(Towards) Photon Production in the Early Stage of uRHICs

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Plan of the talk

• Statement of the problem
• Abelian Flux Tubes model for early stages
• Relativistic Transport Theory for HICs  
  See also Greco’s talk
• Results
  - Initial fields decay
  - Timescale for QGP production
  - Photon production in the early stage of HICs
• Conclusions
Direct photons in HICs

Photons are produced during *all the lifetime* of the fireball produced in HICs.

Photons are good candidate for representing:
- *Thermometer of QGP* [Heinz et al., PRL]
- *Clock of QGP* [Liu et al., PRC79 (2009), Liu and Liu, PRC89 (2014)]

Some sources

**Pre-equilibrium stage**
- Prompt
- *Pre-eq parton scattering*

**Viscous qgp+hadron phase evolution**
- *Thermal QGP*
- Thermal hadrons

see also Moritz Greif’s talk
Jean F. Paquet’s talk
Direct photons in HICs

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Photons are good candidate for representing:
• *Thermometer of QGP* [Heinz et al., PRL]
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**Our sources**

• **Pre-eq photons**
  Partons arising from the initial classical color fields

• **Thermal QGP photons**
  Produced during the thermalized QGP phase
Focus on a single flux tube:

- Neglect magnetic part of Glasma fields;
- Assume chromoelectric fields evolve as classical abelian fields;
- Initial field is longitudinal: $E_x(t=0) = E_y(t=0) = 0$;
- Assume Schwinger effect takes place: Color-electric field decays into quark-antiquark as well as gluon pairs.
The initial condition

Initial chromo-electric field: smooth in transverse plane

\[ E_z(x_\perp) = \mathcal{E}_0 \left[ c\rho_{\text{coll}}(x_\perp) + (1 - c)\rho_{\text{part}}(x_\perp) \right] \]

What we do
We prepare a fireball such that:
- Has some classical color field dynamics
- Matches MCGlauber fireball at t=0.6 fm/c:
  - Eccentricity
  - Multiplicity
- Has a pre-equil. evolution from t=0+

What we do not
Prepare a more realistic initial condition
(IP-Glasma, Schenke et al. 2013
see also Raju Venugopalan’s talk)

Although a bit far from Glasma, picture arising agrees qualitatively (and to some extent quantitatively) with results obtained from Glasma+CYM when physical quantities are computed.

Florkowski and Ryblewski, PRD 88 (2013)
M. R. et al., PRC 92 (2015)
Boltzmann equation for QGP and fields

In order to simulate the temporal evolution of the fireball we solve the Boltzmann equation for the parton distribution function $f$:

$$(p_{\mu} \partial^{\mu} + gQ F^{\mu\nu} p_{\mu} \partial^{p}_{\nu}) f = C[f]$$

- **Field interaction**: change of $f$ due to interactions of the partonic plasma with a field (e.g. color-electric field).

- **Collision integral**: change of $f$ due to collision processes in the phase space volume centered at $(x,p)$. Responsible for deviations from ideal hydro (non vanishing $\eta/s$).
Boltzmann equation for QGP and fields

In order to permit *particle creation* from the vacuum we need to add a *source term* to the rhs of the Boltzmann equation:

\[ (p_\mu \partial^\mu + gQ_{jc} F^{\mu\nu} p_\mu \partial^\nu) f_{jc} = p_0 \frac{\partial}{\partial t} \frac{dN_{jc}}{d^3x d^3p} + \mathcal{C}[f] \]

**Invariant source term:** change of \( f \) due to particle creation in the volume at \((x,p)\).

**Field interaction**

We have to solve self-consistently *Boltzmann and field equations*.

Florkowski and Ryblewski, PRD 88 (2013)
From field to QGP

Fields at midrapidity averaged on the transverse plane

Decay times about 0.4 fm/c

Field decay timescale sets qgp formation time:

Quark and gluon numbers

Timescale and quark abundance in agreement with:
Lappi et al., PRL96 (2006)
Scardina et al., PLB 724 (2013)
M. R. et al., NPA 941 (2015)
Partonic photon spectra: contributions

Au-Au 20-40% @ RHIC 200 AGeV

PRELIMINARY

Flux tube (pre+qgp thermal)
Flux tube at t=0.6 fm/c
Glauber (qgp thermal)
Partonic photon spectra: contributions

Main contribution of pre-eq
\[ p_T \geq 1.5 \text{ GeV} \]
giving a result at least:
2 x thermal qgp
20 x hadron thermal gas

Produced by a medium with
\[ \langle p_T^2 \rangle \propto gE \]
\[ \approx (2 - 3 \text{ GeV})^2 \]
but missing in the Th-QGP
Partonic photons from pre-eq stage

\[ \frac{dN}{dp_T} \]

Au-Au 20-40% @ RHIC 200 AGeV

\[ 4\pi\eta/s = 1 \]

- **Flux tube (pre+qgp thermal)**
- **Flux tube at t=0.6 fm/c**
- **Glauber (qgp thermal)**

\[ p_T \text{ [GeV]} \]
Partonic photons from pre-eq stage

About 35% of partonic photons is produced in the first 0.6 fm/c.

Typical lifetime of RHIC fireball: approx 5-6 fm/c.

In \( \approx \) one/tenth of fireball lifetime, partons produce \( \approx 1/3 \) of the photons they can produce in the full lifetime.

but

less than the ones produced assuming \( T \propto \tau^{-1/3} \)
Direct photon spectra

We can check how the pre-eq contribution changes photon spectrum:

**Contributions added**

1) *Prompt photons* from Paquet et al. [PRC93 (2016)]

2) *Hadrons thermal* from Paquet et al. by a subtraction: *Paquet’s thermal – our Glauber qgp*

**The message**

Photons from pre-eq:
- Signature in $1.5 \text{ GeV} < p_T < 3 \text{ GeV}$
- *Might be important to understand data in the intermediate $p_T$ region*
Direct photon spectra

We can check how the pre-eq contribution changes photon spectrum:

Contributions added
1) Prompt photons from Paquet et al. [PRC93 (2016)]
2) Hadrons thermal from E. Bratkovskaya et al. [PRC92 (2015)]

The message
Photons from pre-eq:
- Signature in $1.5 \text{ GeV} < p_T < 3 \text{ GeV}$
- Might be important to understand data in the intermediate $p_T$ region
Conclusions

- *Relativistic Transport Theory*, coupled to a *decay mechanism for initial color fields*, permits to study early time dynamics of heavy ion collisions.

- *Schwinger tunneling* allows a *fast QGP production*, typically a small fraction of fm/c.
Conclusions

• **Relativistic Transport Theory**, coupled to a *decay mechanism for initial color fields*, permits to study early times dynamics of heavy ion collisions.

• **Schwinger tunneling** allows a *fast QGP production*, typically a small fraction of fm/c.

• **No dark age for QGP**
Pre-equilibrium partons produce abundantly photons, comparable in number with those produced by equilibrated QGP during the whole fireball lifetime.

• **Domain of pre-equilibrium photons**
Substantial contribution in the range \(1.5 \text{ GeV} < p_T < 3 \text{ GeV}\) where both *thermal hadrons* and *thermal QGP* do not contribute significantly.

*Pre-equilibrium photons might be important to understand experimental data at RHIC in the aforementioned \(p_T\) domain*
Thanks for your attention

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- NSFC Projects (11135011 and 11575190)

Io stimo più il trovar un vero, benché di cosa leggera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna.
Appendix

APPENDIX
The initial condition

**Initial chromo-electric field:**
- **Boost invariant in the longitudinal direction**
- **Smooth in transverse plane:**

\[
E_z(x_\perp) = E_0 [\rho_{\text{coll}}(x_\perp) + (1 - c) \rho_{\text{part}}(x_\perp)]
\]

Set up to match *MCGlauber* for RHIC collision at $b=7.5$ fm:
- **Eccentricity at $\tau = 0.6$ fm/c**
- **Multiplicity**

Total particle numbers

- MCGlauber gluons
- Schwinger gluons ($N_f=2$)
- MCGlauber quarks
- Schwinger quarks ($N_f=2$)
Our problem: partonic photons

Among the many photon sources in uRHICs, in our fireball we consider the partonic ones:

**Partonic photons**

- **Pre-eq stage**
  During classical field decay
- **Thermal QGP**
  During QGP evolution

What we do not have in the present implementation

- **Thermal hadrons contribution**. However notice that:
  1. Thermal hadrons contribute to a different $p_T$ region in the photon spectrum
  2. We add by hand thermal hadrons contribution, see final figure

- **Bremstrahlung** [AMY, JHEP 0112 (2001)]
- **Photons from anomaly** [Kharzeev et al. (2012)]
- **Gluon fusion** [Ayala et al. (2016)]
- **Classical EM photon production** [Tanji (2016)]

M. R. et al., in preparation
Direct photon spectra

Paquet et al. (2016)

ALICE (2016)
Direct photon spectra

Liu et al. PRC79 (2009)

$Au+Au \rightarrow \gamma \; \sqrt{s_{NN}} = 200\text{GeV} \; 20-40\%$

Paquet et al. (2016)
Direct photon spectra

\[ \text{Au+Au} \rightarrow \gamma \quad \sqrt{s_{NN}}=200\text{GeV} \quad 20-40\% \]

**Direct photon spectrum**

\[ \frac{d^2N}{d\eta d^2p_T} \text{(GeV}^{-2}) \]

\[ p_T \text{(GeV/c)} \]

**Contributions**

\[ \text{thermal} \quad \text{LO} \quad \text{Frag}_\text{wi} \quad \text{jpc}_\text{wi} \]
Direct photon spectra

Nice agreement with PHSD calculation:

E. Bratkovskaya et al., PRC92 (2015)
Schwinger effect in Chromodynamics

Non abelian and time effects

It is quite remarkable that the Schwinger effect, that we have discussed for the case of an abelian classical field, can be derived also in the case of non-abelian gauge theory and time-dependent color-electric field.

\[
\frac{dW_{q(\bar{q})}}{dt d^3x d^2p_T} = - \frac{1}{4\pi^3} \sum_{j=1}^{3} |g \Lambda_j(t)| \ln\left[1 - e^{-\frac{\pi (p_T^2 + m^2)}{|g \Lambda_j(t)|}} \right]
\]

\[
\frac{dW_{g(\bar{g})}}{dt d^3x d^2p_T} = \frac{1}{4\pi^3} \sum_{j=1}^{3} |g \Lambda_j(t)| \ln\left[1 + e^{-\frac{\pi p_T^2}{|g \Lambda_j(t)|}} \right]
\]

In the abelian limit the above equations agree with the ones quoted before.

Nayak and Nieuwenhuizen, PRD 71 (2005)
Nayak and Cooper, PRD 73 (2006)
G. Nayak, EJTP 8 (2011)
G. Nayak, EPJ C59 (2009)
G. Nayak, IJMP A25 (2010)
Schwinger effect in Chromodynamics

Abelian Flux Tube Model

Focus on a single flux tube:

(.) neglect color-magnetic fields;
(.) assume abelian dynamics for color-electric fields;
(.) assume **Schwinger effect** takes place:

*Color-electric color field decays into quark-antiquark as well as gluon pairs*

\[
\frac{dN_{jc}}{d\Gamma} = p_0 \frac{dN_{jc}}{d^4xd^2p_Tdp_z} = R_{jc}(p_T)\delta(p_z)p_0
\]

\[
R_{jc}(p_T) = \frac{E_{jc}}{4\pi^3} \ln \left(1 \pm e^{-\frac{\pi p_T^2}{E_{jc}}}\right)
\]

\[
E_{jc} = (g|Q_{jc}E| - \sigma_j) \theta (g|Q_{jc}E| - \sigma_j)
\]

(.) Energy per unit length has to be larger than the QCD string tension
(.) Effective electric field is smaller due to string tension effect
Transport rephrased to hydro

Total Cross section is computed in each configuration space cell according to Chapman-Enskog equation to give the wished value of $\eta/s$.

\[
\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D) \rho \sigma} \cdot 1
\]

(\cdot) Collision integral is gauged in each cell to assure that the fluid dissipates according to the desired value of $\eta/s$.

(\cdot) Microscopic details are not important: the specific microscopic process producing $\eta/s$ is not relevant, only macroscopic quantities are, in analogy with hydrodynamics.

**Transport**

Description in terms of parton distribution function

**Hydro**

Dynamical evolution governed by macroscopic quantities

See also Greco’s talk
Transport gauged to hydro

We use Boltzmann equation to simulate a fluid at fixed $\eta/s$ rather than fixing a set of microscopic processes. Total Cross section is computed in each configuration space cell according to Chapman-Enskog equation to give the wished value of $\eta/s$.

There is agreement of hydro with transport also in the non dilute limit

Transport gauged to hydro, again

We use Boltzmann equation to simulate a fluid at fixed \( \eta/s \) rather than fixing a set of microscopic processes.

Total Cross section is computed in each configuration space cell according to Chapman-Enskog equation to give the wished value of \( \eta/s \).

There is agreement of hydro with transport also in the non dilute limit.

S. Plumari, private archive

Bhalerao et al., PLB627 (2005)
Photon number fraction versus time

\[ \approx 40\% \]
Isotropization for a 3+1D expansion

Pressure isotropization 3+1D expansion

Florkowski and Ryblewski, PRD 88 (2013)
M. R. et al., PRC 92 (2015)

Qualitative agreement with the 1+1D calculation
Isotropization for 3+1D expansion

Pressure isotropization 3+1D expansion

Small $\eta/s$ Almost isotropic in 1 fm/c

1+1D

Florkowski and Ryblewski, PRD 88 (2013)
M. R. et al., PRC 92 (2015)

Nice agreement with the 1+1D calculation

$1 > P_L / P_T > 0.6$
Isotropization for T-dependent $\eta/s$

Local temperature in realistic collisions evolves in time:

$\eta/s$ should be time-dependent

Plumari et al., arXiv:1304.6566
A hydro regime

Proper particles energy density

Small $\eta/s$
After a short transient, the hydro regime begins:

$$\varepsilon \propto t^{-4/3}$$

Large $\eta/s$
After a short transient:
(.). dissipation keeps the system temperature higher;
(.). oscillations arising from the field superimpose to power law decay

In agreement with ideal hydro calculations:
Gatoff et al., PRD 36 (1987)

This is quite interesting because it proves that transport theory is capable to describe, even in conditions of quite strong coupling (small $\eta/s$), the evolution of physical quantities in agreement with calculations based on hydrodynamics, once the microscopic cross section is put aside in favor of fixing $\eta/s$. 
Thermalization

Comparison of produced particles spectra with thermal spectra at the same energy density.

Small viscosity:
Very fast thermalization $\tau < 1 \text{ fm/c}$

Large viscosity:
Particle spectra is quite different from the thermal spectrum with the same energy density
Abelian flux tube model

(. ) neglect magnetic part of Glasma fields;
(. ) assume chromoelectric fields evolve as classical abelian fields;
(. ) initial field is longitudinal: $E_x(t=0) = E_y(t=0) = 0$
(. ) assume Schwinger effect takes place:
Color-electric field decays into quark-antiquark as well as gluon pairs

Pressure isotropization
3+1D expansion

A path to hydrodynamization

Temperature 3+1D expansion
Temperature evolution

![Graph showing temperature evolution over time. The graph includes lines for different power laws, with plots for bulk and photons. The x-axis represents time (t) in fm/c, and the y-axis represents temperature (T) in GeV. The graph is labeled with 'Au-Au 20-40% @ RHIC 200 AGeV' and '4πη/s = 1.' ]