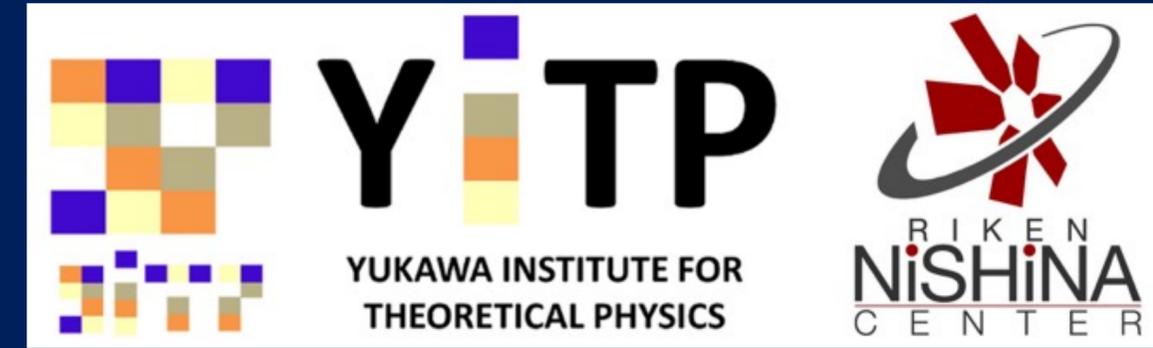


31st July to 2nd August 2016



# Welcome to MIN16

- Meson in Nucleus 2016 -

Ryugo S. Hayano  
The University of Tokyo



The Nobel Prize in Physics 1949

Hideki Yukawa

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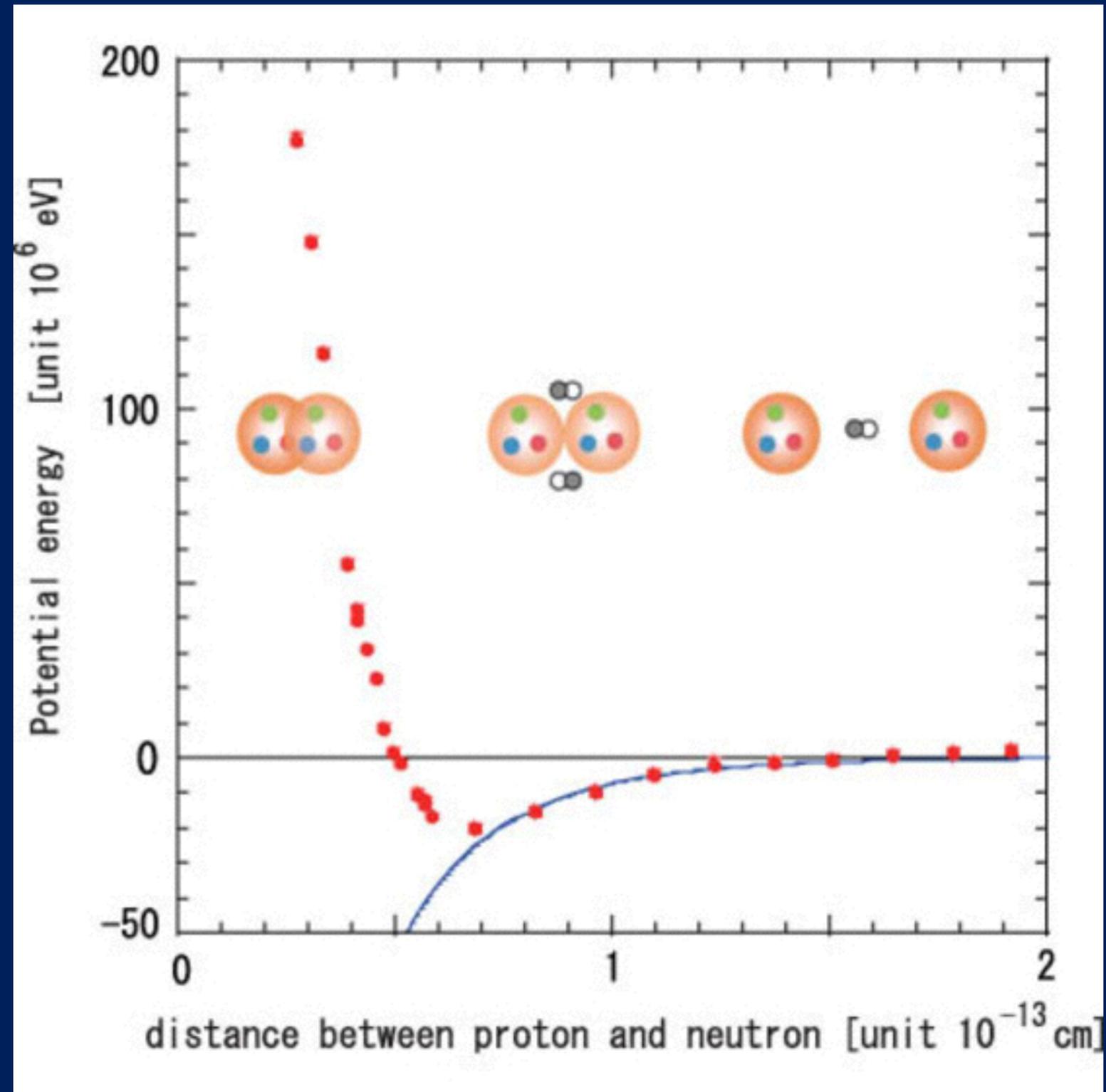
# The Nobel Prize in Physics 1949



Hideki Yukawa

Prize share: 1/1

The Nobel Prize in Physics 1949 was awarded to Hideki Yukawa *"for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces"*.

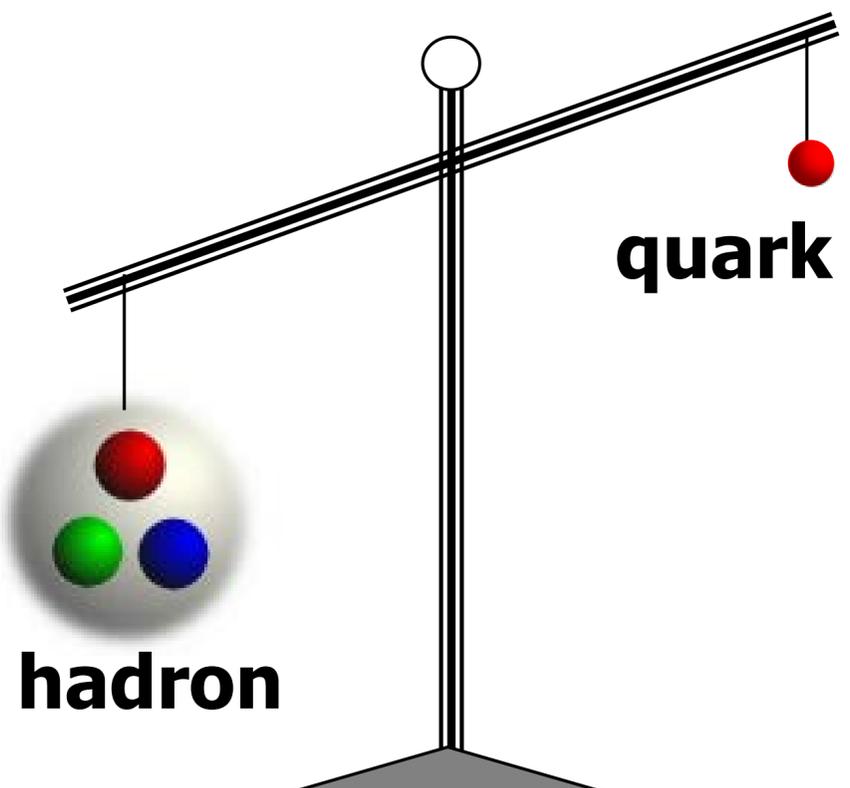
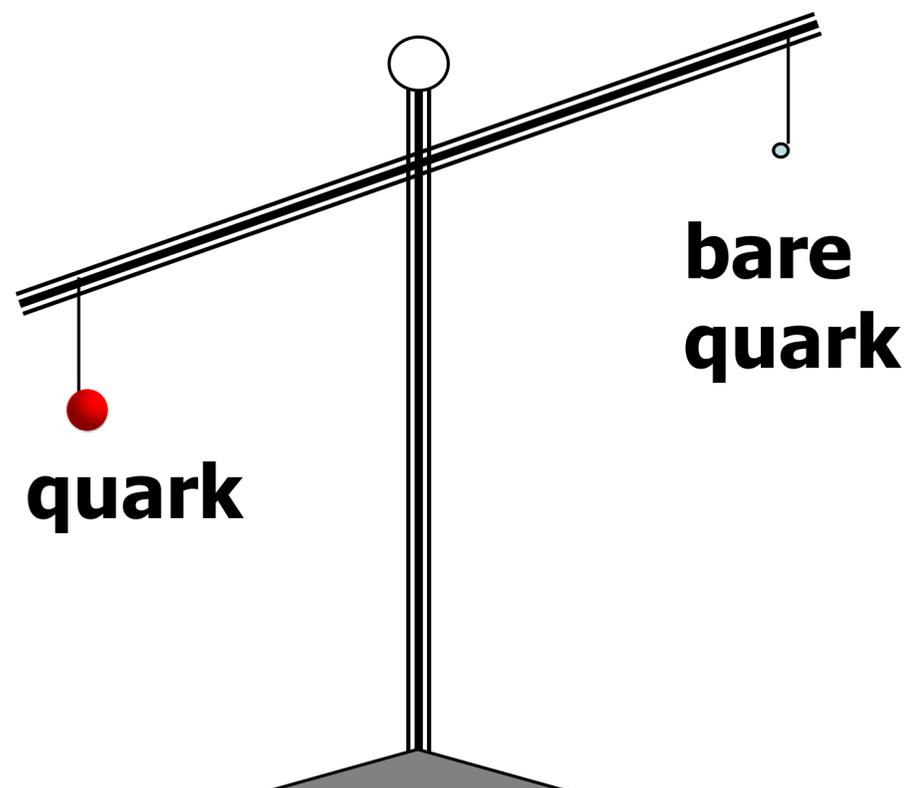


Ishii N., Aoki, S. & Hatsuda, T. Nuclear force from lattice QCD. PRL 99, 022001 (2007)

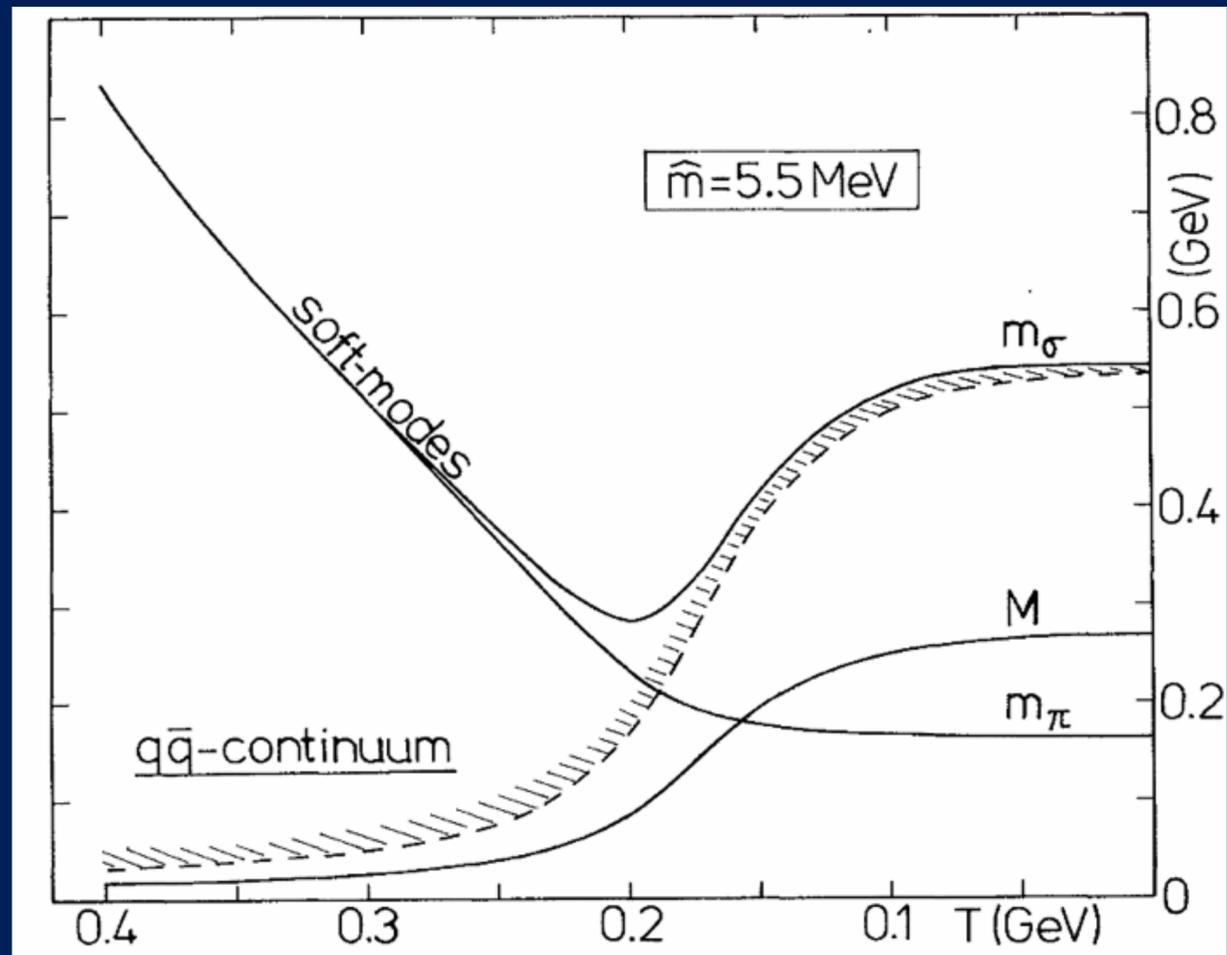
# MIN2016 Topics

- Fundamental theories of QCD
- Mesonic atoms
- Mesonic nuclei
- Hadron formation in nuclear medium
- Hadron-hadron interaction
- New facilities

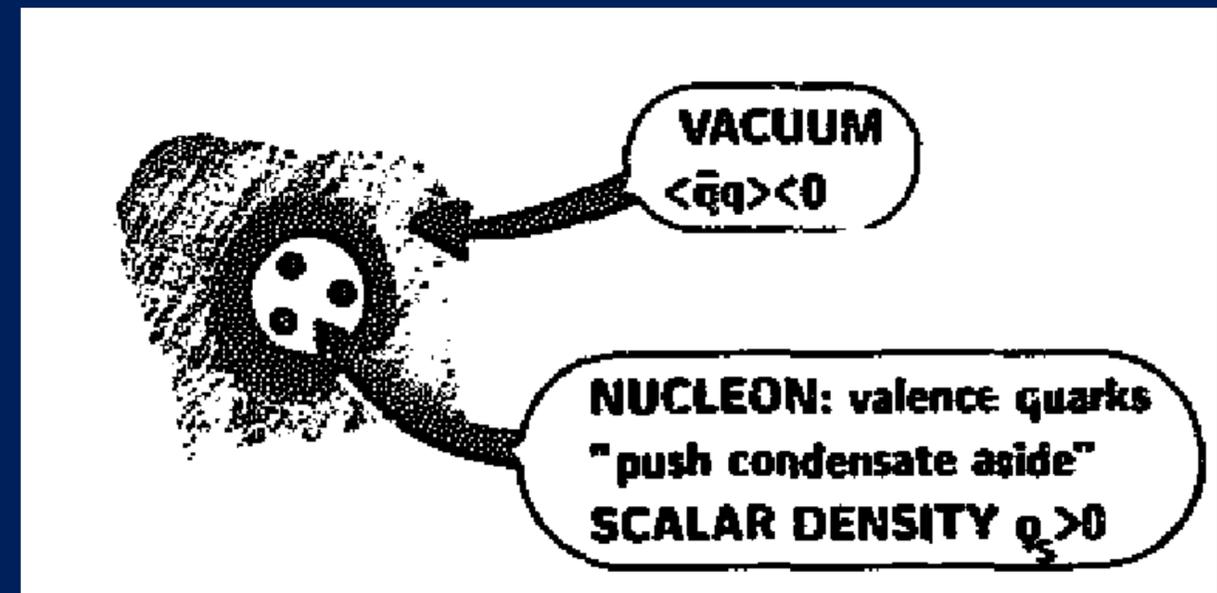
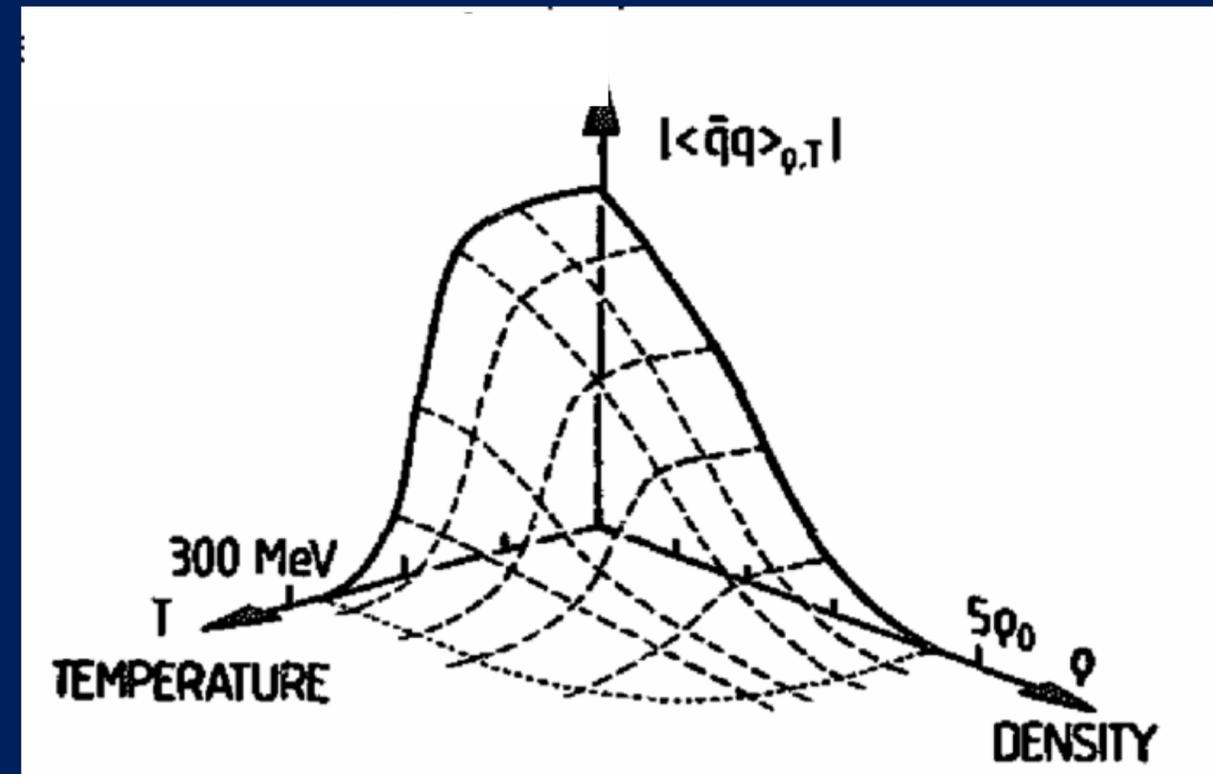
All related to a fundamental question:

 <p><b>hadron</b></p> <p><b>quark</b></p>	 <p><b>quark</b></p> <p><b>bare quark</b></p>
$m_q \simeq 3 \text{ MeV}$ $m_N \simeq 1000 \text{ MeV}$	$m_0 = 0$ $m_q \simeq 3 \text{ MeV}$
<p><b>“Chiral” condensate</b> Nambu (1960)</p>	<p><b>“Higgs” condensate</b> Englert-Brout, Higgs (1964)</p>

we have been asking  
a similar set of questions  
over and over  
for quite some time



T Hatsuda; T Kunihiro, PRL 55 (1985) 158



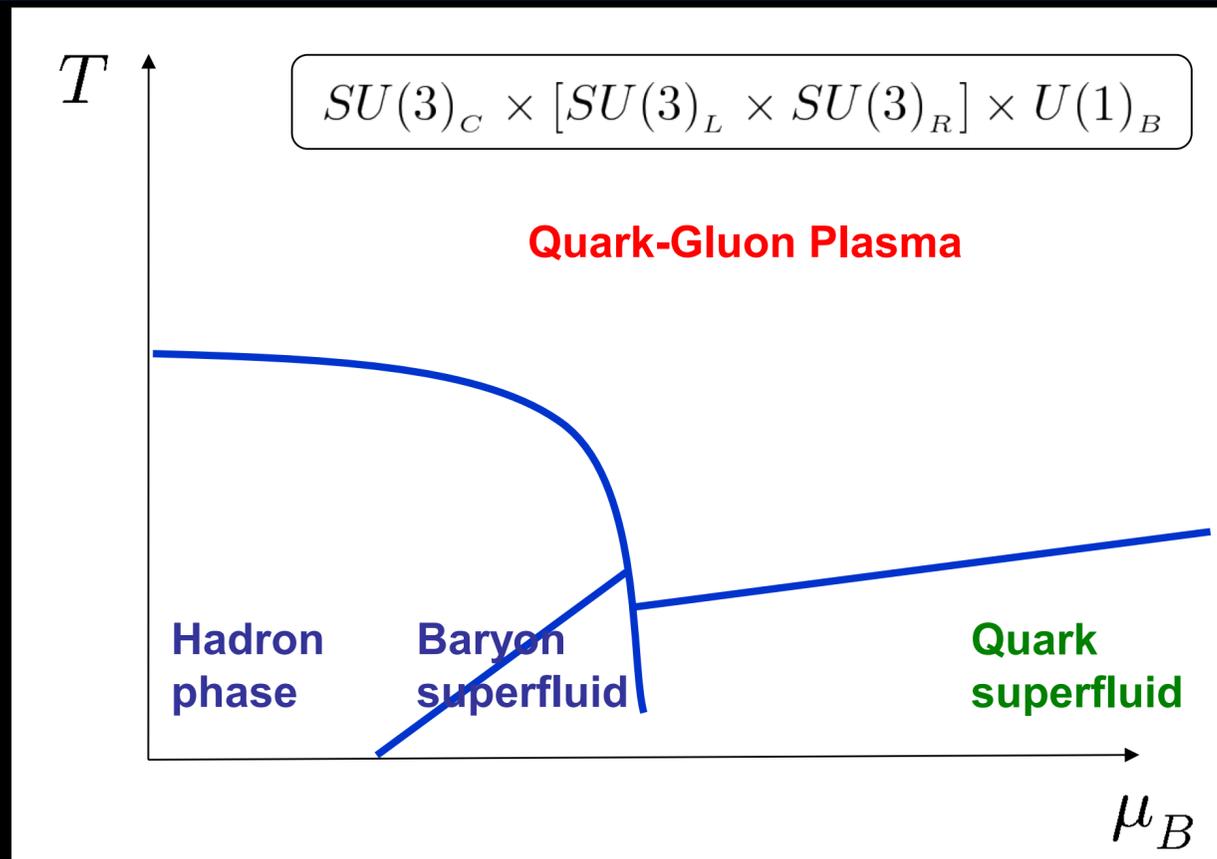
W Weise, Nucl.Phys.A553 (1993) 59c

Where are we now?

# Experimentally-accessible regions are rather limited

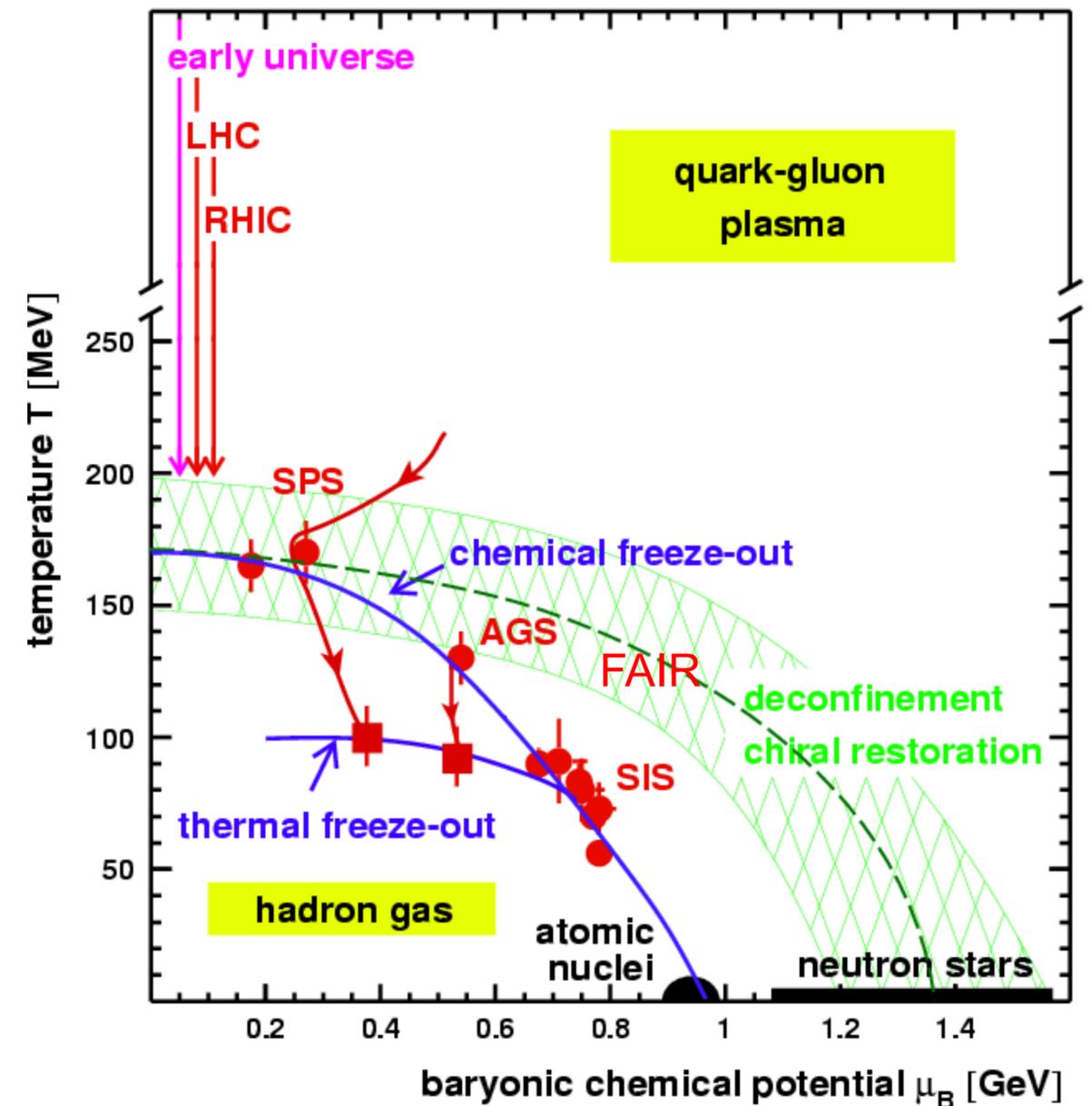
Lattice is powerful, but is limited to  $\mu_B \sim 0$

## Hadron-Quark Continuity in dense QCD ( $N_c=3, N_f=3$ )



$\langle \bar{q}_L q_R \rangle \neq 0$	$\langle BB \rangle \neq 0$	$\langle (q_L q_L)(\bar{q}_R \bar{q}_R) \rangle \neq 0$
$SU(3)_C \times SU(3)_{L+R} \times U(1)_B$	$SU(3)_C \times SU(3)_{L+R}$	$SU(3)_C \times SU(3)_{L+R}$

Chiral symmetry is always broken at finite density



NuPECC report

A good starting point for

MIN2016

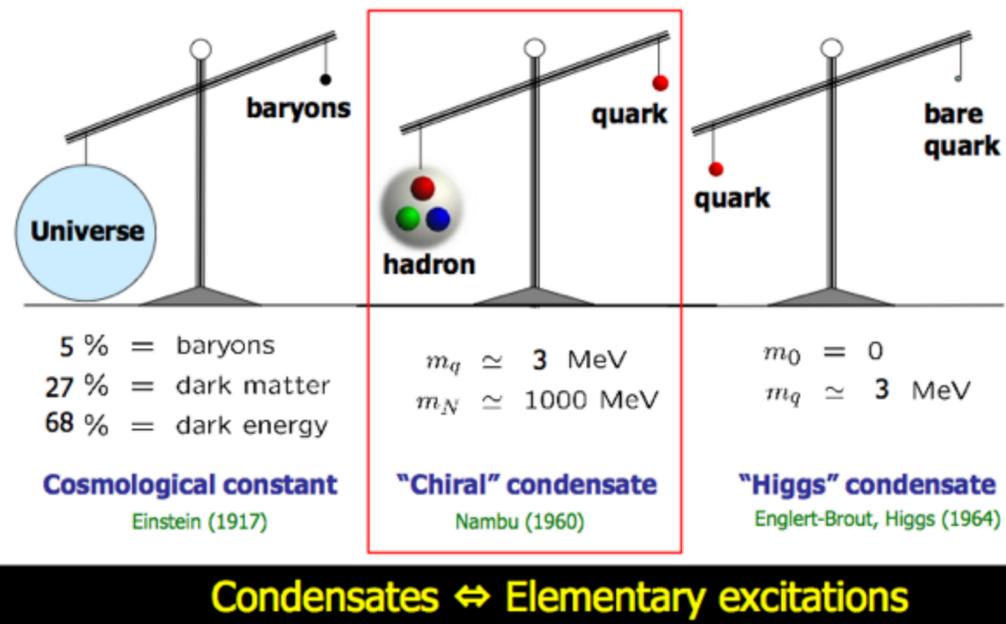
would be to recall

what were discussed at

HIN2013 (held @ YITP)

# In-medium Hadrons -- A Theoretical Overview --

T. Hatsuda (RIKEN)

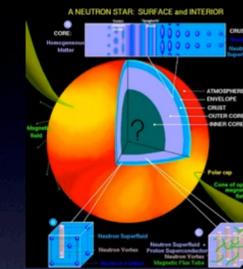


T Hatsuda, In-medium Hadrons - A Theoretical Overview -

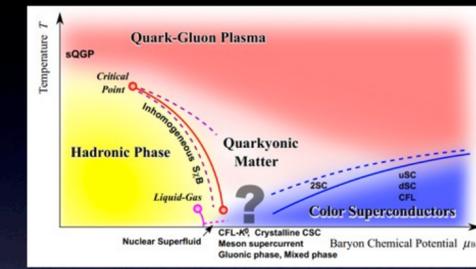
# Introduction: NS observations

1/16

## NS observations



## QCD phase diagram



Fukushima, Hatsuda (2010)

### Mass

$(1.97 \pm 0.04) M_{\odot}$  Demorest et al. (2010)  
 $(2.01 \pm 0.04) M_{\odot}$  Antoniadis et al. (2013)

### Cooling

Cooling of CAS-A Heinke et al. (2010)

### EOS

Relation to stiffness of EOS and the existence of the exotic components ?

### Superfluid / Superconducting phase

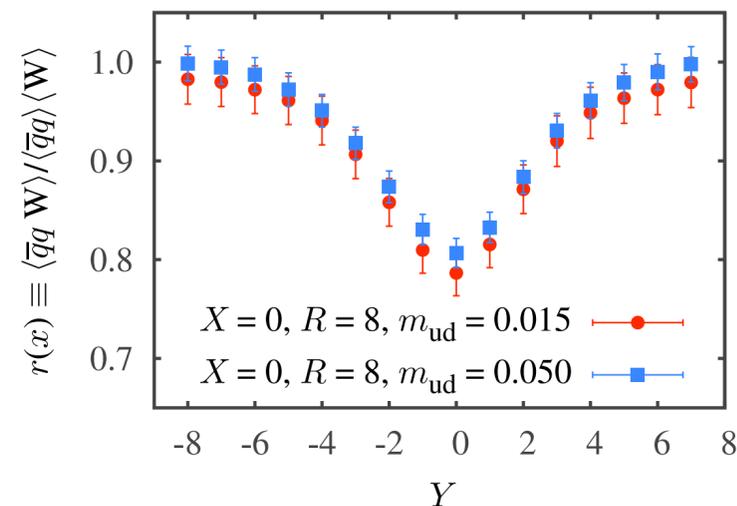
Relation to nucleon and quark superfluidity inside NSs ?

K Masuda, Hadron-Quark Crossover and Neutron Star Observations

## Quark Mass Dependence of Chiral Condensate Reduction

$16^3 \times 48$  lattice with low-lying 120 eigenmodes

- $m_{ud} = 0.015$  :  $m_{\pi} \sim 0.30$  GeV
- $m_{ud} = 0.050$  :  $m_{\pi} \sim 0.53$  GeV

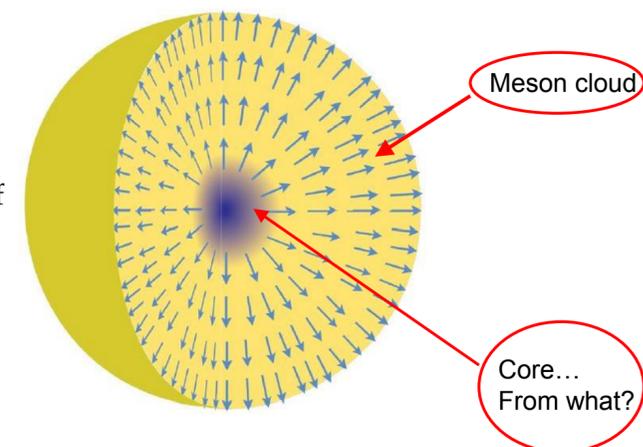


T Iritani, Partial restoration of chiral symmetry in the flux tube from lattice QCD

## Topological models and soliton

### Structure

- What is a nucleon and, in particular, its core?
- At large number of colors it still has the mesonic content

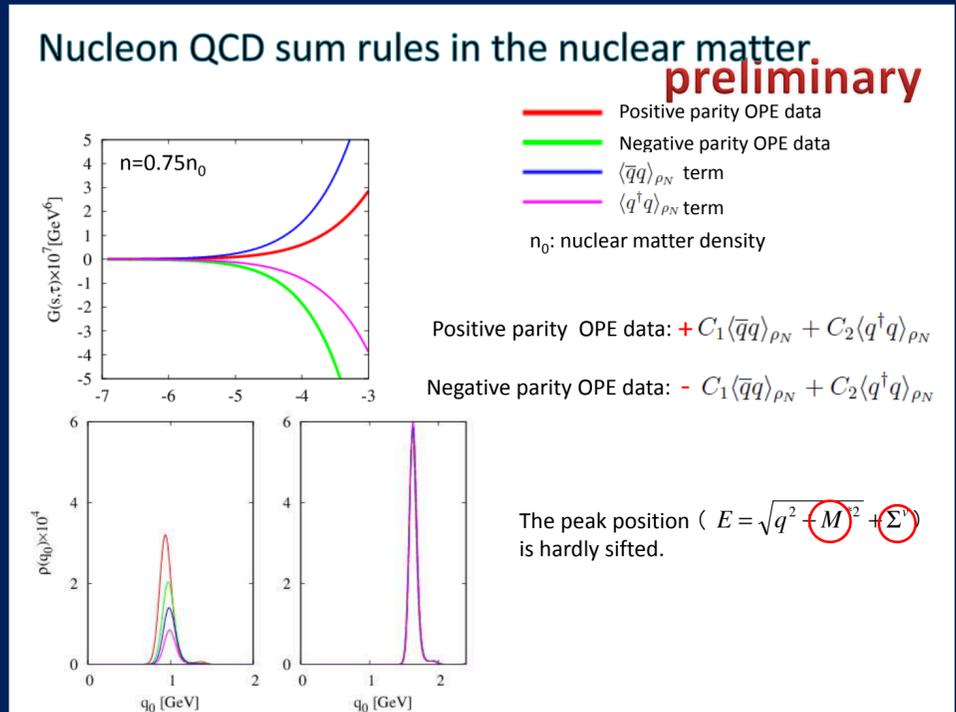


October 31, 2013

Talk @ YITP, Kyoto 2013

3

U Yakhshiev, Structure changes of the nucleon in nuclear matter



K Ohtani, Nucleon spectral function in nuclear medium from QCD sum rules

### Medium effect of $\Lambda$ hyperon

#### Modification of magnetic moment in medium

$B(M1) = (2J_{up} + 1)^{-1} |\langle \Psi_{low} || \mu || \Psi_{up} \rangle|^2$   
 $= (2J_{up} + 1)^{-1} |\langle \Psi_{\Lambda 1} \Psi_c || \mu || \Psi_{\Lambda 1} \Psi_c \rangle|^2$   
 $\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c) J_\Lambda$   
 $= \frac{3}{8\pi} \frac{2J_{low} + 1}{2J_c + 1} (g_\Lambda - g_c)^2 [\mu_N^2]$   
 $\Gamma = BR / \tau = \frac{16\pi}{9} E_\gamma^3 B(M1)$  (If Br M1 = 100%,  $\tau = 1/\Gamma_{M1}$ )

$g_c$ : g-factor of core nuclei  
 $g_\Lambda$ : g-factor of  $\Lambda$

$E_\gamma$  and lifetime ( $\tau$ ) can be measured by  $\gamma$ -ray spectroscopy using Ge detectors of a few keV resolution

### Main motivation of J-PARC E13

M Ukai, Study of the  $\Lambda$  g-factor in hypernuclei via the  $\gamma$ -ray spectroscopy at J-PARC

It's Halloween, today. My talk is:

## In-medium Tomozawa-Weinberg Relation with nuclear correlation effects

Ryoichi Seki  
California State University, Northridge

Hadrons in Nucleus, YITP 10/3/2013

R Seki, In-medium Tomozawa-Weinberg Relation with nuclear correlation effects

## $\gamma N \rightarrow \pi^0 \pi^\pm N$ cross section

- Acceptance correction using Geant4 based Monte-Carlo simulation with obtained detector efficiency.
- Those plots with higher energy above 800 MeV are newly obtained.
- Our data covers 2<sup>nd</sup> and 3<sup>rd</sup> resonance region.

Total cross section (ub) vs  $E_\gamma$  (MeV/c<sup>2</sup>)  
 Legend:  $\circ$  DAPHNE(1995),  $\triangle$  Mainz(2001),  $\square$  Mainz(2003)  
 Curves:  $\gamma p \rightarrow \pi^0 \pi^+ n$ ,  $\gamma p \rightarrow \pi^0 \pi^+ n$ ,  $\gamma n \rightarrow \pi^0 \pi^- p$

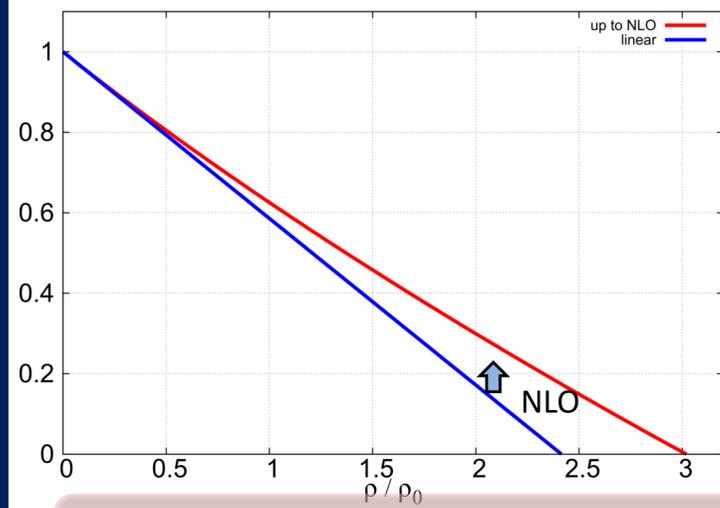
A. Braghieri et al., Phys. Lett. B 363 (1995) 46  
 W. Langgartner et al., Phys. Rev. Lett. 87 (2001) 052001  
 J. Ahrens et al., Phys. Lett. B 551 (2003) 49

S Matsumoto,  $\pi^0 \pi^\pm$  photoproduction on the deuteron at ELPH

## Density dependence of pion decay const.

$$\frac{f_\pi^{*2}}{f_\pi^2} = 1 - \frac{\rho}{f_\pi^2} \left[ \frac{\sigma_{\pi N}}{m_\pi^2} + \left(1 + \frac{m_\pi}{m_N}\right) \frac{4\pi f_\pi^2 a^+}{m_\pi^2} \right] + \frac{g_A^2 k_F^4}{3\pi^4 f^4} F\left(\frac{k_F}{2m_\pi}\right).$$

In symmetric nuclear matter



—  $O(\rho)$   
— up to  $O(\rho^{4/3})$

•Input

$$\sigma_{\pi N} = 45 \text{ MeV} \quad g_A = 1.27$$

$$f = 92.4 \text{ MeV}$$

S-wave isoscalar  $\pi N$  sca. len.

$$a^+ = 0.76(31) \cdot 10^{-2} m_\pi^{-1}$$

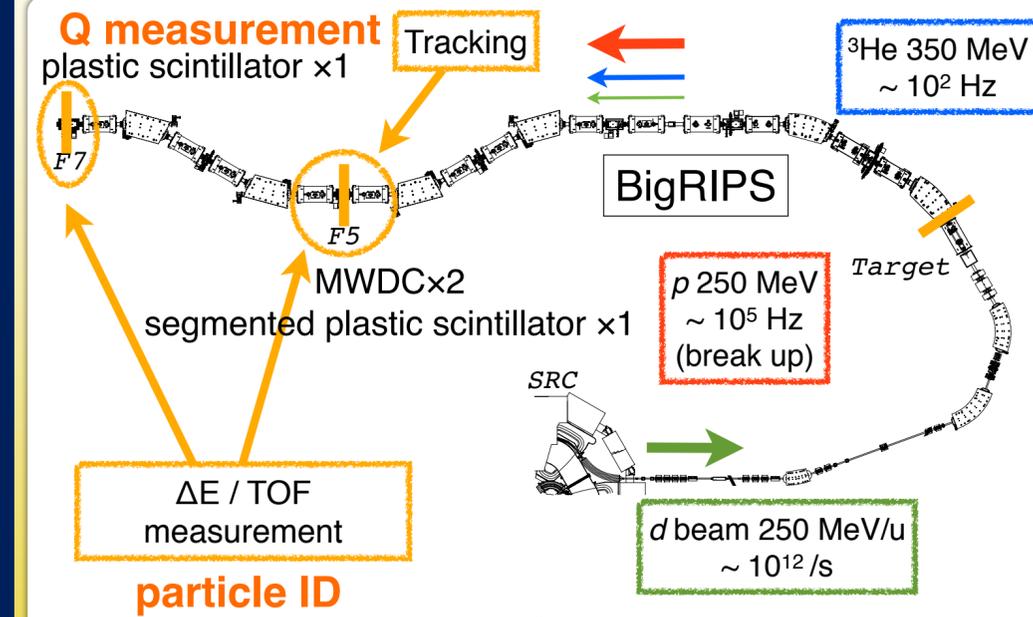
V. Baru et al, PLB (2011)

- NLO contribution is small around normal nuclear density.
- Within NLO, linear density approximation is good up to  $\rho_0$ .

S Goda, Partial Restoration of Chiral Symmetry and In-medium Pion Properties

YITP workshop on Hadron in Nucleus, 31st Oct. 2013 in Kyoto University

## Experimental setup



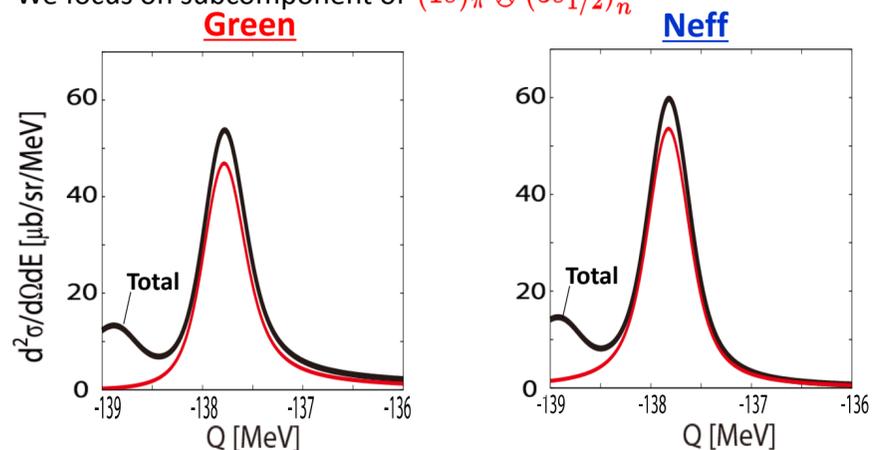
18

T Nishi, Systematic study of deeply-bound pionic atom and future perspectives

## Numerical results: Green vs. Neff

We focus on subcomponent of  $(1s)_\pi \otimes (3s_{1/2})_n^{-1}$

Energy resolution  $\Delta E = 300 \text{ keV}$



Different behavior of peak structure (Green: Asymmetric, Neff: Symmetric)

→ Precise theoretical spectrum is important to deduce pion properties in nuclei from future high resolution experiment

N Ikeno, Formation spectra of deeply bound pionic atoms in the  $(d, ^3\text{He})$  reactions

## In-medium $\bar{K}$ & $\eta$ mesons

Mesic Nuclei, JU Krakow, Sept. 2013  
Hadrons in Nuclei, YITP Kyoto, Oct. 2013

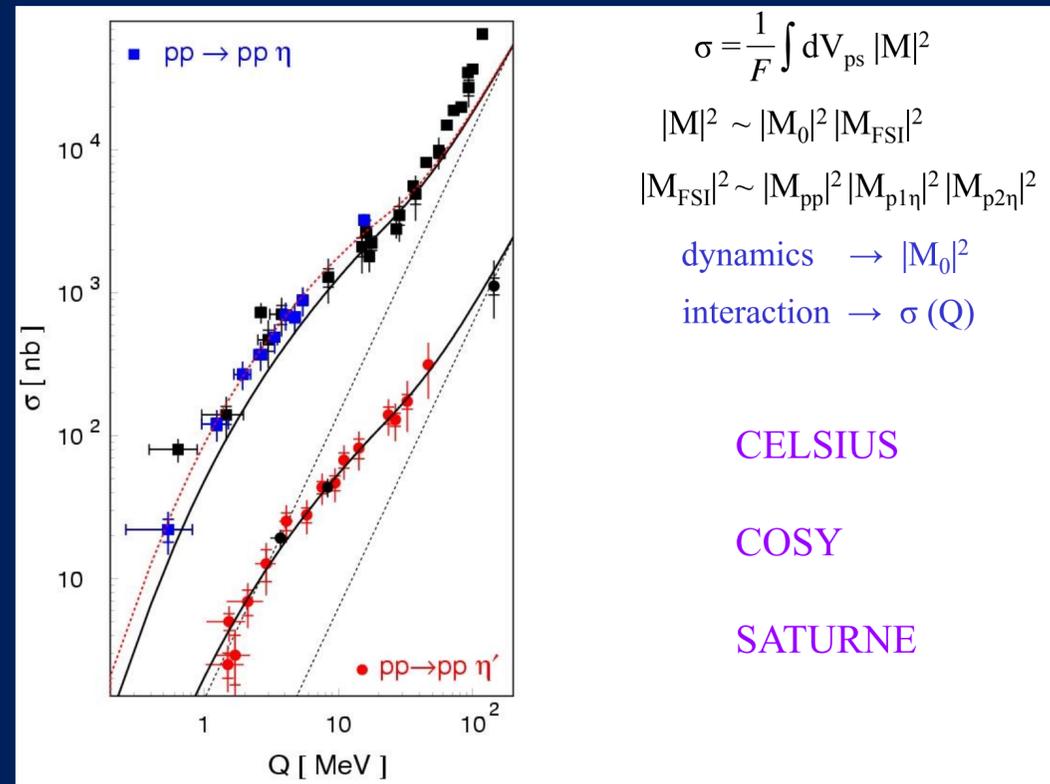
Avraham Gal

Racah Institute of Physics, Hebrew University, Jerusalem

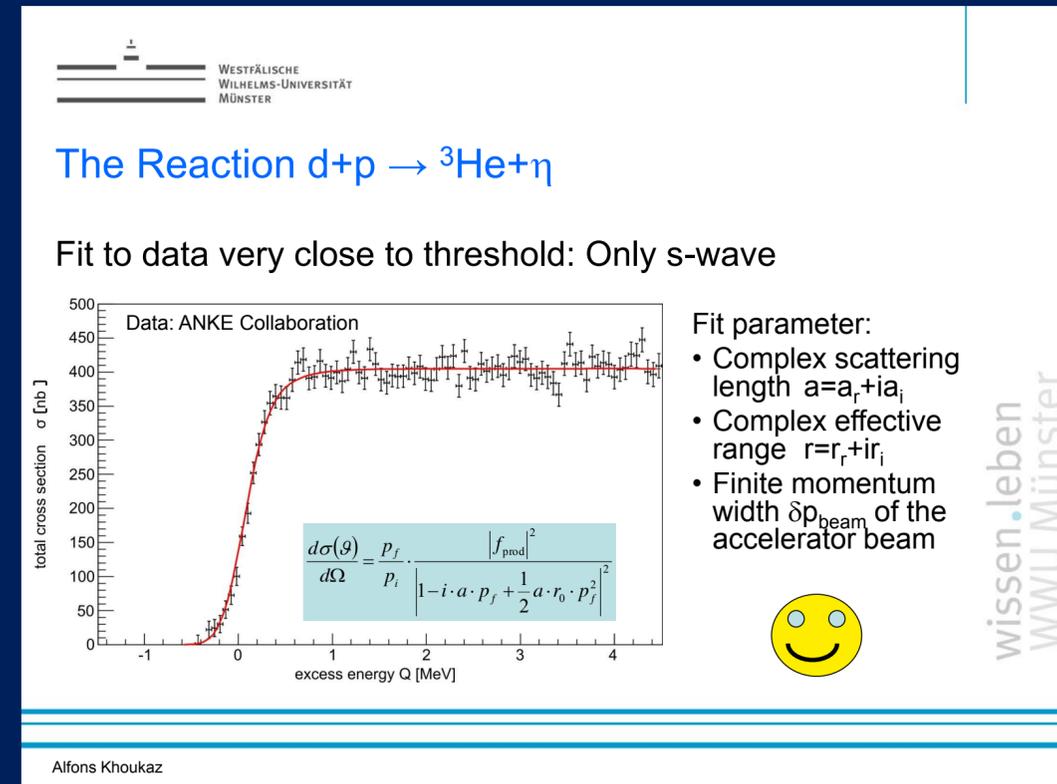
- $\bar{K}N - \pi Y$  chiral dynamics and its consequences
- $\bar{K}$  nuclear few-body systems
- $\bar{K}$ -nucleus potentials from  $K^-$  atoms  
A.Gal in HYP2012 Proc., NPA 914 (2013) 270
- Quest for  $\eta$  nuclear quasibound states  
E.Friedman, A.Gal, J.Mareš, PLB 725 (2013) 334

1

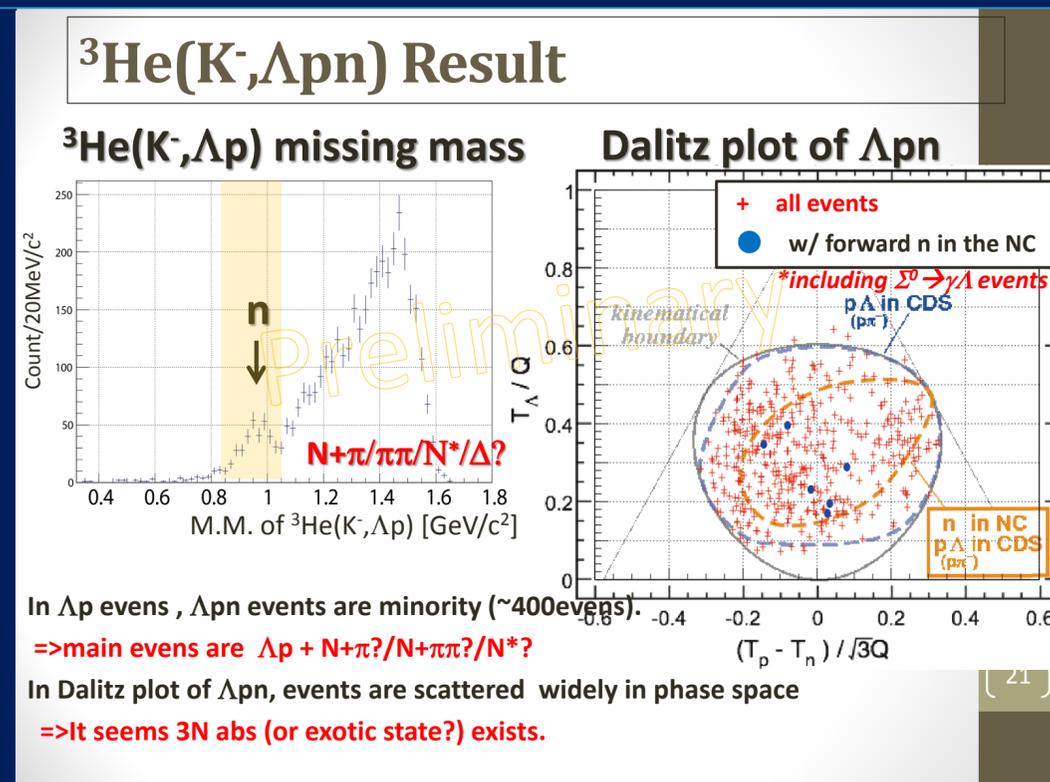
A Gal, In-medium  $K^{\text{bar}}$  &  $\eta$  mesons



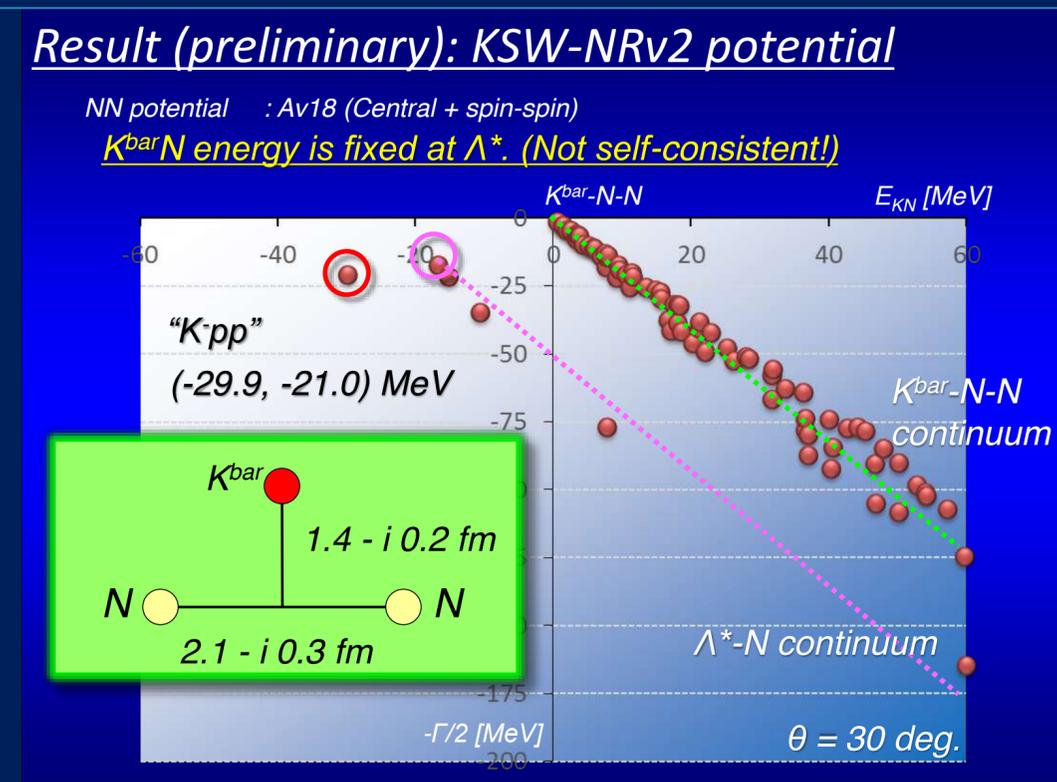
P Moskal: Search for the eta-mesic helium in the deuteron-deuteron fusion reaction



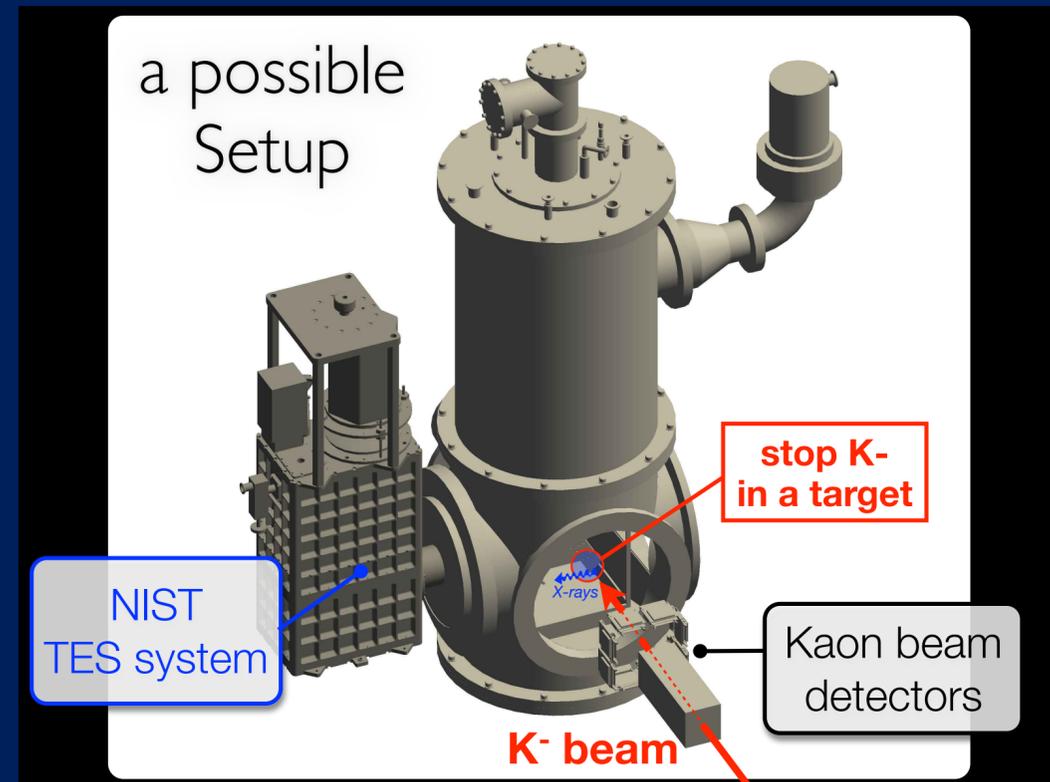
A Khoukaz, Investigation of the  ${}^3\text{He}-\eta$  system in deuteron-proton collisions at COSY-ANKE



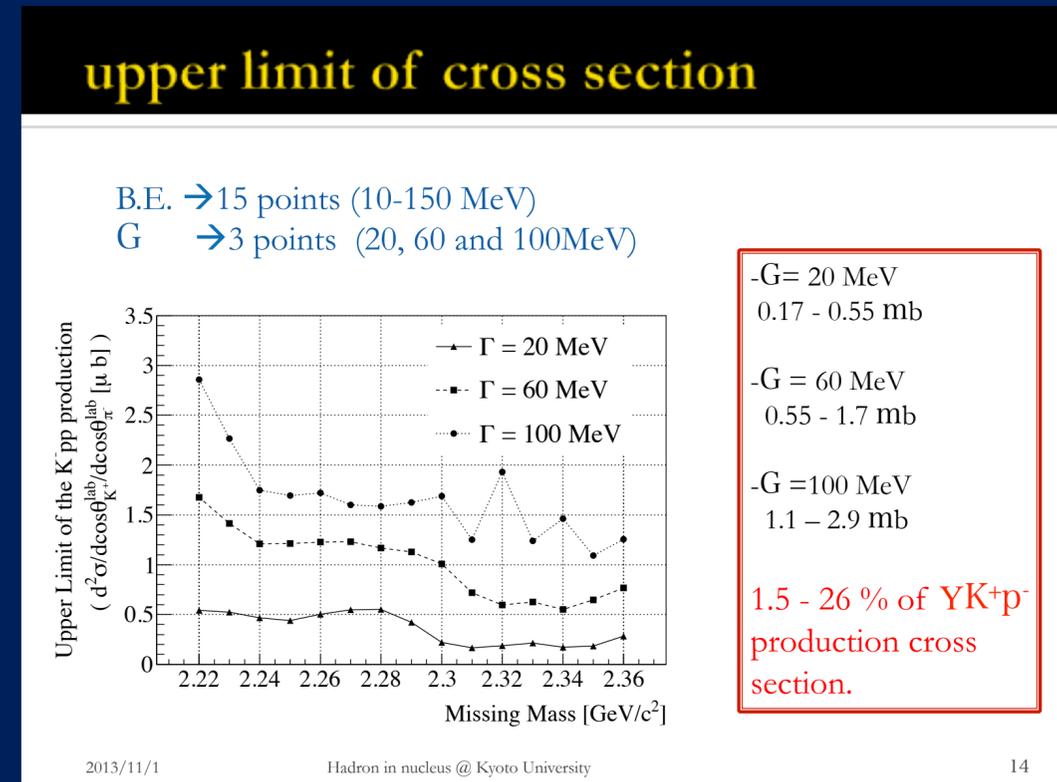
Y Sada, Analysis status of the J-PARC E15 experiment



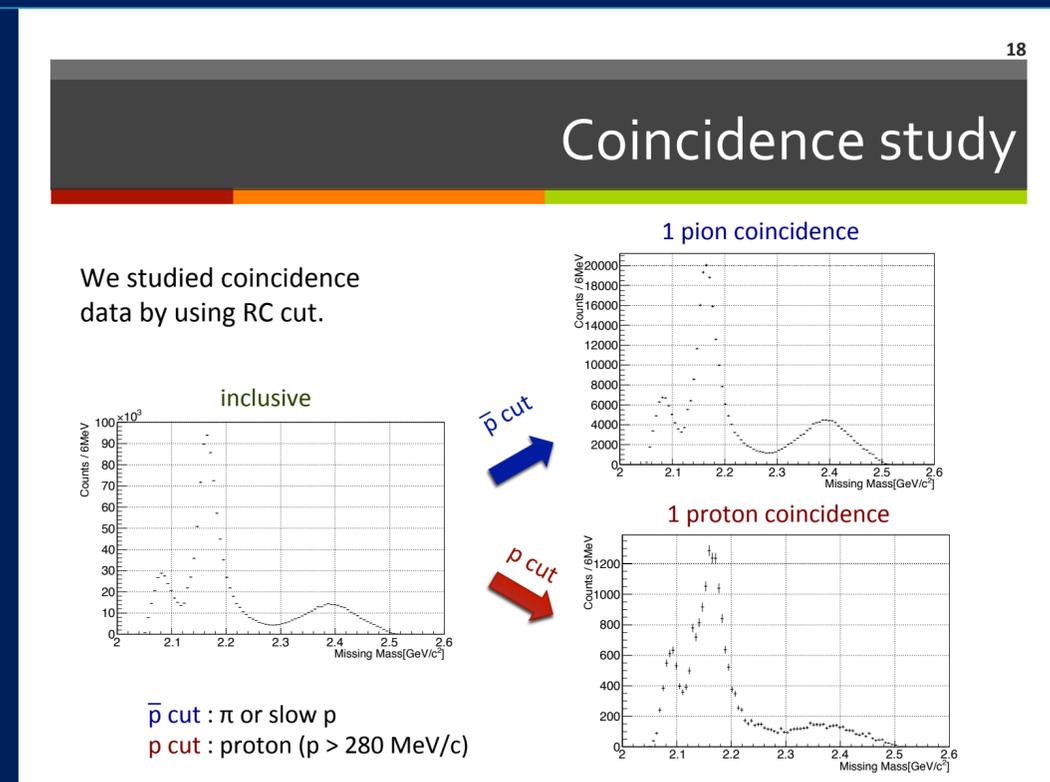
A Doté, Study of  $K^{\text{bar}}pp$  with an effective  $K^{\text{bar}}N$  potential on coupled-channel complex scaling model



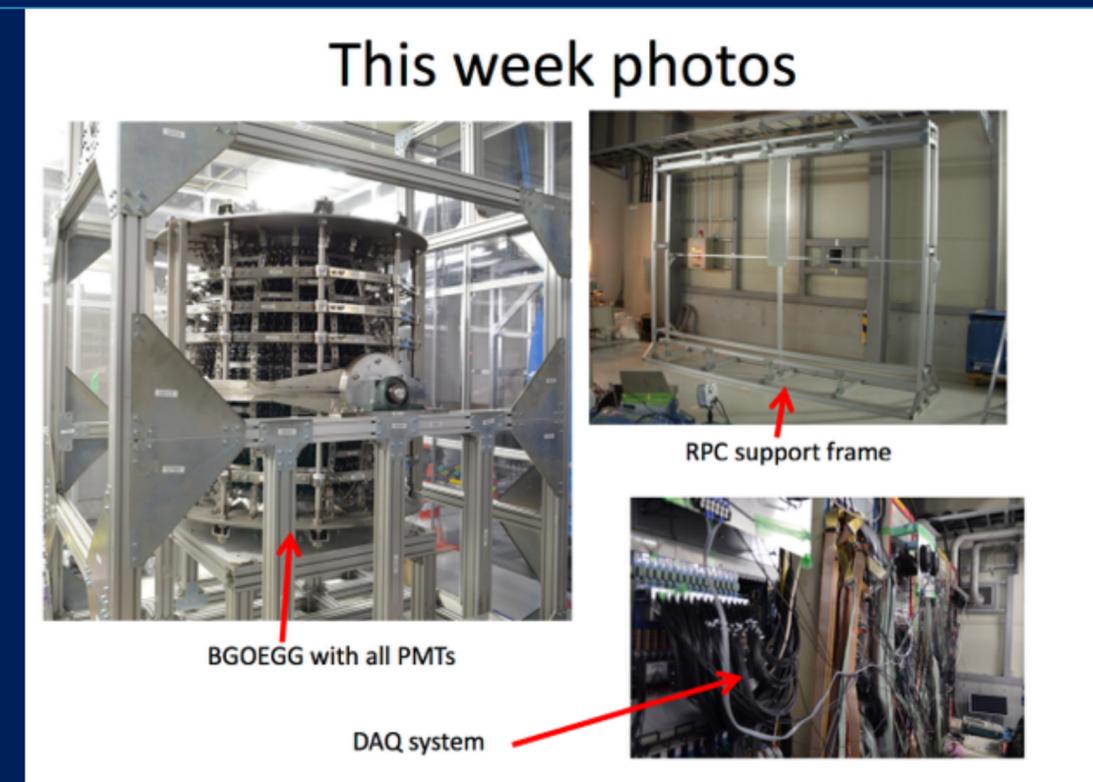
S Okada, High-resolution hadronic-atom x-ray spectroscopy with transition-edge-sensor micro-calorimeters



AO Tokiyasu, Search for the  $K^-pp$  bound state via photon-induced reaction



H Ekawa,  $K^-pp$  search experiment in the  $d(p, K^+)$  reaction at J-PARC



M Miyabe, Recent status and plans at SPring-8 LEPS2 facility

### Witten-Veneziano formula at finite $T$ (Kwon, Morita, Wolf, Lee: PRD 12)

Large  $N_c$  counting

$$P(k) = i \int dx e^{ikx} \langle G\tilde{G}(x), G\tilde{G}(0) \rangle_m$$



$N_c^2$        $N_c^2$        $N_c$

At finite temperature, only gluonic effect is important

$$P(k) = \underbrace{\bullet \frac{\langle 0 | G\tilde{G} | \text{glueball} \rangle^2}{k^2 m_n^2}}_{\text{Glue } N_c^2} + \underbrace{\bullet \frac{\langle 0 | G\tilde{G} | \text{meson} \rangle^2}{k^2 m_n^2}}_{\text{Quark } N_c} + \text{Scattering Term}$$

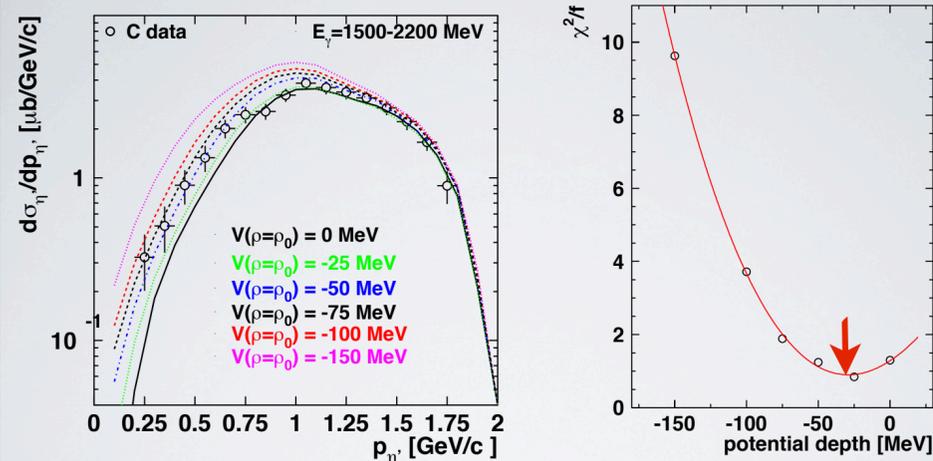
Glue  $N_c^2$       Quark  $N_c$       Quark  $N_c^2$   
?

$$P(k=0) = P_0(0) \frac{\langle 0 | G\tilde{G} | \text{meson} \rangle^2}{m^2} + \text{scattering?}$$

12

SH Lee, Another look at  $\eta'$  in medium

### estimation of the of $\eta'$ -nucleus potential depth from the $\eta'$ momentum distribution

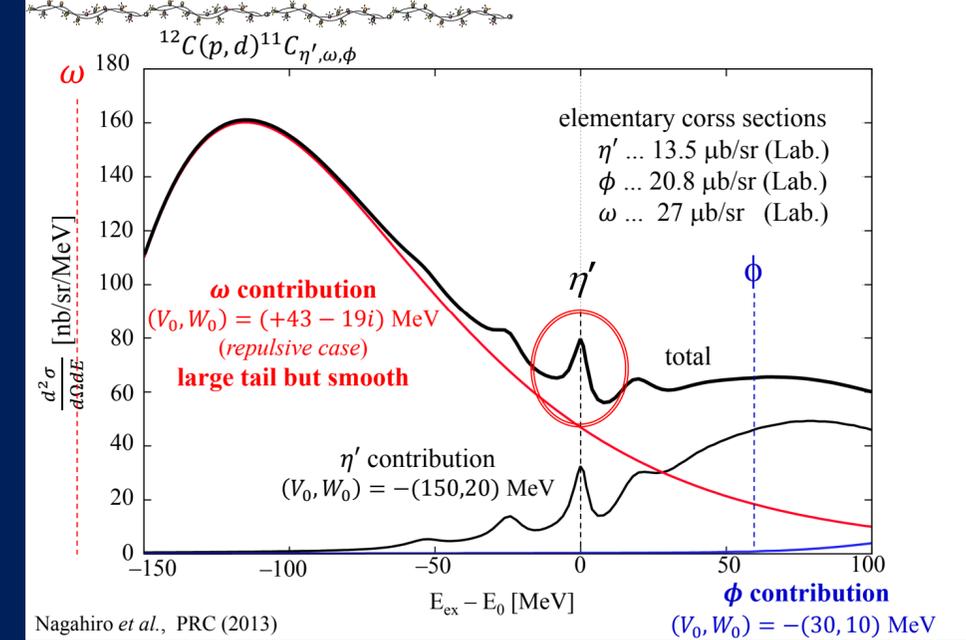


consistent with predictions by:  
S. Bass and A.W.Thomas, Acta Phys. Pol. B 41 (2010) 2239  
H. Nagahiro et al., PLB 709 (2012) 87.  
 $W(\rho=\rho_0) = -10 \pm 2.5$  MeV, M. Nanova et al., PLB 710 (2012) 600.  
 $|V| \gg |W| ! \Rightarrow$  search for  $\eta'$  mesic states promising

11

M Nanova,  $\eta'$ -nucleus optical potential and the search for  $\eta'$  mesic states in photo nuclear reactions

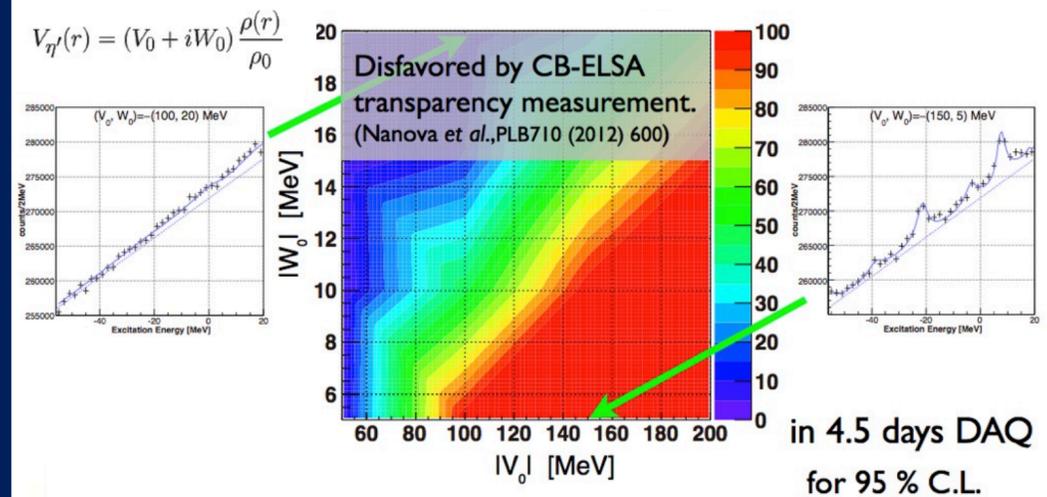
### Contributions from $\omega$ and $\phi$ mesons



Nagahiro et al., PRC (2013)

H Nagahiro,  $\eta'$ (958)-nucleus bound states and their formations by missing mass spectroscopies

### Structure-finding sensitivity

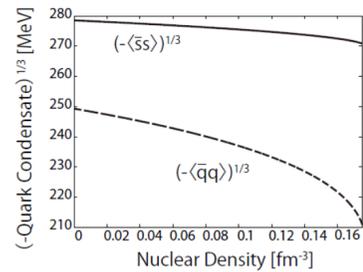


in 4.5 days DAQ  
for 95 % C.L.

25

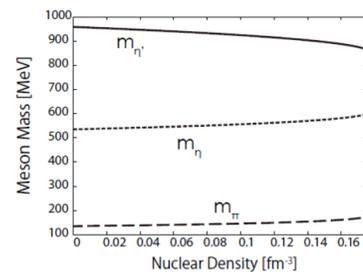
YK Tanaka, Plan of  $\eta'$  mesic nucleus spectroscopy with (p,d) reaction at GSI and FAIR

## In-medium $\eta'$ mass with linear sigma model



35% reduction of  $\langle q^{bar}q \rangle$  @  $\rho = \rho_0$  is input.

$\pi$  atom: K. Suzuki, et al., PRL92,72302(2004).  
 $\pi$ -nucleus elastic scattering: E. Friedman, et al., PRL93,122302(2004).



About 80MeV reduction of  $\eta'$  mass @  $\rho = \rho_0$   
 About 50MeV enhancement of  $\eta$  mass @  $\rho = \rho_0$

➔ Mass difference between  $\eta$  and  $\eta'$  reduces about 130MeV.  
 (The partial restoration of chiral symmetry leads to the degeneracy of  $\eta$  and  $\eta'$ )

From the  $\eta'$  mass reduction, the  $\eta'$ N 2body interaction is expected to be attractive.

15

S Sakai, In-medium  $\eta'$  mass and  $\eta'$ N interaction in vacuum based on a chiral effective theory

## Quarks & Gluons

Chiral symmetry

$m \rightarrow 0$

Heavy quark symmetry

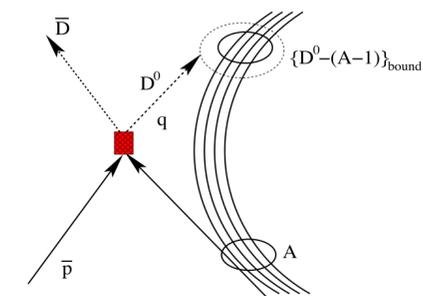
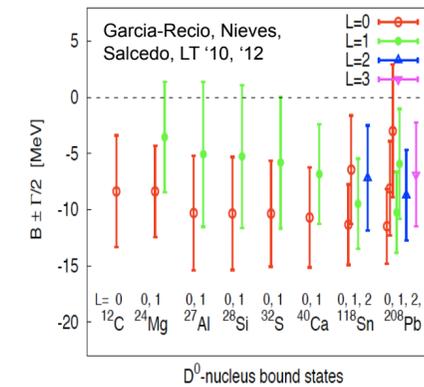
$m \rightarrow \infty$

S Yasui, Charm hadrons in nuclear medium

## D mesic nuclei

Initially predicted in  $^{208}\text{Pb}$  within QMC model Tsushima et al. '99

Within the self-consistent coupled-channel approach that incorporates HQSS



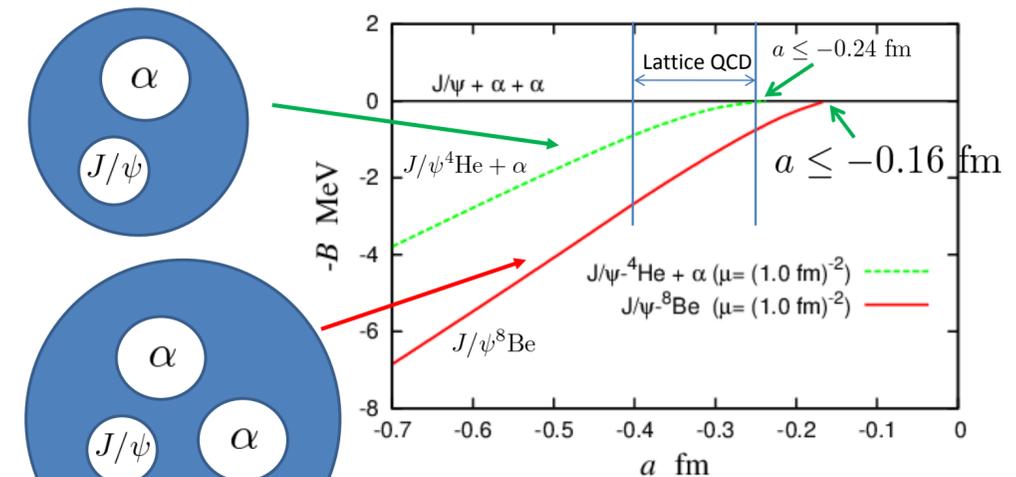
PANDA @FAIR?

Working on analyzing hidden charm states, eg.  $J/\psi$ ,  $\psi(3770)$ ,... in matter (at finite temperature) for PANDA/CBM @ FAIR. Signal for deconfinement?

L Tolós, Strange and Charmed Mesons in Nuclear Matter and Nuclei

## $J/\psi - \alpha - \alpha$ 3-body system

Relations between scattering length  $a$  of  $J/\psi - N$  and binding energy  $B$  of  $J/\psi - ^4\text{He}$  and  $J/\psi - \alpha - \alpha$



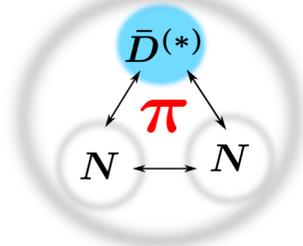
$\alpha$ - $\alpha$  interaction : folding Hasegawa-Nagata potential with OCM  
 A. Hasegawa, S. Nagata, Prog. Theor. Phys. 45, 1786 (1971)

$^8\text{Be}$  is a resonance state, 0.09 MeV above the  $\alpha + \alpha$  break-up threshold with narrow width  $\Gamma = 6$  eV.

A Yokota, Possible existence of charmonium-nucleus bound states

## Outline

- 1 Introduction
  - Heavy Quark Spin Symmetry
  - $\pi$  exchange potential between heavy meson and nucleon.
- 2 Results of  $\bar{D}^{(*)}NN$  and  $B^{(*)}NN$
- 3 Results of  $P^{(*)}NN$  in  $m_Q \rightarrow \infty$
- 4 Summary



3-body system

11/1, 2013

Y. Yamaguchi(RCNP)

Exotic dibaryons with a heavy antiquark @ YITP

1

Y Yamaguchi, Exotic dibaryons with a heavy antiquark

## Theory

### Decay Constants

- The decay constants are evaluated using the relation[15],

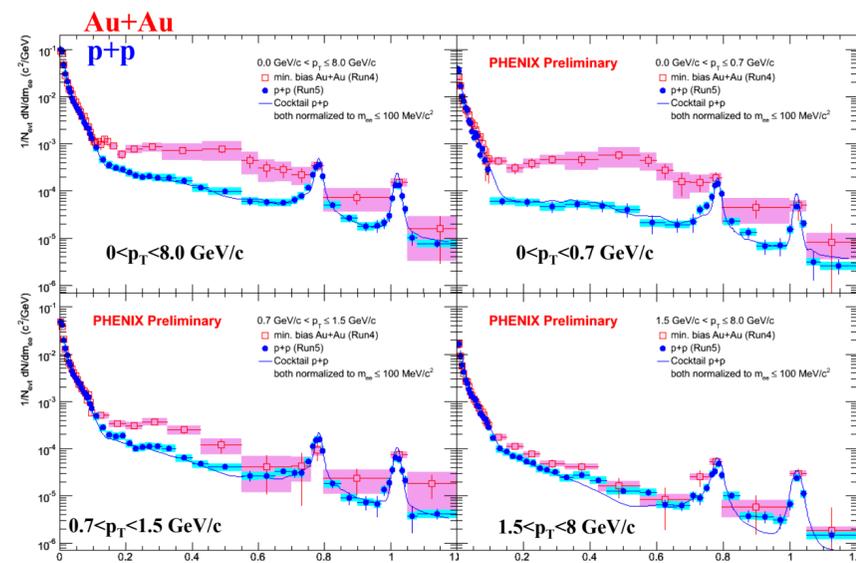
$$f_{P/V}^2 = \frac{12 |\psi_{P/V}(0)|^2}{M_{P/V}} \bar{C}^2(\alpha_S) \quad (8)$$

Where  $\bar{C}(\alpha_S)$  is the QCD correction factor given by[16]

$$\bar{C}^2(\alpha_S) = 1 - \frac{\alpha_S}{\pi} \left[ 2 - \frac{m_Q - m_{\bar{Q}}}{m_Q + m_{\bar{Q}}} \ln \frac{m_Q}{m_{\bar{Q}}} \right] \quad (9)$$

AK Rai, Quarkonia and their decay properties

## Low Mass Enhancement in Low- $p_T$



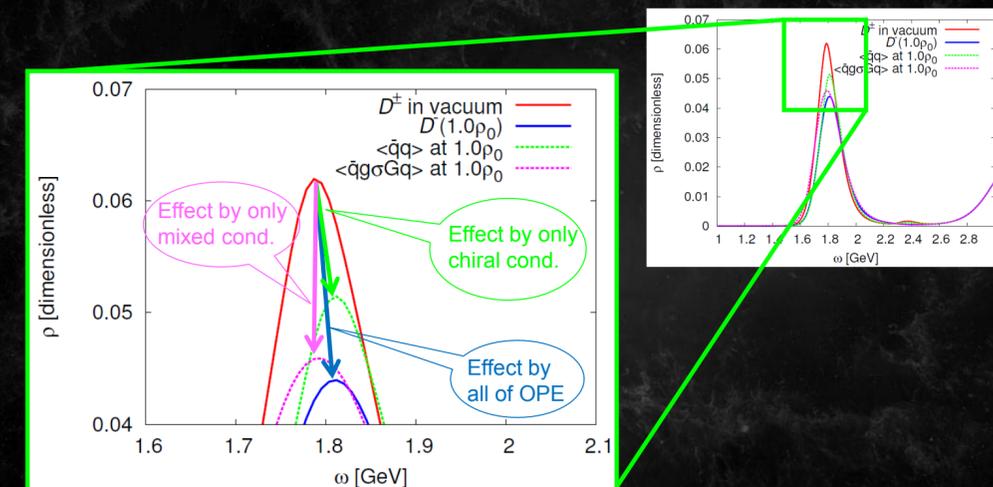
Low mass excess in Au-Au concentrated at low  $p_T$

2013/11/02

YITP workshop on "Hadron in Nucleus" at YITP, Kyoto University, Oct. 31 - Nov. 2, 2013

H Hamagaki, Study of Hadron Properties in QCD Medium using the High-Energy Heavy-Ion Collisions

## Contribution of vacuum condensates



⇒ Most dominant contribution of mass shift to higher energy is D-dependence of chiral condensate

2/Nov/2013

Hadron in Nucleus at YITP

18

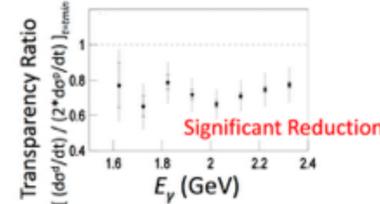
K Suzuki, Medium modification of heavy meson spectra from QCD sum rules

## Related(?) Topic

Result & Discussion

$\phi$  photo-production from the **deuteron target**  
W.C. Chang et al. Phys.Lett., B684:6-10, 2010.

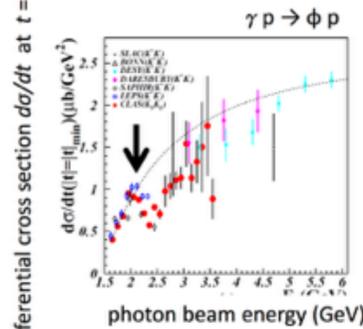
Transparency ratio at forward angles:



the nuclear medium effect is minimal since the deuteron is composed of a loosely bound proton and neutron

some effect other than nuclear density at forward angles?

$\phi$  photo-production on **proton target**  
arXiv:1308.1363 [hep-ex]



21

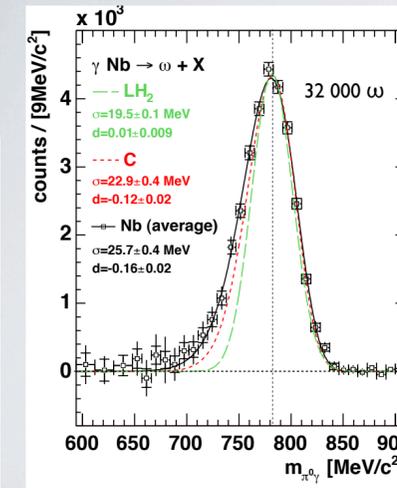
**CB@MAMI**  
 $E_\gamma = 0.9 - 1.3$  GeV

$\omega \rightarrow \pi^0 \gamma$  lineshape analysis

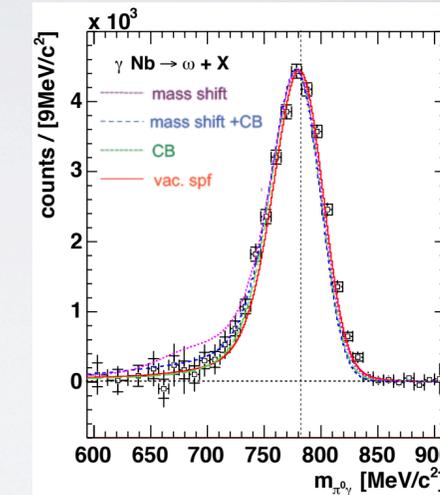
M.Thiel et al., Eur. Phys. J. A49 (2013) 132

comparison with reference measurement on LH<sub>2</sub>

comparison with GiBUU calculations for different in-medium scenarios (J.Weil, U. Mosel)



no significant structure in spectral function; signal on Nb,C slightly broader than on LH<sub>2</sub>



data consistent with collisional broadening; mass shift scenario less likely

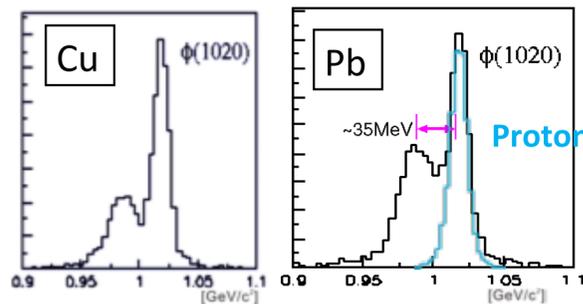
20

T Sawada, Backward  $\phi$  photo-production from C and Cu targets at  $E_\gamma = 1.5 - 2.4$  GeV

V Metag, In-medium properties of hadrons studied with CBELSA/TAPS and HADES

## The double-peak structure of $f$ expected at J-PARC E16

- Mass modification of  $f$ 
  - The mass shift is 3.4% at E325 if the excess is interpreted as the shift of the peak position
- Double-peak structure on invariant mass distribution
  - Observe  $f$  decayed inside and outside the nucleus
  - In addition to the mass dist. obtained w/ proton target (CH<sub>2</sub>), we can **understand the mass distribution of  $f$**



E16 expectation (bg<0.5 & s=5MeV)

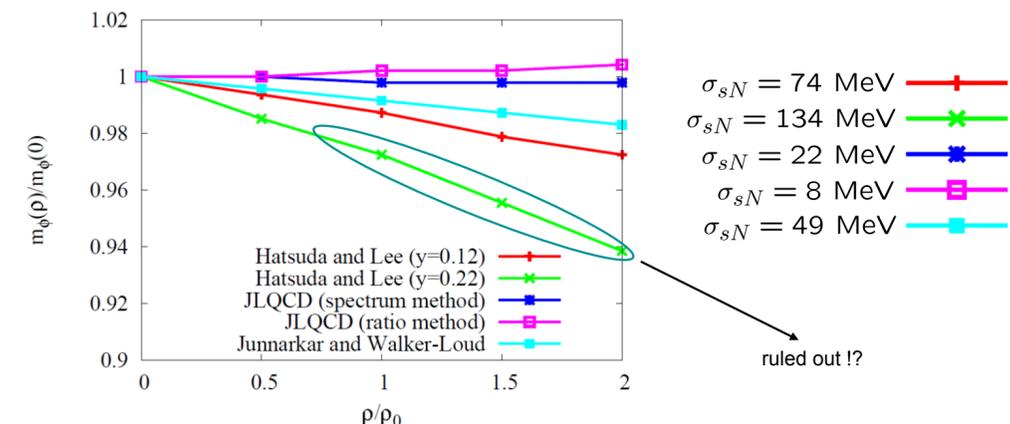
Nov. 2, 2013

YITP workshop on Hadron in Nucleus @ Kyoto

13

Y Aramaki, Experimental approach to the mass modification in nucleus by the J-PARC E16 experiment

## $\phi$ meson at finite density



The  $\phi$  meson mass shift strongly depends on the strange sigma term.

P. Gubler, The phi meson at finite density from a QCD sum rules + MEM approach

$\pi, K, \eta, \eta'$

vector mesons

$N, \Lambda$

$K, p, p$

$c, b, \dots$

HEHI

neutron star

Theory - Experiment interaction  
essential in this field

However ...

# Theorist's dreams are...

## Wish list by an innocent theorist

- 1 Spectral difference between chiral partners  
 $\pi$ - $\sigma$ ,  $\rho$ - $a_1$ ,  $\omega$ - $f_1$ , etc

Determination of D=6 chiral condensates in the vacuum?  
Tau-decay in nuclei ?

- 2 Individual properties of NG and “Higgs” bosons  
 $\pi$ ,  $K$ ,  $\eta$  (NG),  $\sigma$  (Higgs),  $\eta'$  (anomaly)

$\sigma \rightarrow 2\gamma$ ,  $\eta \rightarrow 2\gamma$ ,  $\eta' \rightarrow 2\gamma$

Mesic nuclei  
Dipion

- 3 Individual properties of vector bosons  
 $\rho$ ,  $\omega$ ,  $K^*$  and  $\phi$

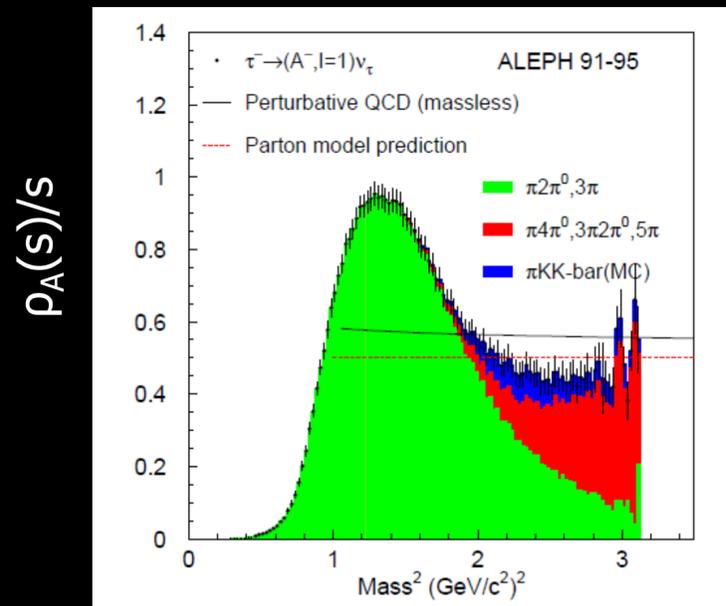
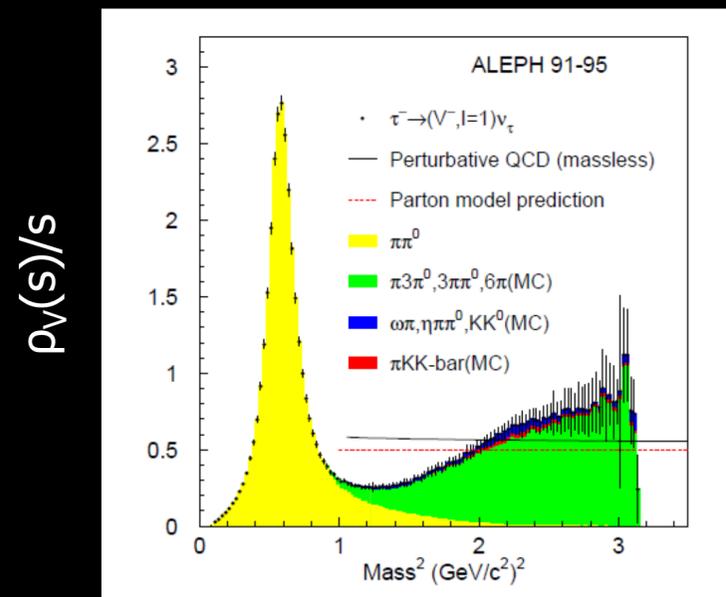
Precision/systematic studies  
(dispersion relation, different targets, ...)

Dileptons  
Hadronic decay

# Experimentalist's nightmare

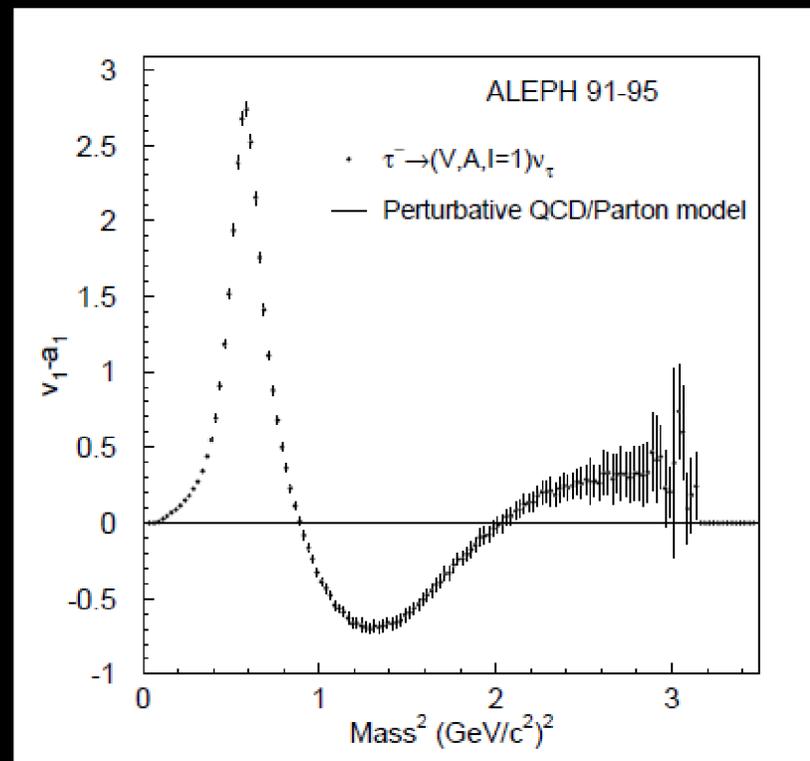
e.g., how to do this  $\downarrow$  in medium??

$\langle VV \rangle - \langle AA \rangle$  from  $\tau$ -decays at LEP-1



$[\rho_V(s) - \rho_A(s)] / s$

ALEPH Collaboration,  
Phys. Rep. 421 (2005) 191



hatsuda

MIN2016 -

New (young) people

New results

New ideas

Lively discussion