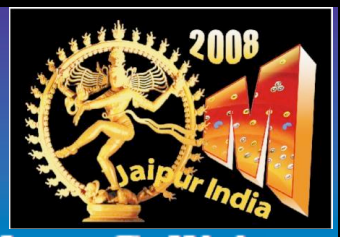

Quark Matter 2008




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**

Jefferson Lab
Thomas Jefferson National Accelerator Facility

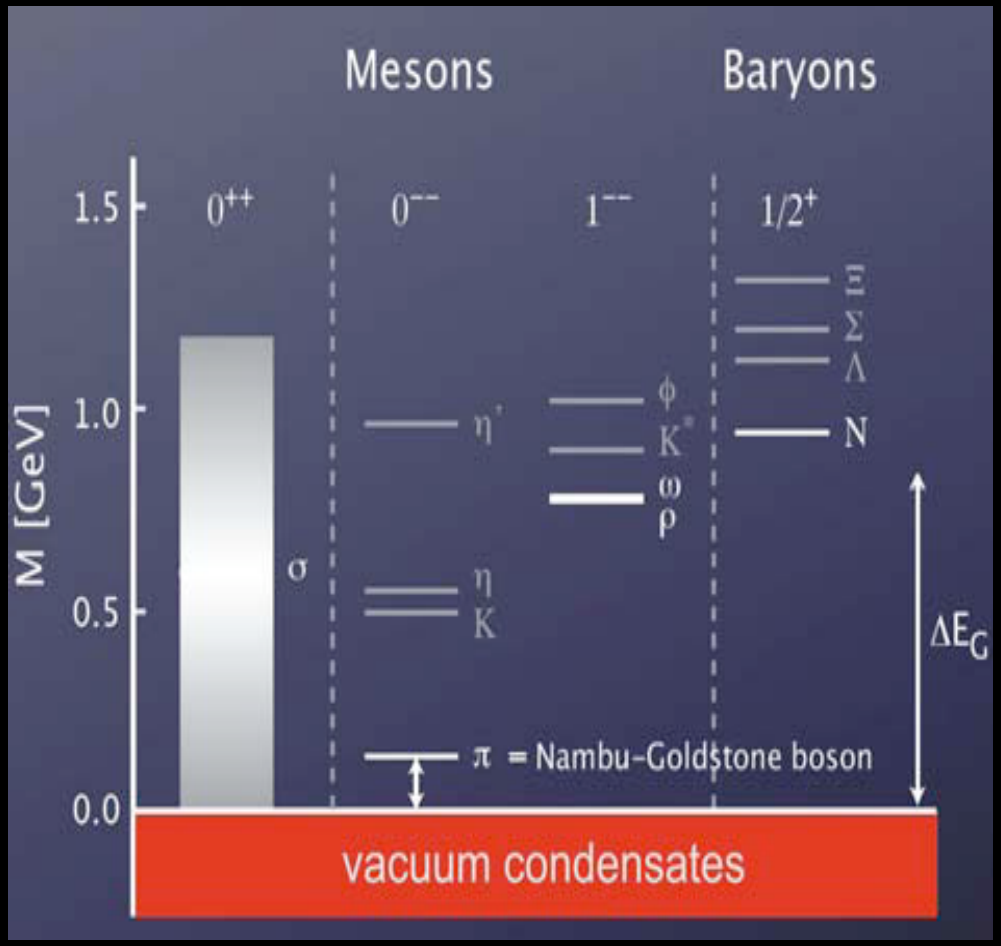
University of South Carolina

# Outline

- Physics Motivations
  - Why study in medium hadrons?
  - Models and Predictions
- Some key experiments
- Photo-production of vector mesons at JLab
  - $\rho$ meson mass spectra
  - $\omega$ and $\phi$ 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 may 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.**

# 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***

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

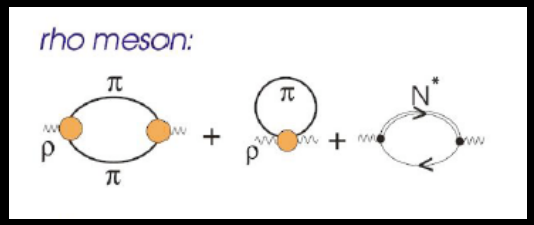
## QCD sumrules:

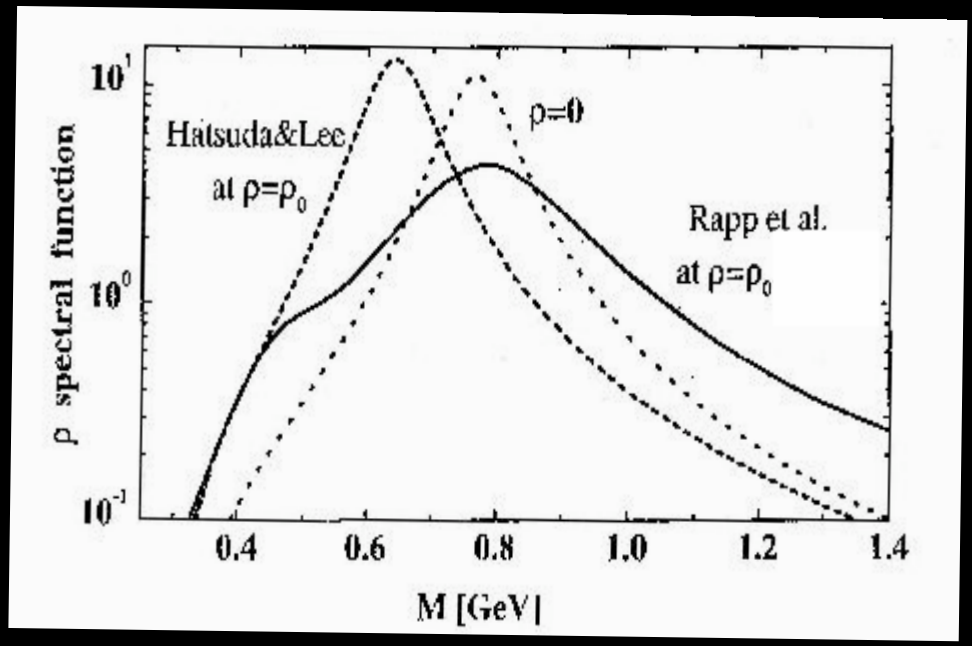
T. Hatsuda and S. Lee ***Phys. Rev. C46 (1992) R34***

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

## Many body effects:

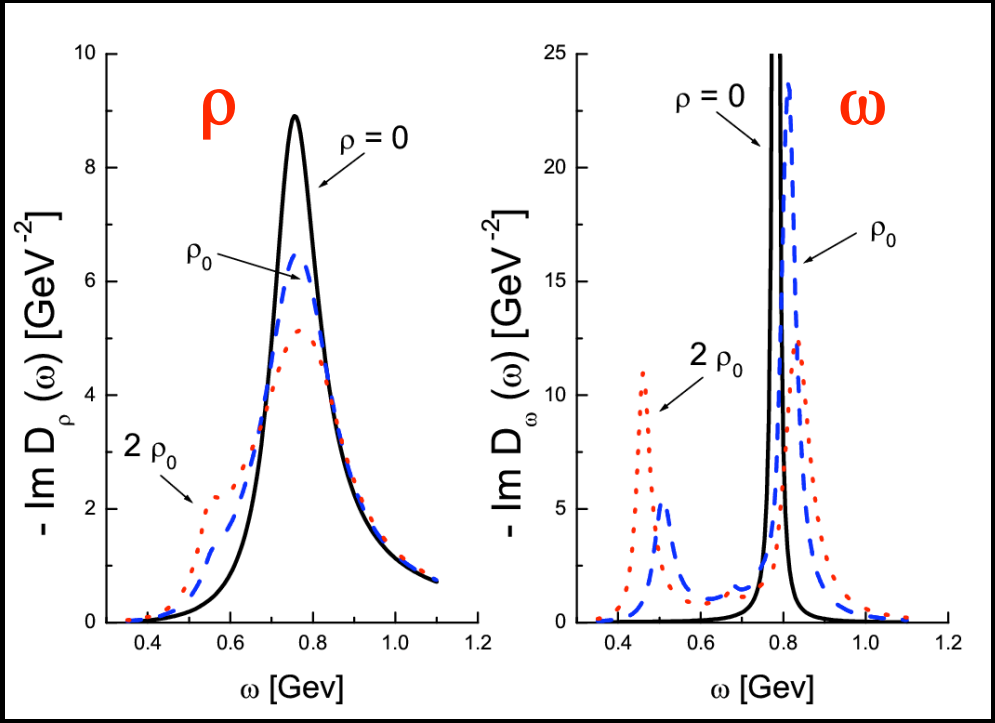
B Friman, H.J. Pirner,
***Nucl Phys. A617 (1997) 496***
R. Rapp, G. Chanfray, J Wambach,
***Nucl Phys. A617 (1997) 472***



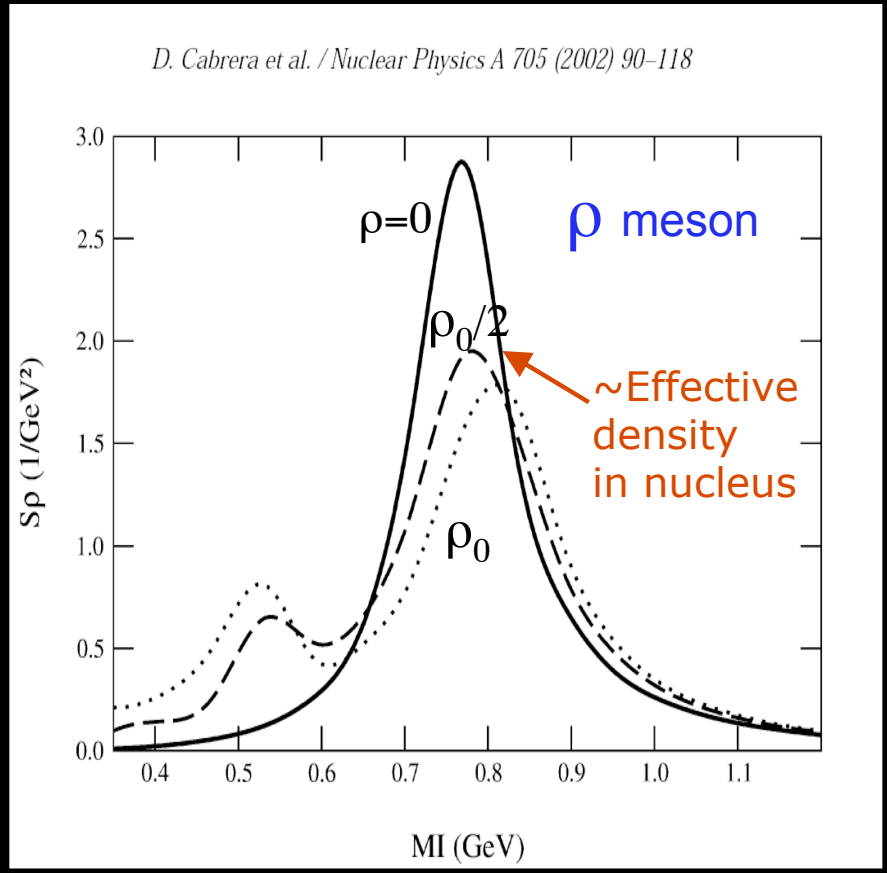
# Model predictions of the in medium properties of vector mesons

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



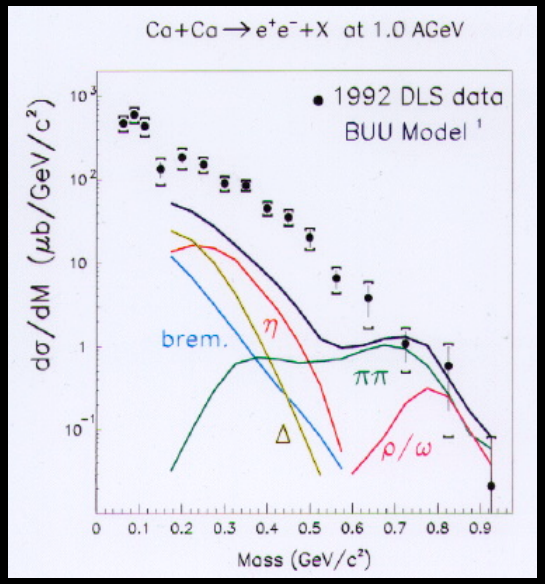

**Coupling to baryon resonances**

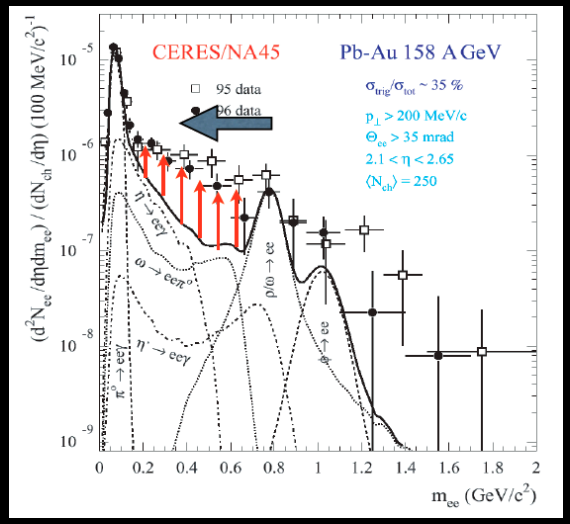
*D. Cabrera et. al. , Nucl. Phys. A 705 (2002) 90*

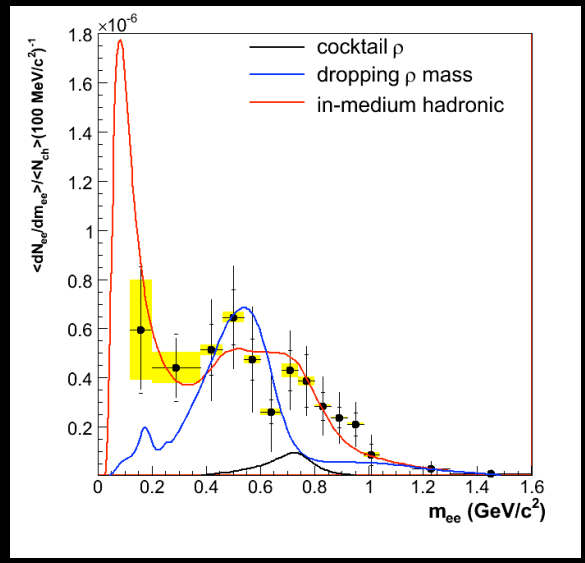


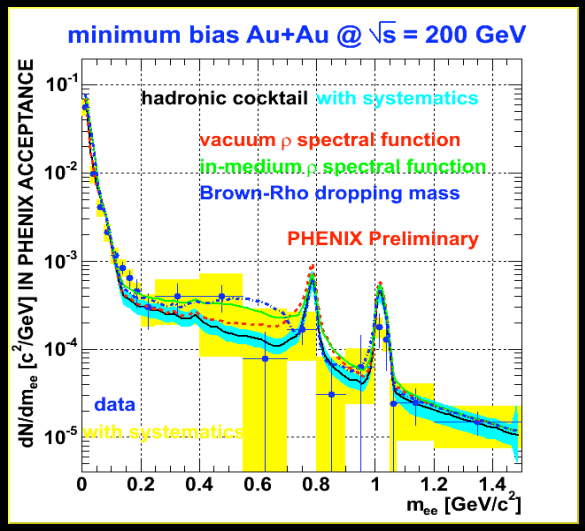

**Any observations??**

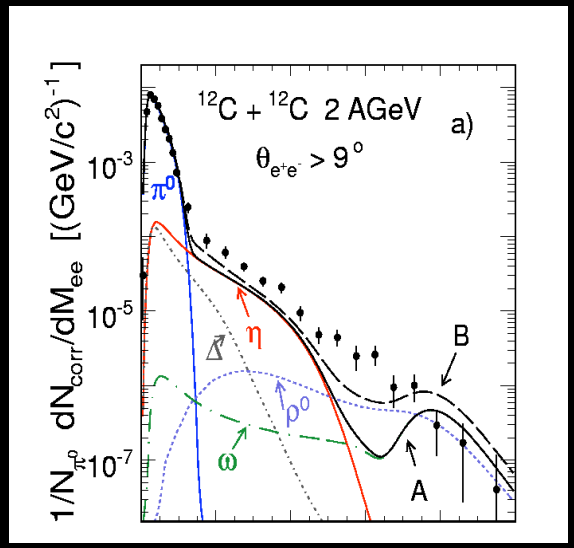
# In RHI collisions (nuclear matter under extreme conditions)

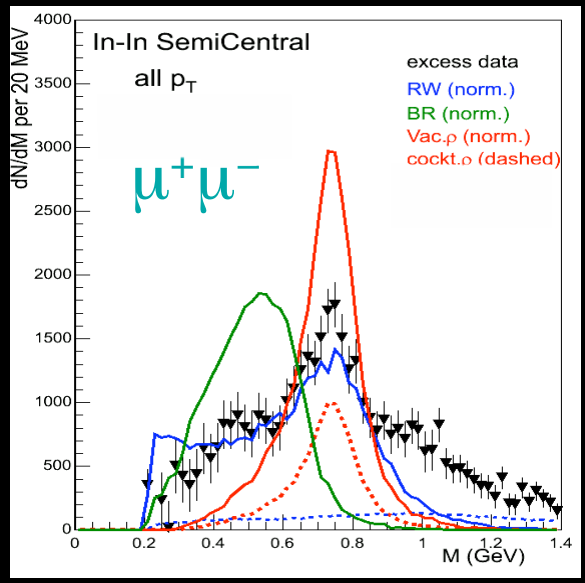


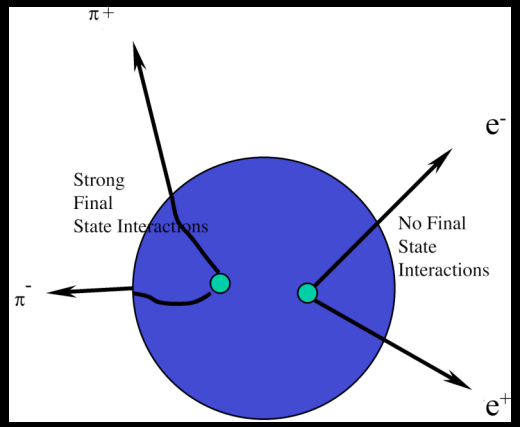

**Clear excess of di-leptons observed. NA60: Γ ↗ , "no ΔM"**

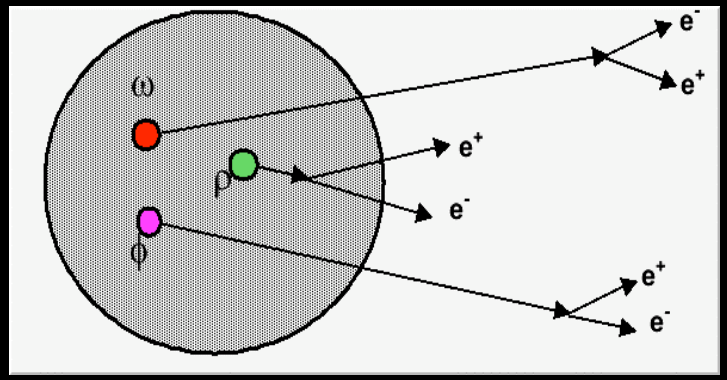
# Medium modification of vector mesons properties in nuclei

**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,p,**

**• (probe) + A --> V X --> $e^+e^-$ X ( no FSI)**




Decay inside

| Vector mesons $J^P=1^-$ | | | | |
|---|---|---|---|---|
| | ρ: | M=768 MeV | Γ= 149 MeV | cτ~1.3 fm |
| | 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) |

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

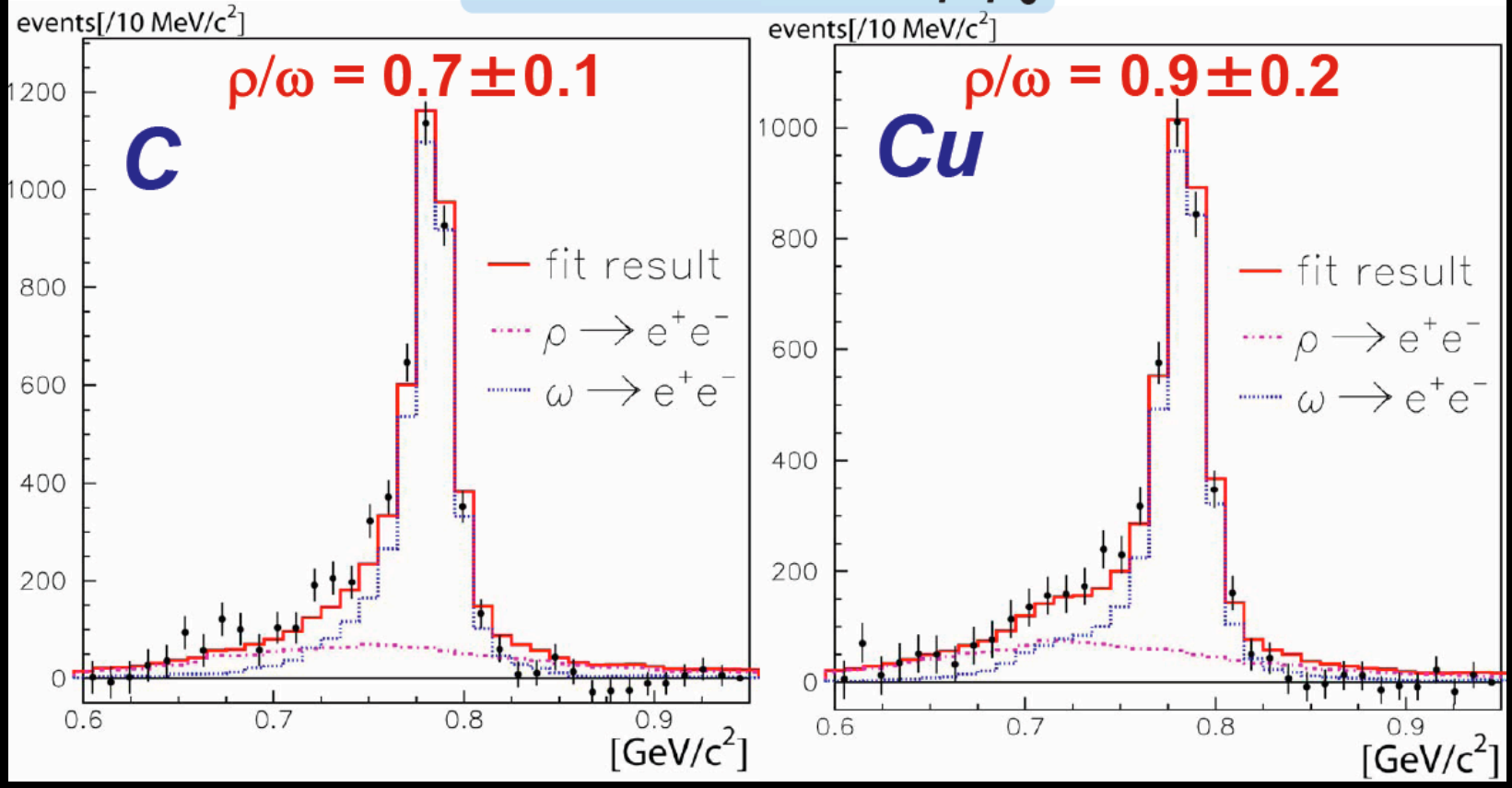
# KEK-PS E325 (ρ, ω)

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.**

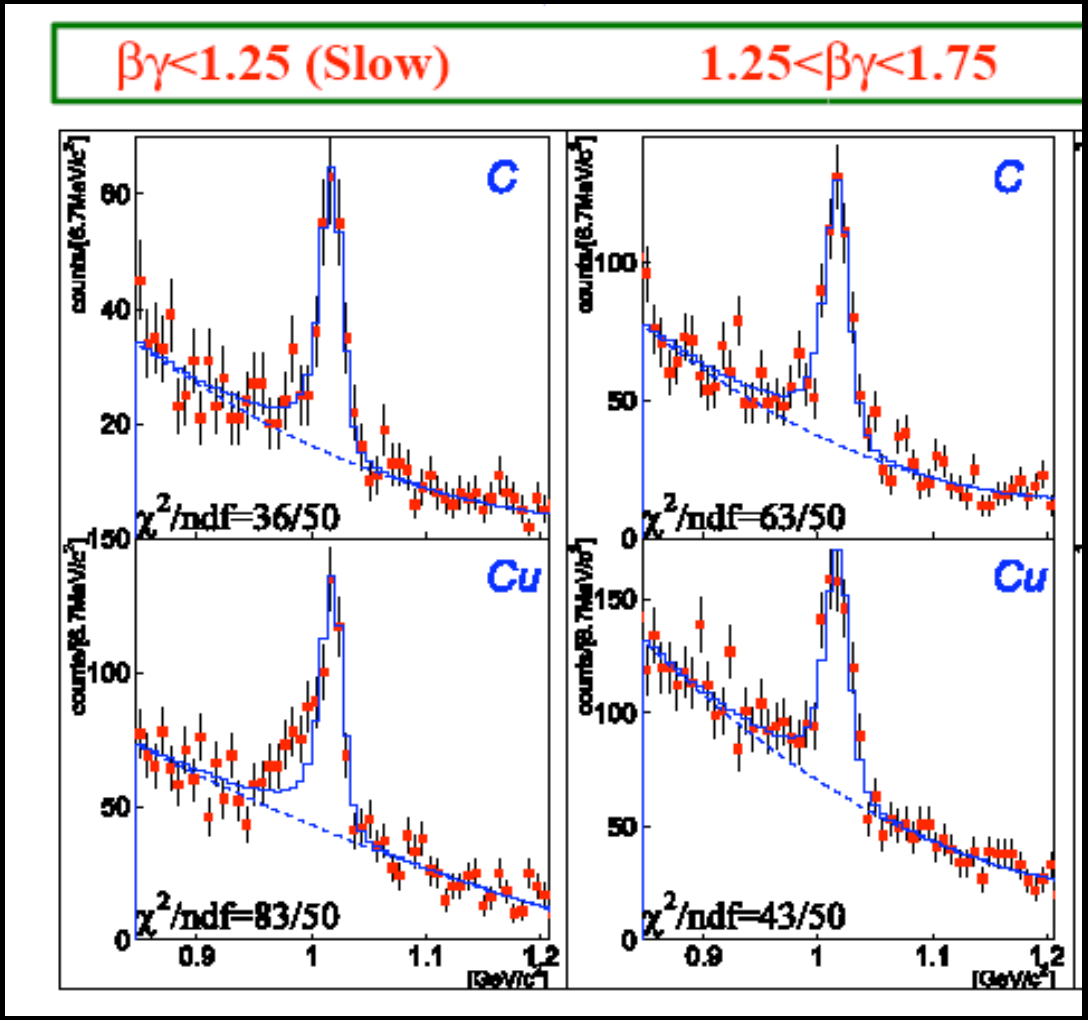
$m^*/m = 1 - 0.092\ \rho/\rho_0$




**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 ± 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

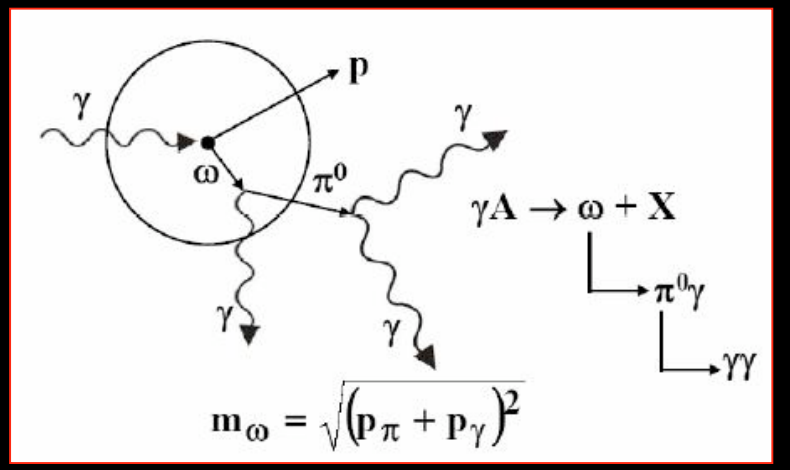
$\gamma + A \rightarrow \omega + X$ ($\omega \rightarrow \pi^0 \gamma$)

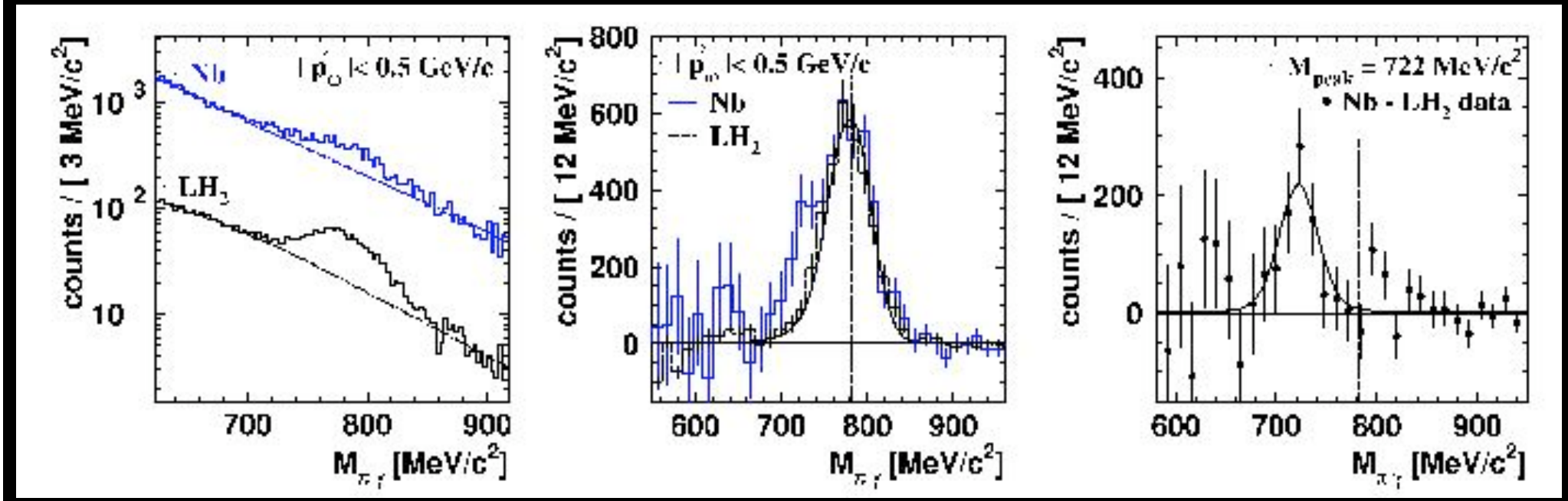
**clean ( no ρ ) channel, however FSI of π**

Small signal to background ratio

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

$\Gamma_\omega$ ($\rho=\rho_0$, $\langle|p_\omega|\rangle \approx 750$ 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'<br>VM → e+e- | γ A → ω A'<br>ω → $\pi^0\gamma$ | p+Au,Pb+Au<br>ρ → e+e- | In+In<br>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** | $\Delta m_\rho$~-9%<br>$\Delta m_\phi$ ~ -4% | $\Delta m_\omega$ ~ -14%* | Δm not favored | No mass shift |
| **Width** | $\Delta\Gamma_\rho$ = 0 MeV<br>$\Gamma_\phi(\rho=\rho_0)$ = 47 MeV | $\Gamma_\omega(\rho=\rho_0)\approx$140 MeV<br>(new unpublished) | Broadening favored | Strong broadening |
| **Note** | **No direct extraction of ρ meson (BKGD)** | **$\pi^0$ FSI**<br>**Large background** | **ρ, T not constant** | **ρ, T not constant** |

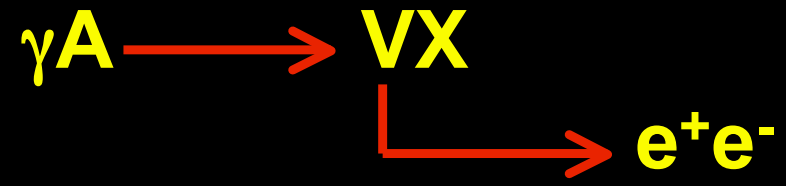
R. Muto et al., *PRL 98 (2007)*

*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"

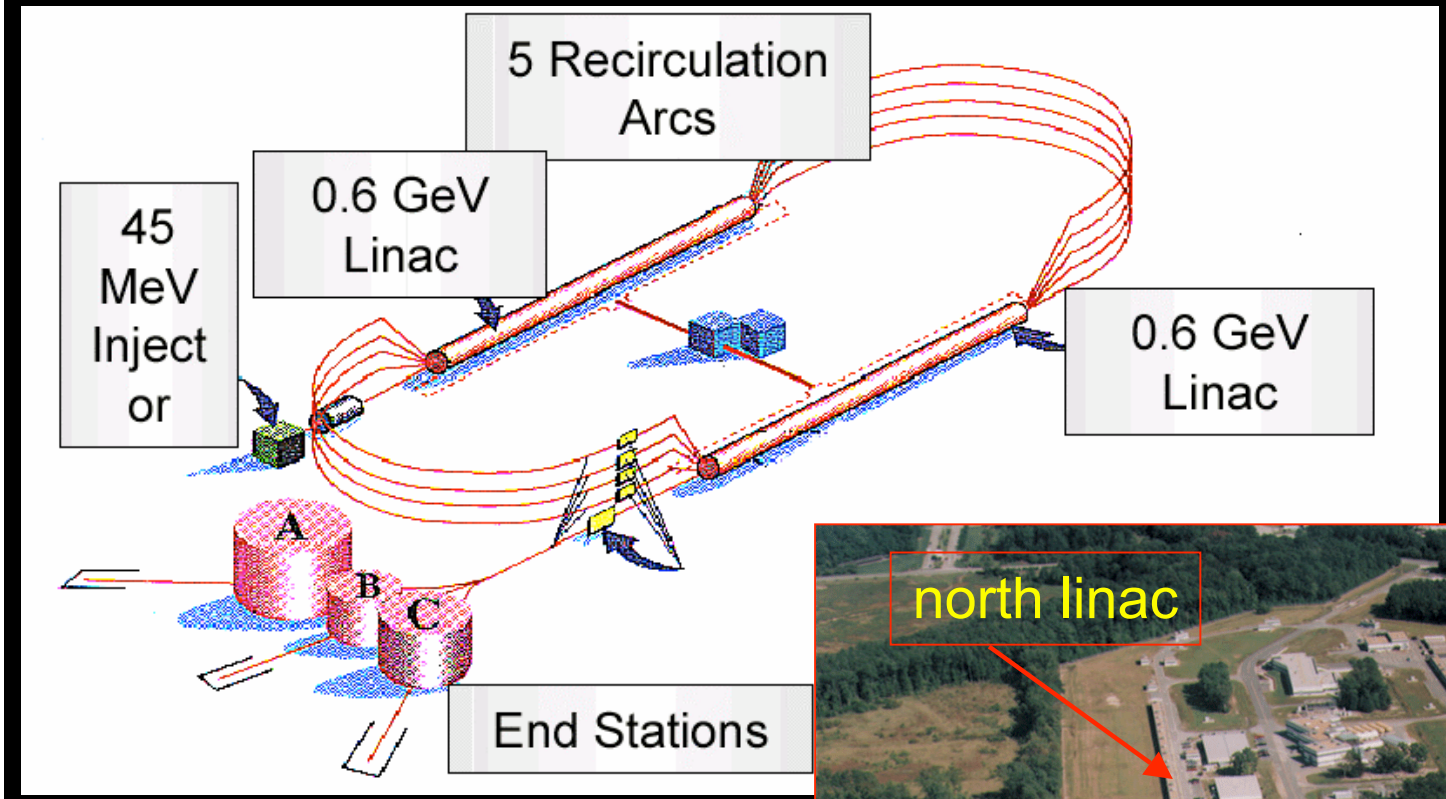



- **Original idea:**
  P. Y. Bertin and P. A. M. Guichon, Phys Rev C42, 1133 (1990)
- **Jlab Experiment E01-112 ( also called g7)**
  Spokespersons: C. Djalali (USC), M. Kossov (ITEP),
  D. Weygand (Jlab)
- **Photon beam (minimal disturbance to initial sate) :**
  $E_\gamma$ ~ .6 to 3.8 GeV (tagged $\gamma$)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

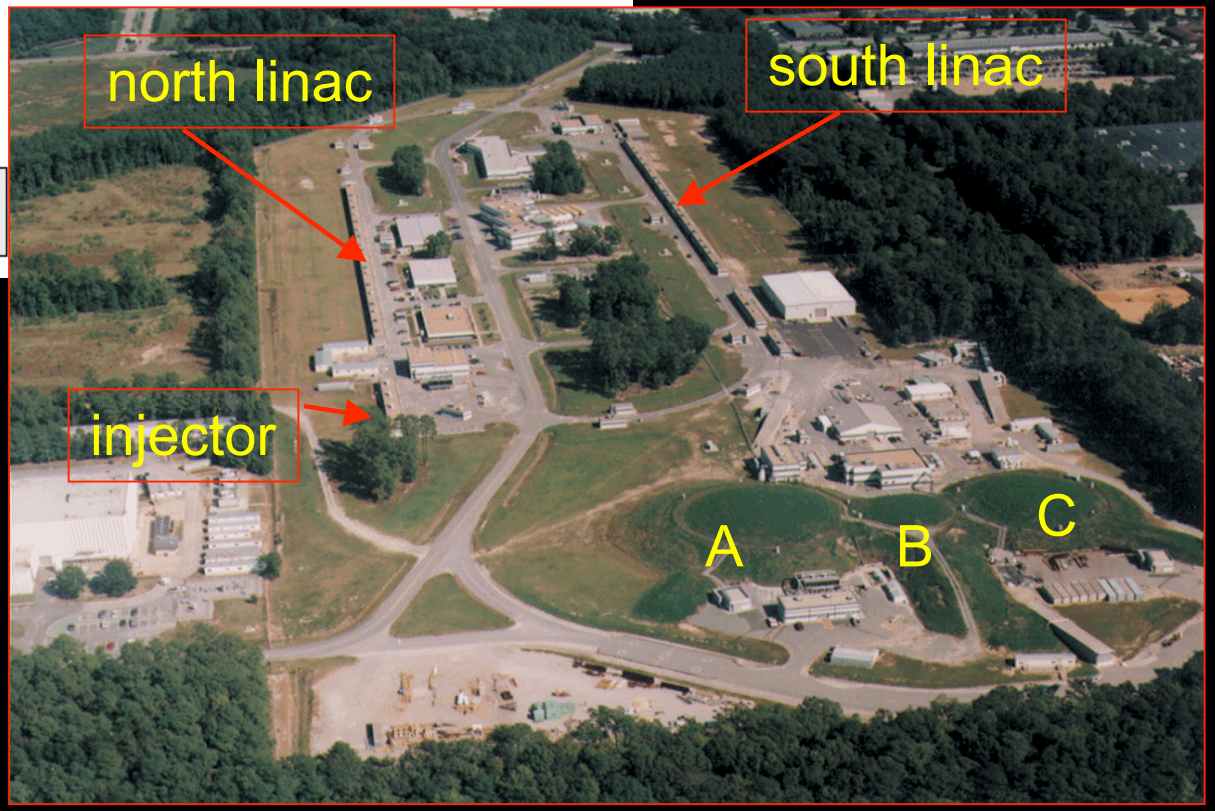
  Low branching ratio : ~5 $10^{-5}$

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

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



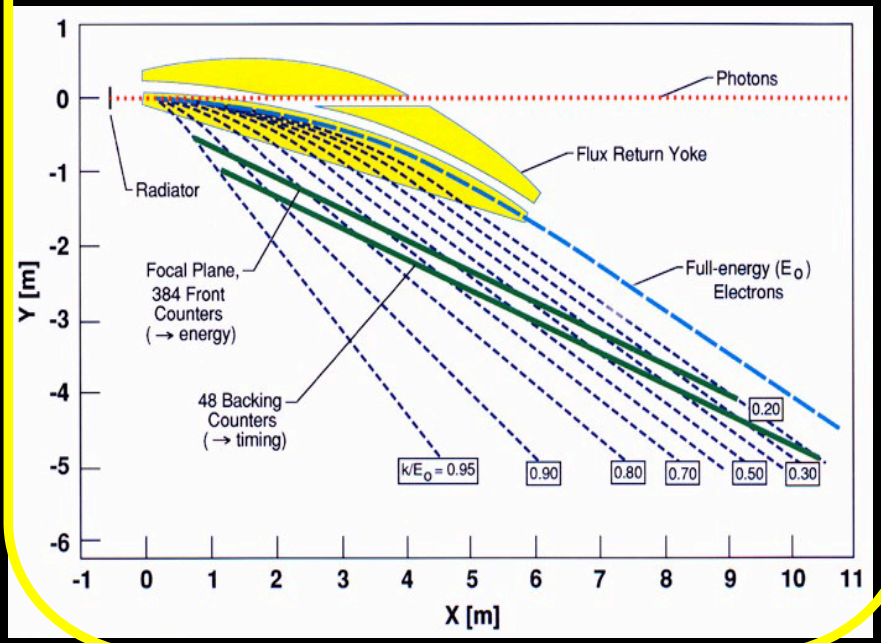

$E_{max}$ ~ 6 GeV
$I_{max}$ ~ 200 μA
Duty Factor ~ 100%
$\sigma_E/E$ ~ $2.5\ 10^{-5}$
Beam P ~ 80%
$E_{\gamma(tagged)}$ ~ 0.8- 5.5 GeV

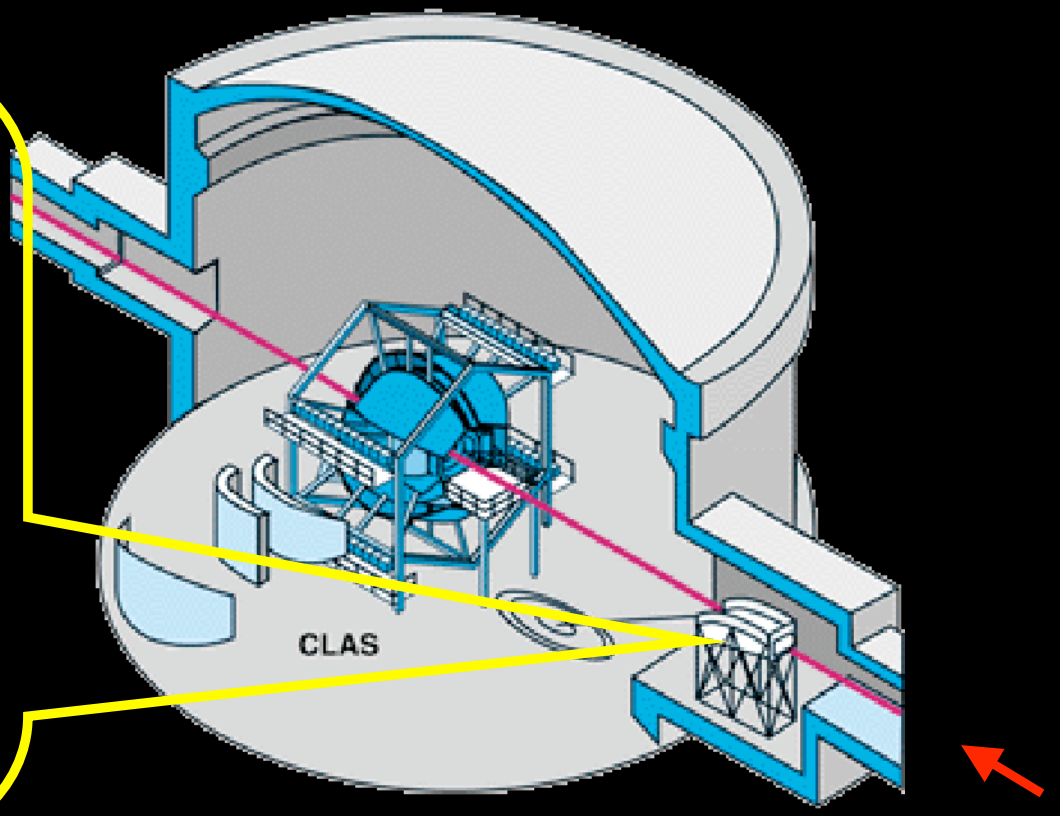


# Hall B @ Jlab ( The tagger)

3. $10^{-4}$ RL

**Photon Tagger**

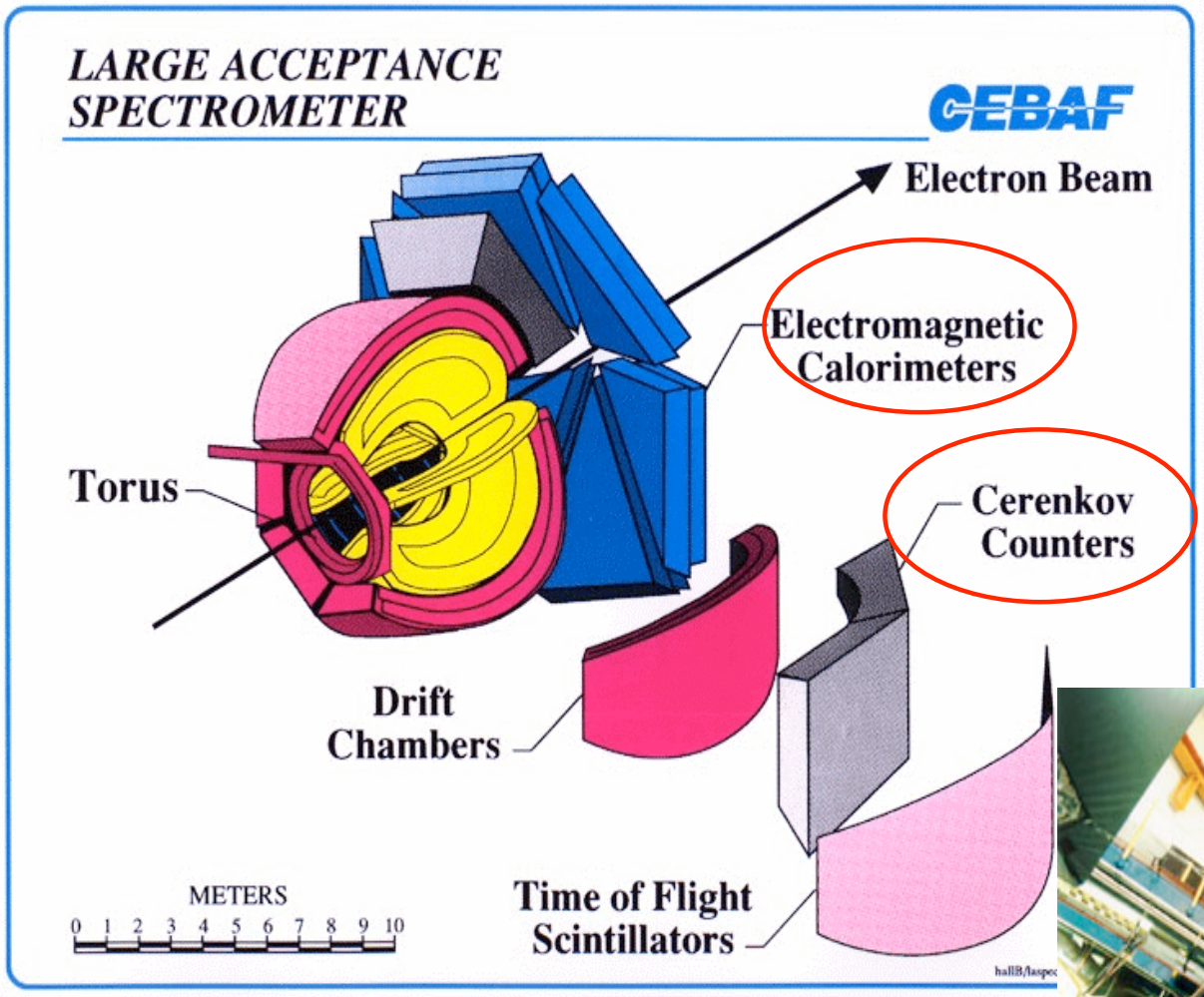



Bremsstrahlung Tagging Spectrum (20%-95%)

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

# Hall B @ Jlab (CLAS)

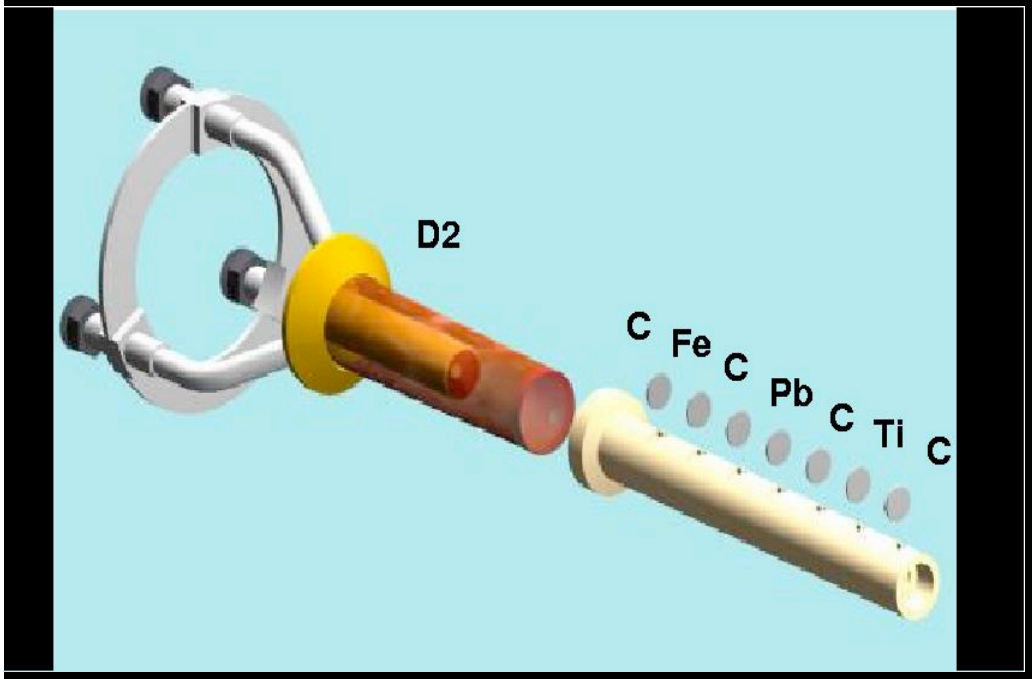


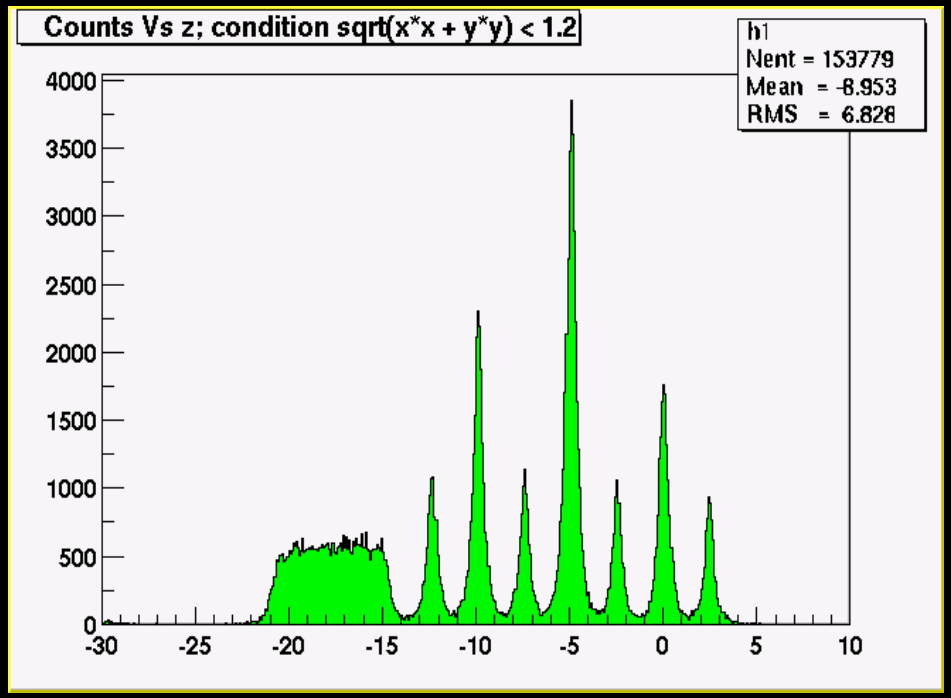

>150 physicists,
>10 countries

- 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/cm$^2$ and diameter 1.2 cm
- Approximately same number of nucleons/target

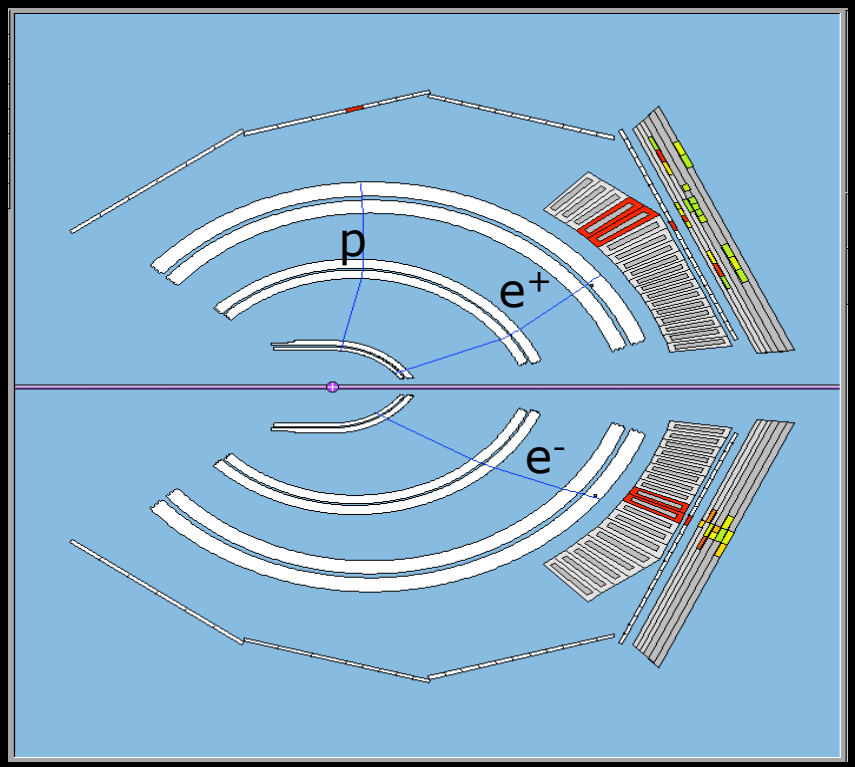


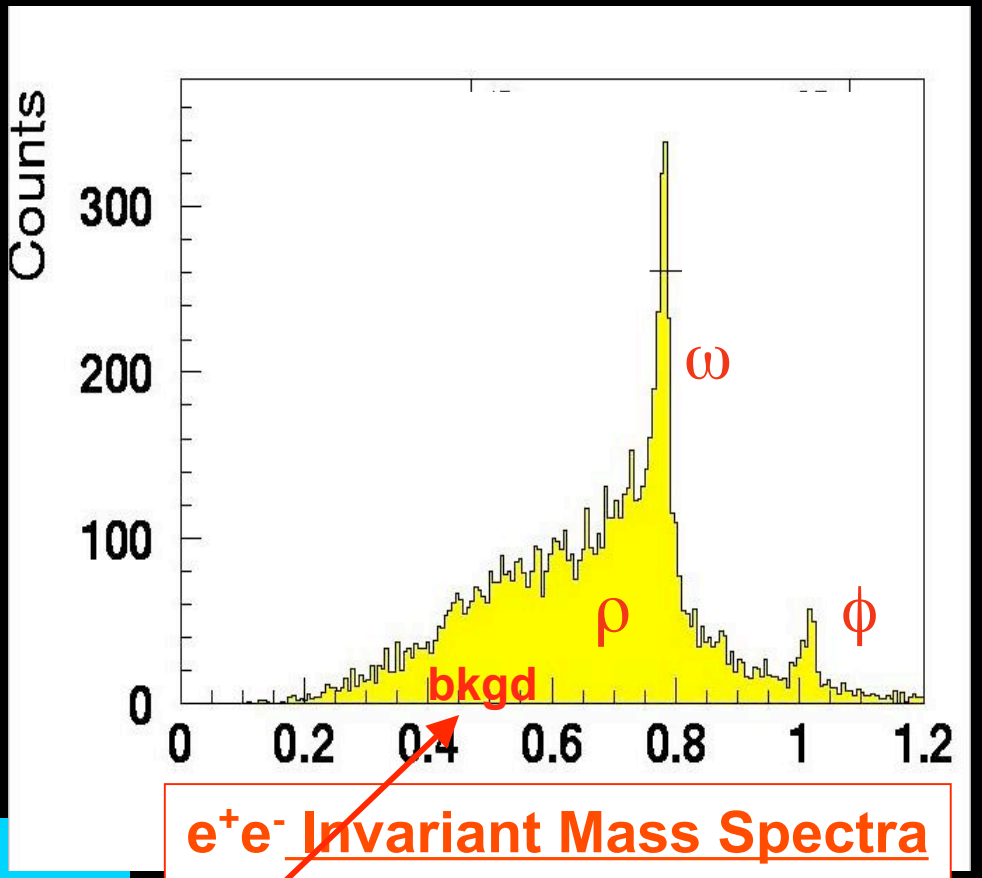




- Proper spacing 2.5 cm to reduce multiple scattering
- Deuterium target as reference, small nucleus, no modification is expected.

# Particle Detection with CLAS

## coincident electron pairs in the CLAS




- 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: $5.4 \times 10^{-4}$ for one and $2.9 \times 10^{-7}$ 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**

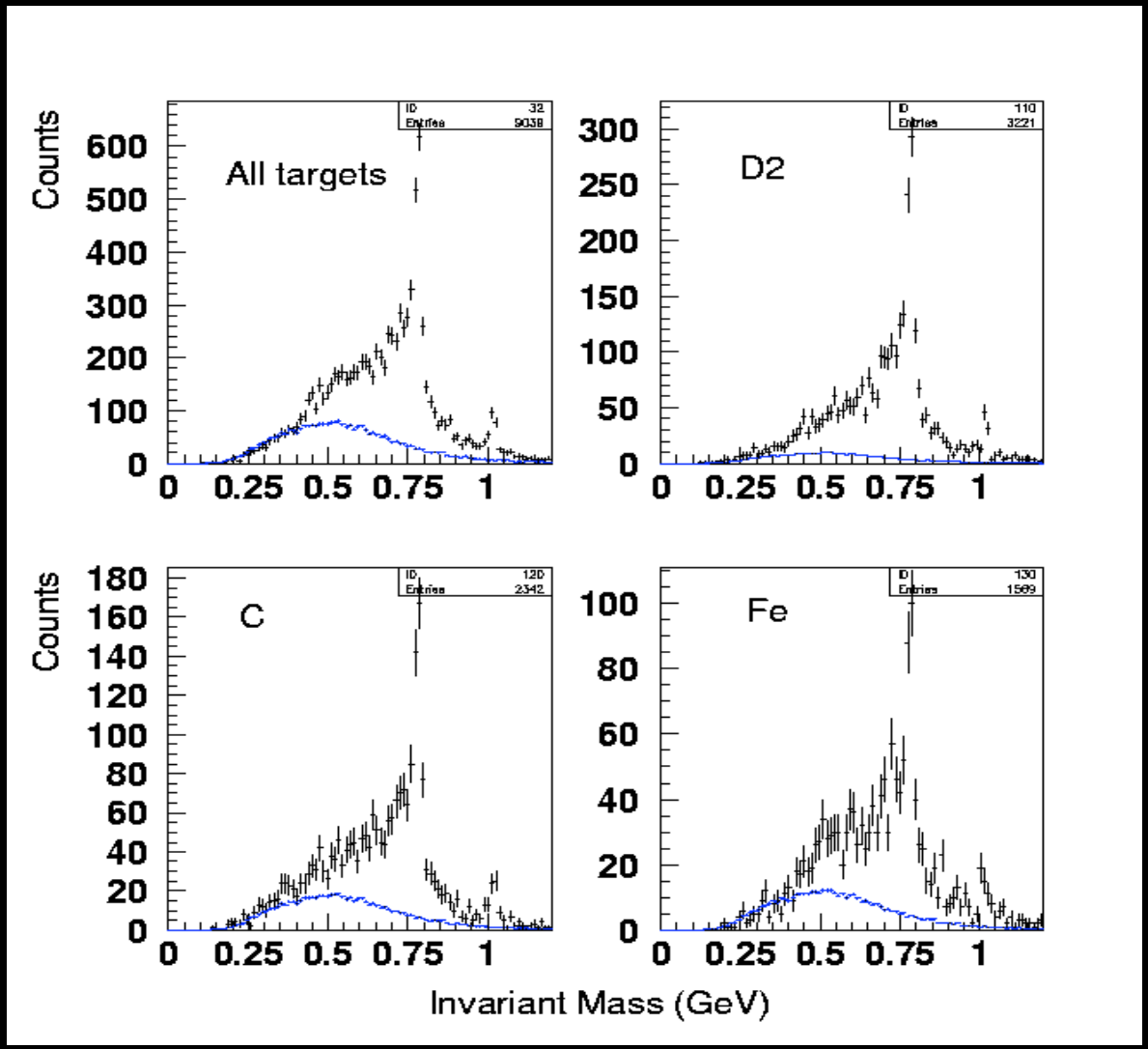
**"Semi-correlated":**

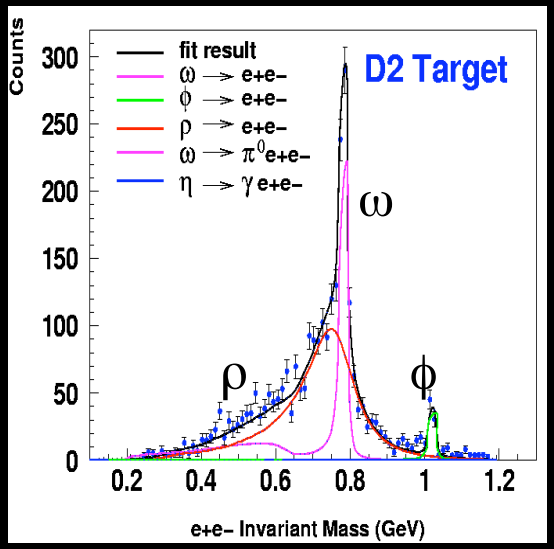
- Bethe-Heitler — calculated by Mosel's group → negligible
- $\gamma A \rightarrow \pi^0 \pi^0 X \rightarrow \gamma$ e+e- $\gamma$ e+e- — 2 $\pi^0$ Dalitz decay mixed → negligible
- $\pi^0 \rightarrow$ e+e- e+e- — double Dalitz → low mass

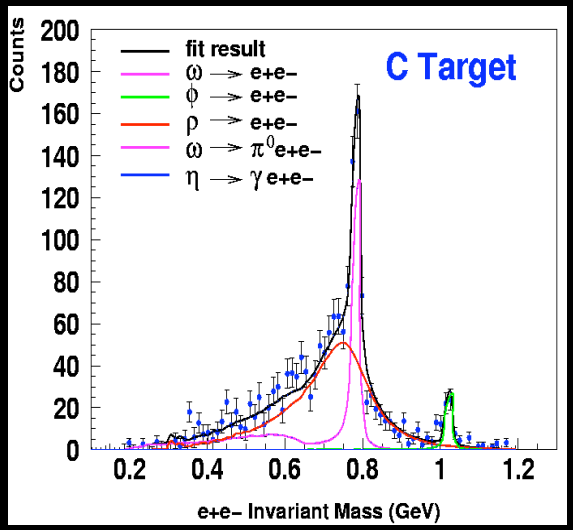
**Uncorrelated:**

- 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)



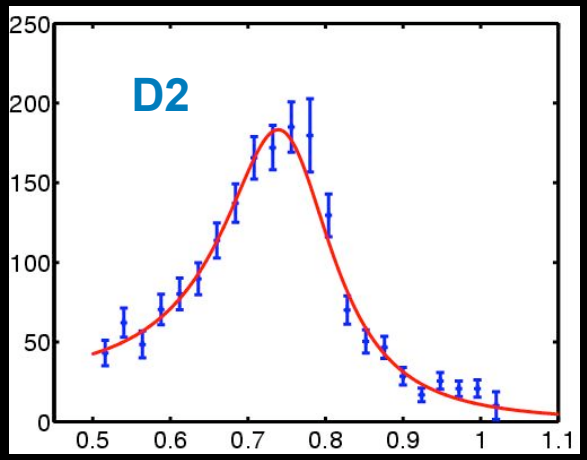



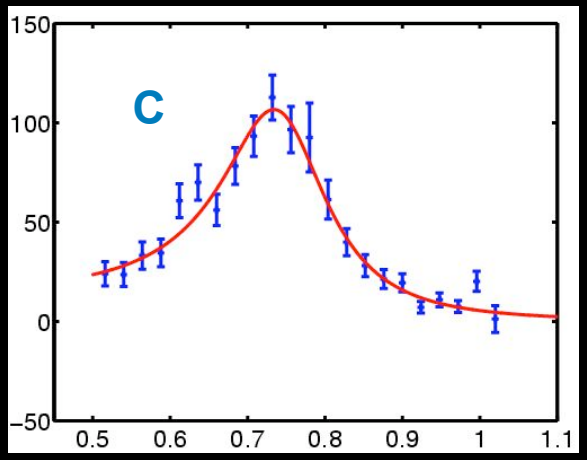



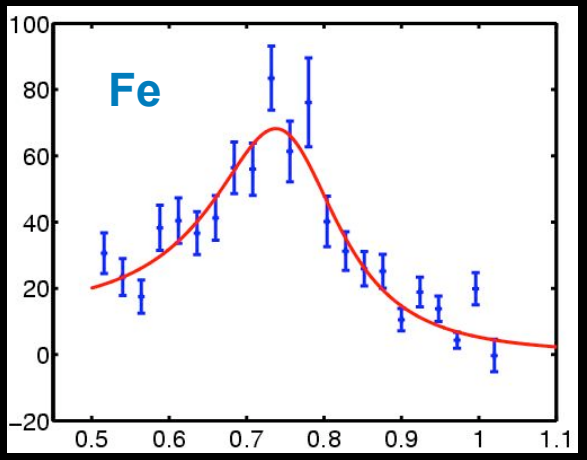

μ+μ− measurement: at CERN-SPS ***IPNO-DR-02.015 (2002)***
π+π− measurement: at CERN-ISR ***(Nucl. Phys. B124 (1977) 1-11).***
**e+e-** measurement: at RHIC ***(Nucl.Phys. A774 (2006) 743-746).***

# The ρ Mass Spectra

After removing the ω, ϕ, and background contributions:



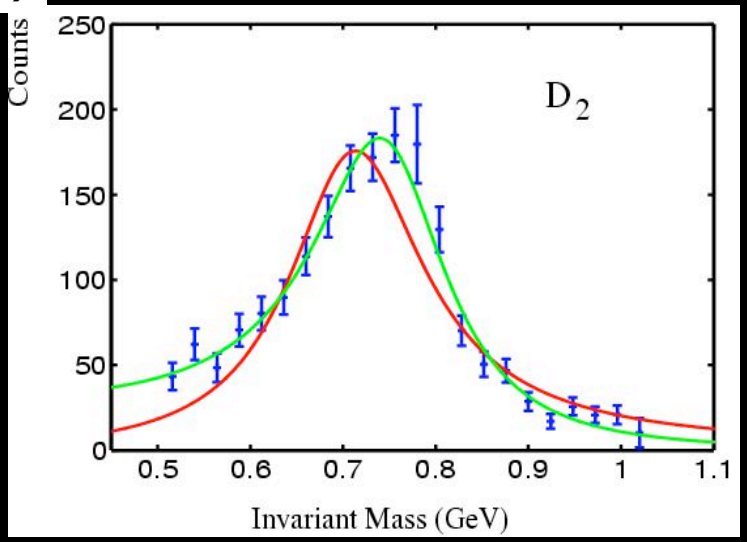

$e^+e^-$ Invariant Mass (GeV)

## Fit function:

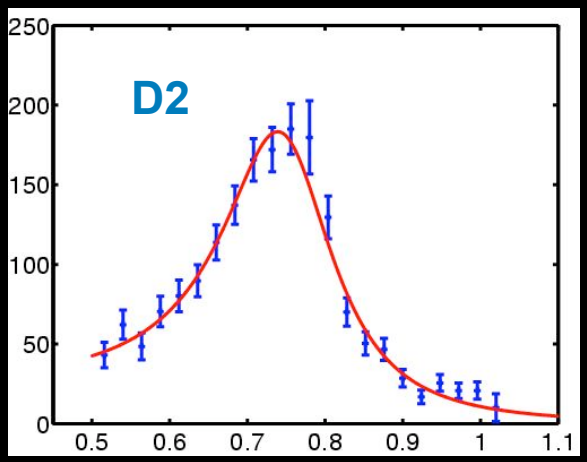
$$\text{(Breit – Wigner)} \times \frac{1}{M^4} \times M = \frac{\text{(Breit – Wigner)}}{M^3}$$

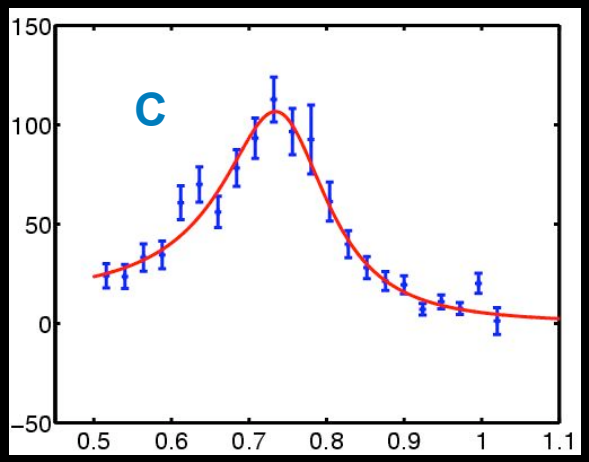
Photon propagator

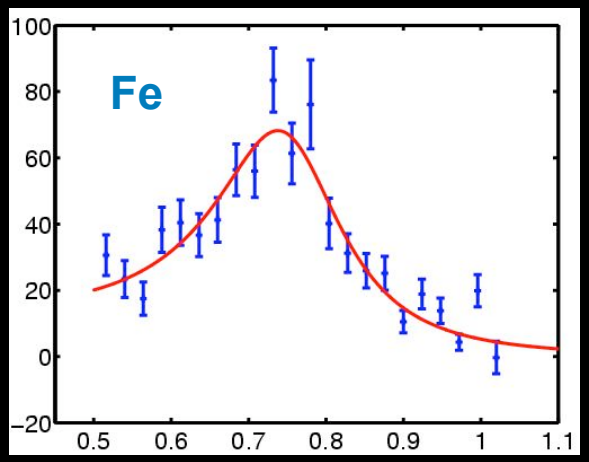
Breakup momentum phase space



# 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 MeV/$c^2$ and Γ=150 MeV. Broadening of the width is consistent with many-body effects.**

# Summary on the ρ meson

-Our result ($\alpha$ =0.02 ± 0.02) is compatible with no mass shift
-Result does not confirm the KEK results ($\alpha$ ~0.09).
-Rule out $\Delta$M à la Brown/Rho ( 20%) and
Hatsuda/Lee ($\alpha$ ~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

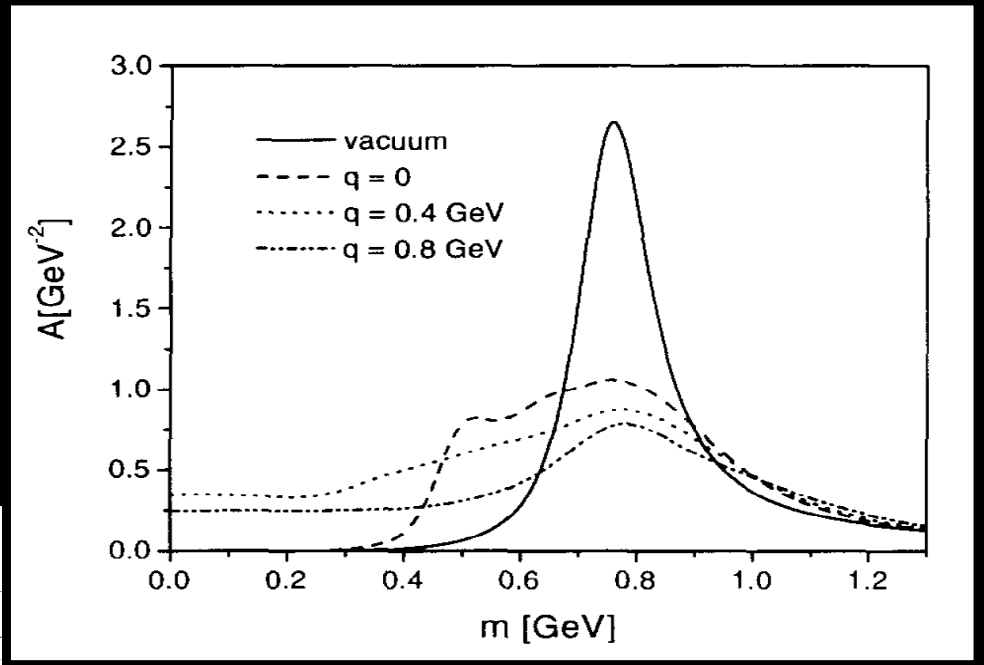
•PRL published – **R. Nasseripour *et al.*, PRL 99 (2007) 262302**
•PRC article will be submitted mid February 2008.

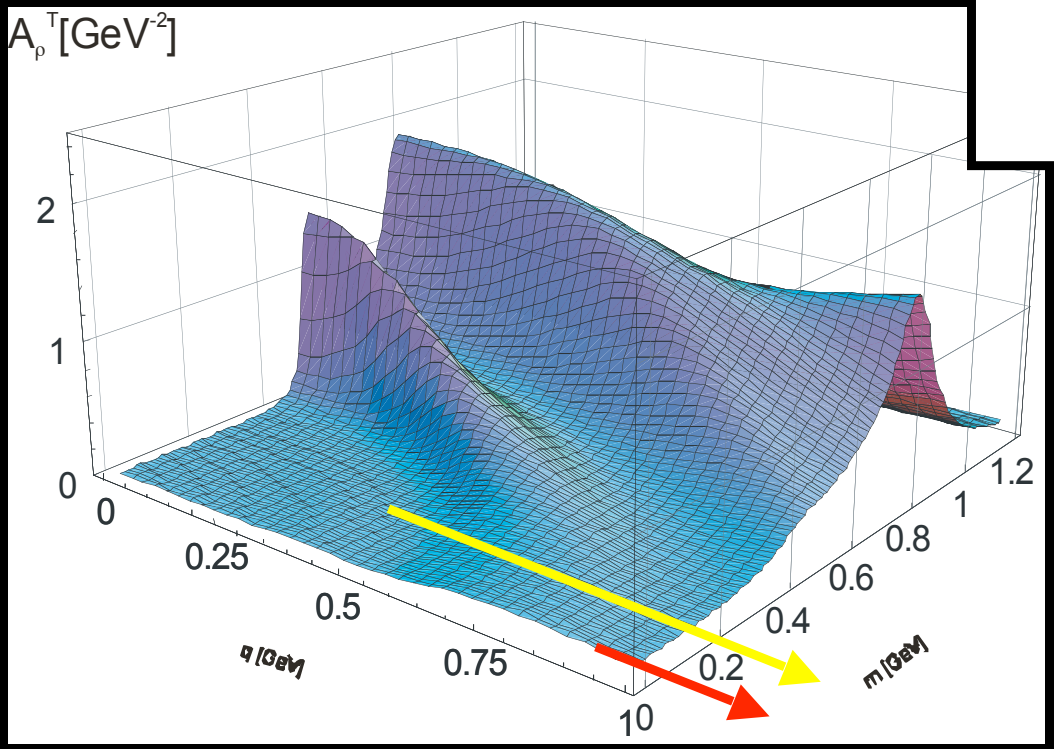
# Momentum Dependence – ρ Meson

## 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.



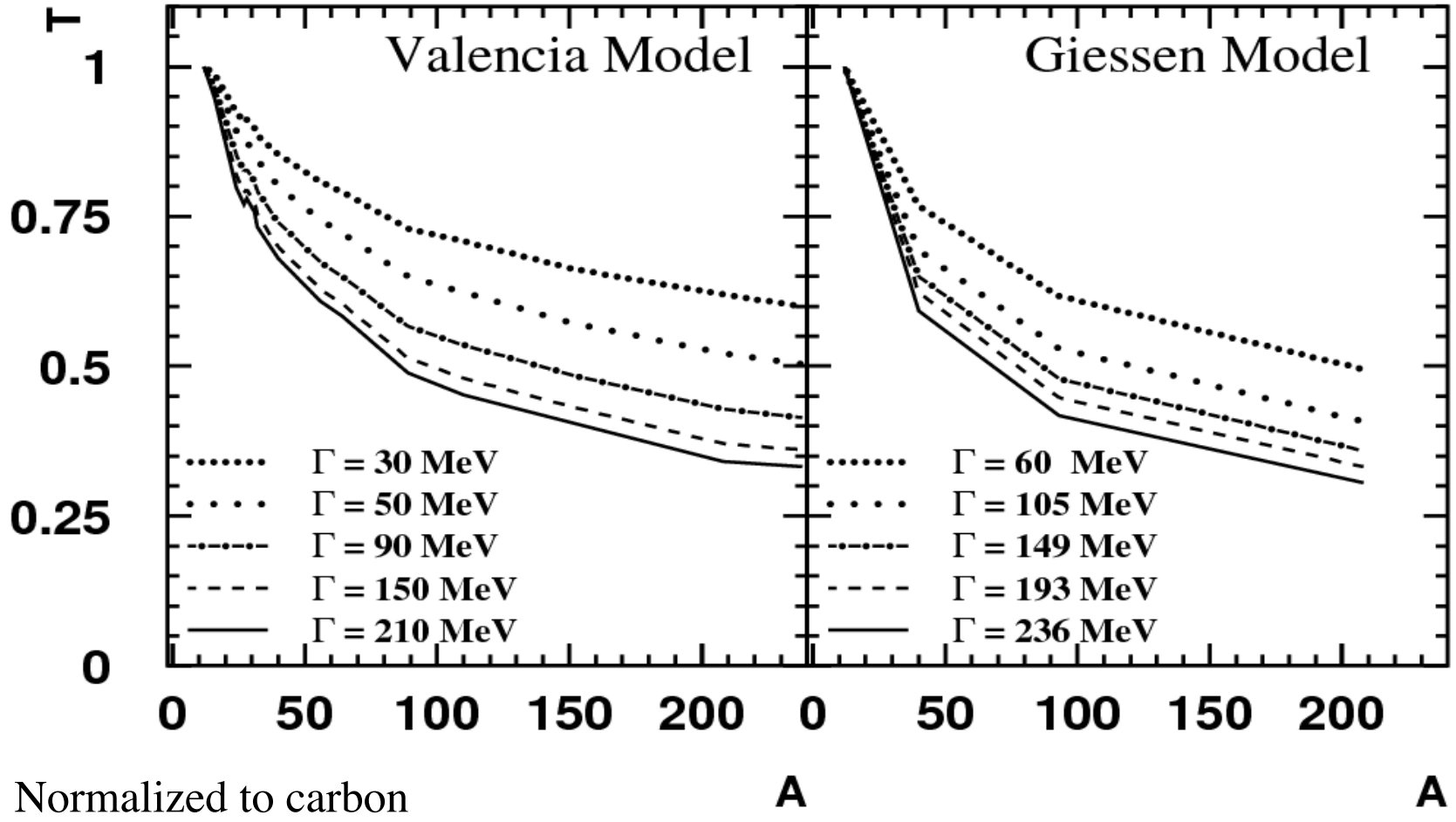

g7a

Planned g7b
Conditionally approved

# Absorption of ω Meson and its In-medium width

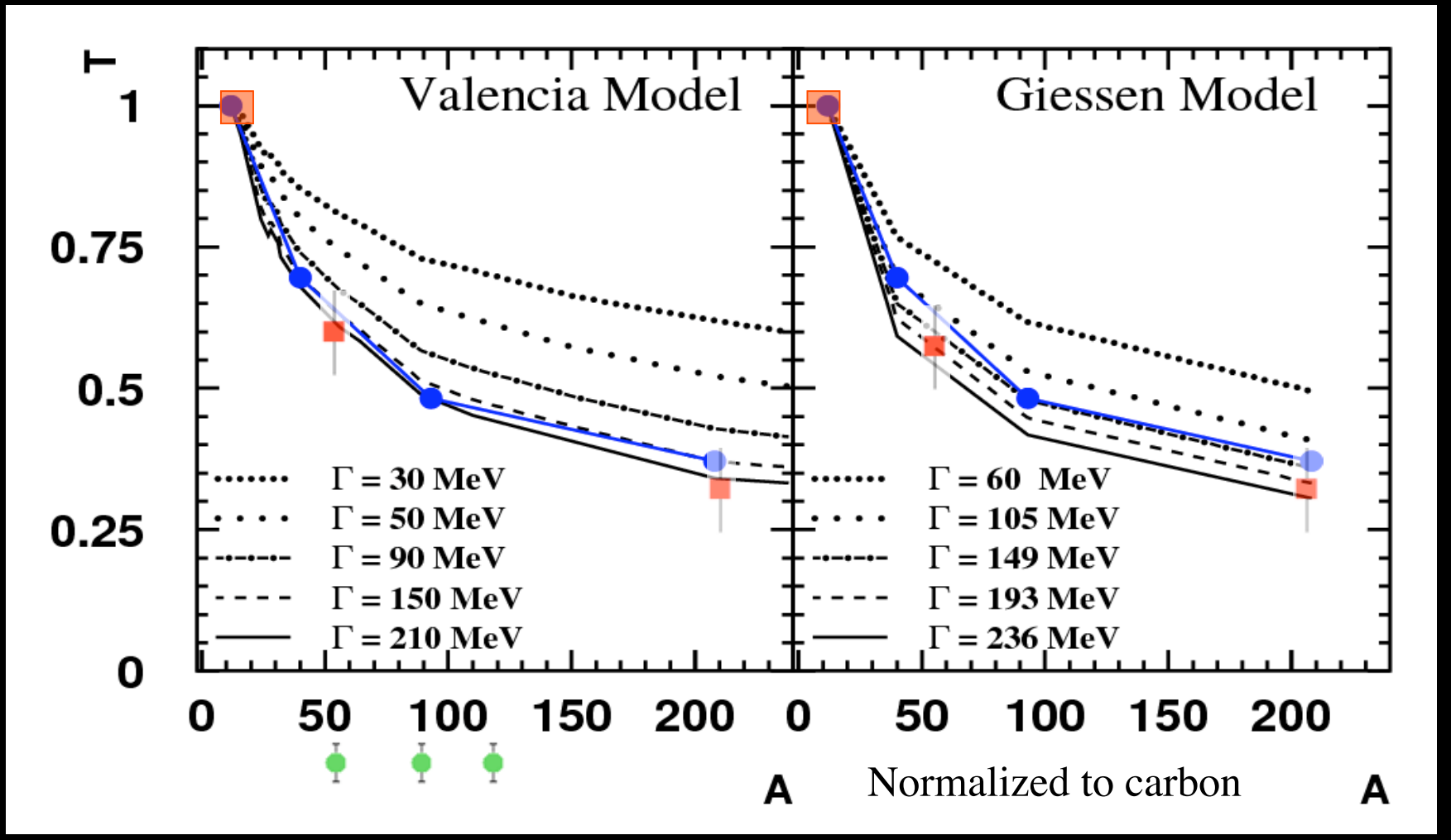
**The in-medium width is $\Gamma=\Gamma_0+\Gamma_{coll}$ where $\Gamma_{coll} = \gamma\rho v\sigma^*_{VN}$**

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




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

# Comparison to Theory – ω Meson



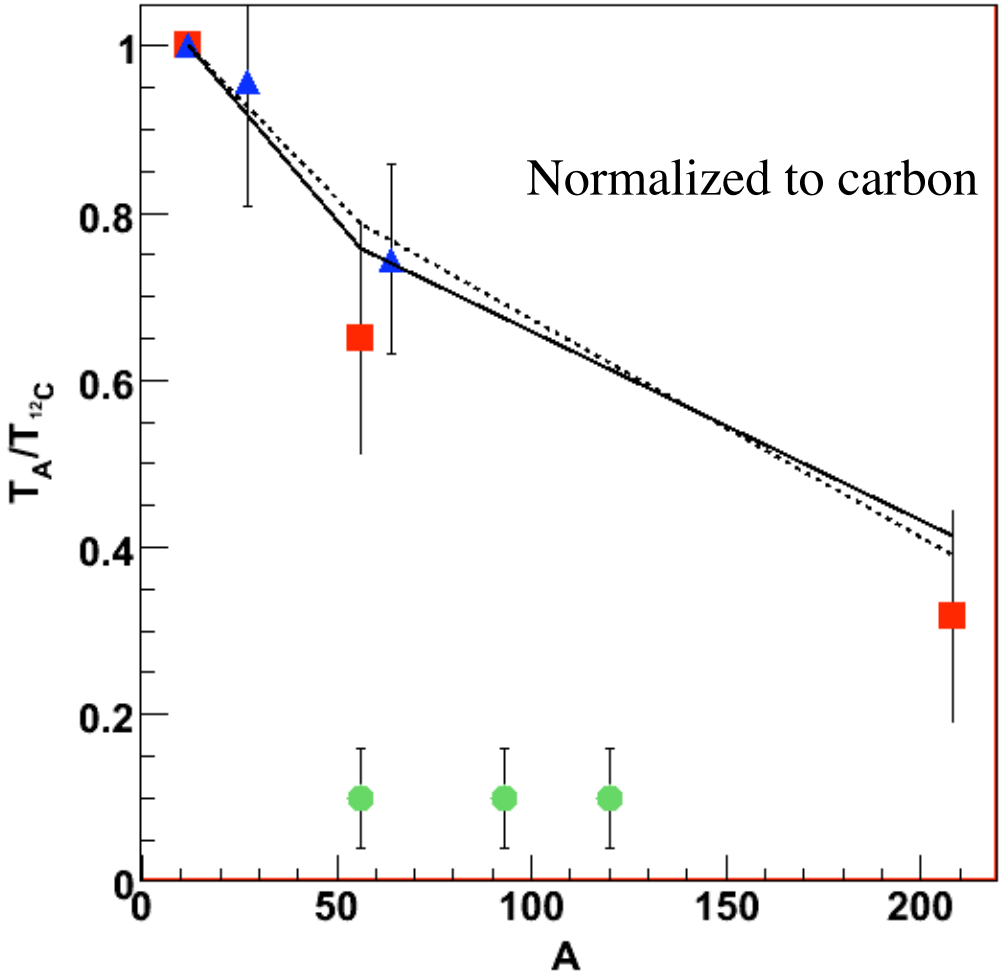

**Preliminary g7a result showed greater absorption than TAPS!!!**

**Latest TAPS** $\Gamma_\omega$~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)



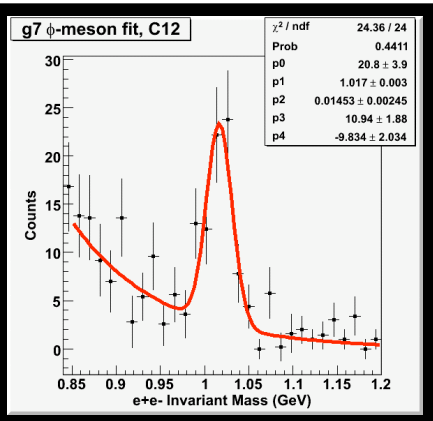

——— Giessen calculations

– – – – 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 $\rho$, $\omega$ and $\phi$ signals in the invariant mass spectrum.
- "Mixed-event" technique gives both shape and normalization of the combinatorial background.

**The $\rho$ meson ( Final):**

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

**The $\omega$ meson ( preliminary):**

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

**The $\phi$ 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 $\rho$ meson mass spectra in four momentum bites from 0.4 to 2 GeV/c and transparency ratios.