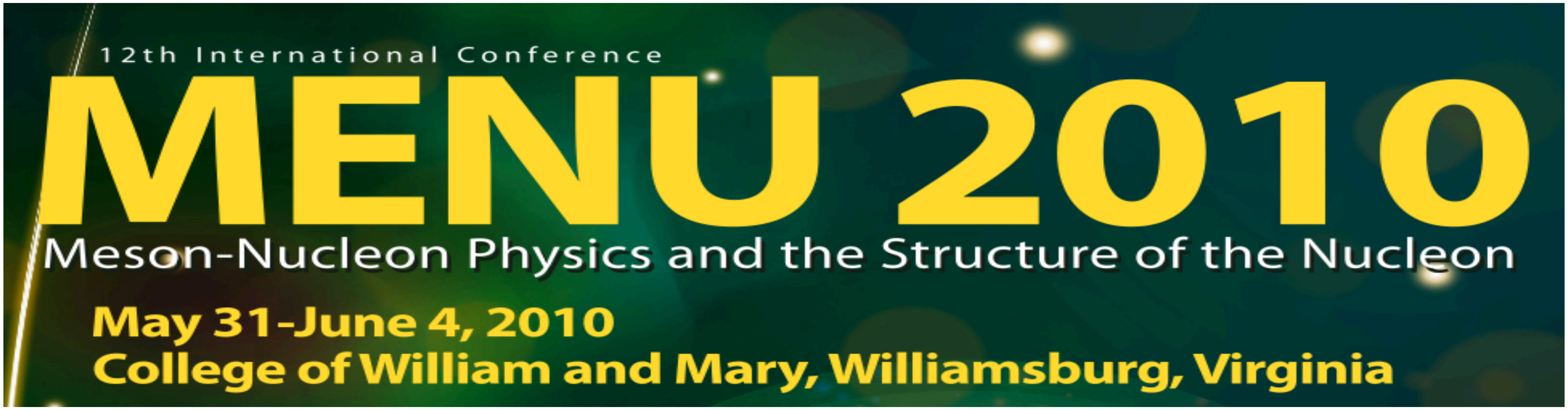
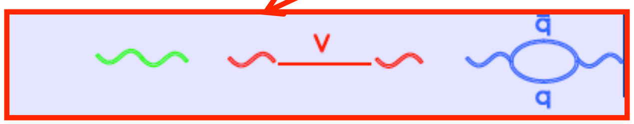
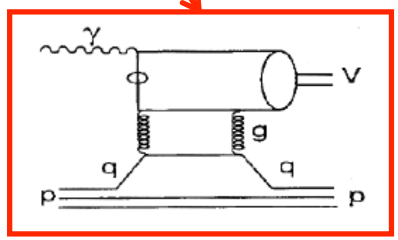
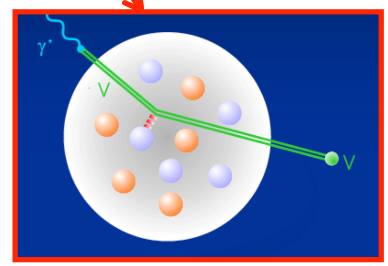


Vector Meson Photoproduction on Nuclei

ρ,ω,φ







C. Djalali
University of South Carolina)

Jefferson Lab
THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

UNIVERSITY OF SOUTH CAROLINA

Outline

- Light vector mesons (ρ, ω and ϕ)
- Photoproduction mechanism on p
- Photoproduction in nuclei (Medium Modifications of Vector Mesons)
  - ρ meson mass spectrum
  - ω meson mass spectrum
  - Transparency ratios for ω and ϕ
- Summary and Outlook

Disclaimer: Not all experiments and models listed!

The "protagonists" all have $J^{PC} = 1^{--}$

γ

$I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-35}$ e
Mean life τ = Stable

"1905"

$\rho(770)$ [j]

$I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 775.49 \pm 0.34$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV

1961

$\omega(782)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 782.65 \pm 0.12$ MeV (S = 1.9)
Full width $\Gamma = 8.49 \pm 0.08$ MeV

1961

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1019.455 \pm 0.020$ MeV (S = 1.1)
Full width $\Gamma = 4.26 \pm 0.04$ MeV (S = 1.4)

1962

Predictions for the existence of vector mesons

- **Applying notions such as conserved currents, gauge principle to strong interaction physics. Sakhurai ("Currents and Mesons" 1960) predicted the existence of vector mesons.**
- **Interpreting the first electromagnetic form factors of the nucleons measured in electron scattering, indirect evidence for the existence of an isoscalar vector meson $\omega \rightarrow 3\pi$ was given by Nambu [*PR106,1366 (1957)*] and for an isovector meson $\rho^0 \rightarrow 2\pi$ by Frazer and Fulco [*PRL2,365(1959)*].**

Shortly after (1961-1962) the ρ, ω and ϕ were discovered

The Rho meson (1961)

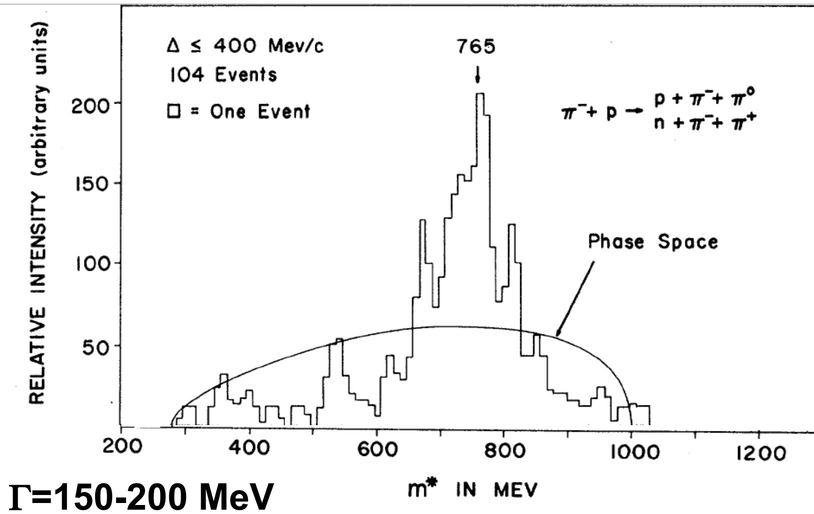
EVIDENCE FOR A π-π RESONANCE IN THE $I=1$, $J=1$ STATE*

A. R. Erwin, R. March, W. D. Walker, and E. West

Brookhaven National Laboratory, Upton, New York and University of Wisconsin, Madison, Wisconsin

(Received May 11, 1961)

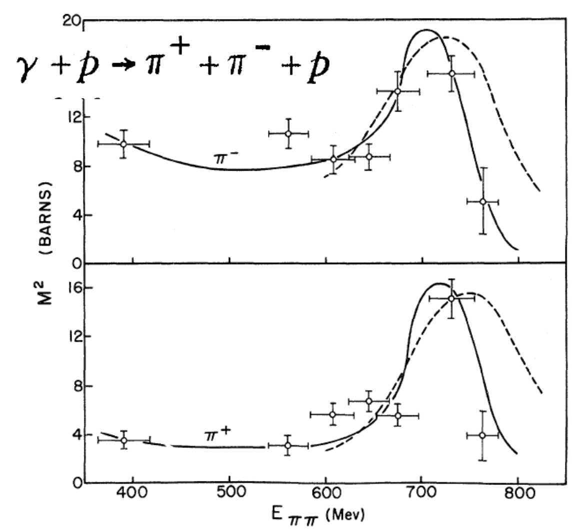
PRL 6, 628 (1961)



M=765 MeV and Γ=150-200 MeV

First observation of ρ meson in photoproduction experiment using the Bremsstrahlung beam at the Cornell synchrotron

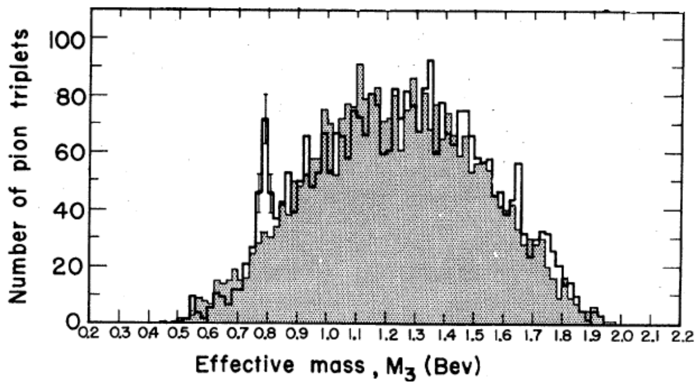
D. McLeod et al, PRL 7, 383 (1961)

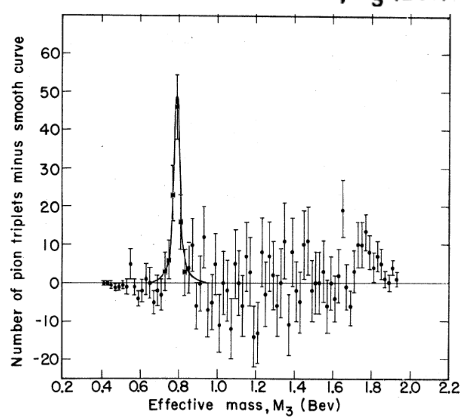


The Omega meson (1961)

EVIDENCE FOR A $T = 0$ THREE-PION RESONANCE

B. C. Maglic et al.,PRL 7 (1961) 178





$$\bar{p} + p \rightarrow \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^0$$

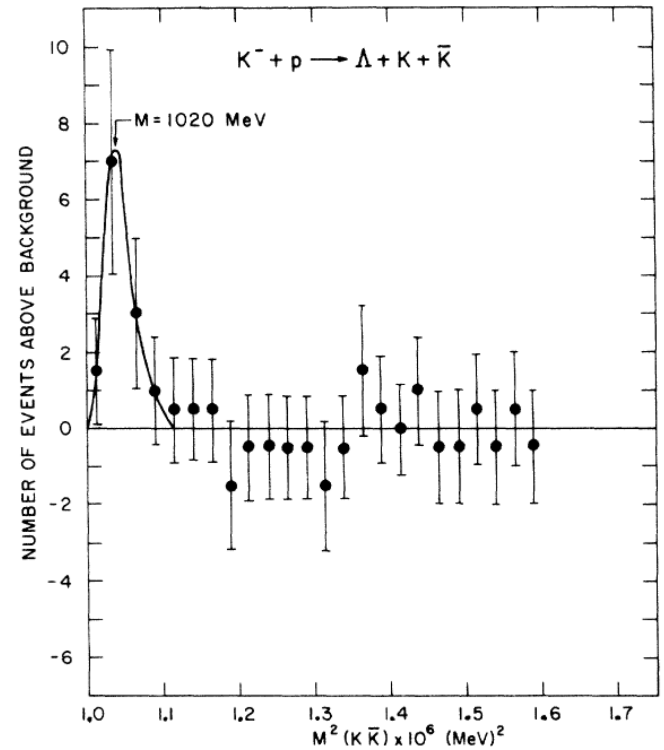
@ the LBL 72" H-Bubble Chamber

M=787 MeV and Γ=15 MeV

The Phi meson (1962)

POSSIBLE RESONANCES IN THE $\Xi\pi$ AND $K\bar{K}$ SYSTEMS

L. Bertanza et al.,PRL 9 (1962) 180



@ the BNL 20" H-Bubble Chamber

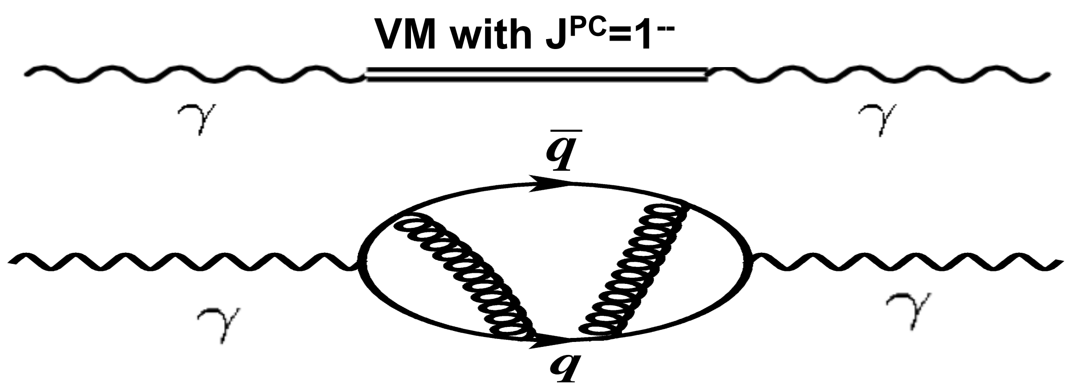
< 40 events!

M=1020 MeV and Γ=20 MeV

Hadronic "structure" of the photon

Analogies between photon- and hadron- induced processes such as a total cross section that varies very slowly with energy, diffractive pattern at small t, shadowing, etc… lead to the Vector Meson Dominance Model (VMD or VDM). The photon fluctuates between a "bare photon" and its hadronic component which undergoes conventional hadronic interactions.
The distance the photon travels as a Vector meson is given by the coherence length

$$l_\rho \approx \frac{2E_\gamma}{Q^2 + M_V^2}$$



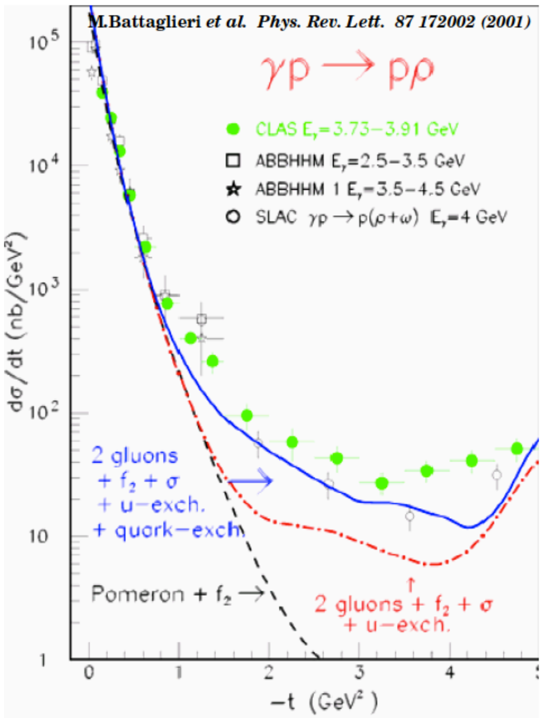
VMD limits the VM to only ρ, ω and ϕ
Generalized VMD (GVMD) allows for heavier VM

The photo production of VM on the nucleon has been extensively studied at different Eγ and t.
A coherent picture of the reaction mechanism has emerged.

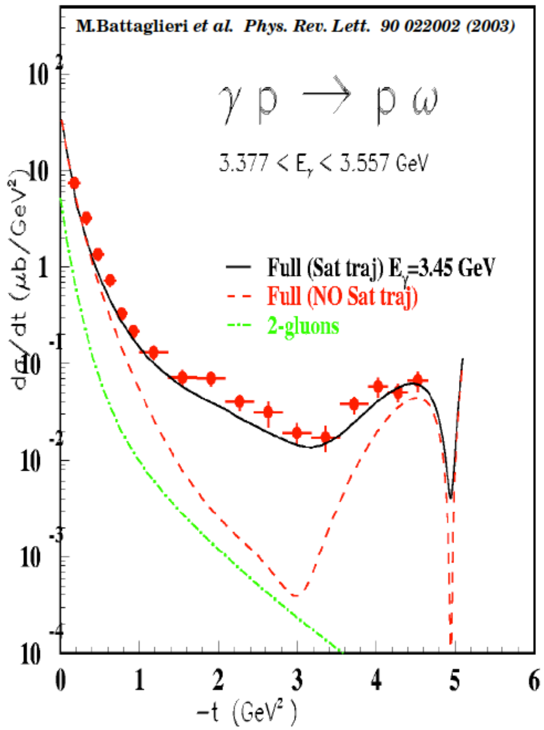
Vector Meson Photoproduction on the proton

(M. Battaglieri)

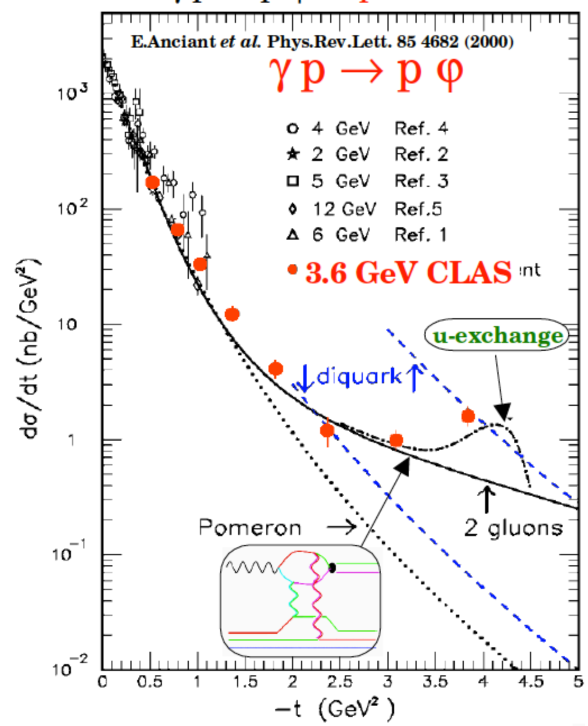
$\gamma\, p \to p\, \rho \to p\, \pi^+ \pi^-$



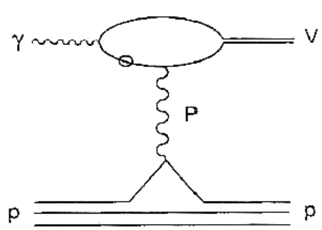
$\gamma\, p \to p\, \omega \to p\, \pi^+ \pi^- \pi^0$



$\gamma\, p \to p\, \varphi \to p\, k^+ k^-$

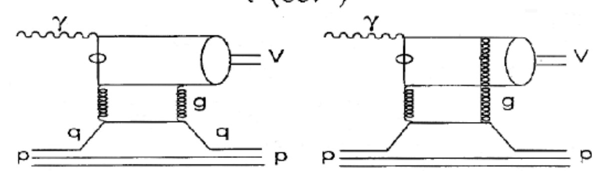


Low t:
VMD, Diffractive behavior,
Pomeron Exchange

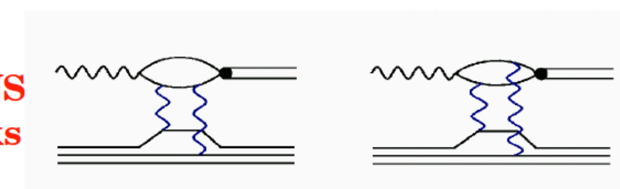


High t:

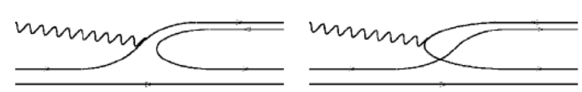
POMERON
resolves
in 2 gluons



CORRELATIONS
between quarks



QUARK
EXCHANGE



Photoproduction in Nuclei

Motivation:

Nucleus as a laboratory/detector (a strongly interacting medium in equilibrium at T=0 and known density) to study the properties of hadrons.

One can study:

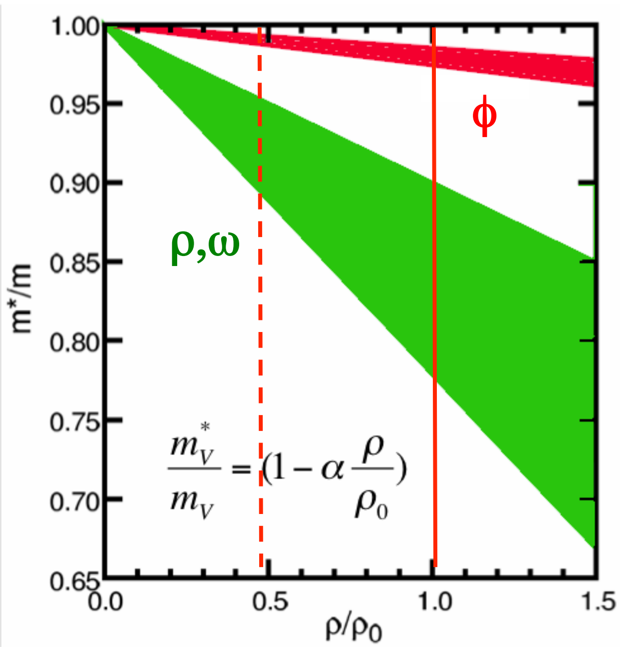
- **Meson-nucleon interactions through final state interaction**
- **Hadronization**
- **Bound states of mesons in nuclei**
- **Partial restoration of chiral symmetry**
- **Color transparency**
- **Short range correlations**
- **Jets in cold matter**
- **Medium modifications of mesons properties**
- **…**

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

QCD Sum Rules (QCDSR) - Mass scaling - QMC

QCDSR 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

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)

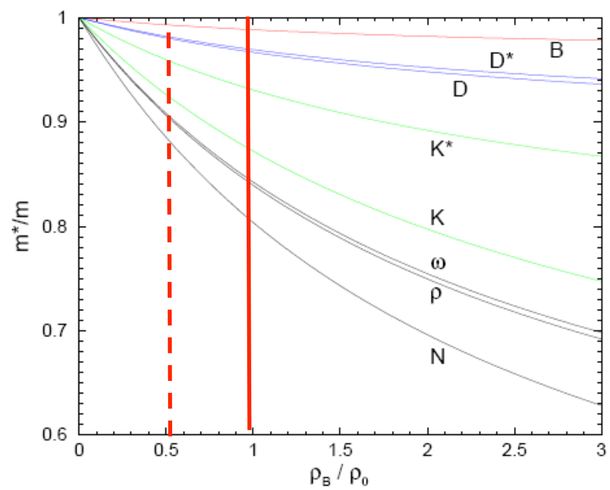


Mass Scaling Conjecture: Effective chiral Lagrangians with scaling properties of QCD lead to approximate in-medium scaling law.
Brown and Rho, PRL66 (1991) 2720
T. Harada et al, PRD66, (2002)016003 ; PLB537 (2002)280; PRD73, (2006)036001.

"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

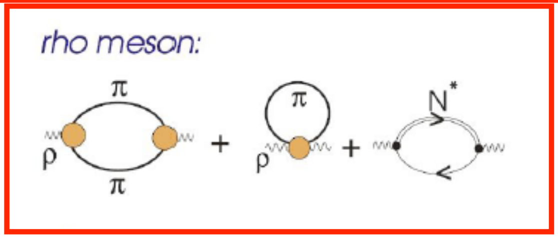


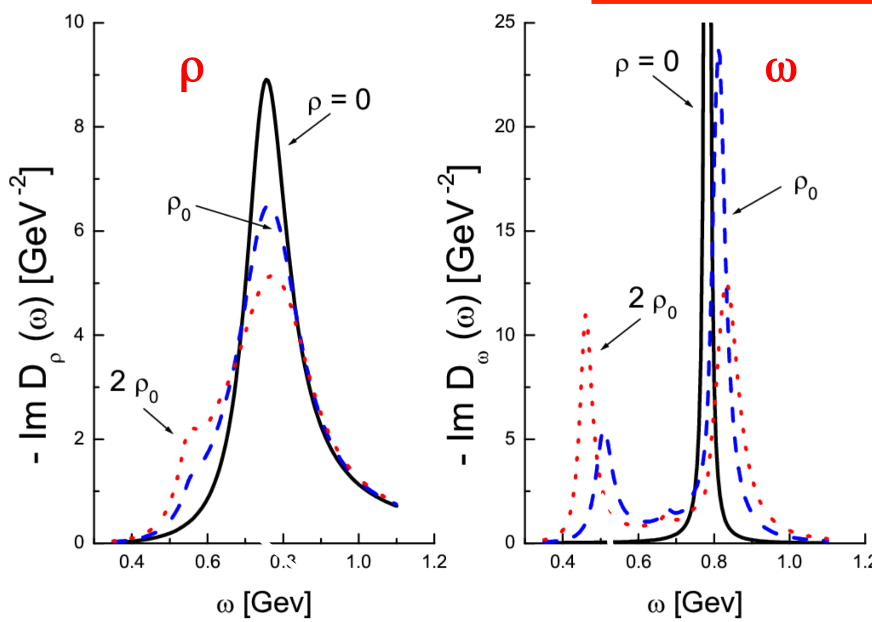
Hadronic models

-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…)

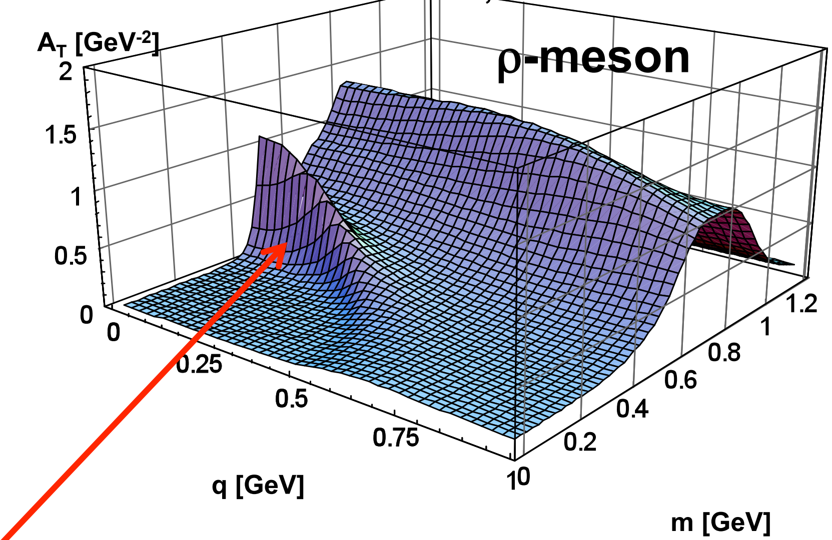
Rapp, Wambach, EPJA 6 (1999) 415
B Friman et al, *NPA617 (1997) 496*
R. Rapp et al, *NPA617 (1997) 472*

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





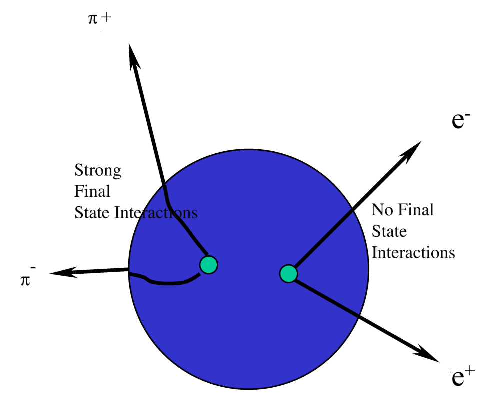
M. Post et al., nucl-th/0309085



structures in spectral functions due to coupling to baryon resonances

Vector mesons in Medium

Properties of Vector Mesons					
Meson	Mass (MeV/c²)	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	~782	~8	23	$\pi^+\pi^-\pi^0$ (~90%)	~7
ϕ	~1019	~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}).
- "Large" combinatorial background.
- Most ω and ϕ (if not absorbed) decay outside of the medium, need low momentum cut.

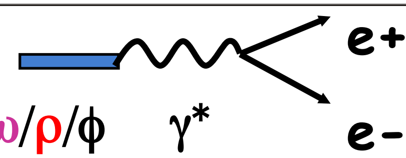
Example of model describing the photo production of vector mesons in medium, its propagation and decay into dileptons

$\gamma A \rightarrow VX;\ V \rightarrow e^+e^-$

INGREDIENTS

- Incoming photon as hadron
- Shadowing: hadronic character of photon
- Primary production in first reaction (use what we have learned from elementary reaction on N)
- In-medium propagation of produced particles : self-energies, widths,
- Coupling to nuclear resonances
- Final State Interaction: absorption (Glauber approach), side-feeding by CC effects
- Decay channels
- Taking into account all processes feeding a particular decay channel

i	Dilepton channel	
1	Dalitz decay of π^0:	$\pi^0 \rightarrow \gamma e^+e^-$
2	Dalitz decay of η:	$\eta \rightarrow \gamma e^+e^-$ (or $\mu^+\mu^-$)
3	Dalitz decay of ω:	$\omega \rightarrow \pi^0 e^+e^-$
4	Dalitz decay of Δ:	$\Delta \rightarrow N e^+e^-$
5	direct decay of ω:	$\omega \rightarrow e^+e^-$
6	direct decay of ρ:	$\rho \rightarrow e^+e^-$
7	direct decay of ϕ:	$\phi \rightarrow e^+e^-$
8	direct decay of J/Ψ:	$J/\Psi \rightarrow e^+e^-$
9	direct decay of Ψ':	$\Psi' \rightarrow e^+e^-$
10	Dalitz decay of η':	$\eta' \rightarrow \gamma e^+e^-$
11	pn bremsstrahlung:	$pn \rightarrow pne^+e^-$
12	$\pi^\pm N$ bremsstrahlung:	$\pi^\pm N \rightarrow \pi N e^+e^-$, where $N = p$ or n



Strongly *m-dependent near threshold*

Spectral Function

IMPORTANT for hadrons in final state

$$\sigma_{BW} \sim \frac{\pi}{k^2}\Gamma_{in}\frac{s\Gamma_{tot}}{(s-m^2)^2+s\Gamma_{tot}^2}B_{out} \times \text{FSI}$$

Can be strongly *m-dependent*

From U. Mosel

Photoproduction in nuclei looking for medium modifications of vector mesons

$\gamma A \longrightarrow V\,X$

$\quad\quad \hookrightarrow e^+e^-,\ \pi^+\pi^-,\ \pi^0\gamma,\ K^+K^-, \ldots$

(not exhaustive list)

Photoproduction Experiment	*Reactions*	*Final State*
TAGX	$\gamma + {}^2H, {}^3He, C \dashrightarrow \rho + X$	$(\rho \dashrightarrow \pi^+\pi^-)$
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 $\dashrightarrow (\rho,\omega,\phi) + A^*$	$(\rho,\omega,\phi \dashrightarrow e^+e^-)$

-TAGX and Spring-8 have hadronic FS ($\pi^+\pi^-$; K^+K^-)

-TAPS has semi-hadronic FS ($\pi^0\gamma$)

-JLab has pure electromagnetic FS (e^+e^-)

TAGX Collaboration (@1.3 GeV INS Electron Synchrotron-Tokyo Univ)

-First experiment looking at the in-medium modification of the ρ^0 in the elementary reaction ^2H, ^3He, $^{12}C(\gamma,\pi^+\pi^-)$. Tagged photon beam E_γ~0.6 -1.12 GeV.

-Their first claim of of finding a ρ^0 mass shift of −160 ± 35MeV in ^3He (*Lolos et al., PRL80(98)241*) was met with skepticism.

Severe FSI, limited phase space, large effect in ^3He!!

-A subsequent helicity analysis (*Huber et al.,PRC68(03) 065202*) using the QMC model (*Saito et al, PRC55(1997)2637*) claimed a smaller mass shifts of -45 to -75 MeV in 3He.

-There was no mass shift observed in ^{12}C!

-Why TAGX observed such a large effect only in 3He is not yet understood!

-Theoretical calculations (Giessen group) have shown that FSI in the pion decay channel are so strong that they wash out any medium modification signal

→ To Avoid ambiguities due to FSI, it is critical to STUDY LEPTONIC DECAY CHANNELS

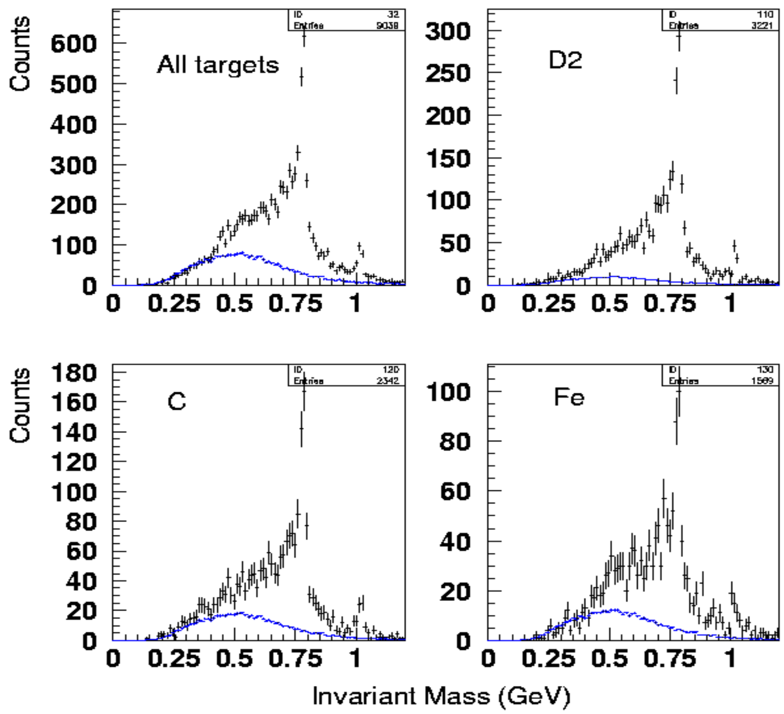
JLab CLAS Experiment E01-112 (g7)

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)

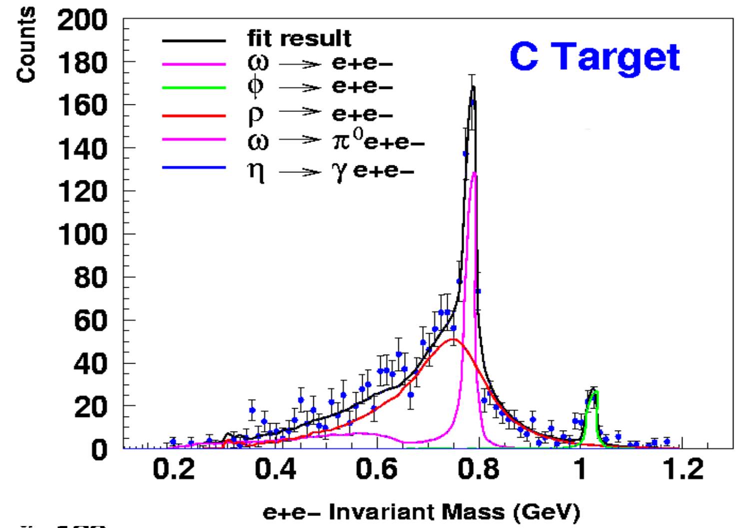
Decay channel: e+e- (noFSI)

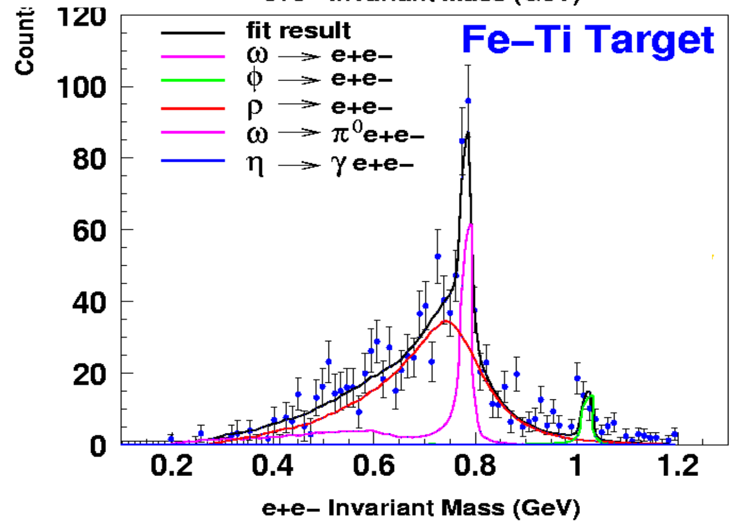
Excellent e/π discrimination



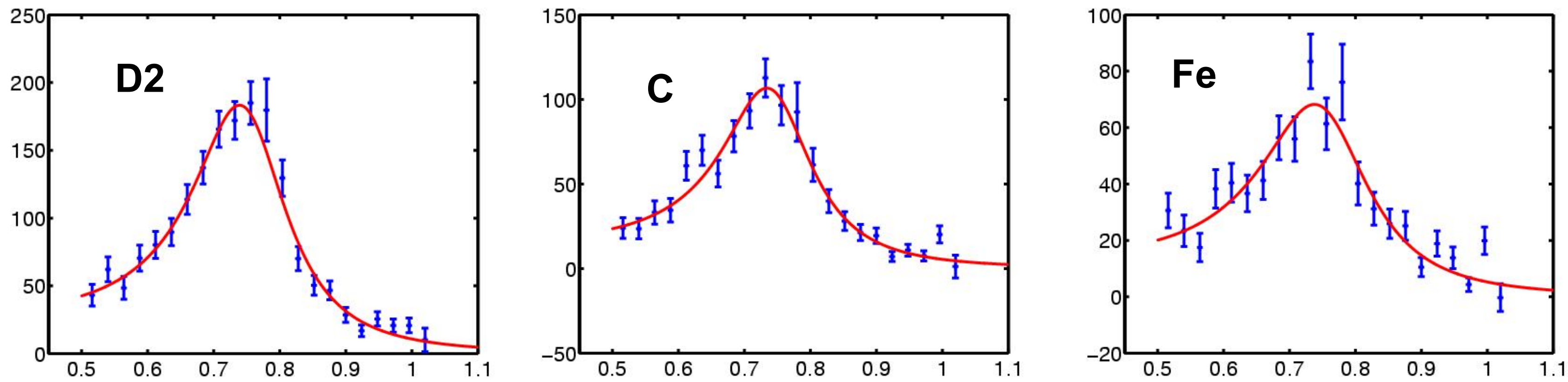
Combinatorial background well understood

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/c²) CLAS data	Width(MeV/c²) CLAS data	Mass(MeV/c²) Giessen BUU	Width(MeV/c²) 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

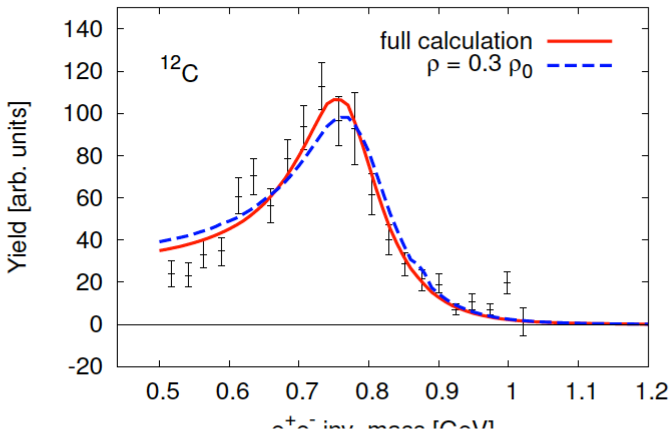
The mass of the ρ meson consistent with no shift.
Broadening of the width (ΔΓ~70 MeV) consistent with many-body effects

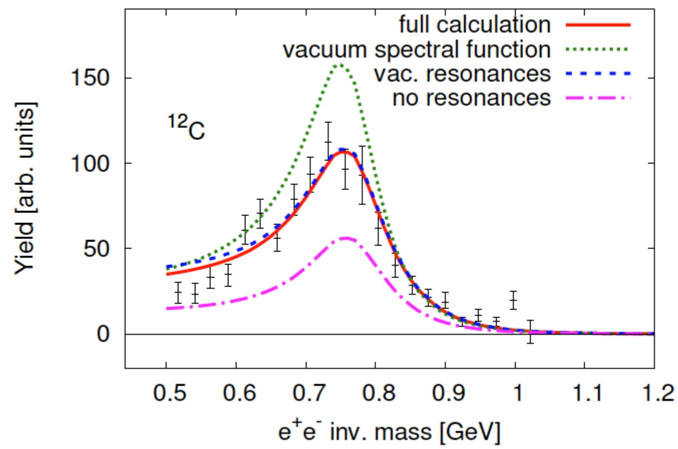
CLAS data:
Nasseripour et al., PRL 99 (2007) 262302
Wood et al., PRC 78 (2008) 015201

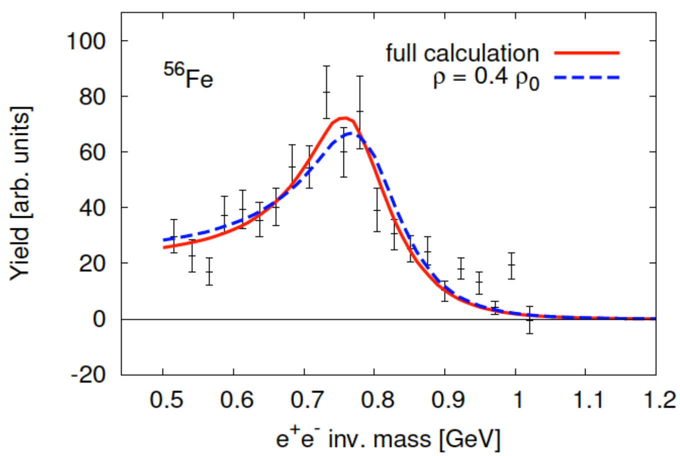
GiBUU calculations:
Mosel et al., NPA671, 501(2000)
Effenberger etal., PRC62, 014605(2000); PRC60, 027601 (1999).

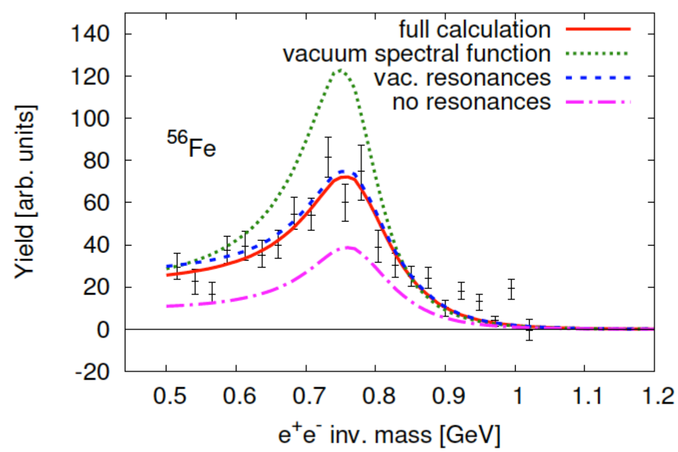
Recent calculations by Texas A&M

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.

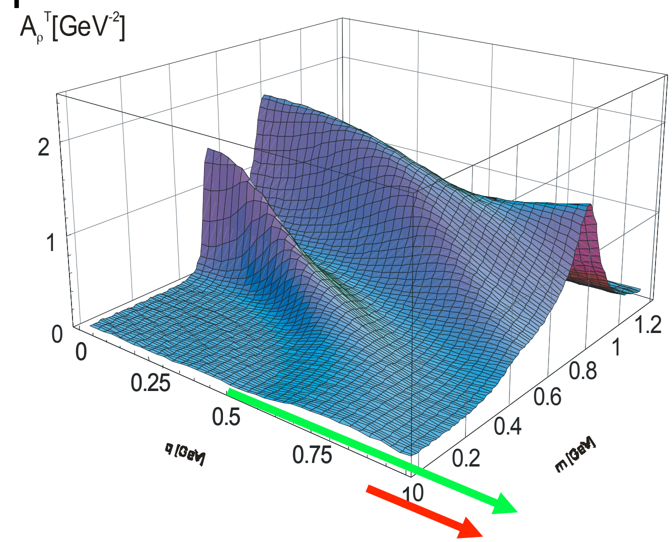
Need measurements at lower momenta.

Summary on the ρ meson

- TAGX reports downward mass shift in ^{3}He but not in C. However the large FSI casts doubts on these conclusions.
- CLAS has extracted ρ mass spectra in 2H, C and Fe and the results are compatible with no mass shift and a broadening consistent with many body effects.
- CLAS results do not confirm the KEK results (9% downward mass shift).
- CLAS results rule out ΔM à la Brown/Rho (-20%) and Hatsuda/Lee (− 16%)

- NOTE: in CLAS experiment, momenta of ρ between 0.8 and 2 GeV.

One needs to produce ρ with lower momenta/medium

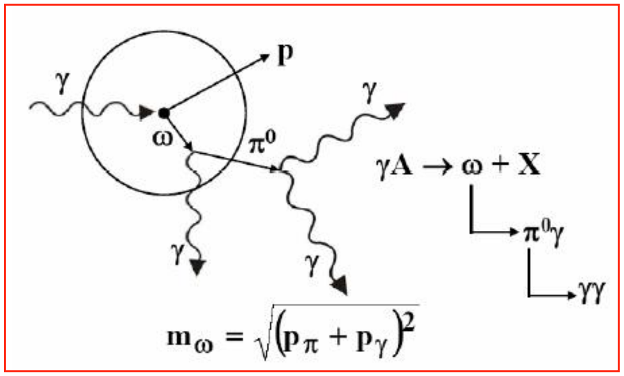


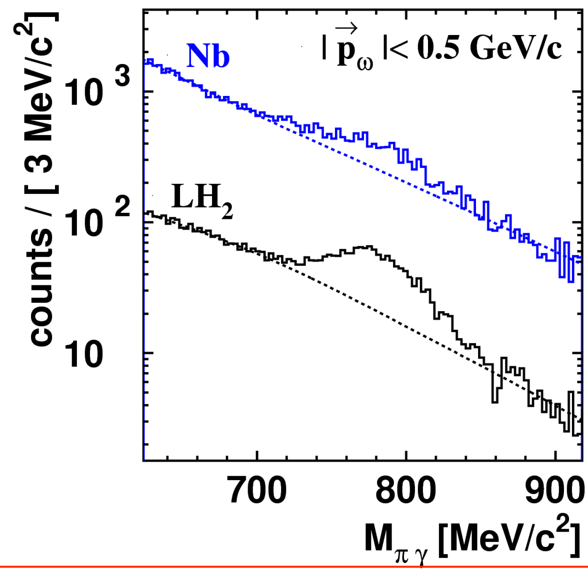
CLAS g7a (red line)

CLAS g7b
Conditionally approved (green line)

ω mass spectrum (CBELSA-TAPS first analysis)

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





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

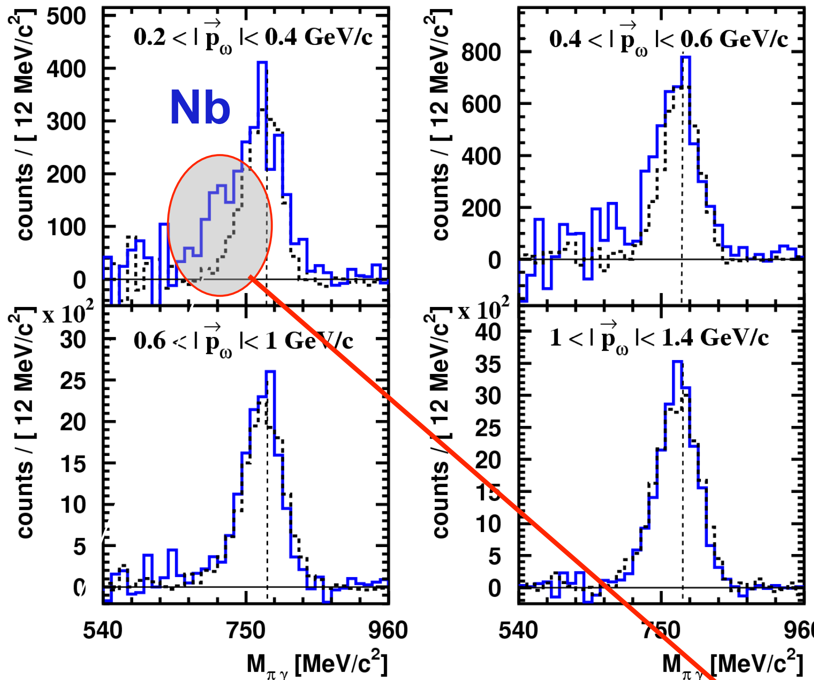
Pro:

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

Con:

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

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

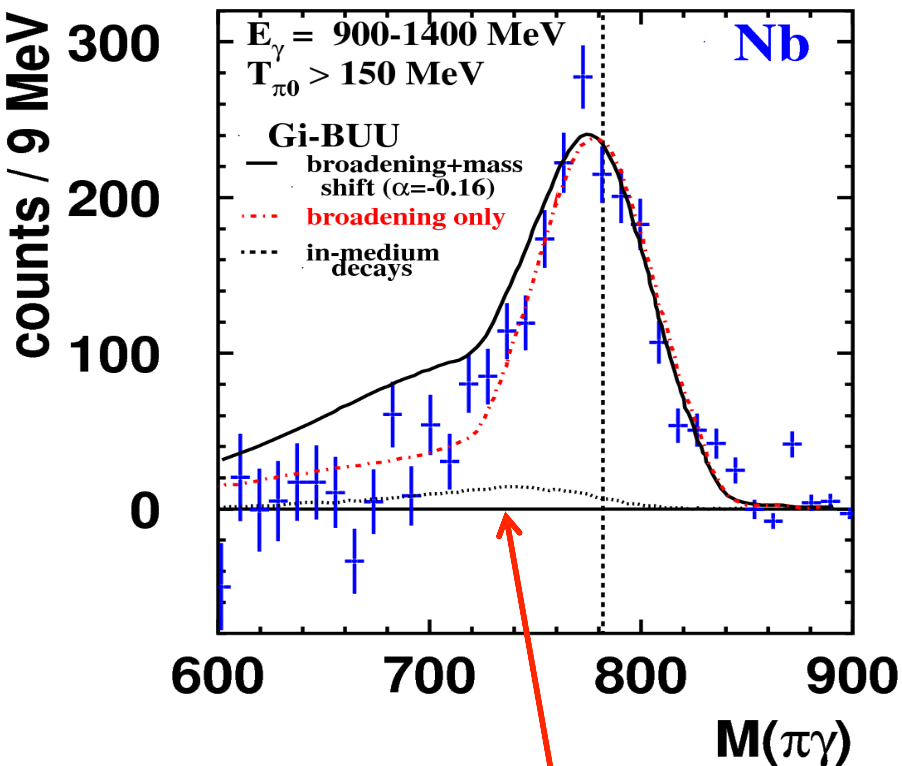


Slow ω decaying inside

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

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



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

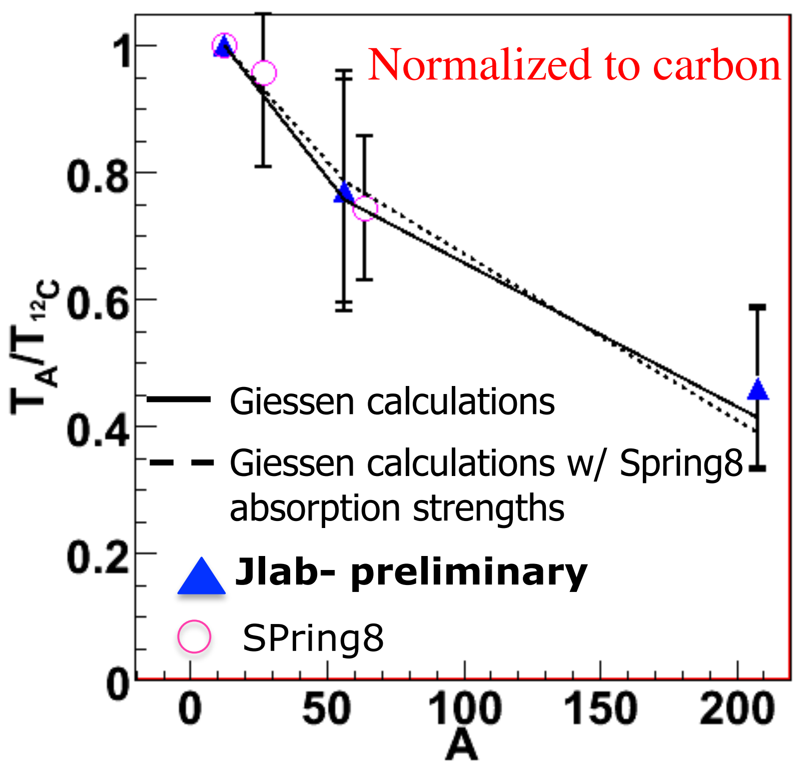
Strong broadening of the ω (as seen in transparency ratios) drastically suppresses sensitivity to direct observation of ω decaying in the medium

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

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

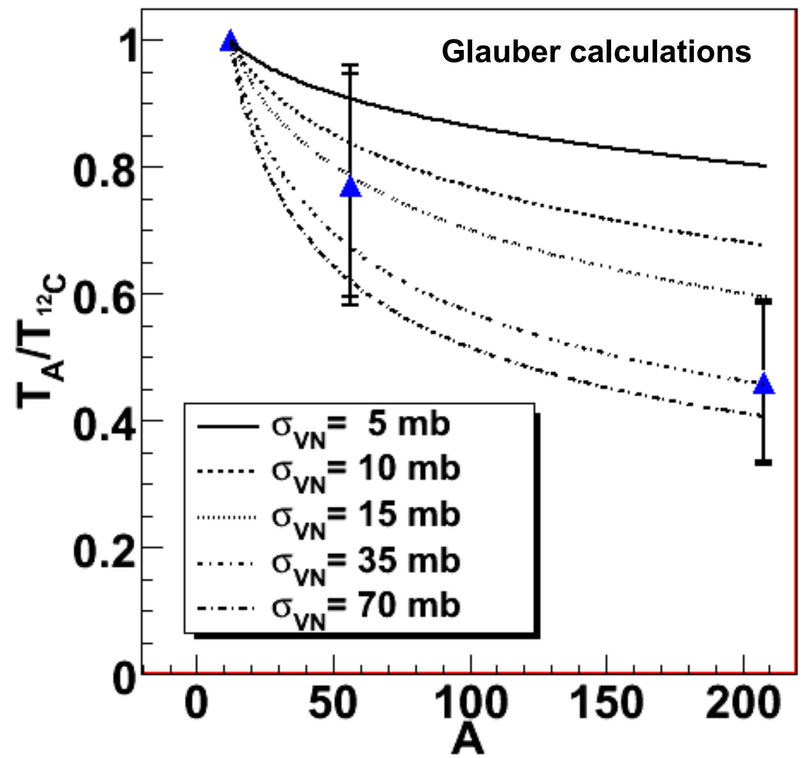
ϕ Absorption (Clas-g7 and LEPS-SPring8)

SPring8 γ A $\rightarrow \phi$ A′ $\rightarrow$ K^+K^- A′ (Eγ=1.5-2.4 GeV)
T. Ishikawa et al. Phys. Lett. B 608, 215 (2005)



Transparency ratio:

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



The incoherent photo-production yield from Li, C, Al, and Cu at forward angles has been found to be ~A $^{0.72\pm0.07}$ → $\sigma_{\phi N}$ in medium = 35^{+17}_{-11} mb !!!
~3 to 4 times $\sigma_{\phi N}$ (free)

In-medium: $\sigma^*_{\phi N}$ ~ 15 – 70 mb
Large error bars
Consistent with LEPS results
JLab data: M. Wood et al, to be submitted

ω Absorption (Clas-g7 and CBELSA/TAPS)

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

Transparency ratio:

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

Giessen calculations

P. Mühlich et al., NPA 773, 156 (2006)

Valencia calculations

Kaskulov et al., EPJ A 31, 245 (2007)

TAPS DATA

M. Kotulla et al. PRL 100 (2008)192302

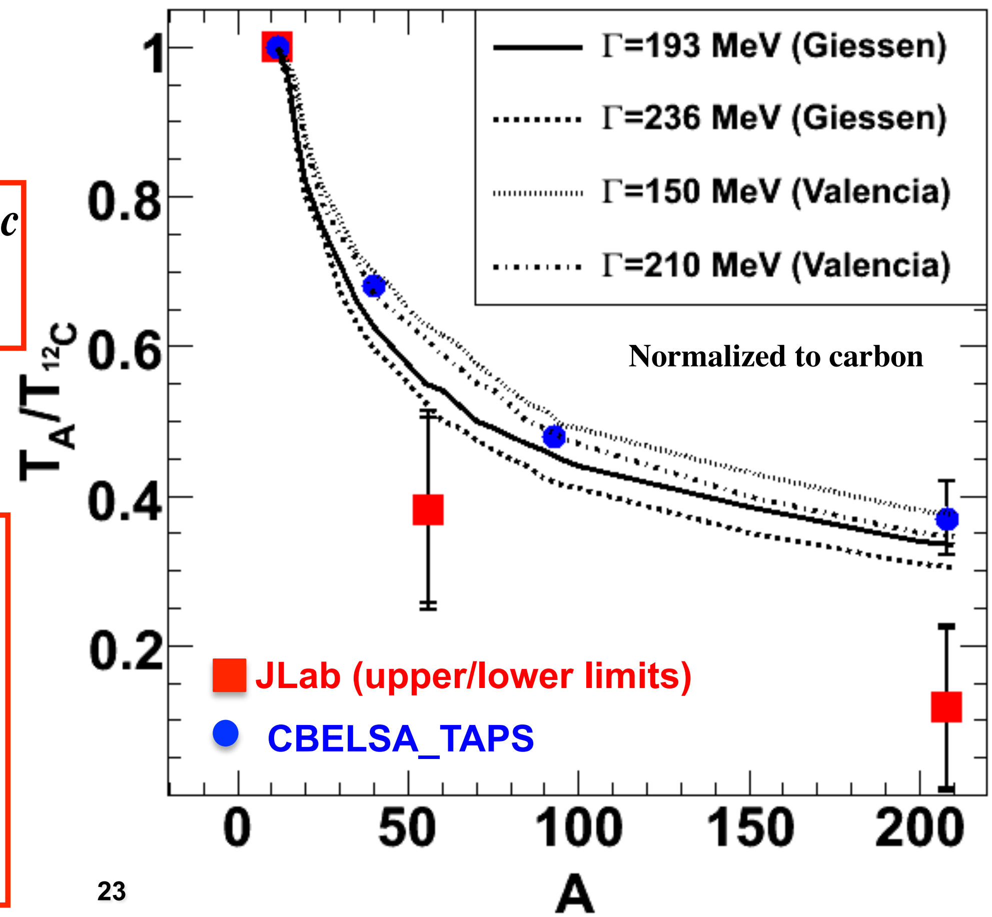
$$\Gamma_\omega(\rho_0) \approx 130-150\ MeV\ for\ \langle p_\omega \rangle \approx 1.1\ GeV/c$$

$$\Gamma_\omega(\rho=\rho_0) \approx 16 \cdot \Gamma_0$$

JLAB preliminary data
(M. Wood et al, to be submitted

Γ_ω >200 MeV!
Much larger value than TAPS.

Possible reasons:
- Higher average momenta $\langle p_\omega \rangle$~1.7 GeV/c
- Destructive ρ−ω interference in the di-lepton channel can reduce the yield.



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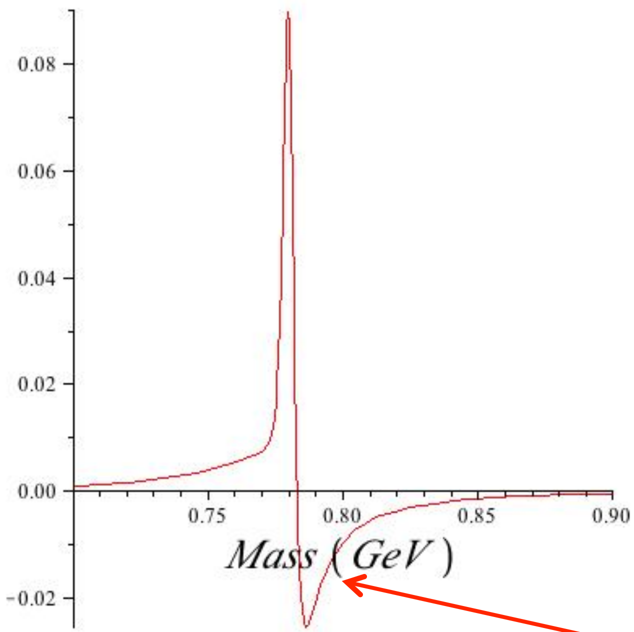
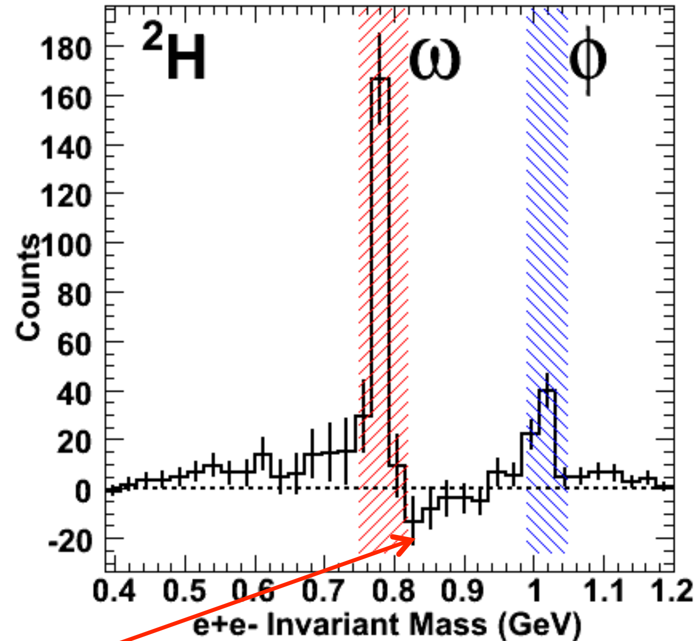
Possible ρ−ω Interference in di-lepton decay channel

The e^+e^- amplitude is modeled as $F = f_\rho + ie^{i\varphi} f_\omega$ where $f_{\rho,\omega}$ are relativistic BW shapes.

Expected shape of the invariant e^+e^- mass spectrum in the ω region after subtracting the ρ meson. (Destructive interference)

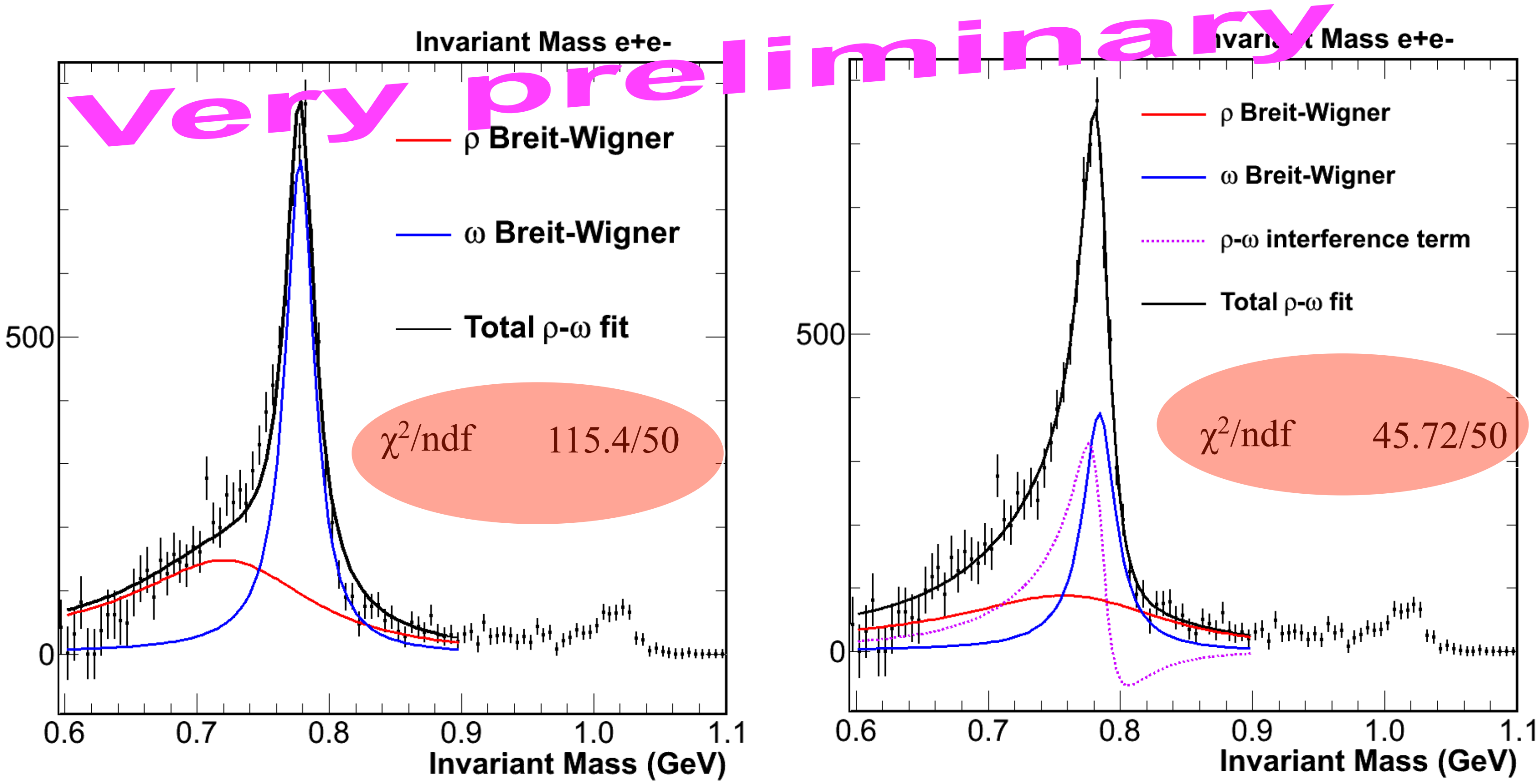


CLAS-g7 data from the ^2H target



Studying ρ−ω Interference in $\gamma p \rightarrow e^+e^-p$ →

CLAS-g12 $\gamma p \rightarrow e^+e^-p$ analysis (Michael Paolone)



without interference **with interference**

The fit shows destructive interference and results in "correct" masses and widths for ρ and ω

WORK IN PROGRESS

In-medium m and Γ of vector mesons compared to hadron experiments

exp	reaction	Momentum Acceptance	ρ	ω	ϕ
KEK	pA 12 GeV	p >0.6 GeV/c	$(\Delta m/m)$=-9% $\Delta\Gamma$ ~0	$(\Delta m/m)$=-9% $\Delta\Gamma$ ~0	$(\Delta m/m)$=-3.4% (Γ^*/Γ) ~3.6
JLab	γA 0.6-3.8 GeV	p >0.8 GeV/c	Δm ~ 0 ΔΓ ~70 MeV $(\rho \sim \rho_0/2)$	$\Delta\Gamma(\rho_0)$ ~200 MeV $<p_\omega>$ >1.7 GeV/c	ΔΓ compatible with Spring8
TAPS	γA 0.9-2.2 GeV	p >0 MeV/c	NA	Δm ~ 0 p_ω<0.5 GeV/c $\Delta\Gamma(\rho_0)$ ~ 150 MeV $<p_\omega>$ = 1.1 GeV/c	NA
Spring8	γA 1.5-2.4 GeV	p >1.0 GeV/c	NA	NA	$\Delta\Gamma(\rho_0)$ ~ 70 MeV $<p_\phi>$ = 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	Δm ~ 0 Strong broadening	NA	NA

Majority of experiments →no mass shift but broadening
KEK and TAGX only ones still claiming a mass shift

Summary and Conclusions

Photoproduction excellent tool for studying vector mesons in nuclei

- The ideal decay channel of vector mesons in the medium is e^+e^- (no FSI).
- Thorough treatment of the combinatorial background is critical.
- Elaborate theoretical models are available to interpret the data.
- ρ-meson best suited for a "direct" measurement of medium modifications.
- Most ω and ϕ decay outside the nucleus. Indirect information about their in-medium width is derived through transparency ratios.

The ρ meson

- CLAS No mass shift, only a width increased by 40% in Fe (consistent with GiBUU predictions and HI results).
- TAGX reports a downward shift of the ρ mass in ^{3}He. However the large FSI of the pions coupled to no shift in C, cast doubt on the conclusions.

The ω meson

- TAPS has retracted the original claim of -14% mass shift.
- Transparency ratios show a huge increase of the in-medium width ~150 MeV
- CLAS transparency ratios show even larger absorption ($\rho-\omega$ interference?)

The ϕ meson

- Transparency ratios show in medium total cross section ~ 20-70 mb!

Medium modification studies continue to be a hot topic!

- Substantial theoretical and experimental efforts are being carried out and/or planned.
- Goal: to produce the mesons with as low a momentum (relative to medium) as possible.