STATUS of $\bar{\mathrm{K}}\mathrm{N}$ and $\bar{\mathrm{K}}\mathrm{NN}$ INTERACTIONS

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KEYWORDS:

- **LOW-ENERGY QCD** with **STRANGE QUARKS** realized as an **EFFECTIVE FIELD THEORY**: **SU**(**3**) octet of pseudoscalar Nambu-Goldstone bosons coupled to the baryon octet

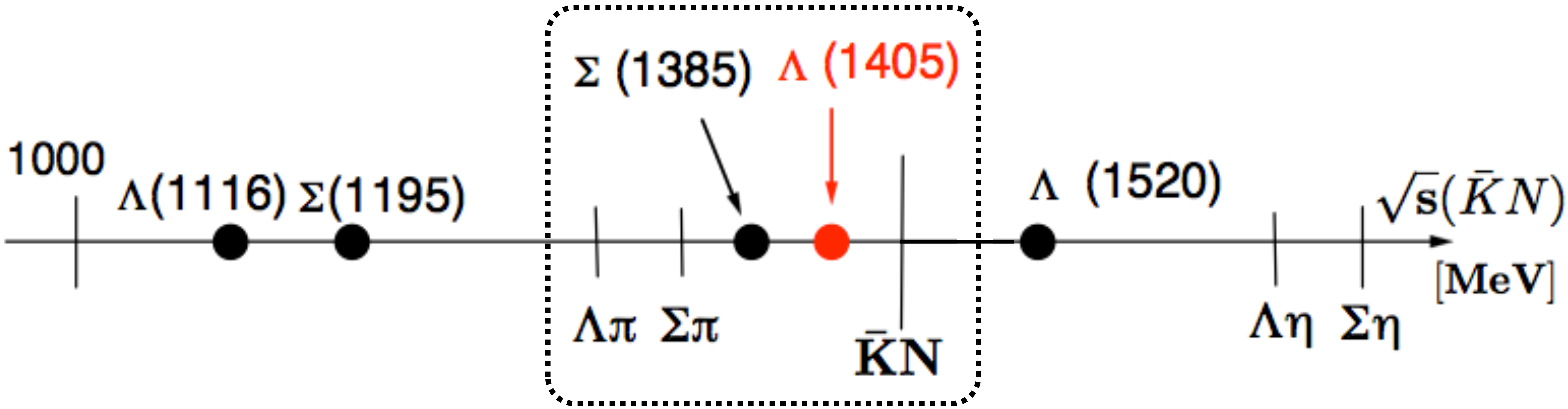
- **Update on $\bar{\mathrm{K}}\mathrm{N}$ and $\bar{\mathrm{K}}\mathrm{NN}$ interactions**
  Scattering lengths, quasibound states, two-poles scenario, ...

BASIC ISSUES

- **Strange quarks** are intermediate between "**light**" and "**heavy**":
  - interplay between **spontaneous** and **explicit chiral symmetry breaking** in low-energy QCD
- Testing ground: high-precision **antikaon-nucleon** threshold physics
  - strongly **attractive** low-energy $\bar{\mathrm{K}}\mathrm{N}$ interaction
- Nature and structure of $\Lambda(1405)$ $(\mathrm{B}=1,\ \ \mathrm{S}=-1,\ \ \mathrm{J}^{\mathrm{P}}=1/2^{-})$
  - **three-quark** valence structure vs. "**molecular**" meson-baryon system ?
- Quest for quasi-bound **antikaon-nuclear** systems ?
- Role of **strangeness** in dense baryonic matter ?
  - new constraints from **neutron stars**

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

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



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

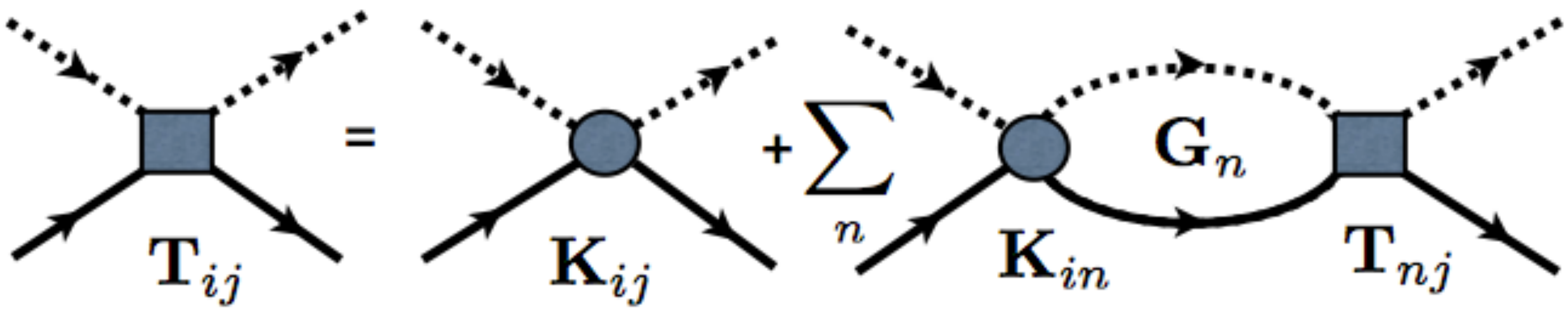
► chiral perturbation theory **NOT** applicable

- Strategy:

Non-perturbative Coupled-Channels Dynamics
based on **Chiral SU(3) Effective Lagrangian**

CHIRAL SU(3) DYNAMICS with COUPLED CHANNELS

Pseudoscalar meson octet
$(\pi, K, \bar{K}, \eta)$



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

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

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

Kernel $\mathbf{K}_{ij}$ from
CHIRAL SU(3) EFFECTIVE MESON-BARYON LAGRANGIAN

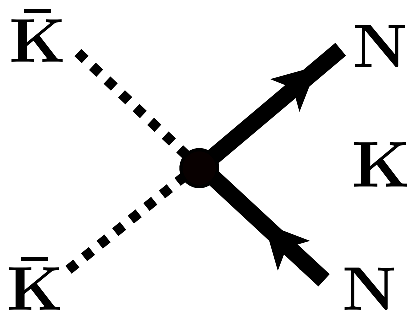
CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

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

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

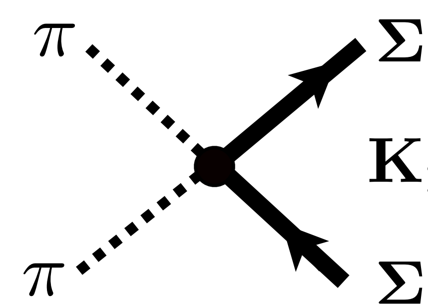
  Note: **ENERGY DEPENDENCE** characteristic of Nambu-Goldstone Bosons

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



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

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



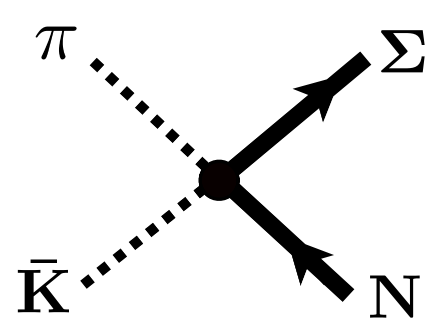
$$\mathbf{K_{22} = \frac{2}{f_\pi^2}(\sqrt{s} - M_\Sigma)}$$

- driving interactions individually **strong** enough to produce

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

$$\mathbf{f_\pi = 92.4 \pm 0.3\ MeV}$$
$$\mathbf{f_K = 110.0 \pm 0.9\ MeV}$$

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

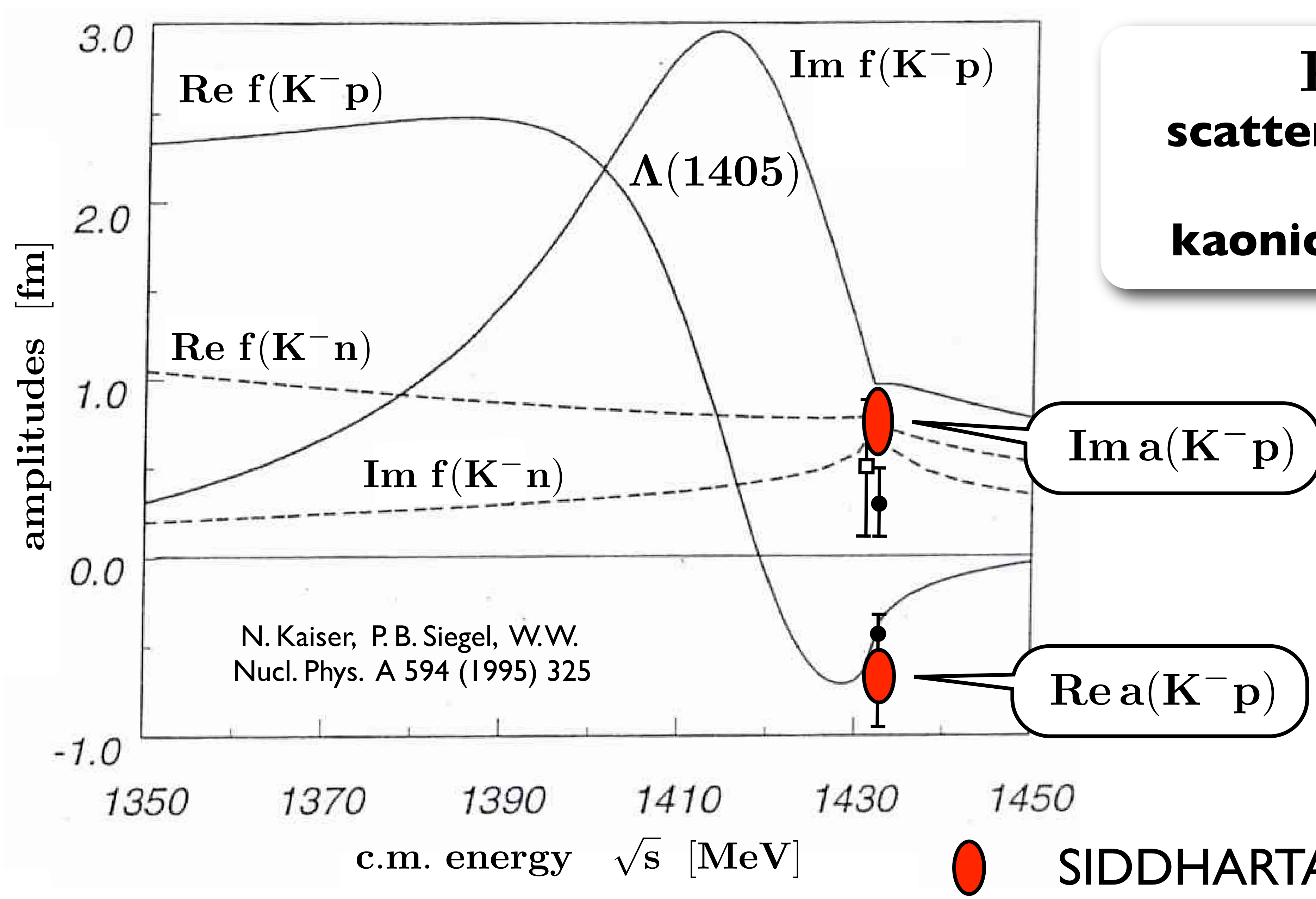


$$\mathbf{K_{12} = \frac{-1}{2\, f_\pi\, f_K}\sqrt{\frac{3}{2}}\left(\sqrt{s} - \frac{M_\Sigma + M_N}{2}\right)}$$

$\bar{K}$ N AMPLITUDES - past and present -

CHIRAL SU(3) EFFECTIVE FIELD THEORY with COUPLED CHANNELS

leading order (Tomozawa - Weinberg) terms



K^-p scattering length from kaonic hydrogen

KEK

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

DEAR @ LNF

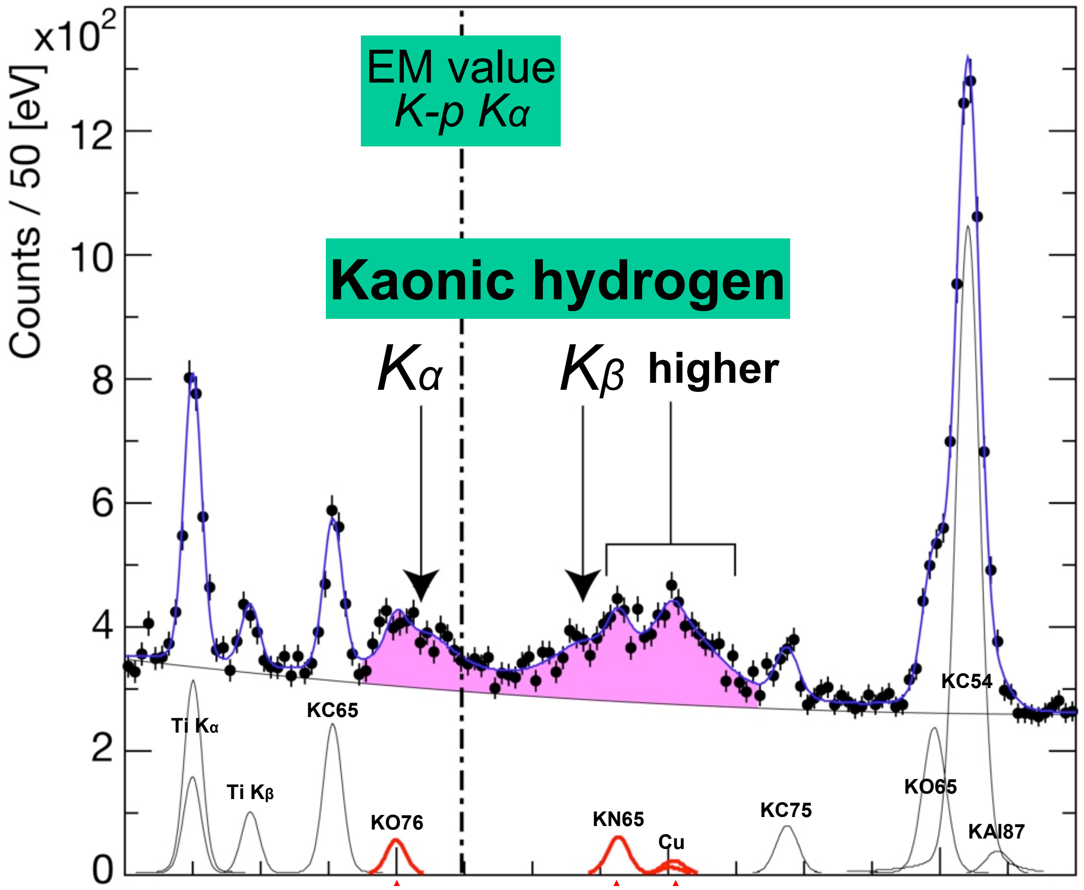
G. Beer et al. Phys. Rev. Lett. 94 (2005) 212302

SIDDHARTA @ LNF

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

NEWS from SIDDHARTA

- **Kaonic hydrogen** precision data



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

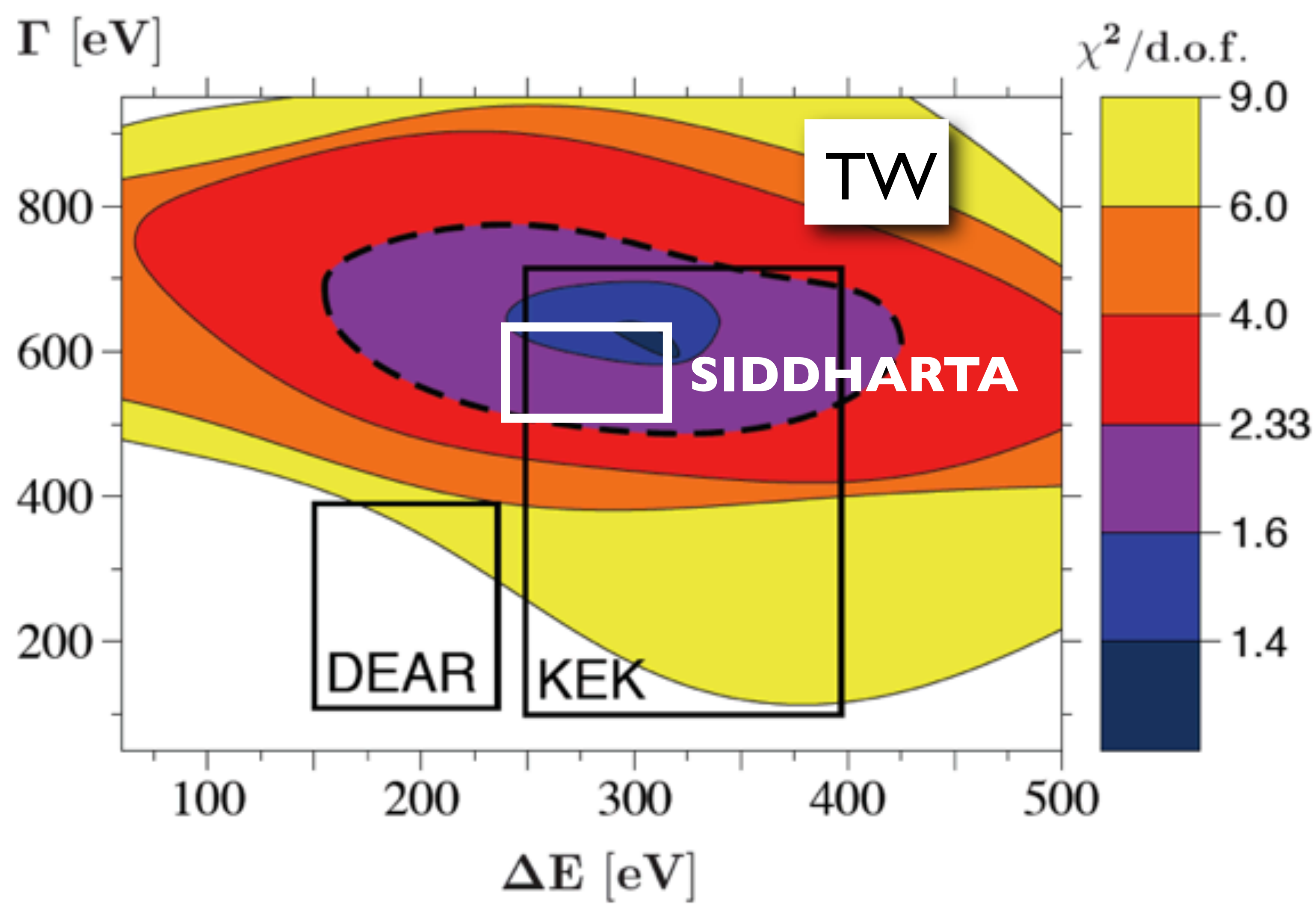
- Theory:
  leading order
  (Tomozawa - Weinberg)

B. Borasoy, R. Nißler, W.W. Eur. Phys. J. A25 (2005) 79
B. Borasoy, U.-G. Meißner, R. Nißler PRC74 (2006) 055201

- strong interaction shift and width:

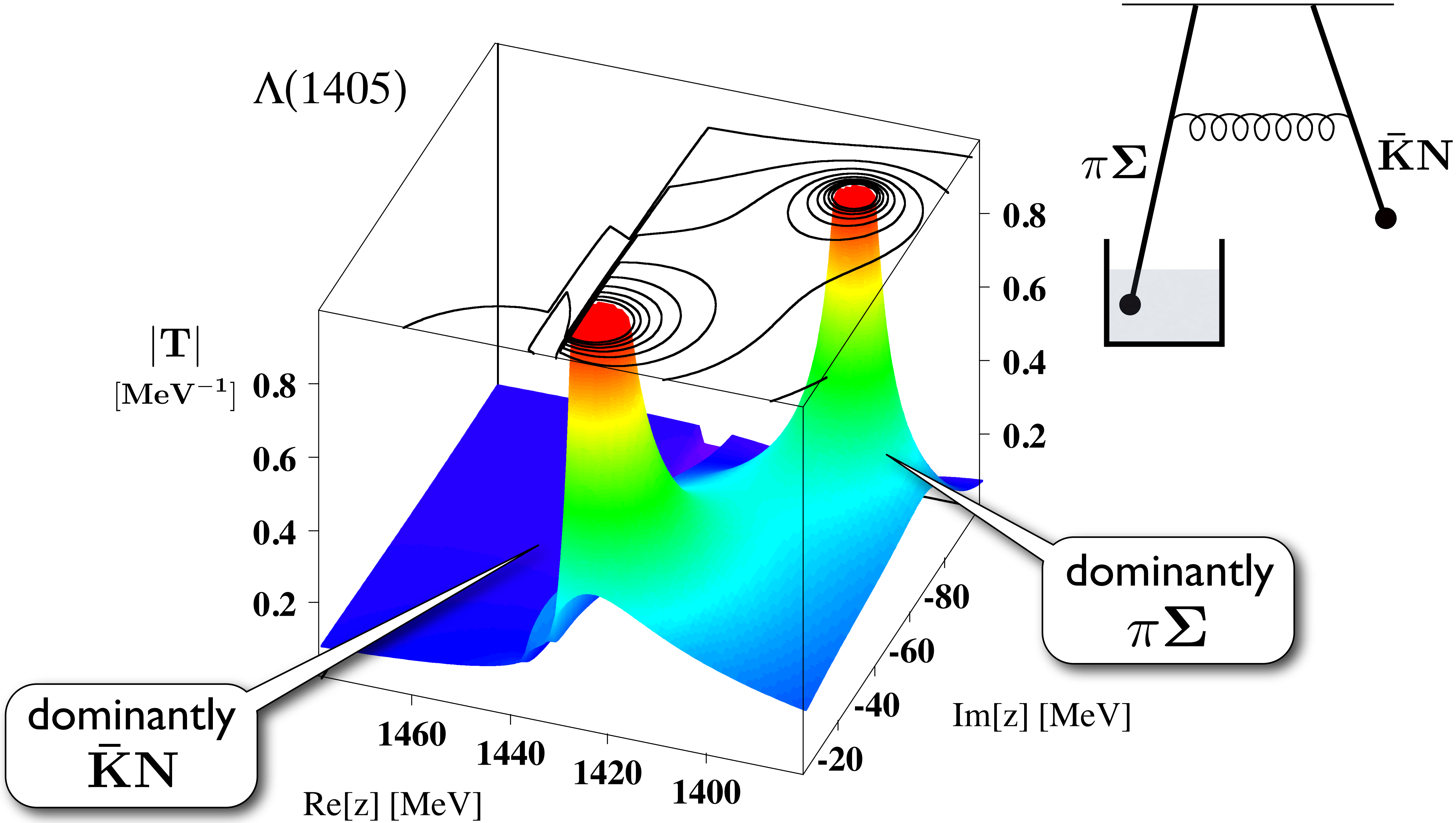
$$\Delta E = 283 \pm 36\,(stat) \pm 6\,(syst)\ \ \mathrm{eV}$$

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



R. Nißler PhD thesis (2008)

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

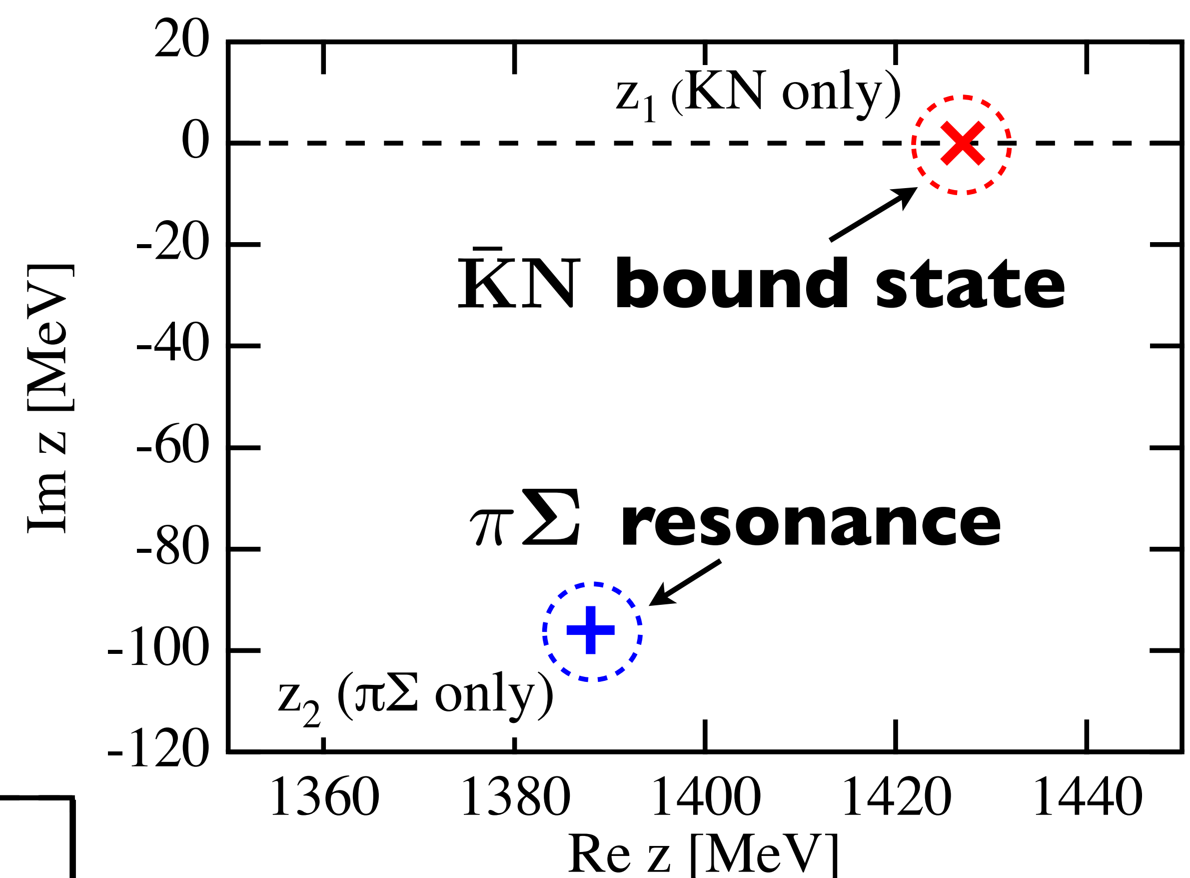
The TWO POLES scenario

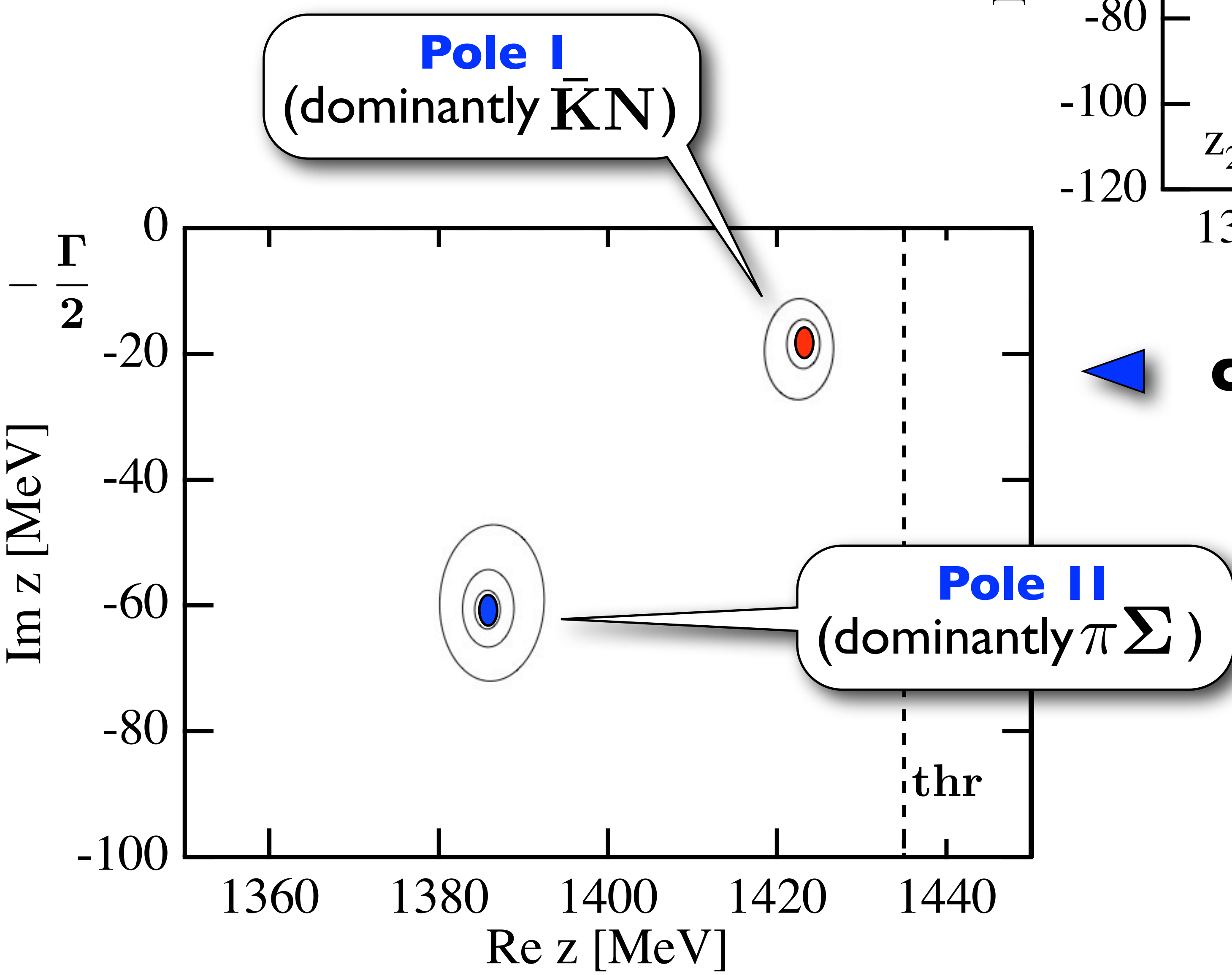
D. Jido et al.
Nucl. Phys. A725 (2003) 181

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

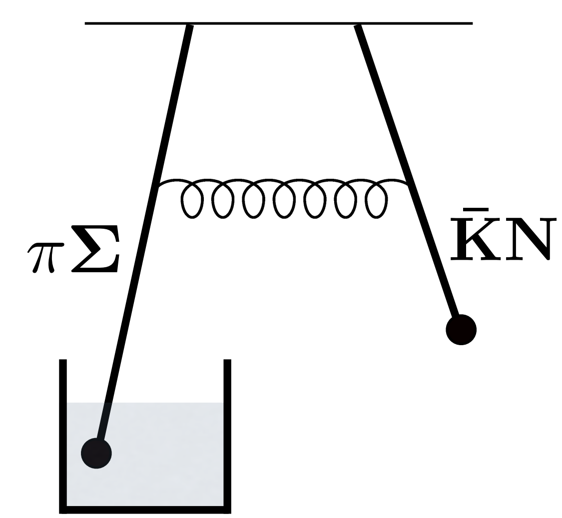
- Singularities of $\bar{K}N$ amplitude in the complex energy plane

starting point:
no channel coupling ▶



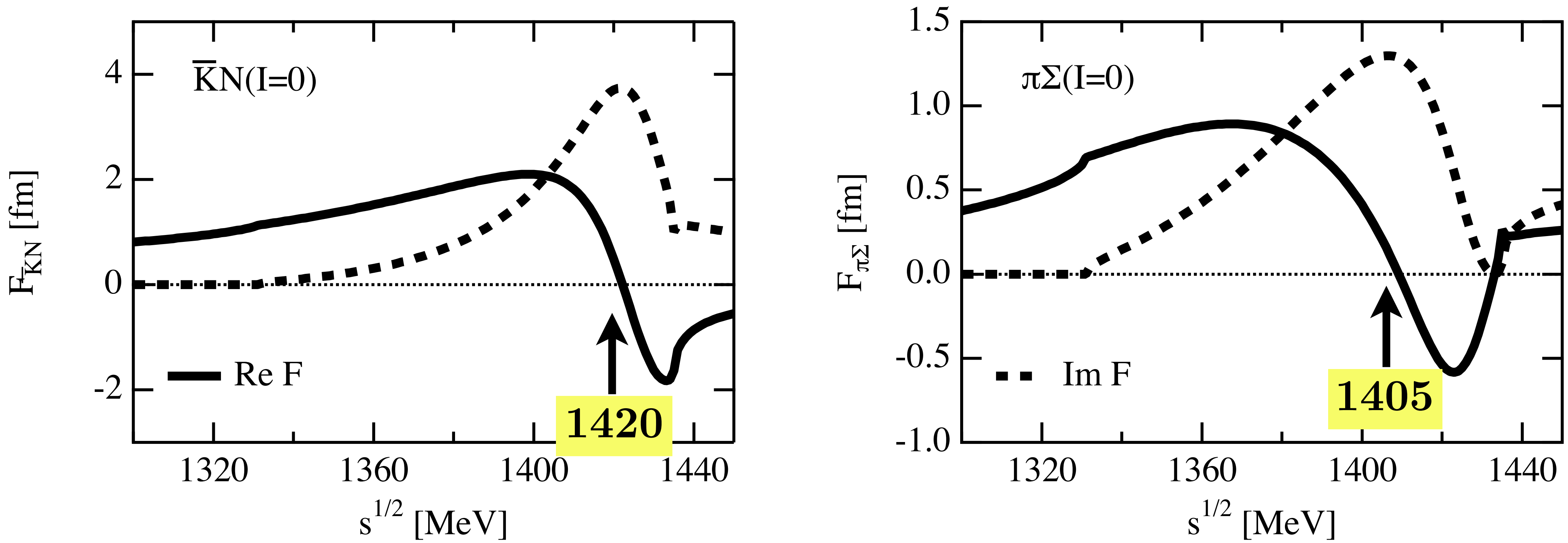


◀ **channel coupling** at work



The TWO POLES scenario (contd.)

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



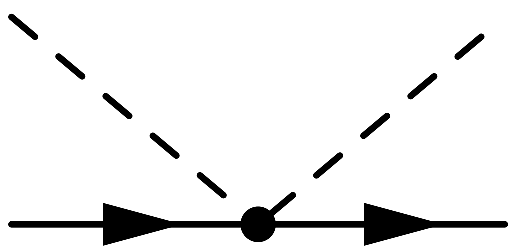
T. Hyodo, W.W.: Phys. Rev. C77 (2008) 03524

- **Note difference** in spectral maxima 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)

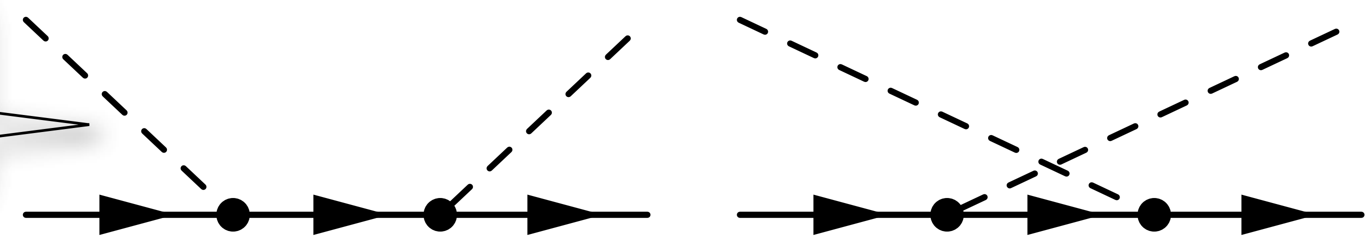
CHIRAL SU(3) COUPLED CHANNELS DYNAMICS:

- NLO hierarchy of driving terms -



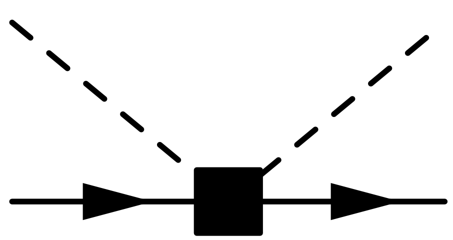
leading order (**W**einberg-**T**omozawa) terms
input: physical pion and kaon decay constants

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



$$g_A = D + F = 1.26$$

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

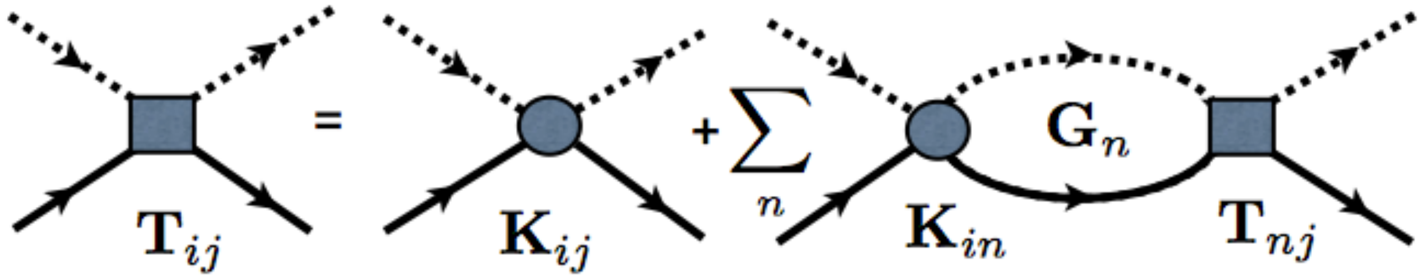


next-to-leading order (**NLO**)
input: 7 s-wave low-energy constants $\mathcal{O}(p^2)$

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

CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

(contd.)



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

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

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

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

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

$$G(q^2) = a(\mu) + \frac{1}{32\pi^2 q^2}\left\{ q^2 \left[\ln\left(\frac{m_\phi^2}{\mu^2}\right) + \ln\left(\frac{M_B^2}{\mu^2}\right) - 2 \right] \right.$$
$$\left. + (m_\phi^2 - M_B^2) \ln\left(\frac{m_\phi^2}{M_B^2}\right) - 8\sqrt{q^2}\,|\mathbf{q}_{cm}|\ \mathrm{artanh}\left(\frac{2\sqrt{q^2}\ |\mathbf{q}_{cm}|}{(m_\phi + M_B)^2 - q^2}\right) \right\}$$

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

Y. Ikeda, T. Hyodo, W.W. Physics Letters B 706 (2011) 63 Nucl. Phys. A 881 (2012) 98

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

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

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

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

UPDATED ANALYSIS of $K^- p$ THRESHOLD PHYSICS with SIDDHARTA constraints

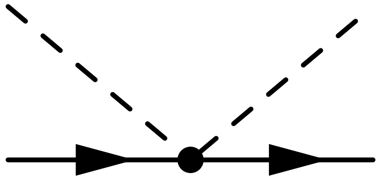
Y. Ikeda, T. Hyodo, W.W. Physics Letters B 706 (2011) 63

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

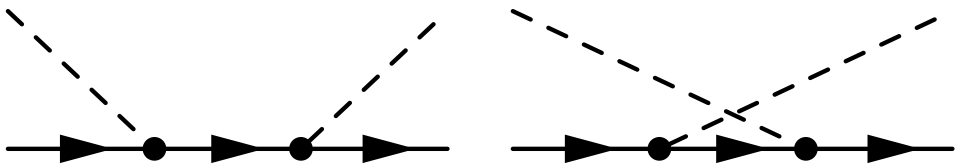
f_K (MeV)	110.0
f_η (MeV)	118.8

$(f_\pi = 92.4\ MeV)$

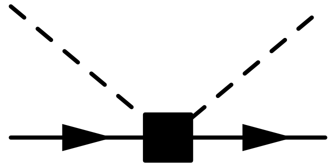
- **Tomozawa-Weinberg** terms **dominant**



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



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



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

	TW	TWB	NLO
$a_{\bar{K}N}$ (10^{-3})	-1.57	-1.04	-2.38
$a_{\pi\Lambda}$ (10^{-3})	-107.97	-8.06	-16.57
$a_{\pi\Sigma}$ (10^{-3})	2.31	2.96	4.35
$a_{\eta\Lambda}$ (10^{-3})	-0.20	-3.46	-0.01
$a_{\eta\Sigma}$ (10^{-3})	216.37	3.52	1.90
$a_{K\Xi}$ (10^{-3})	39.48	12.51	15.83
f_K (MeV)	110.8	109.0	110.0
f_η (MeV)	124.5	124.6	118.8
$\bar{b}_0$ $(10^{-2}$ GeV$^{-1})$	–	–	-4.79
$\bar{b}_D$ $(10^{-2}$ GeV$^{-1})$	–	–	0.48
$\bar{b}_F$ $(10^{-2}$ GeV$^{-1})$	–	–	4.01
d_1 $(10^{-2}$ GeV$^{-1})$	–	–	8.65
d_2 $(10^{-2}$ GeV$^{-1})$	–	–	-10.62
d_3 $(10^{-2}$ GeV$^{-1})$	–	–	9.22
d_4 $(10^{-2}$ GeV$^{-1})$	–	–	6.40
χ^2/d.o.f.	1.12	1.15	0.96

Table 2: Parameters resulting from the systematic χ^2 analysis, using leading order (TW) plus Born terms (TWB) and full NLO schemes. Shown are the isospin symmetric subtraction constants $a_i(\mu)$ at $\mu = 1$ GeV, the meson decay constants f_K and f_η, the renormalized NLO constants $\bar{b}_i$ and d_i, and χ^2/d.o.f. of the fit.

- Consistent LO → NLO hierarchy

	TW	TWB	NLO
ΔE [eV]	373	377	306
Γ [eV]	495	514	591
γ	2.36	2.36	2.37
R_n	0.20	0.19	0.19
R_c	0.66	0.66	0.66
pole positions [MeV]	$1422 - 16\,i$ $1384 - 90\,i$	$1421 - 17\,i$ $1385 - 105\,i$	$1424 - 26\,i$ $1381 - 81\,i$

Table 3: Results of the systematic χ^2 analysis using leading order (TW) plus Born terms (TWB) and full NLO schemes. Shown are the energy shift and width of the 1s state of kaonic hydrogen (ΔE and Γ), threshold branching ratios (γ, R_n and R_c), and the pole positions of the isospin $I = 0$ amplitude in the $\bar{K}N$-$\pi\Sigma$ domain.

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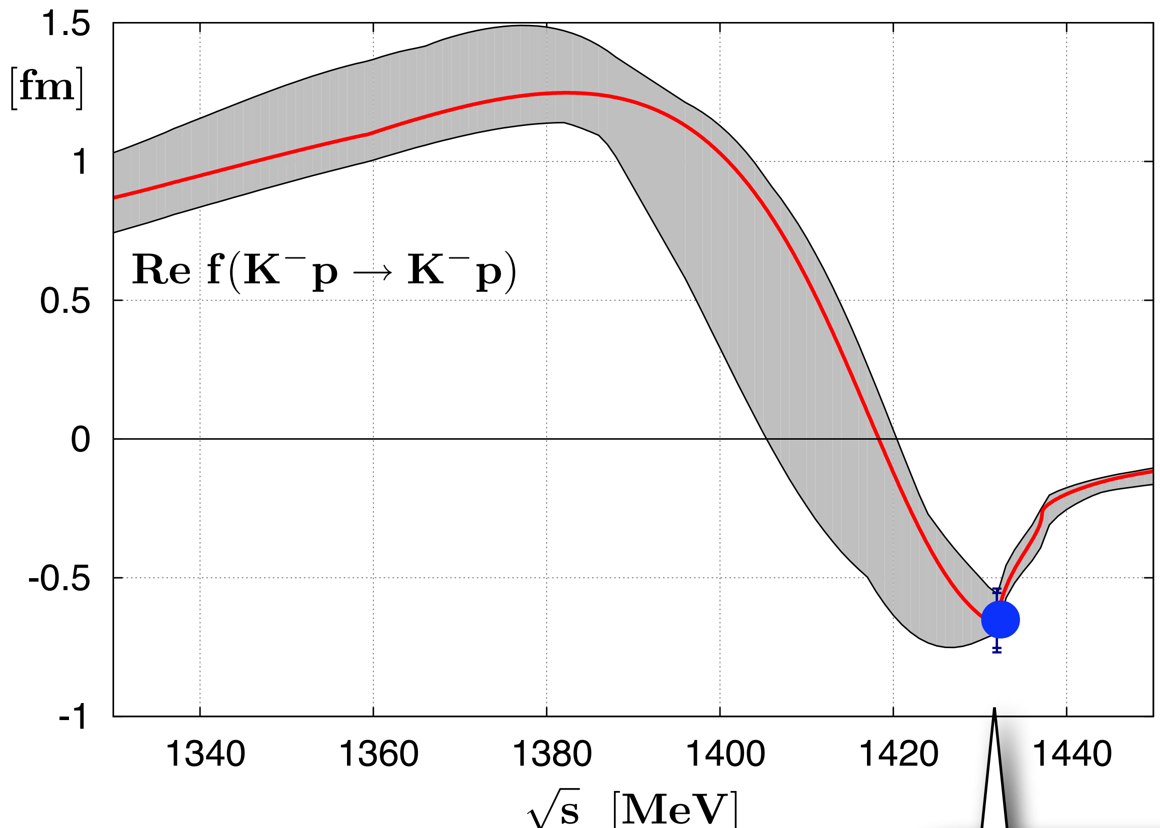
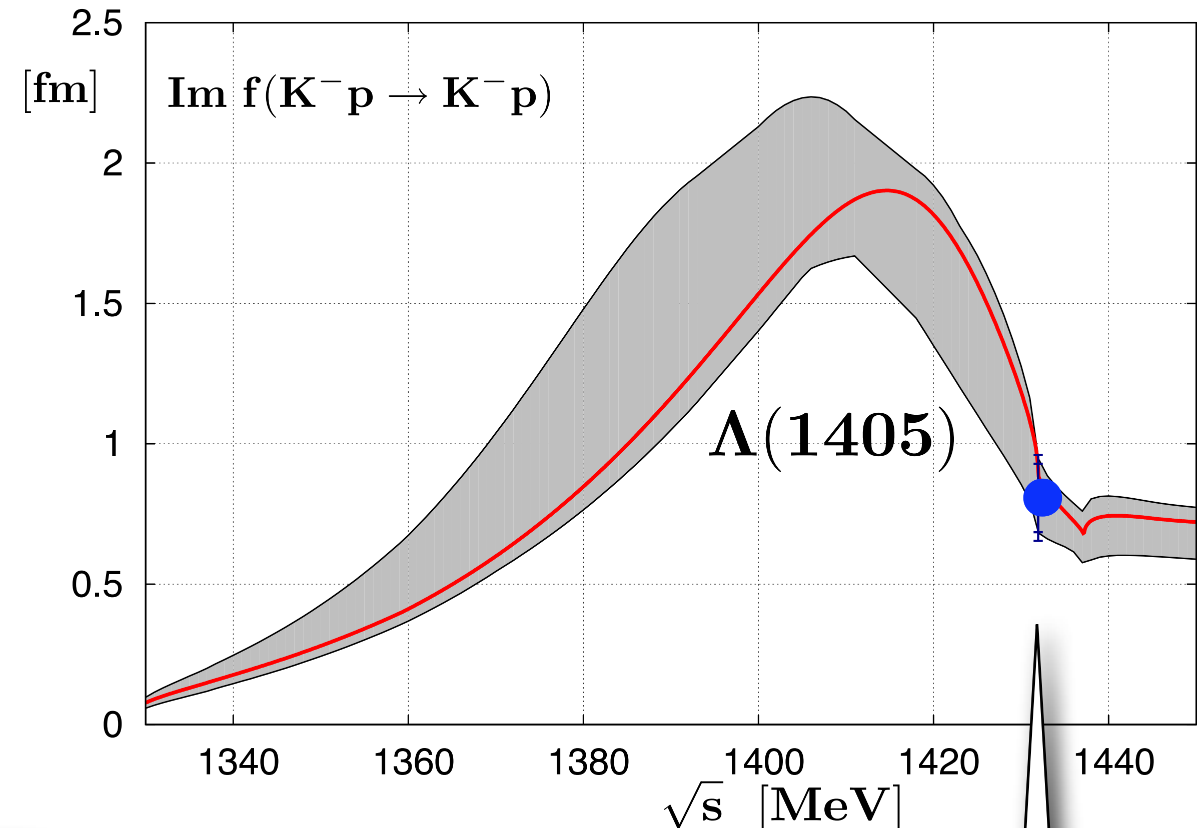
$\mathbf{K^-p}$ SCATTERING AMPLITUDE

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

- threshold region and subthreshold extrapolation:

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





$\mathrm{Re}\ a(K^-p)$

$\mathrm{Im}\ a(K^-p)$

- complex scattering length (including Coulomb corrections)

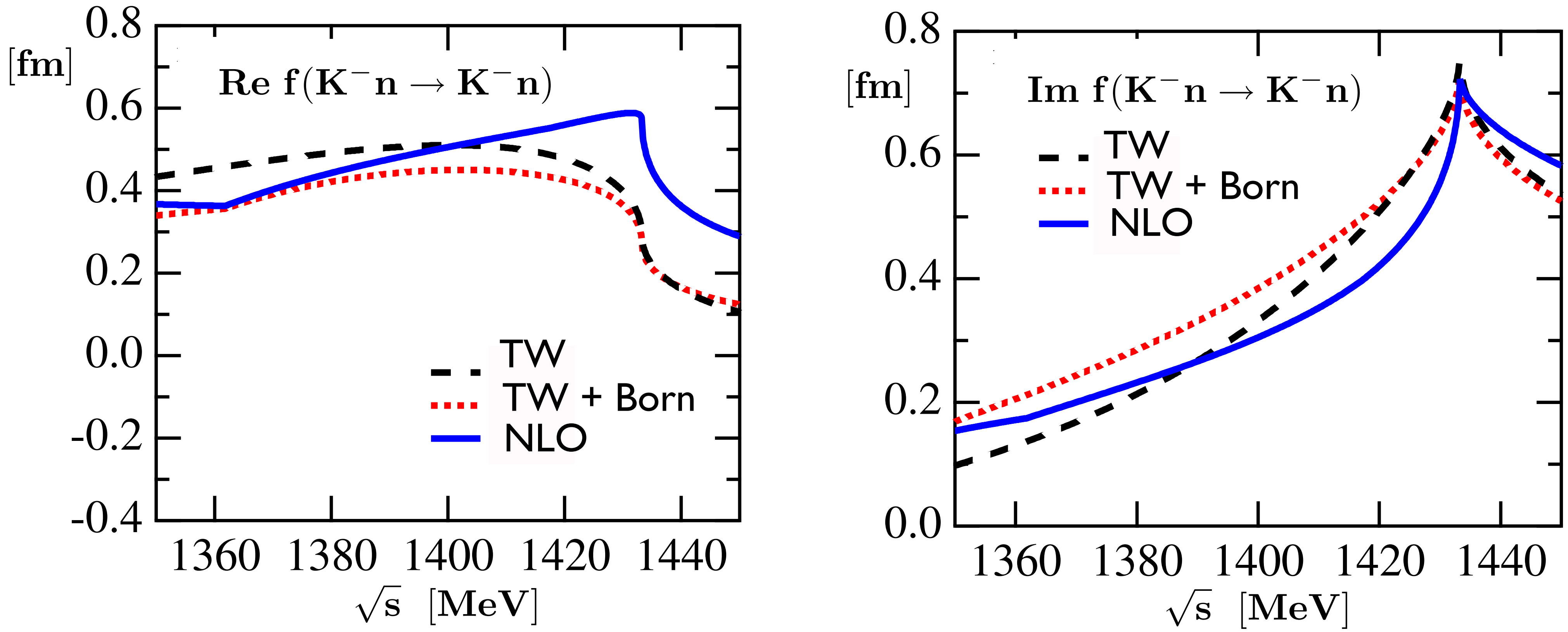
$\mathrm{Re}\ a(K^-p) = -0.65 \pm 0.10\ \ \mathrm{fm}$

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

CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

- Predicted antikaon-neutron amplitudes at and below threshold

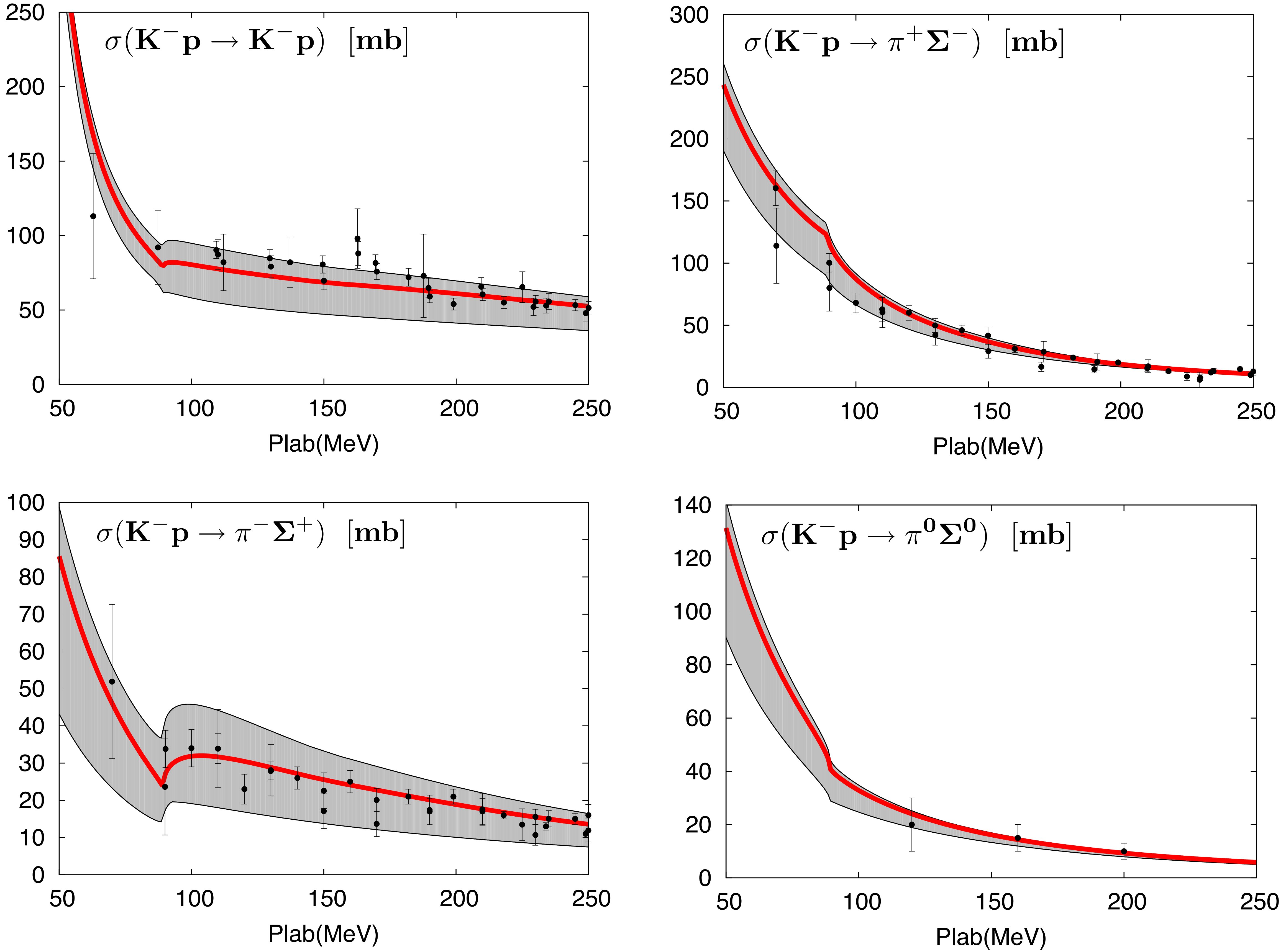
Y. Ikeda, T. Hyodo, W. Weise : Phys. Lett. B 706 (2011) 63 , Nucl. Phys. A 881 (2012) 98



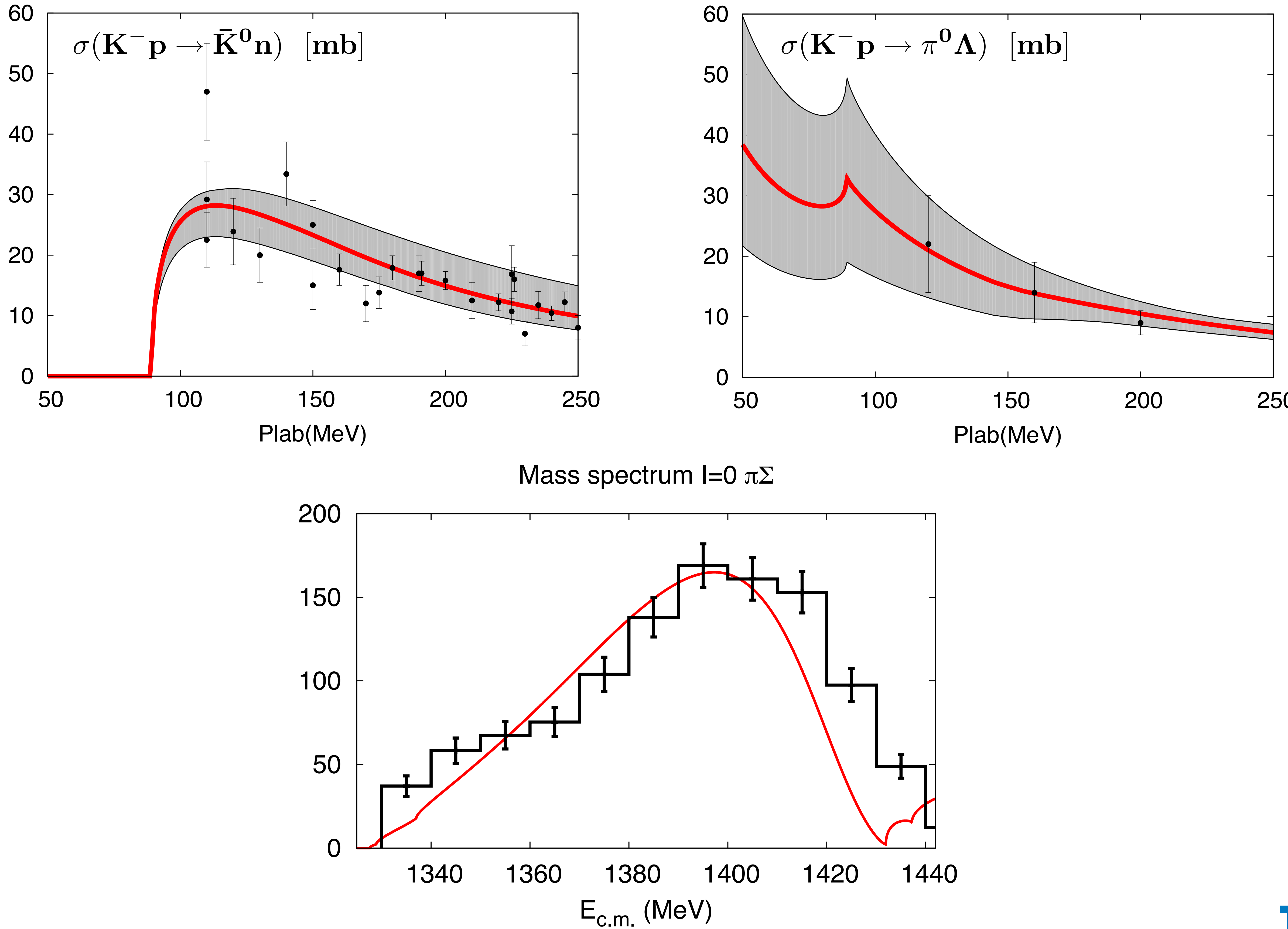
$$a(K^-n) = 0.57^{+0.04}_{-0.21} + \mathrm{i}\,0.72^{+0.26}_{-0.41} \quad \mathrm{fm}$$

- **Needed**:
  accurate constraints from antikaon-deuteron threshold measurements
  - **complete** information for both isospin $\mathbf{I = 0}$ and $\mathbf{I = 1}$ $\bar{\mathbf{K}}\mathbf{N}$ channels
  - first measurement of **K-deuteron** scattering length
    (including potentially important information about **K-NN absorption**)

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



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



The TWO POLES scenario

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

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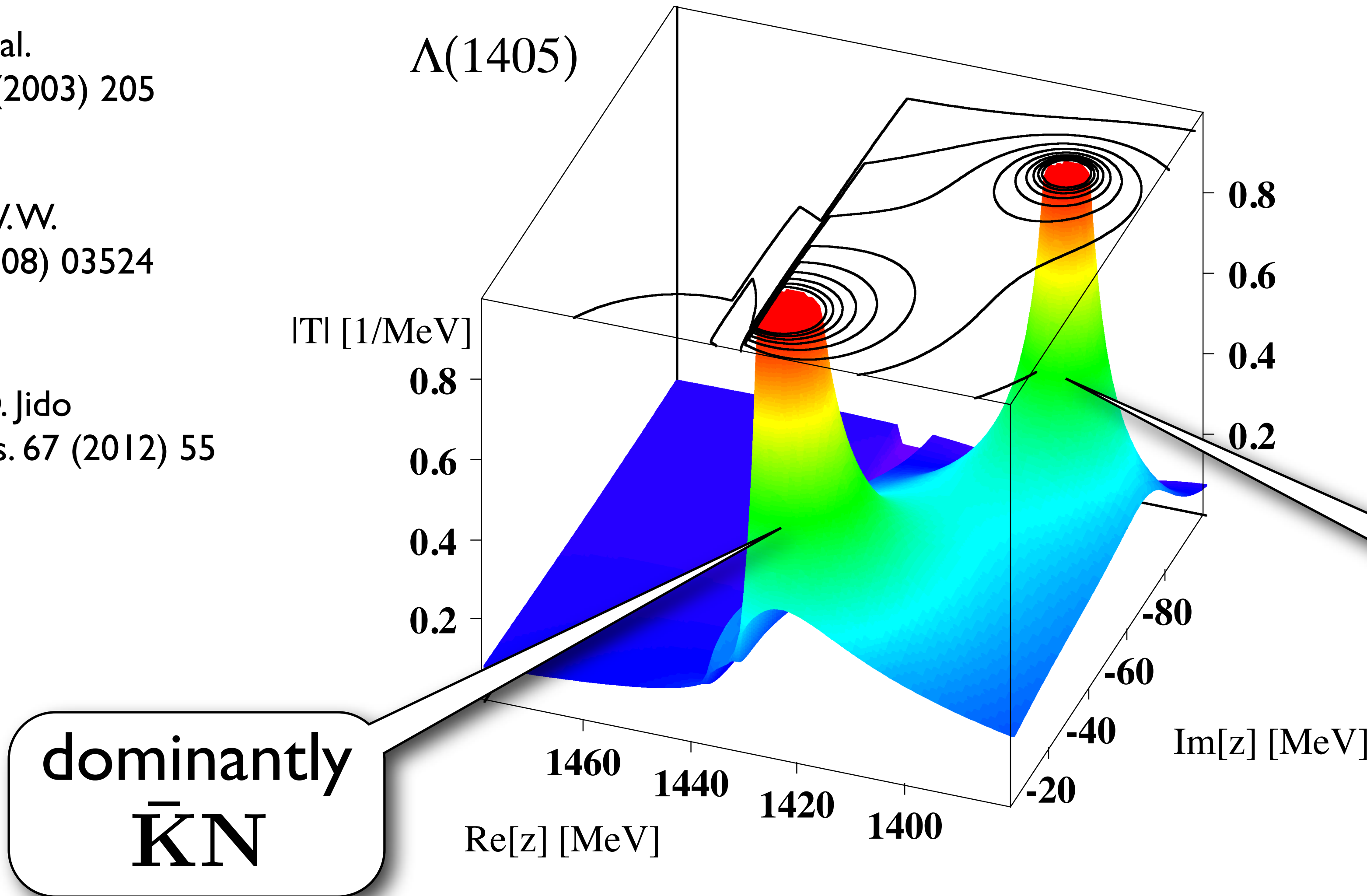
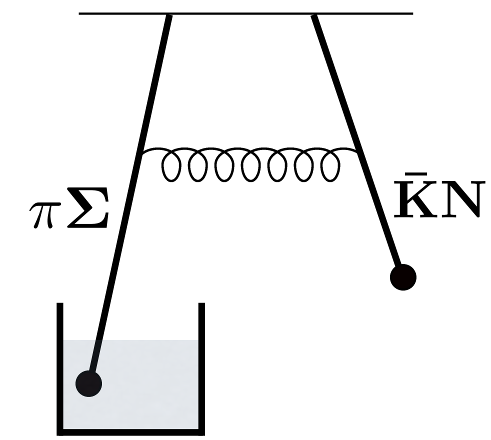
Prog. Part. Nucl. Phys. 67 (2012) 55





- Pole positions from chiral SU(3) coupled-channels calculation with SIDDHARTA threshold constraints:

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

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

Implications & Comments

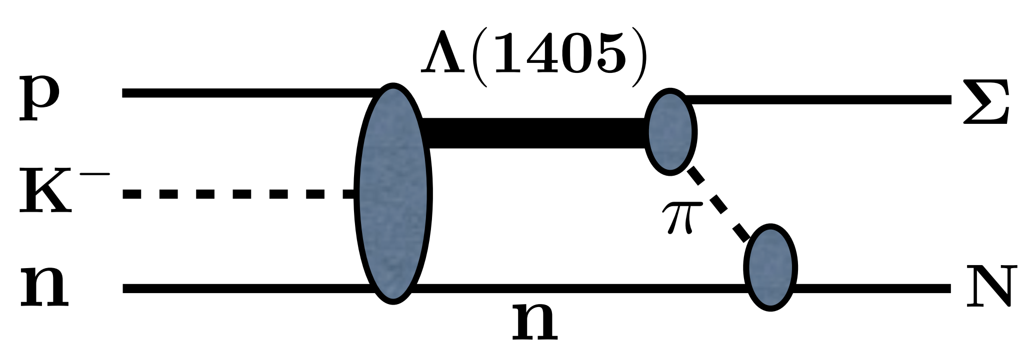
- $\mathbf{K^-p}$ scattering length more accurately determined than $\mathbf{K^-n}$ (SIDDHARTA constraints)

- Uncertainties in $\mathbf{\bar{K}N}$ $\mathbf{(I=1)}$ interaction primarily from large uncertainties in the $\mathbf{K^-p \to \pi^0 \Lambda}$ channel

- **Kaonic deuterium** measurements important for providing further constraints on $\mathbf{K^-n}$ interaction

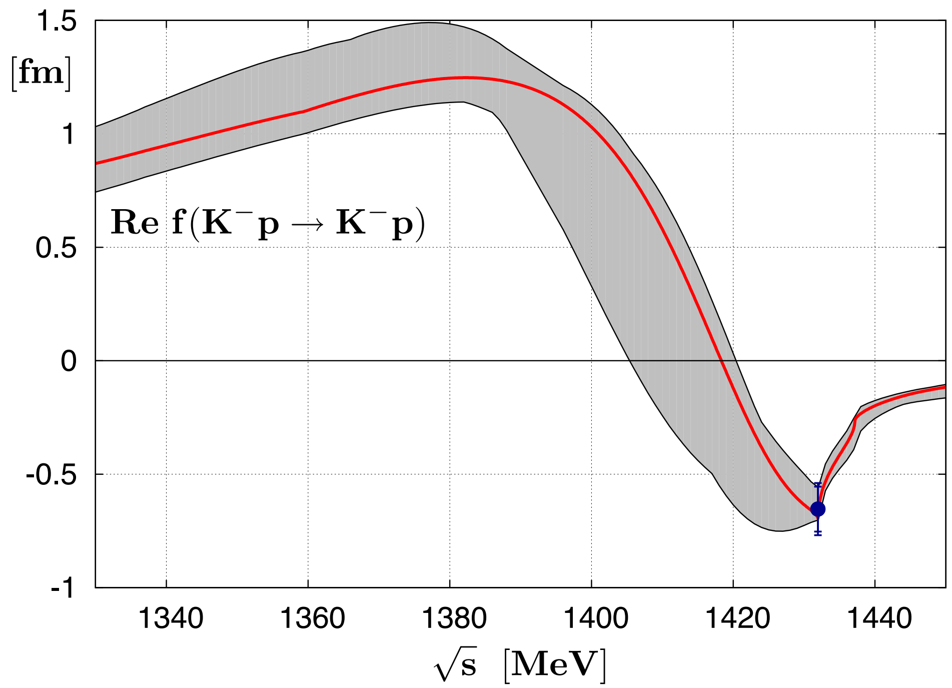
- B = 2 systems - key issue: $\mathbf{\bar{K}NN \to YN}$ absorption into non-mesonic hyperon-nucleon final states

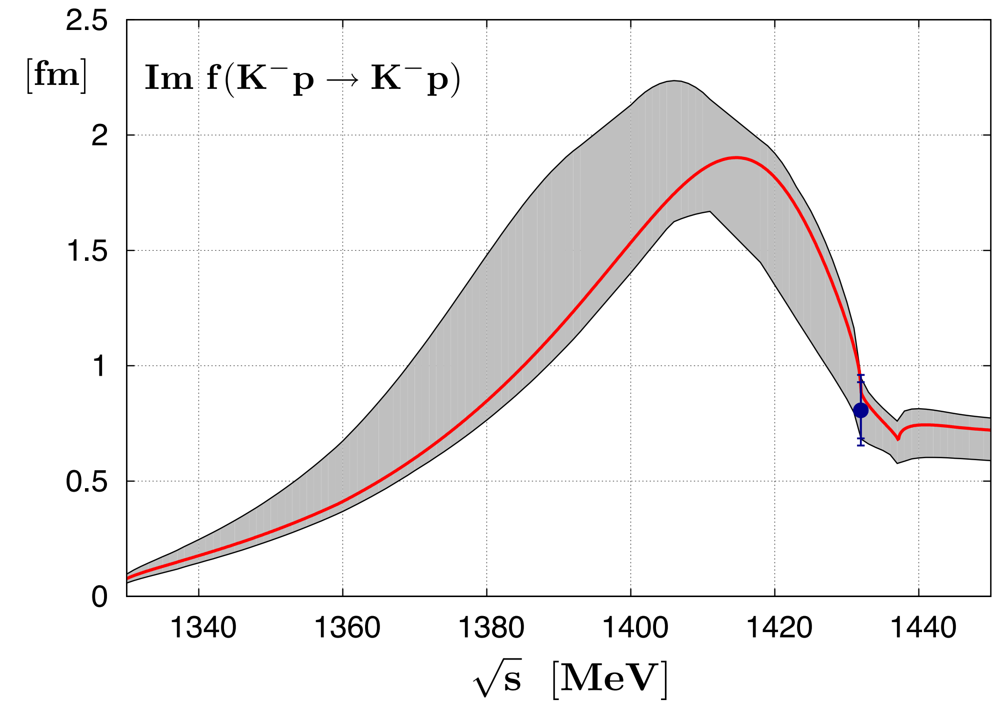
e.g.:



ALTERNATIVE OPTIONS ?

- Reproducing **kaonic hydrogen** and **low-energy scattering** data does not give **unique** answer - **subthreshold** constraints important





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W. W.

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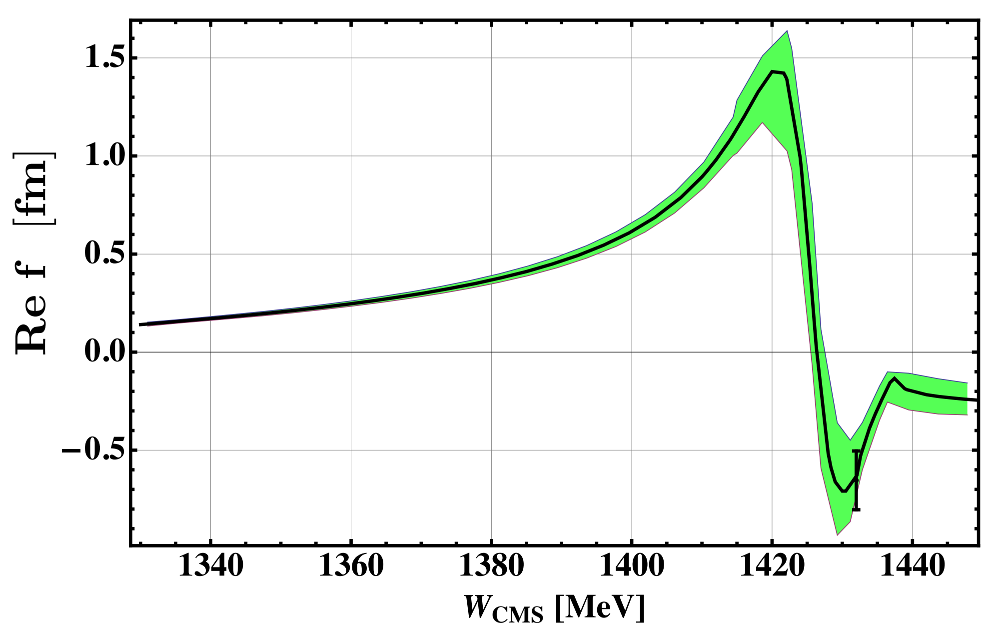
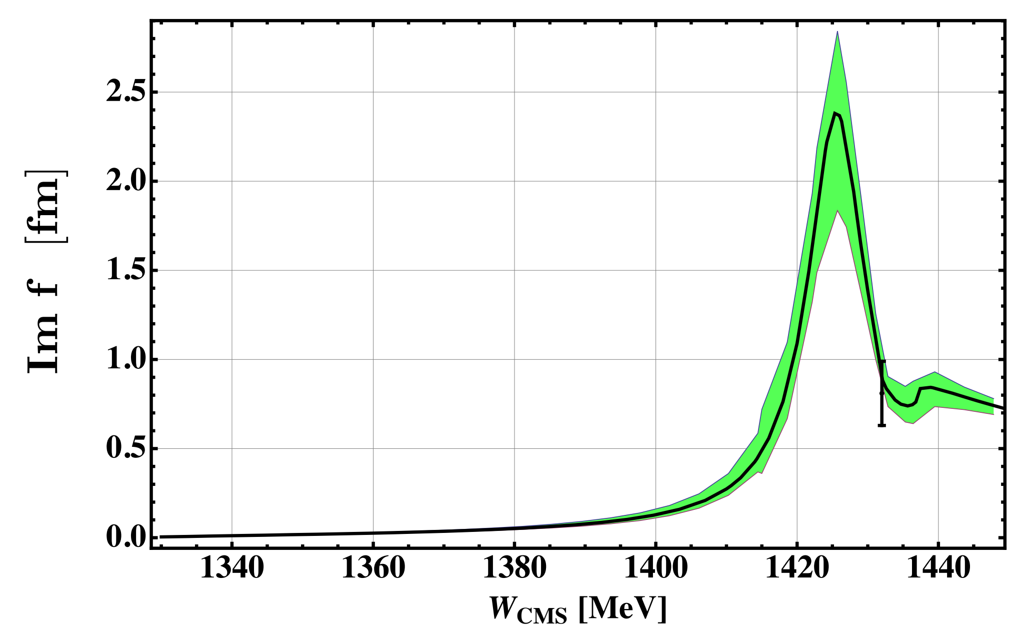
NPA881 (2012) 98



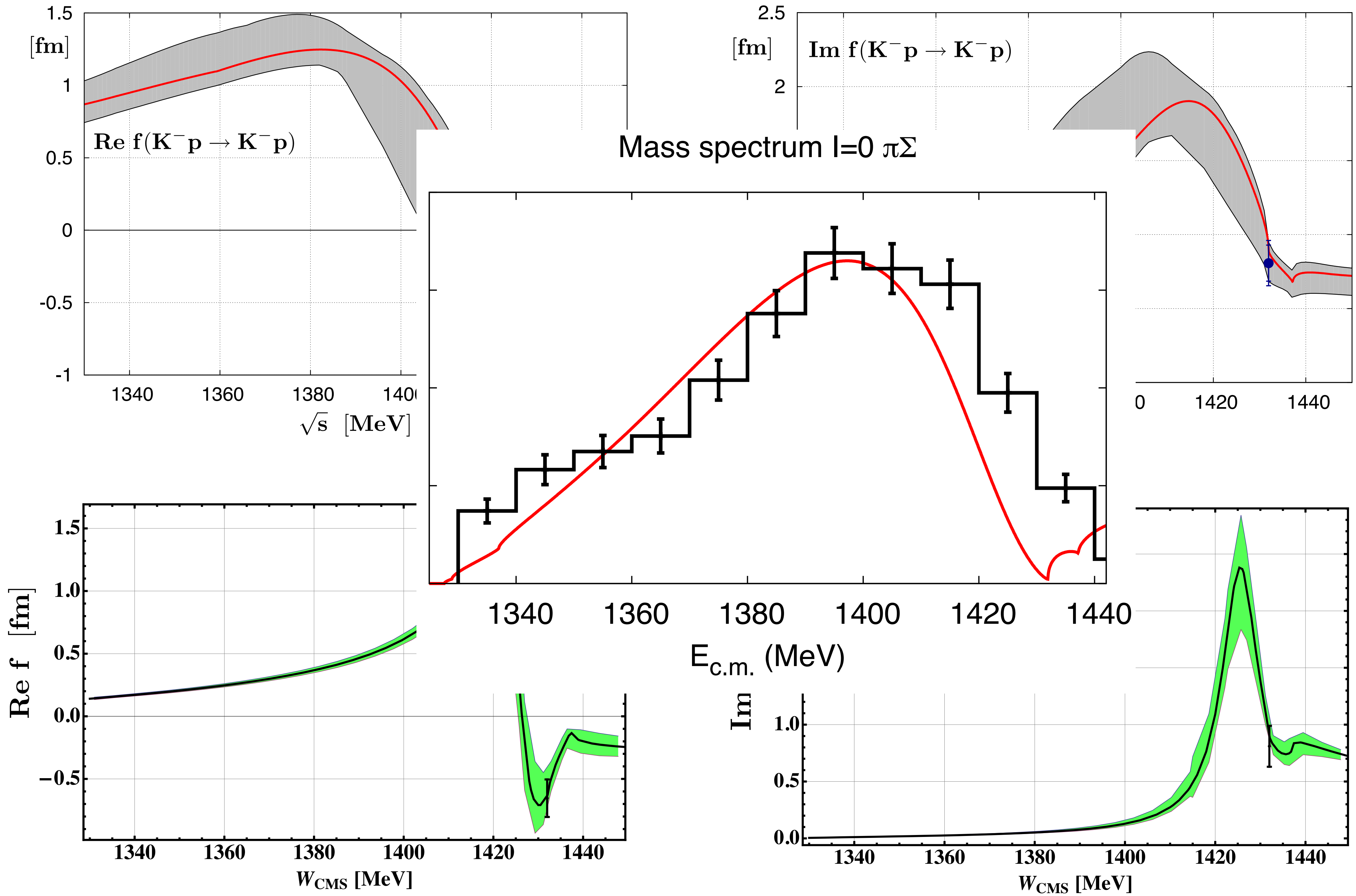


M. Mai,
U.-G. Meißner

arXiv:
1202.2030
[nucl-th]

ALTERNATIVE OPTIONS ?

- Reproducing **kaonic hydrogen** and **low-energy scattering** data does not give **unique** answer - **subthreshold** constraints important



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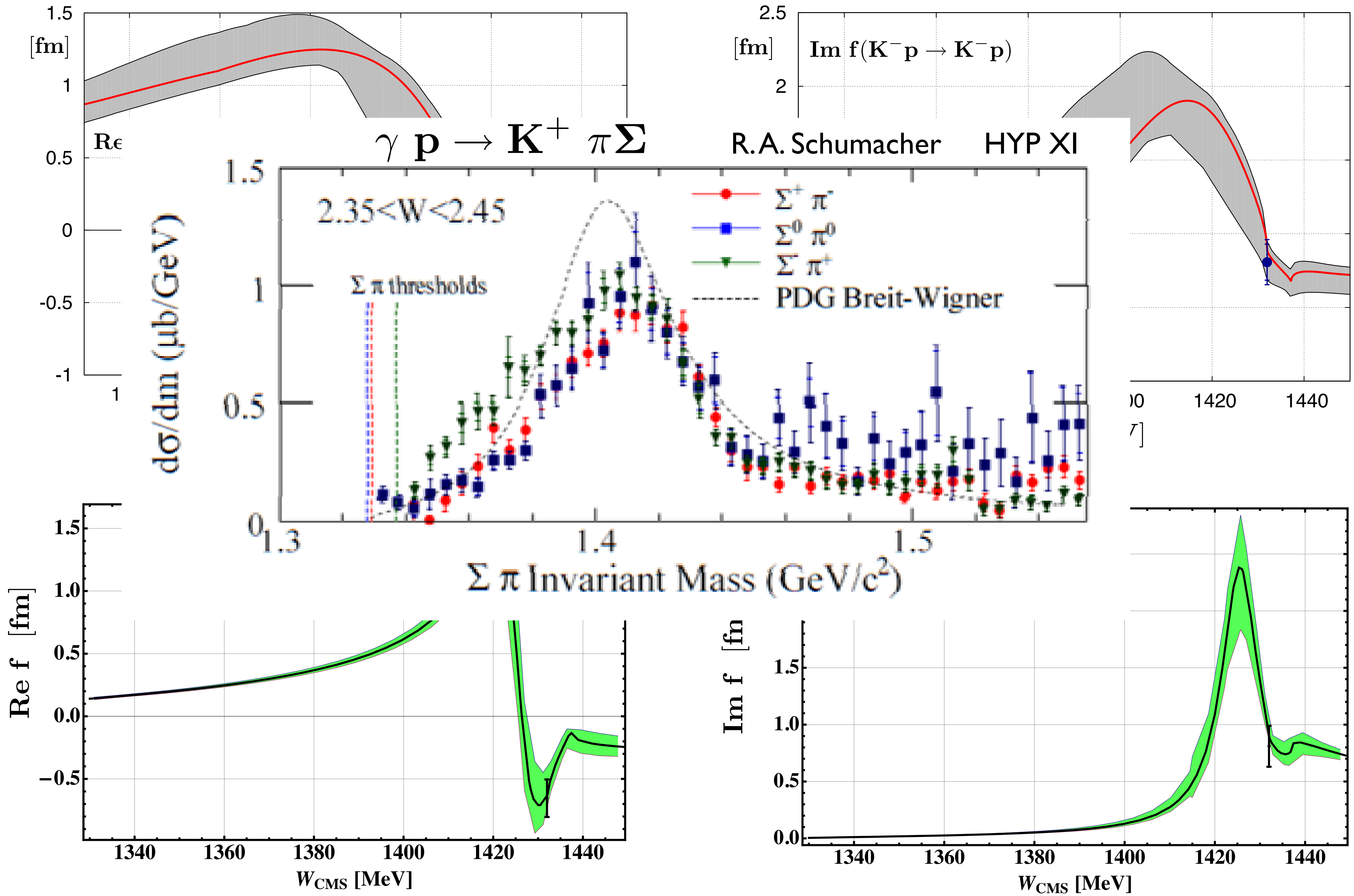

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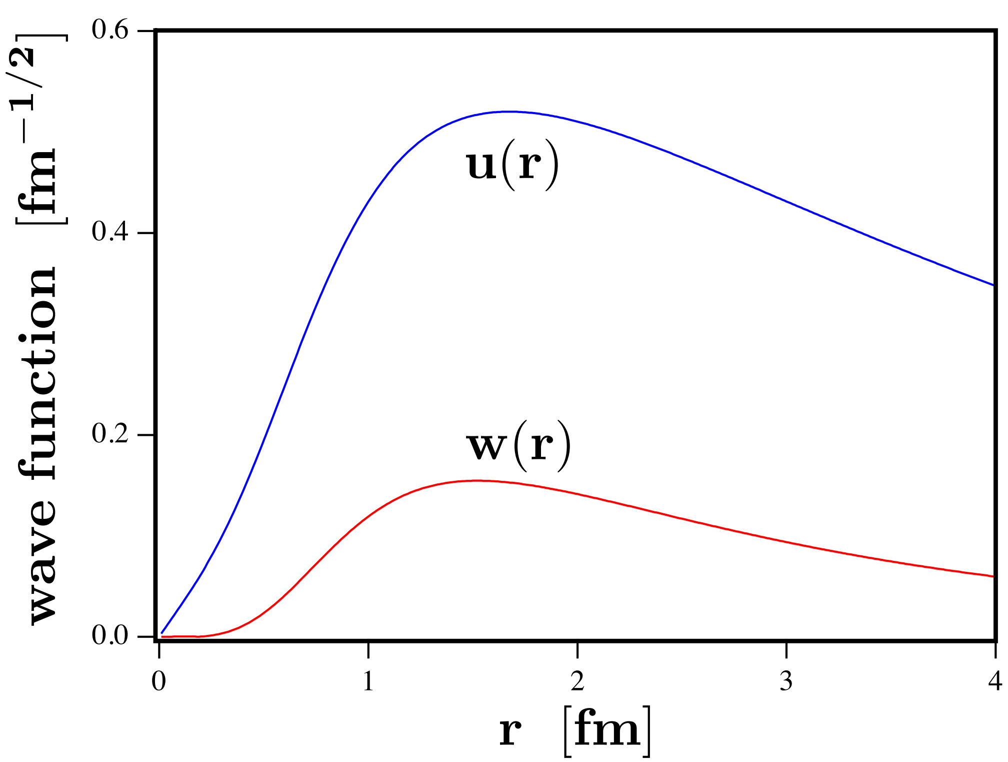
ANTIKAON - DEUTERON THRESHOLD PHYSICS

... looking forward to **SIDDHARTA 2**

- **Strategies**: Multiple scattering (MS) theory vs. three-body (Faddeev) calculations with Chiral SU(3) Coupled Channels input
- **MS approach** (fixed scatterer approximation): $K^- d$ **scattering length**

S.S. Kamalov, E. Oset, A. Ramos: Nucl. Phys. A 690 (2001) 494

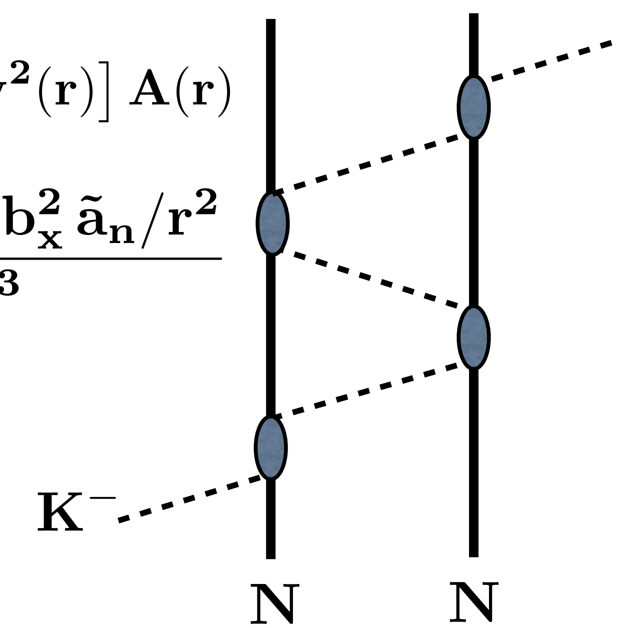


$$a(K^-d) = \left(1 + \frac{m_K}{M_d}\right)^{-1} \int_0^\infty dr\, [u^2(r) + w^2(r)]\, A(r)$$

$$A(r) = \frac{\tilde{a}_p + \tilde{a}_n + (2\,\tilde{a}_p\,\tilde{a}_n - b_x^2)/r - 2\,b_x^2\,\tilde{a}_n/r^2}{1 - \tilde{a}_p\,\tilde{a}_n/r^2 + b_x^2\,\tilde{a}_n/r^3}$$

$$\tilde{a}_p = \left(1 + \frac{m_K}{M_N}\right) a(K^-p \to K^-p)$$

$$\tilde{a}_n = \left(1 + \frac{m_K}{M_N}\right) a(K^-n \to K^-n)$$



b_x incorporates $K^-p \to \bar{K}_0\, n$ and $\bar{K}_0\, n \to \bar{K}_0\, n$

- Using IHW input scattering lengths constrained by SIDDHARTA kaonic hydrogen:

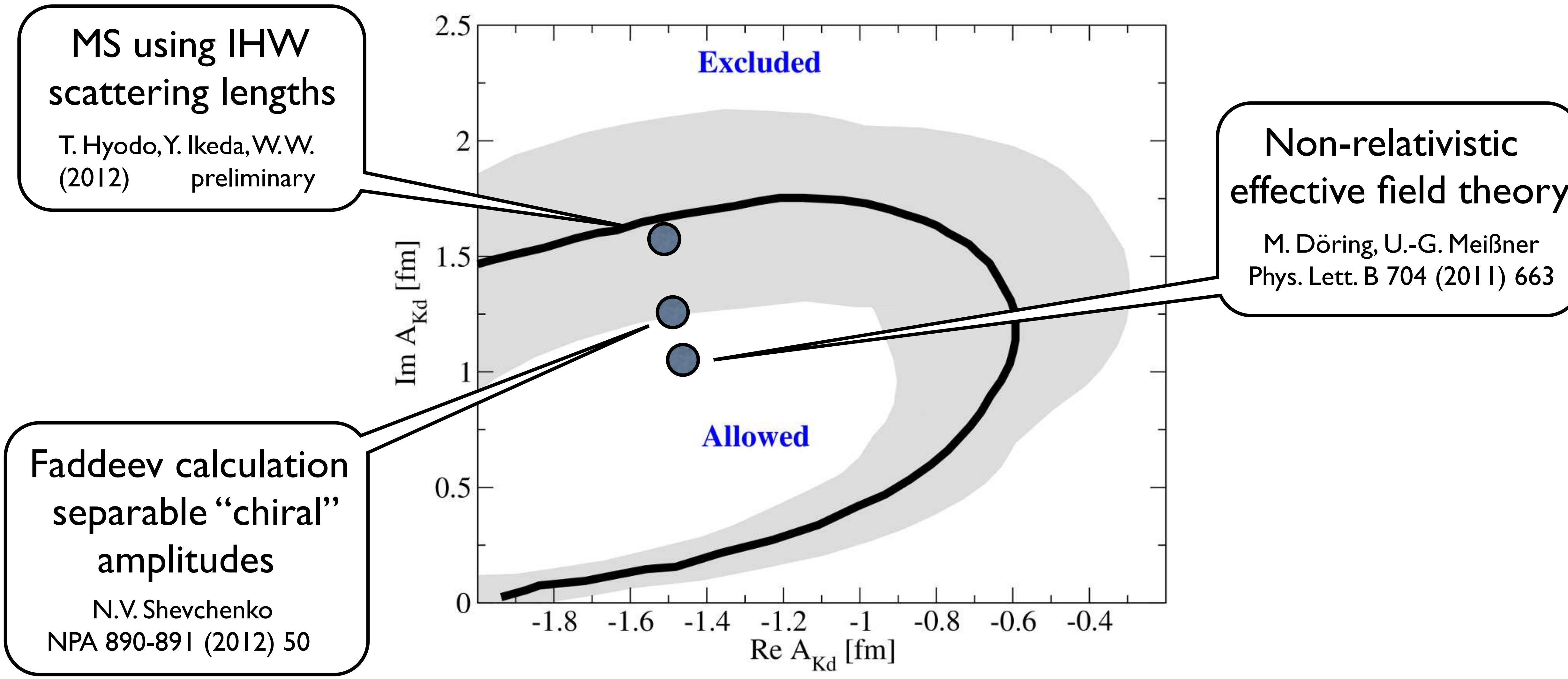
$a(K^-d)$ [fm]

full MS	$-1.54 + i1.64$
no charge exchange	$-1.04 + i1.34$
impulse approximation	$-0.13 + i1.81$

T. Hyodo, Y. Ikeda, W.W. (2012) preliminary

ANTIKAON - DEUTERON SCATTERING LENGTH

- Recent calculations using SIDDHARTA - constrained input

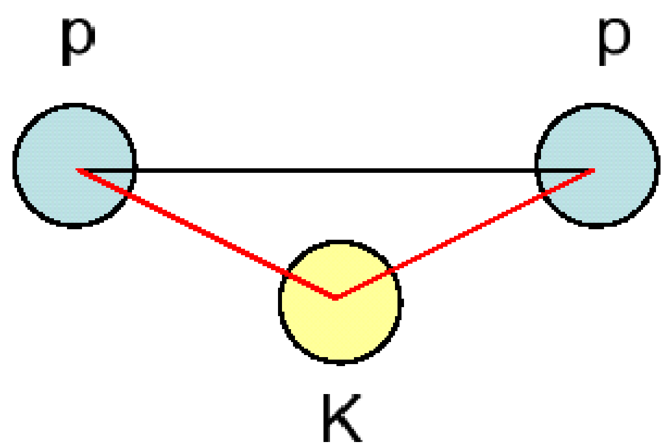


- Primary theoretical uncertainties from $\mathbf{K^- n}$ amplitude
- Predicted energy **shift** and **width** of kaonic deuterium (Faddeev calculation):

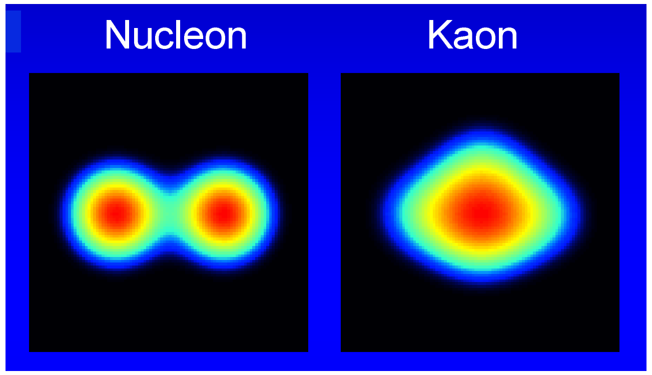
$$\mathbf{\Delta E_{1s} = -794\ eV} \qquad \mathbf{\Gamma_{1s}(K^- d) = 1012\ eV}$$

- Not included: $\mathbf{K^- d \rightarrow YN}$ absorption

UPDATE on QUASIBOUND K^-pp



3-Body (Faddeev) calculations



Variational calculations

- ...now consistently using amplitudes from **Chiral SU(3) coupled-channels** dynamics including **energy dependence** in subthreshold extrapolations

- Calculated **binding energy** and **width** (in MeV) of the K^-pp system

modest binding
large width

	[1]	[2]	[3]
B	16	17–23	9–16
Γ	41	40–70	34–46

remarkable degree of consistency

[1] Variational (hyperspherical harmonics): N. Barnea, A. Gal, E.Z. Livets ; Phys. Lett. B 712 (2012) 132

[2] Variational (Gaussian trial wave functions): A. Doté, T. Hyodo, W.W. ; Phys. Rev. C 79 (2009) 014003

[3] Faddeev: Y. Ikeda, H. Kamano, T. Sato ; Prog. Theor. Phys. 124 (2010) 533