日本原子力研究開発機構 原子力科学研究部門
先端基礎研究センター
Japan Atomic Energy Agency Sector of Nuclear Science Research
Advanced Science Research Center

Future Directions of Hadron Physics

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Hadron Properties in a nuclear medium
from the quark and gluon degrees of freedom

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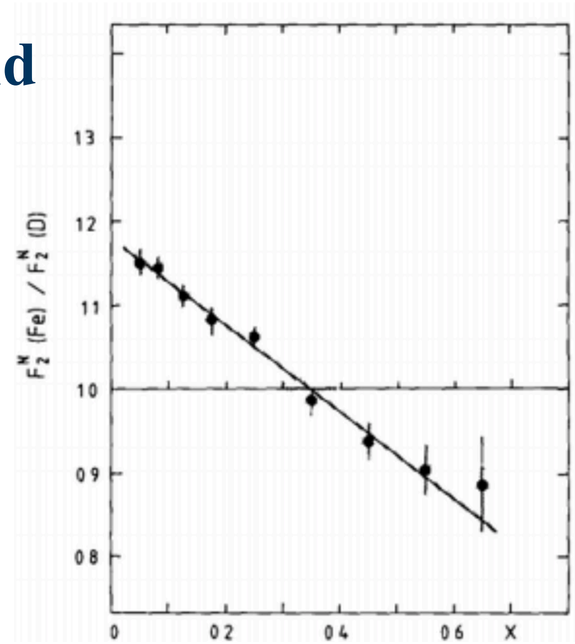
Future Directions of Hadron Physics

I am not a *Prophet*.

prophet: a person who is believed to have a special power that allows them to say what a god wishes to tell people, especially about things that will happen in the future

Knowing the Past is Seeing the Future 温故知新



- **Almost 40 years since the EMC effect was found**
  EMC collaboration, *Phys. Lett. 123 (1983) 275*

  Distributions of Quarks (and Gluons)
  are "modified" in nuclei.

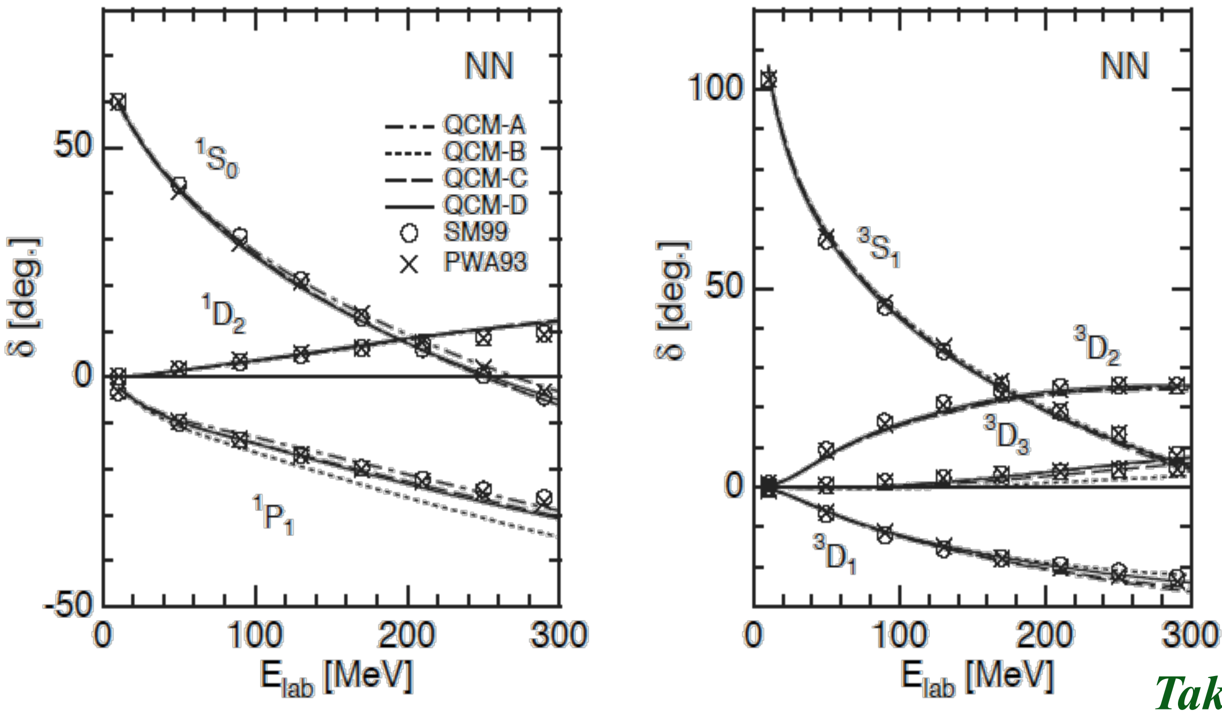
  by What?
  speculations and debates up to now
  modified by mean fields in medium
  exchanging quarks, change of scale
  short-range correlation

  We still have unsolved problems like spin EMC.

- **Even before EMC, we had known that Quarks do matter in nuclei!**

Nuclear Force

- Nuclear force has several different components. Yukawa predicted the nuclear attraction due to pion exchange.
  → long range part of nuclear force
  Two and more pions are exchanged to give medium range attraction. Heavy mesons may represent multi-pions.
- At short distances, nuclear force is strongly repulsive.



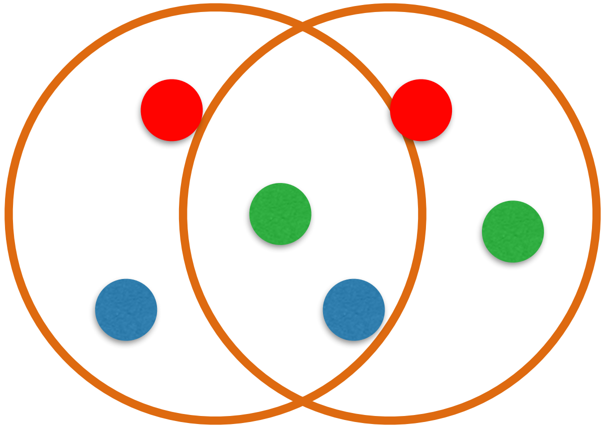
$$\frac{d\delta}{dk} \sim -0.5 \text{ fm}$$

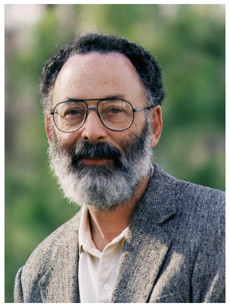
at E_{lab} = 200 MeV

Takeuchi, et al., PTP S137 (2000)

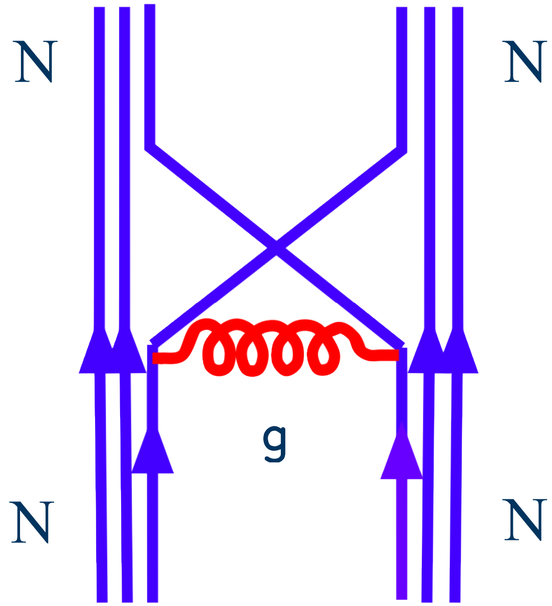
Nuclear Force

- As the nucleon (charge & matter) radius > 0.5 fm, the nucleons overlap significantly at distances R < 0.5 fm.





Nathan Isgur



- **Quark exchanges** are the source of strong NN repulsion at the range of the nucleon size. The **color-spin interactions** of quarks and the **Pauli exclusion principle** are responsible for the channel dependences of the short-range repulsion.

Generalized nuclear force

- **Strange sector: $SU(3)_f$ classification of two-baryon systems**
  $8 \times 8 = 1 + 8_S + 27 + 8_A + 10 + 10^{bar}$
  $NN(I=1) \subset 27, \quad NN(I=0) \subset 10^{bar}$
- **The other representations are realized only in strange systems.**
  $8 \times 10 = 8 + 10 + 27 + 35$
  $10 \times 10 = 10^{bar}{}_A + 27_S + 35_A + 28_S$
- **Pauli-principle prediction based on $SU(6) \supset SU(3)_f \times SU(2)_s$**
  two ground-state (36) baryons => [51] + [33] for L=0
  Color-singlet [51] states are forbidden at short distances.
- **Ex. S = -2, I = J = 0 system coupled to ΛΛ, NΞ, ΣΣ, Σ*Σ***

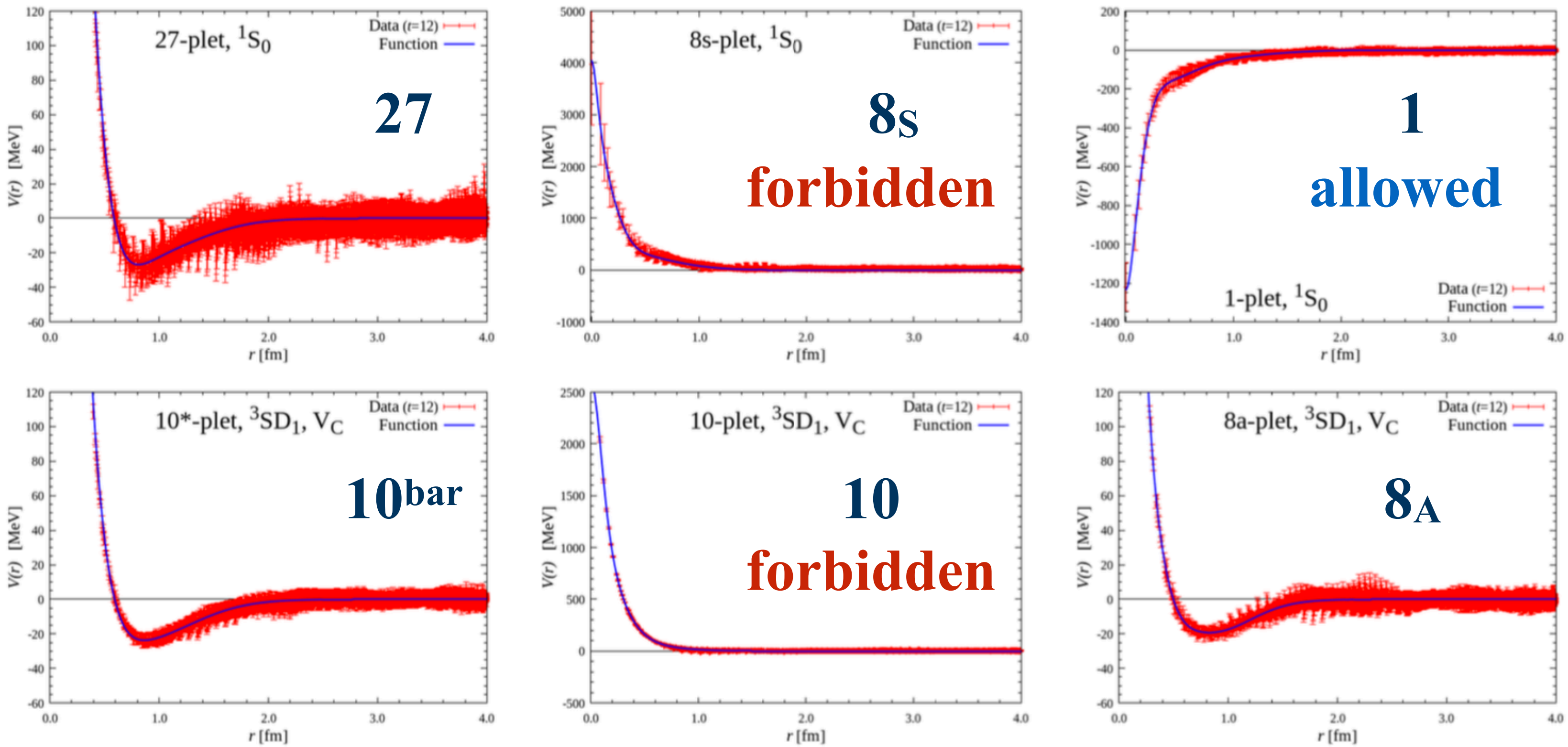
$$\begin{pmatrix} \Lambda\Lambda \\ N\Xi_S \\ \Sigma\Sigma \\ \Sigma^*\Sigma^* \end{pmatrix} = \frac{1}{\sqrt{360}} \begin{pmatrix} -\sqrt{45} & \sqrt{135} & -\sqrt{72} & -\sqrt{108} \\ \sqrt{180} & \sqrt{60} & \sqrt{72} & -\sqrt{48} \\ \sqrt{135} & -\sqrt{5} & -\sqrt{216} & \sqrt{4} \\ 0 & -\sqrt{160} & 0 & -\sqrt{200} \end{pmatrix} \begin{pmatrix} [33]\,\mathbf{1} \\ [33]\,\mathbf{27} \\ [51]\,\mathbf{8} \\ [51]\,\mathbf{27} \end{pmatrix}$$

[51] is forbidden at short distances.

Recent Developments

- **Lattice QCD approach to the potentials between two baryons by HAL-QCD**

N. Ishii, S. Aoki, T. Hatsuda, Phys Rev Lett. (2007) 99:022001
S. Aoki, T. Hatsuda, N. Ishii, Prog. Theor. Phys. 123 (2010) 89
T. Inoue, et al., Prog. Theor. Phys. 124 (2010) 591



T. Inoue, HYP2018 AIP Conf.Proc. 2130 (2019) 1, 020002

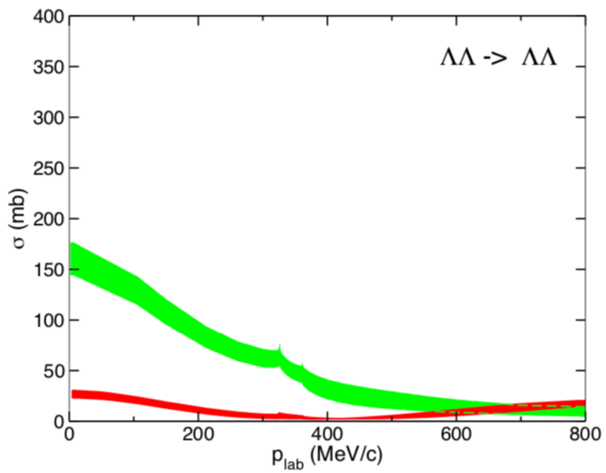
Recent Developments

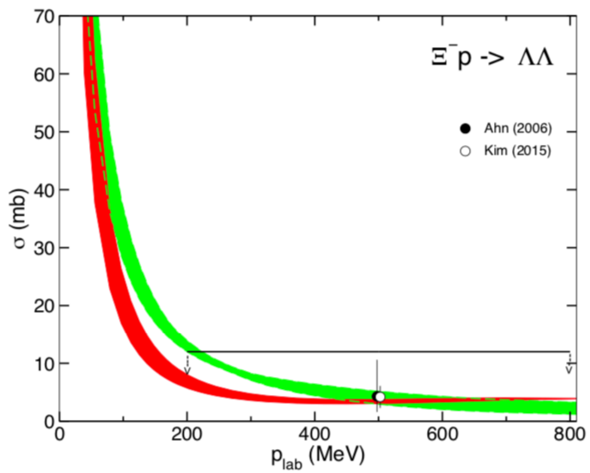
- **Chiral Effective Field Theory (Chiral EFT)**
  S.Weinberg, "Nuclear Forces from Chiral Lagrangians", PL B251 (1990) 288-292.
  H. Polinder, J. Haidenbauer, U.G. Meissner, Nucl. Phys. A779 (2006) 244-266
- **Short-range interactions in NLO are given by the contact terms**
  J. Haidenbauer et al., Nucl. Phys. A954 (2016) 273, for S= -2 BB systems

Λ		500	550	600	650
$^1S_0$	$\tilde{C}^{27}_{^1S_0}$	0.1520	0.3296	0.6139	1.0752
	$\tilde{C}^{8_s}_{^1S_0}$	0.1970	0.1930	0.1742	0.1670
	$\tilde{C}^{1}_{^1S_0}$	−0.015	−0.010	0.000	0.010
	$C^{27}_{^1S_0}$	2.260	2.260	2.260	2.260
	$C^{8_s}_{^1S_0}$	−0.200	−0.206	−0.0816	−0.0597
	$C^{1}_{^1S_0}$				

$$C = \tilde{C} + C(p^2 + p'^2)$$

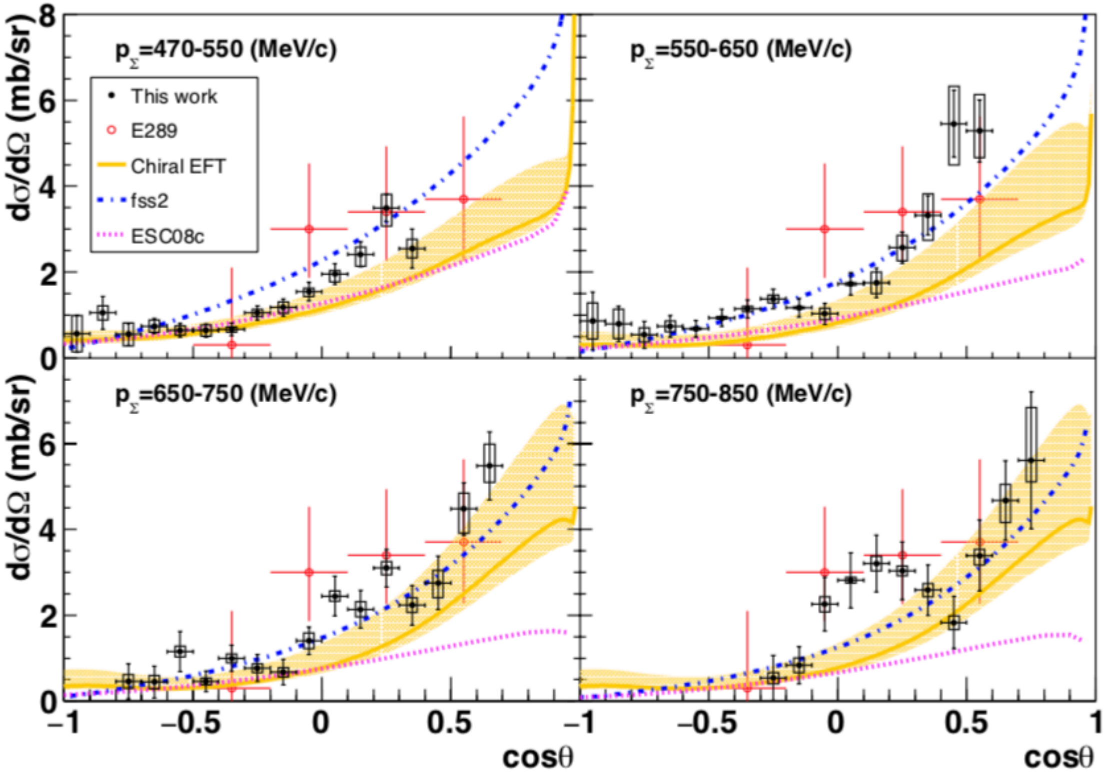
No repulsion but mildly attractive





Recent Developments (Experiments)

- **Baryon-Baryon scattering experiments**
  Huge data set of pp scattering plus significant pn and nn scattering
  Hyperon(Y)-Nucleon(N) scattering data
  Bubble chamber measurements in old days
  NEW **J-PARC YN scattering experiment (E40)**
  K. Miwa et al., Σ^-p cross section measurements, arXiv:2104.13608

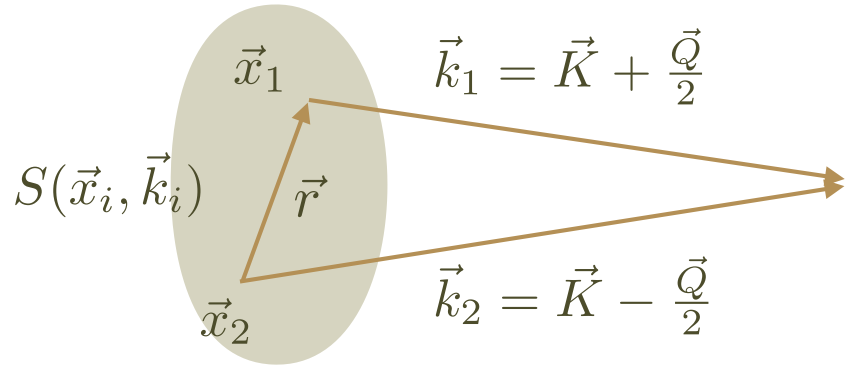


Coming soon:
Σ^+p scattering cross sections and others at J-PARC

Recent Developments (Experiments)

- **Two-body (hadron) correlations (HBT) in High Energy collisions**

$$C_2(\vec{Q},\vec{K}) \equiv \frac{W_2(\vec{k}_1,\vec{k}_2)}{W_1(\vec{k}_1)W(\vec{k}_2)}$$



$$W_i(\vec{k}_i) = \int d^4x_i S(\vec{x}_i,\vec{k}_i) \sim \int d^4x_i S(\vec{x}_i,\vec{K})$$

$$W_2(\vec{k}_1,\vec{k}_2) = \int d^4x_1 \int d^4x_2 S(\vec{x}_1,\vec{K})S(\vec{x}_2,\vec{K}) \left|\Psi(\vec{Q},\vec{x}_1-\vec{x}_2)\right|^2$$

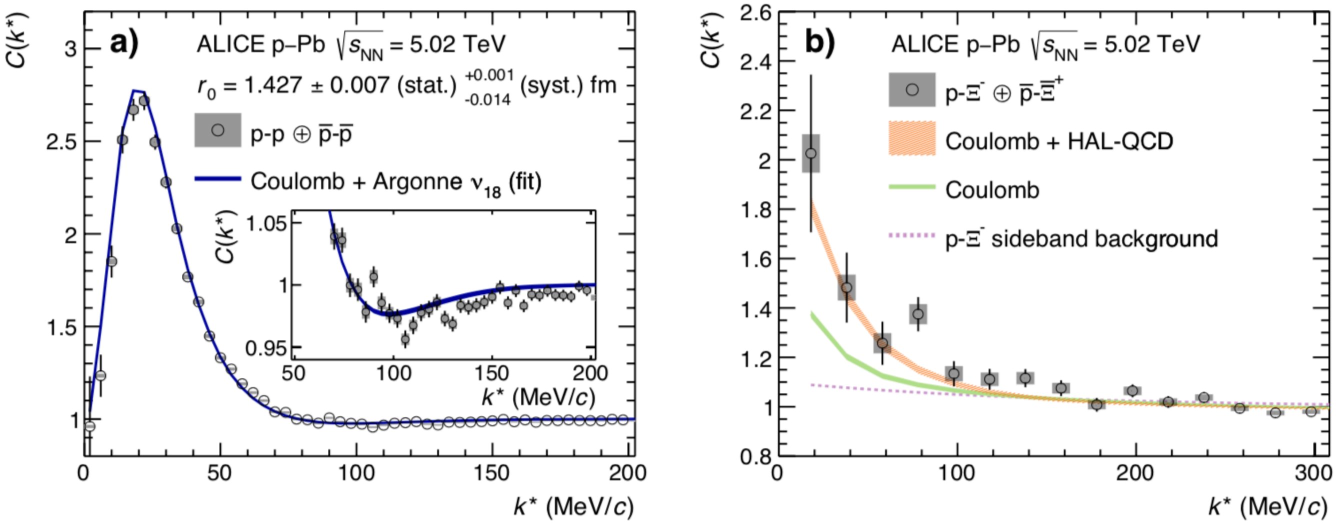
- **Assuming the source functions, S, the low energy (S-wave) scattering data are extracted from the correlation at Q→0.**

R. Hanbury Brown, R.Q. Twiss, Phil. Mag. 45 (1954) 663
G. Goldhaber, S. Goldhaber, W. Lee and A. Pais, PR 120 (1960) 300
E.V. Shuryak, PL 44B (1973) 387
U.A. Wiedemann, U.W. Heinz, Phys. Rept. 319 (1999) 145

Recent Developments (Experiments)

- Recent active Femtoscopy is developed in high energy p-p, p-A and A-A collisions.

ALICE, PRL 123 (2019) 112002 **pp and pΞ interactions**

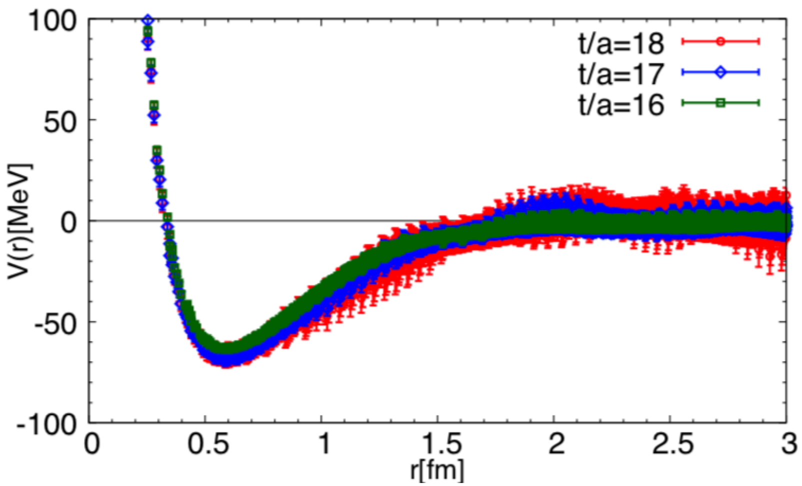


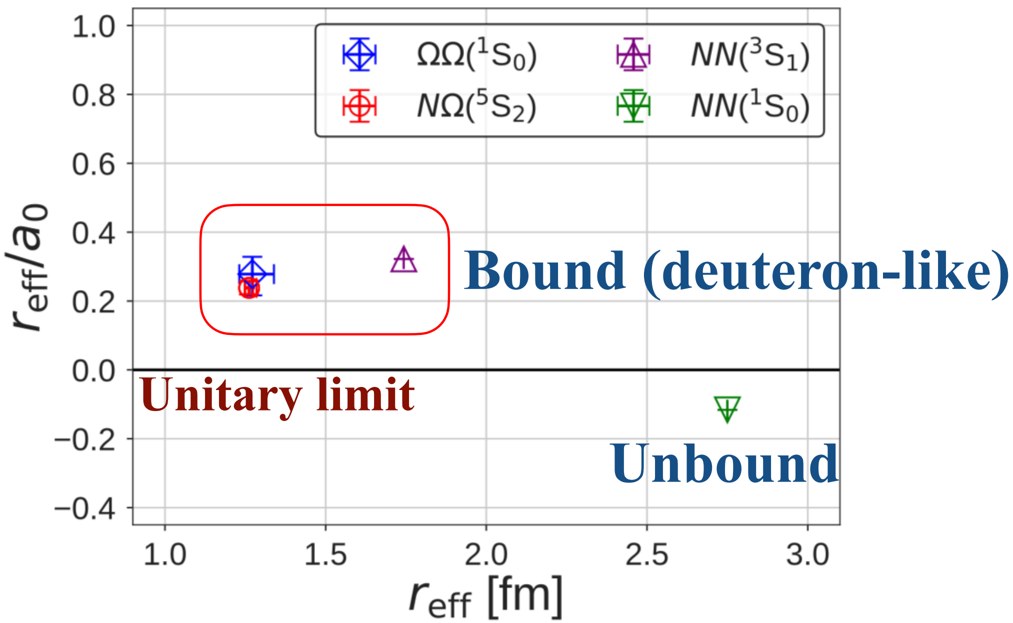
- With all these efforts, we complete the generalized BB forces soon. They will reveal the origin of the short-range NN interaction, properties of quarks in nuclei and roles of strangeness in neutron stars.

Dibaryons (compact 6 quark)

- **Jaffe (1977) H (uuddss, I=0, S=0) in the MIT bag model**
  No bound state is found below the ΛΛ threshold.
  A resonance above ΛΛ but below NΞ may remain as a possibility.
- **Recent Lattice calculation shows bound states in**
  ΩΩ (ssssss, S=0) ***Gongyo et al. (HAL QCD) PRL 120 (2018) 212001***
  NΩ (sssuud, S=2) ***Iritani et al. (HAL QCD), Phys.Lett.B 792 (2019) 284-289***

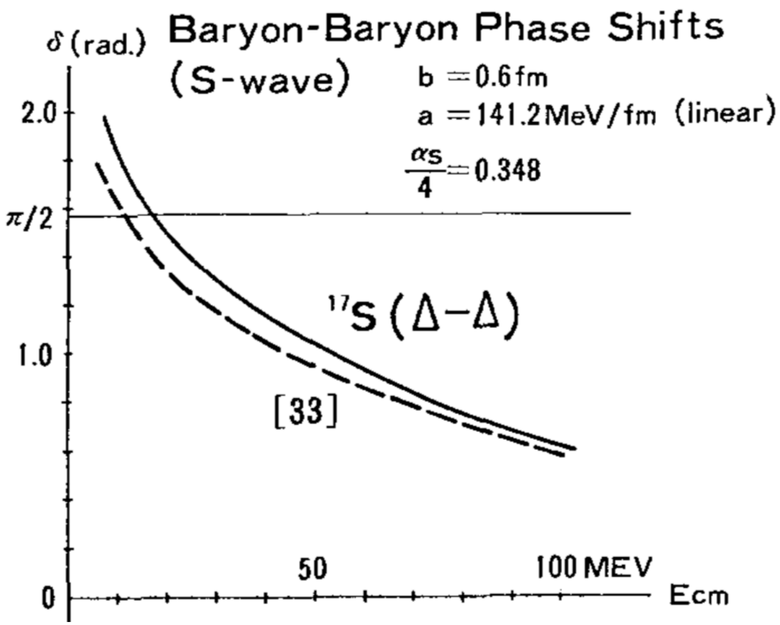
ΩΩ ($^1S_0$) central potential



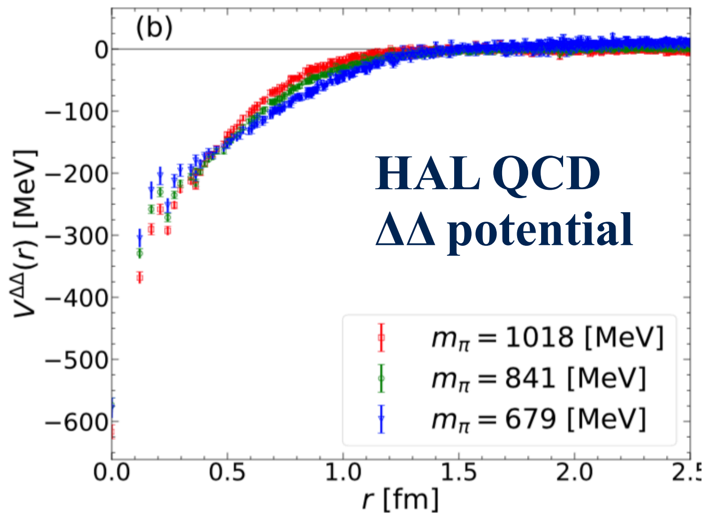


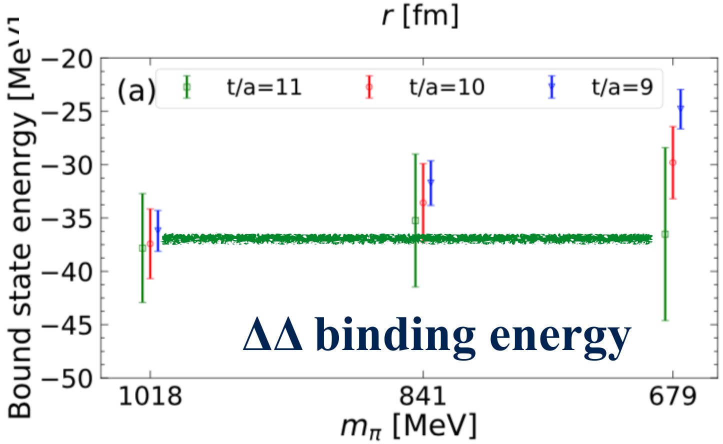
Dibaryons (compact 6 quark)

- **ΔΔ (I=0, S=3) bound state is predicted in the quark cluster model**
  MO, K. Yazaki, Phys. Lett. 90B (1980) 41
  Short-range quark exchange force is attractive in this channel.
- **Lattice QCD**
  Gongyo et al. Phys. Lett. B 811 (2020) 135935



MO, K. Yazaki, Phys. Lett. 90B (1980) 41





d*(2370) resonance

T. Kamae, T. Fujita, Phys. Rev. Lett. 38 (1977) 471

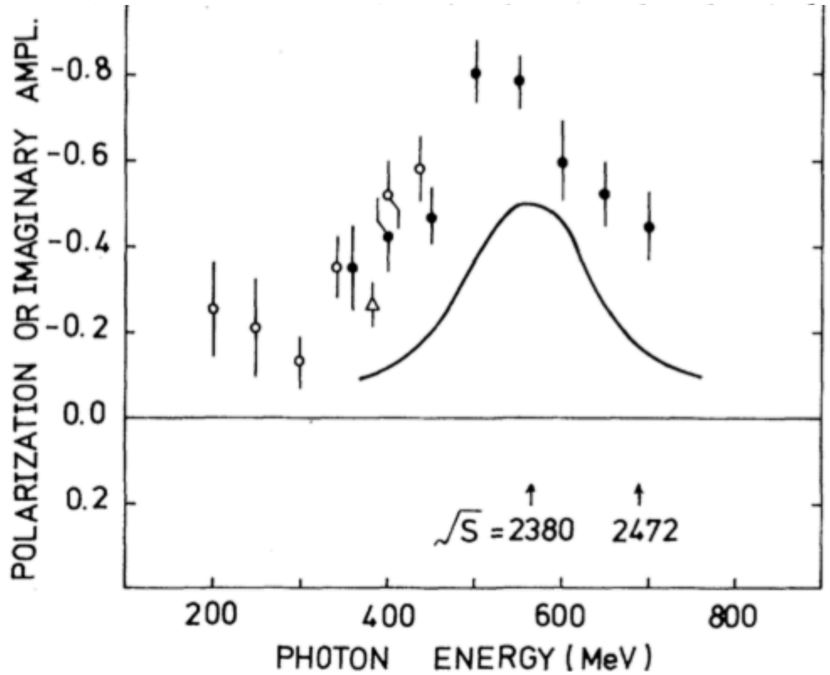
$\gamma + d \rightarrow p + n$ polarization of p measured

WASA@COSY, Phys. Rev. Lett. 106 (2011) 242302

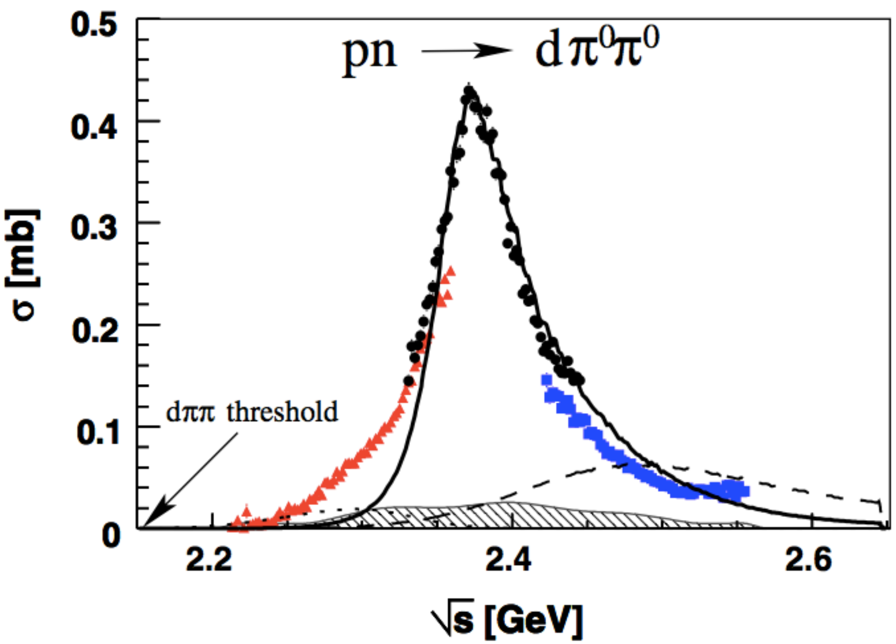
$p + n(d) \rightarrow d + \pi^0 + \pi^0$ (+$p_{spectator}$) at T_p=1.0, 1.2, 1.4 GeV

Possible Existence of a Deeply Bound Δ-Δ System

T. Kamae and T. Fujita*



WASA@COSY
***m*$_R$=2.37 GeV and Γ=68 MeV**



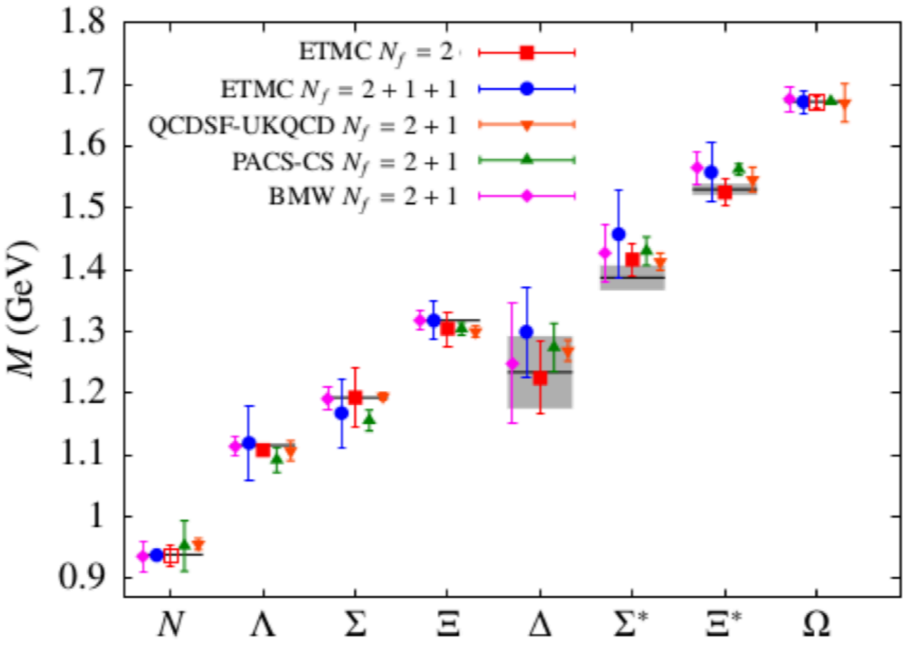
New Era of Hadron Spectroscopy

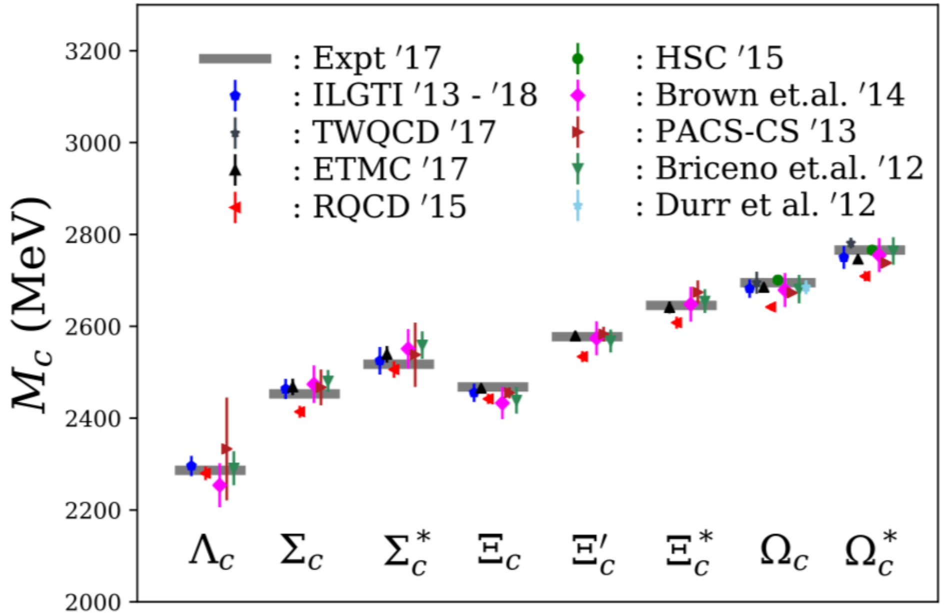
- **Many unexpected "multi-quark" hadrons, such as X(3872), Z(4430), Θ^+, P_c, …, have been observed since 2003.**
- **Their properties vary and are not systematically understood. Many of them contain explicit or hidden heavy quark(s).**
- **Most of them are resonances located closely to the decay threshold and couple strongly to the decaying channels.**
  The dynamics of the resonance-threshold couplings may give essential information on the confinement mechanism of quarks in multi-quark systems.

- **Hadron resonances are good examples of strongly-coupled "open quantum systems".**
- **Exploring multi-quark open quantum problems is challenging. Quark model example: tetraquarks, pentaquarks**

Lattice QCD

- Roles of Lattice QCD in the study of hadron spectroscopy and interactions are increasingly important. The lattice data of hadron mass spectrum, form factors, hadronic interactions (scatterings), etc. play roles of experimental data.
- Masses of the ground state mesons and baryons are very well reproduced in various settings of LQCD.





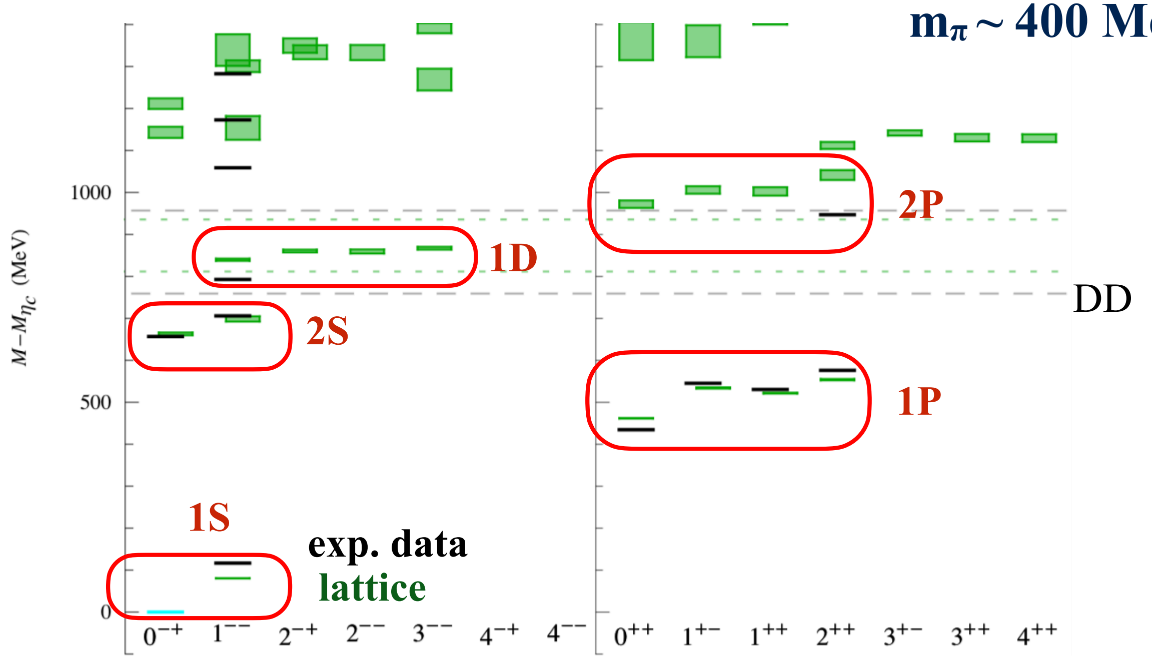
Padmanath arXiv:1905.10168

Lattice QCD

- **Excited states may be obtained by diagonalizing cross correlators with multiple source/sink operators.**
  ex. charmonium spectrum

Liuming Liu et al., JHEP 07 (2012) 126

$m_\pi \sim 400$ MeV

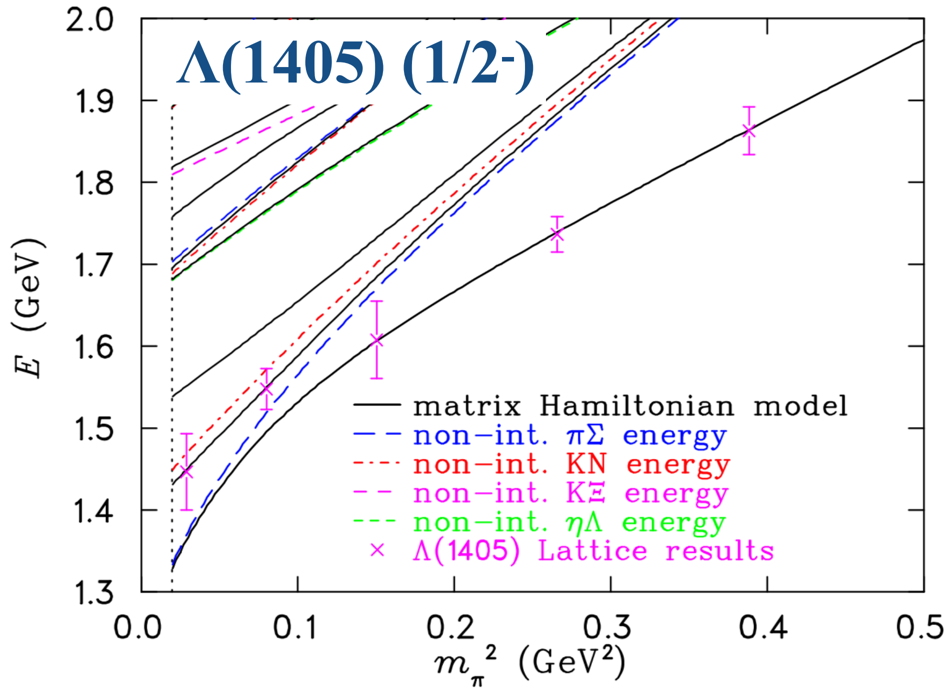


- **Newly-observed exotic resonances, such as X(3872), may couple strongly to two-hadron or tetra-quark states, which are not well accounted on the lattice only with qqbar operators.**

Lattice QCD

- **Resonance, *a pole at a complex energy*, is NOT directly accessible by lattice QCD, because the eigen-energies on finite-volume lattice are always real and discrete.**
- **Above the hadronic threshold, we need an analysis taking account of couplings to the scattering states.**

J.M.M.Hall, et al, PRL 114, 132002 (2015)



The thresholds are higher for large m_q, where resonances are bound, but in the course of chiral extrapolation, they cross with thresholds and become resonances.
Physical m_q simulations require to discriminate resonances from scattering states.

Lattice QCD

- **Analysis of lattice QCD data corresponding to resonant states requires effective theories in extrapolating the data to infinite volume.**
  A. Martinez Torres, et al., Phys. Rev. C 86 (2012) 055201
  R. Molina, M. Doring, Phys. Rev. D 94 (2016) 056010
  Y. Tsuchida, T. Hyodo, Phys. Rev. C 97 (2018) 055213
- **Analysis of $\Lambda(1/2^-)$ resonances via chiral unitary approach**
  R. Pavao, P. Gubler, P. Fernandez-Soler, J. Nieves, MO, T.T. Takahashi, Phys. Lett. B820 (2021) 136473
- **Analysis of D_s $(0^+,1^+,2^+)$ via quark model with quark pair creation model**
  Z. Yang, G.J. Wang, J.J. Wu, MO, S.L. Zhu, arXiv:2107.04860

Lattice *v.s.* Chiral Unitary Approach

- **Chiral unitary approach for Λ(1405) (1/2⁻)**

$\pi\Sigma, \bar{K}N, \eta\Lambda, K\Xi$

$$T = [1 - VG]^{-1} V$$

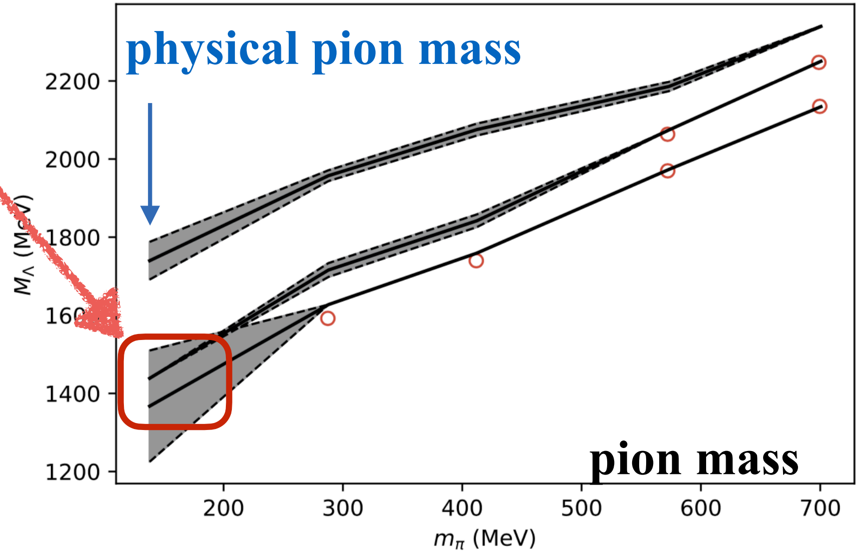
$$V_{ij}^{WT}(s) = D_{ij} \frac{2\sqrt{s} - M_i - M_j}{4 f_i f_j}$$

$$D = \begin{pmatrix} -4 & \sqrt{\frac{3}{2}} & 0 & -\sqrt{\frac{3}{2}} \\ \sqrt{\frac{3}{2}} & -3 & -\sqrt{\frac{9}{2}} & 0 \\ 0 & -\sqrt{\frac{9}{2}} & 0 & \sqrt{\frac{9}{2}} \\ -\sqrt{\frac{3}{2}} & 0 & \sqrt{\frac{9}{2}} & -3 \end{pmatrix}$$

$$\overline{G}_i(s) = \frac{2M_i}{16\pi^2} \left\{ \left[\frac{M_i^2 - m_i^2}{s} - \frac{M_i - m_i}{M_i + m_i} \right] \log \frac{M_i}{m_i} + \frac{2|\boldsymbol{k}_i|}{\sqrt{s}} \left[\log \frac{1 + \sqrt{\frac{s - s_{i+}}{s - s_{i-}}}}{1 - \sqrt{\frac{s - s_{i+}}{s - s_{i-}}}} - i\pi \right] \right\}$$

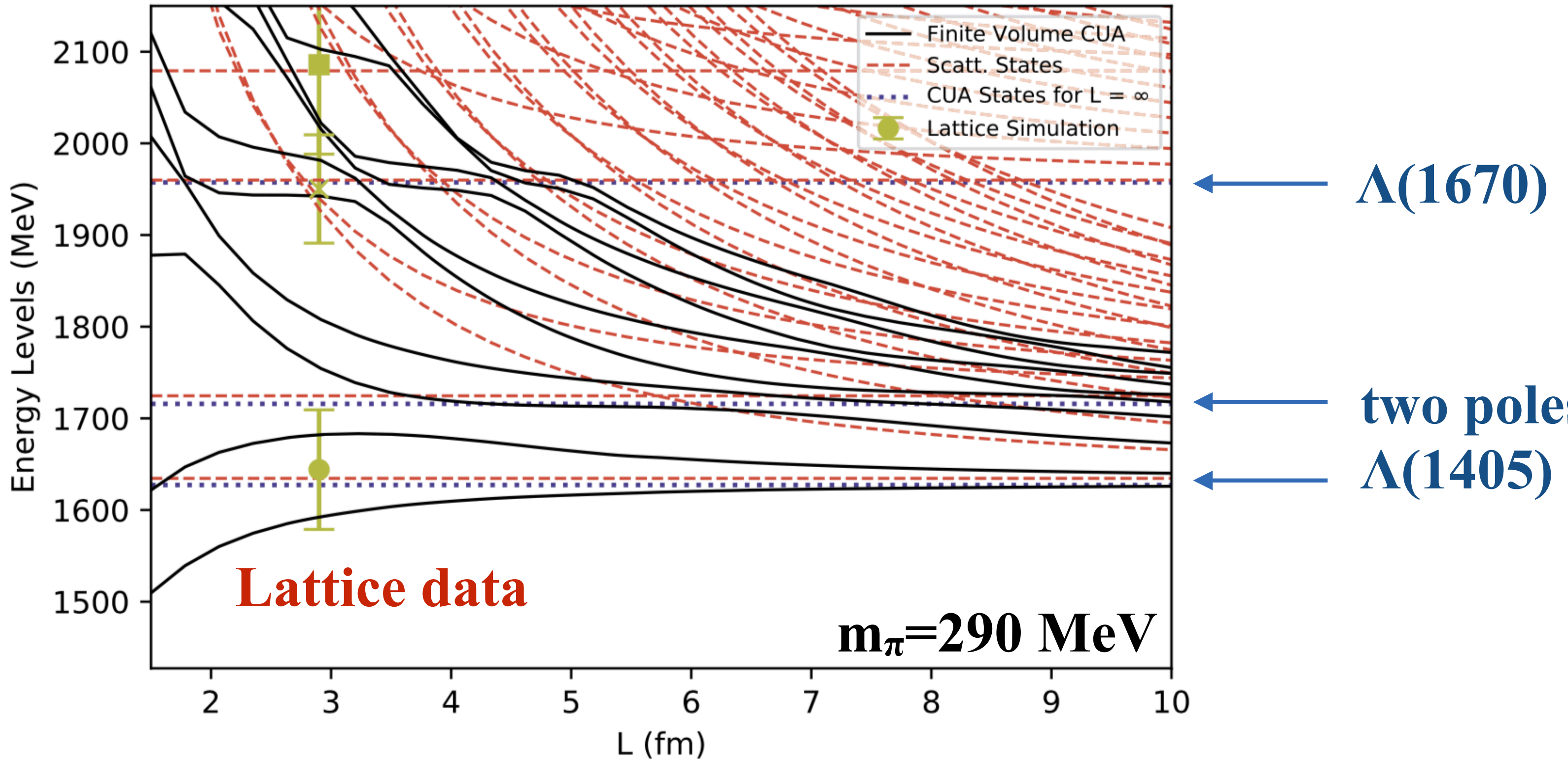
- **Two pole structure of Λ(1405)**

J. Oller, U.G. Meissner, PL B500 (2001)
D. Jido, et al., NP A725 (2003) 181
T. Hyodo, D. Jido,
Prog. Part. Nucl. Phys. 67 (2012) 55



Lattice *v.s.* Chiral Unitary Approach

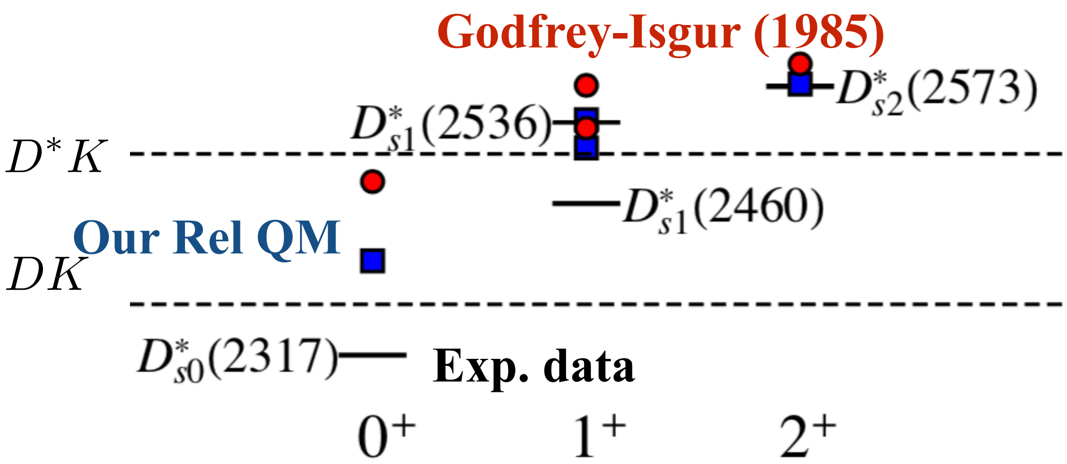
- ***Finite volume* CUA** *Pavao et al., Phys. Lett. B820 (2021) 136473*



- **No one-to-one correspondence between the poles at infinite volume and the finite-volume discrete energy spectrum. Two poles mix with scattering state and only one state survives at finite volume.**

Lattice *v.s.* Quark Model

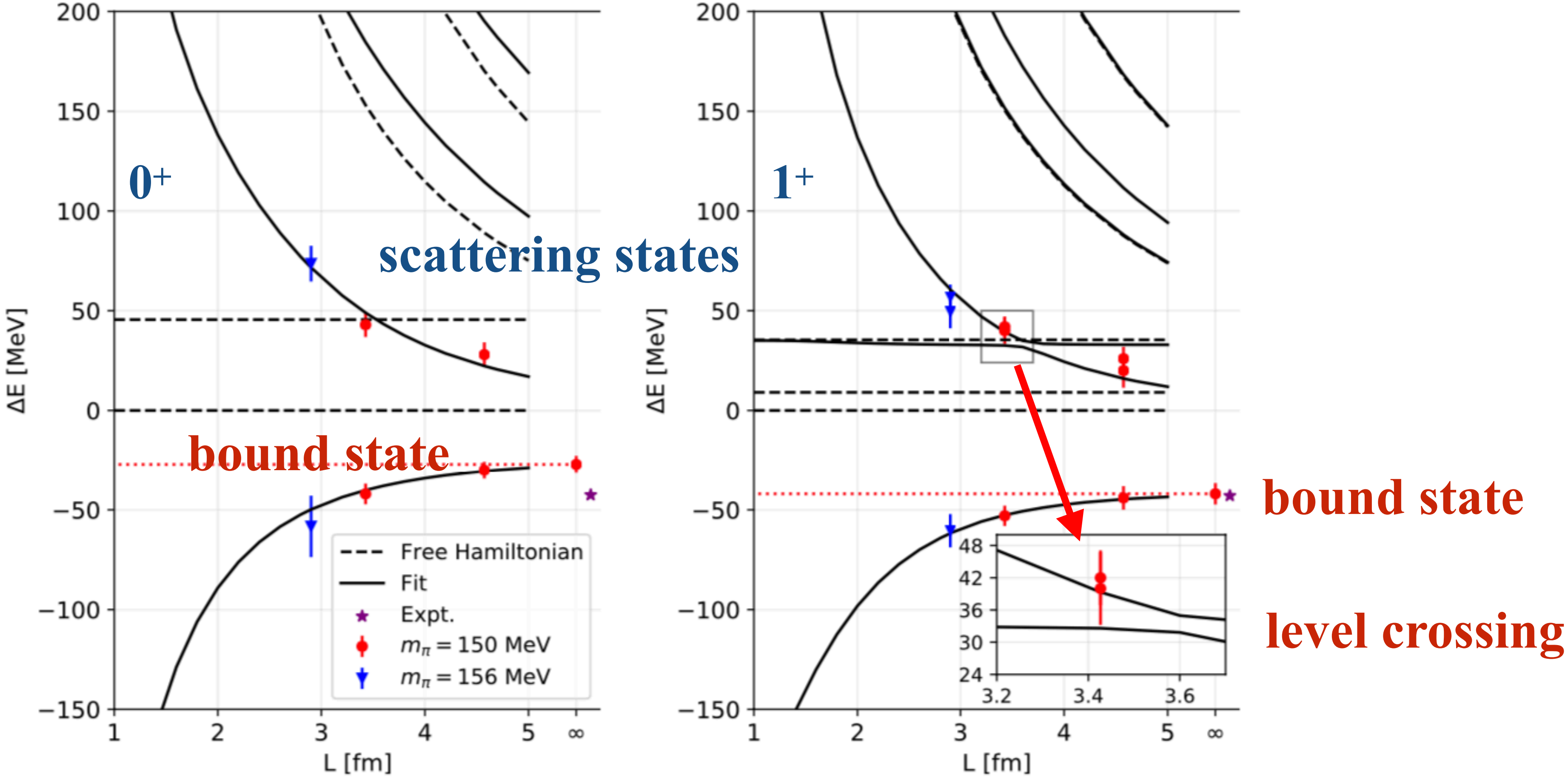
- **P-wave D_s states, D_s (0^+), $(1^+)^2$, (2^+)**



- **The $D_{s0}(2317)$ and $D_{s1}(2460)$ masses are too high in QMs. They may couple strongly to the nearby DK and D^*K threshold.**
- **Effective Hamiltonian approach with the $^3P_0$ pair creation vertex and ρ and ω exchange potential between $D^{(*)}$-K.**
  Z. Yang, G.J. Wang, J.J. Wu, MO, S.L. Zhu, arXiv: 2107.04860
- **Similar approach by *A. Martinez Torres, et al., JHEP 05 (2015)153*.**

Lattice *v.s.* Quark Model

- **Lattice Data from**
  C.B. Lang et al., *PR D90 (2014) 034510* and
  G.S. Bali et al., *PR D96 (2017) 074501* (with $D^{(*)}K$ couplings).



Z. Yang, G.J. Wang, J.J. Wu, MO, S.L. Zhu, arXiv: 2107.04860

QCD at Extreme Conditions

- **QCD at finite μ is an unexplored region of the phase diagram of QCD ground state ("vacuum").**
- **Sign problem prohibits lattice QCD to access baryonic matter.**
  → QCD sum rules, Effective theories
- ***Hadron properties in matter*** **is an important clue.**
  vector mesons and heavy hadrons in nuclear matter and nuclei
  isospin imbalance and mixings of isospin (ex. Λ and Σ)
- ***Neutron Star*** **is also an obvious target of dense QCD.**
  It is a hot topic with recent active astronomical observations.
  Microscopic picture of NS is really challenging because of the large scale difference, NS size 10^4 m *v.s.* B-B range 10^{-15} m.
- **Hyperon puzzle**
  Appearance of hyperons in NS seem to require *new* dynamics, such as repulsive 3-body force, or medium modification.

QCD at Extreme Conditions

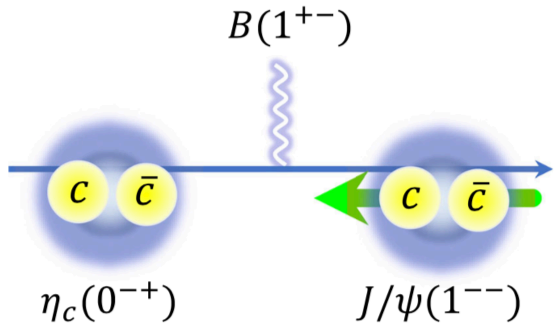
More . . .

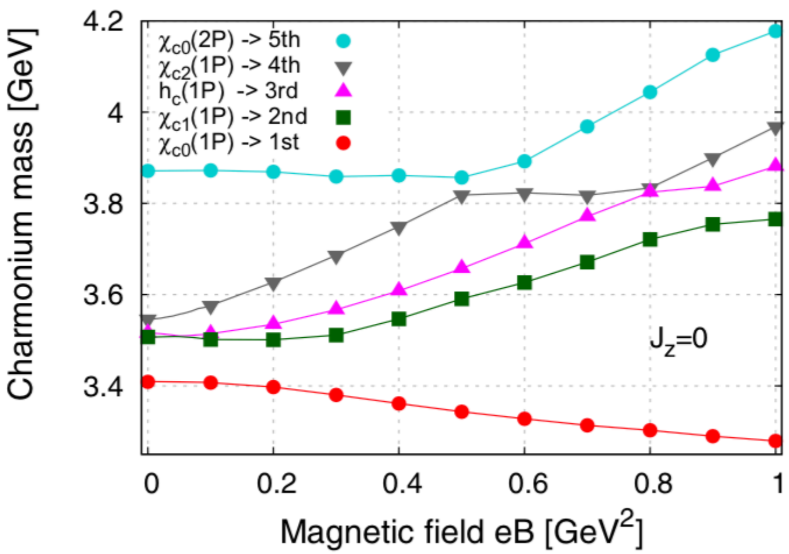
There are many more interesting physics issues, such as color superconductor, strong magnetic field, vortices, . .

- **String magnetic field in HI collisions, NS**
  → spin mixings and mass splittings of quarkonium
  J. Alford, M. Strickland, PR D88, 105017 (2013)
  S. Cho, K. Hattori, S. H. Lee, K. Morita, S. Ozaki, PRL 113, 172301 (2014)
  K. Suzuki, T. Yoshida, PR D93 (2016) 051502, PR D94 (2016) 074043
  S. Iwasaki, MO, K. Suzuki, T. Yoshida, Phys. Lett. B790 (2021) 71
  S. Iwasaki, MO, K. Suzuki (review), Eur. Phys. J. A57 (2021) 222
  S. Iwasaki, D. Jido, MO, K. Suzuki, Phys. Lett. in print. arXiv:2104.13989
- **Vortices (in HI collisions) induce spin imbalance of quarks**
  → spin-dependent production rates of hadrons
  H. Taya, A. Park, S. Cho, P. Gubler, K. Hattori, J. Hong, X.-G. Huang, S.H. Lee, A. Monnai, A. Ohnishi, MO, D.L. Yang (ExHIC-P Coll.), Phys. Rev. C 102 (2020) 021901(R)

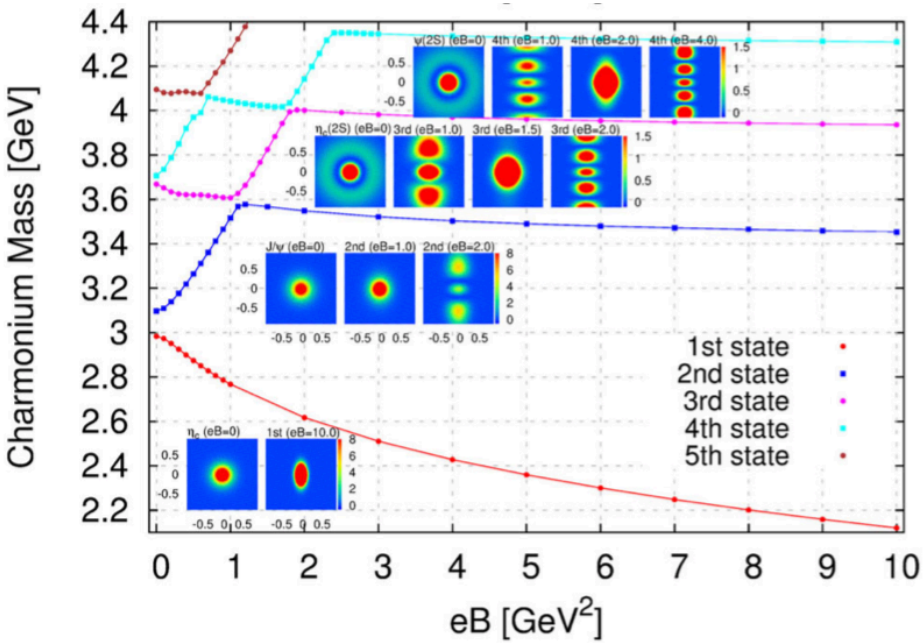
Hadrons in Strong Magnetic Field

- **Quarkonia in strong magnetic field undergo several effects**
  (1) Zeeman effects
  mixing of J=0 and 1
  (2) Landau level effects
  squeezing wave functions
  (3) Paschen-Back effects
  P-wave charmonia





S. Iwasaki, et al., PL B790 (2021) 71



T. Yoshida et al., PR D94 (2016) 074043

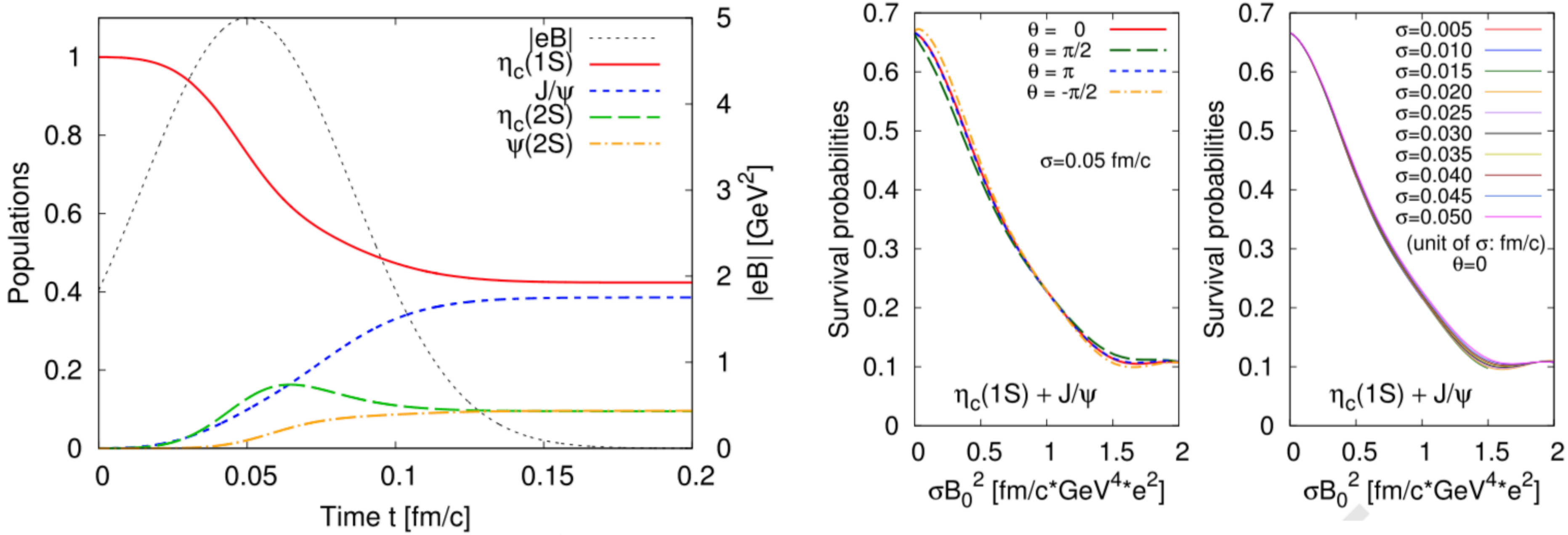
Hadrons in Strong Magnetic Field

Quarkonia in rapidly-changing magnetic field

Survival probabilities of charmonia as a clue to measure transient magnetic fields

Sachio Iwasaki [a], Daisuke Jido [a], Makoto Oka [b,c], Kei Suzuki [b]

Phys. Lett. B on line, arXiv:2104.13989



Hadrons in Vortical Environment

Signatures of the vortical quark-gluon plasma in hadron yields

Hidetoshi Taya,[1,2] Aaron Park,[3] Sungtae Cho,[4] Philipp Gubler,[5] Koichi Hattori,[6] Juhee Hong,[3] Xu-Guang Huang,[1,7] Su Houng Lee,[3] Akihiko Monnai,[8,9] Akira Ohnishi,[6] Makoto Oka,[5] and Di-Lun Yang[10]
(ExHIC-P Collaboration)

Phys. Rev. C 102 (2020) 021901(R)

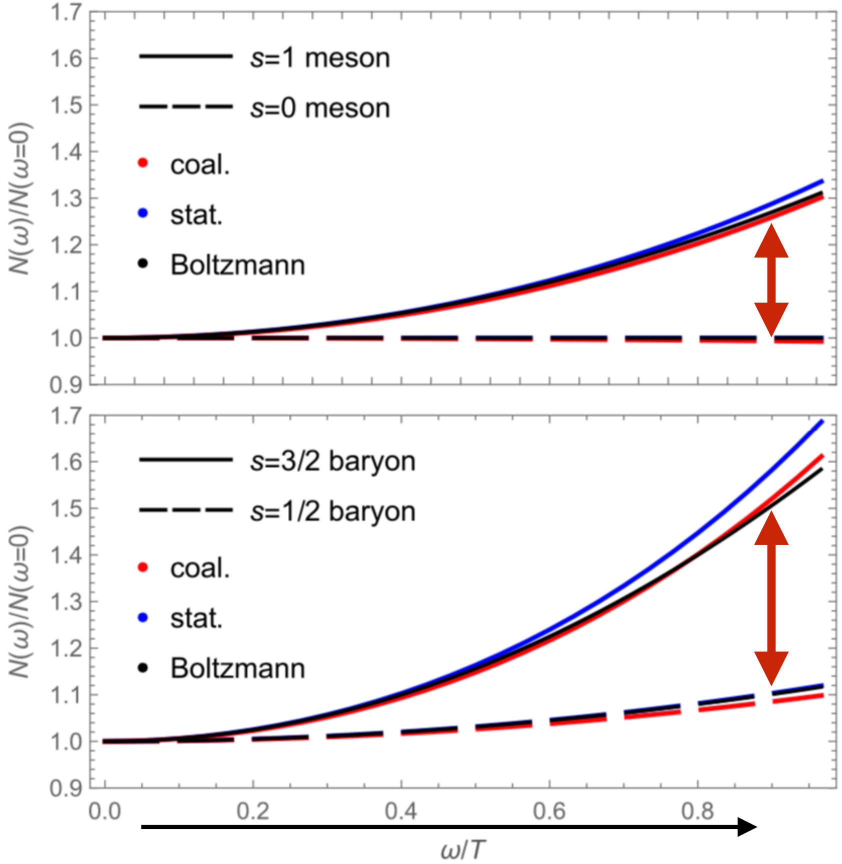
local vorticity **ω** *in HI collision*

↓

Quark spin distribution ∝ exp (- S・ω/T)

↓

Hadron production depends on spin.
Hadrons with larger spin are produced more.



local vorticity **ω** *increases*

Summary

- **Workshop has covered many interesting subjects in hadron physics and QCD at finite density.**

  nuclear parton distributions, form factors in medium
  meson masses in medium, vector mesons, heavy mesons
  meson bound states in nuclei
  neutron star, EoS, strangeness, dark matter in NS
  exotic hadrons, heavy multiquarks, resonances
  dense QCD, phase diagram, thermo-magnetic effect

- **These are the subjects to be discussed continuously. We further have new interesting subjects.**
- **Exchanging ideas with the other side of the earth is very exciting and useful.**