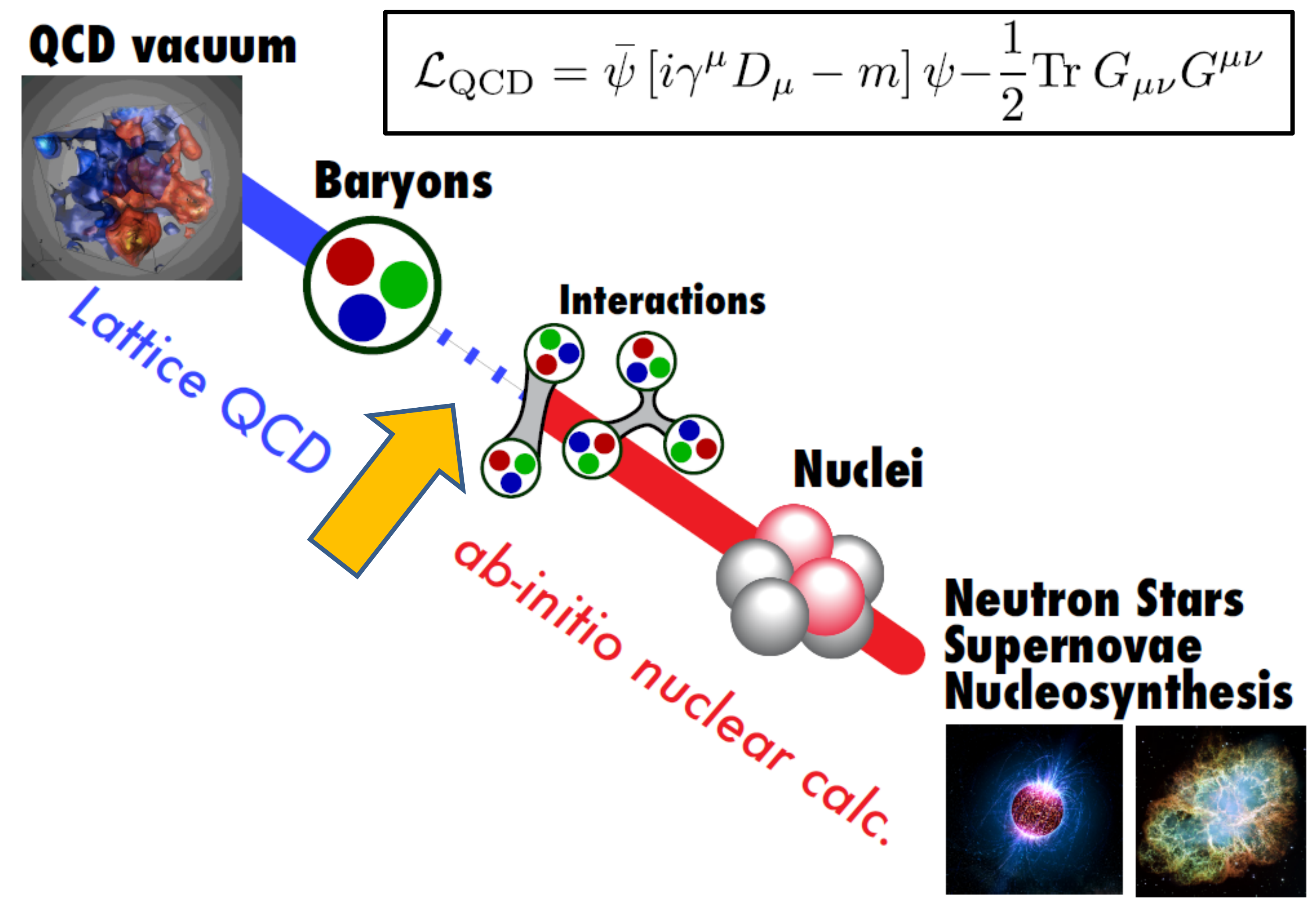
# Baryon Interactions from Lattice QCD



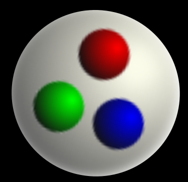

Tetsuo Hatsuda (iTHEMS, RIKEN)

NFQCD @ YITP (June 14, 2018)

# Di-Omega and all that from Lattice QCD

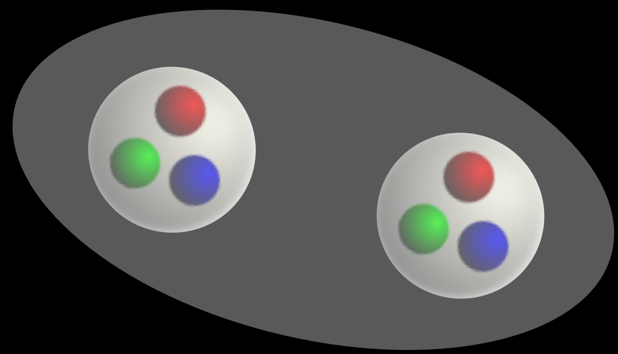
Gongyo+ [HAL QCD Coll.],
Phys. Rev. Lett. 120 (2018) 212001

## Baryon



**Proton, Neutron, Hyperons, . . .**

## Dibaryon

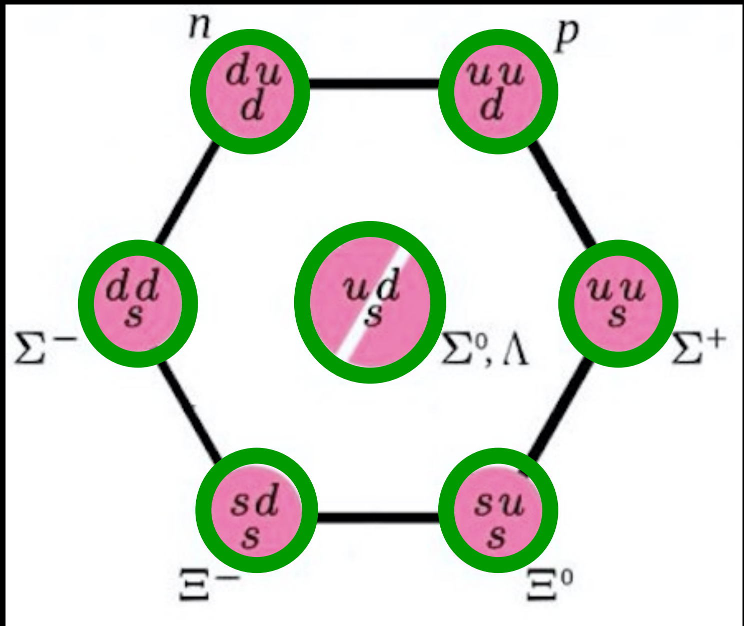


**Deuteron (1931, Urey)**
**No more?**

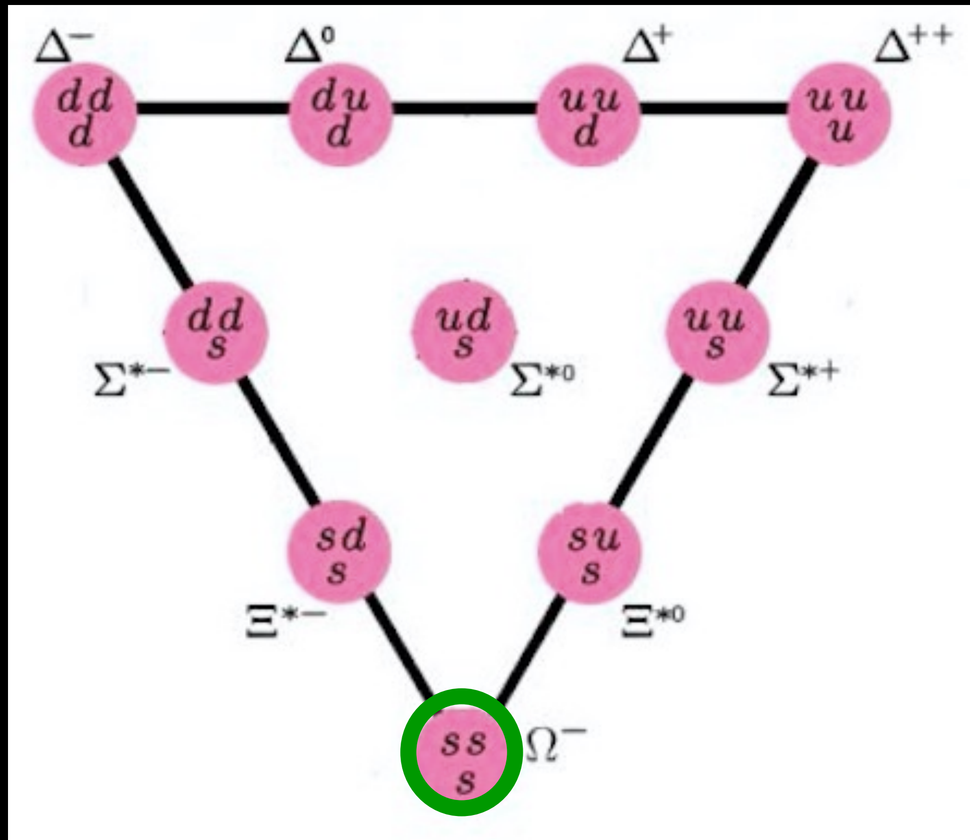
# Contents

# Flavor SU(3) Classification : B=1

## 8 (Octet)

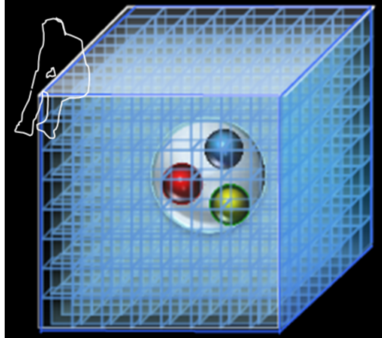



## 10 (Decuplet)




$\Omega^-$ (1672)
Only weak decay (→ΛK, Ξπ)
Mean Life ~ 0.8 x $10^{-10}$ sec

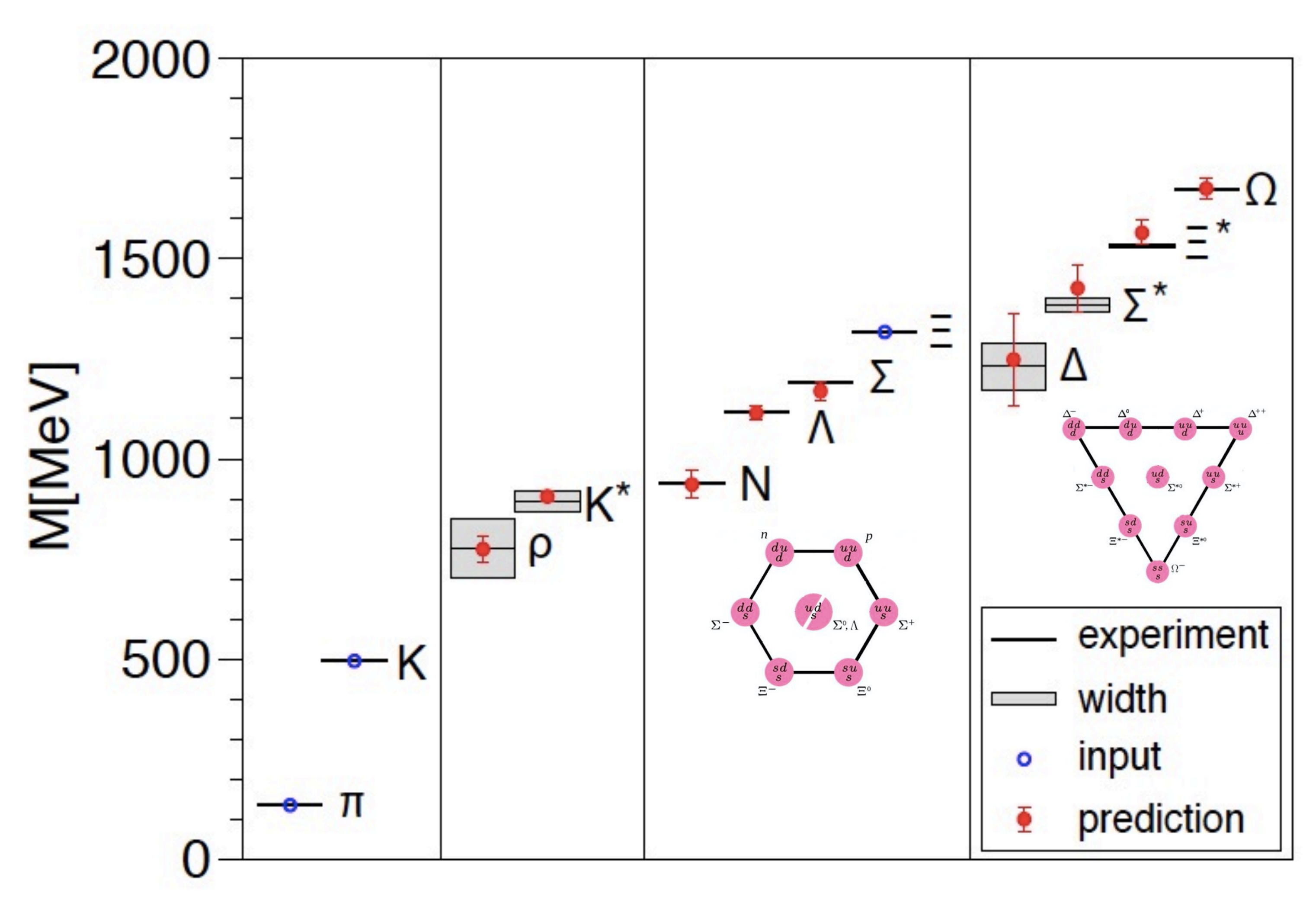
# Octet and Decuplet Baryons from Lattice QCD



$a_{min}$ = 0.065 fm

$L_{max}$ = 4.1 fm

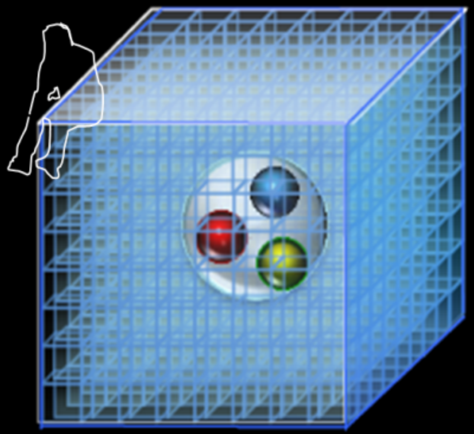
$m_{\pi,min}$ =190 MeV




taken from Fodor and Hoelbling, Rev. Mod. Phys. 84 (2012) 449

# Lattice QCD with isospin breaking

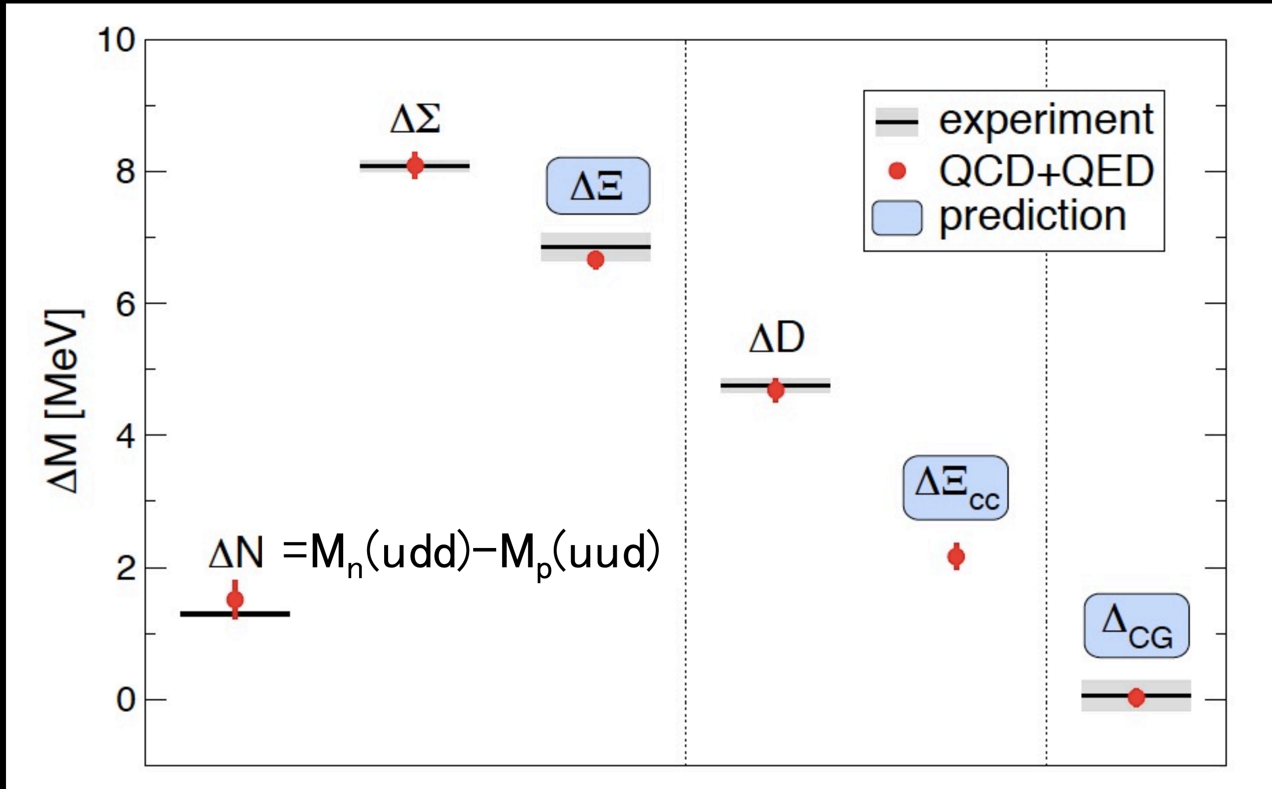
BMW Coll., Science 347 (2015) 1452



$a_{min} = 0.054$ fm

$L_{max} = 8$ fm

$m_{\pi,min} = 190$ MeV

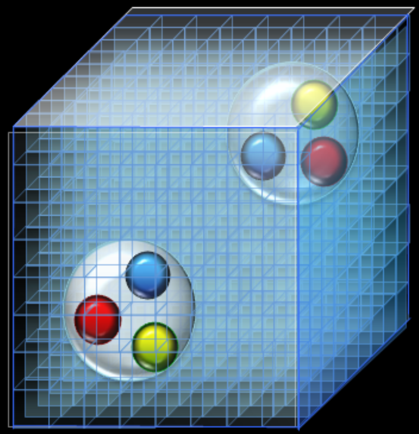



$(M_n - M_p)_{lat} = 1.51(16)(23)$ MeV

$(M_n - M_p)_{exp} = 1.29$ MeV

# BB Interactions from LQCD at almost physical point

Hadrons to Atomic nuclei HAL from Lattice QCD

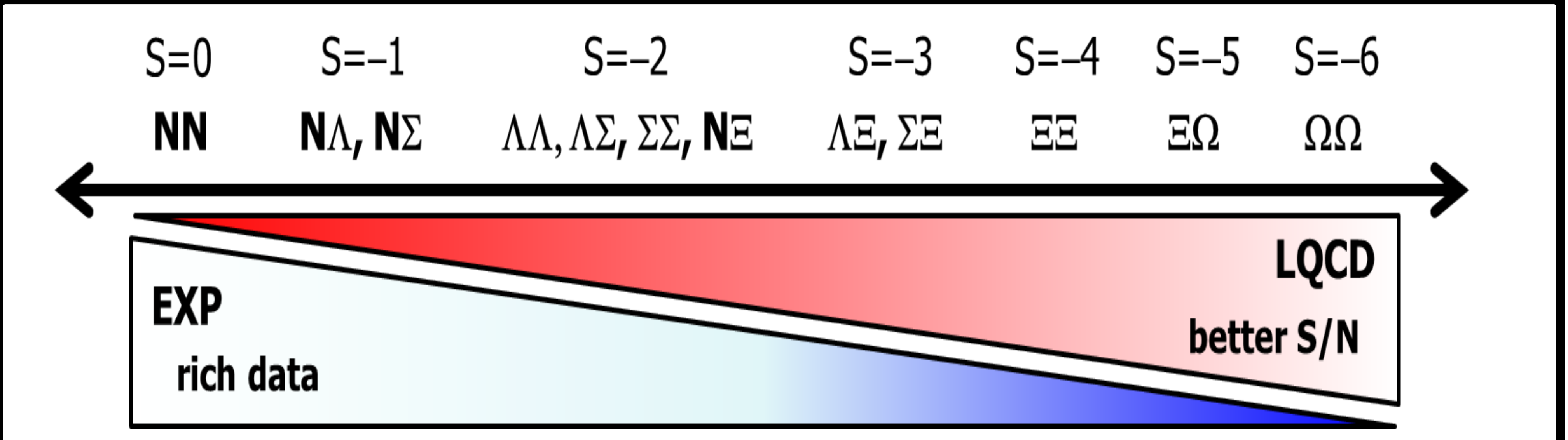


$a = 0.085$ fm

$L = 8.1$ fm

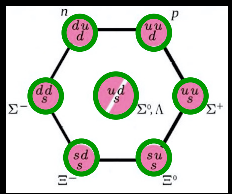
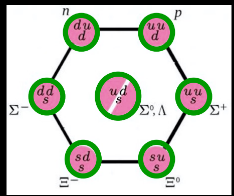
$m_\pi = 146$ MeV

$M_K = 525$ MeV

# Flavor SU(3) Classification of BB system

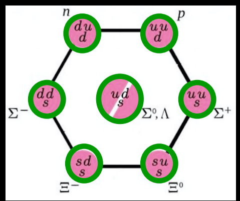
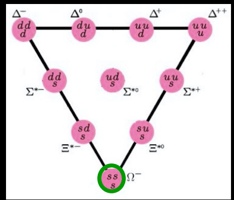
c.f. Dyson & Xoung, PRL 14 (1965)

 x 

$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$

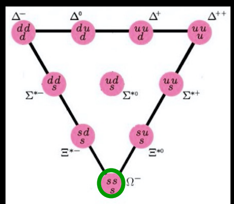
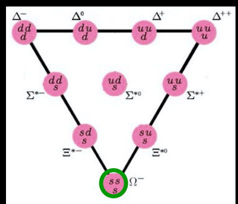
$H_{\Lambda\Lambda-N\Xi-\Lambda\Sigma}$ (J=0) — Jaffe (1977)

$D_{pn}$ (J=1) — Rarita-Schwinger (1941)

 x 

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

$N\Omega$ (J=2) — Goldman et al (1987)

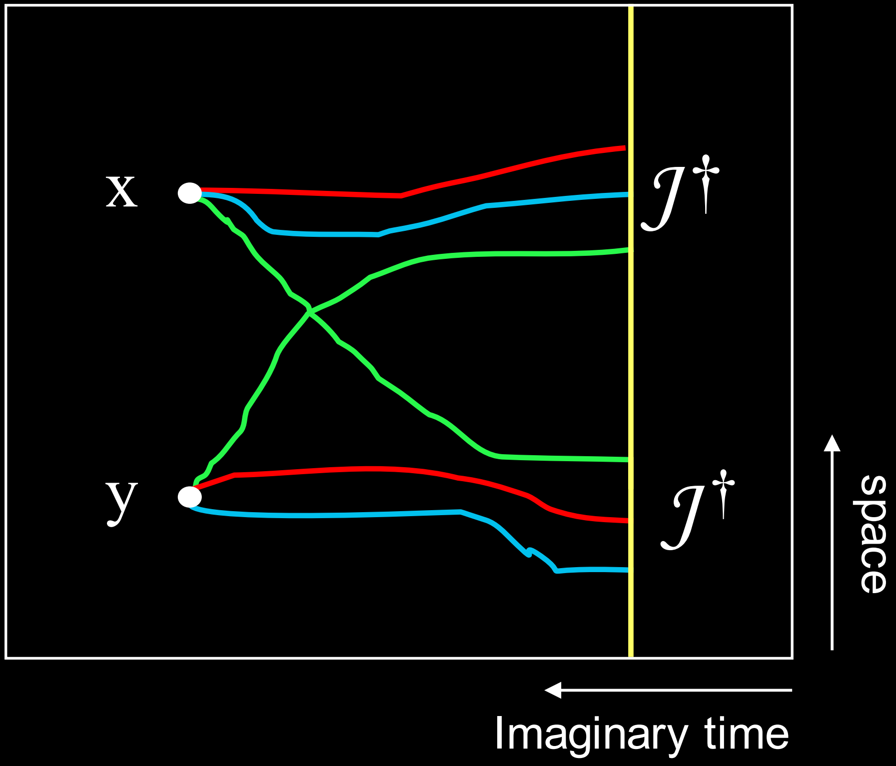
 x 

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

Di-Omega (strangeness = −6)

$\Omega\Omega$(J=0) — Zhang et al (1997)

# Scattering problem in LQCD




$$\langle N_1(\mathbf{x},t)N_2(\mathbf{y},t)\mathcal{J}_1^\dagger(0)\mathcal{J}_2^\dagger(0)\rangle = \sum_n \langle 0|N_1(\mathbf{x})N_2(\mathbf{y})|n\rangle a_n e^{-E_n t} \xrightarrow{t>t^*} \phi(\mathbf{r},t) = \sum_{n<n^*} b_n \phi_n(\mathbf{r}) e^{-E_n t}$$

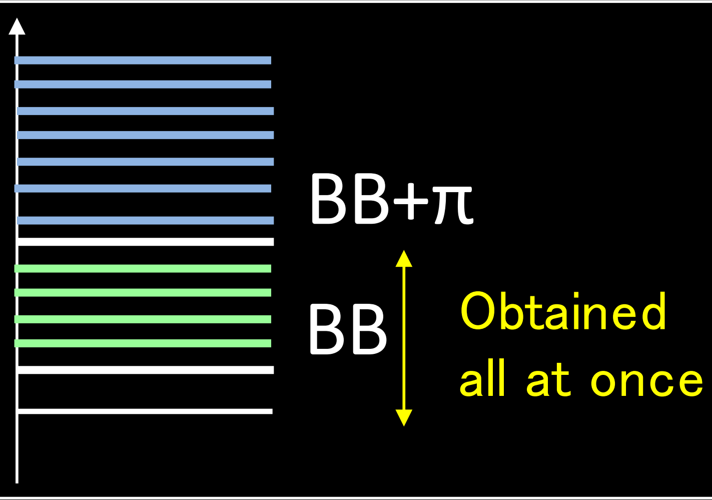
## HAL QCD Method

$\phi$(r,t) → 2PI kernel (T=U+GUT)

→ phase shift, binding energy

Ishii, Aoki & Hatsuda, PRL 99 (2007) 022001

Ishii et al. [HAL QCD Coll.], PLB 712 (2012) 437



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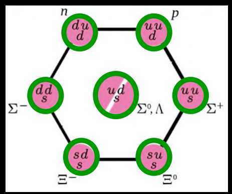
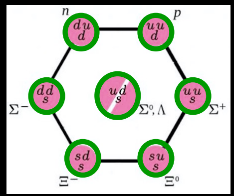


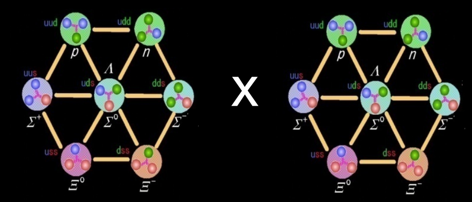

x




$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$

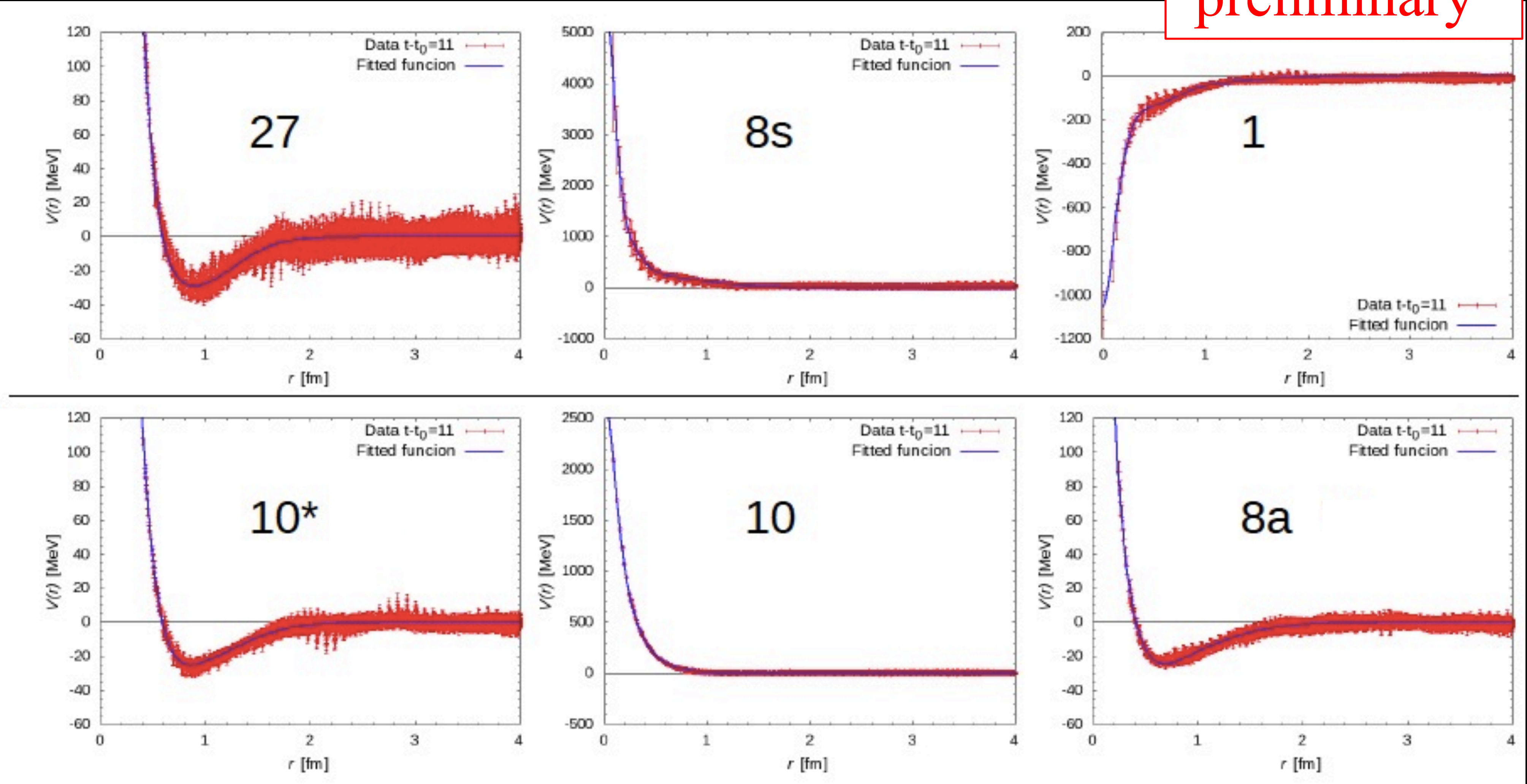
# 8x8 BB interactions with flavor basis: $V_C(r)$

K. Sasaki+ HAL QCD Coll.
T. Inoue+ HAL QCD Coll.



$$8 \times 8 = \underbrace{27 + 8s + 1}_{^1S_0} + \underbrace{10^* + 10 + 8a}_{^3S_1,\ ^3D_1}$$

preliminary



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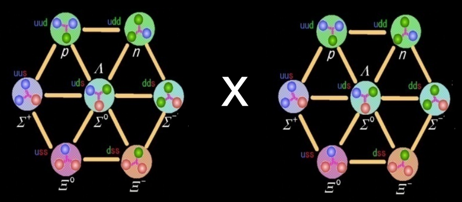
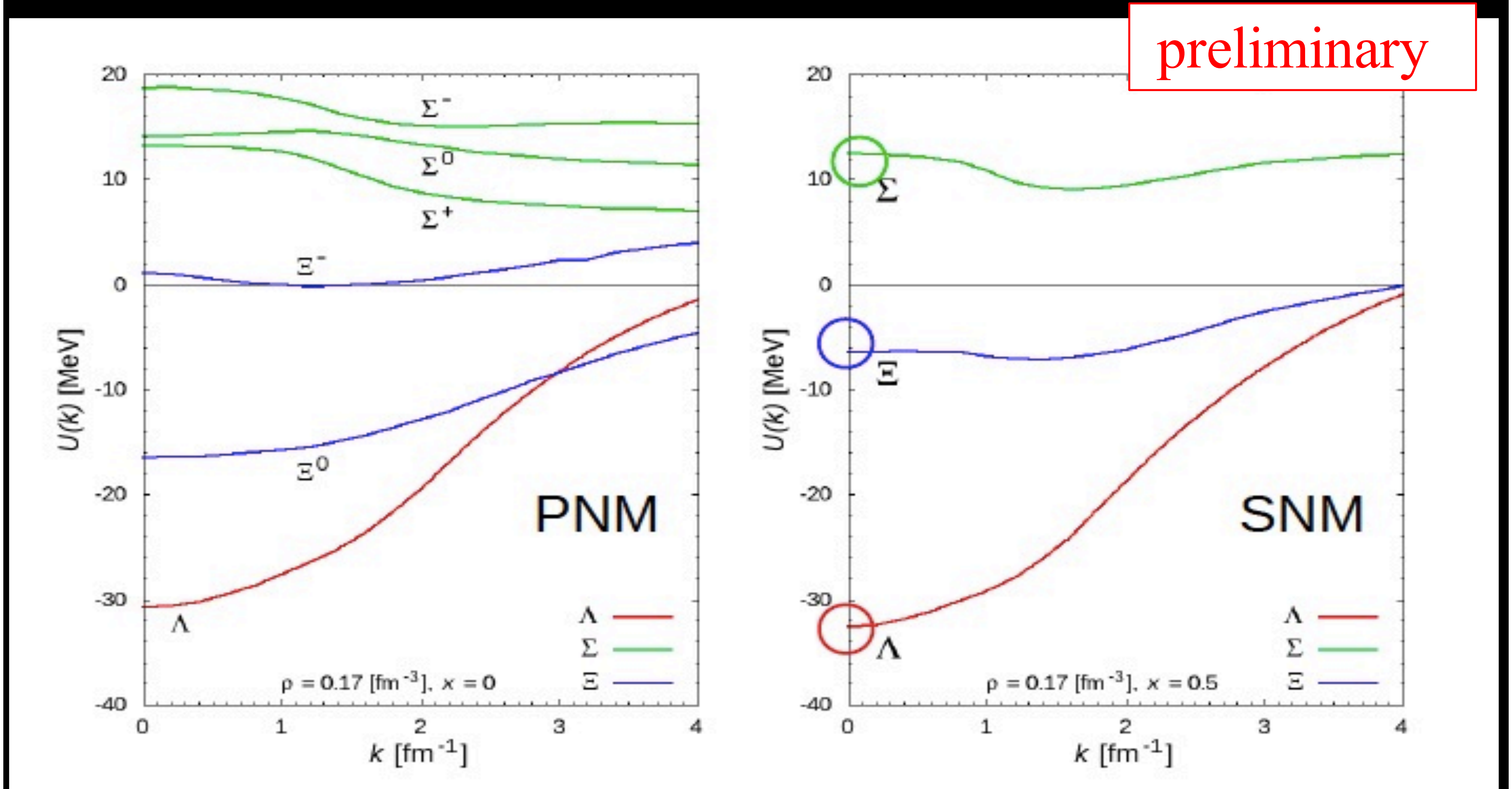
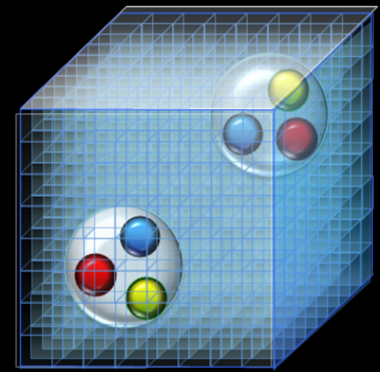


$$8 \times 8 = \underbrace{27 + 8s + 1}_{^1S_0} + \underbrace{10^* + 10 + 8a}_{^3S_1,\ ^3D_1}$$



# S=-2 BB interactions in particle basis: $V_C(r)$

K. Sasaki+ HAL QCD Coll.

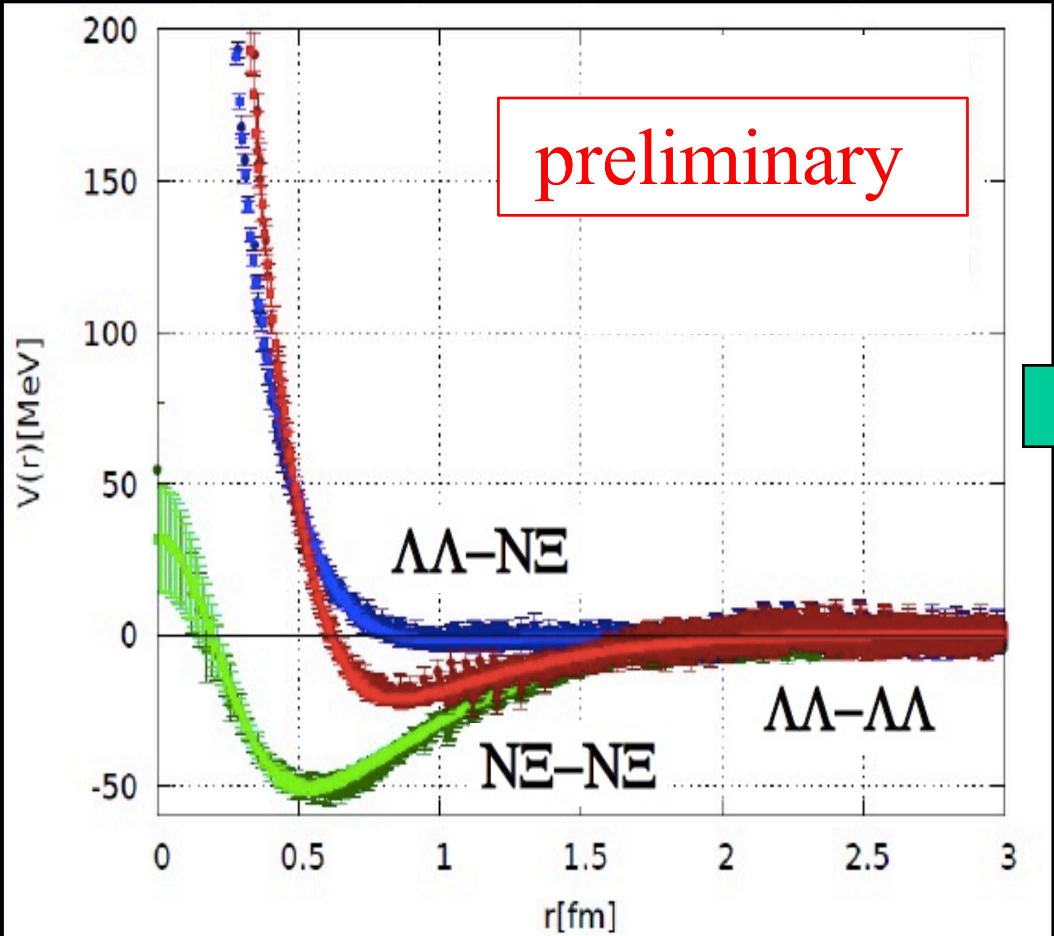


$a$ = 0.085 fm

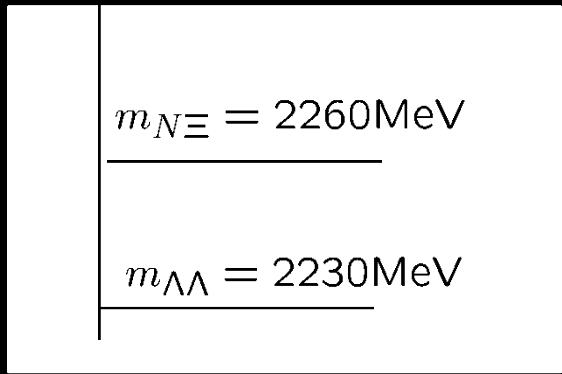
$L$ = 8.1 fm

$m_\pi$ = 146 MeV

$M_K$ = 525 MeV

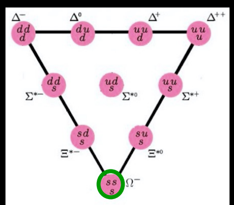



Coupled channel analysis
to search for H-like resonances

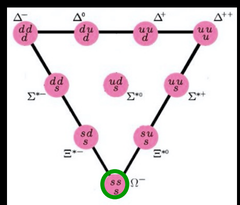


# Flavor SU(3) Classification : B=2

c.f. Dyson & Xoung, PRL 14 (1965)



x



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

Di-Omega (strangeness = −6)

$\Omega\Omega(J=0)$

Zhang et al (1997)

# Di-Omega: ΩΩ ($^1S_0$)

Gongyo+ [HAL QCD Coll.],
Phys. Rev. Lett. 120 (2018) 212001

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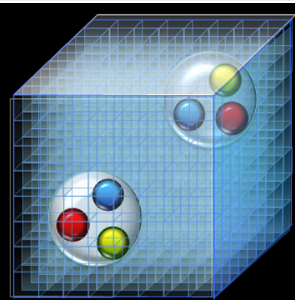
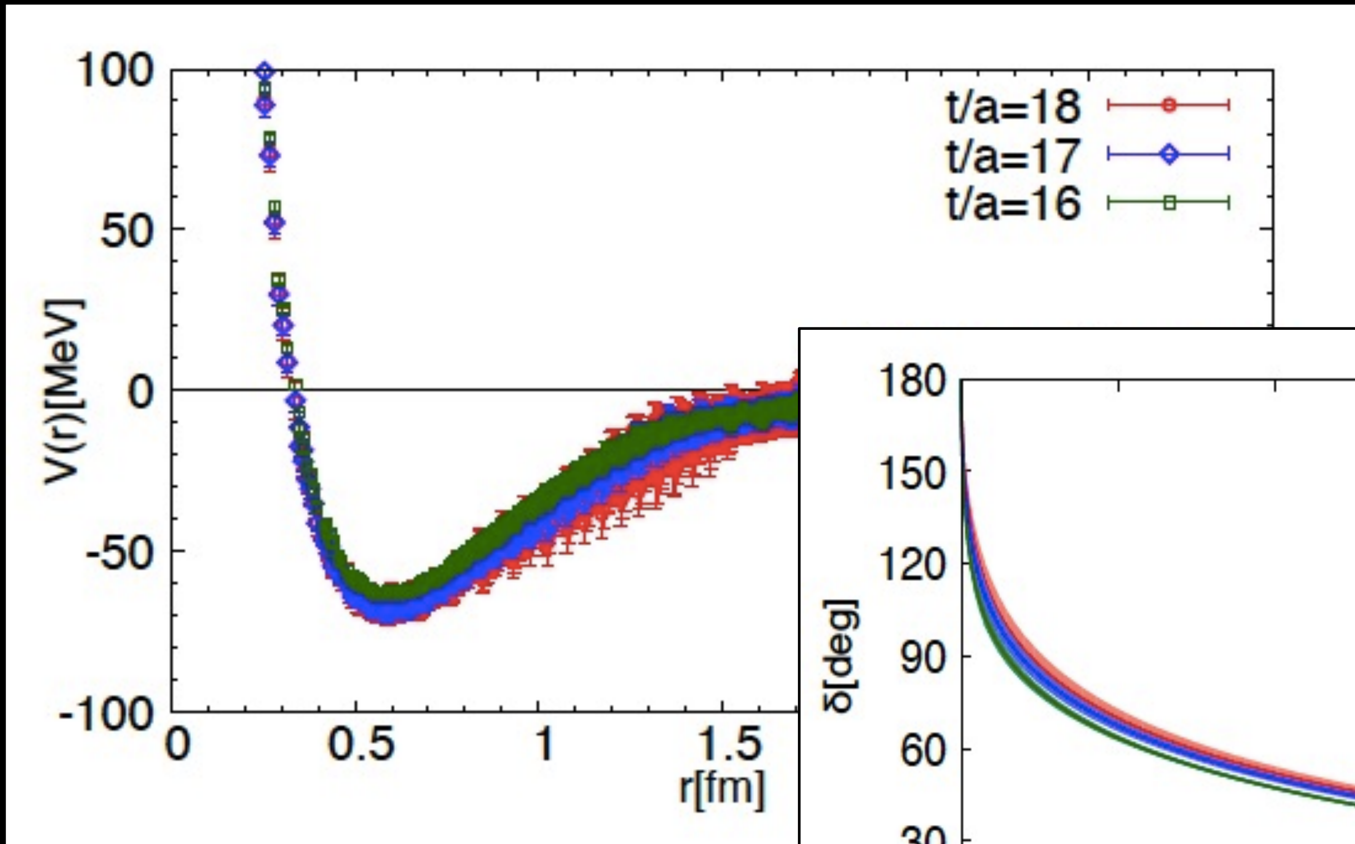
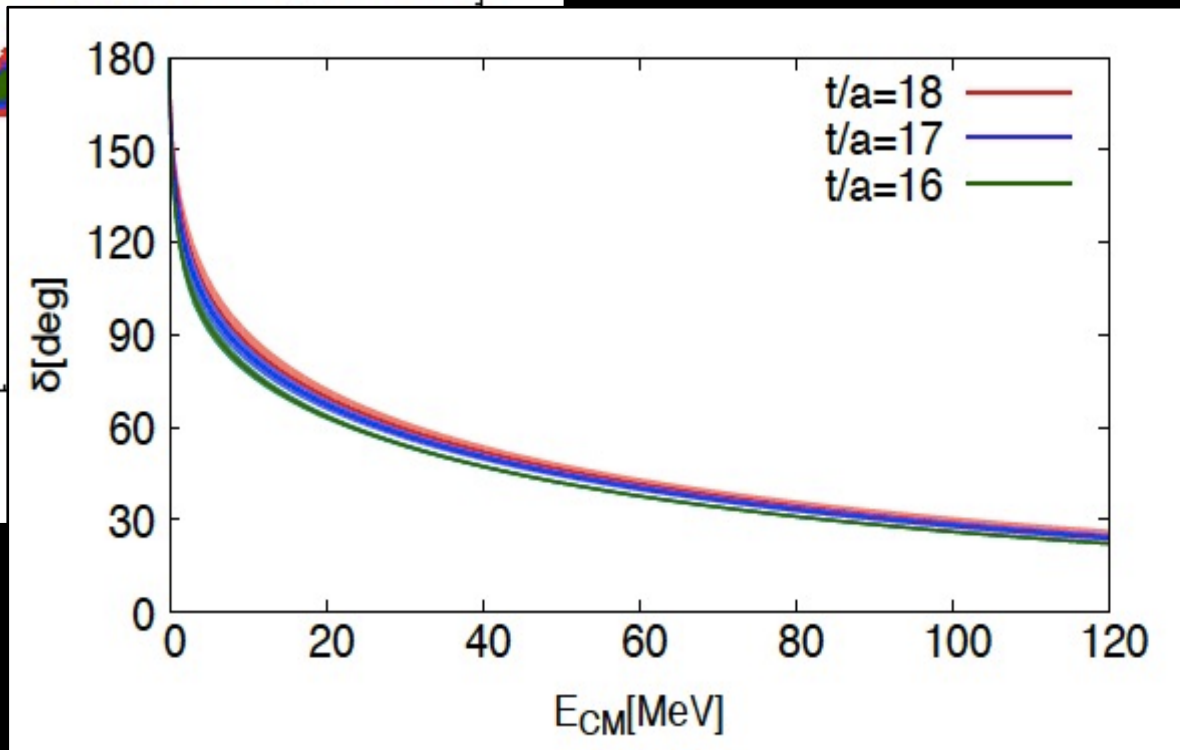


S. Gongyo



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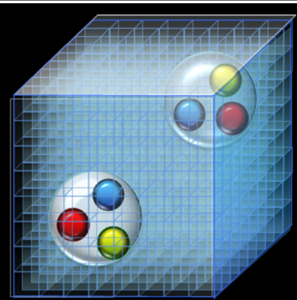
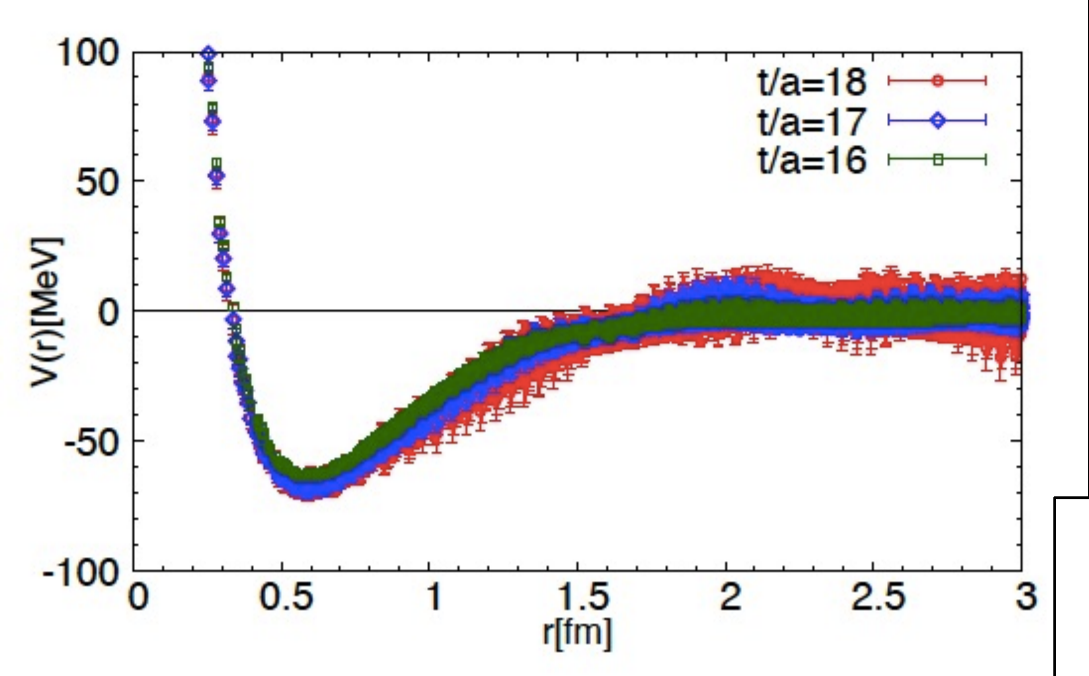
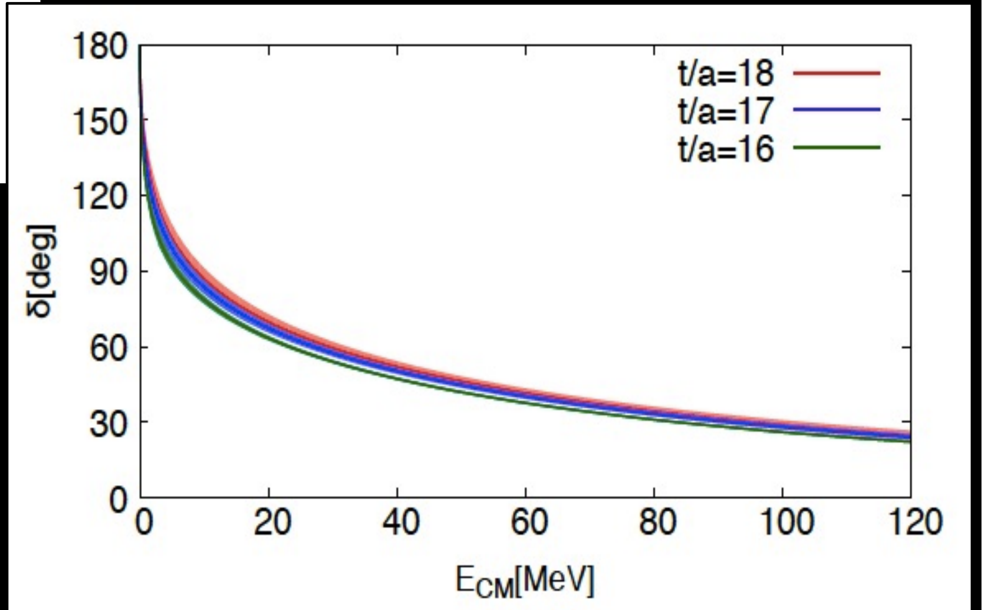


S. Gongyo

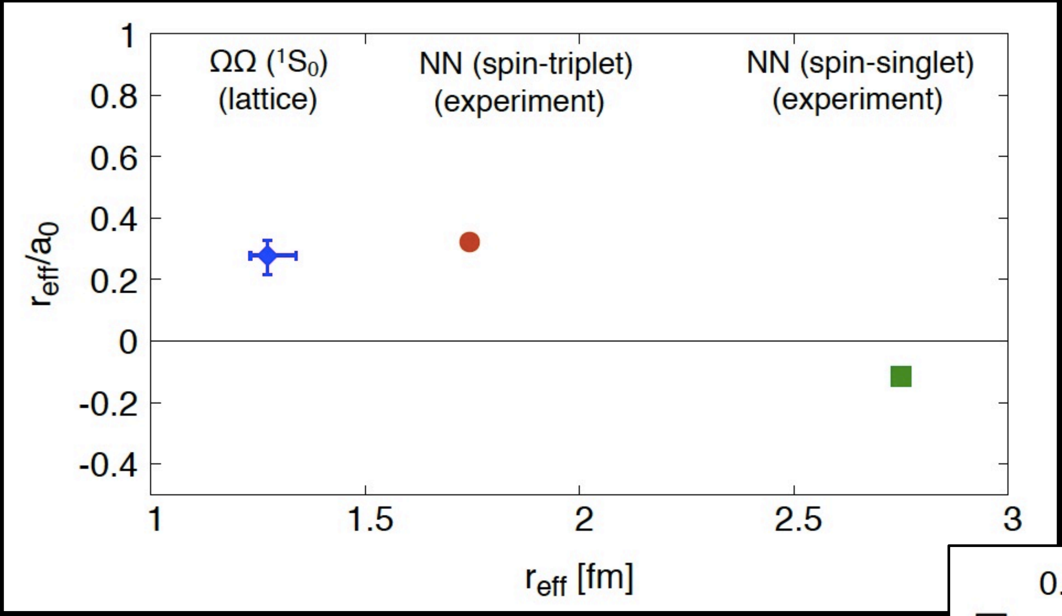


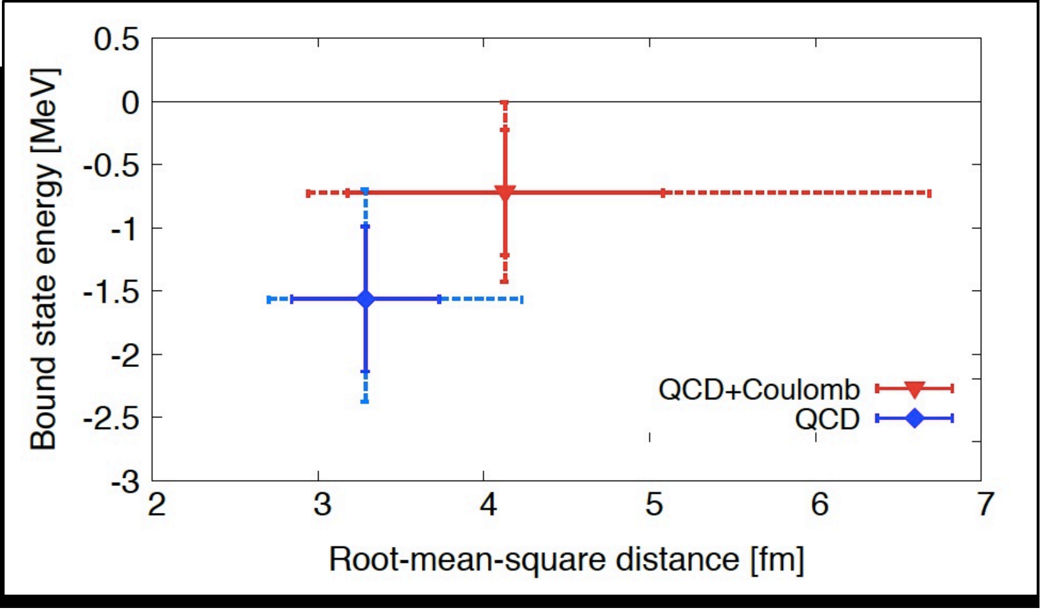



# ΩΩ near unitarity

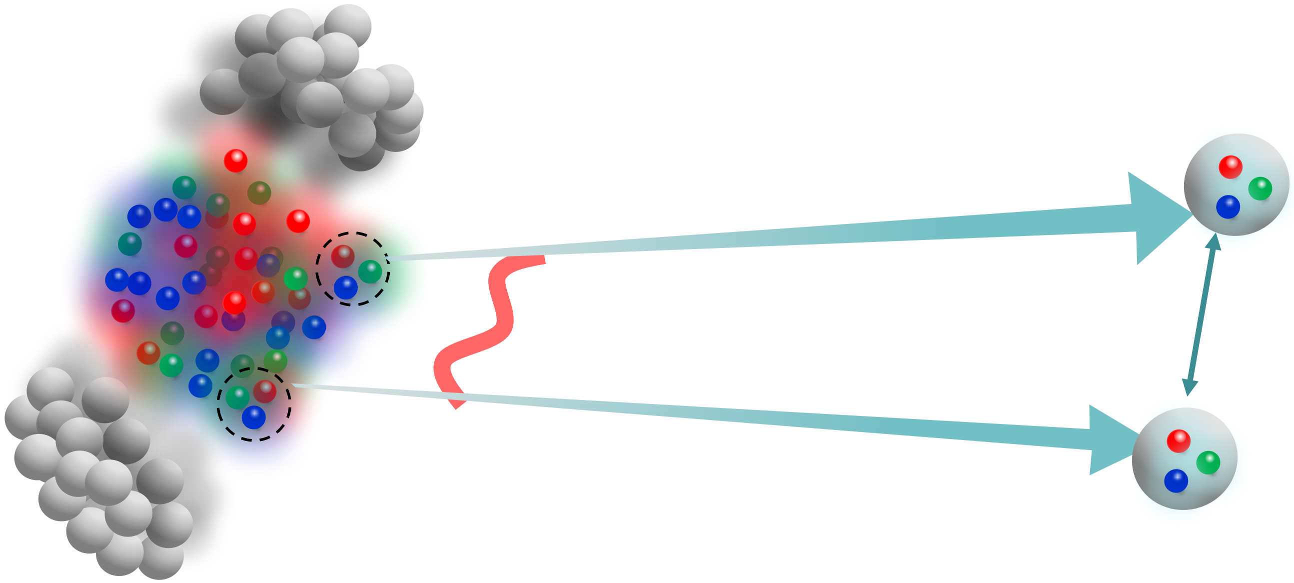
$$k \cot \delta(k) = -\frac{1}{a_0} + \frac{1}{2} r_{\rm eff} k^2 + \cdots$$

$$a_0^{(\Omega\Omega)} = 4.6(6)(^{+1.2}_{-0.5}) \quad \text{fm},$$
$$r_{\rm eff}^{(\Omega\Omega)} = 1.27(3)(^{+0.06}_{-0.03}) \quad \text{fm}.$$



# How HIC can tell us about interaction?



$$Q = \sqrt{-\left(\frac{p_1 - p_2}{2} - \frac{(p_1 - p_2)\cdot P}{P^2} P\right)^2}$$

Measuring Pair Correlation → Constraint on Pairwise Interaction

$$C_{AB}(Q) = \frac{N_{AB}^{\text{pair}}(Q)}{N_A N_B(Q)} = \begin{cases} 1 & \textbf{No Correlation} \\ \text{others} & \textbf{Interaction, Quantum Interference etc} \end{cases}$$

# Correlation from FSI

Lednicky+ 1982

$$C_{AB}(Q) - 1 = \frac{4\pi}{(2\pi R^2)^3} \int dr r^2 S^{\mathrm{rel}}(r)[|\chi_Q(r)|^2 - |j_0(Qr)|^2]$$

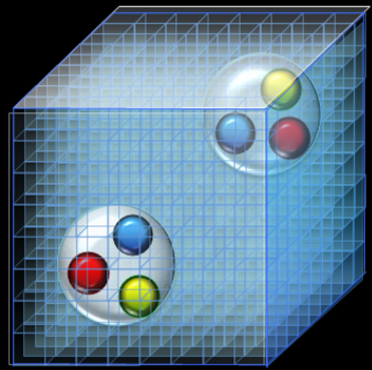
Static/Spherical Source:

$$S^{\mathrm{rel}}(r) \sim (\pi R^2)^{3/2} \exp\left(-\frac{r^2}{4R^2}\right)$$

Asymptotic wave function:

$$\chi_Q(r) \sim \sin(Qr + \delta)/(Qr)$$

$$Q \cot \delta = -\frac{1}{a_0} + \frac{1}{2} r_{\mathrm{eff}} Q^2$$



$a$ = 0.085 fm

$L$ = 8.1 fm

$m_\pi$ = 146 MeV

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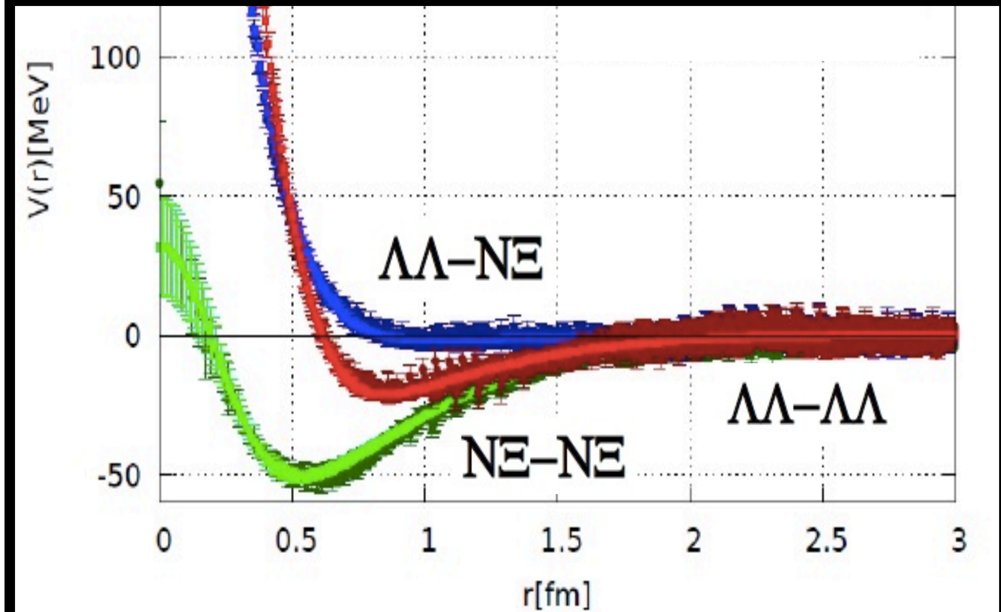
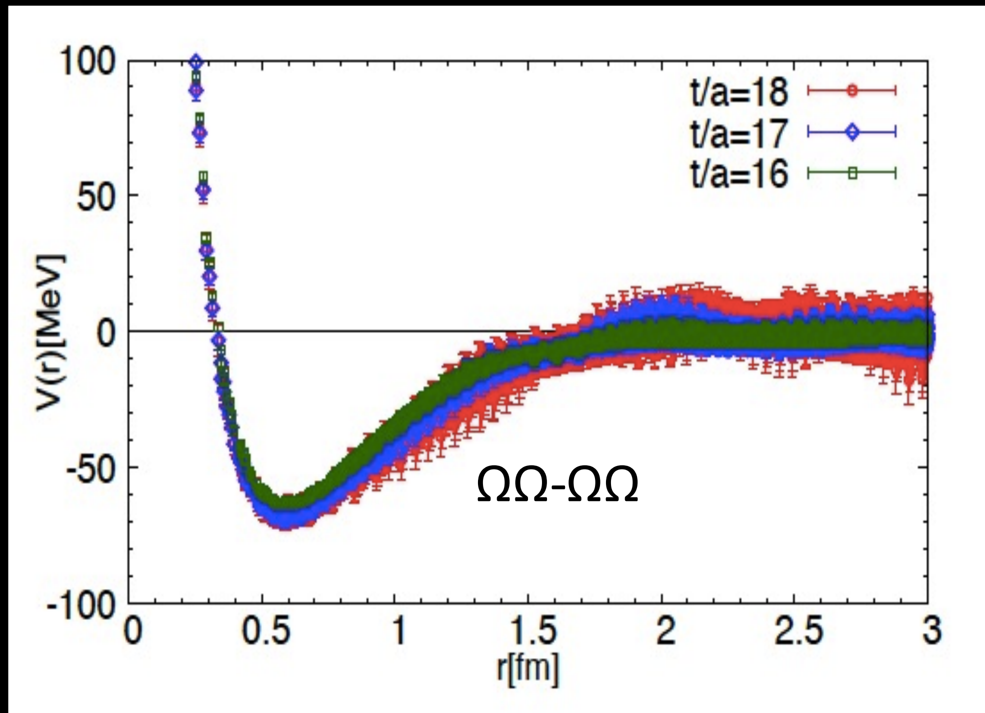
# HAL QCD Potential for $J^P=0^+$

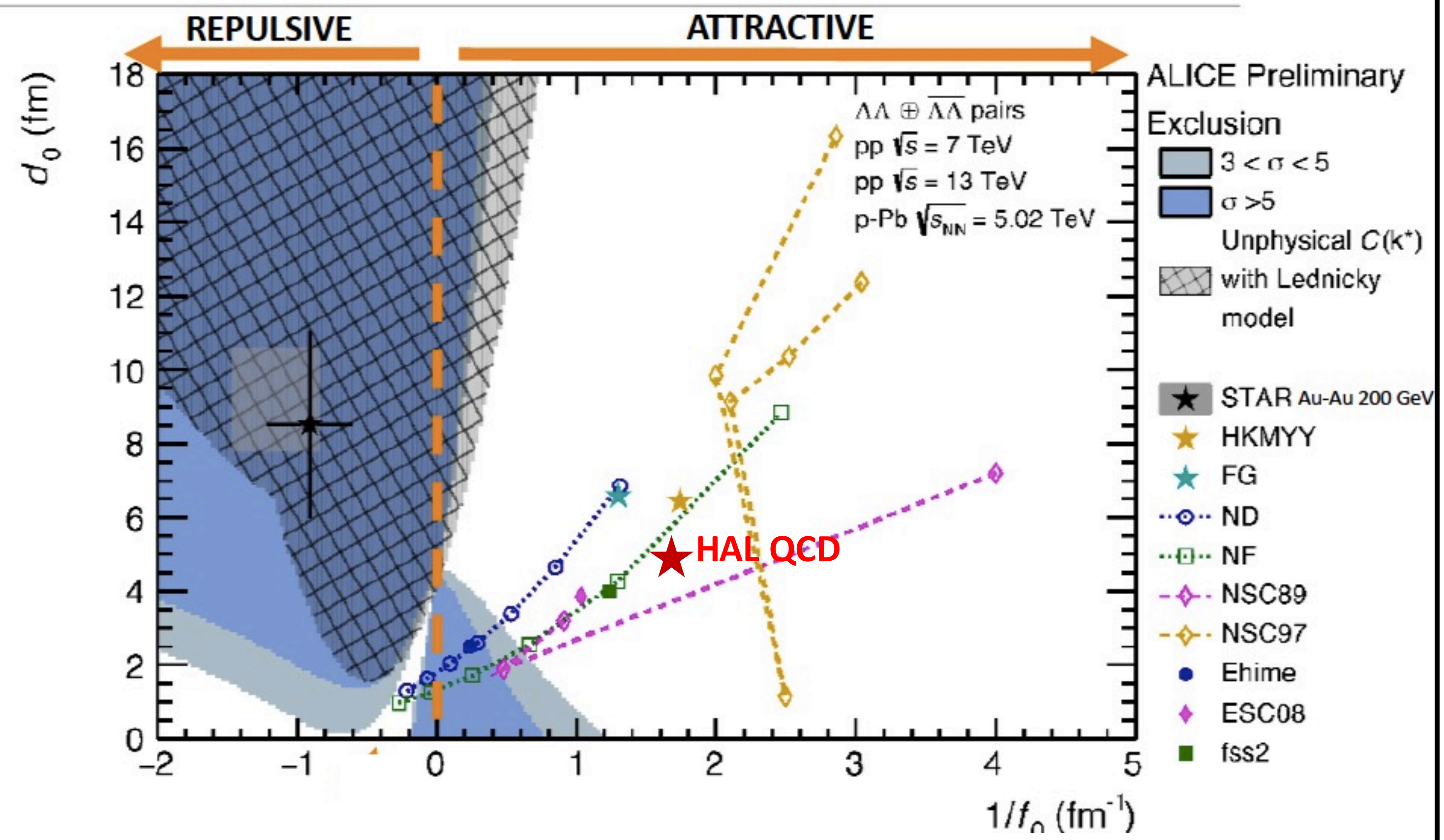
S=-2




S=-6



# Λ–Λ Correlations: Combined Exclusion Plot



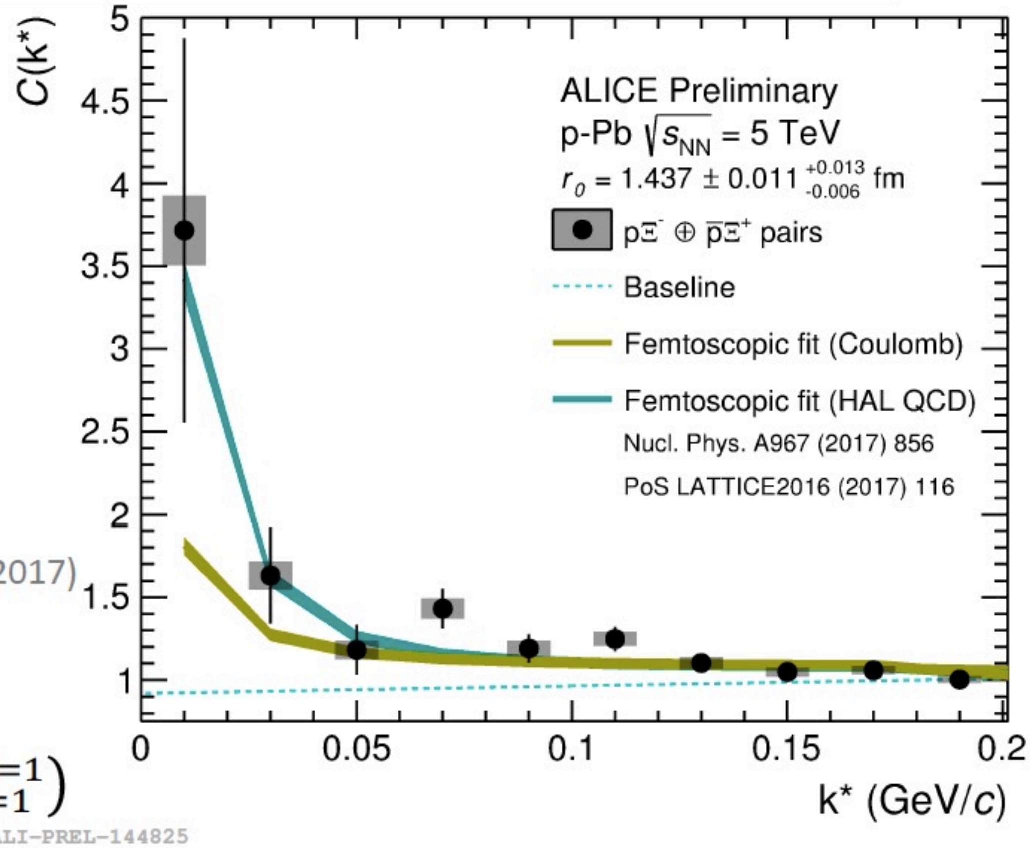



Talk by Valentina Mantovani Sarti (TUM) at MESON2018 (June 8, 2018)
See also, ALICE Coll. arXiv:1805.12455 (2018)

# p-Ξ⁻ Correlation Function in p-Pb 5.02 TeV

- **First observation of strong attractive interaction in p-Ξ⁻**
  - p-Value with and without strong potential (Coulomb only): 0.055 vs. 0.004
- modeled with preliminary QCD strong potential by the HAL QCD collaboration (Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)

$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

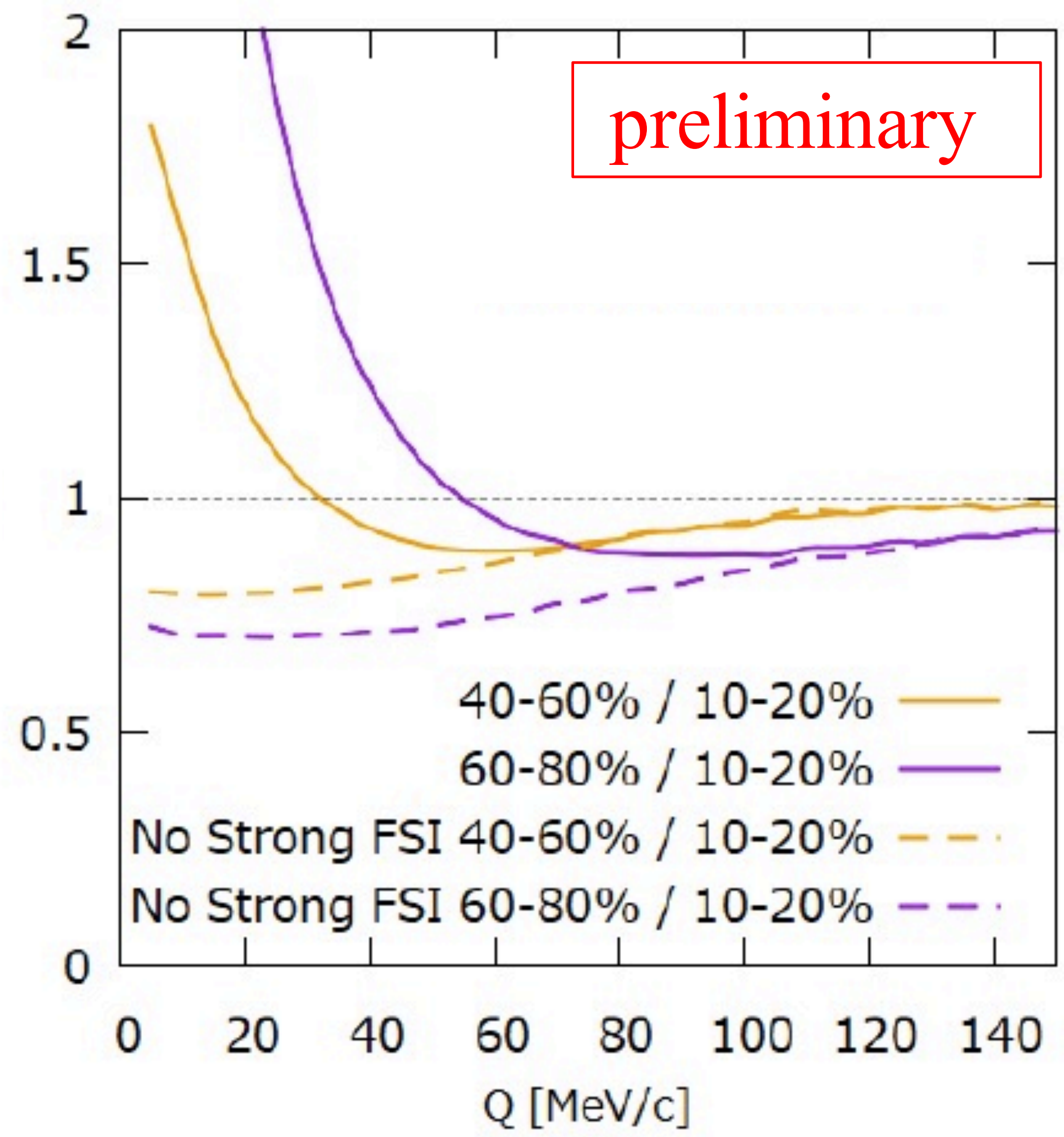





Talk by Valentina Mantovani Sarti (TUM) at MESON2018 (June 8, 2018)

# ΩΩ correlation from HIC

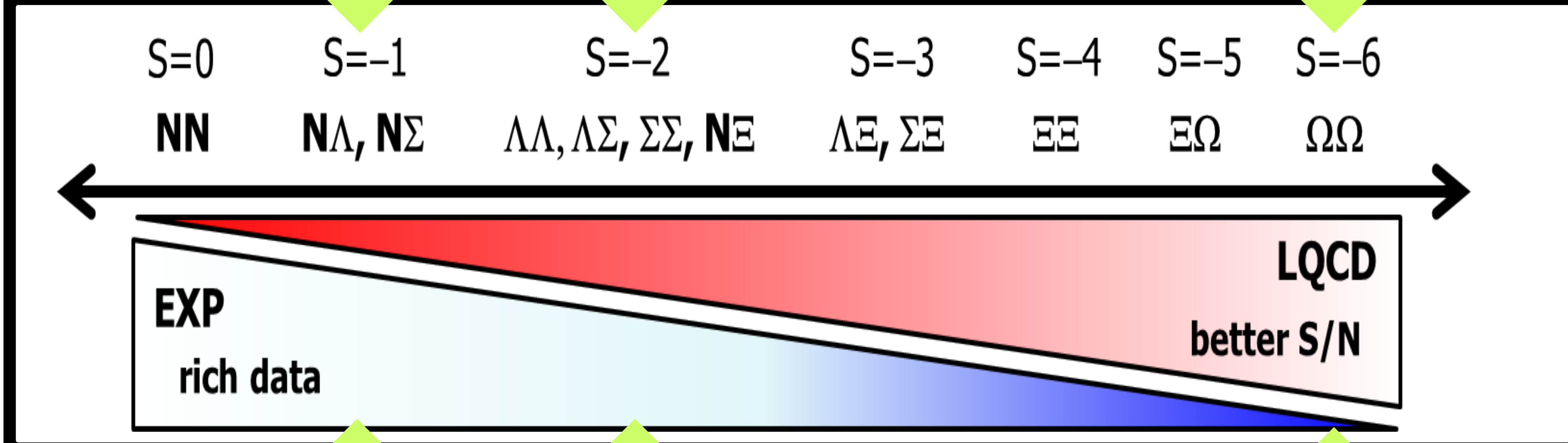
$$C^{SL}(Q) = C^{\text{Small-R}}(Q)/C^{\text{Large-R}}(Q)$$




Morita+
(in preparation)

# Summary

BB interactions on the latttice (L=8.1fm, $m_\pi$=146 MeV, $m_K$= 525 MeV)
Prediction by HAL QCD Collaboration

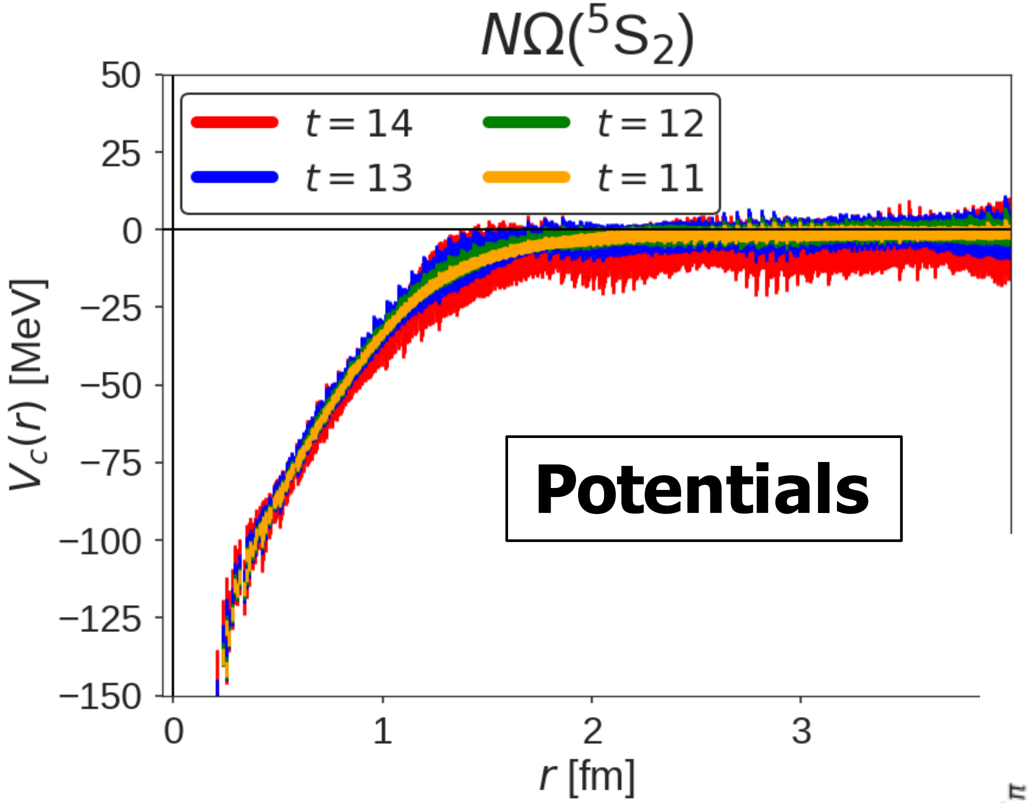



Hypernuclei
FSI at RHIC, LHC

FSI in
Future HIC

# Backup slides

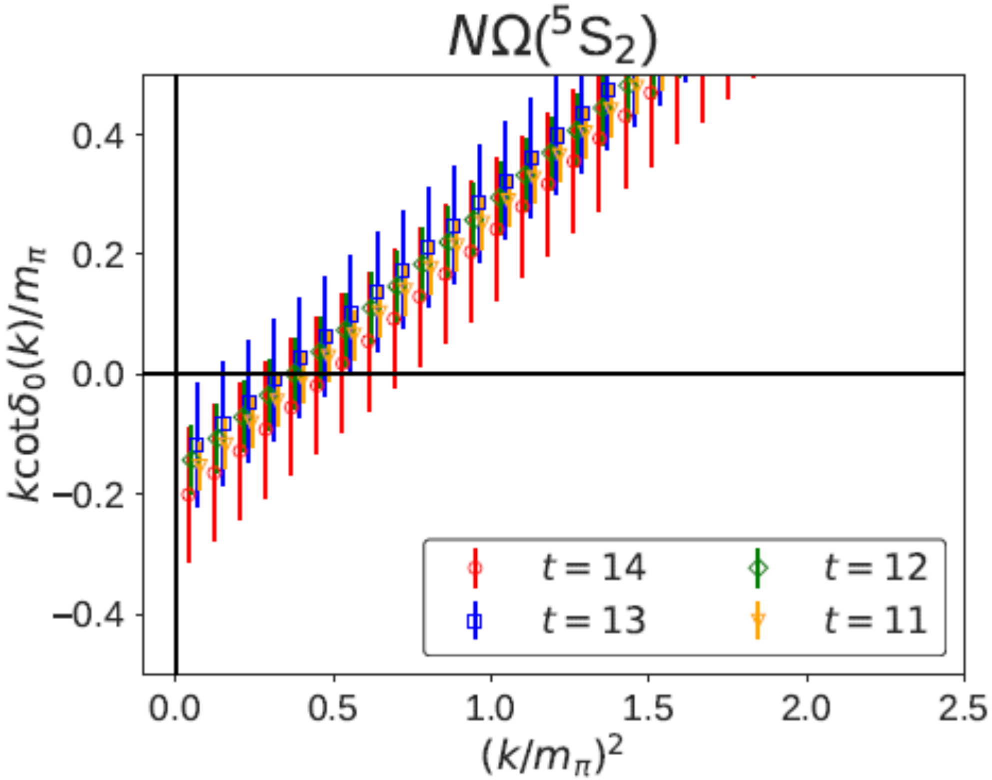
# NΩ system ($^5S_2$)




**Potentials**

**preliminary**

**Phase Shifts**




**Strong Attraction**

**possibly "Bound"**

⟺ **NΩ correlation in HIC**

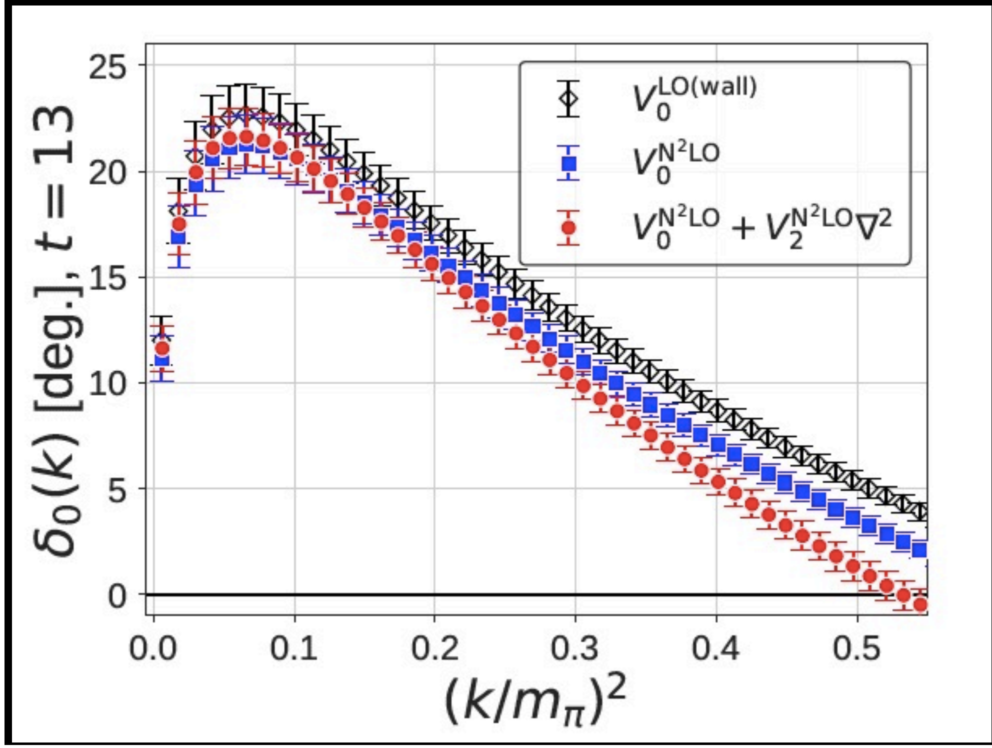
(200conf x 4rot x 48src)

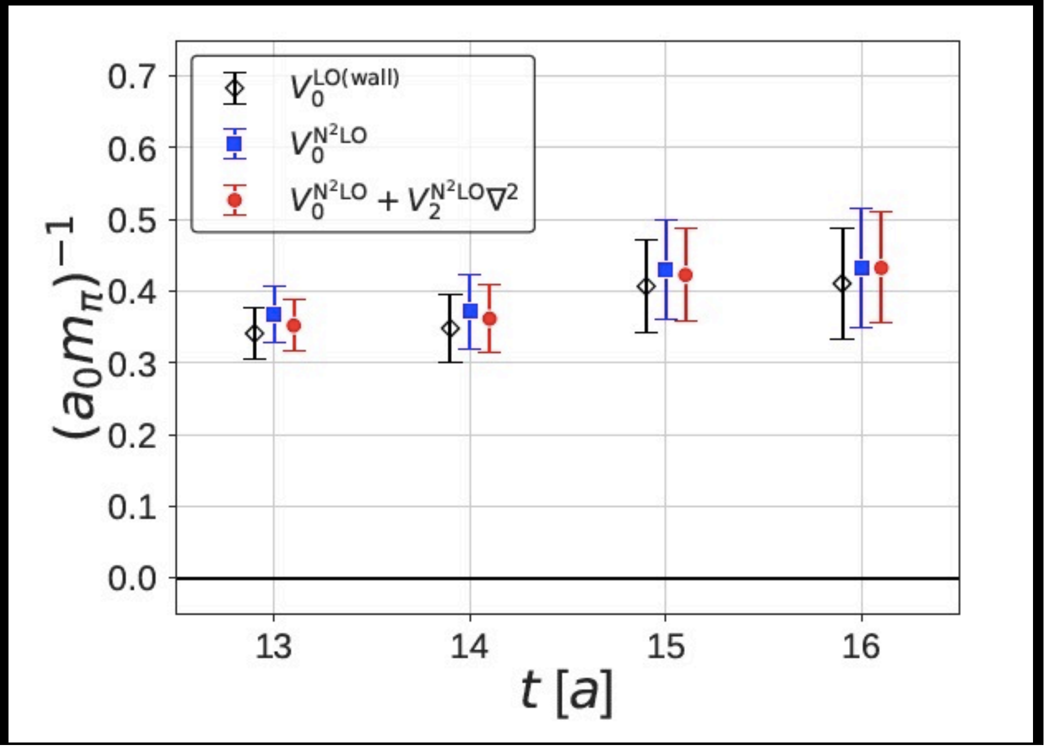
# Systematics of the HAL QCD Potential at Low Energies in Lattice QCD

Takumi Iritani,[1] Sinya Aoki,[2,3] Takumi Doi,[1,4] Shinya Gongyo,[1] Tetsuo Hatsuda,[4,1] Yoichi Ikeda,[5] Takashi Inoue,[6] Noriyoshi Ishii,[5] Hidekatsu Nemura,[5] and Kenji Sasaki[2]

(HAL QCD Collaboration)

$$U(\vec{r},\vec{r'}) = \{V_0^{\mathrm{N^2LO}}(r) + V_2^{\mathrm{N^2LO}}(r)\nabla^2\}\delta(\vec{r}-\vec{r'}).$$



# The fate of the direct method (check on NN)

T. Iritani et al. (HAL Coll.) PRD96(2017)034521

| | $NN(^1S_0)$ | | | | $NN(^3S_1)$ | | | |
|---|---|---|---|---|---|---|---|---|
| Data | Source independence | Sanity check (i) | Sanity check (ii) | Sanity check (iii) | Source independence | Sanity check (i) | Sanity check (ii) | Sanity check (iii) |
| YKU2011 [24] | † | No | No | * | † | No | No | * |
| YIKU2012 [25] | No | † | No | * | No | † | No | * |
| YIKU2015 [26] | † | † | No | * | † | † | No | No |
| NPL2012 [27] | † | † | No | * | † | † | * | * |
| NPL2013 [28, 29] | No | * | * | No | No | * | * | ? |
| NPL2015 [30] | † | No | * | No | † | No | * | No |
| CalLat2017 [31] | No | ? | * | No | No | ? | * | No |

All data for NN by the direct method fail these "minimum" tests so far

➔ Studies w/ the variational method are mandatory