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

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In collaboration with Iurii Karpenko, Mark Gorenstein, Leonid Satarov, Igor Mishustin, Burkhard Kämpfer, and Horst Stoecker

based on arXiv:1604.06346

Transport Meeting

ITP, Frankfurt
24 May 2016

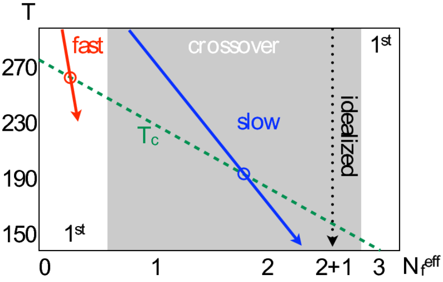
Outline

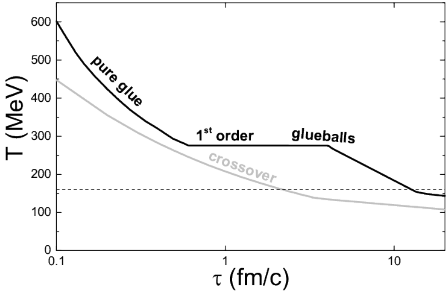
Pure glue scenario

Pure glue scenario for ultrarelativistic HIC

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

H. Stoecker et al., J. Phys. G 43, 015105 (2016).





(2+1)-flavor vs YM: equation of state

Equation of state for two limiting cases is known from lattice

(2+1)-flavor QCD

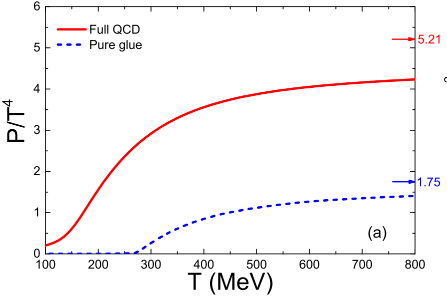
- Crossover transition from hadrons to QGP
- No phase transitions at $\mu = 0$

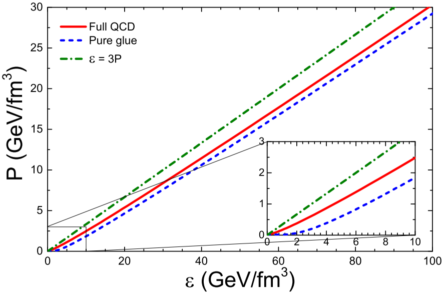
Borsanyi et al., PLB (2014)

Pure SU(3)

- First-order deconfinement PT
- Critical temperature at $T_c \simeq 270$ MeV

Borsanyi et al., JHEP (2012)

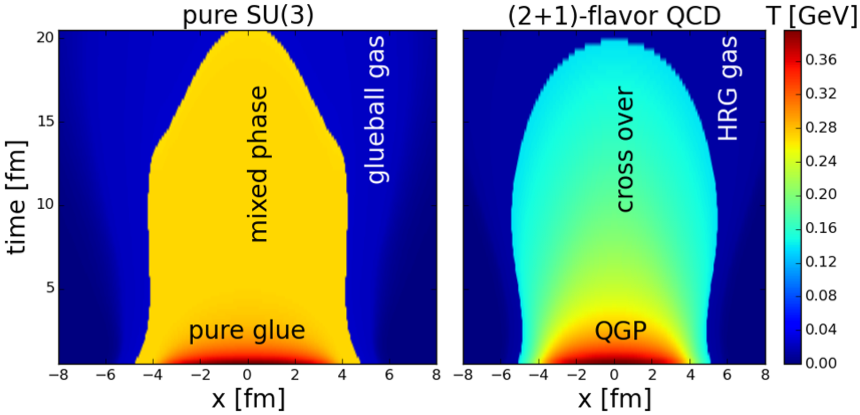




Very different number of degrees of freedom and temperature dependence, but very similar $p(e)$ dependence at high densities

(2+1)-flavor vs YM: ideal hydro results

Hydro evolution in limiting cases looks very different
Simulation: Glauber IC, normalization to get same T_0, top RHIC energy

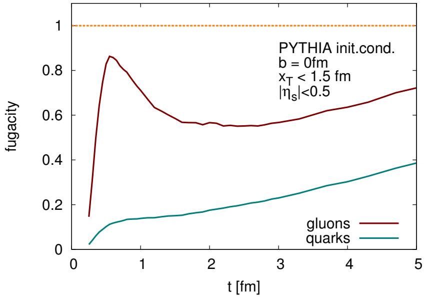


Much longer evolution in pure SU(3) case, long phase transition, glueballs at freeze-out

L.G. Pang, V. Vovchenko, H. Niemi, H. Stoecker, in preparation.

Modeling chemical non-equilibrium

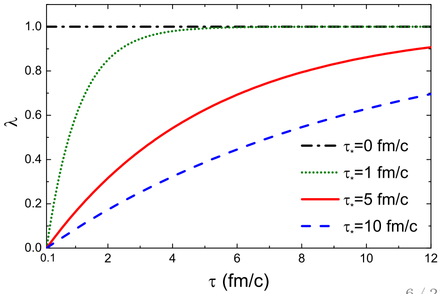
In a more realistic scenario quarks appear after some time



- 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: $\lambda_q(\tau) = 1 - \exp\left(\frac{\tau_0 - \tau}{\tau_*^{\mathrm{eq.}}}\right)$
- Equation of state becomes time-dependent



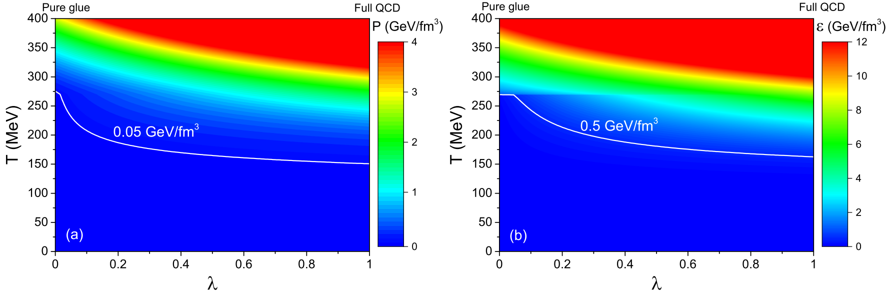
Equation of state for chemical non-equilibrium QCD

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

Lattice-based EoS for chemical non-equilibrium QCD

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

- 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]



[1] V. Vovchenko et al., Phys. Rev. C 93, 014906 (2016).
[2] V.V. Begun, M.I. Gorenstein, O.A. Mogilevksy, IJMPE 20, 1805 (2011).

Hydrodynamic modeling of a pure glue scenario

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

Code: modified vHLLE (viscous Harten-Lax-van Leer-Einfeldt)[3], Milne coordinates (τ, x, y, η)

Modifications:

- Solution for the space-time profile of the proper time τ_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 τ_P
- Calculation of electromagnetic observables (photons and dileptons)
- The dependence $P = P(\varepsilon, \lambda)$ determined from

$$P\,(T,\lambda) = \lambda\, P_{\rm FQ}(T) + (1-\lambda)\, P_{\rm PG}(T)\,,$$
$$\varepsilon\,(T,\lambda) = \lambda\, \varepsilon_{\rm FQ}(T) + (1-\lambda)\, \varepsilon_{\rm PG}(T)\,.$$

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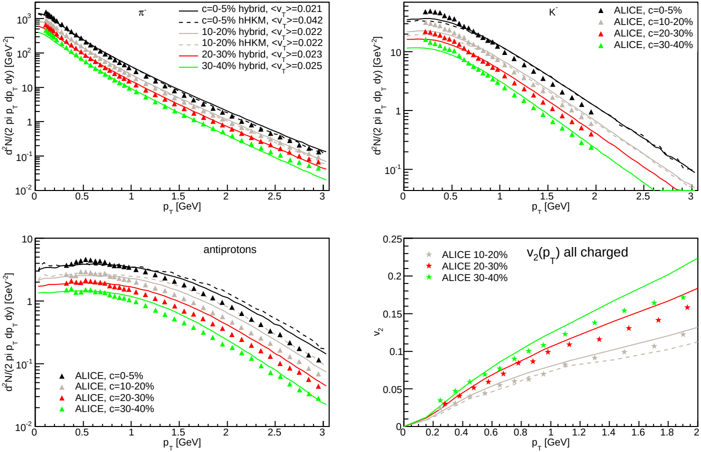
[3] Iu. Karpenko et al., Comput. Phys. Commun. 185, 3016 (2014) code available at GitHub github.com/yukarpenko/vhlle

Initial conditions and hadron spectra

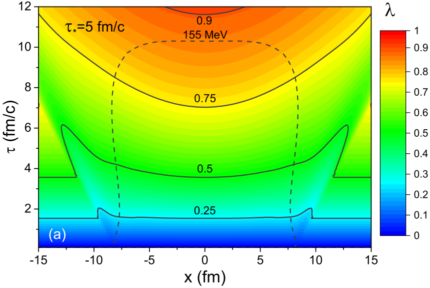
Initial conditions: $\tau_0 = 0.1$ fm/c and averaged MC-Glauber $\varepsilon(x, y)$ profile

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



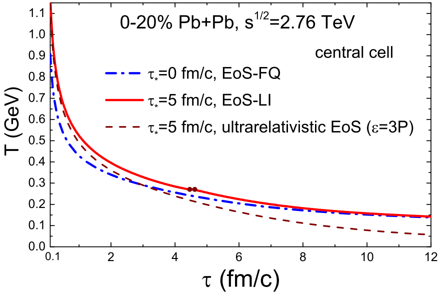
Iu. Karpenko, Yu. Sinyukov, K. Werner, Phys. Rev. C 87, 024914 (2013).

Hydrodynamic evolution



- ALICE 0-20% central Pb+Pb
- $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV
- $\tau_* = 5$ fm$/c$
- λ close to 1 at the end
- However still smaller than 1 $\rightarrow$ baryon suppression?

- 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

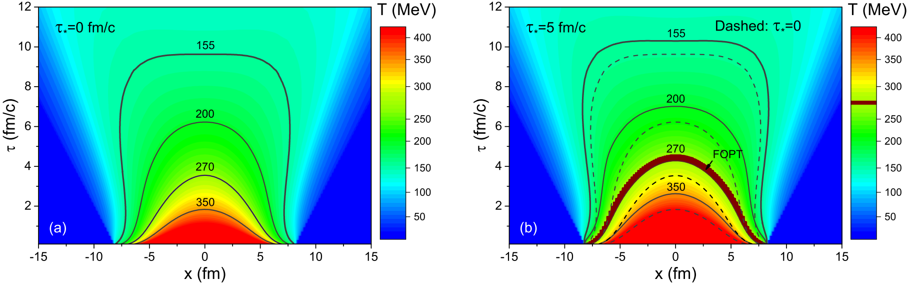


Hydrodynamic evolution: temperature profile

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

Temperature profile

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

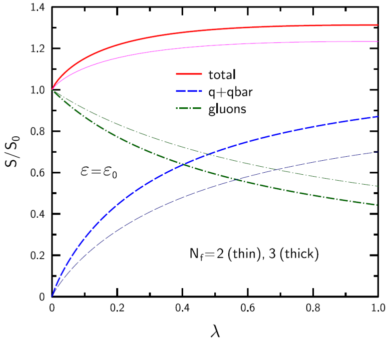
$$s(T,\lambda) = \lambda\, s_{\rm FQ}(T) + (1-\lambda)\, s_{\rm PG}(T) - n_q(T,\lambda) \ln\lambda,$$

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

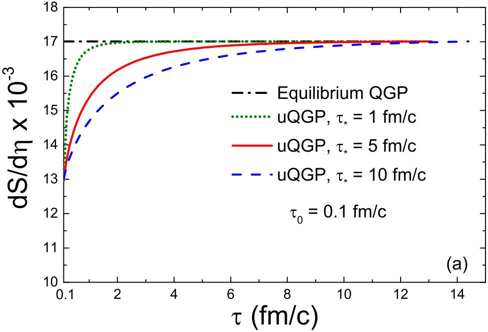
Initially $\lambda = 0$, in the end $\lambda \simeq 1$, in non-equilibrium S not conserved

Simple model: gas of massless partons ($\varepsilon = 3P$) and Bjorken-like hydro[4]

Box



Bjorken-like hydro, 2.76 TeV

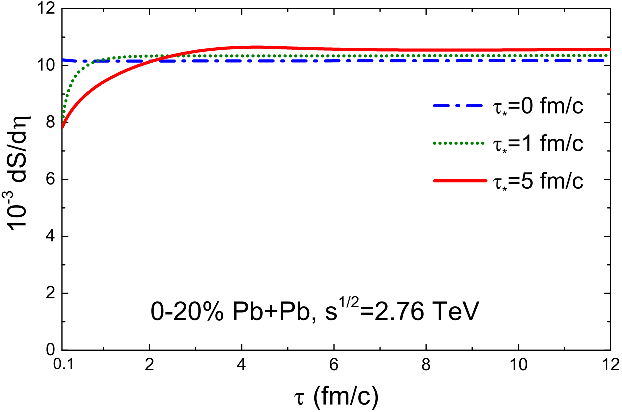


[4] V. Vovchenko et al., Phys. Rev. C 93, 014906 (2016).

Entropy production

ALICE 0-20% central Pb+Pb @ $\sqrt{s_{\rm NN}} = 2.76$ TeV
(2+1) hydro with lattice-based EoS

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



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
  J.F. Paquet et al., Phys.Rev. C 93, 044906 (2016)
  H. Hees et al., Nucl. Phys. A 933, 256 (2015)
  R. Chatterjee et al., Phys. Rev. C 85, 064910 (2012)
- Coarse-grained transport
  S. Endres et al., Phys. Rev. C 93, 054901 (2016)
  T. Galatyuk et al., Eur. Phys. J. A 52, 131 (2016)
- 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

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

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

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

Implementation:

- At each τ 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

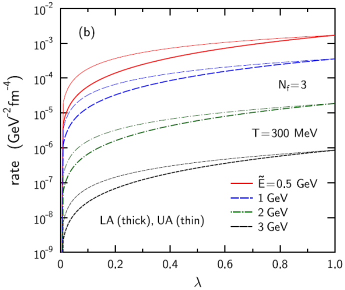
Photon production rate

- QGP emission described by AMY rate[5]
- Applied at $T > 155$ MeV
- Chemical non-equilibrium introduces λ factors[6]

$$\text{LA:} \quad \Gamma(\widetilde{E}, T, \lambda) = \lambda\, \Gamma_1 + \lambda^2 (\Gamma - \Gamma_1)$$

$$\text{UA:} \quad \Gamma(\widetilde{E}, T, \lambda) = \lambda^2\, \Gamma_2 + \lambda\, (\Gamma - \Gamma_2)$$

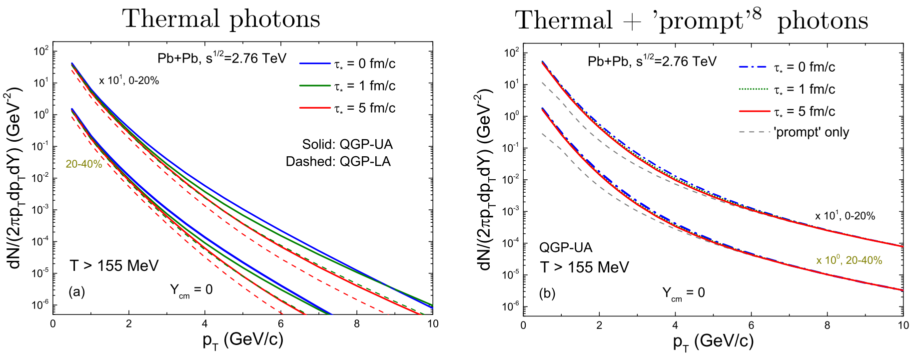
In our hydro calculations difference between LA and UA turns out to be rather small



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

[5] P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 12, 009 (2001).
[6] Similar to F.-M. Liu, S.-X. Liu, Phys. Rev. C 89, 034906 (2014).
[7] M. Heffernan et al., PRC 91, 027902 (2015); S. Turbide et al., PRC 69, 014903 (2004).

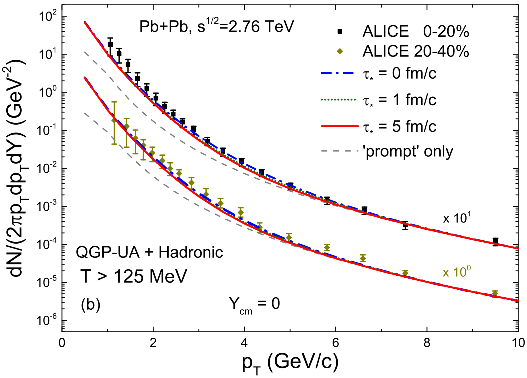
Calculation results: Photon yield

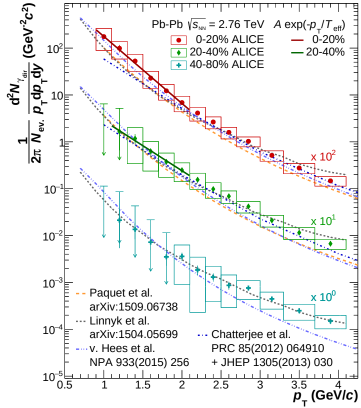


- Pure glue scenario has strong effect on high-p_T thermal photons
- High-p_T thermal spectrum depends on choice of AMY non-equilibrium rate
- 'Prompt' photons dominate high p_T of direct photon spectra, pure glue effect is masked, much weaker dependence on details of modeling

[8] pQCD pp yield scaled by N_{coll}, taken from J. Adam et al. [ALICE Collaboration], Phys. Lett. B 754, 235 (2016).

Direct photon yield measured experimentally



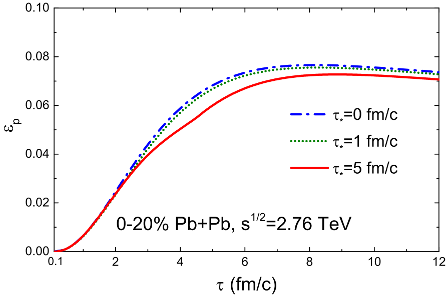


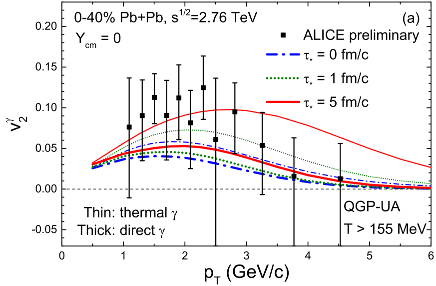
- Fair description of data and generally consistent with other models
- Underestimation of low p_T yield in most central collisions
- Present data does not conclusively discriminate between different scenarios/models

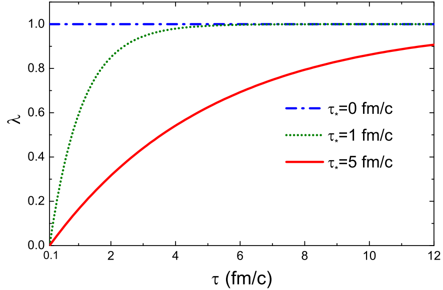
Photon elliptic flow

$$v_2^\gamma = \langle \cos 2\varphi \rangle$$

- Strong enhance of thermal v_2
- Consequence of initial suppression of production
- Effect masked by 'prompt' photons



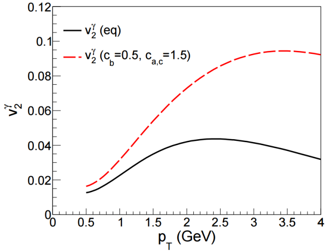




Photon elliptic flow

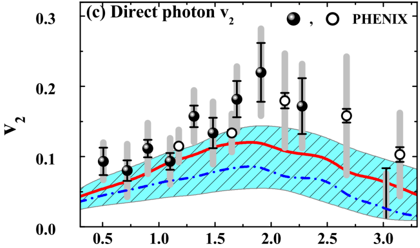
Effect of slow quark equilibration was studied before, in particular at RHIC

Thermal photon v_2 in hydro



A. Monnai

Direct photon v_2 in PHSD



P. Moreau et al.

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

- A. Monnai, Phys. Rev. C 90, 021901 (2014).
- F.-M. Liu, S.-X. Liu, Phys. Rev. C 89, 034906 (2014).

and microscopic

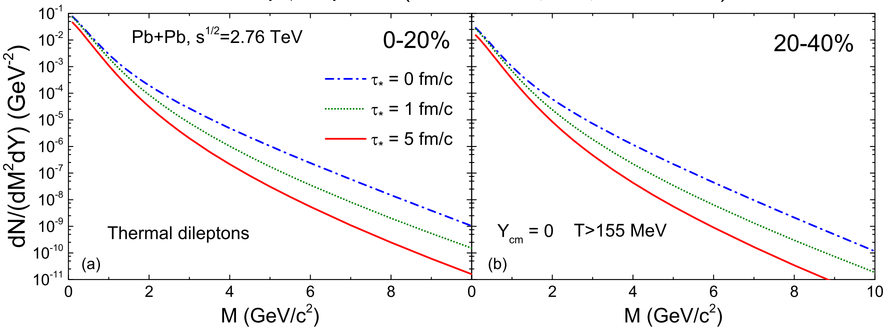
- PHSD model, P. Moreau et al., Phys. Rev. C 93, 044916 (2016).
- BAMPS, M. Greif et al., in preparation.

models.

Thermal dilepton $q\bar{q} \to e^+e^-$ production rate in undersaturated QGP[9]

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

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



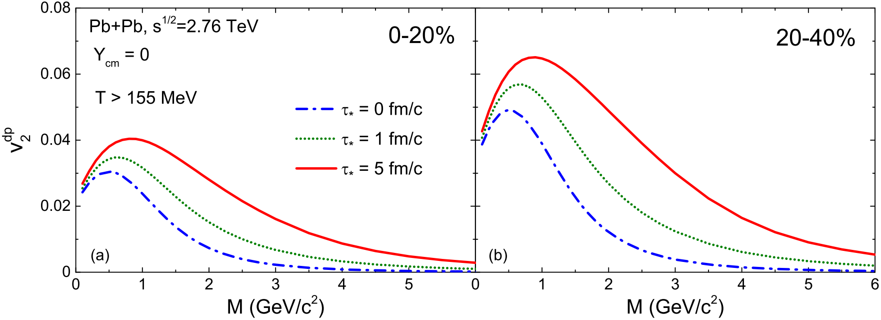
- Thermal QGP dilepton yield clearly suppressed in PG initial state scenario
- Similar result for RHIC within same scenario reported within PHSD[10]

[9] M. Strickland, PLB (1994); B. Kämpfer et al., PRC (1995).
[10] P. Moreau et al., Phys. Rev. C 93, 044916 (2016).

Thermal dileptons

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

where φ is angle between $Q_\perp$ and x-axis.



- Momentum anisotropy of thermal dileptons is clearly enhanced
- Dileptons appear to be potentially more sensitive

Summary

1. Lattice-based equation of state for chemically non-equilibrium QCD is constructed by linear interpolation of two limiting cases.
2. Evolution of chemically non-equilibrium QGP is modeled by ideal hydrodynamics with time-dependent equation of state.
3. About 25% of total entropy is generated during the ideal hydro evolution of initially pure glue system.
4. 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