The Abdus Salam
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# Medium Modifications of Light Vector Mesons in Nuclei


C. Djalali, M. H. Wood (University of South Carolina)
R. Nasseripour ( George Washington University)

D. P. Weygand (Jefferson Lab)

and CLAS Collaboration


Jefferson Lab
Thomas Jefferson National Accelerator Facility

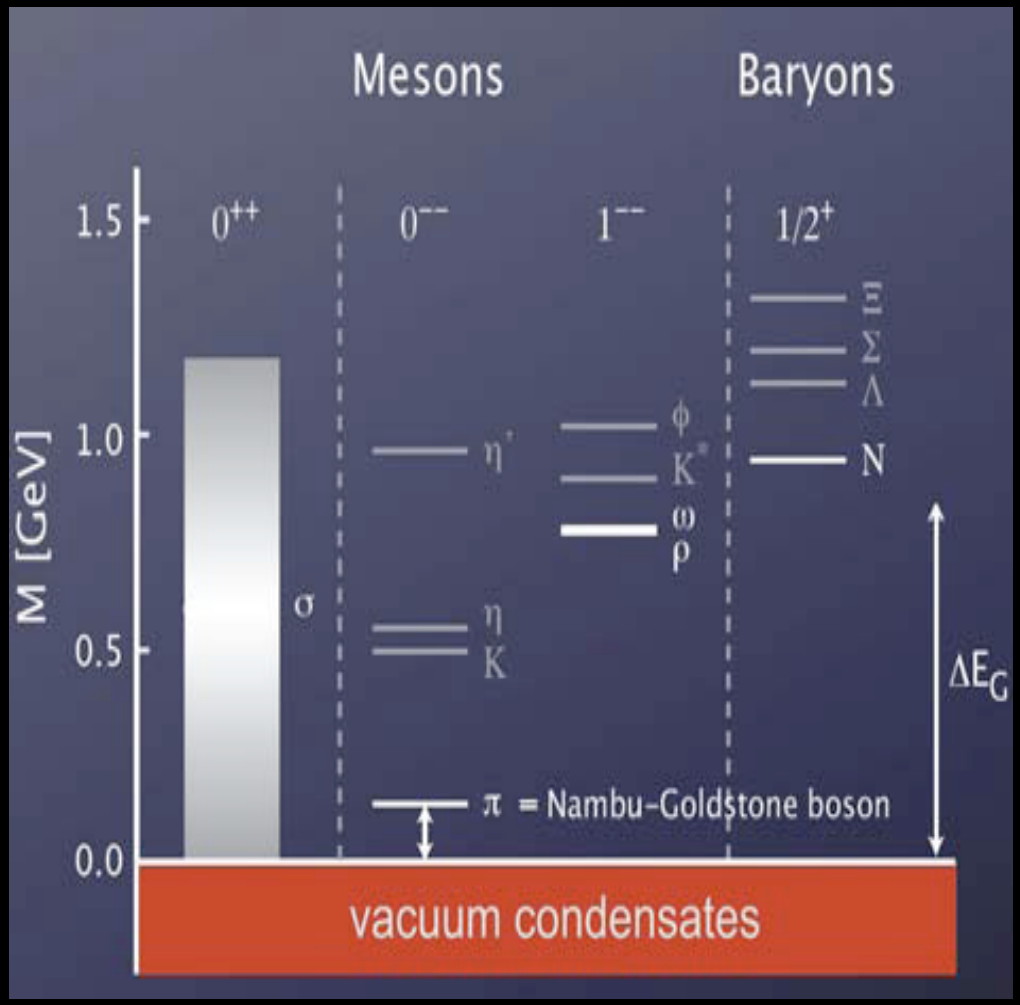
University of South Carolina

# Outline

- **Physics Motivations**
  - **Models and Predictions**
- **Some key experiments**
- **Photo-production of vector mesons at JLab**
  - $\rho$ **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 (?).

# 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*

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

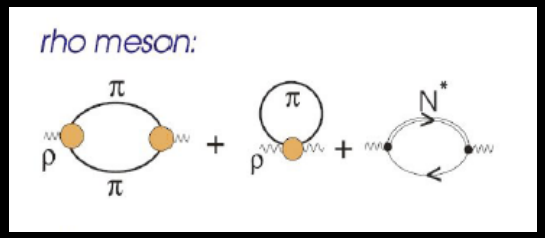
## QCD sumrules:

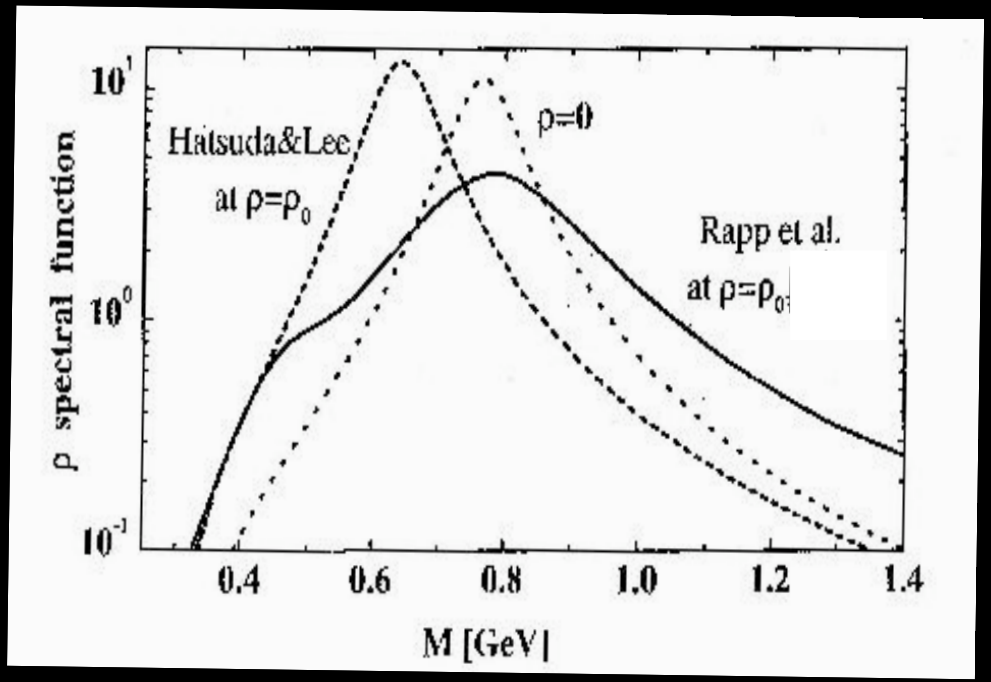
T. Hatsuda and S. Lee *Phys. Rev. C46 (1992) R34*

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

## Many body effects:

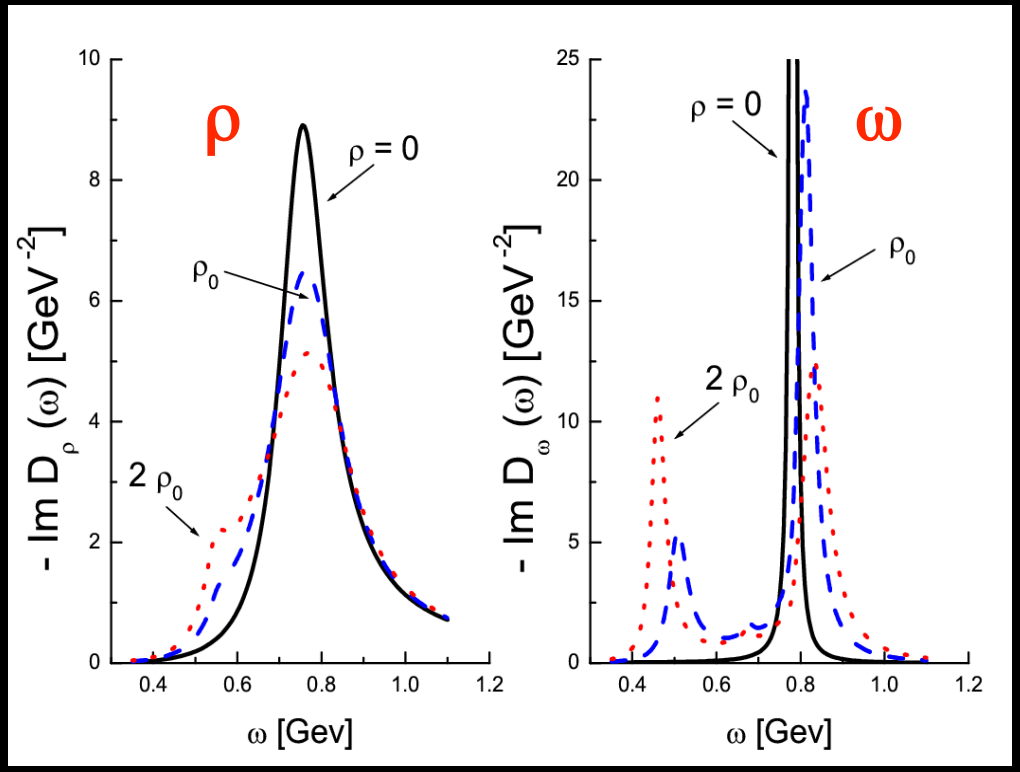
B Friman, H.J. Pirner,
***Nucl Phys. A617 (1997) 496***
R. Rapp, G. Chanfray, J Wambach,
***Nucl Phys. A617 (1997) 472***



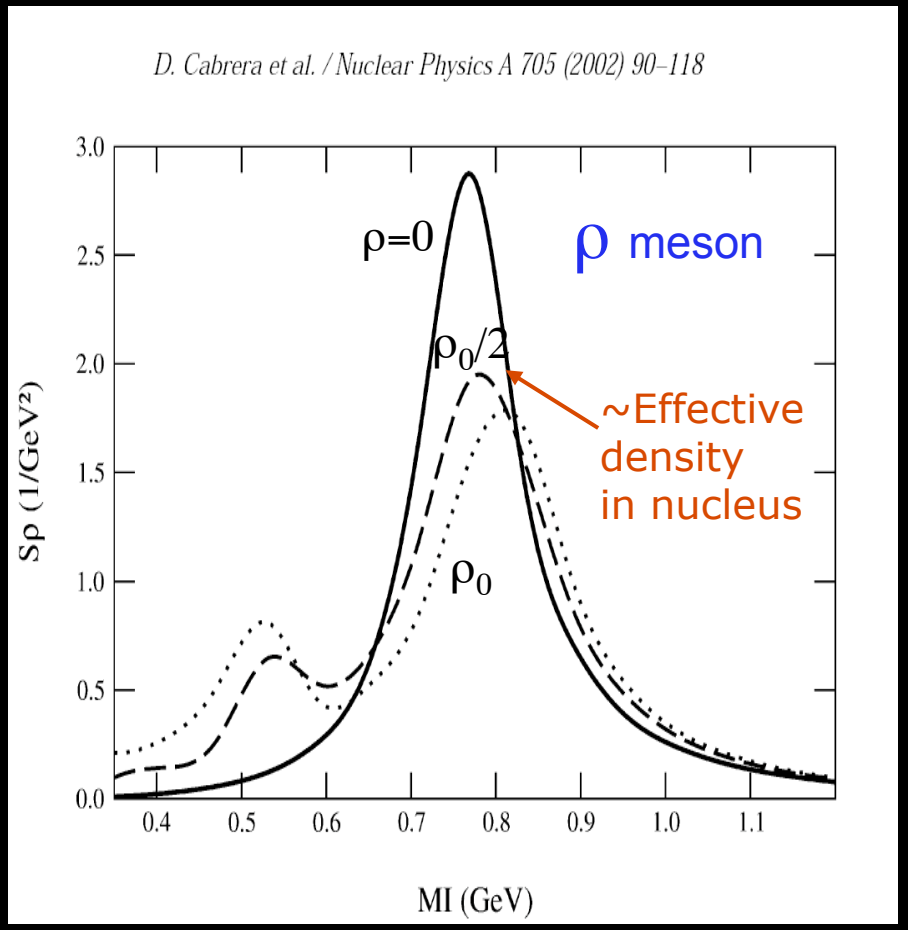



# Model predictions of the in medium properties of vector mesons

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



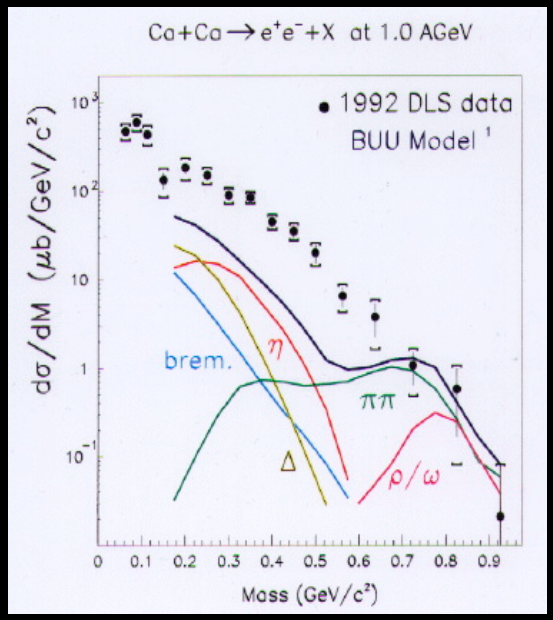

*D. Cabrera et. al. , Nucl. Phys. A 705 (2002) 90*

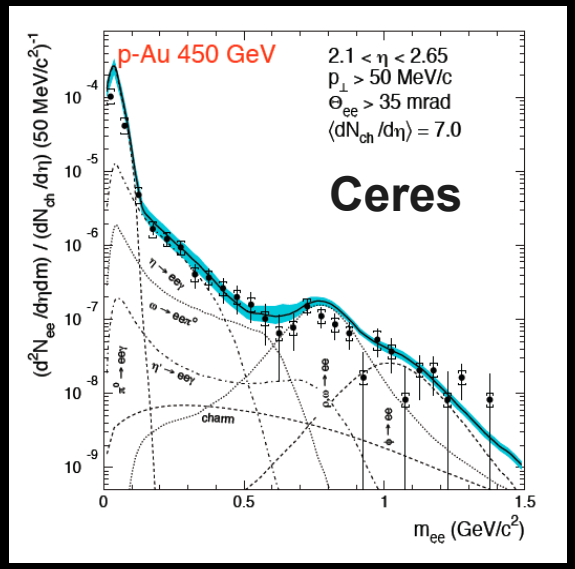


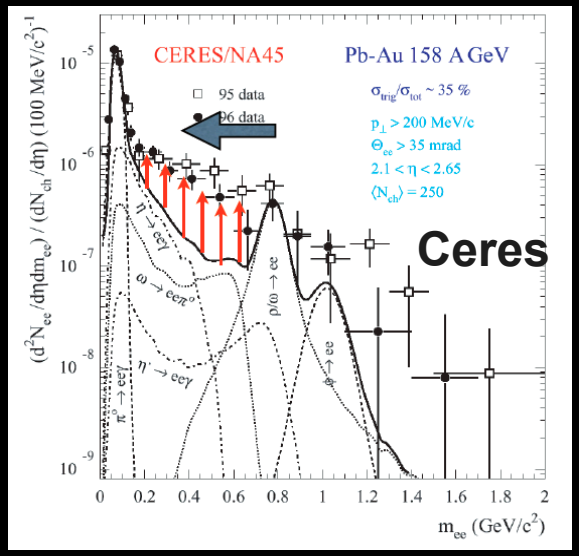

**Coupling to baryon resonances**

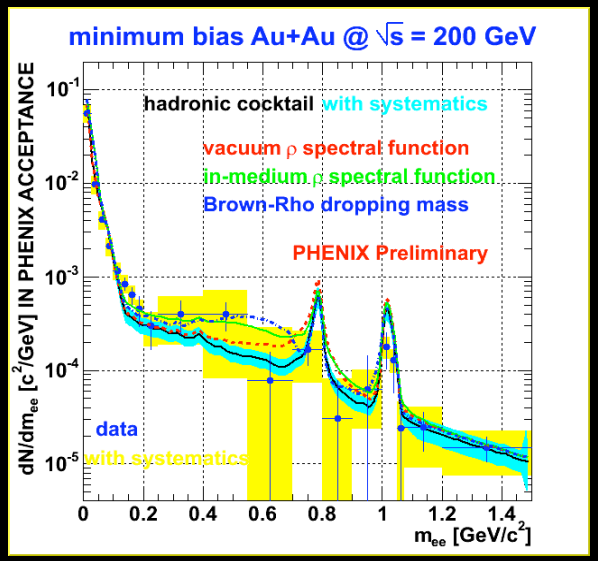
**Any observations??**

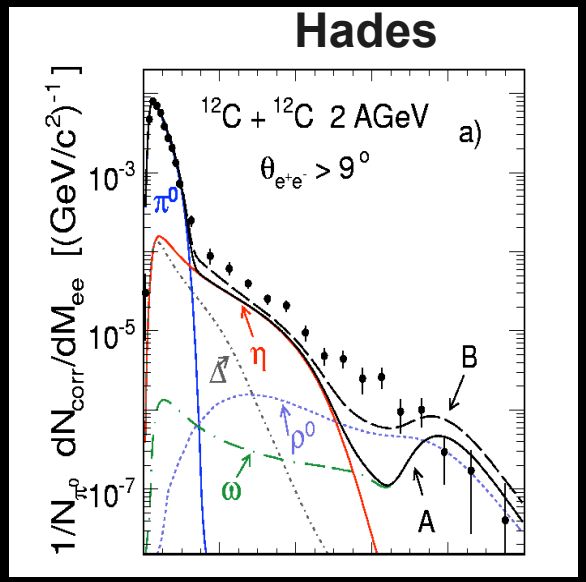
# In RHI collisions (nuclear matter under extreme conditions)

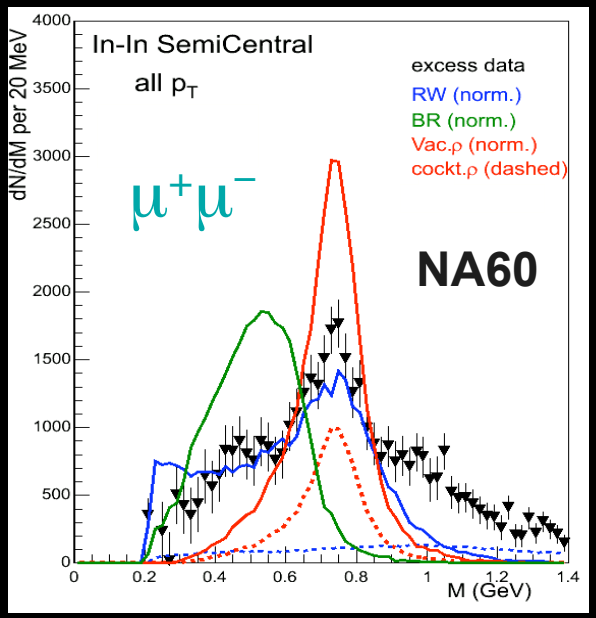


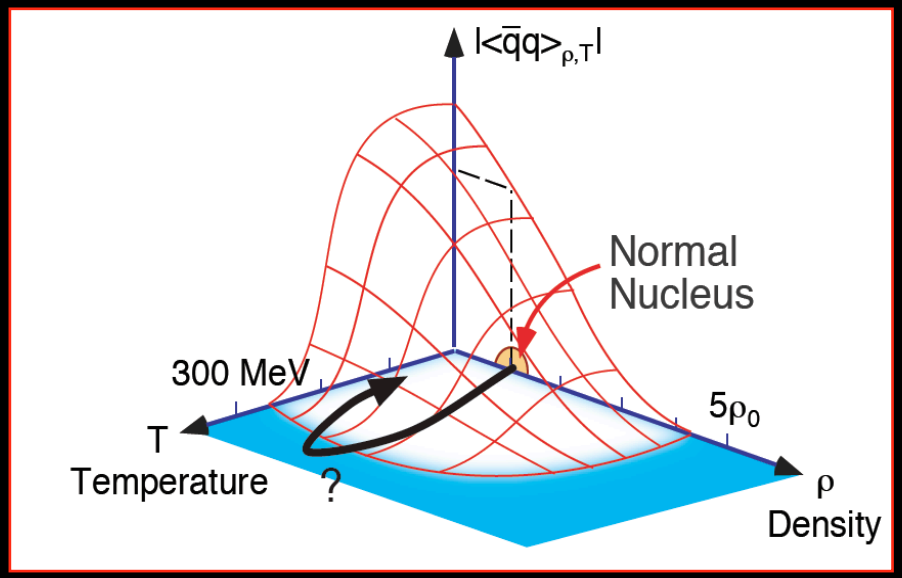



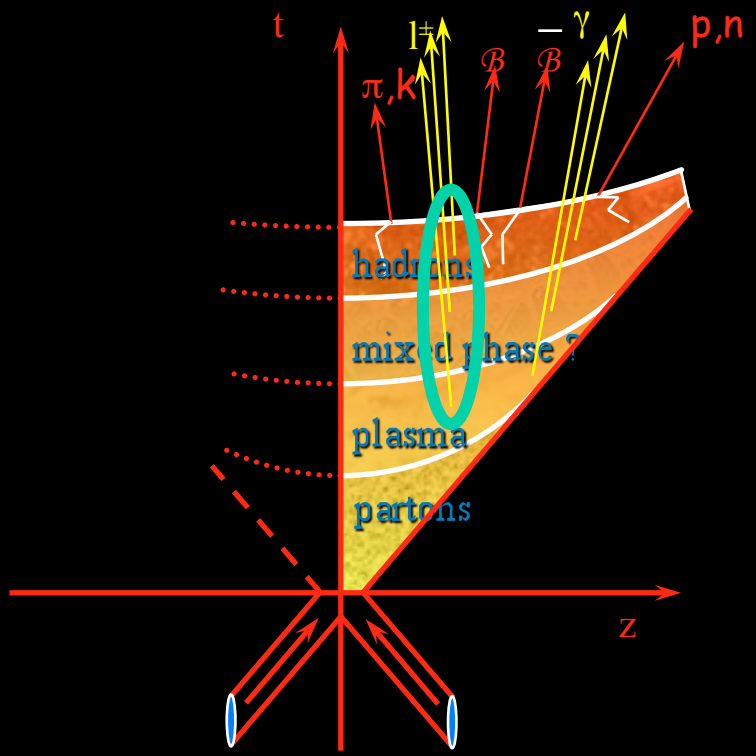




**Clear excess of di-leptons observed. NA60: Γ „/ no ΔM"**

# 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

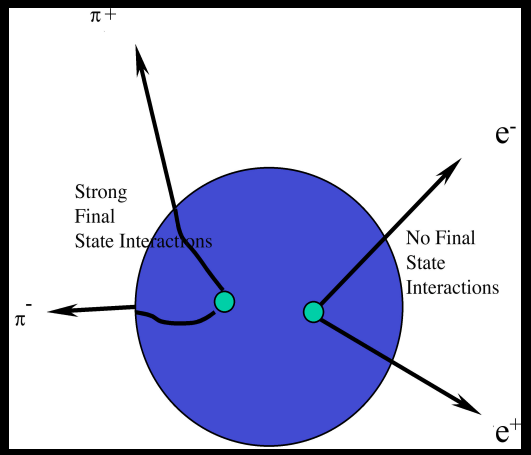


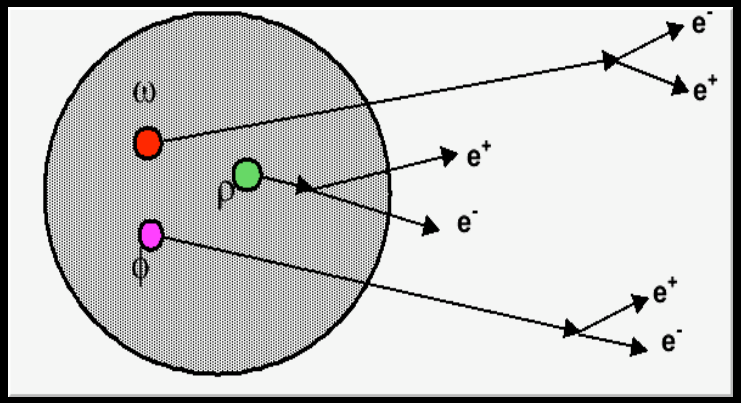



# Medium modification of vector mesons properties in nuclei

**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):

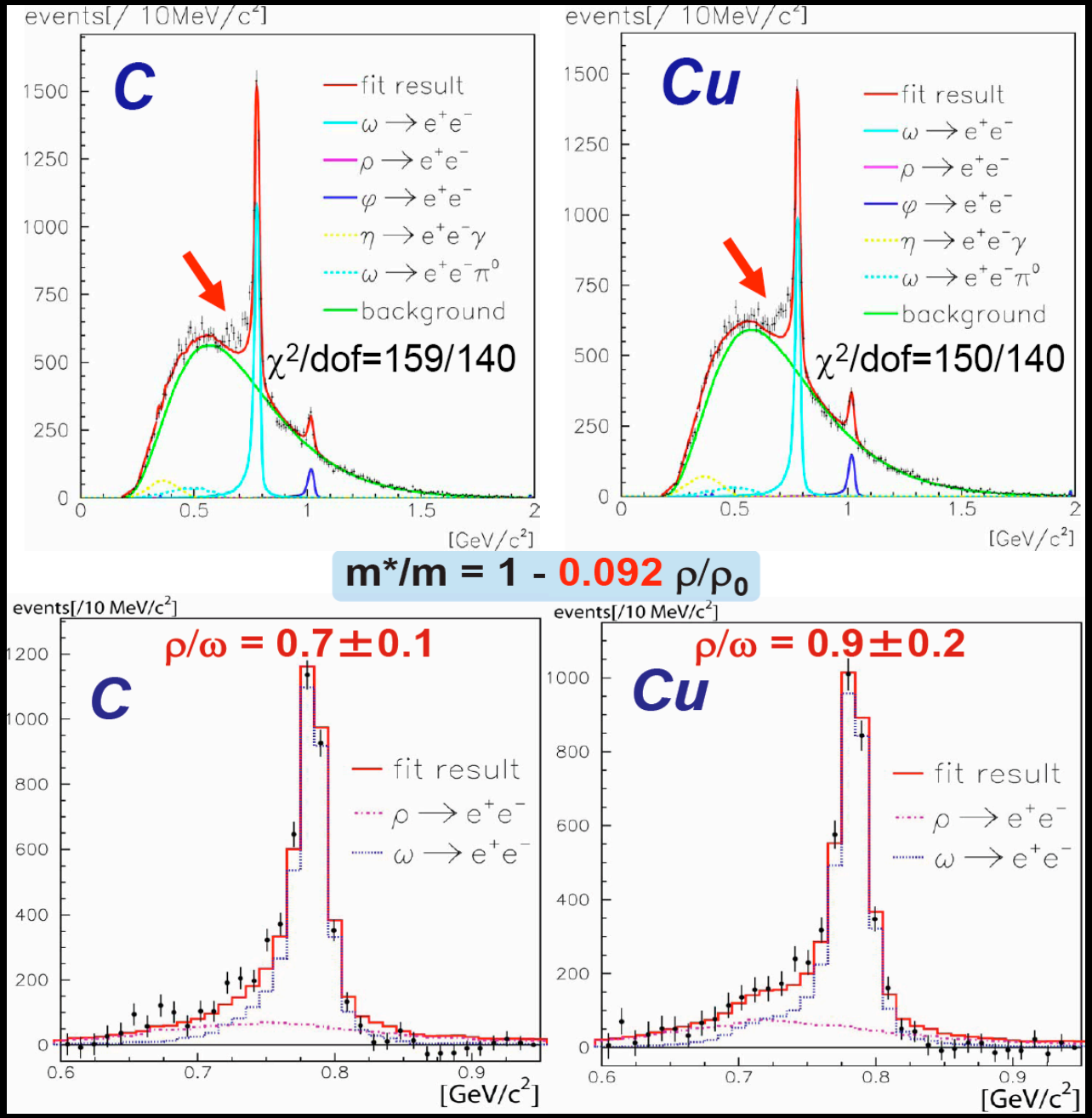
| *Experiment* | *Reactions* | *Results* |
|---|---|---|
| TAGX | $\gamma + {}^3He \rightarrow \rho + X$ ($\rho \rightarrow \pi^+\pi^-$) | full BR, $\alpha \sim 0.06$ |
| KEK | $p + A \rightarrow \rho,\omega,\phi + X$ ($\rho,\omega \rightarrow e^+e^-$) | $\alpha = 0.092 \pm 0.002$ |
| KEK | $p + A \rightarrow \phi + X$ ($\phi \rightarrow e^+e^-$) | $\alpha \sim 0.04$ |
| 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*

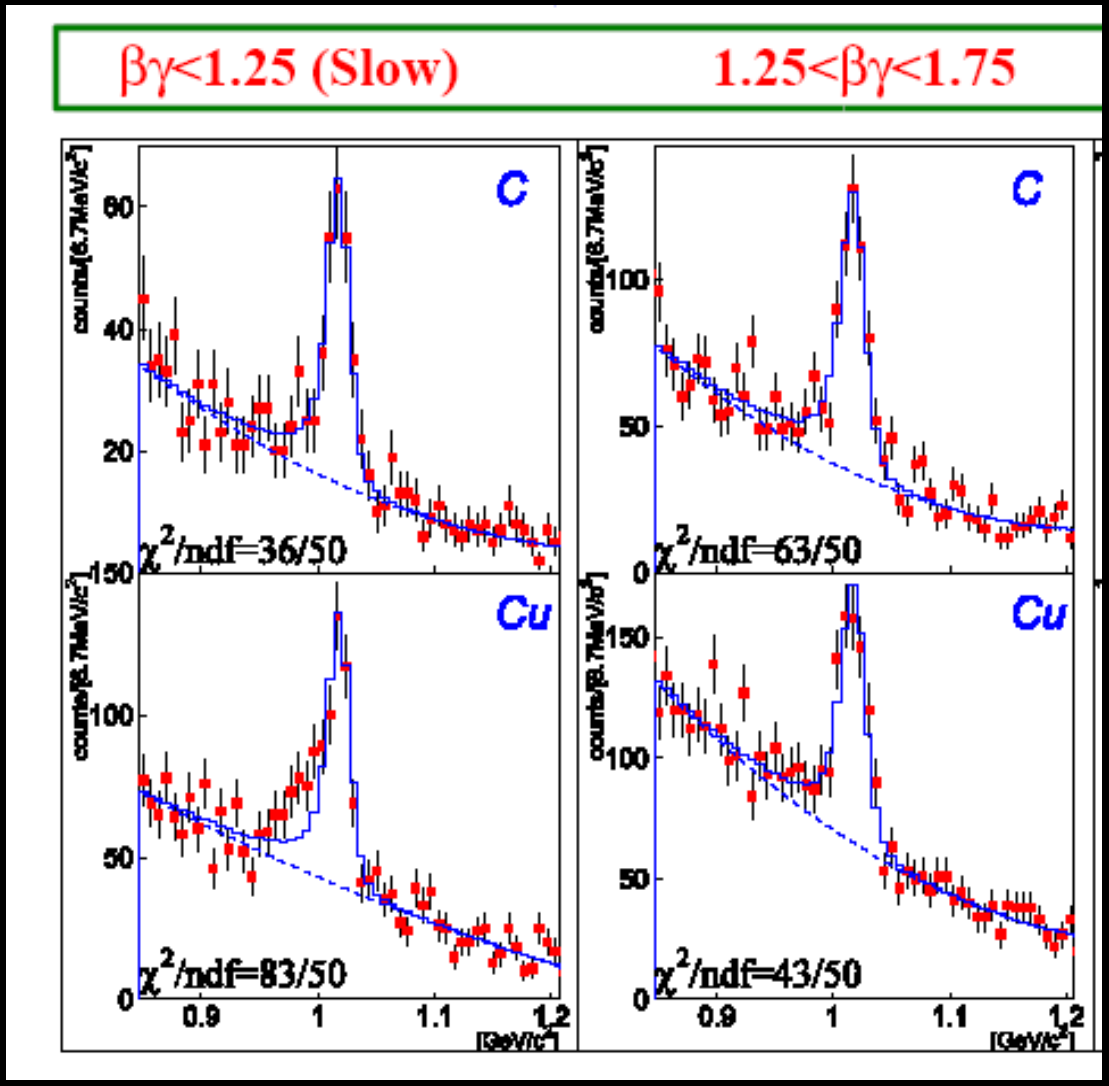



**Subtract the background and constrain the ω/ρ ratio to include ρ**
**Using a model that predicts the probability for ρ mesons decaying inside the nucleus.**

**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

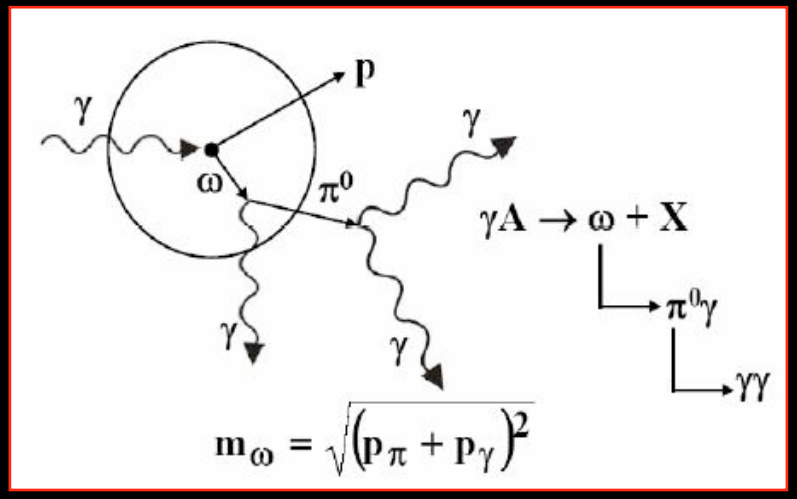
$\gamma + A \rightarrow \omega + X$ ($\omega \rightarrow \pi^0 \gamma$)

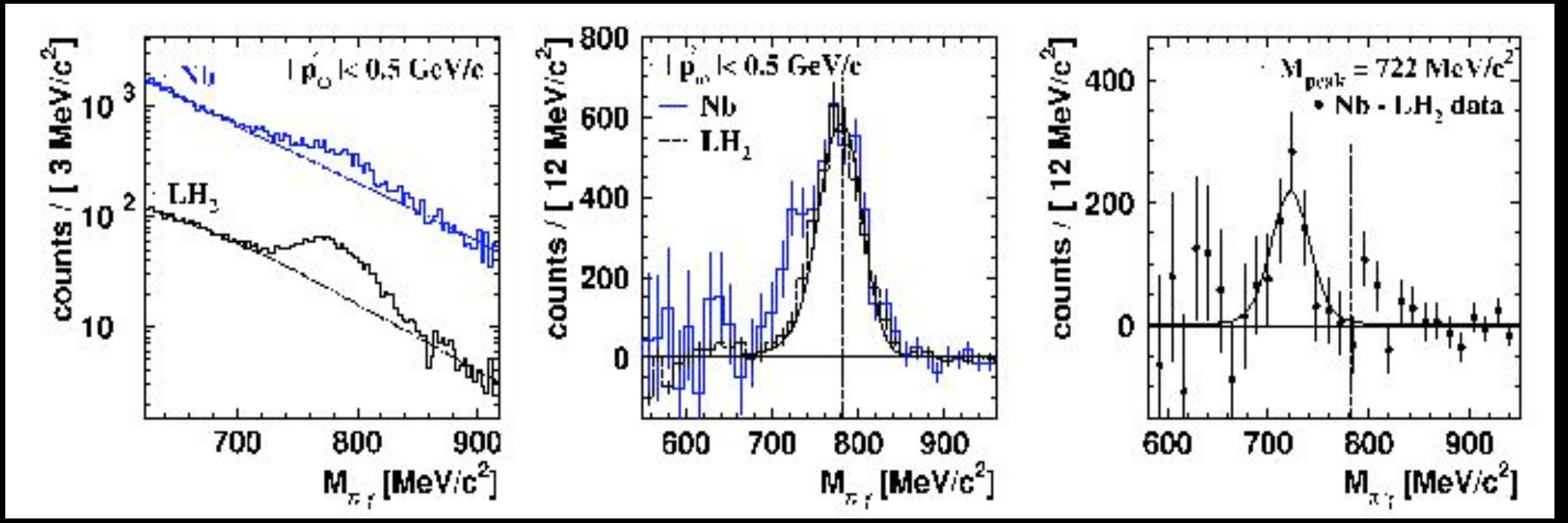
**clean ( no ρ ) channel, however FSI of π**

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$140 MeV<br>(newly published) | Broadening favored | Strong broadening |
| **Note** | **No direct extraction of ρ meson (BKGD)** | **$\pi^0$ FSI<br>Large background** | **ρ, T not constant** | **ρ, T not constant** |

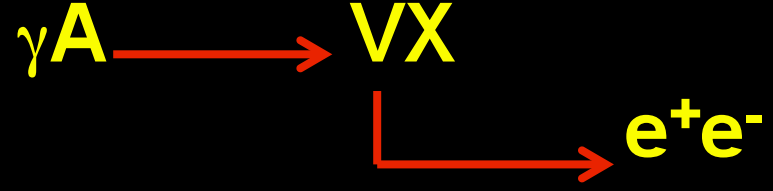
R. Muto et al., *PRL 98 (2007)*

*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"

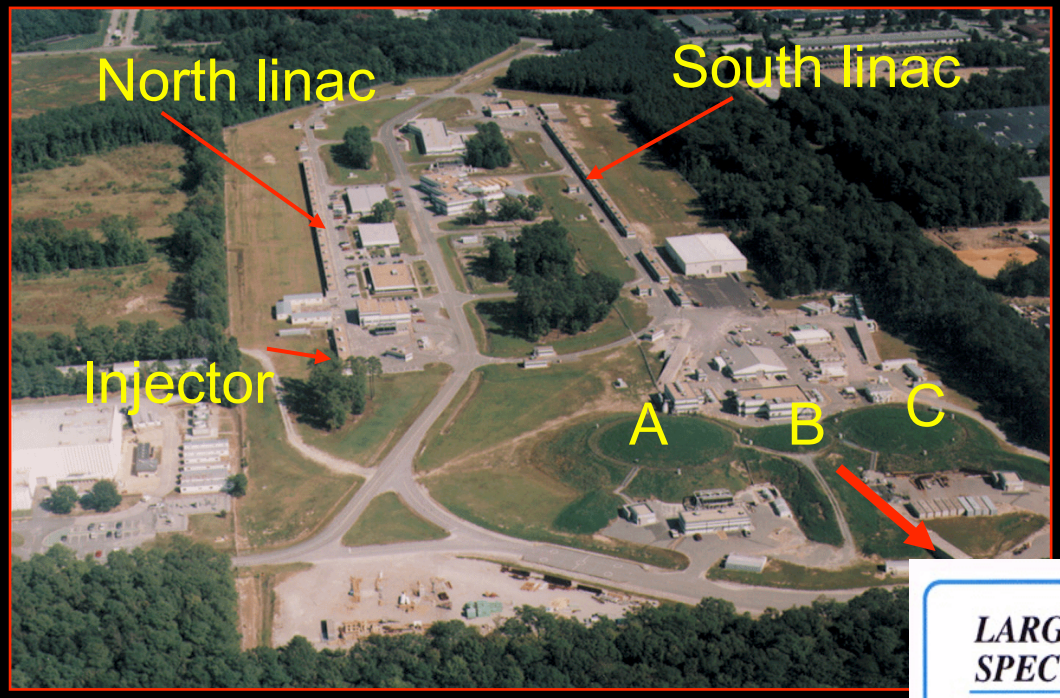



- **Original idea:**
  P. Y. Bertin and P. A. M. Guichon, Phys Rev C42, 1133 (1990)
- **Jlab Experiment E01-112 ( also called g7)**
  Spokespersons: C. Djalali (USC), M. Kossov (ITEP),
  D. Weygand (Jlab)
- **Photon beam (minimal disturbance to initial sate) :**
  $E_\gamma$ ~ .6 to 3.8 GeV (tagged $\gamma$)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

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

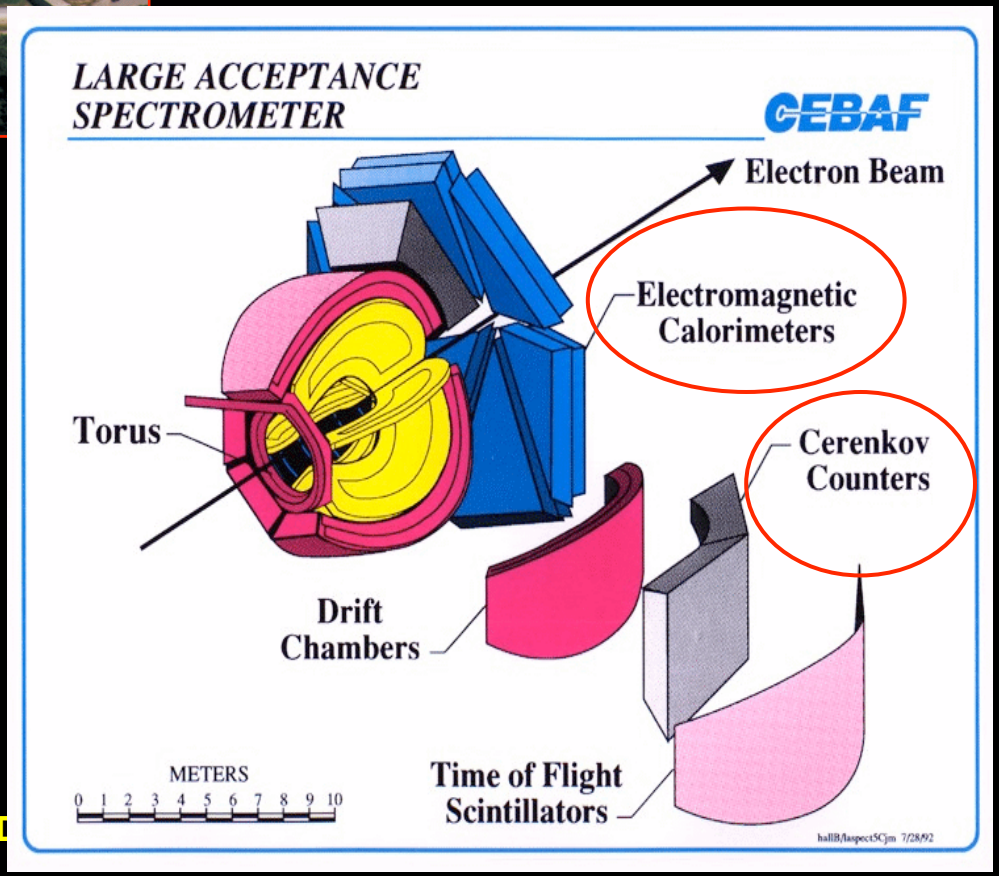
  needs high photon flux : 5 $10^7$ tagged $\gamma$/s

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




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

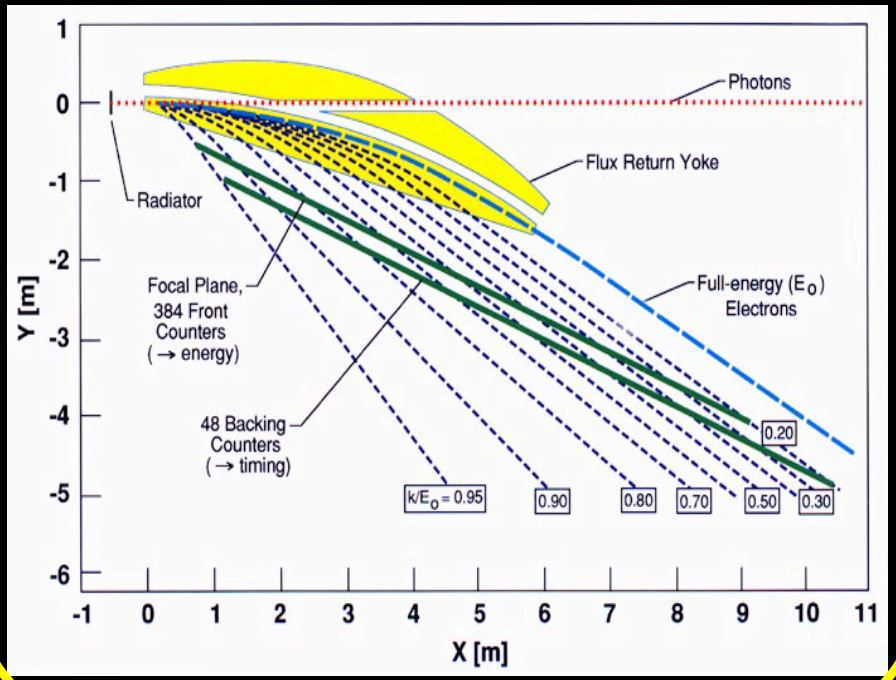
- Toroidal magnetic field (6 superconducting coils ), Drift chambers, Scintillators, Cerenkovs, Electromagnetic Calorimeter.

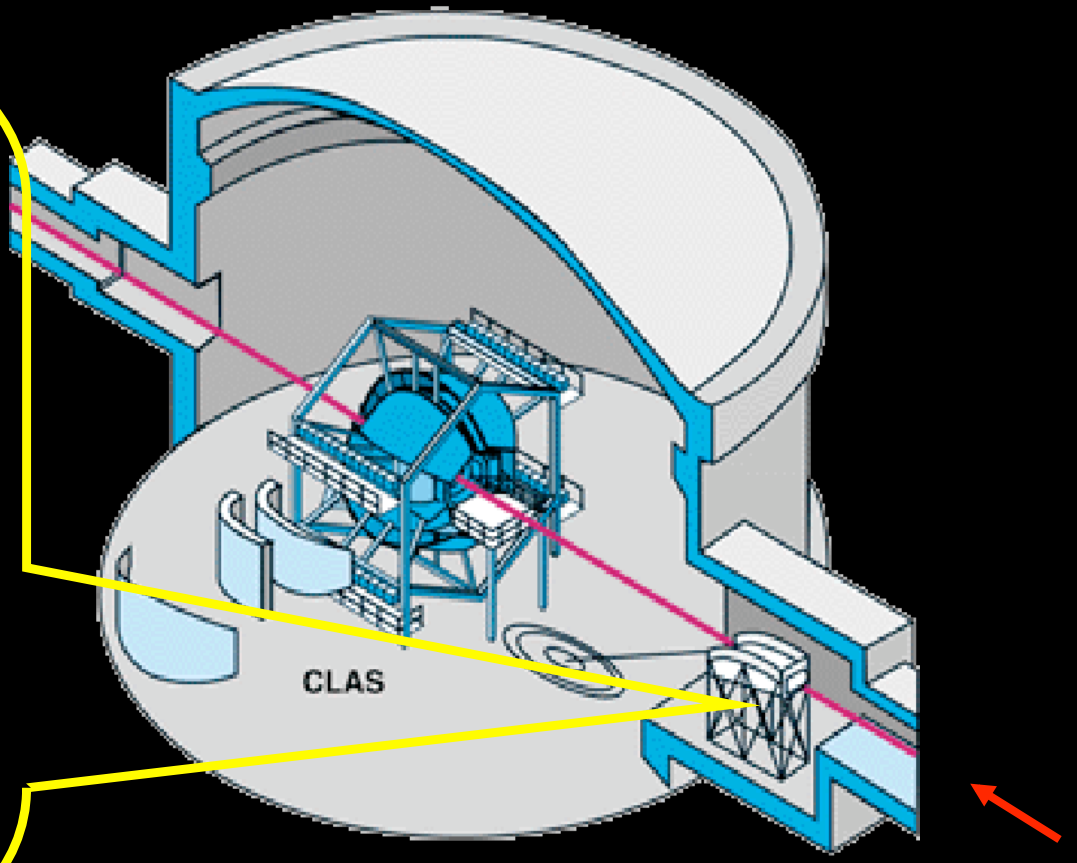


# Hall B @ Jlab ( The tagger)

3. $10^{-4}$ RL

**Photon Tagger**



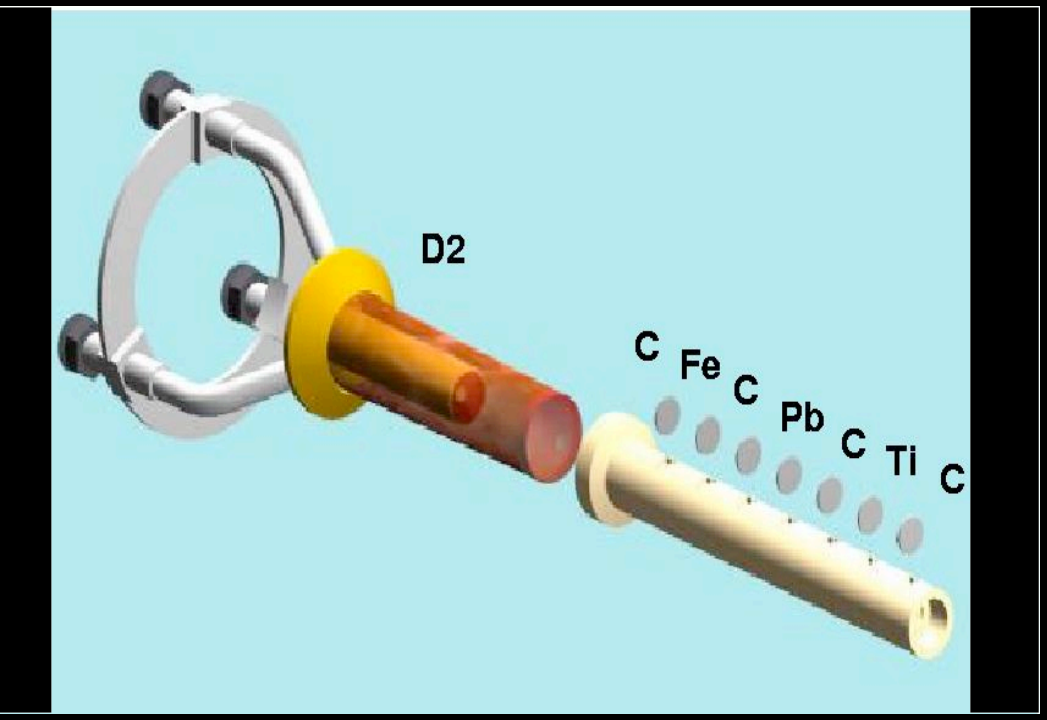



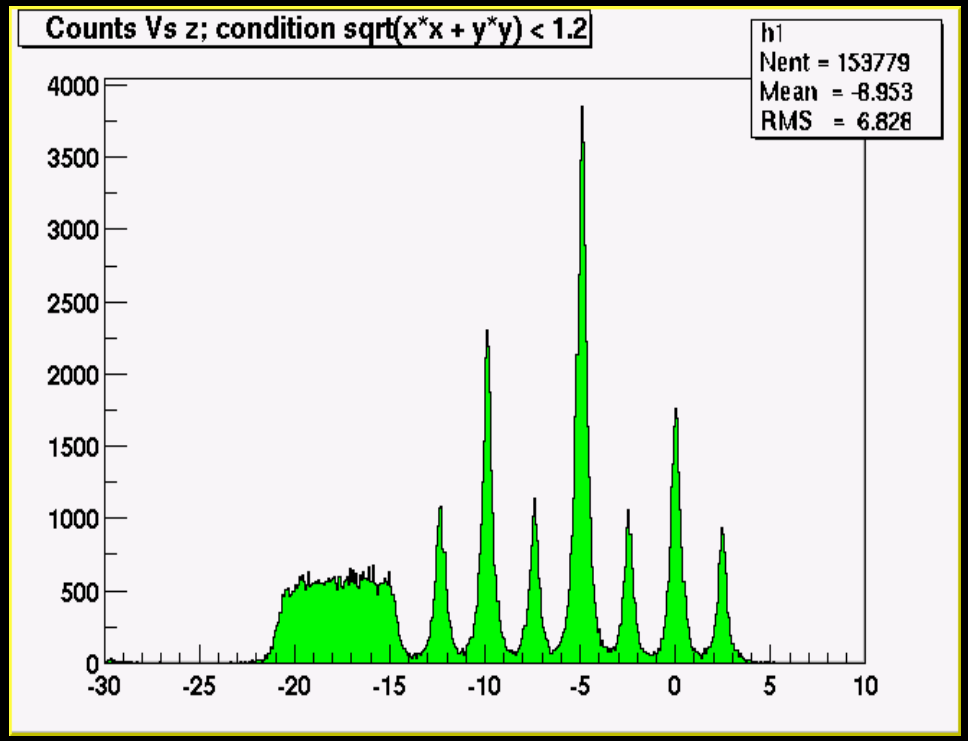

Bremsstrahlung Tagging Spectrum (20%-95%)

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

# 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

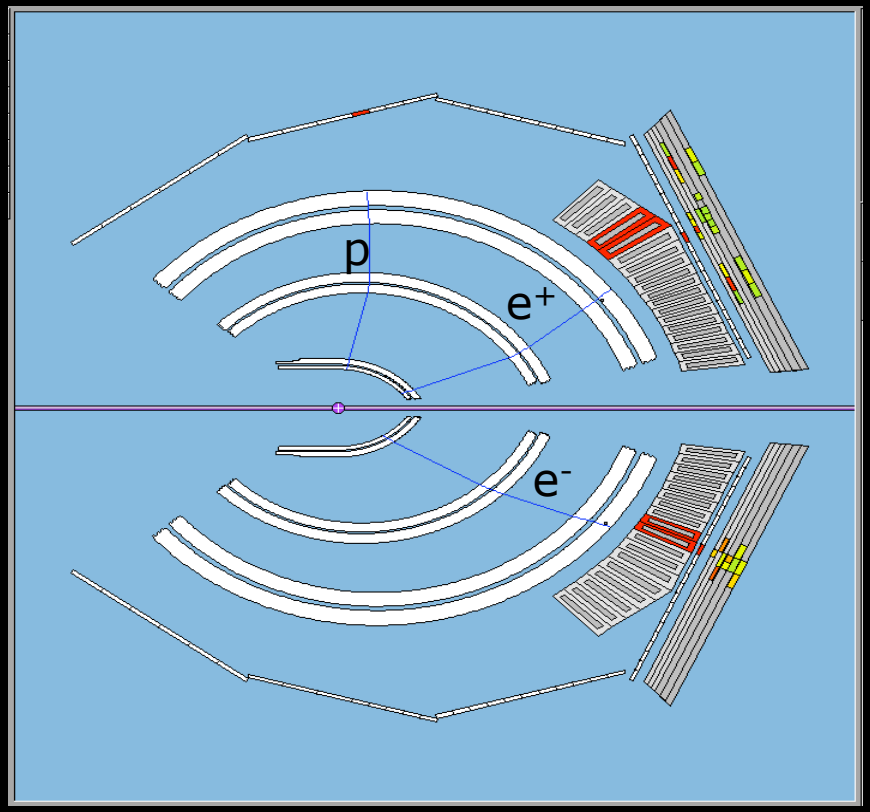


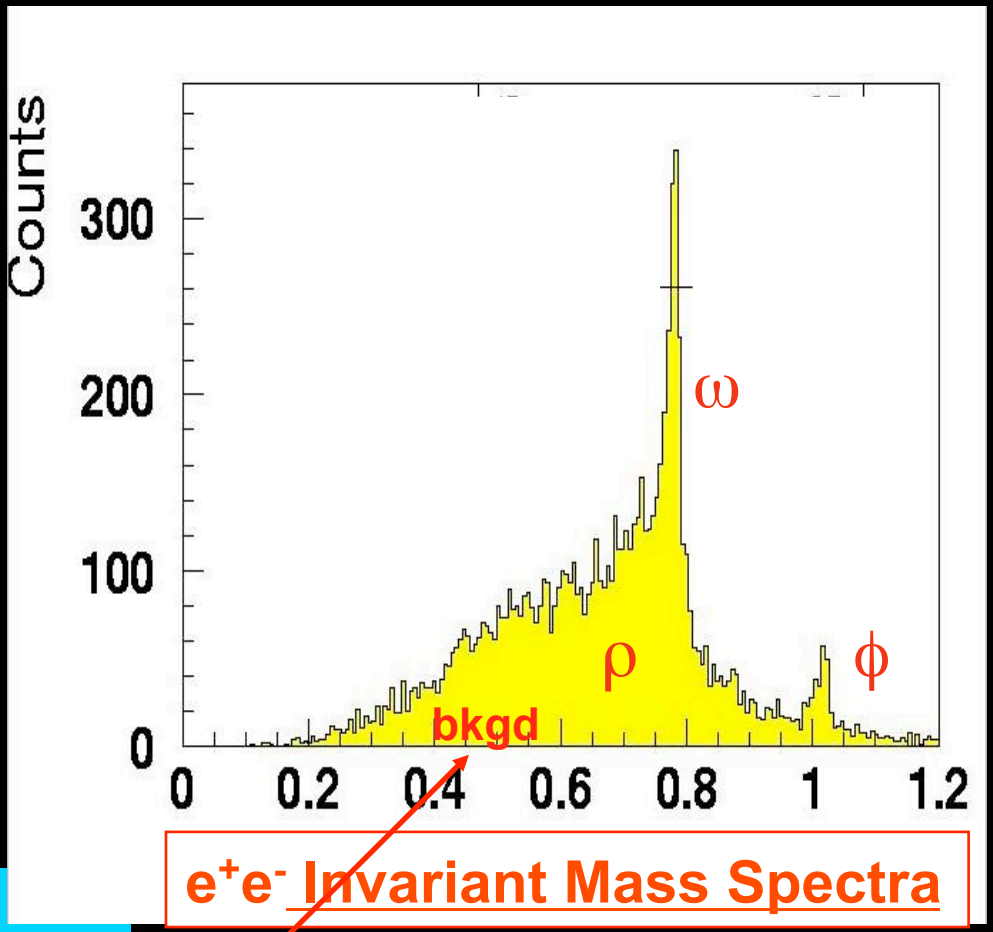




- Proper spacing 2.5 cm to reduce multiple scattering
- Deuterium target as reference, small nucleus, no modification is expected.

# 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 (Giessen BUU) (Nucl. Phys. A671, 503 (2000)) including various decay channels and nuclear effects, and CLAS detector.

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

→ **GiBUU Code**

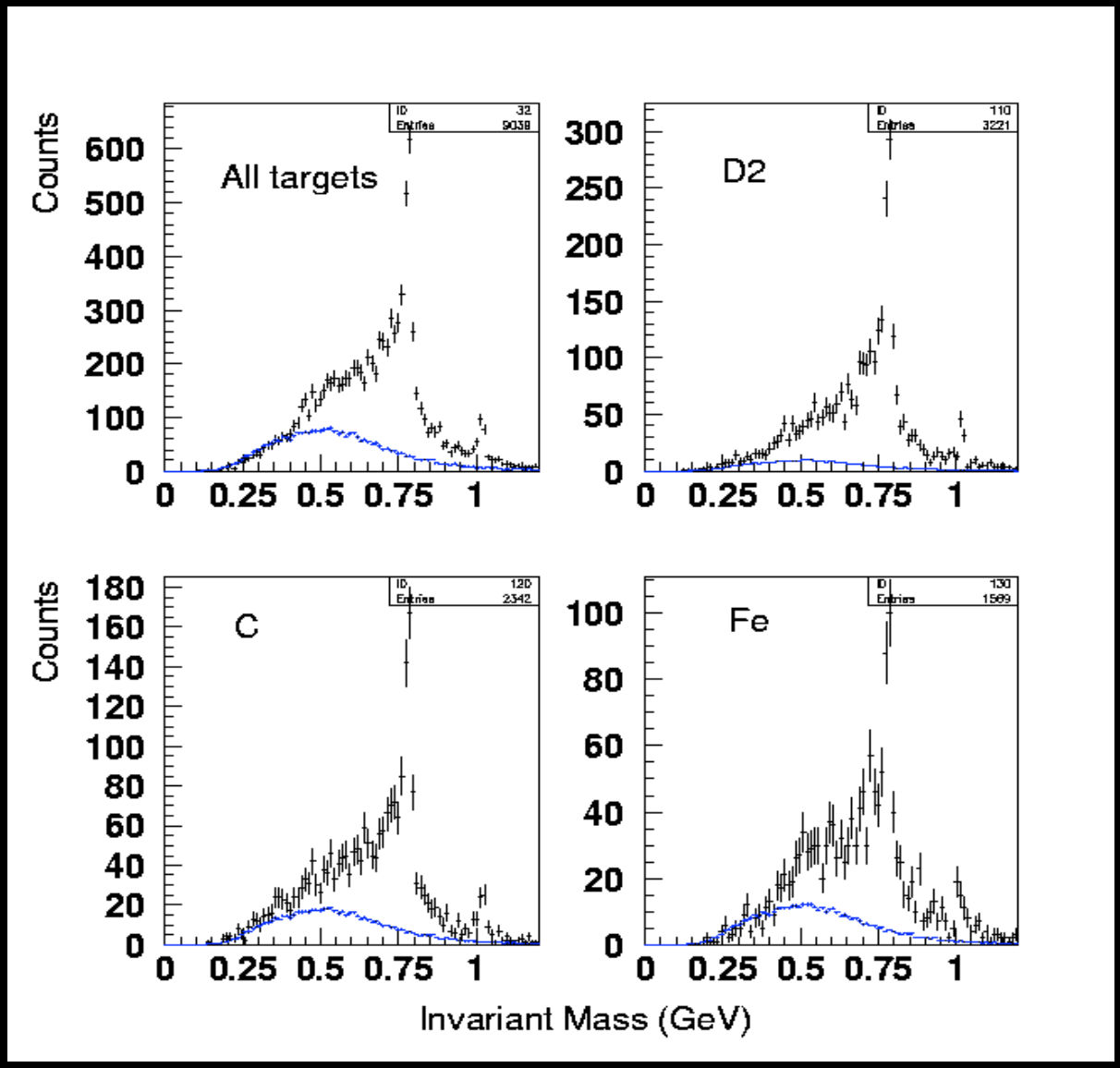
**"Semi-correlated":**

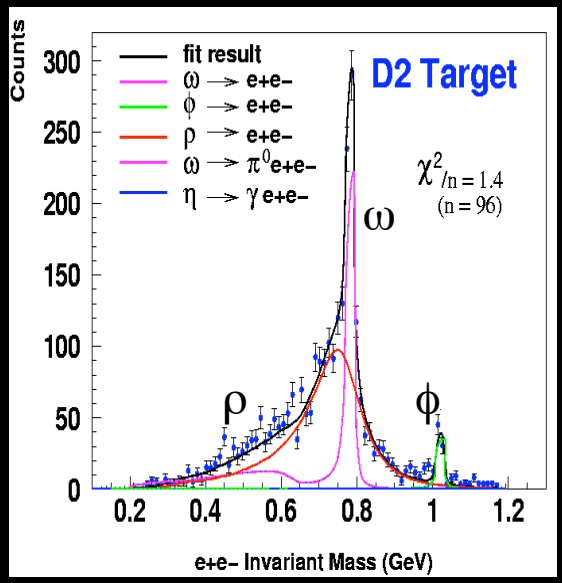
- Bethe-Heitler — calculated by Mosel's group → negligible
- $\gamma A \rightarrow \pi^0 \pi^0 X \rightarrow \gamma\, e^+e^-\, \gamma\, e^+e^-$ — 2 $\pi^0$ Dalitz decay mixed → negligible
- $\pi^0 \rightarrow e^+e^-\, e^+e^-$ — double Dalitz → low mass

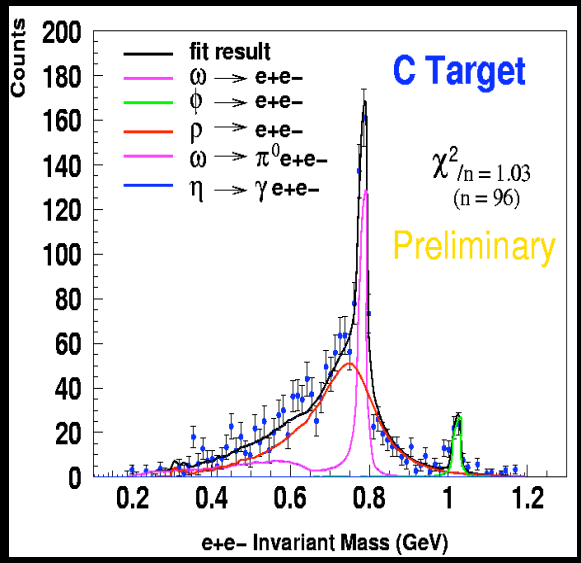
**Uncorrelated:**

- 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)



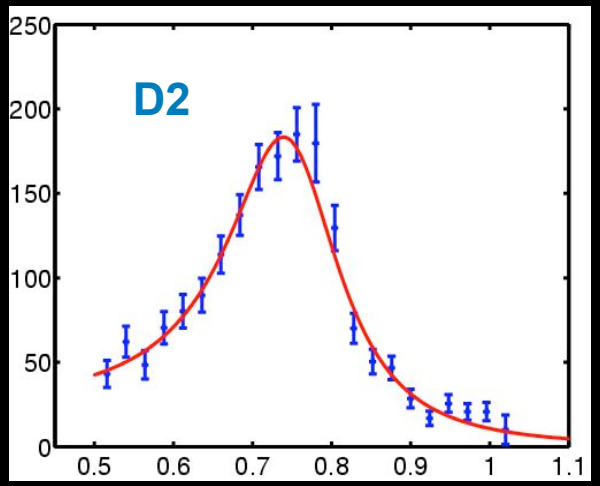



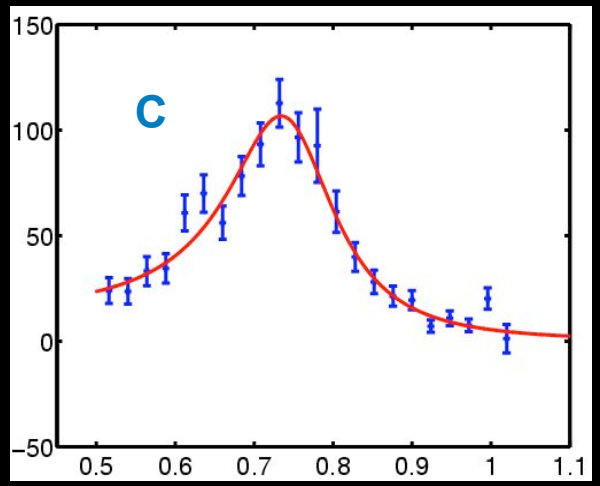



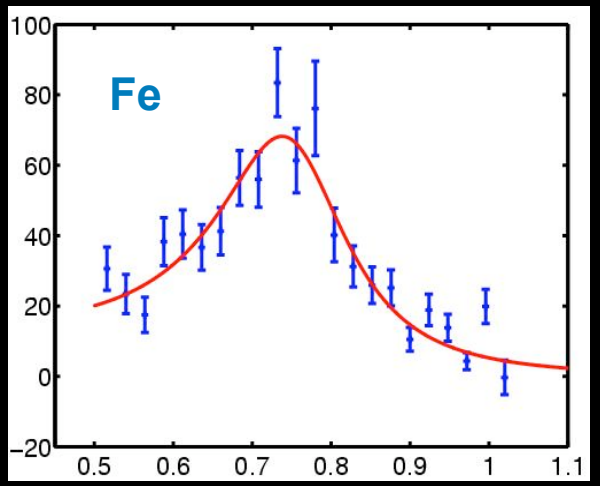

μ+μ− measurement: at CERN-SPS ***IPNO-DR-02.015 (2002)***
π+π− measurement: at CERN-ISR ***(Nucl. Phys. B124 (1977) 1-11).***
**e+e-** measurement: at RHIC ***(Nucl.Phys. A774 (2006) 743-746)***.

# The ρ Mass Spectra

After removing the ω, ϕ, and background contributions:



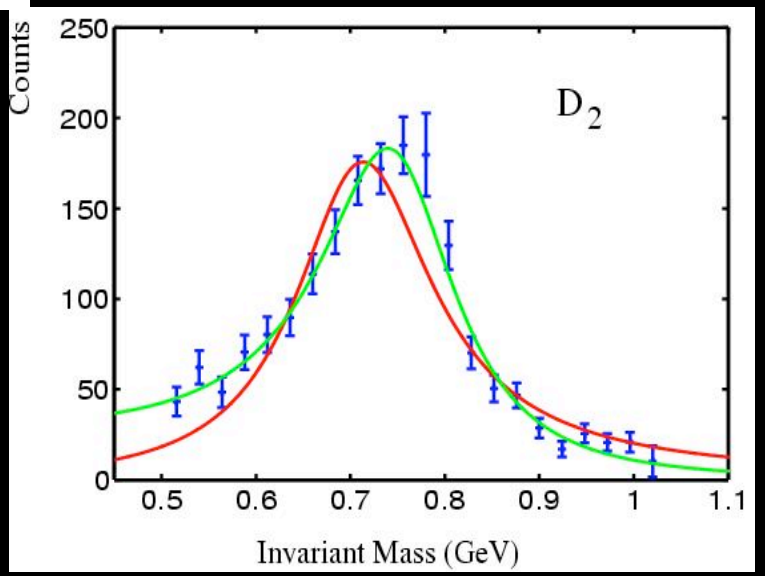

$e^+e^-$ Invariant Mass (GeV)

## Fit function:

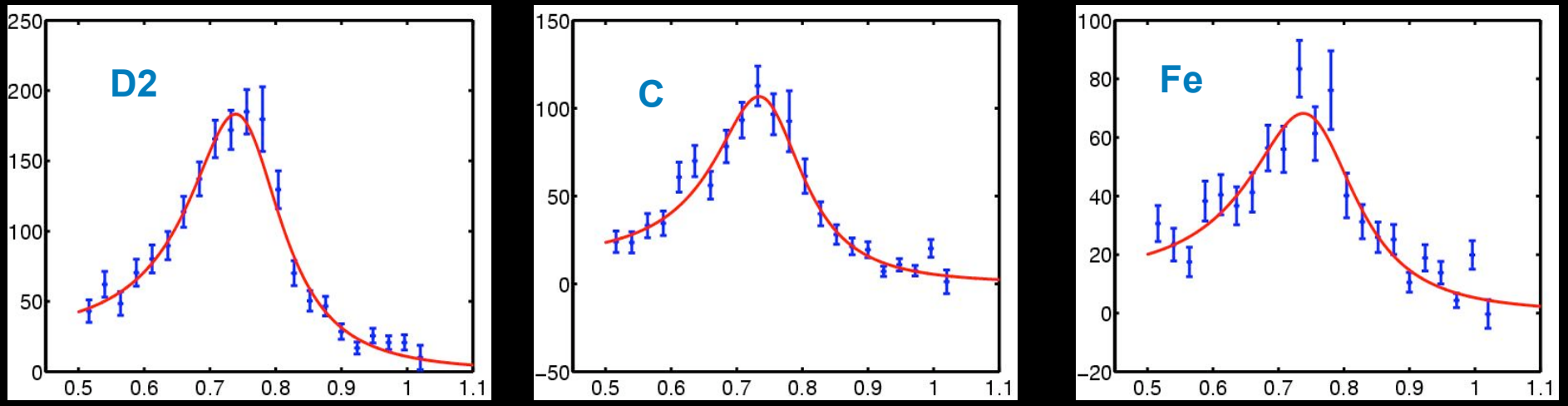
$$\text{(Breit – Wigner)} \times \frac{1}{M^4} \times M = \frac{\text{(Breit – Wigner)}}{M^3}$$

Photon propagator

Breakup momentum phase space



# The ρ Mass Spectra




| 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 ($\alpha$ =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.

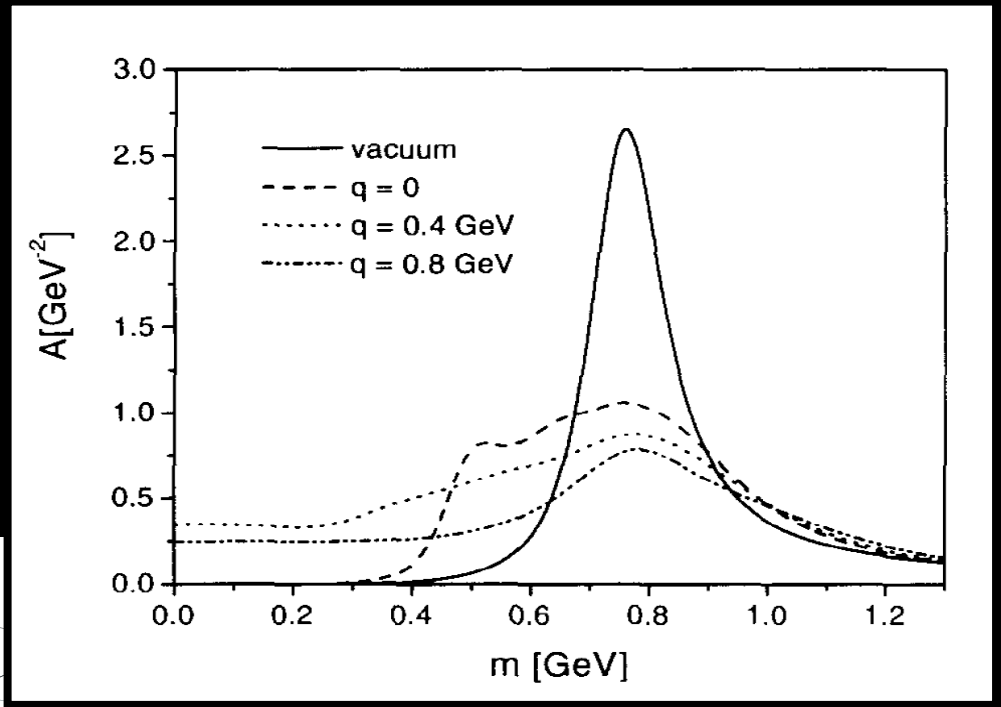
•PRL published – **R. Nasseripour *et al.*, PRL 99 (2007) 262302**
•PRC article submitted March 2008. **arXiv:0803.0492v1 [nucl-ex]**

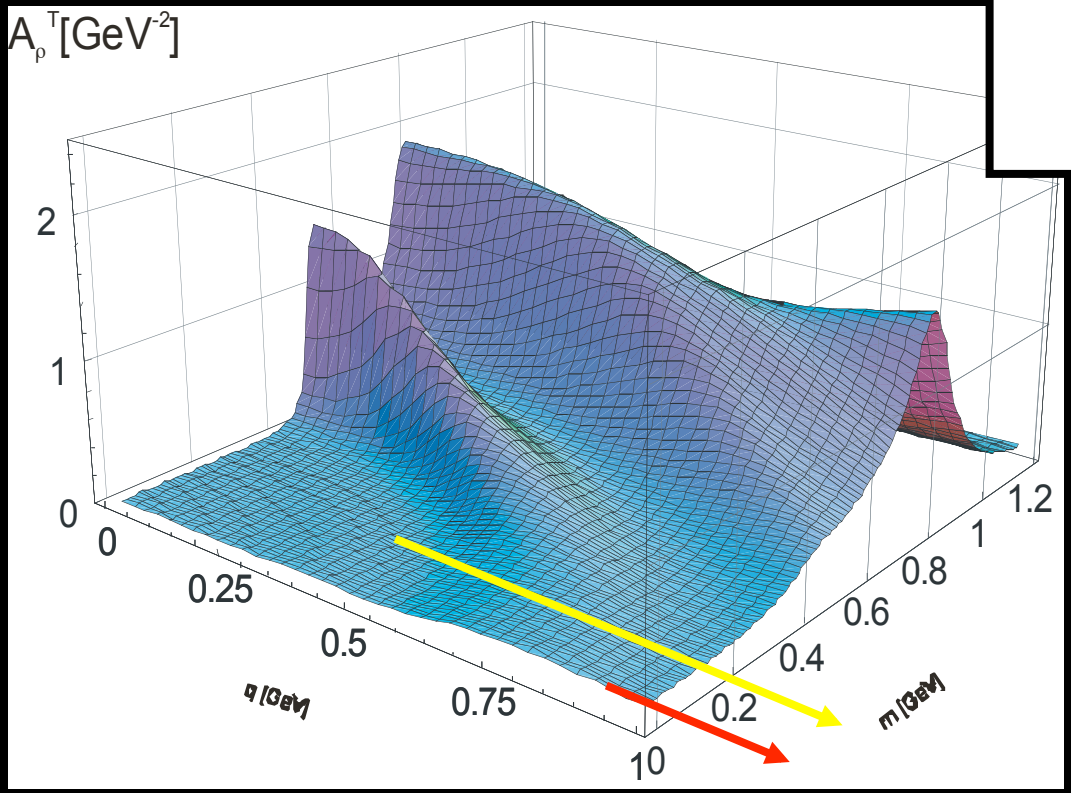
# Momentum dependence – ρ meson

## 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.



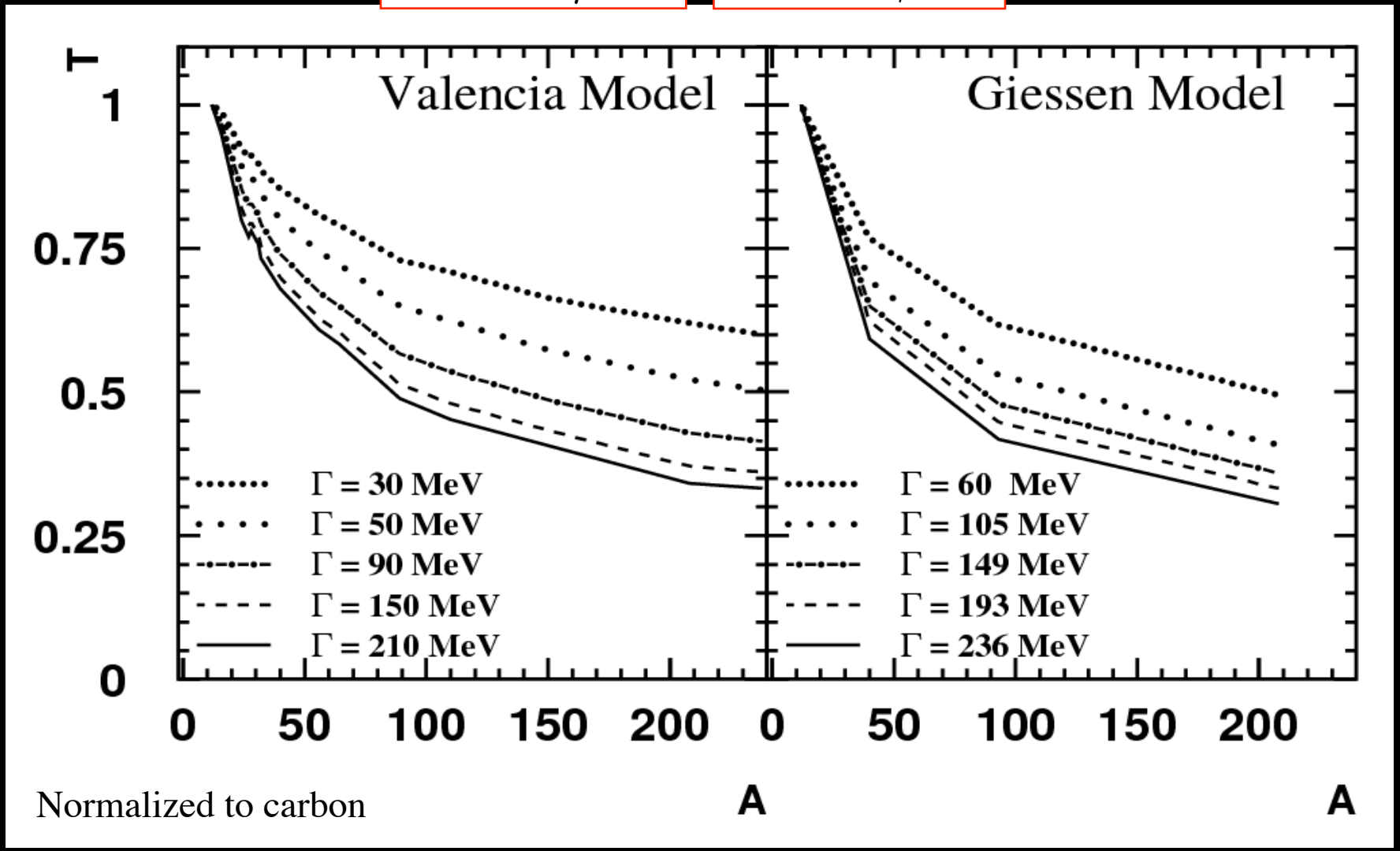

**g7a**

**Planned g7b**
**Conditionally approved**

# Absorption of ω Meson and its In-medium width

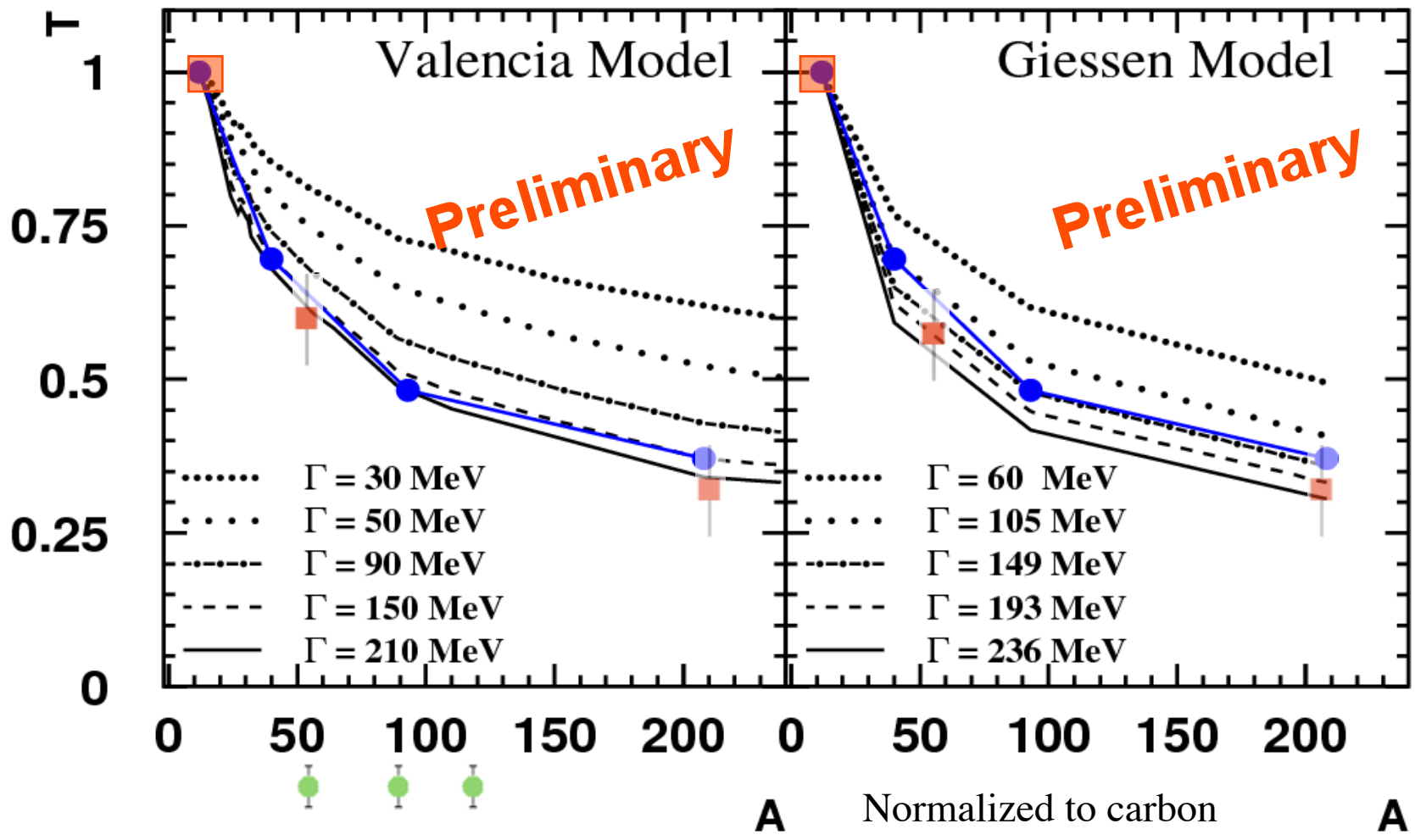
**The in-medium width is $\Gamma=\Gamma_0+\Gamma_{coll}$ where $\Gamma_{coll} = \gamma\rho v\sigma^*_{VN}$**

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




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

# Comparison to Theory – ω Meson



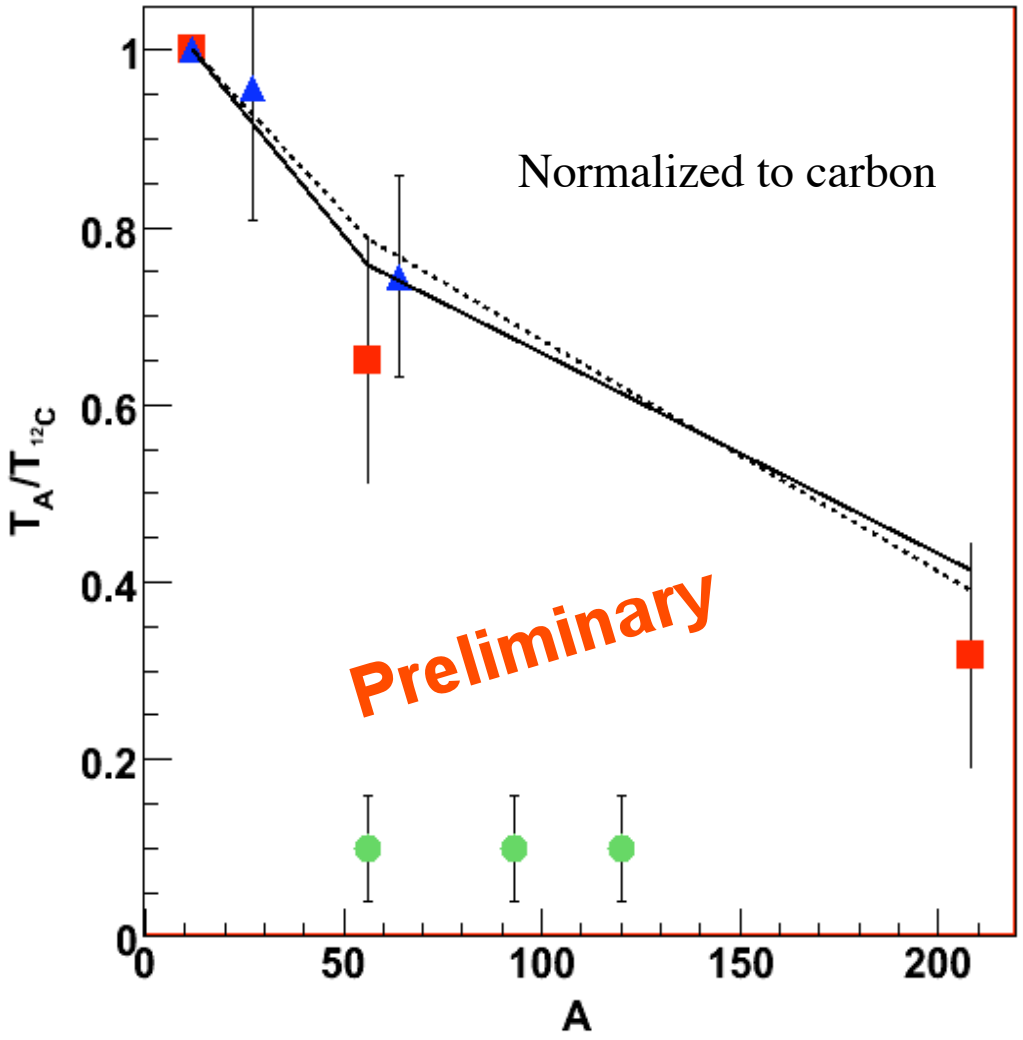

**Preliminary g7a result showed greater absorption than TAPS!!!**

**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. – $\phi$ Meson

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



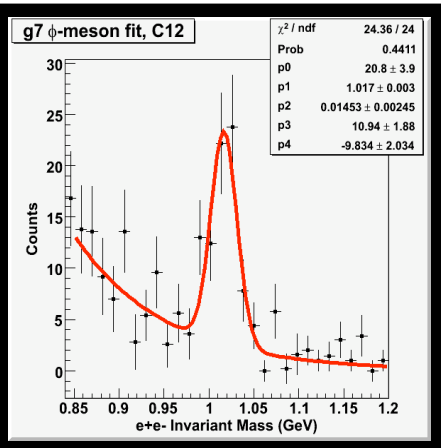

Giessen calculations

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 $\rho$, $\omega$ 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 $H_2$ ( Currently running with g12)
- 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.