Quark-Hadron Duality and the Transition to pQCD

Laboratori Nazionali di Frascati, June 6-8 2005

Hidden QCD Scales and Diquark Correlations

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M. Shifman and A.V. hep-ph/0501200,
Phys. Rev. D

Introduction

QCD with massless flavors (the chiral limit) classically contains no scale and conformally invariant. Quantum effects break this invariance, and the physical scale $\Lambda_{\rm QCD}$ appears due to so called dimensional transmutation,

$$\Lambda_{\rm QCD} = M_{\rm UV} e^{-\frac{8\pi^2}{b\, g^2_{\rm UV}}}$$

It is in one-loop approximation for the running coupling g, $M_{\rm UV}$ is the ultraviolet cut-off, $b = \frac{11}{3} N_c - \frac{2}{3} N_f$ and $g_{\rm UV} = g(M_{\rm UV})$.

Phenomenologically $\Lambda_{\rm QCD}$ is of order of few hundred MeV. In terms of hadronic masses the one of the ρ meson can be taken as a characteristic hadronic scale,

$$m_\rho = {\rm const} \times \Lambda_{\rm QCD} = 770 \text{ MeV}$$

Although parametrically $\Lambda_{\rm QCD}$ is the only scale in QCD indeed there are some evidences for an existence of numerically much larger hadronic scales.

- $\Delta I = 1/2$ enhancement in weak nonleptonic decays, the $\Delta I = 1/2$ amplitudes are about 10 times larger than the $\Delta I = \frac{3}{2}$ ones. Related is an enhancement in the ratio ϵ'/ϵ of the parameters of CP violation in *K* decays.
- A number of phenomena in heavy flavor decays, including a value of the Λ_b lifetime 10-15 % shorter than expected, large rates for $B \to \eta' X$ decays, importance of penguins in $b \to s$ transitions and problem with quark-hadron duality in $b \to u$ transitions.

- Large mass (958 MeV) of η'. Theoretically $\frac{m^2_{\eta'}}{m^2_N} \propto \frac{1}{N_c^3}$. In reality this ratio close to 1.
- Enhancement in comparison to perturbative QCD estimates in many exclusive processes with large momentum transfer.
- Large duality interval in 0^-, 0^+ quark channels.
- Large s-wave $\pi\pi$ interaction without prominent resonances.
- A small value of α', a slope of the pomeron, the vacuum Regge trajectory.
- Jet production in e^+e^- annihilation -- the total energy should be around 10 GeV to see clear-cut jets.
- Striking (and unexpected) experimental evidence from heavy ion collisions at RHIC. Instead of weakly coupled quark-gluon plasma hydrodynamical flow is seen.

Glueballs and low-energy theorems

Breaking of conformal invariance in QCD by quantum effect can be expressed as an anomaly in the trace of energy-momentum tensor θ^μ_μ

$$\theta^\mu_\mu = \frac{\beta(\alpha_s)}{4\alpha_s}\, G^a_{\mu\nu} G^{a\mu\nu}\,, \qquad \beta(\alpha_s) = \mu\,\frac{\mathrm{d}\alpha_s(\mu)}{\mathrm{d}\mu} = -b\,\frac{\alpha_s^2}{2\pi} + \ldots$$

The dilation feature of θ^μ_μ leads to the low-energy theorems

Novikov, Shifman, A.V., Zakharov '81

$$\int \mathrm{d}x\,\left\langle 0|T\left\{\frac{\beta(\alpha_s)}{4\alpha_s}\,G^2_{\mu\nu}(x), \mathcal{O}(0)\right\}|0\right\rangle = -(d+\gamma)\,\langle 0\,|\mathcal{O}(0)|\,0\rangle$$

d is canonical and γ is anomalous dimension of the local operator $\mathcal{O}$. For $\mathcal{O} = G^2_{\mu\nu}$

$$\int \mathrm{d}x\,\left\langle 0|T\left\{\frac{\alpha_s}{\pi}\,G^2_{\mu\nu}(x), \frac{\alpha_s}{\pi}\,G^2_{\gamma\delta}(0)\right\}|0\right\rangle = \frac{32}{b}\left\langle 0\left|\frac{\alpha_s}{\pi}\,G^2_{\mu\nu}(0)\right|0\right\rangle$$

Using the phenomenological value for gluon condensate

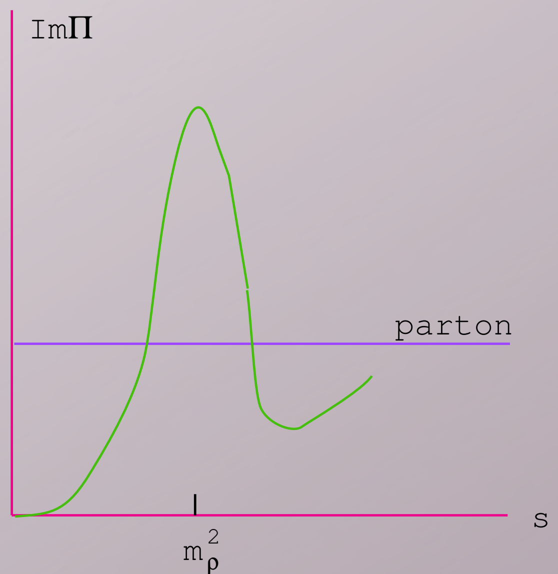
$$\left\langle 0 \left| \frac{\alpha_s}{\pi} G^2_{\mu\nu}(0) \right| 0 \right\rangle = (330 \text{ MeV})^4$$

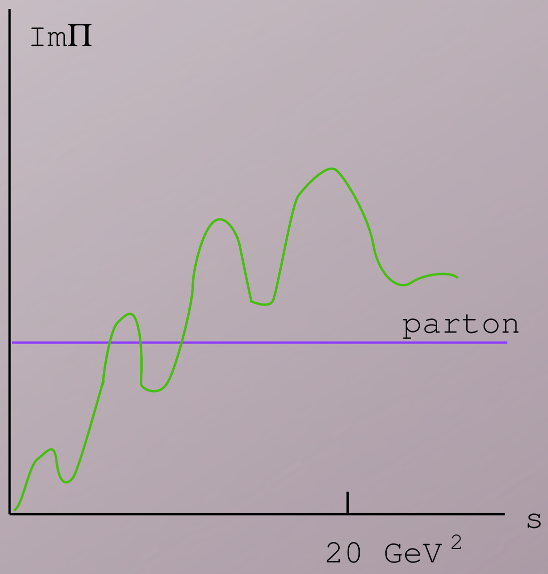
We find a large momentum scale λ_G at which perturbative and nonperturbative effects are comparable,

$$\lambda_G^2 = 20 \text{ GeV}^2$$

Compare with the scale in the 1^- isovector quark channel

$$\lambda_\rho^2 = m_\rho^2 = 0.6 \text{ GeV}^2$$





Hadronic spectroscopy and diquark correlations

- Hadron spectroscopy -- constituent quark model is very successful
- Other correlations: light pion in 0^- $q\bar{q}$
- Diquark correlations

Instanton considerations

Schafer, Shuryak, Verbaarschot ‘94
Cristoforetti, Faccioli, Shuryak, Triani ‘04

Enhancement in weak nonleptonic decays

Stech ‘87, Dosch, Jamin, Stech ‘89, Neubert, Stech ‘91
Shifman, A.V., Zakharov ‘77

Pentanquarks

Predicted in the chiral-quark-soliton model

Praszalowicz '87, Diakonov, Petrov, Polyakov '97

Diquarks as an alternative explanation for pentaquark. Other phenomenological evidences from hadron spectroscopy. "Good" diquarks: color-flavor locked antisymmetric combination

Karliner, Lipkin '03, 04
Jaffe, Wilczek '03, Jaffe '04
Shuryak, Zahed '04

Size of diquark

Considerably smaller than the nucleon size. Same for the constituent quark. A few GeV for 0^- $q\bar{q}$
We argue that a similar scale shows up in diquarks

Special role of diquarks in large-N expansion.

Of course, introduction of diquarks is not to replace the quark model which is quite successful. For instance,

$$\frac{\mu_p}{\mu_n} = -1.47$$

can be compared with -3/2 predicted by the quark model.

Pion matrix elements

We know about "abnormally strong" interaction in $0^- \, q\bar{q}$ channel where the light pion exists. One can present a strong argument for a short-range core in the pion. Consider,

$$\langle 0|\bar{d}\gamma_\mu\gamma_5 u|\pi^+\rangle = i f_\pi \, q_\mu \, ,$$

$$\langle 0|\bar{d}\gamma_5 u|\pi^+\rangle = i f_\pi \, \frac{m_\pi^2}{m_u + m_d} \, .$$

The second matrix element is enhanced by

$$\frac{m_\pi^2}{m_u + m_d} \approx 1.8 \text{ GeV}$$

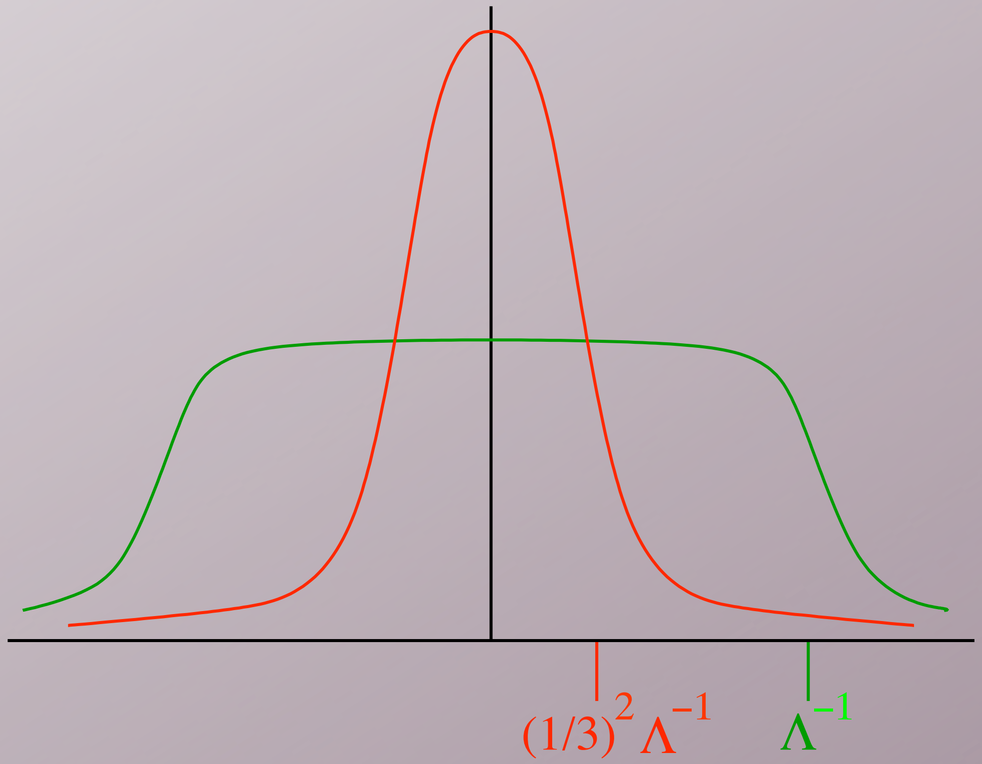
Smooth in the chiral limit $m_q \to 0$, rather large numerically.

Within QCD sum rules it shows as difference in duality intervals

$$\bar{d}\gamma_\mu\gamma_5 u \; : \qquad 0.6\ \mathrm{GeV}^2,$$
$$\bar{d}\gamma_5 u \; : \qquad 1.9\ \mathrm{GeV}^2.$$

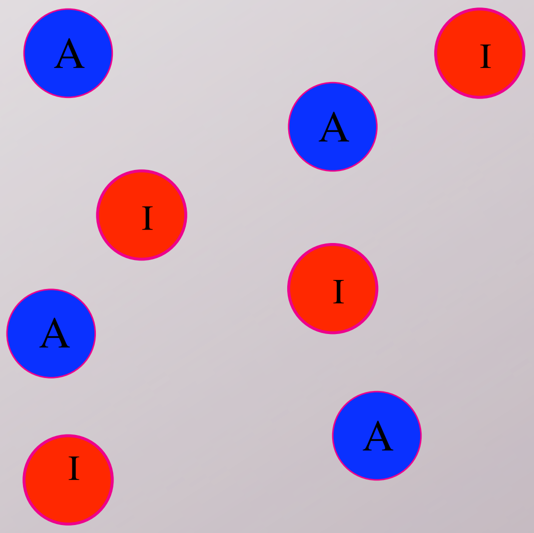
How we can interpret this large scale in the $\bar{d}\gamma_5 u$ channel? Matrix elements as $\psi_t(\vec{r}=0)$, twist $t=2,3$

$$\psi = \alpha_2\psi_{t=2} + \alpha_3\psi_{t=3}$$



In the instanton liquid model

$$\rho = 0.48\,\Lambda_{\rm QCD}^{-1} \qquad R = 1.35\,\Lambda_{\rm QCD}^{-1}$$



In Minkowski world ρ^{-1} is the geometrical mean between $\Lambda_{\rm QCD}$ and the higher glueball scale $\Lambda_{\rm gl}$

$$\Lambda_{\rm gl} \sim 3^2 \Lambda_{\rm QCD}$$

Diquarks' progenitors

What about diquarks' sizes? Can be related to the pion ones when the color SU(3) is replaced by SU(2).
Flavor group becomes SU(4)

$$\chi^i = \begin{pmatrix} u_L \\ d_L \\ \bar{d}_R \\ -\bar{u}_R \end{pmatrix}$$

and the the pattern of the spontaneous breaking is

$$\mathrm{SU}(4) \to \mathrm{SO}(5)$$

Dimopoulos '80, Peskin '80
Kogan, Shifman, Vysotsky '85

Antysymmetric $\chi^i\chi^j$ is 6-vector of O(6).
Vacuum average is aligned as

$$\langle \bar{u}u + \bar{d}d \rangle = \langle \bar{u}_R u_L + \bar{u}_L u_R + \bar{d}_R d_L + \bar{d}_L d_R \rangle \neq 0$$

Five Godstones corresponding to

$$\bar{u}_R u_L - \bar{d}_R d_L - (R \leftrightarrow L) = -\bar{u}\gamma_5 u + \bar{d}\gamma_5 d\,,$$

$$\bar{u}_R d_L - (R \leftrightarrow L) = -\bar{u}\gamma_5 d\,, \qquad \bar{d}_R u_L - (R \leftrightarrow L) = -\bar{d}\gamma_5 u\,,$$

$$u_L d_L + (R \leftrightarrow L) = -uC\gamma_5 d\,, \qquad \bar{d}_L \bar{u}_L + (R \leftrightarrow L) = -\bar{d}C\gamma_5 \bar{u}\,.$$

Two-component spatial structure is the same for pions and diquarks.
Symmetry does not hold for the SU(3) color group but an approximate similarity could be there.

't Hooft 1/N expansion 't Hooft '74

Topological expansion, N_f scales as N Veneziano '76

Recent "orientifold" expansion Armoni, Shifman, Veneziano '03

based on treating quarks as two-index antisymmetric representation of the color SU(N).

Different from the 't Hooft 1/N expansion for

- quark mass dependence of vacuum energy
- the OZI rule

Two fundamental relations

$$\frac{d}{dm_q}\mathcal{E}_{\rm vac} = \langle \bar{q}\, q \rangle \qquad \mathcal{E}_{\rm vac}\Big|_{m_q=0} = \frac{\beta(\alpha_s)}{16\alpha_s}\left\langle G^a_{\mu\nu}\, G^{\mu\nu\, a}\right\rangle$$

imply that $\mathcal{E}_{\rm vac}$ changes by factor 2 when m_s increases from 0 to 150 MeV.

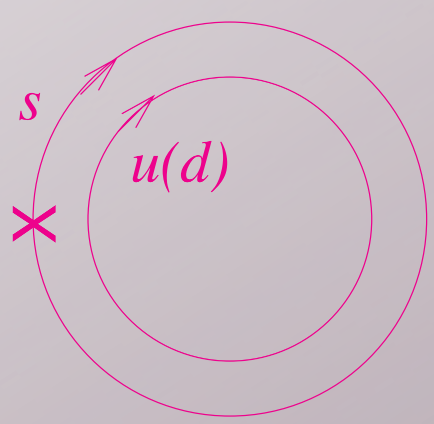
OZI rule works for 1^- but fails for $0^\pm$.

“Direct” instantons were suggested as a source.

Novikov, Shifman, A.V., Zakharov ‘81

What is the relevant Minkowski picture?
In $0^{\pm}$ glueball channels a large scale of order of 4 GeV, appears, order of magnitude larger the conventional one.

Diquarks contribute without 1/N suppression as pointlike bosons for momenta below R_{dq}^{-1}



Contribution of diquarks to $\langle \bar{s}s \rangle$

Possibility of 4-quark exotic mesons

Diquarks and weak nonleptonic decays

In case of light quarks the theoretical problem is to explain an enhancement (of order of 10) of the $\Delta I = 1/2$ amplitude in strangeness-changing decays. One of relevant operators can be written in the form

$$O_1 = 2\left[\epsilon_{kji} d^j C \frac{1-\gamma_5}{2} u^i\right]^\dagger \left[\epsilon_{knm} u^n C \frac{1-\gamma_5}{2} s^m\right]$$

which relates its matrix element with $\psi(0)$ of diquarks. Stech '87, Dosch, Jamin, Stech '89, Neubert, Stech '91

Earlier, together with penguin operators O_1 was used to fit the hyperon decays.

Shifman, A.V., Zakharov '77

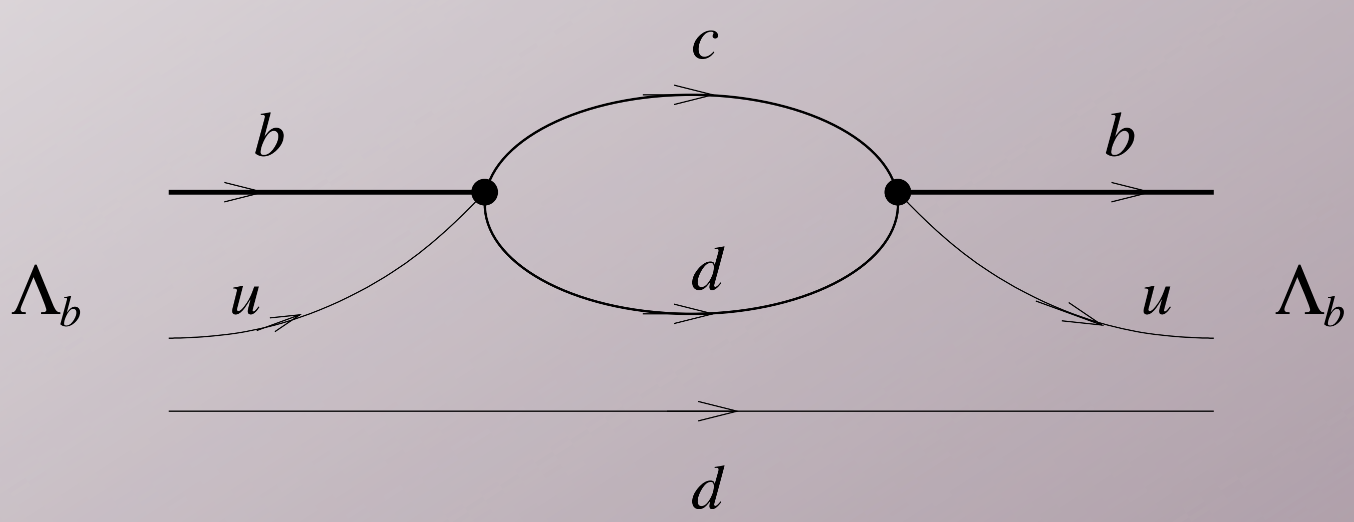
For b-containing baryons diquarks could play a role in the problem of lifetimes, $\tau(\Lambda_b)$ in particular.

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} \sim 0.8 - 0.9$$

Pre-asymptotic m_b^{-3} corrections Shifman, Voloshin '85

$$O_- = 2\,(j_k)^\dagger\,(j_k)$$

$$j_k = \varepsilon_{kji}\, b^j C\, \frac{1-\gamma_5}{2}\, u^i$$



Hidden scale and deep inelastic processes

At first sight diquark correlation could result in enhancement of the higher twist corrections $Q^{(-t+2)}$
The effect does not show up, however, at the twist 4, $1/Q^2$, which is next-to-leading one. Jaffe, A.V. '04

Still at Q smaller than the hidden scale diquarks act as pointlike spin 0 bosons. This implies a strong impact on longitudinal structure functions. The experimental situation with σ_L seems inconclusive.

Lattice calculations

Signals of a shorter scale in some lattice calculations: the size of the 0^+ glueball is about 0.2 fm (versus 1 fm)

Forcrand, Liu '92, A. Hasenfratz, Nieter '98

Conclusions

- Numerous evidences signal existence of hidden QCD scales.
- When the gauge group is reduced to SU(2) diquarks are well-defined objects related to pions by a global symmetry. Both have a two-component structure with a relatively short-range core. Semi-quantitatively may stay for the SU(3) color.
- Short-ranged diquark correlations play an important role in QCD vacuum structure resolving large-N problems.
- These correlations seems to be instrumental in understanding weak nonleptonic decays for hyperons and baryons containing heavy quarks.