Hadron mass generation and the structure of the strong interaction

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Starting point

- **In the hierarchy of quantum systems hadrons represent the smallest substructure known inside of atoms and nuclei, which should be build directly on the absolute vacuum of fluctuating gluon fields with absolute energy <E>=0.**
- **This is possible only, if the vacuum of the theory (of the strong interaction) is close to the absolute vacuum, requiring that the elementary fermions (quarks) have only a <u>very small mass</u>.**

- **This is not fulfilled in QCD**

Possible other problems of QCD

- Axion problem: non-zero quark masses may require the existence of Axions.

- Difficulties to understand the strong scalar potentials in hadrons, densities of hadrons, scalar transition densities for hadron resonances, hadron compressibility. Mass obtained in a very indirect way.

- Relation of QCD to other fundamental forces

  Realisation of supersymmetry? ...

→ Although QCD describes many aspects of hadron structure very well, there is the suspicion that the real theory of the strong interaction might be slightly different (with simpler symmetry properties).

Do the strong scalar fields observed show the real character of the strong interaction?

→Description of mass and the strong scalar fields in hadrons <u>may require</u> a scalar two-gluon coupling

→ **Interaction term (gluon-gluon coupling) in the Lagrangian is of the form g-g(0^+) → $(\bar{q}q)^n$**

Lagrangian

$$L_{SI} = \Psi^* i\gamma_\mu D^\mu \Psi - \frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - G_\mu G^\mu)$$

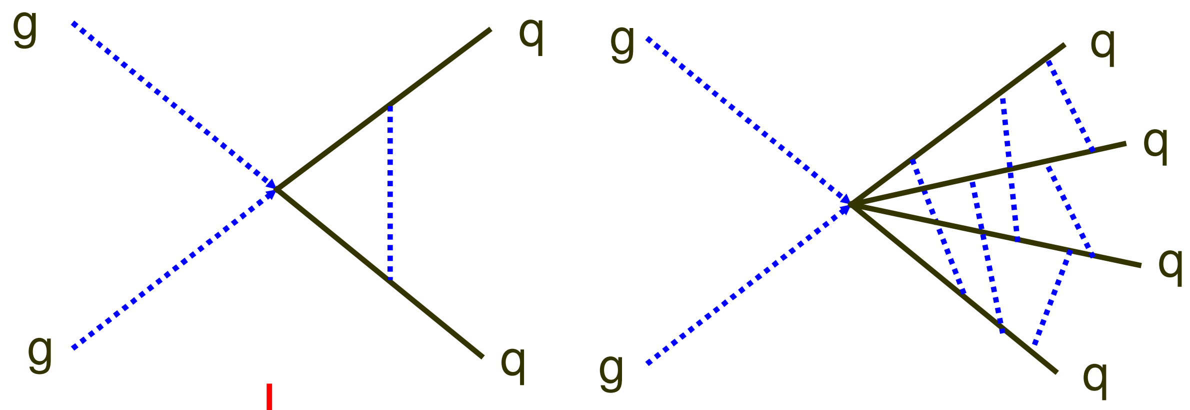
$$with\ D^\mu = \partial^\mu - ig_s A^\mu \quad and \quad F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

$$G^\mu = -g_s^{'} A^\mu \left[b_1(\Psi^* V_{1g} \Psi) + b_2(\Psi^* V_{1g} \Psi)^2 + b_3(\Psi^* V_{1g} \Psi)^3 + \ldots \right]$$

$G_\mu G^\mu$ couples two gluons (with the quantum numbers of the vacuum) to $\bar{q}q$-pairs. This term implies a colour neutral coupling of two gluon fields

→ the colour degree of freedom is <u>not needed</u>.

Feynman diagrams



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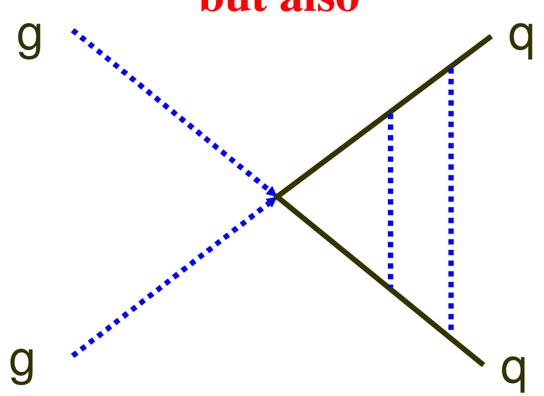

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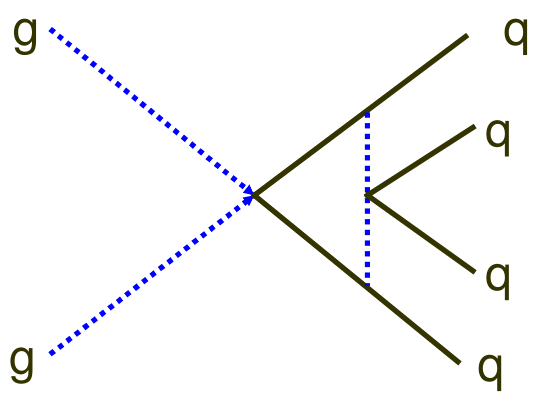


Assumption: Hadrons are stationary states with solutions $\Phi(x)=\Phi(r)\, e^{-i\omega t}$

$$\Phi(r = r_1 - r_2) = g_s'^{\,2} < A_1(r_1) \left| \left[b_1(a_q^t V_{1g} a_q) + b_2(a_q^t V_{1g} a_q)^2 + \ldots \right]^2 \right| A_2(r_2) >$$

$(a_q^\dagger V_{1g} a_q)$ is described by a $\bar{q}$ q-density folded with an effective 1-gluon exchange interaction.

The $\bar{q}$ q-density is the probability of finding a $\bar{q}$ q-pair in a volume during a time interval Δt (related to the lifetime)
→ 1-gluon exchange between quarks is possible in all time slices $\Delta t/n=(r_1-r_2)/c$. For n>1 the folding method is applicable.

In the following only a few aspects will be discussed:

1. **2-gluon and $\bar{q}$ q-densities and mass of the $\bar{q}$ q-pair**
2. **Confinement potential**
3. **Binding energies and the masses of mesons**
4. **Asymptotic freedom**
5. **Baryons**

1. 2-gluon and $\bar{q}$q-densities and the mass of the created $\bar{q}$q-pair

We require

$$\rho_\Phi(r) \to \rho_{q\bar{q}}(r) = -V_{qq}(r) = -4\pi \int dr' \rho^p_{q\bar{q}}(r') V^{eff}_{1g}(r - r')$$

$$where\ V^{eff}_{1g}(r) = \nu(\alpha_s / r) e^{-cr} \approx \nu(\alpha_s / r) \rho_{q\bar{q}}(r)$$

Important: the vector coupling of the $\bar{q}$ q-pair requires a p-wave density

$$\rho^p_{qq}(\check{r}) = \rho^p_{qq}(r)\ Y_{1m}(\Theta,\Phi)$$

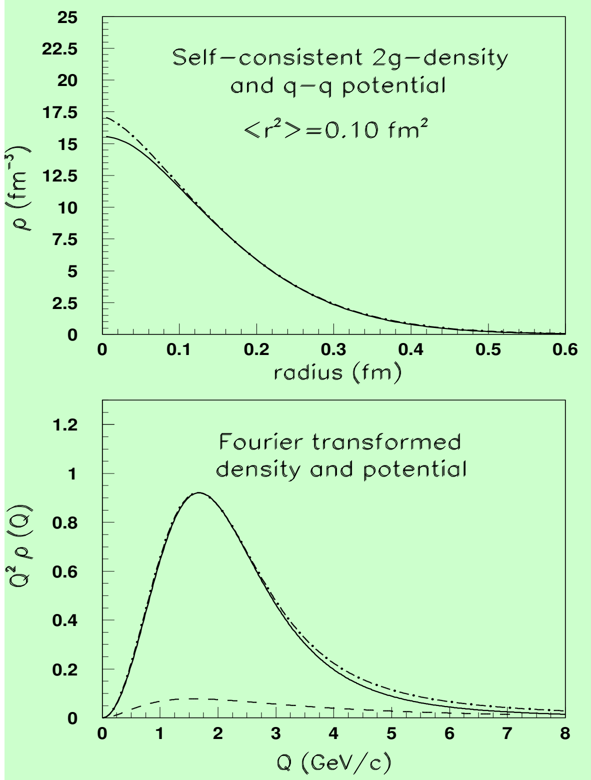
with the constraint $<r> = \int d\tau\, r \rho^p_{qq}(r) = 0$ (suppression of spurious motion)

Self-consistent density

$\rho(r) = \rho_o[\exp(-r/a)^\kappa]^2$ with $\kappa \sim 1.5$

→ density is constraint in radius, indicating that a **bound state** is obtained.

Analysis in momentum space: no inelasticity → **created $\bar{q}$ q-pair has no mass!**



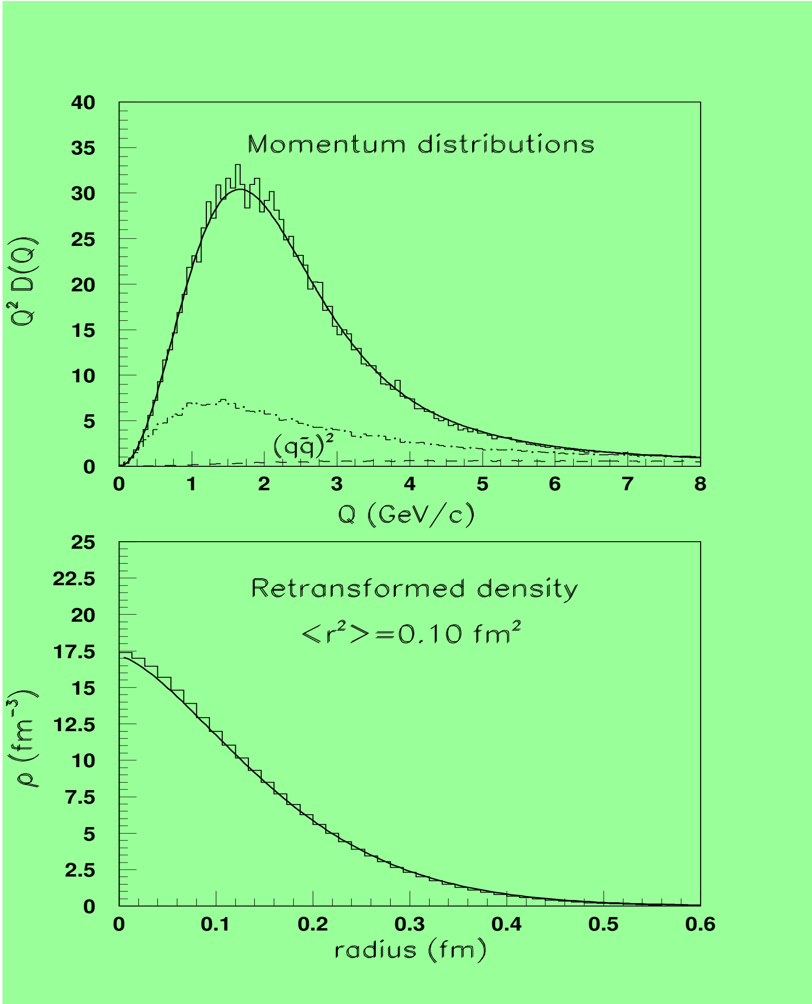
Monte Carlo simulations of $(\bar{q}q)^n$ creation

For inclusion of $(\bar{q}q)^n$ emission:

1. **$V_{qq}(Q)$ calculated as above**
2. **momenta of created quarks determined randomly by the Monte Carlo method**

→ **good description of 2-gluon densities (mesons)**

→ **self-consistent description of baryon densities**

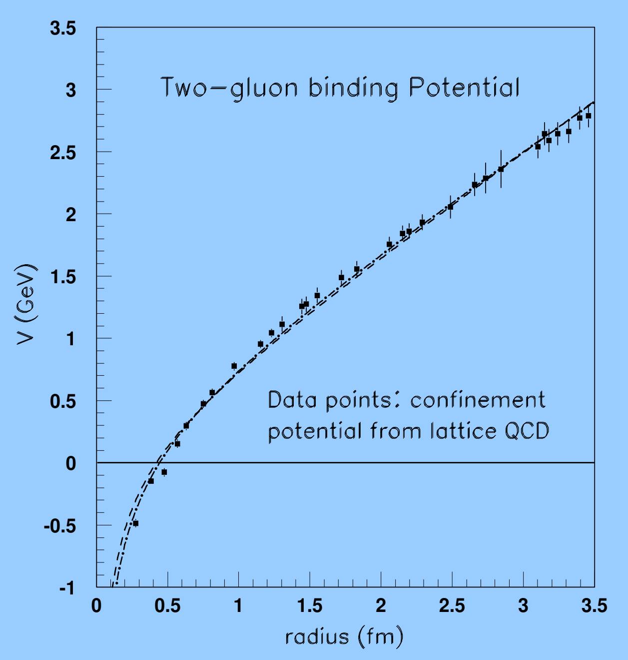


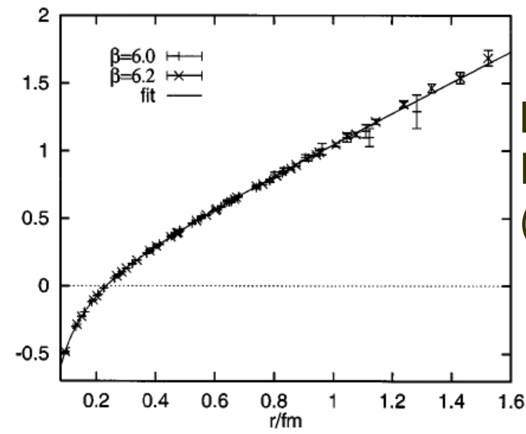
2. Confinement potential

($2g \rightarrow \bar{q}q$) system forms a bound state → Binding potential can be obtained from a 3-dim. reduction of the Bethe-Salpeter eq. in form of a relativistic Schrödinger equation

$$-\left(\frac{hbar^2}{2\mu_\Phi}\left[\frac{d^2}{dr^2}+\frac{2}{r}\frac{d}{dr}\right]-V_\Phi(r)\right)\psi_\Phi(r)=E_i\psi_\Phi(r) \quad with \quad \rho_\Phi(r)=\left|\psi_\Phi(r)\right|^2$$

μ_Φ *is relativistic mass parameter*





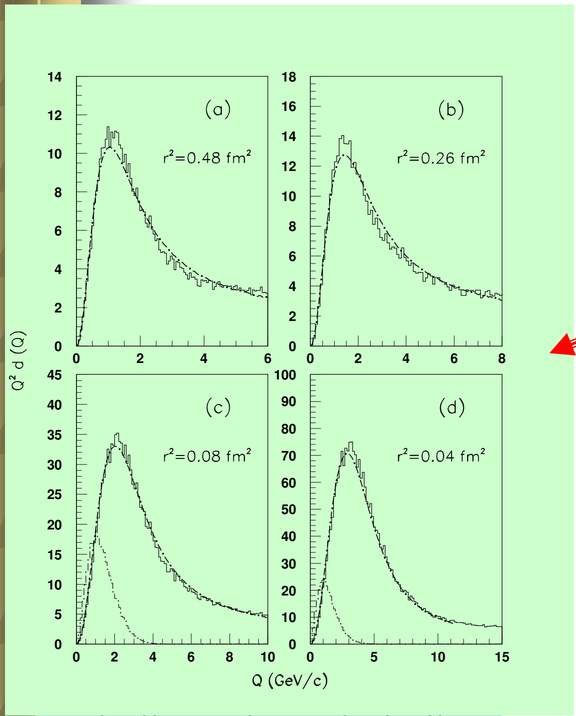
G. 2. Corrected static potential $V_{0,\,\mathrm{cont}}$ at $\beta=6.0$ and
.2. The fit curve correspon
the parameter values liste

Bali et al. Phys. Rev. D 62, 054503 (2000)

Resulting binding potential is consistent with confinement potential deduced from lattice QCD (Bali et al.)

What are the eigenstates in this potential?

3. Binding energies and masses of mesons

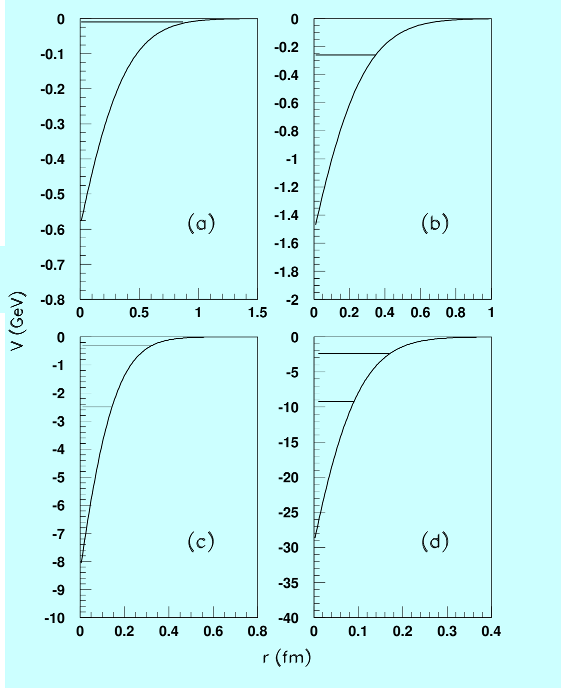


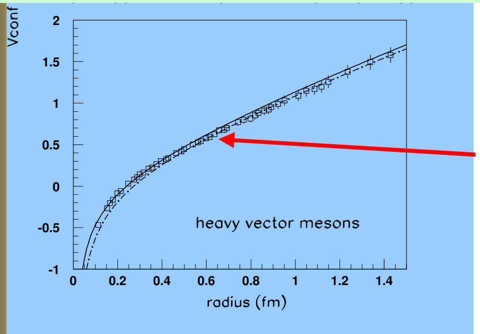
Self-consistent densities deduced (with massless quarks)

The mass is given by the binding energy in the folding potential $V_{qq}(R)$

$$V_{qq}(R) = \int v_{1g}(R-r')\,\rho_{\Phi}(r')\,dr'$$

Folding potential





Excited states are given by the binding energy in the self-induced confinement potential

Radial ambiguity (radius of system not constrained)!

<u>Discrete spectrum of 0^{++} states</u> obtained by application of a vacuum sum rule

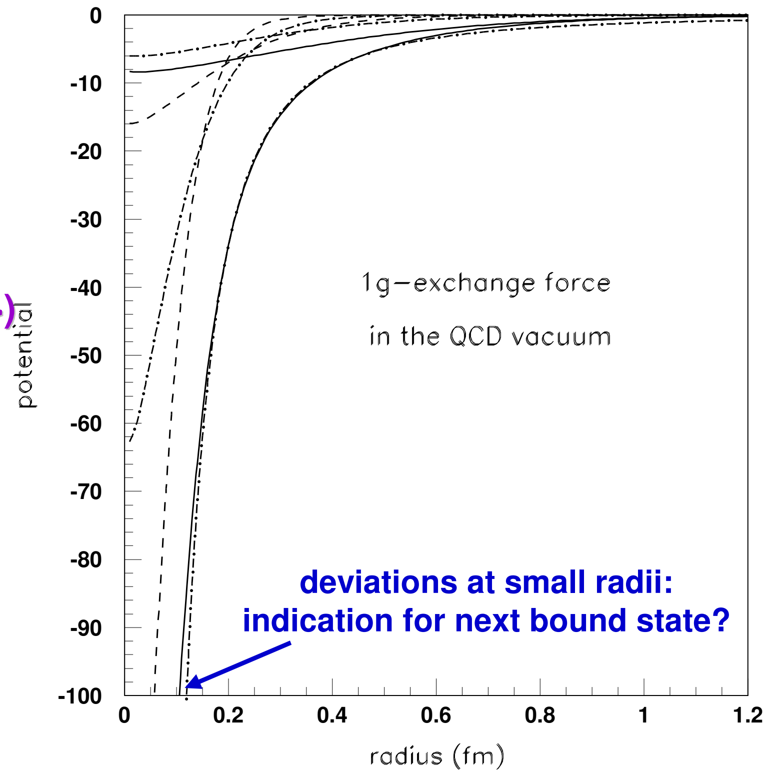
<u>q-q force in the vacuum</u>

q-q force is dominated by 1-gluon exchange (~Q^2) but should be cut by 1/Q → vacuum structure ~Q!

(explains also the relation M ~ 1 / < r^2 >)

This is confirmed by our Monte-Carlo simulations: self-consistent solutions are obtained only by random Q-distributions (linear in Q).

$$V(q\text{-}q) = \Sigma_i V_i(q\text{-}q)$$



This allows only five 0^{++} bound states with masses of about 0.6 GeV, 1.3 GeV, 2.3 GeV, 5.3 GeV, and 22 GeV
Corresponding vector 1^{--} states are consistent with the 'flavour states' ω(782), Φ(1020), J/ψ(3097), Υ(9460) and their radial excitations.

4. Asymptotic freedom

It has been shown by D. Gross, H.D. Politzer, and F. Wilczek, that QCD has the property of asymptotic freedom. This feature of the theory is essential to describe the bulk of data on deep-inelastic scattering. **Therefore, any valid theory of the strong interaction must show this property!**

Our Lagrangian has a scalar interaction term, which is very different from gluon-gluon coupling in QCD. Therefore, asymptotic freedom in our theory could not be understood by paramagnetic spin-effects.

Is asymptotic freedom obtained by screening of the 2-gluon density by the emitted $\bar{q}q$-pairs?

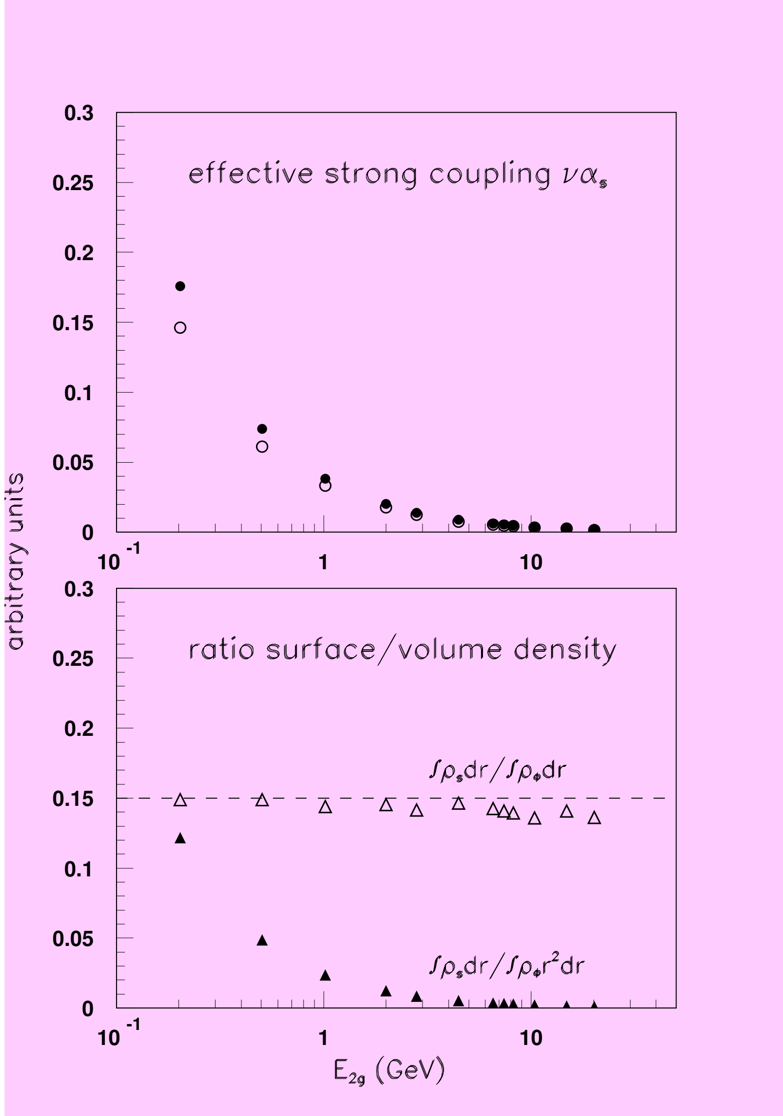
Very preliminary results

Study of self-consistent 2-gluon densities and the related effective 1-gluon exchange force as a function of E_{2g}

The same effect is observed in the quantity

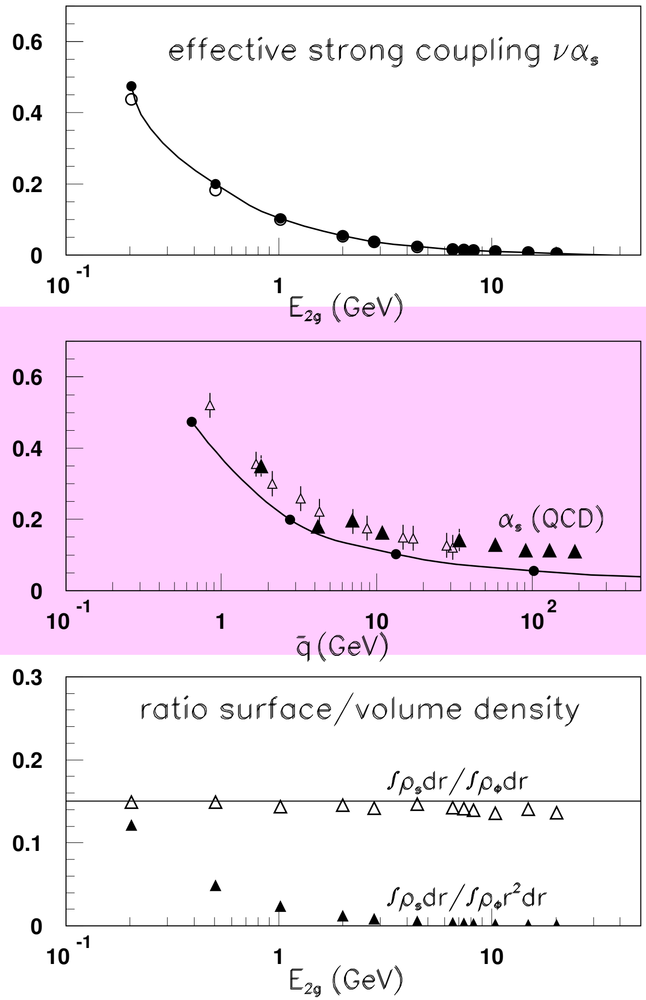
$\int \rho^{p}_{qq}(r)\, dr \,/\, \rho_{qq}(r)\, d\tau$

→ indication for screening



Comparison of the effective coupling (arbitrarily normalised) with α_s (QCD)

plotted as a function of the average momentum <Q>



5. Baryons

$gg \rightarrow (\bar{q}q)^{n>1}$ yield rather flat momentum distributions, which do not lead to confined bound states.

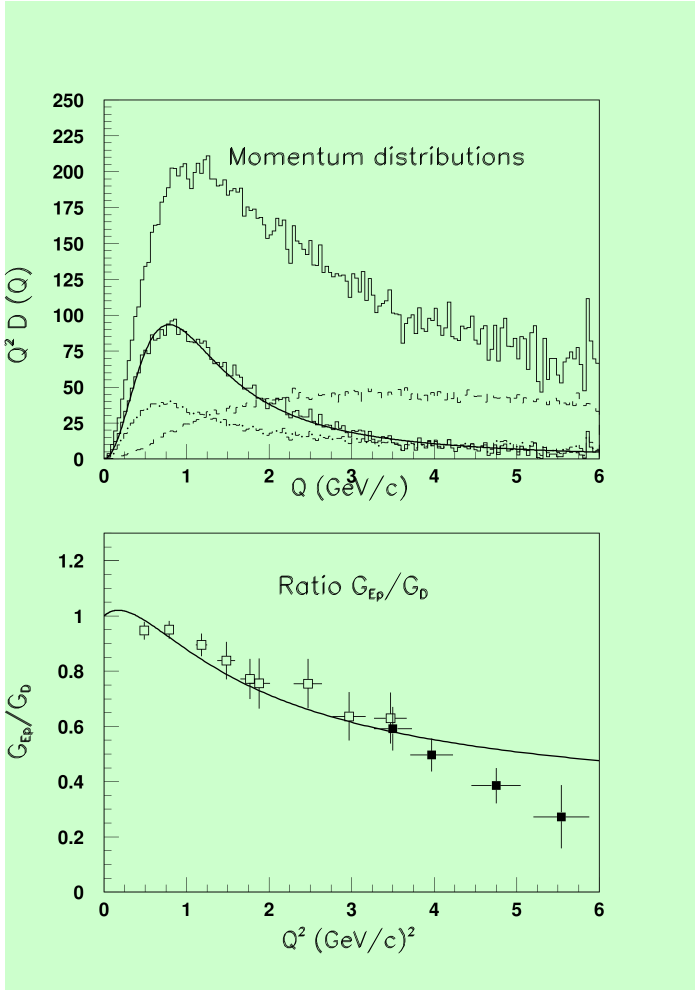
However, interference of $gg \rightarrow (\bar{q}q)^3$ and $gg \rightarrow (\bar{q}q)^5$ leads to stable baryon-antibaryon systems.

Simulation of the nucleon density assuming a configuration

$$gg \rightarrow | b_3 (\bar{q}q)q + b_5 (\bar{q}q)^2 q |^2.$$

The resulting density is consistent with the data on the electric form factor of the proton.

But the fit requires also a scalar nucleon density consistent with the N-sigma term (not seen in electron scattering).



Summary I

A gluon-gluon coupling in the Lagrangian $gg(0^+) \rightarrow (\bar{q}q)^n$ is used, which is slightly different from the Yang-Mills term in QCD, but has no colour and no flavour (massless quarks).

This leads to the five points discussed:

1. Direct coupling of hadron bound states to the vacuum (with massless quarks) → the vacuum of the theory is close to the absolute vacuum.
2. The confinement potential is obtained directly from the self-consistent $\bar{q}q$ densities.
3. Masses of 0^{++} and 1^{--} mesons are well described.
4. Preliminary results on the Q-dependence of the effective interaction are consistent with asymptotic freedom.
5. Baryons are obtained by the interference of $(\bar{q}q)^3$ and $(\bar{q}q)^5$ consistent with experimental data.

But there are many open questions to be investigated!!!

First results 1.-3. are in arXiv:0906.1742 [hep-ph]

Summary II: Consequences

I. **The structure of the theory is much simpler than that of QCD (no colour and no flavour degree of freedom): only two massless quarks with different charge (0 and 1) and one gluon.**

II. **No conflict with other fundamental forces, no supersymmetry!**

III. **Mesons are described by $(\bar{q}q)+\varepsilon(\bar{q}q)^2$ structure.**

IV. **Baryons are described by $(\bar{q}q)q+(\bar{q}q)^2q$ structure (best coupling to the vacuum!)**

V. **By the coupling to the absolute vacuum our theory leads back to the beginning of the universe.**

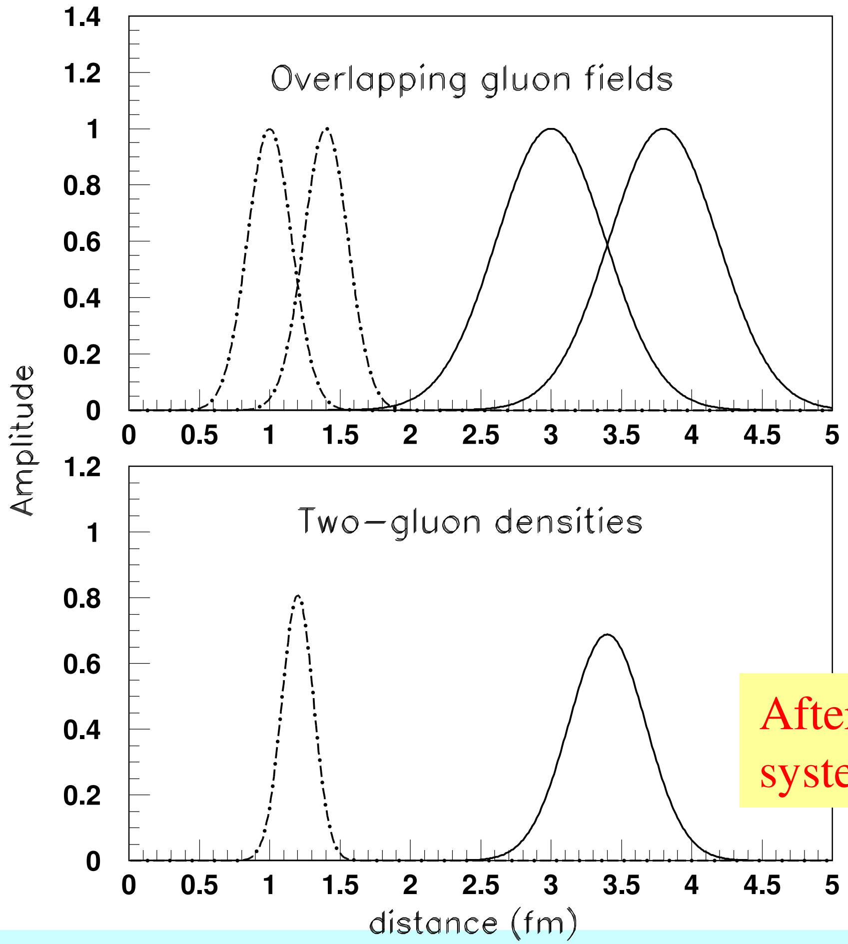
VI. **Interesting point: asymmetry in baryon and anti-baryon production → leads to decay of anti-baryons to baryons (matter-antimatter non-equilibrium as seen in nature).**

Was this the cause of the BIG BANG explosion?

VII. **What can we expect to see at LHC?**

No supersymmetric particles, no Higgs-particles coupling strongly to quarks, but possibly the next higher excited states of hadrons.

Overlapping fluctuating gluon fields in the vacuum and 2 gluon-densities, from which a $\bar{q}q$ pair is created.



After $\bar{q}q$ creation system is confined!

This mechanism is also important for cosmology!

Additional constraints by coupling the quark-gluon states to the vacuum

- **Energy-momentum conservation**

$$E_{tot} = \sqrt{\overline{Q}^2 + (2m_q)^2} + E_{bind}$$

- **In the vacuum the average energy of the fluctuating gluon fields <E_{tot}> ~0.**

1. **This can be fulfilled only, if m_q=0 (<u>all quark masses must be 0</u>).**
2. **The hadron masses are due to binding effects with**

E_{bind}= - <Q>

- **m_q=0 is required from our self-consistency constraint!**
→ coupling to the vacuum is naturally included in our approach !