Electromagnetic probes of a pure-glue initial state in nucleus-nucleus collisions at LHC

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6 Summary
Pure glue scenario for ultrarelativistic HIC

- Created system is initially quarkless
- Yang-Mills theory is relevant
- Possible appearance of deconfinement first-order phase transition

Equation of state for two limiting cases is known from lattice

**(2+1)-flavor QCD**
- Crossover transition from hadrons to QGP
- No phase transitions at $\mu = 0$

Borsanyi et al., PLB (2014)

**Pure SU(3)**
- First-order deconfinement PT
- Critical temperature at $T_c \simeq 270$ MeV

Borsanyi et al., JHEP (2012)

Very different number of degrees of freedom and temperature dependence, but very similar $p(e)$ dependence at high densities
Hydro evolution in limiting cases looks very different.
Simulation: Glauber IC, normalization to get same $T_0$, top RHIC energy.

Much longer evolution in pure SU(3) case, long phase transition, glueballs at freeze-out.

Modeling chemical non-equilibrium

In a more realistic scenario quarks appear after some time

- Slow chem. equil. of quarks
- Quarks suppressed compared to gluons
- Rough estimates of equil. time from transport models
  
  T.S. Biro et al., PRC (1993)
  Z. Xu, C. Greiner, PRC (2005)
  J.P. Blaizot et al., NPA (2013)

- Model by time-dependent (anti)quark fugacity
- Ansatz: \( \lambda_q(\tau) = 1 - \exp\left(\frac{\tau_0 - \tau}{\tau_{eq.}^{*}}\right) \)
- Equation of state becomes time-dependent
Equation of state for chemical non-equilibrium QCD

Equation of state for intermediate $0 < \lambda < 1$ needed

Lattice-based EoS for chemical non-equilibrium QCD

Ansatz: $P(T, \lambda) = \lambda P_{FQ}(T) + (1 - \lambda) P_{PG}(T)$

- Linear interpolation between limiting cases
- Can be obtained in several analytic models, i.e. within massless gas of partons$^1$ and modified bag model $^2$

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Hydrodynamic modeling of a pure glue scenario

Modeling: longitudinally boost-invariant (2+1)D ideal hydro to describe ALICE Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

Code: modified vHLLE (viscous Harten-Lax-van Leer-Einfeldt)$^3$, Milne coordinates $(\tau, x, y, \eta)$

Modifications:

- Solution for the space-time profile of the proper time $\tau_P$ of a fluid cell element
  
  \[ u^\mu \partial_\mu \tau_P(x) = 1 , \]
  
  \[ \tau_P(\tau_0, x, y, \eta) = \tau_0 . \]

- Explicit dependence of equation of state on $\tau_P$

- Calculation of electromagnetic observables (photons and dileptons)

- The dependence $P = P(\varepsilon, \lambda)$ determined from
  
  \[ P(T, \lambda) = \lambda P_{\text{FQ}}(T) + (1 - \lambda) P_{\text{PG}}(T) , \]
  
  \[ \varepsilon(T, \lambda) = \lambda \varepsilon_{\text{FQ}}(T) + (1 - \lambda) \varepsilon_{\text{PG}}(T) . \]

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code available at GitHub | [github.com/yukarpenko/vhlle](github.com/yukarpenko/vhlle)
Initial conditions and hadron spectra

Initial conditions: \( \tau_0 = 0.1 \) fm/\( c \) and averaged MC-Glauber \( \varepsilon(x, y) \) profile

Normalization fixed to reproduce hadron spectra in chemical equilibrium, same initial profile used for all other scenarios

Hydrodynamic evolution

- Initial temperatures much higher in PG scenario
- Very similar $T$-dependence at the later stages of hydro evolution
- In PG scenario matter undergoes FOPT
- With ideal gas QGP EoS cools down too quickly

- ALICE 0-20% central Pb+Pb
- $\sqrt{s_{NN}} = 2.76$ TeV
- $\tau_* = 5$ fm/c
- $\lambda$ close to 1 at the end
- However still smaller than 1 → baryon suppression?
Hydrodynamic evolution: temperature profile

ALICE 0-20% central Pb+Pb @ $\sqrt{s_{NN}} = 2.76$ TeV

Temperature profile

- $\tau_* = 0 \text{ fm}/c$
- $\tau_* = 5 \text{ fm}/c$

- Longer evolution in PG initial scenario compared to equilibrium case
- Region with FOPT at $T = 270$ MeV
- Much higher temperatures at the initial stage in PG
Entropy production

Entropy for chemical non-equilibrium EoS

$$s(T, \lambda) = \lambda s_{FQ}(T) + (1 - \lambda) s_{PG}(T) - n_q(T, \lambda) \ln \lambda,$$

$$n_q(T, \lambda) = \frac{\lambda}{T} (P_{FQ} - P_{PG}).$$

Initially $\lambda = 0$, in the end $\lambda \simeq 1$, in non-equilibrium $S$ not conserved

Simple model: gas of massless partons ($\varepsilon = 3P$) and Bjorken-like hydro

Box

Bjorken-like hydro, 2.76 TeV

\[ V. \text{Vovchenko et al., Phys. Rev. C 93, 014906 (2016).} \]
ALICE 0-20% central Pb+Pb @ $\sqrt{s_{_{NN}}} = 2.76$ TeV

$(2+1)$ hydro with lattice-based EoS

$$\frac{dS(\tau)}{d\eta} = \tau \int d^2x_\perp \gamma_\perp(\tau, x_\perp)s(\tau, x_\perp).$$

About 25% of total entropy generated during ideal hydro evolution
Electromagnetic probes

- Photons and dileptons irradiated from all stages of HIC
- Potentially carry more information about initial stage than hadrons
- Measured by different experiments: HADES, NA49, RHIC BES, ALICE

Models for description

- Hydrodynamics

- Coarse-grained transport

- Microscopic transport
  O. Linnyk et al., Prog. Part. Nucl. Phys. 87, 50 (2016)
  M. Greif et al. (2016)
Photons in hydro models

Photon production rate $\Gamma(\tilde{E}, T, \lambda)$ convoluted with hydro space-time profile

$$\frac{dN^{th}_\gamma}{d^2p_T dY} = \int d^2x_T \int_\tau_0^{+\infty} d\tau \int_{-\infty}^{+\infty} d\eta \Gamma[\tilde{E}, T(x), \lambda(x)],$$

$$\frac{dN^{th}_\gamma}{2\pi p_T dp_T dY} = \frac{1}{2\pi} \int_0^{2\pi} d\varphi \frac{dN^{th}_\gamma}{d^2p_T dY},$$

with $\tilde{E} = p^\mu u_\mu = \gamma_\perp p_T [\cosh(Y - \eta) - v_x \cos \varphi - v_y \sin \varphi]$ in (2+1)D.

Implementation:

- At each $\tau$ step contributions from all transverse cells calculated
- Very CPU intensive, takes much longer than solving hydro itself
- Contribution from each cell can be calculated independently $\Rightarrow$ embarrassingly parallel task
- Calculation moved to GPU with NVIDIA CUDA $\Rightarrow$ 20-30x speedup over CPU, photons no longer bottleneck the simulation
- QGP emission described by AMY rate\textsuperscript{5}
- Applied at $T > 155$ MeV
- Chemical non-equilibrium introduces $\lambda$ factors\textsuperscript{6}
  
  LA: $\Gamma(\tilde{E}, T, \lambda) = \lambda \Gamma_1 + \lambda^2 (\Gamma - \Gamma_1)$
  
  UA: $\Gamma(\tilde{E}, T, \lambda) = \lambda^2 \Gamma_2 + \lambda (\Gamma - \Gamma_2)$

In our hydro calculations difference between LA and UA turns out to be rather small

Additionally, at $T < 155$ MeV emission from hadronic stage considered. This includes in-medium $\rho$-meson and $\pi\pi$-bremsstrahlung\textsuperscript{7}, and assumes $\lambda = 1$

\textsuperscript{5}P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 12, 009 (2001).
\textsuperscript{7}M. Heffernan et al., PRC 91, 027902 (2015); S. Turbide et al., PRC 69, 014903 (2004).
Pure glue scenario has strong effect on high-$p_T$ thermal photons

High-$p_T$ thermal spectrum depends on choice of AMY non-equilibrium rate

'Prompt' photons dominate high $p_T$ of direct photon spectra, pure glue effect is masked, much weaker dependence on details of modeling

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Direct photon yield measured experimentally

- Fair description of data and generally consistent with other models
- Underestimation of low $p_T$ yield in most central collisions
- Present data does not conclusively discriminate between different scenarios/models
 Photon elliptic flow

\[ v_2^\gamma = \langle \cos 2\varphi \rangle \]

- Strong enhance of thermal \( v_2 \)
- Consequence of initial suppression of production
- Effect masked by ’prompt’ photons

\[ \begin{align*}
\text{0-40\% Pb+Pb, } s^{1/2} &= 2.76 \text{ TeV} \\
Y_{cm} &= 0 \\
\text{Thin: thermal } \gamma \\
\text{Thick: direct } \gamma
\end{align*} \]

\[ \begin{align*}
0.1 & \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \\
\tau \text{ (fm/c)} &
\end{align*} \]

\[ \begin{align*}
0.0 & \quad 0.02 \quad 0.04 \quad 0.06 \quad 0.08 \quad 0.10 \\
\varepsilon_p &
\end{align*} \]

\[ \begin{align*}
0.1 & \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \\
\tau \text{ (fm/c)} &
\end{align*} \]

\[ \begin{align*}
0.0 & \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \\
\lambda &
\end{align*} \]
Effect of slow quark equilibration was studied before, in particular at RHIC

Thermal photon $v_2$ in hydro

Direct photon $v_2$ in PHSD

Suppression of yield and enhancement of $v_2$ of photons was obtained in hydro


and microscopic

- BAMPS, M. Greif et al., in preparation.
Thermal dileptons $q\bar{q} \rightarrow e^+e^-$ production rate in undersaturated QGP\textsuperscript{9}

$$\frac{dN}{d^4xd^4Q} = C_q \lambda^2 \exp \left(-\frac{Qu}{T}\right)$$

with $Q = p_+ + p_- = (M_\perp \cosh Y, Q_\perp, M_\perp \sinh Y)$.

- Thermal QGP dilepton yield clearly suppressed in PG initial state scenario
- Similar result for RHIC within same scenario reported within PHSD\textsuperscript{10}

\textsuperscript{9}M. Strickland, PLB (1994); B. Kämpfer et al., PRC (1995).
Thermal dileptons

\[ v_2^{dp} = \langle \cos 2\varphi \rangle \]

where \( \varphi \) is angle between \( Q_\perp \) and \( x \)-axis.

- Momentum anisotropy of thermal dileptons is clearly enhanced
- Dileptons appear to be potentially more sensitive
Lattice-based equation of state for chemically non-equilibrium QCD is constructed by linear interpolation of two limiting cases.

Evolution of chemically non-equilibrium QGP is modeled by ideal hydrodynamics with time-dependent equation of state.

About 25% of total entropy is generated during the ideal hydro evolution of initially pure glue system.

Photon and dilepton yields are suppressed in pure glue scenario while their momentum anisotropies are enhanced. Dileptons appear to be more sensitive.

Outlook

- More consistent treatment of hadron observables in chemical non-equilibrium case.
- Lower energies and/or smaller systems.
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Thanks for your attention!
Backup slides
Photon elliptic flow

Pb+Pb, $s^{1/2}=2.76$ TeV
$Y_{cm}=0$  QGP-UA

T > 155 MeV

Thin: thermal $\gamma$
Thick: direct $\gamma$

0-20%

$\tau_* = 0$ fm/c
$\tau_* = 1$ fm/c
$\tau_* = 5$ fm/c

20-40%

$V_2$ vs p$_T$ (GeV/c)