$\bar{K}N$相互作用と$\Lambda(1405)$

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$\bar{K}$ meson and $\bar{K}N$ interaction

Two aspects of $K(\bar{K})$ meson

- **NG boson of chiral $SU(3)_R \otimes SU(3)_L$ --> $SU(3)_V$**
- **massive by strange quark: m_K ~ 496 MeV**

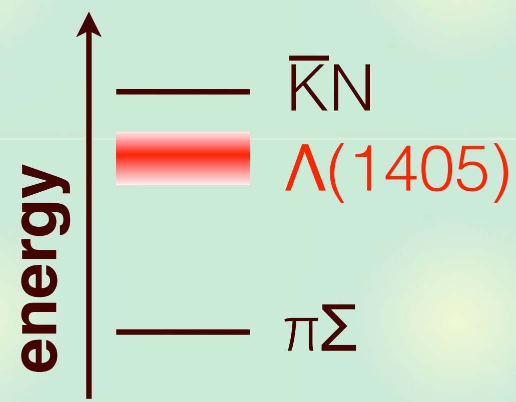
--> spontaneous/explicit symmetry breaking

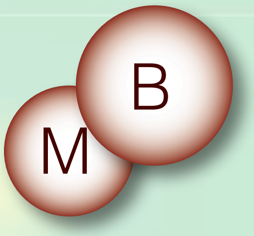
$\bar{K}N$ interaction ...

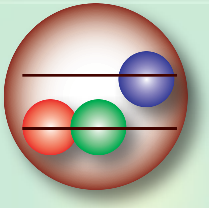
- **is coupled with $\pi\Sigma$ channel**
- **has a resonance below threshold**

--> $\Lambda(1405)$

meson-baryon v.s. qqq state, ...







- **is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...**

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

$\bar{K}$ nuclei v.s. normal nuclei

$\bar{K}N$ interaction

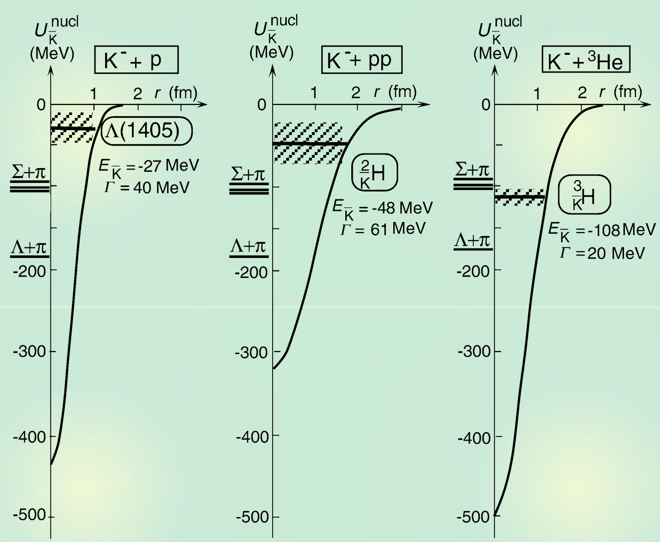
- **strong attraction**
- **no repulsive core?**

	I=0	I=1
NN	**deuteron (2 MeV)**	**attractive**
$\bar{K}N$	Λ(1405) **(15-30 MeV)**	**attractive**

--> (quasi-)bound $\bar{K}$ in nuclei

Y. Nogami, Phys. Lett. 7, 288, (1963)

T. Yamazaki, Y. Akaishi, Phys. Lett. B535, 70 (2002)



--> we need a realistic $\bar{K}N$ interaction!

Constraints for $\bar{K}N$ interaction

K^-p **total cross sections to** K^-p, $\bar{K}^0n$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$, $\pi^0\Lambda$.

- **old experiments, large error bars, some contradictions**
- **wide energy range above the threshold**

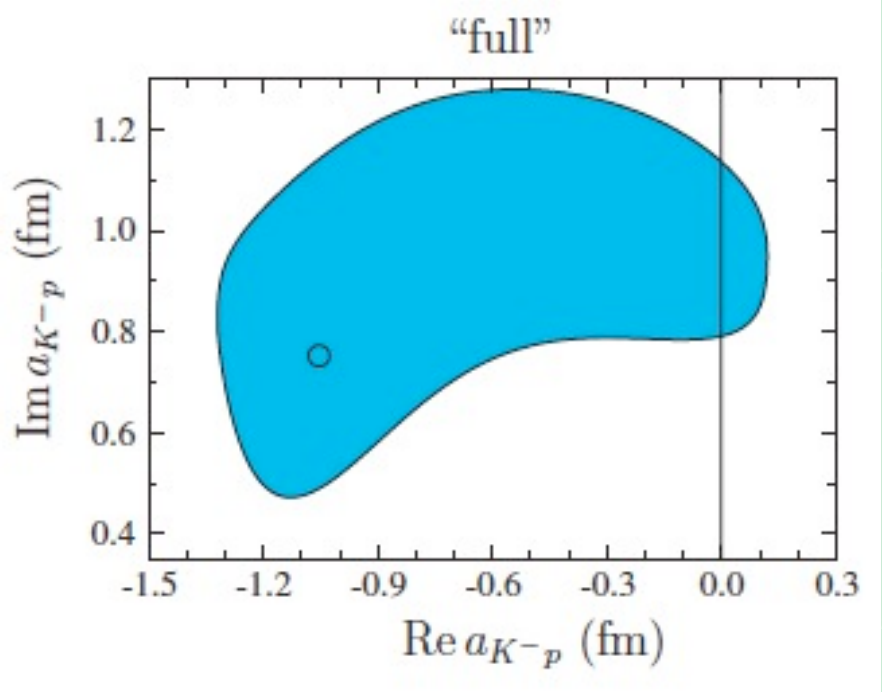
Threshold branching ratios

- **very accurate**
- **only at** $W = m_{K^-} + M_p$

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

$$R_c = \frac{\Gamma(K^-p \to \text{charged})}{\Gamma(K^-p \to \text{all})} = 0.664 \pm 0.011,$$

$$R_n = \frac{\Gamma(K^-p \to \pi^0\Lambda)}{\Gamma(K^-p \to \text{neutral})} = 0.189 \pm 0.015,$$



Determination of the scattering length by these constraints

B. Borasoy, U.G. Meissner, R. Nissler, Phys. Rev. C 74, 055201 (2006)

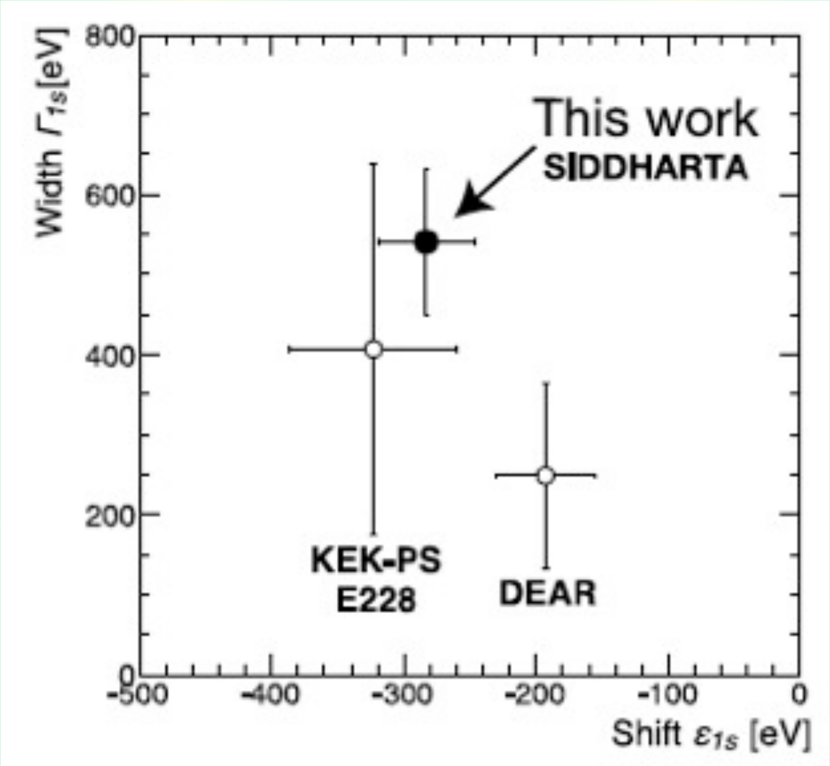
--> large uncertainty!

SIDDHARTA measurement

Measurements of the kaonic hydrogen

- **shift and width of atomic state <--> K-p scattering length**
- **SIDDHARTA experiment**

M. Bazzi, *et al.*, Phys. Lett. B704, 113 (2011)



--> New constraint on the $\bar{K}N$ interaction

Contents

Chiral unitary approach

Description of S = -1, $\bar{K}N$ s-wave scattering: Λ(1405) in I = 0

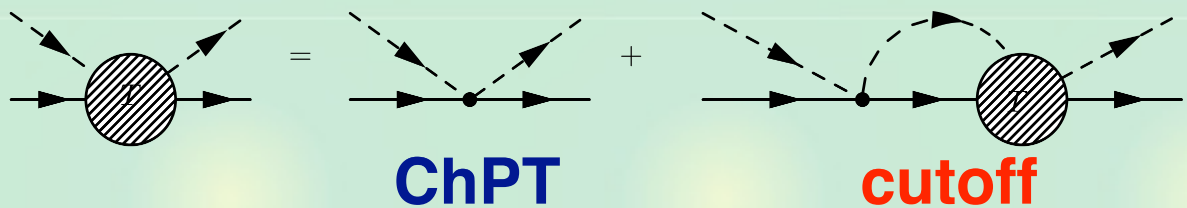
- **Interaction <-- chiral symmetry**

  Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

- **Amplitude <-- unitarity in coupled channels**

  R.H. Dalitz, T.C. Wong, G. Rajasekaran, Phys. Rev. 153, 1617 (1967)

$$T = \frac{1}{1 - VG} V$$



(c.f. Chiral EFT for nuclear force)

N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

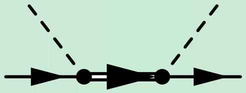
It works successfully in various hadron scatterings.

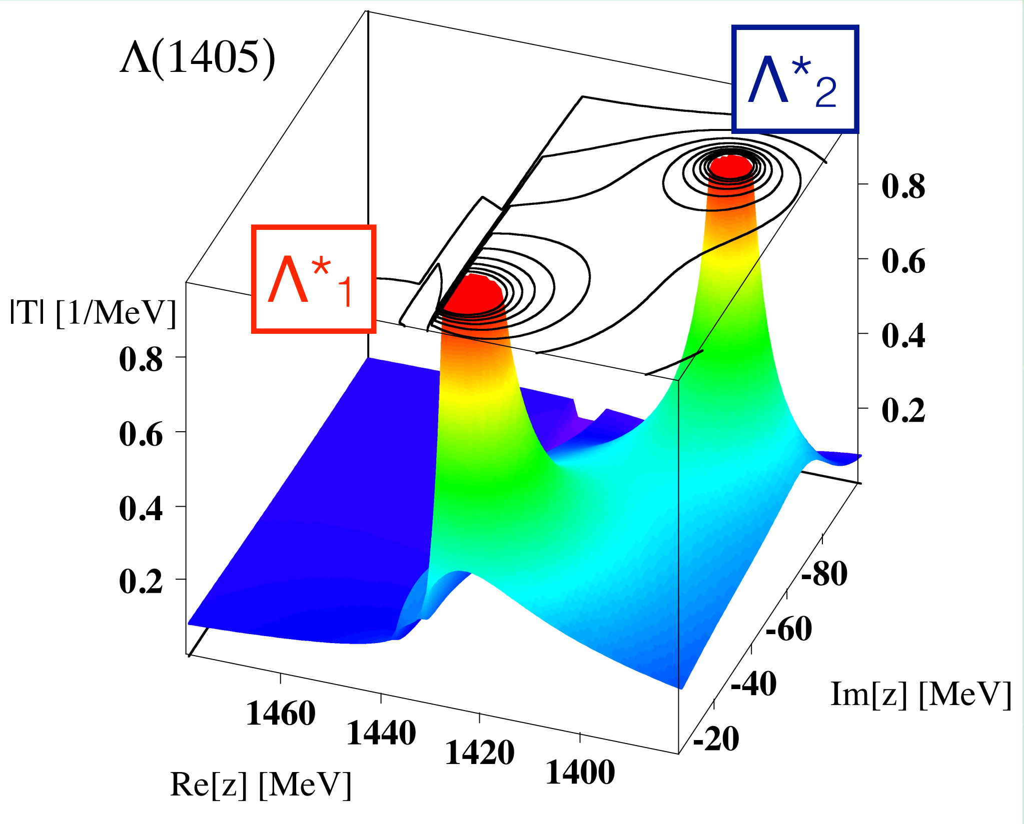
Pole structure in the complex energy plane

Resonance state ~ pole of the scattering amplitude

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A723, 205 (2003)

$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$

$\sim$ 



T. Hyodo, D. Jido, PPNP 67, 55 (2012)

Two poles for one resonance (bump structure)

--> Superposition of two states ?

Coupling properties:

Λ^*_1 ~ $\bar{K}N$ channel, Λ^*_2 ~ $\pi\Sigma$ channel

Origin of the two-pole structure

Leading order chiral interaction for K̄N-πΣ channel

T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

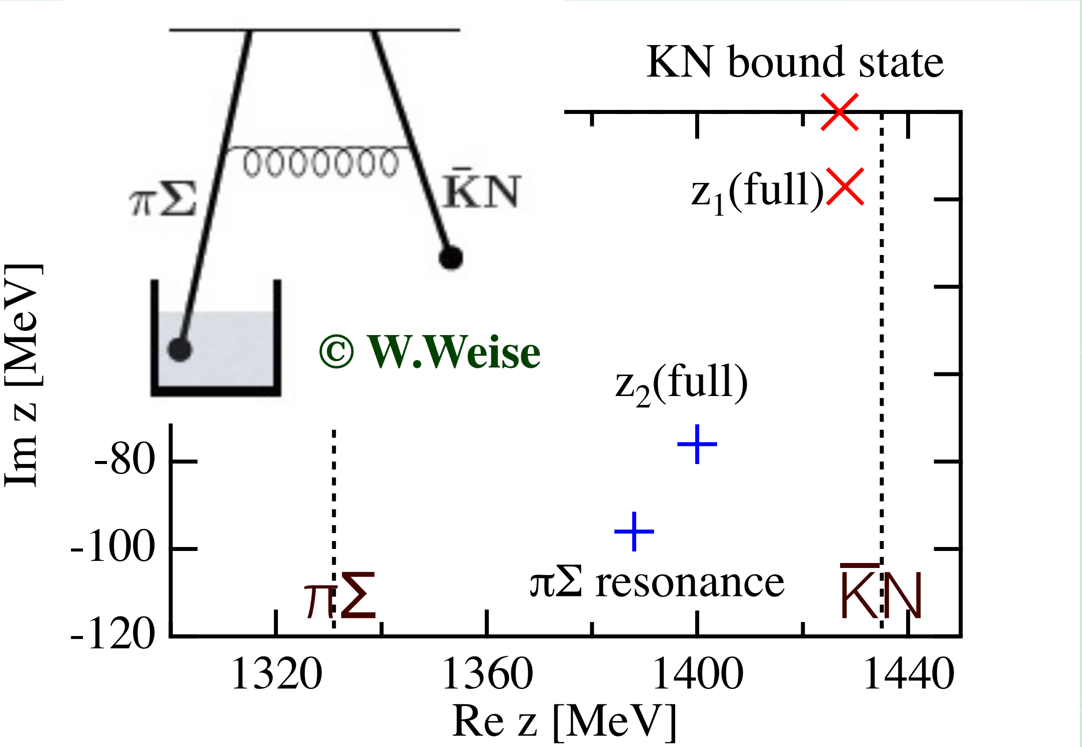
$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

$$\begin{array}{cc} & \begin{array}{cc} \bar{K}N & \pi\Sigma \end{array} \\ C_{ij} = & \begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix} \end{array}$$

at threshold

$$\omega_i \sim m_i, \quad 3.3m_\pi \sim m_K$$

$$\Rightarrow V_{\bar{K}N} \sim 2.5V_{\pi\Sigma}$$



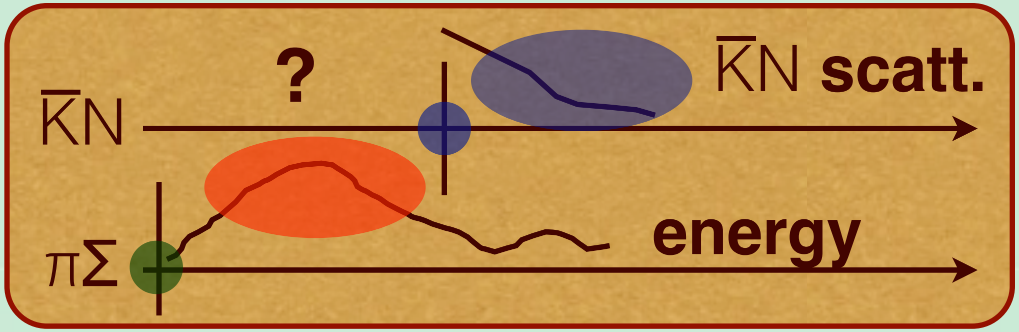
Very strong attraction in K̄N (higher energy) --> bound state
Strong attraction in πΣ (lower energy) --> resonance

Model dependence? Effects from higher order terms?

Experimental constraints for S=-1 MB scattering

K-p total cross sections

$\bar{K}N$ threshold branching ratios, K-p scattering length



$\pi\Sigma$ mass spectra

- **New data is now available (LEPS, HADES, CLAS, ...)**
- **No model-independent way to relate two-body amplitude.**
- **Consistency of the result should be checked.**

$\pi\Sigma$ scattering length (no data at present)

Y. Ikeda, T. Hyodo, D. Jido, H. Kamano, T. Sato, K. Yazaki, PTP 125, 1205 (2011);
T. Hyodo, M. Oka, Phys. Rev. C 83, 055202 (2011)

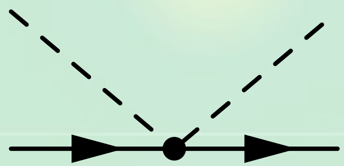
Construction of the realistic amplitude

Systematic χ^2 fitting with SIDDHARTA data

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B706, 63 (2011); Nucl. Phys. A881 98 (2012);

- Interaction kernel: NLO ChPT

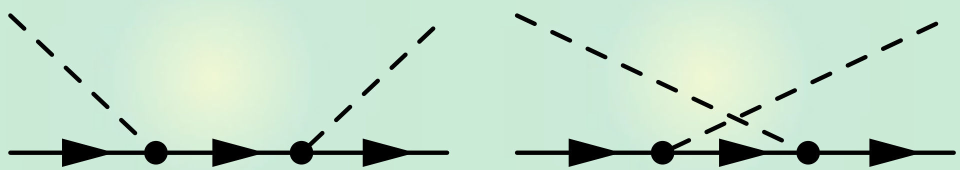
1) TW term



$\mathcal{O}(p)$

TW model

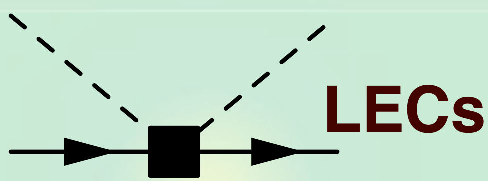
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



$\mathcal{O}(p^2)$

NLO model

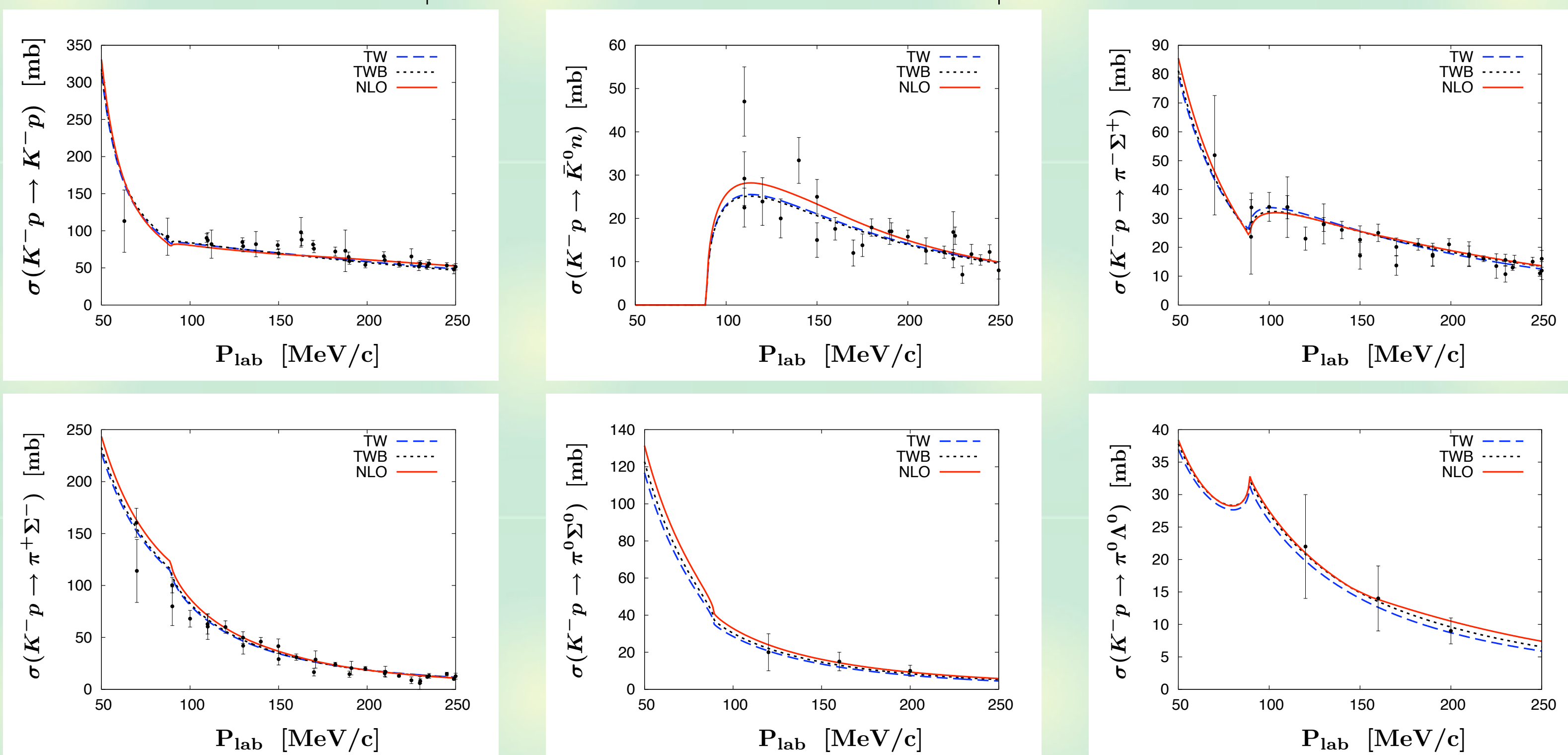
Parameters: 6 cutoffs (+ 7 low energy constants in NLO)

2. Realistic $\bar{K}N$-$\pi\Sigma$ interaction with SIDDHARTA

Best-fit results

		TW	TWB	NLO	Experiment	
K-p	ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[10]
	Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[10]
BR	γ	2.36	2.36	2.37	2.36 ± 0.04	[11]
	R_n	0.20	0.19	0.19	0.189 ± 0.015	[11]
	R_c	0.66	0.66	0.66	0.664 ± 0.011	[11]
	χ^2/d.o.f	1.12	1.15	0.96		

cross sections

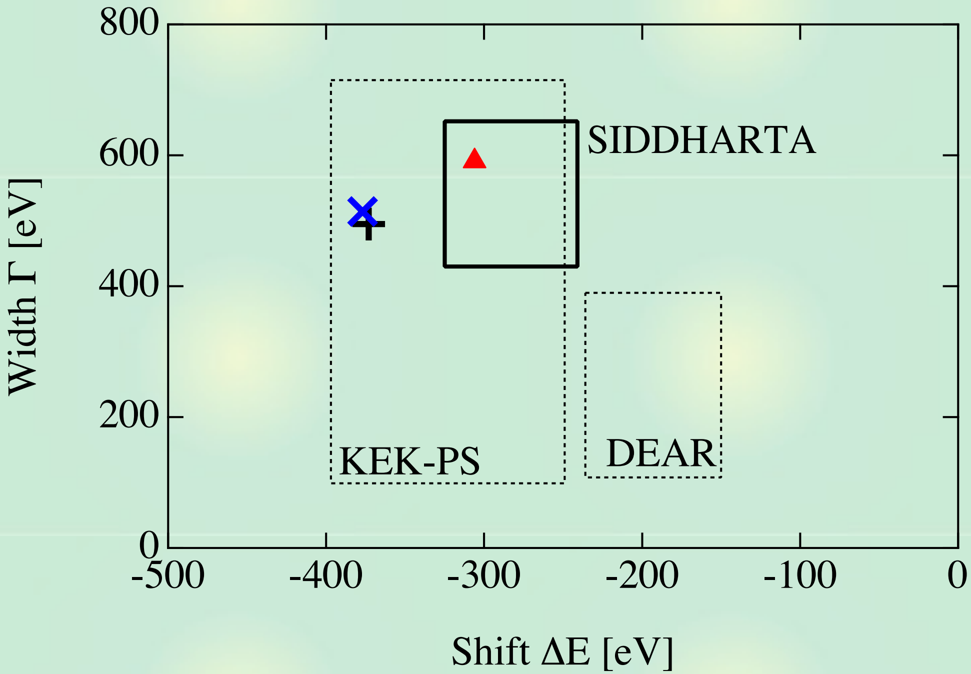


Good χ2: SIDDHARTA is consistent with cross sections

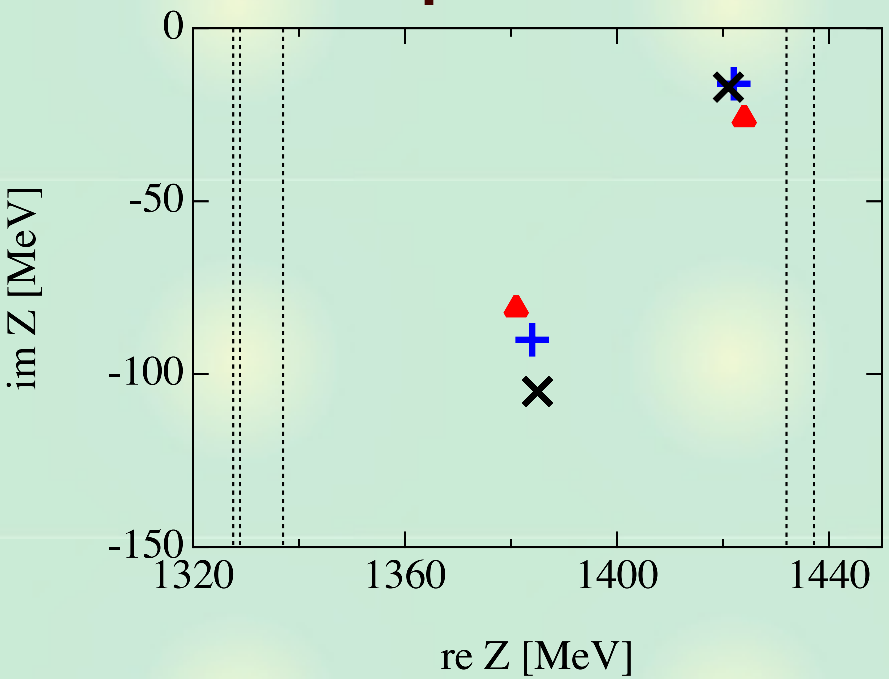
Shift, width, and pole positions

	TW	TWB	NLO
χ^2/d.o.f.	1.12	1.15	0.957

Shift and width



Pole positions

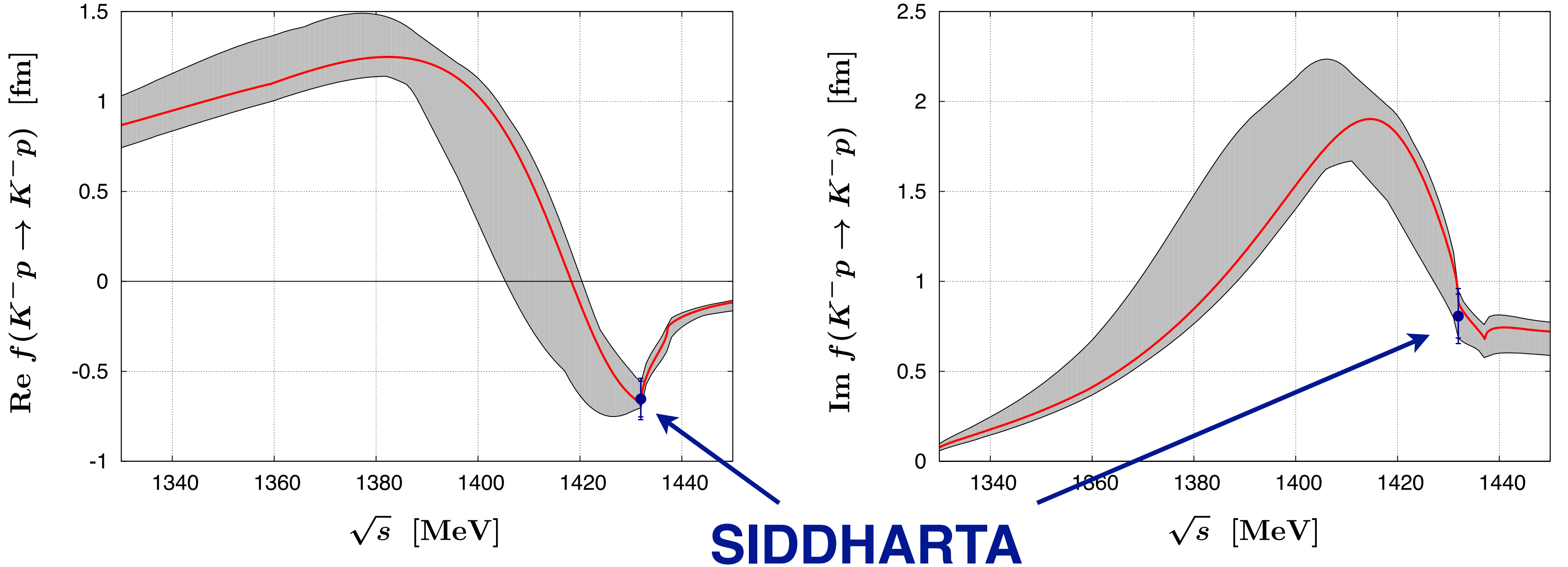


TW and TWB are reasonable, while best-fit requires NLO.
Pole positions are now converging.

Subthreshold extrapolation

Behavior of K-p amplitude below threshold

- Properties (structure) of Λ(1405)
- $\bar{K}$ bound state in nucleus ($\bar{K}N$ interaction)



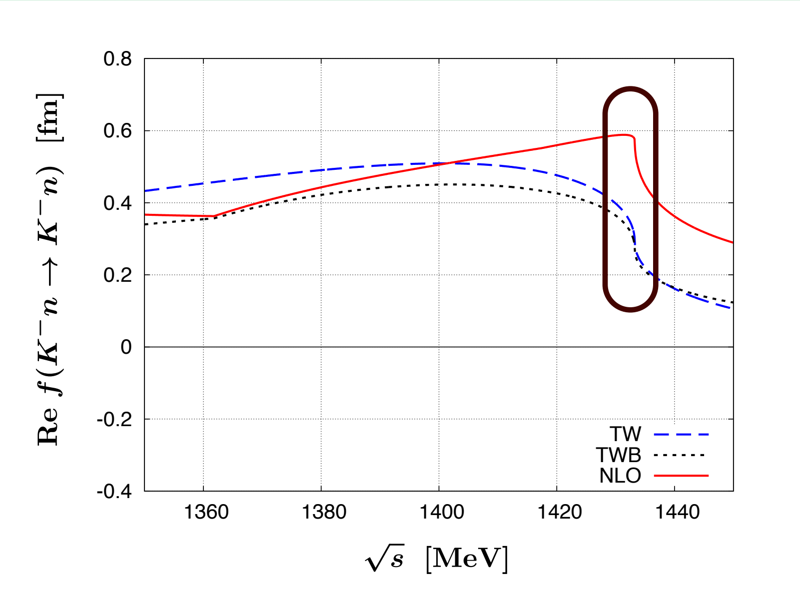
Ambiguity is significantly reduced.

Remaining ambiguity

For $\bar{K}$-nucleon interaction, we need both K-p and K-n.

$$a(K^-p) = \frac{1}{2}a(I=0) + \frac{1}{2}a(I=1) + \dots, \quad a(K^-n) = a(I=1) + \dots$$

$$a(K^-n) = 0.29 + i0.76 \text{ fm} \quad (\text{TW}) \quad ,$$
$$a(K^-n) = 0.27 + i0.74 \text{ fm} \quad (\text{TWB}) \quad ,$$
$$a(K^-n) = 0.57 + i0.73 \text{ fm} \quad (\text{NLO}) \quad .$$



Some deviation: constraint on K-n? (<-- kaonic deuterium?)

J=0 $\bar{K}NN$ system

Theoretical calculations of $\bar{K}NN$ system (~ K^-pp)

	SGM07	IS07	YA07	DHW09	IKS10*	BGL12
Method	Fadd.	Fadd.	Var.	Var.	Fadd.	Var.
$\bar{K}N$ int.	E-indep	E-indep	E-indep	E-dep	E-dep	E-dep
$B_{\bar{K}NN}$ [MeV]	55-70	60-95	48	17-23	9-16	15.7
$\Gamma_{\pi YN}$ [MeV]	90-110	45-80	61	40-70	34-46	41.2

N.V. Shevchenko, A. Gal, J. Mares, Phys. Rev. Lett. 98, 082301 (2007),
Y. Ikeda, T. Sato, Phys. Rev. C76, 035203 (2007),
T. Yamazaki, Y. Akaishi, Phys. Rev. C76, 045201 (2007),
A. Dote, T. Hyodo, W. Weise, Phys. Rev. C79, 014003 (2009),
Y. Ikeda, Kamano, T. Sato, Prog. Thoer. Phys. 124, 533 (2010),
* there is another pole at B = 67-89 MeV with large width.
N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B712 (2012)

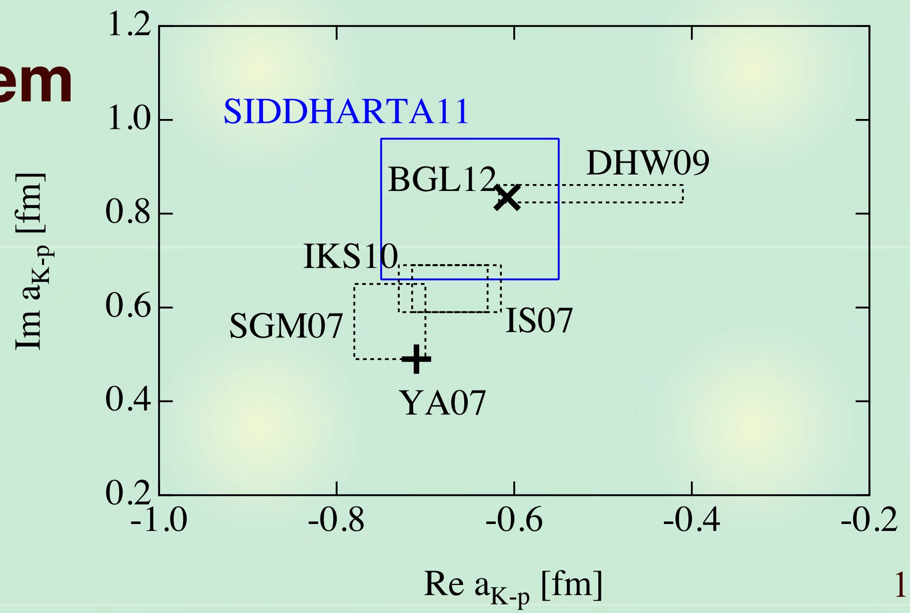
$\bar{K}NN$ system forms a quasi-bound state with large width.

Comparison of K-p scattering length

Theoretical calculations of $\bar{K}NN$ system (~ K-pp)

	SGM07	IS07	YA07	DHW09	IKS10	BGL12
Method	Fadd.	Fadd.	Var.	Var.	Fadd.	Var.
$\bar{K}N$ int.	E-indep	E-indep	E-indep	E-dep	E-dep	E-dep
$B_{\bar{K}NN}$ [MeV]	55-70	60-95	48	17-23	9-16	15.7
$\Gamma_{\pi YN}$ [MeV]	90-110	45-80	61	40-70	34-46	41.2

- **New constraint on $\bar{K}NN$ system**
- **SIDDHARTA11 is obtained by the improved DT formula**
- **Models: isospin symmetric. Breaking is important at th.**



J=1 $\bar{K}NN$ system

J=1 system (~ K^-d)

- $I_{NN}=0$ --> $\bar{K}N(I=0)$:$\bar{K}N(I=1)$ = **1:3**

Small I=0 component : less attractive

	UHO11	Oset et al. (12)	BGL12
Model	Λ^*N potential	FCA	Three-body variational
$B_{\bar{K}NN}$ [MeV]	> M_{Λ^*N}	9	> M_{Λ^*N}
$\Gamma_{\pi YN}$ [MeV]	-	30	-

T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A868-869, 53 (2011)
E. Oset, *et al.*, Nucl. Phys. A881, 127 (2012)
N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B712 (2012)

Weakly bound state may appear (above Λ^*N)
--> Closely related with K^-d scattering length?

Estimation of the K-d scattering length

K-d scattering length with EFT (fixed center approximation)

U.-G. Meissner, U. Raha, A. Rusetsky, Eur. Phys. J. C35, 349 (2004)

deuteron w.f.

$$A_{Kd} = \left(1 + \frac{m_K}{M_d}\right)^{-1} \int_0^\infty dr (u^2(r) + w^2(r)) \hat{a}_{kd}(r)$$

$\bar{\mathrm{K}}$N scattering lengths

$$\hat{a}_{kd}(r) = \frac{\tilde{a}_p + \tilde{a}_n + (2\tilde{a}_p\tilde{a}_n - b_x^2)/\tilde{r} - 2b_x^2\tilde{a}_n/\tilde{r}^2}{1 - \tilde{a}_p\tilde{a}_n/\tilde{r}^2 + b_x^2\tilde{a}_n/\tilde{r}^3} + \delta\hat{a}_{kd}$$

NLO model + I=1 prediction + deuteron w.f.

- s-wave only

$$A_{Kd} = -1.48 \pm 0.19 + i(1.35 \pm 0.24)\ \mathrm{fm}$$

- realistic wave function (CD-Bonn)

$$A_{Kd} = -1.54 + i1.64\ \mathrm{fm}$$

- three-body calculation...

Y. Ikeda, T. Hyodo, W. Weise, work in progress

σ term and QCD

Definition of the nucleon σ term:

See T.P. Cheng and L.F. Li, *Gauge theory of elementary particle physics*, 5.4, 5.5

$$\sigma \sim \lim_{\text{soft}} \mathrm{F.T.}\langle N | [A_0, \partial^\mu A_\mu] | N \rangle$$

- **commutator of axial current and its divergence.**
- **zero, if no explicit breaking.**

Relation to QCD

$$\sigma \sim \mathrm{F.T.}\langle N | [A_0, [\mathcal{H}_{\mathrm{QCD}}, A_0]] | N \rangle \sim \langle N | [Q_5, [Q_5, m_q \bar{q} q]] | N \rangle \sim m_q \langle N | \bar{q} q | N \rangle$$

- **quark content of hadron**
- Q=0 **of the scalar form factor**

Lattice QCD data + Feynman-Hellmann theorem

P.E. Shanahan, A.W. Thomas, R.D. Young, arXiv:1205.5365 [nucl-th]

$$\sigma_{\pi N} = \bar{m}\langle N | \bar{u}u + \bar{d}d | N \rangle = \bar{m}\frac{\partial M_N}{\partial \bar{m}} = 45 \pm 6 \text{ MeV}$$

$$\sigma_s = m_s \langle N | \bar{s}s | N \rangle = m_s \frac{\partial M_N}{\partial m_s} = 21 \pm 6 \text{ MeV}$$

σ term and πN scattering

Relation to πN scattering amplitude

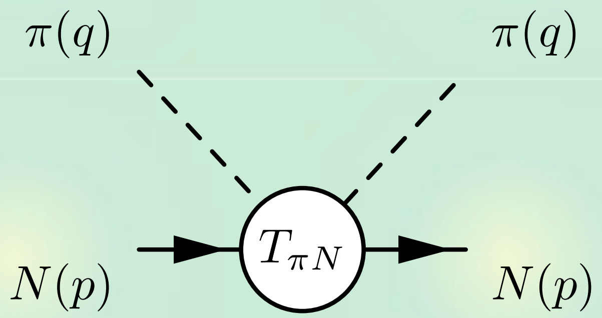
- **Nucleon matrix element : chiral Ward identity**

$$\partial^\mu \partial^\nu T(A_\mu A_\nu) = T(\partial^\mu A_\mu \partial^\nu A_\nu) + \delta(x_0 - y_0)[A_0, \partial^\nu A_\nu] - \partial^\mu \left(\delta(x_0 - y_0)[A_\mu, A_0]\right)$$

- **PCAC,** [A,A]=V**, forward scattering, soft limit (**q^2 --> 0**)**

$$i g_A^2 \nu = -i f_\pi^2 T_{\pi N}(\nu) - i\sigma + i\nu \qquad \nu = \frac{p \cdot q}{M} = E_\pi^{\mathrm{lab}}$$

Born terms **σ term** **WT term**



Amplitude at ν=0 : σ term

$$\sigma = -f_\pi^2 T_{\pi N}(\nu = 0, q^2 = 0)$$

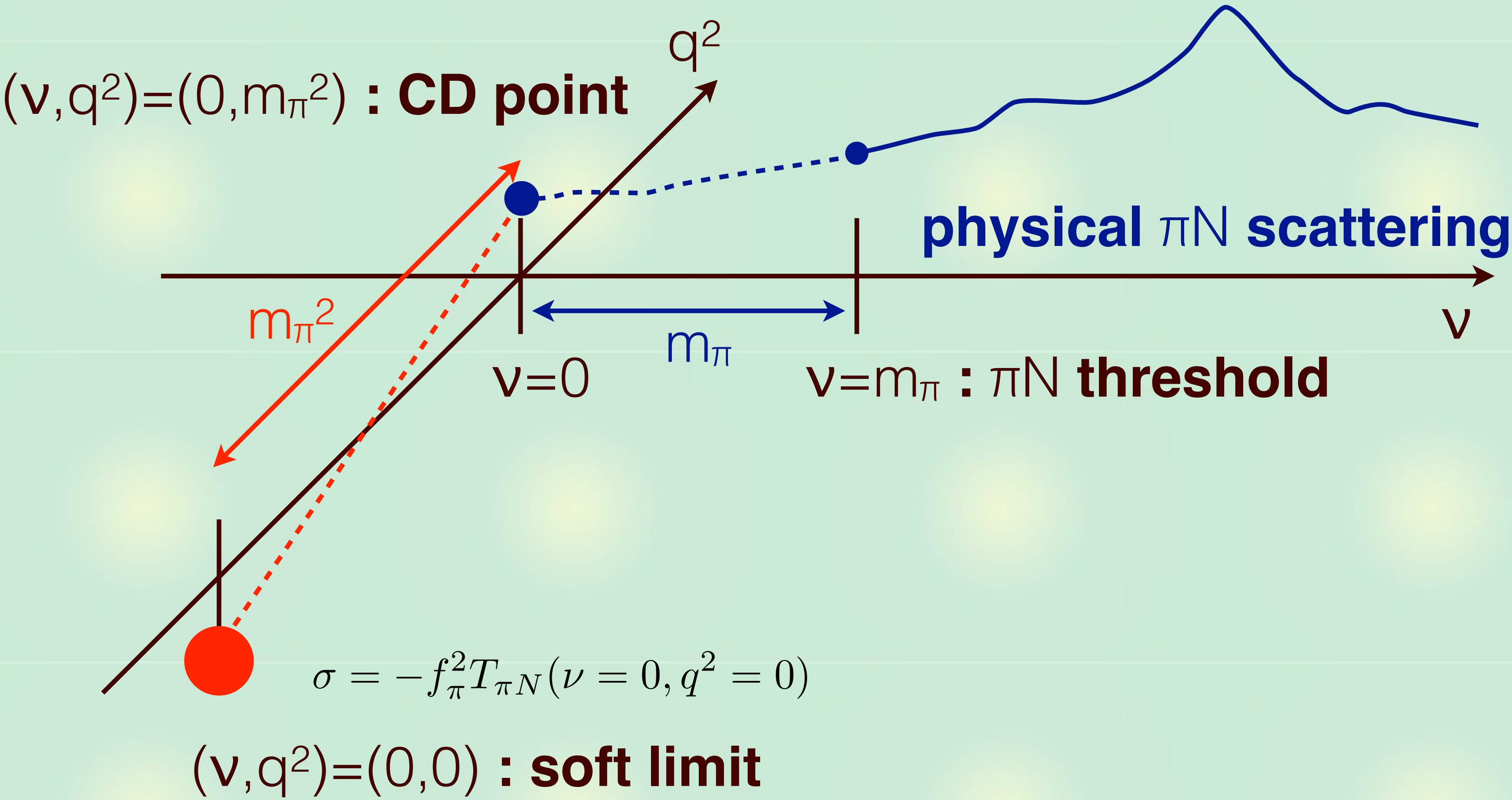
Adler consistency condition

$$\sigma = -f_\pi^2 T_{\pi N}(\nu = 0, q^2 = 0) = f_\pi^2 T_{\pi N}(\underline{\nu = 0, q^2 = m_\pi^2}) + \mathcal{O}(m_\pi^4)$$

- **amplitude at Cheng-Dashen point (**E_π --> 0 **with on-shell)**

σ term and πN scattering

Schematic illustration of the extrapolation



Long way to the amplitude at soft limit ~ m_π

σ term and $\bar{K}N$(KN) scattering

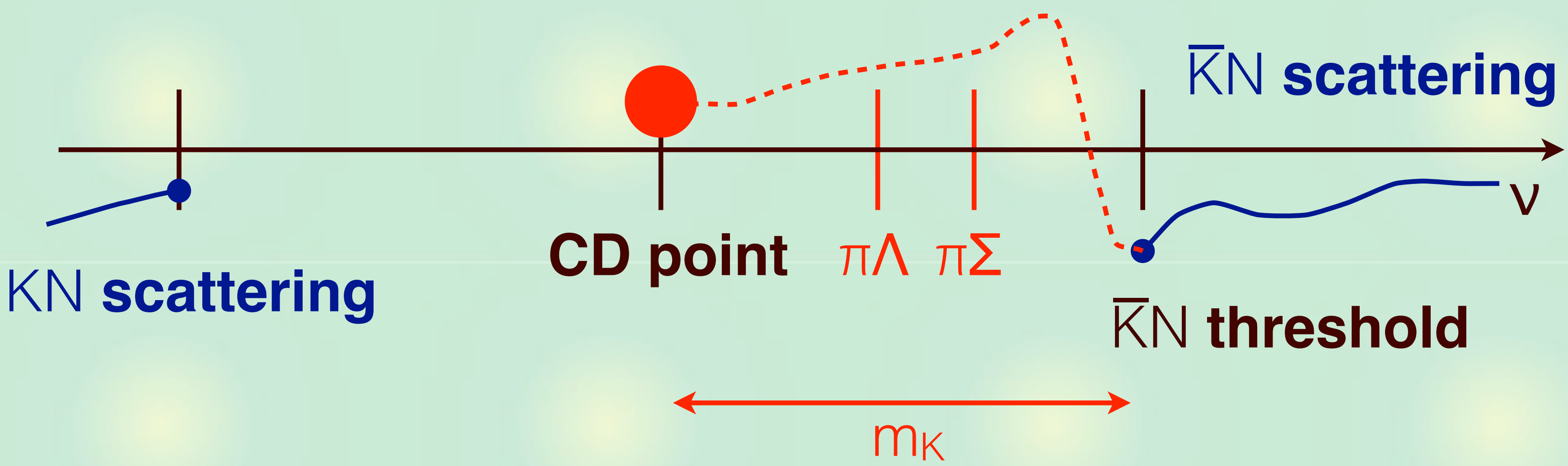
$\bar{K}N$ scattering case:

$$T_{\bar{K}N} = T^{\rm IS} + T^{\rm IV}\vec{\tau}_{\bar{K}}\cdot\vec{\tau}_N, \quad T^{\rm IS} = \frac{1}{2}(T^{K^-p} + T^{K^-n}), \quad T^{\rm IV} = \frac{1}{2}(-T^{K^-p} + T^{K^-n})$$

$$\sigma^{\rm IS} = \frac{\bar{m}+m_s}{4}\langle N|\bar{u}u + \bar{d}d + \underline{2\bar{s}s}|N\rangle, \quad \sigma^{\rm IV} = \frac{\bar{m}+m_s}{4}\langle N|\underline{\bar{u}u - \bar{d}d}|N\rangle$$

isospin breaking

- m_π **-->** m_K **: much longer extrapolation**
- $\pi\Sigma$ **and** $\pi\Lambda$ **channels below** $\bar{K}N$
- **existence of** $\Lambda(1405)$



low energy KN **scattering (no resonance, no threshold,...)?**

Summary 1

We study the $\bar{K}N$-$\pi\Sigma$ interaction based on chiral coupled-channel approach.

- $\Lambda(1405)$ **is interpreted as a quasi-bound $\bar{K}N$ state in the resonating $\pi\Sigma$ continuum.**

- **Accurate K-hydrogen data help us to construct realistic $\bar{K}N$-$\pi\Sigma$ interaction. Ambiguity in subthreshold extrapolation is significantly reduced.**

Summary 2

We study the $\bar{K}N$-$\pi\Sigma$ interaction based on chiral coupled-channel approach.

- **New $\bar{K}N$ interaction will reduce uncertainties of $\bar{K}$ few-nucleon systems.**

- **Determination of KN sigma term from $\bar{K}N$ scattering is difficult. Crossed channel (KN sector) may help the extrapolation.**