Parton Production Via Vacuum Polarization

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We discuss the production mechanism of partons via vacuum polarization during the very early, gluon dominated phase of an ultrarelativistic heavy-ion collision in the framework of the background field method of quantum chromodynamics.

For high matter and/or energy densities a deconfined state of matter, the so-called quark-gluon plasma (QGP) has been predicted to exist \[1\]. Its production is expected for ultrarelativistic heavy-ion collisions (URHIC) at RHIC and LHC. No direct signatures for its presence are experimentally accessible. In order to be able to decide which indirect ones could be available, detailed knowledge about the production and evolution of the (QGP) is needed.

At the beginning, an URHIC is expected to be dominated by gluonic degrees of freedom. The gluons are likely to be so abundant that they can be described as a classical vector potential $A$. We are now interested in finding out whether the production of quark-antiquark pairs (see Fig.(1)) or the production of gluon pairs (see Fig.(2)) from the field dominates. The concise way to handle a classical vector potential and quantum fluctuations simultaneously is the field method of quantum chromodynamics (QCD). In it, the gauge field $B$ is split into a classical vector potential $A$ plus quantum fluctuations $Q$: $B \rightarrow A + Q$. The classical background field $A$ is equal to the expectation value of the entire field $B$: $\langle B \rangle = \langle dQ \rangle$; its expectation value is equal to zero: $\langle Q \rangle = 0$. The gauge transformation properties of the entire gauge field $B$ have got to be redistributed, so that the classical vector potential $A$ satisfies the same relations under the gauge transformation $U$ as $B$ beforehand: $T^a A^a_{\mu} \rightarrow T^a A^a_{\mu} = UT^a A^a_{\mu} U^{-1} - \frac{i}{g} \bar{q}(\partial_{\mu} U)U^{-1}$. Only for this choice does the background field $A$ satisfy the classical Yang-Mills equations. In order to conserve the sum, the field of the quantum fluctuations $Q$ has got to transform according to: $T^a Q^a_{\mu} \rightarrow T^a Q^a_{\mu} = UT^a Q^a_{\mu} U^{-1}$. This set of gauge transformations is called type-(I)-gauge transformations \[2\]. At the end, a gauge fixing term, the so-called background field gauge, is chosen which leaves the resulting effective action gauge invariant under type-(I)-gauge transformations \[3\].

The range of applicability of perturbative calculations is limited. The described particles must have an energy $p^0$ much greater than the typical field strength $A$ of the classical vector potential multiplied by the coupling constant $g$. As we are going to be dealing with a decaying field this is always satisfied if we take $p^0$ above $gA_{in}$, where $A_{in}$ is the initial field strength. Further, the product $gA$ has got to be much larger than the other non-perturbative scale of QCD, $\Lambda_{QCD}$. This results in the fact that the approach becomes invalid after a maximum time $t_f$ after which the quantity $gA$ reaches the scale $\Lambda_{QCD}$. If this description of the gluonic sector is sufficient, depends on whether quantum gluons are important for momenta below $gA$. Generally speaking, for a field that decays more rapidly as compared to another with the same initial field strength, soft quantum corrections are less important. For the quarks there is no means of description for the low momentum sector here. This feature has got to be added in a later study. For field strengths above $\Lambda_{QCD}$ one would expect that a description via the constant-field Schwinger approach \[3\] would be adequate, but there the relatively big slopes of the decaying field are ignored totally. Nevertheless, a comparison to calculations involving that formula would be interesting.

Even for our perturbative approach the general expressions are very complicated \[4\]. That is why we choose a special form for a purely time-dependent field in order to get some insight into the behavior of the obtained source terms for quarks and gluons: $A^a_{in}(t) = A_{in} e^{-|t|/t_0}$, $t_0 > 0$, $a = 1, ..., 8$, and all other components are equal to zero. Many other forms could have been taken. Its time structure is similar to one obtained from a different numerical study \[4\]. Using this field, one obtains the following expressions for the source terms:

\begin{equation}
\frac{dW_{gg}}{d^2x^3k} = 16 \frac{\alpha_s}{(2\pi)^2} (A_{in})^2 e^{-2i\omega t} e^{-|t|/t_0} \frac{t_0}{1 + 4\omega^2 t_0^2} \frac{m_T^2}{\omega^2},
\end{equation}

and:

\begin{equation}
\frac{dW_{gg}}{d^2x^3k} = 24 \frac{\alpha_s}{(2\pi)^2} (A_{in})^2 e^{-2i\omega t} e^{-|t|/t_0} \frac{t_0}{1 + 4(k^0)^2 t_0^2} \frac{(-3 - \frac{k_T^2}{(k^0)^2})}{(k^0)^2} + 3 \frac{36 \alpha_s}{2\pi} (A_{in})^2 e^{-2i\omega t} e^{-|t|/t_0} \frac{t_0}{1 + (k^0)^2 t_0^2} \frac{1}{(k^0)^2}.
\end{equation}
Note, that the real part of these expressions has got to be taken. The contribution of the interference term for the production of gluons vanishes for all fields of the form $A^{a\mu}(x) = A^{a\mu}_{in}f(x)$.

For LHC one expects the following parameters which are consistent with a predicted energy density of $1 \text{TeV/fm}^3$:

for the initial value of the field $A_{in} = 1500 \text{MeV}$, for the coupling constant $\alpha_S = 0.15$, and for the decay-time $t_0 \in \{0.1 \text{fm}, 1.0 \text{fm}\}$. It can be checked that for $gA_{in} >> \Lambda_{QCD}$ the production of quantum particles after the final time of applicability $t_f$ can be neglected [5].

In order to decide which parton production channel dominates, it is recommendable to investigate the ratio of produced gluon pairs over produced quark-antiquark pairs in the kinematic region mentioned above for LHC. For lower momenta gluon production clearly dominates over quark production, which is evident from an extra $1/(k^0)^2$ in the second term in Eq. (2). For the momentum range we are interested in ($p_t \simeq 2 \text{ GeV}$) all kind of scenarios are possible depending upon the value of $t_0$. The ratio of gluon to quark source term as a function of $t_0$ is shown in Fig.(3) for $p_t = 2 \text{ GeV}$ at LHC.

There quark production prevails over gluon production for smaller values of the decay time $t_0$. For larger values of $t_0$, the gluon channel is the dominant one. A selfconsistent calculation yielding the decay-time as an output has got to decide between the scenarios.

That result would also be important in another sense. In the case of the dominance of gluon pair creation additional fermions and antifermions have got to be produced in subsequent inelastic collisions, not to forget about intermediate elastic rescatterings [6]. These quarks can play a crucial role in hadron production at RHIC and LHC. Of course all this would have to be explored in extensive calculations where fragmentations of gluons have got to be taken into account.

REFERENCES

[1] L. Riccati, M. Masera and E. Vercellin, Nucl. Phys. A 661 (1999) 1.
[2] B. W. Lee and J. Zinn-Justin, Phys. Rev. D7, 1049 (1973); H. Kluberg-Stern and J. B. Zuber, Phys. Rev. D12, 482 (1975).
[3] R. S. Bhalerao and G. C. Nayak, Phys. Rev. C 61 (2000) 054907 [arXiv:hep-ph/9907322].
[4] D. D. Dietrich, G. C. Nayak and W. Greiner, Phys. Rev. D 64 (2001) 074006 [arXiv:hep-ph/0007130]; G. C. Nayak, D. D. Dietrich and W. Greiner, Published in Rostock 2000/Trento 2001, Exploring quark matter 71-78, arXiv:hep-ph/0104030.
[5] D. D. Dietrich, G. C. Nayak and W. Greiner, arXiv:hep-ph/0009178.
[6] J. Ruppert, G. C. Nayak, D. D. Dietrich, H. Stocker and W. Greiner, Phys. Lett. B 520 (2001) 233 [arXiv:hep-ph/0109043].
[7] B. S. Dewitt, Phys. Rev. 162 (1967) 1195; and Phys. Rev. 162 (1967) 1239; G. ’t Hooft, Nucl. Phys. B 62 (1973) 444; L. F. Abbott, Nucl. Phys. B 185 (1981) 189.
[8] J. S. Schwinger, Phys. Rev. 82 (1951) 664.
Fig. 1: The production of a quark-antiquark pair by coupling to the field once is the dominant contribution for particles with an energy higher than the value of the field multiplied by the coupling constant.

Fig. 2: The production of a gluon pair by coupling to the field at one vertex is the dominant contribution for particles with an energy higher than the value of the field multiplied by the coupling constant. The chosen gauge is not physical, so the corresponding ghost contributions have got to be taken into account.

Fig. 3: Time integrated source term for gluon production divided by the one for quark production versus the decay time $t_0$. 