

# Domain wall network as QCD vacuum: confinement - deconfinement, chiral symmetry breakdown and restoration

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G.V. Efimov, Ya. Burdanov, B. Galilo, A. Kalloniatis, L. von Smekal, S. Solunin

H. Pagels, and E. Tomboulis // Nucl. Phys. B143. 1978.

P. Minkowski, Nucl. Phys. B 177, 203 (1981);

H. Leutwyler, Phys. Lett. B**96**, 154 (1980); Nucl. Phys. B**179**, 129 (1981).

A. Eichhorn, H. Gies, J. M. Pawłowski, Phys. Rev. D**83** (2011)

November 3, 2016

- **Confinement of both static and dynamical quarks**  $\rightarrow$   

$$W(C) = \langle \text{Tr P } e^{i \int_C dz_\mu \hat{A}_\mu} \rangle$$

$$S(x, y) = \langle \psi(y) \bar{\psi}(x) \rangle$$
- **Dynamical Breaking of chiral  $SU_L(N_f) \times SU_R(N_f)$  symmetry**  $\rightarrow \langle \bar{\psi}(x) \psi(x) \rangle$
- **$U_A(1)$  Problem**  $\rightarrow \eta'$  ( $\chi$ , Axial Anomaly)
- **Strong CP Problem**  $\rightarrow Z(\theta)$
- **Colorless Hadron Formation:**  $\rightarrow$  Effective action for colorless collective modes:  
hadron masses,  
form factors, scattering

**Light** mesons and baryons, **Regge spectrum** of excited states of light hadrons,  
**heavy-light** hadrons, **heavy quarkonia**

**QCD vacuum as a medium** characterized by certain condensates,  
quarks and gluons - elementary coloured excitations (confined),  
mesons and baryons - collective colorless excitations

**Deconfinement, chiral symmetry restoration under "extreme" conditions**

**Quantum effective action of QCD**

- QCD effective action and vacuum gluon configurations
- Gluon condensates and domain wall network as QCD vacuum
- Testing the domain model - static characteristics of QCD vacuum
- Bosonization – Effective meson action
- Meson properties
- ”Projection” to other approaches: FRG, DSE+BS, 4-dim. oscillator - harmonic confinement
- Strong electromagnetic field as a trigger of deconfinement
- Summary

# QCD effective action and vacuum gluon configurations

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

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

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

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

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

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

$A_\mu^a = B_\mu^a + Q_\mu^a$ , background gauge fixing condition  $D(B)Q = 0$ :

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

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

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

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

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

$$= \int_{\mathcal{B}} DB \exp\{-S_{\text{eff}}[B]\}$$

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

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

$$n = T^3 \cos \xi + T^8 \sin \xi.$$

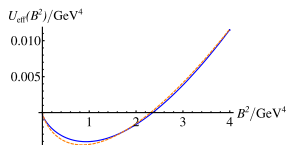
$$G(z^2) \sim \frac{e^{-Bz^2}}{z^2}, \quad \tilde{G}(p^2) \sim \frac{1}{p^2} \left(1 - e^{-p^2/B}\right)$$

H. Pagels, and E. Tomboulis, Nucl. Phys. B 143 (1978) 485  
 P. Minkowski, Nucl. Phys. B 177 (1981) 203  
 H. Leutwyler, Nucl. Phys. B 179 (1981) 129

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

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

Gluon propagator  $\Rightarrow$  Regge trajectories



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

# Gluon condensates and domain wall network

Pure gluodynamics - Ginzburg-Landau approach:

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4\Lambda^2} \left( D_\nu^{ab} F_{\rho\mu}^b D_\nu^{ac} F_{\rho\mu}^c + D_\mu^{ab} F_{\mu\nu}^b D_\rho^{ac} F_{\rho\nu}^c \right) - U_{\text{eff}}$$
$$U_{\text{eff}} = \frac{\Lambda^4}{12} \text{Tr} \left( C_1 F^2 + \frac{4}{3} C_2 F^4 - \frac{16}{9} C_3 F^6 \right),$$

where

$$D_\mu^{ab} = \delta^{ab} \partial_\mu - i A_\mu^{ab} = \partial_\mu - i A_\mu^c (T^c)^{ab},$$
$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - i f^{abc} A_\mu^b A_\nu^c,$$
$$F_{\mu\nu} = F_{\mu\nu}^a T^a, \quad T_{bc}^a = -i f^{abc}$$
$$C_1 > 0, \quad C_2 > 0, \quad C_3 > 0.$$

B.V. Galilo, S.N. , 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]]

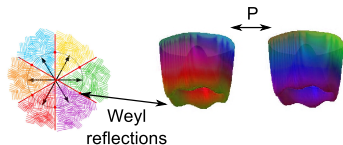
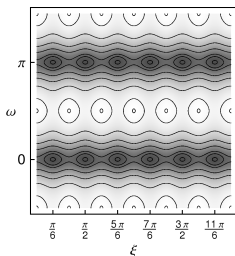
$U_{\text{eff}}$  possesses degenerate discrete minima:

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

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

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

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



## Domain wall network

$\xi, \langle g^2 F^2 \rangle \rightarrow$  vacuum values

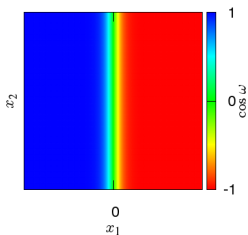
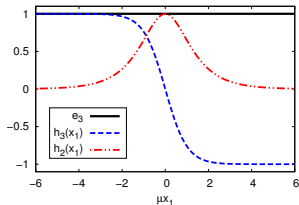
$$\mathcal{L}_{\text{eff}} = -\frac{1}{2}\Lambda^2 b_{\text{vac}}^2 \partial_\mu \omega \partial_\mu \omega - b_{\text{vac}}^4 \Lambda^4 (C_2 + 3C_3 b_{\text{vac}}^2) \sin^2 \omega,$$

leads to sine-Gordon equation

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

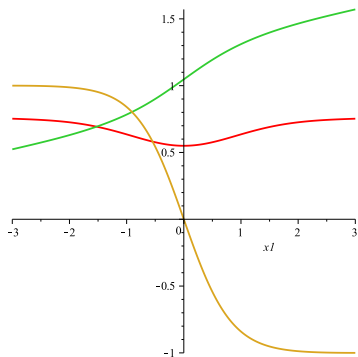
and the standard kink solution

$$\omega(x_\nu) = 2 \arctg(\exp(\mu x_\nu))$$





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



The general kink configuration can be parametrized as

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

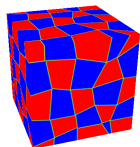
A single lump in two, three and four dimensions is given by

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

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

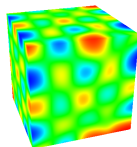
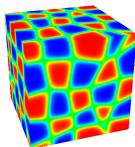
$$\omega = \pi \sum_{j=1}^{\infty} \prod_{i=1}^k \zeta(\mu_{ij}, \eta_\nu^{ij} x_\nu - q^{ij})$$

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



$$\langle F^2 \rangle = B^2$$

$$\langle |F\tilde{F}| \rangle = B^2$$



$$\langle F^2 \rangle = B^2$$

$$\langle |F\tilde{F}| \rangle \ll B^2$$

**What could stabilize a finite mean size of the domains?**

Lower dimensional defects?

Quark (quasi-)zero modes?

In general near the boundaries

$$\operatorname{div}\vec{H} \neq 0, \quad \operatorname{div}\vec{E} \neq 0$$

The description of the domain walls as well as separation of the Abelian part in the general network in terms of the vector potential requires application of the gauge field parametrization suggested by [L.D. Faddeev, A. J. Niemi \(2007\)](#); [K.-I. Kondo, T. Shinohara, T. Murakami \(2008\)](#); [Y.M. Cho \(1980, 1981\)](#); [S.V. Shabanov \(1989,1999\)](#)

The Abelian part  $\hat{V}_\mu(x)$  of the gauge field  $\hat{A}_\mu(x)$  is separated manifestly,

$$\begin{aligned} \hat{A}_\mu(x) &= \hat{V}_\mu(x) + \hat{X}_\mu(x), \quad \hat{V}_\mu(x) = \hat{B}_\mu(x) + \hat{C}_\mu(x), \\ \hat{B}_\mu(x) &= [n^a A_\mu^a(x)]\hat{n}(x) = B_\mu(x)\hat{n}(x), \\ \hat{C}_\mu(x) &= g^{-1}\partial_\mu\hat{n}(x) \times \hat{n}(x), \\ \hat{X}_\mu(x) &= g^{-1}\hat{n}(x) \times \left( \partial_\mu\hat{n}(x) + g\hat{A}_\mu(x) \times \hat{n}(x) \right), \end{aligned} \quad (1)$$

where  $\hat{A}_\mu(x) = A_\mu^a(x)t^a$ ,  $\hat{n}(x) = n_a(x)t^a$ ,  $n^a n^a = 1$ , and

$$\partial_\mu\hat{n} \times \hat{n} = if^{abc}\partial_\mu n^a n^b t^c, \quad [t^a, t^b] = if^{abc}t^c.$$

$$[\hat{V}_\mu(x), \hat{V}_\nu(x)] = 0$$

Both the color and space orientation of the field can become frustrated at the junction location and, thus, develop the singularities in the vector potential. [The potential singularities cover the whole range of defects – vortex-like, dyon-like and zero-dimensional instanton-like defects.](#)

## 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);*

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

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

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

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

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

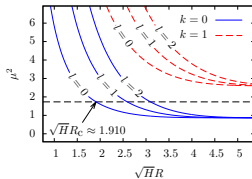
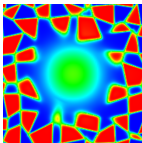
The eigenfunctions and eigenvalues - 4-dim. harmonic oscillator

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

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

# Domain wall junctions - deconfinement

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



The color charged scalar field inside junction:

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

The solutions are quasi-particle excitations

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

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

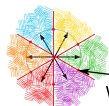
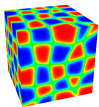
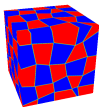
$$p_0^2 = p_3^2 + \mu_{akl}^2, \quad p_0 = \pm\omega_{akl}(p_3), \quad \omega_{akl} = \sqrt{p_3^2 + \mu_{akl}^2},$$

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

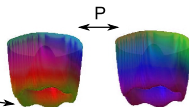
An ensemble of almost everywhere (in  $R^4$ ) homogeneous Abelian (anti-)self-dual gluon fields

$$\langle : g^2 F^2 : \rangle \neq 0, \quad \chi = \int d^4x \langle Q(x) Q(0) \rangle \neq 0, \quad \langle Q(x) \rangle = 0$$

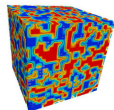
$$\text{Topological charge density } Q(x) = \frac{g^2}{32\pi^2} F_{\mu\nu}^a(x) \tilde{F}_{\mu\nu}^a(x)$$



Weyl  
reflections



Domain wall network (S.N., V.E. Voronin, EPJA (2015); A. Kalloniatis, S.N., PRD (2001))



Lattice confining configuration (P.J. Moran, D.B. Leinweber, arXiv:0805.4246v1 [hep-lat] )

## Spherical domains

A.C. Kalloniatis and S.N. , Phys. Rev. D 64 (2001); Phys. Rev. D 69 (2004); Phys. Rev. D 71 (2005); Phys. Rev. D 73 (2006), Eur.Phys.J. A51 (2015), arXiv:1603.01447 [hep-ph] (2016)

### Area law

Spontaneous chiral symmetry breaking

$U_A(1)$  is broken by anomaly

There is no strong CP violation

# Hadronization

G.V. Efimov and S.N. , Phys. Rev. D 51 (1995); Phys. Rev. D 54 (1996)

A.C. Kalloniatis and S.N. , Phys. Rev. D 64 (2001); Phys. Rev. D 69 (2004); Phys. Rev. D 71 (2005);

Phys. Rev. D 73 (2006)

$$\mathcal{Z} = \int dB \int_{\Psi} \mathcal{D}\psi \mathcal{D}\bar{\psi} \int_{\mathcal{Q}} \mathcal{D}Q \delta[D(B)Q] \Delta_{\text{FP}}[B, Q] e^{-S^{\text{QCD}}[Q+B, \psi, \bar{\psi}]} =$$
$$\int dB \int_{\Psi} \mathcal{D}\psi \mathcal{D}\bar{\psi} \exp \left\{ \int dx \bar{\psi} (i \not{\partial} + g \not{B} - m) \psi \right\} W[j]$$

$$W[j] = \exp \left\{ \sum_n \frac{g^n}{n!} \int dx_1 \dots \int dx_n j_{\mu_1}^{a_1}(x_1) \dots j_{\mu_n}^{a_n}(x_n) G_{\mu_1 \dots \mu_n}^{a_1 \dots a_n}(x_1, \dots, x_n | B) \right\}$$
$$j_{\mu}^a = \bar{\psi} \gamma_{\mu} t^a \psi,$$

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





Effective meson action for composite colorless fields:

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

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

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

$$\Gamma_{\mathcal{Q}_1 \mathcal{Q}_2}^{(2)} = \overline{G_{\mathcal{Q}_1 \mathcal{Q}_2}^{(2)}(x_1, x_2) - \Xi_2(x_1 - x_2) G_{\mathcal{Q}_1}^{(1)} G_{\mathcal{Q}_2}^{(1)}},$$

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

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

$$\overline{G_{\mathcal{Q}_1 \dots \mathcal{Q}_k}^{(k)}(x_1, \dots, x_k)} = \int dB_j \text{Tr} V_{\mathcal{Q}_1}(x_1 | B^{(j)}) S(x_1, x_2 | B^{(j)}) \dots \\ \dots V_{\mathcal{Q}_k}(x_k | B^{(j)}) S(x_k, x_1 | B^{(j)})$$

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

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

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

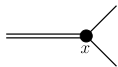
$$W = \sqrt{2B^2 (J_{\mu\nu} J_{\mu\nu} \pm J_{\mu\nu} \tilde{J}_{\mu\nu})}$$

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

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



Meson-quark vertex operators  $\Leftarrow J_{\mu_1 \dots \mu_l}^{\alpha J l n} = \bar{q}(x) V_{\mu_1 \dots \mu_l}^{\alpha J l n} q(x)$



$$V_{\mu_1 \dots \mu_l}^{\alpha J l n}(x) = M^{\alpha} \Gamma^J \left\{ \left\{ F_{nl} \left( \frac{\overleftrightarrow{D}(x)}{B^2} \right) T_{\mu_1 \dots \mu_l}^{(l)} \left( \frac{1}{i} \frac{\overleftrightarrow{D}(x)}{B} \right) \right\} \right\},$$

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

$$\overleftrightarrow{D} = \overleftarrow{D} \xi_{f'} - \overrightarrow{D} \xi_f, \xi_f = \frac{m_f}{m_f + m_{f'}}$$

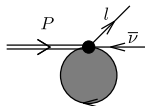
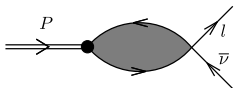
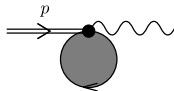
Quark propagator in homogeneous Abelian (anti-)self-dual field

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

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

$$\tilde{H}_f(p|B) = \frac{m}{2v\Lambda^2} \mathcal{H}_S(p^2) \mp \gamma_5 \frac{m}{2v\Lambda^2} \mathcal{H}_P(p^2) + \gamma_{\alpha} \frac{p_{\alpha}}{2v\Lambda^2} \mathcal{H}_V(p^2) \pm i \gamma_5 \gamma_{\alpha} \frac{f_{\alpha\beta} p_{\beta}}{2v\Lambda^2} \mathcal{H}_A(p^2) \quad (2) \\ + \sigma_{\alpha\beta} \frac{m f_{\alpha\beta}}{4v\Lambda^2} \mathcal{H}_T(p^2).$$

# Weak and electromagnetic interactions



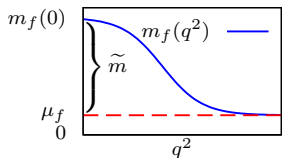
# Masses of radially excited mesons

The parameters of the model are

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

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

Dynamical chiral symmetry breaking:



$$\tilde{m} = 136 \text{ MeV}$$

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

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

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

$$\Lambda^2 \Phi_{Q_1}^{(0)} = \sum_{k=1}^{\infty} \frac{g^k}{k} \sum_{Q_1 \dots Q_k} \Phi_{Q_2}^{(0)} \dots \Phi_{Q_k}^{(0)} \Gamma_{Q_1 \dots Q_k}^{(k)}$$

$$\text{---} + \text{---} \overset{\Phi_n^{(0)}}{\bullet} \text{---} + \text{---} \bullet \text{---} \bullet \text{---} + \dots = \text{---}$$

$F_{n0}$

Figure : Mass corrections to the quark propagator due to the constant scalar condensates  $\Phi_n^{(0)}$  coupled to nonlocal form factor  $F_{n0}$ . Summation over the radial number  $n$  is assumed.

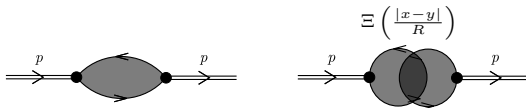
Asymptotic Regge spectrum :

$$M_n^2 \sim Bn, \quad n \gg 1$$

$$M_l^2 \sim Bl, \quad l \gg 1$$

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

$\eta$  and  $\eta'$ !





## Polarization operator

Polarization operation for  $l = 0$ :

$$\Pi_J^{nn'}(-M^2; m_f, m_{f'}; B) = \frac{B}{4\pi^2} \text{Tr}_v \int_0^1 dt_1 \int_0^1 dt_2 \int_0^1 ds_1 \int_0^1 ds_2 \left( \frac{1-s_1}{1+s_1} \right)^{m_f^2/4vB} \left( \frac{1-s_2}{1+s_2} \right)^{m_{f'}^2/4vB} \times \\ \times t_1^n t_2^{n'} \frac{\partial^n}{\partial t_1^n} \frac{\partial^{n'}}{\partial t_2^{n'}} \frac{1}{\Phi_2^2} \left[ \frac{M^2}{B} \frac{F_1^{(J)}}{\Phi_2^2} + \frac{m_f m_{f'}}{B} \frac{F_2^{(J)}}{(1-s_1^2)(1-s_2^2)} + \frac{F_3^{(J)}}{\Phi_2} \right] \exp \left\{ \frac{M^2}{2vB} \frac{\Phi_1}{\Phi_2} \right\}.$$

$$\Phi_1 = s_1 s_2 + 2(\xi_1^2 s_1 + \xi_2^2 s_2)(t_1 + t_2)v,$$

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

$$F_1^{(P)} = (1 + s_1 s_2) [2(\xi_1 s_1 + \xi_2 s_2)(t_1 + t_2)v + \\ 4\xi_1 \xi_2 (1 + s_1 s_2)(t_1 + t_2)^2 v^2 + s_1 s_2 (1 - 16\xi_1 \xi_2 t_1 t_2 v^2)],$$

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

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

$$F_3^{(P)} = 4v(1 + s_1 s_2)(1 - 16\xi_1 \xi_2 t_1 t_2 v^2), \quad F_3^{(V)} = 2v(1 - s_1 s_2)(1 - 16\xi_1 \xi_2 t_1 t_2 v^2).$$

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

Meson	$n$	$M_{\text{exp}}$ ( MeV)	$M$ (MeV)	$\widetilde{M}$ (MeV)	Meson	$n$	$M_{\text{exp}}$ ( MeV)	$M$ (MeV)	$\widetilde{M}$ (MeV)
$\pi$	0	140	140	0	$\rho$	0	775	775	769
$\pi(1300)$	1	1300	1310	1301	$\rho(1450)$	1	1450	1571	1576
$\pi(1800)$	1	1812	1503	1466	$\rho$	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
$\eta$	0	548	621	0	$\omega$	0	775	775	769
$\eta'$	0	958	958	872	$\phi$	0	1019	1039	769
$\eta(1295)$	1	1294	1138	1361	$\phi(1680)$	1	1680	1686	1576
$\eta(1475)$	1	1476	1297	1516	$\phi$	2	2175	1897	2098

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

$m_{u/d}, \text{ MeV}$	$m_s, \text{ MeV}$	$m_c, \text{ MeV}$	$m_b, \text{ MeV}$	$\Lambda, \text{ MeV}$	$\alpha_s$	$R, \text{ fm}$
145	376	1566	4879	416	3.45	1.12

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

Meson	$n$	$M_{\text{exp}}$ (MeV)	$M$ (MeV)	Meson	$n$	$M_{\text{exp}}$ (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

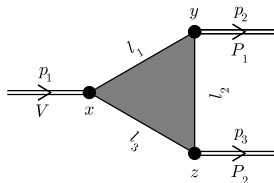
Table : Masses of heavy quarkonia.

Meson	$n$	$M_{\text{exp}}$ (MeV)	$M$ (MeV)
$\eta_c(1S)$	0	2981	2751
$\eta_c(2S)$	1	3639	3620
$\eta_c$	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

Table : Decay and transition constants of various mesons

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

## Strong decays: $g_{VPP}$



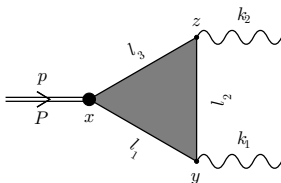
Decay	$g_{VPP}$ [*]	$g_{VPP}$
$\rho^0 \rightarrow \pi^+ \pi^-$	5.95	7.58
$\omega \rightarrow \pi^+ \pi^-$	0.17	0
$K^{*\pm} \rightarrow K^\pm \pi^0$	3.23	3.54
$K^{*\pm} \rightarrow K^0 \pi^\pm$	4.57	5.01
$\varphi \rightarrow K^+ K^-$	4.47	5.02
$D^{*\pm} \rightarrow D^0 \pi^\pm$	8.41	7.9
$D^{*\pm} \rightarrow D^\pm \pi^0$	5.66	5.59

**local color  
gauge  
invariance**

[\*] K.A. Olive et al. (Particle Data Group) Chinese Phys. C 38,090001, 2014

## Pion transition form factor – "BaBar puzzle"

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



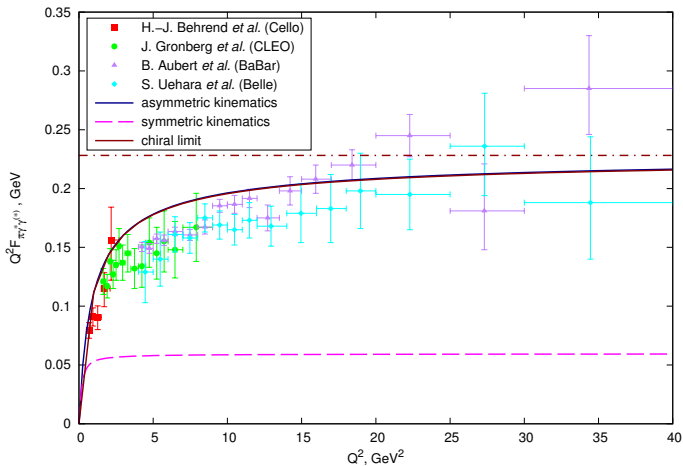
In momentum representation, the diagram has the following structure:

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

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

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

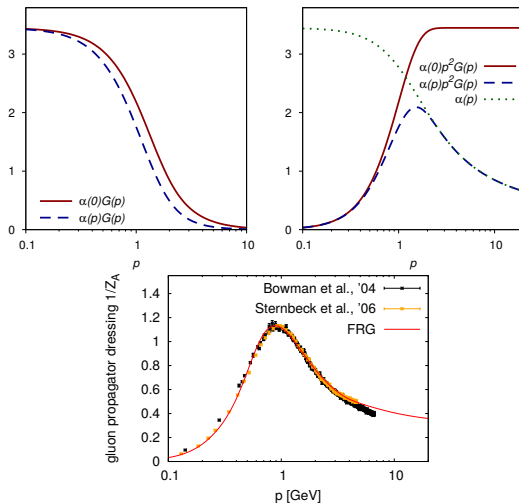
$$g_{P\gamma\gamma} = T(-M_P^2, 0, 0) = F_{P\gamma}(0).$$



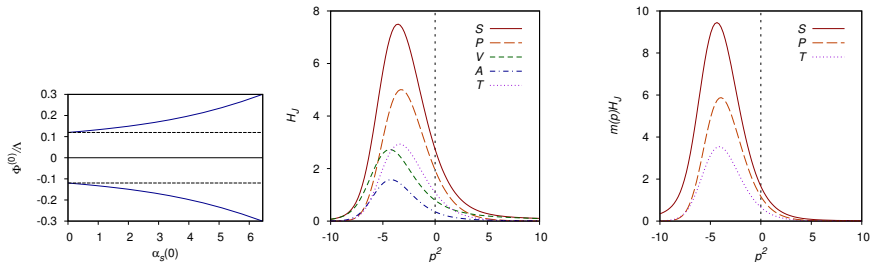
$$g_{\pi\gamma\gamma} = 0.272\text{GeV}^{-1} \quad (g_{\pi\gamma\gamma}^{\text{exp}} = 0.274\text{GeV}^{-1}).$$

$$F_{\pi\gamma^*\gamma^*}(Q^2) = T(-M_P^2, Q^2, Q^2).$$





Functional RG, DSE, Lattice QCD



**Figure** : Scalar quark condensate (LHS). Momentum dependence of the scalar (solid line), pseudoscalar (long dash), vector (dash), axial (dash dot) and tensor (dot) form factors (central plot) in the quark propagator (4), and scalar, pseudoscalar and tensor form factors (RHS plot) multiplied by the quark mass.

$$\Lambda^2 \Phi_{\mathcal{Q}_1}^{(0)} = \sum_{k=1}^{\infty} \frac{g^k}{k} \sum_{\mathcal{Q}_1 \dots \mathcal{Q}_k} \Phi_{\mathcal{Q}_2}^{(0)} \dots \Phi_{\mathcal{Q}_k}^{(0)} \Gamma_{\mathcal{Q}_1 \dots \mathcal{Q}_k}^{(k)},$$

$$m(p) = \bar{m}(0) F_{00}(p^2), \quad F_{00}(p) = \left[ 1 - \exp\left(-\frac{p^2}{\Lambda^2}\right) \right] \frac{\Lambda^2}{p^2}, \quad \bar{m}(0) = \frac{1}{3} g \Phi^{(0)}, \quad (3)$$

$$\tilde{H}(p) = \frac{m}{2v\Lambda^2} \mathcal{H}_S(p^2) \mp \gamma_5 \frac{m}{2v\Lambda^2} \mathcal{H}_P(p^2) + \gamma_\alpha \frac{p_\alpha}{2v\Lambda^2} \mathcal{H}_V(p^2) \pm i\gamma_5 \gamma_\alpha \frac{f_{\alpha\beta} p_\beta}{2v\Lambda^2} \mathcal{H}_A(p^2) \quad (4)$$

# Bethe-Salpeter approach

S. Kubrak, C. S. Fischer and R. Williams, arXiv:1412.5395 [hep-ph]

C. S. Fischer, S. Kubrak and R. Williams, Eur. Phys. J. A **51**, no. 1, 10 (2015) [arXiv:1409.5076 [hep-ph]]

C. S. Fischer, S. Kubrak and R. Williams, Eur. Phys. J. A **50**, 126 (2014) [arXiv:1406.4370 [hep-ph]].

S. M. Dorkin, L. P. Kaptari and B. Kampfer, arXiv:1412.3345 [hep-ph]

S. M. Dorkin, L. P. Kaptari, T. Hilger and B. Kampfer, Phys. Rev. C **89**, no. 3, 034005 (2014)

[arXiv:1312.2721 [hep-ph]]

$$S^{-1}(p) = Z_2 S_0^{-1}(p) + 4\pi Z_2^2 C_F \int \frac{d^4 k}{(2\pi)^4} \gamma^\mu S(k+p) \gamma^\nu (\delta_{\mu\nu} - k_\mu k_\nu / k^2) \frac{\alpha_{\text{eff}}(k^2)}{k^2},$$
$$\alpha_{\text{eff}}(q^2) = \pi \eta^7 x^2 e^{-\eta^2 x} + \frac{2\pi \gamma_m (1 - e^{-y})}{\ln[e^2 - 1 + (1+z)^2]}, \quad x = q^2 / \Lambda^2, \quad y = q^2 / \Lambda_t^2, \quad z = q^2 / \Lambda_{\text{QCD}}^2$$

**Talk of Richard Williams at our meeting!**

## Harmonic confinement - 4-dim. oscillator

R. P. Feynman, M, Kislinger, and F. Ravndal, Phys. Rev. D **3** (1971) 2706.

H. Leutwyler and J. Stern, “Harmonic Confinement: A Fully Relativistic Approximation to the Meson Spectrum,” Phys. Lett. B **73** (1978) 75;

H. Leutwyler and J. Stern, “Relativistic Dynamics on a Null Plane,” Annals Phys. **112** (1978) 94.

### Laguerre polynomials

$$\begin{aligned} \mathcal{S}_2 &= -\frac{1}{2} \int d^4x \int d^4z D(z) \Phi_{J_c}^2(x, z) \\ &\quad - 2g^2 \int d^4x d^4x' d^4z d^4z' D(z) D(z') \Phi_{J_c}(x, z) \Pi_{J_c, J'c'}(x, x'; z, z') \Phi_{J'c'}(x', z'), \\ \Phi^{aJ}(x, z) &= \sum_{nl} (z^2)^{l/2} \varphi^{nl}(z) \Phi^{aJln}(x). \end{aligned}$$

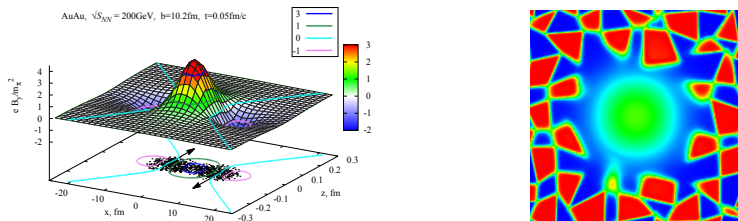
# ”Polarization of QCD vacuum by the strong electromagnetic fields”

## • 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!**

# One-loop quark contribution to the effective potential in the presence of arbitrary homogenous Abelian fields

$$U_{\text{eff}}(G) = -\frac{1}{V} \ln \frac{\det(i\mathcal{D} - m)}{\det(i\mathcal{D}' - m)} = \frac{1}{V} \int_V d^4x \text{Tr} \int_m^\infty dm' [S(x, x|m') - S_0(x, x|m')] |$$

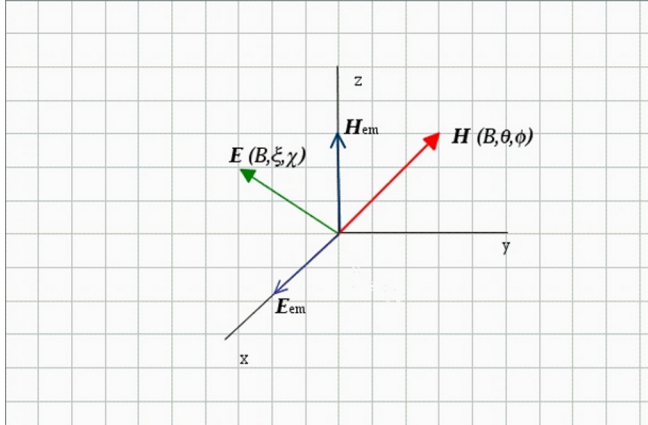
$$U_{\text{eff}}^{\text{ren}}(G) = \frac{B^2}{8\pi^2} \int_0^\infty \frac{ds}{s^3} \text{Tr}_n \left[ s\kappa_+ \coth(s\kappa_+) s\kappa_- \coth(s\kappa_-) - \mathbf{1} - \frac{s^2}{3} (\kappa_+^2 + \kappa_-^2) \right] e^{-\frac{m^2}{B}s},$$

$$\kappa_\pm = \frac{1}{2B} \sqrt{Q\sigma_\pm} = \frac{1}{2B} \left( \sqrt{2(\mathcal{R} + \mathcal{Q})} \pm \sqrt{2(\mathcal{R} - \mathcal{Q})} \right),$$

$$\mathcal{R} = (H^2 - E^2)/2 + \hat{n}^2 B^2 + \hat{n}B(H \cos(\theta) + iE \cos(\chi) \sin(\xi))$$

$$\mathcal{Q} = \hat{n}BH \cos(\xi) + i\hat{n}BE \sin(\theta) \cos(\phi) + \hat{n}^2 B^2 (\sin(\theta) \sin(\xi) \cos(\phi - \chi) + \cos(\theta) \cos(\xi))$$

Y. M. Cho and D. G. Pak, Phys.Rev. Lett., 6 (2001) 1047

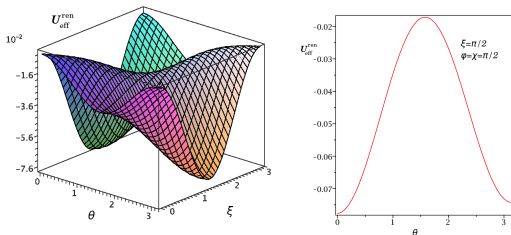


$$H_i = H\delta_{i3}, \quad E_j = E\delta_{j1}, \quad H^c = \{B, \theta, \phi\}, \quad E^c = \{B, \xi, \chi\}$$

$H \neq 0, E \neq 0$  and arbitrary gluon field

$$\Im(U_{\text{eff}}) = 0 \implies \cos(\chi) \sin(\xi) = 0, \sin(\theta) \cos(\phi) = 0$$

Effective potential (in units of  $B^2/8\pi^2$ ) for the electric  $E = .5B$  and the magnetic  $H = .9B$  fields as functions of angles  $\theta$  and  $\xi$  ( $\phi = \chi = \pi/2$ )



Minimum is at  $\theta = \pi$  and  $\xi = \pi/2$ :

orthogonal to each other chromomagnetic and chromoelectric fields:  $Q = 0$ .

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

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

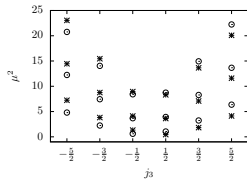
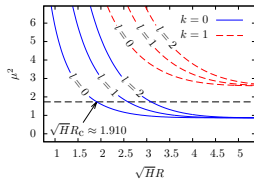
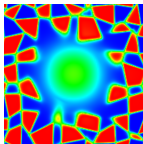
M. D'Elia, M. Mariti and F. Negro, Phys. Rev. Lett. **110**, 082002 (2013)

G. S. Bali, F. Bruckmann, G. Endrodi, F. Gruber and A. Schaefer, JHEP **1304**, 130 (2013)



# Domain wall junctions - deconfinement

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



The color charged scalar field inside junction:

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

The solutions are quasi-particle excitations

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

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

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

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

”Confining properties of QCD in strong magnetic backgrounds” M. D’Elia, C. Bonati, M. Mariti, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo  
arXiv:1607.08160

### **LQCD conclusions:**

”Confining properties of QCD in strong magnetic backgrounds” M. D’Elia, C. Bonati, M. Mariti, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo

The magnetic field leads to a quadrupole-like deformation of the static quark-antiquark potential.

Most of the effect seems related to a modification of the string tension.

We have hints that  $\sigma_{||}$  could vanish in the vacuum for  $eB$  of the order of  $10 \text{ GeV}^2$ . Future simulations on finer lattice spacings could confirm this possibility.

At finite  $T$ , the main effect is a general suppression of the potential leading to a precocious loss of confining properties: deconfinement catalysis. That could be important for heavy ion physics in the thermal medium, think for instance of  $J\psi$  suppression and related issues.

## Summary

$\langle g^2 F^2 \rangle \neq 0 \rightarrow$  domain wall network, almost everywhere abelian (anti-)self-dual gluon fields.

An ensemble of almost everywhere Abelian homogeneous (anti-)self-dual gluon fields represented by the domain wall networks looks like a suitable framework for studying mechanisms of confinement, chiral symmetry realisation and hadronization.

Background of domain wall networks - harmonic confinement.

(Anti-)self-duality - quark zero mode driven realization of chiral symmetry.

Quark and gluon propagators - qualitative agreement with FRG and DSE.

Meson effective action - quantitatively correct phenomenology both with respect to confinement and chiral symmetry.

Polarization effects in QCD vacuum due to the strong electromagnetic fields, deconfinement, chiral symmetry restoration.