Electromagnetic Probes III

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Outline

1. Dileptons in AA collisions
2. Bulk-medium evolution with transport and coarse graining
   - coarse-graining in UrQMD
3. Dileptons in heavy-ion collisions: Theory vs. experiment
   - Dielectrons (SIS/HADES)
   - Dimuons (SPS/NA60)
   - Dielectrons at RHIC
   - Dielectrons at FAIR/RHIC-BES
4. Signatures of the QCD-phase structure?
5. Flash Talks
6. Quiz
Dileptons in AA collisions
Why Electromagnetic Probes?

- $\gamma, \ell^\pm$: only e.m. interactions
- whole matter evolution

Fig. by A. Drees (from [RW00])
Dilepton and photon production rates

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f$)
- McLerran-Toimela formula (cf. Lecture II)

\[
\Pi^{\leq}_{\mu \nu}(q) = \int d^4 x \exp(iq \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 n_B(q_0) \text{Im} \Pi^{(\text{ret})}_{\mu \nu}(q)
\]

\[
q_0 \frac{dN_\gamma}{d^4 x d^3 \vec{q}} = -\frac{\alpha_{\text{em}}}{2\pi^2} g^{\mu \nu} \text{Im} \Pi^{(\text{ret})}_{\mu \nu}(q, u) \bigg|_{q_0=|\vec{q}|} f_B(p \cdot u)
\]

\[
\frac{dN_{e^+e^-}}{d^4 x d^4 k} = -g^{\mu \nu} \frac{\alpha^2}{3q^2\pi^3} \text{Im} \Pi^{(\text{ret})}_{\mu \nu}(q, u) \bigg|_{q^2=M_{e^+e^-}^2} f_B(p \cdot u)
\]

- manifestly Lorentz covariant (dependent on four-velocity of fluid cell, $u$)
- to lowest order in $\alpha$: $4\pi \alpha \Pi_{\mu \nu} \simeq \Sigma^{(\gamma)}_{\mu \nu}$
- derivable from underlying thermodynamic potential, $\Omega$!
Vector Mesons and chiral symmetry

\[ \text{from [Rap03]} \]

\[ \text{from [Rap05]} \]
Bulk-medium evolution
established transport models for **bulk evolution**
- e.g., UrQMD, GiBUU, BAMPS, (p)HSD,...
- solve Boltzmann equation for hadrons and/or partons
- vacuum cross sections used in collision terms

**dilemma:** need medium-modified dilepton/photon emission rates
usually available only in equilibrium QFT calculations

ways out:
- use (ideal) hydrodynamics ⇒ local thermal equilibrium ⇒ use equilibrium rates
- use transport-hydro hybrid model: treat early stage with transport,
  then coarse grain ⇒ switch to hydro
  ⇒ switch back to transport (**Cooper-Frye “particlization”**)  

**here:** UrQMD transport for entire bulk evolution
⇒ use coarse graining in space-time cells ⇒ extract $T, \mu_B, \mu_\pi, \ldots$
⇒ use equilibrium rates locally

[EHWB15a, EHB16b, EHWB15b, EHB16a]
Coarse-grained UrQMD (CGUrQMD)

- problem with medium modifications of spectral functions/interactions
- only available in equilibrium many-body QFT models
- use “in-medium cross sections” naively: double counting?!?
- way out: map transport to local-equilibrium fluid
- use ensemble of UrQMD runs with an equation of state
- space-time grid with $\Delta t = 0.2 \text{ fm}/c$, $\Delta x = 0.8 \text{ fm}$
- fit temperature, chemical potentials, flow-velocity field from anisotropic energy-momentum tensor [FMRS13]

$$T^{\mu\nu} = (\epsilon + P_\perp) u^\mu u^\nu - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^\mu V^\nu$$

- thermal rates from partonic/hadronic QFT become applicable
- here: extrapolated lattice QGP and Rapp-Wambach HMBT
- caveat: consistency between EoS, matter content of QFT model/UrQMD!
Coarse-grained UrQMD (CGUrQMD)

- $T_c = 170 \text{ MeV}; T > T_c \Rightarrow \text{lattice EoS}; T < T_c \Rightarrow \text{HRG EoS}$
Coarse-grained UrQMD (CGUrQMD)

- pressure anisotropy (for In+In @ SPS; NA60)

![Graph showing the anisotropy parameter x and relaxation function r(x) for In+In collisions at 158 AGeV.](image-url)
Coarse-grained UrQMD (CGUrQMD)

- energy/baryon density ⇒ $T, \mu_B$ (for In+In @ SPS; NA60)
- central “fluid” cell!

![Graph showing energy density and baryon density over time](image)

**Graph (a):**
- In+In @ 158 AGeV
- $<dN_\text{ch}/d\eta>=120$
- Central cell ($x=y=z=0$)

- Energy density $\epsilon/\epsilon_0$ (blue line)
- Baryon density $\rho/\rho_0$ (dashed blue line)

**Graph (b):**
- Lattice EoS
- Hadron Gas EoS
- In + In @ 158 AGeV
- $<dN_\text{ch}/d\eta>=120$
- Central cell ($x=y=z=0$)

- Temperature $T$ (red line)
- Baryon chemical potential $\mu_B$ (green line)
- Pion chemical potential $\mu_\pi$ (dotted blue line)
Coarse-grained UrQMD (CGUrQMD)

- energy ($\varepsilon$) and baryon ($\rho$) density profiles (for In+In@SPS; NA60)

![Diagram of energy and baryon density profiles for In+In@158 AGeV](image)
Dielectrons (SIS/HADES)
- coarse-graining method works at low energies!
- UrQMD-medium evolution + RW-QFT rates
dielectron spectra from $\text{Ar} + \text{KCl}(1.76 \text{ AGeV}) \rightarrow e^+e^-$ (SIS/HADES)

$m_t$ spectra

$M_{ee} < 0.13 \text{ GeV}$
dielecotron spectra from Ar + KCl (1.76 AGeV) → e⁺e⁻ (SIS/HADES)

- $m_t$ spectra
- 0.13 GeV $M_{ee} < 0.3$ GeV
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

- dielectron spectra from Ar + KCl(1.76 AGeV) → e⁺e⁻ (SIS/HADES)
- $m_t$ spectra
- 0.3 GeV $M_{ee} < 0.45$ GeV
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

- dielectron spectra from Ar + KCl(1.76 AGeV) → e⁺e⁻ (SIS/HADES)
- $m_t$ spectra
- 0.45 GeV $M_{ee} < 0.65$ GeV
- dielectron spectra from Ar + KCl (1.76 AGeV) → e⁺e⁻ (SIS/HADES)
- $m_t$ spectra
- $M_{ee} > 0.65$ GeV
CGUrQMD: Ar+KCl (1.76 AGeV) (SIS/HADES)

- dielectron spectra from Ar + KCl(1.76 AGeV) → e⁺e⁻ (SIS/HADES)
- \(m_t\) spectra
- rapidity spectrum (\(M_{ee} < 0.13\) GeV)
good agreement between models and data

consistency between two independent coarse-grained-UrQMD simulations

based on same Rapp-Wambach in-medium rates
Dimuons (SPS/NA60)
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158 \text{ AGeV}) \rightarrow \mu^+ \mu^-$ (NA60) [EHWB15b]
- min-bias data ($dN_{\text{ch}}/dy = 120$)

![Graph showing dimuon spectra from In+In collisions at 158 AGeV.](image)

For comparison: In+In @ 158 AGeV
HG-EoS + Lattice EoS

- In-medium $\rho$
- Non-thermal $\rho$
- QGP (Lattice)
- Multi $\pi$
- Sum

For comparison:
- Thermal $\rho$
- (no baryons)
- Perturb. $q\bar{q}$
dimuon spectra from $\text{In + In}(158\text{ AGeV}) \rightarrow \mu^+ \mu^-$ (NA60) [EHWB15b]

- min-bias data ($dN_{ch}/dy = 120$)
- higher IMR: provides averaged true temperature
  \[ \langle T \rangle_{1.5\text{ GeV} \leq M \leq 2.4\text{ GeV}} = 205-230 \text{ MeV} \]
- clearly above $T_c \simeq 150-160 \text{ MeV}$
  (no blueshifts in the invariant-mass spectra!)
dimuon spectra from $\text{In} + \text{In}(158\,\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15b]

- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $p_T < 0.2\,\text{GeV}$
dimuon spectra from \( \text{In} + \text{In}(158 \text{ AGeV}) \rightarrow \mu^+ \mu^- \) (NA60) [EHWB15b]

- min-bias data \( (dN_{\text{ch}}/dy = 120) \)
- \( 0.2 \text{ GeV} < p_T < 0.4 \text{ GeV} \)
dimuon spectra from In+In(158 AGeV) → μ⁺μ⁻ (NA60) [EHWB15b]
min-bias data (dN_{ch}/dy = 120)
0.4 GeV < p_T < 0.6 GeV
dimuon spectra from $\text{In} + \text{In}(158\,\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60) [EHWB15b]

- min-bias data ($dN_{\text{ch}}/dy = 120$)
- $0.6\,\text{GeV} < p_T < 0.8\,\text{GeV}$
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60) [EHWB15b]
- min-bias data (dN_{ch}/dy = 120)
- 0.8 GeV < p_T < 1.0 GeV
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60) [EHWB15b]
- min-bias data (dN_{ch}/dy = 120)
- 1.0 GeV < p_T < 1.2 GeV

![Graph](image-url)
dimuon spectra from In + In(158 AGeV) → \(\mu^+\mu^-\) (NA60) [EHWB15b]

- min-bias data (\(dN_{\text{ch}}/dy = 120\))
- \(1.2 \text{ GeV} < p_T < 1.4 \text{ GeV}\)
**CGUrQMD: In+In (158 AGeV) (SPS/NA60)**

- dimuon spectra from $\text{In} + \text{In} (158 \text{ AGeV}) \rightarrow \mu^+ \mu^- \ (\text{NA60})$ [EHWB15b]
- min-bias data $(dN_{\text{ch}}/dy = 120)$
- $1.4 \text{ GeV} < p_T < 1.6 \text{ GeV}$

![Graph showing dimuon spectra](image-url)
• dimuon spectra from In + In (158 AGeV) → μ^+ μ^- (NA60) [EHWB15b]
• min-bias data (dN_{ch}/dy = 120)
• 1.6 GeV < p_T < 1.8 GeV
dimuon spectra from In + In(158 AGeV) → \( \mu^+ \mu^- \) (NA60) [EHWB15b]
min-bias data (dN_{ch}/dy = 120)
1.8 GeV < \( p_T \) < 2.0 GeV
dimuon spectra from In + In(158 AGeV) → µ⁺µ⁻ (NA60) [EHWB15b]
min-bias data (dN_{ch}/dγ = 120)
2.0 GeV < p_T < 2.2 GeV
dimuon spectra from In+In(158 AGeV) → \( \mu^+ \mu^- \) (NA60) [EHWB15b]
min-bias data \((dN_{\text{ch}}/dy = 120)\)
2.2 GeV < \( p_T \) < 2.4 GeV
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- Dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60) [EHWB15b]
- Min-bias data (dN_{ch}/dy = 120)

### (a) In+In @ 158 AGeV

HG-EoS + Lattice EoS

<\text{d}N_{ch}/\text{d}\eta> = 120

**0.2 < M < 0.4 \text{ GeV}**

- In-medium \(\rho\)
- Non-thermal \(\rho\)
- QGP (Lattice)
- Multi \(\pi\)
- Sum

\(1/(m)\text{d}N^2/\text{d}m/d\eta\) [GeV⁻²]
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → $\mu^+\mu^-$ (NA60) [EHWB15b]
- min-bias data ($dN_{ch}/dy = 120$)
- dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60) [EHWB15b]
- min-bias data (dN_{ch}/dy = 120)
dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60) [EHWB15b]
min-bias data (dN_{ch}/dy = 120)
Dielectrons at RHIC
CGUrQMD: Au+Au ($\sqrt{s}_{NN} = 200$ GeV) (RHIC/STAR)

Coarse-grained UrQMD
- $\rho$
- $\pi_0$
- $\eta$
- $\omega$
- $\phi$
- $\rho$ (fo)
- $\omega$ (fo)

STAR data

$\rho_T^e > 0.2$ GeV/c
$|\eta^e| < 1$, $|y_{ee}| < 1$

$M_{ee}$ [GeV/c$^2$]

$dN/dM_{ee}$ [1/(GeV/c$^2$)]

$|p_T^e| > 0.2$ GeV/c
$|\eta^e| < 1$, $|y_{ee}| < 1$

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Electromagnetic Probes III
June 24-29, 2017 22 / 47
CGUrQMD: Au+Au ($\sqrt{s}_{NN} = 200$ GeV) (RHIC/PHENIX)

![Graph showing Au+Au collisions at $\sqrt{s}_{NN} = 200$ AGeV (0-10% centr.)](image)

**Legend:**
- $p_T^e > 0.2$ GeV/c
- $|y^e| < 1$, $\Theta_{ee} > 0.1$ rad
- PHENIX HBD data
- Coarse-grained UrQMD
- Rapp in-med $\rho$
- Rapp in-med $\omega$
- Multi-pion
- QGP (Lattice)
- $\pi_0$
- $\eta$
- $\omega$ (fo)
- $\rho$ (fo)
- $\phi$
Dielectrons at RHIC-BES/FAIR/NICA
CGUrQMD: Au+Au \((E_{\text{lab}} = 2-35\text{ AGeV})\)

NB: also photon spectra \([\text{EHB16b}]\)
Signatures of the QCD-phase structure?
hadronic observables like $p_T$ spectra: “snapshot” of the stage after kinetic freezeout

particle abundancies: chemical freezeout

em. probes: emitted during the whole medium evolution life time of the medium ⇒ “four-volume of the fireball”

use CGUrQMD to study system-size dependence

study $AA$ collisions for different $A$ [EHWB15b]

“excitation functions”: systematics of $\ell^+\ell^-$ (and $\gamma$) emission vs. beam energy [EHB16b, RH16]

similar study in [GHR+16]

caveat: phase transition not really implemented!!!
central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76$ AGeV

$$\frac{V_{\text{AA}}^{(4)}/A}{V_{\text{CC}}^{(4)}/12}$$ of cells larger than various $T$

how to explain “scaling behavior”?
Lifetime of the central cell

- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76 \text{ AGeV}$

\[ \Delta t \propto A^{1/3} \]

\[ A \propto V^{(3)} \text{ of nuclei} \Rightarrow A^{1/3} \propto d_{\text{nucl}} \]

fireball lifetime $\propto$ time of nuclei to traverse each other
Lifetime of the central cell

- Central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76 \, A\text{GeV}$
- $\frac{\text{yield}_{AA}/A}{\text{yield}_{CC}/12}$

![Graph showing the yield as a function of mass number A.](a)

- $\text{yield}_{\text{had}} \propto A \propto V_{\text{fo}}^{(3)}$
- $\text{yield}_{\text{non-thermal ee}} \propto A \propto V_{\text{fo}}^{(3)}$
- $\Rightarrow$ Hadronic decays after kinetic freeze-out
Scaling behavior of thermal-dilepton yield

- central collisions from C+C to Au+Au at $E_{\text{kin}} = 1.76 \text{ AGeV}$

- thermal-dilepton yield roughly $\propto V_{\text{therm}}^{(4)} \propto A^{4/3} \propto A_{\text{therm}} \propto N^{4/3}_{\pi^0}$

- at low(est) beam energies:
  - lifetime of “medium” $\hat{=}\text{ time nuclei pass through each other}$
Dilepton systematics in the beam-energy scan

- $T$ and $\mu_B$ vs. $t$ [EHB16b, EHB16a]

![Graph showing dilepton systematics in Au+Au collisions at 19.6 and 200 GeV](image)

**UrQMD**

**Coarse-graining**

**STAR data**
Dilepton systematics in the beam-energy scan

thermal four-volume (fm$^4$) [EHB16b, EHB16a]
Dilepton systematics in the beam-energy scan

- $T$ and $\mu_B$ vs. $t$ [EHB16b, EHB16a]
Dilepton systematics in the beam-energy scan

- $\mu_{\pi/K}$-temperature relation \cite{EHB16b, EHB16a}

![Graph showing $\langle \mu_{\pi/K} \rangle$ vs. temperature for Au+Au (0-10% centr.) at 4, 15, and 35 AGeV.]
Dilepton systematics in the beam-energy scan

- mass-temperature relation in dilepton emission [EHB16b, EHB16a]
Dilepton systematics in the beam-energy scan

- excitation function $e^+ e^- / \gamma$ yield and QGP fraction [EHB16b, EHB16a]

(a) Thermal Dilepton Yield
- $M_{ee} < 0.3$ GeV/c$^2$
- $0.3 < M_{ee} < 0.6$ GeV/c$^2$
- $M_{ee} > 1.0$ GeV/c$^2$

(b) Fraction of QGP emission
- $\mu_x = \mu_K = 0$
- $0.5 < p_t < 1.0$ GeV/c
- $p_t > 1.0$ GeV/c
- $M_{ee} < 0.3$ GeV/c$^2$
- $0.3 < M_{ee} < 0.6$ GeV/c$^2$
- $M_{ee} > 1.0$ GeV/c$^2$
Dilepton systematics in the beam-energy scan

- thermal-fireball model \([\text{RH16, EHB16a}]\)
- invariant-mass slope in IMR ⇒ true temperature!
- no blue shift from radial flow as in \(p_T/m_T\) spectra

![Central AA Collisions](image)

- \(T_s\) (M=1.5-2.5 GeV)
- \(T_i\)

\(T\) (MeV) vs. \(s^{1/2}\) (GeV)
Dilepton systematics in the beam-energy scan

- excitation function $e^+ e^- / \gamma$ yield and QGP fraction [EHB16b, EHB16a]
Dilepton systematics in the beam-energy scan

- thermal-fireball model \[\text{RH16}\]
- beam-energy scan at RHIC and lower energies at future FAIR and NICA accelerators
- dilepton yield as fireball-lifetime clock

\[
\frac{N_{\ell^+\ell^-}}{N_{\text{ch}} \cdot 10^6} = \tau_{\text{fb}} / (\text{fm/c})
\]

\[\sum_{\text{hadronic QGP}} \times 3.75 \]

\[
0.3 \text{GeV} < M < 0.7 \text{GeV}
\]


http://dx.doi.org/10.1007/BF02705167

http://arxiv.org/abs/nucl-th/0409054

http://dx.doi.org/10.1016/j.physletb.2015.12.065

http://dx.doi.org/10.1007/0-306-47101-9_1
Flash Talks
What is the “coarse-graining approach” to model the bulk-medium evolution and why do we need it?
(slides 8-13, [EHWB15a])

What's making the medium at GSI-SIS energies and how can one try to observe it probably in experiment?
(slides 28-31, [EHWB15b])

Why gives the slope of the $M_{\ell^+\ell^-}$ spectrum (integrated over all $p_T$) a true temperature, while (transverse-)momentum spectra of dileptons and photons don't?
[HR08] (Sect. 5.2)

In which sense may dileptons provide a clock and thermometer of the fireball?
(Slides 38-40, [RH16])
Quiz
1. What's the problem with using transport models to describe the bulk-medium evolution for predicting dilepton and photon production in heavy-ion collisions?

2. What are ways out of this problem?

3. What's the “coarse-graining method” and how can it be used for bulk-medium evolution simulations?

4. What's an equation of state and what means that it is compatible with a transport model?

5. How can dileptons help to measure the “true space-time-weighted average” of the fireball temperature?