「第5回　J-PARCにおける高エネルギーハドロン物理」

J-PARCに活きる南部先生のアイデア

plan

1. Introdution
2. Stability of hadronic matter
3. Chiral symmetry in vacuum & in medium
4. No summary

references

○ Y. Nambu, "Broken Symmetry", Selected Papers of Y. Nambu, World Scientific (1995).

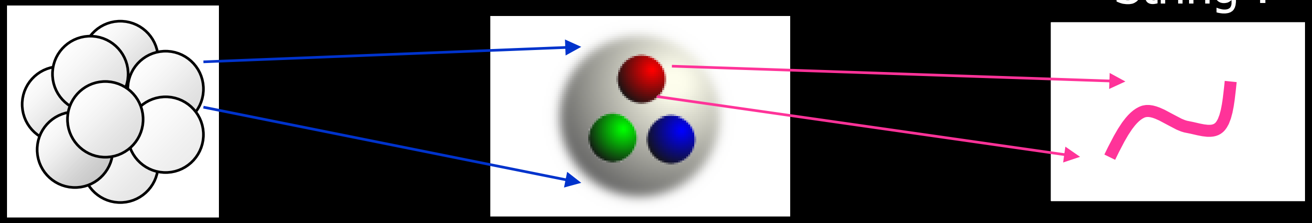
○ Y. Nambu, "Spontaneus symmetry breaking in particle physics: a case of cross fertilization", Nobel Lecture (Dec. 8, 2008) pp.1-25.

○ T. Hatsuda & T. Kunihiro, "QCD phenomenology based on a chiral effective lagrangian", Phys. Rep. Vol. 247 (1994) pp.221-367.

○ R. Hayano & T. Hatsuda, "Hadron properties in the nuclear medium", Rev. Mod. Phys. (2009) [arXiv:0812.1702 [nucl-ex]]

T. Hatsuda (Univ. of Tokyo) KEK, Jan. 8, 2009

Subatomic structure of matter



Nuclei

Hadron

String？

r ∼10 [fm]

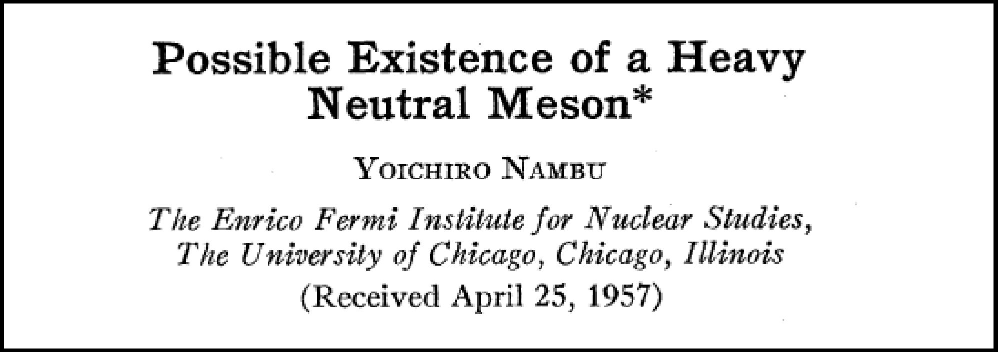
r ∼1 [fm]

r << 10^{-4} [fm]

Y. Nambu at INPC2007

1. Repulsive core in nuclear force:
   "Possible existence of a heavy neutral meson", *Phys. Rev.* 106 (1957) 1366.
2. Dynamical breaking of chiral symmetry (with G. Jona-Lasinio):
   "Dynamical model of elementary particles based on an analogy with superconductivity I, II", *Phys. Rev*. 122 (1961) 345, *ibid*. 124 (1961) 246.
3. Quantum chromodynamics:
   "A systematics of hadrons in subnuclear physics",
   in *Preludes in Theoretical Physics* (North-Holland, Amsterdam, 1966) .
4. String theory:
   "Duality and hadrodynamics",
   note prepared for the Copenhagen High Energy Symposium, A*ug. 1970.*

Repulsive core in nuclear force

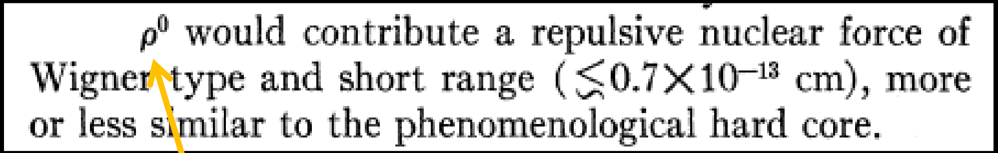


Possible Existence of a Heavy Neutral Meson*

YOICHIRO NAMBU

The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois

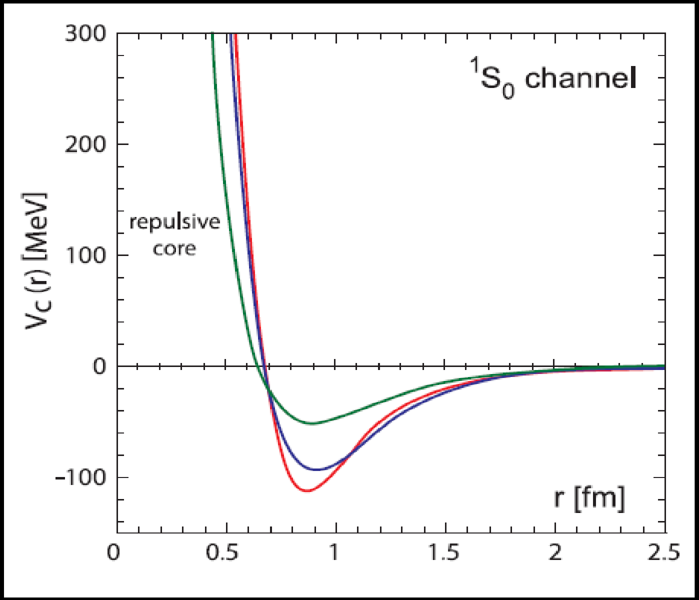
(Received April 25, 1957)



ρ^0 would contribute a repulsive nuclear force of Wigner type and short range ($\lesssim 0.7\times10^{-13}$ cm), more or less similar to the phenomenological hard core.

ω-meson

Phys. Rev. 106 (1957) 1366



after 50 years
powered by QCD

- NN,YN and YY interactions in lattice QCD
  (Aoki, Ishii, Nemura & Hatsuda, 2008)
- YN and YY interactions at J-PARC
- Structure of neutron stars

Origin of the fermion mass

Two revolutionary ideas proposed in 1961

1. massless fermion ⇒ massive fermion + massless composite boson

Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122 ('61) 345

2. massless boson ⇒ massive topological fermion + massless boson

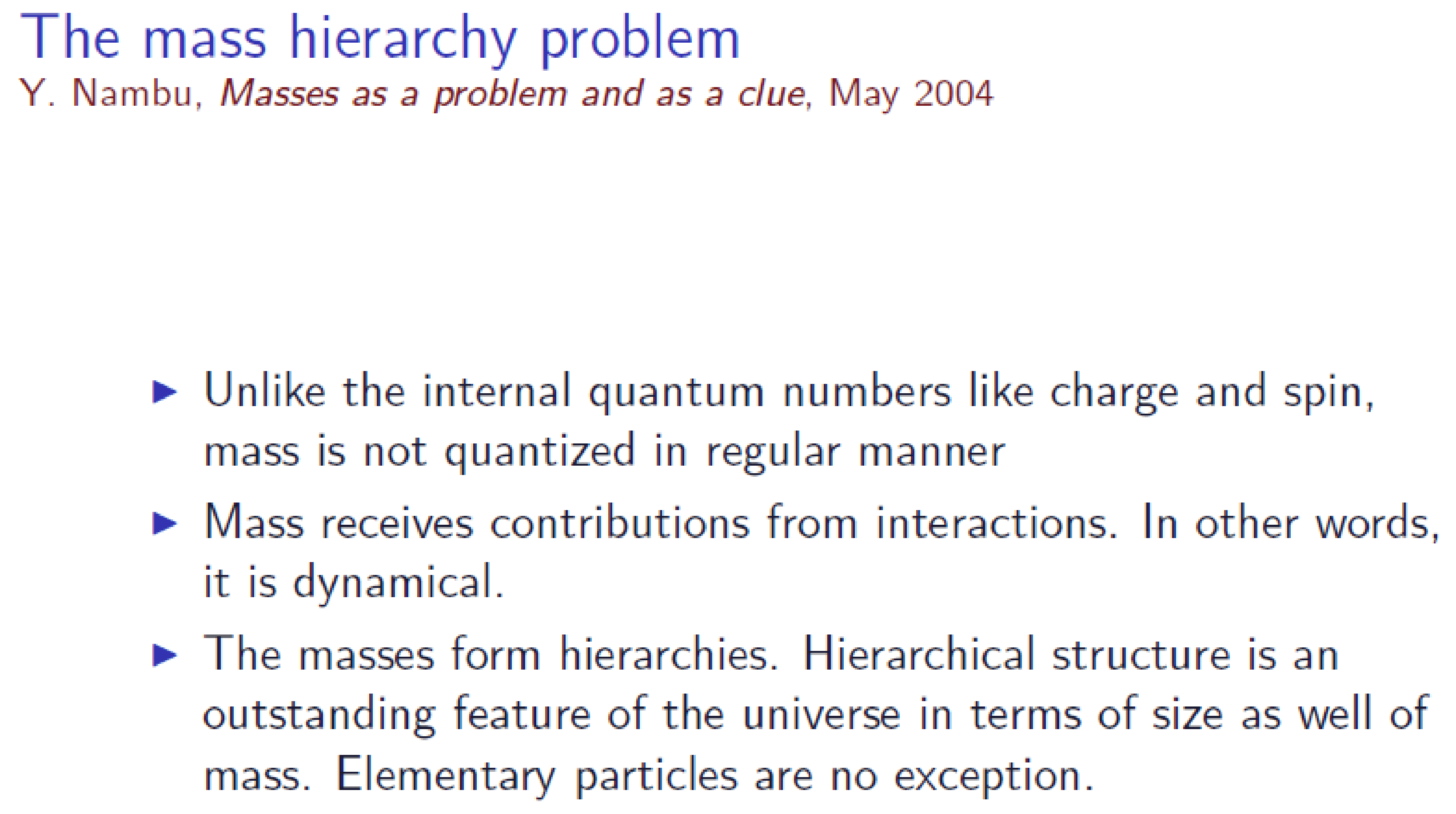
T.H.R. Skyrme, Proc. Roy. Soc. Lond. A260 ('61) 127

These ideas are relevant in QCD and are dual

relevant
Nambu's fermion/boson = quark/pion
Skyrme's fermion/boson = nucleon/pion

dual
bosonized Nambu = Skyrme

Y. Nambu, Nobel Lecture (Dec.8, 2008), page 22/25

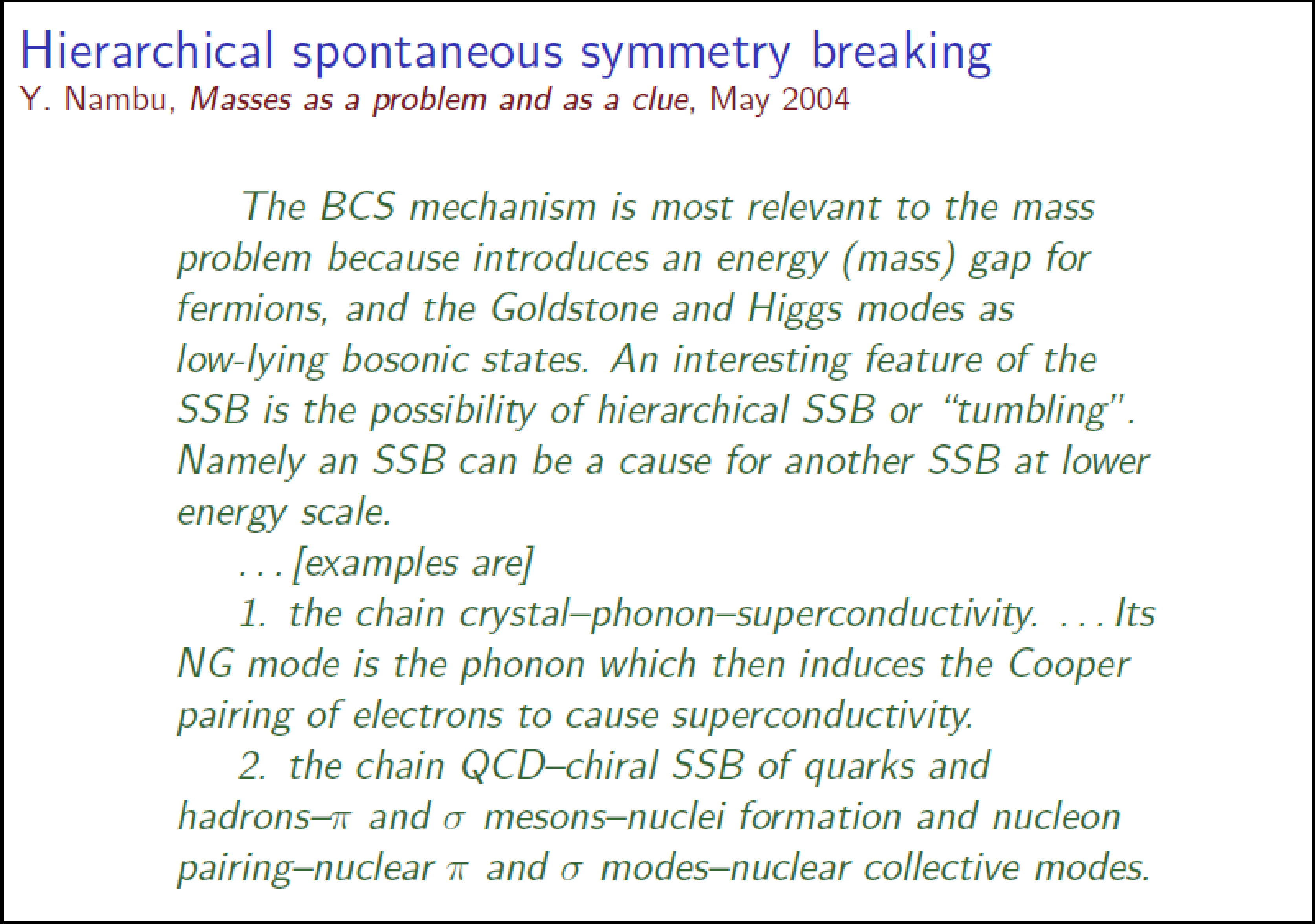


The mass hierarchy problem

Y. Nambu, *Masses as a problem and as a clue*, May 2004

- Unlike the internal quantum numbers like charge and spin, mass is not quantized in regular manner
- Mass receives contributions from interactions. In other words, it is dynamical.
- The masses form hierarchies. Hierarchical structure is an outstanding feature of the universe in terms of size as well of mass. Elementary particles are no exception.

Y. Nambu, Nobel Lecture (Dec.8, 2008), page 24/25

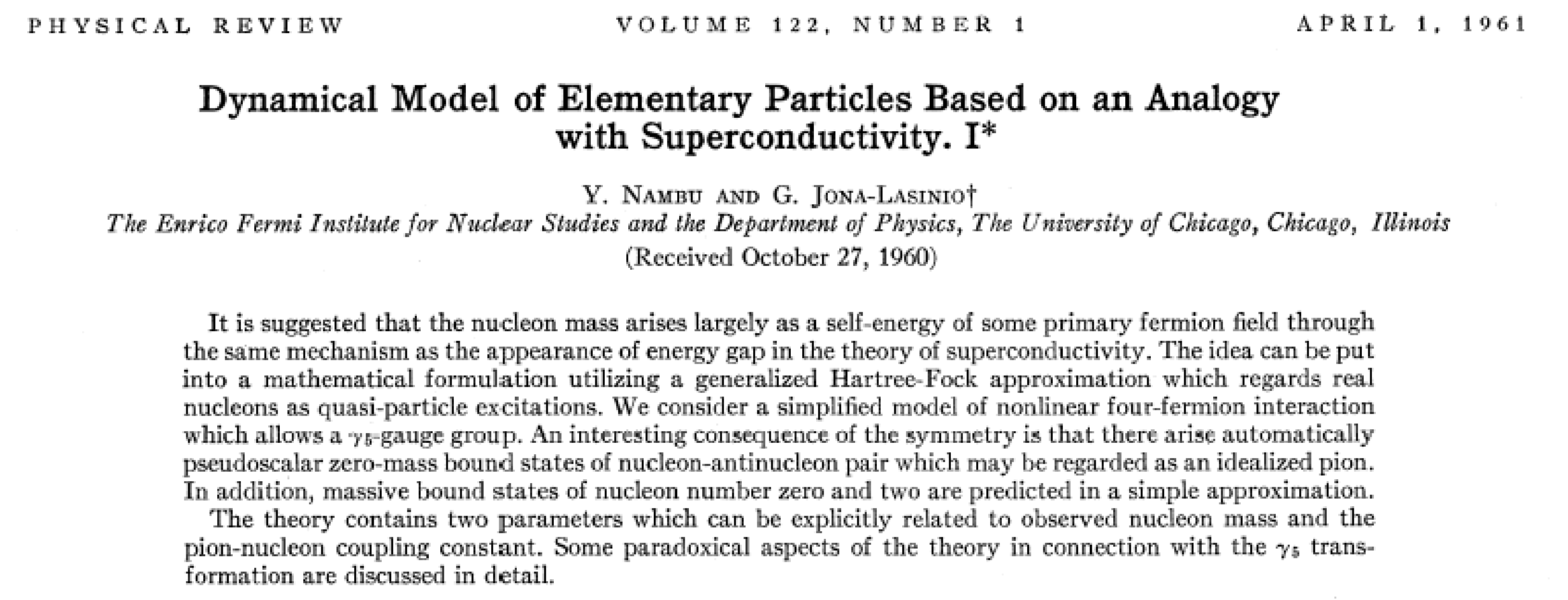


Hierarchical spontaneous symmetry breaking

Y. Nambu, *Masses as a problem and as a clue*, May 2004

> *The BCS mechanism is most relevant to the mass problem because introduces an energy (mass) gap for fermions, and the Goldstone and Higgs modes as low-lying bosonic states. An interesting feature of the SSB is the possibility of hierarchical SSB or "tumbling". Namely an SSB can be a cause for another SSB at lower energy scale.*
>
> *. . . [examples are]*
>
> *1. the chain crystal–phonon–superconductivity. . . . Its NG mode is the phonon which then induces the Cooper pairing of electrons to cause superconductivity.*
>
> *2. the chain QCD–chiral SSB of quarks and hadrons–π and σ mesons–nuclei formation and nucleon pairing–nuclear π and σ modes–nuclear collective modes.*

One-page summary of NJL



PHYSICAL REVIEW VOLUME 122, NUMBER 1 APRIL 1, 1961

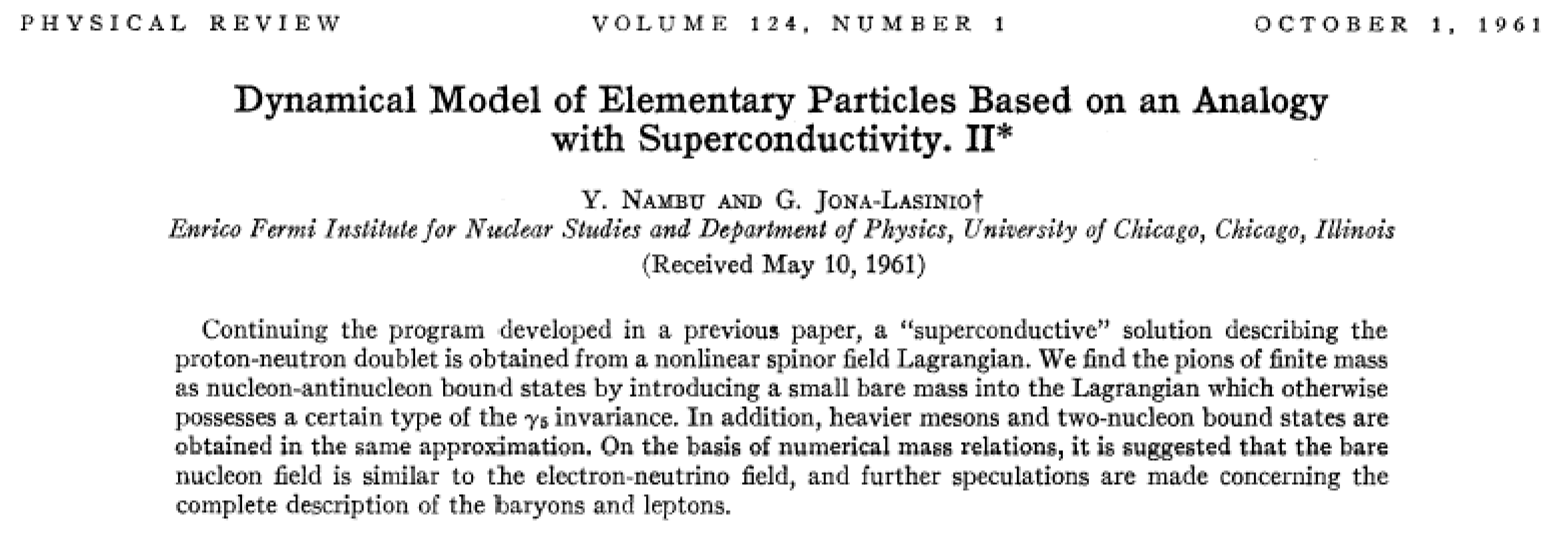
Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I*

Y. NAMBU AND G. JONA-LASINIO†
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois

(Received October 27, 1960)

It is suggested that the nucleon mass arises largely as a self-energy of some primary fermion field through the same mechanism as the appearance of energy gap in the theory of superconductivity. The idea can be put into a mathematical formulation utilizing a generalized Hartree-Fock approximation which regards real nucleons as quasi-particle excitations. We consider a simplified model of nonlinear four-fermion interaction which allows a γ_5-gauge group. An interesting consequence of the symmetry is that there arise automatically pseudoscalar zero-mass bound states of nucleon-antinucleon pair which may be regarded as an idealized pion. In addition, massive bound states of nucleon number zero and two are predicted in a simple approximation.

The theory contains two parameters which can be explicitly related to observed nucleon mass and the pion-nucleon coupling constant. Some paradoxical aspects of the theory in connection with the γ_5 transformation are discussed in detail.



PHYSICAL REVIEW VOLUME 124, NUMBER 1 OCTOBER 1, 1961

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. II*

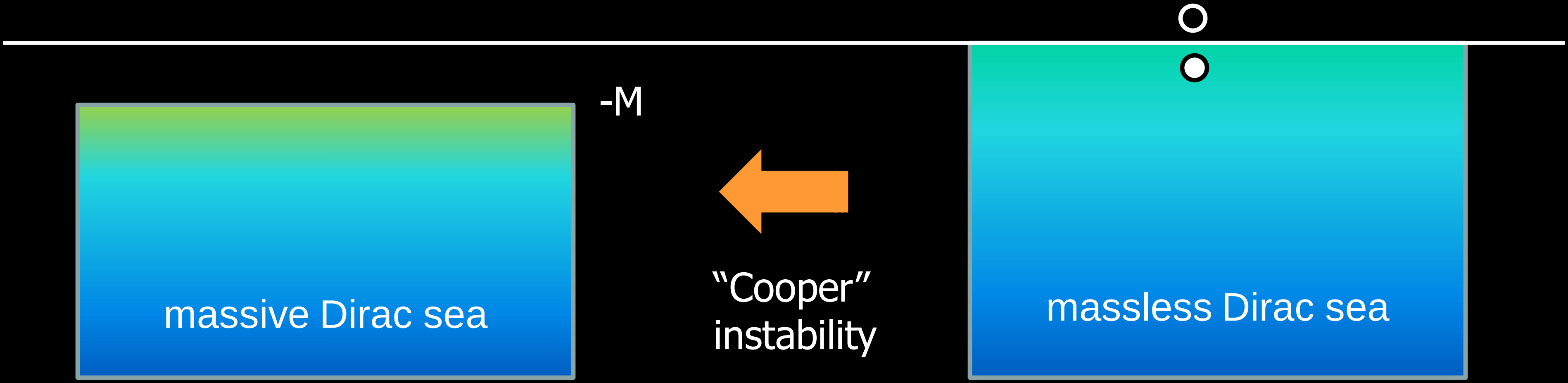
Y. NAMBU AND G. JONA-LASINIO†
Enrico Fermi Institute for Nuclear Studies and Department of Physics, University of Chicago, Chicago, Illinois

(Received May 10, 1961)

Continuing the program developed in a previous paper, a "superconductive" solution describing the proton-neutron doublet is obtained from a nonlinear spinor field Lagrangian. We find the pions of finite mass as nucleon-antinucleon bound states by introducing a small bare mass into the Lagrangian which otherwise possesses a certain type of the γ_5 invariance. In addition, heavier mesons and two-nucleon bound states are obtained in the same approximation. On the basis of numerical mass relations, it is suggested that the bare nucleon field is similar to the electron-neutrino field, and further speculations are made concerning the complete description of the baryons and leptons.

One-page summary of NJL

$$\mathcal{H}_{\rm NJL}=\bar\psi(-i\gamma\cdot\nabla)\psi-g[(\bar\psi\psi)^2+(\bar\psi i\gamma_5\psi)^2]$$



-M

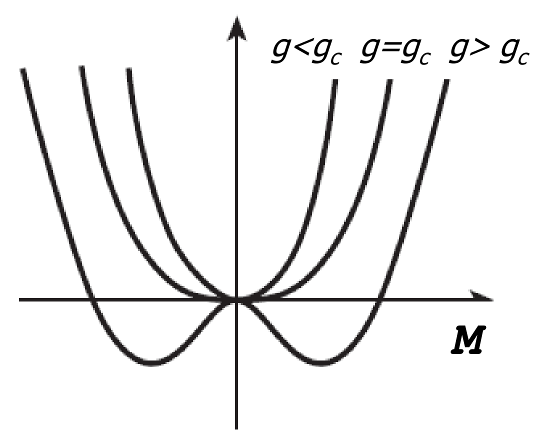
massive Dirac sea

"Cooper" instability

massless Dirac sea

- Dynamical mass $M=-2g\langle\bar\psi\psi\rangle$
- Vacuum energy

$$\frac{E_{\rm vac}}{V}=\frac{1}{V}\sum_{\mathbf{p},s}[-\sqrt{\mathbf{p}^2+M^2}]+g\langle\bar\psi\psi\rangle^2$$



What about QCD ?

[QCD]
- most attractive channels : scalar & pseudo-scalar
- running coupling : large at low energies

⇒ NJL mechanism is expected to take place

	Superconductivity	**Strong interaction**
Microscopic theory (relevant symmetry)	electron + phonon (global gauge symmetry)	quark + gluon (global chiral symmetry)
Effective theory for fermions	BCS model for electrons $e_\uparrow(x)$ & $e_\downarrow(x)$	NJL model for quarks $q_L(x)$ & $q_R(x)$
Effective theory for soft modes	Ginzburg-Landau theory for Cooper pair $\Delta(x)$	Chiral perturbation theory for pion $\pi(x)$

The NJL model as a low-energy effective theory of QCD

e.g. T. Hatsuda, T. Kunihiro, Phys. Rep. **247**, 221 (1994)

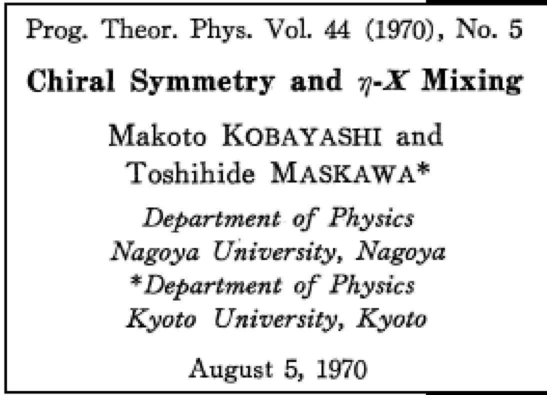
The NJL model has been reinterpreted in terms of quark variables. One is interested in the low energy degrees of freedom on a scale smaller than some cut-off $\Lambda \sim 1$ Gev. The short distance dynamics above Λ is dictated by perturbative QCD and is treated as a small perturbation. Confinement is also treated as a small perturbation. The total Lagrangian is then

$$L_{\mathrm{QCD}} \simeq L_{\mathrm{NJL}} + L_{\mathrm{KMT}} + \varepsilon\left(L_{\mathrm{conf}} + L_{\mathrm{OGE}}\right)$$

where the Kobayashi–Maskawa–'t Hooft term

$$L_{\mathrm{KMT}} = g_D \det_{i,j}\left[\bar{q}_i(1-\gamma_5)q_j + \mathrm{h.c.}\right]$$

mimics the axial anomaly and L_{OGE} is the one gluon exchange potential.



Prog. Theor. Phys. Vol. 44 (1970), No. 5

Chiral Symmetry and η-X Mixing

Makoto KOBAYASHI and
Toshihide MASKAWA*

Department of Physics
Nagoya University, Nagoya
**Department of Physics*
Kyoto University, Kyoto

August 5, 1970

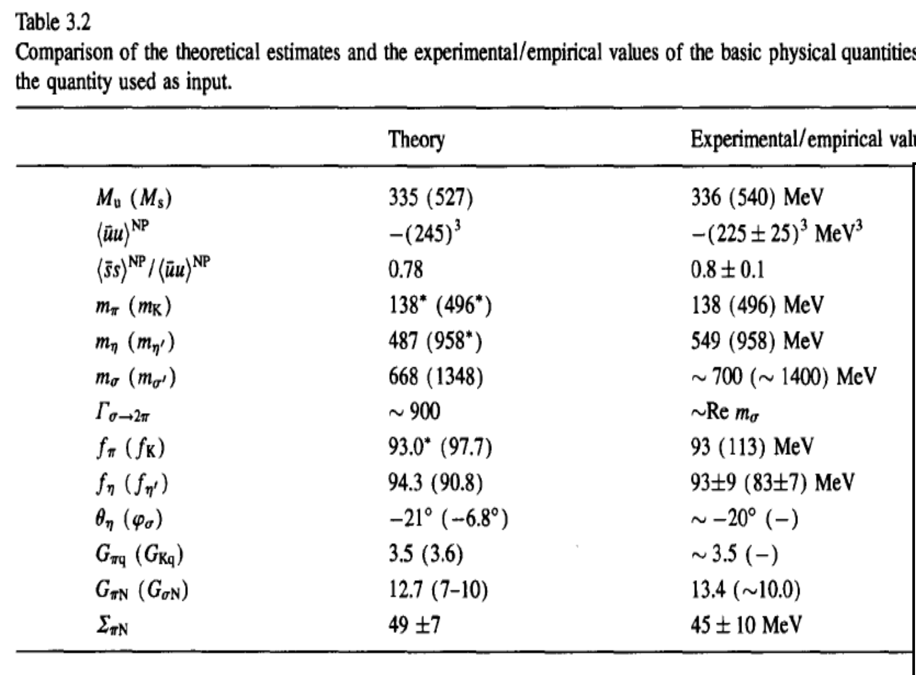


Table 3.2

Comparison of the theoretical estimates and the experimental/empirical values of the basic physical quantities. * indicates the quantity used as input.

	Theory	Experimental/empirical values
M_u (M_s)	335 (527)	336 (540) MeV
$\langle \bar{u}u \rangle^{NP}$	$-(245)^3$	$-(225 \pm 25)^3$ MeV^3
$\langle \bar{s}s \rangle^{NP} / \langle \bar{u}u \rangle^{NP}$	0.78	0.8 ± 0.1
m_π (m_K)	138* (496*)	138 (496) MeV
m_η ($m_{\eta'}$)	487 (958*)	549 (958) MeV
m_σ ($m_{\sigma'}$)	668 (1348)	~ 700 (~ 1400) MeV
$\Gamma_{\sigma \to 2\pi}$	~ 900	~Re m_σ
f_π (f_K)	93.0* (97.7)	93 (113) MeV
f_η ($f_{\eta'}$)	94.3 (90.8)	93±9 (83±7) MeV
θ_η (φ_σ)	−21° (−6.8°)	~ −20° (−)
$G_{\pi q}$ (G_{Kq})	3.5 (3.6)	~ 3.5 (−)
$G_{\pi N}$ ($G_{\sigma N}$)	12.7 (7–10)	13.4 (~10.0)
$\Sigma_{\pi N}$	49 ±7	45 ± 10 MeV

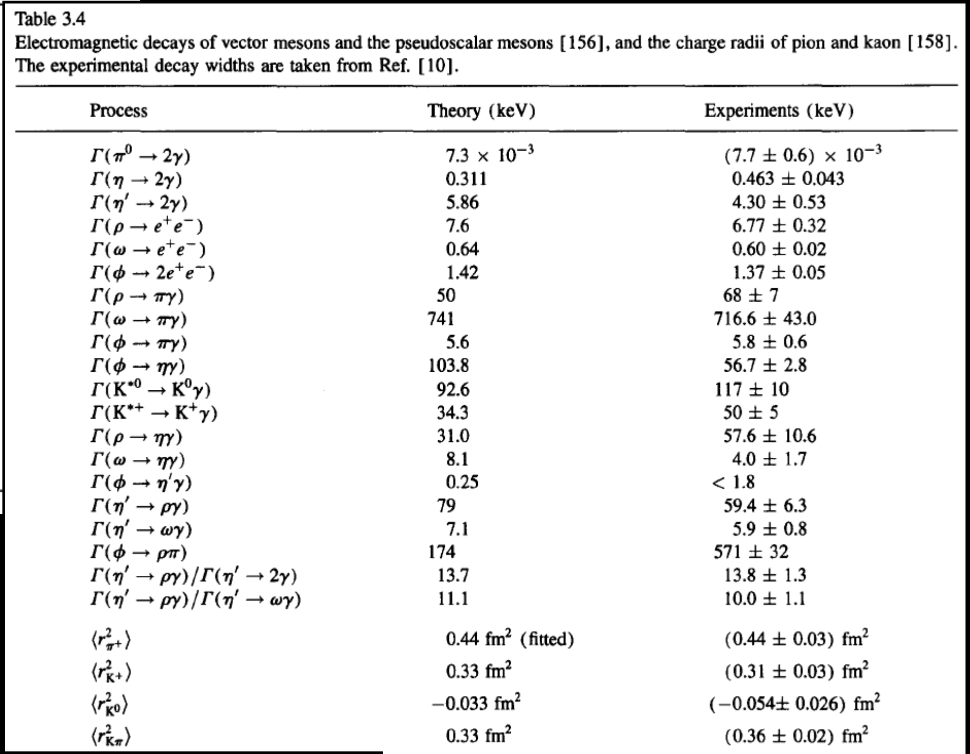


Table 3.4

Electromagnetic decays of vector mesons and the pseudoscalar mesons [156], and the charge radii of pion and kaon [158]. The experimental decay widths are taken from Ref. [10].

Process	Theory (keV)	Experiments (keV)
$\Gamma(\pi^0 \to 2\gamma)$	7.3×10^{-3}	$(7.7 \pm 0.6) \times 10^{-3}$
$\Gamma(\eta \to 2\gamma)$	0.311	0.463 ± 0.043
$\Gamma(\eta' \to 2\gamma)$	5.86	4.30 ± 0.53
$\Gamma(\rho \to e^+e^-)$	7.6	6.77 ± 0.32
$\Gamma(\omega \to e^+e^-)$	0.64	0.60 ± 0.02
$\Gamma(\phi \to 2e^+e^-)$	1.42	1.37 ± 0.05
$\Gamma(\rho \to \pi\gamma)$	50	68 ± 7
$\Gamma(\omega \to \pi\gamma)$	741	716.6 ± 43.0
$\Gamma(\phi \to \pi\gamma)$	5.6	5.8 ± 0.6
$\Gamma(\phi \to \eta\gamma)$	103.8	56.7 ± 2.8
$\Gamma(K^{*0} \to K^0\gamma)$	92.6	117 ± 10
$\Gamma(K^{*+} \to K^+\gamma)$	34.3	50 ± 5
$\Gamma(\rho \to \eta\gamma)$	31.0	57.6 ± 10.6
$\Gamma(\omega \to \eta\gamma)$	8.1	4.0 ± 1.7
$\Gamma(\phi \to \eta'\gamma)$	0.25	< 1.8
$\Gamma(\eta' \to \rho\gamma)$	79	59.4 ± 6.3
$\Gamma(\eta' \to \omega\gamma)$	7.1	5.9 ± 0.8
$\Gamma(\phi \to \rho\pi)$	174	571 ± 32
$\Gamma(\eta' \to \rho\gamma)/\Gamma(\eta' \to 2\gamma)$	13.7	13.8 ± 1.3
$\Gamma(\eta' \to \rho\gamma)/\Gamma(\eta' \to \omega\gamma)$	11.1	10.0 ± 1.1
$\langle r^2_{\pi^+} \rangle$	0.44 fm^2 (fitted)	(0.44 ± 0.03) fm^2
$\langle r^2_{K^+} \rangle$	0.33 fm^2	(0.31 ± 0.03) fm^2
$\langle r^2_{K^0} \rangle$	−0.033 fm^2	(-0.054 ± 0.026) fm^2
$\langle r^2_{K\pi} \rangle$	0.33 fm^2	(0.36 ± 0.02) fm^2

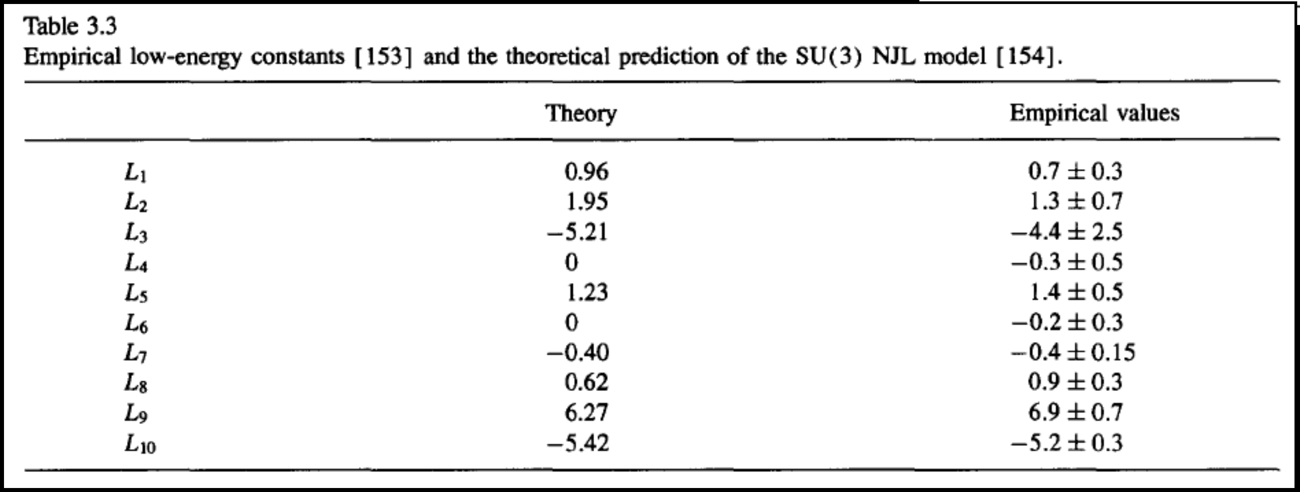


Table 3.3

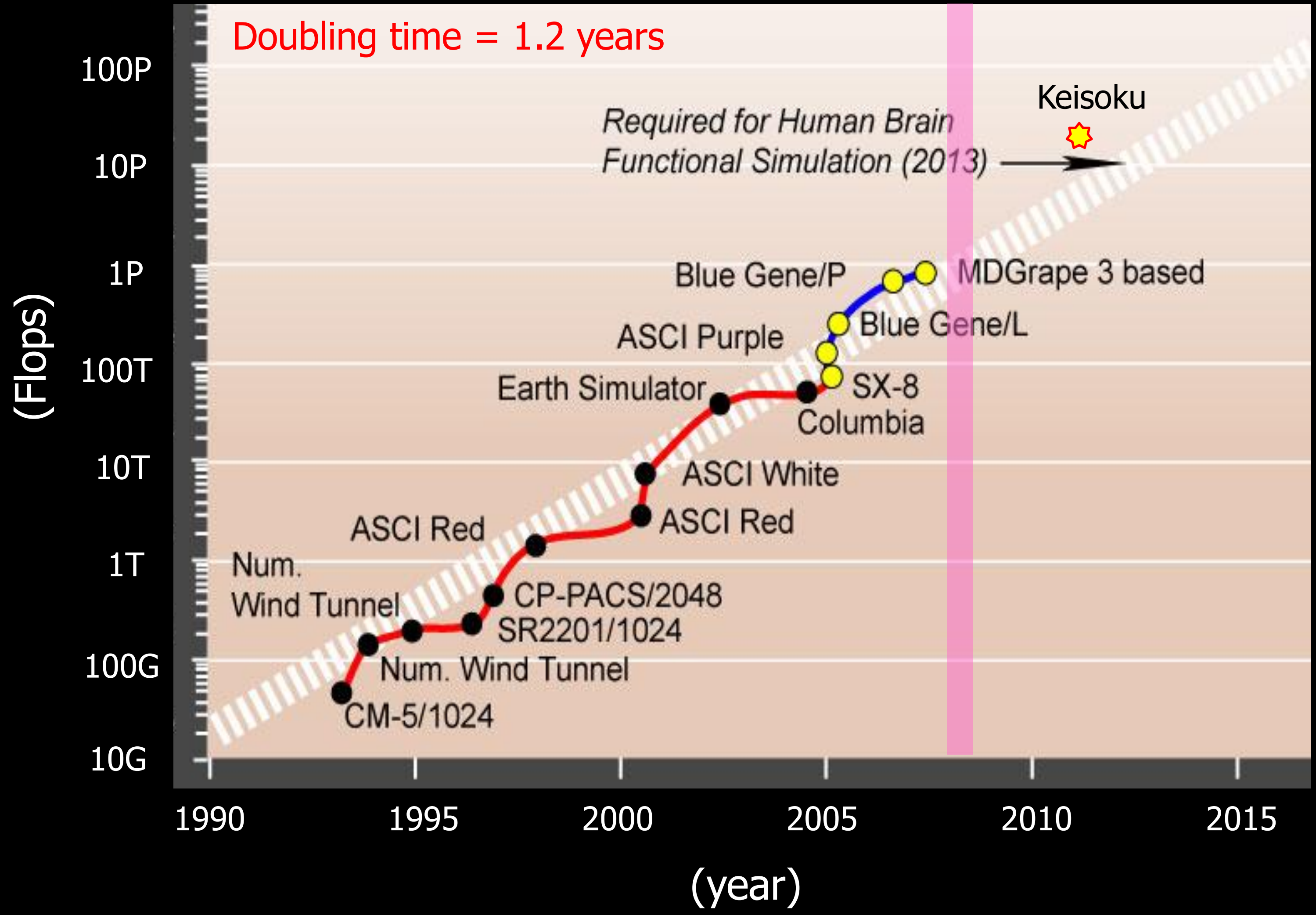
Empirical low-energy constants [153] and the theoretical prediction of the SU(3) NJL model [154].

	Theory	Empirical values
L_1	0.96	0.7 ± 0.3
L_2	1.95	1.3 ± 0.7
L_3	−5.21	-4.4 ± 2.5
L_4	0	-0.3 ± 0.5
L_5	1.23	1.4 ± 0.5
L_6	0	-0.2 ± 0.3
L_7	−0.40	-0.4 ± 0.15
L_8	0.62	0.9 ± 0.3
L_9	6.27	6.9 ± 0.7
L_{10}	−5.42	-5.2 ± 0.3

NJL+KMT vs. Exp. data

taken from
Hatsuda & Kunihiro,
Phys.Rep. 247 (1994).

Growth in Supercomputer peak performance



Adapted from Wikimedia Commons

Dim.3 chiral condensate (Nambu condensate) in the QCD vacuum

Gell-Mann-Oakes-Renner (GOR) formula (1968)

$$f_\pi^2 m_\pi^2 = -(m_u + m_d)\langle\bar{q}q\rangle_0 + O(m_{u,d}^2)$$

⇨ $-\langle\bar{q}q\rangle_0 \simeq [242\ \mathrm{MeV}]^3$ at 2 GeV

Di Vecchia-Veneziano formula (1980)

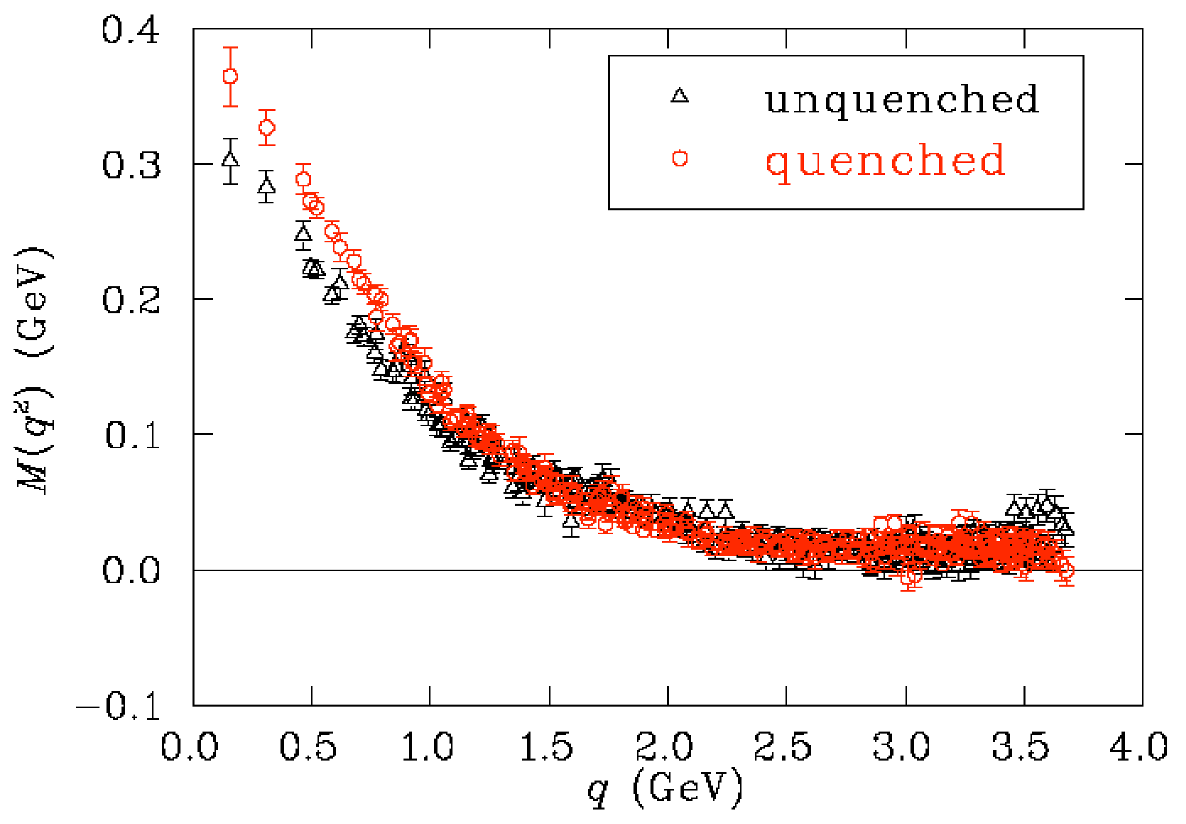
$$\chi_{\rm top} = \frac{-\langle\bar{q}q\rangle_0}{1/m_u + 1/m_d + 1/m_s} + O(m_u^2)$$

⇨ $-\langle\bar{q}q\rangle_0 = [249(4)(2)\ \mathrm{MeV}]^3$ at 2 GeV

Lattice QCD calculation by
JLQCD+TWQCD Collaborations, arXiv:0810.0085 [hep-lat]

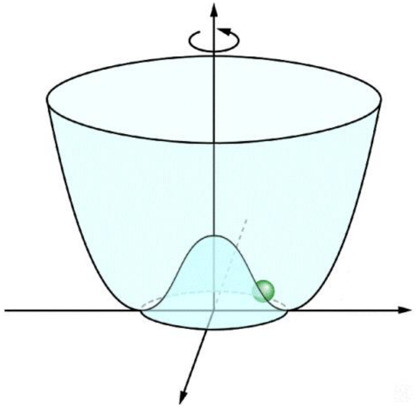
Dynamical quark-mass in the QCD vacuum

M (0) ~ 300-400 MeV



Lattice QCD calculation in Landau gauge,
20^3x64, a=0.125fm, MILC config.
P. O. Bowman et al., Phys. Rev. D71 (2005) 054507

Spectral evidence of DBCS in QCD

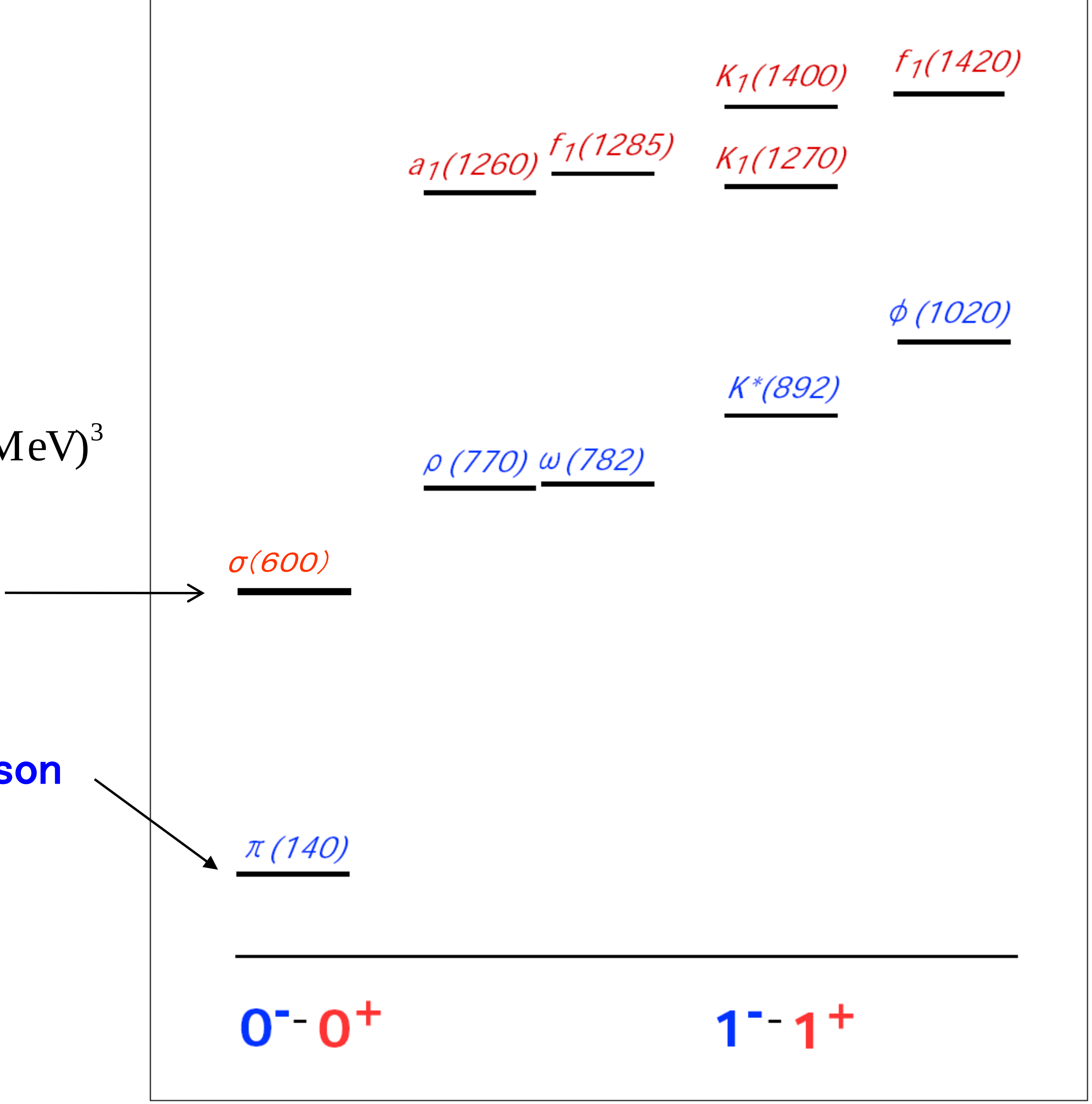


Nambu condensate

$$\langle \bar{q}q \rangle_{\kappa=2\mathrm{GeV}} \cong -(250\,\mathrm{MeV})^3$$

“Higgs” in QCD

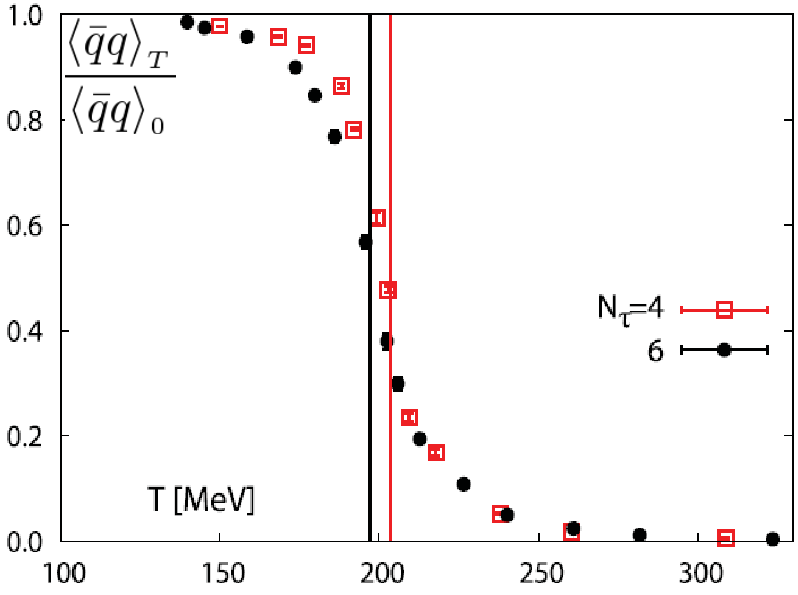
Nambu–Goldstone boson



(Theoretical) Nambu condensate in the QCD medium

Finite Temperature

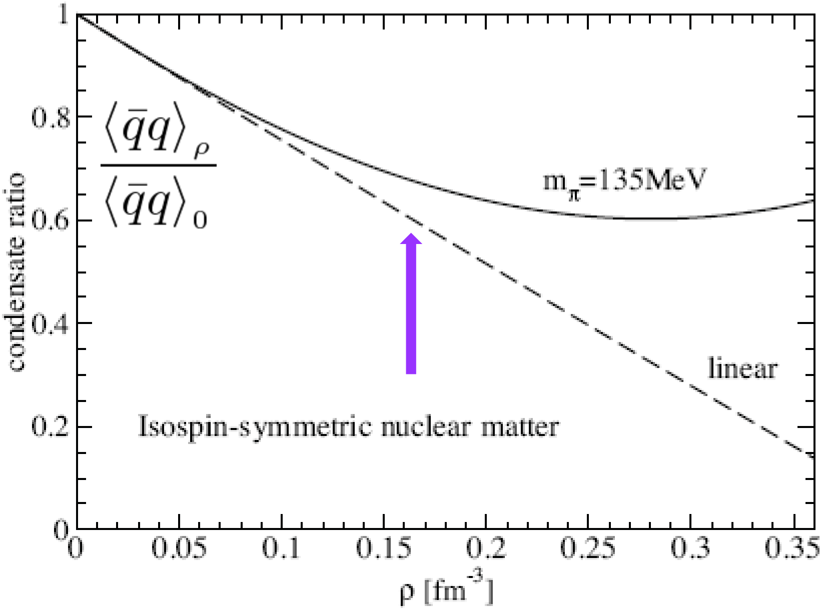
$$\langle \bar{q}q \rangle_T = -\frac{\partial P(T)}{\partial m_q}$$



Lattice QCD, (2+1)-flavor
Cheng et al., PRD 77 (2008)

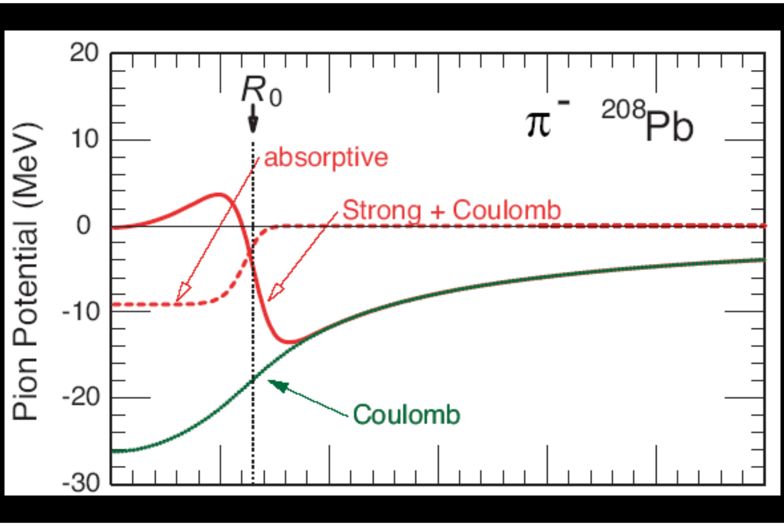
Finite Baryon Density

$$\langle \bar{q}q \rangle_\rho = \langle \bar{q}q \rangle_0 + \rho \frac{d}{dm_q}\left(\frac{E}{A}\right)$$

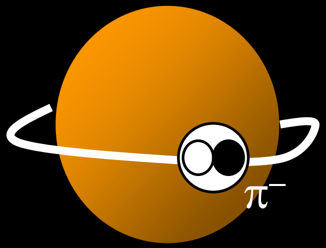


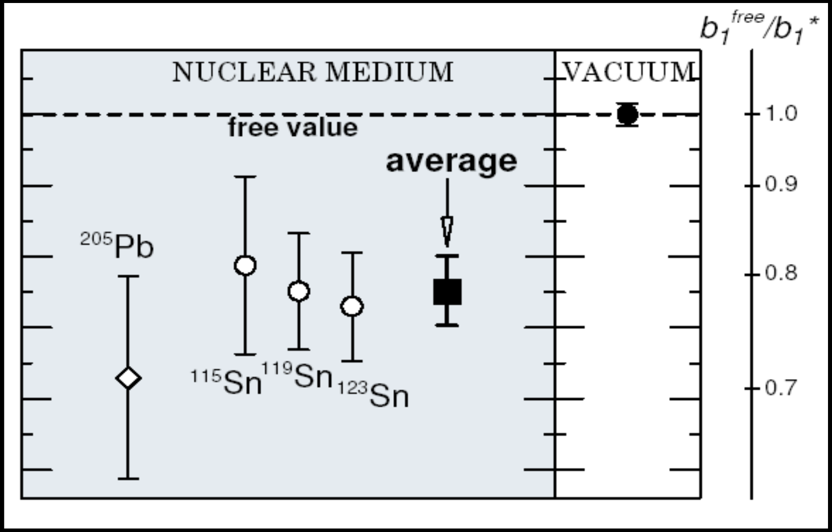
Nuclear chiral perturbation
Kaiser et al., PRC 77 (2008)

Experimental determination of in-medium Nambu condensate from deeply bound pionic atom



Toki, Hirenzaki, Yamazaki & Hayano,
NP A501 (1989) 653





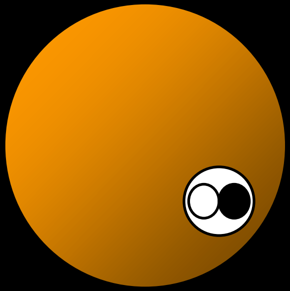
Suzuki et al., PRL 92 (2004) 72302

$$\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} \simeq Z_\pi^{1/2}(\rho)\left(\frac{b_1}{b_1(\rho)}\right)^{1/2}$$

$$\simeq 1 - 0.37\frac{\rho}{\rho_0}$$

Jido, Hatsuda & Kunihiro, PL B670 (2008) 109
Hayano & Hatsuda, Rev. Mod. Phys. (2009)

What about other mesons (ρ, ω, φ, σ, η, η’ …) ?



- Many models proposed (BR scaling, HLS, Bag, ….)
- None of them are exact except for spectral sum rules from OPE

e.g. Weinberg-type sum rules

$$\int_0^\infty \frac{d\omega^2}{\omega^2}(\rho_V(\omega) - \rho_A(\omega)) = 0$$

$$\int_0^\infty d\omega^2(\rho_V(\omega) - \rho_A(\omega)) = 0$$

$$\int_0^\infty d\omega^2\omega^2(\rho_V(\omega) - \rho_A(\omega)) = -\frac{4\pi}{3}\alpha_s\langle\mathcal{O}_{4q}\rangle$$

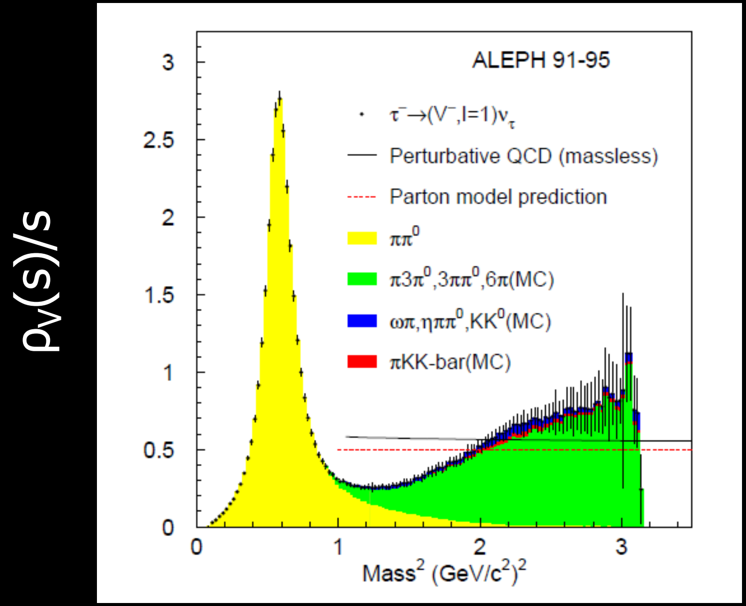
Dim.6 chiral condensate

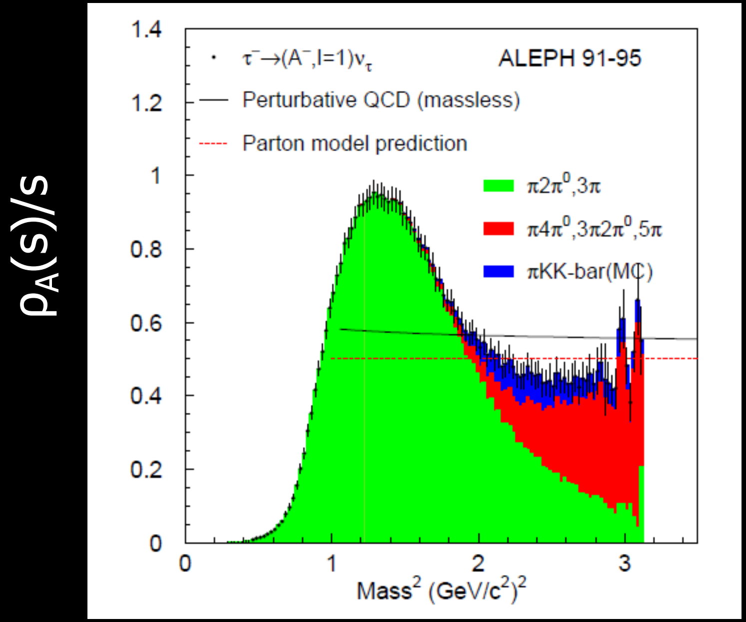
$$\mathcal{O}_{4q} = \mathcal{O}^\mu_\mu + 2\mathcal{O}^{00}$$

$$\mathcal{O}_{\mu\nu} = \frac{4}{3}(\bar{q}_L\gamma_\mu t^\alpha_C t^a_F q_L)(\bar{q}_R\gamma_\nu t^\alpha_C t^a_F q_R)$$

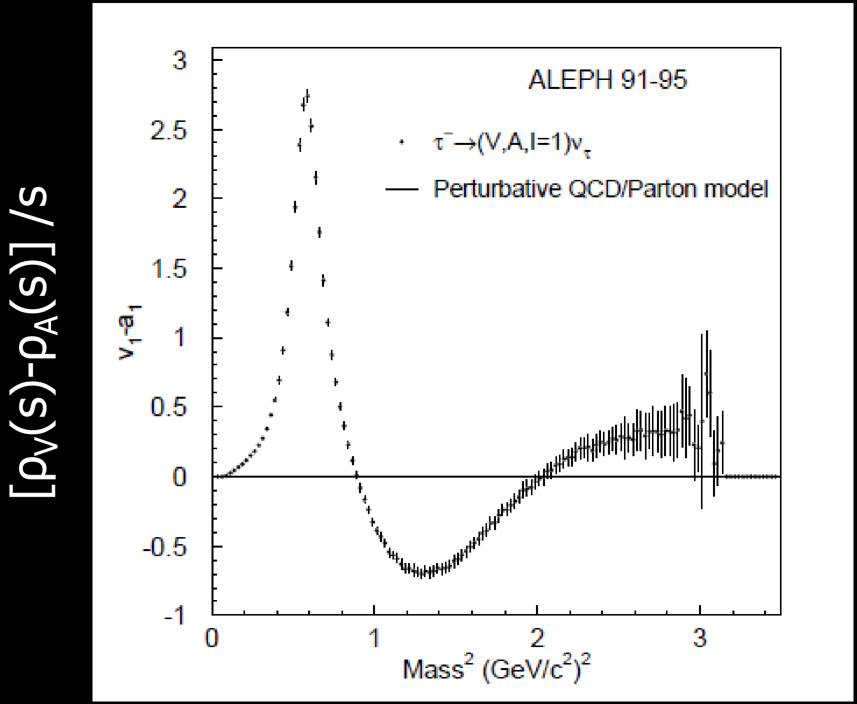
Hatsuda, Koike & Lee. Nucl. Phys. B394 (1993) 221
Kapusta & Shuryak, Phys. Rev. D49 (1994) 4694

V & A spectral functions in the QCD vacuum from τ -decay at LEP-1





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



⟶ Precision measurement at KEKB ?

"Origin of hadron mass = Nambu condensate" ?

$$\int_0^\infty \frac{d\omega^2}{\omega^2}(\rho_V(\omega)-\rho_A(\omega))=0$$

$$\int_0^\infty d\omega^2(\rho_V(\omega)-\rho_A(\omega))=0$$

$$\int_0^\infty d\omega^2\omega^2(\rho_V(\omega)-\rho_A(\omega))=-\frac{4\pi}{3}\alpha_s\langle\mathcal{O}_{4q}\rangle$$

Dim.6 chiral condensate

$$\mathcal{O}_{4q}=\mathcal{O}^\mu_\mu+2\mathcal{O}^{00}$$

$$\mathcal{O}_{\mu\nu}=\frac{4}{3}(\bar{q}_{\mathrm{L}}\gamma_\mu t^\alpha_{\mathrm{C}}t^a_{\mathrm{F}}q_{\mathrm{L}})(\bar{q}_{\mathrm{R}}\gamma_\nu t^\alpha_{\mathrm{C}}t^a_{\mathrm{F}}q_{\mathrm{R}})$$

Messages

1. DBCS is best seen in the spectral difference: <VV>-<AA>, <SS>-<PP>, etc
2. Spectral difference in different channels ⇔ different chiral condensates
3. "Origin of hadron mass = Nambu condensate" : true for the pion (GOR)
   BUT, ρ, ω, N, … could be massive even if chiral restoration takes place

→ Theretically, we need further logical step
Experimentally, precision measurement of SPF at J-PARC

Spectral sum at finite T on the lattice (π, σ, δ)

$$\chi_{\mathcal{O}} = \int_0^\infty d\omega^2 \frac{\rho_{\mathcal{O}}(\omega)}{\omega^2}$$

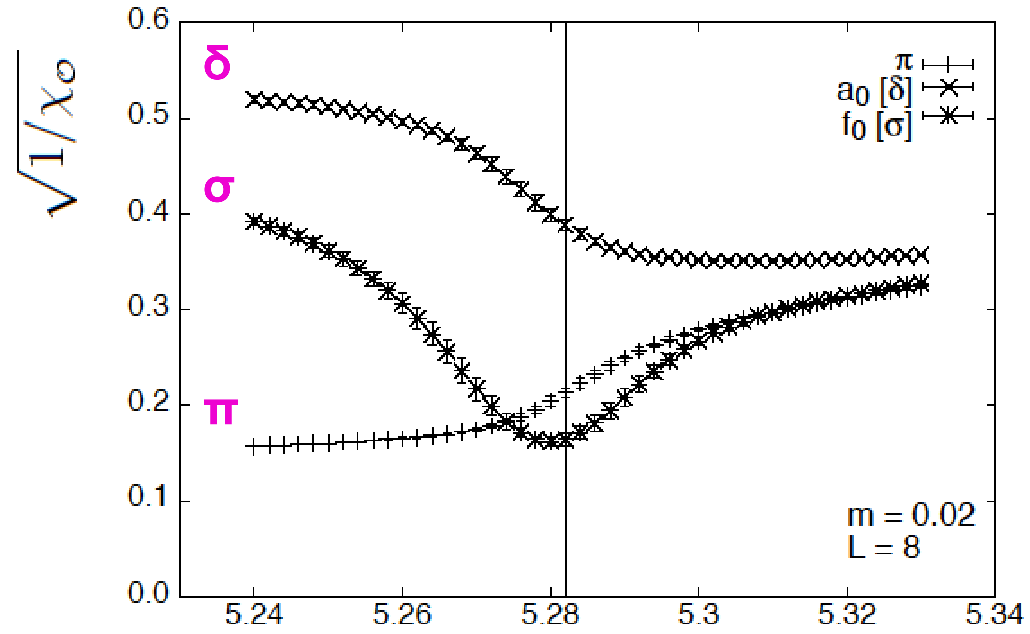
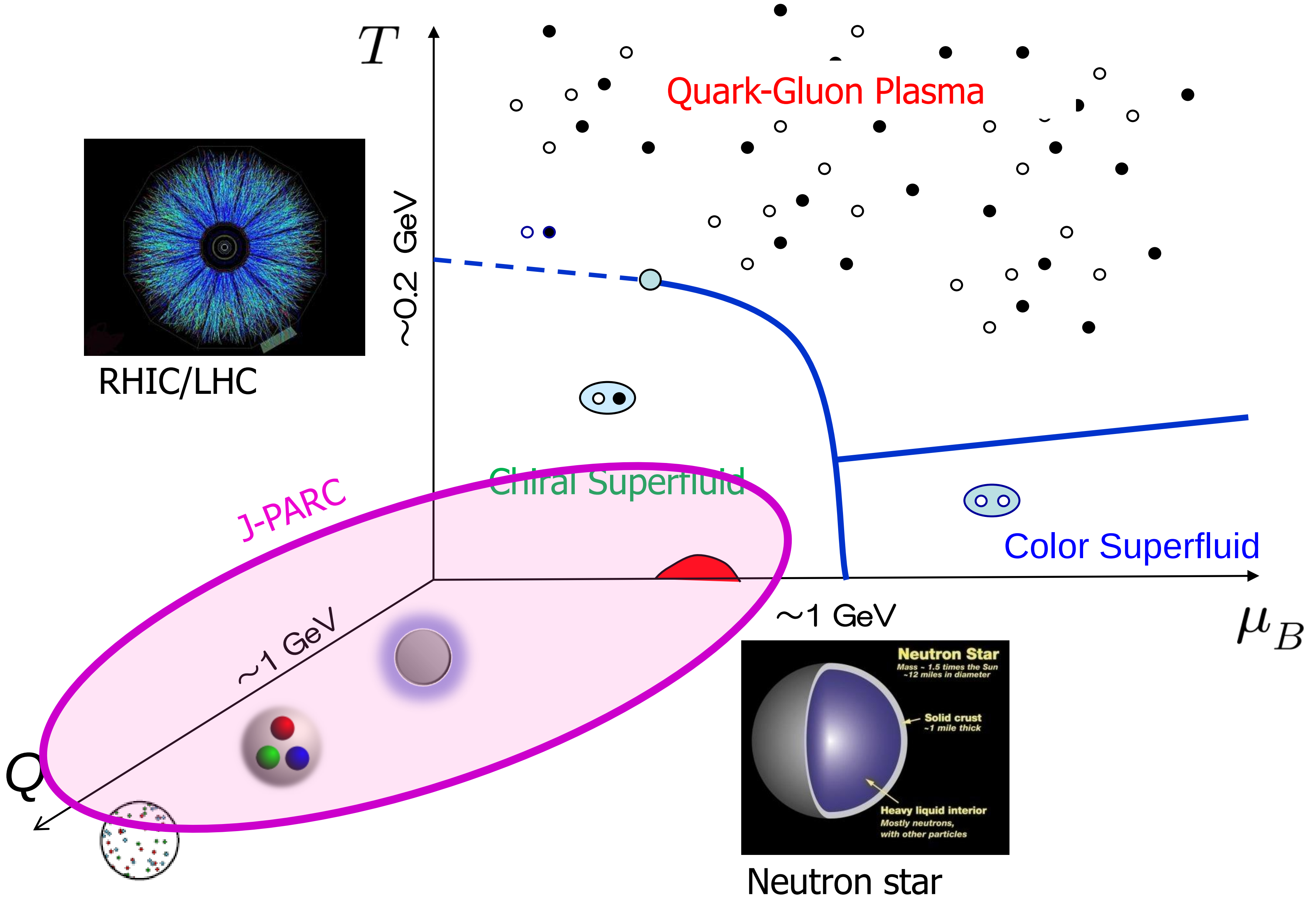
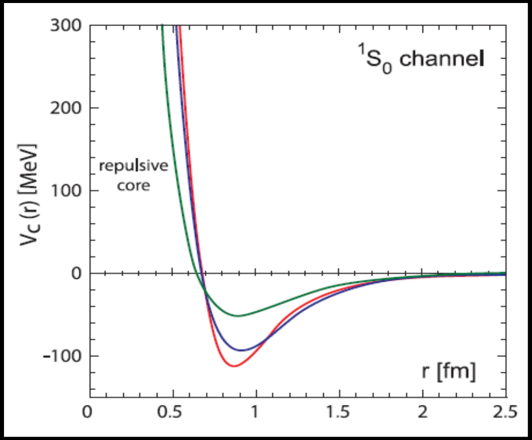


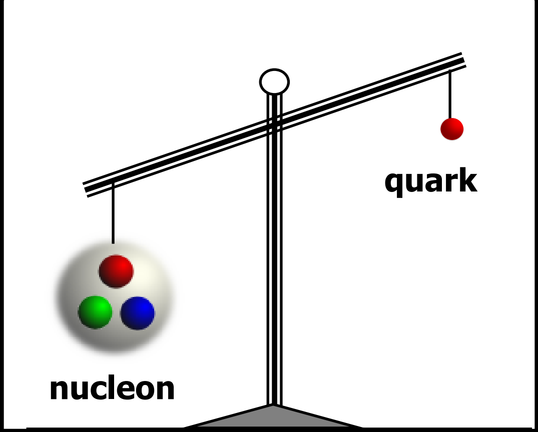
FIG. 8 Thermal susceptibilities in three different channels (π,σ, and δ) for two-flavor QCD with staggered fermion on the $8^3 \times 4$ lattice with $m_{u,d}a = 0.02$. The vertical (horizontal) axis denotes $\sqrt{1/\chi_{\mathcal{O}}}$ (the lattice coupling : $6/g^2$) (Karsch, 2002). Low (high) T corresponds to the left (right) of the figure.

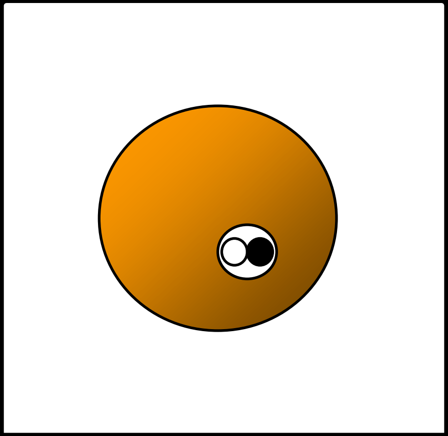
“Phase” diagram of QCD



J-PARCに活きる南部先生のアイデア「物質安定性の起源と質量の起源」







J-PARC as a QCD machine