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"Properties of Light Mesons in the Nuclear Medium"

FROM LECTURE ONE

-In the light quark sector (u, d), χ_s is a very good symmetry of the QCD Lagrangian,
-However, χ_s symmetry is spontaneously broken in the vacuum.
-Non zero order parameters ($<0|q\bar{q}|0>$ and f_π "measure" how much the symmetry is broken).
-As T or ρ of the medium increases, χ_s is restored. Properties of mesons are predicted to change.

-So far only "solid evidence" for partial chiral restoration" comes from pionic atom studies (~30% drop of quark condensate).

-Hadrons in final state, BEWARE OF FSI.

LECTURE TWO

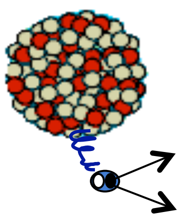
Properties of Vector Meson in the medium (di-lepton decay)
- In relativistic heavy ion collisions
  - DLS, HADES, CERES, NA60, PHENIX
- In nuclei
  - TAGX, KEK,TAPS,JLAB

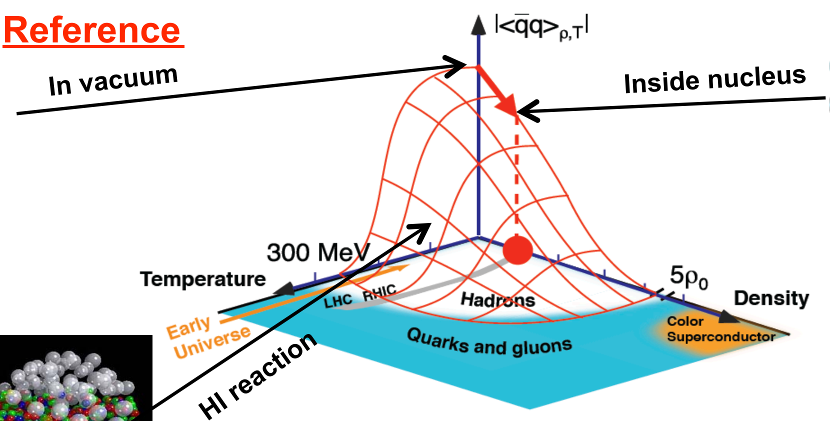
Summary-Conclusions-Outlook

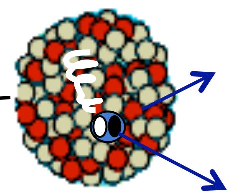
Lot of predictions, now what?

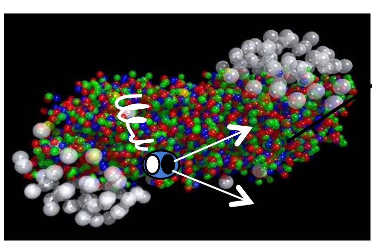
Many different predictions of modification of hadron properties in the medium (mass shift, change in interaction, widening, extra peaks, etc..). Experimentally, one needs to measure and <u>compare the properties of these hadrons in the vacuum and in different media</u> (T and/or ρ ≠ 0).

We are going to look at the properties of vector mesons ρ, ω and ϕ in nuclei and Relativistic Heavy Ion (RHI) collisions.









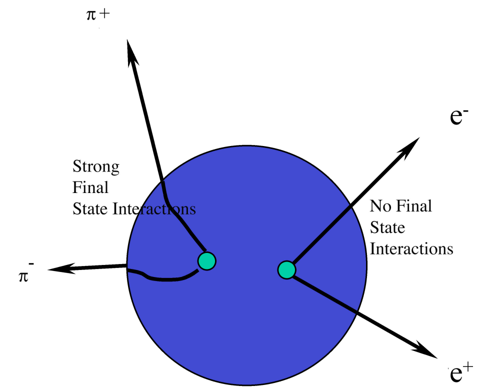
γ+H, γ +²H, γ +³He, γ +Li,
γ+C, , γ +Al, γ +Fe, γ +Nb, γ +Pb
Eγ ~0.6-4 GeV
p+C, p+Cu (E_p=12 GeV)

p+p, d+p, p+ Be, p+Au,p+Nb, p+W
C+C, Ca+Ca, S+Au, Pb+Au, Ar+KCl
In+In, Au+Au
@ 1 to 200 AGeV

Vector mesons in Medium

Meson	Mass (MeV/c^2)	Γ (MeV/c2)	$c\tau$ (fm)	Main decay	$\Gamma_{e+e-}/\Gamma_{tot}$ (x10^{-5})	$\Gamma_{\mu+\mu-}/\Gamma_{tot}$ (x10^{-5})
ρ	775.49 ±0.34	149.4±1.0	1.3	$\pi^+\pi^-$ (~100%)	4.7	4.6
ω	782.65 ±0.12	8.49±0.08	23.2	$\pi^+\pi^-\pi^0$ (89%)	7.2	9.0
ϕ	1019.45 ±0.02	4.26±0.04	46.2	K^+K^- (49%)	3.1	3.2

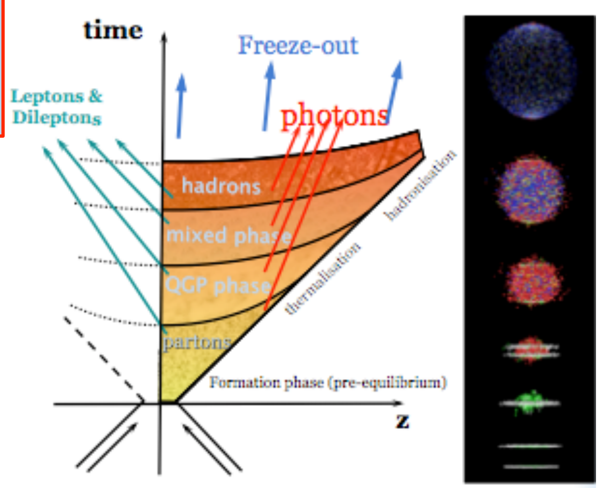
Properties of Vector Mesons $J^p=1^-$ (PDG-2008)



-The **predicted medium modifications are large** (even at normal nuclear density, they can be observed).
-Decay fast enough to **test the medium** (specially the ρ)
-D<u>i-leptons</u> (**no FSI**) carry "clean information" of the system at the time of production (either a nucleus or a fire ball in HI collisions).

However, these are **very difficult measurement**. The di-lepton decay has a **very small branching ratio** (~10^{-5}). One needs:

1) excellent **lepton-hadron discrimination**,
2) to **control "huge" combinatorial background** (severe in HIC).
3) to account for all other physics channels leading to di-leptons,

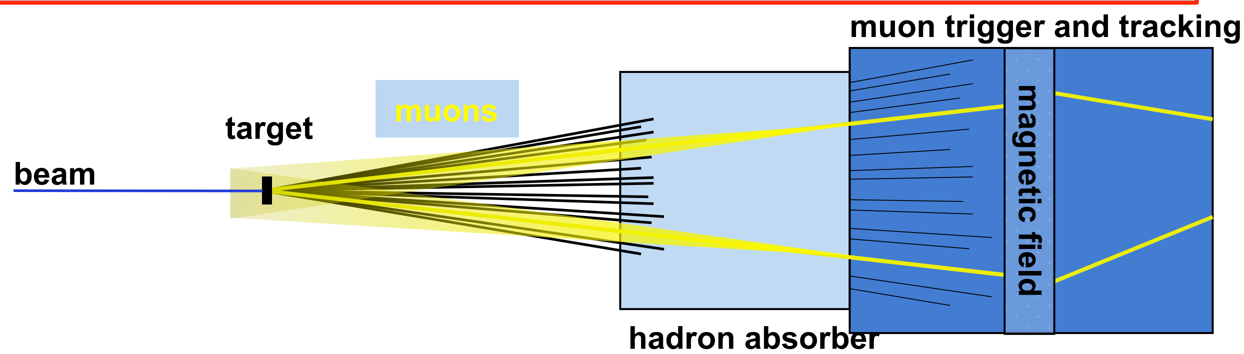


Vector mesons in Medium (lepton-hadron discrimination)

Detecting $\mu^+\mu^-$ final state.

-Muons from pion and kaon decays are orders of magnitude more abundant than those from the vector meson decay → it is essential to have a thick absorber as close as possible to interaction area.
Multiple scattering (especially for low energy muons) affects invariant mass resolution.
Good magnetic spectrometer to measure momentum of muons

Standard dimuon detection: NA50, PHENIX, ALICE, …



Detecting e^+e^- final state.

Excellent π-e discrimation needed (π-pair suppression ~10^{-6} needed). Done with combination of Cerenkov detectors (standard or ring imaging) and electromagnetic calorimeters.
-Good magnetic spectrometer (to measure momentum of electron, positrons) needed for good invariant mass resolution.
-understand and control all sources of electromagnetic background (minimize high Z materials)
-thin multilayer targets

Vector mesons in Medium (combinatorial background)

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

Di-lepton pairs from uncorrelated events:

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

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

Pairs of identical (e^+e^+, e^-e^-) leptons, which are produced only by uncorrelated processes, will provide both a natural normalization and shape of the combinatorial background (CB). If enough same sign pairs measured, then in each invariant mass channel :

$$Signal = N_{+-}^{meas} - CB = N_{+-}^{meas} - 2\sqrt{N_{++}^{meas} N_{--}^{meas}}$$

(same acceptances for + and -)

$$Signal = N_{+-}^{meas} - CB = N_{+-}^{meas} - 2\sqrt{N_{++}^{meas} N_{--}^{meas}}\,\frac{A_{+-}}{\sqrt{A_{++}A_{--}}}$$

(≠ acceptances for + and -)

experiment	NA60	PHENIX	NA45	HADES	KEK	TAPS	JLab
Signal/CB	1/11	1/100	1/22	~1	1/2 - 1	0.7-1	2-3

For more details see references:

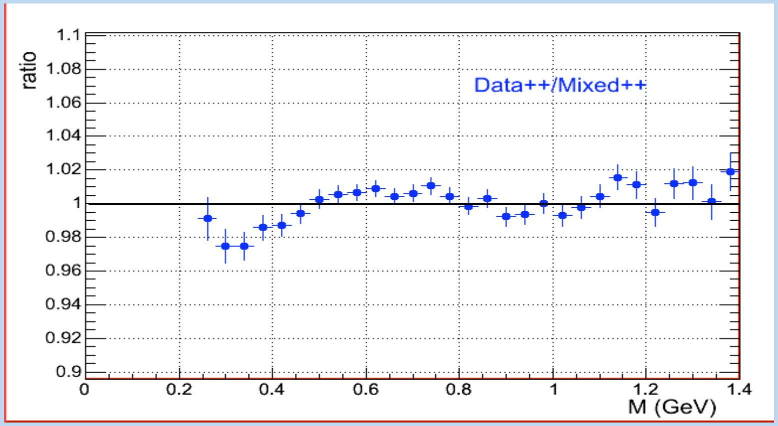
$\mu+\mu-$ measurement: at CERN-SPS *IPNO-DR-02.015 (2002)*
$\pi+\pi-$ measurement: at CERN-ISR *(Nucl. Phys. B124 (1977) 1-11).*
e+e- measurement: at RHIC *EJPC49(2007)243; NPA774(2006)743).*

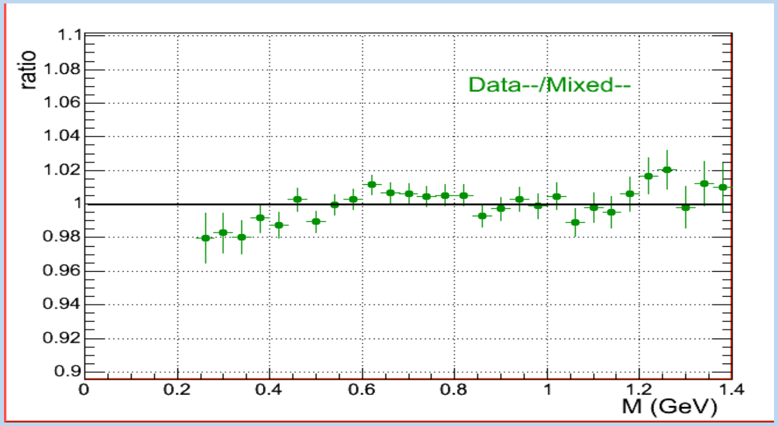
Vector mesons in Medium (combinatorial background)

If not enough identical pairs have been collected, then to reduce statistical uncertainties on the background:

-One randomly mixes unlike sign tracks from different measured event with same event topology (this is repeated until a high statistics background spectra is obtained)

-Making sure shape of measured and generated same sign spectra are close





The generated unlike sign background spectrum can then be normalized by CB:

$$CB = 2\sqrt{N_{++}^{meas} N_{--}^{meas}}$$

$where : N_{++}^{meas}, N_{--}^{meas}$ **are summed over all invariant mass channels**

Vector mesons in Medium (other sources of di-leptons)

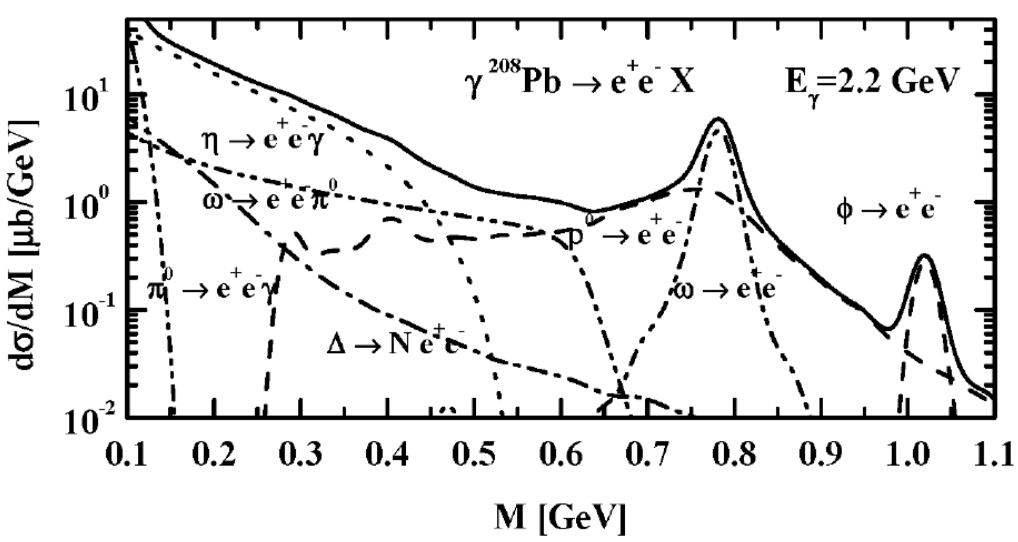
1) After clean di-lepton spectrum is obtained (lepton-hadron discrimination)
2) Combinatorial background is subtracted (same sign pairs method)
3) All contributions from physical sources have to be determined (called COCKTAIL) and compared to the measured spectrum to look for excess or lack of strength

Direct: $\rho \rightarrow e+e-$, $\omega \rightarrow e+e-$, $\phi \rightarrow e+e-$, $J/\psi \rightarrow e+e-$, $\psi' \rightarrow e+e-$

Dalitz: $\pi^0 \rightarrow \gamma e+e-$, $\eta \rightarrow \gamma e+e-$, $\omega \rightarrow \pi^0 e+e-$, $\phi \rightarrow \eta e+e-$, $\Delta \rightarrow N e+e-$

Heavy flavor: $cc \rightarrow e+e- +X$, $bb \rightarrow e+e- +X$

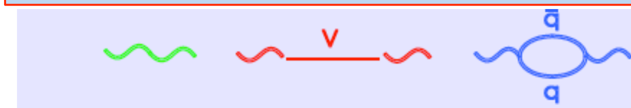
Drell-Yan: $qq \rightarrow e+e-$



Many Transport codes are available (HSD, UrQMD, RQMD, IQMD, BRoBUU, GiBUU, …) to calculate all these channels. One passes the predictions through the acceptance of the detector before comparing to data

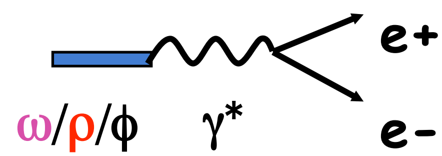
Vector mesons in Medium (ingredients of models)

Photo-production case



-Incoming photon as hadron
-Shadowing: hadronic character of photon
-Primary production in first reaction
-In-medium propagation of produced particles out of nuclear volume: self-energies, widths,
-All nuclear resonances,
-Final State interaction interaction: : absorption absorption, side-feeding by CC effects

i	Dilepton channel	
1	Dalitz decay of π^0:	$\pi^0 \to \gamma e^+ e^-$
2	Dalitz decay of η:	$\eta \to \gamma e^+ e^-$ (or $\mu^+\mu^-$)
3	Dalitz decay of ω:	$\omega \to \pi^0 e^+ e^-$
4	Dalitz decay of Δ:	$\Delta \to N e^+ e^-$
5	direct decay of ω:	$\omega \to e^+ e^-$
6	direct decay of ρ:	$\rho \to e^+ e^-$
7	direct decay of ϕ:	$\phi \to e^+ e^-$
8	direct decay of J/Ψ:	$J/\Psi \to e^+ e^-$
9	direct decay of Ψ':	$\Psi' \to e^+ e^-$
10	Dalitz decay of η':	$\eta' \to \gamma e^+ e^-$
11	pn bremsstrahlung:	$pn \to pne^+e^-$
12	$\pi^\pm N$ bremsstrahlung:	$\pi^\pm N \to \pi N e^+ e^-$, where $N = p$ or n



Strongly *m-dependent near threshold*

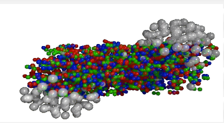
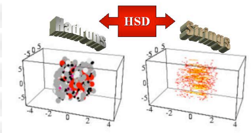
Spectral Function

$$\sigma_{\rm BW} \sim \frac{\pi}{k^2} \Gamma_{\rm in} \frac{s\Gamma_{\rm tot}}{(s-m^2)^2 + s\Gamma_{\rm tot}^2} B_{\rm out} \times \text{FSI}$$

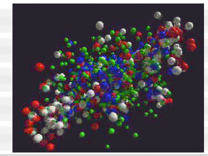
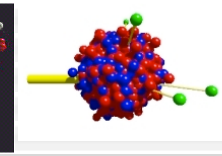
IMPORTANT for hadrons in final state

Can be strongly *m-dependent*

From U. Mosel, WWND09

Some Transport Codes

- **HSD** (Hadron-String Dynamics)

http://th.physik.uni-frankfurt.de/~brat/hsd.html

- **UrQMD) (**Ultra relativistic Quantum Molecular Dynamics)

http://th.physik.uni-frankfurt.de/~urqmd/

- **RQMD (Tübingen)(**Relativistic Quantum Molecular Dynamics)
- **IQMD (Nantes) (**Isospin-QMD)

http://www-subatech.in2p3.fr/~theo/qmd/

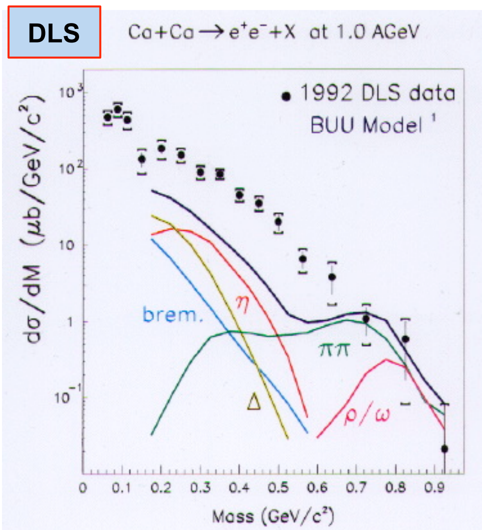
- **BRoBUU (Rossendorf)**
- **GiBUU (Giessen** Boltzmann-Ühling-Uhlenbeck)

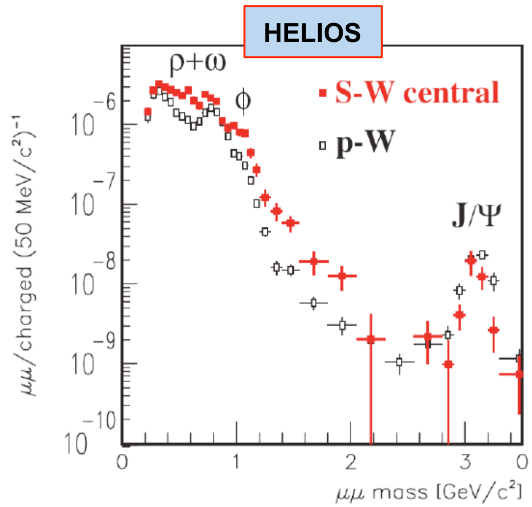
http://gibuu.physik.uni-giessen.de/GiBUU

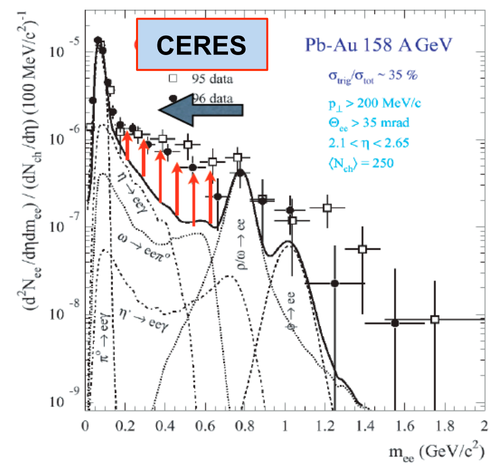
Not exhaustive list

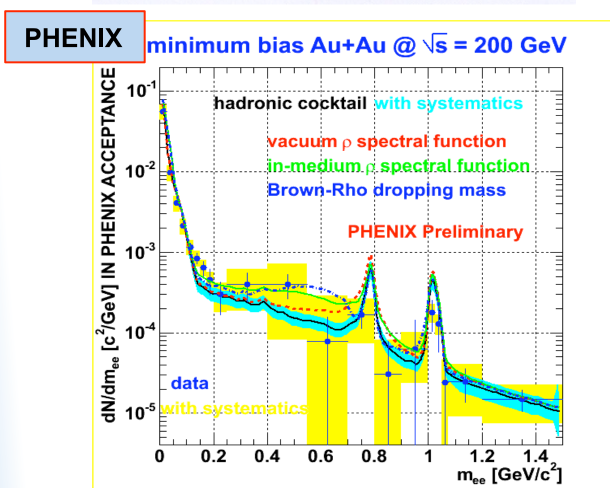
Vector mesons in Medium (Any observations?)

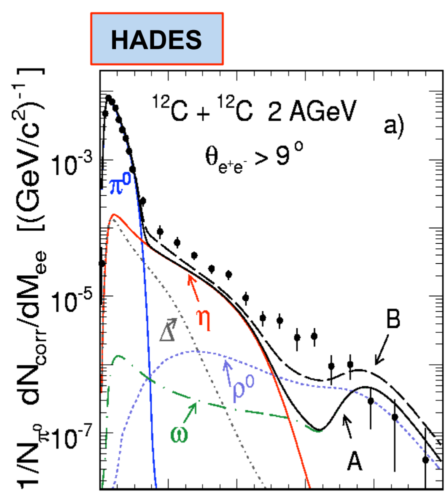
First measurements of possible medium modification of VM came from RHI collisions

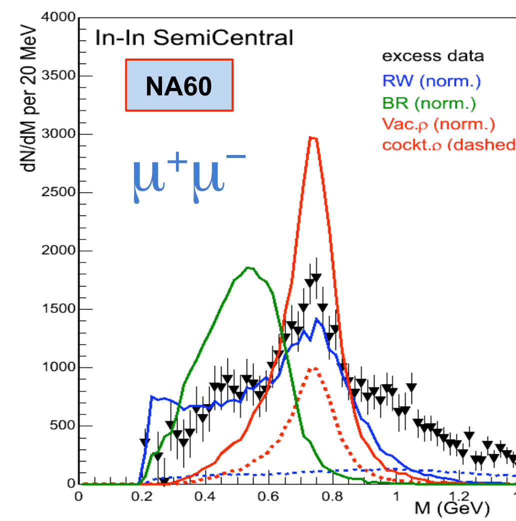






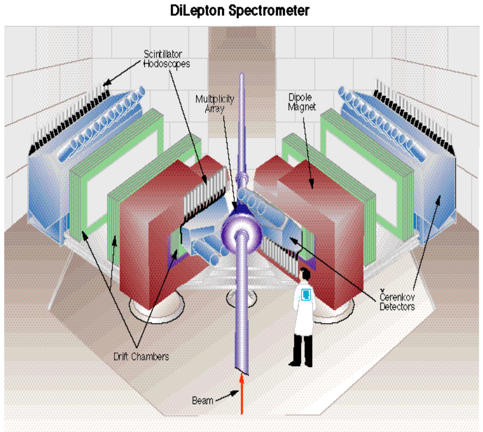


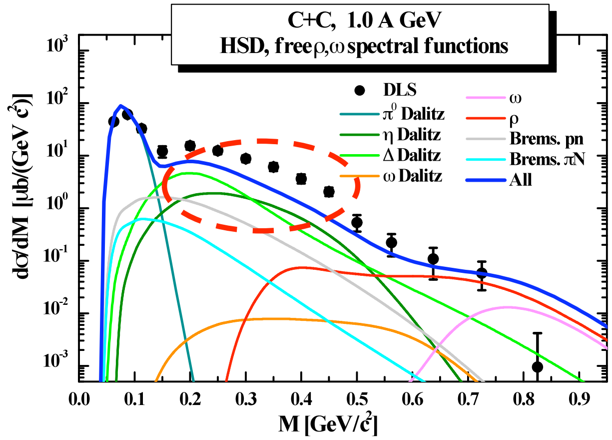


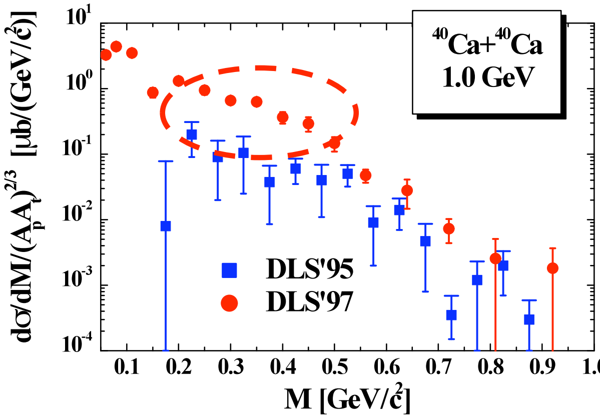


DLS(@ Bevalac): C+C, Ca+Ca at 1AGeV

DLS reported the first di-lepton excess in the VM mass region







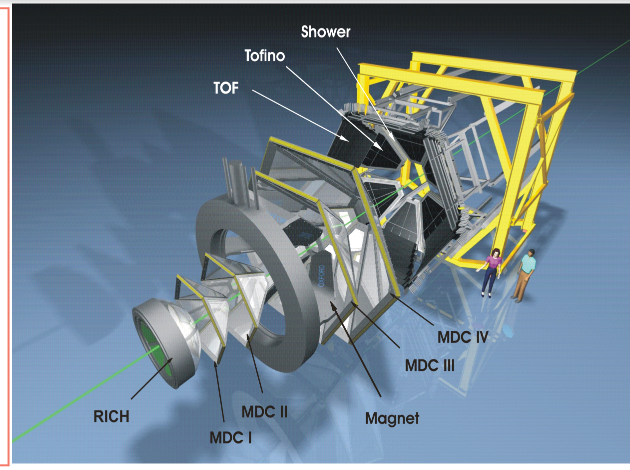
PRL 61 (1988) 1069; PRL62 (1989) 2652; PRL79 (1997) 1229

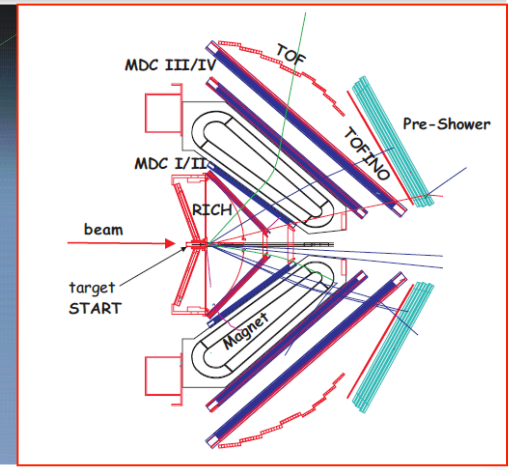
Until recently even with best transport model calculations (even including in medium ρ modification), theory under predicted measured e+e- yield by ~3 in the **0.15 < M < 0.5 GeV** range!!

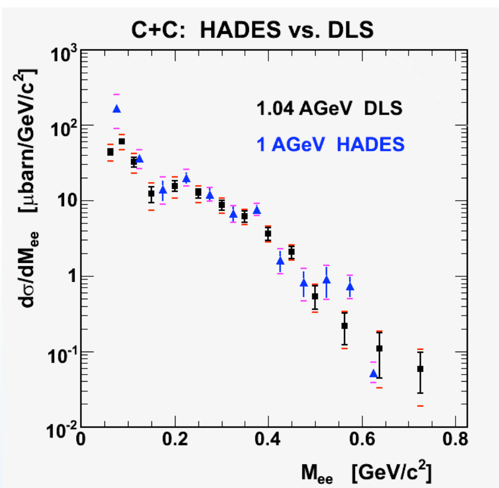
Since 1997, this was called the DLS puzzle
Recently solved by HADES

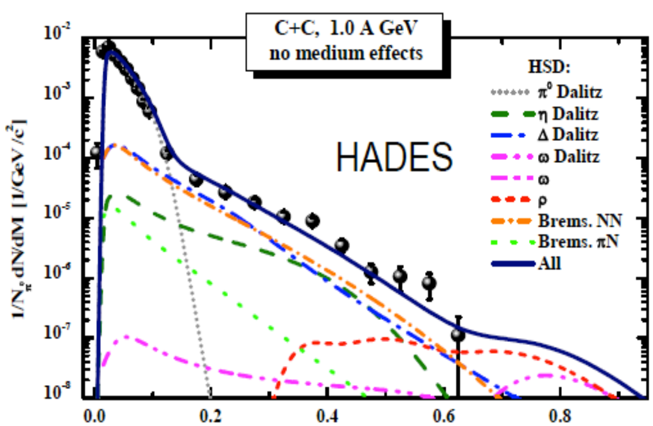
High Acceptance Di-Electron Spectrometer (HADES) at GSI

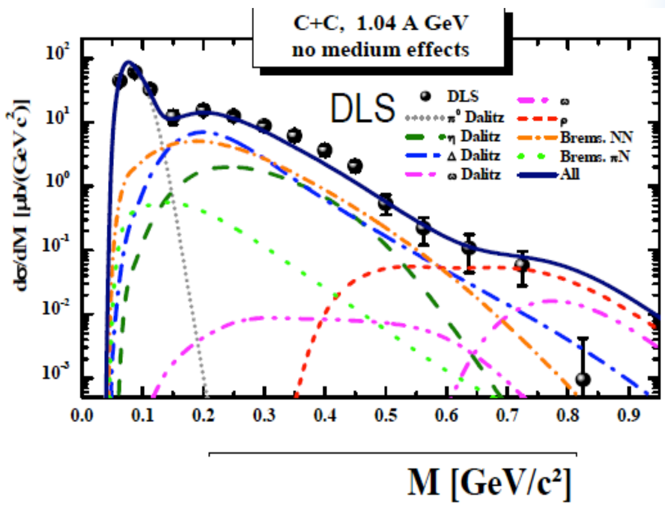
Beams: π, p and Nuclei 1-2 AGeV
Full azimuth, polar angles 18°-85°
Pair acceptance ≈ 0.35
seg. solid or LH_2 targets
RICH: π − suppression: 10^4
super-conducting toroid: $B\rho$ = 0.34 Tm
$\Delta m/m$~2% at ρ-mass
C+C (1,2AGeV); p+p (1.2, 2.2, 3.5 GeV); d+p (1.25 GeV),p+Nb (3.5AGeV),..









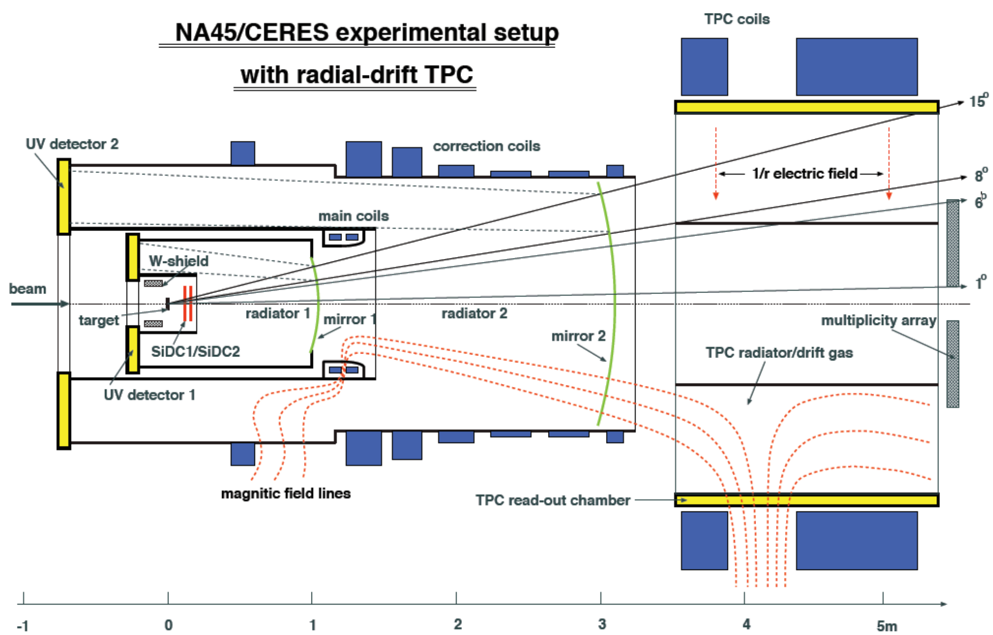


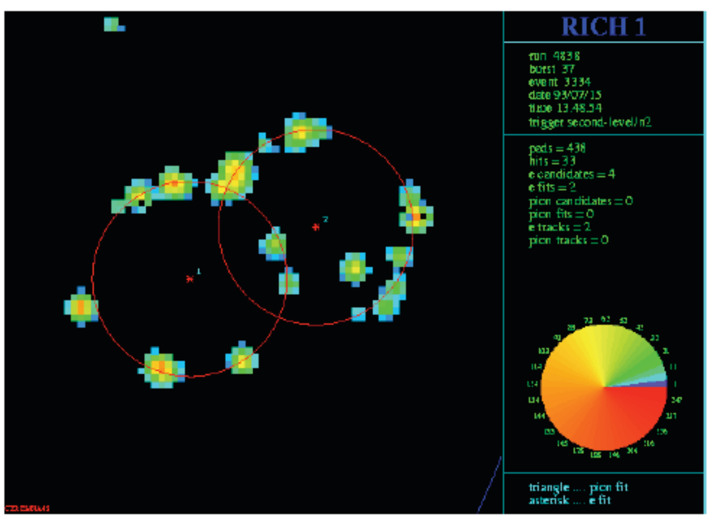
DLS puzzle solved !

HADES and DLS agree, and are compatible with new Transport calculations (with some ρ broadening and better NN Bremsstrahlung) [NPA807(2008)214]

NA45 (CERES) @ SPS CERN

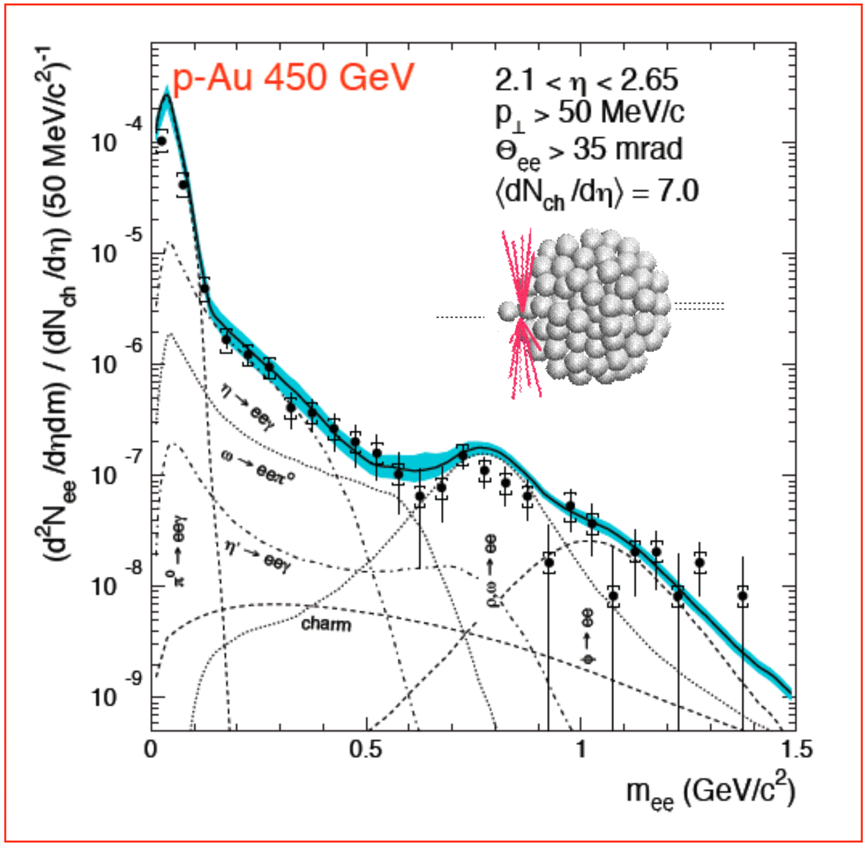
-Studying low mass region region up to ~1.5 GeV/c^2
-e^+e^- measured in p+Be, p+Au, S+Au (NA45-1) with $\Delta m/m$ ~7% at ρ-mass
-upgrading detector Pb+Au (NA45-2) with $\Delta m/m$ ~2% at ρ-mass.
Signal/CB ~ 1/22 !!!

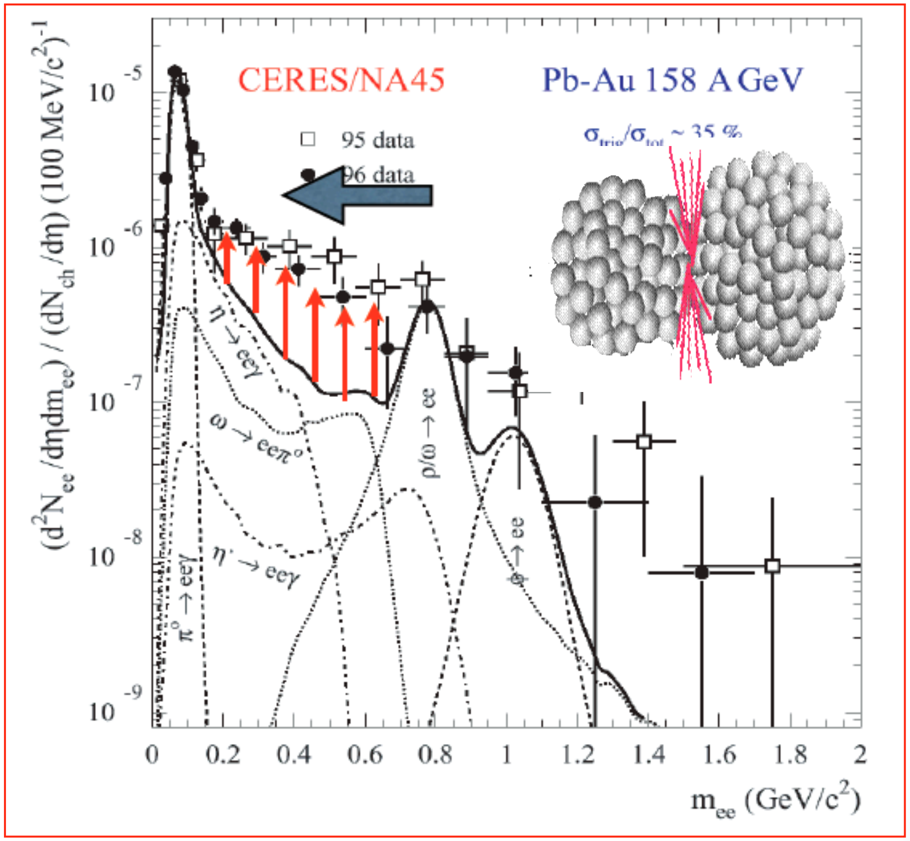




In a large background of hadron particles, Ring Imaging CHerenkov (RICH) critical to discriminate between e^+,e^- and π^+, π^-

NA45(CERES) SPS CERN

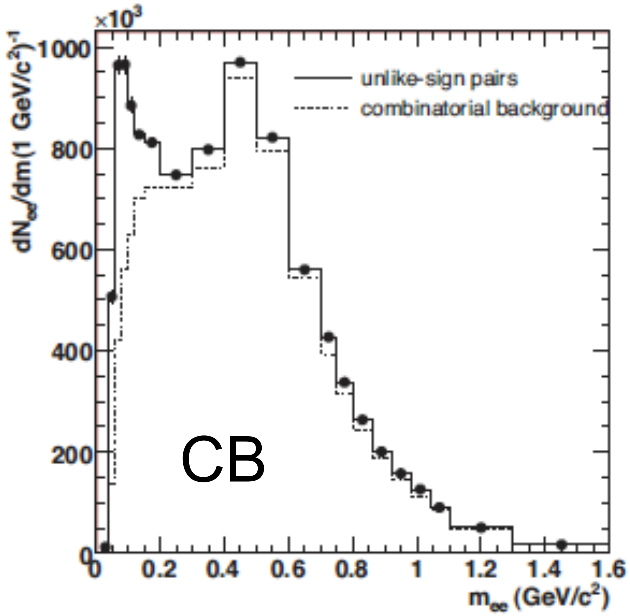




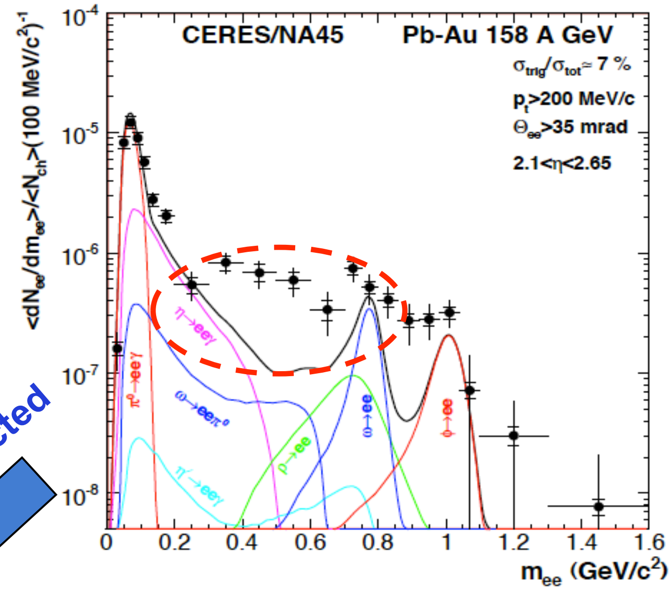
p+Au understood in terms of p+p superposition

Large excess observed in Pb+Au below 0.7 Gev/c². ρ/ω mass shift??

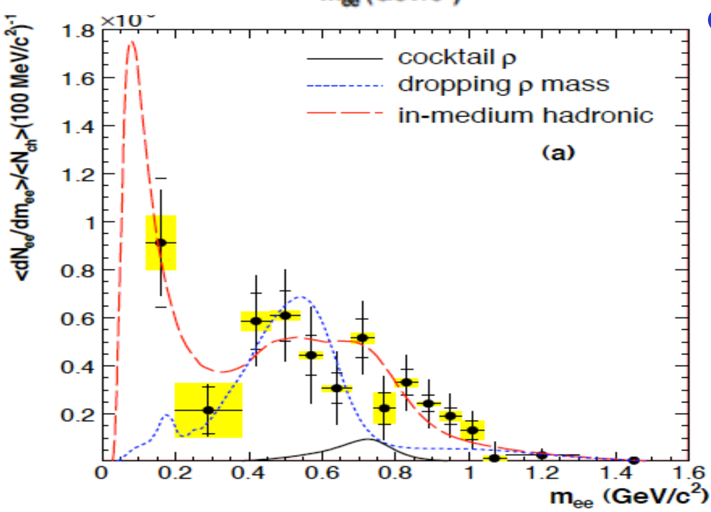
NA45(CERES) [Recent data: PLB666(2008)425]



CB subtracted

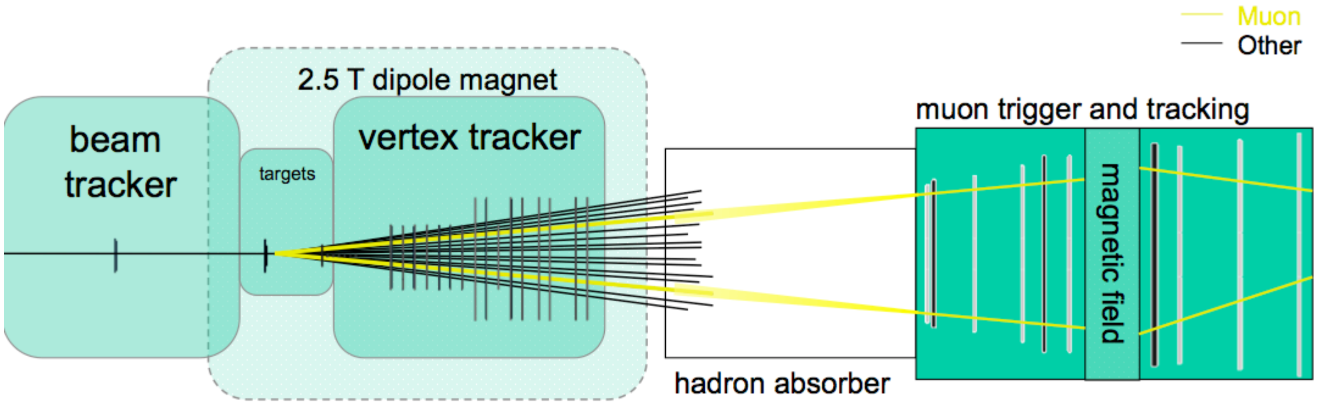


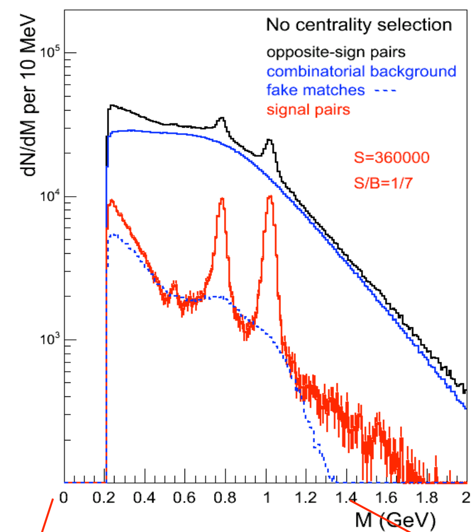
Cocktail subtracted



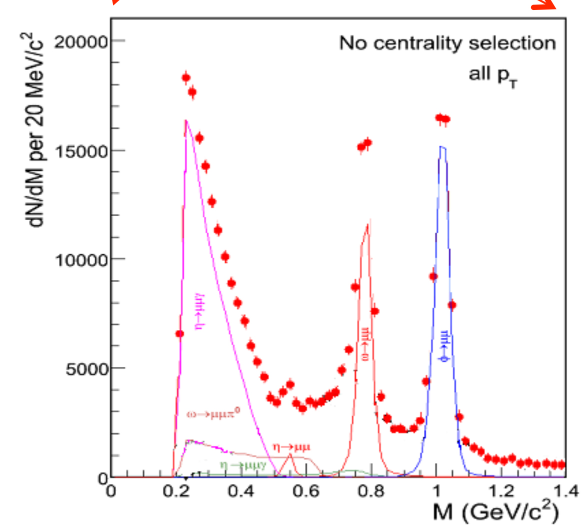
Broadening favored , no mass shift!

NA60 ($\mu^+\mu^-$ with In + In at 158 AGeV) @ CERN





CB subtracted



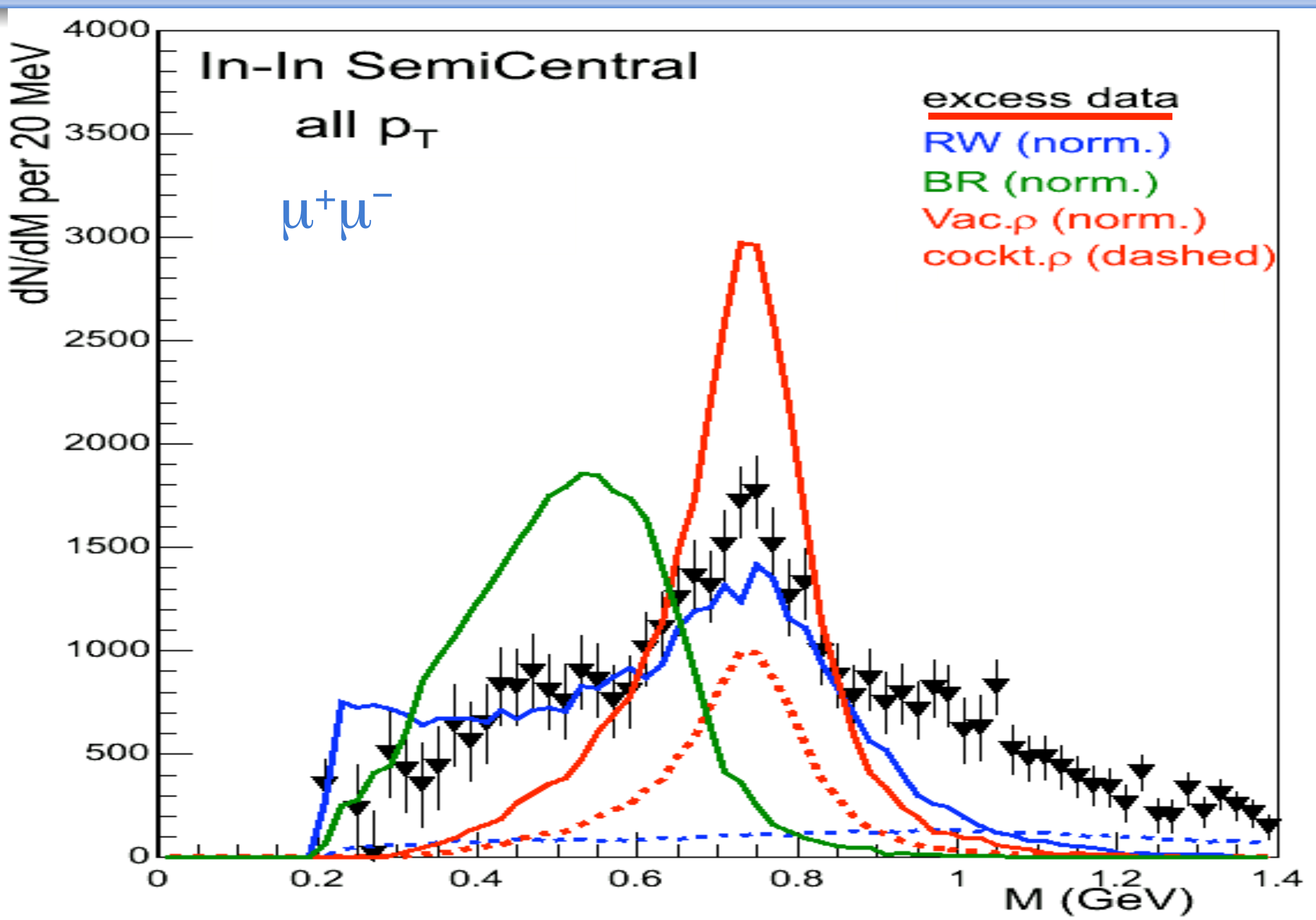
-Si-pixel detector between target and absorber → $\Delta m/m$ ~2% at ρ-mass (20 MeV/c^2)

-Sig/Back~1/11

-ω and ϕ clearly seen for first time in HIC.

-able to extract invariant mass spectrum for ρ after cocktail subtraction.

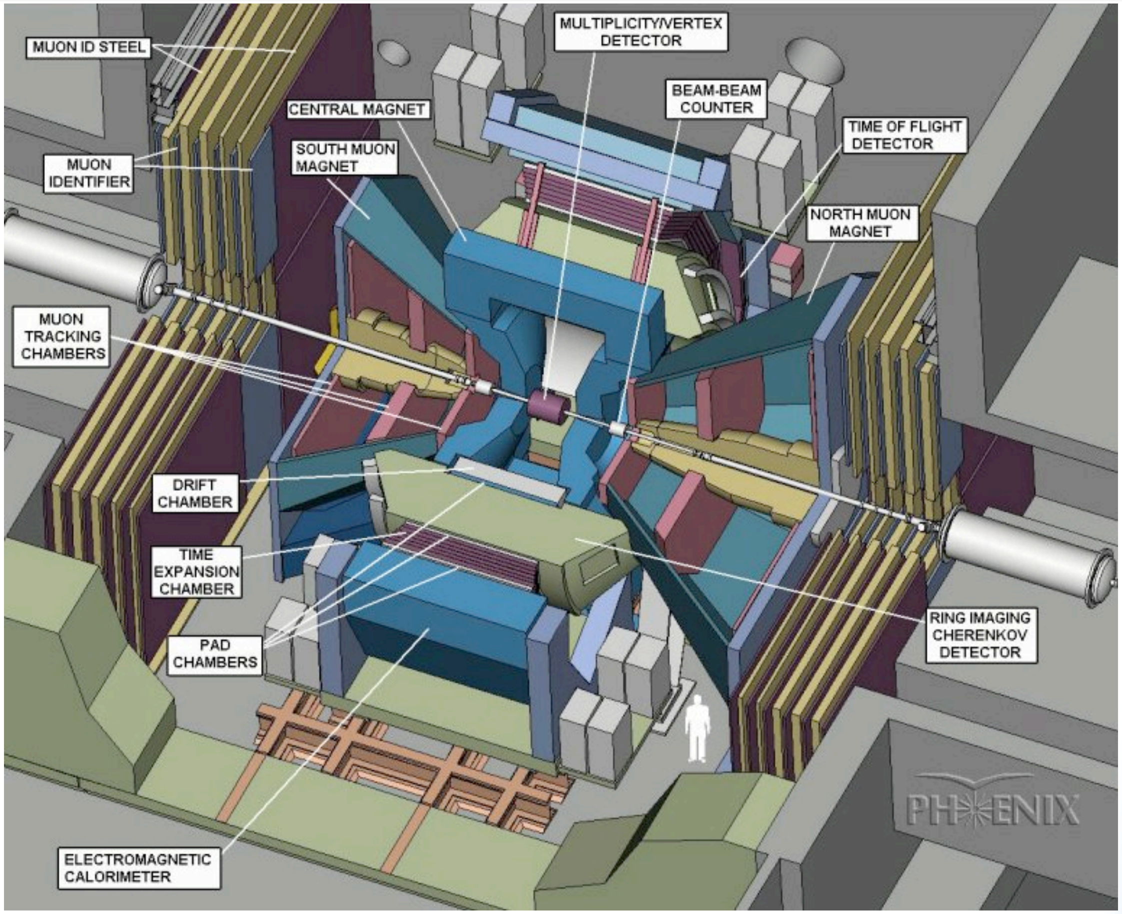
NA60 (measuring di-muons in HI collisions)



Only broadening of ρ (à la Rapp-Wambach) observed, No mass shift (à la Brown-Rho)

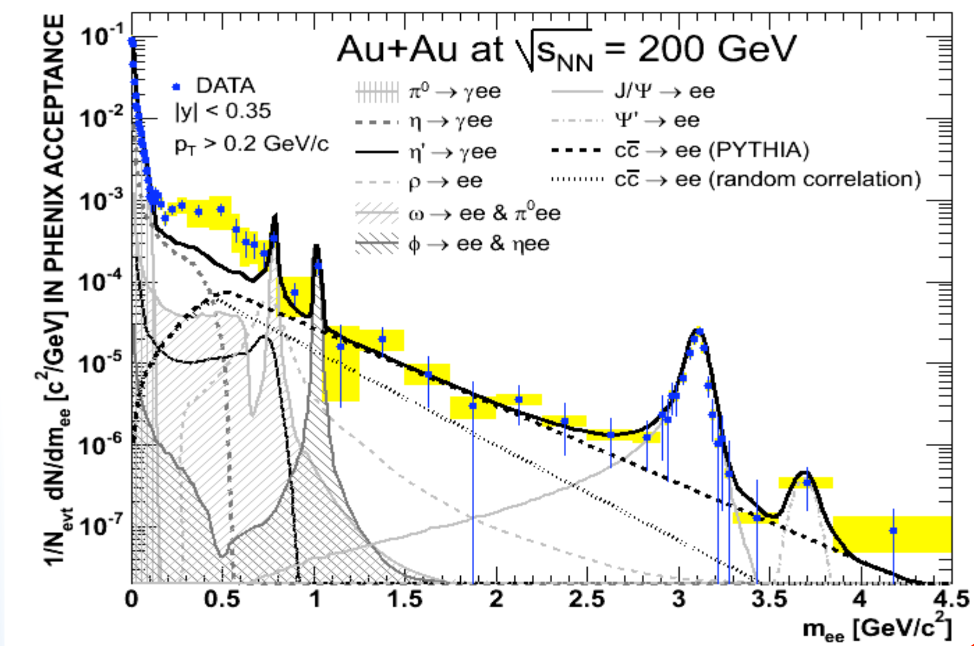
PHENIX at RHIC (Au+Au at $\sqrt{s_{NN}}$ =200 GeV)

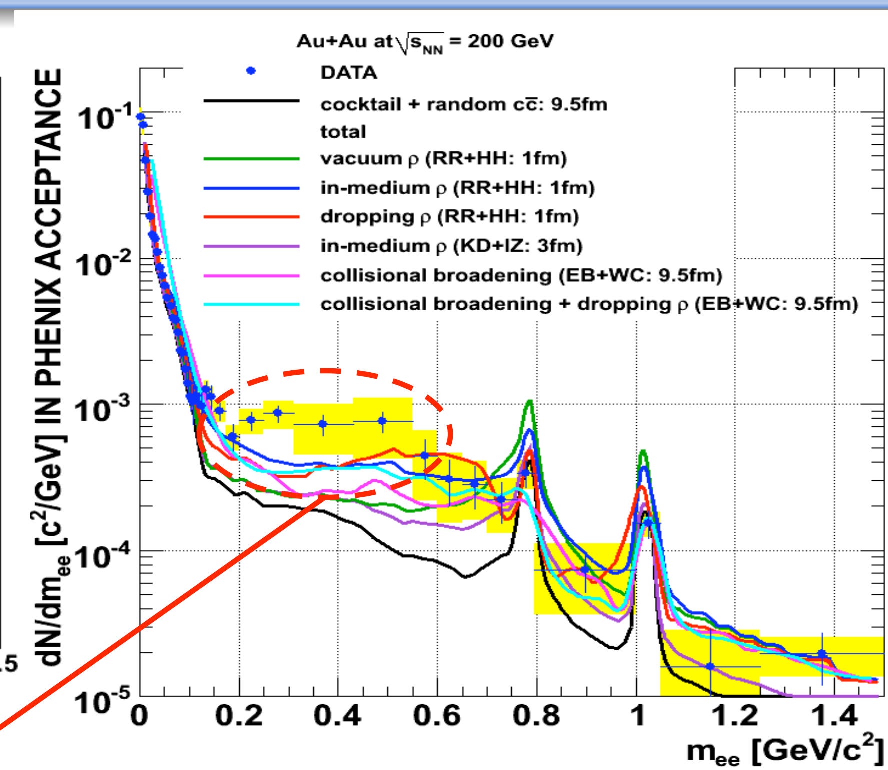
- ○Two central arm spectrometer
- ○Tracking (DC, PC)
- ○EM calorimeter
- ○TOF
- ○RICH
- ○Measures everything



Before Background subtraction : <u>Signal/Background ≥ 1/100 in Au-Au</u>
Combinatorial background obtained with same sign pairs

PHENIX





Low mass region

Data below 150 MeV/c² well described by the cocktail

Enhancement observed in

150 < m_{ee} < 750 MeV

Intermediate mass region

Absence of excess

Excess over cocktail ~ 3
Increases with centrality

Low mass region

- **M>0.5GeV/c²: some calculations OK**
- **M<0.5GeV/c²: not reproduced**

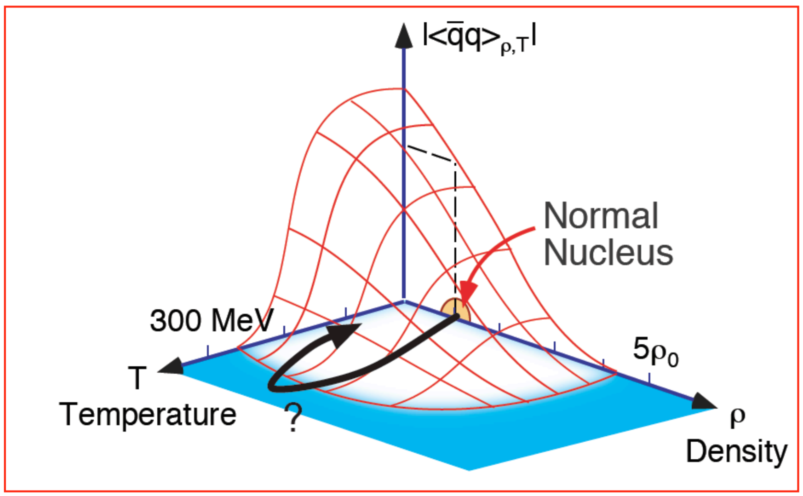
Analysis ongoing

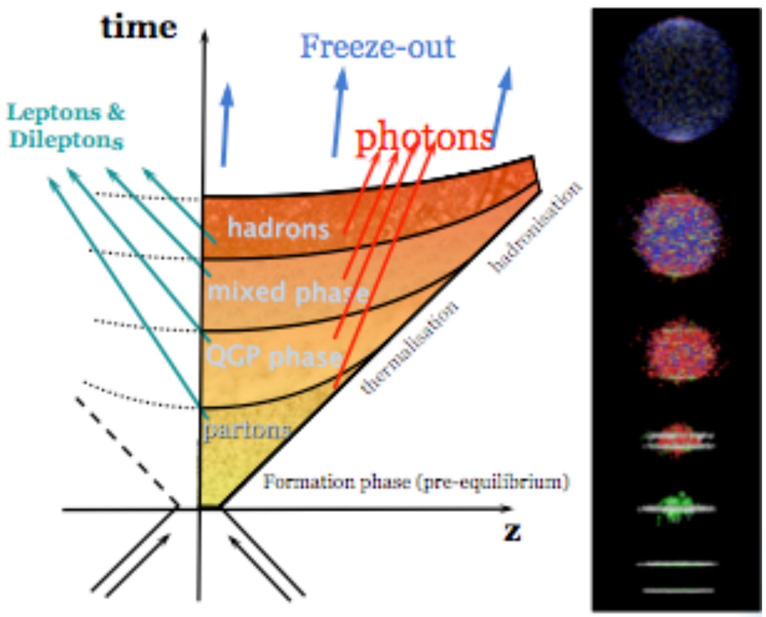
What have we learned from Heavy Ion Collisions

Broadening (NO MASS SHIFT) of ρ-Meson can 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 phases are involved

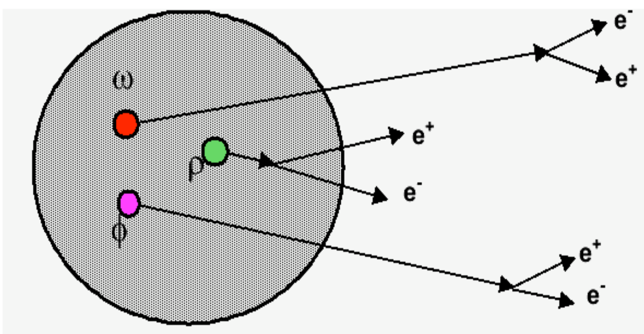




Vector mesons in Nuclei (T=0 and $\rho \sim \rho_0$)

The predicted medium modifications at normal nuclear density are large enough to 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



$$m_{\rho,\omega,\phi}(\vec{p},\rho,T) = \sqrt{(P_{e^+} + P_{e^-})^2}$$

m : invariant mass of meson
P : 4-momentum of lepton
p: 3-momentum of meson/medium

Decay inside

Vector mesons	ρ:	M=775 MeV	Γ= 149 MeV	$c\tau \sim$1.3 fm
	ω:	M=782 MeV	Γ = 8 MeV	$c\tau \sim$23 fm
	ϕ:	M=1019 MeV	Γ = 4 MeV	$c\tau \sim$46 fm

Need very low p

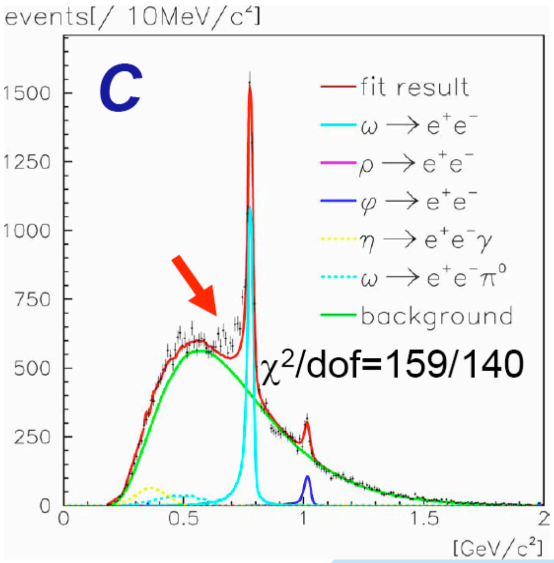
Elementary Reactions (not exhaustive list)

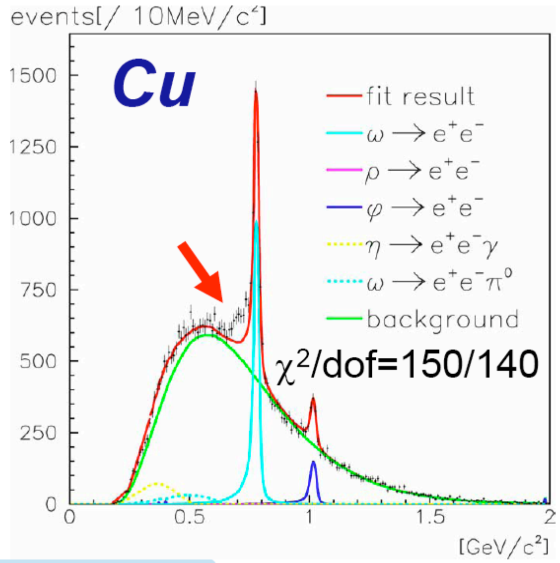
Experiment	*Reactions*
TAGX	γ **+^{3}He-->ρ+X (ρ->$\pi^+\pi^-$)**
KEK	**p+A->ρ,ω,ϕ+X (ρ,ω->e^+e^-)**
KEK	**p+A->ϕ+X (ϕ->e^+e^-)**
SPring-8	γ **+ A-->ϕ+A*(ϕ--> K^+K^-)**
TAPS	γ**+A-->ω+X (ω --> π^0 γ)**
JLab-g7a	γ+A-->(ρ,ω,ϕ)+A* (VM-->e^+e^-)
HADES	**p+p,d->ρ,ω,ϕ+X (ρ,ω,ϕ->e^+e^-)**

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

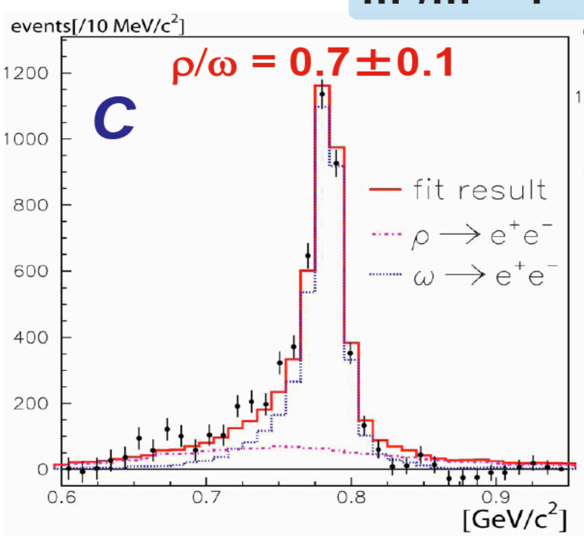
KEK (Japan)-PS E325: p+A → ρ,ω+X (ρ,ω → e+e-)

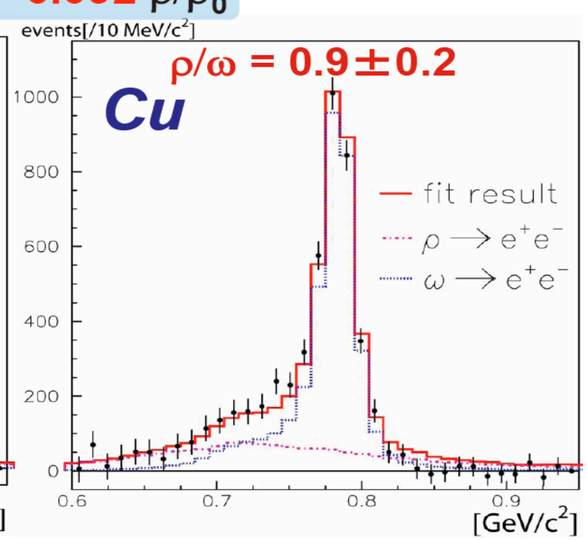
M. Naruki et al, PRL 96 (2006) 092301





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





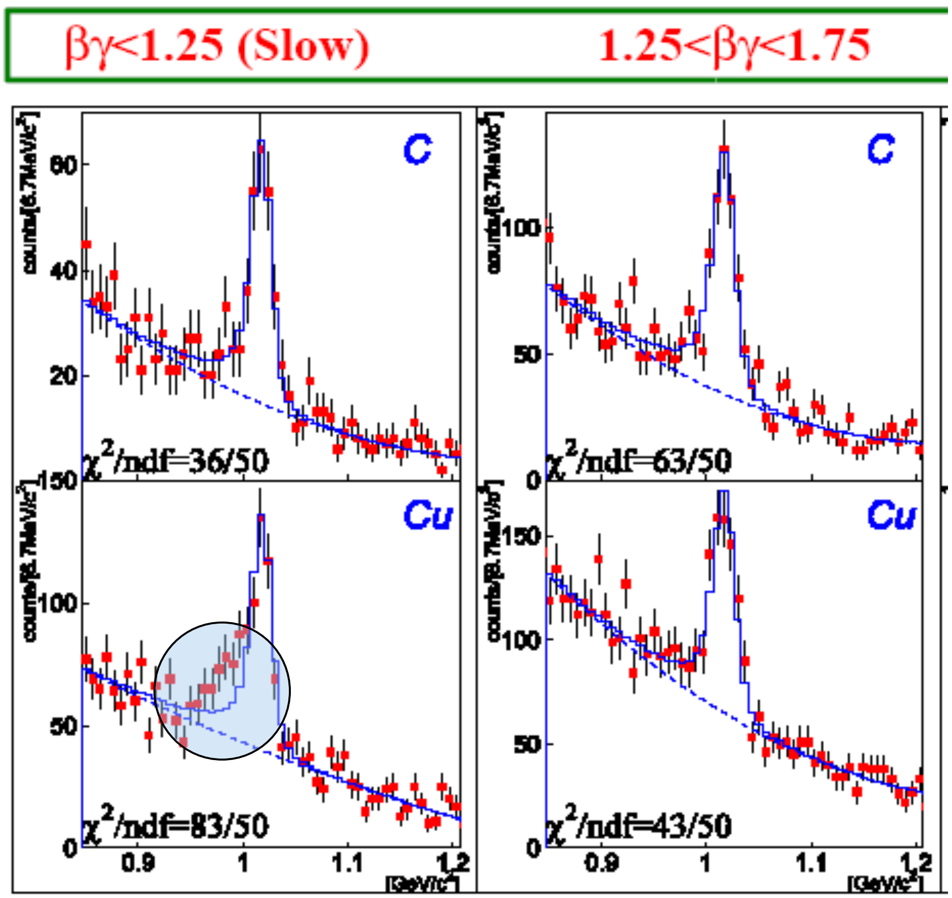
No absolute normalization of the background → background part of the fit

Constrain the ω/ρ ratio to include ρ
Using a model that predicts the probability for ρ mesons decaying inside the nucleus.
Results of fit for the ρ:

Mass shift: α ~ 9.2%
No ΔΓ

KEK-PS E325: p+A → ϕ+X (ϕ → e+e-)

R.Muto et al., PRL 98 (2007) 042501



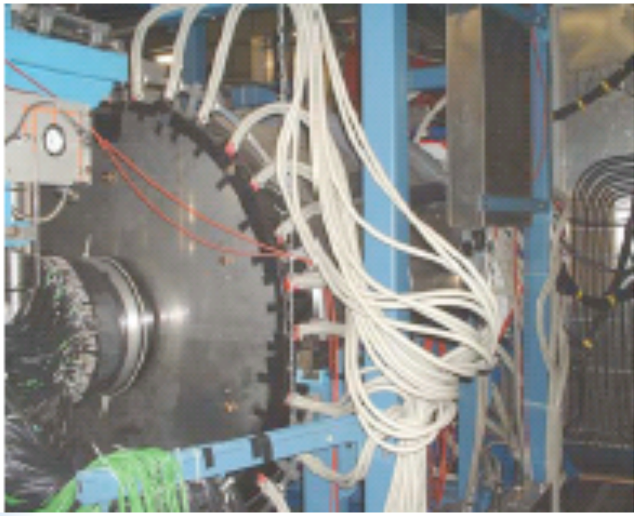
mass shift for low recoil momenta ϕ in Cu

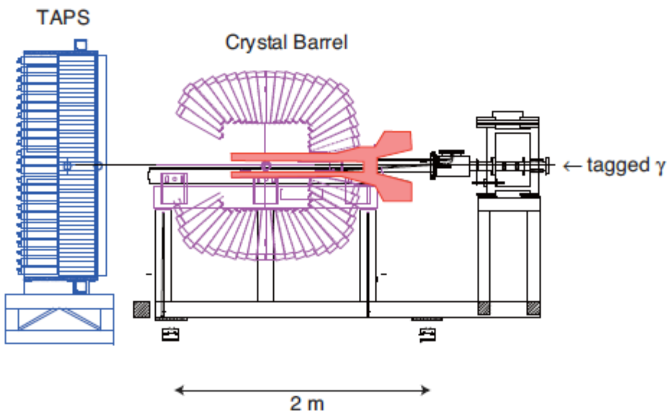
$$m^*/m = 1 - k_1\ \rho/\rho_0,$$
$$\Gamma^*/\Gamma = 1 + k_2\ \rho/\rho_0$$

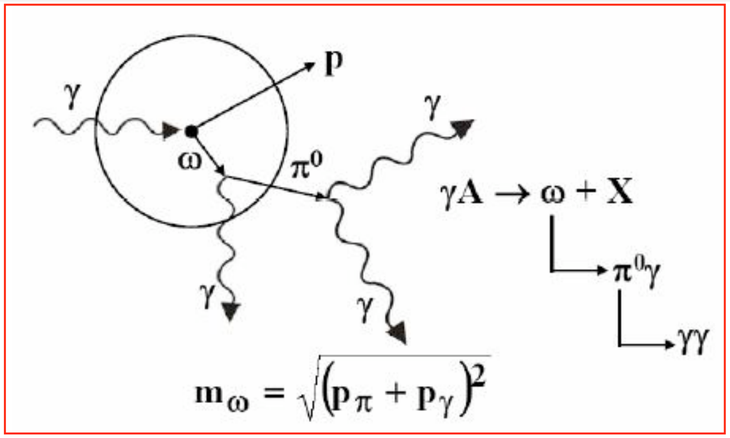
Best Fit Values		
	ρ, ω	ϕ
k_1	9.2 ± 0.2%	$3.4^{+0.6}_{-0.7}$%
k_2	0 (fixed)	$2.6^{+1.8}_{-1.2}$

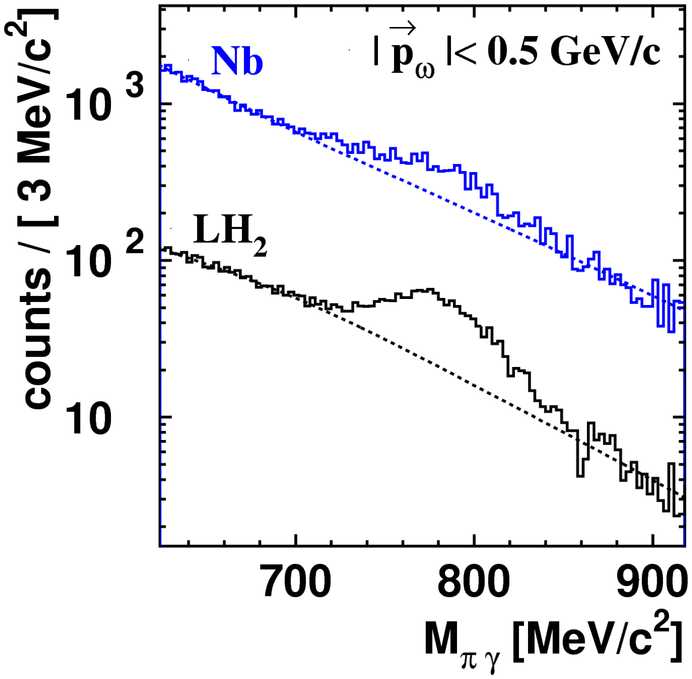
CBELSA-TAPS – γ+A-->ω+X (ω --> π^0 γ)

Eγ = 0.64-2.53 GeV on LH2 and Nb
Clean channel (ρ suppressed by 10^2)
however FSI of π^0



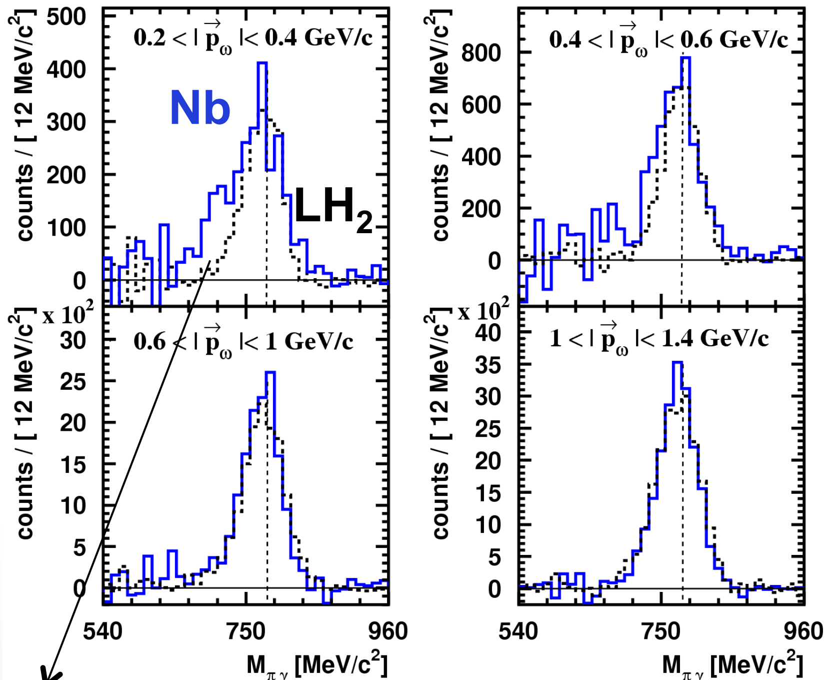




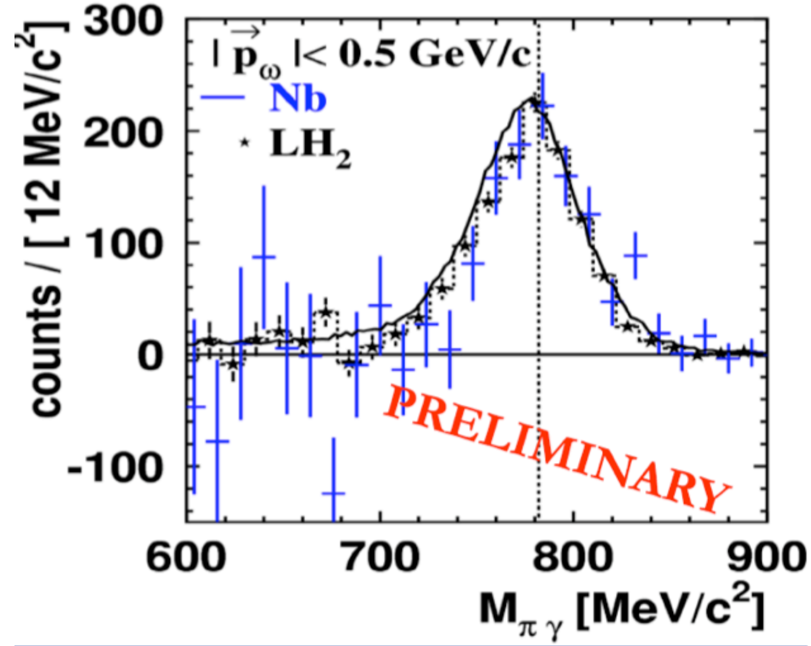


CBELSA-TAPS – γ+A-->ω+X (ω --> π^0 γ)

after background subtraction



NEW ANALYSIS with combinatorial background



Slow ω decaying inside

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

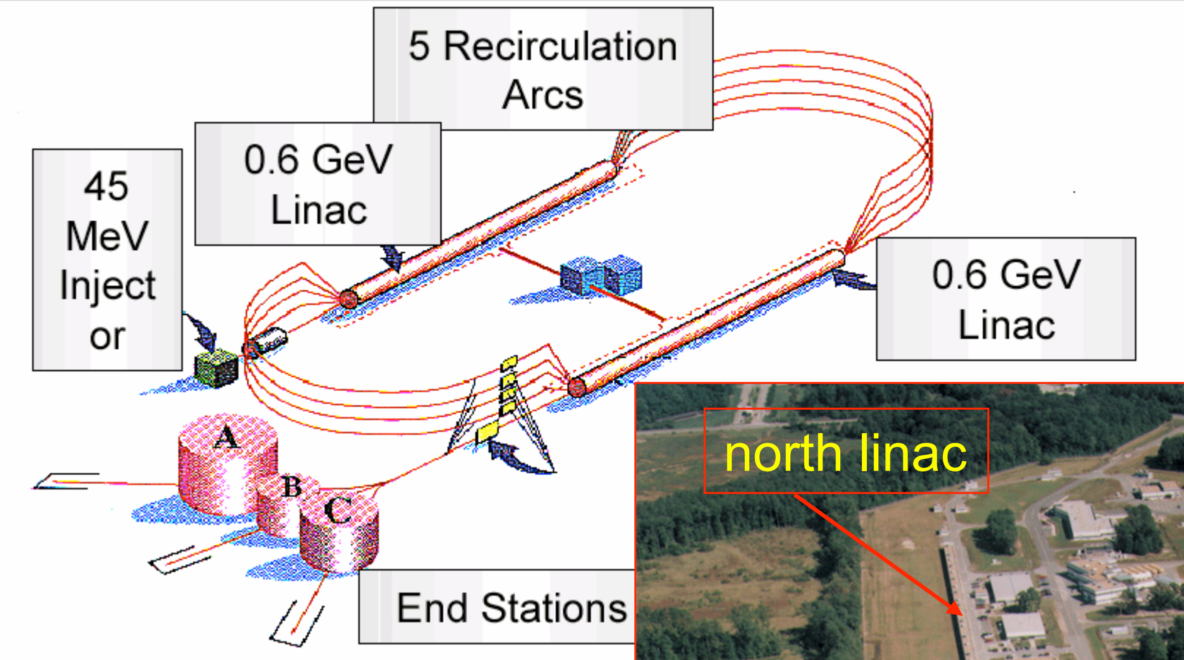
$$m^* \cong m_0$$

Objections about treatment of BKGD were raised questioning Δm; EJP J A 31 (2007) 245

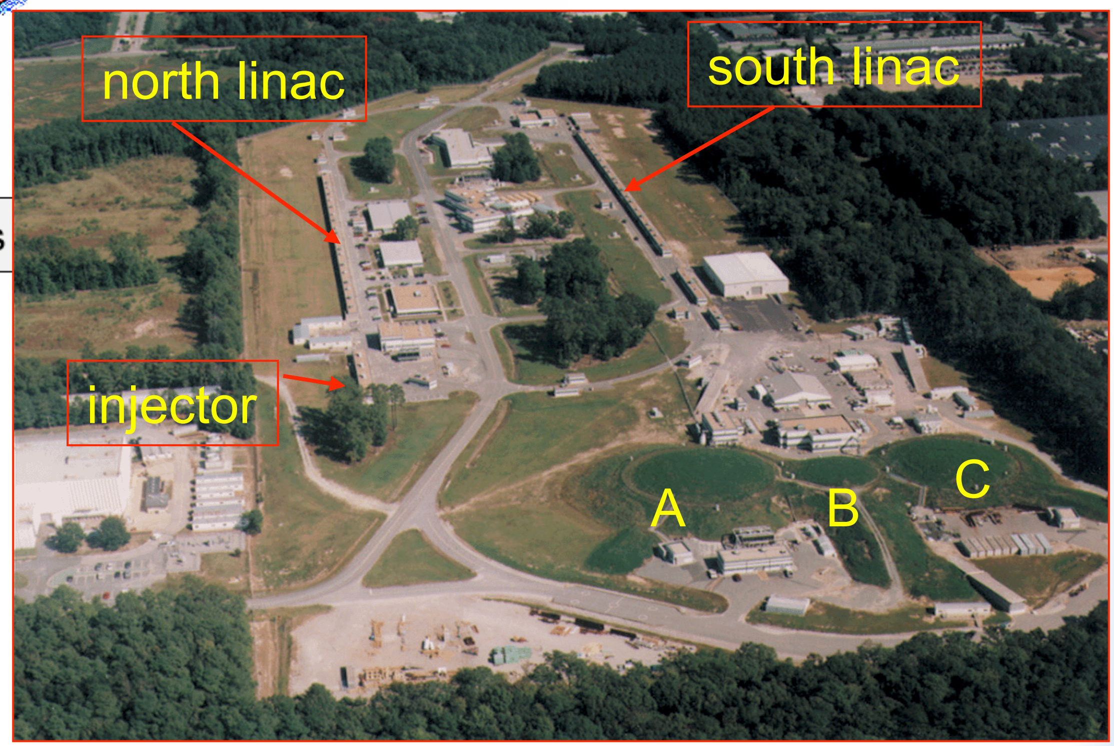
published results: PRL94 (2005) 192303

High statistics run at MAMI planned

Jlab-CEBAF: The 6 GeV CW Electron Accelerator

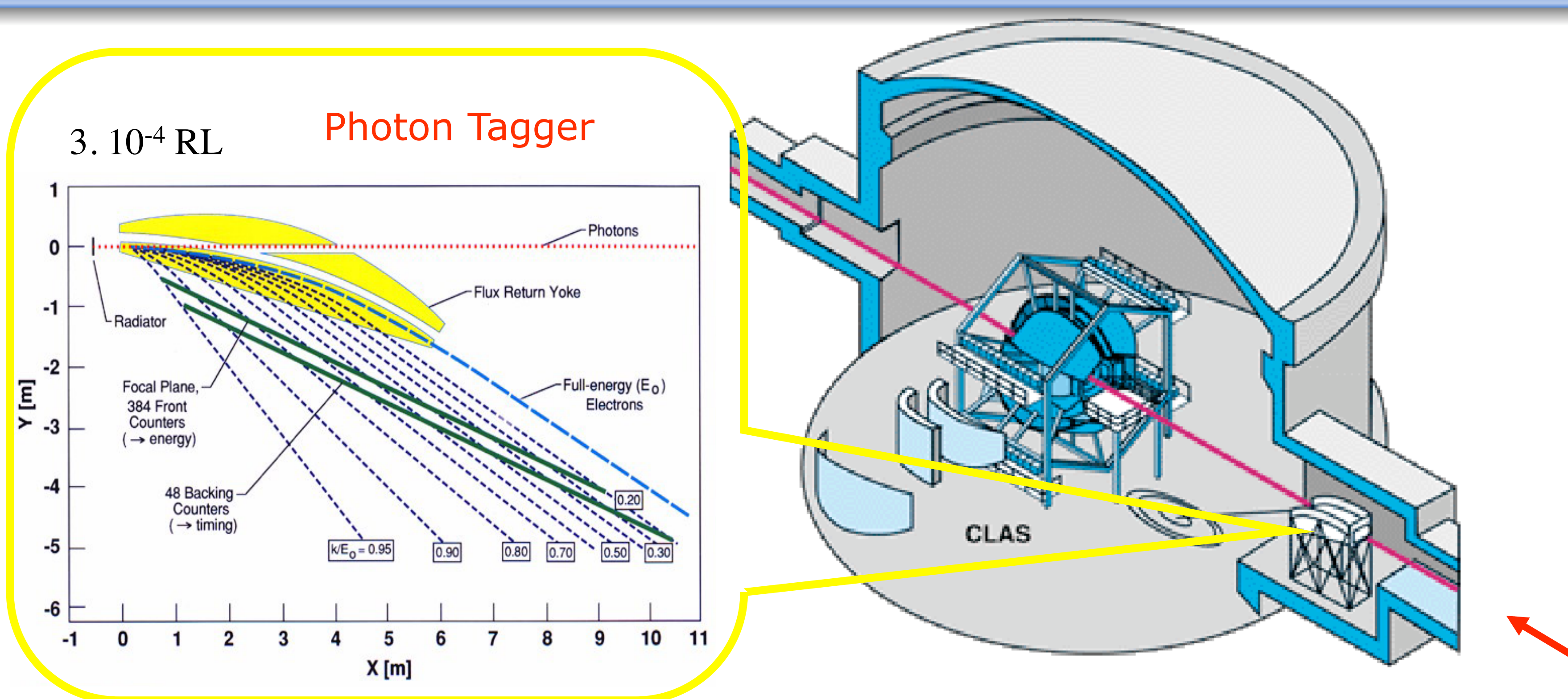


E_{max}	~ 6 GeV
I_{max}	~ 200 μA
Duty Factor	~ 100%
σ_E/E	~ 2.5 10^{-5}
Beam P	~ 80%
E_g(tagged)	~ 0.8- 5.5 GeV



HALL B:
>200 Physicists
~ 15 countries

JLab-HALL-B: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

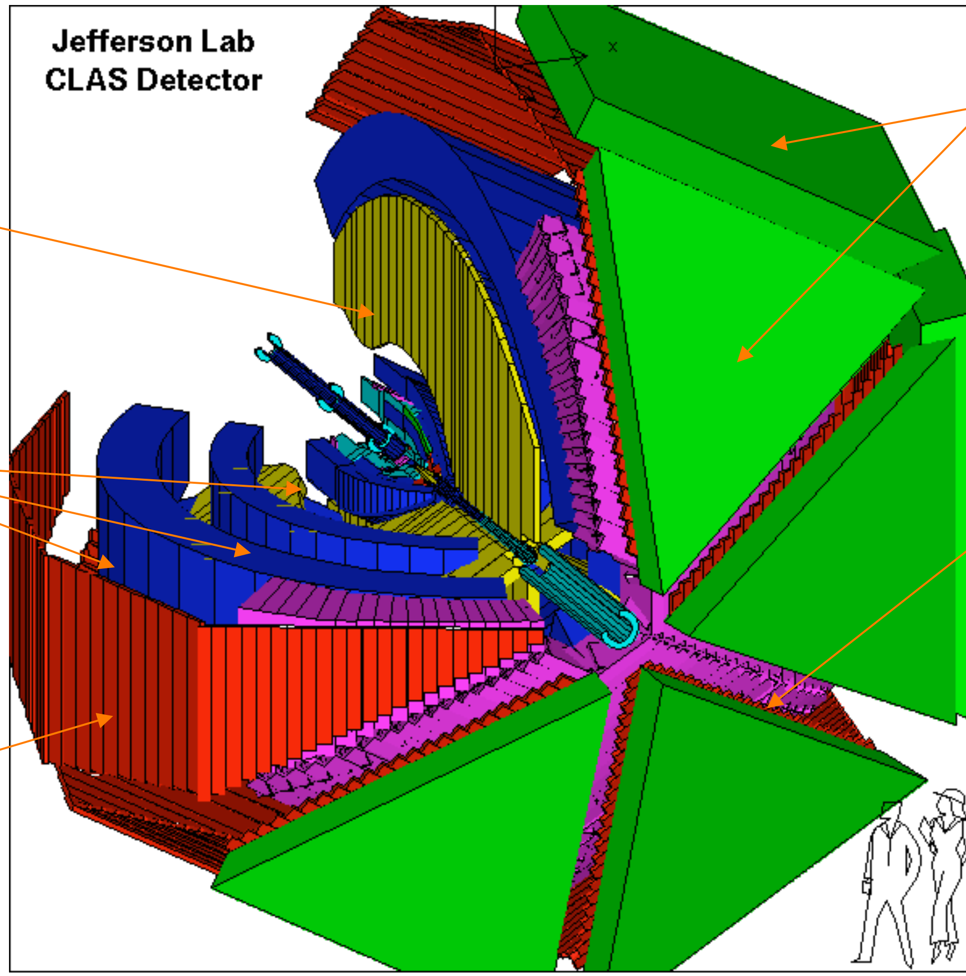
CEBAF Large Acceptance Spectrometer (CLAS)

Superconducting Torus Magnet
6 Superconducting coils for deflecting charged particles

e^- : inbending tracks
e^+: outbending tracks

Drift Chambers
Ar-CO_2
6500 channels/sector
to measure the path of a charged particle

Time-of-Flight Hodoscope
48 Scintillators/sector
for measuring a particle's travel time



Electromagnetic Calorimeter
Lead-Scintillator for detecting electrons

EC e/π rejection factor : $\sim 10^{-2}$

Gas Cherenkov Counter
e/π separation

CC e/π rejection factor : $\sim 10^{-1}$

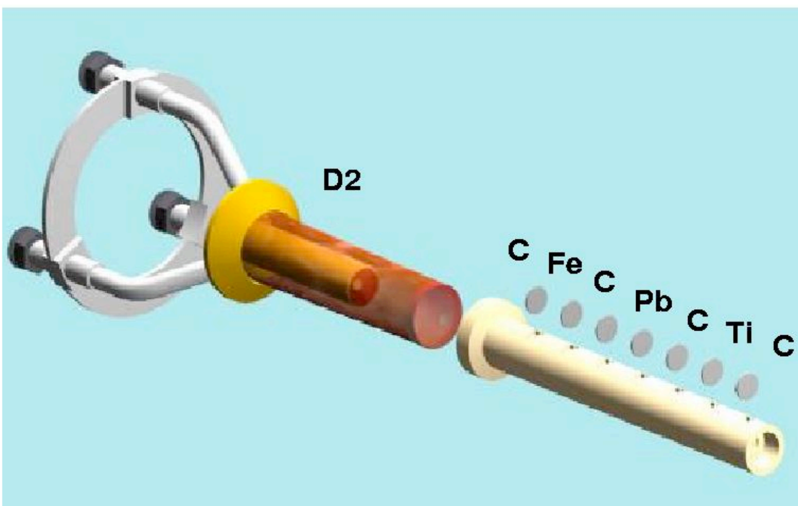
EC/CC rejection factor : $\sim 10^{-3}$

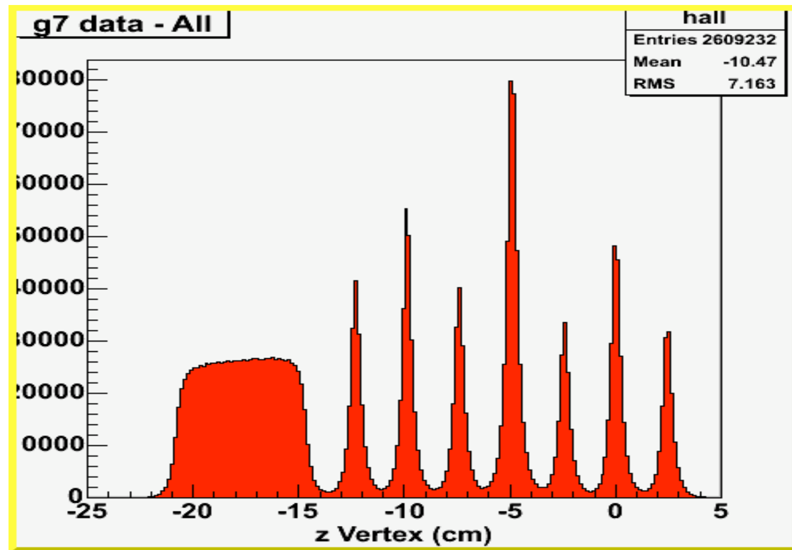
Rejection factor for e^+e^- better than 10^{-6}

Jlab-HALL-B Experiment E01-112 (also called g7)

$\gamma A \rightarrow \rho,\omega,\phi\ X$ ($\rho,\omega,\phi \rightarrow e^+e^-$) $E_\gamma \sim .6$ to 3.8 GeV, High γ flux : 5 10^7 tagged γ/s

- 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

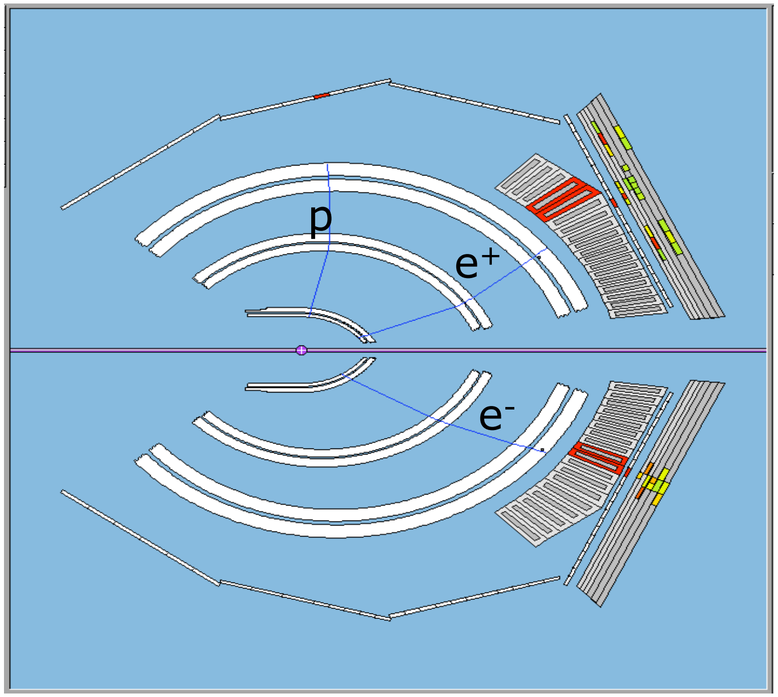


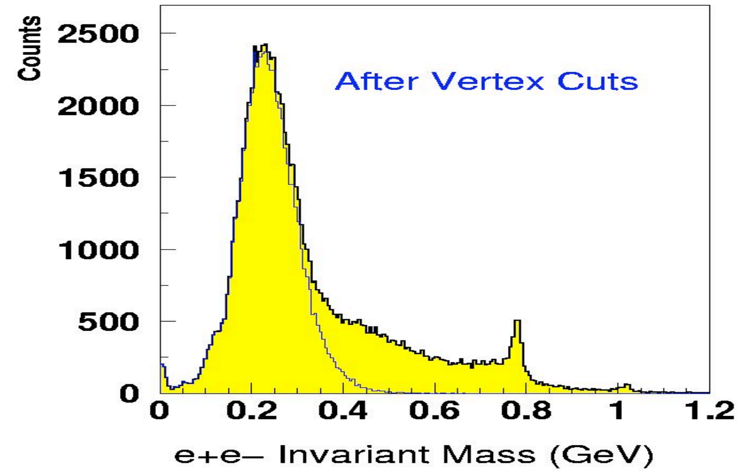


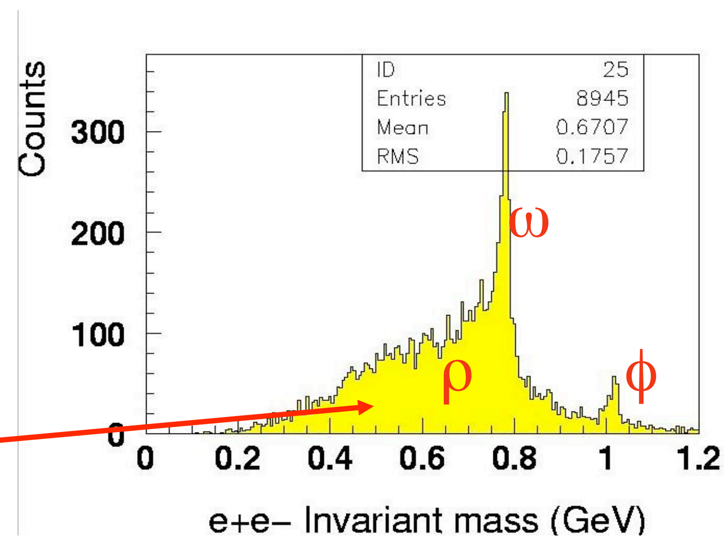
- Proper spacing 2.5 cm to reduce multiple scattering
- Deuterium target as reference, small nucleus, no modification is expected.

e^+e^- Invariant Mass Spectra

coincident electron pairs in the CLAS







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

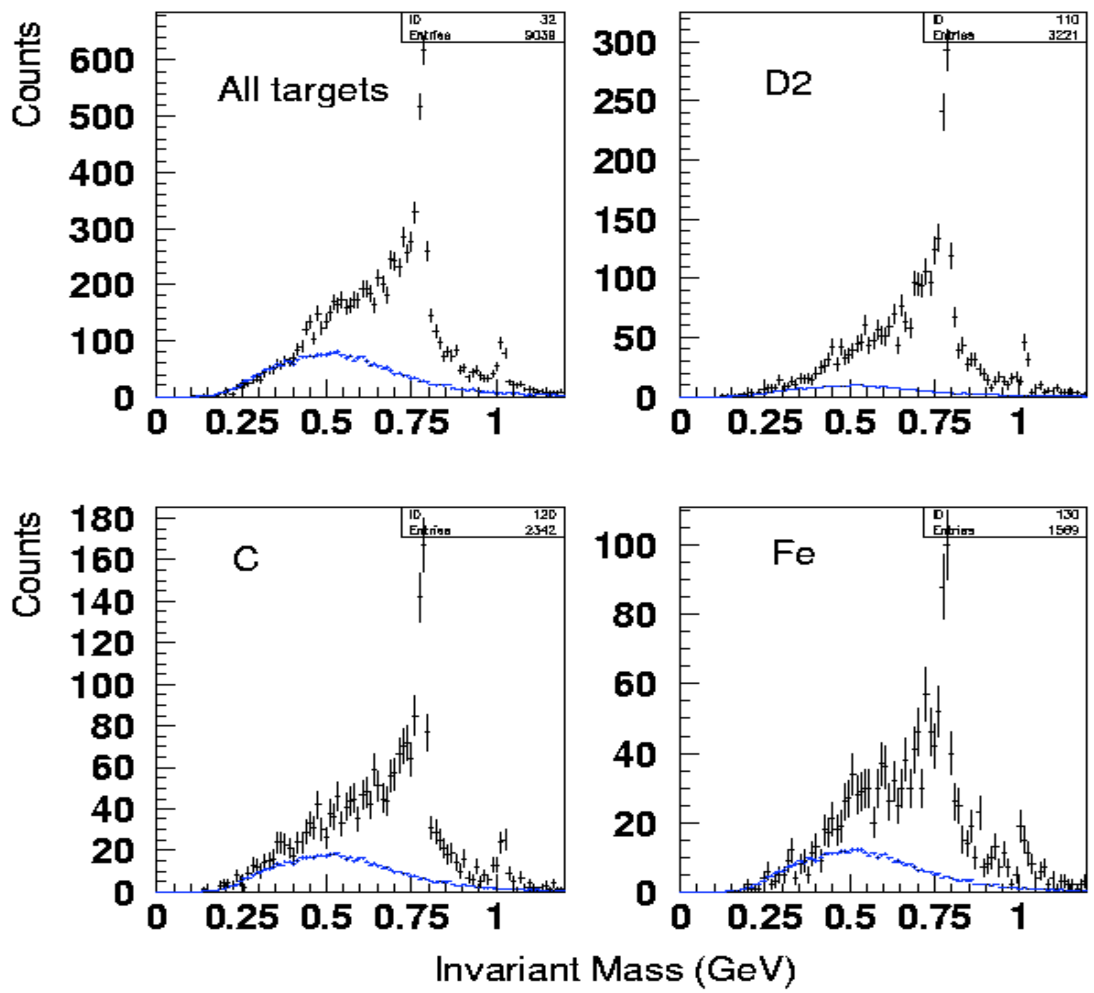
Excellent π/e discrimination: ~10^{-3} for one and ~10^{-6} for two arms.

Normalized Combinatorial Background

Mixed event technique:

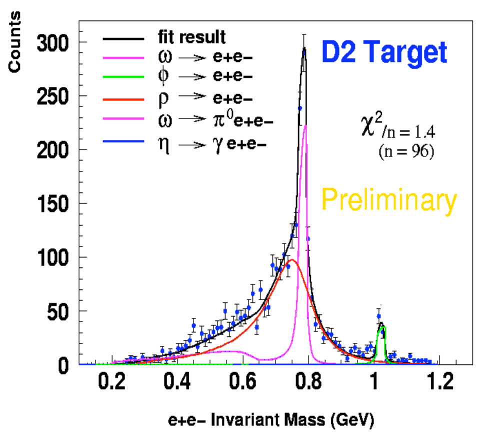
Pairs of identical (e+e+, e-e-) leptons, which are produced only by combinatorial background provide a natural normalization and samples of uncorrelated particles.

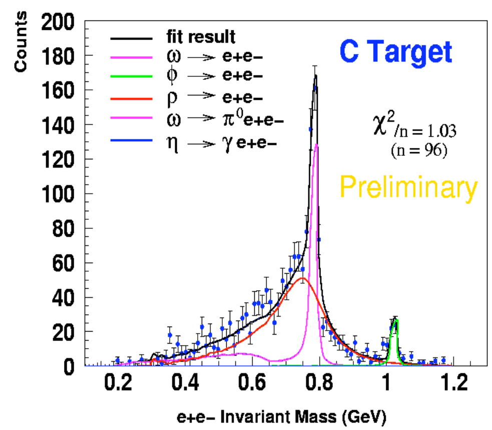
$$N_{-+} = 2\sqrt{N_{--}N_{++}}$$

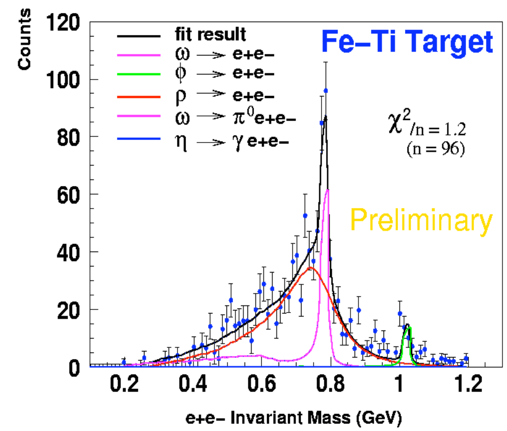


Background Subtracted Fits

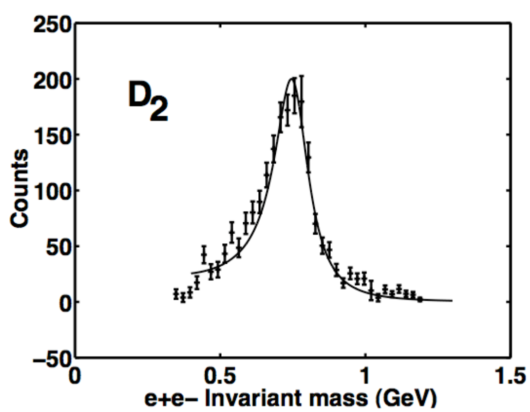
All the contributing channels to e^+e^- mass spectra studied with GiBUU model.
Narrow ω and ϕ can be subtracted from spectrum, leaving "pure" ρ

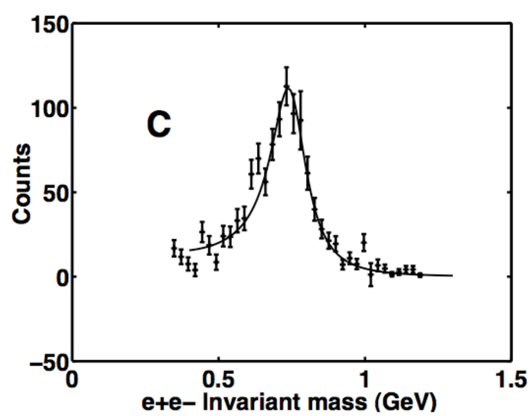


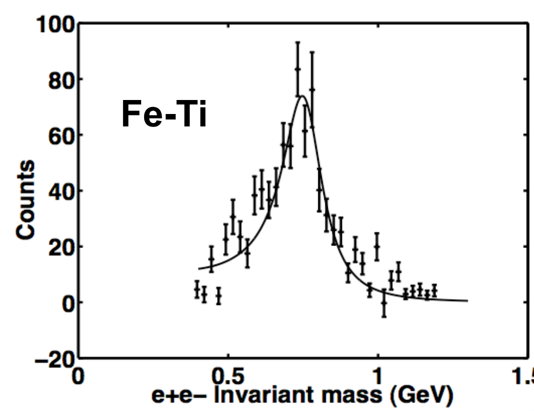




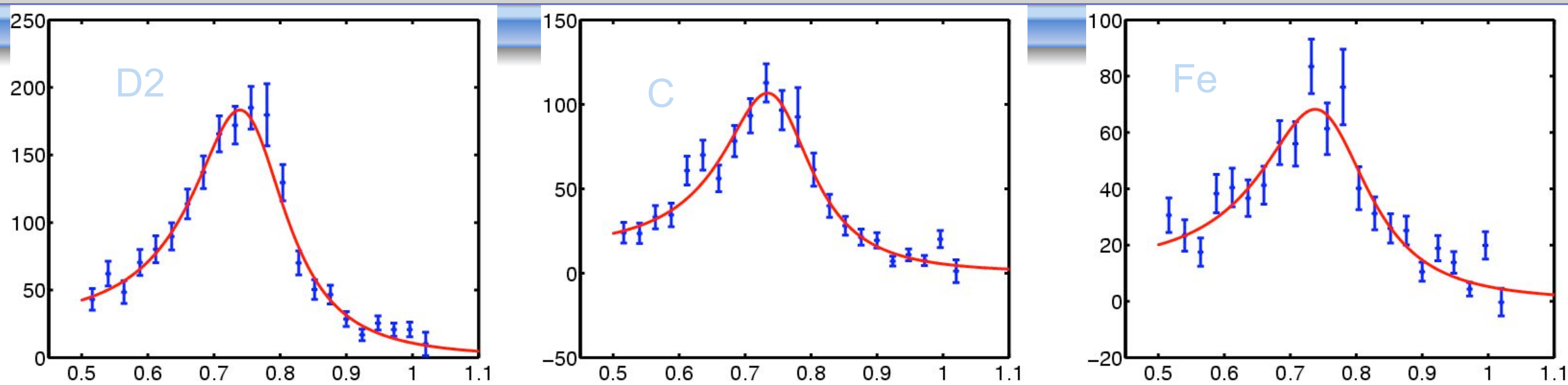
Extracted ρ "spectral functions"







Masses and Widths for Extracted ρ



Target	Mass (MeV/c²) CLAS data	Width(MeV/c²) CLAS data	Mass(MeV/c²) Giessen BUU	Width(MeV/c²) 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 mass of the ρ meson consistent with no shift.
Broadening of the width (ΔΓ~70 MeV).

Absorption of ω Meson and its in-medium width

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

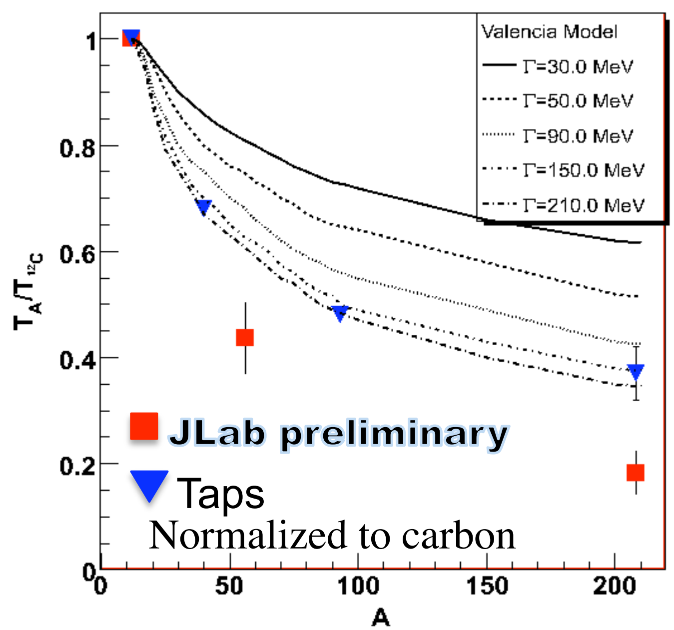
Transparency ratio:

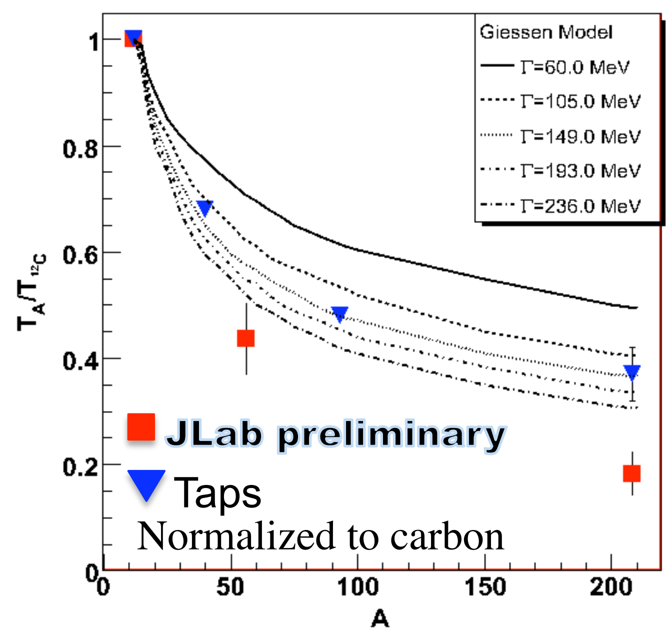
$$T_A = \frac{\sigma_{\gamma A \to \omega X}}{A \cdot \sigma_{\gamma N \to \omega X}}$$

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

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

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



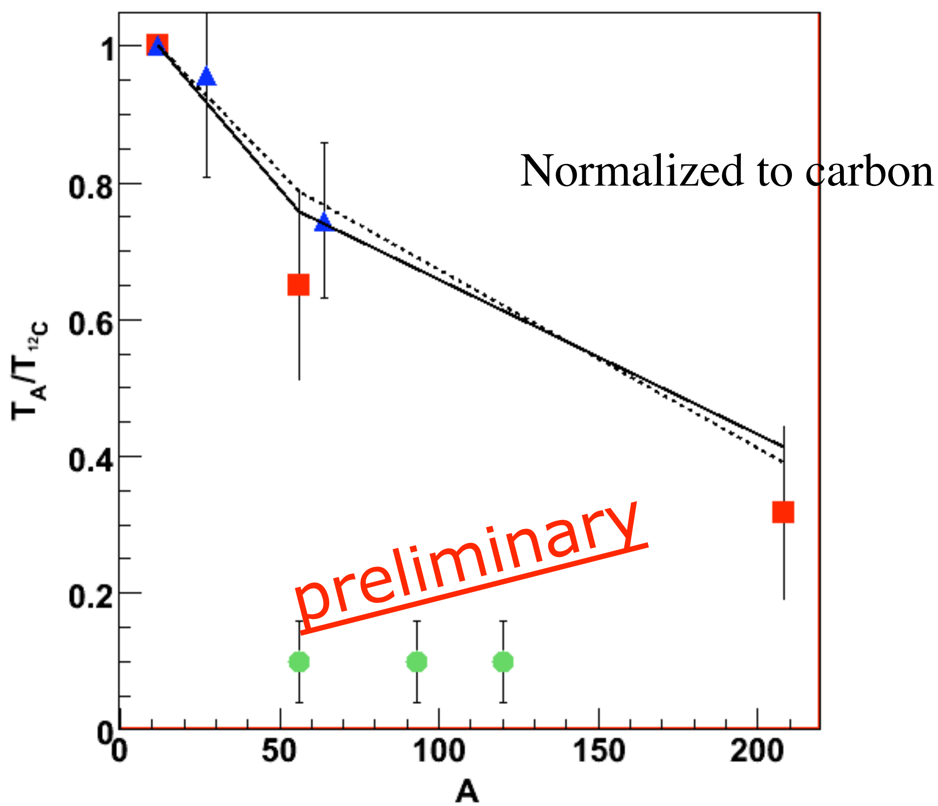


Latest TAPS Γ_ω~130-150 MeV
JLAB preliminary results -> larger width (>200 MeV)

- TAPS (PRL100(2008)192302)

ϕ-Meson absorption in medium

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



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

Γ_ϕ(~ 70 MeV) compatible with Spring8

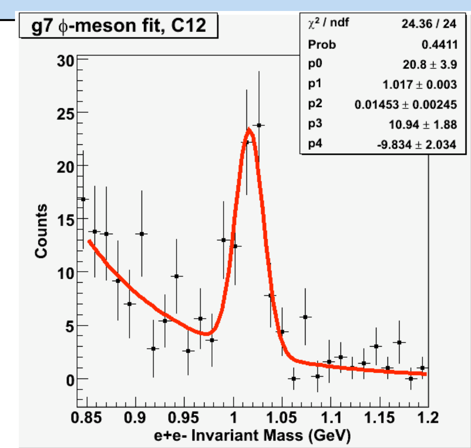
Giessen calculations

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.

In-medium m and Γ of vector mesons (elementary reactions)

exp	reaction	Momentum Acceptance	ρ	ω	ϕ
KEK	pA 12 GeV	p >0.6 GeV/c	$(\Delta m/m)$=-9% $\Delta\Gamma$ ~0	$(\Delta m/m)$=-9% $\Delta\Gamma$ ~0	$(\Delta m/m)$=-3.4% (Γ^*/Γ) ~3.6
JLab	γA 0.6-3.8 GeV	p >0.8 GeV/c	Δm ~ 0 $\Delta\Gamma$ ~70 MeV $(\rho \sim \rho_0/2)$	$\Delta\Gamma(\rho_0)$ > 200 MeV $<p_\omega>$ >1 GeV/c	Compatible with Spring8
TAPS	γA 0.9-2.2 GeV	p >0 MeV/c	NA	Δm ~ 0 p_ω<0.5 GeV/c $\Delta\Gamma(\rho_0)$ ~ 130 MeV $<p_\omega>$ = 1.1 GeV/c	NA
Spring8	γA 1.5-2.4 GeV	p >1.0 GeV/c	NA	NA	$\Delta\Gamma(\rho_0)$ ~ 70 MeV $<p_\phi>$ = 1.8 GeV/c
CERES	Pb+Au 158 AGeV	p_t >0 GeV/c	Broadening favored over mass shift	NA	NA
NA60	In+In 158 AGeV	p_t >0 GeV/c	Δm ~ 0 Strong broadening	NA	NA

Summary and Conclusions

- The chiral condensate $< 0 | q\bar{q} | 0 >$ is a measure of the breaking of chiral symmetry and its study is as important as the search for the Higgs to understand the origin of the mass of hadrons.
- Evidences for partial restoration of Chiral Symmetry ?
  - Strongest is reported in deeply bound pionic states

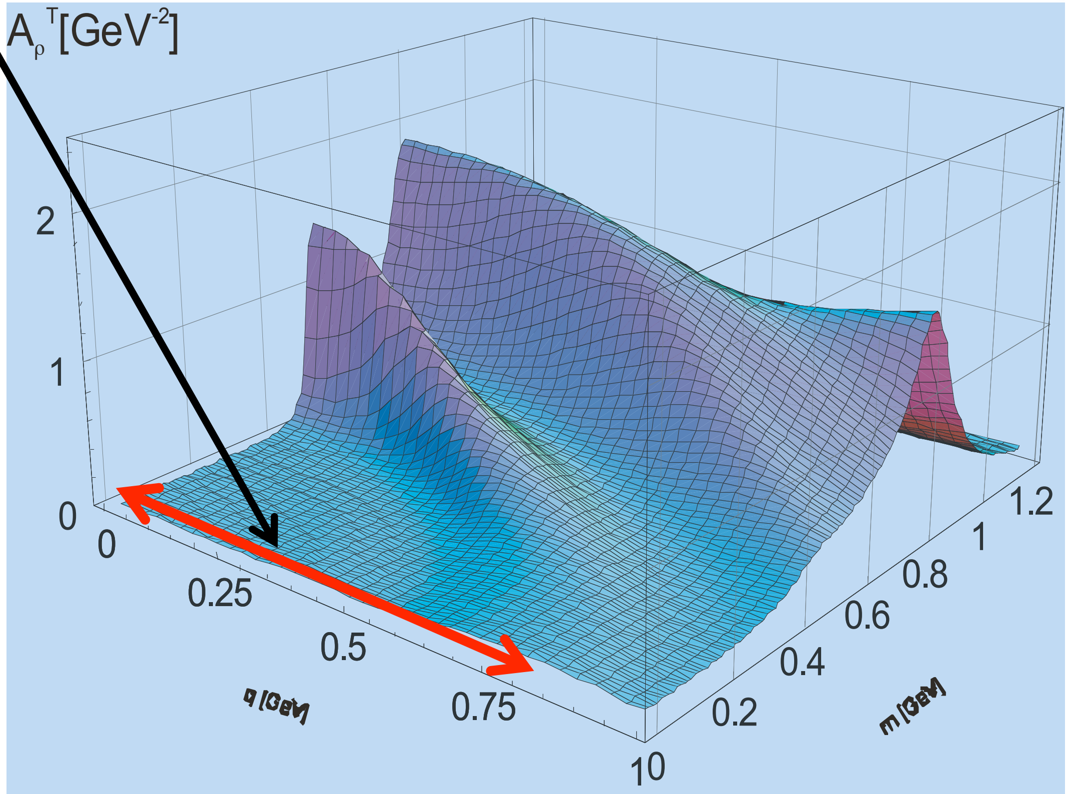
    $< 0 | q\bar{q} | 0 >$ drops by 33% in nuclei
  - Enhancement in the σ channel near the $2m_\pi$ threshold is explained by final state interactions
  - Excess of dileptons in RHIR in the region of vector mesons can be explained by a widening of the ρ.
  - Several "elementary reactions" report medium modifications for the ρ, the ω and the ϕ mainly broadening. Only one experiment report a mass shift.
- Substantial theoretical and experimental efforts are being carried out in this very active field.

ONE OF THE MAIN GOALS OF HADRONIC PHYSICS

What's Next ?

Experiments looking at vector mesons with low momentum relative to medium (p<800 MeV/c) are needed with di-leptons in final state.

-Experiment g7b at Jlab.
−ρ and ω studies at JPARC



Mesic atoms (K, η, ω, φ…) experiments at JPARC

HI experiments at RHIC and Alice at CERN

PANDA and CBM at FAIR

Other mesons

I) Low Mass Region

- Vector mesons in medium

II) Intermediate Mass Region

- Thermal dileptons
- Heavy quarks continuum : open charm

III) High Mass Region

- Heavy quarks resonances

(J/ψ) **sensitive to the gluon condensate,** $\Delta m \leq 10\, MeV$

$D(c\bar{q})/\bar{D}(q\bar{c}) \quad \Delta m = -50\,(\rho/\rho_0)\,MeV$

Experiences @FAIR, JPARC,JLAB12,CERN