EINN 2005, Milos

Probing **QCD** in the **CONFINEMENT DOMAIN**

Wolfram Weise
TU München

**CONFINEMENT
and its IMPLICATIONS**

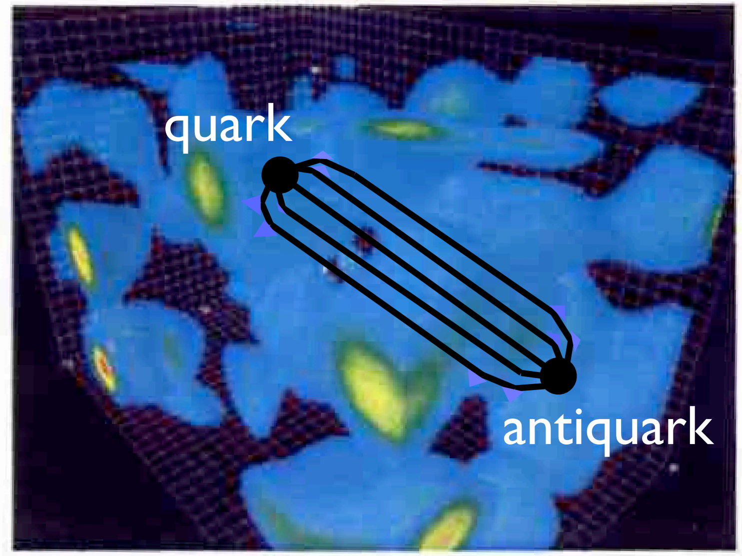
**Spontaneous
CHIRAL SYMMETRY BREAKING**

**CORRELATIONS and QUASIPARTICLES
in QCD**

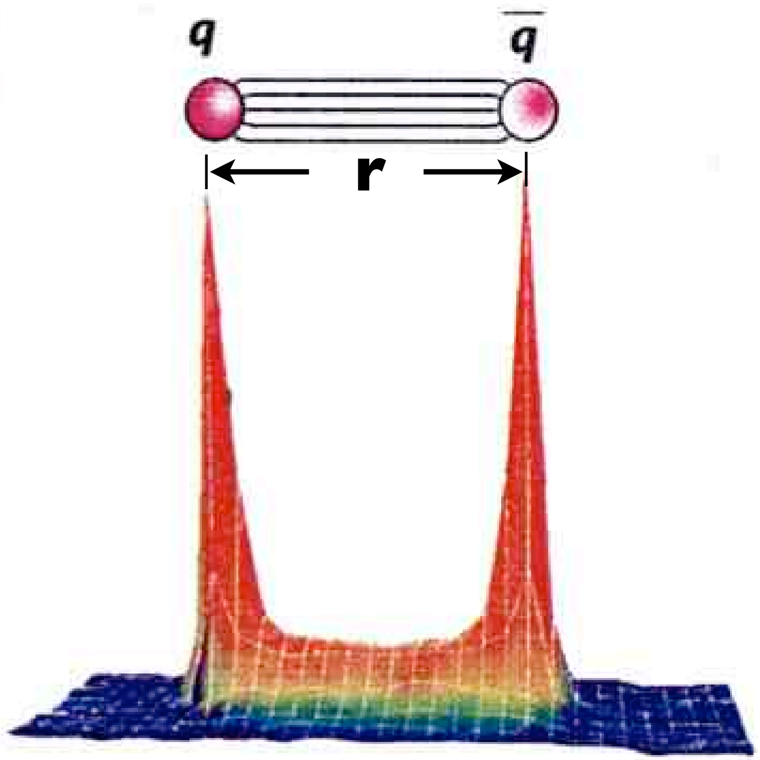
1.
INTRODUCTORY SURVEY

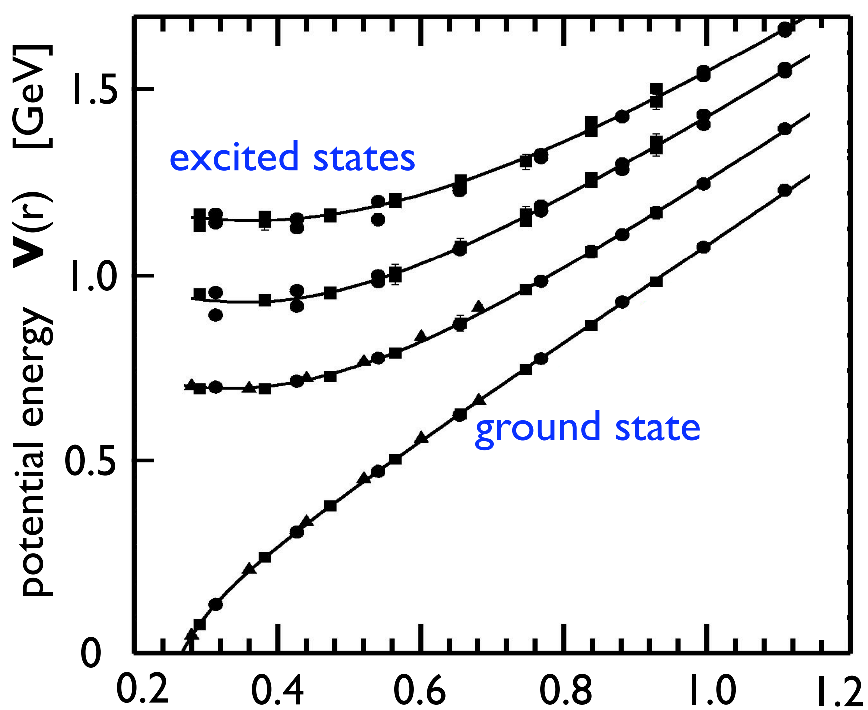
CONFINEMENT

Gluonic Flux Tube
and
Confining Potential
between Heavy Quarks



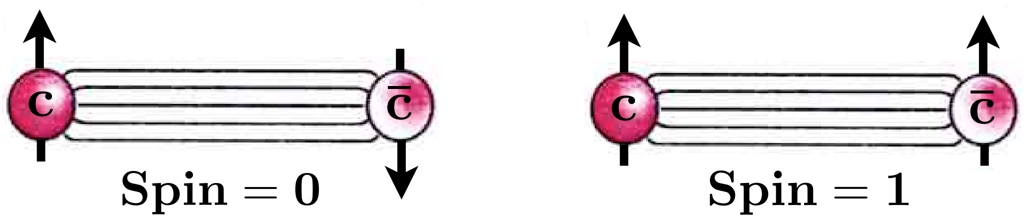
Energy Density of Color Fields

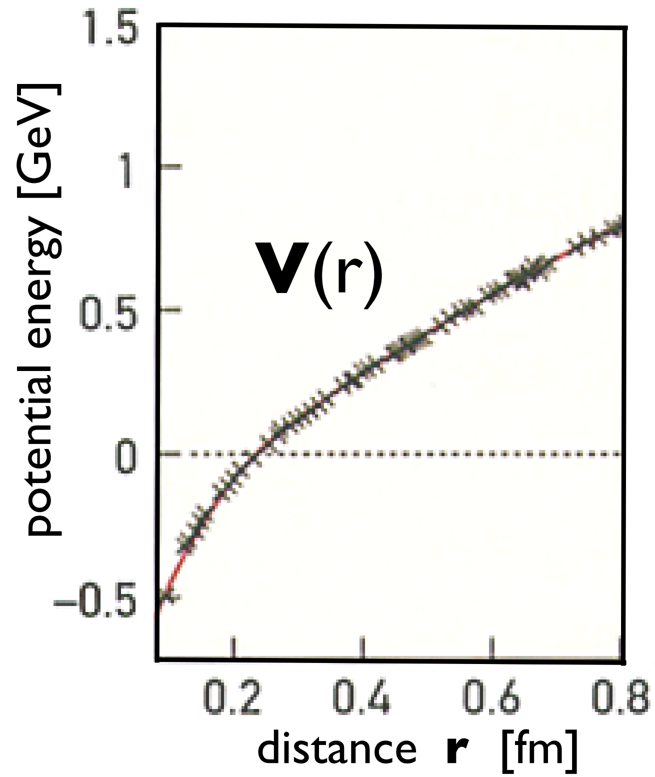


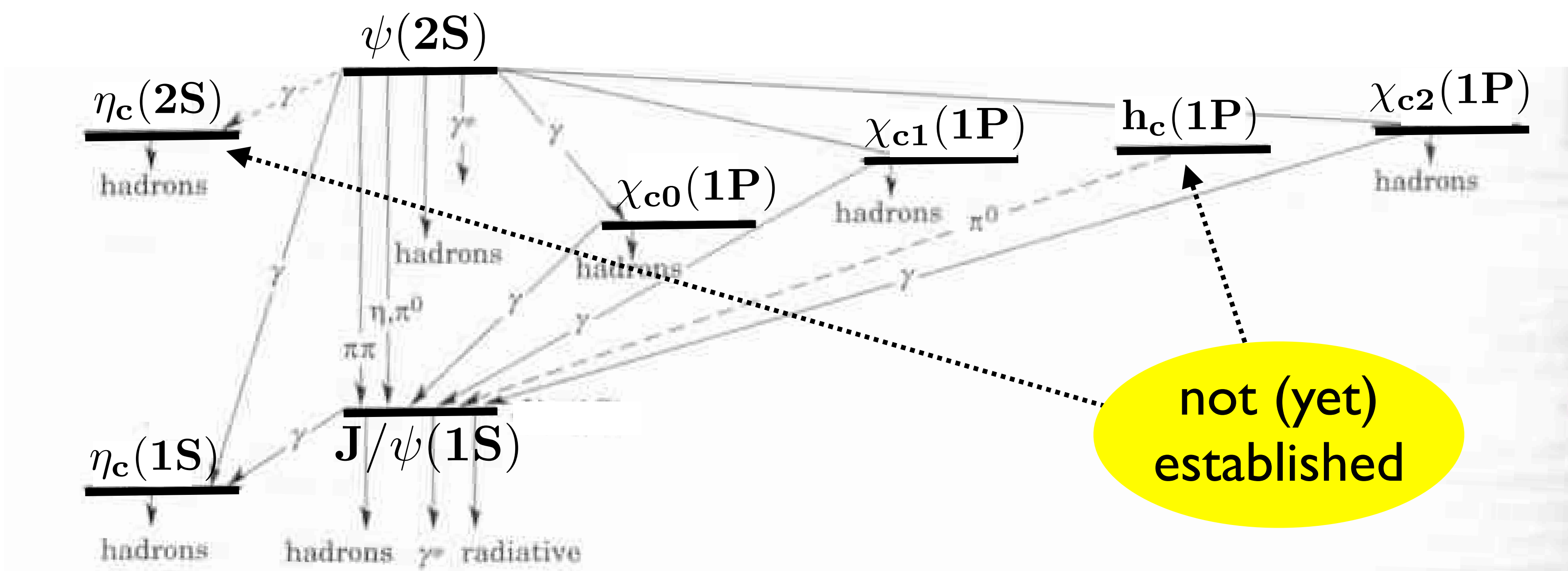


(Bali et al. 2001)

CHARMONIUM


c
c̄
Spin = 0
c
c̄
Spin = 1

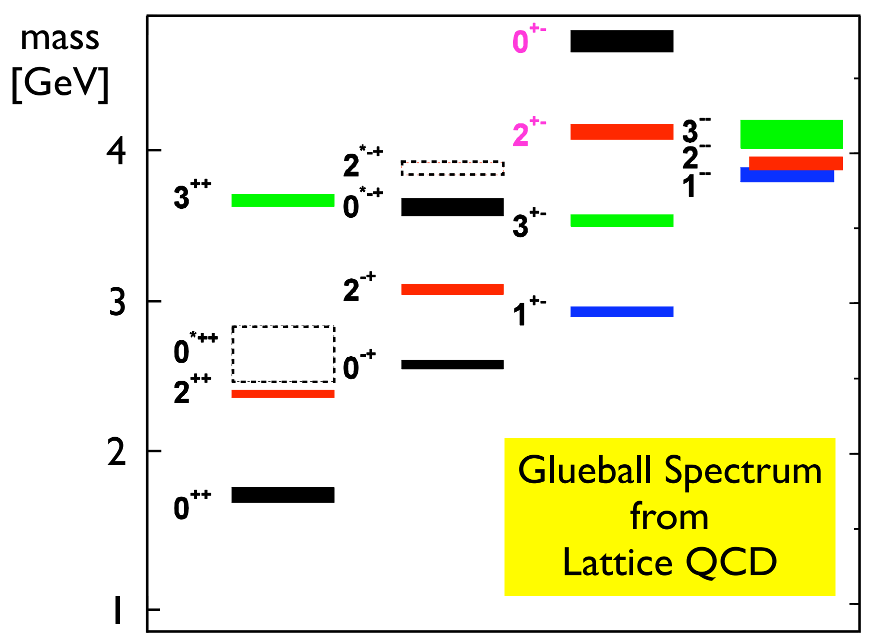

V(r)
potential energy [GeV]
1.5
1
0.5
0
−0.5
0.2
0.4
0.6
0.8
distance r [fm]


ψ(2S)
η_c(2S)
χ_c0(1P)
χ_c1(1P)
h_c(1P)
χ_c2(1P)
η_c(1S)
J/ψ(1S)
hadrons
hadrons
hadrons
hadrons
hadrons
hadrons
hadrons
γ* radiative
η,π^0
ππ
π^0
not (yet) established

STRUCTURES yet to be DISCOVERED

• GLUEBALLS

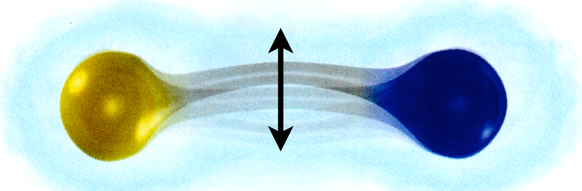
QCD predicts existence of GLUON-rich states

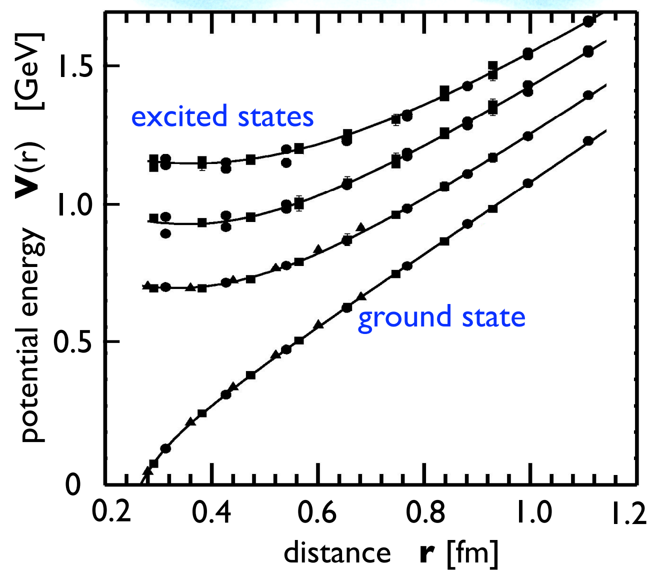


(Morningstar et al. 1999)

• HYBRIDS

QCD predicts quark-antiquark states with "excited" GLUE



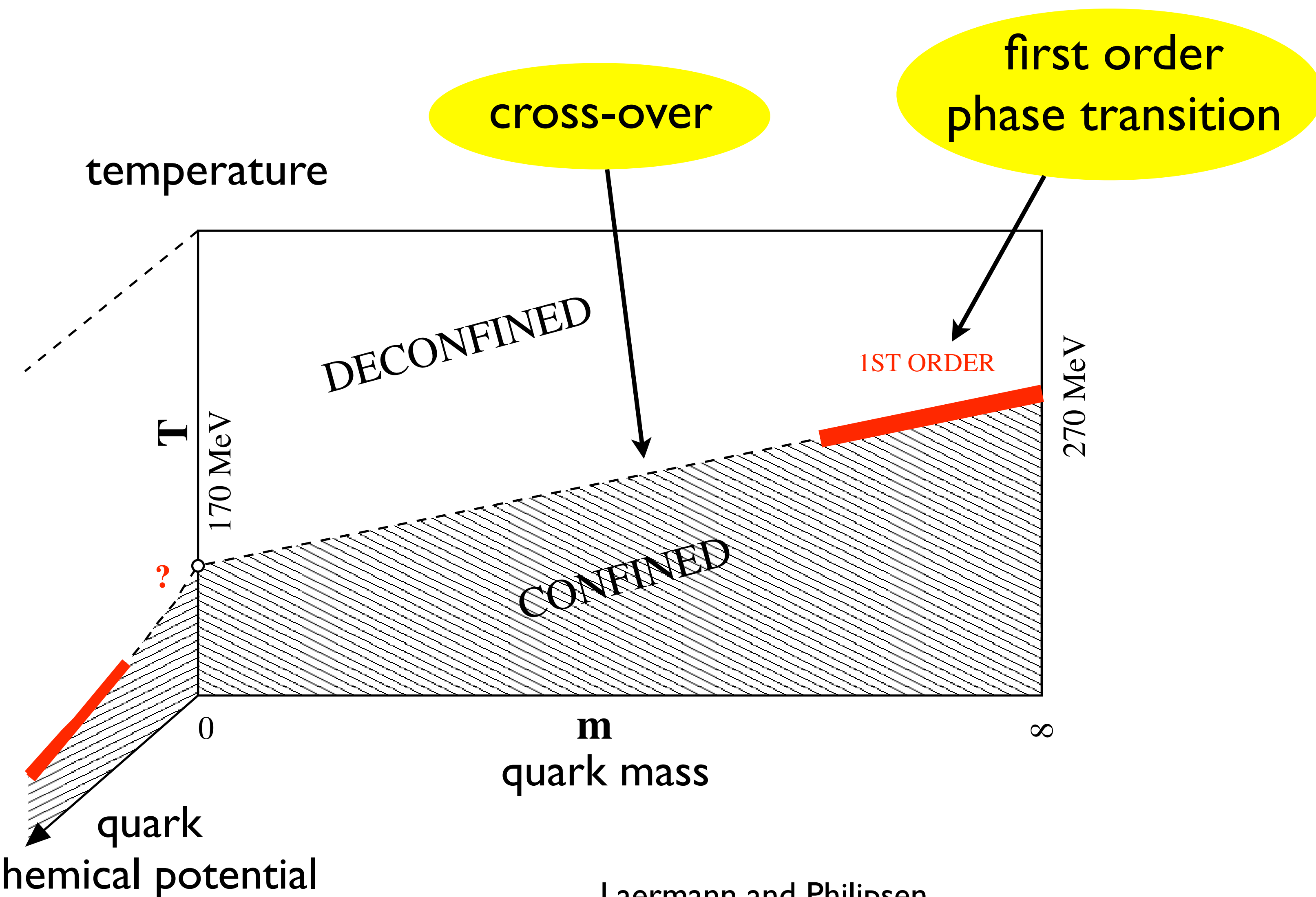


Question:

- How do these IDEALIZED pictures translate into actual OBSERVABLES ?
- Projects: FAIR (Darmstadt) , GlueX / Hall D (Jefferson Lab)

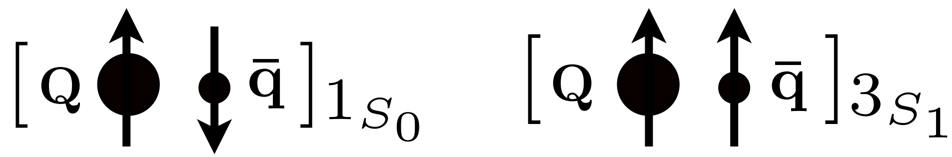
CONFINEMENT and QUARK MASSES

- Qualitative difference between HEAVY and LIGHT QUARKS

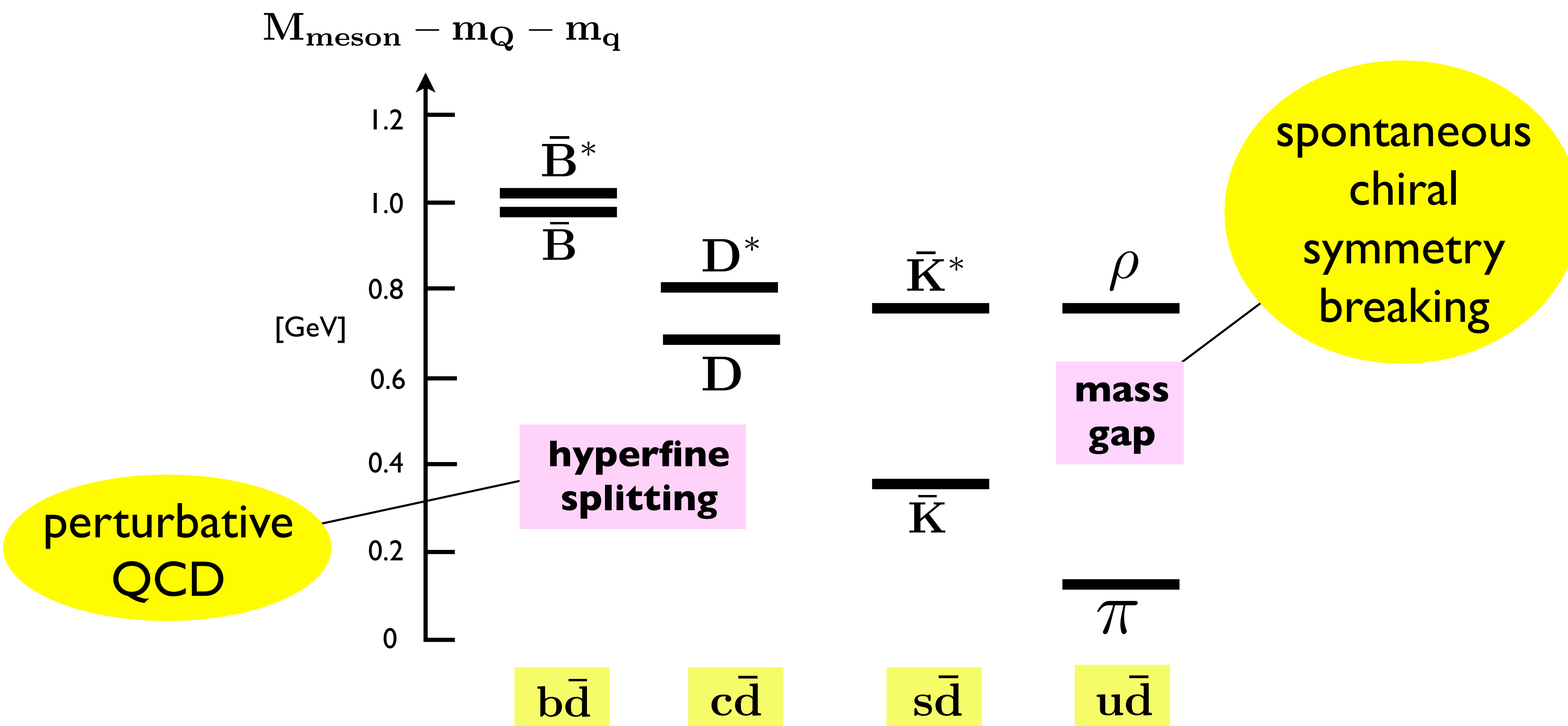


Laermann and Philipsen,
Ann. Rev. Nucl. Part. Sci. 53 (2003) 163

MASS SPLITTINGS of SINGLET and TRIPLET states



Spectroscopic patterns: **LIGHT** versus **HEAVY**



2.
CONFINEMENT
and
CHIRAL SYMMETRY BREAKING

Chiral Effective Field Theory
and
Selected Applications

CHIRAL SYMMETRY

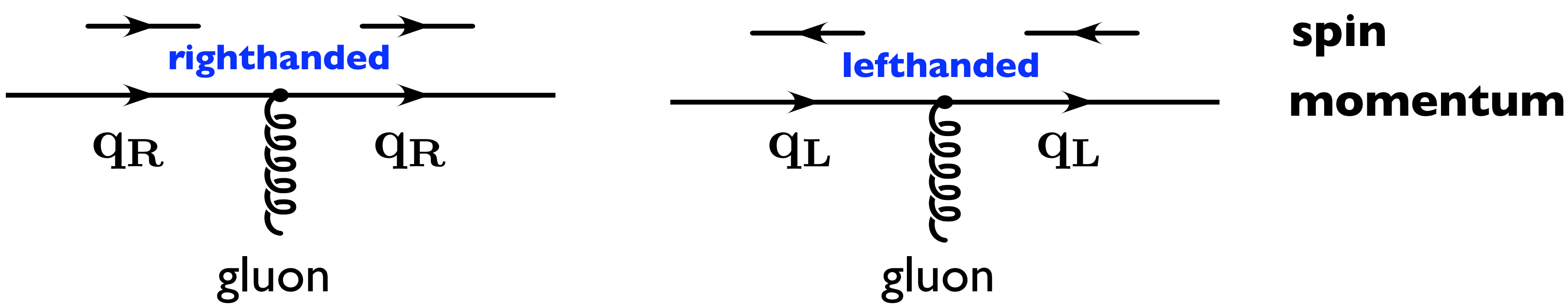
- QCD with $N_f = 2$ MASSLESS QUARKS

$$\mathcal{L}_{QCD} = \bar{\psi}_R \, i\gamma_\mu \mathcal{D}^\mu \, \psi_R + \bar{\psi}_L \, i\gamma_\mu \mathcal{D}^\mu \, \psi_L + \mathcal{L}_{GLUE}$$

$$\psi_R = \frac{1}{2}(1+\gamma_5)\psi \qquad \psi_L = \frac{1}{2}(1-\gamma_5)\psi$$

- ... invariant under $\psi_{R,L} \rightarrow exp\left[i \frac{\theta^a_{R,L} \tau_a}{2} \right] \psi_{R,L}$

CHIRAL $SU(2)_L \times SU(2)_R$ SYMMETRY



LOW - ENERGY QCD

- Physics in the **HADRONIC** (low T) phase of QCD

$$\mathcal{Z} = tr\, exp\left[-\frac{H_{QCD}}{k_B T}\right] = \sum_n \langle n|e^{-E_n/k_B T}|n\rangle$$

- **CONFINEMENT** at $T < T_{crit}$:

➡ Eigenstates $|n\rangle$ are (colour-singlet) **HADRONS**

- Spontaneously broken **CHIRAL SU(2) x SU(2) SYMMETRY**

➡ low-mass collective excitations :

GOLDSTONE BOSONS (PIONS)

... interact weakly at low energy / momentum

➡ non-trivial VACUUM $|0\rangle$:

CHIRAL (QUARK) CONDENSATE $\langle\bar{\mathbf{u}}\mathbf{u}\rangle = \langle\bar{\mathbf{d}}\mathbf{d}\rangle \neq 0$

CHIRAL EFFECTIVE FIELD THEORY

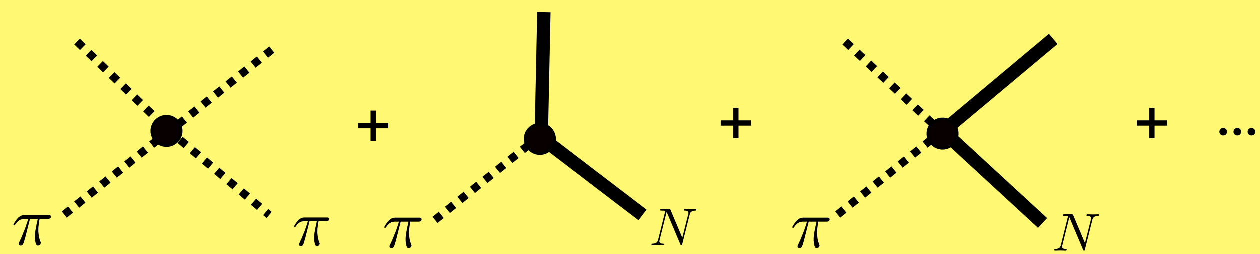
(Weinberg; Gasser & Leutwyler)

- **LOW-ENERGY QCD**: Effective Field Theory of weakly interacting **GOLDSTONE BOSONS** (PIONS)

- Interacting systems of PIONS coupled to BARYONS

(Weinberg ('68); modern developments: Ecker et al. ('94), Bernard, Kaiser, Meissner ('95) + many others)

$$\mathcal{L}_{eff}(U, \partial U, ..., N, ...); \qquad U(x) = exp[i\tau_a \pi_a(x)/f_\pi] \in SU(2)$$



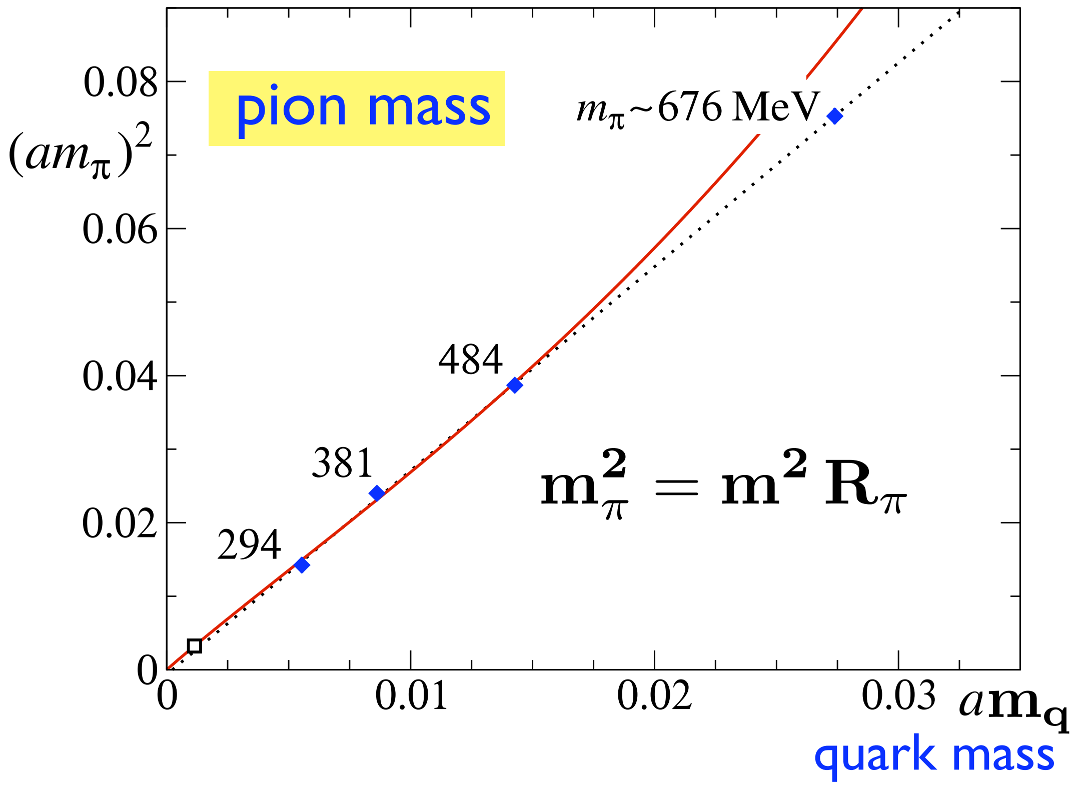
- Low-Energy Expansion: **CHIRAL PERTURBATION THEORY**

"small parameter": $\frac{\mathrm{p}}{4\pi\, \mathrm{f}_\pi}$ $\frac{\text{energy / momentum / pion mass}}{\text{mass gap of order 1 GeV}}$

Example I:

GOLDSTONE BOSON in LATTICE QCD

$32 \cdot 24^3$ lattice

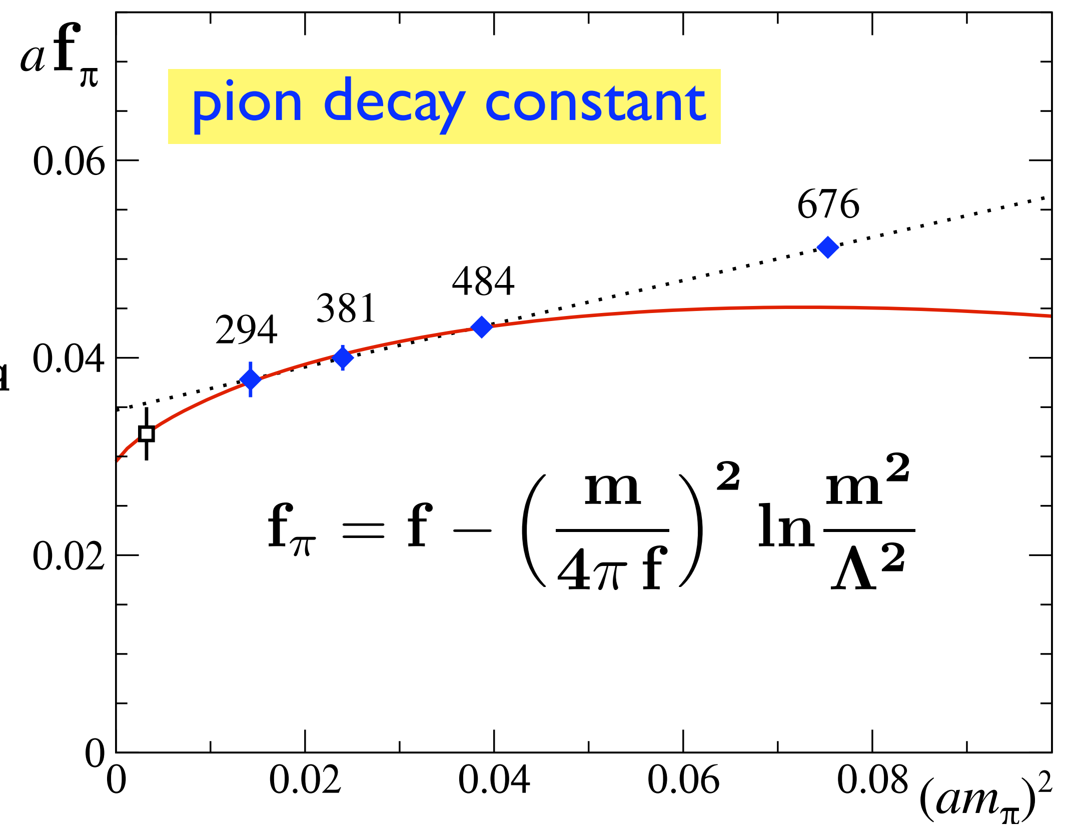


- PCAC: $\mathbf{m^2 = -\frac{2\, m_q}{f^2} \langle \bar{q} q \rangle}$

  (Gell-Mann, Oakes, Renner)

- ChPT correction:

  $\mathbf{R_\pi = 1 + \frac{1}{2}\left(\frac{m}{4\pi\, f}\right)^2 \ln\left(\frac{m^2}{\Lambda^2}\right) + \ldots}$



Lattice QCD data compatible
with 1-loop ChPT
up to $m_\pi \simeq 500$ MeV

M. Lüscher, Lattice Conf., Dublin, July 2005

ORIGIN of MASS

● HOW does the rest mass of the PROTON arise ? ●

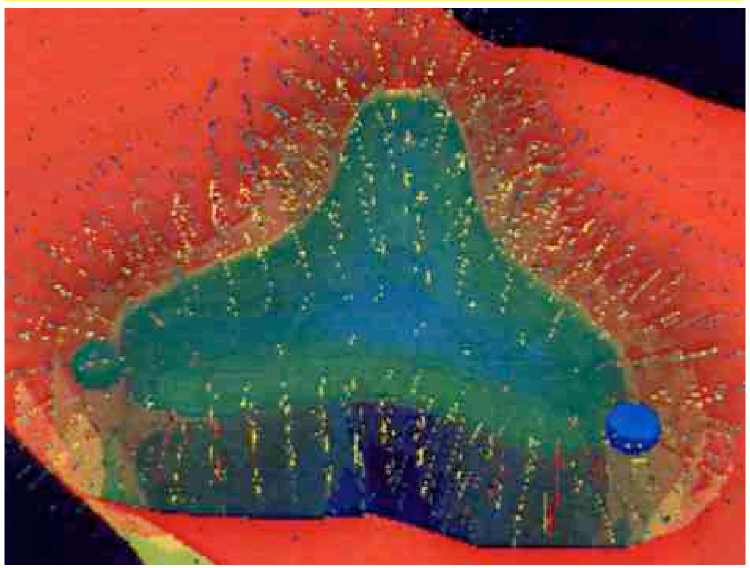
$$m_u \simeq 3\,\text{MeV} \quad m_d \simeq 6\,\text{MeV}$$

$$u + u + d = \text{proton}$$

$$\text{mass}: \quad 3 + 3 + 6 \neq 938\,!$$

answer:

mostly **GLUONS**

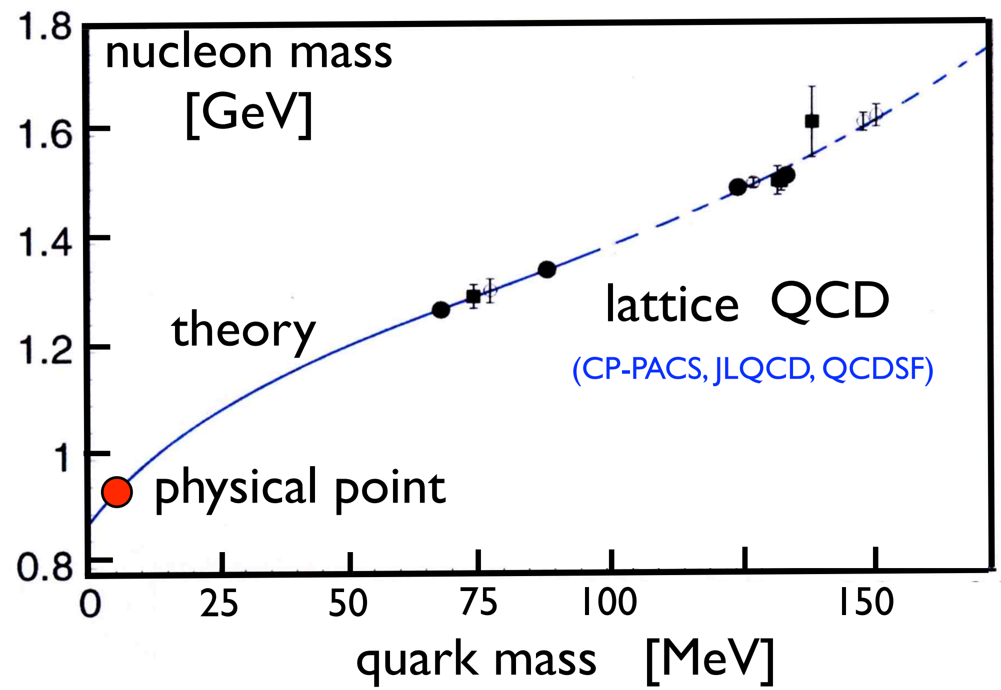


(D. Leinweber et al. 2004)

... at the same time:

$$M_N \sim \langle \bar{q}q \rangle$$

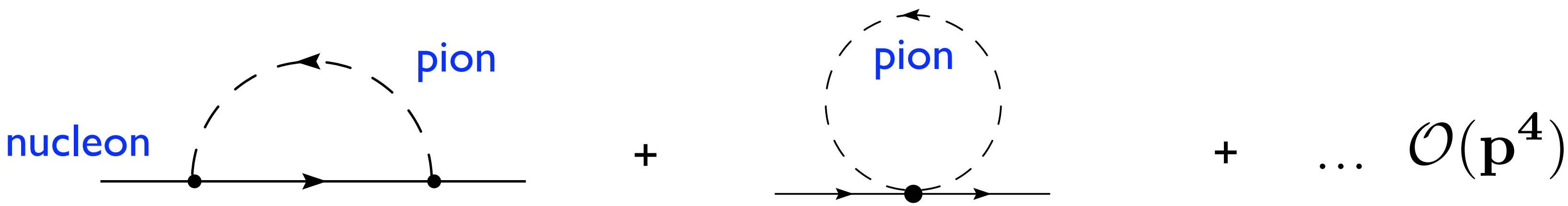
LATTICE QCD
and
CHIRAL EFFECTIVE FIELD THEORY



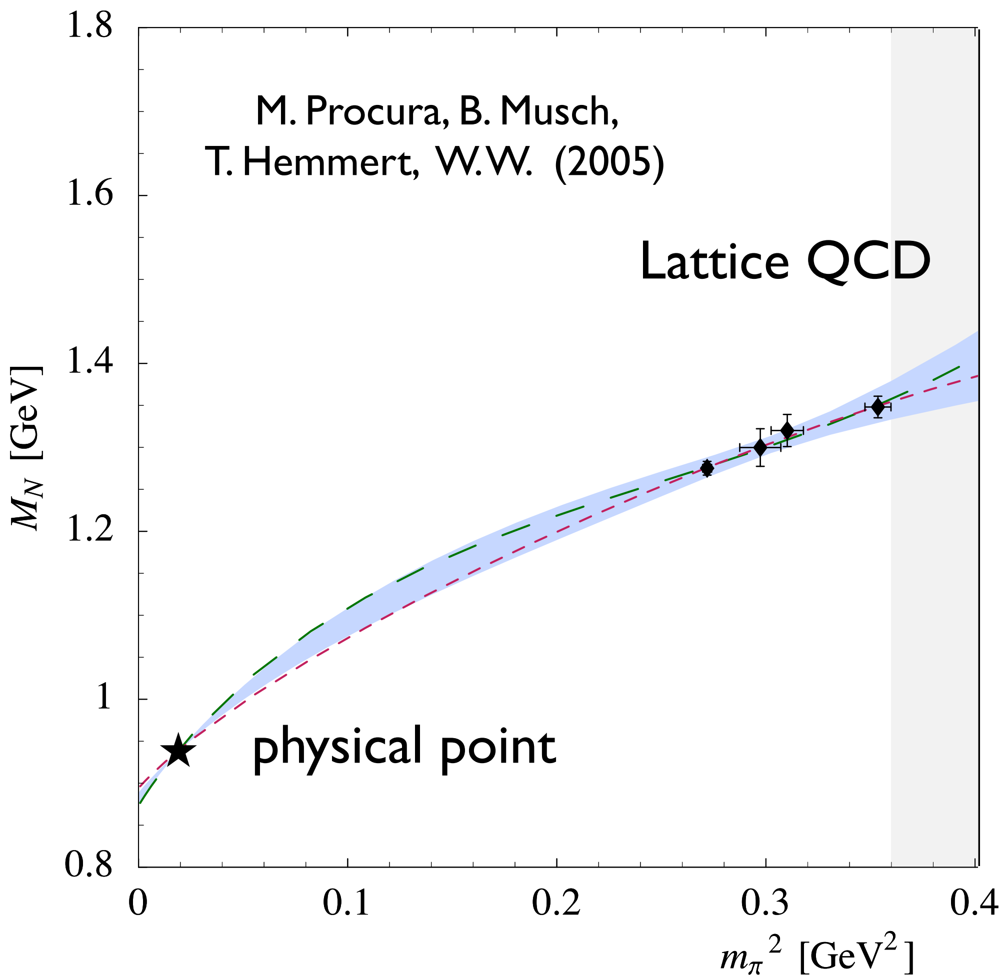
M. Procura, Th. Hemmert, W.W.
Phys. Rev. D69 (2004) 034505

(see also: Adelaide / JLab group,
D. Leinweber, A.W. Thomas et al.)

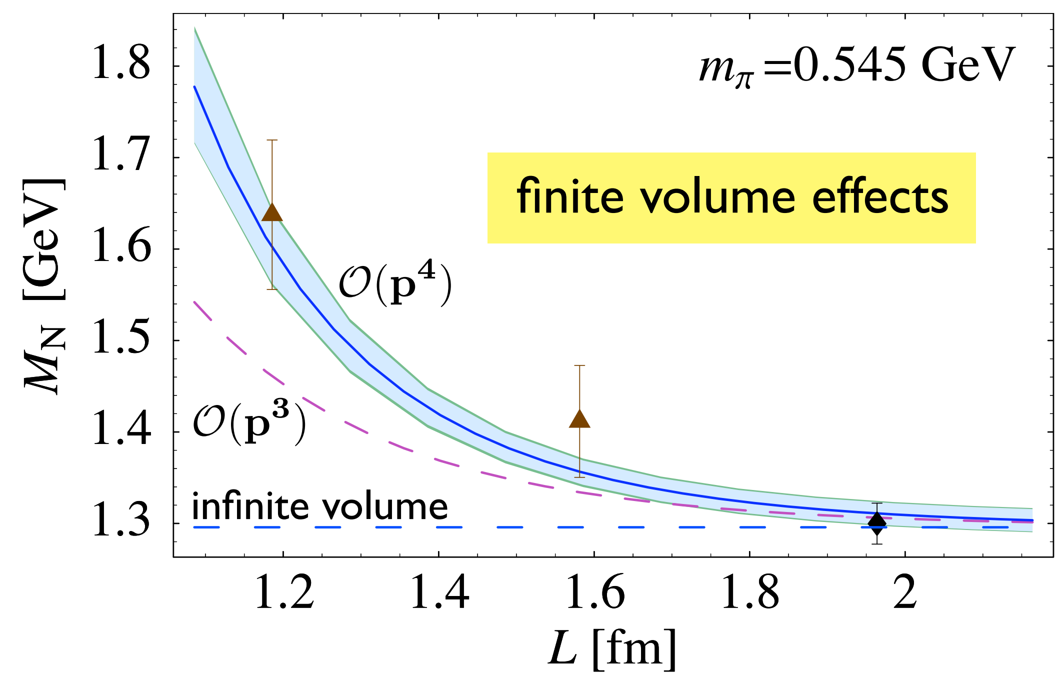
Example II: Chiral Extrapolation of **NUCLEON MASS**



$$M_N = M_0 + c\, m_\pi^2 + d\, m_\pi^4 + \frac{3\pi}{2}\, g_A^2\, m_\pi \left(\frac{m_\pi}{4\pi f_\pi}\right)^2 \left[1 + \frac{m_\pi^2}{4M_0^2}\right] + \mathcal{O}(m_\pi^6)$$

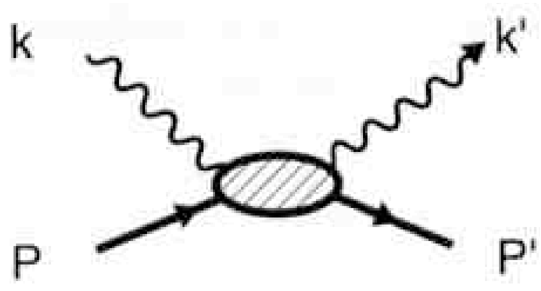


Parameters consistent with
ChPT analysis of low-energy
pion-nucleon scattering



Example III:
COMPTON SCATTERING on PROTON and DEUTERON

- Goal: determine PROTON and NEUTRON e.m. POLARIZABILITIES



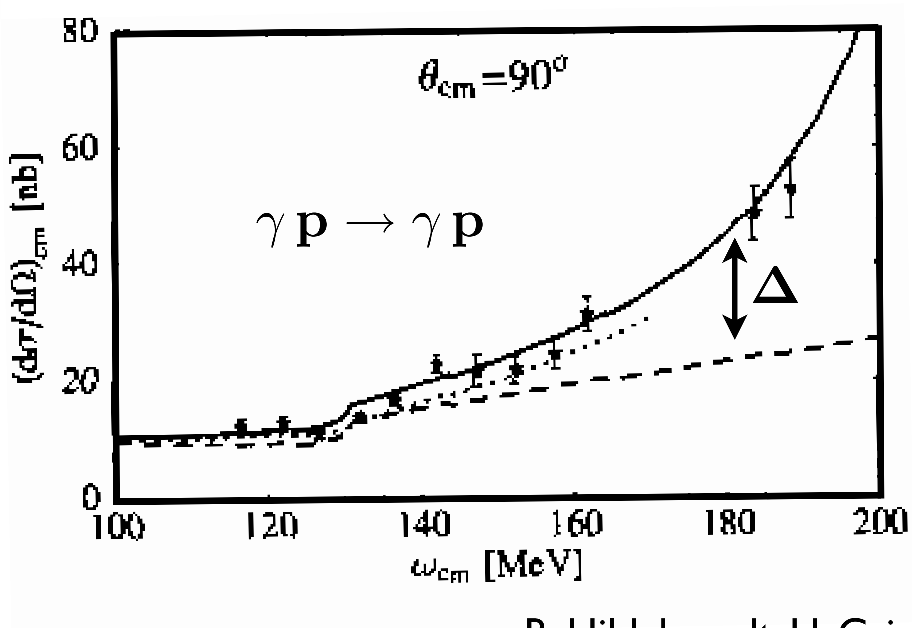
$$\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega} - \left(\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega}\right)_{\mathbf{point}} = -\frac{\mathbf{e^2}}{\mathbf{4\pi M}}\,\omega\,\omega'\left[\frac{\alpha_\mathbf{E}+\beta_\mathbf{M}}{\mathbf{2}}\,(\mathbf{1}+\cos\theta)^\mathbf{2}+\frac{\alpha_\mathbf{E}-\beta_\mathbf{M}}{\mathbf{2}}\,(\mathbf{1}-\cos\theta)^\mathbf{2}\right]$$

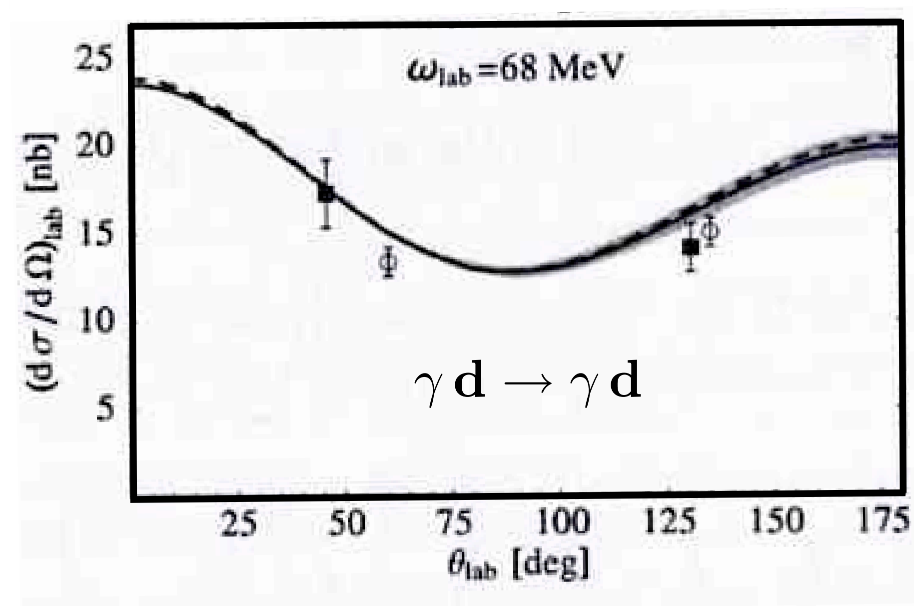
- Use **CHIRAL EFFECTIVE FIELD THEORY** for NUCLEON and DEUTERON

- Analyze detailed ENERGY DEPENDENCE of amplitudes: separate PARAMAGNETISM $(\mathbf{\Delta}(\mathbf{1230}))$ from DIAMAGNETISM

COMPTON SCATTERING on PROTON and DEUTERON

- contd. -





R. Hildebrandt, H. Grießhammer, T. Hemmert, D. Phillips:
Nucl. Phys. A 748 (2005) 573

POLARIZABILITIES:

proton

$$\alpha_E^p = (11.0 \pm 1.4) \cdot 10^{-4}\,\text{fm}^3$$

$$\beta_M^p = (2.8 \mp 1.4) \cdot 10^{-4}\,\text{fm}^3$$

neutron

$$\alpha_E^n = (11.6 \pm 2.1) \cdot 10^{-4}\,\text{fm}^3$$

$$\beta_M^n = (3.6 \mp 2.1) \cdot 10^{-4}\,\text{fm}^3$$

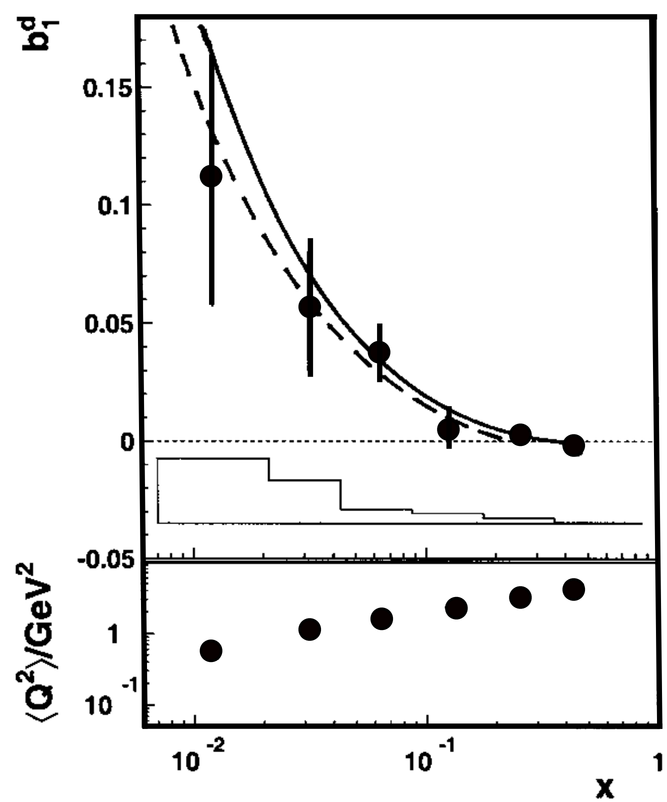
Example IV: TENSOR STRUCTURE FUNCTION b_1 of the DEUTERON

- Deep-inelastic scattering from a POLARIZED DEUTERON (spin-one) target

$$b_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left[q^{m=0}(x, Q^2) - q^{|m|=1}(x, Q^2) \right]$$

- Sensitive to TENSOR component of GOLDSTONE BOSON (pion) exchange between PROTON and NEUTRON

- Physics at the interface between partons and hadrons / nuclei



HERMES data:
C. Riedl et al. (2005)

THEORY (prediction):
J. Edelmann, G. Piller, W.W.
Phys. Rev. C 57 (1998) 3392

3.
CORRELATIONS
and
QUASI-PARTICLES
in QCD

Field Strength Correlation Length

Quasiparticles:
Nambu & Jona-Lasinio Model

Diquarks and related

GLUONIC FIELD STRENGTH CORRELATIONS
from LATTICE QCD

- **Gluon Condensate:**

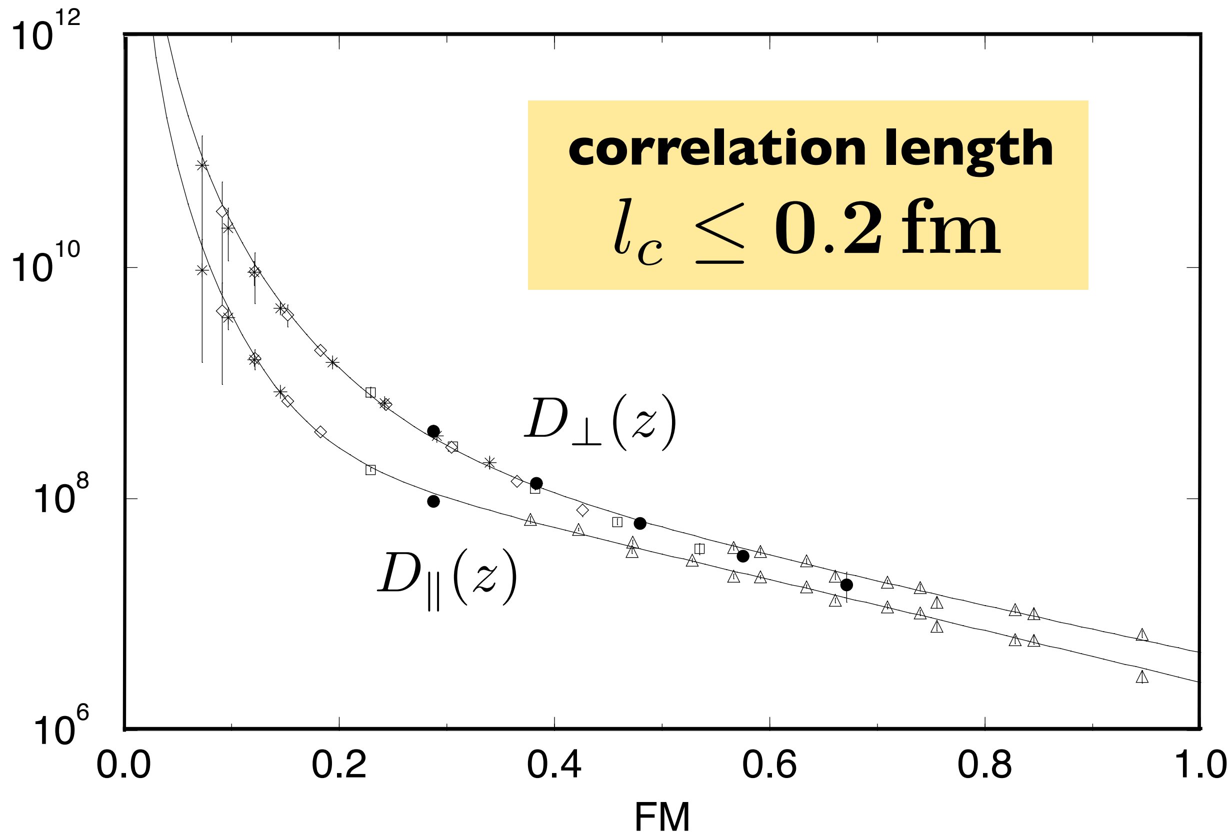
$$\mathcal{G}_0 \equiv \langle \frac{2\alpha_s}{\pi} Tr\, G_{\mu\nu} G_{\mu\nu} \rangle \sim 1.6\, GeV\ fm^{-3}$$

$$(G_{\mu\nu} \equiv \frac{\lambda_a}{2} G^a_{\mu\nu})$$

- **Field Strength Correlation Function:**

$$\mathcal{D}(x,y) \equiv \langle \frac{2\alpha_s}{\pi} Tr\, G_{\mu\nu}(x) \mathcal{S}(x,y) G_{\mu\nu}(y) \mathcal{S}^\dagger(x,y) \rangle \sim \mathcal{G}_0\, exp(-|x-y|/l_c)$$

A. Di Giacomo, H. Panagopoulos: Phys. Lett. B 285 (1992) 133



A. Di Giacomo et al.: Phys. Reports 372 (2002) 319

A SCHEMATIC MODEL: **NJL**

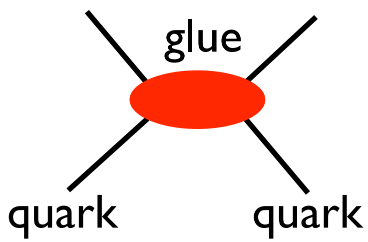
Y. **N**ambu, G. **J**ona-**L**asinio: Phys. Rev. 122 (1961) 345

... updates with applications to HADRON PHYSICS:
U.Vogl, W.W.; Prog. Part. Nucl. Phys. 27 (1991) 195
T. Hatsuda, T. Kunihiro; Phys. Reports 247 (1994) 221

- **QUARK COLOUR CURRENT**: $$\mathbf{J}^a_\mu(x) = \bar{\psi}(x)\gamma^\mu \frac{\lambda^a}{2}\psi(x)$$

- Assume: **short correlation range** for **"color transport"** between quarks

l_c < 0.2 fm



$G_c \sim g^2\, l_c^2$

$$\mathcal{L} = \bar{\psi}(x)\left(i\gamma^\mu\partial_\mu - \mathbf{m}_0\right)\psi(x) + \mathcal{L}_{int}$$

$$\mathcal{L}_{int} = -G_c\,\mathbf{J}^a_\mu(x)\,\mathbf{J}^\mu_a(x)$$

LOCAL SU(N_c) gauge symmetry of QCD

⬇

GLOBAL SU(N_c) symmetry of NJL model

- from local interaction of quark colour currents ...

$$\mathcal{L}_{int} = -G_c \, \mathbf{J}^a_\mu(x) \, \mathbf{J}^\mu_a(x)$$ (+ instanton-induced interaction)

- via Fierz transform to ...

➡ **QUARK-ANTIQUARK** channels

$$\mathcal{L}_{q\bar{q}} = G\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2\right] + \dots$$

+ vector
+ axial vector
+ colour octet terms

➡ **DIQUARK** channels

$$\mathcal{L}_{qq} = H(\bar{\psi}\,\Gamma^\dagger\,\bar{\psi}^T)(\psi^T\,\Gamma\,\psi) + \quad \dots$$

- from (light) current quarks to (massive) **CONSTITUENT QUARKS**

➡ $M = m_0 - 2G\langle\bar{\psi}\psi\rangle$ (gap equation)

➡ spontaneous **C**hiral **S**ymmetry **B**reaking

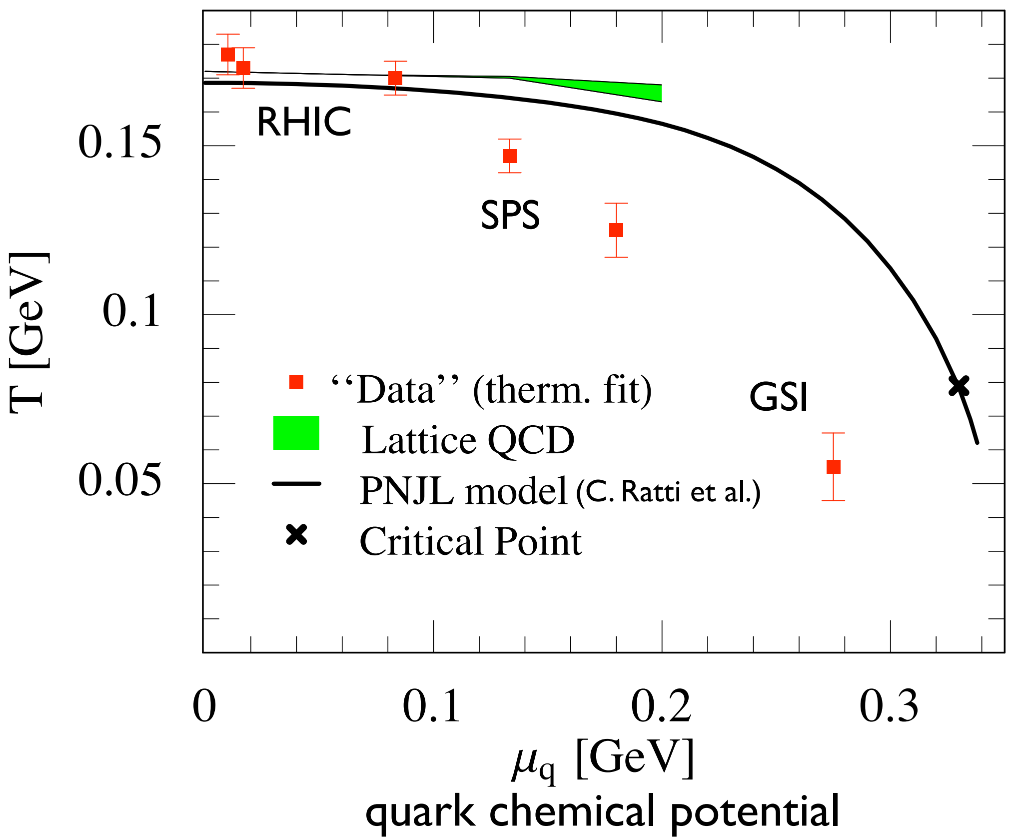
- pseudoscalar meson spectrum incl. **GOLDSTONE PIONS**
- NEW developments:

➡ synthesis **NJL** & **POLYAKOV LOOP** (confinement)

➡ modeling **QCD THERMODYNAMICS**

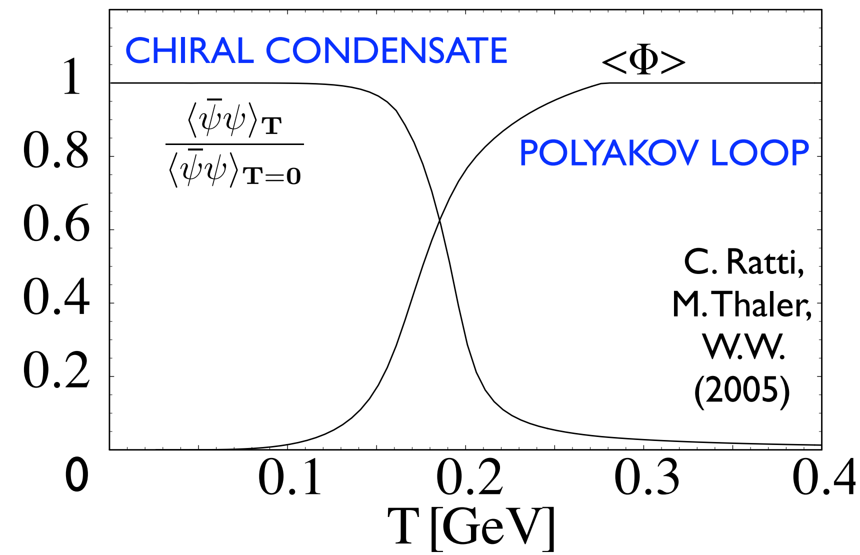
QCD THERMODYNAMICS

PHASE DIAGRAM

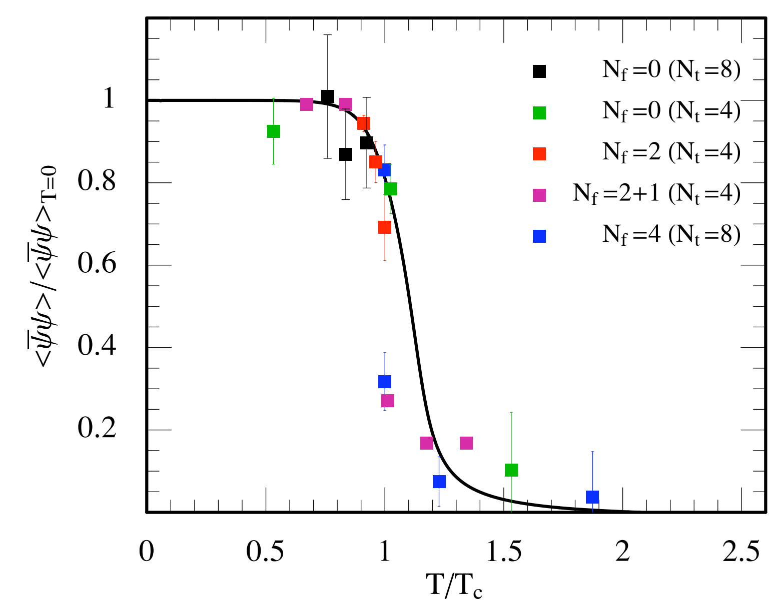


PNJL

(Synthesis NJL & Polyakov/Wilson)



CHIRAL and **DECONFINEMENT** transitions (almost) coincide !



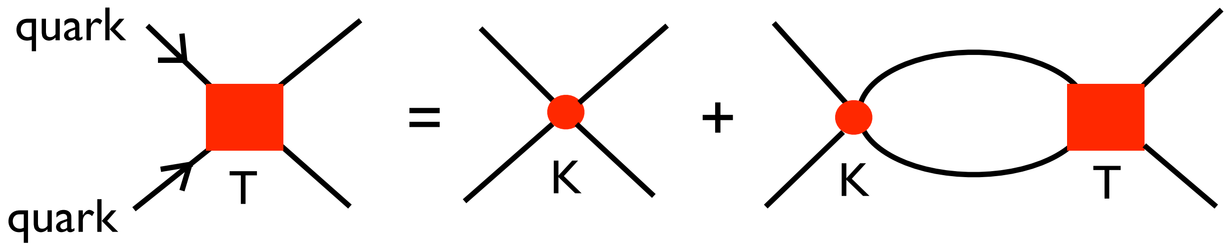
Lattice:
G. Boyd et al., Phys. Lett. B349 (1995) 170

BCS-type pairing of quarks into **DIQUARKS** at low T, large μ_q

(Rajagopal, Wilczek, ... **Colour superconductivity)**

the quest for **DIQUARKS**

- Bethe-Salpeter Equation in DIQUARK channels:



- Scalar Diquarks: $[\,\mathbf{q}\!\uparrow\;\downarrow\!\mathbf{q}\,]_{^1S_0}$ strongly attractive correlations

with NJL constituent quark masses $M_{u,d}$ = 0.35 GeV, M_s = 0.55 GeV:

➡ M(ud-du) = 0.3 GeV
SCALAR - ISOSCALAR

M(us-su) = 0.6 GeV

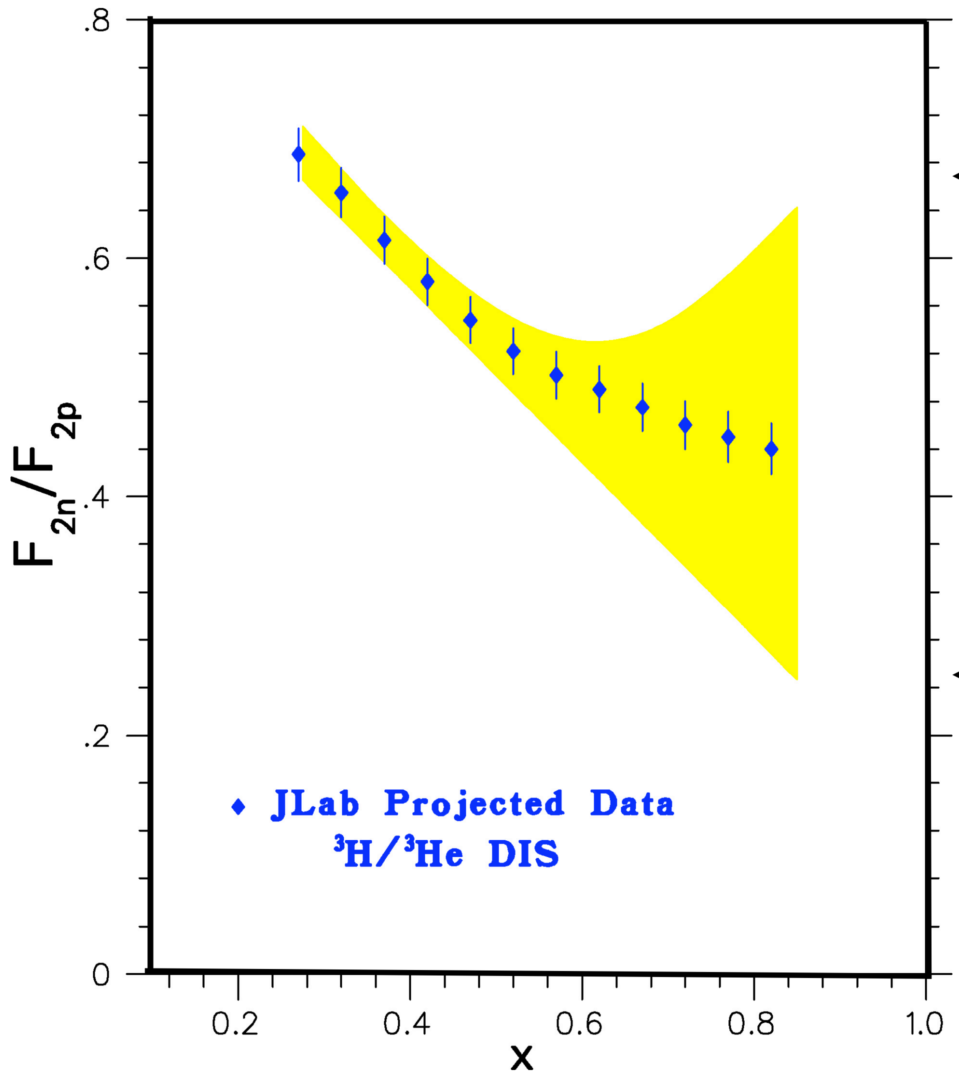
U.Vogl, W.W.: Prog. Part. Nucl. Phys. 27 (1991) 195

- Origin of Jaffe - Wilczek interpretation of the $[\mathrm{ud}]^2\bar{\mathrm{s}}$ pentaquark

R. Jaffe, F. Wilczek: Phys. Rev. Lett. 91 (2003) 232003

Correlations and Quasiparticles in DIS ?

- $\mathbf{F_2^{neutron}/F_2^{proton}}$ in the VALENCE QUARK region $\mathbf{x \to 1}$



SU(6) quark model

DIQUARK dominance of nucleon wave functions

4.
SUMMARY

- Confinement: "hidden" phenomenon, but:
  resulting symmetry breaking patterns govern LOW-ENERGY QCD

- Change of Paradigm in Hadron Physics;
  from naive quark-antiquark mesons and 3-quark-baryons to:

HADRONS as **MANY-BODY** systems

QCD VACUUM STRUCTURE and **THERMODYNAMICS**:
Condensed Matter Problem

Spontaneously broken **CHIRAL SYMMETRY** implies:
PIONS as long-wavelength constituents of nucleons (and other hadrons)

... also implies strong pairing correlations between quarks: **DIQUARKS**