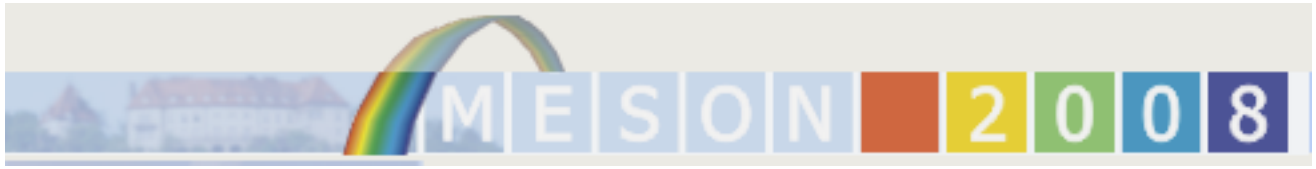


10th International Workshop on Meson Production, Properties and Interaction
KRAKÓW, POLAND 6 - 10 June 2008

Medium modifications of light vector mesons in photoproduction reactions at JLab

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

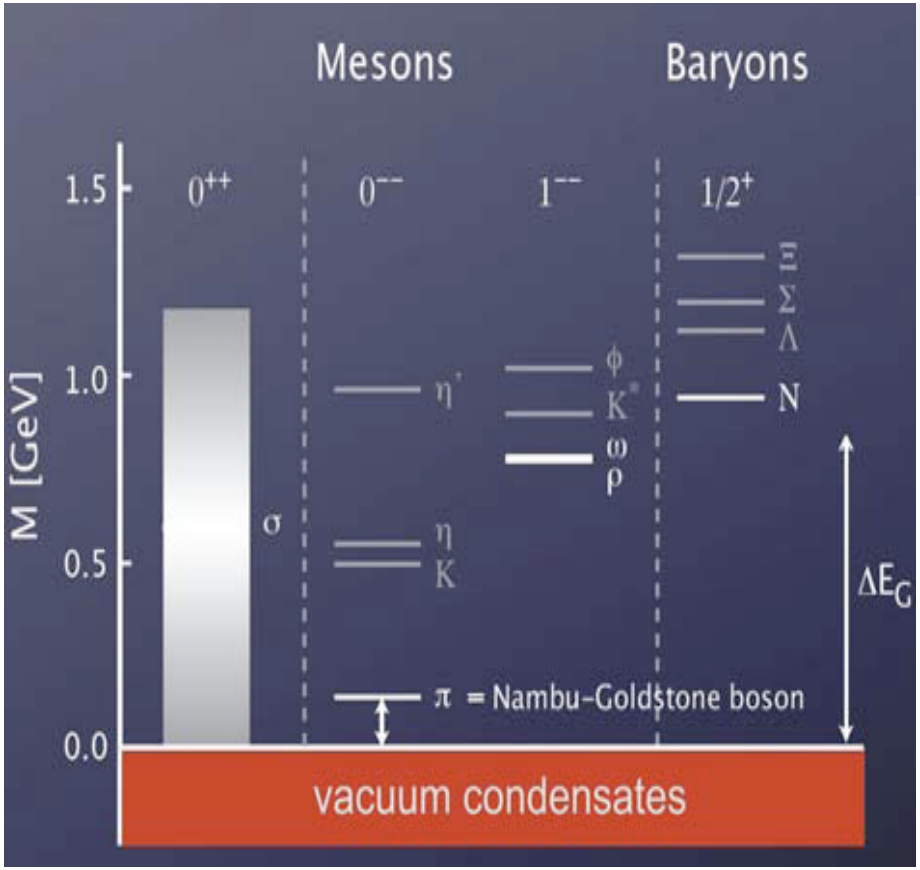
University of South Carolina

Outline

- Physics Motivations
  - 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 on Medium Modifications
- [ϕ photo-production on the nucleon]

➢ **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

Bernard and Meissner, NPA 489 (1988) 647

Scale invariance in effective Lagrangian:

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

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

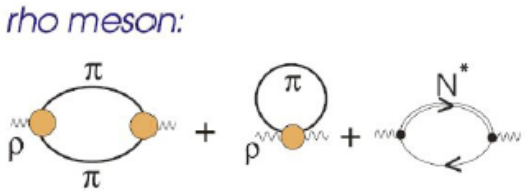
QCD sumrules:

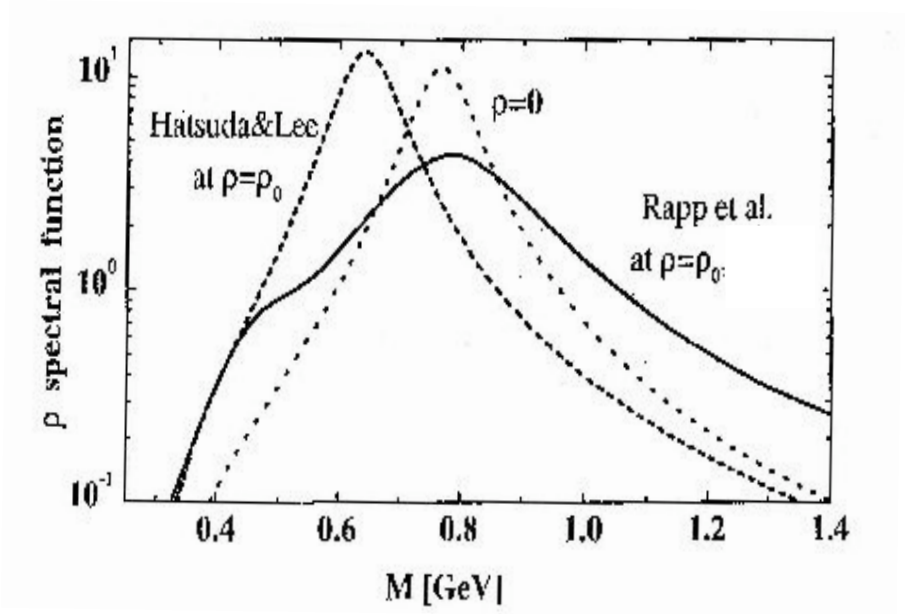
T. Hatsuda and S. Lee *Phys. Rev. C46 (1992) R34*

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

Many body effects:

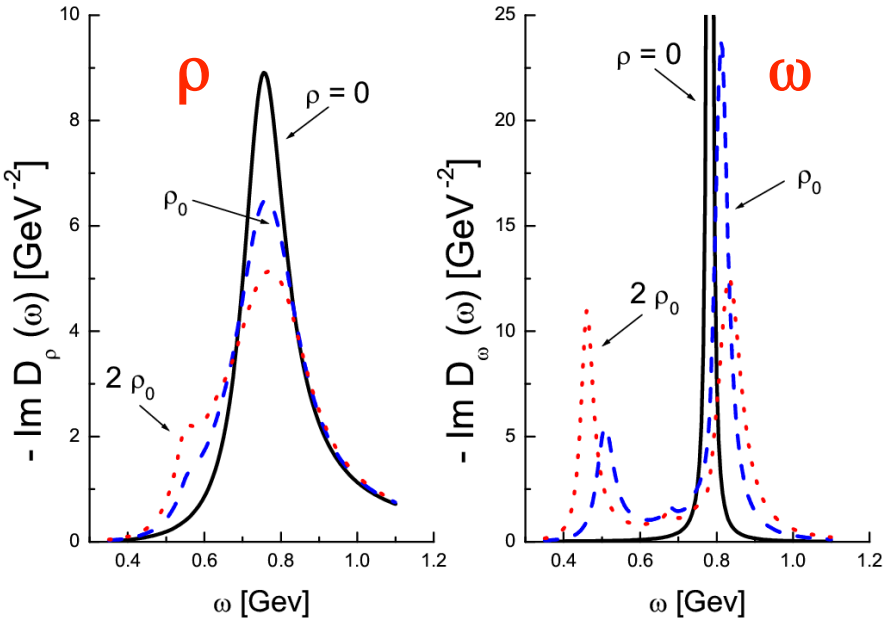
B Friman, H.J. Pirner,
Nucl Phys. A617 (1997) 496
R. Rapp, G. Chanfray, J Wambach,
Nucl Phys. A617 (1997) 472



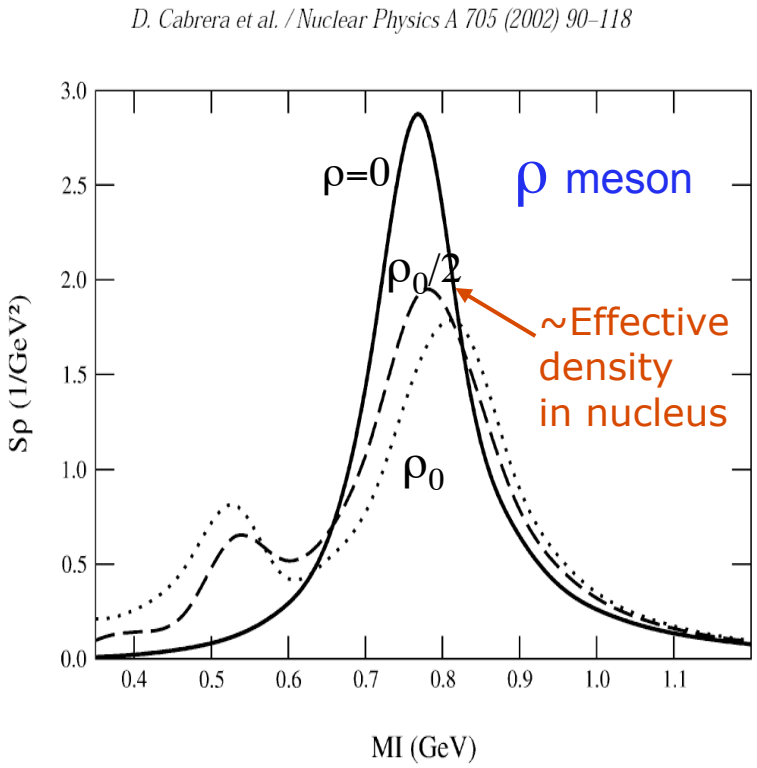


Model predictions of the in medium properties of vector mesons

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



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



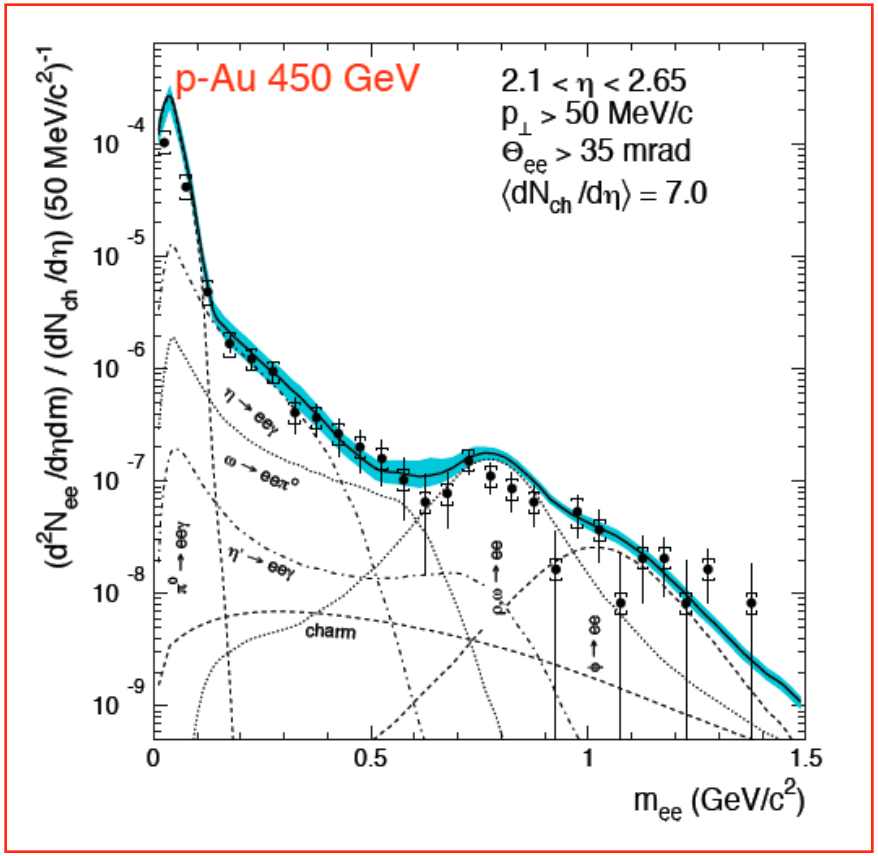
Coupling to baryon resonances

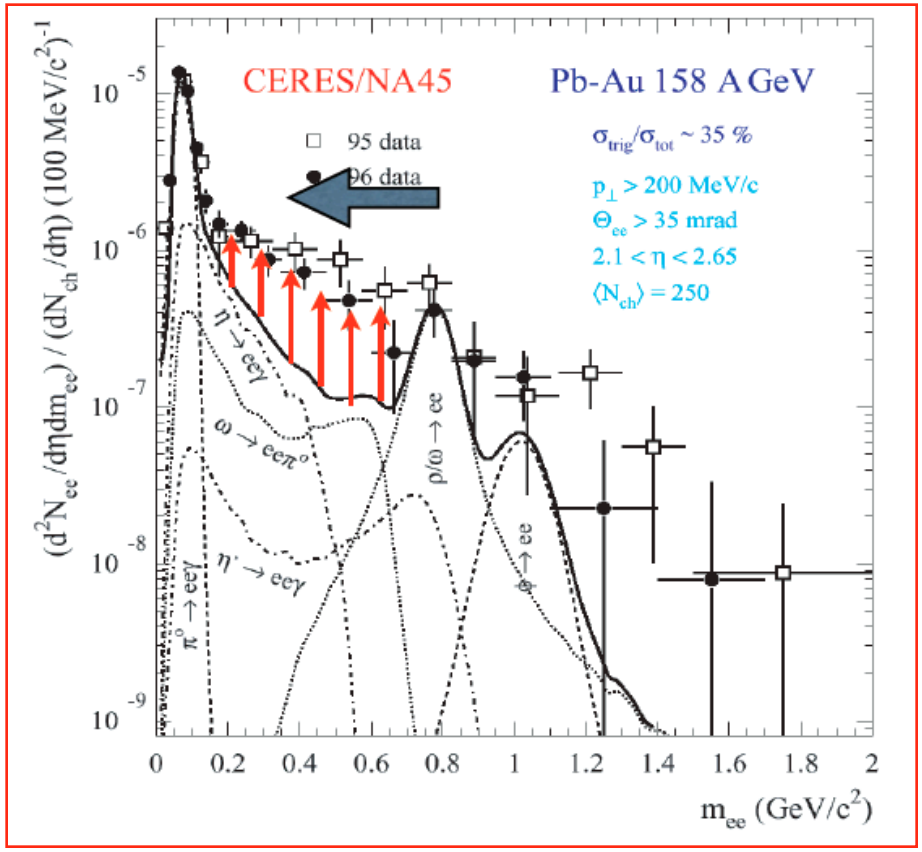
Any observations??

In RHI collisions (nuclear matter under extreme conditions)

First hint in e^+e^- measurements CERES/NA45

D. Adamová *et al.*,
arXiv:nucl-ex/0611022

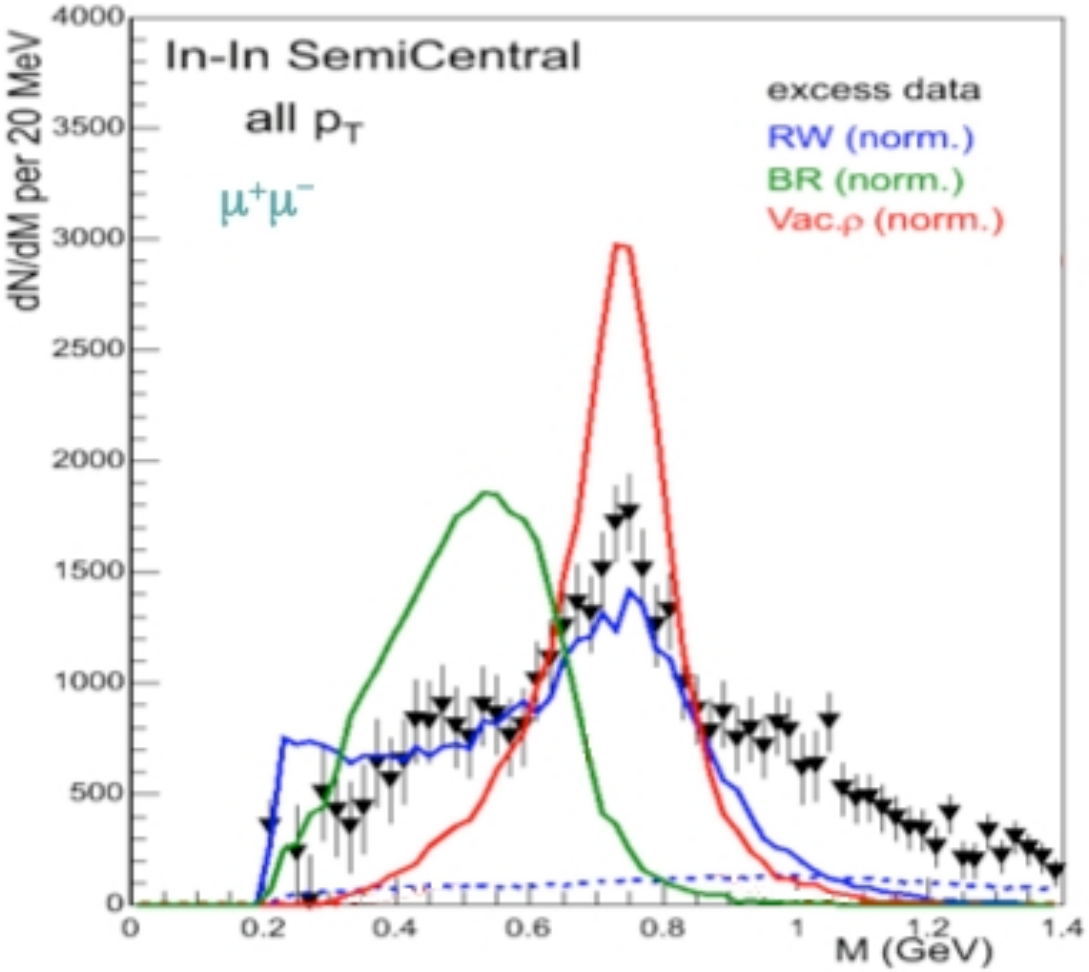




p+Au understood in terms of p+p superposition

- **Large excess observed in Pb+Au below 0.7 Gev/c²**
- **Recent analysis favors Γ↗ ; no Δm**

NA60: R Arnaldi *et al.*, *Phys. Rev. Lett.* 96, 162302 (2006).



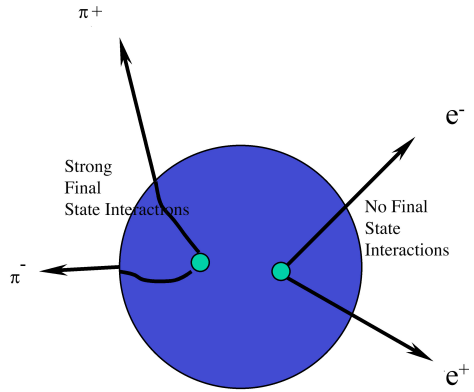
Clear excess of dileptons observed. Γ ↗ , no ΔM

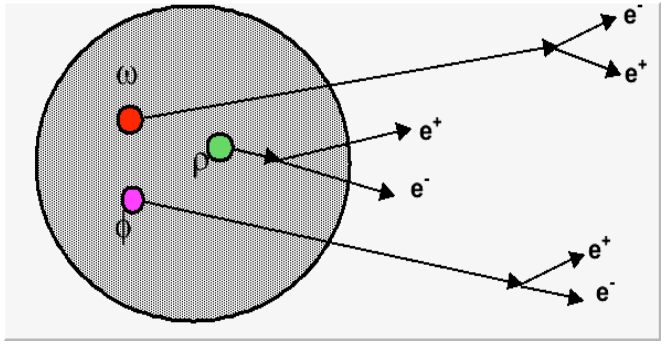
Medium modification of vector mesons properties in nuclei

The predicted medium modifications are large enough that even at normal nuclear density, one can expect to observe them, 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

"Elementary reactions" (not exhaustive list):

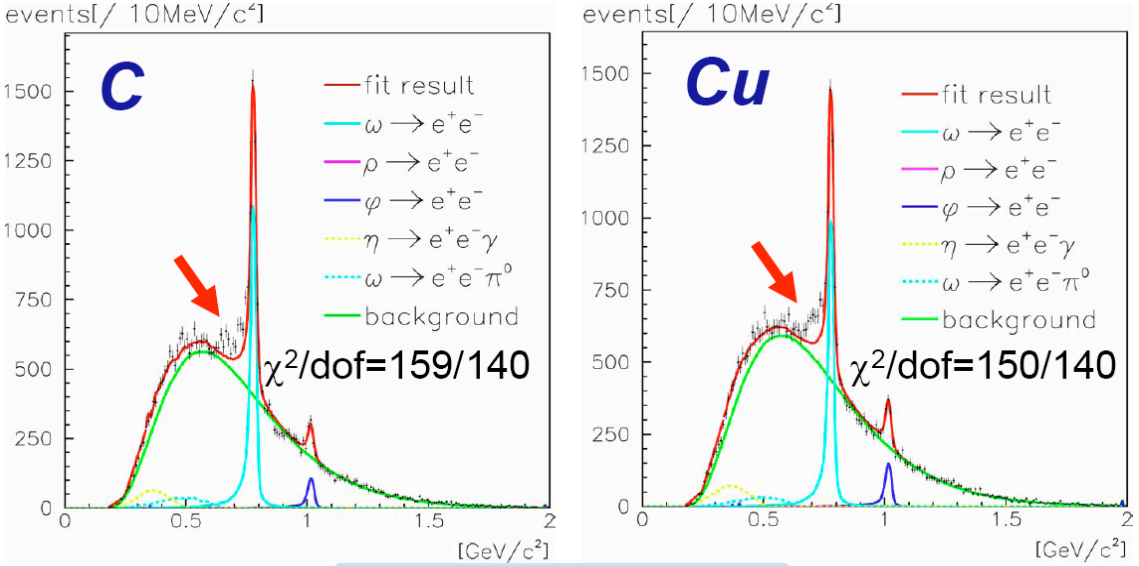
Experiment	*Reactions*	*Results*
TAGX	$\gamma + {}^3He \rightarrow \rho + X$ ($\rho \rightarrow \pi^+\pi^-$)	full BR, $\alpha \sim 0.06$
KEK	$p+A \rightarrow \rho,\omega,\phi + X$ ($\rho,\omega \rightarrow e^+e^-$)	$\alpha = 0.092 \pm 0.002$
KEK	$p+A \rightarrow \phi + X$ ($\phi \rightarrow e^+e^-$)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

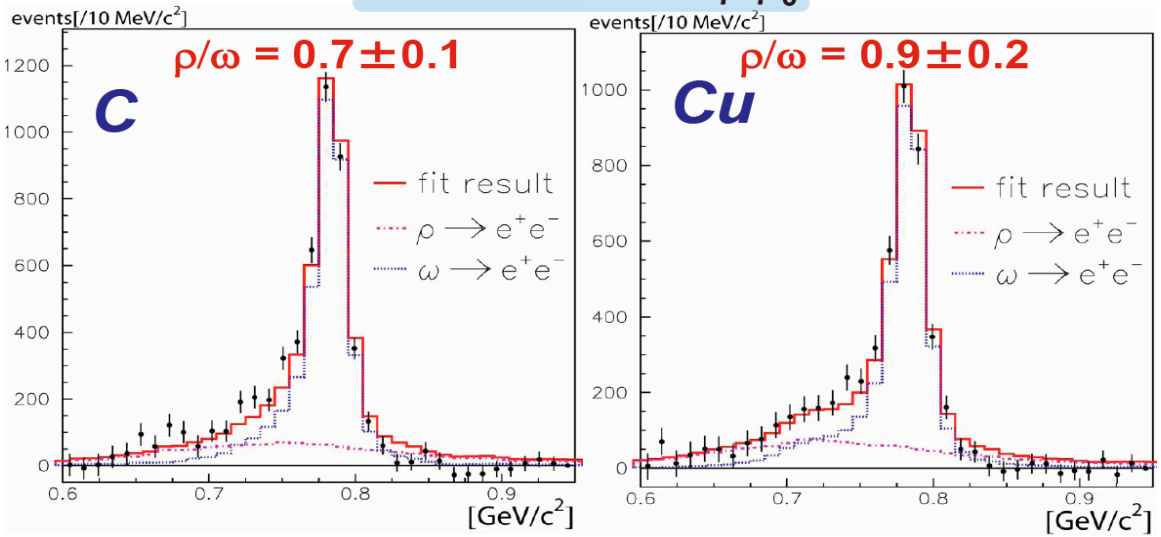
KEK-PS E325 (ρ, ω)

p+A → ρ,ω,ϕ+X (ρ,ω,ϕ → e+e-)

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



m*/m = 1 - 0.092 ρ/ρ₀

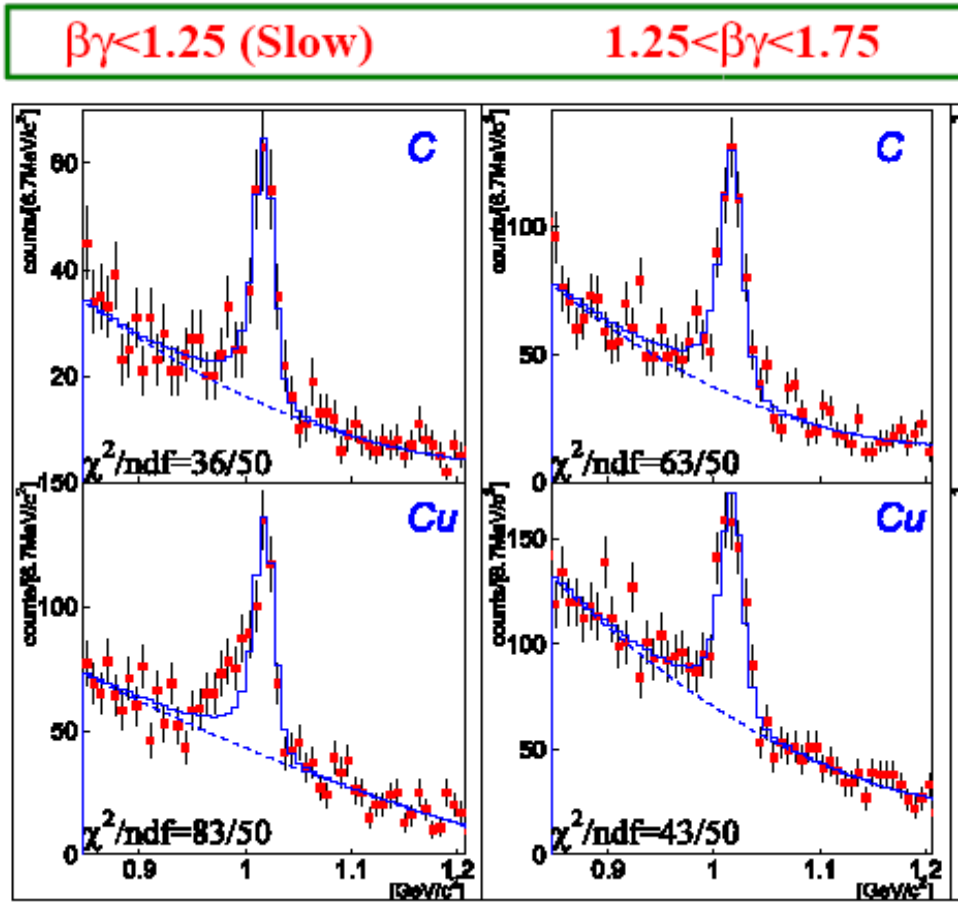


Subtract the background and constrain the ω/ρ ratio to include ρ
Using a model that predicts the probability for ρ mesons decaying inside the nucleus.

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

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	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**
	M. Naruki et al, PRL96 (2006) R. Muto et al.,*PRL98(2007)*	D. Trnka et al., PRL 94 (2005) M. Kotulla et al,*PRL 100(2008)*	D. Adamova et al,*PRL9(2003)* arXiv:nucl-ex/0611022(2006)	R. Arnaldi et al, *PRL96 (2006)*

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

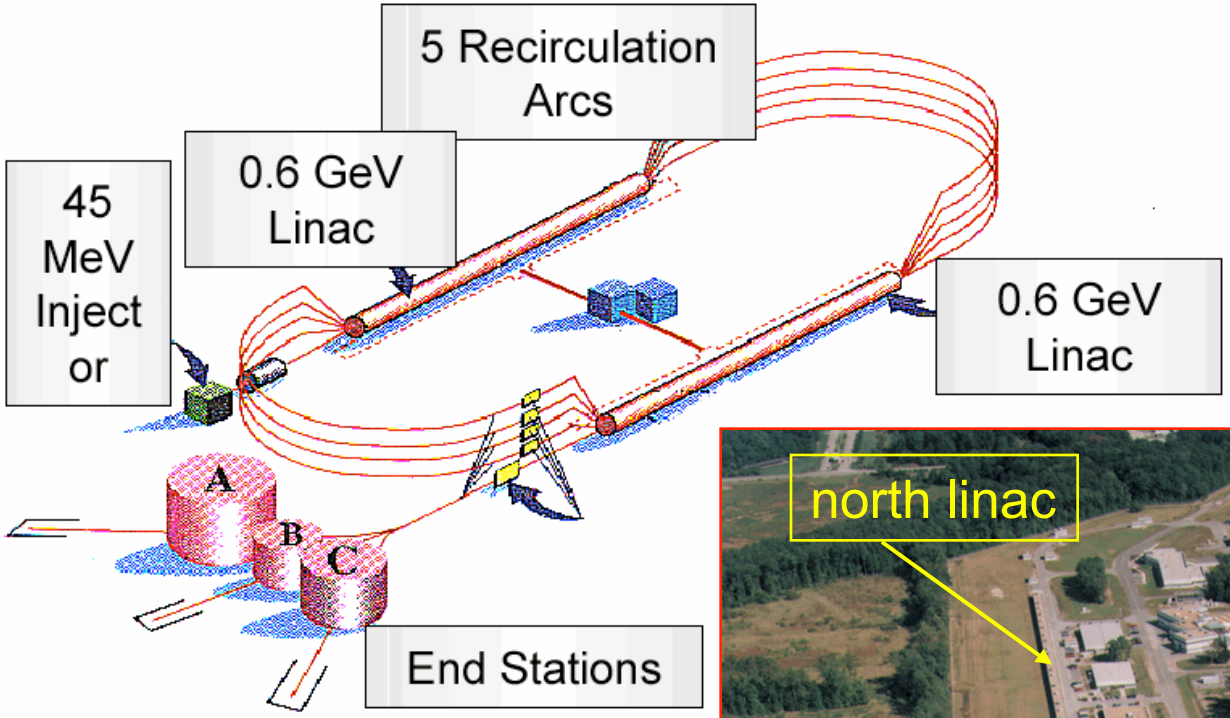
$$\gamma A \longrightarrow VX \longrightarrow e^+e^-$$

- **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!)

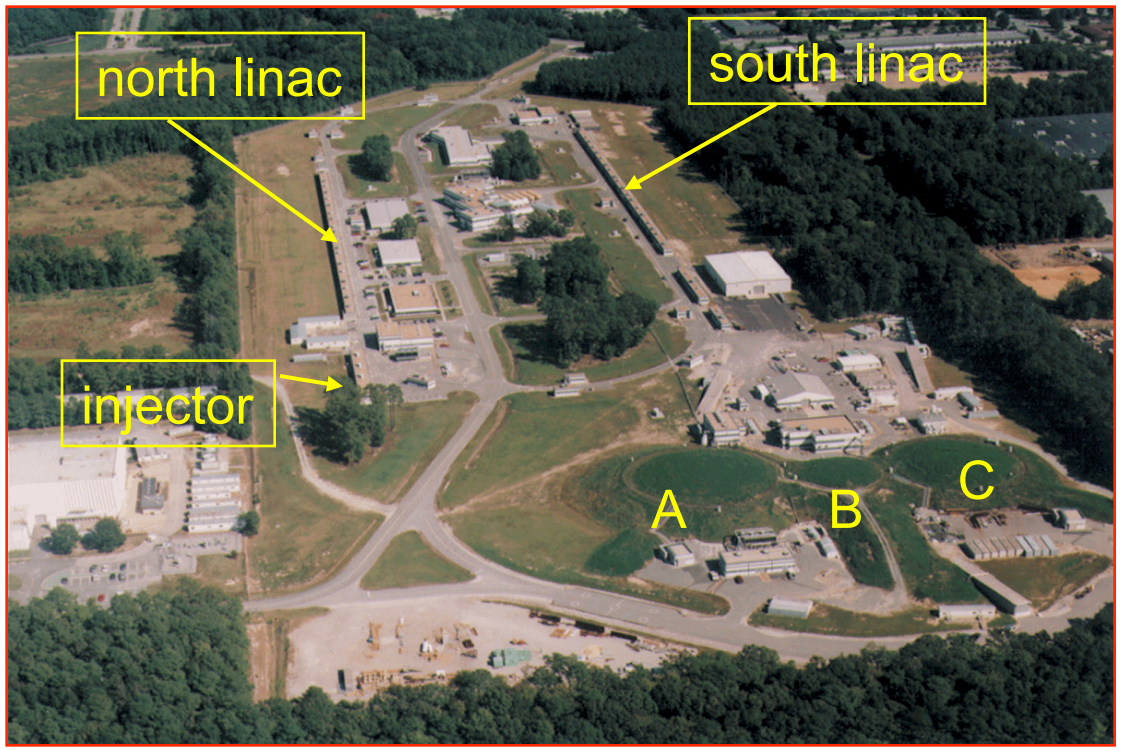
  Low branching ratio : ~5 10^{-5}

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

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



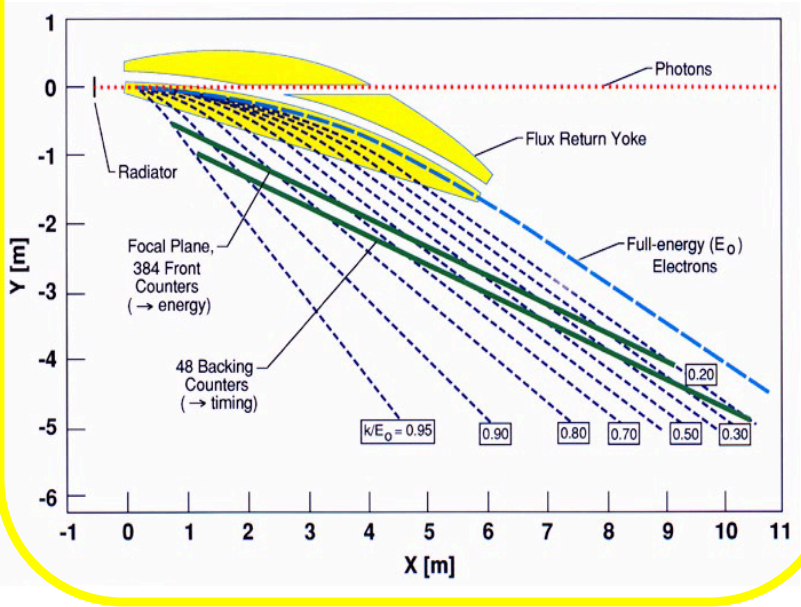
E_{max} ~ 6 GeV
I_{max} ~ 200 μA
Duty Factor ~ 100%
σ_E/E ~ $2.5\ 10^{-5}$
Beam P ~ 80%
$E_{g(tagged)}$ ~ 0.8- 5.5 GeV

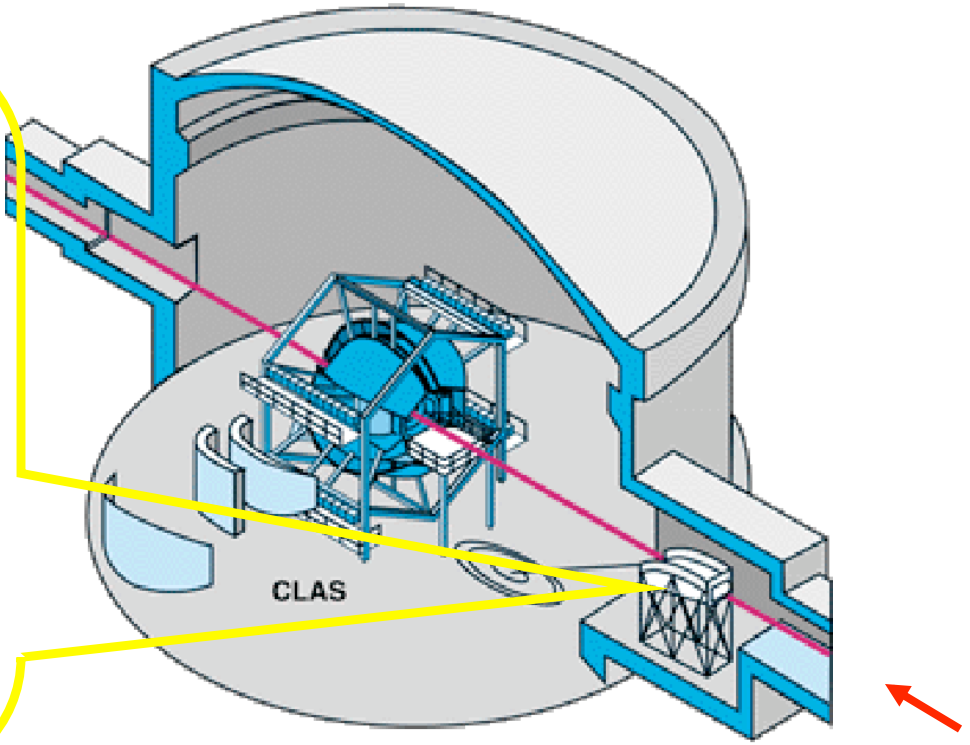


Hall B @ Jlab (The tagger)

3. 10^{-4} RL

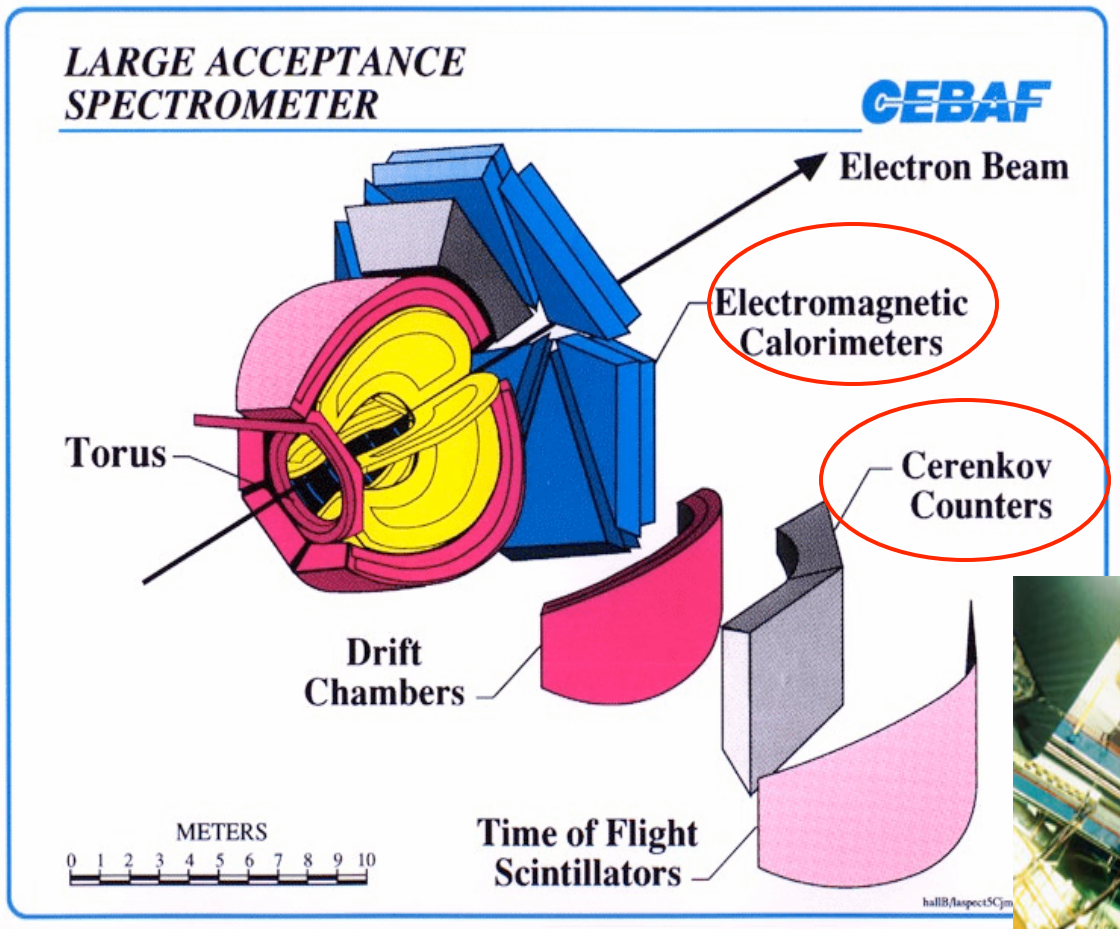
Photon Tagger





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**



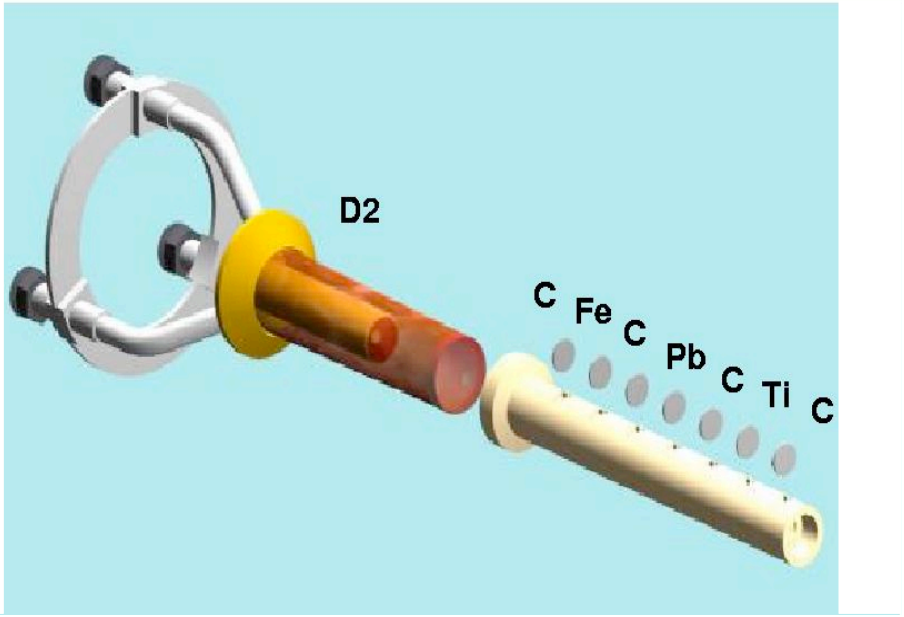
Hall B @ Jlab (CLAS)

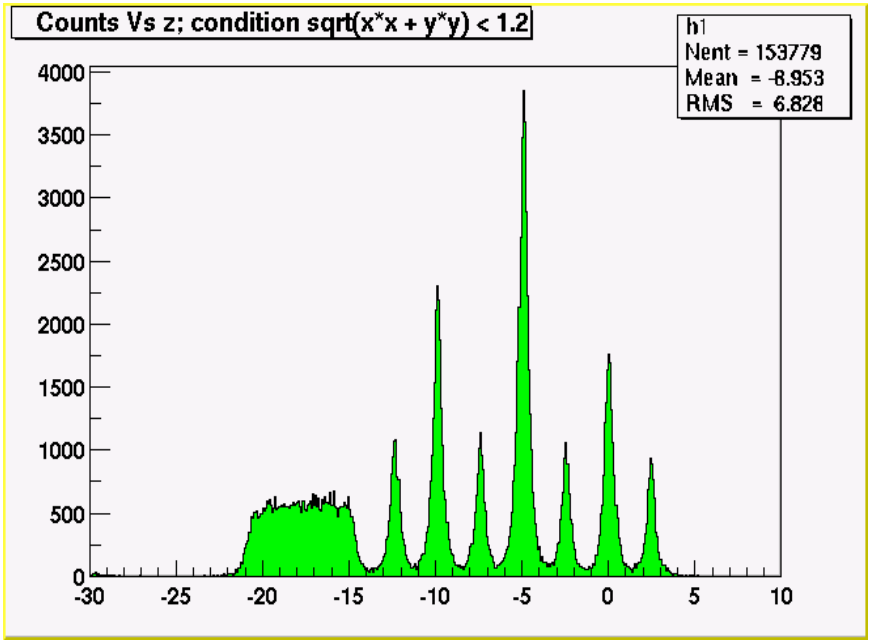
>150 physicists,
>10 countries

- 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

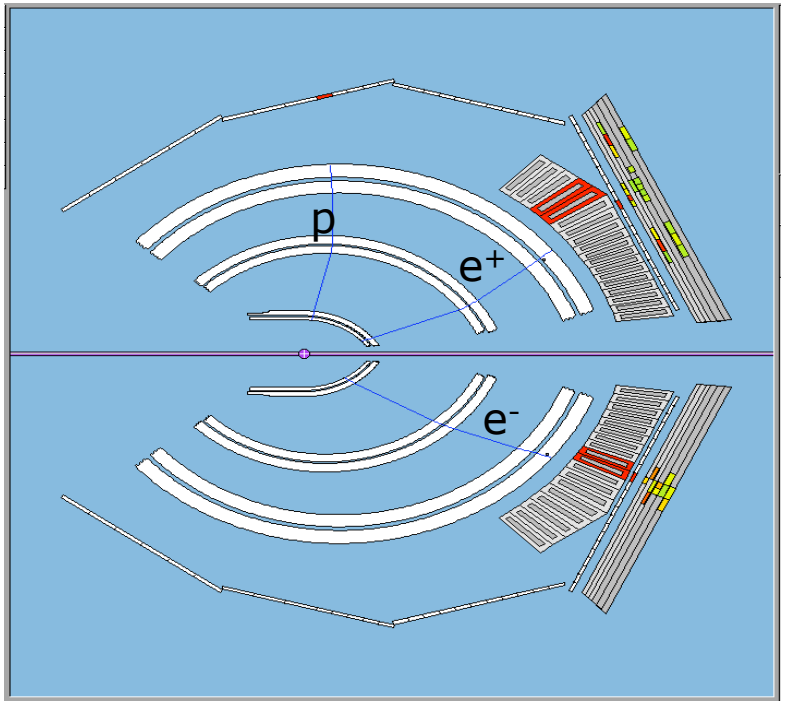


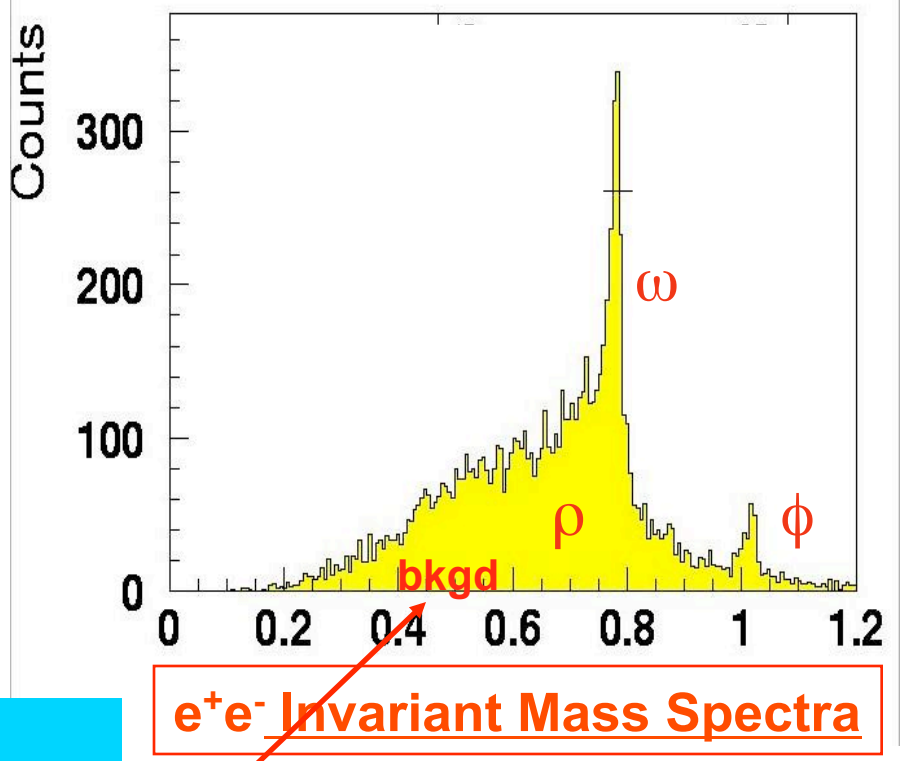


- Proper spacing 2.5 cm to reduce multiple scattering
- Deuterium target as reference, small nucleus, no modification is expected.

Particle Detection with CLAS

coincident electron pairs in the CLAS





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 (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**

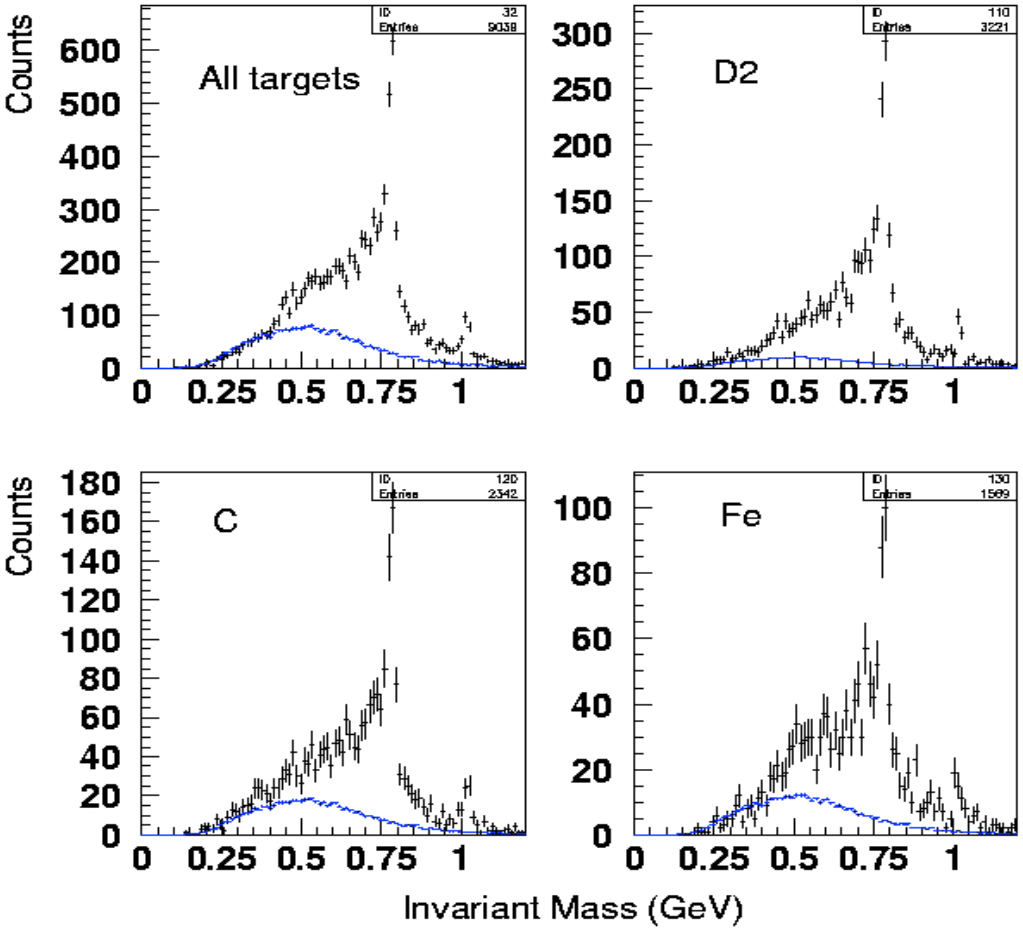
"Semi-correlated":

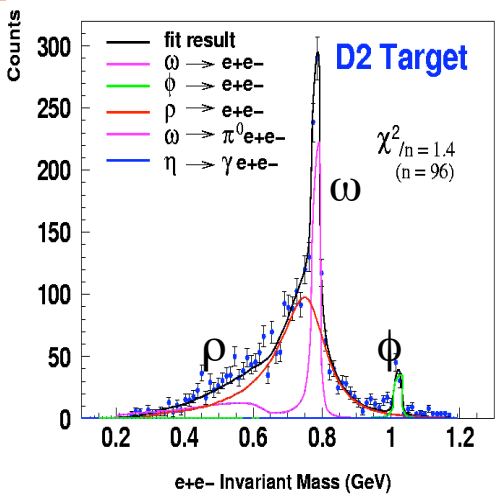
- **Bethe-Heitler** — calculated by Mosel's group → negligible
- $\gamma A \rightarrow \pi^0 \pi^0 X \rightarrow \gamma$ e+e- γ e+e- — 2 π^0 Dalitz decay mixed → negligible
- $\pi^0 \rightarrow$ e+e- e+e- — double Dalitz → low mass

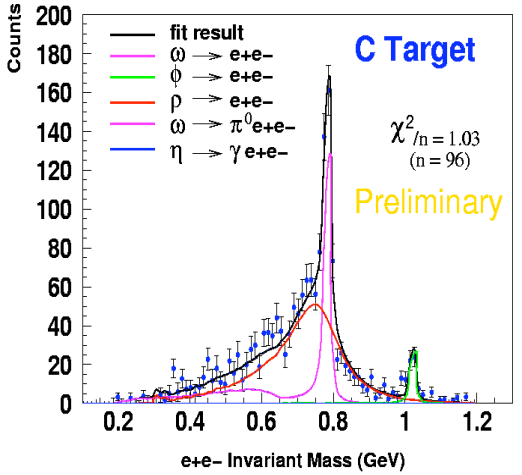
Uncorrelated:

- **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)





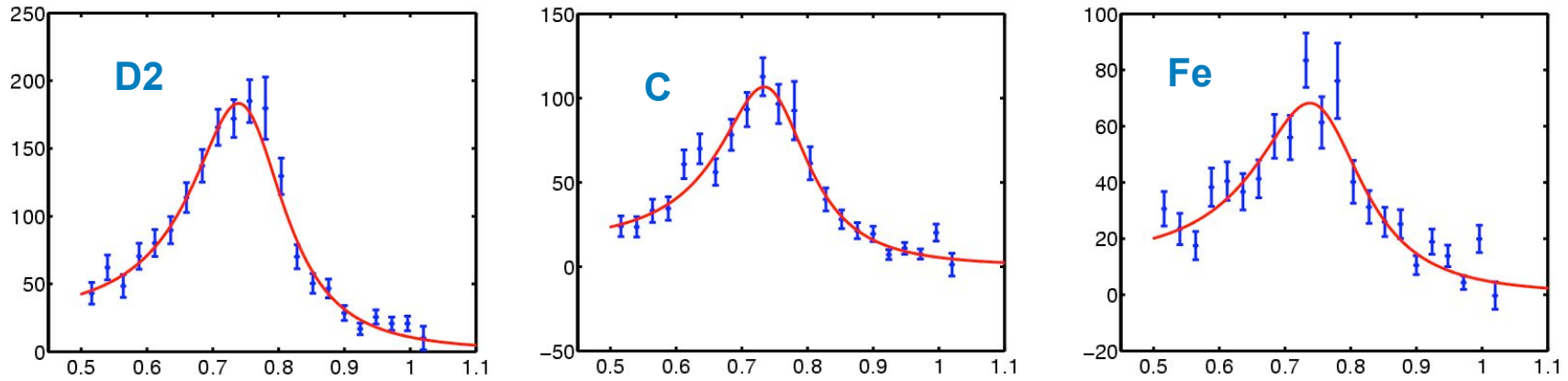


μ+μ− measurement: at CERN-SPS ***IPNO-DR-02.015 (2002)***
π+π− measurement: at CERN-ISR ***(Nucl. Phys. B124 (1977) 1-11).***
e+e- measurement: at RHIC ***(Nucl.Phys. A774 (2006) 743-746).***

Krakow, June 7, 2008 **C. Djalali**

The ρ Mass Spectra

After removing the ω, ϕ, and background contributions:

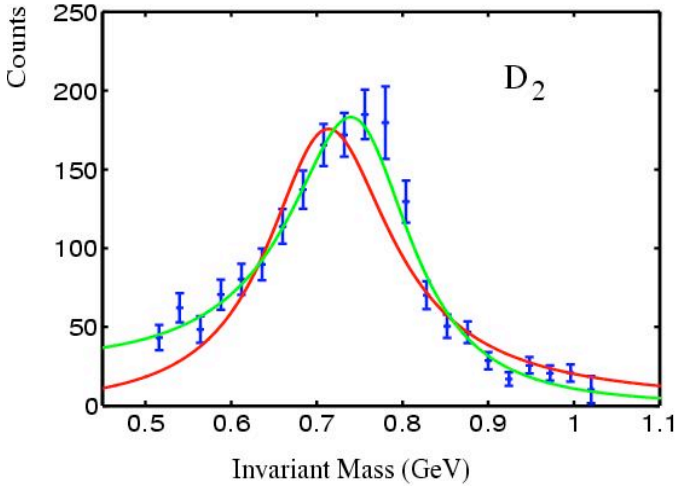


Fit function:

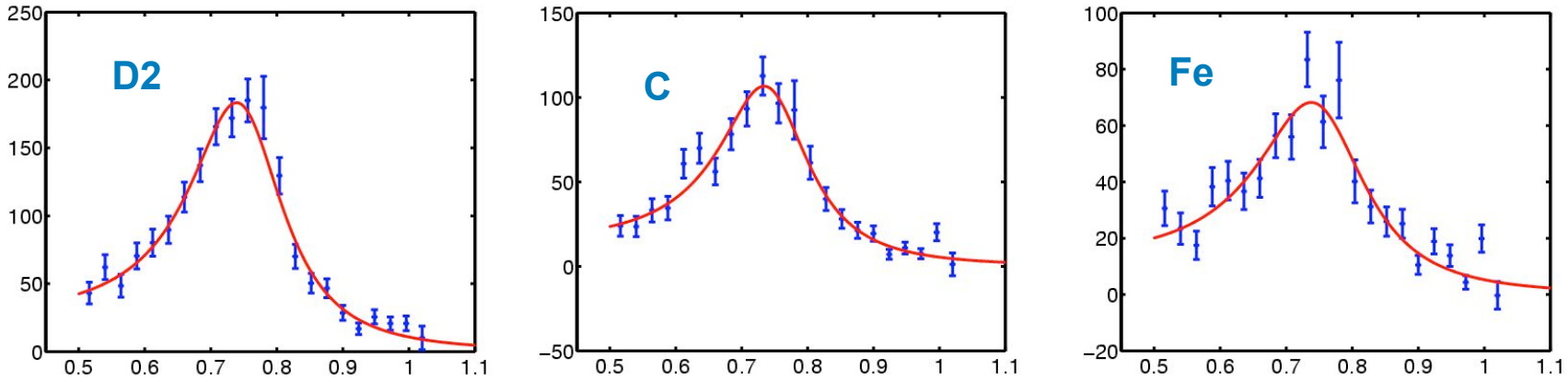
$$\left(\textbf{Breit – Wigner}\right) \times \frac{1}{M^4} \times M = \frac{\left(\textbf{Breit – Wigner}\right)}{M^3}$$

Photon propagator

Breakup momentum phase space



The ρ Mass Spectra



Target	Mass (MeV/c^2) CLAS data	Width(MeV/c^2) CLAS data	Mass(MeV/c^2) Giessen BUU	Width(MeV/c^2) Giessen BUU
^{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 (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

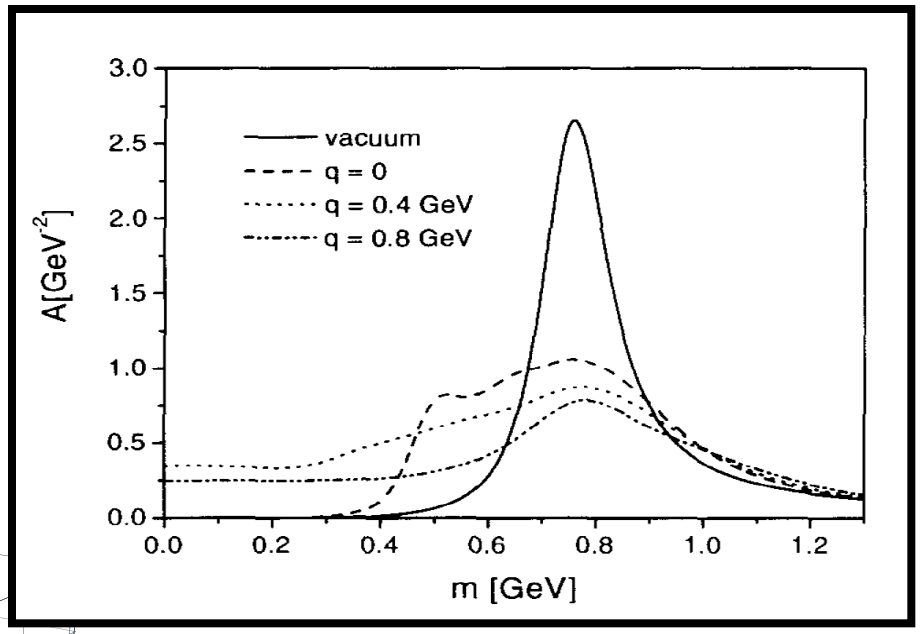
- PRL published – **R. Nasseripour *et al.*, PRL 99 (2007) 262302**
- PRC submitted February 2008. **M. Wood *et al.*, arXiv:0803.0492v1 [nucl-ex]**

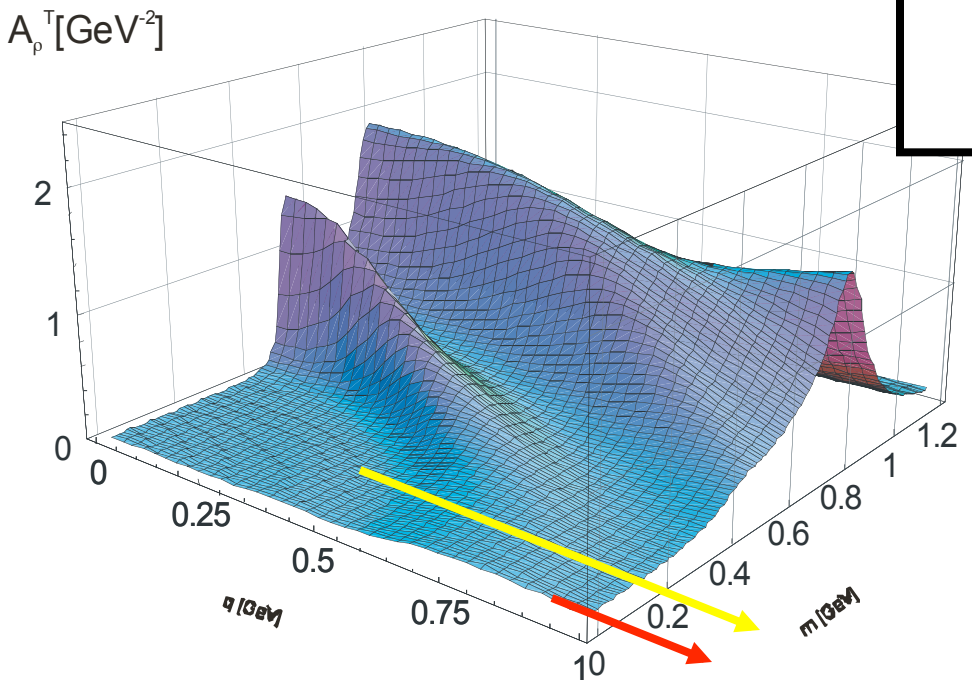
Momentum Dependence – ρ Meson

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

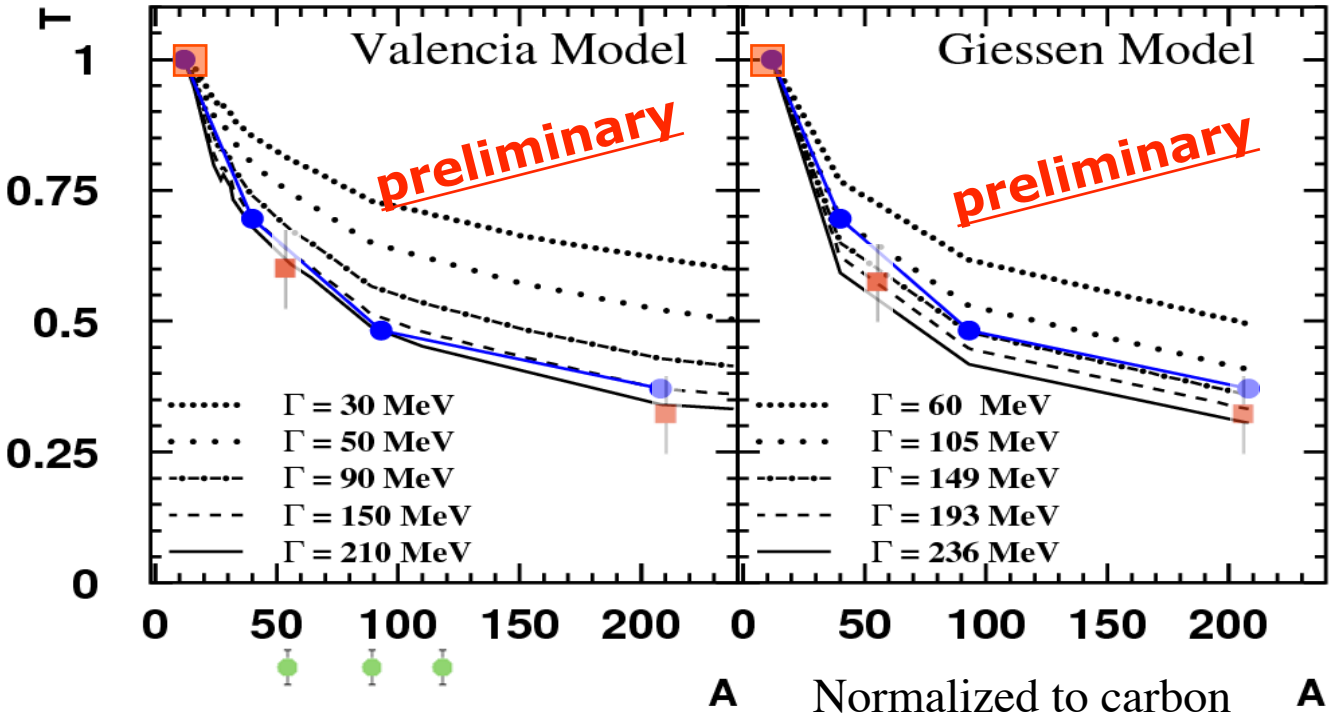
Planned g7b
Conditionally approved

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

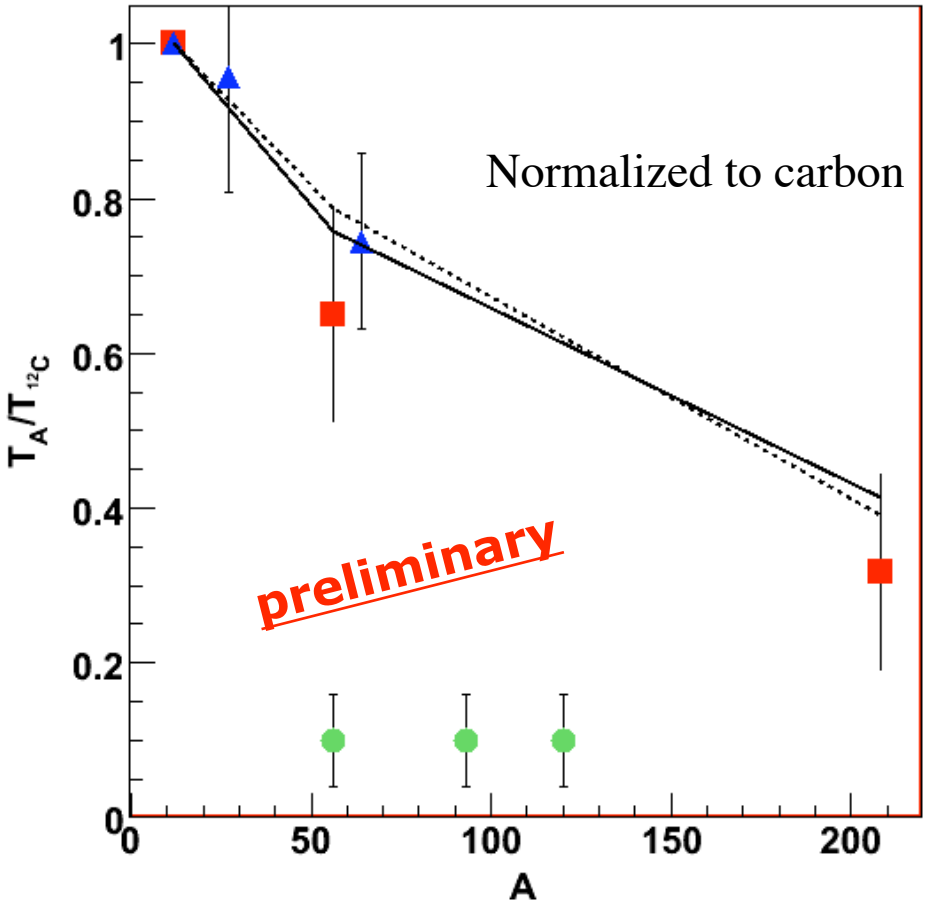


Latest TAPS Γ_ω~130-150 MeV
JLAB preliminary results consistent!

- JLab (preliminary)
- TAPS (PRL100(2008)192302)
- Proposed JLab run

Comparison to Theory – ϕ–Meson

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



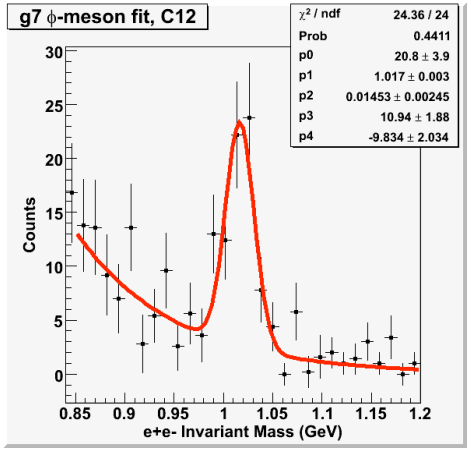
Giessen calculations

Giessen calculations w/ Spring8 absorption strengths

JLab (preliminary)

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

Proposed Jlab run



Large statistical error bars.

Summary and Conclusions (Medium Modifications)

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 ~ 150 – 200 MeV!

The ϕ meson (preliminary):

- From transparency ratios, in medium total cross section ~ 30 - 40 mb

Medium modification studies continue to be a hot topic!

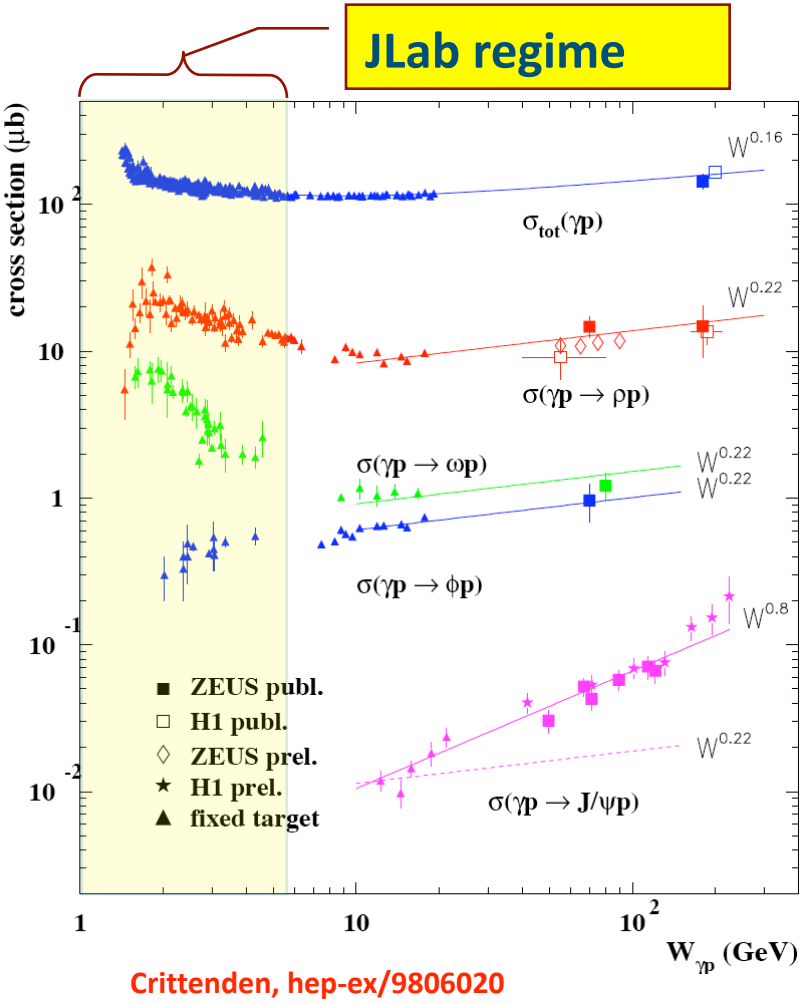
Next at Jlab by g7 group:

- 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.

ϕ Photoproduction (Total Cross Section)

Dave Tedeschi (USC, tedeschi@sc.edu)

Outstanding questions due to the lack of data near threshold.



Crittenden, hep-ex/9806020

Jefferson Lab energy regime can probe the transition from low energy (CQM,Phenom. Models) to the high energy (pQCD, dim. Scaling).

- CLAS (JLab)
  - g1c : 1.6 < Eγ < 2.4 GeV
  - g11 : 1.6 < Eγ < 3.6 GeV
- LEPS (SPring-8)
  - 1.6 < Eγ < 2.4 GeV
  - Mibe *et al.*, Phys. Rev. Lett. 95, 182001 (2005).
- SAPHIR (Bonn)
  - 1.6 < Eγ < 2.8 GeV
  - Barth *et al.*, Eur. Jour. Phys A17, 269 (2003).

The Experiment

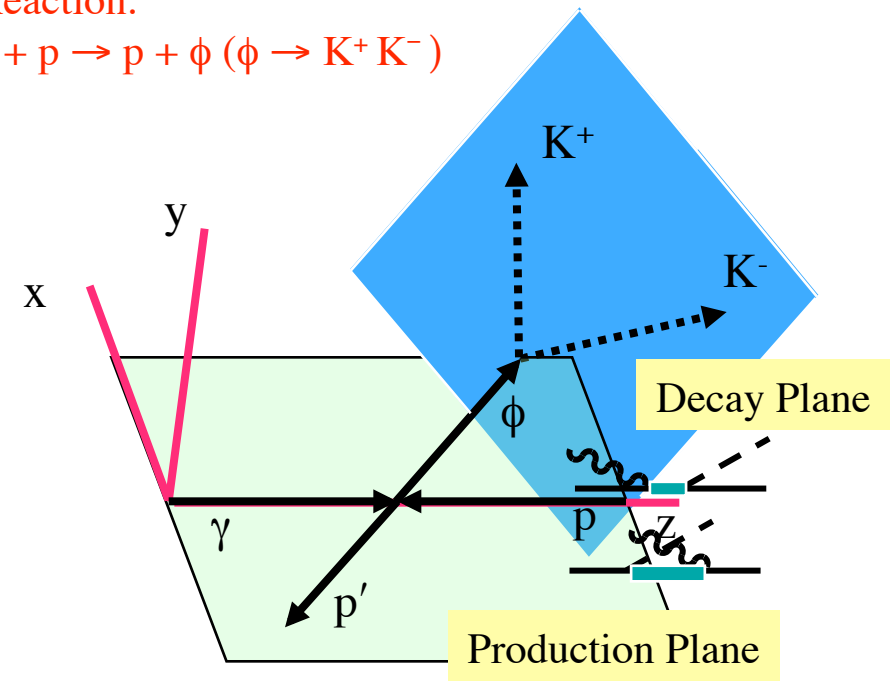
Measure over range of (s,t)

Differential cross section dσ/dt (production plane)

Decay angular distribution dσ/dcos(θ) (decay plane)

Reaction:

$\gamma + p \rightarrow p + \phi\ (\phi \rightarrow K^+ K^-)$

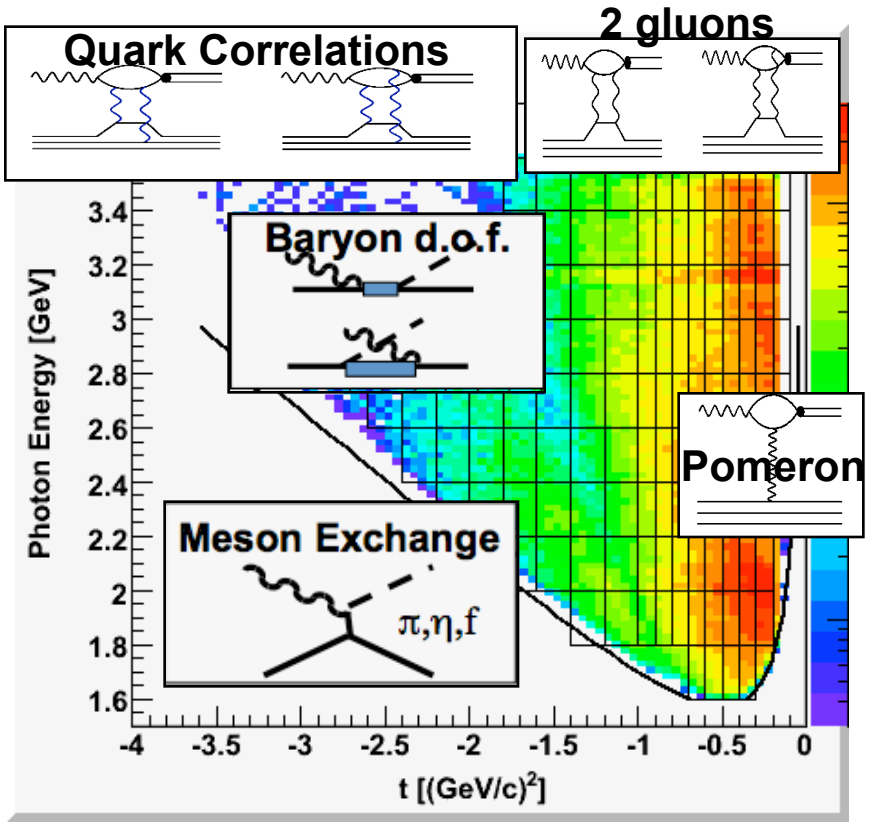


large |t|: Parton structure important

→ Dressed quark and gluon propagators

→ Constituent quark wave functions

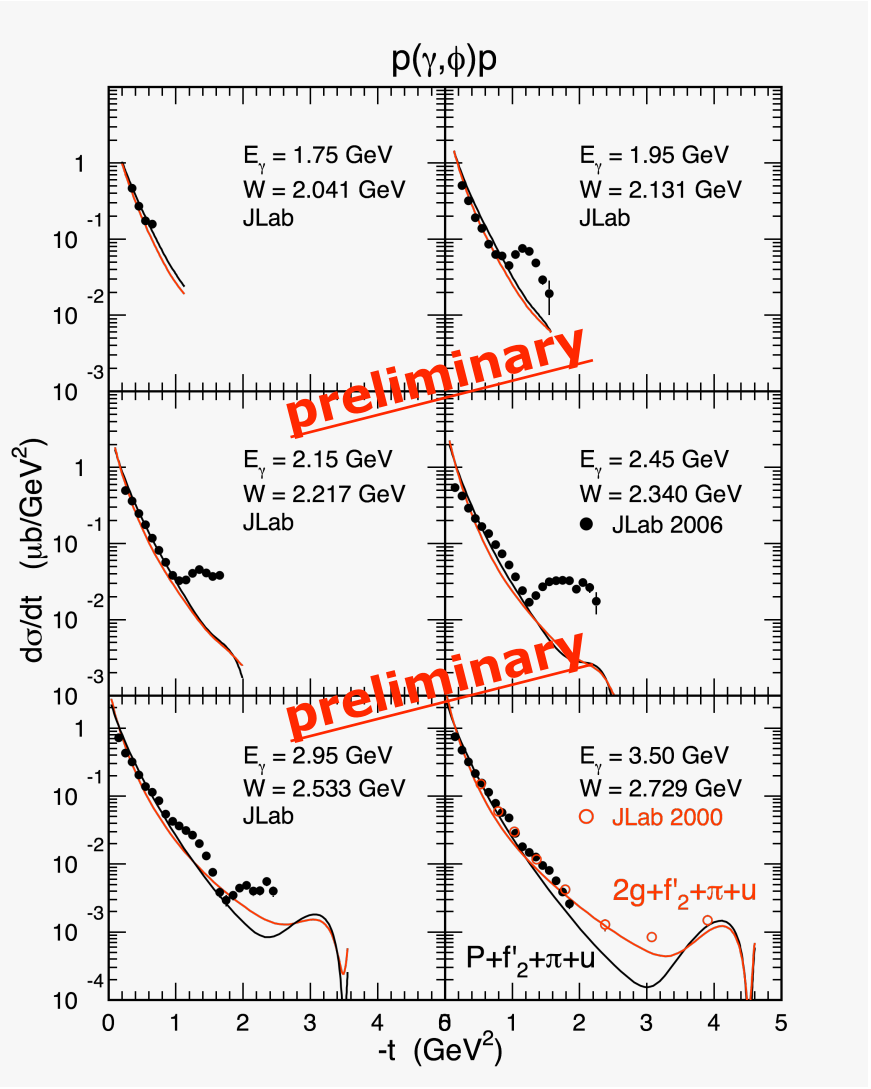
low |t|: cross section driven by integral properties (2g ~ P)



Mechanisms have different kinematic and spin signatures

Separate contributions through angular distributions and asymmetries

Comparison w/ Regge Theory



- Saturated Regge Trajectories
- No Baryon Resonances
- Model is successful for both photo and electroproduction
  - Moderate-t rise not accounted for
  - High-t rise in cross section accounted for by u-channel only at high energy

J.M. Laget, Private Communication

Work in progress