Modifications of hadrons in the nuclear medium - experimental overview

C. Djalali (University of South Carolina)

Outline

-Main Motivation

Nuclear medium as a laboratory to study the properties of hadrons.

-Nucleon properties in the medium

-Structure functions

-Form factors

-Meson properties in the medium

Meson-Nucleon interactions in the medium

-Pionic states

-Sigma channel in 2π production on nuclei

-Kaons in the medium

Light vector mesons properties in the medium

-In relativistic heavy ion collisions

-In nuclei

-Summary-Conclusions-Outlook

Jefferson Lab
Thomas Jefferson National Accelerator Facility

University of South Carolina

QCD: Main theory of the strong interaction

-At sufficiently high nuclear density and/or temperature, the correct degrees of freedom are quarks and gluons.

-At low energies, conventional nuclear physics (with nucleons and mesons) is quite successful in describing the nucleus.

-Understanding the transition from nucleon and meson degrees of freedom to quarks and gluons is one of the main goals of hadronic physics.

-Lattice QCD simulations have improved drastically and may eventually give reliable information on the density and temperature dependence of hadron properties in the nuclear medium.

-Meanwhile, QCD inspired models provide a very important step to understand the main feature of nuclear phenomena and structure of finite nuclei based on the quark and gluon degrees of freedom.

-The medium is used as a laboratory to test these models. The QCD "vacuum" is modified in the medium (**critical role of Chiral Symmetry**) → Hadrons are expected to change.

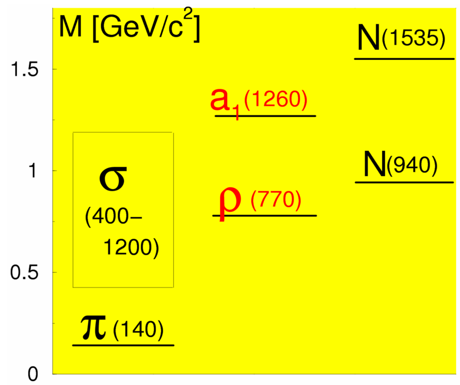
Chiral symmetry (χ_s) is spontaneously broken in vacuum

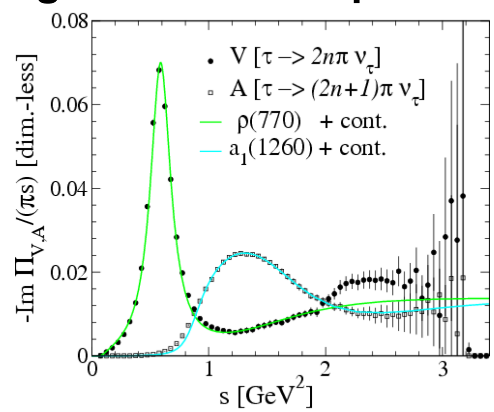
In the light quark sector (u, d), χ_s is a very good symmetry of the QCD Lagrangian, However, QCD vacuum doesn't possess the symmetry of the Lagrangian,

χ_s is spontaneously broken in the vacuum (origin of 98% of the mass of hadrons).

The (almost massless) pions are the Nambu-Goldstone bosons.

Spectral evidence of χ_s breaking: we have non degenerate chiral partners





(non zero order parameters "measure" how much the symmetry is broken).

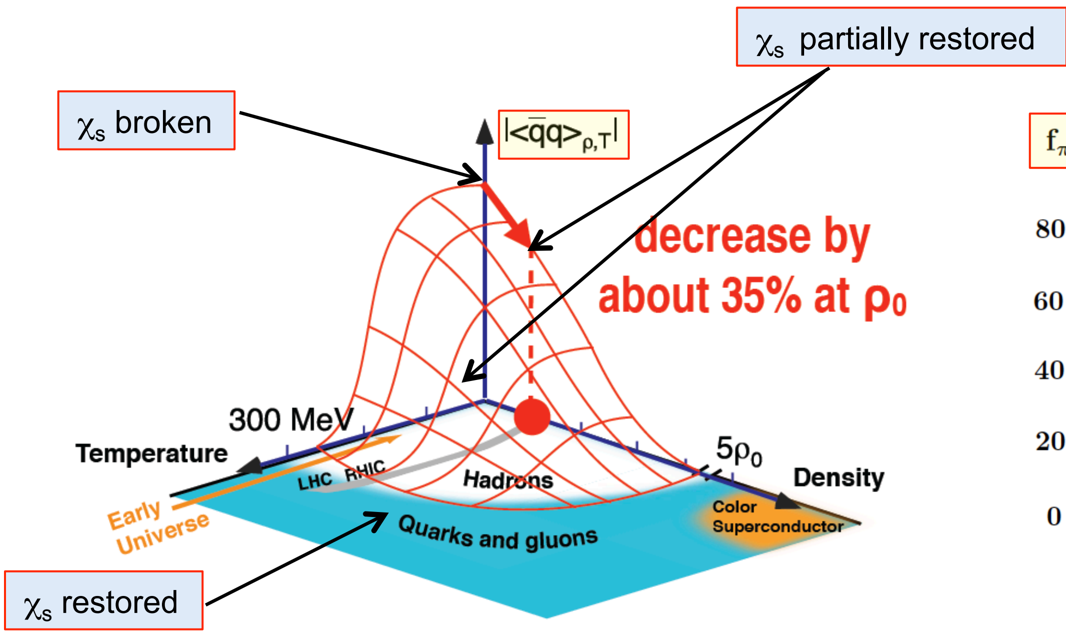
In vacuum
- **-quark condensate** $\boxed{\langle 0 | q\bar{q} | 0 \rangle \approx -(250\mathrm{MeV})^3 \pm 10\%}$
- **-pion decay constant** $\boxed{f_\pi}$ **~ 93 MeV**

Gell-Mann- Oakes – Renner (GOR) relation

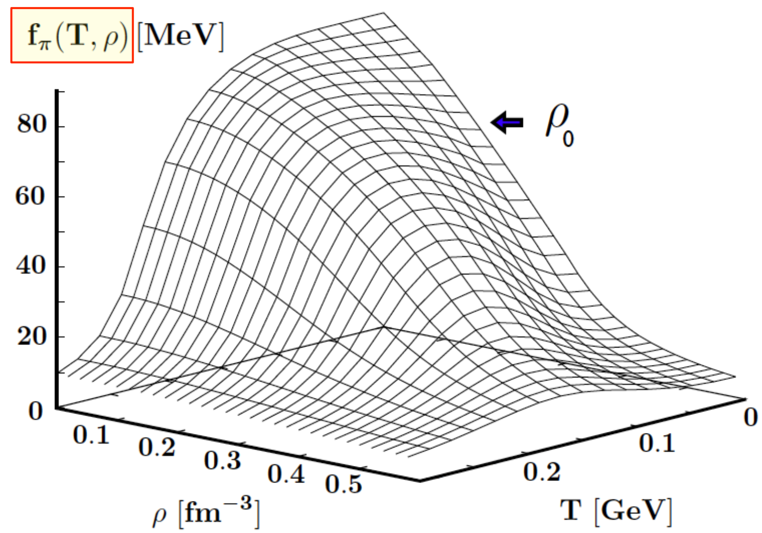
$$\boxed{m_\pi^2 f_\pi^2 = -2(m_u + m_d) < 0 | q\bar{q} | 0 > + O(m_q^q)}$$

Properties of $<0|q\bar{q}|0>$ and f_π in medium

As temperature (T) and/or density (ρ) increases in the medium, both order parameters drop and χ_s is restored.



Hatsuda et al, PRL55 (1985)158
Weise et al, NPA 553(1993)59



Ratti et al, PRD73(2006)014019
S. Klimt et al, PLB249(1990)386

With T and ρ dependence of the type:

$$\frac{f_\pi^2(T,\rho)}{f_\pi^2(0)} \approx \frac{<0|q\bar{q}|0>_{T,\rho}}{<0|q\bar{q}|0>_0} = 1 - aT^2 - b\rho + \ldots$$

NPB 321 (1989) 387.
PRC 45 (1992) 1881.
PLB 357(1995)199

Nuclear Medium Effects on Bound Nucleons

The nucleus is used as a laboratory to study the changes in the properties of the nucleon. Several effects are observed:

- **-EMC effect (experimentally well established) (See next talk)**
- **-Coulomb Sum Rule quenching ? (still no consensus) 10 to 30% increase in r_p? Jlab results might clarify the situation. (Meziani et al)**
- **-Electromagnetic Form Factor Modifications in ^{4}He Medium modification vs FSI.**
- **-Short range correlations : Accessing cold dense nuclear matter**
- **-Color Transparency**
- **-Quark propagation in nuclear matter.**
- **-GPD in medium; …..**

JLab experiments

In-Medium Properties	Reaction	Target	Experiment
Form Factors	$(\vec{e},e'\vec{p})$	^{1}H, ^{2}H, ^{4}He, ^{16}O	E89-028,E93-049, E03-104,E89-033
Nucleon Charge	(e,e')	^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb	E05-110
Structure Function F_2	(e,e')	^{1}H, ^{2}H, ^{3}He, ^{4}He, Be, C, Al, Fe, Cu, Au	E89-008,E02-019, E03-103
Structure Function F_2, σ_L/σ_T	(e,e')	^{1}H, ^{2}H, C, Al, Fe	E99-118,E04-001
Vector mesons	(γ,e^+e^-)	^{2}H, C, Ti-Fe, Pb	E01-112
Fragmentation functions	$(e,e'x)$	C, Al, Fe, ^{120}Sn, Pb	E02-104

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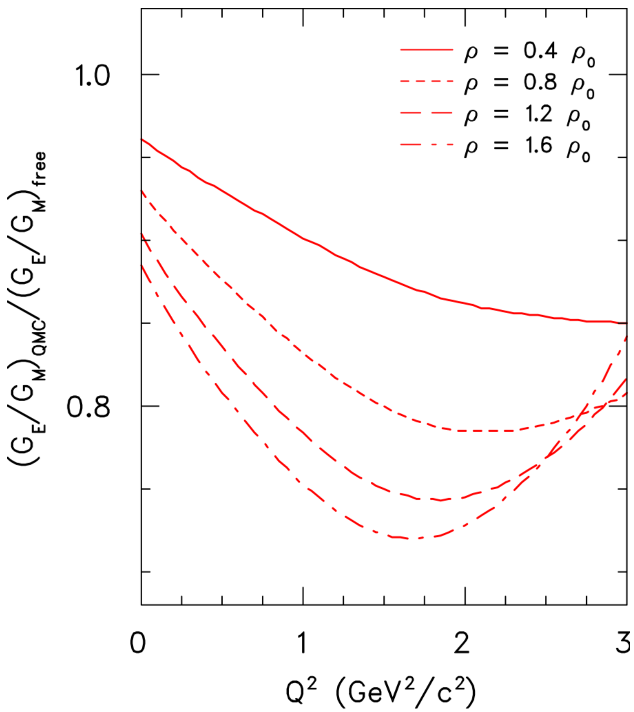
In medium changes of the nucleon electromagnetic form factors

Quark Meson Coupling Model (QMC)

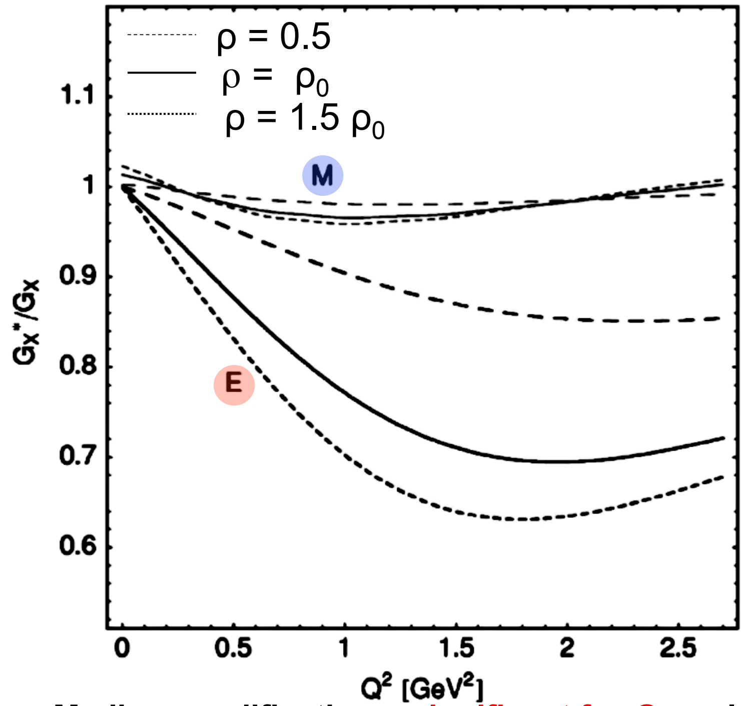
Phys. Lett. B 417, 217 (1998)
Phys. Rev. C 60, 068201 (1999)



- Electromagnetic rms radii and magnetic moments of the bound proton are increased
- At low Q^2: Charge form factor much more sensitive to the nuclear medium than the magnetic ones

Chiral Quark Soliton Model (CQS)

Phys. Rev. C 70, 065205 (2004)



- Medium modifications: significant for G_E, only moderate for G_M
- no strong enhancement of the magnetic moment
- sea quarks almost completely unaffected

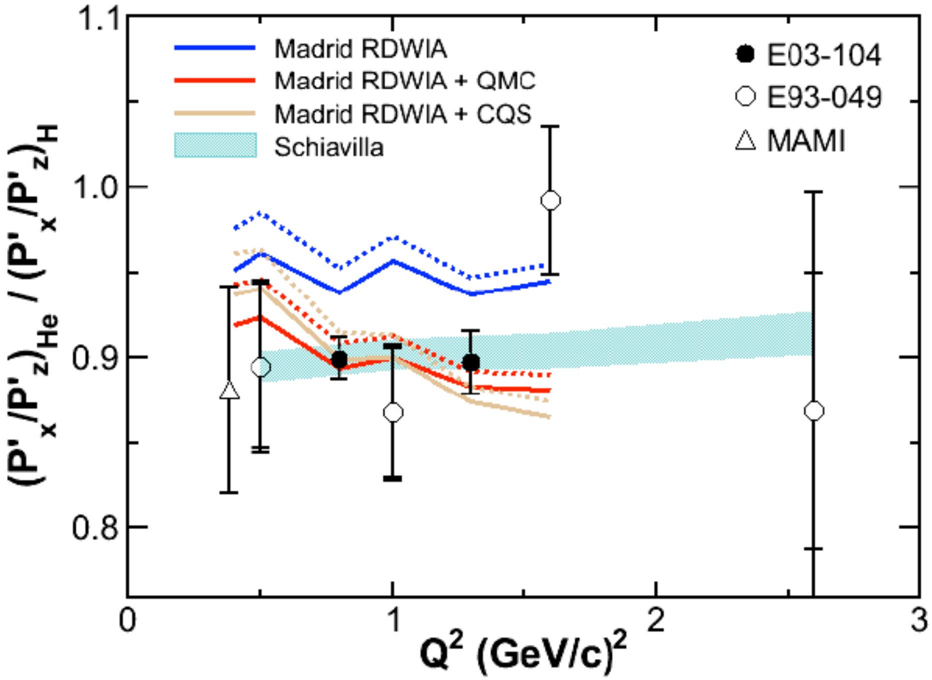
Proton Recoil Polarization in $^4He(\vec{e},e'\vec{p})^3H$ [E03-104]

M. Paolone et al, arXiv:1002.2188v5 [nucl-ex], accepted in PRL
S. Malace et al., to be submitted to PRL

Two polarization observables act together to constrain the interpretation of the data

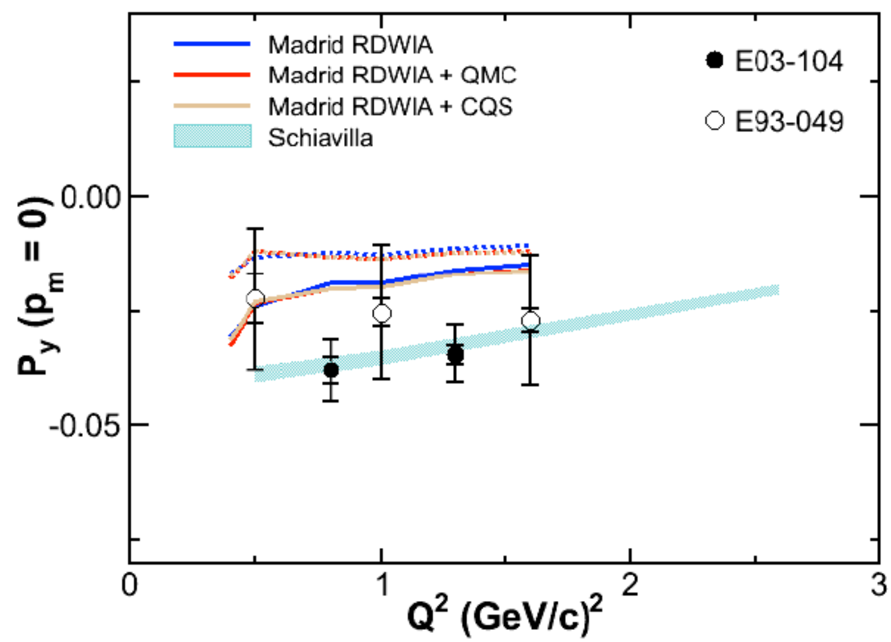
Polarization transfer
sensitive to in-medium form factors

$$\frac{G_E}{G_M} \propto -\frac{P'_X}{P'_Z}$$



Clear medium modification of form factors described by QCM and CQS

Induced polarization
sensitive to final-state interactions
not sensitive to in-medium form factors

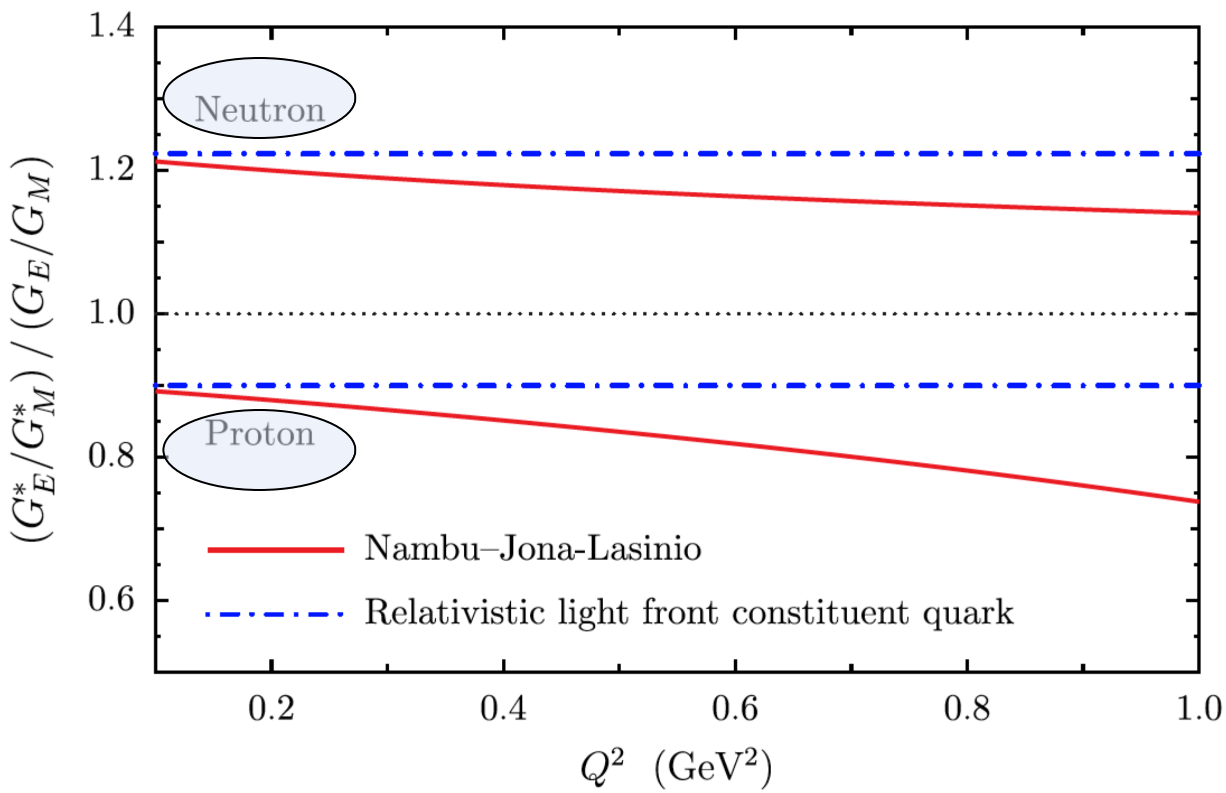


P_y data crucial to clarify role of FSI

Medium-modified proton form or a spin-dependent charge-exchange FSI??

Neutron Recoil Polarization in $^4He(\vec{e},e'\vec{n})^3He$

I. C. Cloet et al, PRL 103, 082301 (2009)



Different predicted medium modification for n and p

$(\vec{e},e'\vec{n})$ measurements on nuclear targets can provide important additional and complementary information to existing $(\vec{e},e'\vec{p})$ data!

LOI-10-007 accepted and new proposal being prepared

Summary and Outlook (Nucleon)

- EMC effect: No doubt that the nucleon quark distributions are modified in medium however no single model has yet been able to explain the effect over all x and A.
- Recent EMC measurement on light nuclei indicates the important role of local density (clusters in nuclei).
- Polarization transfer experiments seem to indicate that the nucleon electromagnetic form factors are modified in ^{4}He. (Role of FSI?)
- Coulomb Sum rules: High precision results coming soon from JLab
- Changes in Static properties? swelling 10 to 30% in size?

  effective mass dropping by ~20%?

Planned experiments at new facilities JLab12, FAIR, JPARC:

- Polarized EMC
- Polarization transfer for neutron
- EMC effect for sea quarks, gluons (Drell Yan and open charm)
- GPDs in the medium

Medium Modification of Light Mesons

Many models with different degrees of sophistication predict substantial changes in the properties of mesons. QCD inspired models show that Chiral restoration in the medium leads to changes in the mass of mesons.

As chiral symmetry is restored, the magnitude of the order parameter drops.

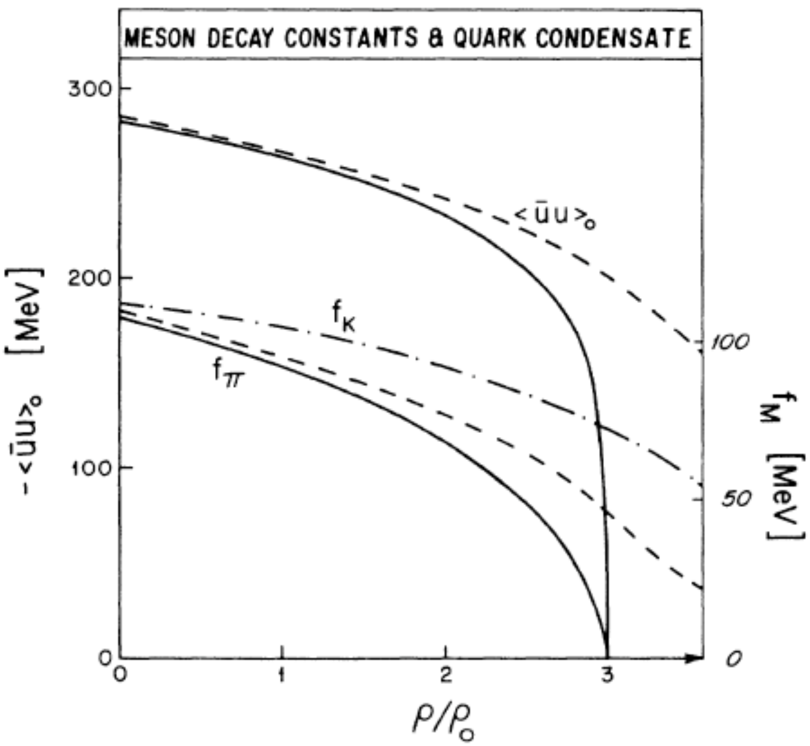
However the quark condensate is not an observable. We need theoretical models to relate the quark condensate to actual experimental observations. Unambiguous links between the in medium properties of hadrons and $<0|q\bar{q}|0>$ are not yet fully established.

What are the predictions ?? →

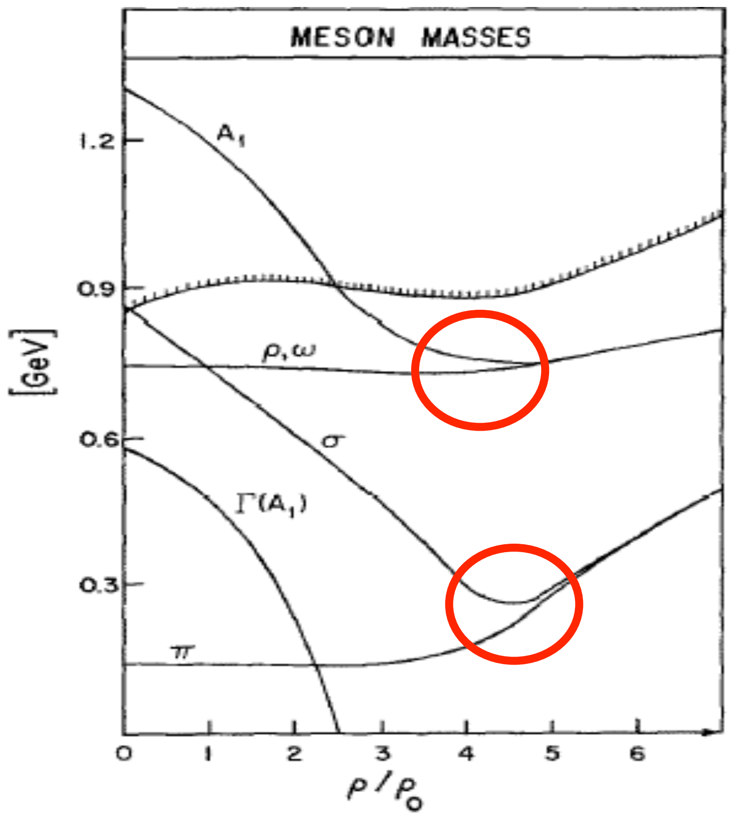
Nambu-Jona-Lasinio model at finite T and ρ

Dynamical treatment of mass generation and meson properties

V. Bernard et al,PRL. 59 (1987) 966 and PRD38 (1988) 1551, NPA489 (1988) 647
T. Hatsuda et al, PRL55 (1985) 158 and PLB185 (1987) 304
U. Vogl et al,, Prog. PNP 27 (1991)195.



$< 0 | q\bar{q} | >$ and f_π as a function of ρ



As density increases, $m_{\pi,\rho,\omega}$ ~ constant
Degeneracy of chiral partners

QCD Sum Rules (QCDSR) - Mass scaling - QMC

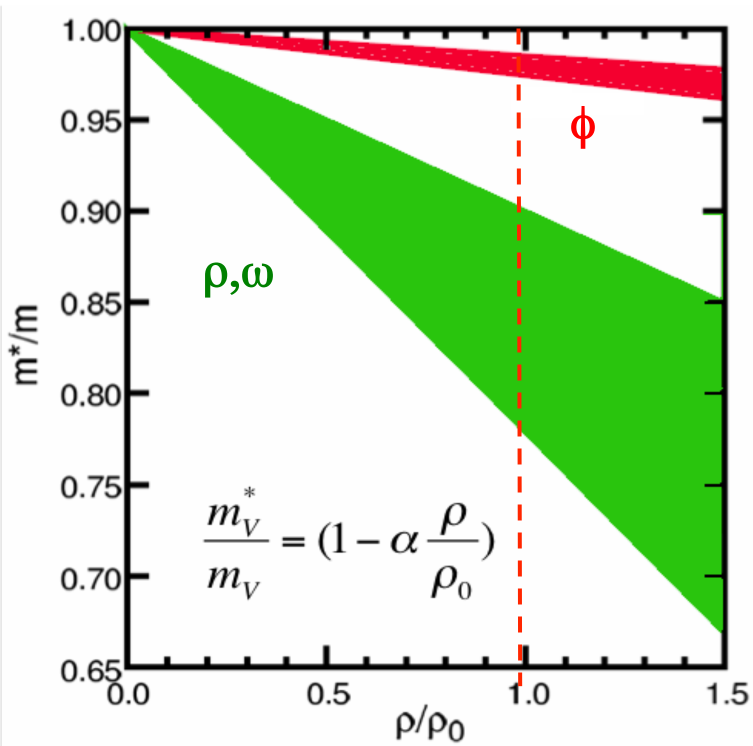
<u>QCDSR</u> give useful constraints. Only averages not detail shapes of spectral functions.
M. A. Shifman et al., NPB147 (1979)385, 448
T. Hatsuda et al, PRC46 (1992) R34; NPB394 (1993) 221
Y. Kwon et al, PRC78 (2008) 055

<u>Mass Scaling Conjecture</u>: Effective chiral Lagrangians with scaling properties of QCD lead to approximate in-medium scaling law.
Brown and Rho, PRL66 (1991) 2720
T. Harada et al, PRD66, (2002)016003 ; PLB537 (2002)280; PRD73, (2006)036001.

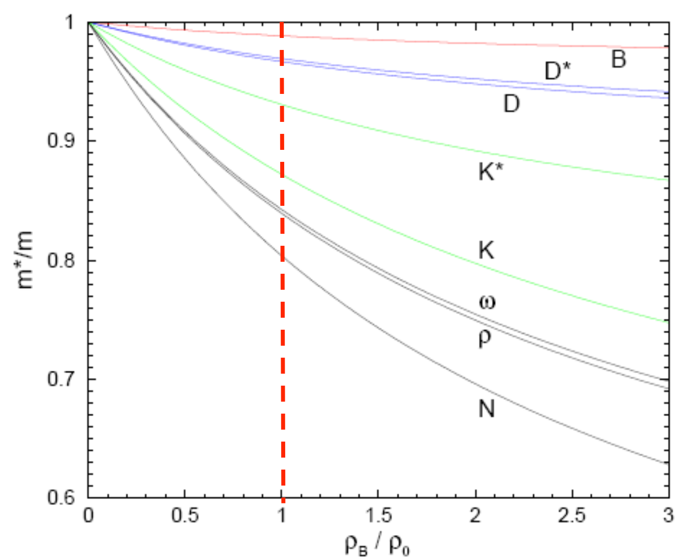
ρ_0 is normal nuclear density 0.17 fm^{-3}
α~0.18±0.06 for V= ρ ,ω
α~0.15y for V= ϕ (y nucleon strangeness content)

"Brown-Rho Scaling"

$$\frac{m_\sigma^*}{m_\sigma} \approx \frac{m_N^*}{m_N} \approx \frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \frac{f_\pi^*}{f_\pi} \approx 0.8\,(\rho \approx \rho_0)$$



Phenomenological theory confining quarks and gluons in a "bag". In-medium mesons feel a scalar potential → universal scaling law.
K. Saito et al, PRC55 (1997) 2637

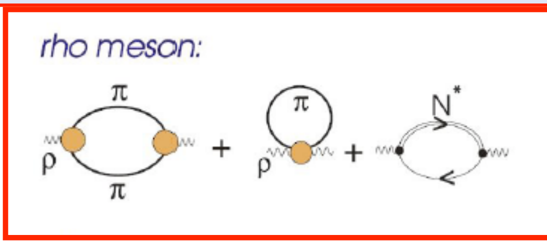


Hadronic models

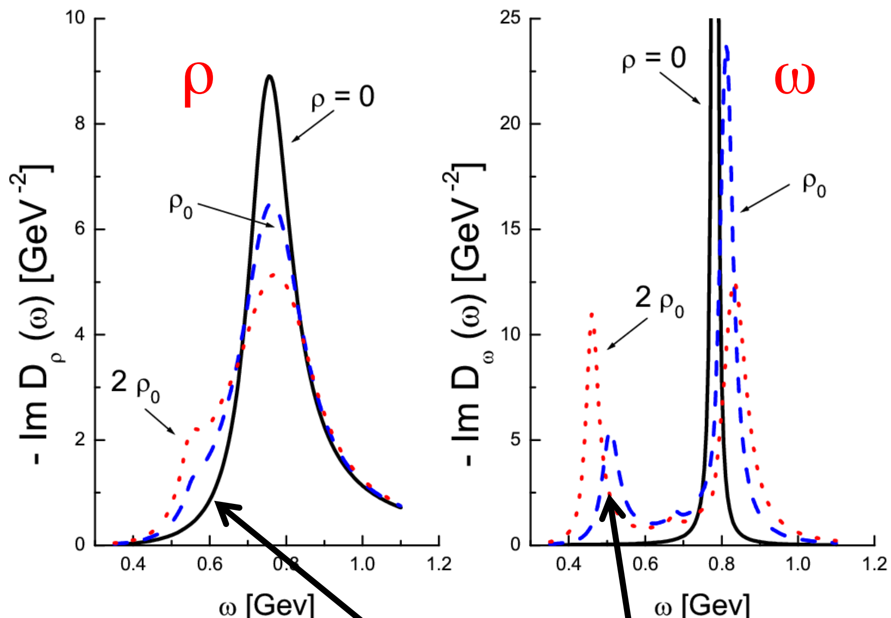
-Contrary to the models described so far (which gave average constraints), hadronic models calculate the spectral function of the mesons in the medium.. **Mesons are propagating in medium and coupling to resonances** → "richer predictions" (spectral shift, broadening, new spectral peaks, etc…)

Rapp, Wambach, EPJA 6 (1999) 415
B Friman et al, *NPA617 (1997) 496*
R. Rapp et al, *NPA617 (1997) 472*

M. Lutz et. al. , Nucl. Phys. A 705 (2002) 431



M. Post et al., nucl-th/0309085



A_T [GeV^{-2}]

ρ-meson

q [GeV]

m [GeV]

structures in spectral functions due to coupling to baryon resonances

Mesons as probe of Chiral Symmetry restoration

Experiments roughly fall under two categories

1) **Looking at the modification of the meson-nucleon interaction in medium:**

   -pionic atoms (capture and nuclear reaction),

   -elastic pion-nucleus scattering at low energy

   -Double pion production in nuclei and the σ.

   -Kaons in nuclei

2) **Mass and width changes of light vector mesons ρ, ω and ϕ:**

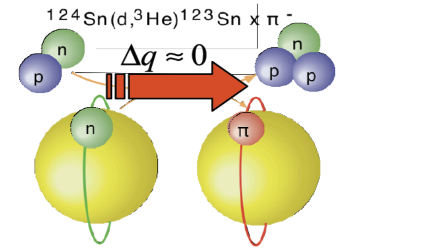
   -direct observation of mass spectra of modified mesons

   -determining in-medium width through transparency ratios

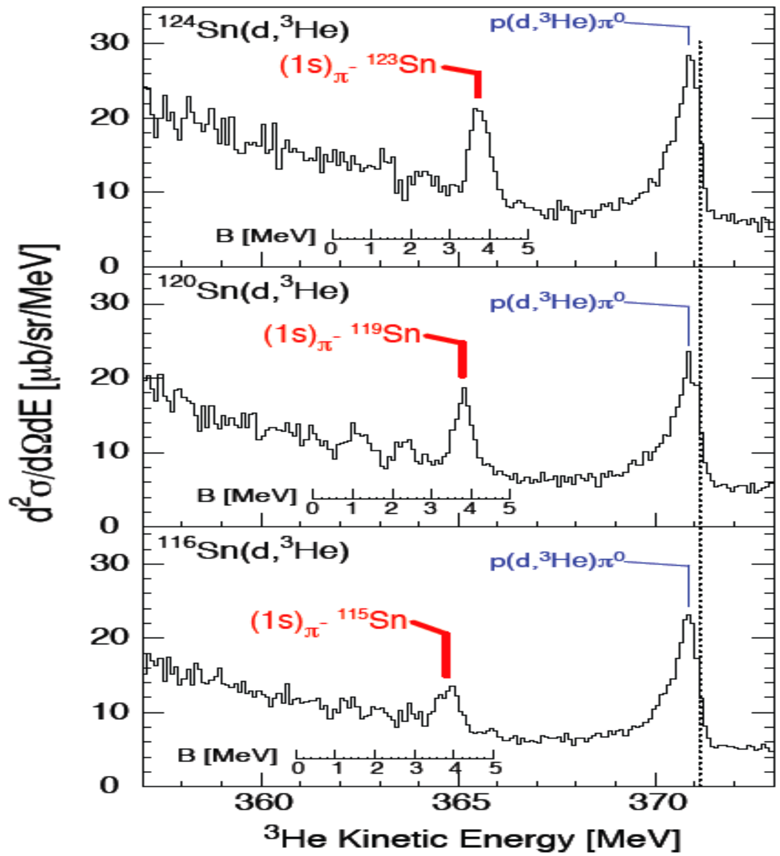
Deeply bound pionic state spectroscopy (GSI-FRS)

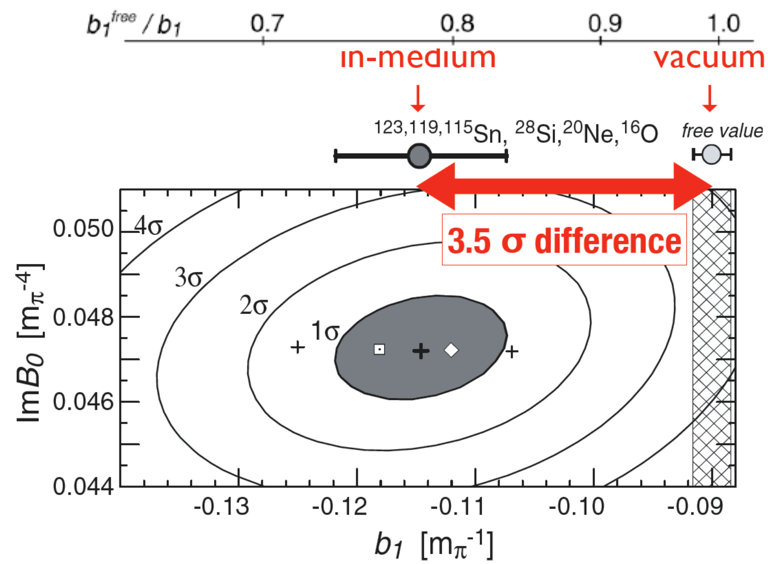
Pionic 1s states in Sn isotopes: [Suzuki et al, PRL 92 (2004) 072302]

- $(1s)_\pi$ peak seen in ^{115,119,123}Sn
- Isotope shift seen for the first time in deeply bound states



Spectator proton → High resolution





Issues: uncertainties on neutron radii in Sn isotopes

$\rho_{eff} \sim 0.6\rho_0$

$$R = \frac{b_1^{\text{free}}}{b_1} = \frac{f_\pi^*(\rho_\varepsilon)^2}{f_\pi^2} = 0.78 \pm 0.05$$

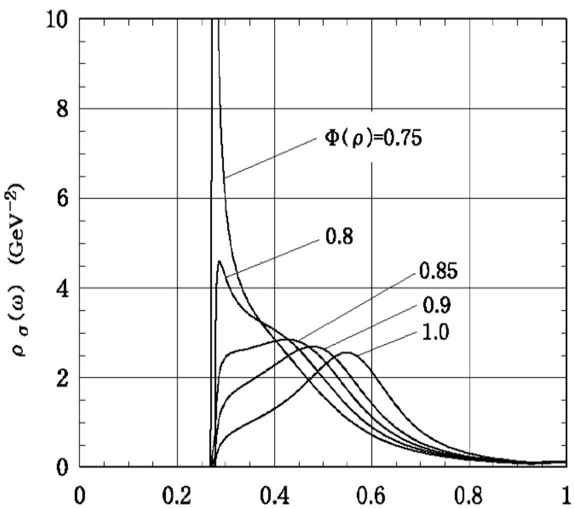
$$\Rightarrow \frac{<0|q\bar{q}|0>_{\rho_0}}{<0|q\bar{q}|0>_0} \approx 0.67$$

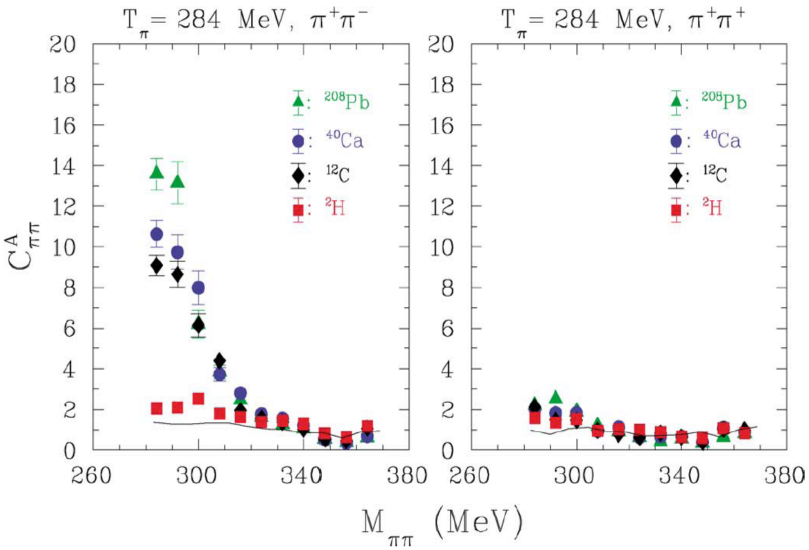
⇒ **strongest evidence of partial restoration of chiral symmetry**
consistent with low energy elastic π-scattering

The “σ” and low mass $\pi^+\pi^-$ enhancement in nuclei

Predictions As Chiral symmetry is partially restored,
-The σ mass drops (σ-π degenerate in chiral limit).
-Phase space for σ →2π closes, σ “becomes narrower” as if shifts to lower masses.

Hatsuda, Kunihiro, Shimizu PRL82(1999)2840





Studying ππ channel

$\pi^+\pi^-$ (I=0, J=0, quantum # of σ and vacuum)

$\pi^+\pi^-$ and $\pi^0\pi^0$ compared to $\pi^+\pi^+$ and $\pi^-\pi^-$

CHAOS: A(π,ππ)X [E_π = 243-305 MeV] observes an enhancement of correlated pions with I=0 close to $2m_\pi$ threshold BUT NO enhancement in $\pi^+\pi^+$ [NPA763 (2005)80]

TAPS: A(γ, $\pi^0\pi^0$)X and A(γ, $\pi^0\pi^\pm$) X [A=(H,C, Ca and Pb) & Eγ=400-500 MeV] observes enhancement in $\pi^0\pi^0$ channel close to 2 m_π threshold [PPNP55 (2005)35]

-First explanation: Chiral restoration is observed!

HOWEVER:

-**Final State Interactions (FSI)** calculations **reproduce the enhancement (due to rescattering) !!!!**

[Buss et al, EPJA32 (2007)219]

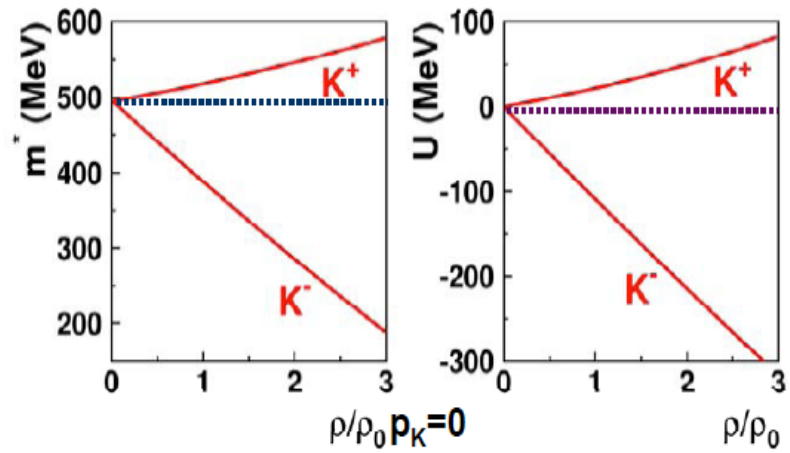
Kaons in Medium

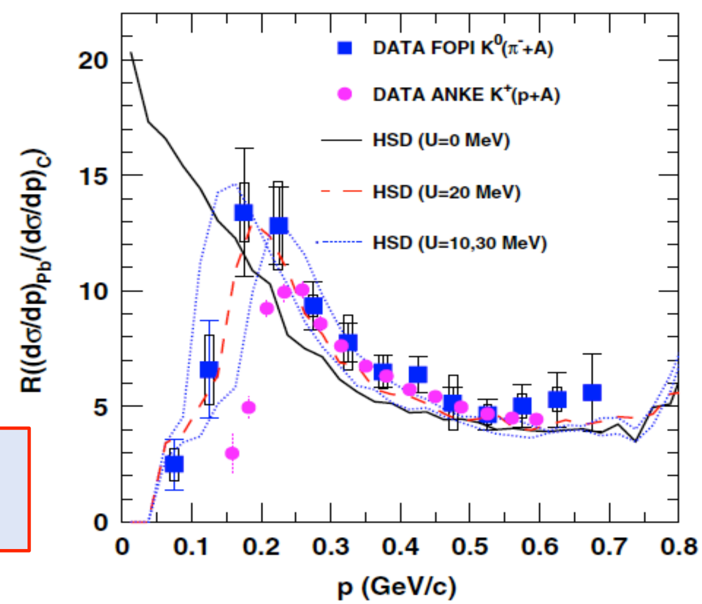
Theoretical models [NPA567(19940937; NPA610(1996)35c; NPA625 (1997)372] predict modifications of masses and coupling constants for kaons and antikaons.

As density increases, $m_{eff}(K^+)$ rises slightly while $m_{eff}(K^-)$ drops "fast".

The FOPI collaboration at GSI has measured the in-medium K^0 inclusive cross sections in $A(\pi^-, \pi^+\pi^-)X$, [A=C, Al, Cu, Sn, Pb; p_π=1.15 GeV/c] PRL102, (2009)1825

The ANKE collaboration at COSY has measured the in-medium K^+ inclusive cross sections in $A(p, K^+)X$, [A=Cu, Au; E_p=2.3 GeV] EJPA15, (2004)30

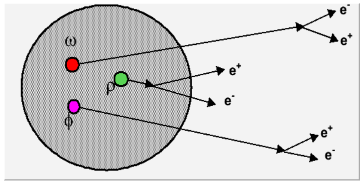




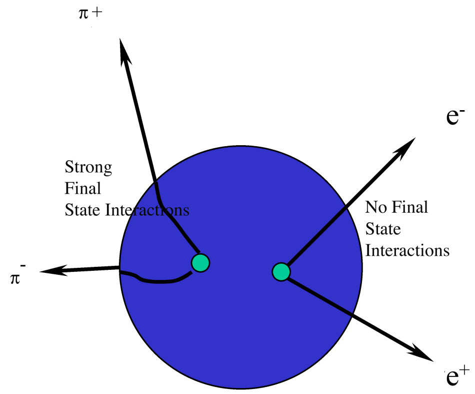
A repulsive KN potential of 20 ± 5 MeV (at normal nuclear density) explains the FOPI and ANKE results

A repulsive KN potential of ~40MeV (at normal nuclear density) has been reported by HADES in RHI collisions [arXiv:1004.3881v1 [nucl-ex]- 22 April 2010]

Vector mesons in Medium



Properties of Vector Mesons $J^p=1^-$ (PDG-2008)					
Meson	Mass (MeV/c^2)	Γ (MeV/c2)	$c\tau$ (fm)	Main decay	$\Gamma_{e+e-}/\Gamma_{tot}$ (x10^{-5})
ρ	~775	~150	1.3	$\pi^+\pi^-$ (~100%)	~5
ω	~783	~8	23	$\pi^+\pi^-\pi^0$ (~90%)	~7
ϕ	~1020	~4	46	K^+K^- (~50%)	~3



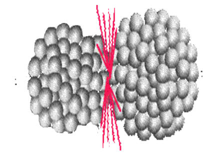
SOME ADVANTAGES

- The **predicted medium modifications** at normal nuclear density **are large**.
- The ρ meson decays fast enough **to test the medium.**
- Di-lepton decay channel available: "cleanest channel" (**no FSI**)

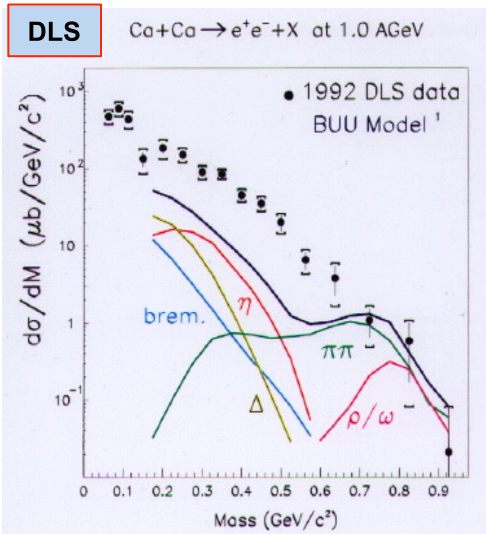
SOME CHALLENGES

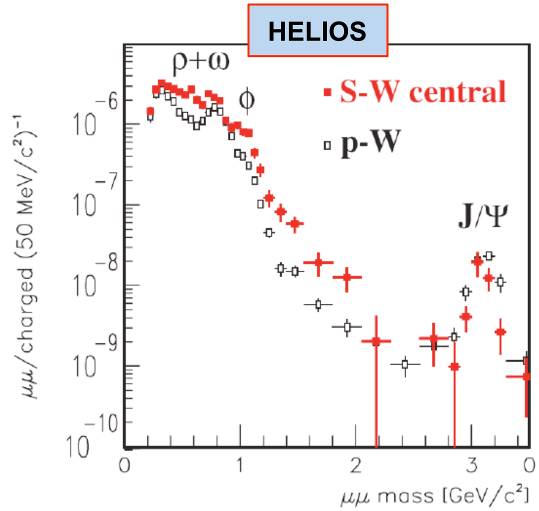
-**Very difficult measurements**. di-lepton decay channel has a **very small branching ratio (~10^{-5})** excellent **lepton-hadron discrimination required**
- **"Large" combinatorial background**.
- Most ω and ϕ (if not absorbed) decay outside of the medium, need low momentum cut.

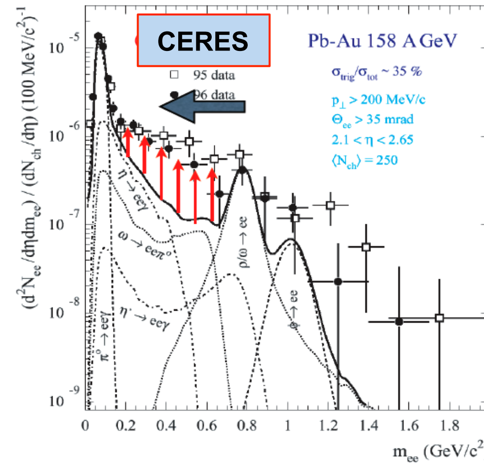
Vector mesons in Medium (Any observations?)

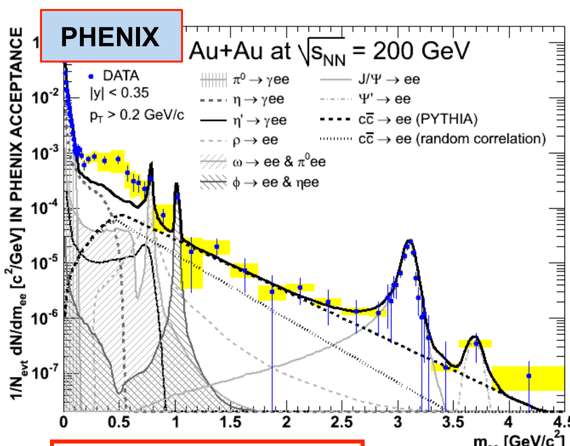


First measurements of possible medium modification of VM came from RHI collisions

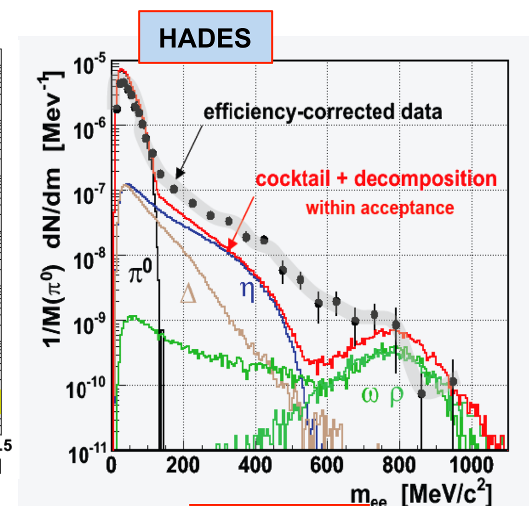




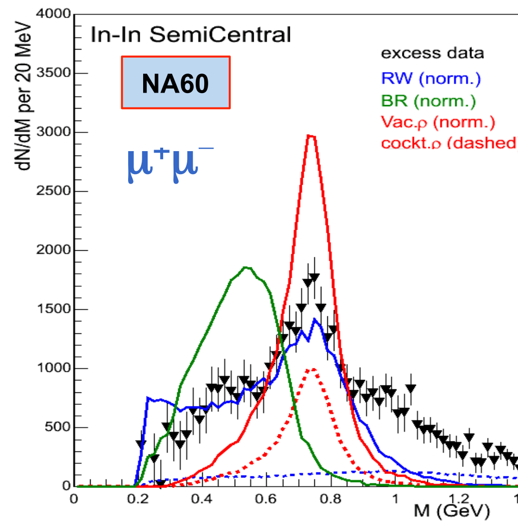




Analysis ongoing

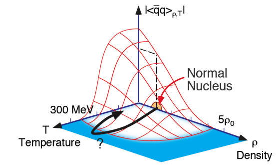


HADES



Broadening favored , no simple mass shift!

What have we learned from Heavy Ion Collisions?



Broadening (NO MASS SHIFT à la BR) of ρ-Meson can explain HI results

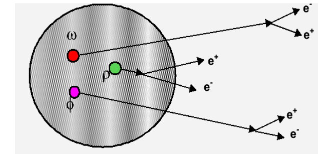
1) In A+A collisions, the results are integrated over a whole range of ρ and T
3) In A+A collisions, the medium is far from equilibrium, making it hard to directly compare to the theoretical models which all assume equilibrium.
3) In A+A collisions, many phases are involved

We need to study the elementary process with probes that leave the nucleus in almost an equilibrium state $\gamma,\pi,p + A \dashrightarrow V\ X$

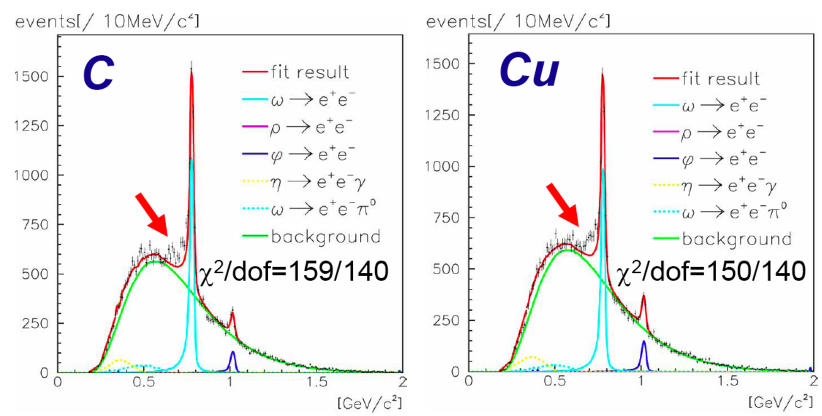
Experiment	*Reactions*	*Final State*
TAGX	$\gamma + {}^2H, {}^3He, C \dashrightarrow \rho + X$	$(\rho \dashrightarrow \pi^+\pi^-)$
KEK	$p + C, Cu \dashrightarrow \rho,\omega,\phi + X$	$(\rho,\omega,\phi \dashrightarrow e^+e^-)$
SPring-8	γ + Li,C,Al,Cu $\dashrightarrow \phi + A^*$	$(\phi \dashrightarrow K^+K^-)$
CBELSA/TAPS	γ + H, Nb $\dashrightarrow \omega + X$	$(\omega \dashrightarrow \pi^0\ \gamma)$
JLab-g7a	$\gamma + {}^2H, C, Fe, Pb \dashrightarrow (\rho,\omega,\phi) + A^*$	$(\rho,\omega,\phi \dashrightarrow e^+e^-)$
HADES	$\pi, p + A \dashrightarrow (\rho,\omega,\phi) + A^*$	$(\rho,\omega,\phi \dashrightarrow e^+e^-)$

-TAGX and Spring-8 have hadronic FS ($\pi^+\pi^-$; K^+K^-)
-TAPS has semi-hadronic FS ($\pi^0\gamma$)
-JLab, KEK, HADES have pure electromagnetic FS (e^+e^-)
-JLab only electromagnetic in IS and FS.

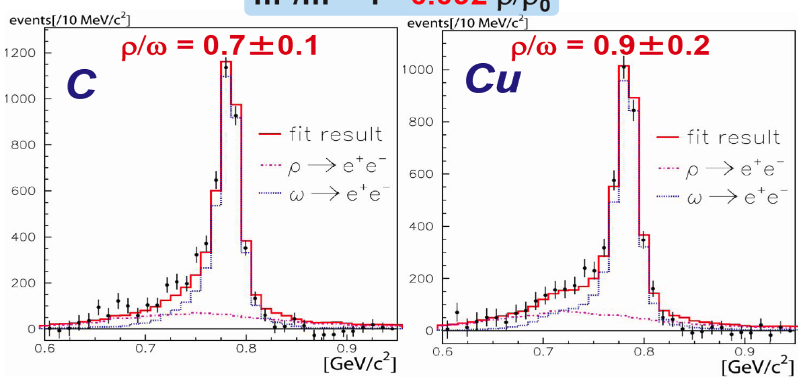
KEK (Japan)-PS E325: p+A → ρ,ω,ϕ+X (ρ,ω,ϕ→e+e-)



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

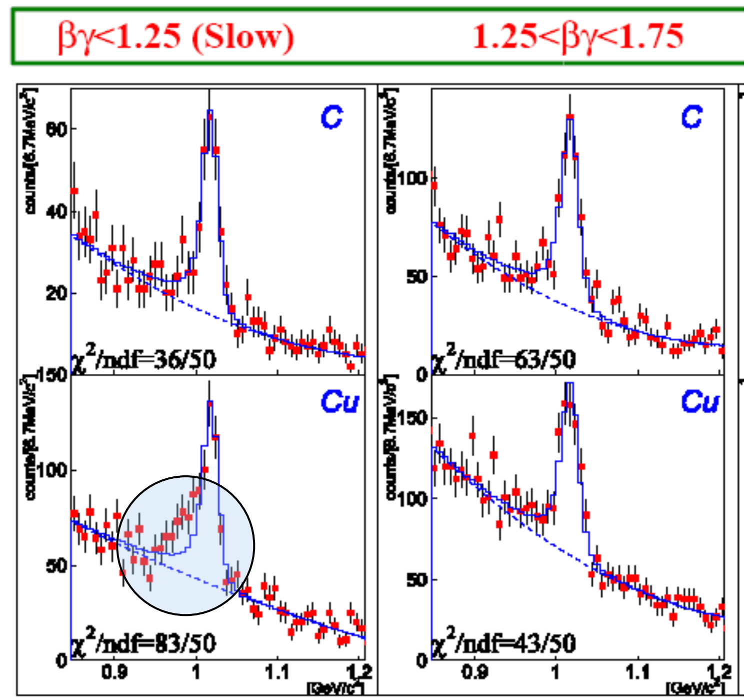


$m^*/m = 1 - 0.092\ \rho/\rho_0$



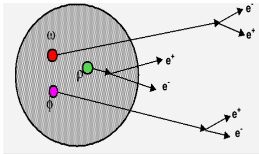
$$m^*/m = 1 - k_1\ \rho/\rho_0,$$
$$\Gamma^*/\Gamma = 1 + k_2\ \rho/\rho_0$$

R.Muto et al., PRL 98 (2007) 042501

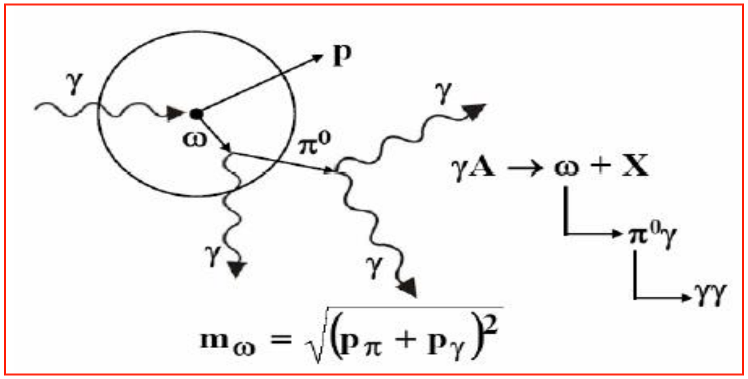


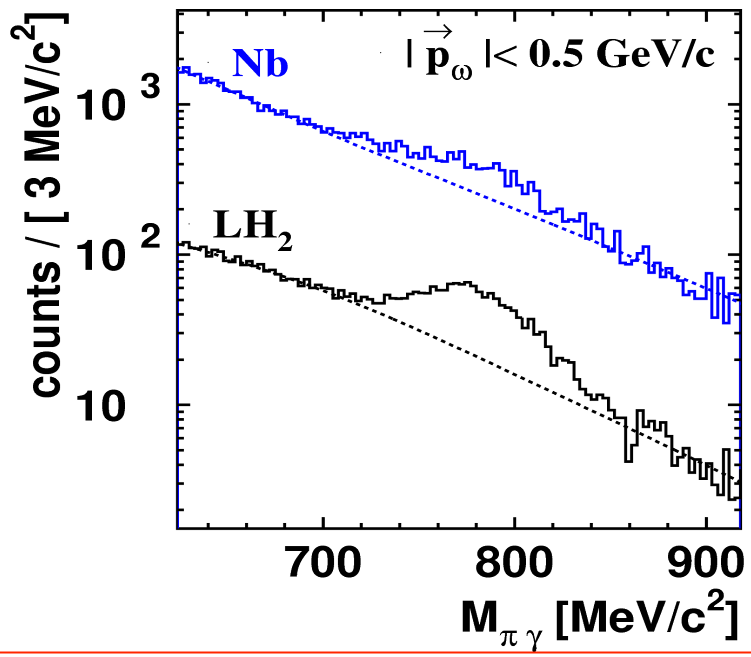
Best Fit Values		
	ρ, ω	ϕ
k_1	9.2 ± 0.2%	$3.4^{+0.6}_{-0.7}$%
k_2	0 (best fit)	$2.6^{+1.8}_{-1.2}$

ω mass spectrum (CBELSA-TAPS first analysis)



γ+A-->ω+X (ω --> π^0 γ)
Eγ = 0.64-2.53 GeV on LH2 and Nb





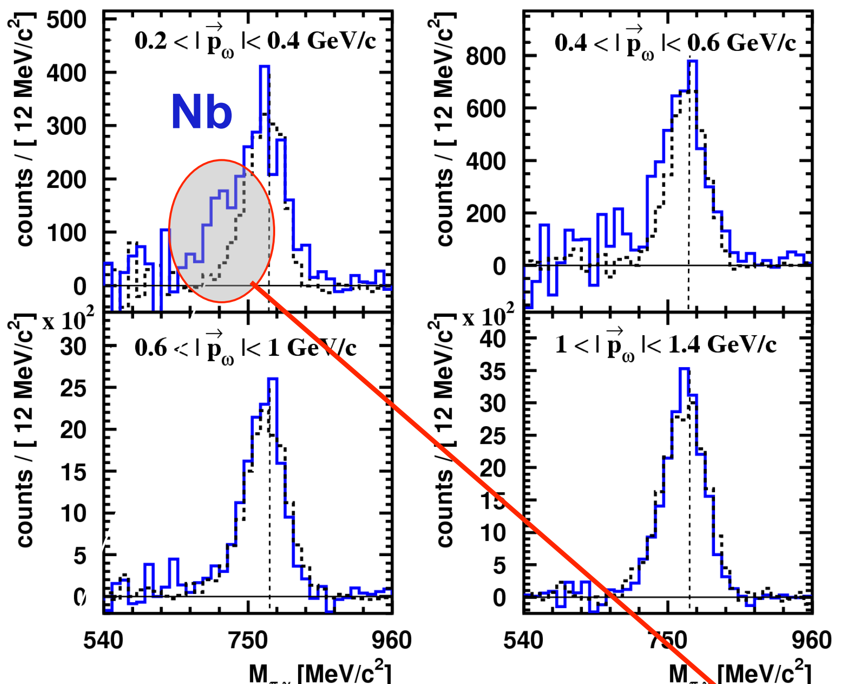
Pro:

- $\pi^0\gamma$ large branching ratio ($8.3 \cdot 10^{-2}$)
- no ρ-contribution ($\rho \to \pi^0\gamma$: $7 \cdot 10^{-4}$)

Con:

- π^0-rescattering (requires T_π>150 MeV cut)
- large combinatorial background (3γ)

D. Trnka et al., PRL94 (2005) 192303



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

Slow ω decaying inside

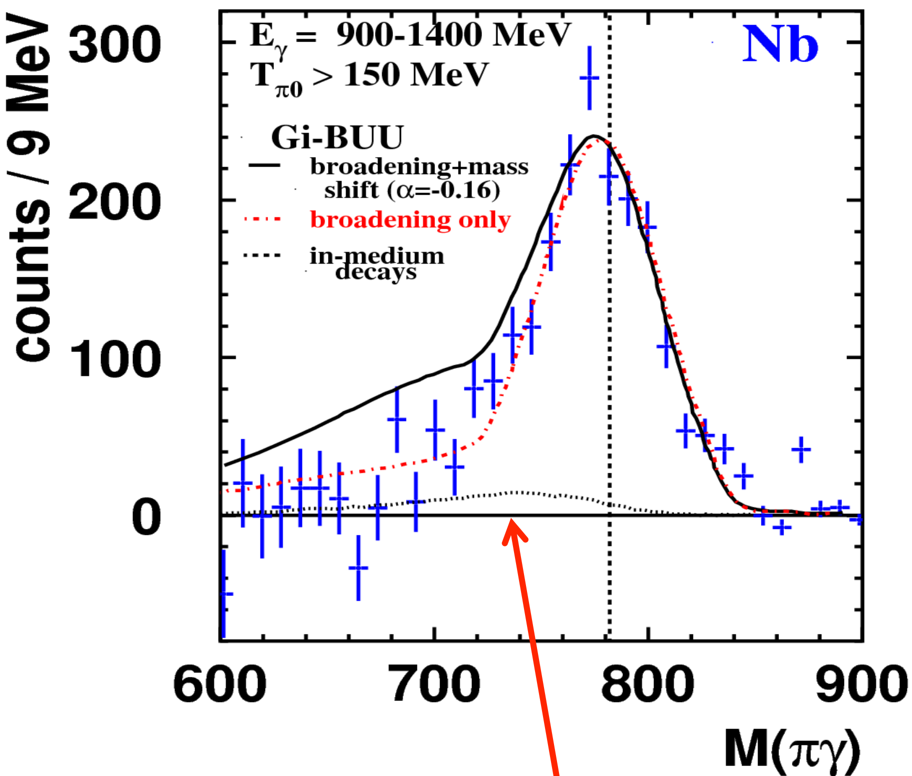
$$m^* = m_0\left(1 - 0.14\,\rho/\rho_0\right)$$

ω mass spectrum Reanalysis of CBELAS/TAPS data

(new treatment of combinatorial background)

Gi-BUU simulations: K. Gallmeister et al. Prog. Part. Nucl. Phys. 61 (2008) 283

M. Nanova et al, (May 28,2010) arXiv:1005.5694v1 nucl-ex]



Experimental data closer to line shape predicted for "broadening only", no mass shift!

Strong broadening of the ω (as seen in transparency ratios) drastically suppresses sensitivity to direct observation of ω decaying in the medium

Ongoing anaysis on data taken at MAMI C with 2 times higher statistics in Eγ = 800-1400 MeV;

Preliminary results from MAMI C data are consistent with the conclusions from the re-analysis of CBELSA/TAPS data for incident photon energies 900-1400 MeV

JLab CLAS Experiment E01-112 (g7)

Photon beam:

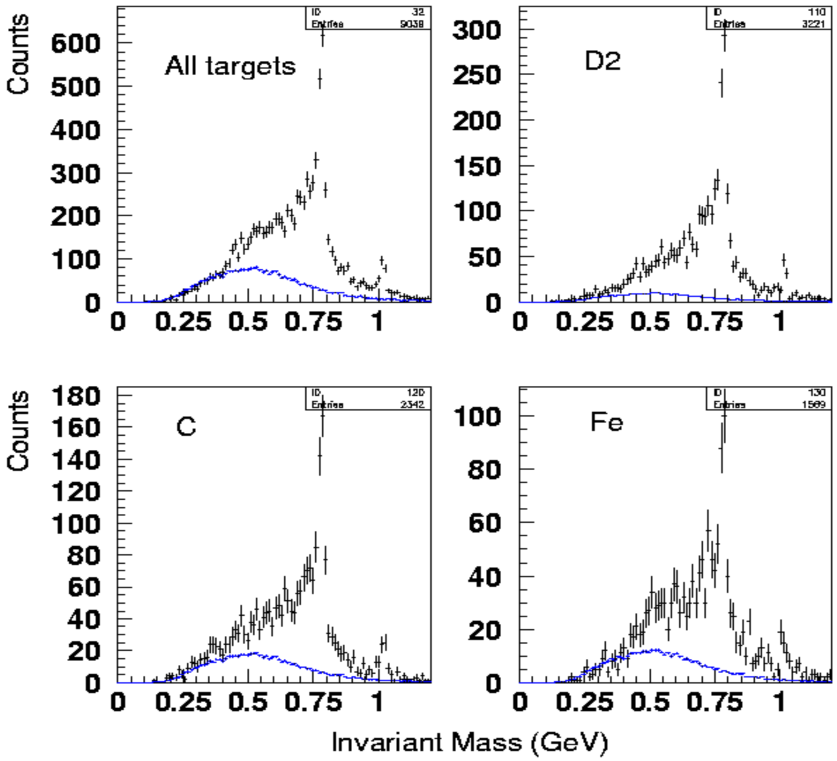
E_γ ~ 0.6 to 3.8 GeV (tagged γ)

High flux : 5 10^7 tagged γ/s

Targets: LD_2, C, Ti, Fe, (Pb)

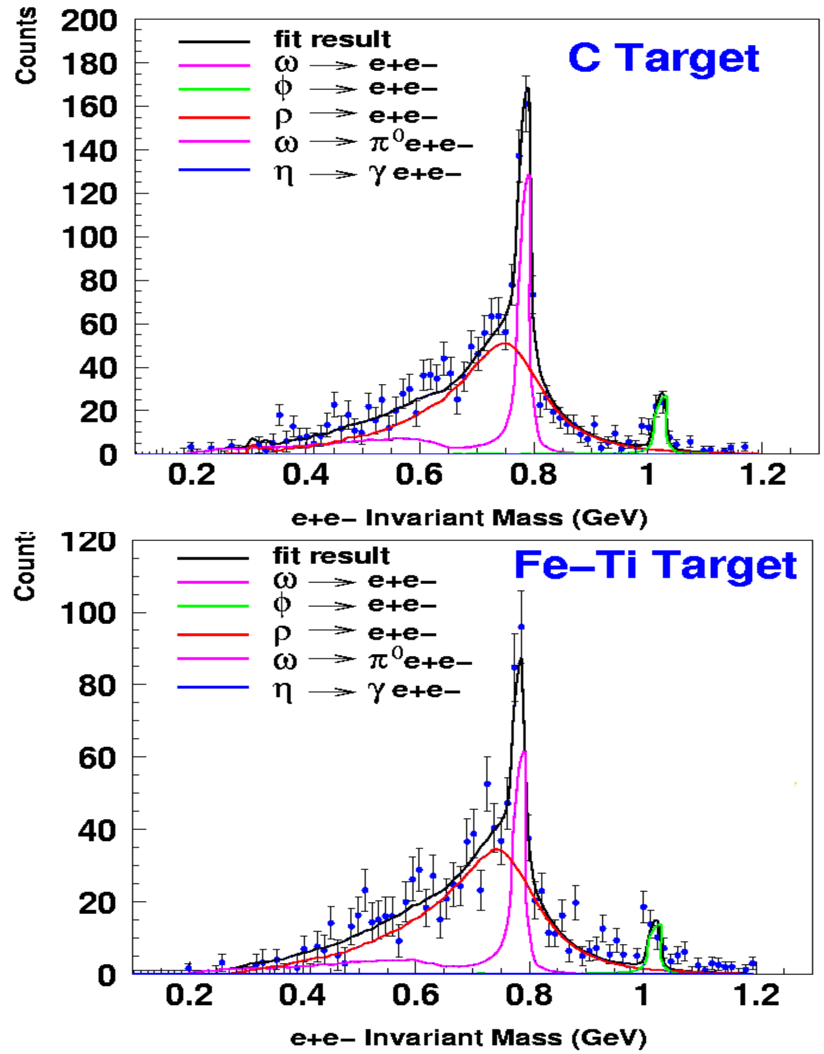
Decay channel: e+e- **(noFSI)**

Excellent e/π discrimination

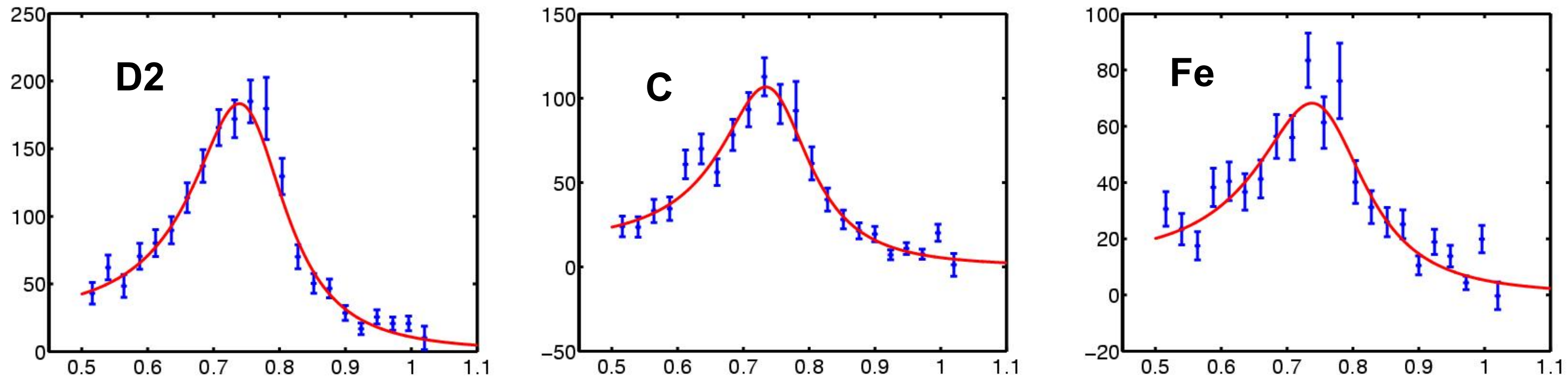


Combinatorial background well understood

After Background subtraction, mass spectra mainly ρ , ω and ϕ.



CLAS-g7-experiment: Extracted ρ mass spectra



e^+e^- Invariant Mass (GeV)

Target	Mass (MeV/c^2) CLAS data	Width(MeV/c^2) CLAS data	Mass(MeV/c^2) Giessen BUU	Width(MeV/c^2) Giessen BUU
^{12}C	**768.5 +/- 3.7**	**176.4 +/- 9.5**	773.8 +/- 0.9	177.6 +/- 2.1
^{48}Ti-^{56}Fe	**779.0 +/- 5.7**	**217.7 +/- 14.5**	773.8 +/- 5.4	202.5 +/- 11.6

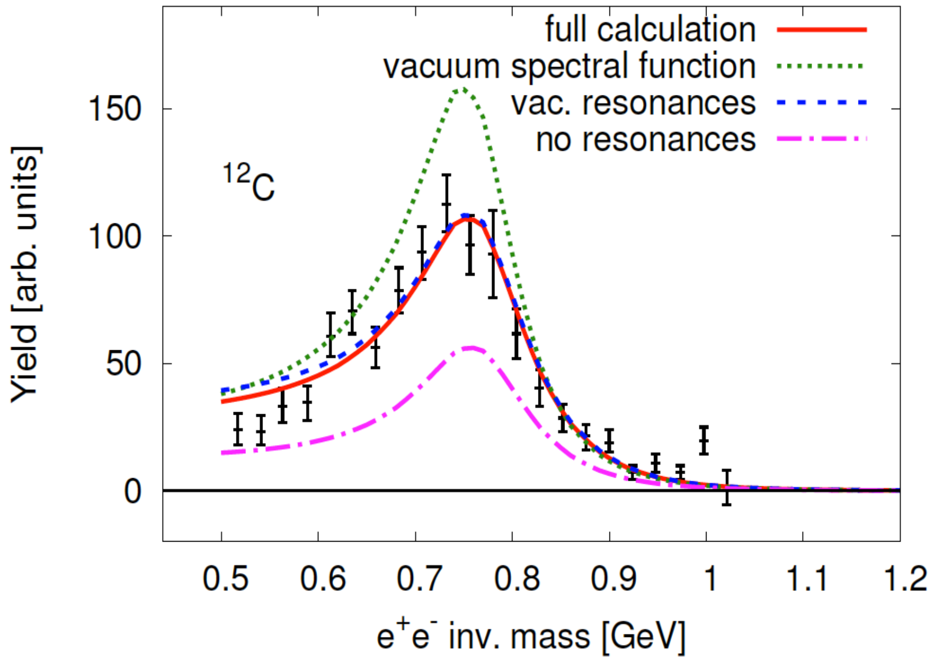
The mass of the ρ meson consistent with no shift.
Broadening of the width ($\Delta\Gamma$~70 MeV) consistent with many-body effects

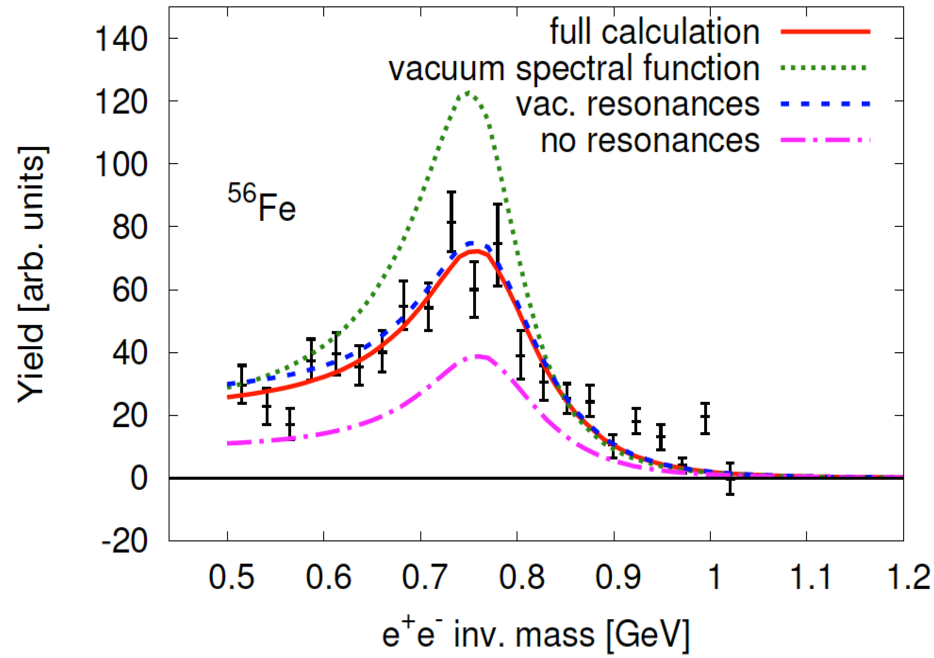
CLAS data:
Nasseripour et al., PRL 99 (2007) 262302
Wood et al., PRC 78 (2008) 015201

GiBUU calculations:
Mosel et al., NPA671, 501(2000)
Effenberger etal., PRC62, 014605(2000); PRC60, 027601 (1999).

Recent calculations by Texas A&M group for JLab-g7 results

F. Riek et al., Phys Let B 677 (2009) 116;
F. Riek et al., arXiv:1003.0910v1 (March 2010)

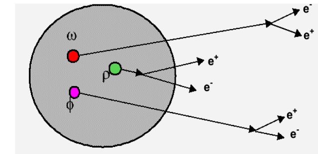




Calculations nicely reproduce g7 data. Confirms no major medium effect (beyond standard collisional broadening) expected for momenta Pρ > 1 GeV.

Need measurements at lower momenta → GOAL of experiment g7b

Absorption of ω and φ-mesons and their in-medium widths



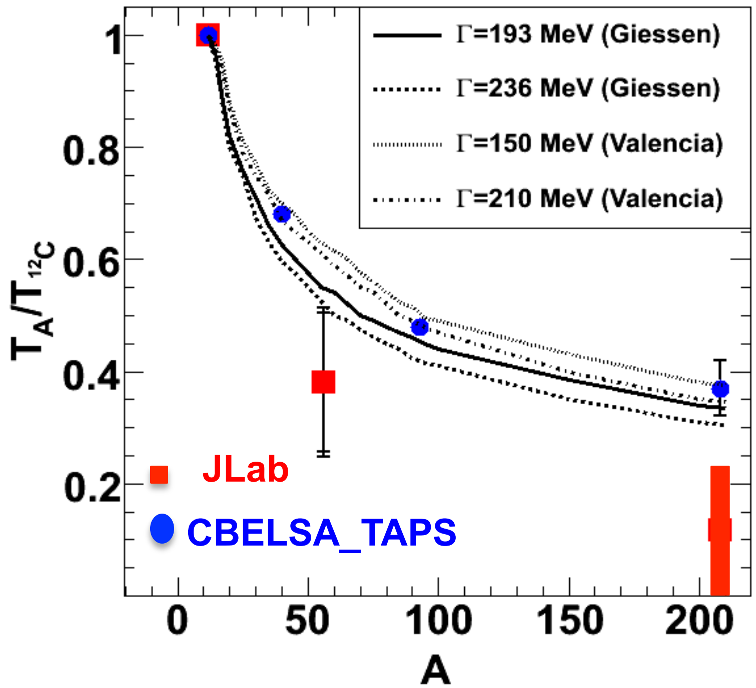
The in-medium width is $\Gamma = \Gamma_0 + \Gamma_{coll}$ where $\Gamma_{coll} = \gamma \rho v \sigma^*_{VN}$

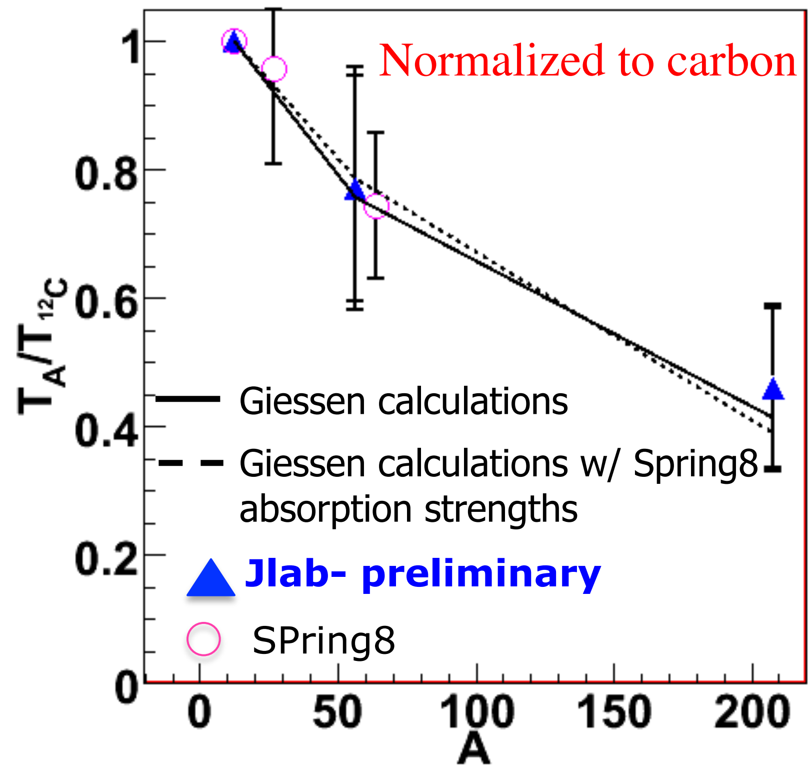
Transparency ratio:

$$T_A = \frac{\sigma_{\gamma A \to \omega X}}{A \cdot \sigma_{\gamma N \to \omega X}} \qquad T_{norm} = \frac{12 \cdot \sigma_{\gamma A \to \omega X}}{A \cdot \sigma_{\gamma ^{12}C \to \omega X}}$$

Spring8 γ A →φ A′ → K⁺K⁻ A′
(Eγ=1.5-2.4 GeV)
PLB 608 (2005) 215

Giessen calculations: NPA 773, 156 (2006)
Valencia calculations: EPJ A 31, 245 (2007)





Latest TAPS Γ_ω~130-150 MeV (PRL100 (2008)192302)
JLAB preliminary results -> much larger width (Γ_ω >200 MeV)
Possible ρ−ω interference

$\sigma_{\phi N}$ ~ 25−55 mb
Γ_ϕ(~ 70 MeV) compatible with Spring8
JLab data: M. Wood et al, to be submitted

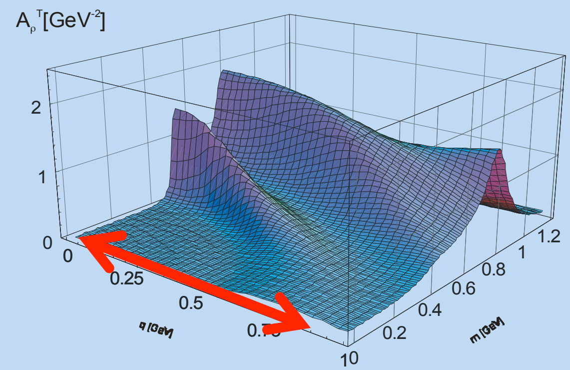
In-medium m and Γ of vector mesons

exp	reaction	Momentum Acceptance	ρ	ω	ϕ
KEK	pA 12 GeV	p >0.6 GeV/c	$(\Delta m/m)=-9\%$ $\Delta\Gamma \sim 0$	$(\Delta m/m)=-9\%$ $\Delta\Gamma \sim 0$	$(\Delta m/m)=-3.4\%$ $(\Gamma^*/\Gamma) \sim 3.6$
JLab	γA 0.6-3.8 GeV	p >0.8 GeV/c	$\Delta m \sim 0$ $\Delta\Gamma \sim 70$ MeV $(\rho \sim \rho_0/2)$	$\Delta\Gamma(\rho_0) \sim 200$ MeV $\langle p_\omega \rangle > 1$ GeV/c	$\Delta\Gamma$ compatible with Spring8
TAPS	γA 0.9-2.2 GeV	p >0 MeV/c	NA	$\Delta m \sim 0$ $p_\omega < 0.5$ GeV/c $\Delta\Gamma(\rho_0) \sim 130$ MeV $\langle p_\omega \rangle = 1.1$ GeV/c	NA
Spring8	γA 1.5-2.4 GeV	p >1.0 GeV/c	NA	NA	$\Delta\Gamma(\rho_0) \sim 70$ MeV $\langle p_\phi \rangle = 1.8$ GeV/c
CERES	Pb+Au 158 AGeV	$p_t > 0$ GeV/c	Broadening favored over mass shift	NA	NA
NA60	In+In 158 AGeV	$p_t > 0$ GeV/c	$\Delta m \sim 0$ Strong broadening	NA	NA

Majority of experiments → no mass shift but broadening

Summary and Outlook (Mesons)

- Strongest evidence for χ_s restoration is reported in deeply bound pionic states $< 0 | q\overline{q} | 0 >$ drops by 33% in nuclei
- Enhancement in the "σ channel" near the $2m_\pi$ threshold is entirely explained by FSI
- Excess of dileptons in the region of vector mesons seen by CERES and NA60 can be explained by a broadening of the ρ.
- K−N potential repulsive in medium: ~20 to 40 MeV
- Most "elementary reactions" report mainly an in-medium broadening, no mass shift!
- The ρ-meson best candidate for direct measurement of medium modifications
- Transparency ratios ideal to study long-lived mesons
- Need data for mesons produced with low momentum
- BEWARE OF FSI FSI FSI FSI FSI !!!!!!!!
- Photoproduction followed by e^+e^- decay turns out to be ideal experiment!



Substantial theoretical and experimental efforts carried out in this very active field.
High statistics experiments are planned at different facilities:

- -JLab C3 experiment g7b (ρ, ω, ϕ and K^0_S, K* in medium)
- -COSY, JPARC (meson bound states)
- -PHENIX is analyzing the observed excess in A+A
- -HADES is analyzing A+A data and will soon run π+A
- -ALICE will soon come online
- -PANDA &CBM at FAIR, JLab, JPARC will look into the Charm sector →