LOW-ENERGY QCD with STRANGE QUARKS

- from antikaon-nuclear interactions to hyperons in neutron stars -

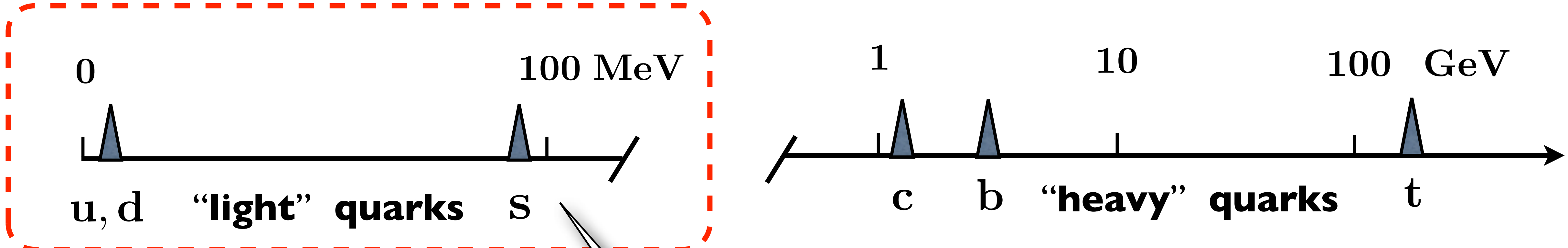
Wolfram Weise

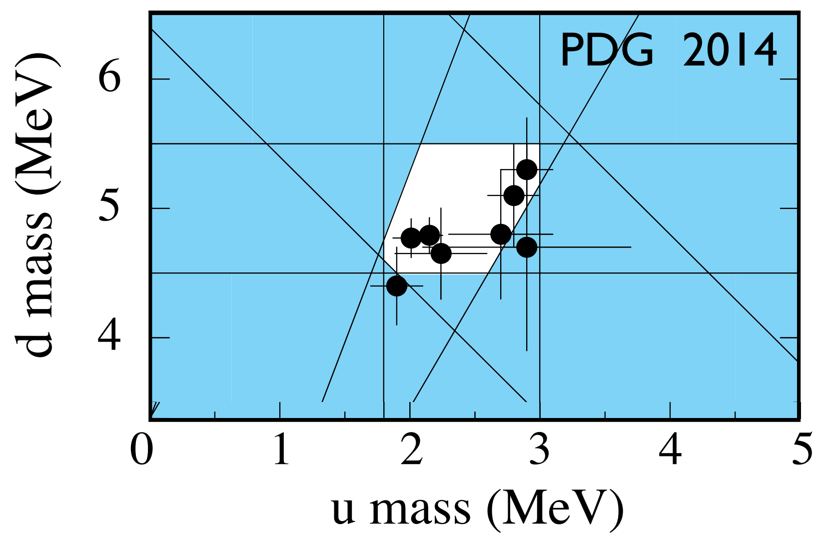
ECT* Trento and **T**echnische **U**niversität **M**ünchen

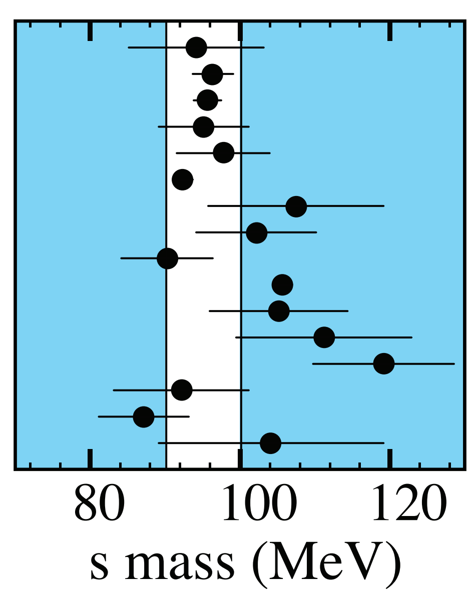
- **Symmetry breaking scenarios** in **Low-Energy QCD** :
  Chiral SU(3) **Effective Field Theory**
- **Near-threshold strong interaction physics** :
  kaons and **antikaons** interacting with **nucleons** & **nuclei**
- **Hyperon-nucleon interactions** - new developments :
  Chiral SU(3) **EFT** and **Lattice QCD**
- **Strangeness** in **dense baryonic matter** :
  new **constraints** from **neutron stars**

Hierarchy of **QUARK MASSES** in **QCD**

- separation of scales -







Basic principles of

LOW-ENERGY QCD :

Confinement of quarks & gluons in hadrons

Chiral Symmetry

spontaneously broken
(QCD dynamics)

explicitly broken
by non-zero
quark masses

special role of STRANGE QUARKS

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

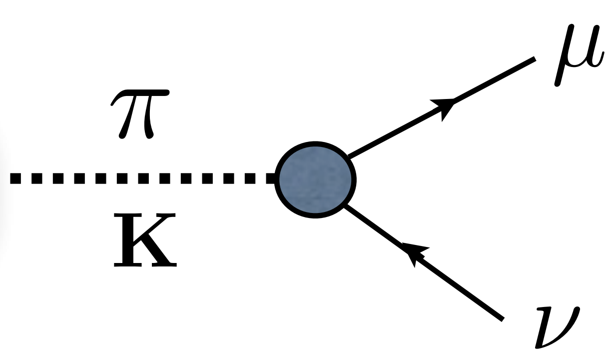
- **NAMBU - GOLDSTONE BOSONS**:

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

- **DECAY CONSTANTS**:

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

axial current



Chiral limit: $\mathrm{f} = 86.2\ \mathrm{MeV}$
(**order parameter**)

$$\mathrm{f}_\pi = 92.4 \pm 0.3\ \mathrm{MeV}$$
$$\mathrm{f_K} = 110.0 \pm 0.9\ \mathrm{MeV}$$

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

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

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

\+ higher order corrections

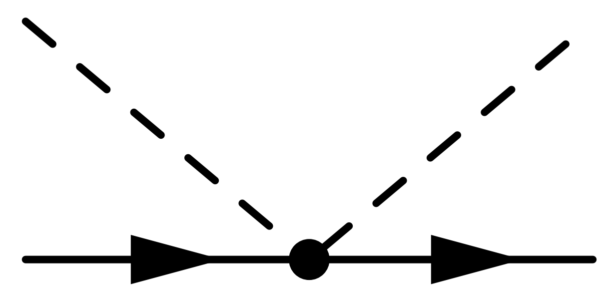
CHIRAL SU(3) EFFECTIVE FIELD THEORY

ordered hierarchy of driving interactions

- Leading-order terms (**W**einberg & **T**omozawa)

PS **meson octet** [8]

baryon octet [8]



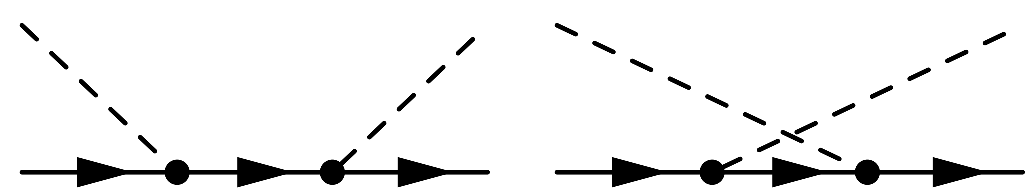
- Examples: $\bar{K}N$ (S = -1) and KN (S = +1) threshold (s wave) amplitudes :

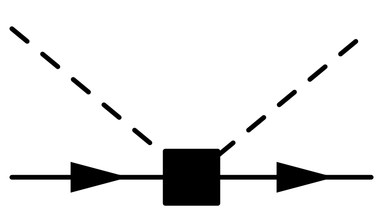
$$\mathbf{T(K^+p)_{thr} = 2\,T(K^+n)_{thr} = -\frac{m_K}{f^2}}$$ **repulsive**

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

explicit chiral symmetry breaking

order parameter of **spontaneous** chiral symmetry breaking

\+ 

\+ 

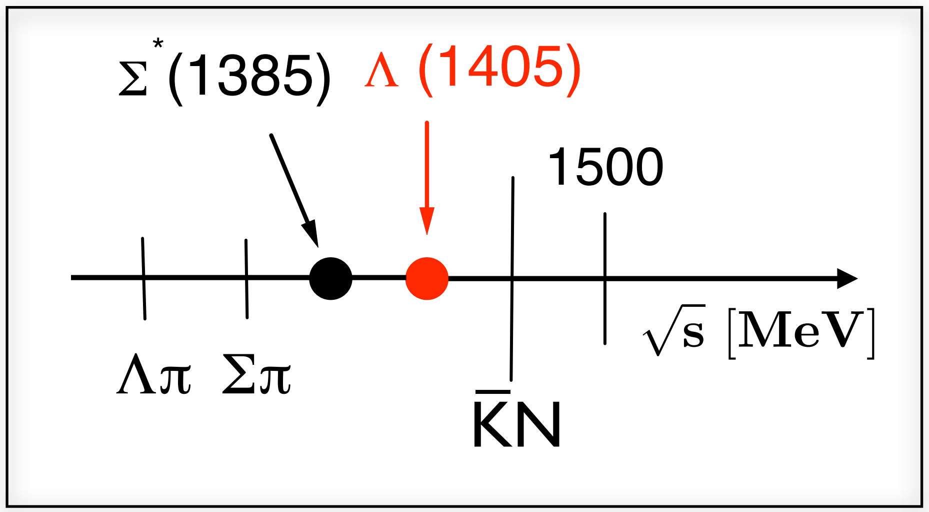
next-to-leading order (**NLO**) $\mathcal{O}(p^2)$

input: several low-energy constants

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

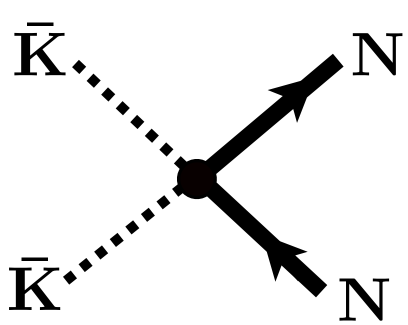
- Framework: **Chiral SU(3) Effective Field Theory** … but :
- Chiral Perturbation Theory **NOT** applicable:
  $\Lambda(1405)$ resonance 27 MeV below $\mathrm{K^-p}$ threshold

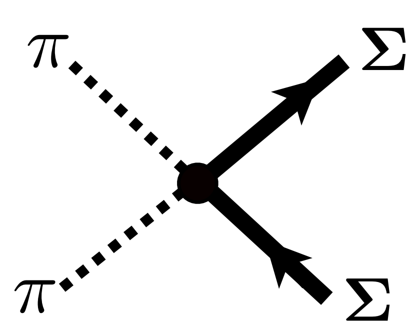
N. Kaiser, P. Siegel, W.W. (1995)
E. Oset, A. Ramos (1998)

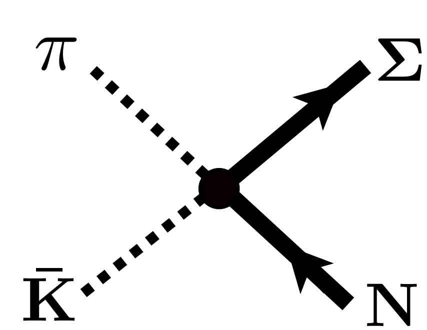


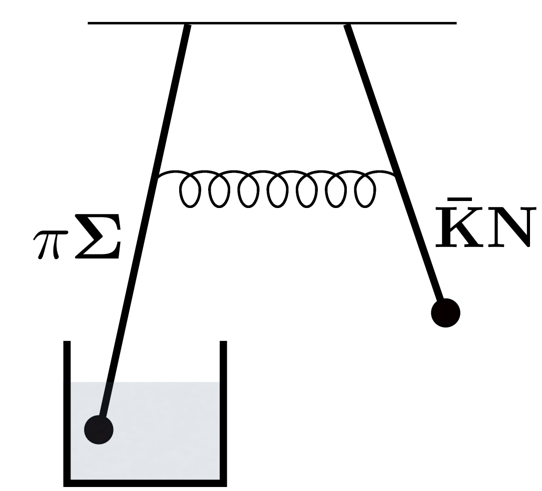
Non-perturbative
Coupled Channels
approach based on
Chiral SU(3) Dynamics

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







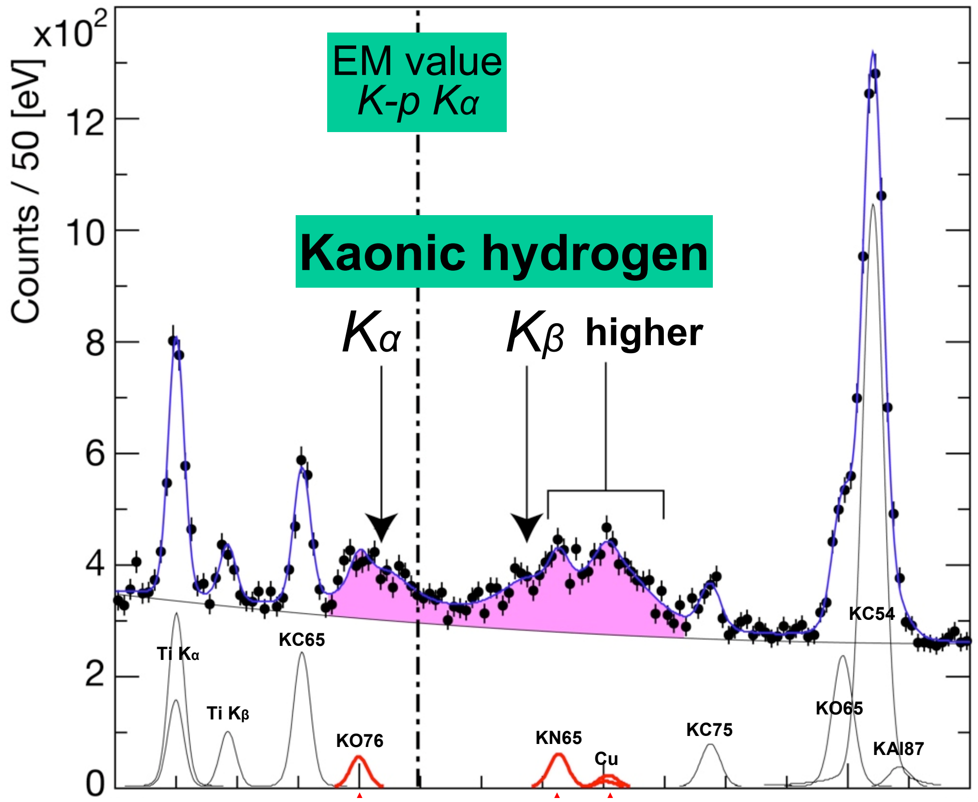


channel coupling

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

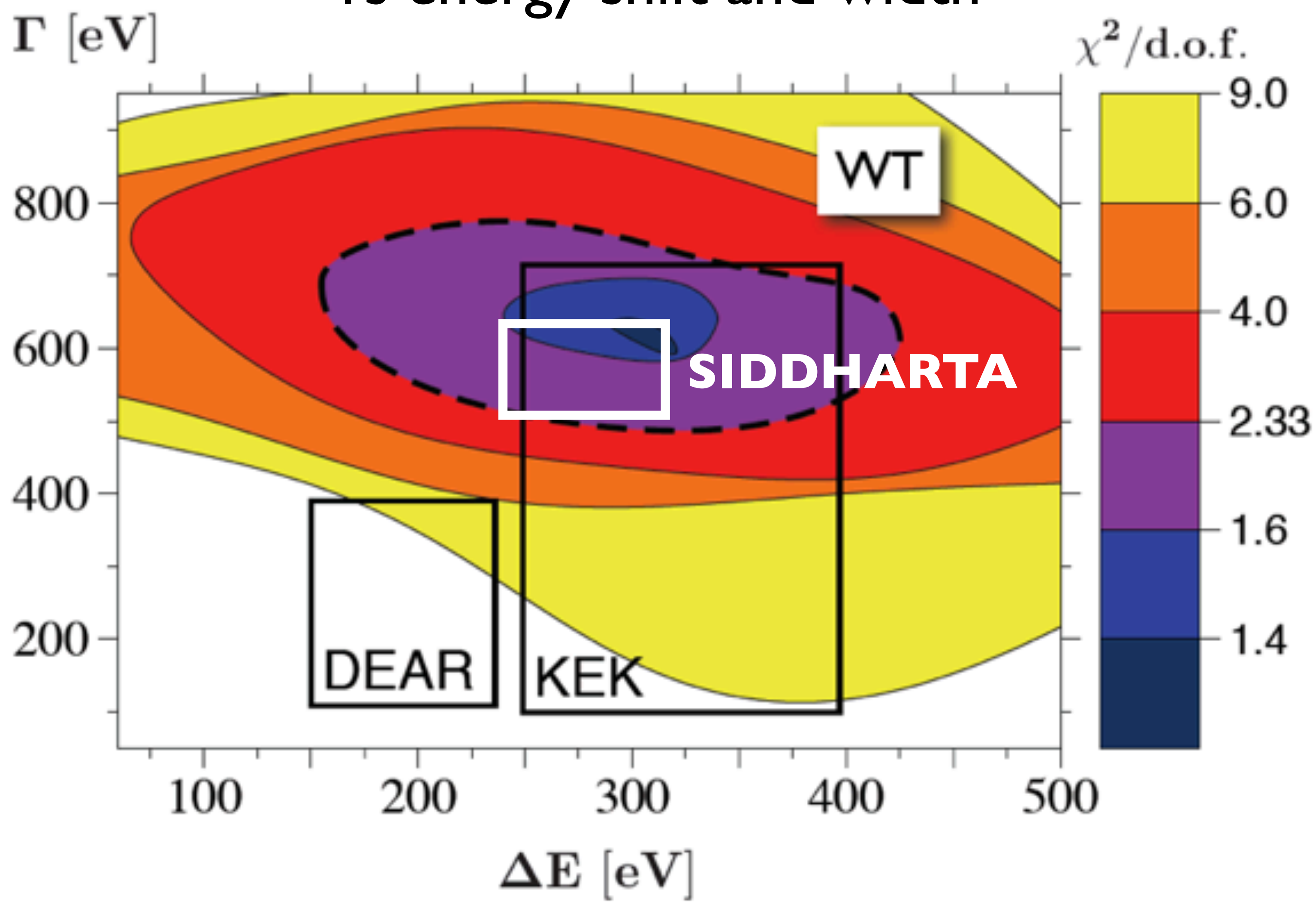
CONSTRAINTS from SIDDHARTA

- **Kaonic hydrogen**
  precision data



M. Bazzi et al. (SIDDHARTA)
Phys. Lett. B 704 (2011) 113

- **Strong interaction**
  1s energy shift and width



$$\mathbf{\Delta E = 283 \pm 36}\,(stat) \pm \mathbf{6}\,(syst) \quad \mathbf{eV}$$

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

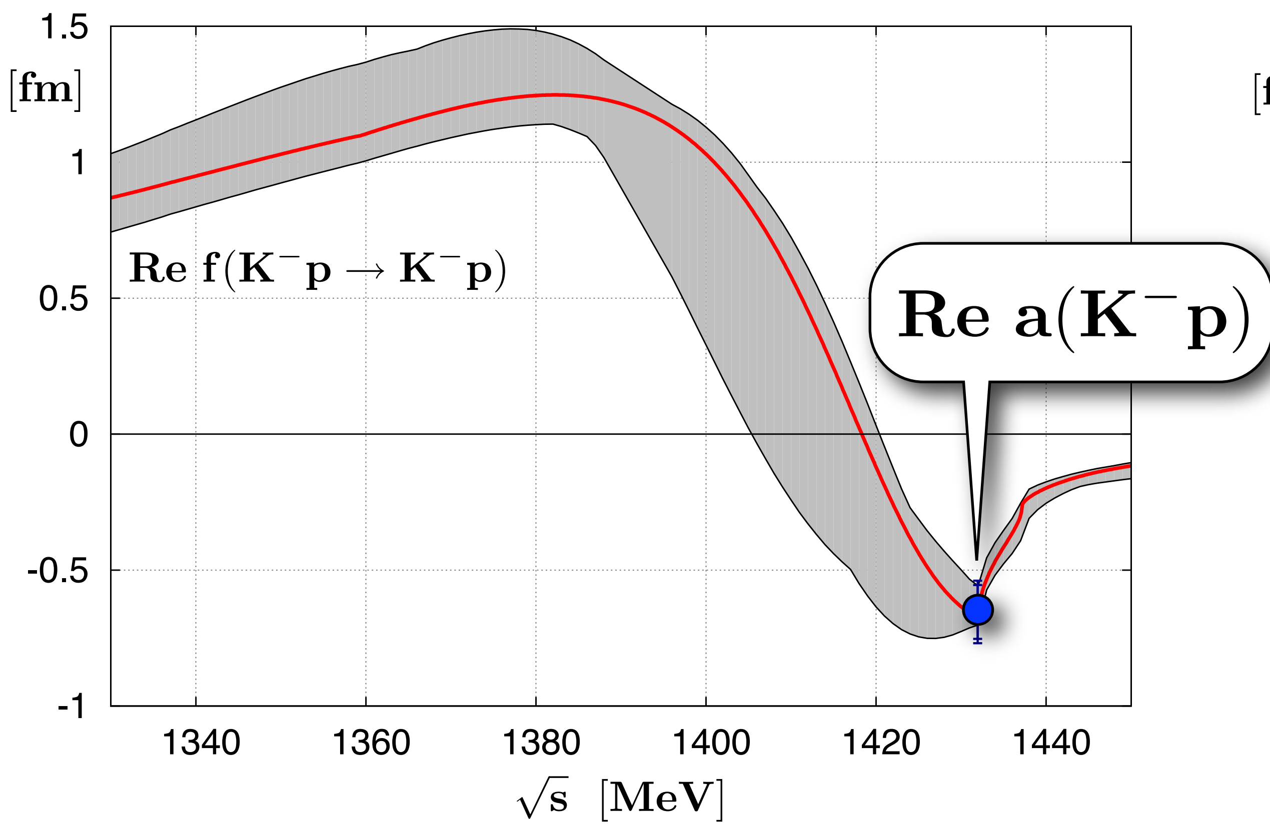
$\mathrm{K^-p}$ SCATTERING AMPLITUDE from CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

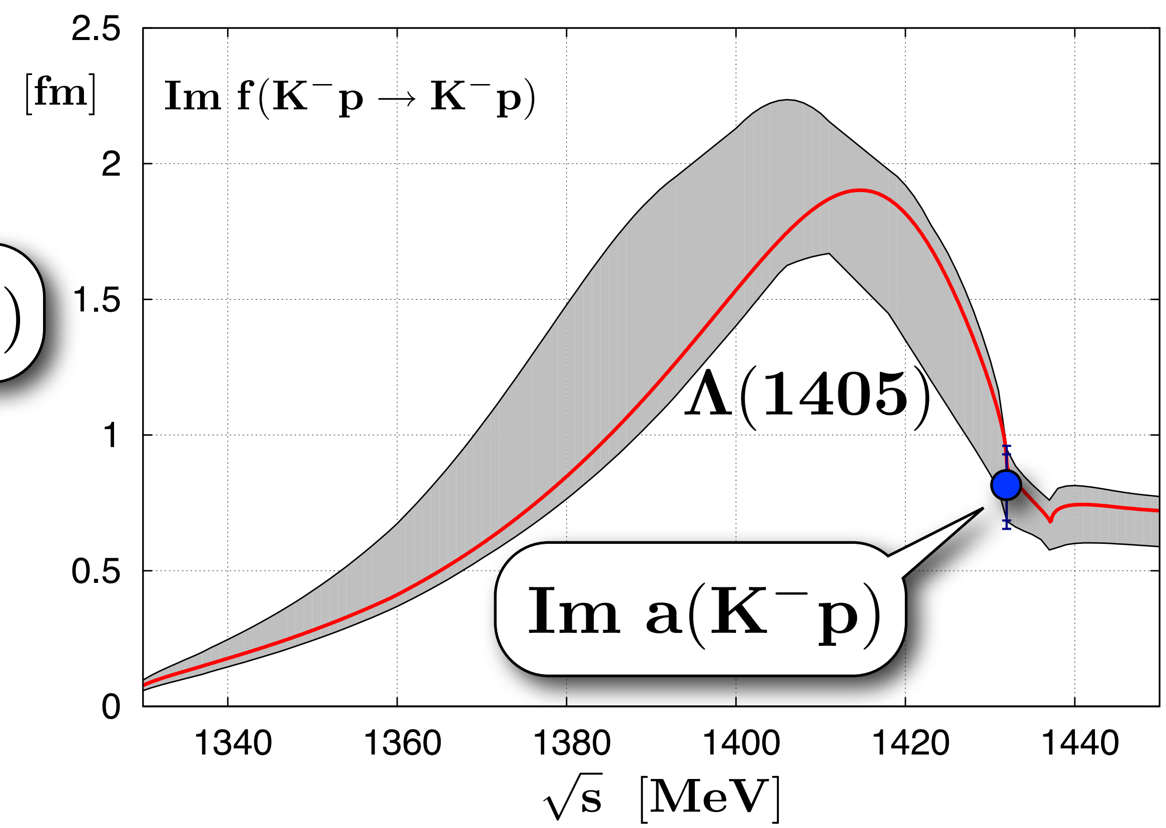
$$\mathbf{f(K^-p)} = \frac{1}{2}\left[\mathbf{f_{\bar{K}N}(I=0)} + \mathbf{f_{\bar{K}N}(I=1)}\right]$$

Y. Ikeda, T. Hyodo, W.W.
PLB 706 (2011) 63
NPA881 (2012) 98

$\mathbf{\Lambda(1405)}$: $\mathrm{\bar{K}N}$ $\mathbf{(I=0)}$ **quasibound state** embedded in the $\pi\Sigma$ continuum

Prototype example for emergence of **resonant structure** close to a threshold





Complex scattering length (including Coulomb corrections)

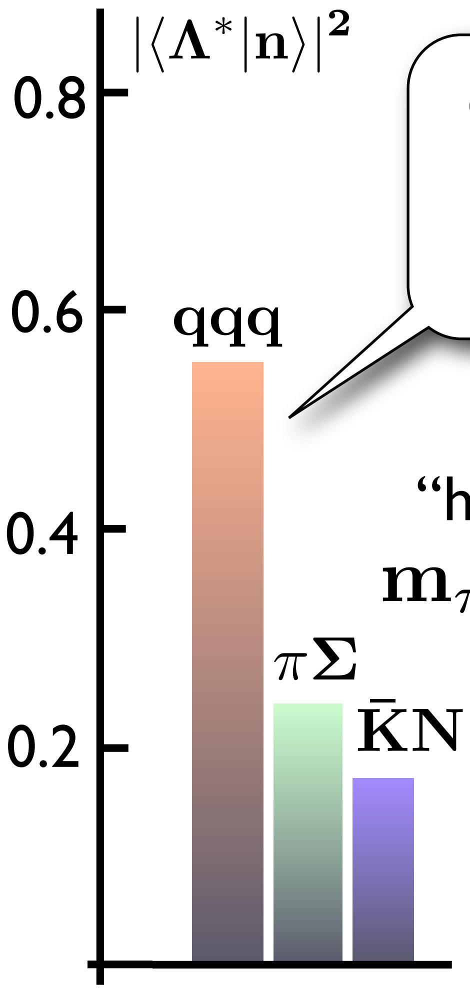
$$\mathbf{Re\ a(K^-p) = -0.65 \pm 0.10\ \ fm}$$

$$\mathbf{Im\ a(K^-p) = 0.81 \pm 0.15\ \ fm}$$

New developments:

Structure of $\Lambda(1405)$ from Lattice QCD

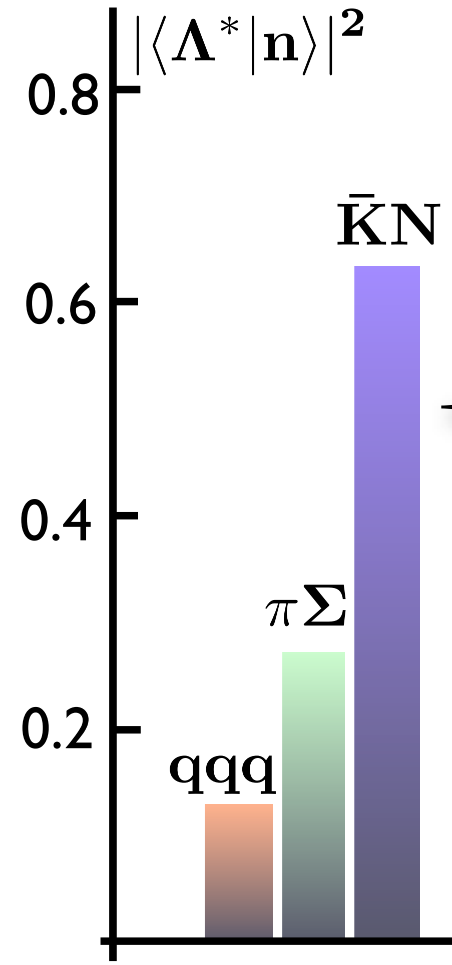
- $|\mathbf{\Lambda^*}\rangle = \mathbf{a}|\mathbf{uds}\rangle + \mathbf{b}|(\mathbf{udu})(\bar{\mathbf{u}}\mathbf{s})\rangle + \ldots$

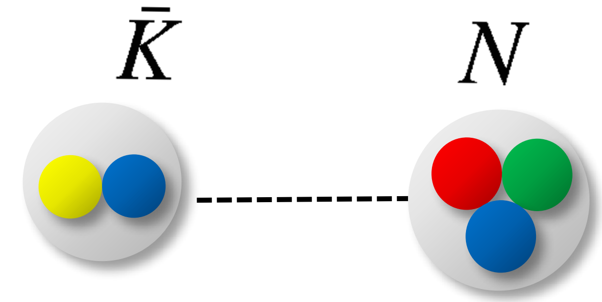


constituent quark dominated

"heavier" quarks
$\mathbf{m_\pi \simeq 0.6\ GeV}$

J.M.M. Hall et al.
(Adelaide group 2014)





quasi molecular $\bar{\mathrm{K}}\mathrm{N}$ structure

"light" quarks
$\mathbf{m_\pi \simeq 0.3\ GeV}$
(not quite physical yet)

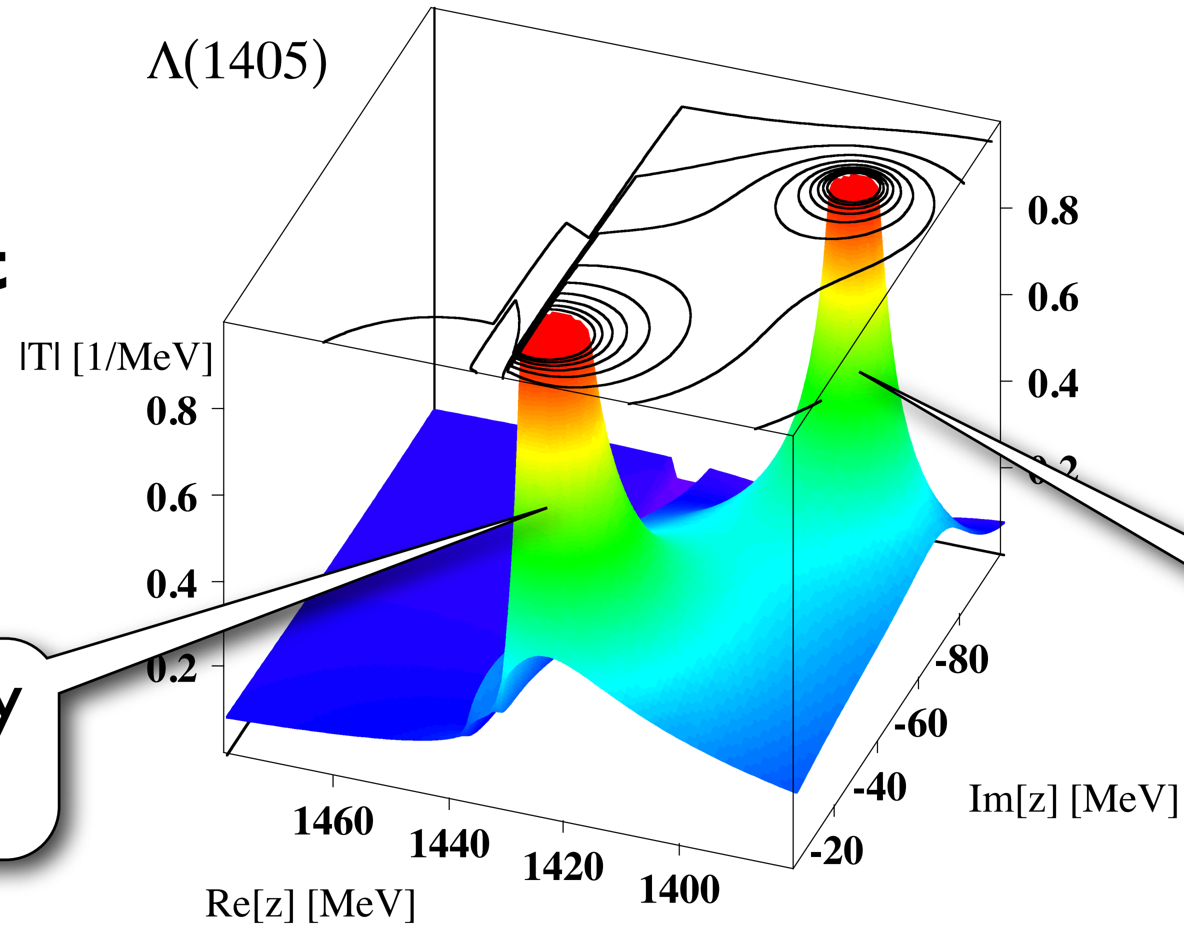
- Note: **qualitative** structural change depending on quark mass
  (interplay of **spontaneous** & **explicit** chiral symmetry breaking)

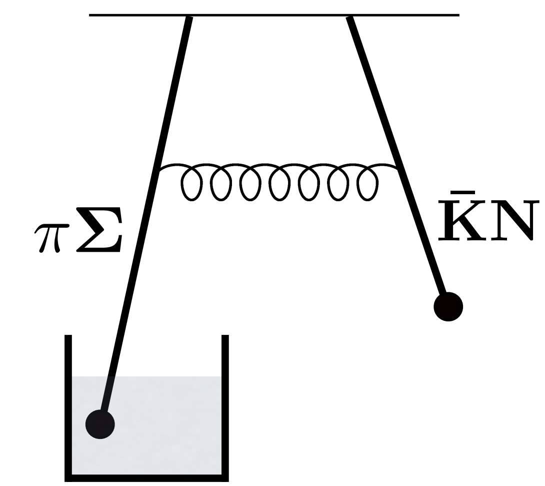
The TWO POLES scenario

- Characteristic feature of **Chiral SU**(3) **Dynamics** :

Coupled channels
with
energy dependent
driving interactions

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





- Pole positions from **chiral SU**(3) **coupled-channels calculation** using **SIDDHARTA** $\mathrm{K^-p}$ threshold constraints:

$\mathbf{E_1 = 1424 \pm 15\ MeV}$	$\mathbf{E_2 = 1381 \pm 15\ MeV}$
$\mathbf{\Gamma_1 = 52 \pm 10\ MeV}$	$\mathbf{\Gamma_2 = 162 \pm 15\ MeV}$

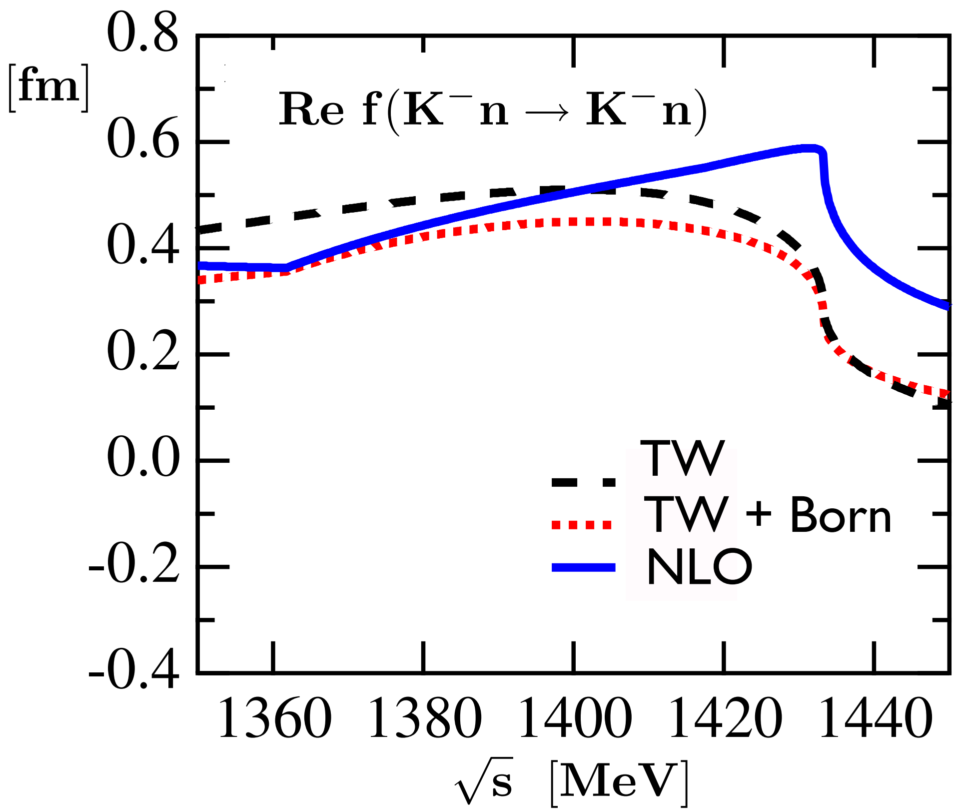
Y. Ikeda, T. Hyodo, W.W. :
Nucl. Phys. A 881 (2012) 98

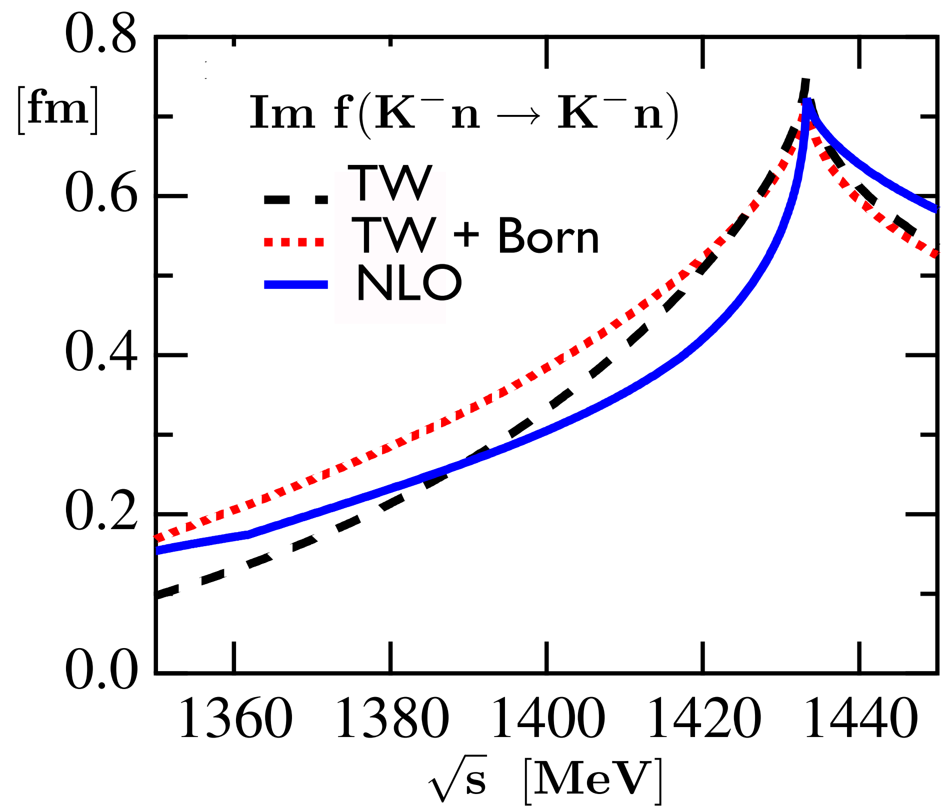
- Dynamics explored and tested in several experiments at **J-PARC**, **JLab**, **GSI-HADES**

Missing information : the $I = 1$ $\bar{K}N$ system

- Predicted **antikaon-neutron** amplitudes at and below threshold

Y. Ikeda et al : Phys. Lett. B 706 (2011) 63 , Nucl. Phys. A 881 (2012) 98





. . . plus many other theory activities

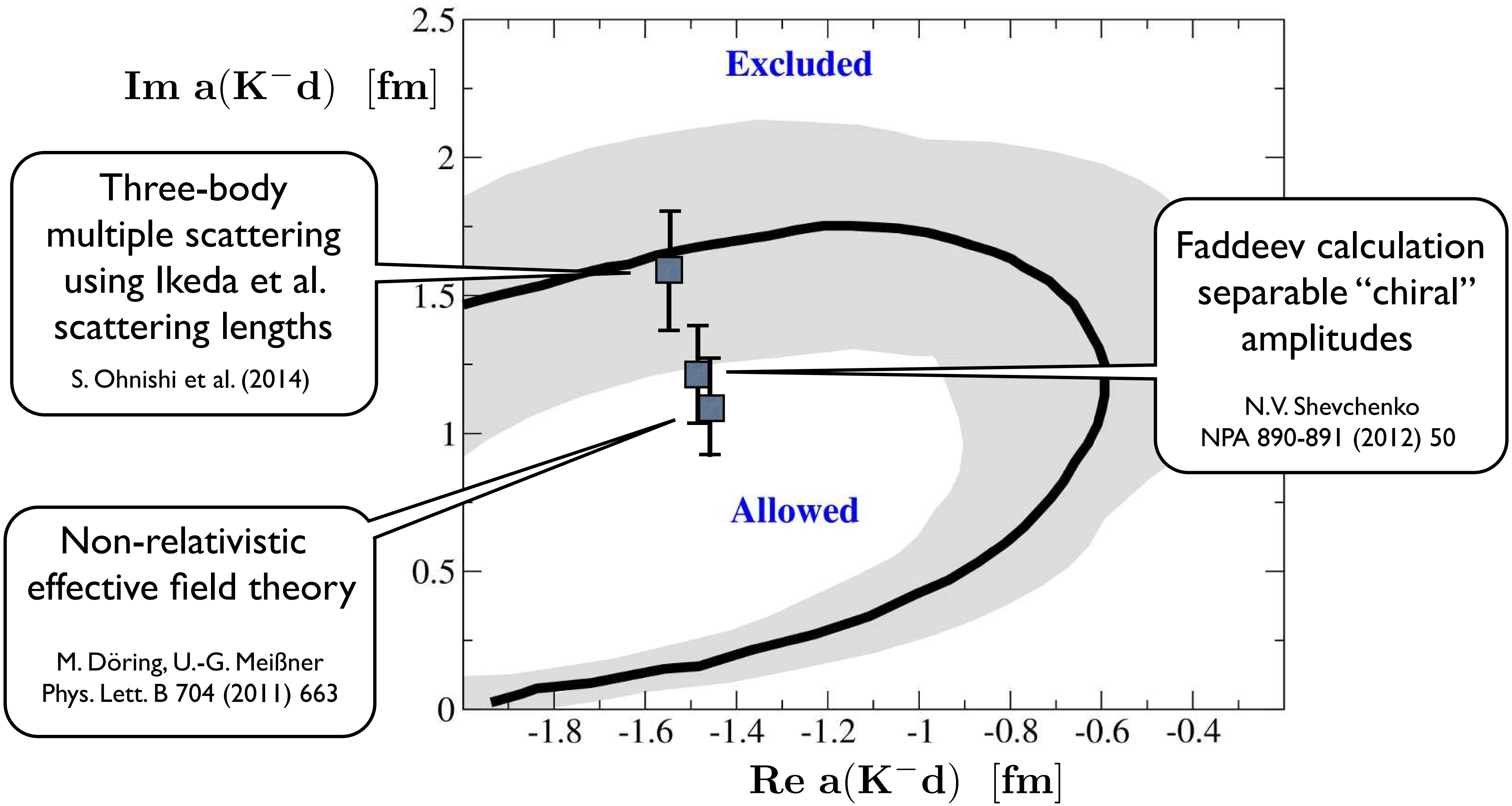
$$\mathbf{a(K^-n) = 0.57^{+0.04}_{-0.21} + i\,0.72^{+0.26}_{-0.41}\ \ fm}$$

a case for **SIDDHARTA-2**

- **Needed**: accurate constraints from **antikaon-deuteron** threshold measurements
  - **complete** information for both isospin $I = 0$ and $I = 1$ $\bar{K}N$ channels
  - plus potentially important information about **K-NN absorption**

ANTIKAON - DEUTERON SCATTERING LENGTH

- Recent calculations using SIDDHARTA - constrained input



- Sources of (15 - 20 %) uncertainties:

  - "Fixed scatterer" approximation
  - $K^- n$ amplitude
  - $K^- d \rightarrow YN$ absorption

KAONIC DEUTERIUM
STRONG INTERACTION ENERGY SHIFT & WIDTH

- Recent result constrained by SIDDHARTA $\mathbf{K^-p}$ input:

$$\mathbf{a(K^-d) = (-1.55 + i\,1.66)\ fm} \qquad (\pm\mathbf{20}\,\%)$$

S. Ohnishi et al. (2014)

- Estimate of kaonic deuterium energy shift and width using **improved Deser formula** (U.-G. Meißner, U. Raha, A. Rusetsky : Eur. Phys. J. C 35 (2004) 349)

$$\mathbf{\Delta E - \frac{i}{2}\Gamma = -\frac{2\mu^2\alpha^3\,a(K^-d)}{1 - 2\mu\alpha(1 - \ln\alpha)\,a(K^-d)}}$$

using $\mathbf{K^-d}$ scattering length based on chiral SU(3) dynamics

$$\mathbf{\Delta E = 0.87\ keV} \qquad \mathbf{\Gamma = 1.19\ keV}$$

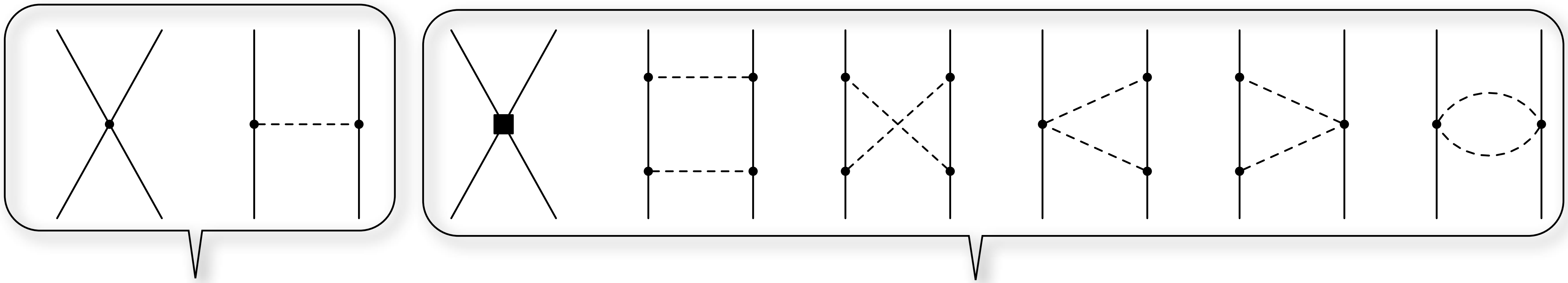
with ~ 20 % uncertainty.

- Intense theoretical activities (e.g. Faddeev calculations), but so far no measurement

New developments:

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

J. Haidenbauer et al.: Nucl. Phys. A 915 (2013) 24



LO **NLO**

- Interaction terms involving baryon and pseudoscalar meson octets …

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

$$\mathcal{L}_1 = -\frac{\sqrt{2}}{2 f_0} \operatorname{tr}\big(D \bar{B} \gamma^\mu \gamma_5 \{\partial_\mu P, B\} + F \bar{B} \gamma^\mu \gamma_5 [\partial_\mu P, B]\big)$$

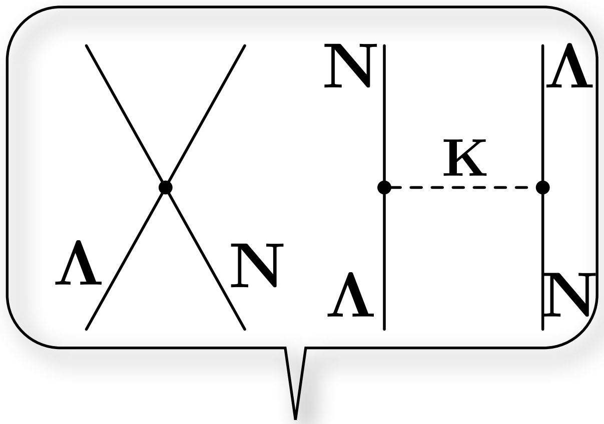
$$\mathcal{L}_2 = \frac{1}{4 f_0^2} \operatorname{tr}\big(\mathrm{i} \bar{B} \gamma^\mu [[P, \partial_\mu P], B]\big)$$

- … generate Nambu-Goldstone boson exchange processes

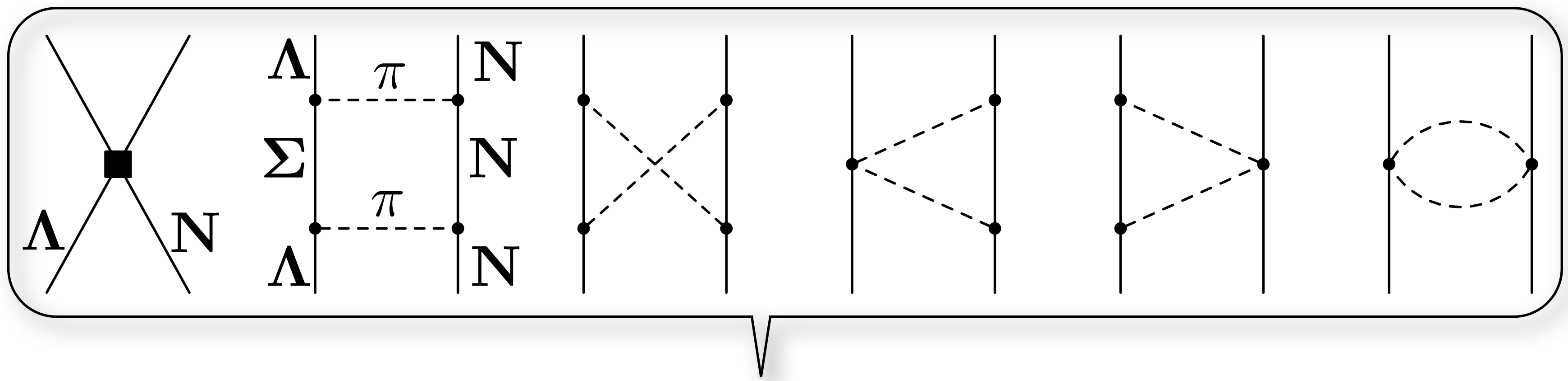
New developments:

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

J. Haidenbauer et al.: Nucl. Phys. A 915 (2013) 24



LO



NLO

- Interaction terms involving baryon and pseudoscalar meson octets . . .

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

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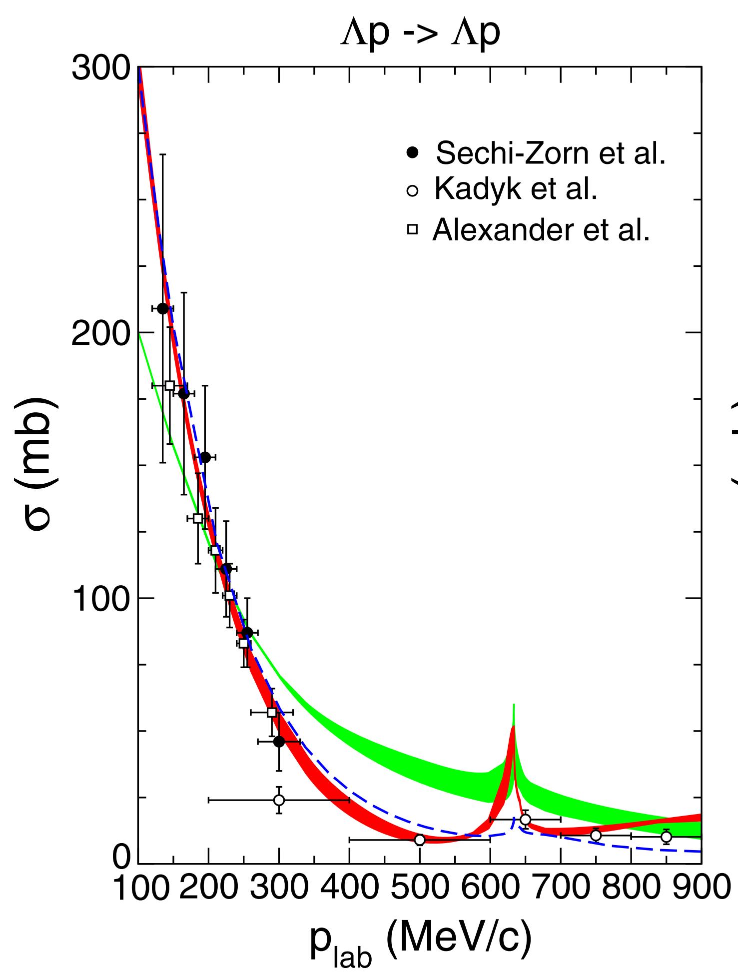
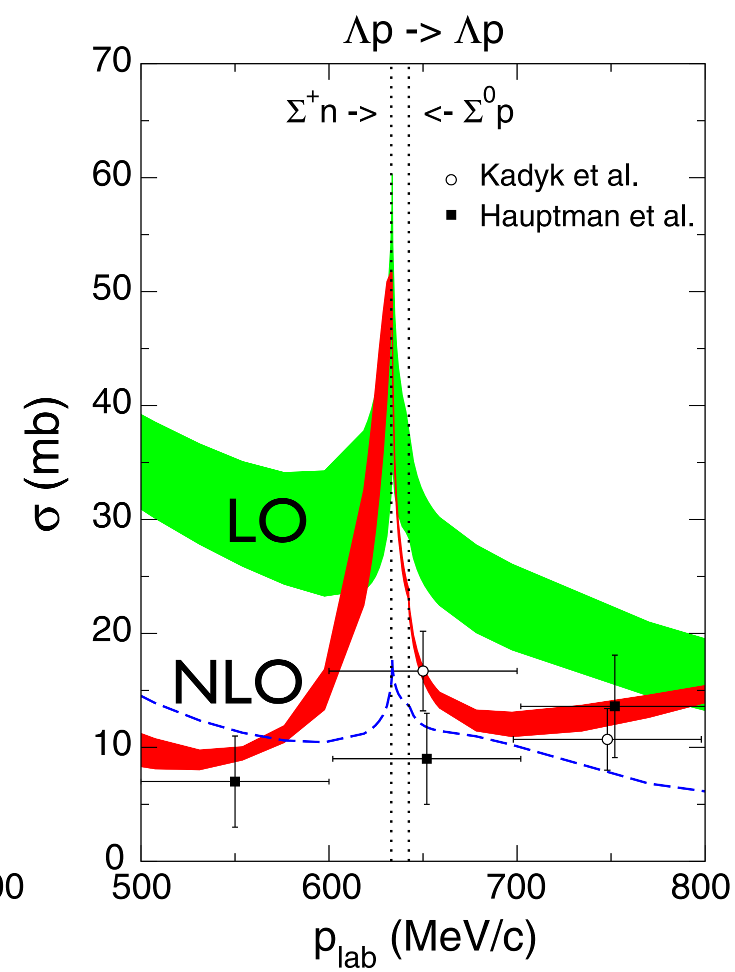
$$\mathcal{L}_2 = \frac{1}{4 f_0^2}\,\mathrm{tr}\big(\mathrm{i}\bar{B}\gamma^\mu\big[[P, \partial_\mu P], B\big]\big)$$

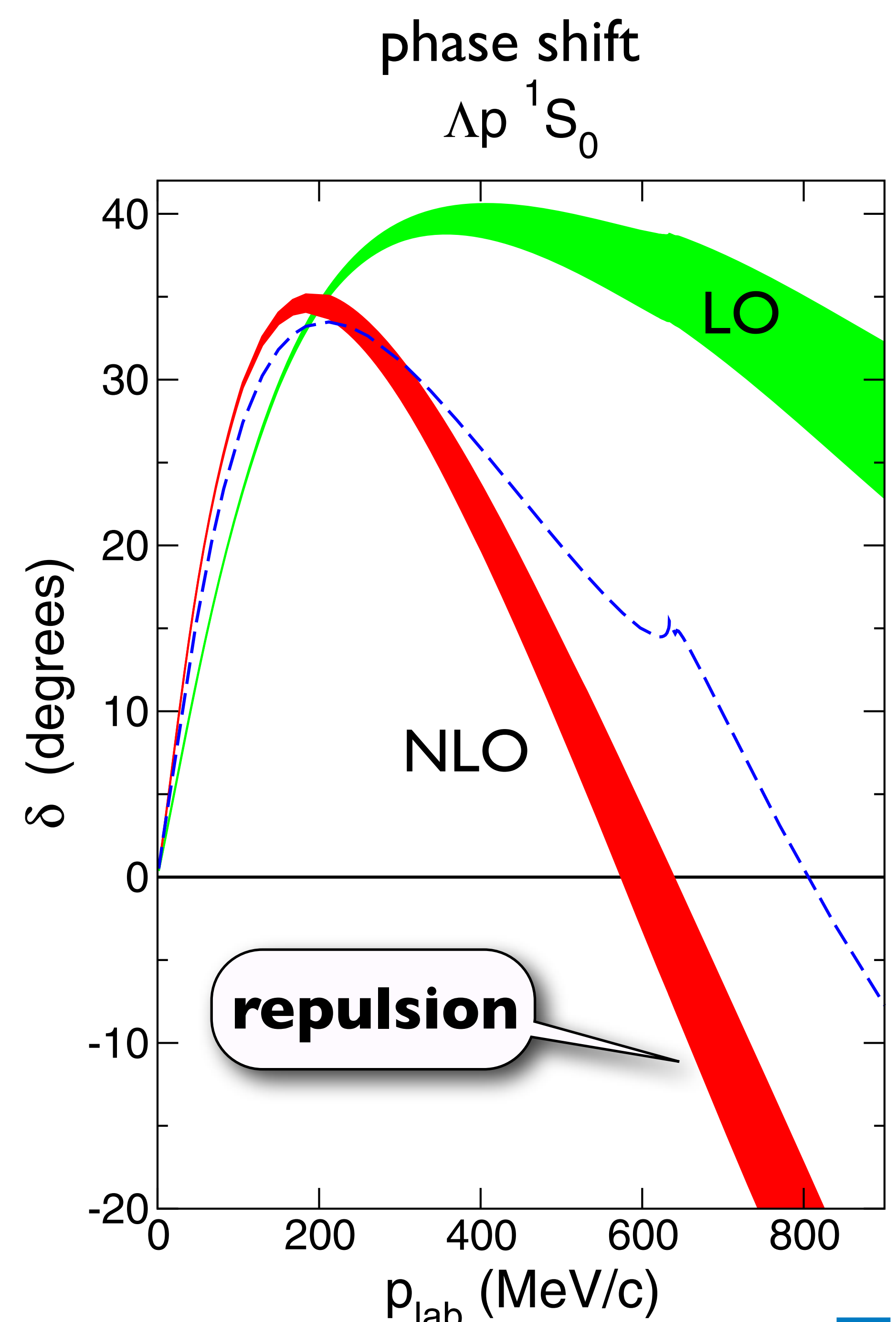
- . . . generate Nambu-Goldstone boson exchange processes

Hyperon - Nucleon Interaction
(contd.)





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



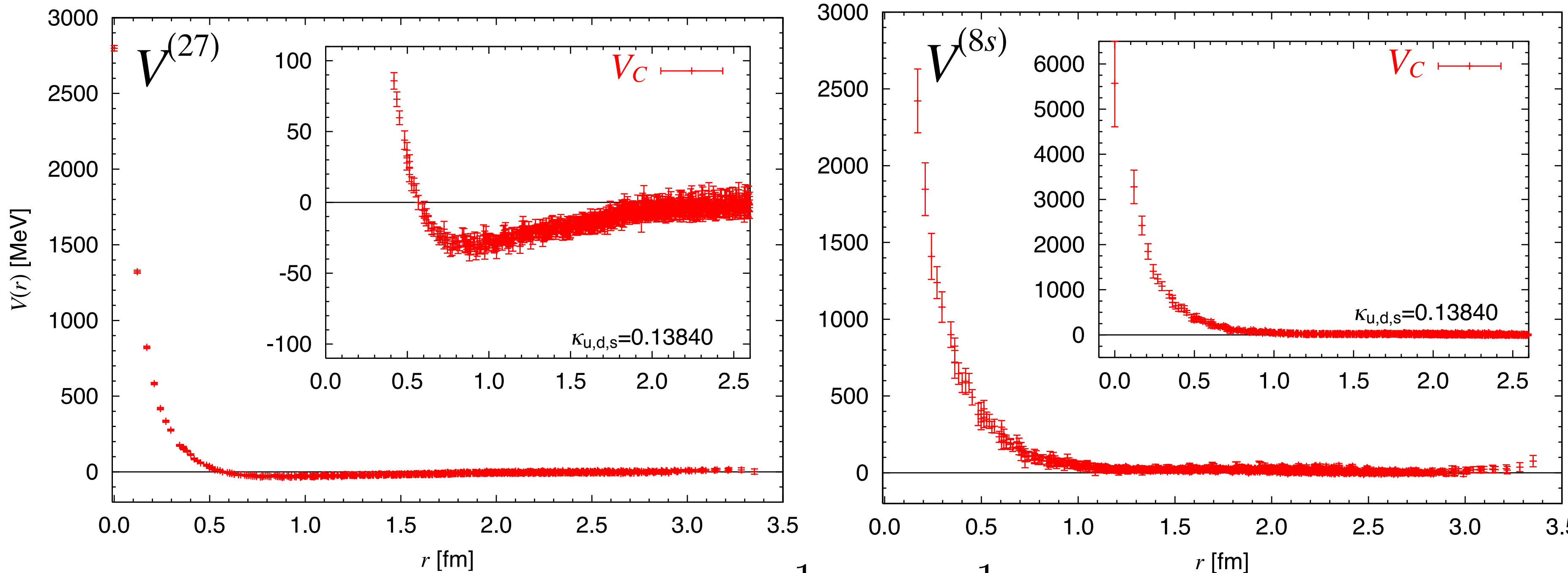
- note:
  moderate attraction at low momenta
  strong repulsion at higher momenta
- … but **missing:**
  accurate data base of **YN scattering**

ECT*

Technische Universität München

Hyperon - Nucleon Interactions from **Lattice QCD**

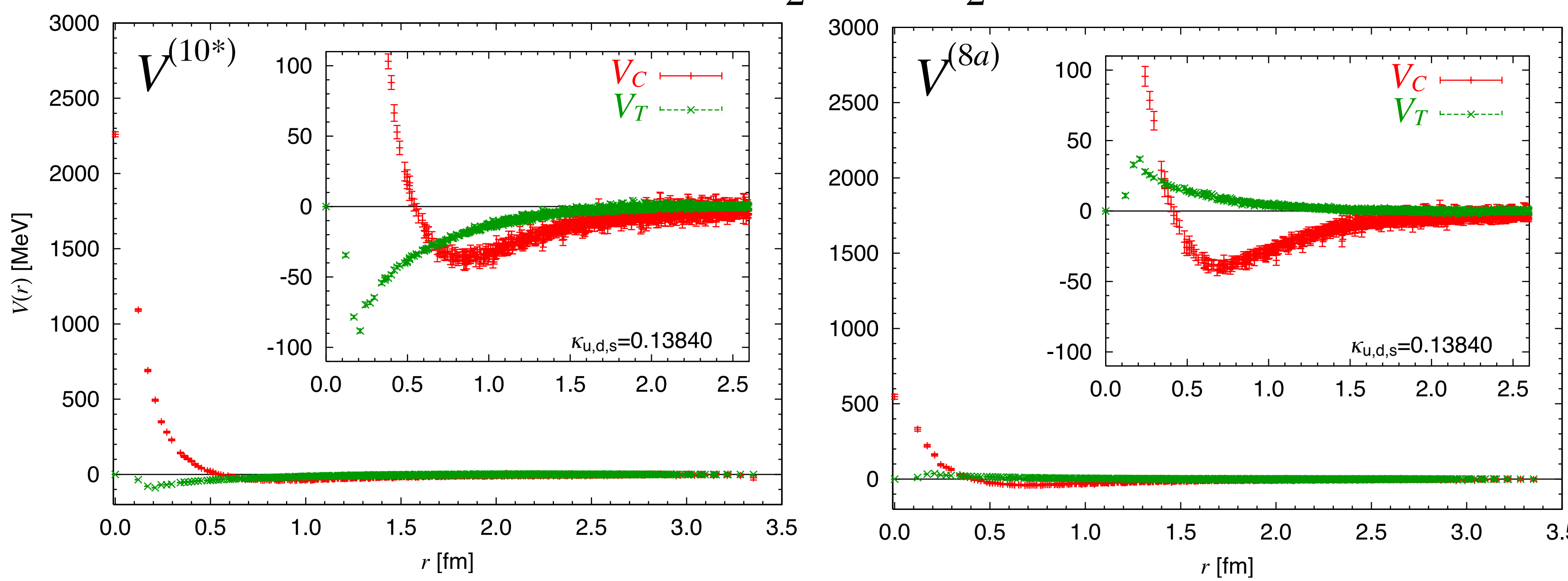
$$\Lambda\mathrm{N}(^1\mathrm{S}_0) = \frac{9}{10}[\mathbf{27}] + \frac{1}{10}[\mathbf{8_s}]$$



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

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

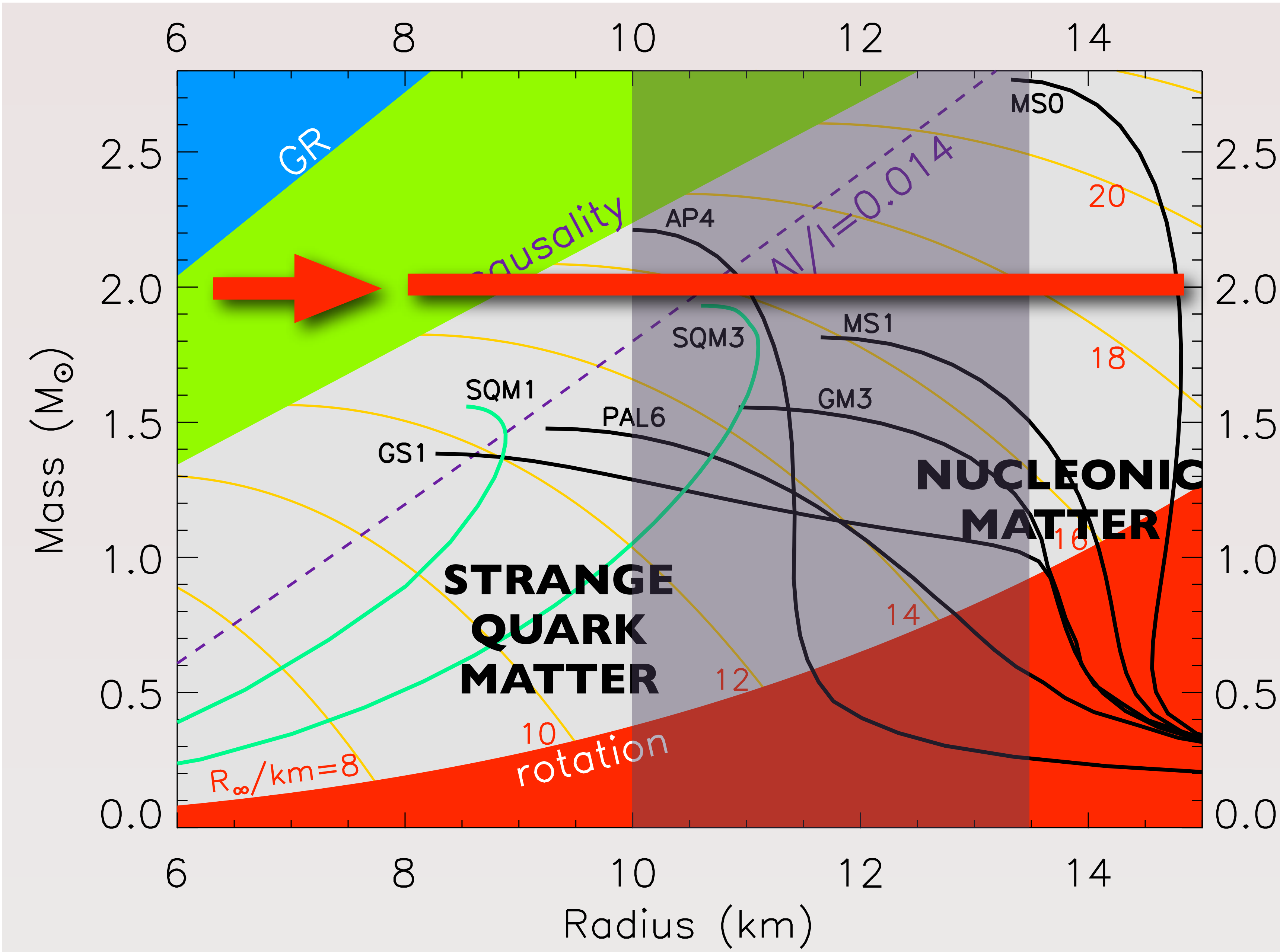
$$\Lambda\mathrm{N}(^3\mathrm{S}_1) = \frac{1}{2}[\mathbf{10^*}] + \frac{1}{2}[\mathbf{8_a}]$$



towards
physical
quark
masses

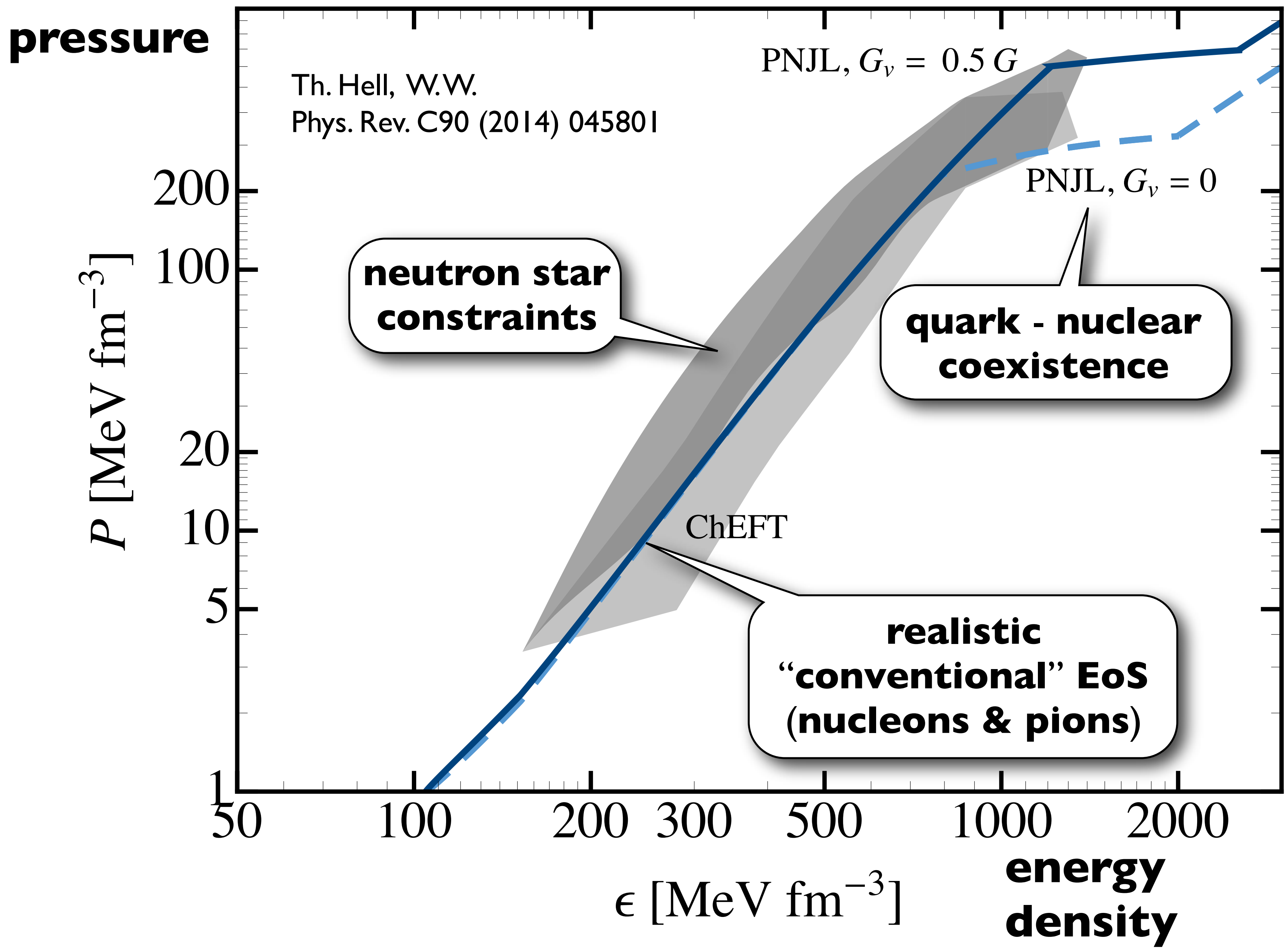
- note: strong short-distance **repulsive** interaction

New constraints
from **2-solar-mass NEUTRON STARS**



- sufficiently **stiff equation of state** required:
  exotic scenarios (quark matter, kaon condensation etc.) unlikely

NEUTRON STAR MATTER
Equation of State



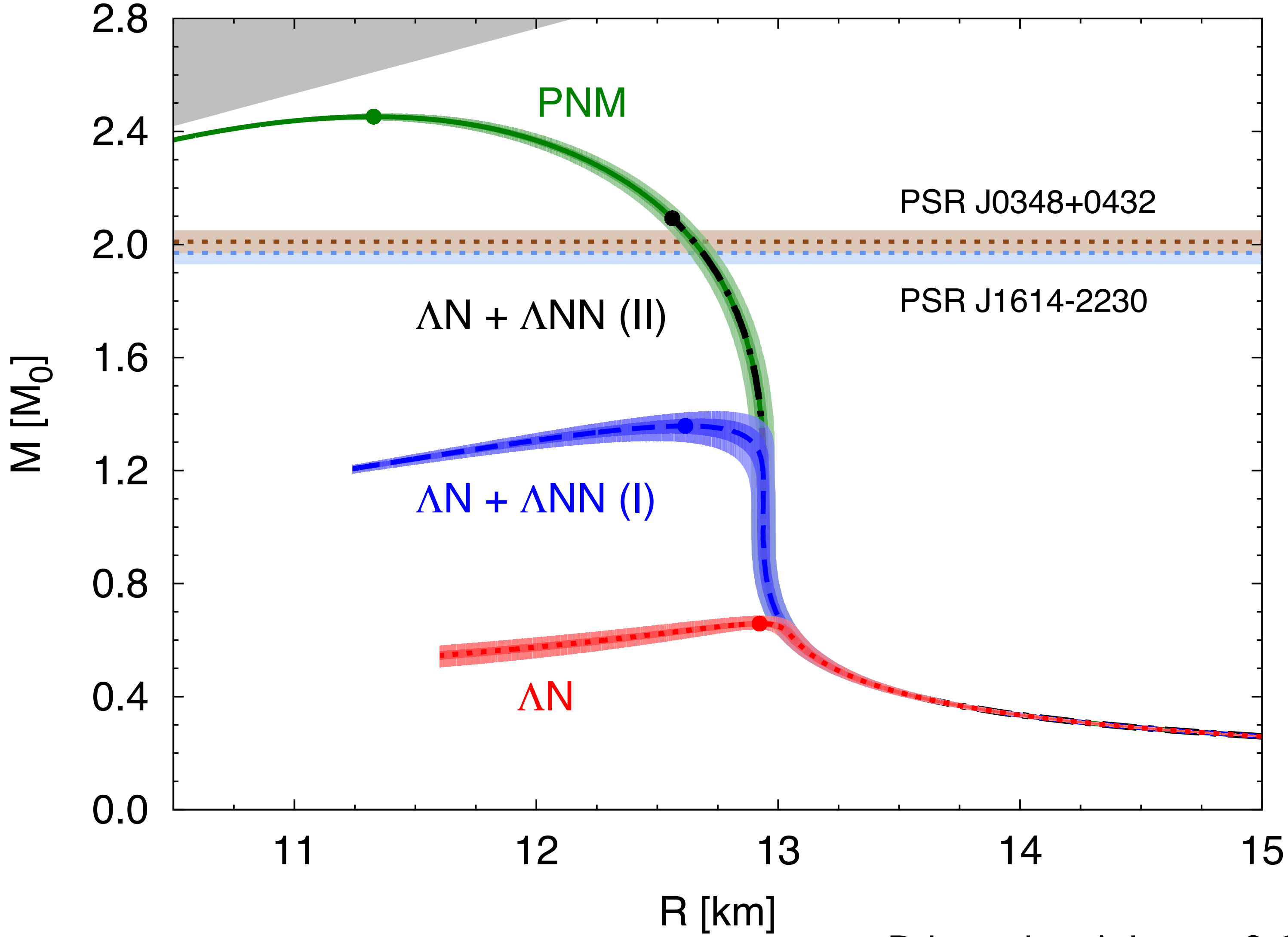
- conventional (**hadronic**) equation of state seems to work
- **quark-nuclear** coexistence occurs (if at all) only at baryon densities

$$\rho > 5\,\rho_0$$
$$(\rho_0 = 0.16\,\mathrm{fm}^{-3})$$

see also:
K. Masuda, T. Hatsuda, T. Takatsuka
PTEP (2013) 7, 073D01

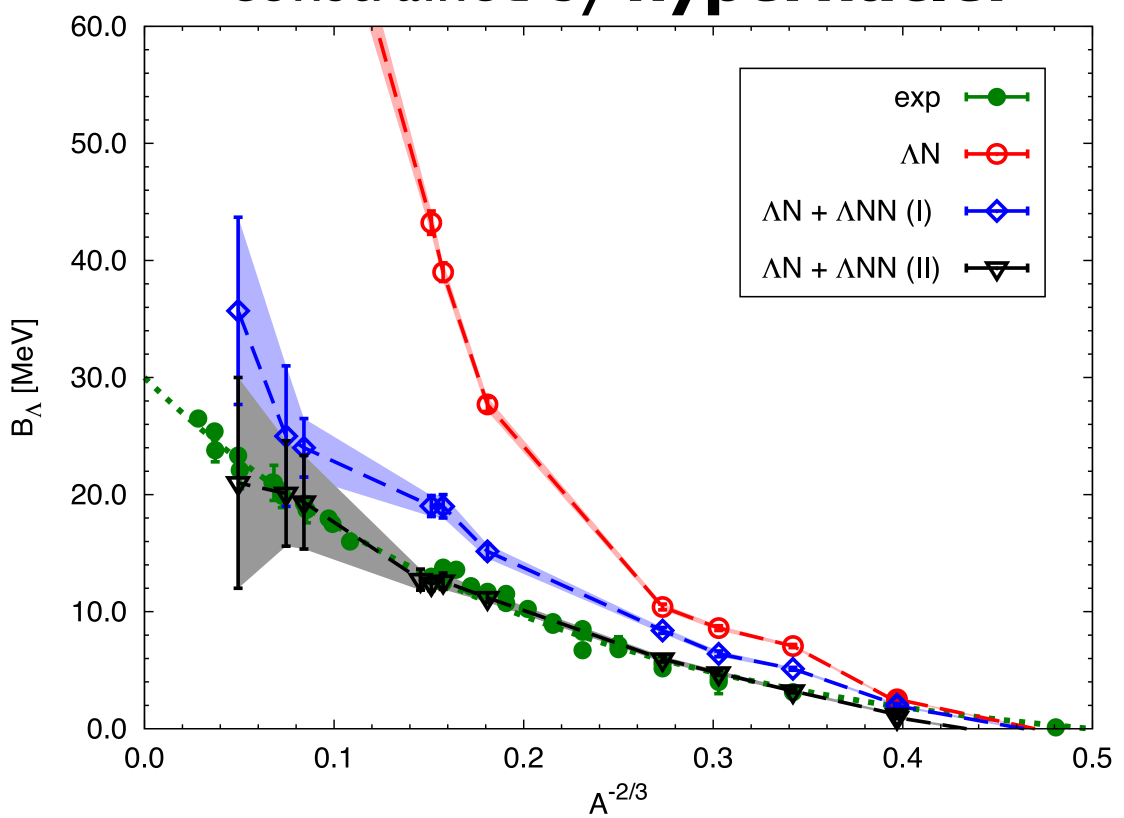
NEUTRON STAR MATTER including HYPERONS

Mass - radius relation of neutron stars



new **QMC calculations**
using phenomenological hyperon-nucleon
& hyperon-NN **three-body** interactions

constrained by **hypernuclei**

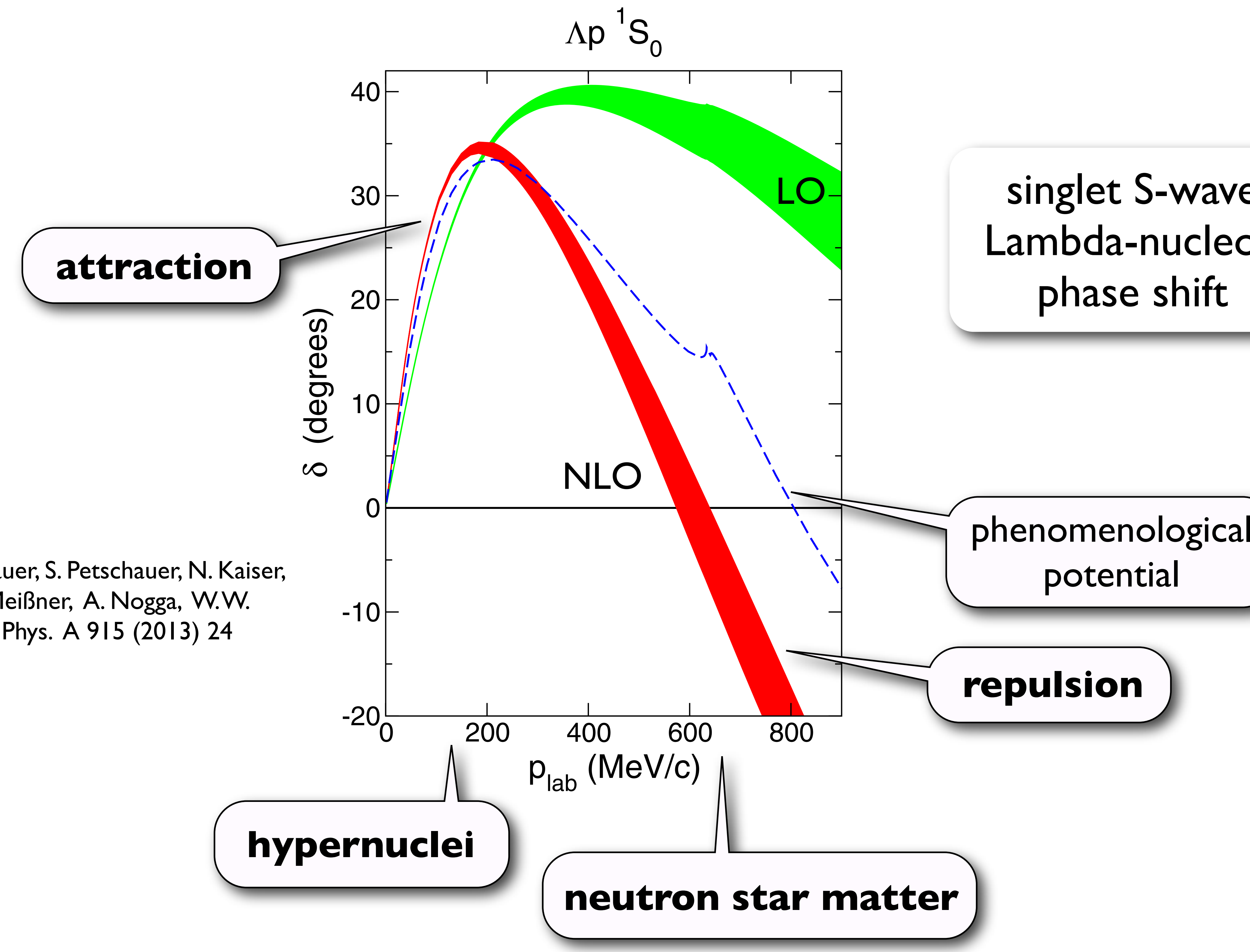


D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva; arXiv:1407.4448

with inclusion of hyperons: EoS **too soft** to support 2-solar-mass star
unless strong short-range **repulsion** in YN and / or YNN interactions

recall:

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



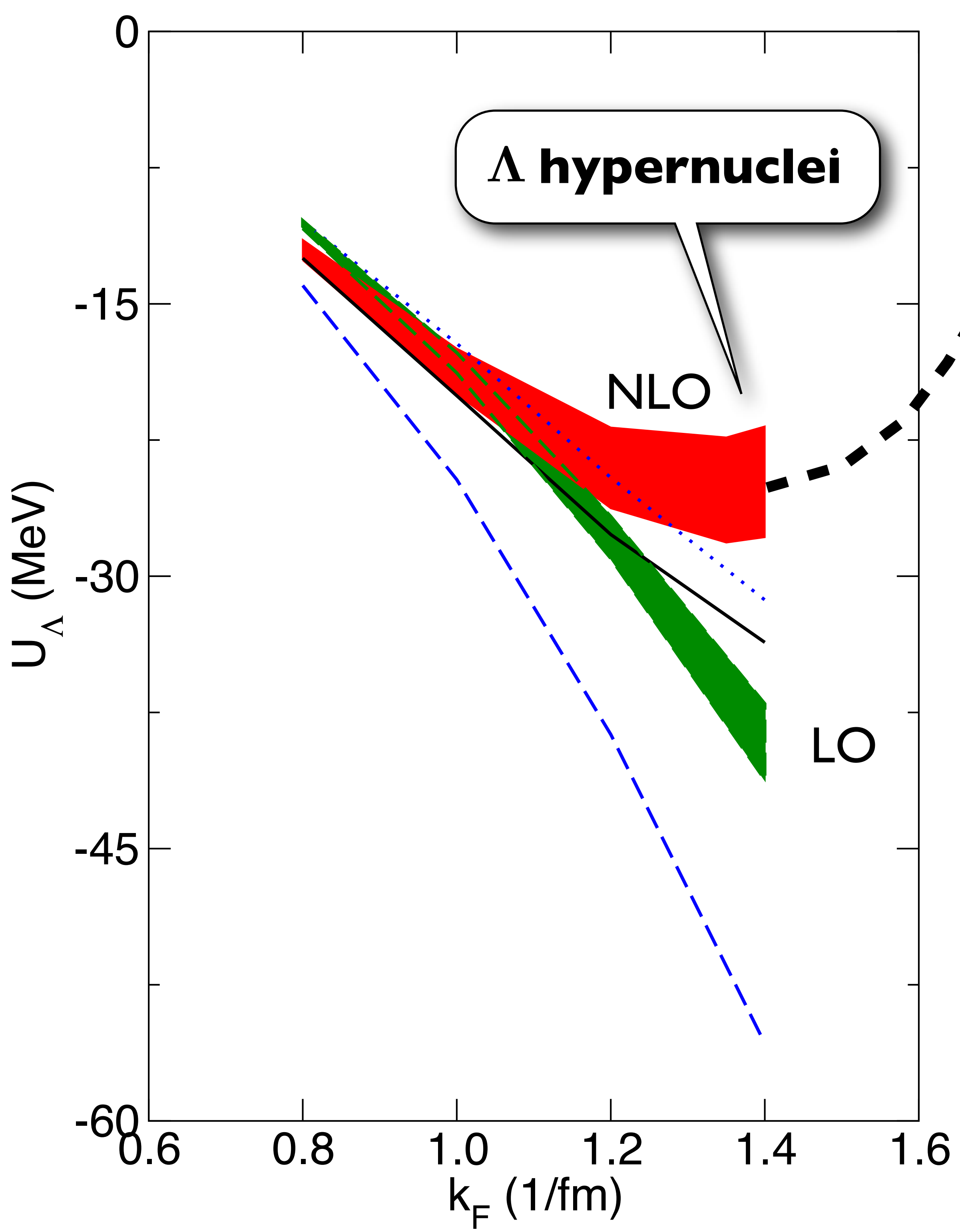
singlet S-wave Lambda-nucleon phase shift

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

Density dependence of
Λ **single particle potential** in **nuclear and neutron matter**

Brueckner calculation using **Chiral SU**(3) (coupled channels) hyperon-nucleon interaction

J. Haidenbauer et al.
(**preliminary**)



Λ hyperons in neutron stars ?

needed :

improved constraints from **accurate hyperon-nucleon scattering and hypernuclear data**

SUMMARY

- **Chiral SU**(3) **Effective Field Theory**: approved concept & tool
  - realization of **low-energy QCD**; special role of **strangeness**
  - well organized coupled-channels framework for both **antikaon**- and **hyperon**-nuclear systems
- Systems with **strangeness S = -1** and baryon no. **B = 1,2**:
  - **progress** in understanding the unusual structure of the $\Lambda(1405)$ (quasi-molecular $\bar{\mathrm{K}}\mathrm{N}$ state imbedded in strongly coupled $\pi\Sigma$ continuum)
  - $\bar{\mathrm{K}}\mathrm{N}$ and $\bar{\mathrm{K}}\mathrm{NN}$ **threshold** and **subthreshold** physics

  required: high-precision kaonic deuterium → **SIDDHARTA-2**

- Role of **strangeness** in **dense baryonic matter**
  - new constraints from **two-solar-mass neutron stars**: very **stiff equation-of-state**
  - new conditions for hyperon-nuclear two- and three-body interactions: quest for strong short-/intermediate-distance **repulsion**

  required: much improved **hyperon-nucleon** data base + **hypernuclei**