In-Medium Properties of Vector Mesons
in a Transport Approach

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1 motivation: in-medium physics

2 the GiBUU transport model

3 dileptons from HADES:
   \( p + p \) @ 3.5 GeV
   \( p + \text{Nb} \) @ 3.5 GeV

4 conclusions

[not covered here: photoproduction of omega mesons on nuclei, as measured by CB/TAPS, cf. EPJ A47 (2011)]
Motivation: Hadrons in Medium

- how do vector mesons behave inside a hadronic medium?
- Hatsuda/Lee: mass shift
  \[ m_V^*(\rho)/m_V \approx 1 - \alpha(\rho/\rho_0) , \]
  \[ \alpha \approx 0.16 \pm 0.06 \]
- collisional broadening (LDA):
  \[ \Gamma_{\text{coll}} = \rho < v_{rel}\sigma VN > \]
- extended sum-rule analysis by Leupold/Peters/Mosel, including finite width (NPA 628, 1998)
- coupling to resonances can introduce additional structures in the spectral function (Post, 2003)
The GiBUU Transport Model

- BUU-type hadronic transport model
- unified framework for various types of reactions ($\gamma A$, $eA$, $\nu A$, $pA$, $\pi A$, $AA$) and observables
- BUU equ.: space-time evolution of phase space density

\[
\left( \partial_t + (\nabla \vec{p} H_i) \nabla \vec{r} - (\nabla \vec{r} H_i) \nabla \vec{p} \right) f_i(\vec{r}, t, \vec{p}) = I_{\text{coll}}[f_i, f_j, ...]
\]

- Hamiltonian $H_i$:
  - hadronic mean fields, Coulomb, “off-shell potential”
- collision term $I_{\text{coll}}$:
  - decays and scattering processes (2- and 3-body)
  - low energy: resonance model, high energy: PYTHIA
- http://gibuu.physik.uni-giessen.de

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

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In-medium properties of vector mesons

$P + P @ 3.5 \text{ GeV, mass spectrum}$

data (A. Rustamov)

GiBUU total

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

$\omega \rightarrow e^+ e^-$

$\phi \rightarrow e^+ e^-$

$\omega \rightarrow \pi^0 e^+ e^-$

$\pi^0 \rightarrow e^+ e^- \gamma$

$\eta \rightarrow e^+ e^- \gamma$

$\Delta \rightarrow N e^+ e^-$

$\eta' \rightarrow e^+ e^- \gamma$
Dalitz decay

- transition form factor $\Delta \rightarrow N\gamma^*$
  - space-like region: data from electroproduction
  - basically unknown in time-like region (no data)
- best available guess for time-like region:
  - two-component quark model (Wan/Iachello, IJMP A20, 2005)
  $$F \sim (1 - \gamma e^{i\theta}q^2)^{-2} \cdot F_\rho(q^2)$$

![Graph showing $|F(q^2)|^2$ vs. $q^2$](image)

Data (A. Rustamov)

- $\rho \rightarrow e^+e^-$
- $\omega \rightarrow e^+e^-$
- $\phi \rightarrow e^+e^-$
- $\omega^0 \rightarrow \pi^+e^+e^-$
- $\pi^0 \rightarrow e^+e^+\gamma$
- $\eta \rightarrow e^+e^+\gamma$
- $\Delta \rightarrow N e^+e^-$

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In-medium properties of vector mesons
$p_p @ 3.5 \text{ GeV}, \ p_T \text{ and rap. spectra}$

- $p_T$: perfect agreement (when including Delta FF!)
- small discrepancies at forward rapidity (filtering problem?)
cocktail composition basically fixed by $p+p$
(elementary cross sections, branching ratios, form factors, ...)

use $p+p$ as a base line for $p+\text{Nb}$

additional medium effects:
1) FSI, absorption, rescattering
2) secondary production processes
3) modified spectral functions

vector mesons in medium:
$\rho$: sensitive to direct modification of mass spectrum?
$\omega/\phi$: transparency ratio / absorption

unfortunately $p+p$ still leaves us with some uncertainties
(largest one: Delta form factor)
$p+Nb@3.5\ GeV$, mass spectrum

**VM: vacuum spectral functions**

- Delta: no form factor needed
- Omega absorption: consistent with TAPS transparency ratio
P+Nb@3.5 GeV, mass spectrum

VM: collisional broadening

Data (M. Weber)
GiBUU total
\[ \rho \rightarrow \, e^+ e^- \]
\[ \omega \rightarrow \, e^+ e^- \]
\[ \phi \rightarrow \, e^+ e^- \]
\[ \omega \rightarrow \, \pi^0 e^+ e^- \]
\[ \pi^0 \rightarrow \, e^+ e^- \gamma \]
\[ \eta \rightarrow \, e^+ e^- \gamma \]
\[ \Delta \rightarrow \, N e^+ e^- \]

\( \frac{d\sigma}{dm_{ee}} \) [\( \mu b/\text{GeV} \)]

Dilepton mass \( m_{ee} \) [GeV]

- consistent treatment of collisional broadening / absorption
- slightly better agreement

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- rho strength shifted downward
- even better agreement
Conclusions

1. VM properties in (cold) nuclear matter: a challenging problem!

2. GiBUU: a valuable tool to study in-medium physics

3. HADES: we need to understand elementary reactions before we can draw hard conclusions on p+A and A+A
   (in particular: we need to understand the transition form factor of the Delta Dalitz decay)
Back-Up Slides
**Delta cross section**

**Δ⁺ production cross sections (inclusive/exclusive)**

- $pp \rightarrow p\Delta^+$ data
- $pp \rightarrow \Delta^+X$
- $pp \rightarrow p\Delta^+$

In-medium properties of vector mesons

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**In-medium properties of vector mesons**
ω Dalitz decay: $\omega \rightarrow \pi^0 e^+ e^-$

- inclusive $\omega$ production cross section fixed by $\omega \rightarrow e^+ e^-$, BR($\omega \rightarrow e^+ e^-$) well known: $7.2 \cdot 10^{-5}$
- $\omega$ Dalitz branching also well known
- form factor fixed by NA60 data (Arnaldi et al., PLB 677)
DIRECT $\eta$ DECAY: $\eta \rightarrow e^+ e^-$

- exp. upper limit (WASA, Berlowski et al., PRD 77, 2008):
  $$\text{BR}(\eta \rightarrow e^+ e^-) < 2.7 \cdot 10^{-5}$$
- HADES might be able to push down this limit ...
- theor. prediction (Browder et al., PRD 56, 1997):
  $$\text{BR}(\eta \rightarrow e^+ e^-) \approx 10^{-9}$$

![Graph showing $d\sigma/dm_{ee}$ vs. dilepton mass $m_{ee}$ from data (A. Rustamov), GiBUU total, and various vector meson decays.](attachment:image.png)

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**In-medium properties of vector mesons**
- pions are important for normalization
- can serve as a cross check for dilepton spectra
- GiBUU nicely describes inclusive pion data by HARP (Gallmeister, NPA 826, 2009)
HADES: $p + p \ @ \ 3.5$ GeV ($p < 800$ MeV)

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