Some aspects of dilepton production in HIC

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Electromagnetic Probes of Strongly Interacting Matter
ECT* Trento, May 20-24, 2013
Outline

1. Introduction, see e.g. T. Galatyuk’s talk.
2. Many body effective theory + hydro simulation
3. $T_{\text{eff}}$ as probe to EOS of dense matter
4. Comparison with STAR di-electron data
5. Summary and conclusion
Dilepton production in Au+Au collisions at 200 GeV in IMR. QGP phase: $q\bar{q}$ annihilation; Hadron phase (many body EFT): $D_\rho$ with vertices $\rho\pi X$ ($X$: all mesons below 1300 GeV), and vertices of $\rho NN^*$ and $\rho N\Delta^*$ ($N^*$ and $\Delta^*$: baryon resonances); $D_\omega$ with vertices $\omega\rho\pi$, $\omega 3\pi$; and $D_\phi$ with vertices $\phi KK$-bar.

Space-time evolution of medium is described by a 2+1 ideal hydro model.

Slope parameters show distinct features from two phases.

Use in-medium T-matrix and Hydro-Langevin simulation to model open charm contribution, and compare to STAR di-electron data.
Hydrodynamics for HIC

- Assumption: thermalization, Ideal or Viscous
- Inputs: EOS, initial conditions, freeze-out conditions
- Outputs: space-time evolution
- Comparison with data: pt-spectra, flows, ...
- Further application: fluctuation & correlation, non-equilibrium statistics, ...


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Vector Meson Dominance Model (VDM)

- VDM (Kroll, Lee, Zumino, 67'). The Lagrangian for $\rho\pi\gamma e$ system:

$$L = (D_\mu \pi)^*(D^\mu \pi) - m_\pi^2 \pi^* \pi - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \frac{1}{2} m_\rho^2 \rho_\mu \rho^\mu + \bar{\psi}(i\gamma_\mu D^\mu_A - m)\psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{e}{2g} F_{\mu\nu} G^{\mu\nu}$$

where

$$D^\mu = \partial^\mu + ig\rho^\mu + ieA^\mu$$
$$D^\mu_A = \partial^\mu - ieA^\mu$$

- EOM for EM field

$$\partial_\sigma F^{\alpha\sigma} \approx e\bar{\psi}\gamma^\alpha \psi - \frac{e}{g} m_\rho^2 \rho^\alpha$$

(keep terms linear in $e/g$)

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Dilepton emission rate (1)

In-medium di-lepton rate

\[
\frac{d^8 N}{d^4x d^4p} = -\frac{\alpha}{4\pi^4} \frac{1}{M^2} n_B (p \cdot u) L(M) \text{Im} \Pi^R (p)
\]

\[
L(M) = \left(1 + \frac{2m_i^2}{M^2}\right) \sqrt{1 - \frac{4m_i^2}{M^2}}
\]

Photon selfenergy (VDM + quark)

\[
\text{Im} \Pi^R = \left\{ \begin{array}{ll}
\sum_{V=\rho,\omega,\phi} e^2 \left(\frac{m_V^2}{g_V}\right)^2 \text{Im} D_V & \text{hadronic source} \\
-\frac{N_c M^2}{12} \left(1 + \frac{\alpha_s}{\pi}\right) \sum_{i=u,d,s} e_i^2 & \text{quark source}
\end{array} \right.
\]

Imaginary part of Retarded propagator of rho meson

\[
\text{Im} D_V (M, q, T) = \frac{1}{3} \text{Im} D^L_V (M, q, T) + \frac{2}{3} \text{Im} D^T_V (M, q, T)
\]

\[
\text{Im} D^{L,T}_V (M, q, T) = \frac{\text{Im} \Sigma^{L,T}_V (M, q, T)}{|M^2 - (m_V^0)^2 + \Sigma^{L,T}_V (M, q, T)|^2}
\]

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Freezeout (FO) dilepton rate is related to FO vector meson rate. Most of $\rho$ mesons decay inside medium. But most of $\omega$ and $\varphi$ meson decays take place after FO due to their long life time.

\[ \frac{d N_{ll}^{fo}}{d^4 p} = \frac{\alpha}{3} \left( \frac{e}{g} \right)^2 \frac{m_V}{\Gamma_V} \frac{d N_V^{fo}}{d^4 p} \]

\[ \frac{d N_V^{fo}}{d^4 p} = \frac{g_s^\rho}{4\pi^4} \int_{T_f} d\Sigma_{\mu} p^\mu \text{Im} D_V n_B(p \cdot u) \]
Meson Contribution
$X = \pi, \omega, h_1(1170)$
$a_1(1260), \pi'(1300)$

Baryon Contribution:
$N(1700), N(1720), N(1900)$
$N(2000), N(2080), N(2090)$
$N(2100), N(2190), \Delta(1700), \Delta(1900), \Delta(1905),$ 
$\Delta(1940), \Delta(2000)$

Eletsky, Belkacem, Ellis, Kapusta, 
PRC 64, 035202(2001);
Eletsky, Kapusta, 
PRC 59, 2757(1999)
Rho self energy (2)
Re and Im: meson contribution

Rapp & Gale, PRC 60,024903(1999);

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Rho self energy (3): \( \text{Im } D_\rho \) w/o NN*+NΔ* contribution

The imaginary parts of the in-medium \( \rho \) meson propagators (or in-medium spectral functions) with (thick lines) and without (thin lines) baryonic contributions. The chemical potentials in the PCE EOS are used.

The imaginary part of the propagator is sensitive to temperature, but insensitive to its momentum.


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Im of $\omega$ and $\phi$ propagator

Rapp, Gale, PRC 60,024903(1999);

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T_{eff} as probe to EOS of dense matter
Effective temperature for hadrons and dileptons

The transition region may signal a transition from a hadronic source to a partonic source.

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\[ T_{\text{eff}} = T_0 + M \nu_T^2 \]

NA60, PRL100, 022302(2008); EPJC59, 607(2009)
Transverse flow: slope parameter

\[
\frac{d^4 N}{p_T dp_T M dM d\phi_p} \approx -\frac{\alpha}{2\pi^4} \frac{1}{M^2} \left(1 + \frac{2m^2}{M^2}\right) \sqrt{1 - \frac{4m^2}{M^2}} 
\times \int d^4x \exp \left[\frac{1}{T} \gamma_T M_T \nu_T p_T \cos(\phi_v - \phi_p)\right] K_0 \left(\frac{\gamma_T M_T}{T}\right) \text{Im}\Pi^R
\]

- differential rate
- space-time integral
- transverse fluid velocity
- azimuthal angle of fluid

spectra in transverse momentum and invariant mass

\[
\frac{d^2 N}{m_T dm_T M dM} \sim \sqrt{\frac{T}{\gamma_T}} \sqrt{\frac{m_T + M}{m_T}} \exp \left(-\frac{m_T + M}{T_{eff}}\right)
\]

- slope parameter

\[T_{eff} \sim \begin{cases} 
\frac{T + M^* v_T^2}{T \sqrt{\frac{1 + v_T}{1 - v_T}}}, & \text{for } p_T \ll M \\
\frac{T}{T} \sqrt{\frac{1 + v_T}{1 - v_T}}, & \text{for } p_T \gg M
\end{cases}\]

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Dense or hot QCD matter EOS

Bernard et al, (MILC) PRD 75 (07) 094505,
Cheng et al, (RBC-Bielefeld) PRD 77, 014511(2008);


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Four equations of state (EOS)

Massless ideal QGP

\[ \epsilon = 3p = 16T^4 \]

Resonance Hadron gas

[Braun-Munzinger, Redlich, Stachel, nucl-th/0304013]

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Slope parameter: pt and EOS dependence

\[ T_{eff} \sim T \sqrt{\frac{1+u_T}{1-u_T}} \]

Slope parameter as functions of \( M \) for the mixed phase (left panel) and the lattice (right panel) EOS.


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Parameter dependences of the slope parameter with the lattice EOS. Left panel: the initial time for the hydrodynamic evolution $\tau_0 = 0.2; 0.6$ fm/c. Right panel: the phase transition temperature $T_c = 180, 150$ MeV. $m_T=2.5$ GeV.

Comparison to STAR di-electron data
In-medium and freezeout contribution in full space

Total = Partonic + In-medium hadronic + Freezeout


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Charm quarks in medium: Fokker-Planck-Langevin equation

Fokker-Planck equation describes the momentum diffusion of a heavy quark in medium (Brownian motion)

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p^i} \left[ A(E) p^i f + \frac{\partial}{\partial p^j} \left( B^{ij}(p) f \right) \right]$$

where

$$A(E) = \frac{1}{2E_p} \int \frac{d^3 q}{(2\pi)^3 E_q} f_i(x, q) \int \frac{d^3 p'}{(2\pi)^3 E_{p'}} \int \frac{d^3 q'}{(2\pi)^3 E_{q'}} \left( 1 - \frac{p \cdot p'}{p^2} \right) \times |\mathcal{M}(s)|^2 (2\pi)^4 \delta^4(p + q - p' - q')$$

Svetitsky, PRD37, 2484 (1988)

Scatterings of charm quarks by medium partons:
$$Q(p) + (u,d,s,g)(q) \rightarrow Q(p') + (u,d,s,g)'(q')$$

$$f_i(x, p):$$ distribution of thermal partons

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Scatterings of charm quark by thermal partons: in-medium T-matrix

- Non-perturbative resonance scatterings of heavy quarks by thermal partons \((u,d,s,g)\)
- BS equation \(\rightarrow\) reduce scheme and relativistic correction
- In-medium T-matrix equation for non-perturbative potential inspired by LQCD

van Hees, Mannarelli, Greco, Rapp, PRL100, 192301 ('08)
Riek, Rapp, PRC82, 035201 ('10), Huggins, Rapp, NPA896, 24 ('12)
He, Fries, Rapp, PRC86, 014903 ('12), etc.

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Charm quarks in medium: Fokker-Planck-Langevin equation

Langevin equation describes the phase space change of a heavy quark in medium (test particle method)

\[ dx = \frac{p}{E} dt \]
\[ dp = -\Gamma(E)p dt + \sqrt{2D(E)} dB(t) \]

Drag force    Random force

where

\[ D(E) = E\tau\Gamma(E) \]
\[ \Gamma(E) \approx A(E) \]

\( \Gamma(E) \): relaxation rate
\( D(E) \): diffusion constant

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Hydro-Langevin simulation

PYTHIA: \( pp \rightarrow \) initial heavy quarks

Hydro (2+1)D: \( T(x_i), u_\mu(x_i) \rightarrow \Gamma, D \)

Langevin equation:
\[
(x_i, p_i) \rightarrow (x_{i+1}, p_{i+1})
\]

LRF of fluid cell

\( i \rightarrow i + 1 \)

If \( T(x_{i+1}) < T_{out} \)

Yes

\( (x_{i+1}, p_{i+1}) \rightarrow \) PYTHIA: hadronization + decay

No

van Hees, Mannarelli, Greco, Rapp,
PRL100,192301('08)
Riek, Rapp,
PRC82,035201('10)
Huggins, Rapp,
NPA896,24('12)
He, Fries, Rapp,
PRC86,014903('12)
......
Charm quark relaxation rate

(a) Charm quark relaxation rates as functions of 3-momenta at different temperatures. (b) Charm quark relaxation rates from scatterings by light and strange quarks and gluon. The temperature is set to $T = 294 \text{ MeV}$.


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Di-electrons in pp collisions

The rescaled di-electron cross section from semi-leptonic decays of open charm hadrons in p+p collisions by PYTHIA with the PHENIX detector acceptance. The data are taken from PHENIX

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Electrons from open charm: pt spectra and angular correlation

(a) The angular correlation of charm quark pairs in the initial and final states. The different $<p_T>$ cutoffs are chosen. The freezeout temperature is set to $T_c = 184$ MeV.

(b) The nuclear modification factors with Hydro-Langevin evolution for charm quarks in partonic medium for two values of $<k_T>$ in PYTHIA.

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pt spectra of D0 and R_AA of electron from open charm

(a) The pT spectra and the nuclear modification factor of D0 mesons.  
(b) The nuclear modification factor of electrons from semileptonic decays of charm hadrons. The data are taken from PHENIX.

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The pT spectra of di-electrons from semi-leptonic decays of correlated charm hadrons in the mass range 1.1 < M < 2.5 GeV. The nuclear modification factor of di-electrons is shown in the inset.

The angular correlation of di-electrons from semi-leptonic decays of correlated charm hadrons in the mass range $1.1 < M < 2.5\text{GeV}$.
The invariant mass spectra of di-electrons in comparison with the STAR preliminary data in the most central (0–10%) Au+Au collisions with the STAR detector acceptance.

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• $T_{\text{eff}}$ of di-lepton can serve as a probe to EOS of the dense matter in high energy HIC
• Rho meson self-energy from meson resonances below 1300 MeV and baryon resonances (from $\rho NN^*+\rho N(\Delta,\Delta^*)$ couplings) are taken into account
• In-medium and freezeout contributions are identified.
• Open charm contribution is modeled in Hydro-Langevin simulation with in-medium $T$-matrix
• Comparison with STAR data is made with good agreement
Thanks!