Конфайнмент и свойства мезонов в доменной модели вакуума КХД

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Plan

QCD effective action and vacuum gluon configurations

In Euclidean functional integral for YM theory one has to allow the gluon condensates to be nonzero:

$$Z = N \int\limits_{\mathcal{F}_B} DA \int\limits_{\Psi} D\psi D\bar{\psi} \exp\{-S[A, \psi, \bar{\psi}]\}$$

$$\mathcal{F}_B = \left\{ A : \lim_{V\to\infty} \frac{1}{V} \int_V d^4x g^2 F^a_{\mu\nu}(x) F^a_{\mu\nu}(x) = B^2 \right\}.$$

B.V. Galilo and S.N. Nedelko, Phys. Rev. D84 (2011) 094017

L. D. Faddeev, [arXiv:0911.1013 [math-ph]]

H. Leutwyler, Nucl. Phys. B 179 (1981) 129

$A^a_\mu = B^a_\mu + Q^a_\mu$, background gauge fixing condition $D(B)Q = 0$:

$$1 = \int\limits_{\mathcal{B}} DB\Phi[A, B] \int\limits_{\mathcal{Q}} DQ \int\limits_{\Omega} D\omega \delta[A^\omega - Q^\omega - B^\omega]\delta[D(B^\omega)Q^\omega]$$

Q^a_μ – local (perturbative) fluctuations of gluon field with zero gluon condensate: $Q \in \mathcal{Q}$;
B^a_μ are long range field configurations with nonzero condensate: $B \in \mathcal{B}$.

$$Z = N' \int\limits_{\mathcal{B}} DB \int\limits_{\mathcal{Q}} DQ \int\limits_{\Psi} D\psi D\bar{\psi} \det[D(B)D(B+Q)]\delta[D(B)Q] \exp\{-S[B+Q, \psi, \bar{\psi}]\}$$

The character of background fields B has yet to be identified by the dynamics of fluctuations:

$$Z = N' \int\limits_{\mathcal{B}} DB \int\limits_{\Psi} D\psi D\bar{\psi} \int\limits_{\mathcal{Q}} DQ \det[D(B)D(B+Q)]\delta[D(B)Q] \exp\{-S_{\mathrm{QCD}}[B+Q,\psi,\bar{\psi}]\}$$
$$= \int\limits_{\mathcal{B}} DB \exp\{-S_{\mathrm{eff}}[B]\}$$

Global minima of $S_{\mathrm{eff}}[B]$ – field configurations that are dominant in the thermodynamic limit $V \to \infty$. Homogeneous Abelian (anti-)self-dual fields are of particular interest.

$$B_\mu = -\frac{1}{2} n B_{\mu\nu} x_\nu,\ \tilde{B}_{\mu\nu} = \pm B_{\mu\nu}$$
$$n = T^3 \ \cos\xi + T^8 \ \sin\xi.$$

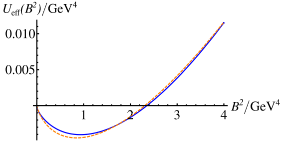
H. Pagels, and E. Tomboulis, Nucl. Phys. B 143 (1978) 485
P. Minkowski, Nucl. Phys. B177 (1981) 203
H. Leutwyler, Nucl. Phys. B 179 (1981) 129

$$G\left(z^2\right) \sim \frac{e^{-Bz^2}}{z^2}, \quad \tilde{G}\left(p^2\right) \sim \frac{1}{p^2}\left(1 - e^{-p^2/B}\right)$$

H. Leutwyler, Phys. Lett. B 96 (1980) 154

Gluon propagator $\Rightarrow$ Regge trajectories

G.V. Efimov, and S.N. Nedelko, Phys. Rev. D 51 (1995)



A. Eichhorn, H. Gies and J. M. Pawlowski, Phys. Rev. D 83, 045014 (2011)

Gluon condensates and domain wall network

Pure gluodynamics - Ginzburg-Landau approach:

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4\Lambda^2}\left(D^{ab}_{\nu}F^{b}_{\rho\mu}D^{ac}_{\nu}F^{c}_{\rho\mu} + D^{ab}_{\mu}F^{b}_{\mu\nu}D^{ac}_{\rho}F^{c}_{\rho\nu}\right) - U_{\text{eff}}$$

$$U_{\text{eff}} = \frac{\Lambda^4}{12}\mathrm{Tr}\left(C_1 F^2 + \frac{4}{3}C_2 F^4 - \frac{16}{9}C_3 F^6\right),$$

B.V. Galilo, S.N. Nedelko, Phys. Part. Nucl. Lett., 8 (2011) 67

D. P. George, A. Ram, J. E. Thompson and R. R. Volkas, Phys. Rev. D 87, 105009 (2013) [arXiv:1203.1048 [hep-th]]

where

$$D^{ab}_{\mu} = \delta^{ab}\partial_{\mu} - iA^{ab}_{\mu} = \partial_{\mu} - iA^{c}_{\mu}(T^{c})^{ab},$$

$$F^{a}_{\mu\nu} = \partial_{\mu}A^{a}_{\nu} - \partial_{\nu}A^{a}_{\mu} - if^{abc}A^{b}_{\mu}A^{c}_{\nu},$$

$$F_{\mu\nu} = F^{a}_{\mu\nu}T^{a}, \quad T^{a}_{bc} = -if^{abc}$$

$$C_1 > 0,\ C_2 > 0,\ C_3 > 0.$$

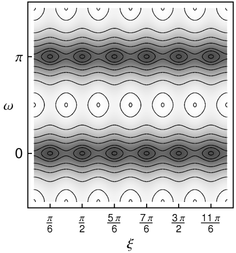
U_{eff} possesses 12 degenerate discrete minima:

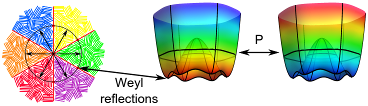
$$B_\mu = -\frac{1}{2} n_k B_{\mu\nu} x_\nu, \; \tilde{B}_{\mu\nu} = \pm B_{\mu\nu},$$

matrix n_k belongs to the Cartan subalgebra of $su(3)$

$$n_k = T^3 \; \cos\left(\xi_k\right) + T^8 \; \sin\left(\xi_k\right), \quad \xi_k = \frac{2k+1}{6}\pi, \; k = 0, 1, \ldots, 5,$$

$$\vec{E}\vec{H} = B^2 \cos(\omega)$$





Domain wall network

ξ, $\langle g^2 F^2 \rangle \longrightarrow$ vacuum values

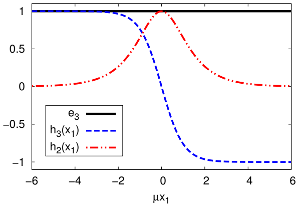
$$\mathcal{L}_{\text{eff}} = -\frac{1}{2}\Lambda^2 b_{\text{vac}}^2 \partial_\mu \omega \partial_\mu \omega - b_{\text{vac}}^4 \Lambda^4 \left(C_2 + 3C_3 b_{\text{vac}}^2\right) \sin^2 \omega,$$

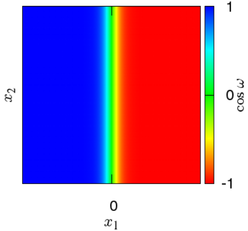
leads to sine-Gordon equation

$$\partial^2 \omega = m_\omega^2 \sin 2\omega, \quad m_\omega^2 = b_{\text{vac}}^2 \Lambda^2 \left(C_2 + 3C_3 b_{\text{vac}}^2\right),$$

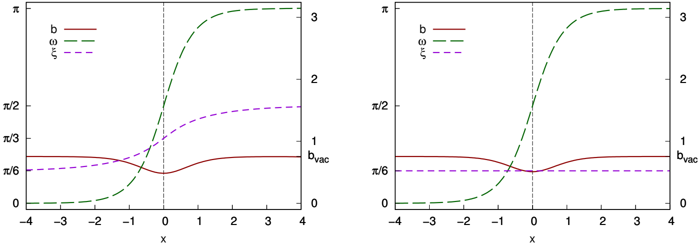
and the standard kink solution

$$\omega(x_\nu) = 2\ \text{arctg}\left(\exp(\mu x_\nu)\right)$$





Domain wall involving the topological charge density (in units of $\langle g^2 F^2 \rangle$), $su(3)$ angle ξ and the background action density simultaneously



The general kink configuration can be parametrized as

$$\zeta(\mu_i, \eta^i_\nu x_\nu - q^i) = \frac{2}{\pi} \arctan \exp(\mu_i(\eta^i_\nu x_\nu - q^i)).$$

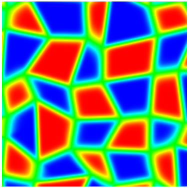
A single lump in two, three and four dimensions is given by

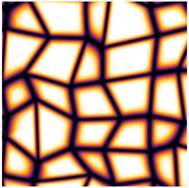
$$\omega(x) = \pi \prod_{i=1}^{k} \zeta(\mu_i, \eta^i_\nu x_\nu - q^i).$$

for $k = 4, 6, 8$, respectively. The general kink network is then given by the additive superposition of lumps

$$\omega = \pi \sum_{j=1}^{\infty} \prod_{i=1}^{k} \zeta(\mu_{ij}, \eta^{ij}_\nu x_\nu - q^{ij})$$

S.N. Nedelko, V.E. Voronin, Eur.Phys.J. A51 (2015) 4





Domain bulk - harmonic confinement

Elementary color charged excitations - fluctuations, eigenmodes decay in all four directions.

Eigenvalue problem for scalar field in $\mathbb{R}^4$: H. Leutwyler, Nucl. Phys. B 179 (1981);

$$B_\mu = B_{\mu\nu} x_\nu, \widetilde{B}_{\mu\nu} = \pm B_{\mu\nu}, B_{\mu\alpha} B_{\nu\alpha} = B^2 \delta_{\mu\nu}.$$

$$-\left(\partial_\mu - i B_\mu\right)^2 G = \delta \quad \longrightarrow \quad G\left(x-y\right) \sim \frac{e^{-B(x-y)^2/4}}{(x-y)^2}$$

$$-\left(\partial_\mu - i\breve{B}_\mu\right)^2 \Phi = \lambda\Phi \quad \longrightarrow \quad \left[\beta_\pm^+ \beta_\pm + \gamma_+^+ \gamma_+ + 1\right] \Phi = \frac{\lambda}{4B}\Phi,$$

$$\beta_\pm = \frac{1}{2}(\alpha_1 \mp i\alpha_2), \quad \gamma_\pm = \frac{1}{2}(\alpha_3 \mp i\alpha_4), \quad \alpha_\mu = \frac{1}{\sqrt{B}} x_\mu + \partial_\mu,$$

$$\beta_\pm^+ = \frac{1}{2}(\alpha_1^+ \pm i\alpha_2^+), \quad \gamma_\pm^+ = \frac{1}{2}(\alpha_3^+ \pm i\alpha_4^+), \quad \alpha_\mu^+ = \frac{1}{\sqrt{B}} x_\mu - \partial_\mu.$$

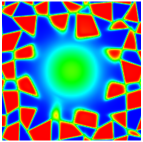
The eigenfunctions and eigenvalues - 4-dim. harmonic oscillator

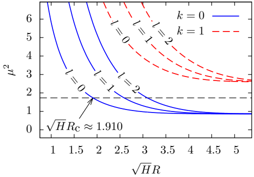
$$\Phi_{nmkl}(x) = \frac{1}{\pi^2\sqrt{n!m!k!l!}} \left(\beta_+^+\right)^k \left(\beta_-^+\right)^l \left(\gamma_+^+\right)^n \left(\gamma_-^+\right)^m \Phi_{0000}, \ \Phi_{0000} = e^{-\frac{1}{2}Bx^2}$$

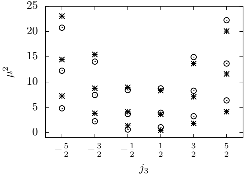
$$\lambda_r = 4B(r+1), \ r = k+n \text{ self-dual field}, \ r = l+n \text{ anti-self-dual field}$$

Domain wall junctions: quasiparticles, deconfinement

S.N. Nedelko, V.E. Voronin, Eur.Phys.J. A51 (2015) 4







The color charged scalar field inside junction:

$$-\left(\partial_\mu - i\breve{B}_\mu\right)^2 \Phi = 0, \quad \Phi(x) = 0, \quad x \in \mathcal{T} = \left\{x_1^2 + x_2^2 < R^2,\ (x_3, x_4) \in \mathrm{R}^2\right\}$$

The solutions are quasi-particle excitations

$$\phi^a(x) = \sum_{lk} \int_{-\infty}^{+\infty} \frac{dp_3}{2\pi} \frac{1}{\sqrt{2\omega_{alk}}} \left[a^+_{akl}(p_3) e^{ix_0\omega_{akl} - ip_3x_3} + b_{akl}(p_3) e^{-ix_0\omega_{akl} + ip_3x_3}\right] e^{il\vartheta} \phi_{alk}(r),$$

$$\phi^{a\dagger}(x) = \sum_{lk} \int_{-\infty}^{+\infty} \frac{dp_3}{2\pi} \frac{1}{\sqrt{2\omega_{alk}}} \left[b^+_{akl}(p_3) e^{-ix_0\omega_{akl} + ip_3x_3} + a_{akl}(p_3) e^{ix_0\omega_{akl} - ip_3x_3}\right] e^{-il\vartheta} \phi_{alk}(r),$$

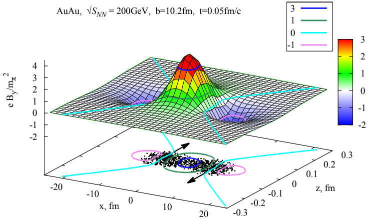
$$p_0^2 = p_3^2 + \mu_{akl}^2, \quad p_0 = \pm\omega_{akl}(p_3), \quad \omega_{akl} = \sqrt{p_3^2 + \mu_{akl}^2},$$

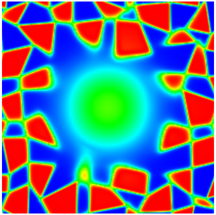
$$k = 0, 1, \ldots, \infty, \quad l \in \mathbb{Z},$$

Polarization of QCD vacuum by the strong electromagnetic fields

- **Relativistic heavy ion collisions - strong electromagnetic fields**

V. Skokov, A. Y. Illarionov and V. Toneev, Int. J. Mod. Phys. A **24** (2009) 5925
V. Voronyuk, V. D. Toneev, W. Cassing, E. L. Bratkovskaya,
V. P. Konchakovski and S. A. Voloshin, Phys. Rev C 84 (2011)





Strong electro-magnetic field plays catalyzing role for deconfinement and anisotropies!

B.V. Galilo and S.N. Nedelko, Phys. Rev. D84 (2011) 094017.
M. D'Elia, M. Mariti and F. Negro, Phys. Rev. Lett. **110**, 082002 (2013)
G. S. Bali, F. Bruckmann, G. Endrodi, F. Gruber and A. Schaefer, JHEP **1304**, 130 (2013)

Hadronization

G.V. Efimov and S.N. Nedelko, Phys. Rev. D 51 (1995); Phys. Rev. D 54 (1996)
A.C. Kalloniatis and S.N. Nedelko, Phys. Rev. D 64 (2001); Phys. Rev. D 69 (2004); Phys. Rev. D 71 (2005); Phys. Rev. D 73 (2006)

S. N. Nedelko and V. E. Voronin, Phys. Rev. D 93 (2016)

$$\mathcal{Z} = \int dB \int_\Psi \mathcal{D}\psi \mathcal{D}\bar\psi \int_\mathcal{Q} \mathcal{D}Q \delta[D(B)Q]\Delta_{\mathrm{FP}}[B,Q] e^{-S^{\mathrm{QCD}}[Q+B,\psi,\bar\psi]} =$$

$$\int dB \int_\Psi \mathcal{D}\psi \mathcal{D}\bar\psi \exp\left\{\int dx \bar\psi \left(i\not\partial + g\not B - m\right)\psi\right\} W[j]$$

$$W[j] = \exp\left\{\sum_n \frac{g^n}{n!}\int dx_1 \ldots \int dx_n j^{a_1}_{\mu_1}(x_1)\ldots j^{a_n}_{\mu_n}(x_n) G^{a_1\ldots a_n}_{\mu_1\ldots\mu_n}(x_1,\ldots,x_n|B)\right\}$$

$$j^a_\mu = \bar\psi \gamma_\mu t^a \psi,$$

Next step: $W[j]$ is truncated up to the term including two-point gluon correlation function.

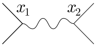
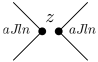
$$\mathcal{Z} = \int dB \int_{\Psi} \mathcal{D}\psi \mathcal{D}\bar{\psi} \exp\left\{\int dx \bar{\psi}\left(i\partial\!\!\!/ + gB\!\!\!/ - m\right)\psi \right.$$
$$\left. + \frac{g^2}{2}\int dx_1 dx_2 G^{a_1 a_2}_{\mu_1\mu_2}(x_1, x_2|B) j^{a_1}_{\mu_1}(x_1) j^{a_2}_{\mu_2}(x_2)\right\}$$

Fierz transform, center of mass coordinates $\longrightarrow \int dz dx G(z|B) J^{aJ}(x,z) J^{aJ}(x,z)$

$$\alpha_s \sim\!\sim\!\sim = \alpha_s(0) \sim\!\sim\!\sim \left[1 + \Pi^{\mathrm{R}}(p^2)\right]; \ \Pi^{\mathrm{R}}(0) = 0$$

$$0 \sim\!\sim\!\sim z \ \rightarrow \frac{e^{-\frac{1}{4}Bz^2}}{4\pi^2 z^2}$$

$$\rightarrow \alpha_s(p^2)\frac{1-\exp\left(-p^2/B\right)}{p^2}$$

$\int dx_1\, dx_2$  $= \int dz \sum_{aJln}$ 

$$J^{aJ}(x,z) = \sum_{nl}\left(z^2\right)^{l/2} f^{nl}_{\mu_1\ldots\mu_l}(z) J^{aJln}_{\mu_1\ldots\mu_l}(x), \quad J^{aJln}_{\mu_1\ldots\mu_l}(x) = \bar{q}(x) V^{aJln}_{\mu_1\ldots\mu_l}\left(\frac{\overleftrightarrow{D}(x)}{B}\right) q(x),$$

$$f^{nl}_{\mu_1\ldots\mu_l} = L_{nl}\left(z^2\right) T^{(l)}_{\mu_1\ldots\mu_l}(n_z), \quad n_z = \frac{z}{\sqrt{z}}.$$

$T^{(l)}_{\mu_1\ldots\mu_l}$ are irreducible tensors of four-dimensional rotational group

$$\int_0^\infty du \rho_l(u) L_{nl}(u) L_{n'l}(u) = \delta_{nn'}, \quad \rho_l(u) = u^l e^{-u} \leftrightarrow \frac{e^{-Bz^2}}{z^2} \quad \text{gluon propagator}$$

Effective meson action for composite colorless fields:

$$Z = \mathcal{N} \lim_{V\to\infty} \int D\Phi_{\mathcal{Q}} \exp\left\{ -\frac{B}{2} \frac{h^2_{\mathcal{Q}}}{g^2 C_{\mathcal{Q}}} \int dx \Phi^2_{\mathcal{Q}}(x) - \sum_k \frac{1}{k} W_k[\Phi] \right\}, \quad \mathcal{Q} = (aJln)$$

$$1 = \frac{g^2 C_{\mathcal{Q}}}{B} \tilde{\Gamma}^{(2)}_{\mathcal{Q}\mathcal{Q}}(-M^2_{\mathcal{Q}}|B), \quad h^{-2}_{\mathcal{Q}} = \frac{d}{dp^2} \tilde{\Gamma}^{(2)}_{\mathcal{Q}\mathcal{Q}}(p^2)|_{p^2=-M^2_{\mathcal{Q}}}.$$

$$W_k[\Phi] = \sum_{\mathcal{Q}_1\ldots\mathcal{Q}_k} h_{\mathcal{Q}_1} \ldots h_{\mathcal{Q}_k} \int dx_1 \ldots \int dx_k \Phi_{\mathcal{Q}_1}(x_1) \ldots \Phi_{\mathcal{Q}_k}(x_k) \Gamma^{(k)}_{\mathcal{Q}_1\ldots\mathcal{Q}_k}(x_1, \ldots, x_k|B)$$

$$\Gamma^{(2)}_{\mathcal{Q}_1\mathcal{Q}_2} = \overline{G^{(2)}_{\mathcal{Q}_1\mathcal{Q}_2}(x_1,x_2)} - \Xi_2(x_1 - x_2)\overline{G^{(1)}_{\mathcal{Q}_1} G^{(1)}_{\mathcal{Q}_2}}, \quad \leftarrow \text{diagonalization}$$

$$\Gamma^{(3)}_{\mathcal{Q}_1\mathcal{Q}_2\mathcal{Q}_3} = \overline{G^{(3)}_{\mathcal{Q}_1\mathcal{Q}_2\mathcal{Q}_3}(x_1,x_2,x_3)} - \frac{3}{2}\Xi_2(x_1 - x_3)\overline{G^{(2)}_{\mathcal{Q}_1\mathcal{Q}_2}(x_1,x_2) G^{(1)}_{\mathcal{Q}_3}(x_3)}$$
$$+\frac{1}{2}\Xi_3(x_1,x_2,x_3)\overline{G^{(1)}_{\mathcal{Q}_1}(x_1) G^{(1)}_{\mathcal{Q}_2}(x_2) G^{(1)}_{\mathcal{Q}_3}(x_3)},$$

$$\Gamma^{(4)}_{\mathcal{Q}_1\mathcal{Q}_2\mathcal{Q}_3\mathcal{Q}_4} = \overline{G^{(4)}_{\mathcal{Q}_1\mathcal{Q}_2\mathcal{Q}_3\mathcal{Q}_4}(x_1,x_2,x_3,x_4)} - \frac{4}{3}\Xi_2(x_1 - x_2)\overline{G^{(1)}_{\mathcal{Q}_1}(x_1) G^{(3)}_{\mathcal{Q}_2\mathcal{Q}_3\mathcal{Q}_4}(x_2,x_3,x_4)}$$
$$-\frac{1}{2}\Xi_2(x_1 - x_3)\overline{G^{(2)}_{\mathcal{Q}_1\mathcal{Q}_2}(x_1,x_2) G^{(2)}_{\mathcal{Q}_3\mathcal{Q}_4}(x_3,x_4)}$$
$$+\Xi_3(x_1,x_2,x_3)\overline{G^{(1)}_{\mathcal{Q}_1}(x_1) G^{(1)}_{\mathcal{Q}_2}(x_2) G^{(2)}_{\mathcal{Q}_3\mathcal{Q}_4}(x_3,x_4)}$$
$$-\frac{1}{6}\Xi_4(x_1,x_2,x_3,x_4)\overline{G^{(1)}_{\mathcal{Q}_1}(x_1) G^{(1)}_{\mathcal{Q}_2}(x_2) G^{(1)}_{\mathcal{Q}_3}(x_3) G^{(1)}_{\mathcal{Q}_4}(x_4)}.$$

$$\overline{G^{(k)}_{\mathcal{Q}_1\dots\mathcal{Q}_k}(x_1,\dots,x_k)} = \int dB_j \mathrm{Tr} V_{\mathcal{Q}_1}\left(x_1|B^{(j)}\right) S\left(x_1,x_2|B^{(j)}\right)\dots$$
$$\dots V_{\mathcal{Q}_k}\left(x_k|B^{(j)}\right) S\left(x_k,x_1|B^{(j)}\right)$$

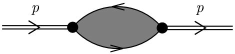
$$\overline{G^{(l)}_{\mathcal{Q}_1\dots\mathcal{Q}_l}(x_1,\dots,x_l) G^{(k)}_{\mathcal{Q}_{l+1}\dots\mathcal{Q}_k}(x_{l+1},\dots,x_k)} =$$
$$\int dB_j \mathrm{Tr}\left\{V_{\mathcal{Q}_1}\left(x_1|B^{(j)}\right) S\left(x_1,x_2|B^{(j)}\right)\dots V_{\mathcal{Q}_k}\left(x_l|B^{(j)}\right) S\left(x_l,x_1|B^{(j)}\right)\right\}$$
$$\times \mathrm{Tr}\left\{V_{\mathcal{Q}_{l+1}}\left(x_{l+1}|B^{(j)}\right) S\left(x_{l+1},x_{l+2}|B^{(j)}\right)\dots V_{\mathcal{Q}_k}\left(x_k|B^{(j)}\right) S\left(x_k,x_{l+1}|B^{(j)}\right)\right\},$$

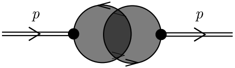
Bar denotes integration over all configurations of the background field with measure dB_j.

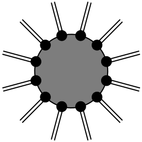
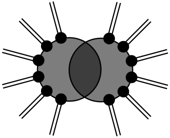
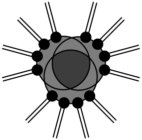
$$\boxed{\begin{gathered}\langle\exp(iB_{\mu\nu}J_{\mu\nu})\rangle = \frac{\sin W}{W} \\ W = \sqrt{2B^2\left(J_{\mu\nu}J_{\mu\nu} \pm J_{\mu\nu}\widetilde{J}_{\mu\nu}\right)}\end{gathered}}$$

$J_{\mu\nu}$ is a tensor, composed of the momenta $p_{1\mu_1}\dots p_{n\mu_n}$ - arguments of the meson vertex

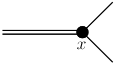
$$\tilde{\Gamma}^{(n)}(p_{1\mu_1}\dots p_{n\mu_n})$$

$\Gamma^{(2)}_{\mathcal{Q}_1\mathcal{Q}_2} =$ 

$+$ 

$\Gamma^{(n)}_{\mathcal{Q}_1\mathcal{Q}_2\ldots\mathcal{Q}_n} =$  $+\cdots+$  $+\cdots+$  $+\ldots$

Meson-quark vertex operators $\Leftarrow J^{aJln}_{\mu_1\dots\mu_l} = \bar{q}(x) V^{aJln}_{\mu_1\dots\mu_l} q(x)$



$$\boxed{V^{aJln}_{\mu_1\dots\mu_l}(x) = M^a \Gamma^J \left\{ \left\{ F_{nl}\left(\frac{\overset{\leftrightarrow}{D}{}^2(x)}{B^2} \right) T^{(l)}_{\mu_1\dots\mu_l}\left(\frac{1}{i} \frac{\overset{\leftrightarrow}{D}(x)}{B} \right) \right\} \right\}},$$

$$F_{nl}(s) = s^n \int_0^1 dt t^{n+l} \exp(st) = \int_0^1 dt t^{n+l} \frac{\partial^n}{\partial t^n} \exp(st),$$

$$\overset{\leftrightarrow}{D} = \overset{\leftarrow}{D} \xi_{f'} - \vec{D} \xi_f, \xi_f = \frac{m_f}{m_f + m_{f'}}$$

Quark propagator in homogeneous Abelian (anti-)self-dual field

$$\longrightarrow = \frac{\longrightarrow}{m(0)} \left[1 + \Sigma^{\mathrm{R}}(p^2) \right]; \ \Sigma^{\mathrm{R}}(0) = 0 \qquad \boxed{S(x,y) = \exp\left(-\frac{i}{2} x_\mu B_{\mu\nu} y_\nu \right) H(x-y)},$$

$$\widetilde{H}_f(p|B) = \frac{1}{\upsilon B^2} \int_0^1 ds e^{(-p^2/\upsilon B^2)s} \left(\frac{1-s}{1+s} \right)^{m_f^2/2\upsilon B^2} \left[p_\alpha \gamma_\alpha \pm i s \gamma_5 \gamma_\alpha \frac{B_{\alpha\beta}}{\upsilon B^2} p_\beta + \right.$$

$$\left. + m_f \left(P_\pm + P_\mp \frac{1+s^2}{1-s^2} - \frac{i}{2} \gamma_\alpha \frac{B_{\alpha\beta}}{\upsilon B^2} \gamma_\beta \frac{s}{1-s^2} \right) \right]$$

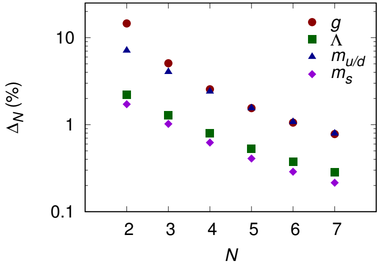
$$\tilde{H}_f(p|B) = \frac{m}{2\upsilon\Lambda^2} \mathcal{H}_S(p^2) \mp \gamma_5 \frac{m}{2\upsilon\Lambda^2} \mathcal{H}_P(p^2) + \gamma_\alpha \frac{p_\alpha}{2\upsilon\Lambda^2} \mathcal{H}_V(p^2) \pm i\gamma_5\gamma_\alpha \frac{f_{\alpha\beta} p_\beta}{2\upsilon\Lambda^2} \mathcal{H}_A(p^2)$$

$$+ \sigma_{\alpha\beta} \frac{m f_{\alpha\beta}}{4\upsilon\Lambda^2} \mathcal{H}_T(p^2).$$

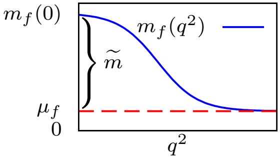
S. N. Nedelko and V. E. Voronin, Phys. Rev. D 93 (2016)

$$\boxed{\alpha_s\,(0) \quad m_{u/d}(0) \quad m_s(0) \quad m_c(0) \quad m_b(0) \quad B \quad R}$$

$$\langle \alpha_s F^2 \rangle = \frac{B^2}{\pi} \qquad \chi_{\mathrm{YM}} = \frac{B^4 R^4}{128\pi^2}$$



Dynamical chiral symmetry breaking:



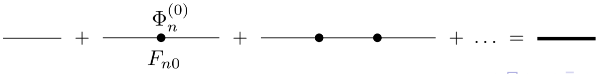
$$\widetilde{m} = 136\ \mathrm{MeV}$$

$$\mu_{u/d} = m_{u/d} - \widetilde{m}$$

$$\mu_s = m_s - \widetilde{m}$$

$$\frac{\mu_s}{\mu_{u/d}} = 26.7$$

$$\Lambda^2 \Phi^{(0)}_{\mathcal{Q}_1} = \sum_{k=1}^{\infty} \frac{g^k}{k} \sum_{\mathcal{Q}_1 \ldots \mathcal{Q}_k} \Phi^{(0)}_{\mathcal{Q}_2} \ldots \Phi^{(0)}_{\mathcal{Q}_k} \Gamma^{(k)}_{\mathcal{Q}_1 \ldots \mathcal{Q}_k},$$



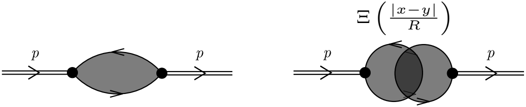
Masses of radially excited mesons

Asymptotic Regge spectrum :

$$M_n^2 \sim Bn,\ n \gg 1$$
$$M_l^2 \sim Bl,\ l \gg 1$$

G.V. Efimov and S.N. Nedelko, Phys. Rev. D 51 (1995)

η and η'!



Polarization operator: diagonalization

Polarization operation for $l=0$: S. N. Nedelko and V. E. Voronin, Phys. Rev. D 93 (2016)

$$\Pi_J^{nn'}\left(-M^2;m_f,m_{f'};B\right)=$$

$$\frac{B}{4\pi^2}\mathrm{Tr}_\upsilon\int\limits_0^1 dt_1\int\limits_0^1 dt_2\int\limits_0^1 ds_1\int\limits_0^1 ds_2\left(\frac{1-s_1}{1+s_1}\right)^{m_f^2/4\upsilon B}\left(\frac{1-s_2}{1+s_2}\right)^{m_{f'}^2/4\upsilon B}\times$$

$$\times\, t_1^n t_2^{n'}\frac{\partial^n}{\partial t_1^n}\frac{\partial^{n'}}{\partial t_2^{n'}}\frac{1}{\Phi_2^2}\left[\frac{M^2}{B}\frac{F_1^{(J)}}{\Phi_2^2}+\frac{m_f m_{f'}}{B}\frac{F_2^{(J)}}{(1-s_1^2)(1-s_2^2)}+\frac{F_3^{(J)}}{\Phi_2}\right]\exp\left\{\frac{M^2}{2\upsilon B}\frac{\Phi_1}{\Phi_2}\right\}.$$

$$\Phi_1=s_1s_2+2\left(\xi_1^2s_1+\xi_2^2s_2\right)(t_1+t_2)\upsilon,$$

$$\Phi_2=s_1+s_2+2(1+s_1s_2)(t_1+t_2)\upsilon+16(\xi_1^2s_1+\xi_2^2s_2)t_1t_2\upsilon^2,$$

$$F_1^{(P)}=(1+s_1s_2)\left[2(\xi_1s_1+\xi_2s_2)(t_1+t_2)\upsilon+\right.$$
$$\left.4\xi_1\xi_2(1+s_1s_2)(t_1+t_2)^2\upsilon^2+s_1s_2(1-16\xi_1\xi_2t_1t_2\upsilon^2)\right],$$

$$F_1^{(V)}=\left(1-\frac{1}{3}s_1s_2\right)\left[s_1s_2+16\xi_1\xi_2t_1t_2\upsilon^2+2(\xi_1s_1+\xi_2s_2)(t_1+t_2)\upsilon\right]+$$
$$4\xi_1\xi_2(1-s_1^2s_2^2)(t_1-t_2)^2\upsilon^2,$$

$$F_2^{(P)}=(1+s_1s_2)^2,\quad F_2^{(V)}=(1-s_1^2s_2^2),$$

$$F_3^{(P)}=4\upsilon(1+s_1s_2)(1-16\xi_1\xi_2t_1t_2\upsilon^2),\ F_3^{(V)}=2\upsilon(1-s_1s_2)(1-16\xi_1\xi_2t_1t_2\upsilon^2).$$

Таблица: Model parameters fitted to the masses of $\pi, \rho, K, K^*, \eta', J/\psi, \Upsilon$ and used in calculation of all other quantities.

$m_{u/d}$, MeV	m_s, MeV	m_c, MeV	m_b, MeV	Λ, MeV	α_s	R, fm
145	376	1566	4879	416	3.45	1.12

Таблица: Masses of light mesons. $\tilde{M}$ denotes the value in the chiral limit.

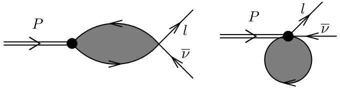
Meson	n	M_{exp} (MeV)	M (MeV)	$\widetilde{M}$ (MeV)	Meson	n	M_{exp} (MeV)	M (MeV)	$\widetilde{M}$ (MeV)
π	0	140	140	0	ρ	0	775	775	769
$\pi(1300)$	1	1300	1310	1301	$\rho(1450)$	1	1450	1571	1576
$\pi(1800)$	1	1812	1503	1466	ρ	2	1720	1946	2098
K	0	494	494	0	K^*	0	892	892	769
$K(1460)$	1	1460	1302	1301	$K^*(1410)$	1	1410	1443	1576
K	2		1655	1466	$K^*(1717)$	1	1717	1781	2098
η	0	548	621	0	ω	0	775	775	769
η'	0	958	958	872	ϕ	0	1019	1039	769
$\eta(1295)$	1	1294	1138	1361	$\phi(1680)$	1	1680	1686	1576
$\eta(1475)$	1	1476	1297	1516	ϕ	2	2175	1897	2098

Таблица: Masses of heavy-light mesons and their lowest radial excitations .

Meson	n	$M_{\rm exp}$ (MeV)	M (MeV)	Meson	n	$M_{\rm exp}$ (MeV)	M (MeV)
D	0	1864	1715	D^*	0	2010	1944
D	1		2274	D^*	1		2341
D	2		2508	D^*	2		2564
D_s	0	1968	1827	D_s^*	0	2112	2092
D_s	1		2521	D_s^*	1		2578
D_s	2		2808	D_s^*	2		2859
B	0	5279	5041	B^*	0	5325	5215
B	1		5535	B^*	1		5578
B	2		5746	B^*	2		5781
B_s	0	5366	5135	B_s^*	0	5415	5355
B_s	1		5746	B_s^*	1		5783
B_s	2		5988	B_s^*	2		6021
B_c	0	6277	5952	B_c^*	0		6310
B_c	1		6904	B_c^*	1		6938
B_c	2		7233	B_c^*	2		7260

Таблица: Masses of heavy quarkonia.

Meson	n	M_{exp} (MeV)	M (MeV)
$\eta_c(1S)$	0	2981	2751
$\eta_c(2S)$	1	3639	3620
η_c	2		3882
$J/\psi(1S)$	0	3097	3097
$\psi(2S)$	1	3686	3665
$\psi(3770)$	2	3773	3810
$\Upsilon(1S)$	0	9460	9460
$\Upsilon(2S)$	1	10023	10102
$\Upsilon(3S)$	2	10355	10249



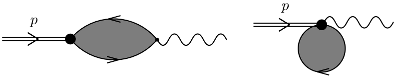
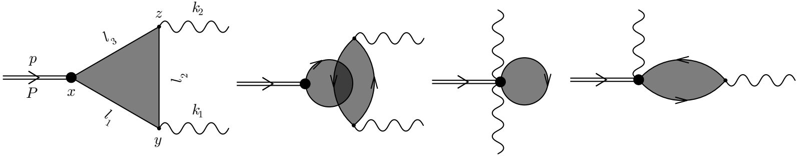


Таблица: Decay and transition constants of various mesons

Meson	n	f_P^{exp} (MeV)	f_P (MeV)	Meson	n	$g_{V\gamma}^{\mathrm{exp}}$	$g_{V\gamma}$
π	0	130	140	ρ	0	0.2	0.2
$\pi(1300)$	1	—	29	ρ	1		0.034
K	0	156	175	ω	0	0.059	0.067
$K(1460)$	1	—	27	ω	1		0.011
D	0	205	212	ϕ	0	0.074	0.069
D	1	—	51	ϕ	1		0.025
D_s	0	258	274	J/ψ	0	0.09	0.057
D_s	1	—	57	J/ψ	1		0.024
B	0	191	187	Υ	0	0.025	0.011
B	1	—	55	Υ	1		0.0039
B_s	0	253	248				
B_s	1	—	68				
B_c	0	489	434				
B_c	1		135				

Pion transition form factor

$$T_a^{\mu\nu}(x,y,z) = h_P \sum_n u_n^a \int d\sigma_B \mathrm{Tr}\ t_a e_f^2 V^n(x)\gamma_5 S(x,y|B)\gamma_\mu S(y,z|B)\gamma_\nu S(z,x|B),$$



In momentum representation, the first diagram has the following structure:

$$T_a^{\mu\nu}(p^2,k_1^2,k_2^2) = ie^2\delta^{(4)}(p-k_1-k_2)\varepsilon_{\mu\nu\alpha\beta}k_{1\alpha}k_{2\beta}T_a(p^2,k_1^2,k_2^2).$$

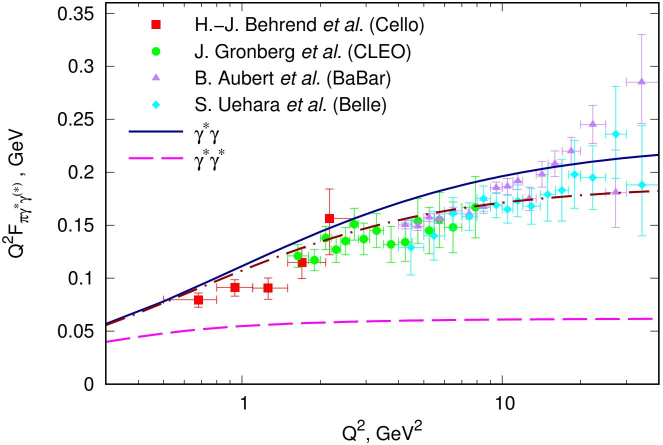
$$F_{P\gamma^*\gamma}\left(Q^2\right) = T\left(-M_P^2,Q^2,0\right), \quad F_{\pi\gamma^*\gamma^*}\left(Q^2\right) = T\left(-M_P^2,Q^2,Q^2\right).$$

$$\Gamma(P\to\gamma\gamma) = \frac{\pi}{4}\alpha^2 M_P^3 g_{P\gamma\gamma}^2$$

$$g_{P\gamma\gamma} = T(-M_P^2,0,0) = F_{P\gamma}\left(0\right).$$

Таблица: Two-photon decay constants of pseudoscalar mesons.

meson	$g^{\exp}_{P\gamma\gamma}$, GeV^{-1}	$g_{P\gamma\gamma}$, GeV^{-1}
π^0	0.274	0.272
η	0.274	0.267
η'	0.344	0.44
η_c	0.067	0.055



$$g_{\pi\gamma\gamma} = 0.269\mathrm{GeV}^{-1} \qquad (g^{\mathrm{exp}}_{\pi\gamma\gamma} = 0.274\mathrm{GeV}^{-1}).$$

$$F_{\pi\gamma^*\gamma} \sim \varkappa \frac{\sqrt{2} f_\pi}{Q^2}, \quad \varkappa \approx 1.23$$

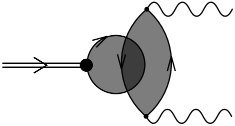
$$F_{\pi\gamma^*\gamma^*} \sim \frac{\sqrt{2} f_\pi}{3Q^2}.$$

$$\langle \exp(iB_{\mu\nu}J_{\mu\nu})\rangle = \frac{\sinh W}{W}$$

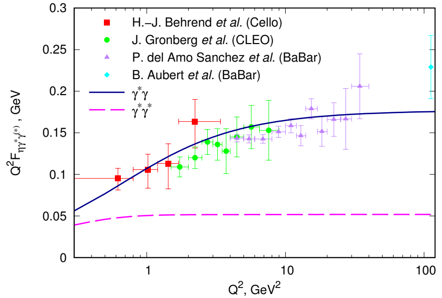
$$J_{\mu\nu} = \Psi(s_1, s_2, s_3, t)\frac{k_{1\mu}k_{2\nu} - k_{1\nu}k_{2\mu}}{2}, \quad W = \Psi(s_1, s_2, s_3, t)\sqrt{k_1^2 k_2^2 - (k_1 k_2)^2}$$

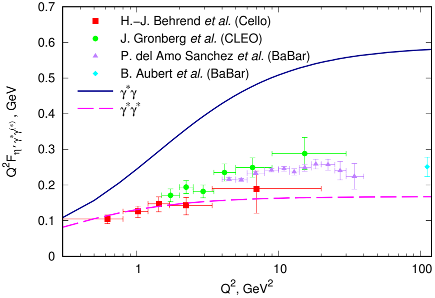
$$W = \Psi(s_1, s_2, s_3, t)\frac{\sqrt{(m_\pi^2 + Q^2)^2}}{2} \quad \text{for} \quad k_1^2 = Q^2, k_2^2 = 0.$$

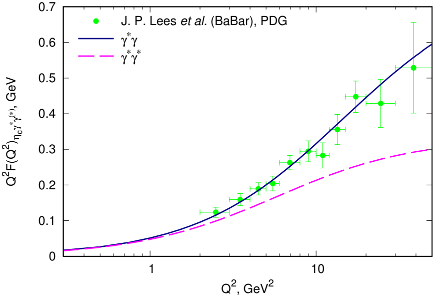
$$W = \Psi(s_1, s_2, s_3, t)\frac{\sqrt{m_\pi^2\,(m_\pi^2 + 4Q^2)}}{2} \quad \text{for} \quad k_1^2 = k_2^2 = Q^2.$$



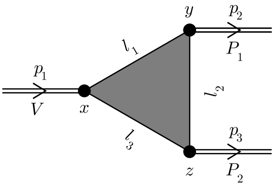
N. I. Kochelev and V. Vento, Gluonic components of the pion and the transition form factor $\gamma * \gamma * \to \pi_0$, Phys. Rev. D **81**, 034009 (2010)







Stong decays: g_{VPP}



Decay	g^{exp}_{VPP}	g_{VPP}	g^{*}_{VPP}
$\rho^0 \to \pi^+\pi^-$	5.95	7.61	1.14
$\omega \to \pi^+\pi^-$	0.17	0	0
$K^{*\pm} \to K^\pm\pi^0$	3.23	3.56	0.65
$K^{*\pm} \to K^0\pi^\pm$	4.57	5.03	0.91
$\varphi \to K^+K^-$	4.47	5.69	1.11
$D^{*\pm} \to D^0\pi^\pm$	8.41	7.94	16.31
$D^{*\pm} \to D^\pm\pi^0$	5.66	5.62	11.53

local color gauge invariance

Положения, выносимые на защиту

- В подходе к квантовому эффективному действию глюонного поля найдены решения уравнений для глюонного поля, интерполирующие между дискретными глобальными минимумами эффективного действия. Минимумы соответствуют разным абелевым (анти)самодуальным конфигурациям глюонного поля. На основе этих решений построен ансамбль почти всюду однородных абелевых (анти)самодуальных полей как сеть доменных стенок.
- Найдены спектры и собственные моды кварков, глюонов и духов Фаддеева-Попова внутри домена и на доменных стенках. Собственные моды заряженных по цвету полей на доменных стенках соответствуют квазичастицам, характерные для режима деконфайнмента. На примере пересечения доменных стенок с цилиндрической симметрией (хромомагнитная трубка) показано, что существует критический размер области, занимаемый доменной стенкой, при котором глюонные квазичастичные моды становятся тахионными вследствие нестабильности Нильсена-Олсена.

- Построено нелокальное эффективное мезонное действие, диагональное по радиальному квантовому числу. Действие включает электромагнитные и слабые взаимодействия, а также инвариантно относительно калибровочных преобразований фонового поля. Массы радиально возбуждённых мезонов, состоящих из u, d, s, c, b-кварков, константы лептонных распадов псевдоскалярных мезонов и электромагнитные переходные константы векторных мезонов (включая радиально возбуждённые), сильные константы распада векторных мезонов g_{VPP} рассчитаны взаимно согласованным образом. Показано, что для корректного описания g_{VPP} критически важна инвариантность эффективного мезонного действия относительно калибровочных преобразований фонового поля.
- Согласованно с массами и константами распадов рассчитаны переходные электромагнитные формфакторы $F_{P\gamma^*\gamma}$ и константы $g_{P\gamma\gamma}$. Показано, что $Q^2 F_{P\gamma^*\gamma}$ приближается к константе при асимптотически больших Q^2, которая превышает предел Бродского-Лепажа, что обусловлено влиянием конфайнмирующих глюонных полей. В то же время стандартный факторизационный предел достигается для $Q^2 F_{P\gamma^*\gamma^*}$, так как конфайнмирующие абелевы (анти)самодуальные поля не дают вклада в асимптотику в этом кинематическом режиме. Рассчитаны и проанализированы особенности формфакторов η, η', η_c.

Апробация

Основные результаты работы докладывались на семинарах Лаборатории теоретической физики им. Н.Н. Боголюбова, Гейдельбергского университета имени Рупрехта и Карла, Гисенского университета имени Юстуса Либиха, а также на международных совещаниях и конференциях конференциях:

- 22nd International Baldin Seminar on High Energy Physics Problems : Relativistic Nuclear Physics and Quantum Chromodynamics (September 15–20, 2014, Dubna, Russia);
- XIX International Conference of Young Scientists and Specialists (February 16–20, 2015, Dubna, Russia);
- 9th Joint International Hadron Structure '15 Conference (June 29–July 3, 2015, Horný Smokovec, Slovakia Republic);
- International Session-Conference of the Section of Nuclear Physics of PSD RAS (April 12–15, 2016, JINR Dubna)
- Quantum Field Theory at the Limits : from Strong Fields to Heavy Quarks (July 18–30, 2016, Dubna, Russia);
- 12th Conference on Quark Confinement and the Hadron Spectrum (August 28–September 04, 2016, Thessaloniki, Greece);
- 23rd International Baldin Seminar on High Energy Physics Problems : Relativistic Nuclear Physics & Quantum Chromodynamics (September 19–24, 2016, Dubna, Russia).

Публикации

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- S. N. Nedelko and V. E. Voronin, “Regge spectra of excited mesons, harmonic confinement and QCD vacuum structure,” Phys. Rev. D **93**, no. 9, 094010 (2016) [arXiv:1603.01447 [hep-ph]].
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