ANTIKAON INTERACTIONS with NUCLEONS and NUCLEI

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PART I: Low-Energy QCD with Strange Quarks

- Chiral SU(3) effective field theory
- Low-energy $\bar{\mathrm{K}}\mathrm{N}$ interactions and coupled channels
- Nature and properties of the $\Lambda(1405)$

PART II: $\bar{\mathrm{K}}$-Nuclear Systems

- $\bar{\mathrm{K}}$-nucleon and -nuclear effective potentials
- $\bar{\mathrm{K}}\mathrm{NN}$ quasibound states ? Theory status review
- Outlook: kaon condensation in neutron stars ?

1.

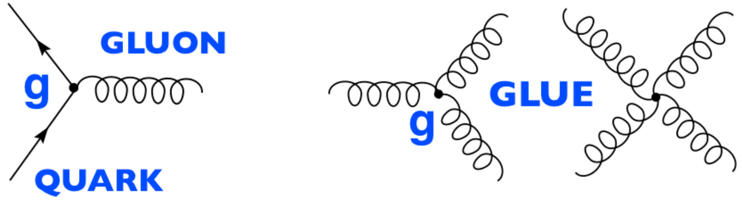
Basics of Low-Energy QCD:

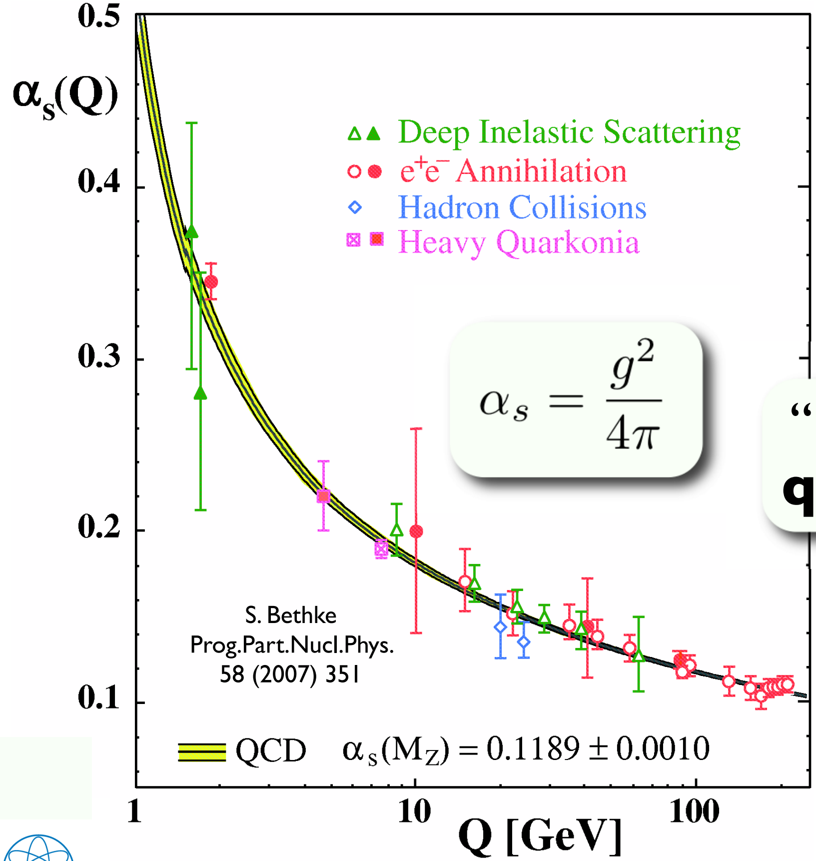
Symmetries and Symmetry Breaking Pattern

- Hierarchy of quark masses in QCD
- Chiral symmetry and spontaneous symmetry breaking
- Pseudoscalar mesons as Nambu-Goldstone bosons
- Low-energy QCD:
  from quarks and gluons to chiral effective field theory

QUANTUM CHROMO DYNAMICS

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\left(i\gamma_\mu \mathcal{D}^\mu - \mathbf{m}\right)\psi - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}$$



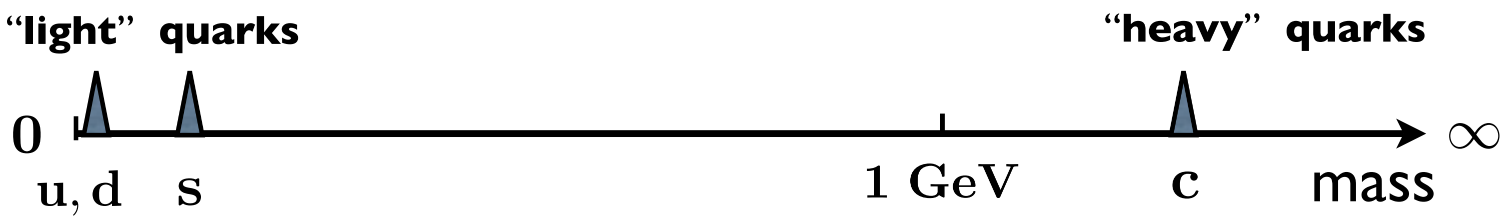


$$\alpha_s = \frac{g^2}{4\pi}$$

"light" quarks

Quarks spin = 1/2		
Flavor	**Approx. Mass GeV/c²**	**Electric charge**
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

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



$m_u/m_d \sim 0.3 - 0.6$

$m_d \simeq 3 - 7$ MeV

$m_s \simeq 70 - 120$ MeV

$(\mu \simeq 2$ GeV$)$

- **LOW-ENERGY QCD**: **CHIRAL EFFECTIVE FIELD THEORY**
- **expansion in** m_q **and in powers of low momentum**

$m_c \simeq 1.25$ GeV

$m_b \simeq 4.2$ GeV

$m_t \simeq 174$ GeV

- **N**on-**R**elativistic **QCD**: **HEAVY QUARK EFFECTIVE THEORY**
- **expansion in powers of** $1/m_Q$

QCD

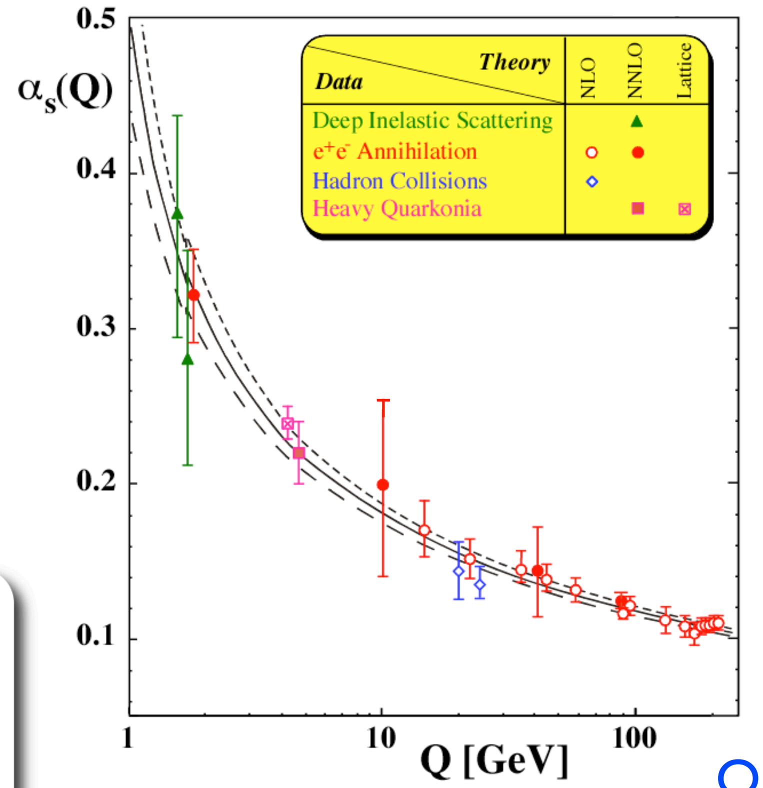
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\,(i\gamma_\mu \mathcal{D}^\mu - \mathbf{m})\,\psi - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}$$

BASIC CONCEPTS and **STRATEGIES**

"LOW - Q"
(<< 1 GeV)
↕
LONG DISTANCE
(~ 1 fm)

↓

SPONTANEOUS
(CHIRAL)
SYMMETRY BREAKING



"HIGH - Q"
(> several GeV)
↕
SHORT DISTANCE
(< 0.1 fm)

↓

Theory of
WEAKLY INTERACTING
QUARKS and GLUONS

↘

Effective Field Theory of WEAKLY INTERACTING
NAMBU-GOLDSTONE BOSONS

CHIRAL $\mathrm{SU(2)_L \times SU(2)_R}$ SYMMETRY

- QCD with $N_f = 2$ **MASSLESS QUARKS** $\quad \psi = (u,d)^T$

$$\psi_R = \frac{1}{2}(1+\gamma_5)\psi \qquad \psi_L = \frac{1}{2}(1-\gamma_5)\psi$$

- Invariance of $\mathcal{L}_{QCD}$ under $\quad \psi_{R,L} \to exp\left[i\frac{\theta^a_{R,L}\tau_a}{2}\right]\psi_{R,L}$

- Conserved currents: $\quad J^\mu_{R,L} = \bar\psi_{R,L}\,\gamma^\mu\frac{\tau}{2}\,\psi_{R,L} \qquad \partial_\mu J^\mu_{R,L} = 0$

- **VECTOR** and **AXIAL VECTOR CURRENTS**:

$$\mathbf{V}^\mu_a = J^\mu_{R,a} + J^\mu_{L,a} = \bar\psi\,\gamma^\mu\frac{\tau_a}{2}\,\psi \qquad \mathbf{A}^\mu_a = J^\mu_{R,a} - J^\mu_{L,a} = \bar\psi\,\gamma^\mu\gamma_5\frac{\tau_a}{2}\,\psi$$

- Conserved charges:

$$\mathbf{Q}^V_a = \int d^3x\,\psi^\dagger(x)\,\frac{\tau_a}{2}\,\psi(x) \qquad \mathbf{Q}^A_a = \int d^3x\,\psi^\dagger(x)\,\gamma_5\frac{\tau_a}{2}\,\psi(x)$$

Realizations of **CHIRAL SYMMETRY** in QCD

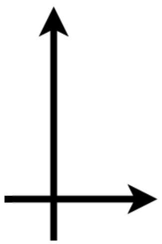
- **QCD** with (almost) **MASSLESS u-** and **d-QUARKS** ($N_f = 2$)

$$\mathbf{SU(2)_L \times SU(2)_R}$$

$$\psi = (\mathbf{u}, \mathbf{d})^T$$

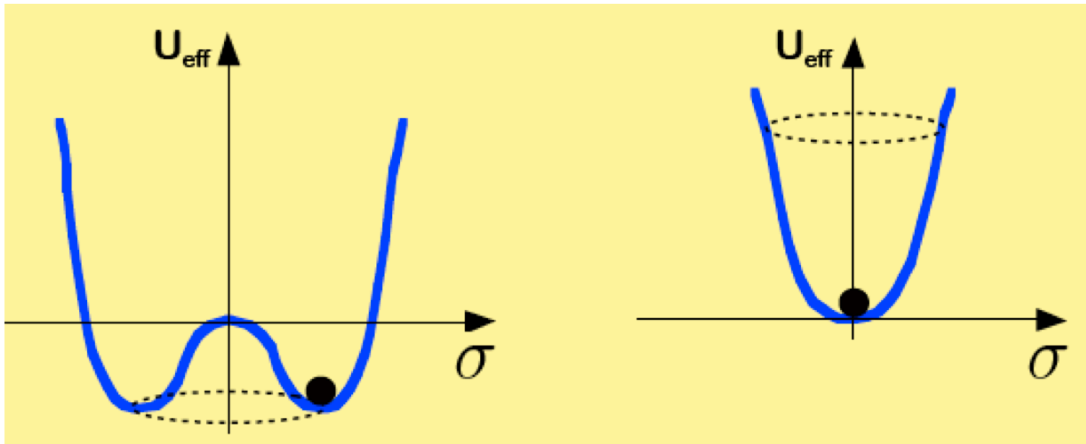
- Realizations of CHIRAL SYMMETRY:

pseudoscalar
isovector
$$\pi^a \leftrightarrow \bar{\psi}\,\gamma_5\,\mathbf{t}^a\,\psi$$



scalar
isoscalar
$$\sigma \leftrightarrow \bar{\psi}\,\psi$$

invariant:
$$\sigma^2 + \pi^2 = \mathbf{f^2}$$



Nambu-Goldstone	Wigner-Weyl
$\langle \bar{\psi}\psi \rangle \neq 0$	$\langle \bar{\psi}\psi \rangle = 0$
(at low energy)	(at high energy)

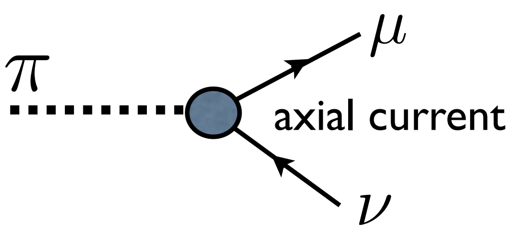
Spontaneously Broken CHIRAL SYMMETRY

- Axial charge acting on vacuum:

$$0 \neq \mathbf{Q}_a^A|0\rangle \sim |\pi_a\rangle$$ **massless** pseudoscalars

- **NAMBU - GOLDSTONE BOSONS**: **PIONS**

- **ORDER PARAMETER**: **PION DECAY CONSTANT**



$$\langle 0|\mathbf{A}_a^\mu(x)|\pi_b(p)\rangle = i p^\mu \, \mathbf{f}_\pi \, \delta_{ab} \, e^{-ip\cdot x}$$

$$\mathbf{f}_\pi = 92.4\,\mathrm{MeV}$$ (exp.)

chiral limit: $\mathbf{f} = 86.2\ \mathrm{MeV}$

- Non-trivial QCD vacuum:

CHIRAL (Quark) CONDENSATE

$$\langle 0|\bar{\psi}\psi|0\rangle \neq 0$$

explicit SB

$$\mathbf{m}_\pi^2\,\mathbf{f}^2 = -\mathbf{m_q}\,\langle\bar{\psi}\psi\rangle + \mathcal{O}(m_q^2)$$

spontaneous SB

Gell-Mann, Oakes, Renner

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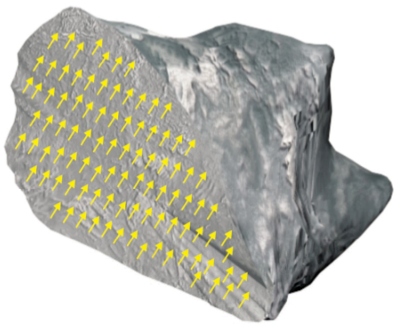
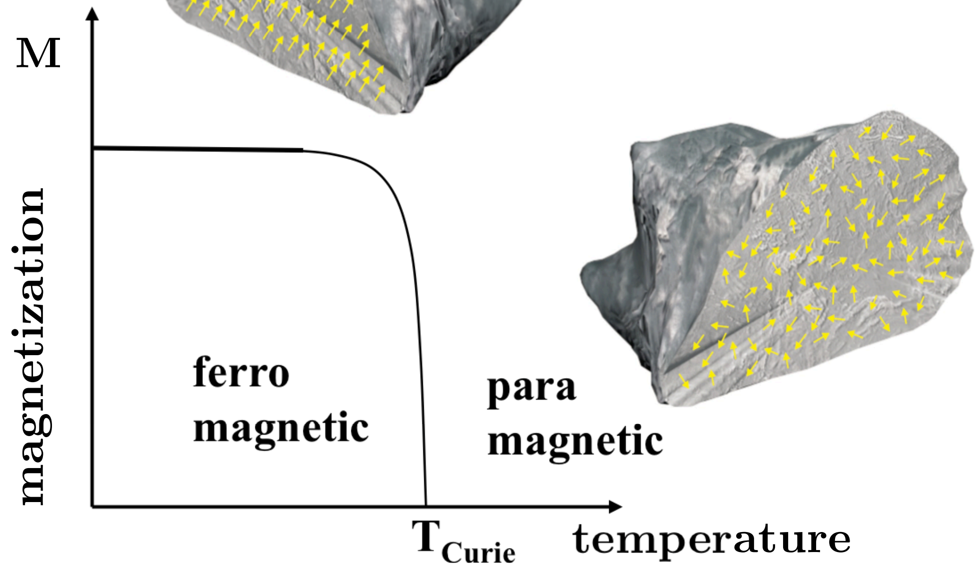
Spontaneously Broken Symmetry: Ferromagnetism



- Low temperature:
  spontaneously broken
  rotational O(3) symmetry



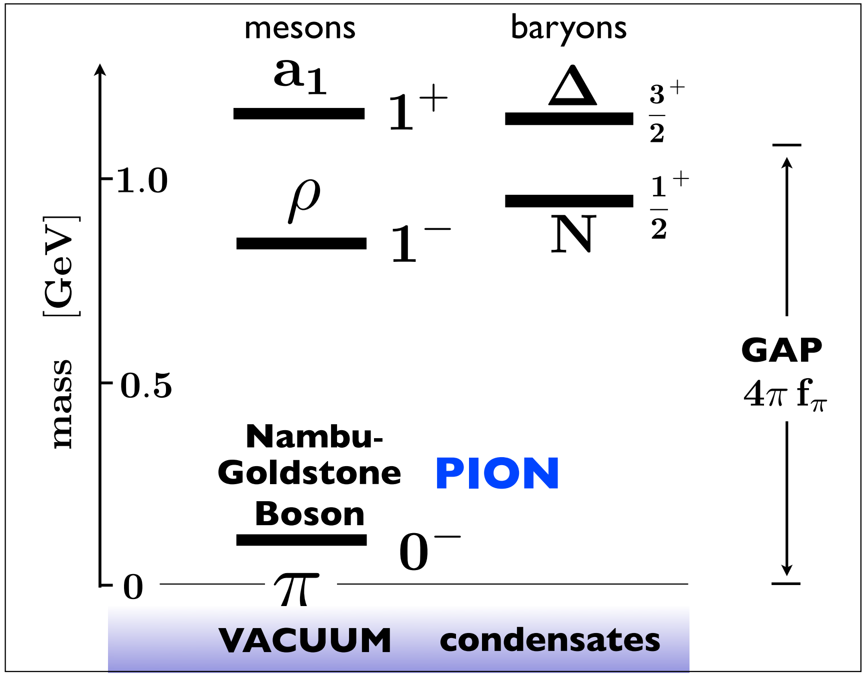
- Nambu-Goldstone boson:
  spin wave (magnon)

- above Curie temperature:
  rotational symmetry restored
  (paramagnet)

- Analogues in spontaneously broken symmetries:

magnetization M	$\longleftrightarrow$	order parameter	$\longleftrightarrow$	chiral condensate $\langle\bar{\psi}\,\psi\rangle$
spin wave	$\longleftrightarrow$	Nambu-Goldstone boson	$\longleftrightarrow$	**pion**

Spontaneously Broken CHIRAL SYMMETRY (contd.)



SYMMETRY BREAKING SCALE ↔ MASS GAP $\Lambda_\chi = 4\pi\,\mathrm{f} \sim 1\,\mathrm{GeV}$

- **Low-energy** limit of **QCD** is realized in the form of a **Chiral Effective Field Theory**
- **Nambu-Goldstone bosons** (pions) are the active (almost massless) degrees of freedom

CHIRAL EFFECTIVE FIELD THEORY

Weinberg (`79), Gasser & Leutwyler (`84, `85)

- **LOW-ENERGY QCD**: **E**ffective **F**ield **T**heory of **weakly** interacting **Nambu-Goldstone Bosons** (pions) representing QCD at scales $\mathbf{Q} << 4\pi\, \mathbf{f}_\pi \sim 1\,\mathbf{GeV}$

- Effective Lagrangian (meson sector):

$$\mathcal{L}_{eff} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \ldots$$

chiral field

$$\mathbf{U}(x) = \exp[i\tau_a \pi_a(x)/f_\pi]$$

$$\mathcal{L}^{(2)} = \frac{\mathbf{f}^2}{4}\mathbf{Tr}[\partial^\mu \mathbf{U}^\dagger \partial_\mu \mathbf{U}] + \frac{\mathbf{f}^2}{2} B_0\, \mathbf{Tr}[\mathbf{m}(\mathbf{U}^\dagger + \mathbf{U})]$$

non-linear sigma model

$$\mathbf{m} = \mathbf{diag}(m_u, m_d)$$

symmetry breaking mass term

- Higher order terms . . .

$$\mathcal{L}^{(4)} = \frac{\ell_1}{2}\left(\mathbf{Tr}[\partial^\mu \mathbf{U}^\dagger \partial_\mu \mathbf{U}]\right)^2 + \frac{\ell_2}{2}\mathbf{Tr}[\partial^\mu \mathbf{U}^\dagger \partial^\nu \mathbf{U}]\,\mathbf{Tr}[\partial_\mu \mathbf{U}^\dagger \partial_\nu \mathbf{U}]$$

$$+\frac{\ell_3}{2}B_0^2\left(\mathbf{Tr}[\mathbf{m}(\mathbf{U}^\dagger + \mathbf{U})]\right)^2 + \frac{\ell_4}{2}B_0\,\mathbf{Tr}[\partial^\mu \mathbf{U}^\dagger \partial_\mu \mathbf{U}]\,\mathbf{Tr}[\mathbf{m}(\mathbf{U}^\dagger + \mathbf{U})]$$

. . . introduce additional low-energy constants ℓ_i

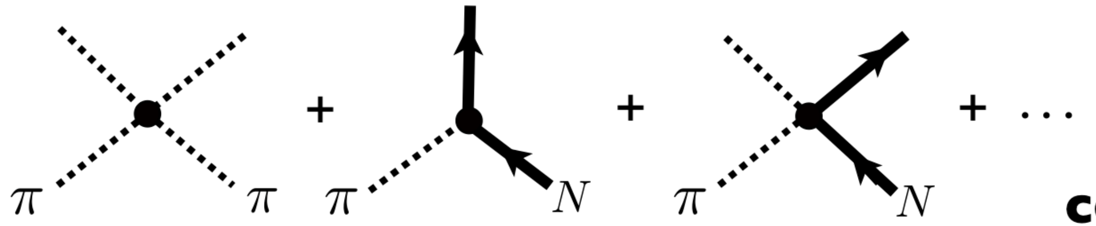
CHIRAL EFFECTIVE FIELD THEORY
with inclusion of BARYONS

Interacting systems of
PIONS (light / fast) and **NUCLEONS** (heavy / slow):

$$\mathcal{L}_{eff} = \mathcal{L}_\pi(U, \partial U) + \mathcal{L}_N(\Psi_N, U, \ldots)$$

$$U(x) = exp[i\tau_a \pi_a(x)/f_\pi]$$

- Construction of Effective Lagrangian: **Symmetries**



short distance dynamics: **contact terms**

Low-Energy Expansion:
CHIRAL PERTURBATION THEORY

- **small parameter**:

$$\frac{Q}{4\pi f_\pi} \qquad \frac{\textbf{energy} / \textbf{momentum} / \text{pion mass}}{1\,\mathrm{GeV}}$$

successfully applied to:

➡ **PION-PION** scattering

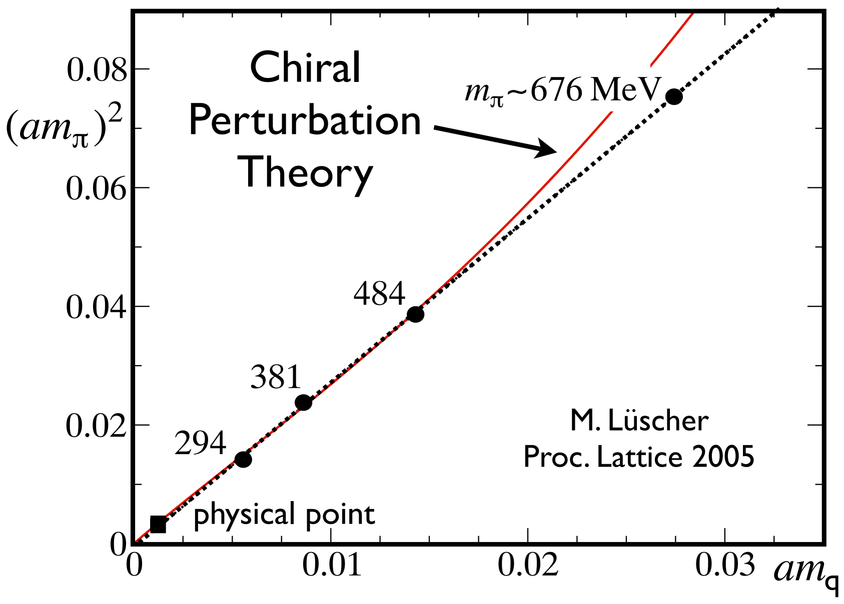
➡ **PION-NUCLEON** scattering

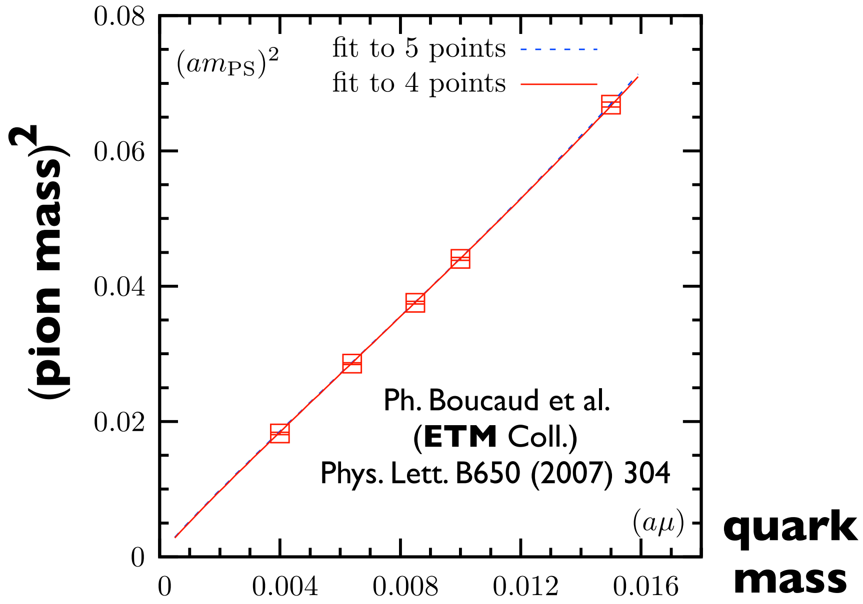
➡ **PION photoproduction** and COMPTON scattering on the NUCLEON

➡ long range **NUCLEON-NUCLEON** interaction

➡ **NUCLEAR MATTER** and **NUCLEI**

Chiral Symmetry Breaking Scenario
- ChPT vs. Lattice QCD -





- **G**ell-Mann, **O**akes, **R**enner relation works

$$m_\pi^2 = -\frac{m_u + m_d}{\mathbf{f}_\pi^2}\langle\bar{\mathbf{q}}\mathbf{q}\rangle + \mathcal{O}(m_q^2)$$

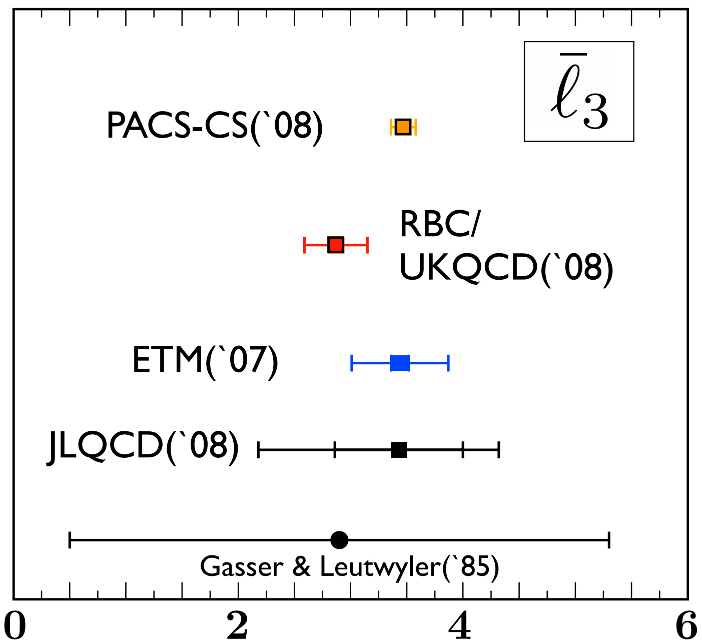
- **Ch**iral **P**erturbation **T**heory applicable up to pion masses $\lesssim$ 500 MeV

confirmation of "standard" spontaneous symmetry breaking with **Pion** as **Nambu-Goldstone Boson** and **Strong Chiral Condensate**

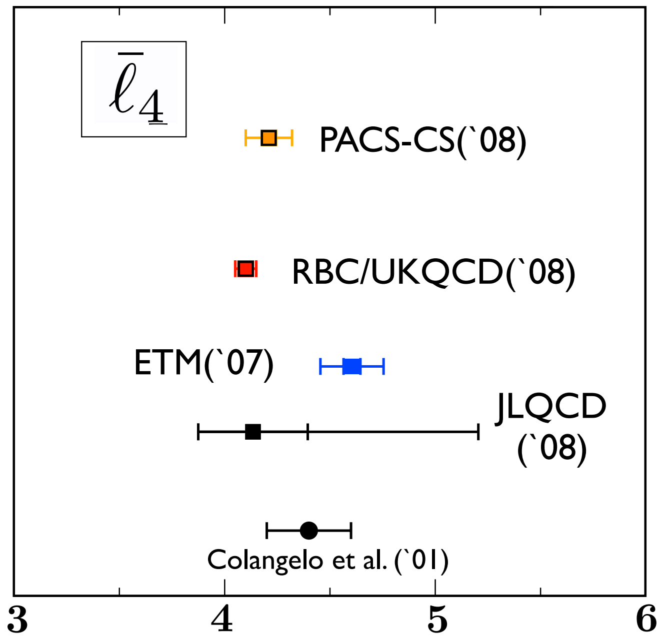
Test of **Chiral Symmetry Breaking Scenario**
- **Low-Energy Constants** from **Lattice QCD** -

- Chiral Perturbation Theory at NLO vs. Lattice QCD: $\left(m_\circ^2 = -\frac{m_q}{f^2}\langle\bar{\psi}\psi\rangle\right)$

$$m_\pi^2 = m_\circ^2\left[1 + \frac{m_\circ^2}{32\pi^2 f^2}\ln\frac{m_\circ^2}{\Lambda_3^2} + \mathcal{O}(m_\circ^4)\right] \qquad f_\pi = f\left[1 - \frac{m_\circ^2}{16\pi^2 f^2}\ln\frac{m_\circ^2}{\Lambda_4^2} + \mathcal{O}(m_\circ^4)\right]$$



$$\bar{\ell}_3 \equiv \ln\frac{\Lambda_3^2}{m_\pi^2}$$



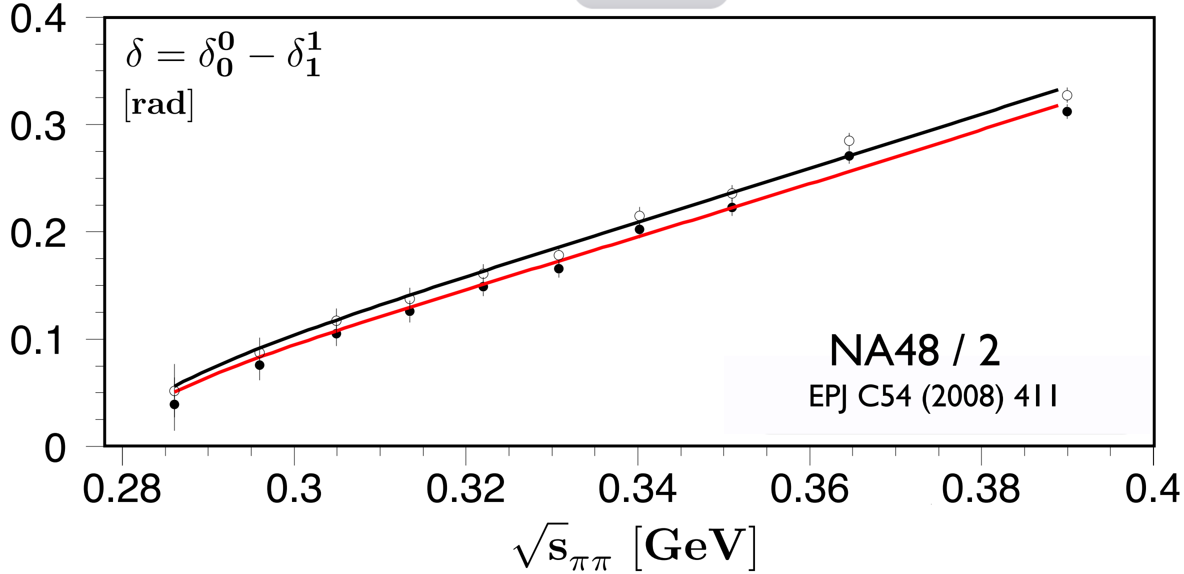
$$\bar{\ell}_4 \equiv \ln\frac{\Lambda_4^2}{m_\pi^2}$$

Test of **Chiral Symmetry Breaking Scenario**
- Pion-Pion Scattering -

- Precision measurements of $\pi\pi$ scattering lengths $a_0, \ a_2$
- Sensitivity to $\bar{\ell}_3, \bar{\ell}_4$

Theory: Chiral Symmetry + Roy Equations
G. Colangelo et al. Nucl. Phys. B 603 (2001) 125

$$K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$$



	Theory (ChPT)	Exp (NA48/2)
a_0	0.220 ± 0.005	0.218 ± 0.013
a_2	-0.044 ± 0.001	-0.0457 ± 0.0084

2.

Low-Energy QCD with Strange Quarks:

Chiral SU(3) Dynamics

- Effective field theory with strangeness:
  Chiral SU(3) Lagrangian

- Tomozawa - Weinberg interactions

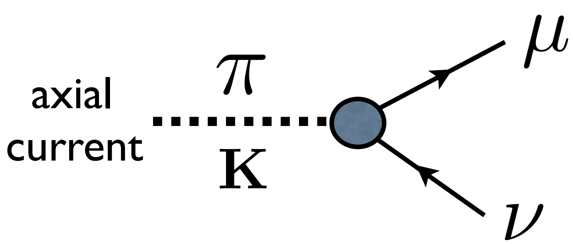
- Meson-baryon dynamics with strangeness:
  why "eightfold way" chiral perturbation theory does not work

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

- Low-Energy QCD with $N_f = 3$ MASSLESS QUARKS $\psi = (u, d, s)^T$
- **Axial Vector Current**: $\mathbf{A}_a^\mu(x) = \bar\psi(x)\,\gamma^\mu\gamma_5\,\frac{\lambda_a}{2}\psi(x)$
- **NAMBU - GOLDSTONE BOSONS**:

  Pseudoscalar SU(3) meson octet $\{\phi_a\} = \{\pi,\, \mathbf{K},\, \bar{\mathbf{K}}, \eta_8\}$
- **ORDER PARAMETERS**: **DECAY CONSTANTS**

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



$\mathbf{f_\pi = 92.4 \pm 0.3\ MeV}$

$\mathbf{f_K = 113.0 \pm 1.3\ MeV}$

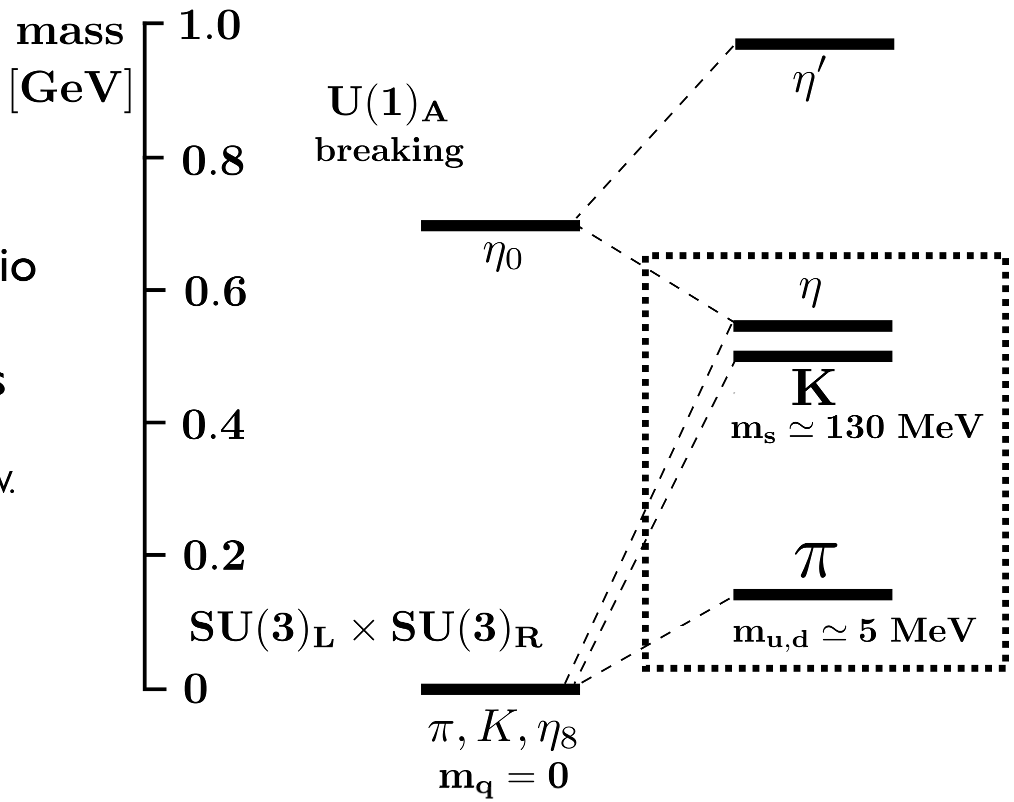
($\mathbf{f = 86.2\ MeV}$ chiral limit)

SYMMETRY BREAKING PATTERN

PSEUDOSCALAR MESON SPECTRUM

calculation:
Nambu & **J**ona-**L**asinio
model with
N_f = 3 quark flavors

S. Klimt, M. Lutz, U. Vogl, W. W.
Nucl. Phys. A 516 (1990) 429



- **PCAC**: Gell-Mann - Oakes - Renner Relations

$$m_\pi^2\, \mathbf{f}_\pi^2 \doteq -\frac{1}{2}(m_u + m_d)\langle \bar{u}u + \bar{d}d\rangle \qquad m_K^2\, \mathbf{f}_K^2 \doteq -\frac{1}{2}(m_u + m_s)\langle \bar{u}u + \bar{s}s\rangle$$

CHIRAL SU(3) EFFECTIVE LAGRANGIAN
- Meson Sector -

Starting point: Spontaneously broken

CHIRAL SU(3) x SU(3) SYMMETRY of QCD

with $N_f = 3$ massless u-, d- and s-quarks

- **GOLDSTONE BOSON** (octet) FIELD:

$$U(x) = exp[i\Phi(x)/\mathbf{f}] \in \mathbf{SU(3)}$$

$$\Phi \equiv \lambda_a \phi_a = \sqrt{2} \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

$$\mathcal{L}_{eff} = \frac{\mathbf{f}^2}{4} Tr\left[\partial^\mu U^\dagger \partial_\mu U\right] + \frac{B\mathbf{f}^2}{2} Tr\left[\mathcal{M}(U + U^\dagger)\right] + \ldots$$

$$\mathbf{f \simeq 0.1\,GeV}$$

NON-LINEAR SIGMA MODEL

+

explicit symmetry breaking: mass term

$$\mathcal{M} = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

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CHIRAL SU(3) EFFECTIVE LAGRANGIAN
- including Baryons -

- BARYON (octet) FIELD:

$$\Psi_B \equiv \frac{1}{\sqrt{2}}\lambda_a \Psi_B^a = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

- Effective LAGRANGIAN: $\mathcal{L}_{eff} = \mathcal{L}_{mesons}(\Phi) + \mathcal{L}_B(\Phi, \Psi_B)$

$$\mathcal{L}_B = Tr\left[\bar{\Psi}_B(i\gamma_\mu \mathcal{D}^\mu - M_0)\Psi_B\right]$$

$$+\,\mathbf{F}\,Tr\left[\bar{\Psi}_B\gamma_\mu\gamma_5[\mathcal{A}^\mu, \Psi_B]\right] + \mathbf{D}\,Tr\left[\bar{\Psi}_B\gamma_\mu\gamma_5\{\mathcal{A}^\mu, \Psi_B\}\right] + \ldots$$

$\mathbf{F} = \mathbf{0.47} \pm \mathbf{0.01}$ $\quad$ $\mathbf{D} = \mathbf{0.80} \pm \mathbf{0.01}$ $\quad$ $(\mathbf{F} + \mathbf{D} = g_A = 1.27)$

- Chiral covariant derivative: $\mathcal{D}^\mu \Psi_B = \partial^\mu \Psi_B + [\mathcal{V}^\mu, \Psi_B]$

- **vector** and **axial vector** chiral fields:

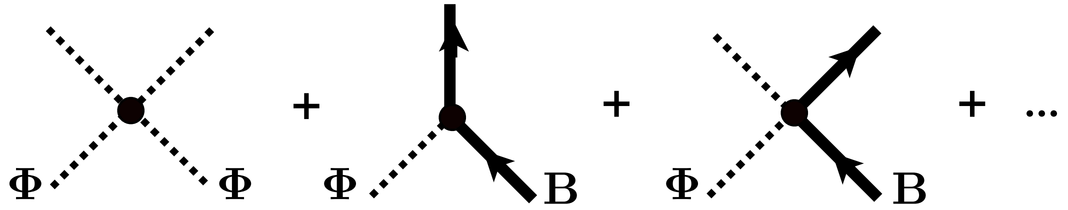
$$\mathcal{V}^\mu = \frac{1}{8\mathbf{f}^2}[\Phi, \partial^\mu\Phi] + \mathcal{O}(\Phi^4) \qquad \mathcal{A}^\mu = -\frac{i}{2\mathbf{f}}\,\partial^\mu\Phi + \mathcal{O}(\Phi^3)$$

CHIRAL SU(3) EFFECTIVE FIELD THEORY

- Interacting systems of **NAMBU-GOLDSTONE BOSONS** (**pions**, **kaons**) coupled to **BARYONS**

$$\mathcal{L}_{eff} = \mathcal{L}_{mesons}(\Phi) + \mathcal{L}_B(\Phi, \Psi_B)$$

- Leading **DERIVATIVE** couplings (involving $\partial^\mu \Phi$) determined by spontaneously broken **CHIRAL SYMMETRY**



higher orders with additional low-energy constants

- Low-Energy Expansion: **CHIRAL PERTURBATION THEORY**

"small parameter": $\frac{\mathrm{p}}{4\pi\,\mathrm{f}_\pi} \sim \frac{\text{energy / momentum}}{1\ \mathrm{GeV}}$

- works well for low-energy **pion-pion** and **pion-nucleon** interactions

▶ ... but **NOT** for systems with **strangeness** $\mathrm{S} = -1$ $(\bar{\mathrm{K}}\mathrm{N},\ \pi\Sigma,\ ...)$

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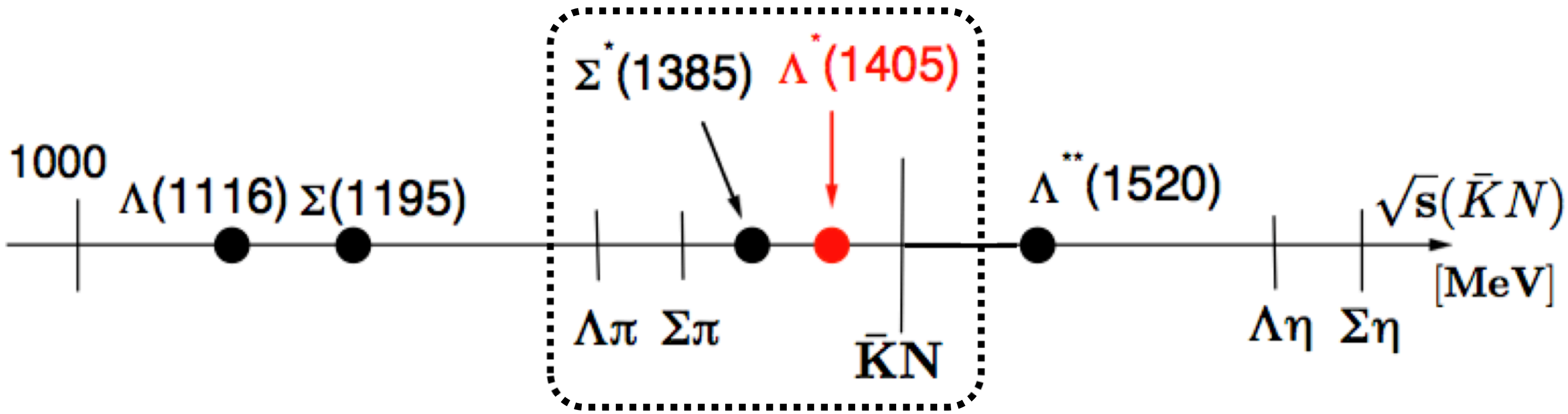
LOW-ENERGY $\bar{K}N$ SYSTEMS

- **Poles** and **thresholds**:



$\Lambda(1405)$ resonance 27 MeV below threshold:

► chiral perturbation theory NOT applicable

- Strategy:

Non-perturbative coupled-channels approach
based on **Chiral SU(3) Dynamics**

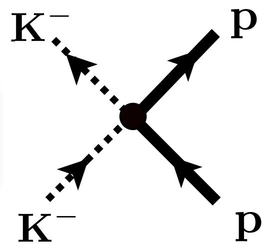
(⟶ next section)

Tomozawa - Weinberg Interaction

- Model-independent leading order terms from chiral effective meson-baryon Lagrangian

- Example: TW interaction in $K^- p \rightarrow K^- p$ channel

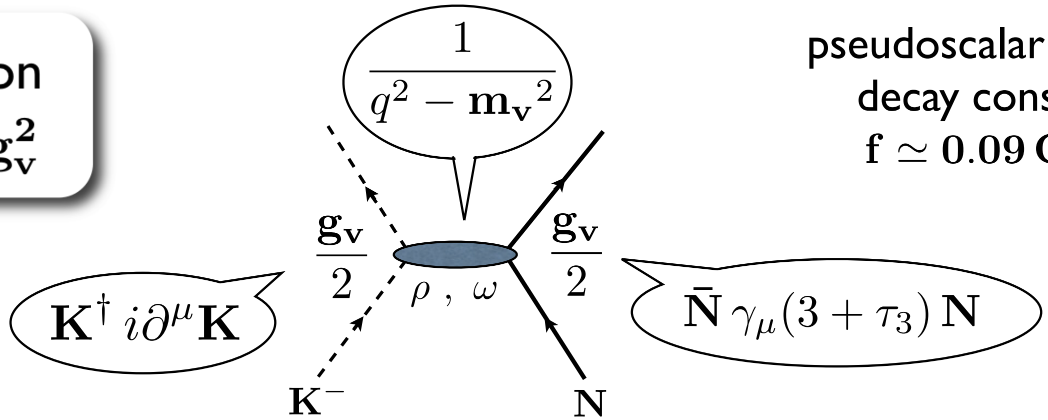
$$\delta \mathbf{H}_{int}^{WT} = -\frac{1}{2\,\mathbf{f}^2} \int d^3x \, \left[\bar{\Psi}_p(x)\,\gamma^\mu\,\Psi_p(x)\right] \, \left[K^+(x)\, i\partial_\mu K^-(x)\right]$$



- Interpretation in terms of **vector meson exchange**:

KSFR relation
$\mathbf{m_v^2 = 2\, f^2\, g_v^2}$

vector coupling
$\mathbf{g_v \simeq 6}$



pseudoscalar meson decay constant
$\mathbf{f \simeq 0.09\, GeV}$

- Vector meson exchange $\longrightarrow$ TW interaction in the limit $\mathbf{q^2 << m_v^2}$

Kaon- and **Antikaon-Nucleon Interactions**
- Leading Order -

- Estimate of $\mathbf{K^{\pm}N}$ interaction strengths at zero momentum:

  T matrix elements $(\omega = \sqrt{s} - M_N)$

$$\mathbf{T}^{(WT)}(K^- p \to K^- p) = -\mathbf{T}^{(WT)}(K^+ p \to K^+ p) = \frac{\omega}{\mathbf{f}^2}$$

$$\mathbf{T}^{(WT)}(K^- n \to K^- n) = -\mathbf{T}^{(WT)}(K^+ n \to K^+ n) = \frac{\omega}{2\,\mathbf{f}^2}$$

- Leading order kaon / antikaon self-energy in (static) nuclear matter:

$$(\Pi(\omega, \vec{q} = 0; \rho) = -\mathbf{T}\,\rho)$$

$$\Pi^{\pm}_{WT} = \pm\frac{\omega}{\mathbf{f}^2}\left[\frac{3}{4}(\rho_p + \rho_n) + \frac{1}{4}(\rho_p - \rho_n)\right] = 2\omega\, U^{\pm}_{WT}$$

repulsive for $\mathbf{K^+}$
attractive for $\mathbf{K^-}$

- Schrödinger type threshold potential for $\mathbf{K^-}$ in N = Z nuclear matter

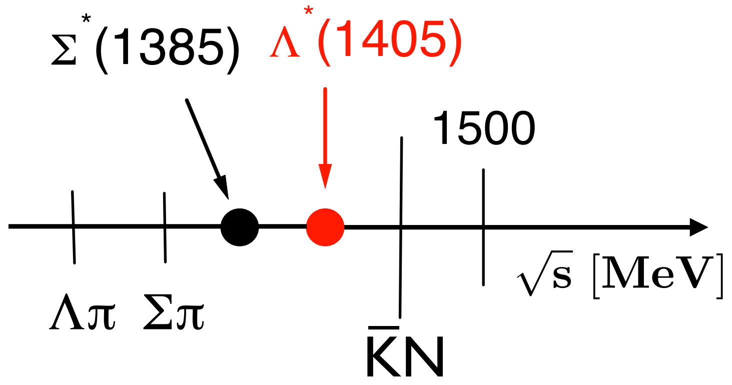
$$U^{-}_{WT} = -\frac{3}{8\,\mathbf{f}^2}\,\rho \sim \mathbf{-50\ MeV} \qquad \text{at} \qquad \rho = \rho_0 = \mathbf{0.16\ fm^{-3}}$$

3.
Chiral SU(3) Dynamics and Low-Energy Antikaon-Nucleon Interactions

- Empirical facts from kaonic hydrogen and $\mathbf{K^- p}$ scattering
- Nature and properties of the $\mathbf{\Lambda(1405)}$
- Effective (energy dependent and complex) $\mathbf{\bar{K} N}$ interaction
- Two-poles scenario of chiral SU(3) coupled-channels dynamics
- $\pi\,\Sigma$ invariant mass distributions

LOW-ENERGY $\bar{K}N$ SYSTEMS

- Chiral perturbation theory with strangeness is **NOT** applicable:



- sacrifice rigorous power counting in favor of important physics: summation of **dominant** chiral SU(3) interactions to **all** orders

  - Non-perturbative **coupled-channels approach**
  - Dynamical generation of $\Lambda(1405)$ as quasi-bound $\bar{\mathrm{K}}\mathrm{N}$ state embedded in strongly interacting $\pi\Sigma$ continuum

(early history: R.H. Dalitz et al.; Phys. Rev. 153 (1967) 1617)

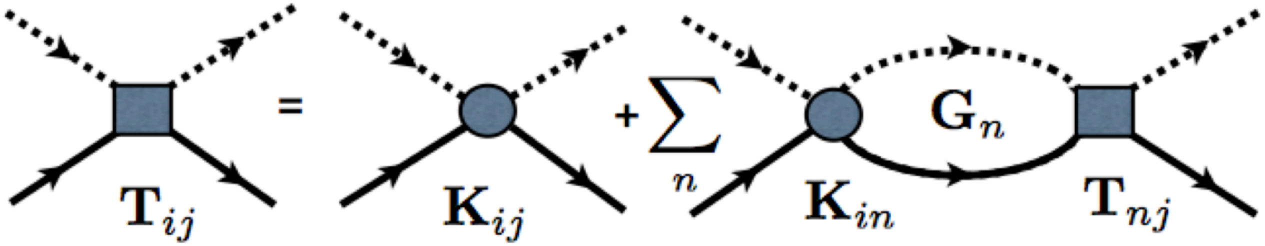
CHIRAL SU(3) DYNAMICS with COUPLED CHANNELS

N. Kaiser, P. B. Siegel, W.W.: Nucl. Phys. A 594 (1995) 325

... plus subsequent work by many groups (A. Ramos et al., M. Lutz and E. Kolomeitsev, D. Jido et al.)

Pseudoscalar meson octet

$(\pi, K, \bar{K}, \eta)$



$(p, n, \Lambda, \Sigma, \Xi)$

Baryon octet

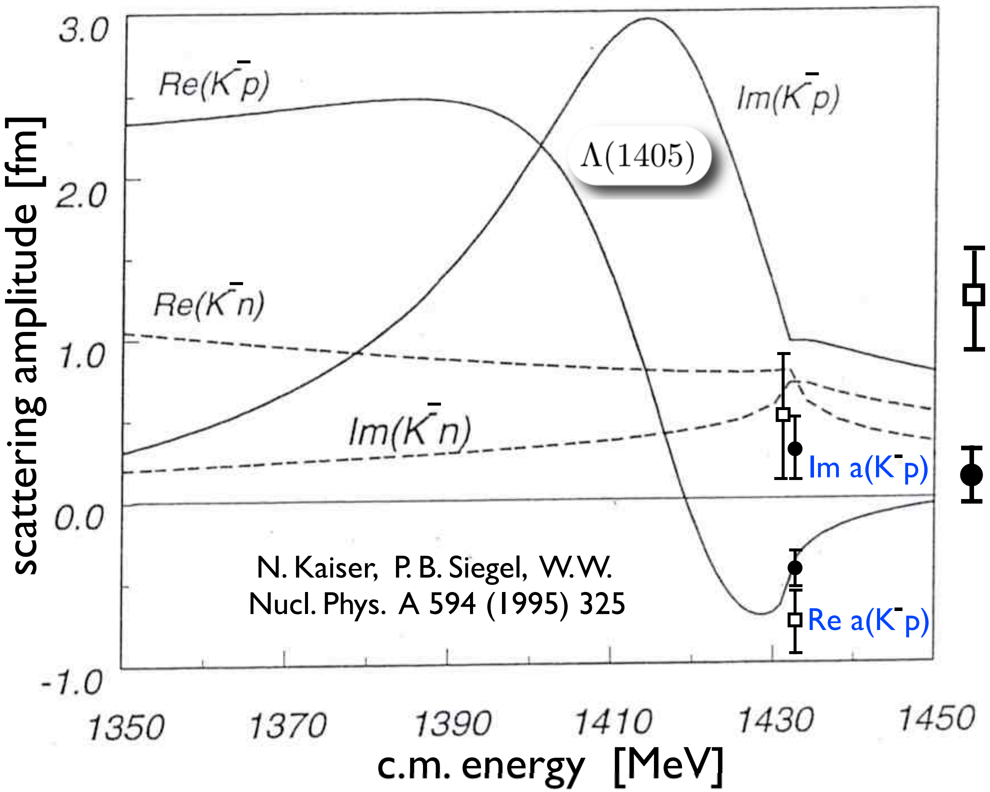
$$\mathbf{T} = \mathbf{K} + \mathbf{K\,G\,T} = (\mathbf{1} - \mathbf{K\,G})^{-1}\,\mathbf{K}$$

$$\mathbf{T}_{ij}(p', p, \sqrt{s}) = \mathbf{K}_{ij}(p', p, \sqrt{s}) + \sum_n \int \frac{d^4q}{(2\pi)^4}\,\mathbf{K}_{in}(p', q, \sqrt{s})\,\mathbf{G}_n(q, \sqrt{s})\,\mathbf{T}_{nj}(q, p, \sqrt{s})$$

Kernel $\mathbf{K}_{ij}$ from

CHIRAL SU(3) EFFECTIVE MESON-BARYON LAGRANGIAN

$\bar{K}$ N AMPLITUDES



CHIRAL SU(3)
EFFECTIVE FIELD THEORY
with
COUPLED CHANNELS
leading (Tomozawa - Weinberg) terms

K^-p scattering length
from
kaonic hydrogen:

KEK

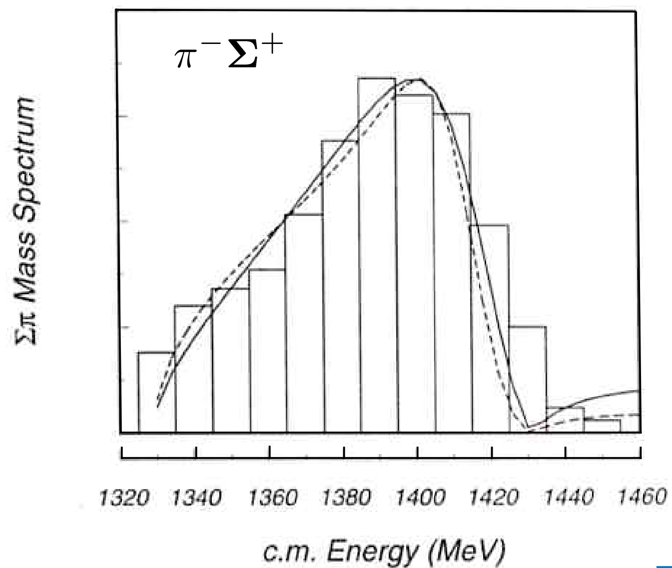
□ $a(K^-p) = \mathbf{-0.78}\ (\pm 0.18) + \mathbf{i\ 0.49}\ (\pm 0.37)$ fm

(M. Iwasaki et al., Phys. Rev. Lett. 78 (1997) 3067)

DEAR / LNF

● $a(K^-p) = \mathbf{-0.47}\ (\pm 0.10) + \mathbf{i\ 0.30}\ (\pm 0.17)$ fm

(G. Beer et al., Phys. Rev. Lett. 94 (2005) 212302)



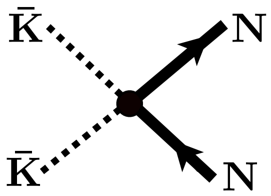
CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

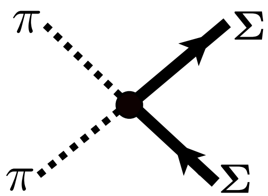
$$\mathbf{T_{ij} = K_{ij} + \sum_n K_{in}\, G_n\, T_{nj}}$$

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

  Note: **ENERGY DEPENDENCE** characteristic of Nambu-Goldstone Bosons

$$|\mathbf{1}\rangle = |\bar{\mathbf{K}}\mathbf{N}, \mathbf{I} = \mathbf{0}\rangle \qquad |\mathbf{2}\rangle = |\pi\mathbf{\Sigma}, \mathbf{I} = \mathbf{0}\rangle$$



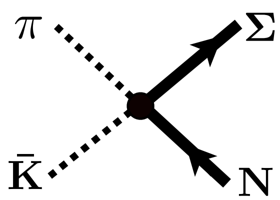


$$\mathbf{K_{11} = \frac{3}{2f^2}(\sqrt{s} - M_N)} \qquad \mathbf{K_{22} = \frac{2}{f^2}(\sqrt{s} - M_\Sigma)}$$

individually **strong** enough (attractive) to produce

- $\bar{\mathrm{K}}\mathrm{N}$ **bound state**
- $\pi\Sigma$ **resonance**

- **strong** channel coupling $\mathbf{12 \leftrightarrow 21}$:

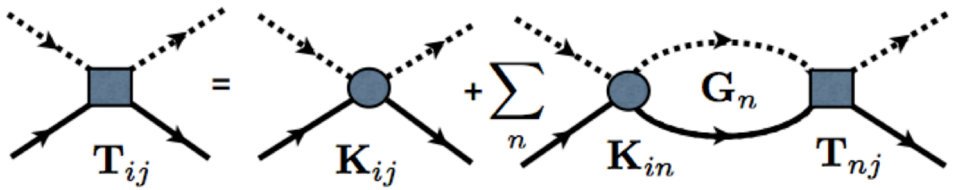


$$\mathbf{K_{12} = \frac{-1}{2f^2}\sqrt{\frac{3}{2}}\left(\sqrt{s} - \frac{M_N + M_\Sigma}{2}\right)}$$

- Note: **all** matrix elements are of roughly **comparable magnitude**

CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

(contd.)



$$\mathbf{T_{ij}} = \mathbf{K_{ij}} + \sum_{\mathbf{n}} \mathbf{K_{in}}\,\mathbf{G_n}\,\mathbf{T_{nj}}$$

- **Loop integrals** (with meson-baryon Green functions) using dimensional regularization:

$$\tilde{G}(q^2) = \int \frac{d^dp}{(2\pi)^d} \frac{i}{[(q-p)^2 - M_B^2 + i\epsilon][p^2 - m_\phi^2 + i\epsilon]}$$

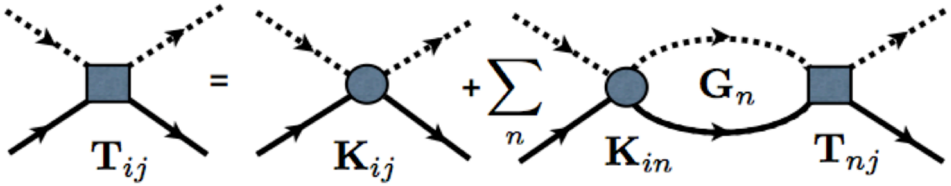
- finite parts including **subtraction constants** $a(\mu)$:

$$G(q^2) = a(\mu) + \frac{1}{32\pi^2 q^2}\left\{ q^2 \left[\ln\left(\frac{m_\phi^2}{\mu^2}\right) + \ln\left(\frac{M_B^2}{\mu^2}\right) - 2 \right] \right.$$

$$\left. + (m_\phi^2 - M_B^2)\ln\left(\frac{m_\phi^2}{M_B^2}\right) - 8\sqrt{q^2}\,|\mathbf{q}_{cm}|\ \mathrm{artanh}\left(\frac{2\sqrt{q^2}\ |\mathbf{q}_{cm}|}{(m_\phi + M_B)^2 - q^2}\right)\right\}$$

CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

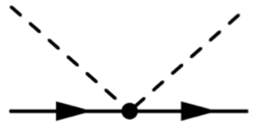
(contd.)



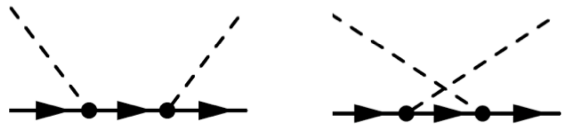
$$\mathbf{T_{ij} = K_{ij} + \sum_n K_{in}\, G_n\, T_{nj}}$$

- Interaction kernel **K**: leading and next-to-leading orders

leading order (LO):
Weinberg-Tomozawa (WT)

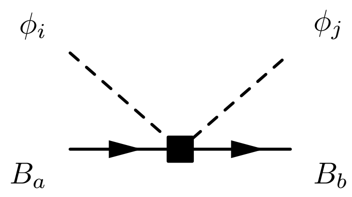


- next-to-leading order (NLO):



direct and crossed Born terms

$$\delta\mathcal{L}_B = \sum_{i=1}^{3} b_i \left\{\bar{\Psi}_B \Phi \mathcal{M} \Phi \Psi_B\right\}_i + \sum_{j=1}^{4} d_j \left\{\bar{\Psi}_B \Phi (\partial\Phi)^2 \Psi_B\right\}_j$$



... for example:

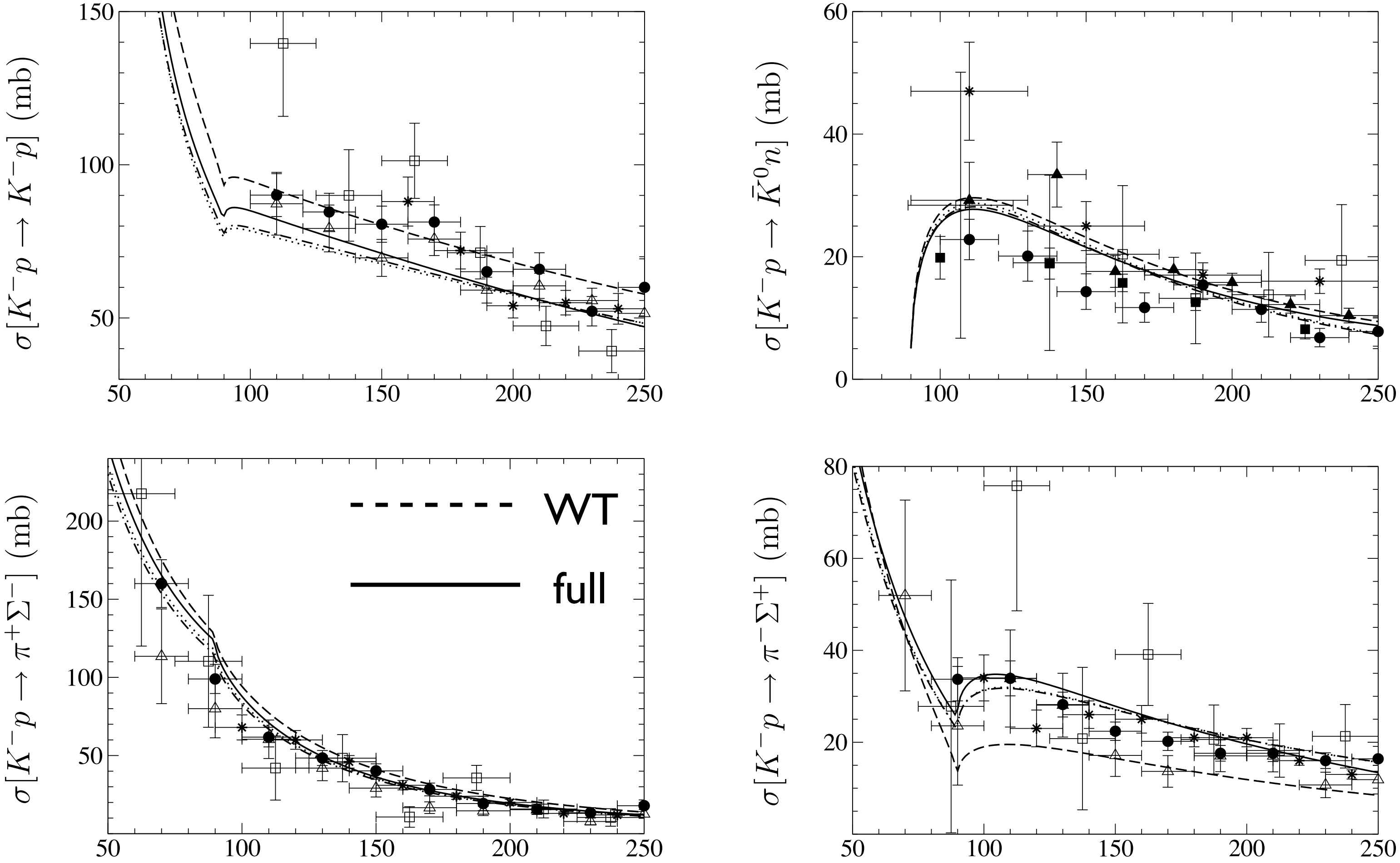
$$\mathbf{K}(K^- p \to K^- p) = \frac{\omega}{f^2} - b_p \frac{m_K^2}{f^2} + d_p \frac{\omega^2}{f^2}$$

RESULTS (part I)

B. Borasoy, R. Nissler, W.W. : Phys. Rev. Lett. 94 (2005) 213401; Eur. Phys. J. A25 (2005) 79

Fit to **SCATTERING DATA**

(without constraint from K^-p SCATTERING LENGTH)



incident K^- lab momentum (MeV/c)

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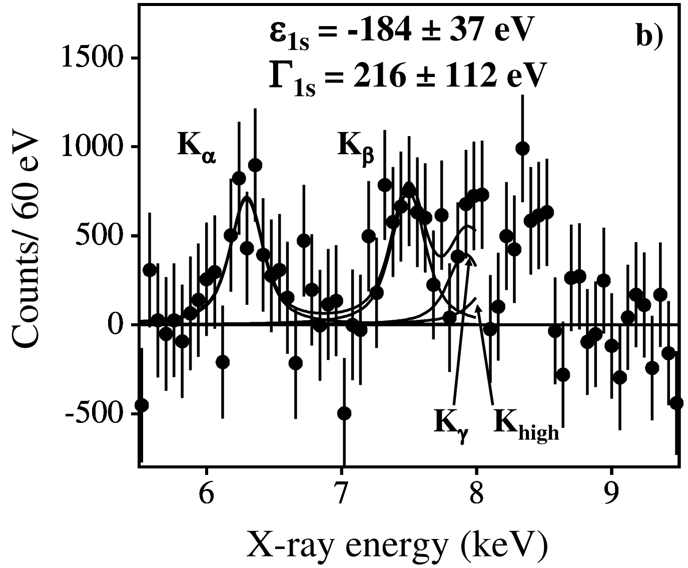
KAONIC HYDROGEN

DEAR (Frascati); G. Beer et al., Phys. Rev. Lett. 94 (2005) 212302



- **K^-p SCATTERING LENGTH**

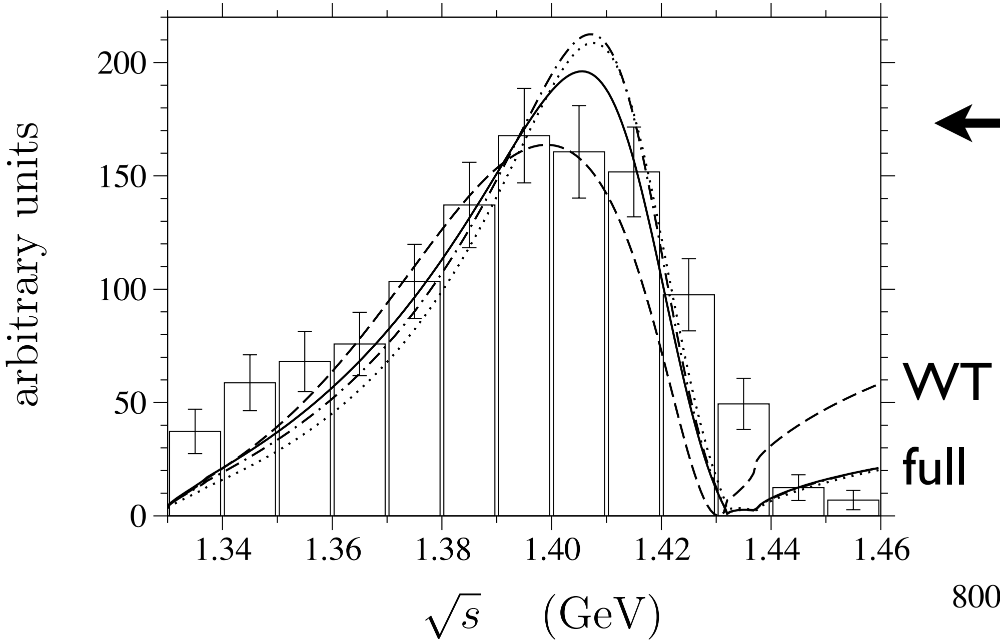
$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2\, a_{K^-p}\left[1 - 2\alpha\mu(\ln\alpha - 1)\, a_{K^-p}\right]$$

Deser & Trueman

Rusetsky et al.

RESULTS (part II)

B. Borasoy, R. Nissler, W.W.: Eur. Phys. J. A25 (2005) 79



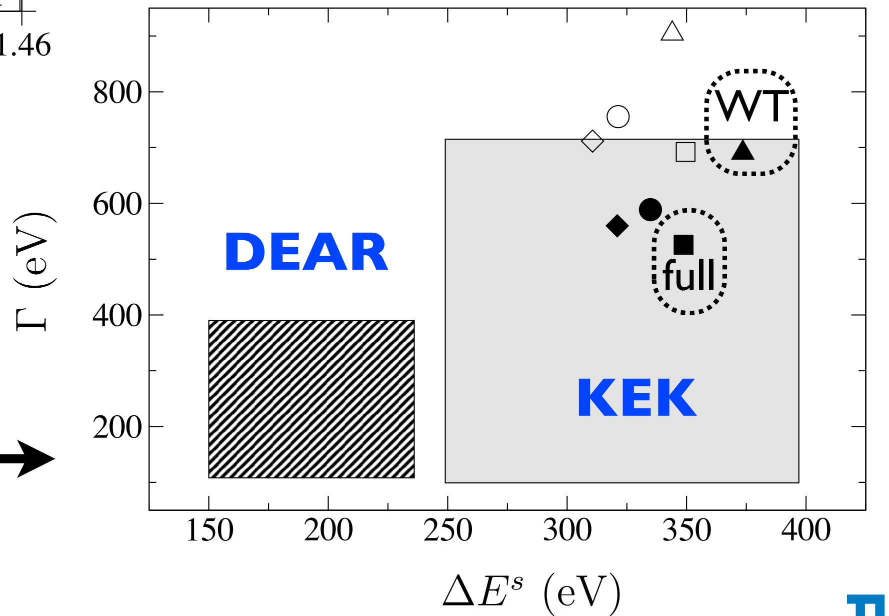
$\Sigma\pi(\mathbf{I}=\mathbf{0})$

MASS SPECTRUM

in comparison with
$\pi^-\Sigma^+$ event distribution

$\mathbf{f}(WT) = \mathbf{111\ MeV} \simeq \mathbf{f_K}$
$\mathbf{f}(full) = \mathbf{103\ MeV}$

Kaonic hydrogen (1s)
strong interaction
SHIFT and **WIDTH**

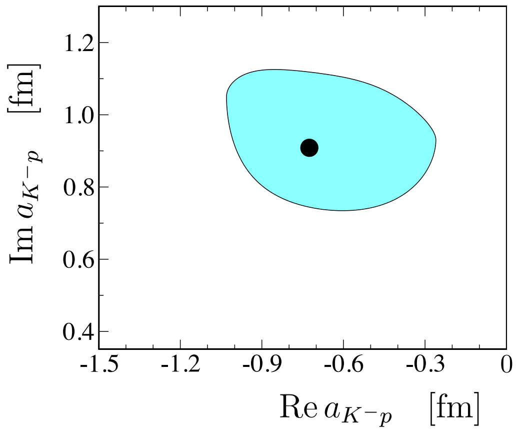


RESULTS (part III)

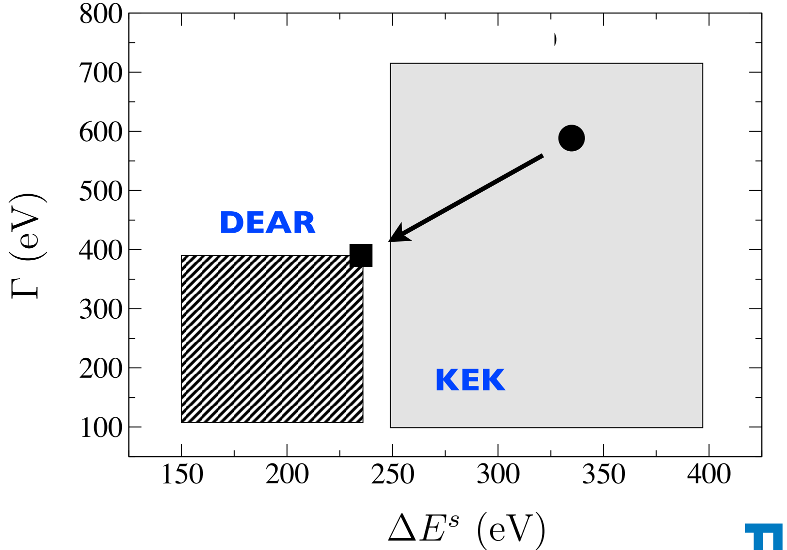
-

threshold branching ratios	WT	full	exp.
$\frac{\Gamma(K^-p \to \pi^+\Sigma^-)}{\Gamma(K^-p \to \pi^-\Sigma^+)}$	2.35	2.36	2.36 ± 0.04
$\frac{\Gamma(K^-p \to \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^-p \to \text{all inelastic channels})}$	0.64	0.66	0.66 ± 0.01
$\frac{\Gamma(K^-p \to \pi^0\Lambda)}{\Gamma(K^-p \to \text{neutral states})}$	0.21	0.19	0.19 ± 0.02

- scattering length



B. Borasoy, R. Nissler, W.W.
Eur. Phys. J. A25 (2005) 79



- enforcement of fit to **DEAR** data implies **inconsistency** with K^-p scattering data

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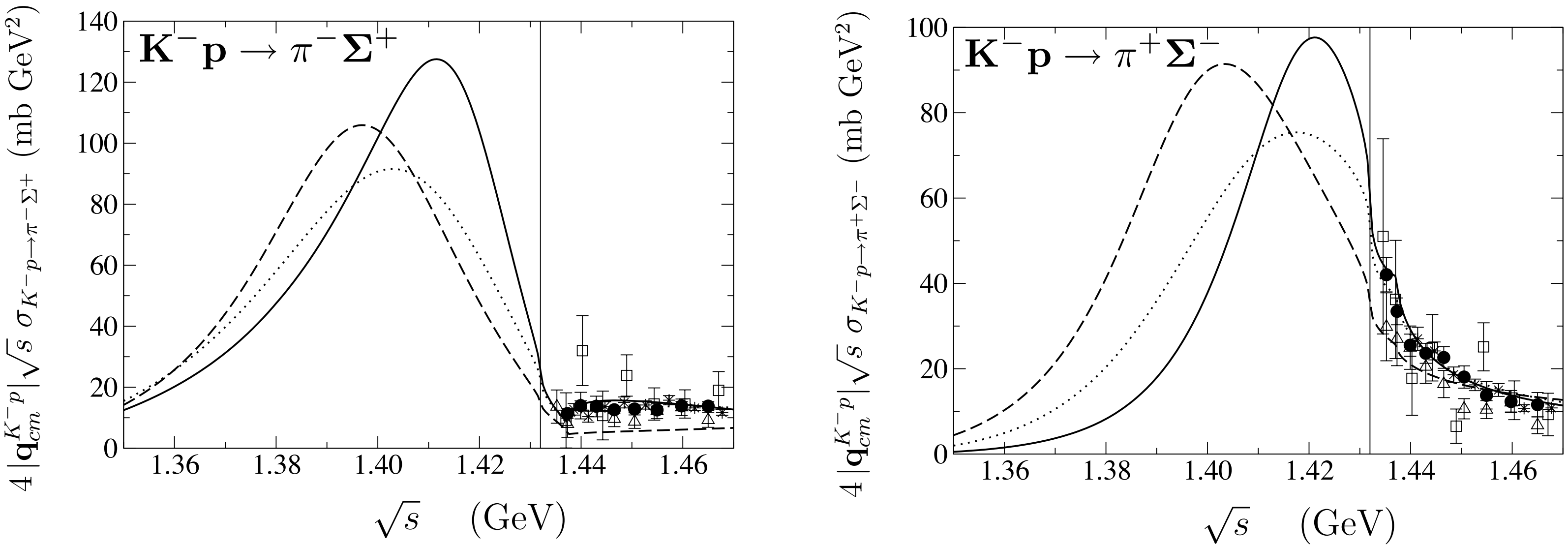
CONSTRAINTS for **SUBTHRESHOLD EXTRAPOLATIONS**

B. Borasoy, R. Nissler, W.W.: Eur. Phys. J. A25 (2005) 79



- - - - - - - with
——— without

DEAR (kaonic hydrogen) constraints

- Sensitivity of $\pi\Sigma$ mass spectrum to $K^- p$ threshold conditions
  - ► need **SIDDHARTA** data (almost final)
  - ► need accurate $\pi\Sigma$ mass distributions

... in order to have sufficient predictive power for subthreshold extrapolations

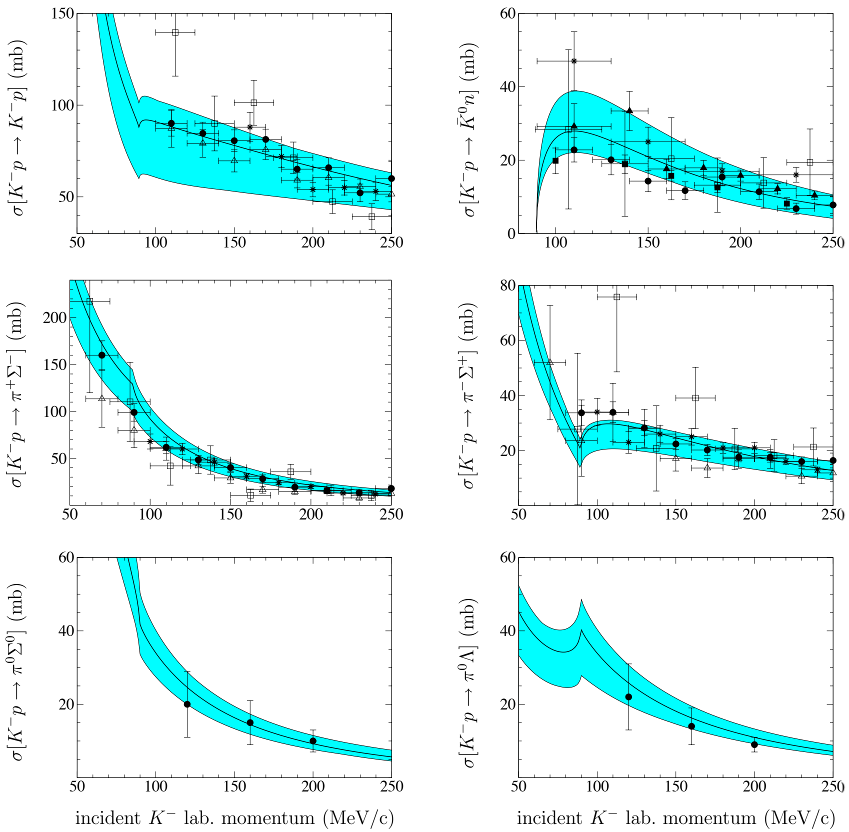
RESULTS (part IV)

- Detailed analysis of uncertainties

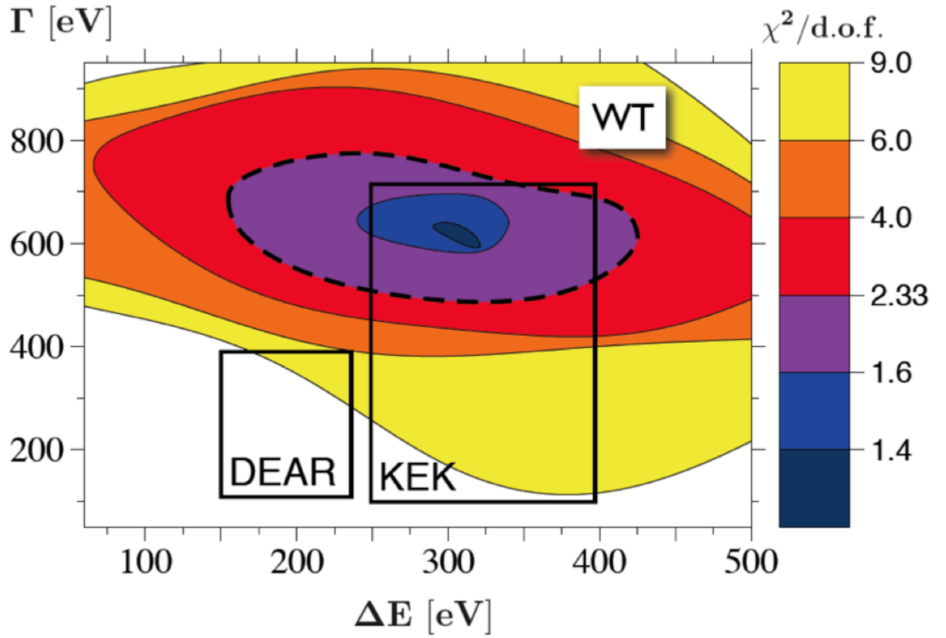
B. Borasoy, R. Nissler, W.W., Eur. Phys. J. A25 (2005) 79

B. Borasoy, U.-G. Meissner, R. Nissler, Phys. Rev. C74 (2006) 055201

R. Nissler PhD thesis (2008)

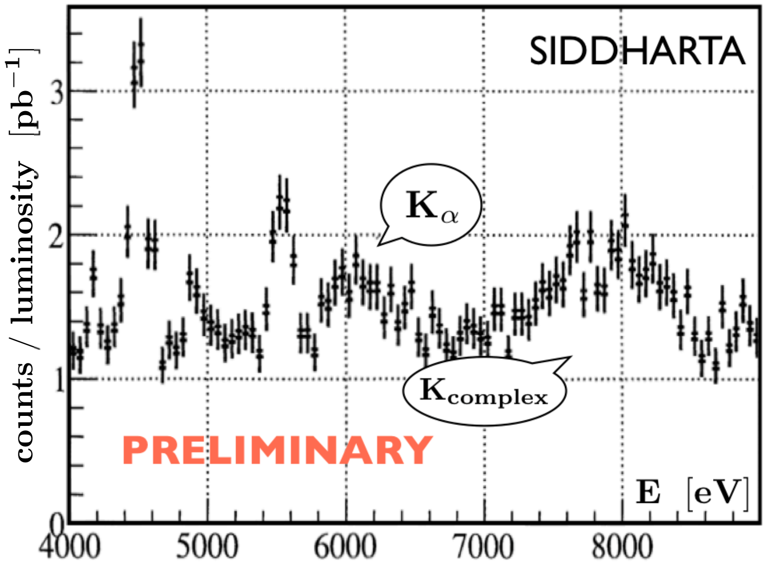


scattering data
and
kaonic hydrogen



NEWS from SIDDHARTA

- New **kaonic hydrogen** precision data (Frascati 2010)



- strong interaction shift and width:

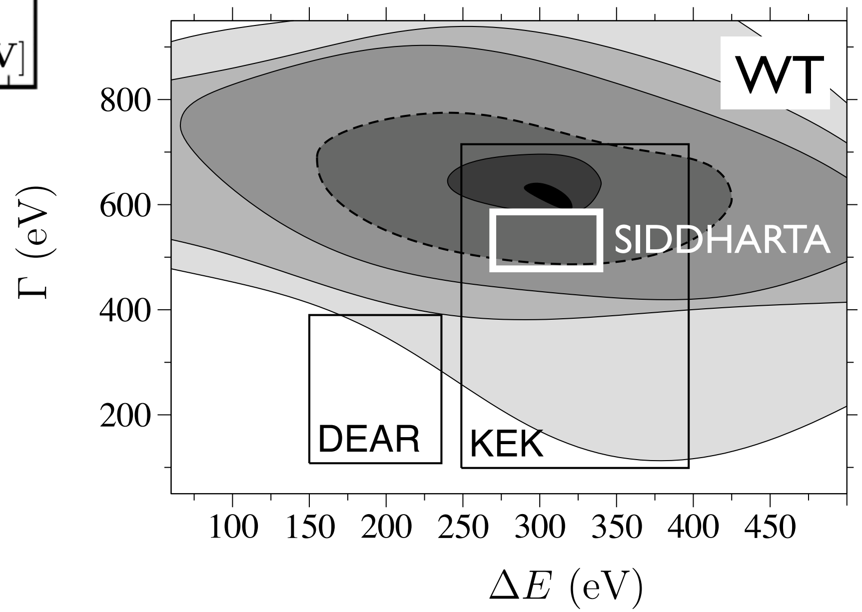
(**preliminary**)

$$\Delta E = 305 \pm 31 \text{ eV}$$

$$\Gamma = 512 \pm 77 \text{ eV}$$

B. Borasoy, R. Nissler, W.W.
Eur. Phys. J. A25 (2005) 79

R. Nissler
PhD thesis (2008)



- note:
  remarkable agreement with
  Tomozawa-Weinberg
  (leading order) prediction
  from chiral SU(3) dynamics

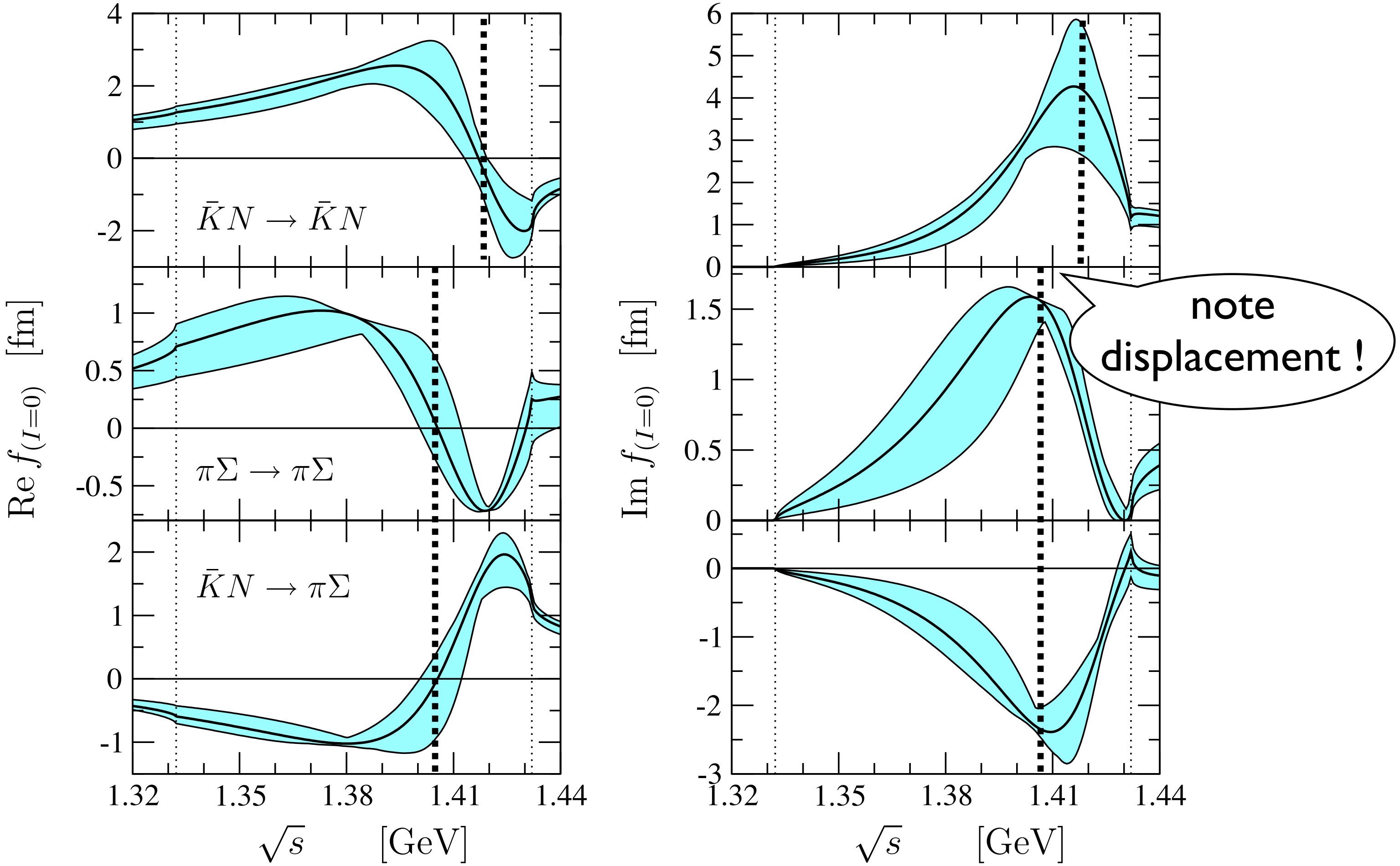
- fine-tuning in progress
  T. Hyodo, Y. Ikeda, W.W. (2010)

Chiral SU(3) Coupled Channels Dynamics

- Relevant amplitudes, subthreshold extrapolations and uncertainty analysis

R. Nissler PhD thesis (2008)

B. Borasoy, R. Nissler, W.W. : Eur. Phys. J. A25 (2005) 79
B. Borasoy, U.-G. Meissner, R. Nissler, Phys. Rev. C74 (2006) 055201



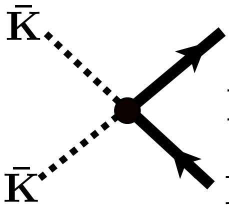
- reduction of uncertainties expected in view of new SIDDHARTA data

CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

$$\mathbf{T_{ij} = K_{ij} + \sum_n K_{in}\, G_n\, T_{nj}}$$

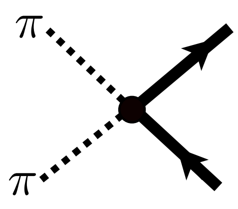
- Leading s-wave I = 0 meson-baryon interactions (Tomozawa-Weinberg)

$|\mathbf{1}\rangle = |\mathbf{\bar{K}N, I = 0}\rangle$



$$\mathbf{K_{11} = \frac{3}{2f^2}(\sqrt{s} - M_N)}$$

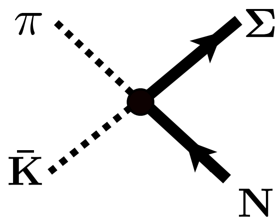
$|\mathbf{2}\rangle = |\pi\mathbf{\Sigma, I = 0}\rangle$



$$\mathbf{K_{22} = \frac{2}{f^2}(\sqrt{s} - M_\Sigma)}$$

- recall: driving interactions individually **strong** enough to produce
  - $\bar{K}N$ **bound state**
  - $\pi\Sigma$ **resonance**

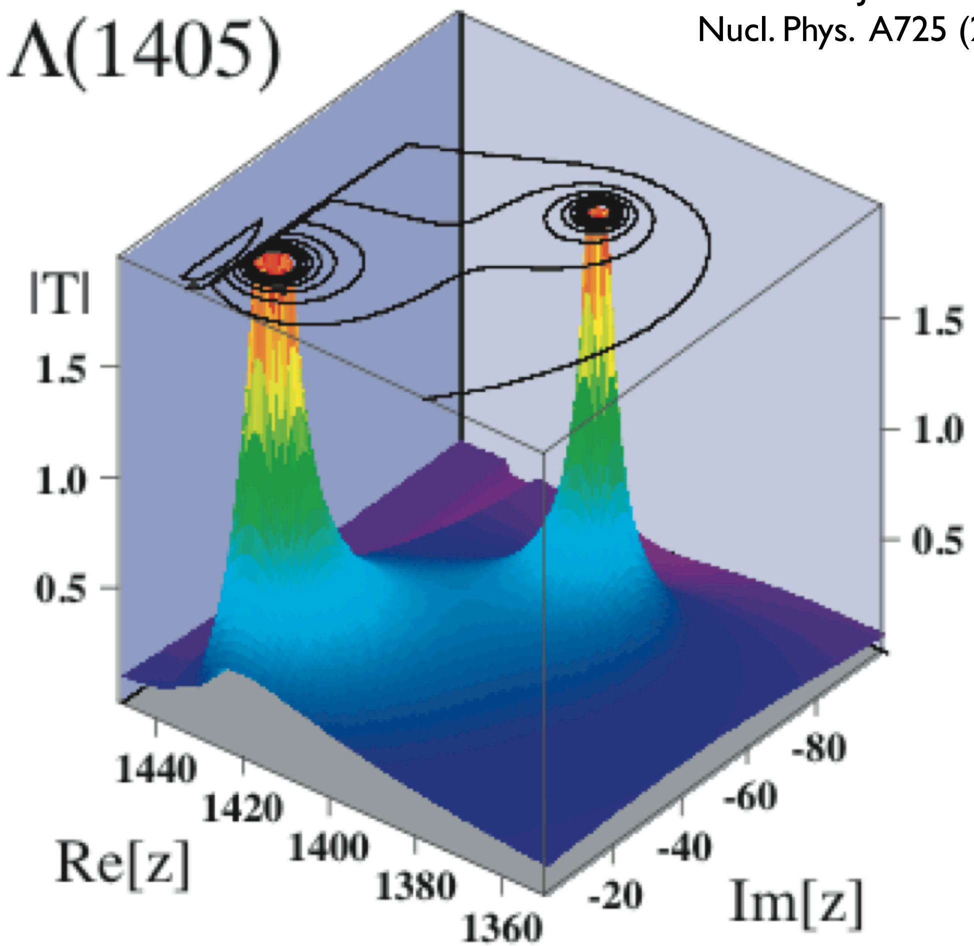
- **strong** channel coupling $\mathbf{12 \leftrightarrow 21}$:



$$\mathbf{K_{12} = \frac{-1}{2f^2}\sqrt{\frac{3}{2}}\left(\sqrt{s} - \frac{M_N + M_\Sigma}{2}\right)}$$

The TWO POLES scenario

D. Jido et al.
Nucl. Phys. A725 (2003) 181



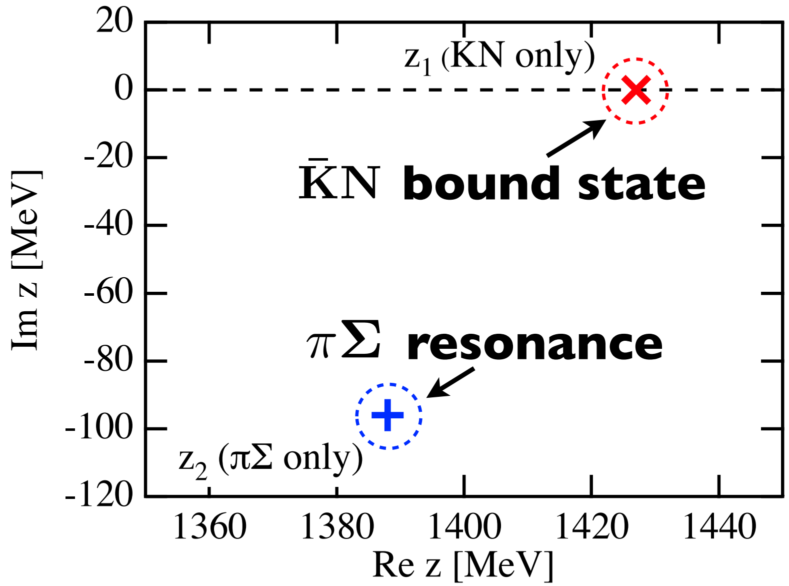
The TWO POLES scenario

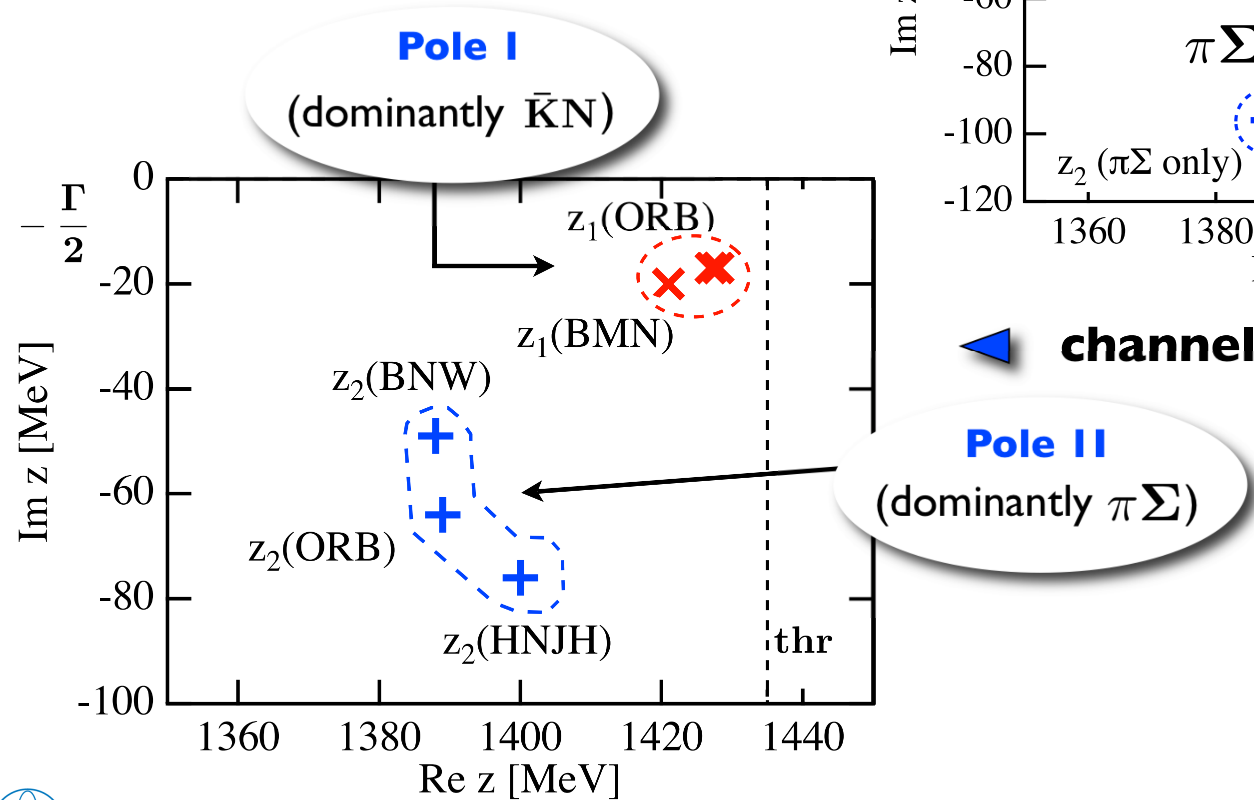
D. Jido et al.
Nucl. Phys. A725 (2003) 181

T. Hyodo, W.W. , Phys. Rev. C77 (2008) 03524

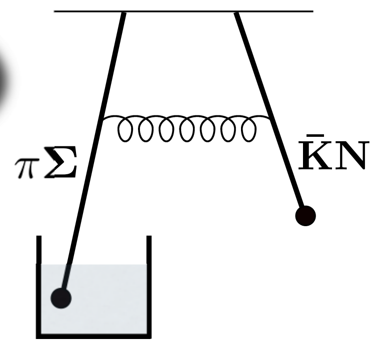
- Singularities of $\bar{K}N$ amplitude in the complex energy plane

starting point:
no channel coupling ▶



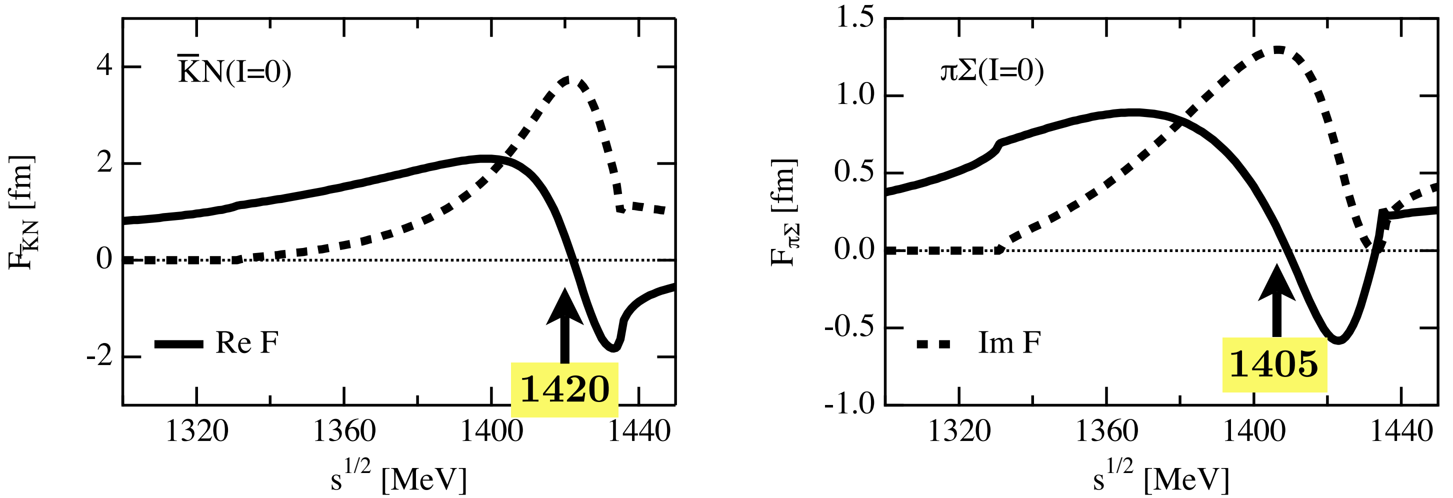


◀ **channel coupling** at work



The TWO POLES scenario (contd.)

- $\bar{\mathrm{K}}\mathrm{N}$ and $\pi\Sigma$ amplitudes

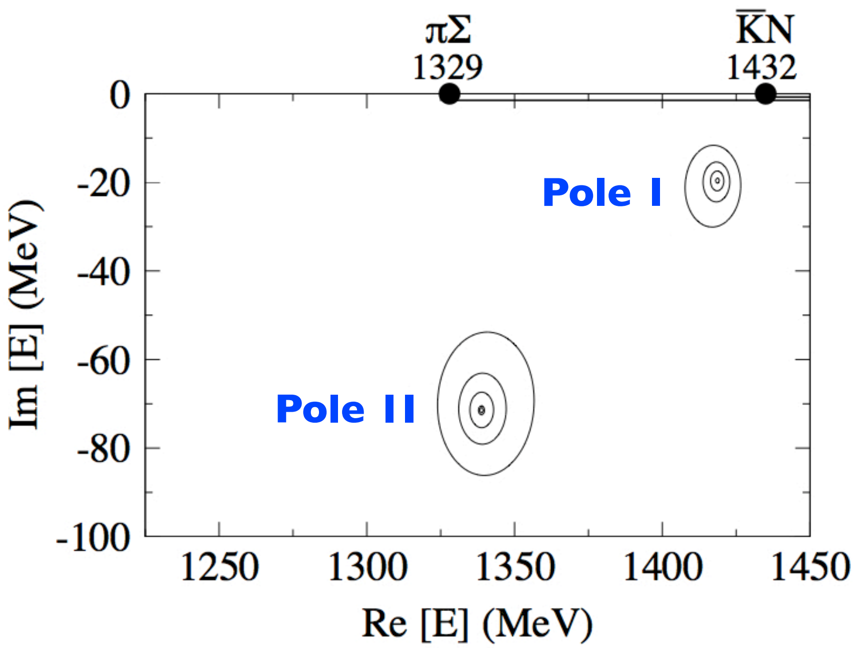


T. Hyodo, W.W. : Phys. Rev. C77 (2008) 03524

▶ **Note difference** in pole positions and spectra of $\bar{\mathrm{K}}\mathrm{N}$ and $\pi\Sigma$
D. Jido et al. , NP A725 (2003) 263

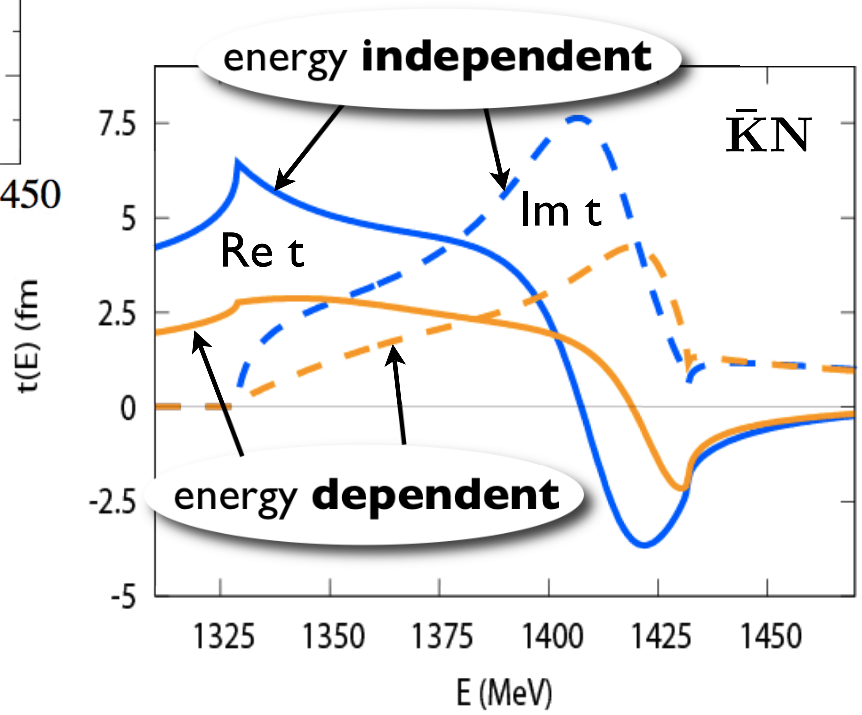
▶ Equivalent $\bar{\mathrm{K}}\mathrm{N}$ **effective interaction** should produce quasibound state at **1420** MeV (**not** 1405 MeV)

The TWO POLES scenario (contd.)



Y. Ikeda, H. Kamano, T. Sato
arXiv:1004.4877 [nucl-th]

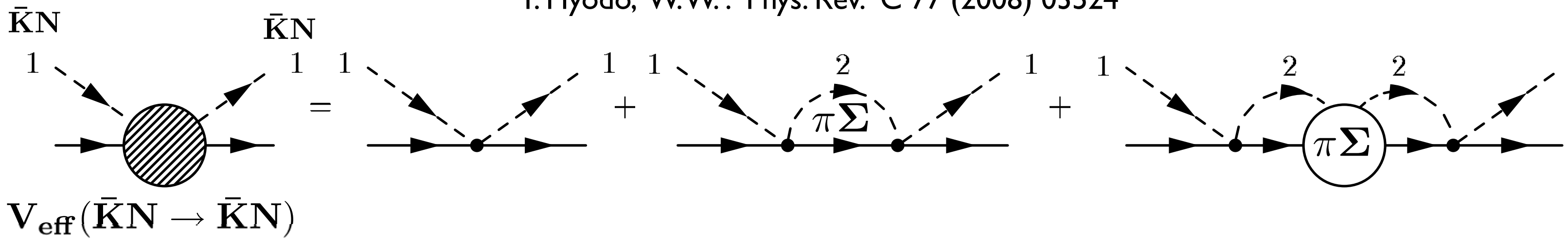
- Two-pole scenario confirmed
- Role of **energy dependent** (chiral) driving interactions



- Note: **NO** differences at and above K̄N threshold
- But: **STRONG** differences for subthreshold extrapolations

I = 0 $\bar{K}N$ Effective Interaction

T. Hyodo, W.W.: Phys. Rev. C 77 (2008) 03524

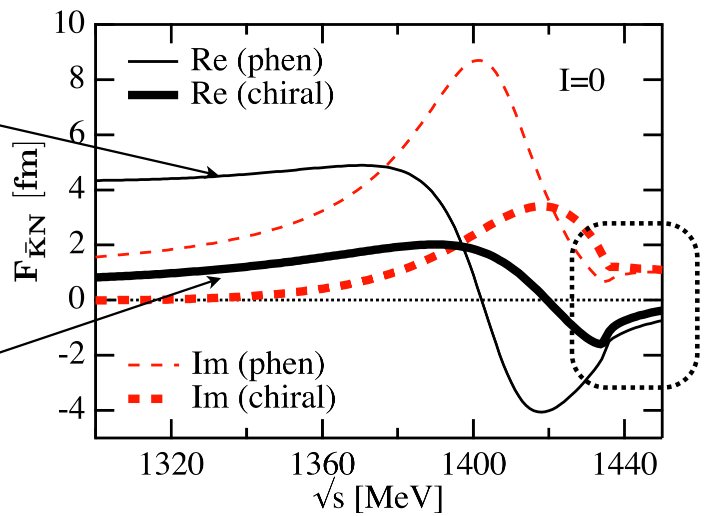


$V_{eff}(\bar{K}N \to \bar{K}N)$ is:

- **complex**
- **energy dependent**
- **non-local**

Akaishi-Yamazaki phenom. potential

chiral SU(3) dynamics



large differences in **subthreshold** extrapolations

- **Chiral dynamics** predicts significantly **weaker attraction** than Akaishi - Yamazaki (local, energy independent) potential

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4.

Coupled Channels Dynamics
and
$\pi\Sigma$ Mass Distributions

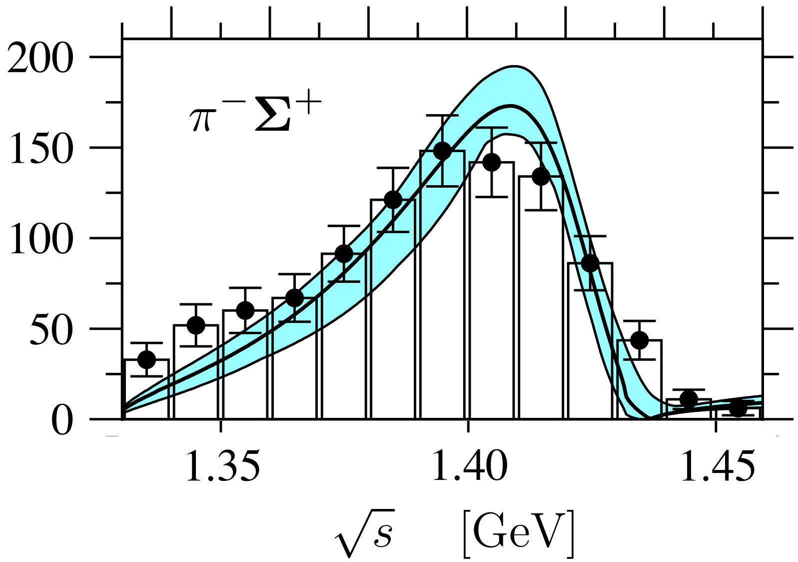
- Two-pole scenario and its implications
- Non-universality of $\pi\Sigma$ mass spectra
- Present empirical situation and new developments

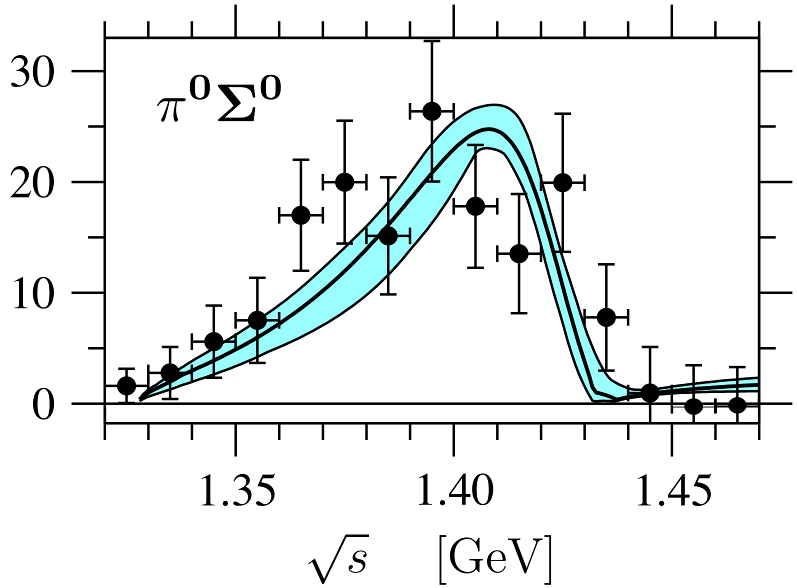
$\pi\Sigma$ MASS SPECTRA

- Chiral SU(3) dynamics with uncertainty analysis

(here: based on Tomozawa-Weinberg interaction with $\mathbf{f} \simeq \mathbf{f_K}$)

R. Nissler, PhD thesis (2008)





"old" data

R.J. Hemingway,
Nucl. Phys. B253 (1985) 742

ANKE data (COSY / Jülich)

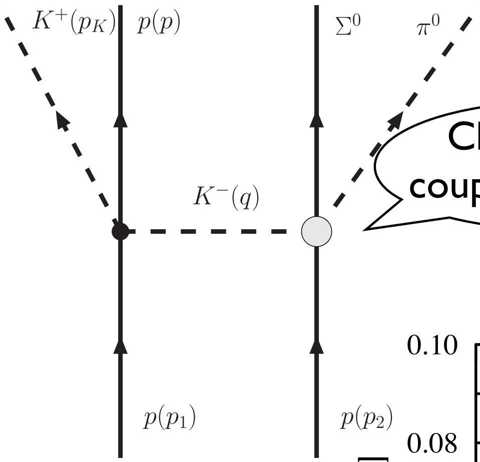
$\mathbf{pp \to K^+ p\, \pi^0 \Sigma^0}$

I. Zychor et al.
Phys. Lett. B660 (2008) 167

$\pi\Sigma$ MASS SPECTRA (contd.)

- ANKE data: $\mathbf{p\,p \rightarrow p\,K^+\,\{\Sigma^0\pi^0\}}$

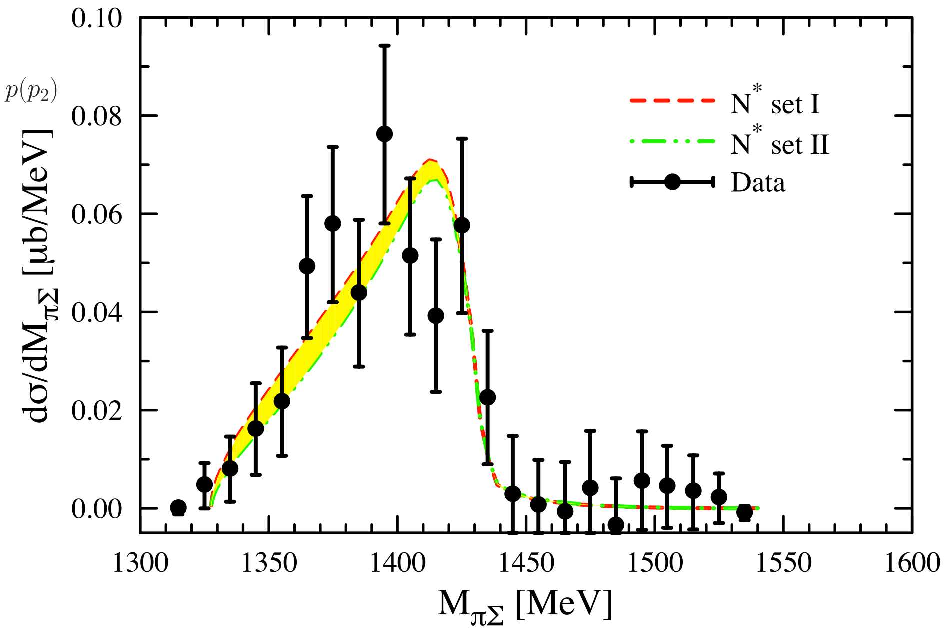
I. Zychor et al.
Phys. Lett. B660 (2008) 167

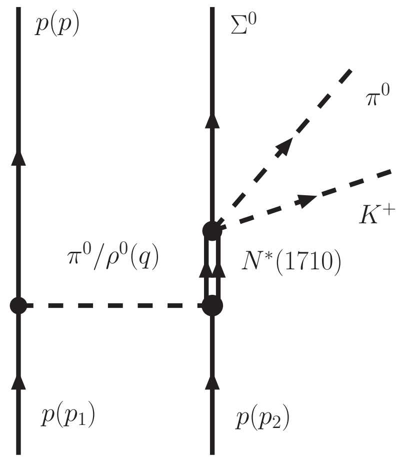


... in comparison with theory:

Chiral SU(3) coupled channels

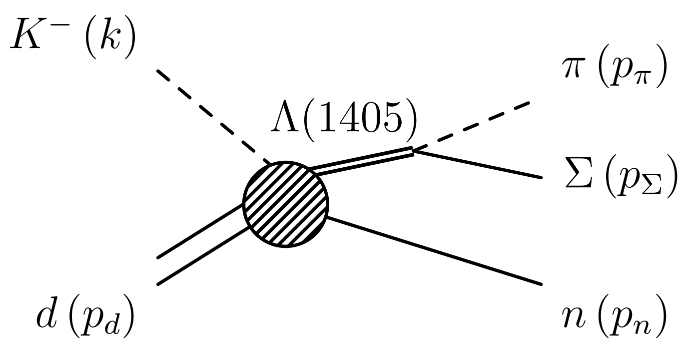
L. Geng, E. Oset
Eur. Phys. J A34 (2007) 405

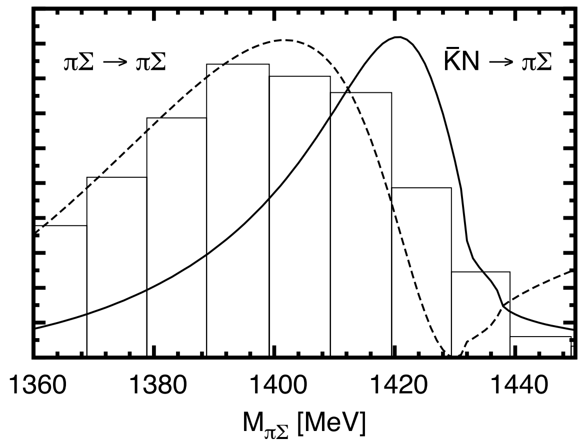




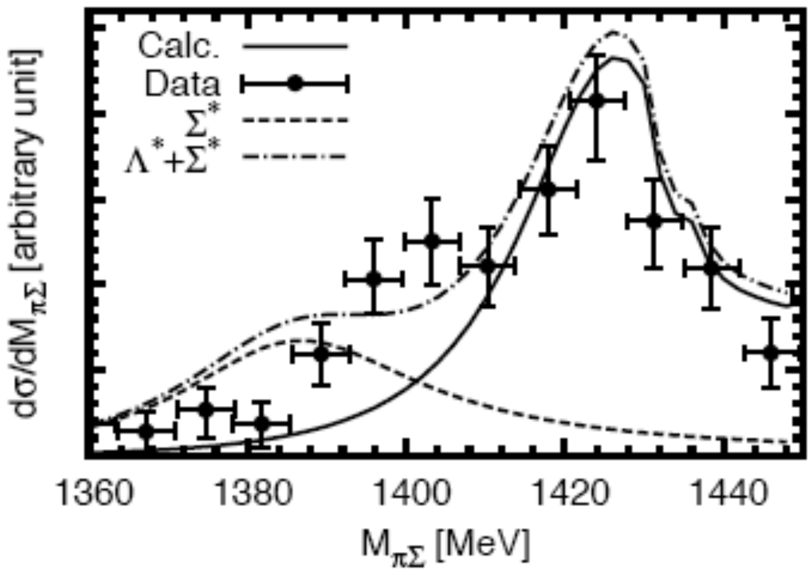
$\pi\Sigma$ **MASS SPECTRA** (contd.)

- Kaonic (in-flight) production of $\Lambda(1405)$ from deuterium





two-poles scenario

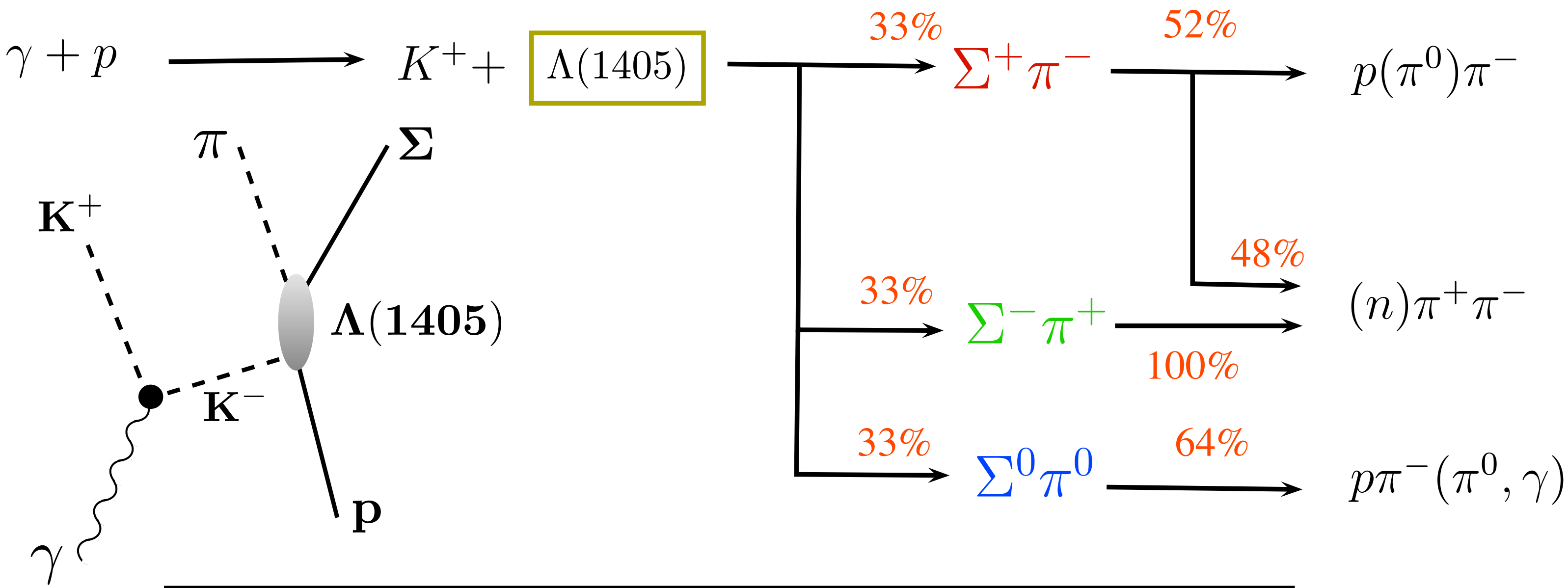


D. Jido, E. Oset, T. Sekihara
Eur. Phys. J. A42 (2009) 268

exp. data:
O. Braun et al.
Nucl. Phys. B129 (1977) 1

$\pi\Sigma$ MASS SPECTRA (contd.)

- Photoproduction of $\Lambda(1405)$ (CLAS @ JLAB) (see also LEPS / SPring-8)



$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

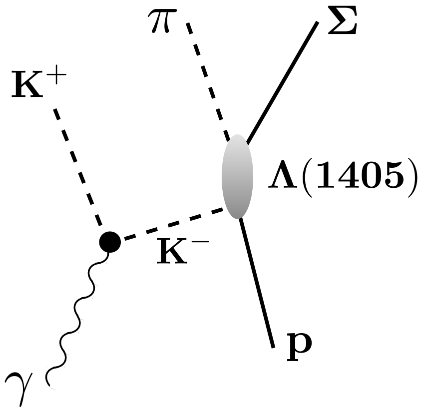
$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}\left|T^{(0)}\right|^2 + O\left(T^{(2)}\right)$$

J. Nacher et al.
Phys. Lett.
B455 (1999) 55

$\pi\Sigma$ **MASS SPECTRA** (contd.)

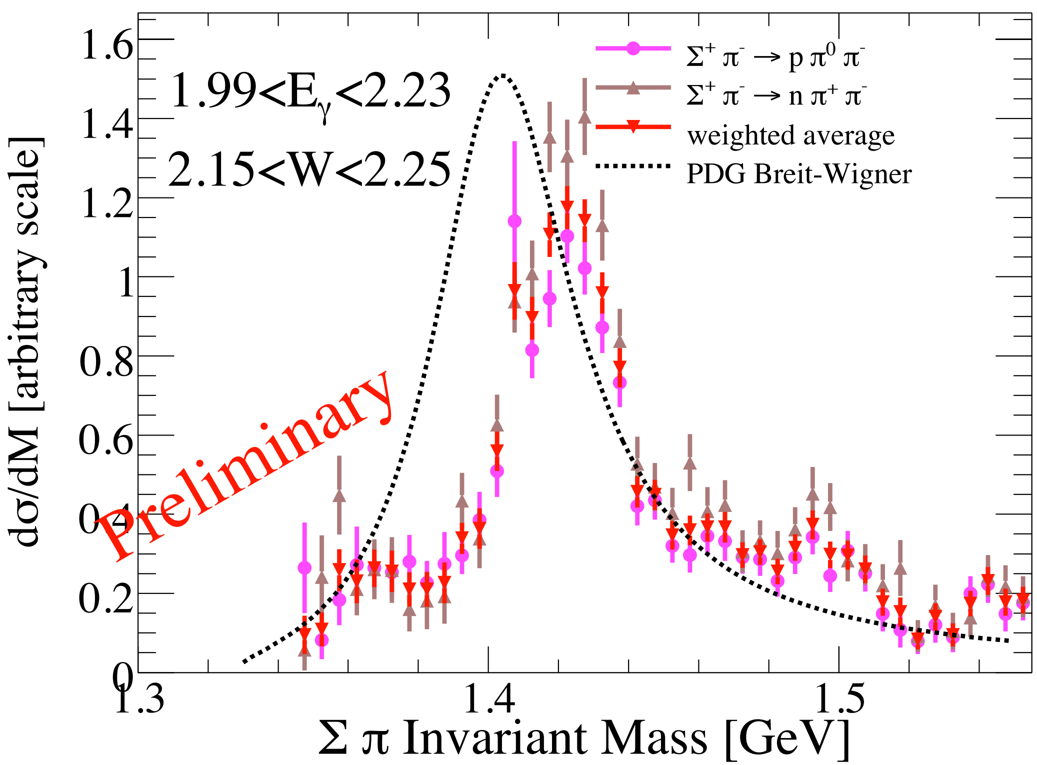
- Photoproduction of $\Lambda(1405)$ (CLAS @ JLAB)



K. Moriya, R. Schumacher
HYP-X Conference (2009)
Nucl. Phys. A 835 (2010) 231

K. Moriya, NFQCD
Kyoto (2010)

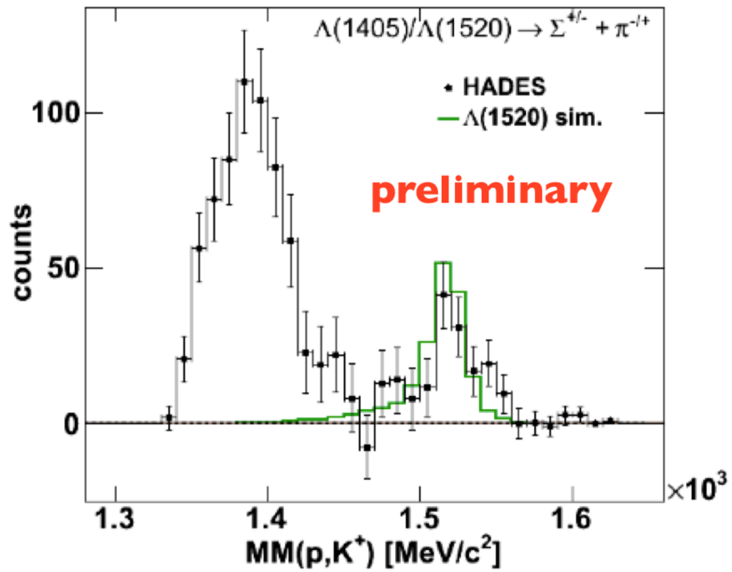
$$\gamma\, p \rightarrow K^+\ \Sigma^+\pi^-$$



- Note: shift of $\Lambda(1405)$ spectrum as compared to "standard" PDG listing

$\pi\Sigma$ MASS SPECTRA (contd.)

- News from HADES $\quad \mathrm{p\,p \to p\,K^+\{\pi^\pm\Sigma^\mp\}}$



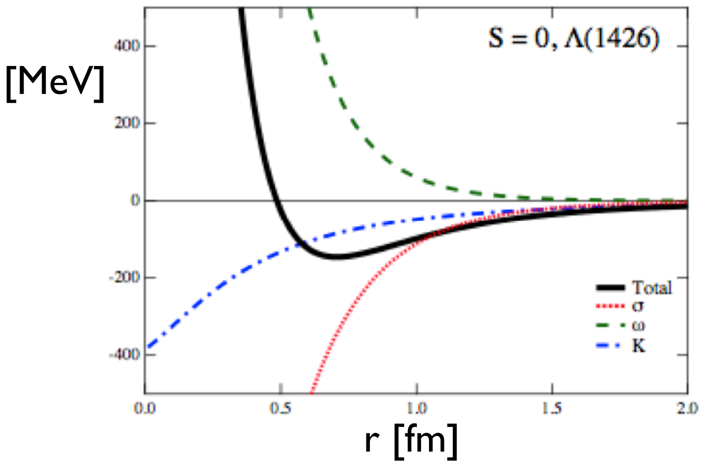
L. Fabbietti,
E. Epple, J. Siebenson,
et al. (2010)

- Downward shift of $\Lambda(1405)$
  by final state interactions ?

- hint:
  model calculation of $\Lambda^*\,\mathrm{N}$ potential

  based on chiral SU(3) coupled channels
  and boson exchange

  T. Hyodo, T. Uchino, M. Oka (2010)



5.

Antikaon Interactions with Nuclear Systems

- Antikaon interactions with few-nucleon systems
- The quest for quasibound $\bar{K}$-nuclear states
- Outlooks: kaon condensation in neutron stars ?

Brief History, Part I

Kaons and Antikaons in Nuclear Matter

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

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

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

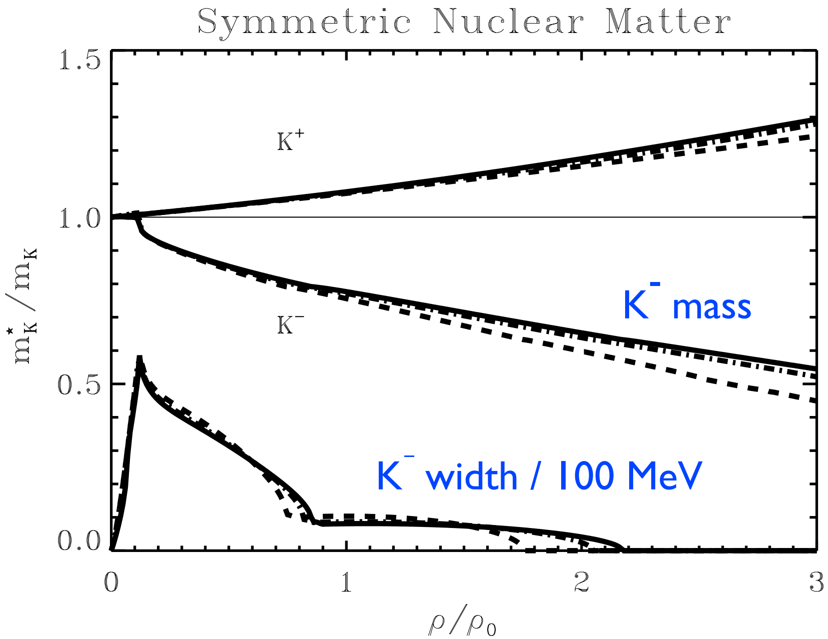
$$\Pi_{K^-} = 2\omega U_{K^-} = -4\pi \left[f_{K^-p}\, \rho_p + f_{K^-n}\, \rho_n \right] + \ldots +$$

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



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

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

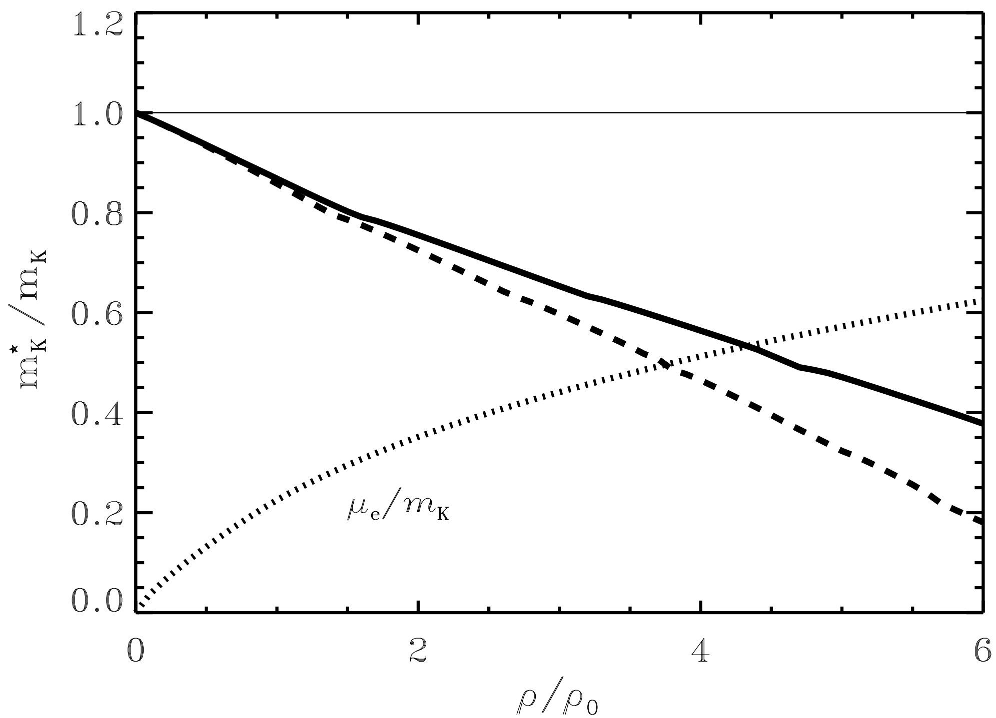
M. Lutz, C.L. Korpa, M. Möller
Nucl. Phys. A 808 (2008) 124

- Note: In-medium $\bar{K}$ width drops when mass falls below $\pi\Sigma$ threshold

Brief History, Part II

Kaon Condensation in Neutron Matter

- first suggested by D. Kaplan, A. Nelson (1985) on the basis of **attractive K^-N Tomozawa - Weinberg term**
- at high density, energetically favourable to condense K^-



T. Waas, M. Rho, W.W. : Nucl. Phys. A 617 (1997) 449

electron chemical potential

incl. **NN correlations**

in-medium chiral SU(3) dynamics

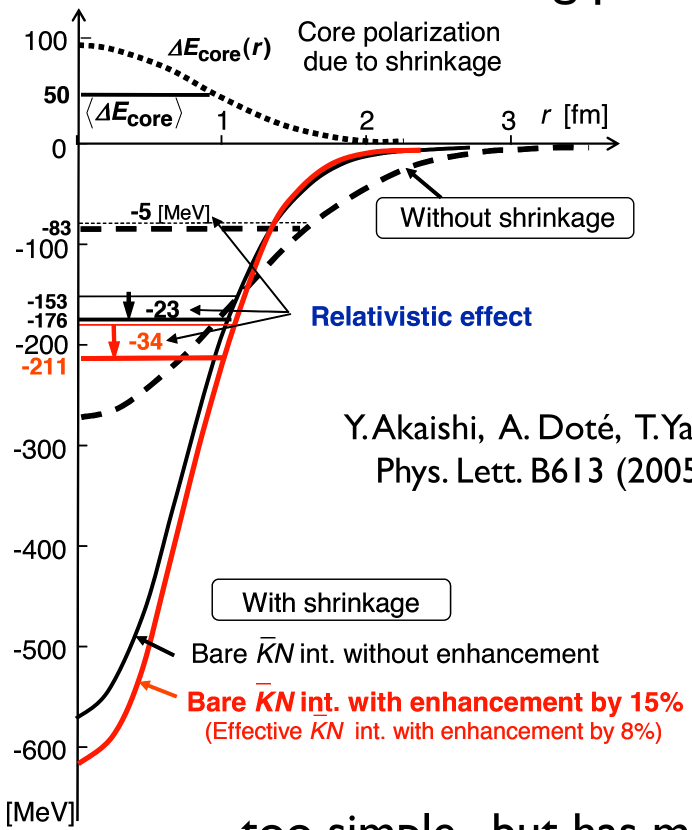
- conversion to hyperons via $K^- NN \rightarrow YN$?

Brief History, Part III

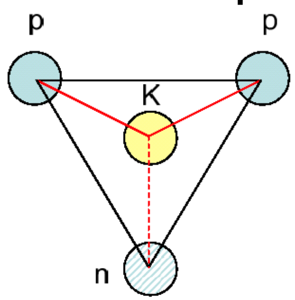
Deeply Bound Antikaon-Nuclear Clusters ?

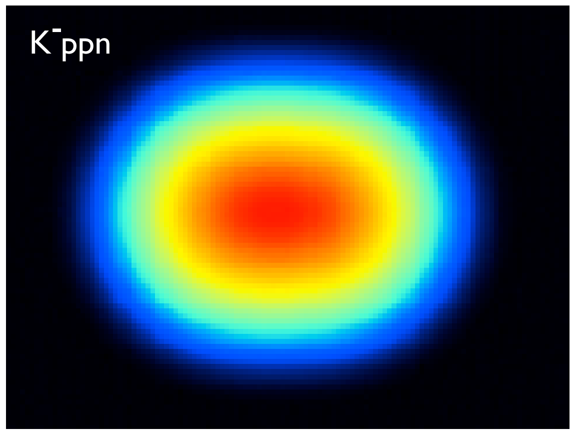
Y. Akaishi, T. Yamazaki, Phys. Rev. C65 (2002) 044005

- Calculation of deeply bound K^-ppn system
  using phenomenological $\bar{K}N$ and NN potentials



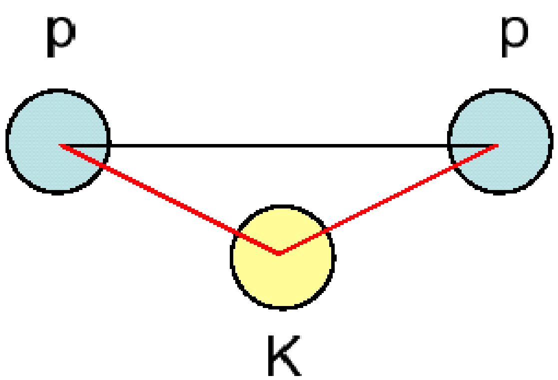
Y. Akaishi, A. Doté, T. Yamazaki,
Phys. Lett. B613 (2005) 140

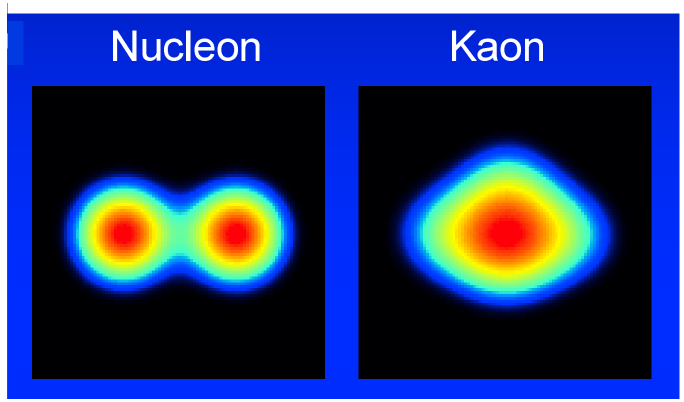




... too simple, but has motivated a great deal of recent activities

Prototype Antikaon-Nuclear Few-Body System: K^-pp





- **3-Body (Faddeev) Calculations**
- **Variational Calculations**
- **Issues** in both approaches:
  energy dependence of basic input amplitudes,
  subthreshold / off-shell extrapolations, necessary approximations

K^-pp System: variational calculation

A. Doté, T. Hyodo, W.W.: Nucl. Phys. A 804 (2008) 197, Phys. Rev. C 79 (2009) 014003

$$\mathbf{H} = \mathcal{T}_{N_1} + \mathcal{T}_{N_2} + \mathbf{V}_{NN} + \mathcal{T}_{K} + \mathbf{V}_{\bar{K}N_1} + \mathbf{V}_{\bar{K}N_2} - \mathcal{T}_{c.m.}$$

- wave function: "**projection before variation**"

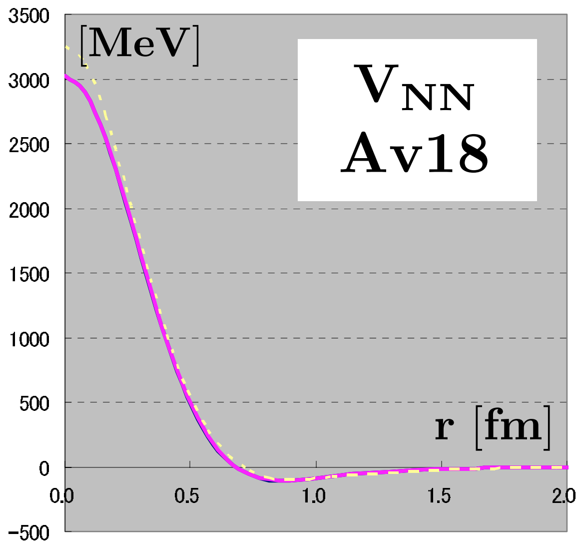
$$|\Psi\rangle = \Phi(\vec{r}_1, \vec{r}_2, \vec{r}_K)|S_{NN} = 0\rangle \,|\, [(NN)_{t=1}\, \bar{K}]^{T_3=1/2}_{T=1/2}\rangle$$

Gaussian wave packets

$$\Phi(\vec{r}_1, \vec{r}_2, \vec{r}_K) = \sum F(\vec{r}_1, \vec{r}_2)\, G(\vec{r}_1) G(\vec{r}_2)\, G(\vec{r}_K)$$

- NN correlation function:

$$F(\vec{r}_1, \vec{r}_2) = 1 - \sum f_n \exp[-\lambda_n (\vec{r}_1 - \vec{r}_2)^2]$$

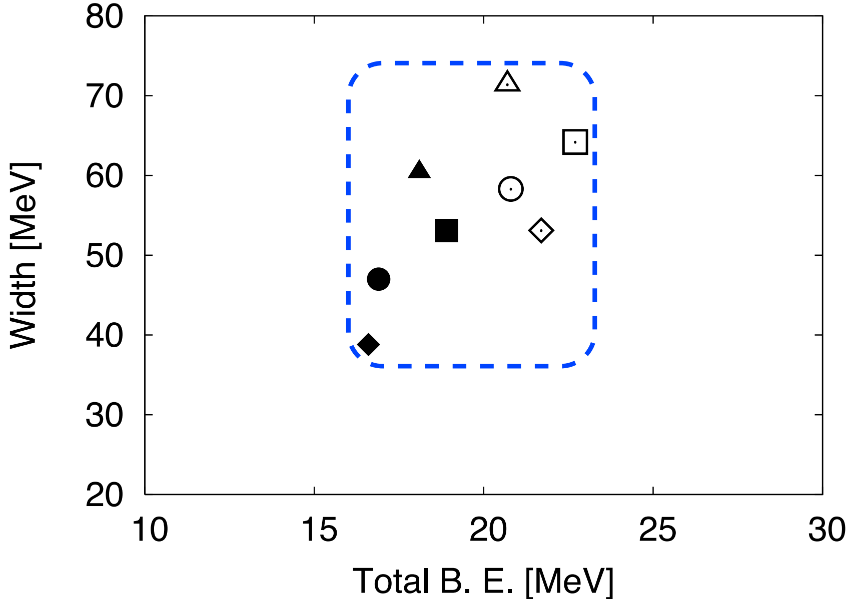


Results: Variational Calculations

A. Doté, T. Hyodo, W.W. : Nucl. Phys. A 804 (2008) 197, Phys. Rev. C 79 (2009) 014003

- Input: **Energy dependent $\bar{\rm K}$N effective interaction** from **chiral SU(3) dynamics** ; realistic NN interaction (Argonne v18)

- $\rm K^-pp$ **binding energy** and **width** using several **chiral model** sets



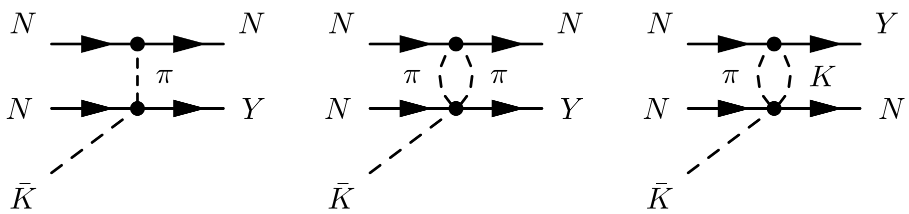
- Result: **weak** binding

$$\mathbf{B(K^-pp) = 19 \pm 3\,MeV}$$
$$\mathbf{\Gamma = 40 - 70\,MeV}$$

- but: $\bar{\rm K}$NN $\leftrightarrow$ $\pi\Sigma$N
3-body dynamics incomplete

- additional increase of width by $\bar{\rm K}$NN $\rightarrow$ YN **absorption**

$$\mathbf{\delta\Gamma_{abs} \simeq 10\ MeV}$$



K^-pp System:
Coupled-Channels Faddeev Approach

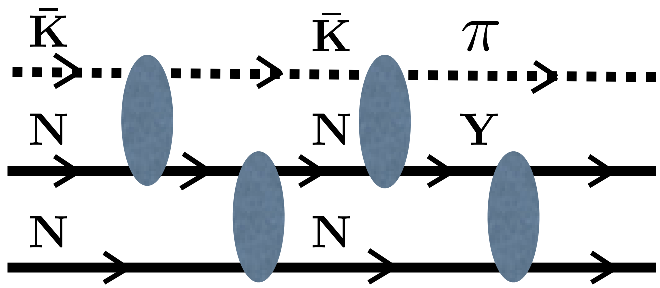
N.V. Shevchenko, J. Mares, A. Gal, PRL 98 (2007) 082301
N.V. Shevchenko, et al., PRC 76 (2007) 044004

Y. Ikeda, T. Sato, PRC 76 (2007) 035203
Y. Ikeda, T. Sato, PRC 79 (2009) 035201

- **Separable** approximation for (s-wave) two-body potentials

$$\mathbf{K^-p \leftrightarrow K^-p} \qquad \mathbf{K^-p \leftrightarrow \pi\Sigma} \qquad \mathbf{NN, \quad \Sigma N}$$

- Constrained by measured cross sections and scattering lengths



spectator
dynamics
is important

- Results:

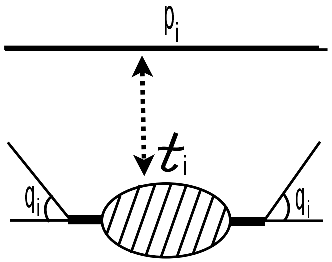
$$\mathbf{B \sim 50 - 70\,MeV}$$
$$\mathbf{\Gamma \sim 90 - 110\,MeV}$$
(Shevchenko et al.)

$$\mathbf{B \sim 60 - 95\,MeV}$$
$$\mathbf{\Gamma \sim 45 - 80\,MeV}$$
(Ikeda & Sato)

► effect of separable approximation on subthreshold behaviour ?

K⁻pp System: Coupled-Channels Faddeev Approach (contd.)

- Importance of full **3-body** coupled-channels dynamics



Y. Ikeda, T. Sato, PRC 79 (2009) 035201

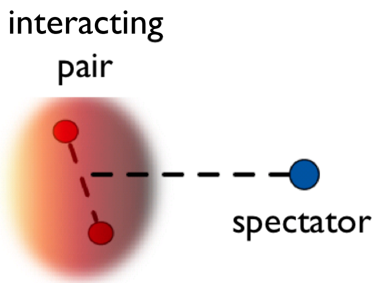
$$t_{\alpha,\beta}(W) = v_{\alpha,\beta} + \sum_{\gamma} v_{\alpha,\gamma} G_0^{\gamma N}(W) t_{\gamma,\beta}(W)$$

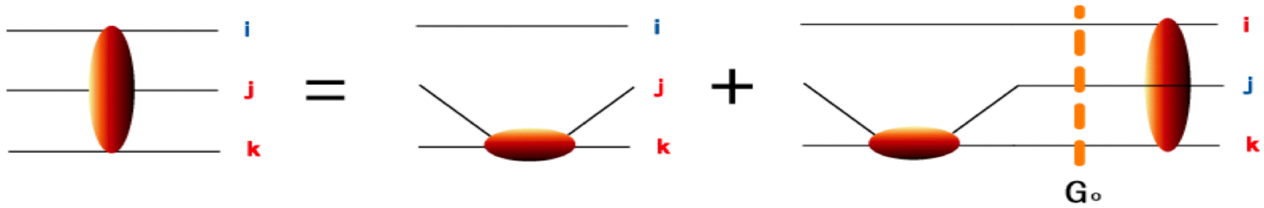
$$G_0^{\alpha N}(W) = \frac{1}{W - E_N(\vec{p}_N) - \sqrt{(E_{M_\alpha}(\vec{q}) + E_{B_\alpha}(\vec{q}))^2 + \vec{p}_N^{\,2}} + i\epsilon}$$

- ... tends to increase binding as compared to variational approaches (with effective single-channel interactions)

K^-pp System: Coupled-Channels Faddeev Approach (contd.)

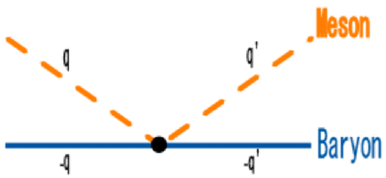
Y. Ikeda, H. Kamano, T. Sato: arXiv:1004.4877 [nucl-th]





- Recent advanced calculation:
  Importance of full, **energy dependent** $\bar{\mathrm{K}}\mathrm{N}$ and $\pi\Sigma$ interactions

based on



chiral SU(3) dynamics

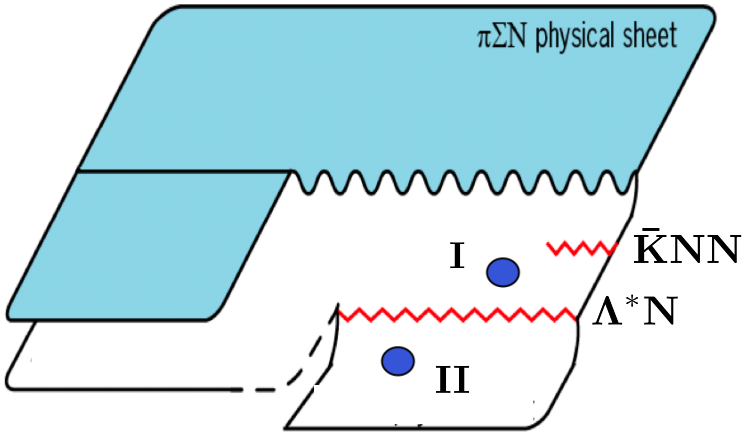
$$V_{MB}(q',q) = -4\pi\lambda^{(I)}_{\alpha\beta}\frac{1}{(2\pi)^3}\frac{1}{8F_\pi^2}\frac{1}{\sqrt{\omega'\omega}}\frac{\omega'+\omega+E'_B+E_B-M'-M}{2}$$

▶ **Two-pole structure** also seen in **3-body** amplitude

K^-pp System: Coupled-Channels Faddeev Approach (contd.)

Y. Ikeda, H. Kamano, T. Sato arXiv:1004.4877 [nucl-th]

- Search for **3-body resonances** on $\bar{K}NN$ physical sheet



- **Energy dependent** interactions
  - ▶ **two poles** in 3-body amplitude

	pole I	pole II
$\bar{K}$- and N-exchanges	$-14.5 - i28.7$	$-36.7 - i109.3$
$\bar{K}$-, N- and π-exchanges	$-13.6 - i27.8$	$-45.8 - i104.0$
Full	$-13.7 - i29.0$	$-37.2 - i93.3$

[MeV]

▶ **weak binding** of $\bar{K}NN$ compound

OVERVIEW

- Binding energies and widths of quasibound $\{\bar{K}[NN]_{T=1}\}_{I=1/2}$

Variational

B [MeV]	Γ	two-body input:	
48	61	phenomenological potential (energy independent)	[1]
20 ± 3	$40 - 70$	chiral SU(3) dynamics	[2]
$40 - 80$	$40 - 85$	coupled channels phenomenological (incl. p wave)	[3]

Faddeev

3-body coupled channels

B [MeV]	Γ	two-body input:	
$50 - 70$	$90 - 110$	phenomenological	[4]
$45 - 80$	$45 - 70$	(energy independent) chiral SU(3) dynamics	[5]
$14^{*)}$	$58^{*)}$	(energy dependent)	[6]

*) KbarNN pole position

[1] T. Yamazaki, Y. Akaishi
Phys. Lett. B535 (2002) 70
Phys. Rev. C76 (2007) 045201

[2] A. Doté, T. Hyodo, W.W.
Nucl. Phys. A804 (2008) 197
Phys. Rev. C79 (2009) 014003

[3] S. Wycech, A.M. Green
Phys. Rev. C79 (2009) 014001

[4] N.V. Shevchenko, A. Gal, J. Mares
Phys. Rev. Lett. 98 (2007) 082301
(+ J. Révay)
Phys. Rev. C76 (2007) 044004

[5] Y. Ikeda, T. Sato
Phys. Rev. C76 (2007) 035203
Phys. Rev. C79 (2009) 035201

[6] Y. Ikeda, H. Kamano, T. Sato
arXiv:1004.4877 [nucl-th] (2010)

OVERVIEW

- Binding energies and widths of quasibound $\{\bar{K}[NN]_{T=1}\}_{I=1/2}$

energy independent

Variational

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Faddeev

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Nucl. Phys. A804 (2008) 197
Phys. Rev. C79 (2009) 014003

[3] S. Wycech, A.M. Green
Phys. Rev. C79 (2009) 014001

[4] N.V. Shevchenko, A. Gal, J. Mares
Phys. Rev. Lett. 98 (2007) 082301
(+ J. Révay)
Phys. Rev. C76 (2007) 044004

[5] Y. Ikeda, T. Sato
Phys. Rev. C76 (2007) 035203
Phys. Rev. C79 (2009) 035201

[6] Y. Ikeda, H. Kamano, T. Sato
arXiv:1004.4877 [nucl-th] (2010)

OVERVIEW

- Binding energies and widths of quasibound $\{\bar{\mathbf{K}}[\mathbf{NN}]_{\mathbf{T=1}}\}_{\mathbf{I=1/2}}$

energy dependent

Variational

$\mathbf{B}$ [MeV]	$\mathbf{\Gamma}$	two-body input:	
48	61	phenomenological potential (energy independent)	[1]
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Faddeev

$\mathbf{B}$ [MeV]	$\mathbf{\Gamma}$	3-body coupled channels two-body input:	
$50 - 70$	$90 - 110$	phenomenological	[4]
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Phys. Lett. B535 (2002) 70
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Nucl. Phys. A804 (2008) 197
Phys. Rev. C79 (2009) 014003

[3] S. Wycech, A.M. Green
Phys. Rev. C79 (2009) 014001

[4] N.V. Shevchenko, A. Gal, J. Mares
Phys. Rev. Lett. 98 (2007) 082301
(+ J. Révay)
Phys. Rev. C76 (2007) 044004

[5] Y. Ikeda, T. Sato
Phys. Rev. C76 (2007) 035203
Phys. Rev. C79 (2009) 035201

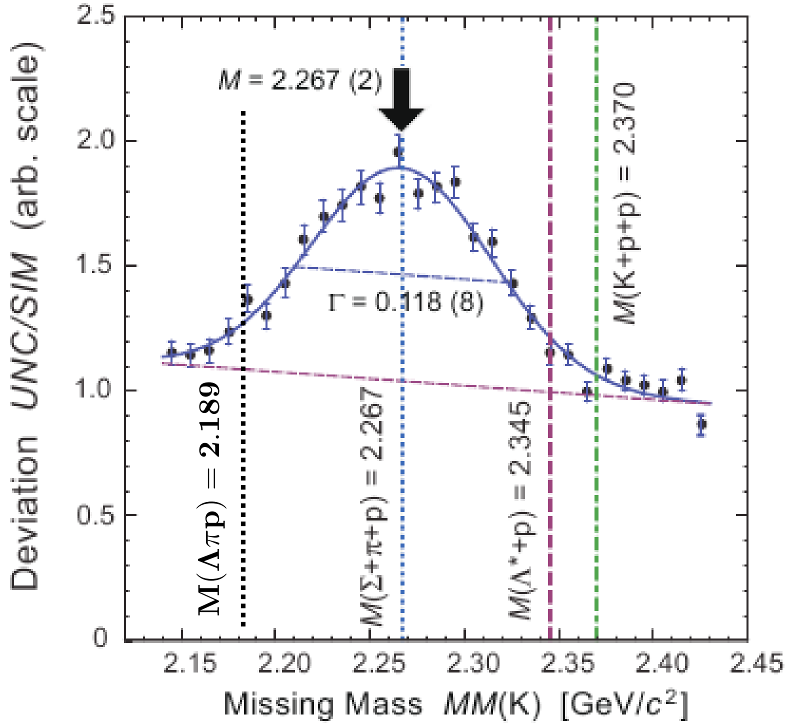
[6] Y. Ikeda, H. Kamano, T. Sato
arXiv:1004.4877 [nucl-th] (2010)

About DISTO

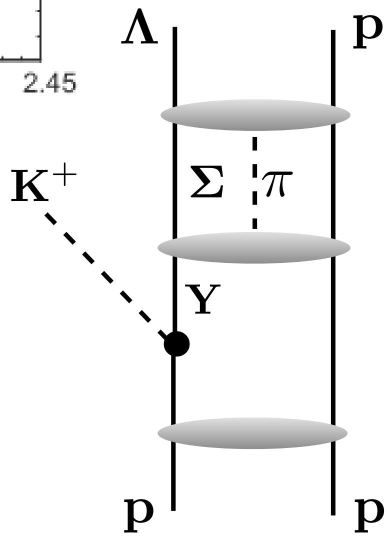
T. Yamazaki et al.
Phys. Rev. Lett. 104 (2010) 132502

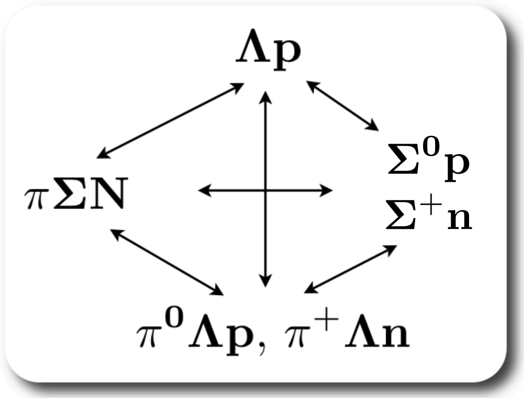
M. Maggiora et al.
Nucl. Phys. A835 (2010) 43

$$\mathrm{p\ p} \rightarrow \mathrm{K}^+\ \Lambda \mathrm{p} \quad (2.85\ \mathrm{GeV})$$



- Open questions:
- How can one make sure that **K⁻pp** is a dominant component of the measured DISTO spectrum **?**
- Why should the "**antikaon-less**" 3-body coupled-channels scenario (πYN) be suppressed **?**
- Can a few-body cluster with a lifetime of less than 2 fm/c be "quasibound" ?
- Note:
  similar questions apply to FINUDA and FOPI





Antikaon Bound States in Heavier Nuclei ?

(exploratory studies)

- Solve **Klein-Gordon equation**:

$$\left[\omega^2 + \vec{\nabla}^2 - \mathbf{m_K^2} - \mathbf{\Pi}(\omega;\, \vec{\mathbf{r}})\right] \phi_{\mathbf{K}}(\vec{\mathbf{r}}) = \mathbf{0}$$

- . . . with **kaon self-energy**:

$$\mathbf{\Pi}(\omega;\, \vec{\mathbf{r}}) = -\mathbf{T}^{s-wave}_{\mathbf{K^-p}}(\omega)\, \rho_{\mathbf{p}}(\vec{\mathbf{r}}) - \mathbf{T}^{s-wave}_{\mathbf{K^-n}}(\omega)\, \rho_{\mathbf{n}}(\vec{\mathbf{r}})$$

$$+\, \tilde{\mathbf{C}}^{p-wave}_{\mathbf{K^-p}}(\omega)\, \vec{\nabla}\rho_{\mathbf{p}}(\vec{\mathbf{r}})\vec{\nabla} + \tilde{\mathbf{C}}^{p-wave}_{\mathbf{K^-n}}(\omega)\, \vec{\nabla}\rho_{\mathbf{n}}(\vec{\mathbf{r}})\vec{\nabla} \quad \Big\}\; \text{“}\mathbf{T}\rho\text{”}$$

$$+\, \delta\mathbf{\Pi_{corr}}(\rho_{\mathbf{p}}, \rho_{\mathbf{n}}) + \delta\mathbf{\Pi_{abs}}(\omega;\, \rho_{\mathbf{p}}, \rho_{\mathbf{n}}) + \delta\mathbf{\Pi_{coul}}(\omega;\, \rho_{\mathbf{p}})$$

correlations **absorption** **Coulomb**

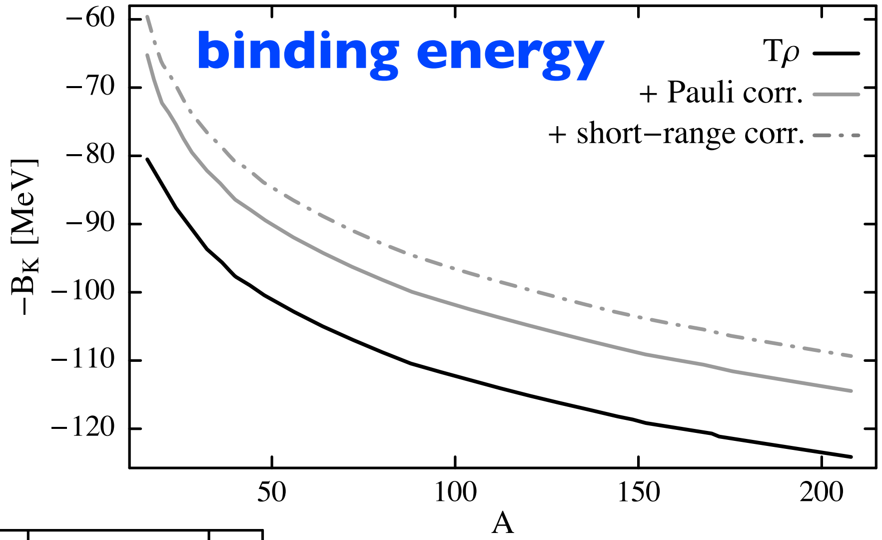
- Woods-Saxon distributions for $\rho_{\mathbf{p}}(\vec{\mathbf{r}}),\ \rho_{\mathbf{n}}(\vec{\mathbf{r}})$
- Search for **bound state** solutions $\omega = \mathbf{Re}\,\omega - \frac{\mathbf{i}}{\mathbf{2}}\mathbf{\Gamma}$

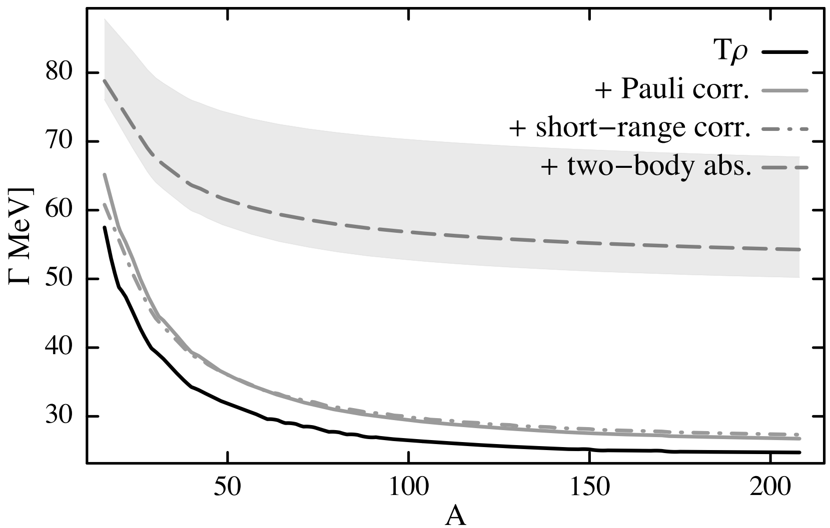
Antikaon - Nuclear Quasibound States

$$\left[\omega^2 + \vec{\nabla}^2 - \mathbf{m_K^2} - \mathbf{\Pi}(\omega;\, \vec{\mathbf{r}})\right] \phi_{\mathbf{K}}(\vec{\mathbf{r}}) = \mathbf{0}$$

- Exploratory studies:

Systematics
as function of
nuclear mass number





decay width

R. Härtle, W.W.
Nucl. Phys. A 804 (2008) 173

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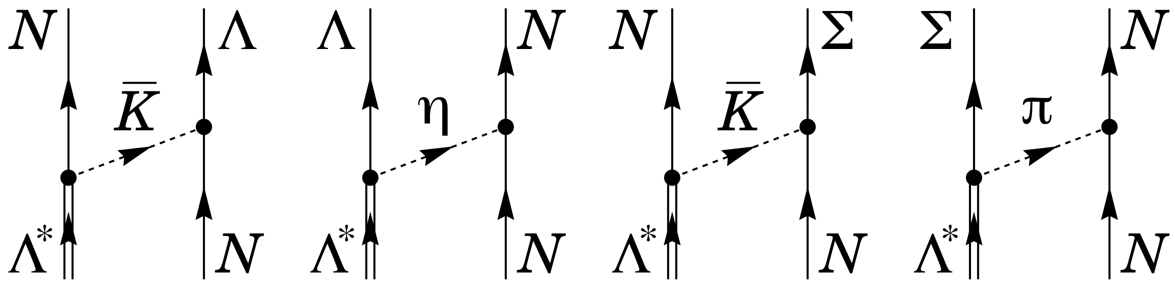
Antikaon Absorption on Nucleon Pairs

T. Sekihara, D. Jido, Y. Kahada-En´yo   Phys. Rev. C79 (2009) 062201

- Basic process: $\mathbf{K^- N N \to \Lambda(1405)\, N \to Y\, N}$



- Result:
  non-mesonic decay width

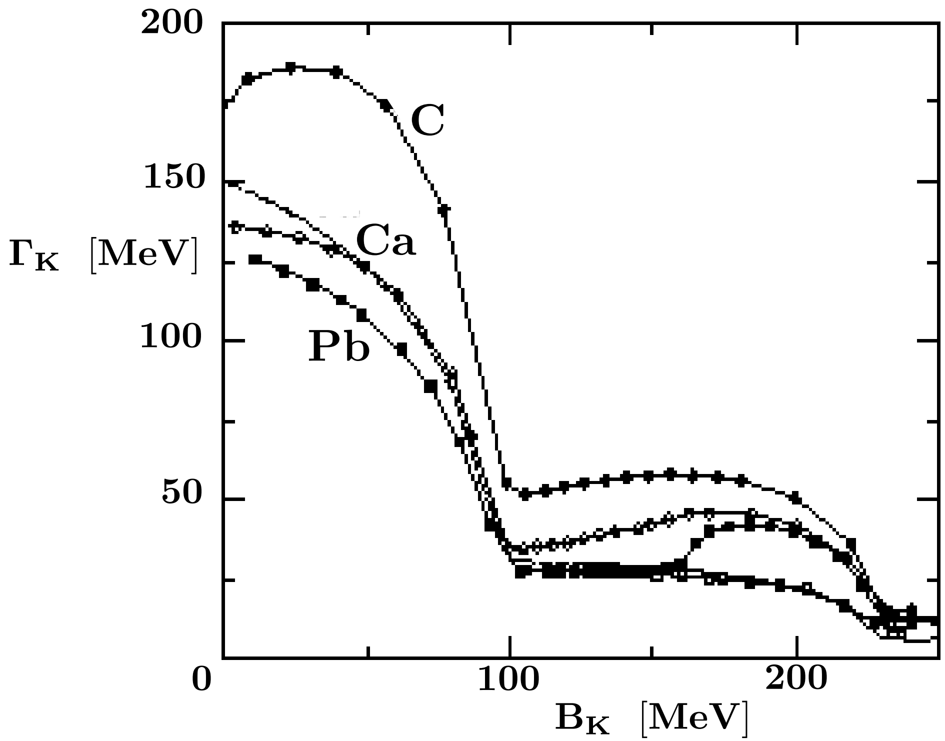
$$\mathbf{\Gamma(\Lambda^* N \to Y\, N) \simeq 22\, MeV}$$

at normal nuclear matter density

Related Work

- K^-- nuclear bound states in a dynamical model

  J. Mares, E. Friedman, A. Gal, Nucl Phys. A 770 (2006) 84



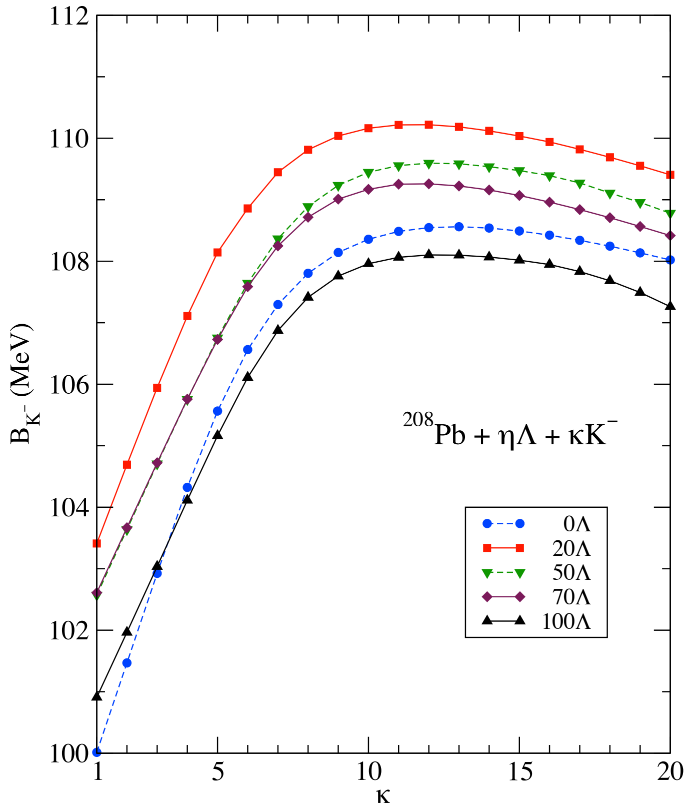
- ... qualitatively similar conclusions reached

Multi K^--Nuclear Systems

D. Gazda, E. Friedman, A. Gal, J. Mares   Phys. Rev. C77 (2008) 045206 & arXiv: 0906.5344 [nucl-th]

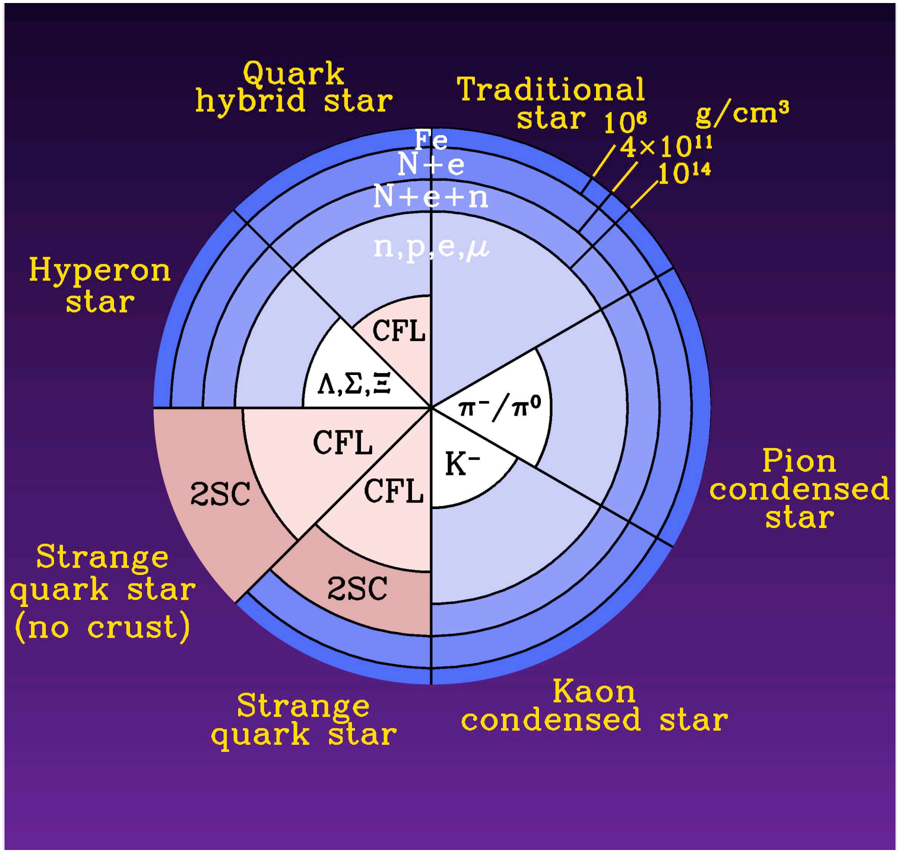
- Relativistic mean-field model for antikaons, nucleons and hyperons

  - Repulsion between antikaons
  - Saturation of antikaon binding energy



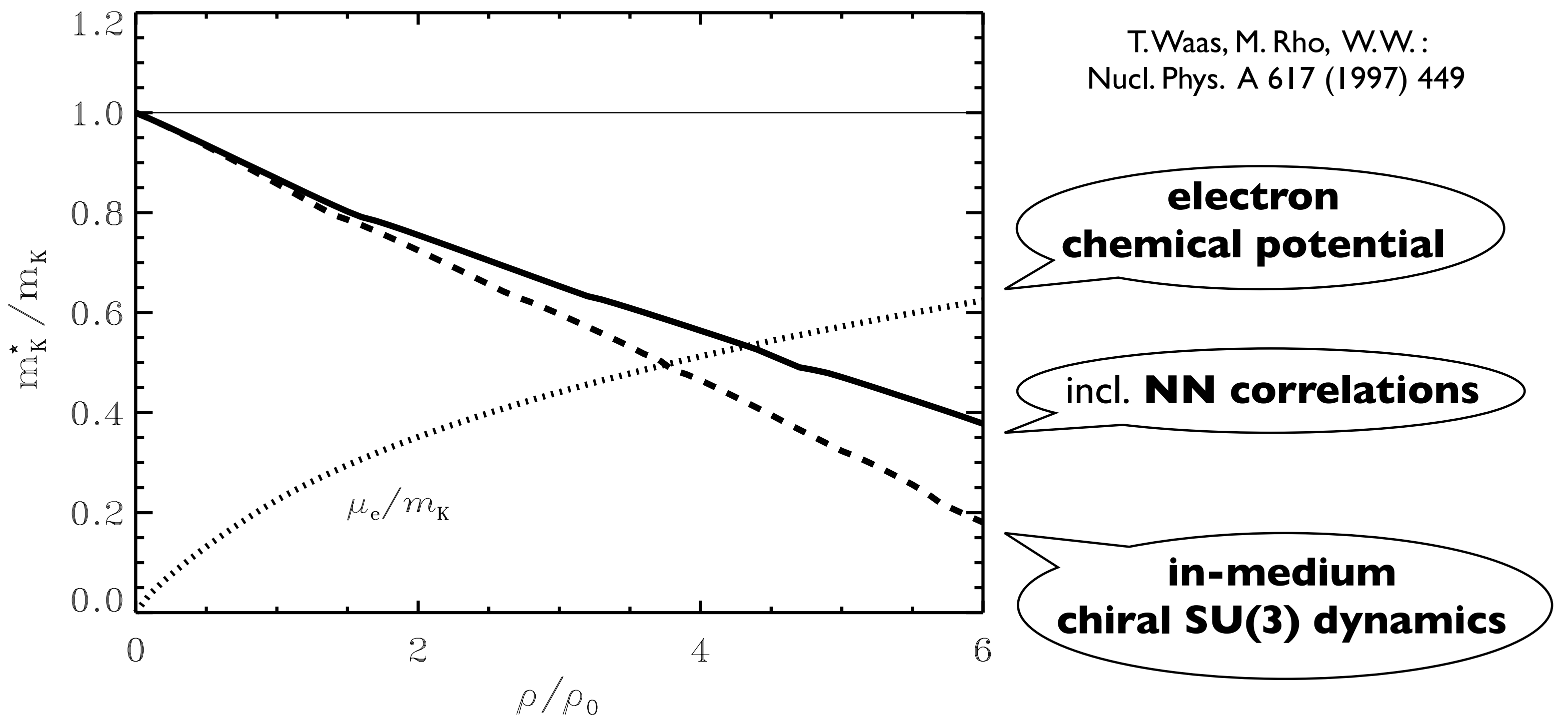
- ... prevents kaon condensation in this approach

6. Outlook : Kaon Condensation in NEUTRON STARS ?



Kaon Condensation in Neutron Matter

- first suggested by D. Kaplan, A. Nelson (1985) on the basis of **attractive K^-N Tomozawa - Weinberg term**
- at high density, energetically favourable to condense K^-



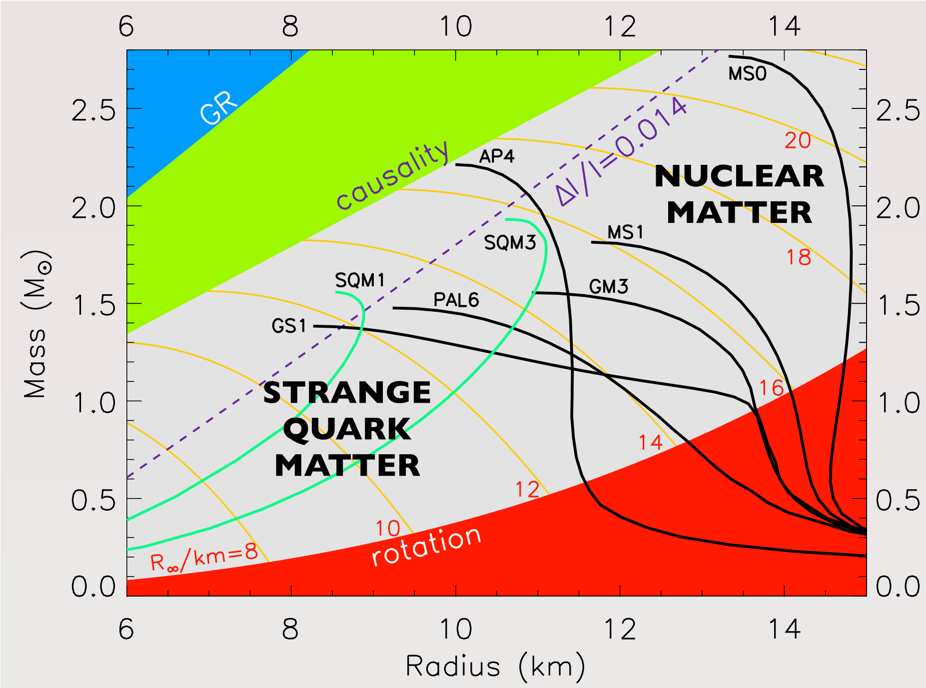
- conversion to hyperons via $K^-NN \rightarrow YN$?

NEUTRON STARS and the EQUATION OF STATE of DENSE BARYONIC MATTER

- **T**olman-**O**ppenheimer-**V**olkov equations

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m + 4\pi p r^3)(\epsilon + p)}{r(r - 2Gm/c^2)} \qquad \frac{dm}{dr} = 4\pi\frac{\epsilon}{c^2}r^2$$

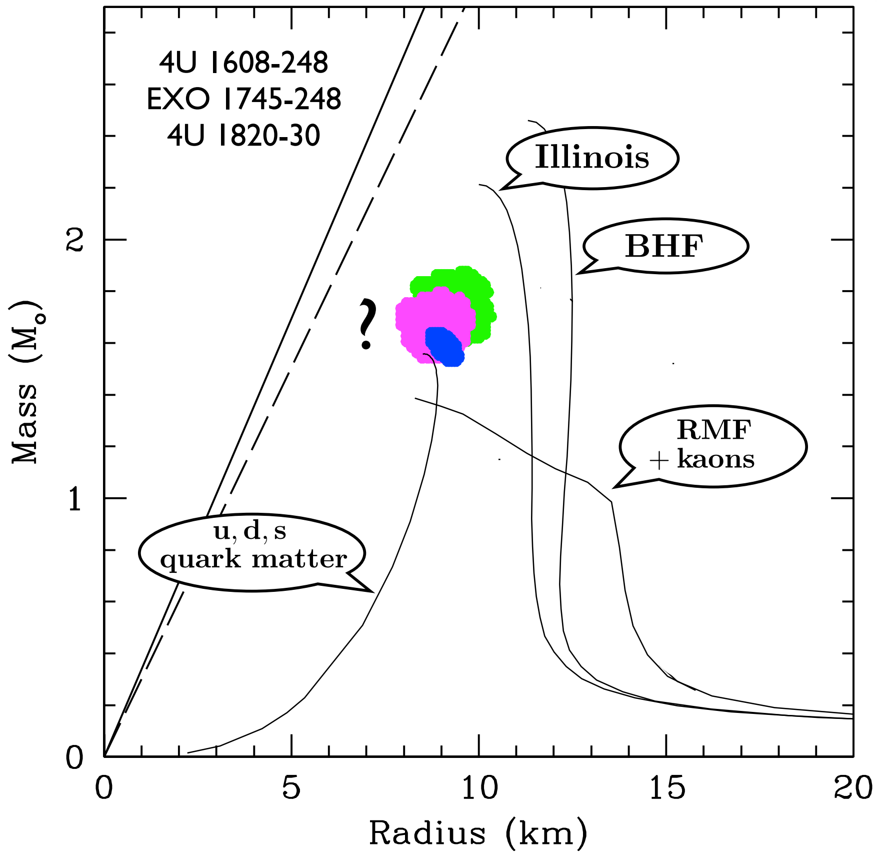
- **Mass-Radius Relation**



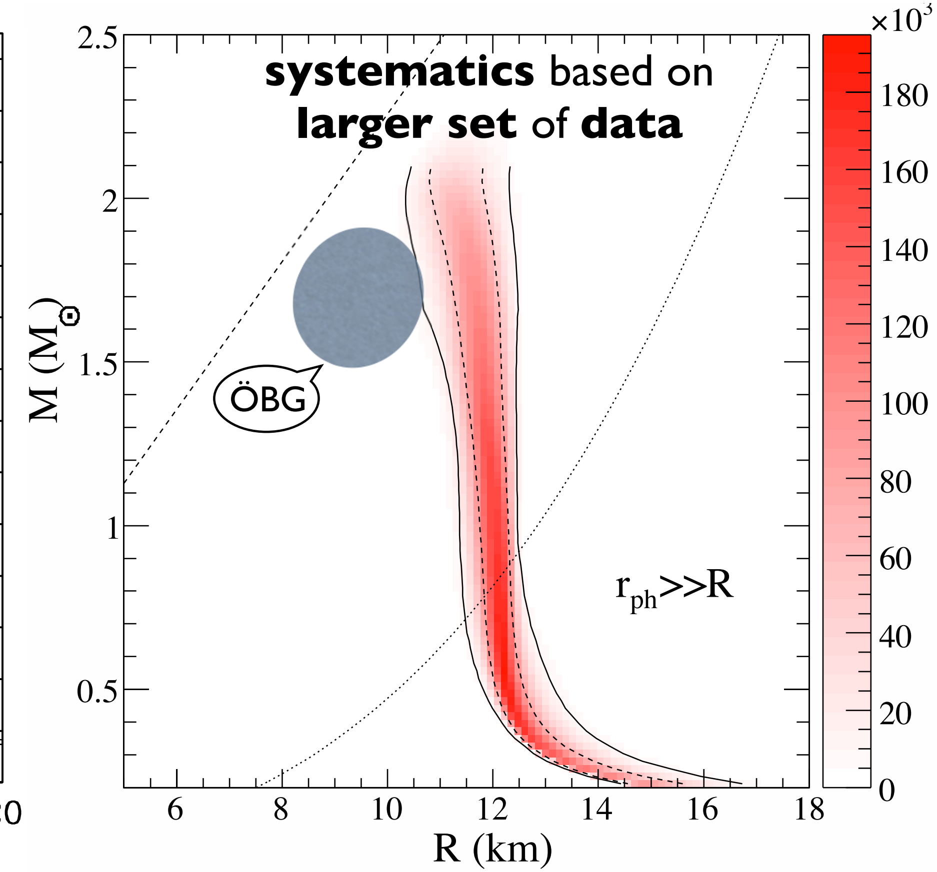
J. Lattimer, M. Prakash: Astrophys. J. 550 (2001) 426 Phys. Reports 442 (2007) 109

New Semi-Empirical Constraints from NEUTRON STARS in BINARIES

. . . using observables such as apparent surface, flux during cooling . . .



F. Özel, G. Baym, T. Güver
arXiv:1002.3153 [astro-ph.HE]



A.W. Steiner, J. Lattimer, E.F. Brown
arXiv:1005.0811 [astro-ph.HE]

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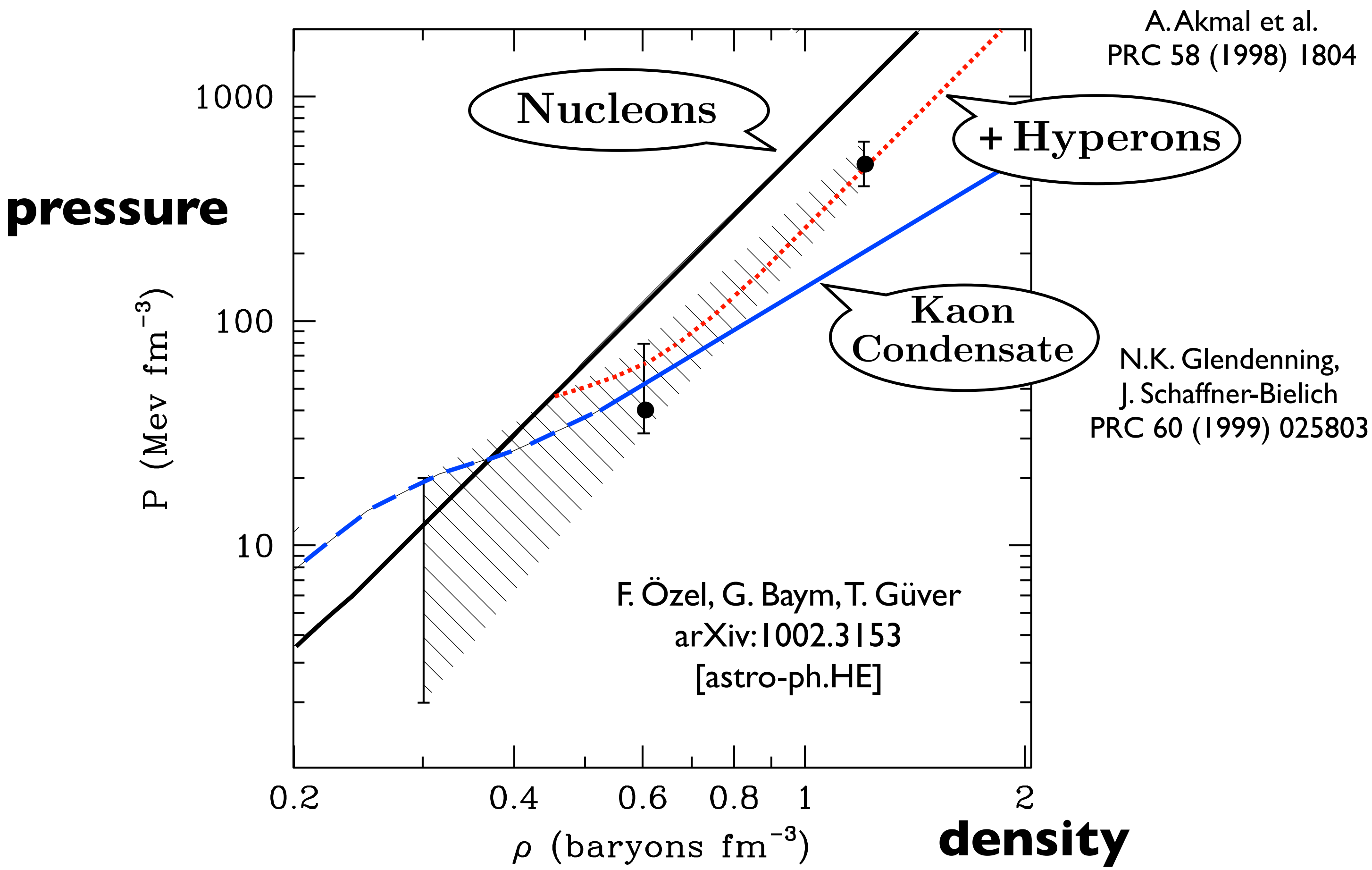
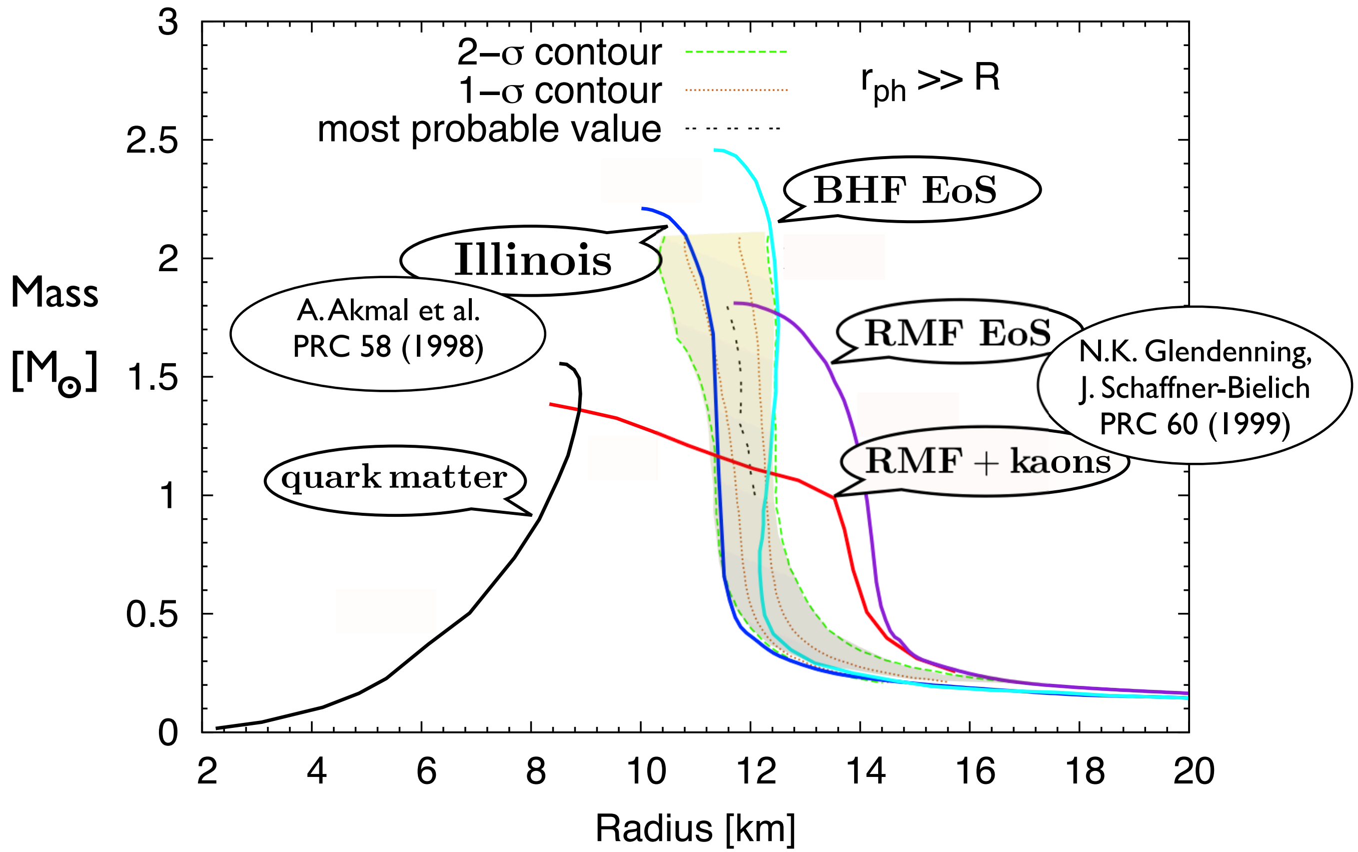
Implications for the EQUATION of STATE



- **Nucleons + Hyperons** more likely than **Kaon Condensate** or **Quark Matter ?**

Implications for the **EQUATION of STATE** (contd.)



- Equations of state compared to "most probable scenario" analysis
- Realistic "**nuclear**" EoS (Illinois) works **?**
- **Quark** matter and **kaon** condensate ruled out **?**
  - Clarify uncertainties of ÖBG and SLB analysis !

A.W. Steiner, J. Lattimer, E.F. Brown
arXiv:1005.0811 [astro-ph.HE]

Summary part I

- **Low-Energy QCD**:
  spontaneous chiral symmetry breaking scenario
  well established
  - **Chiral** SU(3) x SU(3) **Effective Field Theory** :
    Successful framework for low-energy hadron physics with s-quarks
  - Structure of $\Lambda(1405)$ governed by
    chiral SU(3) **coupled-channels** (two-poles scenario)
- Looking forward to:
  - high-precision $\bar{\mathrm{K}}\mathrm{N}$ **threshold data**
  - much improved $\pi\Sigma$ **mass spectra**

SIDDHARTA . . . JLab, J-PARC, AMADEUS, GSI

Summary part II

- **Antikaons** interacting with baryonic few- and many-body systems:
  - $\bar{\mathrm{K}}\mathrm{NN}$ **quasibound** clusters **?**
  - Extrapolations to **far-subthreshold** region still an issue
  - **Weak binding** + **large width** from chiral SU(3) dynamics
  - DISTO (and FINUDA) signals are **not** understood in terms of deeply bound $\bar{\mathrm{K}}\mathrm{NN}$ state ($\rightarrow \pi\mathrm{YN}$ dynamics ?)

- Possible **constraints** from astrophysics / **neutron stars** :
  - **Nucleons** + **hyperons** favored over **kaon condensate ?**
  - Looking forward to advanced **mass-radius analysis** of neutron stars

The End

thanks to:

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