Medium Modification of Vector Meson

Chaden Djalali, Michael Paolone (University of South Carolina)
Mike Wood (Canisius College),
Rakhsha Nasseripour (George Washngton University),
Dennis Weygand (JLab)
and the CLAS Collaboration.

Outline

-Main Motivation

Nuclear medium as a laboratory to study the properties of hadrons and chiral symmetry restoration.

--Vector Meson properties in the medium

In relativistic heavy ion collisions

In nuclei

-Summary-Conclusions-Outlook

Thomas Jefferson National Accelerator Facility

University of South Carolina

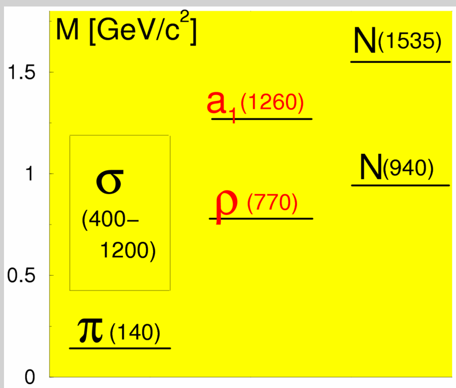
Chiral symmetry (χ_s) is spontaneously broken in vacuum

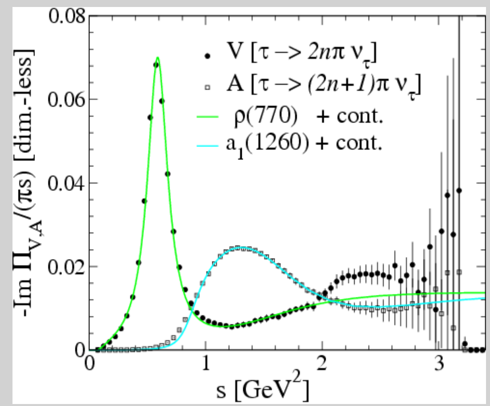
In the light quark sector (u, d), χ_s is a very good symmetry of the QCD Lagrangian, However, QCD vacuum doesn't possess the symmetry of the Lagrangian,

χ_s is spontaneously broken in the vacuum (origin of 98% of the mass of hadrons).

The (almost massless) pions are the Nambu-Goldstone bosons.

Spectral evidence of χ_s breaking: we have non degenerate chiral partners





(non zero order parameters "measure" how much the symmetry is broken).

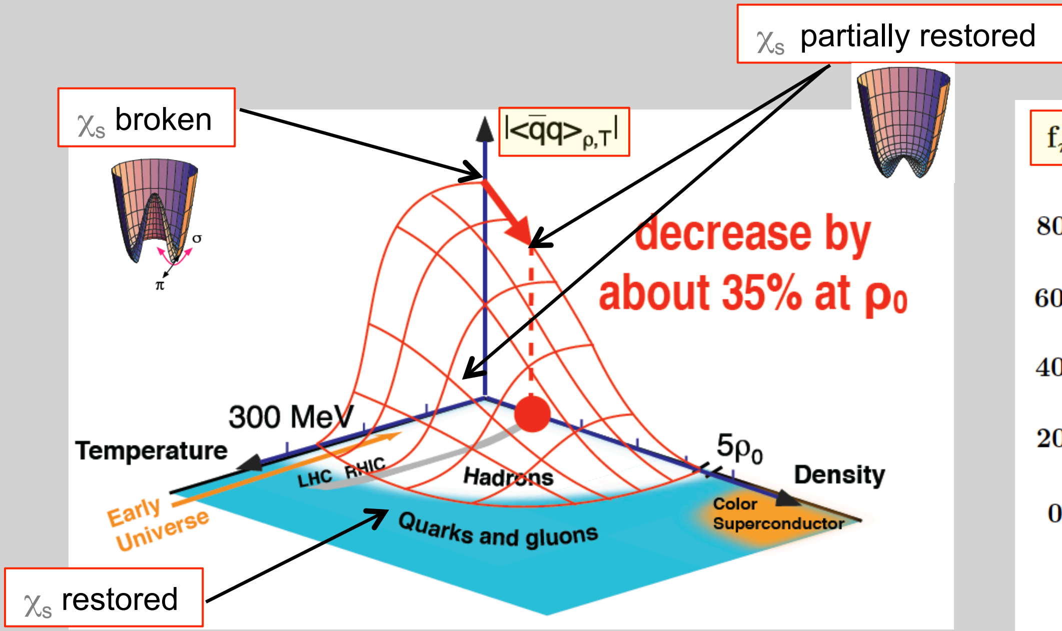
In vacuum ->
- -quark condensate $\langle 0 | q\bar{q} | 0 \rangle \approx -(250\text{MeV})^3 \pm 10\%$
- -pion decay constant f_π ~ 93 MeV

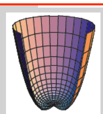
Gell-Mann- Oakes – Renner (GOR) relation

$$m_\pi^2 f_\pi^2 = -2(m_u + m_d) < 0 | q\bar{q} | 0 > + O(m_q^q)$$

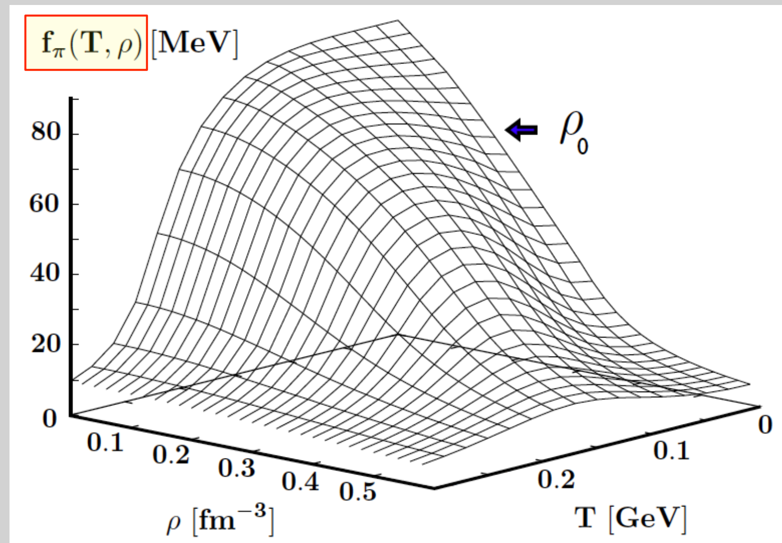
Properties of $<0|q\bar{q}|0>$ and f_π in medium

As temperature (T) and/or density (ρ) increases in the medium, Both order parameter drop and χ_S is restored. LQCD calculations show that χ_S restoration and deconfinement coincide.





Hatsuda et al, PRL55 (1985)158
Weise et al, NPA 553(1993)59



Ratti et al, PRD73(2006)014019
S. Klimt et al, PLB249(1990)386

With T and ρ dependence of the type:

$$\frac{f_\pi^2(T,\rho)}{f_\pi^2(0)} \approx \frac{<0|q\bar{q}|0>_{T,\rho}}{<0|q\bar{q}|0>_0} = 1 - \frac{T^2}{8f_\pi^2} - \frac{\sigma_N}{m_\pi^2 f_\pi^2}\rho + \dots$$

NPB 321 (1989) 387.
PRC 45 (1992) 1881.
PLB 357(1995)199

QCD Sum Rules (QCDSR) - Mass scaling - QMC

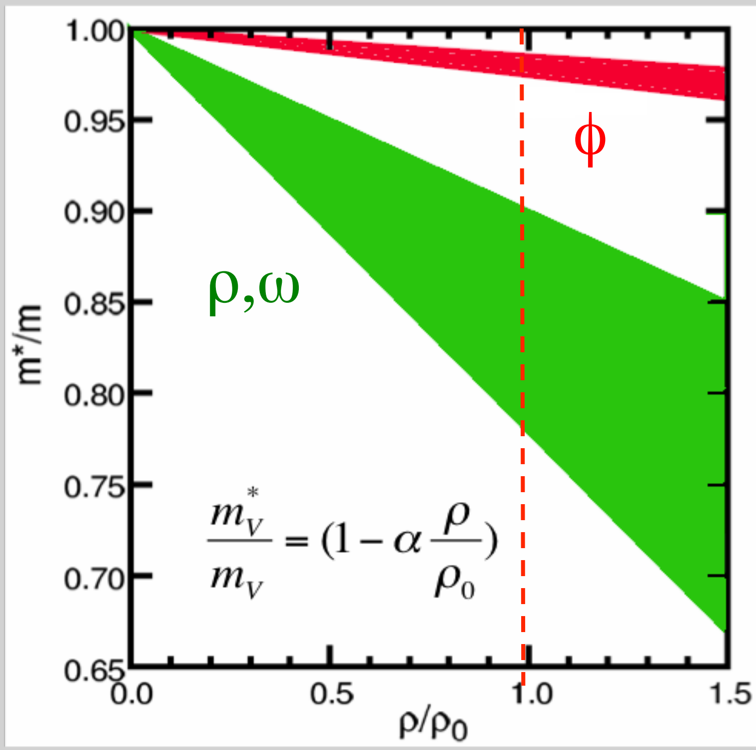
QCDSR give useful constraints. Only averages not detail shapes of spectral functions.
M. A. Shifman et al., NPB147 (1979)385, 448
T. Hatsuda et al, PRC46 (1992) R34; NPB394 (1993) 221
Y. Kwon et al, PRC78 (2008) 055

Mass Scaling Conjecture: Effective chiral Lagrangians with scaling properties of QCD lead to approximate in-medium scaling law.
Brown and Rho, PRL66 (1991) 2720
T. Harada et al, PRD66, (2002)016003 ; PLB537 (2002)280; PRD73, (2006)036001.

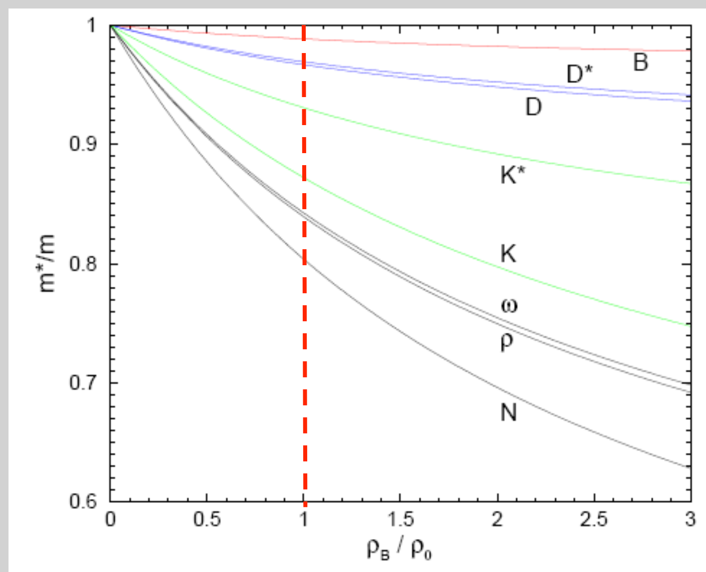
ρ_0 is normal nuclear density 0.17 fm^{-3}
α~0.18±0.06 for V= ρ ,ω
α~0.15y for V= ϕ (y nucleon strangeness content)

"Brown-Rho Scaling"

$$\frac{m_\sigma^*}{m_\sigma} \approx \frac{m_N^*}{m_N} \approx \frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \frac{f_\pi^*}{f_\pi} \approx 0.8 \left(\rho \approx \rho_0\right)$$



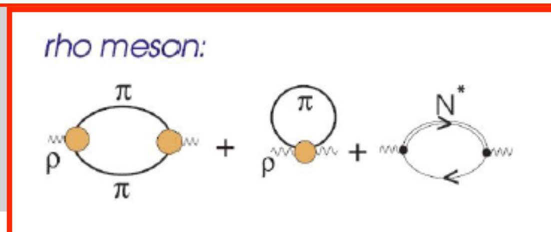
Phenomenological theory confining quarks and gluons in a "bag". In-medium mesons feel a scalar potential → universal scaling law.
K. Saito et al, PRC55 (1997) 2637



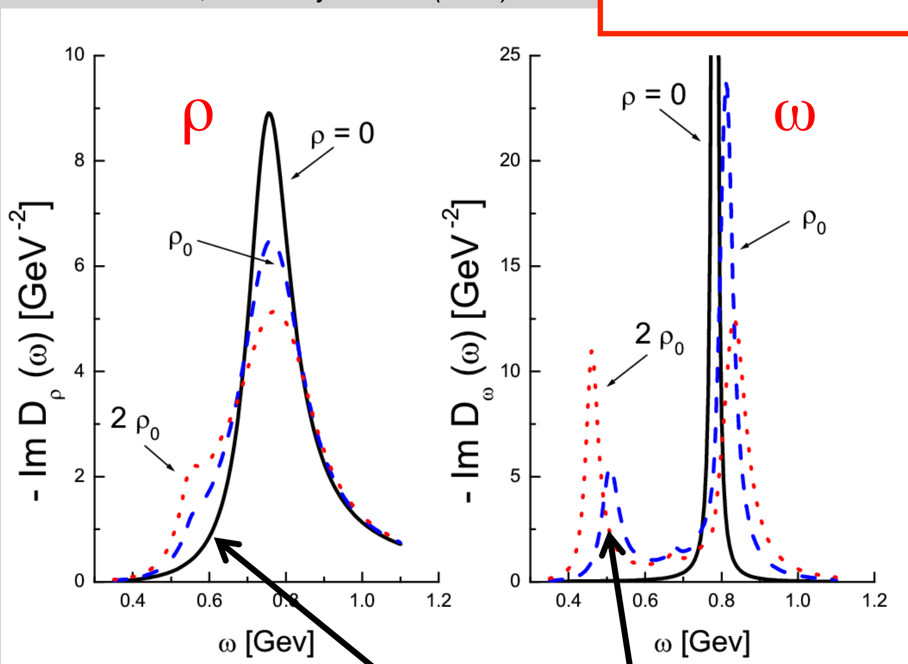
Hadronic models

-Contrary to the models described so far (which gave average constraints), hadronic models calculate the spectral function of the mesons in the medium.. Mesons are propagating in medium and coupling to resonances → "richer predictions" (spectral shift, broadening, new spectral peaks, etc…)

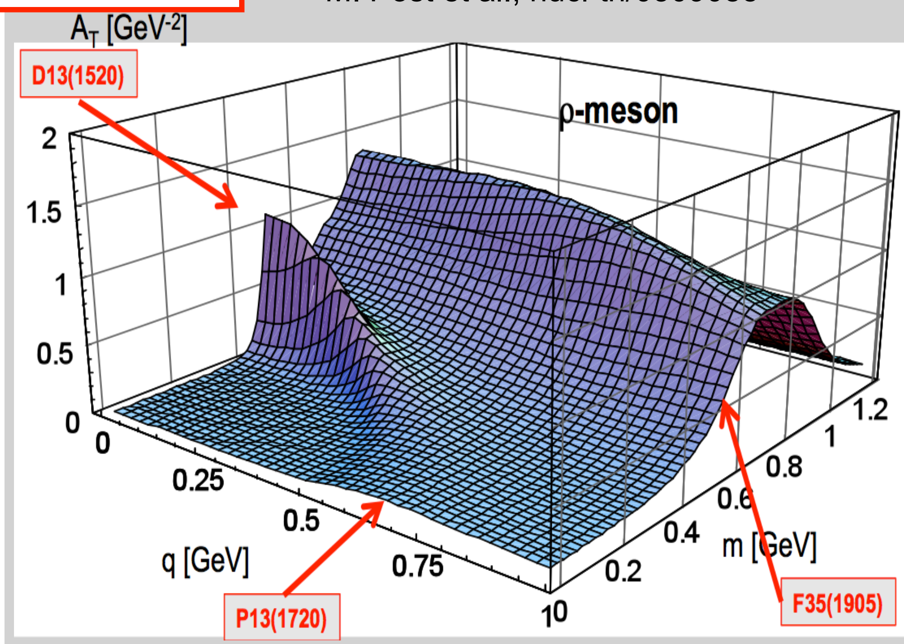
Rapp, Wambach, EPJA 6 (1999) 415
B Friman et al, *NPA617 (1997) 496*
R. Rapp et al, *NPA617 (1997) 472*



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



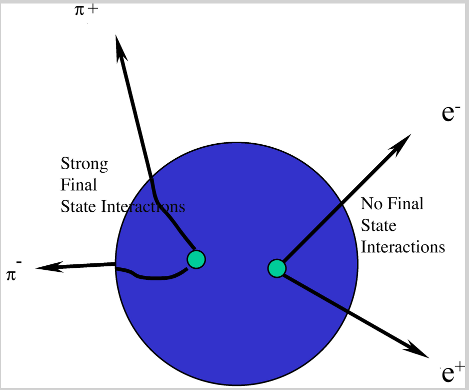
M. Post et al., nucl-th/0309085



structures in spectral functions due to coupling to baryon resonances

Vector mesons in Medium

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



SOME ADVANTAGES

-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)

-Di-leptons (no FSI) carry "clean information" of the system at the time of production (either a nucleus or a fire ball in HI collisions).

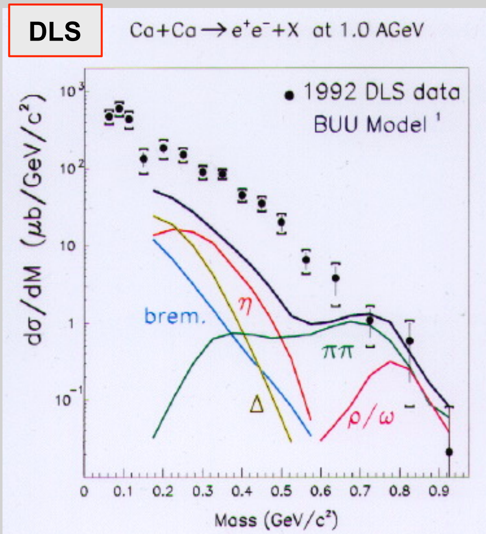
SOME CHALLENGES

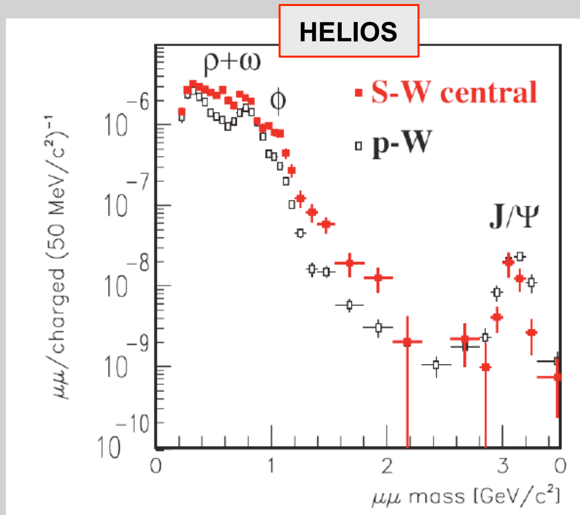
However, these are very difficult measurement. The di-lepton decay has a very small branching ratio (~10^{-5}). One needs:

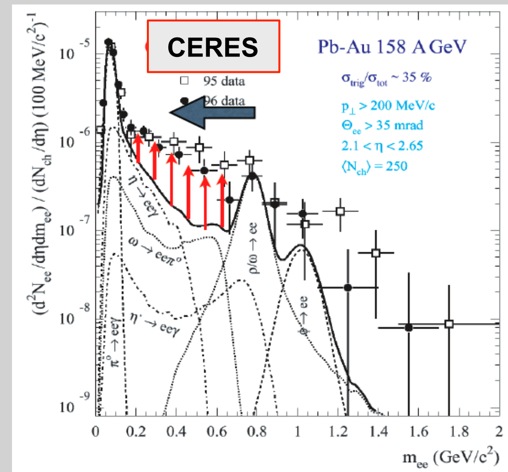
1) excellent lepton-hadron discrimination
2) to control "huge" combinatorial background (severe in HIC).
3) to understand and account for all physics channels leading to di-leptons ("cocktail")

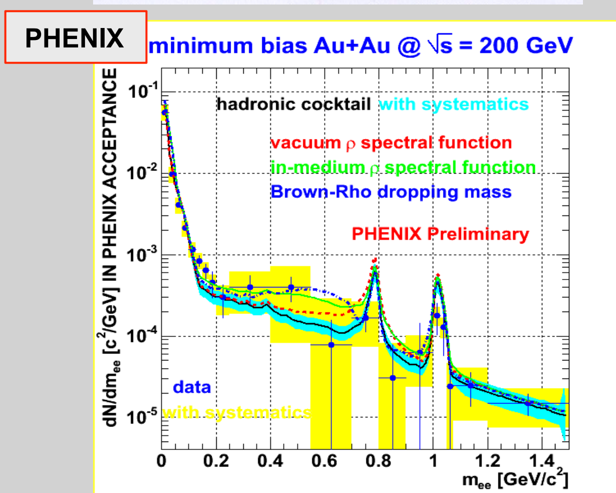
Vector mesons in Medium (Any observations?)

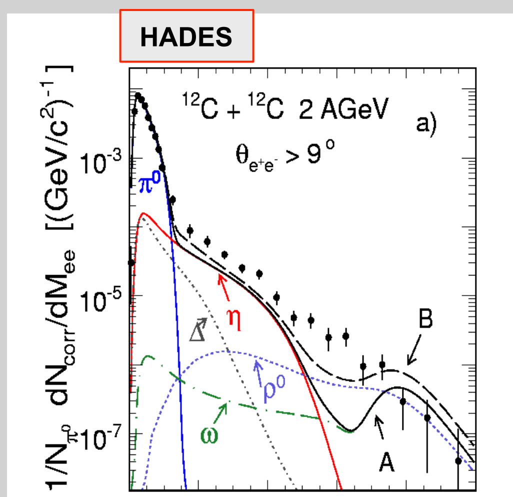
First measurements of possible medium modification of VM came from RHI collisions

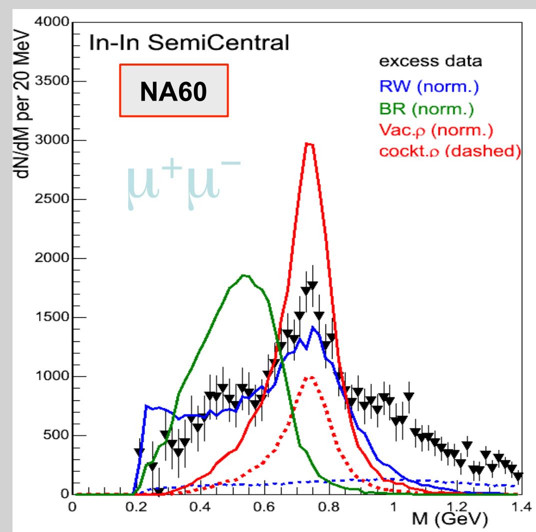












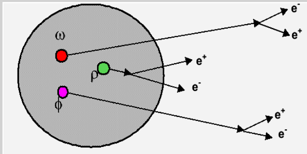
Vector mesons in Nuclei (T=0 and $\rho\sim\rho_0$)

Elementary probes that leave the nucleus in almost an equilibrium state $\gamma,\pi,p + A \to V X$

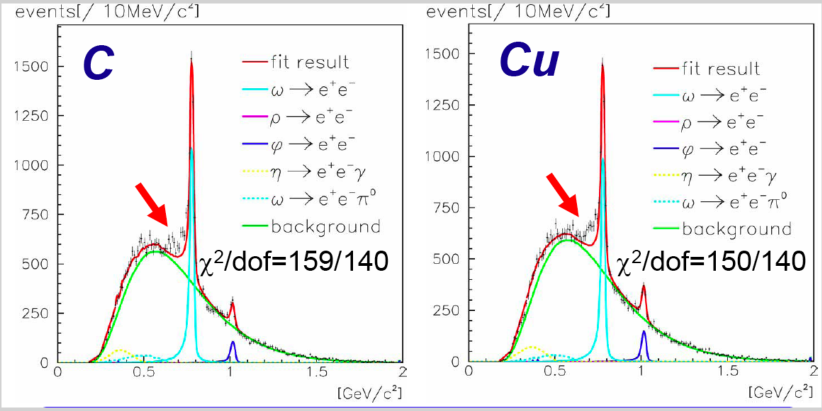
Experiment	*Reactions*
TAGX	$\gamma + {}^3He \to \rho + X$ ($\rho \to \pi^+\pi^-$)
KEK	$p+A \to \rho,\omega,\phi+X$ ($\rho,\omega \to e^+e^-$)
KEK	$p+A \to \phi+X$ ($\phi \to e^+e^-$)
SPring-8	$\gamma + A \to \phi+A^*$($\phi \to K^+K^-$)
TAPS	$\gamma+A \to \omega+X$ ($\omega \to \pi^0 \gamma$)
JLab-g7	$\gamma+A \to (\rho,\omega,\phi)+A^*$ ($VM \to e^+e^-$)
HADES	$\pi,p+A \to \rho,\omega,\phi+X$ ($\rho,\omega,\phi \to e^+e^-$)

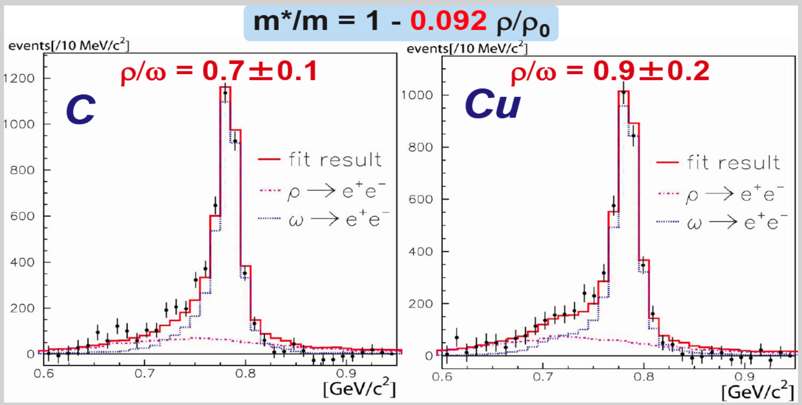
-Only g7 with EM interaction in entrance and exit channels
-TAGX, Spring8 and TAPS have hadronic FSI.

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



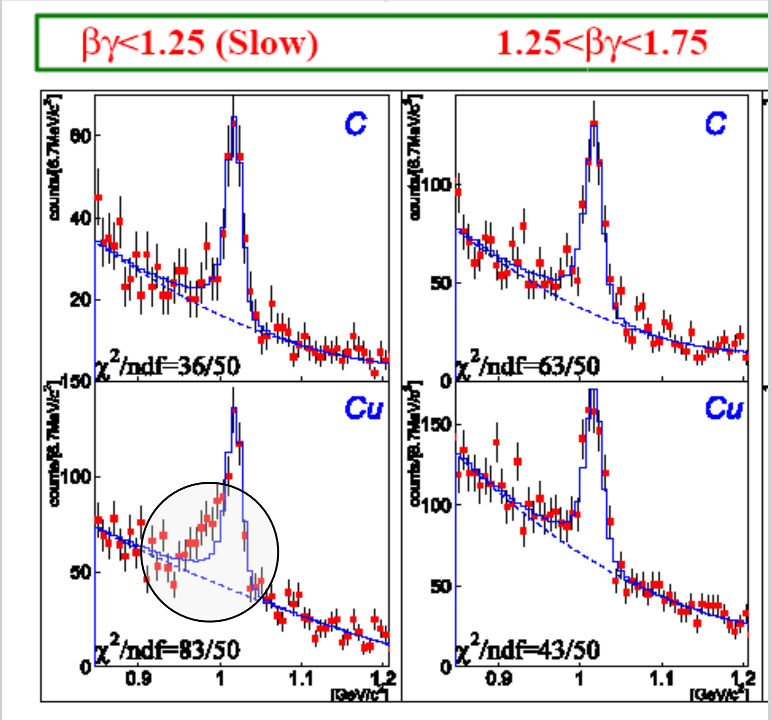
M. Naruki et al, PRL 96 (2006) 092301





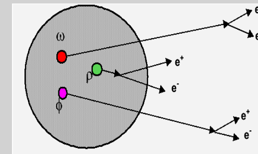
$$m^*/m = 1 - k_1\, \rho/\rho_0,$$
$$\Gamma^*/\Gamma = 1 + k_2\, \rho/\rho_0$$

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

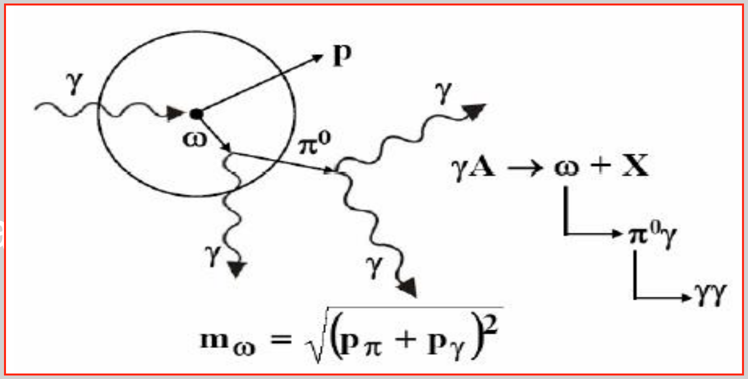


Best Fit Values		
	ρ, ω	φ
k_1	9.2 ± 0.2%	$3.4^{+0.6}_{-0.7}$%
k_2	0 (best fit)	$2.6^{+1.8}_{-1.2}$

ω mass spectrum (CBELSA-TAPS first analysis)



γ+A-->ω+X (ω --> π^0 γ)
Eγ = 0.64-2.53 GeV on LH2 and Nb



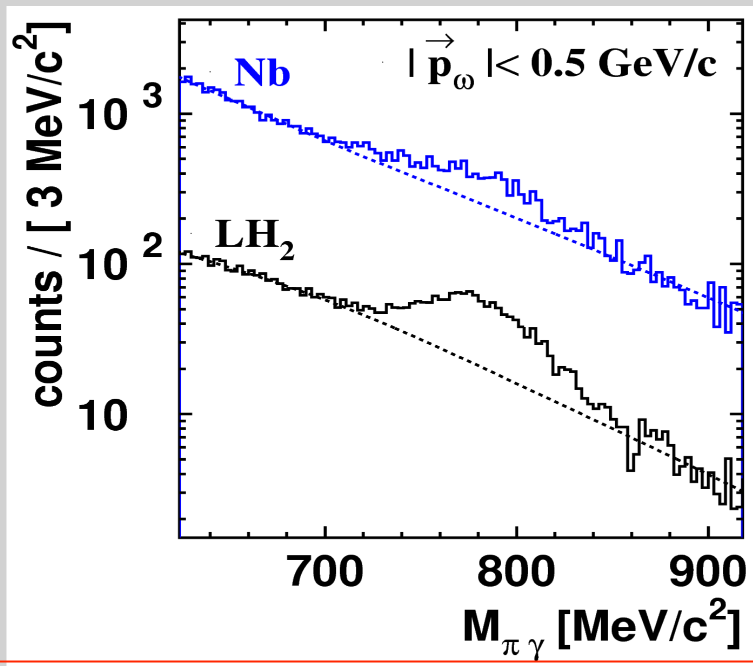
<u>Pro:</u>

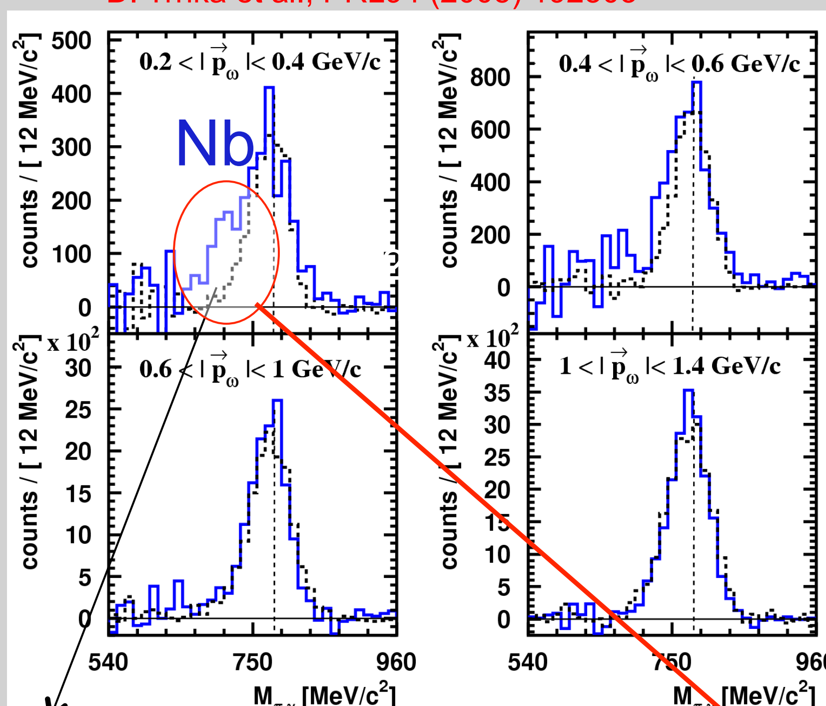
- $\pi^0\gamma$ large branching ratio (8.3 . 10^{-2})
- no ρ-contribution ($\rho \to \pi^0\gamma$: 7 · 10^{-4})

<u>Con:</u>

- π^0-rescattering (requires T_π>150 MeV cut)
- large combinatorial background (3γ)

D. Trnka et al., PRL94 (2005) 192303





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

Slow ω decaying inside

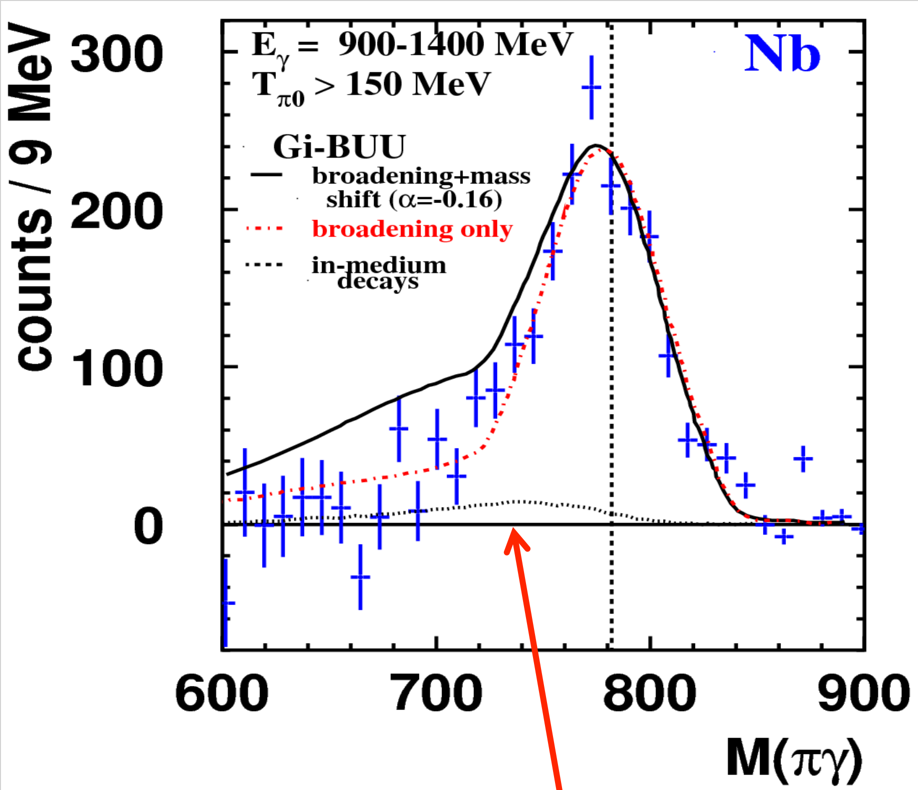
$$m^* = m_0(1 - 0.14\,\rho/\rho_0)$$

ω mass spectrum Reanalysis of CBELAS/TAPS data

(new treatment of combinatorial background)

Gi-BUU simulations: K. Gallmeister et al.
Prog. Part. Nucl. Phys. 61 (2008) 283

M. Nanova et al, (May 28,2010)
arXiv:1005.5694v1 [nucl-ex]



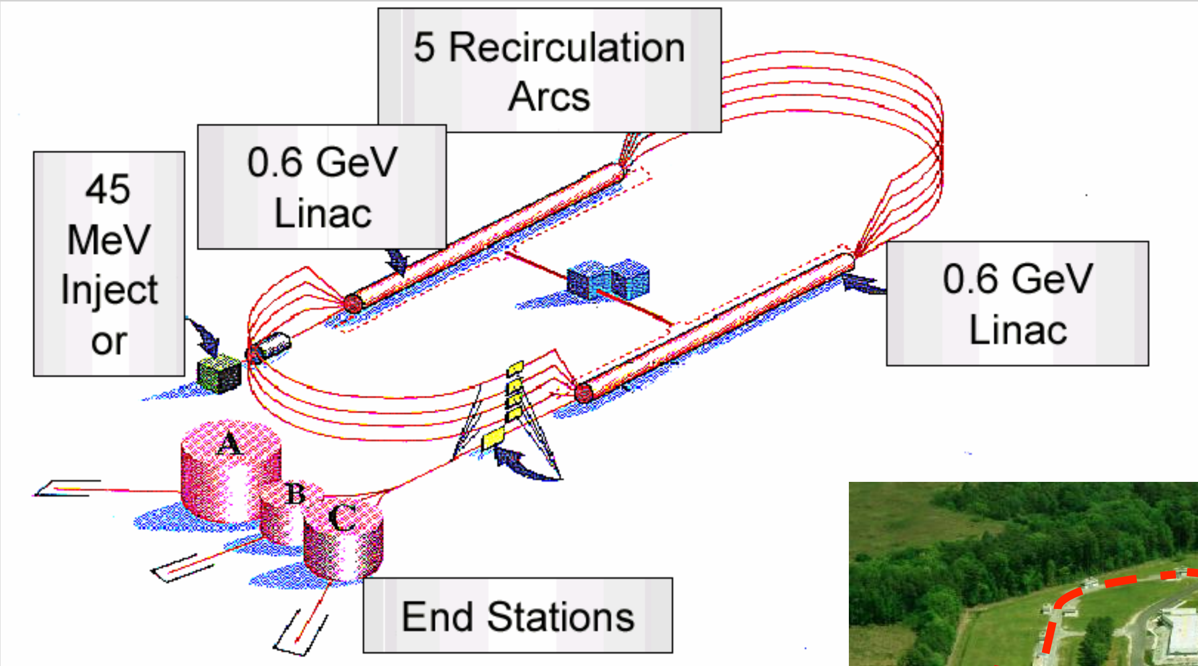
Experimental data closer to line shape predicted for "broadening only", no mass shift!

Strong broadening of the ω (as seen in transparency ratios) drastically suppresses sensitivity to direct observation of ω decaying in the medium

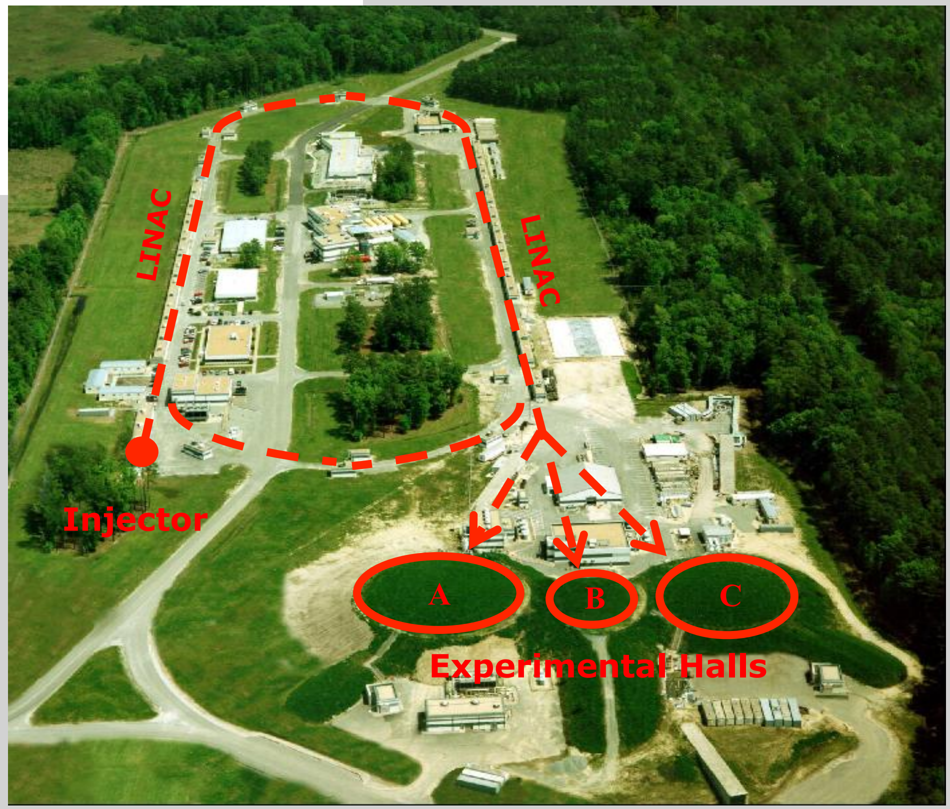
Ongoing anaysis on data taken at MAMI C with 2 times higher statistics in Eγ = 800-1400 MeV;

Preliminary results from MAMI C data are consistent with the conclusions from the re-analysis of CBELSA/TAPS data for incident photon energies 900-1400 MeV

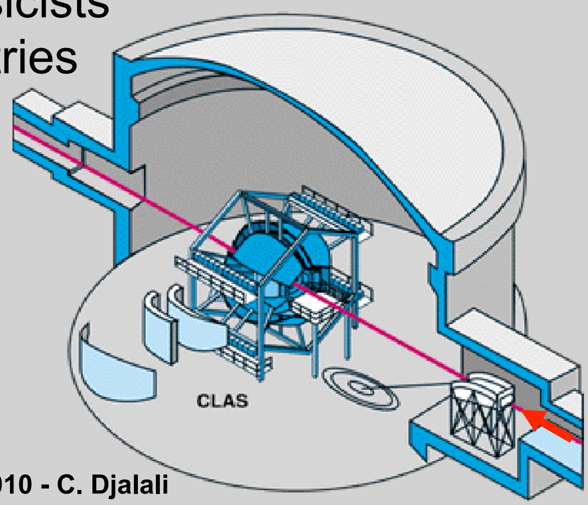
Jlab-CEBAF: The 6 GeV CW Electron Accelerator



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



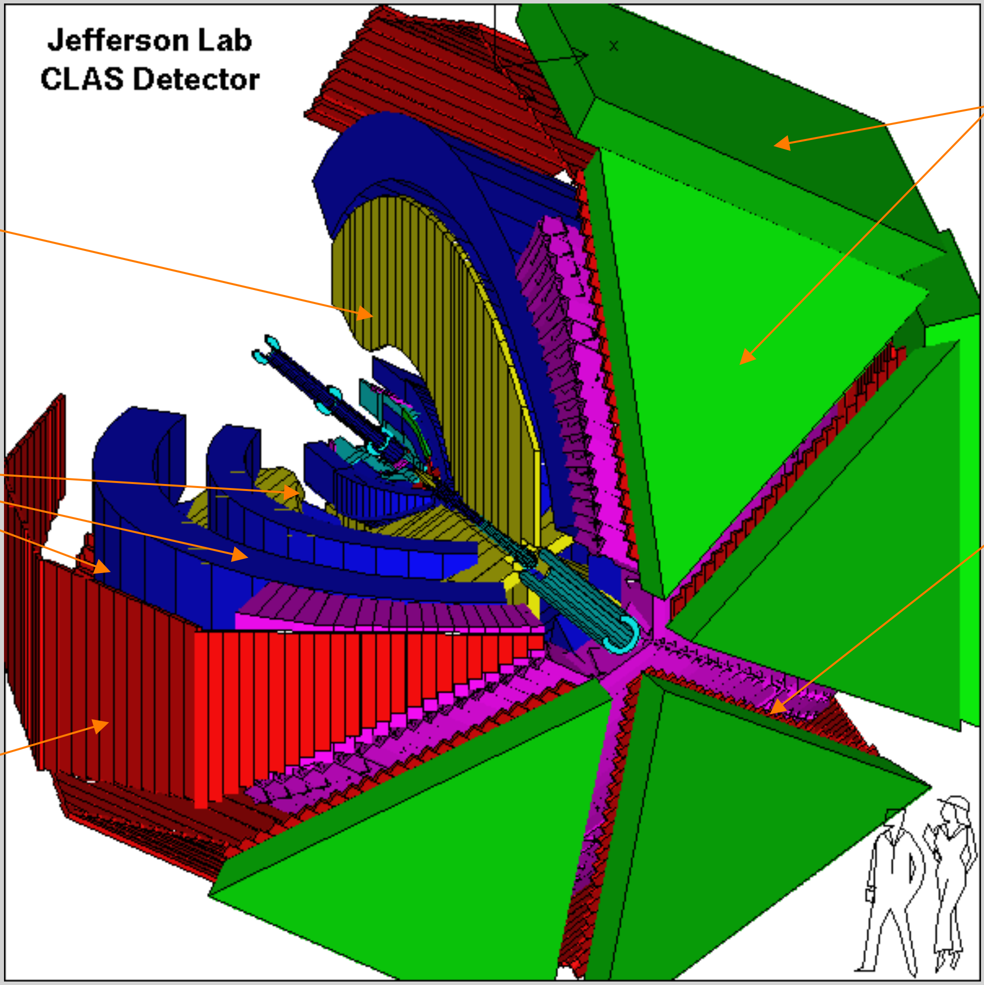
CEBAF Large Acceptance Spectrometer (CLAS)

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 : ~10^{-2}

Gas Cherenkov
Counter
e/π separation

CC e/π rejection
factor : ~10^{-1}

EC/CC rejection
factor : ~10^{-3}

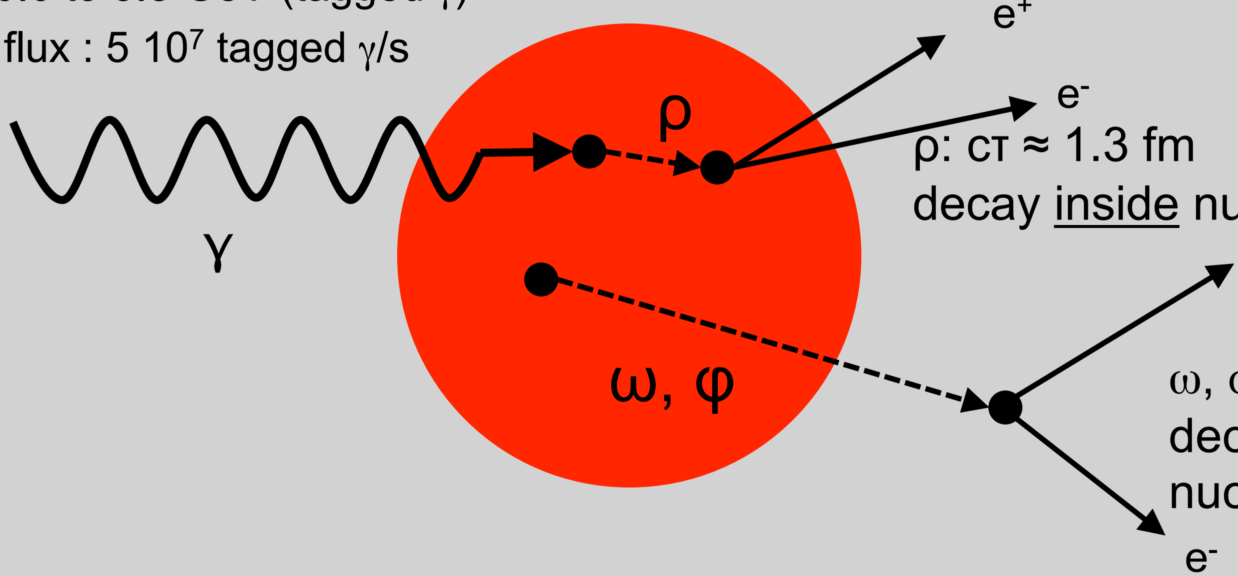
Rejection factor
for e^+e^- better
than 10^{-6}

Photo-production of vector mesons off nuclei in CLAS
Experiment E01-112 (g7)

Photon beam:

E_γ ~ 0.6 to 3.8 GeV (tagged γ)

High flux : 5 10^7 tagged γ/s



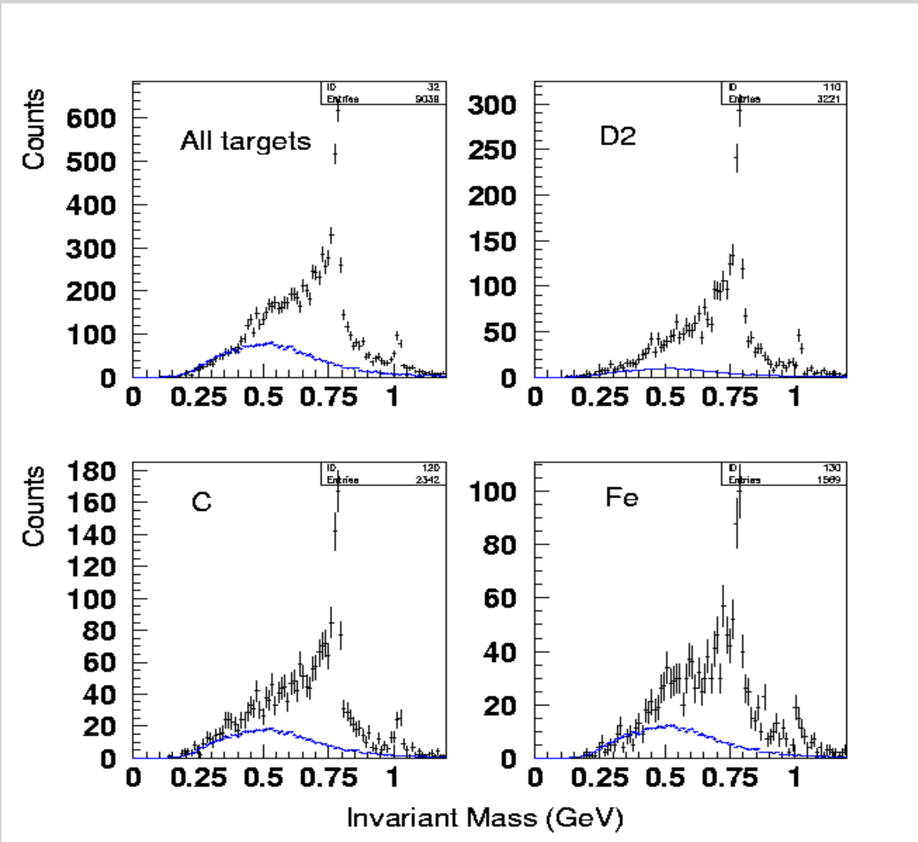
ρ: cτ ≈ 1.3 fm
decay inside nucleus

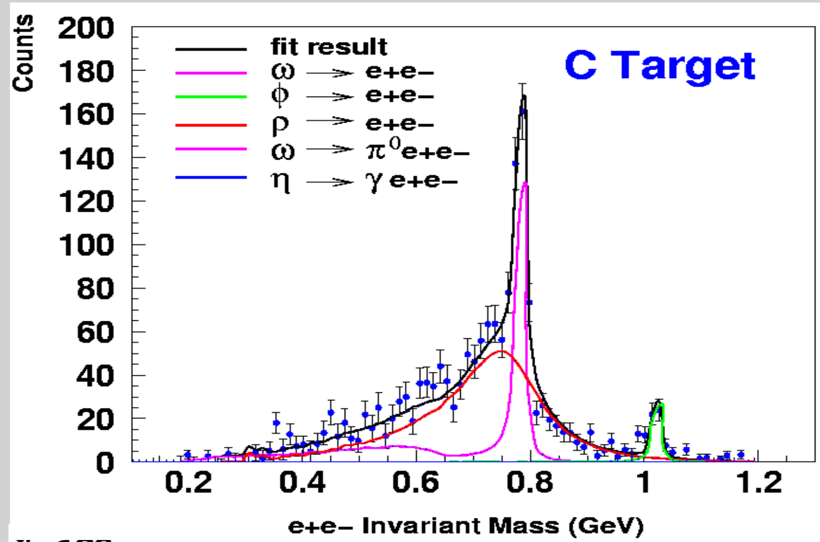
ω, ϕ mostly
decay outside
nucleus

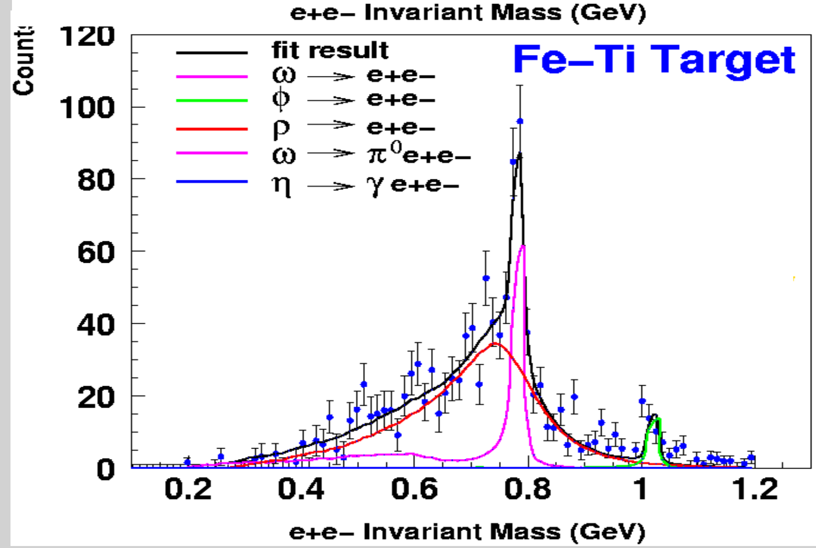
- CLAS g7a Experiment (medium modification at T = 0):
  - Targets: LD2, C, Ti, Fe, (Pb)
  - Leptonic decay with almost no final state interaction; $\Gamma_{e+e-}/\Gamma_{tot}$ ~5×10^{-5}
  - Momentum of ρ between 0.8 and 2 GeV
  - Excellent pion-electron discrimination
  - Study invariant mass distribution, $m(e^+e^-)$

CLAS g7- experiment

After Background subtraction, mass spectra mainly ρ , ω and ϕ.

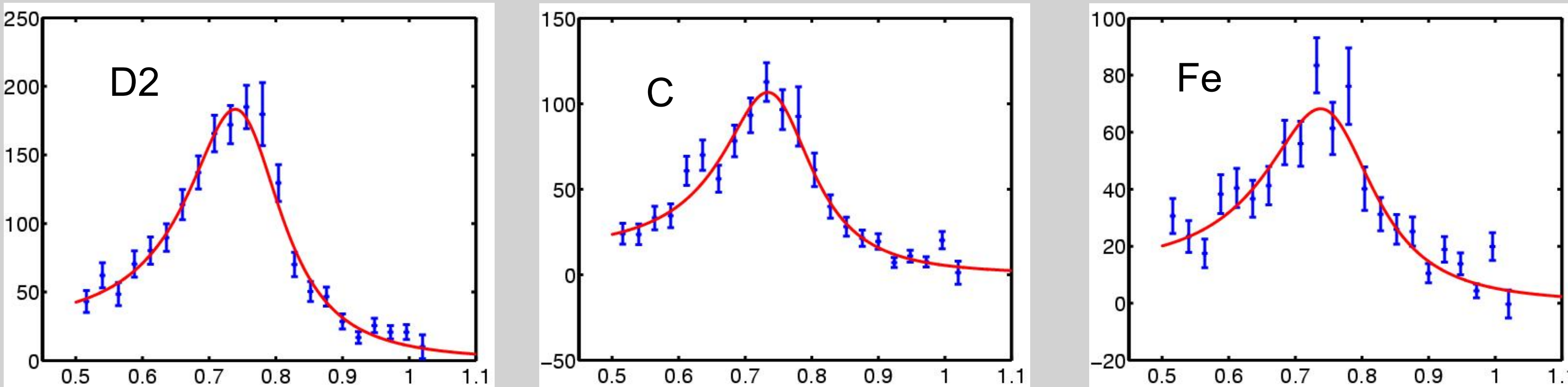






Combinatorial background well understood

CLAS-g7-experiment: Extracted 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
^{12}C	**768.5 +/- 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

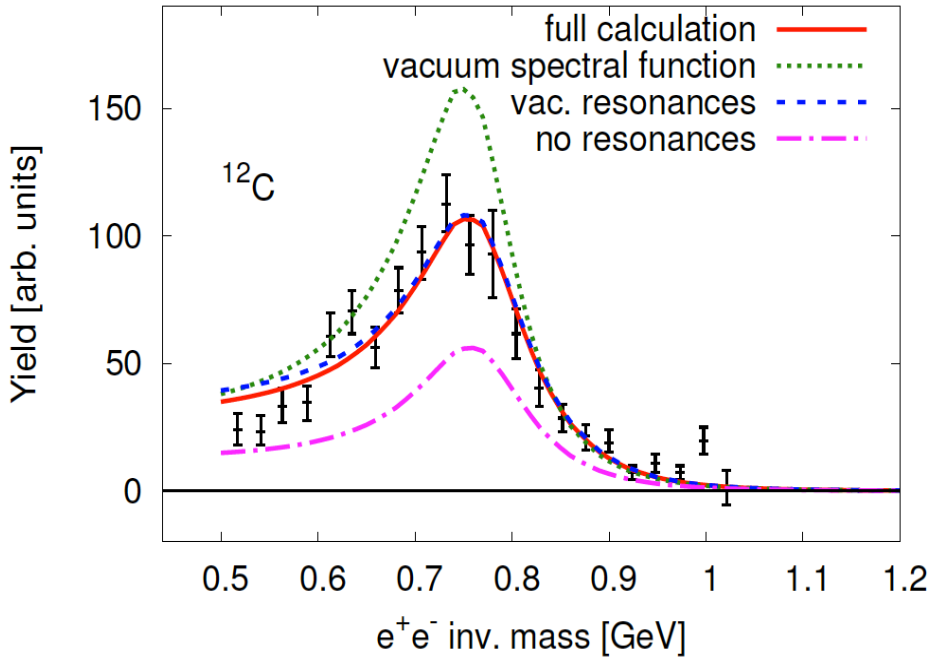
The mass of the ρ meson consistent with no shift.
Broadening of the width ($\Delta\Gamma$~70 MeV) consistent with many-body effects

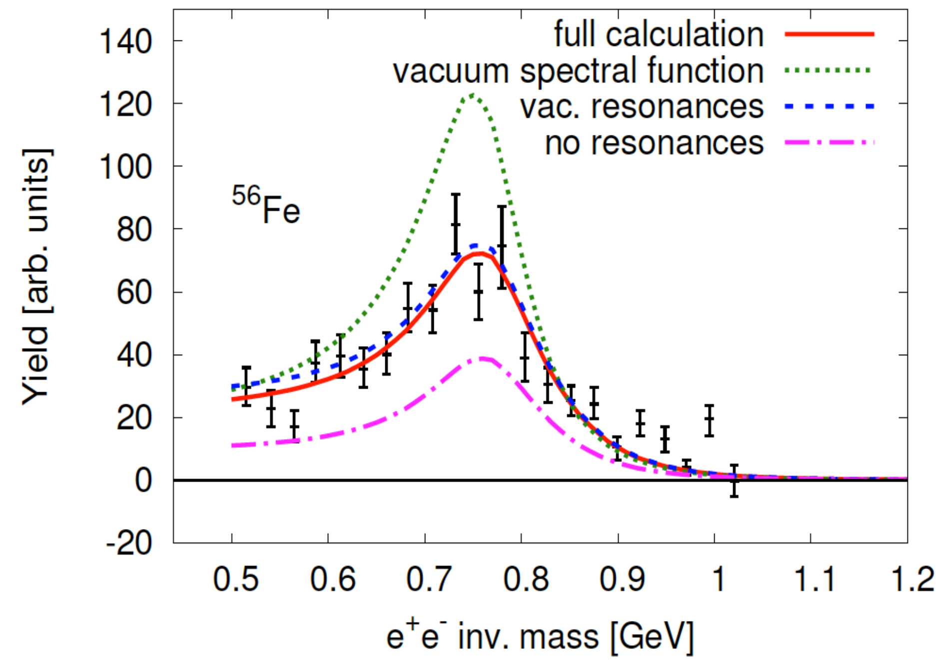
CLAS data:
Nasseripour et al., PRL 99 (2007) 262302
Wood et al., PRC 78 (2008) 015201

GiBUU calculations:
Mosel et al., NPA671, 501(2000)
Effenberger et al., PRC62, 014605(2000); PRC60, 027601 (1999).

Recent calculations by Texas A&M group for JLab-g7 results

F. Riek et al., Phys Let B 677 (2009) 116;
F. Riek et al., arXiv:1003.0910v1 (March 2010)

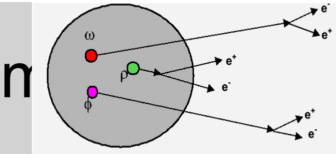




Calculations nicely reproduce g7 data. Confirms no major medium effect (beyond standard collisional broadening) expected for momenta Pρ > 1 GeV.

Need measurements at lower momenta → GOAL of experiment g7b

Absorption of ω and ϕ-mesons and their in-medium



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

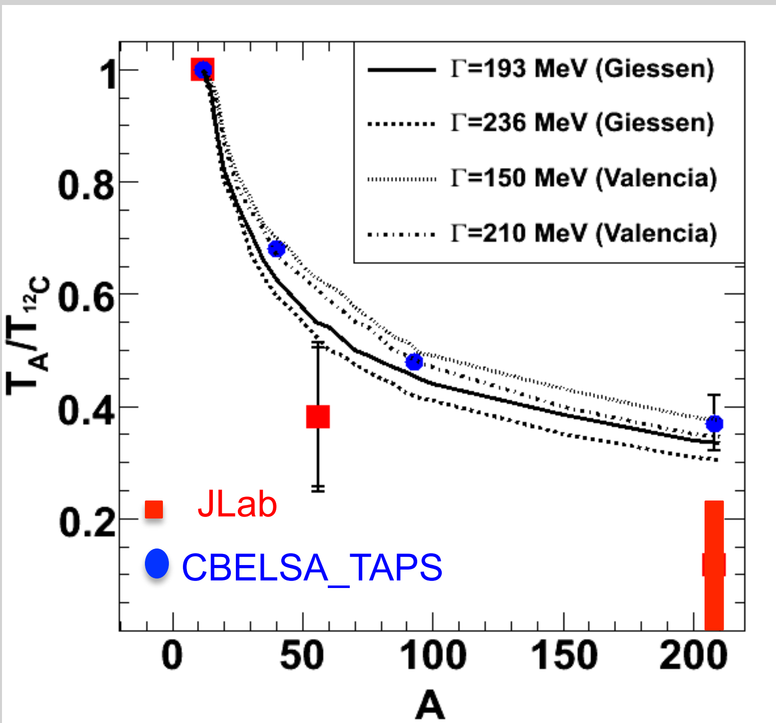
Transparency ratio:

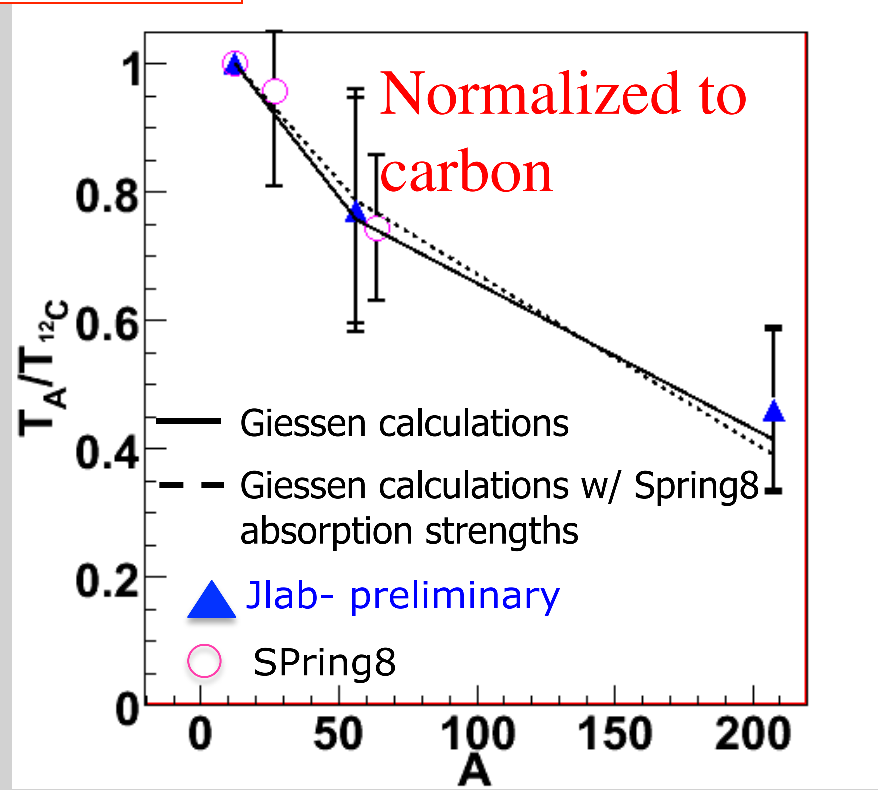
$$T_A = \frac{\sigma_{\gamma A \to \omega X}}{A \cdot \sigma_{\gamma N \to \omega X}}$$

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

Spring8 γ A →ϕ A′ → K^+K^- A′
(Eγ=1.5-2.4 GeV)
PLB 608 (2005) 215

Giessen calculations: NPA 773, 156 (2006)
Valencia calculations: EPJ A 31, 245 (2007)





Latest TAPS Γ_ω~130-150 MeV (PRL100(2008) 192302)
JLAB preliminary results -> much larger width (Γ_ω >200 MeV)
Possible ρ−ω interference

$\sigma_{\phi N}$ ~ 25−55 mb
Γ_ϕ(~ 70 MeV) compatible with Spring8
JLab data: M. Wood et al, submitted to PRL

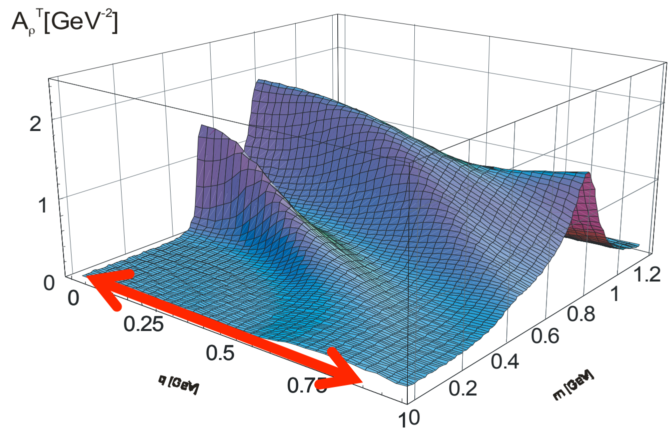
In-medium m and Γ of vector mesons

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 $\langle p_\omega \rangle$ >1 GeV/c	$\Delta\Gamma$ 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 $\langle p_\omega \rangle$ = 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 $\langle p_\phi \rangle$ = 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

Majority of experiments → no mass shift but broadening

Summary and Outlook (Mesons)

- –**Excess of dileptons in the region of vector mesons seen by CERES and NA60 can be explained by a broadening of the ρ.**
- –**Most "elementary reactions" report mainly an in-medium broadening, no mass shift!**
- –**The ρ-meson best candidate for direct measurement of medium modifications**
- –**Transparency ratios ideal to study long-lived mesons**
- –**Photoproduction followed by e^+e^- decay turns out to be ideal experiment!**
- –**Need data for mesons produced with low momentum**



Substantial theoretical and experimental efforts carried out in this very active field.

High statistics experiments are planned at different facilities:

-JLab C3 experiment g7b (ρ, ω ,φ and K^0_S , K* in medium)
-COSY, JPARC (meson bound states)
-PHENIX is analyzing the observed excess in A+A
-HADES is analyzing A+A data and will soon run π+A
-ALICE will soon come online
-PANDA &CBM at FAIR, JLab, JPARC will look into the Charm sector →