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12 - 16 May 2008

Medium Modification of light vector mesons in Nuclei.

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Medium Modifications of Light Vector Mesons in Nuclei

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R. Nasseripour (George Washington University)

D. P. Weygand (Jefferson Lab)

and CLAS Collaboration

Jefferson Lab
Thomas Jefferson National Accelerator Facility

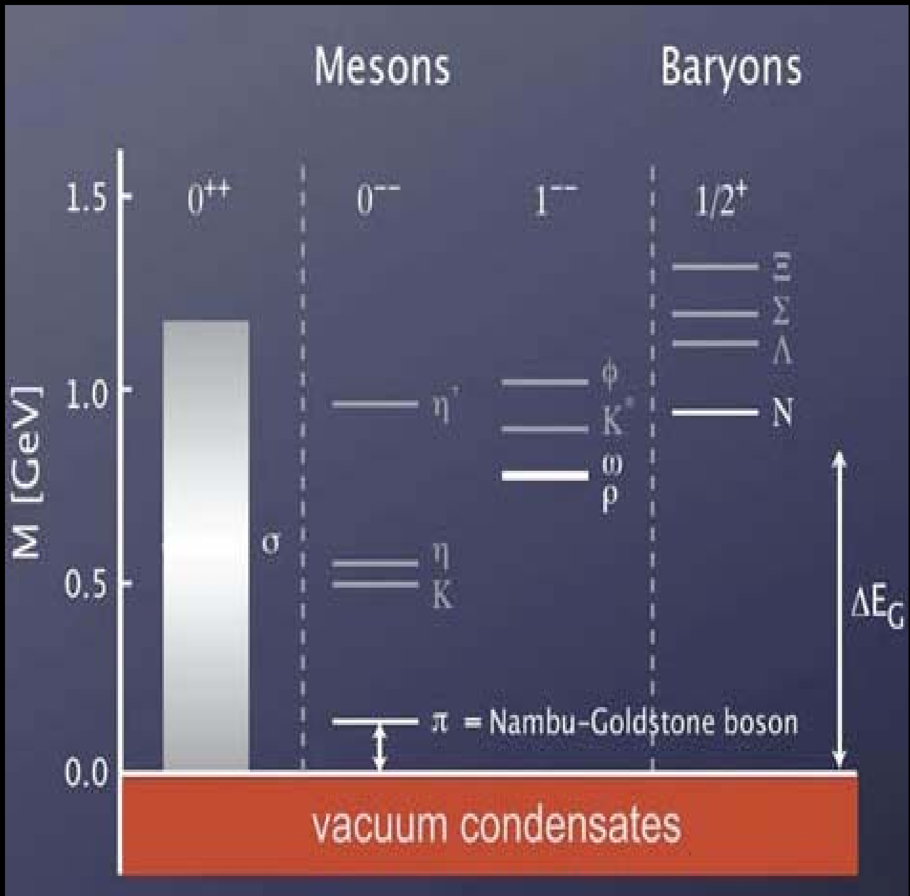
University of South Carolina

Outline

- Physics Motivations
  - Models and Predictions
- Some key experiments
- Photo-production of vector mesons at JLab
  - ρ meson mass spectra
  - ω and ϕ absorption
- Summary and Outlook

➢ Disclaimer: Not all experiments and models listed!

The study of medium modifications of hadrons has a long history in hadronic physics. Widespread theoretical and experimental work.



QCD vacuum is very complicated
<q-qbar>, <GG>,etc…

-The spontaneous breaking of Chiral Symmetry in vacuum is at the origin of 98% of the mass of hadrons.

-The properties of hadrons ("excitations of the QCD vacuum") depend on these condensates.

-Changes in the medium of the properties of hadrons <u>may</u> signal:
- -Chiral symmetry restoration
- -exotic state of matter,….

As $< 0 | q\bar{q} | 0 > \Rightarrow 0$, Restoration of chiral symmetry.

Mass, decay, coupling constants will change (?).

Medium modification of properties of light mesons

Experiments roughly fall under two categories

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

   -Deeply bound pionic states in nuclei (missing mass techniques),

   -elastic pion-nucleus scattering at low energy,

   -Double pion production in nuclei (invariant mass technique),

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

   -in relativistic heavy ion collisions (invariant mass technique),

   -in nuclei (invariant mass technique) ,

Model predictions of the in medium properties of vector mesons

Bernard and Meissner, NPA 489 (1988) 647

Scale invariance in effective Lagrangian:

G.E. Brown and M Rho, *Phys. Rev Lett. 66 (1991) 2720*

$$\frac{m_V^*}{m_V} = \frac{m_N^*}{m_N} = \frac{f_\pi^*}{f_\pi} \approx 0.8 \quad \text{at } \rho_0$$

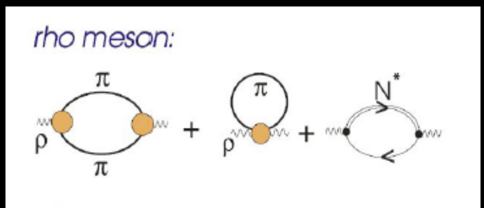
QCD sumrules:

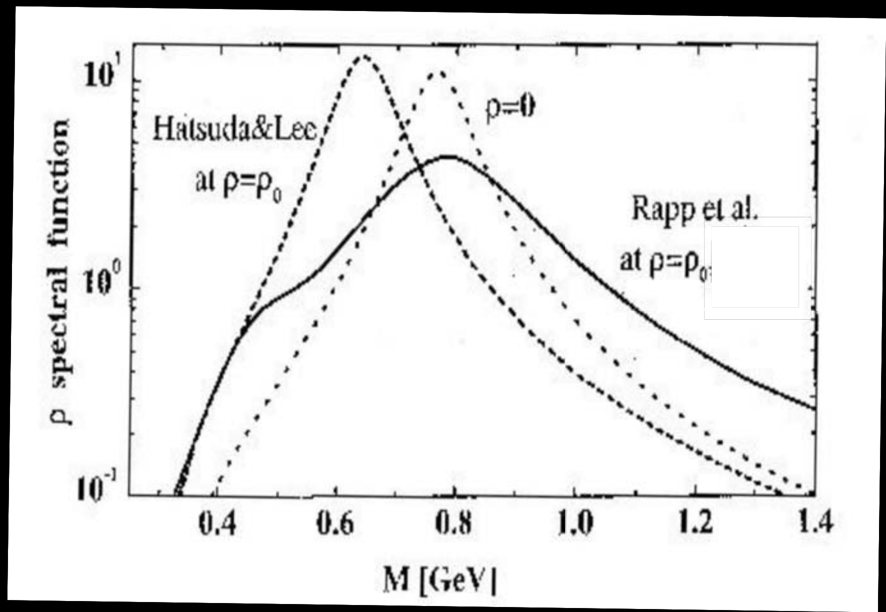
T. Hatsuda and S. Lee *Phys. Rev. C46 (1992) R34*

$$\frac{m_V^*}{m_V} = 1 - \alpha \frac{\rho_B}{\rho_0} \qquad \alpha \approx 0.16 \pm 0.06$$

Many body effects:

B Friman, H.J. Pirner,
Nucl Phys. A617 (1997) 496
R. Rapp, G. Chanfray, J Wambach,
Nucl Phys. A617 (1997) 472

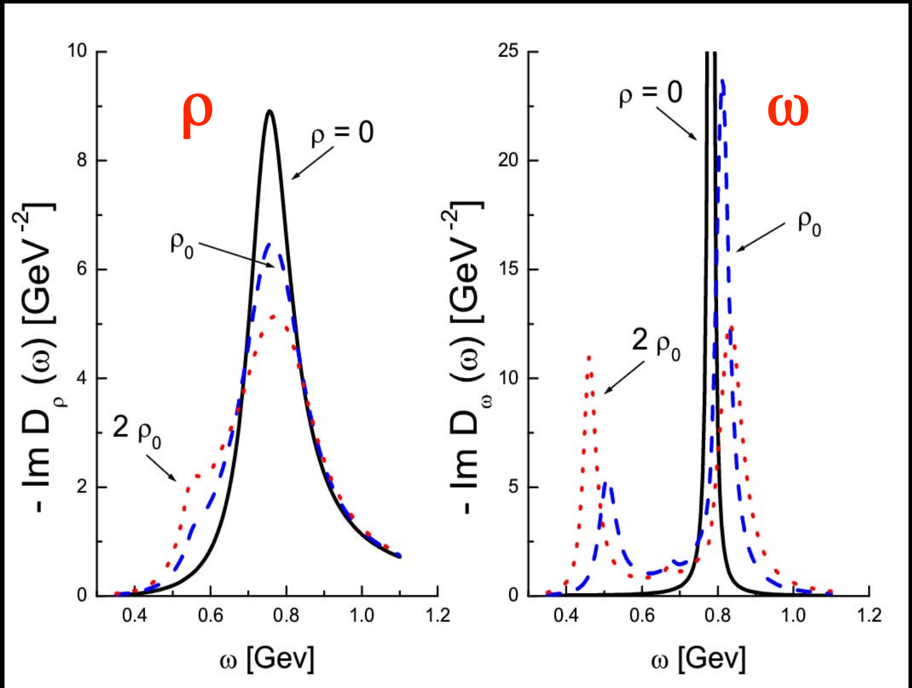


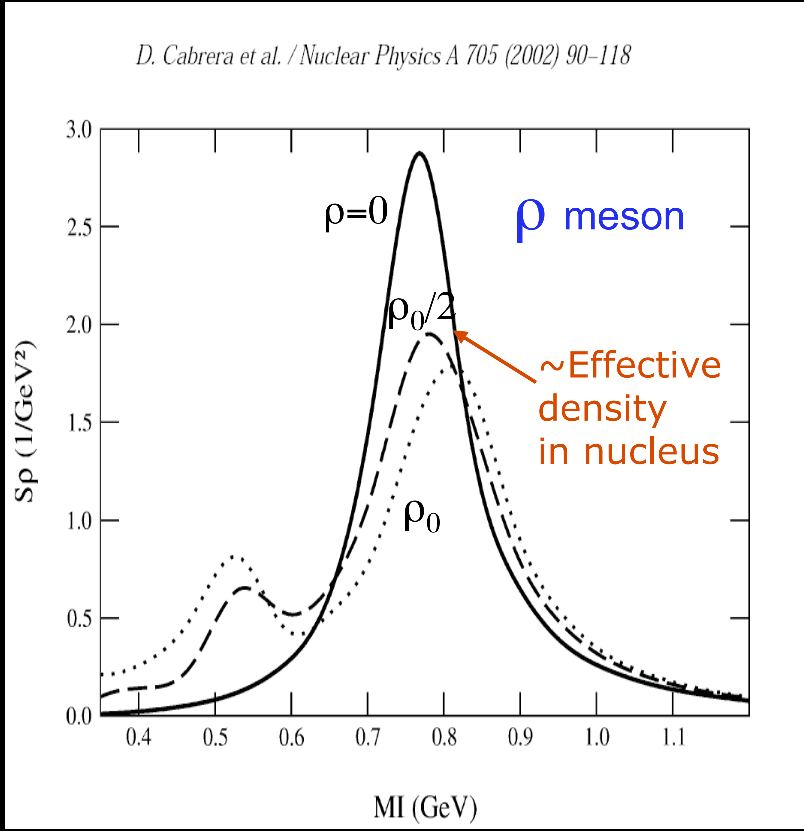


Model predictions of the in medium properties of vector mesons

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

D. Cabrera et. al. , Nucl. Phys. A 705 (2002) 90

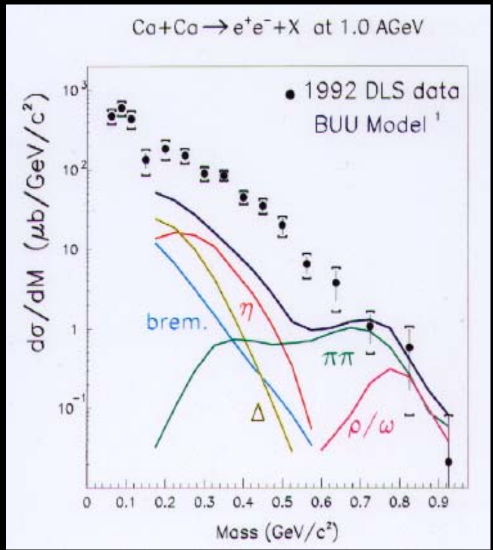


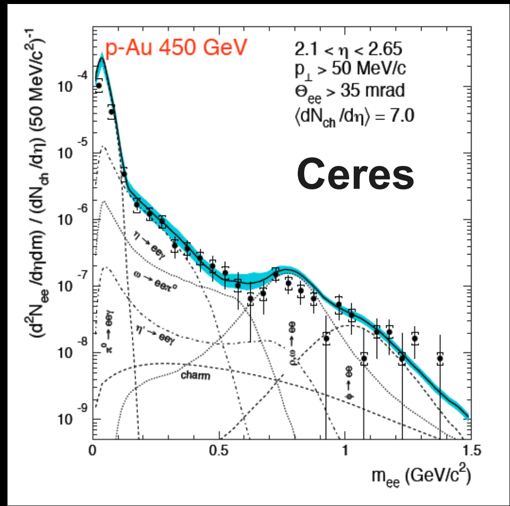


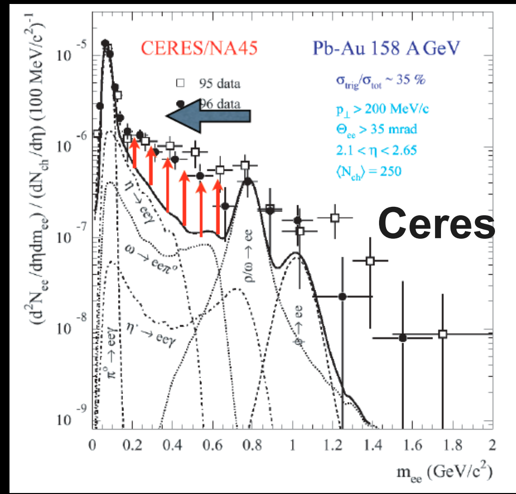
Coupling to baryon resonances

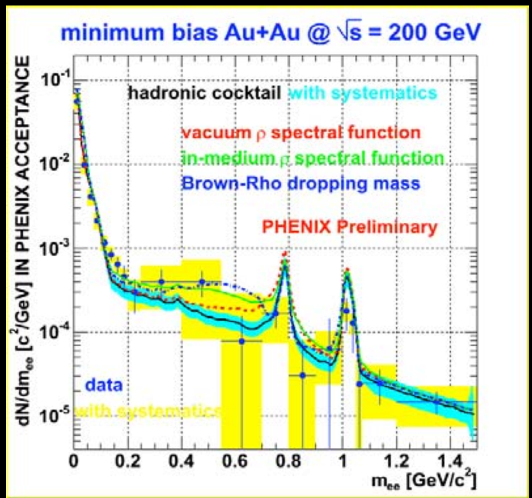
Any observations??

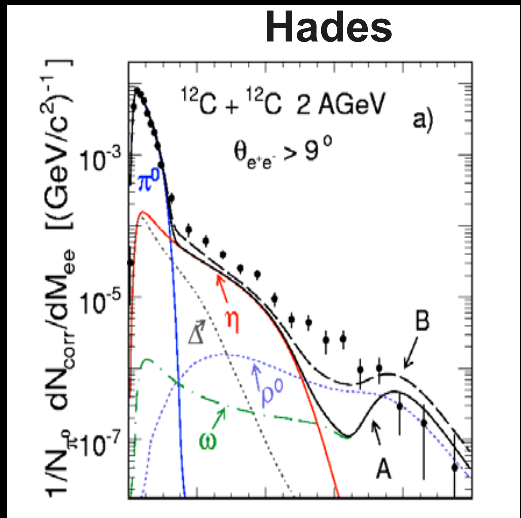
In RHI collisions (nuclear matter under extreme conditions)

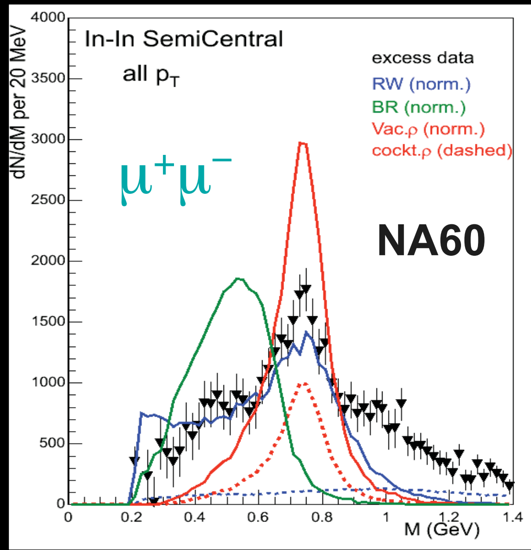








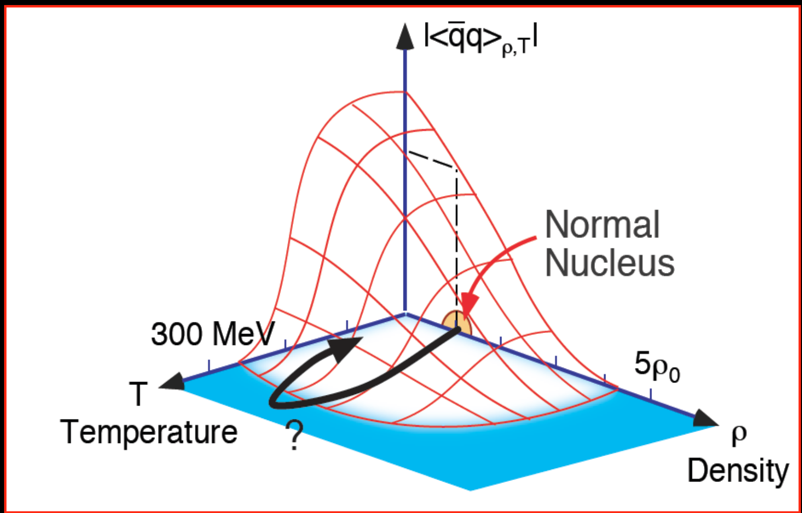


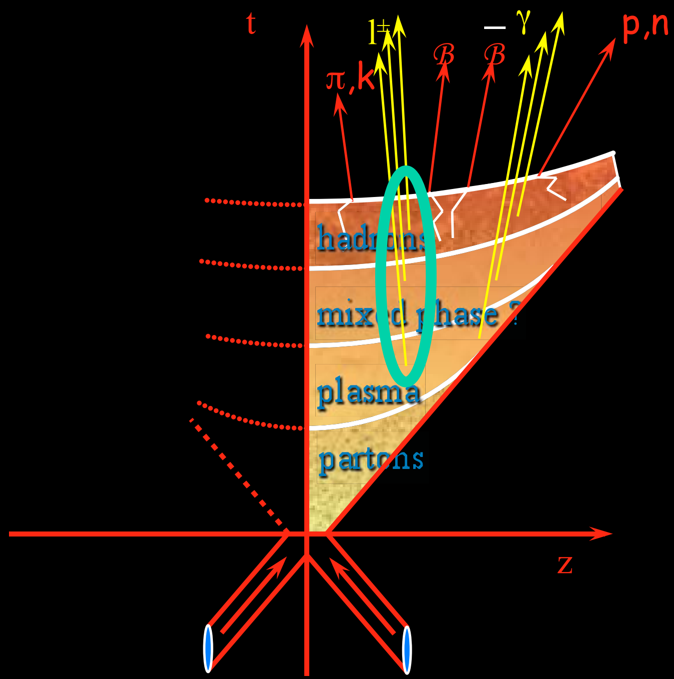


Clear excess of di-leptons observed. NA60: Γ ↗ ,no ΔM”

Medium modification of Vector Meson properties seem to explain HI results HOWEVER

1) In A+A collisions, the results are integrated over a whole range of ρ and T; "it is hard to get easily to the elementary process"!
4) 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 channels are involved

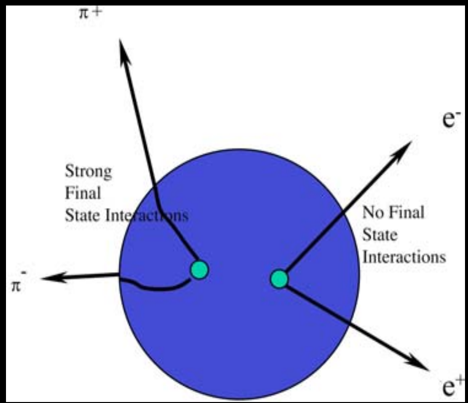


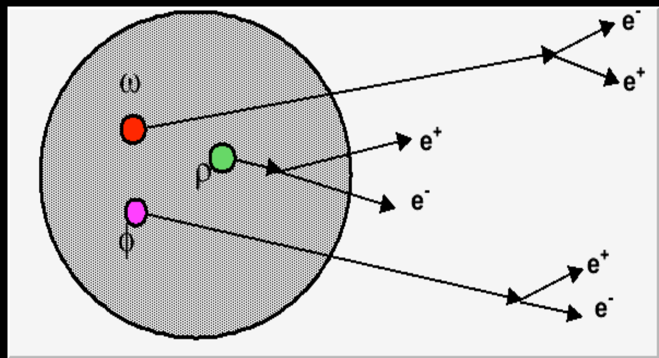


Medium modification of vector mesons properties in nuclei

The predicted medium modifications are so large that even at normal nuclear density, they can be observed, so:

- Vector mesons can be produced in nuclei with probes that leave the nucleus in almost an equilibrium state γ,π,p,
- (probe) + A --> V X --> e^+e^- X (no FSI)





Decay inside

Vector mesons	ρ:	M=768 MeV	Γ= 149 MeV	cτ~1.3 fm
$J^P=1^-$	ω:	M=782 MeV	Γ = 8 MeV	cτ~23.4 fm
	φ:	M=1020 MeV	Γ = 4 MeV	cτ~44.4 fm

Need very low p

Present and planned "elementary reactions" (not exhaustive list):

Experiment	*Reactions*	*Results*
TAGX	$\gamma + ^3He \rightarrow \rho + X$ ($\rho \rightarrow \pi^+\pi^-$)	full BR, $\alpha \sim 0.06$
KEK	$p+A \rightarrow \rho,\omega,\phi + X$ ($\rho,\omega \rightarrow e^+e^-$)	$\alpha = 0.092 \pm 0.002$
KEK	$p+A \rightarrow \phi + X$ ($\phi \rightarrow e^+e^-$)	$\alpha \sim 0.04$
SPring-8	$\gamma + A \rightarrow \phi + A^*$ ($\phi \rightarrow K^+K^-$)	no effect
TAPS	$\gamma + A \rightarrow \omega + X$ ($\omega \rightarrow \pi^0 \gamma$)	$\alpha \sim 0.13$-015
JLab-g7a	$\gamma + A \rightarrow (\rho,\omega,\phi) + A^*$ (VM $\rightarrow e^+e^-$)	$\alpha = 0.02 \pm 0.02$
JPARC	$p+A \rightarrow \rho,\omega,\phi + X$ ($\rho,\omega,\phi \rightarrow e^+e^-$)	proposal #16
HADES	$p+p,d \rightarrow \rho,\omega,\phi + X$ ($\rho,\omega,\phi \rightarrow e^+e^-$)	(running)
	$\pi + A \rightarrow \rho,\omega,\phi + X$ ($\rho,\omega,\phi \rightarrow e^+e^-$)	2009/10

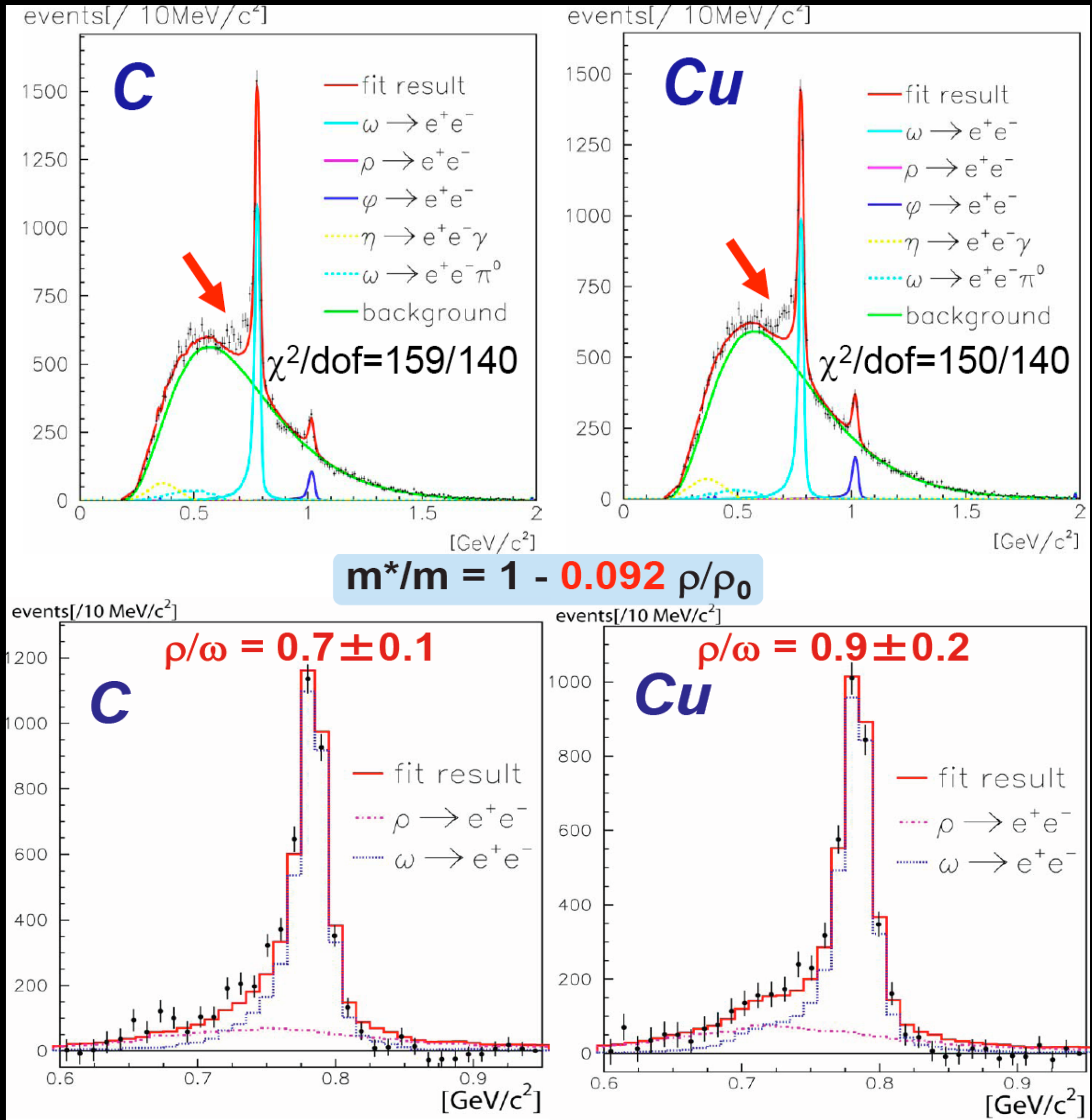
-Only g7 with EM interaction in entrance and exit channels

-TAGX, Spring8 and TAPS have hadronic FSI.

KEK-PS E325 (ρ, ω)

p+A → ρ,ω,ϕ+X (ρ,ω,ϕ → e+e-)

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

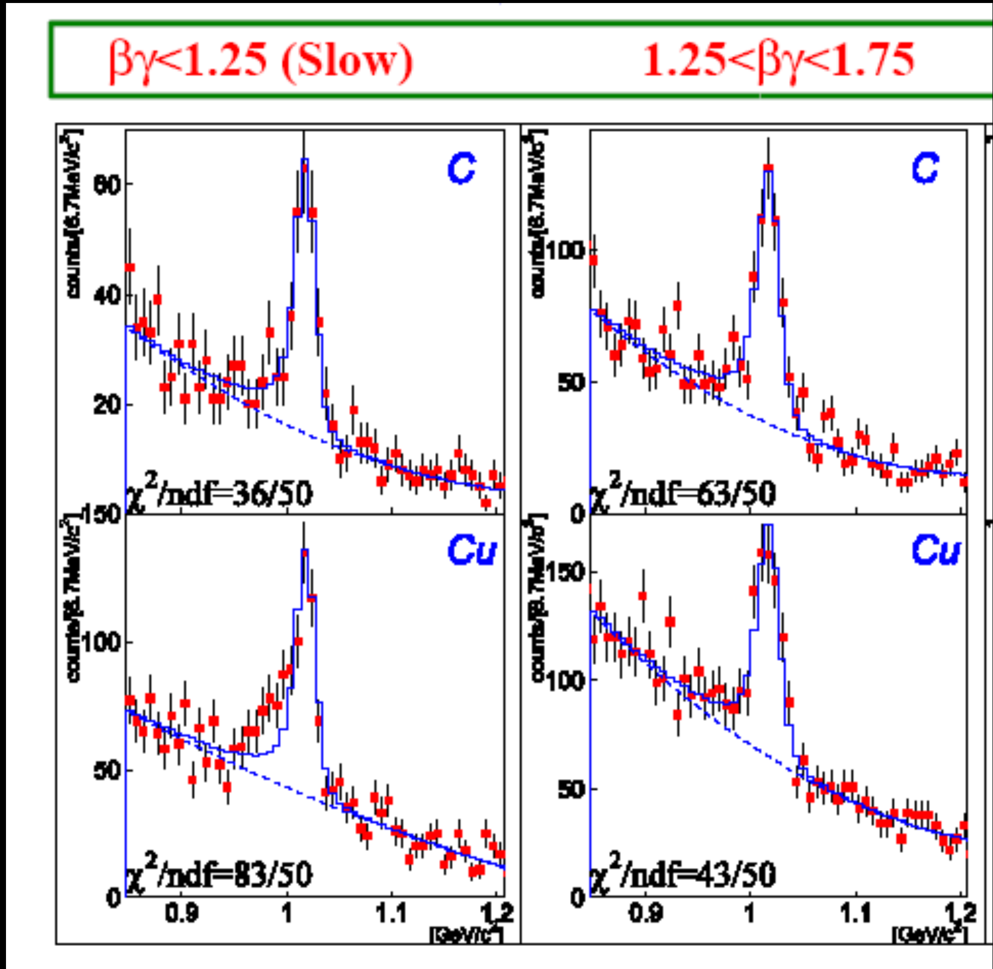


Subtract the background and constrain the ω/ρ ratio to include ρ
Using a model that predicts the probability for ρ mesons decaying inside the nucleus.

α = 0.092 +/- 0.002

"the fit … reproduces the data qualitatively well"

KEK-PS E325(ϕ)



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

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

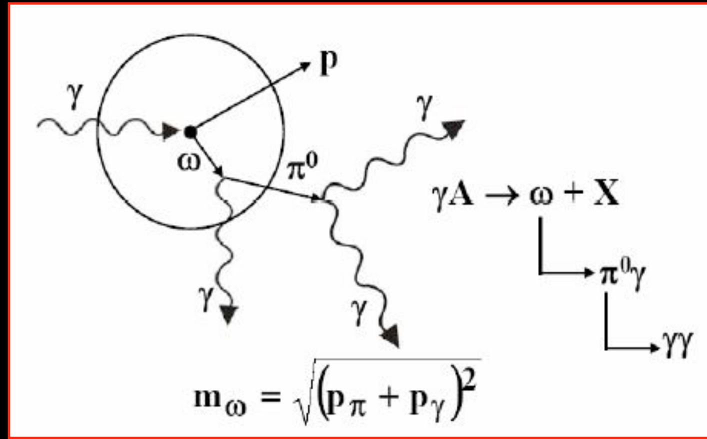
Best Fit Values

	ρ, ω	ϕ
k_1	$9.2 \pm 0.2\%$	$3.4^{+0.6}_{-0.7}\%$
k_2	0 (fixed)	$2.6^{+1.8}_{-1.2}$

mass shift for low recoil momenta ϕ in Cu

Bonn- TAPS results

γ+A-->ω+X (ω --> π^0 γ)

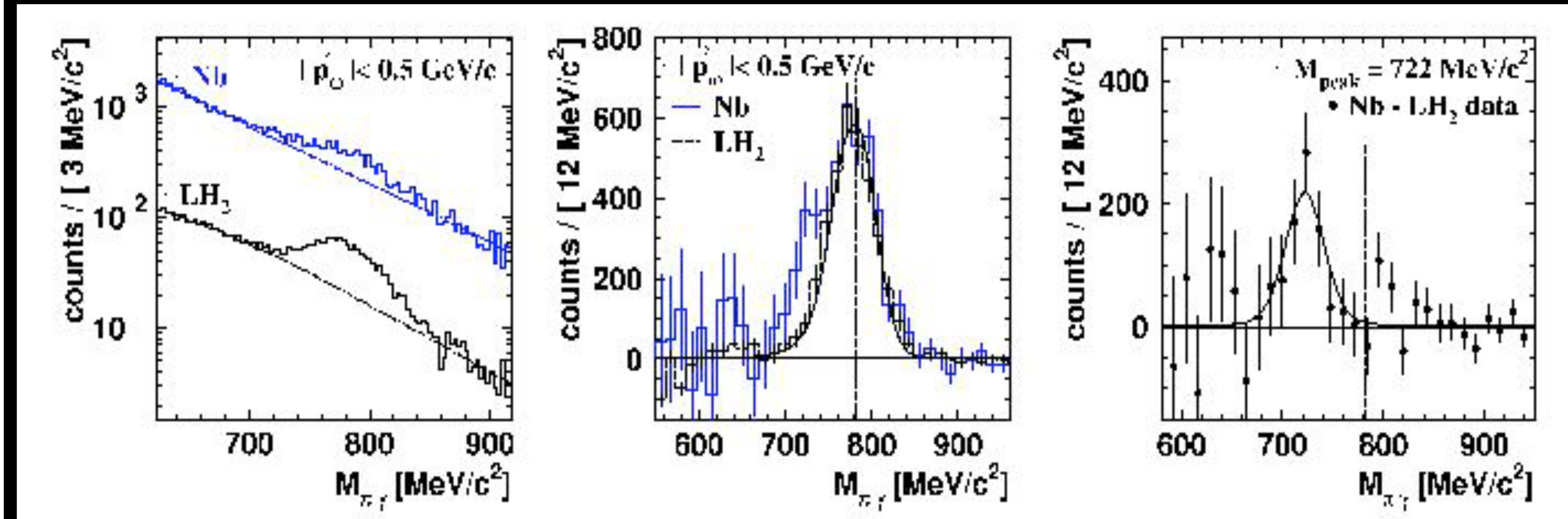


clean (no ρ) channel, however FSI of π

Small signal to background ratio

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

Γ_ω (ρ=ρ_0, <|p_ω|> ≈750 MeV/c) ≈ 95 MeV (old)



D. Trnka et al., Phys.Rev.Lett. 94 (2005) 192303

Valencia group object to the conclusion on Δm; EJP J A 31 (2007) 245

Experimental Results

	Elementary Reactions		Rel. Heavy-Ion	
	KEK	CBELSA/TAPS	CERES	NA 60
Reaction	pA → (ρ,ω,φ) A' VM → e+e-	γ A → ω A' ω → $\pi^0\gamma$	p+Au,Pb+Au ρ → e+e-	In+In ρ → μ+μ-
Condition	$\rho=0.53\rho_0$, T~0 MeV	$\rho=0.55\rho_0$, T~0 MeV	158 A GeV	158 A GeV
Mass	Δm_ρ~-9% Δm_ϕ ~ -4%	Δm_ω ~ -14%*	Δm not favored	No mass shift
Width	$\Delta\Gamma_\rho$ = 0 MeV $\Gamma_\phi(\rho=\rho_0)$ = 47 MeV	$\Gamma_\omega(\rho=\rho_0)\approx$140 MeV (newly published)	Broadening favored	Strong broadening
Note	No direct extraction of ρ meson (BKGD)	π^0 FSI Large background	ρ, T not constant	ρ, T not constant

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

*D. Trnka et al, *PRL 94 (2005)*

D. Adamova et al, *PRL 91 (2003)*

R. Arnaldi et al, *PRL 96 (2006)*

Photoproduction of Vector Mesons off Nuclei "looking for medium modifications"

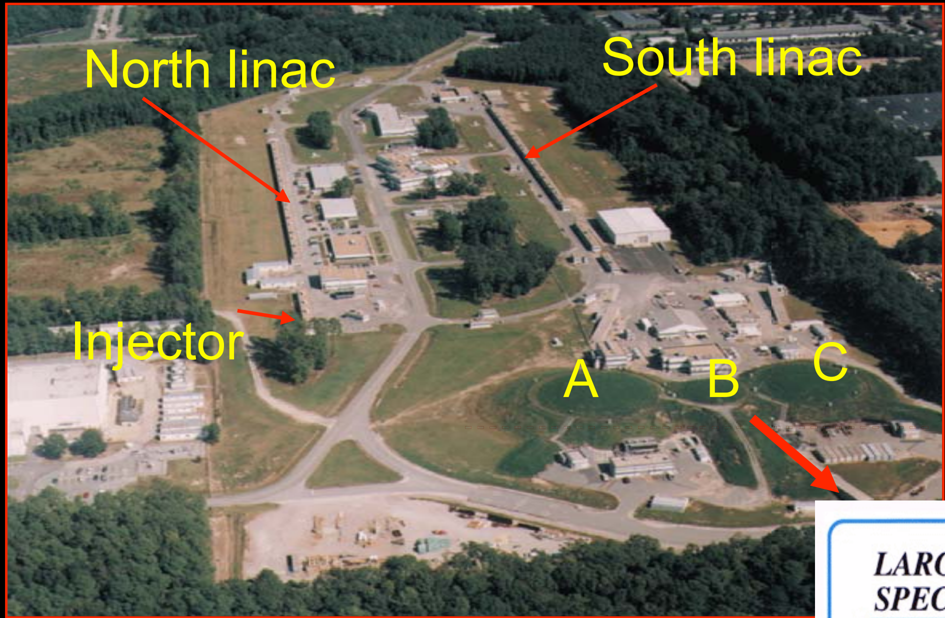
$$\gamma A \longrightarrow VX$$
$$\hookrightarrow e^+e^-$$

- **Original idea:**
  P. Y. Bertin and P. A. M. Guichon, Phys Rev C42, 1133 (1990)
- **Jlab Experiment E01-112 (also called g7)**
  Spokespersons: C. Djalali (USC), M. Kossov (ITEP),
  D. Weygand (Jlab)
- **Photon beam (minimal disturbance to initial sate) :**
  E_γ ~ .6 to 3.8 GeV (tagged γ)
  Targets: LD_2, C, Ti, Fe, (Pb)
- **Leptonic decay :**
  Almost no final state interaction! HOWEVER (NO FREE LUNCH!)

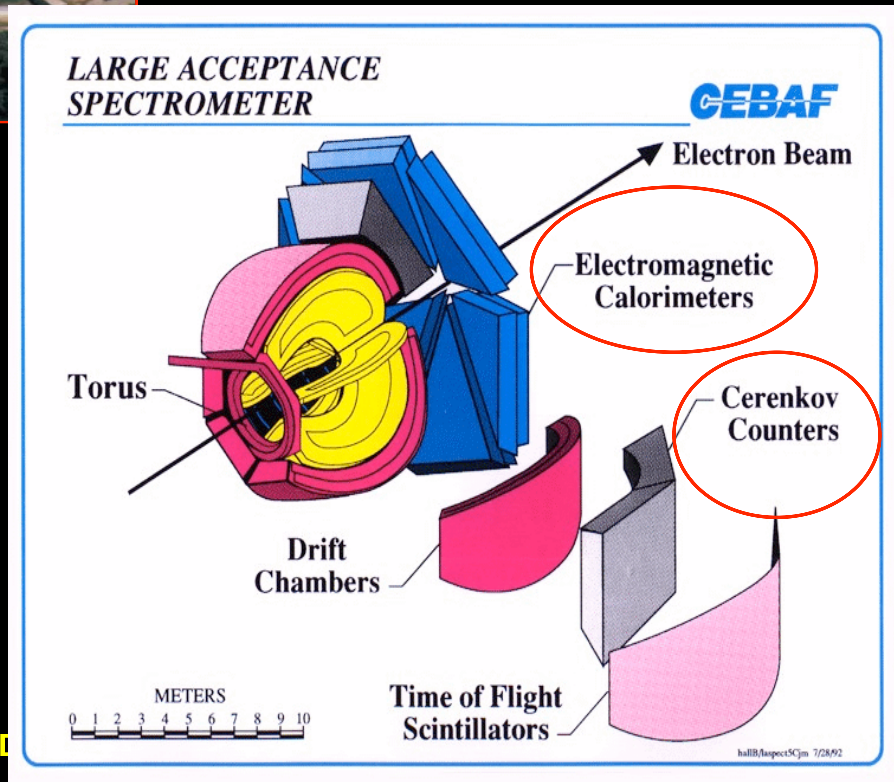
  Low branching ratio : ~5 10^{-5}

  needs high photon flux : 5 10^{7} tagged γ/s

CEBAF (Continuous Electron Beam Accelerator Facility) at Jefferson Laboratory (JLab)

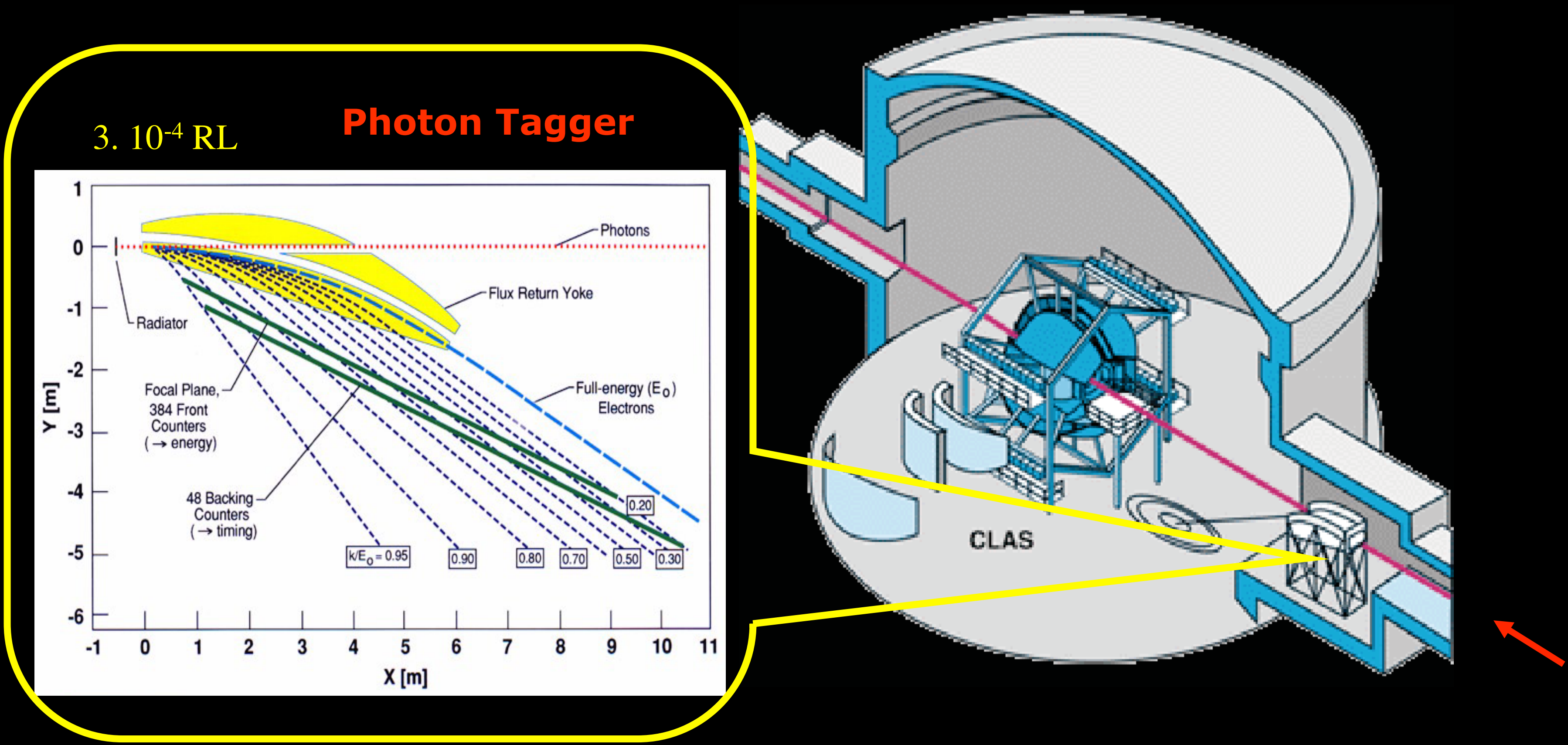


E_{max} ~ 6 GeV
I_{max} ~ 200 μA
Duty Factor ~ 100%



- Toroidal magnetic field
(6 superconducting coils), Drift chambers, Scintillators, Cerenkovs, Electromagnetic Calorimeter.

Hall B @ Jlab (The tagger)

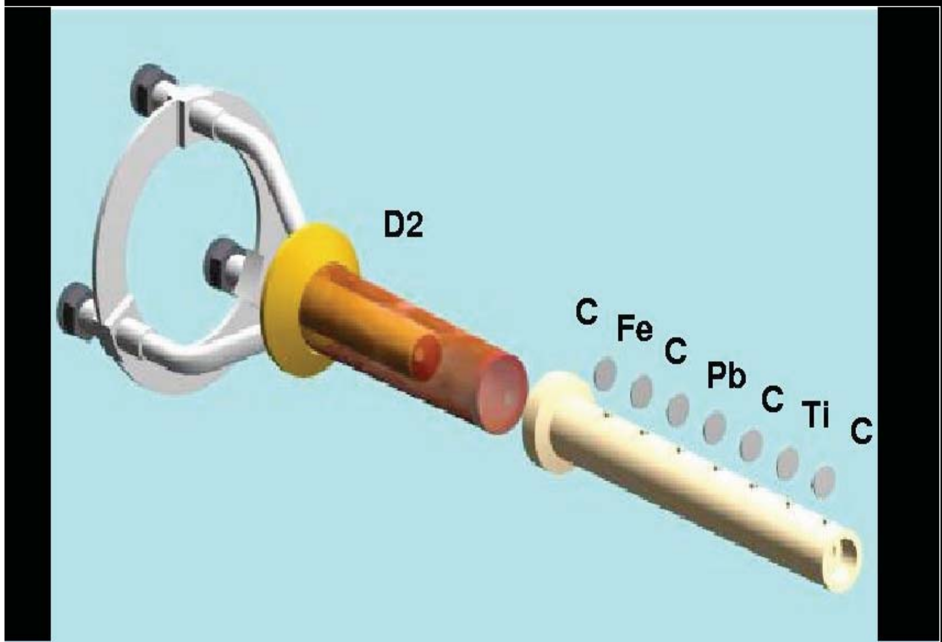


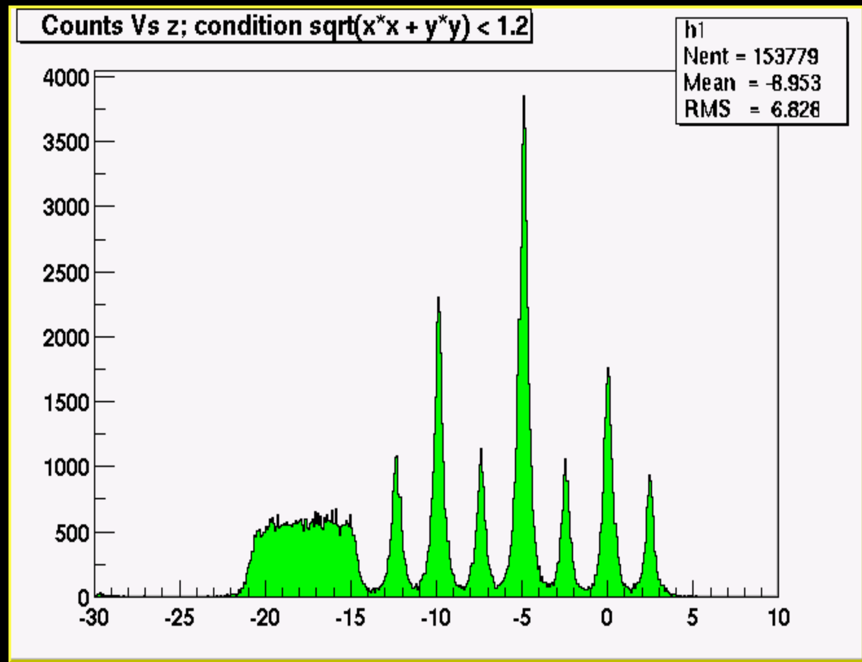
Bremsstrahlung Tagging Spectrum (20%-95%)

- $E(e^-)$ = 3.0 GeV $E(\gamma)$ = 0.60 - 2.85 GeV
- $E(e^-)$ = 4.0 GeV $E(\gamma)$ = 0.80 - 3.80 GeV

Multi-Segment Nuclear Target

- 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
- Approximately same number of nucleons/target

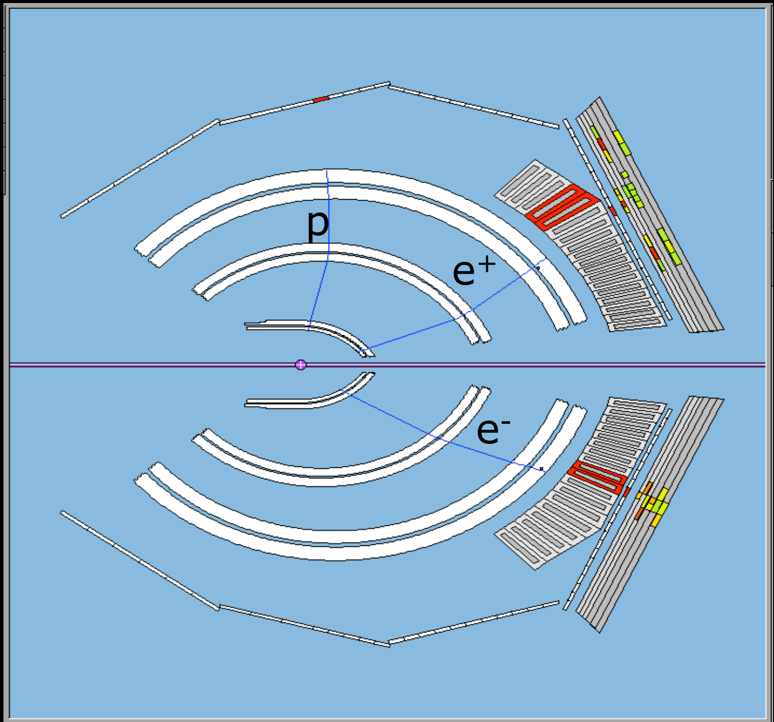


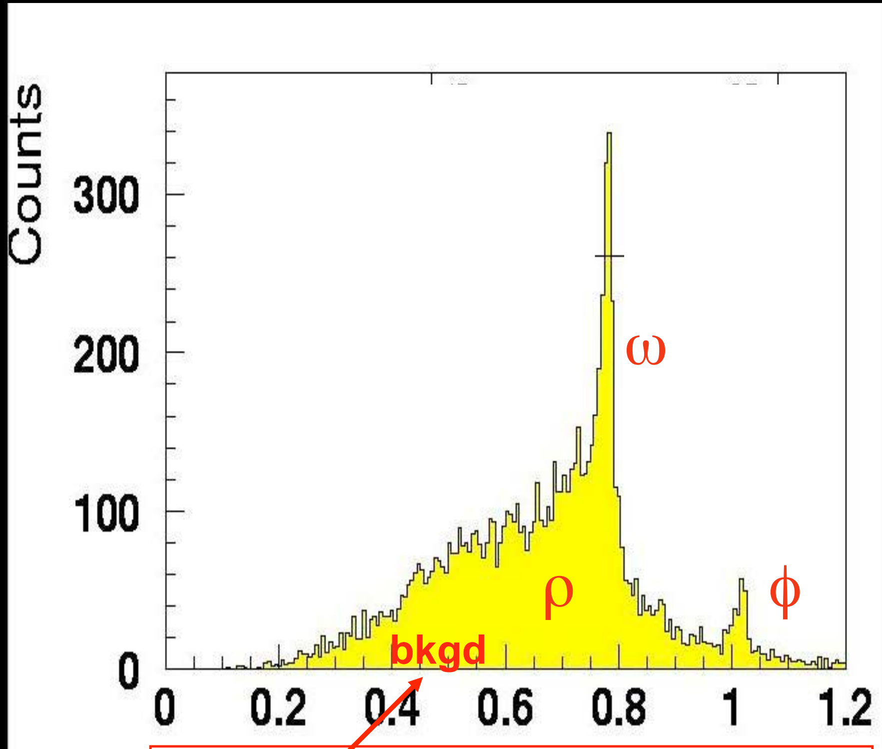


- Proper spacing 2.5 cm to reduce multiple scattering
- Deuterium target as reference, small nucleus, no modification is expected.

Particle Detection with CLAS

coincident electron pairs in the CLAS





e^+e^- Invariant Mass Spectra

- Momentum corrections
- Target energy loss corrections
- Lepton momentum cuts

Caution: The treatment of the background may change the estimation of the signal (ρ).

- Excellent π/e discrimination: 5.4×10^{-4} for one and 2.9×10^{-7} for two arms.

Possible channels that contribute to e^+e^- mass spectrum

Correlated:

- Monte-Carlo simulations using a model (Giessen BUU) (Nucl. Phys. A671, 503 (2000)) including various decay channels and nuclear effects, and CLAS detector.
  - $\omega \to e^+e^-$, $\rho \to e^+e^-$, $\phi \to e^+e^-$
  - $\eta \to \gamma\, e^+e^-$
  - $\omega \to \pi^0\, e^+e^-$

→ **GiBUU Code**

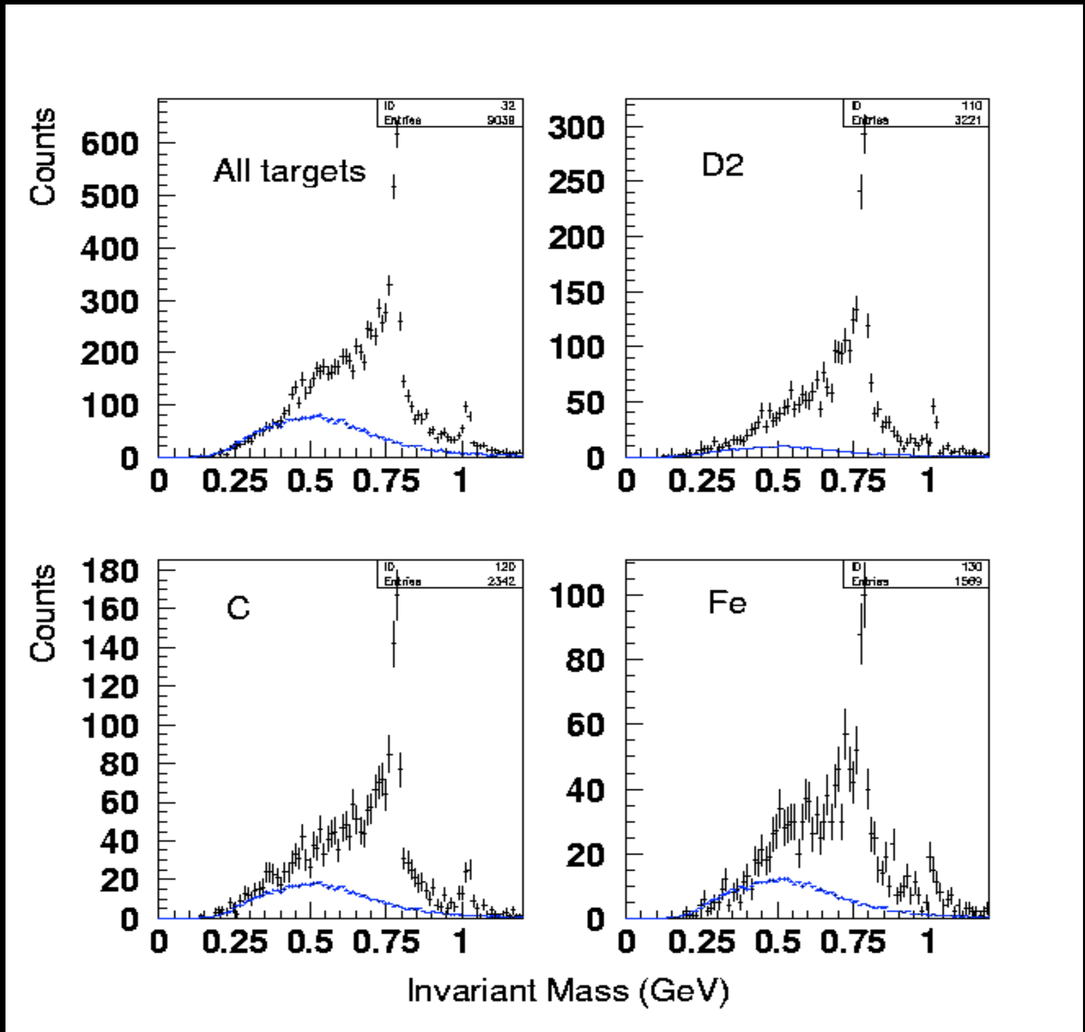
"Semi-correlated":

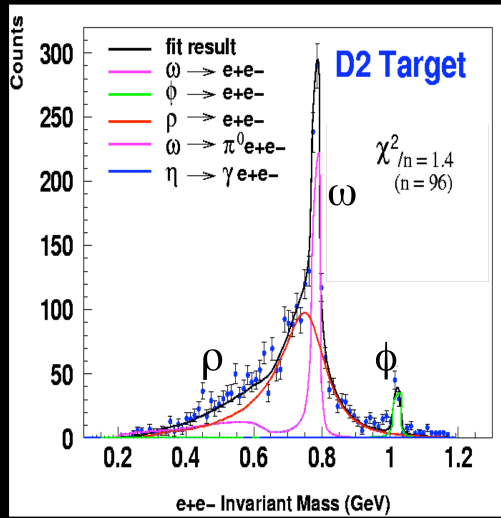
- Bethe-Heitler — calculated by Mosel's group → negligible
- $\gamma A \to \pi^0 \pi^0 X \to \gamma\, e^+e^- \gamma\, e^+e^-$ — 2 π^0 Dalitz decay mixed → negligible
- $\pi^0 \to e^+e^-\, e^+e^-$ — double Dalitz → low mass

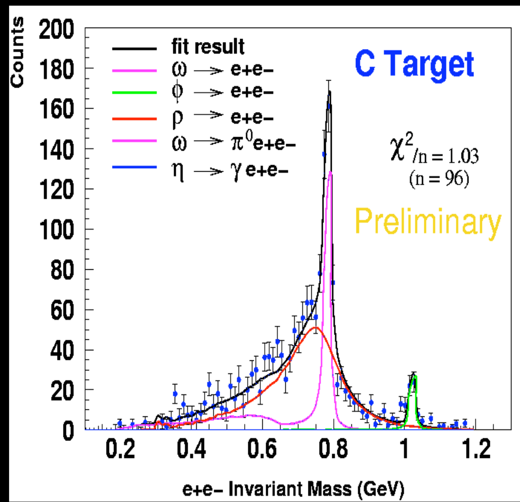
Uncorrelated:

- 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.

Combinatorial Background (mixed events and same sign pairs)







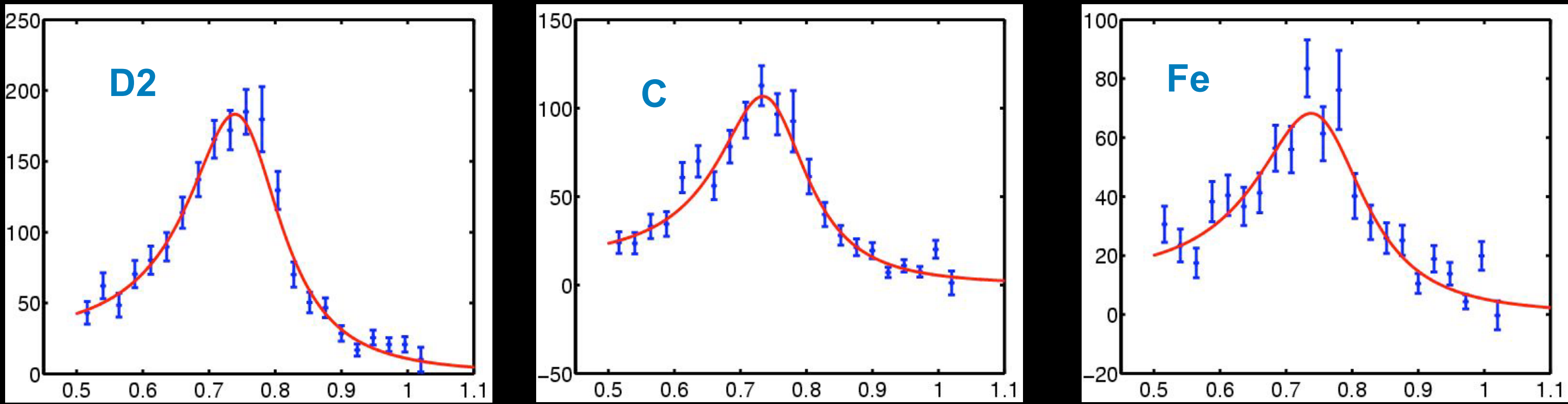
$\mu^+\mu^-$ measurement: at CERN-SPS ***IPNO-DR-02.015 (2002)***

$\pi^+\pi^-$ measurement: at CERN-ISR ***(Nucl. Phys. B124 (1977) 1-11).***

e+e- measurement: at RHIC (***Nucl.Phys. A774 (2006) 743-746***).

The ρ Mass Spectra

After removing the ω, ϕ, and background contributions:



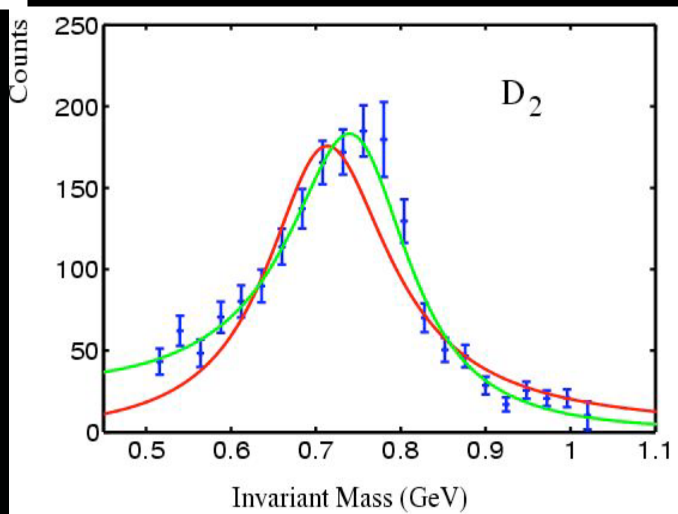
e⁺e⁻ Invariant Mass (GeV)

Fit function:

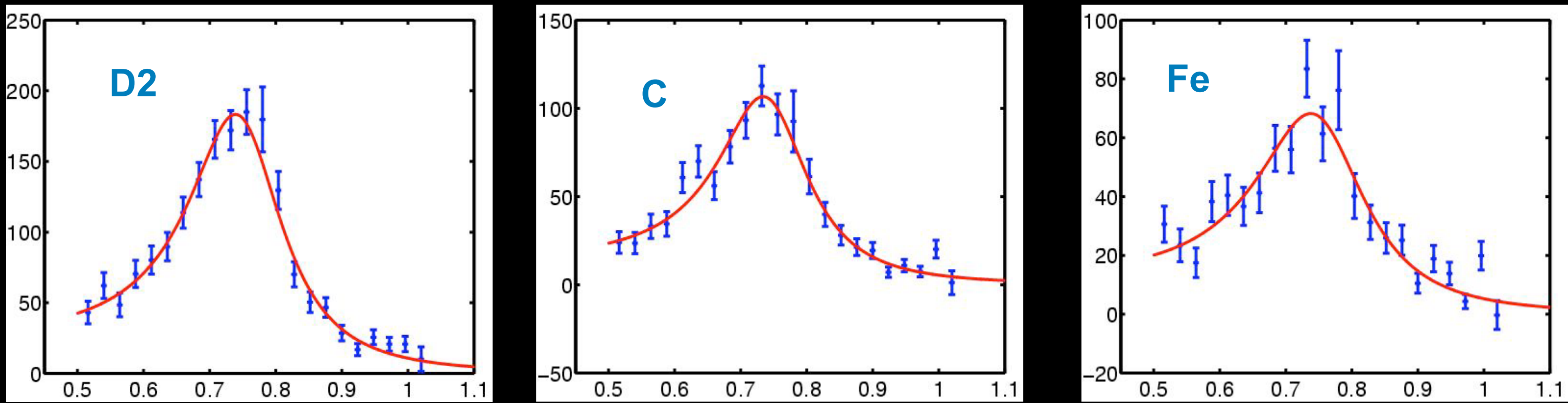
$$(\text{Breit}-\text{Wigner}) \times \frac{1}{M^4} \times M = \frac{(\text{Breit}-\text{Wigner})}{M^3}$$

Photon propagator

Breakup momentum phase space



The ρ Mass Spectra



e^+e^- Invariant Mass (GeV)

Target	Mass (MeV/c²) CLAS data	Width(MeV/c²) CLAS data	Mass(MeV/c²) Giessen Sim.	Width(MeV/c²) Giessen Sim.
^{12}C	762.5 +/- 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 close to vacuum value m ~770 MeV/c² and the broadening of the width is consistent with many-body effects.

Summary on the ρ meson

-Our result (α =0.02 ± 0.02) is compatible with no mass shift.
-Result does not confirm the KEK results (α ~0.09).
-Rule out ΔM à la Brown/Rho (20%) and
Hatsuda/Lee (α ~0.16).
-Width reproduced by GiBUU.
-Mass spectra not directly comparable with spectral function!
-Momentum of ρ between 0.8 and 2 GeV.
-Need to study momentum dependence.

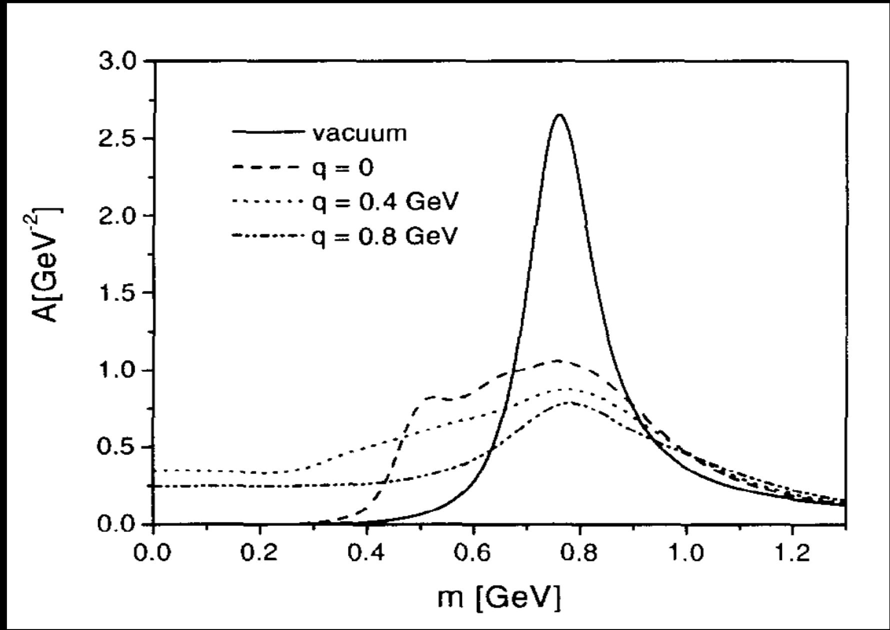
•PRL published – **R. Nasseripour *et al.*, PRL 99 (2007) 262302**
•PRC article submitted March 2008. **arXiv:0803.0492v1 [nucl-ex]**

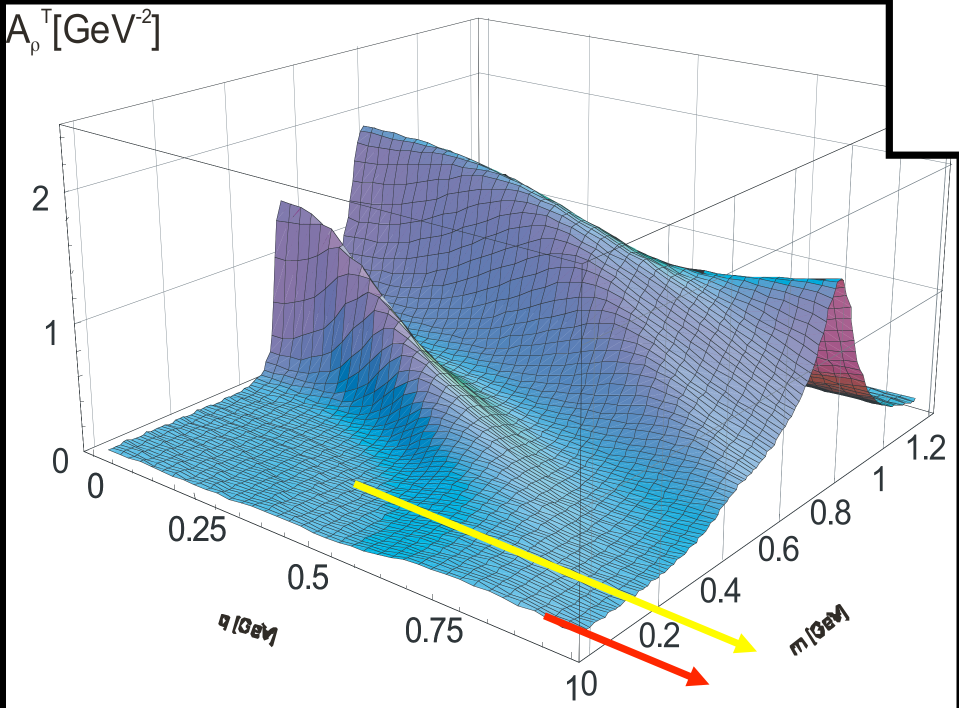
Momentum dependence – ρ meson

Giessen group (U. Mosel):

W. Peters et al., *NPA 632 (1998) 109*
M. Post et al., *NPA 741 (2004) 81*

BUU model of ρ meson production and propagation with nucleon resonance-hole contributions.





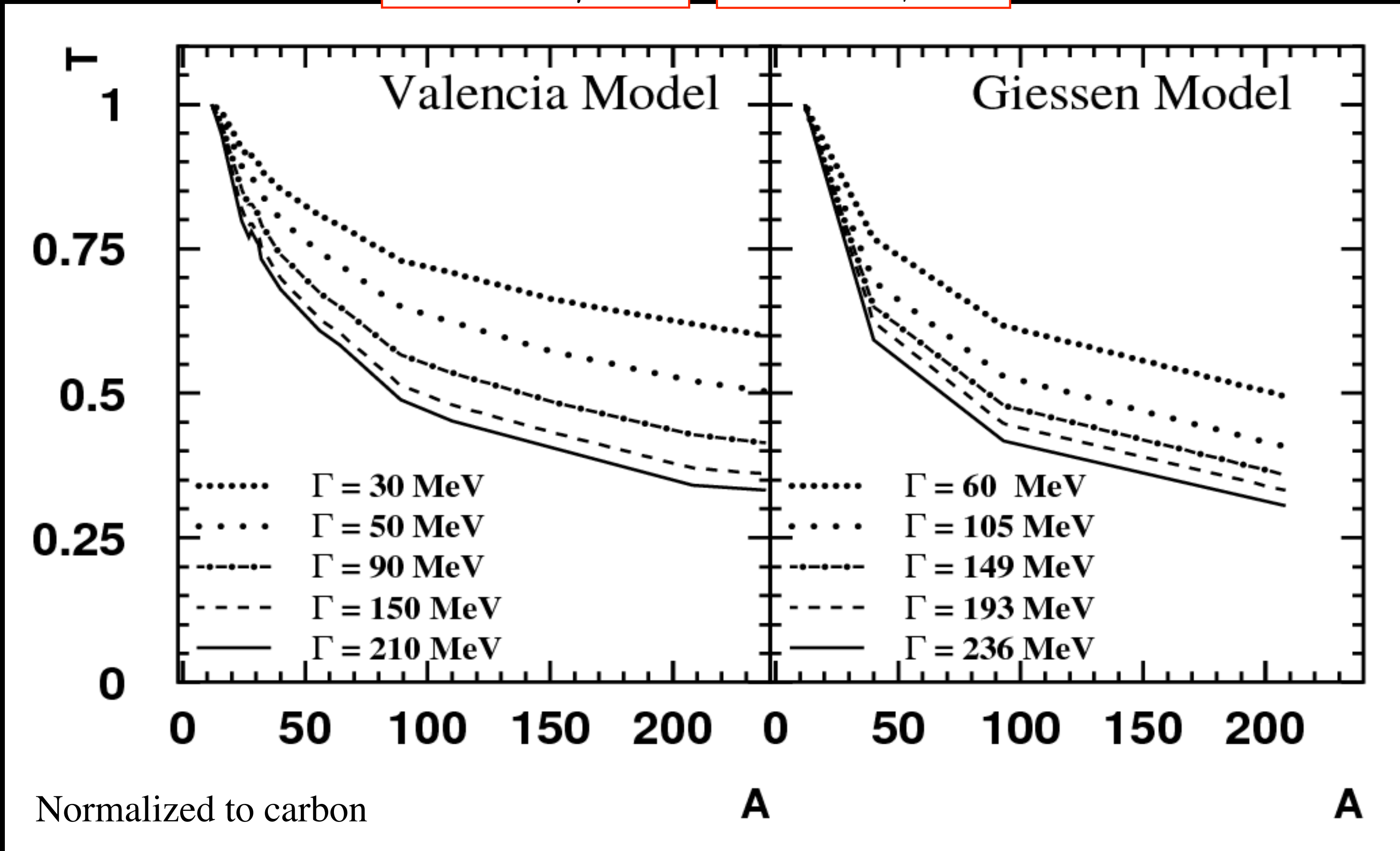
g7a

Planned g7b
Conditionally approved

Absorption of ω Meson and its In-medium width

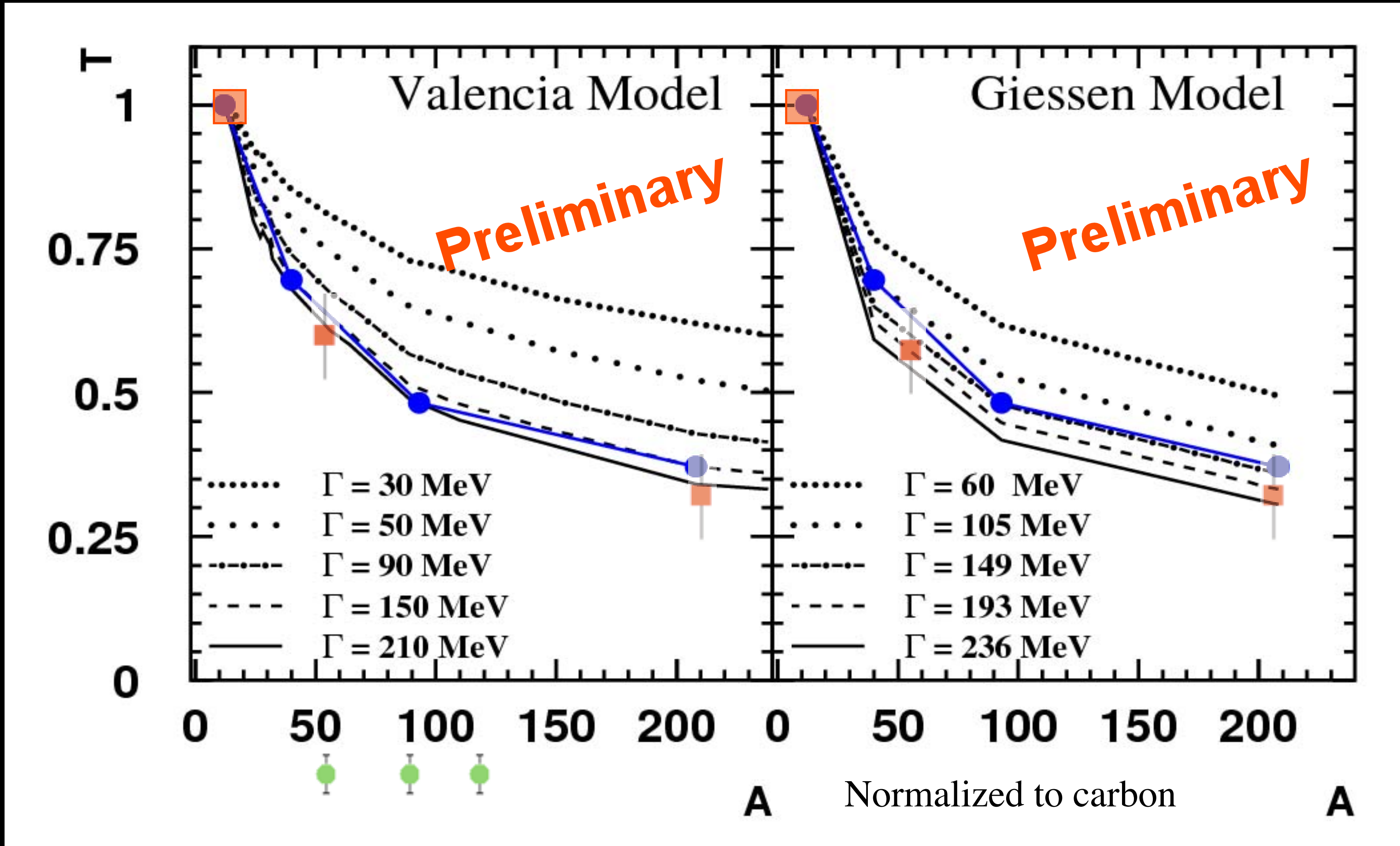
The in-medium width is $\Gamma=\Gamma_0+\Gamma_{coll}$ where $\Gamma_{coll} = \gamma\rho v\sigma^*_{VN}$

Transparency ratio: $T_A = \dfrac{\sigma_{\gamma A \to \omega X}}{A \cdot \sigma_{\gamma N \to \omega X}}$ $\quad T_{norm} = \dfrac{12 \cdot \sigma_{\gamma A \to \omega X}}{A \cdot \sigma_{\gamma ^{12}C \to \omega X}}$



Kaskulov, Hernandez & Oset EPJ A 31 (2007) 245 P. Mühlich and U. Mosel NPA 773 (2006) 156

Comparison to Theory – ω Meson



Preliminary g7a result showed greater absorption than TAPS!!!

Latest TAPS Γ_ω~130-150 MeV **now closer to JLAB results which are larger!**

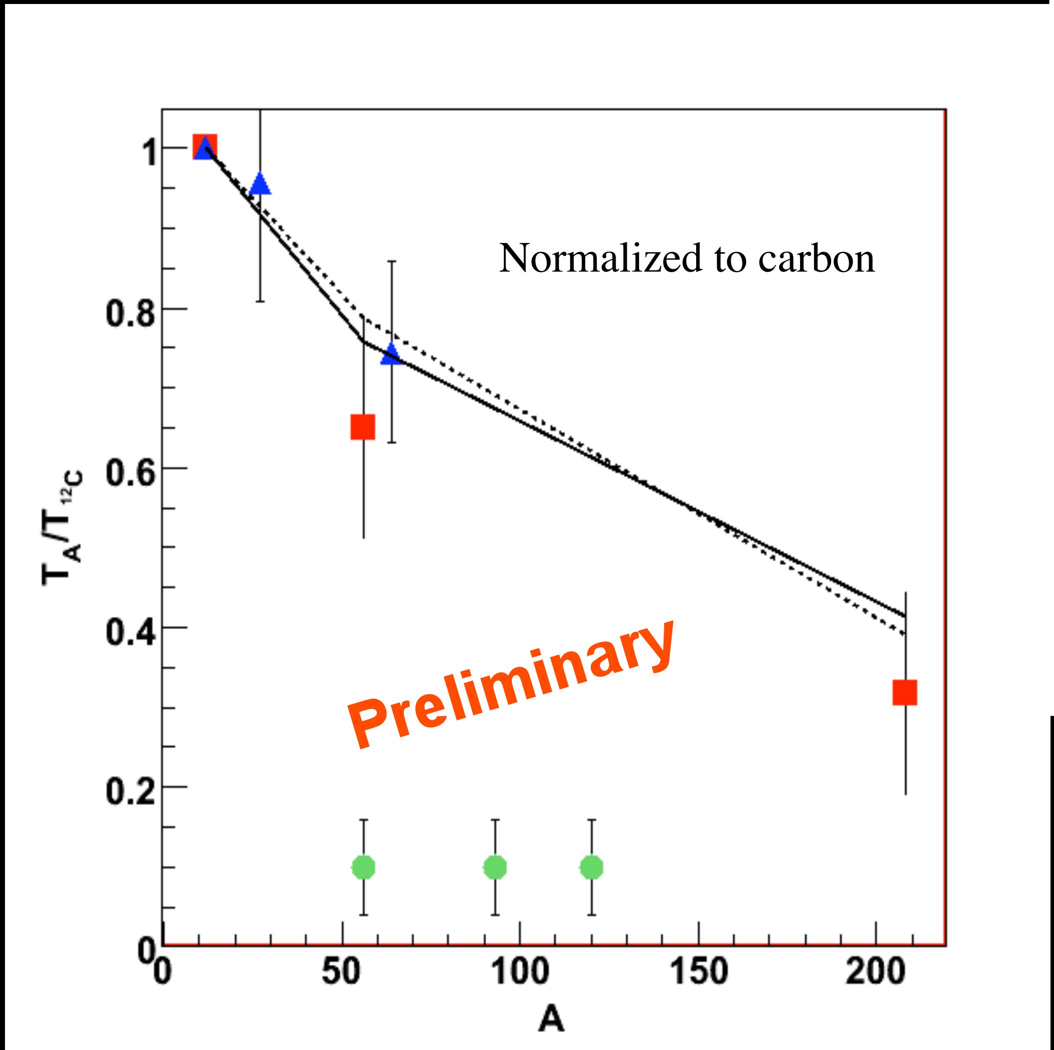
JLab **(preliminary)**

TAPS (latest analysis)

Proposed JLab run

Comparison to Expt. – ϕ Meson

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



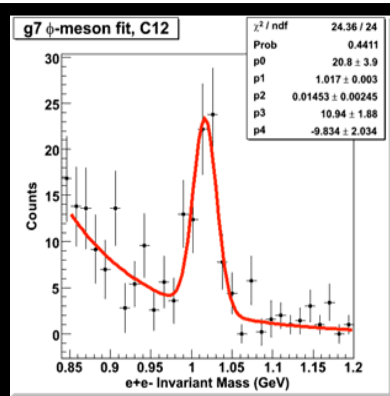
Giessen calculations

Giessen calculations w/ Spring8 absorption strengths

JLab (preliminary)

Spring8
T. Ishikawa et al. Phys. Lett. B 608, 215 (2005)

Planned JLab data



Large statistical error bars.

Summary and Conclusions

CLAS excellent tool for these studies:

- e^+e^- from rare leptonic decay of light vector mesons are identified.
- Clear ρ, ω and ϕ signals in the invariant mass spectrum.
- “Mixed-event” technique gives both shape and normalization of the combinatorial background.

The ρ meson (Final):

- Correct mass shape is extracted.
- No mass shift and width increased by 40% in Fe (as predicted by GiBUU)

The ω meson (preliminary):

- From transparency ratios, width at least ~ 150 MeV!

The ϕ meson (preliminary):

- From transparency ratios, in medium total cross section ~ 30 mb

Medium modification studies continue to be a hot topic!

Next at Jlab by g7 group:

- High Statistics measurement of e^+e^- production on H_2 (Currently running with g12)
- Conditionally approved g7b high statistics data on LD_2, C, Fe, Nb and Sn to measure the ρ meson mass spectra in four momentum bites from 0.4 to 2 GeV/c and transparency ratios.