Phasediagram of QCD
Chiral symmetry and density
Phasediagram of QCD

- Quarks and Gluons
- Hadrons
- Critical point?
- Deconfinement and chiral transition
- Neutron stars
- Color Superconductor?
Measuring high $\mu_B$ with resonances/dileptons
What you need to know to make people uneasy at dilepton meetings
• Several physical effects are density driven, e.g.
  • vector meson spectral function broadening
  • chiral phase transition
  • QGP phase transition
  • quarkyonic matter
  • ...
Before including those density-driven effects into theoretical models one should check:

• the maximum density which is reached in heavy ion collisions

• the behaviour of the system without any medium effects

• from what stage is the information one can gather experimentally from? and how?
Outline

• Quick UrQMD reminder

• Resonance kinematics
  • How deep can we look into heavy ion collisions using resonances/dileptons? (does high transverse momentum change anything?)
  • Baryons @ low energies
  • $a_1$
  • Hadronic cocktail and what we learn from it
## Dileptonic and hadronic decays

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Measuring resonances

- Resonances decay on timescales of fm ⇒ cannot be measured directly

- Resonances are measured via their decay products, cross section follows a Breit-Wigner law
Measuring resonances in p+p

Correlate all protons and kaons in the event, plot invariant mass.

Lots of uncorrelated pairs → background subtraction needed

Still a visible peak, but not as clear as before.
Measuring resonances in A+A

Different methods to subtract the background lead to slightly different results.
Measuring resonances in A+A

Correlate all protons and kaons in the event, plot invariant mass.

Peak?
Dileptonic and hadronic decays

hadronic decay

leptonic decay

late stage

integrated collision
Model selection

initial

final

thermal
hydro
transport
The tool - UrQMD

- Ultra Relativistic Quantum Molecular Dynamics
- Non equilibrium transport model
- All hadrons and resonances up to 2.2 GeV included
- Particle production via string excitation and -fragmentation
- Cross sections are fitted to available experimental data or calculated via detailed balance or the additive quark model
- Does account for canonical suppression

No explicit implementation of in-medium modifications!

Quantum Molecular Dynamics

Nucleon = Gaussian Wave-Packet

\[
\phi_i(\vec{x}; \vec{q}_i, \vec{p}_i, t) = \left( \frac{2}{L\pi} \right)^{3/4} \exp \left\{ -\frac{2}{L}(\vec{x} - \vec{q}_i(t))^2 + \frac{1}{\hbar}i\vec{p}_i(t)\vec{x} \right\}
\]

N-Body-State = product of coherent states

\[
\Phi = \prod_i \phi_i(\vec{x}, \vec{q}_i, \vec{p}_i, t)
\]
QMD

Lagrangian Density

\[
\mathcal{L} = \sum_i \left[ -\dot{\mathbf{q}}_i \mathbf{p}_i - T_i - \frac{1}{2} \sum_{j \neq i} \langle V_{ik} \rangle - \frac{3}{2Lm} \right]
\]

Equations of motion

\[
\dot{\mathbf{q}}_i = \frac{\mathbf{p}_i}{m} + \nabla_{\mathbf{p}_i} \sum_j \langle V_{ij} \rangle = \nabla_{\mathbf{p}_i} \langle H \rangle
\]

\[
\dot{\mathbf{p}}_i = -\nabla_{\mathbf{q}_i} \sum_{j \neq i} \langle V_{ij} \rangle = -\nabla_{\mathbf{q}_i} \langle H \rangle.
\]
QMD

Complicated N-Body Schrödinger Problem

6 \((N_P+N_T)\) equations
Steps in UrQMD

- Initialization
- Propagation of nuclei and produced particles
- Binary scatterings
Initialization

![Graph showing the relationship between V(r)/V₀ and r in femtometers (fm).](image)
Collision criterium

When do particles collide?

1) Know cross section

2) Check collision criterium
Collision criterium

When do particles collide?

1) Know cross section

2) Check collision criterium

\[ \pi d^2 \leq \sigma_{tot} \]
## The tool - UrQMD

<table>
<thead>
<tr>
<th>nucleon</th>
<th>$\Delta$</th>
<th>$\Lambda$</th>
<th>$\Sigma$</th>
<th>$\Xi$</th>
<th>$\Omega$</th>
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The tool - UrQMD

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<td>$K^*$</td>
<td>$K_0^*$</td>
<td>$K_1^*$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$\omega$</td>
<td>$f_0$</td>
<td>$f_1$</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>$\phi$</td>
<td>$f_0^*$</td>
<td>$f_1'$</td>
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</table>

<table>
<thead>
<tr>
<th>$1^{+-}$</th>
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<th>$(1^{--})^*$</th>
<th>$(1^{--})^{**}$</th>
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<td>$K_2^*$</td>
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<td>$h'_1$</td>
<td>$f'_2$</td>
<td>$\phi_{1680}$</td>
<td>$\phi_{1900}$</td>
</tr>
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</table>
Cross sections

\[ \sigma_{1,2\rightarrow 3,4}(\sqrt{s}) \sim (2s_3 + 1)(2s_4 + 1) \frac{\langle p_{3,4} \rangle}{\langle p_{1,2} \rangle} \frac{1}{\sqrt{s}} |M(m_3, m_4)|^2 \]

Global fit with the same kind of matrix element for 5 channels

\[ NN \rightarrow NN^*, N\Delta^*, \Delta\Delta, \Delta N^*, \Delta\Delta^* \]

\[ |M(m_3, m_4)|^2 = A \frac{1}{(m_4 - m_3)^2(m_4 + m_3)^2} \]

Data from elementary reactions are needed as an input into theory! (HADES?)
Density calculation

• Lorentz-transform the CF density to the frame where the three-current vanishes (Eckart frame)

\[
\vec{\beta}_{CF} = \frac{\sum_{j=1}^{N} \left( \frac{\vec{p}_j}{E_j} \right) \cdot P_j}{\sum_{j=1}^{N} P_j}
\]

\[
\begin{pmatrix}
\gamma & -\beta_x \gamma & -\beta_y \gamma & -\beta_z \gamma \\
-\beta_x \gamma & 1 + (\gamma - 1) \frac{\beta_x^2}{\beta^2} & (\gamma - 1) \frac{\beta_x \beta_y}{\beta^2} & (\gamma - 1) \frac{\beta_x \beta_z}{\beta^2} \\
-\beta_y \gamma & (\gamma - 1) \frac{\beta_y \beta_x}{\beta^2} & 1 + (\gamma - 1) \frac{\beta_y^2}{\beta^2} & (\gamma - 1) \frac{\beta_y \beta_z}{\beta^2} \\
-\beta_z \gamma & (\gamma - 1) \frac{\beta_z \beta_x}{\beta^2} & (\gamma - 1) \frac{\beta_z \beta_y}{\beta^2} & 1 + (\gamma - 1) \frac{\beta_z^2}{\beta^2}
\end{pmatrix}
\]

• The zero-component of the transformed four-current is the relevant density
Density calculation

• Local baryon density is the zeroth component of the baryon four-current $j^\mu = (\rho_B, \vec{j})$ when the baryon is at rest.

• UrQMD calculates in the Computational Frame (CF), which is usually the CMS (due to symmetry).

• $j^\mu_{CF} = (\rho_{BCF}, \vec{j}_{CF})$ can be calculated as a sum over Gaussians.

$$
\rho_{CF}(\vec{r}_i) = \sum_{j=1}^{N} \left( \frac{1}{\sqrt{2\pi\sigma}} \right)^3 \gamma_z e^{-\frac{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 \gamma_z^2}{2\sigma^2}}
$$

$$
= \sum_{j=1}^{N} P_j
$$
Rescattering

- well known effect, studied in
  - statistical hadronization models
  - transport models
  - hydrodynamical models

\[
\frac{dN}{dy} \quad K_0(892)
\]


\[
\frac{\Delta(1232)}{\Lambda(1520)}(all)
\]

• well known effect, studied in experiment

Rescattering

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ \frac{dN_{ch}}{dy} \]

\[ p+p \quad A+A \]

\[ K^+/K^- \quad \text{pp & AuAu x 2.9} \]

\[ K^+/K^- \quad \text{CuCu x 2.9} \]

\[ \phi /K^- \quad \text{pp & AuAu x 8.1} \]

STAR preliminary

Time evolution of $\rho_B$

- Central Pb+Pb (Au+Au) collisions
- Averaged over all hadron positions
Reach in density

- Normalized density spectrum
- Most resonances originate from very low density

![Graphs showing density spectra for Au+Au collisions at 30 and 200 AGeV.]
Reconstruction probability

- Probability to reconstruct resonances from a certain density

**Baryons**

**Mesons**
**p_T dependence**

- average transverse momentum depends on density
- reconstructable resonances have higher p_T
$p_T$ dependence

- difference in $p_T$ spectrum between observable and all decayed

- percentage of reconstructable resonances produced at $\rho > 2 \rho_0$ increases with $p_T$
Formation time

- formation time is mass and $p_T$ dependent

- shaded areas indicate the estimated lifetime of the partonic phase
High $p_T$ resonances might shed some light on the dense phase of heavy ion collisions!

(but are they really what we want to measure?)
Dileptons

Using dileptons... how far can we look into the dense phase?

(can we at all?)
Gain/Loss terms

• Resonances can stem from two processes

  • **Collisions** (e.g. \( \pi \pi \rightarrow \rho \))

  • **Decays** of heavier resonances (e.g. \( N_{1520}^* \rightarrow N + \rho \))

• Resonances can be destroyed by two processes

  • **Decays** (e.g. \( \rho \rightarrow e^+ e^- \))

  • **Absorption** (e.g. \( N + \rho \rightarrow N_{1520}^* \))
Density distribution
Density distribution

\[ \frac{dN}{d(\rho_B/\rho_0)} \]

\(2 \text{ A GeV (Au+Au)}\)

\(t [\text{fm}]\)
Density distribution

\[ \frac{dN}{d(B/\rho_0)} \]

2 AG eV (Au+Au)
Density distribution

11 AGeV (Au+Au)

2 AGeV (Au+Au)
Density distribution

\[ \frac{dN}{d(B/\rho_0)} \]

2 A GeV (Au+Au)

11 A GeV (Au+Au)
Density distribution

\[ \frac{dN}{d(\rho_B/\rho_0)} \]

- \( \rho_{\text{decay}} \)
- \( \rho_{\text{absorbed}} \)
- \( \Sigma \)

30 AG eV (Pb+Pb)

2 AG eV (Au+Au)

11 AG eV (Au+Au)
Density distribution

- $\rho$ decays do not reach out to high density
- most resonances at such densities are re-absorbed
Gain/Loss rates of $\rho$ mesons

SiS energies: Most gain from decay
AGS and FAIR energies: More gain from collisions
In the early stage - loss by absorption dominant
Decays set in in the late stage
Gain/Loss rates of $\rho$ mesons

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Integral values

- Consistency check: Sum of gain and collision agree
- Difference gives the number of resonances in the system
Dilepton approaches

1) Shining
   - Evaluate lifetime of the resonance, weight accordingly

2) Full weight only when resonance decays - ignore absorbed resonances
   - Weight decayed resonance with vacuum width / BR

3) Full weight when absorbed/decayed
   - Weight all decayed/absorbed resonances with vacuum width / BR
     (most optimistic approach)
Time integration method ("shining")

\[ BR = \frac{\Gamma_i}{\Gamma_{tot}} \]

\[ \frac{dN_{e^+e^-}}{dM} = \frac{\Delta N_{e^+e^-}}{\Delta M} = \sum_{j=1}^{N\Delta M} \int_{t_j^i}^{t_j^f} dt \Gamma_{e^+e^-}(M) \frac{dt}{\Delta M} \]

decay method

one pair

shining

continuous emission

Ko and Li, Nucl.Phys.A582:731-748,1995
Dileptons

Even in the most optimistic approach dileptons only reach out to 2-3 $\rho_0$
Shining approach only reaches out to 1-2 $\rho_0$
Baryons

What is the deal about them at low energies?
At low energies (~2 AGeV) contributions from baryon resonance decays are dominant.

$N^*_{1520}$ contributes via the decay chain

$N^*_{1520} \rightarrow N + \rho$

$\rho \rightarrow \pi^+\pi^-$ or $\rho \rightarrow e^+e^-$

to the low mass part of the $\rho$ meson mass spectrum.

At higher energies the contribution from baryonic resonance decays become less important.

Note: All curves normalized to the 770 MeV point.
Due to the dependence on the baryon density the mass of the $\rho$ meson is rapidity dependent.

The $\rho$ meson mass drops towards higher rapidity.
Second conclusion

Controlling baryon kinematics is important

(otherwise some spectra seem more interesting than they are)
Measuring Chiral Symmetry

• Can we observe a chirally restored phase? (and how?)

• What happens to the $\rho$ meson in the medium? What happens to the $a_1$ meson?

• What can we learn from reasonable hadronic dynamics (without a chirally restored phase)?
The $a_1$ meson mass is expected to be equal to the mass of the $\rho$ meson, in case of chiral symmetry restoration.

Problem: It is hard to measure.

<table>
<thead>
<tr>
<th>$a_1(1260)$ DECAY MODES</th>
</tr>
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<tbody>
<tr>
<td>Mode</td>
</tr>
<tr>
<td>$\Gamma_1$</td>
</tr>
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<tr>
<td>$\Gamma_3$</td>
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<tr>
<td>$\Gamma_4$</td>
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<td>$\Gamma_5$</td>
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<tr>
<td>$\Gamma_{11}$</td>
</tr>
<tr>
<td>$\Gamma_{12}$</td>
</tr>
</tbody>
</table>
**a₁ meson**

The $a₁$ meson mass is expected to be equal to the mass of the $ρ$ meson, in case of chiral symmetry restoration.

**Problem:**
It is hard to measure.

---

### $a₁(1260)$ DECAY MODES

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<tr>
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<th>Fraction ($Γ_i/Γ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Γ_1$</td>
<td>$π⁺π⁻π⁰$</td>
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<tr>
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<td>$π⁰π⁰π⁰$</td>
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<td>$(ρπ)_D$-wave</td>
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<td>$f₀(980)π$</td>
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<td>$f₀(1370)π$</td>
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<td>$Γ_{10}$</td>
<td>$f₂(1270)π$</td>
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<td>$K K^*(802)$</td>
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<tr>
<td>$Γ_{12}$</td>
<td>$πγ$</td>
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</tbody>
</table>

seen  
not seen  
seen  
seen  
not seen  
seen  
seen  
seen  
seen
a\textsubscript{1} meson

What about the other channels?

Experimentally not feasible:

Higher mass resonances are either not known or the decay channel analyses contradict each other (further exp. studies certainly useful!).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction ($\Gamma_i/\Gamma$)</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<td>$\pi^0\pi^0\pi^0$</td>
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<tr>
<td>$\Gamma_3$</td>
<td>$(\rho\pi)s$–wave</td>
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<tr>
<td>$\Gamma_4$</td>
<td>$(\rho\pi)D$–wave</td>
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<tr>
<td>$\Gamma_5$</td>
<td>$(\rho(1450)\pi)s$–wave</td>
</tr>
<tr>
<td>$\Gamma_6$</td>
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<td>$\Gamma_9$</td>
<td>$f_0(1370)\pi$</td>
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<td>$\Gamma_{10}$</td>
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<td>$K\bar{K}^*(892) + \text{c.c.}$</td>
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<tr>
<td>$\Gamma_{12}$</td>
<td>$\pi\gamma$</td>
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</tbody>
</table>
$a_1$ meson - density

Density at the point of decay of the $a_1$ meson

$Au+Au$

$\frac{dN}{d(\rho/\rho_0)}$

$\rho/\rho_0$

20 GeV all decayed
20 GeV reconstructable
30 GeV all decayed
30 GeV reconstructable
a₁ meson

Idea: Check the mass distribution from the transport code.
Next: trigger on the decay channel $a_1 \rightarrow \gamma \pi$ (assumed width = 640 keV)
a$_1$ meson

→ Mass dependent branching ratios

\[
\Gamma_{i,j}(M) = \Gamma^{i,j}_R \frac{M_R}{M} \left( \frac{\langle p_{i,j}(M) \rangle}{\langle p_{i,j}(M_R) \rangle} \right)^{2l+1} \frac{1.2}{1 + 0.2 \left( \frac{\langle p_{i,j}(M) \rangle}{\langle p_{i,j}(M_R) \rangle} \right)^{2l}}
\]

Low mass a$_1$ favors $\gamma\pi$ decay, not $\rho\pi$

Trigger on a$_1$ → $\gamma\pi$ = trigger on low mass a$_1$ mesons

Below 900 MeV $\gamma\pi$ decay is dominant, $\rho\pi$ is kinematically suppressed.

Branching ratio folded with BW distribution
**a_1 meson**

**Full model calculation**

![Graph showing BR a_1 → ρπ, BR a_1 → γπ, a_1 dN/dm pp @ 20 A GeV (norm.), and BW distribution (normalized).]
$a_1$ meson

\[
dN/dm \, [1/GeV]
\]

\[
m \, [GeV]
\]

- p+p 20 (x200)
- p+p 30 (x200)
- Au+Au 20
- Au+Au 30

$(a_1 \rightarrow \gamma\pi)$
Take home messages

• Experimentally reconstructable resonances are not sensitive to the high density region unless measured at high $p_T$

• Beware of baryons kinematics

• $a_1 \rightarrow \gamma\pi$ might not be the golden channel
Take home messages

• Experimentally reconstructable resonances are not sensitive to the high density region unless measured at high $p_T$

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Thanks!