COMMENT ON TRANSVERSE MASS DEPENDENCE OF
PARTONIC DILEPTON PRODUCTION IN
ULTRA-RELATIVISTIC HEAVY ION COLLISIONS

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Abstract

Response to a recent Comment by M. Asakawa concerning scale-breaking effects in dilepton emission from partons in pre-equilibrium and quark-gluon plasma during the early stage of ultra-relativistic heavy ion collisions.

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In a recent paper M. Asakawa [1] commented a previous letter [2] on $M_\perp$-dependence of dilepton emission [3] calculated with in the framework of the Parton Cascade Model (PCM) [4]. He suggested that the $M_\perp$ scale breaking effects discussed in [2] may possibly be of unphysical origin, arising from the perturbative QCD infrared cut-offs ($\mu_0$ and $p_{\perp\text{cut}}$) inherent to the PCM. I would like to respond first with a number of general remarks, followed by some comments on the PCM approach in particular.

1. It is a fact that QCD is not scale invariant, even for massless particles. The characteristic scale is set by the ”glueball mass” associated with the gluon condensate, which can be interpreted phenomenologically e.g. in terms of the string constant, the energy
density residing in the gluon field, being determined to be of the order of $\kappa \simeq 1$ GeV/fm$^2$. Thus, in any perturbative QCD description that does not account for the rather little understood non-perturbative mechanisms, one must inevitably introduce some invariant mass cut-off around 1 GeV that separates the perturbative regime from the non-perturbative domain. However, this is not an arbitrary, unphysical parameter, but rather reflects the fact that there is a fundamental scale in the problem. In particle physics phenomenology this scale is usually associated with the string constant, the hadronic radius or the typical hadronization time scale $\approx 1$ fm/c.

2. In addition to the above natural QCD scale one is faced with further (external) scale breaking quantities when addressing nucleus-nucleus collisions that modify QCD processes in nuclear matter as compared to free space. (i) The nuclear radii $R_A$ and the collision geometry define a finite size system that give rise volume and surface effects. (ii) The nuclear density $\rho_A$ together with the Lorentz contraction at high energies leads to a initial quark and gluon density already in the initial state. This in turn determines the initial condition for the mean free path or the mean collision frequency of parton interactions. (iii) When following a self-contained dynamical description of nuclear collisions, the materialization and excitation of partons and their energy dissipation will clearly increase the initial density, leading at sufficiently large beam energy to a hot and very dense parton matter. Thus one has a time-dependent density and temperature as further scales in the problem both of which are externally determined by the collision energy, and nuclear size.

3. In a description of high energy nuclear reactions on the basis of ”scaling hydrodynamics” one assumes a priory an ideal fluid dynamical expansion of the matter produced in the central collision region. That is, one assumes local thermalization, a longitudinally boost invariant expansion, absence of radial flow, and no other scales than the temperature are involved in the dynamical evolution [5]. In other words, all of the above mentioned scale breaking quantities are completely ignored here - an approach which is
certainly not illegitimate, but should not be taken as a measure of realistic description. It is interesting to note that a recent study by M. Strickland [6] of the dependence on initial conditions for thermal dilepton production concealed that even the later stages of the thermal expansion will carry information about the initial conditions. Thus, even a presumed thermal evolution must account for those external parameters that determine the initial state and the necessarily generate in scale breaking effects.

Responding to the specific points of Asakawa’s Comment, I state the following:

4. **Mass cut-off $\mu_0$:** The argument that by a time of about $1/\mu_0 = 0.2$ fm/c the partons have reached this invariant mass cut-off and propagate as massive ($\approx 1$ GeV) particles is definitely not correct, because this estimate is based on “free” cascading of virtual partons by successive bremsstrahlung, e.g. in jet evolution of $e^+e^-$ annihilation. In a nuclear collision, that is in the dense matter environment of the central collision region, this gradual deexcitation of virtual particles toward mass shell is considerably delayed due to scatterings and fusions. This has been recently addressed in a different context [7] and is currently investigated in more detail. The more frequent these interactions with the environment is, i.e. the denser the matter is packed, the longer it takes for a parton to reach $\mu_0$. In the PCM calculations for Au+Au at RHIC, it takes about 1 fm/c (!) until the majority of materialized virtual partons do not radiate anymore because they have reached $\mu_0$. I strongly object the summarizing remark in [1] stating that the PCM relies on ”...the use of inappropriately large virtualities $\geq \mu_0$...”. It is well known that in free space jet evolution, the mass $\mu_0$ of the order of a GeV is the typical scale at which non-perturbative collective effects begin to establish a pre-confinement [8]. On the other hand in a dense matter environment, the screening effects generate a Debye mass that corresponds to an effective mass of a particle in the medium, and which takes over the role of $\mu_0$. Of course, in the PCM the parameter $\mu_0$ and also the minimum allowed momentum transfer $p_{\perp \text{cut}}$ in parton collisions are partly responsible for the $M_\perp$ scale breaking in the dilepton spectrum. This has been clearly stated in
Ref. [2] on p. 3078. However, this scale breaking contribution is a physical effect and is intimately connected to the (medium dependent) Sudakov formfactors of the partons that are a direct consequence of the renormalization group improved parton picture. Therefore - in accord with item 1. - it is a physical manifestation of the fundamental fact that QCD is not a scale invariant theory.

5. \(q\bar{q}\) annihilation: As stated in Ref. [3] on p. 1922, the turnover at lower dilepton mass is due to the neglect of contributions from quark antiquark scatterings which are treated with the phenomenological scattering amplitude, if the momentum transfer of a parton collision is below \(p_{\perp \text{cut}}\). These low \(p_{\perp}\) processes were not included in the calculation of the dilepton spectrum, because perturbative QCD does not tell us about the soft physics of these contributions, and they are therefore model dependent. In order not to spoil the results for the perturbative QCD yield of dileptons where the amplitudes are well known, a phenomenological description of soft production was avoided. Notwithstanding the fact of uncertainty in how to calculate the radiation from those softer processes, I am sure that the dilepton mass spectrum would continue to rise at low masses. I doubt that the quark virtualities have much to do with it. On the other hand, Asakawa is ultimately correct in saying that the PCM predictions for dilepton masses less than about 3 GeV should not be taken seriously at this time. But this was stressed in the paper too.

In conclusion, I think that one has to be careful when comparing the PCM calculations with e.g. the solutions of the Bjorken hydrodynamical model. The latter cannot account for the scale breaking effects discussed above, because it assumes a priori that those are absent. On the other hand, I am fully aware that the PCM results are plagued by a number of uncertainties which have been repeatedly discussed in preceding papers. The PCM is not to be misunderstood as a fine tuned ‘event generator’. Rather than that its main purpose - at least at the current stage - is to approach in an explorative way the complicated many particle aspects of quark and gluon dynamics in heavy ion collisions.
From a truly quantitative picture one is still far away.
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