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

Mariana Nanova

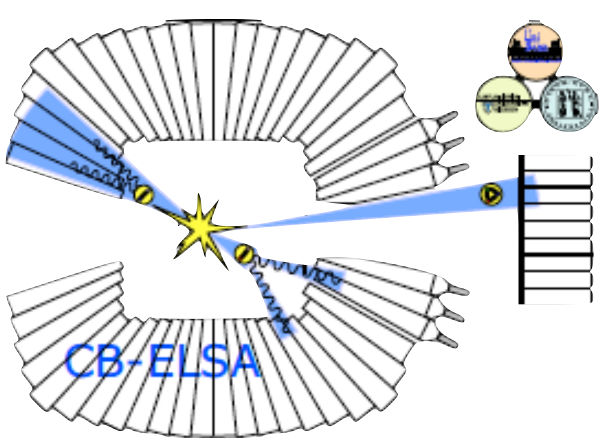
for the CBELSA/TAPS Collaboration

II. Physikalisches Institut

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Outline:

- motivation
- exp. approaches to study the in-medium properties of mesons
- experimental results on the real and imaginary part of the ω- and η'-nucleus optical potential
- summary & outlook



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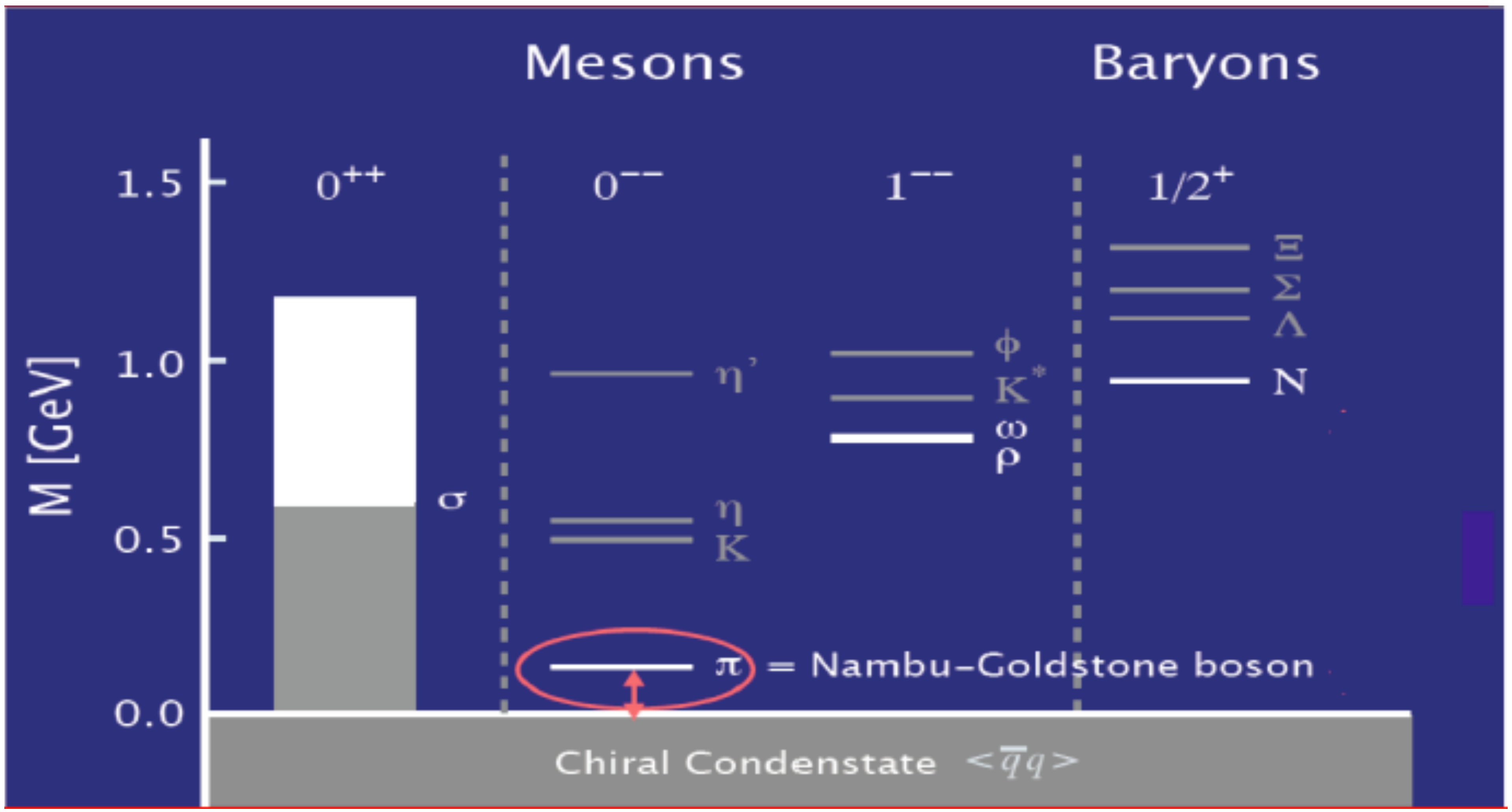
*funded by the DFG within SFB/TR16

baryons and mesons

- QCD vacuum as a Bose-Einstein condensate of $\bar{q}q$
- all states (particles) are created out of the vacuum state ("excitations of the QCD-vacuum")
- the ground-state structure influences the particle properties



if the QCD ground state changes in a medium

⇒ properties of hadrons ("excited states") are also expected to change

hadrons in the medium

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

pioneering papers:

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

"Brown-Rho Scaling"

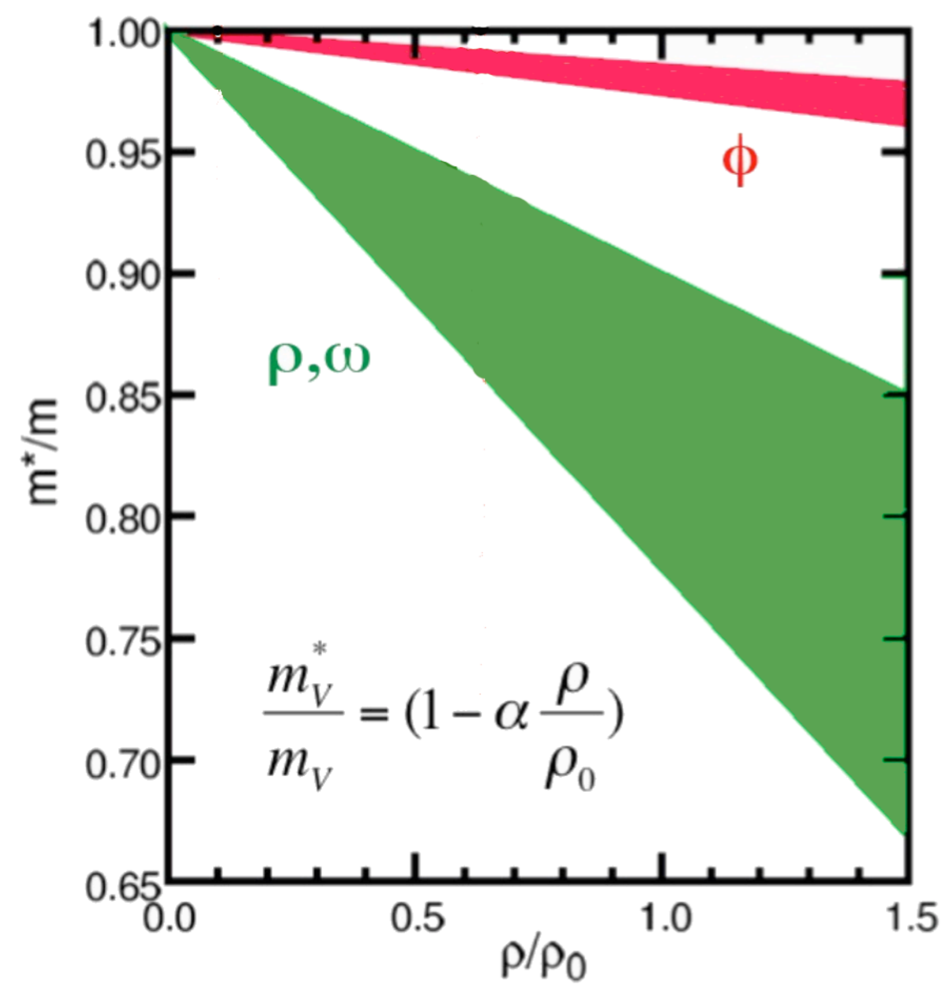
G.E.Brown and M. Rho,
PRL 66 (1991) 2720

$$\frac{m^\star}{m} \approx \frac{<\bar{q}q>^\star}{<\bar{q}q>_0} \approx 0.8(\rho \approx \rho_0)$$

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

$$\frac{m_V^\star}{m_V} = (1 - \alpha\frac{\rho}{\rho_0}); \alpha \approx 0.18$$

QCD sum rule approach:
drop of ρ, ω mass by about 15% at $\rho=\rho_0$

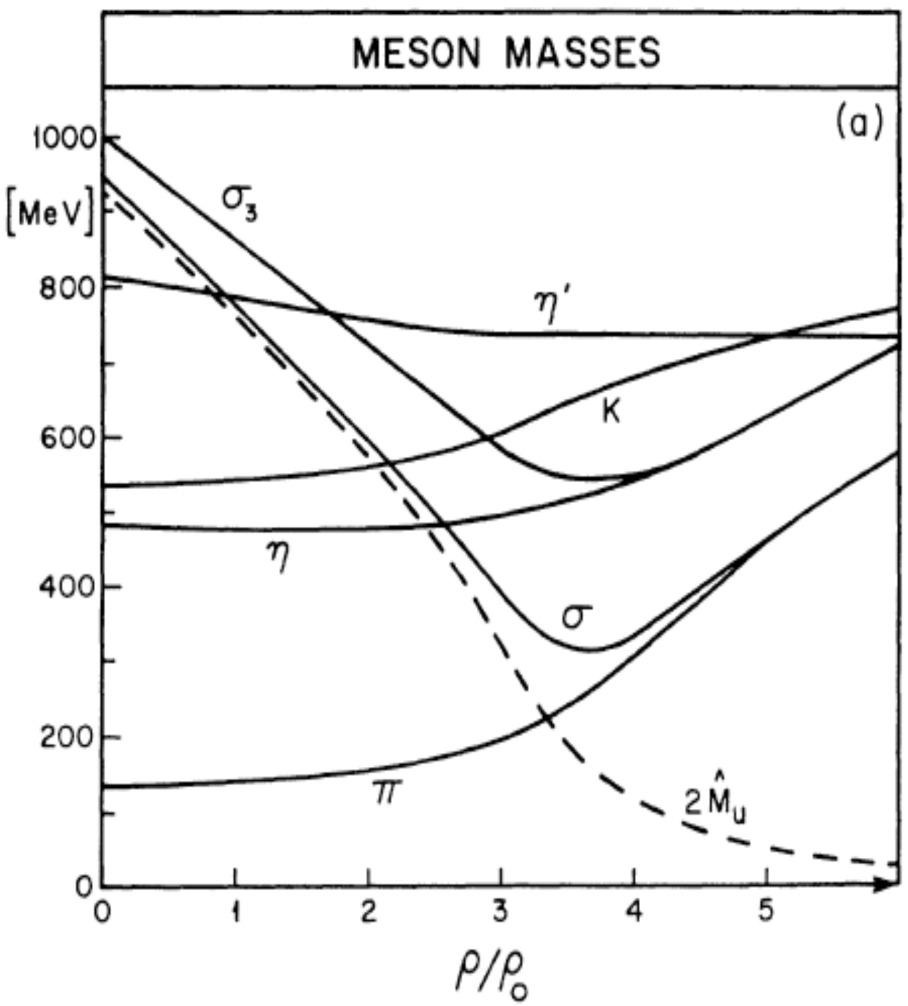


widespread theoretical and experimental activities to search for in-medium modifications of hadrons

hadronic models: predictions for η' in-medium mass

<u>NJL-model</u>

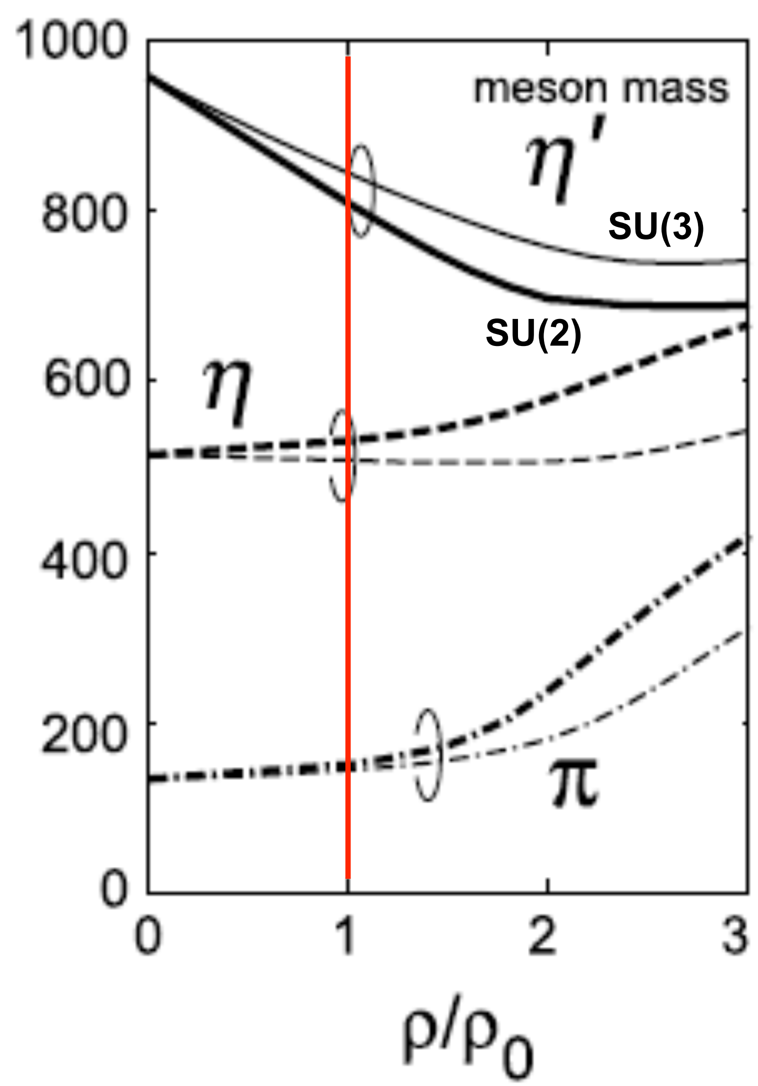
V. Bernard and U.-G. Meissner,
Phys. Rev.D 38 (1988) 1551



almost no dependence of
η' mass on density

<u>NJL-model</u>

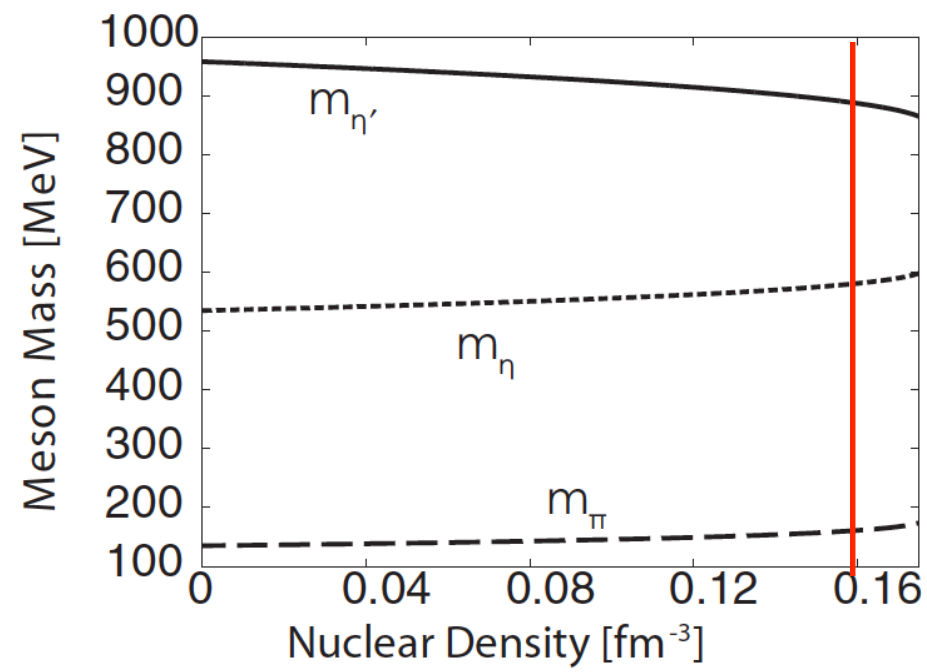
H. Nagahiro et. al,
Phys. Rev. C 74 (2006) 045203



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

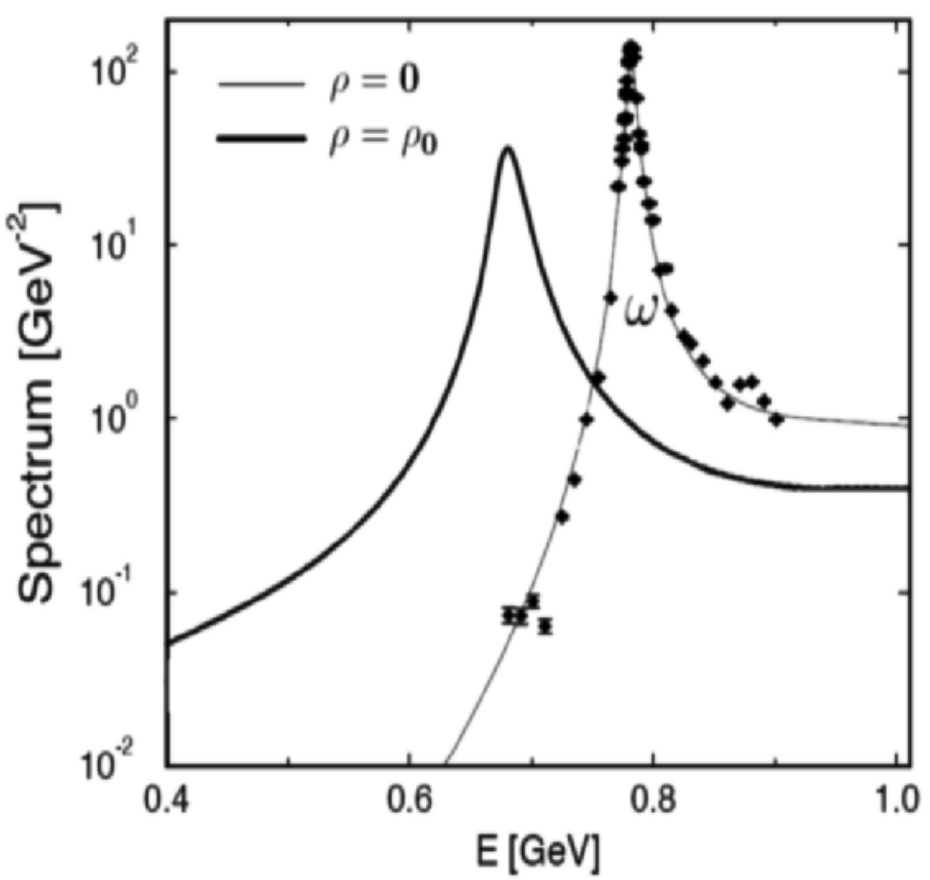
<u>QMC-model</u>

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

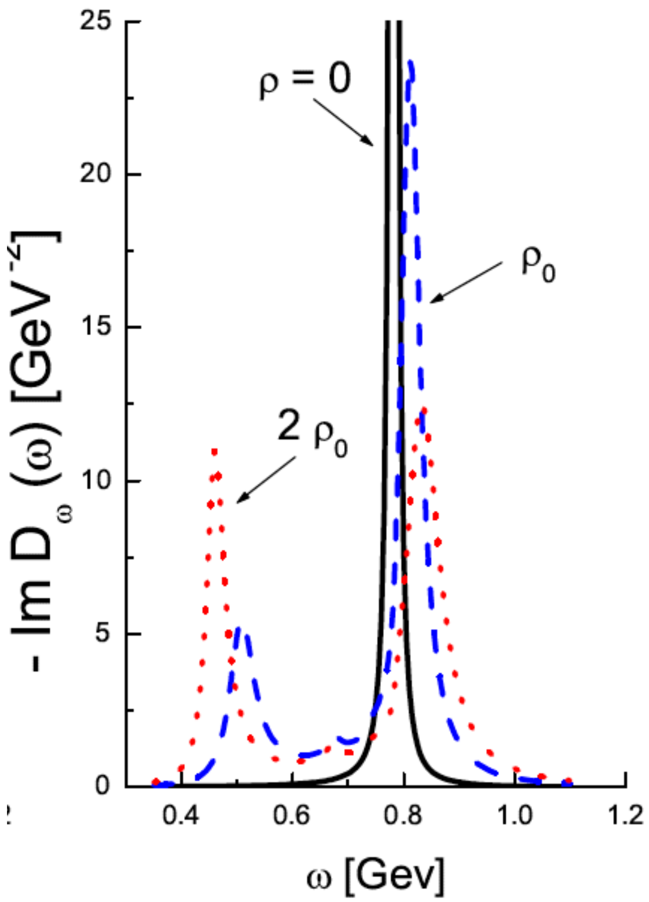


- lowering of in-medium mass
- broadening of resonance

with increasing nuclear density

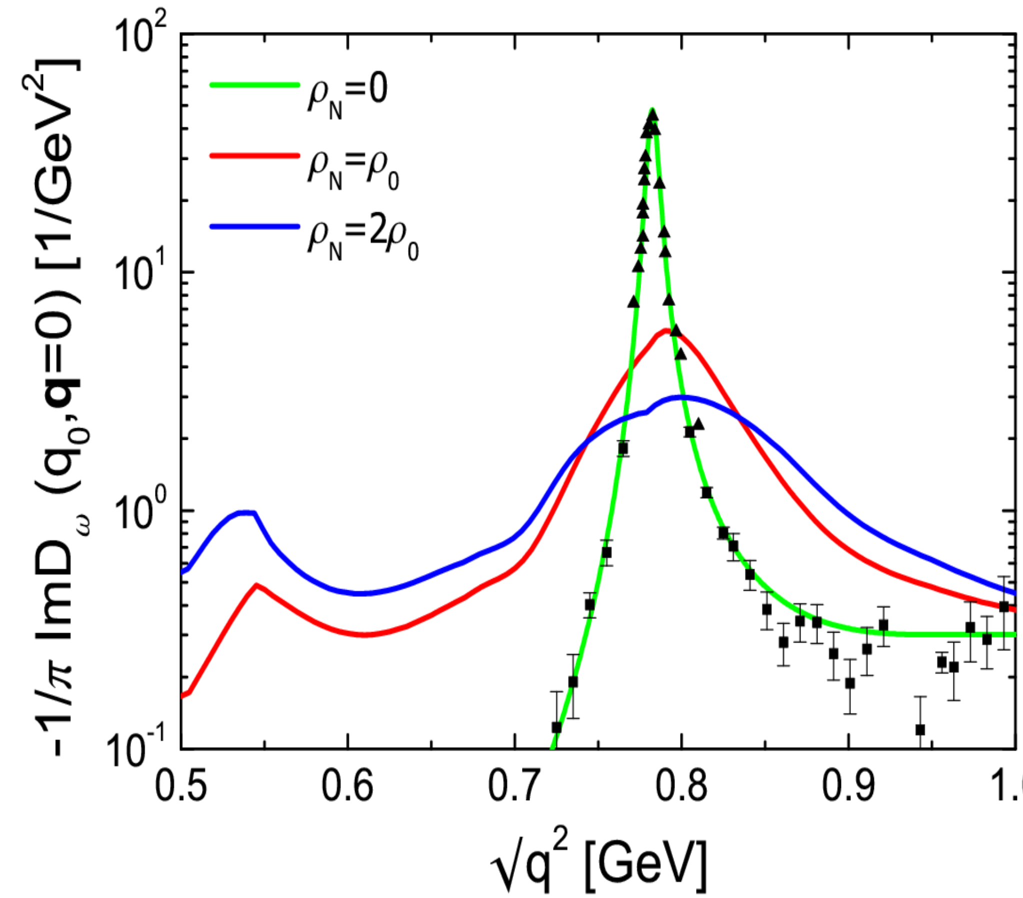
Re(U) ≠0; Im(U) ≠0

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



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

P. Mühlich et al., NPA 780 (2006) 187



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

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

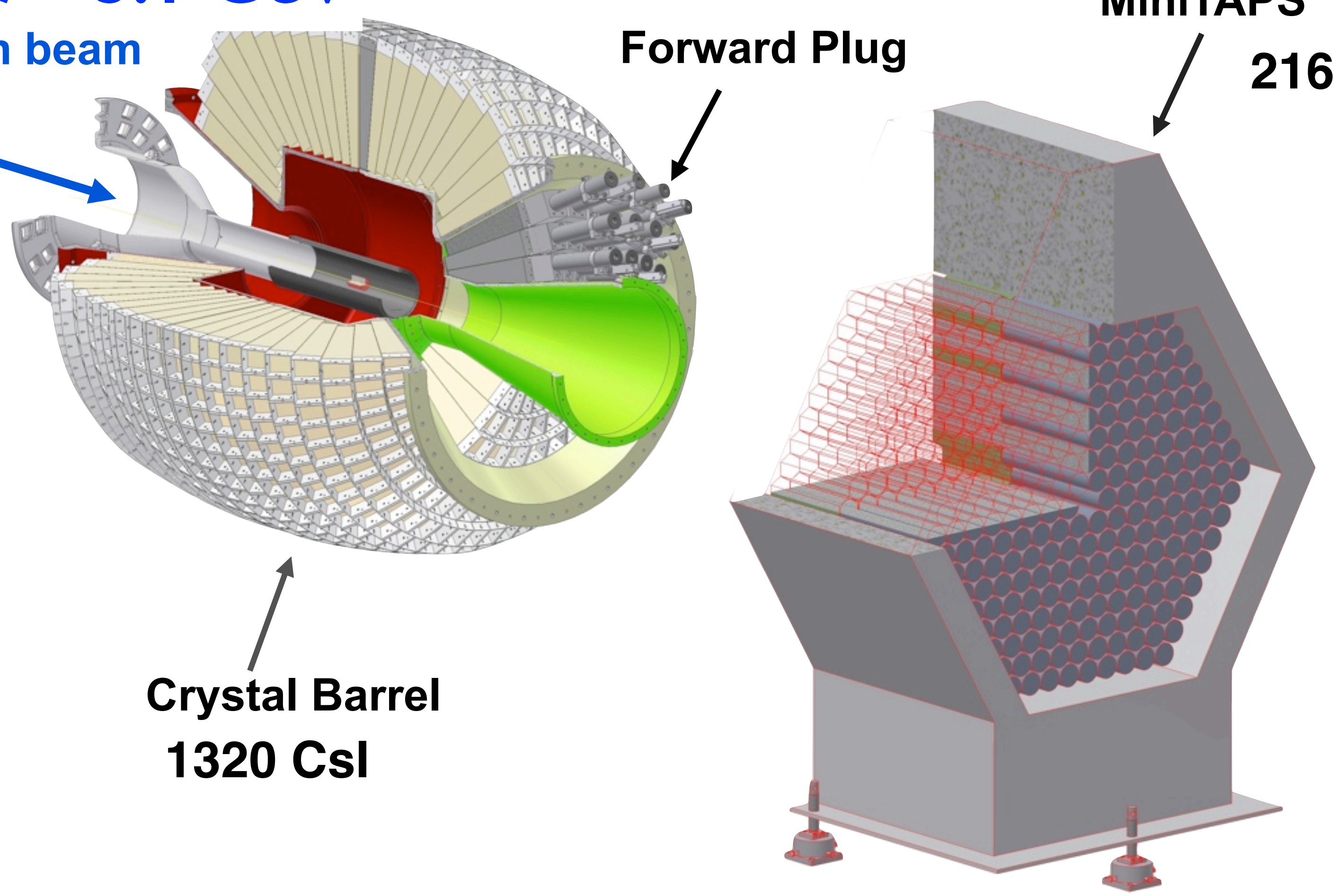
- transparency ratio measurement

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

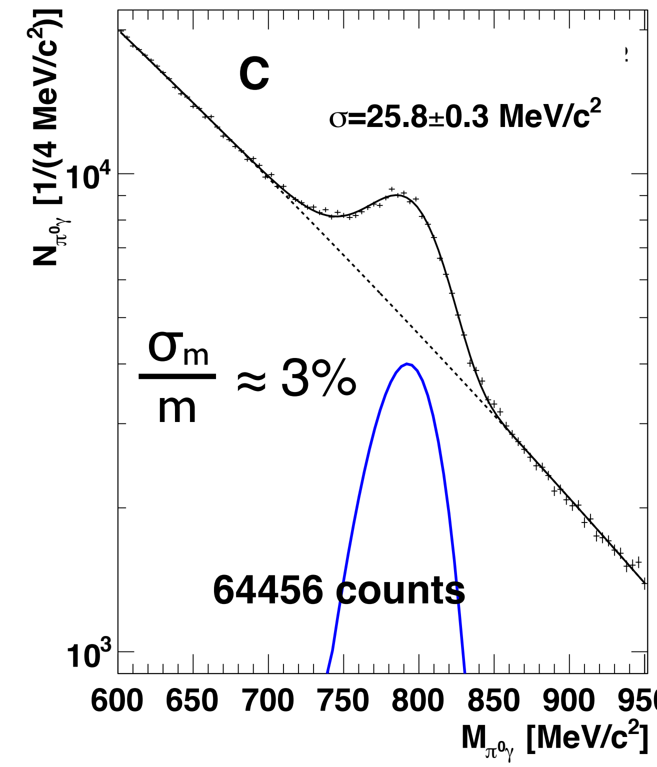
D. Cabrera et al., NPA 733 (2004)130

CBELSA/TAPS experiment

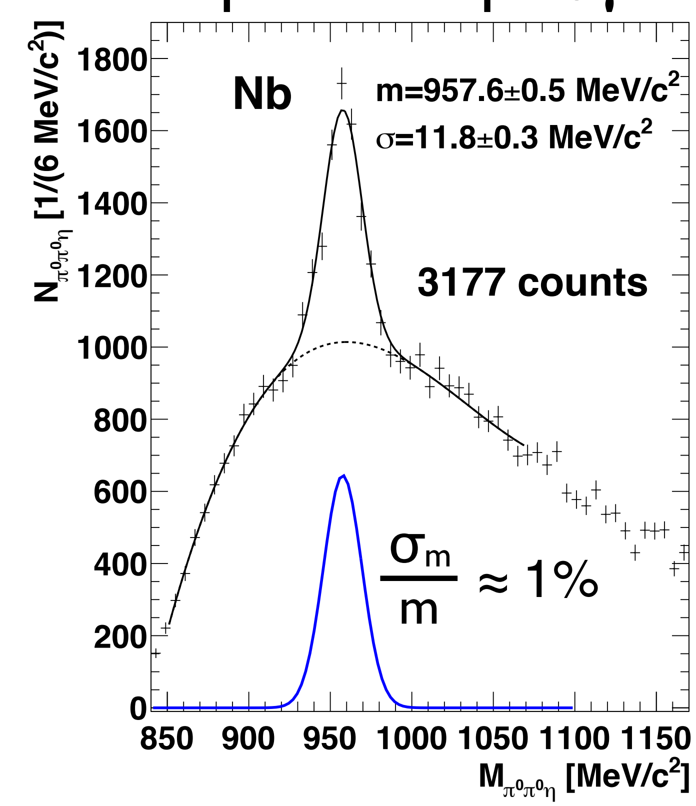
E_γ=0.7 - 3.1 GeV
photon beam



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



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



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 $\omega \to \pi^0\gamma$

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

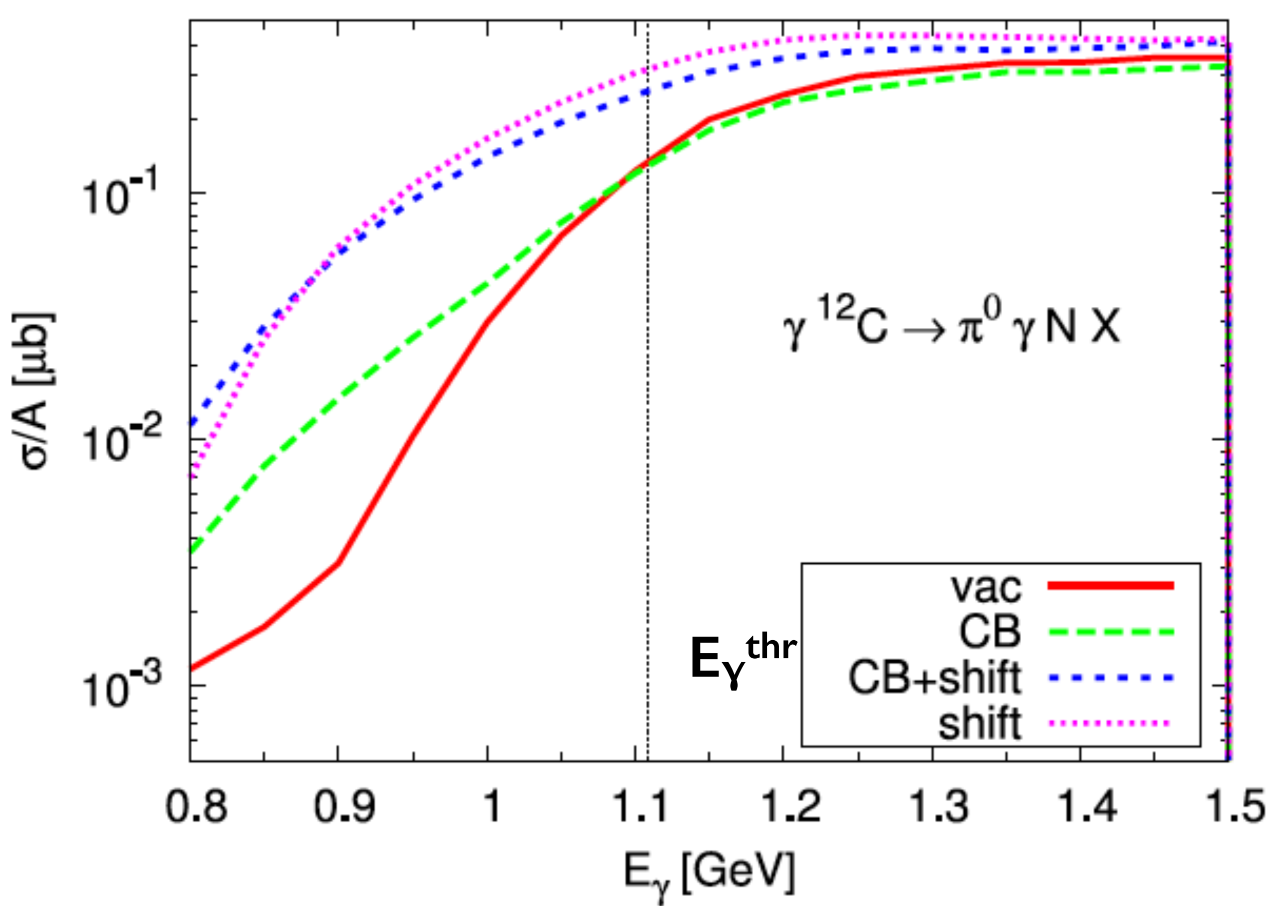
⇨ cross section enhancement

- momentum distribution of the meson:

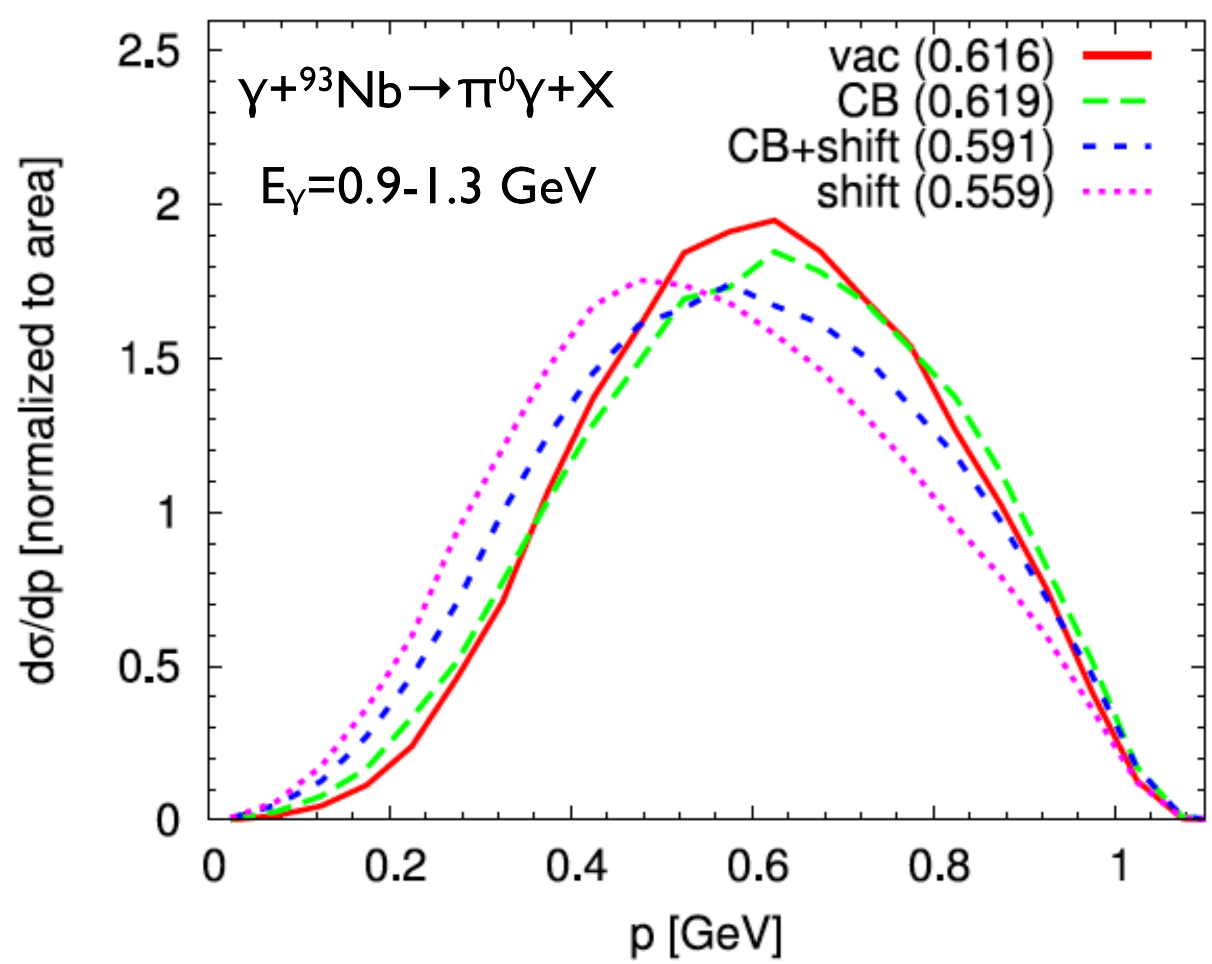
in case of dropping mass - when leaving the nucleus hadron has to become on-shell; mass generated at the expense of kinetic energy

⇨ downward shift of momentum distribution

$\pi^0\gamma$ excitation function



$\pi^0\gamma$ momentum distribution

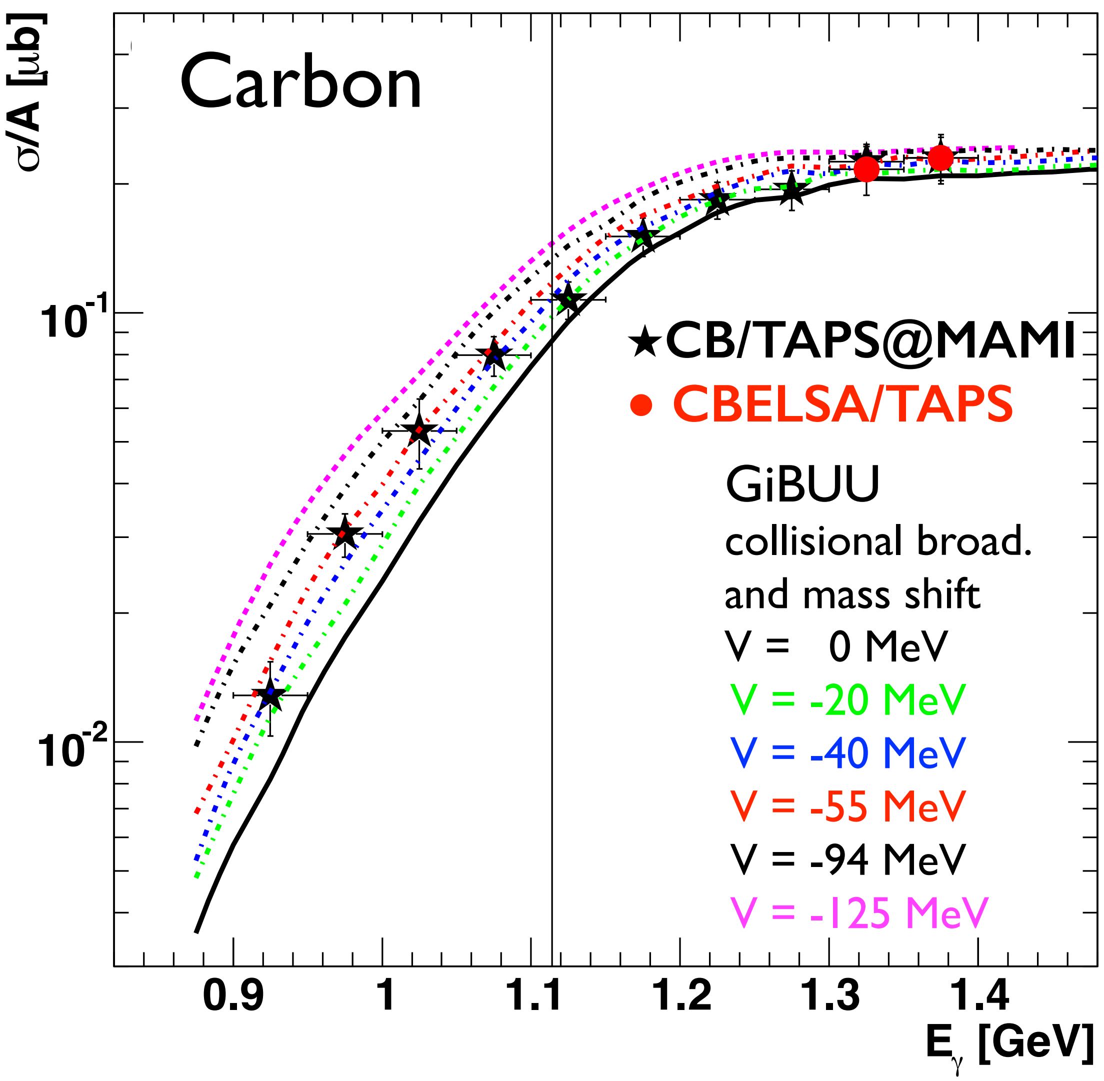


excitation function for ω photoproduction off C comparison with GiBUU calculation

CB/TAPS @ MAMI

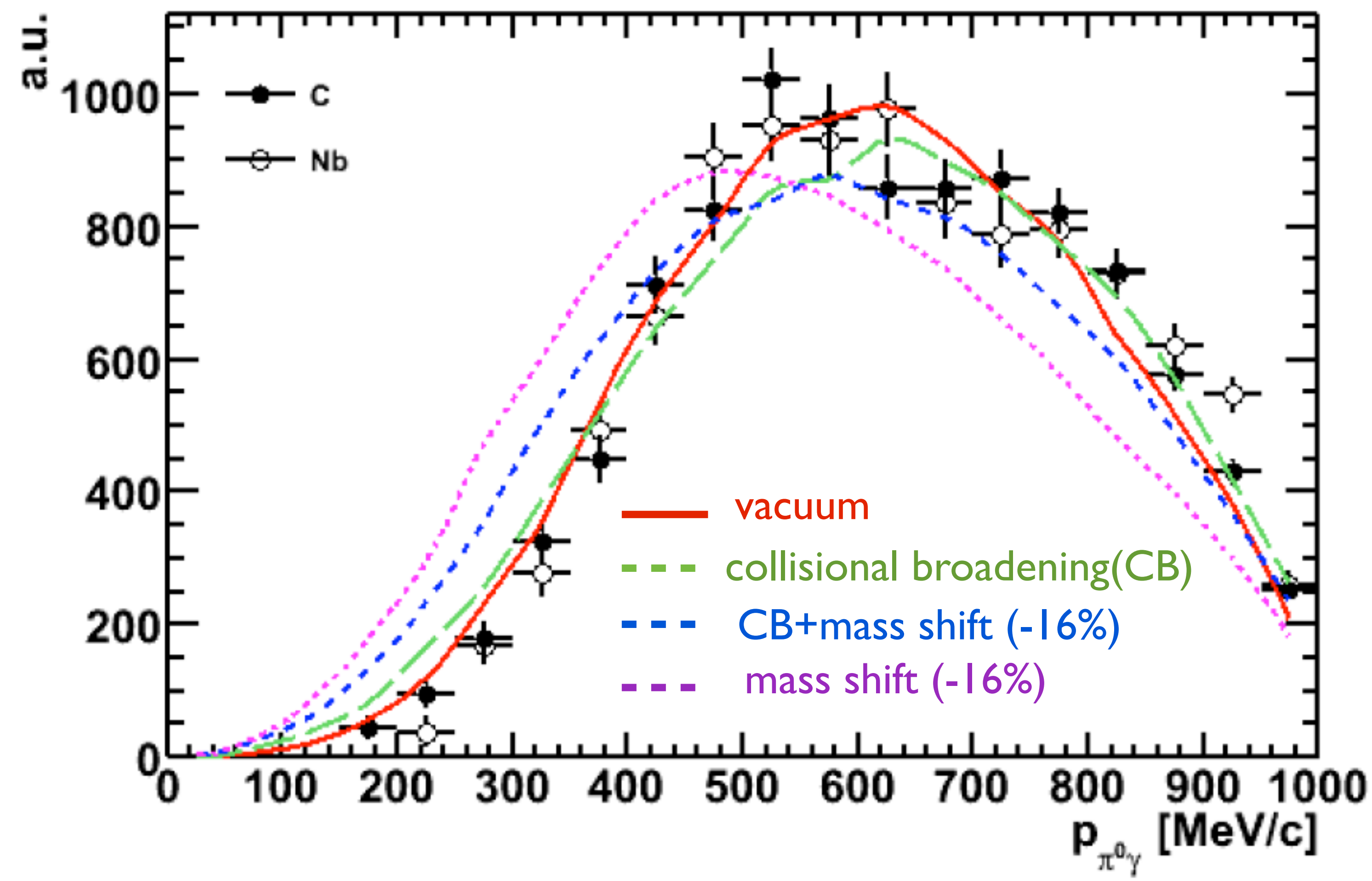
V. Metag et al., PPNP, 67 (2012) 530

excitation function



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

momentum distribution



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

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

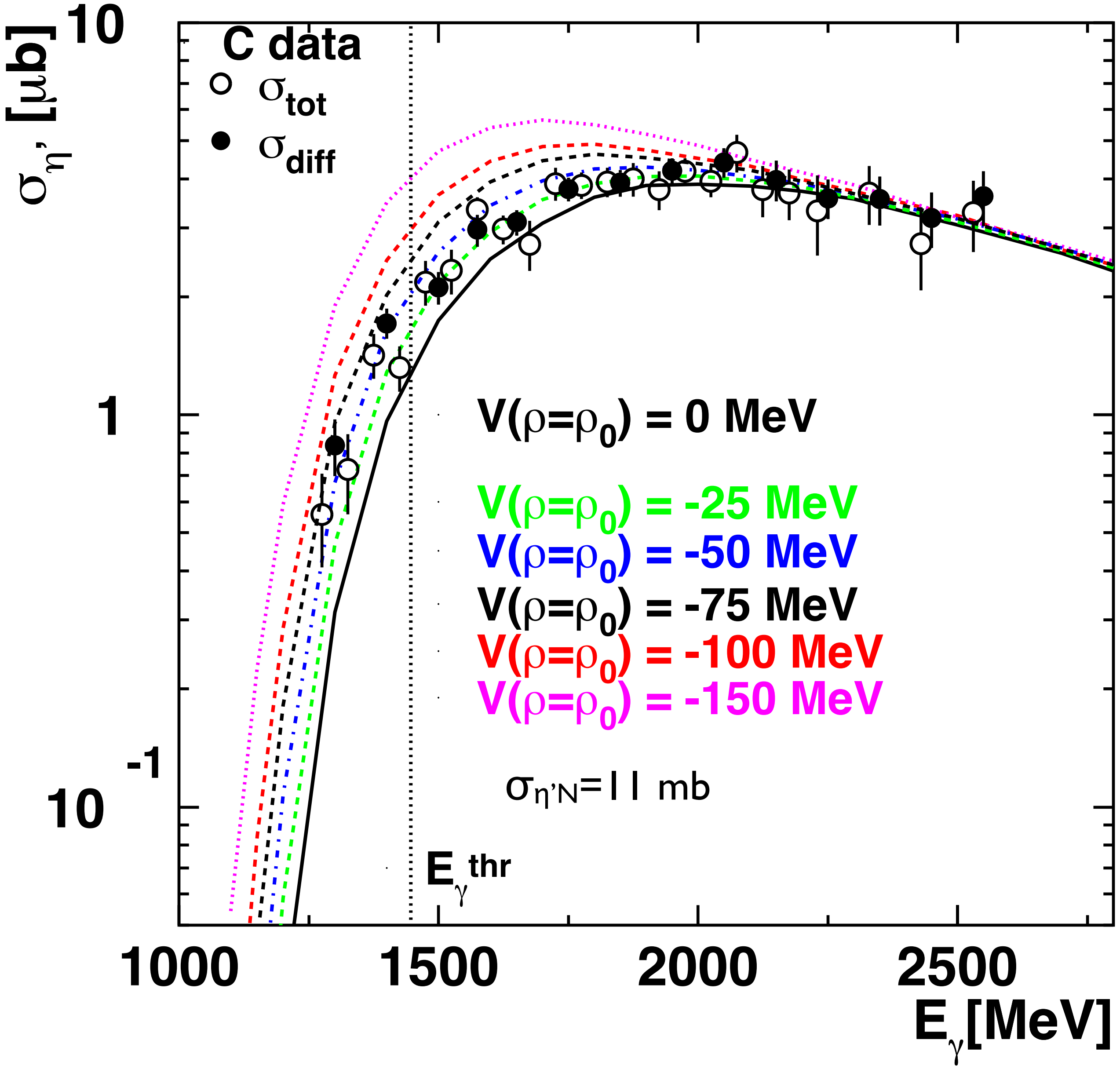
excitation function and momentum distribution for η' photoproduction off C

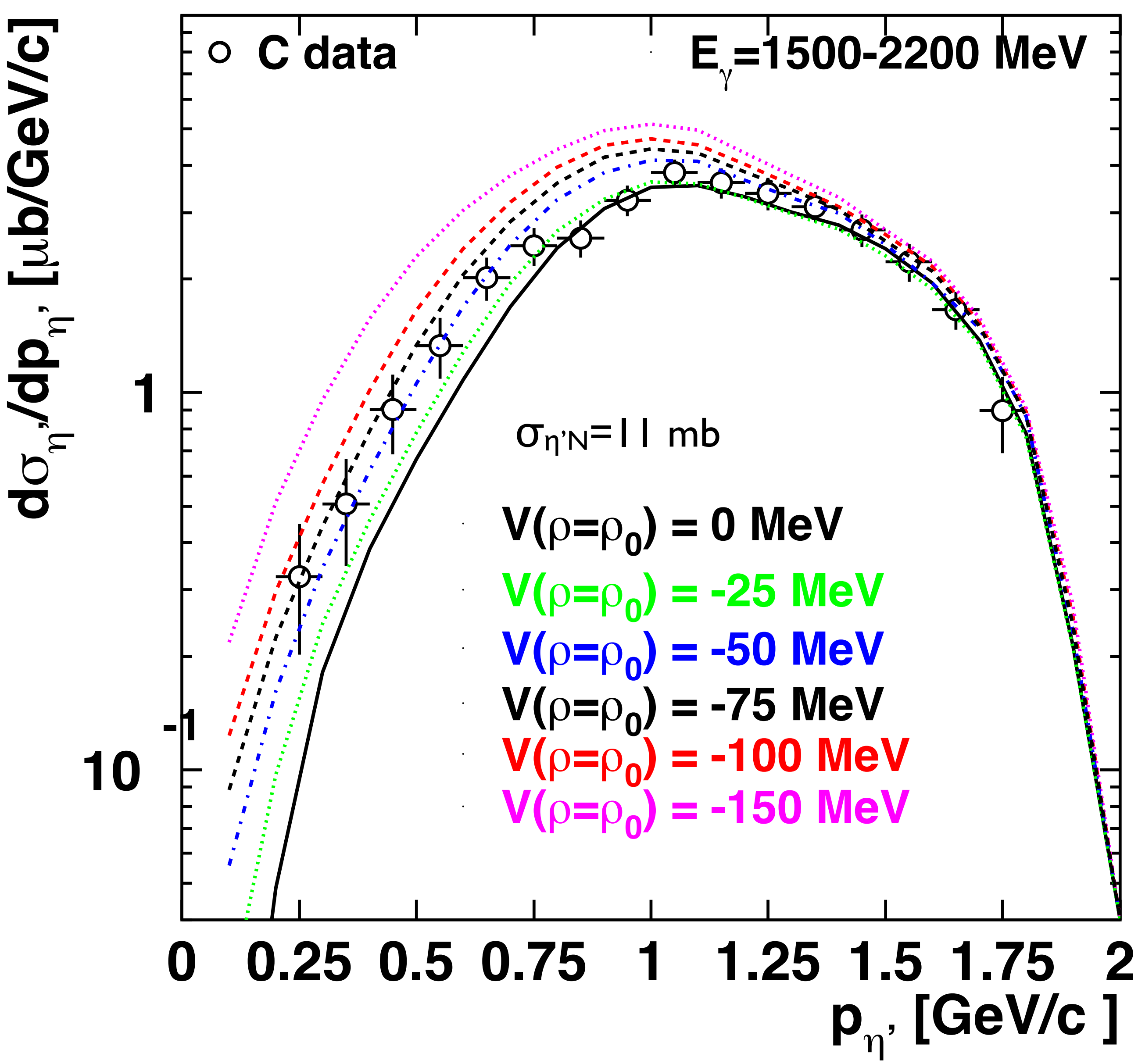
CBELSA/TAPS @ ELSA

$\gamma\, C \rightarrow \eta' X$

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

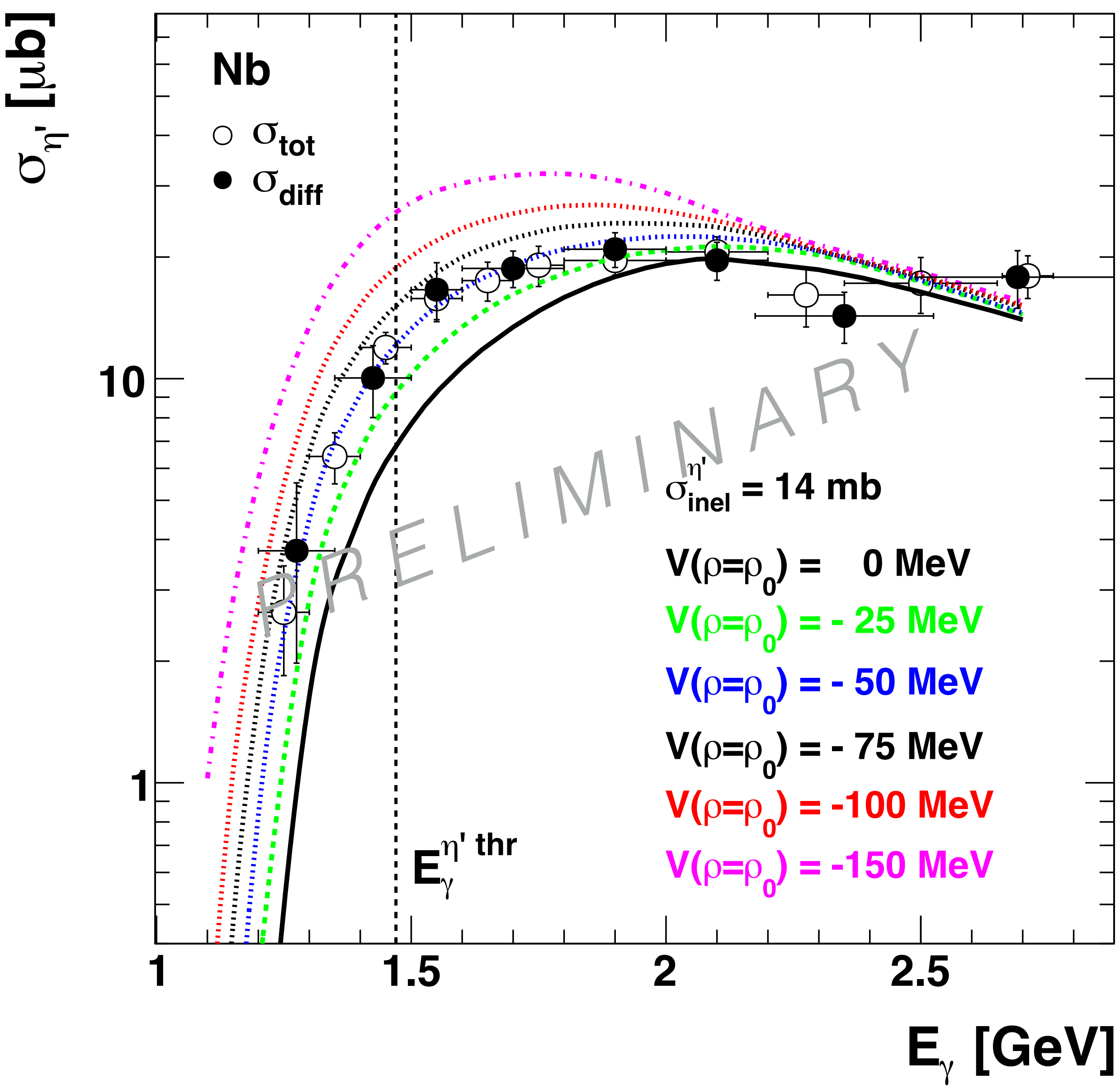
$V_{\eta'}(p_{\eta'}\approx 1.1$ GeV/c$;\rho=\rho_0) = -(32\pm11)$ MeV

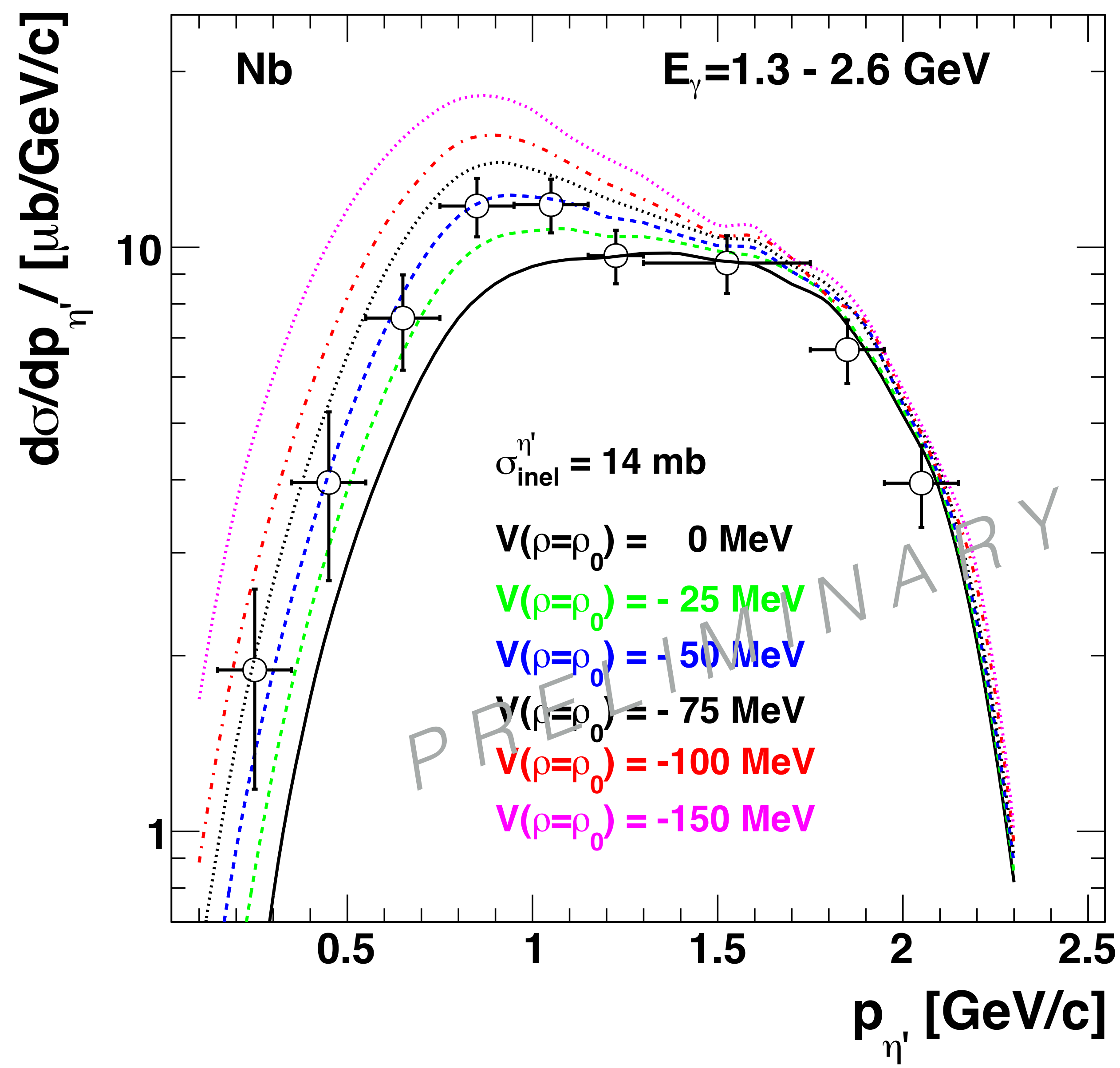
data disfavour strong mass shifts

excitation function and momentum distribution for η' photoproduction off Nb

CBELSA/TAPS @ ELSA

γ Nb $\rightarrow \eta' X$ M. Nanova et al., submitted to PRC for publication





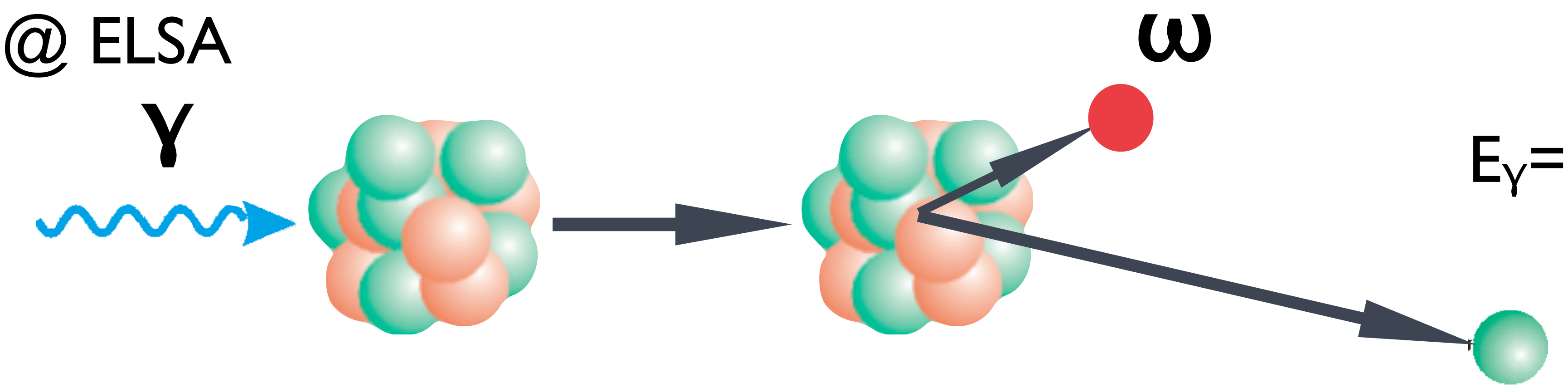
$V_{\eta'}(\rho=\rho_0) = -(46\pm15)$ MeV

$V_{\eta'}(p_{\eta'}\approx 1.14$ GeV/c$;\rho=\rho_0) = -(41\pm22)$ MeV

data disfavour strong mass shifts

real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA



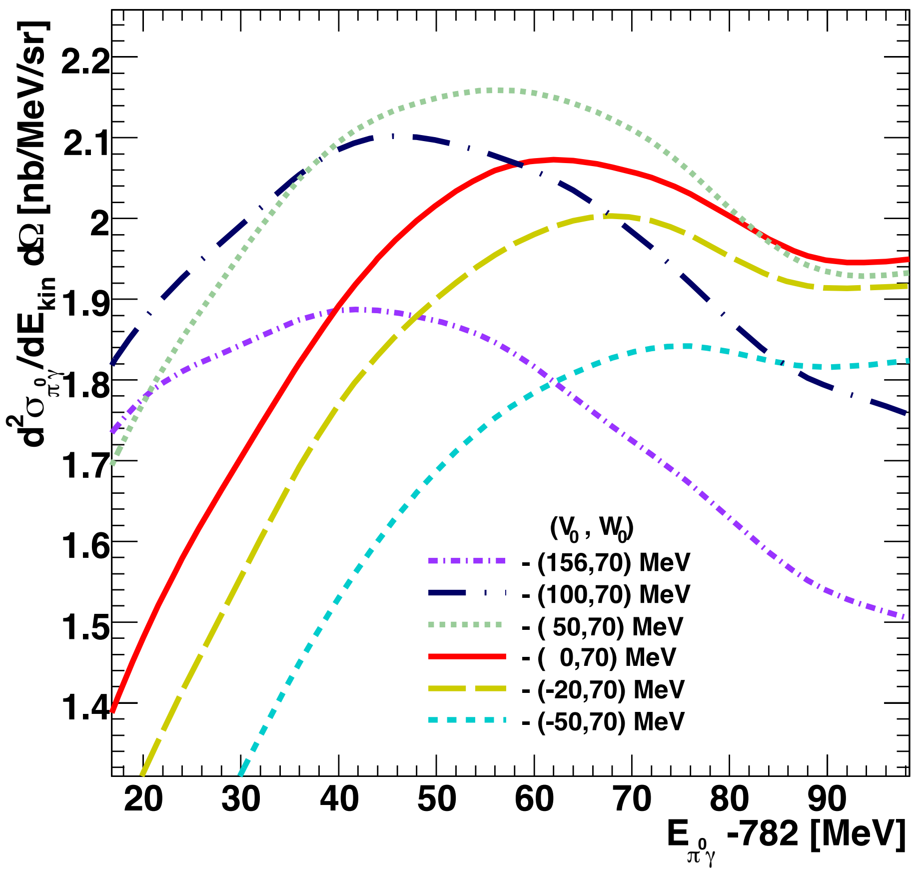
E_γ=1.25-3.1 GeV

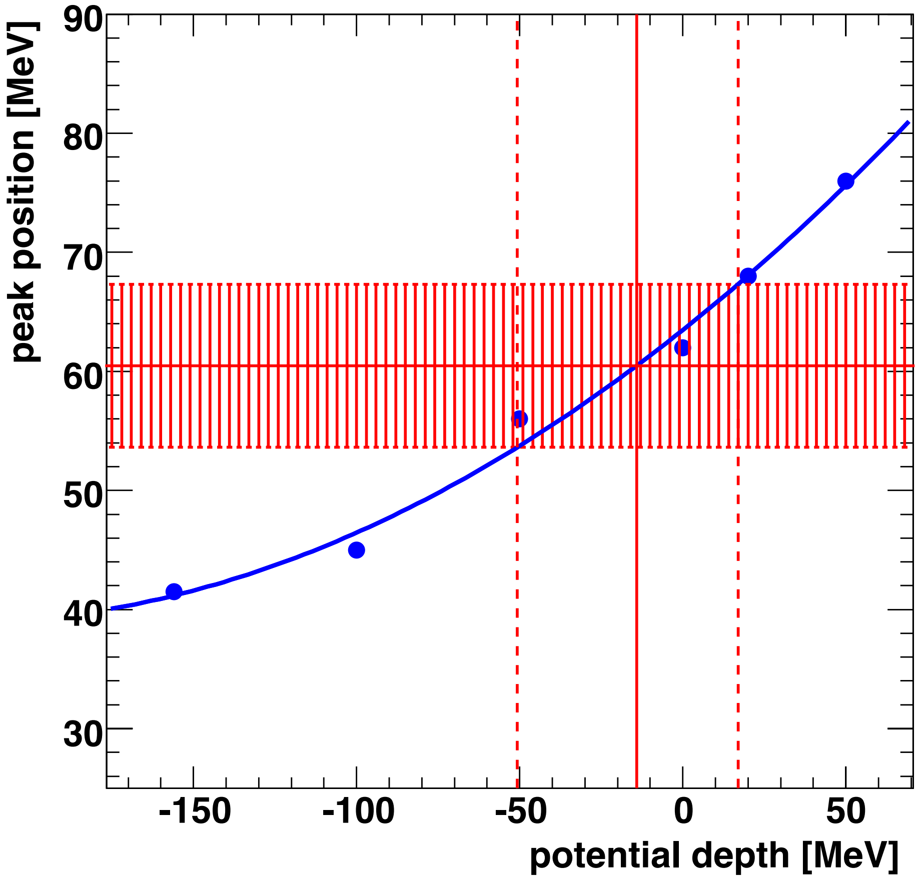
$1^0 \leq \theta_p \leq 11^0$

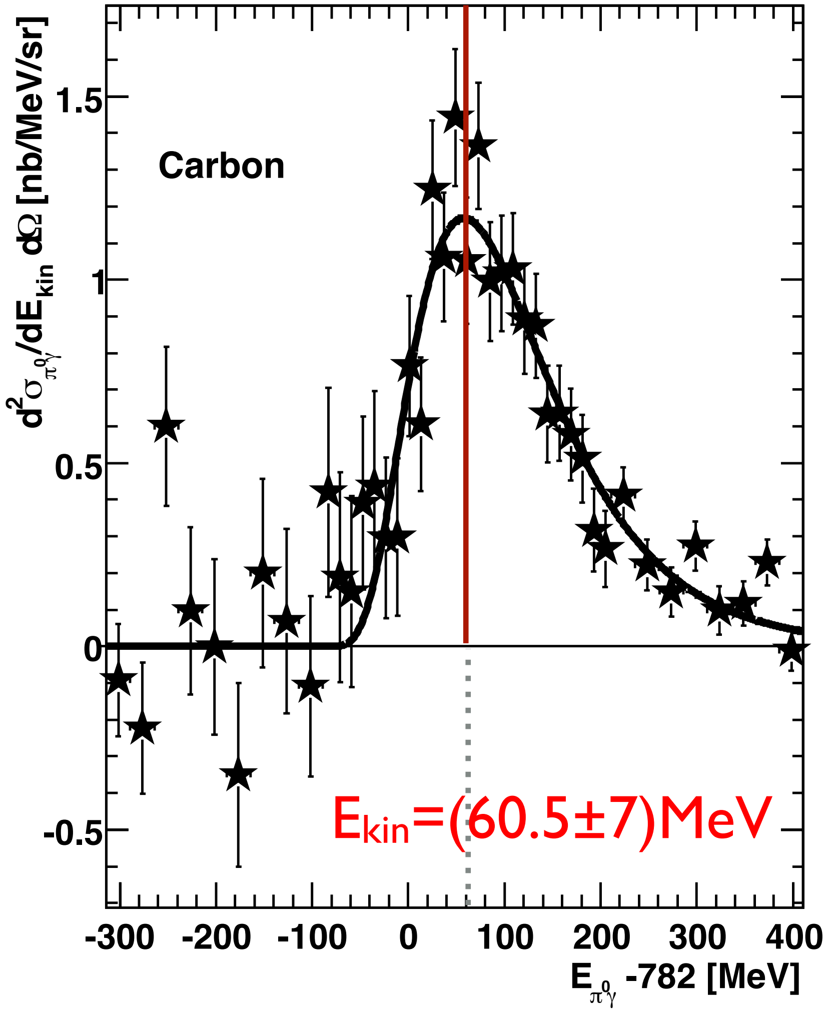
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.

S. Friedrich et al., PLB 736 (2014) 26



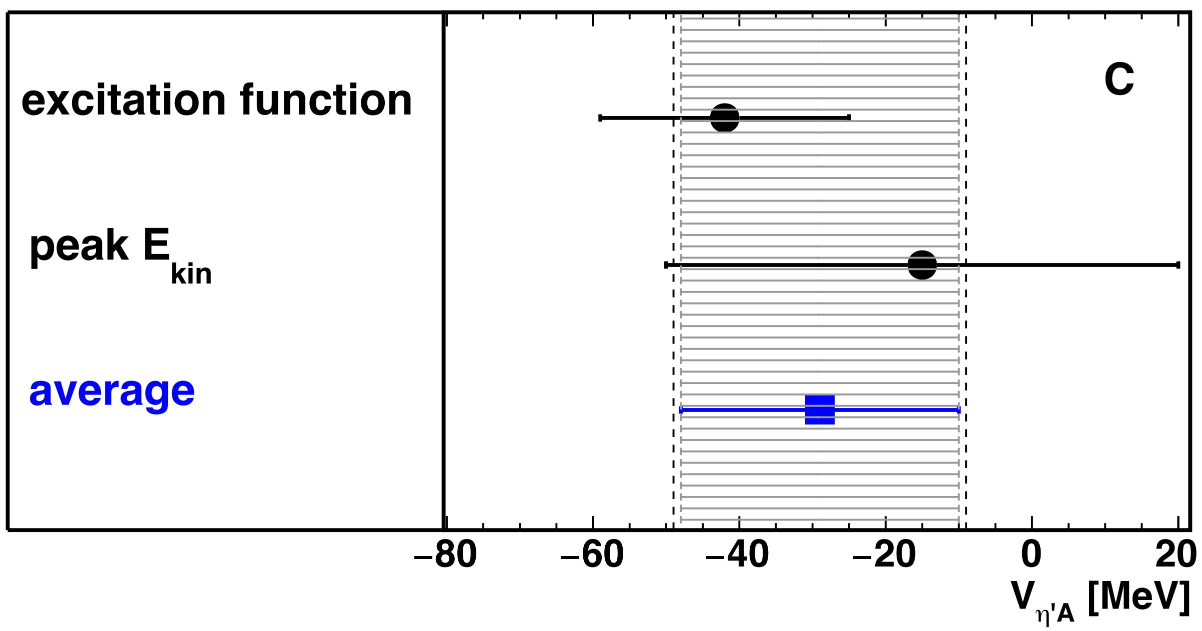




$V_\omega(p_\omega \approx 300$ MeV/c; $\rho=\rho_0)$ = −(15±35) MeV

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

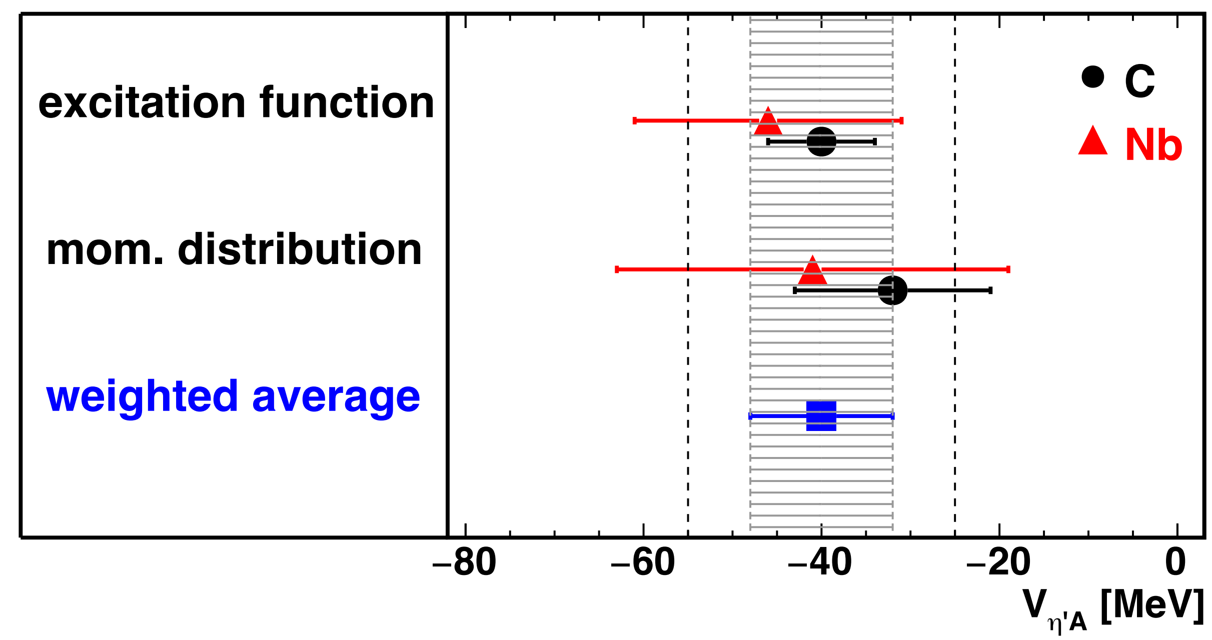
ω



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

−(29±19(stat)±20(syst)) MeV

η’



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

−(40±8(stat)±15(syst)) MeV

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

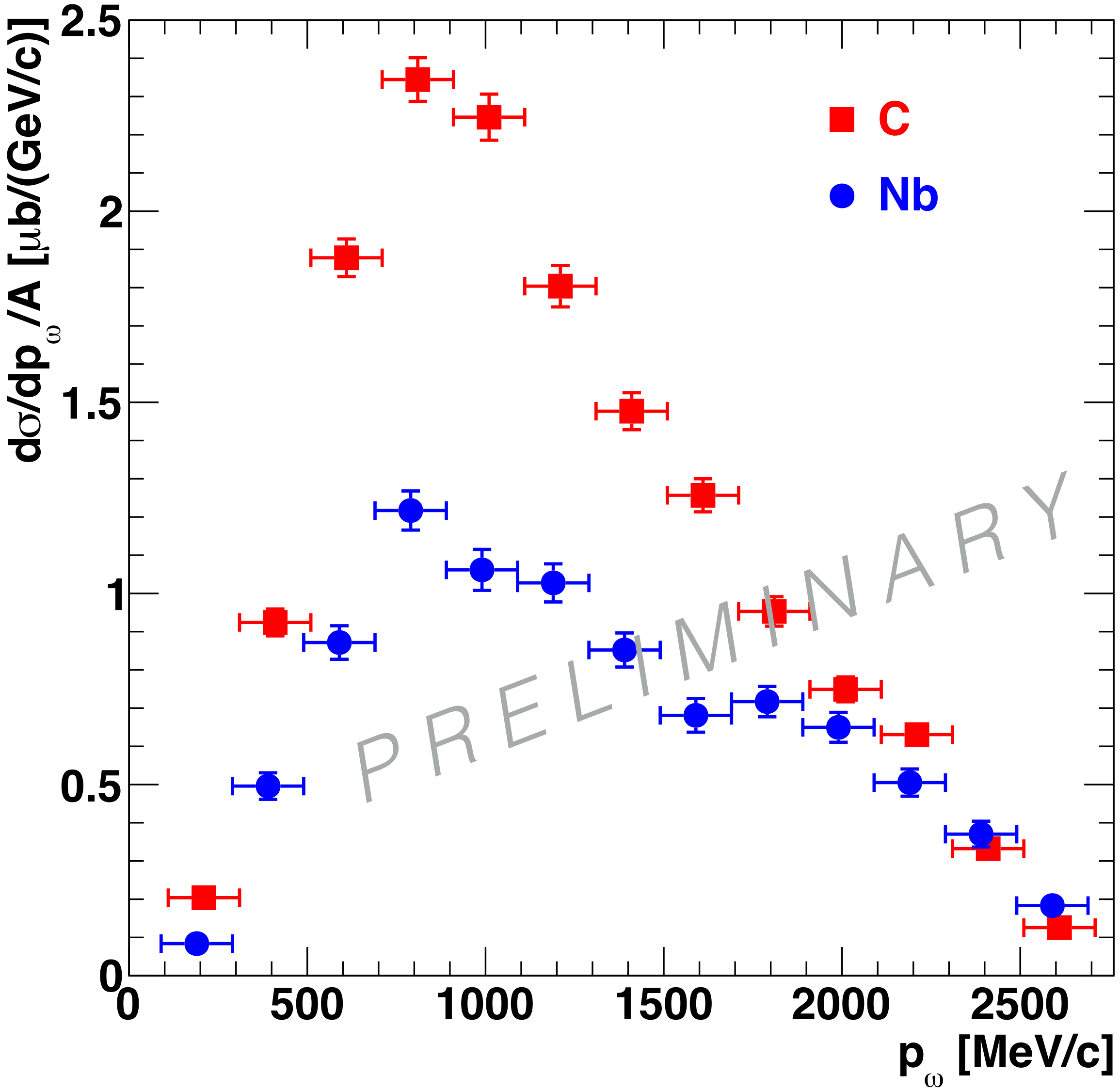
momentum differential cross section for ω, η' produced off C, Nb

ω

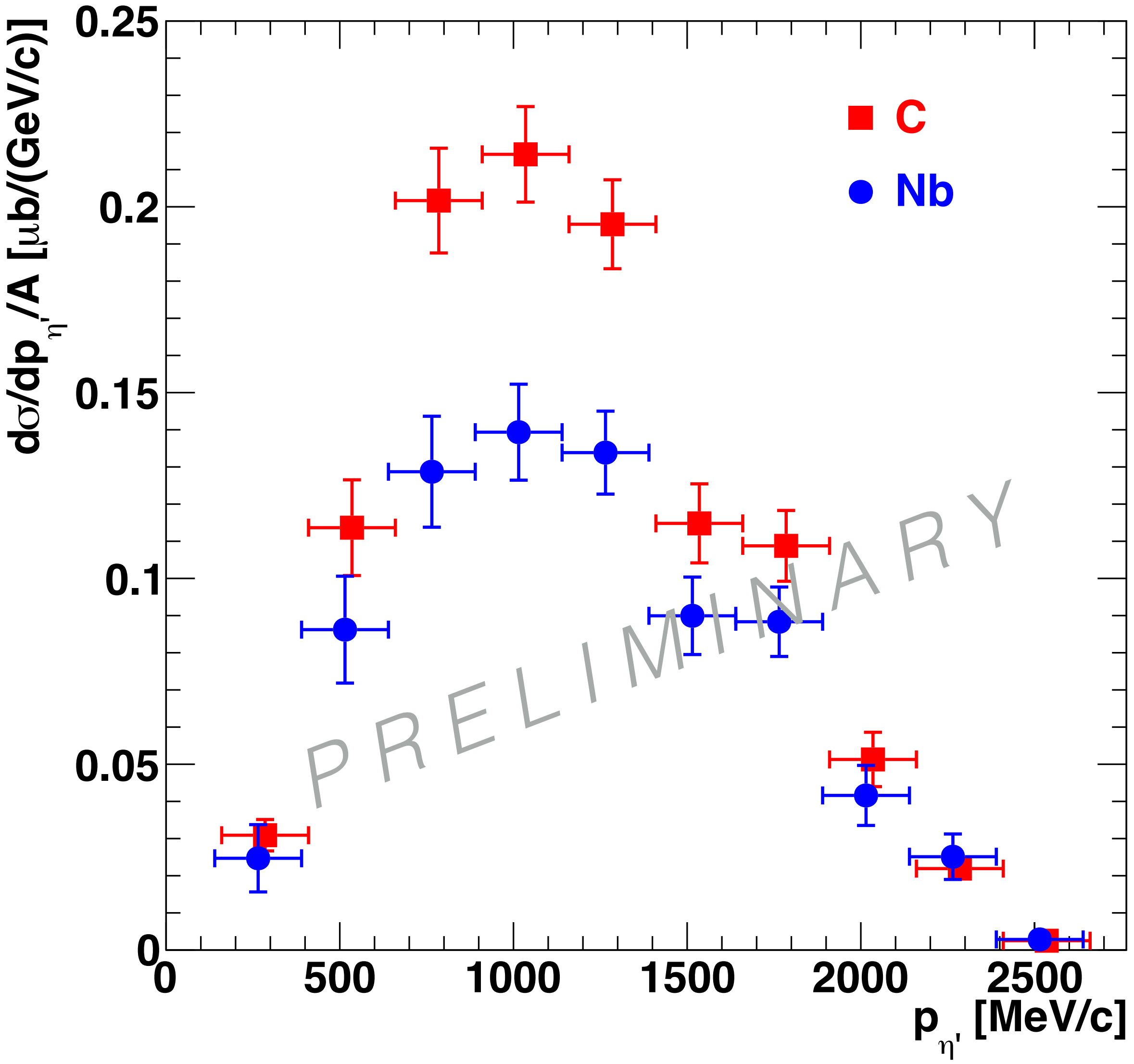
E_γ = 1.2- 2.9 GeV

η'

γ C,Nb → ωX



γ C,Nb →η'X

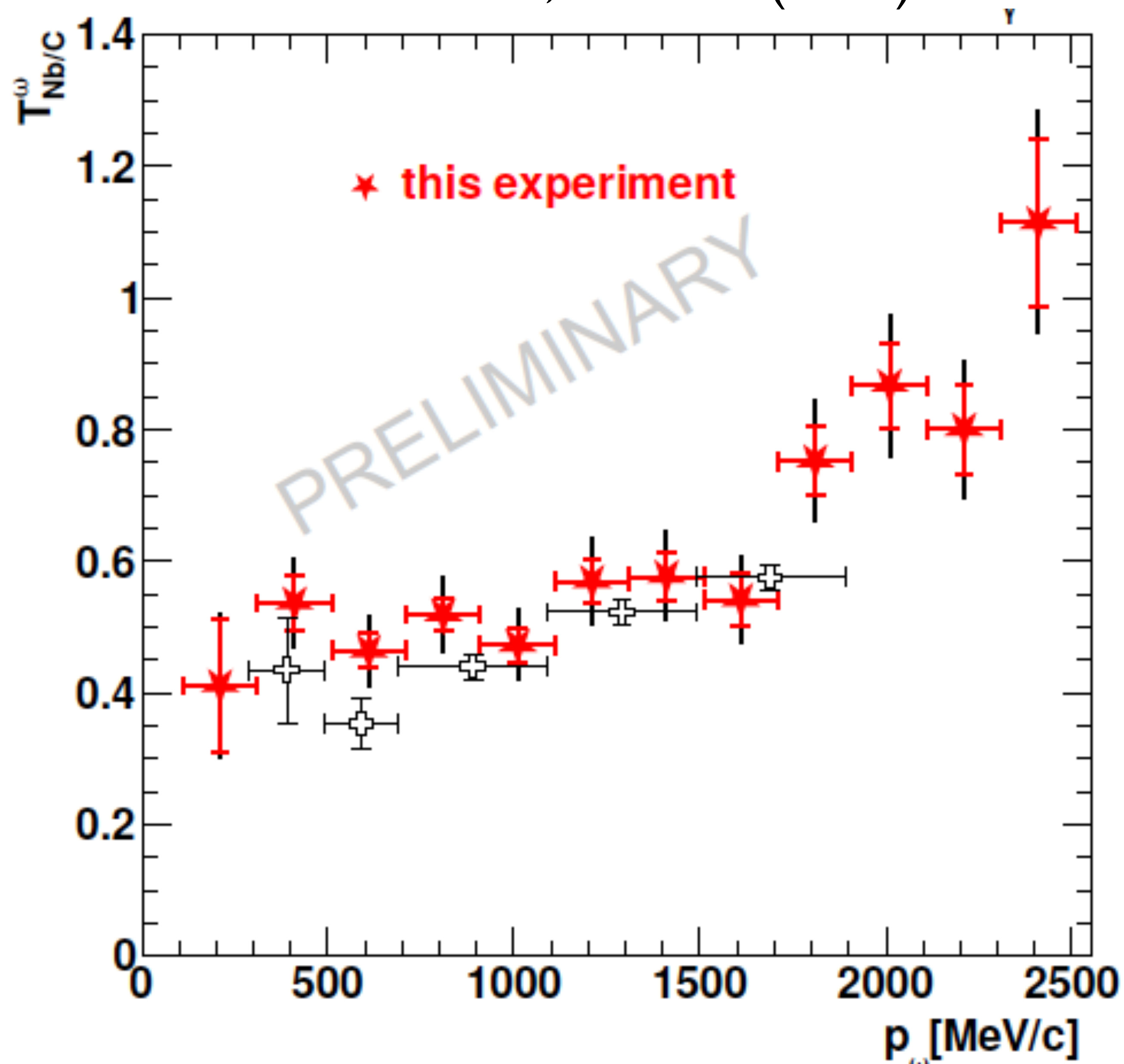


momentum differential cross sections ⇒ $T^{m}_{Nb/C}(p_m) = \dfrac{12 \cdot \sigma_{\gamma Nb \to mX}(p_m)}{93 \cdot \sigma_{\gamma C \to mX}(p_m)}$

momentum dependence of transparency ratio for ω, η'

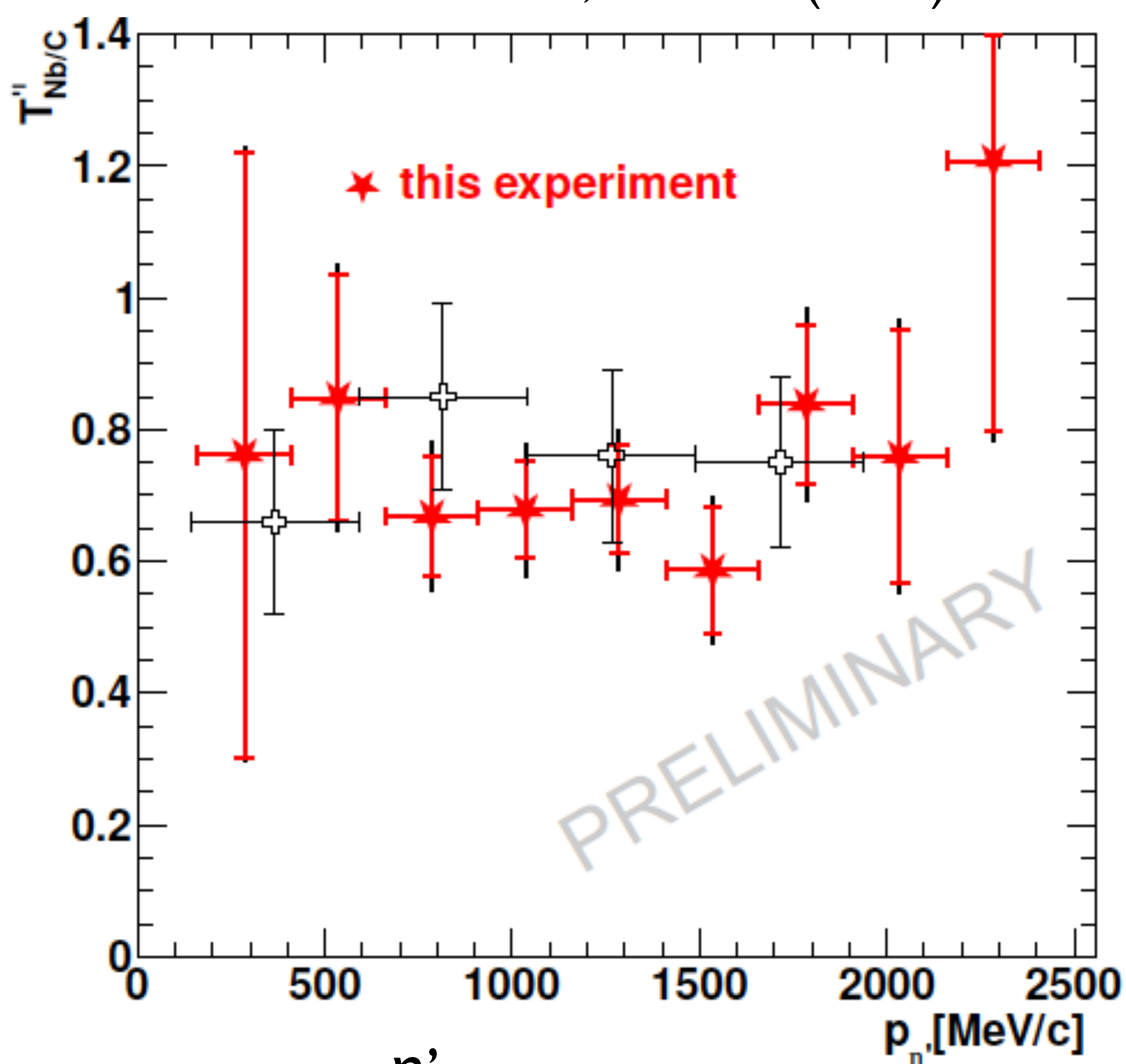
$$T^{m}_{Nb/C}(p_m) = \frac{12 \cdot \sigma_{\gamma Nb \to mX}(p_m)}{93 \cdot \sigma_{\gamma C \to mX}(p_m)}$$

ω



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

η'



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

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

imaginary part of the potential for ω, η'

ω

η'

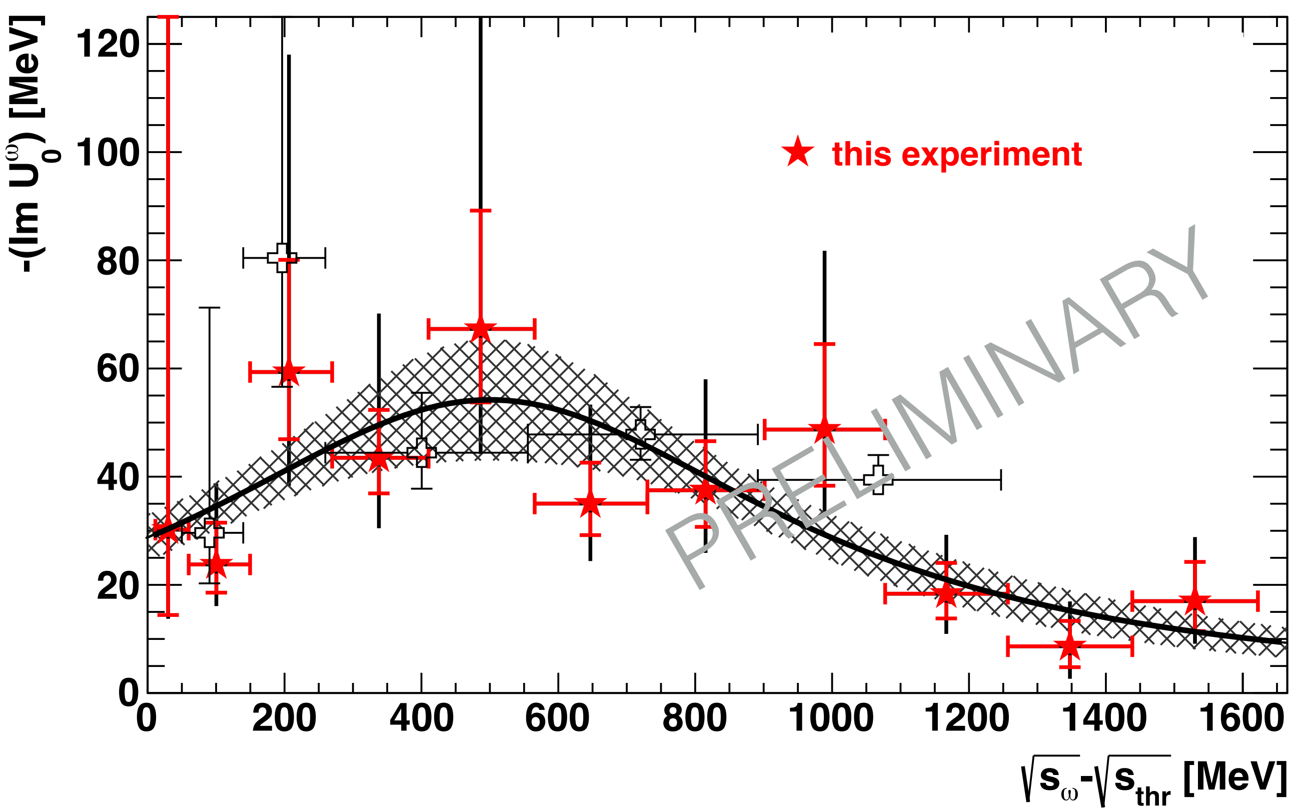
Glauber model: high energy Eikonal approximation

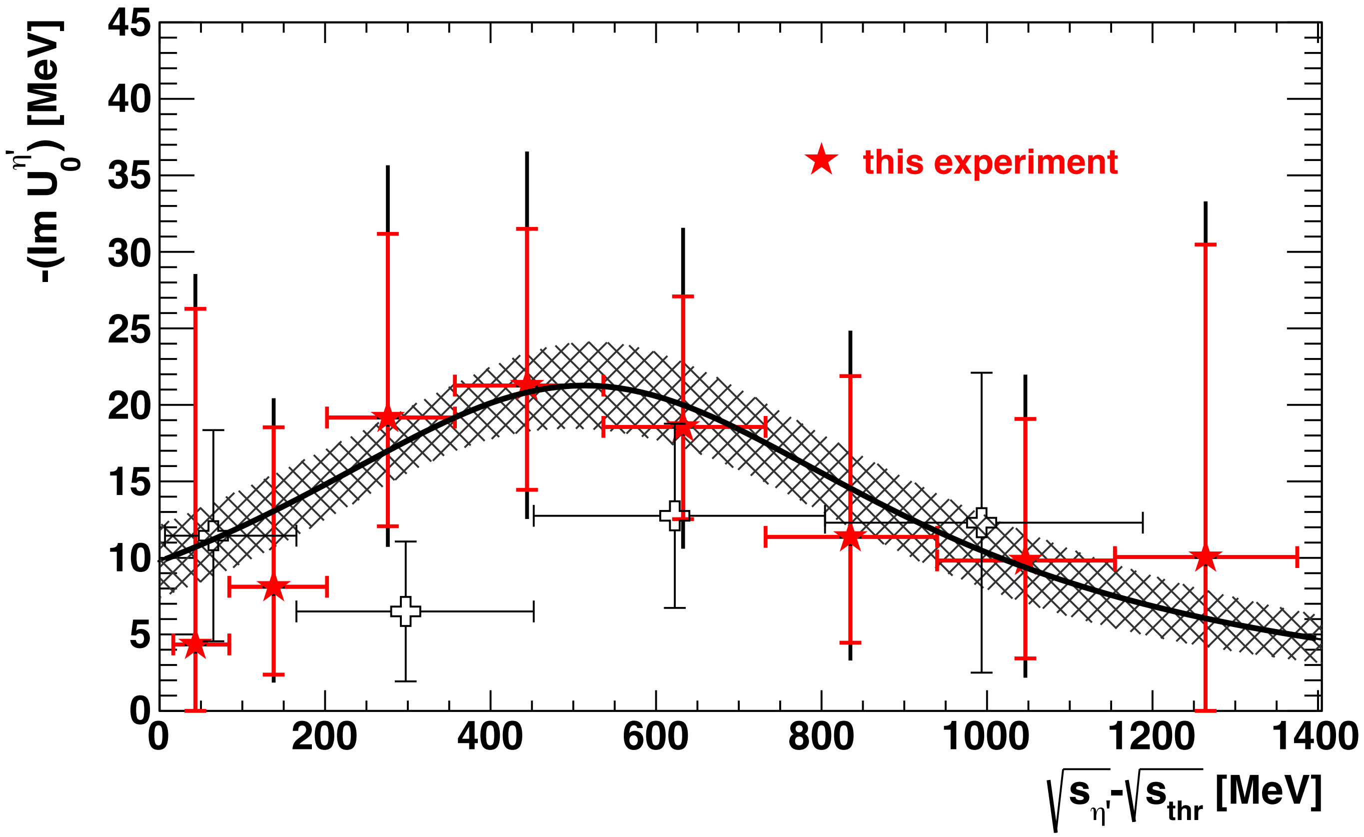
$$T^{m}_{Nb/C}\,(p_m) \Rightarrow \Gamma^{m}_{0}(\rho=\rho_0)\;(p_m) = -\,2\;\mathrm{Im}\;U^{m}_{0}(p_m)$$

S. Friedrich et al., submitted to EPJA for publication

✚ 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

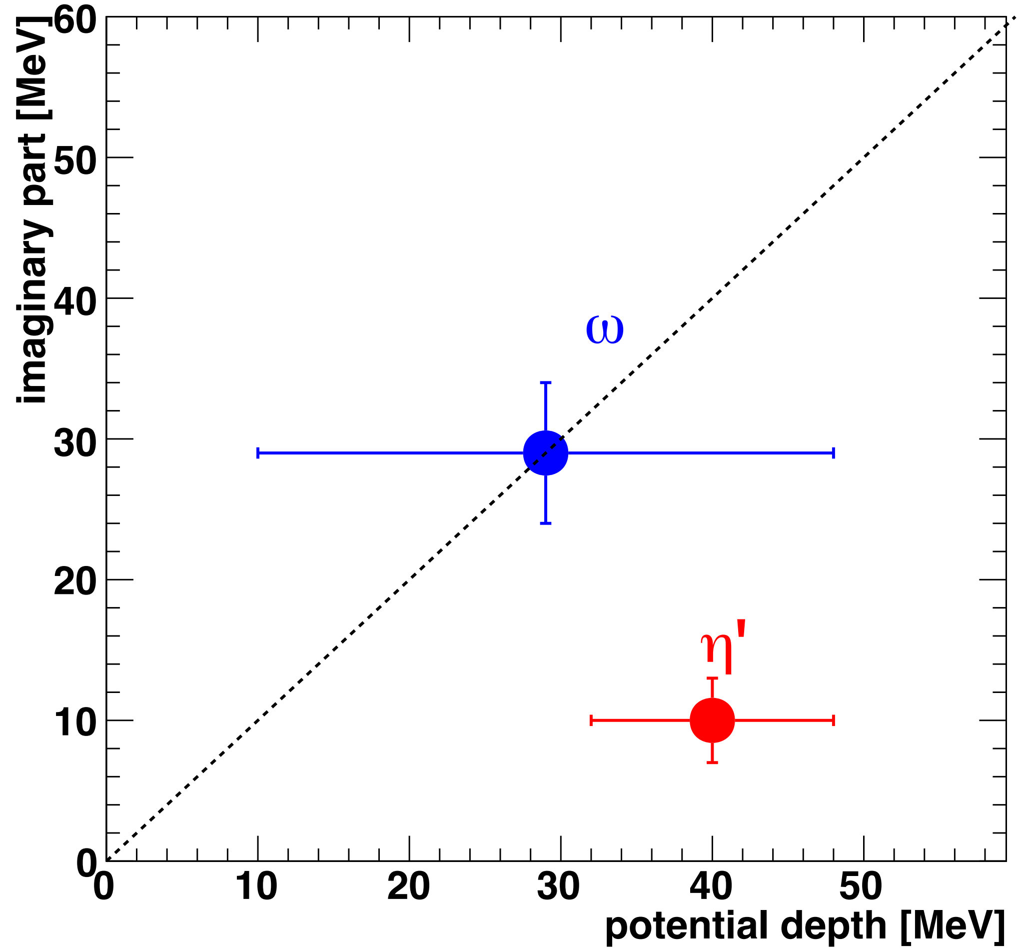
$\mathrm{Im}\;U^{\eta'}_{0}(\rho=\rho_0,p_{\eta'}=0) = -(10\pm3)$ MeV

- 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 $U_{\omega A}(\rho=\rho_0)=$ $-((29\pm19(stat)\pm20(syst) + i(30\pm10))$ MeV

η' $U_{\eta' A}(\rho=\rho_0)=$ $-((40\pm8(stat)\pm15(syst) + i(10\pm3))$ MeV



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

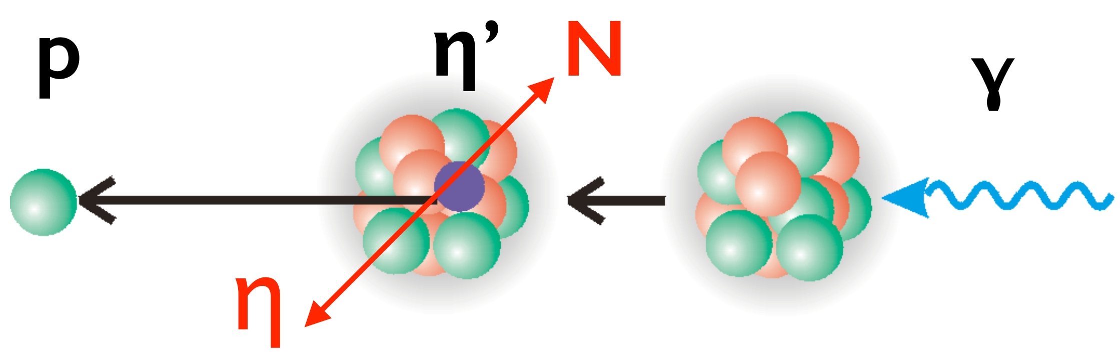
$|Re\ U| >> |Im\ U|$; ⇨ η' promising candidate to search for mesic states

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)

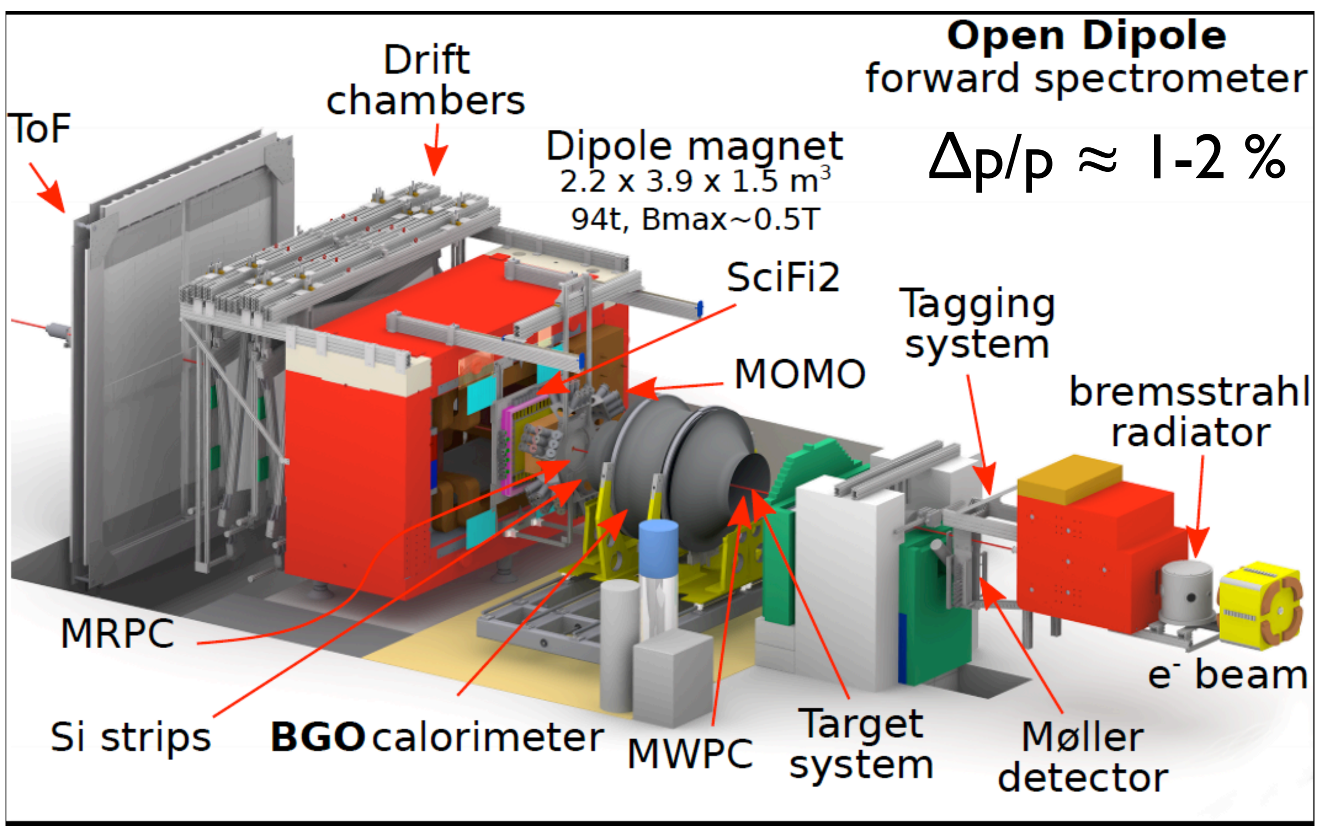
outlook: search for η'-mesic states in photo-nuclear reactions

B1: BGO-OD@ELSA

^{12}C(γ,p) η'X @ 1.5-2.8 GeV



formation and decay of η'-mesic state

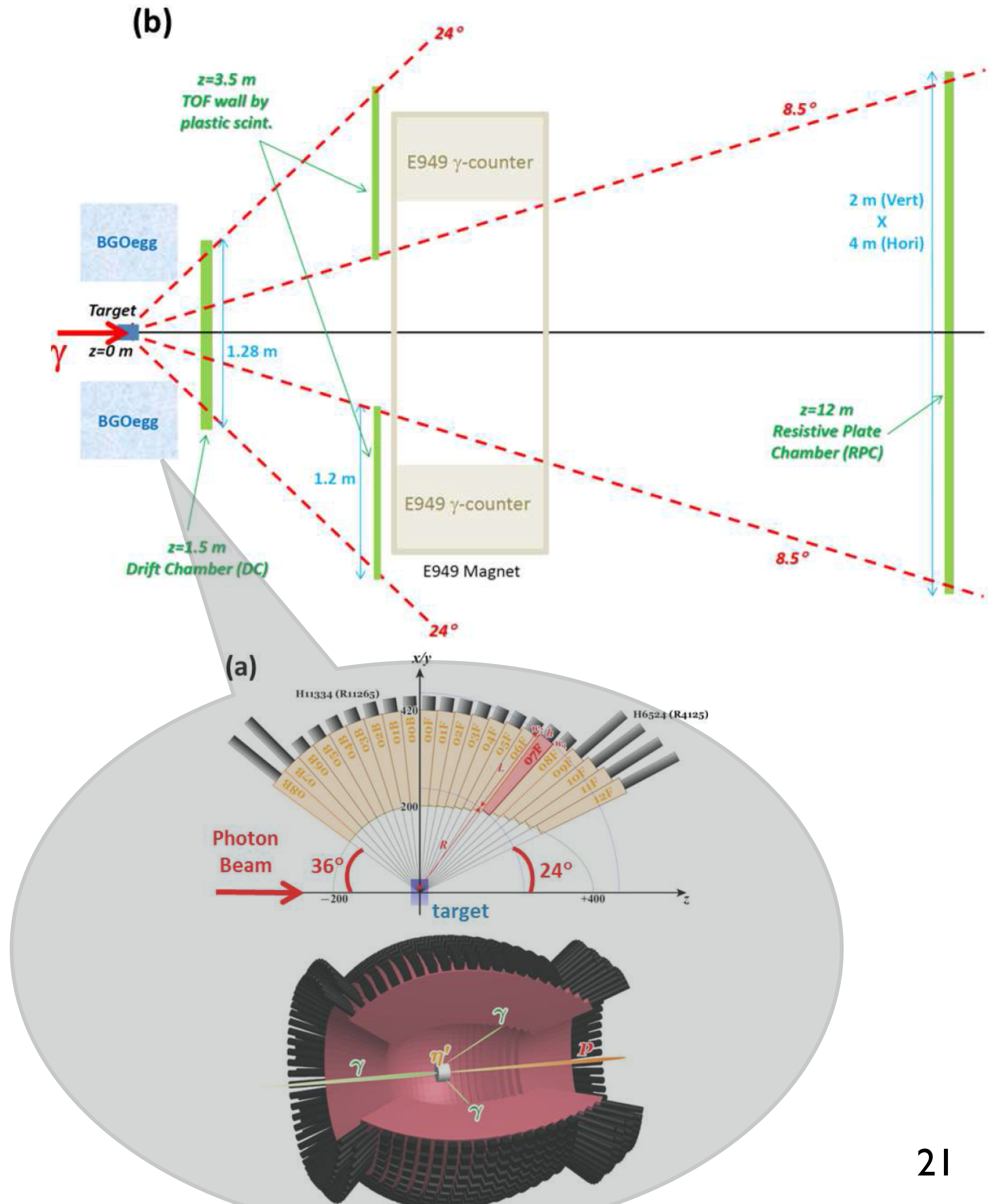


BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

LEPS2@SPring-8

^{12}C(γ,p) η'X @ 1.5-2.4 GeV



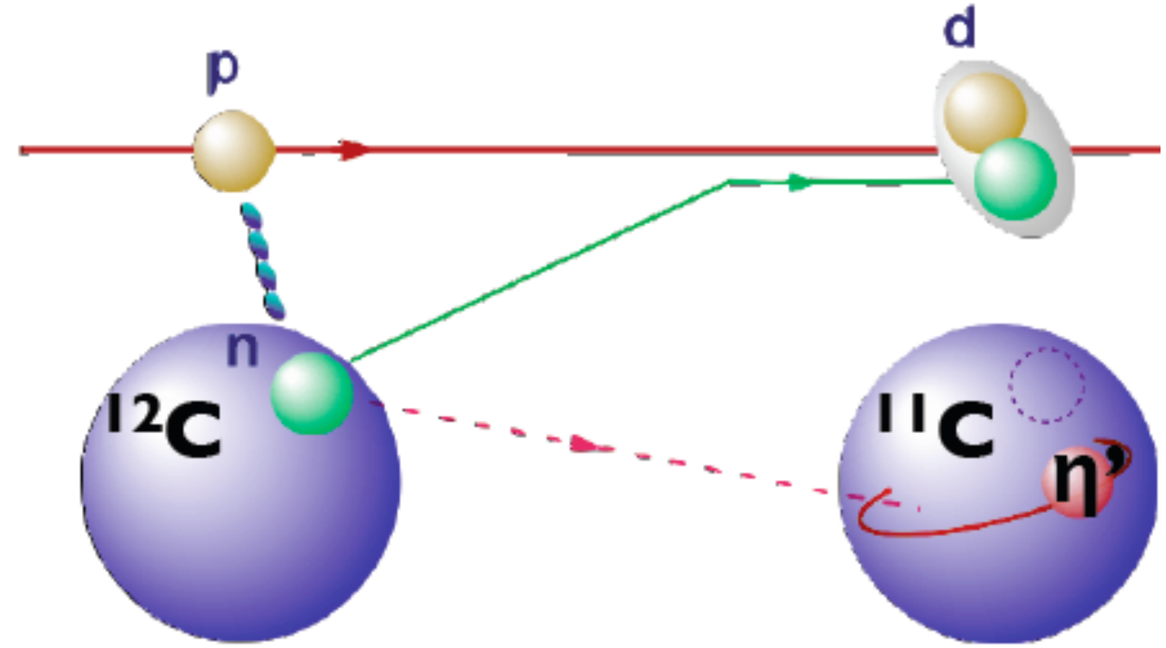
search for η'-mesic states in hadronic reactions

FRS@GSI: PRiME

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

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

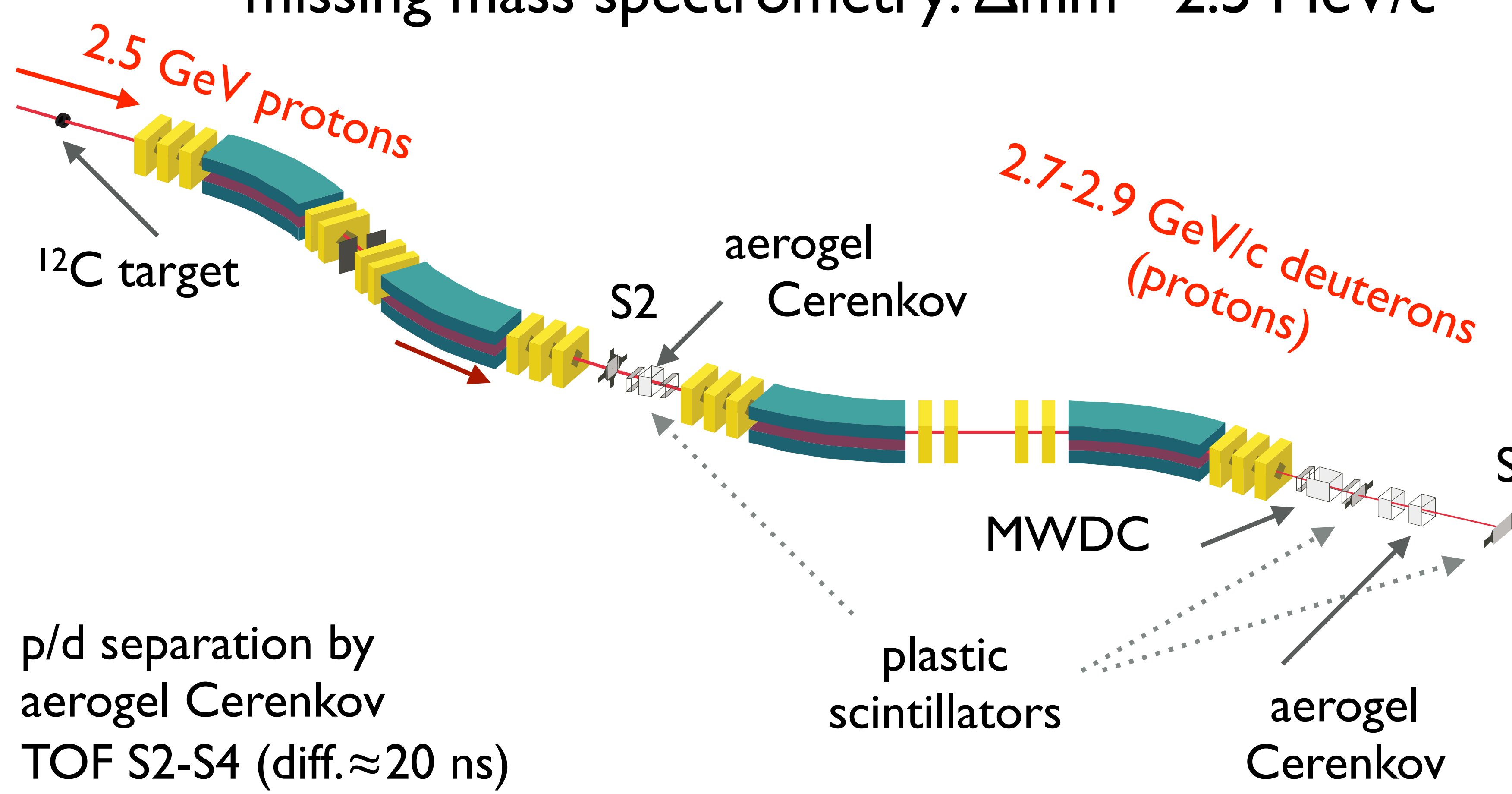
H. Nagahiro et al., PRC 87 (2013) 045201



η' × 11C mesic nuclei

particle identification by time-of-flight

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



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

$\Gamma_{\omega}(\rho=\rho_0; p=0) \approx 60$ MeV; $\Gamma_{\eta'}(\rho=\rho_0; p=0) \approx 15$ 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 $|\mathrm{Im}\ U| << |\mathrm{Re}\ U|$

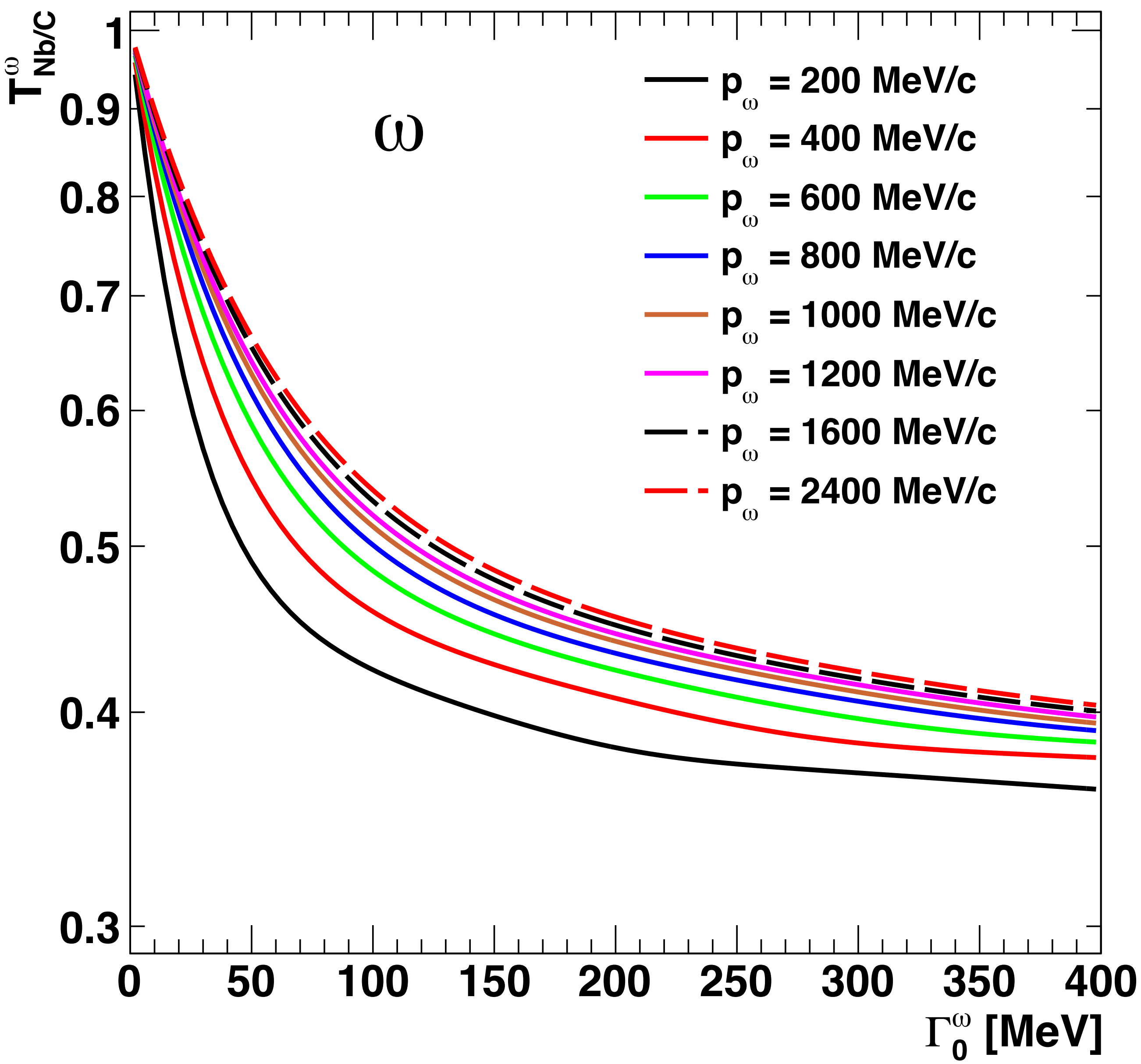
◆ search for η' mesic states ongoing

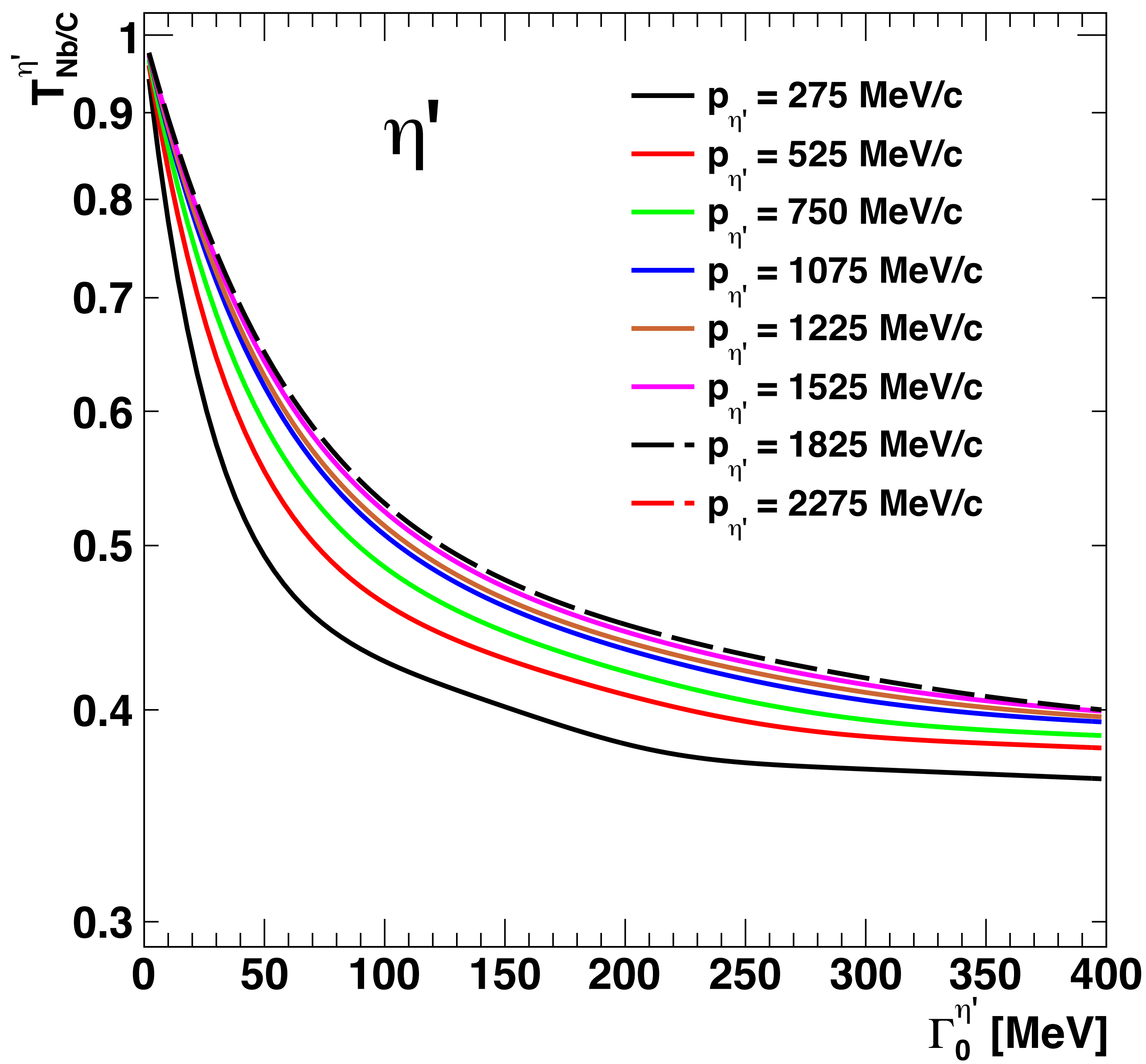
BACKUP

in-medium width from transparency ratio

Glauber model
in high energy eikonal approximation

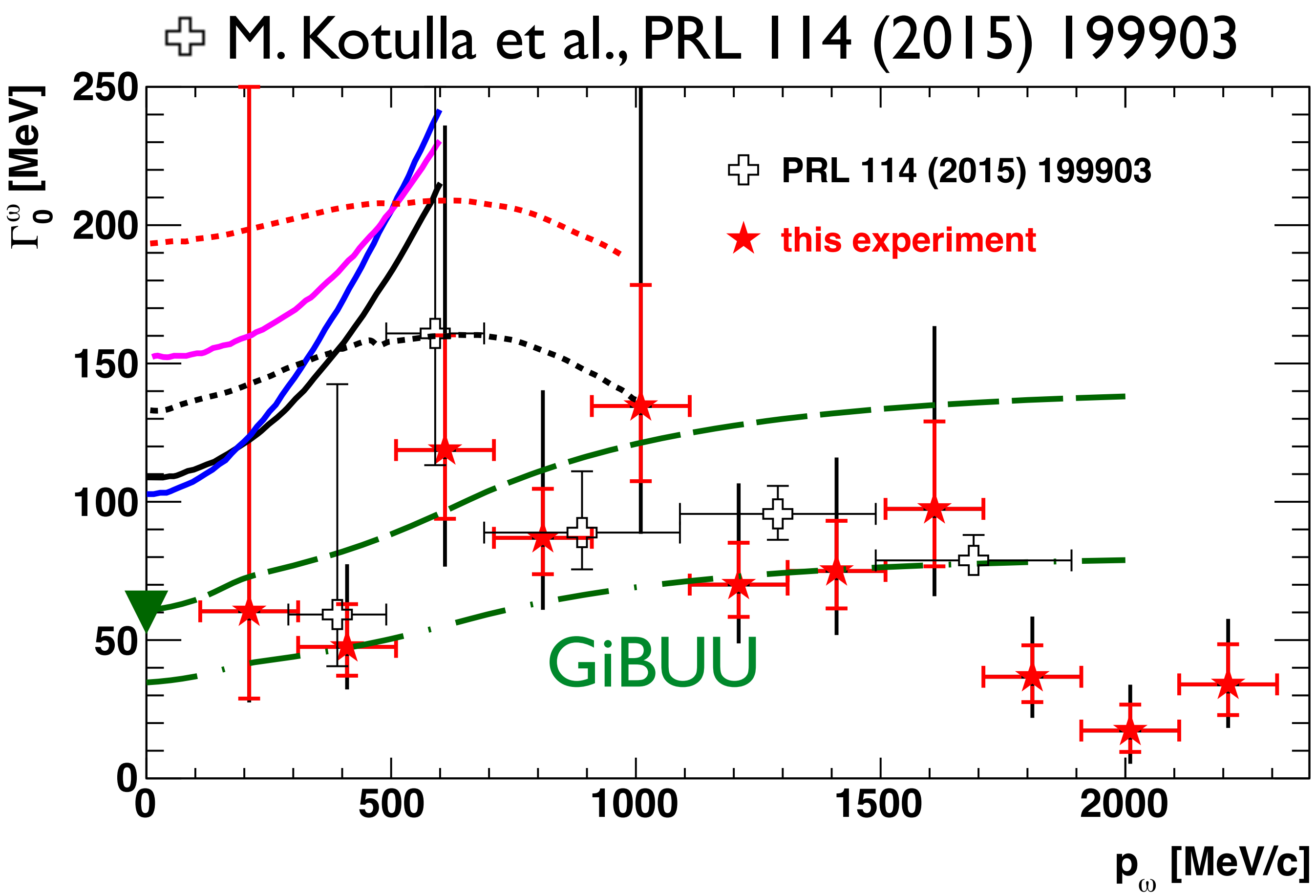
$T_{Nb/C}(p) \longleftrightarrow \Gamma_0(p)$

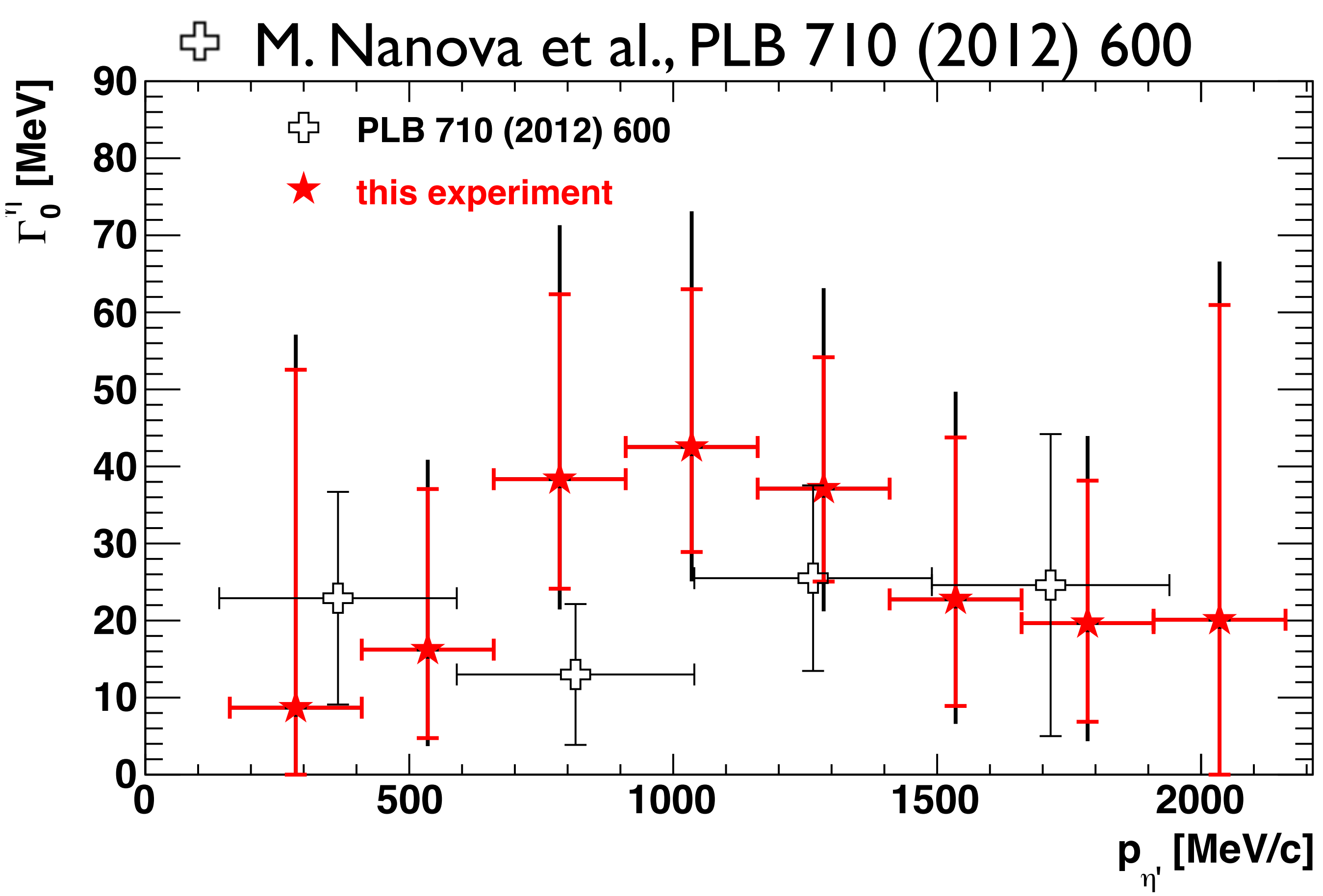




momentum dependence of ω, η' in-medium width

S. Friedrich





P. Mühlich et al.,NPA 780 (2006) 187
O. Buss et al., Phys. Rep. 512 (2012) 1

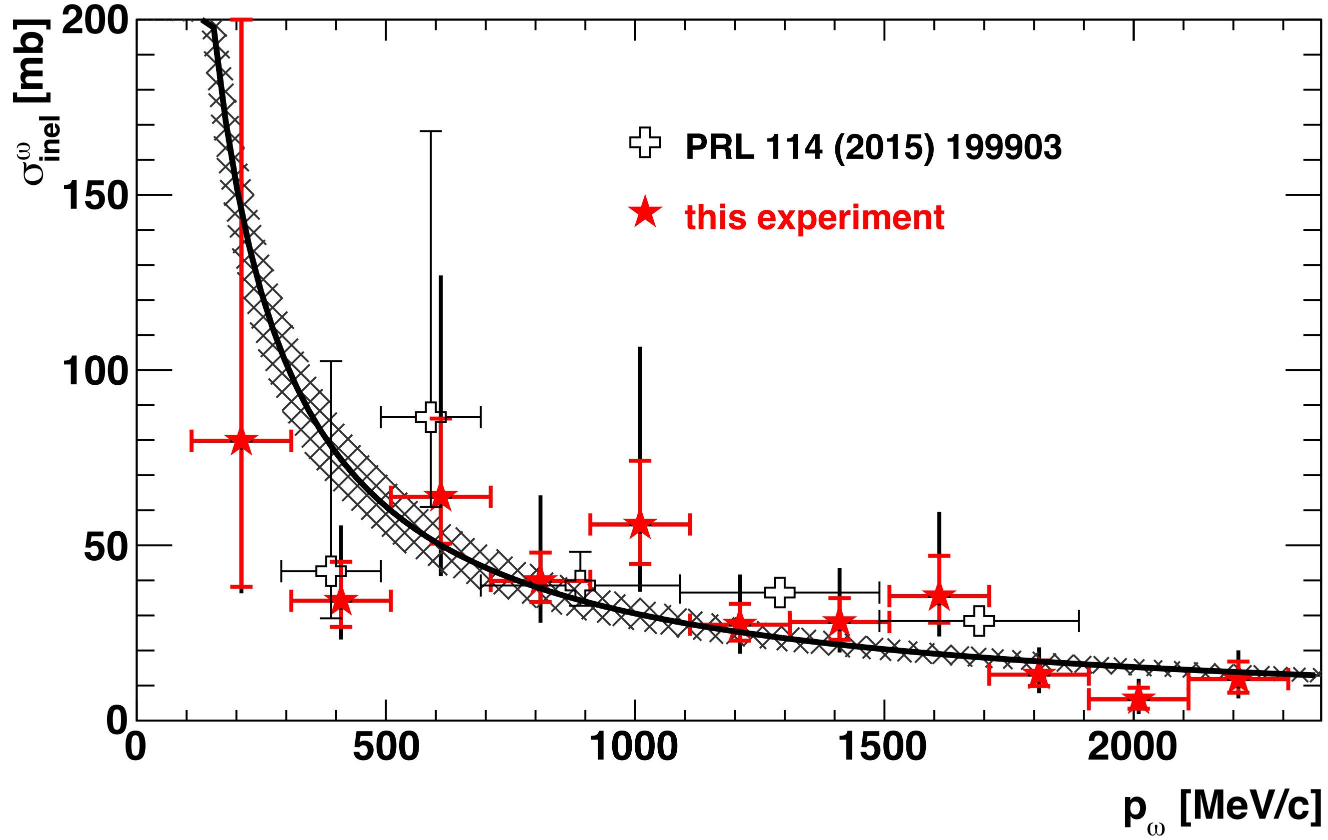
A. Ramos et al., EPJA 49 (2013)148

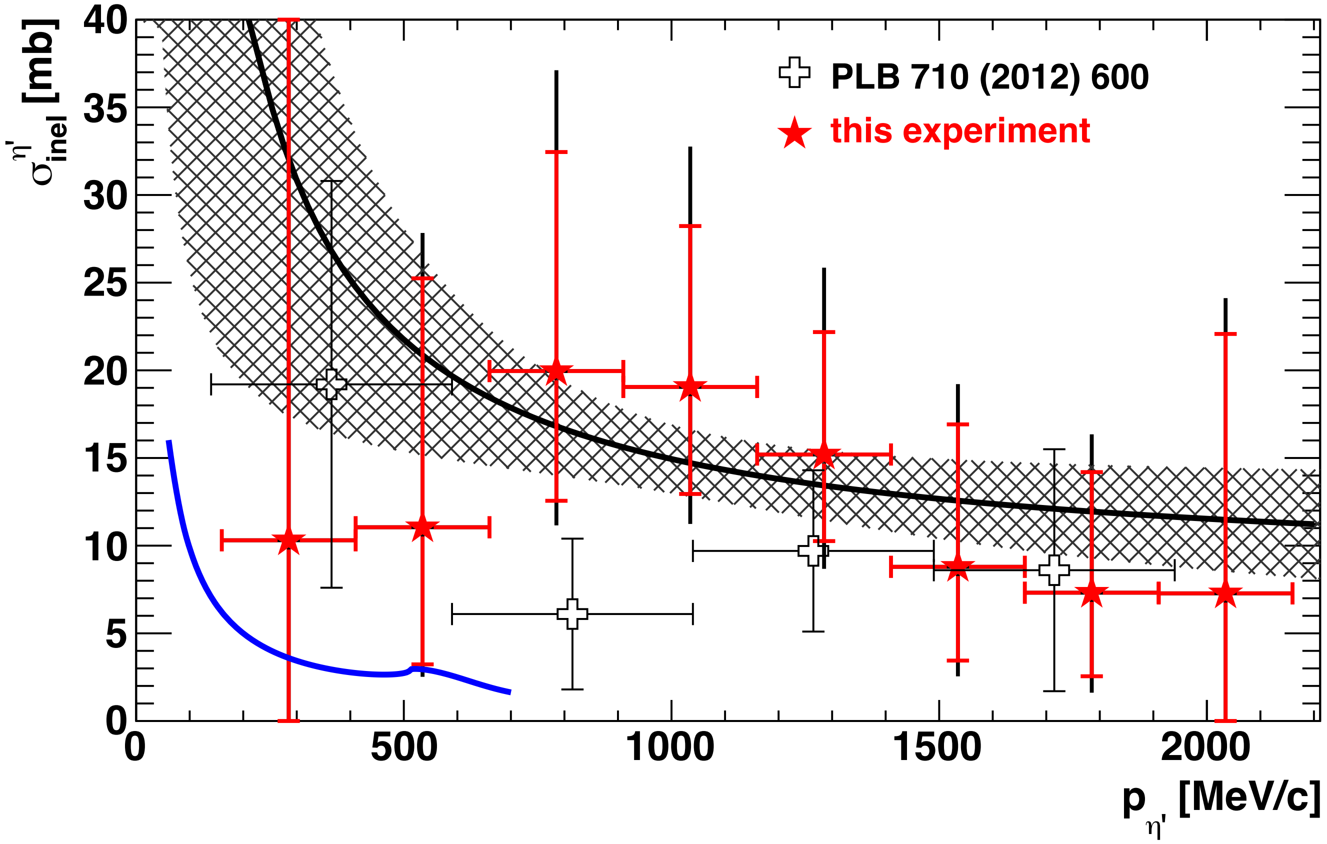
D. Cabrera and R. Rapp, PLB 729 (2014)67

inelastic absorption cross section σ_{inel}

low density approximation

$$\Gamma(p) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}(p) \rightarrow \sigma_{inel}(p) = \frac{\Gamma(p)}{\hbar c \beta \rho_0}$$





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$$\sigma_{inel}(p)[mb] = a + \frac{b}{p[GeV/c]}$$

a=0.0±6.2
b=31±4

a=8.1±9.5
b=6.8±9.8

$\langle \sigma_{inel}(p) \rangle$ = (14±3) mb

Dispersion relation analysis

work in progress (Horst Lenske (B7))

if self-energy Σ of the meson is an analytic function then imaginary and real part related up to a constant by:

$$\mathrm{Re}\,\Sigma(s) = -\frac{1}{\pi} P \int_0^\infty ds' \frac{\mathrm{Im}\,\Sigma(s')}{s-s'} \quad + \text{const}$$