In-medium properties of mesons from photo nuclear reactions

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

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- motivation: theoretical predictions
- In-medium properties of the ω and η‘ meson from the measurement of

  a.) the transparency ratio

  b.) meson line shape

  c.) the meson momentum distribution

  d.) the excitation function for photoproduction off nuclei

  in photonuclear reactions at CBELSA/TAPS (Bonn) and Crystal Ball/TAPS (Mainz)

- summary and conclusions

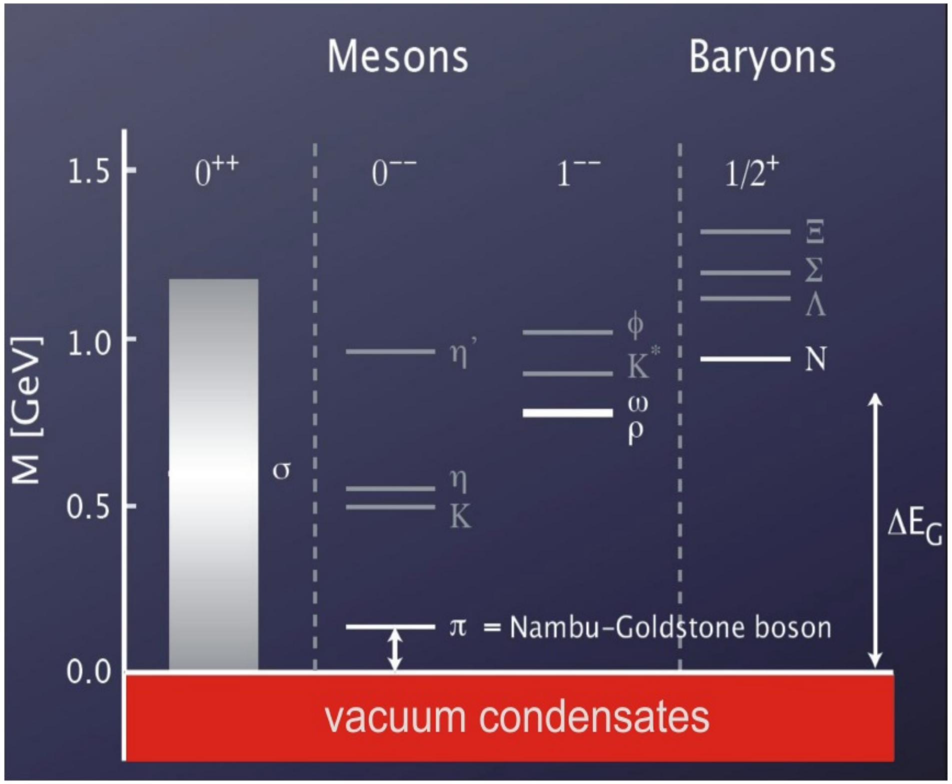
CB-ELSA

40th. International Workshop on Gross Properties of Nuclei and Nuclear Excitations
Hirschegg, Austria, Jan. 15-21, 2012

A2 Collaboration

hadron masses

J.Wambach



- QCD-vacuum: complicated structure characterized by condensates
- in the nuclear medium: condensates are changed

→ change of the hadronic excitation energy spectrum

V. Bernard and U.-G. Meißner, NPA 489 (1988) 647

G.E.Brown and M. Rho, PRL 66 (1991) 2720 $\frac{m^*}{m} \approx \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \approx 0.8 \, (\rho \approx \rho_0)$

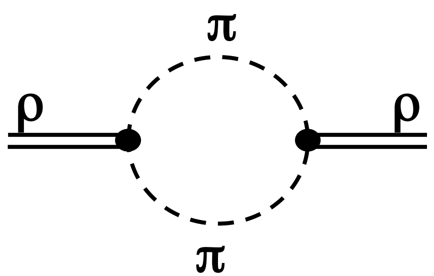
T.Hatsuda and S. Lee, PRC 46 (1992) R34 $\frac{m_V^*}{m_V} = \left(1 - \alpha \frac{\rho_B}{\rho_0}\right) ; \; \alpha \approx 0.18$

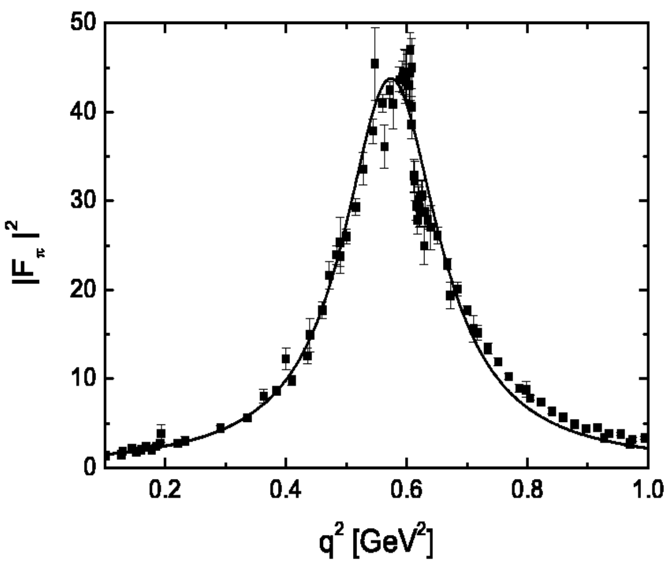
⇒ widespread theoretical and experimental activities to search for in-medium modifications of hadrons

in-medium modifications of the ρ meson through hadronic many body effects

in vacuum:

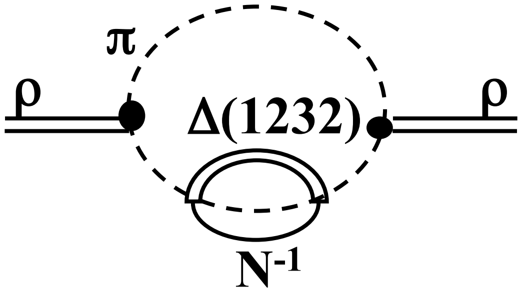
ρ-width determined by coupling to ρ➔ππ channel



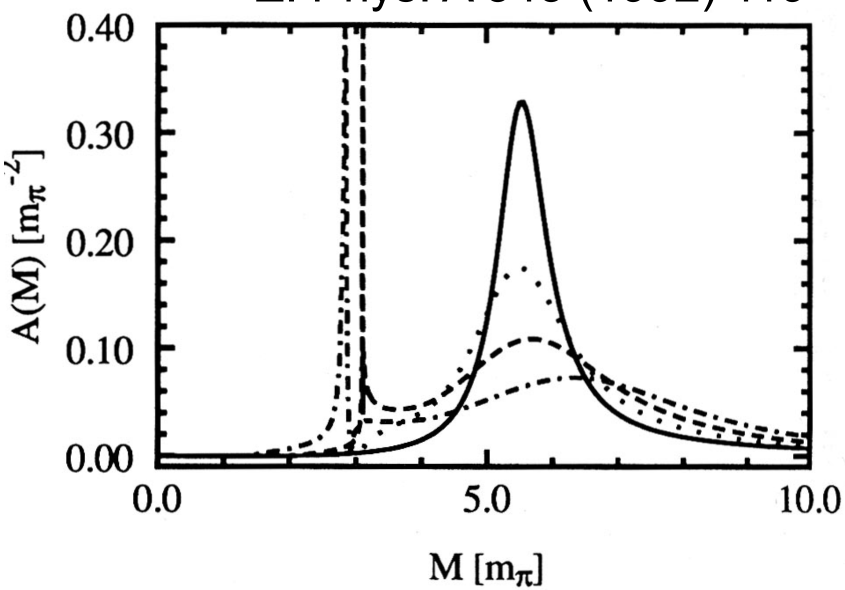


in the nuclear medium:

π of π cloud couple to ΔN^{-1} excitations (Δ width not yet taken into account)



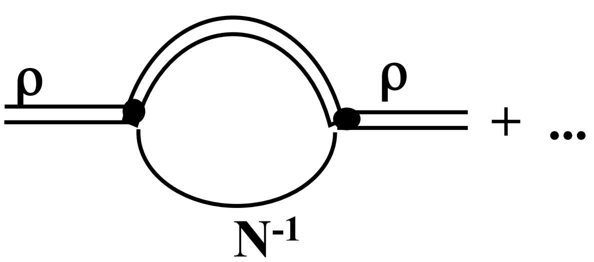
M. Hermann, B. Friman, W. Nörenberg, Z. Phys. A 343 (1992) 119



in-medium modifications of the ρ meson through hadronic many body effects

medium modificatios through coupling to baryon resonances:

B. Friman , H.J.Pirner, NPA 617 (1997) 496

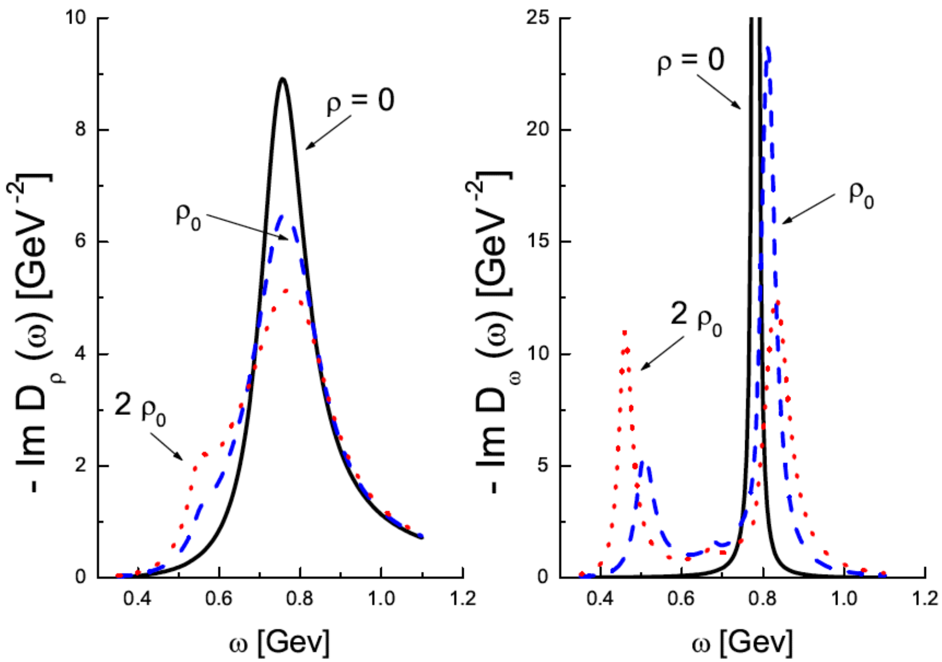


medium effects calculable from elementary γ-,π- induced reactions:

exploit information from coupled channel analyses:
πN, ρN, ωN, πΔ, Nη

M.F.M. Lutz, Gy. Wolf, B. Friman, NPA 706 (2002) 431

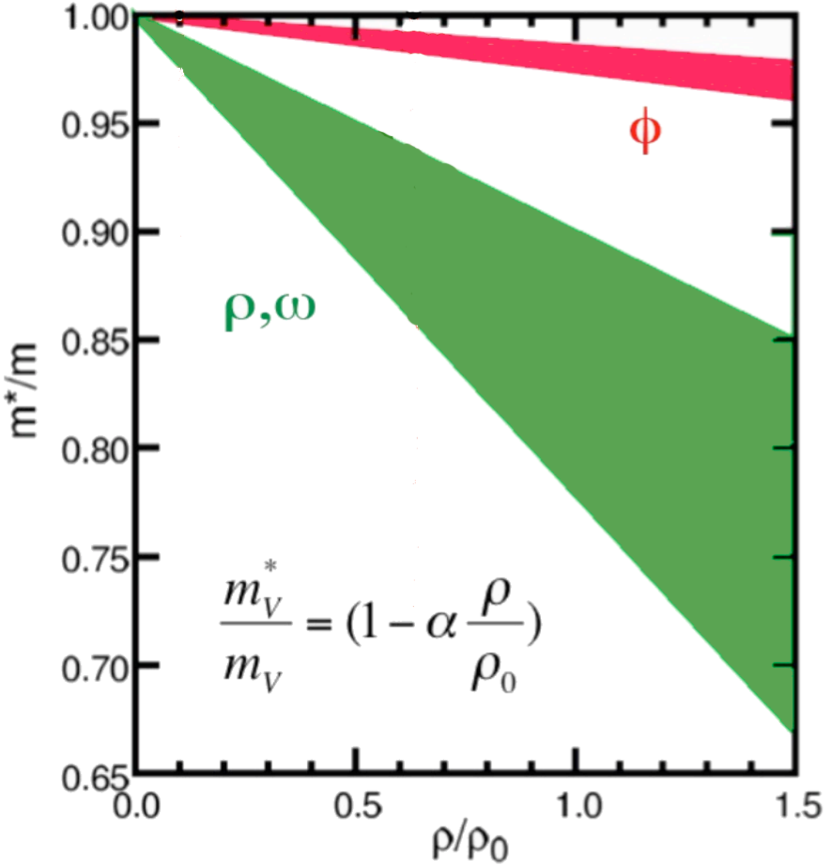
σ (elementary);
unitary coupled channel analysis
$\rightarrow t_{VN} \rightarrow \Pi = t_{VN} \cdot \rho \rightarrow V_{opt}$
low density approximation



structure in spectral function due to coupling to baryon resonances

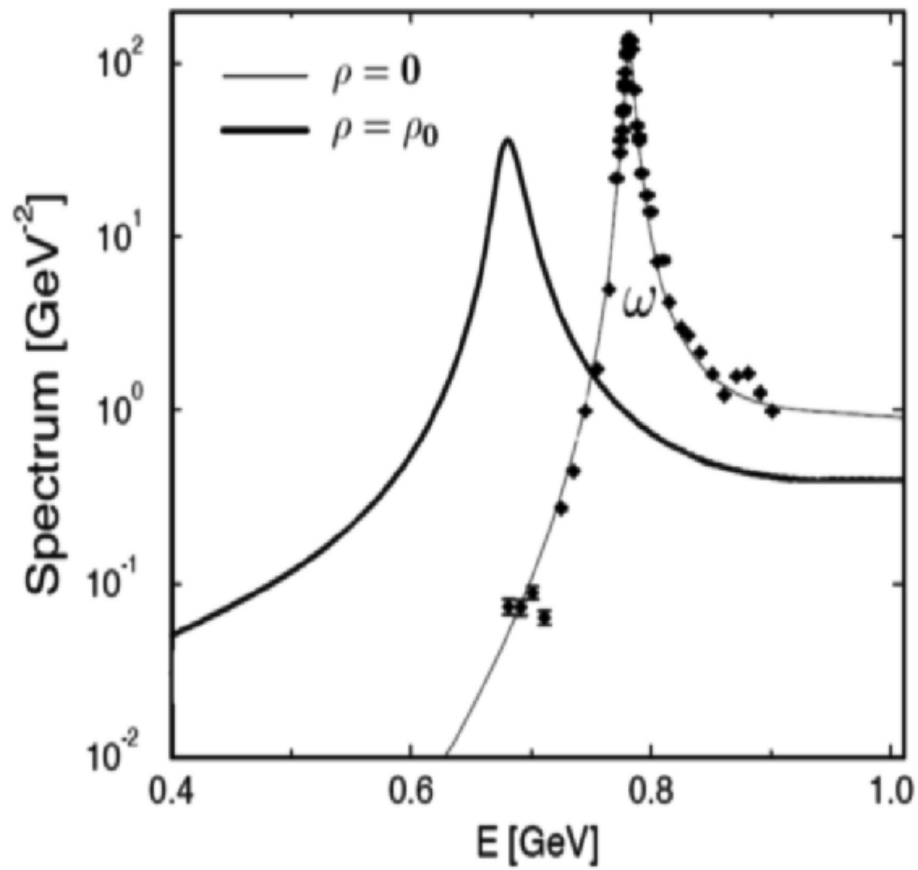
Model predictions for in-medium masses of vector mesons

T. Hatsuda, S.Lee
PRC 46 (1992) R34



QCD sum rule approach:
drop of ρ,ω mass by
≈ 10% at average
nuclear density of 0.6 ρ_0

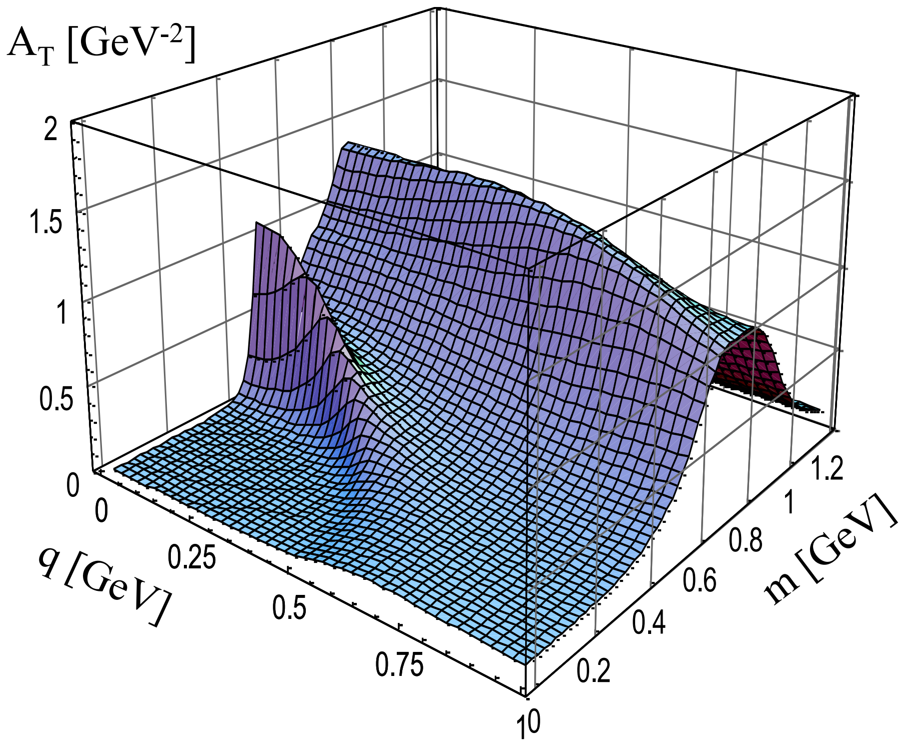
F. Klingl et al. NPA 610 (1997) 297
NPA 650 (1999) 299



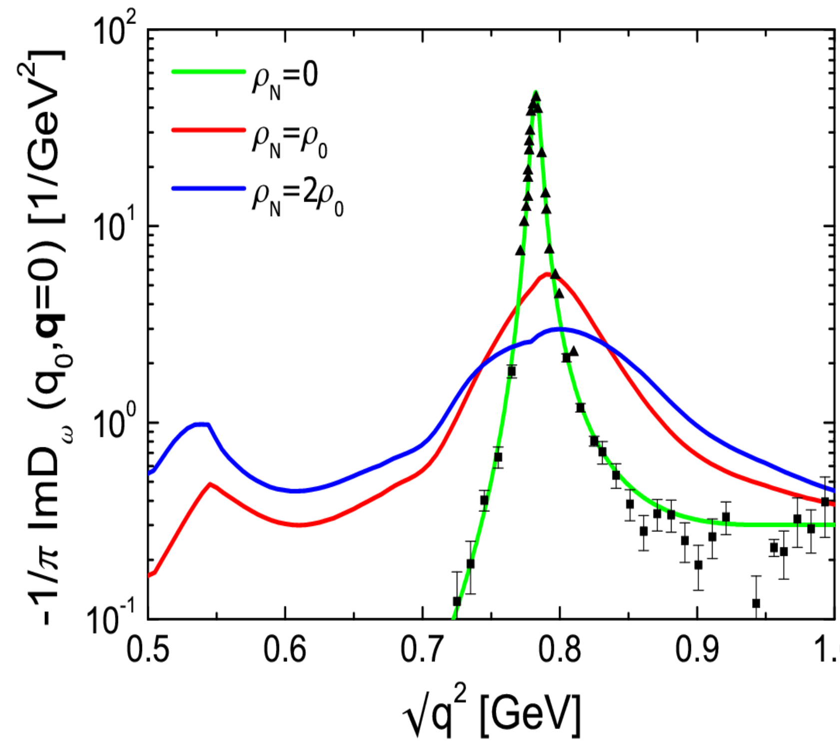
for ρ_B↗:
1.) lowering of in-medium mass: Δm ≈ -100 MeV
2.) broadening of resonance: Γ_{med} ≈ 30 MeV

Model predictions for in-medium masses of vector mesons

M. Post et al., NPA 741 (2004) 81



P. Mühlich et al., NPA 780 (2006) 187

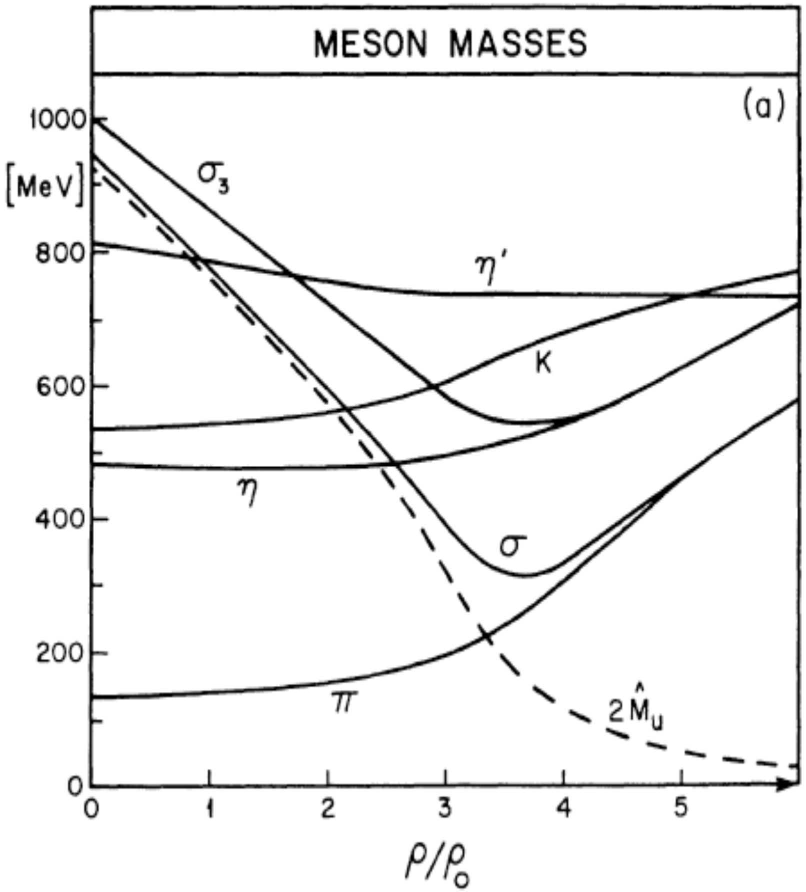


- structure in ρ spectral function due to coupling to baryon resonances
- strong momentum dependence
- modifications most pronounced for small momenta

spectral function for ω mesons at rest: splitting into ω-like and a N^*N^{-1} mode due to coupling to $S_{11,}$ resonance; (level repulsion)

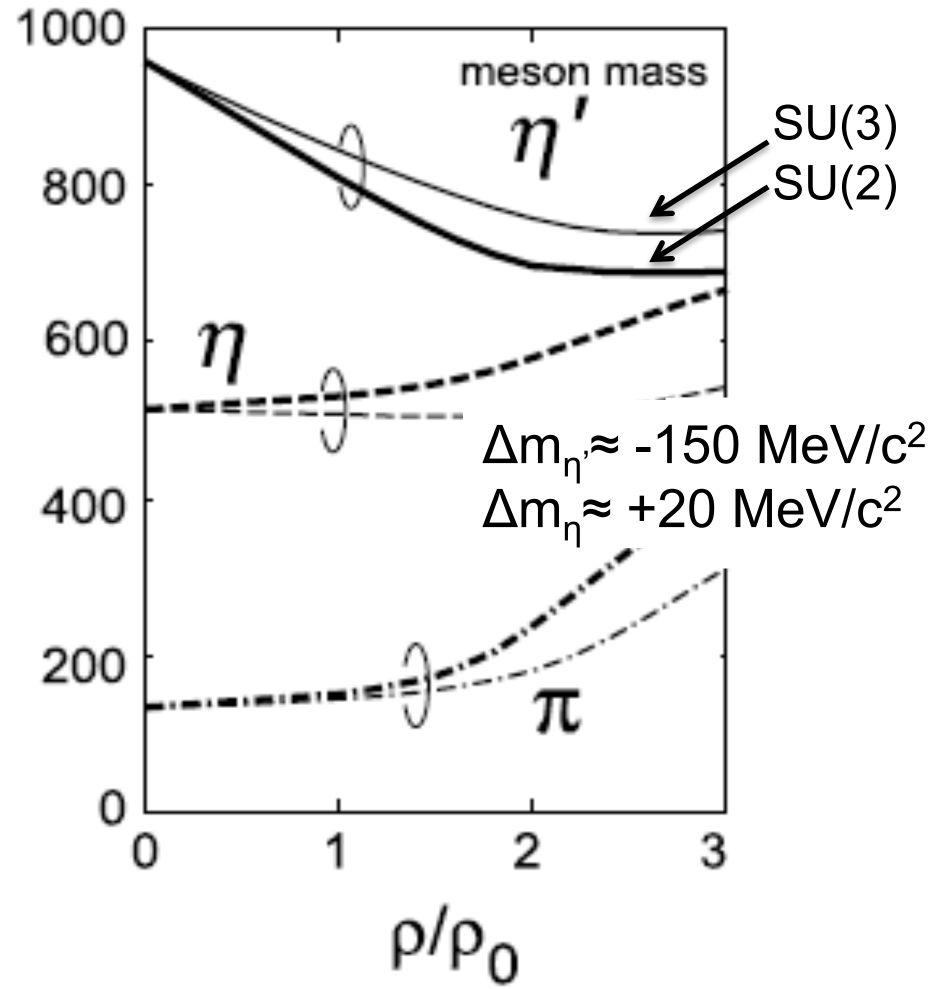
Model predictions for spectral functions of the η‘ meson

V. Bernard, U.- G. Meissner,
Phys. Rev. D 38 (1988) 1551



almost no dependence of
η’ mass on density

H. Nagahiro , M. Takizawa, and S. Hirenzaki,
PRC 74 (2006) 045203



strong variation of η’ mass with density

Experimental approaches and observables to extract in-medium properties of mesons

experimental task: search for { mass shift ? broadening ? structures ? } of hadronic spectral function

ensure sensitivity to low momentum mesons !!

1.) **Transparency ratio**: $T_A = \frac{\sigma_{\gamma A \to VX}}{A \cdot \sigma_{\gamma N \to VX}}$

2.) **Lineshape analysis**: M ➔ $X_1 + X_2$; $\mu_H(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$

3.) **Meson momentum distribution**

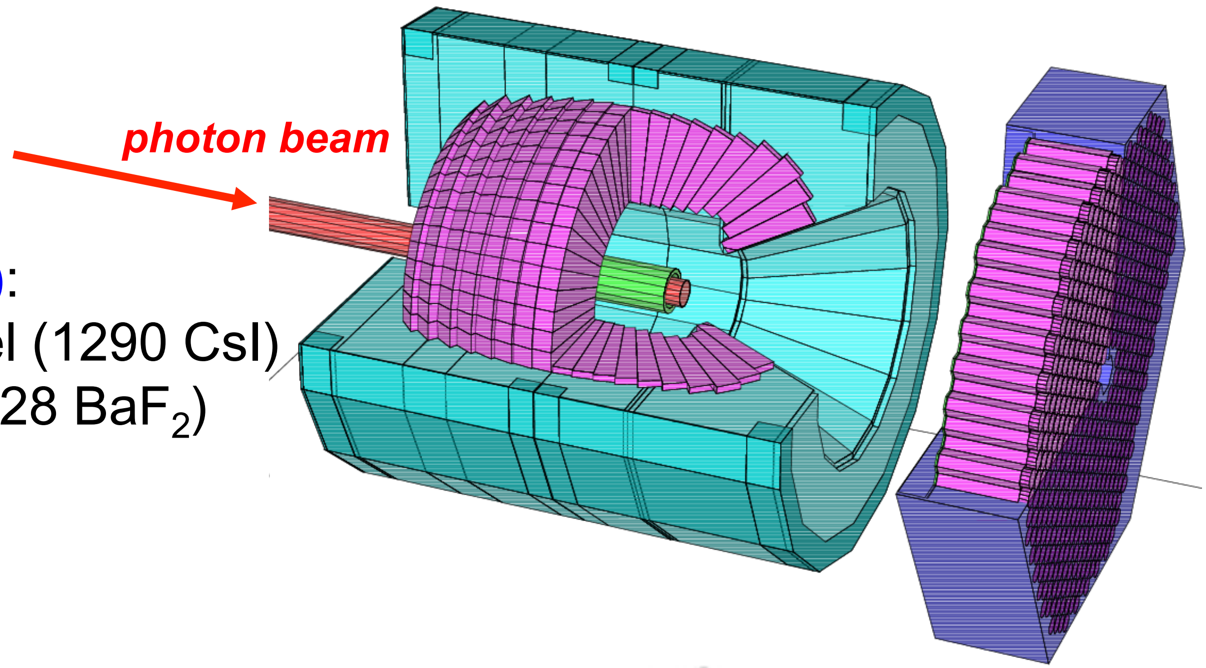
4.) **Excitation function**

Experimental setups

4π photon detectors

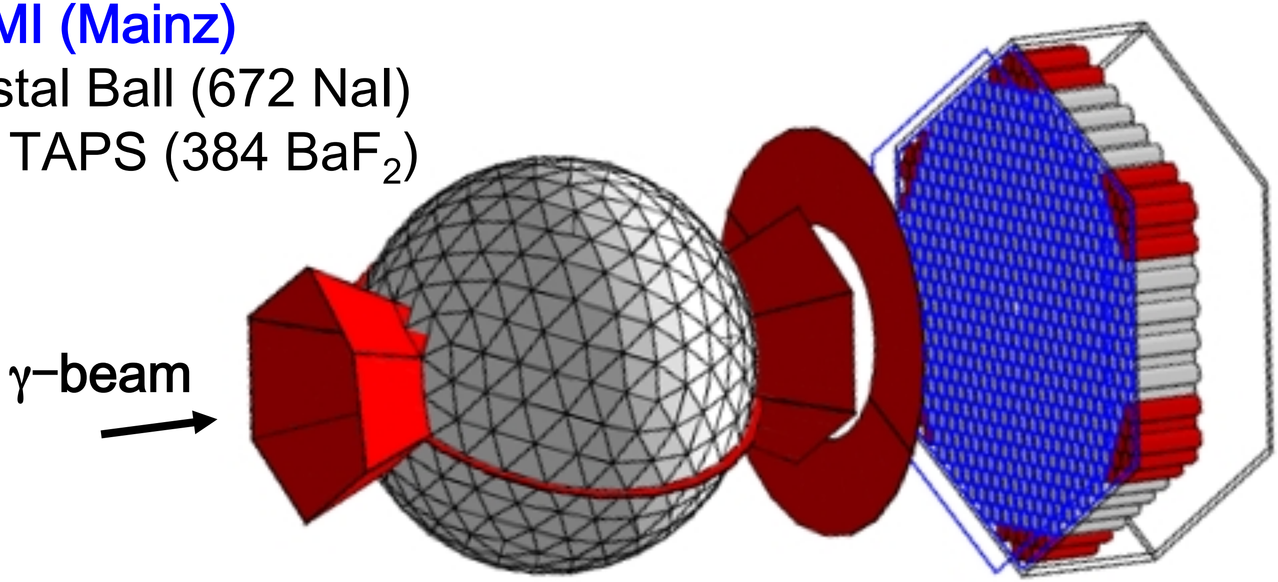
$\omega \rightarrow \pi^0 \gamma \rightarrow 3\gamma$

$\eta' \rightarrow \pi^0 \pi^0 \eta \rightarrow 6\gamma$



ELSA (Bonn):
Crystal Barrel (1290 CsI)
and TAPS (528 BaF_2)

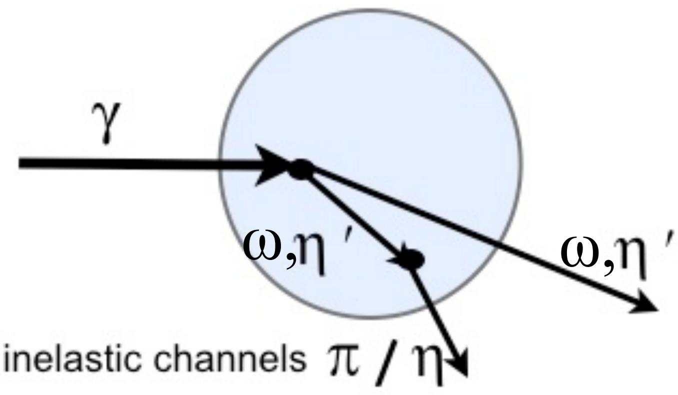
MAMI (Mainz)
Crystal Ball (672 NaI)
and TAPS (384 BaF_2)



I. Measurement of the transparency ratio

Meson attenuation:

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



production probability per nucleon within nucleus compared to production probability on free nucleon

inelastic channels remove ω, η‘-mesons, e.g. ω N, η‘ N→ π N

→ shortening of ω, η‘ - lifetime ⇒ increase in width

low density approximation: $\Gamma(\rho) = -\frac{Im\Pi(\rho)}{E} \sim \rho \cdot v \cdot \sigma_{inel}$

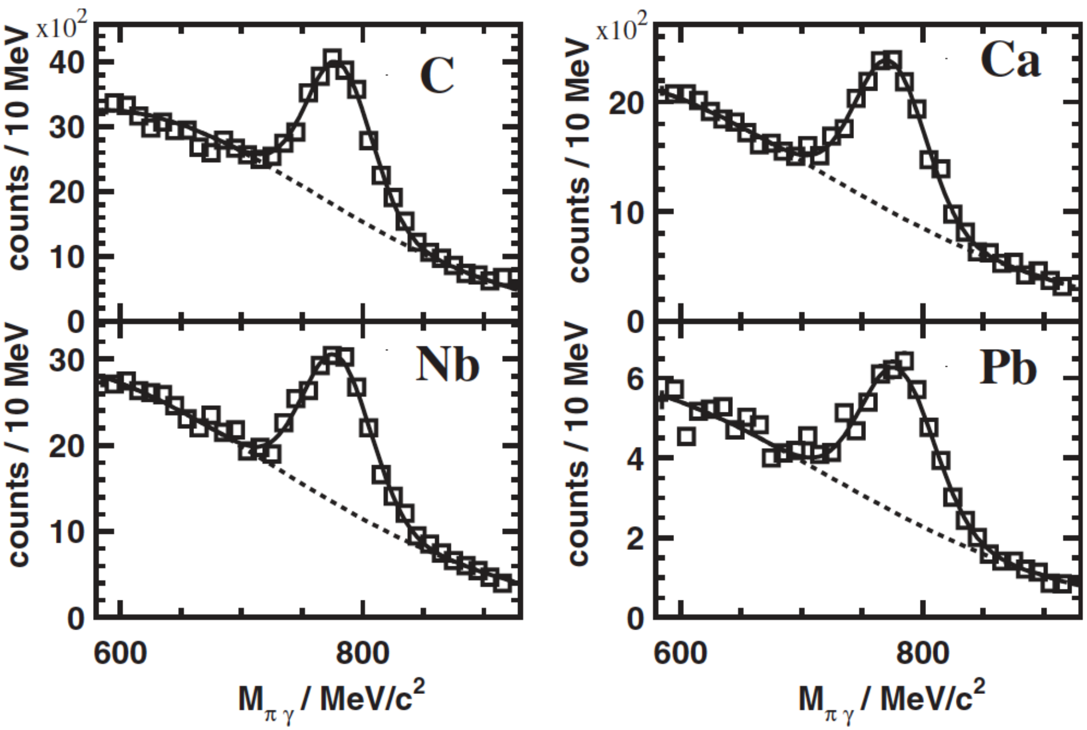
$$\Gamma(\rho) = \Gamma(\rho_0) \cdot \frac{\rho}{\rho_0}$$

in-medium η‘ = quasi-particle; properties reflect interaction with the medium;

applicable to any meson lifetime !!!

Information on in-medium properties of mesons from measuremens of their decay outside of the nucleus

Photoproduction of ω and η’ mesons off C, Ca, Nb, Pb

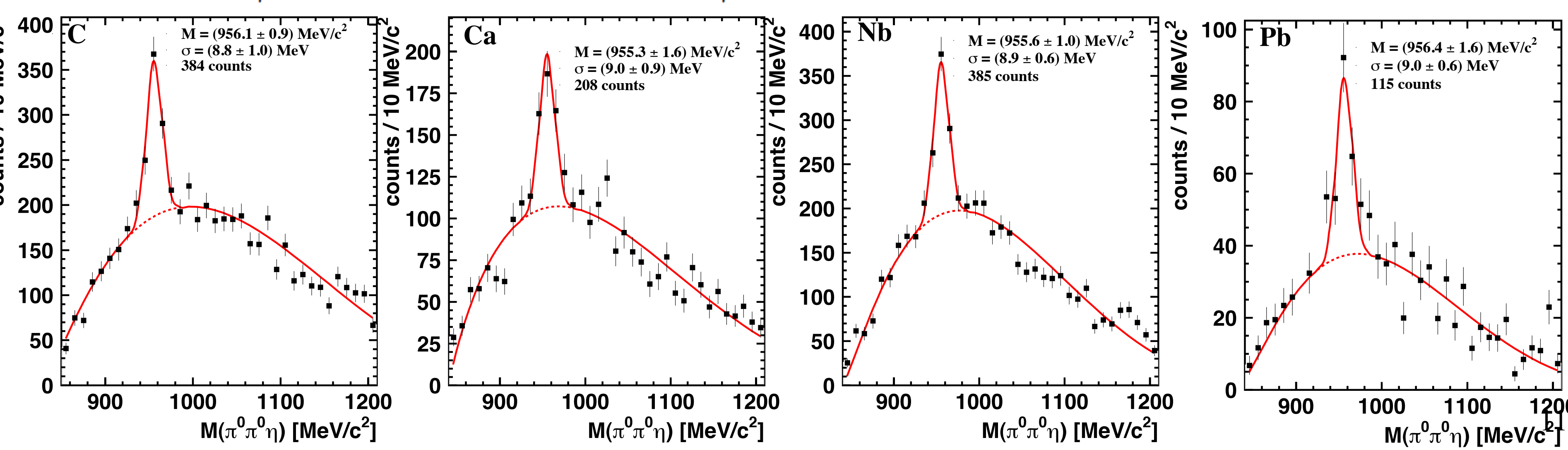


$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$

M. Kotulla et al, PRL 100 (2008)

M. Nanova et al, subm. to PLB

$\eta' \rightarrow \eta\pi^0\pi^0 \rightarrow 6\gamma$



Extraction of in-medium width and inelastic cross section from T_A

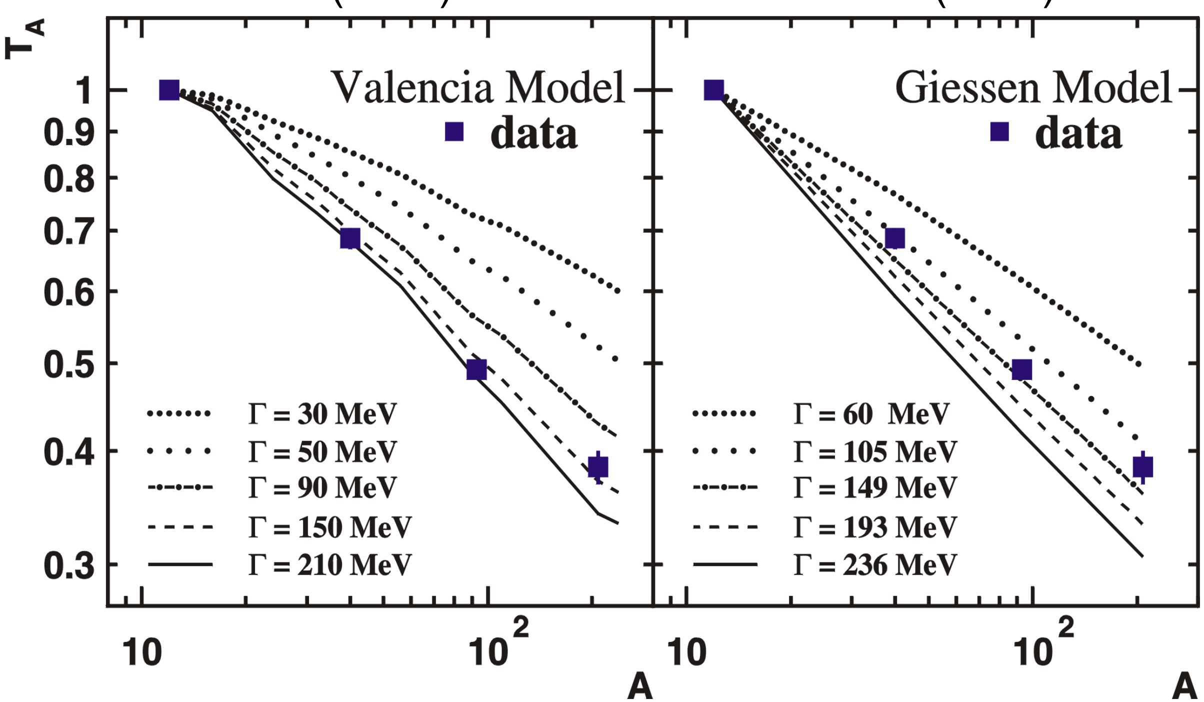
$$\sigma_{\gamma A \to \eta' A'} = C \int d^3 r \rho(\vec{r}) \frac{1}{2\pi} \int_0^{2\pi} d(\phi^{\eta'}_{\mathrm{c.m.}}) \frac{1}{2} \int_{-1}^{1} d(\cos\theta^{\eta'}_{\mathrm{c.m.}}) \frac{d\sigma}{d\Omega}(\gamma p \to \eta' p) P_s(\vec{r})$$

where $P_s(\vec{r})$ is the survival probability $P_s(\vec{r}) = \exp\left[\int_0^\infty dl \frac{\mathrm{Im}\,\Pi_{\eta'}(\rho(\vec{r}\,'))}{|\vec{k}_{\eta'}|}\right]$ with $\vec{r}\,' = \vec{r} + l \frac{\vec{k}_{\eta'}}{|\vec{k}_{\eta'}|}$

ω-meson

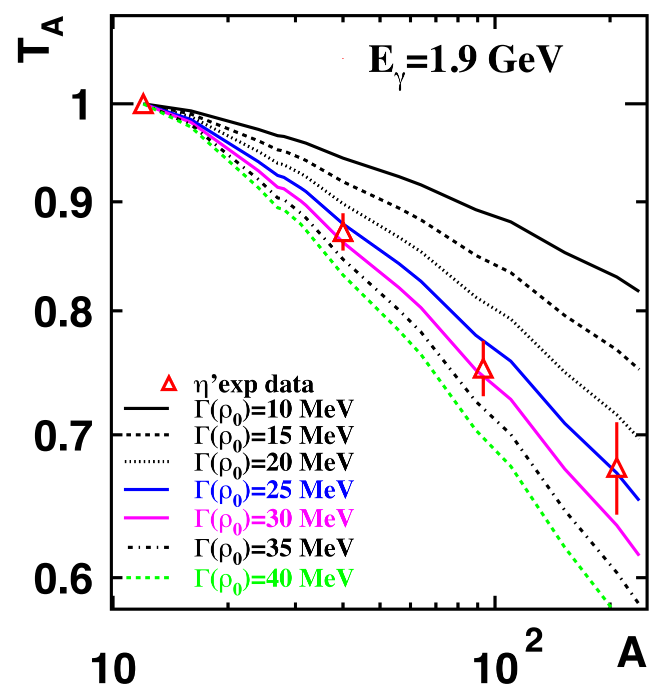
M. Kaskulov, E. Hernandez, E. Oset
EPJ A 31 (2007) 245

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



η'-meson

M. Nanova et al.,



$\Gamma_\omega(\langle p_\omega \rangle = 1.1\ \mathrm{GeV/c}) \approx 130\text{-}150$ MeV; $\sigma_{\omega N}^{inel} \approx 60$ mb

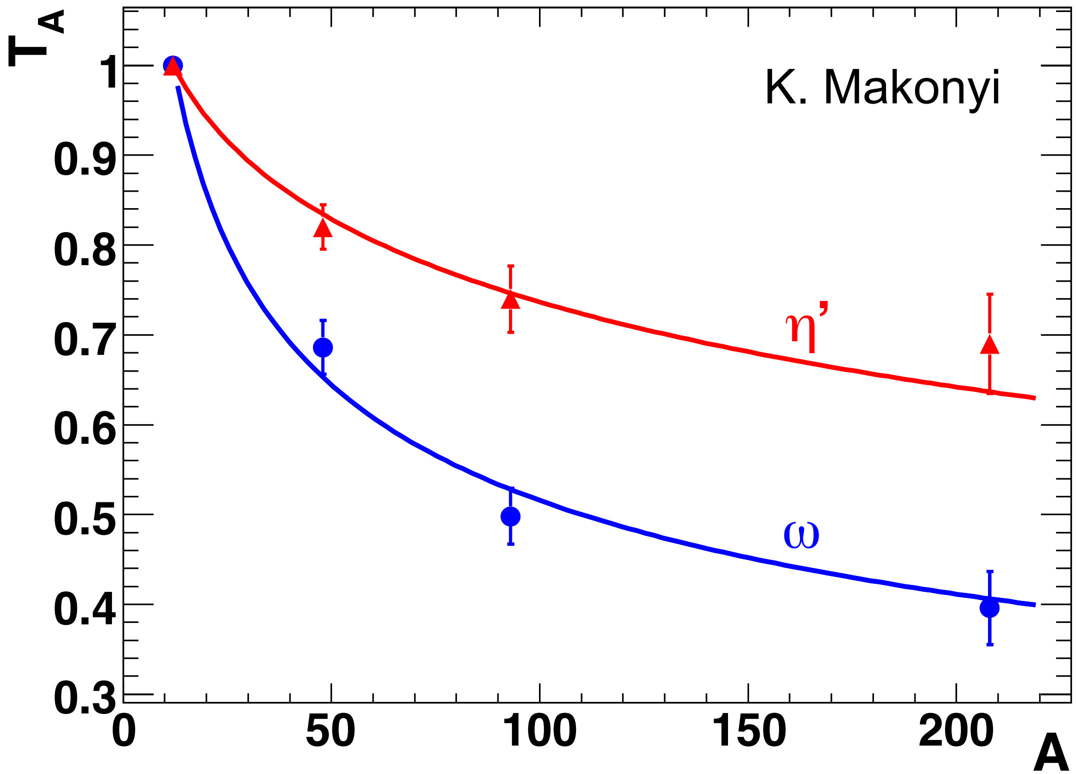
$\Gamma_{\eta'}(\langle p_{\eta'} \rangle = 1.05\ \mathrm{GeV/c}) \approx 25$ MeV; $\sigma_{\eta' N}^{inel} \approx 11$ mb

Extraction of inelastic cross sections within Glauber analysis

approximation of nuclear density distribution:
nucleus = sphere with radius $R=R_0 \cdot A^{1/3}$ homogeneously filled with A nucleons

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

$$T_A = \frac{\pi R^2}{A\sigma_{\eta' N}} \left\{ 1 + \left(\frac{\lambda}{R}\right) \exp\left[-2\frac{R}{\lambda}\right] + \frac{1}{2}\left(\frac{\lambda}{R}\right)^2 \left(\exp\left[-2\frac{R}{\lambda}\right] - 1\right) \right\}$$



meson mean free path:

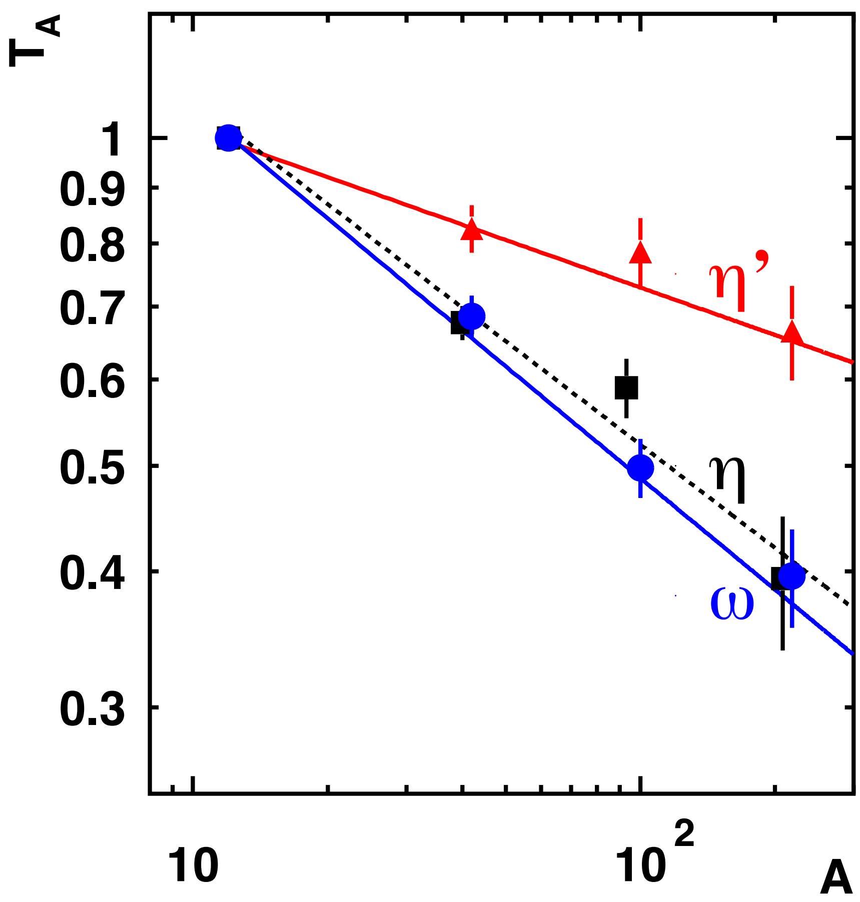
$$\lambda = \left(\rho_0 \sigma_{\eta' N}\right)^{-1}$$

inelastic cross sections:

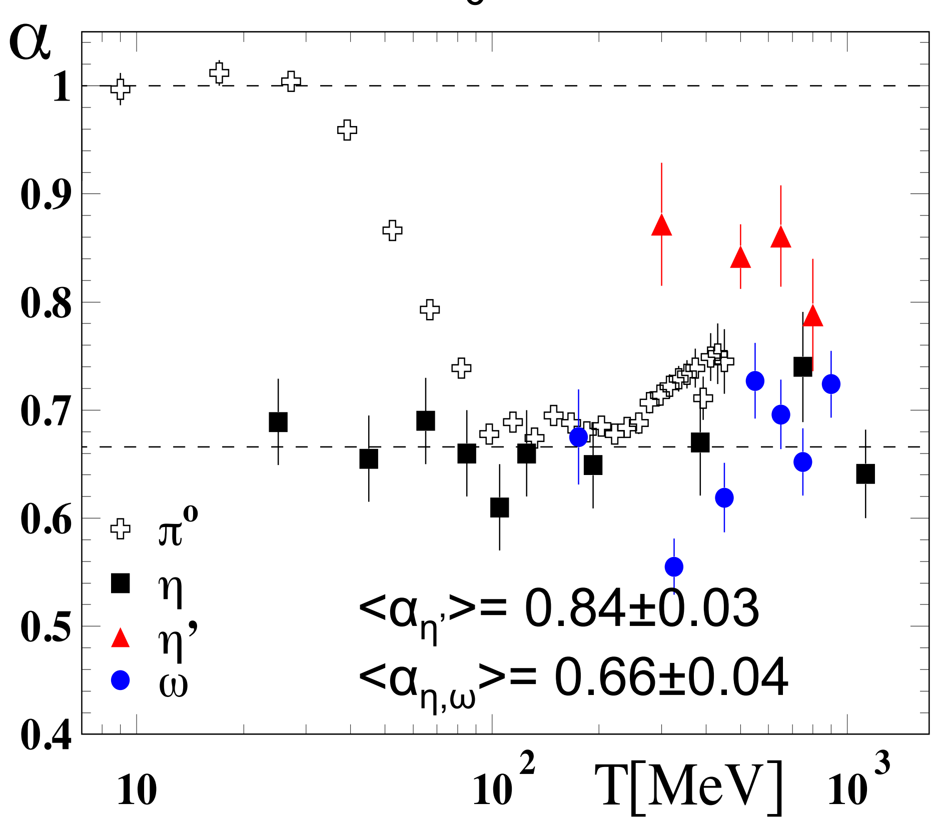
$\sigma_{\eta' N}$ = (11±1.5) mb

$\sigma_{\omega N}$ = (65±30) mb

Comparison with other mesons



$\sigma = \sigma_0 \cdot A^{\alpha(T)}$



η' interaction with nuclear matter much weaker than for π, η, ω mesons

II. Measurement of the meson lineshape

meson decay: $M \rightarrow X_1 + X_2$

$\Rightarrow$ in-medium mass shift ?
broadening ? structures ?

$$\mu_H(\rho,\vec{p}) = \sqrt{(p_1 + p_2)^2}$$

- ensure that decays occur in the medium: select shortlived mesons:
  decay length $s = \beta\gamma \cdot c\tau$ comparable to nuclear dimensions

  for $\beta\gamma = \frac{p}{mc} \approx 1$ $s \approx 1.3$ fm (ρ) ; 23 fm (ω) ; 46 fm (ϕ)

  cut on low meson momenta for ω and ϕ mesons

- avoid distortion of 4-momentum vectors by final state interactions
  $\Rightarrow$ dilepton spectroscopy: $\rho, \omega, \phi \rightarrow e^+e^-$

  disadvantage: branching ratio $\approx 10^{-4} - 10^{-5}$

  decay mode used in our experiments: $\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$ br = 8.9%
  $\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ br = 8.1%

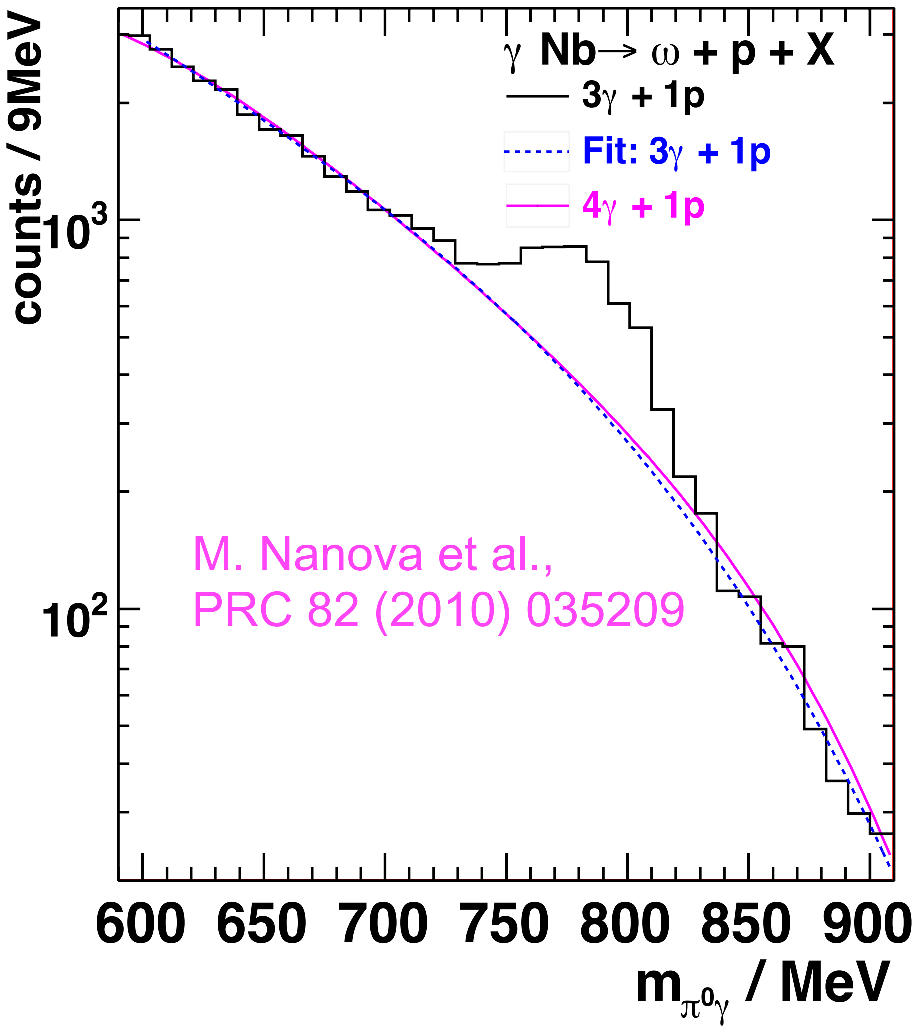
  distortions by π^0 rescattering suppressed by cut $T^{\pi}_{kin} > 150$ MeV

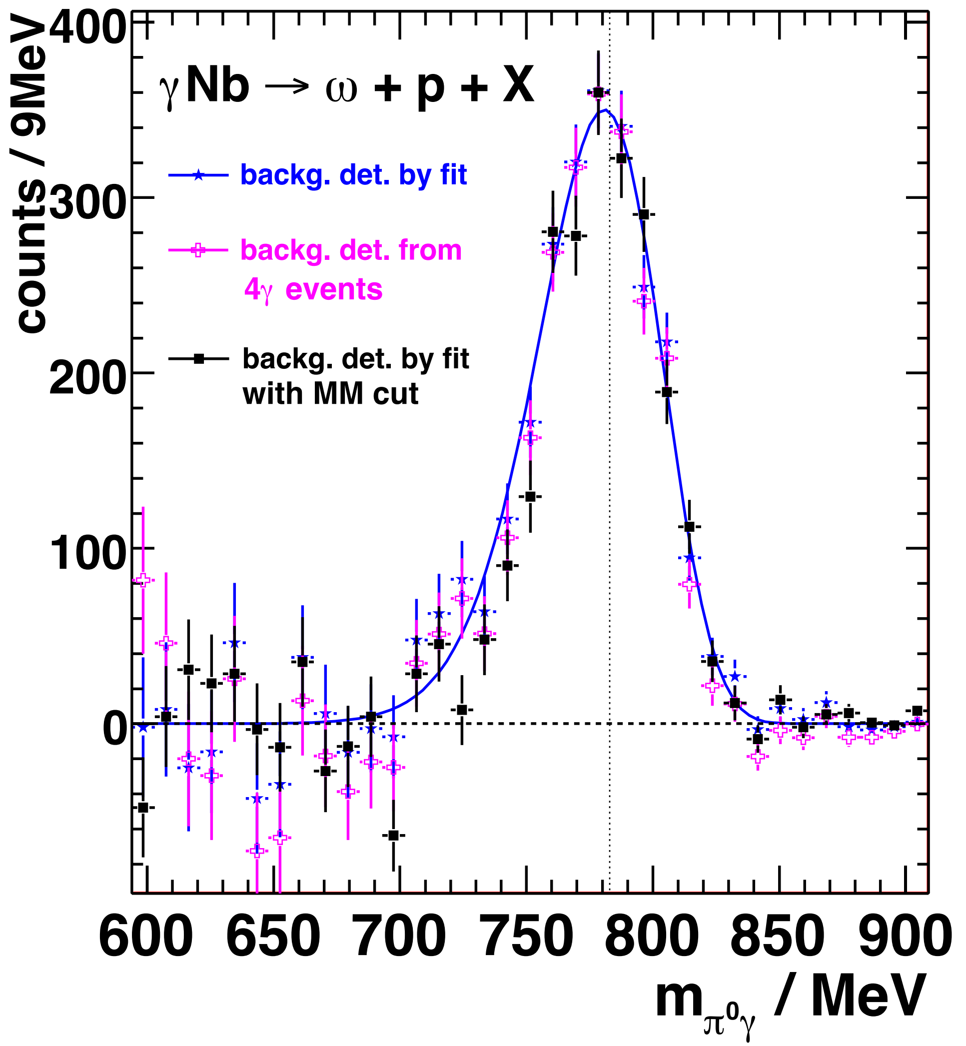
sensitive to nuclear density at decay point !!!!

$\omega \rightarrow \pi^0\gamma$ lineshape analysis

Main problem: background subtraction

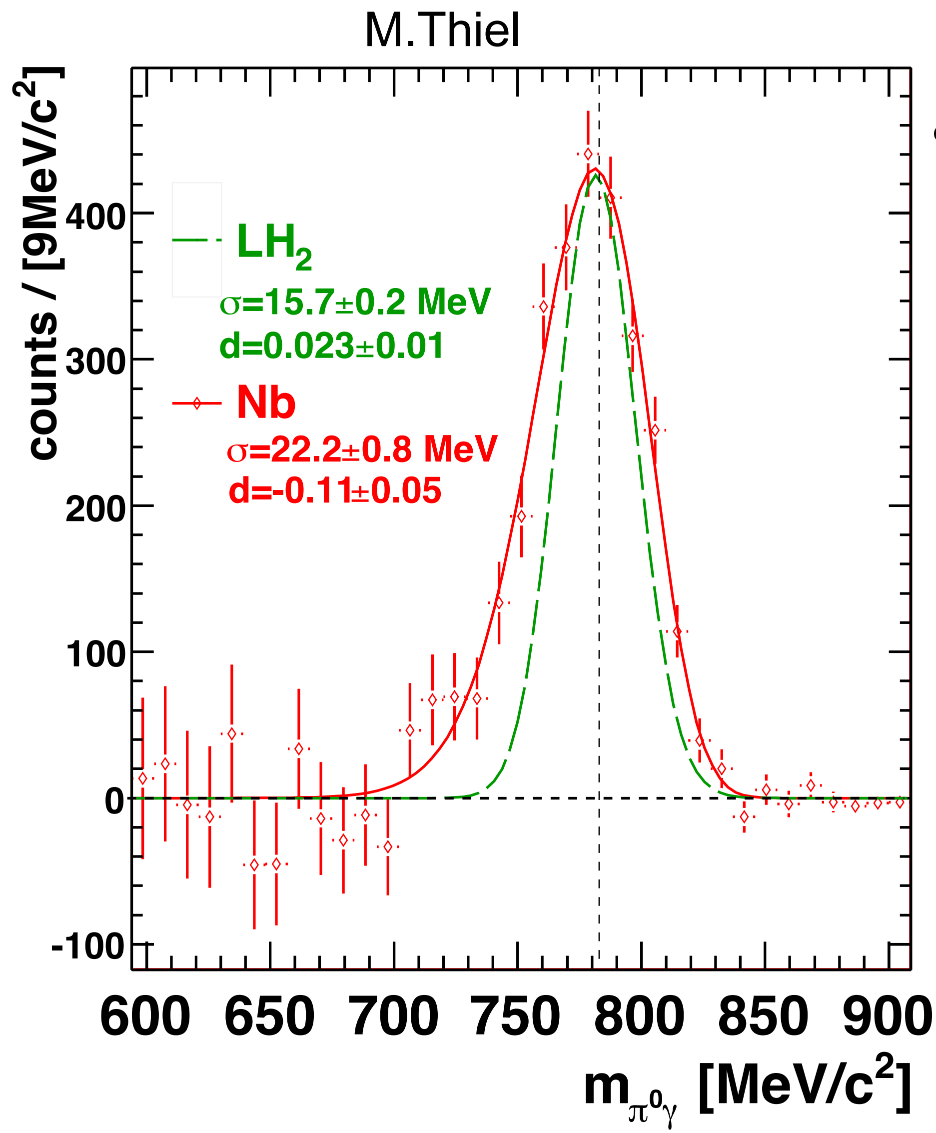
M. Thiel

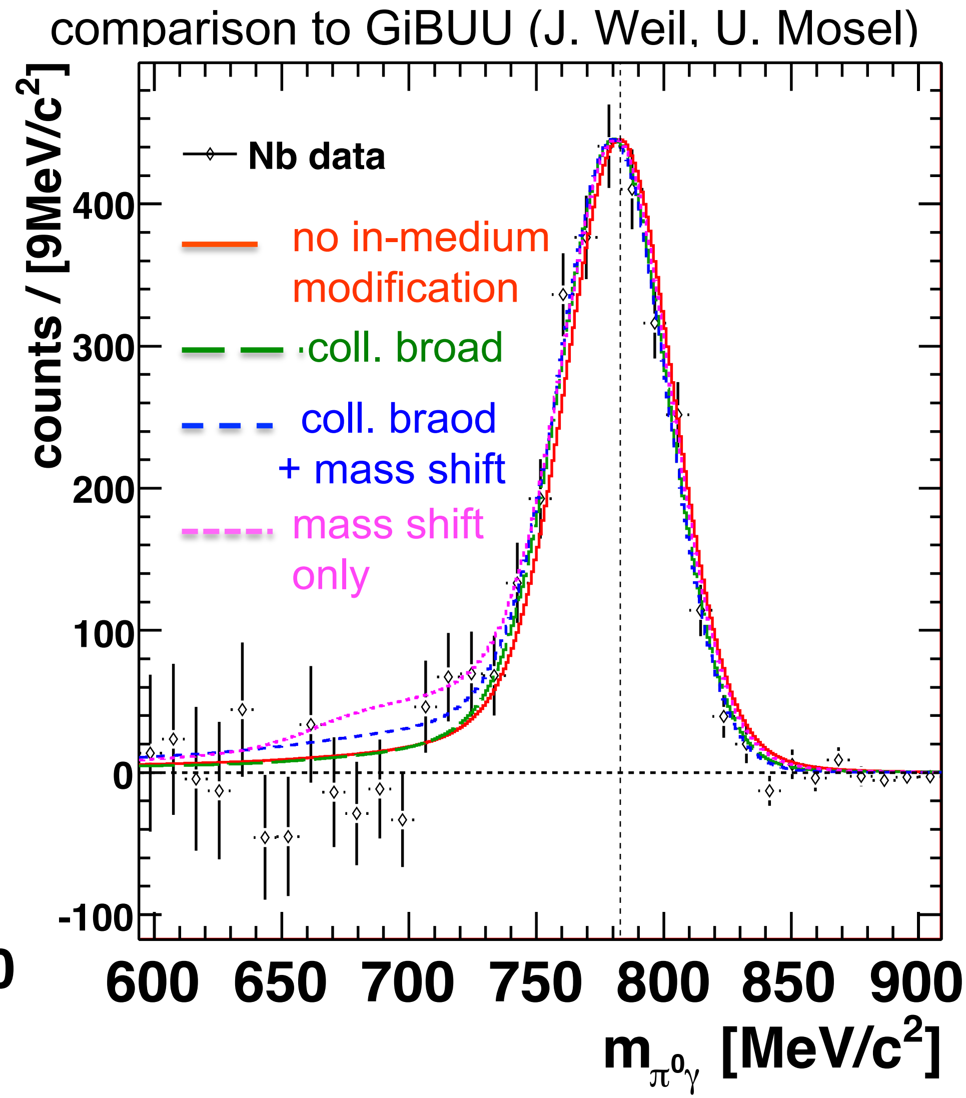




➔ Systematic uncertainties due to different background subtraction approaches

ω lineshape analysis (E_γ = 900 – 1300 MeV)





no significant structure in spectral function; signal on Nb slightly broader than on LH_2; consistent with in-medium broadening of ω

Shift only scenario less likely, limited sensitivity to in-medium scenarios

Limited sensitivity of line shape analysis

three effects limit the sensitivity:

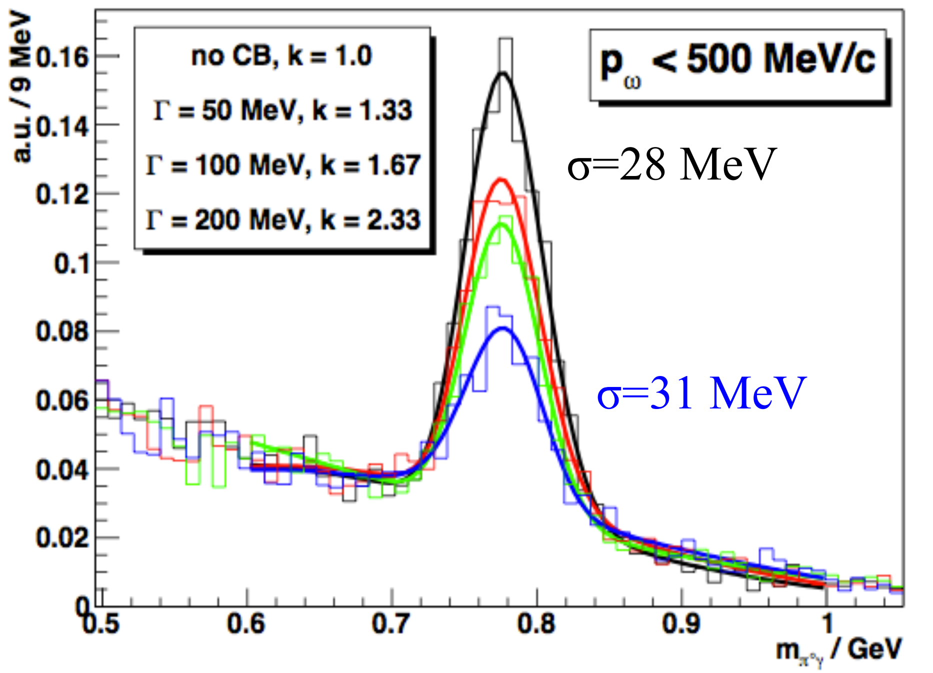
1.) $\omega \rightarrow \pi^0\gamma$ signal reduced by increase of in-medium width ($\Gamma_{med} \approx 16 \cdot \Gamma_{vac}$); ω mesons removed in nuclear medium via inelastic channels (like $\omega N \rightarrow \pi N$)

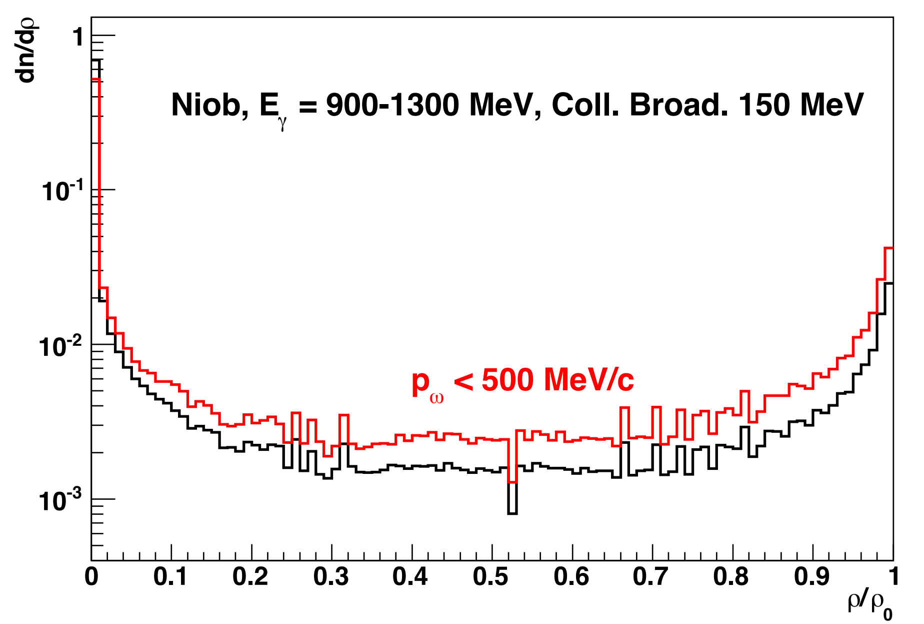
$$\frac{d\sigma_{H\to X_1X_2}}{d\mu} \sim A(\mu) \cdot \frac{\Gamma_{H\to X_1X_2}}{\Gamma_{tot}(\mu)}$$

F. Eichstaedt et al.,
Prog. Theo. Phys. Suppl. 168 (2007) 495

2.) only 30 % of all $\omega \rightarrow \pi^0\gamma$ decays occur within the Nb nucleus at $\langle\rho\rangle \approx 0.5\rho_0$
(50% for $p_\omega < 500$ MeV/c)

3.) ω decays occur over a wide range of densities, thereby smearing out any density-dependent signal



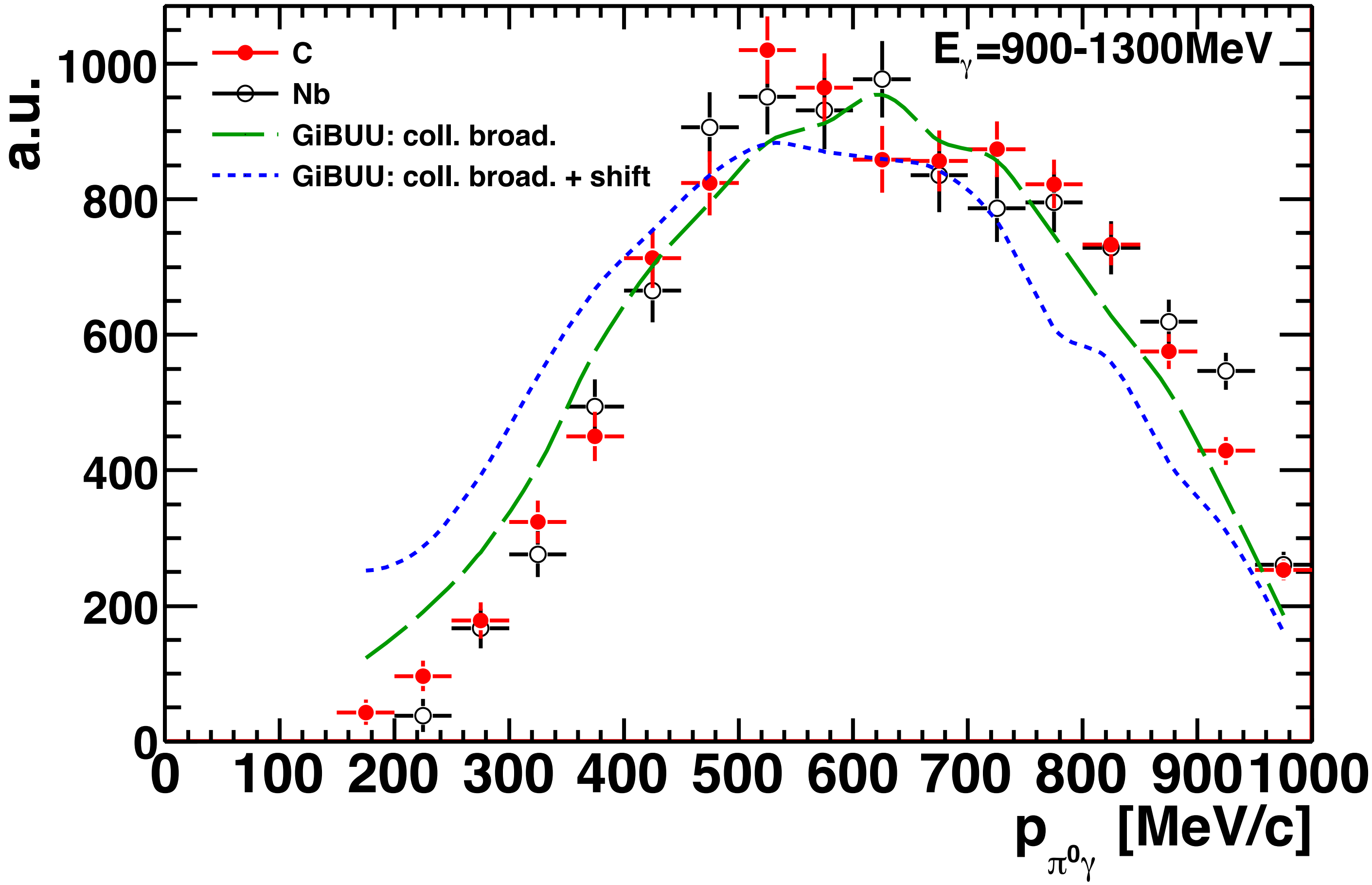


III. Measurement of the momentum distribution of the mesons.

In case of a dropping in-medium mass: when leaving the nucleus hadron has to become on-shell; mass generated at the expense of kinetic energy ⇒ **downward shift of momentum distribution**

applicable to any meson lifetime; sensitive to density at production point !!!

M.Thiel, J. Weil; V. Metag et al., arXiv: 1111.6004

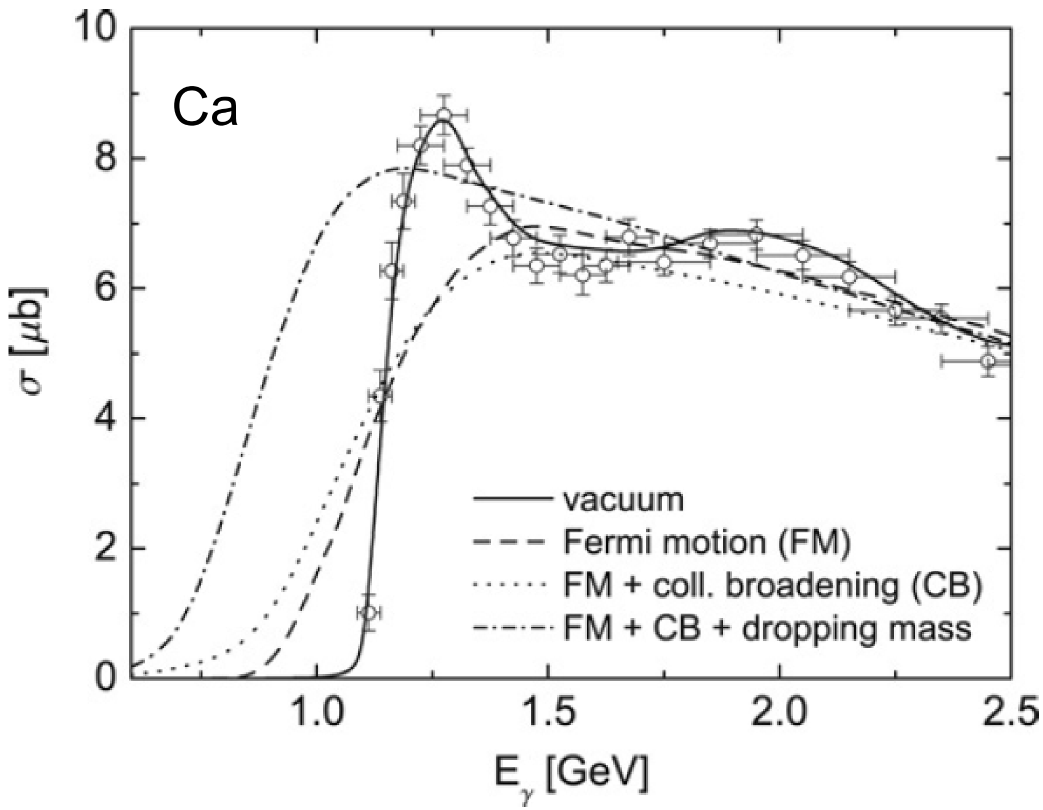


measured momentum distribution favors **"broadening without mass shift"**

IV. Measurement of ω excitation function

in case of dropping mass higher meson yield for given $\sqrt{s}$ because of increased phase space due to lowering of the production threshold

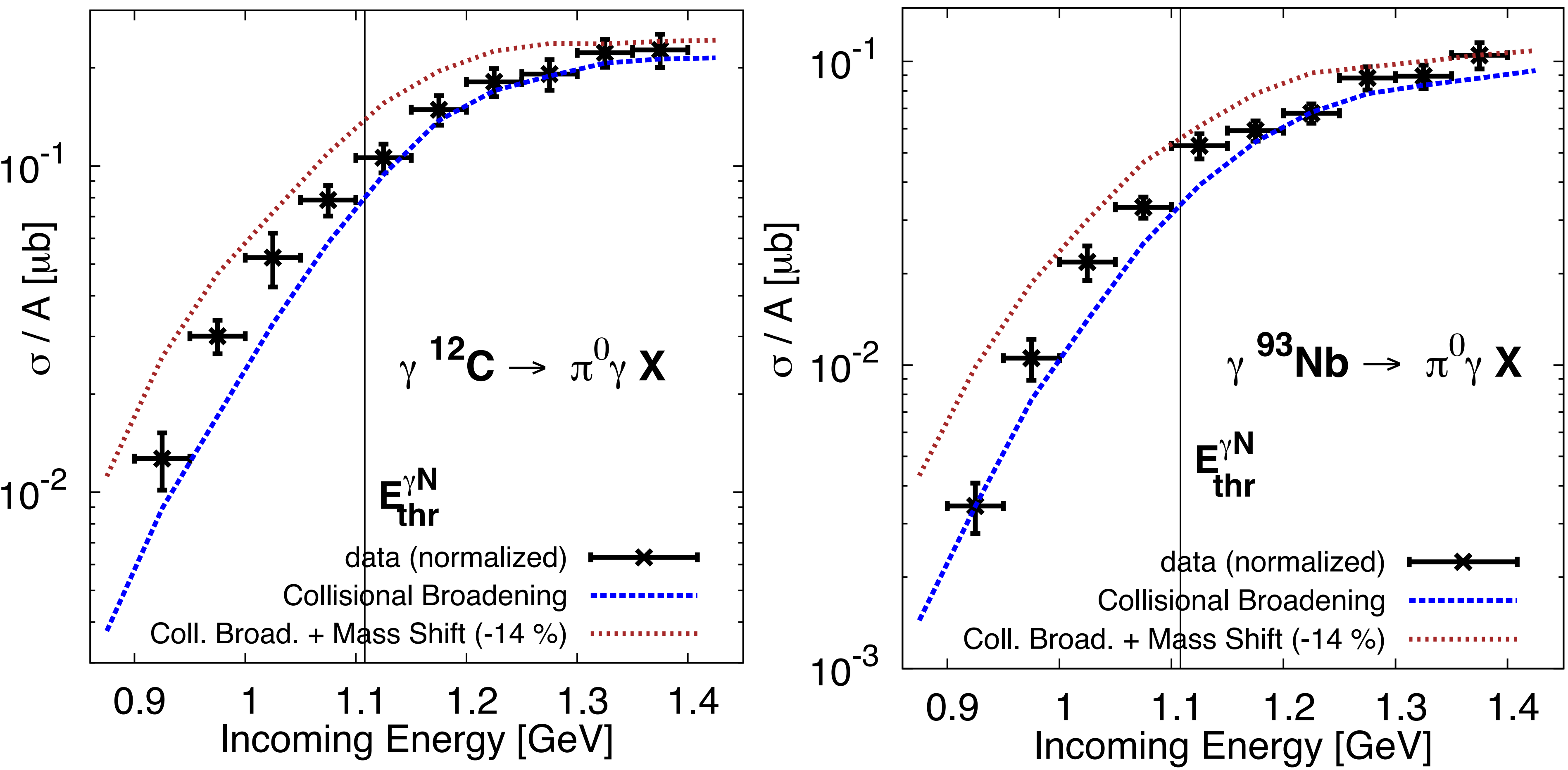
Gi-BUU simulations: P. Mühlich and u. Mosel, NPA 773 (2006) 156
K. Gallmeister et al. Prog. Part. Nucl. Phys. 61 (2008) 283



enhanced ω yield for dropping mass scenario below production threshold on free nucleon; sensitive to density at production point !!!

Comparison of measured excitation function with GiBUU calculations

B. Lemmer, S. Friedrich, H. Berghäuser, M. Thiel, J. Weil



data disfavour „broadening + mass shift (-14%)“ scenario
and favour „collisional broadening without mass shift“ scenario
but small downward shift of spectral strength can not be excluded

Summary and conclusions

- observables for extracting in-medium properties of mesons:
  transparency ratio, line shape, momentum distribution, excitation function

- transparency ratio: in-medium broadening of ω, η' mesons;
  ω: in-medium width ≈ 130 -150 MeV at ρ_0 for p_ω ≈1.1 GeV/c
  η': in-medium width ≈ 25 MeV at ρ_0 for p_ω ≈1.05 GeV/c
  η' interaction with nuclear medium much weaker than for ω meson
  $<\alpha_{\eta'}>= 0.84\pm0.03$; $<\alpha_{\eta,\omega}>= 0.66\pm0.04$; $\sigma = \sigma_0 \cdot A^{\alpha(T)}$

- ω line shape analysis: no evidence for structures or large mass shifts; limited sensitivity due to strong in-medium broadening and small fraction of in-medium decays

- ω momentum distribution favours collisional broadening without mass shift

- ω excitation function favours collisional broadening without mass shift, although small downward shift of spectral strength can not be excluded

- search for ω mesic states: analysis still ongoing

hadron spectral functions do change in the nuclear environment