Workshop
"Future Prospects of Hadron Physics at J-PARC and Large Scale Computational Physics"
Tokai, Japan — 11 February 2012

Chiral Symmetry and Hadron Physics
- selected topics -

Wolfram Weise
Technische Universität München

- Low-energy QCD: **symmetries** and **symmetry breaking** patterns
- **Strangeness** and **chiral SU(3) dynamics**
- The **sigma term** of the nucleon and its implications
- New constraints from **neutron stars**

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

$$\mathrm{m_d} \simeq 4 - 6\ \mathrm{MeV}$$
$$\mathrm{m_u/m_d} \sim 0.3 - 0.6$$
$$\mathrm{m_s} \simeq 80 - 130\ \mathrm{MeV}$$
$$(\mu \simeq 2\ \mathrm{GeV})$$

- **LOW-ENERGY QCD: CHIRAL EFFECTIVE FIELD THEORY**
- **expansion in $\mathrm{m_q}$ and in powers of low momentum**

$$\mathrm{m_c} \simeq 1.25\ \mathrm{GeV}$$
$$m_b \simeq 4.2\ GeV$$
$$m_t \simeq 174\ GeV$$

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

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

- **NAMBU - GOLDSTONE BOSONS**:

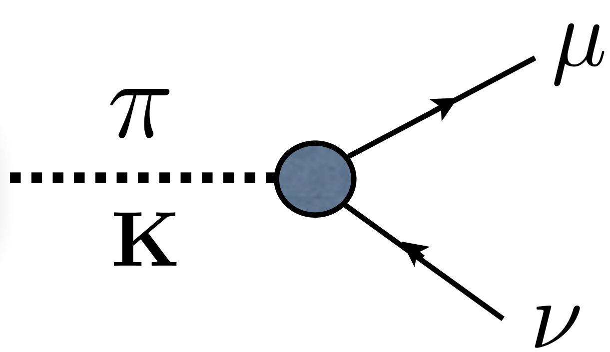
  Pseudoscalar SU(3) meson octet $\quad \{\phi_a\} = \{\pi, \mathbf{K}, \bar{\mathbf{K}}, \eta_8\}$

- **ORDER PARAMETERS**: **DECAY CONSTANTS**

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

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

axial current



$$\mathbf{f}_\pi = 92.4 \pm 0.3\ \mathrm{MeV}$$
$$\mathbf{f}_\mathbf{K} = 110.0 \pm 0.9\ \mathrm{MeV}$$
$$\mathbf{f}_\eta = 120.1 \pm 4.6\ \mathrm{MeV}$$

spontaneous symmetry breaking

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

explicit symmetry breaking

PART 1.
LOW-ENERGY QCD with **STRANGE QUARKS**

… realized as an **EFFECTIVE FIELD THEORY** with SU(3) octet of pseudoscalar Nambu-Goldstone bosons coupled to the baryon octet.

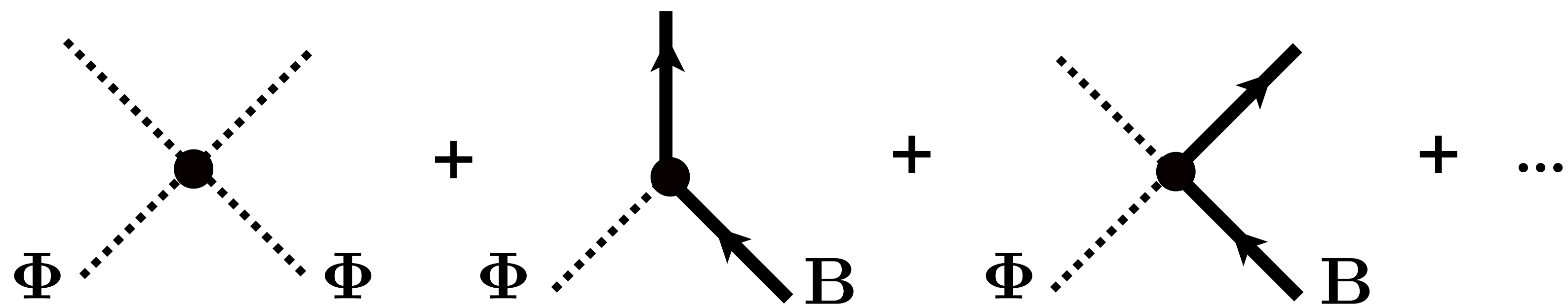
- **Strange quarks** are intermediate between "**light**" and "**heavy**":
  - interplay between **spontaneous** and **explicit chiral symmetry breaking**
- Testing ground: high-precision **antikaon-nucleon** threshold physics
- Nature and structure of $\Lambda(1405)$ $(\mathrm{B} = 1, \ \ \mathrm{S} = -1, \ \ \mathrm{J^P} = 1/2^-)$
- Role of **strangeness** in dense baryonic matter ?
  - new constraints from **neutron stars**

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**

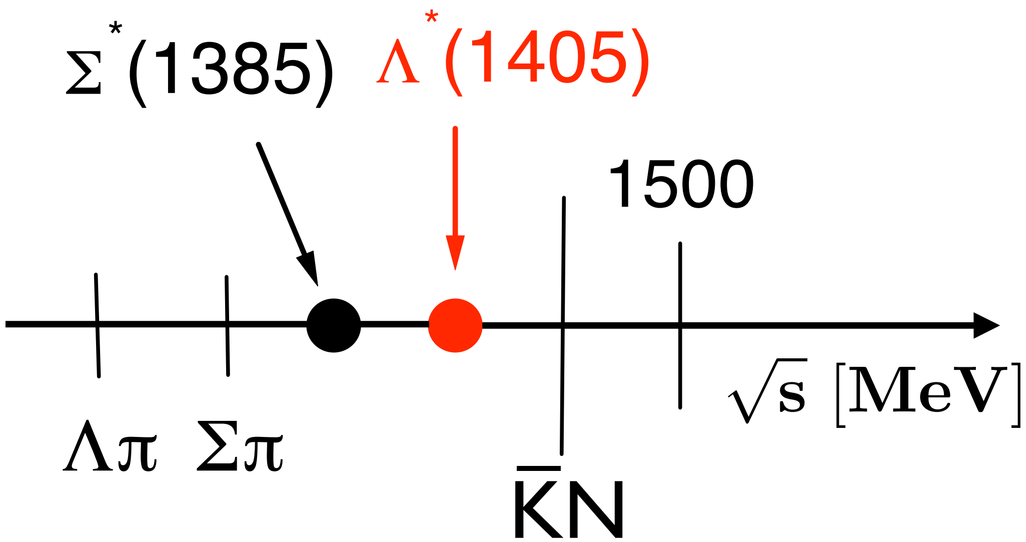
"small parameter": $\dfrac{\mathrm{p}}{4\pi\,\mathrm{f}_\pi} \sim \dfrac{\text{energy / momentum}}{1\ \mathrm{GeV}}$

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

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

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

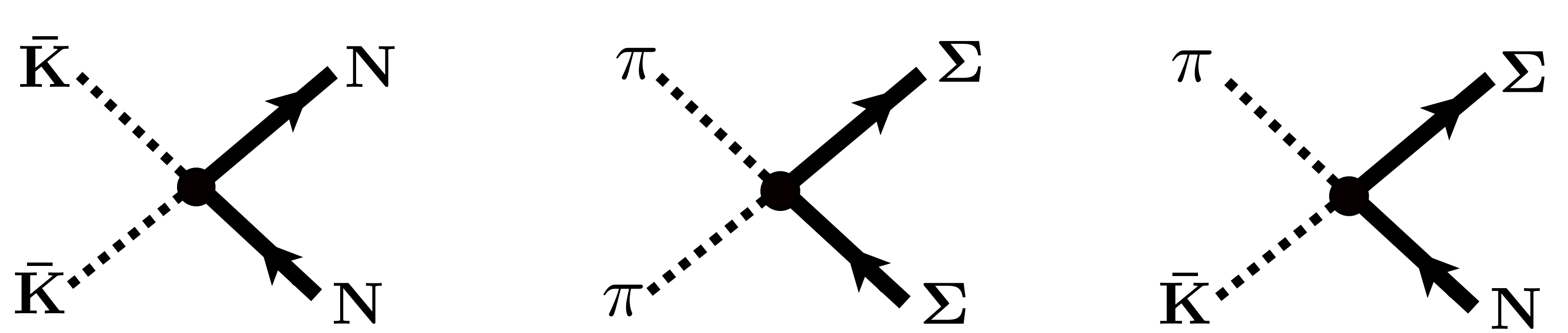
- Chiral Perturbation Theory **NOT** applicable:
  $\Lambda(1405)$ resonance 27 MeV below K^-p threshold



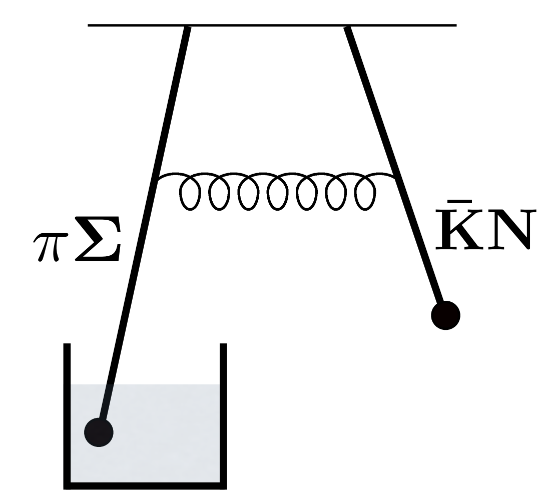
Non-perturbative
Coupled Channels
approach based on
Chiral SU(3) Dynamics

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

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



channel coupling

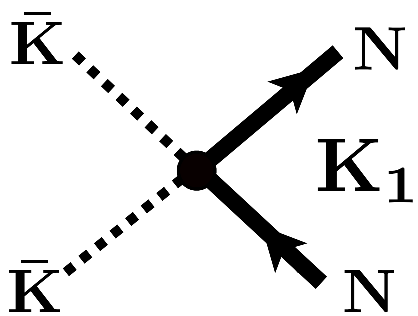


CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

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

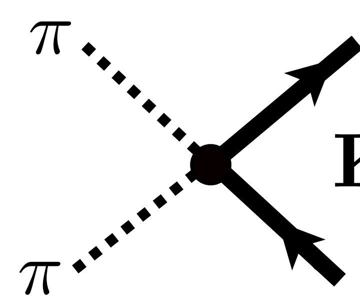
- Leading s-wave I = 0 meson-baryon interactions (Tomozawa-Weinberg)
  Note: **ENERGY DEPENDENCE** characteristic of Nambu-Goldstone Bosons

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



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

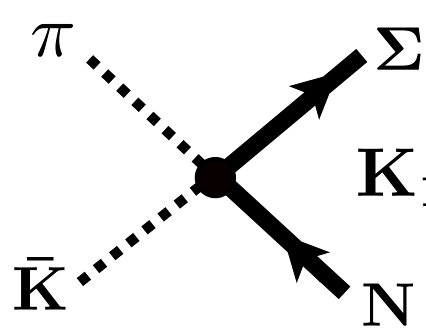
$|\mathbf{2}\rangle = |\pi\mathbf{\Sigma, I = 0}\rangle$



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

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

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



$$\mathbf{K_{12} = \frac{-1}{2\, f_\pi\, f_K}\sqrt{\frac{3}{2}}\left(\sqrt{s} - \frac{M_\Sigma + M_N}{2}\right)}$$

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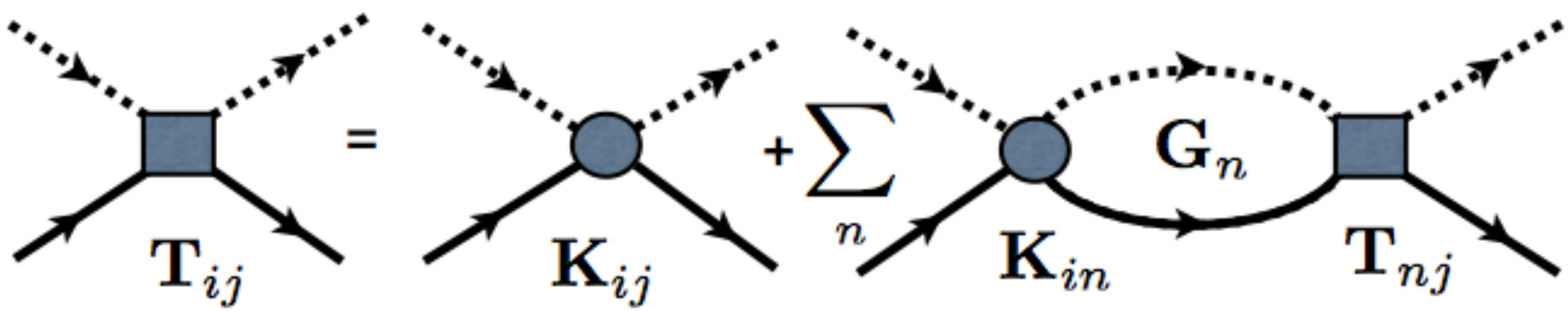
CHIRAL SU(3) COUPLED CHANNELS DYNAMICS



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

input from
chiral SU(3)
meson-baryon
effective Lagrangian

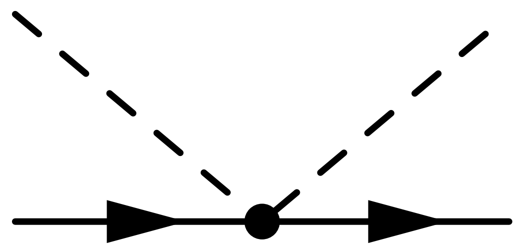
loop functions
(dim. regularization)
with subtraction constants
encoding short distance dynamics

- **coupled channels**:

$$\mathbf{K^- p},\ \mathbf{\bar{K}^0 n},\ \pi^0\mathbf{\Sigma^0},\ \pi^+\mathbf{\Sigma^-},\ \pi^-\mathbf{\Sigma^+},\ \pi^0\mathbf{\Lambda},\ \eta\mathbf{\Lambda},\ \eta\mathbf{\Sigma^0},\ \mathbf{K^+\Xi^-},\ \mathbf{K^-\Xi^0}$$

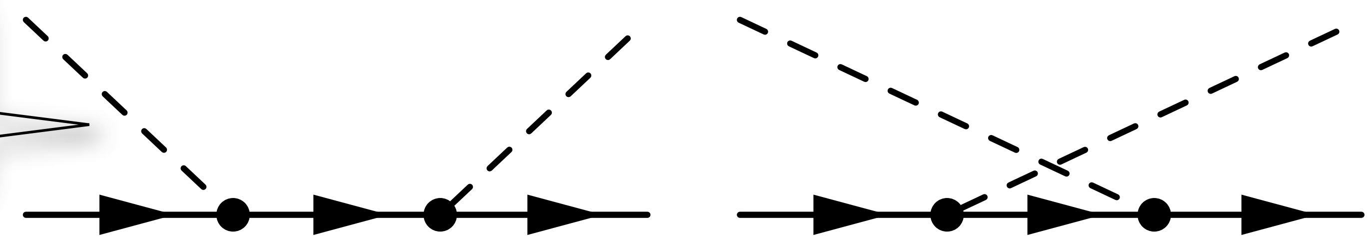
CHIRAL SU(3) COUPLED CHANNELS DYNAMICS:

- NLO hierarchy of driving terms -



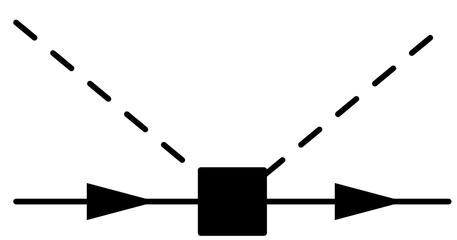
leading order (**W**einberg-**T**omozawa) terms
input: physical pion and kaon decay constants

direct and crossed **Born terms**
input: axial vector constants
D and F from hyperon beta decays



$$g_A = D + F = 1.26$$

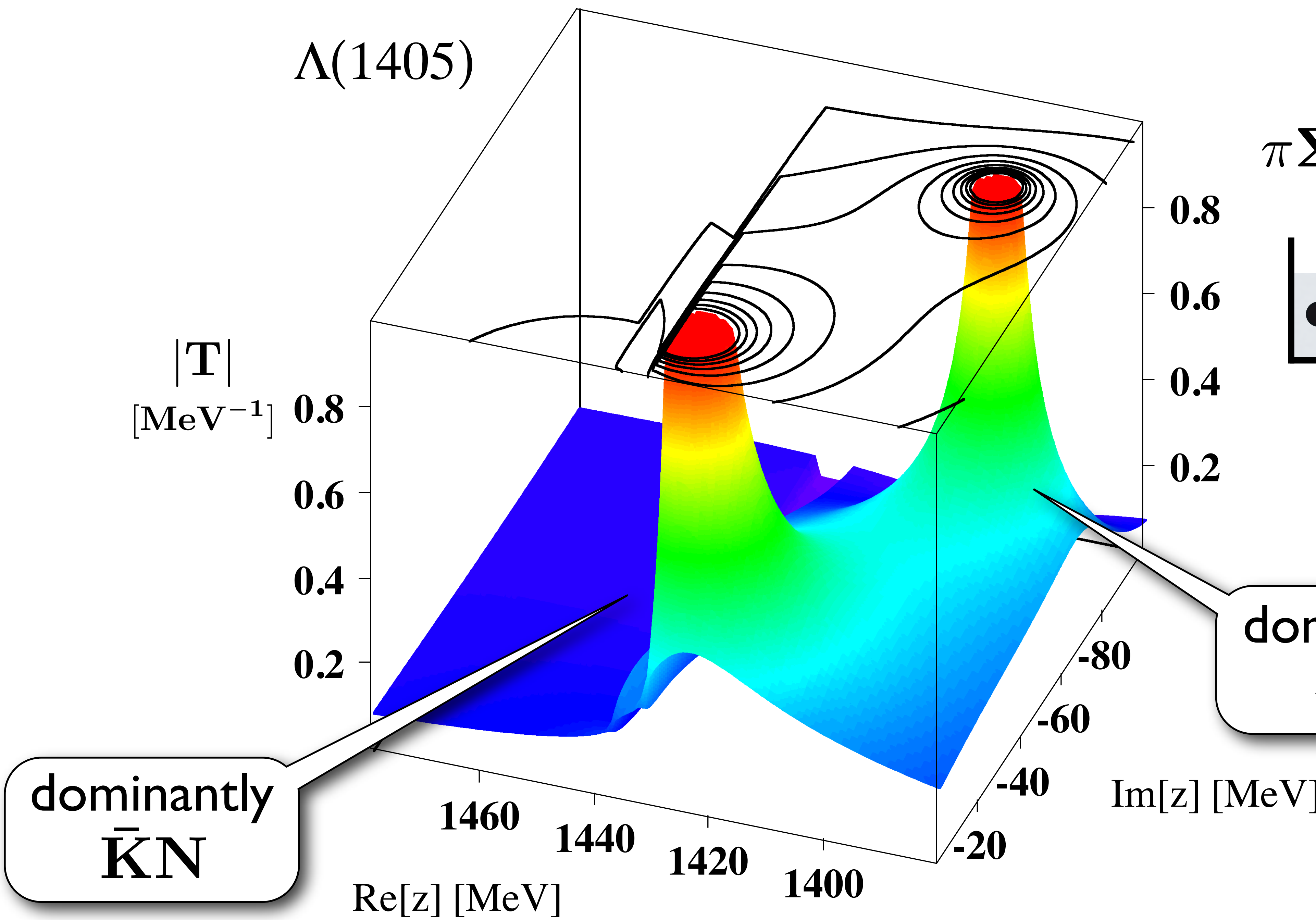
$$\mathcal{L}_1^{MB} = \mathrm{Tr}\left(\frac{D}{2}(\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}) + \frac{F}{2}(\bar{B}\gamma^\mu\gamma_5[u_\mu, B])\right)$$

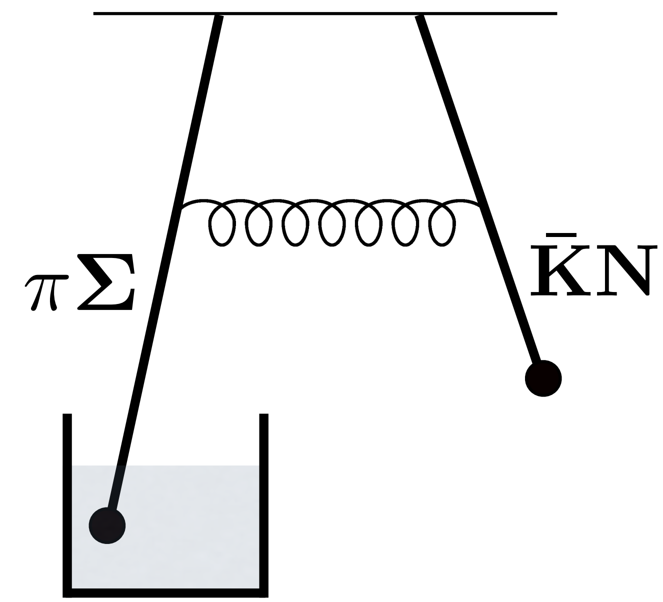


next-to-leading order (**NLO**) $\mathcal{O}(p^2)$
input: 7 low-energy constants

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

The TWO POLES scenario





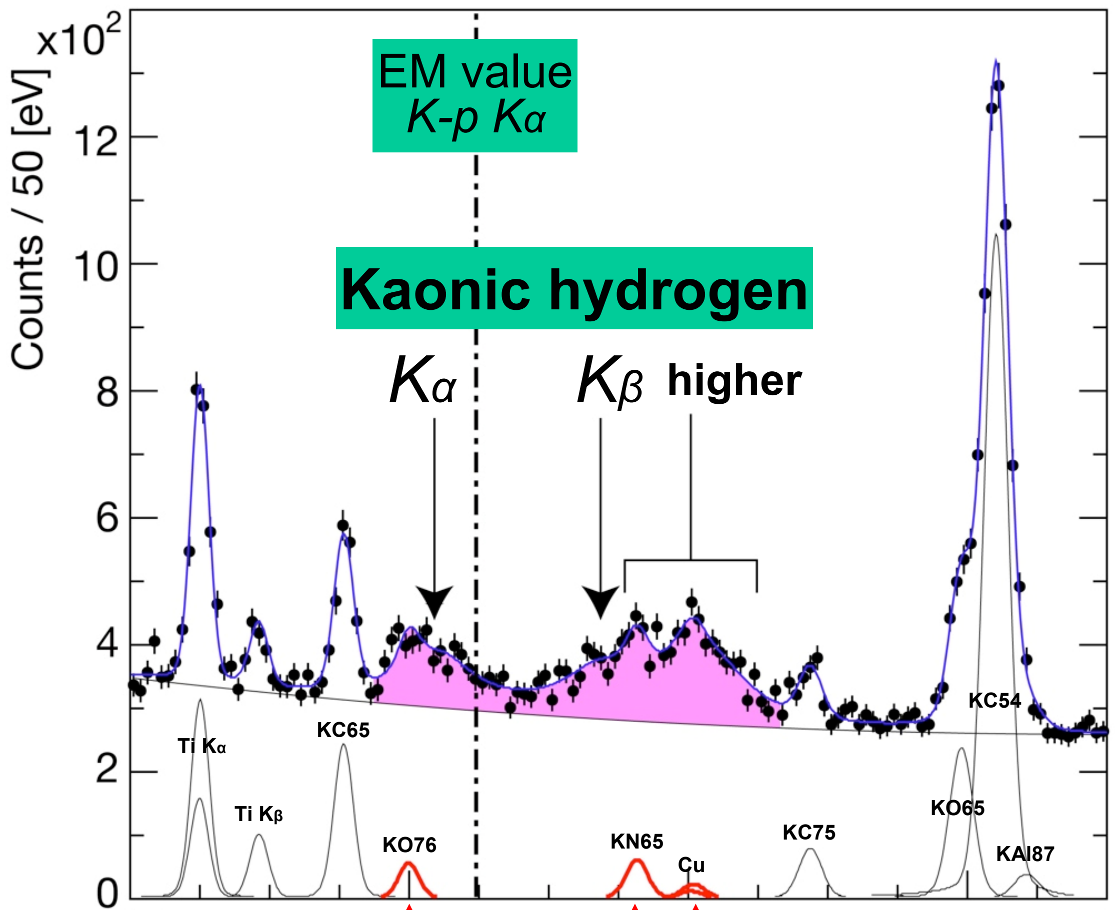
D. Jido et al., Nucl. Phys. A723 (2003) 205

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

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

ANTIKAON - NUCLEON THRESHOLD PHYSICS and LOW-ENERGY OBSERVABLES

- New **kaonic hydrogen** data



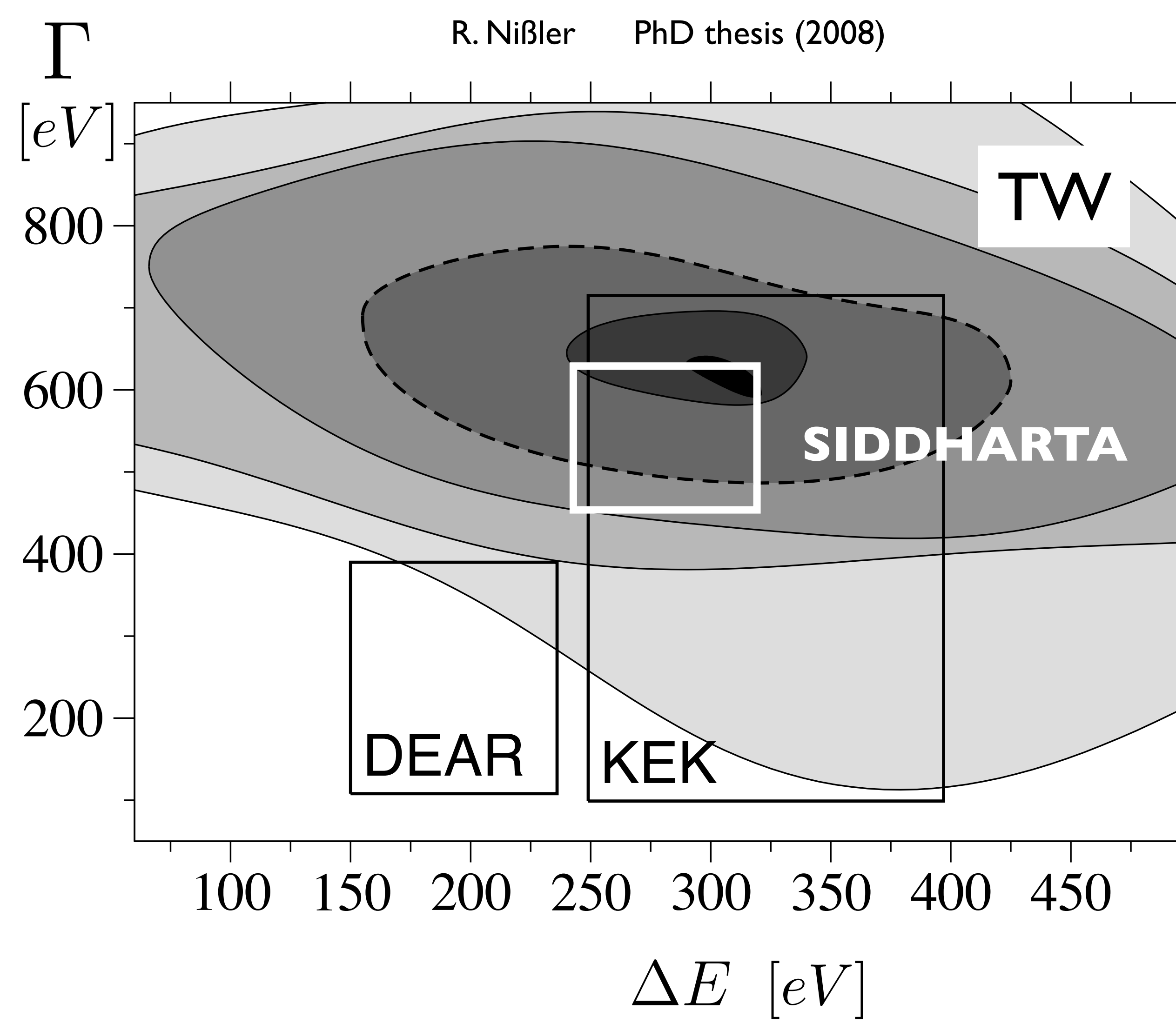
SIDDHARTA
M. Bazzi et al. : Phys. Lett. B 704 (2011) 113

- Theory:
  leading order
  (Tomozawa - Weinberg)

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

B. Borasoy, U.-G. Meißner, R. Nißler PRC74 (2006) 055201

R. Nißler PhD thesis (2008)



- strong interaction shift and width:

$$\mathbf{\Delta E} = \mathbf{283} \pm \mathbf{36}\,(stat) \pm \mathbf{6}\,(syst) \quad \mathbf{eV}$$
$$\mathbf{\Gamma} = \mathbf{541} \pm \mathbf{89}\,(stat) \pm \mathbf{22}\,(syst) \quad \mathbf{eV}$$

Improved constraints on chiral SU(3) dynamics from kaonic hydrogen

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Abstract

A new improved study of K^--proton interactions near threshold is performed using coupled-channels dynamics based on the next-to-leading order chiral SU(3) meson-baryon effective Lagrangian. Accurate constraints are now provided by new high-precision kaonic hydrogen measurements. Together with threshold branching ratios and scattering data, these constraints permit an updated analysis of the complex $\bar{K}N$ and $\pi\Sigma$ coupled-channels amplitudes and an improved determination of the K^-p scattering length, including uncertainty estimates.

arXiv: 1109.3005

Physics Letters B 706 (2011) 63

UPDATED ANALYSIS of $K^- p$ THRESHOLD PHYSICS

Y. Ikeda, T. Hyodo, W.W. Phys. Lett. B 706 (2011) 63 Nucl. Phys. A (2012), in print

- Chiral SU(3) coupled-channels dynamics
  Tomozawa-Weinberg + **Born** terms + NLO

kaonic hydrogen shift & width	theory (NLO)	exp.
ΔE (eV)	306	$283 \pm 36 \pm 6$
Γ (eV)	591	$541 \pm 89 \pm 22$
threshold branching ratios		(SIDDHARTA)
$\frac{\Gamma(K^- p \to \pi^+ \Sigma^-)}{\Gamma(K^- p \to \pi^- \Sigma^+)}$	2.37	2.36 ± 0.04
$\frac{\Gamma(K^- p \to \pi^+ \Sigma^-, \pi^- \Sigma^+)}{\Gamma(K^- p \to \text{all inelastic channels})}$	0.66	0.66 ± 0.01
$\frac{\Gamma(K^- p \to \pi^0 \Lambda)}{\Gamma(K^- p \to \text{neutral states})}$	0.19	0.19 ± 0.02

scattering length (fm) $\mathrm{Re}\, a(K^- p) = -0.65 \pm 0.10$ $\mathrm{Im}\, a(K^- p) = 0.81 \pm 0.15$

best fit achieved with $\chi^2/d.o.f. \simeq 0.9$

UPDATED ANALYSIS of $\mathrm{K^-p}$ THRESHOLD PHYSICS with SIDDHARTA constraints

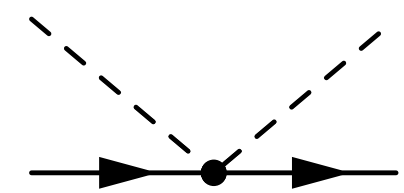
Y. Ikeda, T. Hyodo, W.W. Phys. Lett. B 706 (2011) 63 Nucl. Phys. A (2012), in print

- Non-trivial result:
  best NLO fit prefers **physical** values of **decay constants**:

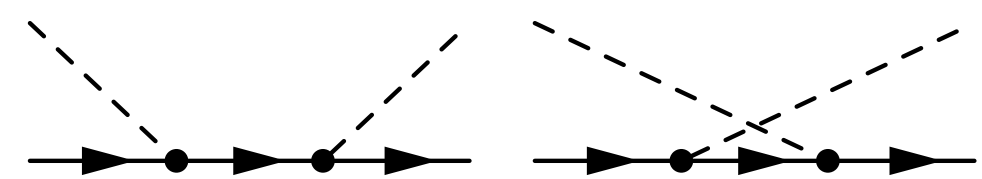
f_K (MeV)	110.0
f_η (MeV)	118.8

$(f_\pi = 92.4\ MeV)$

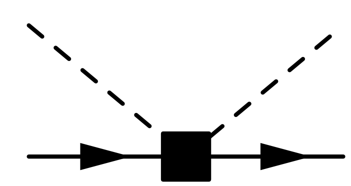
- **Tomozawa-Weinberg** terms **dominant**



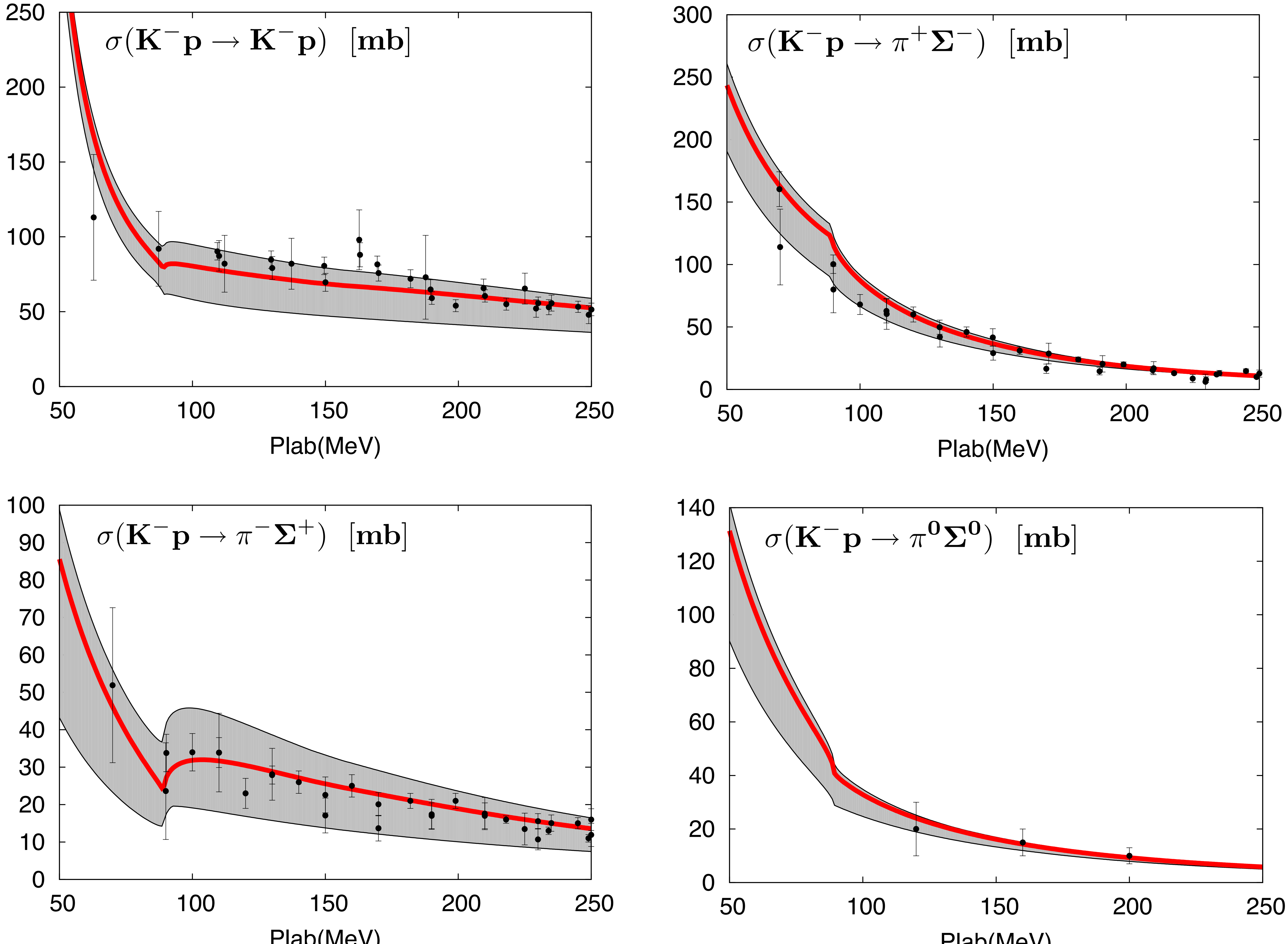
- **Born** terms **significant**



- **NLO** parameters are non-negligible but **small**



UPDATED ANALYSIS of K^-p LOW-ENERGY CROSS SECTIONS

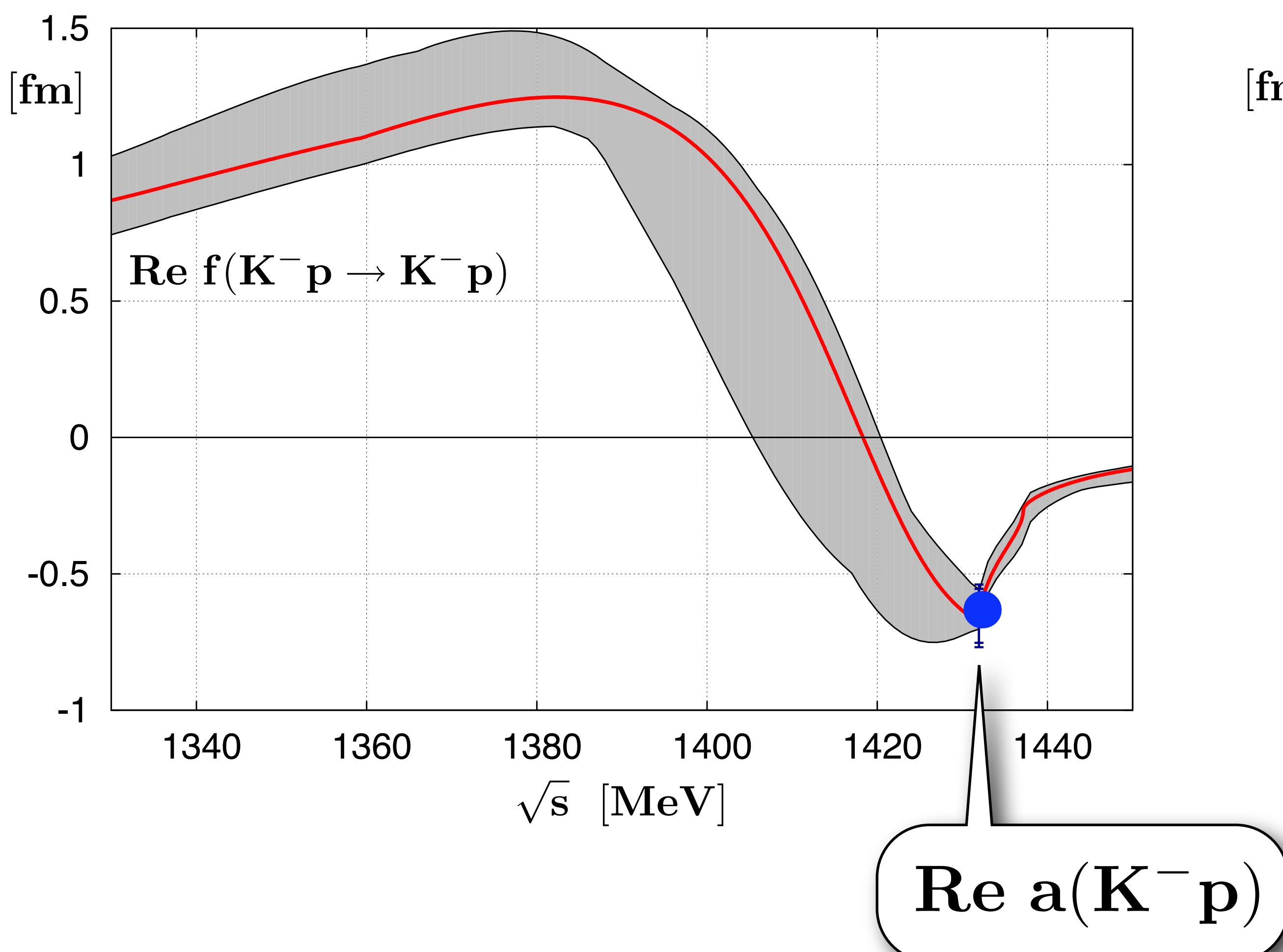


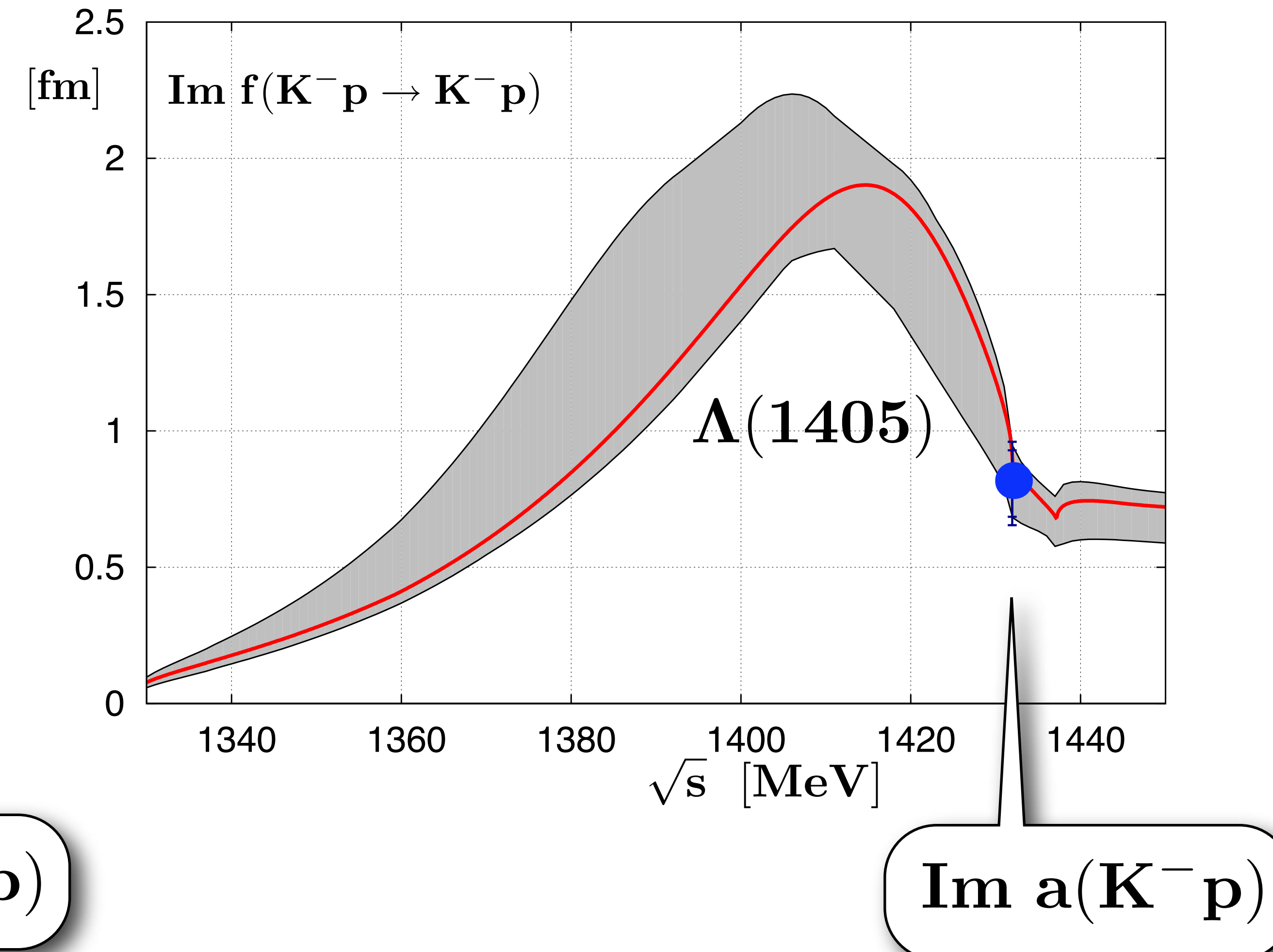
$K^- p$ SCATTERING AMPLITUDE

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

- threshold region and subthreshold extrapolation:

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





- complex scattering length (including Coulomb corrections)

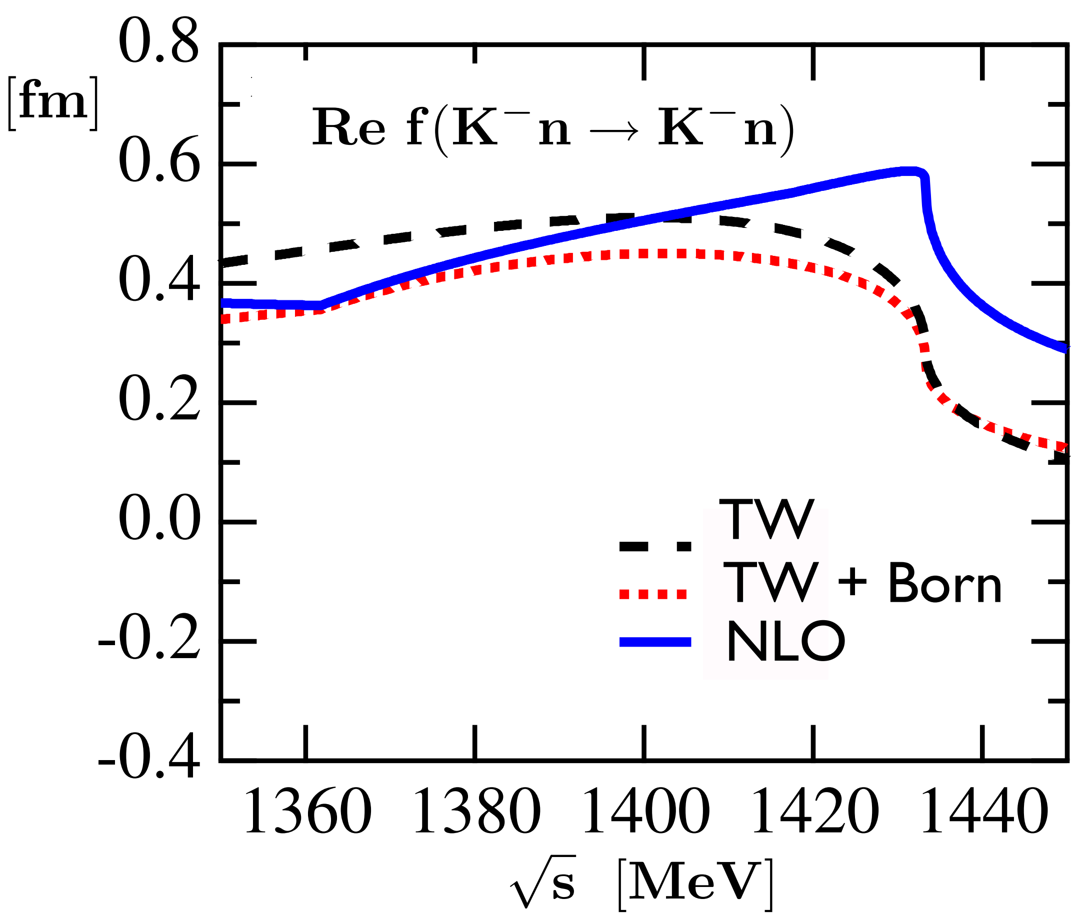
$$\mathrm{Re}\, a(K^- p) = -0.65 \pm 0.10 \quad \mathrm{fm}$$

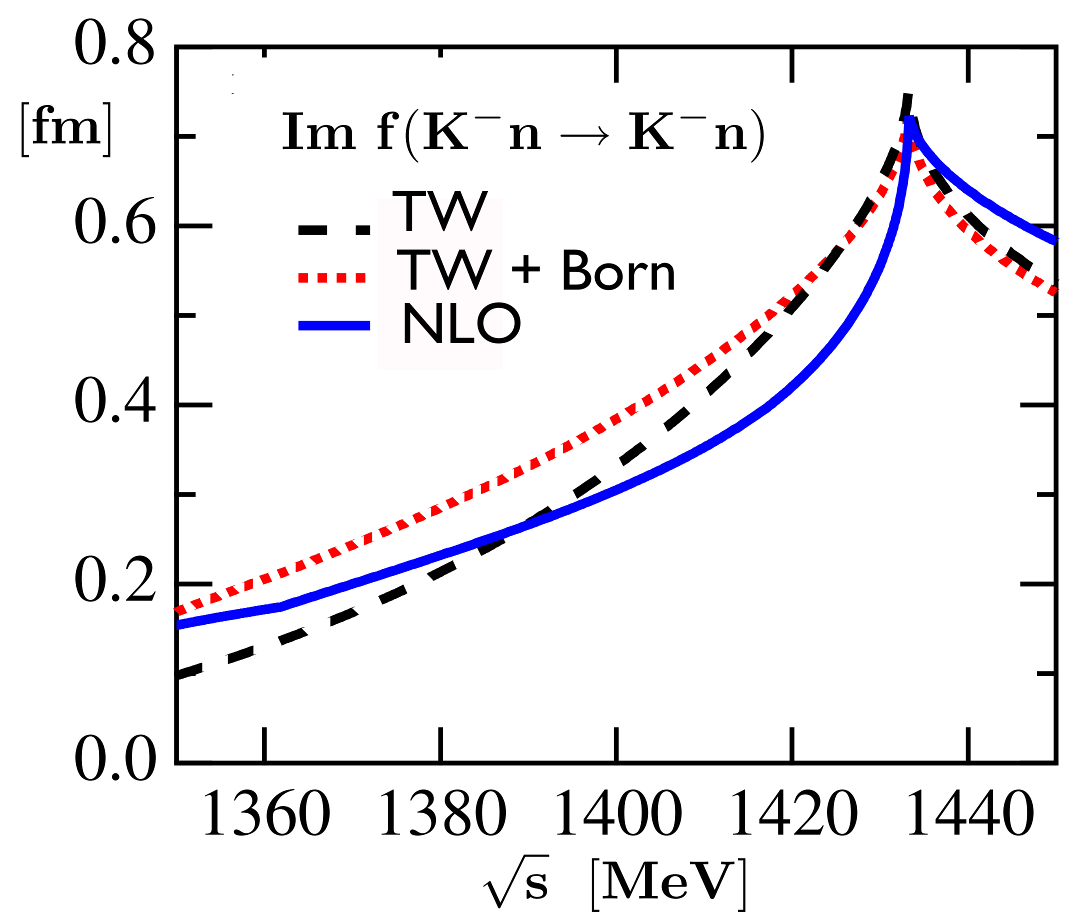
$$\mathrm{Im}\, a(K^- p) = 0.81 \pm 0.15 \quad \mathrm{fm}$$

$\mathbf{K^- n}$ SCATTERING AMPLITUDE

$$\mathbf{f(K^- n) = f_{\bar{K}N}(I = 1)}$$

- threshold region and subthreshold extrapolation





- complex scattering length

$$\mathbf{Re\ a(K^- n) = 0.57^{+0.1}_{-0.2}\ fm}$$

$$\mathbf{Im\ a(K^- n) = 0.72^{+0.3}_{-0.4}\ fm}$$

Y. Ikeda, T. Hyodo, W.W. : Nucl. Phys. A (2012), in print

Implications & Comments

- K^-p scattering length more accurately determined than K^-n (SIDDHARTA constraints vs. uncertainties in $I = 1$ channels)

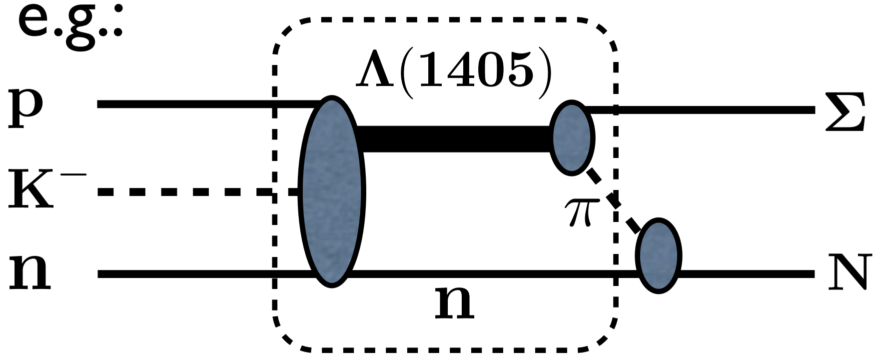
- **Kaonic deuterium** measurements important for providing further constraints on K^-n interaction

- B = 2 systems - key issue:

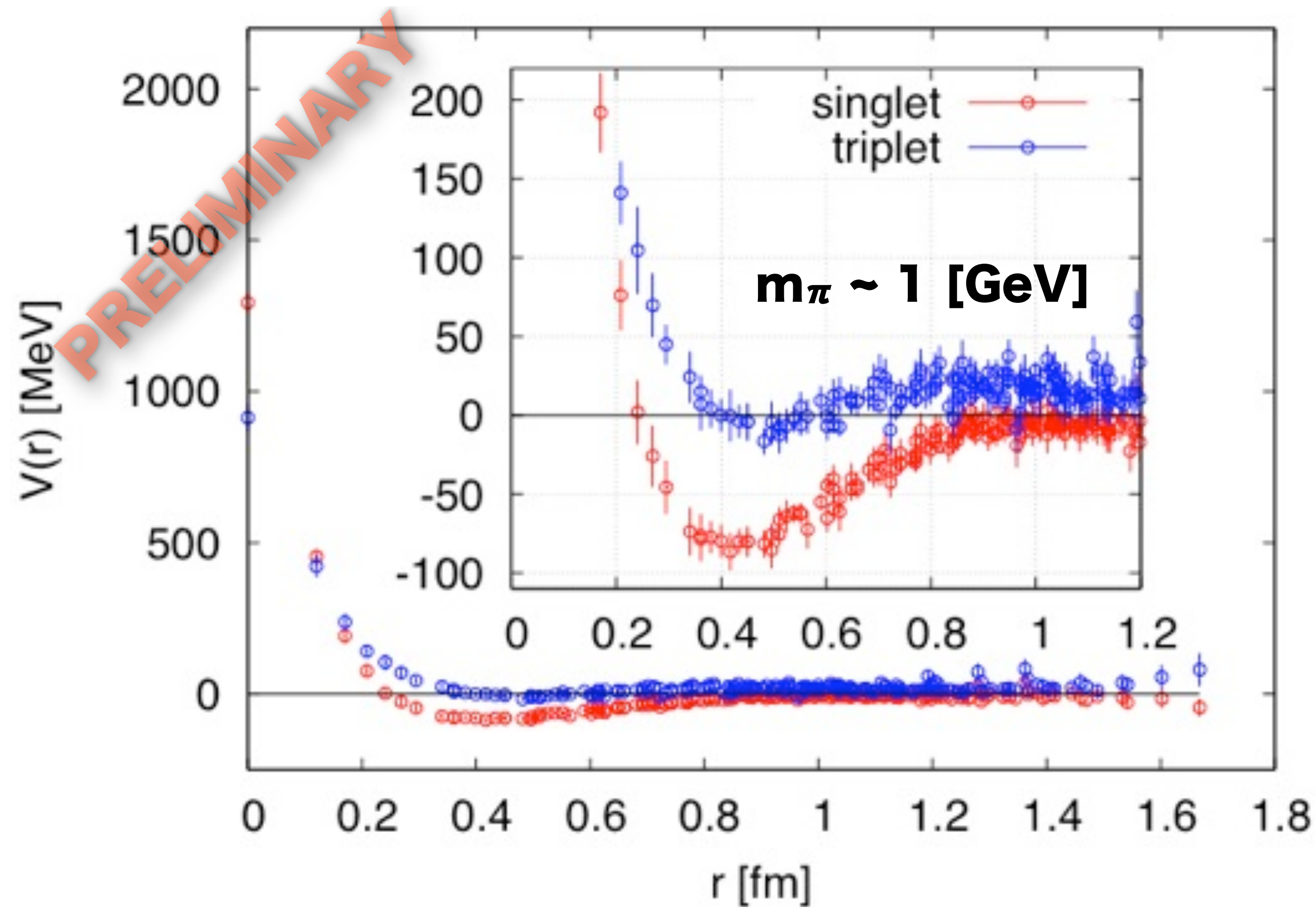
$$\bar{K}NN \rightarrow YN$$

absorption into non-mesonic hyperon - nucleon final states

e.g.:



Repulsive short-distance $\Lambda^*(uds)\,N$ interaction ?



Lattice QCD

Y. Ikeda et al.
(HAL QCD collaboration)

PART 2.

The SIGMA TERM and STRANGENESS in the NUCLEON

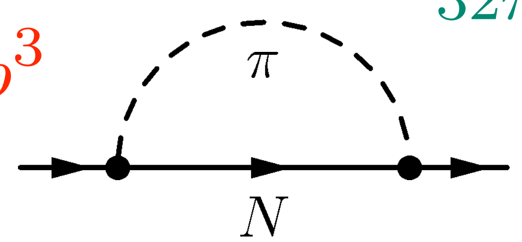
- **Mass** and **scalar density of quarks** in the **nucleon**
- Pion - nucleon **phase shifts** and **sigma term**
- Chiral extrapolations and **Lattice QCD**
- Implications: **chiral condensate** in a **nuclear medium**

MASS of the NUCLEON:
LATTICE QCD + CHIRAL PERTURBATION THEORY

$$\mathbf{M_N} = \langle \mathbf{N} | \frac{\beta(\mathbf{g})}{2\mathbf{g}} \mathbf{Tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) + \sum_{\mathbf{i}} \mathbf{m_i}\, \bar{\mathbf{q}}_\mathbf{i} \mathbf{q}_\mathbf{i} | \mathbf{N} \rangle = \mathbf{M_0} + \Delta \mathbf{M}(\mathbf{m}_\pi)$$

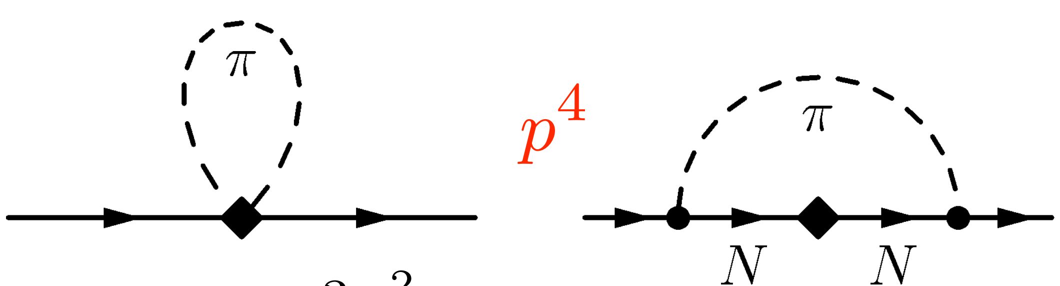
$$M_N = M_0 - 4\, c_1 m_\pi^2 - \frac{3\, g_A^2}{32\pi f_\pi^2}\, m_\pi^3$$

p^3

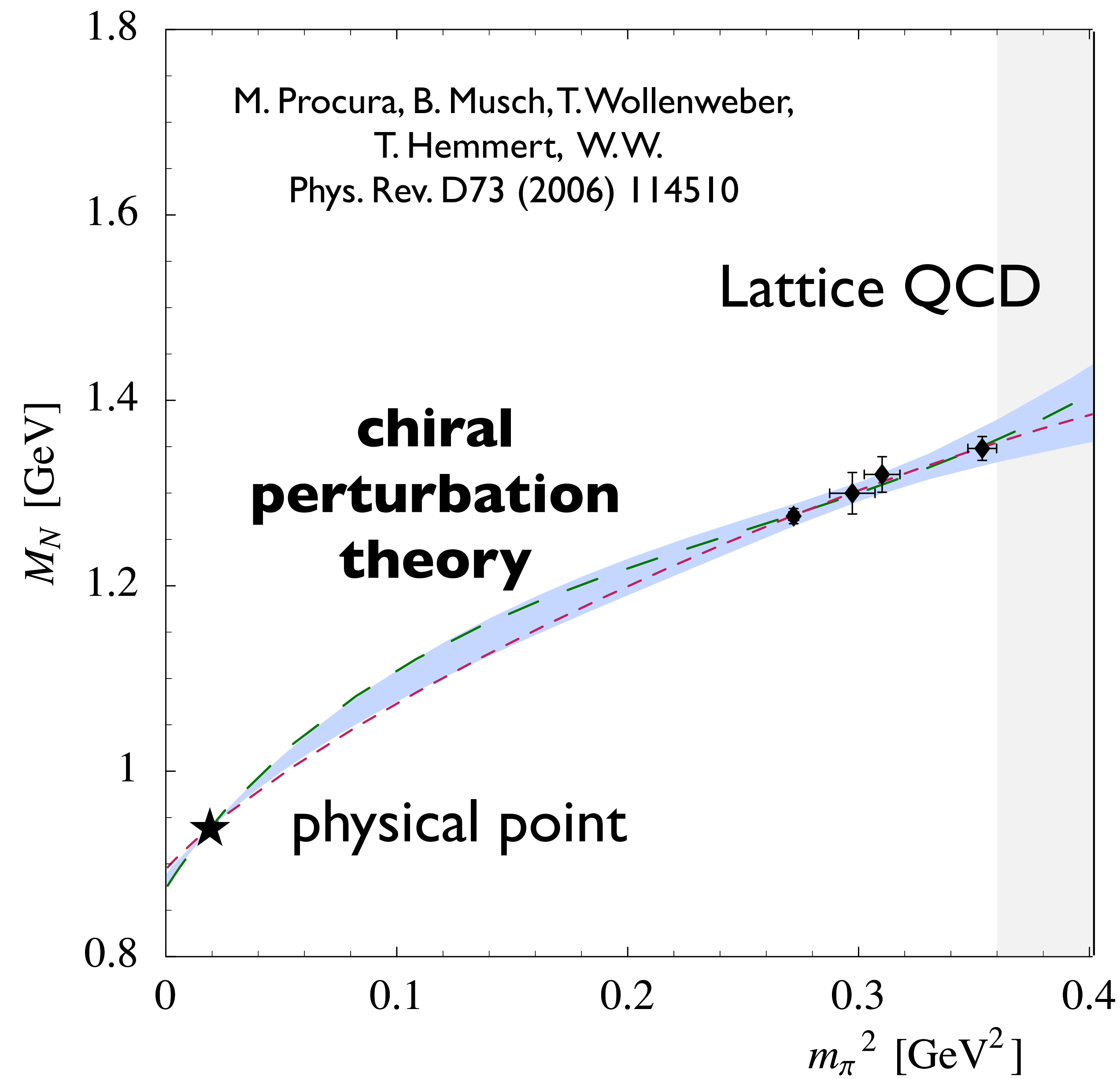


$$+ \left[4\, e_1^r(\lambda) + \frac{3\, c_2}{128\pi^2 f_\pi^2} - \frac{3\, g_A^2}{64\pi^2 f_\pi^2 M_0} - \frac{3}{32\pi^2 f_\pi^2} \left(\frac{g_A^2}{M_0} - 8\, c_1 + c_2 + 4\, c_3 \right) \ln \frac{m_\pi}{\lambda} \right] m_\pi^4$$

p^4

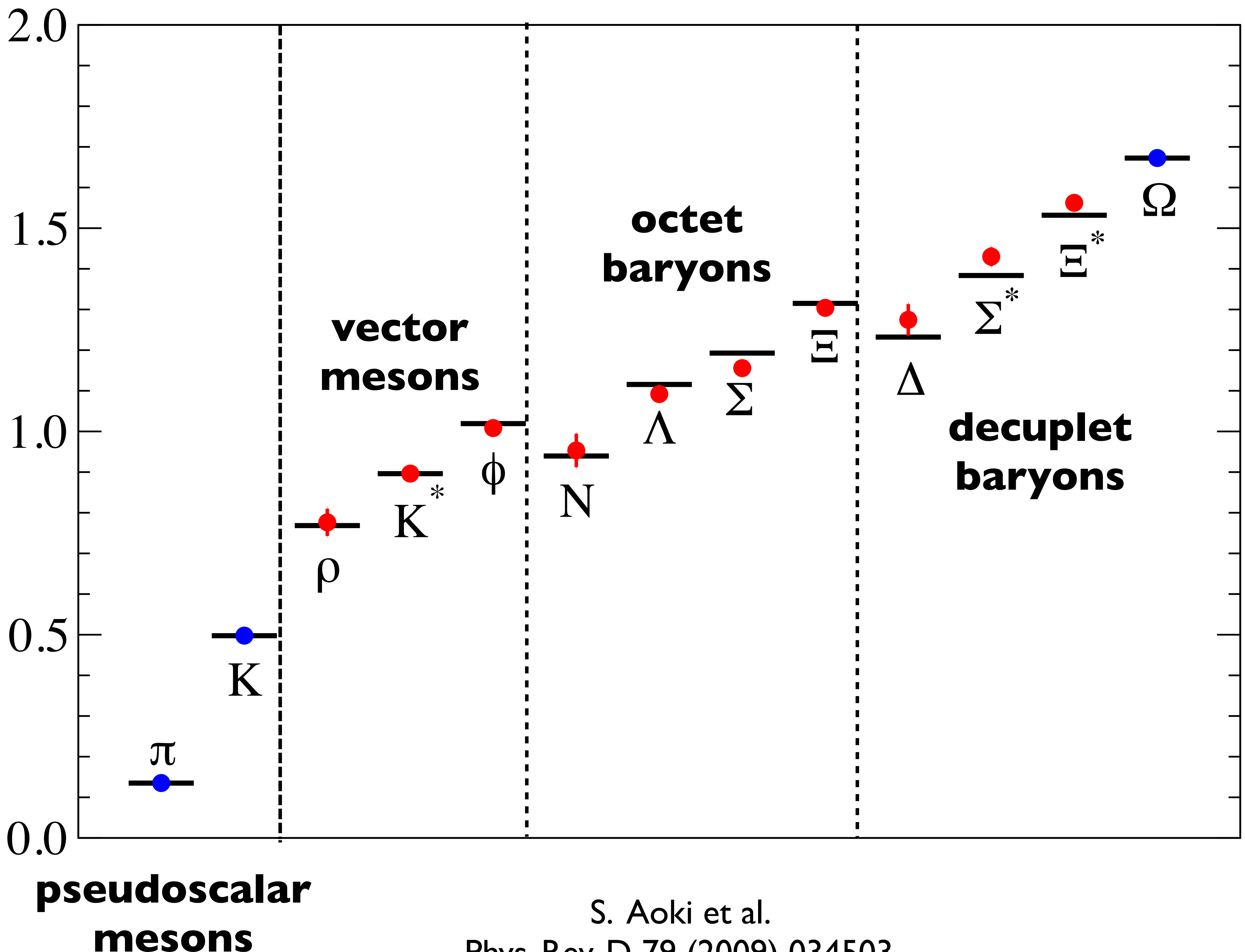


$$+ \frac{3\, g_A^2}{256\pi f_\pi^2 {M_0}^2}\, m_\pi^5 + \mathcal{O}(m_\pi^6)$$



HADRON MASSES from LATTICE QCD

- Full QCD with 2+1 flavors and physical quark masses



S. Aoki et al.
Phys. Rev. D 79 (2009) 034503
Phys. Rev. D 81 (2010) 074503

SIGMA TERMS

- Pion-nucleon **sigma term**:

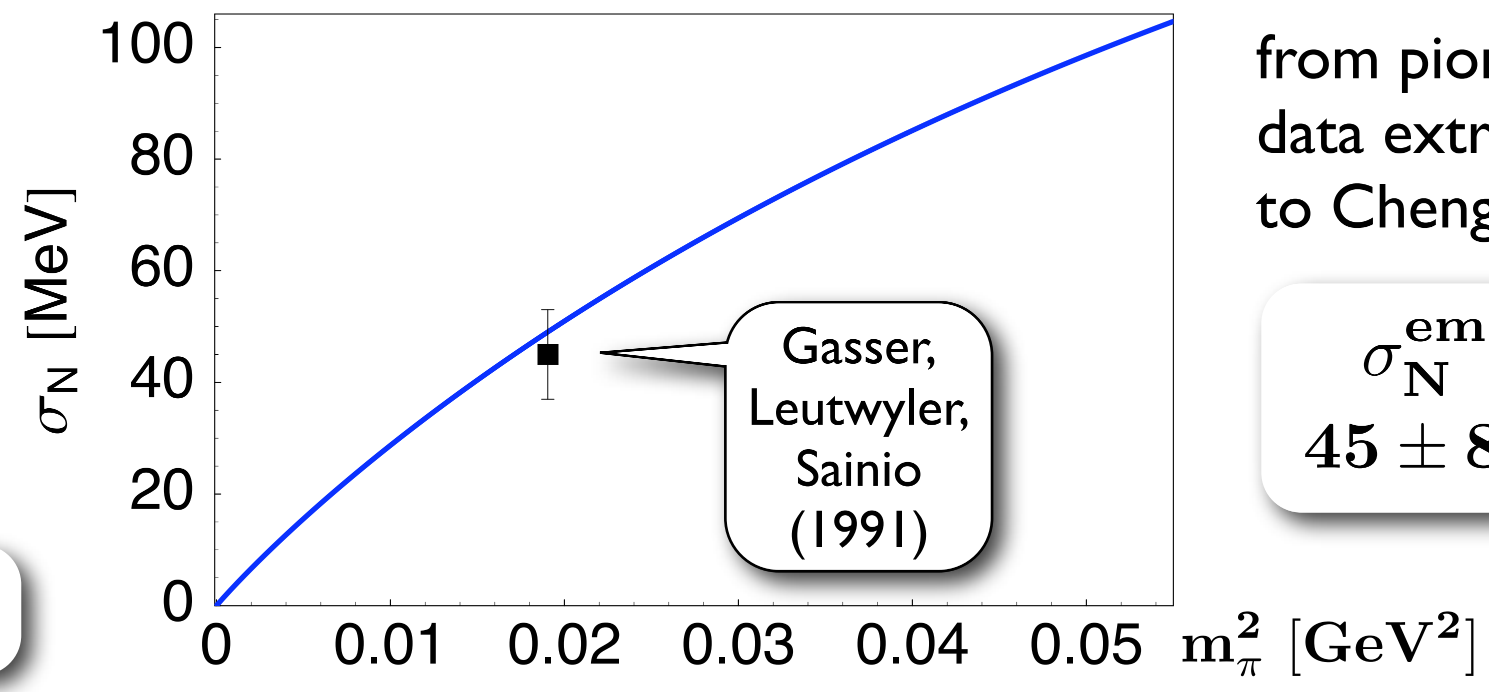
$$\sigma_N = \bar{m}\,\langle N|\bar{u}u + \bar{d}d|N\rangle = \bar{m}\,\frac{\partial M_N}{\partial \bar{m}} \simeq m_\pi^2\,\frac{\partial M_N}{\partial m_\pi^2} \qquad \left(\bar{m} = \frac{m_u + m_d}{2}\right)$$

- Previous status:

from chiral interpolation using older lattice data

M. Procura et al.
Phys. Rev.
D73 (2006) 114510

$$\sigma_N = 49 \pm 6\ \mathrm{MeV}$$



from pion-nucleon data extrapolated to Cheng-Dashen p.

$$\sigma_N^{emp} = 45 \pm 8\ \mathrm{MeV}$$

- **Strangeness content**:

$$\sigma_N = \frac{\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle}{1 - y}$$

$$y = \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle} \simeq 1 - \frac{\bar{m}}{m_s}\,\frac{M_\Xi + M_\Sigma - 2\,M_N}{\sigma_N} \sim 0.2 - 0.3$$

assuming flavour SU(3) symmetry

... but with large uncertainties

B. Borasoy, U.-G. Meißner
Ann. of Phys. 254 (1997) 192

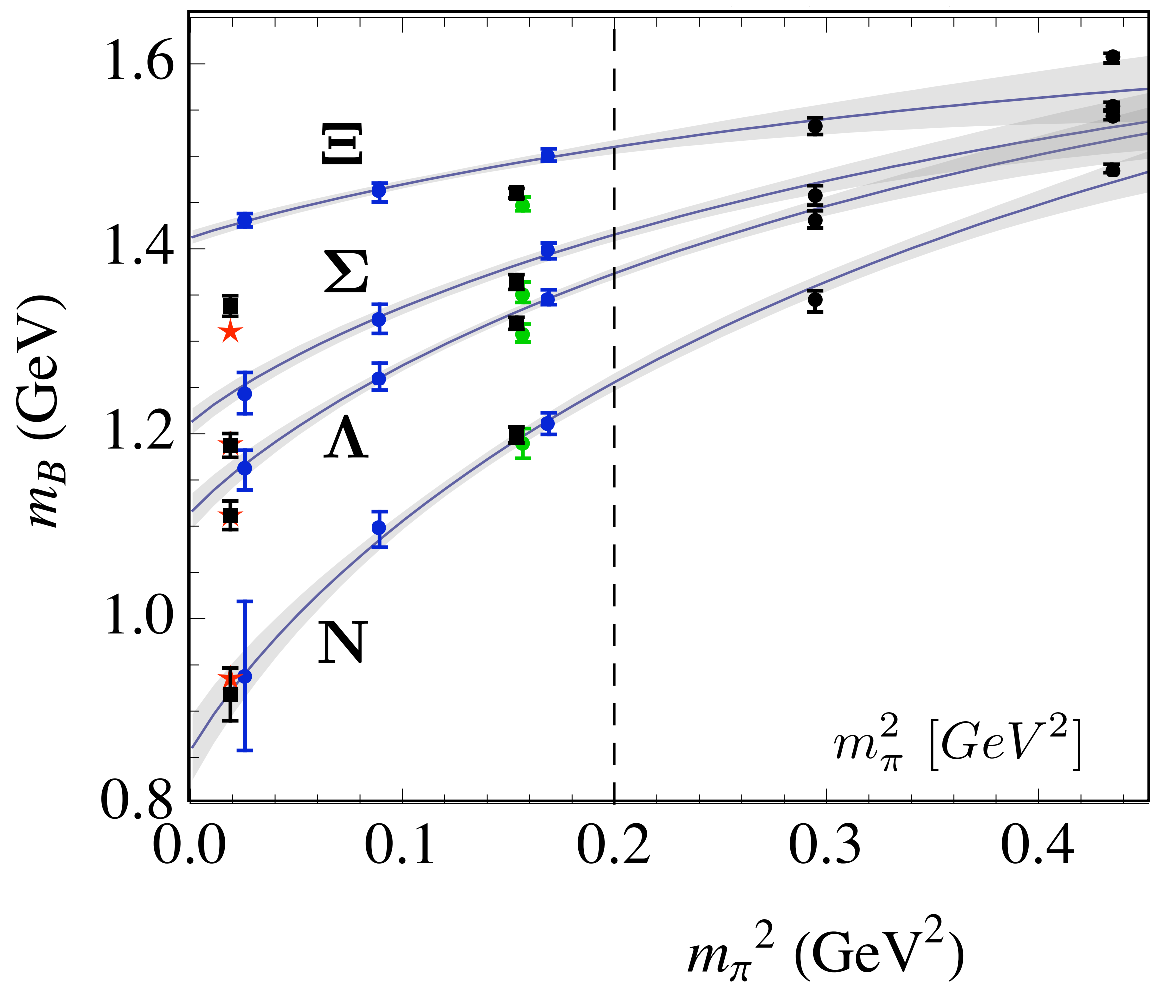
SIGMA TERMS ... more recent

- Combined analysis of baryon octet (and decuplet)

  - $$\sigma_N = 47\,(9)(1)(3)\,\mathrm{MeV}$$
    (statist.) (lattice artifacts) (chiral extrap.)

  - consistent with earlier results and with phenomenology

R.D.Young, A.W.Thomas
Phys. Rev. D81 (2010) 014503



- **Strange quark** contribution

$$\sigma_{Ns} = m_s \langle N|\bar{s}s|N\rangle = m_s \frac{\partial M_N}{\partial m_s}$$

  - $$\sigma_{Ns} = 31\,(15)(4)(2)\,\mathrm{MeV}$$

much smaller than previously expected ! $\quad y \sim (5 \pm 4)\cdot 10^{-2}$

SIGMA TERM … contd.

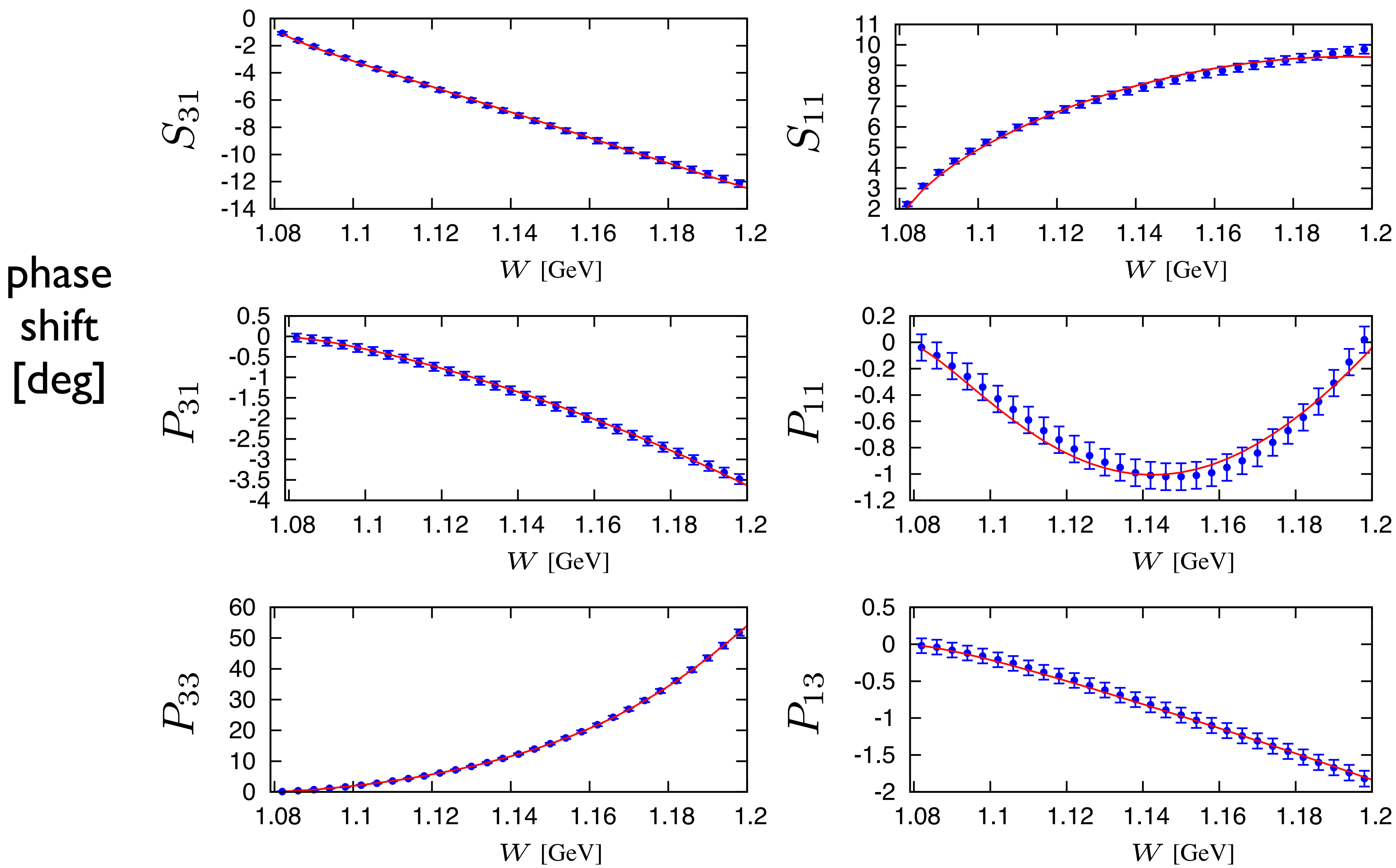
- M. M. Pavan, I. I. Strakovsky, R. L. Workman, R. A. Arndt, PiN Newslett. 16, 110-115 (2002)

  updated pion-nucleon phase shift analysis:

  $\sigma_N = 64 \pm 7$ MeV !

- covariant chiral perturbation theory with explicit $\Delta(1232)$

  J.M. Alarcón, J. Martin Camalich, J.A. Oller; arXiv:1110.3797 [hep-ph]



fix pion-nucleon low-energy constants

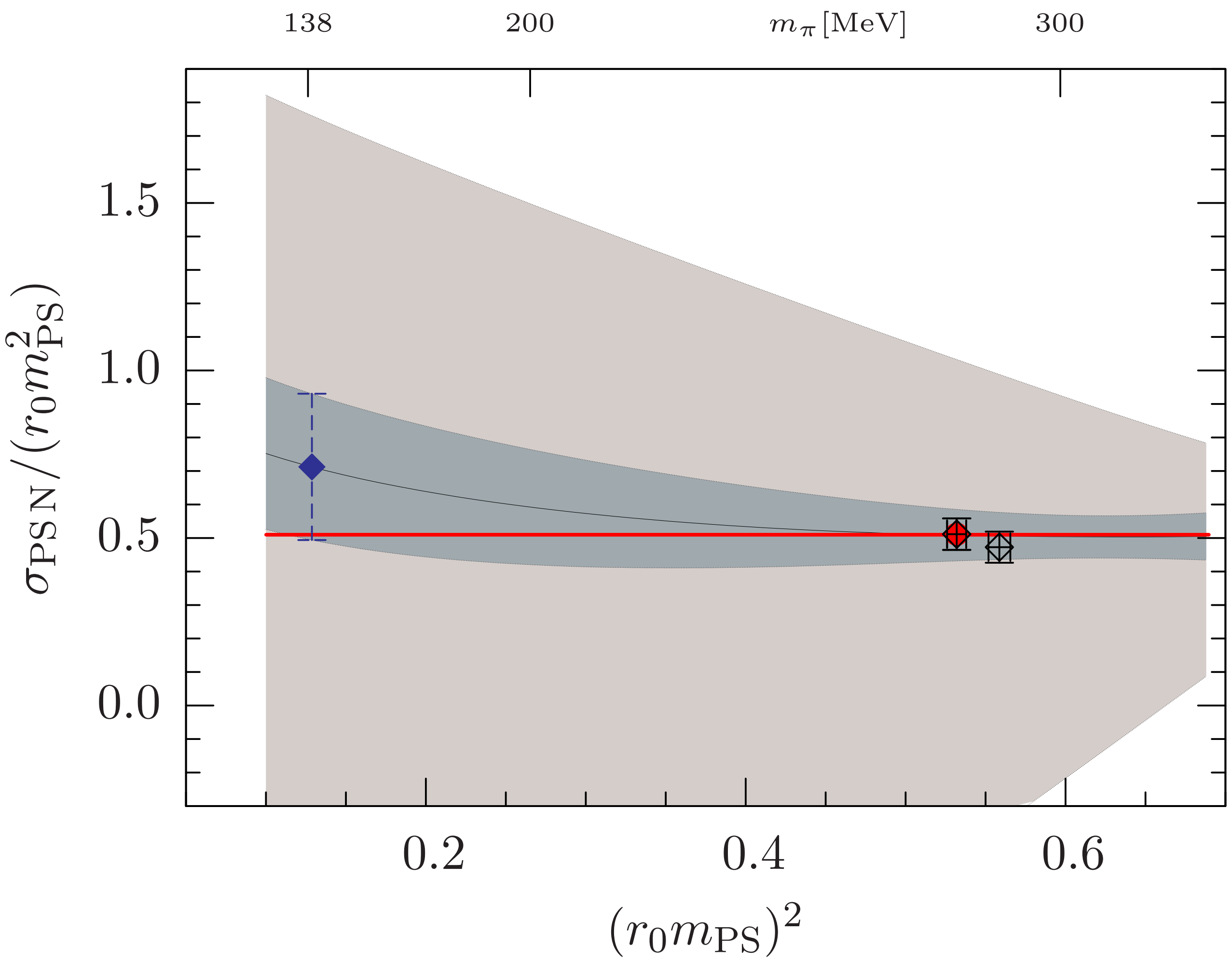
↓

deduce (large) sigma term:

$\sigma_N = 59 \pm 7$ MeV

SIGMA TERM ... contd.

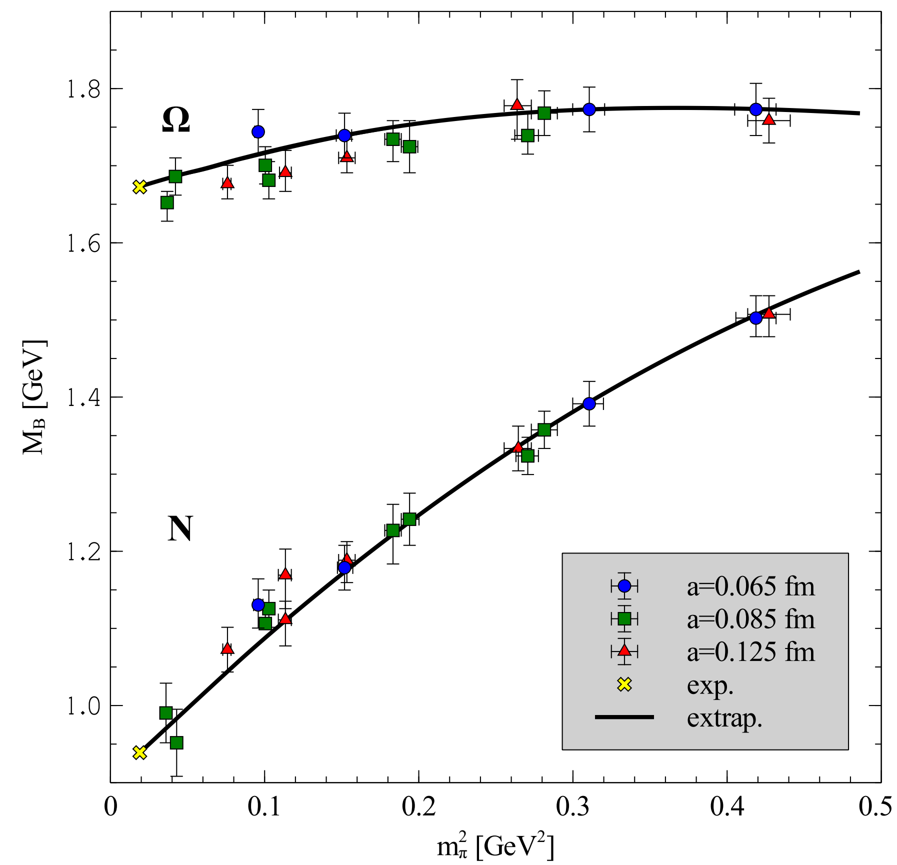
- Update of lattice QCD results and chiral extrapolations



G. Bali et al. (QCDSF) ; arXiv:1110.3797 [hep-ph]

$$\sigma_{\rm N} = 38 \pm 12 \text{ MeV}$$

- Very small scalar strange sea component in the nucleon



lattice QCD

S. Dürr et al. (BMW)
Science 322 (2008) 1224

A. Simke, MFM Lutz ; arXiv:1111.0238 [hep-ph]

- Covariant SU(3) x SU(3) chiral perturbation theory to NNNLO with octet and decuplet baryons

$$\sigma_{\rm N} \sim 40 \text{ MeV}$$

CHIRAL CONDENSATE at finite BARYON DENSITY

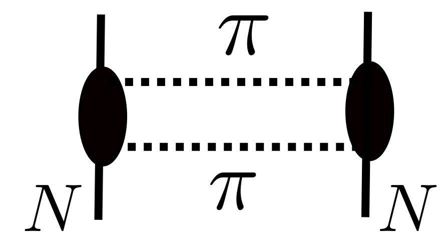
- Chiral (quark) condensate $\langle\bar{q}q\rangle$: $\quad m_\pi^2 f_\pi^2 = -2\, m_q \langle\bar{q}q\rangle$

  Order parameter of spontaneously broken chiral symmetry in QCD

- Hellmann - Feynman theorem: $\langle\Psi|\bar{q}q|\Psi\rangle = \langle\Psi|\frac{\partial \mathcal{H}_{QCD}}{\partial m_q}|\Psi\rangle = \frac{\partial \mathcal{E}(m_q;\rho)}{\partial m_q}$

sigma term $m_q \frac{\partial M_N}{\partial m_q}$

in-medium chiral effective field theory



etc.

$$\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} = 1 - \frac{\rho}{f_\pi^2}\left[\frac{\sigma_N}{m_\pi^2}\left(1 - \frac{3\,p_F^2}{10\,M_N^2} + \ldots\right) + \frac{\partial}{\partial m_\pi^2}\left(\frac{E_{int}(p_F)}{A}\right)\right]$$

(free) Fermi gas of nucleons

nuclear interactions (dependence on pion mass)

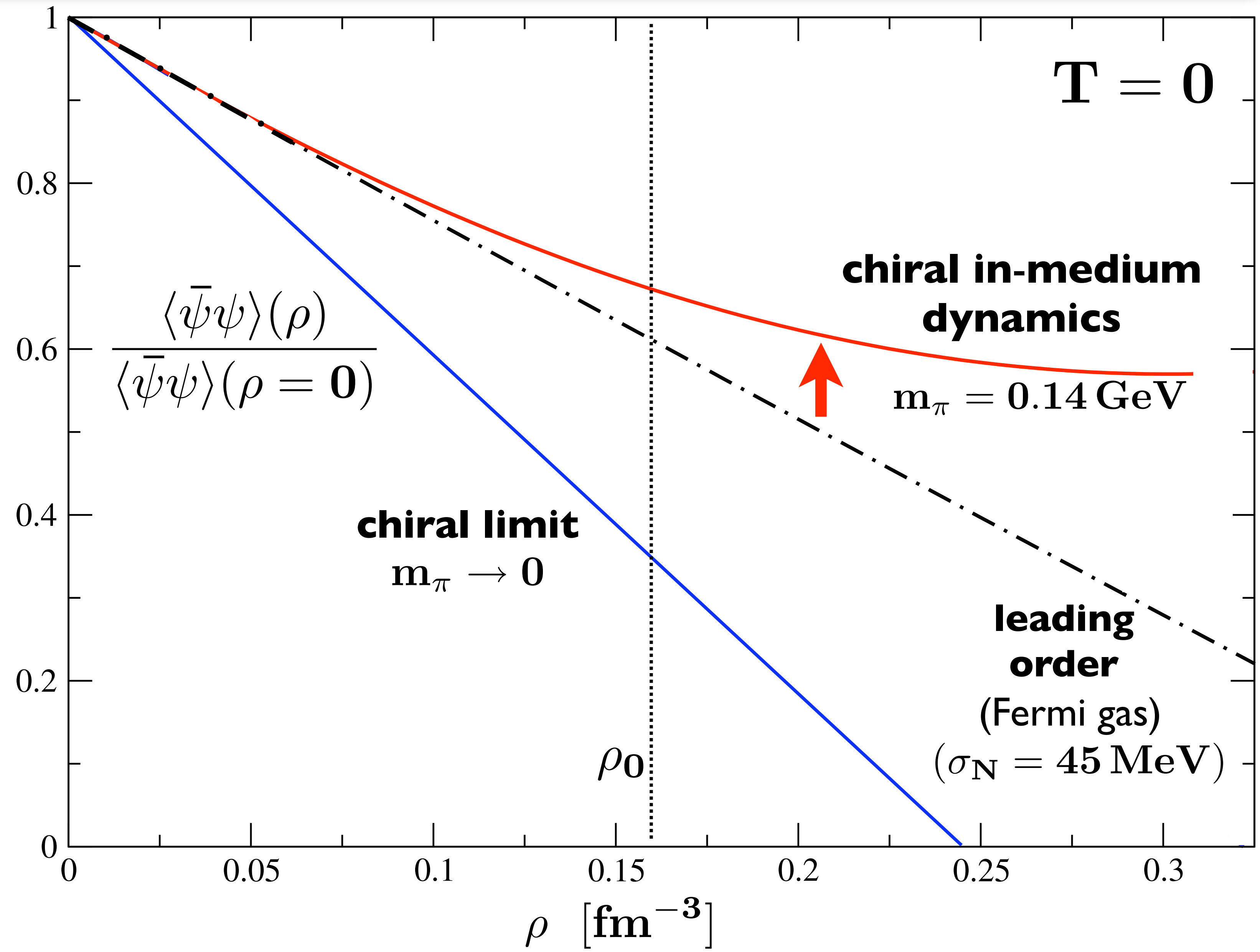
why the **SIGMA TERM** is so important:
DENSITY DEPENDENCE of **CHIRAL CONDENSATE**

- **In-medium Chiral Effective Field Theory**

  (NLO 3-loop)

  constrained by **realistic nuclear equation of state**

  N. Kaiser, Ph. de Homont, W.W.
  Phys. Rev. C 77 (2008) 025204



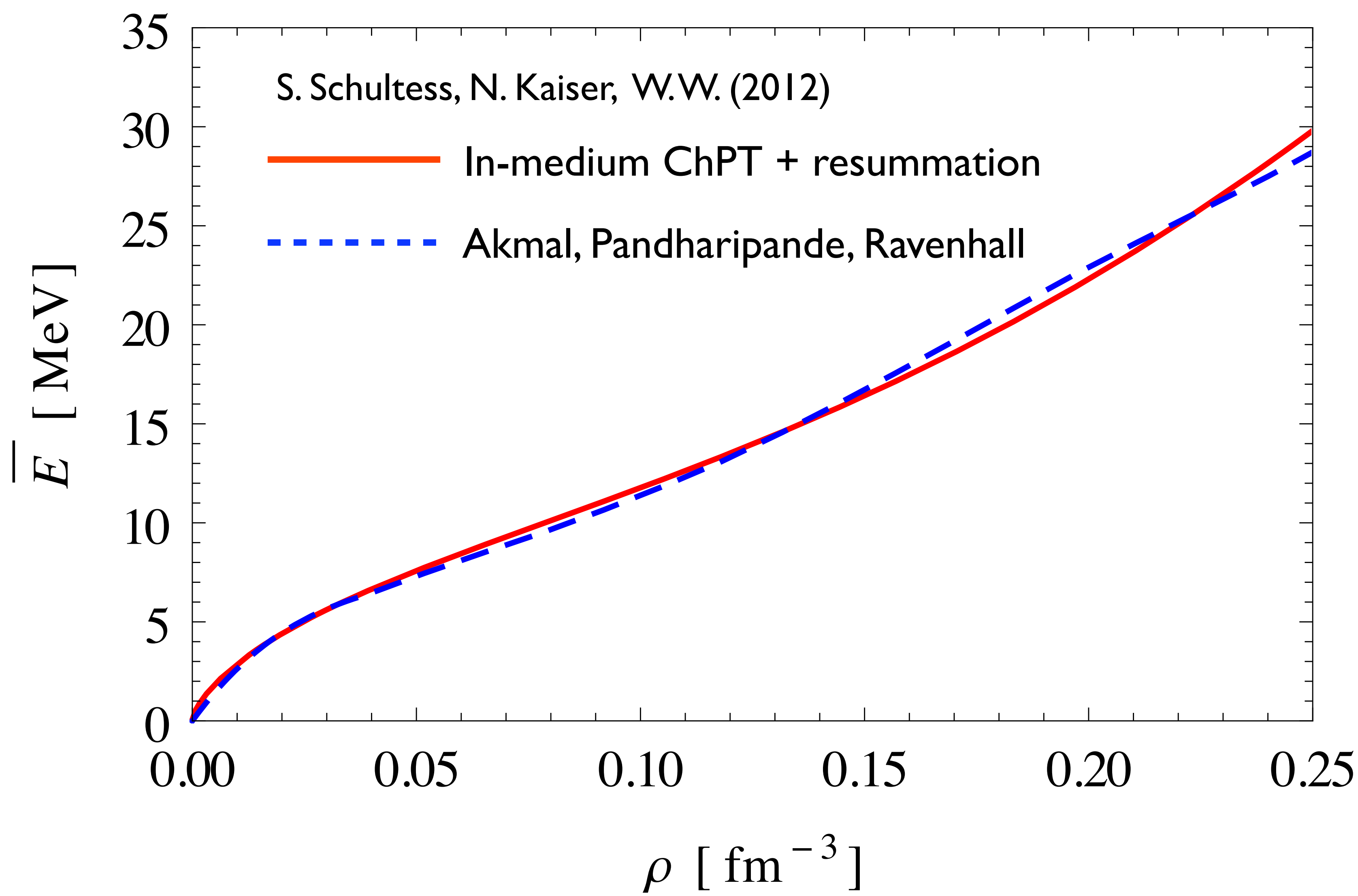
- Substantial **change** of **symmetry breaking scenario** between chiral limit $m_q = 0$ and physical quark mass $m_q \sim 5\,\mathrm{MeV}$

- **Nuclear Physics** would be **very different** in the **chiral limit** !

NEUTRON MATTER

- **In-medium chiral effective field theory** (3-loop) with resummation of short distance contact terms (large nn scattering length, $a_s = 19\ \mathrm{fm}$)

N. Kaiser, Nucl. Phys. A 860 (2011) 370



- perfect agreement with sophisticated many-body calculations

Outlook:

New Constraints

from

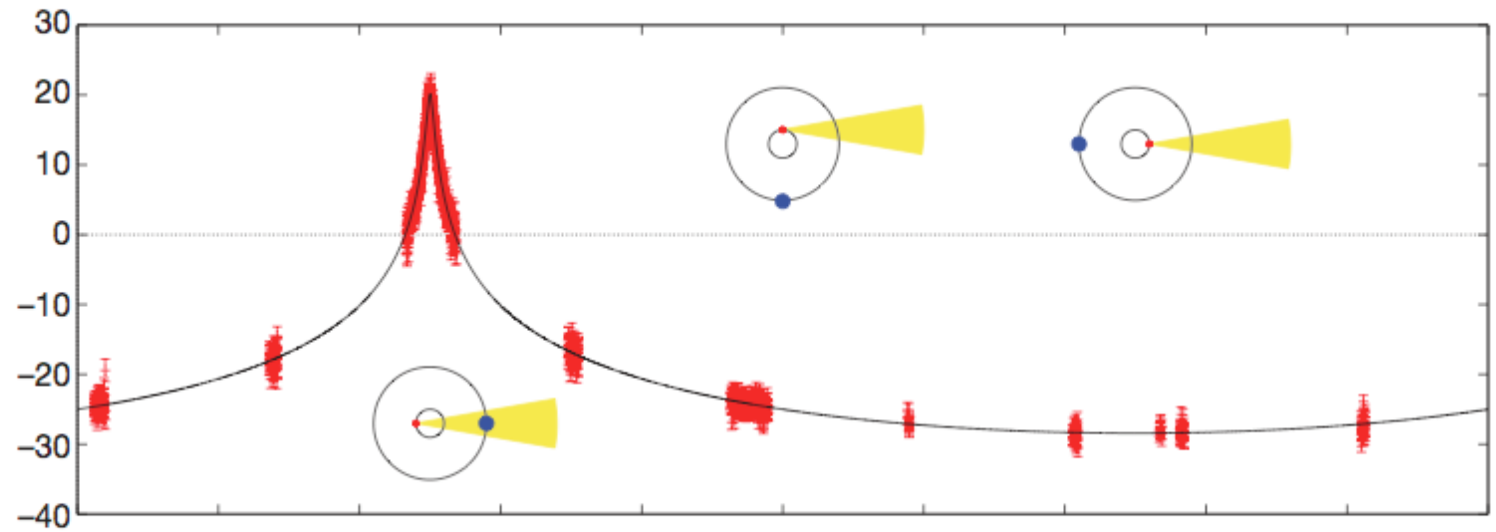
NEUTRON STARS

A two-solar-mass neutron star measured using Shapiro delay

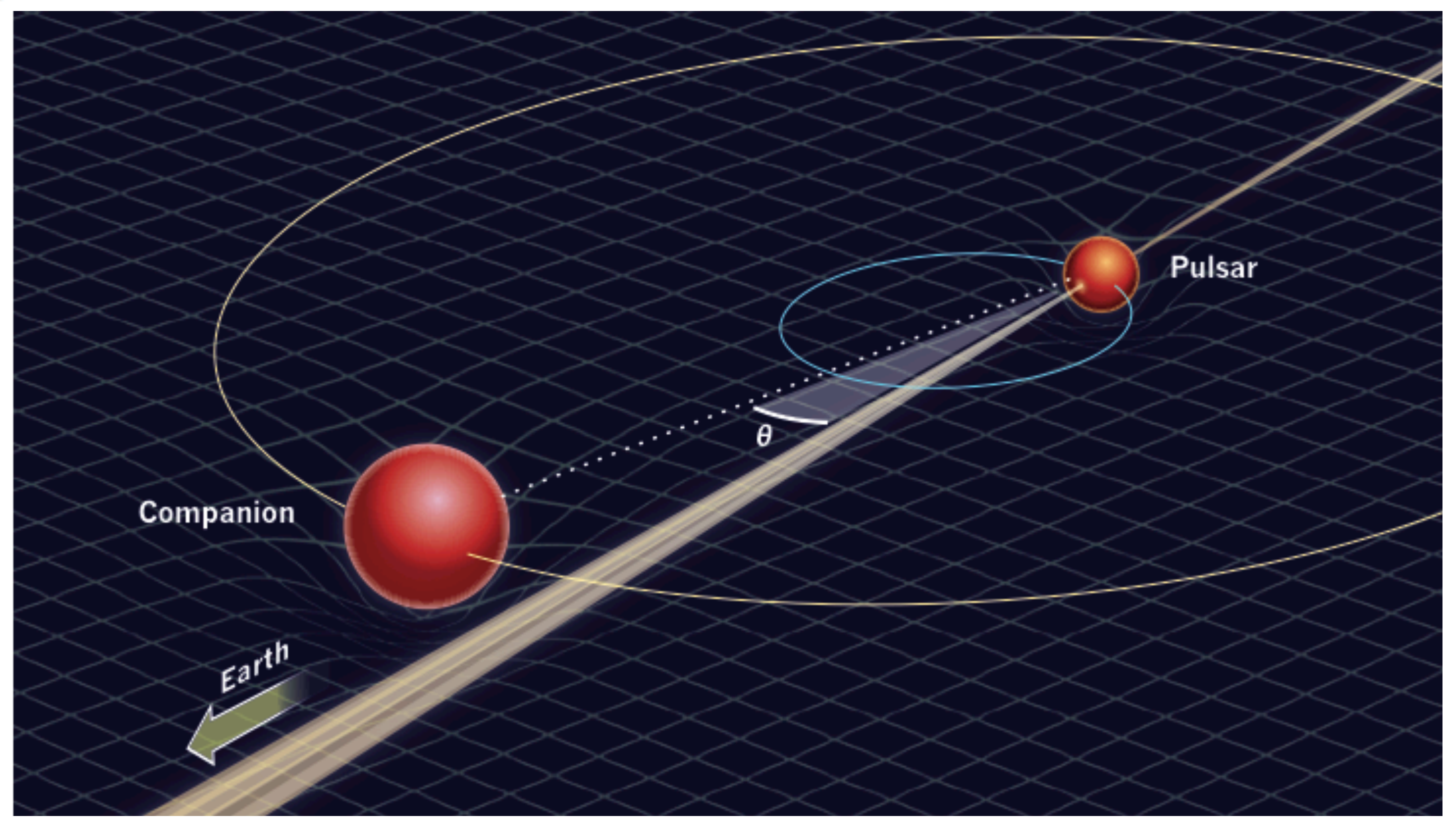
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature, Oct. 28, 2010

direct measurement of neutron star mass from increase in travel time near companion



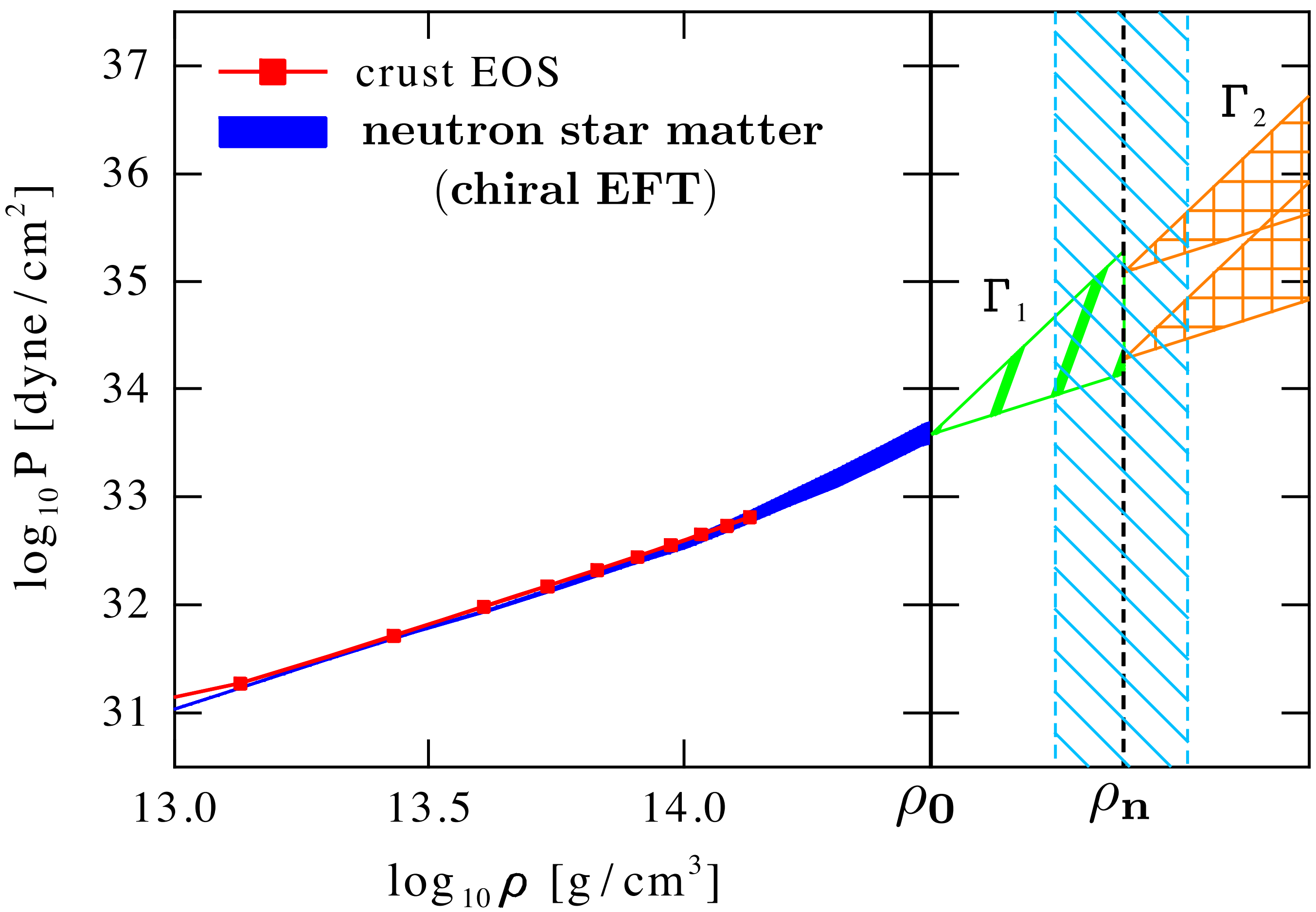
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})



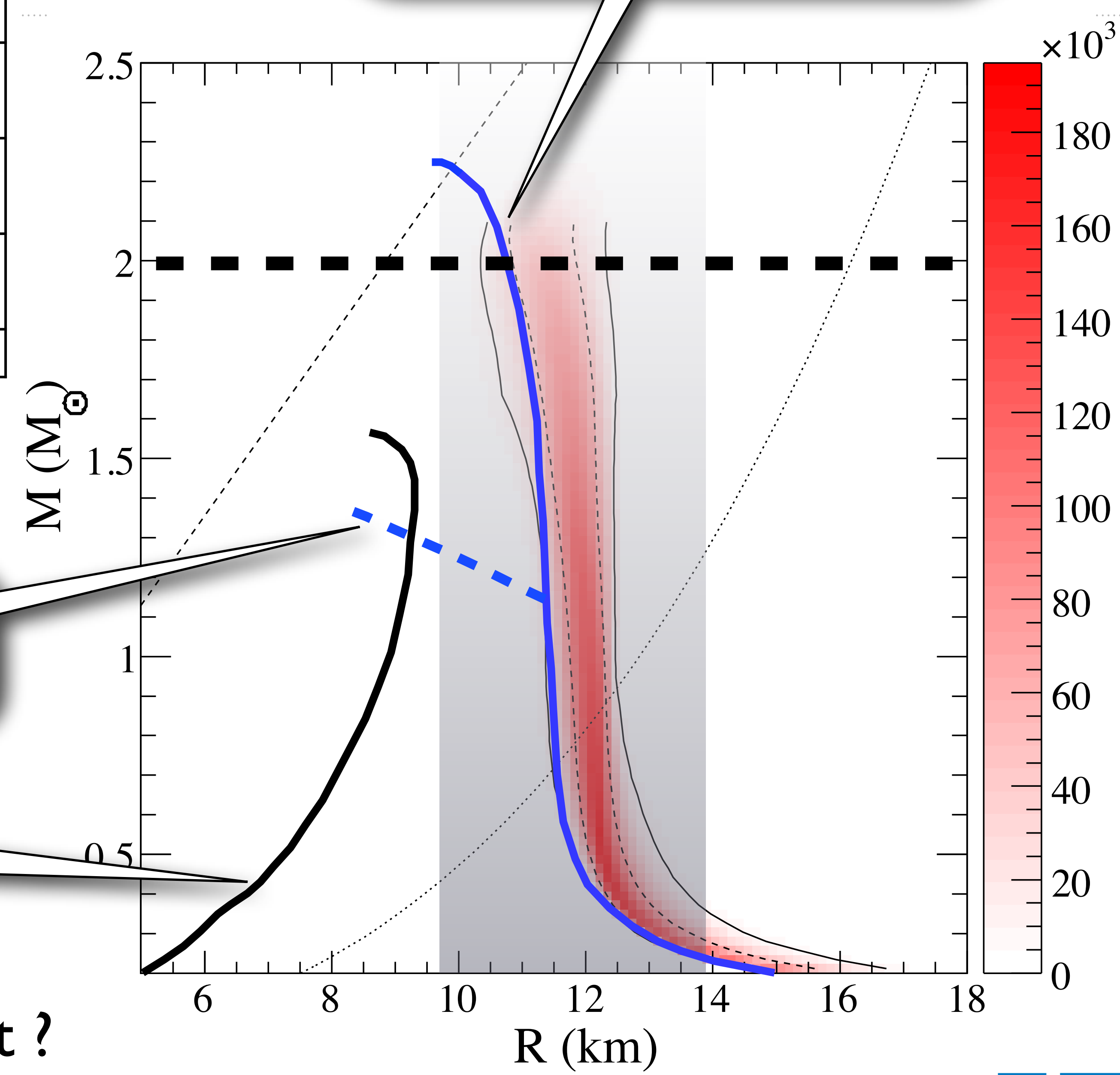
heaviest neutron star with 1.97±0.04 M_{sun}

News from NEUTRON STARS

K. Hebeler, J. Lattimer, C. Pethick, A. Schwenk
PRL 105 (2010) 161102

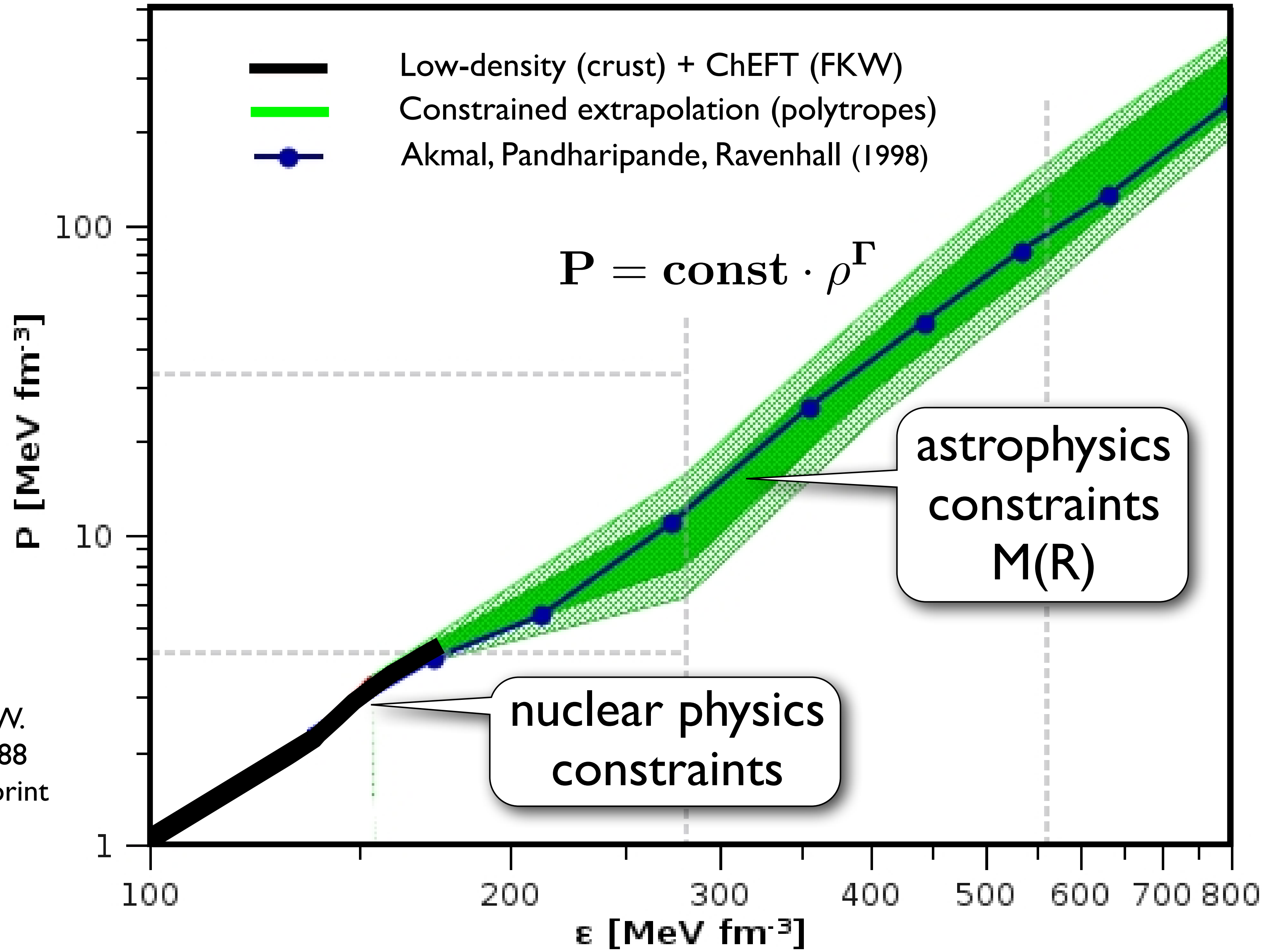


A.W. Steiner, J. Lattimer, E.F. Brown
Astroph. J. 722 (2010) 33



- New constraints from **EFT** and **neutron star observables**
- "**Exotic**" equations of state ruled out ?

NEUTRON STAR MATTER
Equation of State



S. Fiorilla,
N. Kaiser, W.W.
arXiv:1111.3688
NPA (2012) in print

B. Röttgers, W.W.
(2011)

Prog. Part. Nucl. Phys.
(2012) in print

- Including new neutron star constraints plus **C**hiral **E**ffective **F**ield **T**heory at lower density

SUMMARY

- **New**
  consistent analysis of $\bar{\mathrm{K}}\mathrm{N}$ threshold physics and scattering data based on chiral SU(3) effective Lagrangian at next-to-leading order
- **New** evaluation of $\mathrm{K^-p}$ scattering length:

$$\mathbf{a(K^-p) = -0.65 + 0.81\,i \quad [fm]}$$ (~ 15 % accuracy)

deduced: $$\mathbf{a(K^-n) \simeq 0.6 + 0.7\,i \quad [fm]}$$ (less accurate)

- Need kaonic deuterium to complete $\bar{\mathrm{K}}\mathrm{N}$ and set constraints for $\bar{\mathrm{K}}\mathrm{NN}$

- Nucleon **sigma term**:
  Lattice QCD continuously improving towards $\sigma_{\mathbf{N}} \sim \mathbf{40\,MeV}$
  Very small sea of strange quarks in the nucleon

- **New** constraints from two-solar-mass neutron star and window of n-star radii:
  conventional EoS works best - **kaon condensate** ruled out