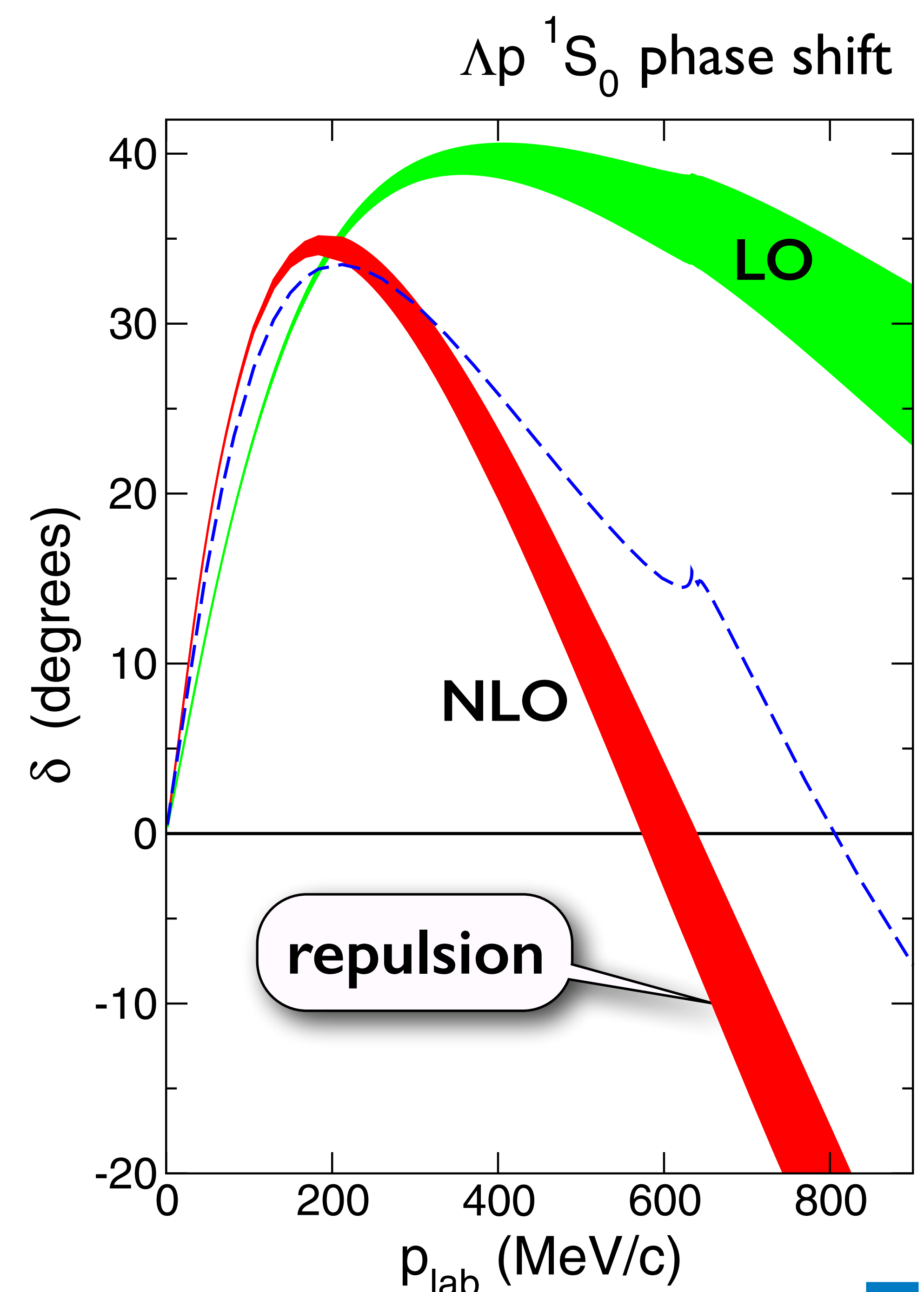
- Relativistic kinematics relating lab. and c.m. momenta
- Momentum space cutoffs: 0.5 - 0.6 GeV

Hyperon - Nucleon Interaction
from Chiral SU(3) EFT





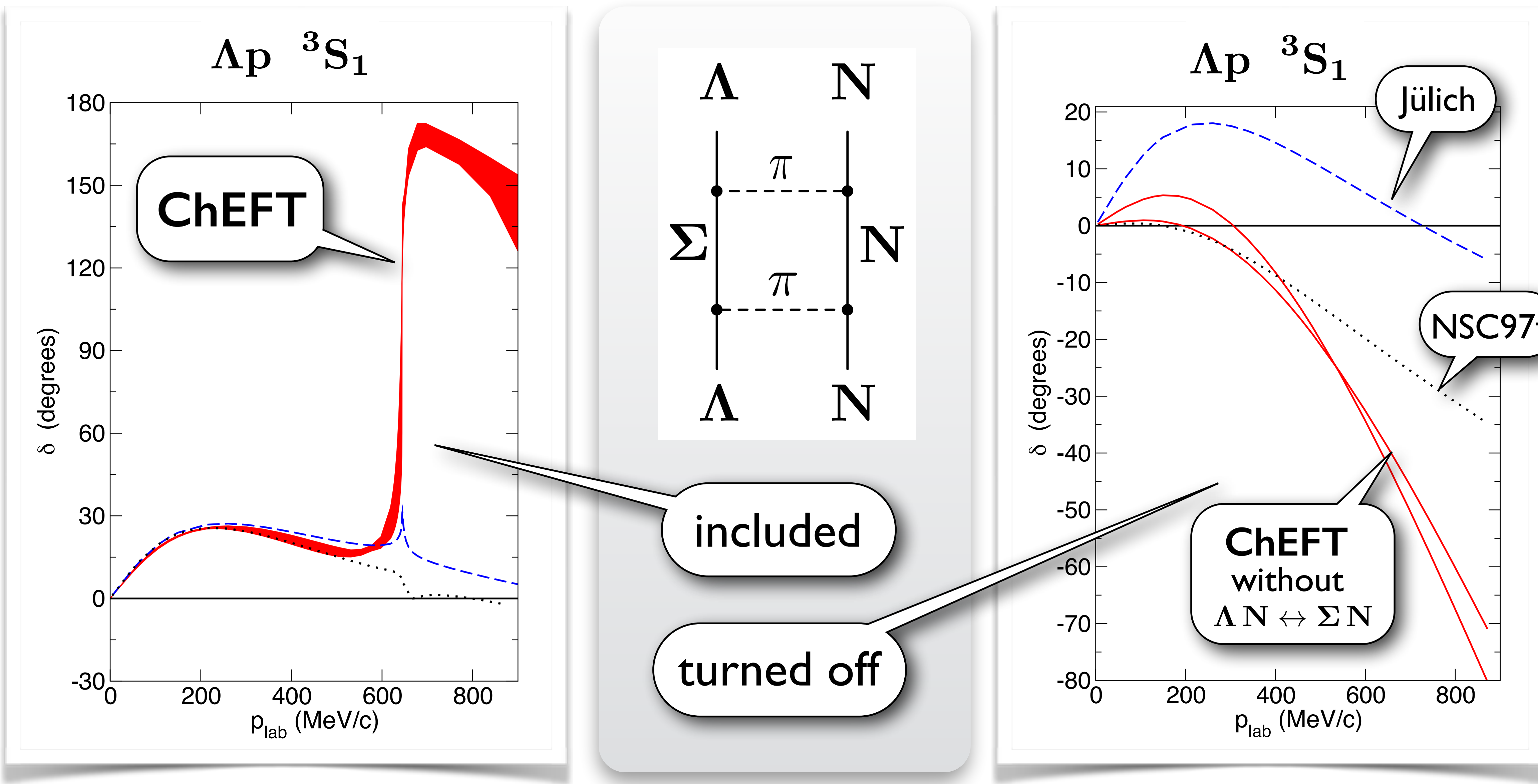
J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W. Nucl. Phys. A 915 (2013) 24



- **moderate attraction** at **low momenta**
  → relevant for **hypernuclei**
- **strong repulsion** at **higher momenta**
  → relevant for **dense baryonic matter**

Hyperon - Nucleon Interaction
(contd.)

- Triplet-S channel and $\Lambda N \leftrightarrow \Sigma N$ **coupling** (2nd order tensor force)



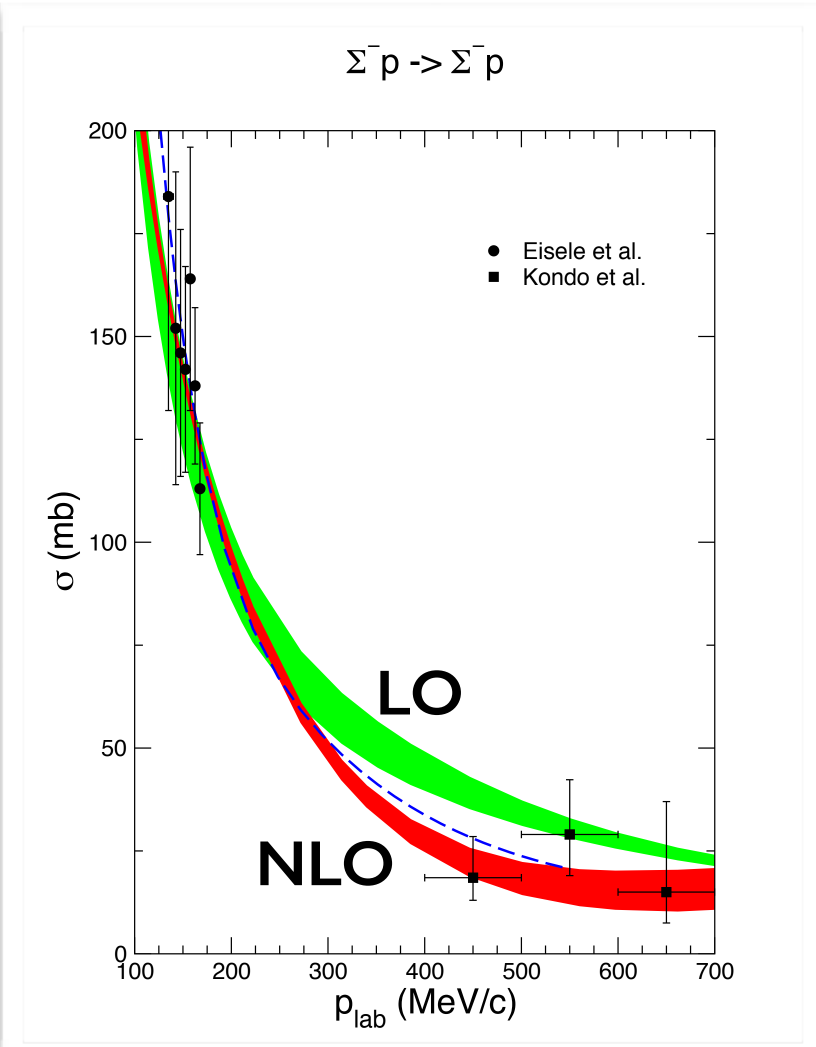
- In-medium (Pauli) **suppression** of $\Lambda N \leftrightarrow \Sigma N$ **coupling :**

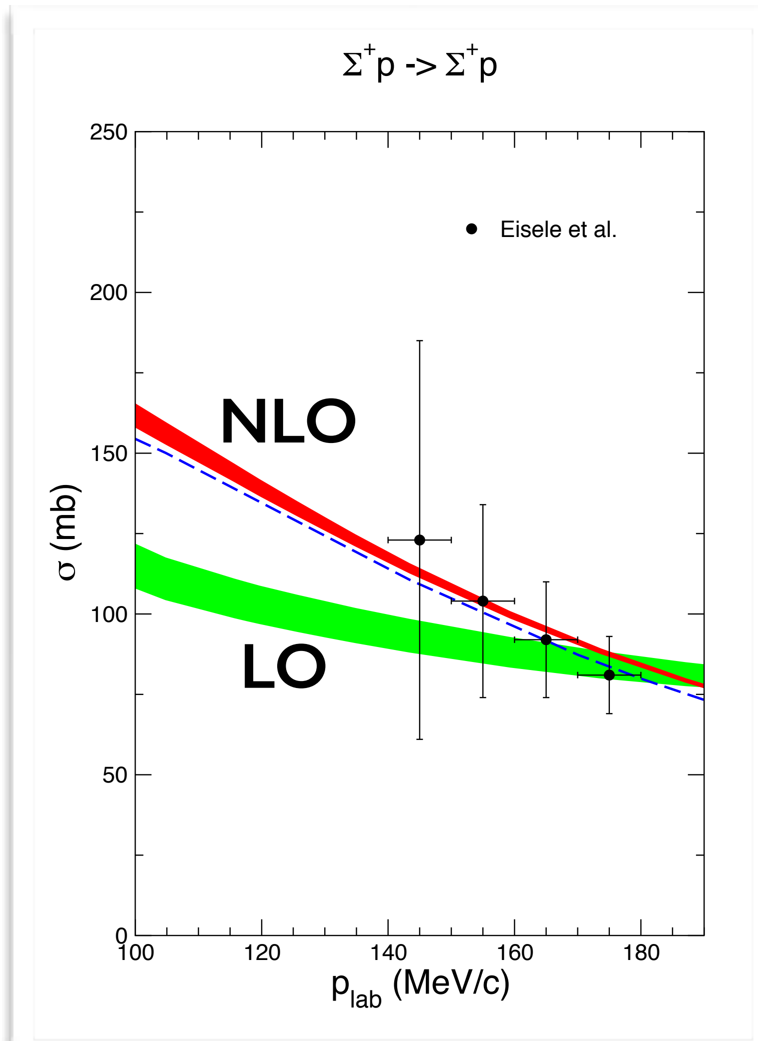
increasing repulsion with rising density

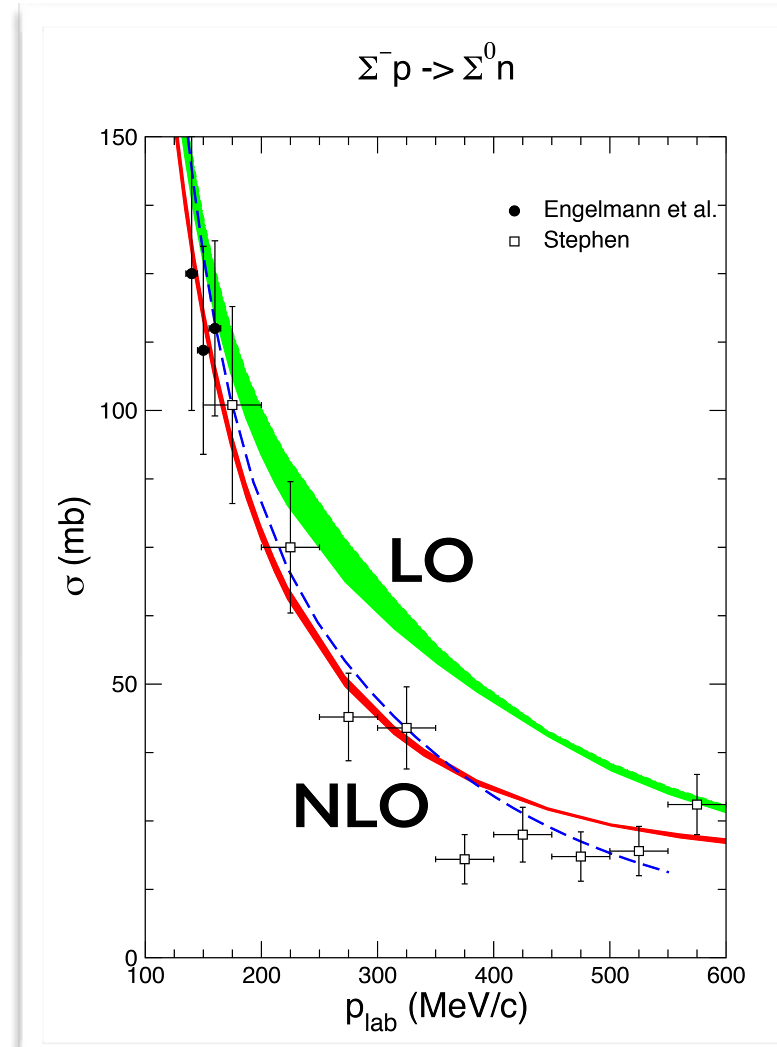
Hyperon - Nucleon Interaction (contd.)

J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W.
Nucl. Phys. A 915 (2013) 24

- **ΣN elastic and charge exchange scattering**







- **Quest for much improved hyperon-nucleon scattering data base !**

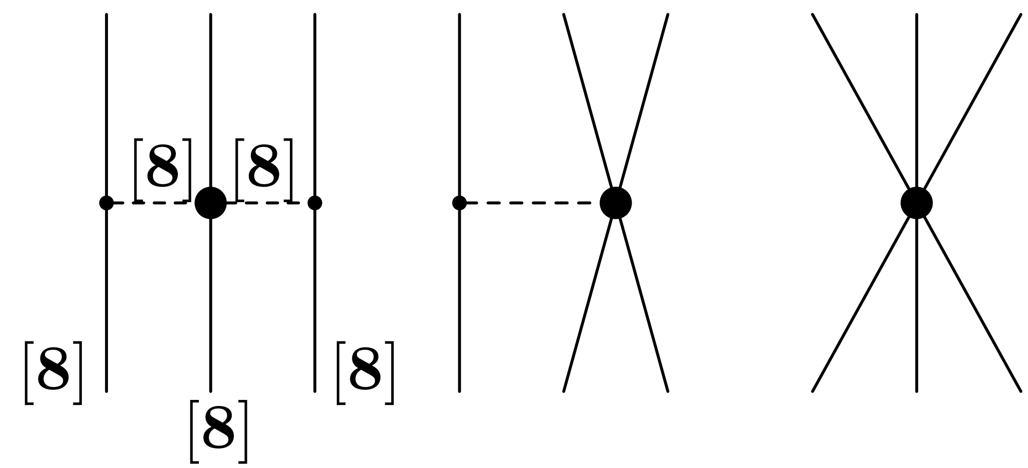
HYPERON - NUCLEON - NUCLEON THREE-BODY FORCES from CHIRAL SU(3) EFT

S. Petschauer et al. Phys. Rev. C93 (2016) 014001

- **Chiral SU(3) Effective Field Theory:**
  interacting pseudoscalar meson & baryon octets + contact terms

3-baryon sector:

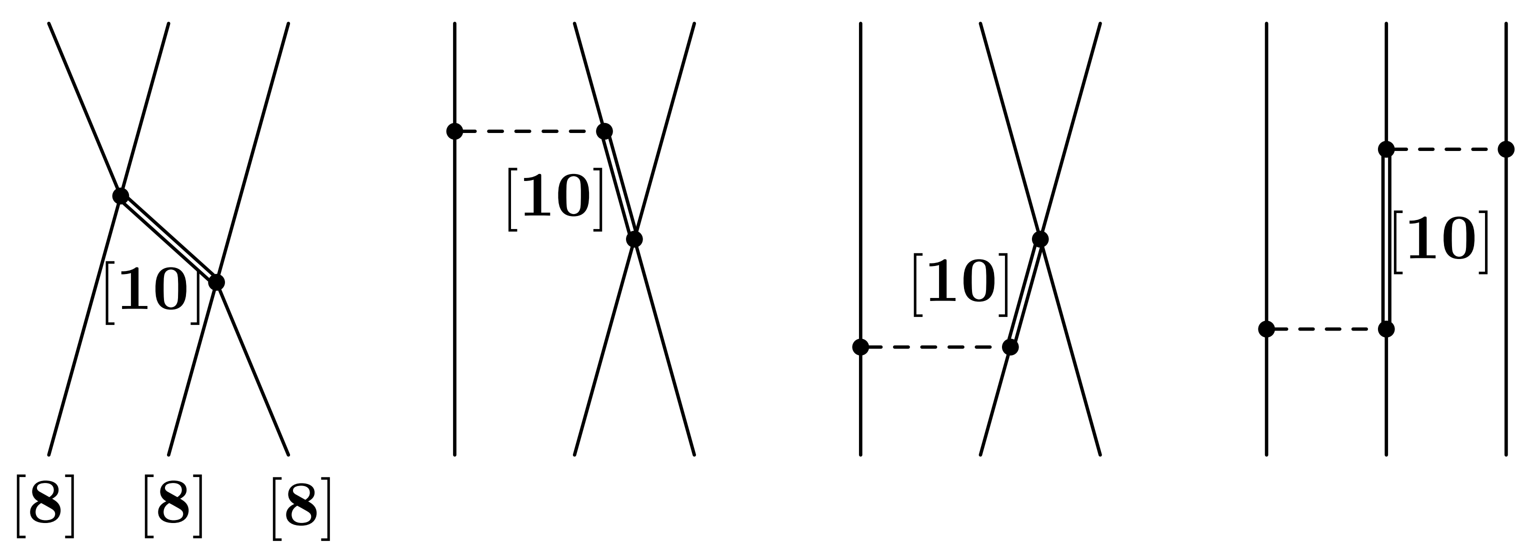
NNLO:



- Chiral SU(3) Effective Field Theory with **explicit decuplet baryons**:

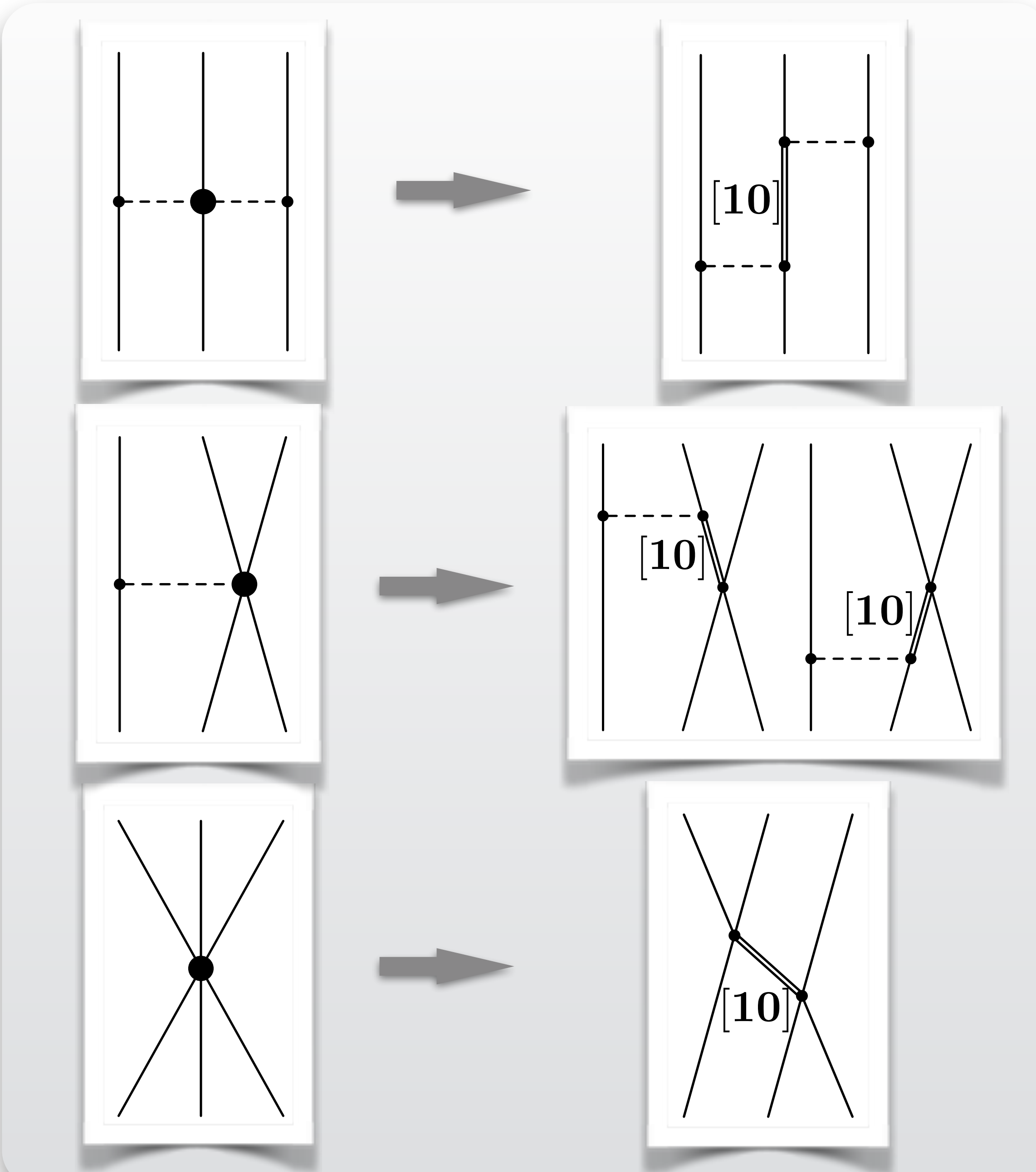
explicit treatment of **baryon decuplet** :

promotion to **NLO**

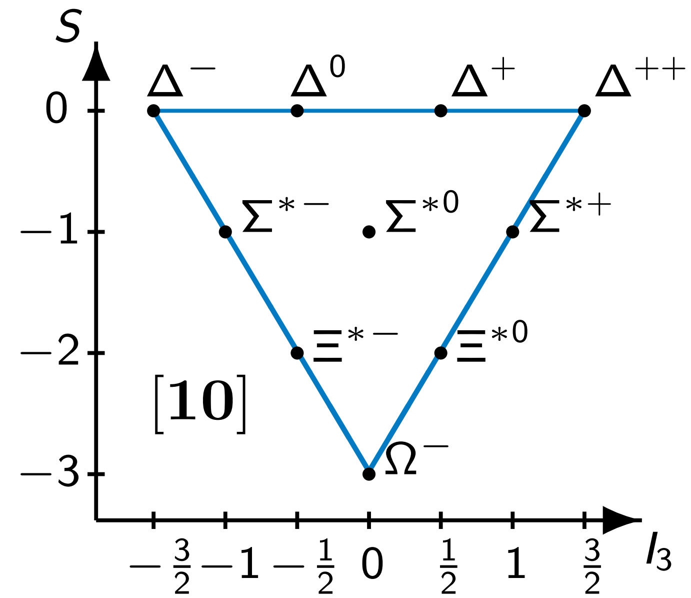


Decuplet Dominance
in YNN three-body forces

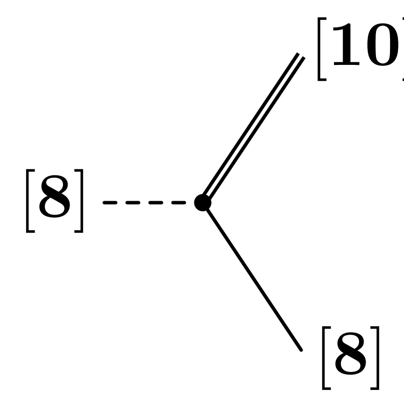
- Estimates of **YNN** 3-body interactions assuming dominant **decuplet** (Σ^*, Δ) intermediate states



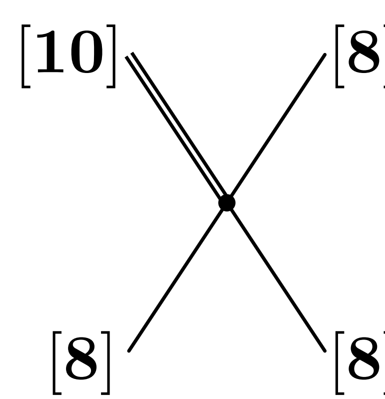
promotion from **NNLO** to **NLO**



- … much reduced set of parameters - **Basic vertices :**



One constant
$(C = \frac{3}{4} g_A \approx 1 \text{ from } \Delta \to N\pi)$



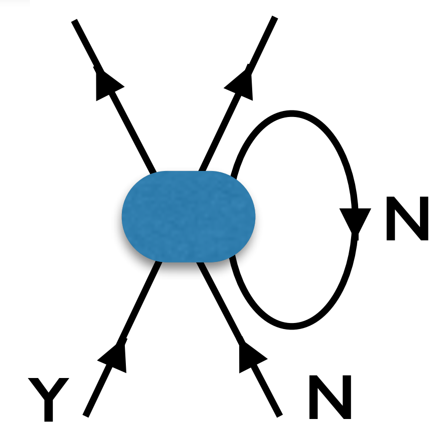
Pauli-forbidden
in NN sector

Two constants
$(\mathbf{H_1},\ \mathbf{H_2})$
(Typical magnitude $|\mathbf{H_i}| \sim \mathbf{f_\pi^{-2}}$**)**

Density-dependent EFFECTIVE HYPERON - NUCLEON INTERACTION from CHIRAL THREE-BARYON FORCES

S. Petschauer, J. Haidenbauer, N. Kaiser, U.-G. Meißner, W.W.   Nucl. Phys. A957 (2017) 347

$$V_{12}^{\text{eff}} = \sum_B \text{tr}_{\sigma_3} \int_{|\vec{k}| \leq k_f^B} \frac{d^3k}{(2\pi)^3} V_{123}$$



- Example: **Λ-neutron** density-dependent effective interaction in a nuclear medium (protons + neutrons)

$$V_{\Lambda n}^{\text{eff},\pi\pi} = \frac{C^2 g_A^2}{2f^4\,\Delta}[\rho_n + 2\rho_p] + \mathcal{F}(k_F^p, k_F^n; p, q) \qquad \textbf{repulsive}$$

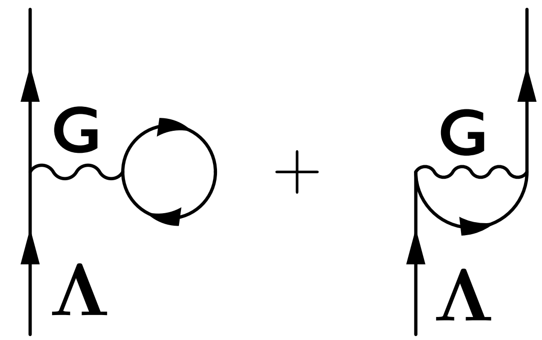
$$V_{\Lambda n}^{\text{eff},\pi} = \frac{C H\, g_A}{9f^2\,\Delta}[\rho_n + 2\rho_p] + \mathcal{G}(k_F^p, k_F^n; p, q) \qquad \textbf{+/-}$$

$$V_{\Lambda n}^{\text{eff},ct} = \frac{H^2}{18\Delta}[\rho_n + 2\rho_p] \qquad (H = H_1 + 3H_2) \qquad \textbf{repulsive}$$

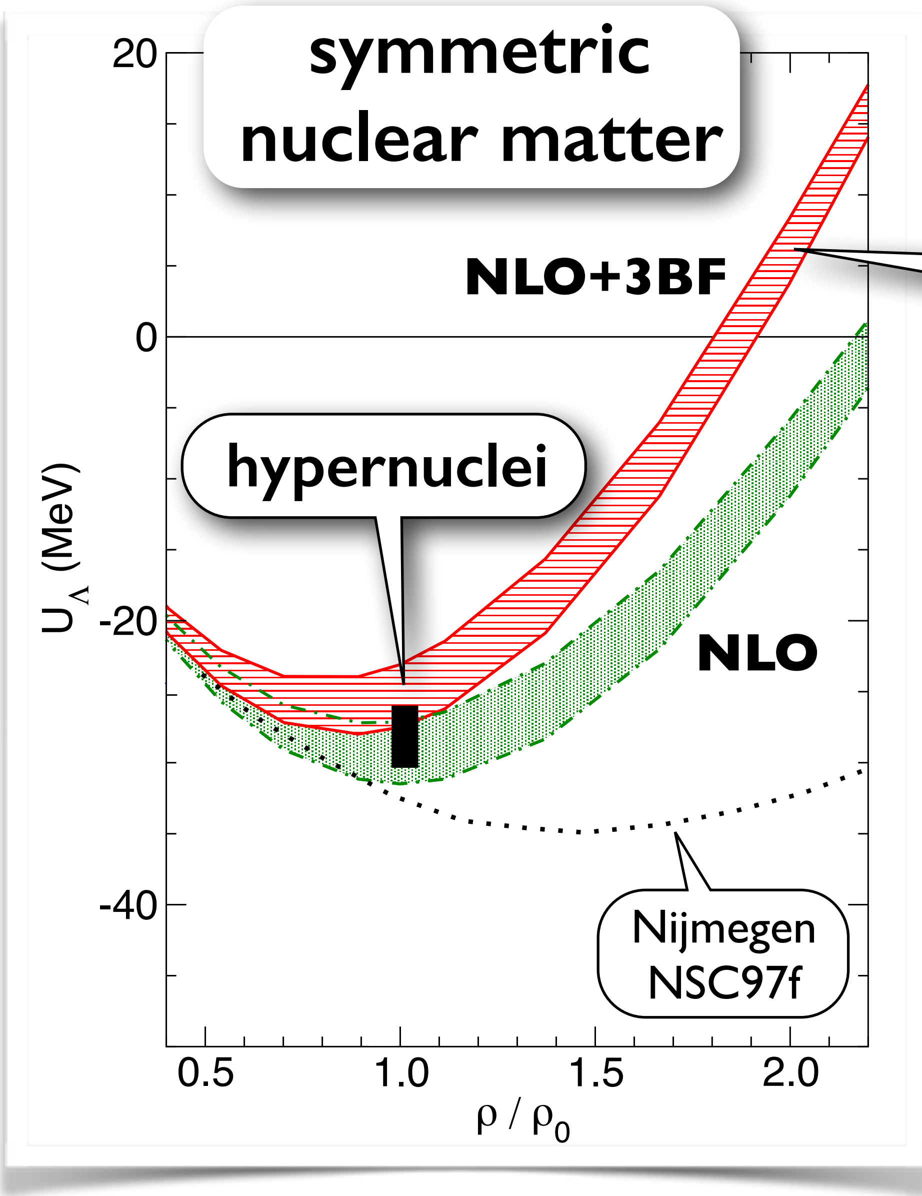
- **Decuplet-octet mass difference** $\Delta = M_{[10]} - M_{[8]} = 270\,MeV$
- **Coupling parameters :** $C = \frac{3}{4} g_A \simeq 1$ $\quad -\frac{1}{f^2} \lesssim H \lesssim +\frac{1}{f^2}$ (dim. arguments natural size)

Density dependence of Λ single particle potential

- **Brueckner calculations**
  using
  chiral SU(3) interactions



$$\mathbf{G}(\omega) = \mathbf{V} + \mathbf{V}\,\frac{\mathbf{Q}}{\mathbf{e}(\omega) + \mathbf{i}\epsilon}\,\mathbf{G}(\omega)$$

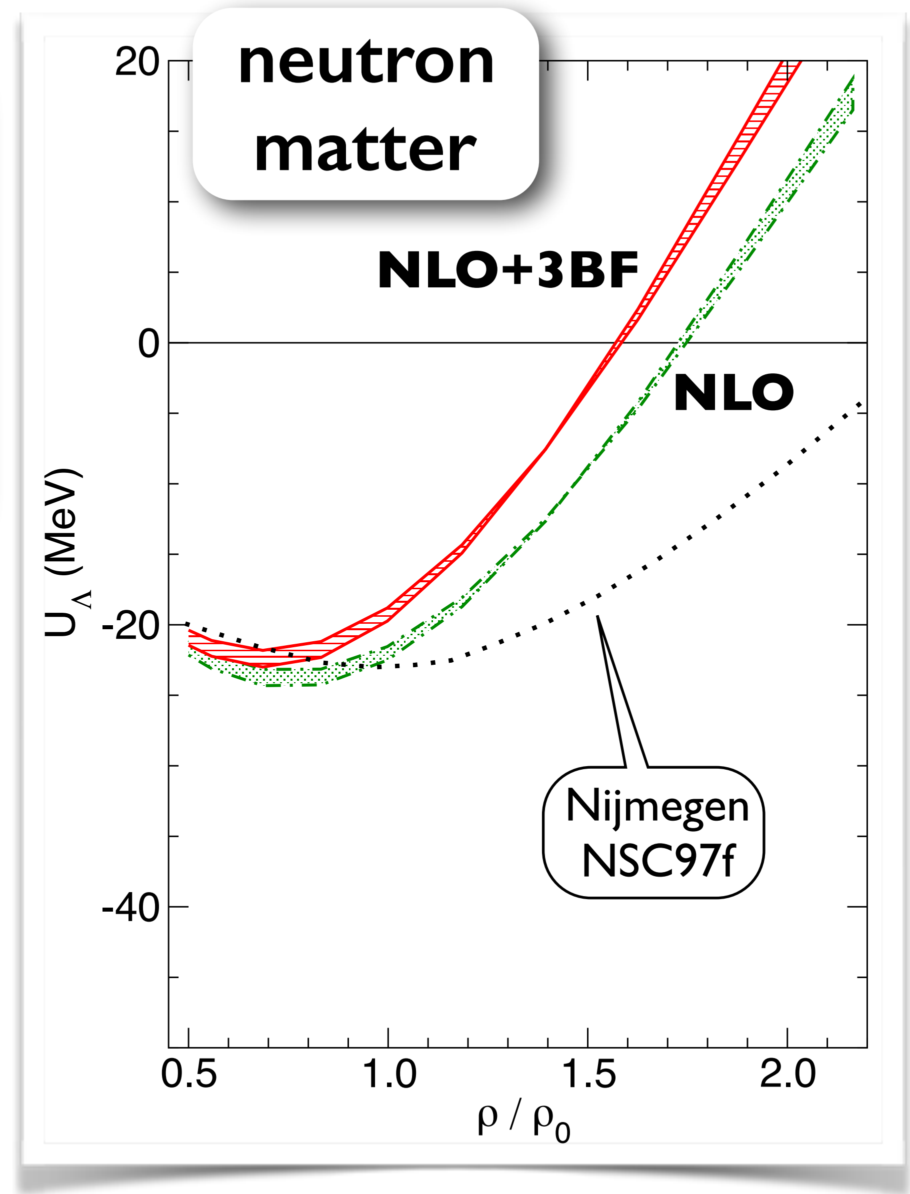


Chiral SU(3) 2- and 3-body forces

$$\left(H = -\frac{1}{f^2}\right)$$

J. Haidenbauer,
U.-G. Meißner,
N. Kaiser,
W.W.

Eur. Phys. J.
A53 (2017) 121

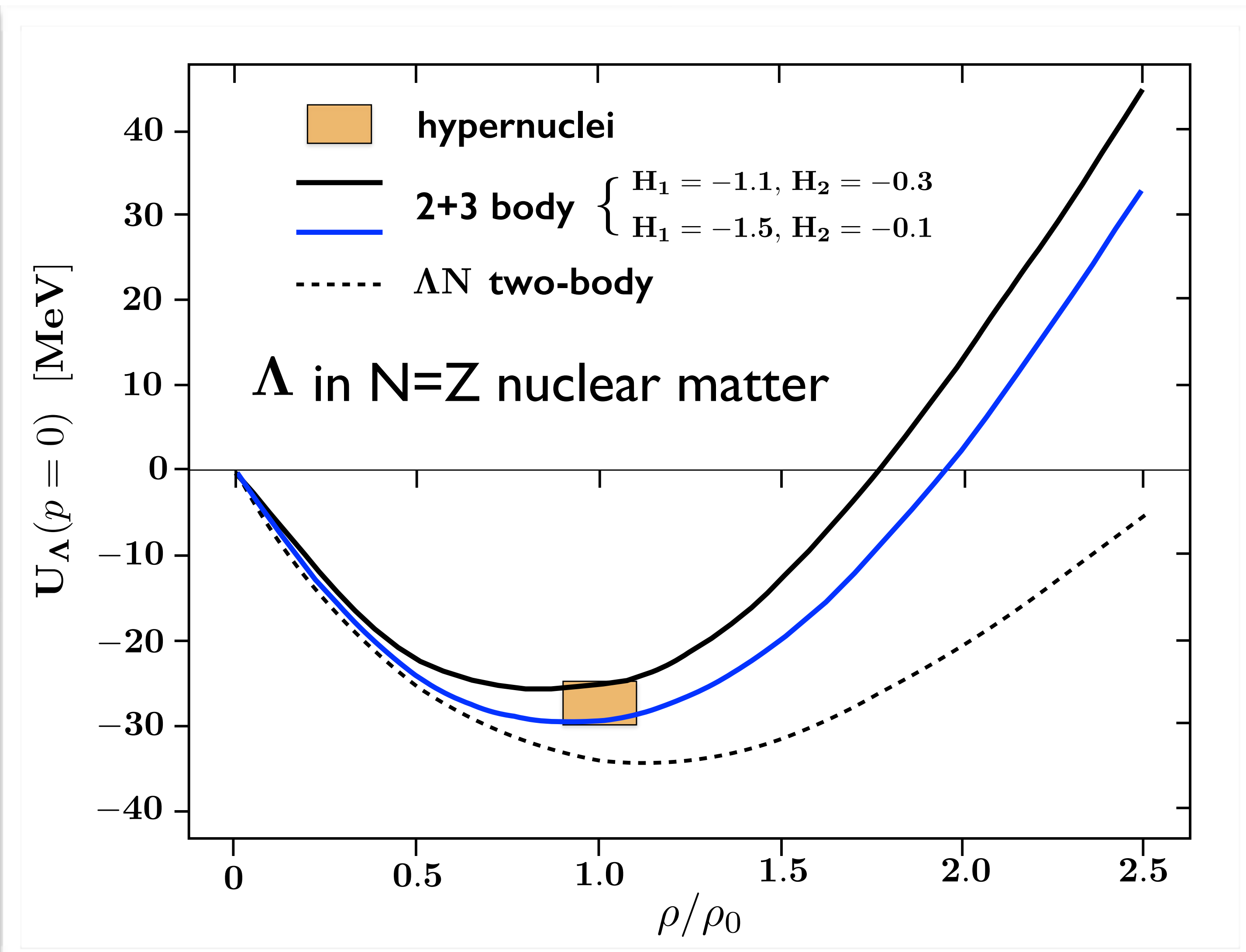


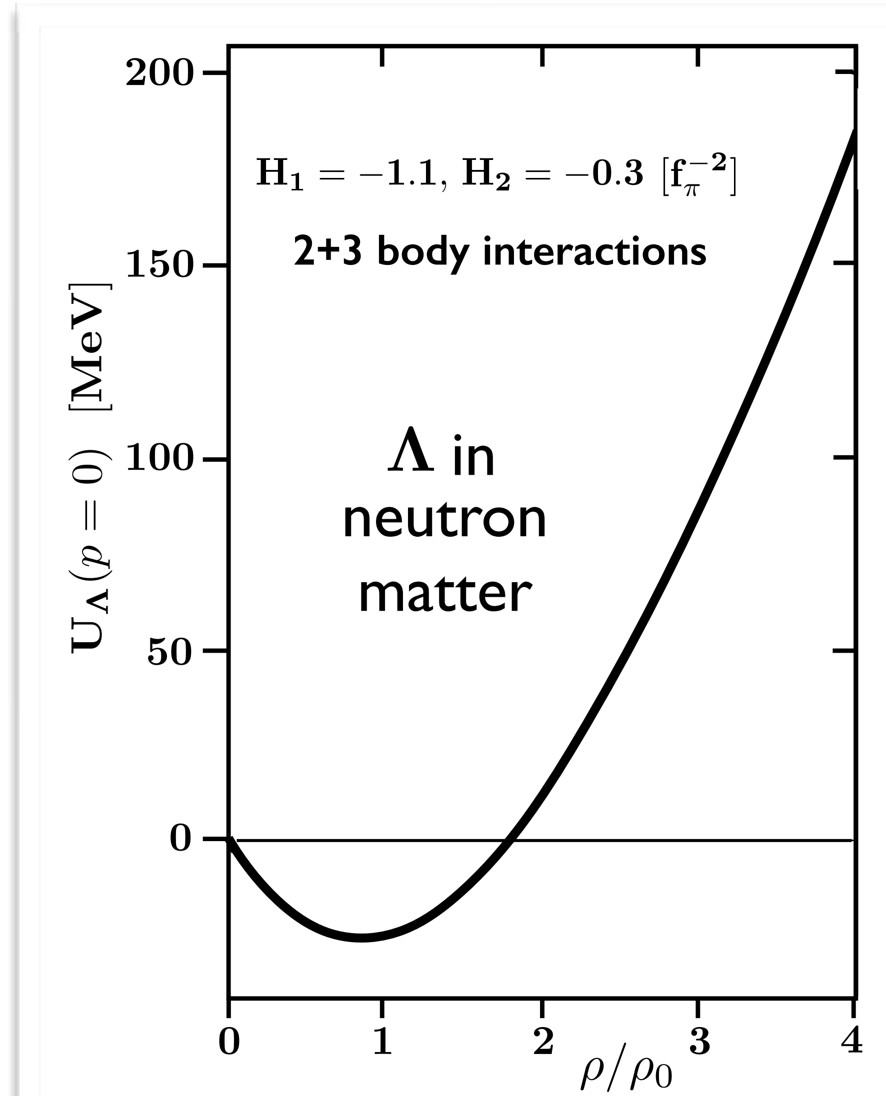
- **… towards a possible solution of the "hyperon puzzle" ?**

Density dependence of Λ single particle potential (contd.)

- **Chiral NN** (N3LO) + **YN** (NLO) **interactions** + **NNN & YNN 3-body** forces
- **Coupled-channels G-matrix including explicit $\Lambda NN \leftrightarrow \Sigma NN$ three-body interactions**

$$\mathbf{G}_{\alpha\beta}(\omega;\rho) = \mathbf{V}_{\alpha\beta}(\rho) + \mathbf{V}_{\alpha\gamma}(\rho)\frac{\mathbf{Q}}{\mathbf{e}(\omega) + \mathbf{i}\epsilon}\mathbf{G}_{\gamma\beta}(\omega;\rho)$$





D. Gerstung, N. Kaiser, W.W. (2018-19)

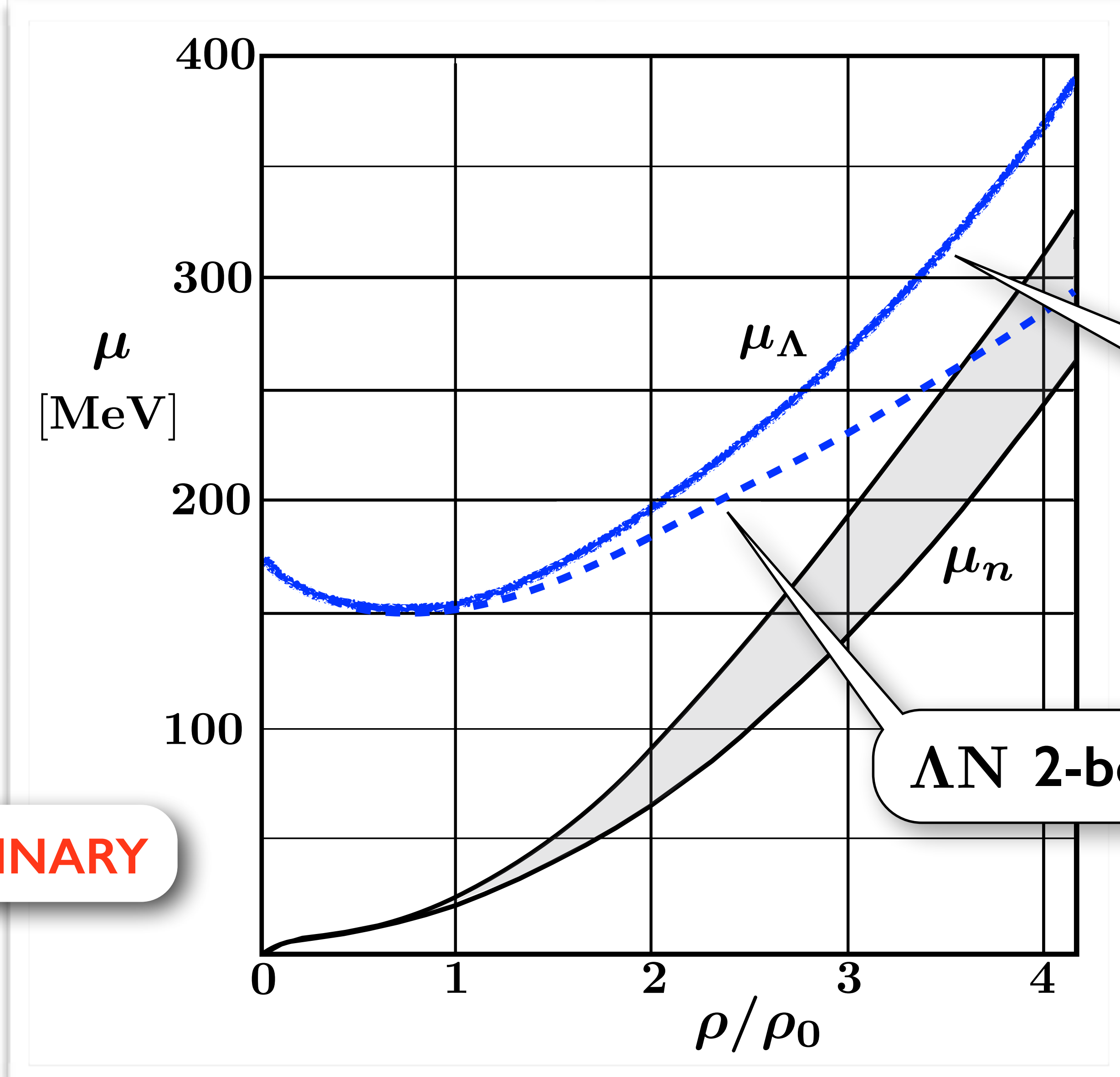
Hyperons in Neutron Stars ?

- Onset condition for appearance of Λ **hyperons in neutron stars :**

chemical potentials

$$\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$

$$\mu_\Lambda = \mu_n$$



PRELIMINARY

- Extrapolations using Λ **single particle potential** in **neutron (star) matter** from **Chiral SU(3) EFT** interactions
- Further calculations in progress

(D. Gerstung, N. Kaiser, W.W. 2018)

SUMMARY

- **Low-energy kaon and antikaon interactions with nucleons and nuclei**
  - Chiral SU(3) EFT + **coupled channels dynamics**
  - **Construction of equivalent local and E-dependent potentials**
  - K^-**-nuclear clusters : weak binding, large widths**

- **Progress in constructing hyperon-nuclear interactions**
  - Chiral SU(3) EFT + **coupled channels dynamics**
  - **YN two-body interactions** at **NLO**
  - **Importance of** $\Lambda N \leftrightarrow \Sigma N$ (2nd order pion exchange tensor force)
  - **YNN three-body forces** (incl. $\Lambda NN \leftrightarrow \Sigma NN$ coupled channels)

- **Single particle potential of a** Λ in **nuclear** and **neutron matter**
  - **Moderately attractive** at low density (**hypernuclei**)
  - **Strongly repulsive** at high density (**2+3 - body interactions**)
    . . . possible solution of "**hyperon puzzle**" in **neutron stars**
  - **"Conventional" neutron star matter seems to work (no first-order chiral phase transition in sight)**

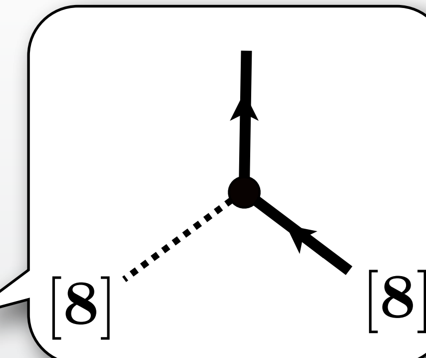
Appendix :
some details
Baryon-Baryon Interactions
from Chiral SU(3) EFT

Chiral $\mathbf{SU(3)_L \times SU(3)_R}$ Effective Field Theory

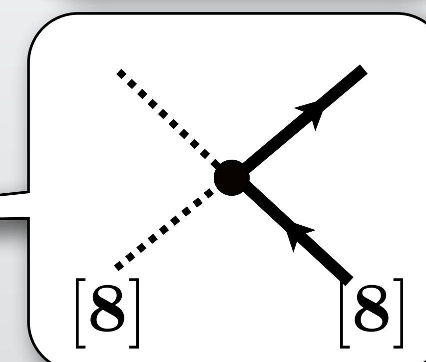
- **Interaction Lagrangian:** expand in powers of meson fields P(x)

$$\mathcal{L}_{int} = \mathcal{L}_1 + \mathcal{L}_2 + \ldots + \textbf{ mass terms}$$

$$\mathcal{L}_1 = -\frac{\sqrt{2}}{2f}\,\mathrm{tr}\big(D\bar{B}\gamma^\mu\gamma_5\{\partial_\mu P, B\} + F\bar{B}\gamma^\mu\gamma_5[\partial_\mu P, B]\big)$$



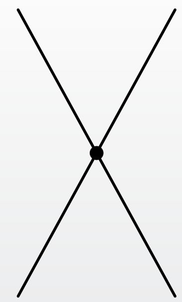
$$\mathcal{L}_2 = \frac{1}{4f^2}\,\mathrm{tr}\big(\mathrm{i}\bar{B}\gamma^\mu\big[[P, \partial_\mu P], B\big]\big)$$



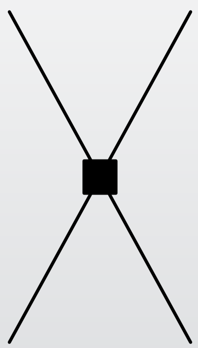
- **Input** : $F = 0.46 \quad D = 0.81$ $\quad f = 0.09\,GeV$
  $(g_A = F + D = 1.27)$

- **Physical** meson and baryon masses (SU(3) breaking)

Hyperon - Nucleon Interaction
Contact Terms



$$V^{(0)}_{BB\to BB} = C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$



$$V^{(2)}_{BB\to BB} = C_1 \mathbf{q}^2 + C_2 \mathbf{k}^2 + \left(C_3 \mathbf{q}^2 + C_4 \mathbf{k}^2\right)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \frac{\mathrm{i}}{2} C_5 (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot(\mathbf{q}\times\mathbf{k})$$
$$+ C_6 (\mathbf{q}\cdot\boldsymbol{\sigma}_1)(\mathbf{q}\cdot\boldsymbol{\sigma}_2) + C_7 (\mathbf{k}\cdot\boldsymbol{\sigma}_1)(\mathbf{k}\cdot\boldsymbol{\sigma}_2) + \frac{\mathrm{i}}{2} C_8 (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\cdot(\mathbf{q}\times\mathbf{k})$$

- **SU(3) symmetry** reduces number of independent constants

$$\mathbf{8}\otimes\mathbf{8} = \mathbf{27}\oplus\mathbf{8_s}\oplus\mathbf{1}\oplus\mathbf{10}\oplus\mathbf{10^*}\oplus\mathbf{8_a}$$

S	Channel	I	$V_{^1S_0,\,^3P_0,\,^3P_1,\,^3P_2}$	$V_{^3S_1,\,^3S_1\text{-}^3D_1,\,^1P_1}$
0	$NN \to NN$	0	–	C^{10^*}
	$NN \to NN$	1	C^{27}	–
-1	$\Lambda N \to \Lambda N$	$\frac{1}{2}$	$\frac{1}{10}\left(9C^{27} + C^{8_s}\right)$	$\frac{1}{2}\left(C^{8_a} + C^{10^*}\right)$
	$\Lambda N \to \Sigma N$	$\frac{1}{2}$	$\frac{3}{10}\left(-C^{27} + C^{8_s}\right)$	$\frac{1}{2}\left(-C^{8_a} + C^{10^*}\right)$
	$\Sigma N \to \Sigma N$	$\frac{1}{2}$	$\frac{1}{10}\left(C^{27} + 9C^{8_s}\right)$	$\frac{1}{2}\left(C^{8_a} + C^{10^*}\right)$
	$\Sigma N \to \Sigma N$	$\frac{3}{2}$	C^{27}	C^{10}

S. Petschauer, N. Kaiser

Nucl. Phys. A 916 (2013) 1-29