Determining the meson-nucleus potential - on the way to mesic states

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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

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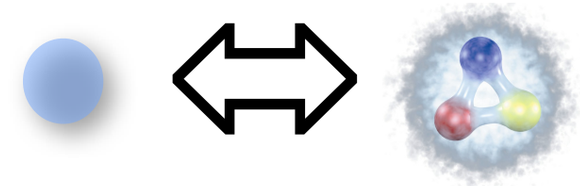
International Conference on
Exotic Atoms and Related Topics
EXA2014
Vienna, Austria, Sept 15-19, 2014

HIC for FAIR
Helmholtz International Center

meson-nucleon/nucleus interaction

I. meson-nucleon interaction:

meson  nucleon

for short-lived mesons (η, ω, η', Φ) no beams available;
study of meson-nucleon interaction by final state interactions
in elementary reactions, e.g. $p + p \Rightarrow p + p + \eta'$
$\Rightarrow$ scattering length (talk by Pawel Moskal)
- interaction attractive or repulsive ?

meson-nucleon/nucleus interaction

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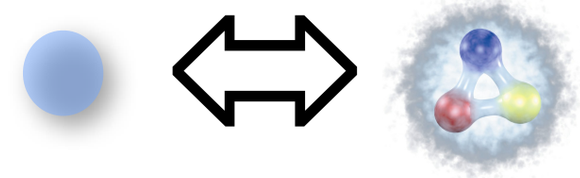
meson  nucleon

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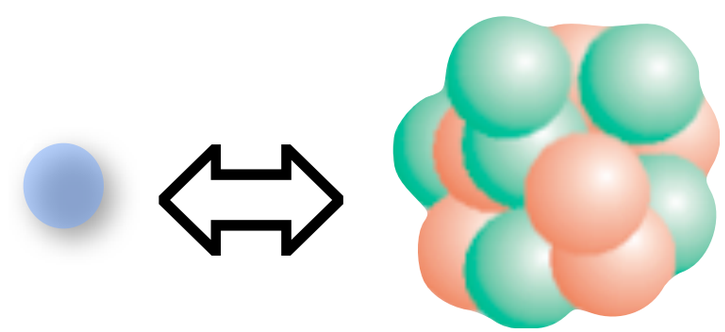
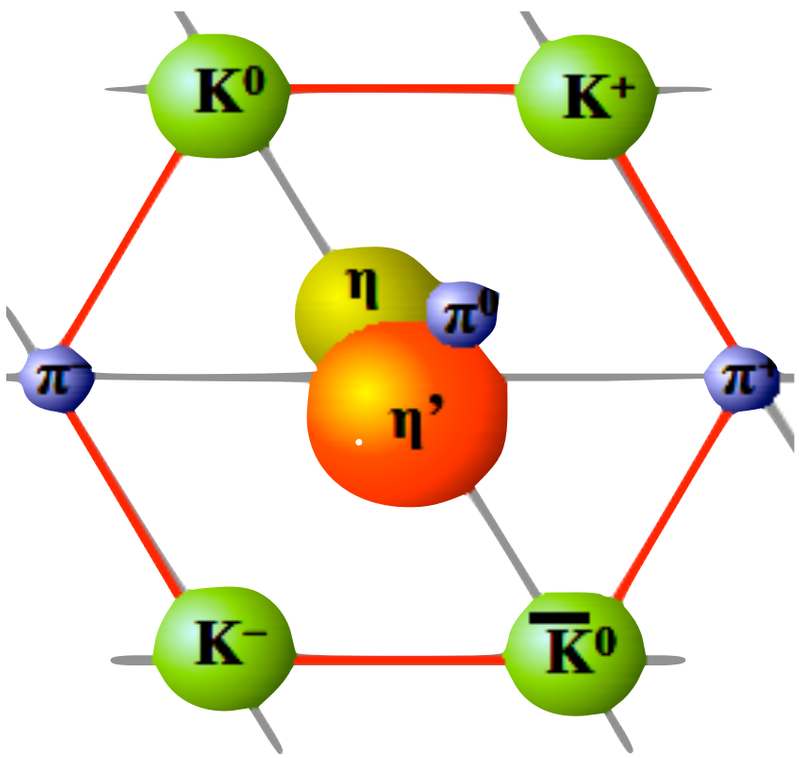
II. meson-nucleus interaction:

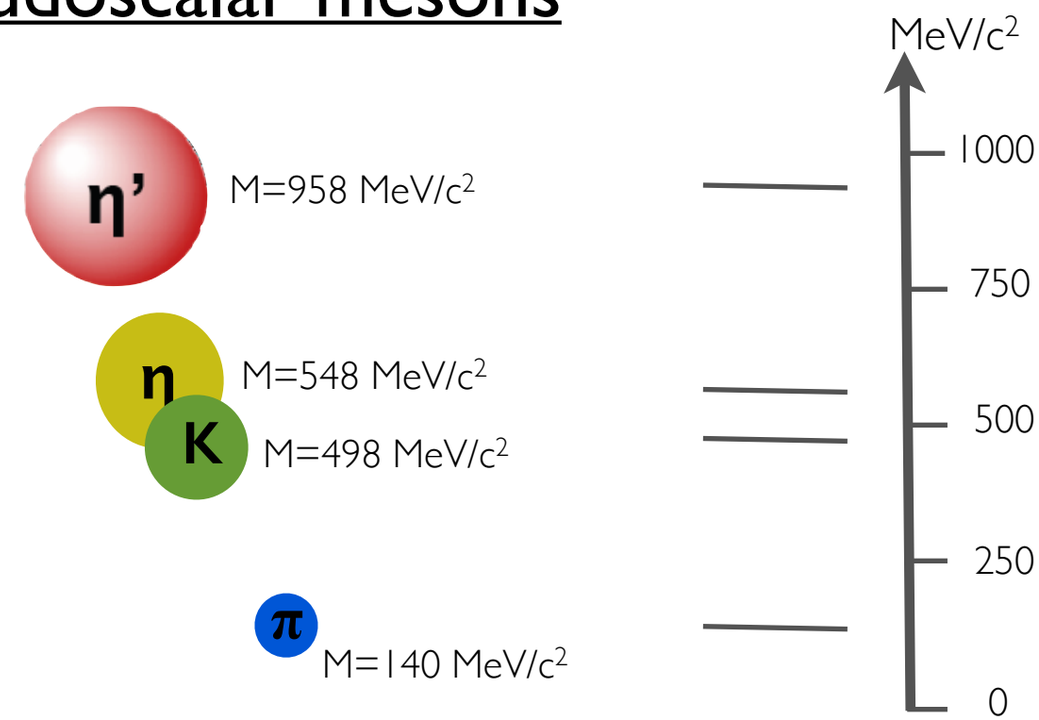
meson  nucleus

- if attractive, interaction strong enough to form meson-nucleus bound states ?
- deeply bound pionic (π^-) states (talk by Kenta Itahashi)
  potential pocket due to superposition of attractive Coulomb and repulsive strong interaction
- search for neutral meson-nucleus bound states, e.g. $\eta' \otimes {}^{11}C$
  (talks by Hiroyuki Fujioka, Daisuke Jido)

symmetry breaking in the hadronic sector

nonet of pseudoscalar mesons

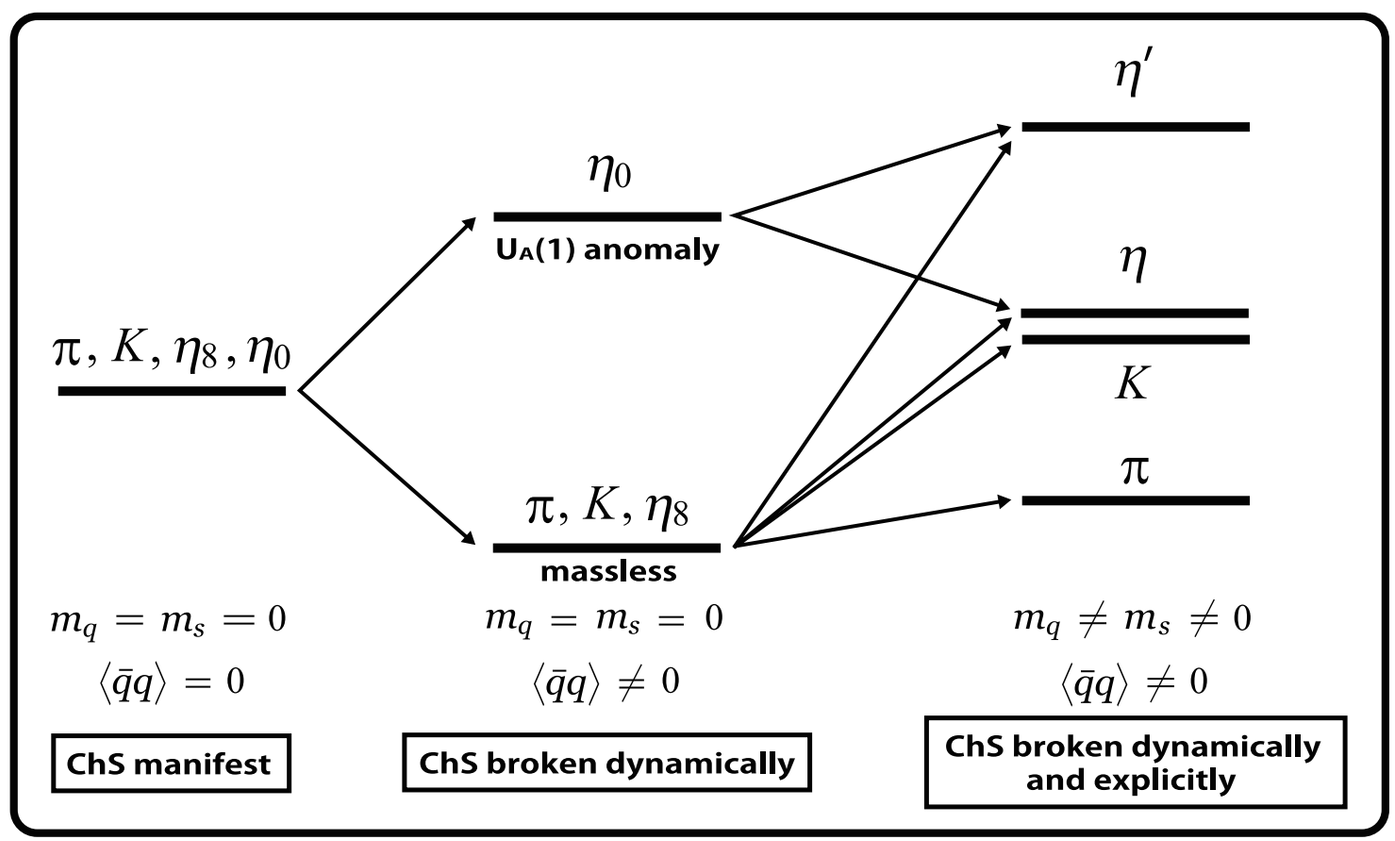




H. Nagahiro et al., PRC 87 (2013) 045201

The NJL Model

mass as a result of symmetry breaking



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

$\Updownarrow$

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

$\Updownarrow$

in-medium mass modification

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

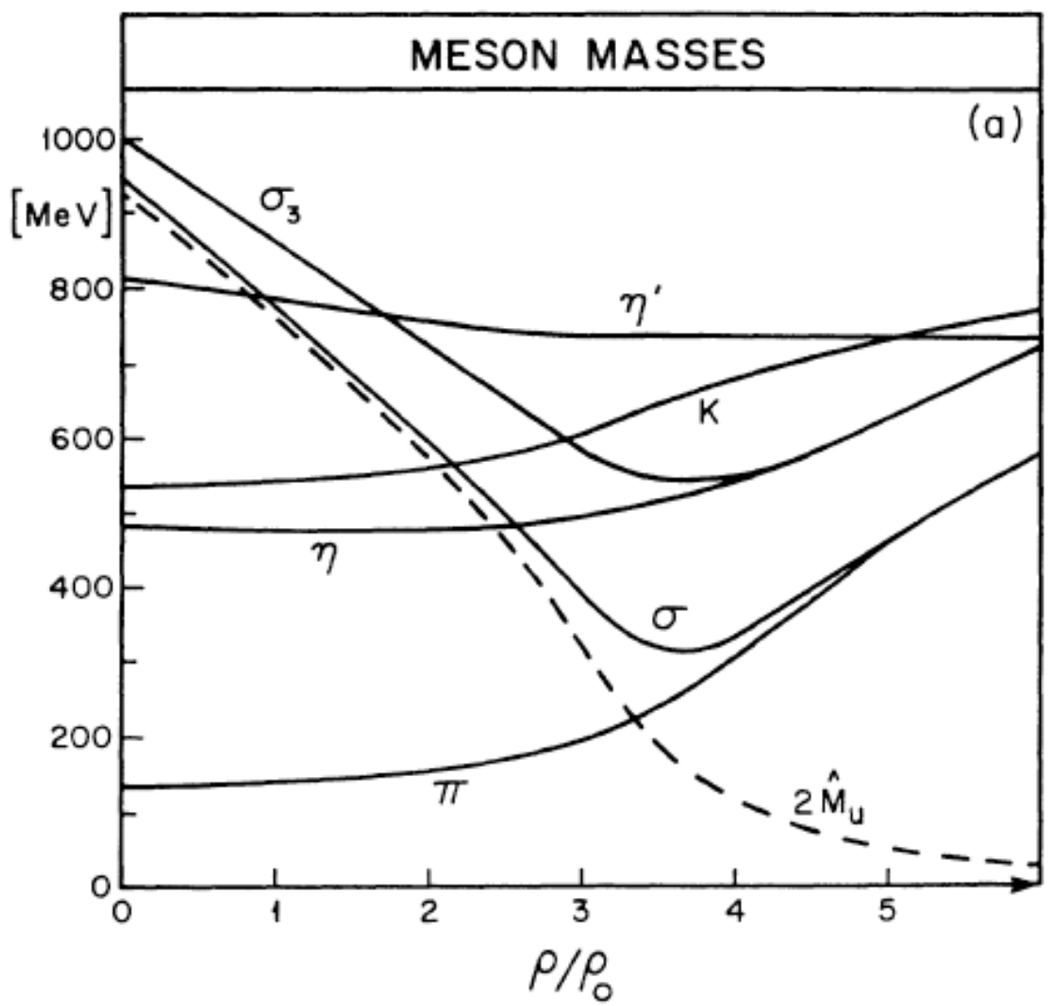
imaginary part

$\Updownarrow$

in-medium width
inelastic cross section

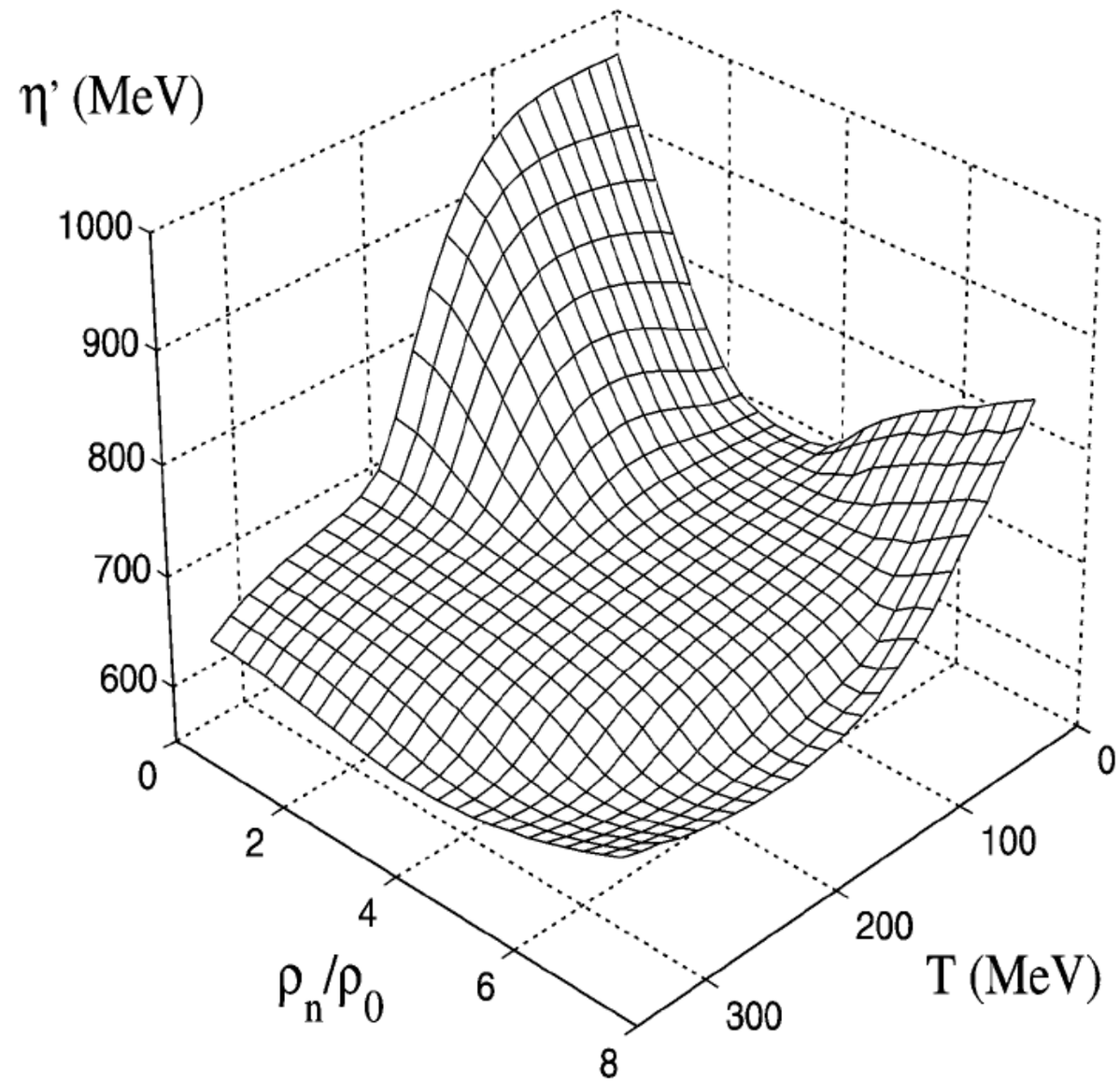
model predictions for the in-medium mass of the η' meson

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



almost no density dependence of in-medium η' mass

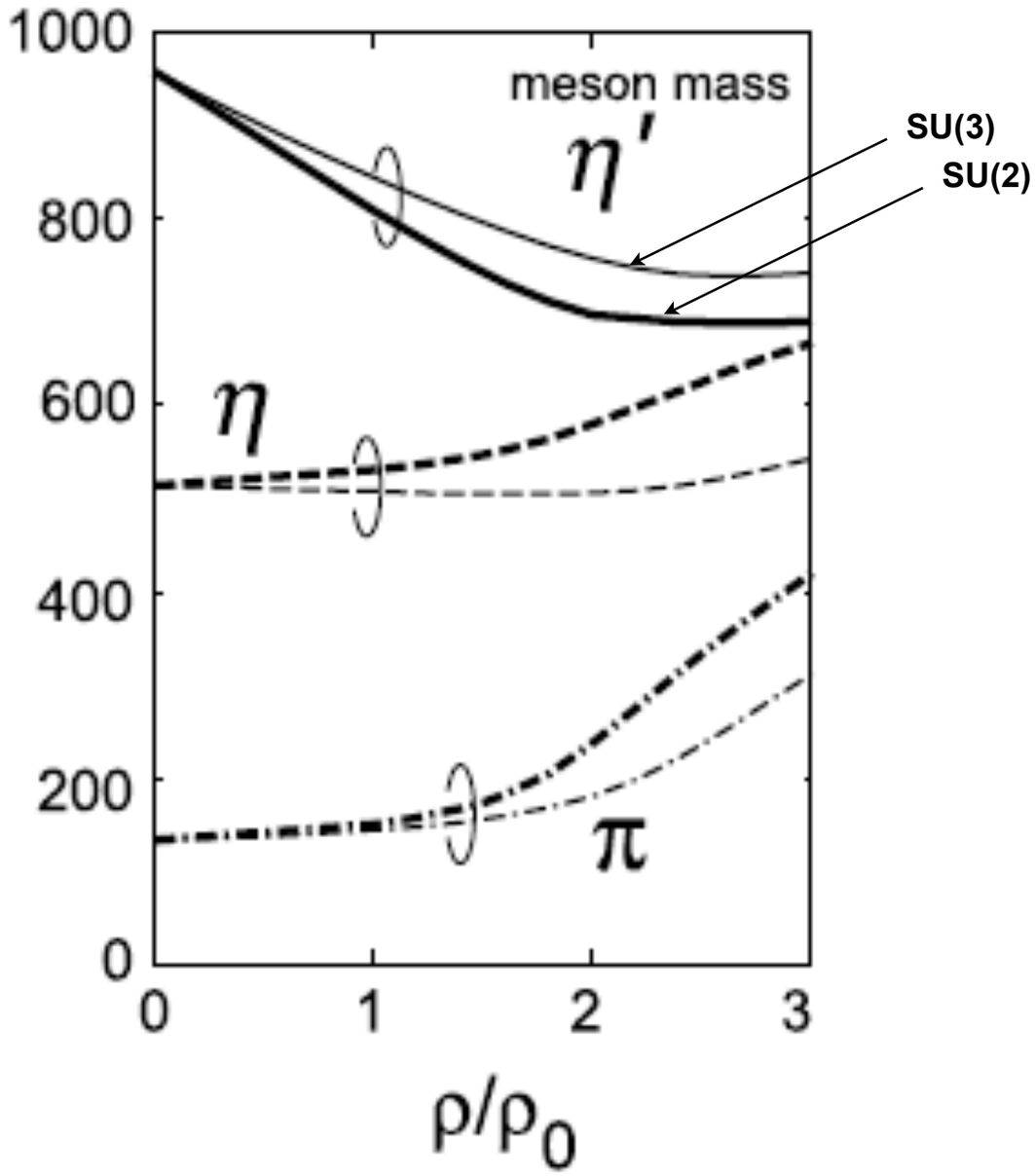
P. Costa et al.,
PLB 560 (2003) 171



$\Delta m_{\eta'}(\rho=\rho_0; T=0) \approx -150$ MeV

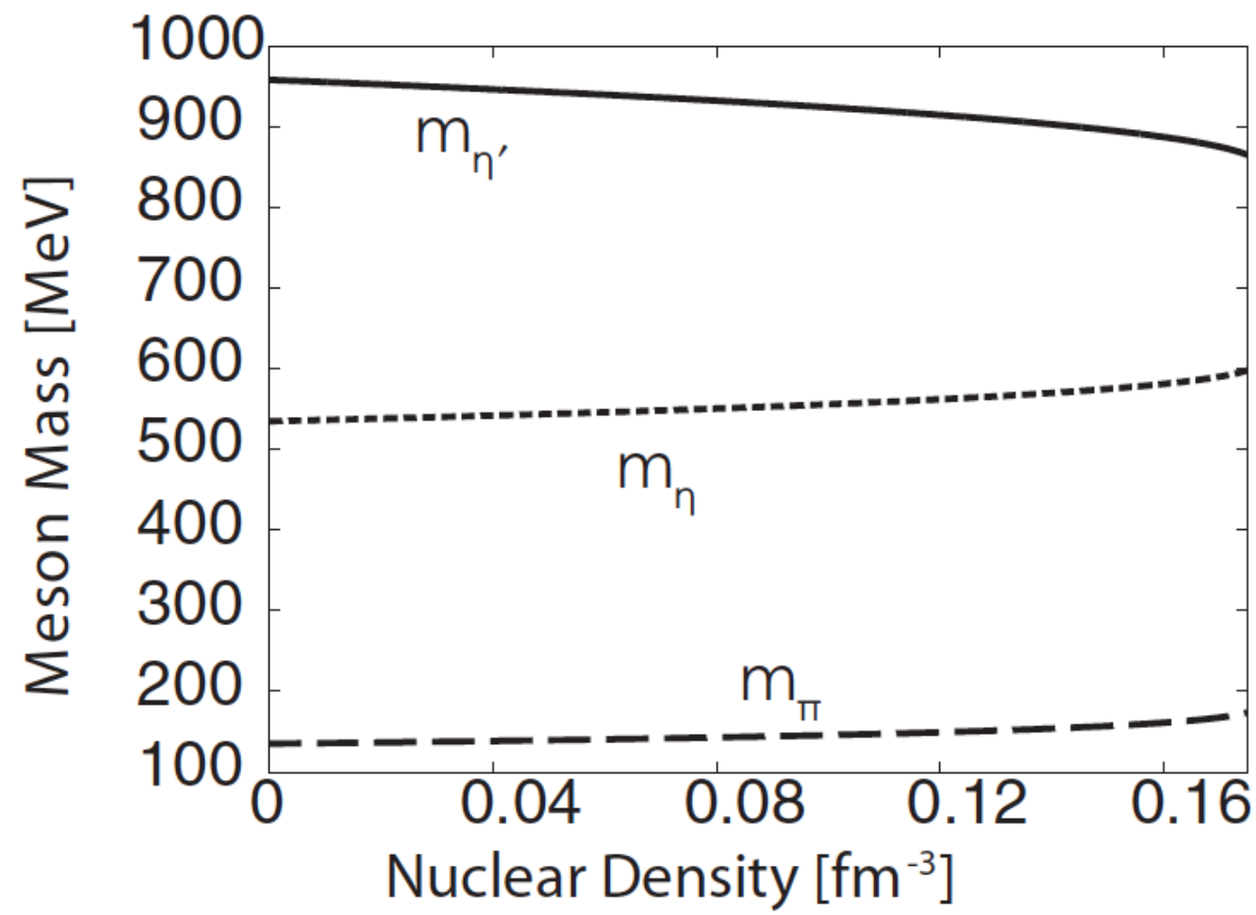
model predictions for the in-medium mass of the η' meson

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

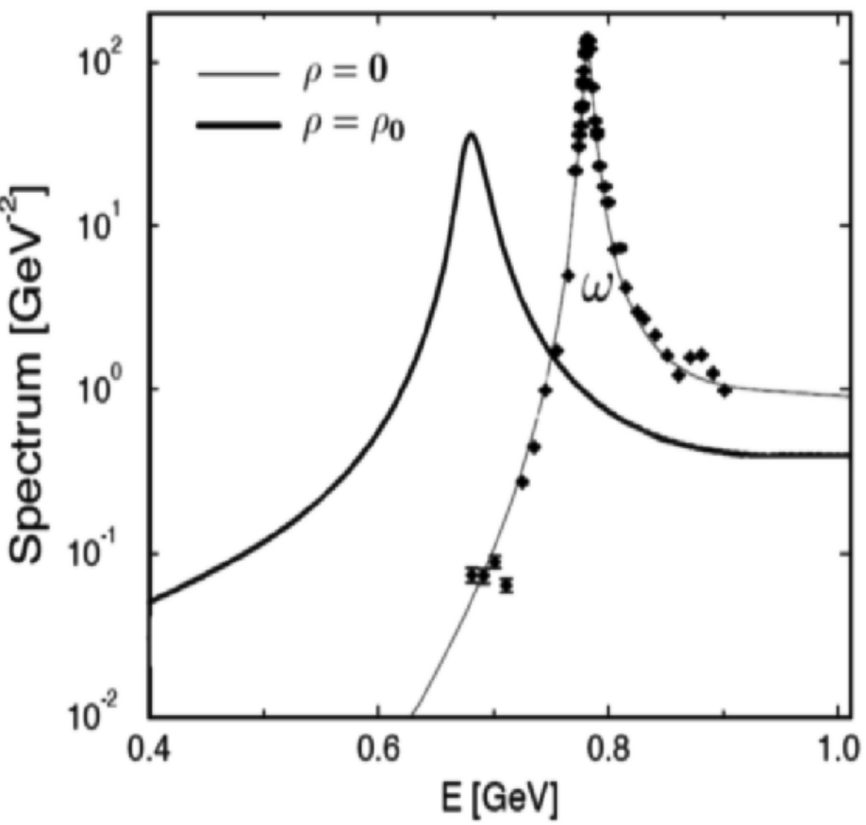


$\Delta m_{\eta'}(\rho_0) \approx -80$ MeV

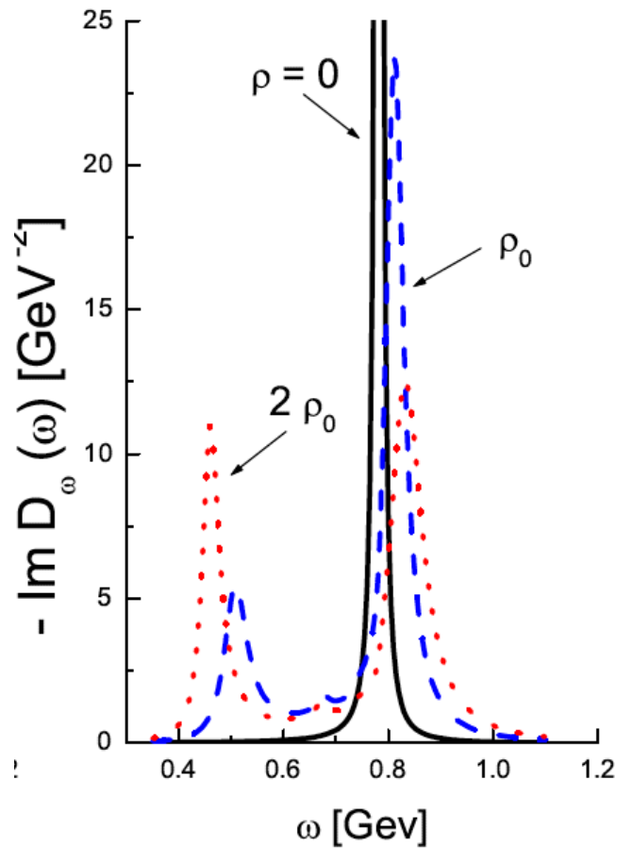
S. Bass and A. Thomas,
PLB 634 (2006) 368
$\Delta m_{\eta'}(\rho_0) \approx -40$ MeV for $\theta_{\eta\eta'} = -20^0$

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

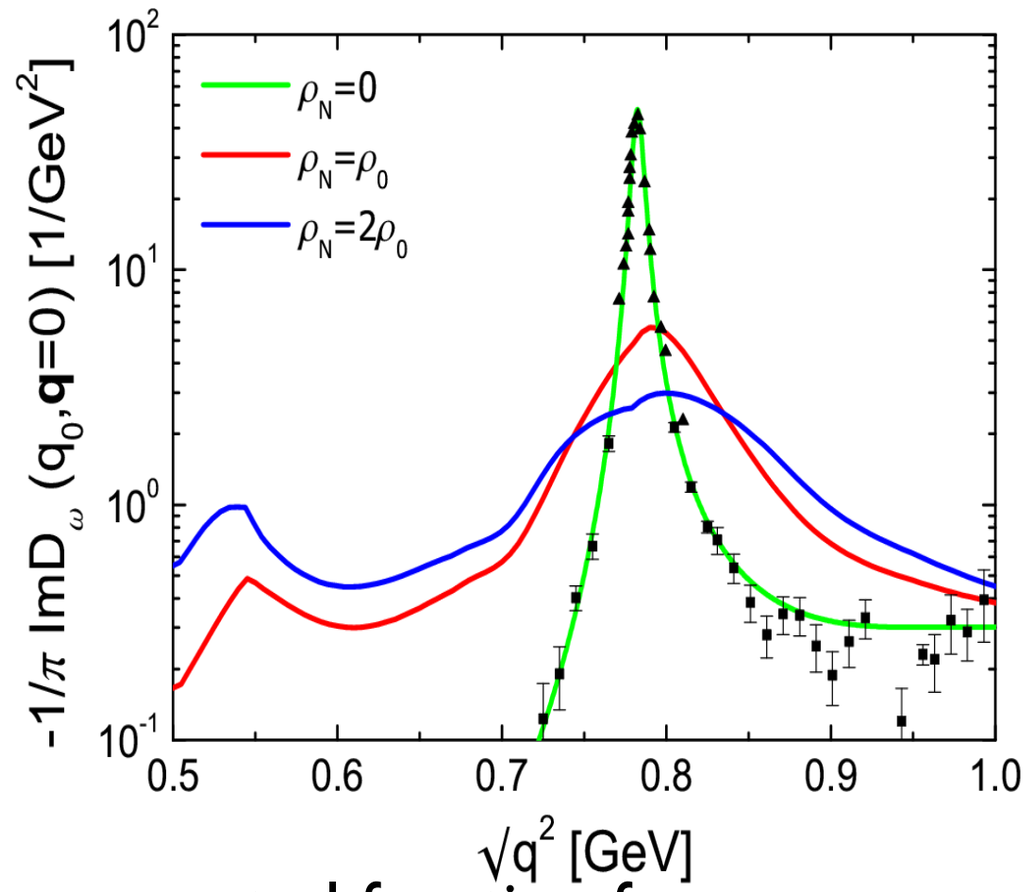
F. Klingl et al.,
NPA 610 (1997) 297;
NPA 650 (1999) 299



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



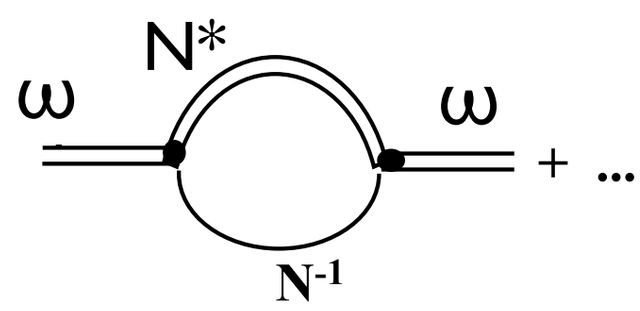
P. Mühlich et al., NPA 780 (2006) 187



- lowering of in-medium mass
- broadening of resonance

with increasing nuclear density

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 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

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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

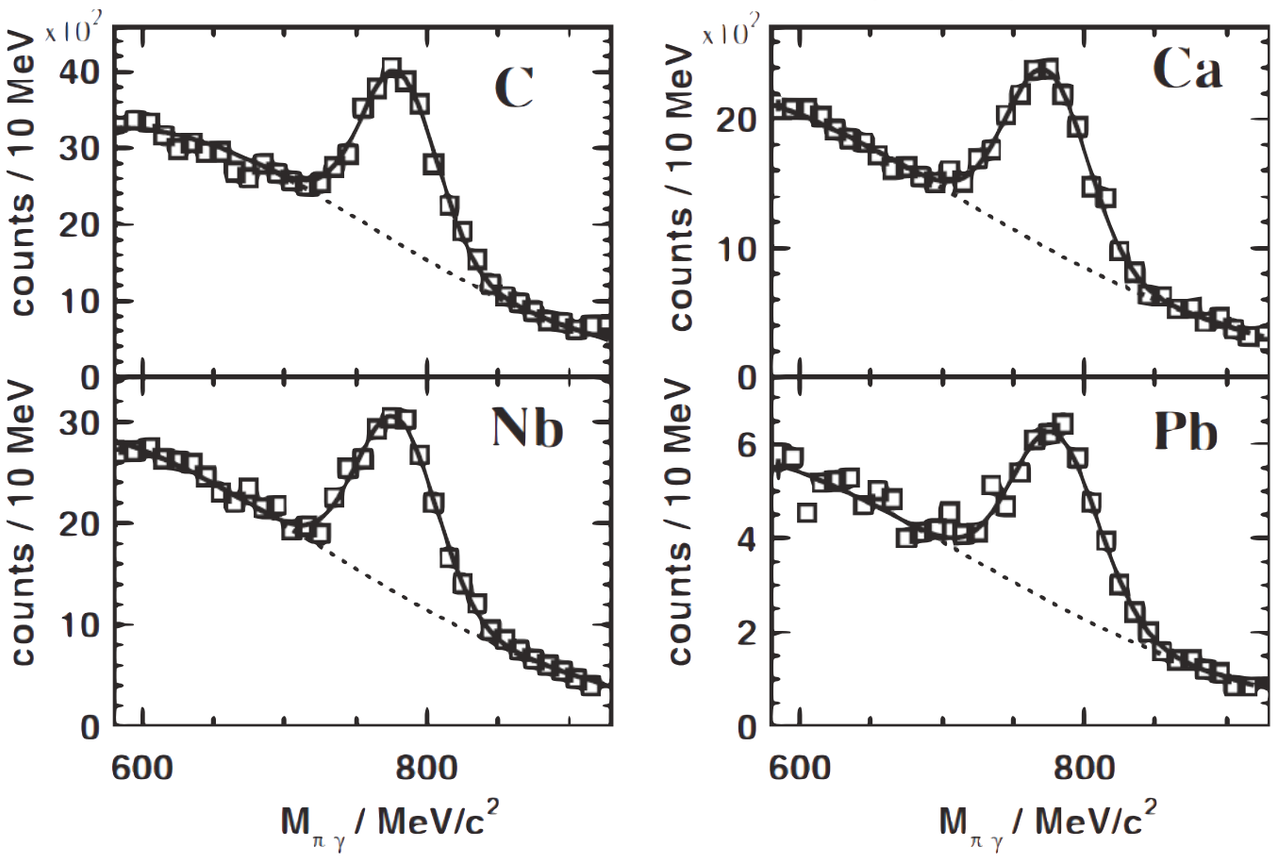
ω

η'

experiments performed with the CBELSA/TAPS detector (Bonn)

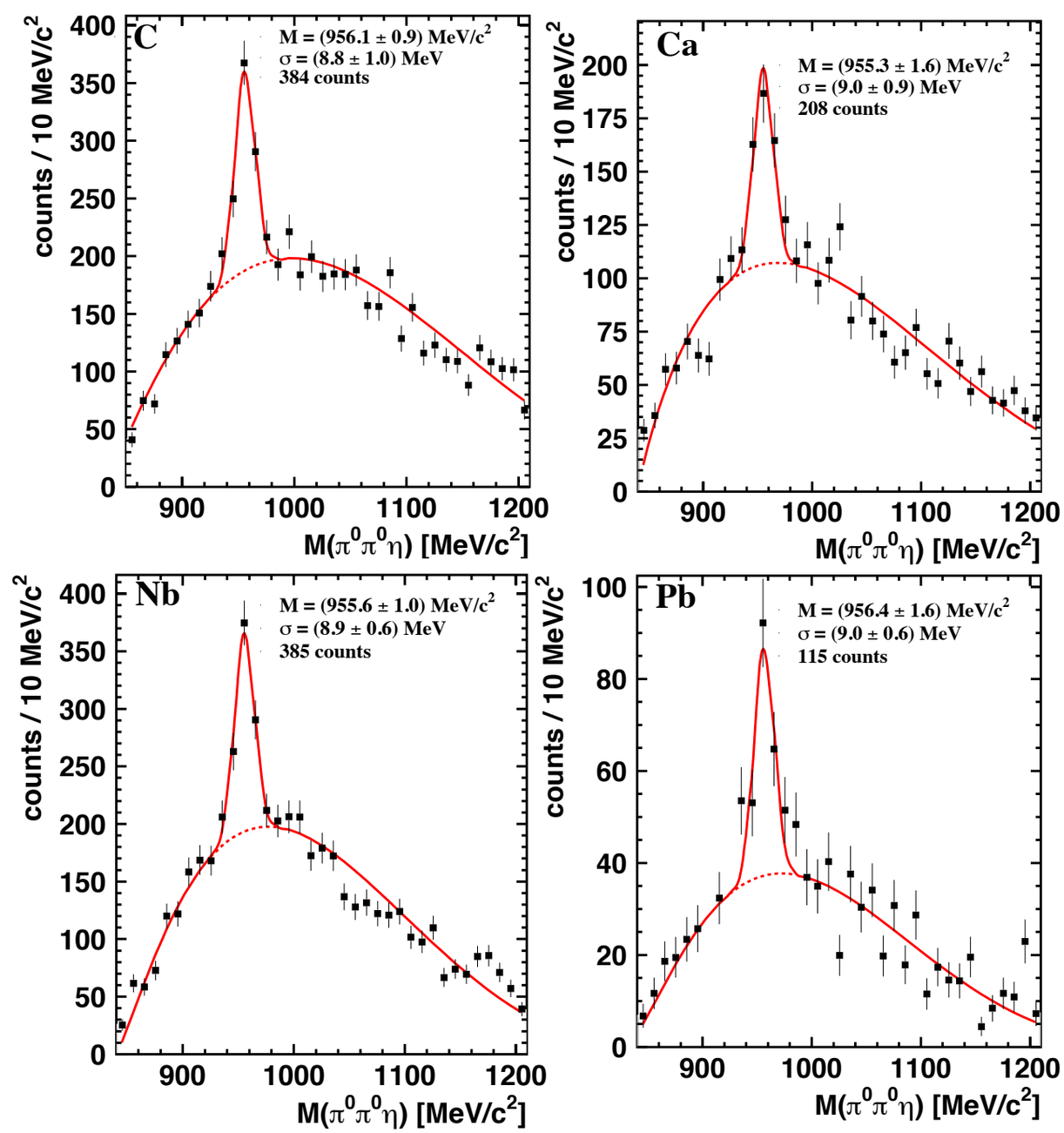
$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$

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



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

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



transparency ratio

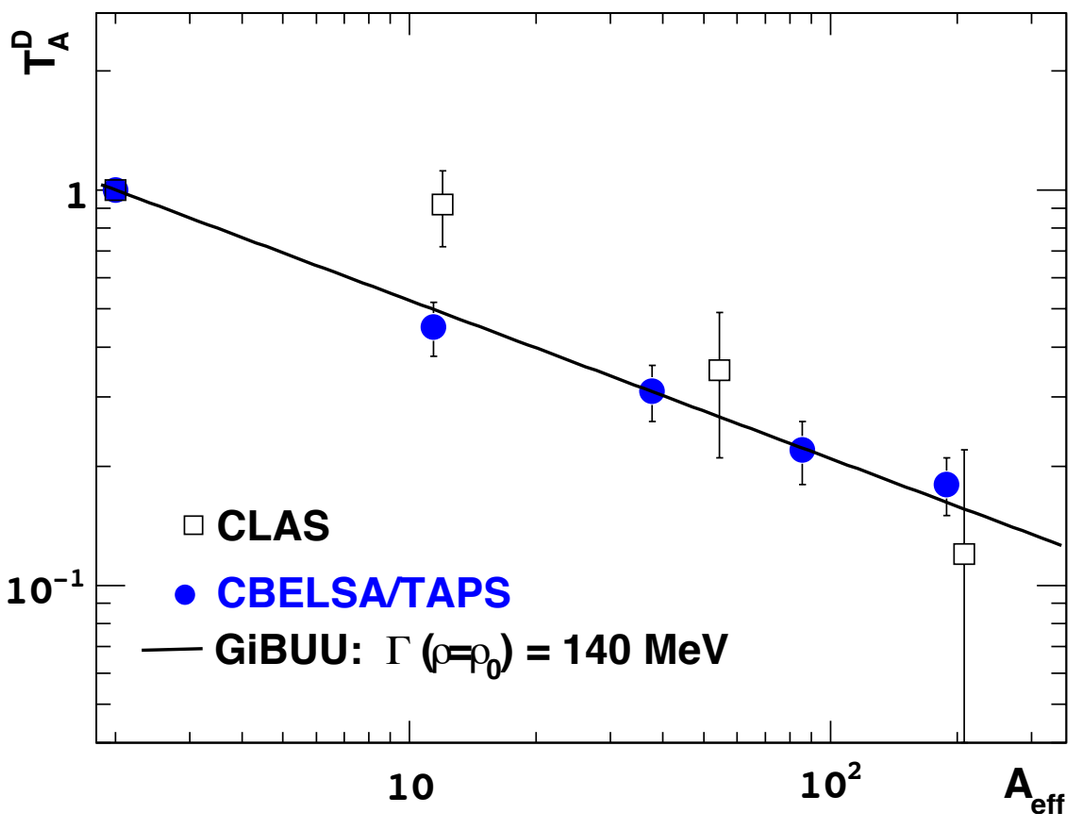
$$T_A = \frac{\sigma_{\gamma A \rightarrow \eta' X}}{A \cdot \sigma_{\gamma N \rightarrow \eta' X}}$$

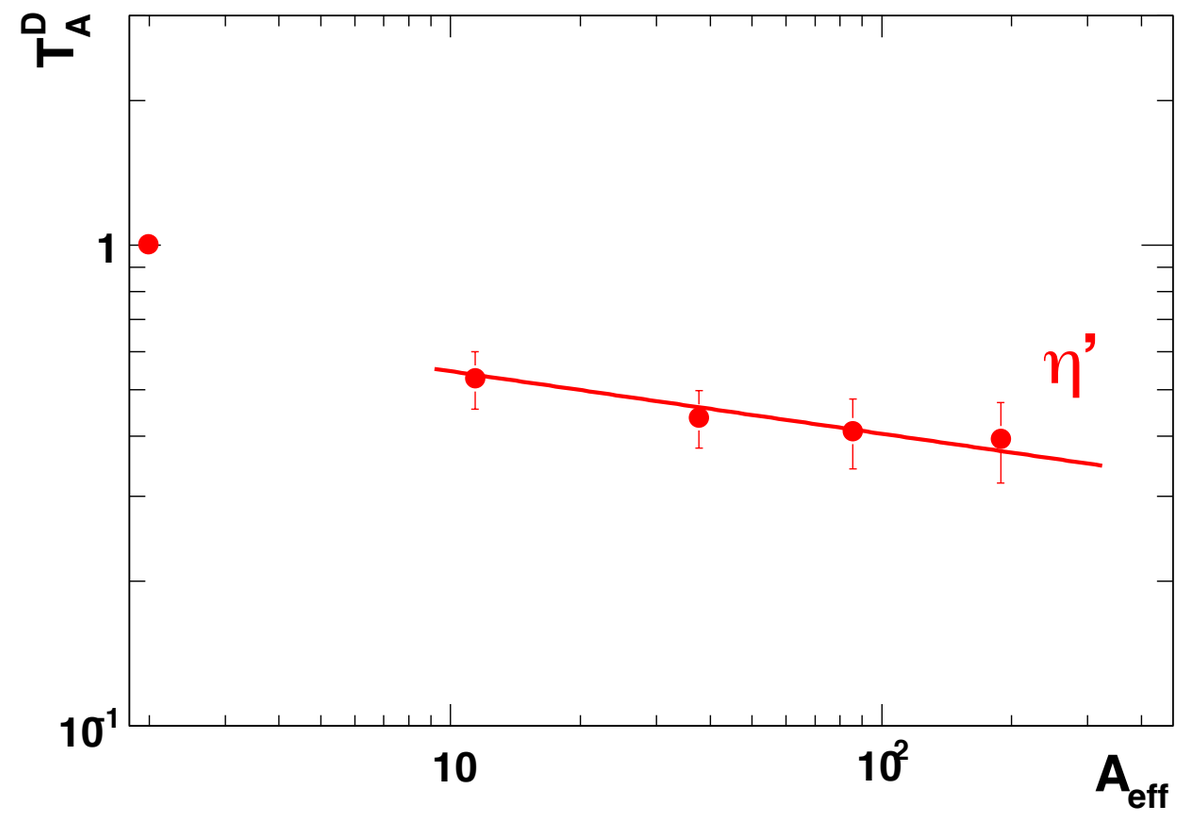
transparency ratio for ω and η' mesons for different nuclei

$$T = \frac{\sigma_{\gamma A \to \omega X}}{Z_{eff} \cdot \sigma_{(\gamma p_{bound} \to \omega p)} + N_{eff} \cdot \sigma_{(\gamma n_{bound} \to \omega n)}}$$

data on photo production cross sections off bound proton and neutron from

ω: F. Dietz et al., subm. to EPJA (2014) η': I. Jaegle et al., EPJA 47 (2011) 11





$\Gamma_\omega(\langle p_\omega \rangle = 1.1$ GeV/c; $\rho=\rho_0) \approx 140$ MeV $\Gamma_{\eta'}(\langle p_{\eta'} \rangle = 1.05$ GeV/c; $\rho=\rho_0) \approx 20$ MeV

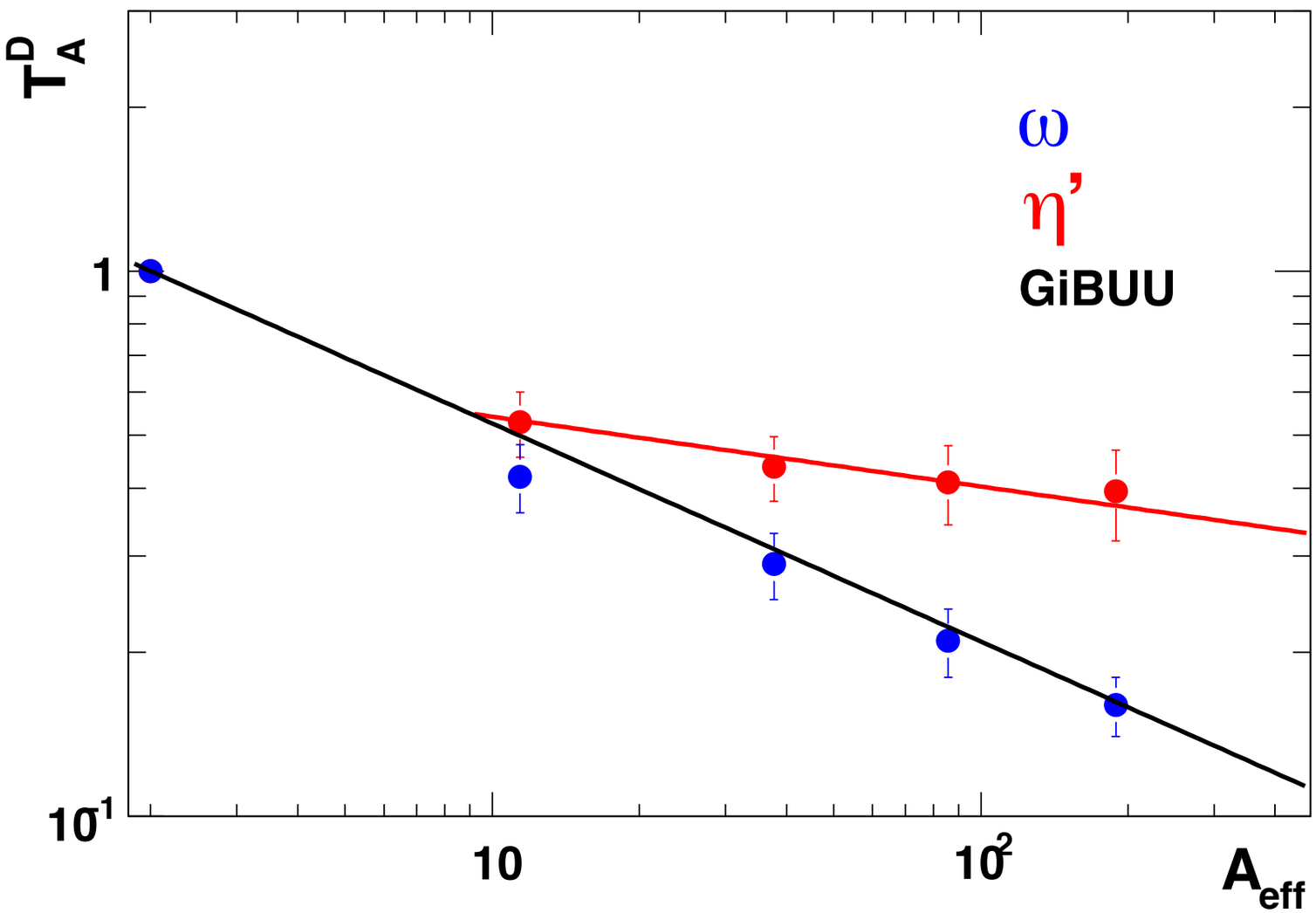
low density approximation: $\Gamma(\rho_0) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}$

$\sigma^{inel}_{\omega N} = (65 \pm 25)$ mb $\sigma^{inel}_{\eta' N} = (10.3 \pm 1.4)$ mb

ω: $W(\rho=\rho_0) = -\Gamma_0/2 \approx -70$ MeV η': $W(\rho=\rho_0) = -\Gamma_0/2 = -(10 \pm 2.5)$ MeV

comparison of transparency ratios for ω and η' mesons

$$T = \frac{\sigma_{\gamma A \to \omega X}}{Z_{eff} \cdot \sigma_{(\gamma p_{bound} \to \omega p)} + N_{eff} \cdot \sigma_{(\gamma n_{bound} \to \omega n)}}$$



ω : W(ρ=ρ$_0$)= -Γ$_0$/2 = - (65-75) MeV

η': W(ρ=ρ$_0$)= -Γ$_0$/2 = - (7.5-12.5) MeV

inelastic interactions with nuclear medium much weaker for η' meson

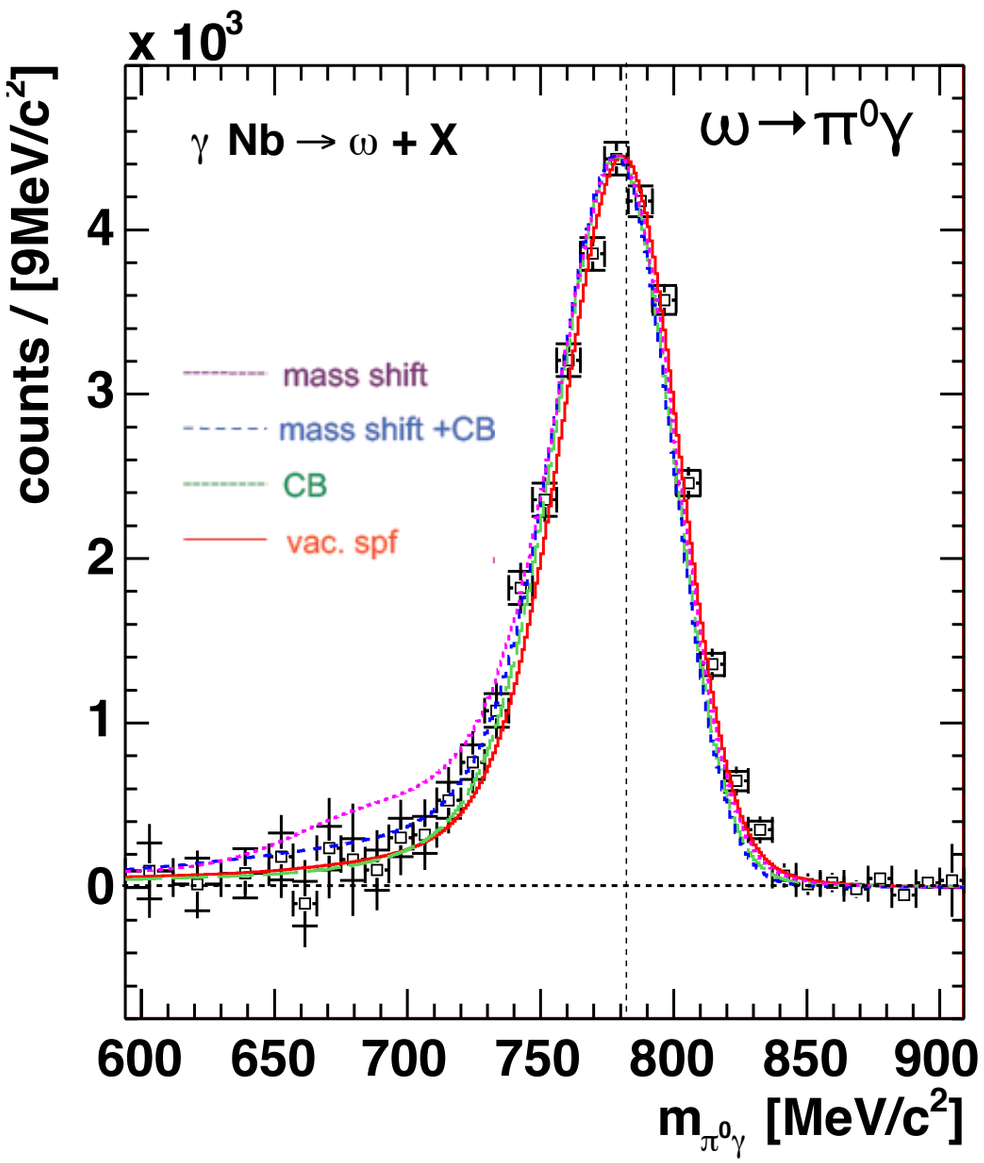
The real part V of the meson-nucleus optical potential

The real part of the ω-nucleus optical potential

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

- line shape analysis: $m(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$

comparison with GiBUU calculations
for different in-medium scenarios



scenarios difficult to distinguish

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

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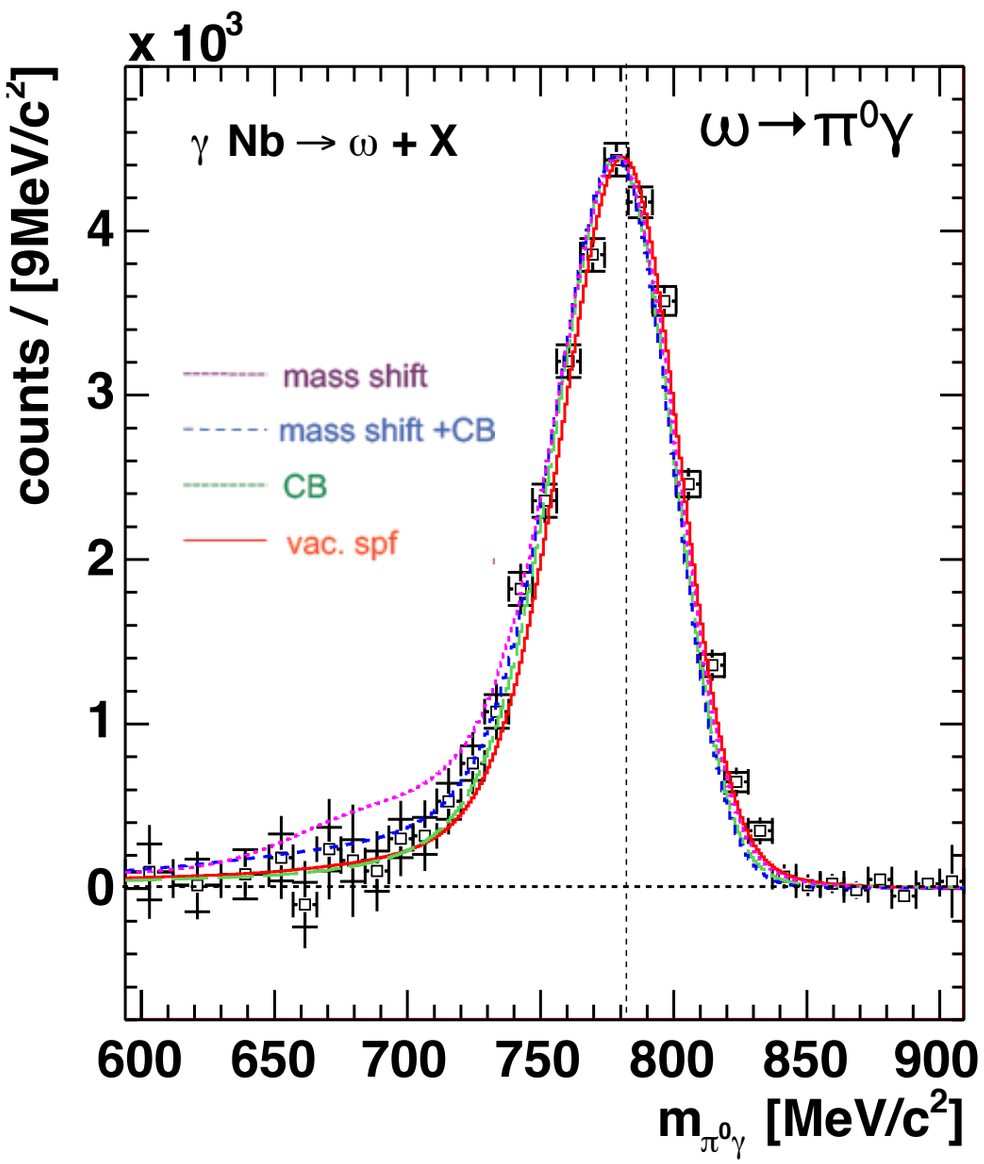


scenarios difficult to distinguish

three effects limit the sensitivity:

1) 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)

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

3) $\omega \rightarrow \pi^0\gamma$ signal smeared out and reduced due to large in-medium width ($\Gamma_{med} \approx 16 \cdot \Gamma_{vac}$); ω mesons removed in nuclear medium via inelastic channels (like $\omega N \rightarrow \pi N$)

The real part of the ω-nucleus potential

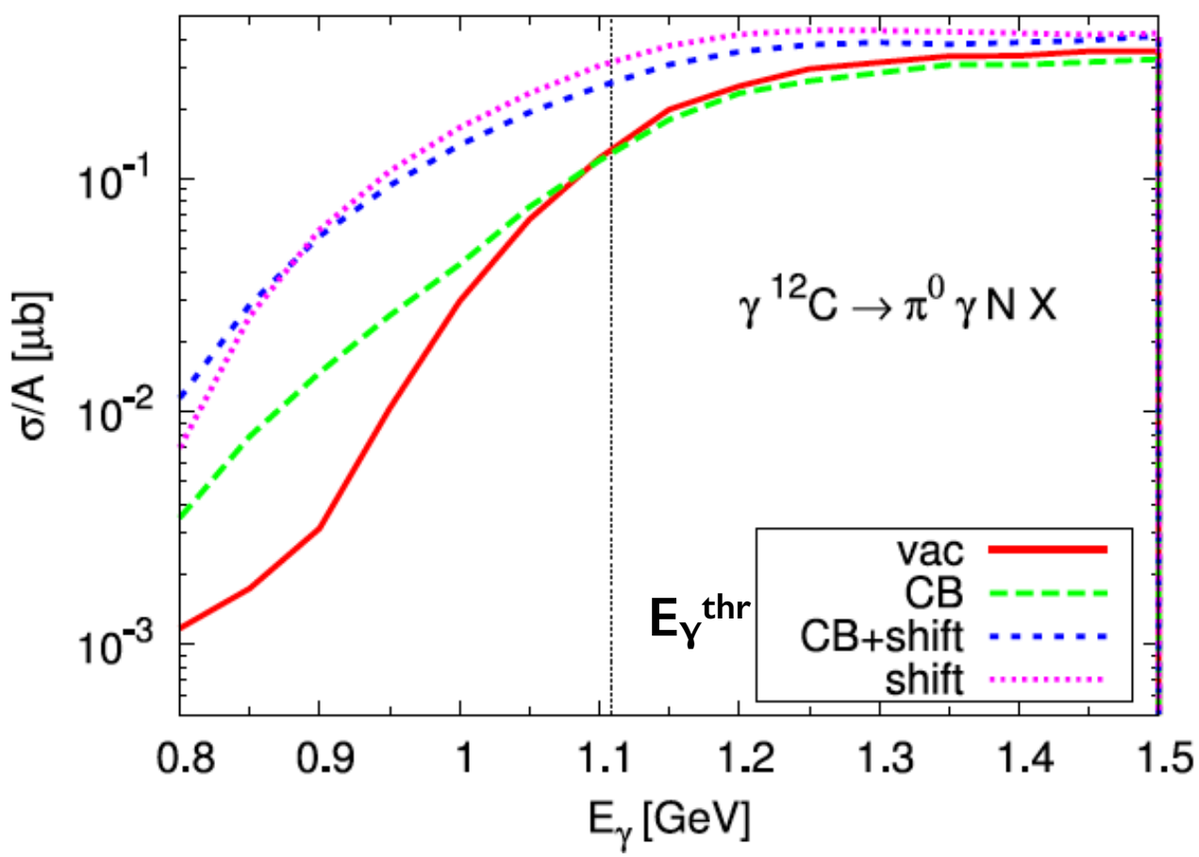
J. Weil, U. Mosel and V. Metag, PLB 723 (2013) 120 $\omega \to \pi^0\gamma$

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

$\pi^0\gamma$ excitation function



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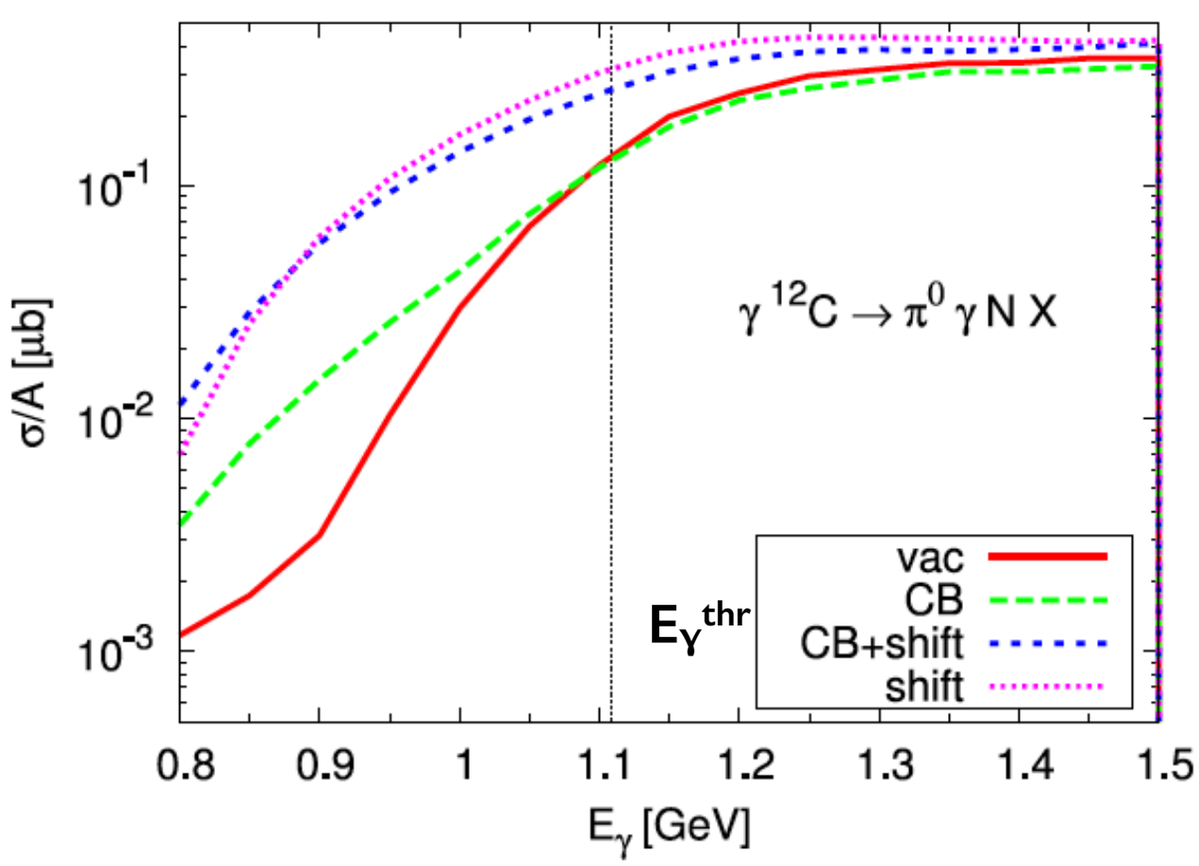
⇨ cross section enhancement

- momentum distribution of the meson:

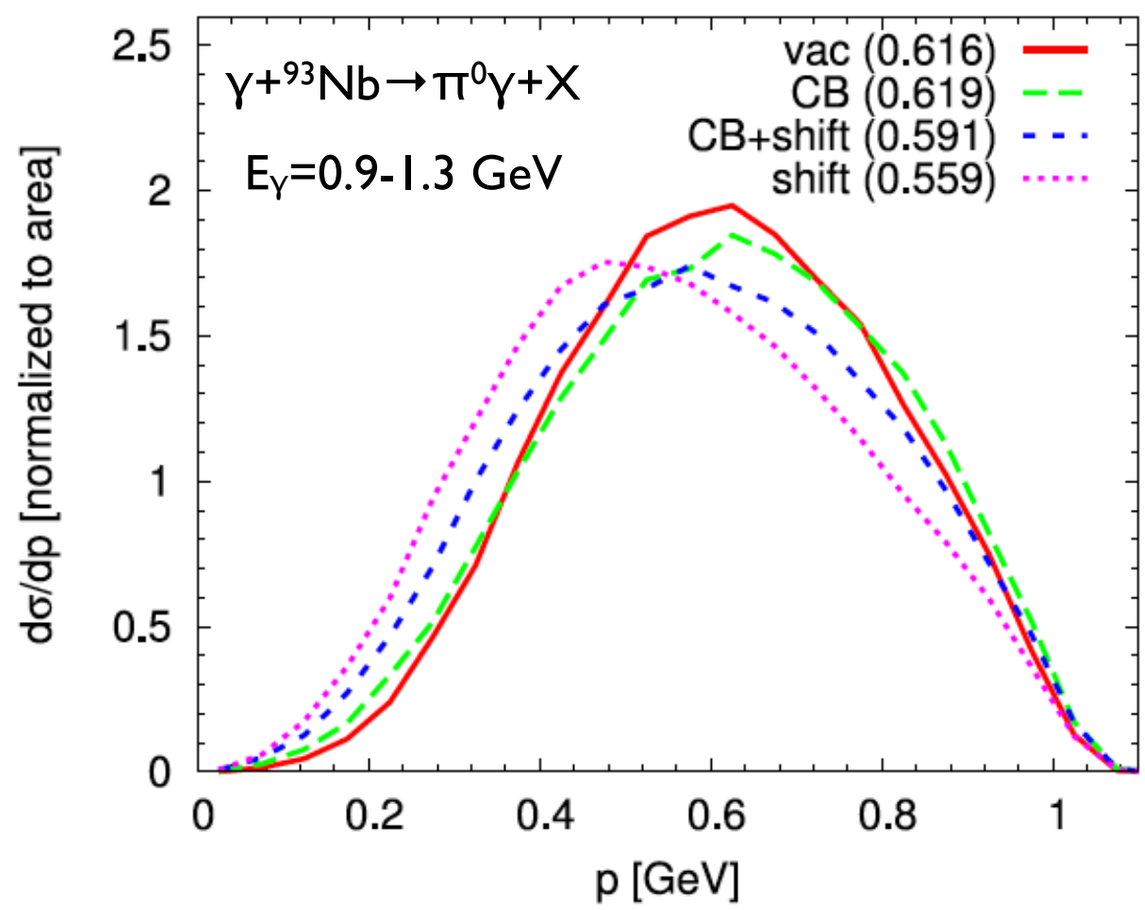
in case of dropping mass - when leaving the nucleus hadron has to become on-shell; mass generated at the expense of kinetic energy

⇨ downward shift of momentum distribution

$\pi^0\gamma$ excitation function



$\pi^0\gamma$ momentum distribution

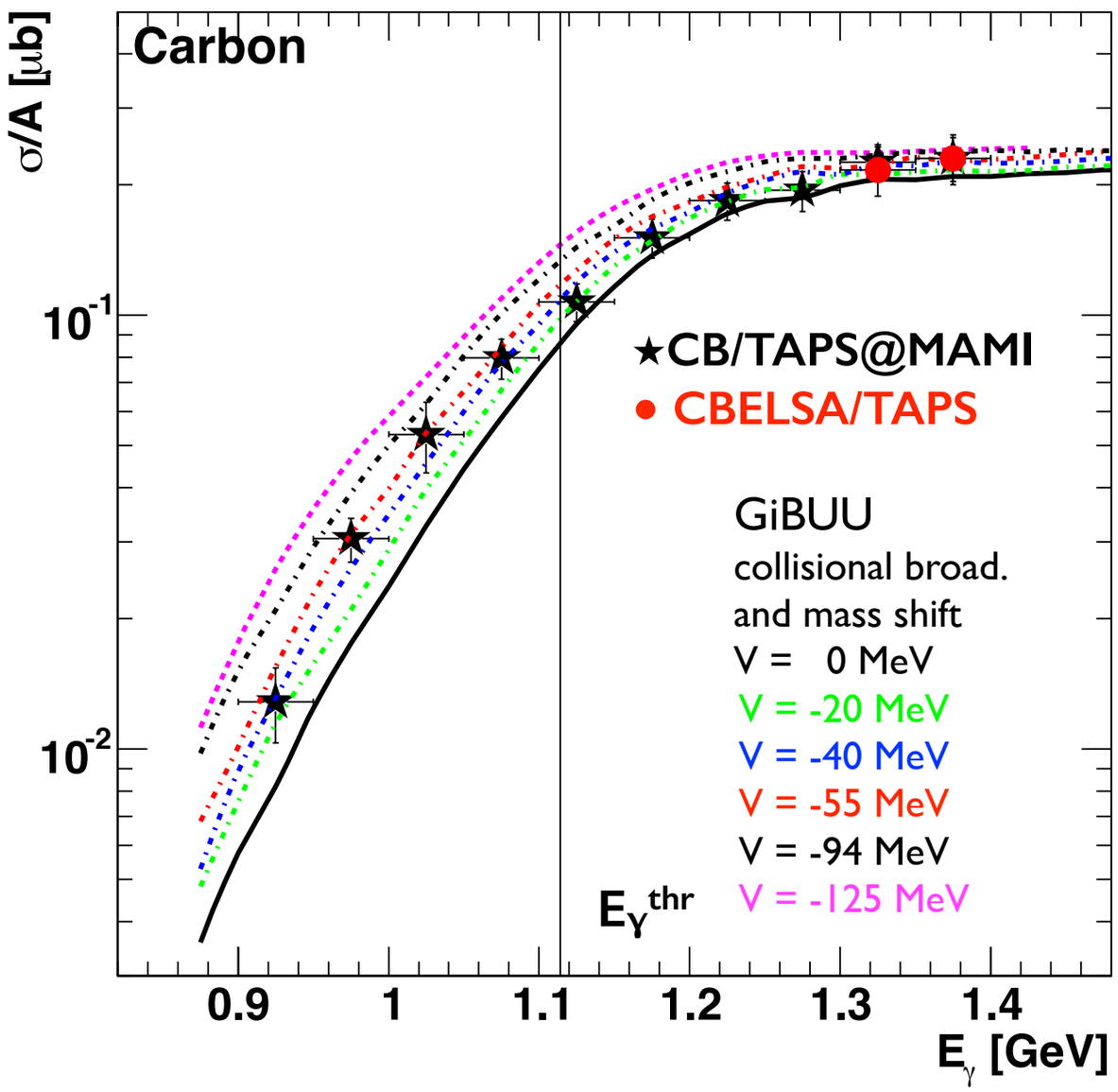


excitation function for ω and η' photoproduction off C

ω

CB/TAPS @ MAMI

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



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

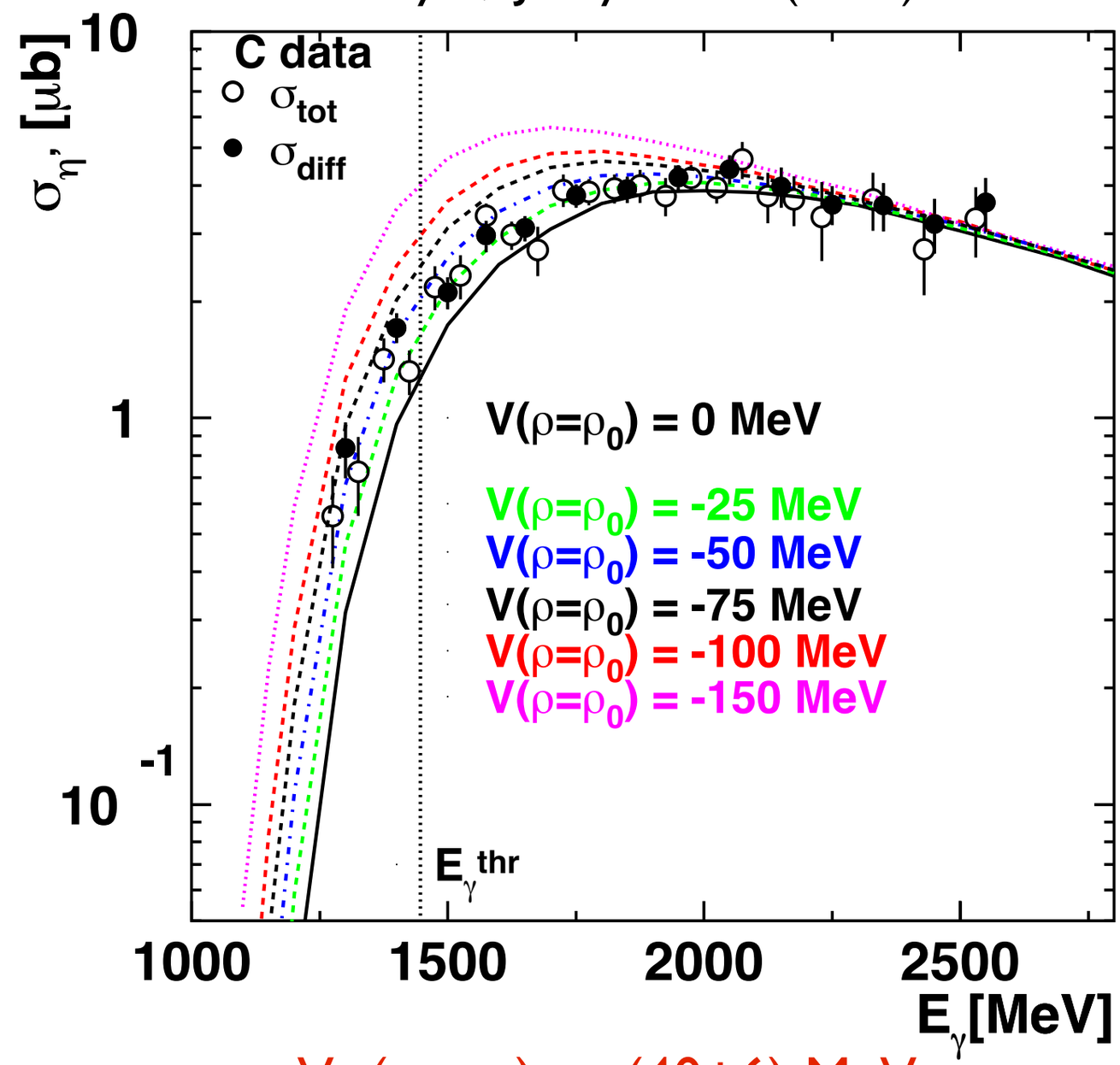
data disfavour scenario:

„broadening and -125 MeV mass shift"

η'

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) MeV

data disfavour strong mass shifts

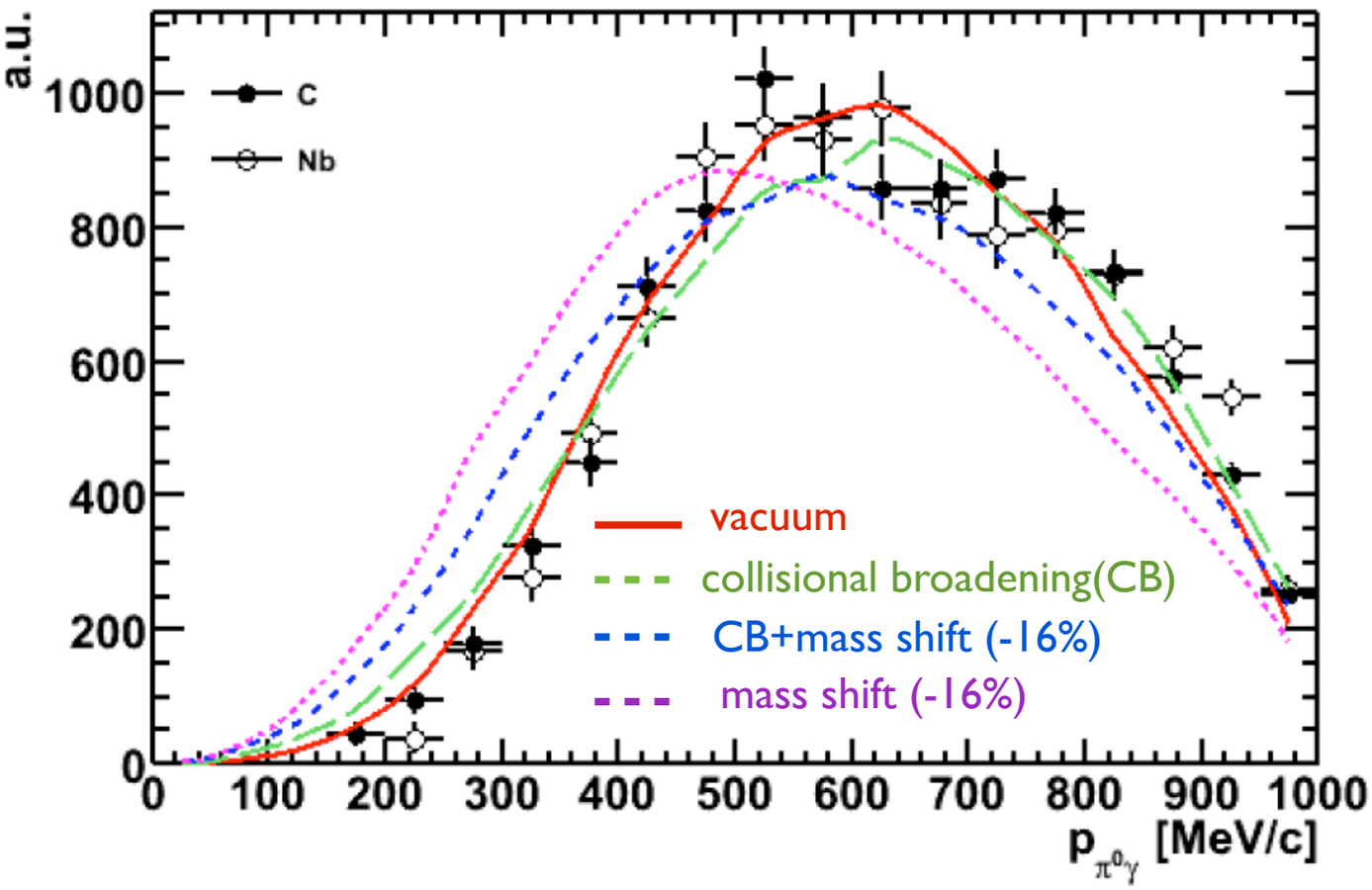
momentum distribution for ω and η' photoproduction

ω

CB/TAPS @ MAMI

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

E_γ=900-1300 MeV

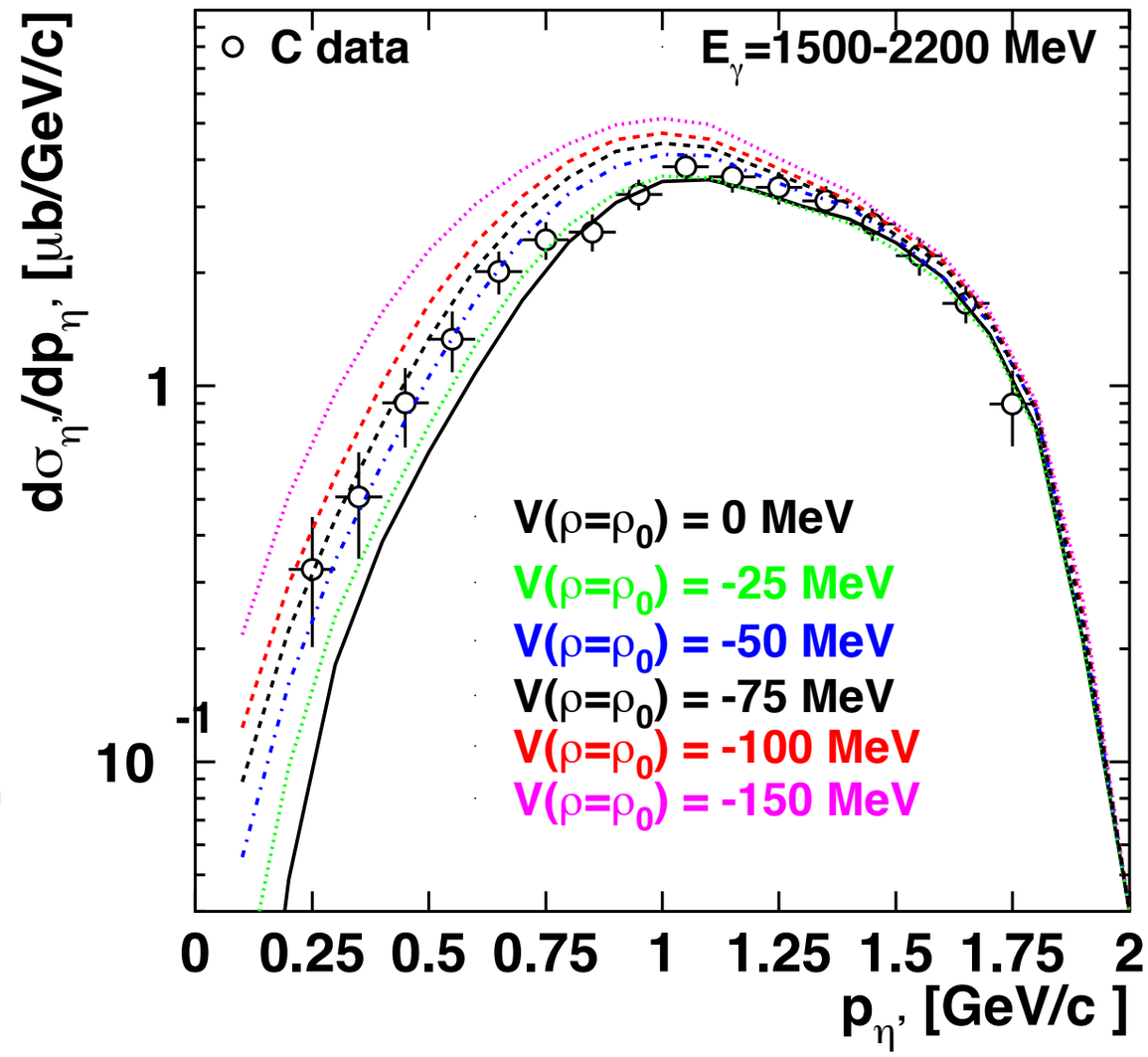


data not consistent with strong mass shift scenario (Δm/m≈-16%)

η'

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

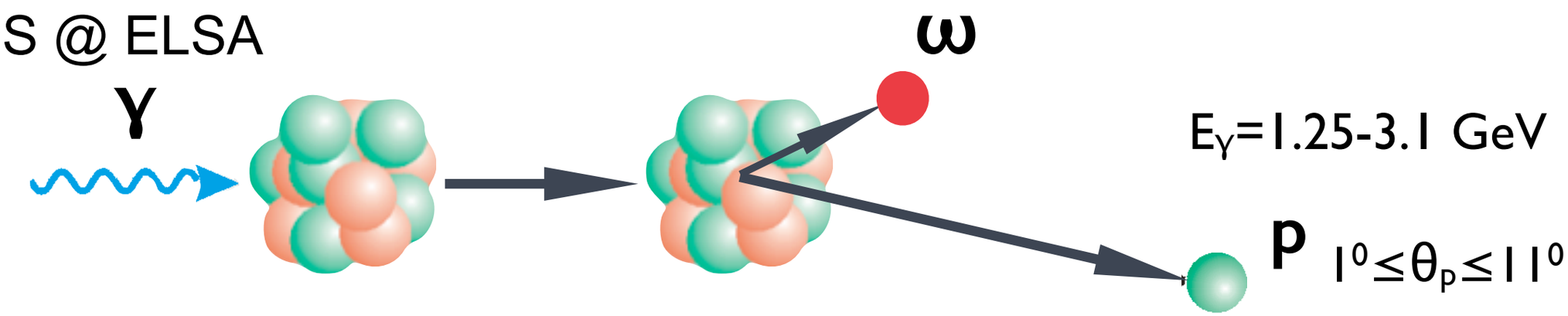
calc.: E. Paryev, J. Phys. G 40 (2013) 025201



$V_{\eta'}(p_{\eta'}\approx 1.1$ GeV/c;$\rho=\rho_0) = -(32\pm 11)$ MeV

real part of ω-nucleus potential from ω kinetic energy

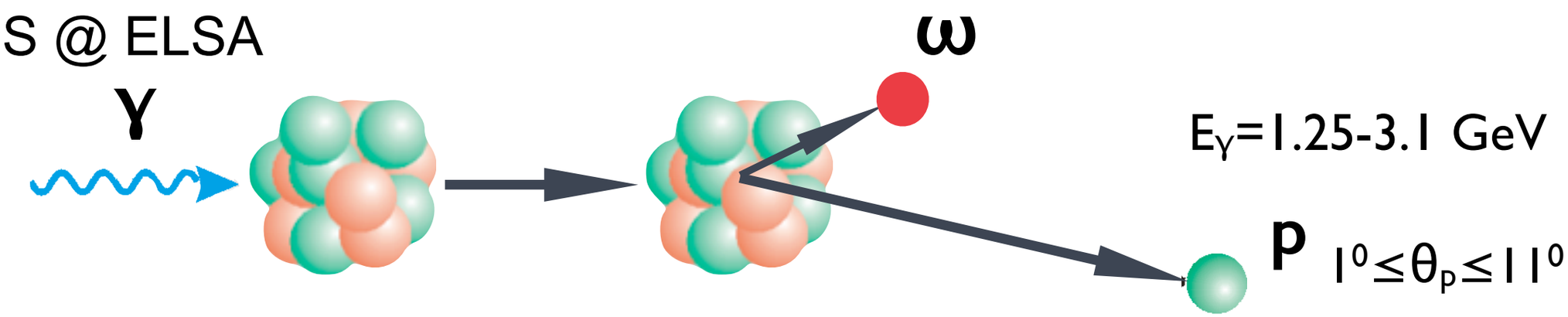
CBELSA/TAPS @ ELSA



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



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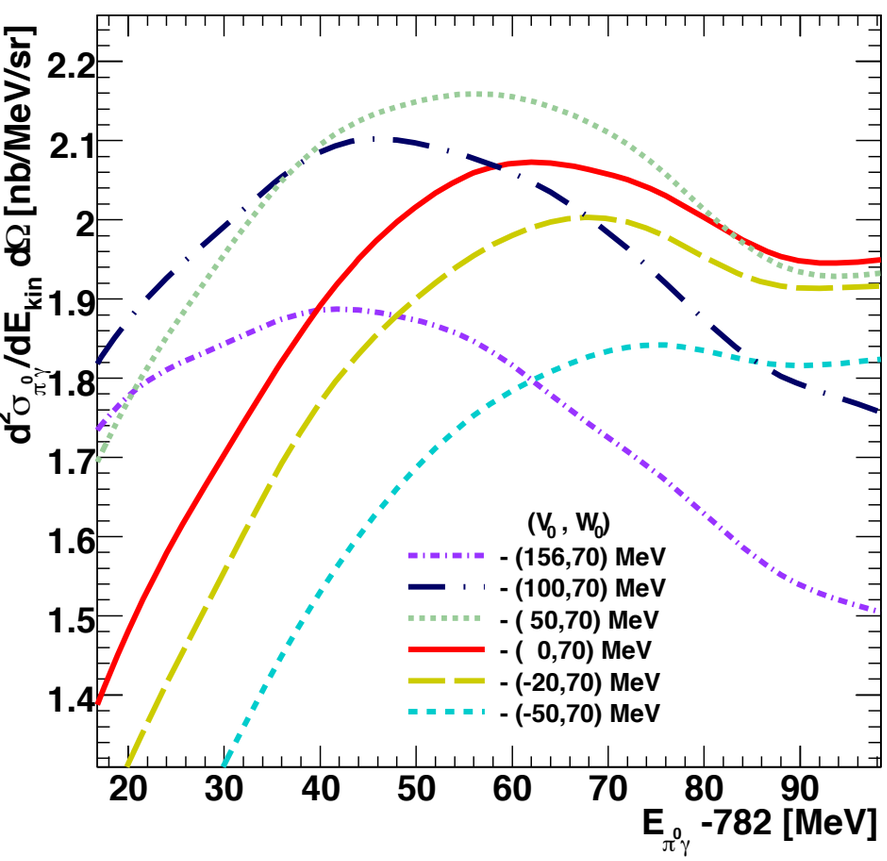
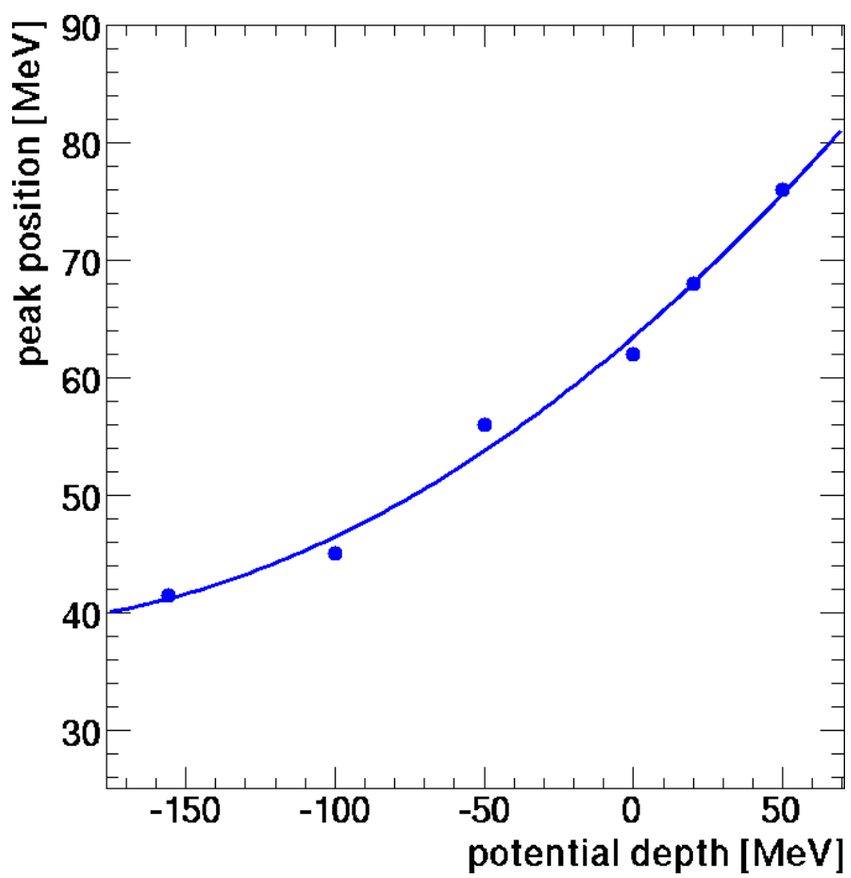
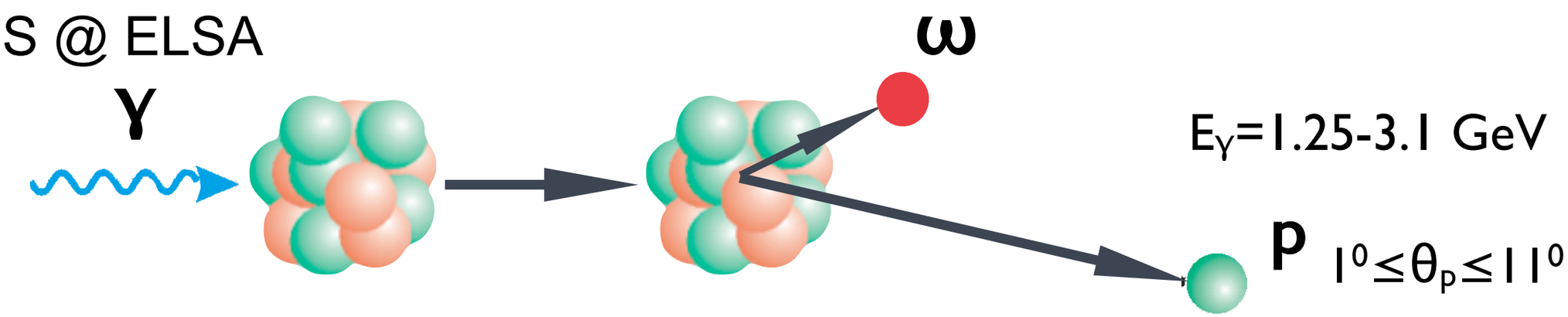
H. Nagahiro, priv. com.





real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA

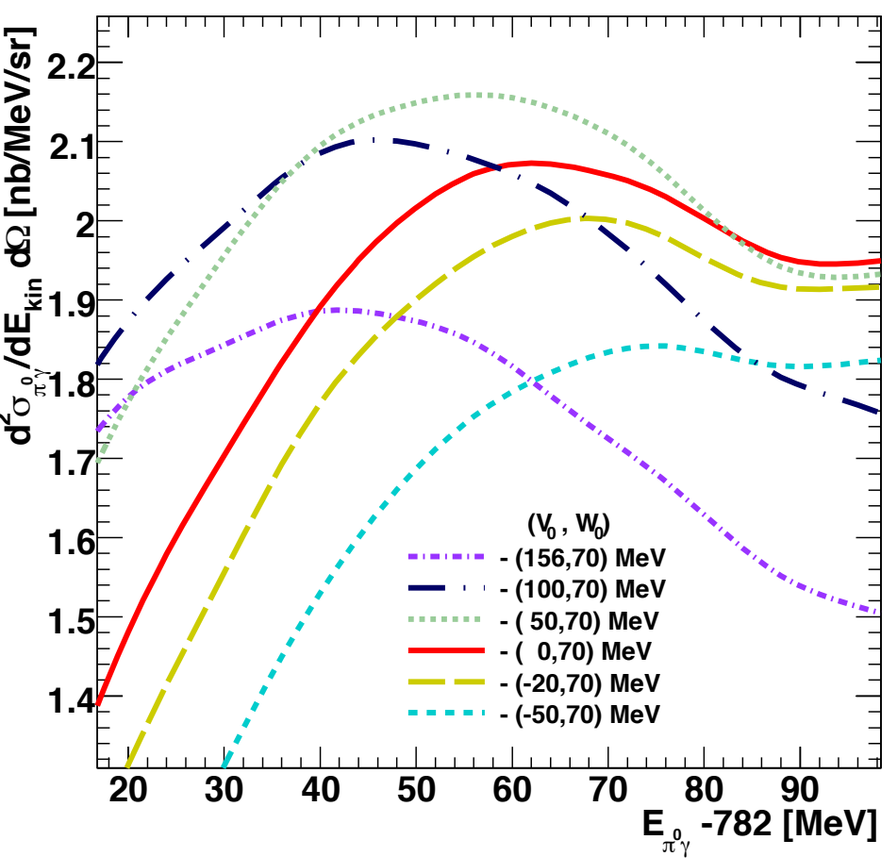


E_γ=1.25-3.1 GeV

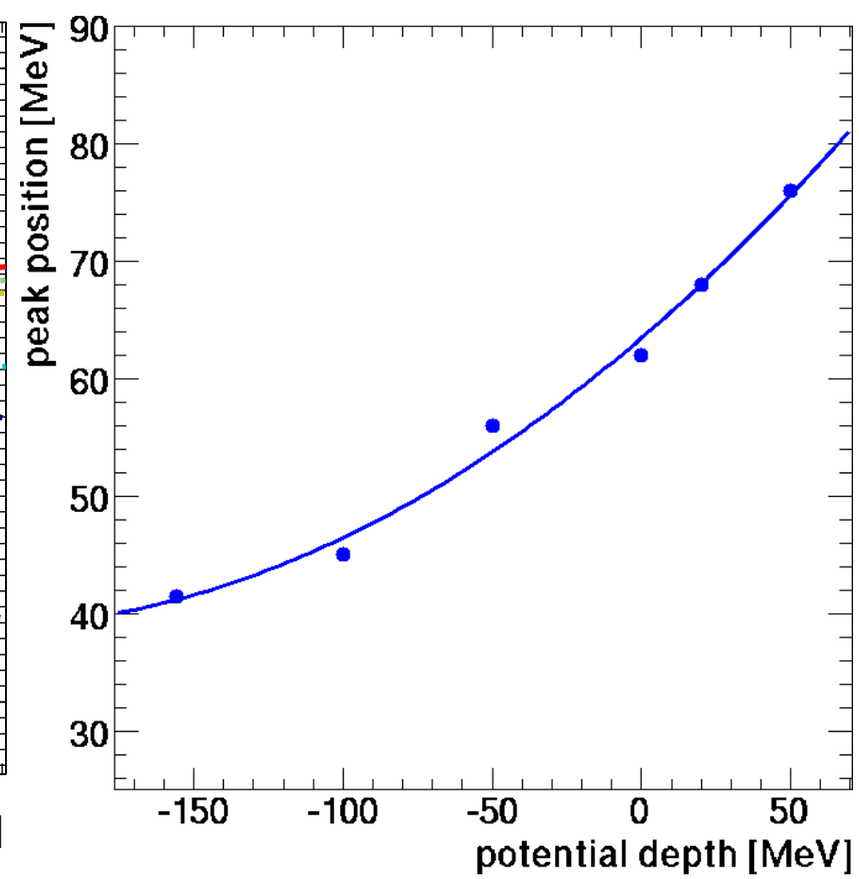
$1^0 \leq \theta_p \leq 11^0$

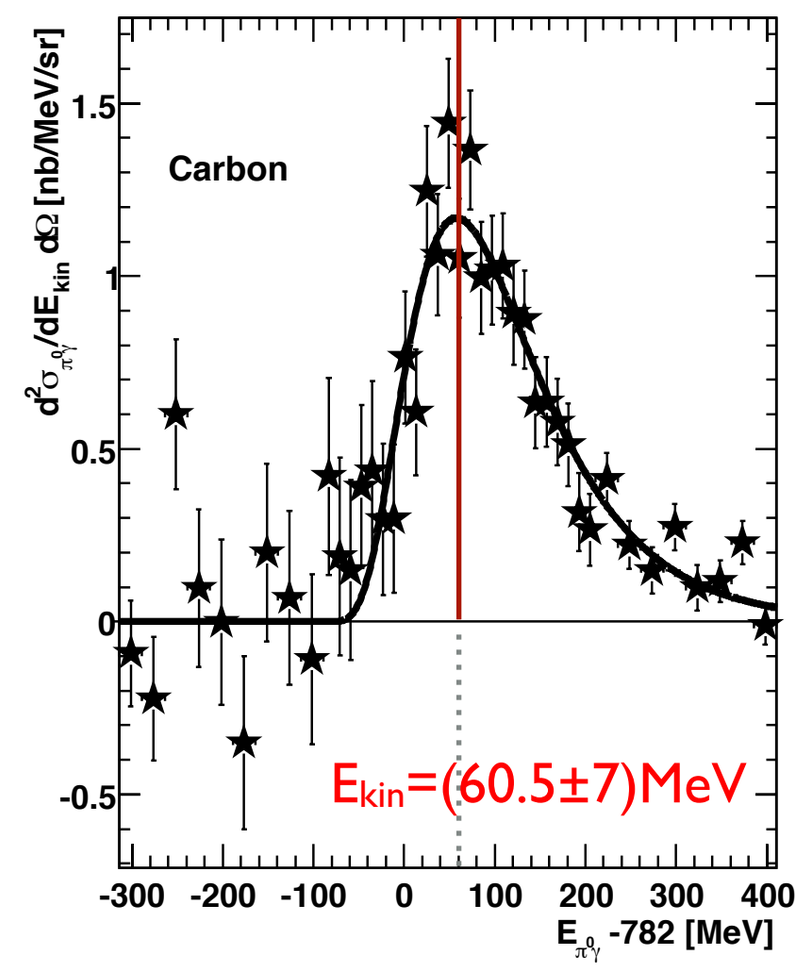
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.



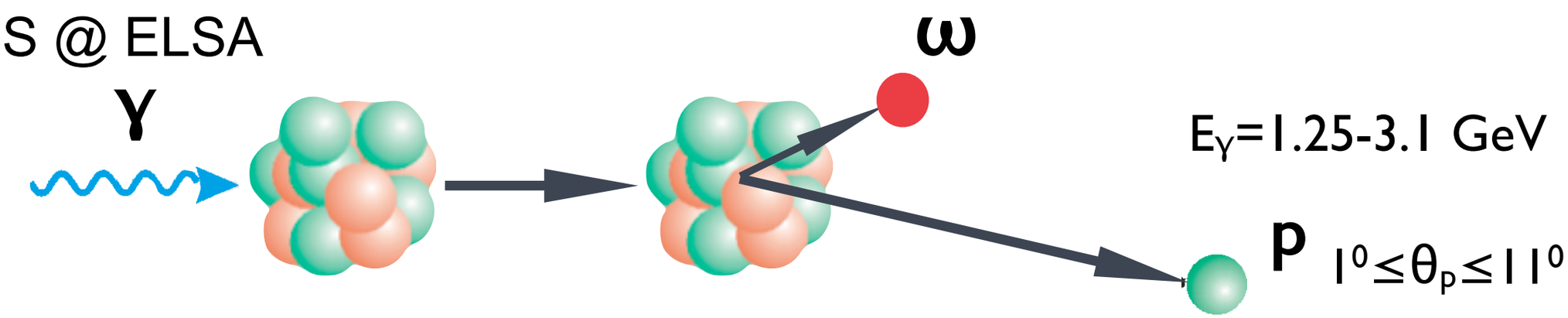
S. Friedrich, PLB 736 (2014) 26





real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA



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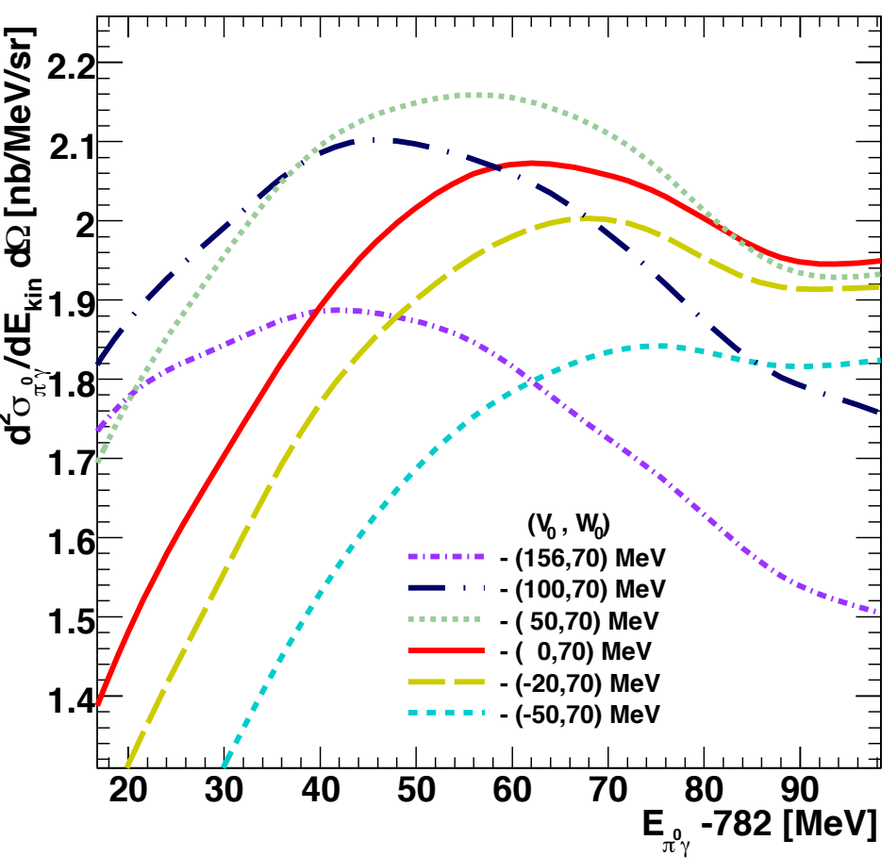
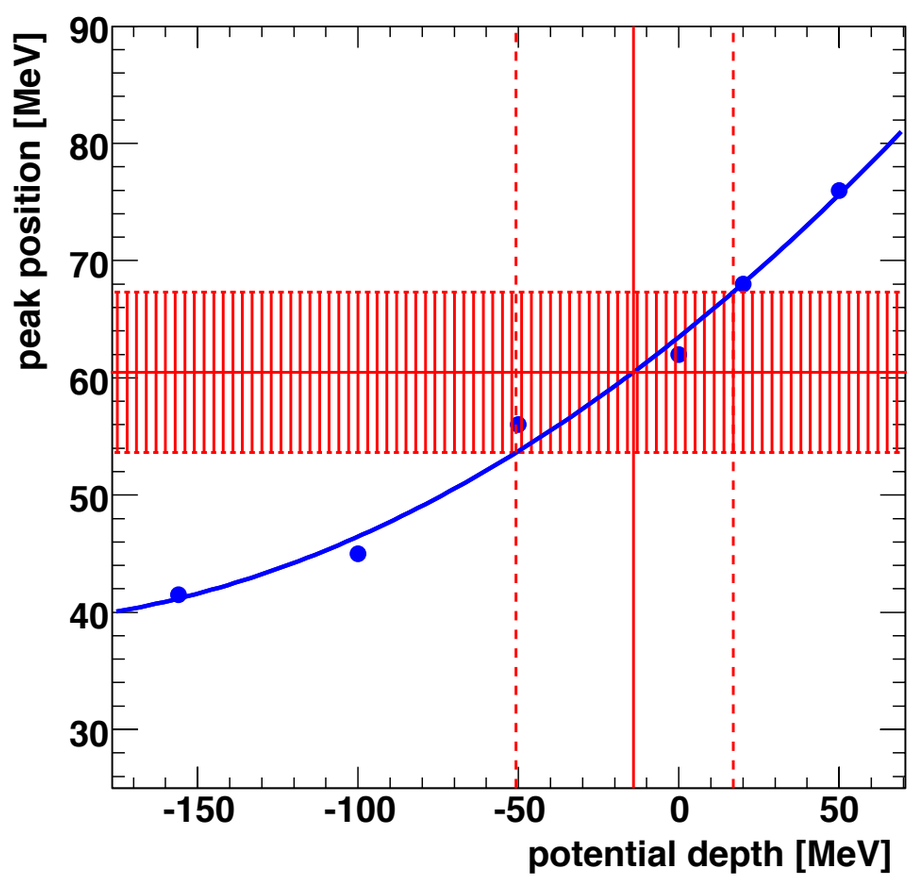
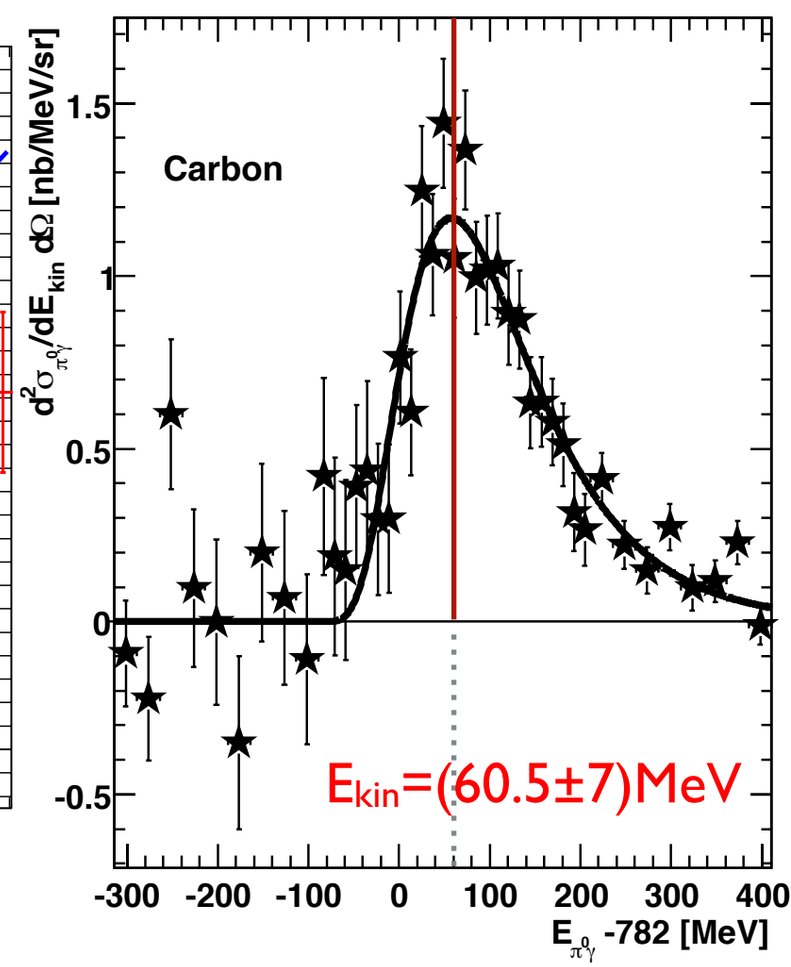
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.



S. Friedrich, PLB 736 (2014) 26

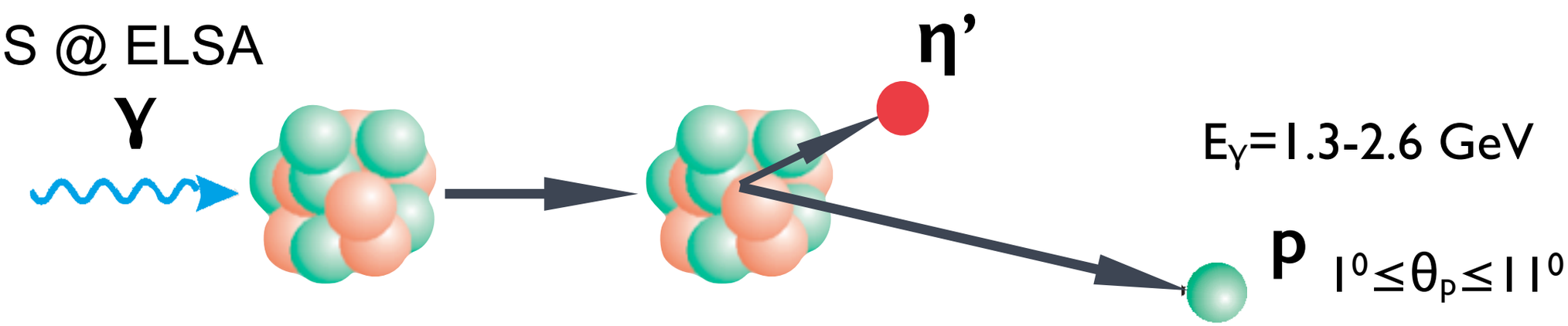




$V_\omega(p_\omega \approx 300$ MeV/c; $\rho=\rho_0) = -(15\pm35)$ MeV

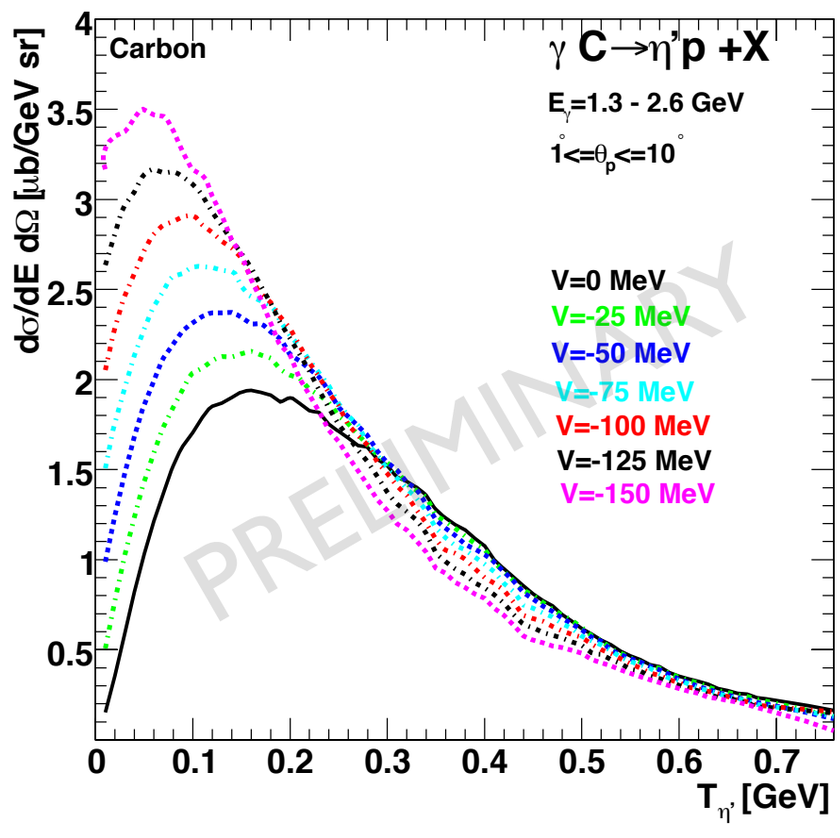
real part of η'-nucleus potential from η' kinetic energy

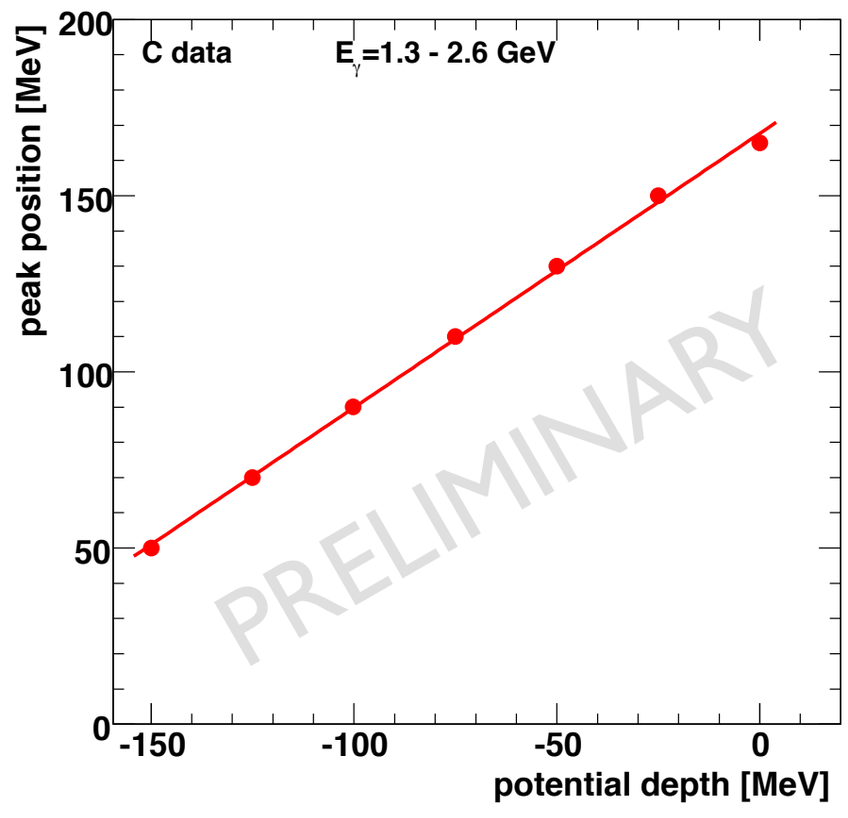
CBELSA/TAPS @ ELSA



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

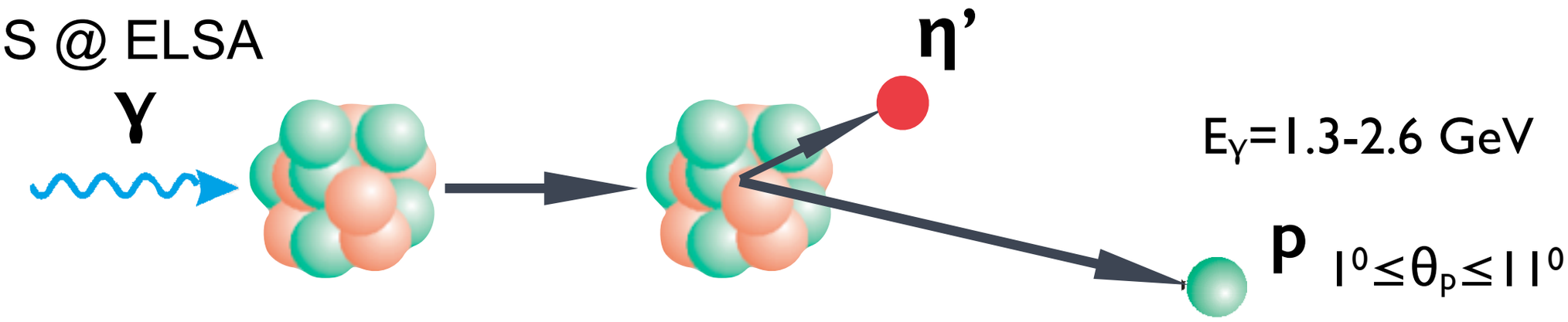
E. Paryev, priv. com.





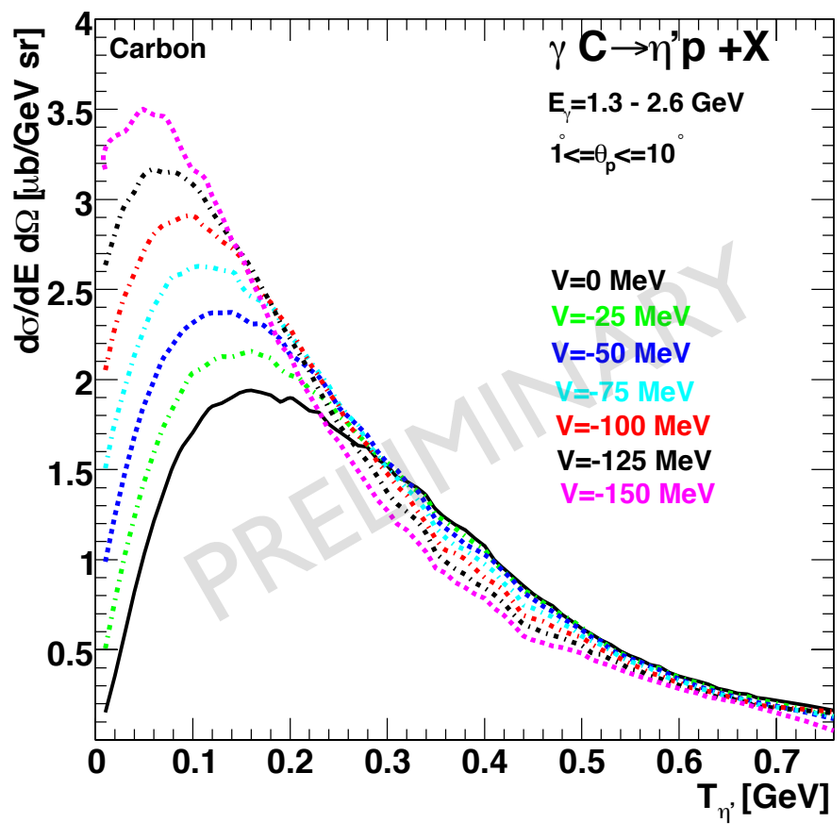
real part of η'-nucleus potential from η' kinetic energy

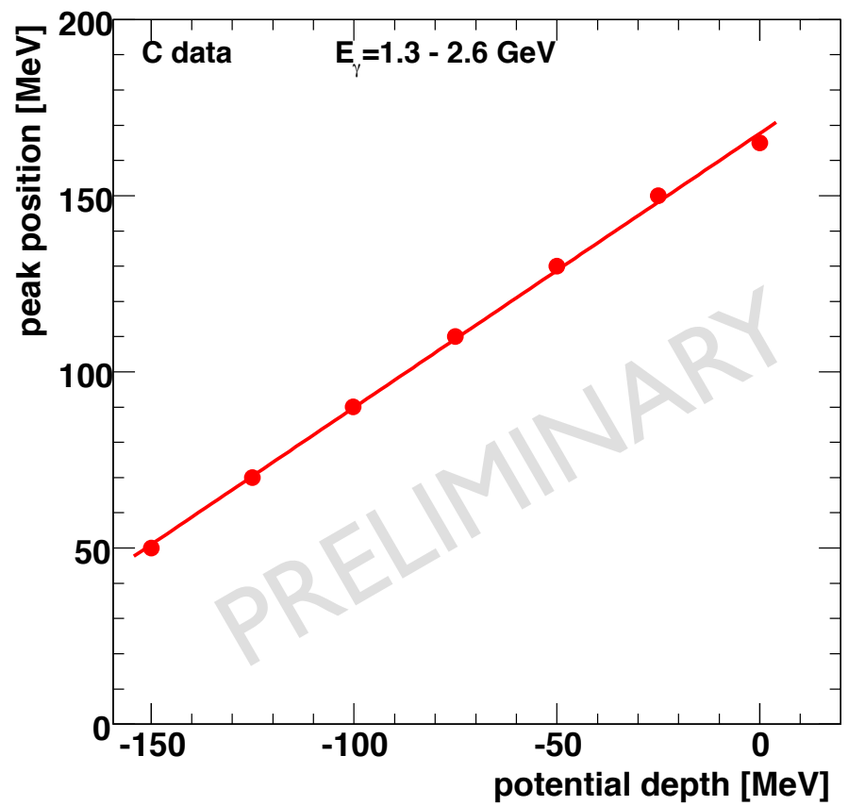
CBELSA/TAPS @ ELSA

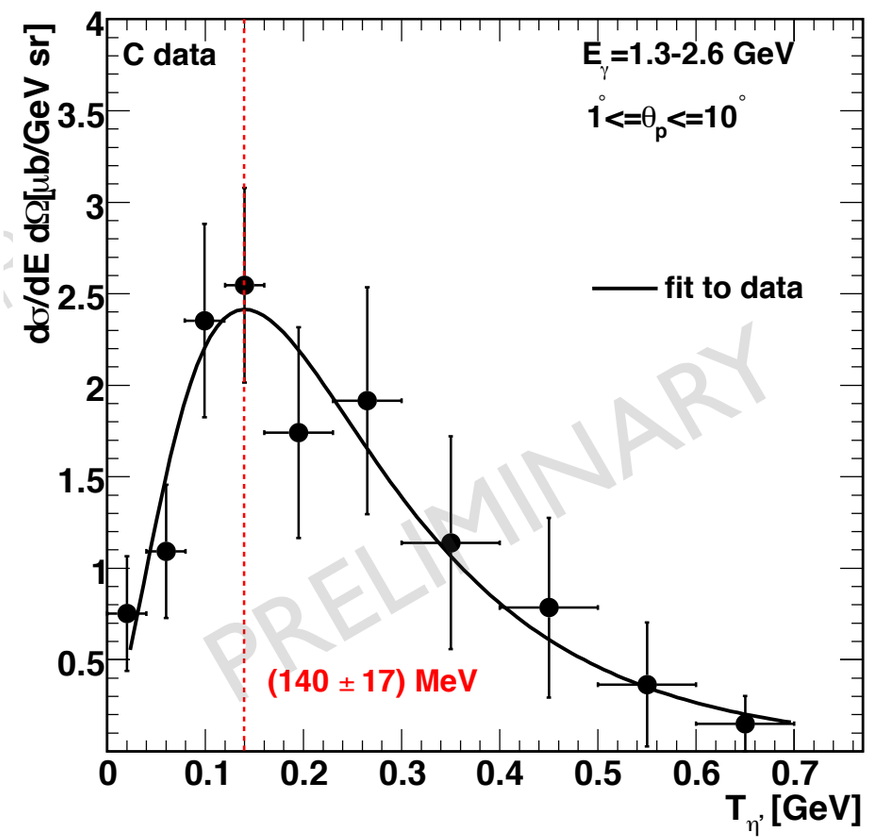


the higher the attraction the lower the kinetic energy of the η' meson

E. Paryev, priv. com.

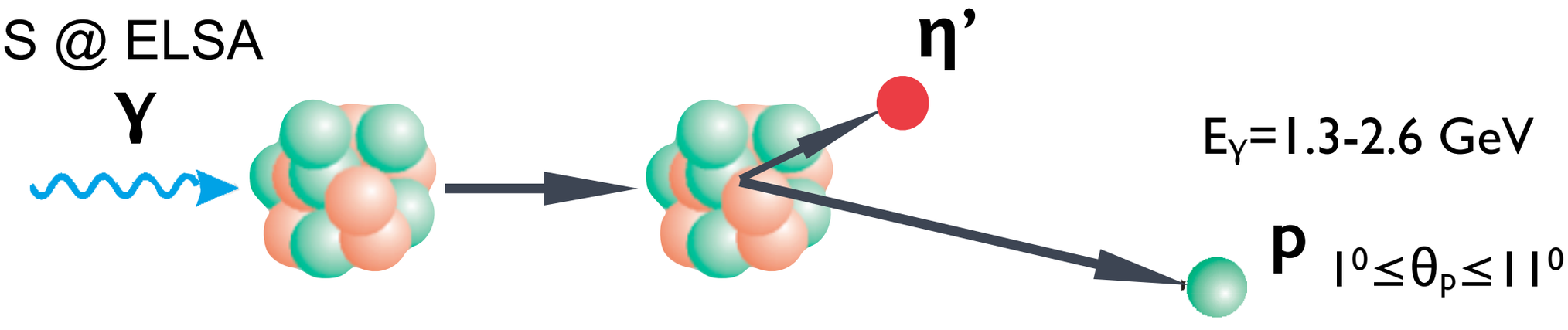






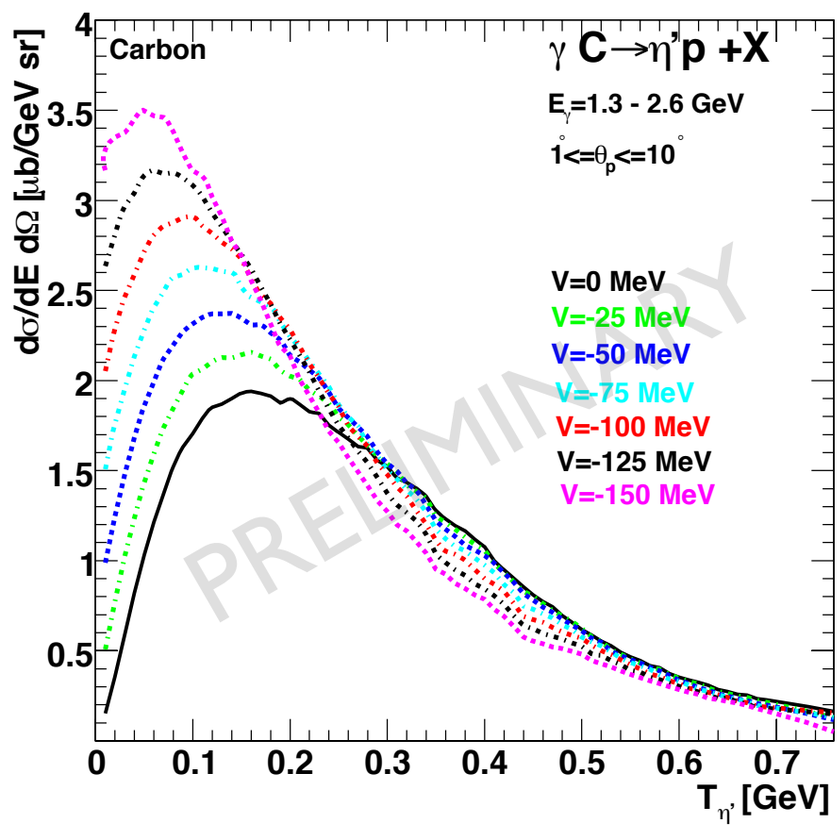
real part of η'-nucleus potential from η' kinetic energy

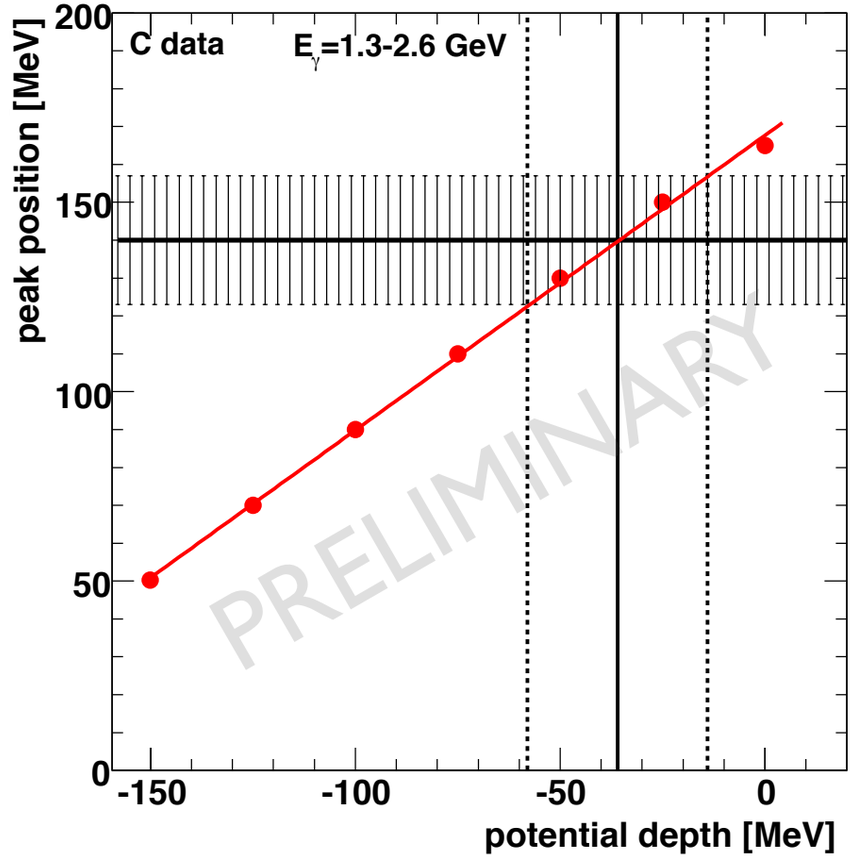
CBELSA/TAPS @ ELSA

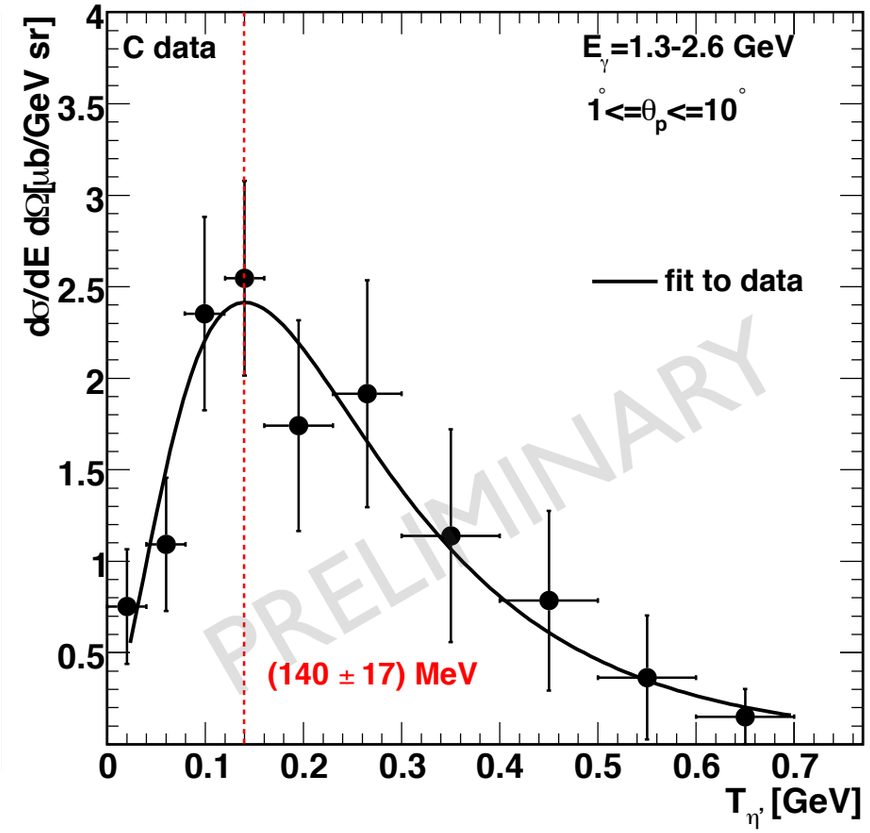


the higher the attraction the lower the kinetic energy of the η' meson

E. Paryev, priv. com.



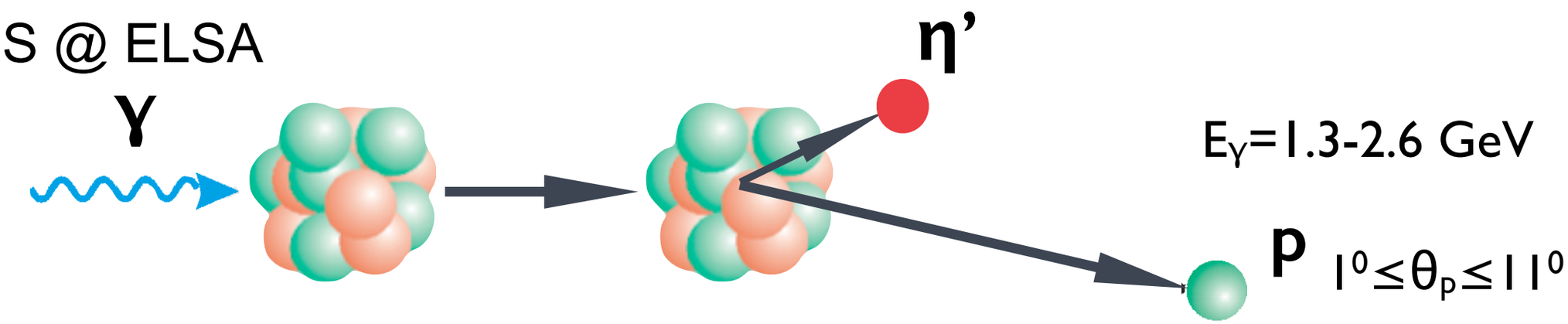




$V_{\eta'}(p_{\eta'} \approx 500\ \text{MeV/c};\ \rho=\rho_0) \approx -(36 \pm 22)$ MeV

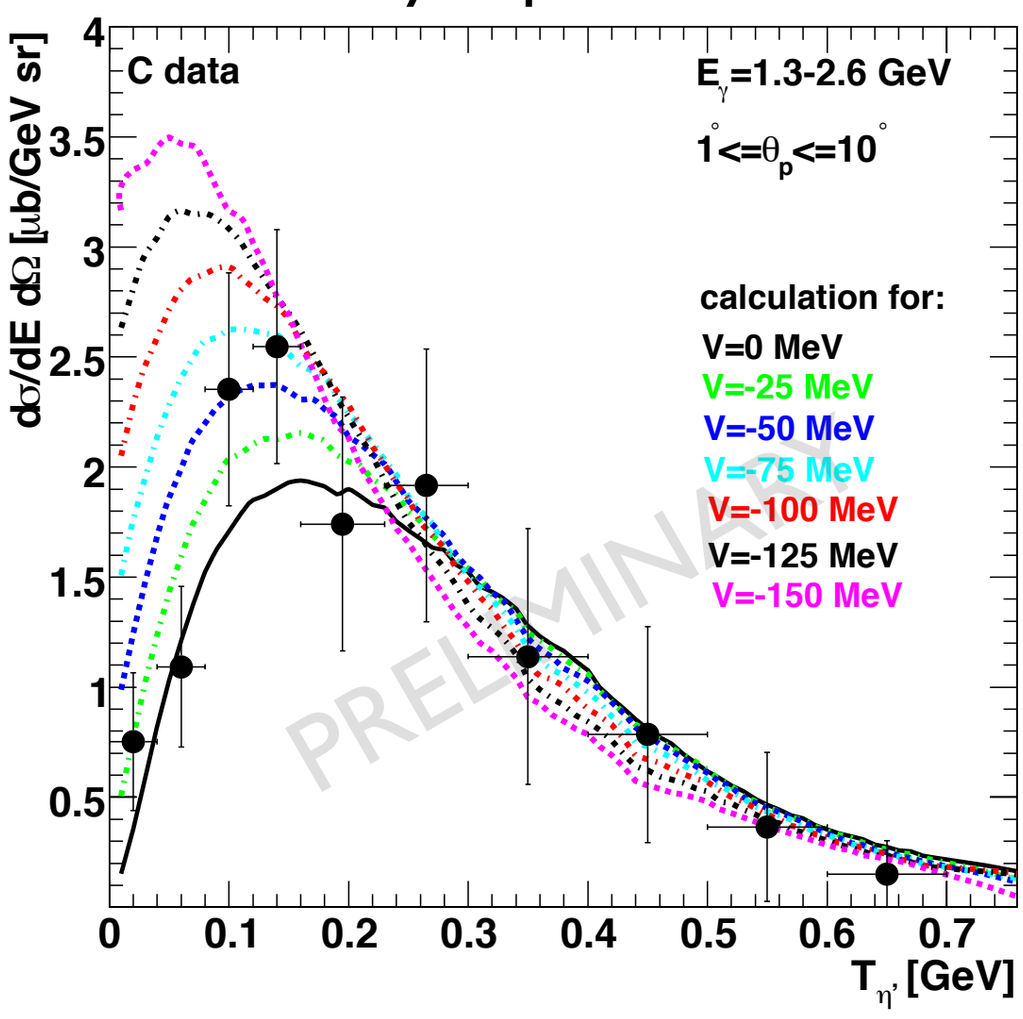
real part of η'-nucleus potential from η' kinetic energy

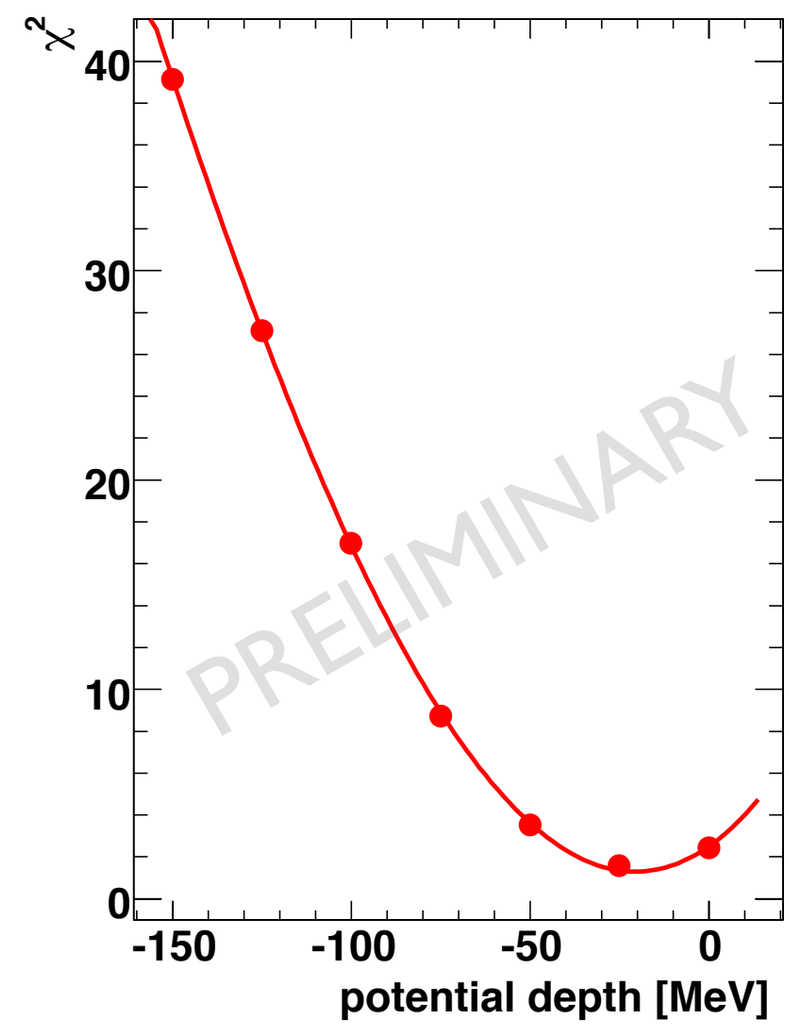
CBELSA/TAPS @ ELSA



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

E. Paryev, priv. com.





$V_{\eta'}(p_{\eta'} \approx 500\ \text{MeV/c};\ \rho=\rho_0) \approx -(21 \pm 18)$ MeV

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

ω

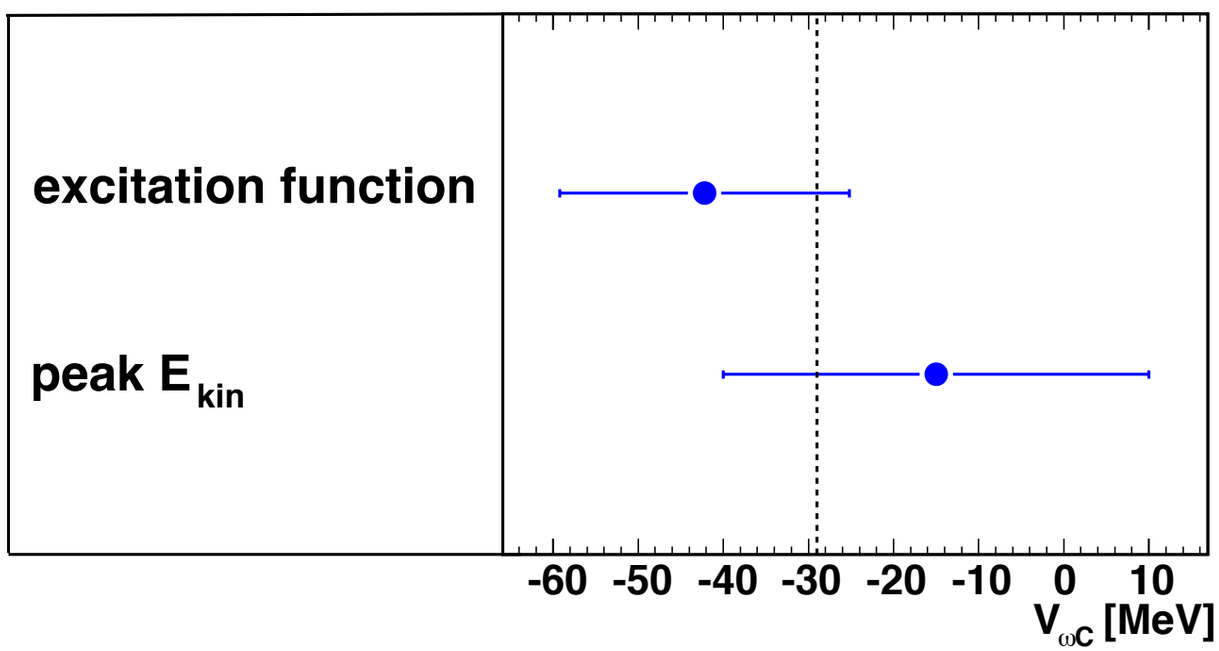
η'

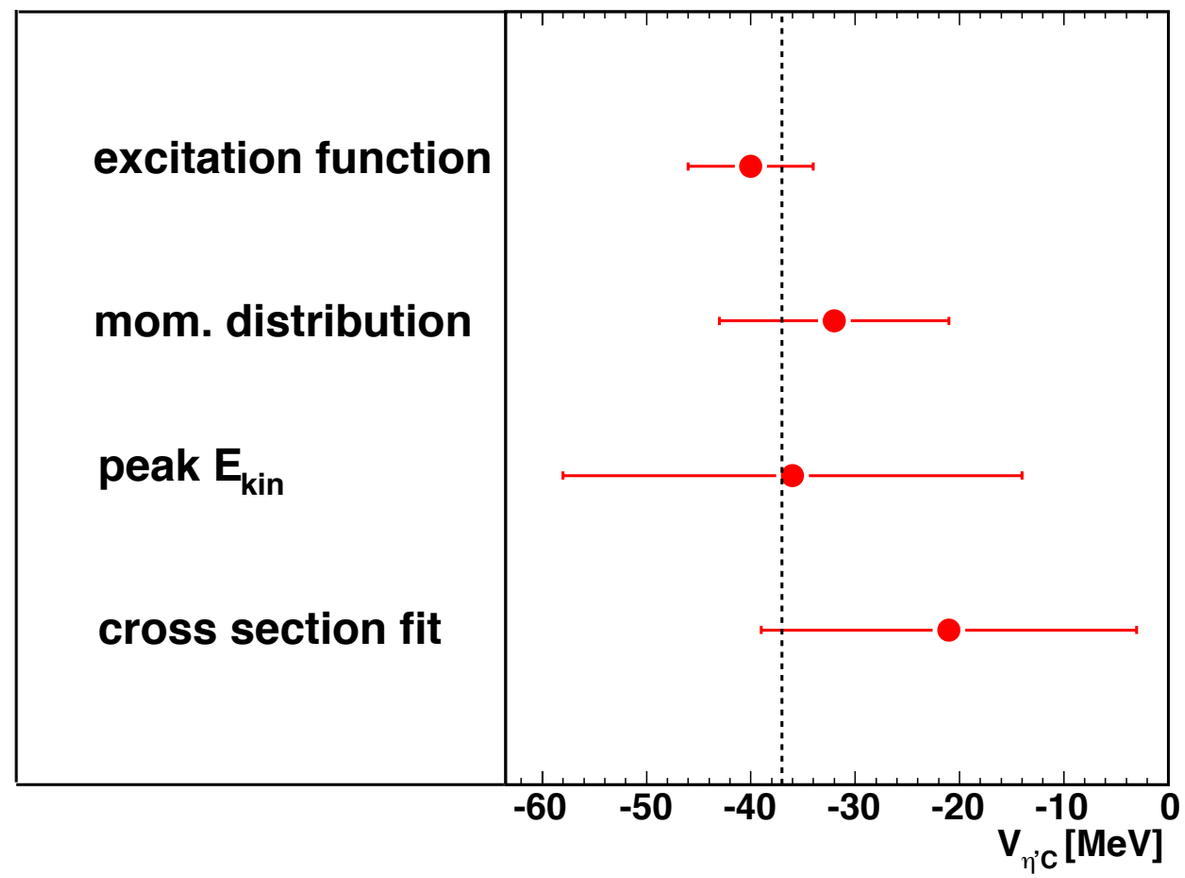
imaginary part:

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

$V_{\eta' A}(\rho=\rho_0) =$
$-(37\pm5(\text{stat})\pm10(\text{syst}))$MeV

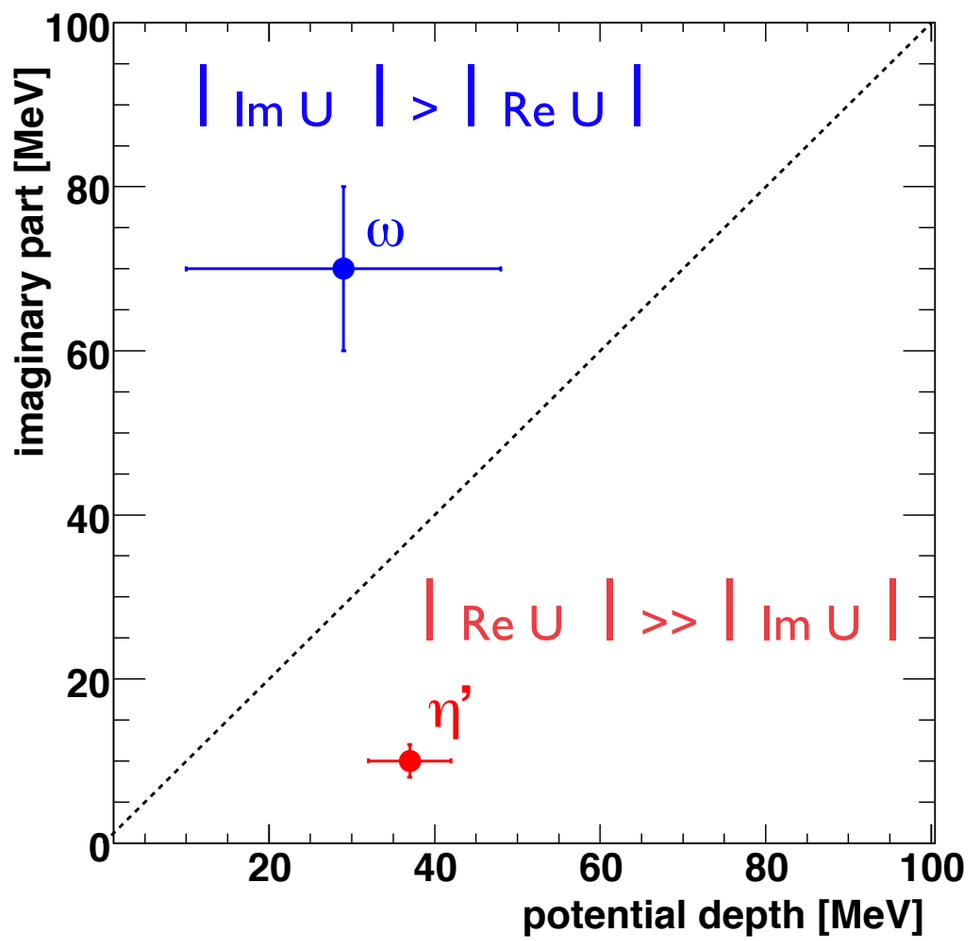
compilation of results for real and imaginary part of the ω, η' -nucleus optical potential

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

$-(29\pm19(stat)\pm20(syst) + i(70\pm10)$ MeV

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

$-(37\pm5(stat)\pm10(syst) + i(10\pm3)$ MeV



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

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

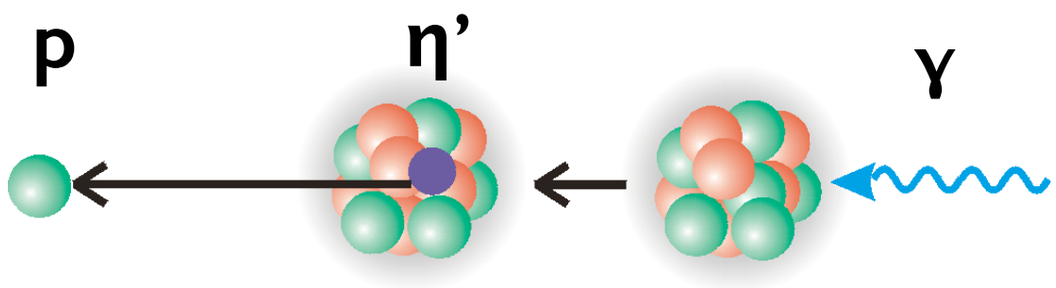
first (indirect) observation of in-medium mass shift of η' at $\rho=\rho_0$ and T=0

in good agreement with QMC model predictions (S. Bass et al., PLB 634 (2006) 368)

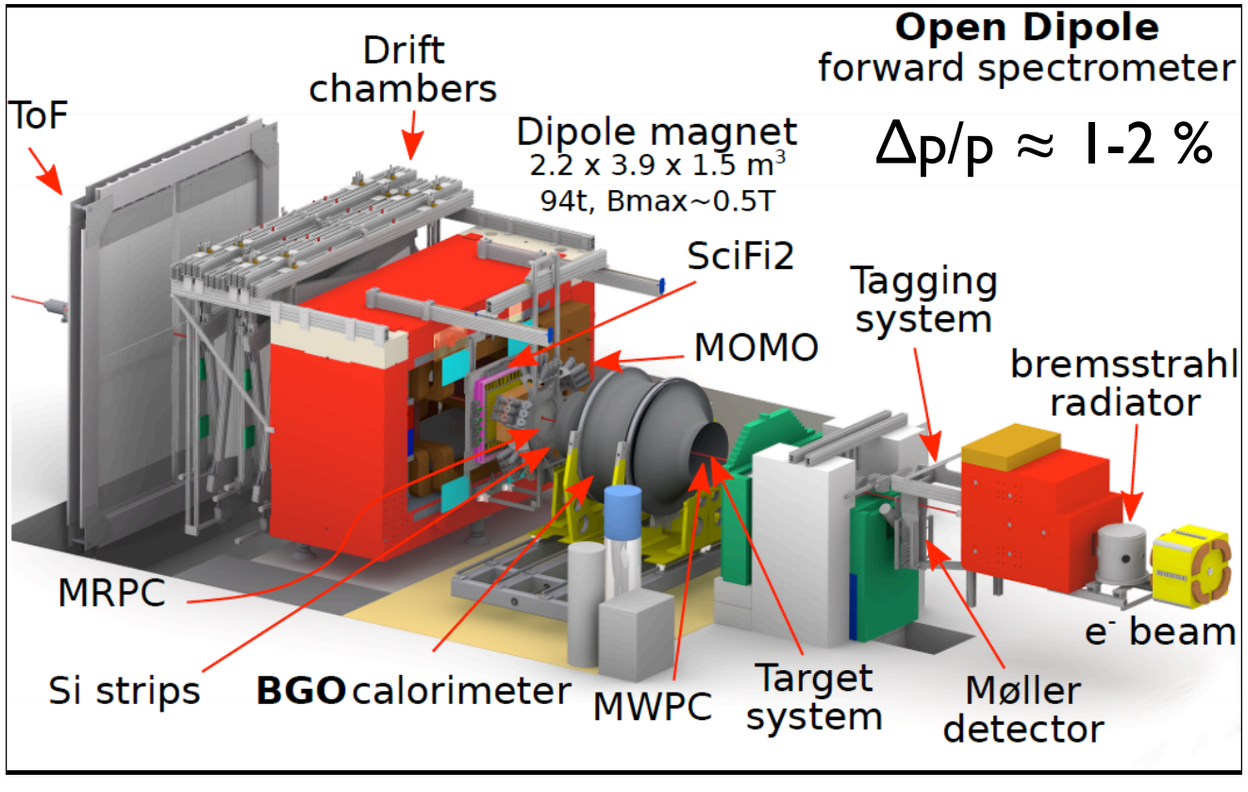
search for η'-mesic states

BGO-OD@ELSA

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



formation and decay of η'-mesic state



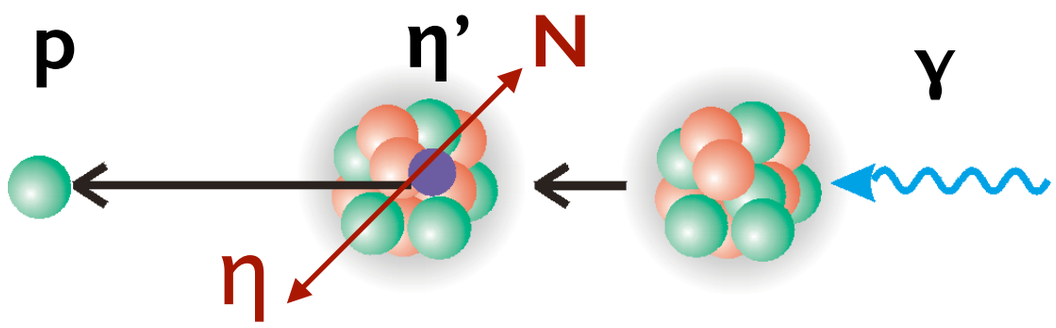
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

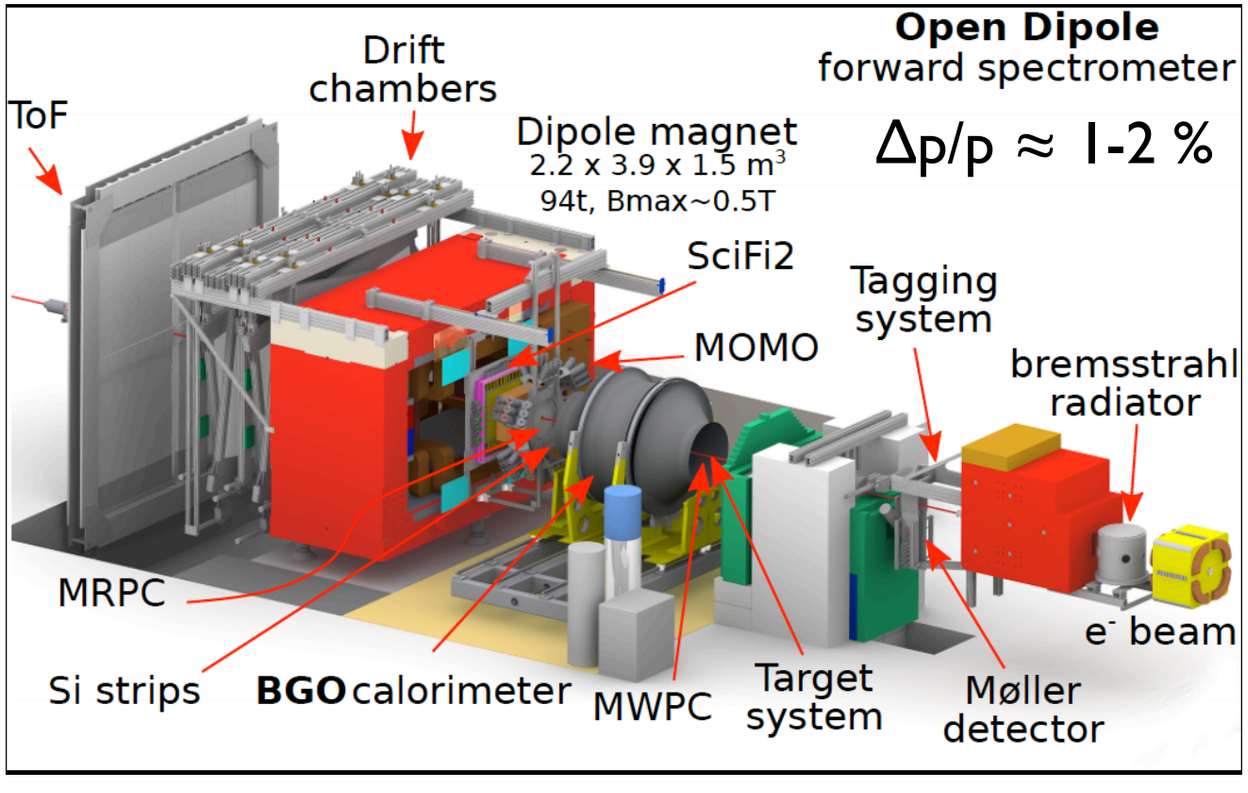
search for η'-mesic states

BGO-OD@ELSA

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



formation and decay of η'-mesic state



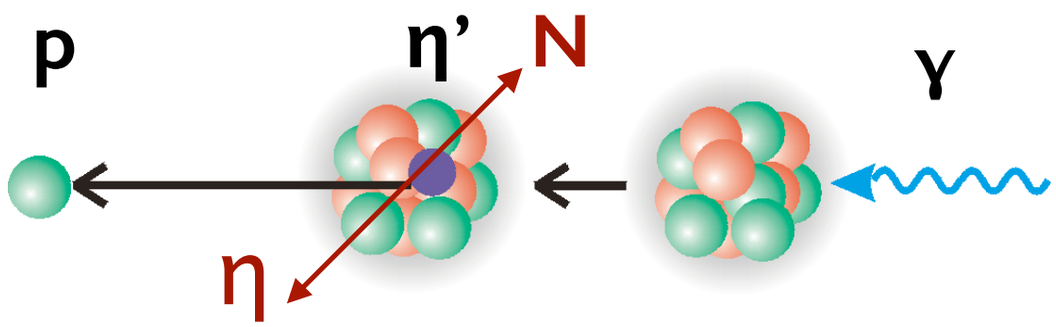
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

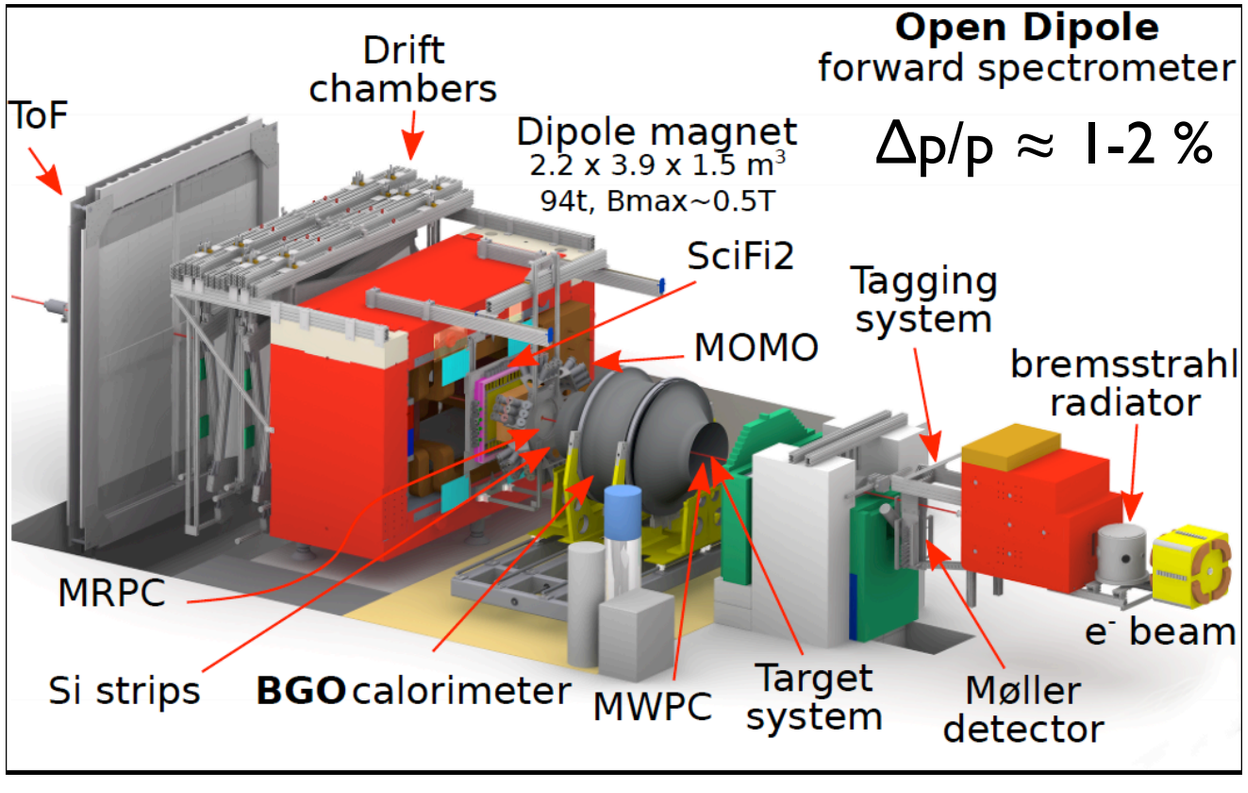
search for η'-mesic states

BGO-OD@ELSA

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



formation and decay of η'-mesic state



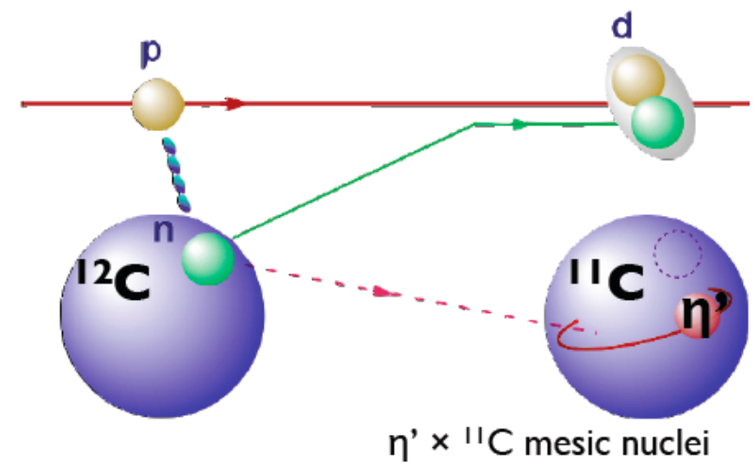
BGO-OD ideally suited for exclusive measurement

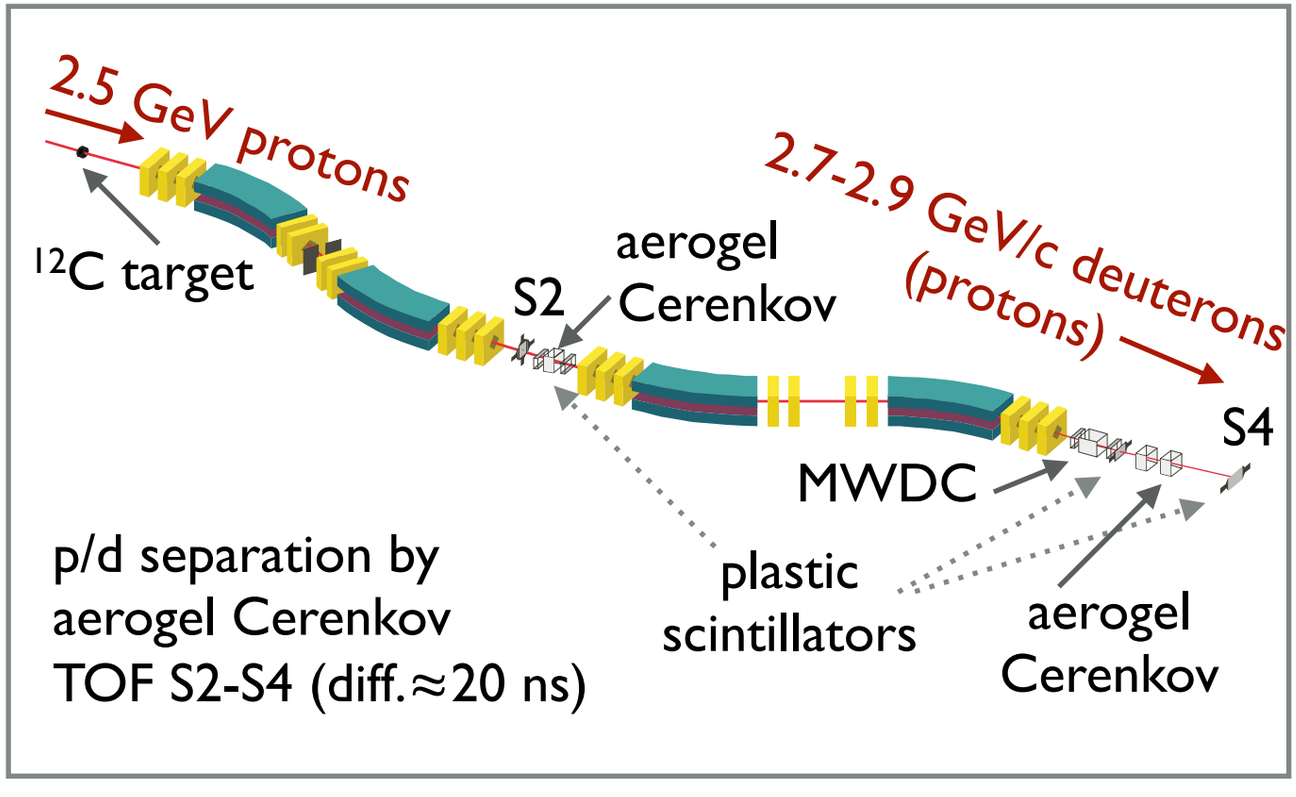
approved proposal: ELSA/3-2012-BGO

FRS@GSI

$^{12}C(p,d)\ \eta'X$ @ 2.5 GeV

K. Itahashi *et al.*, Prog. Theo. Phys. 128(2012) 601





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

status report by Hiroyuki Fujioka