Thermal dileptons as Fireball Probes at SIS Energies

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Electromagnetic probes in heavy-ion collisions

Experiments across the QCD phase diagram

Search for

- phase boundary(ies)
  - fluctuations of conserved quantum numbers
  - flavor production (multi-strange, charm)

- change in microscopic degrees of freedom

- restoration of chiral symmetry

- emitting source temperature
  - electromagnetic probes leave collision zone undistorted
  - real $\gamma$ characterized by transverse momentum
  - dileptons carry extra information: invariant mass

Electromagnetic probes in heavy-ion collisions

CBM cocktail – invariant mass of dielectrons

dilepton spectra reflect the whole history of a collision

necessary ingredients:
- realistic emission rates
- accurate description of fireball evolution
Electromagnetic probes in heavy-ion collisions

Insights from theory

- integrated yield of thermal radiation in the mass range 0.3-0.7 GeV/c² is sensitive to the lifetime of the fireball
  

- dilepton yield determined by interplay between temperature and fireball volume

- slope of dileptons in the intermediate-mass range constitutes a blue-shift free fireball thermometer

- What happens at low energies?
Realistic dilepton emission rates

8-differential thermal production rate

\[ \frac{dN_{\ell\ell}}{d^4xd^4q} = -\frac{\alpha_{EM}^2}{\pi^3 M^2} f_B(q \cdot u; T) \text{Im}\Pi_{EM}(M, q; \mu_B, T) \]

\[ R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \propto \text{Im}\Pi_{EM}^{\text{vac}}(M) \]

\[ \text{Im}\Pi_{EM}^{\text{vac}}(M) = \sum_{v=\rho,\omega,\phi} \left( \frac{m_v^2}{g_v} \right)^2 \text{Im}D_v^{\text{vac}}(M), \quad M < M_{\text{dual}}^{\text{vac}} \simeq 1.5 \text{ GeV}/c^2 \]

\[ -\frac{M^2}{12\pi} \left( 1 + \frac{\alpha_s(M)}{\pi} + \ldots \right) N_c \sum_{q=u,d,s} (e_q)^2, \quad M > M_{\text{dual}}^{\text{vac}} \]
Realistic dilepton emission rates

The $\rho$ meson in nuclear matter

The $\rho$ spectral function strongly broadens in the medium as the $\rho$ meson couples to baryons!

$$D_\rho (M,q;\mu_B,T) = \left[ M^2 - m^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M} \right]^{-1}$$

This formula represents the spectral function of the $\rho$ meson in a medium with baryon density $\rho_B$, temperature $T$, and quark momentum $q$.


Additional contributions to the $\rho$ meson self-energy in the medium.
Realistic dilepton emission rates

Hadronic matter

- parameterization of Rapp-Wambach in-medium $\rho$ spectral function


  depends on

  - temperature $T$
  - effective baryon density $\rho_{\text{eff}}$
  - pion chemical potential $\mu_{\pi}$

  \[ \rho_{\text{eff}} = \rho_N + \rho_{\bar{N}} + \frac{1}{2} (\rho_R + \rho_{\bar{R}}) \]

- reproduces excess in experimental data

  - CERES
  - NA60
  - STAR (including BES)
  - PHENIX with HBD

- at higher masses: include hadronic continuum radiation

  E. V. Shuryak: Rev. Mod. Phys. 69 (1993) 1
Space-time evolution of a heavy-ion collision

Au+Au at 1.23 AGeV ($\sqrt{s_{NN}} = 2.4$ GeV) → HADES energy regime
Description of the fireball evolution

Coarse-graining of hadronic transport

- “combine” the advantages of both descriptions: hydrodynamics & transport
- simulate events with a transport model
  - ensemble average to obtain smooth space-time distributions
- divide space-time evolution into 4-dimesional cells
  - 21 x 21 x 21 space cells (1fm³), 30 time steps \( \rightarrow \approx 280 \text{ k cells} \)
- determine for each cell the bulk properties like \( T, \rho_B \& v_{\text{coll}} \)
- calculate dilepton rates based on these inputs
  - parameterization of RW in-medium spectral function
- sum up the contributions of all cells
- similar approaches by
Determination of bulk properties

(Baryon) density, collective flow velocity & temperature

- baryon density via 4-current
- Lorentz-boost to local rest frame (LRF) where the baryon current vanishes

- in Boltzmann approximation
  \[
  \frac{d^3 N}{d\vec{p}} = \frac{d^3 N}{dp_z \, p_t \, dp_t \, d\theta} \propto \exp(-E/T) \\
  \frac{1}{m_t^{3/2}} \frac{dN}{dm_t} \propto \exp(-m_t/T)
  \]

- fill \( m_t \) spectra with particle momenta in LRF (mean flow \( v_{\text{coll}} \) vanishes)
- fit exponential function to extract \( T \) (species of choice: pions)
Out of chemical equilibrium?

Build-up of effective chemical potentials

- thermal emission rates assume chemical equilibrium
- chemical non-equilibrium possible, e.g. after chemical freeze-out
  - no more inelastic interactions → pion number conserved
  - system in thermal equilibrium cools down further → over-population of pions
  - build-up of an effective chemical potential $\mu_\pi$
- induces a factor $\left(z_\pi\right)^\kappa$ in the dilepton rates with the fugacity $z = \exp\left(\frac{\mu_\pi}{T}\right)$
  - exponent $\kappa$ reflects the main production mechanism of $\rho$ mesons
  - at HADES energies UrQMD suggests $\kappa = 1.12$
Time-evolution

Au+Au at 1.23 AGeV

- evolution of $T$, $\rho_{\text{eff}}$ and $\mu_{\pi}$ in the central cube of 7x7x7 cells
- trajectories of the cells in the temperature-density plane
Dileptons as fireball probes

**Au+Au at 1.23 AGeV**

- Time evolution of cumulative dilepton yield in mass window $M = 0.3\text{--}0.7$ GeV/$c^2$
- Active radiation window $\sim 13$ fm/c follows build-up of collective medium flow $\rightarrow$ fireball lifetime
- Strong medium effects on $\rho$-meson $\rightarrow$ remarkably structure-less low-mass spectrum
- $dR_\|/dM \propto (MT)^{3/2} \exp(-M/T)$
- Inverse slope parameter: $T_S = 88 \pm 5$ MeV in IMR, $T_S = 64 \pm 5$ MeV in LMR

![Graphs showing time evolution and mass spectrum of dileptons](image)

Dileptons as fireball probes

Ar+KCl at 1.76 AGeV ($\sqrt{s_{NN}} = 2.6$ GeV)

- evolution of $T$, $\rho_{\text{eff}}$ and $\mu_\pi$ in the inner cube of 5x5x5 cells
- invariant mass spectrum for the thermal radiation
- window for dilepton radiation & build-up of collectivity $\sim 8$fm/c
Excitation function of dilepton production

Yield in low-mass window tracks fireball lifetime

- fireball dominated by incoming nucleons at lower energies
- number of charged particles $N_{\text{ch}}$ not a good proxy for thermal excitation energy
- normalization to number of charged pions $N_{\pi}$
- lifetime from dilepton yield in mass window 0.3-0.7 GeV/c$^2$: $\frac{N_{l^+l^-} \cdot 10^6 \approx 1.45 \cdot \tau_{\text{fb}}}{N_{\pi^\pm}}$
Comparison to experimental excess spectra

Ar+KCl at 1.76 AGeV & Au+Au at 1.23 AGeV (min. bias)
Exploring the QCD phase diagram –

with dileptons

- chemical freeze-out from measured particle yields analyzed with SHM THERMUS 2.3
- trajectories extracted from inner cube of cells with coarse-grained UrQMD
- time-window of dilepton emission
  - radiation stops shortly after chemical freeze-out
  - access to hot and dense stage of the heavy-ion collision

ArKCl 1.76A GeV
preliminary AuAu 1.23A GeV

Ar+KCl 1.76A GeV
preliminary Au+Au 1.23A GeV

$\langle qq \rangle_{T, \mu}$

$\langle qq \rangle_{T=0, \mu=0}$

B.J. Schaefer and J. Wambach
Exploring the QCD phase diagram –
– with dileptons

- NA60 intermediate mass $\mu^+\mu^-$
- trajectories at SIS18
- trajectories at SIS100

$< qq >_{T, \mu} < qq >_{T=0, \mu=0}$

: B.J. Schaefer and J. Wambach

Summary

- dileptons are excellent fireball probes
  - thermometer & chronometer
  - new insights into the matter created under extreme conditions

- thermal dilepton spectra from highest to lowest energies
  - realistic thermal dilepton emission rates
  - accurate description of fireball evolution in terms of $T$, $\rho_{\text{eff}}$, $v_{\text{coll}}$ and $\mu_{\pi}$
  - coarse-graining of hadronic transport at SIS energies

- baseline for future experimental explorations
  - any significant deviation can indicate new physics!
Outlook

- future HADES measurements in Ag+Ag at 1.67A GeV

- STAR took ~ 4B events of Au+Au at $\sqrt{s_{NN}} = 200$ GeV in 2014 / 2016 with the Heavy Flavor Tracker (HFT)
  - understand $c\bar{c} \rightarrow X + e^{+}e^{-}$ contribution to the intermediate-mass range
  - extract fireball temperature & low-mass excess

- future STAR measurements with Au+Au at $\sqrt{s_{NN}} = 53.5$ GeV, the isobar run (Ru+Ru and Zr+Zr) in 2018 and BES II in 2019 / 2020

- future high precision measurements with CBM at SIS 100
Local thermalization

Momentum distributions of nucleons ($n_{\text{coll}} \geq 3$) & evolution of $n_{\text{coll}}$

- Gaussian shaped $p_z$ distribution builds up for nucleons with $n_{\text{coll}} \geq 3$
- $m_t$ spectra have exponential shape
- check for every cell: deviations are kept in space-time evolution
Interplay temperature – fireball volume

Au+Au at 1.23 AGeV
Excitation function of hadron yields

A. Andronic, arXiv:1407.5003
Virtual photon radiation from hot and dense QCD matter

highly interesting results from RHIC, SPS, SIS18
→ lepton pairs as true messengers of the dense phase
**HADES at GSI, Darmstadt**

- Fixed target

- 50 kHz event rate (400 Mbyte/s peak data rate)

- Full azimuthal coverage, 18° to 85° in polar angle

- Hadron and lepton identification:
  - Tracking with 4x6 Multiwire Drift Chambers and superconducting magnet
  - Time of flight measurement with ToF and RPC Walls
  - Specific energy loss in MDC and ToF
  - RICH and shower detectors to identify leptons
CBM at the future FAIR facility, Darmstadt

- QCD matter equation of state at neutron star core densities studied in heavy-ion collisions
  - Observable: collective phenomena in charged particle phase space distributions

- restoration of chiral symmetry ($\rho$-$a_1$ mixing) observed in heavy-ion collisions
  - Observable: yield of intermediate mass lepton pairs

- evidence for a first order phase transition in QCD matter
  Observables:
  - excitation function of temperatures measured with intermediate mass dileptons
  - excitation function of the yield of multi-antistrange hyperons

- extension of the nuclear chart into the strange sector

CBM Collab., EPJA 53 (2017) 60
STAR at RHIC

- TPC: PID through dE/dx
- TOF: PID through 1/β
- HFT: good DCA resolution ~ 35 μm @ 1 GeV/c (p)
Dileptons

Invariant-mass spectrum

**Invaraint-mass excess spectrum**

**LMR:**
- broadening of $\rho$-spectral function
  - larger excess in support of the decisive role of baryon interactions, will get maximal at low energies (HADES)
  - linked to the chiral symmetry restoration (yet in model dependent way!)
- measure excitation function of $\rho$-spectral function
  - critical point?
  - first order phase transition?

**IMR:**
- $\rho$-$a_1$ chiral mixing $\rightarrow$ signal for $\chi$-symmetry restoration
- onset of QGP radiation
- measure:
  - $\pi a_1 \rightarrow e^+ e^- (\mu^+ \mu^-)$ dominant source at SIS 100 energies (correlated charm, Drell-Yan and QGP contributions decrease with lower the beam energy)
    - direct access to $\rho$-$a_1$ chiral mixing
  - decrease of $T$ for lower beam energies (R.Rapp, arXiv:1411.4612v1 [hep-ph])
    - plateau around onset of deconfinement?

Model: van Hees + Rapp, 2013
Determination of bulk properties

Temperature

- in Boltzmann approximation
  \[ \frac{d^3N}{d\vec{p}} = \frac{d^3N}{dp_z p_t dp_t d\theta} \propto \exp(-E/T) \]

  changing from \( p_t \) to \( m_t \) and from \( p_z \) to \( y \)
  & integrating over the angles yields
  \[ \frac{d^2N}{dy dm_t} \propto 2\pi m_t E \exp(-E/T) \]

  integrating over rapidity yields
  \[ \frac{dN}{dm_t} \propto 2\pi m_t^2 \cdot 2K_1 \left( \frac{m_t}{T} \right) \]

  approximating the Bessel function for large arguments
  \[ \frac{dN}{dm_t} \propto 2\pi m_t^2 \cdot 2 \left( \frac{T}{m_t} \right)^{1/2} \exp(-m_t/T) \]

  \[ \frac{1}{m_t^{3/2}} \frac{dN}{dm_t} \propto \exp(-m_t/T) \]

- subtract mean flow of the cells from particle motion
- fill \( m_t \) spectra & fit exponential function to extract \( T \)
- use different fit ranges to get the systematics
Out of chemical equilibrium?

Derivation of the effective chemical potentials

- particle density in Boltzmann approximation
  \[ n = \frac{g}{(2\pi)^3} \int_{\mathbb{R}^3} d^3\vec{p} \exp(-\beta (E - \mu)) \]

- moving fugacity \( z \) in front of the integral & integrating over the angles
  \[ n = \frac{4\pi g}{(2\pi)^3} z \int_0^\infty dp \, p^2 \exp(-\beta \sqrt{p^2 + m^2}) \]

- carrying out the momentum integral yields
  \[ n = \frac{4\pi g m^3}{(2\pi)^3} z \frac{1}{\beta m} K_2(\beta m) \]

- solving for the chemical potential results in
  \[ \mu = T \ln \left( \frac{2\pi^2 n (\hbar c)^3}{g T m^2 K_2\left(\frac{m}{T}\right)} \right) \]
Final-state pion cocktail

PID of mother particle

- 90% (95%) of pions are emitted before 30 (40) fm/c
Final-state pion spectra

- Dominant contribution: $\Delta(1232)$ decays (cyan)
- Many more resonances contribute especially at higher $p_T$
Final-state pion spectra: density dependent

\[ \frac{\rho}{\rho_0} < 0.1 \text{ at emission or } t_{\text{emission}} > 30\text{fm/c} \]
Final-state pion spectra: density dependent

\[ \rho/\rho_0 < 0.5 \text{ at emission or } t_{\text{emission}} > 30\text{fm}/c \]

\[ \sim 50\% \text{ of all } \pi \]
Final-state pion spectra: density dependent

$\rho/\rho_0 > 1$ at emission

$\rho/\rho_0 > 1$ at emission