Helmholtz-DIAS International Summer School
Quantum Field Theory at the Limits:
from Strong Fields to Heavy Quarks
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GLUEBALLS

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Introduction

Review by Vincent Mathieu, N.K. and Vicente Vento Int. J. Mod. Phys. E **18**, 1 (2009)

- Glueballs in MIT bag Model: two gluon states in cavity

Jaffe and Johnson Phys.Lett.B60 (1976) 201.

$$E = \frac{4\pi B R^3}{3} + \sum_i n_i \frac{x_i}{R}.$$

Energy modes $E_i = x_i/R$ are fixed from boundary condition in cavity:

$$n_\mu G_a^{\mu\nu}(x) = 0 \; at \;\; r = R.$$

$$M(0^{++}) \approx M(2^{++}) \approx 1 GeV, \;\; M(0^{-+}) \approx M(2^{-+}) \approx 1.3 GeV$$

- Results for glueball masses in some of modern phenomenological constituent gluon models based on non-perturbative QCD:

Gerasimov, Kaidalov and Simonov; Anisovich et al; Efimov and Ganbold, Lubovitskij et al Mathieu et al
are in general agreement with lattice results

- But some models:

Vento, Molodtsov et al Mennessier, Minkowski, Ochs, Narison
suggest more light lowest mass 0^{++} glueball (due to σ-glueball mixing)

$$M(0^{++}) \approx 0.5 \div 1.0 GeV.$$

- Glueballs in QCD Sum Rules

S.Narison, H.Forkel, Harnett,Moats and Steele.

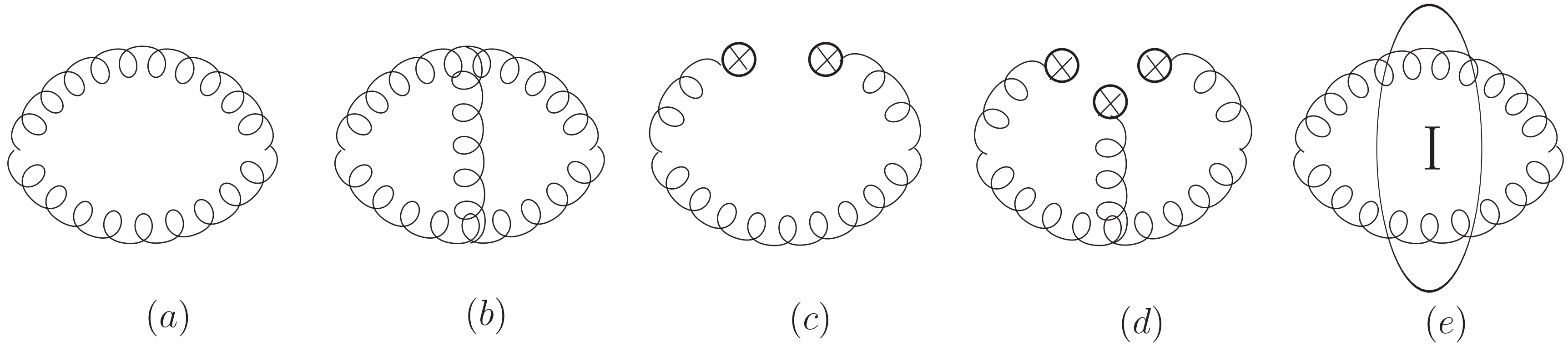

Figure 1: The diagrams (a) and (b) represent pQCD contributions, diagram (c) represents the contribution arising from the gluon condensate $< 0|\alpha_s G^2|0 >$, diagram (d) is the contribution from three-gluon condensate $< 0|gG^3|0 >$ and diagram (e) is so-called direct instanton contribution.

$$M(0^{++}) \approx 1.5GeV, \quad M(0^{-+}) \approx M(2^{++}) \approx 2GeV$$

Lattice Results for Glueballs

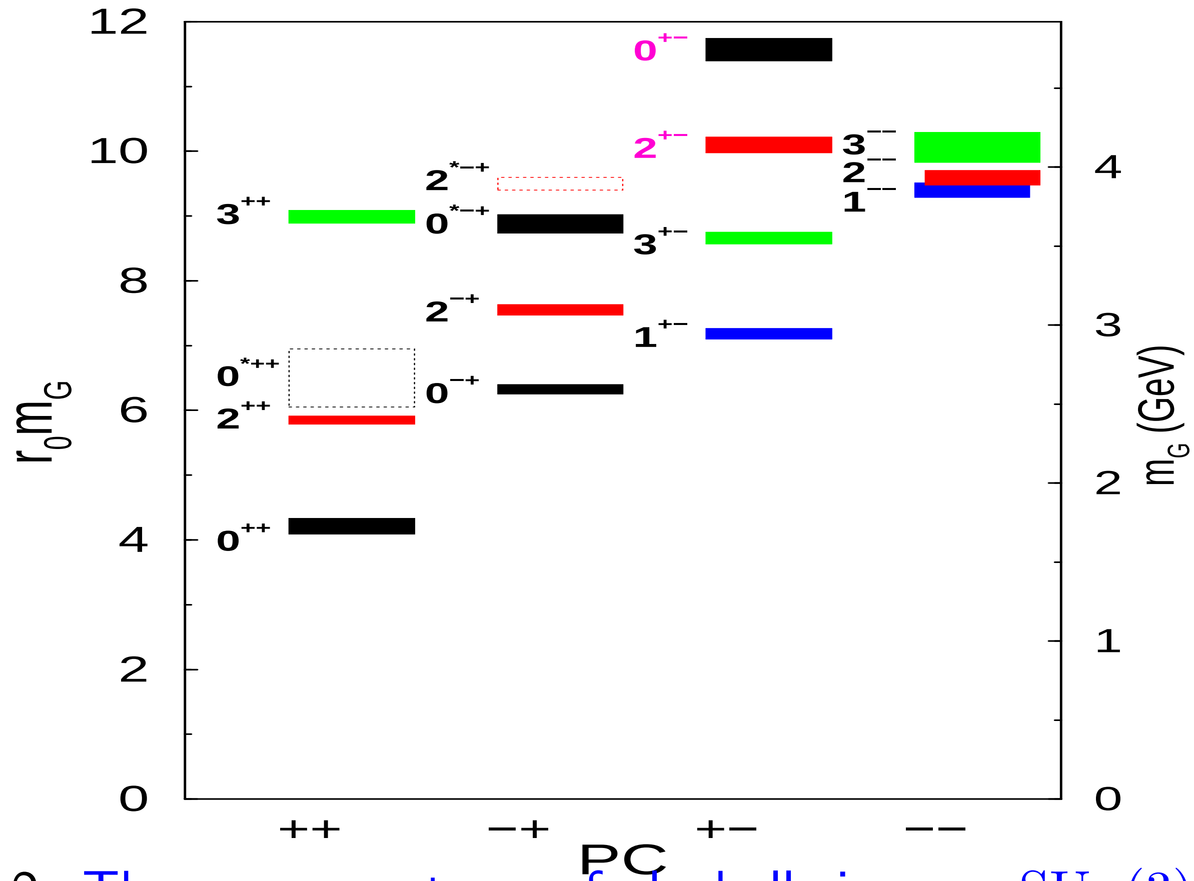

Figure 2: The mass spectrum of glueballs in pure $\mathrm{SU_C}(3)$ gauge theory by Morningstar and Peardon calculation (1999) in an anisotropic lattice ($6^3 \times 30$, $8^3 \times 40$, $10^3 \times 50$ and $15^3 \times 45$). The masses are given in units of the hadronic scale r_0 along the left vertical axis and in GeV along the right vertical axis ($r_0^{-1} = 410 \pm 20 MeV$).

Table 1: Continuum-limit glueball masses M_G for Chen et al. and for Morningstar and Peardon.

J^{PC}	$r_0 M_G$ (Chen et al (2006))	$r_0 M_G$ (Morningstar (1999))
0^{++}	4.16(11)	4.21(11)
2^{++}	5.82(5)	5.85(2)
2^{++}	5.83(4)	5.85(2)
3^{++}	9.00(8)	8.99(4)
3^{++}	8.87(8)	8.99(4)
0^{-+}	6.25(6)	6.33(7)
1^{+-}	7.27(4)	7.18(3)
2^{-+}	7.49(7)	7.55(3)
2^{-+}	7.34(11)	7.55(3)
3^{+-}	8.80(3)	8.66(4)
3^{+-}	8.78(5)	8.66(3)
3^{++}	9.00(8)	8.99(4)
3^{++}	8.87(8)	8.99(4)
0^{-+}	6.25(6)	6.33(7)
1^{+-}	7.27(4)	7.18(3)
2^{-+}	7.49(7)	7.55(3)
2^{-+}	7.34(11)	7.55(3)
3^{+-}	8.80(3)	8.66(4)

- More recent result result by Meyer arXiv:0808.3151

$$r_0 M_{0^{++}} = 3.958(47), \quad r_0 M_{2^{++}} = 5.878(77).$$

All lattice calculations are now consistent and shown that without the quarks in pure $SU(3)_c$ the masses of the lowest states are

$$M(0^{++}) \approx \ 1.7\ GeV, M(2^{++}) \approx \ 2.4\ GeV, M(0^{-+}) \approx \ 2.6\ GeV$$

- Recent result in unquenched QCD by Gregory et al JHEP10(2012) 170

$$M(0^{++}) = 1.795\ GeV, \quad M(2^{++}) = 2.620\ GeV,$$

- Note that quenched lattice calculation for gluon condensate $G_0 = \ < 0\,|\frac{\alpha_s}{\pi} G^a_{\mu\nu} G^a_{\mu\nu}|0 >$ gives value $G_0 = 0.14 \pm 0.02 GeV^4$ but QCD sum rule use $G_0 = 0.012 GeV^4$!

M.D'Elia, A.D.Giacomo and E.Meggiolaro, Phys. Lett. **B408** (1997) 315.

- The size of scalar glueball is very small $r_{0^{++}} \approx 0.2 fm$!!! but the size of tensor is big $r_{2^{++}} \approx 0.8 fm$

The reason is strong attraction induced by instantons in 0^{++} channel.
T. Schafer and E. V. Shuryak, Phys. Rev. Lett. **75**, 1707 (1995)

Experiment

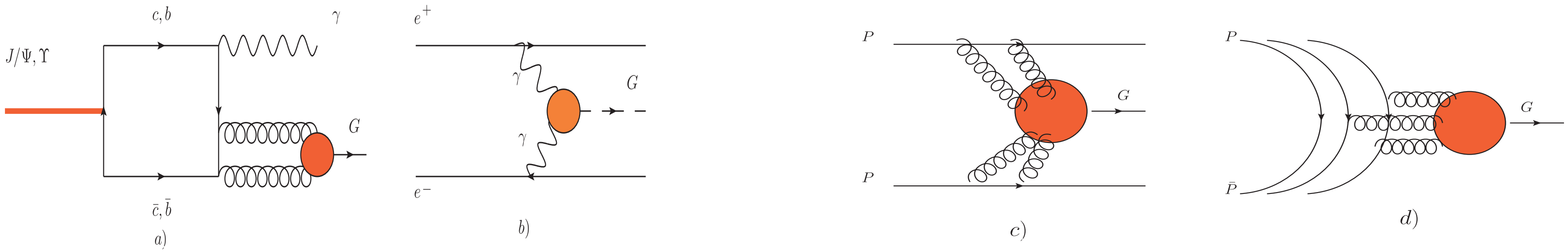

Figure 3: Glueball production in a) heavy quarkonium radiative decays (BESIII,Belle, BaBar, LHCb) , b) in photon-photon fusion (BESIII, Belle, BaBar), c) in the central meson production (RHIC, LHC), d) in proton-antiproton annihilation (PANDA)

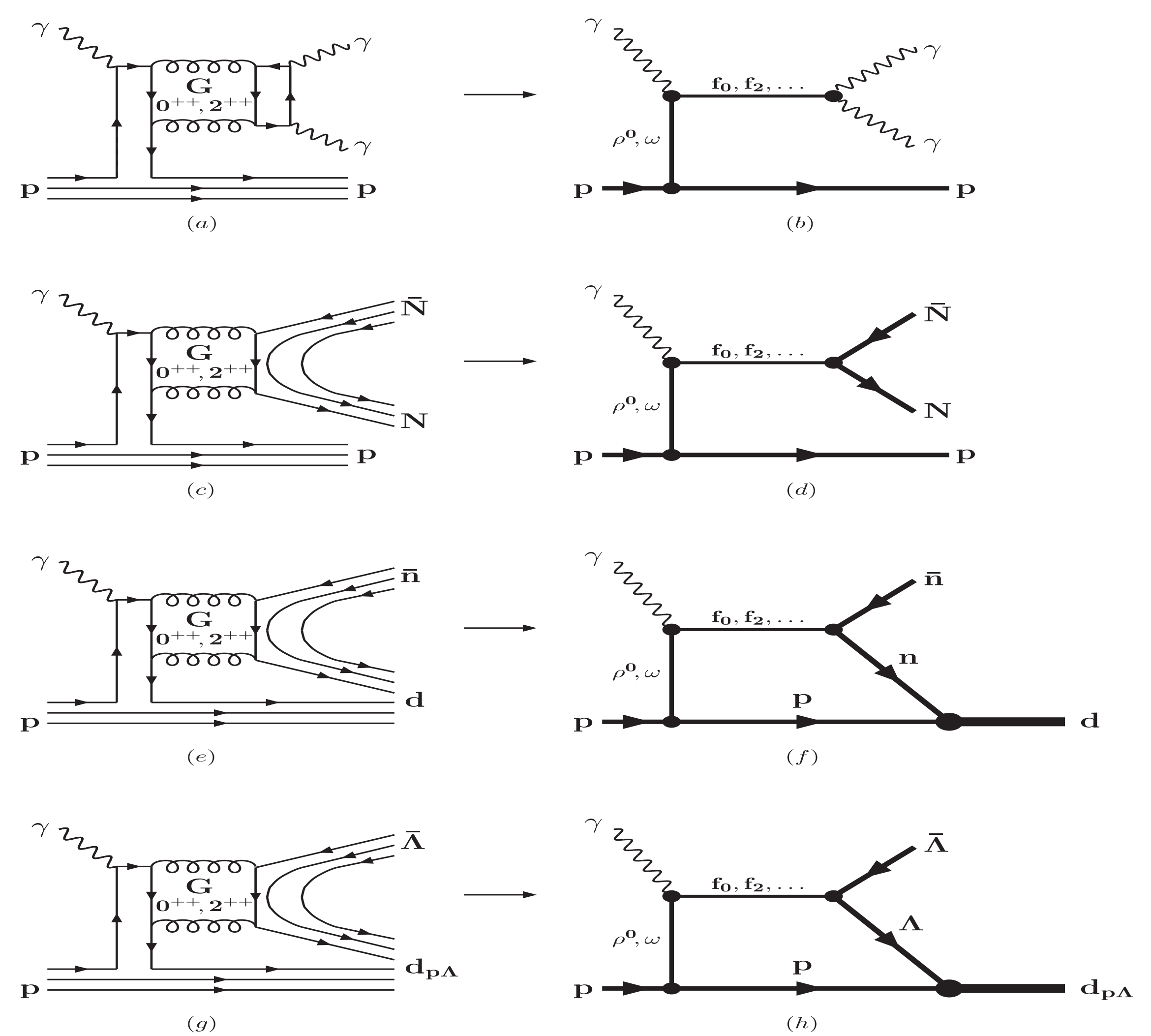

Figure 4: The production of glueballs in γ-proton collision. Proposal for GlueX (JLab) by Lyubovitskij et al arXiv:1605.01035.

- Glueball production in heavy quark weak decays

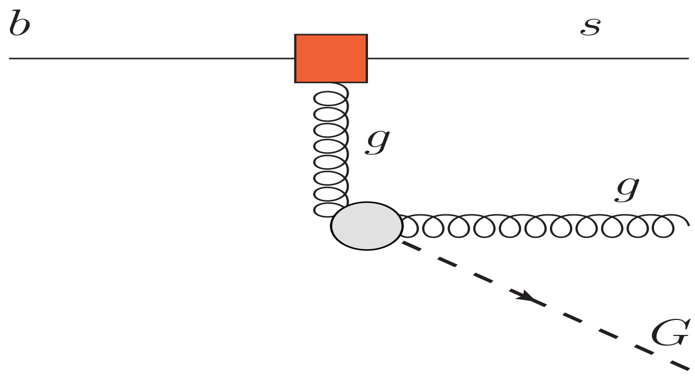

Figure 5: Glueball production in B meson weak decay (LHCb,Belle-II,BaBar)

X. G. He and T. C. Yuan, "Glueball Production via Gluonic Penguin B Decays," Eur. Phys. J. C **75**, no. 3, 136 (2015)

Scalar Glueball Candidates:

$$f_0(600),\quad f_0(980),\quad f_0(1370),\quad f_0(1500),\quad f_0(1710),\quad f_0(1790)$$

Pseudoscalar Glueball Candidates:

$$\eta(1440),\quad X(1835)$$

Tensor Glueball Candidate:

$$f_2(2000)$$

Problems with interpretation:

- Possible mixing with $\bar{q}q$ and $\bar{q}^2q^2$states
- Many states with the same quantum numbers above $M \approx 1GeV$.

Glueballs with exotic quantum numbers (three-gluon bound states-oddballs)

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$$

Production and decays modes of exotic glueballs were discussed in L. Bellantuono, P. Colangelo and F. Giannuzzi, "Holographic Oddballs," JHEP **1510**, 137 (2015) and
D. Parganlija, "Glueballs and vector mesons at NICA," arXiv:1601.05328 [hep-ph]

Problem: The calculation of the masses and decay modes within QCD is very difficult task. The Lattice calculation gives very large mass for exotic glueballs, for example, for 0^{--}, they obtain $M_G = 5166 \pm 1000$ MeV Gregory et al JHEP, v.1210 (2012),170

The fist attempt to calculate masses of oddballs within QCD sum rules was done in C. F. Qiao and L. Tang, "Finding the 0^{--} Glueball," Phys. Rev. Lett. **113**, no. 22, 221601 (2014) and in "Mass Spectra of 0^{+-}, 1^{-+}, and 2^{+-} Exotic Glueballs," Nucl. Phys. B **904**, 282 (2016).

Recalculation exotic glueball masses within QCD sum rule is in progress (N.K. A.Pimikov, Pengming Zhang, Hee-Jung Lee)

- Experiments: BESIII, JLab, COMPASS, PANDA,BELLE-II, BaBar,RHIC, LHCb

Signature for glueballs

- Large branching to decay to mesons with strangeness, for example $0^{++} \to K\bar{K}$.

- Large branching to decay to η and η', for example, $0^{++} \to \eta\eta$ and $0^{-+} \to \eta'\sigma$.

- Weak coupling to $\gamma\gamma$ (determined by glueball-quarkonia mixing) .

- Clean perturbative coupling to the heavy quarks.

Mixing between glueballs and quarkonia

There are many approaches to include effects of mixing to glueball spectroscopy. For example in 0^{++}, to consider $f_0(1370), f_0(1500), f(1710)$ as admixture of quark-antiquark octet-singlet states with glueball (see Hai-Yang Cheng et al arXiv:15.03.0682, Giacosa et al Phys.Rev., D72 (2005) 094006 etc).

In pseudoscalar channel 0^{-+} the possible mixing is between states η, η' and glueball. For heavy pseudoscalar glueball $M_G \approx 2.6$ GeV (quenched lattice QCD result) the possible large mixing with $\eta_c(2983)$ state (Kochelev and Dong-Pil Min Phys. Rev. D **72** (2005) 097502)

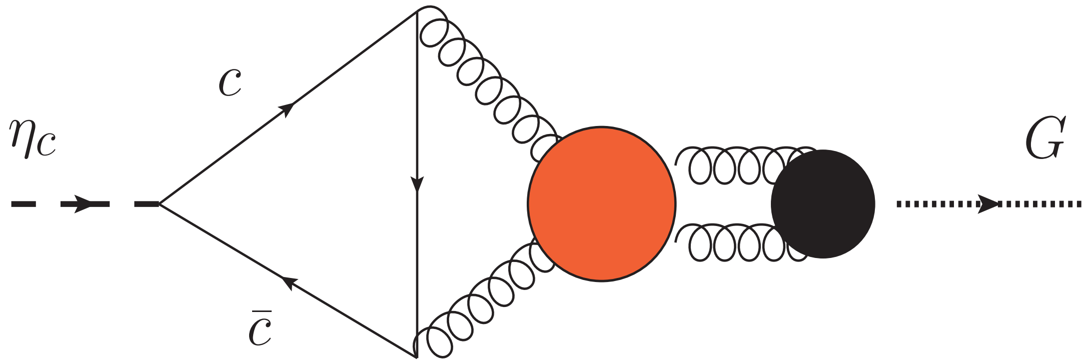

Figure 6: The $\eta_c - 0^{-+}$ glueball mixing induced by instantons

OZI-rule, mixing between different hadron states and XYZ mesons problem

- **Problem of the mixing between different quark and gluon states now is one of the central problems in hadron spectroscopy.**

OZI rule: "Decays that correspond to the disconnected quark diagrams are suppressed" This is a rule but not a law!

In hadron spectroscopy well known example is vector channel 1^{--}. (ρ and ω mesons have very small admixture of strange quarks).

But in some specific channels with strong interaction to QCD vacuum, for example in $0^{-+}, 0^{++}$ OZI rule does not work.

Perturbative and nonperturbative mixing

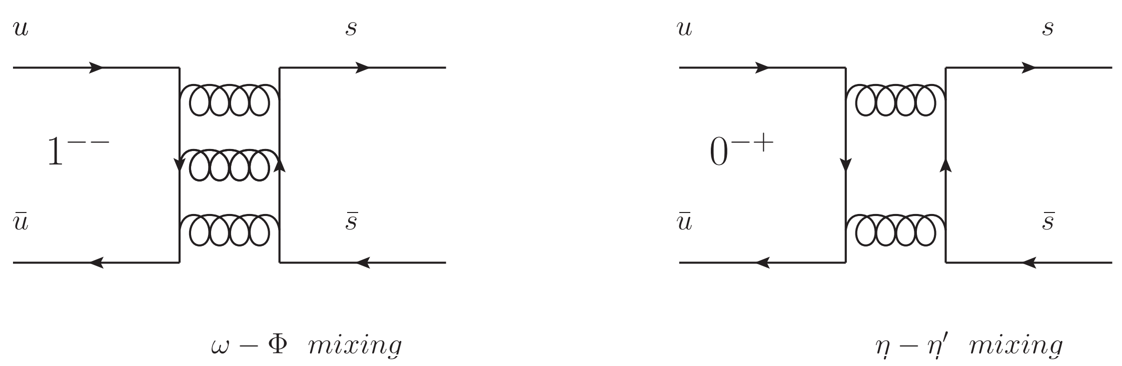

Figure 7: Perturbative mixing induced by gluon exchange

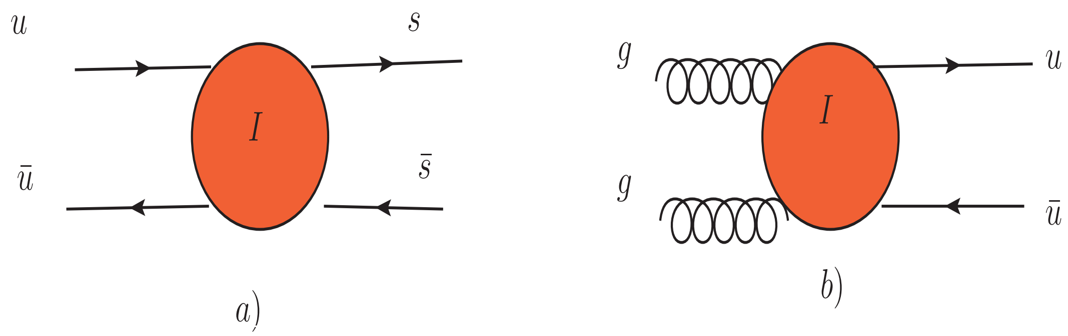

Figure 8: Nonperturbative mixing induced by instantons: a) between quark states, b) between glueball and quarkonium

Instantons in QCD (Introduction was given in talk by Korchagin)

Discovery of instantons (1975) $\rightarrow$ Instanton liquid model (1982)

The model describes the QCD vacuum as a system of instantons and antiinstantons [Callan, Dashen, Gross, Shuryak, Diakonov, Petrov ...]

One can introduce the “density” of instantons

$$n_I(\rho) \sim exp\left(-\frac{2\pi}{\alpha_s(\rho)}\right)$$

R - distance between instantons
$\rho \approx$ 0.3 fm - instanton size
If $R >> \rho \rightarrow$ vacuum is a “gas” of instantons
If $R \approx 3\rho \rightarrow$ vacuum is an instanton “liquid”

Role of instanton induced quark-quark and quark-gluon interactions in the weak decays

Famous multiquark t'Hooft interaction induced by instantons

For $N_f=3$, $q = u, d, s \Rightarrow$ six-quark effective interaction induced by instantons

In $m_u = m_d = m_s \to 0$ limit

$$H_{t'Hooft} = \int d\rho n(\rho) \left(4\pi^2\rho^3\right)^3 \frac{1}{6N_C(N_C^2-1)} \varepsilon_{f_1 f_2 f_3} \varepsilon_{g_1 g_2 g_3} \times \\ \times \left\{ \frac{2N_C+1}{2N_C+4} \bar{q}_R^{f_1} q_L^{g_1} \bar{q}_R^{f_2} q_L^{g_2} \bar{q}_R^{f_3} q_L^{g_3} + \right. \\ \left. + \frac{3}{8(N_C+2)} \bar{q}_R^{f_1} q_L^{g_1} \bar{q}_R^{f_2} \sigma_{\mu\nu} q_L^{g_2} \bar{q}_R^{f_3} \sigma_{\mu\nu} q_L^{g_3} + (R \leftrightarrow L) \right\}$$

Very important in some processes: $K \to \pi\pi$ decays, $\Delta I = 1/2$ rule, CP

violation, etc .. (N.K. and V.Vento, "Instantons and the Delta(I) = 1/2 rule," Phys. Rev. Lett. **87** (2001) 111601)

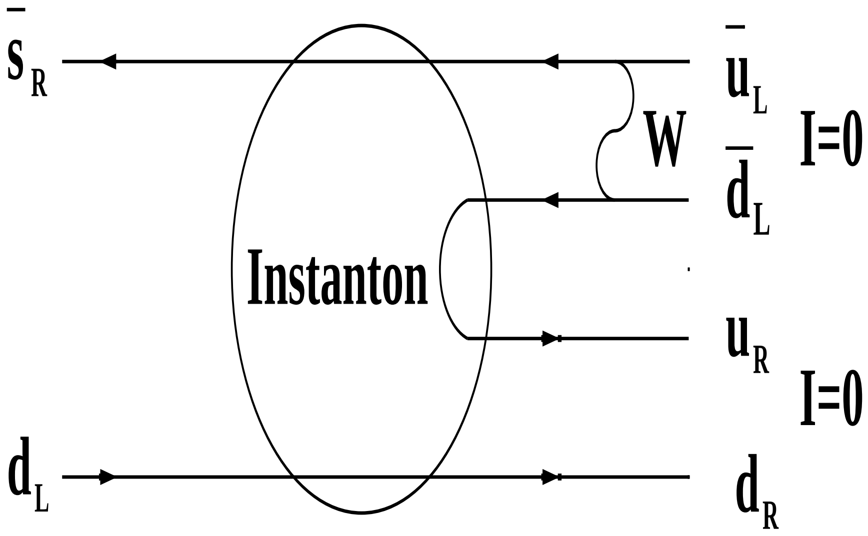

Figure 9: The contribution of the six-quark instanton induced interaction to the $K^0 \to \pi\pi$ decay

Anomalous quark-gluon and quark-gluon-pion interactions induced by instantons

• In the general case, the interaction vertex of massive quark with gluon can be written in the following form:

$$V_\mu(k_1^2,k_2^2,q^2)t^a = -g_s t^a[\gamma_\mu F_1(k_1^2,k_2^2,q^2) + \frac{\sigma_{\mu\nu}q_\nu}{2M_q}F_2(k_1^2,k_2^2,q^2)],$$

where $k_{1,2}^2$ are virtualities of incoming and outcoming quarks and q is momentum transfer. It is similar to the photon-nucleon vertex

$$\Gamma_\mu{}^{QED} = \gamma_\mu F_1(q^2) + \frac{\sigma_{\mu\nu}q_\nu}{2M_N}F_2(q^2),$$

where $F_1(q^2), F_2(q^2)$ are Dirac and Pauli nucleon form factors, correspondently. • Anomalous quark chromomagnetic moment (AQCM):

$$\mu_a = F_2(0,0,0).$$

$$\Delta\mathcal{L} = -\imath\mu_a\frac{g_s}{4M_q}\bar{q}\sigma_{\mu\nu}t^a q G^a_{\mu\nu}$$

The shape of form factor $F_2(k_1^2, k_2^2, q^2)$ within instanton model is fixed:

$$F_2(k_1^2, k_2^2, q^2) = \mu_a \Phi_q(\mid k_1 \mid \rho/2)\Phi_q(\mid k_2 \mid \rho/2)F_g(\mid q \mid \rho) \ ,$$

where

$$\begin{aligned} \Phi_q(z) &= -z\frac{d}{dz}(I_0(z)K_0(z) - I_1(z)K_1(z)), \\ F_g(z) &= \frac{4}{z^2} - 2K_2(z) \end{aligned}$$

are the Fourier-transformed quark zero-mode and instanton fields, respectively, and $I_\nu(z)$, $K_\nu(z)$,are the modified Bessel functions and ρ is the instanton size.
The value of AQCM is determined by the effective density of the instantons $n(\rho)$ in nonperturbative QCD vacuum (N.K. (1996))

$$\mu_a = -\pi^3 \int \frac{d\rho n(\rho)\rho^4}{\alpha_s(\rho)}.$$

Within Shuryak's instanton liquid model the relation between AQCM and dynamical quark mass is

$$\mu_a = -\frac{3\pi(M_q\rho_c)^2}{4\alpha_s(\rho_c)},$$

where $\rho_c \approx 0.3$ fm and $\alpha_s(\rho_c) \approx 0.5$.

Quark-gluon-pion anomalous chromomagnetic interaction

$1/N_c$ correction to AQCM quark-gluon interaction-PCAC (Partially Conserved Axial Current) requirement. Lagrangian of σ model (pion part) from t'Hooft interaction (Diakonov,Petrov etc.):

$$\mathcal{L}_{eff} = \bar{q}[i\hat{\partial} - M_q e^{i\gamma_5\vec{\tau}\vec{\pi}/F_\pi}]q$$

Including AQCM effect gives the effective quark-gluon-pion interaction (Polyakov, Diakonov 2003):

$$\Delta\mathcal{L}_{eff} = -\imath\mu_a \frac{g_s}{4M_q}\bar{q}\sigma_{\mu\nu}e^{i\gamma_5\vec{\tau}\vec{\pi}/F_\pi}t^a q G^a_{\mu\nu}$$

The contribution of anomalous chromomagnetic quark-gluon interaction to weak interaction of heavy quarks

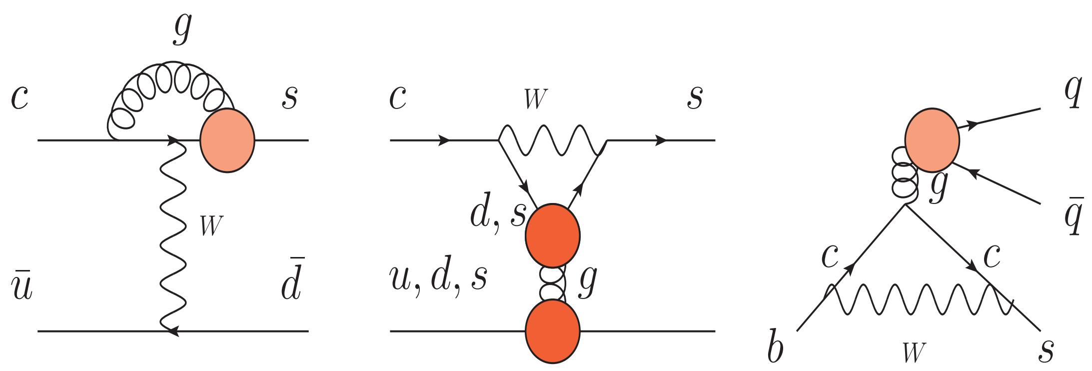

Figure 10: Examples of the corrections induced by instantons to heavy quark weak interactions

XYZ mesons spectroscopy and mixing

- **Many unusual hadron states with heavy quark content were found recently: both neutral and charged ($X(3872), Z_c(3900), Z_c(4020)$ etc. (see talks by Takizawa, Zhemchugov and Bernardo Adeva)**

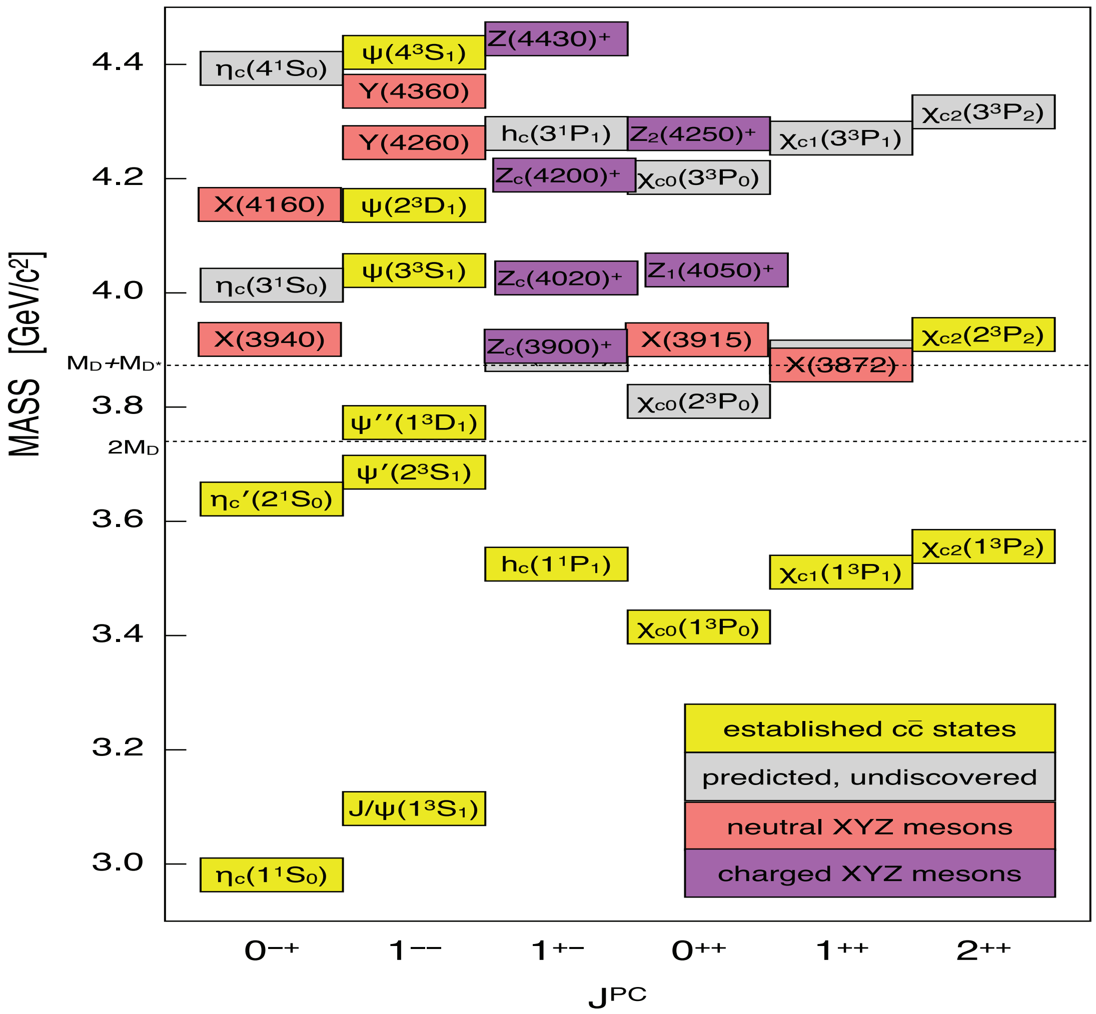

Figure 11: The spectrum of charmonium and charmoniumlike mesons from arXiv:1511.01589 by S.L. Olsen

Plenty of the different models now in the market (tetraquarks, molecules etc, see Ali talk).

(New idea: Kochelev 2015 (unpublished): High radially excited states of the light quark-antiquark system can mix easy with the states which have the heavy quark content and approximately the same mass

It might be that $Z_c(3900)$ is the mixing state of molecular like or/and tetraquark hidden charmed states with high radial excitation of light quark system

Recent paper in spirit of this idea by S. Coito, "Radially excited axial mesons and the enigmatic Z_c and Z_b in a coupled-channel model," Phys. Rev. D **94** (2016) no.1, 014016

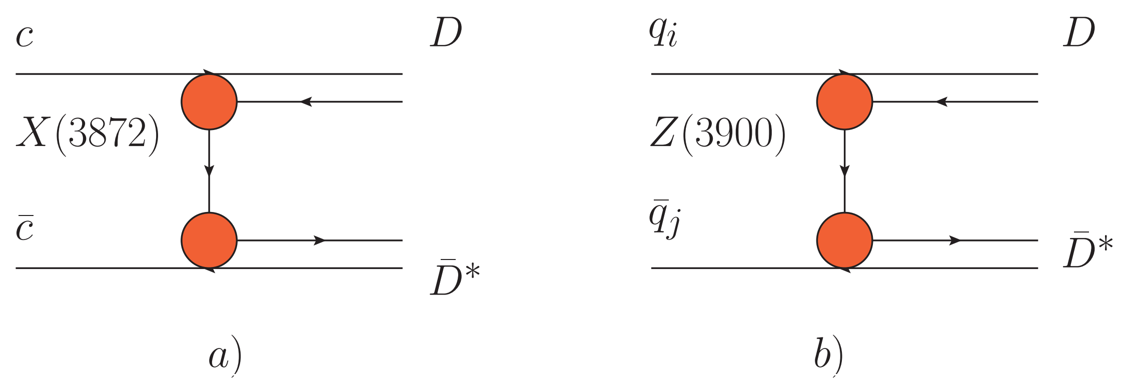

Figure 12: a) Mixing $c\bar{c}$ core with $D\bar{D}^*$ state, b) mixing the light radial excited state with $D\bar{D}^*$

- The small Br to the final state without heavy quarks can be related to the existence of many nodes in the wave function of the light quark system $n_r \approx 7$.

Possible relation to $J/\Psi \to \rho\pi$ puzzle. Violation of so-called 12% rule in hadronic decays of charmonia. Very small Br $\Psi' \to \rho\pi$ due to the node in Ψ' wave function (see S. Brodsky, G. de Teramond and M. Karliner, "Puzzles in Hadronic Physics and Novel Quantum Chromodynamics Phenomenology," Ann. Rev. Nucl. Part. Sci. **62**, 1 (2012) [Ann. Rev.

Nucl. Part. Sci. **62**, 2082 (2011)]).

$$\frac{\Psi' \to h}{\Psi \to h} \approx \frac{\Psi' \to e^+e^-}{\Psi \to e^+e^-} \approx 12\% \qquad (1)$$

Experiment for $h = \rho\pi$ gives 0.2%!

- Is the $Z_c(4020)$ is the result of mixing of the next radial excitation in the light quark system with $n_r = 8$ with hidden charm states? In this case the next exotic state might be around $Z_c \approx 4140$ MeV.

- **Possible connection between high excited states in light quark systems and XYZ mesons!**

Glueballs in the hot quark-gluon plasma

- **Experiments at RHIC and LHC discovered a new type of nuclear matter-***strongly interacted quark-gluon plasma*

- **It looks like a some liquid and does not have expected gas-like behavior.**

- **It is very important from point of view of theory of strong interaction to find the reason for such behavior (glueballs, instantons,monopoles etc.) Fundamental reason is also to understand the role of nonperturbative structure of strong interaction in evolution of our Universe, structure of stars etc.**

New experiments on QGP properties are planed at NICA (Dubna) , FAIR (Darmstadt), RHIC(Brookhaven) and LHC (CERN)

Glueballs production in high energy collisions

The early stage of high multiplicity pp, pA and AA collider is represented by a nearly quarkless, hot and pure gluon plasma. It should be abundant production of glueballs in such events.

V. Vento,
"Glueball enhancement by color de-confinement," Phys. Rev. D **75**, 055012 (2007)

H. Stoecker *et al.*,
"Glueballs amass at RHIC and LHC Colliders! - The early quarkless 1st order phase transition at $T = 270$ MeV
- from pure Yang-Mills glue plasma to GlueBall-Hagedorn states," J. Phys. G **43**, no. 1, 015105 (2016)

Glueballs in hot plasma in the Gluodynamics without quarks and three phases of gluon matter

N.K. EPJA (2016) **52**:186

The description of the thermodynamics of the pure $SU(3)$ gauge theory is one of the benchmarks of the our understanding of the properties of the Quark-Gluon Plasma (QGP). Recently very precise lattice results for the equation of state of this theory at finite T, below and above deconfinement temperature T_c, were presented . They challenge our understanding of QCD dynamics at finite temperatures. One of the more puzzling behaviors of these results is the temperature dependence of the trace anomaly.

- **Trace anomaly** $\Delta(T) = (\epsilon - 3p)/T^4$ **in deconfinement phase and glueballs** $I/T^4 = (\epsilon - 3p)/T^4$. More precisely, just above T_c the trace anomaly grows rapidly up to $T_G \approx 1.1T_c$ and then it decreases as $I/T^4 \sim 1/T^2$ up to $T \approx 5T_c$. We can thus conclude that the thermodynamics of the theory for $T_G \geq T \geq T_c$ is determined only by the light glueballs.

Our starting point is the relation between the lowest scalar glueball mass, m_G, and the gluon condensate, $G^2 =< 0|\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^a_{\mu\nu}|0 >$ at $T = 0$, which appears naturally in the dilaton approach

$$m_G^2 f_G^2 = \frac{11N_c}{6} < 0|\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^a_{\mu\nu}|0 >, \tag{2}$$

where f_G is the glueball coupling constant to gluons. Lattice calculations show that the gluon condensate decreases roughly by factor two at $T = T_c$ due to the strong suppression of its electric component, while slightly above T_c the condensate vanishes very rapidly due to the cancellation between its magnetic and electric components. The temperature behavior of the condensate at $T_G \geq T \geq T_c$ can be described by the equation

$$G^2(T) = G^2\left[1 - \left(\frac{T}{T_G}\right)^n\right]$$

In the case of a temperature dependent boson mass in a hot plasma trace anomaly is

$$\Delta(T) = \frac{N_G}{2\pi^2}\int_0^\infty dx \frac{x^2}{\sqrt{x^2+m(T)^2/T^2}\left(e^{\sqrt{x^2+m(T)^2/T^2}}-1\right)} \times \frac{m(T)^2}{T^2}\left[1-\frac{T}{m(T)}\frac{dm(T)}{dT}\right], \quad (3)$$

where $N_G = 2$ for two glueball states and the mass function for $T_G \geq T \geq T_c$ is given by

$$m(T) = m_0\sqrt{1-\left(\frac{T}{T_G}\right)^4}. \quad (4)$$

Above T_G the massless glueballs can dissociate to massless gluons due to the process $G + G \rightarrow gluon + gluon$, therefore, at $T > T_G$ one should have a mixed glueball-gluon phase.

At very large temperature we have a free gluon gas and the contribution of glueballs to the pressure should be suppressed with respect to the free gluon case by a factor $(T_G/T)^\lambda$ with $\lambda > 0$. Based on the scaling in the trace anomaly $I(T)/T^4(T/T_c)^2$ observed in lattice calculation we use $\lambda = 2$. The pressure above T_G is the sum of glueball and gluon pressures

$$P(T)_{T>T_G} = \frac{N_G\pi^2}{90}T^4\left(\frac{T_G}{T}\right)^2 + \frac{N_g\pi^2}{90}T^4\left[1 - \left(\frac{T_G}{T}\right)^2\right],$$

where $N_g = 2(N_c^2 - 1) = 16$ is the number of the gluon degrees of freedom We obtain for the scale anomaly at $T > T_G$

$$\Delta(T) = \frac{(N_g - N_G)\pi^2}{45}\left(\frac{T_G}{T}\right)^2. \tag{5}$$

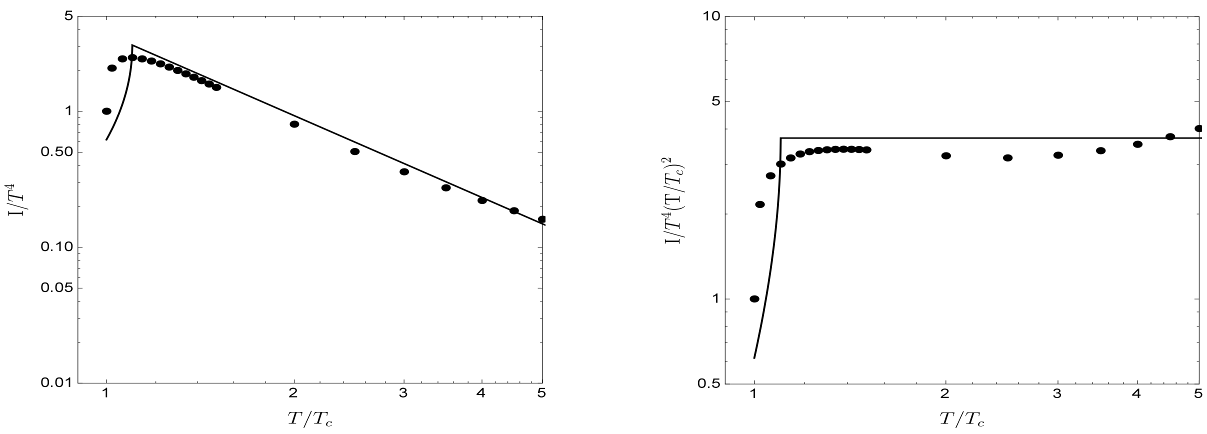

Figure 13: The trace anomaly $I(T)/T^4$ (left panel), and its scaling value $(I(T)/T^4)(T/T_c)^2$ (right panel) as the function of T/T_c. The lattice data presented by the bold spots.

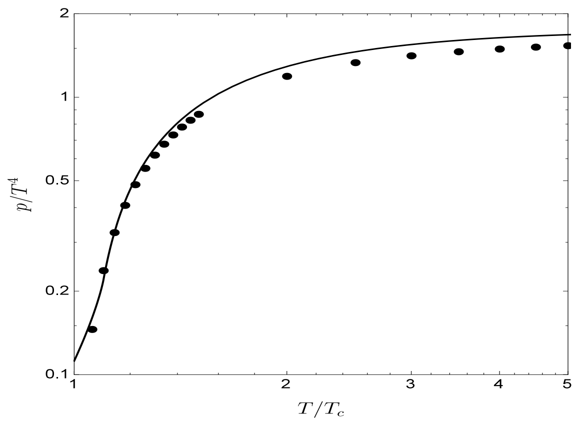

Figure 14: The pressure p/T^4 as the function of T/T_c compared with the lattice data.

Therefore in the pure Gluedynamics, theory without quarks, there are three different phases at finite T should exist. One of these phases is the gas of the massive glueballs at $T < T_c$. Second phase is just above T_c at $T_G \geq T \geq T_c$, where $T_G \approx 1.1T_c$. In this phase the main contribution to equation of state is coming from very light scalar and pseudoscalar mesons. After $T_G \approx 1.1T_c$ there is a mixed phase of massless gluons and scalar-pseudoscalar massless glueballs. In principle, such phases should be exist also in the full QCD with quarks. In this case pseudoscalar glueball aboveT_G should have finite small mass. The question is, have we the possibility to observe the changing of the masses of the lowest scalar and pseudoscalar glueballs in heavy ion collisions? The answer is yes, if the available temperatures in such collision will be above the deconfinement temperature for the full QCD $T_c \approx 155$ MeV.

The best and clean channel to look to the changing of the masses of the scalar and pseudoscalar glueballs in sQGP is to study their decays to 2γ. The most promised candidate for the lowest scalar glueball at $T = 0$ is $f_0(1500)$ GeV state and for pseudoscalar glueball it might be $X(1835)$ state (see Nikolai Kochelev and Dong-Pil Min PLB,B633(2006)283) which was discovered by BES collaboration in the decays $J/\Psi \to \gamma\eta'\pi^+\pi^-$ and $J/\Psi \to \gamma P\bar{P}$

According with the our result the position of the peaks of both resonances should move to the small mass region very rapidly with the increasing of temperature at $T > T_c$. Furthermore, the masses of the scalar and pseudoscalar glueball should be approximately equal in the deconfinement phase. Therefore, such type of the experiment at NICA, FAIR, RHIC and LHC would be very important for the understanding of the role of the gluonic degrees of freedom in the phenomenon of the deconfinement.

Conclusion

- **Glueballs carry out a very important information on structure of strong interaction**

- **Glueball properties are very sensitive to the structure of QCD vacuum**

- **Glueball-quarkonium mixing is important in spectroscopy of glueballs**

- **Anomalous quark-quark and quark-gluon interaction induced by instantons can give strong effects on the weak decays**

- **It might be that XYZ mesons is the result of the mixing of high radial excitations in light quark-antiquark system with the hidden charm states**

- **The drastic changing of scalar and pseudoscalar glueball mass above deconfinement temperature might be the reason behind very unusual properties of Quark-Gluon Matter found at RHIC and LHC**

- **Under investigation: Bose-Einstein Condensation of the glueballs and properties of gluon matter produced in heavy ion collisions**

Thank you very much for your attention!