“Properties of Light Mesons in the Nuclear Medium”

FROM LECTURE ONE

- In the light quark sector (u, d), $\chi_s$ is a very good symmetry of the QCD Lagrangian,
- However, $\chi_s$ symmetry is spontaneously broken in the vacuum.
- Non zero order parameters ($<0|\bar{q}q|0>$ and $f_\pi$) “measure” how much the symmetry is broken.
- As T or $\rho$ of the medium increases, $\chi_s$ is restored. Properties of mesons are predicted to change.

- So far only “solid evidence” for partial chiral restoration” comes from pionic atom studies (~30% drop of quark condensate).

- Hadrons in final state, BEWARE OF FSI.

LECTURE TWO

Properties of Vector Meson in the medium (di-lepton decay)
- In relativistic heavy ion collisions
  DLS, HADES, CERES, NA60, PHENIX
- In nuclei
  TAGX, KEK, TAPS, JLAB
Summary-Conclusions-Outlook
Lot of predictions, now what?

Many different predictions of modification of hadron properties in the medium (mass shift, change in interaction, widening, extra peaks, etc.). Experimentally, one needs to measure and compare the properties of these hadrons in the vacuum and in different media (T and/or $\rho \neq 0$).

We are going to look at the properties of vector mesons $\rho$, $\omega$ and $\phi$ in nuclei and Relativistic Heavy Ion (RHI) collisions.

Reference

$p+p, d+p, p+ Be, p+Au, p+Nb, p+W, C+C, Ca+Ca, S+Au, Pb+Au, Ar+KCl, In+In, Au+Au$

@ 1 to 200 AGeV
Vector mesons in Medium

Properties of Vector Mesons $J^P=1^-$ (PDG–2008)

<table>
<thead>
<tr>
<th>Meson</th>
<th>Mass (MeV/c²)</th>
<th>$\Gamma$ (MeV/c²)</th>
<th>$c\tau$ (fm)</th>
<th>Main decay</th>
<th>$\Gamma_{e^+e^-}/\Gamma_{\text{tot}} \times 10^{-5}$</th>
<th>$\Gamma_{\mu^+\mu^-}/\Gamma_{\text{tot}} \times 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>775.49 ±0.34</td>
<td>149.4±1.0</td>
<td>1.3</td>
<td>$\pi^+\pi^-$ (−100%)</td>
<td>4.7</td>
<td>4.6</td>
</tr>
<tr>
<td>$\omega$</td>
<td>782.65 ±0.12</td>
<td>8.49±0.08</td>
<td>23.2</td>
<td>$\pi^+\pi^-\pi^0$ (89%)</td>
<td>7.2</td>
<td>9.0</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1019.45 ±0.02</td>
<td>4.26±0.04</td>
<td>46.2</td>
<td>$K^+K^-$ (49%)</td>
<td>3.1</td>
<td>3.2</td>
</tr>
</tbody>
</table>

- The predicted medium modifications are large (even at normal nuclear density, they can be observed).
- Decay fast enough to test the medium (specially the $\rho$).
- Di-leptons (no FSI) carry “clean information” of the system at the time of production (either a nucleus or a fire ball in HI collisions).

However, these are very difficult measurement. The di-lepton decay has a very small branching ratio (~10^{-5}). One needs:

1) excellent lepton-hadron discrimination,
2) to control “huge” combinatorial background (severe in HIC).
3) to account for all other physics channels leading to di-leptons,
Vector mesons in Medium (lepton-hadron discrimination)

**Detecting \( \mu^+\mu^- \) final state.**
- Muons from pion and kaon decays are orders of magnitude more abundant than those from the vector meson decay \( \rightarrow \) it is essential to have a **thick absorber** as close as possible to interaction area.
- Multiple scattering (especially for low energy muons) affects invariant mass resolution.
- Good magnetic spectrometer to measure momentum of muons

**Detecting \( e^+e^- \) final state.**
- Excellent \( \pi^-e^- \) discrimination needed (\( \pi^- \)-pair suppression \( \sim 10^{-6} \) needed). Done with combination of Cerenkov detectors (standard or ring imaging) and **electromagnetic calorimeters**.
- Good magnetic spectrometer (to measure momentum of electron, positrons) needed for good invariant mass resolution.
- Understand and control all sources of **electromagnetic background** (minimize high Z materials)
- Thin multilayer targets

Standard dimuon detection: NA50, PHENIX, ALICE, ...

![Diagram of muon detection system]
The combinatorial background is the random combination of pairs (e⁺e⁻, e⁻e⁻, and e⁺e⁺) due to the uncorrelated sources.

Di-lepton pairs from uncorrelated events:
- \( \gamma \rightarrow e^+e^- \)
- \( \pi^0 \rightarrow \gamma e^+e^- \)

Pairs of identical (e⁺e⁺, e⁻e⁻) leptons, which are produced only by uncorrelated processes, will provide both a natural normalization and shape of the combinatorial background (CB). If enough same sign pairs measured, then in each invariant mass channel:

\[
\text{Signal} = N^\text{meas}_{+-} - CB = N^\text{meas}_{+-} - 2\sqrt{N^\text{meas}_{++} N^\text{meas}_{--}} \quad \text{(same acceptances for + and -)}
\]

\[
\text{Signal} = N^\text{meas}_{+-} - CB = N^\text{meas}_{+-} - 2\sqrt{N^\text{meas}_{++} N^\text{meas}_{--}} \frac{A_{+-}}{\sqrt{A_{++} A_{--}}} \quad \text{(≠ acceptances for + and -)}
\]

<table>
<thead>
<tr>
<th>experiment</th>
<th>NA60</th>
<th>PHENIX</th>
<th>NA45</th>
<th>HADES</th>
<th>KEK</th>
<th>TAPS</th>
<th>JLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal/CB</td>
<td>1/11</td>
<td>1/100</td>
<td>1/22</td>
<td>~1</td>
<td>1/2 - 1</td>
<td>0.7-1</td>
<td>2-3</td>
</tr>
</tbody>
</table>

For more details see references:
- \( \mu^+\mu^- \) measurement: at CERN-SPS IPNO-DR-02.015 (2002)
If not enough identical pairs have been collected, then to reduce statistical uncertainties on the background:
- One randomly mixes unlike sign tracks from different measured event with same event topology (this is repeated until a high statistics background spectra is obtained)
- Making sure shape of measured and generated same sign spectra are close

The generated unlike sign background spectrum can then be normalized by CB:

\[
CB = 2\sqrt{N^{meas}_{++} N^{meas}_{--}}
\]

where \(N^{meas}_{++}, N^{meas}_{--}\) are summed over all invariant mass channels
Vector mesons in Medium (other sources of di-leptons)

1) After clean di-lepton spectrum is obtained (lepton-hadron discrimination)
2) Combinatorial background is subtracted (same sign pairs method)
3) All contributions from physical sources have to be determined (called COCKTAIL) and compared to the measured spectrum to look for excess or lack of strength

Direct: $\rho \rightarrow e^+e^-$, $\omega \rightarrow e^+e^-$, $\phi \rightarrow e^+e^-$, $J/\psi \rightarrow e^+e^-$, $\psi' \rightarrow e^+e^-$

Dalitz: $\pi^0 \rightarrow \gamma e^+e^-$, $\eta \rightarrow \gamma e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, $\phi \rightarrow \eta e^+e^-$, $\Delta \rightarrow \Lambda e^+e^-$

Heavy flavor: $cc \rightarrow e^+e^- + X$, $bb \rightarrow e^+e^- + X$

Drell-Yan: $qq \rightarrow e^+e^-$

Many Transport codes are available (HSD, UrQMD, RQMD, IQMD, BRoBUU, GiBUU, ...) to calculate all these channels. One passes the predictions through the acceptance of the detector before comparing to data.
Vector mesons in Medium (ingredients of models)

- Incoming photon as hadron
- Shadowing: hadronic character of photon
- Primary production in first reaction
- In-medium propagation of produced particles out of nuclear volume: self-energies, widths,
- All nuclear resonances,
- Final State interaction interaction: absorption, side-feeding by CC effects

### IMPORTANT for hadrons in final state

\[ \sigma_{BW} \sim \frac{\pi}{k^2} \Gamma_{in} \left( \frac{s}{s - m^2} \right)^2 + s \Gamma_{tot}^2 \]

**Can be strongly \( m \)-dependent**

**Spectral Function**

**From U. Mosel, WWND09**
Some Transport Codes

- **HSD** (Hadron-String Dynamics)
  
  \[ \text{http://th.physik.uni-frankfurt.de/~brat/hsd.html} \]

- **UrQMD** (Ultra relativistic Quantum Molecular Dynamics)
  
  \[ \text{http://th.physik.uni-frankfurt.de/~urqmd/} \]

- **RQMD (Tübingen)** (Relativistic Quantum Molecular Dynamics)

- **IQMD (Nantes)** (Isospin-QMD)
  
  \[ \text{http://www-subatech.in2p3.fr/~theo/qmd/} \]

- **BRoBUU (Rossendorf)**

- **GiBUU (Giessen)** Boltzmann-Ühling-Uhlenbeck
  
  \[ \text{http://gibuu.physik.uni-giessen.de/GiBUU} \]

*Not exhaustive list*
Vector mesons in Medium (Any observations?)

First measurements of possible medium modification of VM came from RHI collisions
DLS(\textregistered Bevalac): C+C, Ca+Ca at 1\textit{A}GeV

DLS reported the first di-lepton excess in the VM mass region

Until recently even with best transport model calculations (even including in medium $\rho$ modification), theory under predicted measured e+e- yield by $\sim3$ in the $0.15 < M < 0.5$ GeV range!!

Since 1997, this was called the DLS puzzle
Recently solved by HADES
High Acceptance Di–Electron Spectrometer (HADES) at GSI

Beams: $\pi$, p and Nuclei 1-2 AGeV
Full azimuth, polar angles $18^\circ$-$85^\circ$
Pair acceptance $\approx 0.35$
seg. solid or LH$_2$ targets
RICH: $\pi$ – suppression: $10^4$
super-conducting toroid: $B_\rho = 0.34$ Tm
$\Delta m/m \sim 2\%$ at $\rho$-mass
C+C (1,2AGeV); p+p (1.2, 2.2, 3.5 GeV);
d+p (1.25 GeV),p+Nb (3.5AGeV),...

DLS puzzle solved!
HADES and DLS agree, and are compatible with new Transport calculations
(with some $\rho$ broadening and better NN Bremsstrahlung) [NPA807(2008)214]
In a large background of hadron particles, Ring Imaging CHERenkov (RICH) critical to discriminate between $e^+$,$e^-$ and $\pi^+$, $\pi^-$. 

- Studying low mass region region up to $\sim$1.5 GeV/c$^2$
- $e^+e^-$ measured in p+Be, p+Au, S+Au (NA45-1) with $\Delta m/m \sim$7% at $\rho$-mass
- Upgrading detector Pb+Au (NA45-2) with $\Delta m/m \sim$2% at $\rho$-mass. Signal/CB $\sim$ 1/22 !!!
p+Au understood in terms of p+p superposition

Large excess observed in Pb+Au below 0.7 Gev/c^2. $\rho/\omega$ mass shift??
NA45(CERES) [Recent data: PLB666(2008)425]

Broadening favored, no mass shift!
NA60 ($\mu^+\mu^-$ with In + In at 158 AGeV) @ CERN

- Si-pixel detector between target and absorber \(\Delta m/m \approx 2\%\) at \(\rho\)-mass (20 MeV/c\(^2\))
- \(\text{Sig/Back} \approx 1/11\)
- \(\omega\) and \(\phi\) clearly seen for first time in HIC.
- Able to extract invariant mass spectrum for \(\rho\) after cocktail subtraction.
Only broadening of $\rho$ (à la Rapp-Wambach) observed,
No mass shift (à la Brown-Rho)
PHENIX at RHIC (Au+Au at $\sqrt{s_{NN}} = 200$ GeV)

- Two central arm spectrometer
- Tracking (DC, PC)
- EM calorimeter
- TOF
- RICH
- Measures everything

Before Background subtraction: Signal/Background $\geq 1/100$ in Au-Au
Combinatorial background obtained with same sign pairs
Low mass region
Data below 150 MeV/c² well described by the cocktail
Enhancement observed in $150 < m_{ee} < 750$ MeV

Intermediate mass region
Absence of excess

Low mass region
- $M>0.5$ GeV/c²: some calculations OK
- $M<0.5$ GeV/c²: not reproduced

Analysis ongoing
What have we learned from Heavy Ion Collisions

1) In A+A collisions, the results are integrated over a whole range of $\rho$ and $T$; “it is hard to get easily to the elementary process”!
2) In A+A collisions, the interesting phase of matter is produced (if at all!) in the very early stages of the reaction, generally far from equilibrium, making it hard to directly compare to the theoretical models which all assume equilibrium.
3) In A+A collisions, many phases are involved
Vector mesons in Nuclei (T=0 and $\rho \sim \rho_0$)

The predicted medium modifications at normal nuclear density are large enough to be observed, so:

• Let’s produce Vector mesons in nuclei.
• Do it with probes that leave the nucleus in almost an equilibrium state $\gamma, \pi, \rho,$
• $(\text{probe}) + A \rightarrow V X \rightarrow e^+e^- X$

The invariant mass of meson $m\rho,\omega,\phi(\vec{P},\rho,T) = \sqrt{(P_{e^+} + P_{e^-})^2}$

$m$: invariant mass of meson
$P$: 4-momentum of lepton
$p$: 3-momentum of meson/medium

<table>
<thead>
<tr>
<th>Vector mesons</th>
<th>$M$</th>
<th>$\Gamma$</th>
<th>$c\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>775 MeV</td>
<td>149 MeV</td>
<td>1.3 fm</td>
</tr>
<tr>
<td>$\omega$</td>
<td>782 MeV</td>
<td>8 MeV</td>
<td>23 fm</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1019 MeV</td>
<td>4 MeV</td>
<td>46 fm</td>
</tr>
</tbody>
</table>

Decay inside

Need very low $p$
# Elementary Reactions (not exhaustive list)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAGX</td>
<td>$\gamma + ^3\text{He} \rightarrow \rho + X$ ($\rho \rightarrow \pi^+\pi^-$)</td>
</tr>
<tr>
<td>KEK</td>
<td>$p + A \rightarrow \rho, \omega, \phi + X$ ($\rho, \omega \rightarrow e^+e^-$)</td>
</tr>
<tr>
<td>KEK</td>
<td>$p + A \rightarrow \phi + X$ ($\phi \rightarrow e^+e^-$)</td>
</tr>
<tr>
<td>SPring-8</td>
<td>$\gamma + A \rightarrow \phi + A^*(\phi \rightarrow K^+K^-)$</td>
</tr>
<tr>
<td>TAPS</td>
<td>$\gamma + A \rightarrow \omega + X$ ($\omega \rightarrow \pi^0\gamma$)</td>
</tr>
<tr>
<td>JLab-g7a</td>
<td>$\gamma + A \rightarrow (\rho, \omega, \phi) + A^*$ ($\text{VM} \rightarrow e^+e^-$)</td>
</tr>
<tr>
<td>HADES</td>
<td>$p + p, d \rightarrow \rho, \omega, \phi + X$ ($\rho, \omega, \phi \rightarrow e^+e^-$)</td>
</tr>
</tbody>
</table>

- Only g7 with EM interaction in entrance and exit channels
- TAGX, Spring8 and TAPS have hadronic FSI.
KEK (Japan)–PS E325: $p+A \rightarrow \rho,\omega+X \ (\rho,\omega \rightarrow e^+e^-)$

M. Naruki et al, PRL 96 (2006) 092301

No absolute normalization of the background $\rightarrow$ background part of the fit

Constrain the $\omega/\rho$ ratio to include $\rho$
Using a model that predicts the probability for $\rho$ mesons decaying inside the nucleus.

Results of fit for the $\rho$:

Mass shift: $\alpha \sim 9.2\%$
No $\Delta \Gamma$
KEK-PS E325: $p+A \rightarrow \phi+X$ ($\phi \rightarrow e^+e^-$)

$\beta \gamma < 1.25$ (Slow)  
1.25 $< \beta \gamma < 1.75$

$\frac{m^*}{m} = 1 - k_1 \frac{\rho}{\rho_0}$,  
$\frac{\Gamma^*}{\Gamma} = 1 + k_2 \frac{\rho}{\rho_0}$

Best Fit Values

<table>
<thead>
<tr>
<th></th>
<th>$\rho$, $\omega$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1$</td>
<td>$9.2 \pm 0.2%$</td>
<td>$3.4^{+0.6}_{-0.7}%$</td>
</tr>
<tr>
<td>$k_2$</td>
<td>$0$ (fixed)</td>
<td>$2.6^{+1.8}_{-1.2}$</td>
</tr>
</tbody>
</table>

mass shift for low recoil momenta $\phi$ in Cu
CBELSA–TAPS – γ+A→ω+X (ω → π⁰ γ)

Eγ = 0.64-2.53 GeV on LH2 and Nb
Clean channel (ρ suppressed by 10^2) however FSI of π⁰
CBELSA-TAPS - γ+A→ω+X (ω → π₀ γ)

after background subtraction

NEW ANALYSIS with combinatorial background

\[ m^* \approx m_0 \]

Slow \( \omega \) decaying inside

Objections about treatment of BKGD were raised questioning \( \Delta m \); EJP J A 31 (2007) 245

published results: PRL94 (2005) 192303

High statistics run at MAMI planned
Jlab-CEBAF: The 6 GeV CW Electron Accelerator

- \( E_{\text{max}} \sim 6 \text{ GeV} \)
- \( I_{\text{max}} \sim 200 \mu\text{A} \)
- Duty Factor \( \sim 100\% \)
- \( \sigma_{E/E} \sim 2.5 \times 10^{-5} \)
- Beam P \( \sim 80\% \)
- \( E_g(\text{tagged}) \sim 0.8 - 5.5 \text{ GeV} \)

HALL B:
- >200 Physicists
- \( \sim 15 \) countries
Bremsstrahlung Tagging Spectrum (20%-95%)

- $E(e^-) = 3.0$ GeV, $E(\gamma) = 0.60 - 2.85$ GeV
- $E(e^-) = 4.0$ GeV, $E(\gamma) = 0.80 - 3.80$ GeV
Superconducting Torus Magnet
6 Superconducting coils for deflecting charged particles

- Clockwise: e⁻: inbending tracks
e⁺: outbending tracks

Drift Chambers
Ar-CO₂
6500 channels/sector to measure the path of a charged particle

Time-of-Flight Hodoscope
48 Scintillators/sector for measuring a particle’s travel time

Electromagnetic Calorimeter
Lead-Scintillator for detecting electrons

- Clockwise: EC e/π rejection factor: ~10⁻²
- Clockwise: CC e/π rejection factor: ~10⁻¹
- Clockwise: EC/CC rejection factor: ~10⁻³

Rejection factor for e⁺e⁻ better than 10⁻⁶
Jlab-HALL-B Experiment E01-112 (also called g7)

\[ \gamma A \rightarrow \rho, \omega, \phi \rightarrow X, \rho, \omega, \phi \rightarrow e^+e^- \] \( E_{\gamma} \sim 0.6 \) to 3.8 GeV, High \( \gamma \) flux: \( 5 \times 10^7 \) tagged \( \gamma/s \)

- Contains materials with different average densities.
- LD2 and seven solid foils of C, Fe, Pb, and Ti.
- Each target material 1 g/cm\(^2\) and diameter 1.2 cm

- Proper spacing 2.5 cm to reduce multiple scattering
- Deuterium target as reference, small nucleus, no modification is expected.
coincident electron pairs in the CLAS

**Caution:** The treatment of the background may change the estimation of the signal ($\rho$).

Excellent $\pi/e$ discrimination: $\sim 10^{-3}$ for one and $\sim 10^{-6}$ for two arms.
Normalized Combinatorial Background

Mixed event technique:

Pairs of identical (e+e+, e-e-) leptons, which are produced only by combinatorial background provide a natural normalization and samples of uncorrelated particles.

\[ N_{-+} = 2\sqrt{N_{-}-N_{++}} \]
Background Subtracted Fits

All the contributing channels to $e^+e^-$ mass spectra studied with GiBUU model. Narrow $\omega$ and $\phi$ can be subtracted from spectrum, leaving “pure” $\rho$

Extracted $\rho$ “spectral functions”
Masses and Widths for Extracted $\rho$

<table>
<thead>
<tr>
<th>Target</th>
<th>Mass (MeV/c$^2$) CLAS data</th>
<th>Width(MeV/c$^2$) CLAS data</th>
<th>Mass(MeV/c$^2$) Giessen BUU</th>
<th>Width(MeV/c$^2$) Giessen BUU</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2$H</td>
<td>770.3 +/- 3.2</td>
<td>185.2 +/- 8.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>762.5 +/- 3.7</td>
<td>176.4 +/- 9.5</td>
<td>773.8 +/- 0.9</td>
<td>177.6 +/- 2.1</td>
</tr>
<tr>
<td>$^{48}$Ti-$^{56}$Fe</td>
<td>779.0 +/- 5.7</td>
<td>217.7 +/- 14.5</td>
<td>773.8 +/- 5.4</td>
<td>202.5 +/- 11.6</td>
</tr>
</tbody>
</table>

The mass of the $\rho$ meson consistent with no shift. Broadening of the width ($\Delta \Gamma \sim$70 MeV).
Absorption of $\omega$ Meson and its in-medium width

The in-medium width is $\Gamma = \Gamma_0 + \Gamma_{\text{coll}}$ where $\Gamma_{\text{coll}} = \gamma \rho v \sigma^*_{VN}$

Transparency ratio:

$$T_A = \frac{\sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma N \rightarrow \omega X}}$$

$$T_{\text{norm}} = \frac{12 \cdot \sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma^{12}C \rightarrow \omega X}}$$

Kaskulov, Hernandez & Oset EPJ A 31 (2007) 245


Latest TAPS $\Gamma_\omega \sim 130-150$ MeV
JLAB preliminary results $\rightarrow$ larger width (>200 MeV)

TAPS (PRL100(2008)192302)
**$\phi$-Meson absorption in medium**

Spring8 $\gamma A \rightarrow \phi A' \rightarrow K^+K^- A'$ ($E_\gamma = 1.5$-$2.4$ GeV)

Normalized to carbon

\[ T_A / T_{12} \]

$\sigma_{\phi N} \sim 25 - 55 \text{mb}$

$\Gamma_{\phi} (\sim 70 \text{ MeV})$ compatible with Spring8

Large statistical error bars.
### In-medium m and $\Gamma$ of vector mesons (elementary reactions)

<table>
<thead>
<tr>
<th>exp</th>
<th>reaction</th>
<th>Momentum Acceptance</th>
<th>$\rho$</th>
<th>$\omega$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK</td>
<td>pA 12 GeV</td>
<td>p &gt;0.6 GeV/c</td>
<td>$\Delta m/m = -9%$</td>
<td>$\Delta \Gamma \sim 0$</td>
<td>$\Delta m/m = -3.4%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Delta \Gamma \sim 0$</td>
<td></td>
<td>$\Delta \Gamma^{(*)/\Gamma} \sim 3.6$</td>
</tr>
<tr>
<td>JLab</td>
<td>$\gamma A$ 0.6-3.8 GeV</td>
<td>p &gt;0.8 GeV/c</td>
<td>$\Delta m \sim 0$</td>
<td>$\Delta \Gamma \sim 70$ MeV \ ($\rho \sim \rho_0/2$)</td>
<td>$\Delta \Gamma(\rho_0) &gt; 200$ MeV \ ($\omega &gt; 1$ GeV/c)</td>
</tr>
<tr>
<td>TAPS</td>
<td>$\gamma A$ 0.9-2.2 GeV</td>
<td>p &gt;0 MeV/c</td>
<td>NA</td>
<td>$\Delta m \sim 0$</td>
<td>$\rho_0 &lt; 0.5$ GeV/c $\Delta \Gamma(\rho_0) \sim 130$ MeV \ ($\omega &gt; 1.1$ GeV/c)</td>
</tr>
<tr>
<td>Spring8</td>
<td>$\gamma A$ 1.5-2.4 GeV</td>
<td>p &gt;1.0 GeV/c</td>
<td>NA</td>
<td>NA</td>
<td>$\Delta \Gamma(\rho_0) \sim 70$ MeV \ ($\phi &gt; 1.8$ GeV/c)</td>
</tr>
<tr>
<td>CERES</td>
<td>Pb+Au 158 AGeV</td>
<td>$p_t &gt; 0$ GeV/c</td>
<td>Broadening favored over mass shift</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>NA60</td>
<td>In+In 158 AGeV</td>
<td>$p_t &gt; 0$ GeV/c</td>
<td>$\Delta m \sim 0$ Strong broadening</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Summary and Conclusions

- The chiral condensate \(< 0 | q\bar{q} | 0 >\) is a measure of the breaking of chiral symmetry and its study is as important as the search for the Higgs to understand the origin of the mass of hadrons.
- Evidences for partial restoration of Chiral Symmetry?
  - Strongest is reported in deeply bound pionic states
    \(< 0 | q\bar{q} | 0 >\) drops by 33\% in nuclei
  - Enhancement in the \(\sigma\) channel near the \(2m_\pi\) threshold is explained by final state interactions
  - Excess of dileptons in RHIR in the region of vector mesons can be explained by a widening of the \(\rho\).
  - Several “elementary reactions” report medium modifications for the \(\rho\), the \(\omega\) and the \(\phi\) mainly broadening. Only one experiment report a mass shift.
- Substantial theoretical and experimental efforts are being carried out in this very active field.

ONE OF THE MAIN GOALS OF HADRONIC PHYSICS
What’s Next?

Experiments looking at vector mesons with low momentum relative to medium (p<800 MeV/c) are needed with di-leptons in final state.

- Experiment g7b at JLab.
- ρ and ω studies at JPARC

Mesic atoms (K, η, ω, φ…) experiments at JPARC

HI experiments at RHIC and Alice at CERN

PANDA and CBM at FAIR
Other mesons

I) Low Mass Region
   o Vector mesons in medium

II) Intermediate Mass Region
   o Thermal dileptons
   o Heavy quarks continuum: open charm

III) High Mass Region
   o Heavy quarks resonances

\((J/\psi)\) sensitive to the gluon condensate, \(\Delta m \leq 10\,\text{MeV}\)

\[ \frac{D(c\bar{q})}{D(q\bar{c})} \quad \Delta m = -50 \left( \frac{\rho}{\rho_0} \right) \text{MeV} \]

Experiences @FAIR, JPARC, JLAB12, CERN