



Quark Matter 2008



20th International Conference on Ultra-Relativistic Nucleus Nucleus Collisions

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Medium Modifications of Light Vector Mesons in Photo-production Reactions at JLab

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and CLAS Collaboration

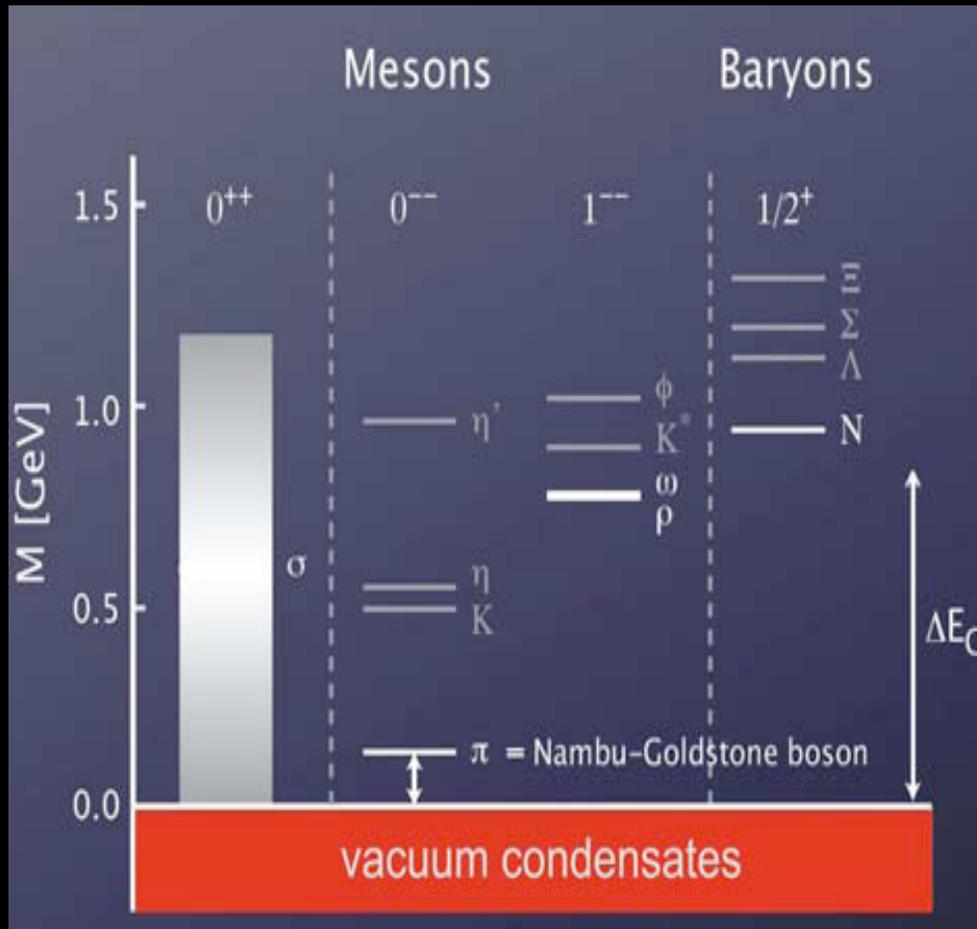


Outline

- **Physics Motivations**
 - **Why study in medium hadrons?**
 - **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
 $\langle q\text{-}q\text{bar} \rangle$, $\langle GG \rangle$, 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 may signal:
 -Chiral symmetry restoration
 -exotic state of matter,....**

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

Mass, decay, coupling constants will change.

Model predictions of the in medium properties of vector mesons

Scale invariance in effective Lagrangian:

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

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

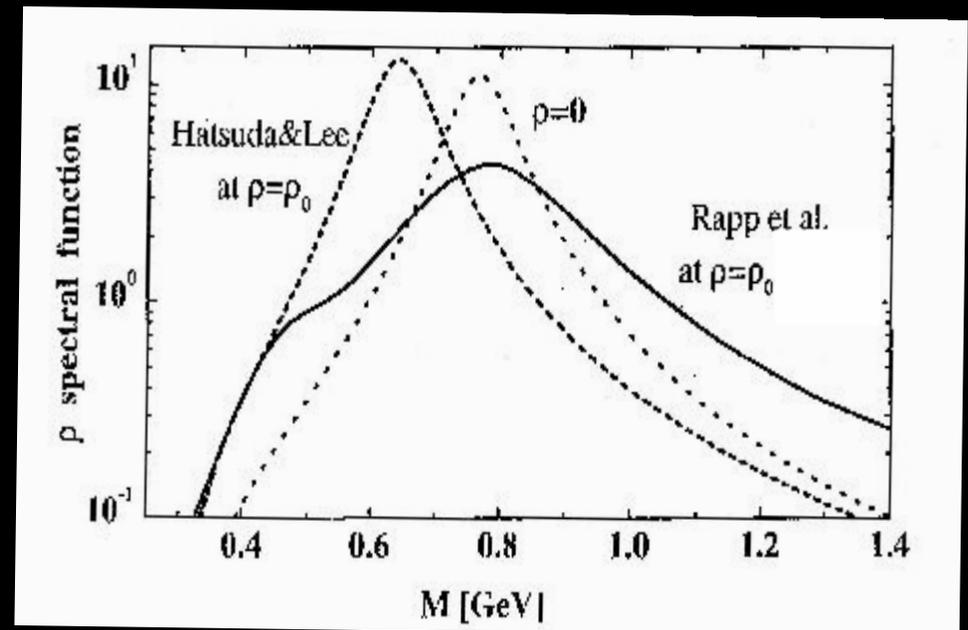
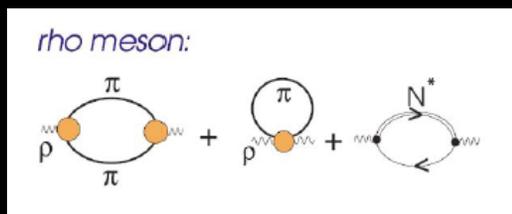
QCD sumrules:

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

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

Many body effects:

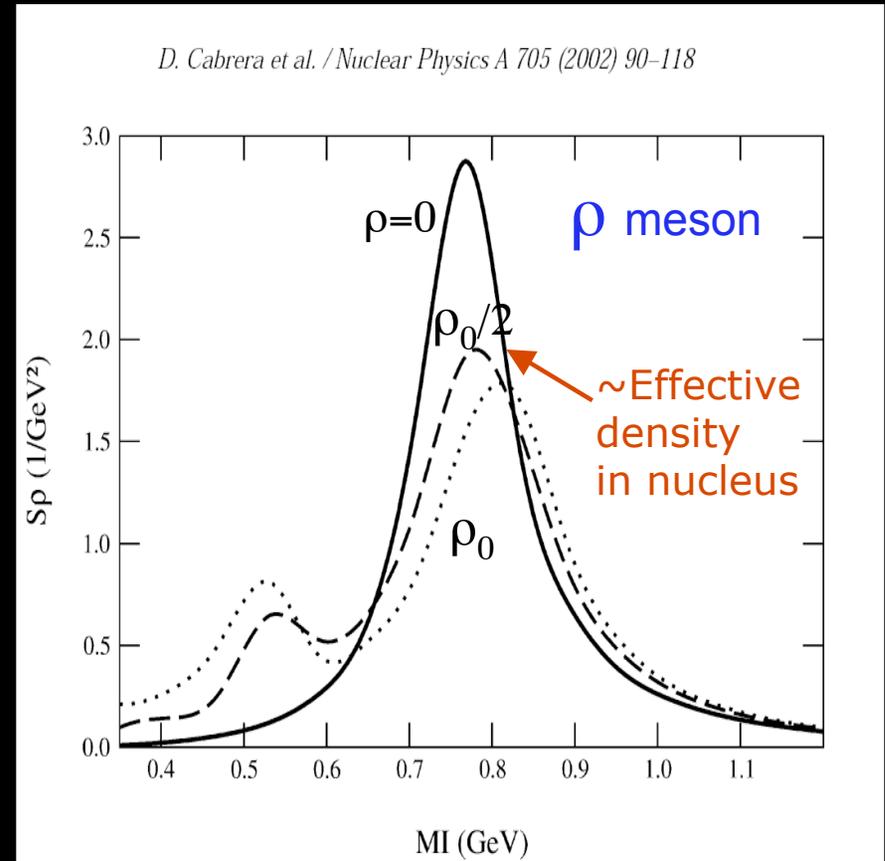
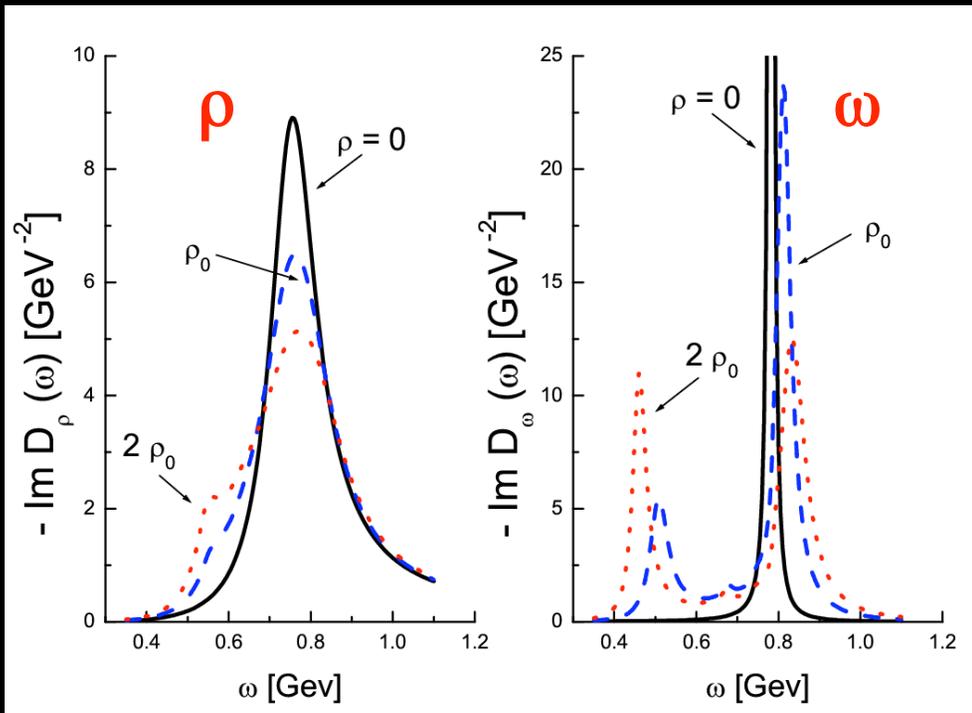
B Friman, H.J. Pirner,
Nucl Phys. **A617** (1997) 496
R. Rapp, G. Chanfray, J Wambach,
Nucl Phys. **A617** (1997) 472



Model predictions of the in medium properties of vector mesons

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

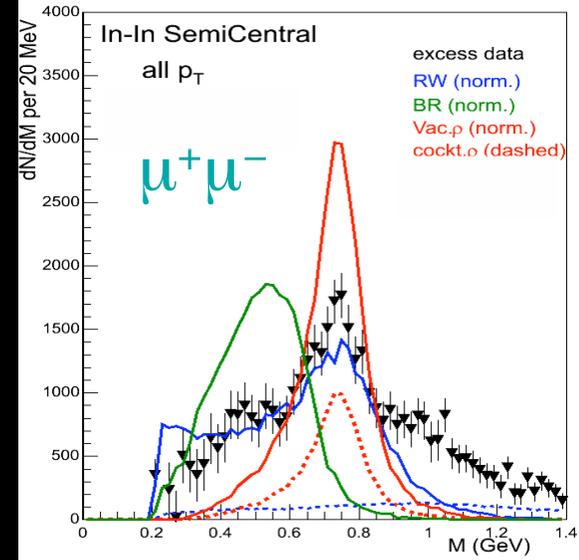
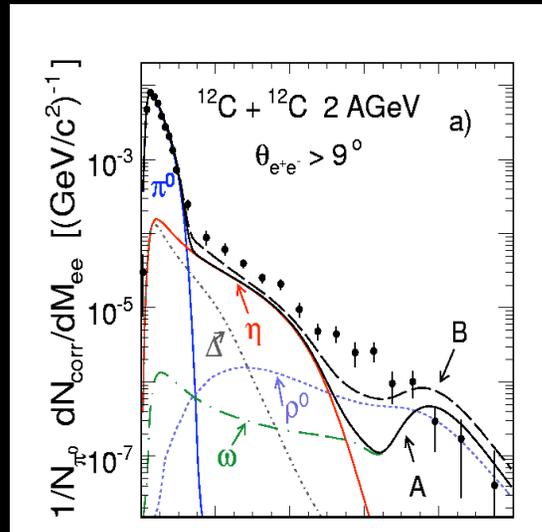
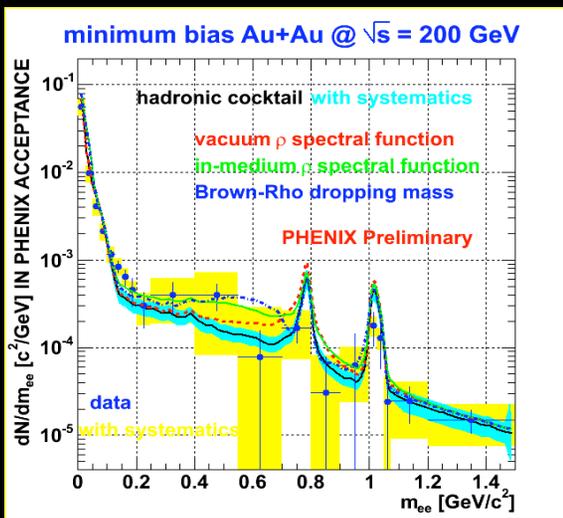
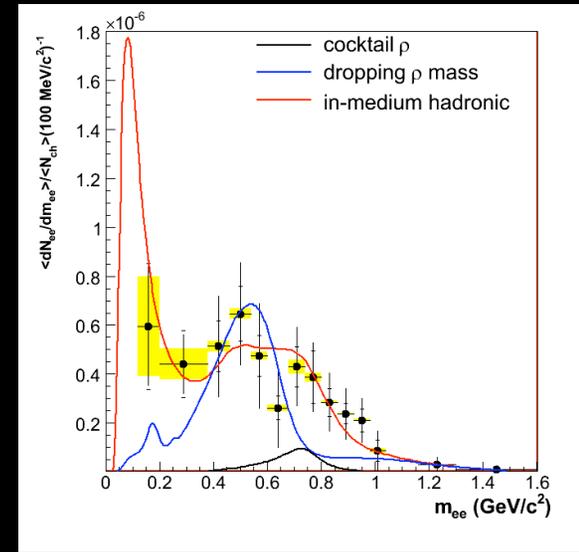
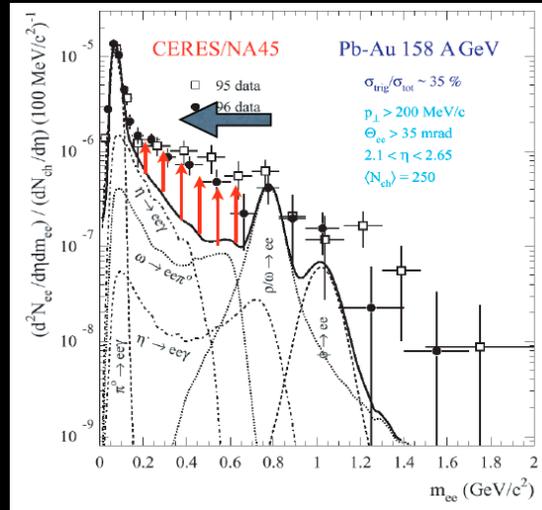
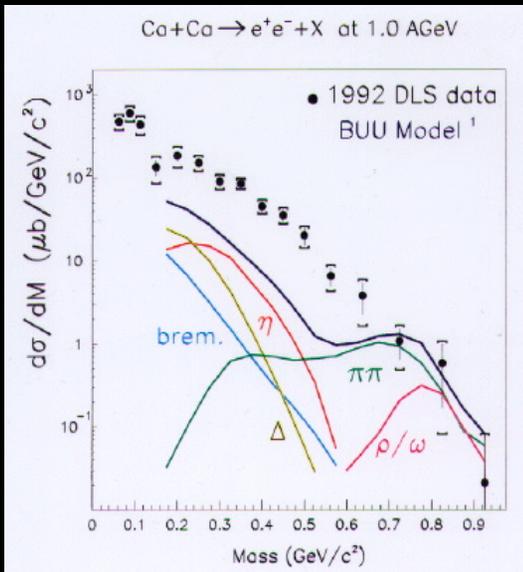
D. Cabrera et al. , Nucl. Phys. A 705 (2002) 90



Coupling to baryon resonances

Any observations??

In RHI collisions (nuclear matter under extreme conditions)

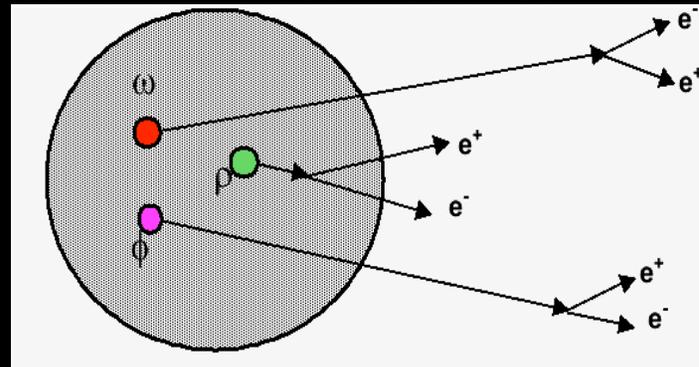
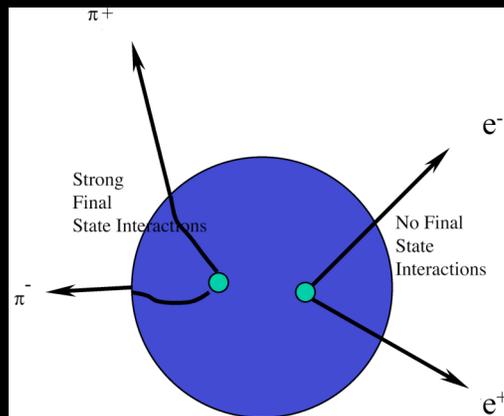


Clear excess of di-leptons observed. NA60: Γ \nearrow , "no ΔM "

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, ρ ,
- **(probe) + A \rightarrow V X \rightarrow e^+e^- X (no FSI)**



Decay inside

| | | | | |
|-----------------------------------------------------|------------|--------------------------------|------------------------------------|----------------------------------------|
| Vector mesons $J^P=1^-$ | ρ : | $M=768$ MeV | $\Gamma=149$ MeV | $c\tau \sim 1.3$ fm |
| | ω : | $M=782$ MeV | $\Gamma=8$ MeV | $c\tau \sim 23.4$ fm |
| | ϕ : | $M=1020$ MeV | $\Gamma=4$ MeV | $c\tau \sim 44.4$ fm |

Need very low p

Present and planned “elementary reactions” (not exhaustive list):

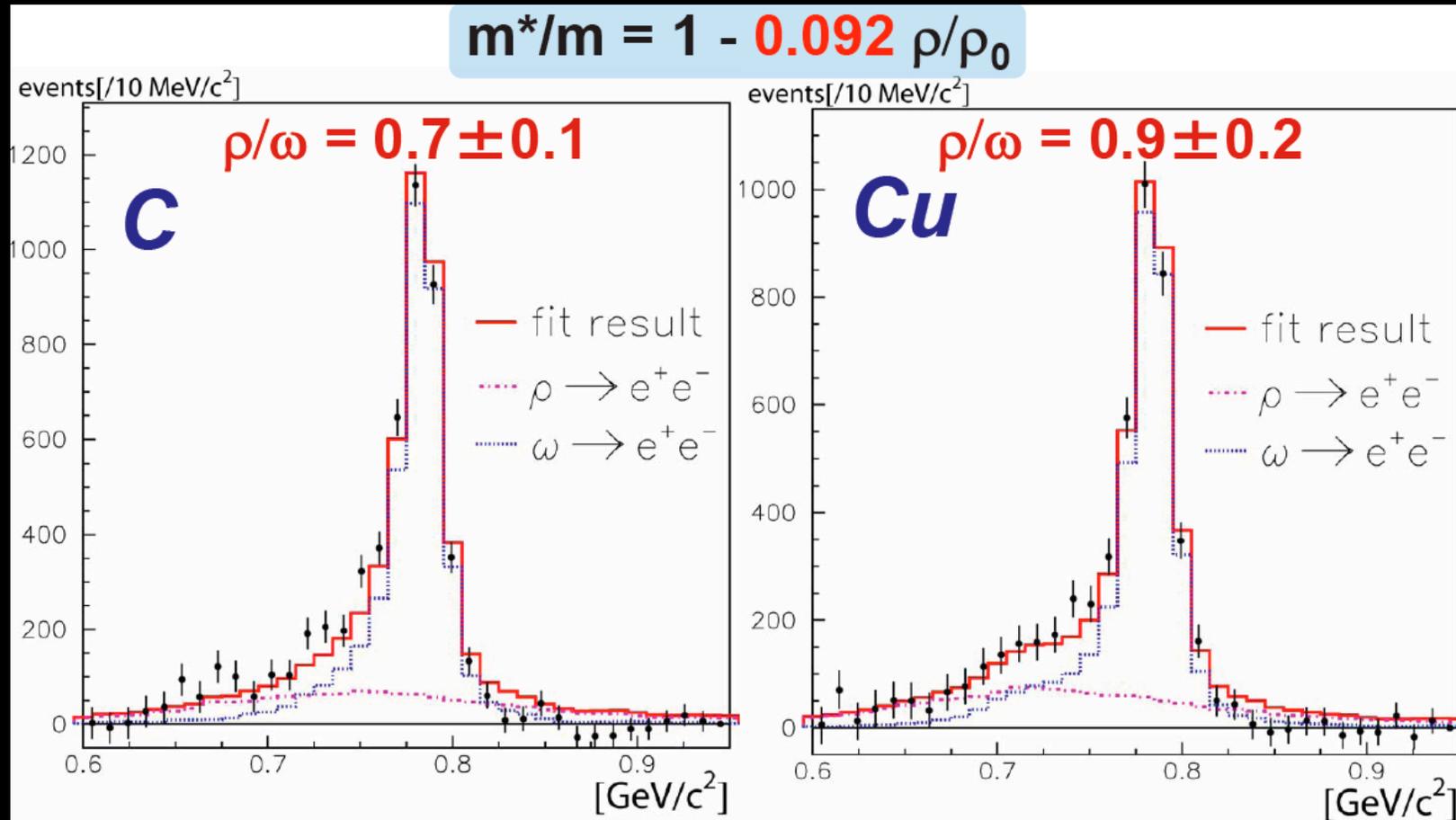
| <u>Experiment</u> | <u>Reactions</u> | <u>Results</u> |
|-------------------|-------------------------------------------------------------------------------------------|-----------------------------|
| TAGX | $\gamma + {}^3\text{He} \rightarrow \rho + X$ ($\rho \rightarrow \pi^+\pi^-$) | full BR, $\alpha \sim 0.06$ |
| <u>KEK</u> | $p + A \rightarrow \rho, \omega, \phi + X$ ($\rho, \omega \rightarrow e^+e^-$) | $\alpha = 0.092 \pm 0.002$ |
| <u>KEK</u> | $p + A \rightarrow \phi + X$ ($\phi \rightarrow e^+e^-$) | $\alpha \sim 0.04$ |
| SPring-8 | $\gamma + A \rightarrow \phi + A^*$ ($\phi \rightarrow K^+K^-$) | no effect |
| <u>TAPS</u> | $\gamma + A \rightarrow \omega + X$ ($\omega \rightarrow \pi^0 \gamma$) | $\alpha \sim 0.13-0.15$ |
| <u>JLab-g7a</u> | $\gamma + A \rightarrow (\rho, \omega, \phi) + A^*$ (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) |

-Only g7 with EM interaction in entrance and exit channels
-TAGX, Spring8 and TAPS have hadronic FSI.

KEK-PS E325 (ρ , ω)

$\rho+A \rightarrow \rho,\omega,\phi+X$ ($\rho,\omega,\phi \rightarrow e^+e^-$)
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.

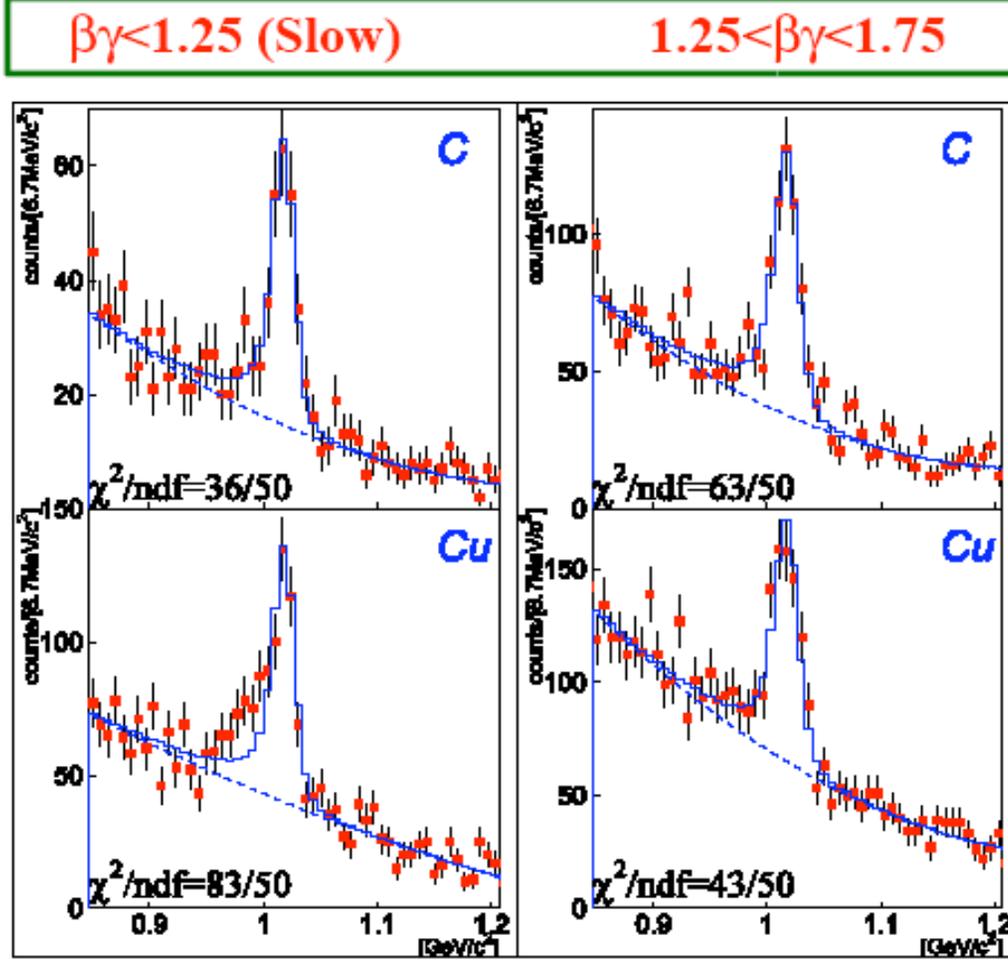


$$\alpha = 0.092 \pm 0.002$$

"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

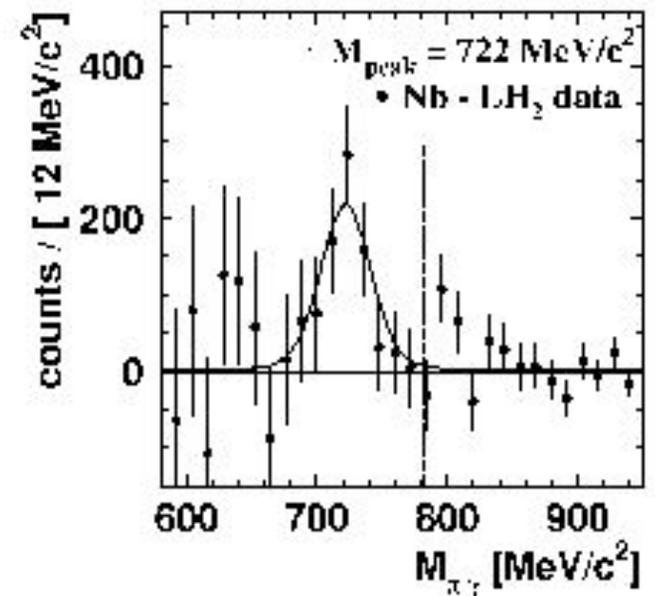
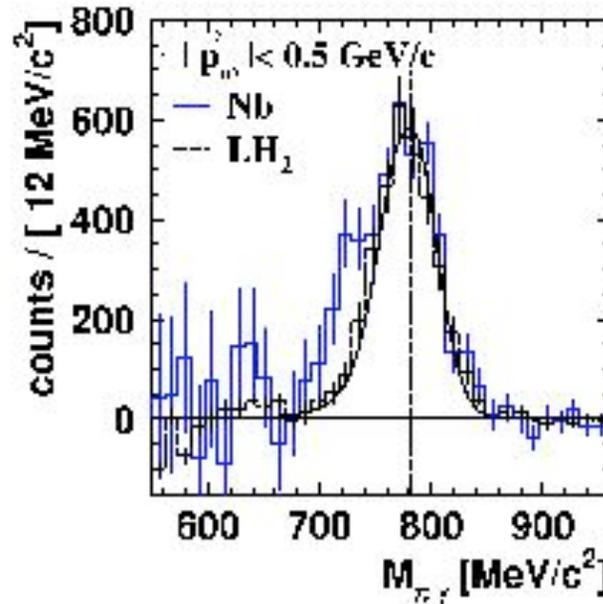
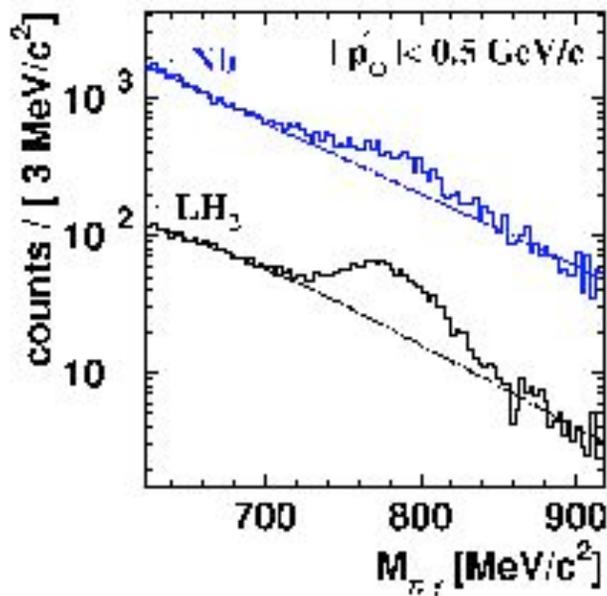
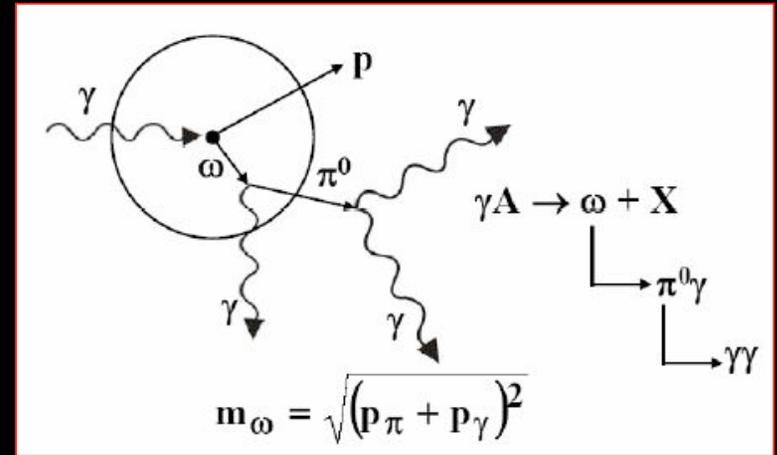
Bonn- TAPS results

$$\gamma + A \rightarrow \omega + X \quad (\omega \rightarrow \pi^0 \gamma)$$

clean (no ρ) channel, however FSI of π
 Small signal to background ratio

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

$$\Gamma_\omega (\rho = \rho_0, \langle |p_\omega| \rangle \approx 750 \text{ MeV}/c) \approx 95 \text{ MeV (old)}$$



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 | $\rho A \rightarrow (\rho, \omega, \phi) A'$ $VM \rightarrow e+e-$ | $\gamma A \rightarrow \omega A'$ $\omega \rightarrow \pi^0 \gamma$ | $\rho + Au, Pb + Au$ $\rho \rightarrow e+e-$ | $In + In$ $\rho \rightarrow \mu + \mu-$ |
| Condition | $\rho = 0.53\rho_0, T \sim 0 \text{ MeV}$ | $\rho = 0.55\rho_0, T \sim 0 \text{ MeV}$ | 158 A GeV | 158 A GeV |
| Mass | $\Delta m_\rho \sim \Delta m_\omega \sim -9\%$ $\Delta m_\phi \sim -4\%$ | $\Delta m_\omega \sim -14\%^*$ | Δm not favored | No mass shift |
| Width | $\Delta \Gamma_\rho \sim \Delta \Gamma_\omega \sim 0 \text{ MeV}$ $\Gamma_\phi(\rho = \rho_0) = 47 \text{ MeV}$ | $\Gamma_\omega(\rho = \rho_0) \approx 140 \text{ MeV}$ (new unpublished) | 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”

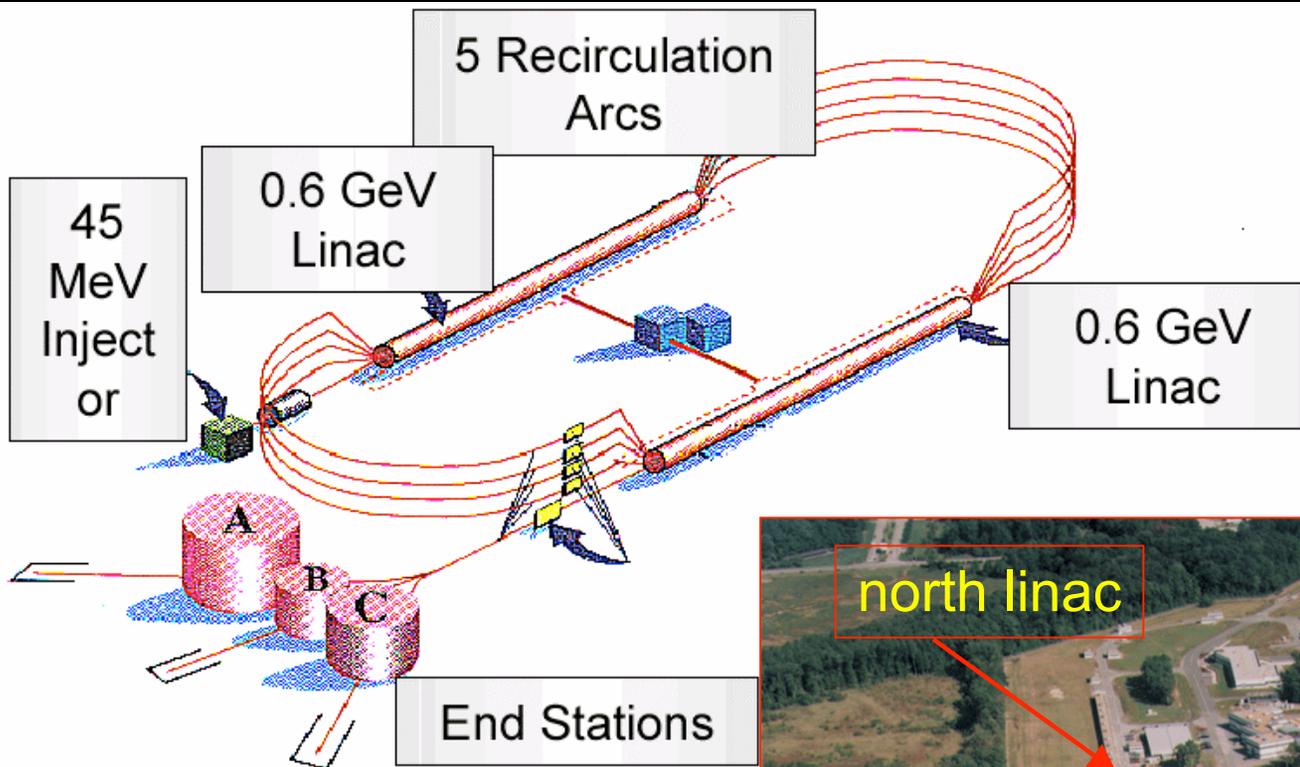


- **Original idea:**
P. Y. Bertin and P. A. M. Guichon, Phys Rev C42, 1133 (1990)
- **Jlab Experiment E01-112 (also called g7)**
Spokespersons: C. Djalali (USC), M. Kossov (ITEP),
D. Weygand (Jlab)
- **Photon beam (minimal disturbance to initial state) :**
 $E_\gamma \sim .6$ to 3.8 GeV (tagged γ)
Targets: LD₂, C, Ti, Fe, (Pb)
- **Leptonic decay :**
Almost no final state interaction! HOWEVER (NO FREE LUNCH!)

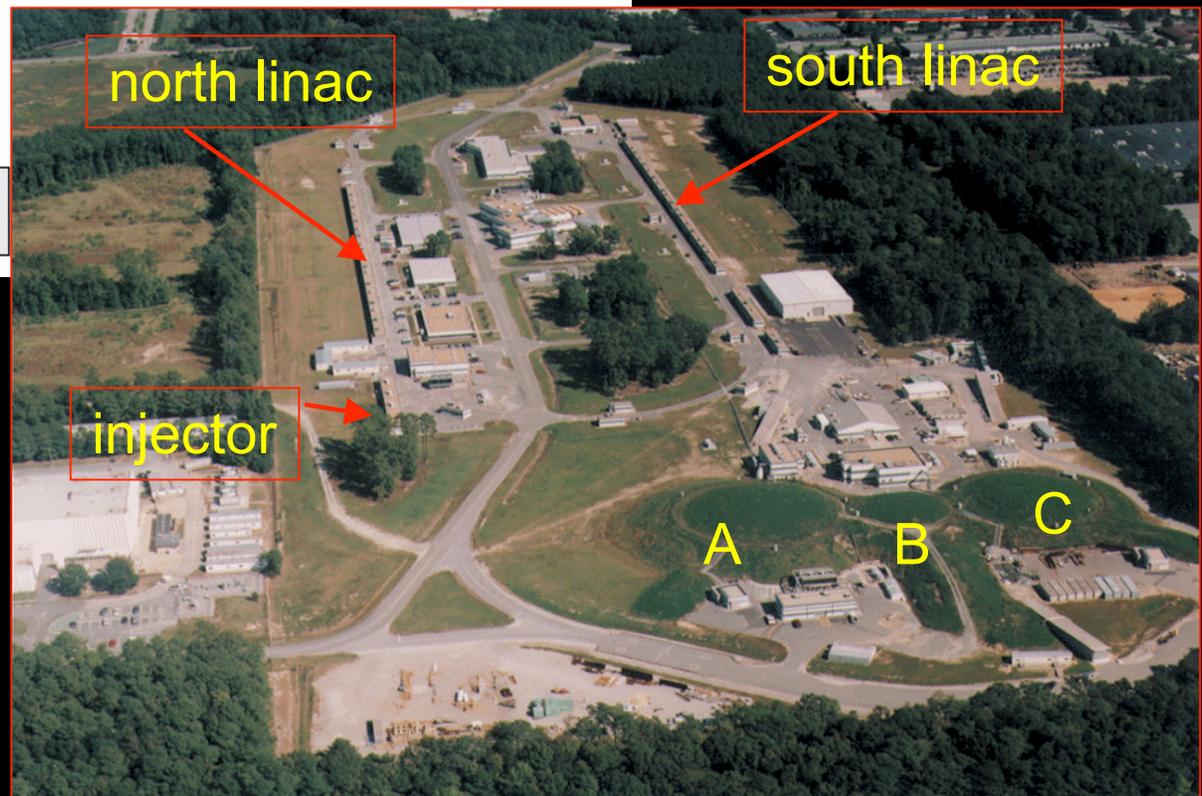
Low branching ratio : $\sim 5 \cdot 10^{-5}$

needs high photon flux : $5 \cdot 10^7$ tagged γ /s

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

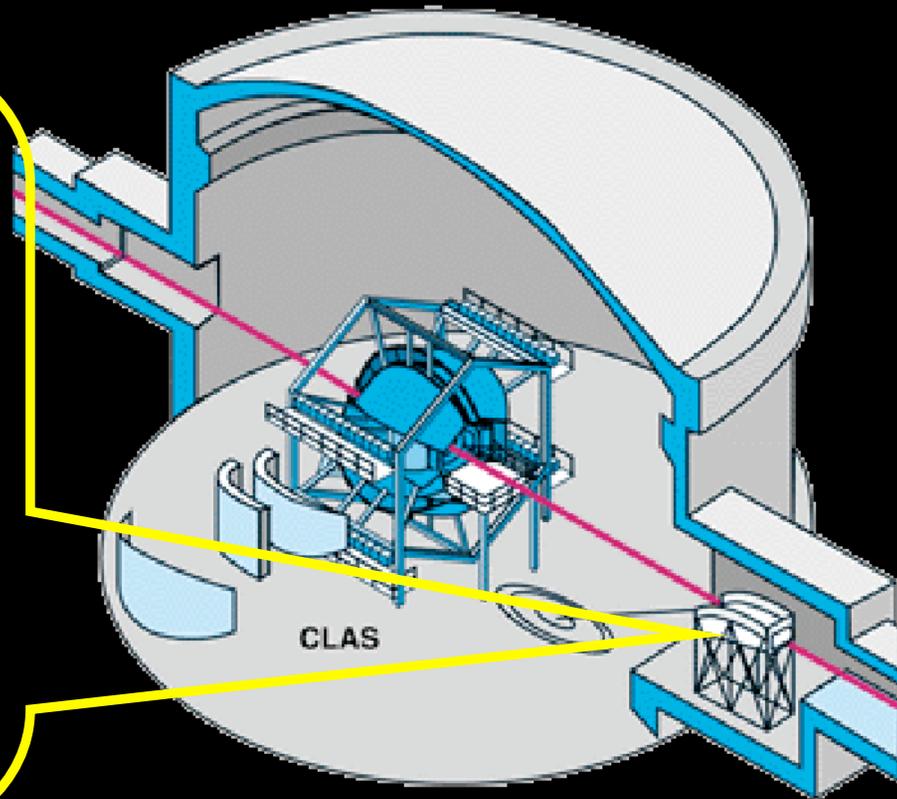
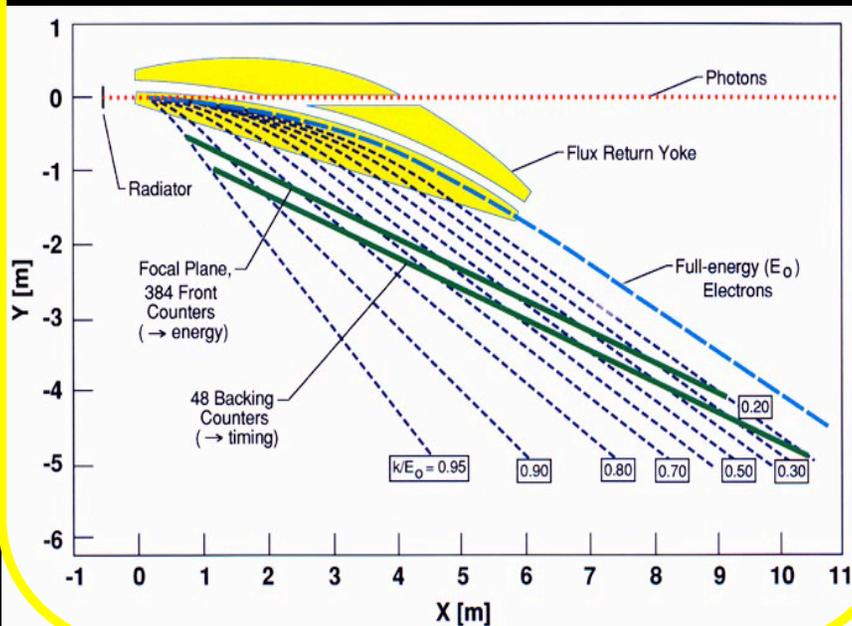


| | |
|-----------------------------|-----------------------|
| E_{\max} | ~ 6 GeV |
| I_{\max} | ~ 200 μA |
| Duty Factor | ~ 100% |
| σ_E/E | ~ $2.5 \cdot 10^{-5}$ |
| Beam P | ~ 80% |
| $E_{\gamma(\text{tagged})}$ | ~ 0.8- 5.5 GeV |



Hall B @ Jlab (The tagger)

3. 10⁻⁴ RL Photon Tagger

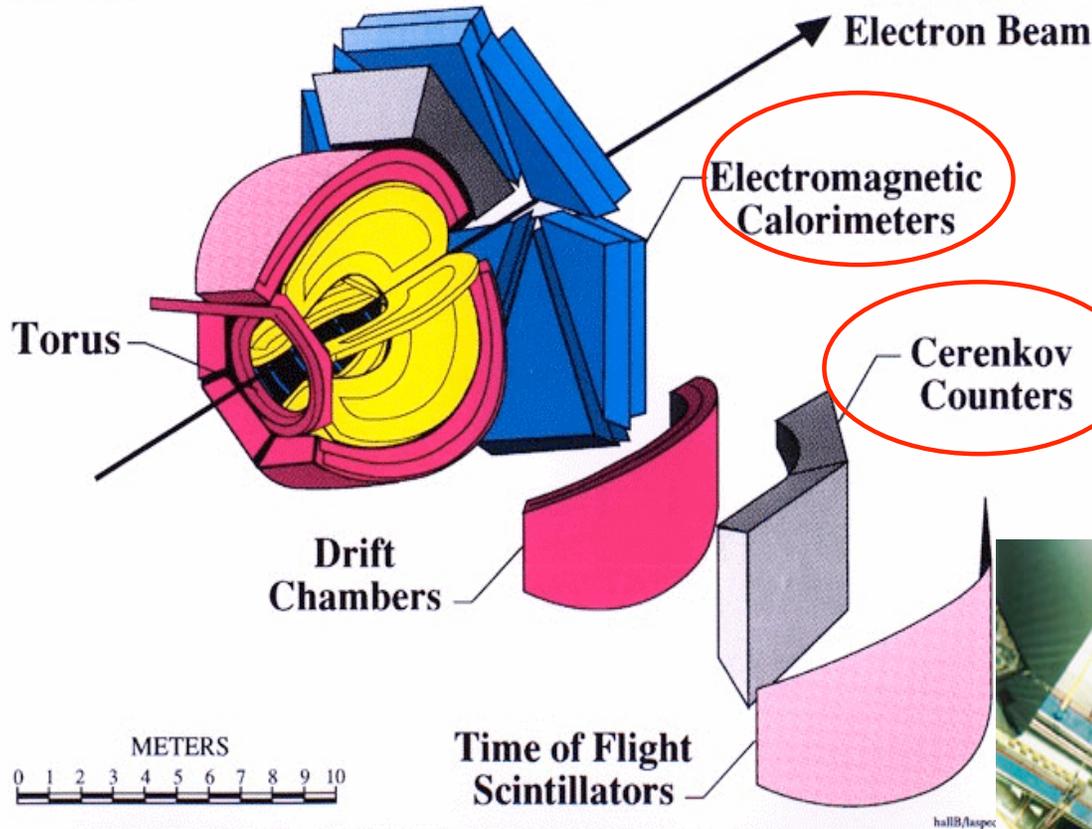


Bremsstrahlung Tagging Spectrum (20%-95%)

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

LARGE ACCEPTANCE SPECTROMETER

CEBAF



Hall B @ Jlab (CLAS)

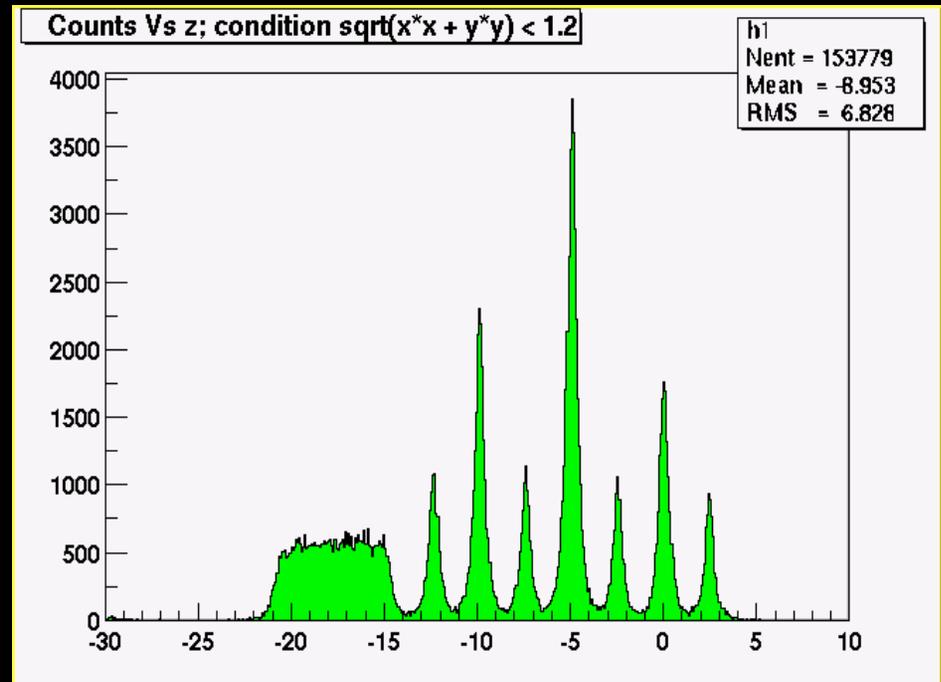
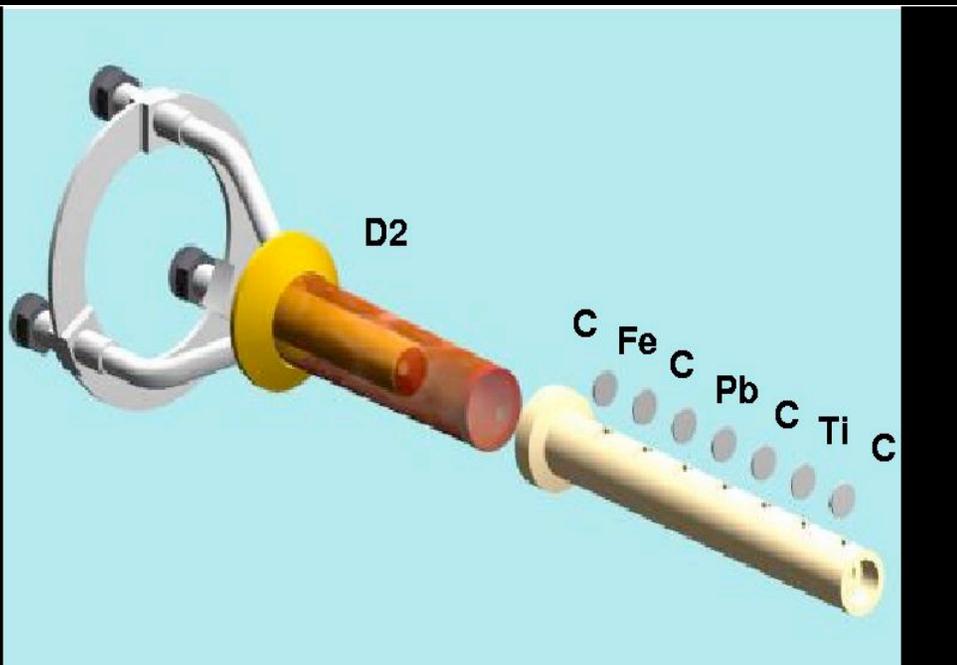
>150 physicists,
>10 countries

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



Multi-Segment Nuclear Target

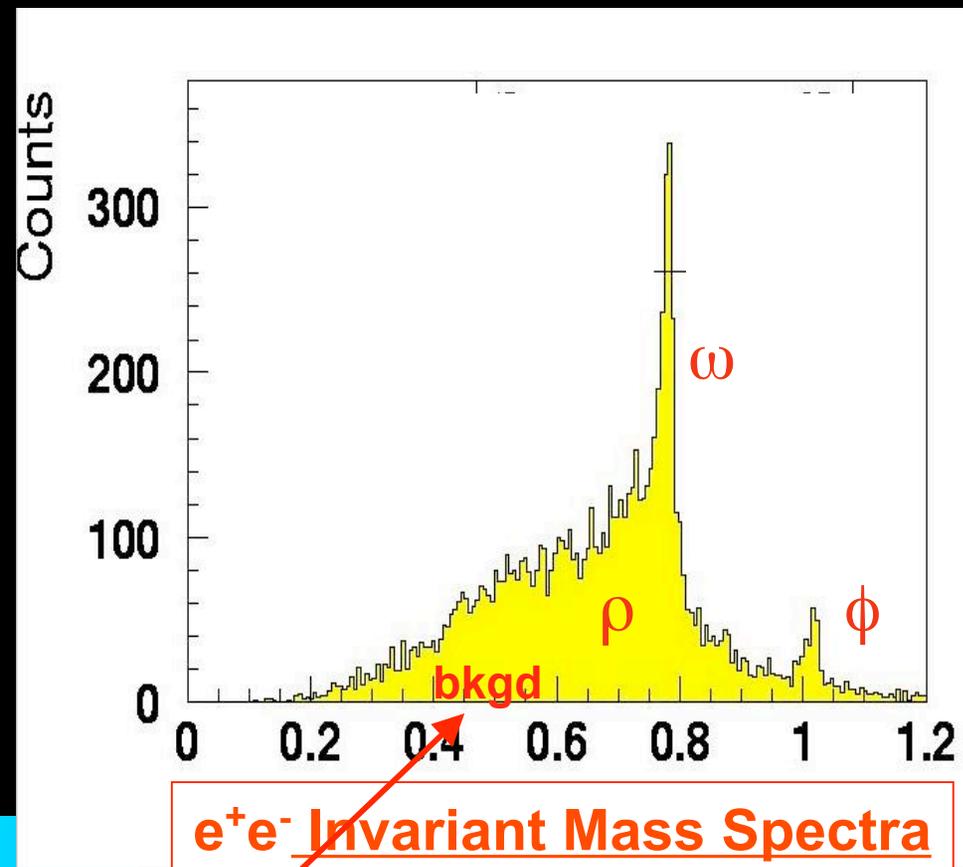
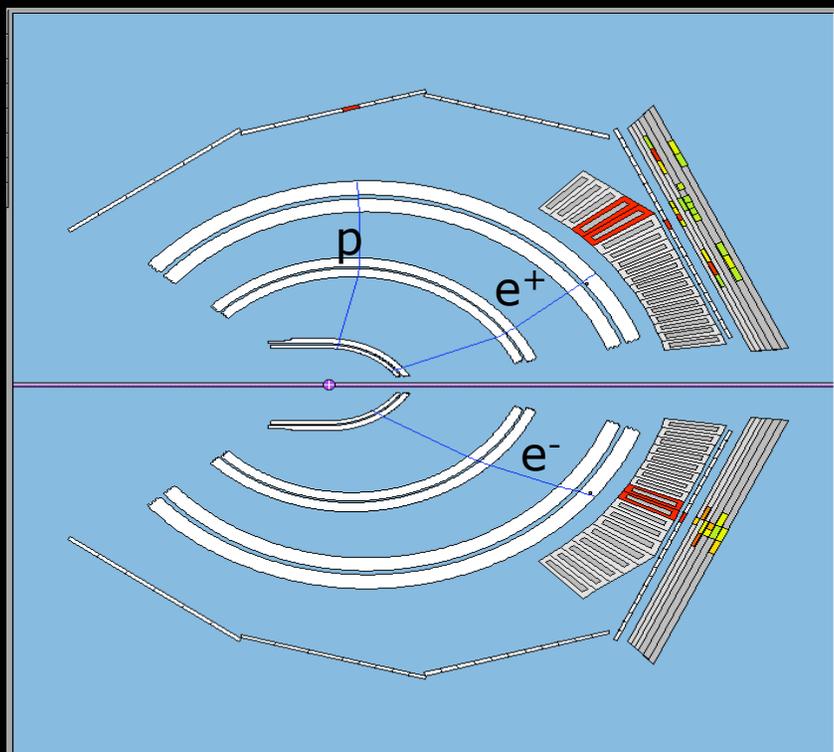
- Contains materials with different average densities.
- LD2 and seven solid foils of C, Fe, Pb, and Ti.
- Each target material 1 g/cm² and diameter 1.2 cm
- Approximately same number of nucleons/target



- 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



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

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

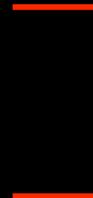
● **Excellent π/e discrimination: 5.4×10^{-4} for one and 2.9×10^{-7} for two arms.**

Possible channels that contribute to e+e- mass spectrum

Correlated:

- Monte-Carlo simulations using a model (BUU) by Mosel et al. (*Nucl. Phys. A671, 503 (2000)*) including various decay channels and nuclear effects, and CLAS detector simulation package (GSIM) Simulations with BUU includes all the e+e- decay channels with same strength.

- $\omega \rightarrow e^+e^-$, $\rho \rightarrow e^+e^-$, $\phi \rightarrow e^+e^-$
- $\eta \rightarrow \gamma e^+e^-$
- $\omega \rightarrow \pi^0 e^+e^-$



GiBUU Code

“Semi-correlated”:

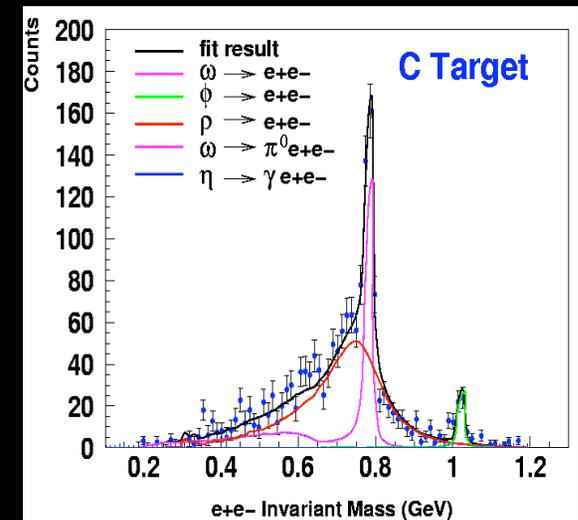
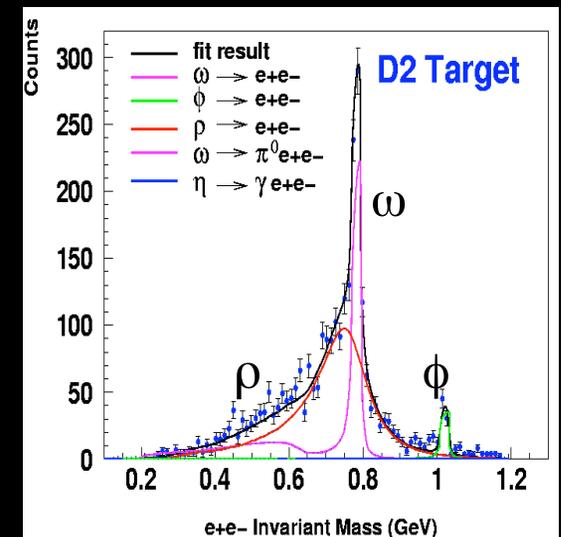
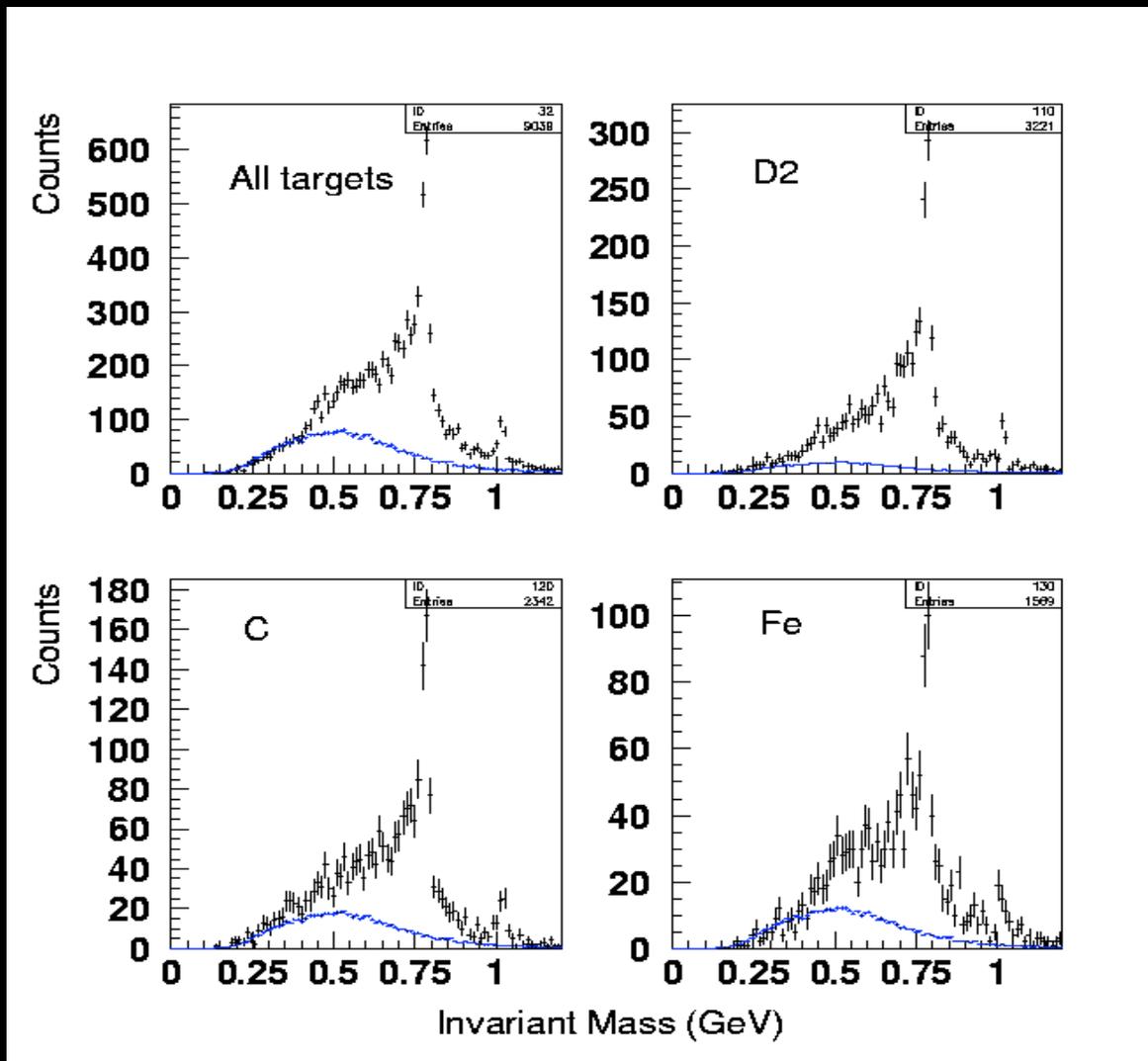
- Bethe-Heitler
- $\gamma A \rightarrow \pi^0 \pi^0 X \rightarrow \gamma e^+e^- \gamma e^+e^-$
- $\pi^0 \rightarrow e^+e^- e^+e^-$

calculated by Mosel's group \rightarrow negligible
2 π^0 Dalitz decay mixed \rightarrow negligible
double Dalitz \rightarrow 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)



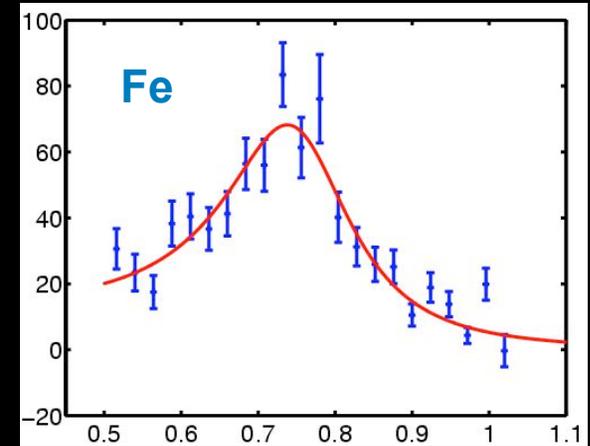
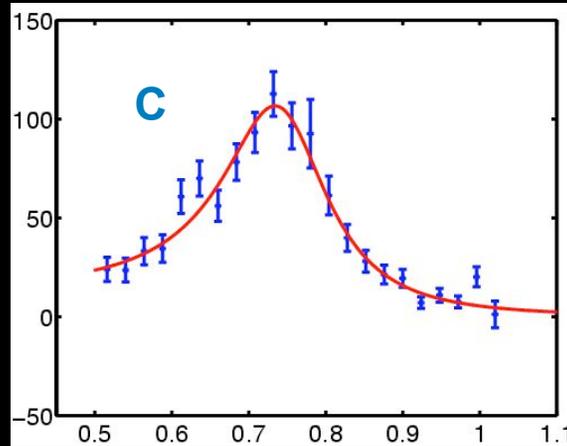
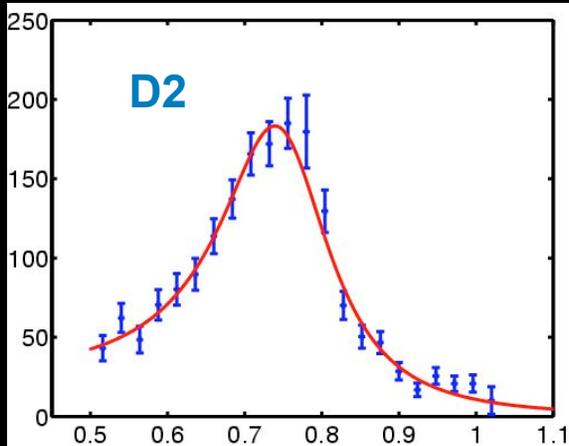
$\mu^+\mu^-$ measurement: at CERN-SPS *IPNO-DR-02.015* (2002)

$\pi^+\pi^-$ 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:



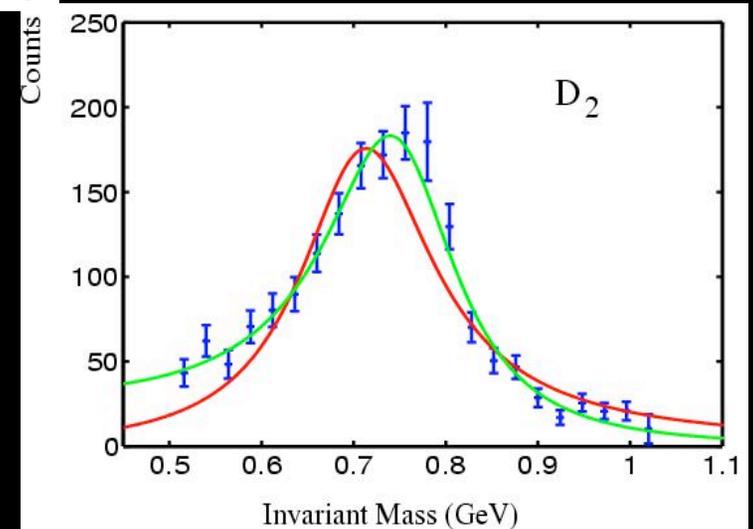
e^+e^- Invariant Mass (GeV)

Fit function:

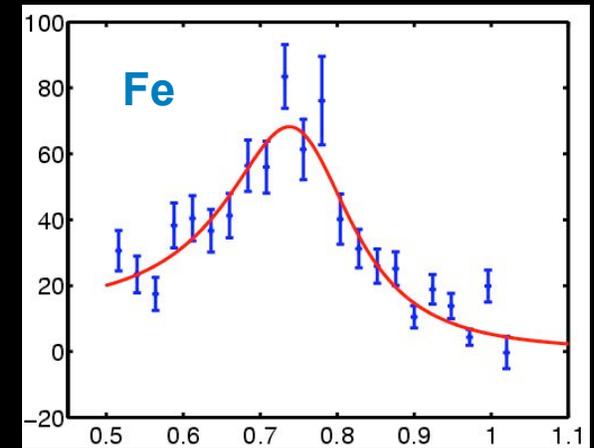
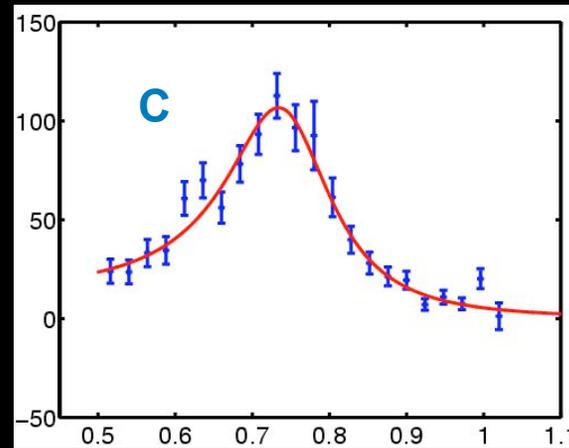
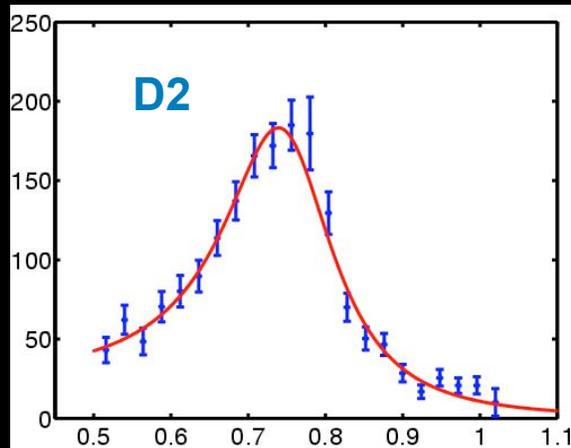
$$\text{Breit - Wigner} \times \frac{1}{M^4} \times M = \frac{\text{Breit - Wigner}}{M^3}$$

Photon propagator

Breakup momentum phase space



The 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 Sim. | Width(MeV/c ²) Giessen Sim. |
|------------------------------------|-----------------------------------------|-----------------------------------------|-------------------------------------------|--------------------------------------------|
| ² H | 770.3 +/- 3.2 | 185.2 +/- 8.6 | - | - |
| 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 vacuum properties of the ρ meson are: **$m=770 \text{ MeV}/c^2$** and **$\Gamma=150 \text{ MeV}$** . Broadening of the width is consistent with many-body effects.

Summary on the ρ meson

- Our result ($\alpha = 0.02 \pm 0.02$) is compatible with no mass shift
- Result does not confirm the KEK results ($\alpha \sim 0.09$).
- Rule out ΔM à la Brown/Rho (20%) and Hatsuda/Lee ($\alpha \sim 0.16$)
- 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 will be submitted mid February 2008.

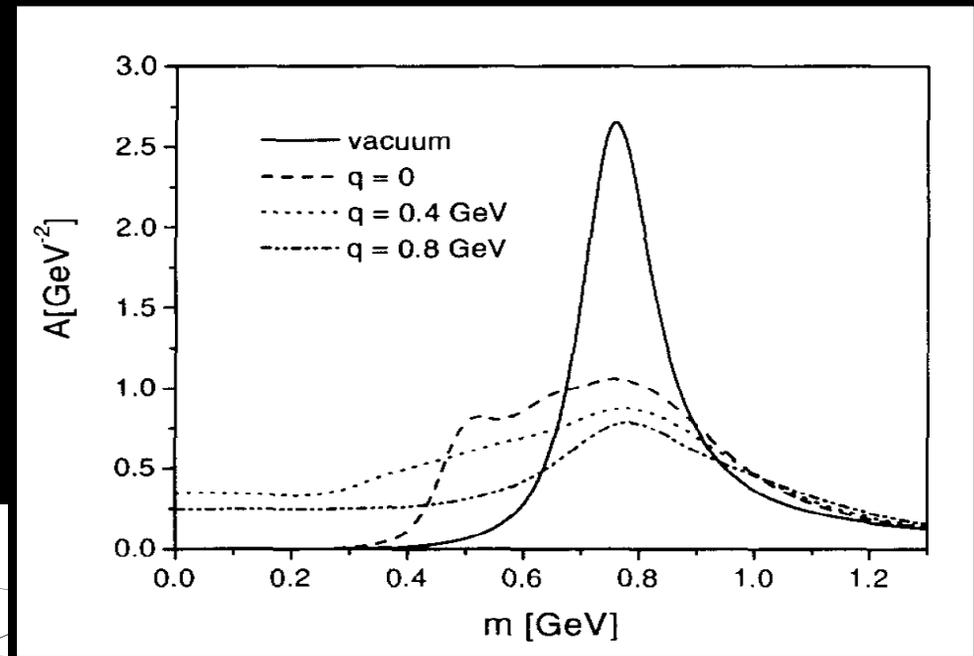
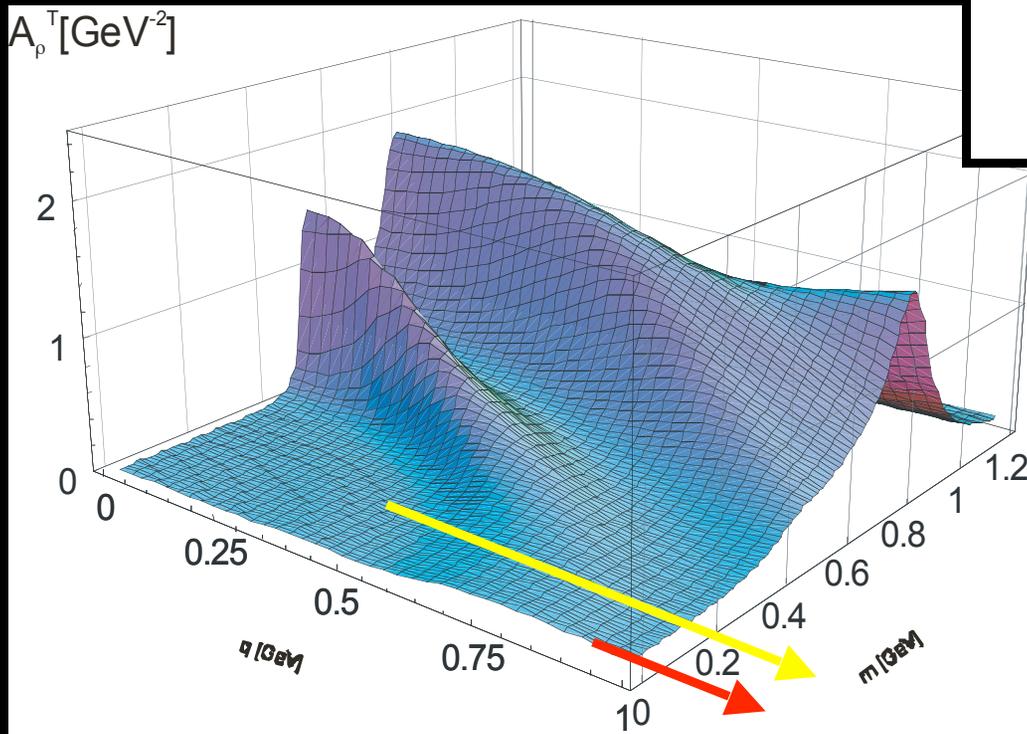
Momentum Dependence – ρ Meson

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

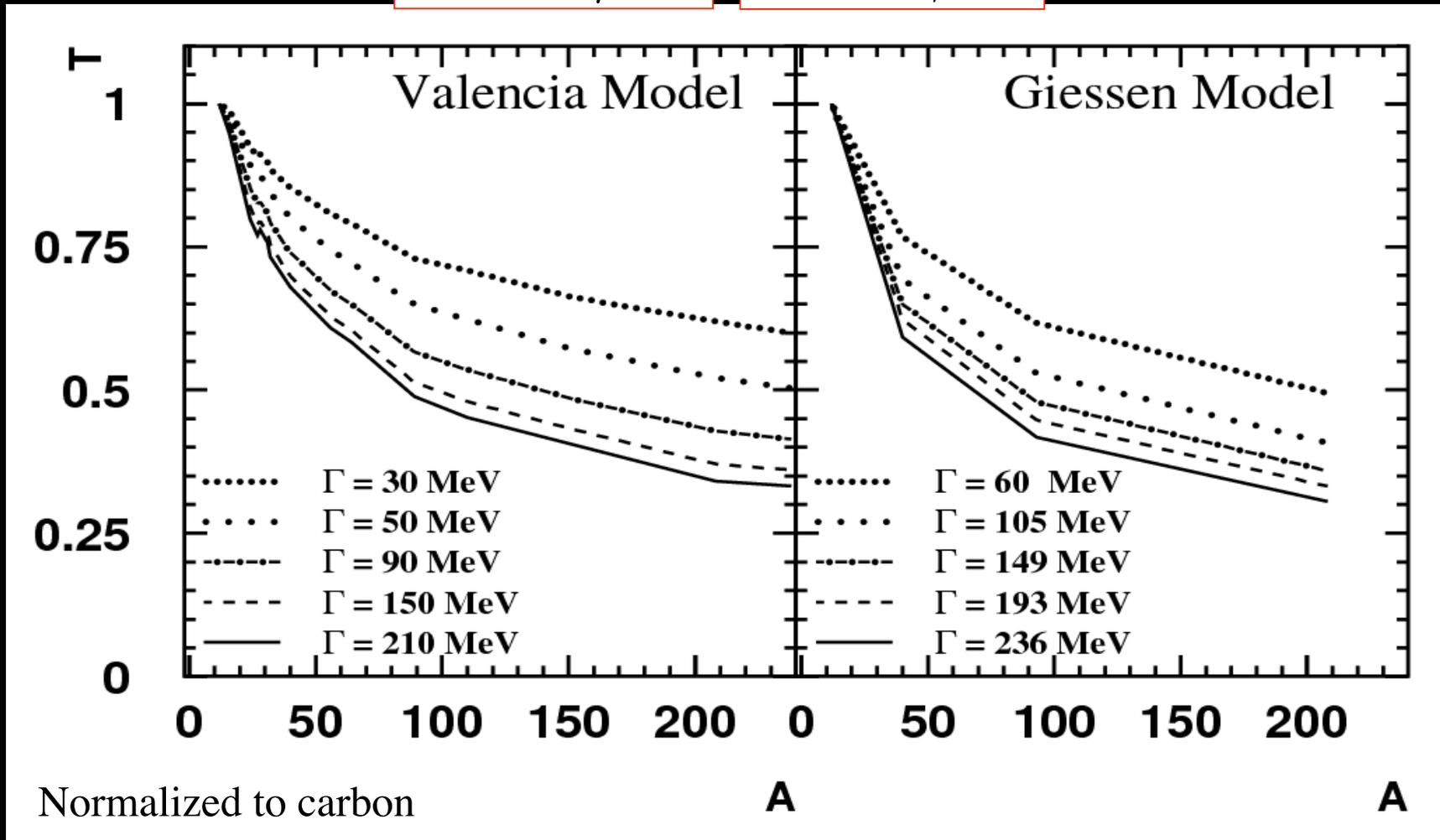
Absorption of ω Meson and its In-medium width

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

Transparency ratio:

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

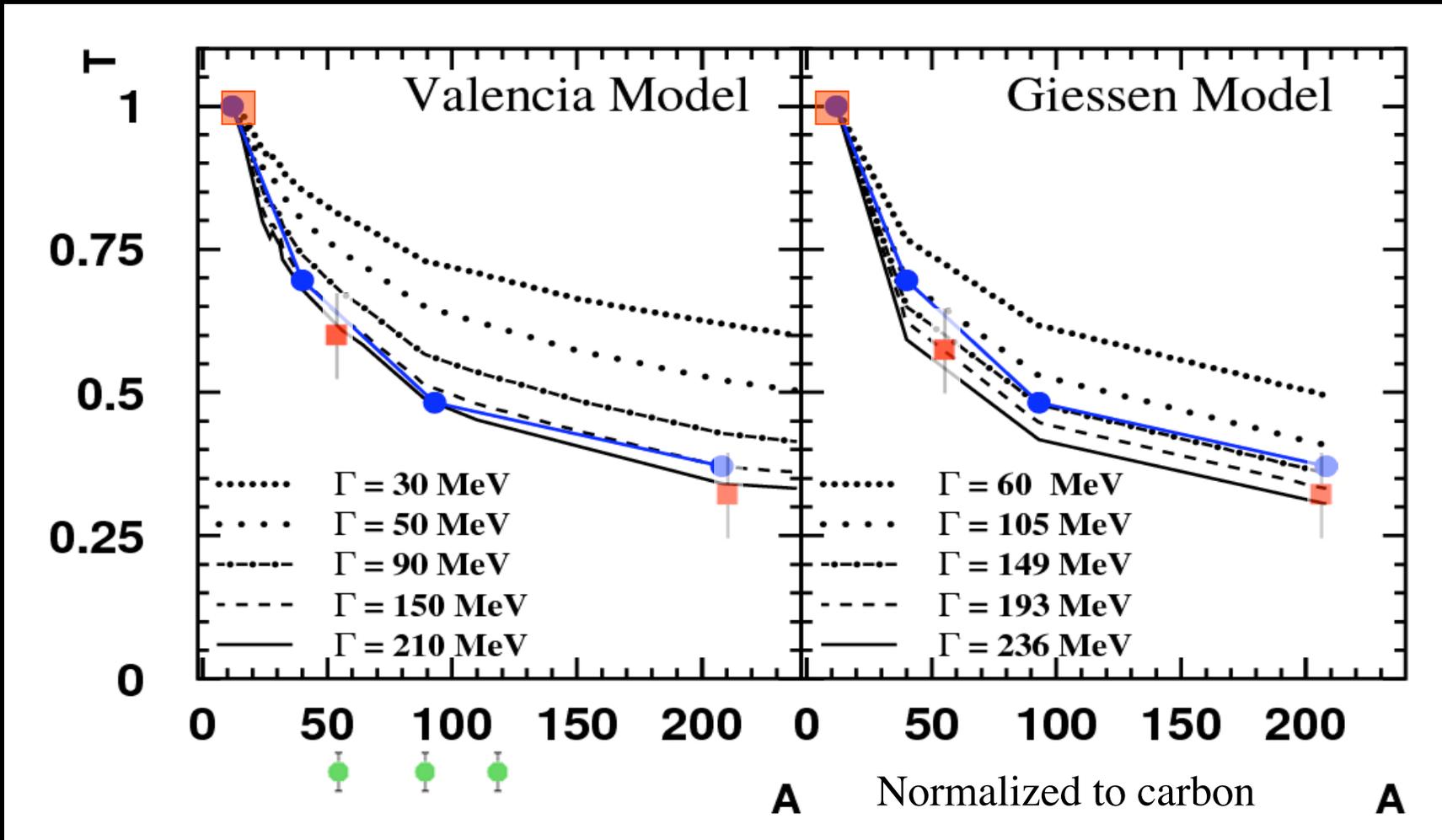
$$T_{\text{norm}} = \frac{12 \cdot \sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma^{12}\text{C} \rightarrow \omega X}}$$



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

P. Mühlich and U. Mosel NPA 773 (2006) 156

Comparison to Theory – ω Meson



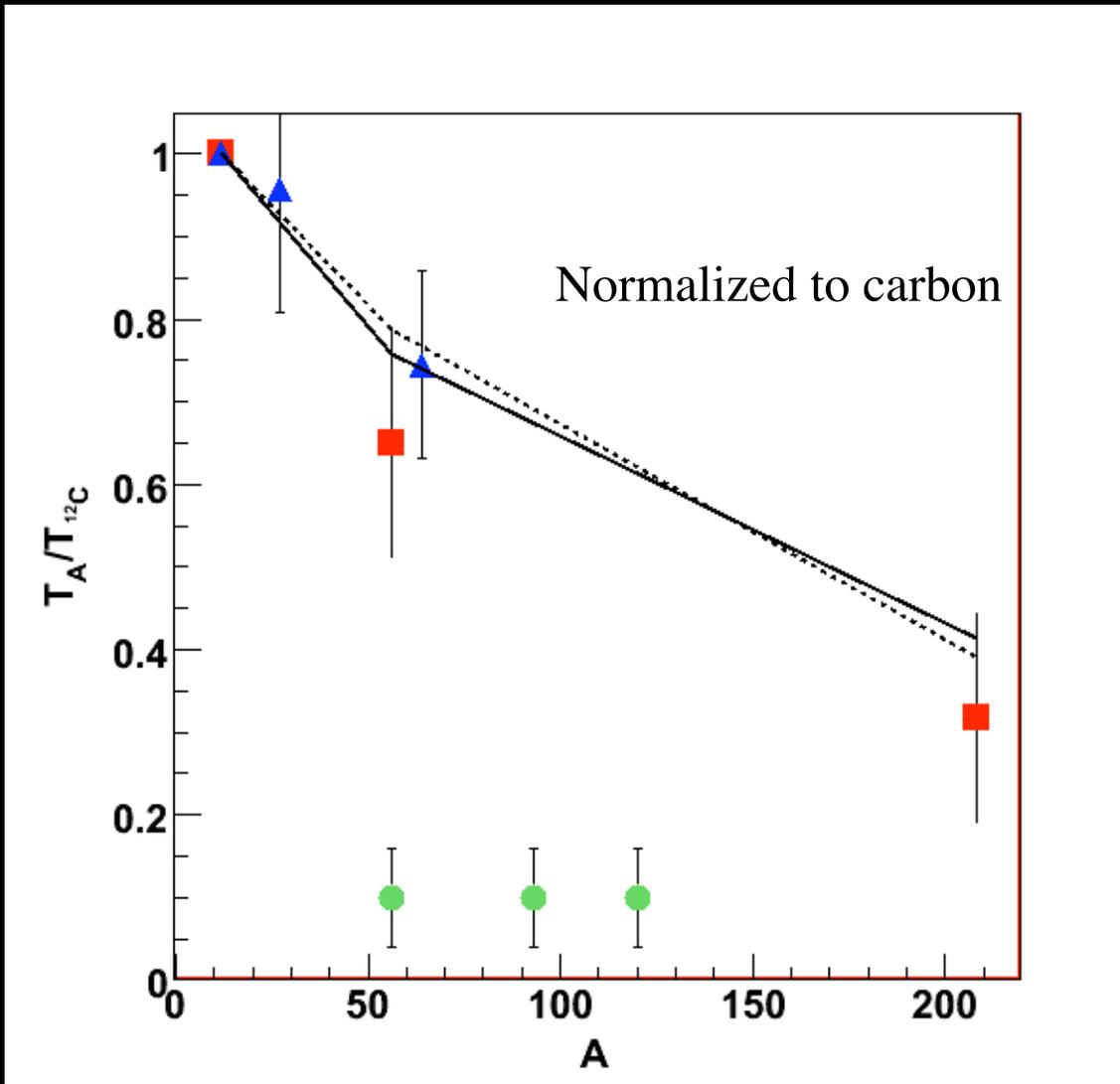
Preliminary g7a result showed greater absorption than TAPS!!!

Latest TAPS $\Gamma_{\omega} \sim 130-150$ MeV now closer to JLAB results which are larger!

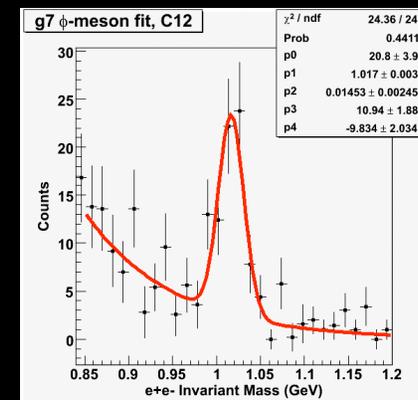
- JLab (preliminary)
- TAPS (latest analysis)
- Proposed JLab run

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)
- New 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
- 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.