Hyperon forces from lattice QCD at the physical point

Takumi Doi

(RIKEN iTHEMS)

With

Kenji Sasaki (U. of Niigata Pref.) : H-dibaryon

Liang Zhang (Fudan U.) : $N\Omega$ dibaryon

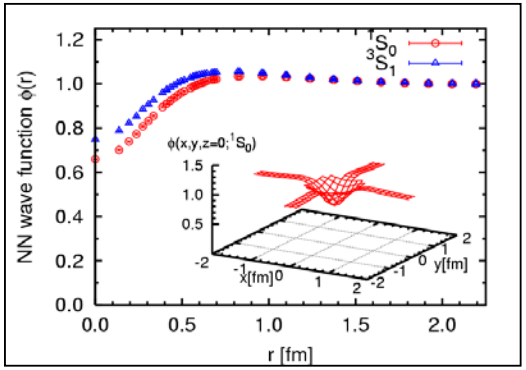
Koichi Murase (Osaka U.) : (next next talk)

for HAL QCD Collaboration

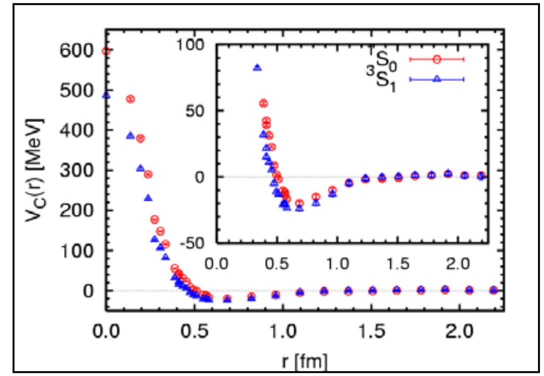
HAL QCD method

Lattice QCD

NBS wave func.



Lat Hadron Force



$$\psi_{\rm NBS}(\vec r) = \langle 0 | H_1(\vec r) H_2(\vec 0) | H_1(\vec k) H_2(-\vec k), in\rangle$$
$$\simeq A_k \sin(kr - l\pi/2 + \delta_l(k))/(kr)$$

$$(k^2/m_N - H_0)\, \psi_{\rm NBS}(\vec r) = \int d\vec r\,' U(\vec r, \vec r\,') \psi_{\rm NBS}(\vec r\,')$$

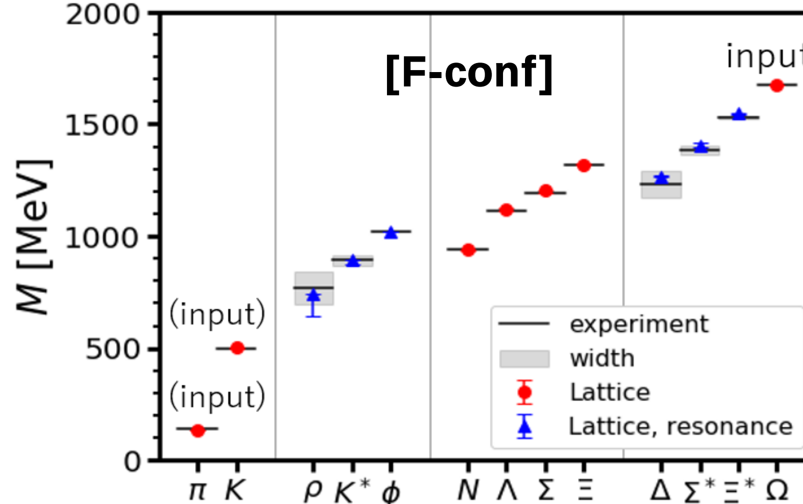
- **Interacting kernel ("potential") from spatial & temporal correlation**
  - Potential → Phase Shifts guaranteed by QFT — Aoki-Hatsuda-Ishii PTP123(2010)89
- **Energy-indep potential** — N.Ishii et al. (HAL Coll.) PLB712(2012)437
  - "Signal" from (elastic) excited states → Ground state saturation NOT required
- **Coupled Channel formalism** — S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509
  - Physics above inelastic threshold → Essential for Hyperon-forces, Exotics
- **Extension to N-body systems (N>=3)** — S. Aoki et al. (HAL Coll.) PRD88(2013)014036 (non-rela approx.)

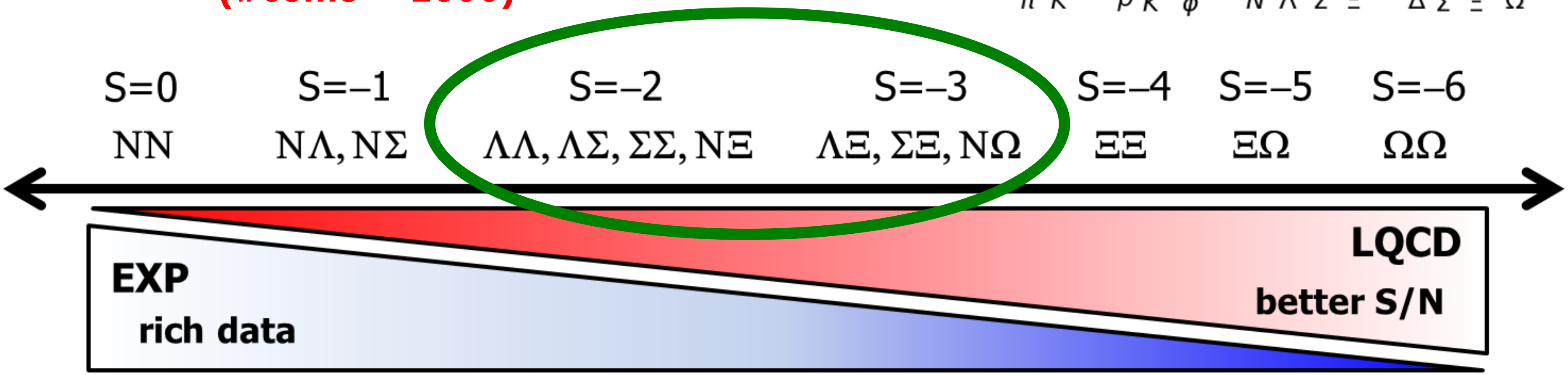
LQCD @ near & on the physical point

- **Nf = 2 + 1 gauge configs**
  - Iwasaki gauge + clover-uds + (quenched) RHQ-charm
  - $V = (96\,a)^4 = (8.1\mathrm{fm})^4$, $1/a = 2339$ MeV

Fugaku (440PFlops)

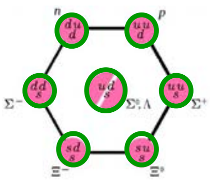
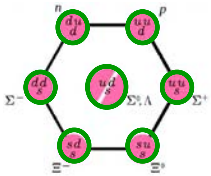
- **[K-conf]**   PACS Coll., PoS LAT2015, 075
  - **(m_π, m_K) = (146, 525) MeV**
  - **(#confs ~= 400)**
- **[F-conf]**   HAL QCD Coll., PRD110(2024)094502
  - **(m_π, m_K) = (137, 502) MeV**
  - **(#confs = 1600)**





(& charmed/bottomed interactions)

Candidates of di-baryons

 X 

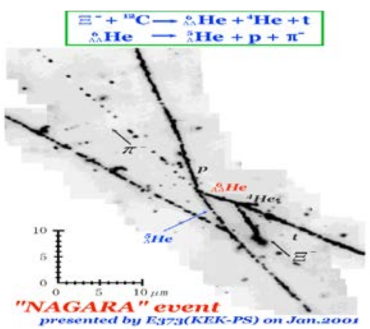
$$8 \times 8 = 27 + 8s + 1 + 10^* + 10 + 8a$$

H-dibaryon
(J=0)

HAL QCD, PRL106(2011)
NPLQCD, PRL106(2011)
J.R. Green+, PRL127(2021)

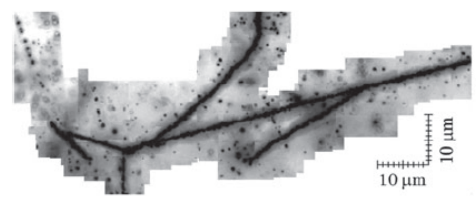
Also relevant to S= -2 hypernuclei

$\Lambda\Lambda$–hypernuclei



NAGARA-event (2001)

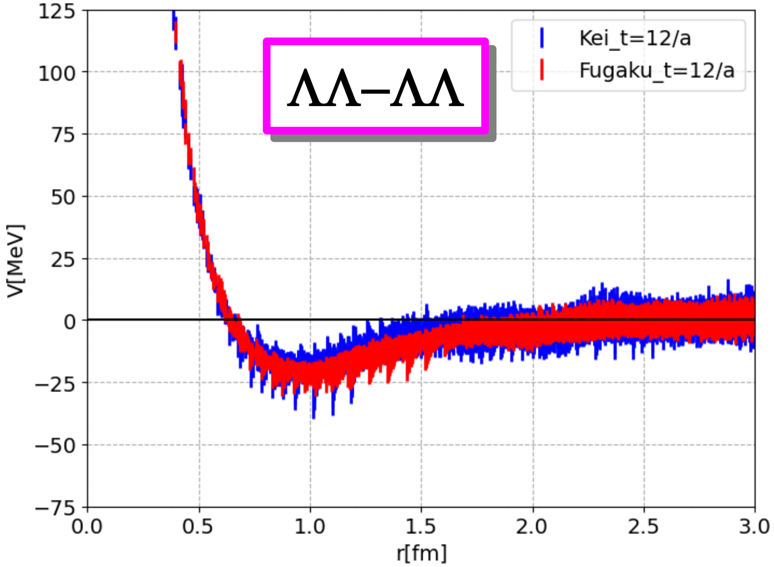
Ξ–hypernuclei

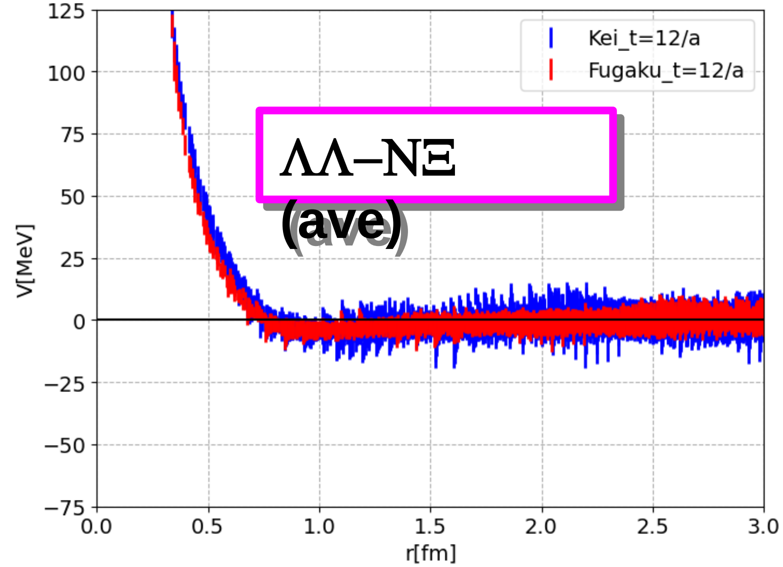


KISO-event (2014)

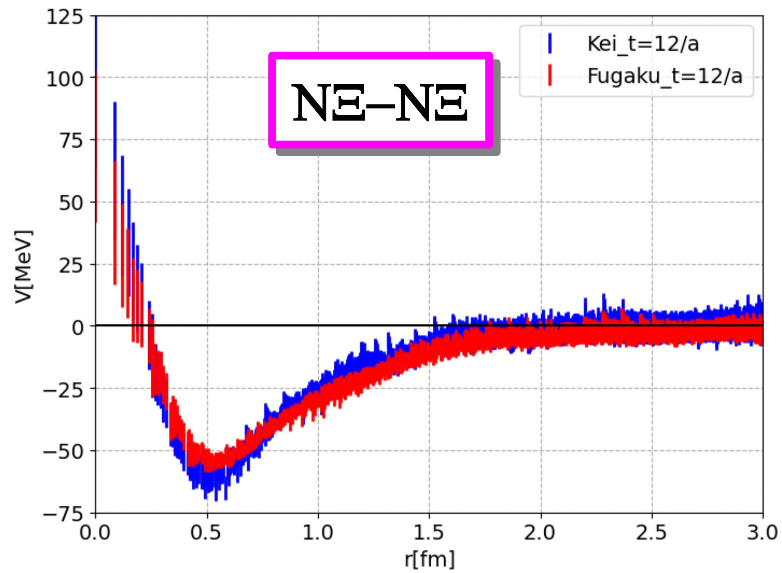
➔ LQCD study w/ SU(3) breaking effects (particle-base)

ΛΛ, NΞ (effective) 2x2 coupled channel analysis





m_π=146MeV [K-conf]
m_π=137MeV [F-conf]



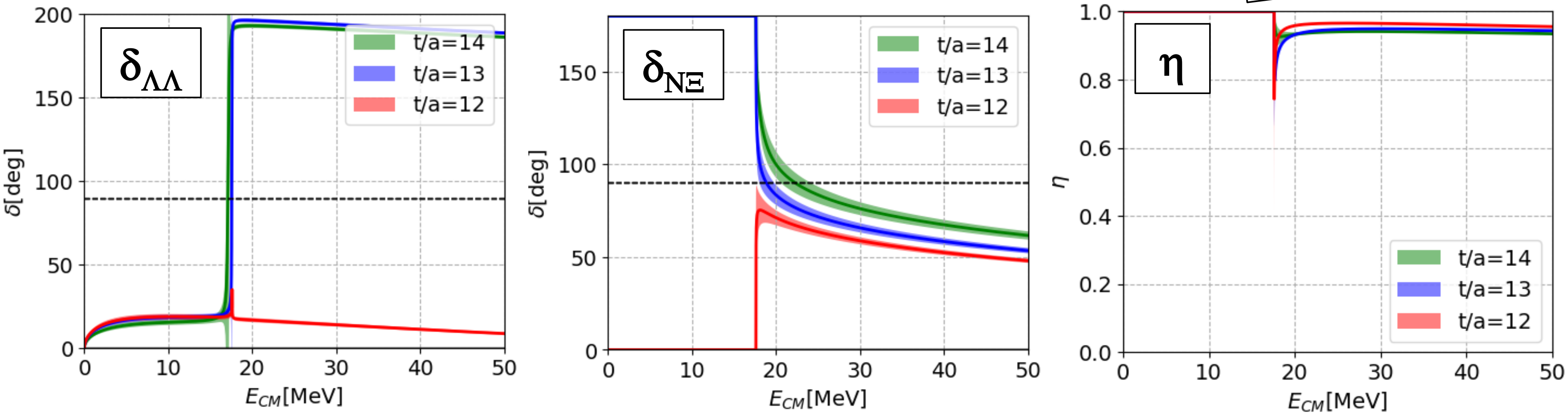
NΞ ($^{11}S_0$) channel is attractive
NΞ–ΛΛ coupling is small

K. Sasaki et al., (HAL Coll.), NPA998(2020)12137
K. Sasaki, Proc. of HYP2025

ΛΛ and NΞ phase shift and inelasticity

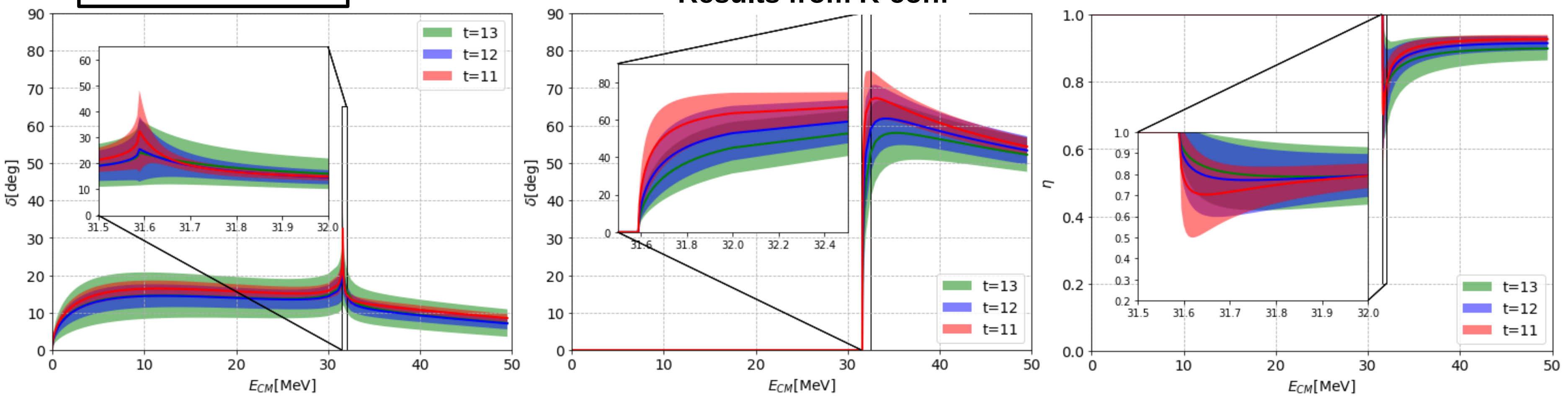
Preliminary

m_π=137MeV



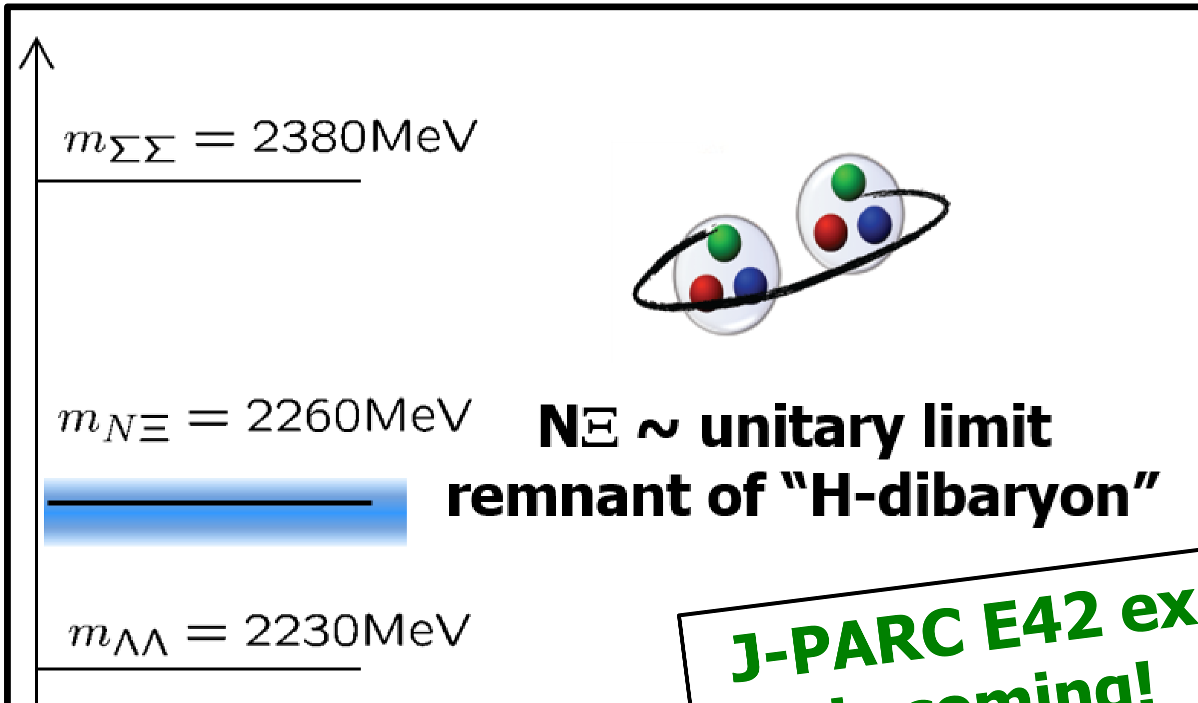
m_π=146MeV

Results from K-conf



[K. Sasaki, Proc. of HYP2025 + updates]

Fate of the H-dibaryon



J-PARC E42 exp
is coming!

NΞ ($^{11}S_0$) channel
is attractive

NΞ–ΛΛ coupling
is small

No bound state
below ΛΛ

m_π=146MeV

NΞ virtual pole in (+,-) sheet

K. Sasaki et al., (HAL Coll.), NPA998(2020)12137

Y. Kamiya, K. Sasaki et al., PRC105(2022)014915

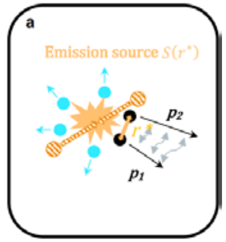
m_π=137MeV

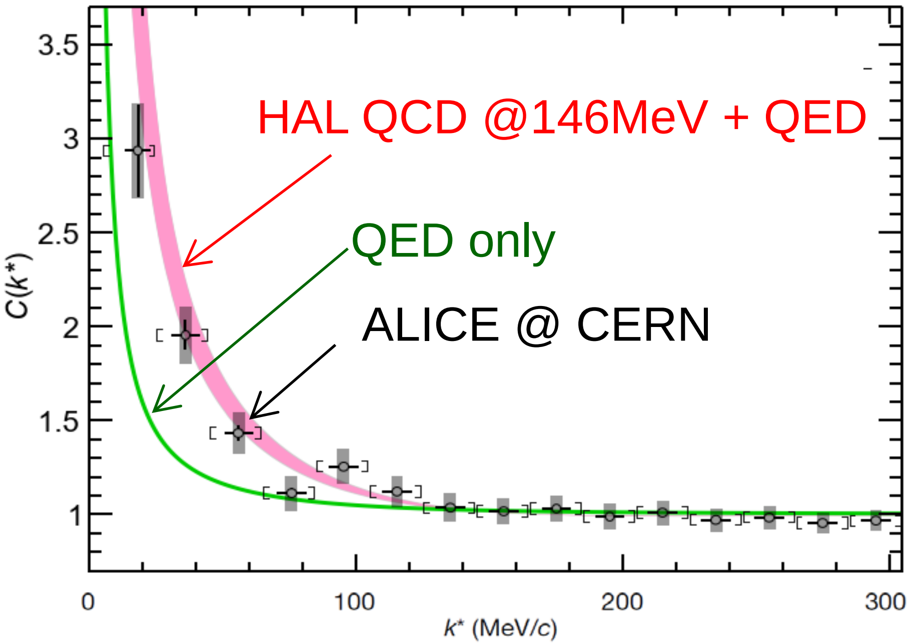
NΞ quasibound resonance pole in (-,+) sheet
is most likely

K. Sasaki, Proc. of HYP2025 + updates

LQCD meet Exp. for NΞ int ($^{11}S_0$,$^{13}S_1$,$^{31}S_0$,$^{33}S_1$)

Femtoscopy in nuclear collision (N-Ξ correlation)

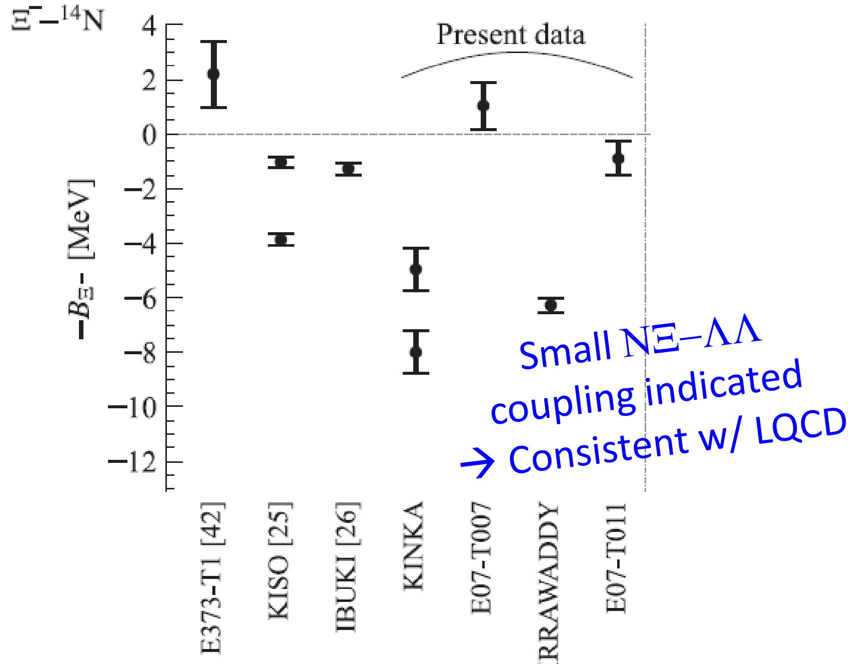




ALICE Coll., Nature 588, 232 (2020)
Y. Kamiya et al., PRC105, 014915 (2022)

LHC-ALICE

Spectrum of Ξ - Hypernuclei



M. Yoshimoto et al., PTEP2021, 073D02
See also W. S. Jung et al., PTEP2025, ptaf064

J-PARC

LQCD meet Exp. for NΞ int ($^{11}S_0$, $^{13}S_1$, $^{31}S_0$, $^{33}S_1$)

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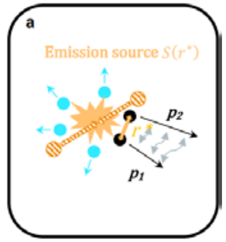

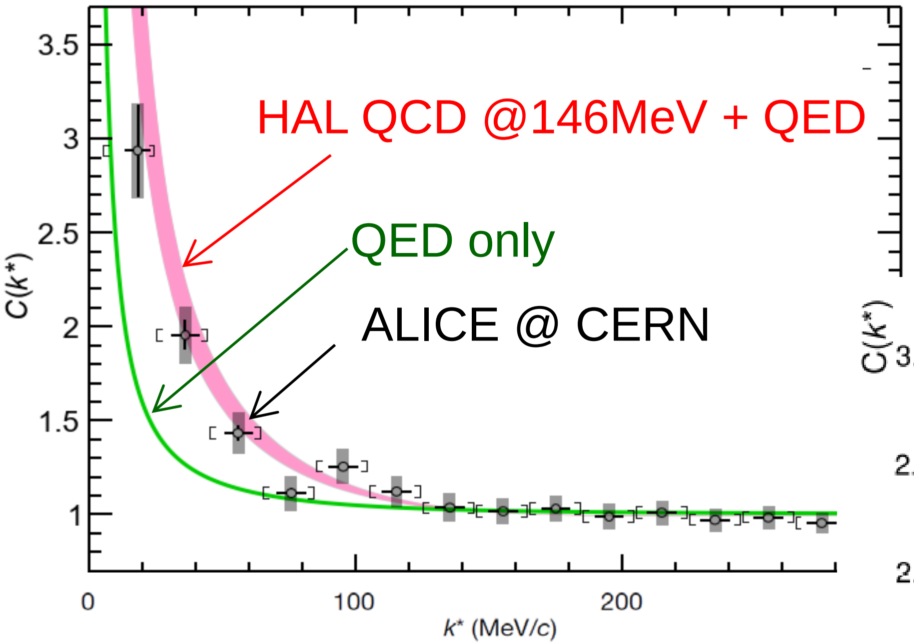

ALICE Coll., Nature 588, 232 (2020)
Y. Kamiya et al., PRC105, 014915 (2022)

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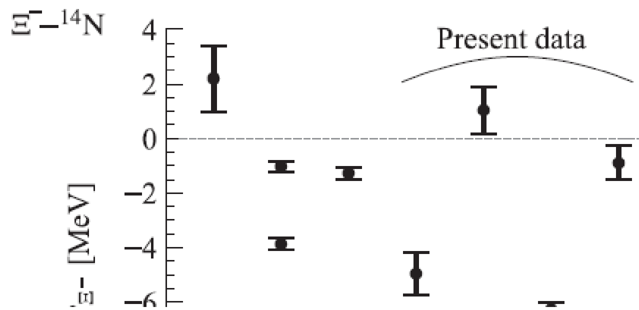
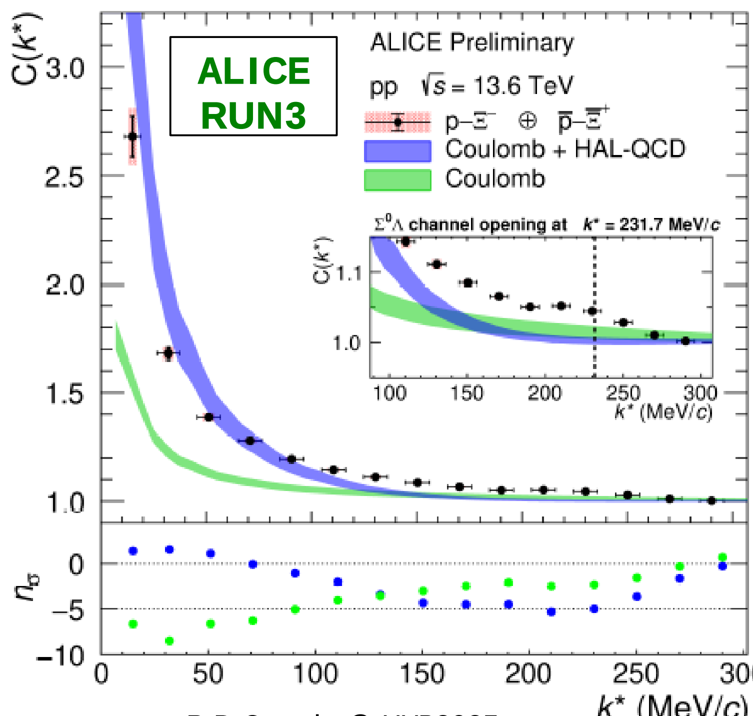


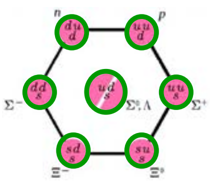
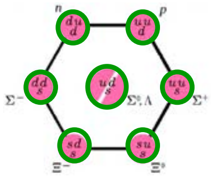
Ξ–ΛΛ
indicated
ent w/ LQCD

002
otaf064



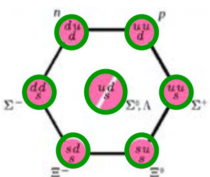
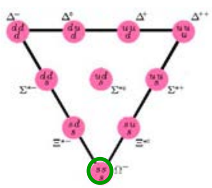
R.D.Grande @ HYP2025

Candidates of di-baryons

 X 

$8 \times 8 = 27 + 8s + 1 + 10^* + 10 + 8s$

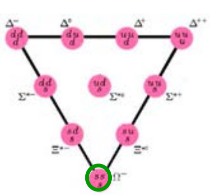
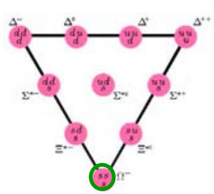
H-dibaryon
(J=0)

 X 

$8 \times 10 = 35 + 8 + 10 + 27$

$N\Omega$ (J=2)

T. Iritani et al. (HAL Coll.), PLB792(2019)284

 X 

$10 \times 10 = 28 + 27 + 10^* + 35$

$\Omega\Omega$ (J=0)

See our prediction

S. Gongyo et al. (HAL Coll.), PRL120(2018)212001 : $\Omega\Omega$

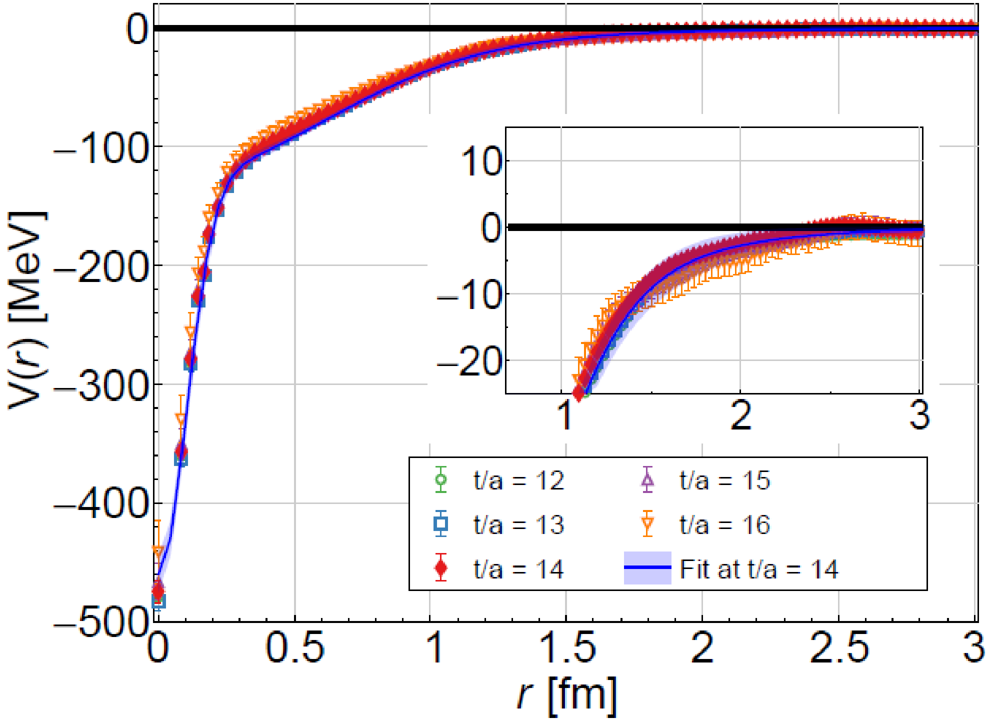
Y. Lyu, H. Tong et al., PRL127(2021)072003 : $\Omega_{ccc}\Omega_{ccc}$

Goldman et al. ('87)
Oka ('88)
Zhang et al. ('97)

Dyson-Xuong ('64)
Kamae-Fujita ('77)
Oka-Yazaki ('80)

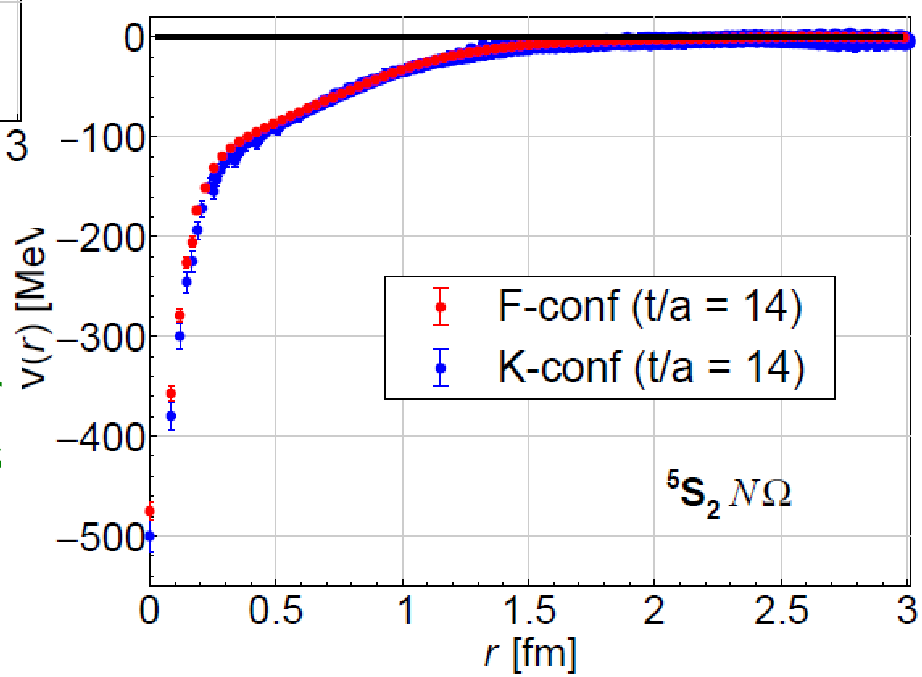
NΩ potential ($^5S_2$)

m_π=137MeV [F-conf]



No visible t-dep; the effect of $\Lambda\Xi$, $\Sigma\Xi$ channels are suppressed (by D-wave)

m_π=137MeV [F-conf] vs.
m_π=146MeV [K-conf]



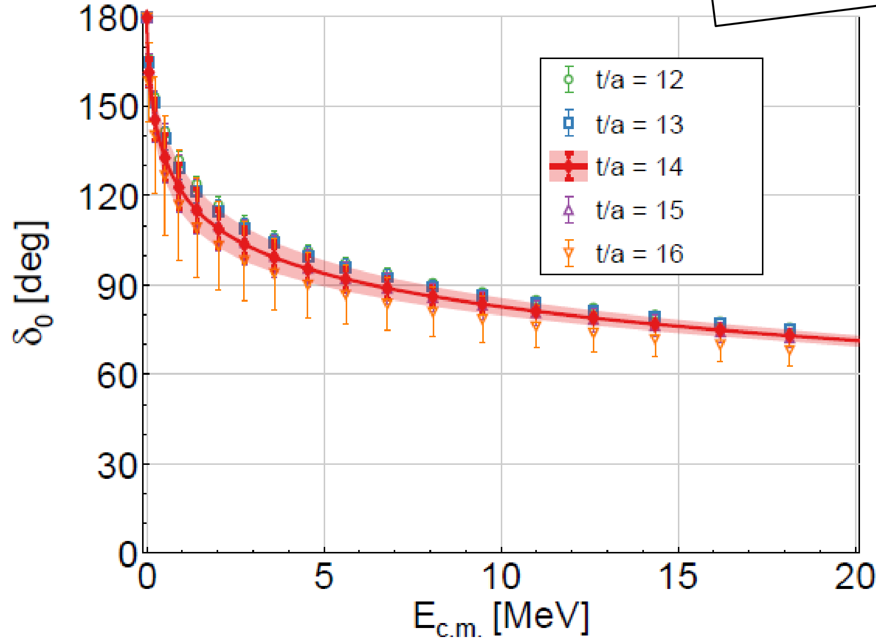
Similar universal attraction observed for
N-ϕ, N-J/ψ, N-η_c , N-Ω_{ccc} interactions

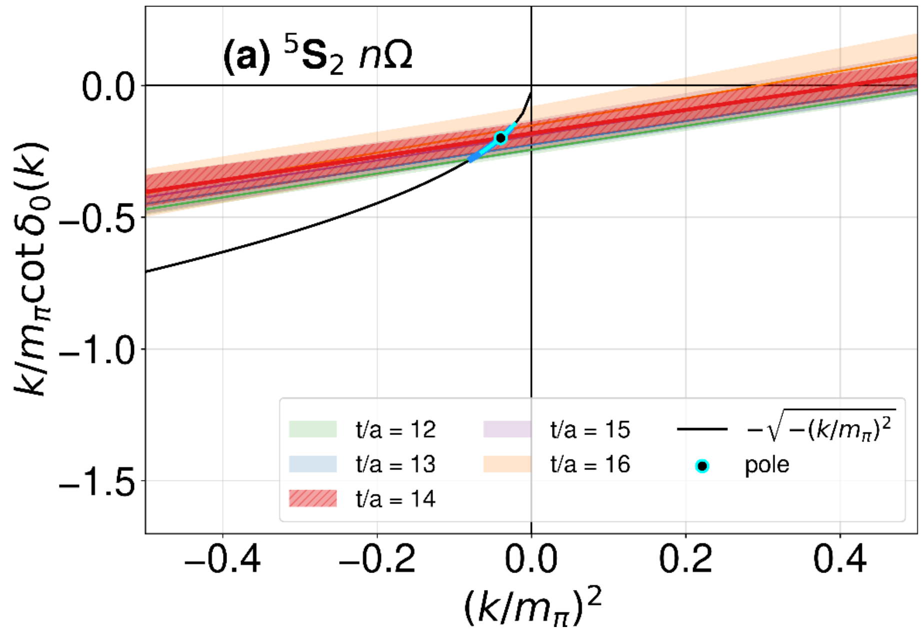
Y. Lyu+, PRD106(2022)074507
Y. Lyu+, PLB860(2025)139178
L. Zhang+, PLB871(2025)139998

NΩ phase shifts at m_π=137MeV

Preliminary

(QCD only)





NΩ ($^5S_2$) has (quasi) bound state near unitarity

m_π=137MeV

Quantity	Center	Stat	Sys
B [MeV]	0.6076	$\left(^{+0.3970}_{-0.2890}\right)$	$\left(^{+0.6019}_{-0.1793}\right)$
$\sqrt{\langle r^2 \rangle}$ [fm]	5.6881	$\left(^{+1.8885}_{-1.0954}\right)$	$\left(^{+1.0785}_{-1.4550}\right)$

m_π=146MeV

$$B_{N\Omega} = 1.54(0.30)\left(^{+0.04}_{-0.10}\right)\ \mathrm{MeV}$$

$$\sqrt{\langle r^2 \rangle}_{N\Omega} = 3.77(0.31)\left(^{+0.11}_{-0.01}\right)\ \mathrm{fm}$$

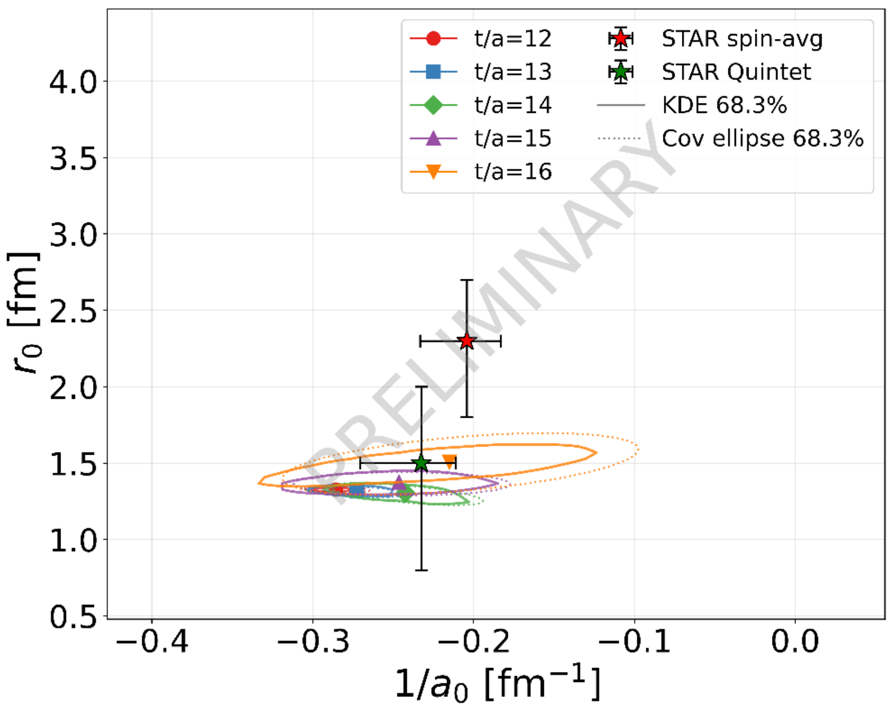
LQCD prediction meet Experiments: $p\Omega^-$ int

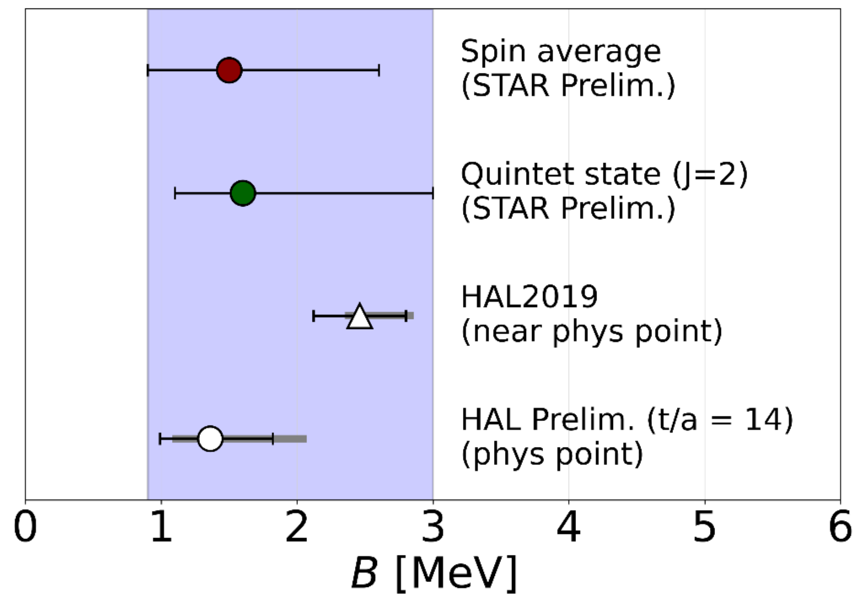
(QCD + Coulomb)

Scatt. parameters

Preliminary

Binding energy





←→ New Femtoscopy analysis from STAR@RHIC

STAR results taken from
B. Fu (STAR Coll.), Proc. For INPC2025, arXiv:2604.01660

Summary

- Hadron interactions by HAL QCD method at physical point
  - (m_π, m_K) = (137, 502) MeV, L ~= 8fm, 1/a ~= 2.3GeV, #traj= 8000
- Hyperon forces in S= -2 channel
  - H-dibaryon : $\Lambda\Lambda$–$N\Xi$ ($^{11}S_0$) coupled channel study
    - No bound state below $\Lambda\Lambda$, but remnant exists near $N\Xi$ threshold
  - $N\Xi$ ($^{11}S_0$, $^{13}S_1$, $^{31}S_0$, $^{33}S_1$) int predicted, compared with femtoscopy exp
- Hyperon forces in S= -3 channel
  - $N\Omega$ ($^5S_2$) interaction: attraction at all distances
  - (quasi)-bound state, compared with femtocsopy exp
- Future
  - Hyperon forces in other channels → K. Murase [Fri], also K. Murakami [Fri]
  - Int w/ charm, bottom, relevant to exotics → W. Yamada [Fri]
  - Calc. w/ optimized op method to control sys err → S. Aoki [Mon]