Meson-nucleus interactions studied in photo-nuclear experiments

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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

*funded by the DFG within SFB/TR16

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Symposium
Kyoto, Japan, March 2-6, 2015

HIC for FAIR
Helmholtz International Center

bound systems

earth ↔ moon

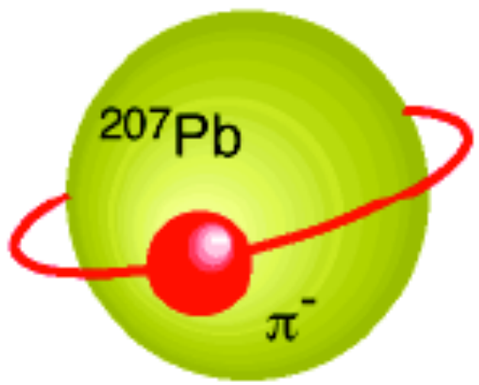
bound by gravitation

bound systems

earth ↔ moon

bound by gravitation

π^- ↔ nucleus



bound by superposition of attractive Coulomb- and repulsive strong interaction

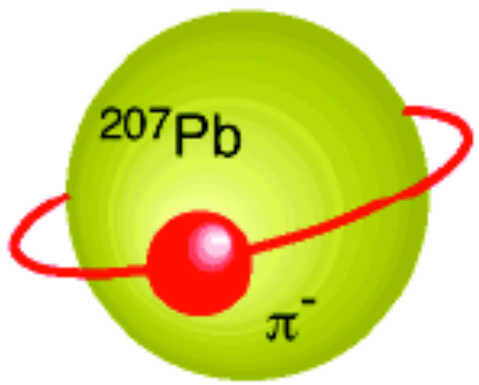
talk by Kenta Itahashi

bound systems

earth ↔ moon

bound by gravitation

π^- ↔ nucleus



bound by superposition of attractive Coulomb- and repulsive strong interaction

talk by Kenta Itahashi

ω, η' ↔ nucleus

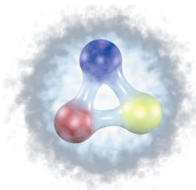
bound solely by the strong interaction

?

talks by Kenta Itahashi and Yoshiki Tanaka

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 ⇒ p + p + η'
⇒ scattering length (talk by Pawel Moskal)

- interaction attractive or repulsive ?

meson-nucleon/nucleus interaction

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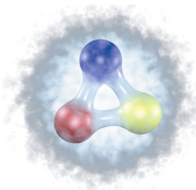
meson  ⇔  nucleon

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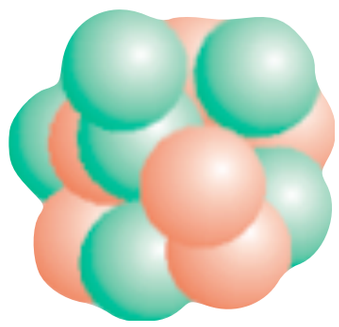
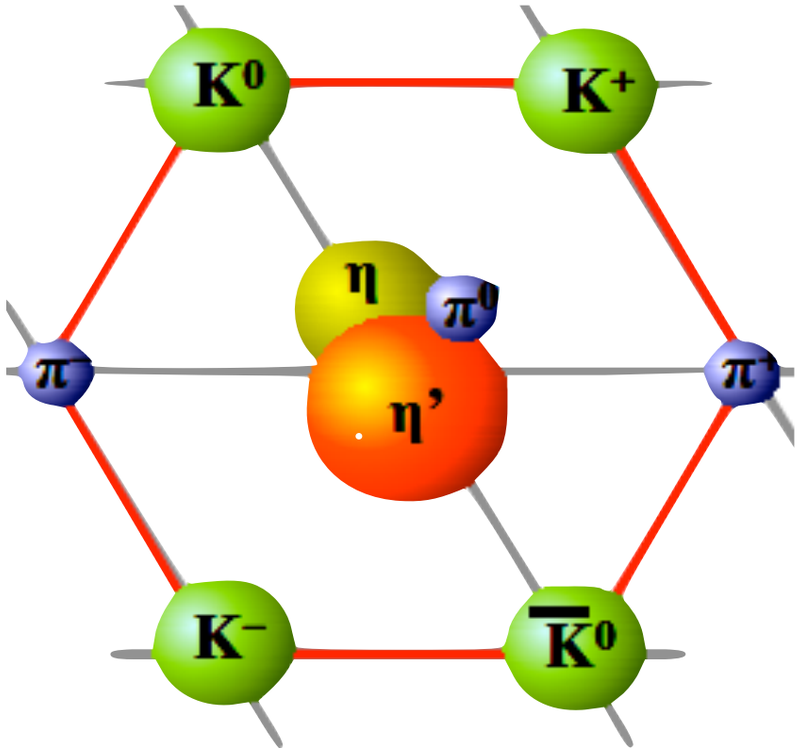
II. meson-nucleus interaction:

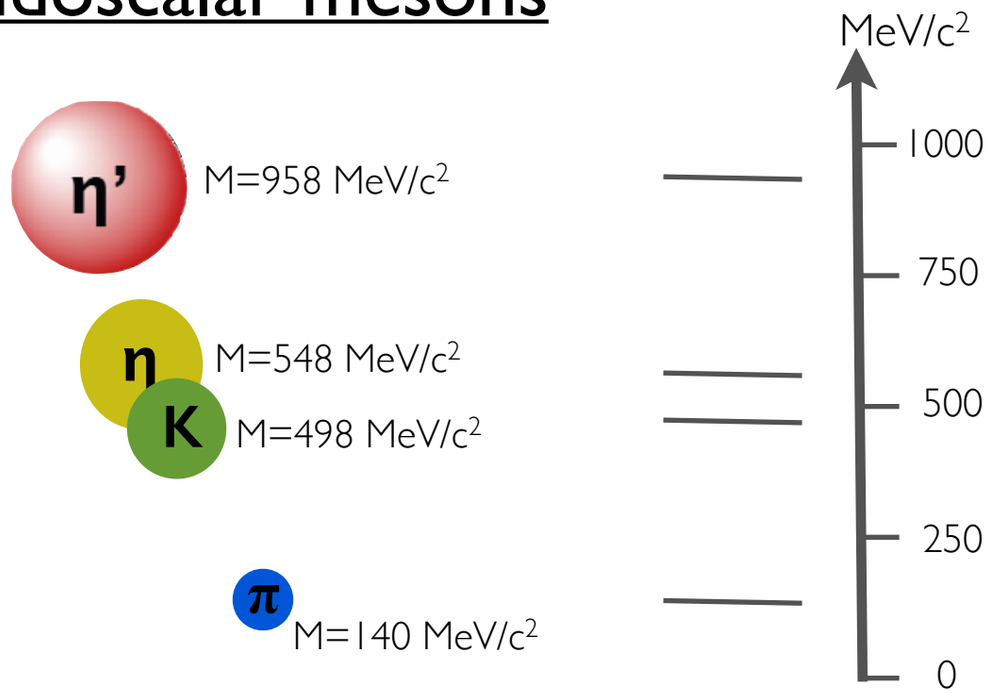
meson  ⇔  nucleus

- if attractive, interaction strong enough to form meson-nucleus bound states ?

symmetry breaking in the hadronic sector

nonet of pseudoscalar mesons





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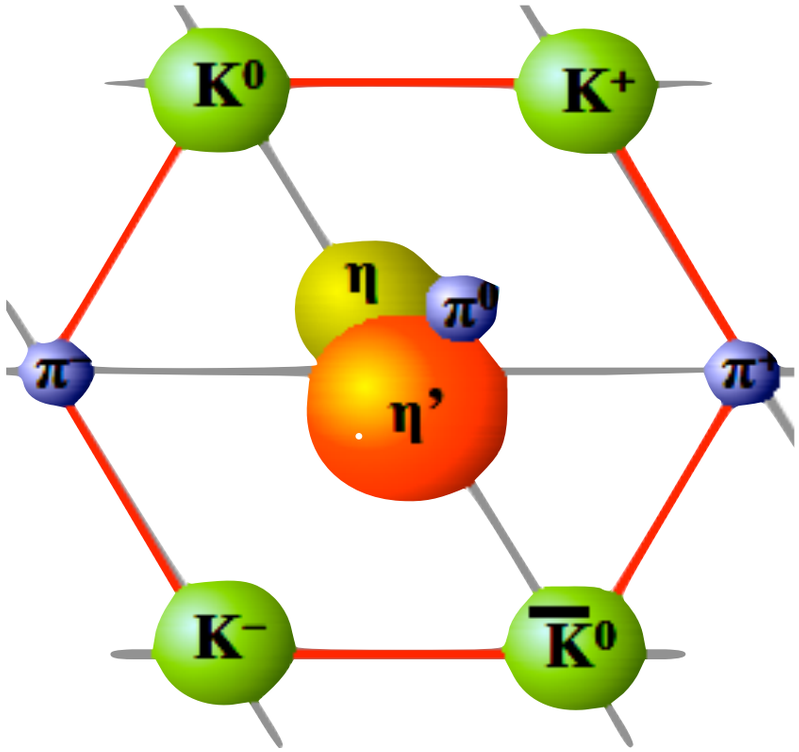
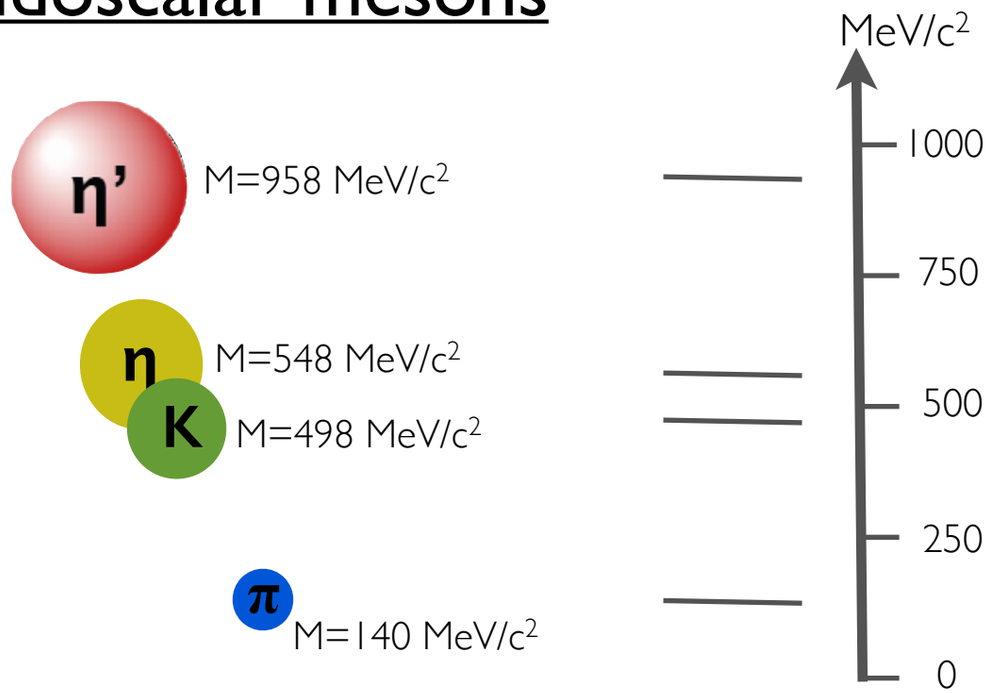
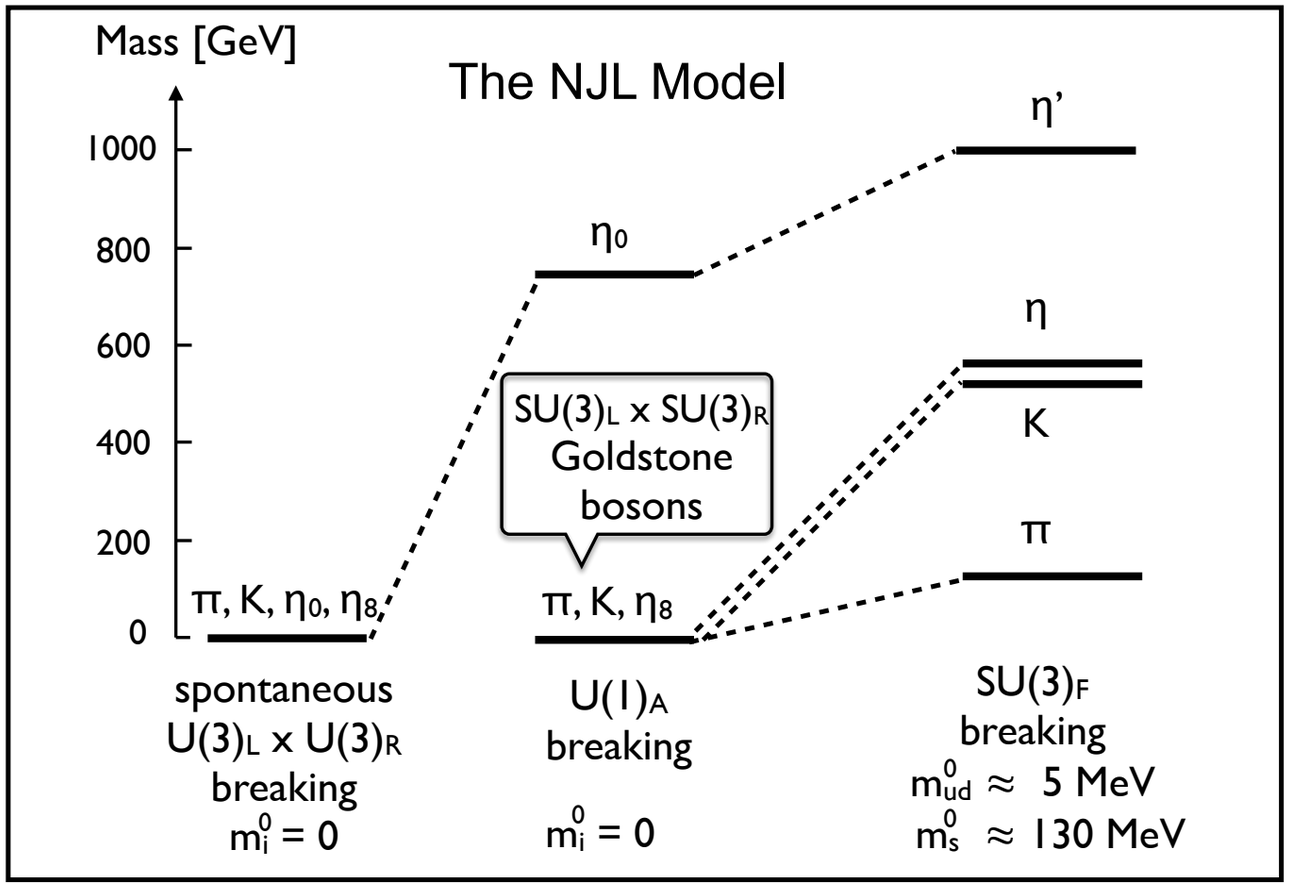




S. Klimt et al., Nucl. Phys. A 516 (1990) 429

mass as a result of symmetry breaking



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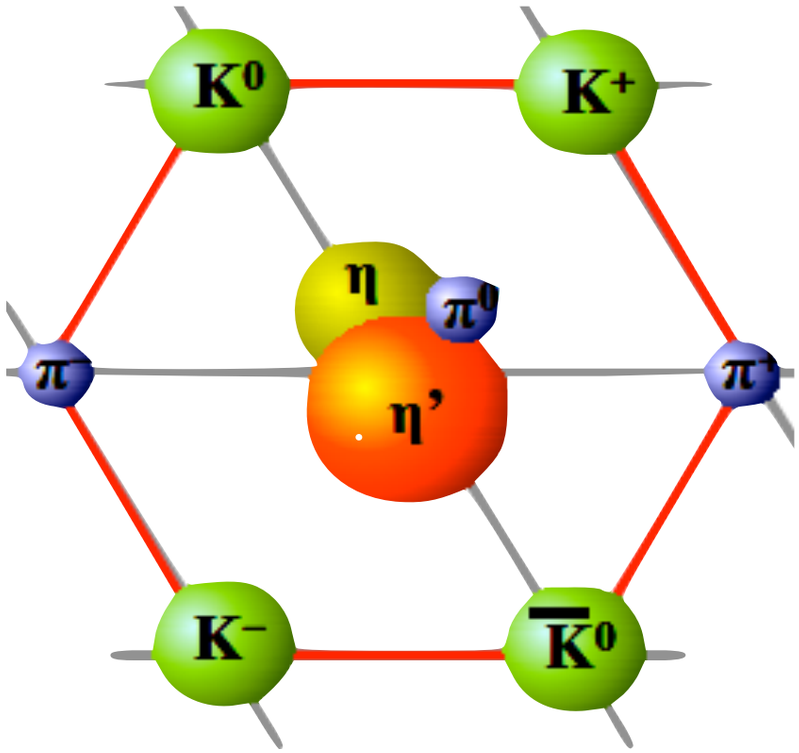
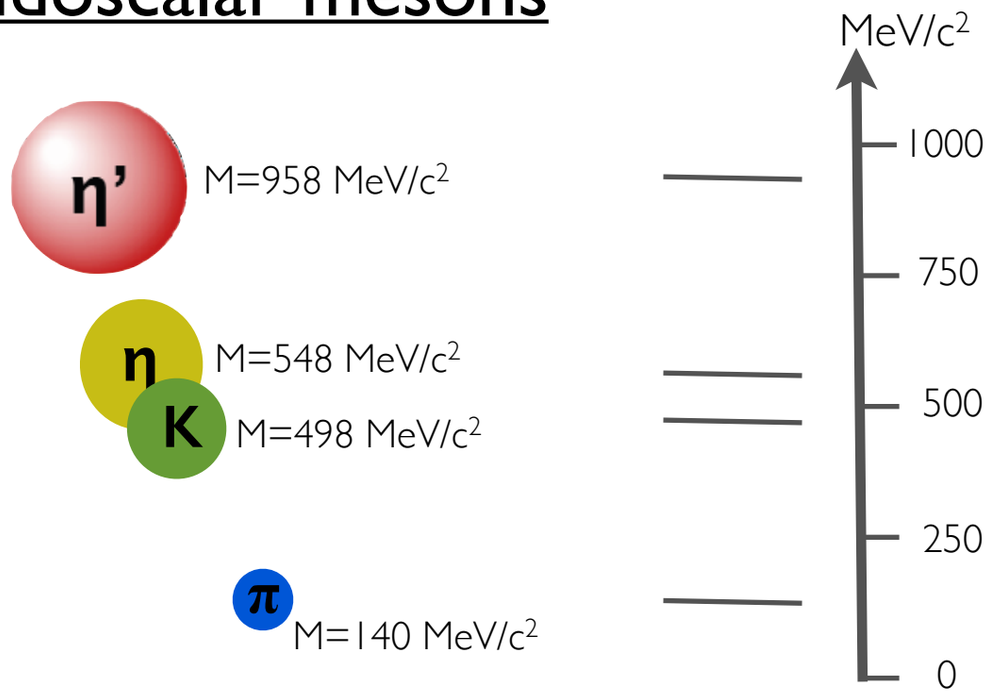


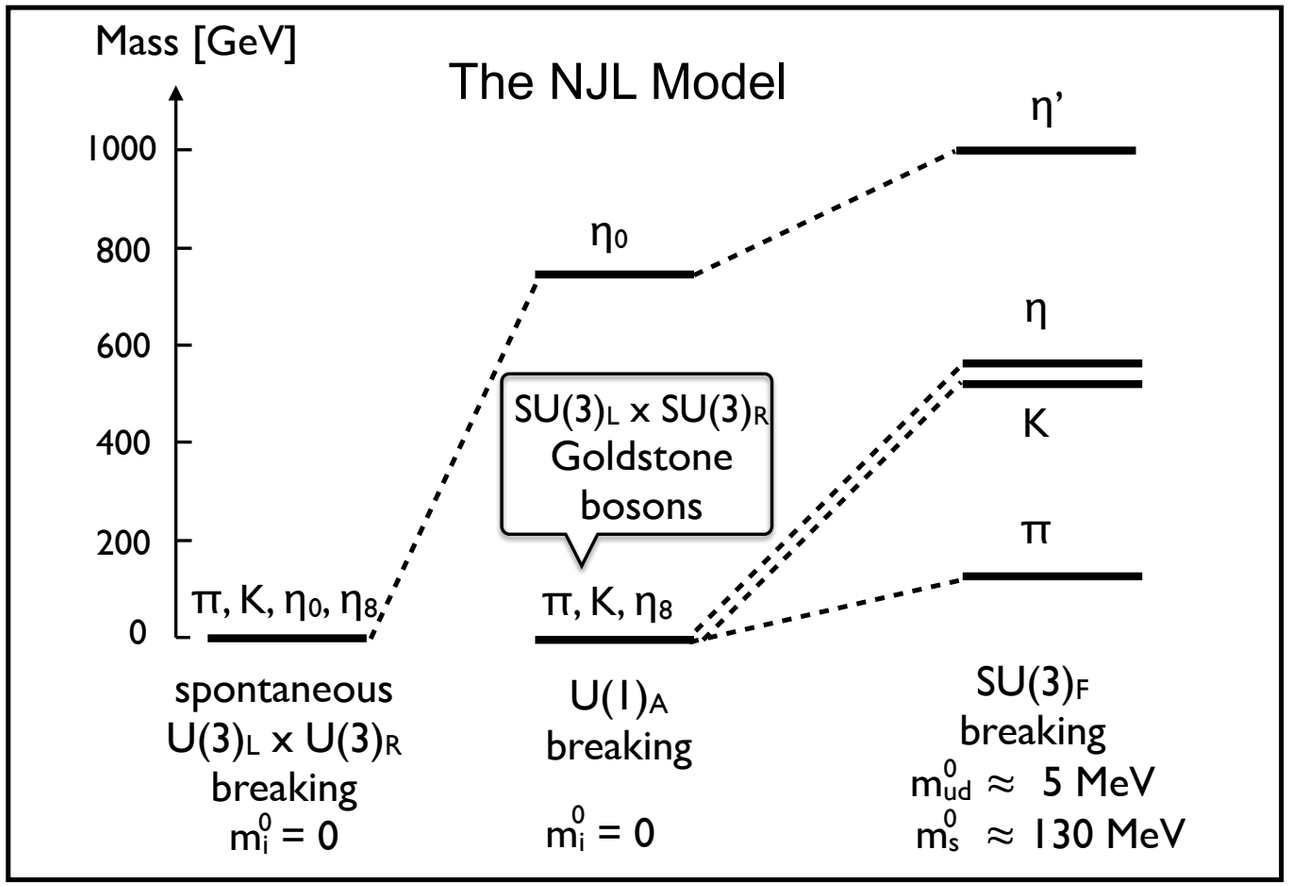


S. Klimt et al., Nucl. Phys. A 516 (1990) 429

mass as a result of symmetry breaking

partial restoration of chiral symmetry predicted in a nucleus

→ impact on in-medium meson masses ??



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

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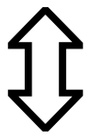
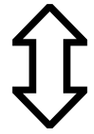


in-medium mass modification

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

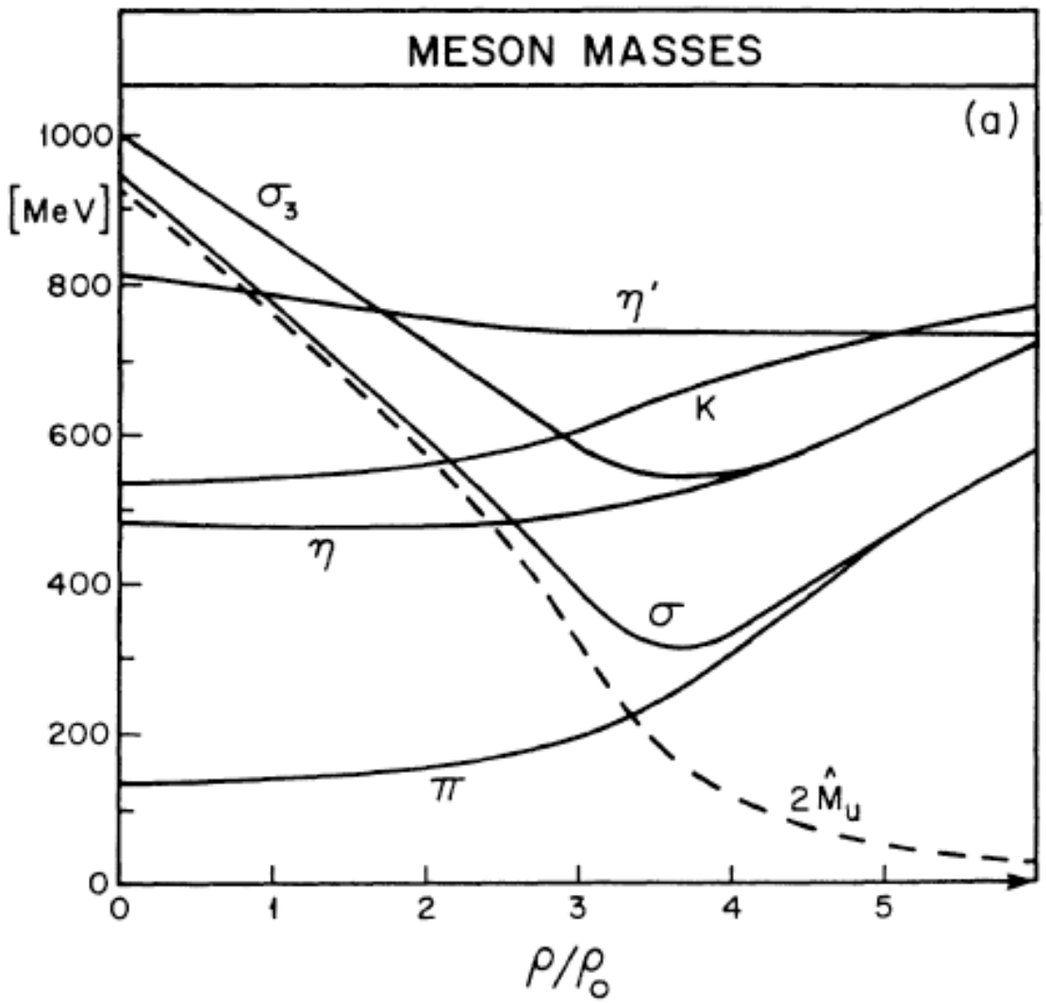
imaginary part



in-medium width
inelastic cross section

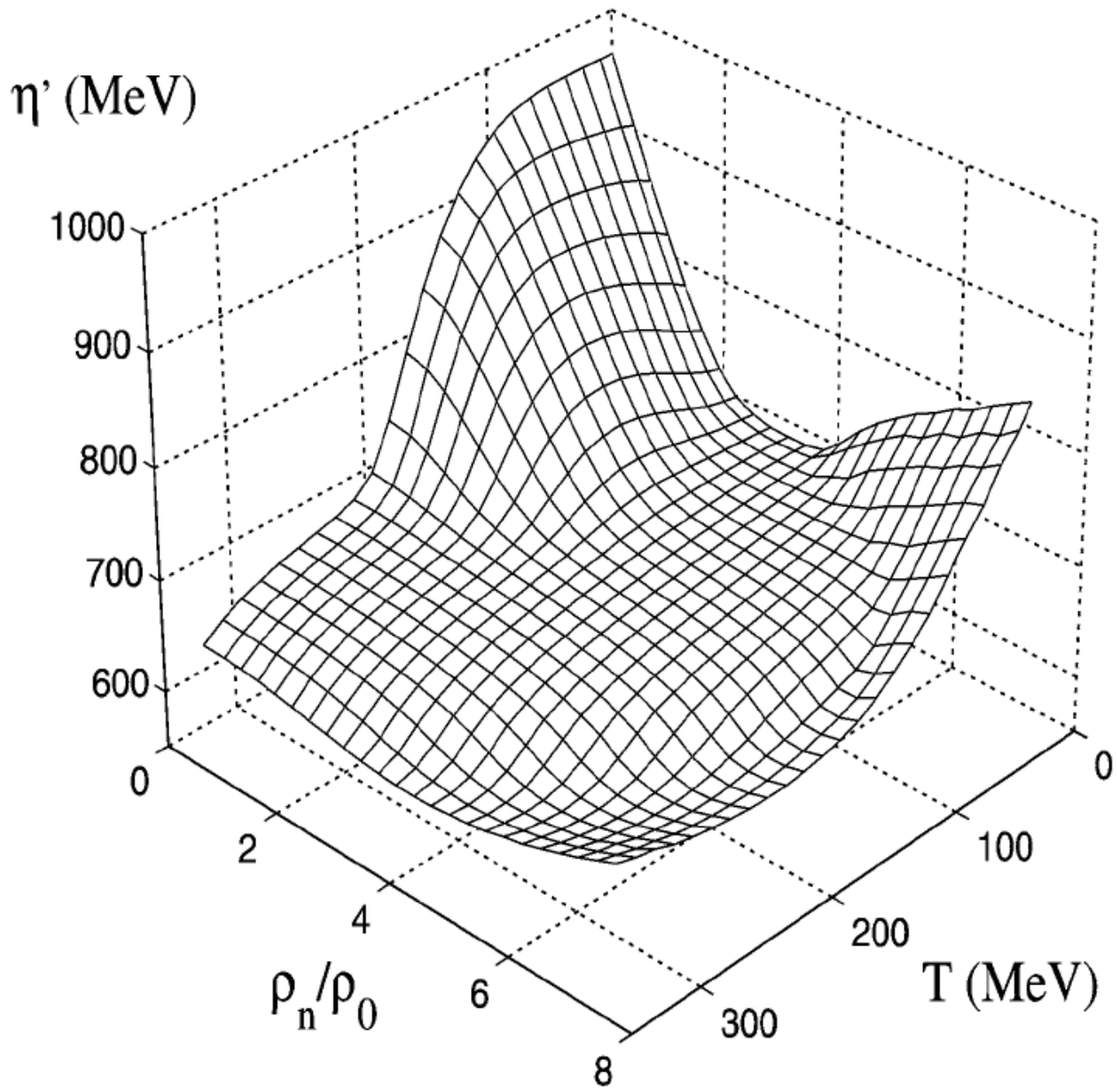
model predictions for the in-medium mass of the η' meson

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



almost no density dependence
of in-medium η' mass

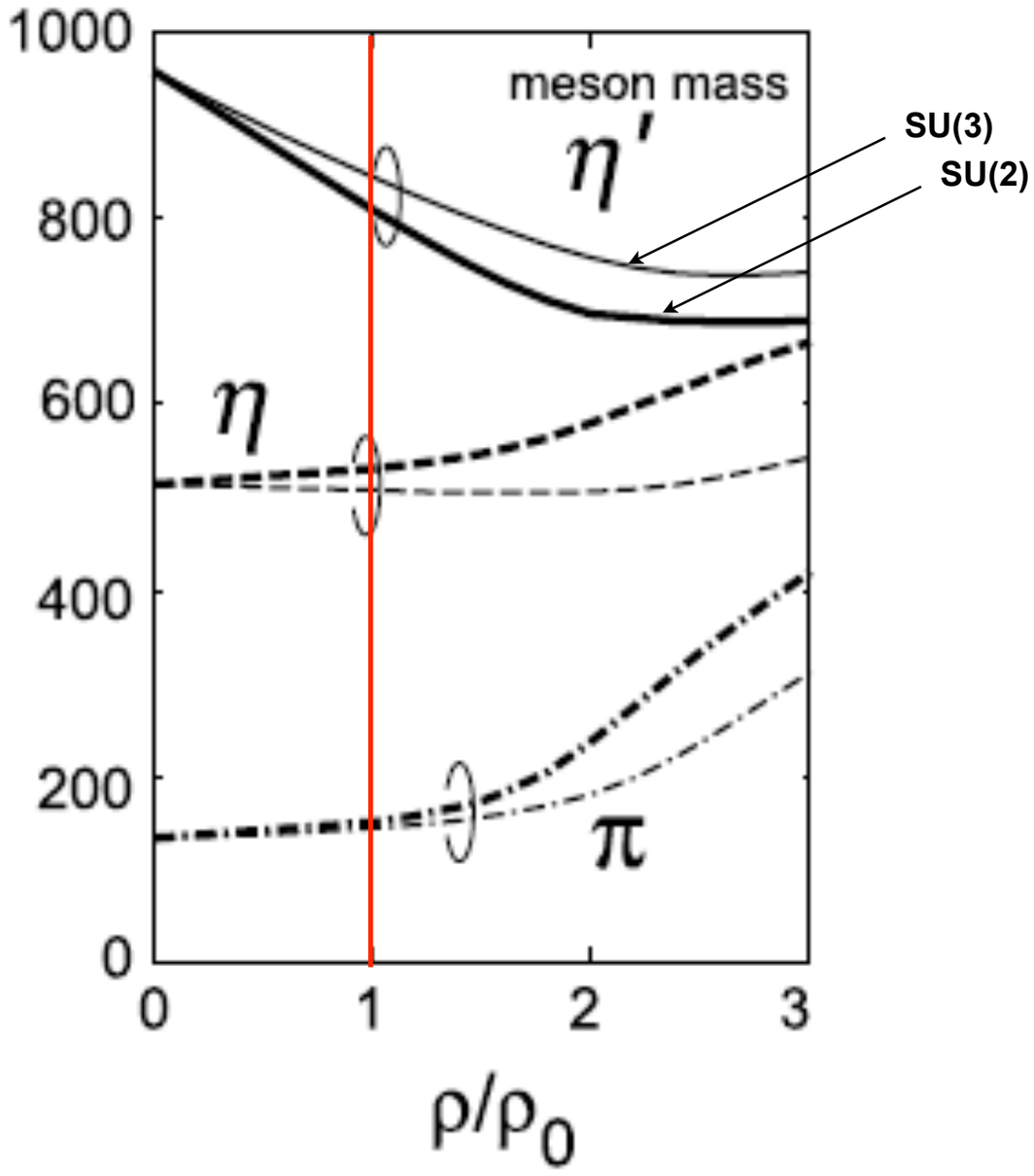
P. Costa et al.,
PLB 560 (2003) 171



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

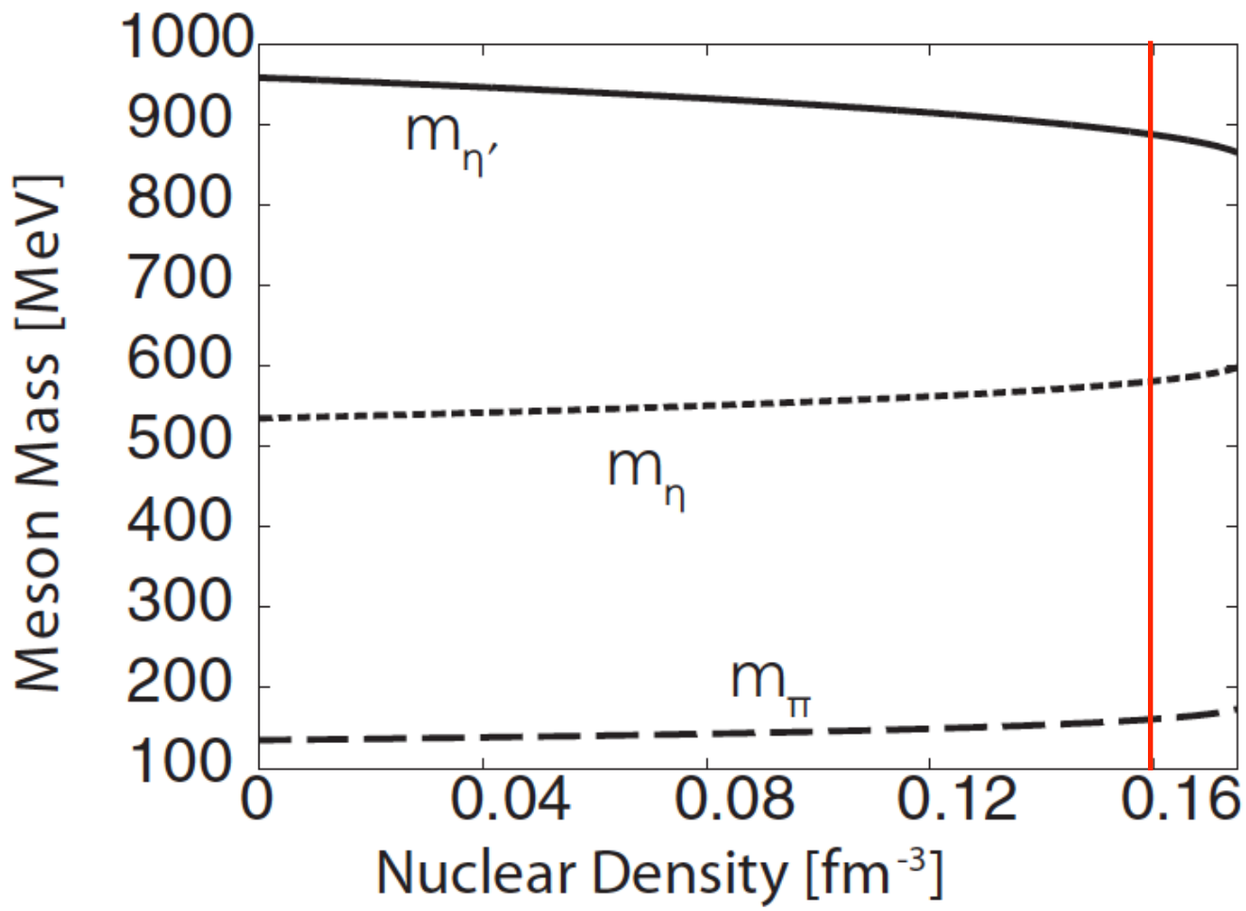
model predictions for the in-medium mass of the η' meson

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

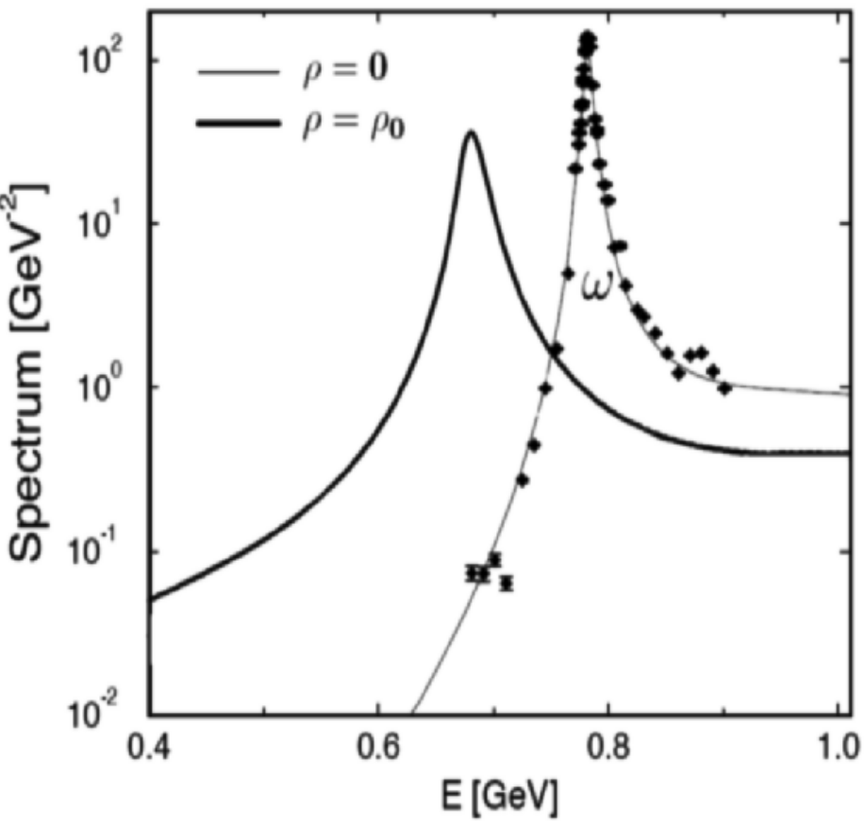


$\Delta m_{\eta'}(\rho_0) \approx -80$ MeV

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

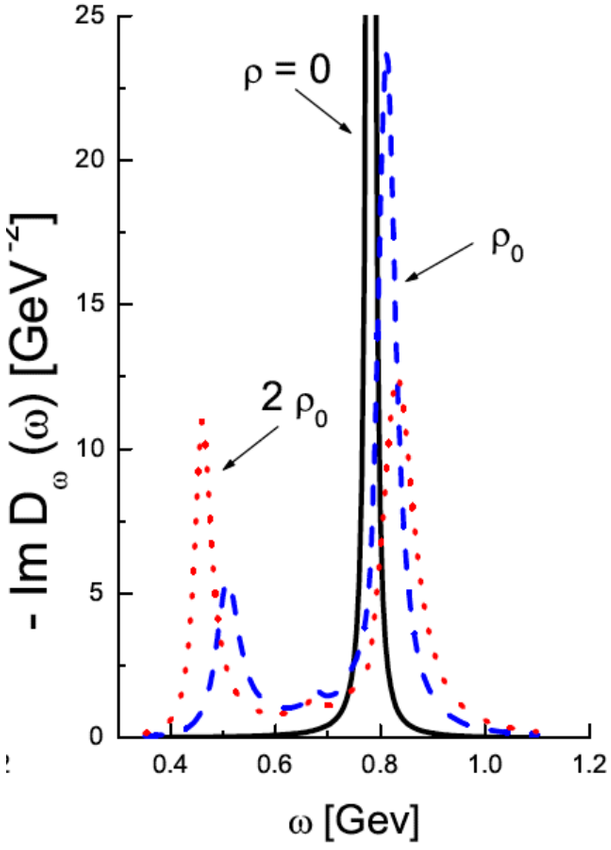
model predictions for in-medium mass/width of the ω meson

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

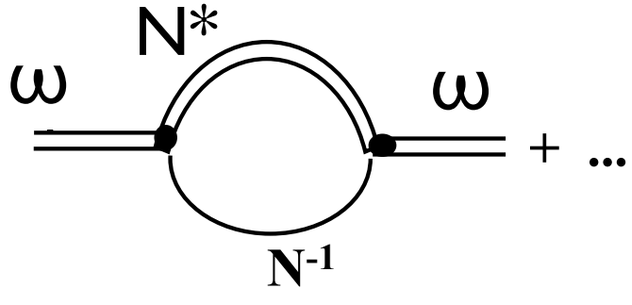


- lowering of in-medium mass
- broadening of resonance
  with increasing nuclear density

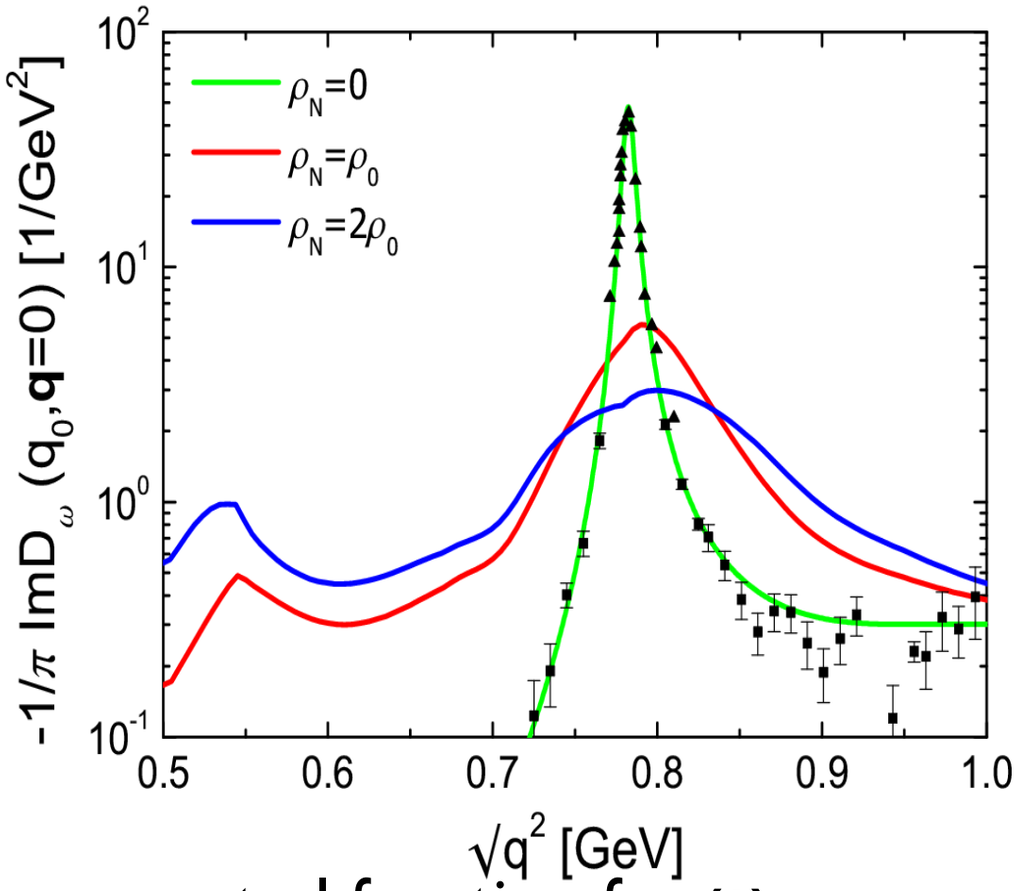
M. Lutz et al.,
NPA 706 (2002) 437



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

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'

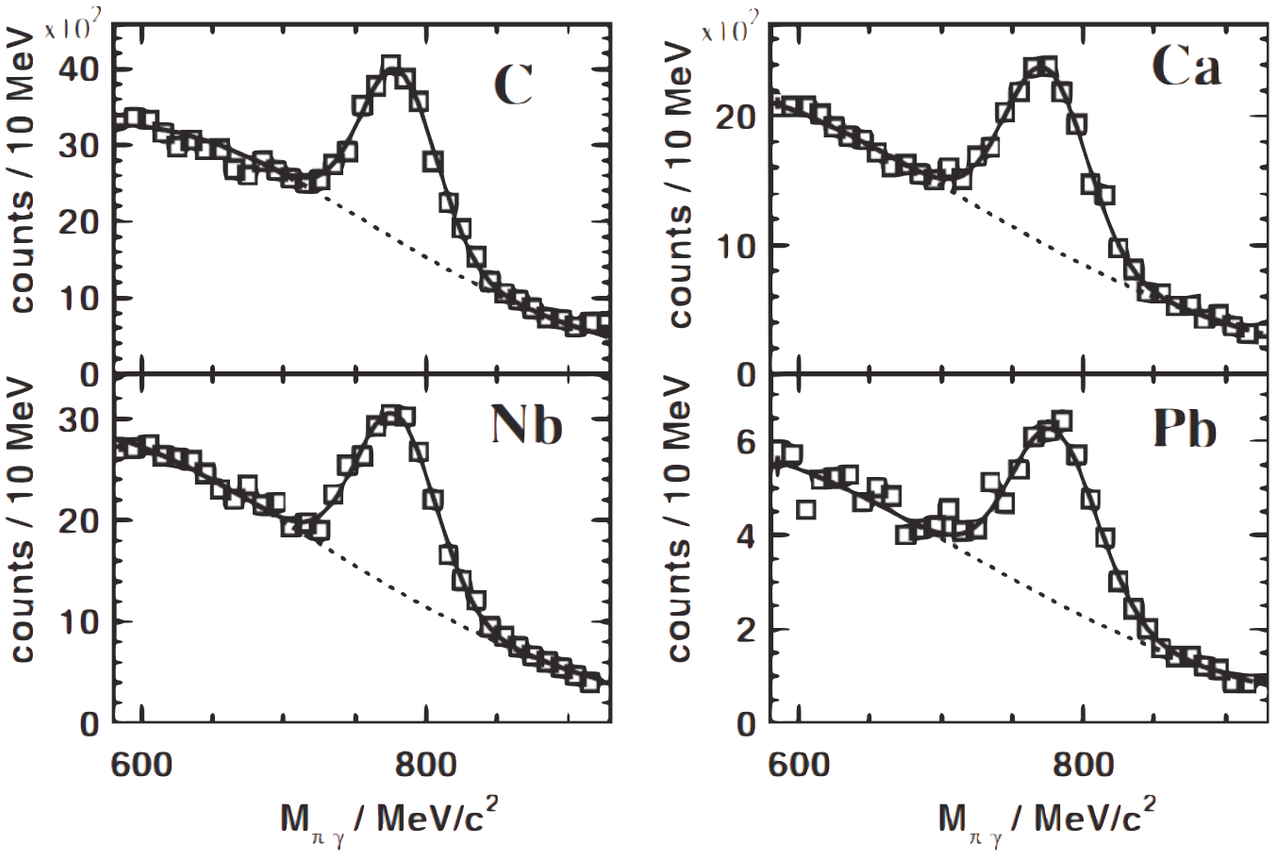
experiments performed with the CBELSA/TAPS detector (Bonn)

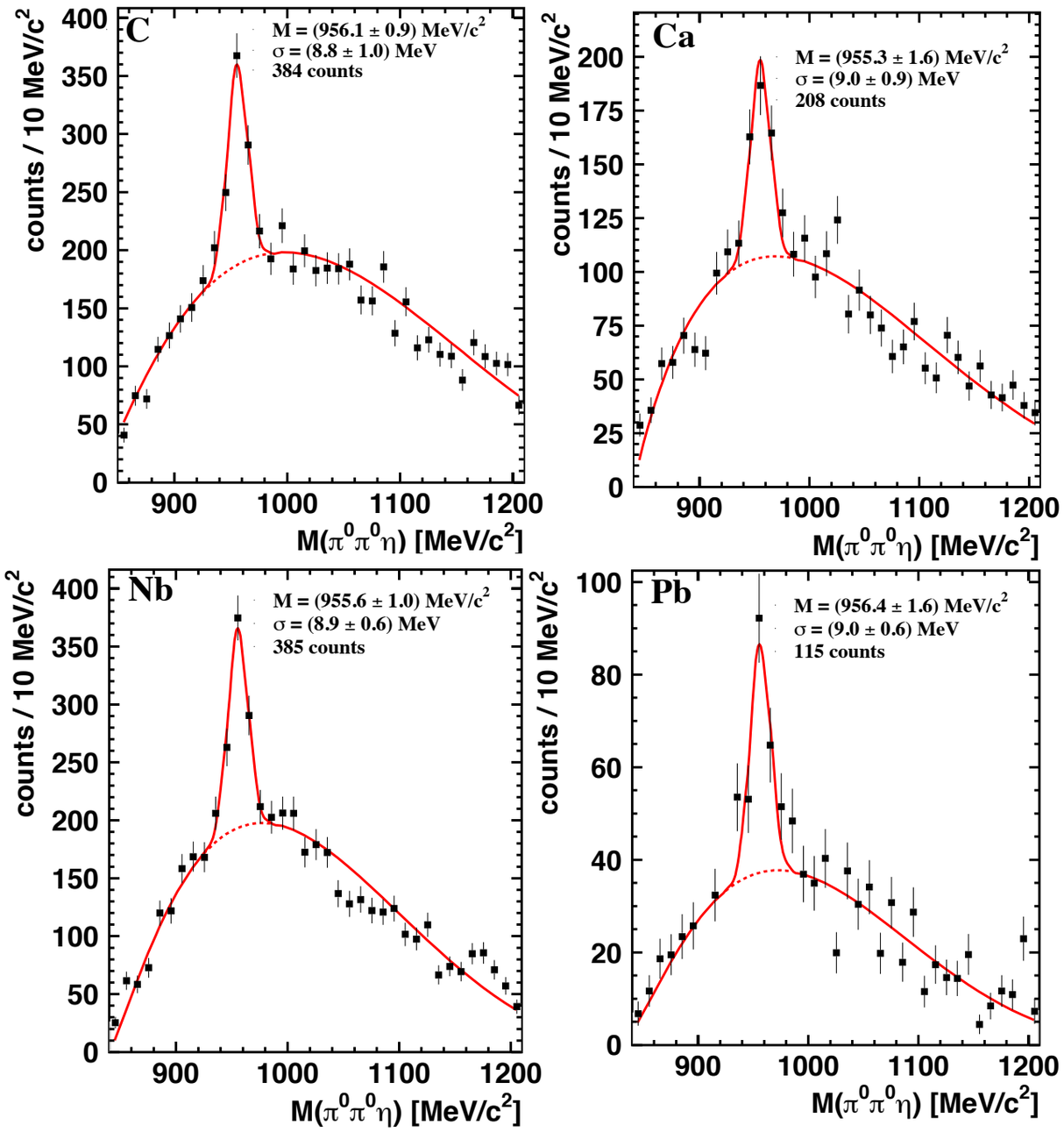
$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$

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

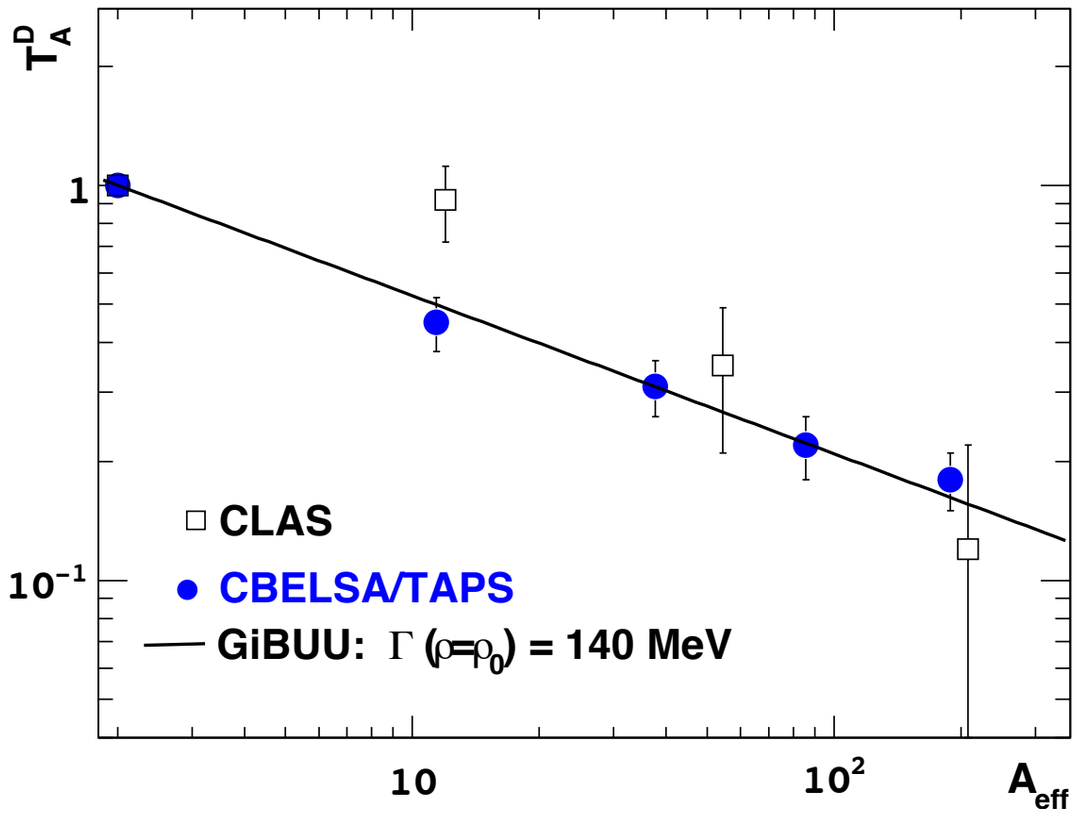
$$T_A = \frac{\sigma_{\gamma A \rightarrow \eta' X}}{A \cdot \sigma_{\gamma N \rightarrow \eta' X}}$$

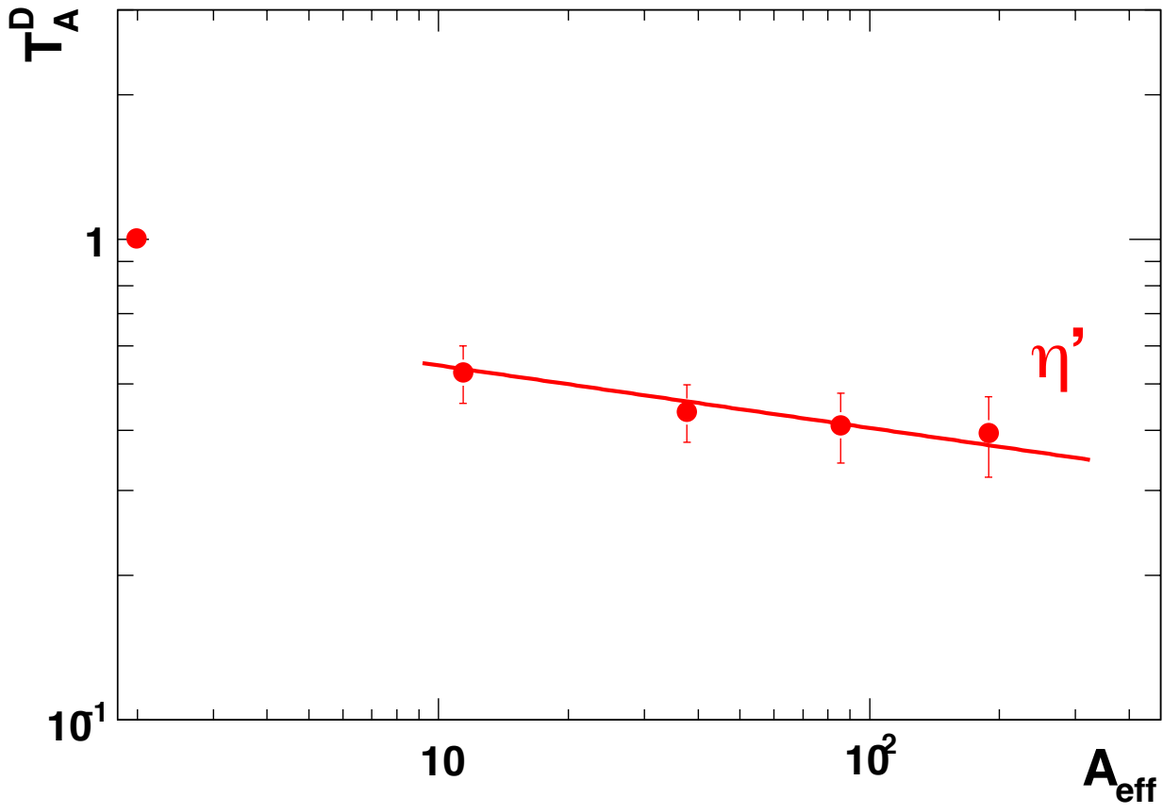
transparency ratio for ω and η' mesons for different nuclei

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

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

ω: F. Dietz et al., EPJA 51 (2015) 6 **η'**: I. Jaegle et al., EPJA 47 (2011) 11





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

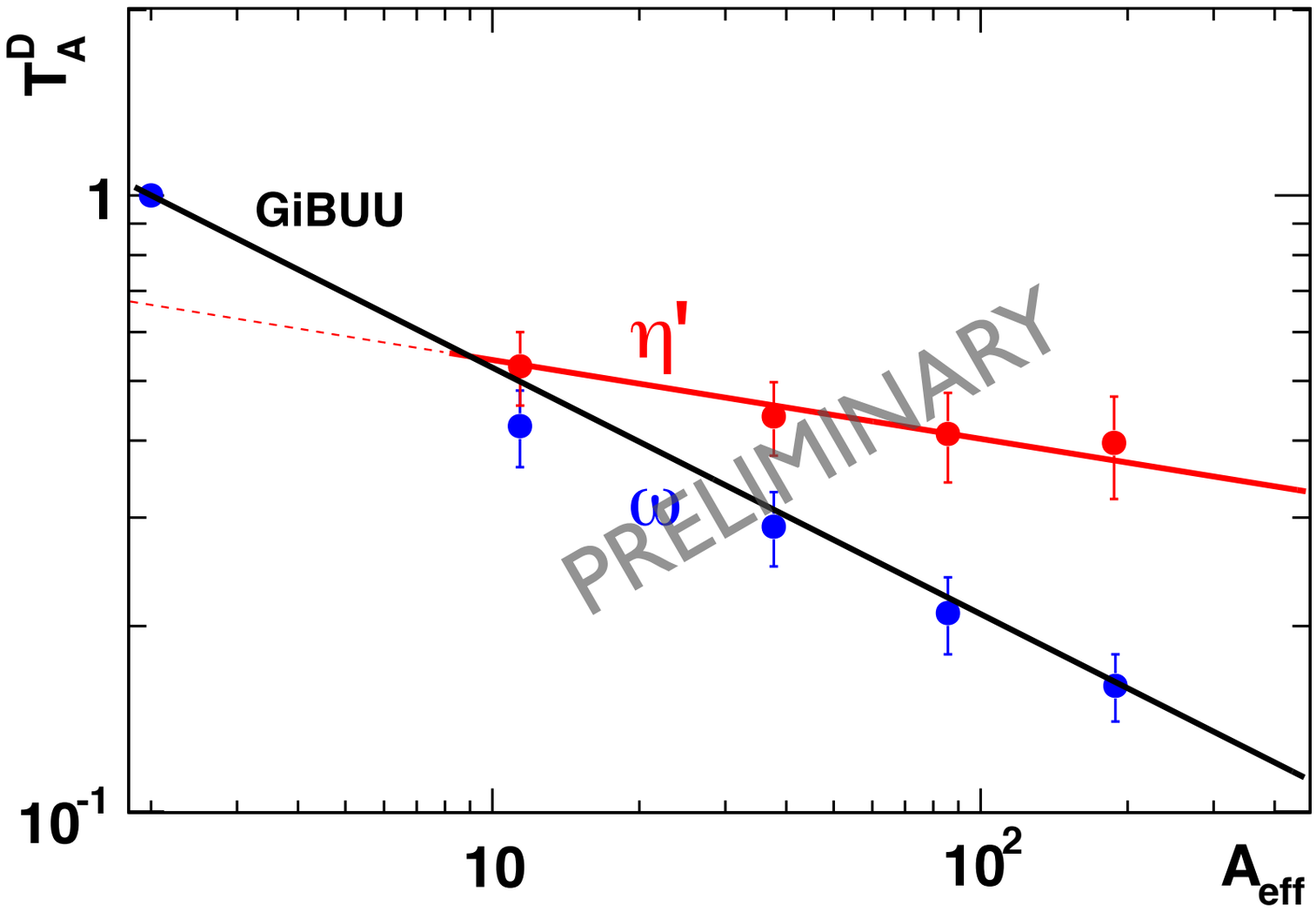
low density approximation: $\Gamma(\rho_0) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}$

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

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

comparison of transparency ratios for ω and η' mesons

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



inelastic interactions with nuclear medium much weaker for η' meson

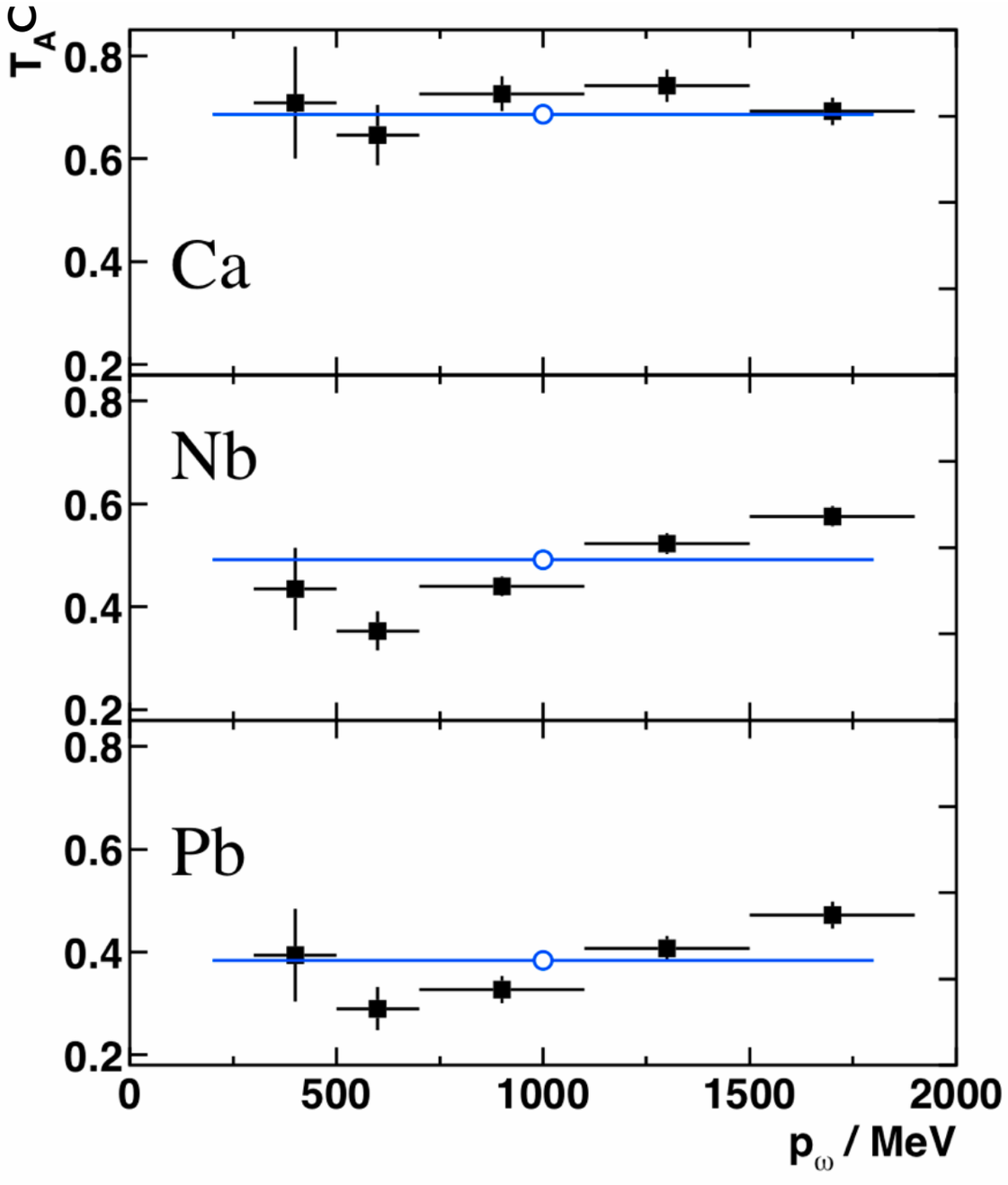
ω: one-body absorption (e.g., ωN→πN) dominant (A. Ramos, EPJA 49 (2013) 148)

η': additional absorption mechanism not present in D; 2-body absorption ??

momentum dependence of transparency ratios for ω and η'

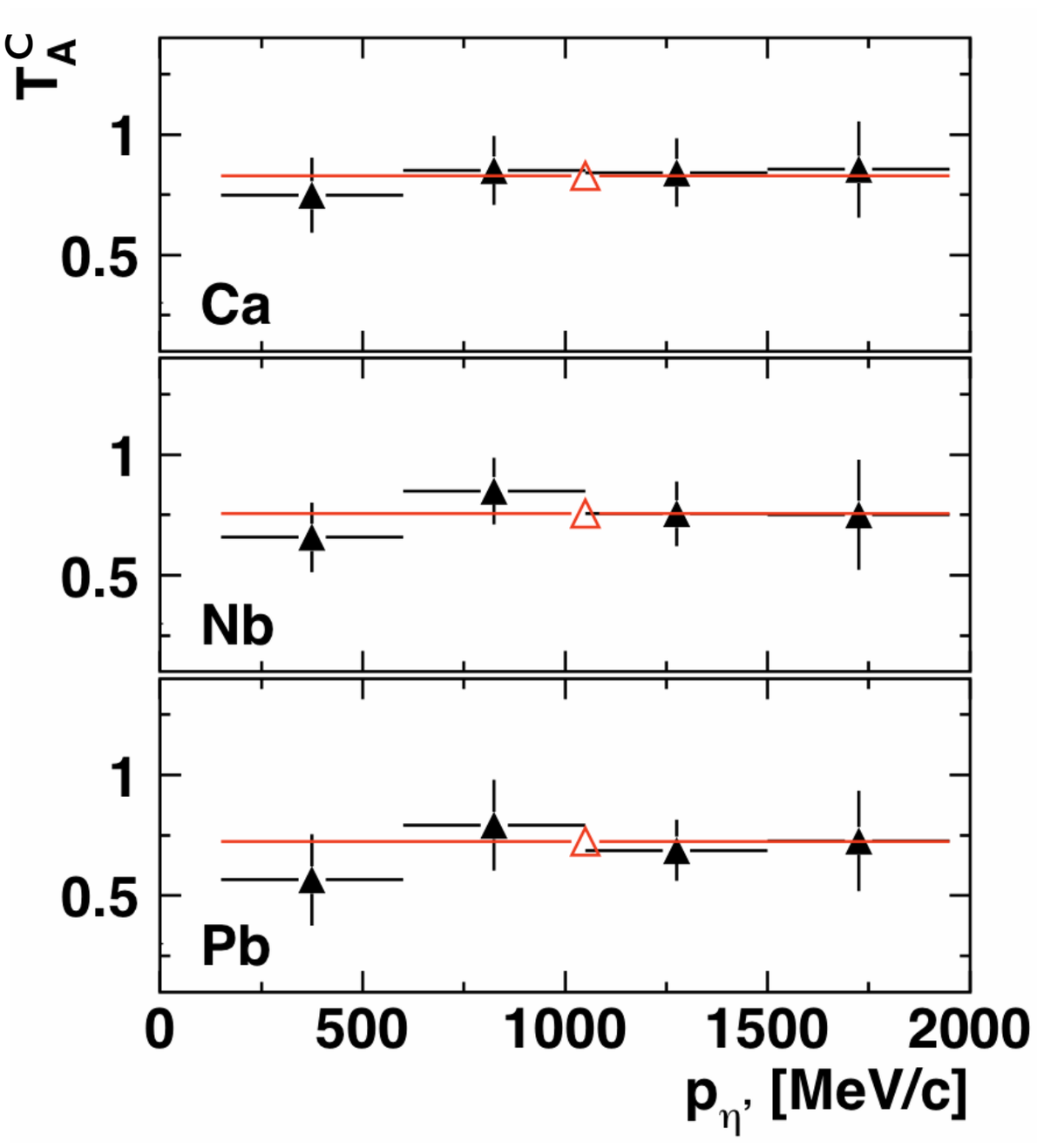
ω

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



η'

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



no strong variation of transparency ratio with meson momentum;

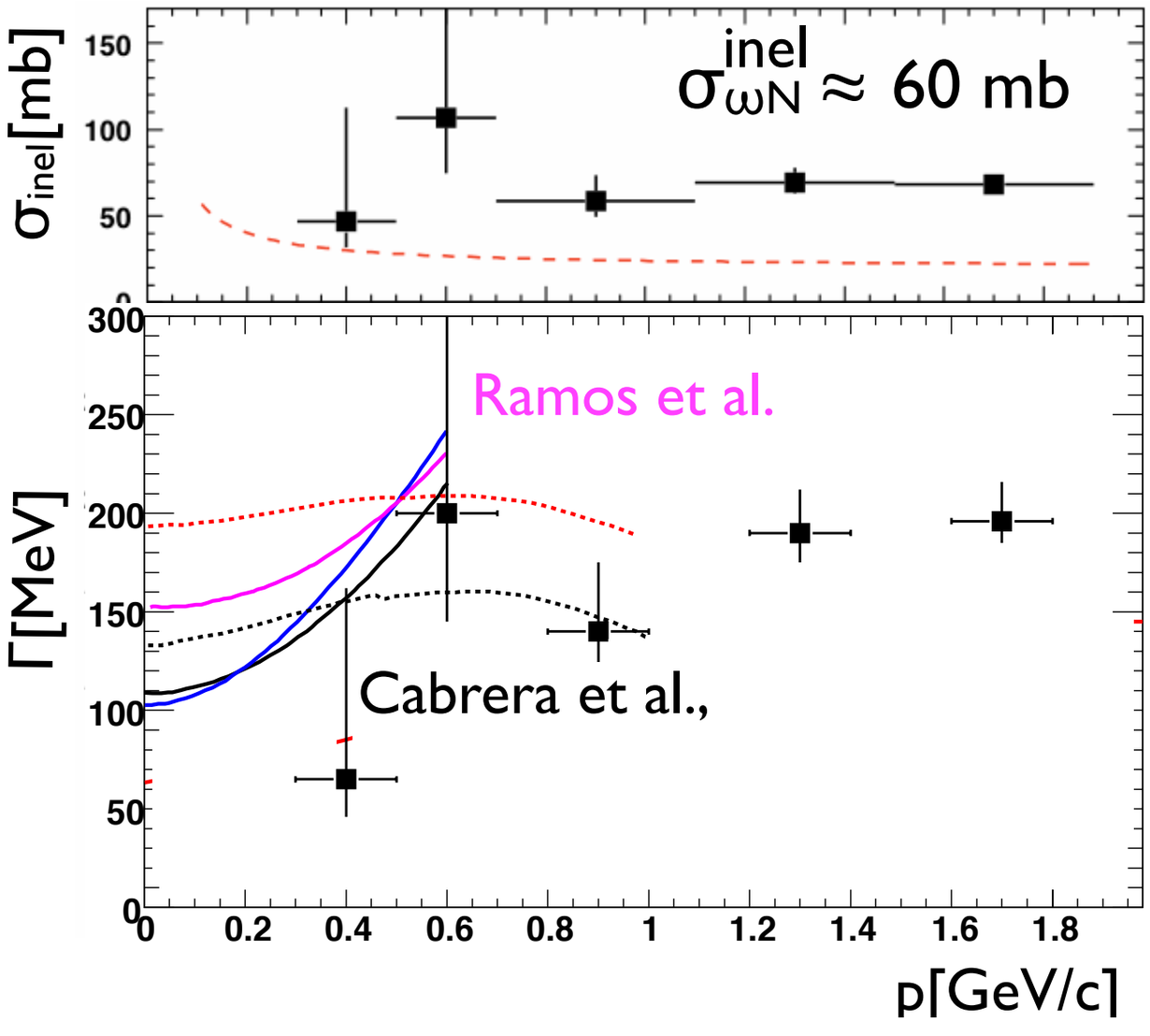
momentum dependence of σ_{inel} and Γ for ω and η' mesons

ω

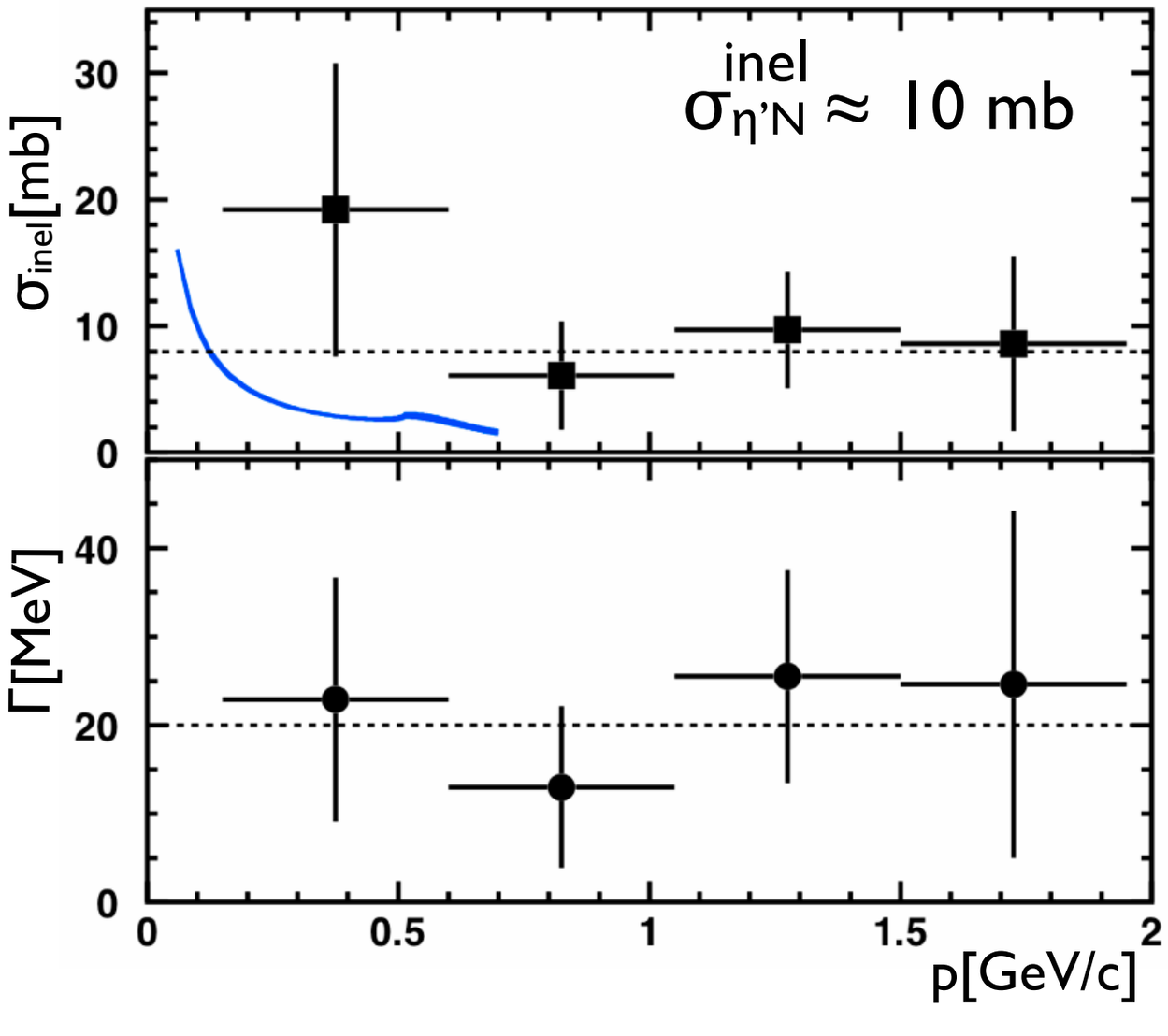
$$\Gamma(\rho_0) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}$$

η'

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



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



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

dotted curves: D. Cabrera, R. Rapp, PLB 729 (2014) 67

curve: E. Oset and A. Ramos, PLB 704 (2011) 334

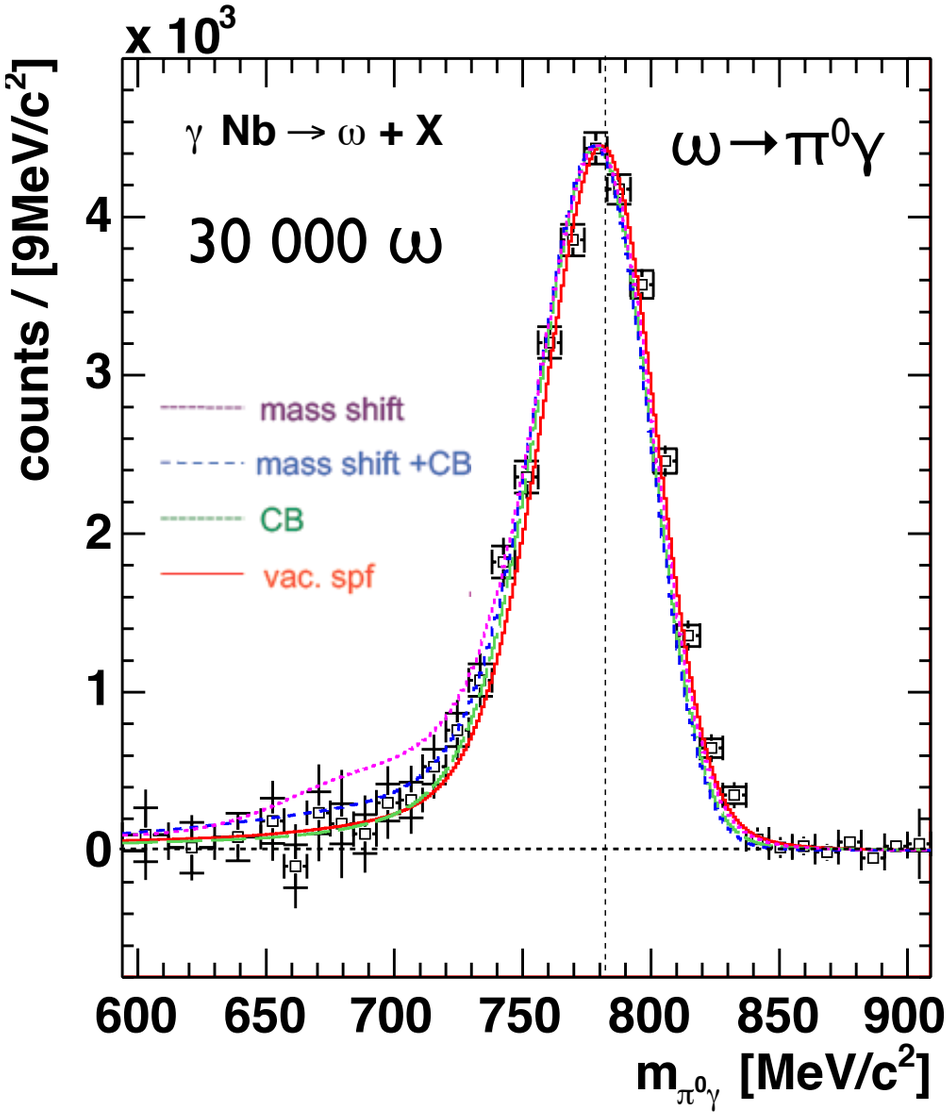
The real part V of the meson-nucleus optical potential

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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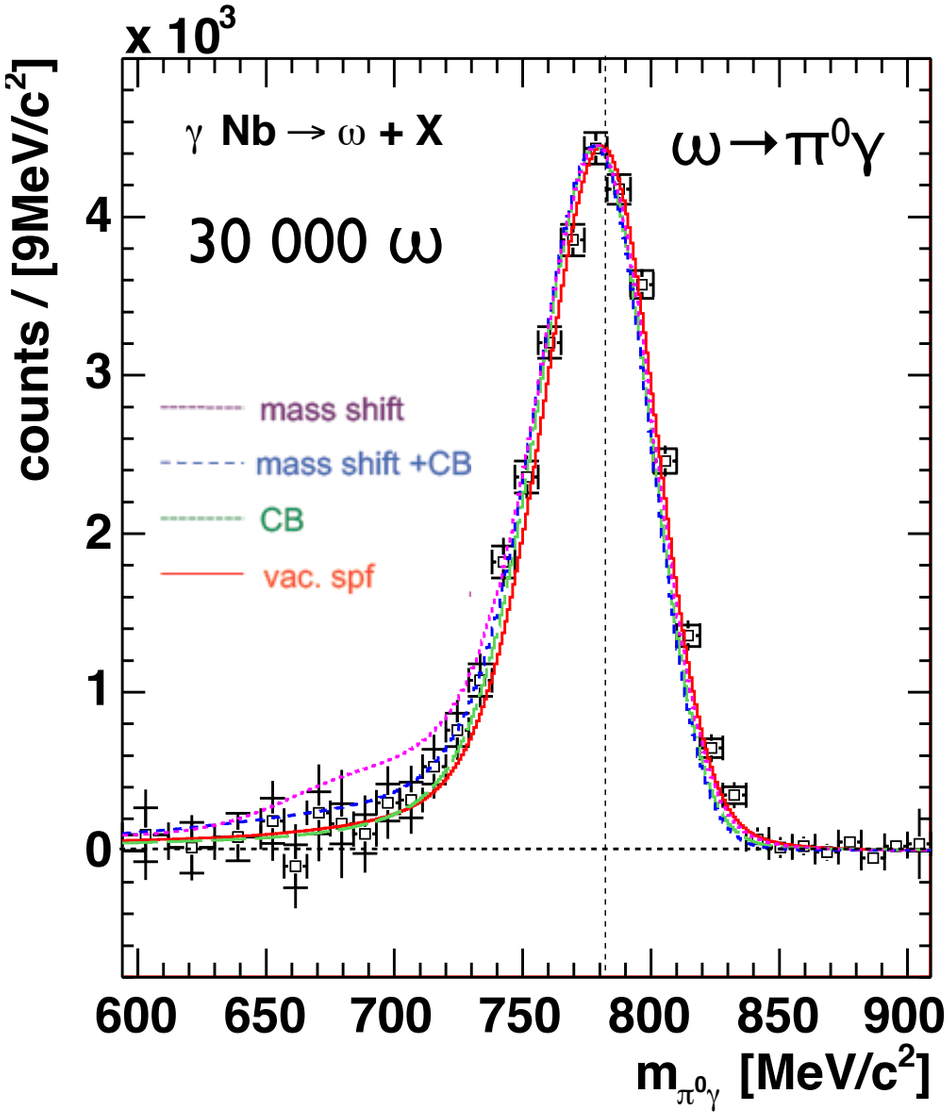

scenarios difficult to distinguish

sensitivity limited by 4 effects:

1) mass resolution σ ≈ 3%;
only mass shifts ≫ 3% observable

2) only 30% of all ω→π⁰γ decays occur within the Nb nucleus

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

4) ω→π⁰γ 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 ωN→πN)

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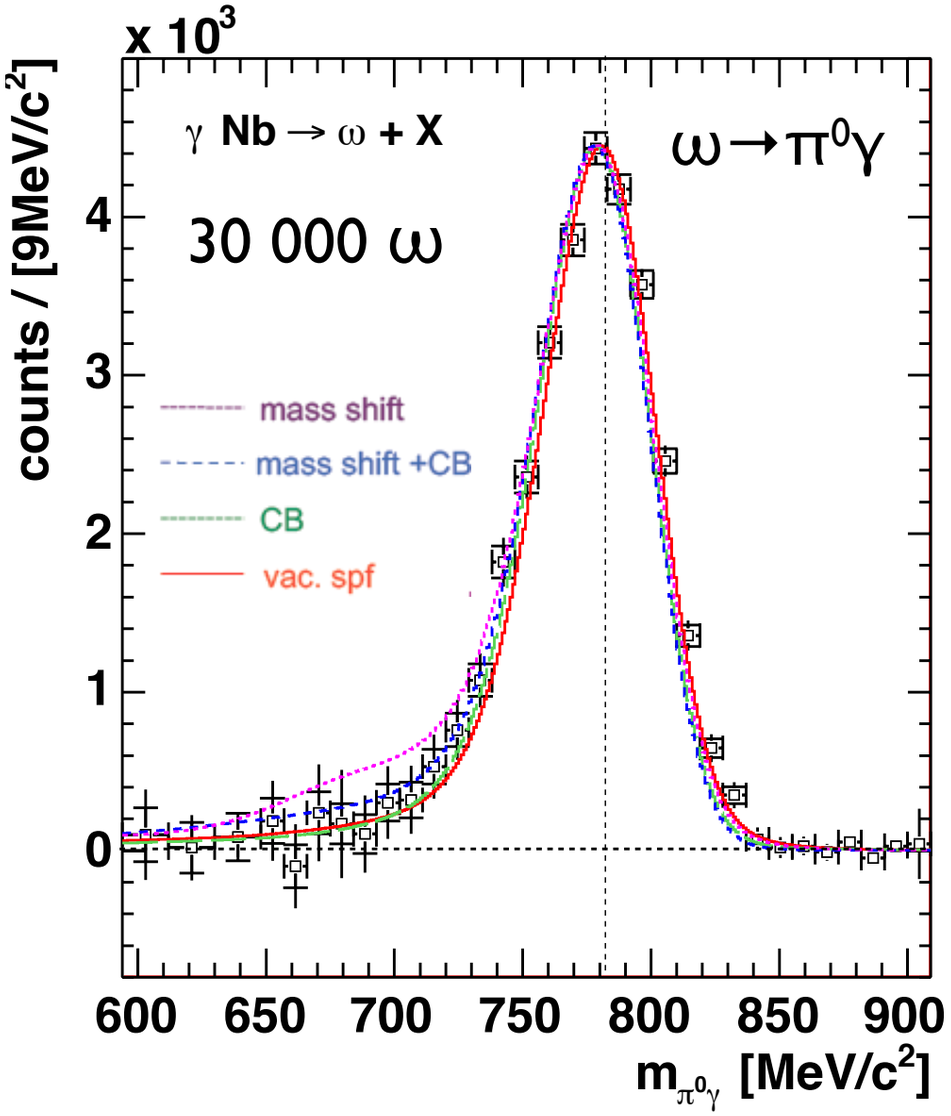

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KEK E325; M. Naruki et al., PRL96 (2006) 092301: $\Delta m(\rho_0)$ = -9.2% ; no broadening

talk by S. Yokkaichi, J-PARC E16

The real part of the ω-nucleus potential

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

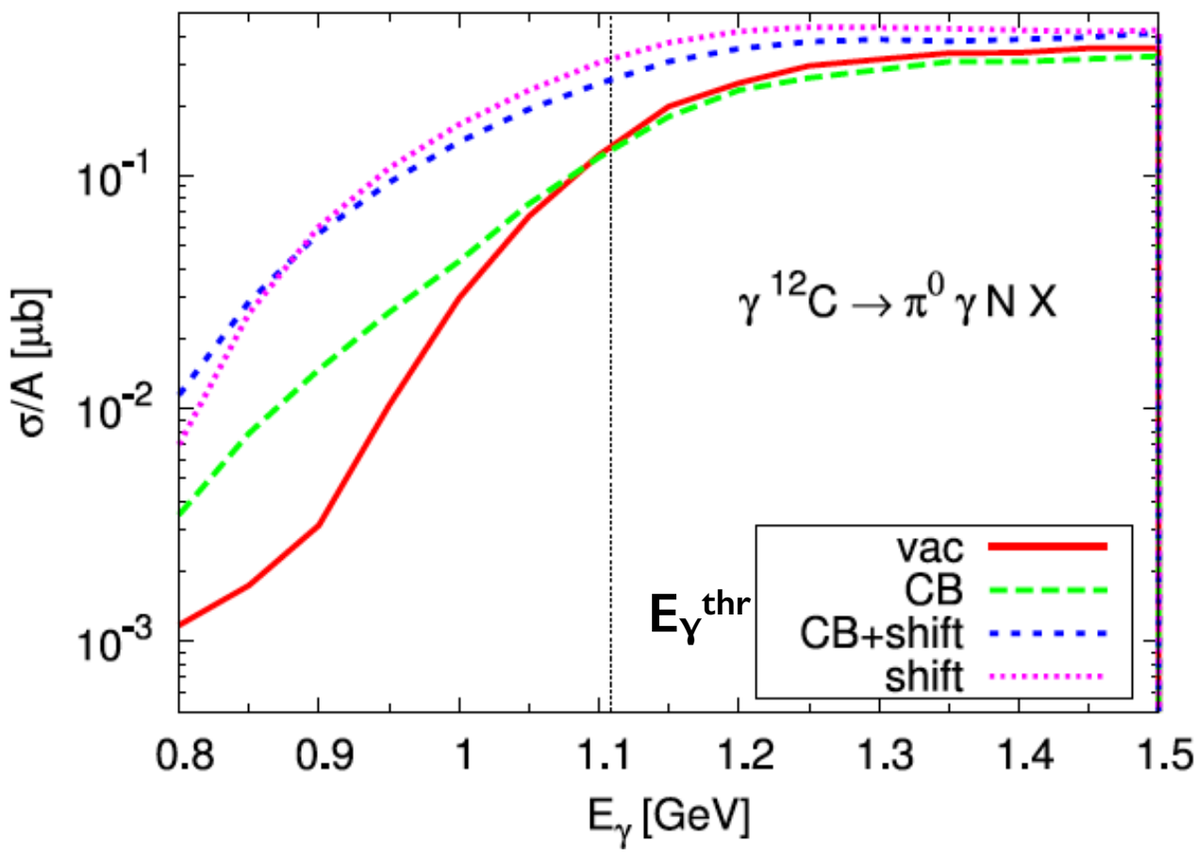
sensitive to nuclear density at production point

- 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



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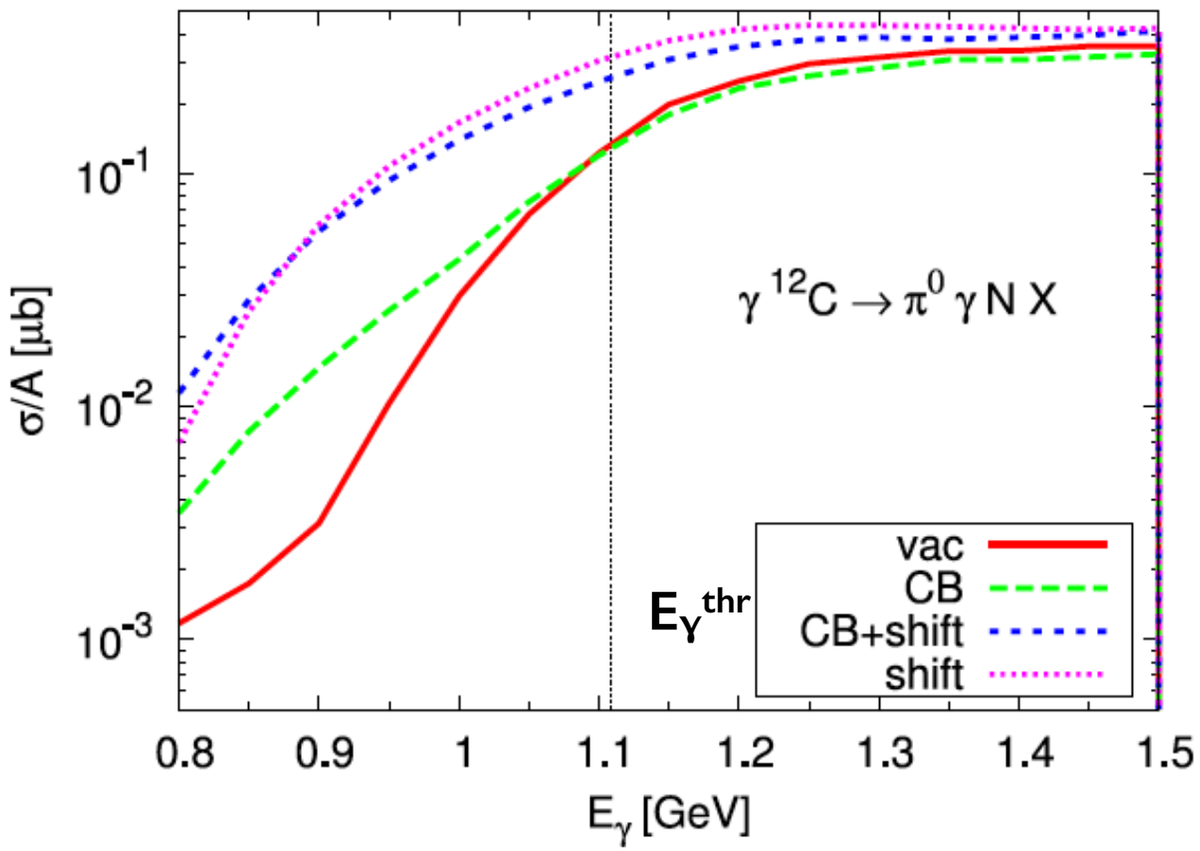
⇨ cross section enhancement

- momentum distribution of the meson:

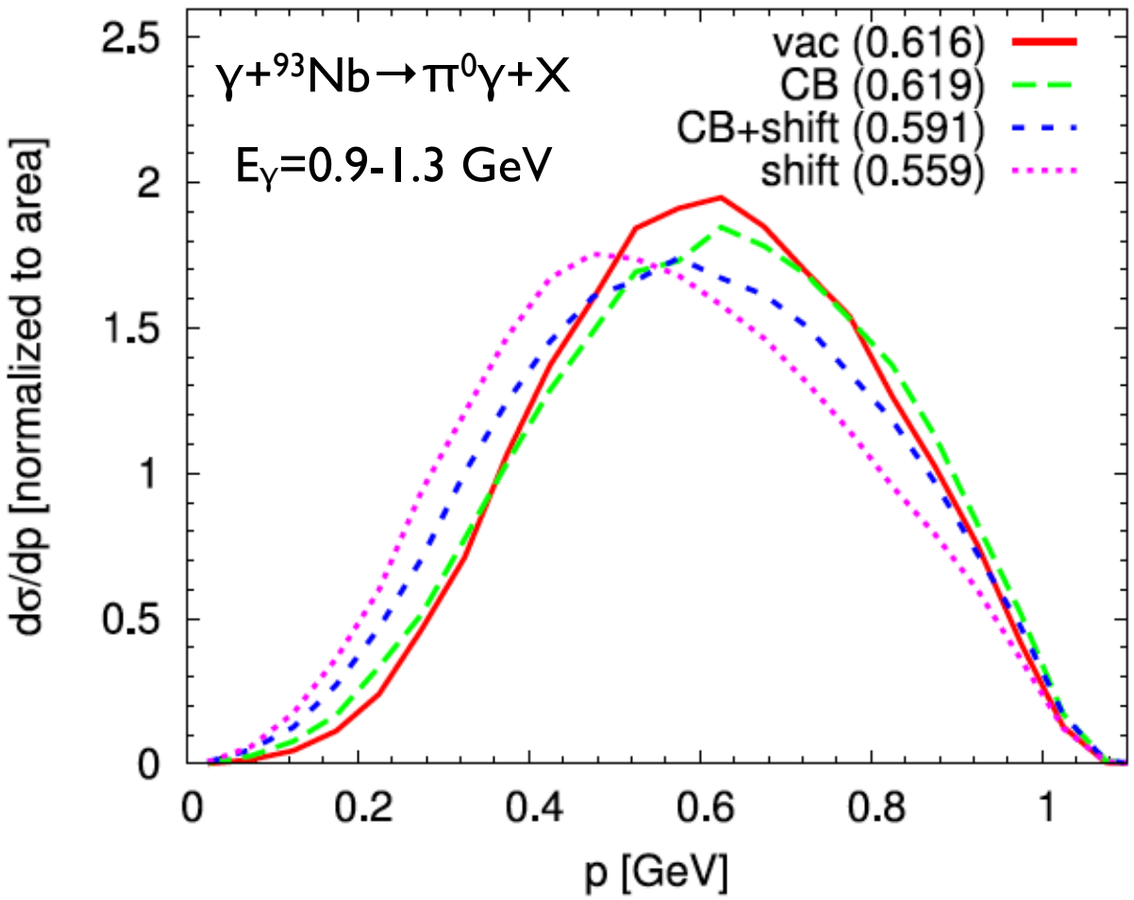
in case of dropping mass - when leaving the nucleus hadron has to become on-shell;
mass generated at the expense of kinetic energy

⇨ downward shift of momentum distribution

$\pi^0\gamma$ excitation function



$\pi^0\gamma$ momentum distribution

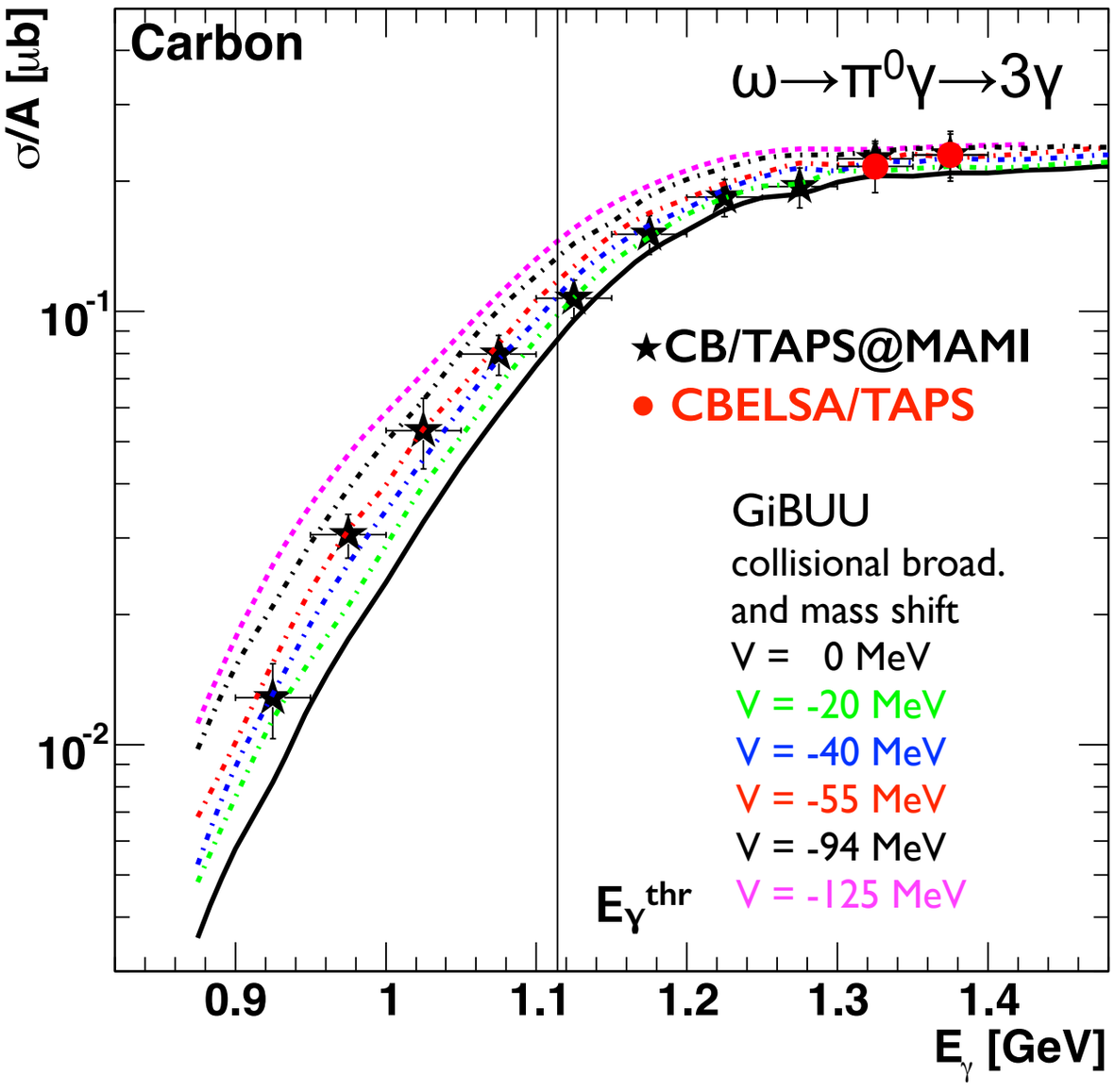


excitation function for ω and η' photoproduction off C

ω

CB/TAPS @ MAMI

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



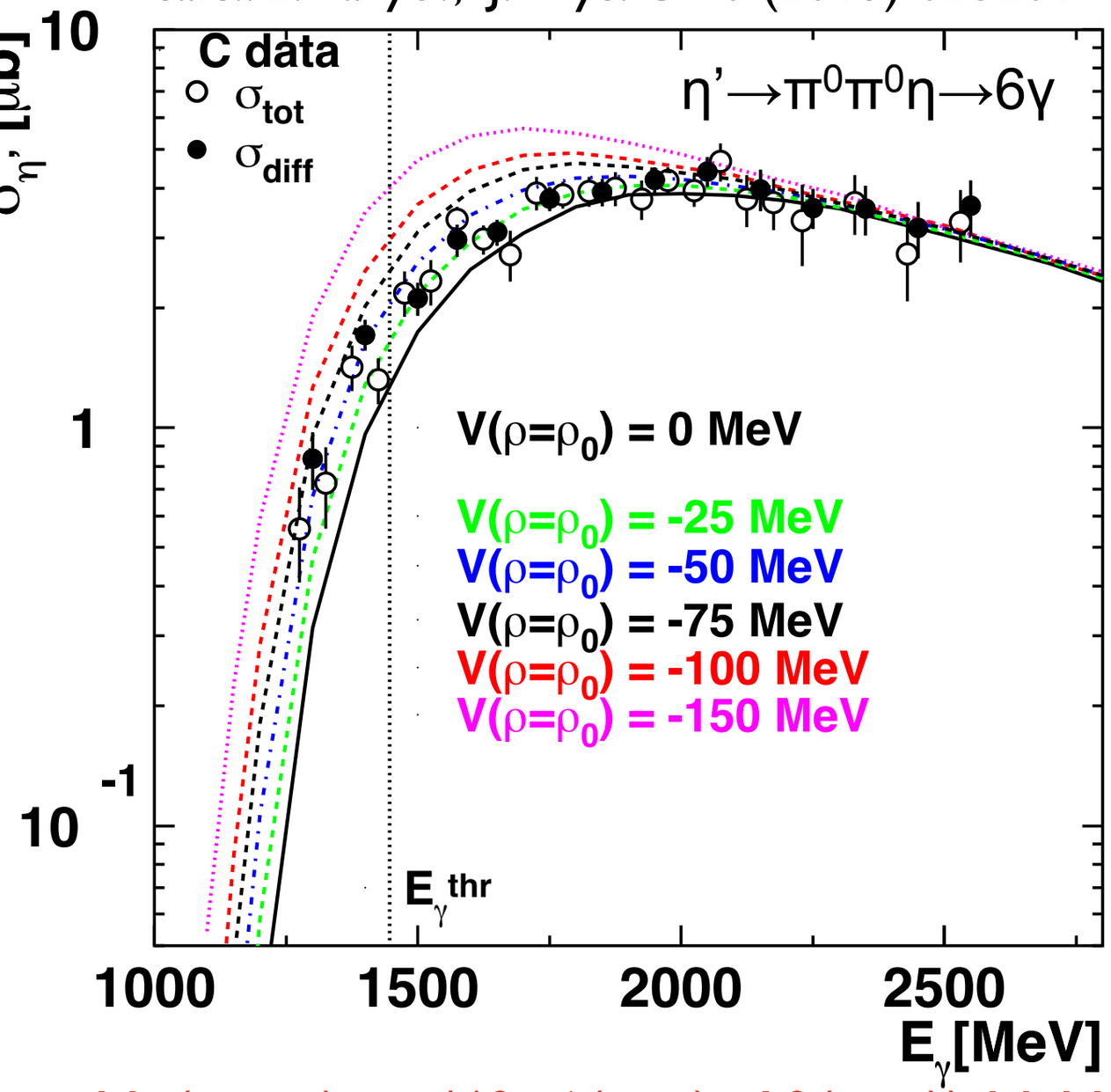
$V_\omega(\rho=\rho_0)$ = -(42±17(stat)±20(syst)) MeV

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(stat)±10(syst)) MeV

data disfavour strong mass shifts

momentum distribution for ω and η' photoproduction

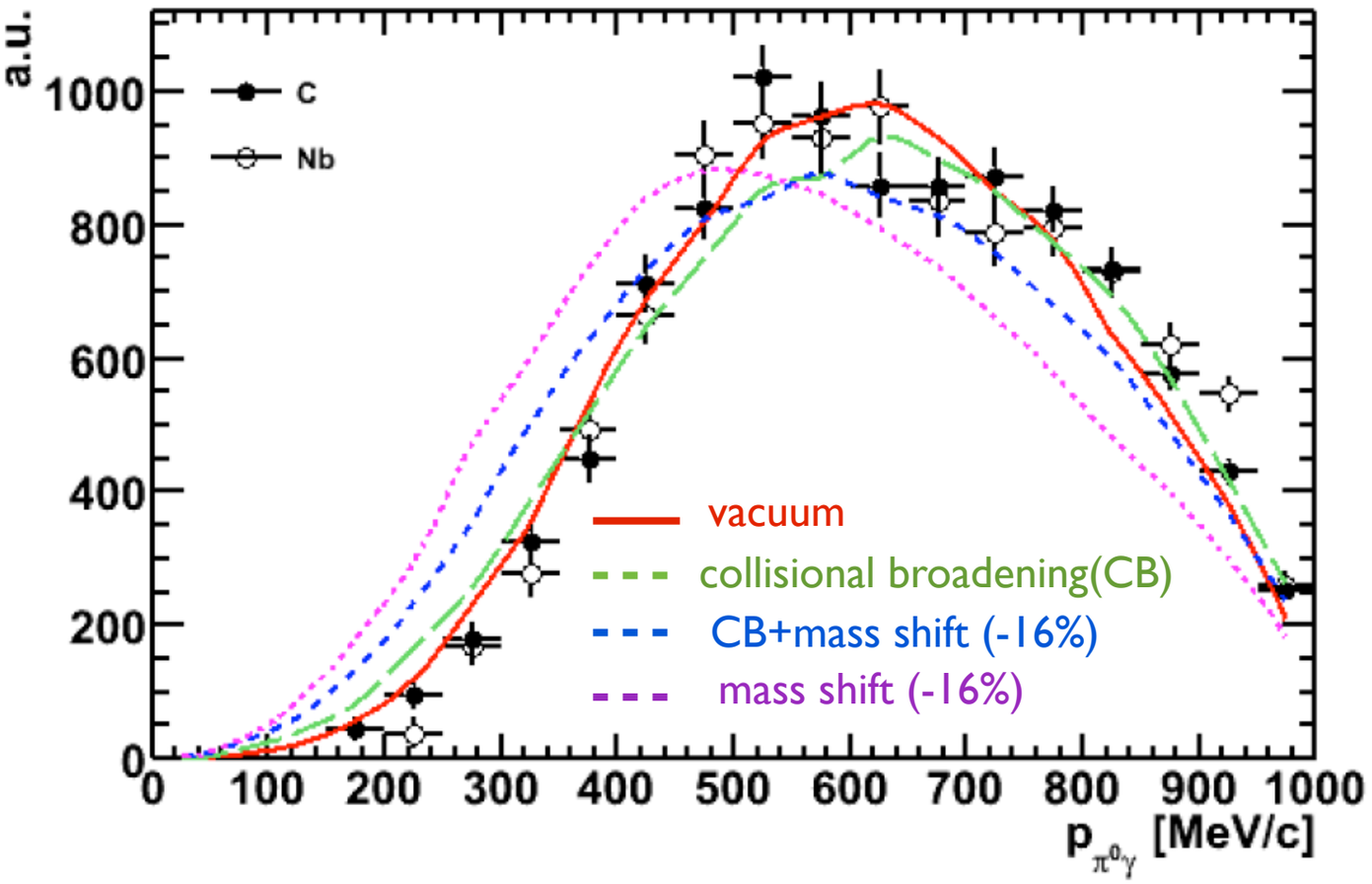
ω

η'

CB/TAPS @ MAMI

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

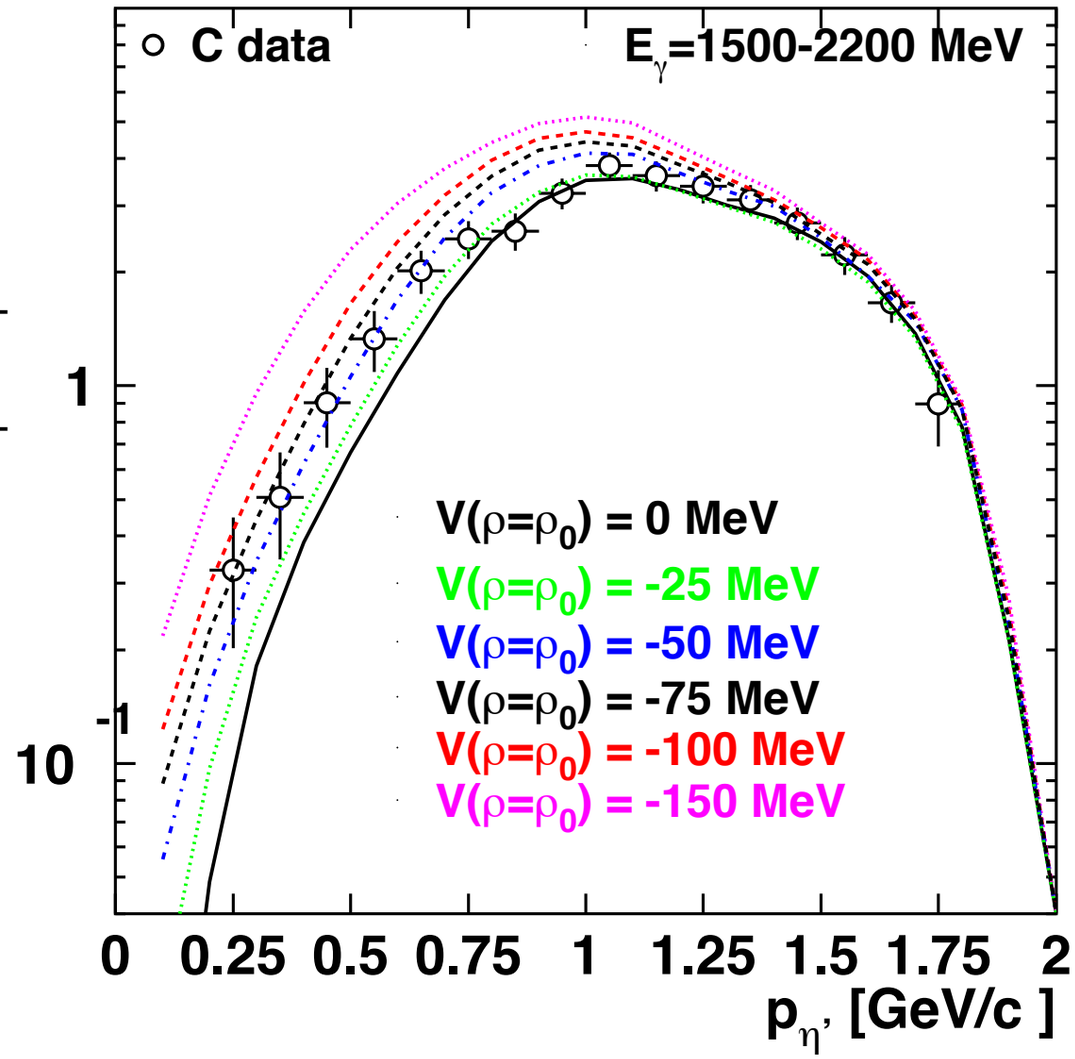
E_γ=900-1300 MeV



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

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

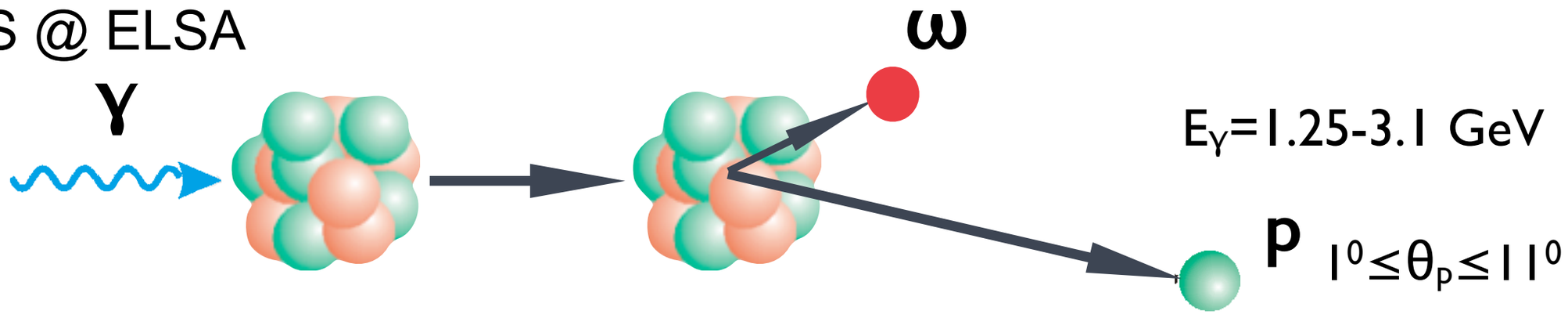
calc.: E. Paryev, J. Phys. G 40 (2013) 025201



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

real part of ω-nucleus potential from ω kinetic energy

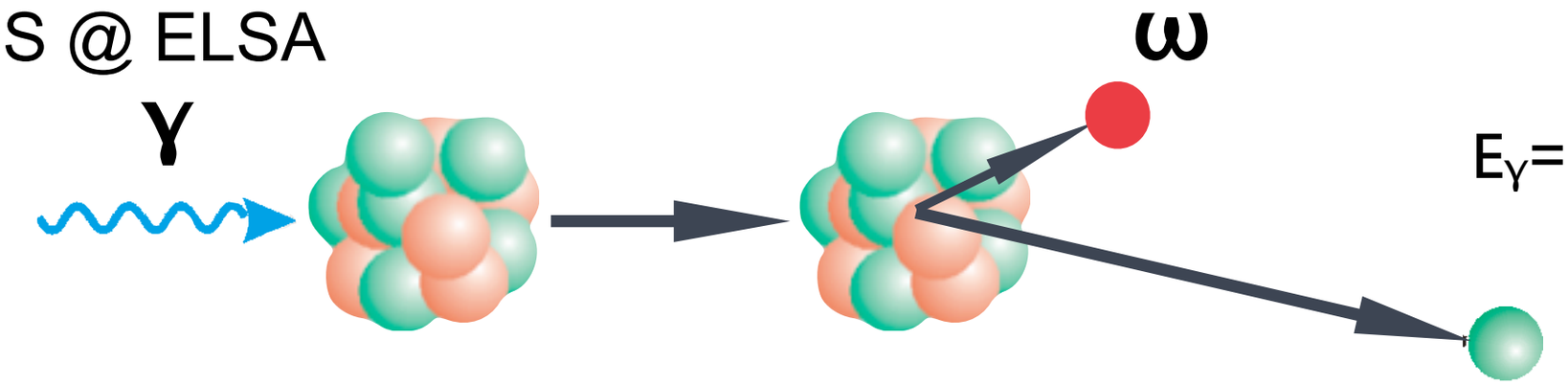
CBELSA/TAPS @ ELSA



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

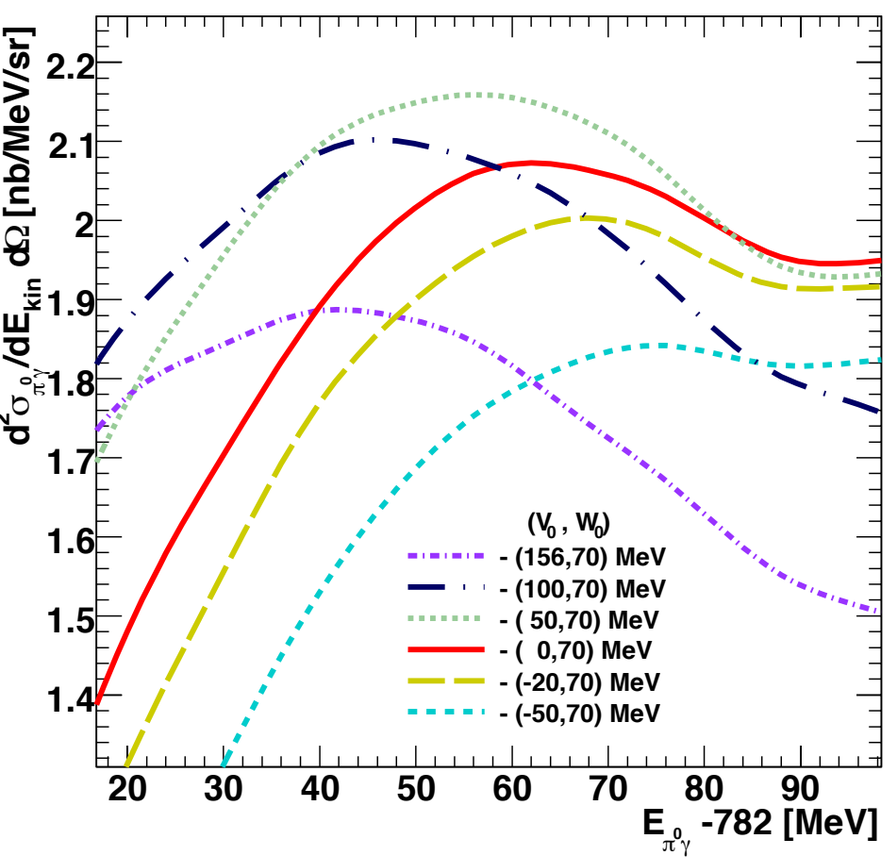


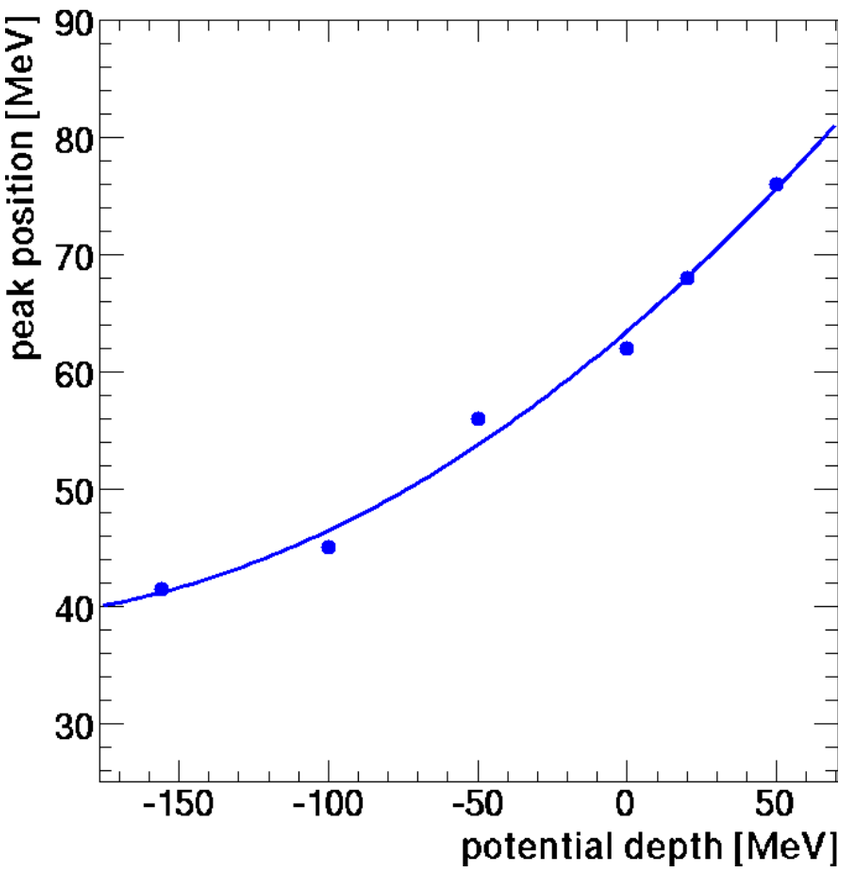
E_γ=1.25-3.1 GeV

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

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

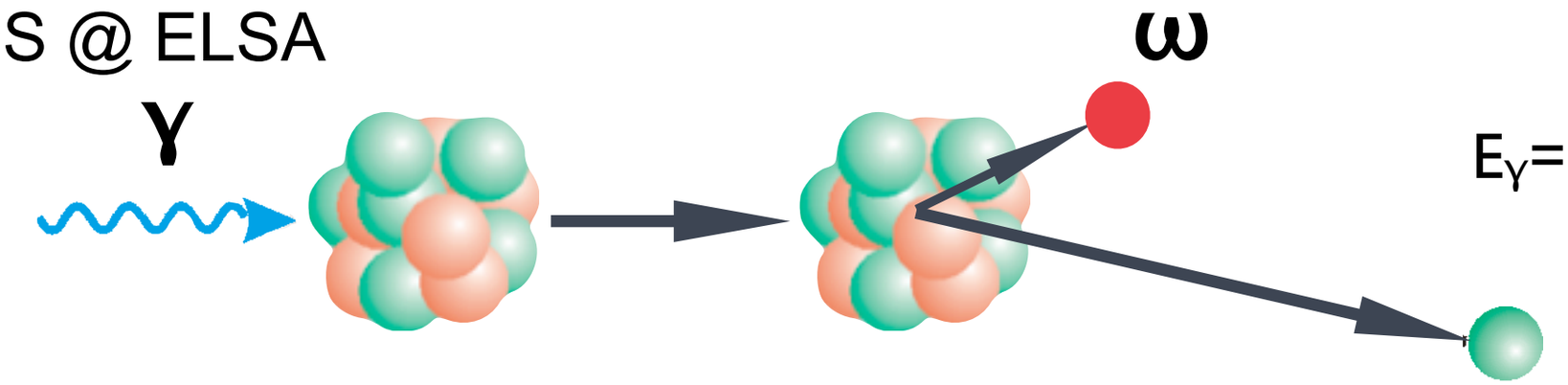
H. Nagahiro, priv. com.





real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA



E_γ=1.25-3.1 GeV

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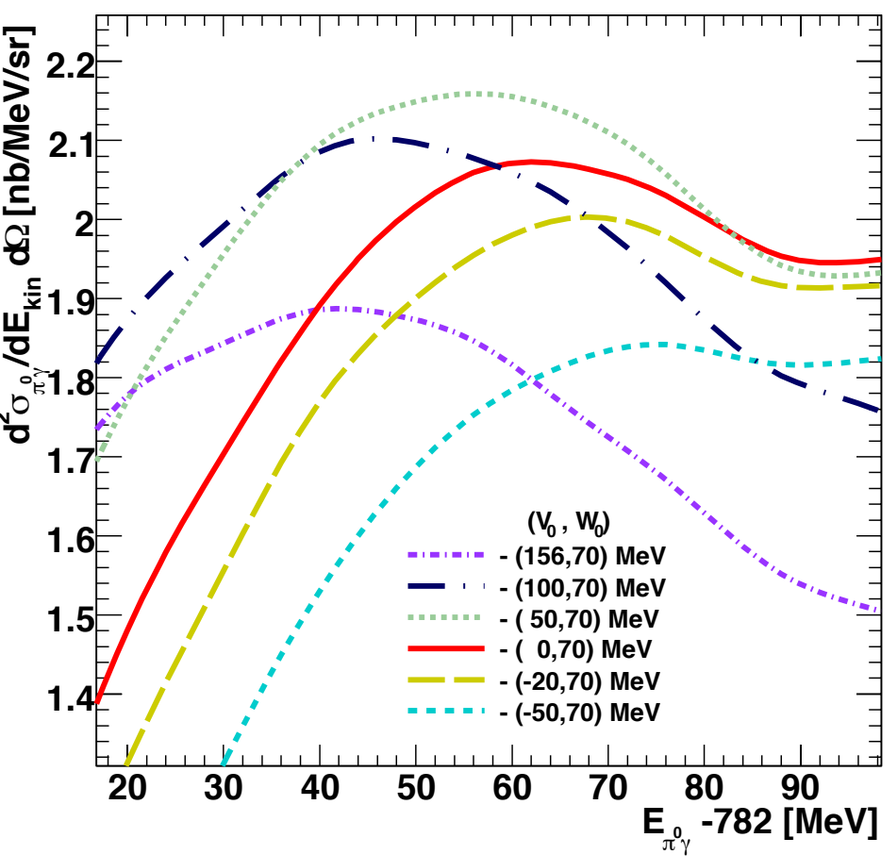
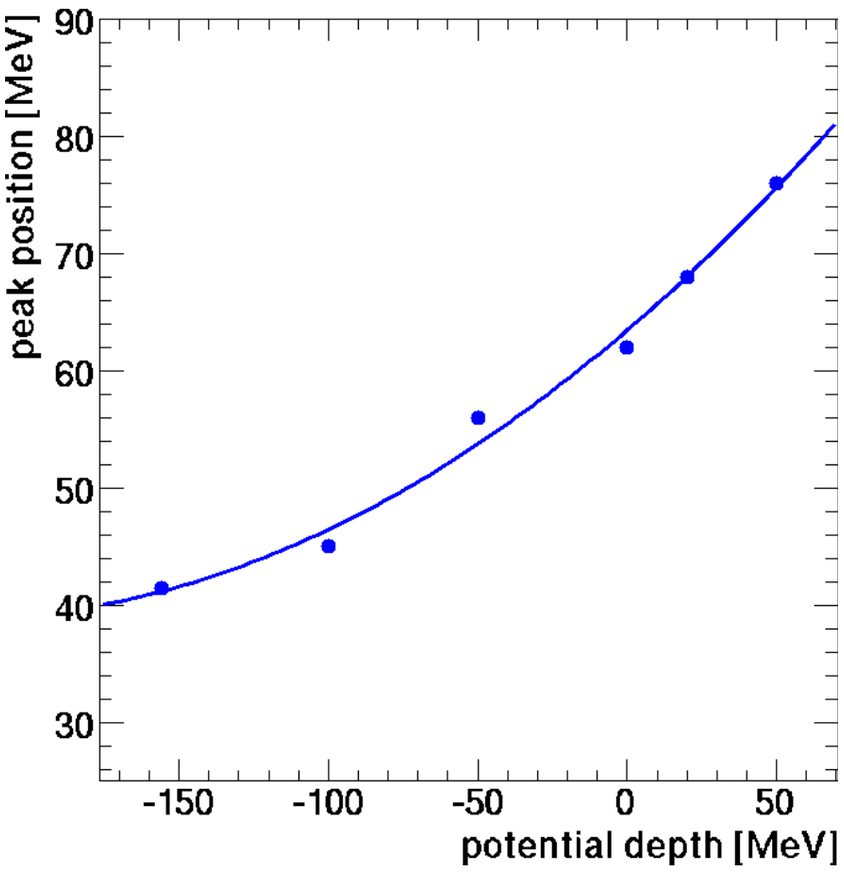
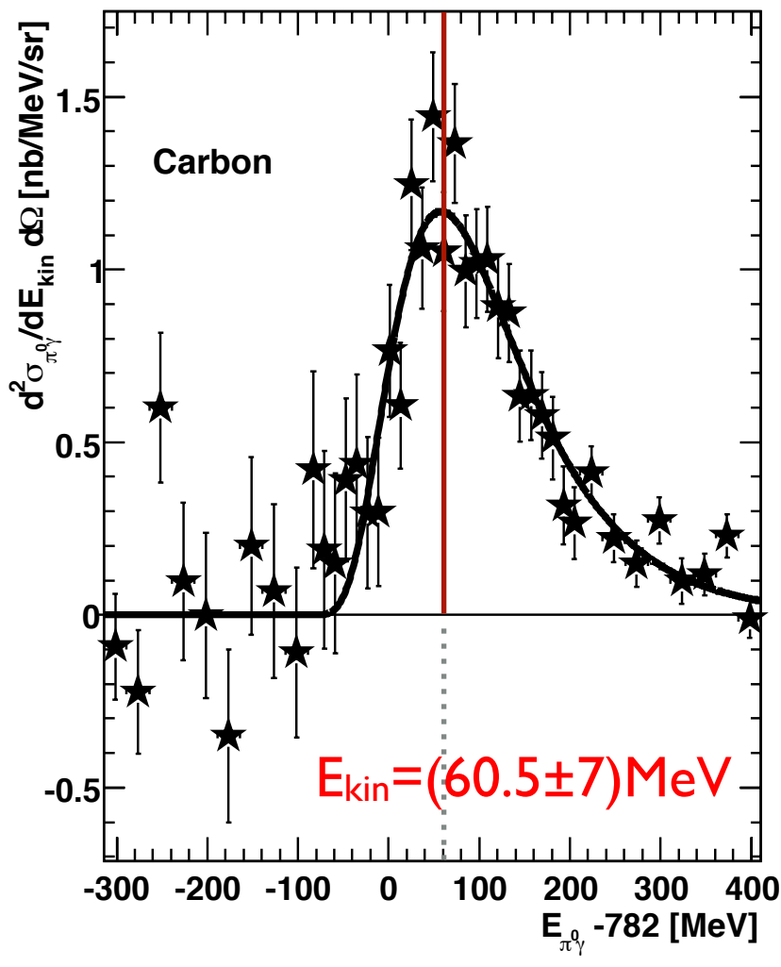
H. Nagahiro, priv. com.

S. Friedrich, PLB 736 (2014) 26

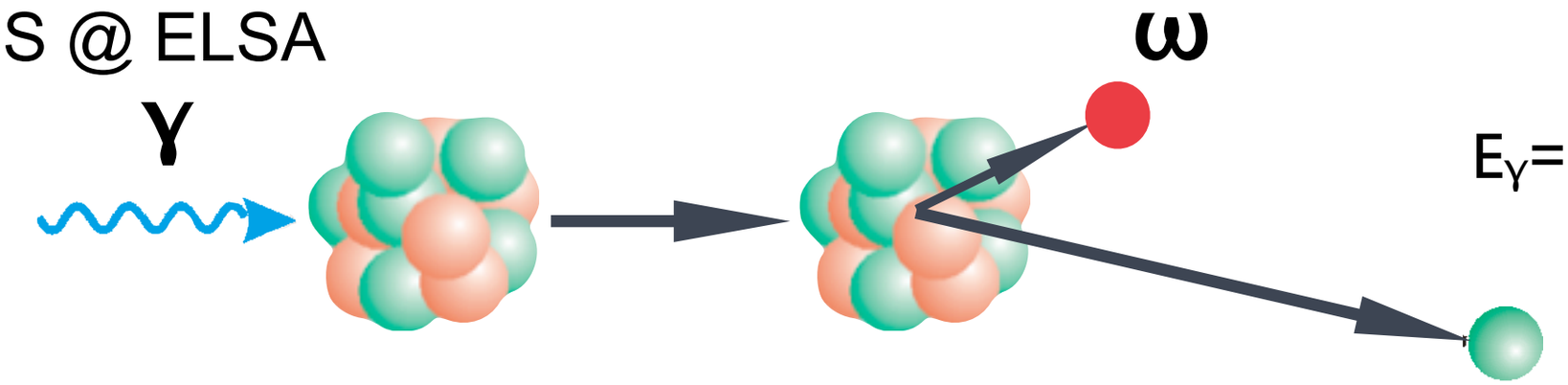






real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA

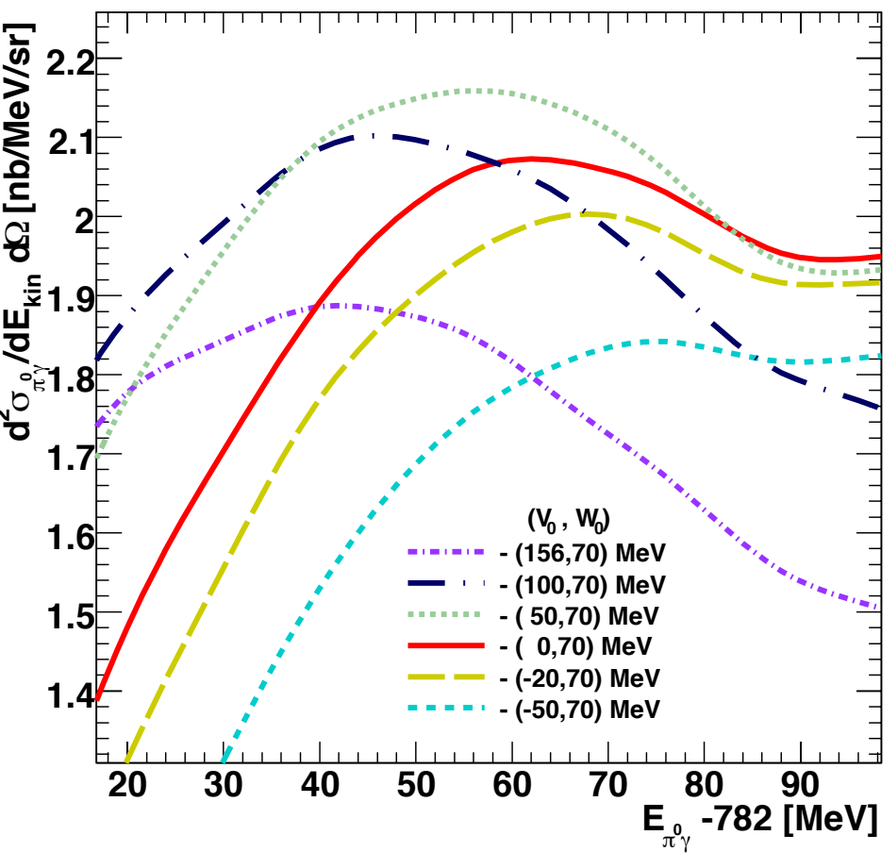


E_γ=1.25-3.1 GeV

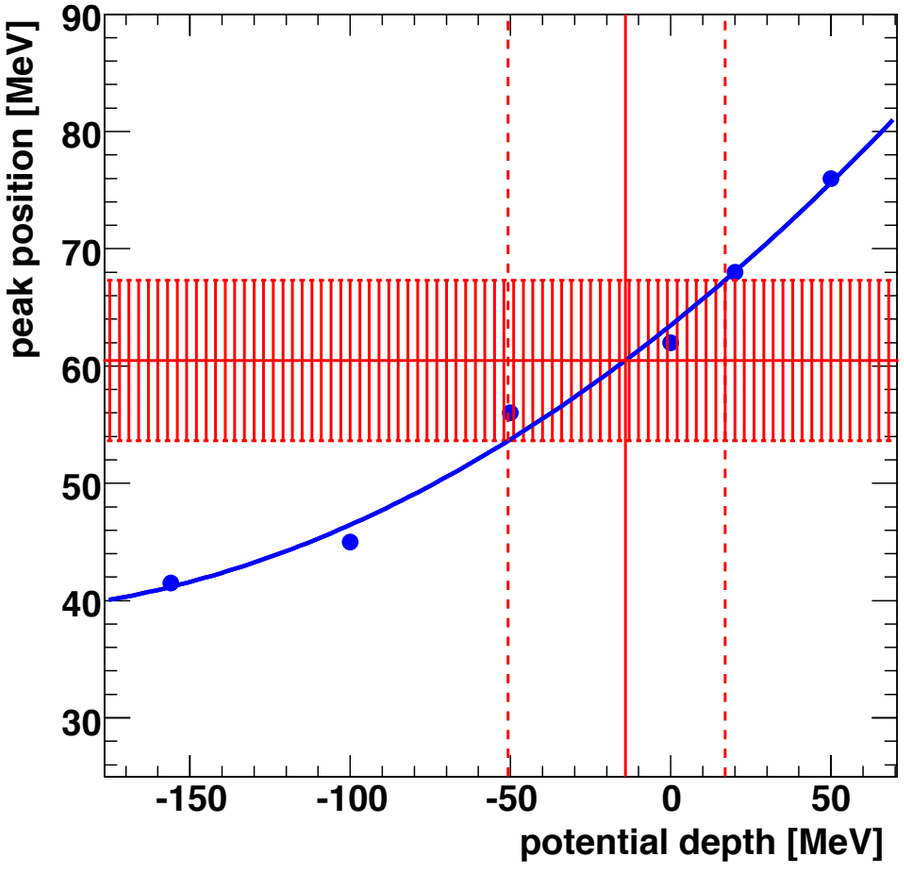
$1^0 \le \theta_p \le 11^0$

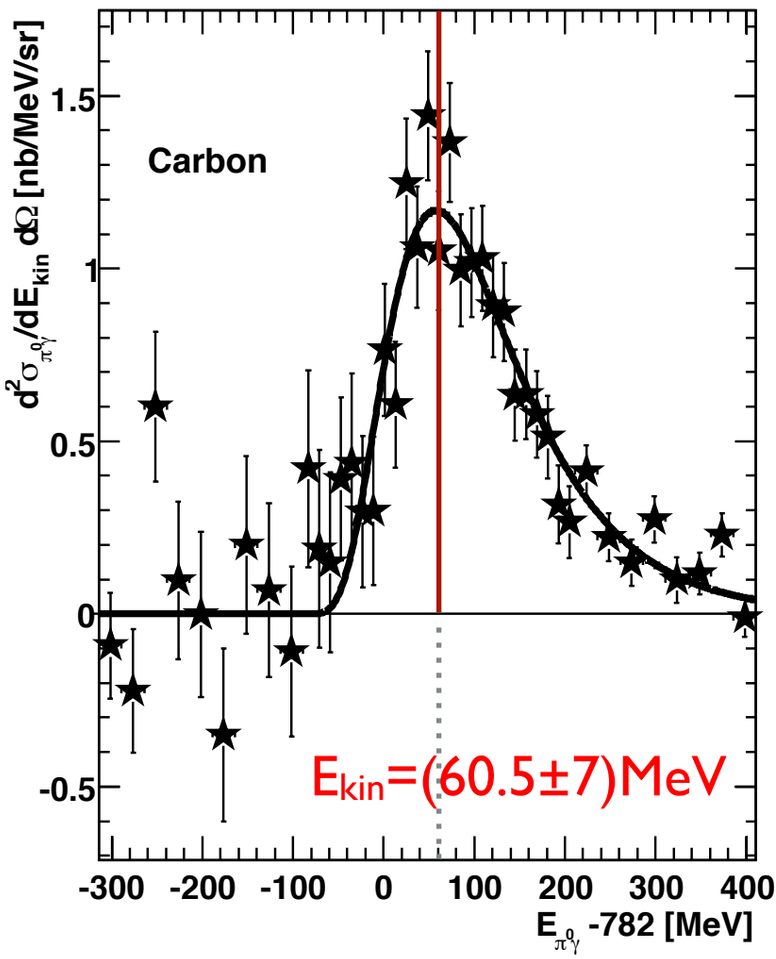
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.



S. Friedrich, PLB 736 (2014) 26





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

ω

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

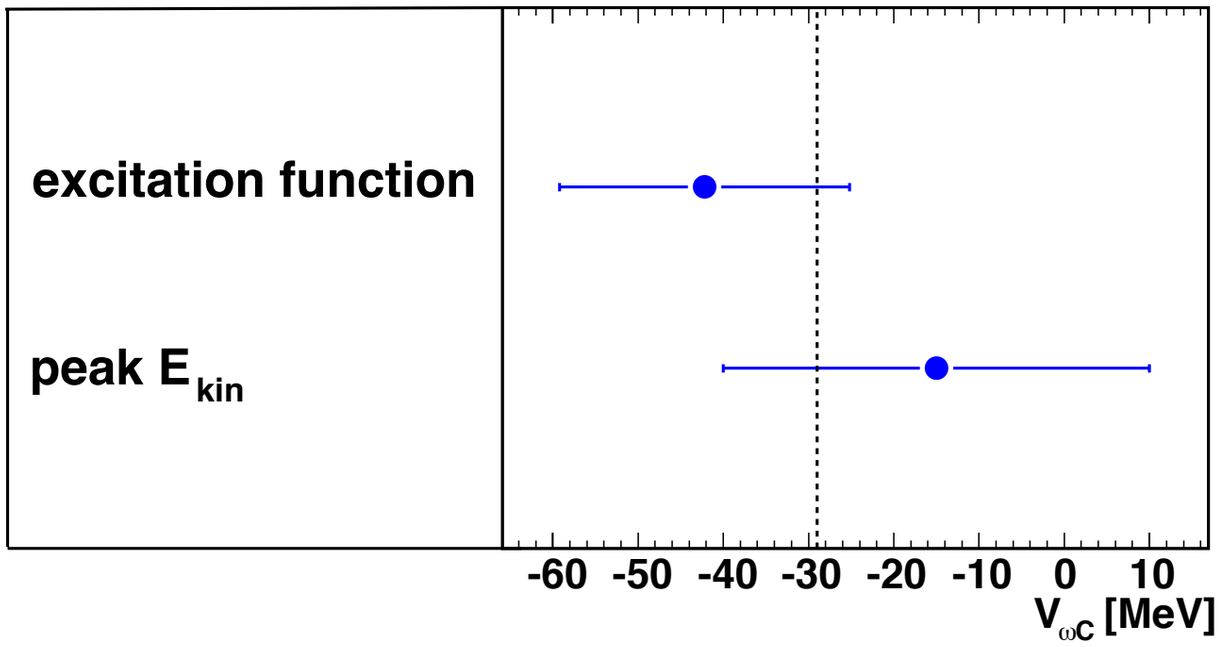
η'

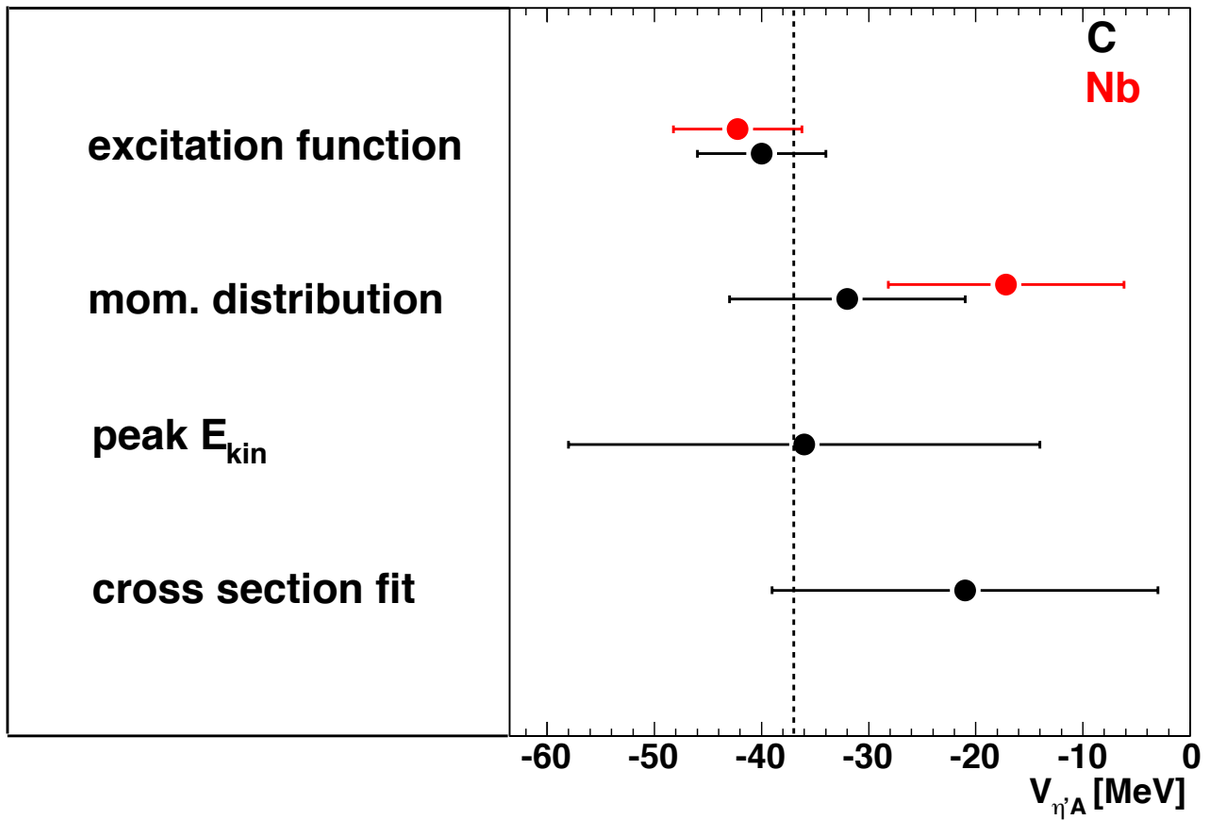
imaginary part:

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

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

real part:





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

-(29±19(stat)±20(syst))MeV

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

-(37±5(stat)±10(syst))MeV

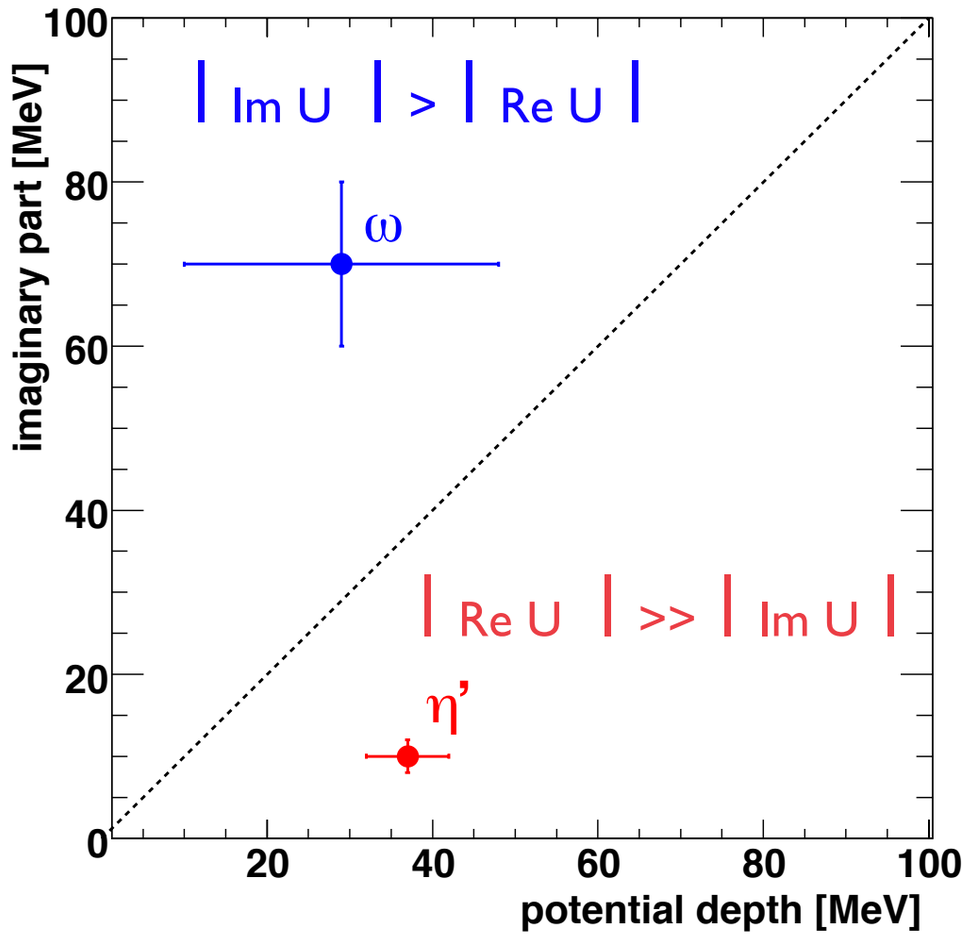
compilation of results for real and imaginary part of the ω, η' -nucleus optical potential

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

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

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

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



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

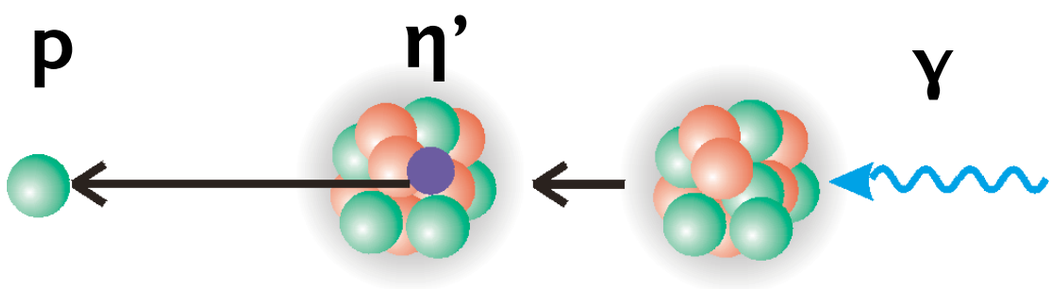
| Re U | >> | Im U | ; ⇨ η' promising candidate to search for mesic states

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)

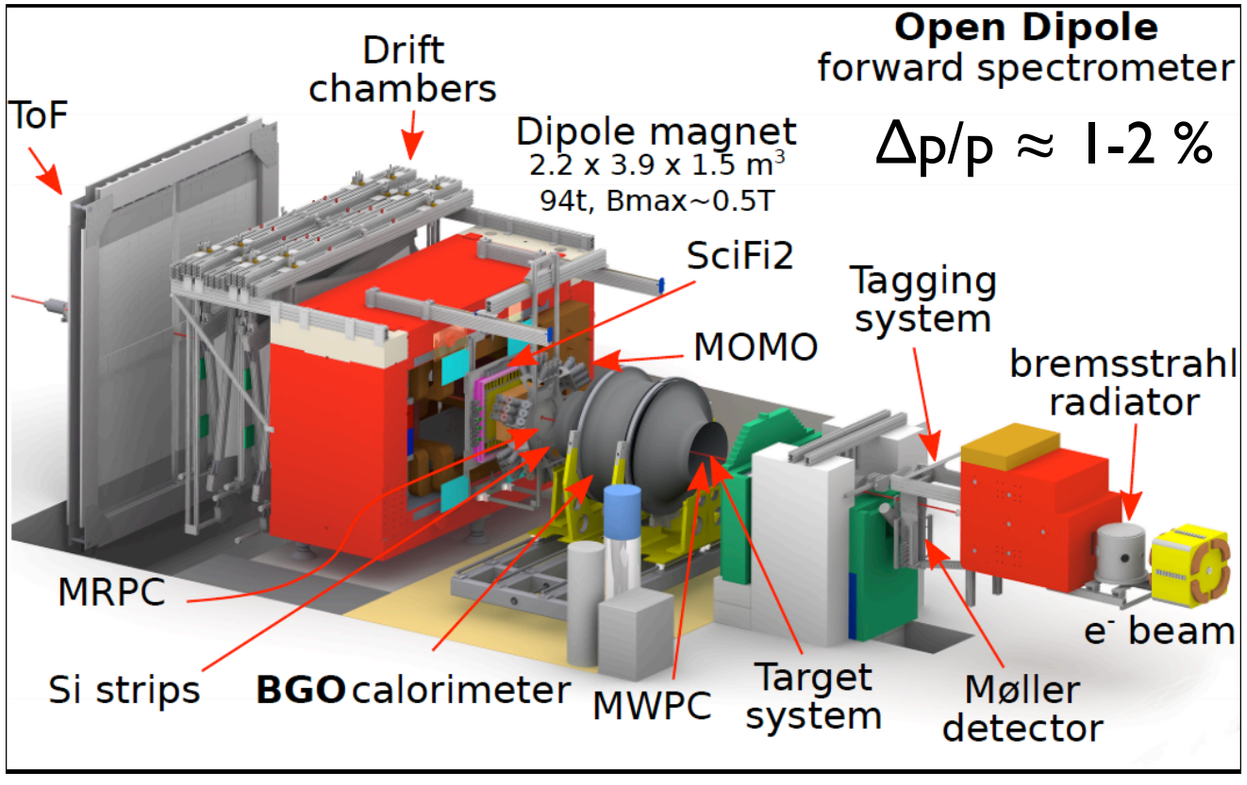
search for η'-mesic states

BGO-OD@ELSA

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



formation and decay of η'-mesic state



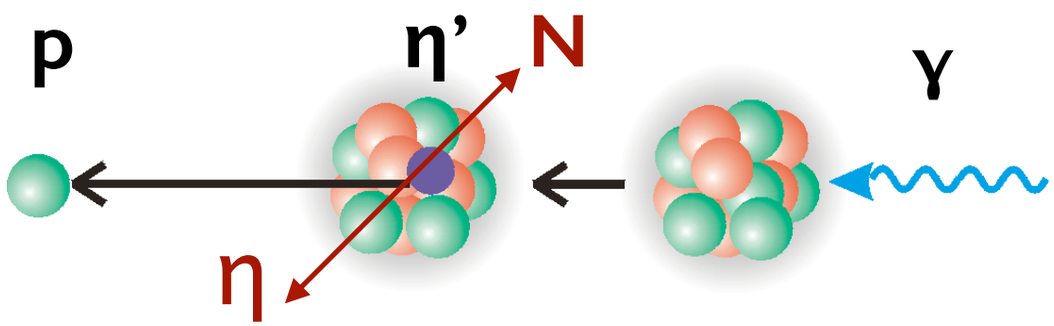
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

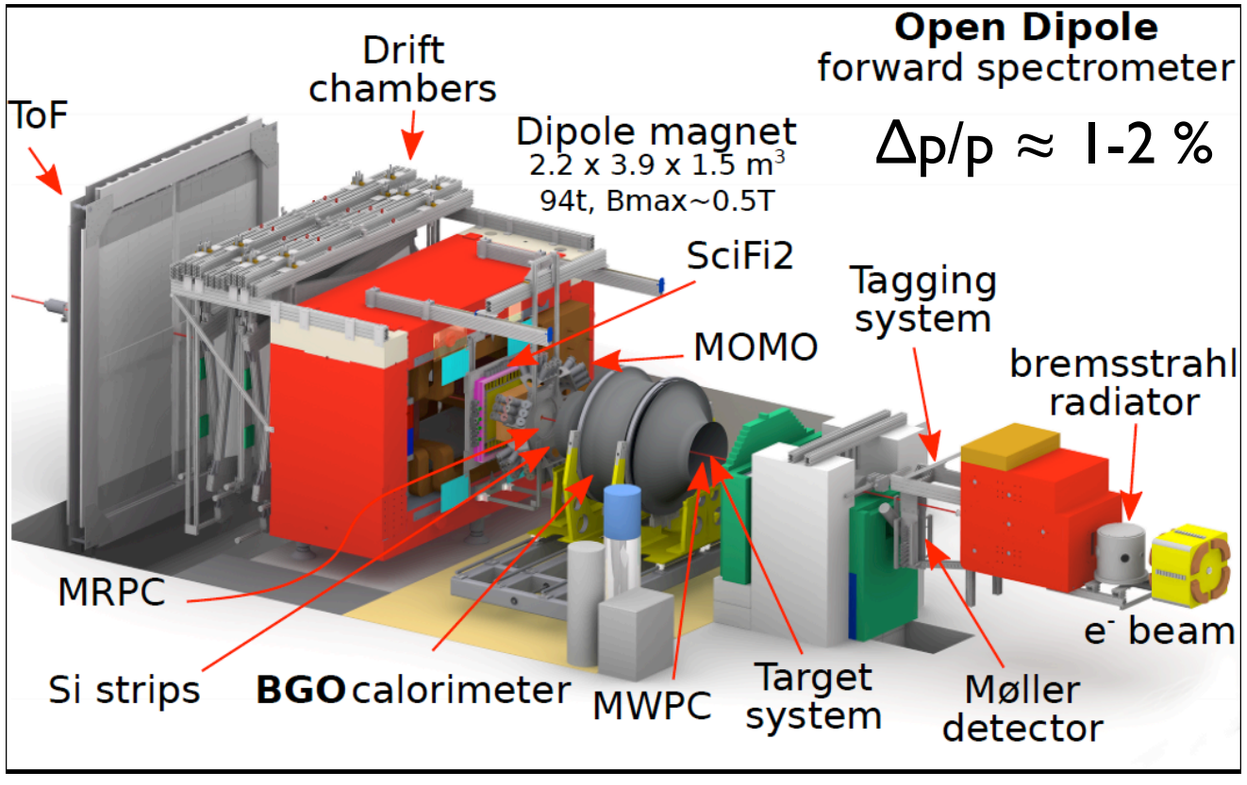
search for η'-mesic states

BGO-OD@ELSA

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



formation and decay of η'-mesic state



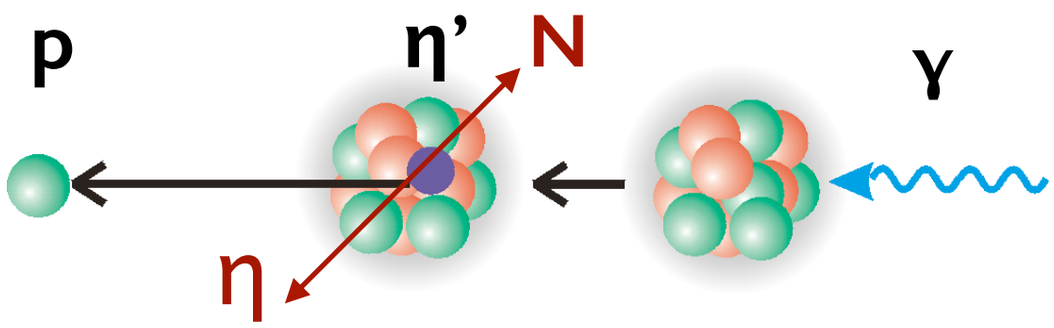
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

search for η'-mesic states

BGO-OD@ELSA

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

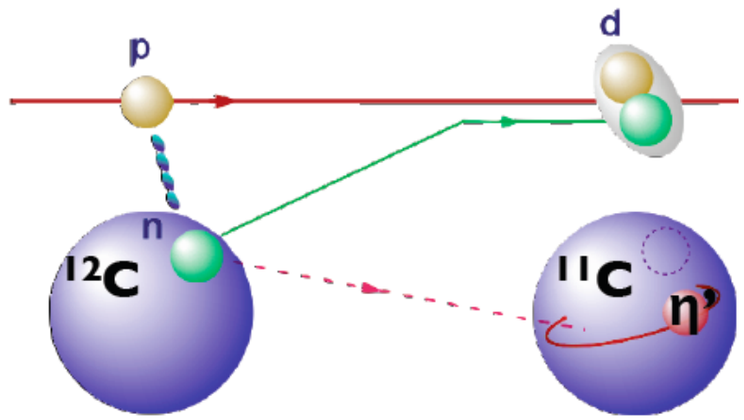


formation and decay of η'-mesic state

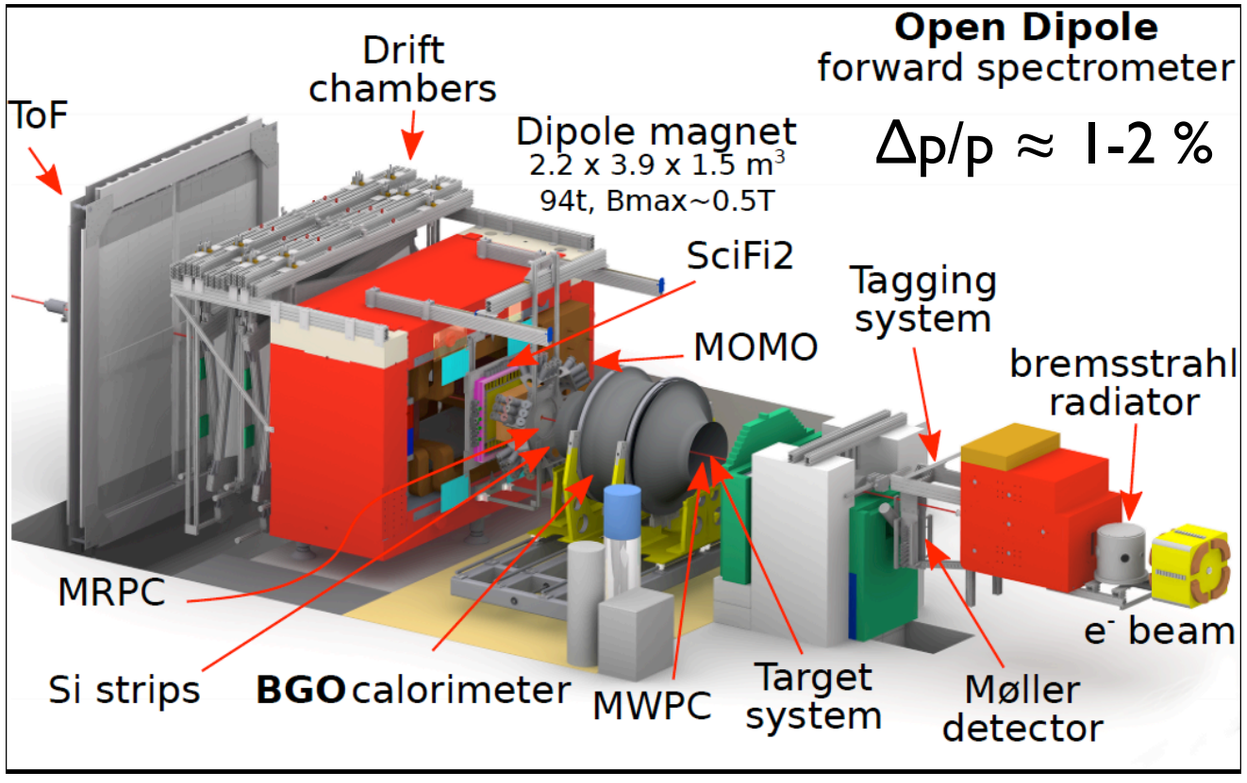
FRS@GSI

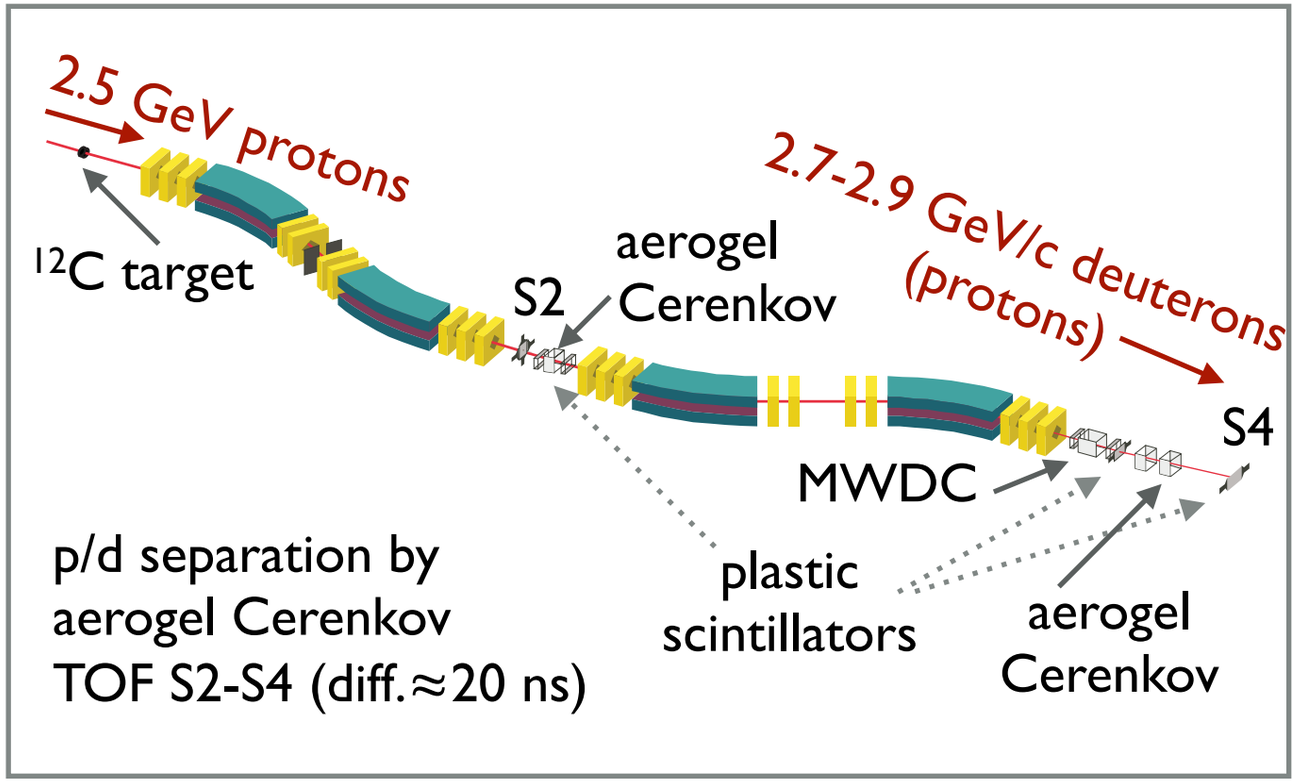
$^{12}C(p,d)\,\eta'X$ @ 2.5 GeV

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



η' × ^{11}C mesic nuclei





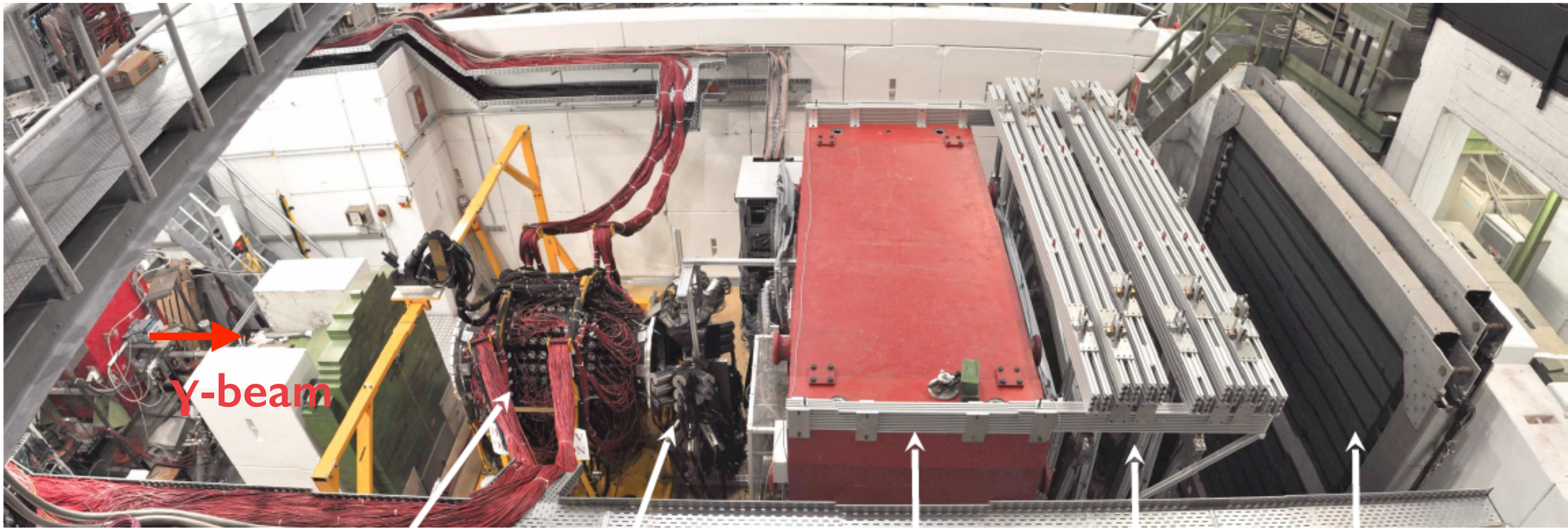
BGO-OD ideally suited for exclusive measurement

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

approved proposal: ELSA/3-2012-BGO

status report by K. Itahashi and Y. Tanaka

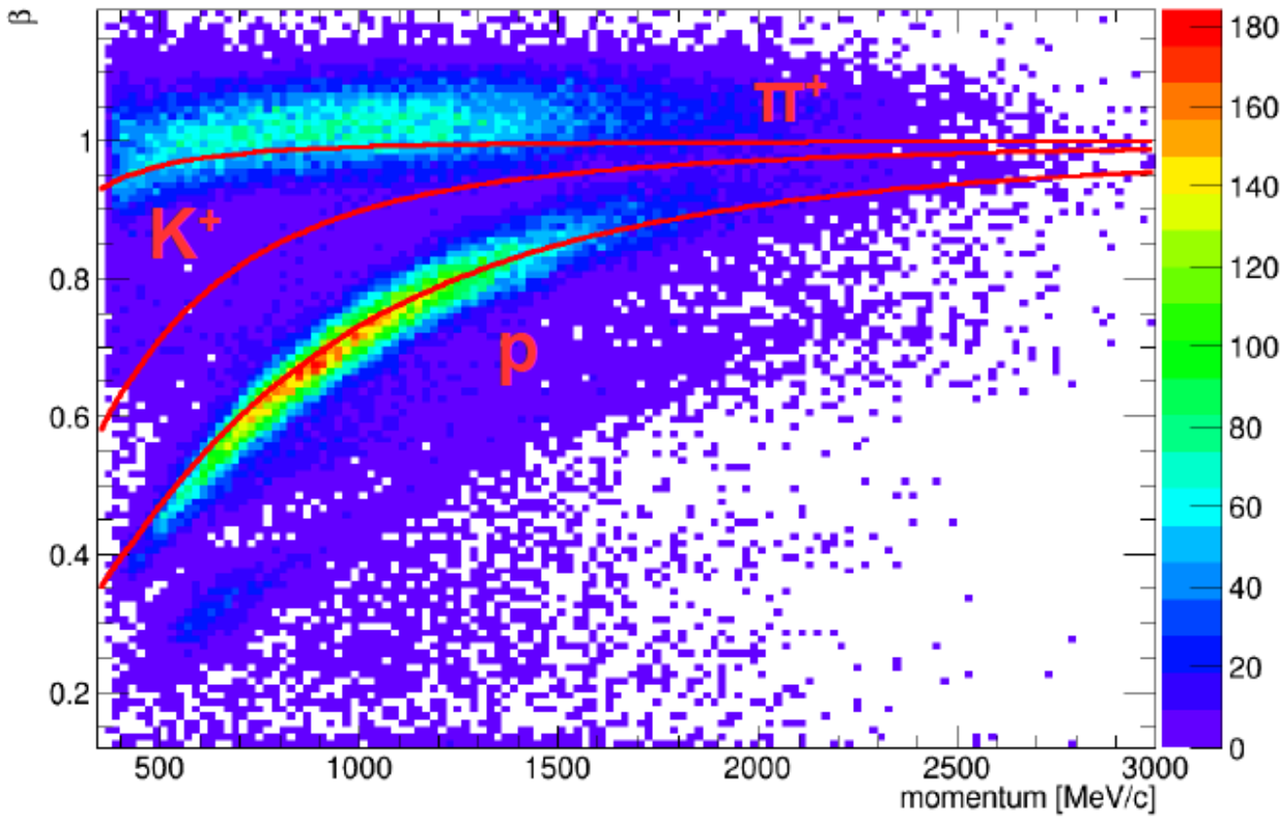
The BGO-OD experiment



BGO-ball scintillating fibers open dipole magnet MWPC TOF

BGO-OD: results of test experiment

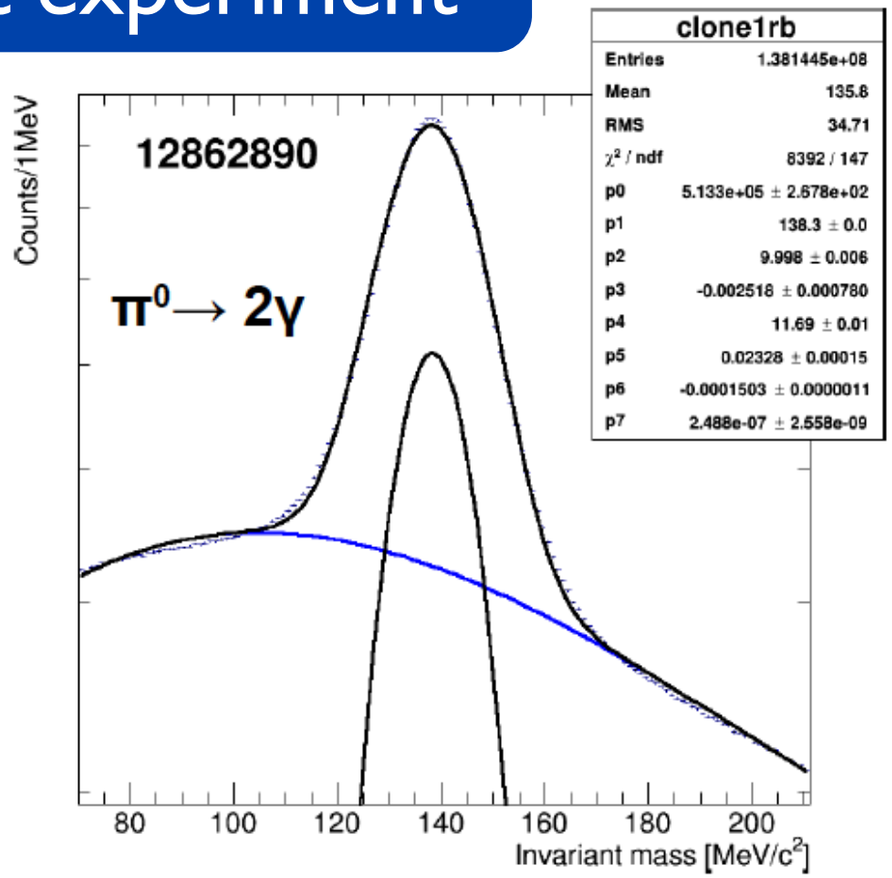
separation and identification
of charged particles in open dipole

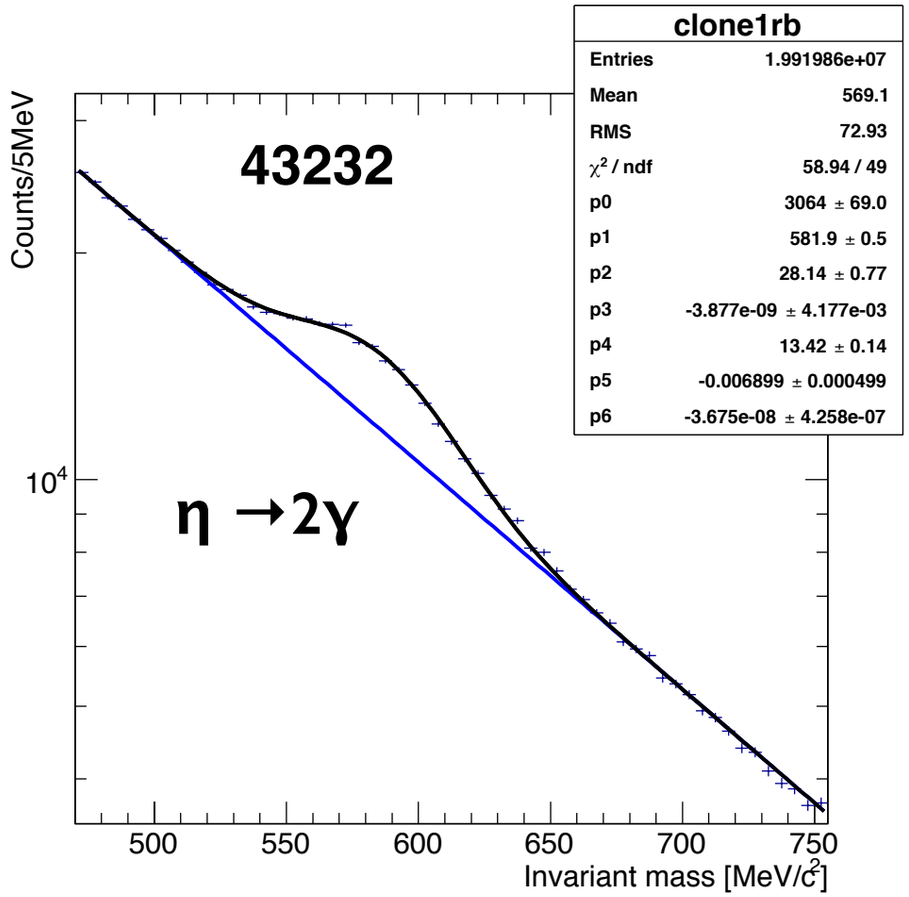


momentum resolution: $\Delta p/p = 1\%$

BGO: $\pi^0, \eta \rightarrow 2\gamma$

run for η'- mesic states has started !!!





summary

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

  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

  T. Nakano

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

  K.Itahashi, Y. Tanaka