Experimental results on the meson-nucleus optical potential and mesic states

Volker Metag
II. Physikalisches Institut
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
for the CBELSA/TAPS Collaboration

Outline:

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

*funded by the DFG within SFB/TR16

International School of Nuclear Physics; 37th Course
Probing Hadron Structure with Lepton and Hadron beams
Erice, Sicily, Sept. 16-24, 2015

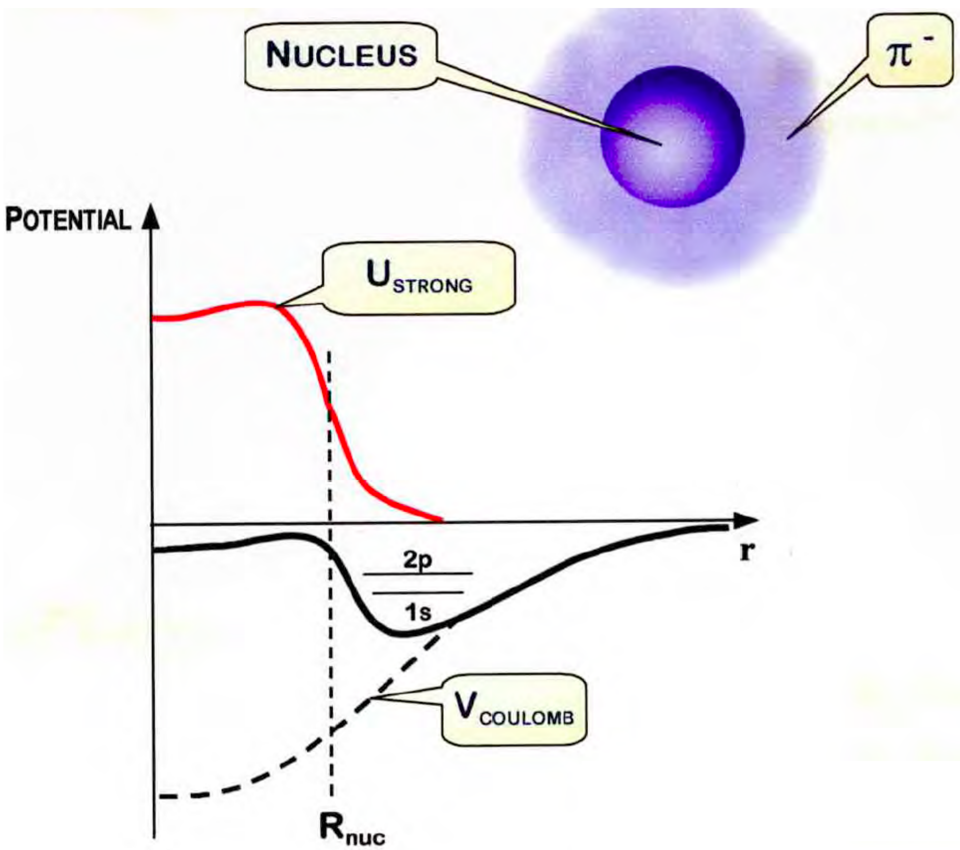
HIC for FAIR
Helmholtz International Center

FRS@GSI
BigRIPS@RIKEN

meson-nucleus interactions; mesic states

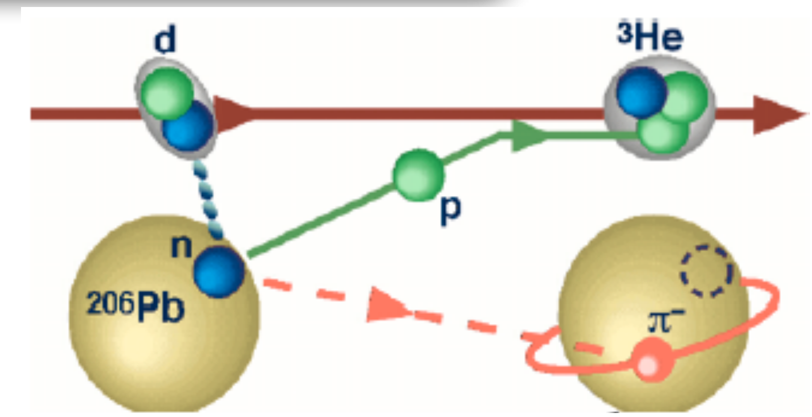
deeply bound pionic states:

Electromagnetic (+Strong) interaction

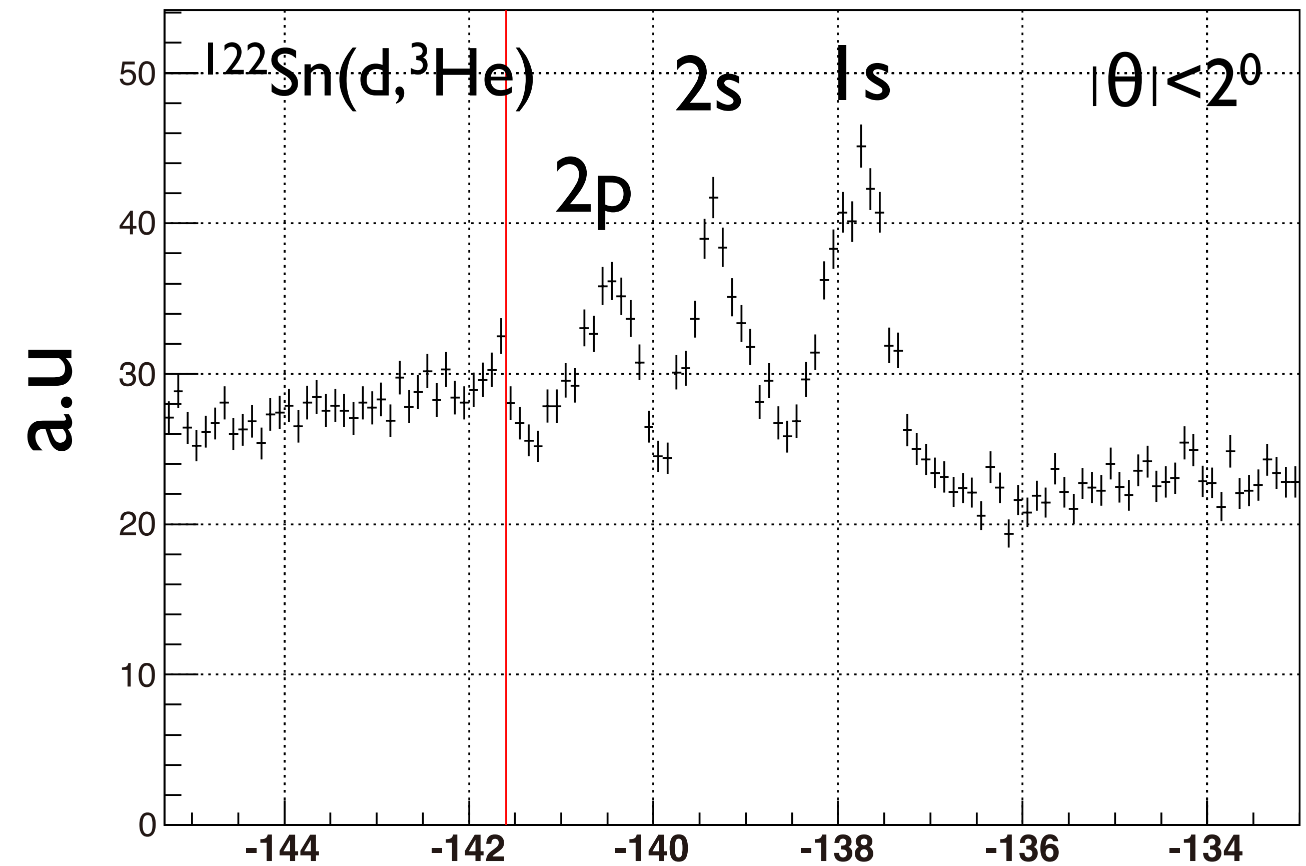


charged pion ⟺ nucleus

bound by superposition of attractive Coulomb- and repulsive strong interaction



Kenta Itahashi priv. com.



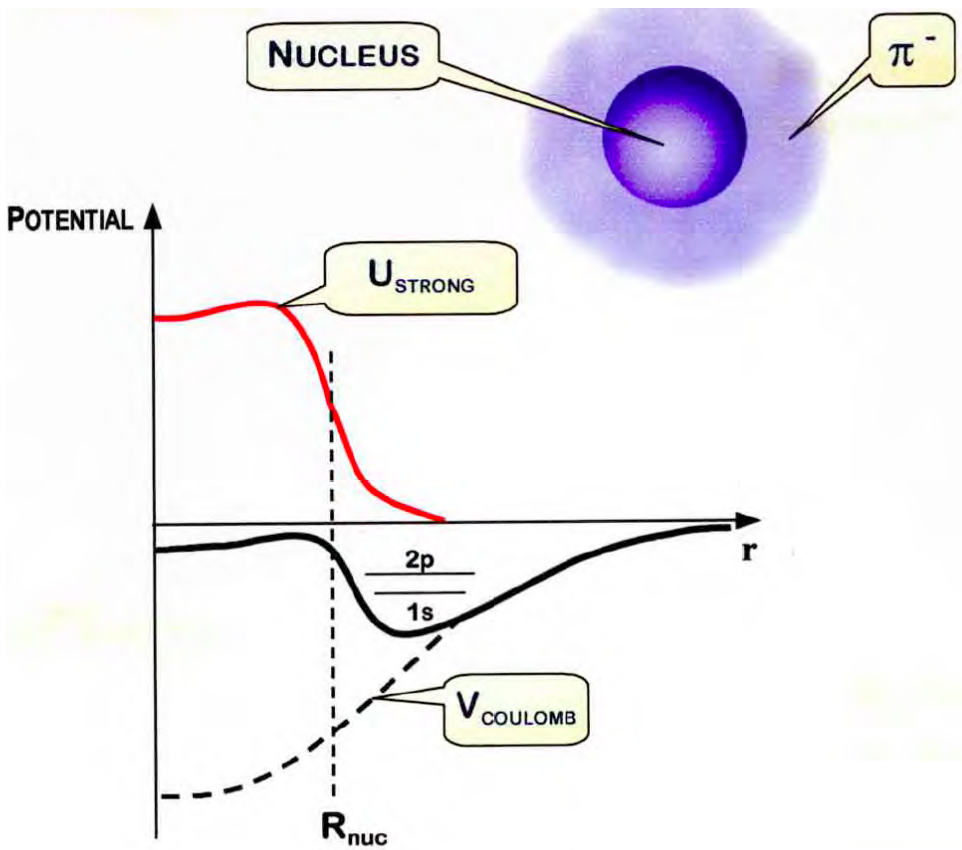
excitation energy spectrum of $\pi^- \otimes {}^{121}In$ system

FRS@GSI
BigRIPS@RIKEN

meson-nucleus interactions; mesic states

deeply bound pionic states:

Electromagnetic (+Strong) interaction



charged pion ⇔ nucleus

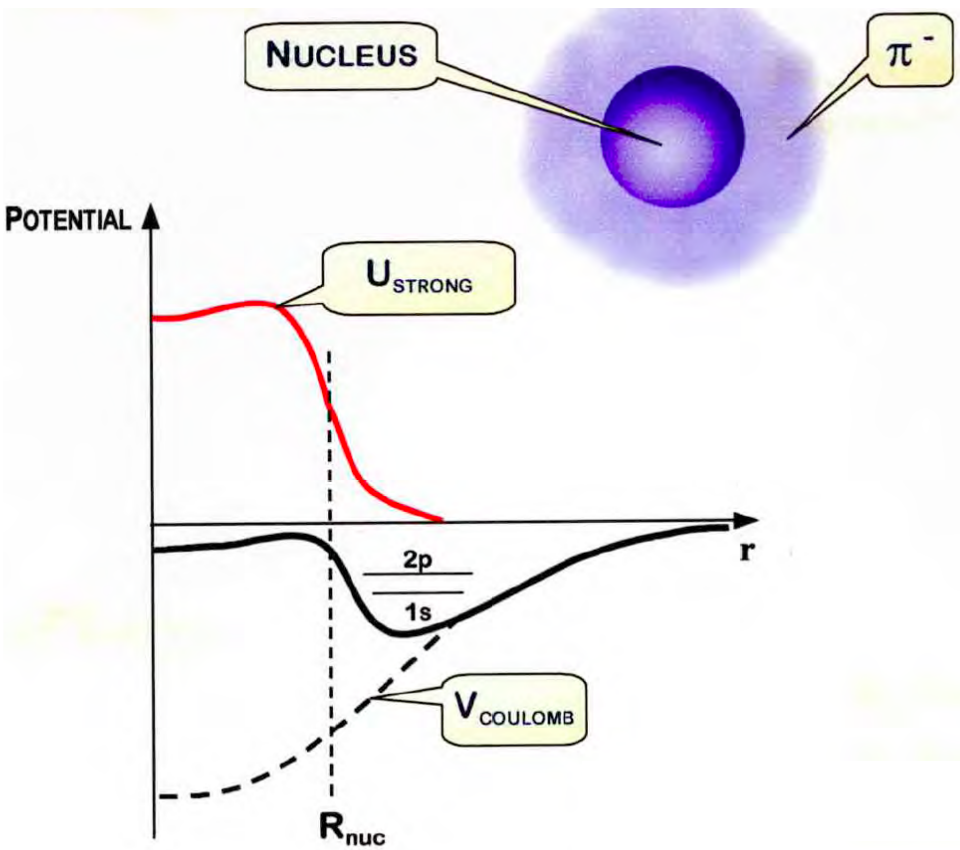
bound by superposition of attractive Coulomb- and repulsive strong interaction

FRS@GSI
BigRIPS@RIKEN

meson-nucleus interactions; mesic states

deeply bound pionic states:

Electromagnetic (+Strong) interaction



charged pion ⇔ nucleus

bound by superposition of attractive Coulomb- and repulsive strong interaction

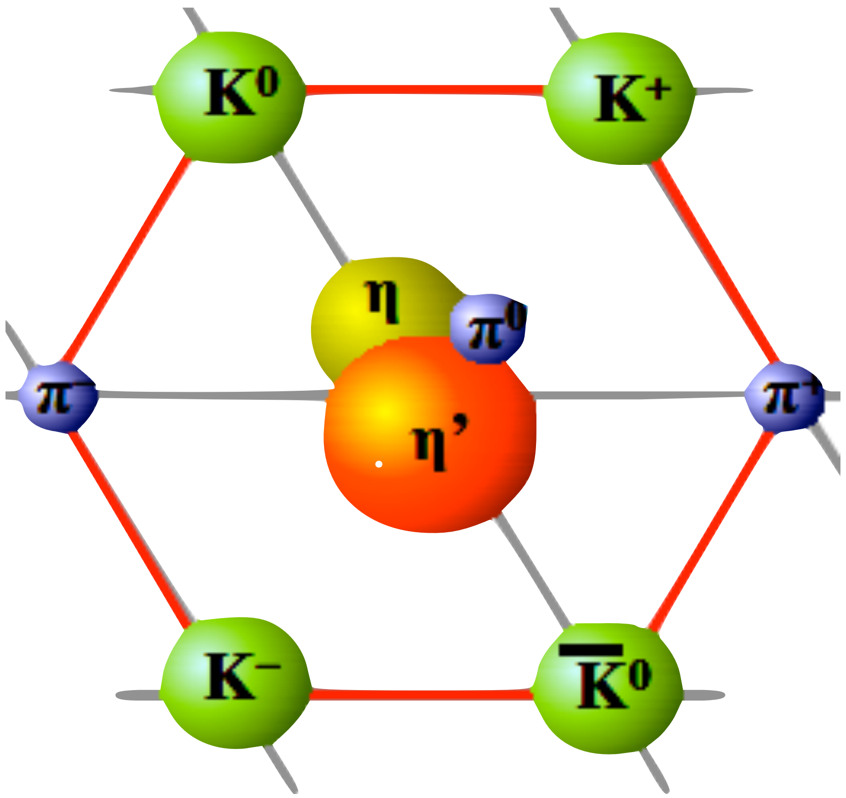
ω, η, η' ↔ nucleus

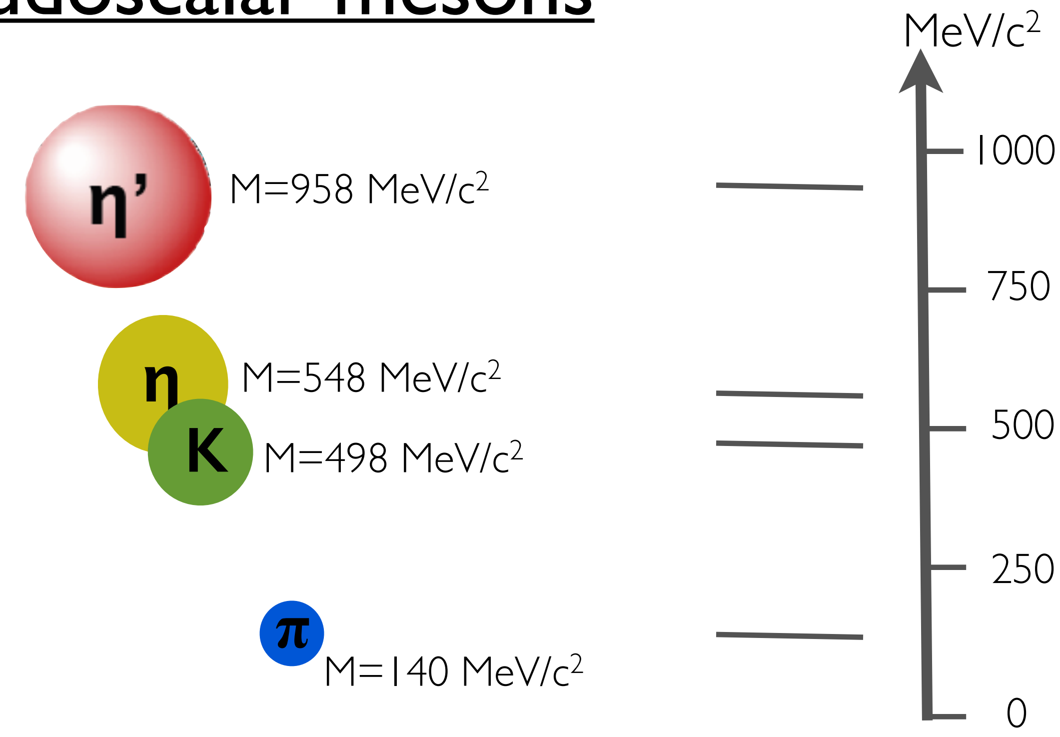
bound solely by the strong interaction

?

symmetry breaking in the hadronic sector

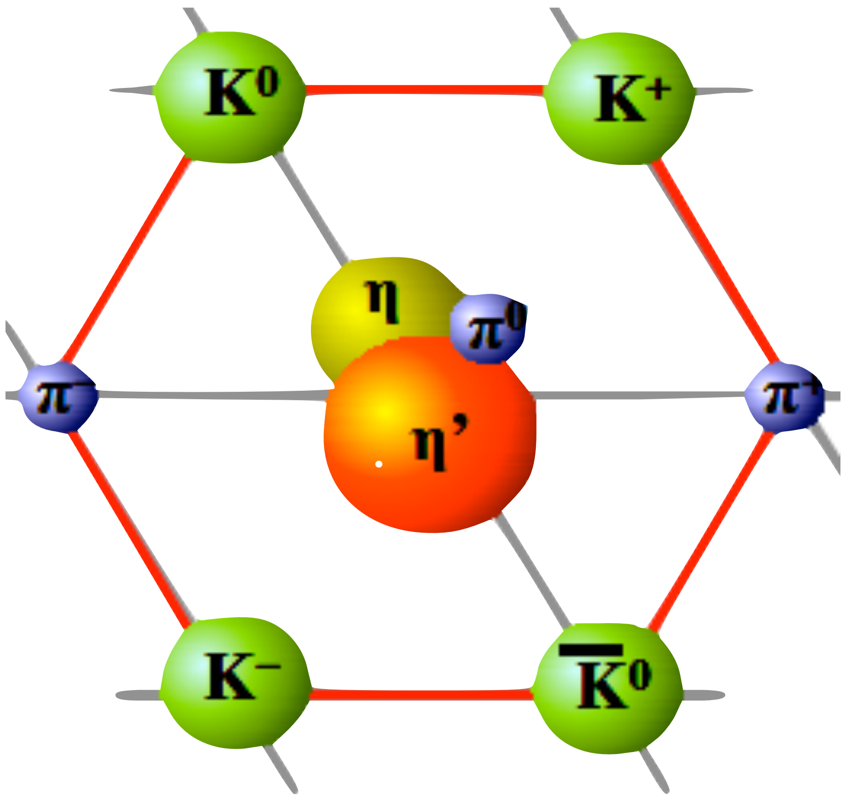
nonet of pseudoscalar mesons

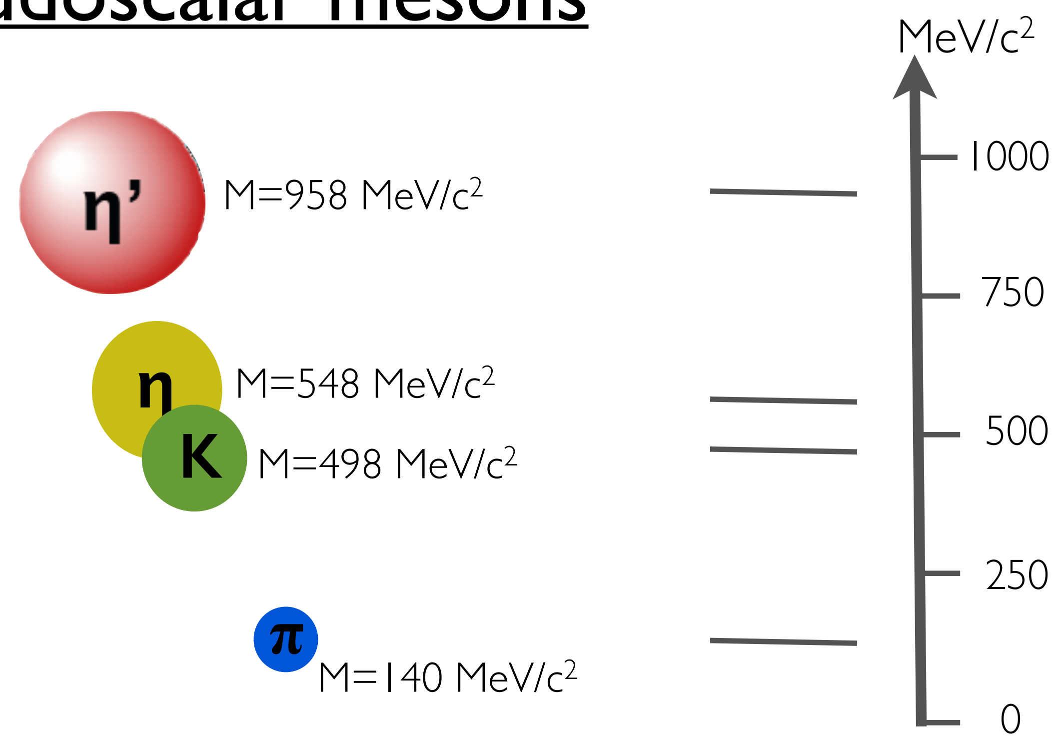




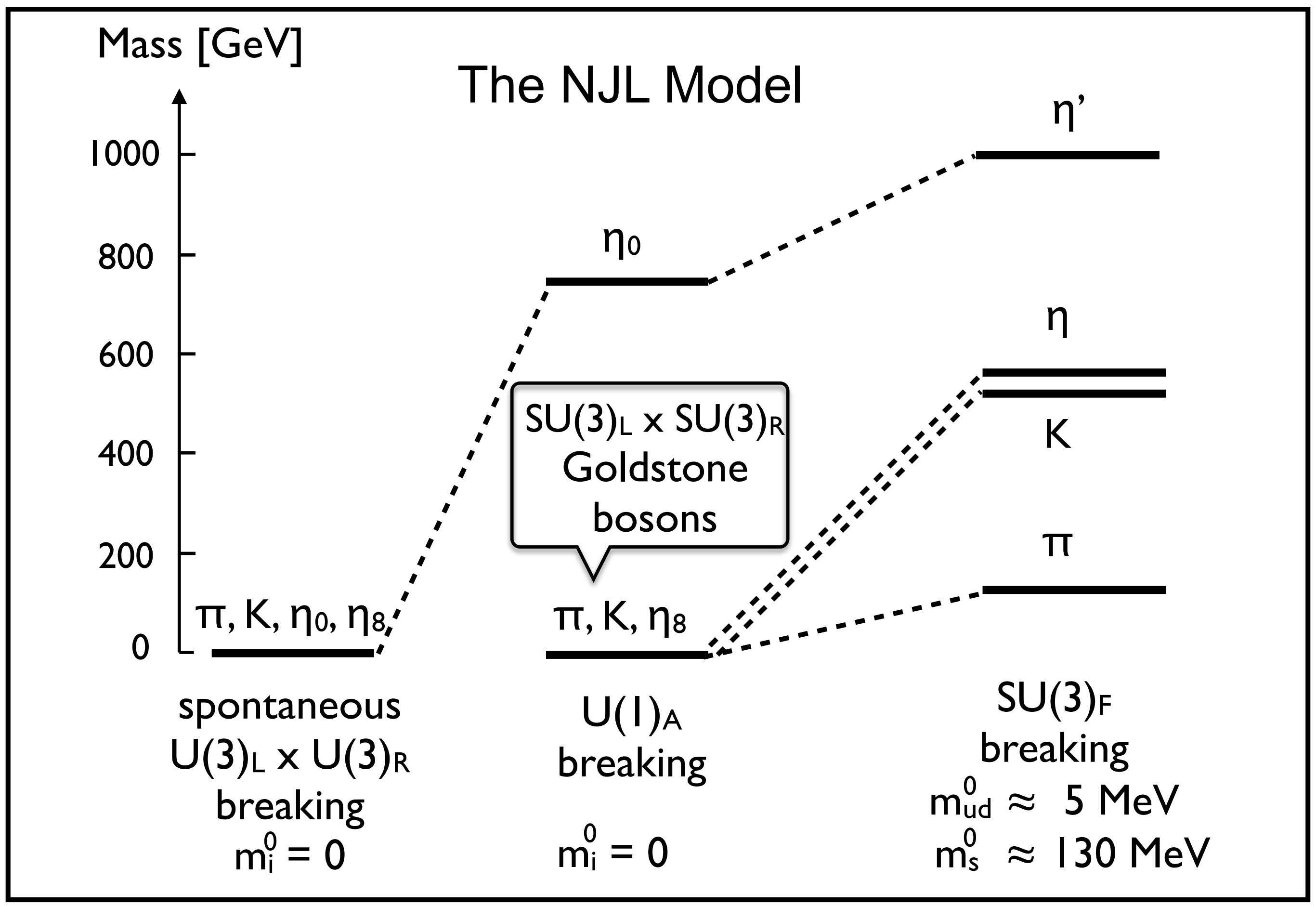
symmetry breaking in the hadronic sector

nonet of pseudoscalar mesons





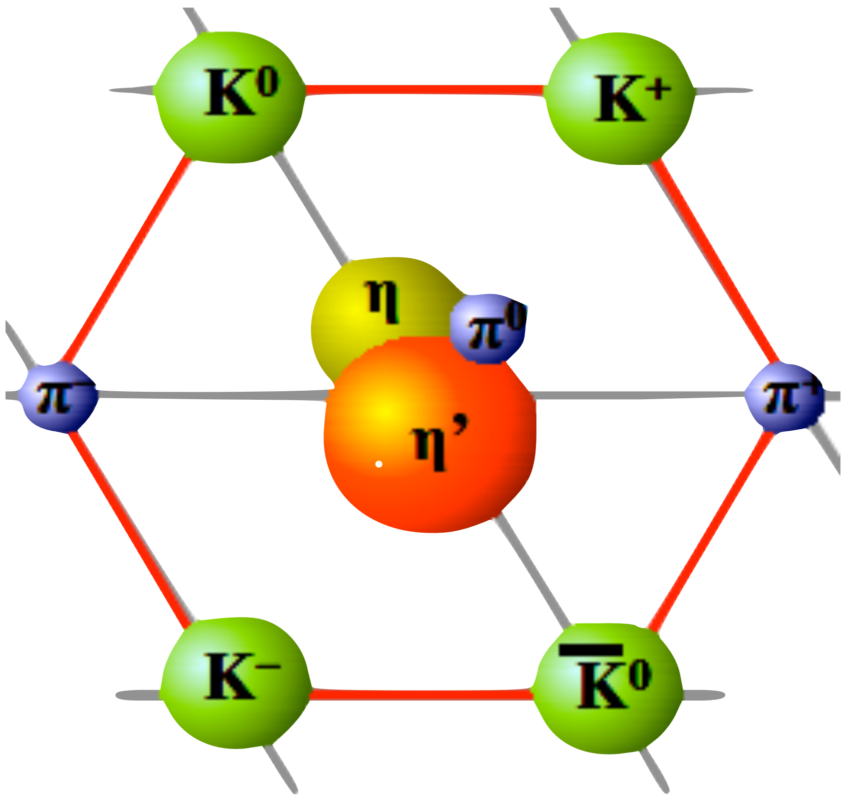
S. Klimt et al., Nucl. Phys. A 516 (1990) 429

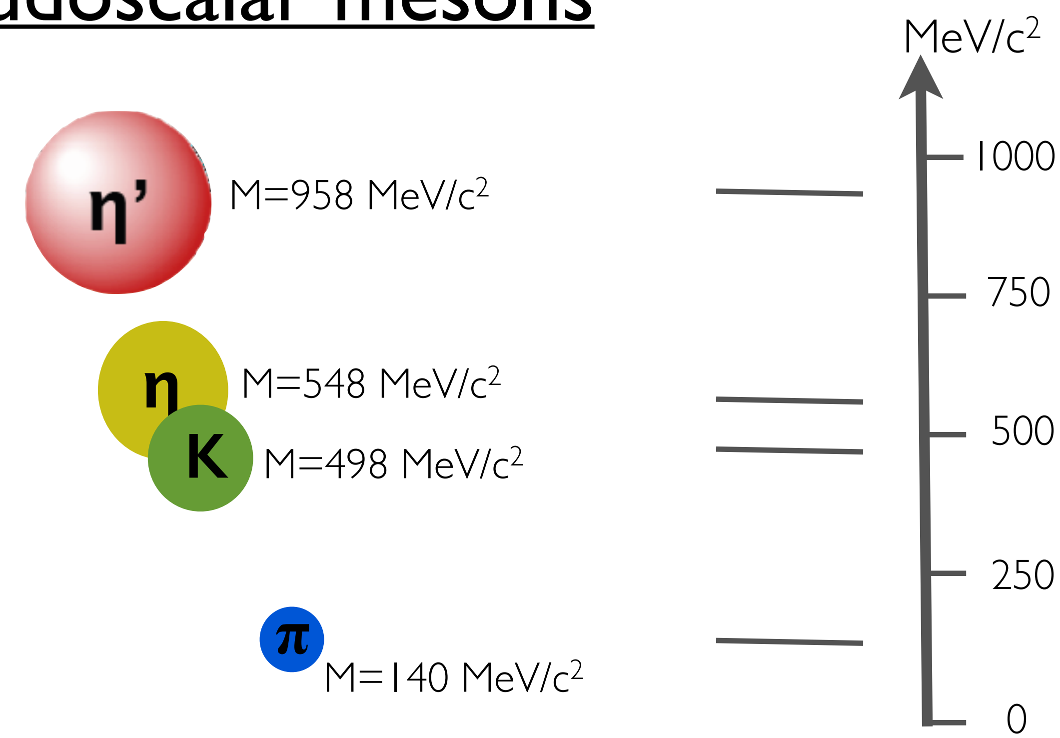


mass as a result of symmetry breaking

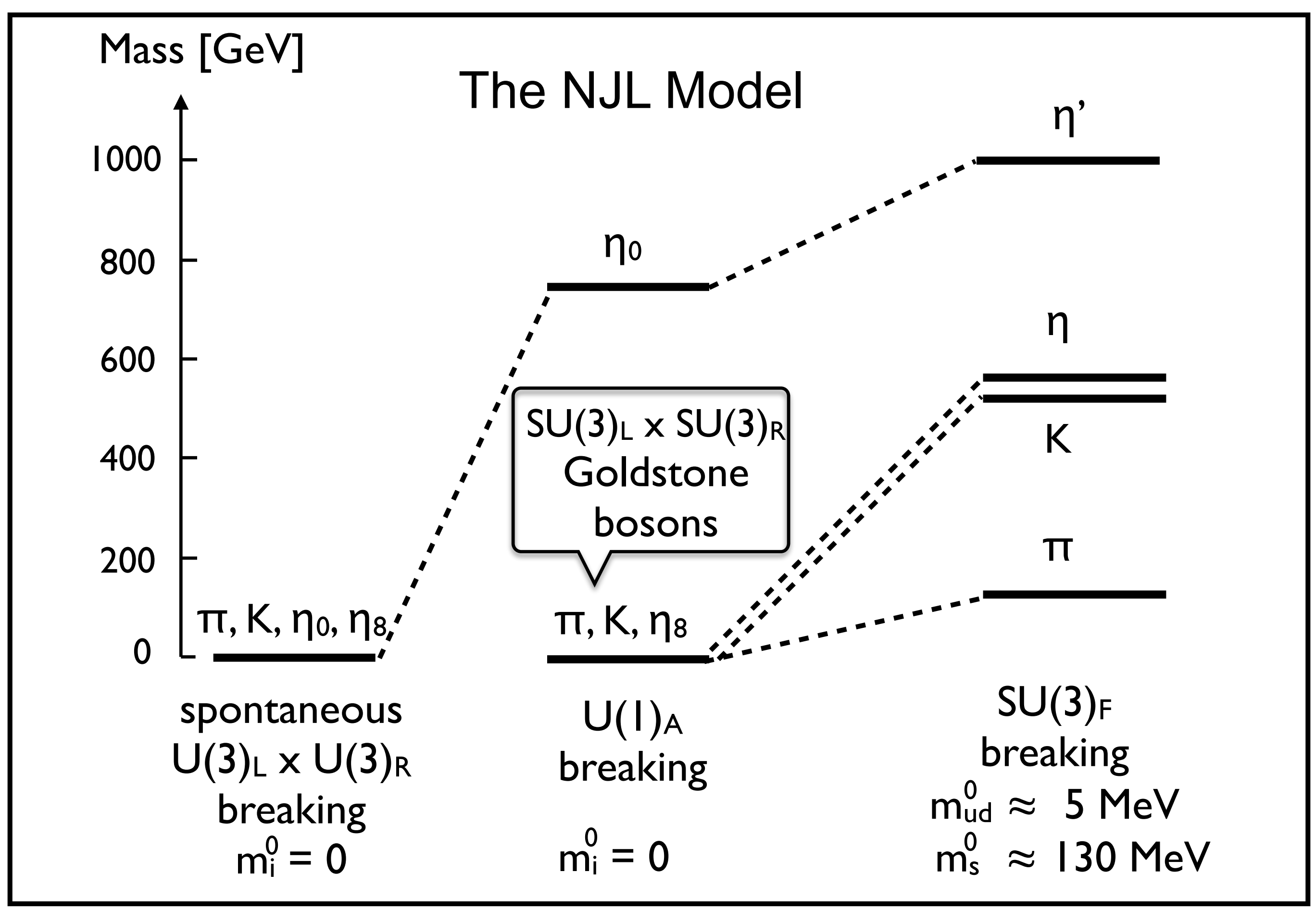
symmetry breaking in the hadronic sector

<u>nonet of pseudoscalar mesons</u>





S. Klimt et al., Nucl. Phys. A 516 (1990) 429

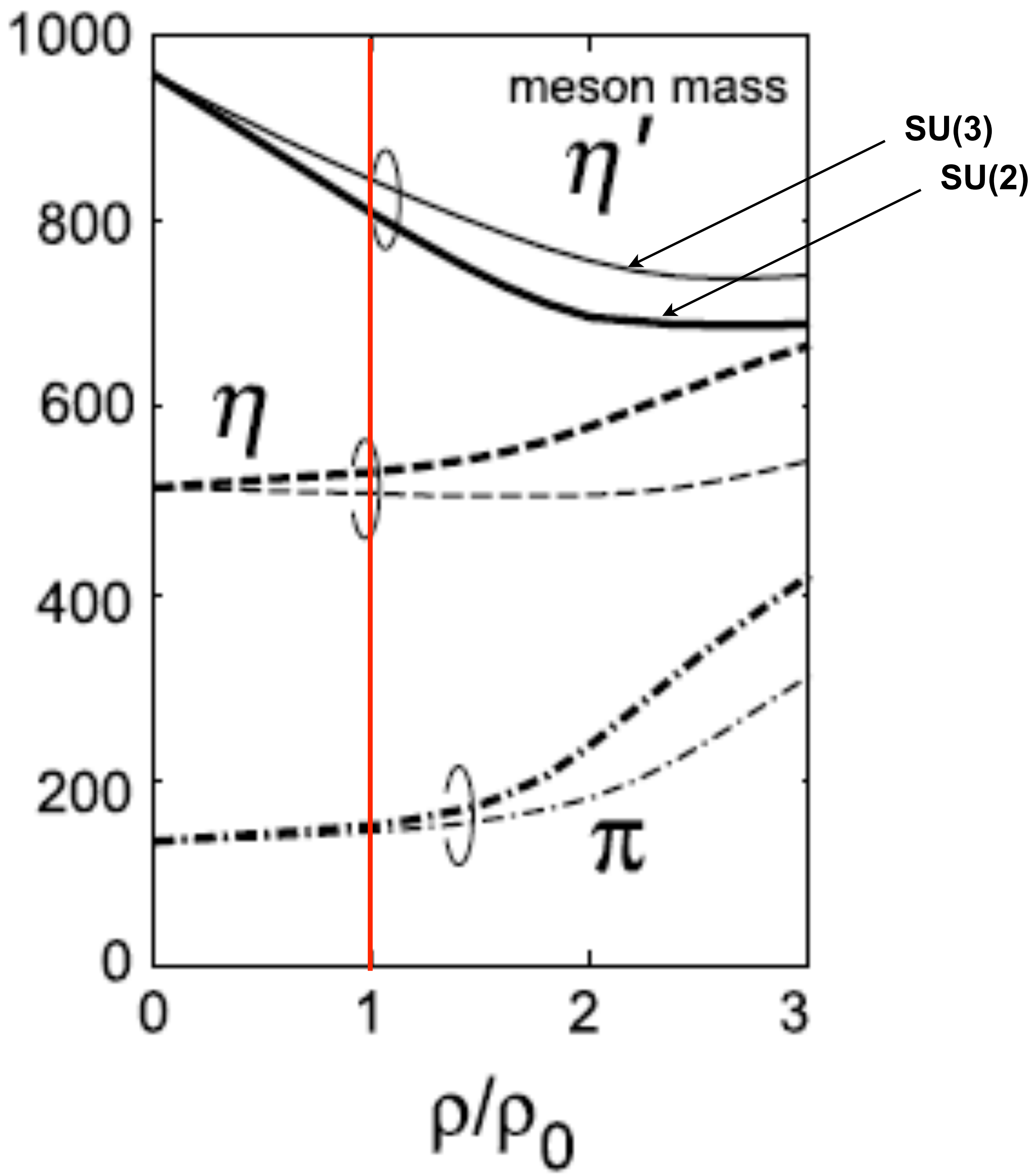


mass as a result of symmetry breaking

partial restoration of chiral symmetry predicted in a nucleus
→ impact on in-medium meson masses ??

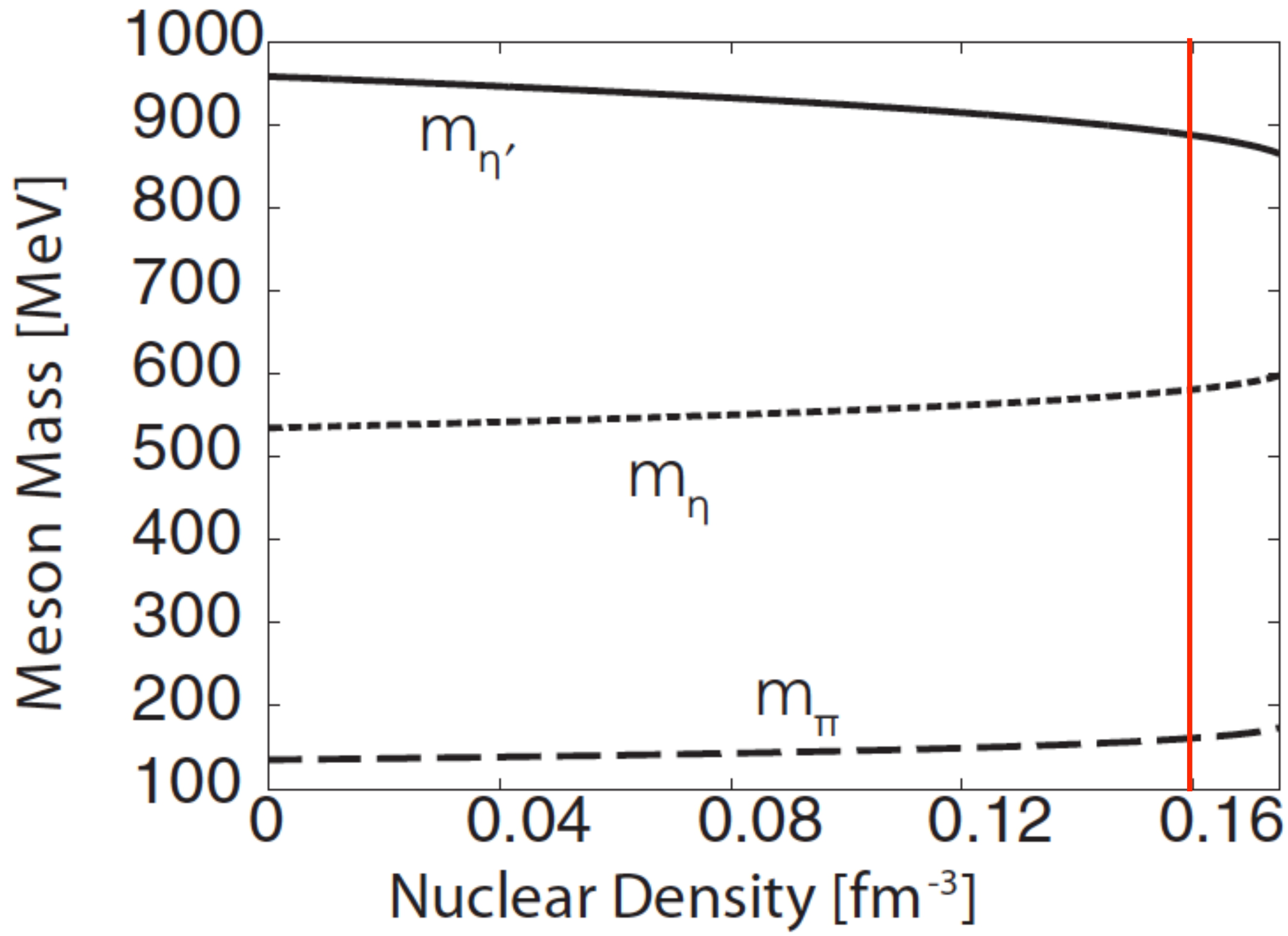
model predictions for the in-medium mass of the η' meson

H. Nagahiro, M. Takizawa and S. Hirenzaki,
Phys. Rev. C 74 (2006) 045203



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

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



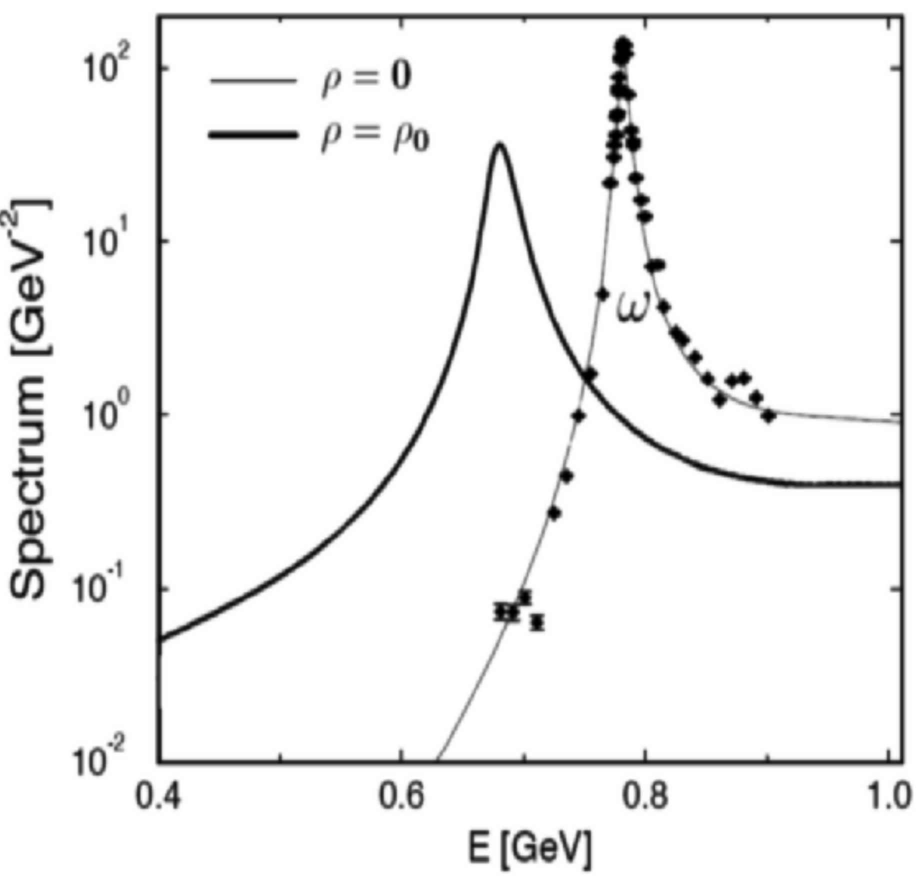
$\Delta m_{\eta'}(\rho_0) \approx -80$ MeV

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

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

model predictions for in-medium mass/width of the ω meson

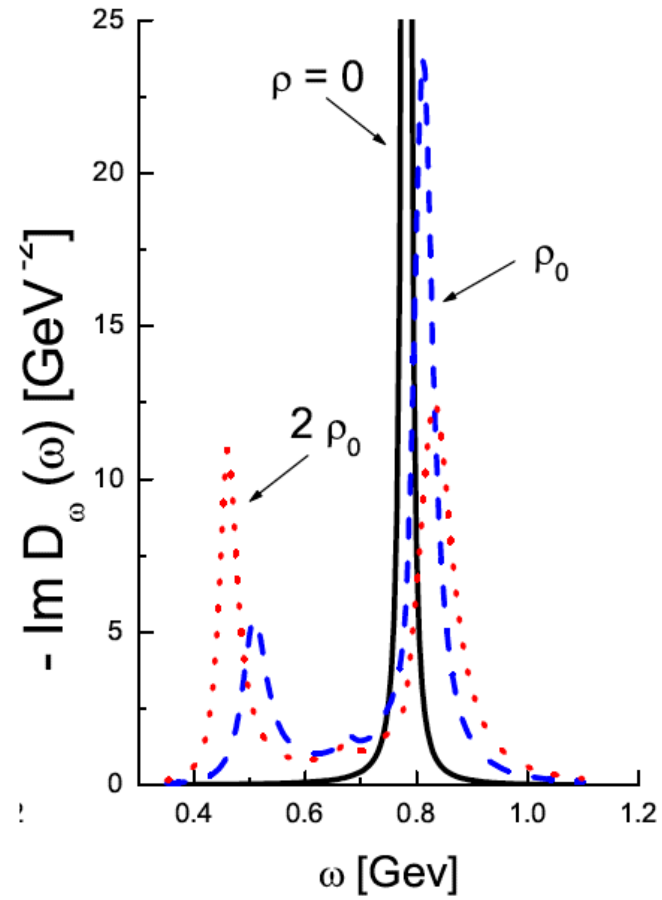
F. Klingl et al.,
NPA 610 (1997) 297;
NPA 650 (1999) 299



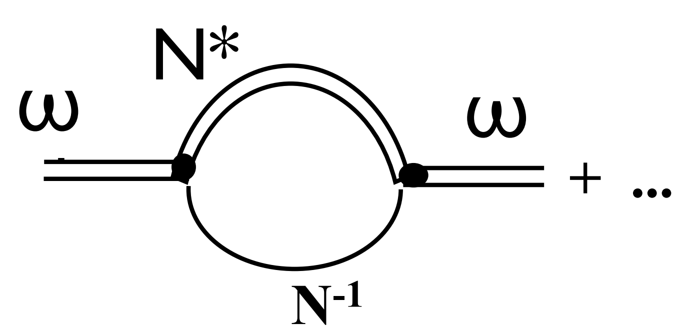
- lowering of in-medium mass
- broadening of resonance

with increasing nuclear density

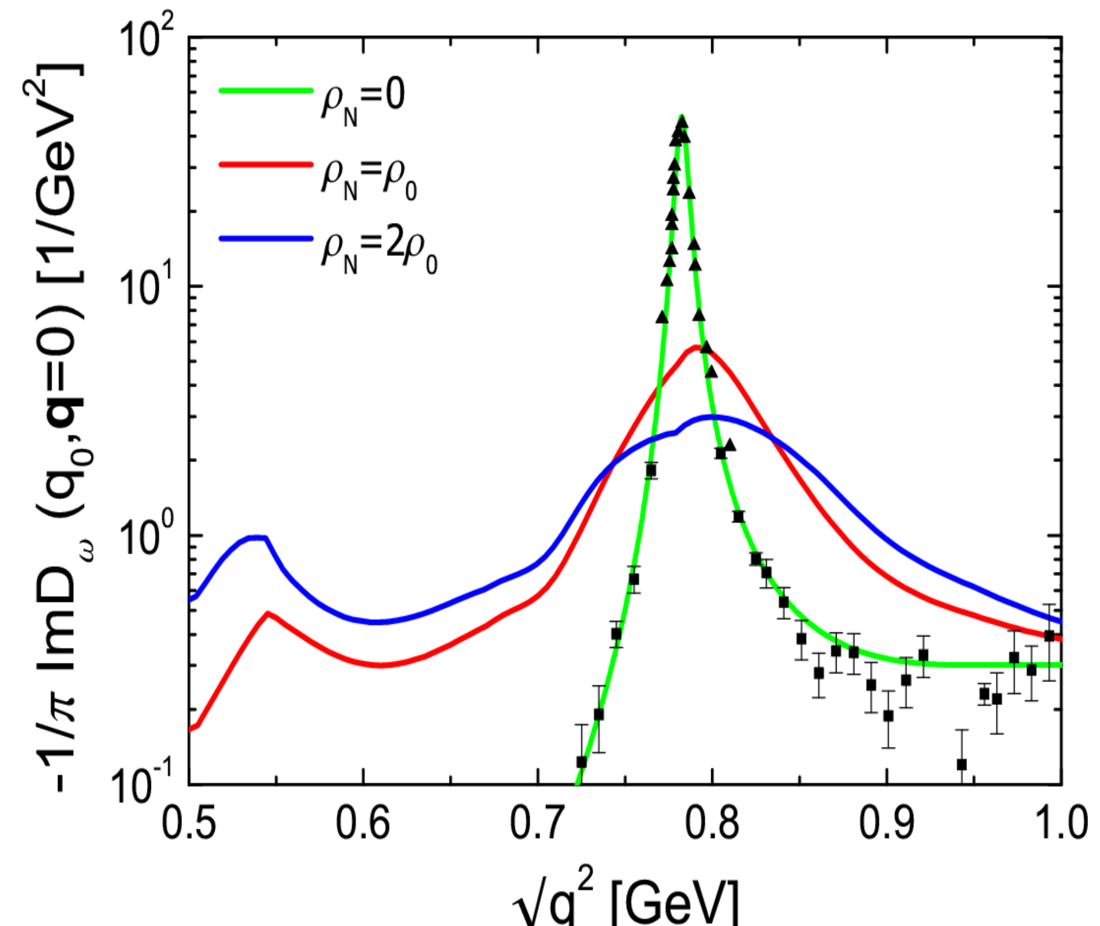
M. Lutz et al.,
NPA 706 (2002) 437



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

meson-nucleus optical potential

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

meson-nucleus optical potential

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

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

real part

⇕

in-medium mass modification

meson-nucleus optical potential

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

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

real part

⇕

in-medium mass modification

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

imaginary part

⇕

in-medium width
inelastic cross section

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

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

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

The imaginary part W of the meson-nucleus optical potential

Photoproduction of ω and η' mesons on nuclei

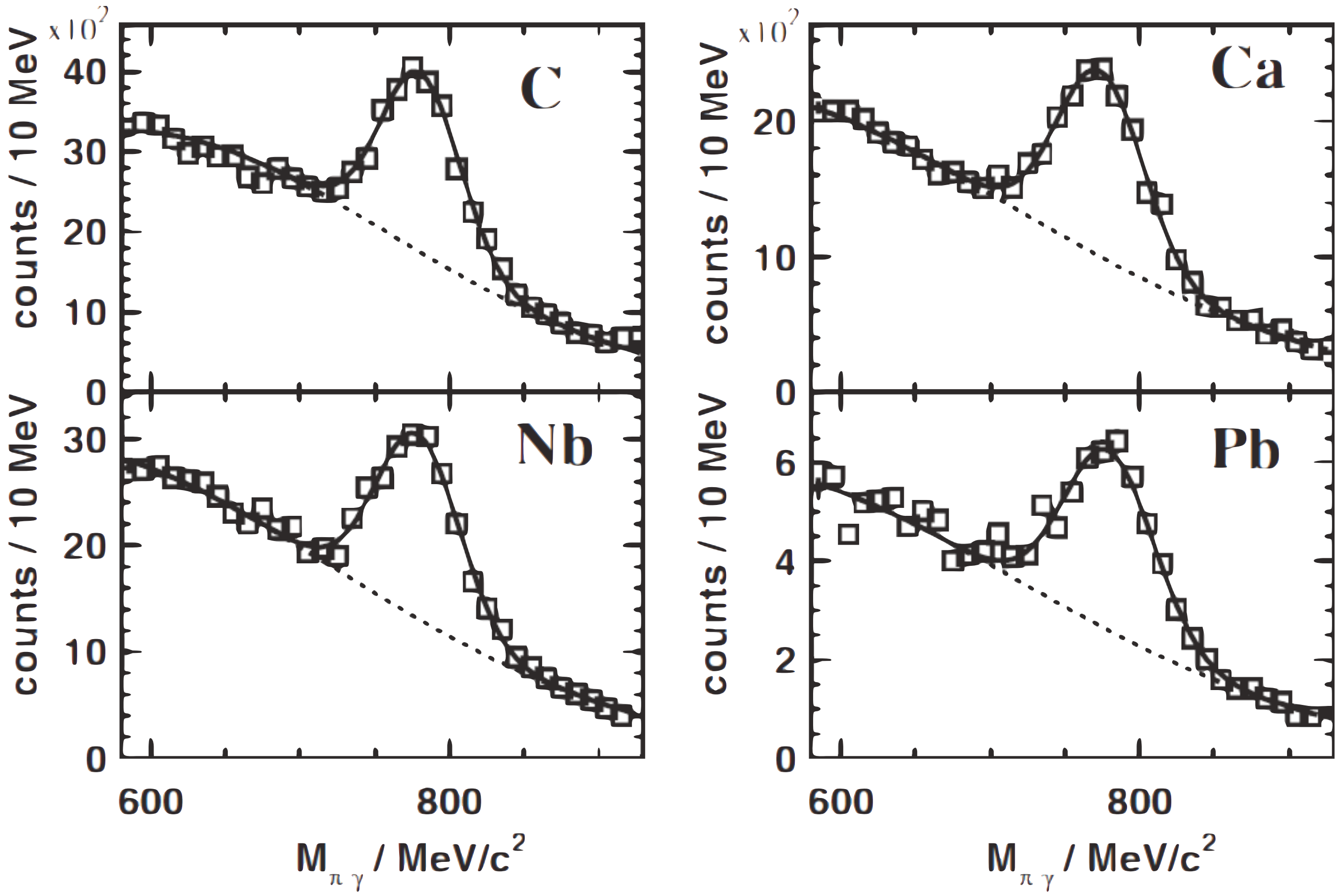
ω

experiments performed with the CBELSA/TAPS detector (Bonn)

η'

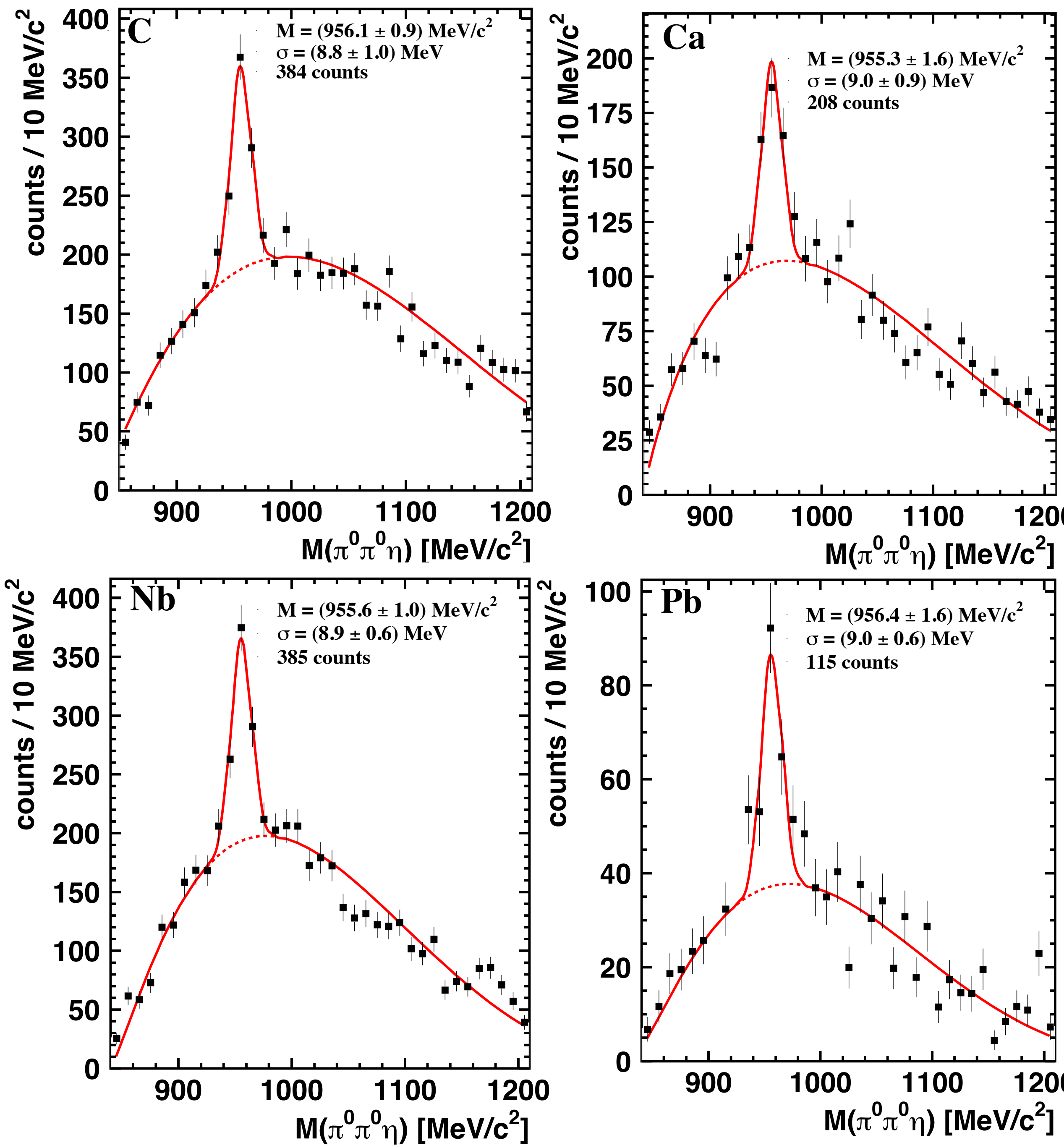
$\omega \to \pi^0 \gamma \to 3\gamma$

M. Kotulla et al, PRL 100 (2008) 19230



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

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



transparency ratio

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

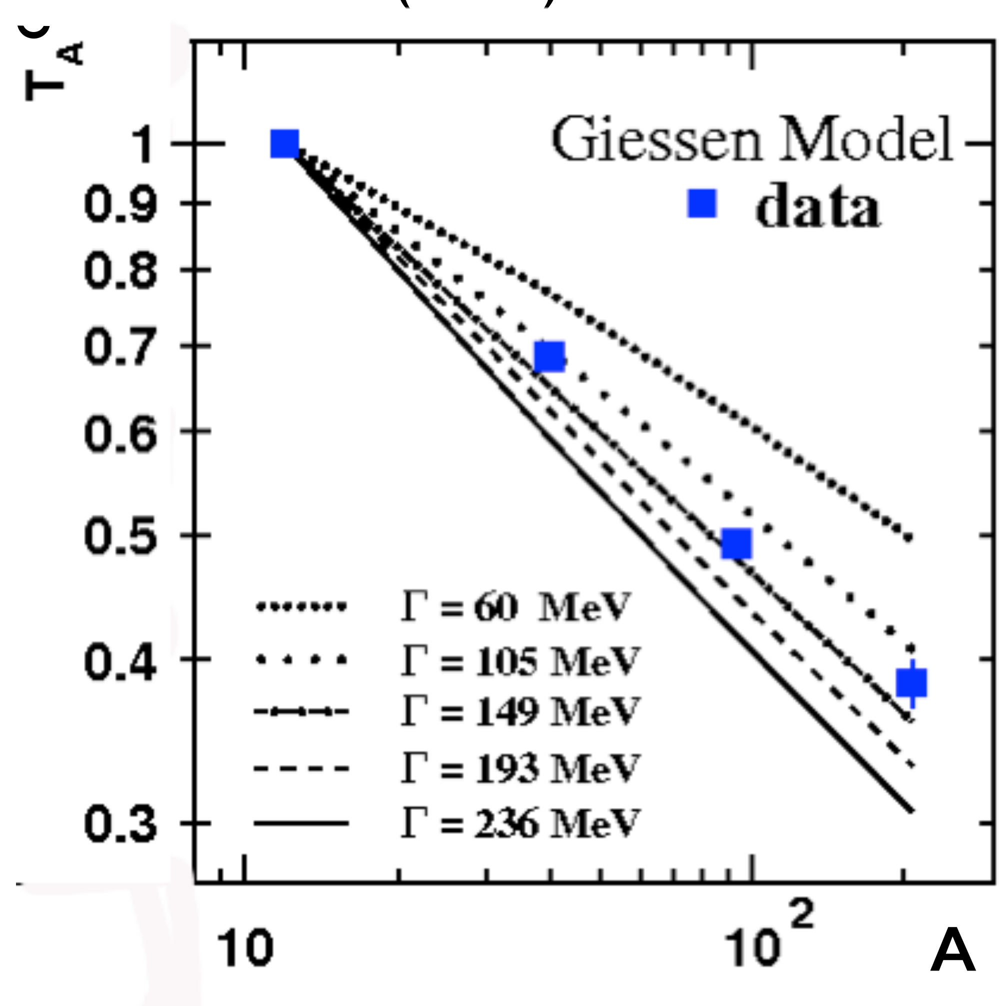
imaginary part of the ω- and η'-nucleus optical potential

ω

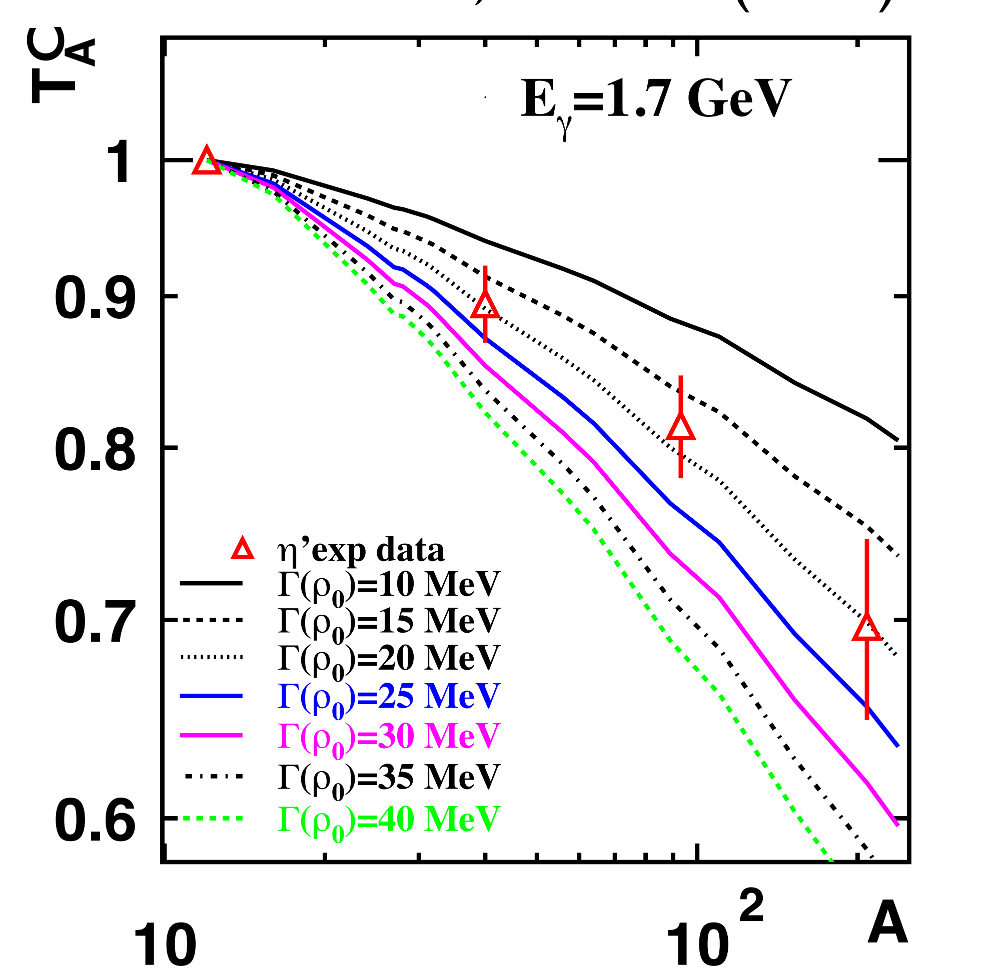
η'

$$T_A^C = \frac{12 \cdot \sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma C \to \eta' X}}$$ normalized to carbon

M. Kotulla et al.,
PRL 100 (2008) 192302,
PRL 114 (2915) 199903



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



low density approximation: $\Gamma(\rho_0) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}$

$\Gamma_\omega(\langle p_\omega \rangle = 1.1$ GeV/c; $\rho = \rho_0) \approx$ 130-150 MeV

$\sigma^\omega_{inel} \approx$ 60 mb

$\Gamma_{\eta'}(\langle p_{\eta'} \rangle \approx 1.05$ GeV/c $) \approx$ 15-25 MeV;

$\sigma^{\eta'}_{inel} \approx$ 3 -10 mb

ω: $W(\rho=\rho_0) = -\Gamma_0/2 = -(70\pm5)$ MeV

η': $W(\rho=\rho_0) = -\Gamma_0/2 = -(10\pm2.5)$ MeV

what have we learned from transparency ratio measurements ?

- transparency ratio measurements provide information on absorption of mesons in nuclei ⇒ imaginary part $W(\rho=\rho_0)$ of meson-nucleus potential; applicable for any meson lifetime

- **ω, η',Φ mesons show broadening in nuclei;**
  lifetime shortened (width increased) by inelastic processes

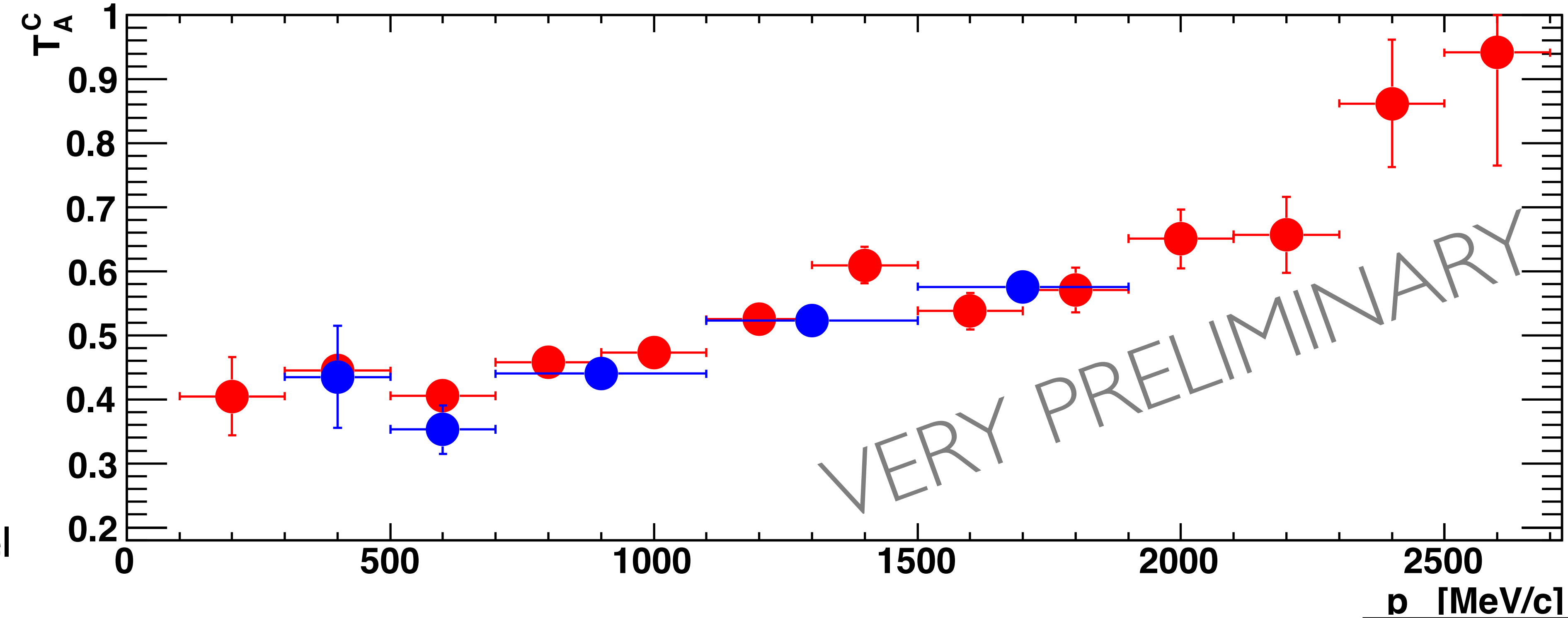
	$\Gamma(\rho_0)$ [MeV]	< p >[GeV/c]	$W(\rho=\rho_0)$ [MeV]	σ_{inel} [mb]	experiment
ω	130-150	1,1	65-75	≈ 60	CBELSA/ TAPS
η'	15-25	1,1	7.5-12.5	3-10	CBELSA/ TAPS
Φ	30-60	0,6-1,4	15-30	14-21	ANKE@ COSY
Φ	100^{+50}_{-30}	1,8	50^{+25}_{-15}	35^{+17}_{-11}	LEPS@ SPring-8

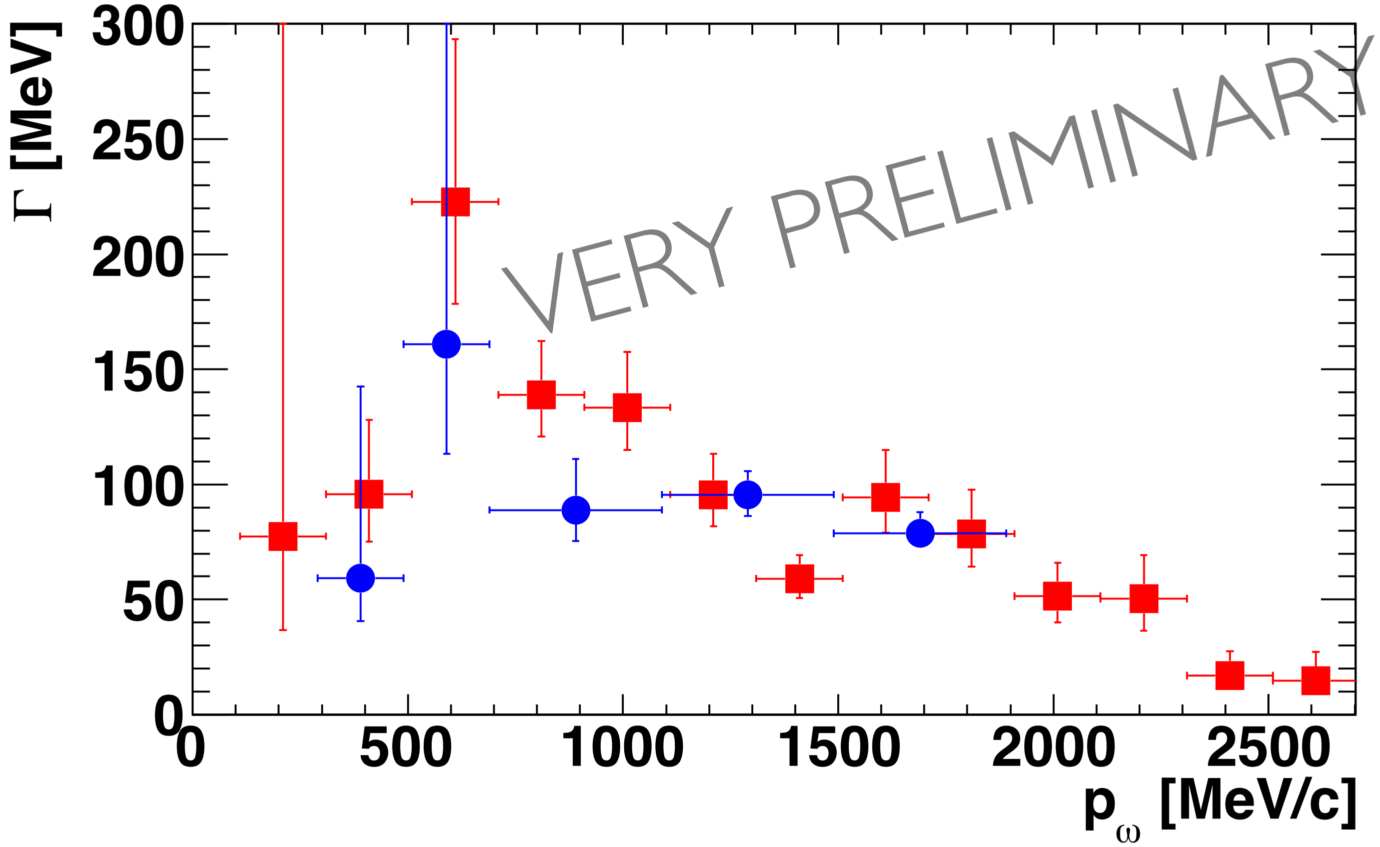
momentum dependence of T_A^C, Γ and σ_{inel} for ω mesons

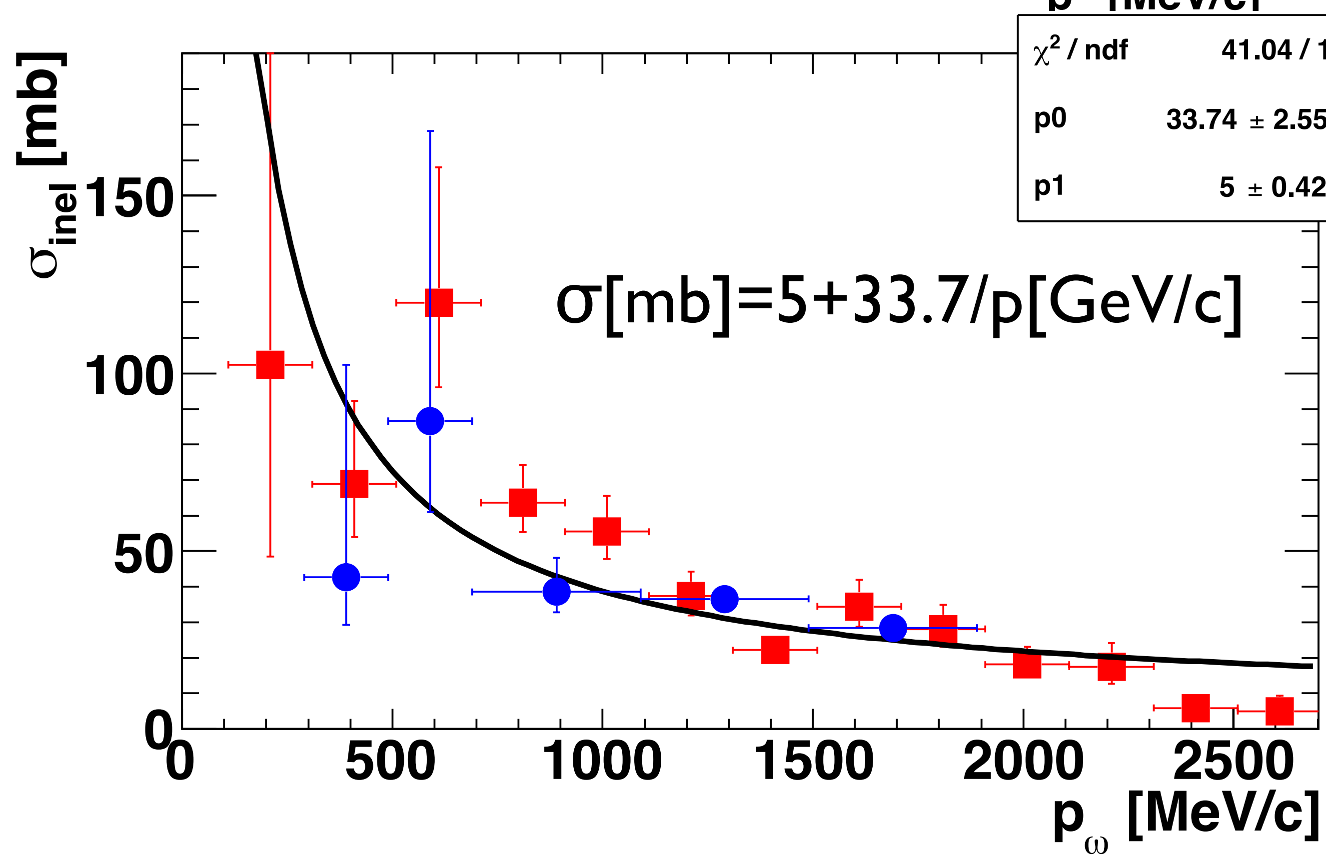
S. Friedrich et al.

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

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





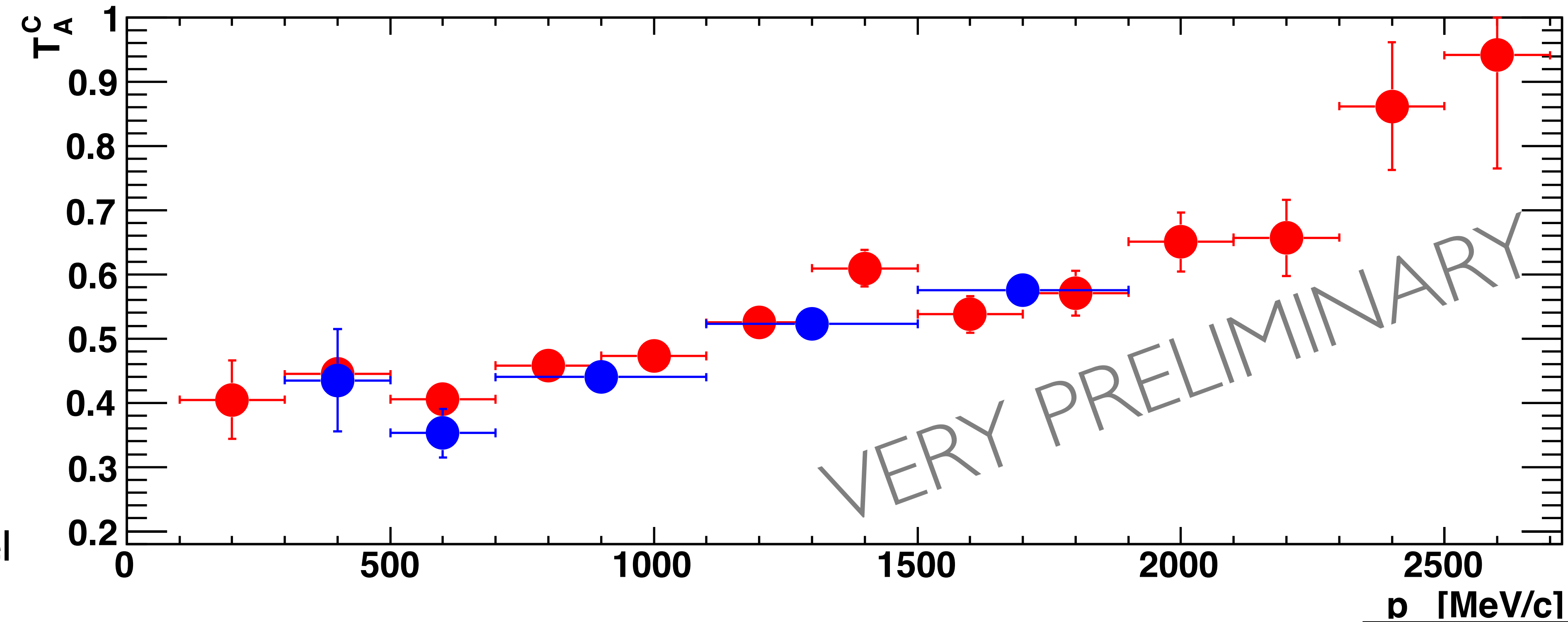


first information on momentum dependence of the imaginary part of the ω-nucleus optical potential

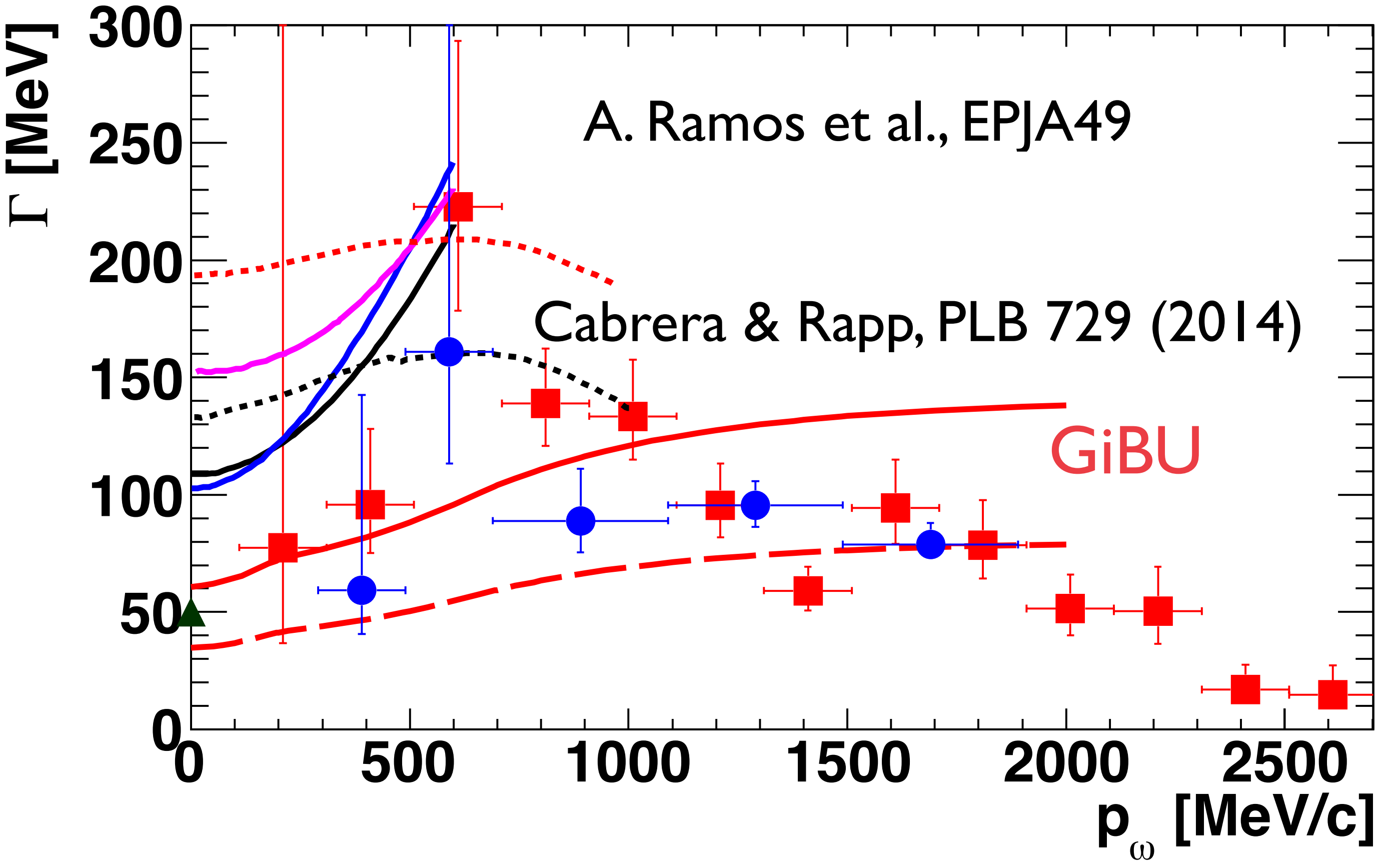
momentum dependence of T_A^C, Γ and σ_{inel} for ω mesons

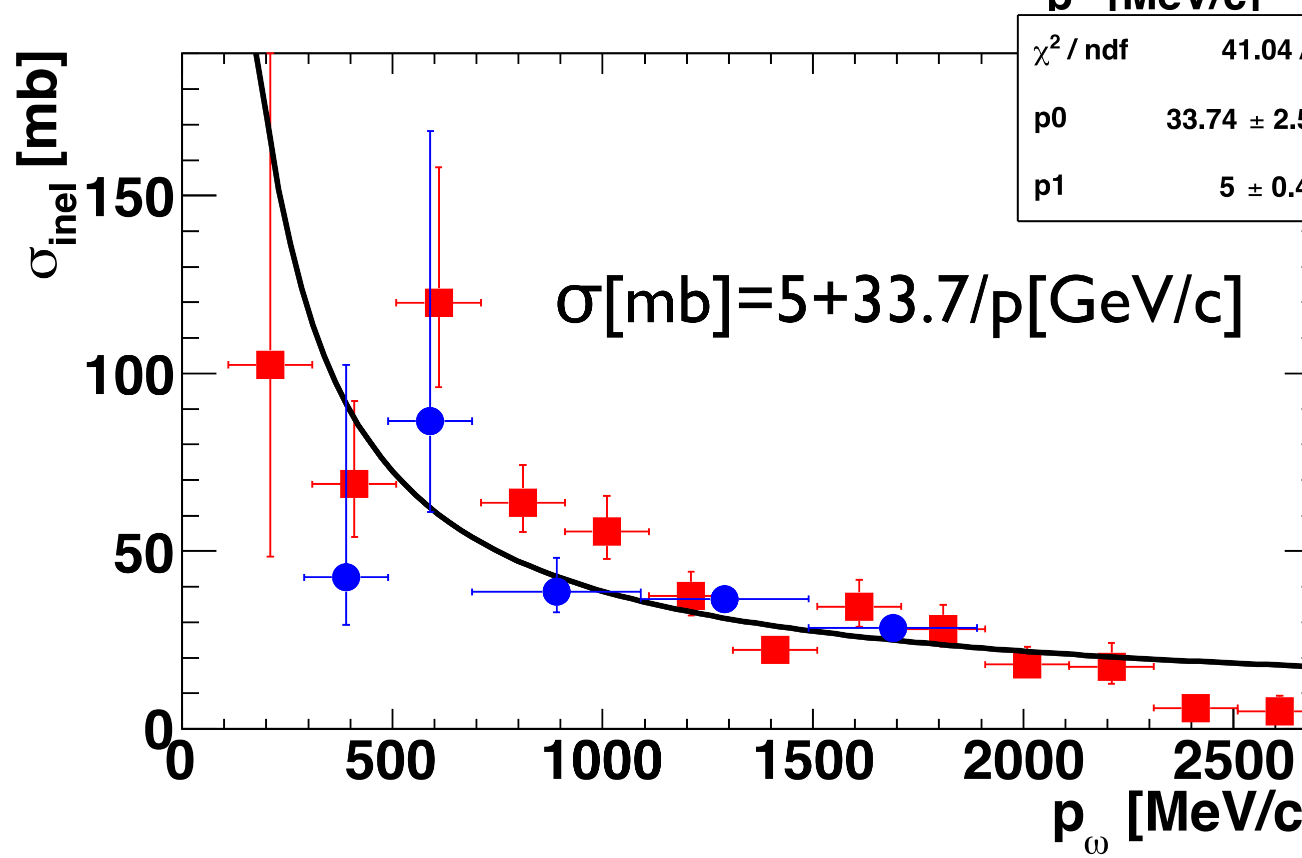
S. Friedrich et al.

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



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





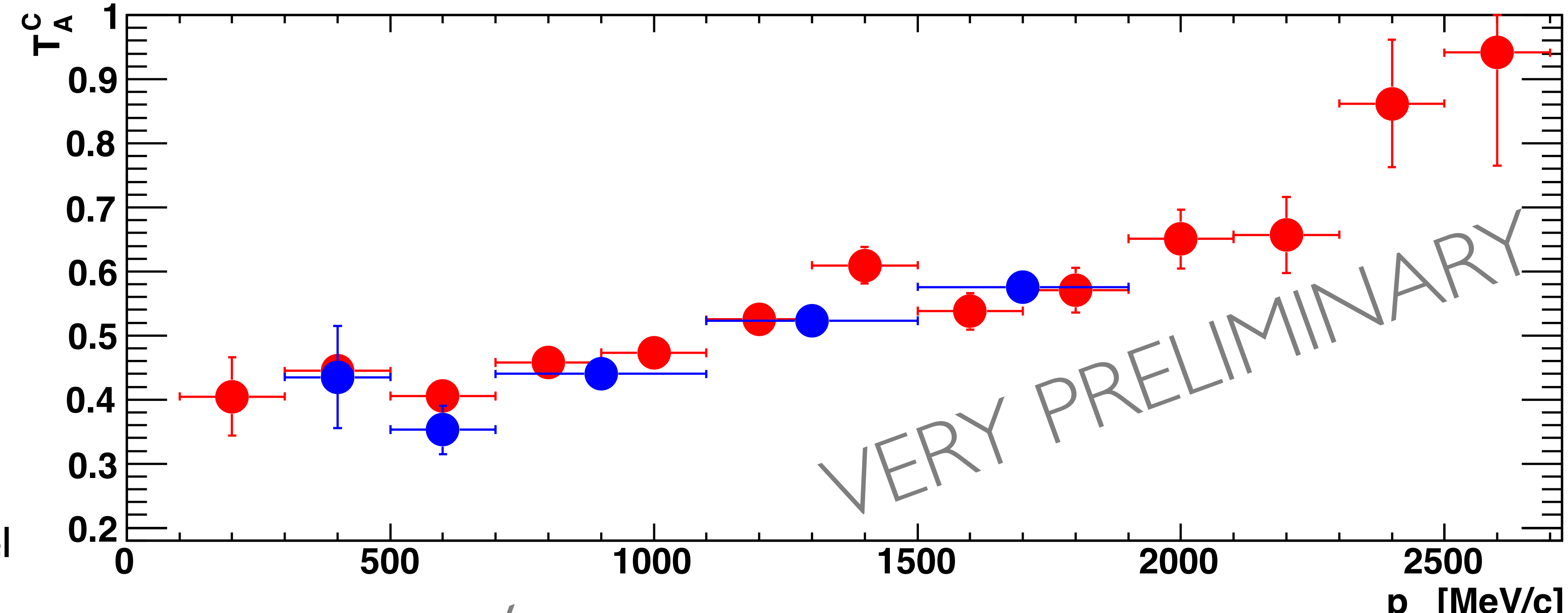
first information on momentum dependence of the imaginary part of the ω-nucleus optical potential

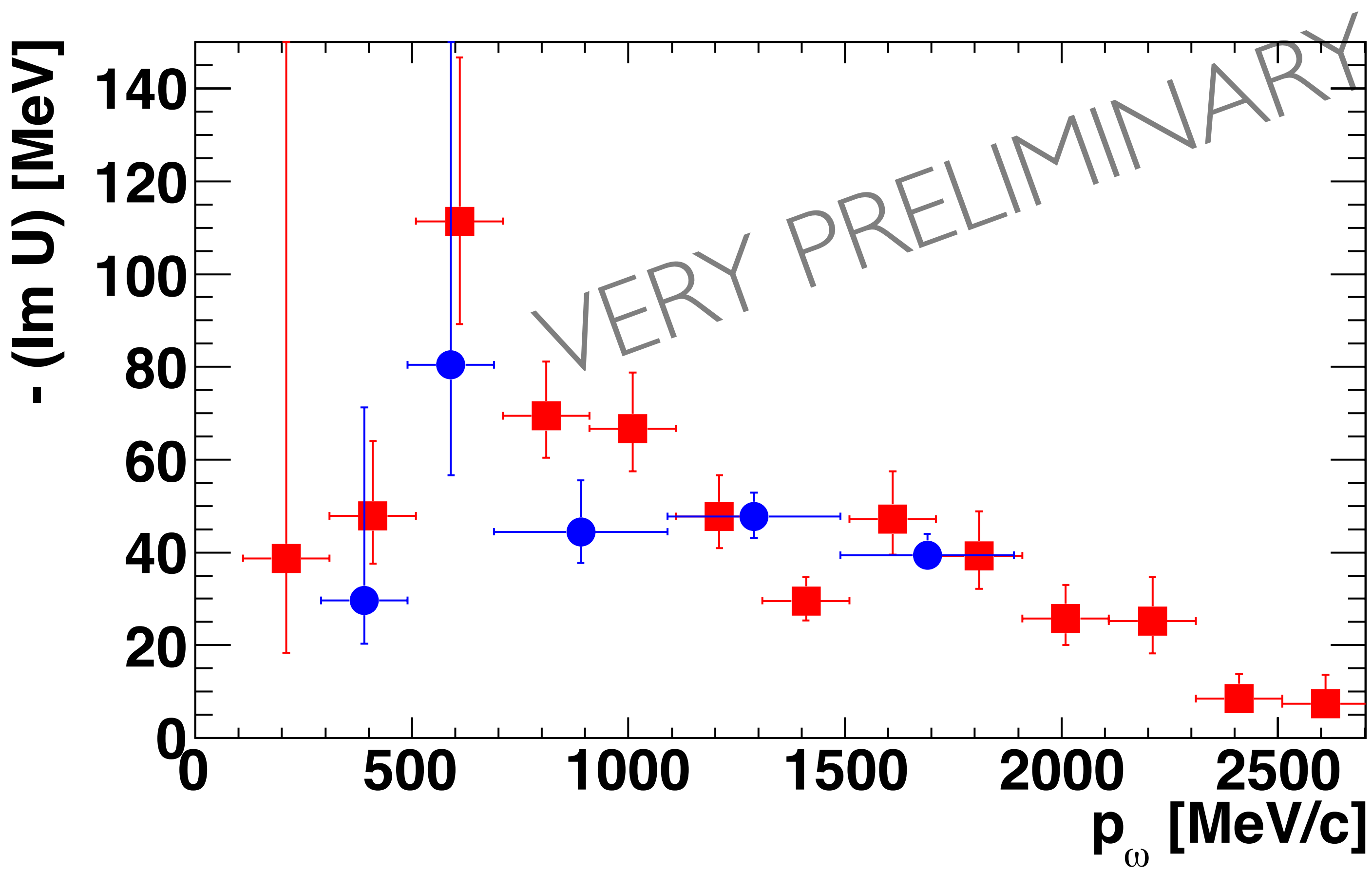
momentum dependence of T_A^C, Γ and σ_{inel} for ω mesons

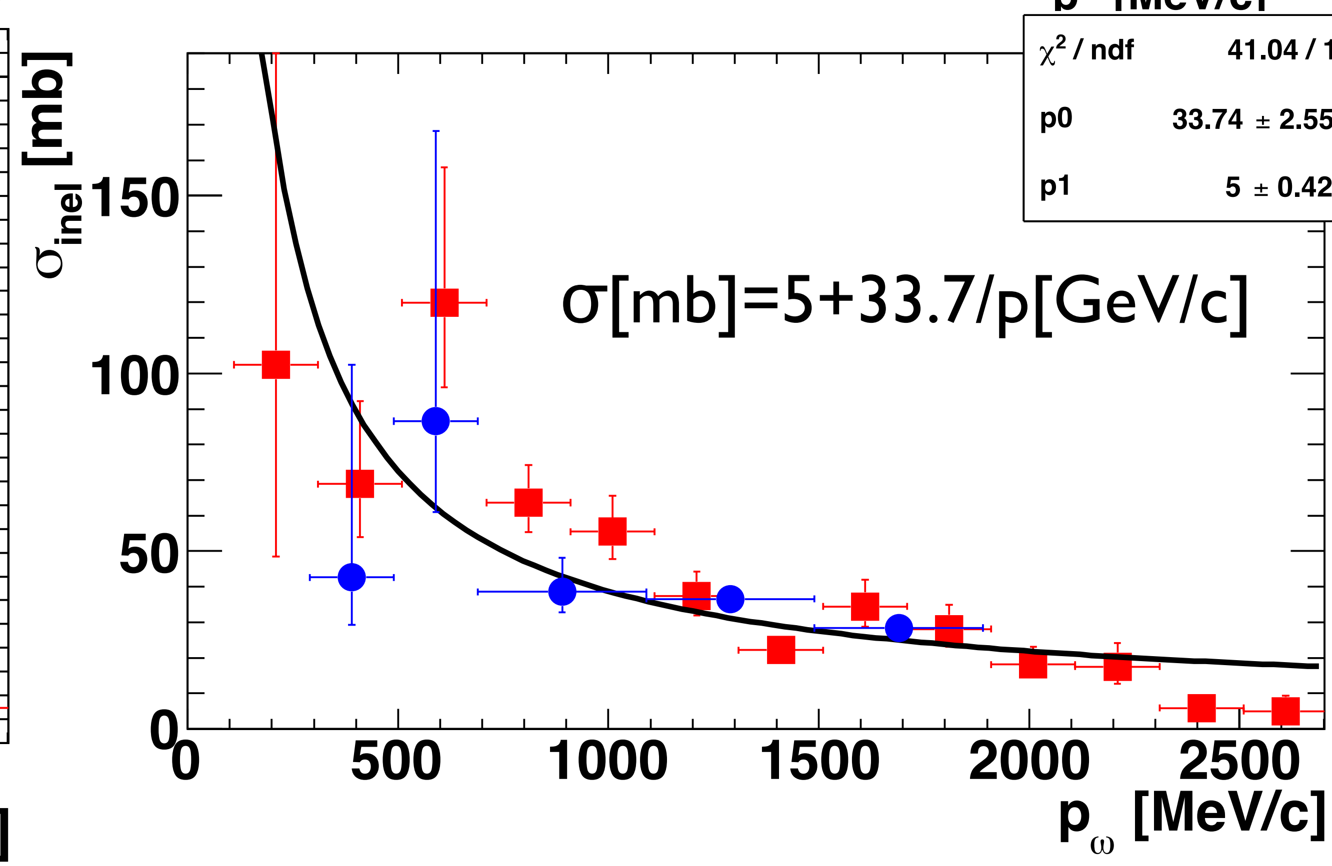
S. Friedrich et al.

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

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







first information on momentum dependence of the imaginary part of the ω-nucleus optical potential

real part of the optical potential from excitation functions and momentum distributions

The real part of the ω-nucleus potential

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

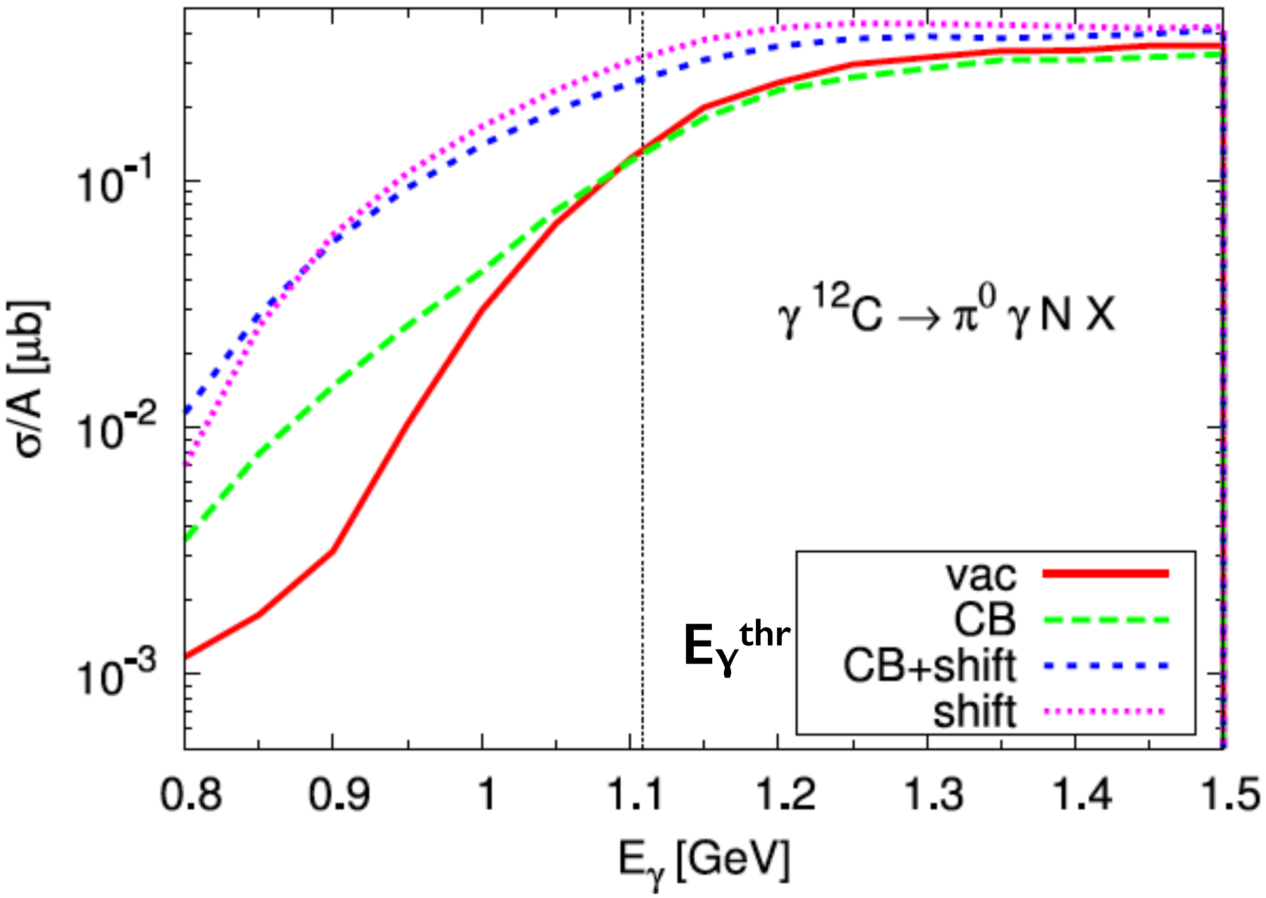
sensitive to nuclear density at production point

- 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



The real part of the ω-nucleus potential

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

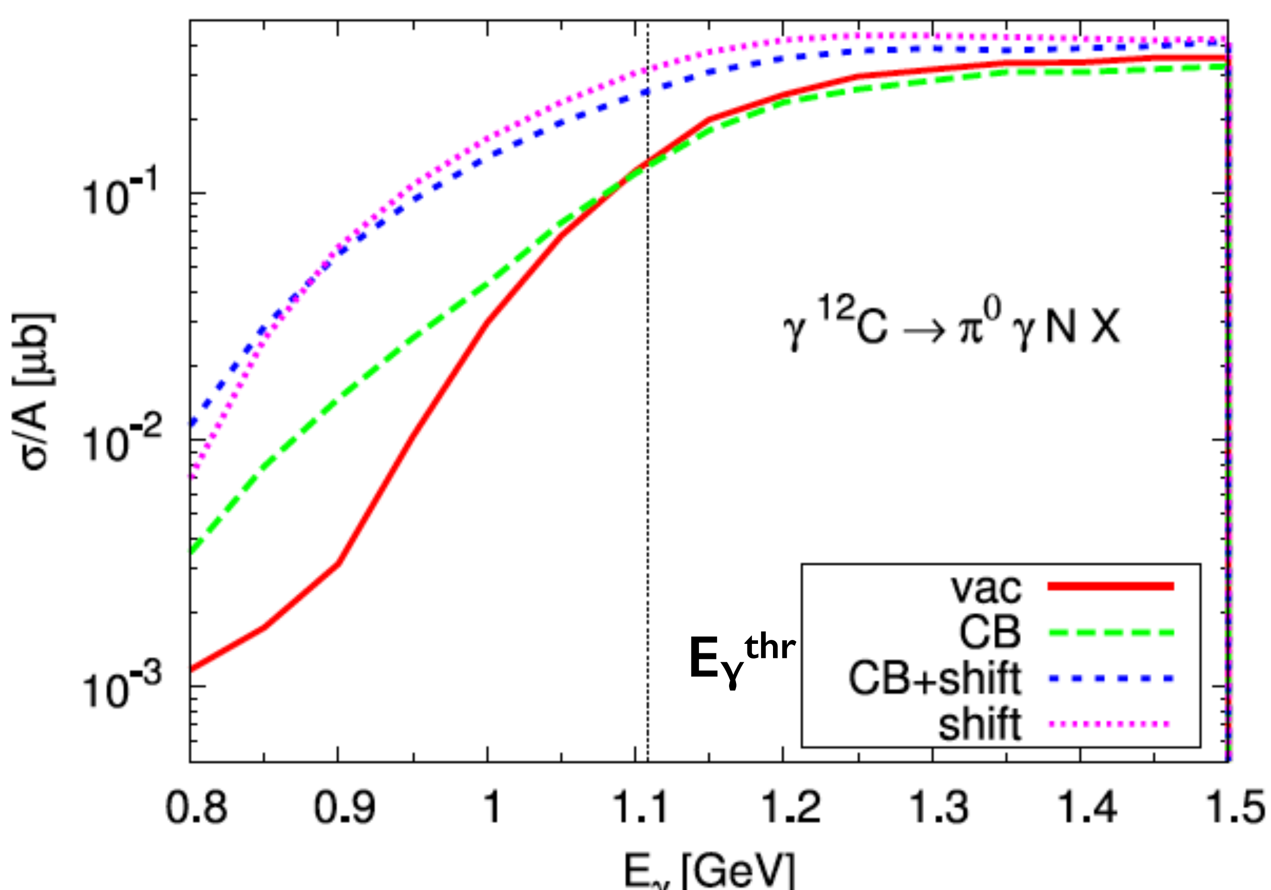
sensitive to nuclear density at production point

- 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

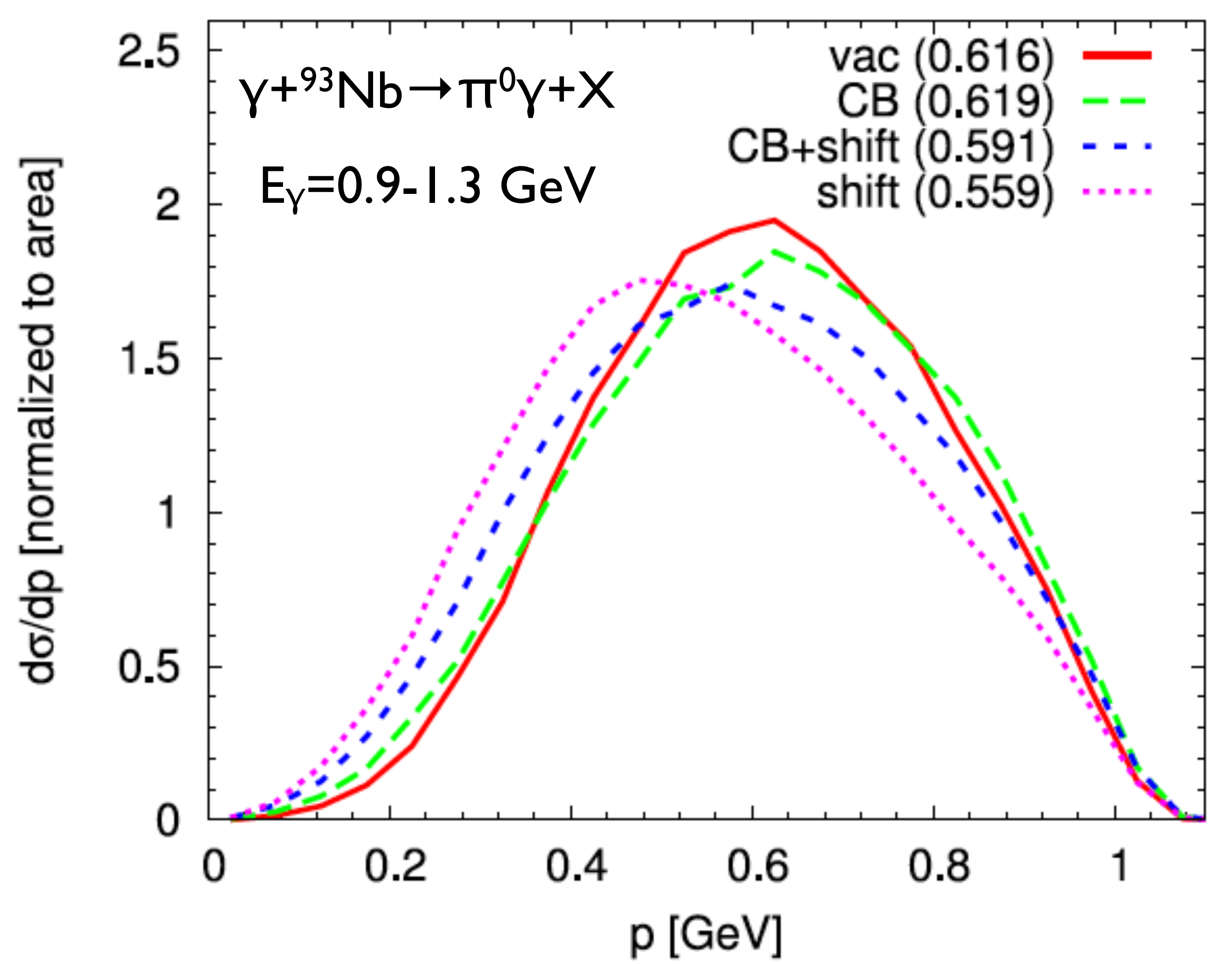


- momentum distribution of the meson:

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



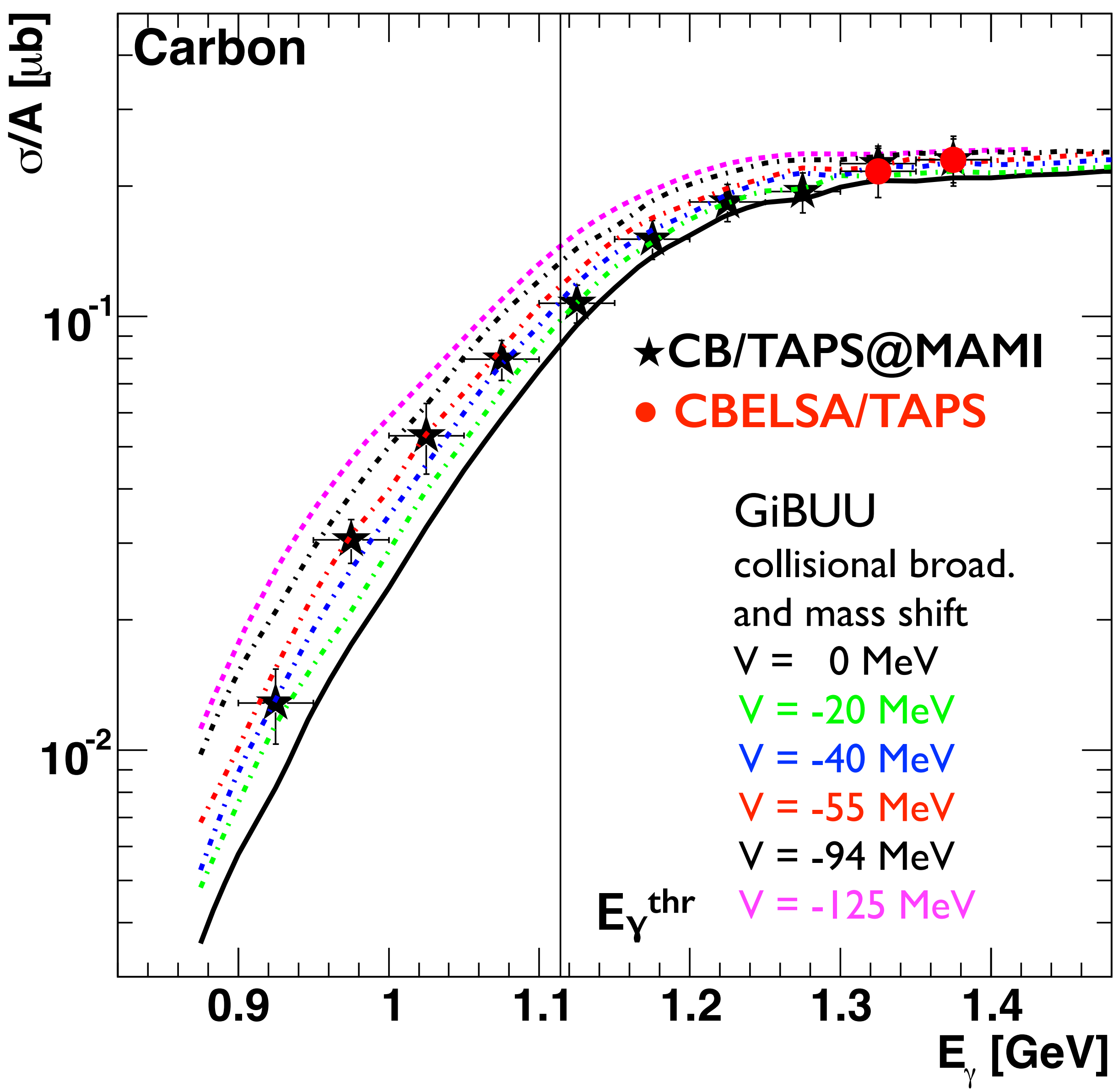
The real part of the ω-nucleus potential

ω

$\gamma A \rightarrow \omega X$

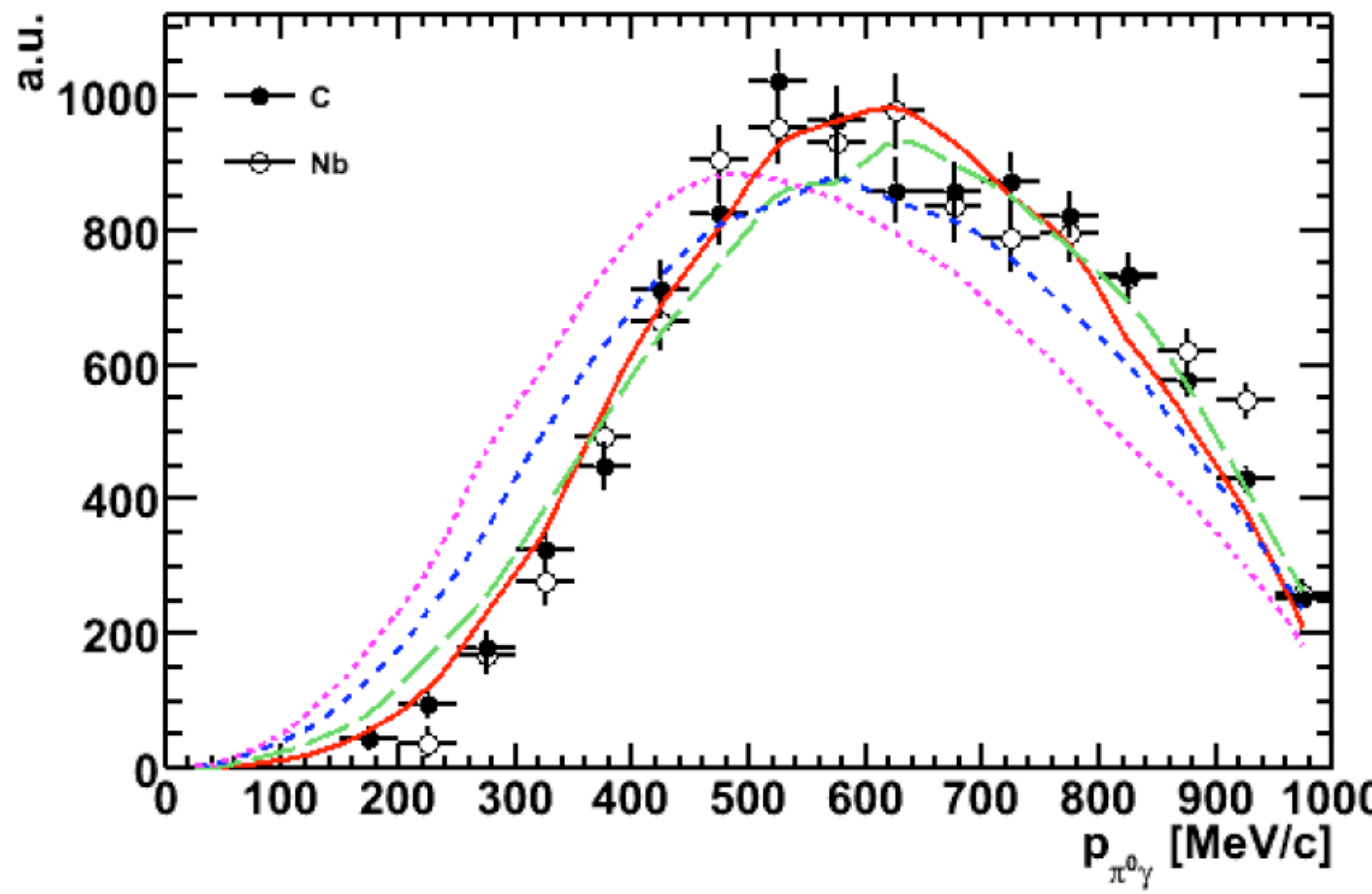
CB/TAPS @ MAMI

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



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

E_γ=900-1300 MeV



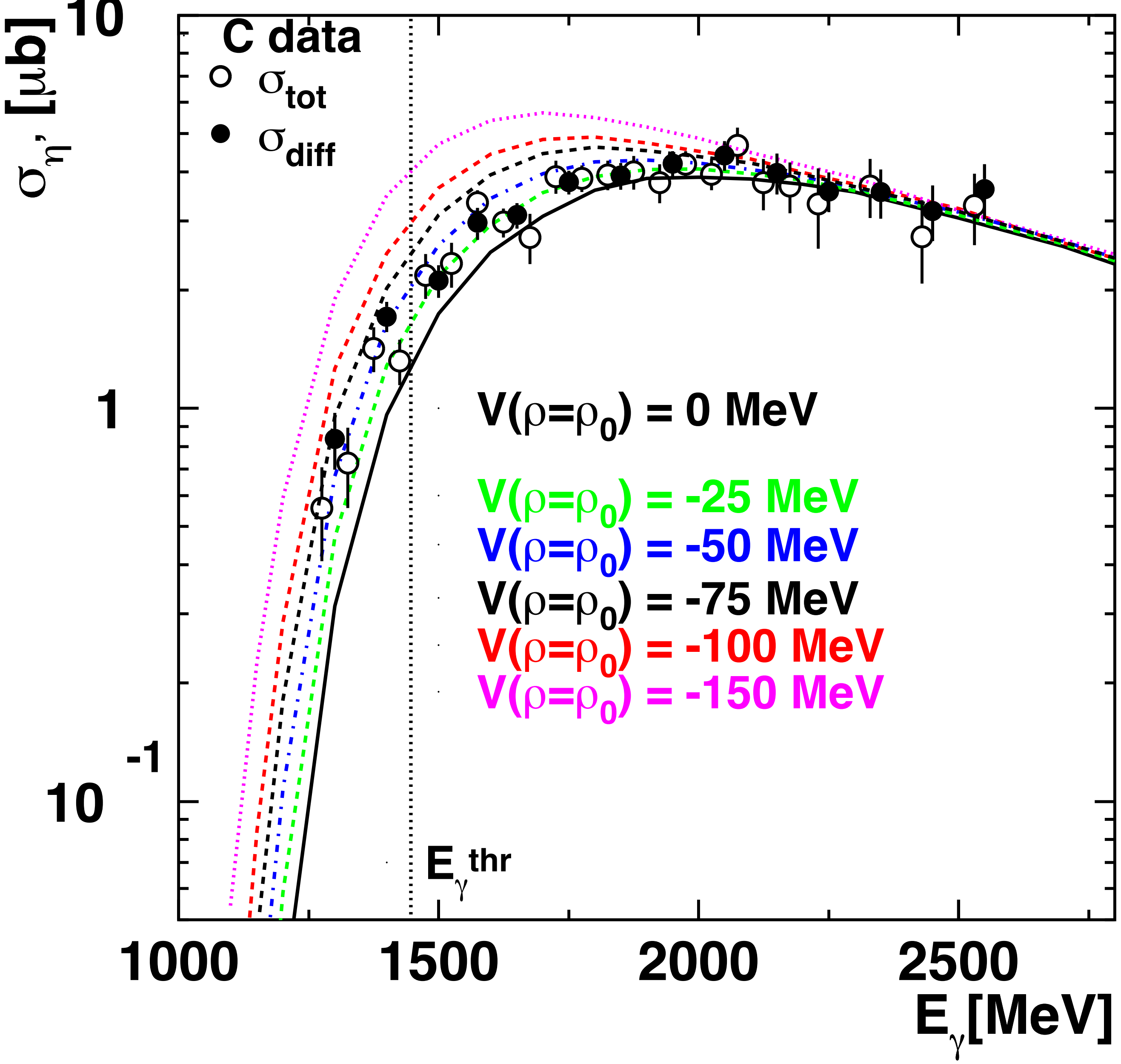
data not consistent with strong mass shift scenario ($\Delta m/m \approx -16\%$)

$V_\omega(\rho=\rho_0)$ = -(42±17(stat)±20(syst)) MeV

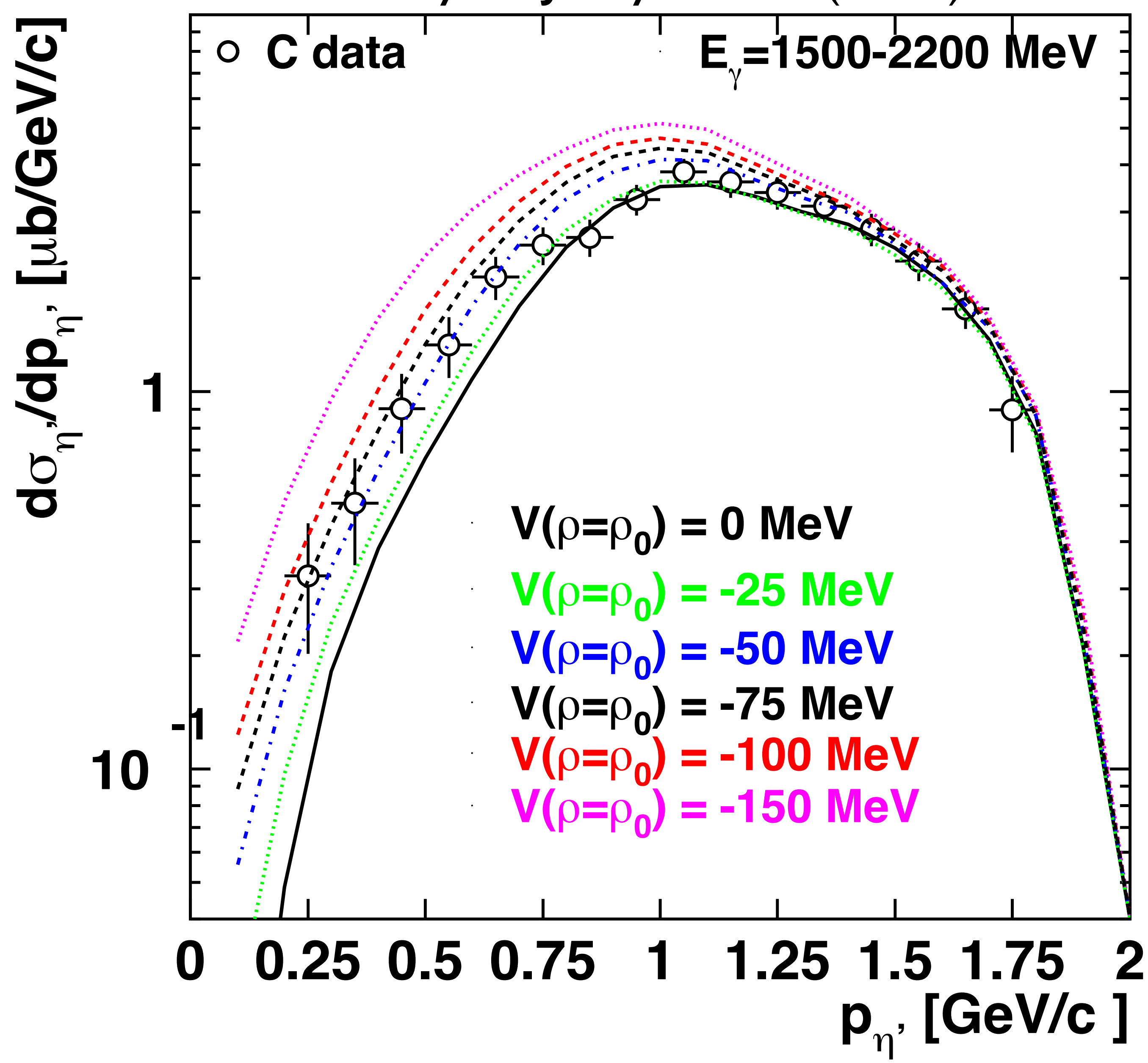
The real part of the η’-nucleus potential

η’

data: M. Nanova et al., PLB 727 (2013) 417
calc.: E. Paryev, J. Phys. G 40 (2013) 025201



data: M. Nanova et al., PLB 727 (2013) 417
calc.: E. Paryev, J. Phys. G 40 (2013) 025201



$V_{\eta'}(\rho=\rho_0)$ = -(40±6(stat)±10(syst)) MeV

data disfavour strong mass shifts

$V_{\eta'}(\rho=\rho_0)$ = -(32±1(stat)±10(syst)) MeV

$\langle p_{\eta'} \rangle \approx 1.1$ GeV/c

The real part of the η'-nucleus potential

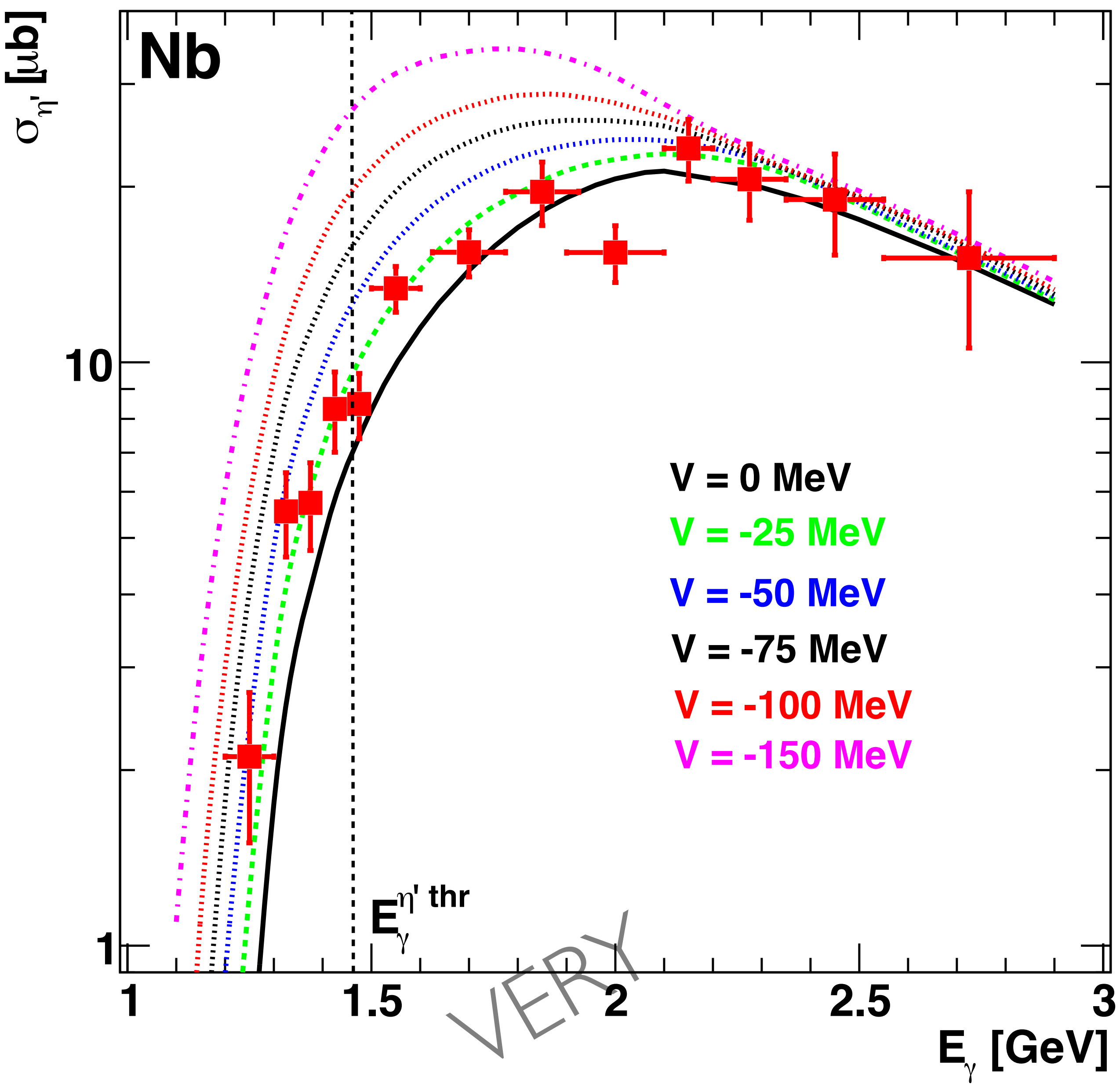
η'

Mariana Nanova

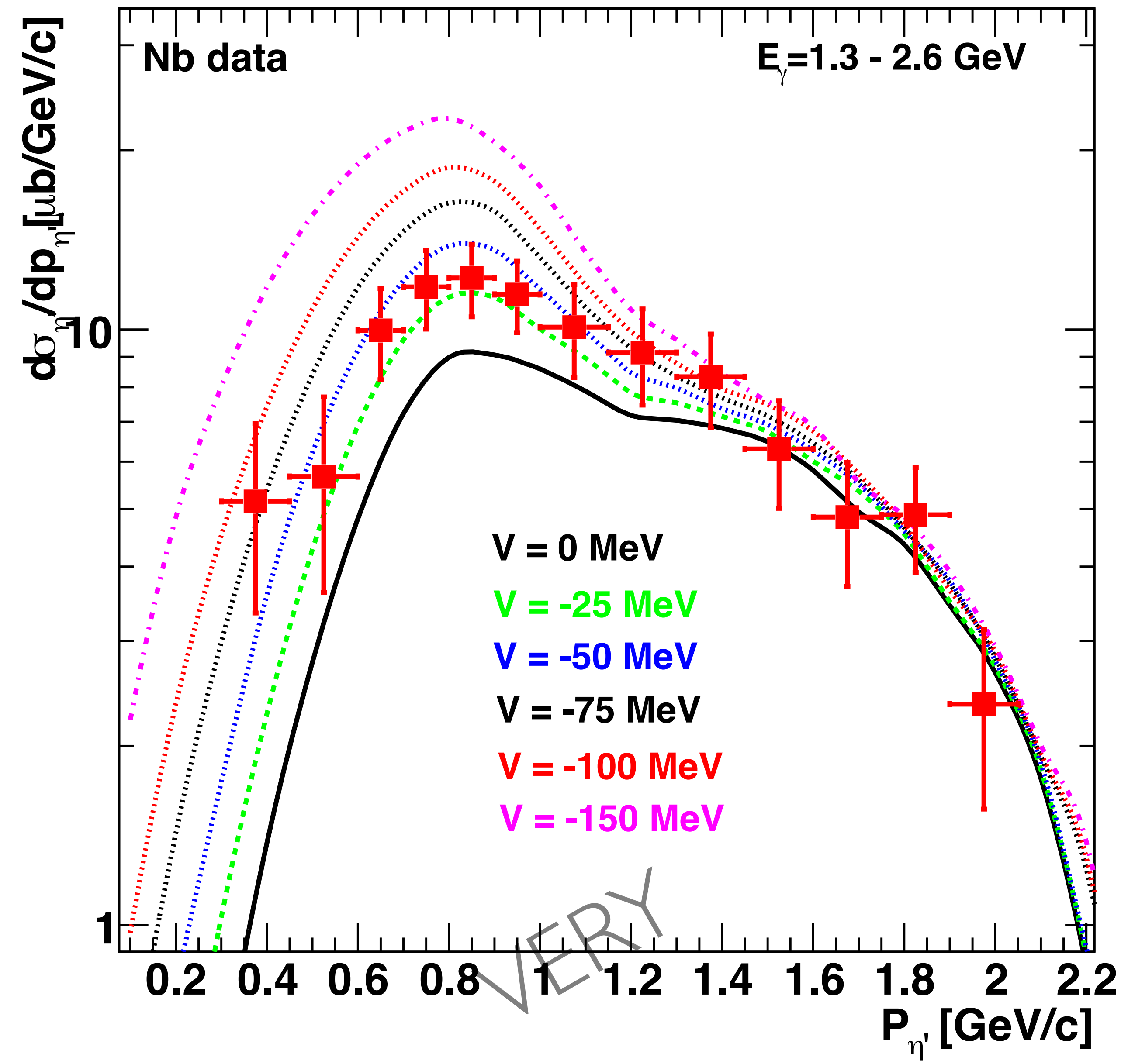
$\gamma A \rightarrow \eta' X$

data compared to calculations by E. Paryev (priv. com.)

excitation function



η' momentum distribution



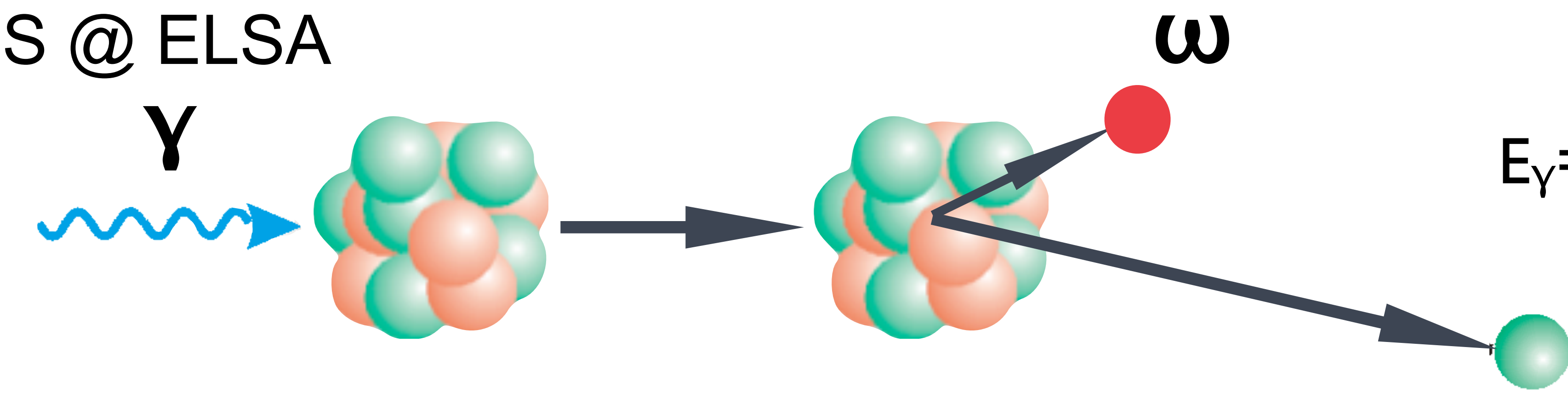
$V_\eta(\rho=\rho_0) = -(22\pm4(stat)\pm15(syst))$ MeV

$V_\eta(\rho=\rho_0) = -(38\pm5(stat)\pm15(syst))$ MeV

$\langle p_{\eta'} \rangle \approx 1.1$ GeV/c

real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA



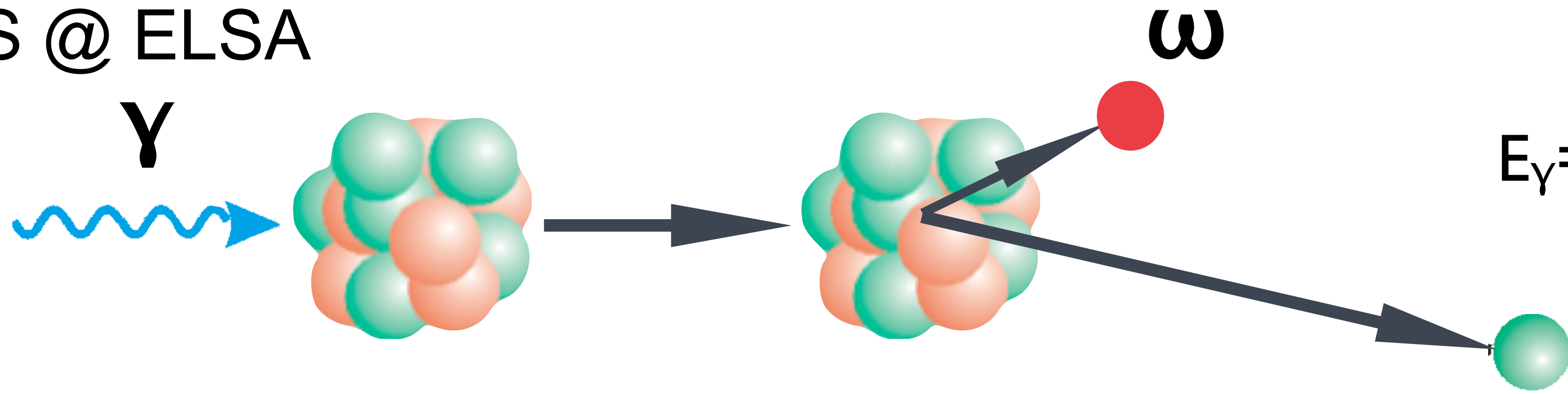
E_γ=1.25-3.1 GeV

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

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

real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA

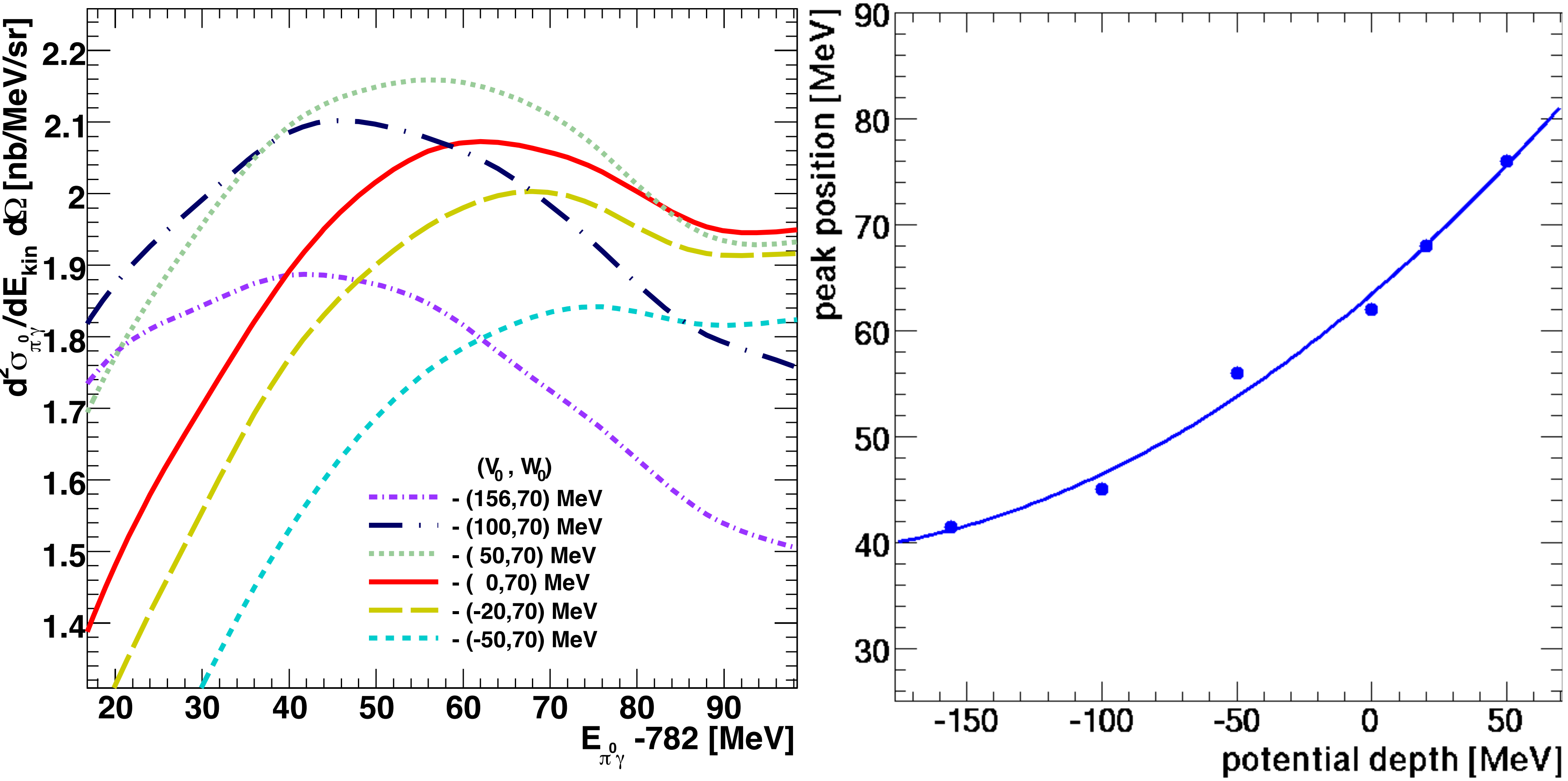


E_γ=1.25-3.1 GeV

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

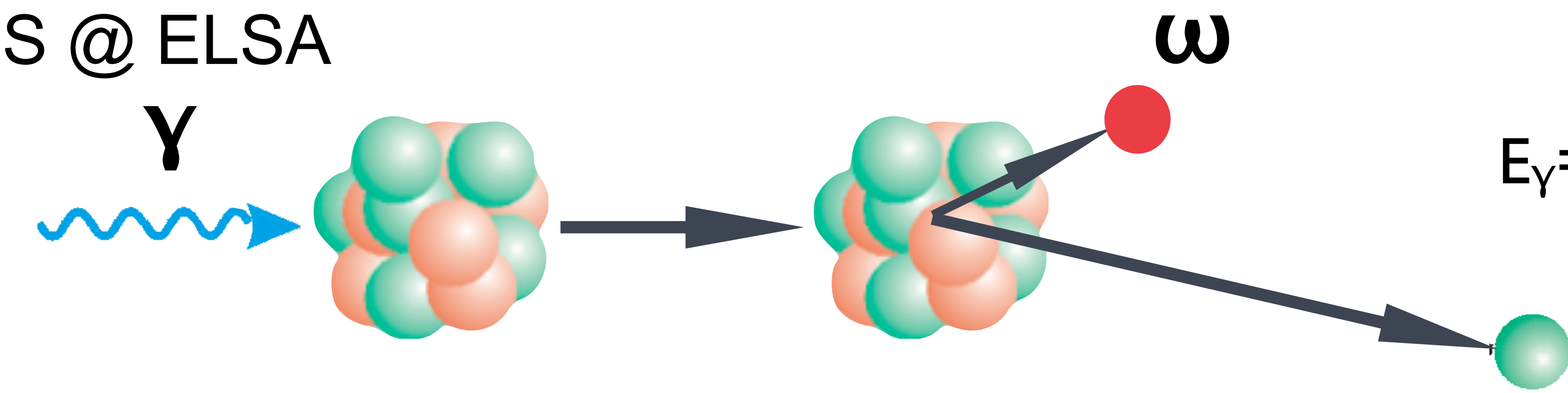
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.



real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA

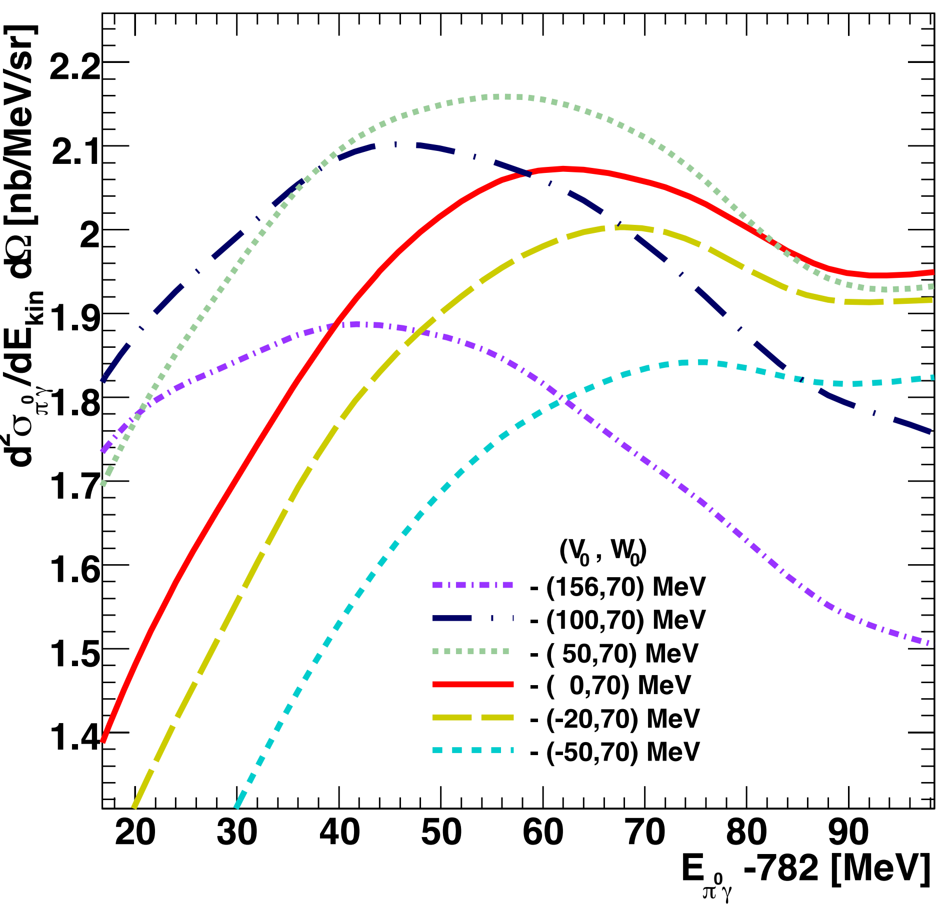


E_γ=1.25-3.1 GeV

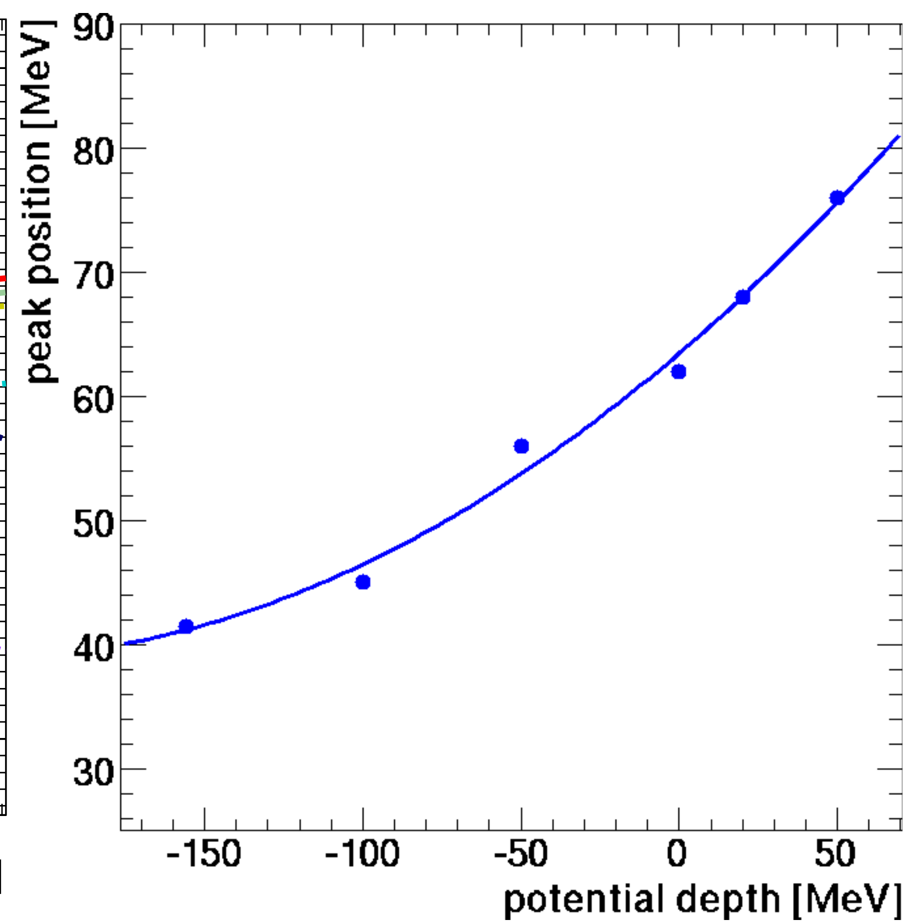
$1^0 \leq \theta_p \leq 11^0$

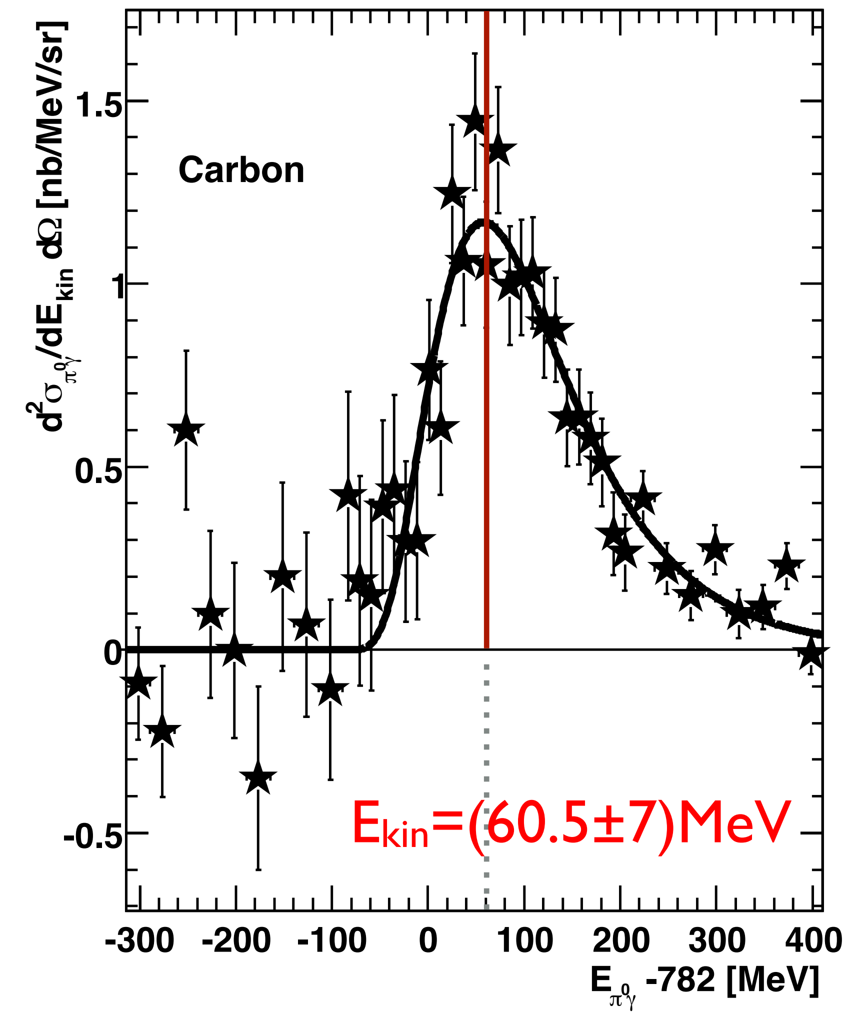
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.



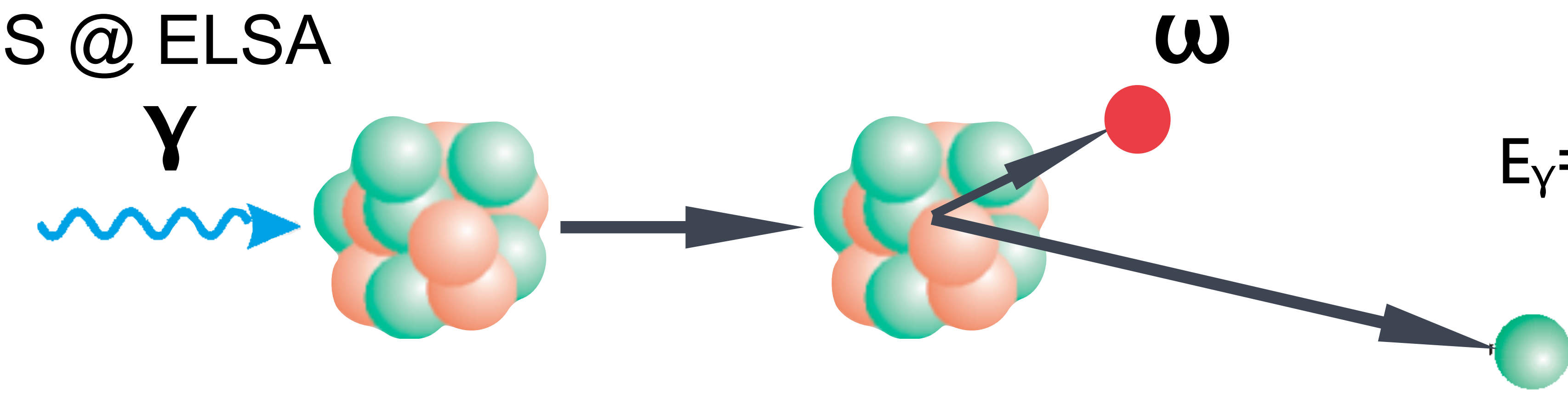
S. Friedrich, PLB 736 (2014) 26





real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA



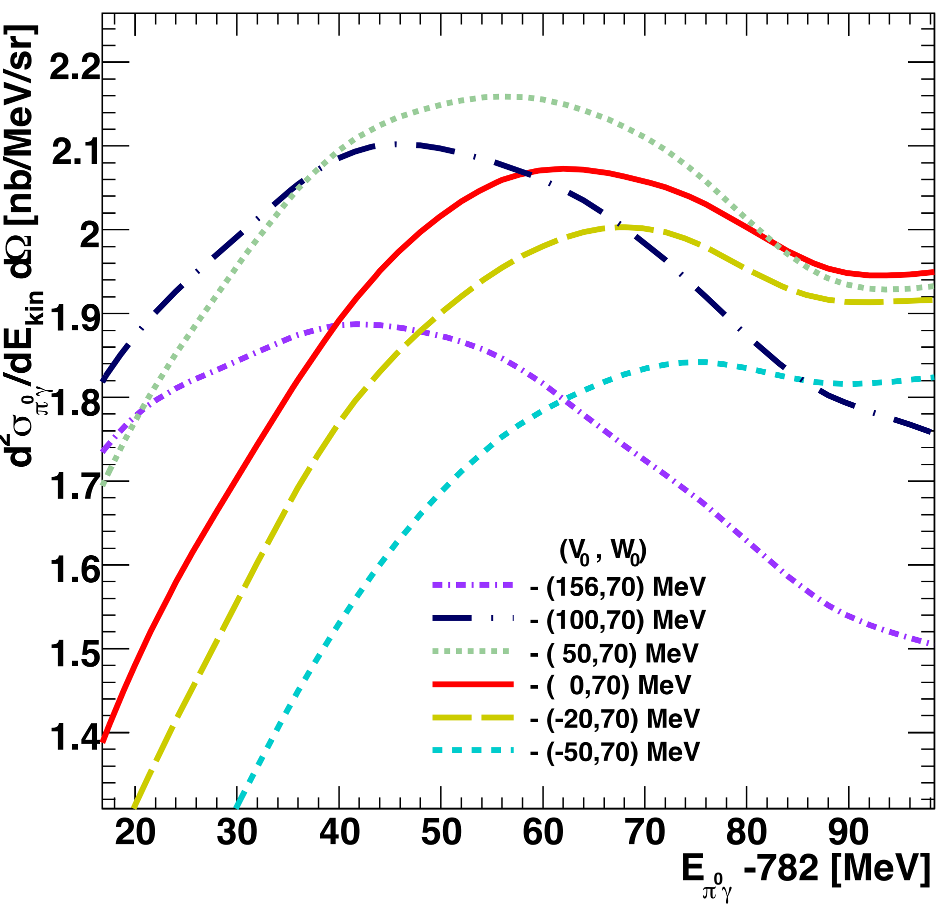
E_γ=1.25-3.1 GeV

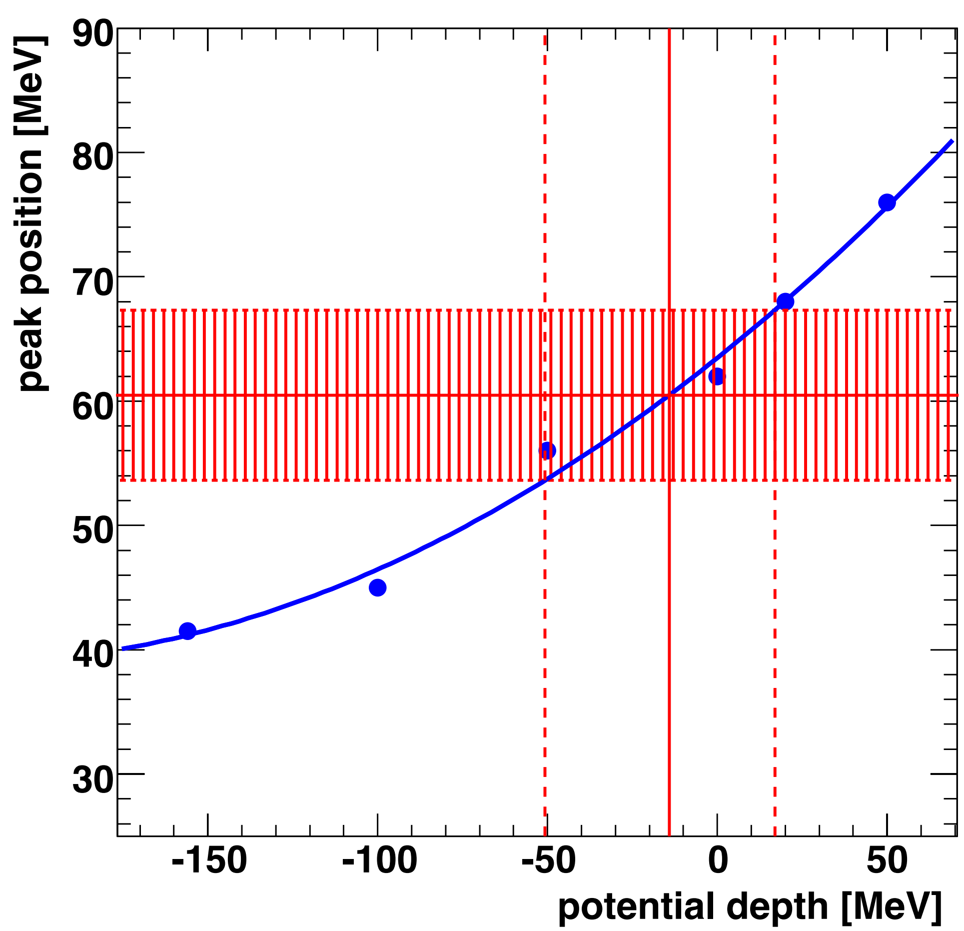
$1^0 \leq \theta_p \leq 11^0$

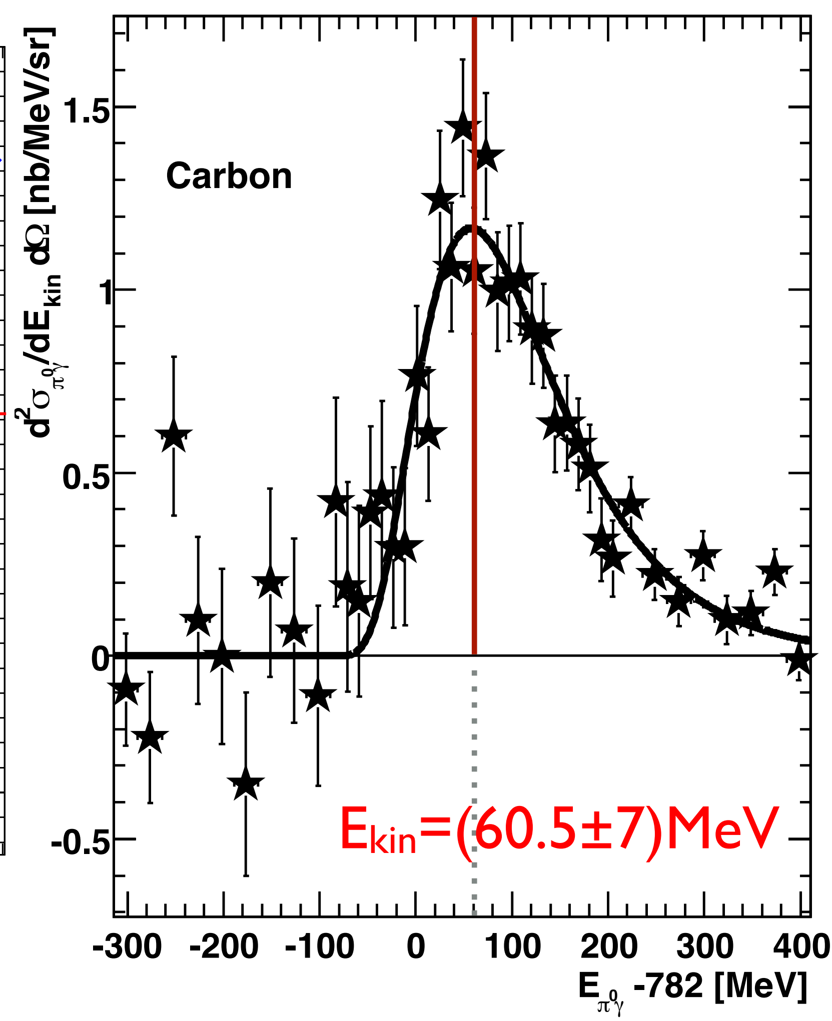
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.

S. Friedrich, PLB 736 (2014) 26





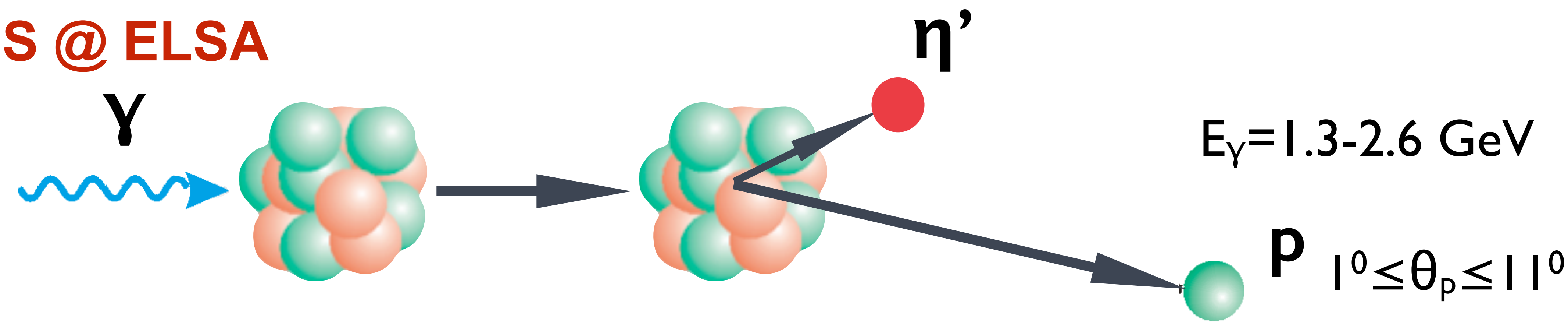


$V_\omega(p_\omega \approx 300$ MeV/c; $\rho=\rho_0)$ = -(15±35) MeV

real part of η'-nucleus potential from η' kinetic energy

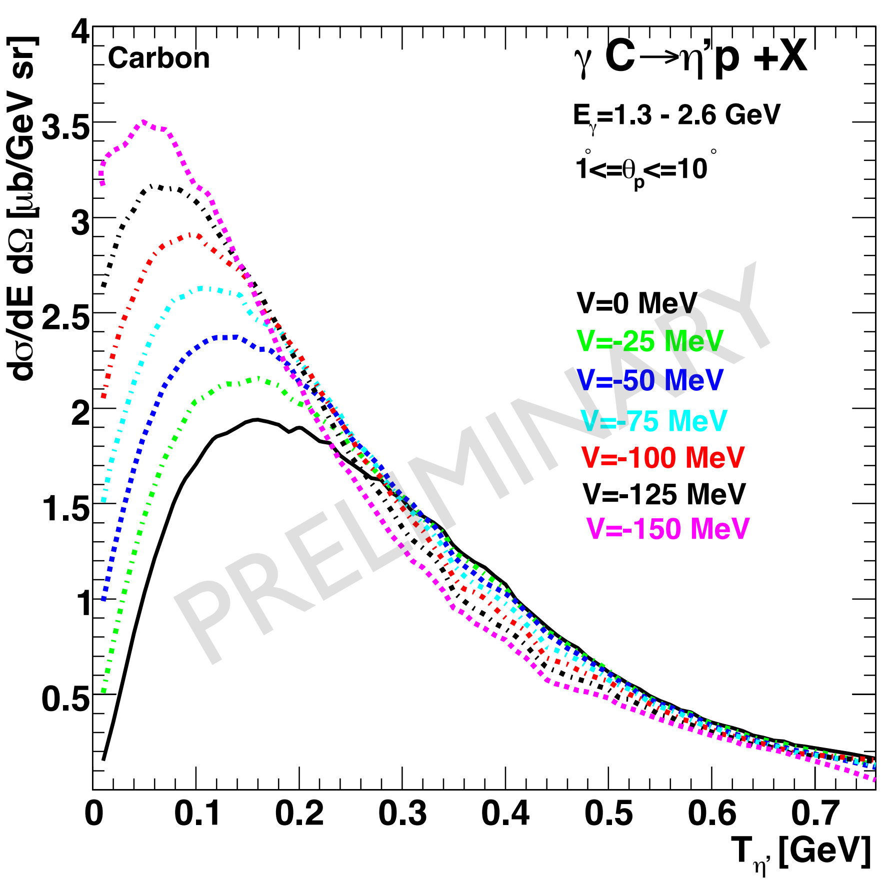
η'

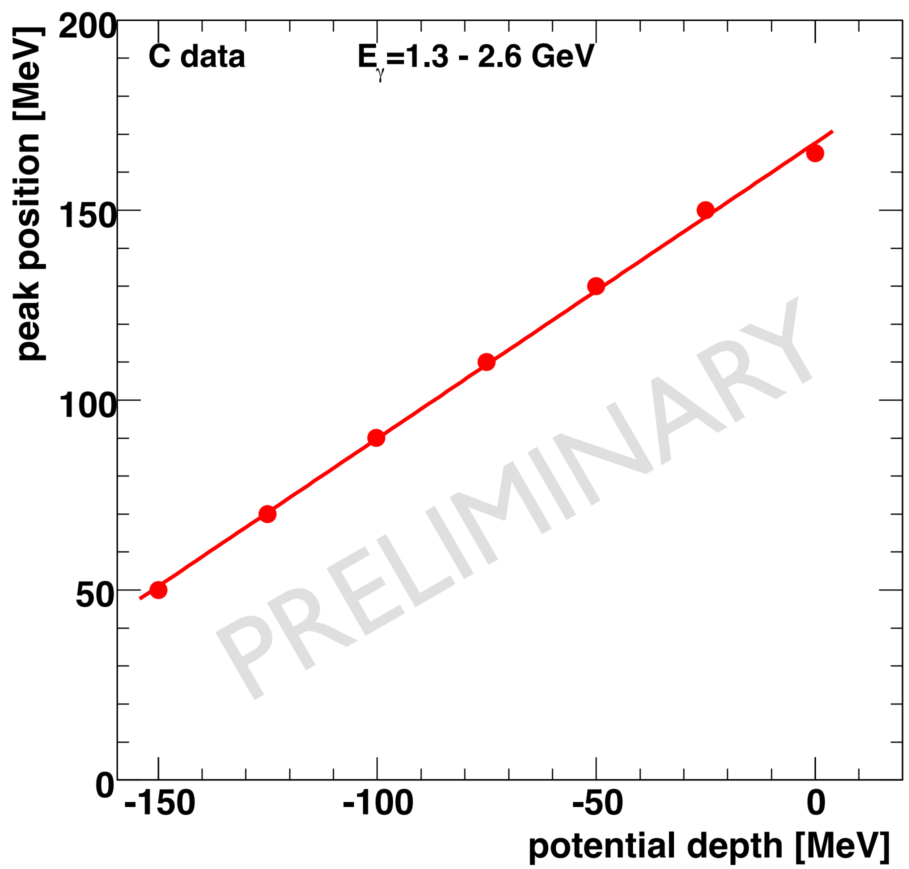
CBELSA/TAPS @ ELSA



the higher the attraction the lower the kinetic energy of the η' meson

E. Paryev, arXiv:1503.09007

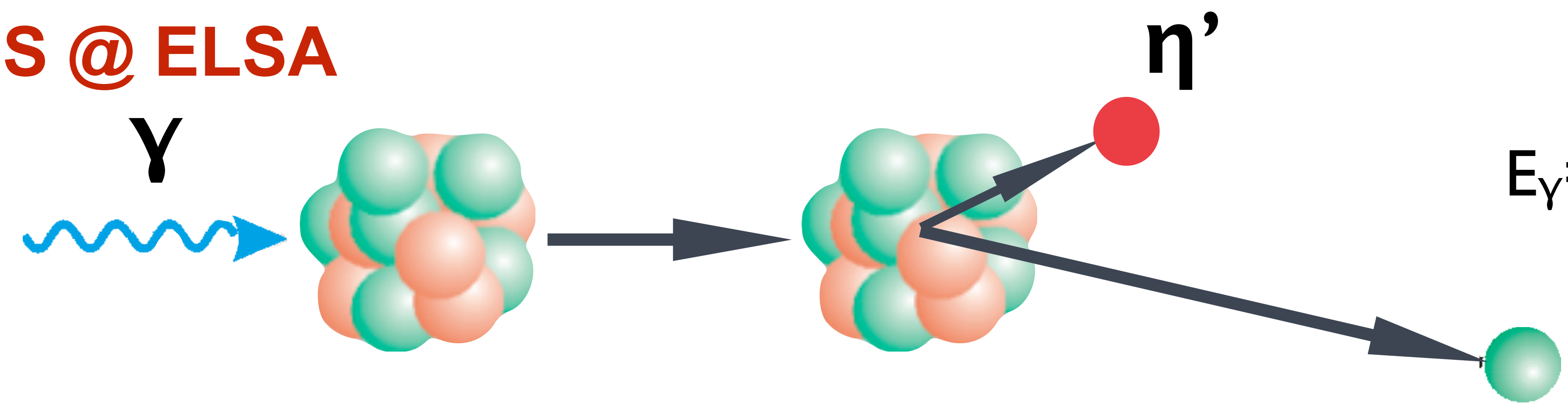




real part of η'-nucleus potential from η' kinetic energy

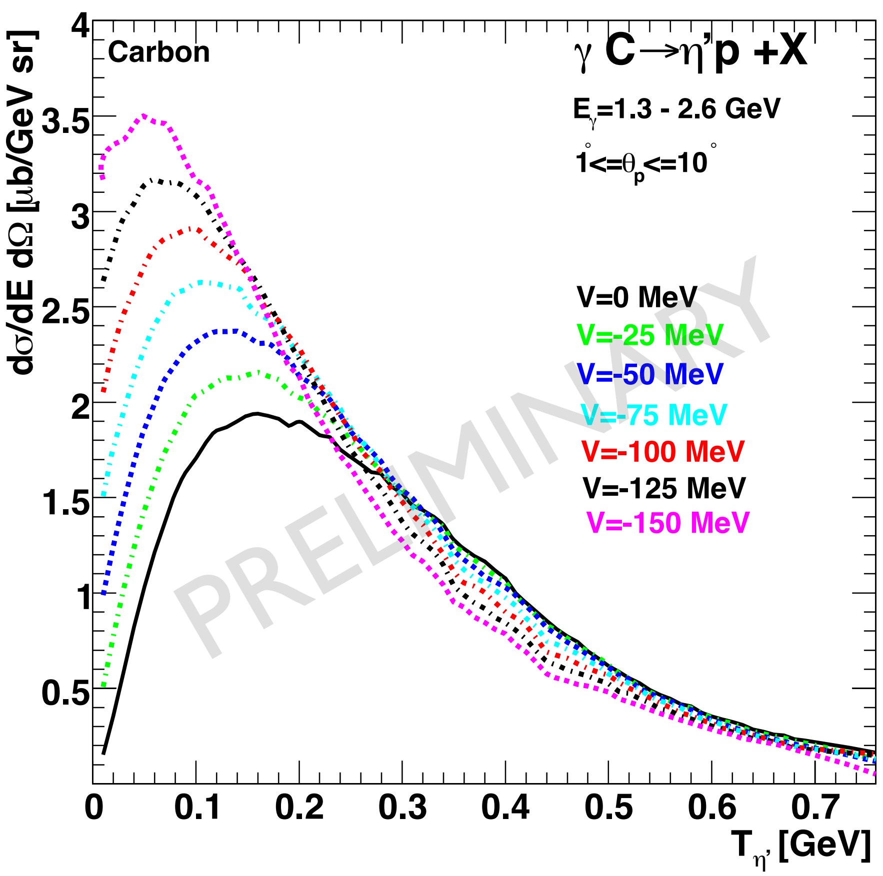
η'

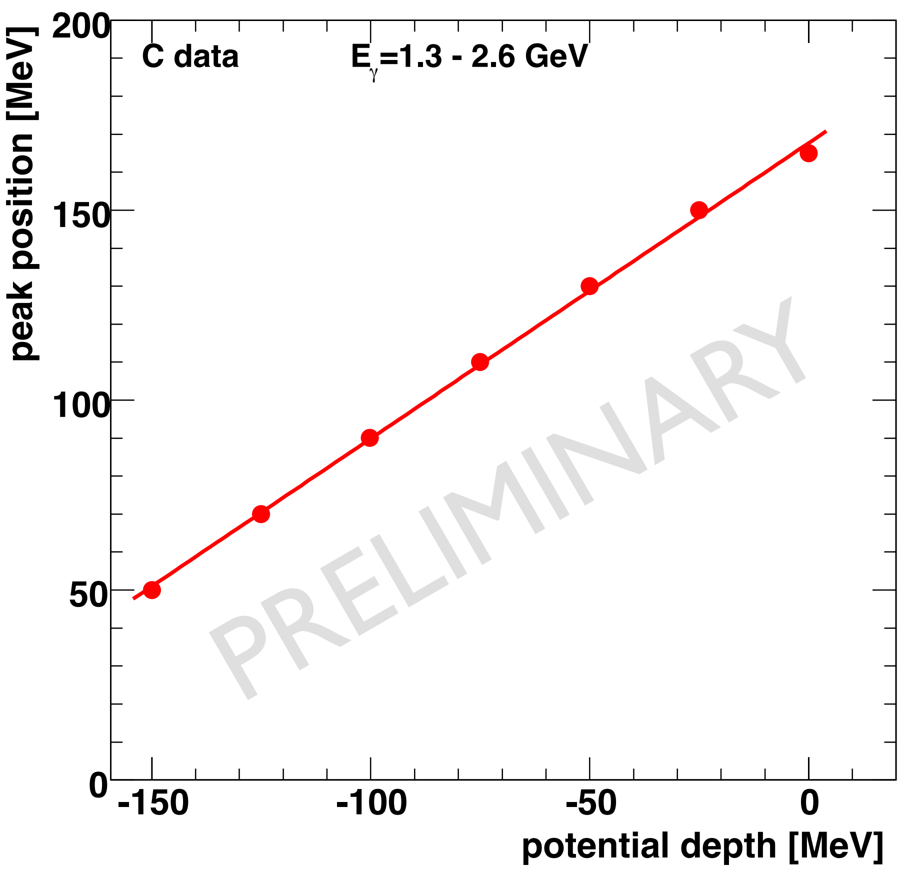
CBELSA/TAPS @ ELSA

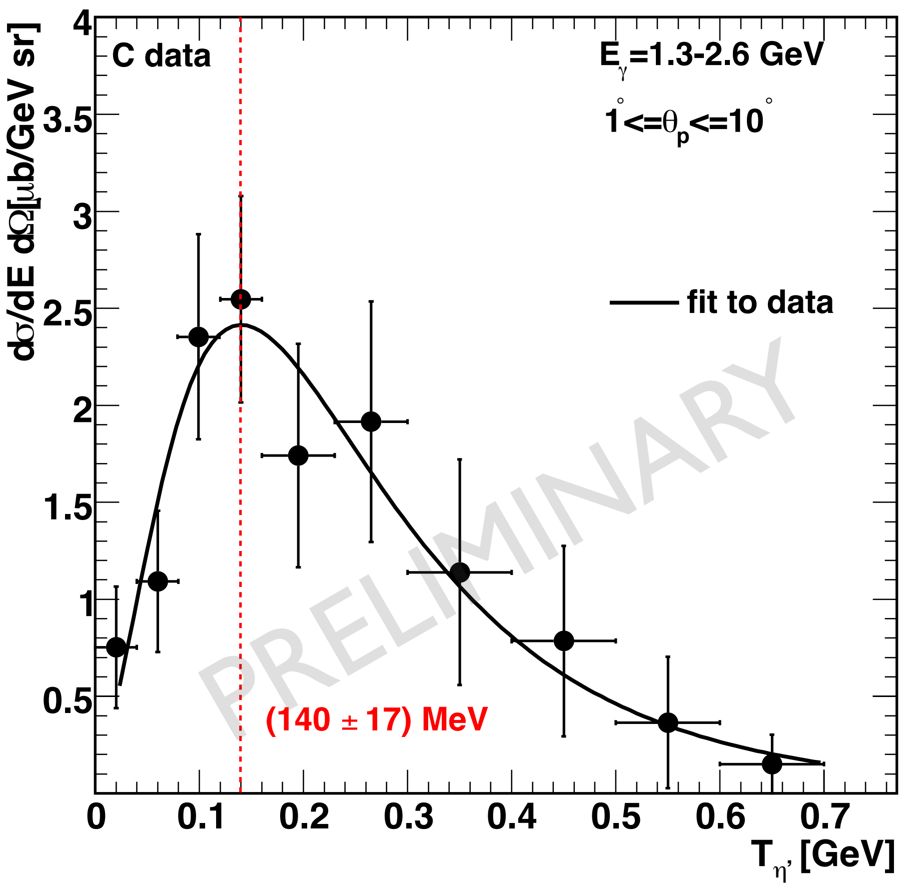


the higher the attraction the lower the kinetic energy of the η' meson

E. Paryev, arXiv:1503.09007



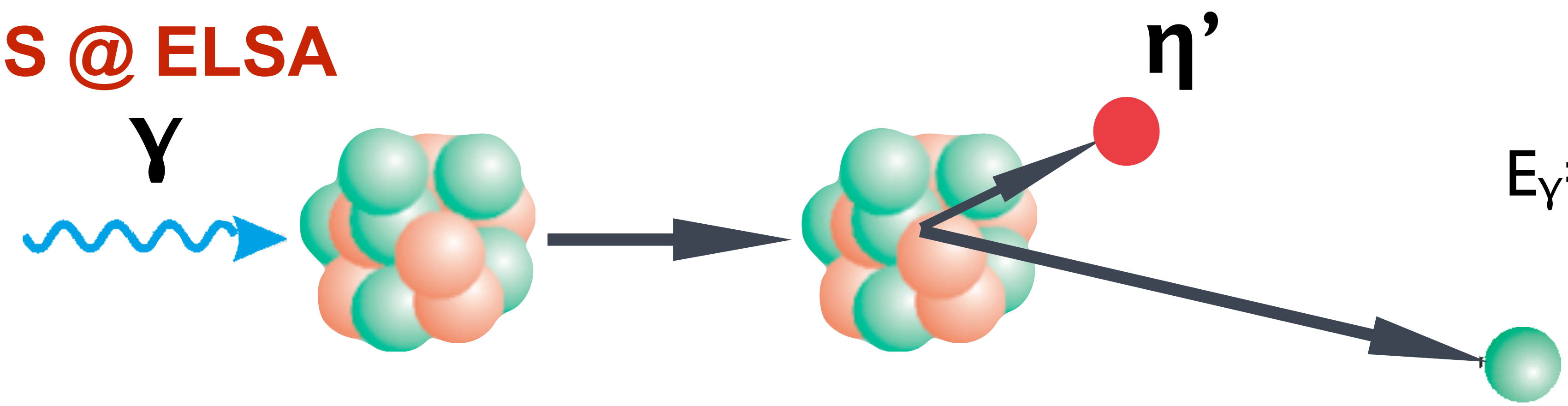




real part of η’-nucleus potential from η’ kinetic energy

η’

CBELSA/TAPS @ ELSA

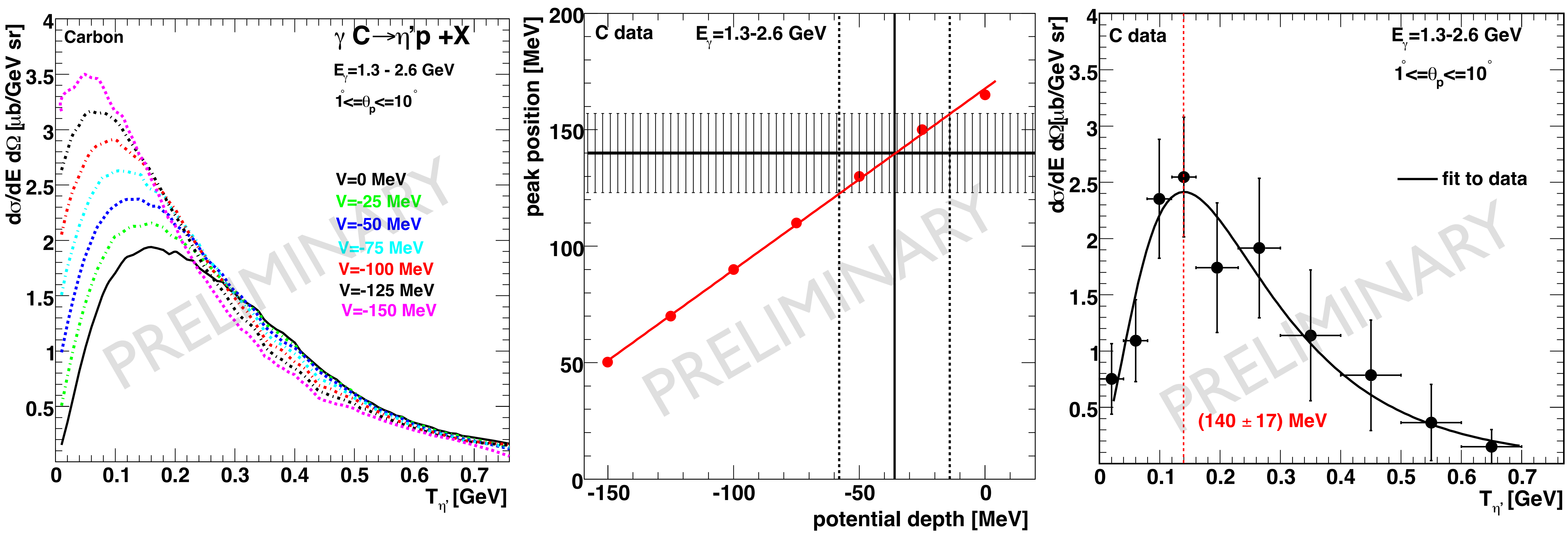


$E_\gamma = 1.3\text{-}2.6$ GeV

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

the higher the attraction the lower the kinetic energy of the η’ meson

E. Paryev, arXiv:1503.09007



$V_{\eta'}(\langle p_{\eta'} \rangle \approx 500\ \text{MeV/c};\ \rho=\rho_0) \approx -(36\pm22)$ MeV

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

ω

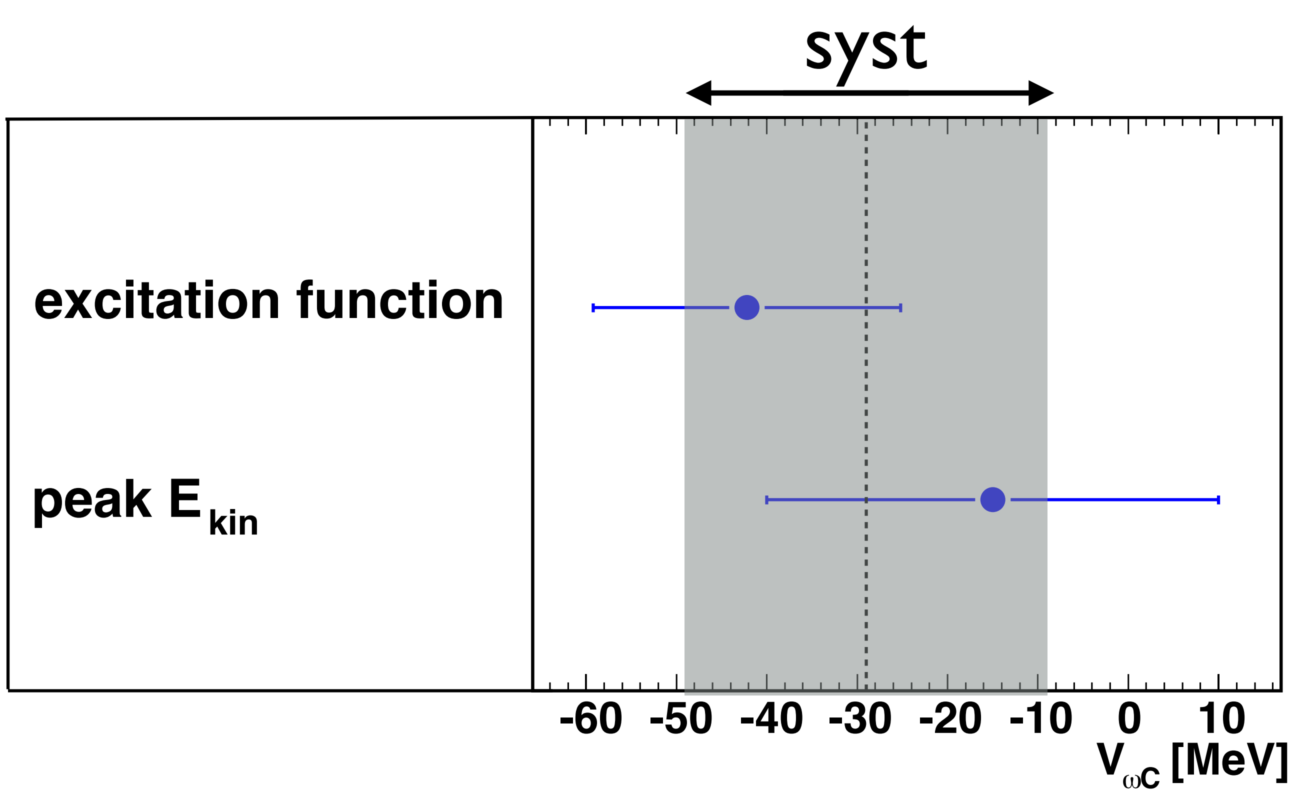
η'

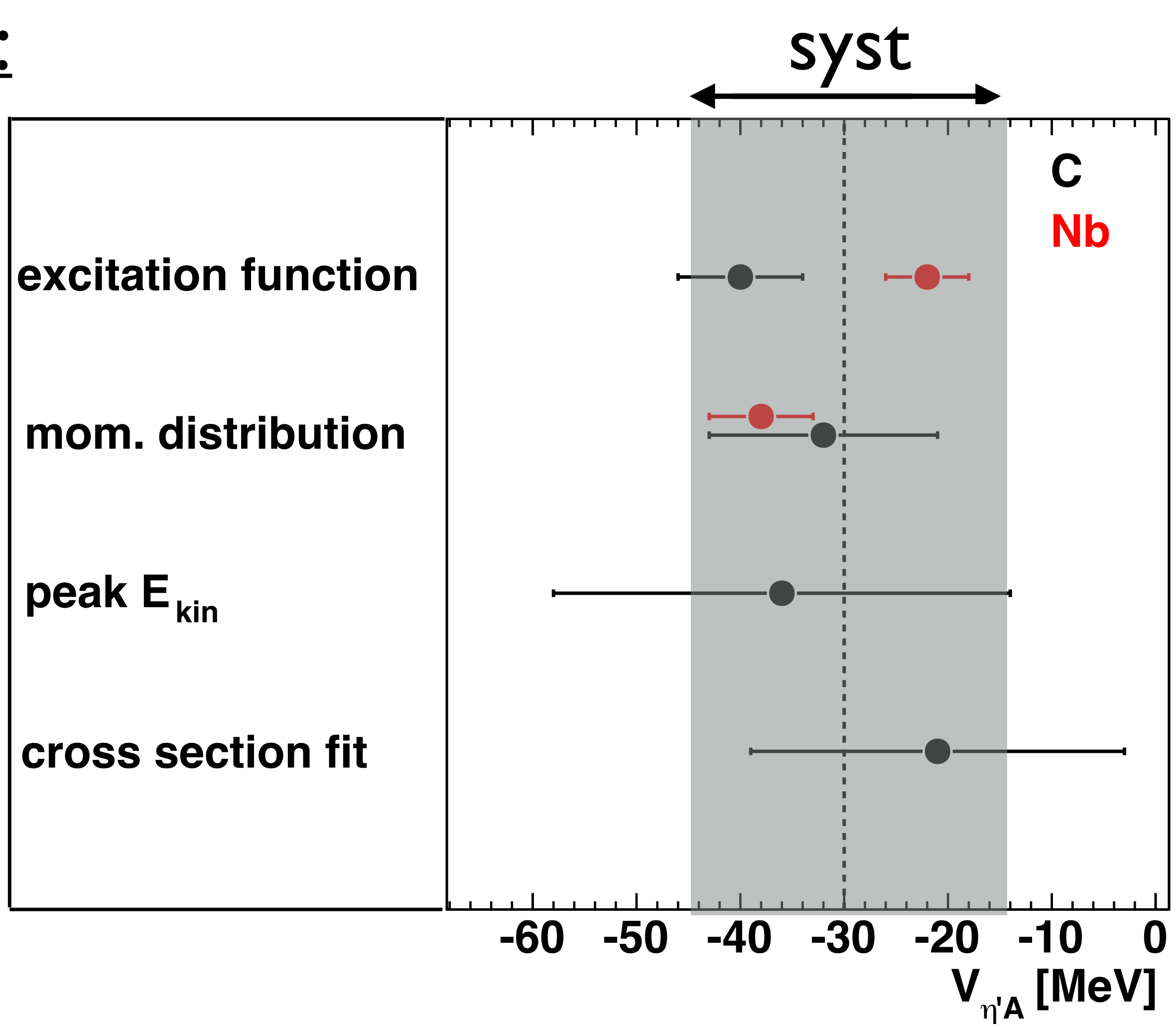
imaginary part:

$W_{\omega A}(\rho=\rho_0) = -\Gamma_0/2 = -(65\text{-}75)$ MeV

$W_{\eta' A}(\rho=\rho_0) = -\Gamma_0/2 = -(7.5\text{-}12.5)$ MeV

real part:





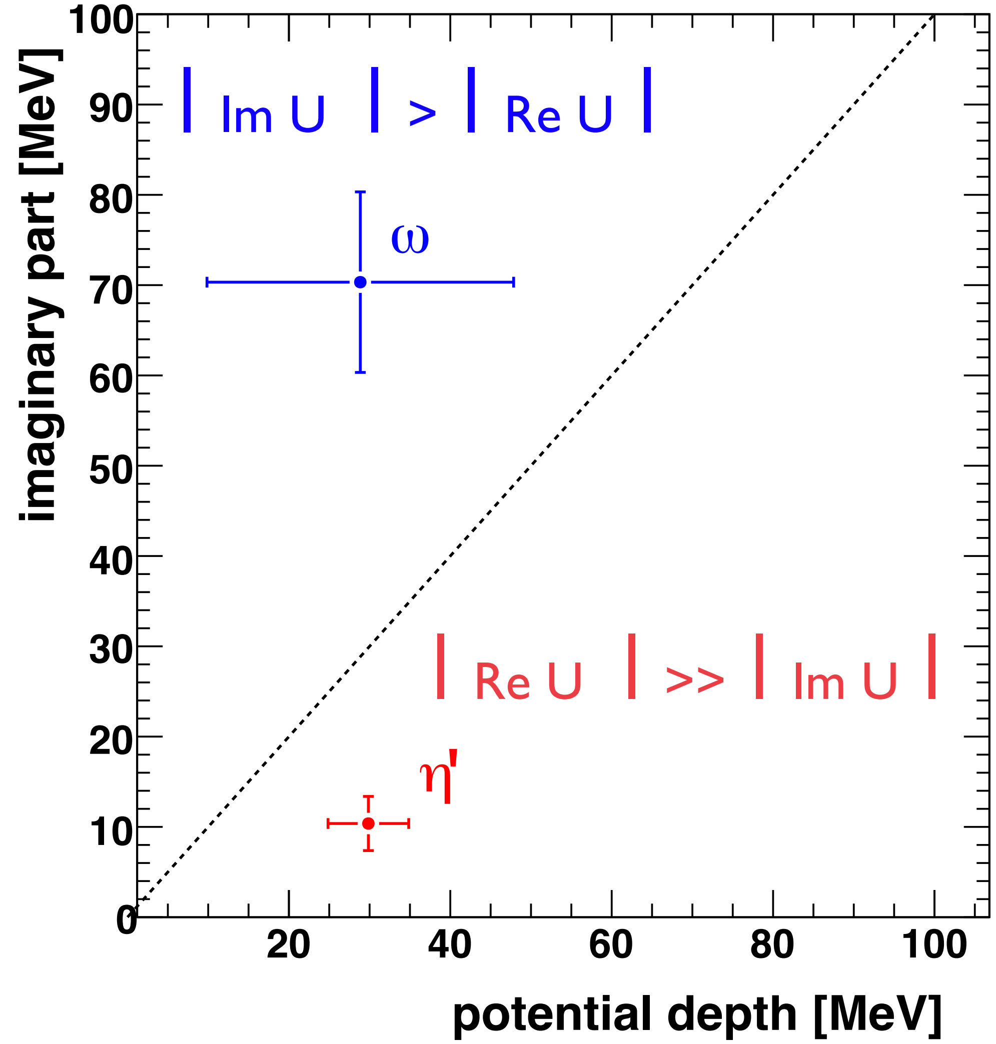
$V_{\omega A}(\rho=\rho_0) = -(29\pm19(\text{stat})\pm20(\text{syst}))$ MeV

$V_{\eta' A}(\rho=\rho_0) = -(30\pm3(\text{stat})\pm15(\text{syst}))$ MeV

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

$U_{\omega A}(\rho=\rho_0)=$
$-((29\pm19(stat)\pm20(syst) + i(70\pm10))$ MeV

$U_{\eta' A}(\rho=\rho_0)=$
$-((30\pm3(stat)\pm15(syst) + i(10\pm3))$ MeV



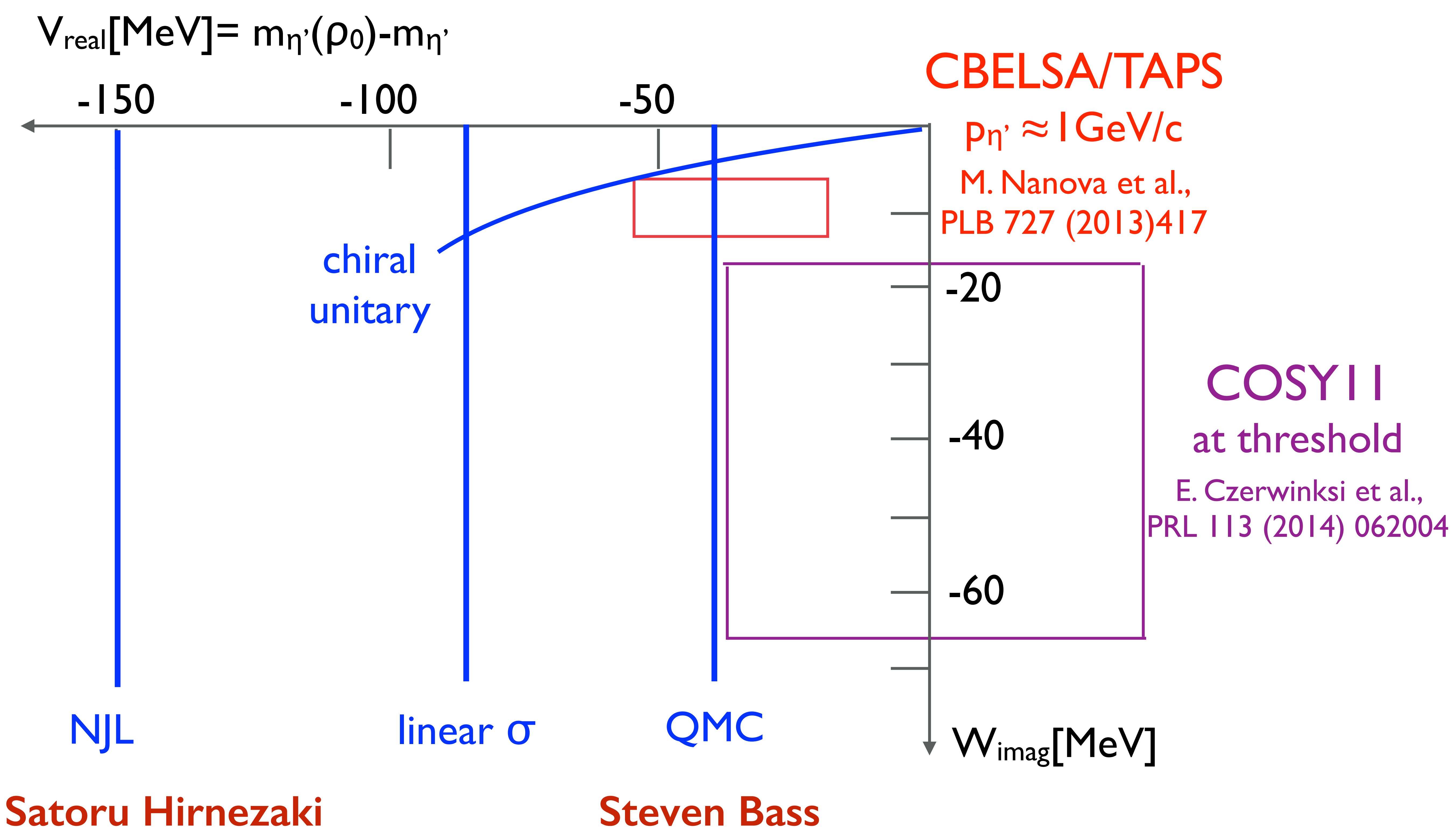
V. Metag
Hyp.Int. 234 (2015) 25

| 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

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)

summary of theoretical predictions and experimental results on $U_{\eta'}(\rho_0)=V_{real}(\rho_0)+i\,W_{imag}(\rho_0)$



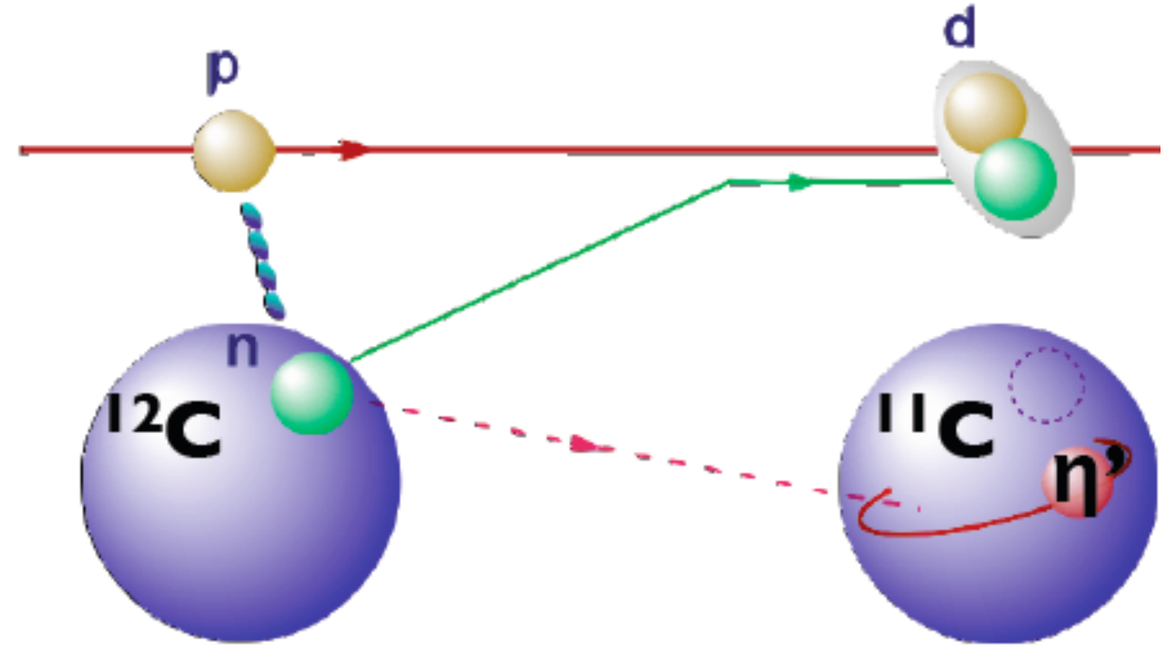
search for η’-mesic states in hadronic reactions

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



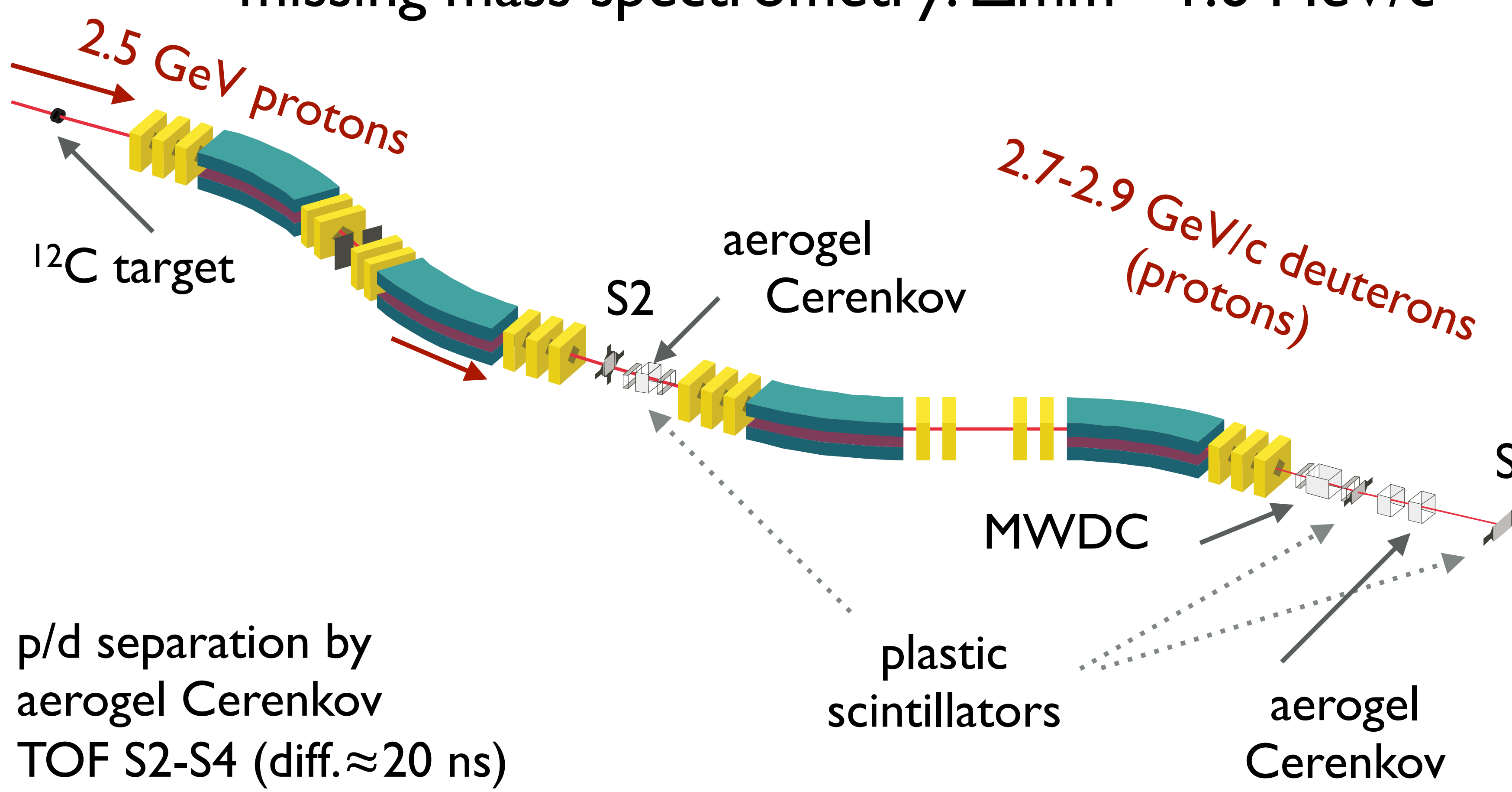
η’ × 11C mesic nuclei

Kenta Itahashi

particle identification by time-of-flight

analysis ongoing

missing mass spectrometry: $\Delta mm = 1.6\ MeV/c^2$

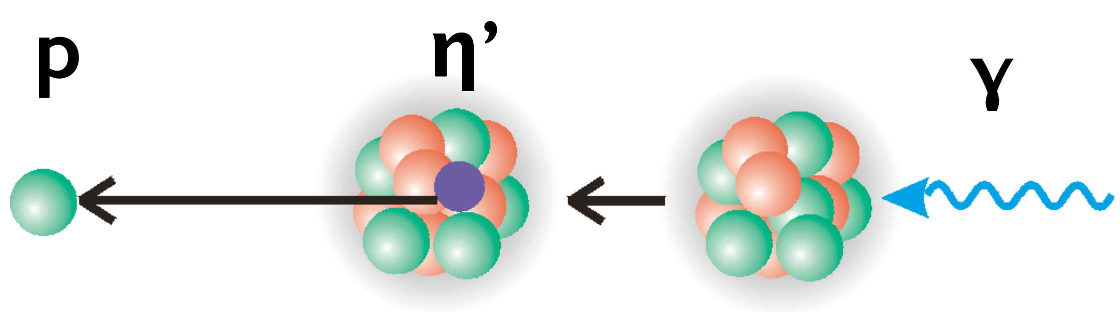


p/d separation by aerogel Cerenkov
TOF S2-S4 (diff.≈20 ns)

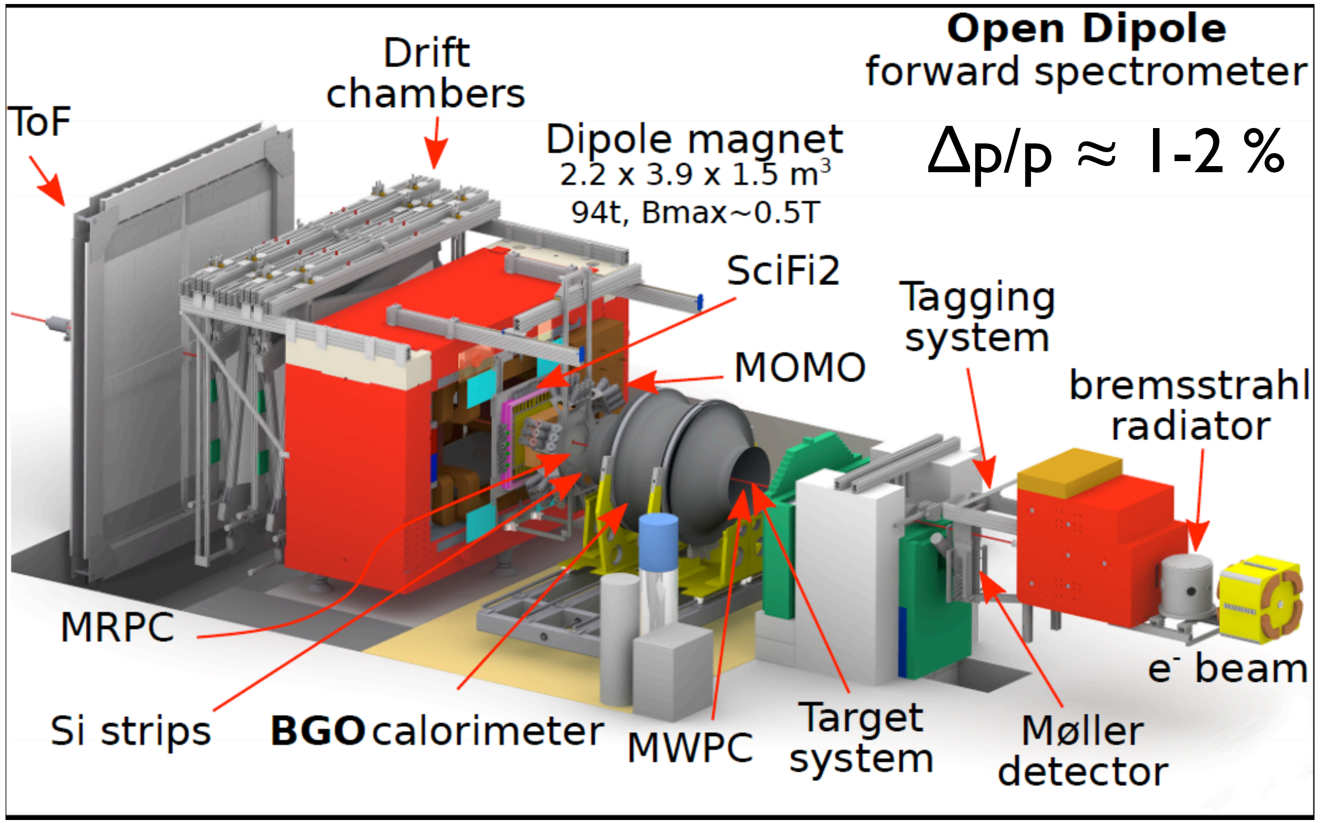
outlook: search for η'-mesic states in photo-nuclear reactions

BGO-OD@ELSA

$^{12}C(\gamma,p)\ \eta' X$ @ 1.5-2.8 GeV



formation and decay of η'-mesic state



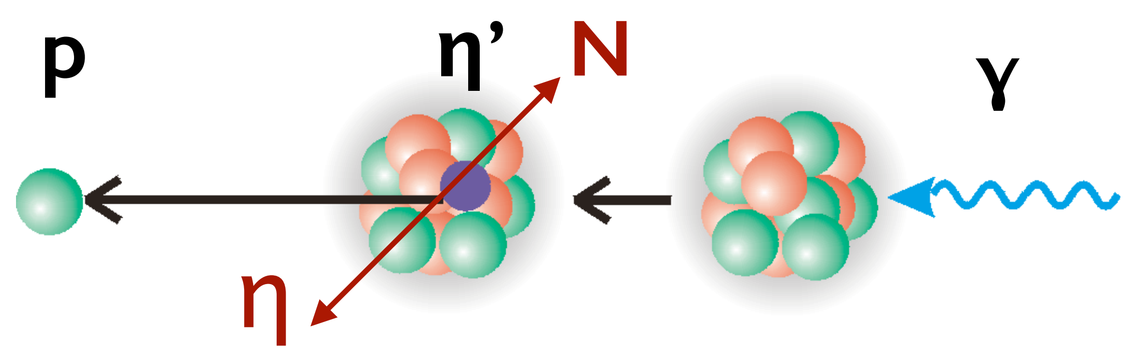
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

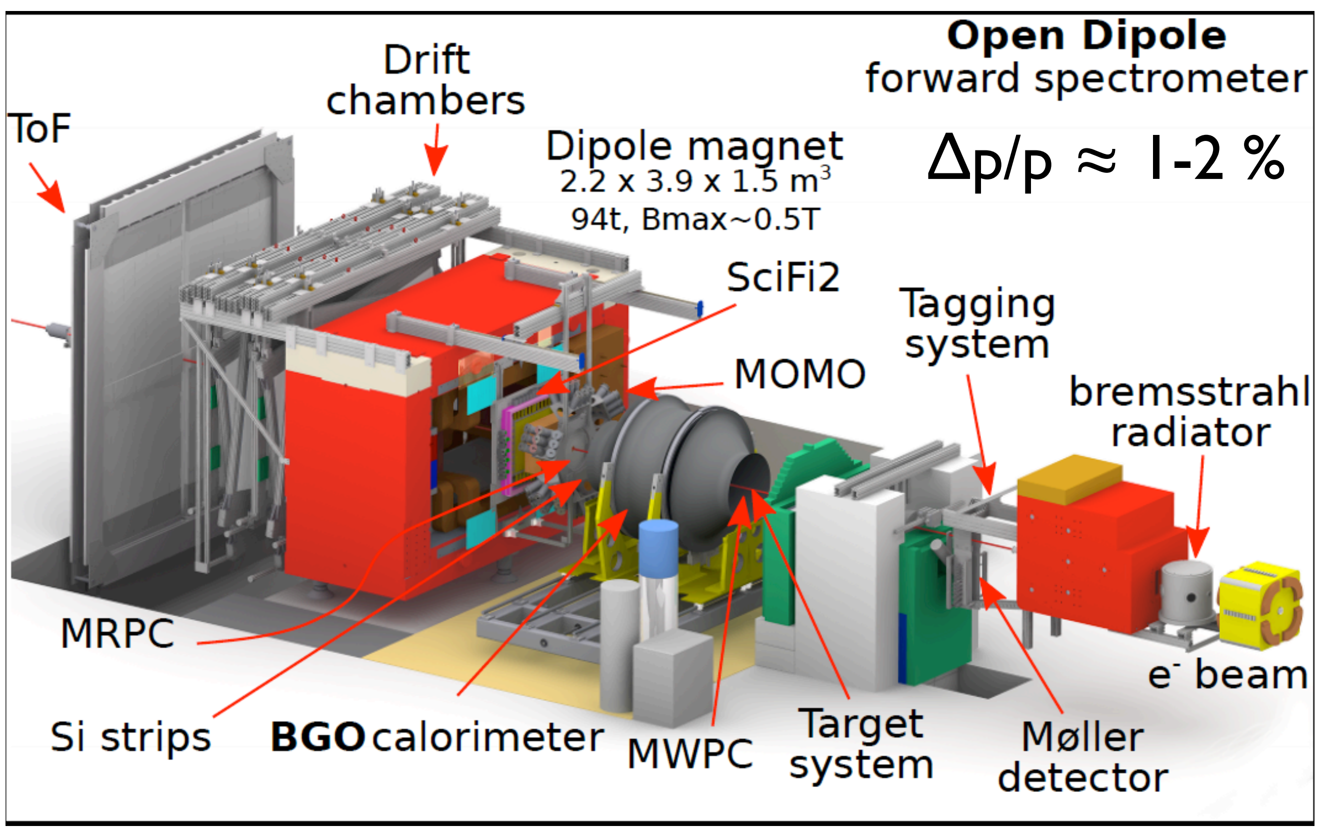
outlook: search for η’-mesic states in photo-nuclear reactions

BGO-OD@ELSA

$^{12}C(\gamma,p)\,\eta'X$ @ 1.5-2.8 GeV



formation and decay of η’-mesic state



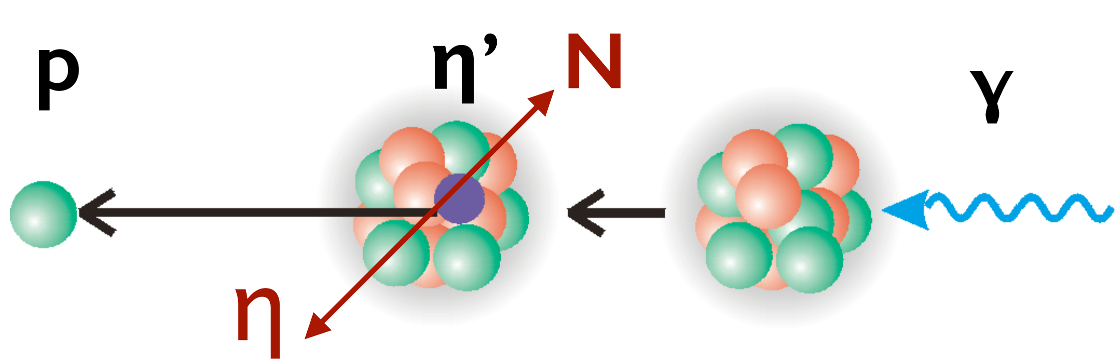
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

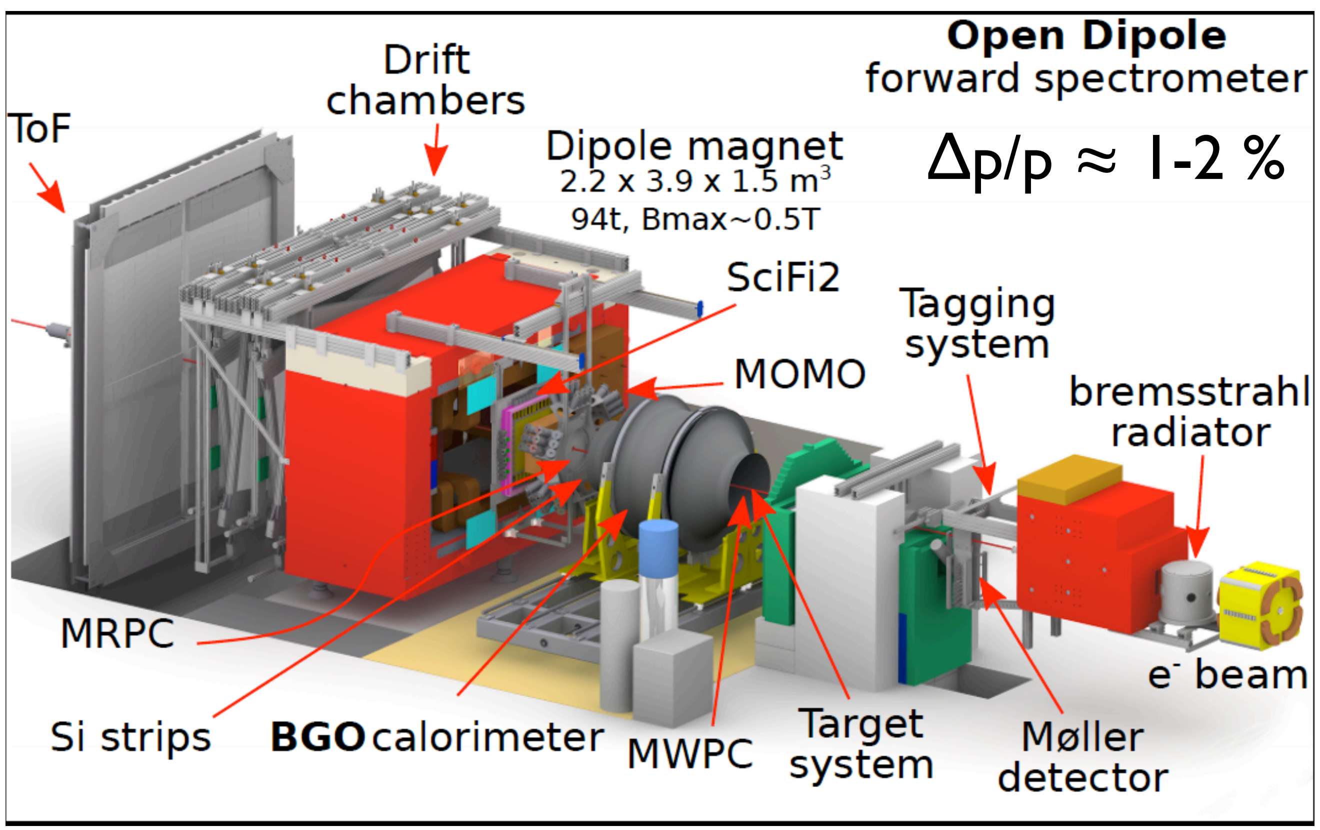
outlook: search for η’-mesic states in photo-nuclear reactions

BGO-OD@ELSA

$^{12}C(\gamma,p)\,\eta' X$ @ 1.5-2.8 GeV



formation and decay of η’-mesic state

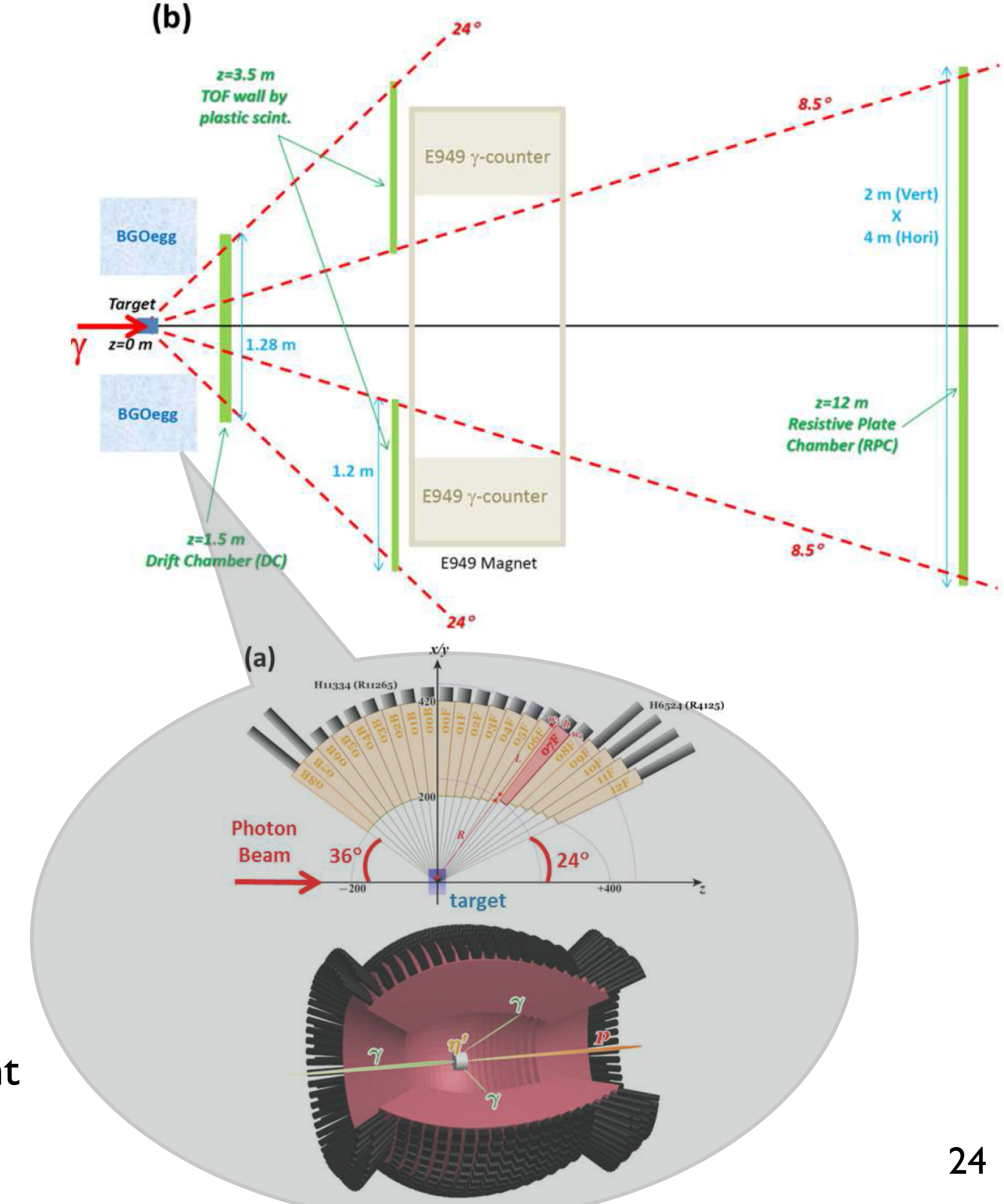


BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

LEPS2@SPring-8

$^{12}C(\gamma,p)\,\eta' X$ @ 1.5-2.4 GeV



summary

- real and imaginary part of the ω and η'-nucleus potential have been determined

first (indirect) observation of an in-medium mass shift of the pseudo-scalar η' meson by $\Delta m(\rho=\rho_0) \approx -30$ MeV

only weak attraction between ω, η' mesons and nuclei

ω: | Im U | > | Re U | → not a good candidate for the search for mesic states

η': | Re U | >> | Im U | → good candidate for the search for mesic states

first results on momentum dependence of the ω- and η'-nucleus optical potential

- The run for η' mesic states has started:

photo-nuclear experiments: LEPS2, BGO-OD: $^{12}C(\gamma, p)$ η'⊗^{11}B

N. Muaramtsu, T. Nakano

hadronic pick-up reaction: FRS@GSI: $^{12}C(p,d)$ η'⊗^{11}C

K.Itahashi, H. Fujioka, Y. Tanaka

The real part of the η'-nucleus potential

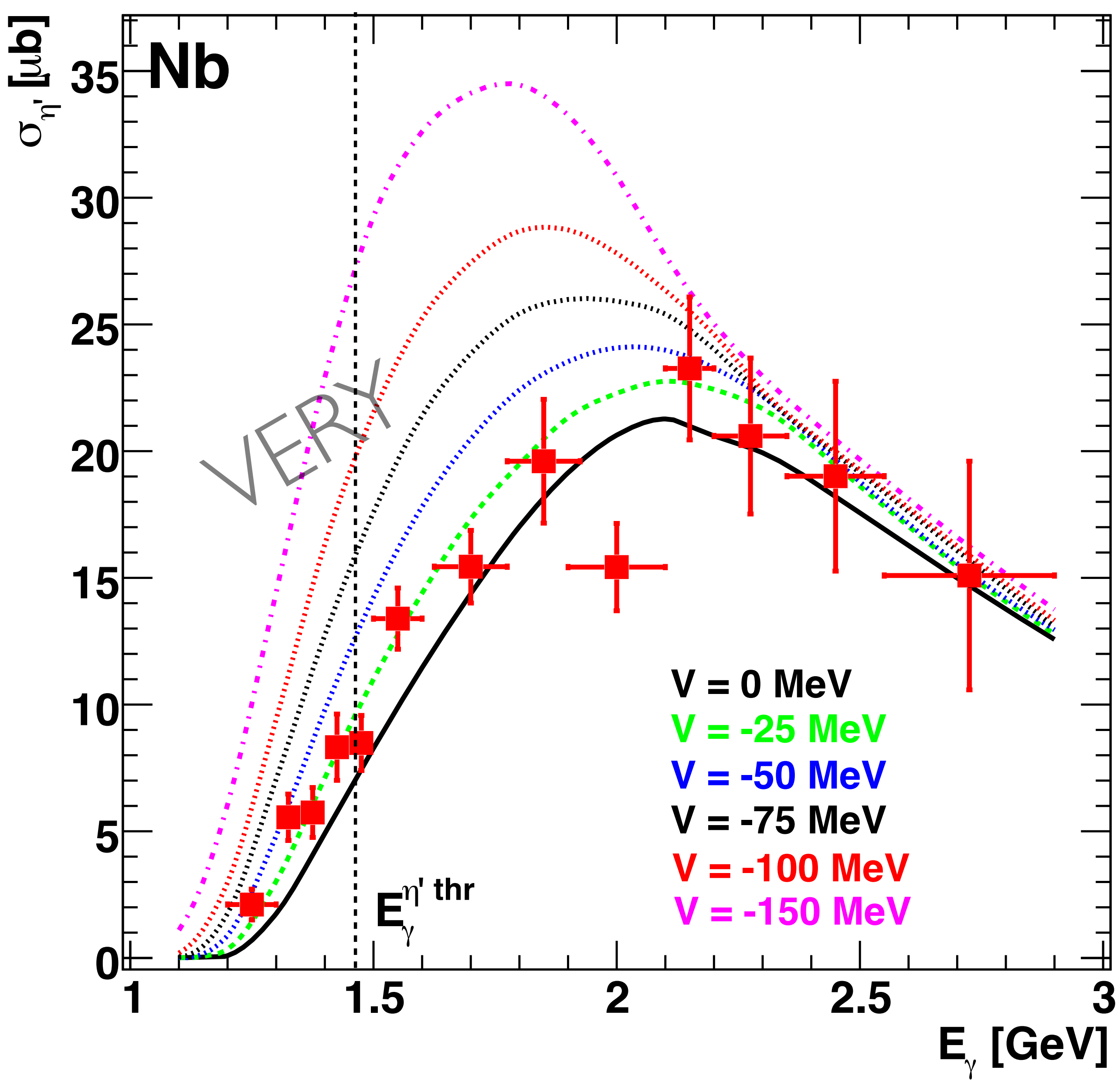
η'

Mariana Nanova

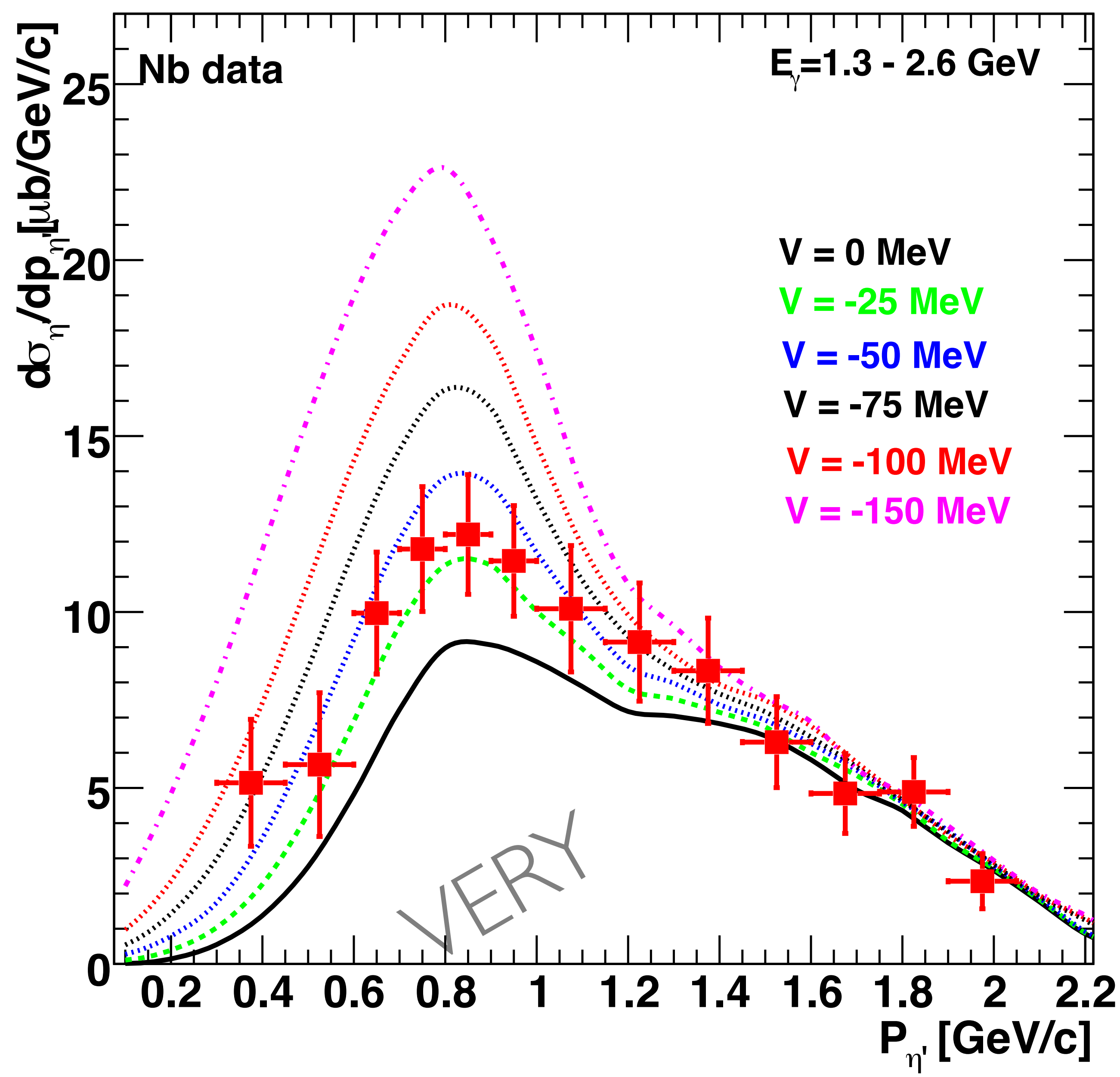
$\gamma A \rightarrow \eta' X$

data compared to calculations by E. Paryev (priv. com.)

excitation function



η' momentum distribution



$V_\eta(\rho=\rho_0) = -(22\pm4(\text{stat})\pm15(\text{syst}))$ MeV

$V_\eta(\rho=\rho_0) = -(38\pm5(\text{stat})\pm15(\text{syst}))$ MeV

$\langle p_{\eta'} \rangle \approx 1.1$ GeV/c