Medium modifications of hadron masses

Osamu Morimatsu, KEK theory center

KEK theory center workshop on
Hadron physics with high-momentum hadron beams at J-PARC in 2013
KEK, Tsukuba, Japan, Jan. 15-18, 2013

What can we learn from hadrons in medium?

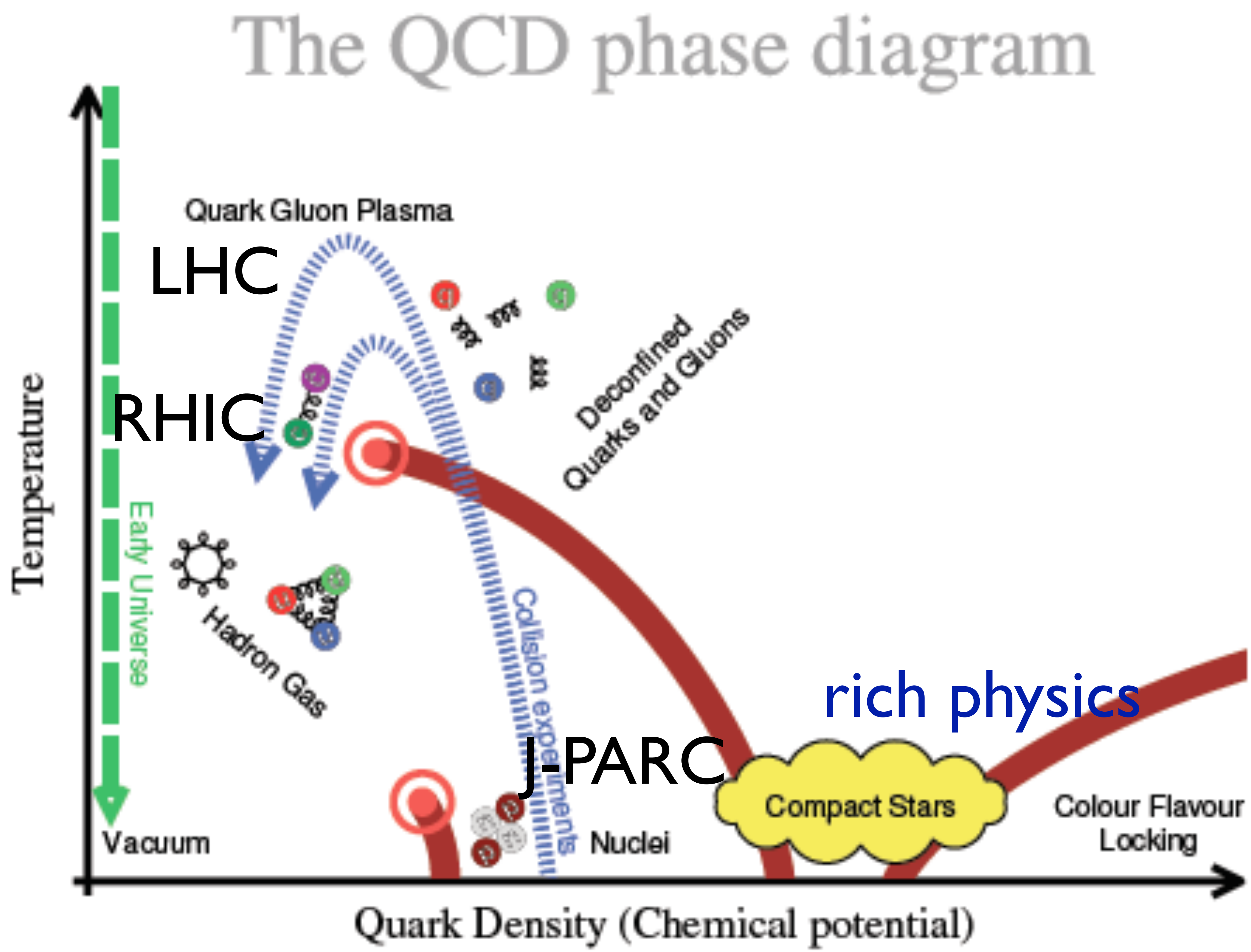
Answers

- properties of medium (modern view)
    - confinement, spontaneous breakdown of chiral symmetry, etc.

      - in-medium hadrons reflect properties of medium -

- hadron-nucleus interactions (classical view)

  relation between these two views ?



The QCD phase diagram
Quark Gluon Plasma
LHC
RHIC
Deconfined Quarks and Gluons
Early Universe
Hadron Gas
Collision experiments
rich physics
J-PARC
Compact Stars
Colour Flavour Locking
Vacuum
Nuclei
Temperature
Quark Density (Chemical potential)

How are in-medium hadron properties related with medium properties?

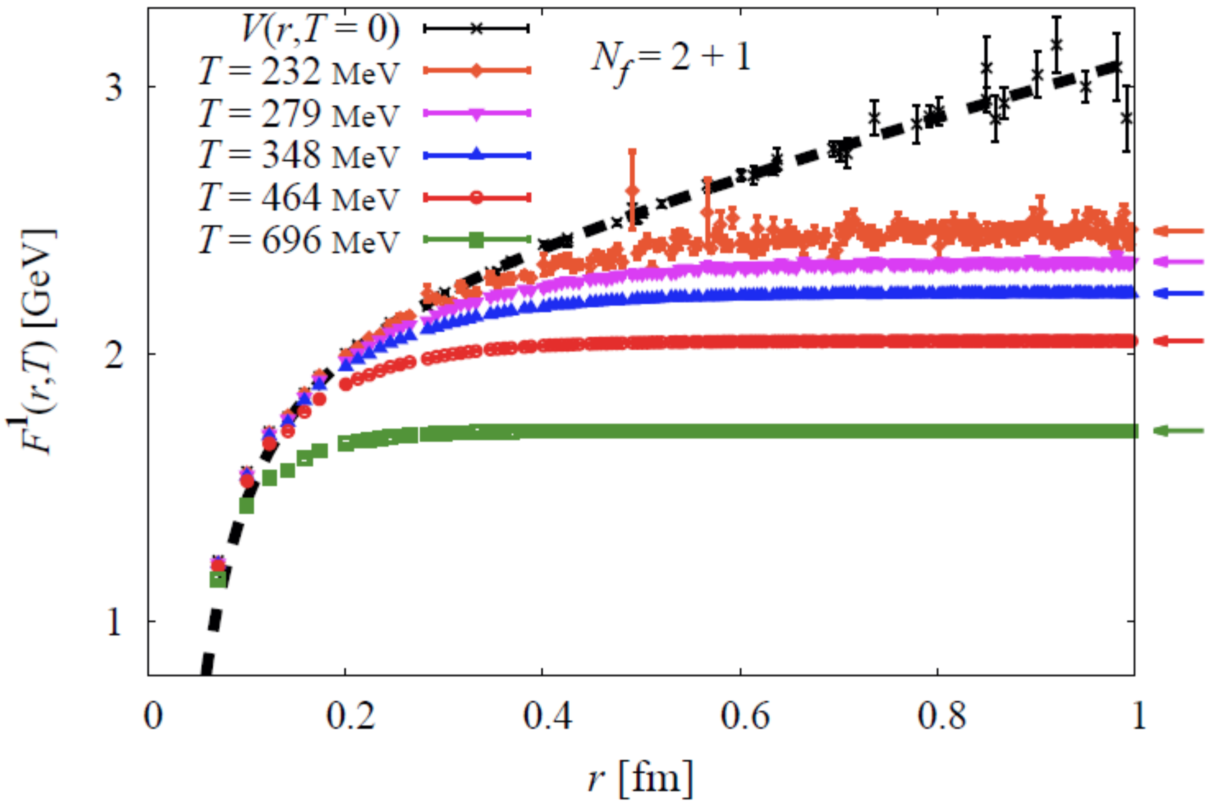
Deconfinement transition in hot medium

J/ψ suppression

- Matsui, Satz
  PLB 178 (1986) 416

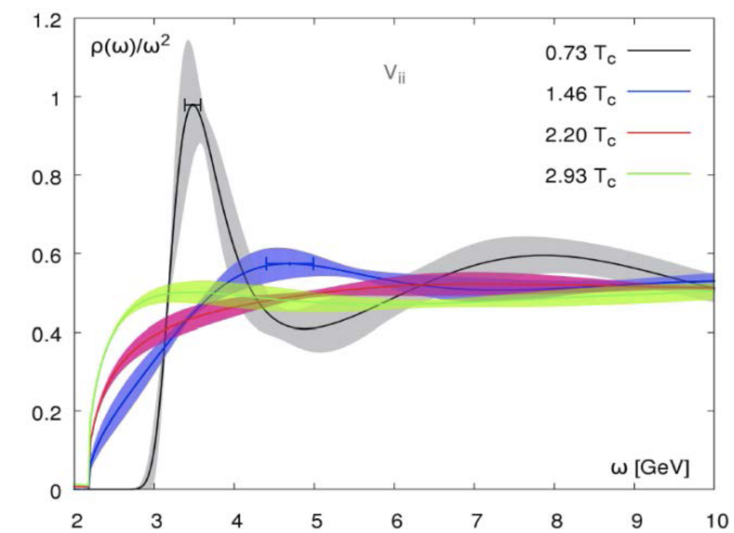
- Hashimoto, Hirose, Kanki, Miyamura
  PRL 57 (1986) 2123

"colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region"

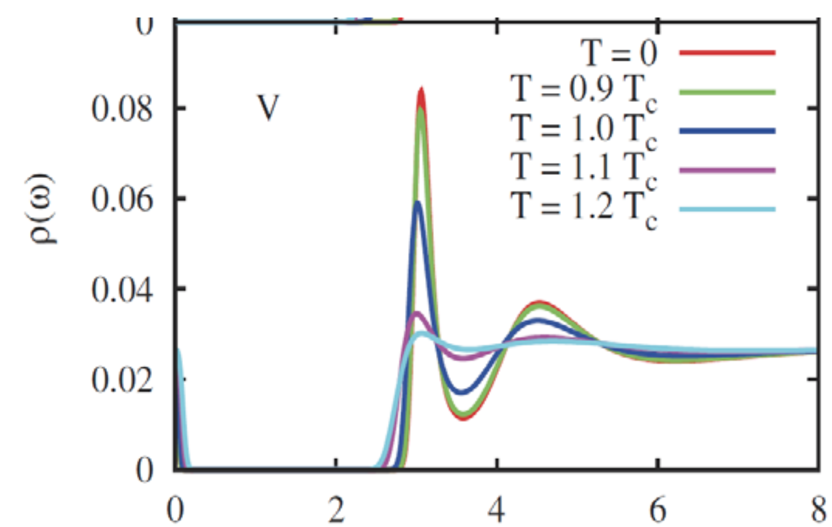


J/ψ spectral function (theory)

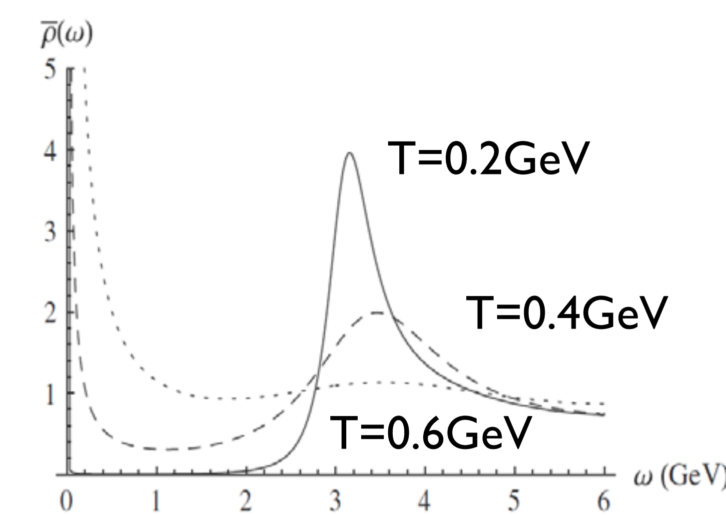
- **Lattice QCD (MEM)**
  - Ding, et al. arXiv:1204.4945



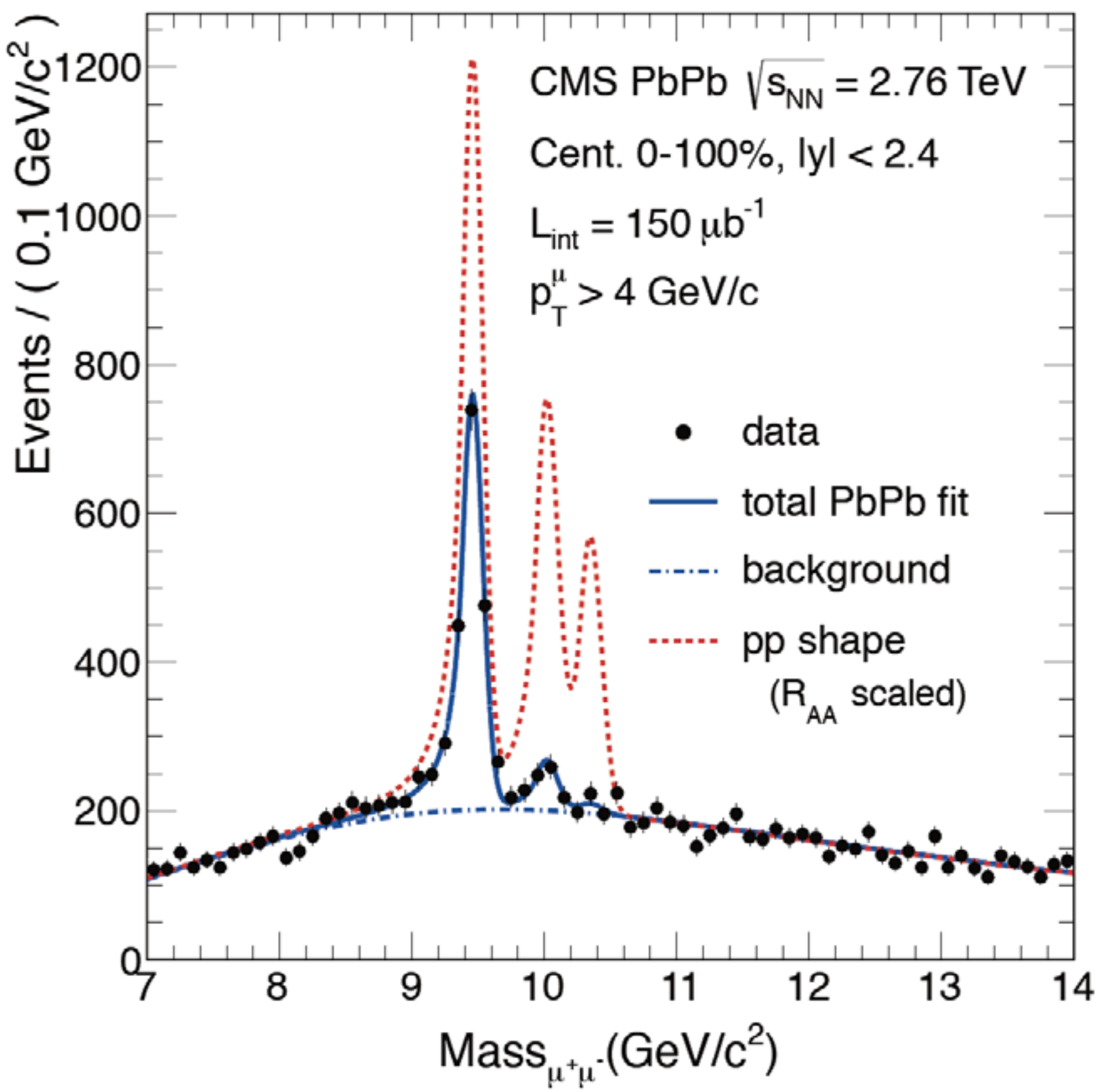
- **QCD sum rule (MEM)**
  - Gubler, Morita, Oka PRL107 (2011) 092003



- **Holographic QCD**
  - Grigoryan, Hohler, Stephanov PRD82 (2010) 026005



Υ suppression (experiment)



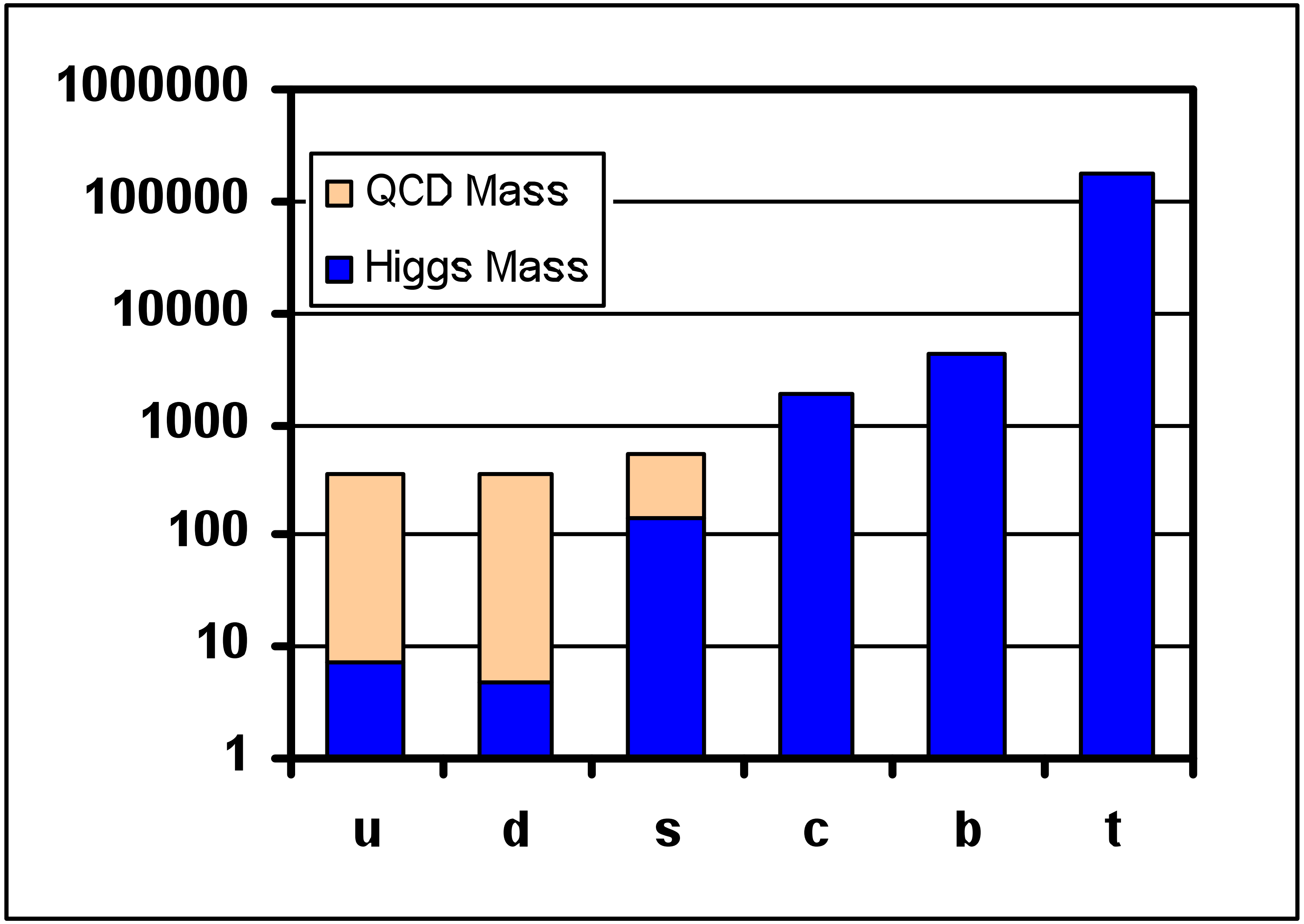
- CMS Coll. arXiv:1208.2826

$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08(\text{stat.}) \pm 0.07(\text{syst})$$
$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04(\text{stat.}) \pm 0.02(\text{syst})$$
$$R_{AA}(\Upsilon(3S)) = 0.03 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst})$$

Restration of chiral symmetry in medium

Origin of mass

- chiral symmetry breaking is the origin of hadron masses



Vector meson modification in dense matter (theory)

- Brown & Rho, PRL 66 (1991) 2720
  BR scaling

  $$m^*/m_0 \sim f_\pi^*/f_\pi \sim 0.8 \; at \; \rho = \rho_0$$

- Hatsuda & Lee, PRC 46 (1992) R34
  QCD sum rule

  $$m^*/m_0 \sim 1 - C(\rho/\rho_0), \qquad C = \begin{cases} 0.18 & \rho, \omega \\ 0.15y \quad with \quad y = 0.12 \sim 0.22 & \varphi \end{cases}$$

- Many other works related (or unrelated) with chiral symmetry breaking.

QCD sum rule

- correlation functions in vacuum and in medium

$$\Pi_{0,T,\rho}(p) = -i \int d^4x e^{ipx} \left\langle T(h(x)h^\dagger(0)) \right\rangle_{0,T,\rho}$$

$$h(x) : \text{interpolating field for hadron } h$$

- dispersion relation

$$\Pi(\omega, \boldsymbol{p}) = -\frac{1}{\pi} \int d\omega' \frac{1}{\omega - \omega'} \mathrm{Im}\Pi(\omega', \boldsymbol{p})$$

OPE
in deep-Euclid region

phenomenology
in physical region

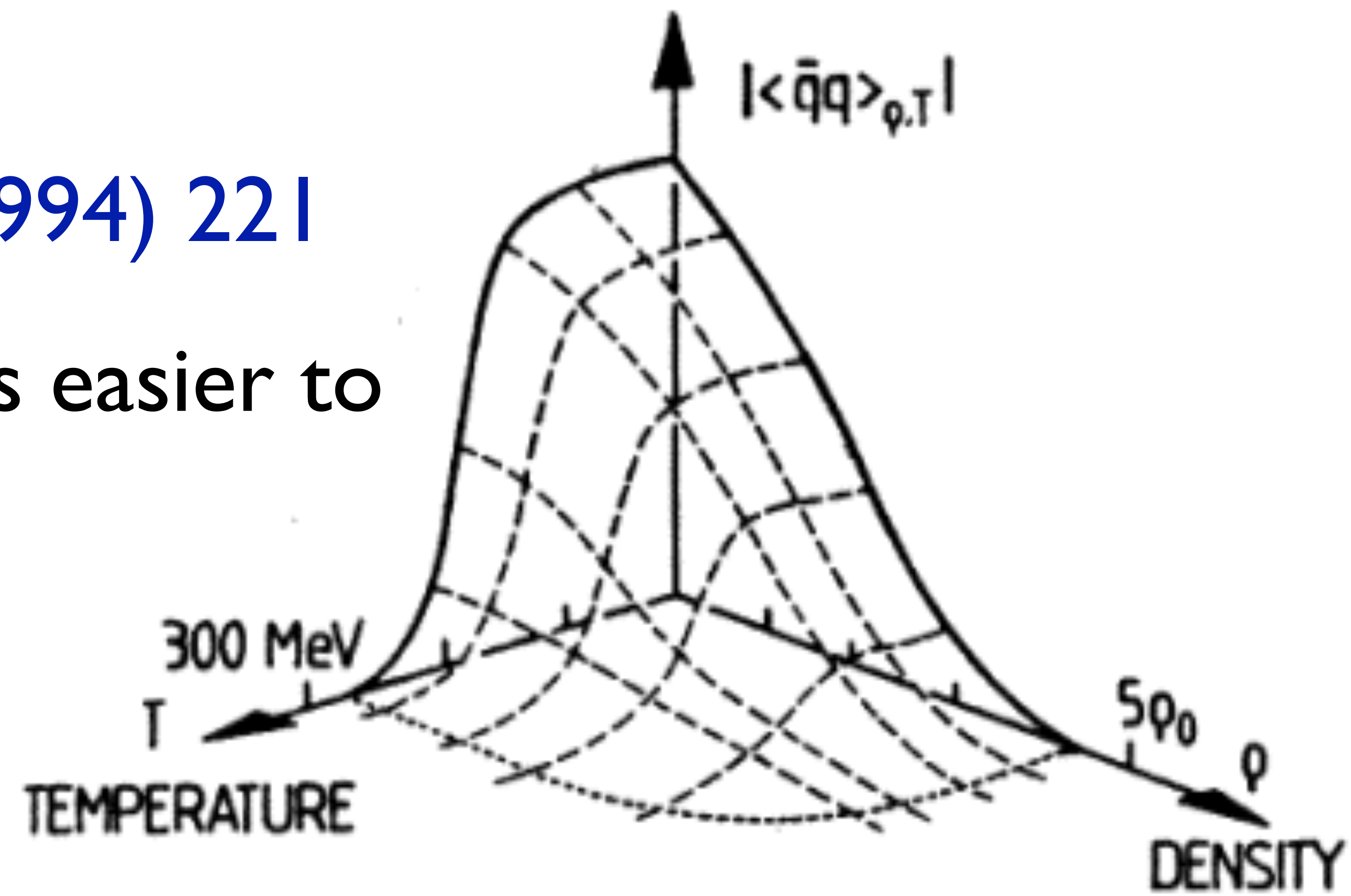
- sum rule

$$m_{0,T,\rho} = C_{\bar{q}q} \left\langle \bar{q}q \right\rangle_{0,T,\rho} + C_{q^\dagger q} \left\langle q^\dagger q \right\rangle_{T,\rho} + C_{G^2} \left\langle G^2 \right\rangle_{0,T,\rho} + \cdots$$

Chiral condensates at finite T and ρ (1)

- NJL model
  - Vogl, Weise
    Prog. Part. Nucl. Phys. 27 (1991) 195
  - Hatsuda, Kunihiro
    Phys. Rept. 247 (1994) 221

Finite density effect is easier to observe?



Chiral condensates at finite T and ρ (2)

- small T
  - J. Gasser and H. Leutwyler
    Phys. Lett. B184 (1987) 83

$$\langle \bar{q}q \rangle_T = \langle \bar{q}q \rangle_0 + \frac{T^2}{8} \langle \bar{q}q \rangle_\pi$$

- small ρ
  - Drukarev and Levin
    Nucl. Phys. A511 (1990) 679, A516 (1990) 715(E)

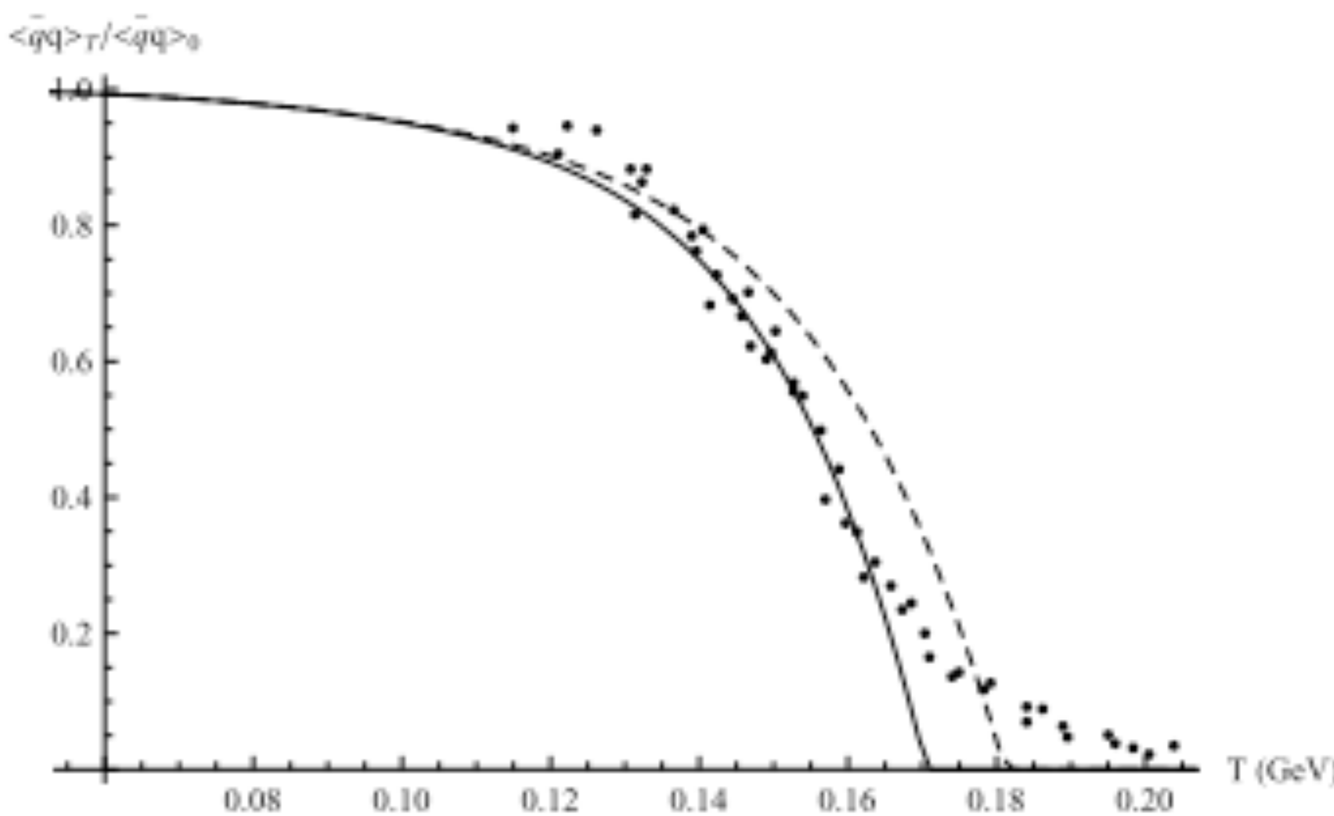
$$\langle \bar{q}q \rangle_\rho = \langle \bar{q}q \rangle_0 + \rho \langle \bar{q}q \rangle_N \,, \quad \langle \bar{s}s \rangle_\rho = \langle \bar{s}s \rangle_0 + \frac{\sigma_s}{m_s} \rho$$

$$\langle \bar{u}u \rangle_\rho = \langle \bar{u}u \rangle_0 + \frac{\sigma_\ell}{2\hat{m}} \rho, \qquad = \langle \bar{s}s \rangle_0 + y \frac{\sigma_\ell}{2\hat{m}} \rho$$

$$\sim 30\% \text{ at } \rho = \rho_0$$

Chiral condensates at finite T and ρ (3)

- Lattice QCD at finite T
  - Wuppertal-Budapest Collaboration JHEP 1009 (2010) 073



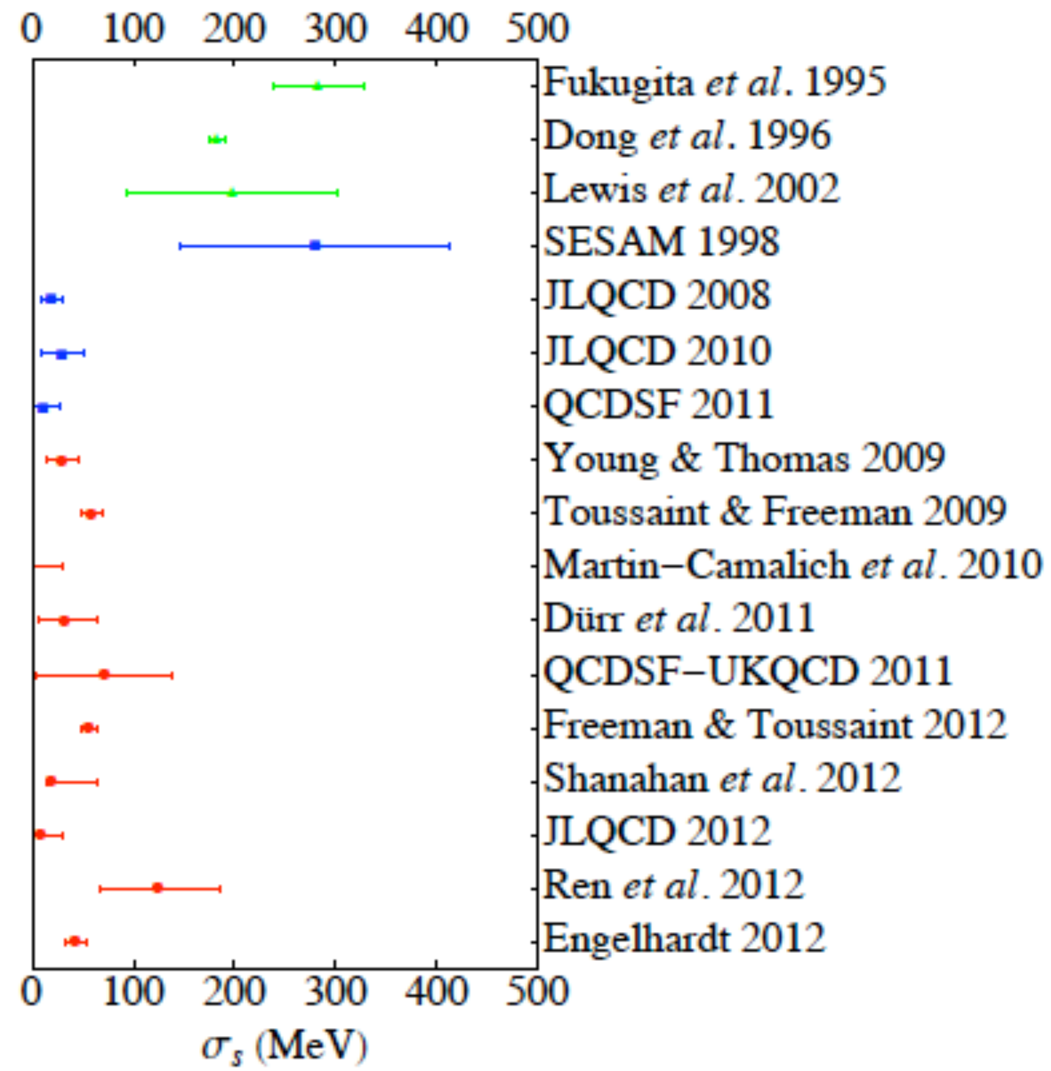
Chiral condensates at finite T and ρ (4)

- Lattice QCD at finite ρ
  still experimental stage

  But, new results for $\langle \bar{s}s \rangle_N$

  Young, arXiv:1301.1765

  "recent determinations of the strange quark sigma term are significantly smaller than had previously been suggested"



This implies the modification of ϕ mass is even smaller.

Systematic studies of

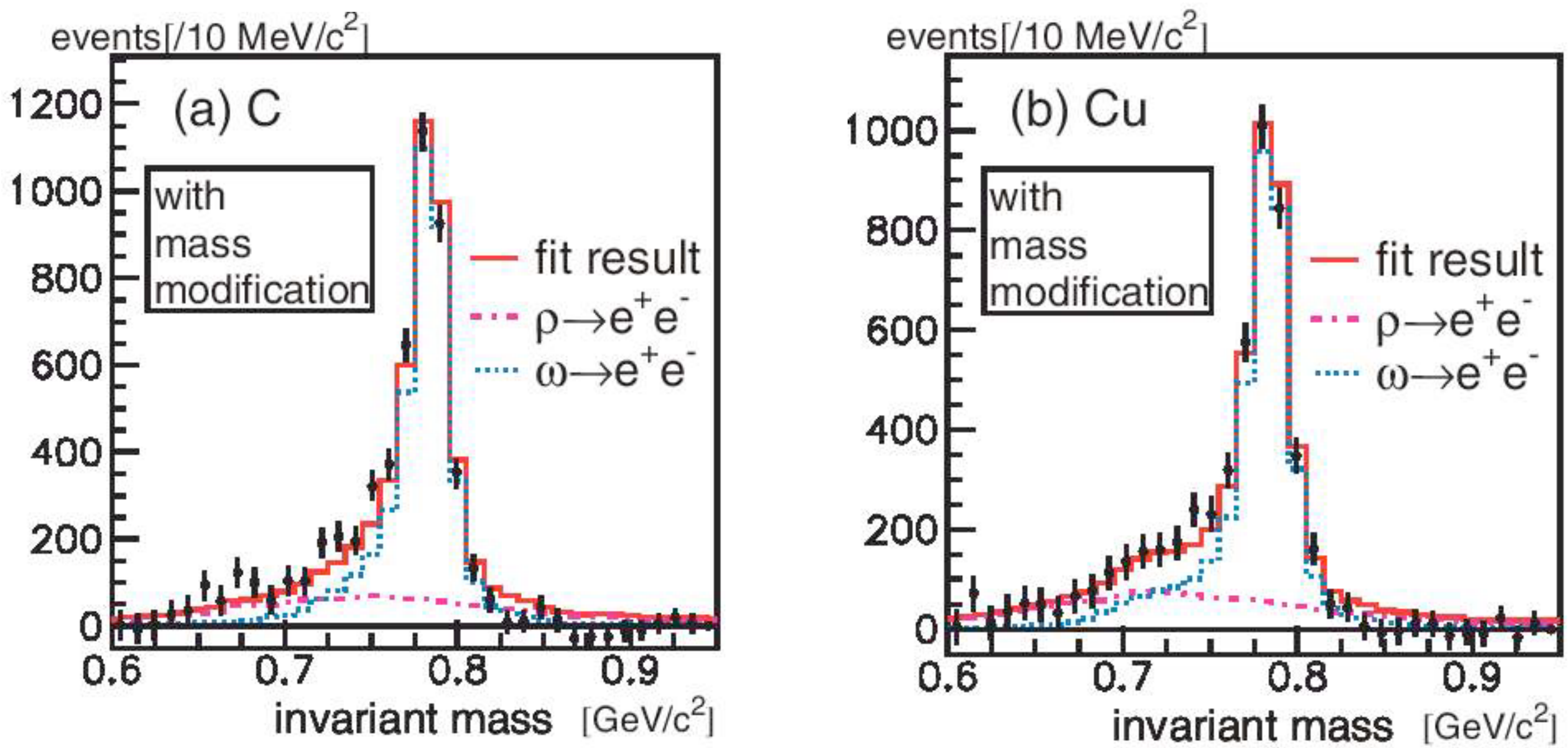
ρ, ω, ϕ mesons would be important.

KEK E325 results

ρ, ω meson

$$m^*/m_0 = 1 - k_1 \rho/\rho_0 \qquad k_1 = 0.092 \pm 0.002$$

$$\Gamma^*/\Gamma_0 = 1 + k_2 \rho/\rho_0 \qquad k_2 = 1$$

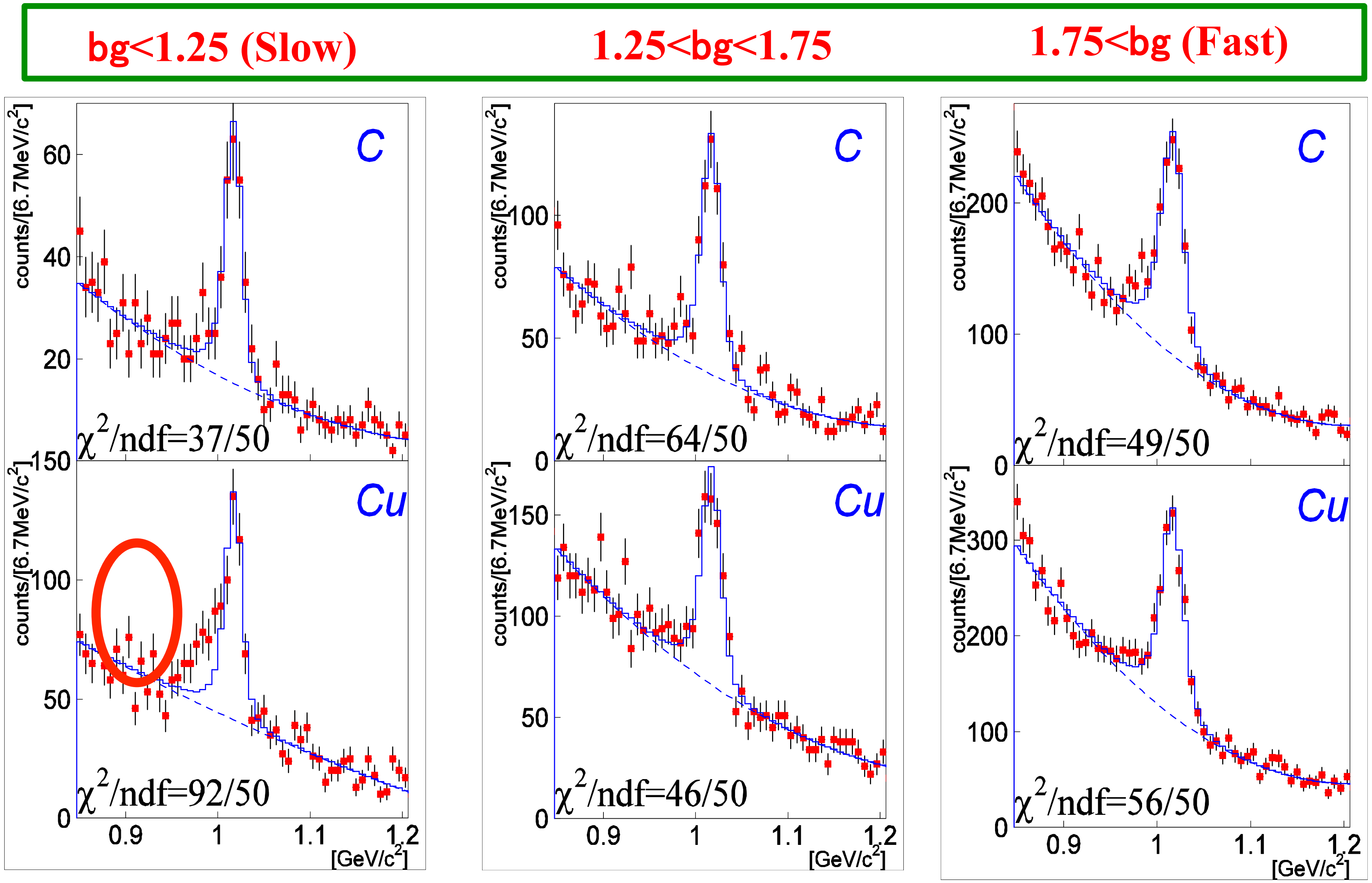


M. Naruki et al., PRL 96 (2006) 092301

KEK E325 results
φ meson

$$m^*/m_0 = 1 - k_1\rho/\rho_0 \qquad k_1 = 0.034^{+0.006}_{-0.007}$$

$$\Gamma^*/\Gamma_0 = 1 + k_2\rho/\rho_0 \qquad k_2 = 2.6^{+1.8}_{-1.2}$$



R. Muto et al., PRL 98 (2007) 042581

change of chiral condensates vs. hadron-nucleus interactions

- O(ρ) term of δm is identified as that of the hN scattering
  - Y. Kondo and O. Morimatsu

    Phys. Rev. Lett. 71(1993) 2855
  - E. Shuryak

    Rev. Mod. Phys. 65 (1993) 1

- correlation function in N

$$\Pi_N(p) = -i \int d^4x e^{ipx} \left\langle T(h(x)h^\dagger(0)) \right\rangle_N$$

$$\sim \frac{T_{hN}}{(p^2 - m_0^2)^2}$$ from LSZ reduction formula

T_{hN} : T-matrix for hN scattering

- expand finite ρ correlation function in ρ

$$\Pi_\rho(p) = \Pi_0(p) + \rho \Pi_N(p)$$

$$\Pi_\rho(p) \sim \frac{1}{p^2 - m_\rho^2} \sim \frac{1}{p^2 - m_0^2} + \frac{\delta m^2}{(p^2 - m_0^2)^2}$$

$$\to \delta m = -2\pi \frac{m + M_N}{m M_N} a_{hN} \rho$$ well-known result

Deeply bound pionic atom experiment

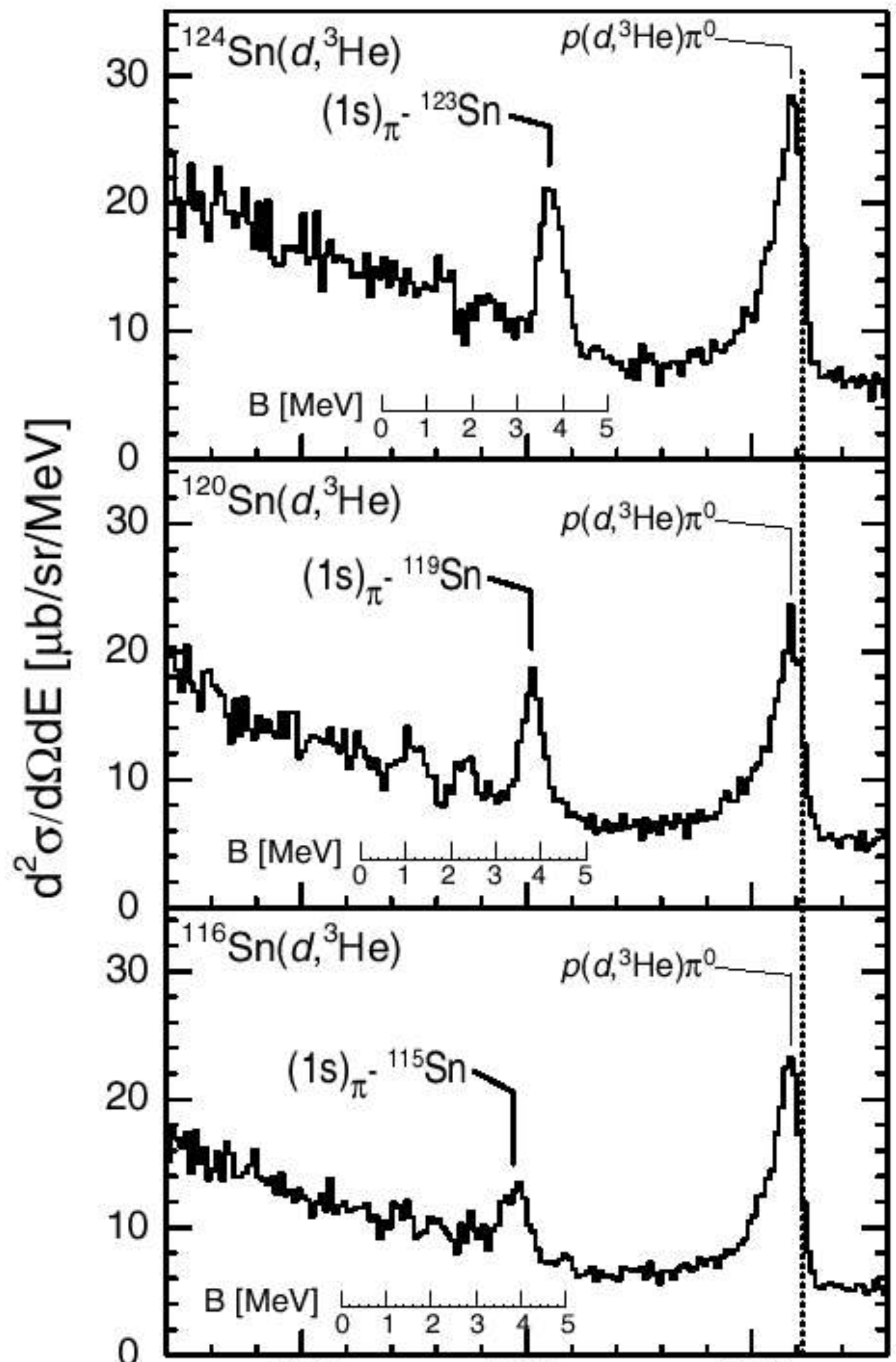
- K.Suzuki et al. PRL92(04)072302

optical potential b_1

$$f_\pi^*(\rho)^2/f_\pi^2 \sim 0.64 \quad at \quad \rho=\rho_0$$

GOR relation

$$\langle \bar{q}q \rangle_{\rho_0} / \langle \bar{q}q \rangle_0 \sim 0.67$$



Summary

- The relation between the properties of in-medium hadrons and the properties of medium is discussed.
- Both theoretical and experiments results for modifications of the vector meson masses are reviewed.
- $O(\rho)$ term of δm in medium is shown to be identified as the hadron-nucleon scattering.
- More theoretical and experimental ideas are needed.