"Medium modifications of light vector mesons in Nuclei"

g7

ρ ρ*

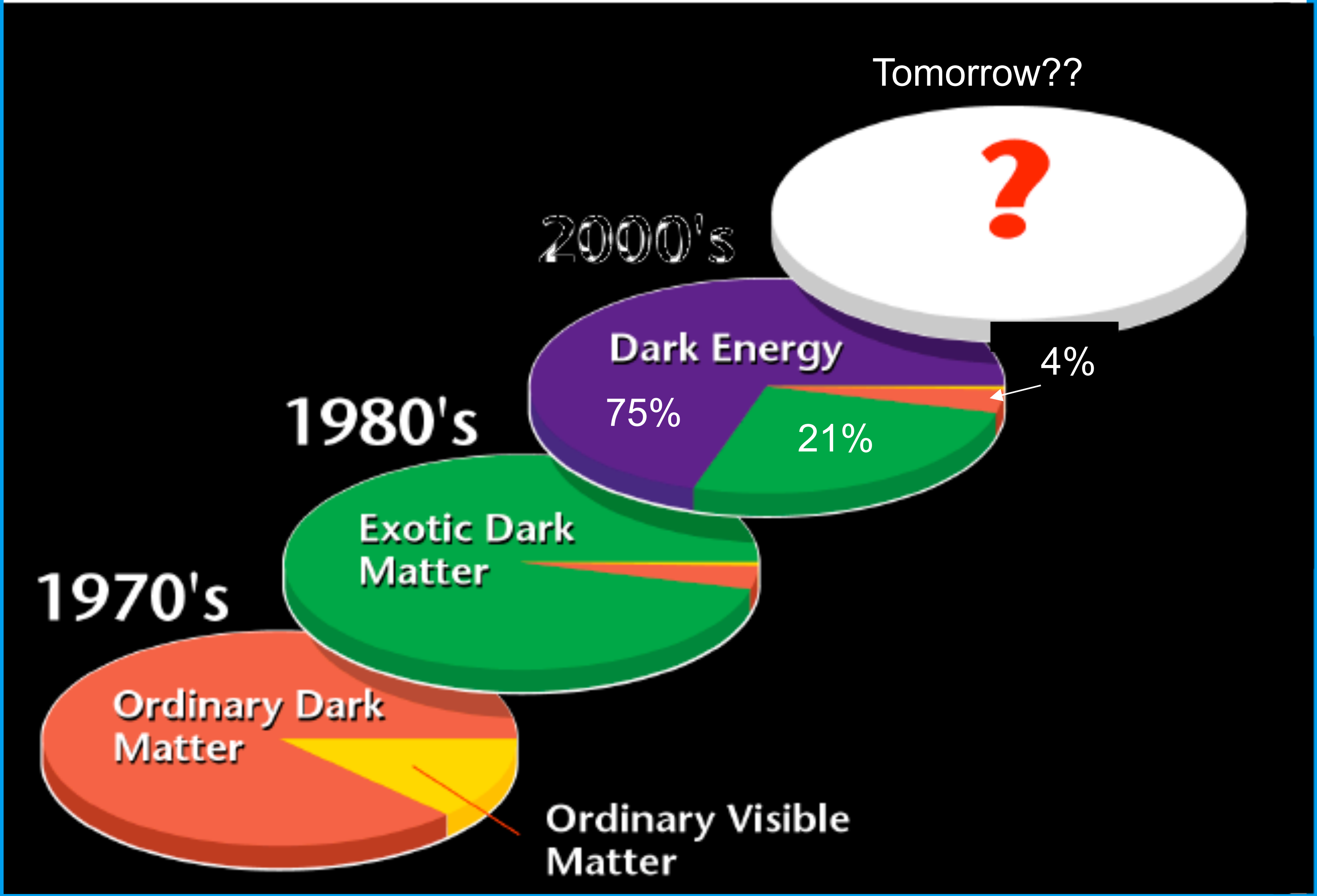
C. Djalali (USC), M. Wood (Canesius College),
R. Nasseripour (GWU),
D. P. Weygand (JLab) and CLAS Collaboration

Outline

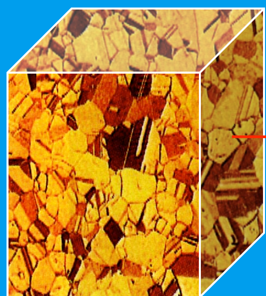
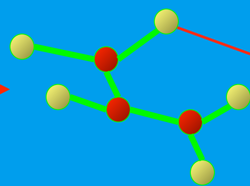
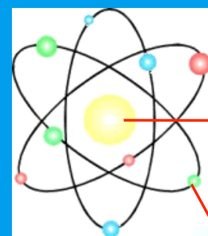
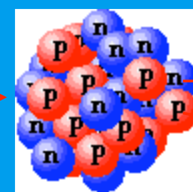
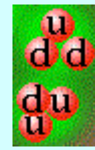
- Physics Motivations
  - Chiral symmetry and hadron masses
- Some key experiments
- Photoproduction of vector mesons at Jlab
  - "g7" experiment
  - Lepton ID, background issues
  - ρ meson mass spectra
  - ω and ϕ absorption
- Summary and Conclusions

➢ Disclaimer: Not all experiments and models listed!

Our changing view of the Universe



Structure of Ordinary Matter

Matter	Molecule	Atom	Nucleus	Baryon (Hadron)	Quark
					
cm	10^{-9}m	10^{-10}m	10^{-14}m	10^{-15}m	$<10^{-19}$m
				protons, neutrons, mesons, etc. π,Ω,Λ...	top, bottom, charm, strange, up, down

Chemistry

Atomic Physics

Nuclear Physics

Electron (Lepton)

$<10^{-18}$m

High Energy Physics

For most composite systems $M \approx \Sigma\, m_i$

$BE_{Atom} \approx 10^{-8}$ $BE_{Nuclei} \approx 10^{-3}$

However, nucleons have $M >> \Sigma\, m_i$

Nucleon's mass is (almost entireley) dynamically generated.

QCD: The Theory of Strong Interactions

(j,k = 1,2,3 refer to color; q = u,d,s refers to flavor; a = 1,..,8 to gluon fields)

$$L_{qcd} = i\sum_q \overline{\psi}_q^{\,j} \gamma^\mu (D_\mu)_{jk} \psi_q^k - \sum_q m_q \overline{\psi}_q^{\,j} \psi_q^k - \tfrac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$

mass of "free" quarks

- **If m_q=0** ⇒ exact chiral symmetry ⇒ chiral doublets, degenerate in mass
- **However m_u, m_d < 10 MeV. This is relatively small** ⇒ approximate chiral symmetry ⇒ chiral doublets degenerate in mass

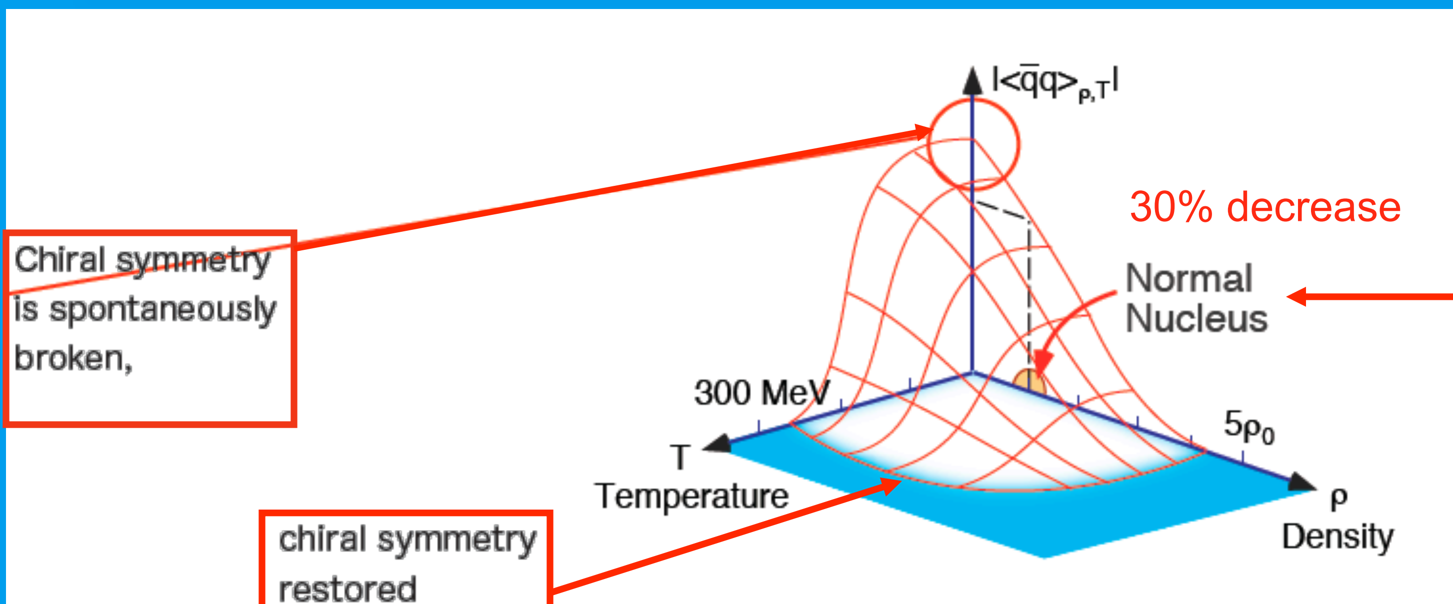
- **However, we observe that not to be true :** $M_N \approx 1\ \mathrm{GeV}$ **and** $M_\rho < M_{a_1}$

The non perturbative nature of the interaction at low energies spontaneously breaks the Chiral symmetry in vacuum resulting in a non vanishing quark condensate $\boxed{\langle 0 | q\overline{q} | 0 \rangle}$ **≠0 .**

Properties of the quark condensate

$< 0 | q\bar{q} | 0 >$ changes with ρ and T

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



T. Hatsuda and T. Kunihiro, Phys. Rev. Lett. 55 (1985) 158.
W. Weise, Nucl. Phys. A443 (1993) 59c.

Partial restoration of chiral symmetry

How to measure changes in quark condensate

The quark condensate is not an observable. We need theoritical model to relate the quark condensate to actual experimental observations

Hadronic properties depend on the chiral condensate $< 0 | q\bar{q} | 0 >$.

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

Mass, decay, coupling etc of hadrons will change.

- **Extensive programs to look at changes in properties of Baryons are not covered in this talk**
- **We will only mention some experiments looking at changes of properties of light mesons which are made of q-qbar similar to the quark condensate**

Vector mesons in the medium

Properties of vector mesons are predicted to change with ρ and T

Scale invariance in effective Lagrangian:

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

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

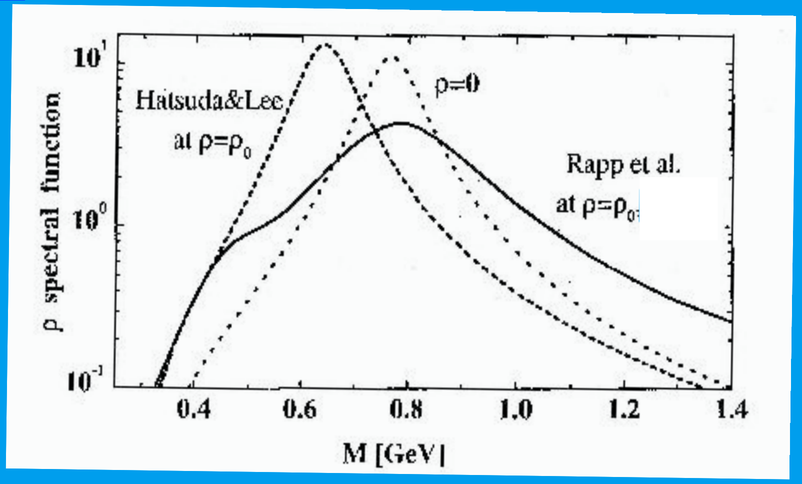
QCD sumrules:

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
R. Rapp, ***arXiv:nucl-th/0608022 (2006)***



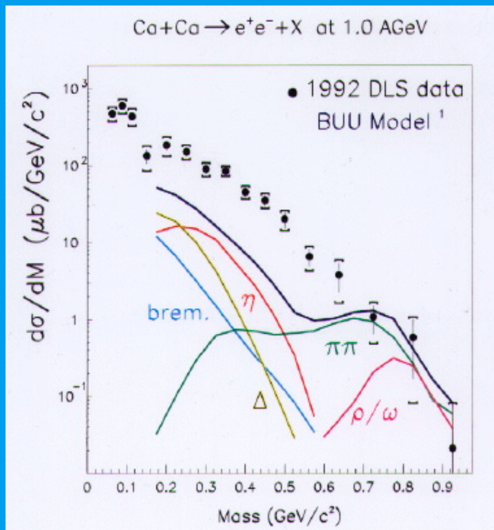
Other predictions:

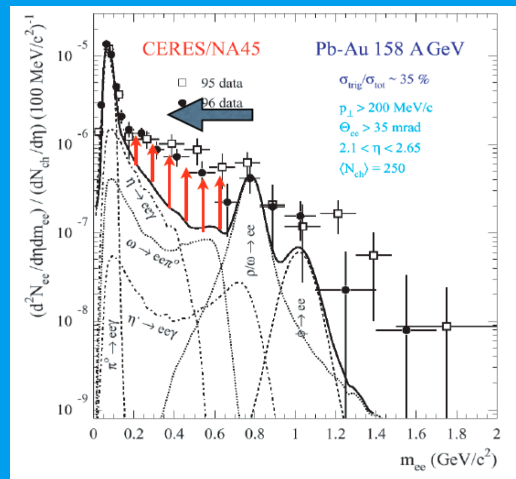
M. Lutz et. al. , Nucl. Phys. A 705 (2002) 431

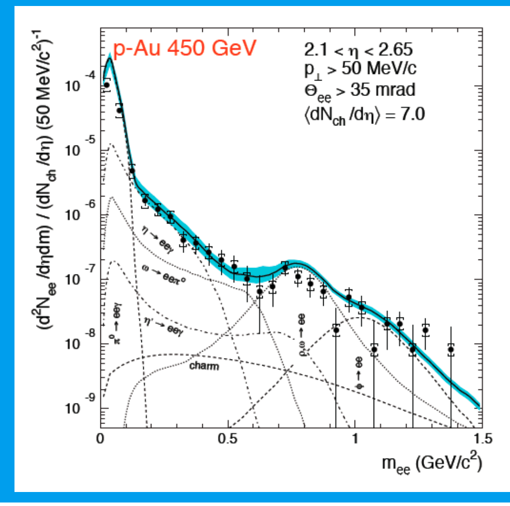
D. Cabrera et. al. , Nucl. Phys. A 705 (2002) 90

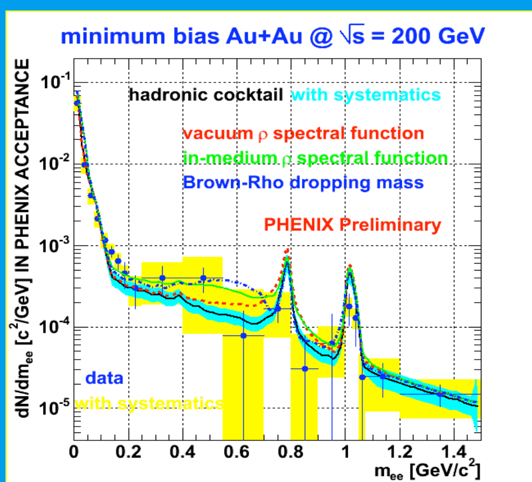
Any observations??

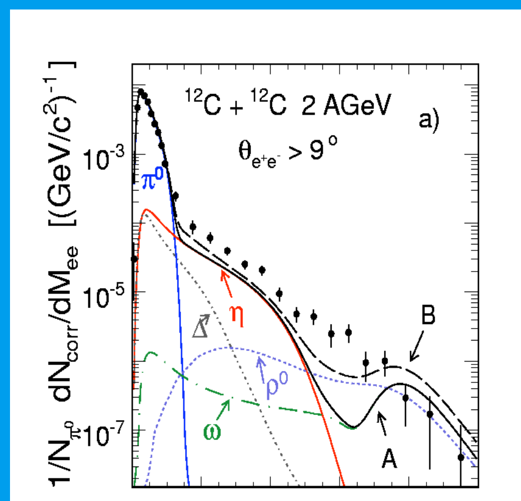
Relativistic heavy ion collisions can produce nuclear matter at different ρ and T

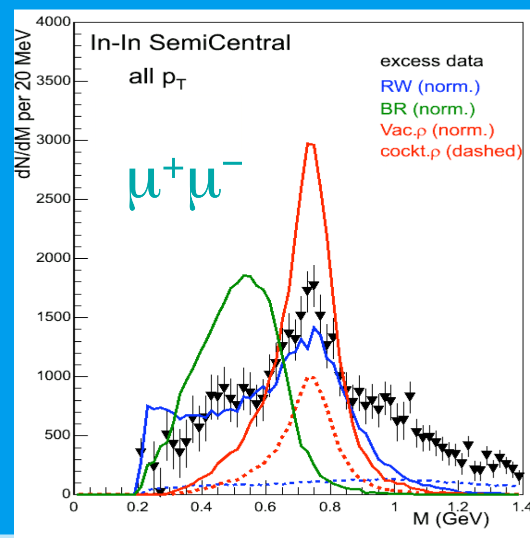








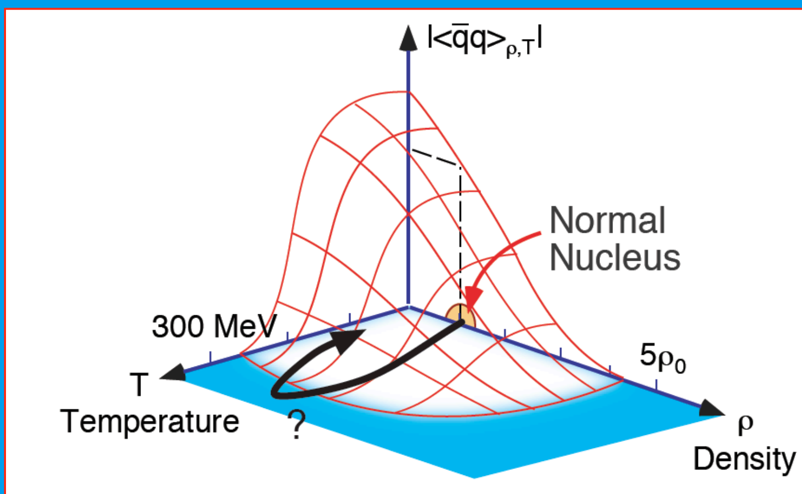


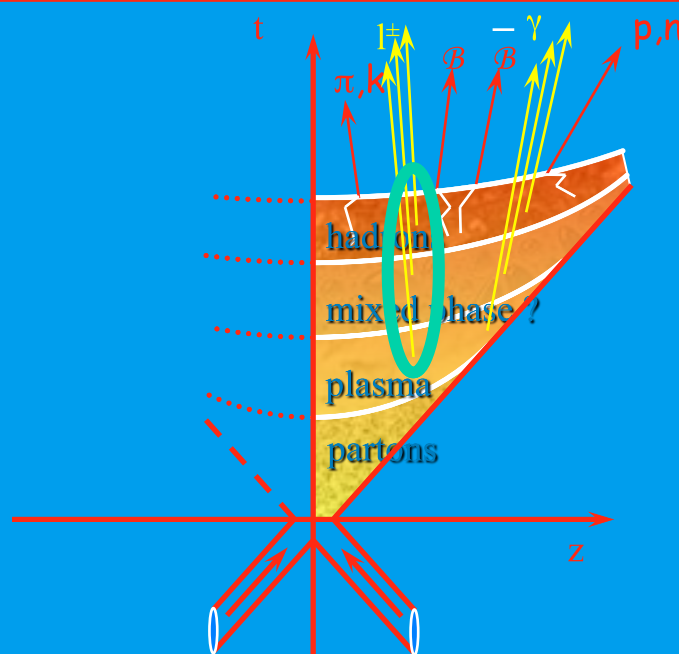


Clear excess of di-leptons observed. NA60: Γ , “no ΔM”

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"!
2) 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

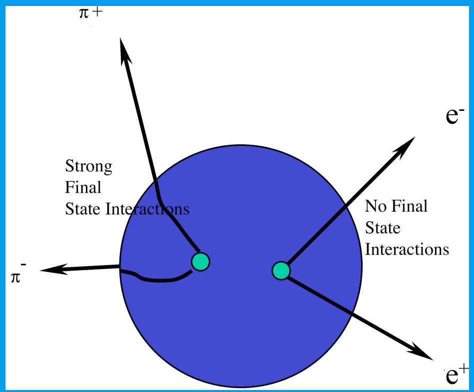


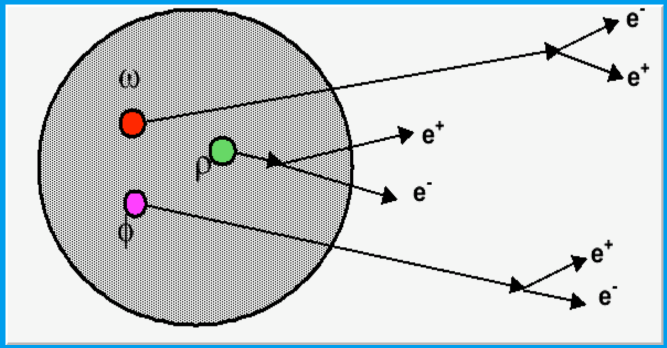


It is interesting to look for medium modification of vector meson properties in nuclei (at T=0 and $\rho \sim \rho_0$)

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

- **Let's produce Vector mesons in nuclei.**
- **Do it with probes that leave the nucleus in almost an equilibrium state γ,π,p,**
- **(probe) + A --> V X --> e^+e^- X**





Decay inside

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

Need very low p

"Elementary reactions" (not exhaustive list):

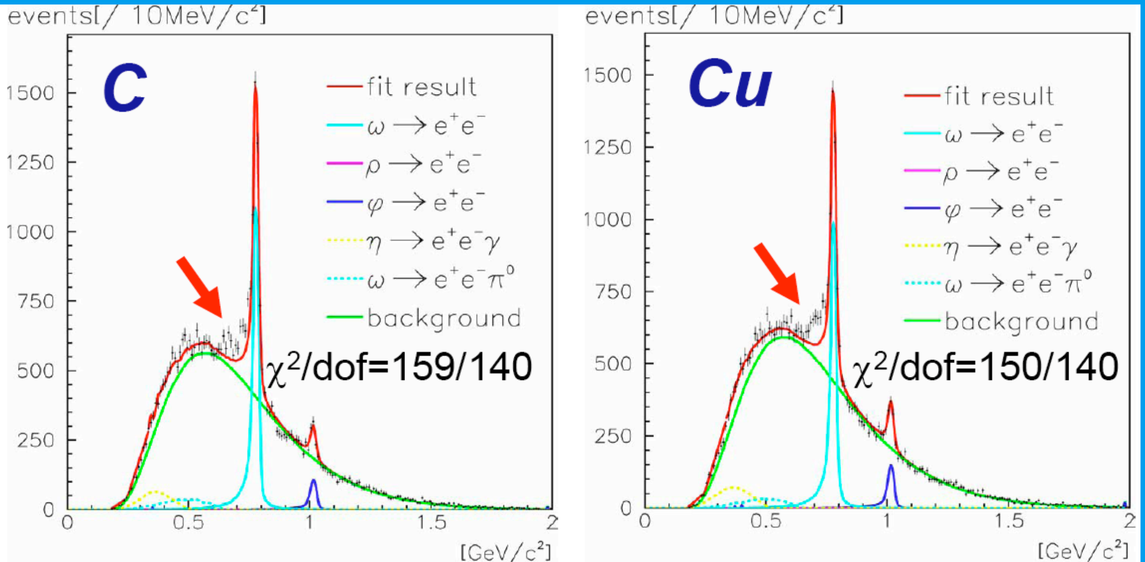
Experiment	*Reactions*	*Results*
TAGX	γ +^{3}He-->ρ+X (ρ->$\pi^+\pi^-$)	full BR, α ~ 0.06
KEK	p+A->ρ,ω,ϕ+X (ρ,ω->e^+e^-)	α = 0.092±0.002
KEK	p+A->ϕ+X (ϕ->e^+e^-)	α ~ 0.04
SPring-8	γ + A-->ϕ+A*(ϕ--> K^+K^-)	no effect
TAPS	γ+A-->ω+X (ω --> π^0 γ)	α~0.~~13-015~~ (now 0!?)
HADES	p+p,d->ρ,ω,ϕ+X (ρ,ω,ϕ->e^+e^-)	(running)

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

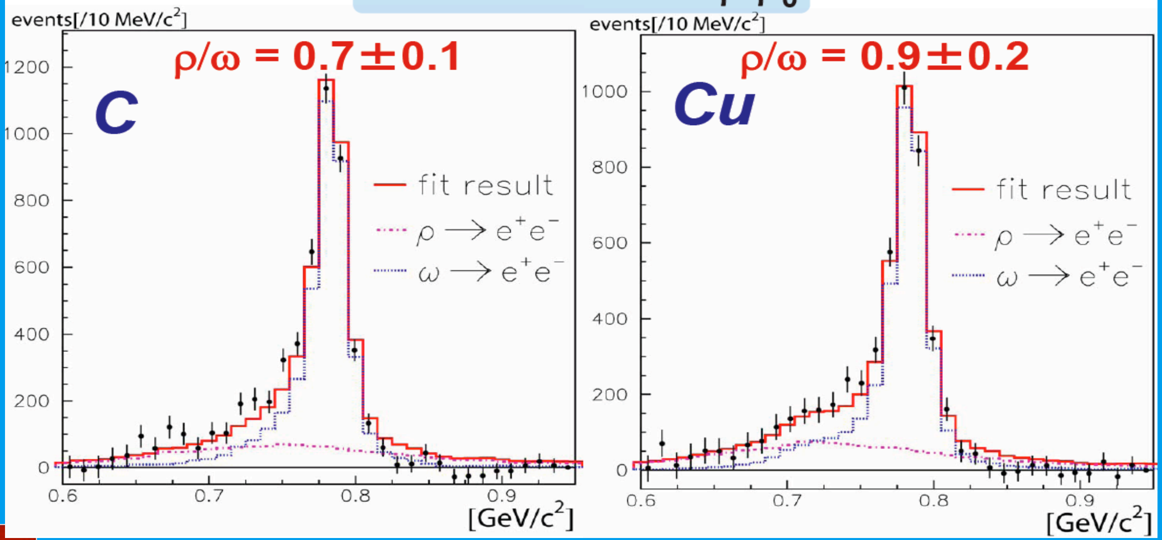
KEK- PS E325 (Japan)

p+A → ρ,ω,ϕ+X (ρ,ω,ϕ → e+e-)

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



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



- **No strong ρ signal.**
- **No absolute normalization of the background → background part of the fit**

Constrain the ω/ρ ratio to include ρ

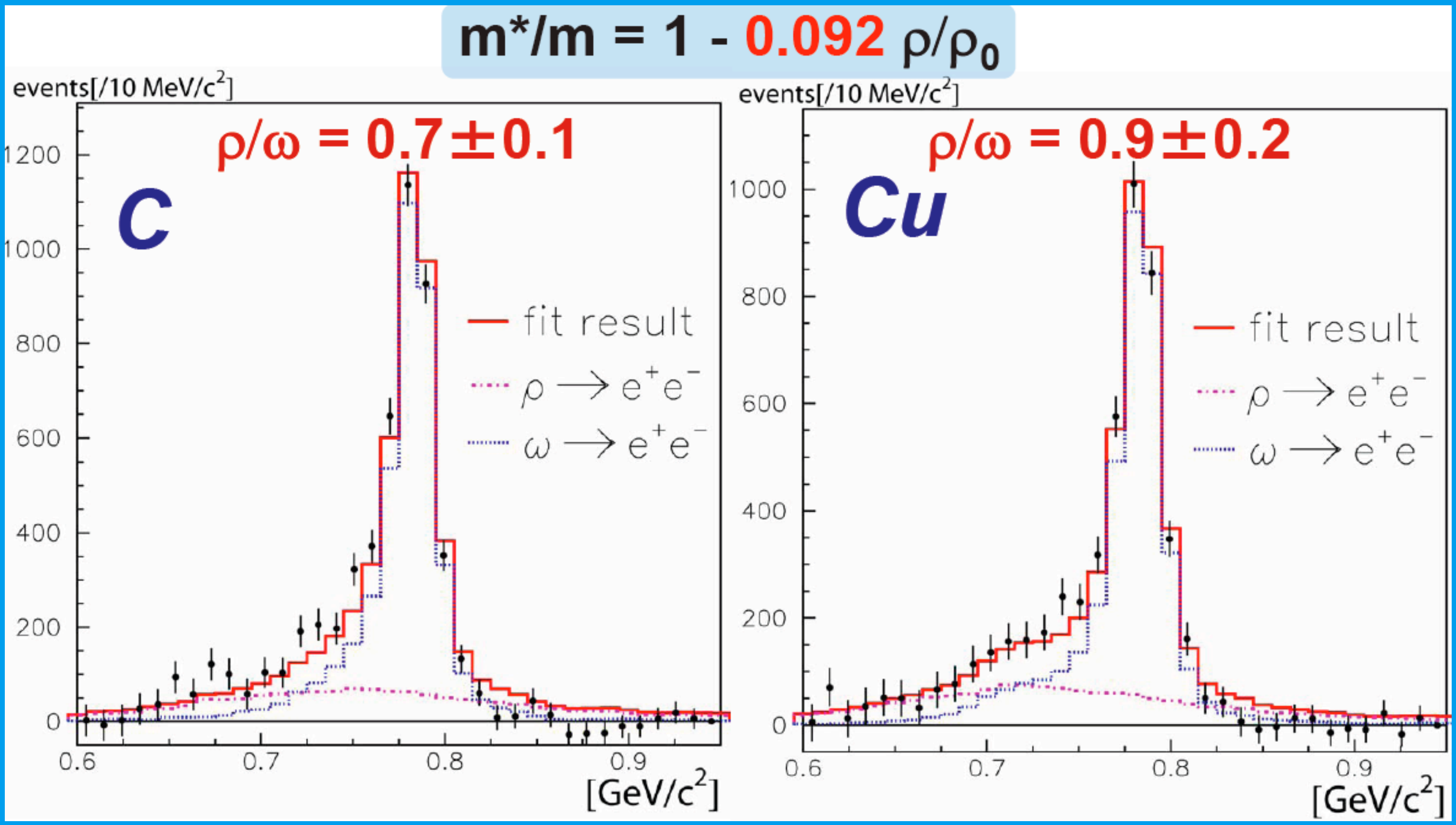
Results of fit for the ρ:

Mass shift: α ~ 9.2%
No ΔΓ

KEK-PS E325 cont

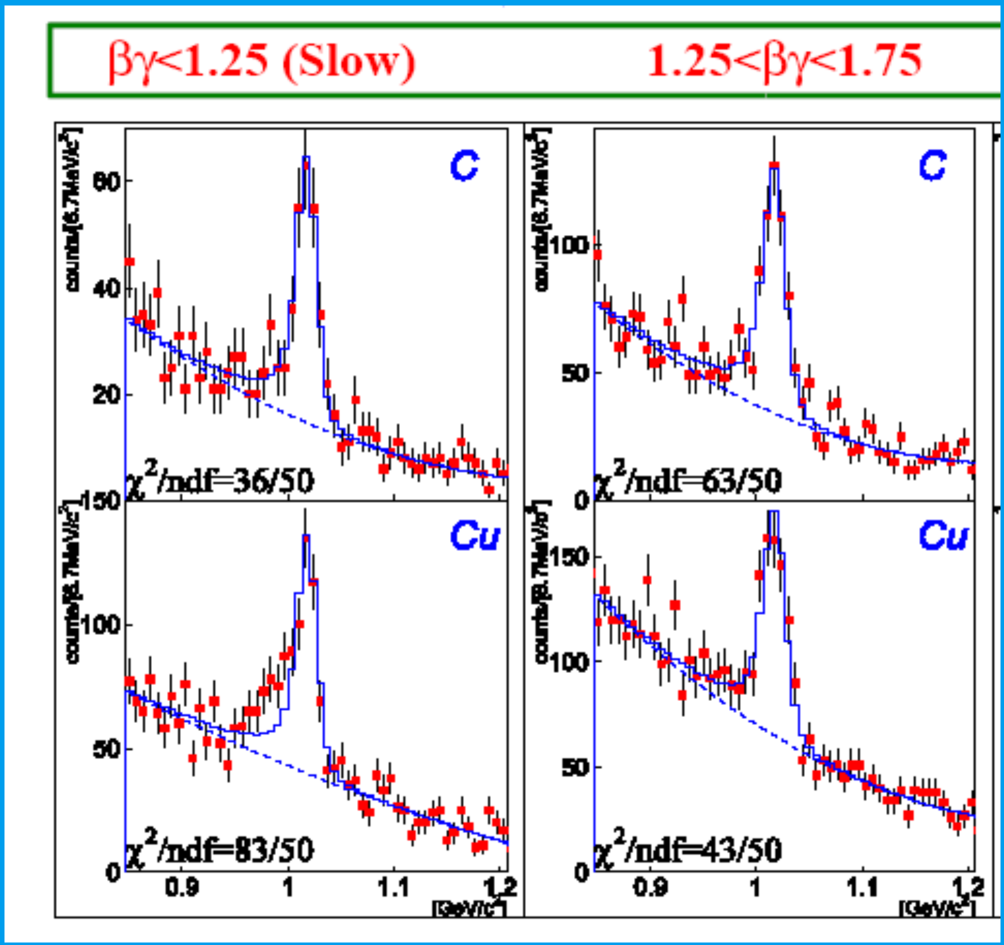
M. Naruki et al, PRL 96 (2006) 092301

Subtract the background and constrain the ω/ρ ratio to include ρ



α = 0.092 +/- 0.002

KEK-E325: p (12 GeV) A→ ρ, ω +X; ϕ → e^+e^-



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)	$2.6^{+1.8}_{-1.2}$

<u>mass shift for low recoil momenta ϕ in Cu</u>

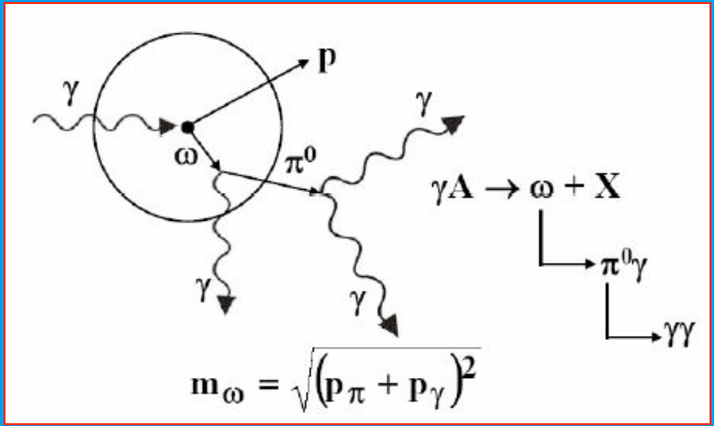
Bonn- TAPS results published

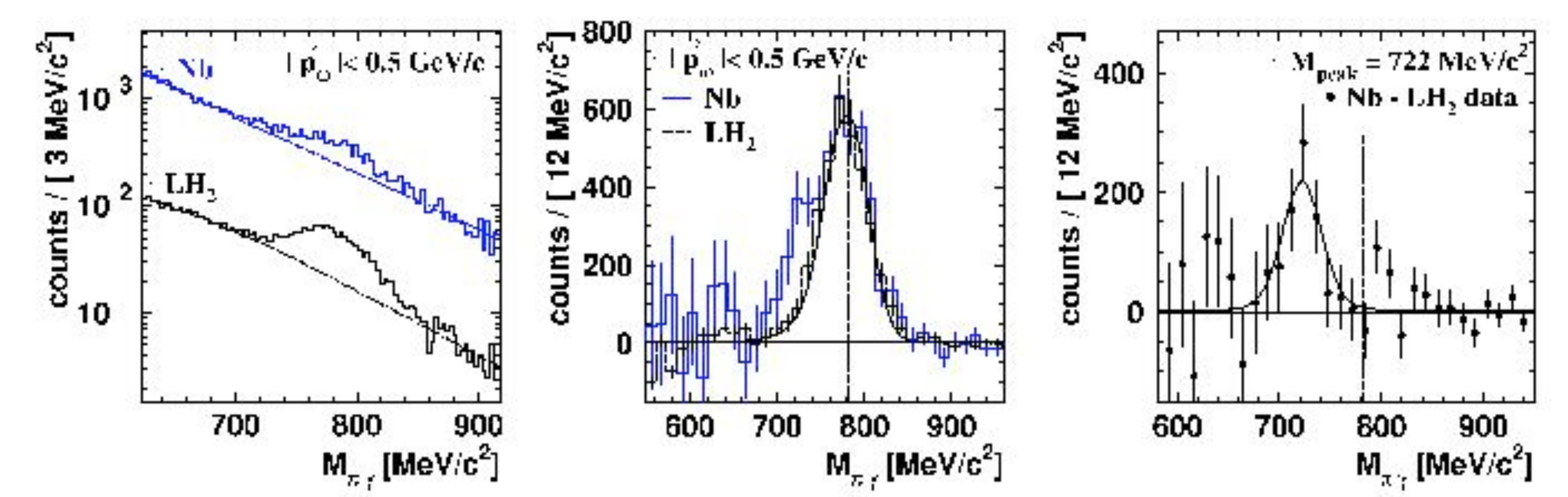
γ+A-->ω+X (ω --> π^0 γ) , clean (no ρ) channel, however FSI of π

Small signal to background ratio

$$m^* = m_0(1 - 0.13\rho/\rho_0)$$

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





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

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

IN NEW ANALYSIS (PRELIMINARY, ΔM is GONE!!)

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

$$\gamma A \longrightarrow VX$$

$$V \longrightarrow e^+e^-$$

- **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)

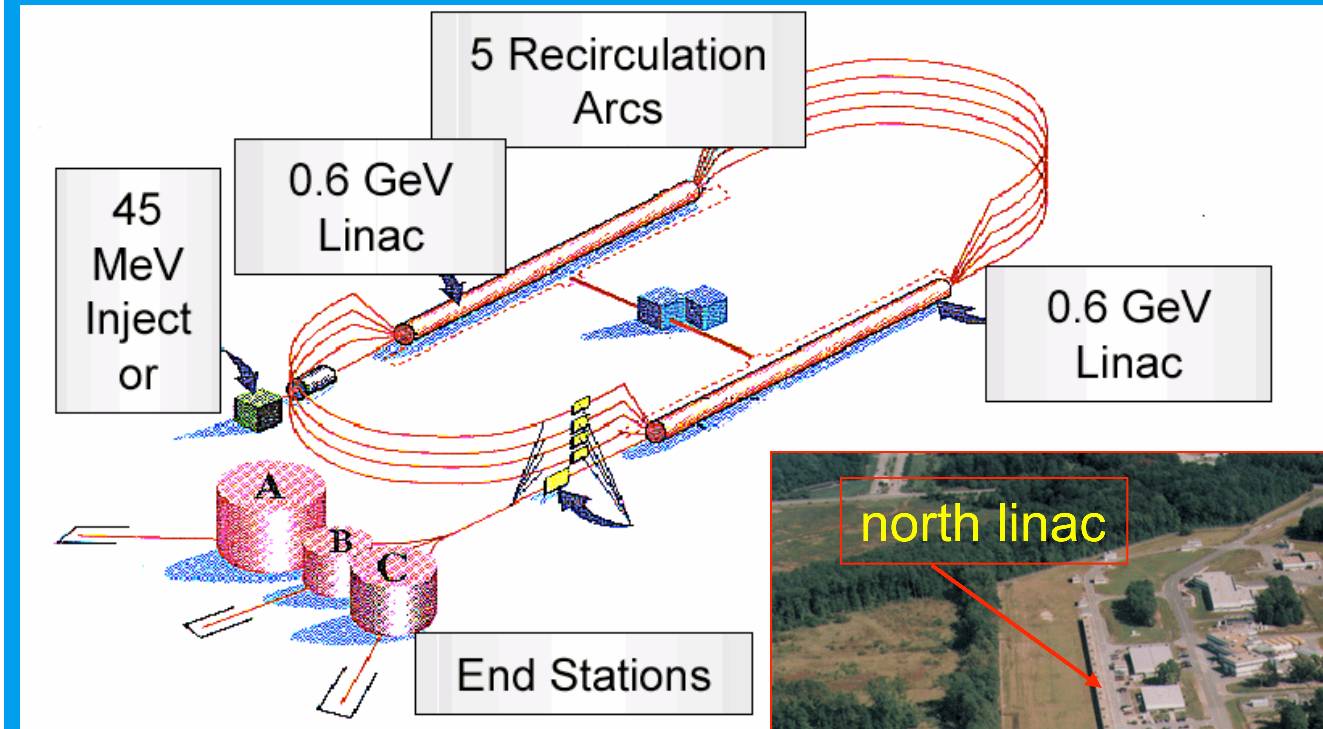
  Targets: LD_2, C, Ti, Fe, (Pb)
- **Leptonic decay :**

  Almost no final state interaction! HOWEVER (NO FREE LUNCH!)

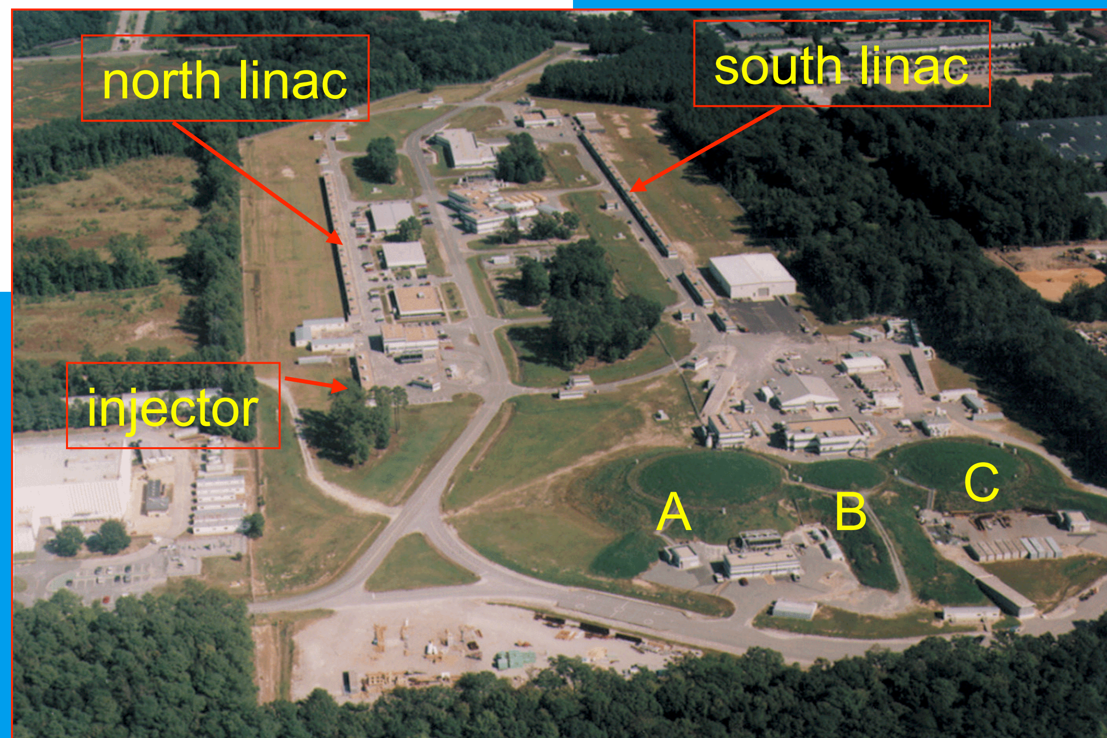
  Low branching ratio : ~5 10^{-5}

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

JLab Site: The 6 GeV CW Electron Accelerator

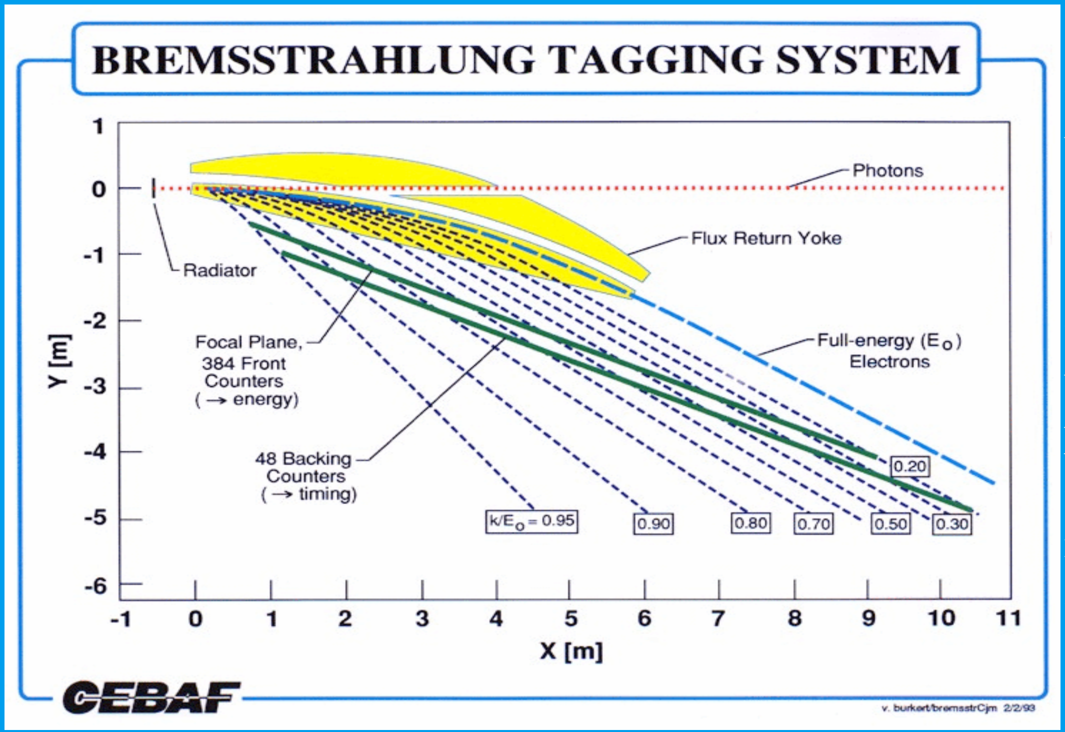


E_{max} ~ 6 GeV
I_{max} ~ 200 μA
Duty Factor ~ 100%
σ_E/E ~ 2.5 10^{-5}
Beam **P** ~ 80%
E_g(tagged) ~ 0.8- 5.5 GeV



The photon beam (the tagger)

$3.\ 10^{-4}$ RL

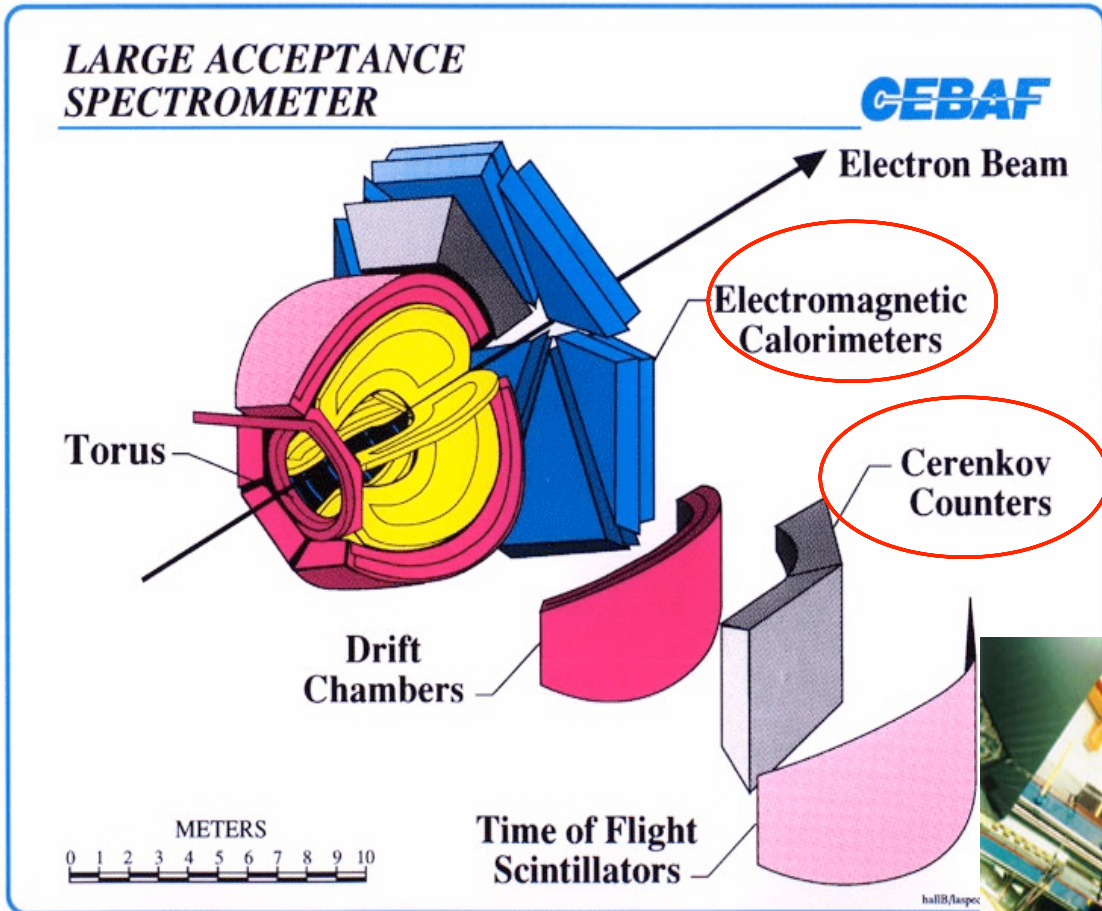


- Photon beam is created by bremsstrahlung using a radiator located on the beam line.
- Energy distribution is $dN(k) \propto \frac{1}{k} dk$
- Electrons are removed from the beam axis using a magnetic dipole and bent onto 2 planes of scintillators.
- The tagger covers [20%, 95%] of the incident electron's energy range.
- The tagger allows to tag the photon with an energy and a time.

Bremsstrahlung Tagging Spectrum (20%-95%)

•E(e^-) = 3.0 GeV E(γ) = 0.60 - 2.85 GeV

•E(e^-) = 4.0 GeV E(γ) = 0.80 - 3.80 GeV

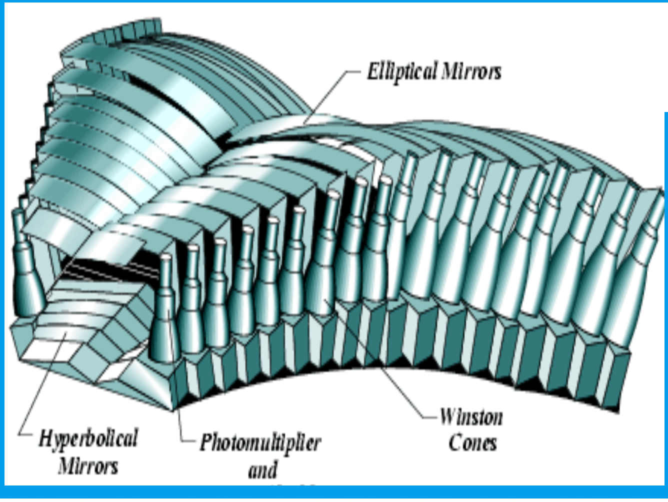


CLAS

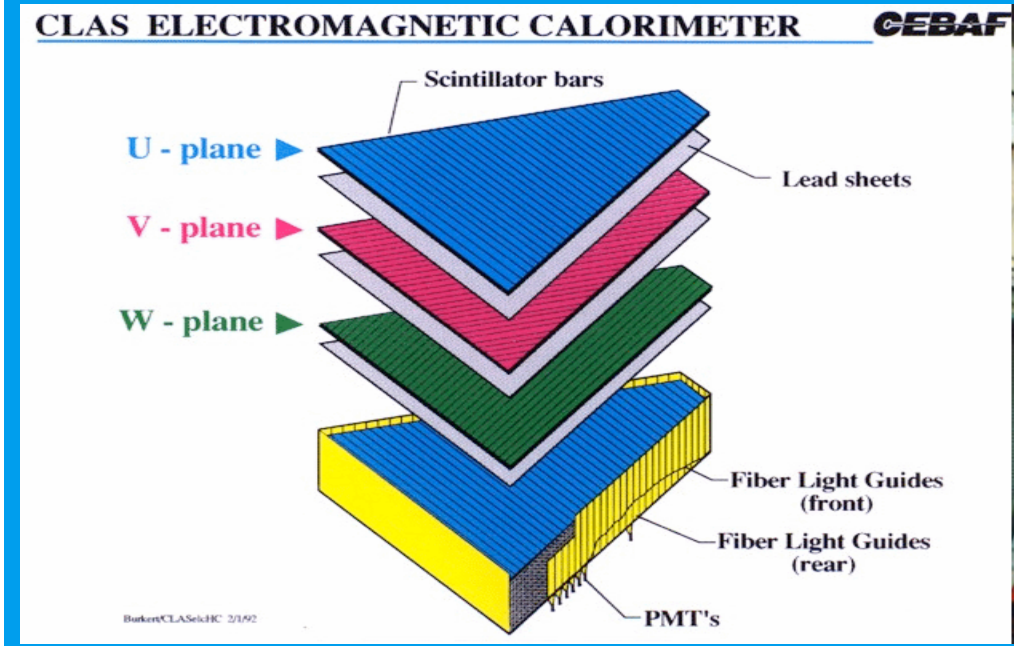
>200 physicists,
>15 countries

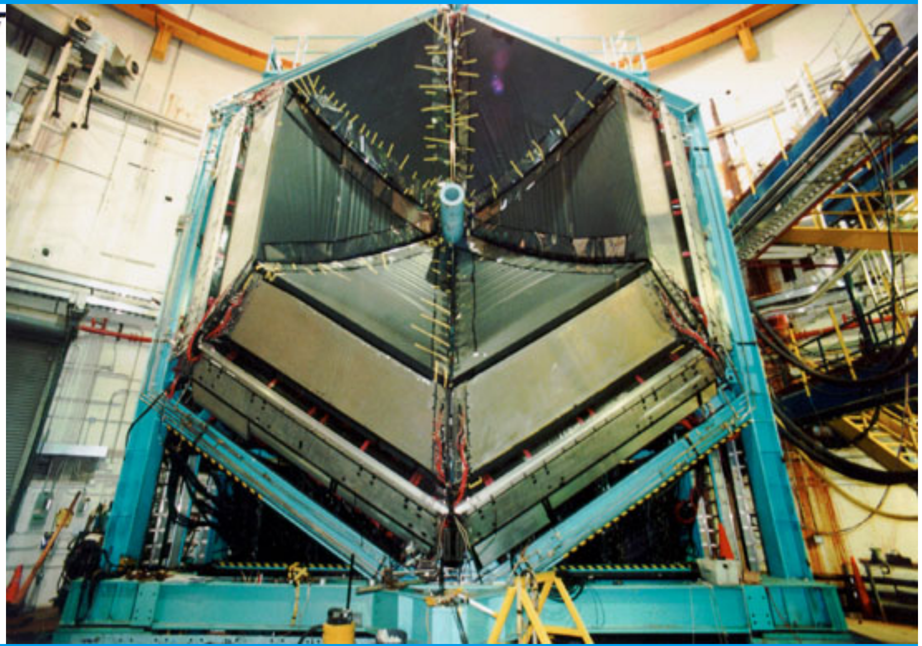
- *Toroidal magnetic field*
  (6 superconducting coils),
- *Drift chambers, Scintillators, Cerenkovs, Electromagnetic Calorimeter.*

The Cerenkov detector



Angular coverage: 8º to 45º in θ and 60º in ϕ

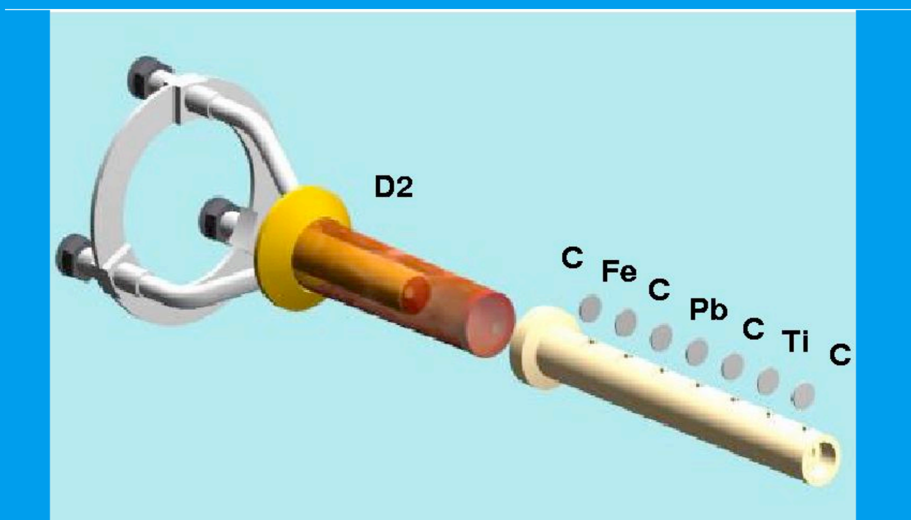


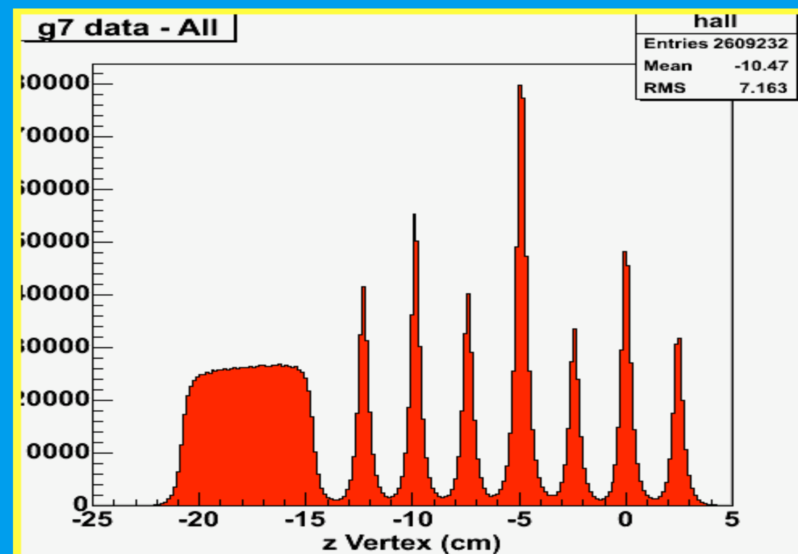


Surface = equilateral triangle (8m²), 39 layers of 1cm scintillator + 2.2 mm sheets of Pb (16λ)
volume = truncated pyramid, located at 5 m from the target and covering 8º<θ<45º ;
EC divided in inner (15 layers) et outer (24 layers) parts

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

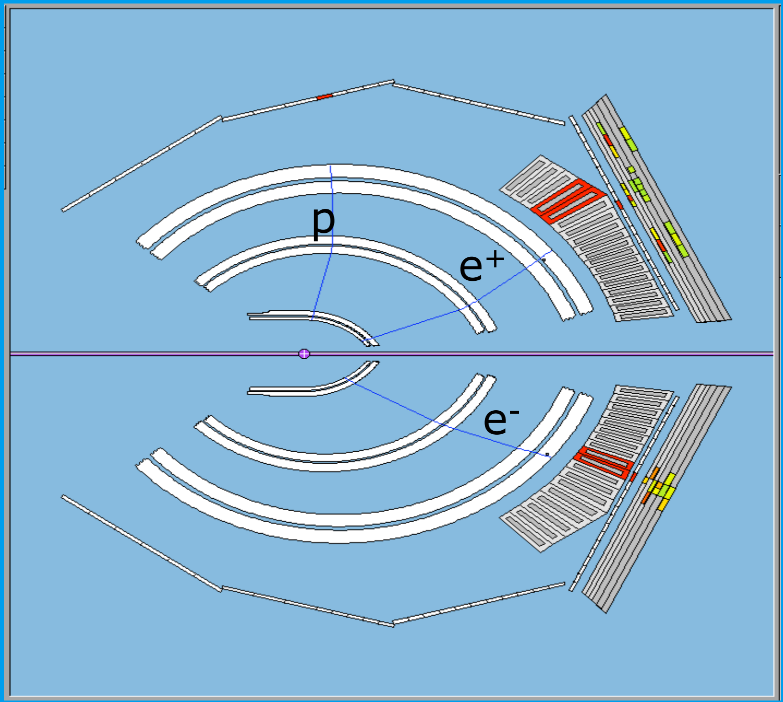




- Proper spacing 2.5 cm to reduce multiple scattering
- Deuterium target as reference, small nucleus, no modification is expected.

Particle Detection with CLAS

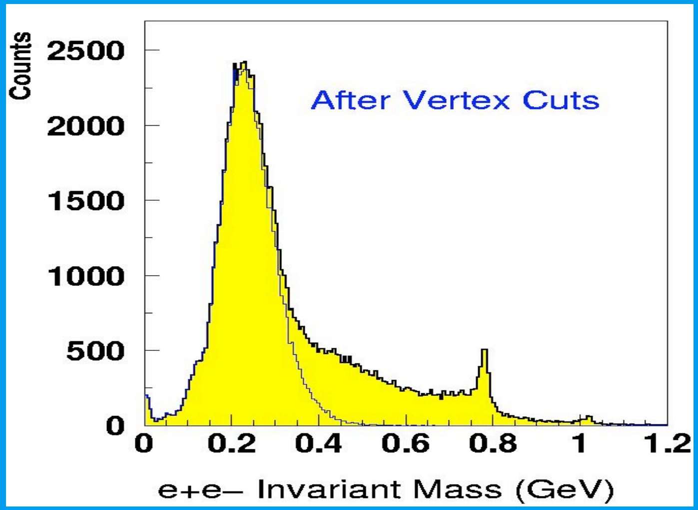
coincident electron pairs in the CLAS

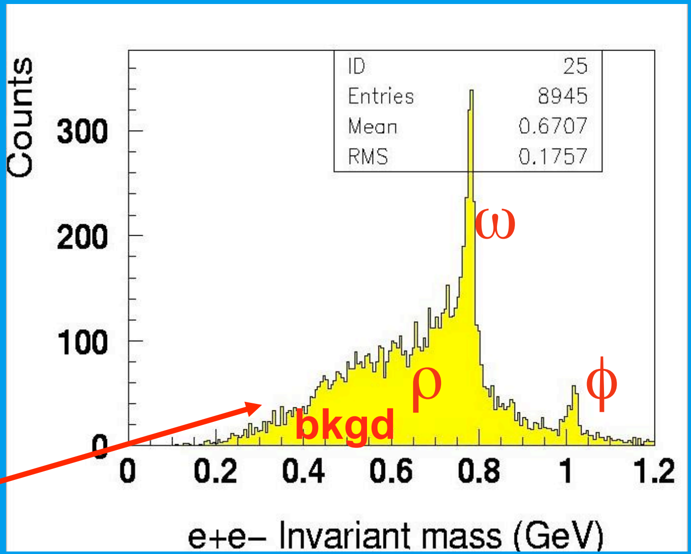


- Momentum corrections
- Target energy loss corrections
- Lepton momentum cuts

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

e^+e^- Invariant Mass Spectra





- **Excellent π/e discrimination: 5.4x10 $^{-4}$ for one and 2.9x10^{-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-

Giesssen BUU Code

"Semi-correlated":

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

Uncorrelated events

The mixed-event technique

The combinatorial background is the random combination of pairs (e^+e^-, e^-e^-, and e^+e^+) due to the uncorrelated sources.

Which belongs to which?

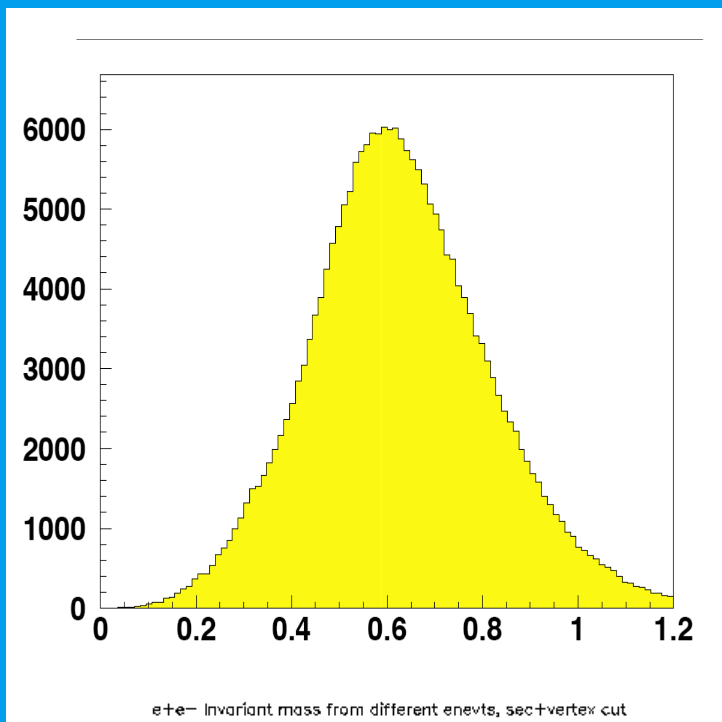
$\gamma \rightarrow e+\ e-$ $\gamma \rightarrow e+\ e-$ $\gamma \rightarrow e+\ e-$ $\gamma \rightarrow e+\ e-$

$\pi^0 \rightarrow \gamma\ e+\ e-$ $\pi^0 \rightarrow \gamma\ e+\ e-$ $\pi^0 \rightarrow \gamma\ e+\ e-$ $\pi^0 \rightarrow \gamma\ e+\ e-$

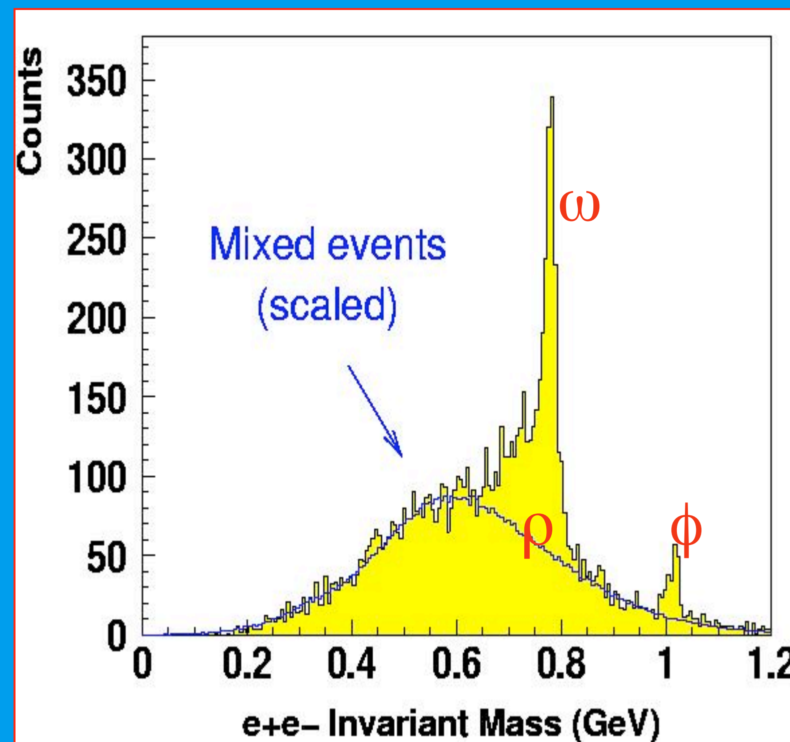
1) Mix e^+ and e^- from different events, use the same acceptance as data to get shape for the uncorrelated background. The normalization of the background comes out of the best fit.

2) Use yield of pairs of identical (e+e+, e-e-) leptons, which are produced only by combinatorial processes, will provide both a natural normalization and shape for the uncorrelated background

Mixed events background without absolute normalization

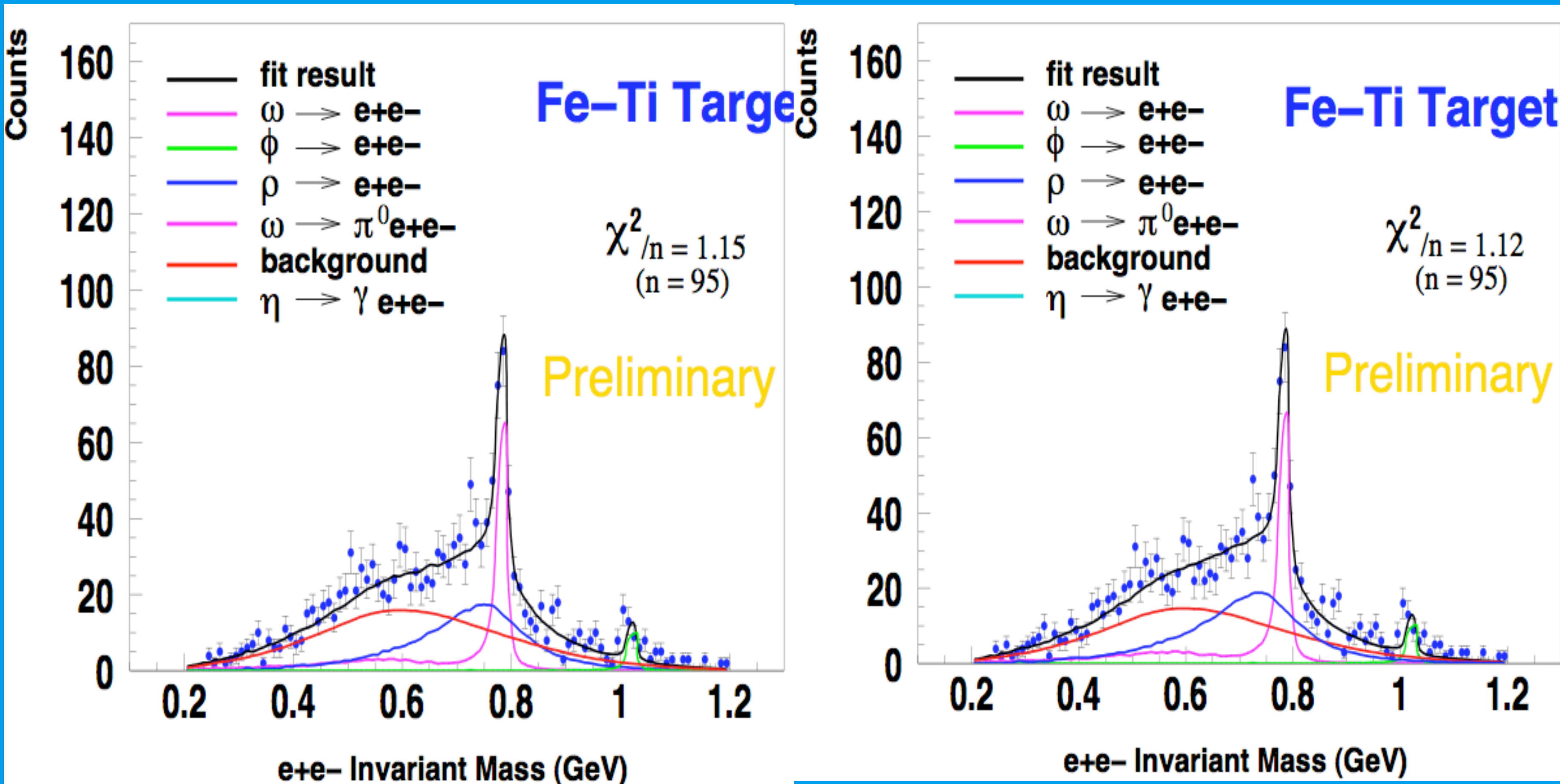


Mixed events background shape for g7 – with sector cuts



In Blue: scaled mixed event background superimposed on g7 data

Fit Results for Fe + Ti



No modification α=0

With modification a la HL α~0.16

Fitting the background together with channels of interest → no credible conclusion

2005 Preliminary conclusions using mixed event shape only

-From χ_2 fit one might conclude (although limited stat) that the data can accommodate a downward mass shift.

-Spectral shape of ρ not well "defined", the "free to move" background **(i.e normalization determined by best fit)** can take away ρ strength.

-In Pb where the background is large, the best fits didn't have a ρ at all, it had to be forced into the fit.

-Overall not satisfactory and hard to conclude

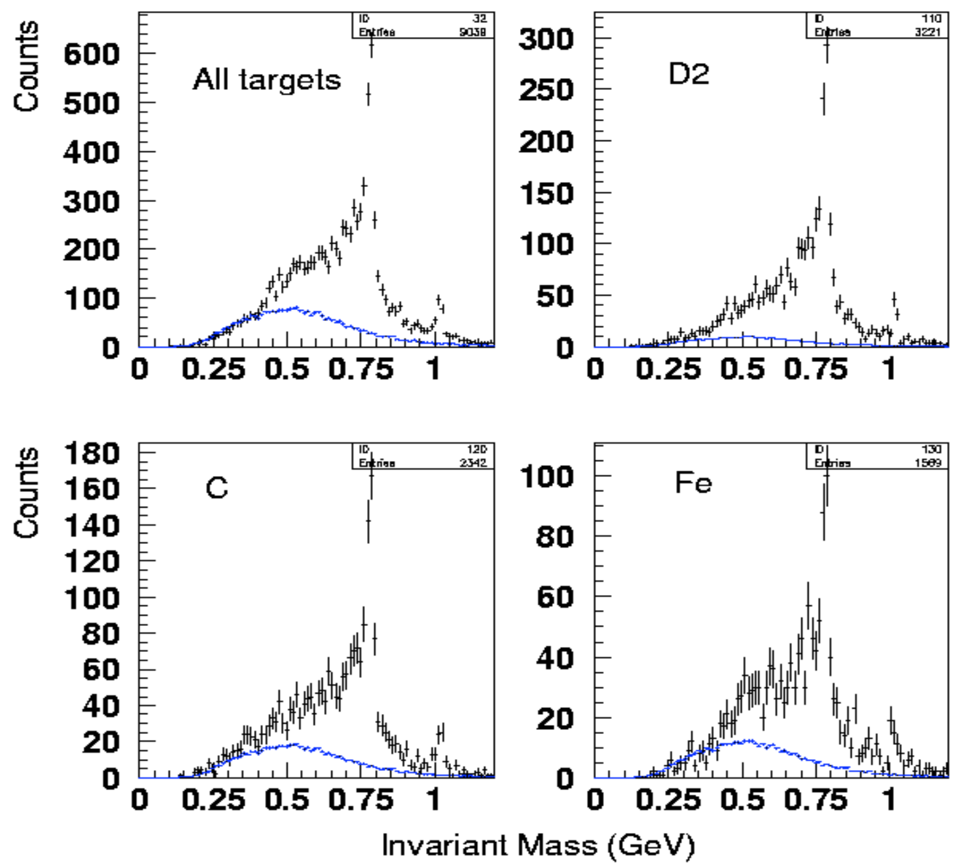
Major improvement of the analysis 2005-2008

- “g7” group went to PAC for more beam time (05).
- PAC required better treatment of mixed event background.
- Group implemented combinatorial mixed events background using same charge pairs ---> much more convincing results (06-07).
  ----> publications
  1 PRL (**Phys. Rev. Lett. 99 (2007) 262302**)
  1 PRC (Phys. Rev. C **78, (2008) 015201**)
  1 PRL in preparation (to submitted 09)
  numerous invited talks

Final Conclusions with Normalized Combinatorial Background

Mixed event technique:

Pairs of identical (e+e+, e-e-) leptons, which are produced by uncorrelated events provide a natural normalization for the combinatorial mixed event background.

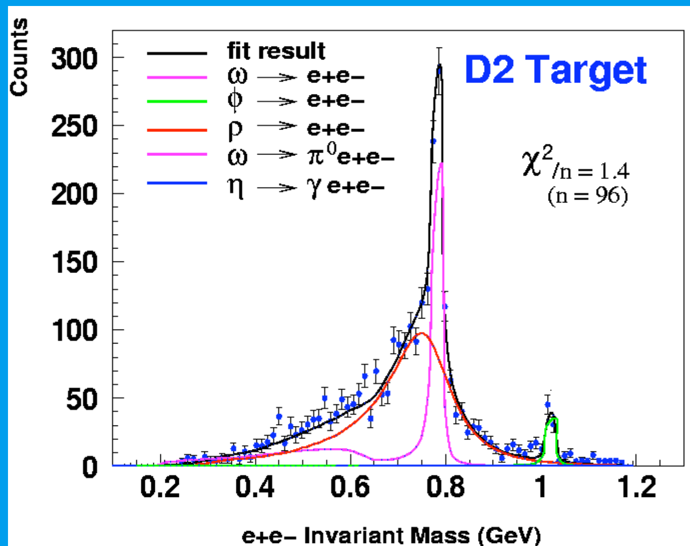


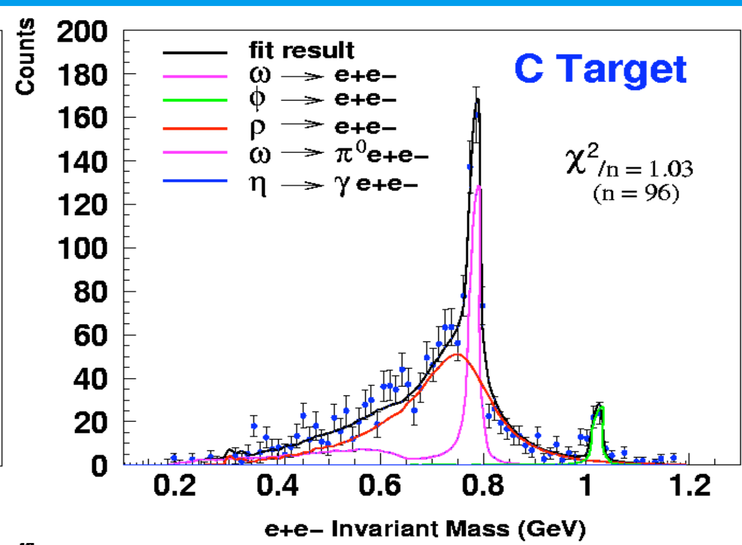
$\mu+\mu-$ measurement: at CERN-SPS ***IPNO-DR-02.015 (2002)***

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

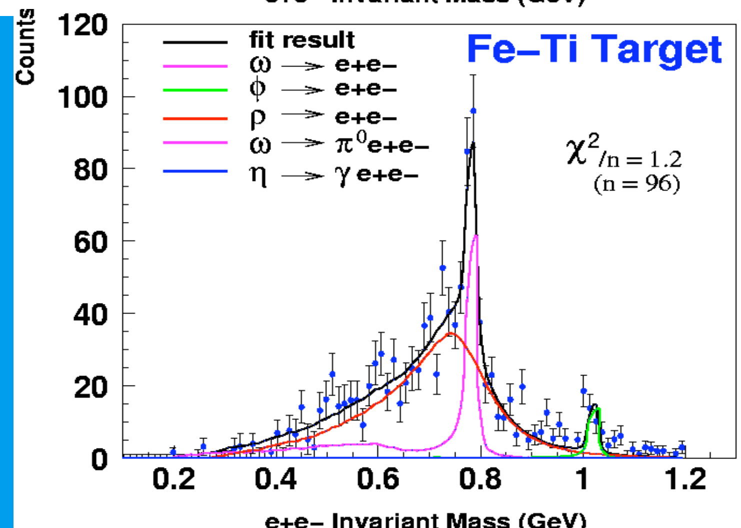
e+e- measurement: at RHIC (***arXiv:nucl-ex/0510006 v1 3 Oct 2005)***

Results: background Subtracted mass spectra

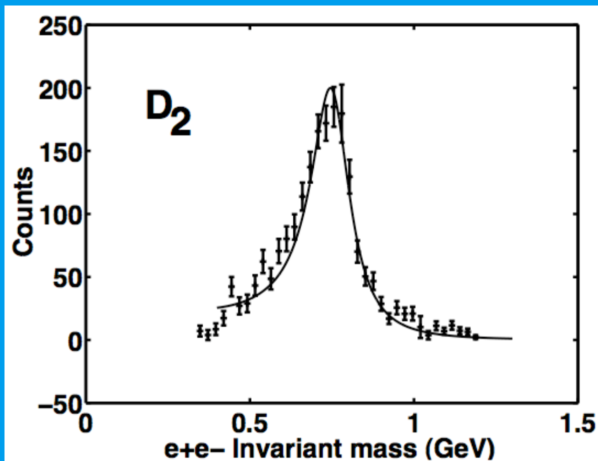


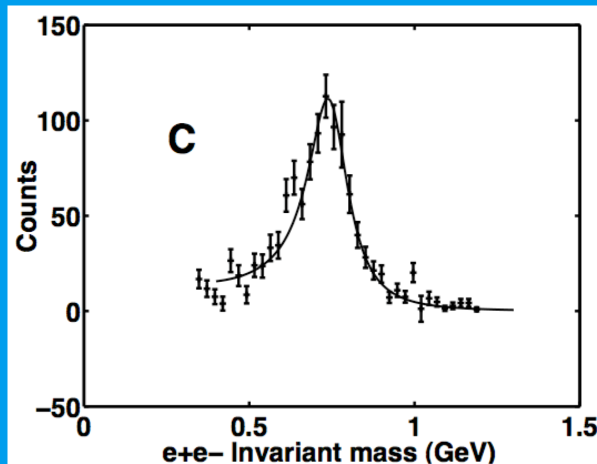


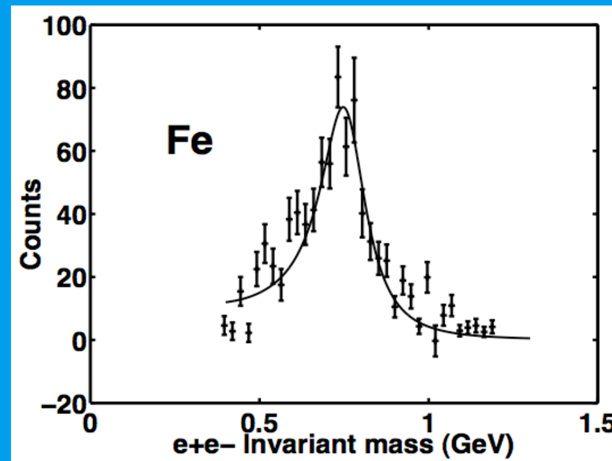
- Data can be described by three vector mesons'decay channels.
- The ϕ and ω contributions are subtracted from these spectra, leaving the measured ρ mass spectra.

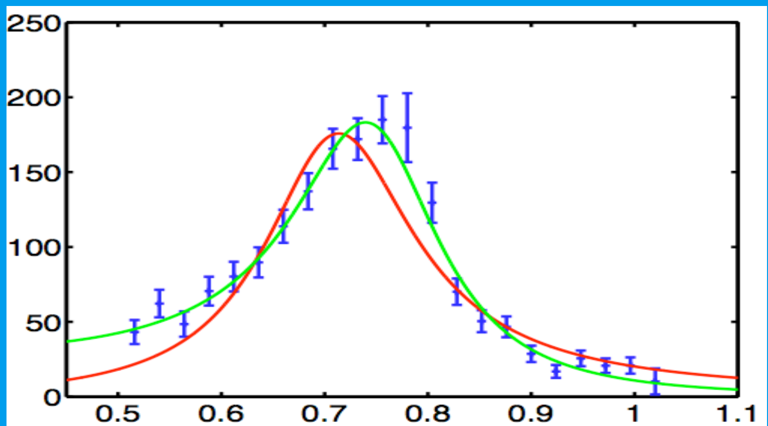


Extracted ρ "mass spectra"





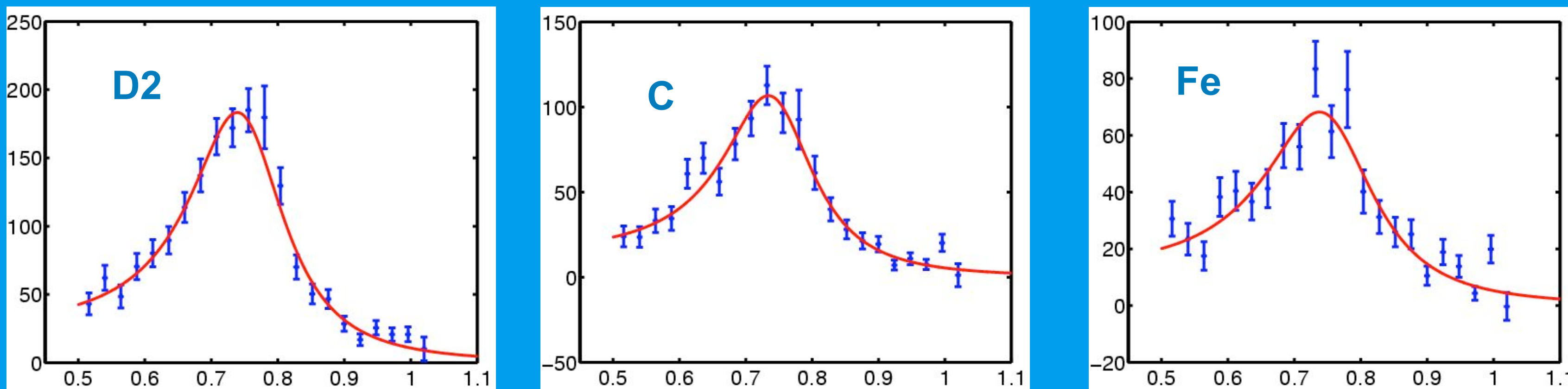




Breit-Wigner

Best fit : includes photon propagator and 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 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.

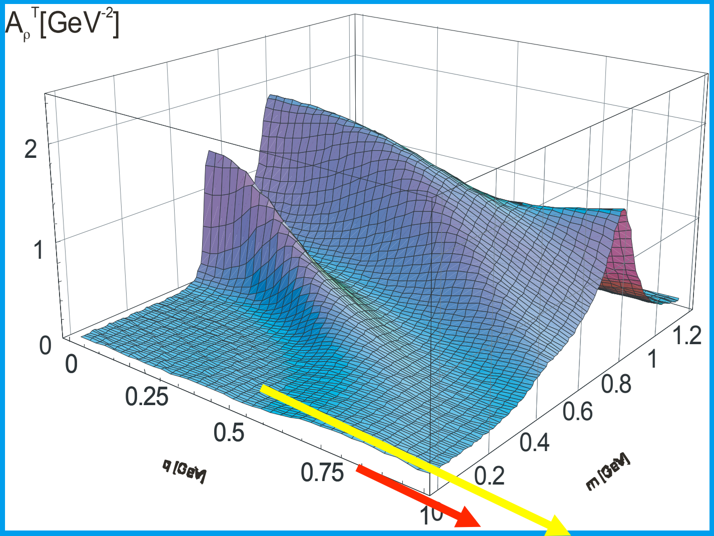
Experimental Results

Elementary Reactions | Rel. Heavy-Ion

	KEK	CBELSA/TAPS		CERES	NA 60
Reaction	$pA \rightarrow (\rho,\omega,\phi)\, A'$ $VM \rightarrow e^+e^-$	$\gamma A \rightarrow \omega A'$ $\omega \rightarrow \pi^0\gamma$		p+Au,Pb+Au $\rho \rightarrow e^+e^-$	In+In $\rho \rightarrow \mu^+\mu^-$
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%~~ RETRACTED(??)		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** **Background (?)**	**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)*

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



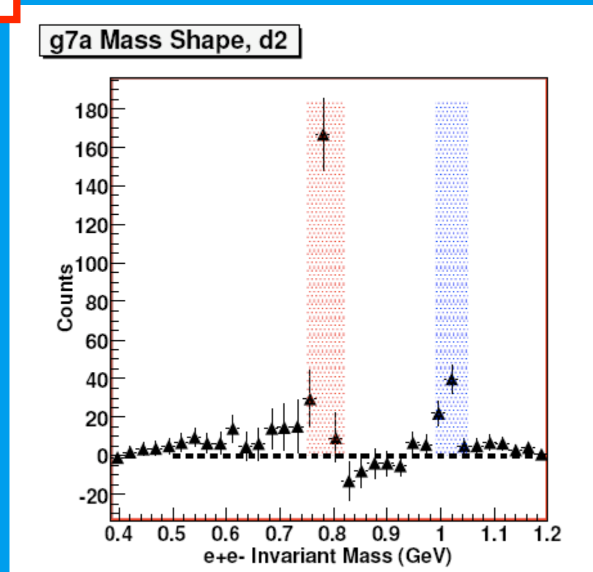
Giessen group (U. Mosel):
W. Peters et al., *NPA 632 (1998) 109*
M. Post et al., *NPA 741 (2004) 81*

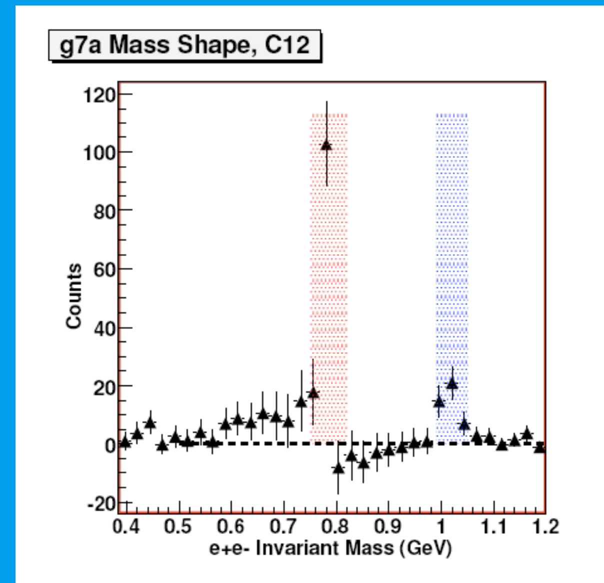
BUU model of ρ meson production and propagation with nucleon resonance-hole contributions.

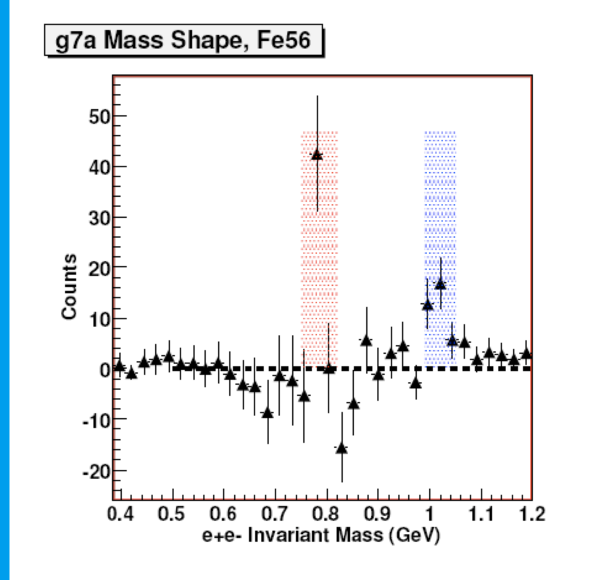
g7a
Planned g7b
Conditionally approved

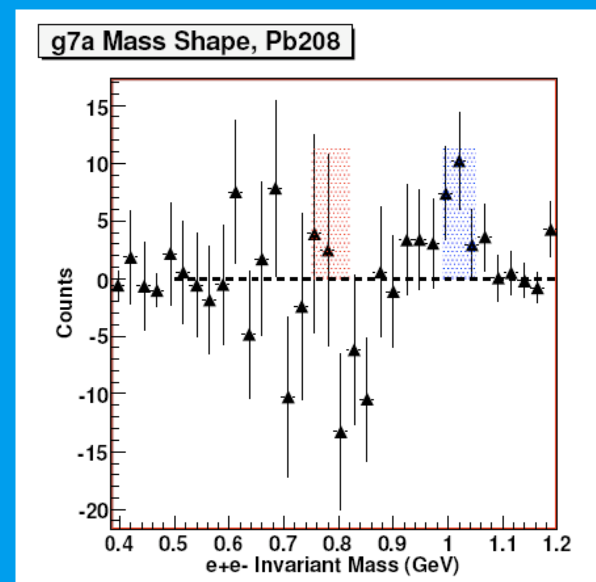
ω/φ Absorption

Mass spectra after subtraction of the ρ meson contribution.









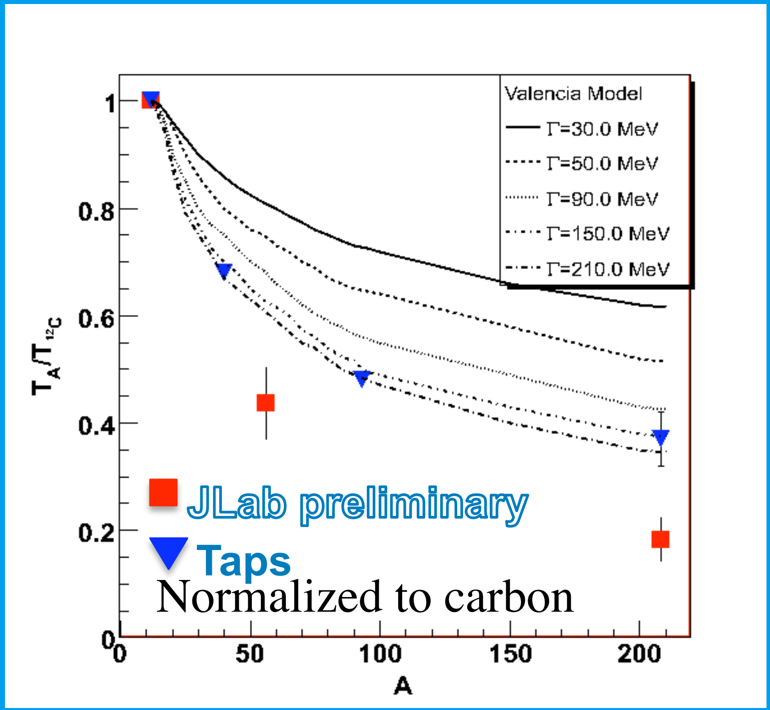
Absorption of ω Meson and its in-medium width

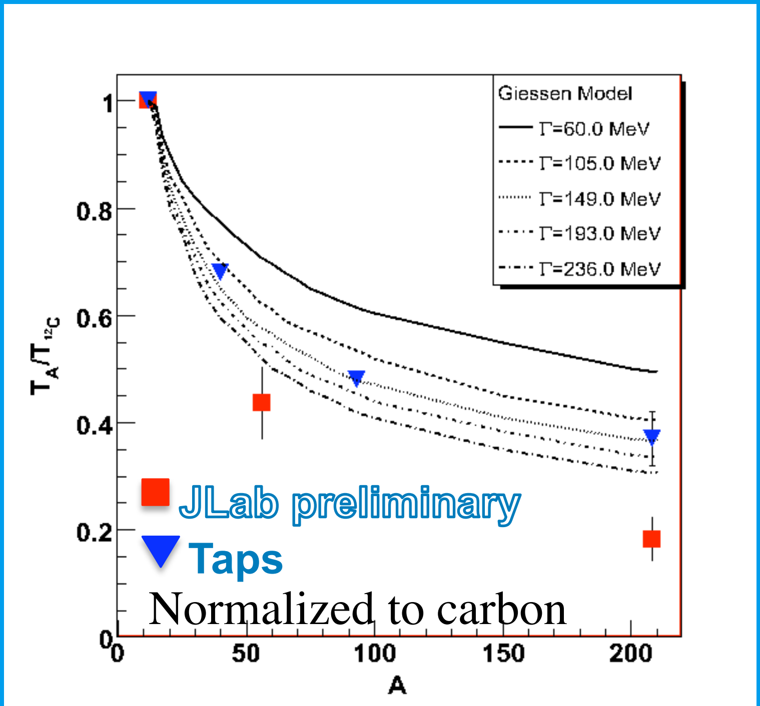
The in-medium width is $\Gamma=\Gamma_0+\Gamma_{coll}$ where $\Gamma_{coll} = \gamma\rho v\sigma^*_{VN}$

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

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

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



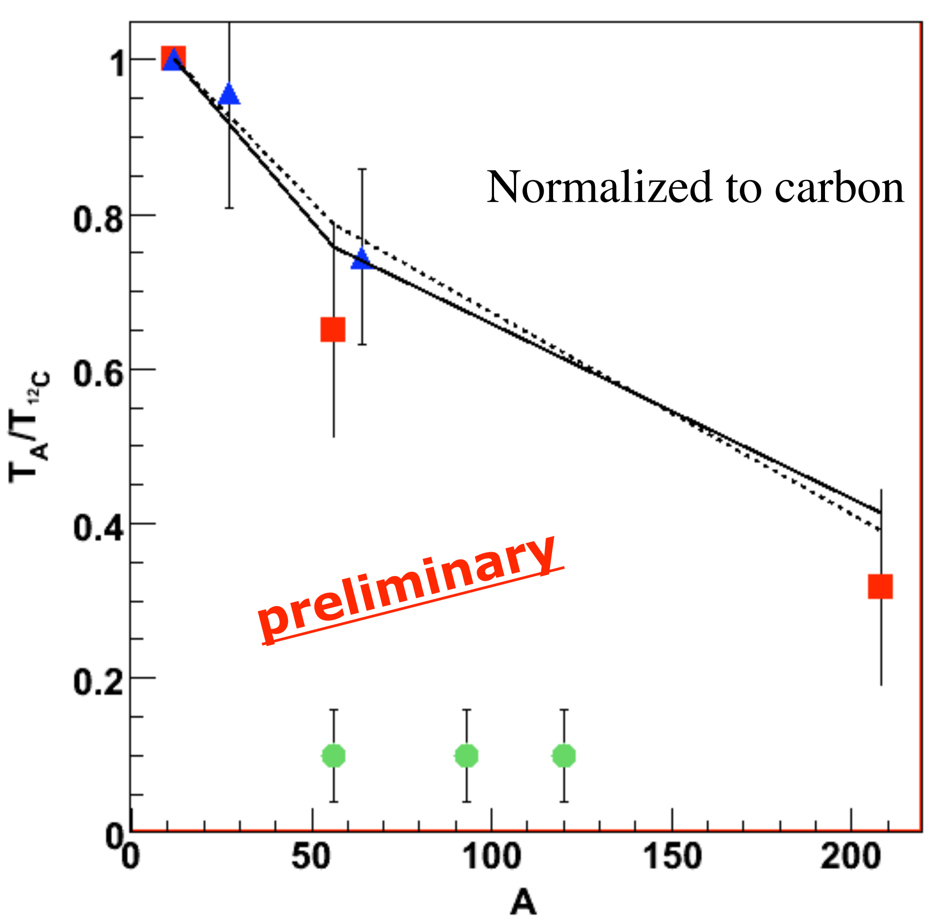


Latest TAPS Γ_ω~130-150 MeV
JLAB preliminary results -> larger width!

- **TAPS (PRL100(2008)192302)**

Comparison to Theory – ϕ–Meson

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



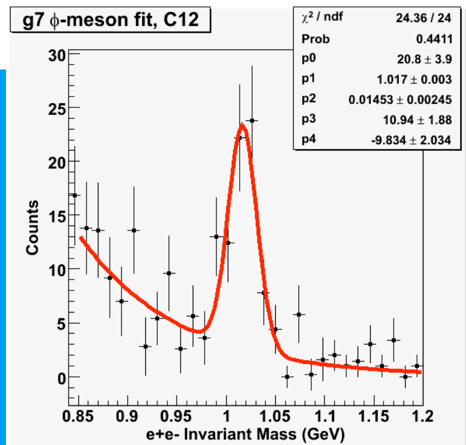
Giessen calculations

Giessen calculations w/ Spring8 absorption strengths

JLab (preliminary)

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

Proposed Jlab run



$$\sigma_{\phi N} \sim 25 - 55 mb$$

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): **PRL 99 (2007) 262302 and Phys. Rev. C 78, 015201 (2008)**

- 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 ~ 200 – 250 MeV!

The ϕ meson (preliminary):

- From transparency ratios, in medium total cross section ~ 25 - 55 mb
-

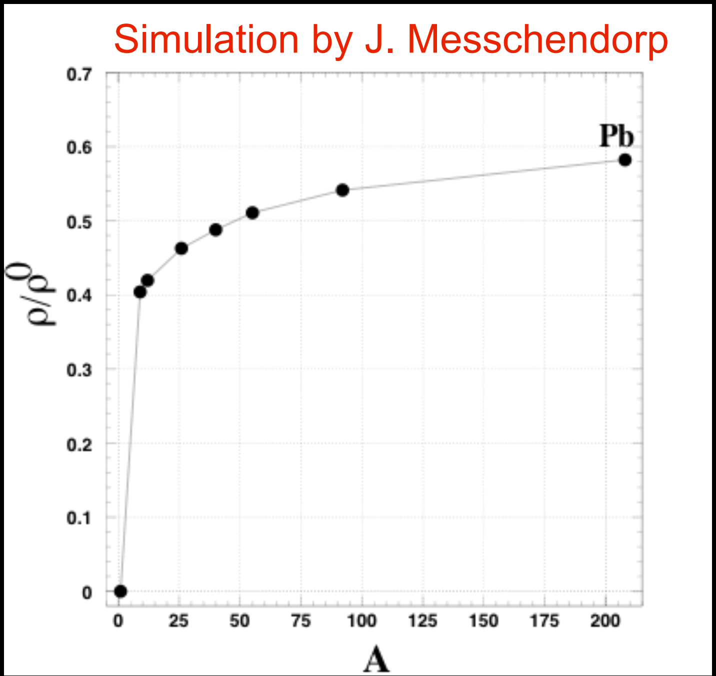
Medium modification studies of vector mesons continue to be a hot topic!

Issues and future plans

More can be done with g7 data:
- Look at Ks absorption in nuclei (analysis in progress)

Use approved experiment g12
- High Statistics measurement of e^+e^- production on H_2

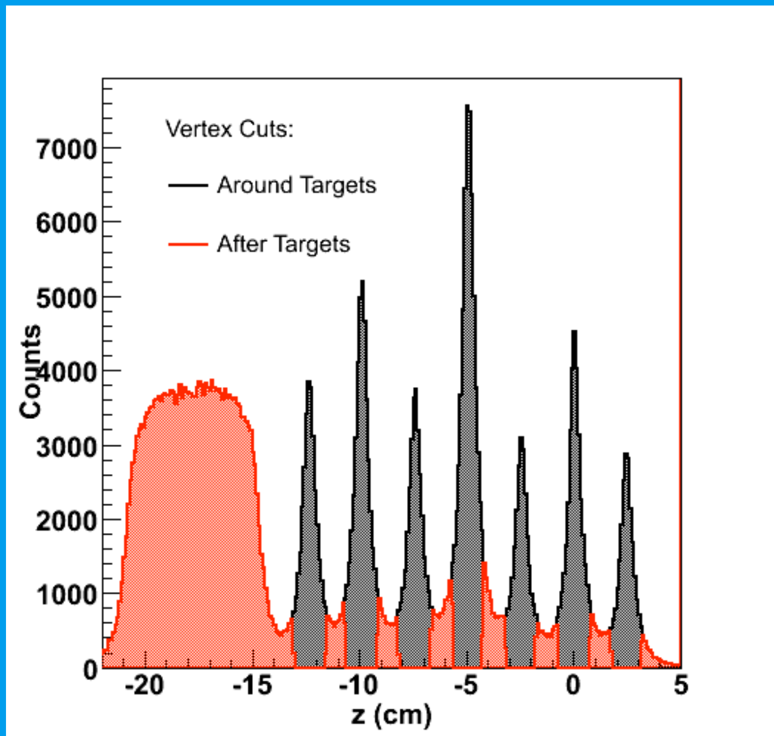
g7b Proposal (approved by PAC 33):
- Experiment with higher statistics → more precise measurement of the ρ mass spectrum in at least one more heavy nucleus.
- Study the momentum dependence of the medium modifications (range from 500 MeV/c to 2.0 GeV/c)
- Compare coherent vs incoherent



On the theory front

- Find how to extract spectral functions from mass spectra
- Mass shift versus width broadening?

K_s Absorption: Event Selection



Selection of $\pi^+\pi^-$ pairs

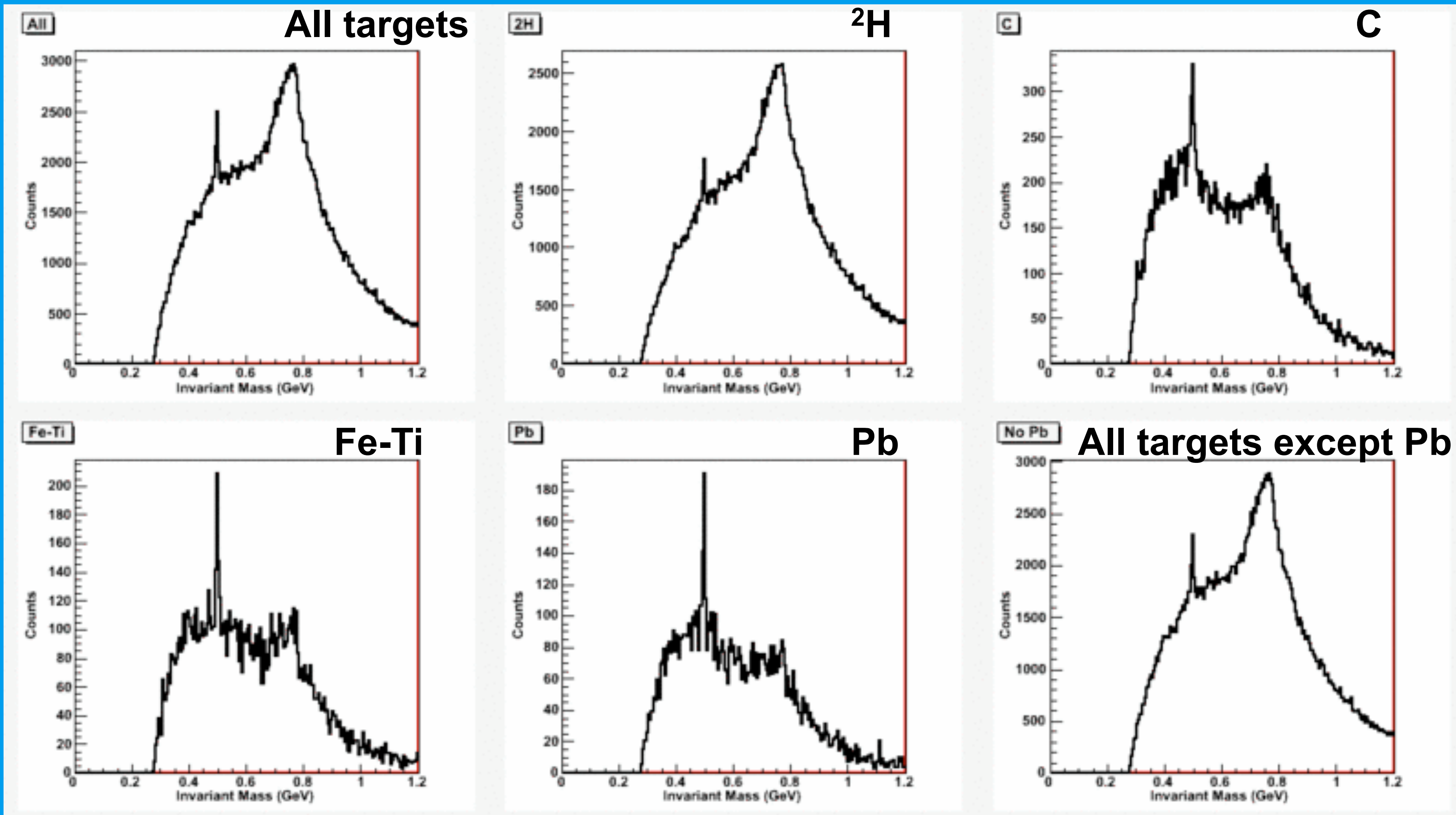
1. At least one π^+ and one π^- per event.
2. Vertex matching
   a) z matching : $\Delta z < 3$ cm
   b) xy cut : $r < 2$ cm
   c) Time matching : $\Delta t < 1.002$ ns

Target selection

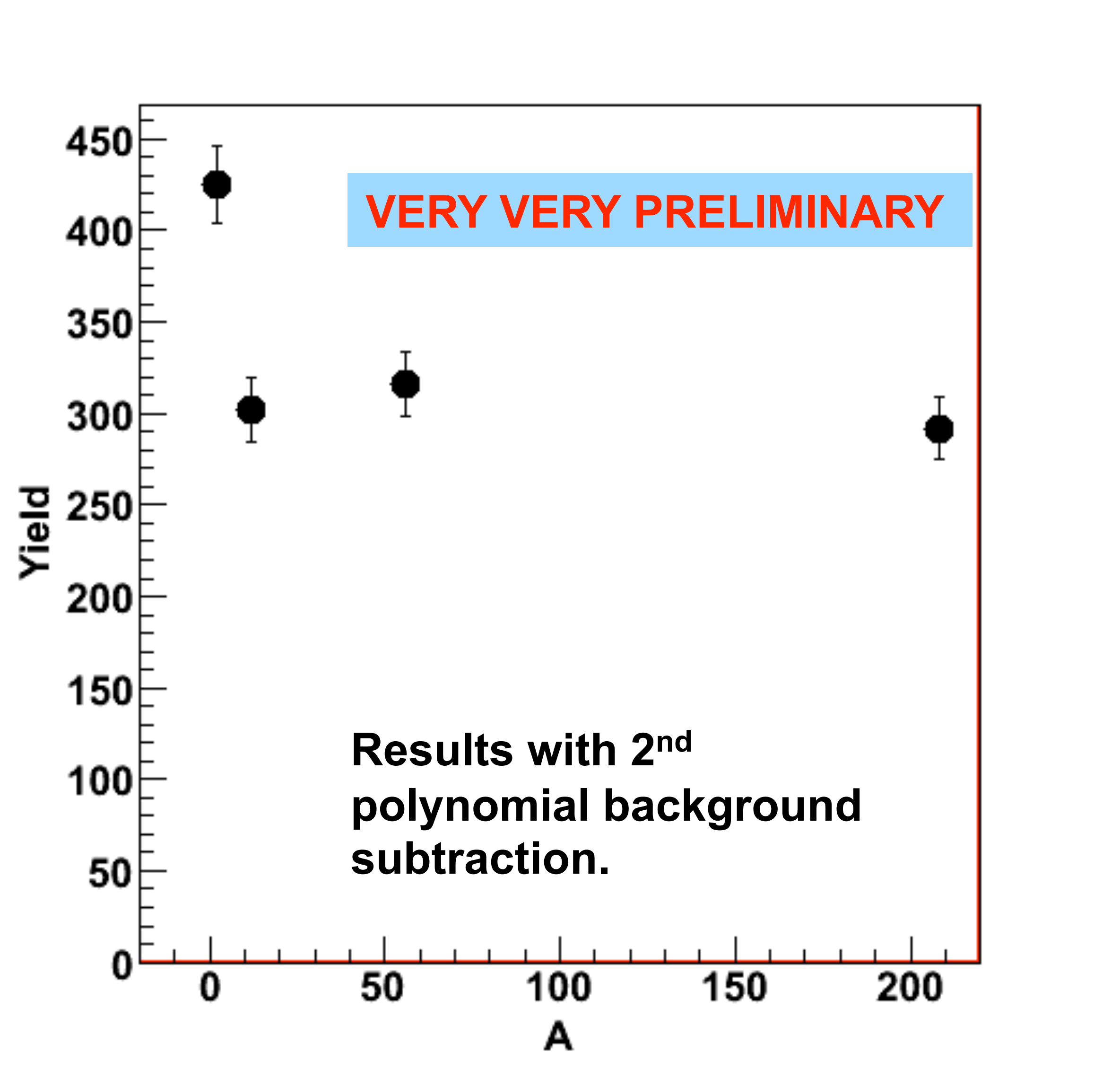
The K_s has a $c\tau$=2.68 cm. The target where the interaction occurred is chosen with the following criteria. The z-vertex of $\pi^+\pi^-$ pairs is

- For the deuterium -> inside the LD2 cell.
- For the solid targets -> after the foil position.

K_s Absorption: $\pi^+\pi^-$ Mass Spectra



K_s Absorption: Preliminary Yields

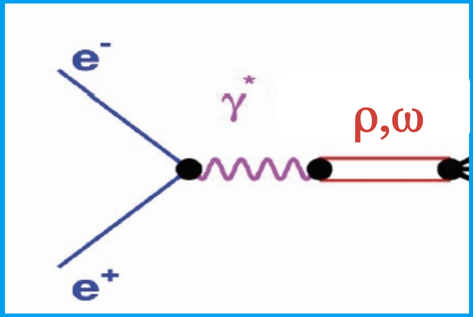


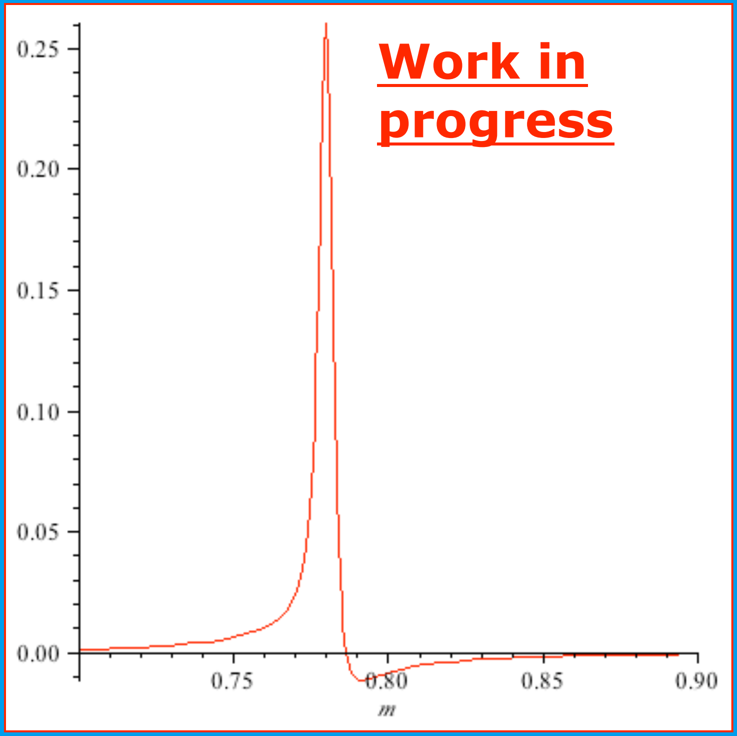
$\rho-\omega$ Interference in H_2 and D_2

The e^+e^- amplitude is modeled as

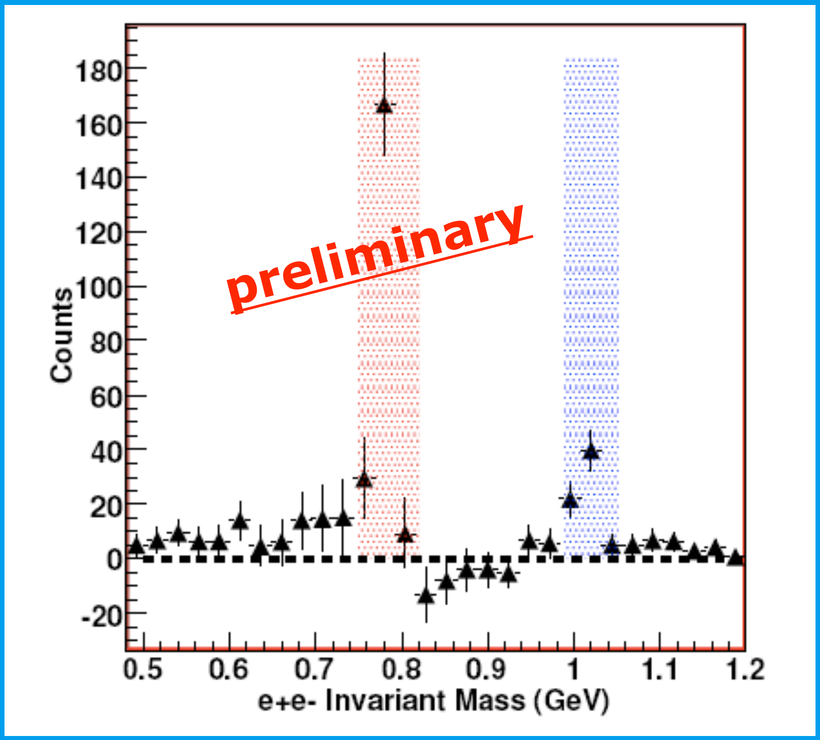
$$F = f_\rho + ie^{i\varphi} f_\omega$$

where $f_{\rho,\omega}$ are relativistic BW shapes.





Interference after subtracting the ρ

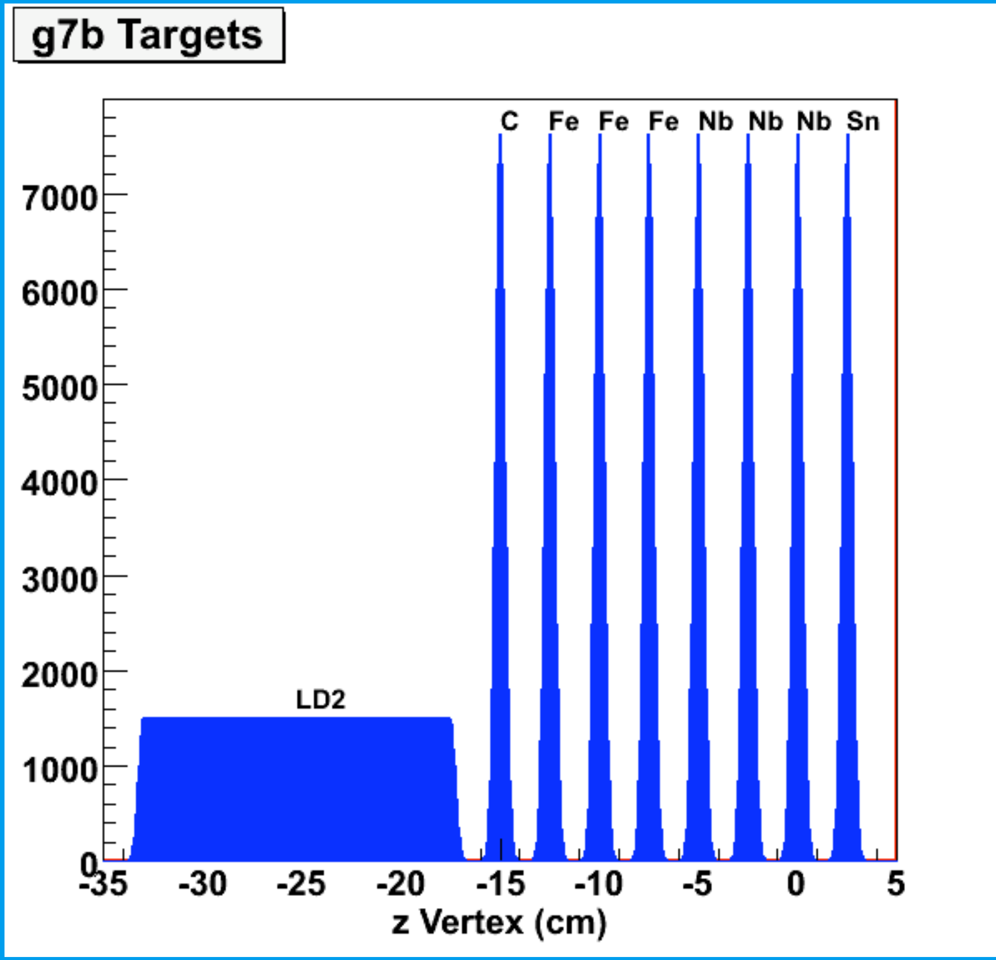


Data from the ^2H target

G7b: New Experiment with CLAS

- Targets:
  LD2, C, Fe, Nb, Sn
- Beam time: 36 days
- Beam energy: 3 GeV

With these running conditions, we will have the statistics to
• study momentum dependence
• confirm Fe results with Nb



Field still very active

- For a nice review : See "*Hadron properties in the nuclear medium*" by Hayano and Hatsuda *eprint arXiv:0812.1702*
- *JPARC experiment on medium modifications (Status?)*
- *Hades pion beam experiments (Planned)*
- *G7b at JLab*
- *Panda at Fair and CLAS12 at JLab*
- *……..*

THANK YOU FOR YOUR ATTENTION