Dilepton Production in Transport-based Approaches

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Intro
  - dilepton physics
  - vector mesons in medium

transport models
  - basic principles
  - assumptions & input

two approaches to dilepton production:
  - 'pure' transport (GiBUU)
  - coarse graining (UrQMD + Rapp SF)

comparison to data
  - HADES (pp and AA)
  - NA60
Intro: Dileptons

- lepton pairs \((e^+ e^-, \mu^+ \mu^-)\) are an ideal probe to study phenomena at high densities and temp.
- in particular: modification of vector-meson spectral function in medium and chiral sym. restoration
- experiments: NA60, STAR/PHENIX, HADES, CBM
Vector Mesons in Medium

- NA60 showed clearly: $\rho^0$ spectral function substantially broadened in medium (but no mass shift)
- mainly driven by baryonic effects (collisions with nucleons, coupling to resonances)
- largest effects at low energies (DLS/HADES), but: also most challenging ('DLS puzzle')

![Graph showing vector mesons in medium](image)
The GiBUU model

- hadronic transport model (microscopic, non-equilibrium), based on the Boltzmann-Uehling-Uhlenbeck equation
- developed for 20+ years in Giessen (in the group of U. Mosel)
- unified framework for electroweak ($\gamma A$, $eA$, $\nu A$) and hadronic ($pA$, $\pi A$, $AA$) nuclear reactions
- code available as open source (http://gibuu.hepforge.org)

Get the code: git://git.hepforge.org/gibuu

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

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The BUU equation

- **BUU equ.:** space-time evolution of phase-space density $F$ (via gradient expansion from Kadanoff-Baym)

\[
\frac{\partial(p_0 - H)}{\partial p_\mu} \frac{\partial F(x,p)}{\partial x^\mu} - \frac{\partial(p_0 - H)}{\partial x_\mu} \frac{\partial F(x,p)}{\partial p^\mu} = C(x,p)
\]

- **degrees of freedom:** hadrons
  (61 baryons and 22 mesons included)

- **Hamiltonian $H$:**
  - hadronic mean fields (Skyrme or RMF), Coulomb, ...

- **collision term $C(x,p)$:** decays and collisions
  - low energy: resonance-model approach
  - high energy: string fragment. (Pythia)

- **solve numerically via test-particle method:**
  \[
  F = \sum_i \delta(\vec{r} - \vec{r}_i)\delta(p - p_i)
  \]
Resonances vs. Strings

- Resonance model can saturate total cross section up to $\sqrt{s} \approx 3.4\, \text{GeV}$ (then: switch to string model)

- HADES $\pi N$ spectra show clear contributions of higher resonances ($N^*$, $\Delta^*$) at $\sqrt{s} = 3.2\, \text{GeV}$ (arXiv:1403.3054)
**Resonance Model**

- at SIS energies: particle production dominated by resonance formation
- GiBUU res. model is based on Manley/Saleski PWA (Phys. Rev. D 45, 1992; including $\pi N \rightarrow \pi N / 2\pi N$ data)
- 13 $N^*/\Delta^*$ states excited in NN collisions

| resonance | rating | $M_0$ [MeV] | $I_0$ [MeV] | $|M^2|/16\pi$ [mb GeV$^2$] | $\pi N$ | $\eta N$ | $\pi\Delta$ | $\rho N$ | $\sigma N$ | $\pi N^* (1440)$ | $\sigma\Delta$ |
|-----------|--------|-------------|-------------|-----------------|--------|--------|---------|--------|--------|---------------|--------|
| $P_{11}(1440)$ | **** | 1462 | 391 | 70 | 69 | 22 | 9 | 9 |
| $S_{11}(1535)$ | *** | 1534 | 151 | 8 | 51 | 43 | 2 | 2 |
| $S_{11}(1650)$ | **** | 1659 | 173 | 4 | 89 | 3 | 3 | 3 |
| $D_{13}(1520)$ | **** | 1524 | 124 | 4 | 50 | 5 | 21 | 21 |
| $D_{15}(1675)$ | **** | 1676 | 159 | 17 | 47 | 53 | 12 | 12 |
| $P_{13}(1720)$ | * | 1717 | 383 | 4 | 13 | 87 | 8 |
| $F_{15}(1680)$ | **** | 1684 | 139 | 4 | 70 | 10P | 12 | 12 |
| $P_{33}(1232)$ | **** | 1232 | 118 | OBE | 100 | 210 | 25S | 25S |
| $S_{31}(1620)$ | ** | 1672 | 154 | 7 | 9 | 62 | 67 | 67 |
| $D_{33}(1700)$ | * | 1762 | 599 | 7 | 14 | 74 | 8 | 8 |
| $P_{31}(1910)$ | **** | 1882 | 239 | 14 | 23 | 25S | 10P | 10P |
| $P_{33}(1600)$ | *** | 1706 | 430 | 14 | 12 | 68P | 20 | 20 |
| $F_{35}(1905)$ | *** | 1881 | 327 | 7 | 12 | 1P | 87P | 87P |
| $F_{37}(1950)$ | **** | 1945 | 300 | 14 | 38 | 18F | 44F | 44F |
$R \rightarrow e^+ e^- N$: THE 'TRADITIONAL' TREATMENT

- $R = \Delta, N^*, \Delta^*
- $photon couplings ($R \rightarrow \gamma N$) known from photoproduction experiments ($\gamma N \rightarrow X$)
- extend to time-like region ($R \rightarrow \gamma^* N$) via em. transition form factor (Wolf et al, Krivoruchenko et al.):

$$\frac{d\Gamma}{d\mu} = \frac{2\alpha}{3\pi\mu} \frac{\alpha (m_R + m_N)^2}{16 m_R^3 m_N^2} \sqrt{(m_R + m_N)^2 - \mu^2 \left[ (m_R - m_N)^2 - \mu^2 \right]^{3/2}} |F(\mu, m_R)|^2$$

- problem: form factor basically unknown in time-like region, often neglected (avail. models: Wan/Iachello, Ramalho/Pena)
assumption: baryons couple to em. sector only through $\rho$ (strict VMD)

in transport model: two-step treatment (factorization), intermediate $\rho$ can be rescattered

$\Delta(1232)$: introduce $\rho N$ coupling with on-shell BR of $5 \cdot 10^{-5}$
Elementary Results

- excellent agreement with all pp data
- significant res. contributions (via VMD)
- dp underestimated (despite inclusion of OBE bremsstrahlung by Shyam et al.)
- further isospin-enhancement of $\rho$ in np required?
SPS/RHIC vs SIS energies

'in-medium' physics at SPS connected to 'vacuum' physics at SIS!
on-shell transport (with vacuum spectral functions) already yields rather good results

further improvements might be obtained by including explicit in-med. spectral functions (via 'coarse graining' or 'off-shell transport')

or: better input? (form factors, rho-baryon coupling)
Coarse Graining

- PhD project of Stephan Endres
- put UrQMD simulation onto space-time grid
- for each cell, determine baryon and energy density
- use equation of state to calculate local temperature and baryo-chemical potential
- calculate thermal dilepton rates using Rapp-Wambach spectral function (Rapp 1997, NPA 617)
Results: NA60

- good agreement with NA60, reproducing Rapp/Hees results
- benchmark/proof of principle
- plus: better fireball description (non-homogeneous)
Results: \textbf{Ar+KCl at 1.76 GeV (HADES)}

- Very good agreement (best description of this data so far)
- Dominant $\rho$ in-medium contribution
- Baryonic effects are crucial
Summary/Conclusions

- Pure transport simulations get close to describing HADES dilepton data, when given proper input ($\rho$-R couplings!)
- Coarsed-grained transport gives almost perfect description using Rapp spectral function
- Open questions:
  - Understand differences in detail
  - Is Rapp SF. in agreement with HADES pp data?
- Future work:
  - HADES Au+Au & pion beam
  - Coarse-graining results for RHIC BES
The End

Thanks for your attention!