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

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with

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References:

Y.I., Hyodo, Weise, PLB 706 (2011) 63.

Y.I., Hyodo, Weise, arXiv:1201.6549 [nucl-th].

Workshop on `Future Prospects of Hadron Physics at J-PARC and Large Scale Computational Physics', Feb. 9-11. 2012

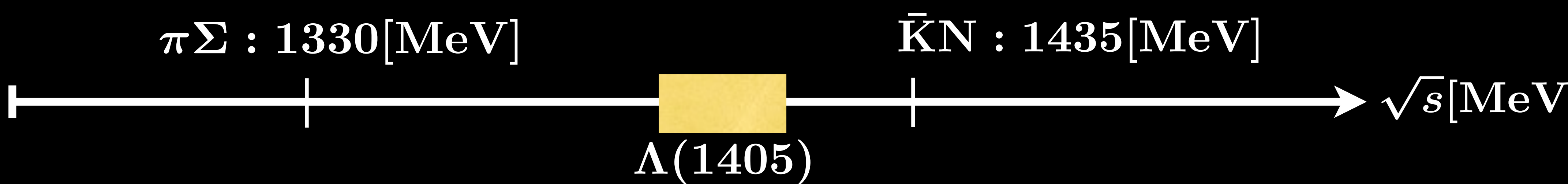
Contents

- Introduction to low energy anti-K -- nucleon interactions
- Chiral SU(3) effective field theory and coupled-channel dynamics
- Improved constraints on chiral SU(3) dynamics by SIDDHARTA kaonic hydrogen results
- Fit results
- Uncertainty analysis from SIDDHARTA results
- Predictions from "improved" chiral SU(3) dynamics
- Summary and future plans

Anti-kaon -- nucleon interactions

Anti-K -- nucleon ($K^{bar}N$) interaction in I=0 is strongly attractive

- √ Presence of Λ(1405) : $K^{bar}N$ quasi-bound state
- √ Repulsive shift of kaonic hydrogen, scattering data, ...



$K^{bar}N$ system strongly couples to πΣ continuum

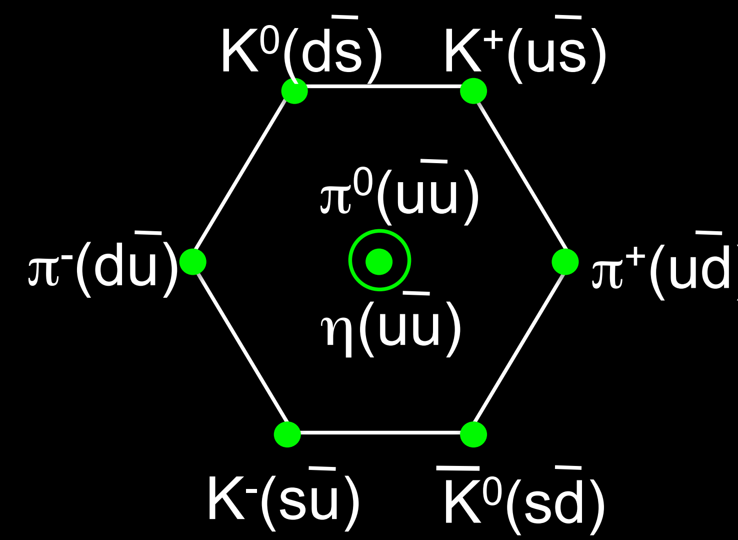
- √ Width of Λ(1405), K^{bar} atoms

$K^{bar}N$ interaction is basic ingredient for application to

- √ K^{bar}-nuclei, K^{bar} in medium, K^{bar} atoms, ...

In order to discuss many application,
evidently determination of $K^{bar}N$ interaction is important issue

Anti-kaon -- nucleon interactions



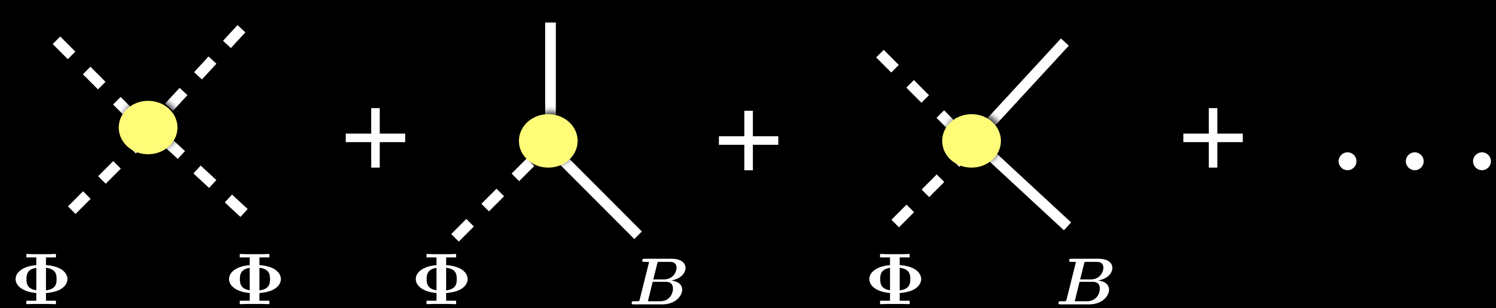
Kaon : Nambu-Goldstone (NG) boson [chiral SU(3)]

Chiral Effective Field Theory :

interactions between NG bosons and baryons

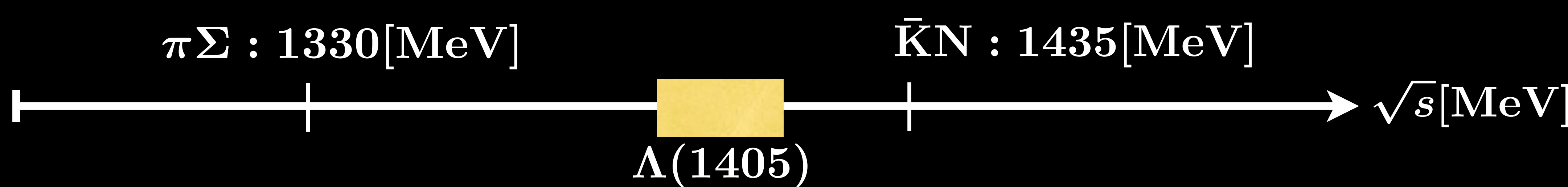
$$\mathcal{L}_{\rm eff}(\Phi, B) = \mathcal{L}_{\rm M}(\Phi) + \mathcal{L}_{\Phi\rm B}(\Phi, B)$$

well organized by systematic low-energy expansion in p/Λ_χ , m_π/Λ_χ



Φ: Meson field, B : Baryon field

Chiral perturbation theory works for low-energy ππ and πN systems,
but not for S=-1 meson-baryon sector ($K^{bar}N$, πΣ, ...)



Non-perturbative coupled-channels dynamics needed

Theoretical framework for MB scattering

Non-perturbative dynamics : coupled-channels Bethe-Salpeter equation

10 channels : $K^{bar}N$=(K^-p, $K^{bar0}n$), $\pi\Lambda$, $\pi\Sigma$=($\pi^0\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$), $\eta\Lambda$, $\eta\Sigma^0$, $K\Xi$=($K^+\Xi^-$, $K^0\Xi^0$)

$$T_{ij}(\sqrt{s}) = V_{ij}(\sqrt{s}) + \sum_n V_{in}(\sqrt{s}) G_n(\sqrt{s}) T_{nj}(\sqrt{s})$$

Interactions determined by matching with chiral EFT order by order

$$V^{(1)} = T^{(1)}(\sqrt{s}),\ V^{(2)} = T^{(2)}(\sqrt{s}),\ V^{(3)} = T^{(3)}(\sqrt{s}) - T^{(1)}(\sqrt{s})G(\sqrt{s})T^{(1)}(\sqrt{s}),\ \cdots$$

Loop integral : finite parts include subtraction constant a(μ)

$$G(\sqrt{s}) = a(\mu) + \frac{1}{32\pi^2}\left[\log\left(\frac{m_\phi^2 M_B^2}{\mu^4}\right) + \frac{m_\phi^2 - M_B^2}{s}\log\left(\frac{m_\phi^2}{M_B^2}\right)\right] - \frac{1}{16\pi^2}\left[1 + \frac{4|\mathrm{q}_{\mathrm{c.m.}}|}{\sqrt{s}}\mathrm{artanh}\left(\frac{2\sqrt{s}|\mathrm{q}_{\mathrm{c.m.}}|}{(m_\phi + M_B)^2 - s}\right)\right]$$

Scattering amplitude T is consistent with

non-perturbative coupled-channels dynamics + chiral SU(3) symmetry

(Coupled-channels chiral SU(3) dynamics)

Kaiser, Siegel, Weise, NPA 594 (1995) 325.

Oset, Ramos, NPA 635 (1998) 99.; Oller, Meissner, PLB 500 (2001) 263. + many others...

Recent review : Hyodo, Jido, PPNP 67 (2012) 55.

Coupled-channels chiral SU(3) dynamics

Leading order contributions from chiral EFT

Leading order (Tomozawa-Weinberg) term : O(p)

$$\mathcal{L}^{\rm TW} = \frac{i}{8f^2}{\rm tr}[\bar{B}\gamma^\mu[v_\mu, B]]$$

Weinberg, PRL 17, 616 (1966).
Tomozawa, Nuov. Cim. 46A, 707 (1966).

$$v_\mu = \Phi(\partial_\mu\Phi) - (\partial_\mu\Phi)\Phi + \cdots$$

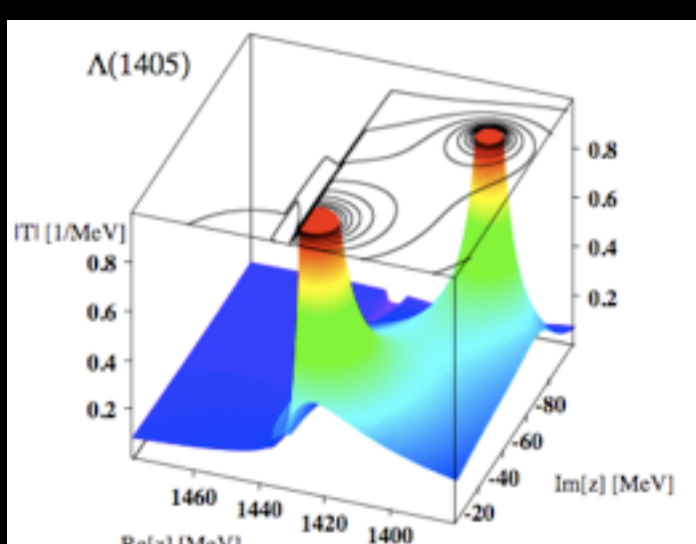
Φ: Meson field , B : Baryon field

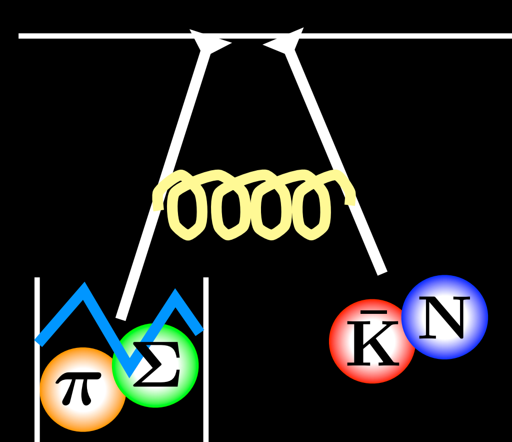
$$V^{\rm TW}_{ij} = -\frac{C_{ij}}{8f_i f_j}\mathcal{N}_i\mathcal{N}_j(\omega_i + \omega_j)$$

$$(\mathcal{N}_i = \sqrt{E_i + M_i})$$

✓ Strength : (physical) meson decay constant
✓ Coupling : chiral SU(3) symmetry
✓ Derivative coupling : (meson) energy dependence

- With TW term alone, low-energy K-p scattering data are described fairly well
- Λ(1405) : two poles ($K^{bar}N$ bound, πΣ resonance)





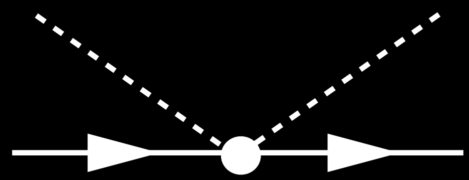
Jido et al., NPA723, 205 (2003).
Hyodo, Weise, PRC77, 035204 (2008).

Coupled-channels chiral SU(3) dynamics

Interaction kernels : chiral EFT up to next-to-leading order

Leading order (Tomozawa-Weinberg) term : O(p)

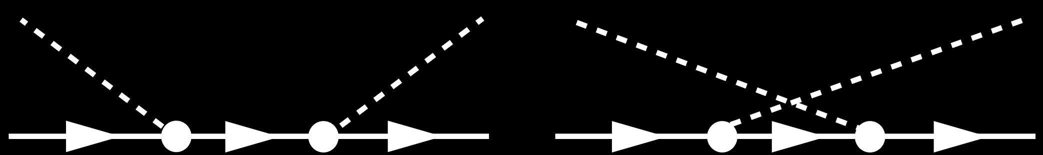
$$\mathcal{L}^{\mathrm{TW}} = \frac{i}{8f^2}\mathrm{tr}[\bar{B}\gamma^\mu[v_\mu, B]]$$



input : meson decay constant

Direct and crossed Born terms : O(p)

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

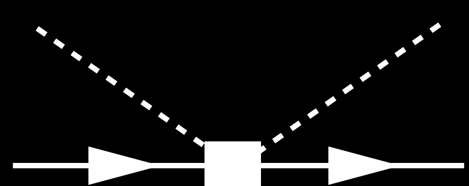


input : axial-vector constants from hyperon beta decays

D=0.80, F=0.46 --> g_A=D+F=1.26

Next-to-leading order (NLO) terms : O(p^2)

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



input : 7 low energy constants

(b_D, b_F, b_0, d_1, d_2, d_3, d_4)

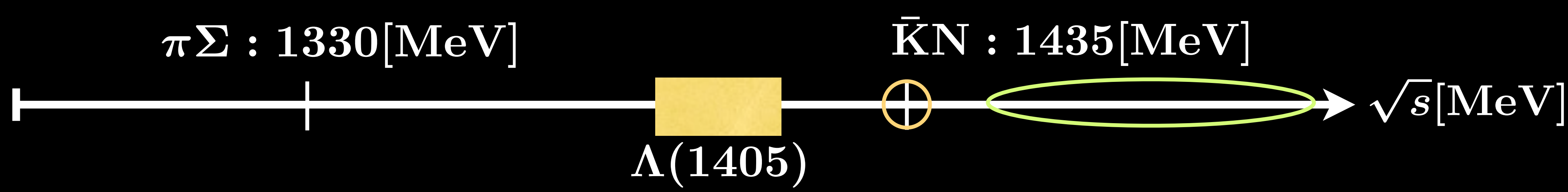
Constraints on chiral SU(3) dynamics

Parameters of coupled-channels chiral SU(3) dynamics

10 channels : $\bar{K}N$=(K^-p, $\bar{K}^0n$), $\pi\Lambda$, $\pi\Sigma$=($\pi^0\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$), $\eta\Lambda$, $\eta\Sigma^0$, $K\Xi$=($K^+\Xi^-$, $K^0\Xi^0$)

a(μ) : 6 isospin symmetric subtraction constants

NLO terms : 7 low energy constants



K^-p cross sections : wide energy range above $\bar{K}N$ threshold

Threshold branching ratios : accurate

$$\frac{\Gamma(K^-p\rightarrow\pi^+\Sigma^-)}{\Gamma(K^-p\rightarrow\pi^-\Sigma^+)} = 2.36 \pm 0.04$$

$$\frac{\Gamma(K^-p\rightarrow\pi^+\Sigma^-,\ \pi^-\Sigma^+)}{\Gamma(K^-p\rightarrow\text{all inelastic channels})} = 0.66 \pm 0.01$$

$$\frac{\Gamma(K^-p\rightarrow\pi^0\Lambda^0)}{\Gamma(K^-p\rightarrow\text{neutral channels})} = 0.19 \pm 0.02$$

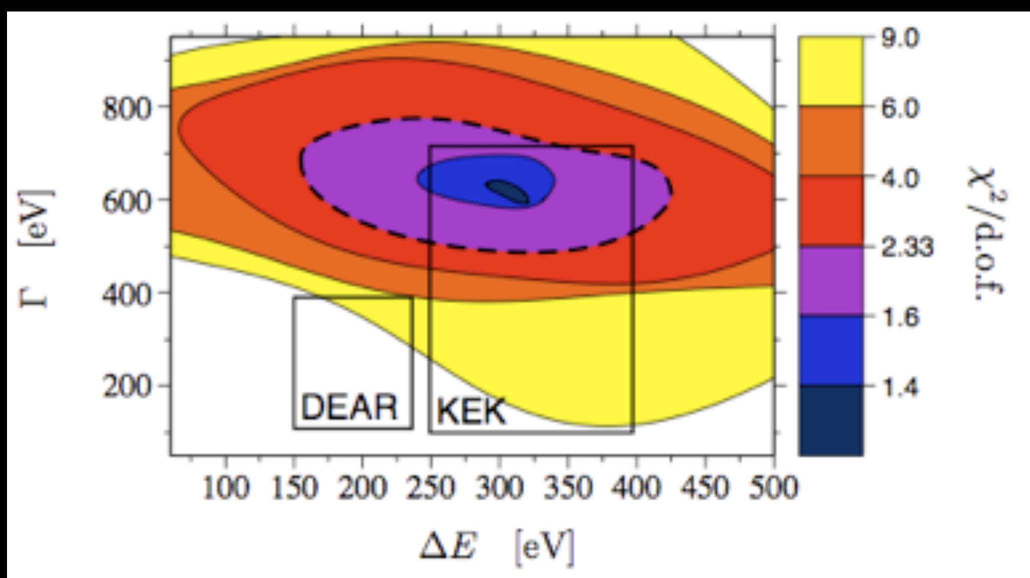
Constraints on chiral SU(3) dynamics

χ^2 analysis w/ cross section data and branching ratios

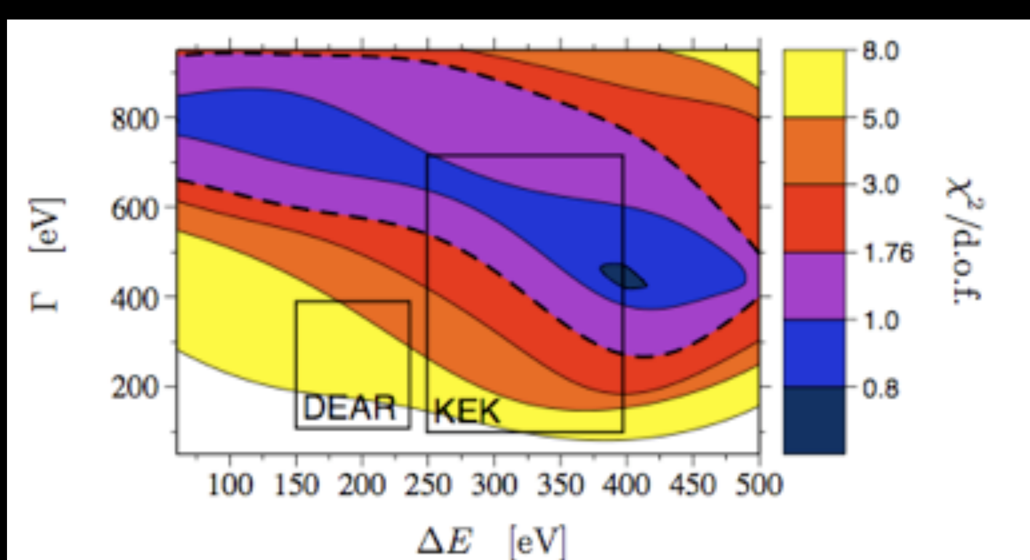
1. predicted kaonic hydrogen shift & width

Nissler, PhD thesis (2008)
Borasoy, Nissler, Weise, EPJA25(2005).
Brasoy, Meissner, Nissler, PRC74(2006).

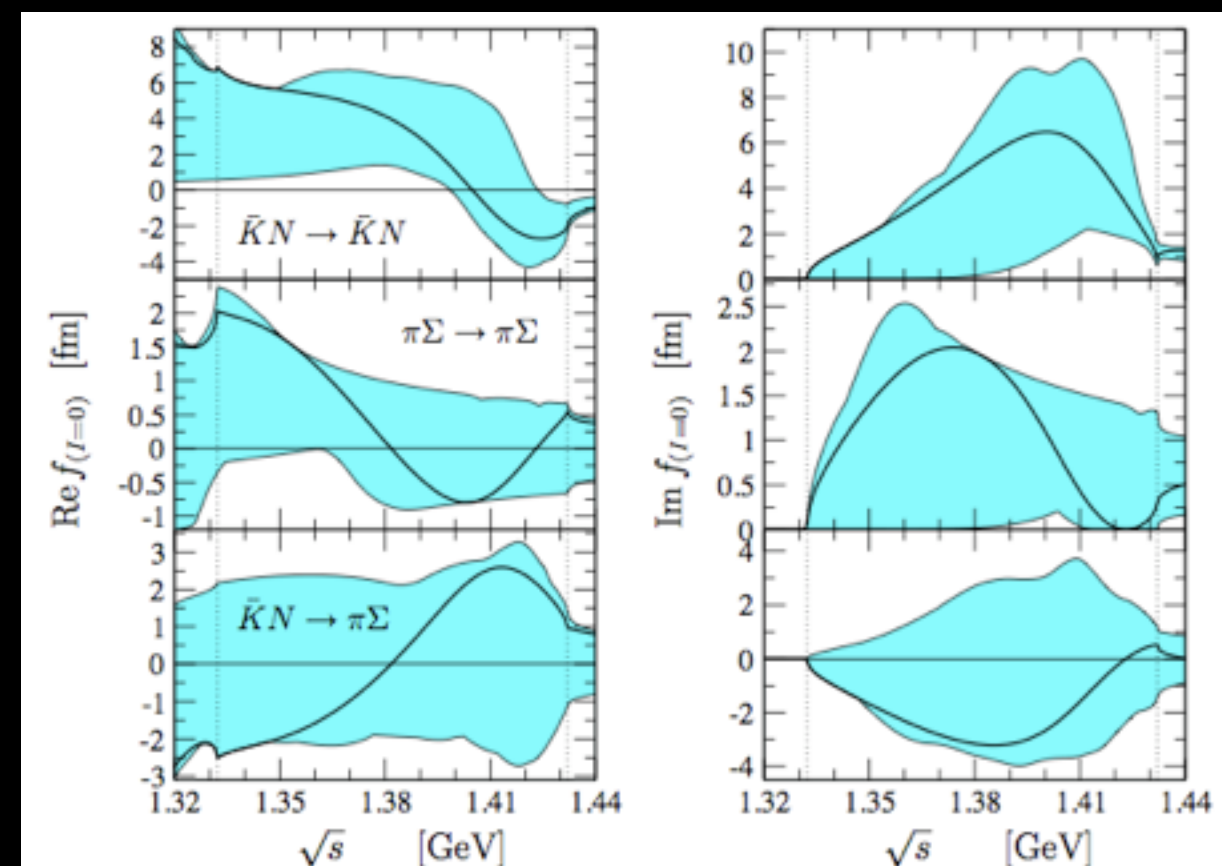
Leading order (TW)



TW+Born+NLO



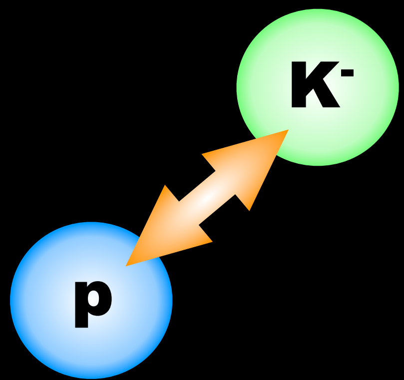
2. amplitudes (NLO), $K^{bar}N$ & $\pi\Sigma$



To determine NLO parameters, we need precise kaonic hydrogen data

SIDDHARTA kaonic hydrogen measurement

Kaonic hydrogen energy shift and width by strong interaction



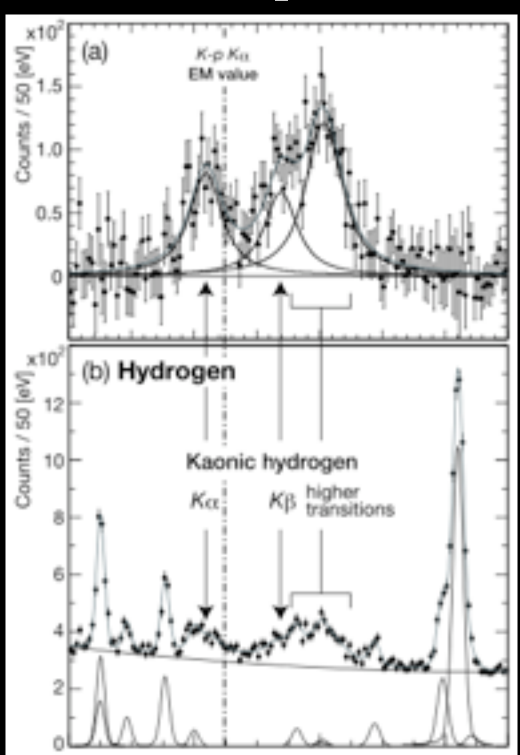
Kaonic hydrogen : mainly EM binding system

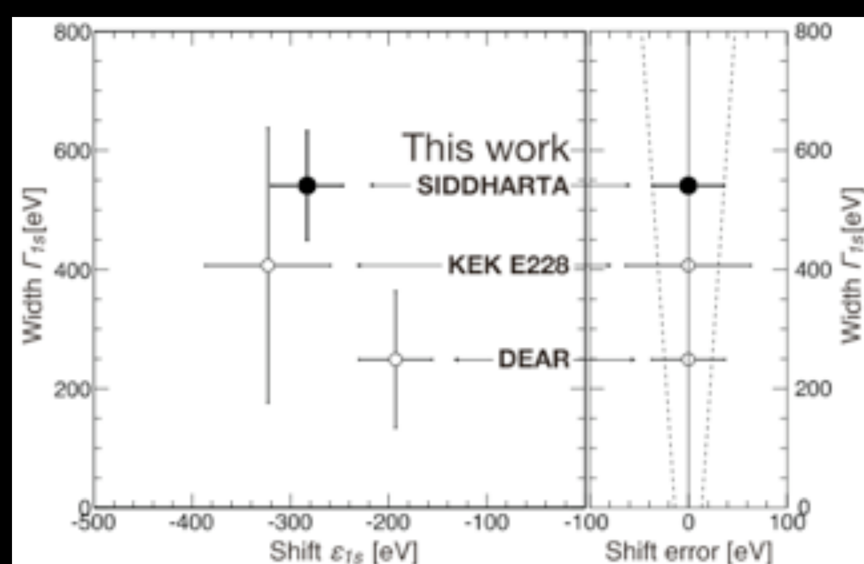
strong interaction -> shift & width -> scattering length

$$\Delta E - \frac{i}{2}\Gamma = -2\alpha^3\mu_c^3 a_{K^-p}[1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}]$$

Meissner, Raha, Rusestky, EPJ C35 (2004).

New precision data of kaonic hydrogen by SIDDHARTA Coll.





Bazzi et al., PLB 704 (2011).

Bazzi et al., arXiv:1201.4635[nucl-ex].

SIDDHARTA shift & width

$$\Delta E = -283 \pm 36 \text{ (stat.) } \pm 6 \text{ (syst.) eV}$$

$$\Gamma = 541 \pm 89 \text{ (stat.) } \pm 22 \text{ (syst.) eV}$$

$$Re\ a_{K^-p} = -0.65 \pm 0.10 \text{ [fm]}$$

$$Im\ a_{K^-p} = 0.81 \pm 0.15 \text{ [fm]}$$

This work :

Systematic χ2 analysis w/

SIDDHARTA results + cross sections + threshold branching ratios

Fit results

We employ physical meson decay constants
(f_π=92.4, f_K=119±1, f_η=130±5 [MeV])

kaonic hydrogen shift & width	TW	TW+Born	NLO (full)	EXP.
-ΔE (eV)	373	377	306	283±36±6
Γ (eV)	495	514	591	541±89±22
Threshold branching ratios				
$\frac{\Gamma(K^-p\to\pi^+\Sigma^-)}{\Gamma(K^-p\to\pi^-\Sigma^+)}$	2.36	2.36	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	0.66	0.66±0.01
$\frac{\Gamma(K^-p\to\pi^0\Lambda^0)}{\Gamma(K^-p\to\text{neutral channels})}$	0.20	0.19	0.19	0.19±0.02
Pole position of Λ(1405) (MeV)	1422-i16 1384-i90	1421-i17 1385-i105	1424-i26 1381-i81	
χ^2/d.o.f.	1.12	1.15	0.96	

Non-trivial observations (NLO):

1. **subtraction constants are all natural size,** a(μ=1GeV) ~ 10^{-2}
2. **NLO parameters are all small** (hierarchy maintains)

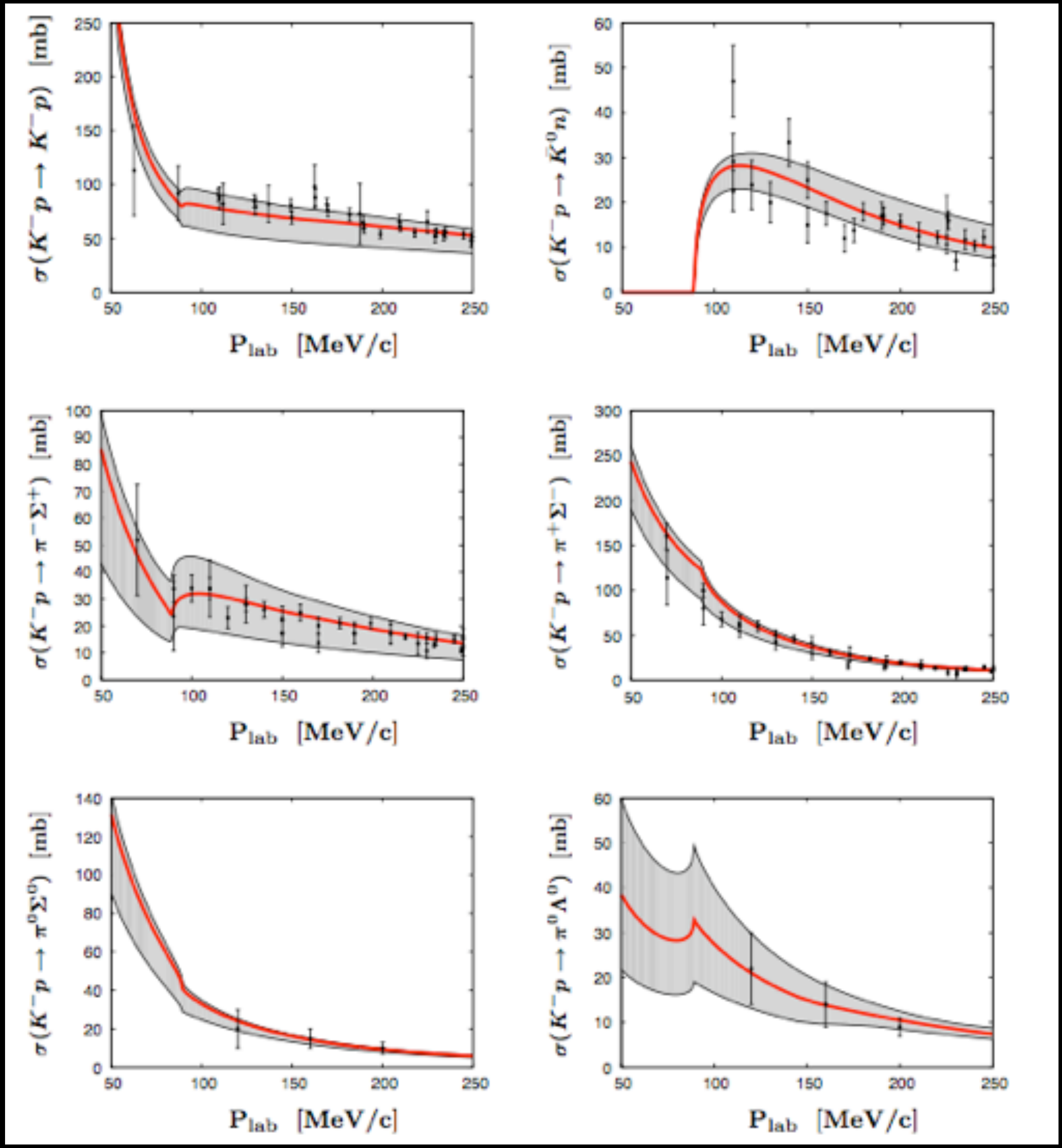
Uncertainty analysis

Uncertainty from SIDDHARTA error & πΛ cross section (I=1)

Total cross sections of K^-p reaction

$$\sigma_{ij}(\sqrt{s}) = \frac{q_i}{q_j} \frac{|T_{ij}(\sqrt{s})|^2}{16\pi s}$$

w/ Coulomb interaction for elastic scattering



SIDDHARTA data :

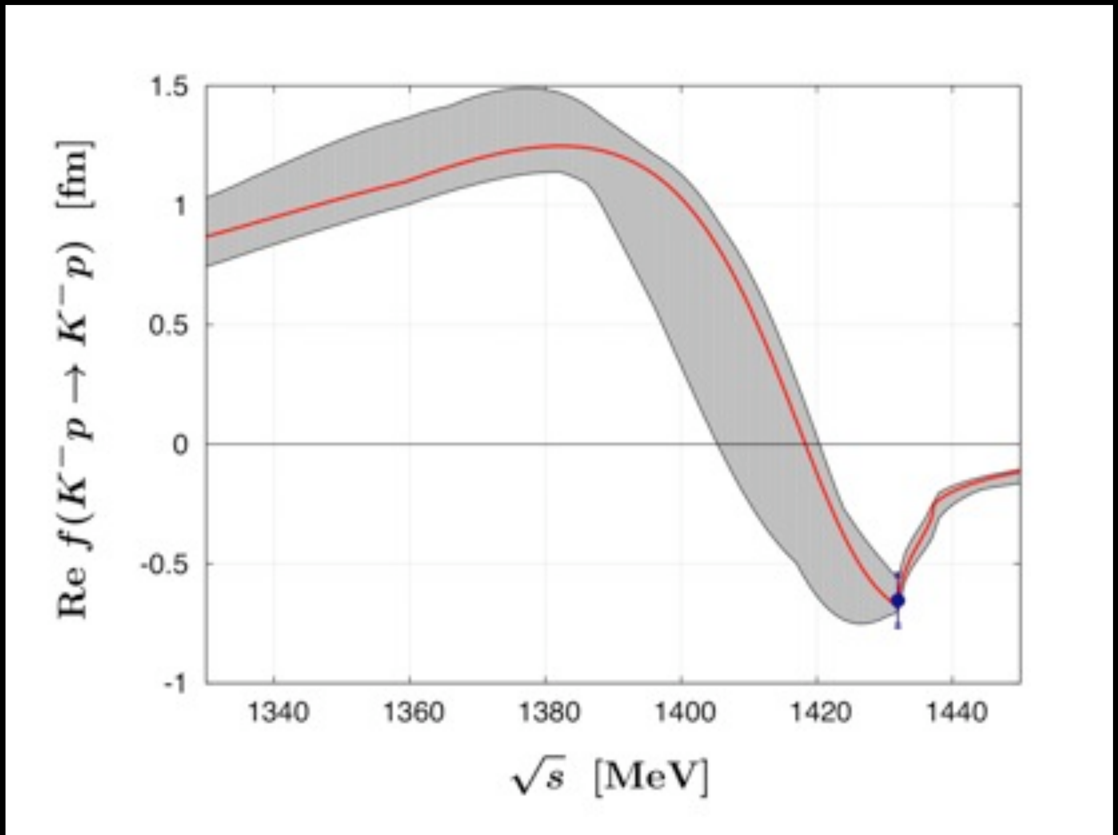
consistent with all of scattering data

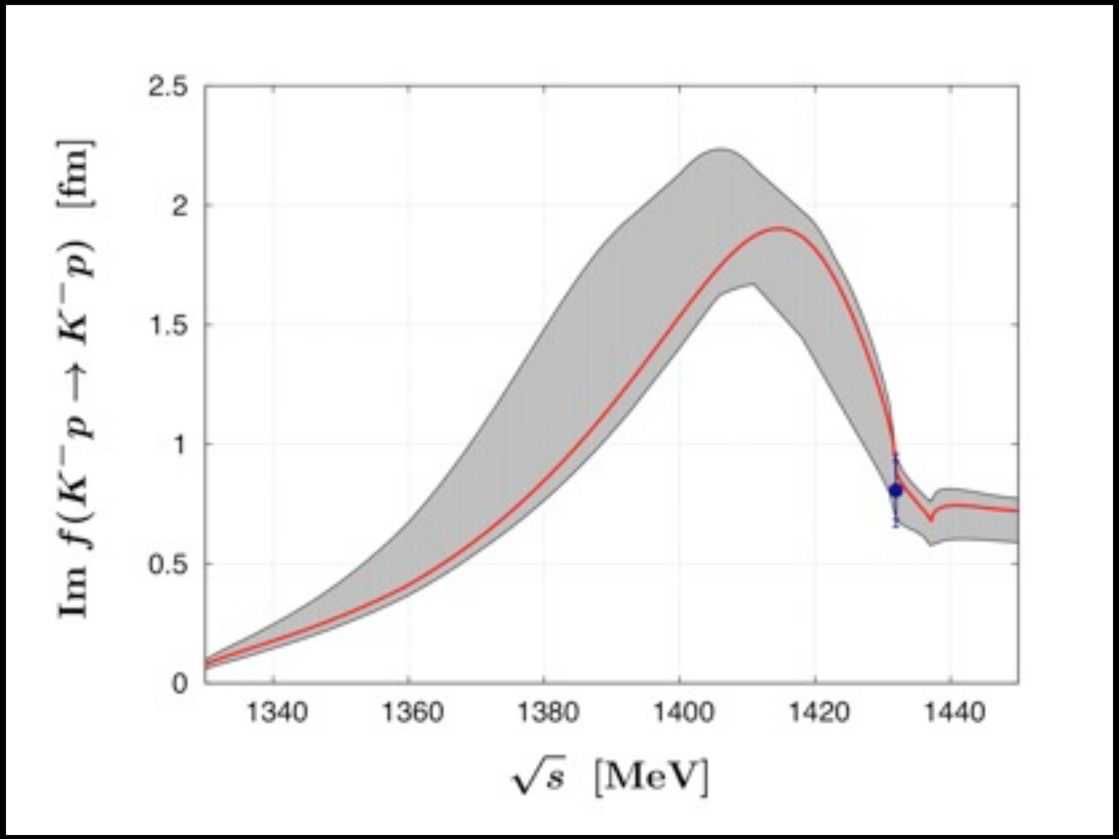
impact on K^-p --> $\pi^0\Sigma^0$ (I=0 channel) cross section

Prediction I. K^-p forward amplitudes

K^-p forward amplitudes near threshold and subthreshold extrapolation

$$f_{ij}(\sqrt{s}) = \frac{1}{8\pi\sqrt{s}} T_{ij}(\sqrt{s})$$





Uncertainties considerably reduced from previous studies

Nissler, PhD thesis (2008)

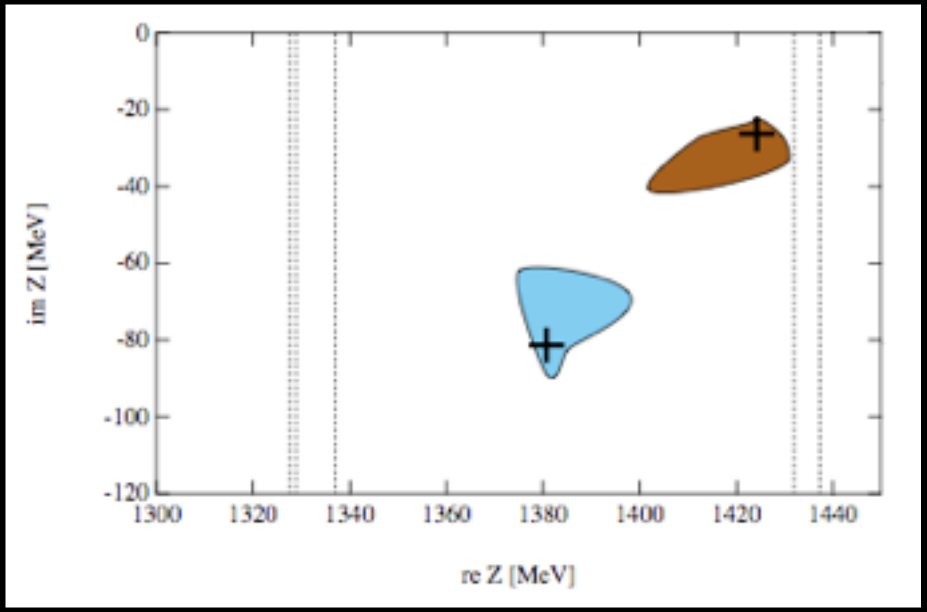
Borasoy, Nissler, Weise, EPJA25(2005).

Brasoy, Meissner, Nissler, PRC74(2006).

--> basic input on K^{bar} bound states (Kaonic nuclei)

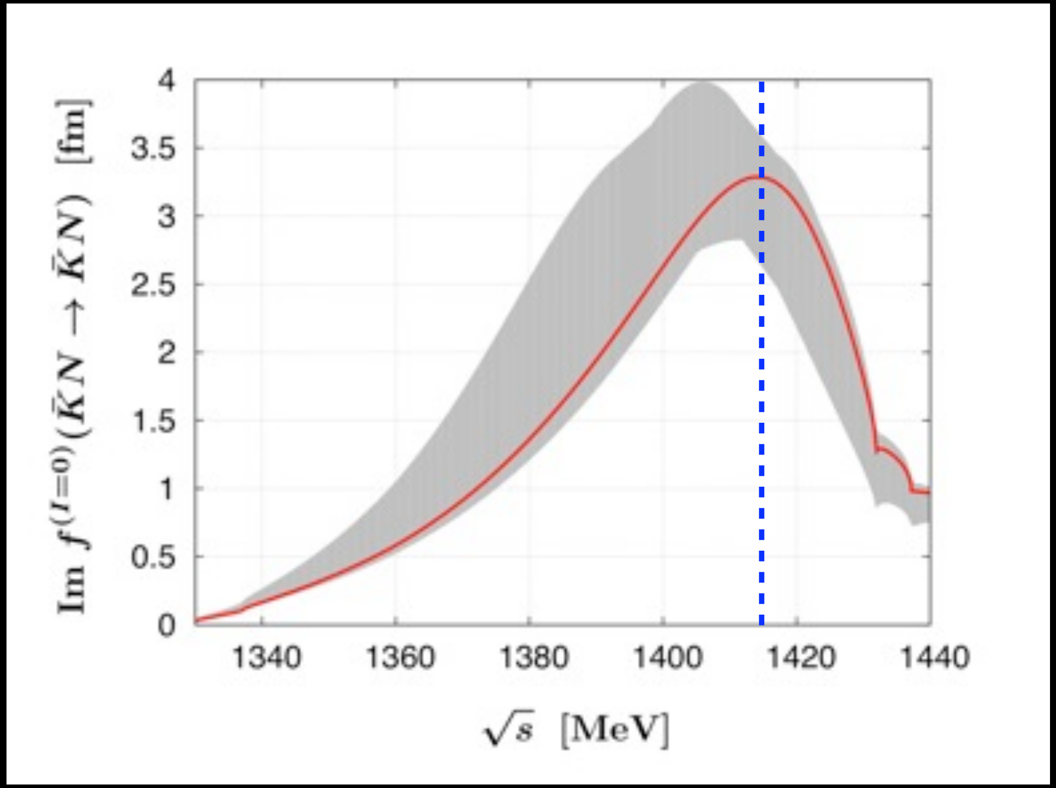
Prediction II. Λ(1405) pole positions

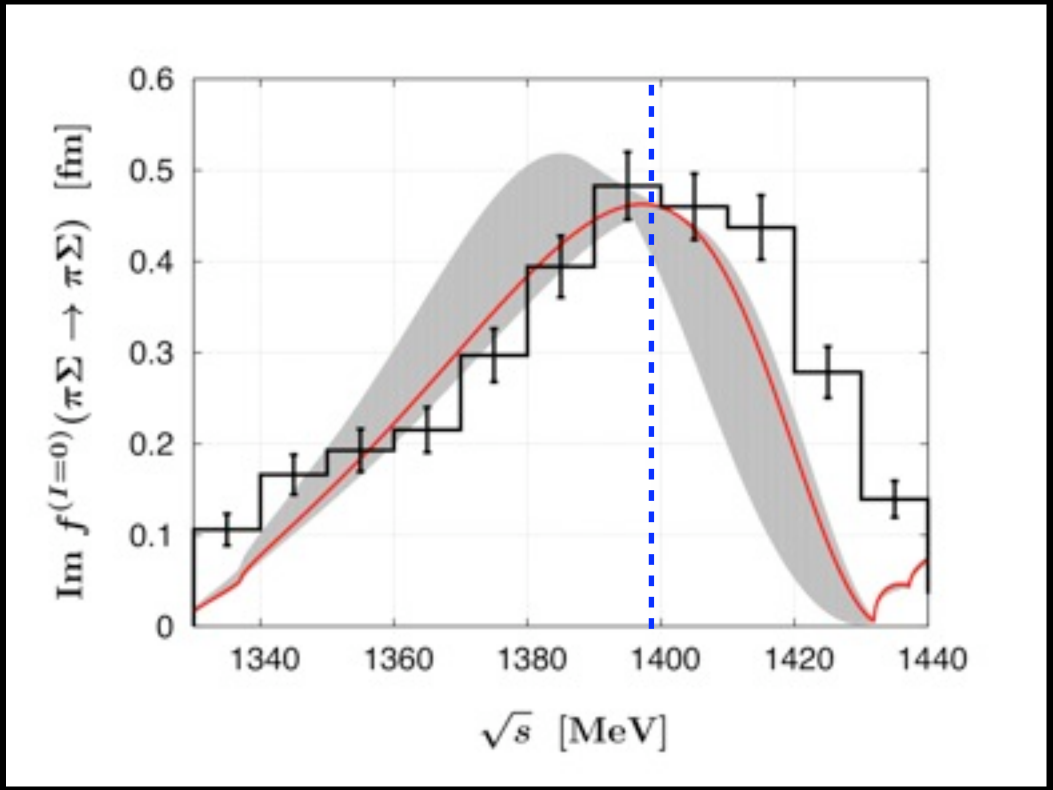
Pole of amplitudes --> resonance energy (mass, width)



Two-pole nature --> channel dependence of mass spectra

Jido et al., NPA723, 205 (2003).





Reaction models to compare with experiments (HADES, CLAS, J-PARC, ...)

Summary

Updated analysis of coupled-channels chiral SU(3) dynamics w/ SIDDHARTA result

Leading order (Tomozawa-Weinberg terms) : dominant contributions
NLO : fine tuning for kaonic hydrogen (small NLO parameters)

Impact on physics involving K^{bar} meson

Update amplitudes : uncertainties considerably reduced
--> Useful for studies of K^{bar} nuclei
More improvements :
πΣ scattering? (heavy baryon decay + LQCD input --> Hyodo's talk)
K^-d atom experiment? (K^-p + K^-n <-> I=0, 1 amplitudes constructed)

Our on-going work

Construct effective potential models
Systematic studies of few-body systems
(energy of K-pp system, K-d scattering, ...)