Recent developments in antikaon-nucleon dynamics

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低エネルギーのQCDの難しさ／面白さ

強い相互作用はQCD（クォーク、グルーオン）で記述される

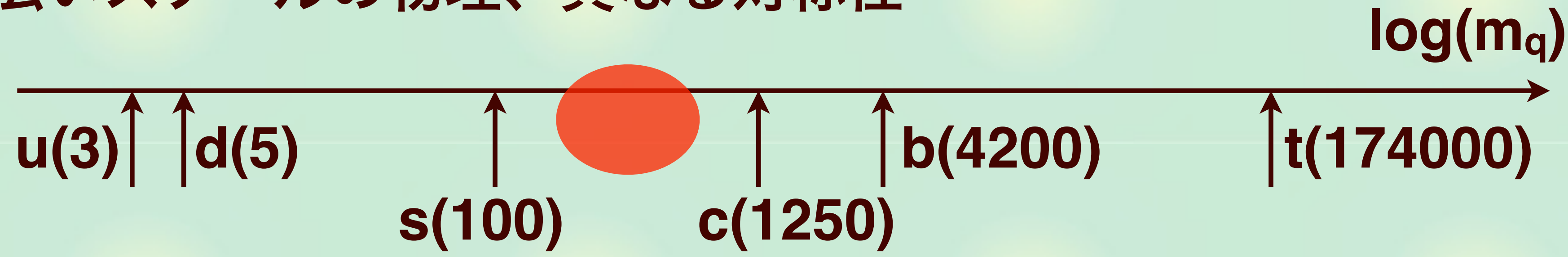
色自由度

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^{\boxed{a}}_{\mu\nu} G^{\mu\nu}_{\boxed{a}} + \bar{q}_{\boxed{\alpha}} (i\gamma^\mu D^{\boxed{\alpha\beta}}_\mu - m\delta^{\boxed{\alpha\beta}}) q_{\boxed{\beta}}$$

QCDは漸近自由性をもち、低エネルギーでは非摂動的

1. カイラル対称性の自発的破れ：真空の変化
2. カラー閉じ込め：観測される自由度はハドロン

幅広いスケールの物理、異なる対称性



$\log(m_q)$

u(3)

d(5)

s(100)

c(1250)

b(4200)

t(174000)

カイラル対称性

m_qで展開

重クォーク対称性

$1/m_q$で展開

ハドロン物理の目標

- 強い相互作用による量子多体系の諸相

既知である基礎理論をもとに、多様な物理を明らかにする（c.f. 原子核物理／核力、物性物理／QED）

例：カラー超伝導 <--> 超伝導

- 少数系での多様性：共鳴状態

約310種の観測されたハドロンのうち、強い相互作用に対して安定なのものは20ほど。残りは全てハドロン散乱内の共鳴状態としてあらわれる。

例：ポテンシャル共鳴、フェッシュバッハ共鳴、、、

導入

ハドロンの多様な性質

ハドロン：強い相互作用による自己束縛系

http://pdg.lbl.gov/

様々な質量、崩壊幅、崩壊モード

粒子の内部構造

ハドロン間の相互作用

p	$1/2^+$	****
n	$1/2^+$	****
N(1		
N(1		
N(1		
$N(1650)$	$1/2$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
N(1		
N(1		
N(1		
N(1		
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
N(1		
N(1		
N(1		
N(1		
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

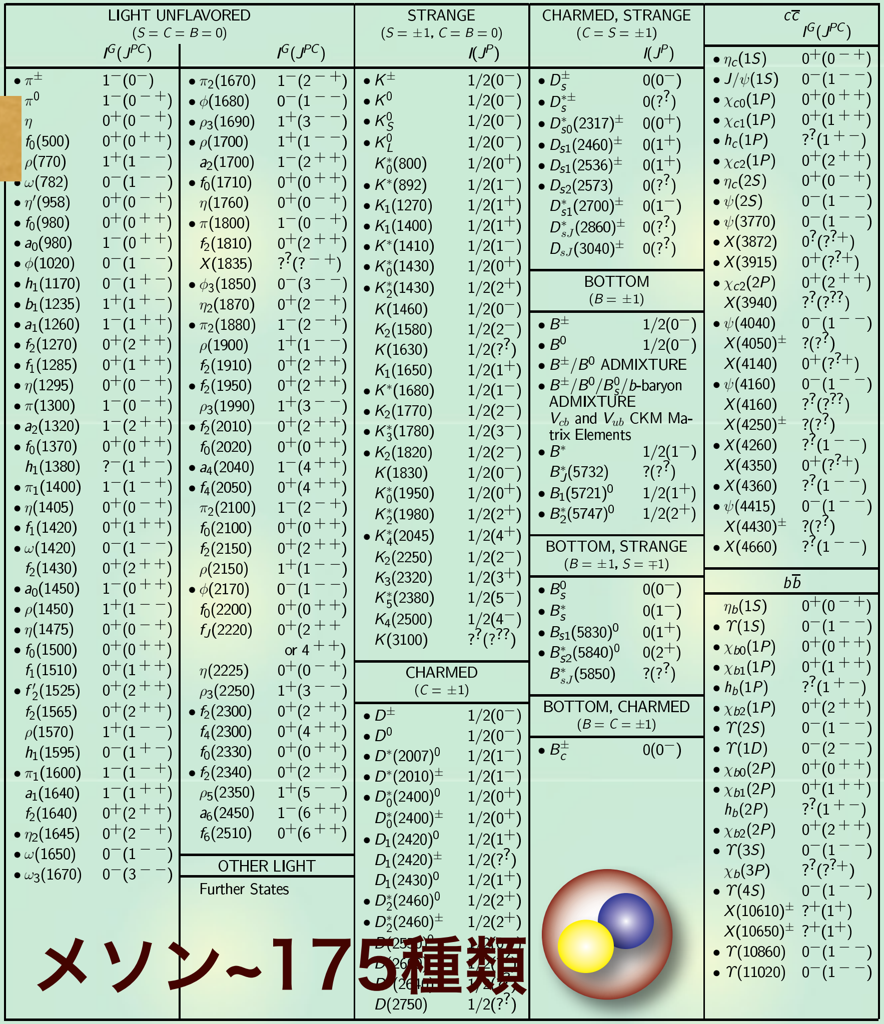
$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1900)$	$1/2$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	**
		***
		****
		**
		***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1820)$	$3/2$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
		***
		**
		**

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
Ω_b^-	$1/2^+$	***

バリオン~135種類



LIGHT UNFLAVORED
$(S = C = B = 0)$

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	• $\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$
• $f_0(1500)$	$0^+(0^{++})$		or $4^{++})$
$f_1(1510)$	$0^+(1^{++})$	$\eta(2225)$	$0^+(0^{-+})$
• $f_2'(1525)$	$0^+(2^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$f_2(1565)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_4(2300)$	$0^+(4^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$f_0(2330)$	$0^+(0^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	• $f_2(2340)$	$0^+(2^{++})$
$a_1(1640)$	$1^-(1^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$f_2(1640)$	$0^+(2^{++})$	$a_6(2450)$	$1^-(6^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

OTHER LIGHT

Further States

STRANGE
$(S = \pm1,\ C = B = 0)$

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED
$(C = \pm1)$

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(25$	
$D(26$	
$D(264$	
$D(2750)$	$1/2(?^?)$

CHARMED, STRANGE
$(C = S = \pm1)$

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
$D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{sJ}^*(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM
$(B = \pm1)$

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE
$(B = \pm1,\ S = \mp1)$

• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED
$(B = C = \pm1)$

• $B_c^\pm$	$0(0^-)$

$c\overline{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
• $X(3915)$	$0^+(?^{?+})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(?^?)$
• $X(4660)$	$?^?(1^{--})$

$b\overline{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
$\chi_b(3P)$	$?^?(?^{?+})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^\pm$	$?^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

メソン~175種類

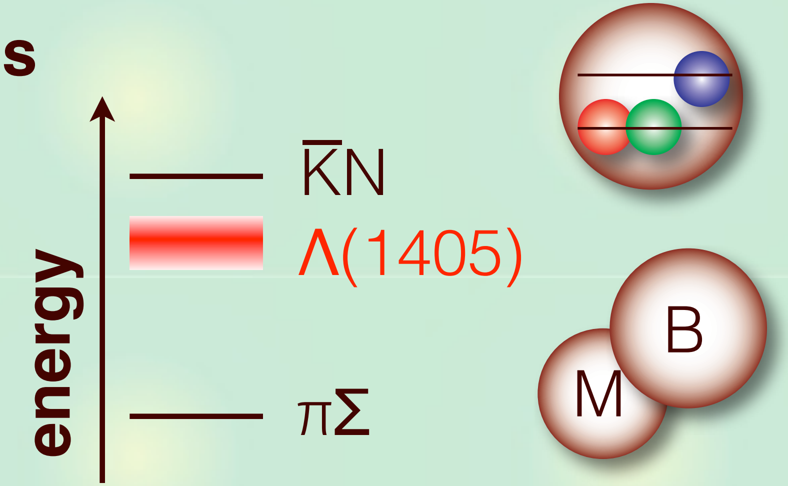
全てがQCDラグランジアンから出てくる

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

Two aspects of $K \sim u\bar{s}, d\bar{s}$ ($\bar{K} \sim \bar{u}s, \bar{d}s$) meson

- **NG boson of chiral $SU(3)_R \otimes SU(3)_L$ --> $SU(3)_V$**
- **relatively massive: $m_K \sim 495$ MeV (m_π, $M_N \sim 140, 940$ MeV)**

--> peculiar role in hadron physics



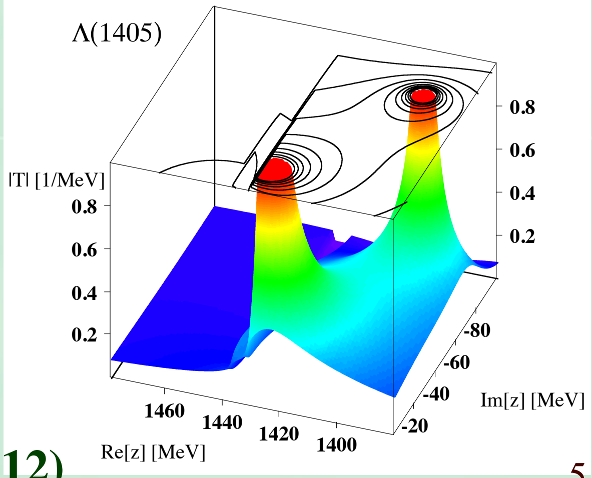
$\bar{K}N$ **interaction is ...**

- **coupled with $\pi\Sigma$ channel**
- **strongly attractive**

--> quasi-bound state $\Lambda(1405)$

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

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



T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)
兵藤哲雄、慈道大介：日本物理学会誌 第67巻第4号226 (2012)

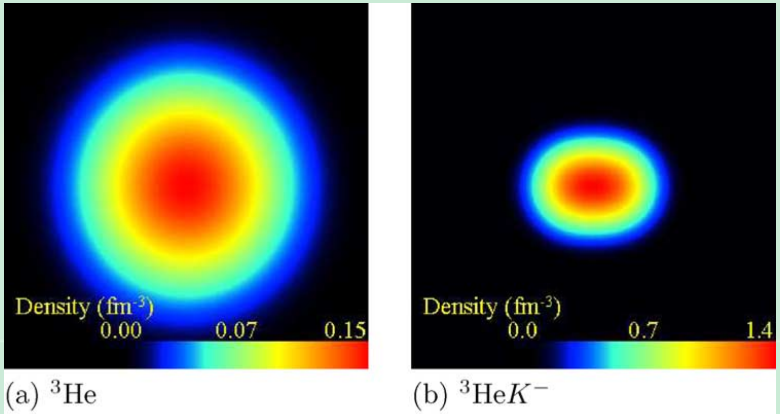
$\bar{K}$ nuclei v.s. normal nuclei

$\bar{K}$N interaction

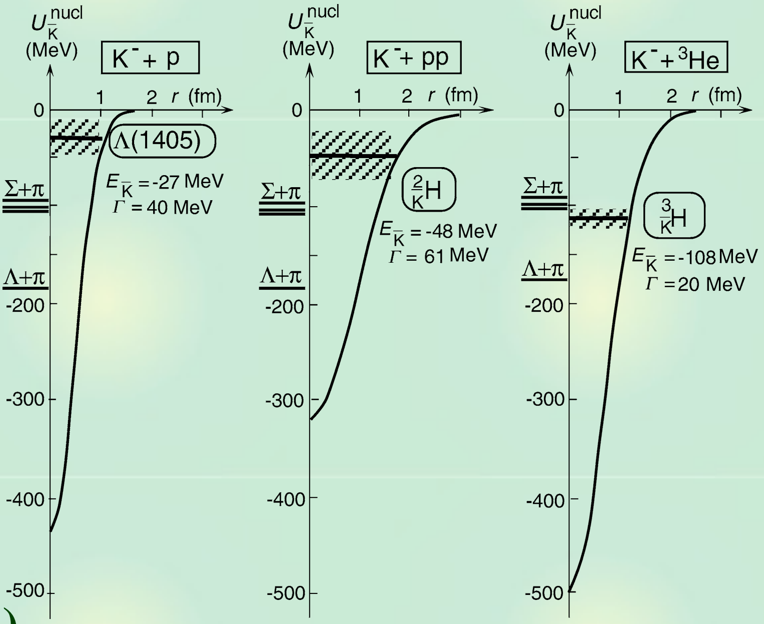
- **strong attraction**
- **no repulsive core?**

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

--> Strong binding of $\bar{K}$ in nuclei
High density (~10 ρ_0)?



(a) ^{3}He (b) ^{3}HeK^-



T. Yamazaki, Y. Akaishi, Phys. Lett. B535, 70 (2002)
A. Dote, Y. Akaishi, H. Horiuchi, T. Yamazaki, Phys. Lett. B590, 51 (2004)

--> $\bar{K}$N interaction: fundamental interaction in $\bar{K}$ nuclei

Constraints for $\bar{K}$N interaction

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

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

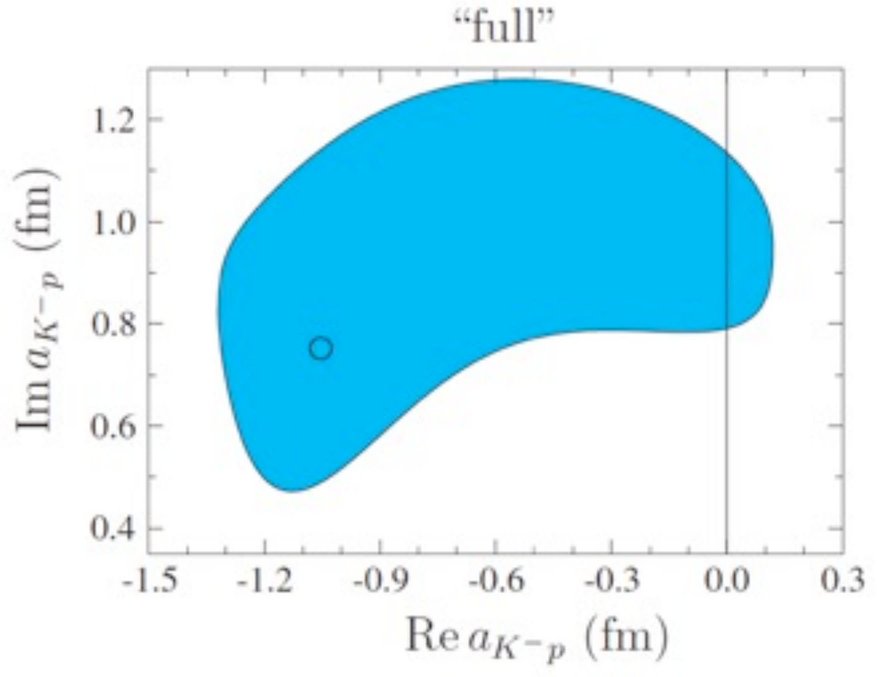
Threshold branching ratios

- **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. C74, 055201 (2006)

--> large uncertainty!

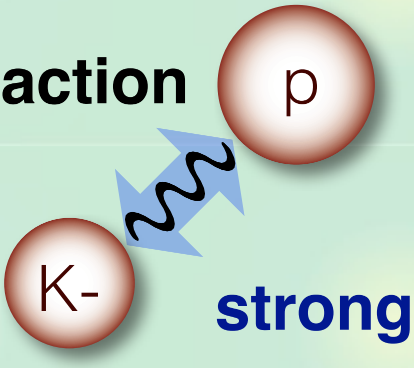
Scattering length from kaonic hydrogen

Measurements of the kaonic hydrogen

- **shift** and **width** of atomic state (Coulomb bound state)

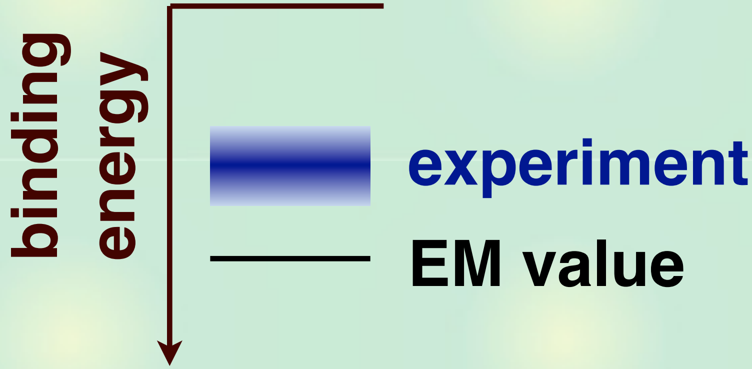
$$\Delta E - \frac{i}{2}\Gamma = -2\alpha^3\mu_c^2 a_{K^-p}[1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}] \longleftarrow \text{scattering length}$$

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



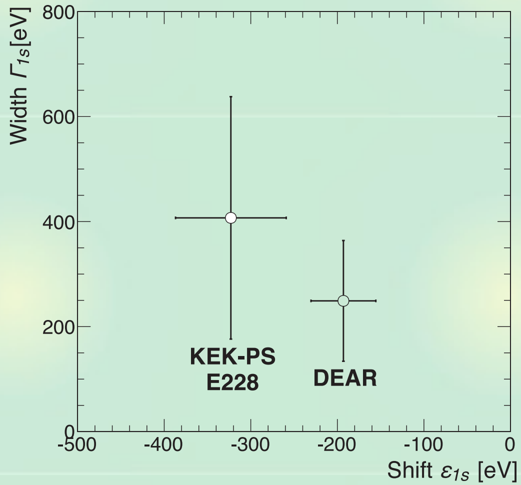
EM interaction

strong interaction



Experiments: KpX and DEAR

M. Iwasaki, *et al.*, Phys. Rev. Lett. 78, 3067 (1997)
G. Beer, *et al.*, Phys. Rev. Lett. 94, 212302 (2005)



- repulsive shift (existence of Λ^*)
- quantitatively inconsistent?

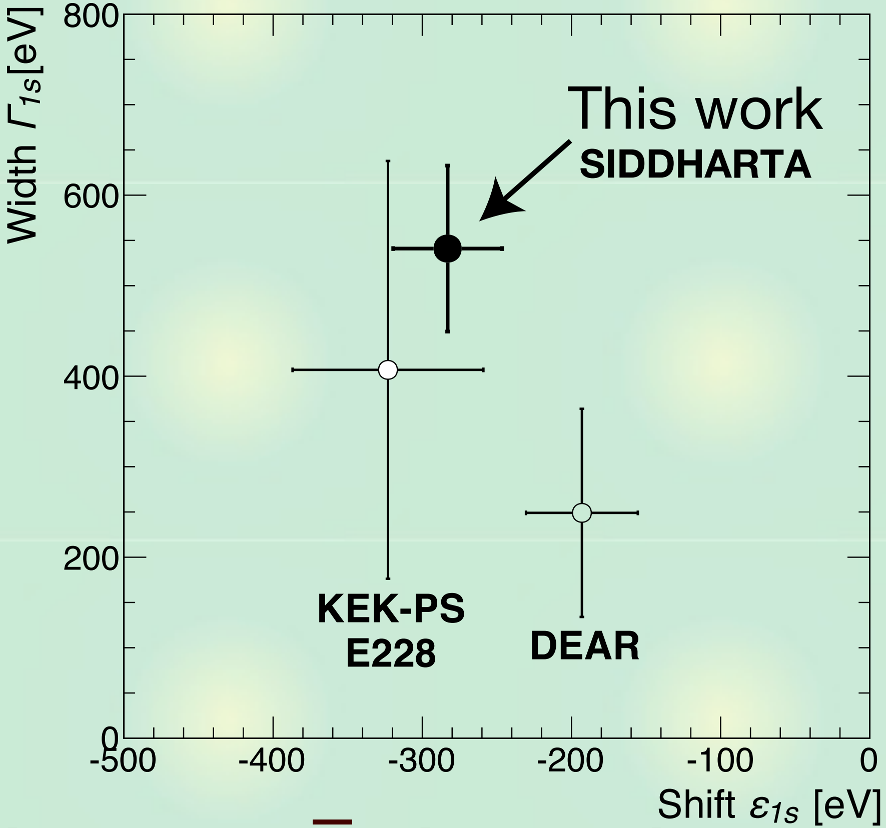
SIDDHARTA measurement

New accurate measurement by SIDDHARTA

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

- smallest uncertainties

$$\Delta E = -283 \pm 36 \pm 6 \text{ eV}, \quad \Gamma = 541 \pm 89 \pm 22 \text{ eV}$$



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

Contents

- **Introduction**
- Λ(1405) **in meson-baryon scattering**
  - **Chiral SU(3) dynamics**
  - **Pole structure of** Λ(1405)

    T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)
- **Systematic χ2 analysis with SIDDHARTA**
  - **Subthreshold extrapolation of** $\bar{K}N$ **amplitude**
  - **Predictions, remaining issues, ...**

    Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011);
    Nucl. Phys. A881 98 (2012)
- **Summary**

Chiral unitary approach

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

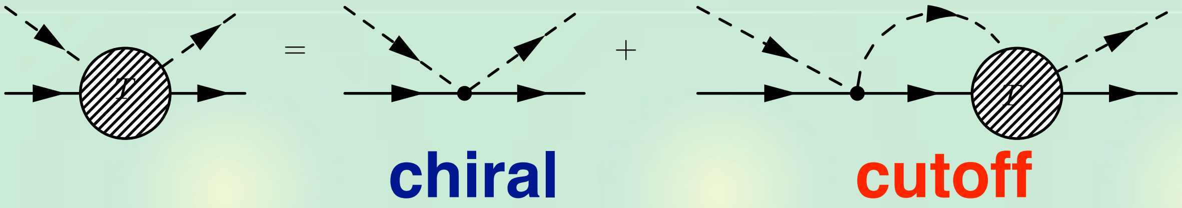
- Interaction <-- chiral symmetry

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)

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



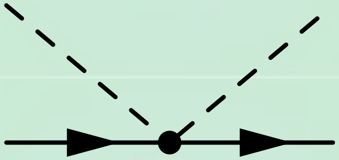
N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

It works successfully in various hadron scatterings.

s-wave low energy interaction in ChPT

NG boson-hadron scattering: chiral perturbation theory

$$\mathcal{L}^{\mathrm{WT}} = \frac{\boxed{1}}{4f^2}\mathrm{Tr}\left(\bar{B}i\gamma^{\mu}[\Phi\boxed{\partial_{\mu}}\Phi - (\partial_{\mu}\Phi)\Phi, B]\right)$$



s-wave contribution: Tomozawa-Weinberg (TW) term

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

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

$$C_{ij} = \sum_{\alpha}[6 - C_2(\alpha)]\left(\begin{array}{cc|c} 8 & 8 & \alpha \\ I_{\bar{i}}, Y_{\bar{i}} & I_i, Y_i & I, Y \end{array}\right)\left(\begin{array}{cc|c} 8 & 8 & \alpha \\ I_{\bar{j}}, Y_{\bar{j}} & I_j, Y_j & I, Y \end{array}\right)$$

$$Y = Y_{\bar{i}} + Y_i = Y_{\bar{j}} + Y_j, \quad I = I_{\bar{i}} + I_i = I_{\bar{j}} + I_j,$$

- **Flavor SU(3) symmetry --> sign and strength**
- **Derivative coupling --> energy dependence**
- **Systematic improvement by higher order terms (later)**

When the interaction is strong, resummation is mandatory.

Scattering amplitude and unitarity

Unitarity of S-matrix: Optical theorem

$$\mathrm{Im}[T^{-1}(s)] = \frac{\rho(s)}{2}$$ ← **phase space (known function)**

General amplitude by dispersion relation

$$T^{-1}(\sqrt{s}) = \boxed{\sum_i \frac{R_i}{\sqrt{s} - W_i} + \tilde{a}(s_0)} + \frac{s - s_0}{2\pi} \int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s' - s)(s' - s_0)}$$

R_i, W_i, a: **not determined in scattering theory**

Identify dispersion integral = loop function G, the rest = V^{-1}

$$\boxed{T(\sqrt{s}) = \frac{1}{V^{-1}(\sqrt{s}) - G(\sqrt{s}; a)}}$$

Scattering amplitude

The function V is determined by the **matching with ChPT**

$$T^{(1)} = V^{(1)}, \quad T^{(2)} = V^{(2)}, \quad T^{(3)} = V^{(3)} - V^{(1)} G V^{(1)}, \quad \dots$$

Amplitude T: consistent with chiral symmetry + unitarity

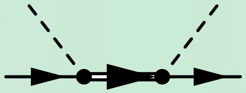
Pole structure in the complex energy plane

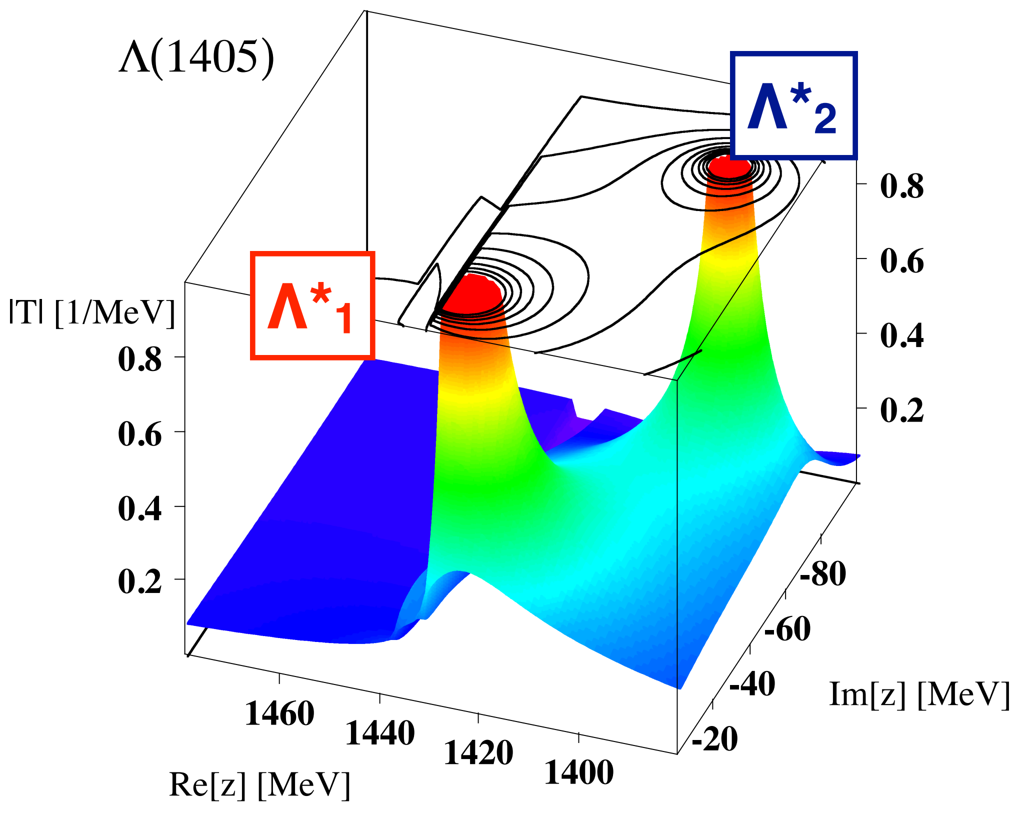
Resonance state ~ pole of the scattering amplitude

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 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 ?

Different πΣ spectra?

K-d --> πΣN **reaction**

Exp.: O. Braun, *et al.*, Nucl. Phys. B129, 715 (1977); J-PARC E31.

Theor.: D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A42, 257 (2009); A47, 42 (2011)

Origin of the two-pole structure

Leading order chiral interaction for $\bar{K}N$-$\pi\Sigma$ channel

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

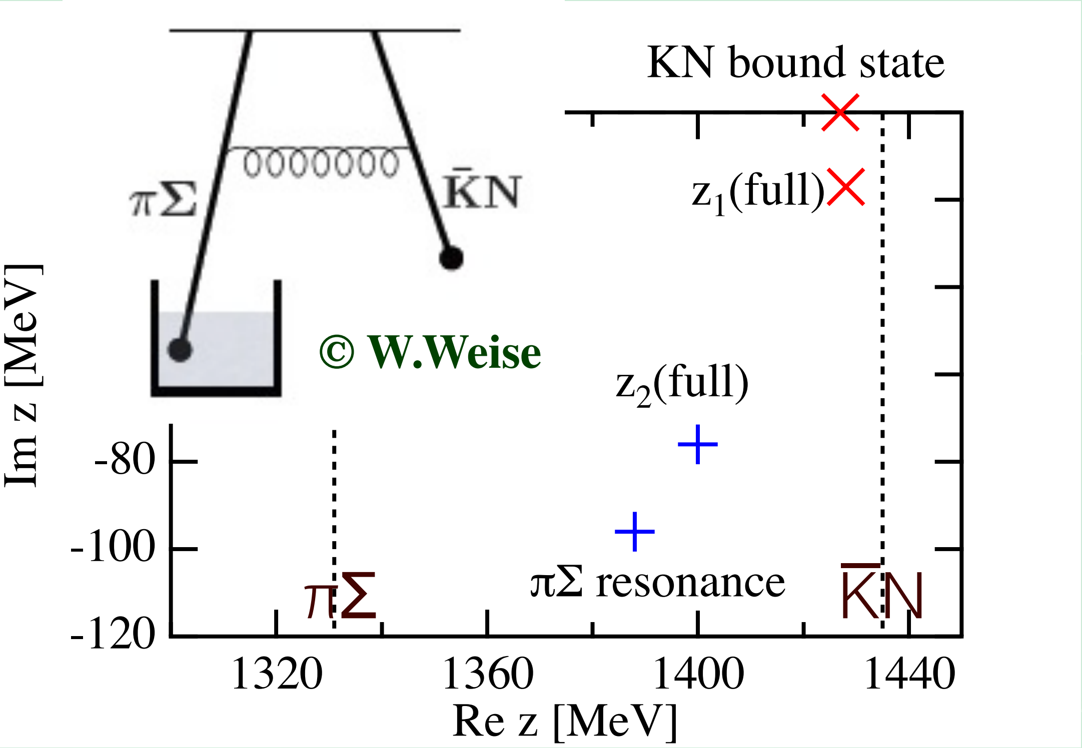
$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

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

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 $\bar{K}N$ (higher energy) --> bound state
Strong attraction in $\pi\Sigma$ (lower energy) --> resonance

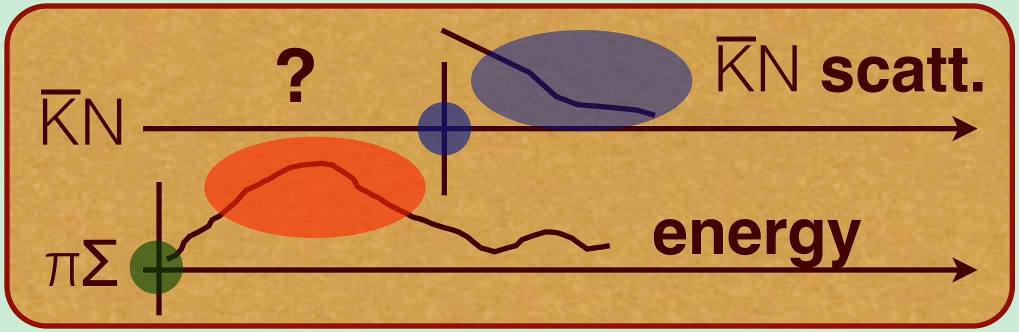
Model dependence? Effects from higher order terms?

Experimental constraints for S=-1 MB **scattering**

K-p **total cross sections**

$\bar{K}N$ **threshold observables**

- **threshold branching ratios**
- K-p **scattering length <-- SIDDHARTA exp.**



$\pi\Sigma$ **mass spectra**

- **new data is becoming available (LEPS, CLAS, HADES,...)**

$\pi\Sigma$ **threshold observables (so far no data)**

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)

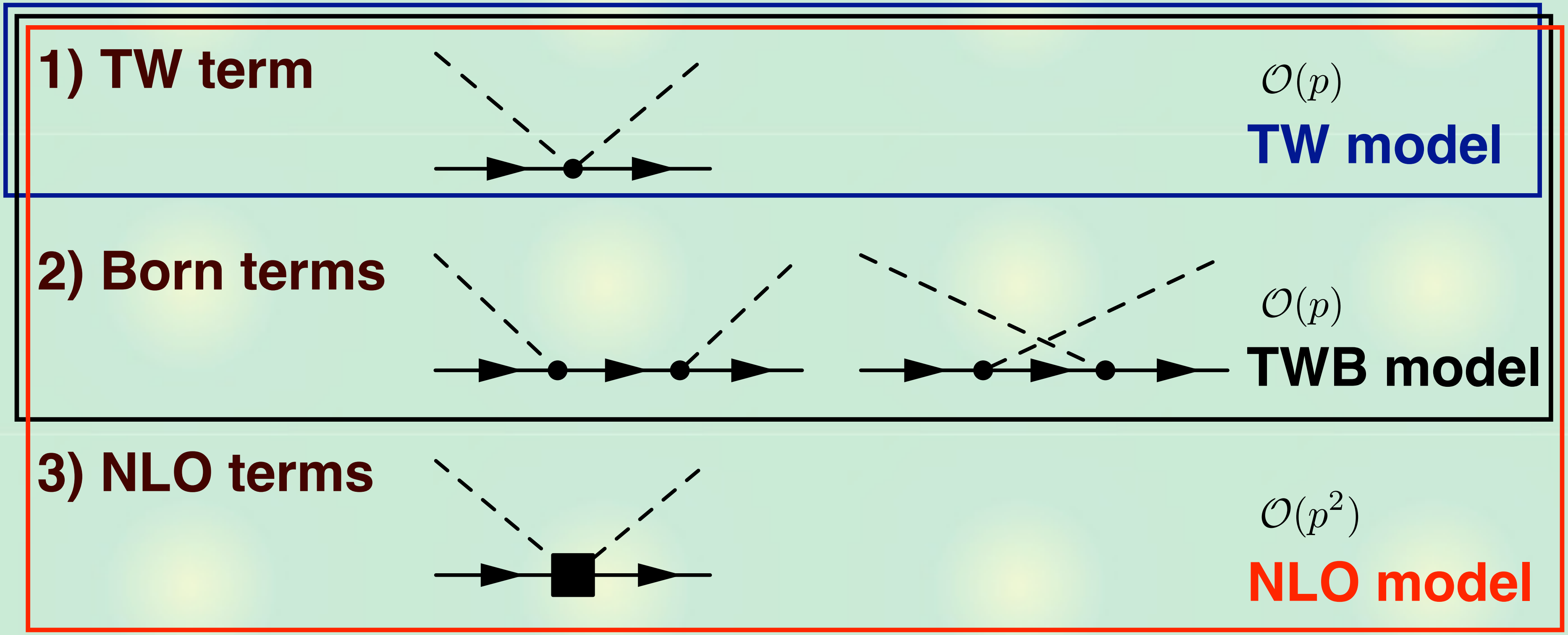
Construction of the realistic amplitude

Systematic χ2 fitting with SIDDHARTA data

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011); Nucl. Phys. A881 98 (2012).

- **Interaction kernel: NLO ChPT**

B. Borasoy, R. Nissler, W. Weise, Eur. Phys. J. A25, 79-96 (2005)



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**

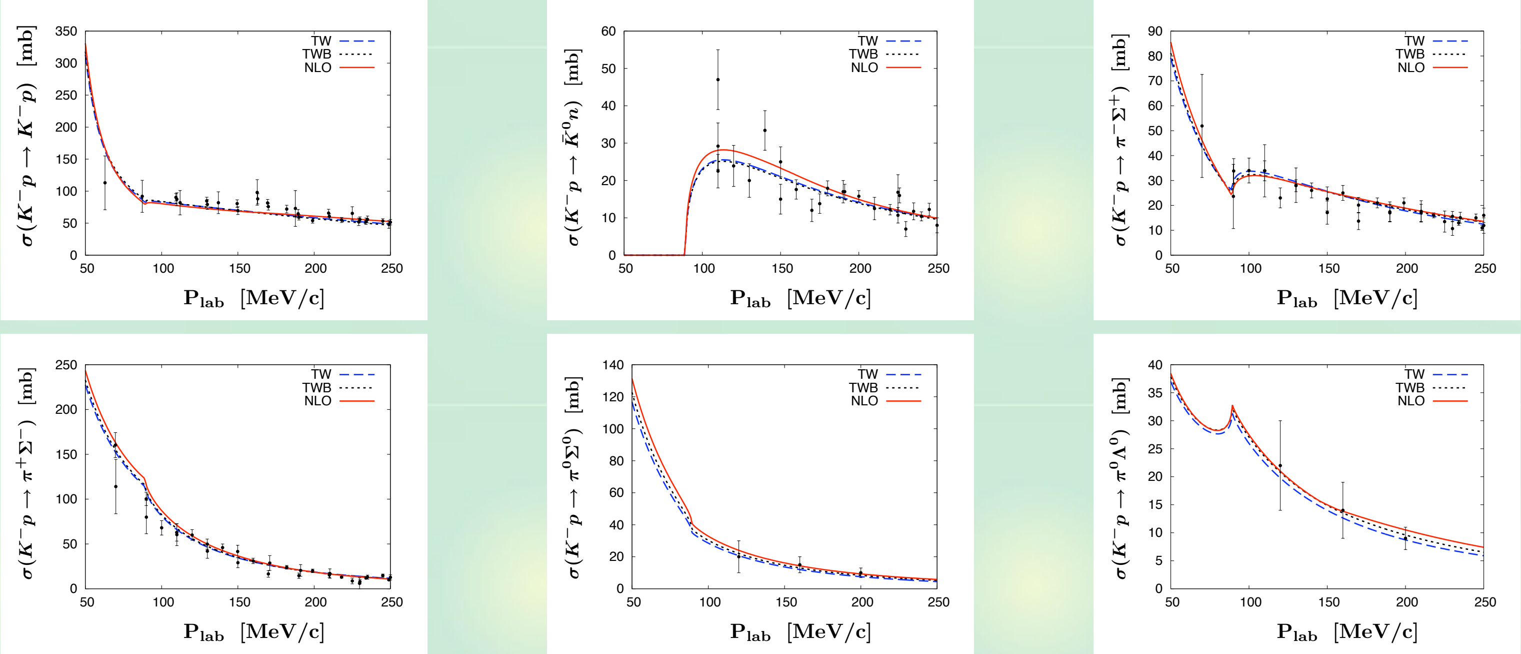
Parameters: 6 cutoffs (+ 7 low energy constants in NLO)

Systematic χ2 analysis with SIDDHARTA

Best-fit results

		TW	TWB	NLO	Experiment	
K-p	ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[7]
	Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[7]
BR	γ	2.36	2.36	2.37	2.36 ± 0.04	[8]
	R_n	0.20	0.19	0.19	0.189 ± 0.015	[8]
	R_c	0.66	0.66	0.66	0.664 ± 0.011	[8]
	χ^2/d.o.f	1.12	1.15	0.96		
	pole positions	$1422 - 16i$	$1421 - 17i$	$1424 - 26i$		
	[MeV]	$1384 - 90i$	$1385 - 105i$	$1381 - 81i$		

cross sections



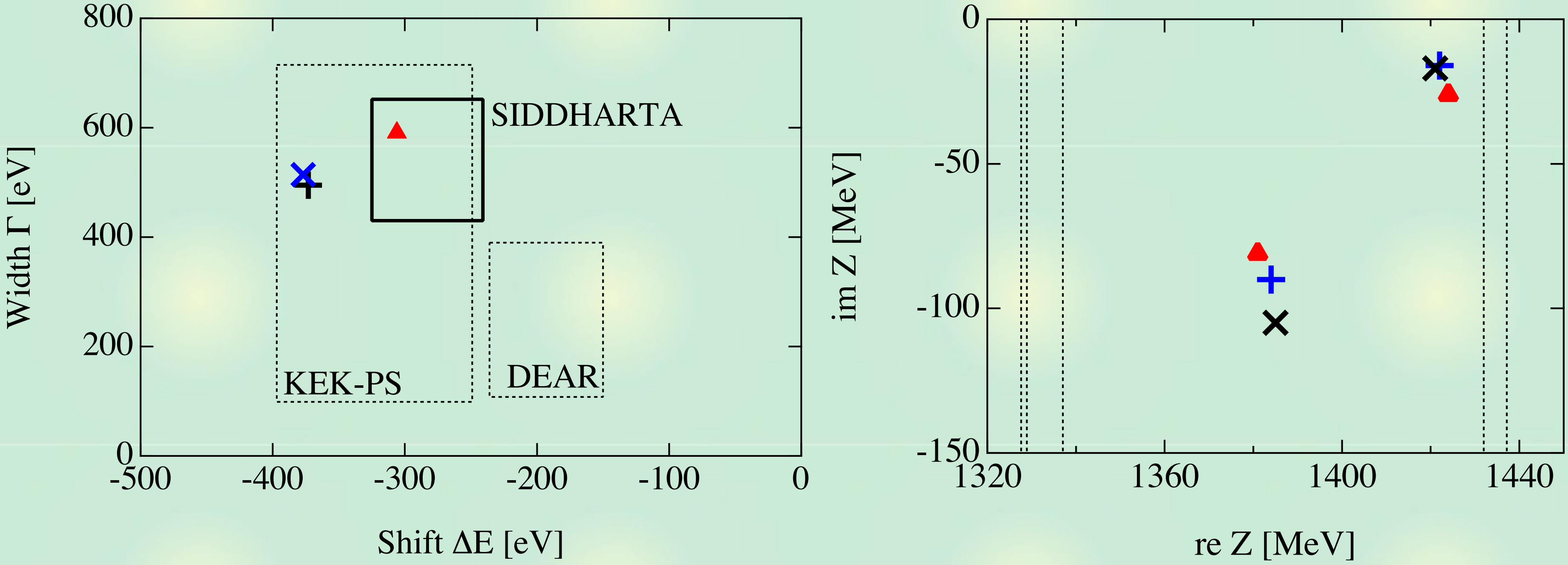
Good χ2: SIDDHARTA is consistent with cross sections

Shift, width, and pole positions

	TW	TWB	NLO
χ2/dof	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.

K-n **scattering amplitude**

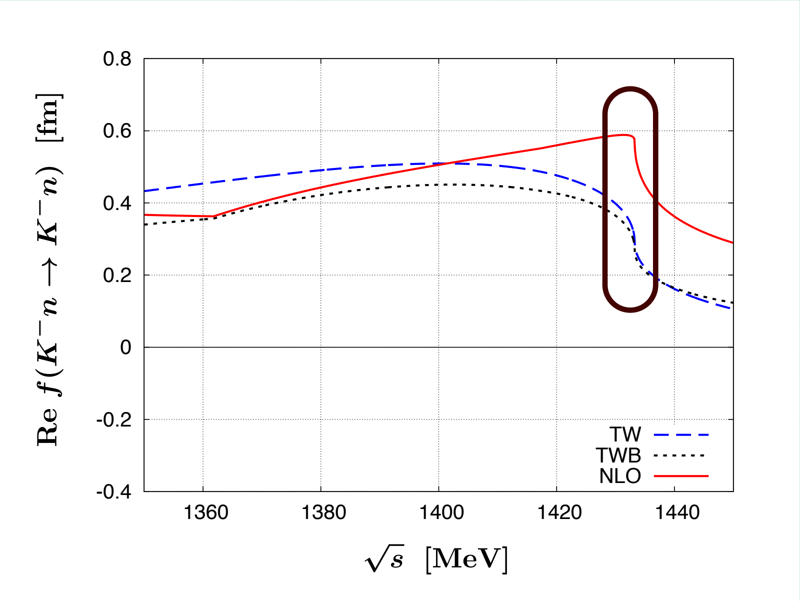
For K-**Nucleon interaction, we need both** K-p **and** K-n**.**

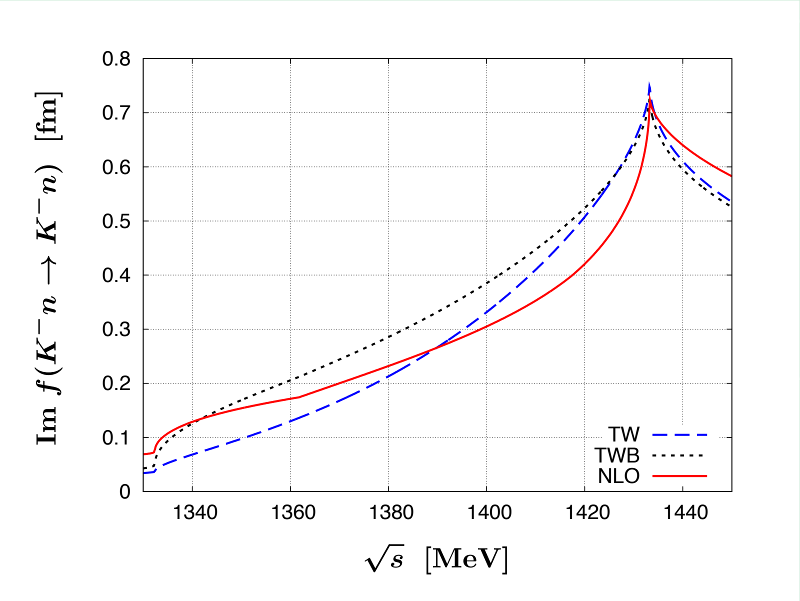
$$a(K^-p) = \frac{1}{2}a(I=0) + \frac{1}{2}a(I=1) + \dots, \quad a(K^-n) = a(I=1) + \dots$$

$$a(K^-p) = -0.93 + i0.82 \text{ fm} \quad (\text{TW}) \quad , \qquad a(K^-n) = 0.29 + i0.76 \text{ fm} \quad (\text{TW}) \quad ,$$

$$a(K^-p) = -0.94 + i0.85 \text{ fm} \quad (\text{TWB}) \quad , \qquad a(K^-n) = 0.27 + i0.74 \text{ fm} \quad (\text{TWB}) \quad ,$$

$$a(K^-p) = -0.70 + i0.89 \text{ fm} \quad (\text{NLO}) \qquad\quad a(K^-n) = 0.57 + i0.73 \text{ fm} \quad (\text{NLO}) \quad .$$





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

Summary 1

We study the $\bar{K}N$-$\pi\Sigma$ interaction and $\Lambda(1405)$ based on chiral SU(3) symmetry and unitarity

- $\bar{K}N$ **interaction is closely related to the structure of** $\Lambda(1405)$ **and the** $\bar{K}$ **nuclei.**

- **Coupled-channel unitarity is important for the strongly interacting** $\bar{K}N$-$\pi\Sigma$**.**

- **Two poles for** $\Lambda(1405)$ **follows from attractive** $\bar{K}N$ **and** $\pi\Sigma$ **interactions**

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

Summary 2

Systematic analysis with new accurate measurement of kaonic hydrogen

- New $\bar{K}N$ **threshold data** by SIDDHARTA
  - consistent with cross section data
- Implication of the improved framework:
  - **Uncertainty** in subthreshold extrapolation is significantly **reduced**.
  - $I=1$ constraint is desired.
- New input for $\bar{K}$ fey-body calculation

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011); Nucl. Phys. A881 98 (2012)