Baryon-Baryon Interactions with |S|≧2

Shoji SHINMURA

Gifu University/KEK, JAPAN

Introduction
OBEP with LQCD-based core
S=-2 ΛΛ and ΞN interactions
Predictions for **S=-3,-4 BB** interactions
Summary

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Introduction :
theoretical models of BB interactions

Potential model based on LQCD calculations
 Direct results of fundamental theory
 (Not only short-range part, but also long-range part)
  HAL-QCD group
Hadron-exchange models with flavor-SU(3) symmetry
 Long-range part: hadron-exchange mechanisms
 Short-range part: 'short-range physics'
  Phenomenological core (form factors)
   NSC, Julich, FG(old version), etc,
  Quark-model : fss, new ESC, etc
  LQCD core : Our new model
Chiral Perturbation models
 Reordering based on chiral symmetry
 Entem et al, Epellbaum et al.,Heidenbauer et al.

These models play complementary roles

Introduction:
Experimental knowledge on BB interactions

Two-body Scattering

Phase shift analyses : NN scattering   New version SAID

Cross sections : YN scattering

Old data for ΛN,ΣN-ΣN,ΣN-ΛN and Σ^+p KEK data

Single Hypernuclear Spectroscopy KEK,JLab,J-PARC, etc

s- and p-shell hypernuclear data → Effective ΛN int.

Mirror hypernuclei → CSB components

Σ-hypernuclei → ΣN interaction

ΛΛ hypernuclei and Ξ-hypernuclei   KEK,J-PARC

Nagara, Mikage events → ΛΛ interaction

Kiso event → ΞN interaction

BB potential models must explain hypernuclear data.

Accurate many-body theoretical calculations

Hadron-Hadron(H-H) Interactions at Low Energies

Baryon-Baryon Interactions

- **S= 0** NN
- **S=-1** $\Lambda N-\Sigma N$
- **S=-2** $\Lambda\Lambda-\Xi N-\Lambda\Sigma-\Sigma\Sigma$
- **S=-3** $\Xi\Lambda-\Xi\Sigma$
- **S=-4** $\Xi\Xi$

Meson-Baryon Interactions

- **S= 1** **KN**
- **S= 0** $\pi N-\eta N-K\Lambda-K\Sigma$
- **S=-1** $K^{bar}N-\pi\Lambda-\pi\Sigma-\eta\Lambda-\eta\Sigma-K\Xi$
- **S=-2** $\pi\Xi-\eta\Xi-K^{bar}\Lambda-K^{bar}\Sigma$
- **S=-3** $K^{bar}\Xi$

Meson-Meson Interactions

- **S= 2** KK
- **S= 1** $K\pi-K\eta$
- **S= 0** $\pi\pi-K^{bar}K-\eta\pi-\eta\eta$
- **S=-1** $K^{bar}\pi-K^{bar}\eta$
- **S=-2** $K^{bar}K^{bar}$

Coupled-Channel Problems

Construction of Coupled -Channel Potentials

Two-body systems

Three-body systems

Many-body systems

Our Goal: to construct a Unified Model

OBE model of baryon-baryon interactions

Old version:
OBEP with cutoff(r_c=0.4fm)
+ SU(3)-symmetric phenomenological short-range core

New version:
OBEP with cutoff (r_c=0.4fm)
+ LQCD-based short-range cores in the SU(3) limit

$$V=V_{core}(r)+(1-\exp(-(r/r_c)^2))^4 V_{OBEP}$$

$$V_{core}(r)=V_c \exp(-(r/r_g)^2)$$

In both versions, V_{OBEP} are defined in the same framework:
ps, s, v-meson-exchange with **physical masses and widths**
Exactly flavor-SU(3)-symmetric coupling constants ⬆

Unique origin of the SU(3) breaking

LQCD-based cores in the new version

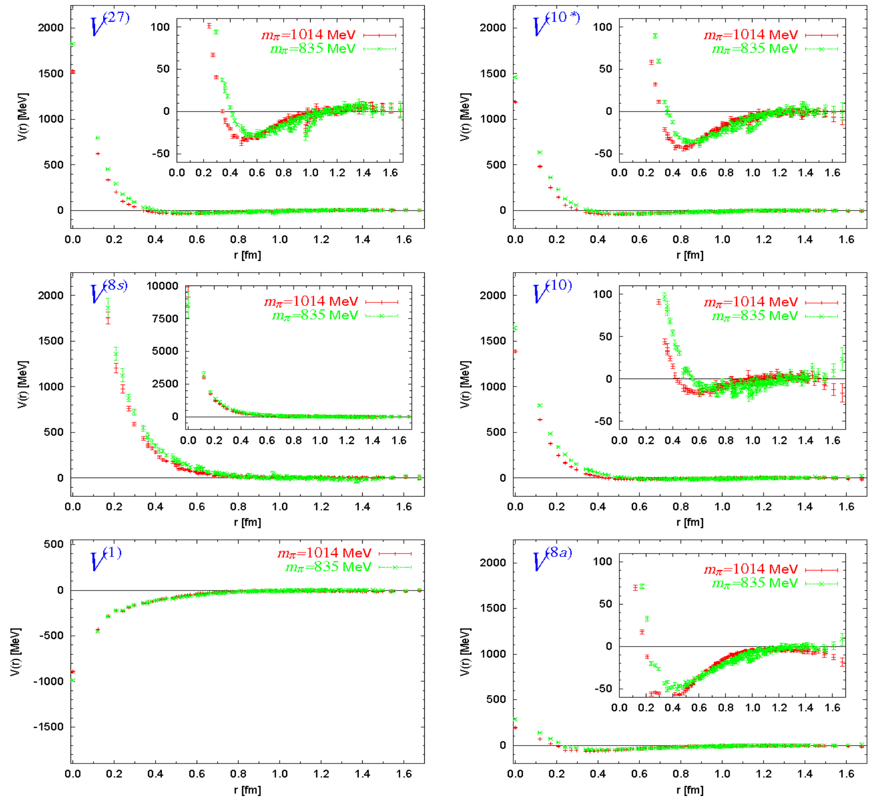


Fig. 2. The six independent BB potentials for S-wave in the flavor SU(3) limit, extracted from the lattice QCD simulation at $m_\pi = 1014$ MeV (red bars) and $m_\pi = 835$ MeV (green crosses).

T. Inoue et al.
(HAL QCD collaboration)
PTP124(2010)591

Flavor SU(3) Limit
Even(1S0,3S1) states

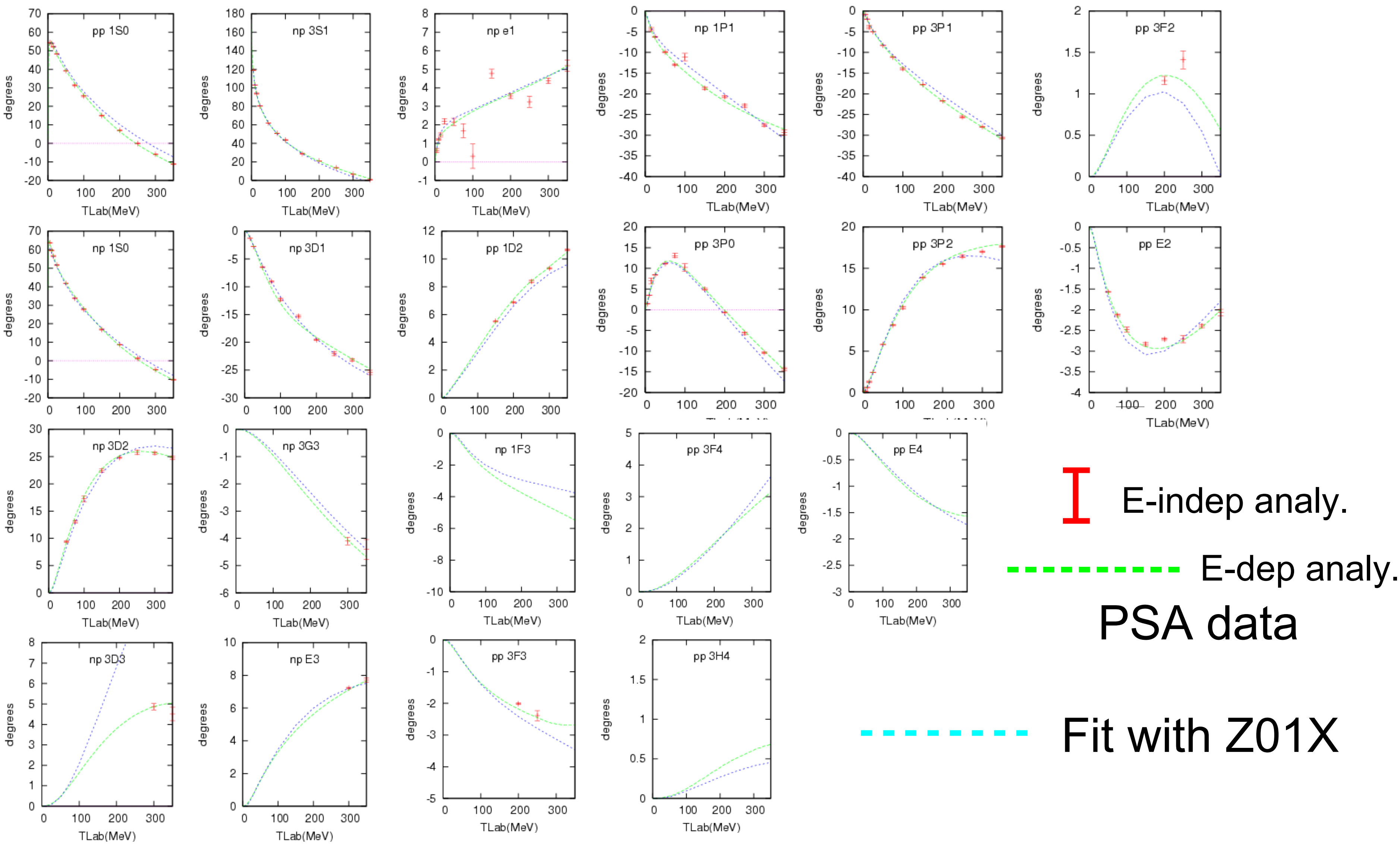
pion mass = 1014 MeV red
pion mass = 835 MeV green

Relative Strengths around r=0.2fm

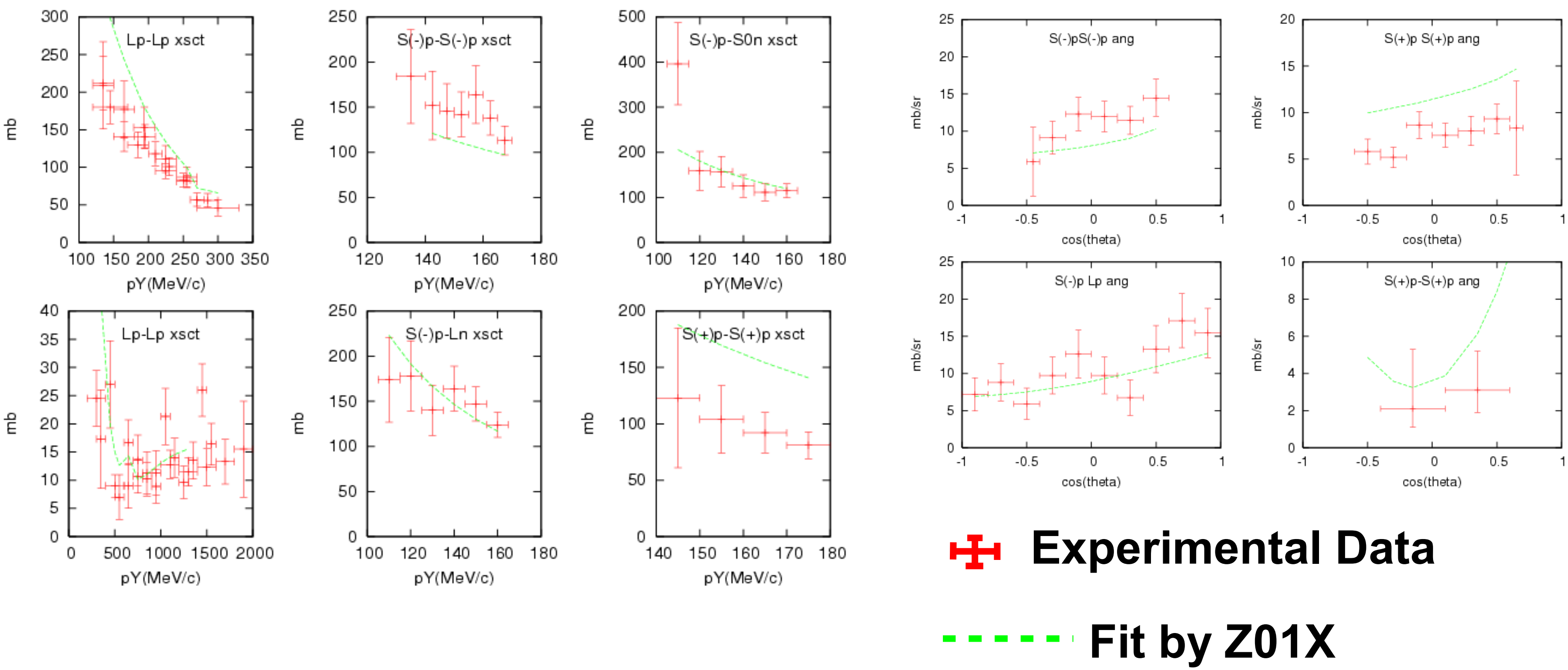
	{27}	{10*}	{10}	{8a}	{8s}	{1}
LQCD	**1**	**0.8**	**1.1**	**0.2**	**4.1**	**−0.6**
FG-A	1	0.8	**0.01**	0.4	**1.3**	0.06
FG-B	1	0.9	**0.03**	0.08	**0.09**	0.01
Z01	**1**	**0.8**	**1.1**	**0.2**	**4.1**	**−0.6**
Z01X	**1**	**0.8**	**1.1**	**0.2**	**4.1**	**−0.6**
	---NN---		-------YN------			--YY--

Z01X is determined with the contraint of attractive-ΞN interaction
10% variations in relative strengths are allowed !

NN phase shifts with new version (Z01X)



YN scattering with new version(Z01X)



Inelastic Capture Ratio

$$\frac{\sigma(\Sigma^- p \to \Sigma^0 n)}{\sigma(\Sigma^- p \to \Sigma^0 n) + \sigma(\Sigma^- p \to \Lambda n)}$$

Z01X	EXP
0.4645	0.33±0.05(1958) 0.474±0.016(1968), 0.465±0.011(1970)

Scatering length $a_{\Lambda\Lambda}(^1S_0)$ and $\Delta B_{\Lambda\Lambda}(^6_{\Lambda\Lambda}He)$ from double hypernuclei and theoretical $\Lambda\Lambda$ potentials

All models predict attractive $\Lambda\Lambda$ potential in $^1S_0$ state

Potential	$a_{\Lambda\Lambda}$ (1S0)	$\Delta B_{\Lambda\Lambda}(^6_{\Lambda\Lambda}He)$
NSC97a	-0.33(-0.11)	
NSC97e	-0.50(-0.25)	
ESC04a	-1.15	1.36
ESC04d	-1.32	0.98
ESC08a	-0.88	
FSS		3.66
fss2		1.41
Ch-EFT	-1.52	
z01	-0.59	
w01	-0.65	
Z01X	**-1.15**	

( ): No ΞN channel

NSC97,ESC-models:
Th.A. Rijken,V.G.J. Stoks, Y.Yamamoto, PRC59(1999)21.
Th.A. Rijken,Y. Yamamoto, PRC73(2006)044008.
Th.A. Rijken, M.M. Nagels, Y.Yamamoto, PTP suppl.185(2010)14.
Ch-EFT:H.Polinder, J.Haidenbauer, U.-G.Meissner, PLB653(2007)29
FSS,fss2(quark model): Y. Fujiwara, M. Kohno, Y. Suzuki, NPA784(2007)161.
Fg2014z,w :S.Shinmura, Ngo Thi Hong Xiem,(2014)

Experimental data:
Nagara and Mikage Events(KEK E373)

$\Delta B_{\Lambda\Lambda}(^6_{\Lambda\Lambda}He)$=0.70±0.17MeV

H. Takahashi, PRL87(2001)212502
K. Nakazawa, NPA835(2010)207

⇩

$a_{\Lambda\Lambda}$(1S0) ∼ -0.8 fm

$a_{\Lambda\Lambda}$(1S0) = -1.2±0.6fm

C.J. Yoon,et al. PRC75(2007)044008.

Ξ-Hypernuclei KISO Event

E373-Experiment 'KISO Event' K. Nakazawa et al., PTEP2015,033D02

$$\Xi^- + {}^{14}N \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$$

$B_\Lambda({}^{10}_{\Lambda}Be)=9.11\pm0.22MeV$ $(8.60\pm0.07\pm0.11MeV)$

$Ex({}^{10}_{\Lambda}Be^*)=3.07$ or $3.27MeV$

$B_\Lambda({}^{5}_{\Lambda}He)=3.12\pm0.02MeV$

Mometum Balance

$B_\Xi({}^{15}_{\Xi}C) =4.38\pm0.25MeV$ $(3.87\pm0.13MeV)$

$B_\Xi({}^{15}_{\Xi}C) =1.31$ or $1.11MeV$ (2p-state of Ξ-${}^{14}N$)

Attractive Ξ^--Nucleus potential

$$V_{\Xi\text{-nucleus}} = V_{WS} + V_{Coulomb}$$

$$V_0 \sim -14\ MeV$$

Attractive ΞN interaction

Ξ^- in symmetric nuclear matter

potentals	U_Ξ	$U_\Xi(n)$	$U_\Xi(p)$
NSC97e	44.7(35.8)	9.69	34.98
ESC04a	15.1		
ESC04b	36.3		
ESC04c	-5.5		
ESC04d	-18.7		
ESC08a	-20.2		
ESC08b	-32.4		
FSS	-14.9		
fss2	-5.3		
FG-A	-6.6(-5.3)	-0.2	-6.5
FG-B	43.6(34.9)	21.8	21.8
GSOBEP	28.1(22.5)	17.6	10.5
w01	22.1(17.7)	16.4	5.7
Z01	15.6(12.5)	11.9	3.7
Z01X	**-7.5(-6.0)**	**0.6**	**-8.0**

Theoretical ΞN Interactions give very scattered results.

Isospin dependence: strongly model-dependent

From KISO Event

$$U_\Xi \sim U_\Lambda/2$$
$$(\sim -14\text{MeV})$$

E07,E03,E05,E42 Experiments at J-PARC

→ Decisive information on S=-2 BB interaction

Attractive interaction

Partial Wave contributions to Ξ single-particle potential in SNM

Ξ^- in symmetric nuclear matter

Partial Wave	Neutron part (I=1)	Proton part	(I=0)
1S0	8.63	1.75	-5.13
3S1-3D1	2.67	0.46	-1.75
1P1	-2.14	-2.57	-3.00
3P0	0.16	-0.97	-2.10
3P1	-3.28	-1.40	0.48
3P2-3F2	-4.25	-4.30	-4.35
Total	0.58	-8.03	-16.64

S-waves(I=0) :Attractive
S-waves(I=1) :Repulsive

U_S=+13.51MeV

P-waves: Attractive

U_P=-18.75MeV

Odd-state contribution may be important for p-shell hypernuclei and their excited states

Extension to S=-3 and -4 BB Interactions

We model the BB interactions in the whole range
Short-range part by LQCD
Long-(medium-) range part by OBE

We can determine the S=-3,-4 BB interactions without any additional parameters.

↓

Predictions in S=-3 and -4 sectors

Scattering Lengths in 1S0 and 3S1 states with S=-3,-4 BB interactions

Scattering lengths(a) and effective ranges(r) (fm)

I	EFT(LO)*	nsc97f	fss2	Z01X
$a_s(\Xi\Lambda)$ 1/2	-33.5 ~ 9.07	-2.11A	-1.08A	-3.65A
$r_s(\Xi\Lambda)$	-1.00 ~ 0.84	3.21	3.55	2.80
$a_t(\Xi\Lambda)$ 1/2	0.33 ~ 0.31	0.33	0.26	-0.61wA
$r_t(\Xi\Lambda)$	-0.36 ~ -0.27	2.79	2.15	8.95
$a_s(\Xi\Sigma)$ 3/2	**4.28 ~ 2.74B**	**2.32B**	-4.63A	**2.81B**
$r_s(\Xi\Sigma)$	0.96 ~ 0.81	1.17	2.39	1.29
$a_t(\Xi\Sigma)$ 3/2	-2.45 ~ -3.89A	**1.71B**	-3.48A	**3.37B**
$r_t(\Xi\Sigma)$	1.84 ~ 1.70	0.96	2.52	1.39
$a_s(\Xi\Xi)$ 1	**3.92 ~ 2.47B**	**2.38B**	0.34	**3.56B**
$r_s(\Xi\Xi)$	0.92 ~ 0.75	1.29	3.20	1.42
$a_t(\Xi\Xi)$ 0	**0.63 ~ 0.52R**	0.48	3.19	**0.17R**
$r_t(\Xi\Xi)$	1.04 ~ 1.11	2.80	0.22	42.1

*Haidenbauer and Meissner, PLB684(2010)275

Qualitatively Similar properties are predicted by all models

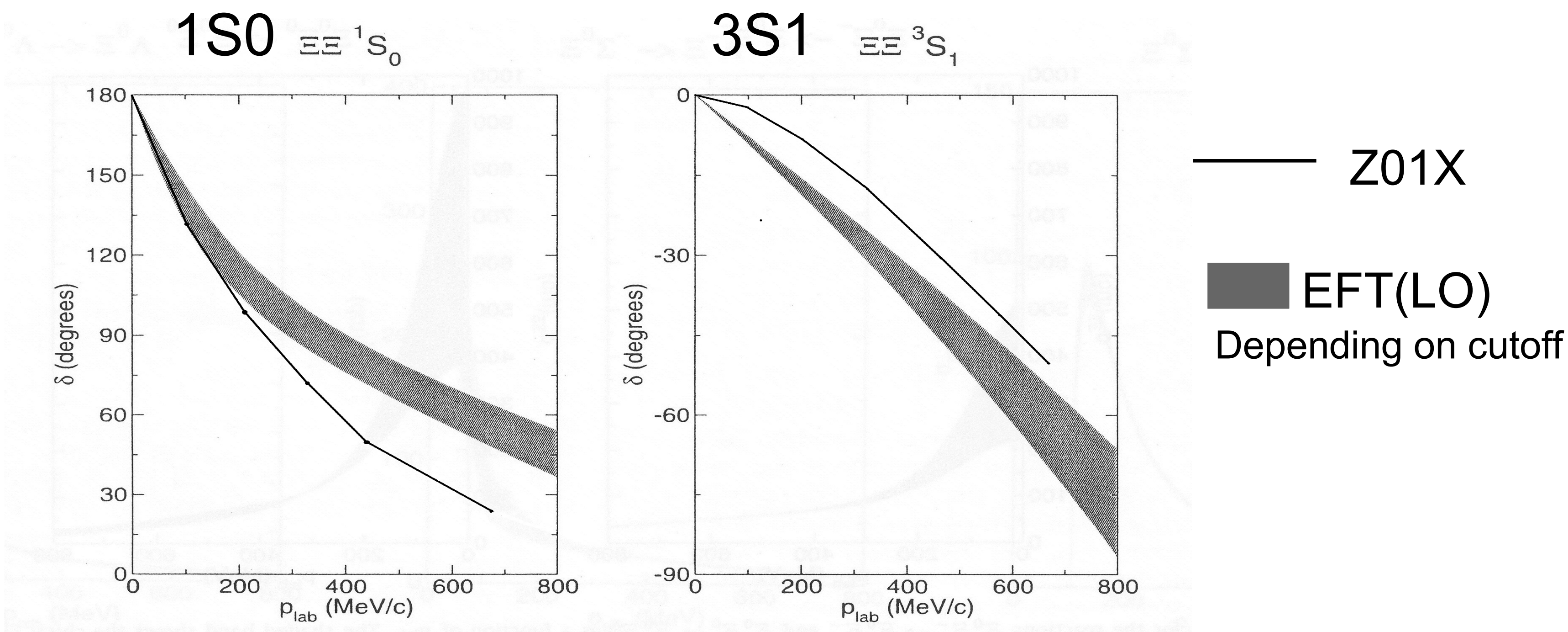
BE=1.5MeV

BE=2.8MeV

BE=4.4MeV

A: attractive
R: repulsive
(w : weakly)
B: bound state

S-wave ΞΞ phase shifts



1S0 state attractive {27} (same with NN 1S0 {27})
BE=2.56 ∼ 7.28MeV EFT(LO) (Haidenbauer and Meissner)
BE=4.44MeV our model(Z01X)

3S1 state repulsive {10} (not same with deuteron: {10*})

Summary

We proposed **a new version of BB potential model**

Long-range part : OBE
Short-range part : LQCD
Flavor-SU(3) symmetry

Our BB potential reproduces reasonably

Repulsive ΣN(I=3/2, 3S1), ΣN(I=1/2,1S0)
Attractive ΣN(I=3/2, 1S0), ΣN(I=1/2,3S1)
Attractive $\Lambda\Lambda$(I=0,1S0)
Attractive U_{Ξ}(SNM) (Attractive P-wave ΞN contribution)
S=-2 (E07,E03,E05, E42) experiments are very important

Predictions for S=-3,-4 BB interactions:

Three s-wave bound states

$\Sigma\Xi$(I=3/2,1S0)(BE=1.5MeV) ($\Sigma^+\Xi^0$, $\Sigma^-\Xi^-$ weak decay only)
$\Sigma\Xi$(I=3/2,3S1)(BE=2.8MeV) ($\Sigma^+\Xi^0$, $\Sigma^-\Xi^-$ weak decay only)
$\Xi\Xi$(I=1,1S0)(BE=4.4MeV) (weak decay only)

Repulsive $\Xi\Xi$(I=0,3S1) interaction
EFT(LO) and OBE models predict similar properties