A Theoretical View on Dilepton Production
Transport Calculations vs. Coarse-grained Dynamics

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Overview

1. Introduction

2. Transport Calculations and their Difficulties

3. Coarse Grained Transport Approach

4. First Results

5. Outlook
Why Dileptons...?

- Dileptons represent a clean and penetrating probe of hot and dense nuclear matter
- Reflect the whole dynamics of a collision
- Once produced they do not interact with the surrounding matter (no strong interactions)
- Aim of studies
  - In-medium modification of vector meson properties
  - Chiral symmetry restoration
Ultra-relativistic Quantum Molecular Dynamics

- Hadronic non-equilibrium transport approach
- Includes all baryons and mesons with masses up to 2.2 GeV
- Two processes for resonance production in UrQMD (at low energies)
  - Collisions (e.g. $\pi\pi \rightarrow \rho$)
  - Higher resonance decays (e.g. $N^* \rightarrow N + \rho$)
- Resonances either decay after a certain time or are absorbed in another collision (e.g. $\rho + N \rightarrow N_{1520}^*$)
- No explicit in-medium modifications!

<table>
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<tr>
<th>Resonance</th>
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Dilepton sources in UrQMD

- **Dalitz Decays**
  \[ \pi^0, \eta, \eta', \omega, \Delta \]
  \[ P \rightarrow \gamma + e^+ e^- \]
  \[ V \rightarrow P + e^+ e^- \]

- **Direct Decays**
  \[ \rho^0, \omega, \phi \]

- Dalitz decays are decomposed into the corresponding decays into a virtual photon and the subsequent decay of the photon via electromagnetic conversion.

- Form factors for the Dalitz decays are obtained from the **vector-meson dominance** model.

- Assumption: Resonance can continuously emit dileptons over its whole lifetime (Time Integration Method / “Shining”)

\[ V \rightarrow \gamma \]
\[ e^- (\mu^-) \]
The Resonance ”Mess”

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<tr>
<th>Resonance</th>
<th>Mass</th>
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<th>$N\eta$</th>
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</table>

- Which **resonances** do I have to include?
- Which resonance is produced with which probability?
- What is the actual **branching ratio** (e.g. to the $\rho$)?
- Many parameters one can ”play” with, as they are not fixed...
# N*/Δ* → Nρ Branching Ratios

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<th>KSU12</th>
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<td>21(4)</td>
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<td>73</td>
<td>1.4(5)</td>
<td>87(5)</td>
<td>10(13)</td>
<td>47.5(21.5)</td>
<td>77.5(7.5)</td>
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<td>5</td>
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<tr>
<td><strong>Δ(1905)5/2⁺</strong></td>
<td>87</td>
<td>80</td>
<td>&lt;6</td>
<td>86(3)</td>
<td>42(8)</td>
<td>&gt;60</td>
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</table>

*Partial courtesy of Piotr Salabura, Sept 2013*
Example: Exclusive Resonance Cross-Sections
Transport Results

- p+p Results look quite nice after adjusting resonance production and branching ratio
We see an excess in heavy-ion collisions (e.g. Ar+KCl @ 1.76 AGeV) not yet described by the model.
Transport Results

- At low energies around $E_{kin} = 1 \text{ GeV}$, a pure transport description becomes difficult as well.
- Processes like $NN$ and $\pi N$ bremsstrahlung become dominant, especially for $p+n$ interactions (How avoid double counting?)
- $\Delta$ form factor? Which / how to determine?

**p+p @ 1.25 GeV**

HADES Acceptance

$\theta_{ee} > 9^{\circ}$, $0.05 < p_e < 1.8 \text{ GeV/c}$

**C+C @ 1 AGeV**

HADES Acceptance

$\theta_{ee} > 9^{\circ}$, $0.0 < p_e < 2.0 \text{ GeV/c}$
The Transport Status Quo

- There has been a lot of **improvement**, especially concerning the exact comparison and adjustment of the many parameters, cross-sections, branching ratios (compare GiBUU results by Janus)
- However, this is a **hard job** and one has to be careful
- Still the models show big differences in some details
Challenges

- Cross-sections not implemented explicitly but intermediate baryonic resonances are used.
- Some cross-sections are even unmeasured or unmeasurable (especially for $\rho$ and $\Delta$ lack of data).
- General difficulties of the transport approach at high density:
  - Off-shell effects
  - Multi-particle collisions

⇒ How can we avoid these problems?
Coarse Graining

- We take an ensemble of UrQMD events and span a grid of small space time cells.
- For those cells we determine baryon and energy density and use Eckart’s definition to determine the rest frame properties $\rightarrow$ use EoS to calculate $T$ and $\mu_B$
- For the Rapp Spectral function, we also extract pion and kaon chemical potential via simple Boltzmann approximation
- At SIS, an equation of state for a free hadron gas without any phase transition is used $[D. Zschiesche et al., Phys. Lett. B547, 7 (2002)]$
- A Chiral EoS is used for the NA60 calculation (including chiral symmetry restoration and phase transition) $[J. Steinheimer et al., J. Phys. G38 (2011)]$
Dilepton Rates

- Lepton pair emission is calculated for each cell of 4-dim. grid, using thermal equilibrium rates per four-volume and four-momentum from a bath at $T$ and $\mu_B$.

- The $\rho$ dilepton emission (similar for $\omega$, $\phi$) of each cell is accordingly calculated using the expression

$$
\frac{d^8N_{\rho \rightarrow ll}}{d^4x d^4q} = -\frac{\alpha^2 m^4}{\pi^3 g_\rho^2} \frac{L(M^2)}{M^2} f_B(q_0; T) \text{Im} D_\rho(M, q; T, \mu_B)
$$

- The $4\pi$ lepton pair production can be determined from the electromagnetic spectral function extracted in $e^+e^-$ annihilation

$$
\frac{d^8N_{4\pi \rightarrow ll}}{d^4x d^4q} = \frac{4\alpha^2}{(2\pi)^2} e^{-q_0/T} \frac{M^2}{16\pi^3 \alpha^2} \sigma(e^+e^- \rightarrow 4\pi)
$$

- QGP contribution is evaluated according to Cleymans et al.

$$
$$

$$

$$
Eletsky Spectral Function

- In-medium self energies of the $\rho$

\[ \Sigma_\rho = \Sigma^0 + \Sigma^{\rho\pi} + \Sigma^{\rho N} \]

were calculated using empirical scattering amplitudes from resonance dominance

[V. L. Eletsky et al., Phys. Rev. C64, 035303 (2001)]

- For $\rho N$ scattering $N^*$ and $\Delta^*$ resonances from Manley and Saleski

- Additional inclusion of the $\Delta_{1232}$ and the $N_{1520}$ subthreshold resonances

$\Rightarrow$ Important, as they significantly contribute!
Rapp Spectral Function

- Includes finite temperature propagators of $\omega$, $\rho$ and $\phi$ meson
  

- Medium modifications of the $\rho$ propagator
  
  $$D_\rho \propto \frac{1}{M^2 - m_\rho^2 - \Sigma^{\rho\pi\pi} - \Sigma^{\rho M} - \Sigma^{\rho B}}$$

  include interactions with pion cloud with hadrons ($\Sigma^{\rho\pi\pi}$) and direct scatterings off mesons and baryons ($\Sigma^{\rho M}$, $\Sigma^{\rho B}$)

- Pion cloud modification approximated by using effective nucleon density
  
  $$\rho_{\text{eff}} = \rho_N + \rho_{\bar{N}} + 0.5(\rho_{B^*} + \bar{B}^*)$$
Previous calculations were done with a fireball model

The zone of hot and dense matter is described by an isentropic expanding cylindrical volume

\[ V_{FB}(t) = \pi \left( r_{\perp,0} + \frac{1}{2} a_{\perp} t^2 \right)^2 \left( z_0 + v_{z,0} t + \frac{1}{2} a_z t^2 \right) \]

**Problem**: How to choose parameters? Is it a plausible description or a too simple picture?

⇒ Make calculations with better constrained input...
The UrQMD input we use gives a more and realistic and nuanced picture of the collision evolution.

Energy and baryon density are by no means homogeneous in the whole fireball ⇒ Different expansion dynamics might lead to significantly differing dilepton spectra.
Temperature and Chemical Potential from Coarse Graining

- For a central cell in an Au+Au collision @ 1.25 AGeV we get very high $\mu_B$ up to 1000 MeV and a maximum temperature of $\approx 100$ MeV
- For In+In at NA60 energy, the baryon density decreases very fast after the start of the collision, the temperature reaches a maximum of 230 MeV
The UrQMD $\rho$ contribution as well as the coarse-graining results for the vacuum and in-medium spectral functions are shown.

In-medium $\rho$ “melts” away at the pole mass while it becomes dominant at lower masses.
Comparison of Eletsky spectral function to existing HADES data shows that the in-medium $\rho$ is dominated by the $\Delta_{1232}$ contribution.

Still below the data for intermediate mass region.
Au + Au @ 1.25 AGeV

- Eletsky and Rapp spectral function agree quite well here
- The Dalitz-$\omega$ from the Rapp spectral function lies on the UrQMD result, while we don’t see a significant (direct-)$\omega$ peak in the coarse-grained result
Looking at NA60 - Eletsky Spectral Function

- In-medium $\rho$ contribution \textit{(blue)} to dimuon excess was calculated with the Eletsky spectral function for a \textbf{chiral EoS}
- $4\pi$ \textit{(orange)} and QGP \textit{(green)} contribution are included as well, they are negligible mostly at low masses, but dominate above 1 GeV

$\Rightarrow$ Eletsky spectral function gives a good overall agreement, but can not describe the low-mass tail of the excess dimuons completely
Rapp Spectral Function for NA60

- Calculation for Rapp spectral function (with $\rho$, $\omega$ and $\phi$ included) and additional QGP and $4\pi$ contribution
- Fits the data quite well at the $\rho$ pole mass, but is too low in the low mass tail
Comparison of EoS

- With the **Hadron Gas EoS** we get a better agreement at low masses
- The lack of QGP lowers the result at high masses
An increase in baryon density (take $\rho_{\text{eff}} = \rho_B + \rho_{\bar{B}}$) leads to a better description.

→ Baryons crucial for description of low mass tail.
The broadening is large at the beginning of the evolution, no peak at the $\rho$ pole mass
- Same order of magnitude for QGP and in-medium $\rho$
Later the $\rho$ dominates, shape of the spectrum is flatter, peak at pole mass evolves.
Dileptons at RHIC

- Comparison between pure transport and transport + in-medium $\rho$ from coarse-graining
Coarse-graining to be done at other energies and compared to further NA60, CERES, RHIC, LHC data

- Investigation of different equations of state
- Further dilepton calculations with hybrid model (transport + hydro)
- Using different input from transport (e.g. from GiBUU)
Summary

- New approach to combine realistic transport calculations with in-medium modified spectral functions for vector mesons.

- Non-equilibrium treatment highly non-trivial ⇒ Use equilibrium rates for a coarse-grained transport dynamics.

- First calculations show that we get a good description of the invariant mass spectrum, the coarse-graining is applicable for all energy regimes.

- Explanation of dilepton measurements is still a challenge for theory ⇒ Need for more experimental input!

- Waiting for HADES Au+Au data and for the pion beam!

- Further work in progress...!