Determination of the ω- and η' -nucleus optical potential

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Outline:

- theoretical predictions for in-medium modifications of hadron properties
- exp. approaches and results on the real part of the ω, η'- nucleus potential
- exp. approaches and results on the imaginary part of the ω, η'- nucleus potential
- search for meson-nucleus bound states
- summary & outlook

*funded by the DFG within SFB/TR16

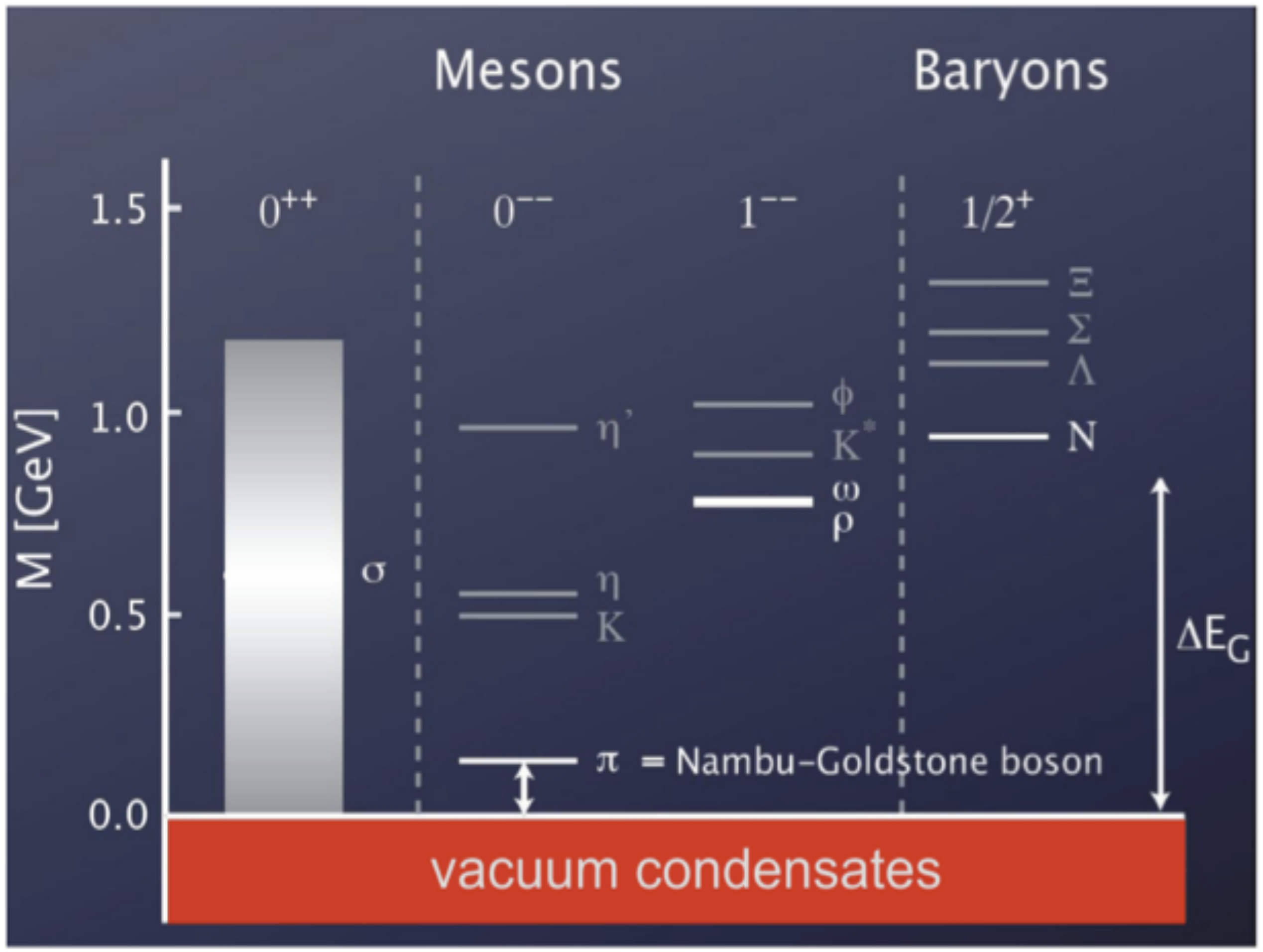
Mesons in Nuclei
International workshop
31.7.-2.8.2016, Kyoto, Japan

HIC for FAIR
Helmholtz International Center

hadron masses

how do hadron properties (mass, width) change in a dense nuclear medium ??

J. Wambach



- mesons = excitations of the QCD vacuum
- 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 $\frac{m^\star}{m} \approx \frac{<\bar{q}q>^\star}{<\bar{q}q>_0} \approx 0.8 (\rho \approx \rho_0)$

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

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

symmetry breaking pattern for pseudoscalar mesons

V. Bernard, R.L. Jaffe, U.-G. Meissner, NPB 308 (1988) 753

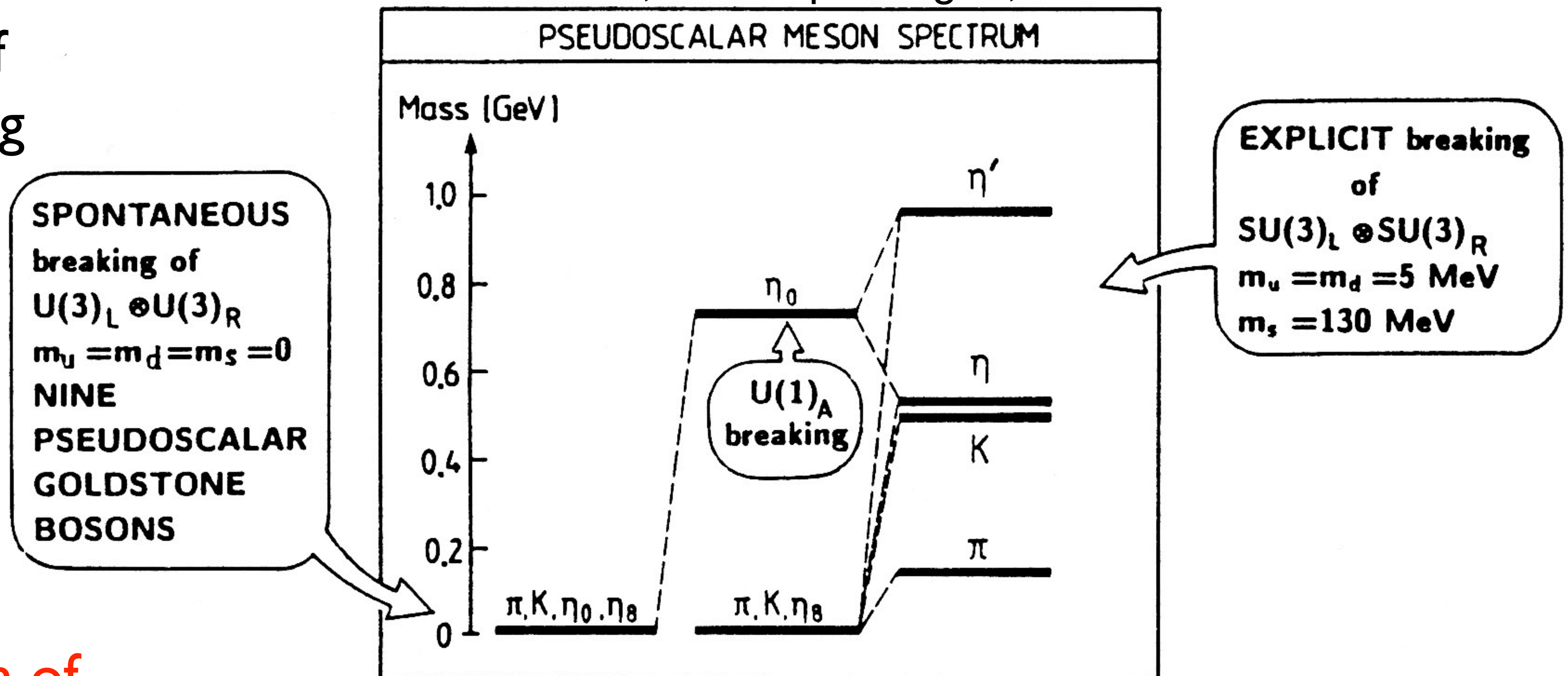
S. Klimt, M. Lutz, U.Vogel, W Weise, NPA 516 (1990) 429

H. Nagahiro et al.,PRC 87 (2013) 045201

D. Jido et al.,arXiv:1208.0982

W. Weise, NBI Copenhagen, 1993

mass as a result of
symmetry breaking



symmetry breaking

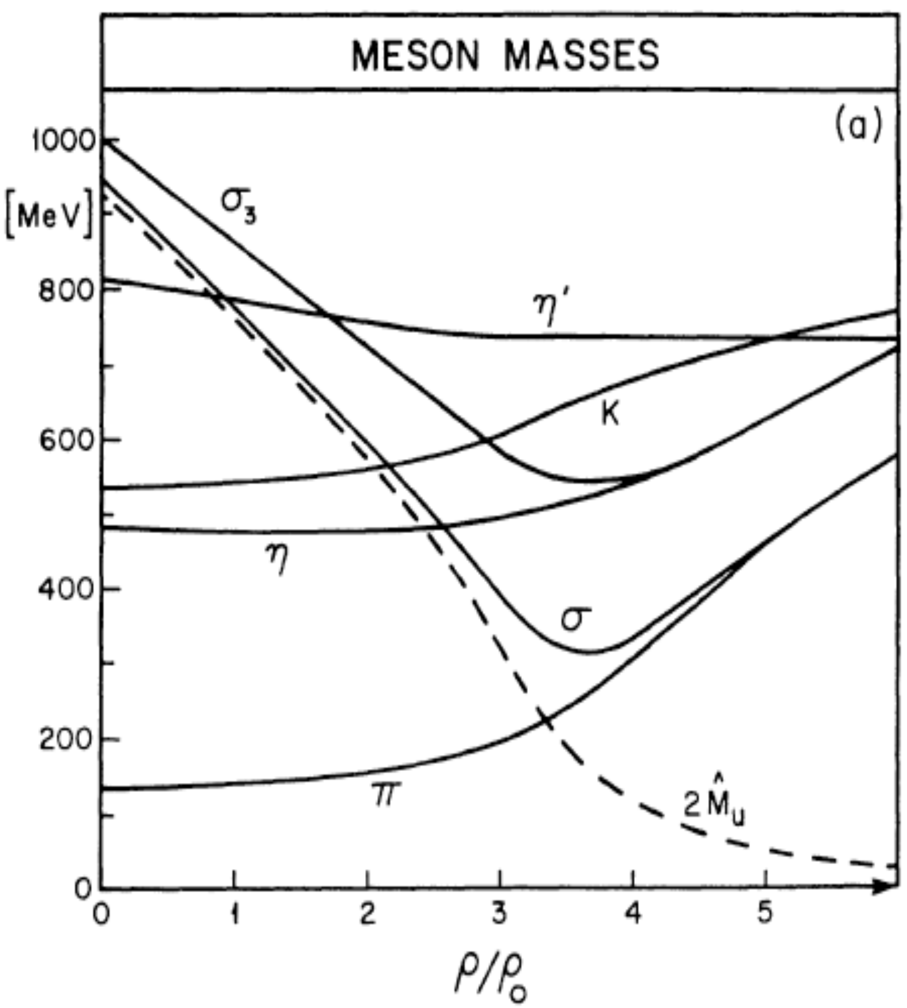
partial symmetry restoration

partial restoration of
chiral symmetry
predicted to occur
in a nucleus ⟹ impact
on meson masses ??

hadronic models: predictions for η' in-medium mass

<u>NJL-model</u>

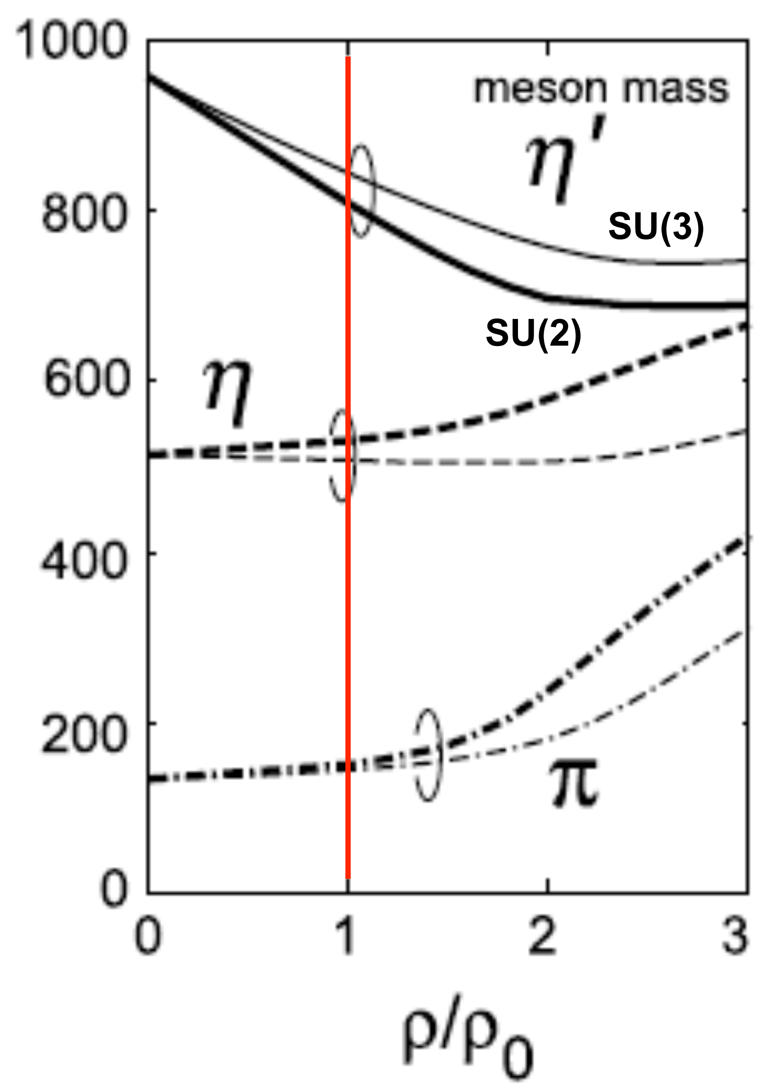
V. Bernard and U.-G. Meissner,
Phys. Rev.D 38 (1988) 1551



almost no dependence of η' mass on density

<u>NJL-model</u>

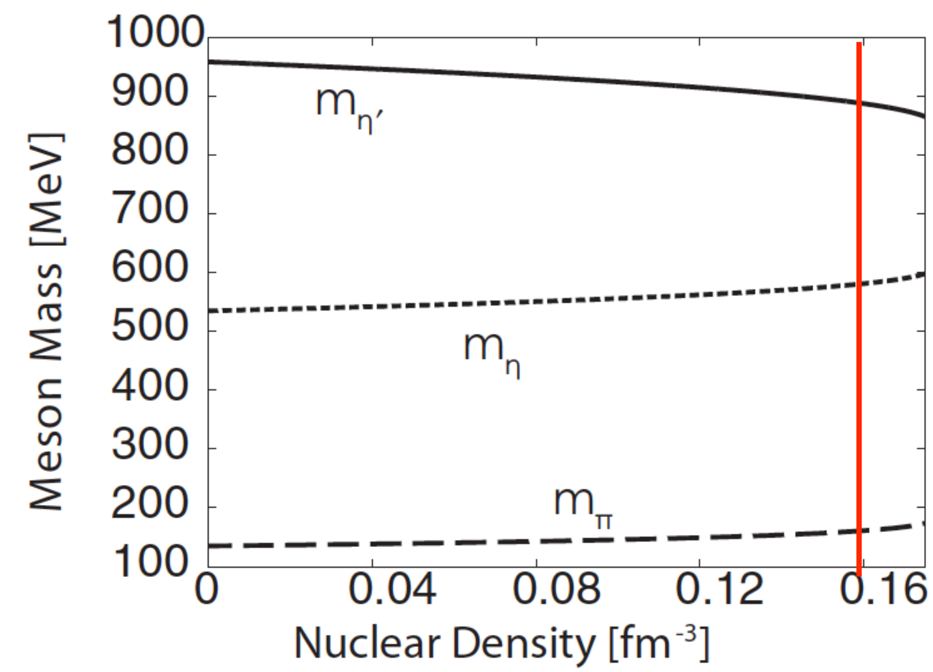
H. Nagahiro et. al,
Phys. Rev. C 74 (2006) 045203



$\Delta m_{\eta'}(\rho_0) \approx -150$ MeV
$\Delta m_{\eta}(\rho_0) \approx +20$ MeV

<u>linear σ model</u>

S. Sakai and D. Jido
PRC 88 (2013) 064906



$\Delta m_{\eta'}(\rho_0) \approx -80$ MeV

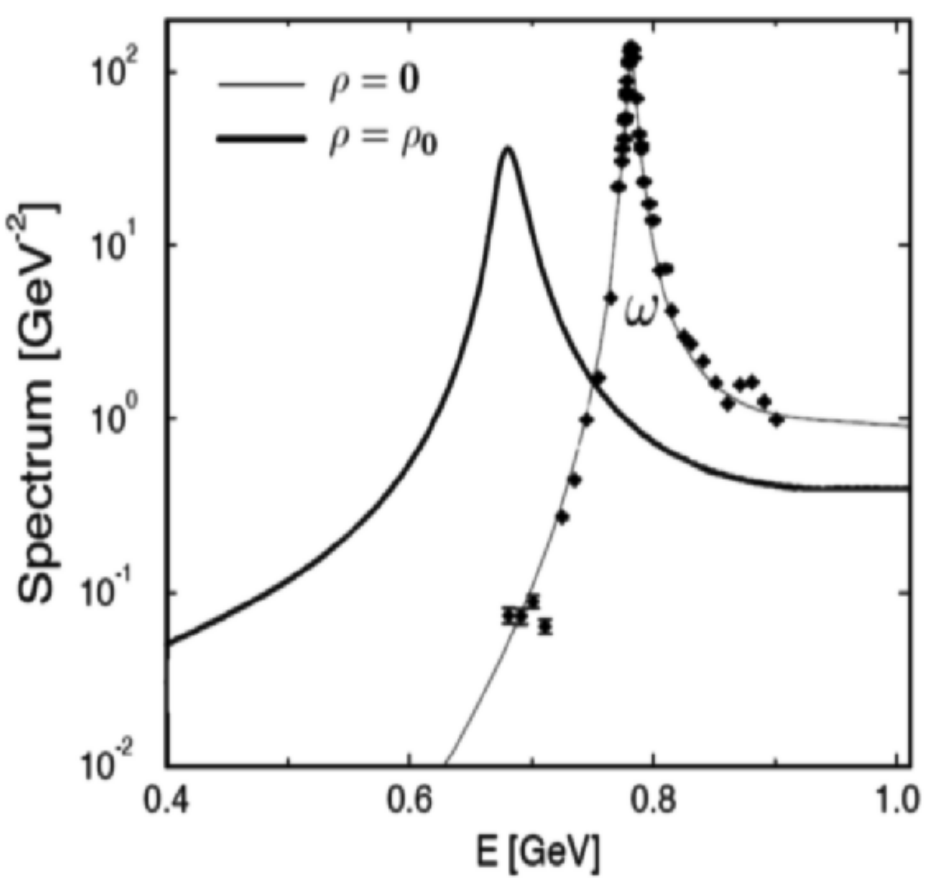
<u>QMC-model</u>

S. Bass and A. Thomas,
PLB 634 (2006) 368

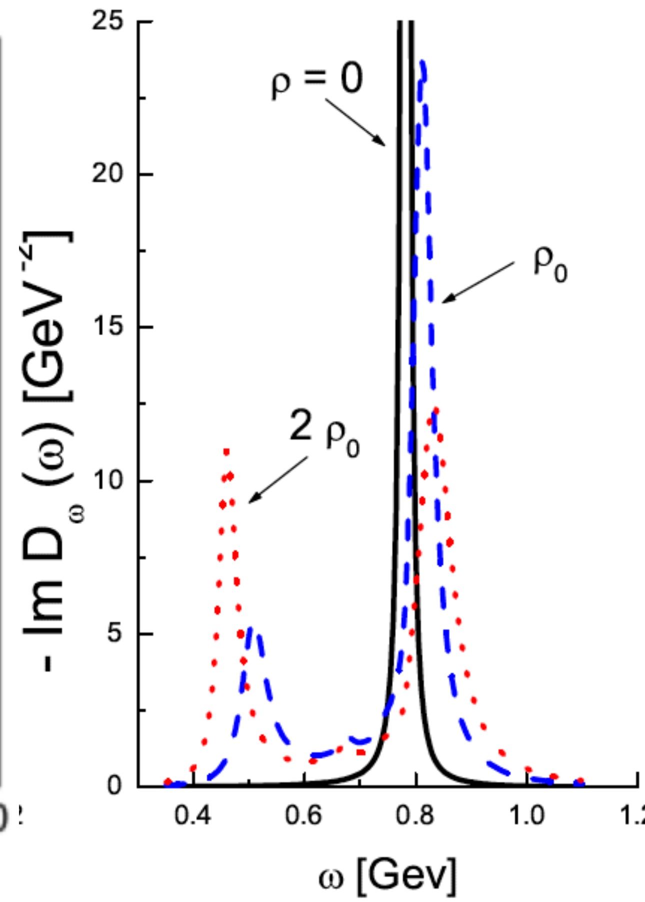
$\Delta m_{\eta'}(\rho_0) \approx -40$ MeV
for $\theta_{\eta\eta'} = -20^0$

hadronic models: predictions for ω-spectral functions

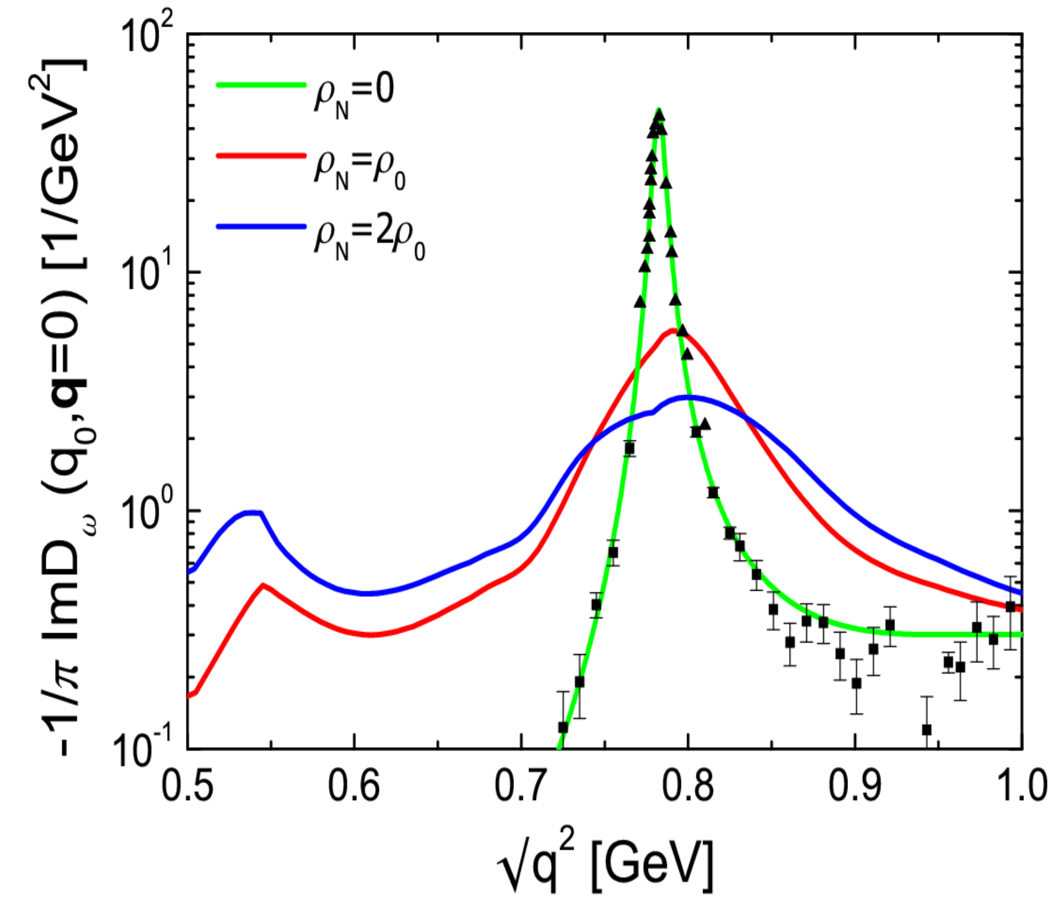
F. Klingl et al.,
NPA 610 (1997) 297;
NPA 650 (1999) 299



M. Lutz et al.,
NPA 706 (2002) 437



P. Mühlich et al., NPA 780 (2006) 187



- lowering of in-medium mass
- broadening of resonance

with increasing nuclear density
Re(U) ≠0; Im(U) ≠0

splitting into ω-like and N^*N^{-1} mode due to coupling to nucleon resonances

spectral function for ω meson at rest:
almost no mass shift;
strong in-medium broadening
Re(U) ≈0; Im(U) large

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

meson-nucleus optical potential

H. Nagahiro an S. Hirenzaki,
PRL 94 (2005) 232503

$$U(r) = V(r) + iW(r)$$

$$V(r) = \Delta m(\rho_0) \cdot \frac{\rho(r)}{\rho_0}$$

$$W(r) = -\Gamma_0/2 \cdot \frac{\rho(r)}{\rho_0}$$
$$= -\frac{1}{2} \cdot \hbar c \cdot \rho(r) \cdot \sigma_{inel} \cdot \beta$$

real part

⇳

in-medium mass modification

imaginary part

⇳

lifetime shortened

in-medium width, absorption
inelastic cross section

mass and lifetime (width) may be changed in the medium

experimental approaches to determine the meson-nucleus optical potential

$$U(r) = V(r) + iW(r)$$

real part

$$V(r) = \Delta m(\rho_0) \cdot \frac{\rho(r)}{\rho_0}$$

- line shape analysis
- excitation function
- momentum distribution
- meson-nucleus bound states

imaginary part

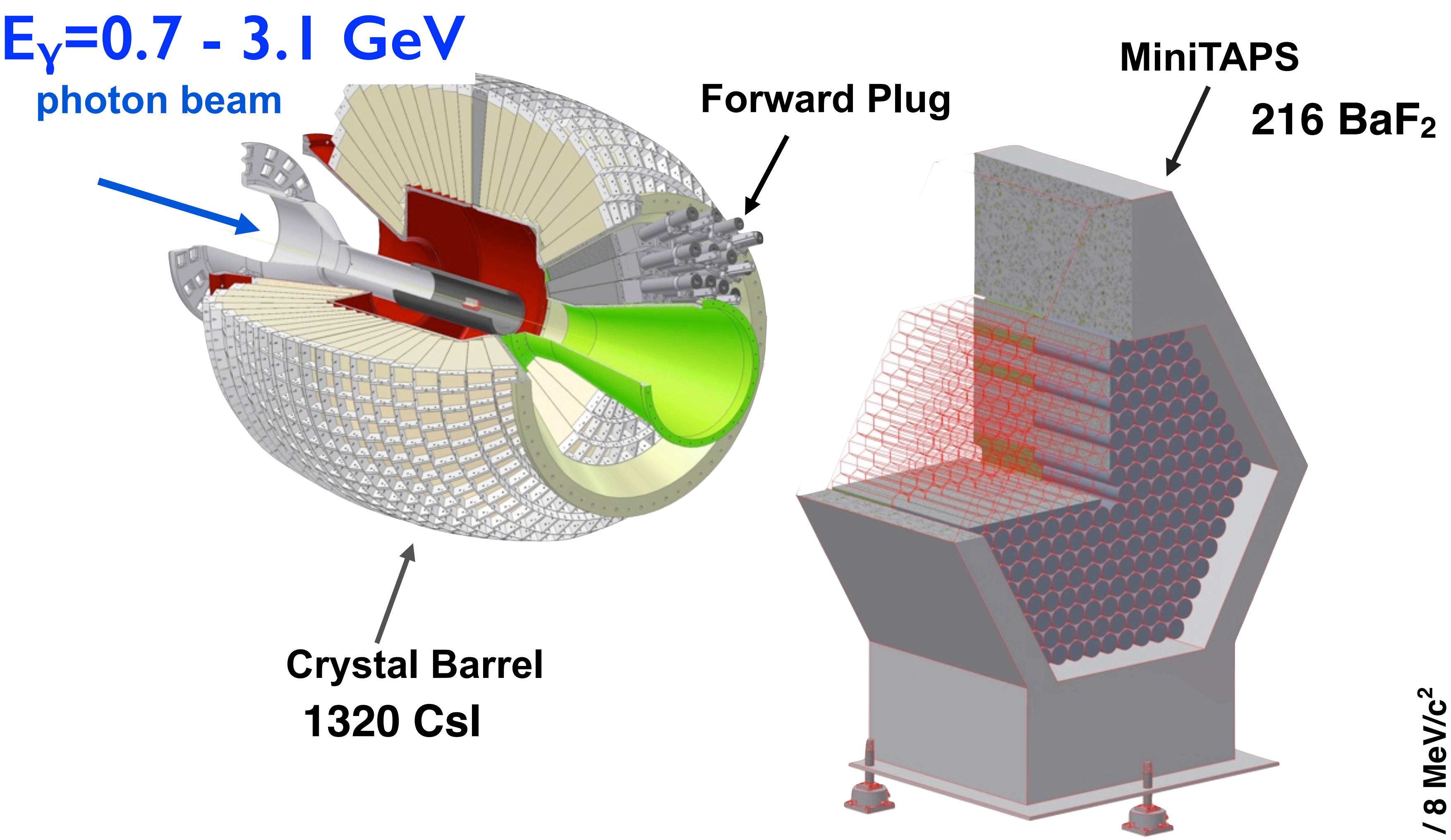
$$W(r) = -\Gamma_0/2 \cdot \frac{\rho(r)}{\rho_0}$$
$$= -\frac{1}{2} \cdot \hbar c \cdot \rho(r) \cdot \sigma_{inel} \cdot \beta$$

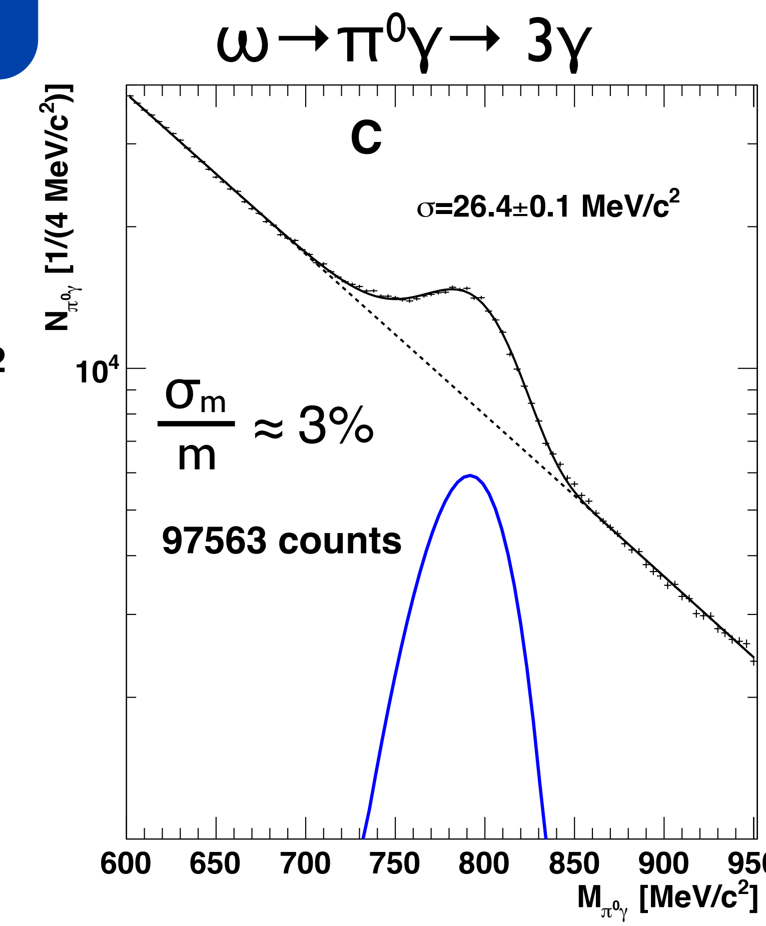
- transparency ratio measurement

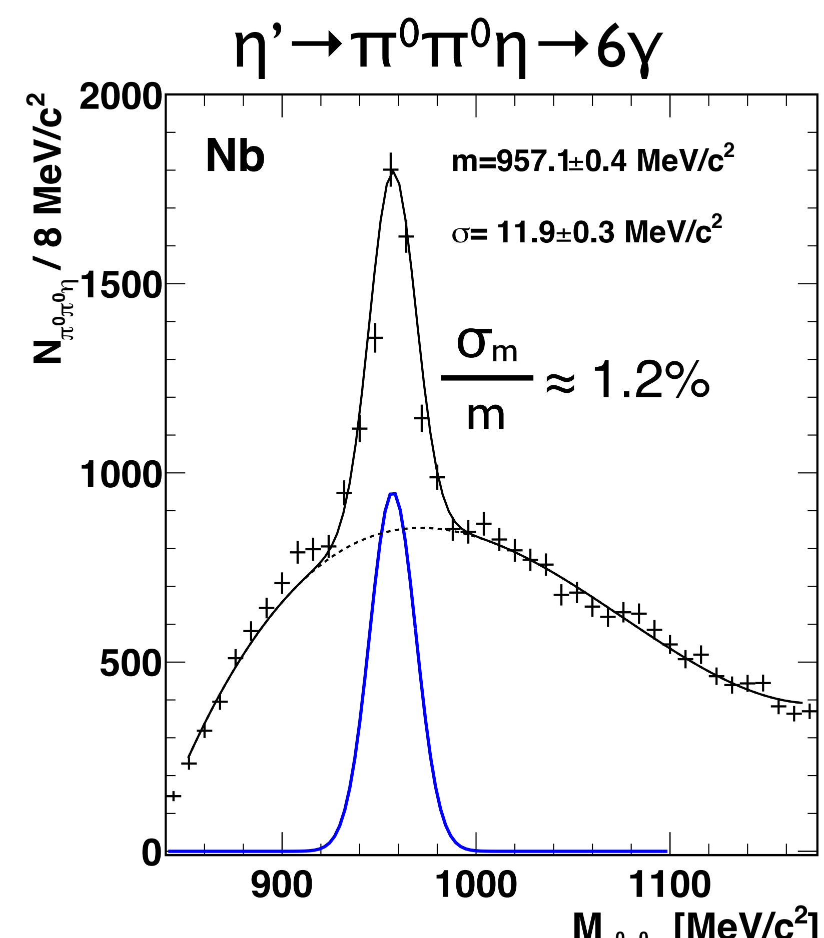
$$T_A = \frac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}}$$

D. Cabrera et al., NPA 733 (2004)130

CBELSA/TAPS experiment







solid target: ^{12}C and ^{93}Nb

4π photon detector: ideally suited for identification of multi-photon final states

$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$ BR 8.2%

$\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ BR 8.5%

The real part of the meson-nucleus optical potential

the real part of the ω-nucleus potential

J. Weil, U. Mosel and V. Metag, PLB 723 (2013) 120 $\omega \rightarrow \pi^0\gamma$

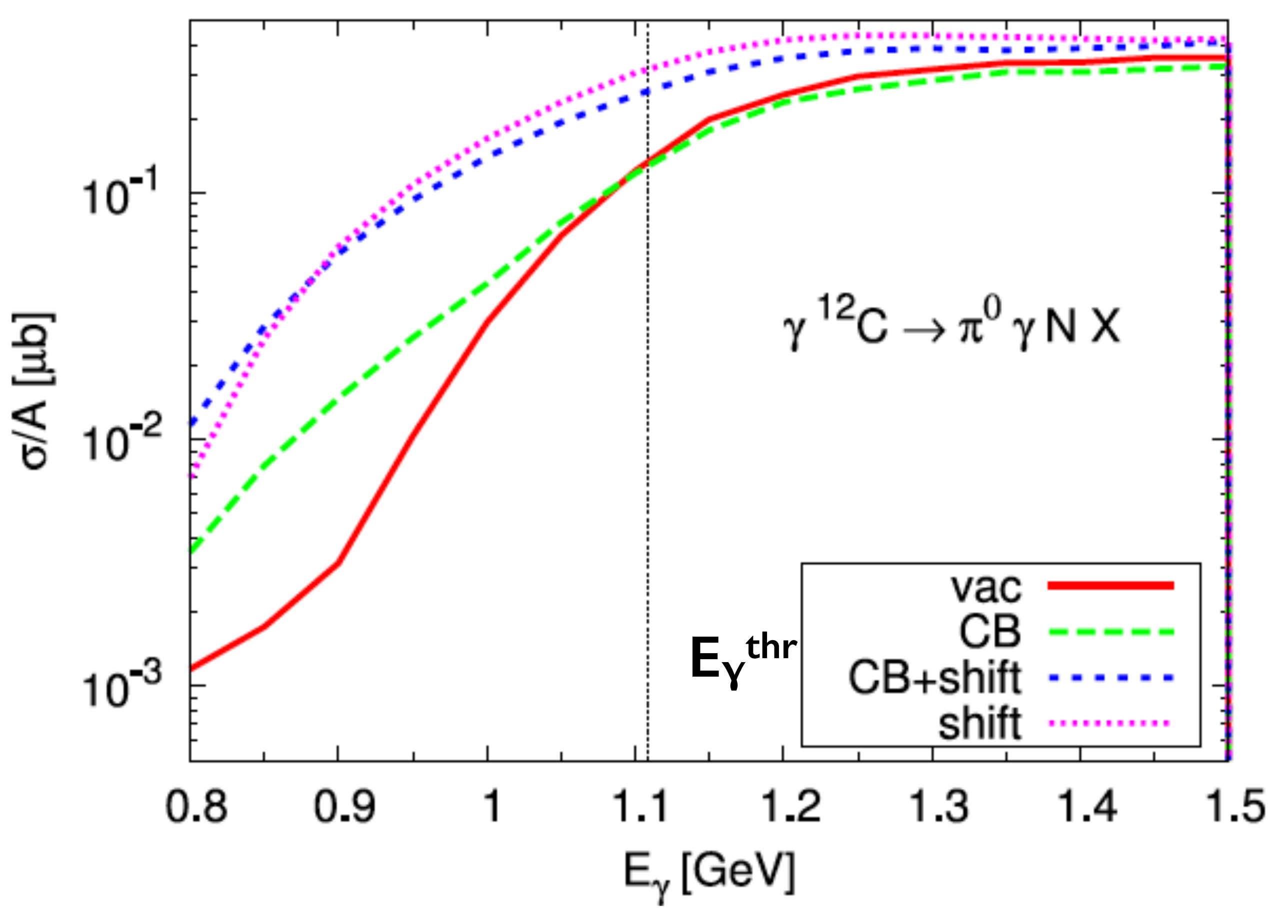
sensitive to nuclear density at production point and not at decay point

- measurement of the excitation function of the meson

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

⇨ cross section enhancement

$\pi^0\gamma$ excitation function

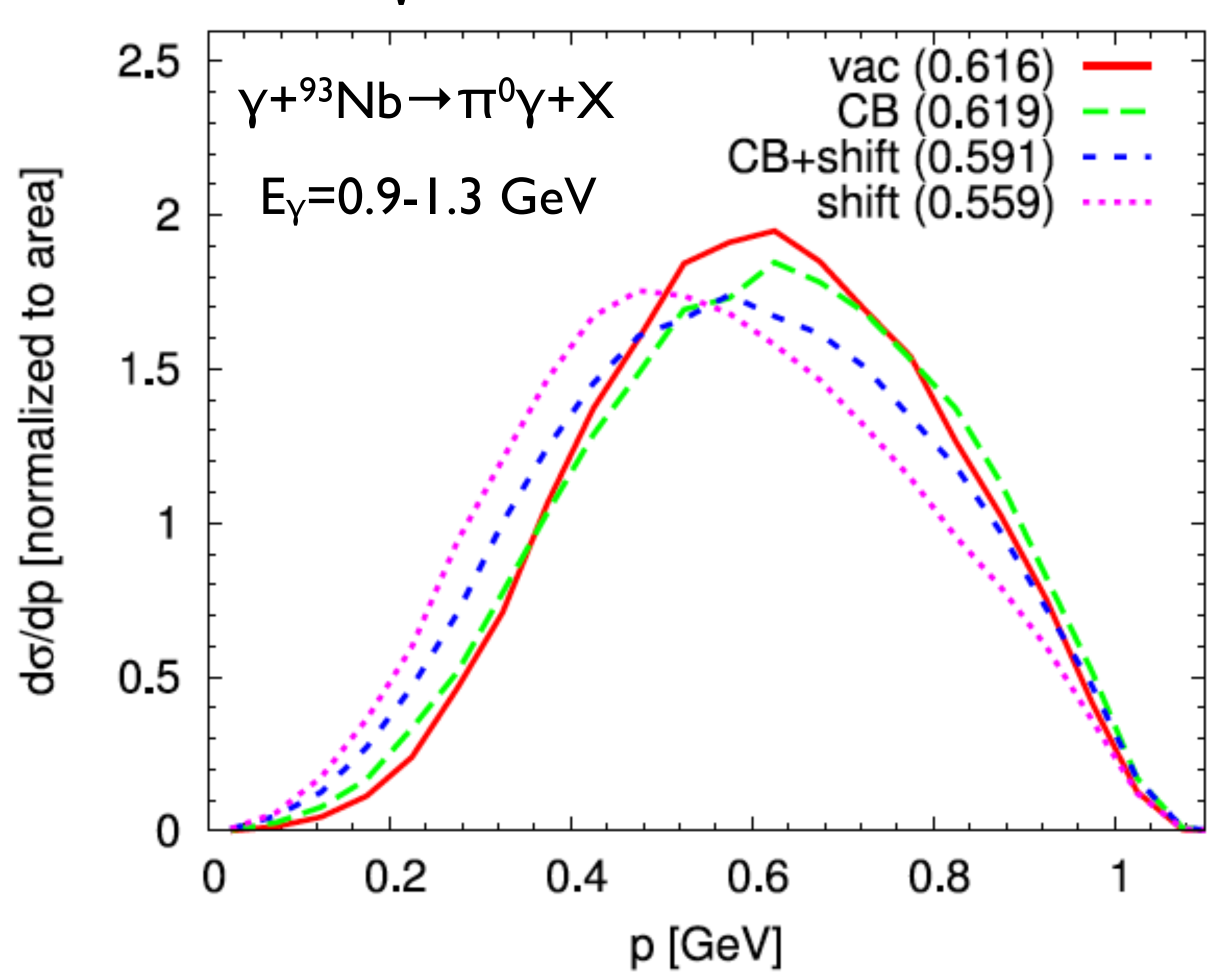


- momentum distribution of the meson:

in case of dropping mass - when leaving the nucleus hadron has to become on-shell; mass generated at the expense of kinetic energy

⇨ downward shift of momentum distribution

$\pi^0\gamma$ momentum distribution

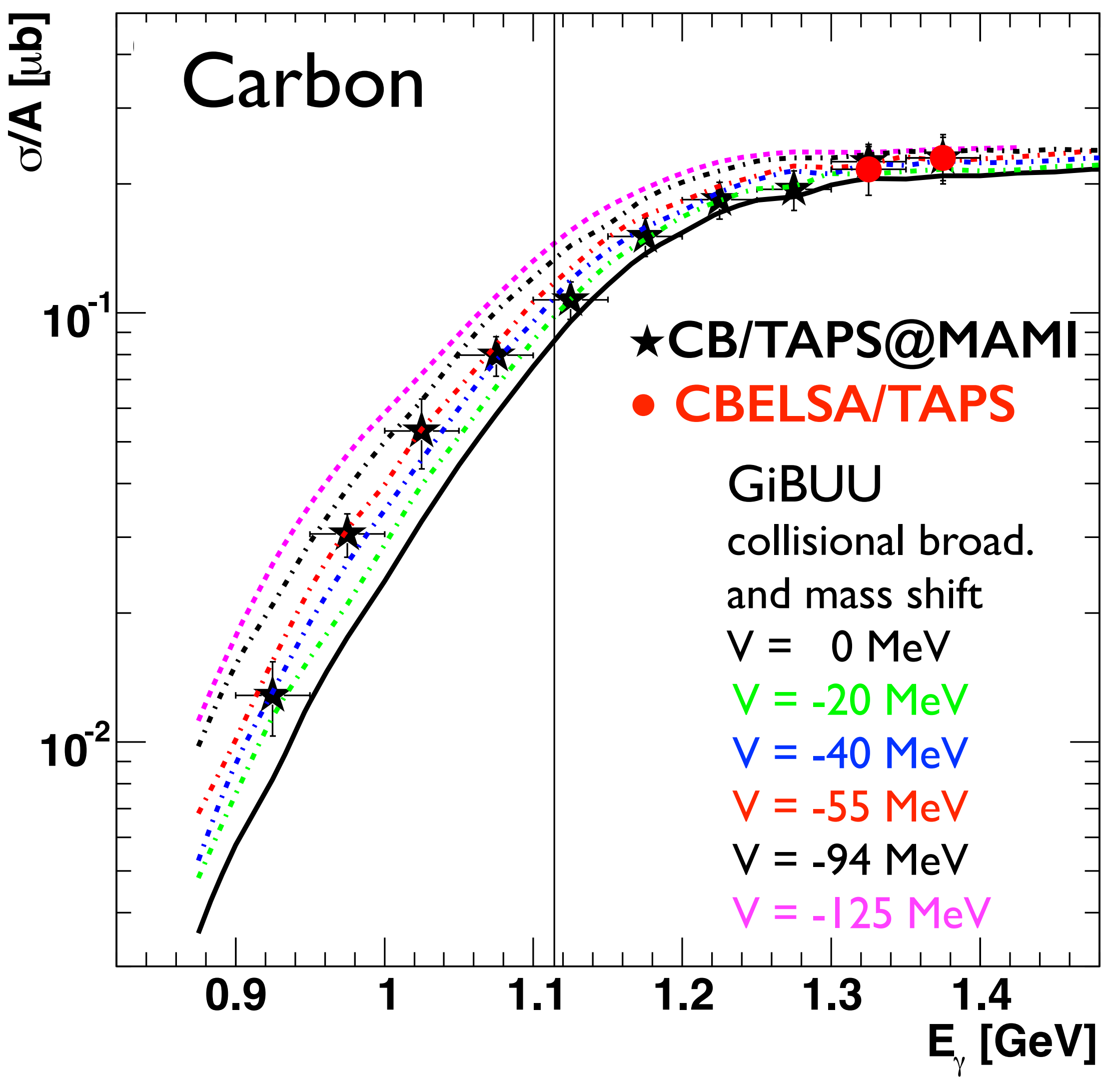


excitation function for ω photoproduction off C comparison with GiBUU calculation

CB/TAPS @ MAMI

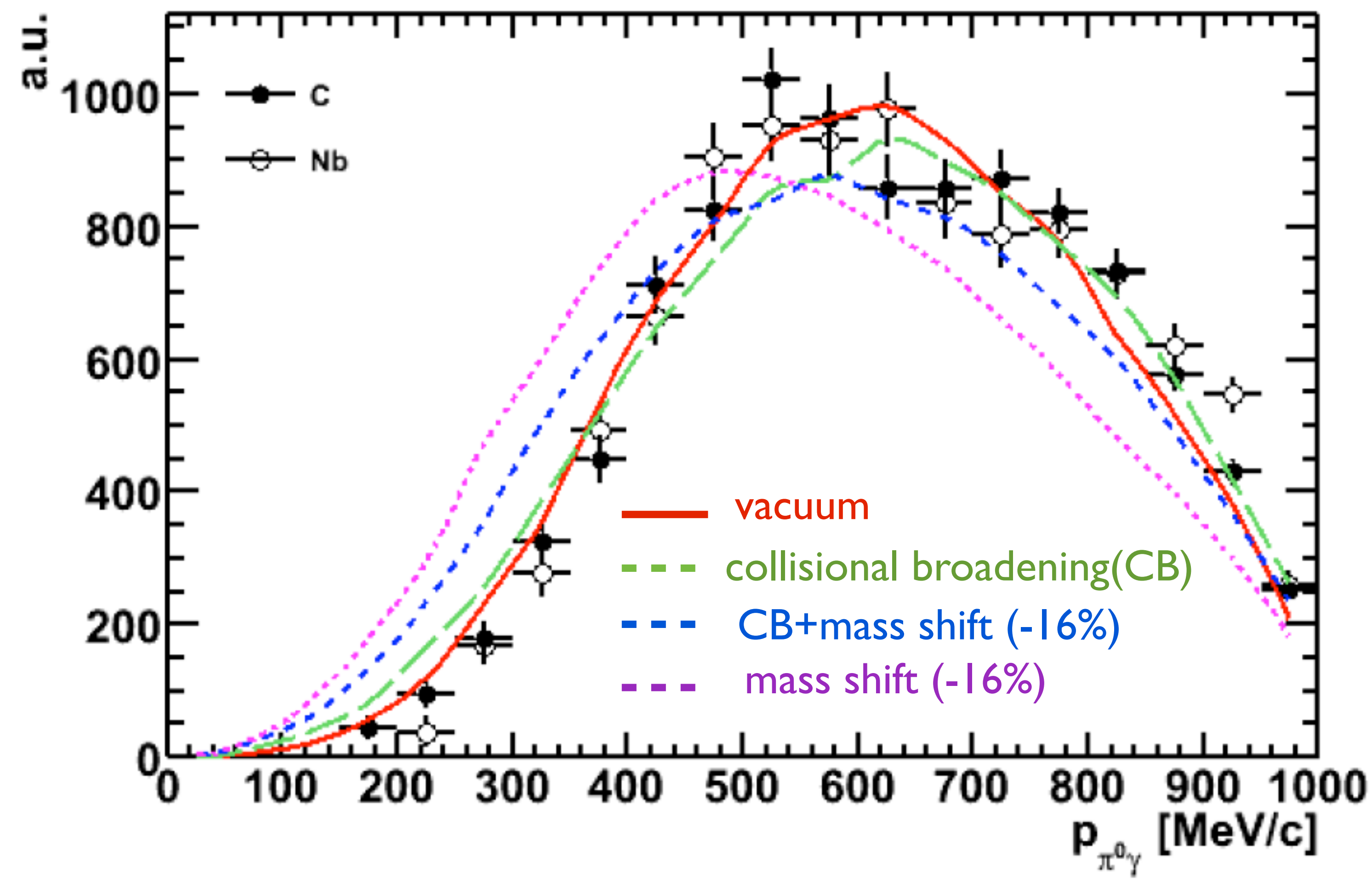
V. Metag et al., PPNP, 67 (2012) 530

excitation function



M. Thiel et al., EPJA 49 (2013) 132

momentum distribution



$V(\rho=\rho_0) = -(42\pm17(stat)\pm20(syst))$ MeV

data not consistent with strong mass shift scenario ($\Delta m/m \approx -16\%$)

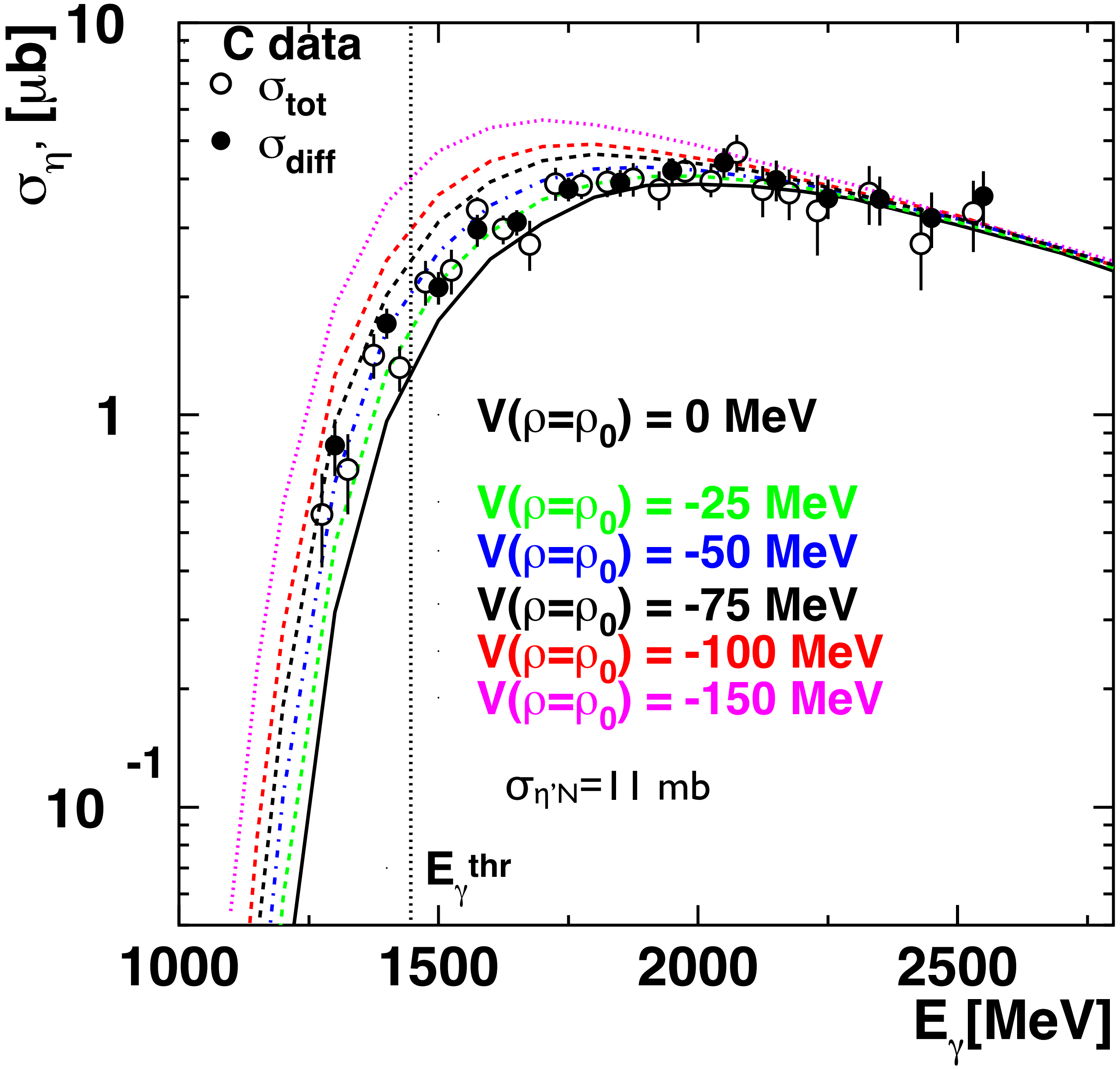
excitation function and momentum distribution for η' photoproduction off C

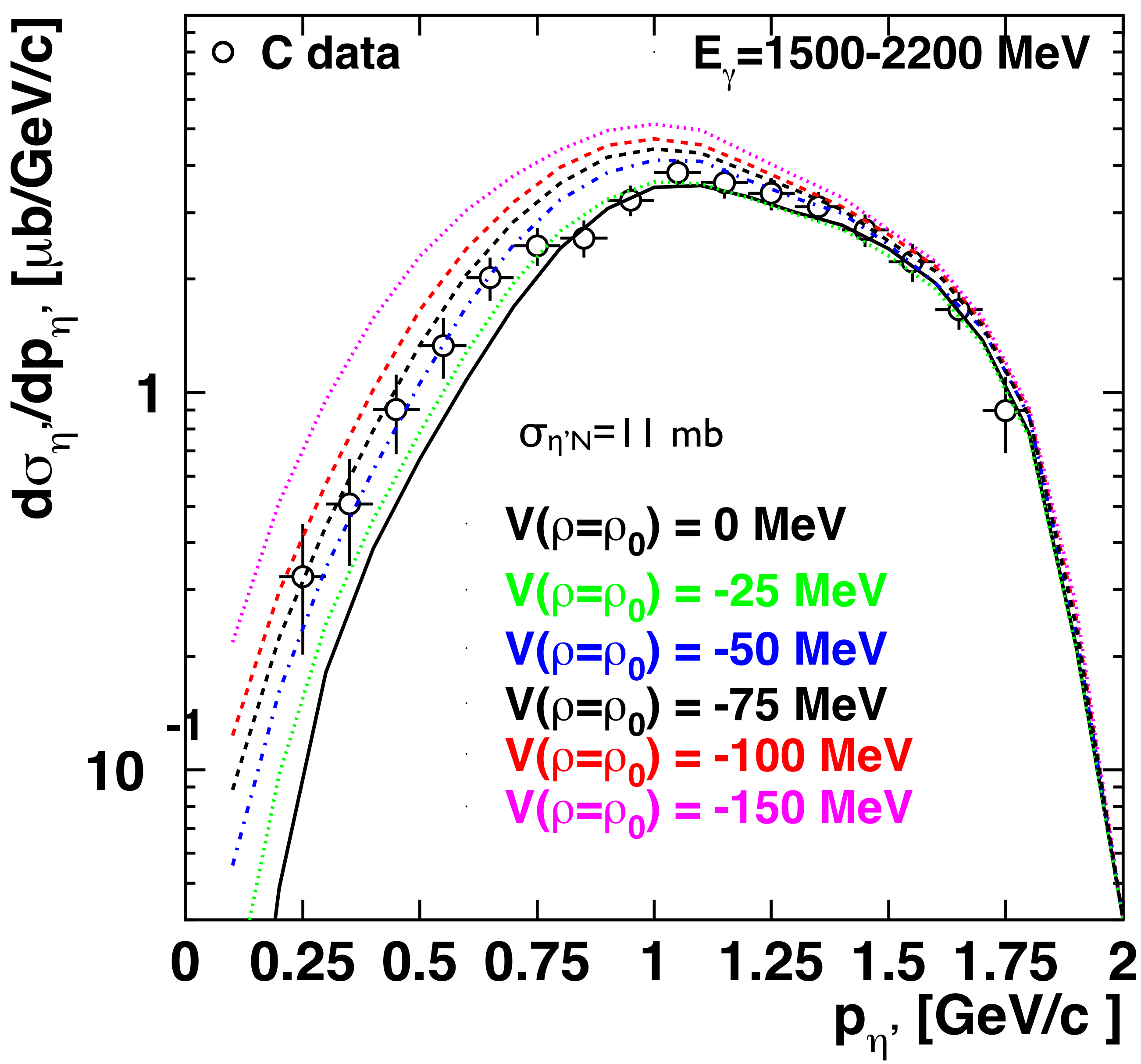
CBELSA/TAPS @ ELSA

γ C → η'X

data: M. Nanova et al., PLB 727 (2013) 417

calc.: E. Paryev, J. Phys. G 40 (2013) 025201





$V_{\eta'}(\rho=\rho_0) = -(40\pm6)$ MeV

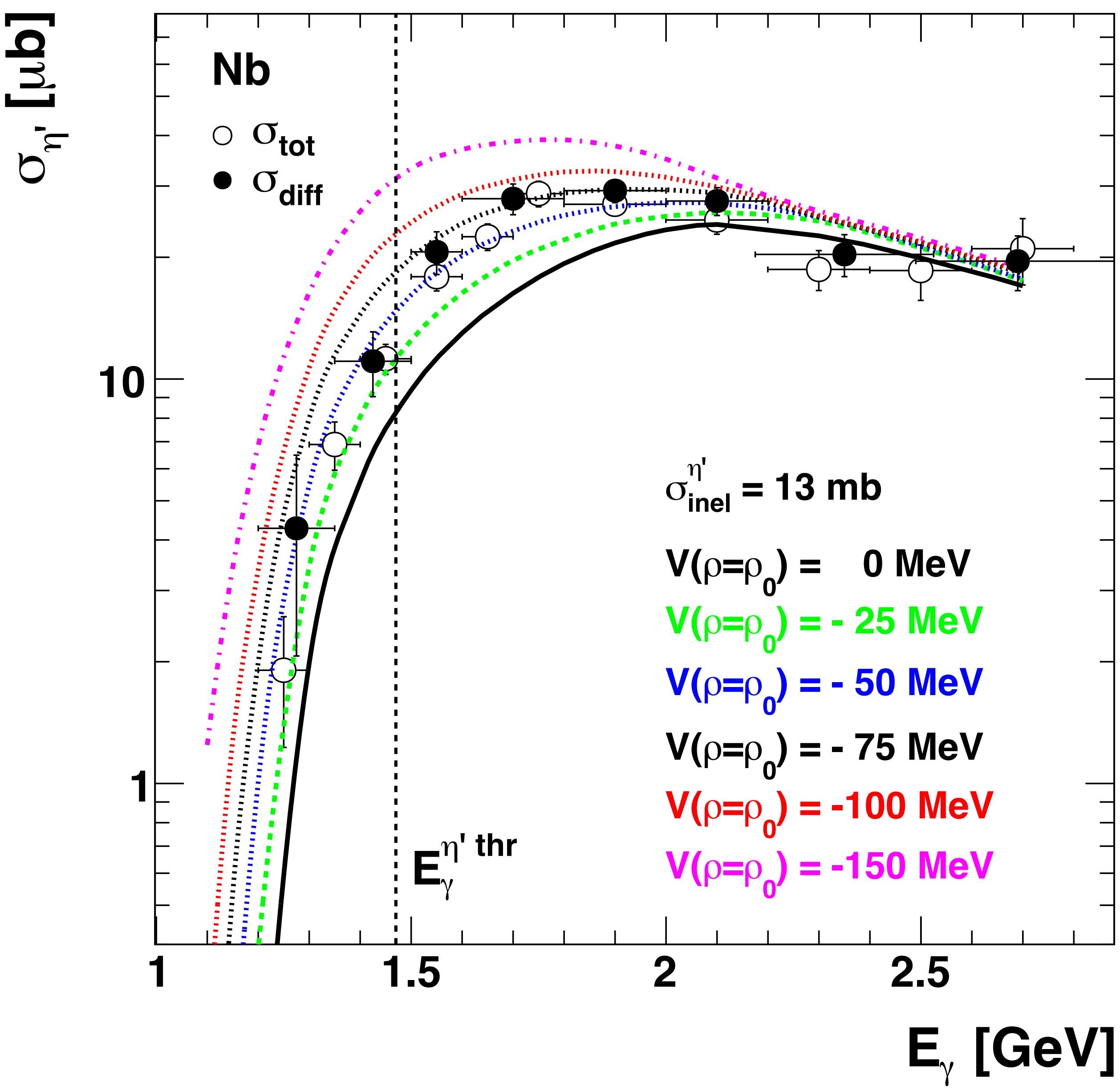
$V_{\eta'}(<p_{\eta'}>\approx 1.1$ GeV/c$;\rho=\rho_0) = -(32\pm11)$ MeV

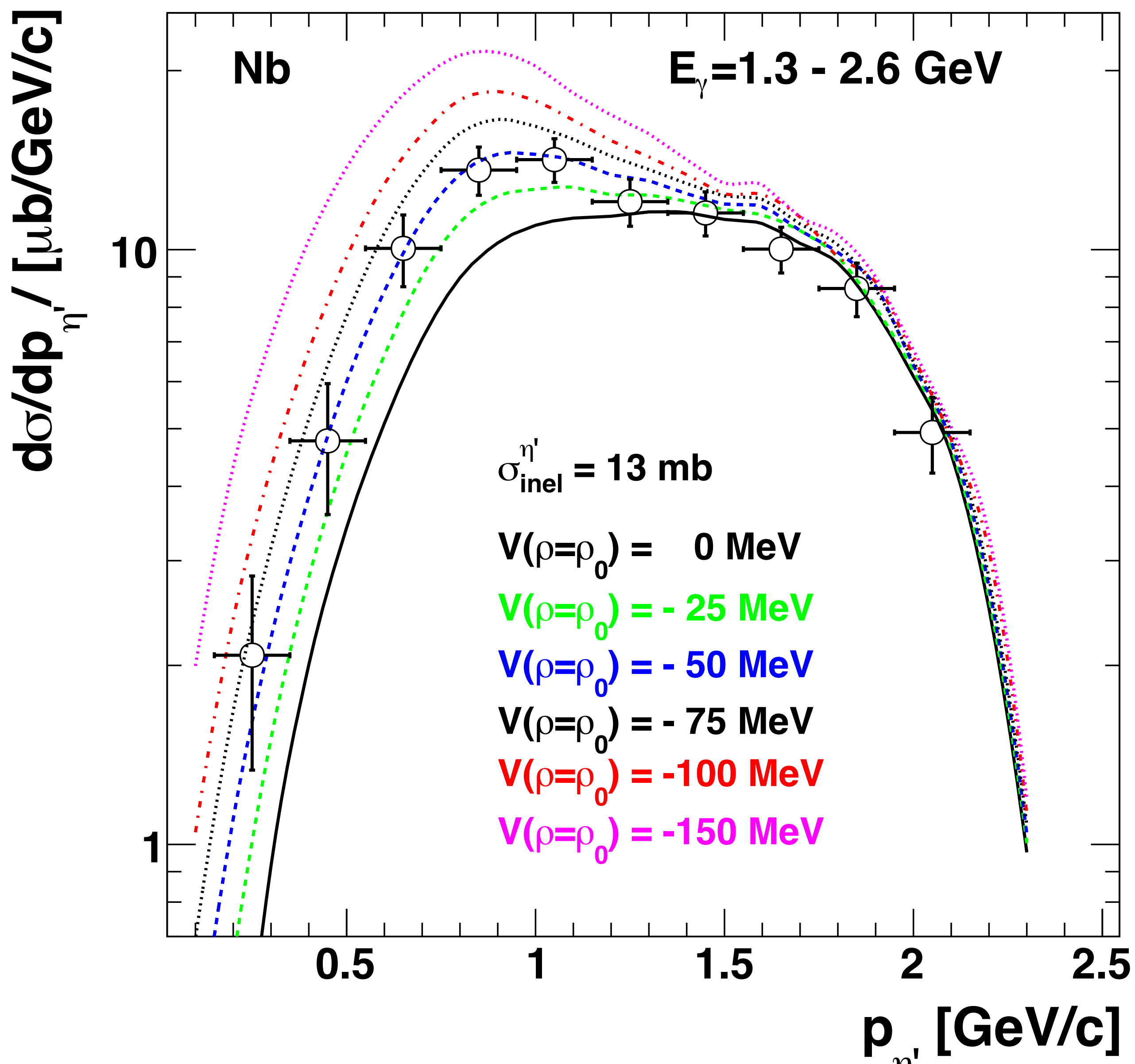
data disfavour strong mass shifts

excitation function and momentum distribution for η' photoproduction off Nb

CBELSA/TAPS @ ELSA

γ Nb → η'X   M. Nanova et al., arXiv:1607.07228; accepted for publication in PRC





$V_{\eta'}(\rho=\rho_0) = -(40\pm12)$ MeV $V_{\eta'}(<p_{\eta'}>\approx 1.14\ \text{GeV/c};\rho=\rho_0) = -(41\pm10)$ MeV

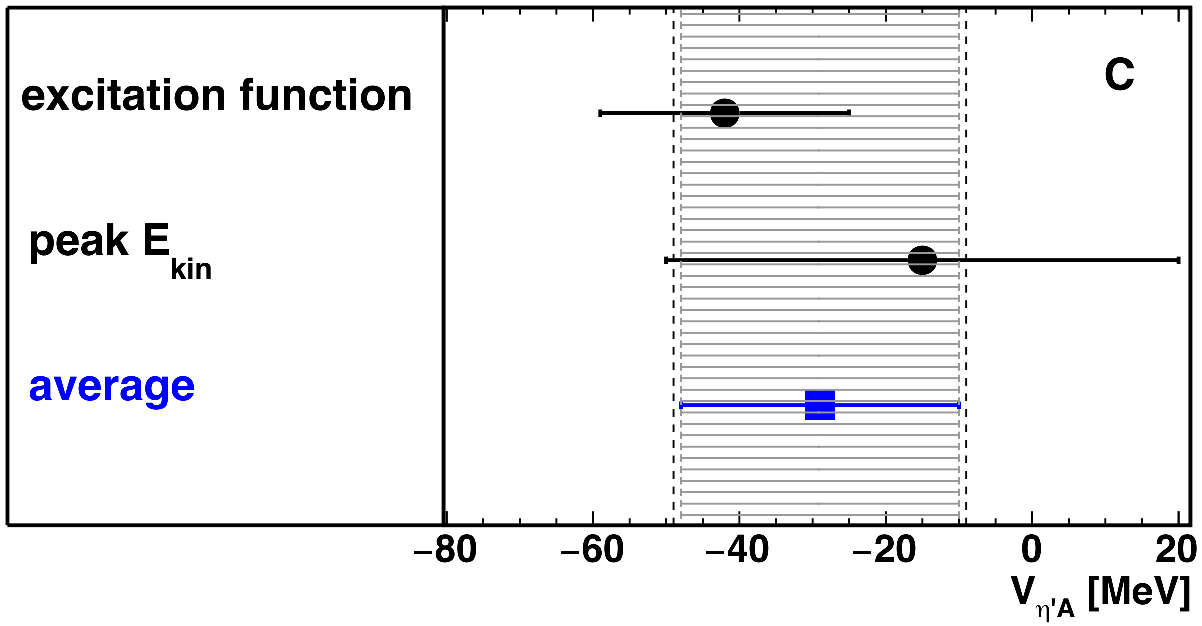
data disfavour strong mass shifts

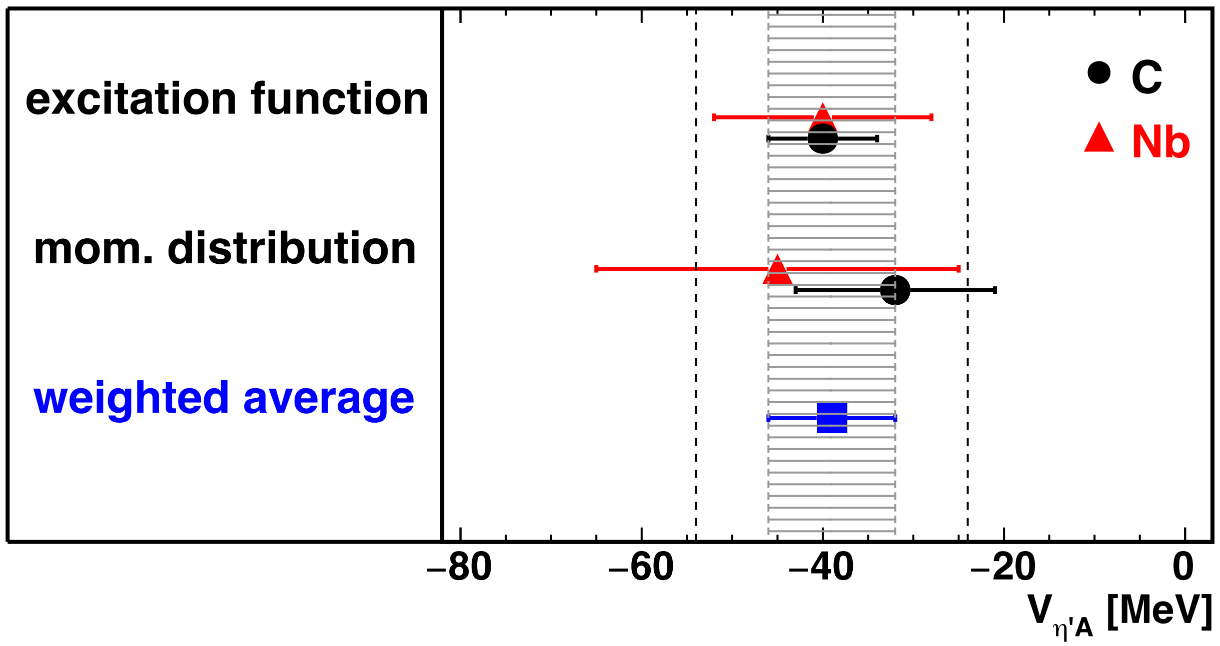
compilation of results for the real part of the ω- and η'-nucleus optical potential

ω

M. Nanova et al., arXiv:1607.07228; accepted for publication in PRC

η'





$V_{\omega A}(\rho=\rho_0)$ = −(29±19(stat)±20(syst)) MeV

$V_{\eta' A}(\rho=\rho_0)$ = −(40±8(stat)±15(syst)) MeV

first (indirect) observation of in-medium mass shift of η' at $\rho=\rho_0$ and T=0
in good agreement with QMC model predictions (S. Bass et al., PLB 634 (2006) 368)

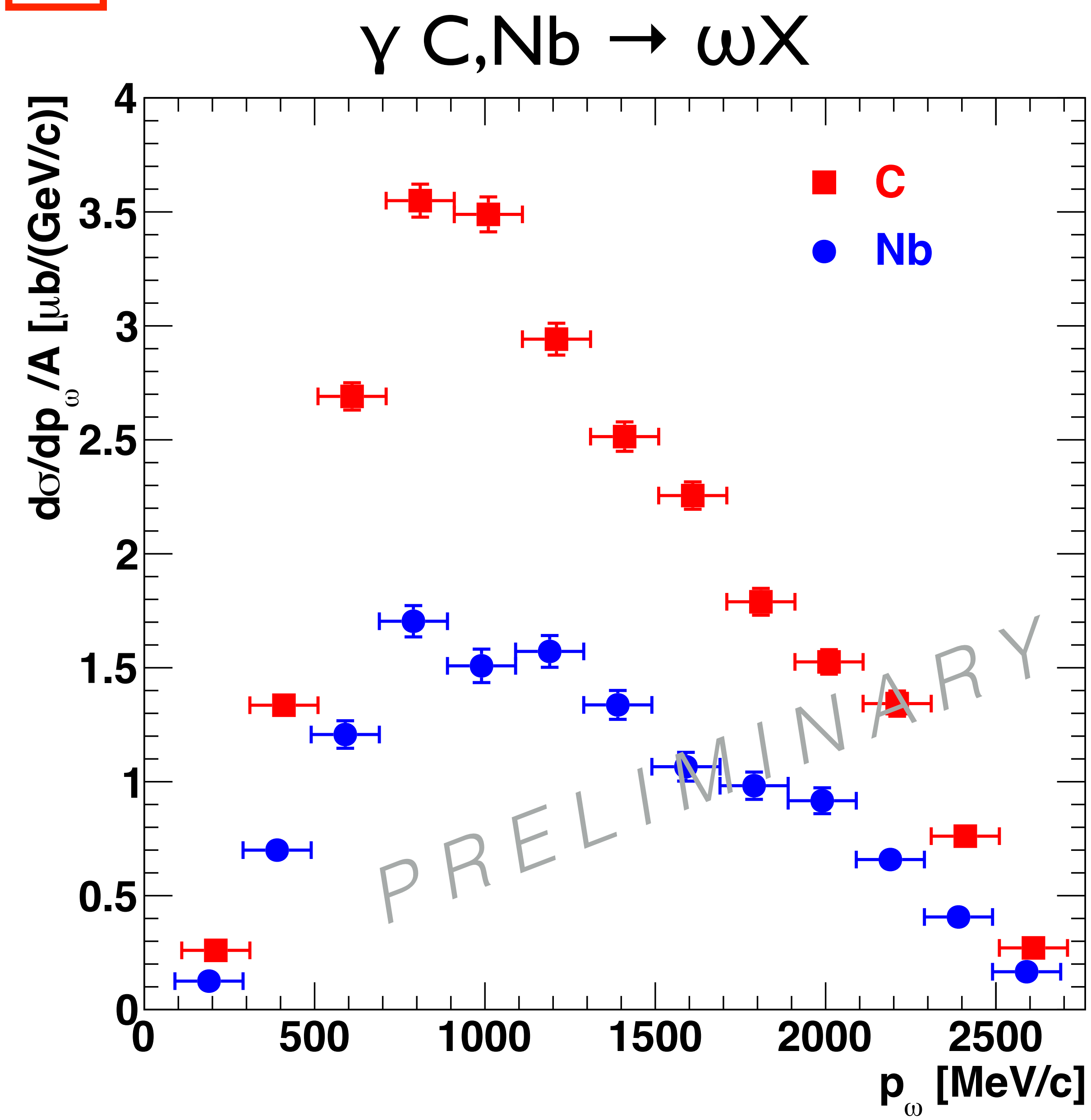
The imaginary part of the meson-nucleus optical potential: momentum dependence

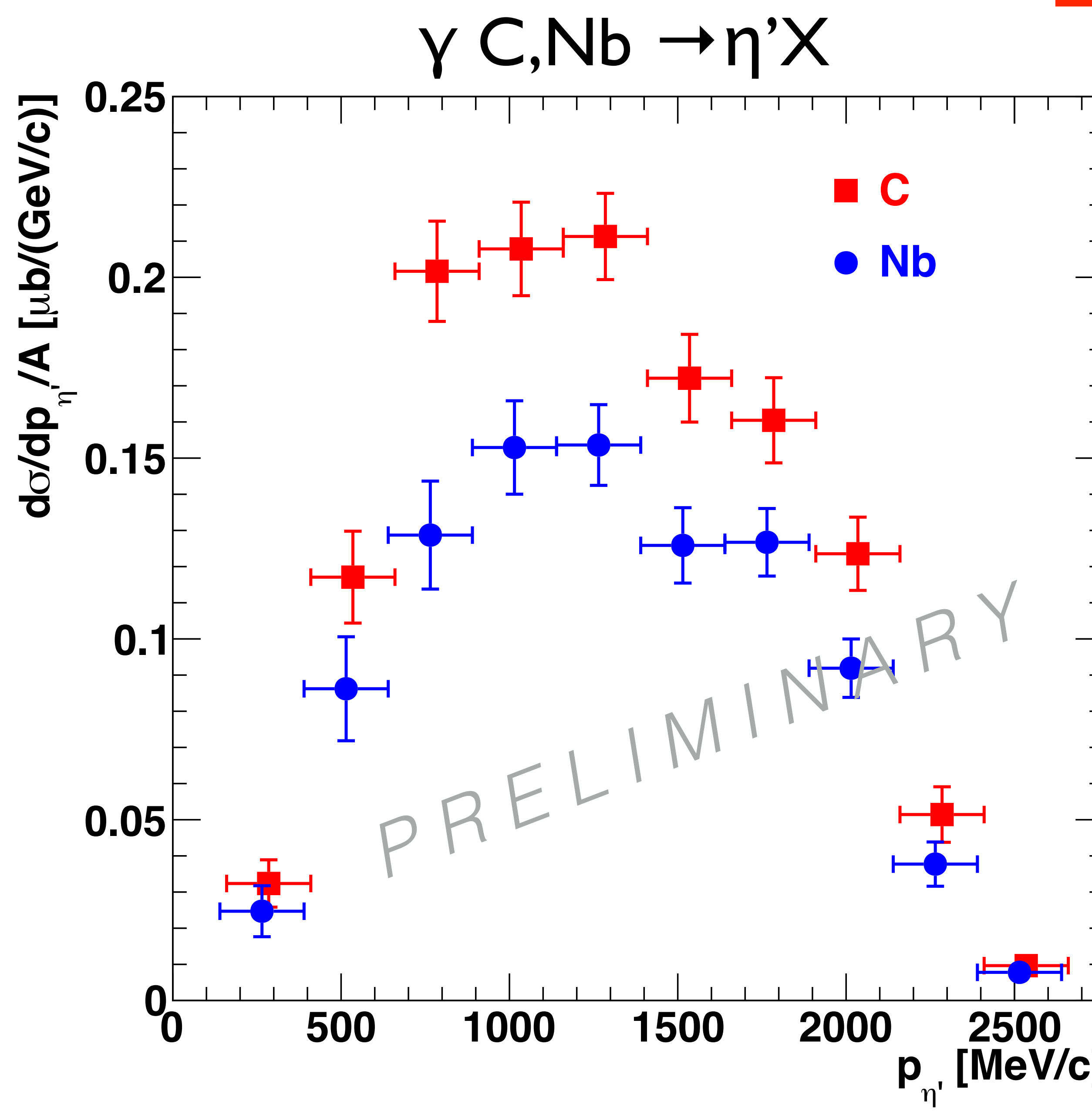
momentum differential cross section for ω, η’ produced off C, Nb

ω

E_γ = 1.2- 2.9 GeV

η’





momentum differential cross sections ⇒ $T^{m}_{Nb/C}(p_m) = \frac{12 \cdot \sigma_{\gamma Nb \rightarrow mX}(p_m)}{93 \cdot \sigma_{\gamma C \rightarrow mX}(p_m)}$

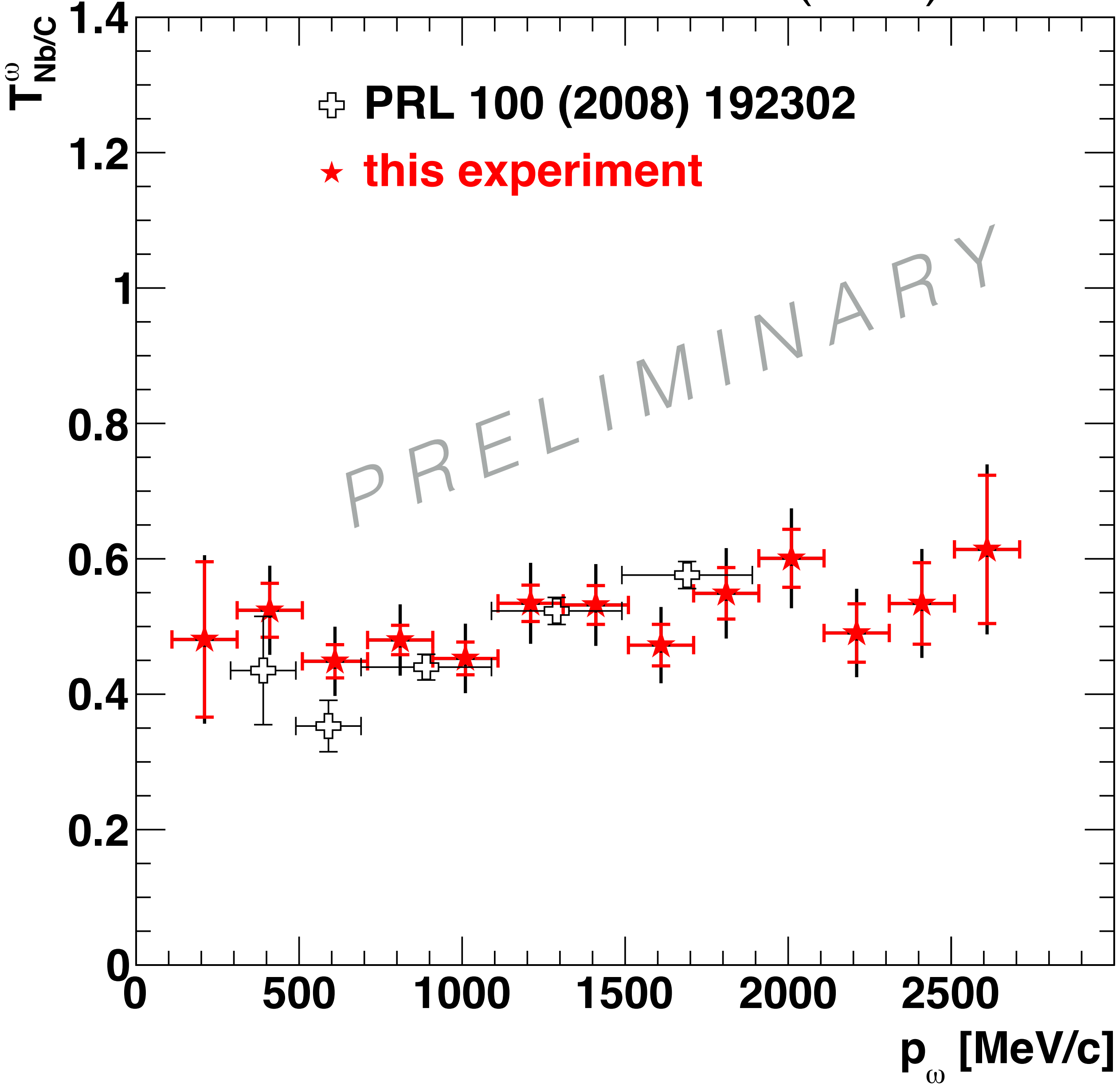
momentum dependence of transparency ratio for ω, η’

$$T^{m}_{Nb/C}(p_m) = \frac{12 \bullet \sigma_{\gamma Nb \rightarrow mX}(p_m)}{93 \bullet \sigma_{\gamma C \rightarrow mX}(p_m)}$$

ω

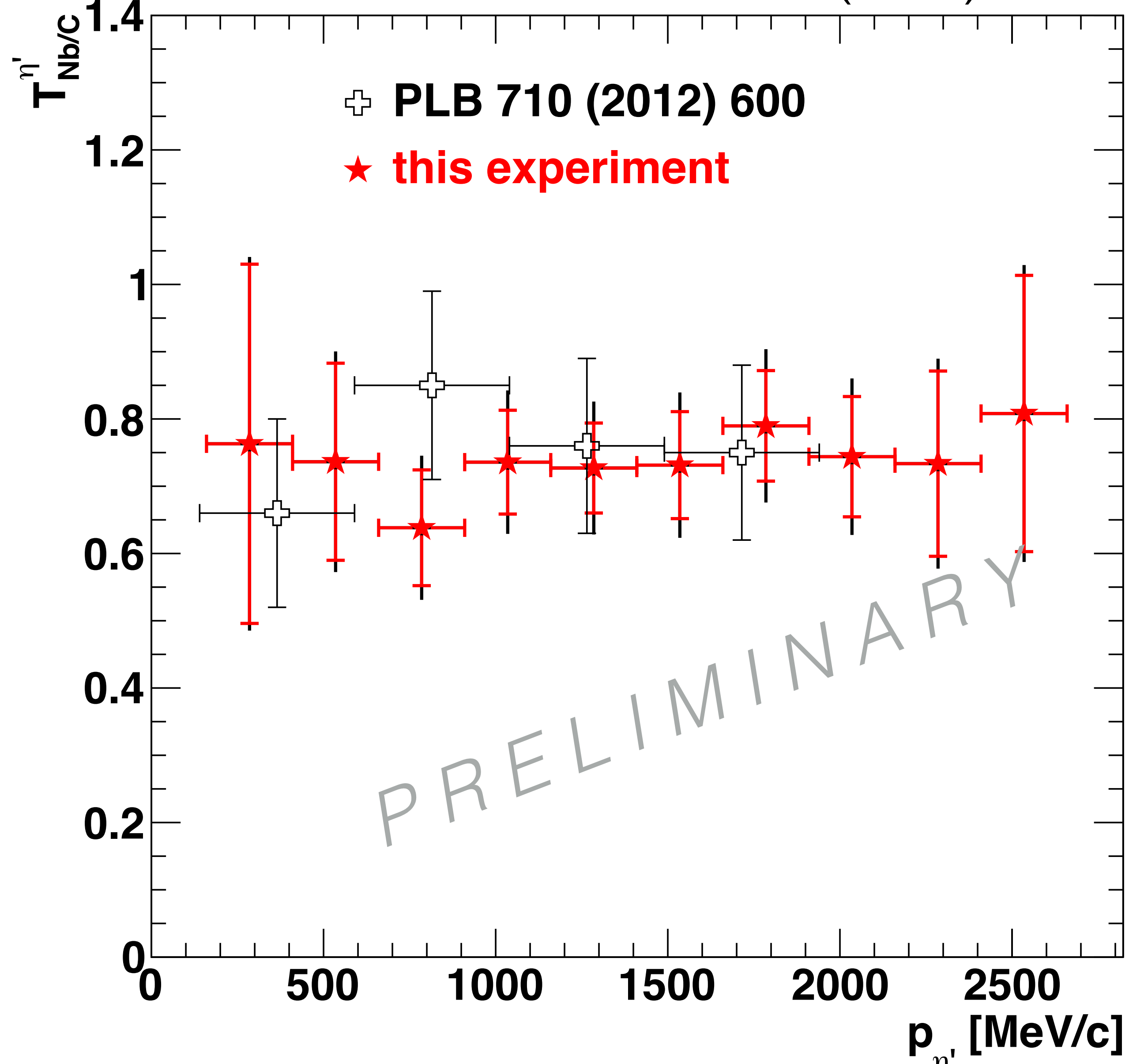
η’

✣ M. Kotulla et al., PRL 100 (2008) 192302



$T^{\omega}_{Nb/C} \approx 0.4\text{-}0.6$

✣ M. Nanova et al., PLB 710 (2012) 600



$T^{\eta'}_{Nb/C} \approx 0.7\text{-}0.8$

absorption of η’ mesons much weaker than for ω mesons !!

momentum dependence of the ω, η' in-medium width

Glauber model: high energy Eikonal approximation

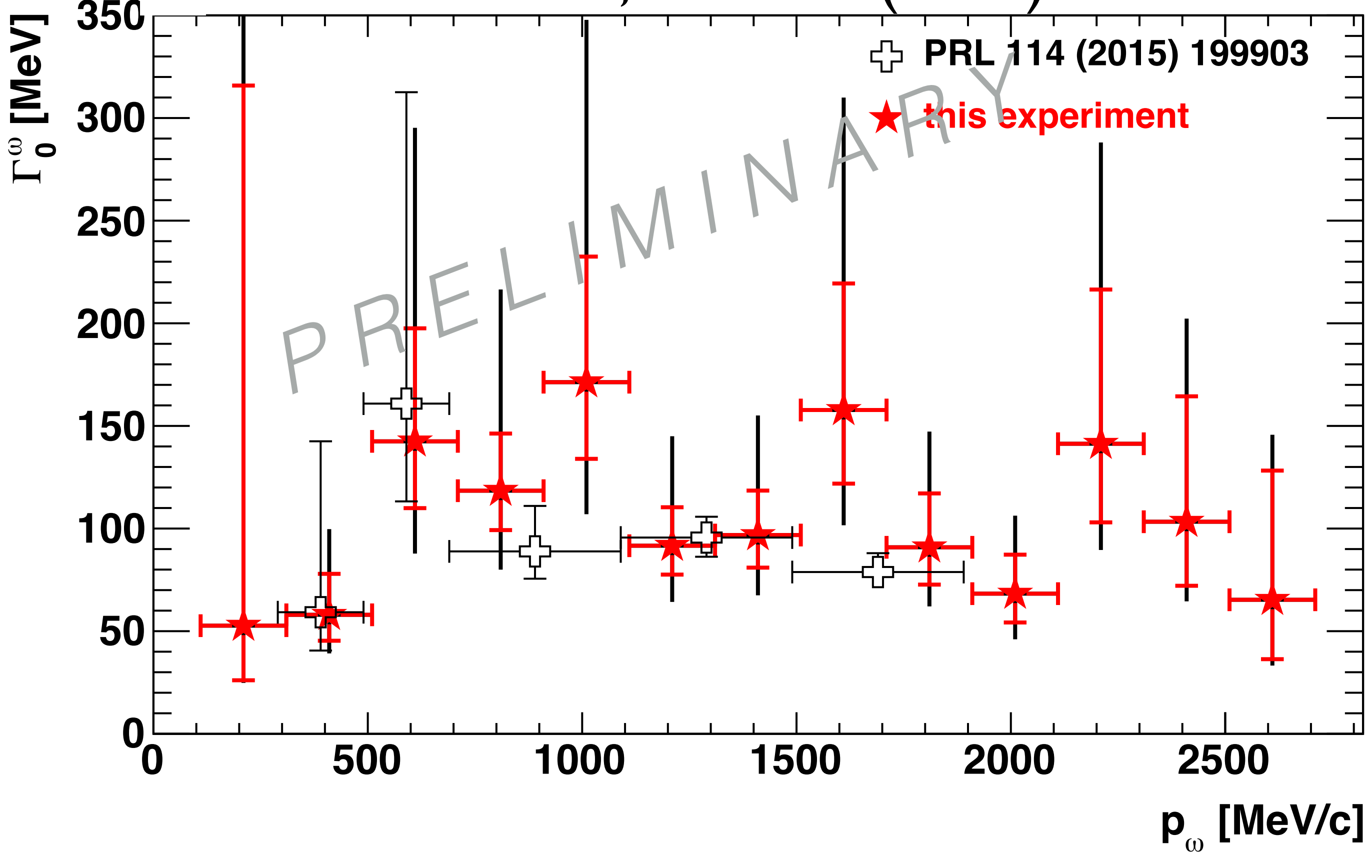
$$T^{m}_{Nb/C}(p_m) \Rightarrow \Gamma^{m}_{0}(\rho=\rho_0)\ (p_m)$$

S. Friedrich et al., submitted to EPJA

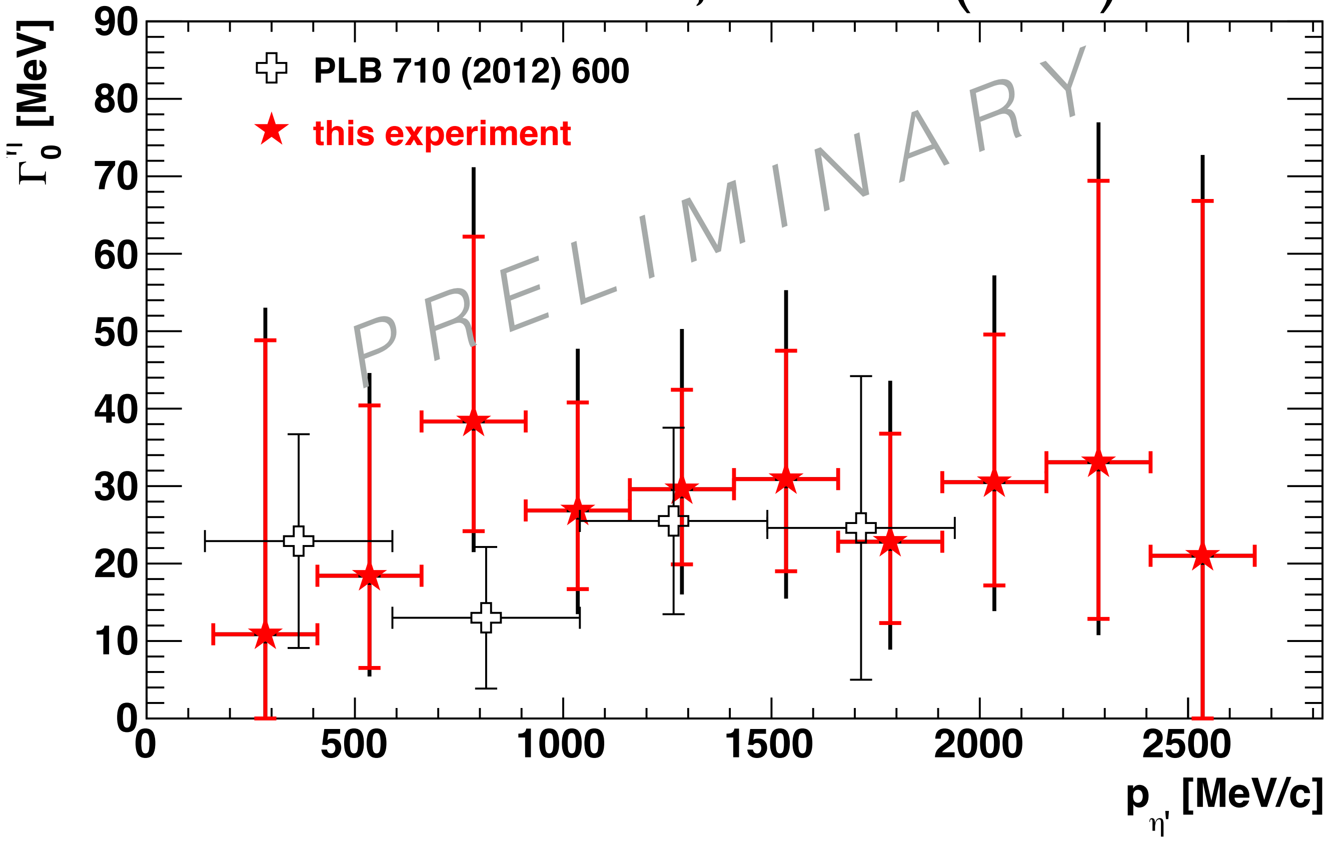
ω

η'

✚ M. Kotulla et al., PRL 114 (2015) 199903



✚ M. Nanova et al., PLB 710 (2012) 600



ω in-medium width ≈ 50-150 MeV

η' in-medium width ≈ 10-30 MeV

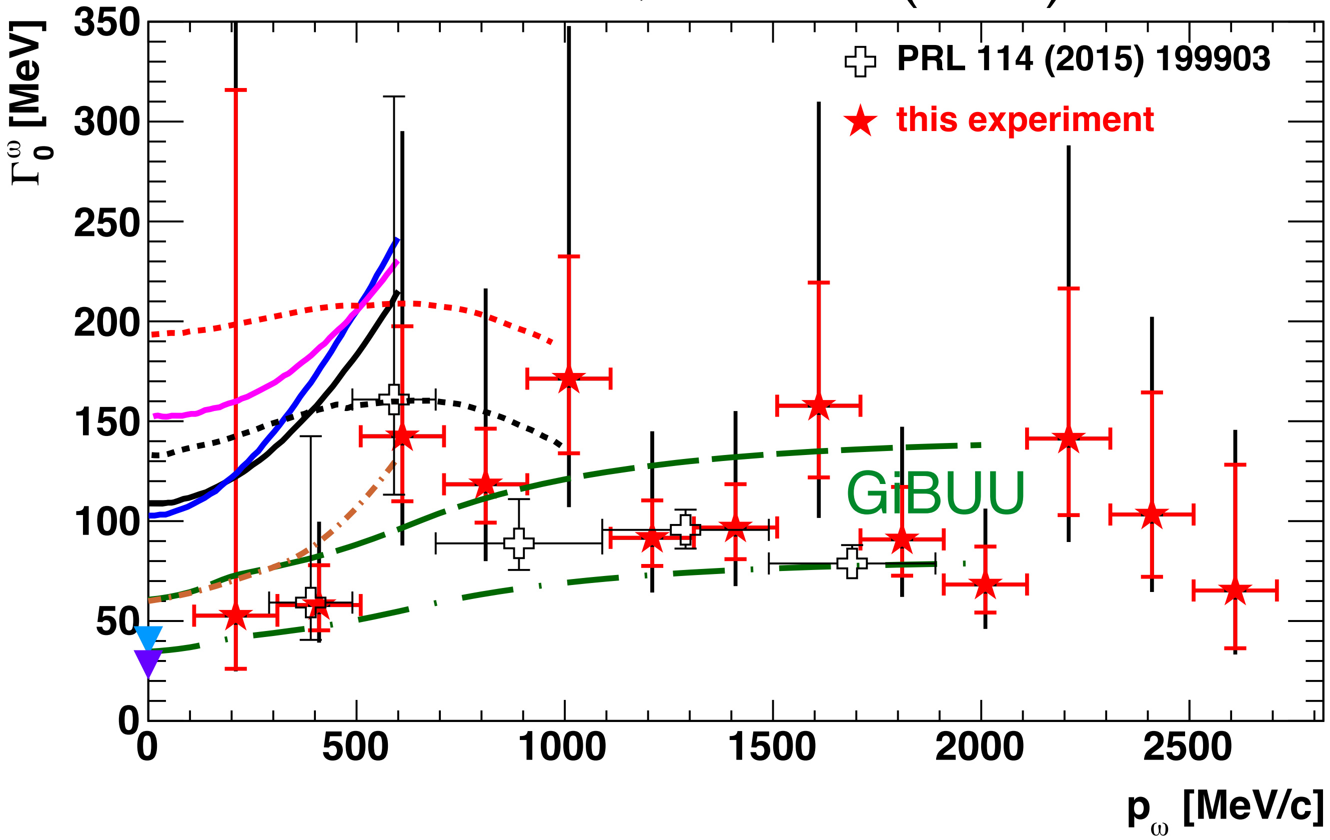
ω in-medium width in comparison to theoretical predictions

ω

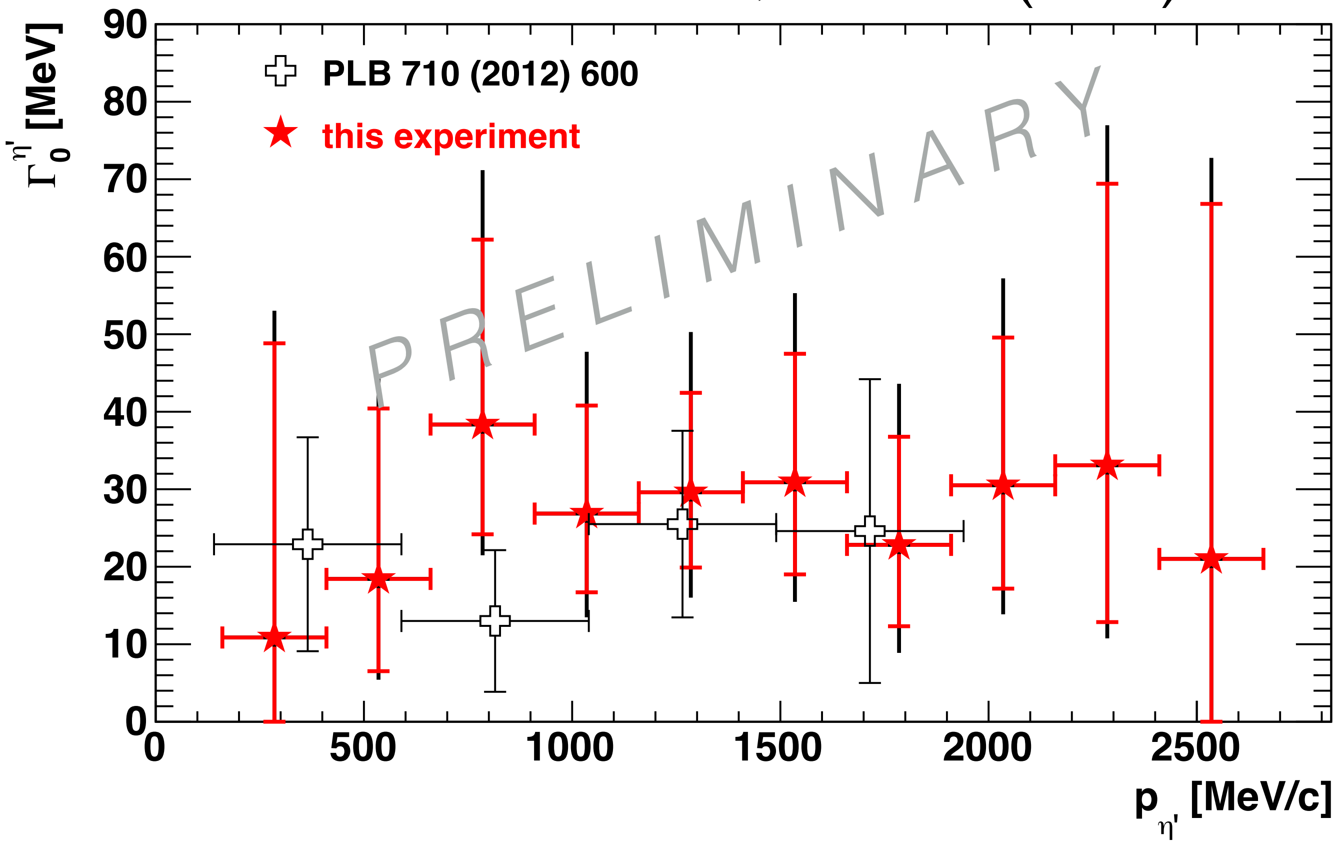
S. Friedrich et al., submitted to EPJA

η’

✣ M. Kotulla et al., PRL 114 (2015) 199903



✣ M. Nanova et al., PLB 710 (2012) 600



two groups of calculations:

$\omega \rightarrow \rho\pi$: D. Cabrera and R. Rapp, PLB 729 (2014) 67

A. Ramos et al., EPJA 49(2013) 148

NN*ω coupl.: F. Klingl et al., NPA 650 (1999) 299

B. Friman et al., arXiv: 9811040

M. Lutz et al., NPA 706 (2002) 437

P. Mühlich et al., NPA 780 (2006) 187

imaginary part of the potential for ω, η’

Glauber model: high energy Eikonal approximation

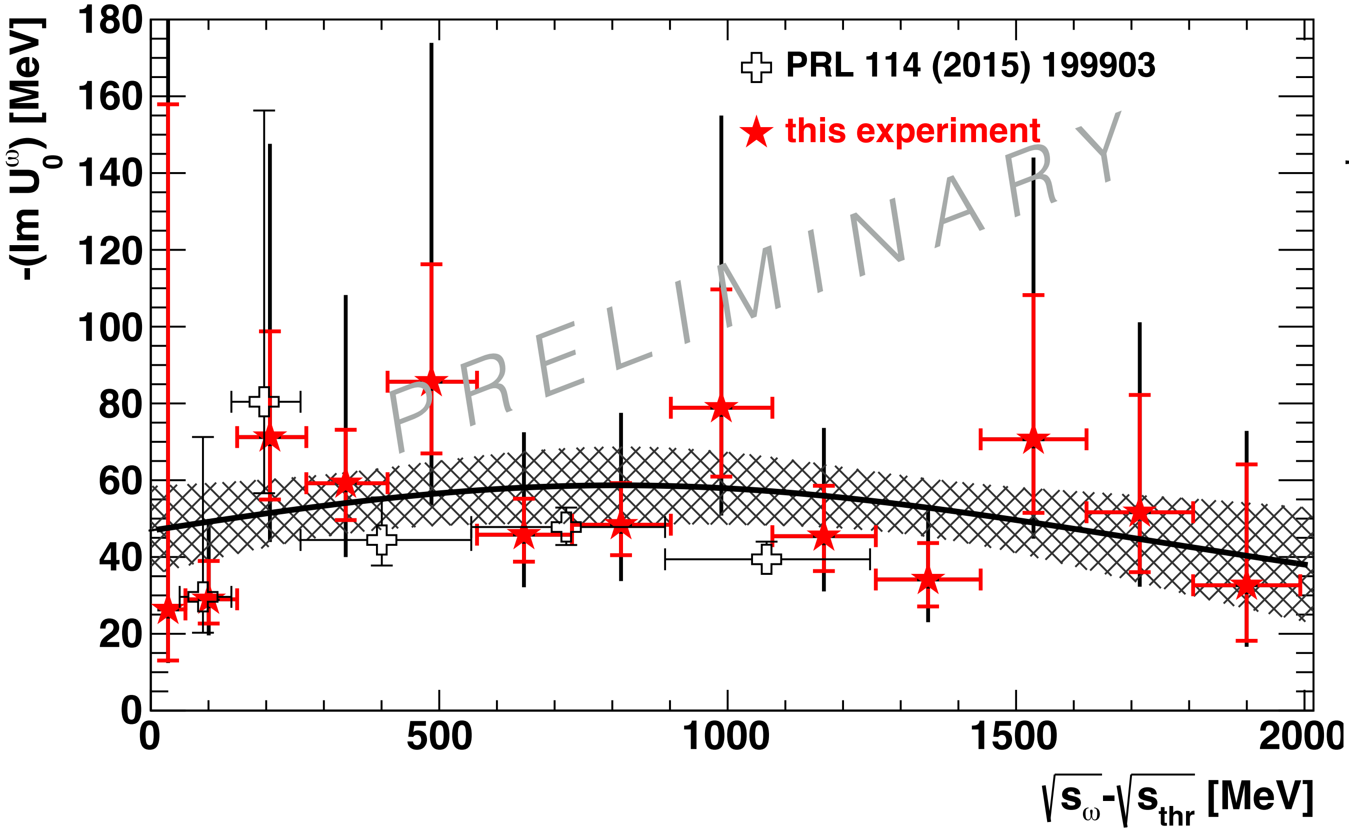
$$T^{m}_{Nb/C}\,(p_m) \Rightarrow \Gamma^{m}_{0}(\rho=\rho_0)\,(p_m) = -\,2\,\mathrm{Im}\,U^{m}_{0}(p_m)$$

ω

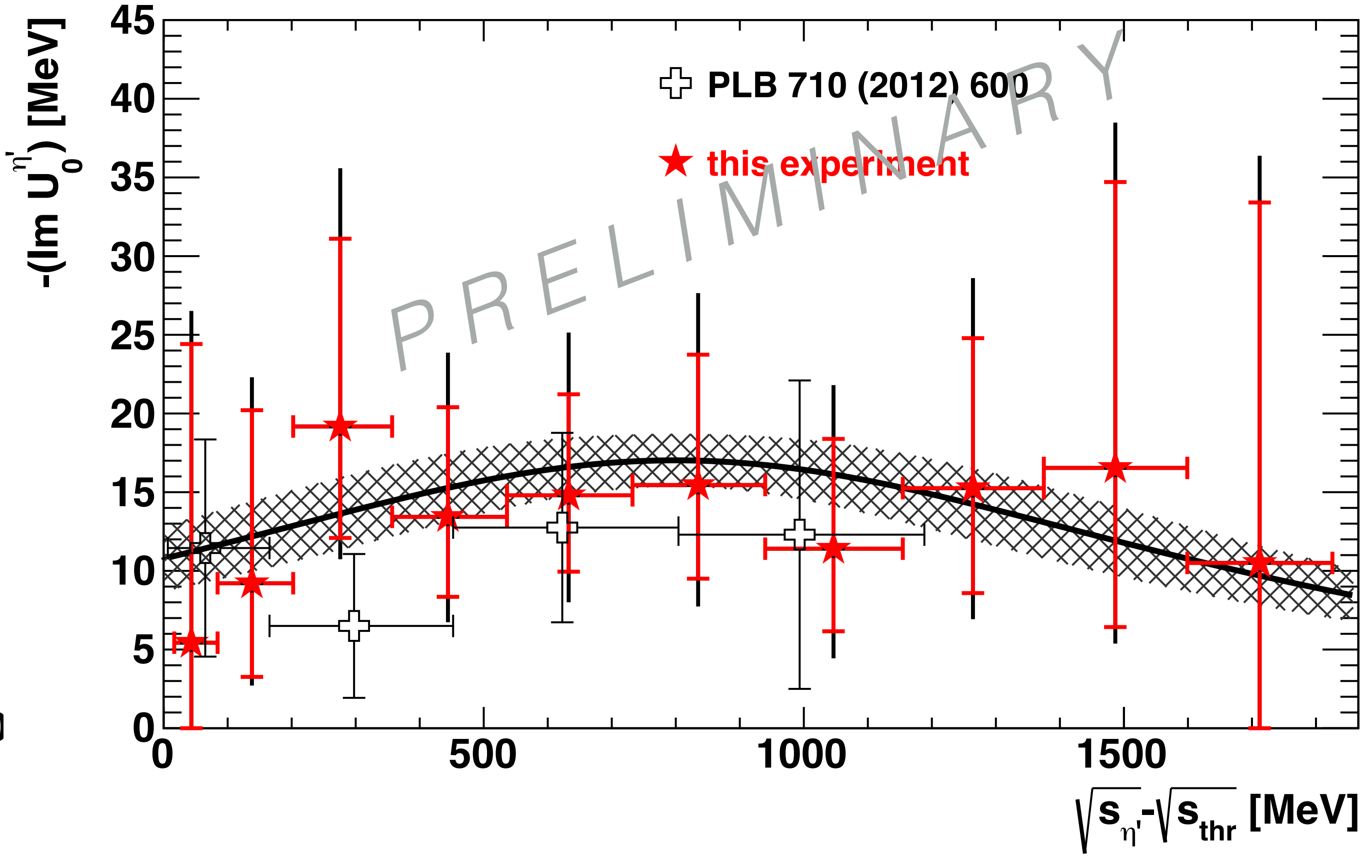
η’

S. Friedrich et al., submitted to EPJA

✣ M. Kotulla et al., PRL 114 (2015) 199903



✣ M. Nanova et al., PLB 710 (2012) 600



- extrapolation to production threshold:

$\mathrm{Im}\,U^{\omega}_{0}(\rho=\rho_0, p_\omega=0) = -(30\pm10)$ MeV

$\mathrm{Im}\,U^{\eta'}_{0}(\rho=\rho_0, p_{\eta'}=0) = -(10\pm3)$ MeV

- extension to higher energies allows for dispersion relation analysis, providing link between real and imaginary part of potential

compilation of results for real and imaginary part of the ω, η' -nucleus optical potential

ω

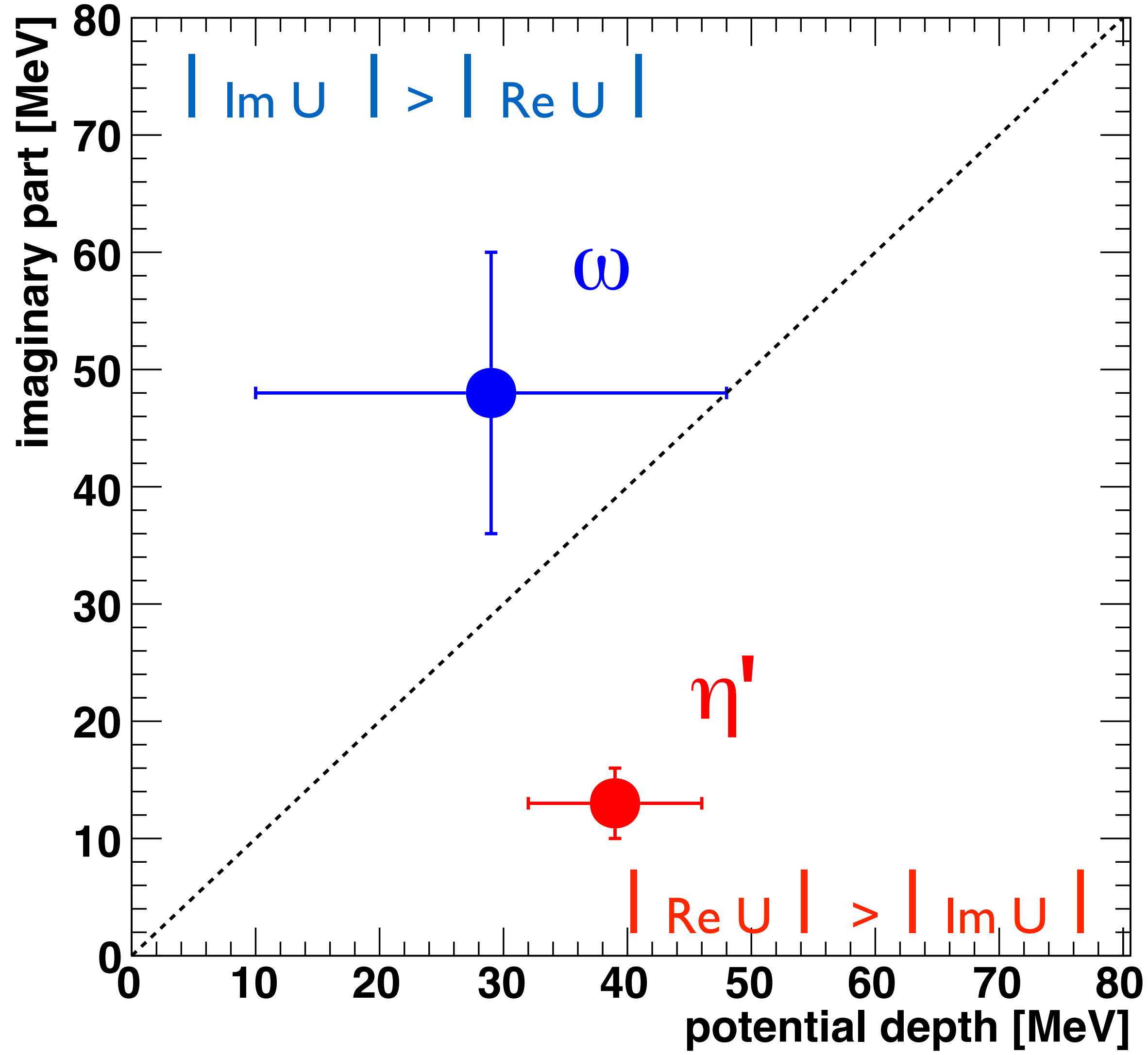
$U_{\omega A}(\rho=\rho_0)=$

$-((29\pm19(stat)\pm20(syst) + i(48\pm10\pm9))$ MeV

η'

$U_{\eta' A}(\rho=\rho_0)=$

$-((40\pm8(stat)\pm15(syst) + i(13\pm3\pm3))$ MeV



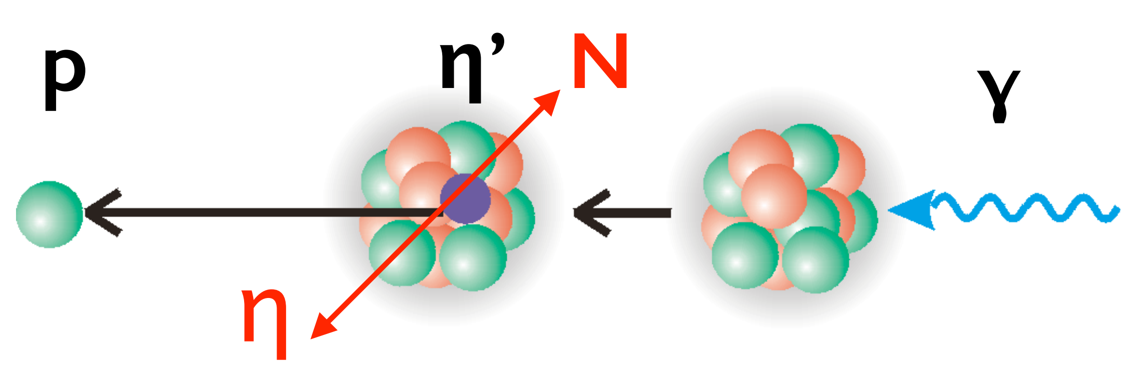
| Im U | ≳ | Re U | ; ⇨ ω not a good candidate to search for meson-nucleus bound states!

| Re U | >> | Im U | ; ⇨ η' promising candidate to search for mesic states

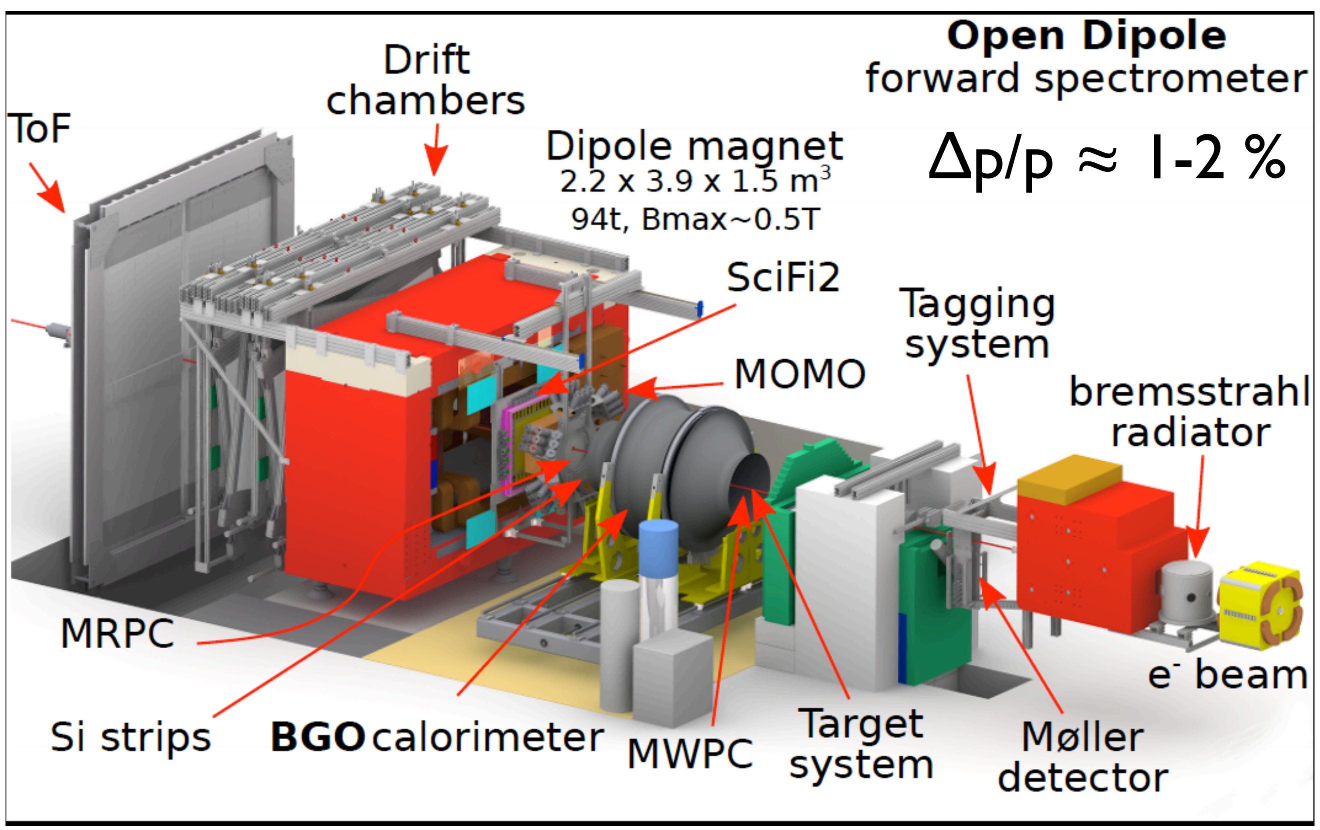
outlook: search for η'-mesic states in photo-nuclear reactions

B1: BGO-OD@ELSA

^{12}C(γ,p) η'X @ 1.5-2.8 GeV



formation and decay of η'-mesic state

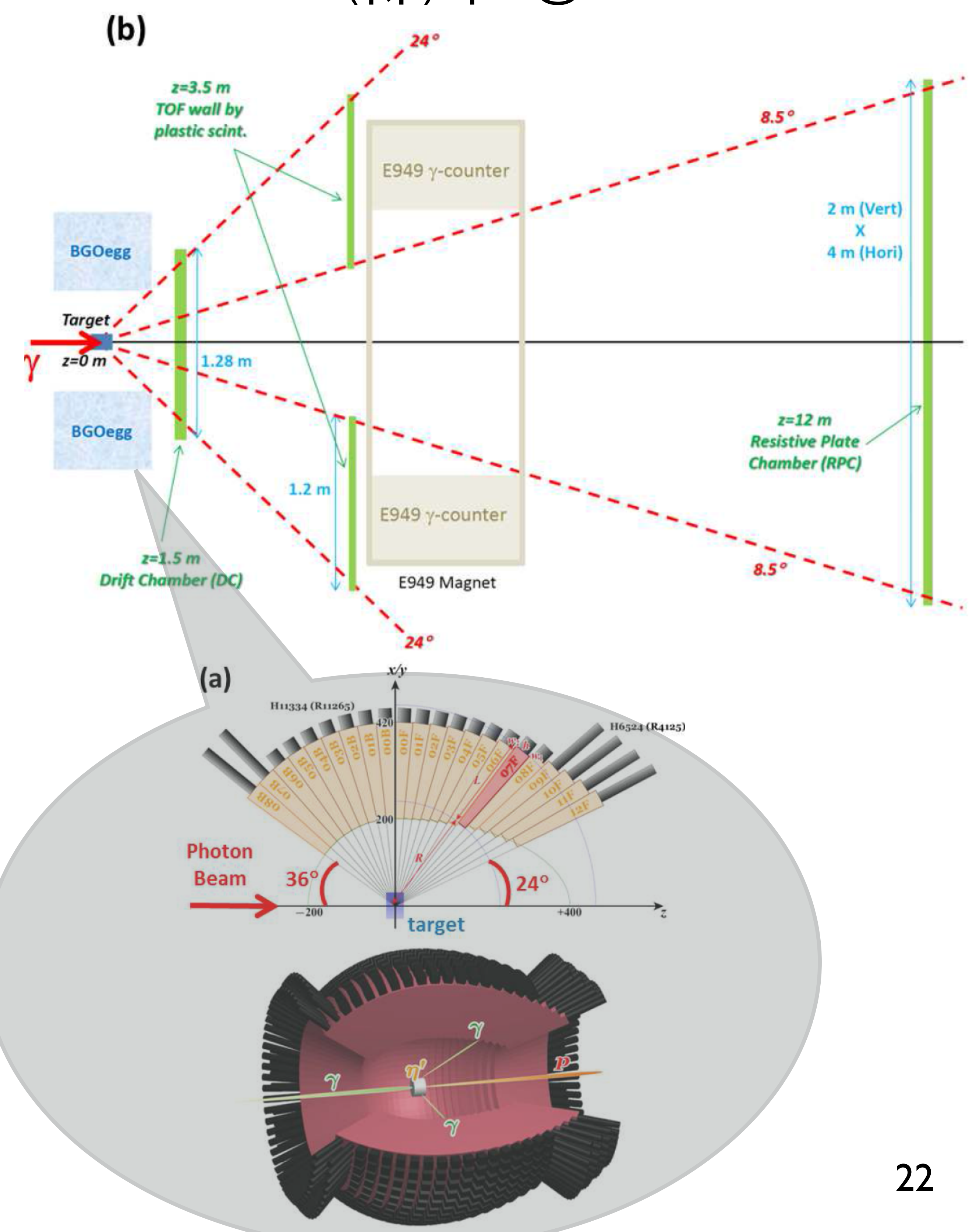


BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

LEPS2@SPring-8

^{12}C(γ,p) η'X @ 1.5-2.4 GeV



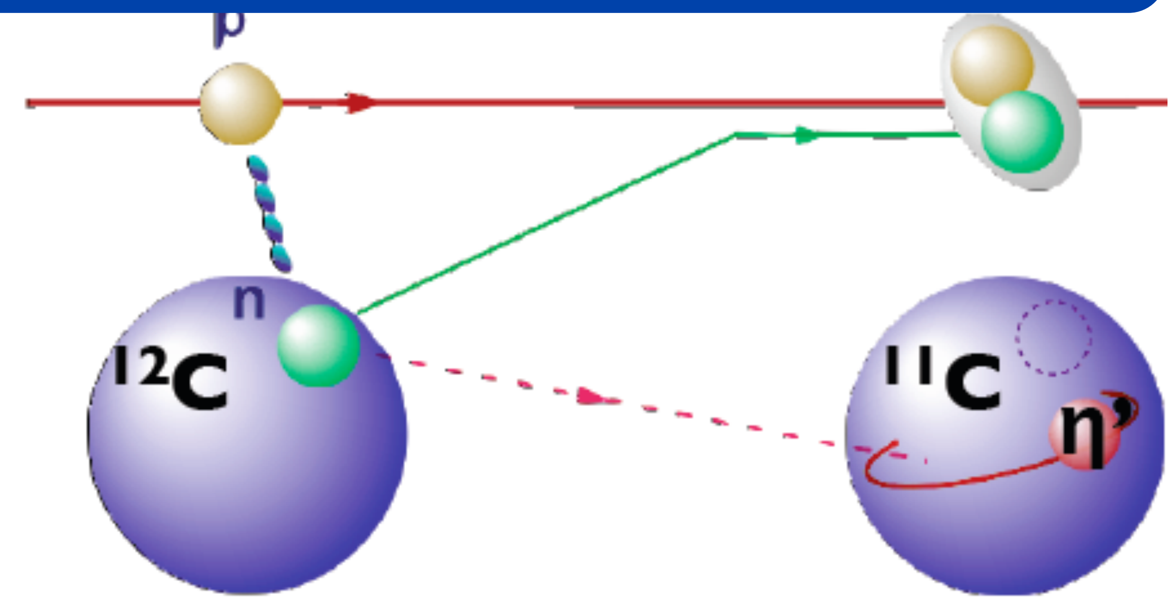
search for η'-mesic states in hadronic reactions

FRS@GSI: PRIME

$^{12}C(p,d)\eta'\otimes{}^{11}C$

K. Itahashi et al., PETP 128 (2012) 601

H. Nagahiro et al., PRC 87 (2013) 045201



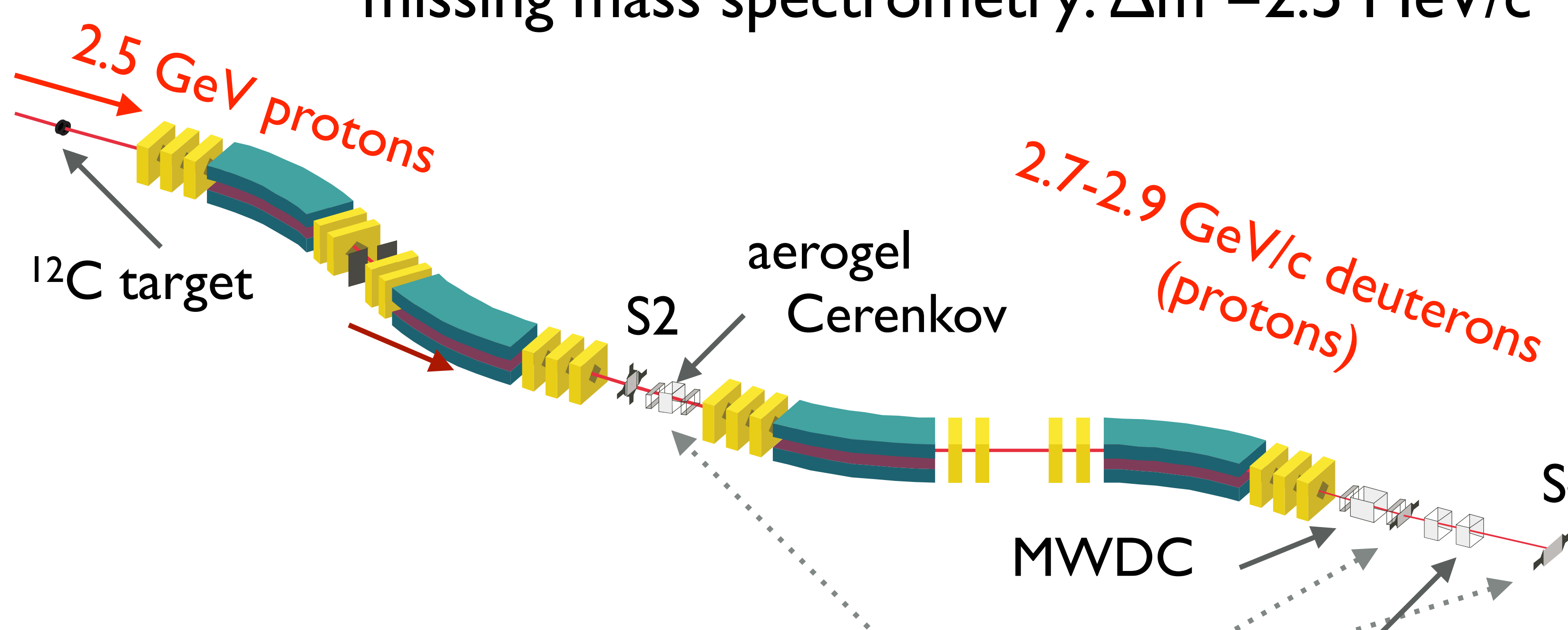
η' × ^{11}C mesic nuclei

FRS@GSI operated as spectrometer

particle identification by time-of-flight

no structures in bound state region observed;
deep potentials with $|V_0| > 100$ MeV excluded

missing mass spectrometry: $\Delta m = 2.5$ MeV/c^2



p/d separation by
aerogel Cerenkov
TOF S2-S4 (diff.≈20 ns)

Summary & Outlook

how do the hadron properties (mass, width) change in a dense nuclear medium ??

meson properties do change in a strongly interacting medium !!

- all mesons are broadened; their lifetime is shortened through inelastic collisions
  $\Gamma_{\omega}(\rho=\rho_0; p=0) \approx 90$ MeV; $\Gamma_{\eta'}(\rho=\rho_0; p=0) \approx 25$ MeV;

- large mass modifications $|\Delta m| > 100$ MeV (as predicted by some calculations) have not been observed

- for the η' meson an in-medium mass drop of $\Delta m\ (\rho=\rho_0) \approx -40$ MeV has been determined

- in-medium effects described within meson-nucleus optical

- the η' meson is a good candidate for forming meson-nucleus bound states since $|\mathrm{Im}\ U| << |\mathrm{Re}\ U|$

- search for η' mesic states ongoing

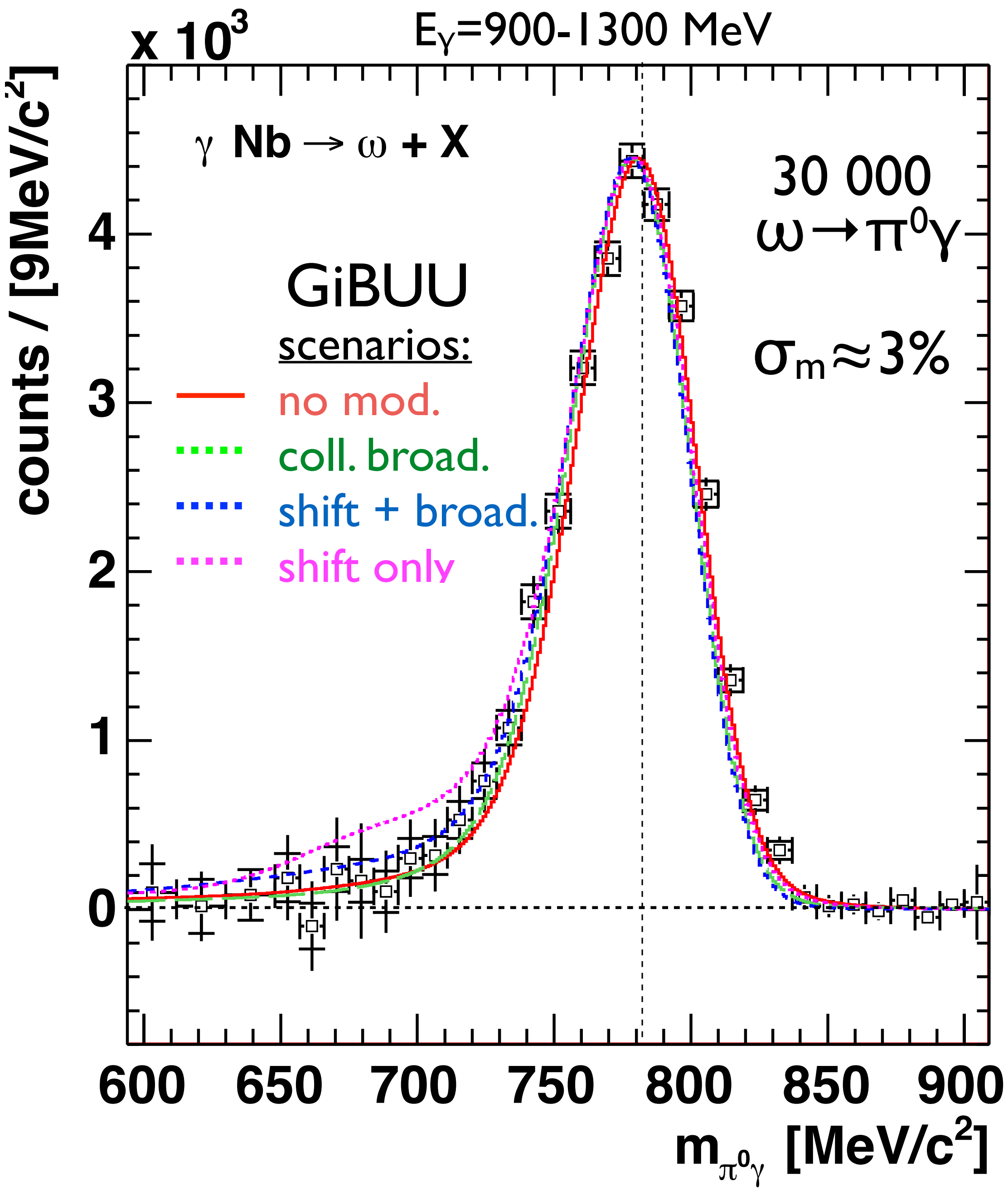
BACKUP

ω line shape from $\omega \rightarrow \pi^0\gamma$ in photo-nuclear reaction

M.Thiel et al., EPJA 49 (2013) 132

CB/TAPS@MAMI

γ Nb$\rightarrow\omega$+X $\rightarrow\pi^0\gamma$+X at E_γ = 0.9-1.3 GeV



different in-medium modification scenarios almost indistinguishable

ω meson

- $c\tau$ = 22 fm/c
  for $<p_\omega>\approx$600 MeV/c: $\beta\gamma c\tau$ = 17 fm
  fraction of ω decays in Nb: $\approx$36%
- only mass shifts $\gg \sigma_m/m$=3% observable
- ω signal smeared out due to in-medium broadening ($\Gamma\approx$140 MeV)
- due to π^0 absorption (π^0-FSI) $\omega\rightarrow\pi^0\gamma$ decays in the center of the nucleus are suppressed

η' meson

- $c\tau$ = 1000 fm/c
  for $<p_{\eta'}>\approx$1000 MeV/c: $\beta\gamma c\tau$ = 1000 fm
  fraction of η' decays in Nb: $\approx$ 0.5%

line shape analysis very difficult or even impossible