Searches for signals of Z' boson and quark-gluon plasma at LHC. Program of DNU

V. V. Skalozub

Dnipro National University
Ukraine

July 17,
Poltava 2018

Abstract

The model-independent search for Abelian Z' boson at the LHC is established. In the applied approach, not only the mass $m_{Z'}$ but also the couplings of the Z' to fermions are arbitrary parameters which must be estimated.

We analyze the CMS data on A_{FB} for the Drell-Yan process at 7 TeV and 8 TeV by means of indirect searches and the ATLAS data on the differential cross sections at 13 TeV by means of the direct searches. The coupling of the Z' to the standard model fermions a_f^2, the couplings of the axial-vector to lepton vector currents $a_f v_l$ and the couplings of the axial-vector to quark vector currents $a_f v_q$ are derived at at 2 σ CL. The optimistic limits on $m_{Z'}$ are established as $3 < m_{Z'} < 7 - 8$ TeV. The obtained results are in an agreement with that of obtained already for the LEP and Tevatron experiment data.

Abstract

It is derived that at LHC experiment energies the QGP should be spontaneously magnetized. The strengths of the large scale temperature dependent chromomagnetic, $B_3(T), B_8(T)$, and usual magnetic, $H(T)$, fields spontaneously generated after the DPT, are estimated. The critical temperature for the magnetized plasma is found to be $T_d(H) \sim 110 - 120$ MeV.
The fields modify the spectrum of the (color) charged particles that influences various processes.

Due to violation of Farry's theorem, in the QGP with A_0 condensate new type phenomena have to be generated. Among them the deviation of the photon beam from its initial direction and the change of the frequency, generation of induced color charges, gluon splitting in two photons. These are the distinguishable signals of the QGP creation.

Research plan of Theoretical physics Department DNU motivated by these results is presented.

Outline

1. Theoretical Physics Department DNU
2. Z' boson, Model-independent (MI) searches at LEP
3. MI interference and direct searches at LHC, results
4. Propositions and approaches for Z' searches
5. New signals of Deconfinement PT
6. QGP, spontaneous magnetization
7. QGP, A_0 condensation
8. Violation of Farry's theorem in QGP
9. Effective $\gamma\gamma G$ and G^3 vertexes in QGP
10. Induced charges and inelastic scattering of photons in QGP
11. Conclusions

Theoretical Physics Department DNU

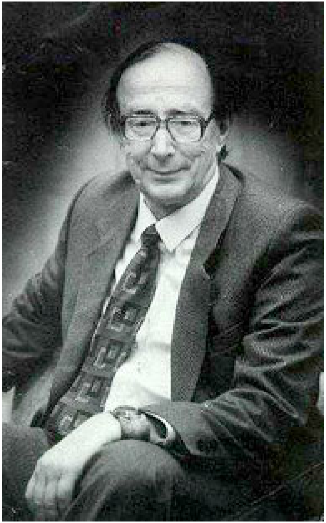
Khalatnikov
Isaak Markovich

(1953) Discovery in collaboration with L. Landau and Ya. Pomeranchuk a zero-charge behavior in QED

Theoretical Physics Department DNU

Ogievetsky
Victor Isaakovich

(1961-63) Derivation in collaboration with M. Polubarinov via "spin principle" the form of all fundamental interactions (weak, strong, gravitation)



Theoretical Physics Department DNU

**Pustovoit
Vladislav Ivanovich**

(1962) Proposition in collaboration with M. Gertsenshtein of principal experiment for detecting gravitation waves.

Vanyashin
Vladimir Stepanovich

(1965) Discovery in collaboration with M. Terent'ev an antiscreening behavior for charged vector particles

Zinoviev
Gennadiy Mikhailovich

First coordinator of scientific cooperation Ukraine – CERN

Theoretical Physics Department DNU

Sinyukov
Yuriy Mikhailovich

(1988) Proposition of pion interferometry method in high energy experiments

Theoretical Physics Department DNU

Sorin
Alexander Savelievich

Chief Scientific Secretary of JINR, Dubna

Theoretical Physics Department DNU

Teryaev
Oleg Valerianovich

(1987) Resolution in collaboration with A. Efremov of proton spin crisis

Abelian Z' boson at LEP

- determined the SM parameters and particle masses at the level of radiation corrections.
- searching for signals of new heavy particles beyond the SM.

At LEP2 experiments. No new particles were discovered,
the energy scale of new physics wasestimated as of the order 1 TeV.

- Experiments at LHC – next stage in high energy physics.

A lot of extended models includes Z' gauge boson – a massive neutral vector particle associated usually with an extra $U(1)$ subgroup of the underlying group.

Z' is predicted by a number of GUTs (the E_6 and $SO(10)$ based models – LR, , $\chi - \psi$ and so on are often discussed).

Present day status of Abelian Z'

$$\Big(SU(2)_{ew} \times U(1)_Y \times SU(3)_c\Big) \times \tilde{U}(1)_{\tilde{Y}} \tag{1}$$

Model-dependent search for Z' at LEP2 gave: $m_{Z'} > 400 - 800$ GeV.

Model-dependent results from Tevatron: $m_{Z'} > 800$ GeV,

and LHC: $m_{Z'} > 3 - 4$ TeV.

Approaches of searches for Z'

- **Model-dependent (MD) searching for Z'**

Effects of Z' are calculated within a specific model beyond SM.
Free parameters are $m_{Z'}$ and $\Gamma_{Z'}$.
All the couplings are fixed.
It is usually believed that Z' is a narrow state with small width:
$\Gamma/m_{Z'} \ll 1$.
About 100 Z' models are discussed.

- **Model-independent (MinD) searching for Z'**

Analysis is covering a lot of models.
Effects of Z' are calculated within a specific low energy effective Lagrangian.

Relations which hold in any renormalizable model of the Z'

Gulov, Skalozub (2000)

Assumptions:

1) Only one Z' exists at energy scale $1 - 10$ TeV;
2) It phenomenologically is described by the known effective Lagrangian (see, below);
3) Z' is decoupled at considered energies and the SM or the THDM are the low energy effective theories;
4) SM is the subgroup of the extended gauge group. So, the only origin of possible three-level interaction Z' with the SM particles is $Z - Z'$ mixing.

These relations (RG relations) are the consequences of a renormalizability (see review Gulov, Skalozub (2010)).

Effective Lagrangian at low energies

At low energies, the Z'-boson can manifest itself by means of the couplings to the SM fermions and scalars as a virtual intermediate state. The Z-boson couplings are also modified due to a Z–Z' mixing.

Such couplings can be described by adding new $\tilde{U}(1)$-terms to EW covariant derivatives D^{ew} in the Lagrangian (Cvetic (1986), Degrassi (1989))

Effective Lagrangian at low energies

$$
\begin{aligned}
L_f &= i\sum_{f_L}\bar{f}_L\gamma^\mu\left(\partial_\mu - \frac{ig}{2}\sigma_a W^a_\mu - \frac{ig'}{2}B_\mu Y_{f_L} - \frac{i\tilde{g}}{2}\tilde{B}_\mu\tilde{Y}_{f_L}\right)f_L \\
&+ i\sum_{f_R}\bar{f}_R\gamma^\mu\left(\partial_\mu - ig'B_\mu Q_f - \frac{i\tilde{g}}{2}\tilde{B}_\mu\tilde{Y}_{f_R}\right)f_R, \qquad (2)\\
L_\phi &= \left|\left(\partial_\mu - \frac{ig}{2}\sigma_a W^a_\mu - \frac{ig'}{2}B_\mu Y_\phi - \frac{i\tilde{g}}{2}\tilde{B}_\mu\tilde{Y}_\phi\right)\phi\right|^2, \qquad (3)
\end{aligned}
$$

$f_L = (f_u)_L, (f_d)_L, \quad f_R = (f_u)_R, (f_d)_R$.
$g, g', \tilde{g}$ are associated with the $SU(2)_L, U(1)_Y$, and the Z' gauge groups,
σ_a are the Pauli matrices,
Q_f – the charge of f, Y_ϕ is the $U(1)_Y$ hypercharge, and $Y_{f_L} = -1$ for leptons and 1/3 for quarks.
$\tilde{Y}_{f_L} = \mathrm{diag}(\tilde{Y}_{f_u}, \tilde{Y}_{f_d})$, $\tilde{Y}_\phi = \mathrm{diag}(\tilde{Y}_{\phi,1}, \tilde{Y}_{\phi,2})$ are diagonal 2×2 matrices.
As for the scalar sector, the Lagrangian can be simply generalized for the case of SM with two Higgs doublets (THDM).

Effective Lagrangian at low energies

Lagrangian (3) leads to the Z–Z' mixing.
The mixing angle θ_0 is

$$\theta_0 = \frac{\tilde{g}\sin\theta_W\cos\theta_W}{\sqrt{4\pi\alpha_{\rm em}}}\frac{m_Z^2}{m_{Z'}^2}\tilde{Y}_\phi + O\left(\frac{m_Z^4}{m_{Z'}^4}\right), \tag{4}$$

where θ_W is the SM Weinberg angle.

$$Z' \text{ couplings: } v_f = \tilde{g}\frac{\tilde{Y}_{L,f}+\tilde{Y}_{R,f}}{2}, \qquad a_f = \tilde{g}\frac{\tilde{Y}_{R,f}-\tilde{Y}_{L,f}}{2}. \tag{5}$$

Lagrangian (2) leads to the interactions:

$$\begin{aligned}
\mathcal{L}_{Z\bar{f}f} &= \frac{1}{2}Z_\mu\bar{f}\gamma^\mu\left[(v^{\rm SM}_{fZ}+\gamma^5 a^{\rm SM}_{fZ})\cos\theta_0 + (v_f+\gamma^5 a_f)\sin\theta_0\right]f,\\
\mathcal{L}_{Z'\bar{f}f} &= \frac{1}{2}Z'_\mu\bar{f}\gamma^\mu\left[(v_f+\gamma^5 a_f)\cos\theta_0 - (v^{\rm SM}_{fZ}+\gamma^5 a^{\rm SM}_{fZ})\sin\theta_0\right]f,
\end{aligned} \tag{6}$$

where f is a SM fermion state; $v^{\rm SM}_{fZ}$, $a^{\rm SM}_{fZ}$ are the SM couplings of the Z-boson.

Effective Lagrangian at low energies

At low energies, the dimensionless couplings

$$\bar{a}_f = \frac{m_Z}{\sqrt{4\pi} m_{Z'}} a_f, \quad \bar{v}_f = \frac{m_Z}{\sqrt{4\pi} m_{Z'}} v_f, \tag{7}$$

which can be constrained by experiments.

MinD (RG) relations between Z' couplings

In a particular model, $\tilde{Y}_\phi$,$\tilde{Y}_{L,f}$, $\tilde{Y}_{R,f}$ take some specific values.

If the model is unknown, these parameters
remain potentially arbitrary numbers.

- This is not the case

if the underlying extended model is a renormalizable one.

MinD (RG) relations between Z' couplings

The couplings are correlated(Gulov, Skalozub (2000)):

$$\tilde{Y}_{\phi,1} = \tilde{Y}_{\phi,2} \equiv \tilde{Y}_{\phi}, \qquad \tilde{Y}_{L,f} = \tilde{Y}_{L,f^*}, \quad \tilde{Y}_{R,f} = \tilde{Y}_{L,f} + 2T_{3f}\, \tilde{Y}_{\phi}. \tag{8}$$

Here f and f^* are the partners of the $SU(2)_L$ fermion doublet ($l^* = \nu_l, \nu^* = l, q_u^* = q_d$ and $q_d^* = q_u$),
T_{3f} is the third component of weak isospin.
Z' couplings to the vector and axial-vector fermion currents (5),

$$v_f - a_f = v_{f^*} - a_{f^*}, \qquad a_f = T_{3f}\tilde{g}\tilde{Y}_{\phi}. \tag{9}$$

Hence it follows:

- The couplings of Z' to the axial-vector fermion current have the universal absolute value proportional to the Z' coupling to the scalar doublet.
- Z–Z' mixing angle (4) can be determined by the axial-vector coupling.

MinD (RG) relations between Z' couplings

Since a_f is universal, we introduce the notation

$$\bar{a} = \bar{a}_d = \bar{a}_{e^-} = -\bar{a}_u = -\bar{a}_\nu, \tag{10}$$

and find

$$\theta_0 = -2\bar{a}\frac{\sin\theta_W \cos\theta_W}{\sqrt{\alpha_{em}}}\frac{m_Z}{m_{Z'}}. \tag{11}$$

From (9) it follows for each fermion doublet

$$\bar{v}_{f_d} = \bar{v}_{f_u} + 2\bar{a}. \tag{12}$$

Thus, Z' couplings can be parameterized by seven independent couplings

$$\bar{a}, \bar{v}_u, \bar{v}_c, \bar{v}_t, \bar{v}_e, \bar{v}_\mu, \bar{v}_\tau. \tag{13}$$

These relations (between numerically arbitrary parameters) are similar to the ones from the SM (for the specific values of the parameters)!

Estimates from LEP1 and LEP2 experiments

MinD limits on Z' couplings from LEP1 and LEP2
at $1-2\sigma$ CL (Gulov, Skalozub (2010))

- Axial-vector coupling $\bar{a}$ can be constrained by LEP1 (through the mixing angle) and LEP2 ($e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$) data with ML value

$$\bar{a}^2 = 1.3 \times 10^{-5} \tag{14}$$

and 2σ CL interval:

$$0 < \bar{a}^2 < 3.61 \times 10^{-4}. \tag{15}$$

- Electron vector coupling $\bar{v}_e$ can be constrained by LEP2 ($e^+e^- \to e^+e^-$)

2σ CL interval:

$$4 \times 10^{-5} < \bar{v}_e^2 < 1.69 \times 10^{-4}. \tag{16}$$

Estimates from LEP1 and LEP2 experiments

Constrain $\bar{v}_u, \bar{v}_c, \bar{v}_t, \bar{v}_\mu, \bar{v}_\tau$ by the widest interval from 2σ CL intervals for $\bar{v}_e$, $\bar{a}$:

$$0 < \bar{v}^2_{other} < 4 \times 10^{-4}. \tag{17}$$

Expected parameters for Z' searching

- spin 1
- charge 0
- mass $m_{Z'} \leq 2 - 3$ TeV, width $\Gamma_{Z'} = 150 - 200$ GeV
- mixing angle Θ_0
- coupling $\tilde{g}$
- axial-vector coupling constant $\bar{a}^2 = 1.3 \times 10^{-5}$
- vector coupling constant $4 \times 10^{-5} < \bar{v}_e^2 < 1.69 \times 10^{-4} (2\sigma\ CL)$

Observable for $\bar{a}$ in Drell-Yan process

- Cross-section (CS) $q\bar{q} \to l\bar{l}$

At parton level, Drell-Yan process

$$p\bar{p}(pp) \to Z' \to l\bar{l} + X \quad (18)$$

is reduced to quark annihilations $q\bar{q} \to (Z, \gamma, Z') \to l\bar{l}$.
CM system

Observable for $\bar{a}$ in Drell-Yan process

Structure of differential CS
Structure of the Z' boson contributions

$$
\begin{aligned}
\Delta\frac{d\sigma}{dz} &= \frac{d\sigma}{dz} - (\frac{d\sigma}{dz})_{SM} = F_a(E,z)\bar{a}^2 \\
&+ F_{av}(E,z)a\bar{v}_q + F_{vv}(E,z)\bar{l}\bar{v}_q + ..., z = \cos\theta
\end{aligned} \tag{19}
$$

where

$$
F_a = \sum_{q=u,d} f_a^q(E,z), F_{av} = \sum_{q=u,d} f_{av}^q(E,z), F_{vv} = \sum_{q=u,d} f_{vv}^q(E,z)... \tag{20}
$$

Observable for $\bar{a}$ in Drell-Yan process

Forward-backward asymmetry A_{FB}

Accounting for symmetries of form-factors, we introduce A_{FB}:

$$A_{FB} = \frac{\int\limits_{-1}^{0} \Delta \frac{d\sigma}{dz} dz - \int\limits_{0}^{1} \Delta \frac{d\sigma}{dz} dz}{\int\limits_{-1}^{1} \Delta \frac{d\sigma}{dz} dz} \tag{21}$$

It is determined by

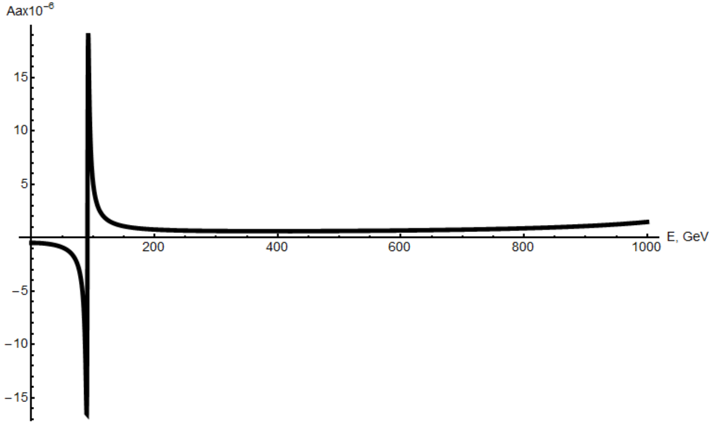
$$A_{FB} = \sum_{i=a,av,vv} A^i, \tag{22}$$

and

$$A^a\left(\int\limits_{-1}^{1} \Delta \frac{d\sigma}{dz} dz\right) = \int\limits_{-1}^{0} F_a dz - \int\limits_{0}^{1} F_a dz, \ldots \tag{23}$$

Observable for $\bar{a}$ in Drell-Yan process

Function $A^a(E)$



Observable for $\bar{a}$ in Drell-Yan process

Values of quark asymmetries A^a, A^{av}, A^{vv}

E (GeV)	100	300	600	800	1000
$A^a \times 10^{-7}$	51.7	6.2	6.7	8.7	14.7
$A^{av} \times 10^{-23}$	1610	1.3	1.3	2.6	5.3
$A^{vv} \times 10^{-23}$	74	0	0	0	0

- Differential CS $pp \to l\bar{l}$

$$\sigma_{AB} = \sum_q \int_0^1 dx_1 \int_0^1 dx_2 f_{q,A}(x_1, Q^2) f_{q,B}(x_2, Q^2) \times \sigma(q\bar{q} \to f\bar{f}), \quad (24)$$

$Q^2 = m_{Z'}$. Packet MSTW PDF was used.

Rapidities $y = \frac{1}{2}(y_{l^+} - y_{l^-}); Y = \frac{1}{2}(y_{l^+} - y_{l^-})$.

Variables in lepton CM system

Rapidities $y_{l^+} = -y_{l^-} = y_*$.

Observable for $\bar{a}$ in Drell-Yan process

Recently, using this MinD approach, and the RG relations, we analyze the CMS data on A_{FB} for the Drell-Yan process at 7 TeV and 8 TeV by means of indirect (interference) searches (Pevzner, Skalozub (2016)) and the ATLAS data on the differential cross sections at 13 TeV (Pevzner, Skalozub, Gulov, Pankov (2018)) by means of the direct searches.
The coupling of the Z' to the standard model fermions a_f^2, the couplings of the axial-vector to lepton vector currents $a_f v_l$ and the couplings of the axial-vector to quark vector currents $a_f v_q$ are derived at at 2 σ CL.
The optimistic limits on $m_{Z'}$ are established as $3 < m_{Z'} < 7 - 8$ TeV.

The obtained results are in an agreement with that of obtained already for the LEP and Tevatron experiment data.

Propositions for Z' searches

On the base of RG relations new type analysis can be applied for either LHC or ILC experiments.

Wide resonances

Interference and direct searches. Any amplitude has the form

$$F_{if} = F_{if}^{SM} + F_{if}^{Z'}. \quad (25)$$

In the cross sections, two types of terms present

$$\sigma^{inf.} \sim F_{if}^{SM} \times (F_{if}^{Z'})^{+}, \quad (26)$$

$$\sigma^{res.} \sim F_{if}^{Z'} \times (F_{if}^{Z'})^{+}. \quad (27)$$

The data treating depends on the choices:

1) energy is fare from the Z' mass pole;

2) energy is close to the Z' mass pole.

In the case 1) the Z' width $\Gamma_{Z'}$ is not important. For 2) it is important. It is usually believed that $\Gamma_{Z'}/m_{Z'} << 1$ (narrow width approximation (NWA)). Used for direct searches. The term $\sigma^{inf.}$ can be neglected.

Propositions for Z' searches

Recently, (Pevzner, Skalozub (2017)), it was demonstrated that the width $\Gamma_{Z'}/m_{Z'} \sim 1$ does not influences the Z boson width Γ_Z which is well measured at LEP experiments. Thus, the wide Z' is not excluded.

We plan to work out a procedure for treating the experimental data assuming the wide Z' resonances. These states could be missed in the present day analysis.

To realize that, we plan to include into consideration the Two-Higgs-Doublet-SM (THDSM) which includes additional scalar particles and can be used to sappy sufficiently wide Z' boson due to new reaction channels.

Propositions for Z' searches

Effective Lagrangian

For the values of mass $m_{Z'} \geq 4$ TeV, it becomes impossible to determine the basic model, even the neutral massive vector resonance will be observed. The identification reach is below this value. To over come this difficulty.

We plan to derive the effective Lagrangian for a given high energy amplitude calculated in a specific model. The procedure of the derivation is grounded on the renormalization group equation and a decoupling theorem. These objects will poses complete information about the models and the intermediate virtual decoupled states of heavy particles.

Propositions for Z' searches

New observables

We plan to treat the data on the Drell-Yan processes accumulated at 131 fb^{-1} and obtain the values of the couplings a^2,... and the mass $m_{Z'}$ by using the interference and the direct searching and compare the obtained results.

For the former approach, we plan to introduce specific for 13 TeV observables which uniquely determine each (for example, a^2) coupling. The mixing angle $\Theta_{(Z-Z')}$ will be determined.

We also have proposed (Skalozub, Kucher (2015)) the observables for searching for the virtual Z' boson in the ILC experiments.

DPT and its signals

Due to asymptotic freedom of non-Abelian gauge field interactions at high temperature $T \geq 150$ MeV quarks are deliberated from hadrons and new matter state – QGP – is formed. The order parameter of the DPT is the Polaykov loop (PL)

$$P(\vec{x}) = T \exp\left[ig \int dx_4 A_0(\vec{x}, x_4)\right]. \tag{28}$$

It equals 0 at low temperature and $P \neq 0$ at $T > T_d$.
If $A_0(x_4) = const$

$A_0 \neq 0$ is also the order parameter of the DPT. $A_0 \neq 0$ violates the $Z(3)$ and gauge symmetries.
Review paper O.A. Borisenko, J. Bohacik, V.V. Skalozub, A_0 condensate in QCD, Fortschr. Phys. v. 43 (1995) 301.

DPT and its signals

Other important order parameter is the temperature dependent chromo (magnetic) fields $H(T) \neq 0$ spontaneously created in the volume of the QGP. This point will not be discussed in this talk. In the literature, numerous applications of the PL in the QGP have been discussed. The combinations of both $A_0 \neq 0$ and $H(T) \neq 0$ were also investigated.
In particular, it was observed that the A_0 is dominant at temperatures not much grater T_d. So, in what follows we consider this case.

We describe some new phenomena and effects taking place due to the A_0 presence.

Spontaneous vacuum magnetization at LHC

Recently (Skalozub, Minaiev (2018)) it was obtained that at LHC experiment energies the QGP should be spontaneously magnetized. The strengths of the large scale temperature dependent chromomagnetic, $B_3(T), B_8(T)$, and usual magnetic, $H(T)$, fields spontaneously generated after the DPT, were estimated.
The critical temperature for the magnetized plasma is found to be $T_d(H) \sim 110 - 120$ MeV. This is essentially lower compared to the zero field value $T_d(H = 0) \sim 160 - 180$ MeV usually discussed in the literature. Due to contribution of quarks, the color magnetic fields act as the sources generating H. The strengths of the fields are $B_3(T), B_8(T) \sim 10^{18} - 10^{19}G$, $H(T) \sim 10^{16} - 10^{17}G$ for temperatures $T \sim 160 - 220$ MeV.

We plan to estimate the role of magnetic fields in QGP for a number of processes with fermions and bosons.

QGP, A_0 condensate

Quarks interact with electromagnetic field and gluons according the form

$$L^{int.} = \bar{\psi}^a[\gamma_\mu(\partial_\mu\delta^{ab} - ie_f A_\mu\delta^{ab} - ig(Q_\mu\frac{\lambda}{2})^{ab}) - m_f\delta^{ab}]\psi^b, \quad (29)$$

where A_μ is potential of electromagnetic fields, Q_μ is potential of gluon field, e_f is electric charge of quark with flavor f, m_f is quark mass, g is charge of strong interactions, a, b are color indexes.
Since quarks carry both electric and strong charges in the QGP the effective interactions of color and white objects are possible due to the quark virtual loops.
The A_0 is an element of the center $Z(3)$ of the $SU(3)$ group. When it is non zero, both of these symmetries are broken.

The A_0 is a specific classical external fields. It can be introduced by splitting $Q^a_\mu = (A_0)^a_\mu + (Q^a_\mu)_{rad.}$ of the gluon field potential. In what follows we consider the case $(A_0)^a_\mu = (A_0)_\mu\delta^{a3}$.

Violation of Farry's theorem in QGP

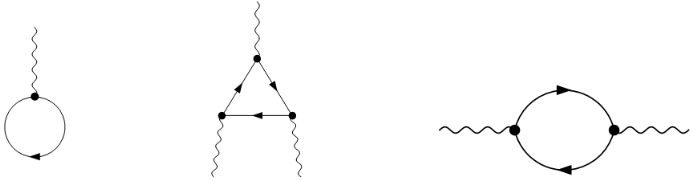
In the vacuum, the Farry theorem holds:

The amplitudes having odd number of photon(gluon) lines, generated by the fermion loops, equal zero.
It is the consequence of C-parity invariance. The contribution of particles cancels the contribution of antiparticles.
The presence of the A_0 condensate violates this symmetry. So that new type processes are permissible.
In particular,

the diagram with one gluon external line results in an induced color charge in the plasma. This may result in the scattering of quarks on this external charge.

Violation of Farry's theorem in QGP

Three line vertex - photon-photon-gluon - relates colored and white states. This is new type effective vertex which generates new observable processes - inelastic scattering of photons, splitting (dissociation) of gluons in two photons in the QGP.



One of our goals is to calculate this vertex and investigate these processes in the plasma.

These can be signals of the creation of QGP.

Gluon and photon spectra in QGP

Before doing that we have to detect the normal photon and gluon modes presented in the QGP with A_0. This can be done by solving the dispersion equations for these fields.

Basically, in the plasma the spectra of the excitations can be obtained from the dispersion relations of the type

$$\omega^2 - \vec{k}^2 = Re\Pi(\omega, \vec{k}), \tag{30}$$

where ω and $\vec{k}$ are the frequency and the momentum of the modes.

In the QGP the transverse and the longitudinal excitations present. They are derived from relevant polarization tensors $\Pi(\omega, \vec{k})_T$ and $\Pi(\omega, \vec{k})_L$. Such type objects must be calculated in the gluon sector of the model.

The A_0 condensate stabilizes the infrared behavior of the plasma and has a lover energy as compared to the empty vacuum case.

Effective $\gamma\gamma G$ vertexes in QGP

Photon-photon-gluon vertex, its dominant term:

$$\Pi_{\mu\nu\lambda} = \delta(k^1 + k^2 + k^3)(-e^2 g\Lambda) \sum_{p_4} \int \frac{d^3p}{(2\pi)^3} (\Gamma^{(1)}_{\mu\nu\lambda} + \Gamma^{(2)}_{\mu\nu\lambda}), \quad (31)$$

$$\Lambda = -16 A_0 m_f^2; \qquad \Gamma^{(1)}_{\mu\nu\lambda} = \frac{\delta_{\mu\nu}\delta_{\lambda 4} + \delta_{\mu\lambda}\delta_{\nu 4} + \delta_{\lambda\nu}\delta_{\mu 4}}{d^2(p) d^2(p,k^1) d^2(p,k^3)}, \quad (32)$$

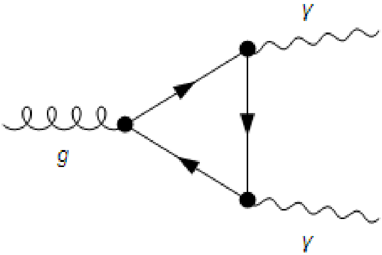
$$\Gamma^{(2)}_{\mu\nu\lambda} = \frac{-2S_{\mu\nu\lambda}}{d^2(p) d^2(p,k^1) d^2(p,k^3)} \Big(\frac{(p+k^3)_4}{d^2(p,k^3)} + \frac{(p-k^1)_4}{d^2(p,k^1)} + \frac{p_4}{d^2(p)} \Big), \quad (33)$$

$$d^2(p) = p^2 + m_f^2, d^2(p,k^1) = (p-k^1)^2 + m_f^2, d^2(p,k^3) = (p+k^3)^2 + m_f^2,$$

$$S_{\mu\nu\lambda} = \delta_{\mu\nu}(p+k^1+k^3)_\lambda + \delta_{\lambda\nu}(p-k^1-k^3)_\mu + \delta_{\mu\lambda}(p-k^1+k^3)_\nu. \quad (34)$$

The terms of the order $O(A_0^3)$ have been neglected.

Effective $\gamma\gamma G$ vertexes in QGP



In the above formulas, k^1, k^3 are momenta of ingoing photons and $k^2 = -(k^1 + k^2)$ is momentum of ingoing color neutral gluon $Q^{a=3}$.

All the other three-vertexes composing photons and gluons are zero.

So, we have a possibility for direct interaction of color and white world. The vertex is proportional to the mass m_f. So that it the effect is additive and proportional to the sum of the quark loops.

Effective $\gamma\gamma G$ vertexes in QGP

The most important points:

1. The vertex is not transversal
2. It relates transversal and longitudinal modes of photons and gluons

In particular, new phenomena such as scattering of photons on the QGP as an effective vertex become possible.

There are two sorts of the processes of interest:
1) Scattering of photons on the plasma as on the external filed generated due to quark current and induced color charge. Radiation of photon pairs from plasma.
2) Scattering on the real gluon excitations in the plasma.

In these processes the plasma exhibits itself via the effective vertex and therefore the inelastic (or even elastic) scattering may be realized. Specific values for these cases depend on the characteristics of QGP.

Induced charge in QGP

Important feature of the QGP is generation of the strong charge due to one-line non-zero diagram.

Its quark loop contribution can be calculate from the expression

$$Q^{quark}_{induced} = -g \sum_{p_4} \int \frac{d^3p}{(2\pi)^3} Tr\gamma_4 [\frac{\lambda^3}{2} \frac{(p+k)_\sigma \gamma_\sigma + m_f}{(p+k)^2 + m_f^2}]. \quad (35)$$

Here, the momentum $p = (p_4 = p_4 \pm A_0, \vec{p})$,
$p_4 = 2\pi T(l + 1/2), l = 0, \pm 1, ...$

Induced charge changes the coupling constant of gluons in the QGP.

We obtain in the high temperature limit $(\beta \to 0)$

$$Q^{quark}_{3ind.} = -gA_0 \Big(\frac{T^2}{3} - \frac{m^3}{T} + O(1/T^3) \Big). \quad (36)$$

The induced classical current is

$$J^3_\nu = -2igQ_{3ind.} u_\nu, \quad (37)$$

u_ν is plasma velocity.

Induced charge in QGP

Scattering of photons in the QGP can be estimated by induced charge and deviation of of the photon beams from an initial direction.

We have neglected the color magnetic fields generated spontaneously in the plasma. We can account for them in a perturbation theory by using as the field Q_μ^3 the potential of these magnetic fields. In such scenario the QGP will exhibits itself in a coherent scattering of photons.

Other important expected process is splitting of the gluon field G^3, G^8 generated by the induced charge $Q^3_{ind.}, Q^8_{ind.}$ in two photons moving along the plasma velocity u_ν.

These processes are basically different from the scattering of photons on chaotically moving particles of usual plasma.

Conclusions

According to basic principles of QCD, the QGP has to be either magnetized with strong long range temperature dependent magnetic fields $B^3(T), B^8(T), H(T)$ (that lowers the deconfiniment transition temperature T_d) or charged with color induced charges $Q^3_{ind.}, Q^8_{ind.}$.

Due to violation of the Farry theorem, in the QGP new type phenomena have to be generated. Among them the deviation of the photon beam from its initial direction and the change of the frequency. Generation of induced color charges, gluon splitting in two photons. These are the distinguishable signals of the QGP creation.

We plan to investigate these processes within our program

Conclusions

Thank you for your attention!