Dilepton production from the quark-gluon plasma using (3+1)D LO anisotropic dissipative hydrodynamics

Radoslaw Ryblewski

Institute of Nuclear Physics PAN

in collaboration with Michael Strickland (Kent State Univ., USA)

R.Ryblewski, M.Strickland, arXiv:1501.03418

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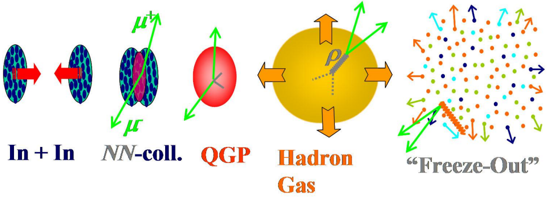
- what is the momentum-space isotropization/thermalization level of partons comprising the QGP?
- hadronic observables reflect mostly the final stages of the interacting system
- electromagnetic probes - unambiguous measurement of early-time/interior dynamics of the fireball[1]



→ weakly coupled to the plasma ($\alpha << \alpha_s = \frac{g^2}{4\pi}$)
→ emission throughout the whole fireball evolution
→ high-energy ($E \gtrsim 2$ GeV) emission dominated by early times
→ low-energy ($E \lesssim 2$ GeV) production receives significant contributions from late-time emissions

- two primary electromagnetic observables: real photons and dileptons (produced via decay of virtual photons)

[1] Shuryak ('78), Domokos, Goldman, Kajantie, Miettinen ('81), Kapusta, McLerran, Mekjian ('86), ...

SOURCES OF DILEPTON PRODUCTION:

- $M \lesssim M_\phi = 1.024$ GeV (late time emission from HG):

  - π^0 and η decays

  - low-mass vector mesons $V(V = \rho, \omega, \phi)$

- $M_\phi \lesssim M \lesssim M_{J/\Psi} = 3.1$ GeV:

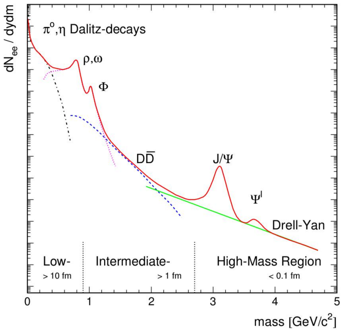
  - continuum radiation coming from QGP (annhilation process between quarks)

  - weak decays: heavy charmonia fragment into $D\bar{D}$ mesons which subsequently decay semileptonically into positrons and electrons

- $M \gtrsim M_{J/\Psi}$:

  - Drell-Yan annihilation of quark and antiquark coming from different nuclei

  - jet conversion



we focus on thermal dilepton production

- dilepton emission rate ($X^\mu = (t, \mathbf{x})$, $P^\mu = (E, \mathbf{p})$)

$$\frac{dR^{l^+l^-}}{d^4P} \equiv \frac{dN^{l^+l^-}}{d^4X d^4P}$$

- based on relativistic kinetic theory at leading order in α ($\mathcal{O}(\alpha^2)$)[2]

$$\frac{dR^{l^+l^-}}{d^4P} = \int \frac{d^3\mathbf{p}_1}{(2\pi)^3} \frac{d^3\mathbf{p}_2}{(2\pi)^3} f_q(\mathbf{p}_1) f_{\bar{q}}(\mathbf{p}_2) v_{q\bar{q}} \sigma_{q\bar{q}}^{l^+l^-} \delta^{(4)}(P^\mu - p_1^\mu - p_2^\mu)$$

$$v_{q\bar{q}} \equiv \frac{\sqrt{\mathbf{p}_1 \cdot \mathbf{p}_2 - m_q^2}}{2E_{\mathbf{p}_1} 2E_{\mathbf{p}_2}}$$

- total cross section for the leading-order quark–anti-quark annihilation process, $q + \bar{q} \to \gamma^* \to l^+ + l^-$

$$\sigma_{q\bar{q}}^{l^+l^-} = \frac{4\pi}{3} \frac{\alpha^2}{M^2} \left(1 + \frac{2m_l^2}{M^2}\right)\left(1 - \frac{4m_l^2}{M^2}\right)^{1/2}$$

- high-energy dilepton pairs ($M \gg m_l$)

some knowledge about the phase-space distribution of QGP constituents is required

[2] J. I. Kapusta, L. D. McLerran, and D. Kumar Srivastava, Phys. Lett. B283, 145 (1992)
A. Dumitru, D. H. Rischke, T. Schonfeld, L. Winckelmann, H. Stocker, and W. Greiner, Phys. Rev. Lett. 70, 2860 (1993)
M. Strickland, Phys. Lett. B331, 245 (1994)

Dilepton production in anisotropic QGP

- thermal medium (fireball) is usually simulated with ideal or viscous hydrodynamic equations based on the perturbative corrections to the equilibrium distributions

$$f(\mathbf{p},T)_{q(\bar{q})} = \underbrace{f^{\rm iso}_{q(\bar{q})}\left(p^\mu u_\mu, T\right)}_{\rm LO} + \underbrace{\delta f(x,p)}_{\rm NLO} \qquad \Rightarrow \qquad T^{\mu\nu}_{vis} = T^{\mu\nu}_{id} + \delta T^{\mu\nu} \quad (\delta T^{\mu\nu} \propto \pi^{\mu\nu})$$

- in ultra-relativistic heavy-ion collisions there is rapid expansion along the longitudinal (beam) direction and transverse expansion is initially relatively quite slow
- this phenomenon inevitably leads to the presence of large momentum-space anisotropies in the phase-space distribution — $\pi^{\eta\eta}$ gives the largest correction

negative contributions to the phase-space distribution possible

- **possible way out**: one-particle distribution function for the quarks and anti-quarks may be described at leading order by the following spheroidal "Romatschke-Strickland" form (close to equilibrium ξ plays a role of $\pi^{\eta\eta}$)

$$f_{q(\bar{q})}(\mathbf{p},\xi,\Lambda) \equiv \underbrace{f^{\rm iso}_{q(\bar{q})}\left(\sqrt{p^\mu \Xi_{\mu\nu} p^\nu},\Lambda\right)}_{\rm LO} + \cancel{\underbrace{\delta\tilde{f}(x,p)}_{\rm NLO}}$$

- dilepton emission rate for anisotropic plasma in LRF[3]

$$\frac{dR^{l^+l^-}}{d^4P}(\xi,\Lambda) = \frac{5\alpha^2}{18\pi^5}\int_{-1}^{1} d(\cos\theta_{p_1})\int_{a_+}^{a_-}\frac{p_1\,dp_1}{\sqrt{\chi}}\, f_q\!\left(p_1\sqrt{1+\xi\cos^2\theta_{p_1}},\Lambda\right)$$
$$\times f_{\bar{q}}\!\left(\sqrt{(E-p_1)^2+\xi(p_1\cos\theta_{p_1}-P\cos\theta_P)^2},\Lambda\right)$$

[3] Martinez and M. Strickland, Phys.Rev. C78, 034917 (2008), arXiv:0805.4552 (hep-ph)

- impact of space-time dependent anisotropies in the system on the dilepton differential spectra included by including space-time dependent $\xi(X)$ and $\Lambda(X)$ using some hydrodynamic model

$$\frac{dN^{l^+l^-}}{MdMdy} = \int_{p_\perp^{\rm min}}^{p_\perp^{\rm max}} p_\perp dp_\perp \int_0^{2\pi} d\phi_p \int d^4X \, \frac{dR^{l^+l^-}}{d^4P} \left(\xi(X), \Lambda(X)\right)$$

$$\frac{dN^{l^+l^-}}{p_\perp dp_\perp dy} = \int_{M^{\rm min}}^{M^{\rm max}} MdM \int_0^{2\pi} d\phi_p \int d^4X \, \frac{dR^{l^+l^-}}{d^4P} \left(\xi(X), \Lambda(X)\right)$$

- one has to boost the LAB frame momentum P'^{ν} to the LRF of the fluid cell using $P^{\mu} = \Lambda^{\mu}_{\ \nu}(u^{\mu}(X))\ P'^{\nu}$

we use the anisotropic hydrodynamics framework to determine space-time dependence of $\Lambda, \xi($ and $u^{\mu})$

Anisotropic hydrodynamics

BE with the collision term treated in the RTA

$$p^\mu \partial_\mu f = \frac{p^\mu u_\mu}{\tau_{\rm eq}} (f_{\rm iso} - f)$$

- equations of motion

zeroth moment of BE – particle production

$$\partial_\mu N^\mu = u_\mu \frac{N^\mu_{\rm eq} - N^\mu}{\tau_{\rm eq}}$$

first moment of BE – energy-momentum conservation

$$\partial_\mu T^{\mu\nu} = 0$$

energy-momentum tensor (spheroidally anisotropic system)

$$T^{\mu\nu} = (\varepsilon + P_\perp)\, u^\mu u^\nu - P_\perp\, g^{\mu\nu} - (P_\perp - P_\parallel) z^\mu z^\nu$$

particle flux

$$N^\mu_{\rm eq} = n_{\rm eq}\, u^\mu$$

$$u^\mu = (u_0 \cosh\vartheta, \mathbf{u}_\perp, u_0 \sinh\vartheta)$$
$$z^\mu = (\sinh\vartheta, \mathbf{0}, \cosh\vartheta)$$

- once EOS is defined we have 5 PDE for $\Lambda, \xi, u_x, u_y, \vartheta$, we consider a system that consists of massless particles described by the anisotropic distribution function of RS form

using standard kinetic theory definitions

$$N^{\mu} \equiv \int d^3P\, p^{\mu} f$$

$$T^{\mu\nu} \equiv \int d^3P\, p^{\mu} p^{\nu} f$$

where $d^3P \equiv d^3p / \left[(2\pi)^3 p^0\right]$, and the tensor decompositions for N^{μ} and $T^{\mu\nu}$ one can calculate the thermodynamic properties of the system

$$\begin{aligned} n(\Lambda,\xi) &= \frac{n_{\rm iso}(\Lambda)}{\sqrt{1+\xi}} \\ \varepsilon(\Lambda,\xi) &= \mathcal{R}(\xi)\, \varepsilon_{\rm iso}(\Lambda) \\ P_{\perp}(\Lambda,\xi) &= \mathcal{R}_{\perp}(\xi)\, P_{\rm iso}(\Lambda) \\ P_{\parallel}(\Lambda,\xi) &= \mathcal{R}_{\parallel}(\xi)\, P_{\rm iso}(\Lambda) \end{aligned}$$

where $n_{\rm iso}$, $\varepsilon_{\rm iso}$, and $P_{\rm iso}$ are the isotropic particle density, energy density, and pressure

Initial conditions

- $\Lambda(\tau_0, \mathbf{x}_\perp, \varsigma)$ from mixed optical Glauber model

$$\Lambda(\tau_0, \mathbf{x}_\perp, \varsigma) = \varepsilon_{\rm iso}^{-1}\left(\varepsilon_0 \frac{\rho(b, \mathbf{x}_\perp, \varsigma)}{\rho(0, \mathbf{0}, 0)}\right)$$

$$\rho(b, \mathbf{x}_\perp, \varsigma) \equiv \Big[(1-\kappa)(\rho^{+}_{\rm WN}(b, \mathbf{x}_\perp) + \rho^{-}_{\rm WN}(b, \mathbf{x}_\perp)) + 2\,\kappa\,\rho_{\rm BC}(b, \mathbf{x}_\perp)\Big] f(\varsigma - \varsigma_S(b, \mathbf{x}_\perp))$$

$$\rho^{\pm}_{\rm WN}(b, \mathbf{x}_\perp) \equiv T\left(\mathbf{x}_\perp \mp \frac{\mathbf{b}_\perp}{2}\right)\left[1 - e^{-\sigma_{in} T\left(\mathbf{x}_\perp \pm \frac{\mathbf{b}_\perp}{2}\right)}\right]$$

$$\rho_{\rm BC}(b, \mathbf{x}_\perp) \equiv \sigma_{in} T\left(\mathbf{x}_\perp + \frac{\mathbf{b}_\perp}{2}\right) T\left(\mathbf{x}_\perp - \frac{\mathbf{b}_\perp}{2}\right)$$

- no initial transverse flow, i.e. $u_x(\tau_0, \mathbf{x}_\perp, \varsigma) = u_x(\tau_0, \mathbf{x}_\perp, \varsigma) = 0$
- Bjorken form of initial longitudinal flow $\vartheta(\tau_0, \mathbf{x}_\perp, \varsigma) = \varsigma$
- homogeneous initial anisotropy parameter $\xi(\tau_0, \mathbf{x}_\perp, \varsigma) = \xi_0$

In order to extract the freeze-out hypersurface, we parameterize space-time in the following way

$$
\begin{aligned}
t &= \tau \cosh \varsigma\,, \\
x &= r \sin\theta \cos\phi\,, \\
y &= r \sin\theta \sin\phi\,, \\
z &= \tau \sinh \varsigma\,,
\end{aligned}
$$

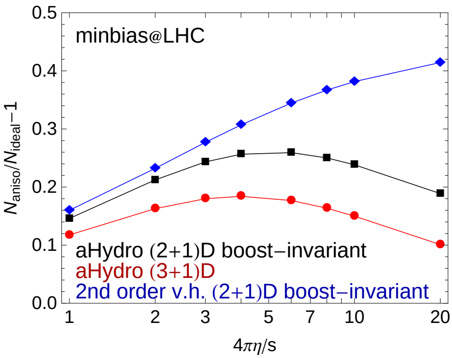
$$
\begin{aligned}
\varsigma &= d(\zeta,\phi,\theta)\cos\theta\,, \\
\tau &= \tau_0 + d(\zeta,\phi,\theta)\sin\theta\sin\zeta\,, \\
r &= d(\zeta,\phi,\theta)\cos\zeta
\end{aligned}
$$

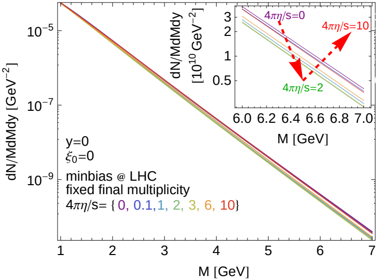
number of particles is calculated using

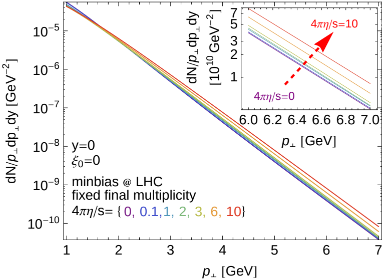
$$N = \int d\Sigma_\mu u^\mu n\left[T_{\rm FO}\mathcal{R}^{-1/4}(\xi(\zeta,\phi,\theta)),\xi(\zeta,\phi,\theta)\right]$$

where the form of $d\Sigma_\mu$ may be obtained with the help of the formula

$$d\Sigma_\mu = \varepsilon_{\mu\alpha\beta\gamma}\frac{\partial x^\alpha}{\partial\zeta}\frac{\partial x^\beta}{\partial\phi}\frac{\partial x^\gamma}{\partial\theta}d\zeta d\phi d\theta$$




dN/MdMdy [GeV^{-2}]
10^{-5}
10^{-7}
10^{-9}
1 2 3 4 5 6 7
M [GeV]
y=0
ξ_0=0
minbias @ LHC
fixed final multiplicity
$4\pi\eta$/s= { 0, 0.1, 1, 2, 3, 6, 10}
dN/MdMdy
[10^{10} GeV^{-2}]
3 2 1 0.5
6.0 6.2 6.4 6.6 6.8 7.0
M [GeV]
$4\pi\eta$/s=0
$4\pi\eta$/s=10
$4\pi\eta$/s=2


dN/$p_\perp$dp$_\perp$dy [GeV^{-2}]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1 2 3 4 5 6 7
$p_\perp$ [GeV]
y=0
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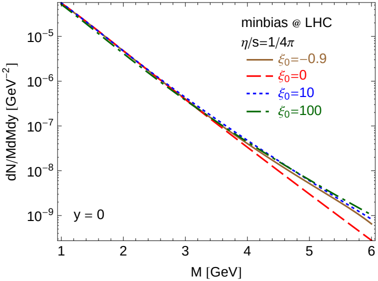
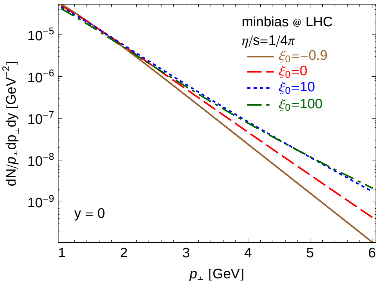
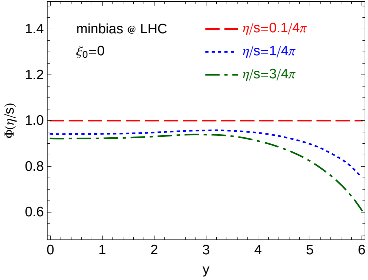
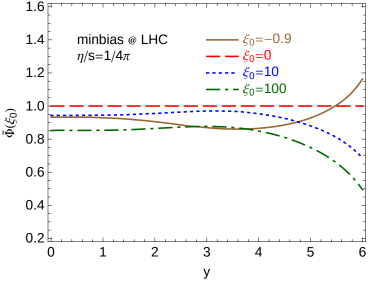
fixed final multiplicity
$4\pi\eta$/s= { 0, 0.1, 1, 2, 3, 6, 10}
dN/$p_\perp$dp$_\perp$dy
[10^{10} GeV^{-2}]
7 5 3 2 1
6.0 6.2 6.4 6.6 6.8 7.0
$p_\perp$ [GeV]
$4\pi\eta$/s=10
$4\pi\eta$/s=0


minbias @ LHC
η/s=1/4π
ξ0=−0.9
ξ0=0
ξ0=10
ξ0=100
y = 0
dN/MdMdy [GeV−2]
M [GeV]


minbias @ LHC
η/s=1/4π
ξ0=−0.9
ξ0=0
ξ0=10
ξ0=100
y = 0
dN/p⊥dp⊥dy [GeV−2]
p⊥ [GeV]





$$\Phi(\bar{\eta}) \equiv \left(\frac{dN^{e^+e^-}(\bar{\eta})}{dy}\right) \Big/ \left(\frac{dN^{e^+e^-}(\bar{\eta}=0.1/4\pi)}{dy}\right)$$

$$\tilde{\Phi}(\xi_0) \equiv \left(\frac{dN^{e^+e^-}(\xi_0)}{dy}\right) \Big/ \left(\frac{dN^{e^+e^-}(\xi_0=0)}{dy}\right)$$

CONCLUSIONS

- dilepton spectra have a weak dependence on the assumed value of η/s (confirms earlier studies)
- the high-mass and high-transverse-momentum dilepton spectra are quite sensitive to the initial level of momentum-space anisotropy ξ_0
- the rapidity dependence of dilepton production is also sensitive to the initial level of momentum-space anisotropy

OUTLOOK

- inclusion of the next-to-leading order rate, such a calculation only exists for an isotropic quark-gluon plasma
- polarized dilepton emission, the polarization asymmetry could be quite sensitive to early-time momentum-space anisotropies and possibly also to the assumed value of η/s
- emission of real photons

Thank you for your attention!

ACKNOWLEDGMENTS

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