Observing In-Medium Properties of Vector Mesons in Elementary Nuclear Reactions

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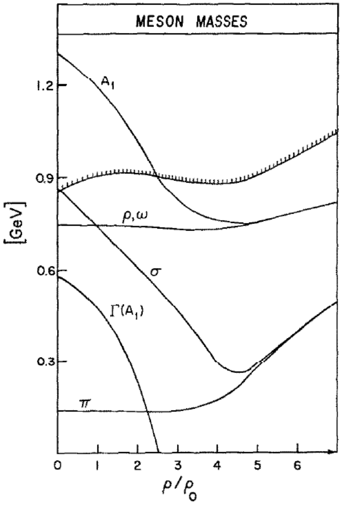
Motivation: Hadrons in Medium

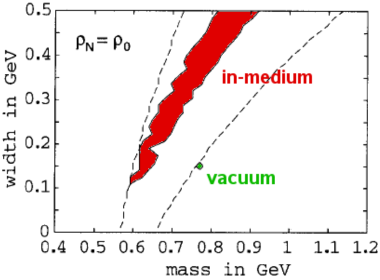
- how do vector mesons behave inside a hadronic medium?
- major prediction: mass shift $\leftrightarrow$ (partial) restoration of chiral symmetry in medium
- Brown/Rho (eff. Lagrang. approach): $m_V^*(\rho_0)/m_V \approx 0.8$
- Hatsuda/Lee (using QCD sum rules, neglecting width): $m_V^*(\rho)/m_V \approx 1 - \alpha(\rho/\rho_0)$, $\alpha \approx 0.16 \pm 0.06$
- mass shift $\Leftrightarrow$ V-N potential $\Leftrightarrow$ bound states?

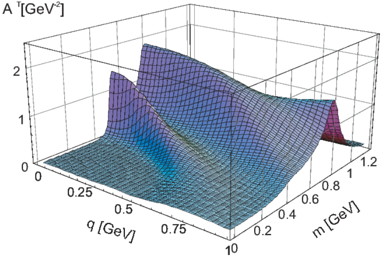
V. Bernard, U.-G. Meissner / Vector and axial-vector mesons



Motivation II

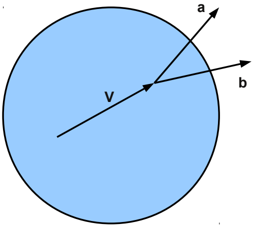
- other effects: collisional broadening, resonance structures, ...
- collisional broadening (LDA):
  $\Gamma_{coll} = \rho < v_{rel} \sigma_{VN} >$
  $\Leftrightarrow$ absorption
- extended sum-rule analysis by Leupold/Peters/Mosel, including finite width (NPA 628, 1998)
- coupling to resonances can introduce additional structures in the spectral function (M. Post, 2003)





How to study in-medium effects?

- basic idea: observe decays $V \to ab$ inside the medium
- reconstruct in-medium mass from invariant mass of decay products: $m_V^* = \sqrt{(p_a + p_b)^2}$



we need:

- reasonably large medium
- short meson lifetime + low momentum
- FSI of decay products should be small

Vacuum Properties of Mesons

	ρ^0	ω	ϕ
M [MeV]	775	782	1020
Γ [MeV]	149	8	4
$c\tau$ [fm]	1.3	23.4	44.4
hadr. BR	2π: 100%	3π: 89% $\pi^0\gamma$: 9% 2π: 2%	$2K$: 84% 3π: 12%
e^+e^- BR	$4.7 \cdot 10^{-5}$	$7.2 \cdot 10^{-5}$	$29.7 \cdot 10^{-5}$

hadronic decays:

- large branching ratios
- but: strong FSI with hadronic medium
- example: $\omega \to \pi^0\gamma$ (CB/TAPS)

leptonic decays:

- typically $V \to e^+e^-$
- small branching ratios: $\sim 10^{-5}$
- very weak FSI (only Coulomb)
- examples: CLAS/g7, HADES

Heavy-Ion Collisions vs. Cold Nuclei

heavy-ion collisions:

- very hot/dense medium
- $\rho > \rho_0, \ T > 0$
- $\Rightarrow$ large medium effects
- however: signal is hard to interpret
- "dirty" environment
- effects are integrated over large ranges of T/ρ

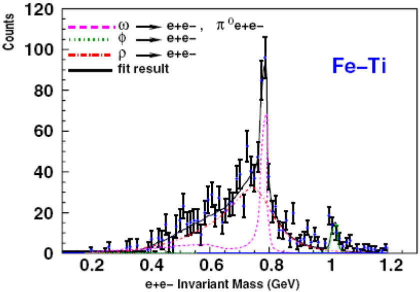
cold nuclei:

- hit nucleus with elementary projectile (γ, p, π, ...)
- preferrable at low energies
- nucleus basically stays in groud state
- $\rho \approx \rho_0, \ T \approx 0$
- $\Rightarrow$ smaller medium effects
- but: cleaner environment
- easier to interpret

Some Experimental Results

CLAS/g7@JLAB:

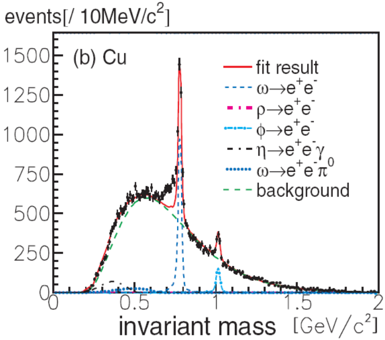
- $\gamma A \rightarrow e^+e^-X$ @ 1 - 4 GeV
- no significant mass shift: $\alpha = 0.02 \pm 0.02$
- some collisional broadening



Nasseripour et al., PRL 99 (2007)

E325@KEK:

- $pA \rightarrow e^+e^-X$ @ 12 GeV
- mass shift: $\alpha = 0.092 \pm 0.002$
- no broadening!



Naruki et al., PRL 96 (2006)

The GiBUU Transport Model

- semi-classical hadronic transport model
- unified framework for various types of reactions (pA, πA, γA, eA, νA, AA) and observables
- modular and well-documented Fortran code
- collaborative effort, SVN-based multi-user environment
- publicly available releases (open source)
- http://gibuu.physik.uni-giessen.de

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

The BUU equation

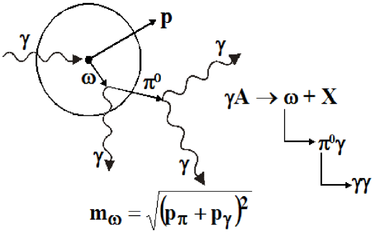
- BUU equation describes time evolution of phase space density $f_i(\vec{r}, t, \vec{p}, \mu)$ for each particle species i $(i = N, \Delta, \pi, \rho, ...)$:

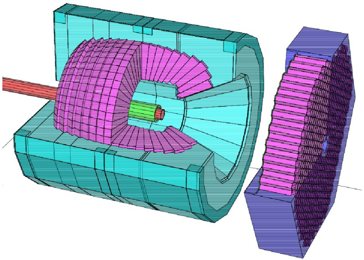
$$\left(\partial_t + (\nabla_{\vec{p}} H_i)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H_i)\nabla_{\vec{p}}\right) f_i(\vec{r}, t, \vec{p}, \mu) = I_{coll}[f_i, f_j, ...]$$

- collision term I_{coll}:
  - depends on all f_i $\Rightarrow$ coupled-channel problem
  - contains gain and loss terms
  - decays of unstable particles
  - two-body scattering processes
  - three-body reactions
- Hamiltonian H_i:
  - hadronic mean-field potential
  - Coulomb potential
  - off-shell transport incorporated through "off-shell potential"

The CB/TAPS detector

- $\gamma A \rightarrow \omega X \rightarrow \pi^0 \gamma X \rightarrow 3\gamma X$
- Bremsstrahlung photon beam (tagged), $E_\gamma = 0.9 - 2.2 GeV$
- at ELSA (Bonn) and MAMI (Mainz)
- measure photon triples
  $\rightarrow$ demand that two make up a π^0
  $\rightarrow$ reconstruct ω mass
- large background from 4γ events (one photon escapes undetected)
- mass resolution $\sim 25 MeV$

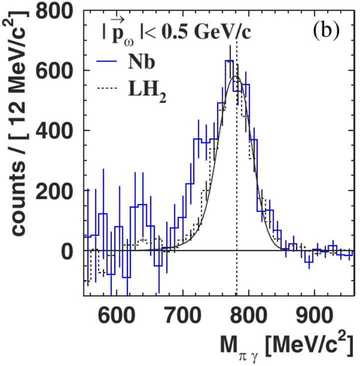




CB/TAPS: earlier results

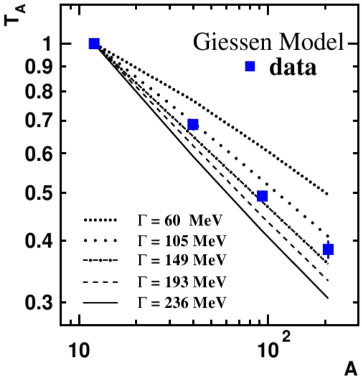
Trnka et al., PRL 94 (2005):

- $E_\gamma = 0.6 - 2.5$ GeV
- $m^*_\omega = 722$ MeV
- $\Gamma^*_\omega = 55$ MeV



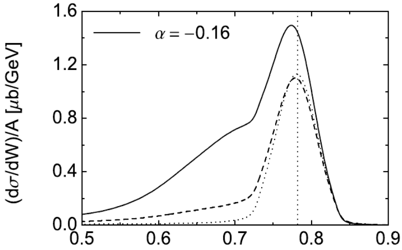
Kotulla et al., PRL 100 (2008):

- $T_A = \frac{12 \cdot \sigma(\gamma A \to \omega X)}{A \cdot \sigma(\gamma^{12} C \to \omega X)}$
- $\Gamma_{coll.} = 130 - 150$ MeV

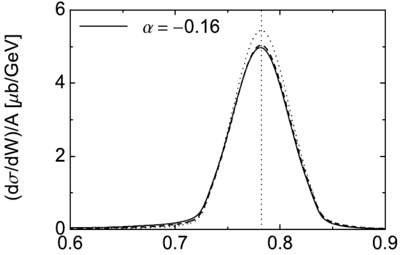


CB/TAPS: BUU simulations by P. Muehlich

- $\gamma + {}^{40}Ca$,
  $E_\gamma = 0.9 - 1.2$ GeV
- large in-medium effects

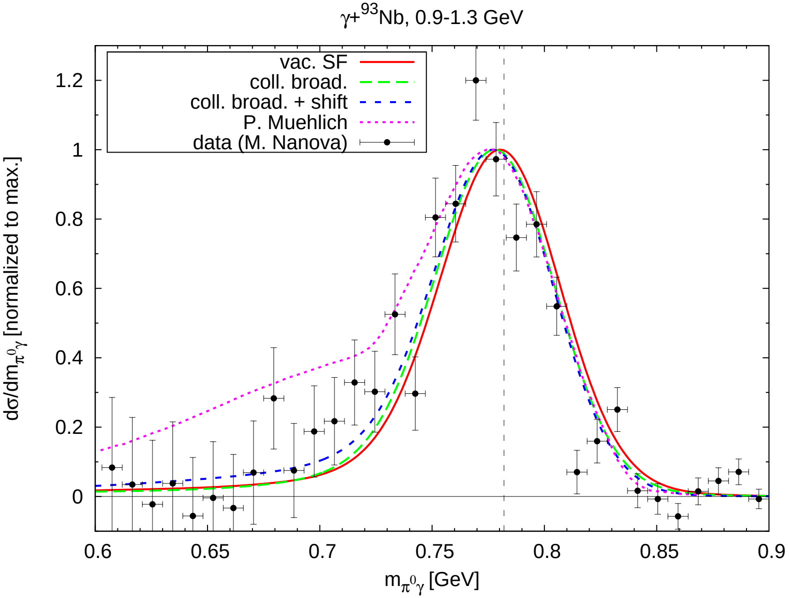


- $\gamma + {}^{40}Ca$,
  $E_\gamma = 1.5 - 2.2$ GeV
- almost to effects



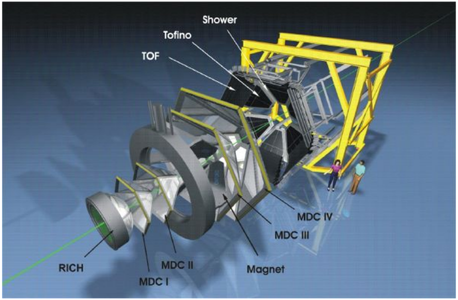
Gallmeister, Kaskulov, Mosel, Muehlich,
Prog. Part. Nucl. Phys. 61 (2008)

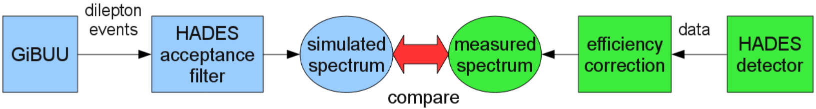
$\pi^0\gamma$ Inv. Mass Spectrum



The HADES detector

- "High Acceptance Di-Electron Spectrometer"
- located at GSI, Darmstadt
- pp, pA, AA $\rightarrow e^+e^-X$
- mass resolution: $\sim$ 15 MeV
- polar angle: $15^\circ < \theta < 85^\circ$





The Dilepton Cocktail

hadronic sources contributing to the dilepton spectrum:

direct decays:

- $\rho^0 \rightarrow e^+e^-$
- $\omega \rightarrow e^+e^-$
- $\phi \rightarrow e^+e^-$
- $(\eta \rightarrow e^+e^-)$

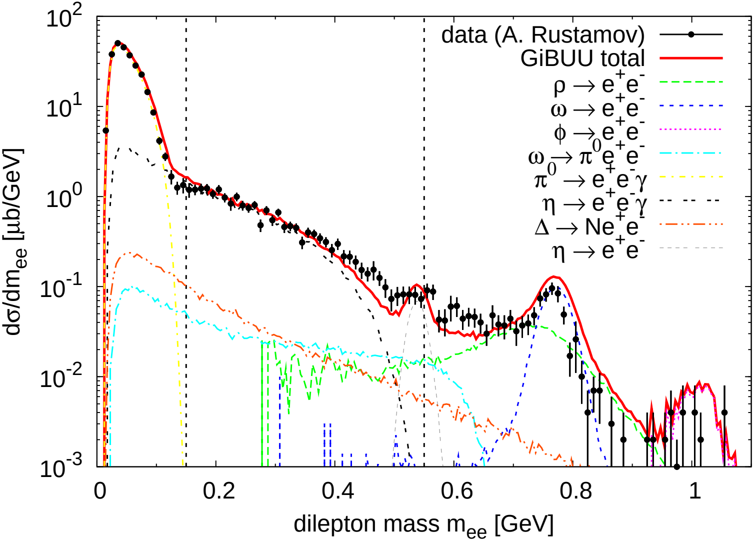
Dalitz decays:

- $\pi^0 \rightarrow e^+e^-\gamma$
- $\eta \rightarrow e^+e^-\gamma$
- $\omega \rightarrow \pi^0 e^+e^-$
- $\Delta \rightarrow Ne^+e^-$

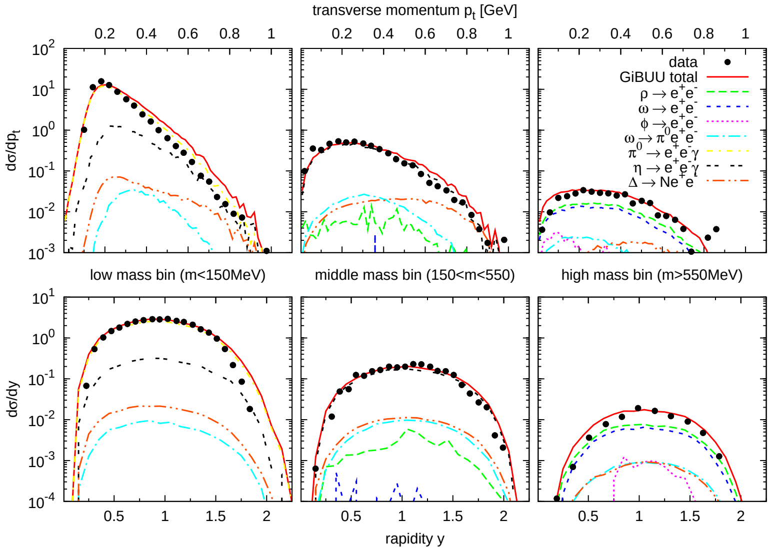
plus "non-hadronic" contributions:

- Bethe-Heitler process: $\gamma N \rightarrow Ne^+e^-$
  (direct photoproduction of a lepton pair)
- NN-Bremsstrahlung: $NN \rightarrow NNe^+e^-$

HADES: $pp \rightarrow e^+e^-X$ @ 3.5 GeV, mass spectrum



HADES: $pp \to e^+e^-X$, p_T AND y SPECTRA



Outlook

1. HADES: p+Nb@3.5GeV
   - investigate possible modifications of mass spectrum
   - transparency ratio measurement
2. CB/TAPS:
   - background studies with GiBUU
   - medium effects in ω excitation function
3. CLAS/g7: (M. Wood, M. Paolone)
   - re-investigate Bethe-Heitler background, rho-omega mixing?
   - determine transparency ratios for ω and ϕ
   - hopefully: new run with better statistics