Theoretical Overview
– Nuclear and Hadron Physics –

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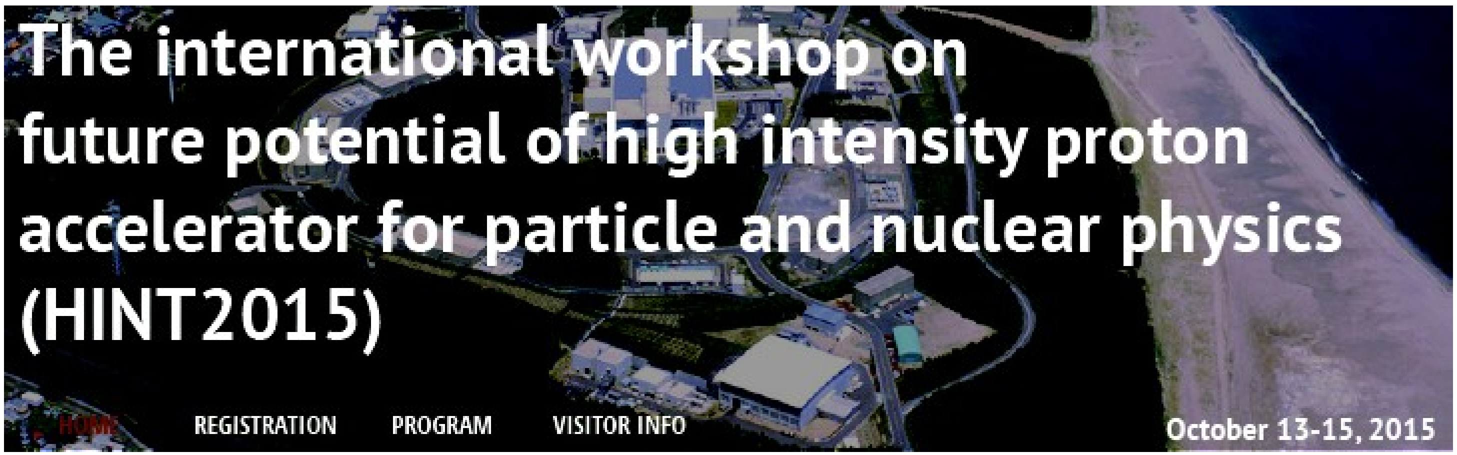
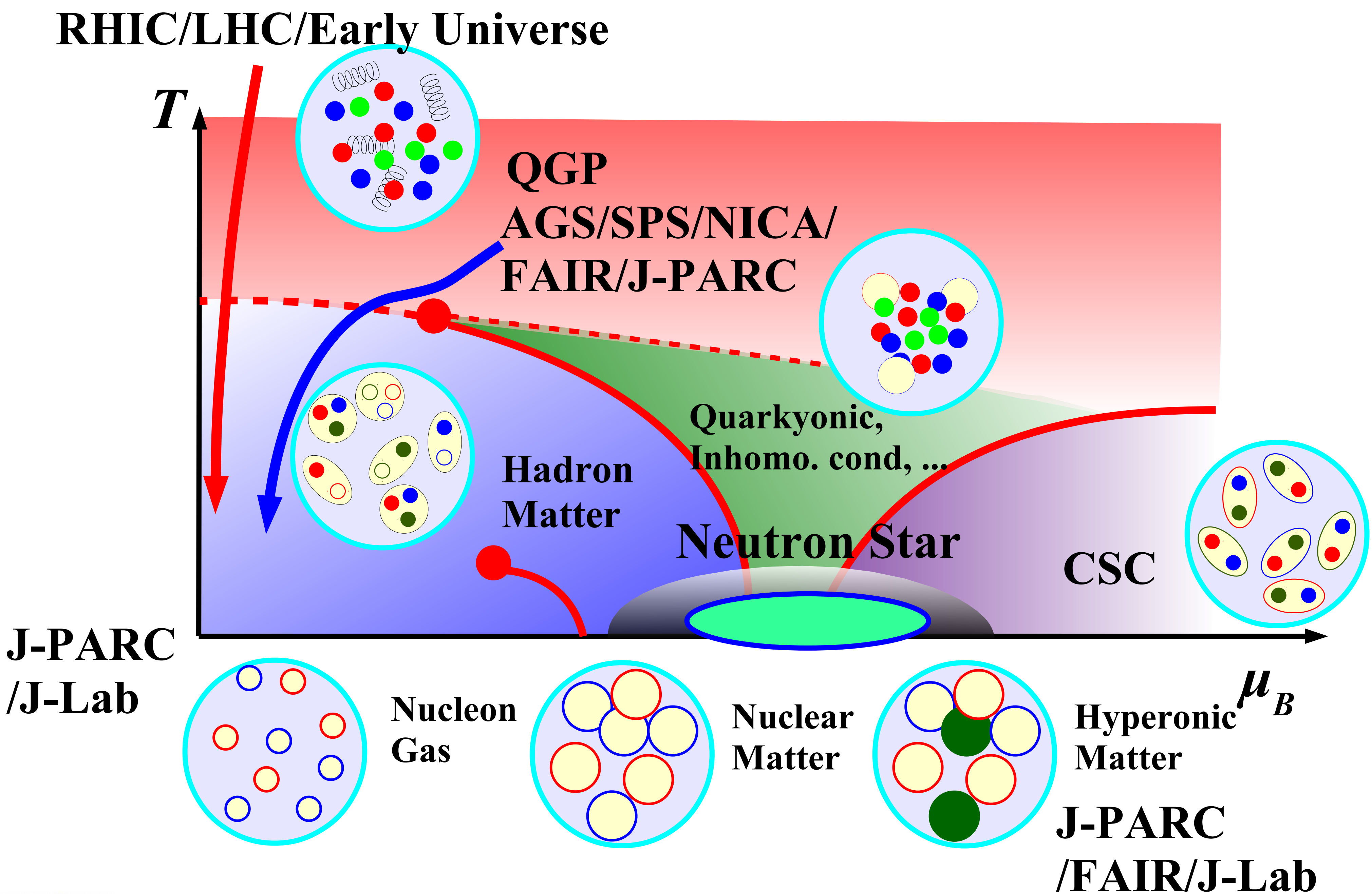


- **Introduction**
- **Physics at J-PARC**
  - **Exotic Hadrons, Interaction between Hadrons, Medium Effects on Hadrons, Dense Matter EOS**
- **Summary**

QCD Phase Diagram

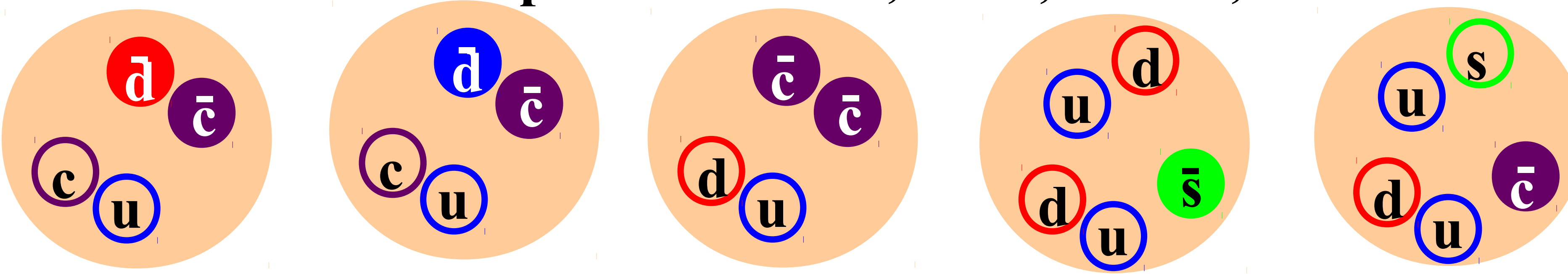


What we can do at J-PARC (personal view)

- **High Intensity proton, pion, kaon beams starting from 30-50 GeV proton**
  - **Production of hadrons with heavy(strange & charm)-quarks**
  - **Rare event search**
  - **pA collisions → medium effects at low T and moderate density (ρ_0)**
  - **With injector installed, heavy-ion beam (10-20 AGeV) is available.**
- **We can investigate Exotic QCD physics at J-PARC**
  - **Exotic Hadrons including charm quark(s)**
  - **Interaction between short lived particles (Exotic Interaction)**
  - **Modification of "vacuum" such as partial restoration of chiral symmetry (Exotic Vacuum)**
  - **EOS of matter composed of exotic particles such as hyperons (Exotic EOS)**
  - **Parton structure of nucleons.**

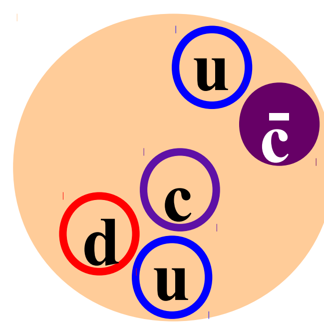
Exotic Hadrons

- Exotic hadrons: Z, X, Y, Θ^+, ... (Tetra-quarks, Penta-quarks, ...)
  → Discovered/Proposed at LEPS, Belle, BaBar, ...

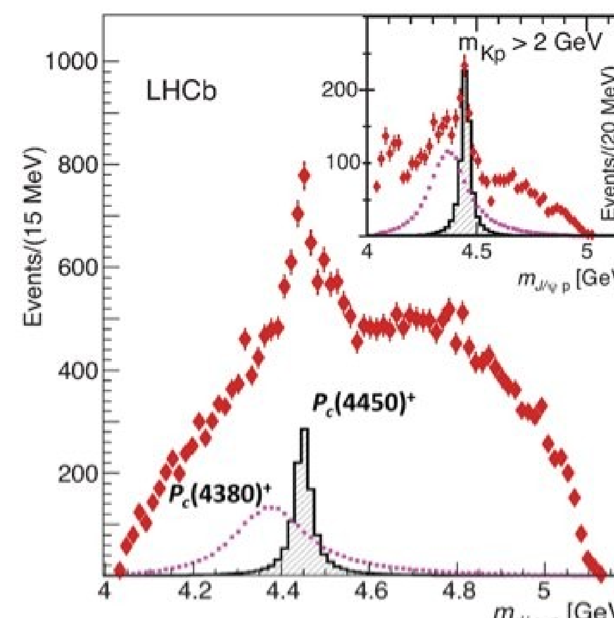


Z(4430) X(3872) T_{cc} Θ^+ Θ^+_{cs}

- Newly discovered Exotic Hadron: $P_c(4450)^+$
  LHCb collab., PRL 115, 072001 (2015) [arXiv:1507.03414]
  - pp (7, 8 TeV) → Λ_b → $P_c(4450)^+ K^-$
    $P_c(4450)^+ \to J/\psi\, p$
  - Mass = 4449.8 ± 1.7 ± 2.5 MeV

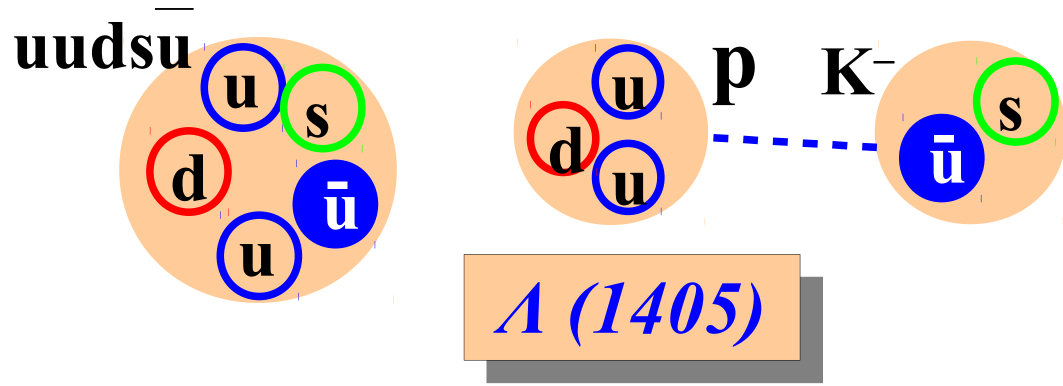


$P_c(4450)^+$



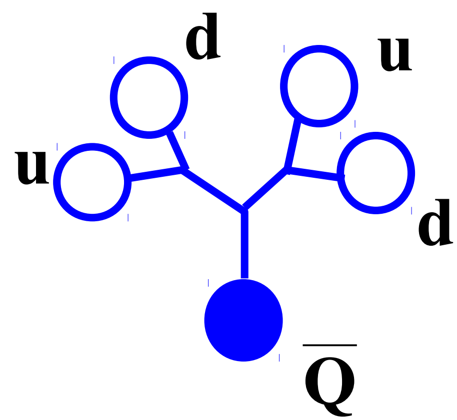
Exotic Hadrons

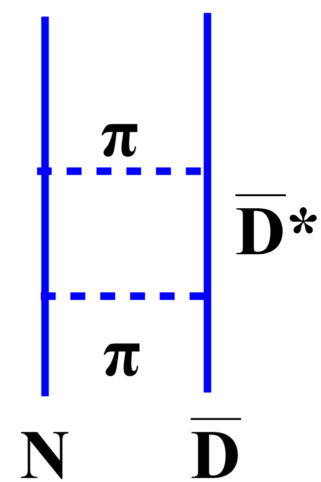
- Various pictures
  - Compact multi-quark state
  - Di-quark component
  - Hadronic molecule
  - $Q\bar{Q}$ couples with $Q\bar{Q}\,q\bar{q}$



Key quantity = Hadron Size

- Origin of attraction
  - Weinberg-Tomozawa interaction (chiral perturbation)
  - Diquarks *Jaffe, Wilczek ('03)*
  - Pion exchange *Yasui, Sudoh ('09)*
  - Coupled channel





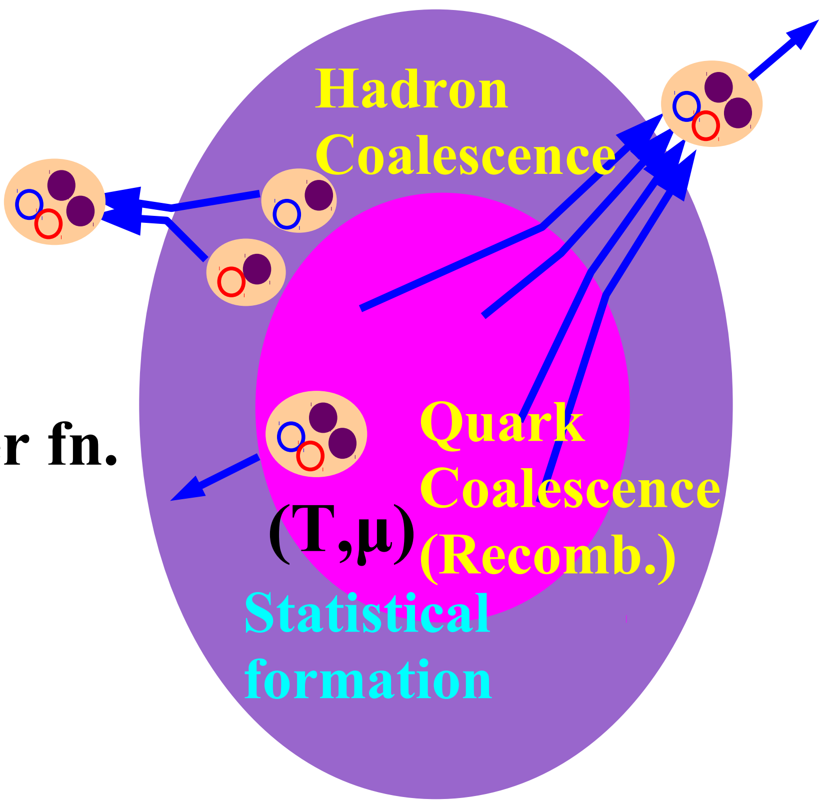
Key observable = Hadron-Hadron Scattering

Hadron Size

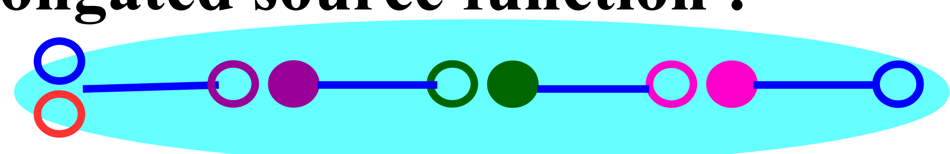
- **Nuclear Size Measurement**
  → electron scattering, total reaction σ, NA scattering, ….
- **Form factor / Fragmentation fn. measurement**
  Sekihara, Hyodo, Jido ('08, '11), Hirai, Kumano, Oka, Sudoh ('08)
- **Production cross section in HIC**
  S. Cho et al. (ExHIC collab., '11)
  - **Coalescence yield reflects source shape in phase space**

$$N_h^{\rm coal} = g_h \int \left[\prod_{i=1}^{n} \frac{1}{g_i} \frac{p_i \cdot d\sigma_i}{(2\pi)^3} \frac{d^3 p_i}{E_i} f(x_i, p_i) \right] \quad \textbf{Const. dist.}$$

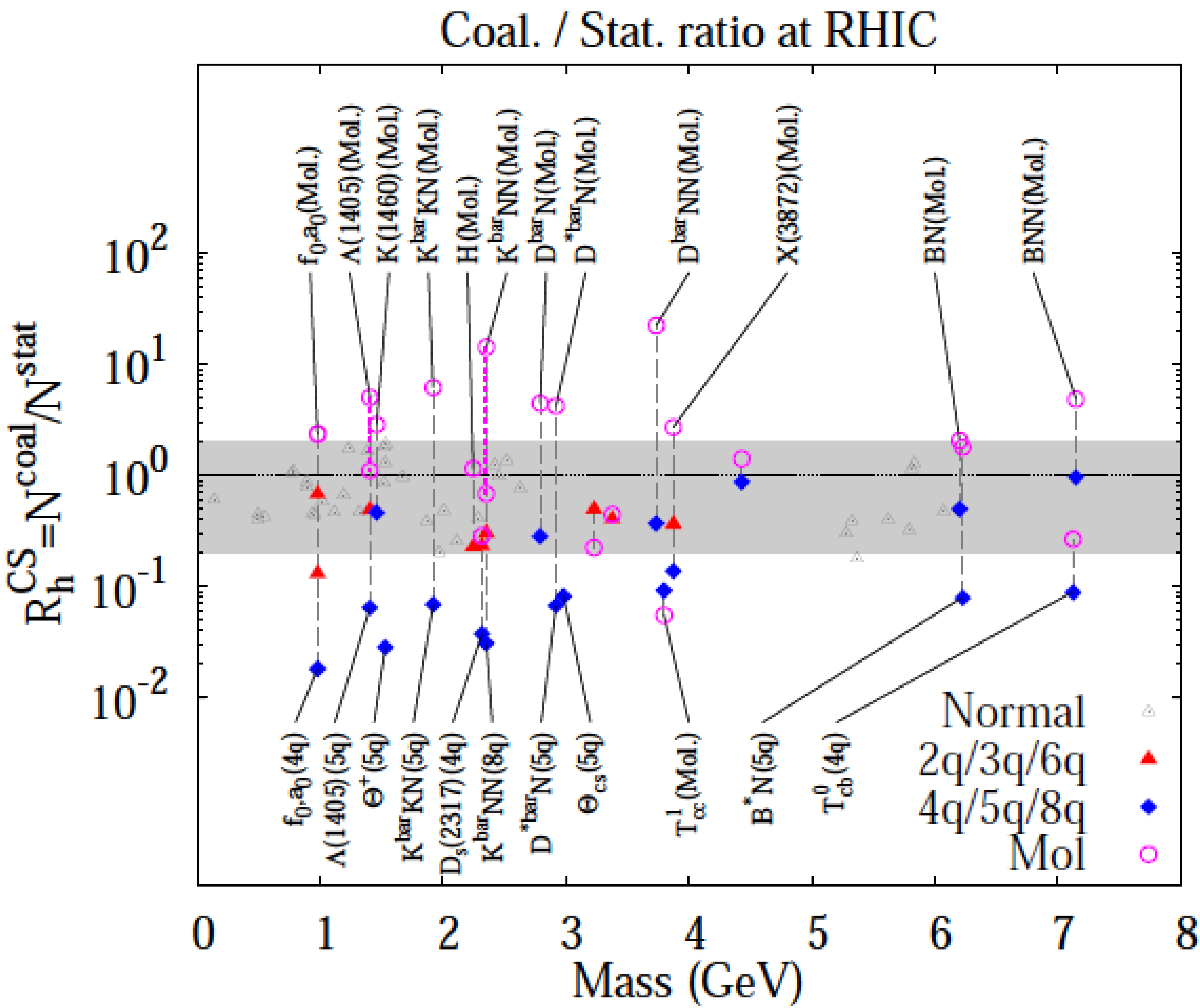
$$\times f^W(x_1, \cdots, x_n : p_1, \cdots, p_n) \quad \textbf{Intr. Wigner fn.}$$



- **How about pp, pA, $e^- e^+$?**
  → Elongated source function !



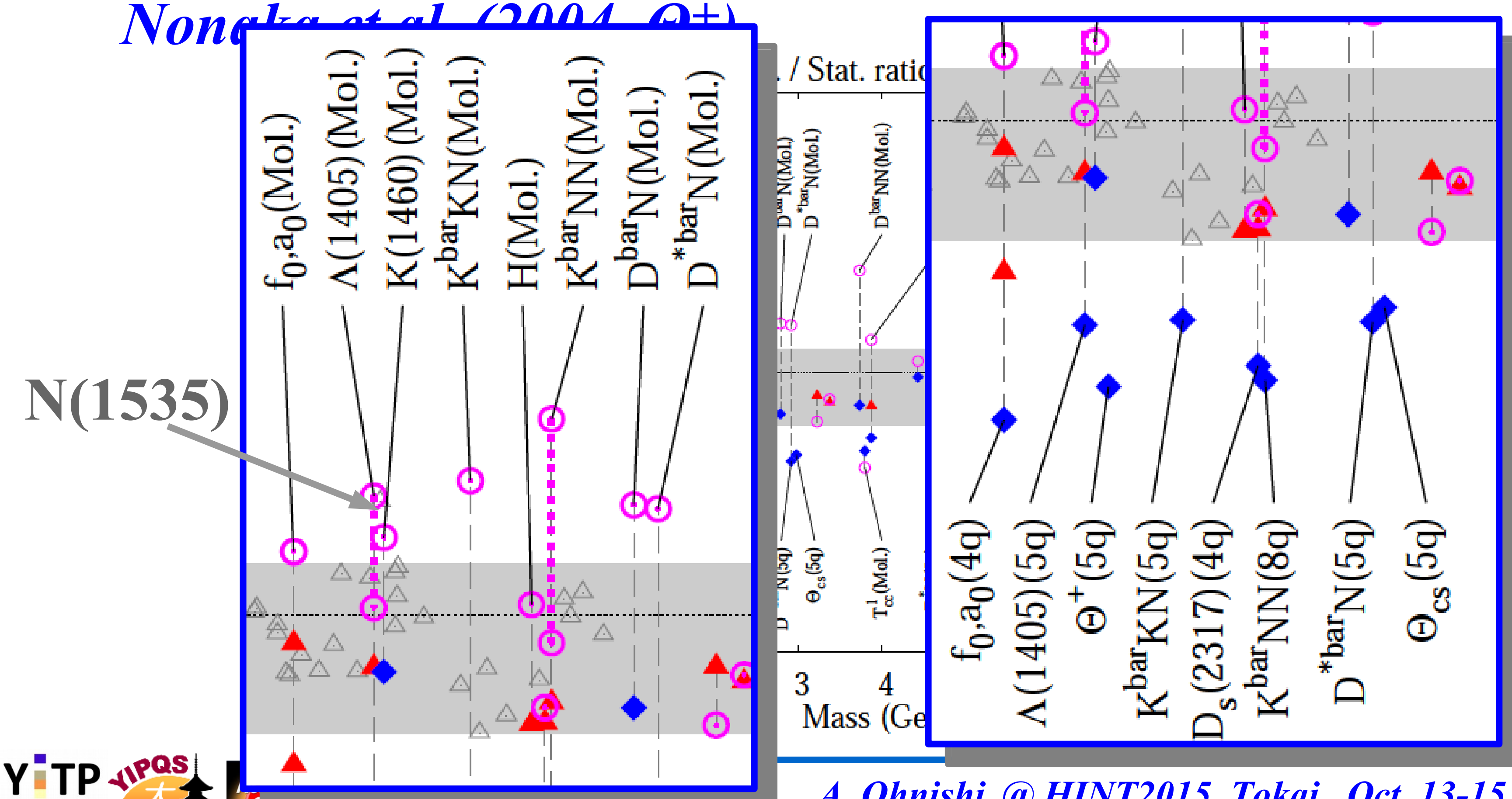
Coalescence / Statistical Ratio



S. Cho et al. (ExHIC Collab.), PRL106('11)212001; PRC 84 ('11) 064910

Coalescence / Statistical Ratio

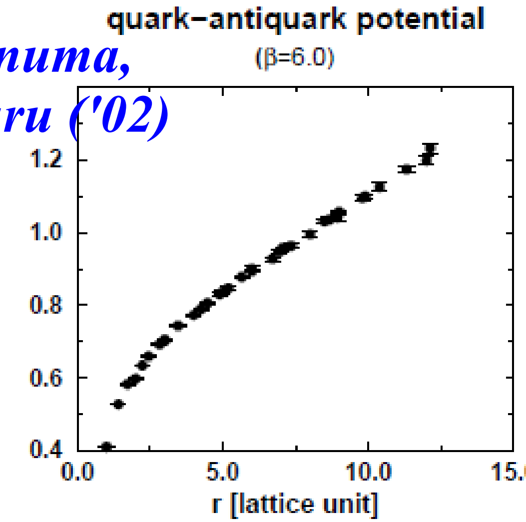
- **Normal hadrons: Rcs = (0.2-2)** *Normal band*
- **Extended hadronic molecule: Large yield is expected, Rcs > 2.**
  Λ(1405)=$\bar{K}$N, $\bar{K}$NN, $\bar{K}$KN, $\bar{D}$NN, … (ħω=(6-50) MeV)
- **Compact Multiquark states will be suppressed in HICs, Rcs < 0.2**
  $f_0/a_0(qq\bar{q}\bar{q})$, $\Theta^+(uudd\bar{s})$, H(uuddss), $\Theta_{cs}(uuds\bar{c})$, …
  Nonaka et al. (2004, Θ+)



Exotic Interaction

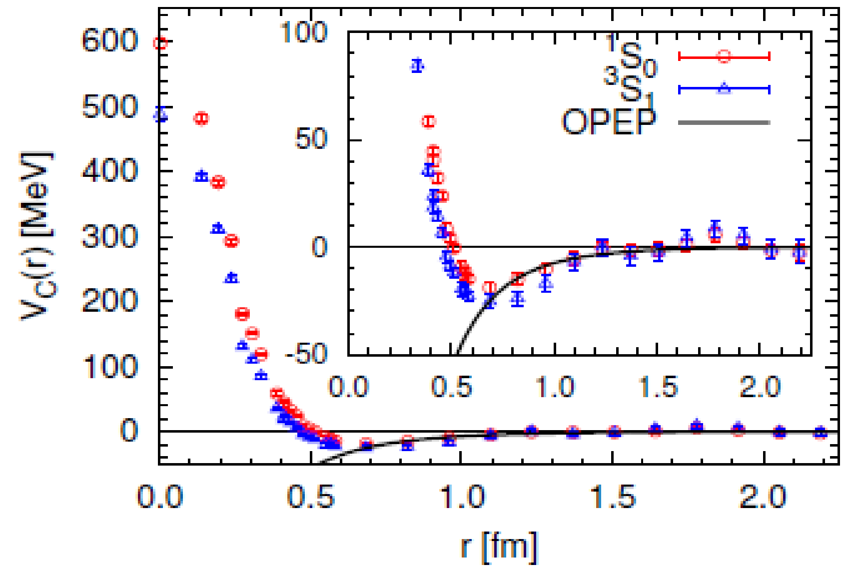
- **Interaction between quarks**
  ~ Linear conf.
  + (color) Coulomb
  + Color-magnetic int.
  + Instanton Induced Int. (KMT)
  + Meson exch.
  + … (What else ?)

Takahashi, Suganuma, Nemoto, Matsufuru ('02)



- **Interaction btw hadrons**
  ~ Meson exchange potential
  + Quark exchange potential
  + Quark Pauli repulsion

- **Lattice QCD Hadron-Hadron Int. HAL QCD Collab.**
  - **NBS amplitude (~ w.f.) → V**
  - **Applicable to various hh pairs**



Ishii, Aoki, Hatsuda ('07)

How can we measure/confirm hh potential ?

hh correlation and hh interaction

- **Hyperon-Nucleon Scattering → Miwa**
- **Two particle correlation from chaotic source** *Bauer, Gelbke, Pratt ('92)*

$$C_{hh}(q) = \frac{\int dx_1 dx_2 S(x_1, p+q) S(x_2, p-q) |\psi^{(-)}(x_{12}, q)|^2}{\int dx_1 dx_2 S(x_1, p+q) S(x_2, p-q)}$$

- **Static spherical source, s-wave only (BB)**

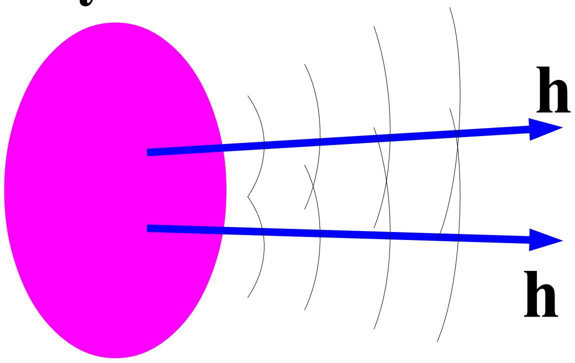
s-wave w.f. enh.

$$C_{hh}(q) \simeq 1 - \frac{1}{2}\exp(-4q^2R^2) + \frac{1}{2}\int dr\, S_{12}(r)\left(|\chi_0(r)|^2 - |j_0(qr)|^2\right)$$

HBT

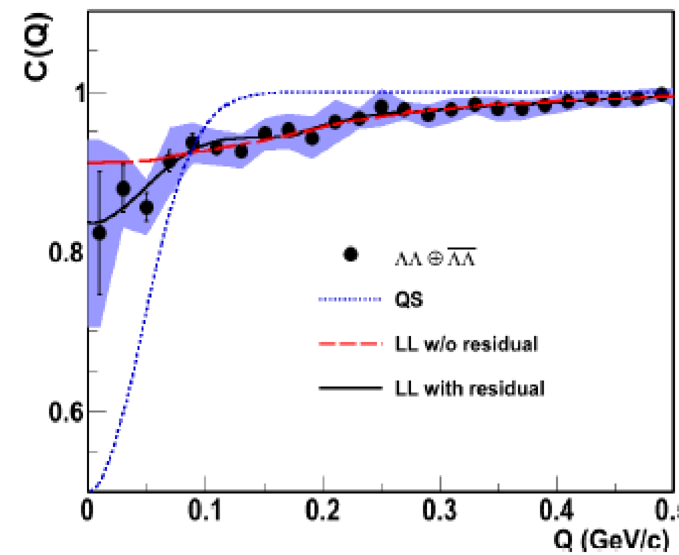
$q=(p_1-p_2)/2$, χ_0: s-wave wf, $S_{12}(x)=r^2 \exp(-r^2/4R^2)/2R^3\sqrt{\pi}$

- **HBT term: Suppression due to (anti-)symmetryzation of w.f.**
  Hanbury Brown, Twiss ('56),
  Goldhaber, Goldhaber, Lee, Pais ('60)
- **Enhancement/suppression of w.f. by hh interaction**

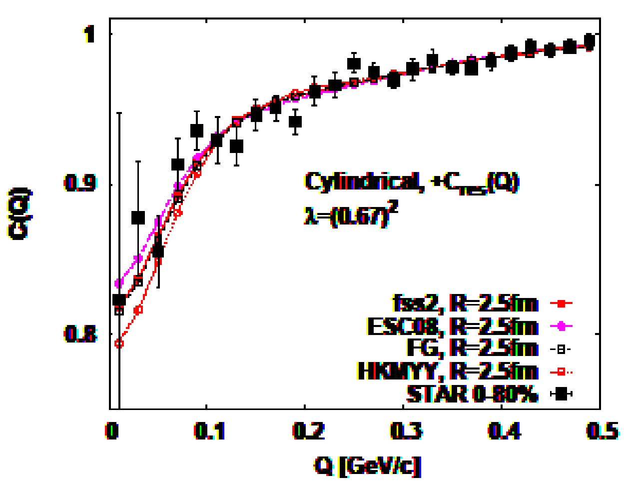


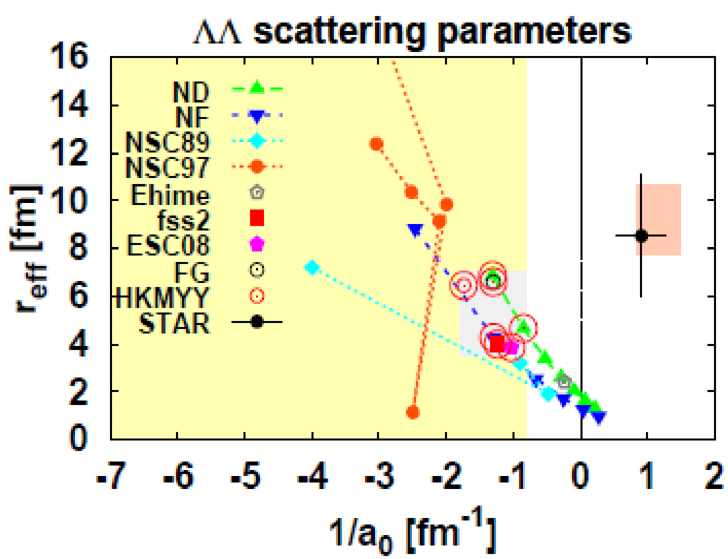
$\Lambda\Lambda$ correlation in HIC and $\Lambda\Lambda$ interaction

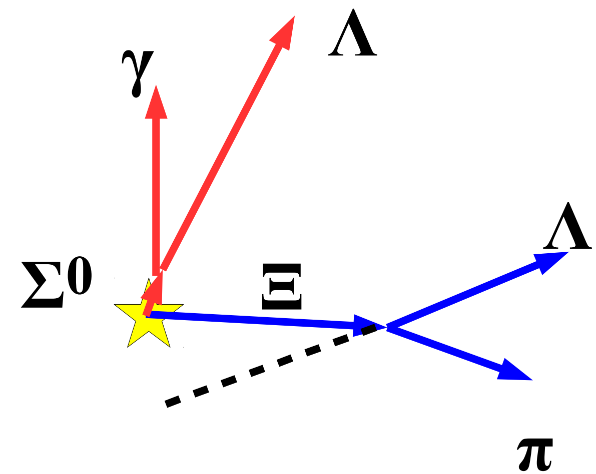
- **Measurement of ΛΛ correlation at RHIC**
  STAR Collab. ('15)
  - **Parent trajectory analysis in TPC**
    → reject weak decay to Λ
    → Better S/N ratio
- **Correlation function analysis**
  Morita, AO, Furumoto ('15)
  - **Bjorken + Transv. flow**
    + Feed down + Res. source → ΛΛ int.



Adamczyk et al. (STAR collab.), PRL 114 ('15) 022301.

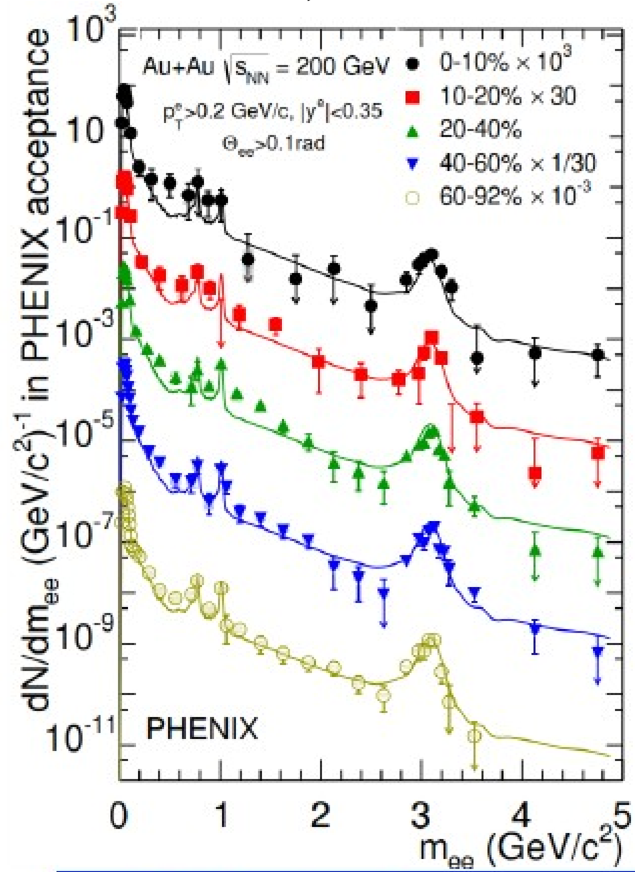






Exotic Vacuum

- **Where and How can we observe (partial) restoration of chiral sym. ?**
  - **Meson mass modification (Hatsuda-Lee / Brown-Rho)**
  - **Pion-nucleus potential**
  - **Mass degeneracy of chiral partners**
- **Low mass dilepton data by PHENIX are updated (QM2015)**
  - **Moderate Enh.**
    → consistent w/ broadened ρ
    (no ρ mass shift required)

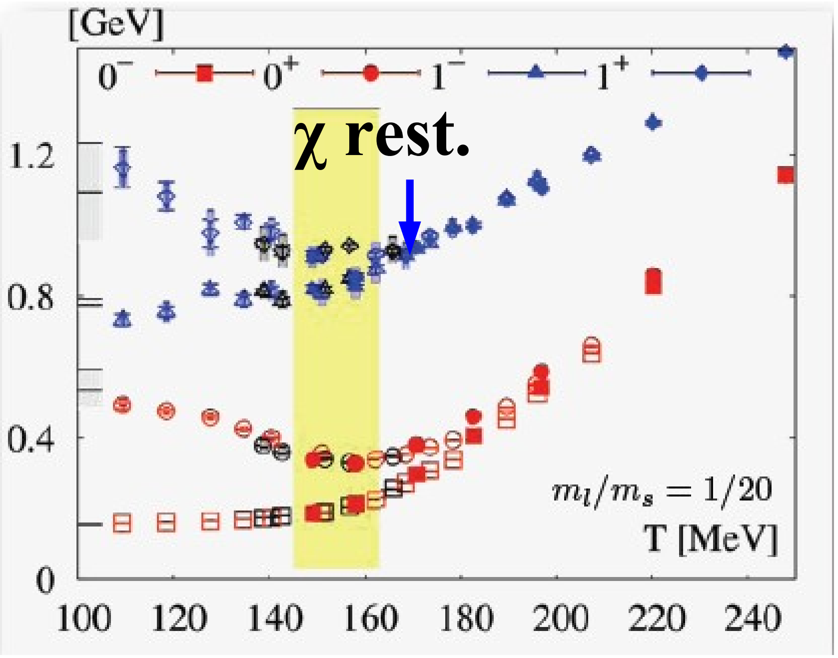


Moderate enhancement consistent with ρ broadening

PHENIX: arXiv1509.04667 (2015)

Meson masses at finite T

- **QCD sum rule** ***Hatsuda, Lee***
  $M(T)/M(vac.) \sim 1 - \alpha T^2$
  $M(\rho)/M(vac.) \sim 1 - \beta \rho$
- **Screening mass from lattice QCD**
  $M_\rho(T)/M(vac.) \sim 1 \ (T < Tc)$
  Lowest Matsubara freq. of quarks
  $\omega = \pi T$
  $\rightarrow$ M(T) approaches $2\pi T$
  if meson is made of $q\bar{q}$.



Maezawa, Karsch, Mukherjee, Petreczky, in prep. (talk @ CPHEHIC)

> ***Where/How do we observe partial restoration of chiral symmetry ?***

Meson masses at finite ρ

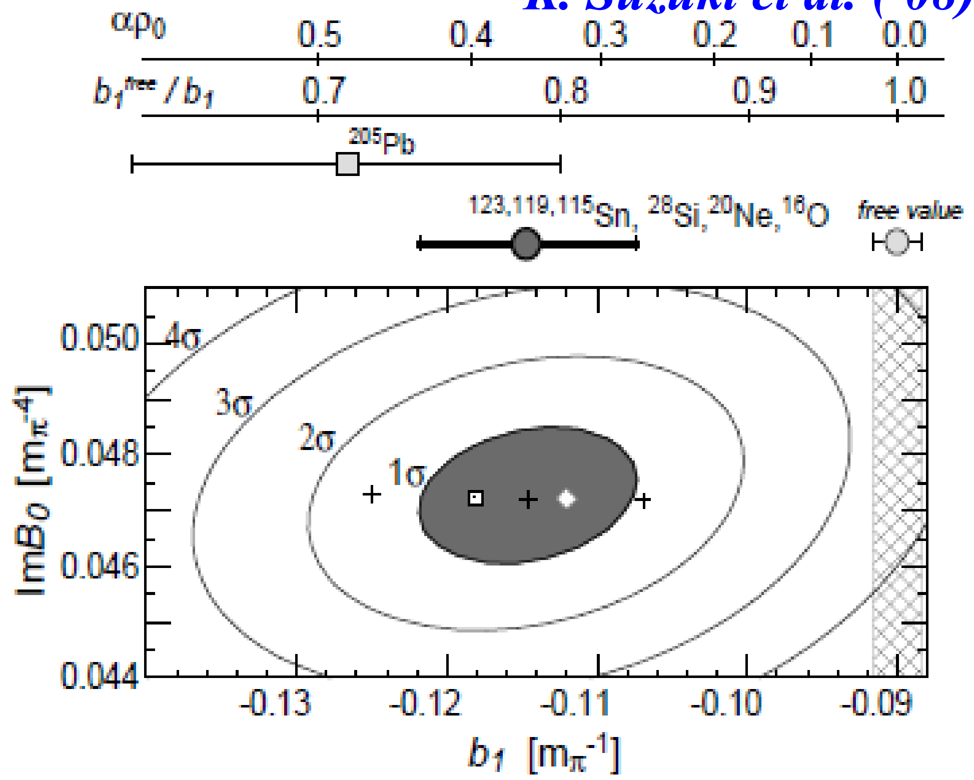
- **Deeply bound pionic atom**
  Drukarev, Levin ('90)
  Kolomeitsev, Kaiser and Weise ('03)
  Gell-Mann, Oakes, Renner ('68)
  K. Suzuki et al. ('08)

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \approx 1 - \frac{\sigma_N}{m_\pi^2 f_\pi^2}\rho,$$

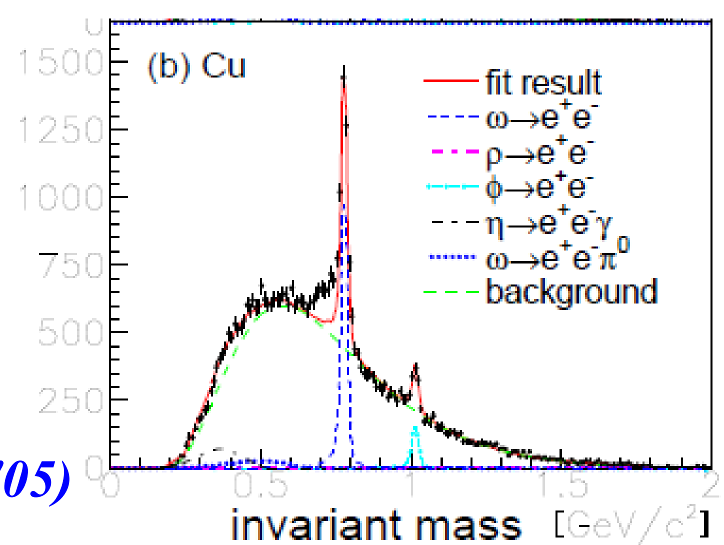
$$R(\rho) = \frac{b_1^{\rm free}}{b_1^*(\rho)} \approx \frac{f_\pi^*(\rho)^2}{f_\pi^2} \approx 1 - \alpha\rho.$$

$$M_\pi^2 = (m_u + m_d) \times |\langle 0|\bar{u}\,u\,|0\rangle| \times \frac{1}{F_\pi^2}$$

K. Suzuki et al. ('08)



- **Vector meson mass modification**
  Naruki et al. ('09)
  - 9 % mass reduction at ρ_0
    ~ QCD sum rule results



Naruki et al. ('05)

Exotic Vacuum: What to do

- **Dense matter (as cold nuclei) has merits than hot matter.**
  - **Partial chiral restoration is expected at finite T and ρ.**
  - **There is no increase of the lowest Matsubara freq. at finite ρ.**
- **Toward the proof of partial chiral restoration**
  - **Vector meson mass modification may emerge at finite ρ, and should be confirmed at J-PARC (not in HIC @ SPS, RHIC, LHC).**
  - **More direct evidence = Spectral function degeneracy of chiral partners (π & σ, ρ & a_1, …) (We may need to start from a_1(1260) identification ….)**

$a_1(1260)$ [k] $I^G(J^{PC}) = 1^-(1^{++})$

Mass $m = 1230 \pm 40$ MeV [l]
Full width $\Gamma = 250$ to 600 MeV

a_1(1260) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$(\rho\pi)_{S-\text{wave}}$	seen	353
$(\rho\pi)_{D-\text{wave}}$	seen	353

$\rho(770)$ [h] $\quad I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 775.26 \pm 0.25$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV
$\Gamma_{ee} = 7.04 \pm 0.06$ keV

ρ(770) DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$	$\sim$ 100 %		363

$a_1(1260)$ [k] $\quad I^G(J^{PC}) = 1^-(1^{++})$

Mass $m = 1230 \pm 40$ MeV [l]
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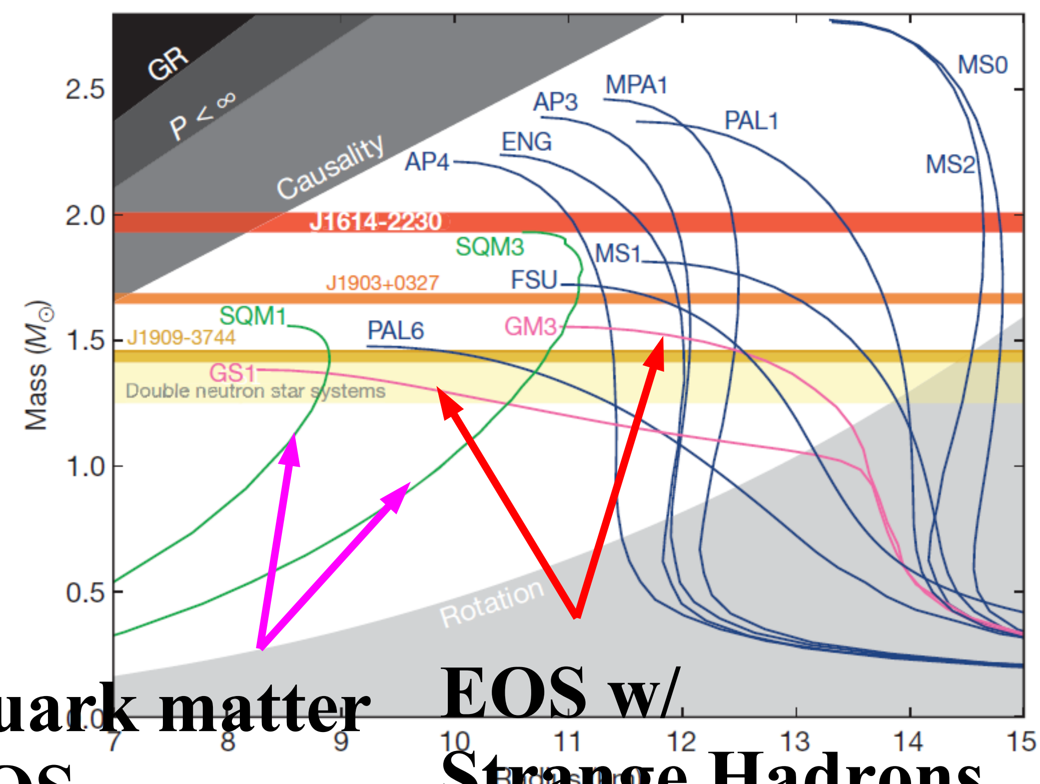
Hyperon Puzzle

- **Observation of massive neutron stars (M ~ 2 $M_\odot$)**
  - **PSR J1614-2230 (NS-WD binary), 1.97 ± 0.04 $M_\odot$**
    Demorest et al., Nature 467('10)1081 (Oct.28, 2010).
    "Kinematical" measurement (Shapiro delay, GR) + large inclination angle
  - **PSR J0348+0432 (NS-WS binary), 2.01 ± 0.04 $M_\odot$**
    Antoniadis et al., Science 340('13)1233232.
  - **Hyperon should appear at (2-4) ρ_0, but softened EOS is ruled out.**
    → Hyperon Puzzle



Quark matter EOS

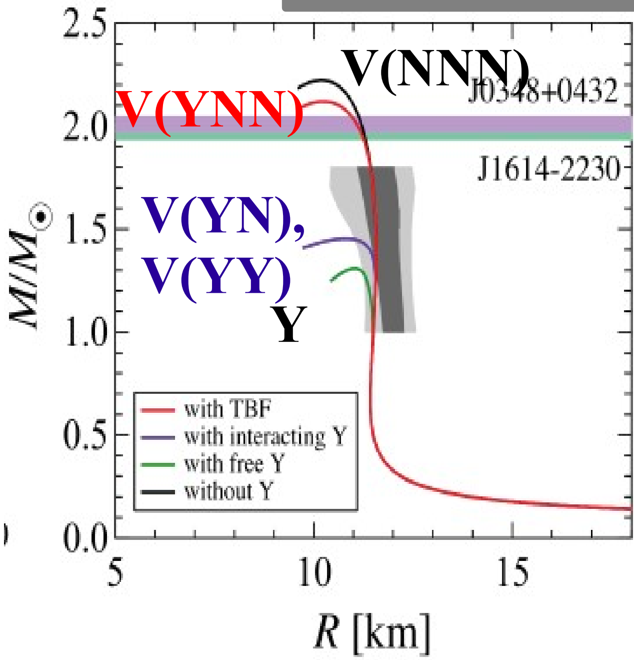
EOS w/ Strange Hadrons

No Exotics in NS ?

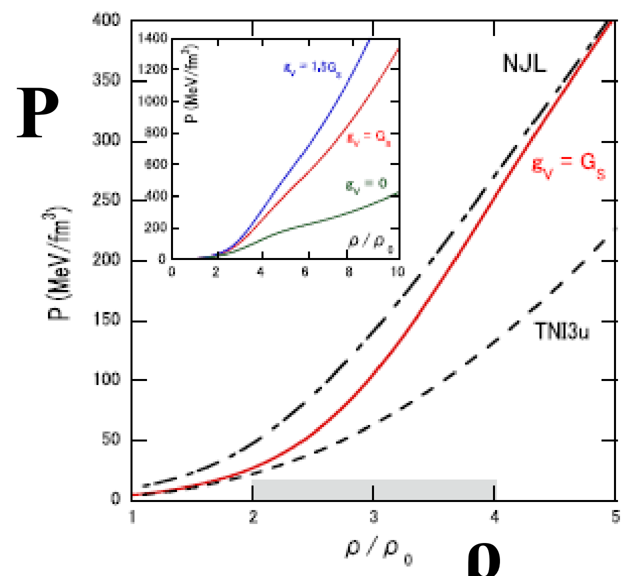
Possible Solutions of Hyperon Puzzle

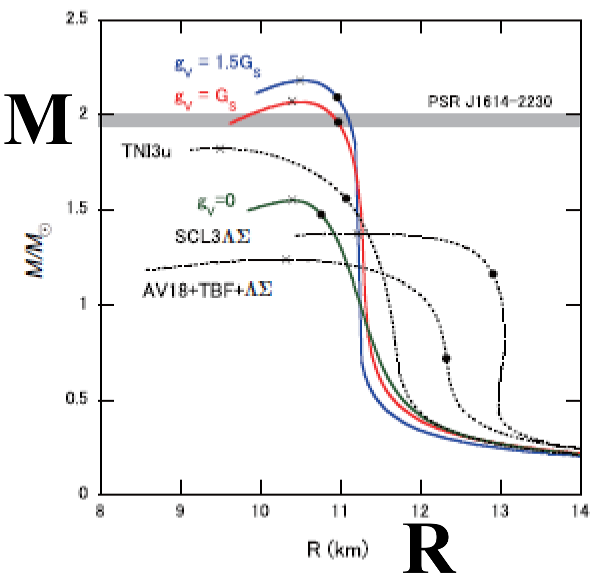
- **Solution 1: Repulsive YNN, YYN and YYY potential**
  S. Nishizaki, T. Takatsuka,Y. Yamamoto ('02); Bednarek, Haensel et al.('11); Miyatsu, Yamamuro, Nakazato (‘13); Tamagaki ('08). Togashi, Hiyama, Takano, Yamamoto, ...
- **Solution 2: Crossover transition to quark matter at low density**
  K. Masuda, T. Hatsuda, T. Takatsuka, ApJ764('13)12

Which is correct ? (or other mechanism ?)



Togashi, Hiyama, Takano, Yamamoto, in prep.

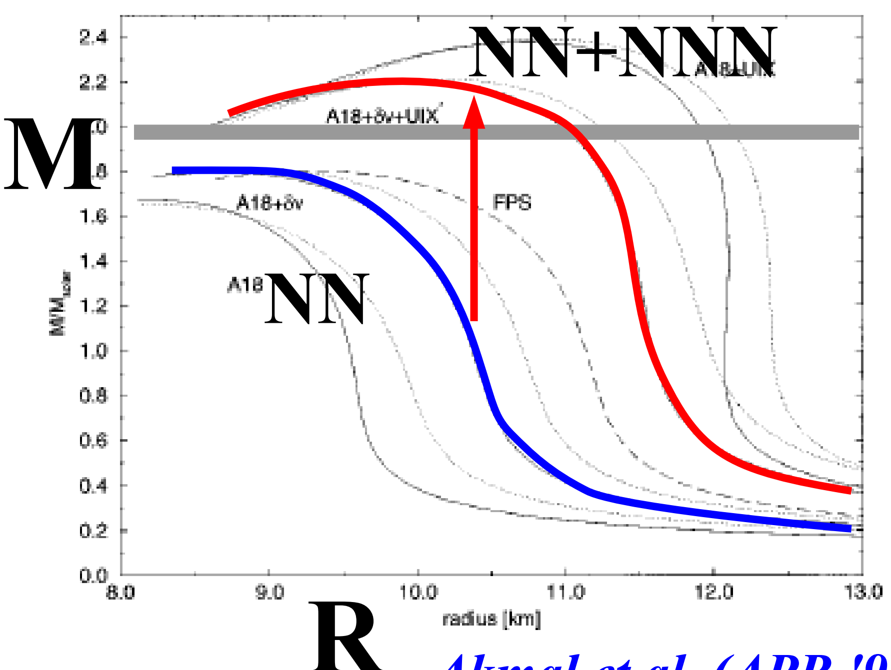




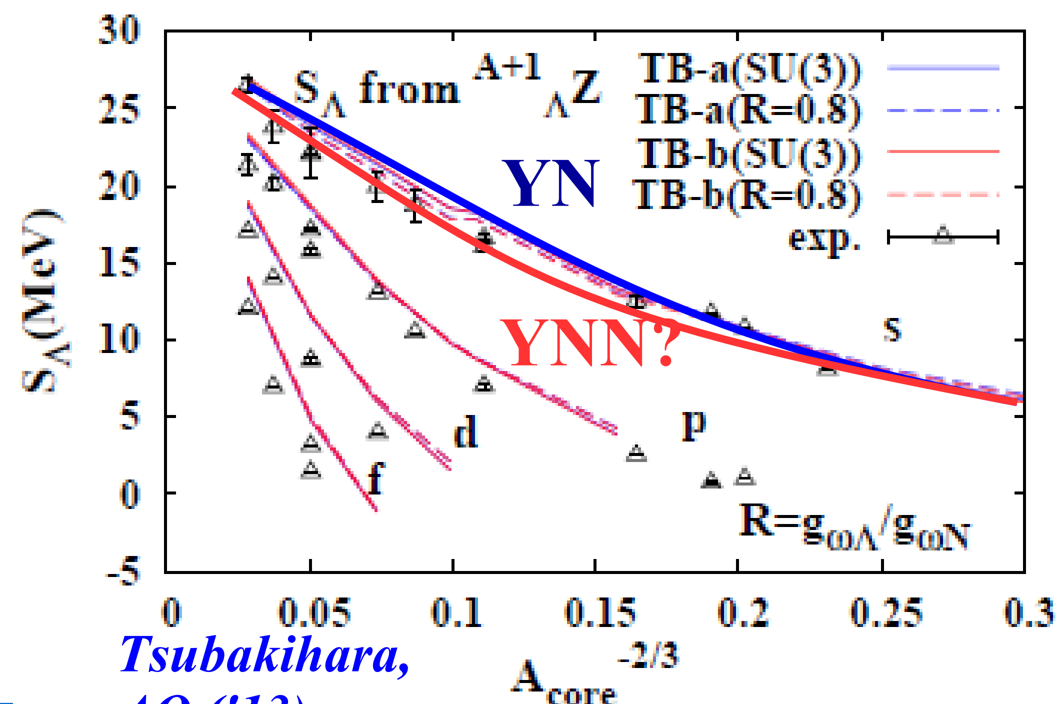
Masuda, Hatsuda, Takatsuka ('13)

Repulsive YNN, YYN and YYY potential

- NNN force is necessary to explain nuclear matter EOS and to support NS with nucleon matter EOS
  → It is natural to introduce BBB potential including Y.
- How can we determine ?
  - Precise measurement of S_Λ over wide mass range → density dep.
    Yamamoto, Furumoto, Yasutake, Rijken ('13), Tsubakihara, AO('13); T.Takahashi
  - Lattice QCD calculation *Doi et al.(HAL QCD collab., '12 for NNN)*



Akmal et al. (APR,'98)



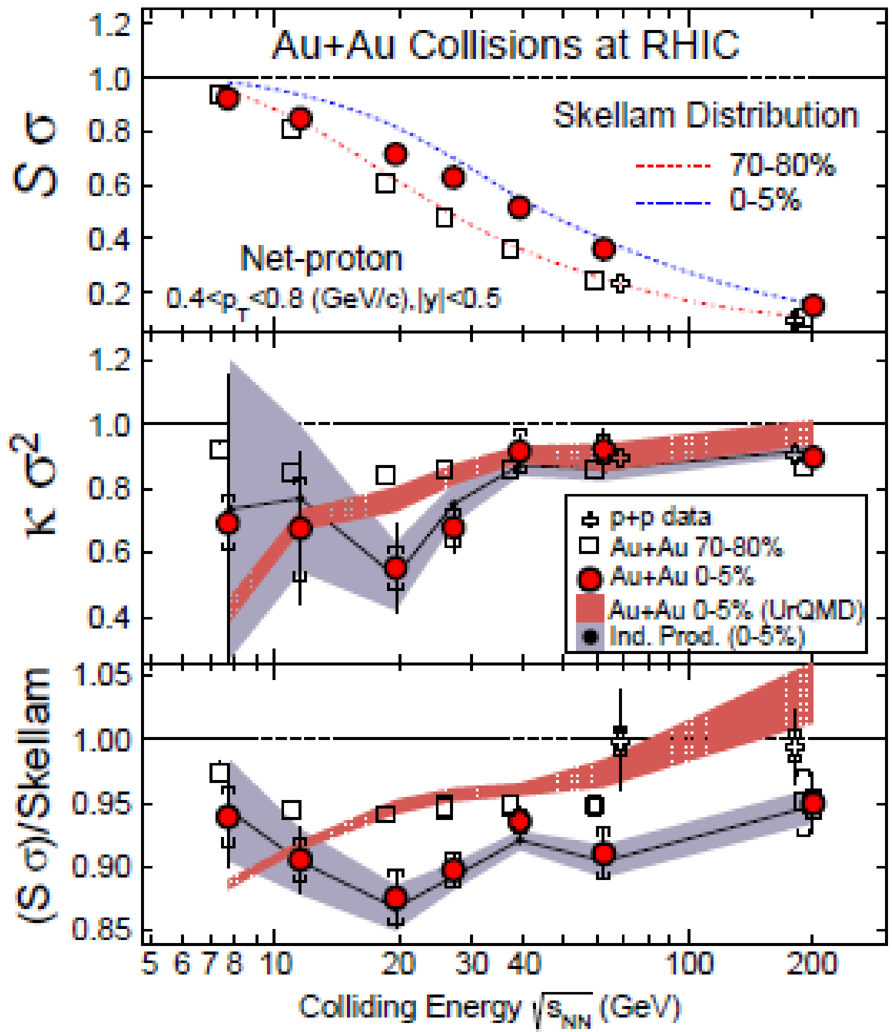
Tsubakihara, AO ('13)

Crossover transition to quark matter at low density

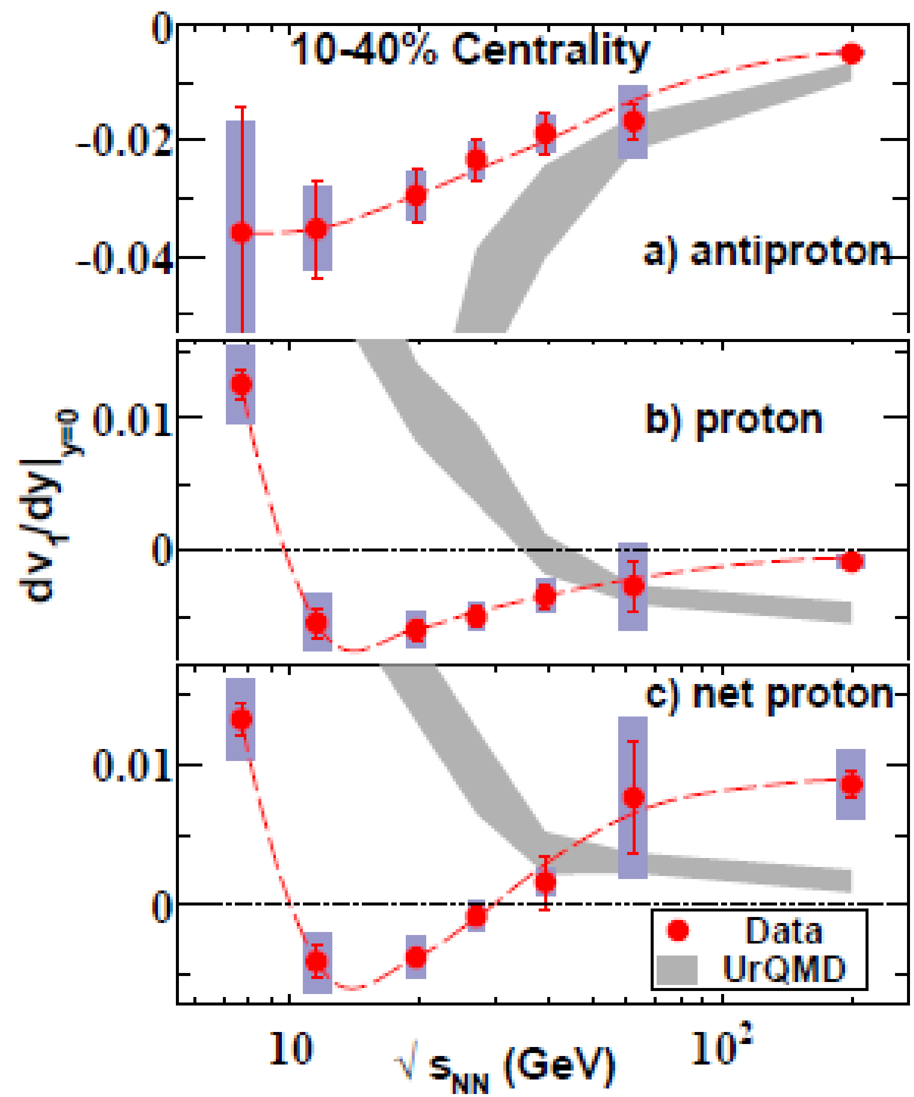
- **To stiffen EOS via crossover transition,
quark matter should start to mix at low densities ((2-4) ρ_0) !
→ J-PARC energy ($\sqrt{s_{NN}}$ = (5-10) GeV) Heavy-Ion Collisions !**
- **Many suggestive data are obtained in the J-PARC energies.**
  - **Net-proton number cumulant, Directed flow, K+/ π+ ratio, …
in Beam Energy Scan (BES) program at RHIC**

Net-Proton Number Moments & Directed Flow

- Non-monotonic behavior of $\kappa\sigma^2$ and dv_1/dy. CP signal ?

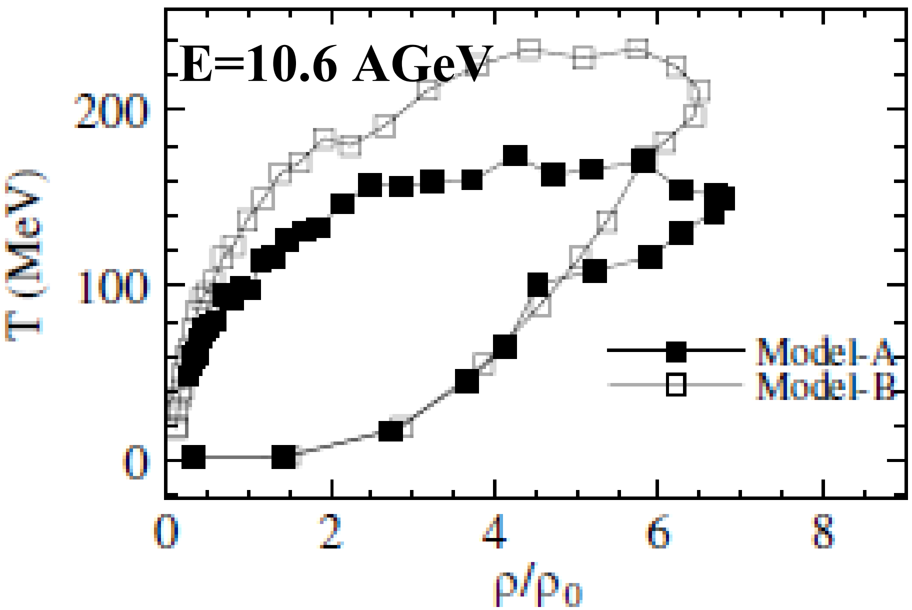


STAR Collab. (PRL 112('14)032302



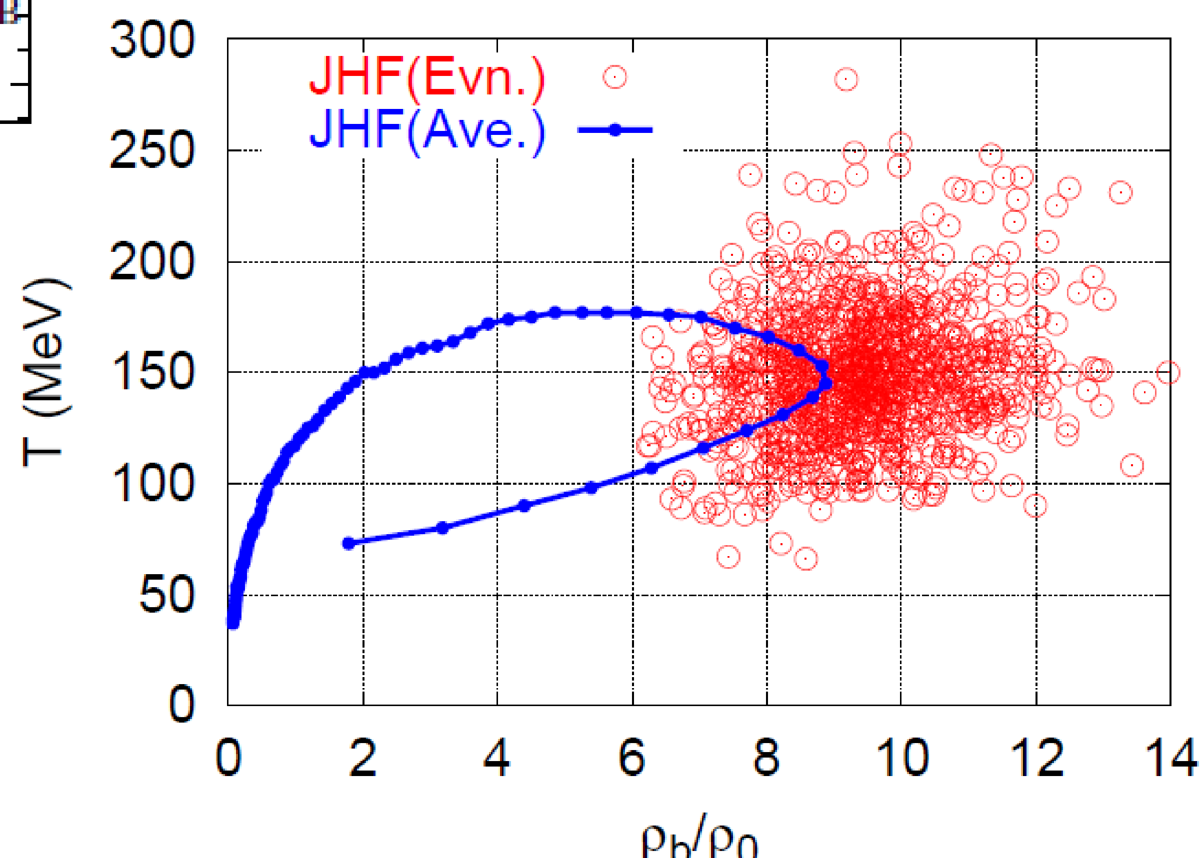
STAR Collab., PRL 112('14)162301.

Highest Density Matter at J-PARC ?



Central 1 fm^3 cube.

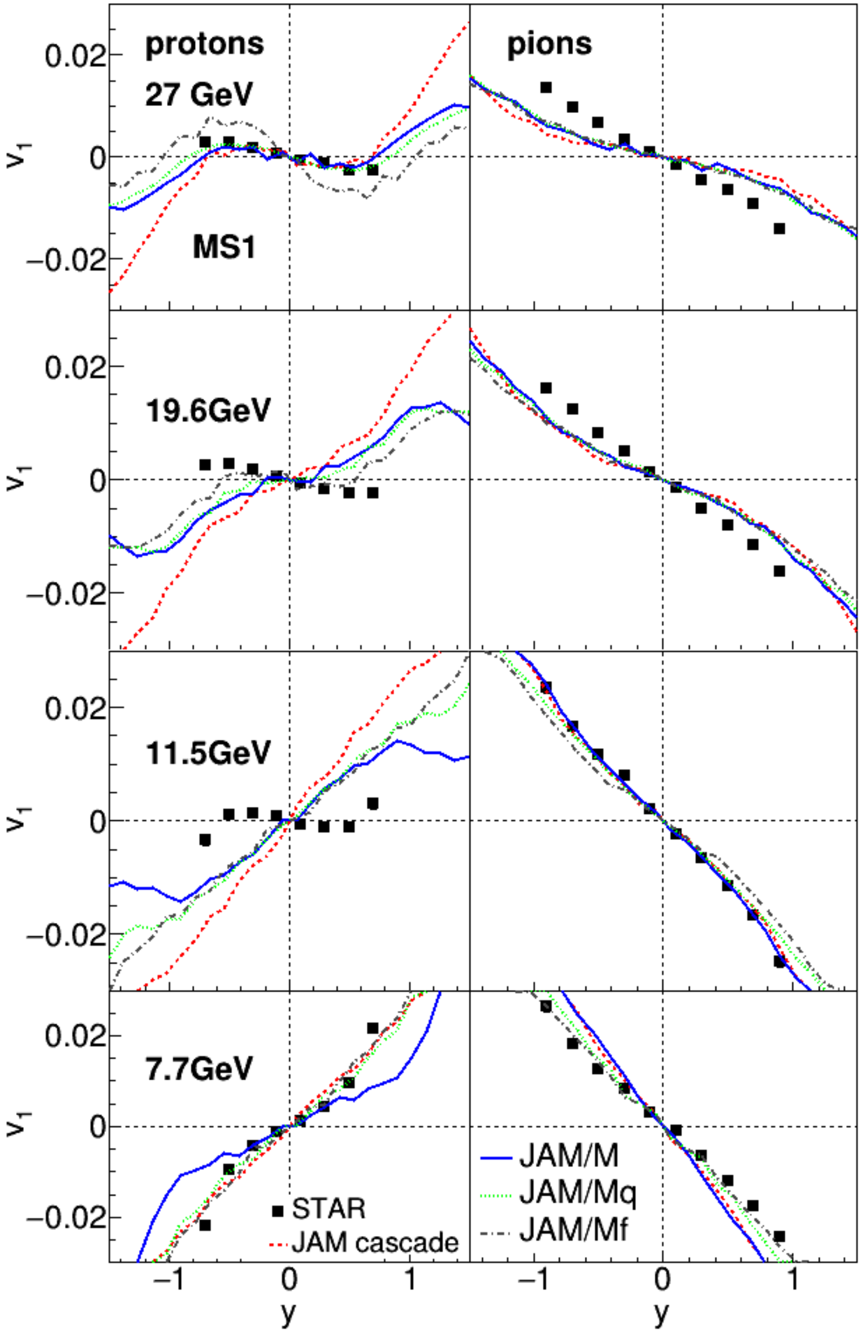
Nara, Otuka, AO, Maruyama ('97)



AO, JHF workshop (2002, unpublished)

Comparison of v1

by Y. Nara



Effects of potential on the v1 is significant

Hadronic approach does not reproduce the correct beam energy dependence of the directed flow.

Something happens around 10-20GeV?

JAM/M: only formed baryons feel potential forces
JAM/Mq: pre-formed hadron feel potential with factor 2/3 for diquark, and 1/3 for quark
JAM/Mf: both formed and pre-formed hadrons feel potential forces.

Nara, AO, in prep.

Crossover transition to quark matter at low density

- **To stiffen EOS via crossover transition, quark matter should start to mix at low densities ((2-4) ρ_0) !**
  → J-PARC energy ($\sqrt{s_{NN}}$ = (5-10) GeV) Heavy-Ion Collisions !
- **Many suggestive data are obtained in the J-PARC energies.**
  - **Net-proton number cumulant, Directed flow, K+/ π+ ratio, … in Beam Energy Scan (BES) program at RHIC**
- **Merit to run HIC at J-PARC = High Intensity (x 10^{3-5})**
  → E.g. Event tagged observables
  - **Produced strangeness tagged flow (T.Sakaguchi)**
    Softened EOS would be measured for events with large number of produced strange particles.
  - **Negative dv_1/dy tagged fluctuation observables, ...**

Summary

- J-PARC has potential to explore Exotic QCD physics.
  - Exotic Hadrons (→ Noumi)
    - J-PARC could enable us to obtain the first systematic spectrum of Charmed Baryons.
    - Yield measurement in pp, pA, $e^- e^+$ and AA should bare the hadron size information.
  - Exotic Interaction (→ Miwa)
    - Direct (Hyperon beam) & Indirect (FSI) Scattering of hh requires high intensity, and could be suitable to J-PARC.
  - Exotic Vacuum (→ Noumi)
    - While high T data show no meson mass shift, finite ρ effects should exist, as already shown in pionic atoms and vector meson spectra.
    - Is it possible to measure $a_1(1260)$ via 3π ?
  - Exotic EOS (→ Miwa, Sako)
    - Precise Hypernuclear data & Rare event HIC data → hyperon puzzle.

Thank you for your attention !