Mesons in the medium - experimental probes for chiral symmetry restoration?

Mariana Nanova

for the CBELSA/TAPS Collaboration

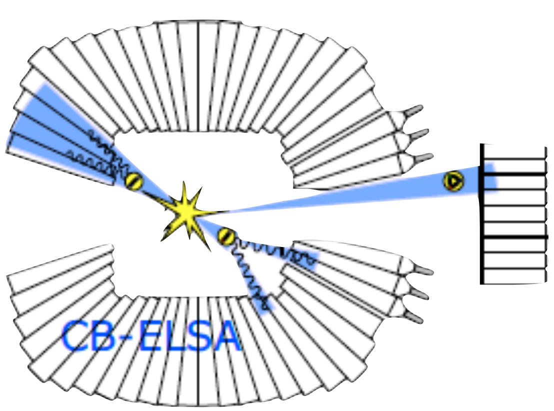
II. Physikalisches Institut

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Outline:

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

*funded by the DFG within SFB/TR16



55. International Winter Meeting on Nuclear Physics
23 - 27 January 2017, Bormio, Italy

Bound systems

Gravitation

Bound system:
Earth $\Longleftrightarrow$ Moon

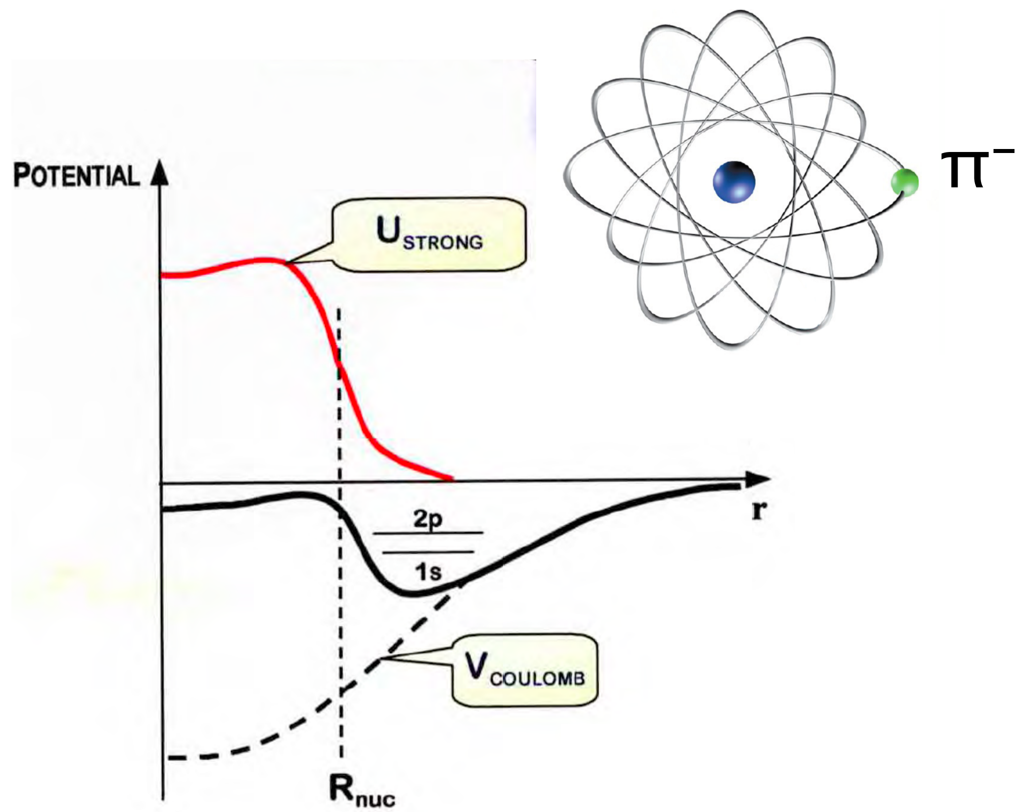
Bound systems

Gravitation

Bound system:

Earth $\Longleftrightarrow$ Moon

Electromagnetic (+strong) interaction



charged pion $\Longleftrightarrow$ nucleus

bound by superposition of attractive Coulomb- and repulsive strong interaction

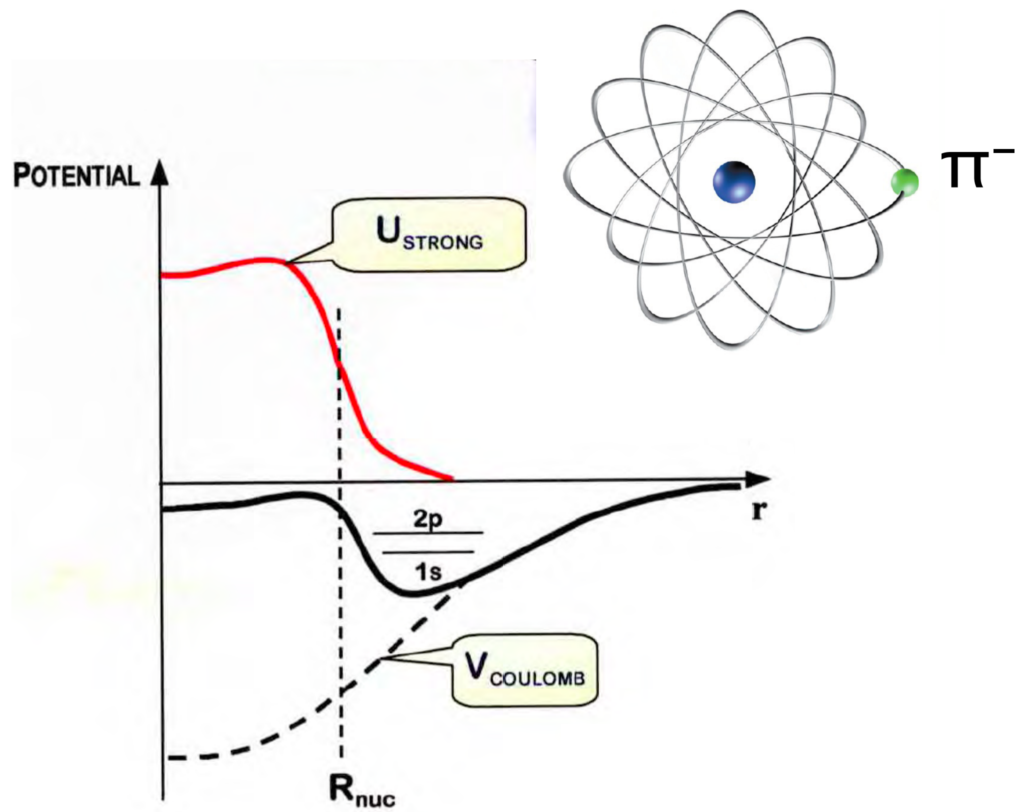
Bound systems

Gravitation

Bound system:

Earth $\Longleftrightarrow$ Moon

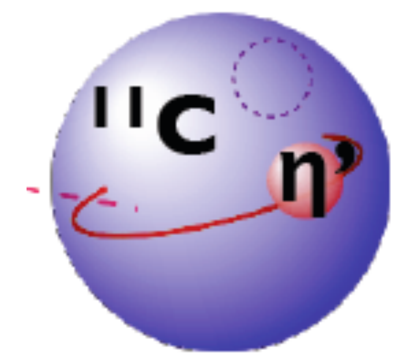
Electromagnetic (+strong) interaction



charged pion $\Longleftrightarrow$ nucleus

bound by superposition of attractive Coulomb- and repulsive strong interaction

strong interaction



ω, η' $\Longleftrightarrow$ nucleus

neutral mesons bound solely by strong interaction

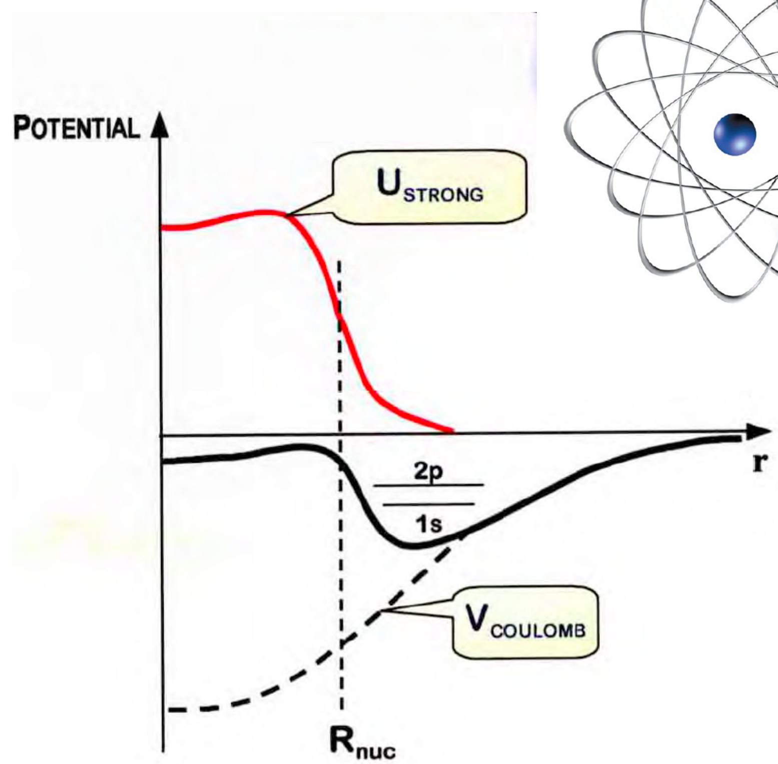
?

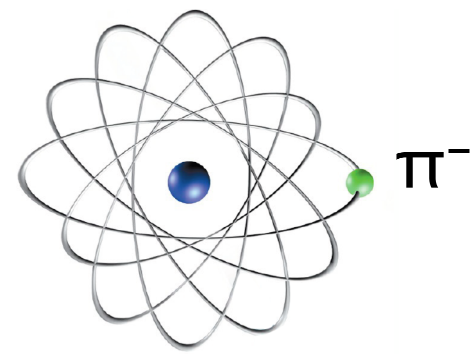
Bound systems

Gravitation

Bound system:
Earth ⟺ Moon

Electromagnetic (+strong) interaction

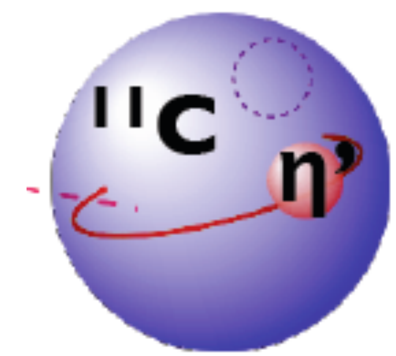




charged pion ⟺ nucleus

bound by superposition of attractive Coulomb- and repulsive strong interaction

strong interaction



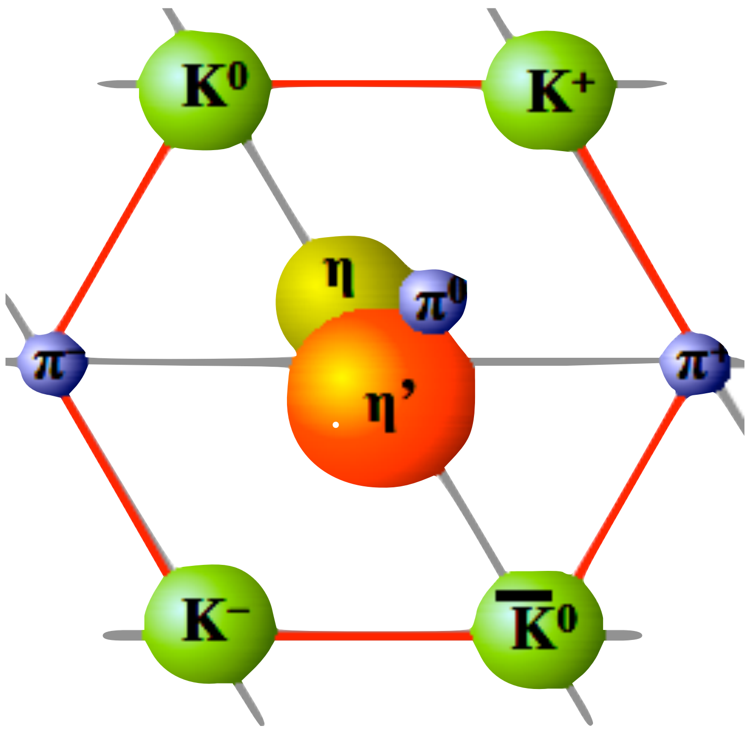
ω, η' ⟺ nucleus

neutral mesons bound solely by strong interaction

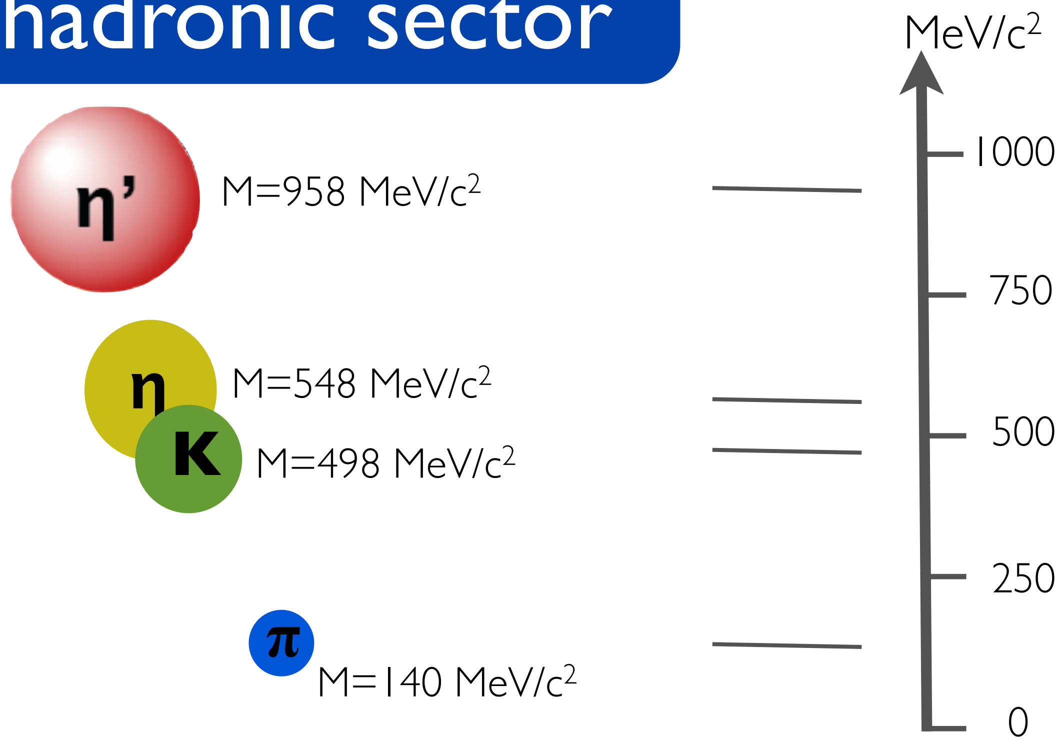
?

meson-nucleus interaction

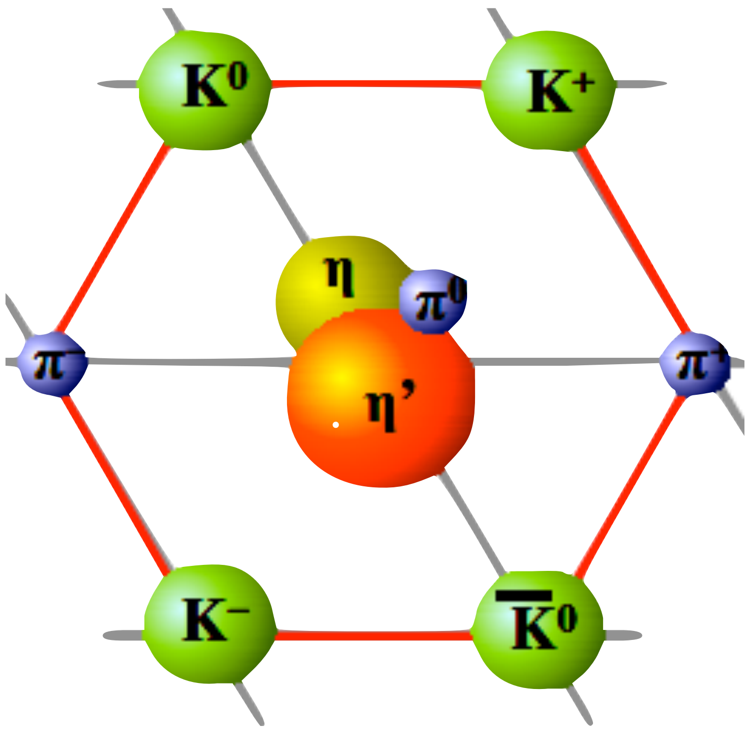
symmetry breaking in the hadronic sector



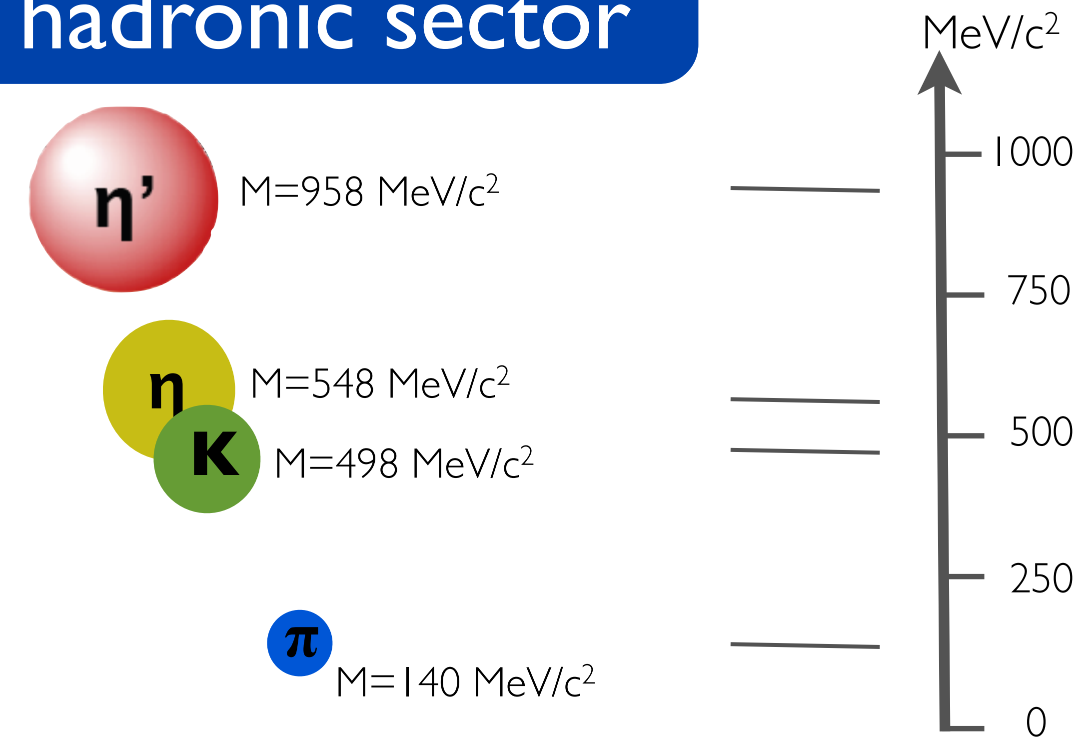
<u>nonet of pseudoscalar mesons</u>



symmetry breaking in the hadronic sector

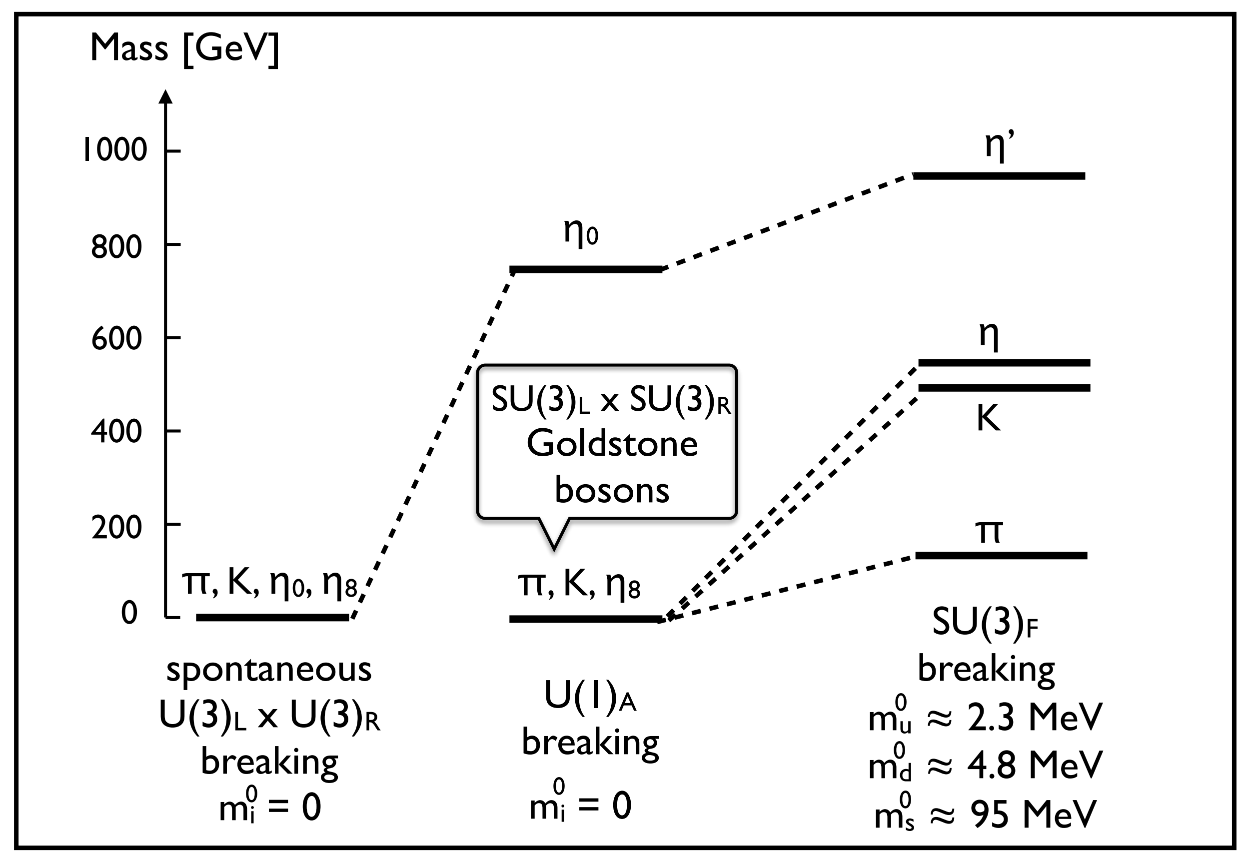


nonet of
pseudoscalar
mesons



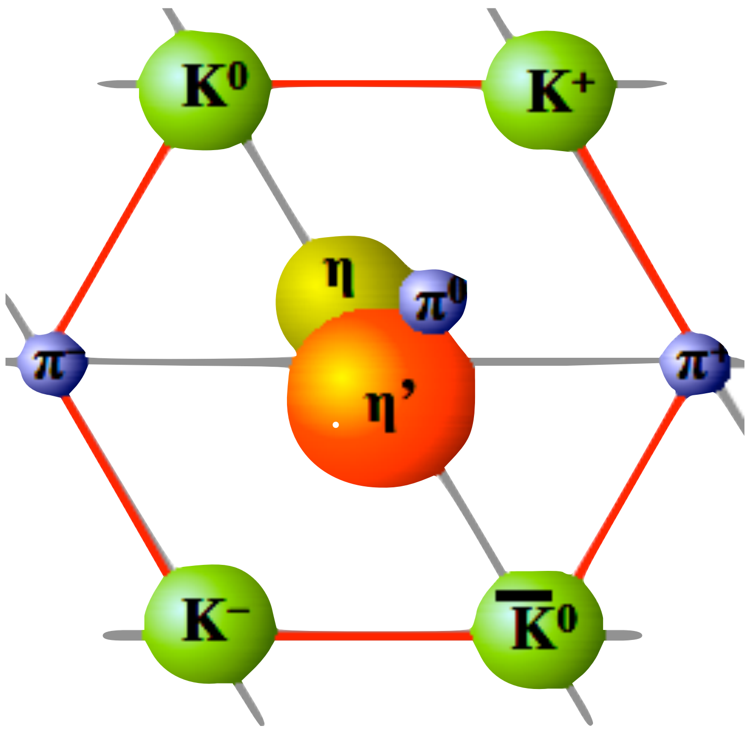
S. Klimt et al., Nucl. Phys. A 516 (1990) 429

mass as a result of symmetry breaking

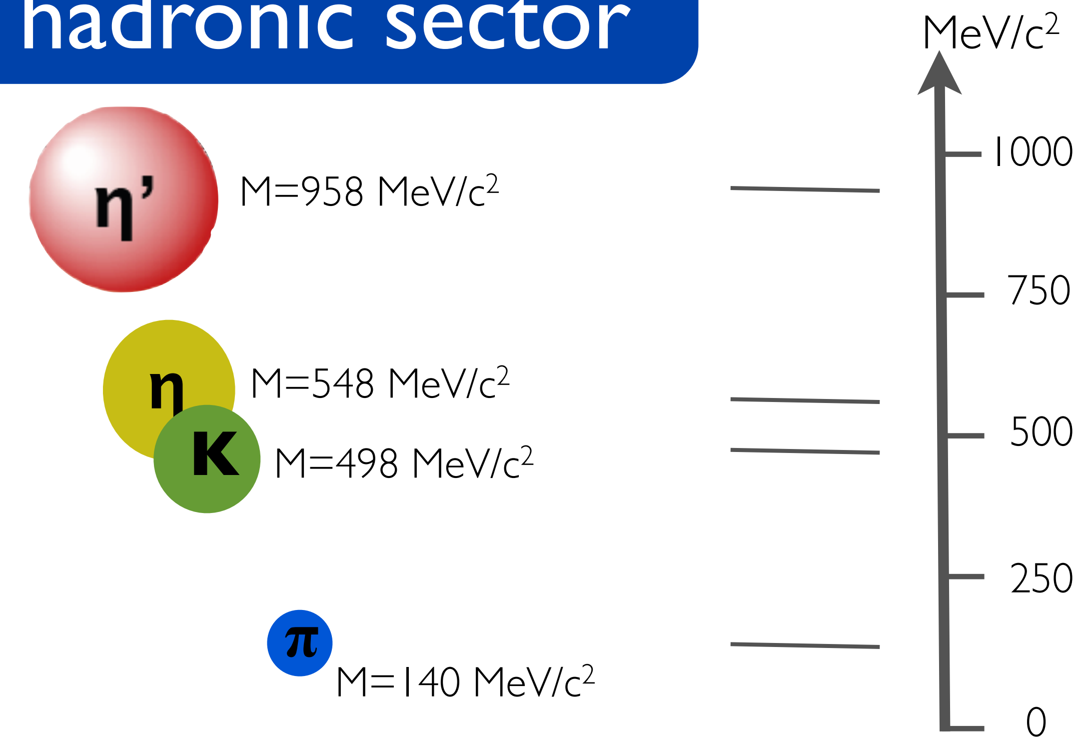


symmetry breaking

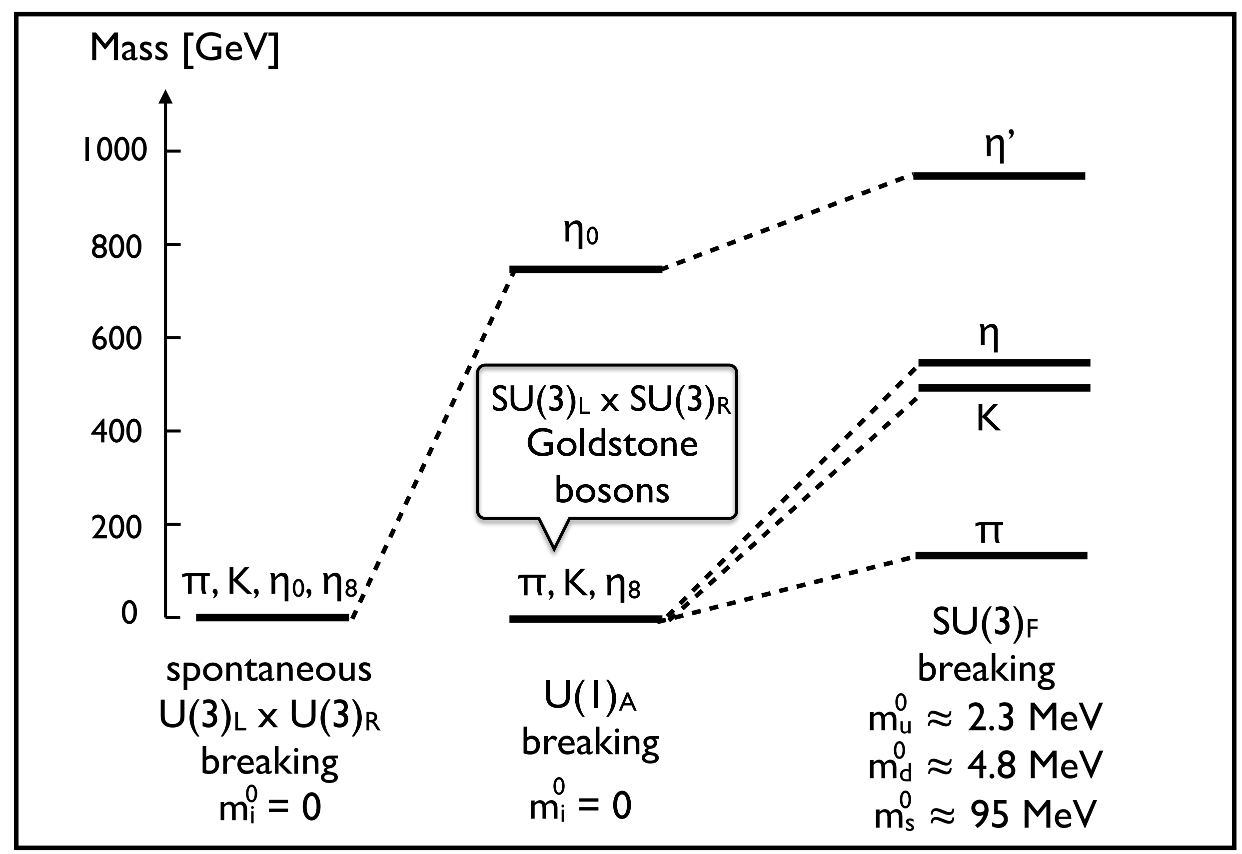
symmetry breaking in the hadronic sector



nonet of pseudoscalar mesons



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



symmetry breaking

partial symmetry restoration

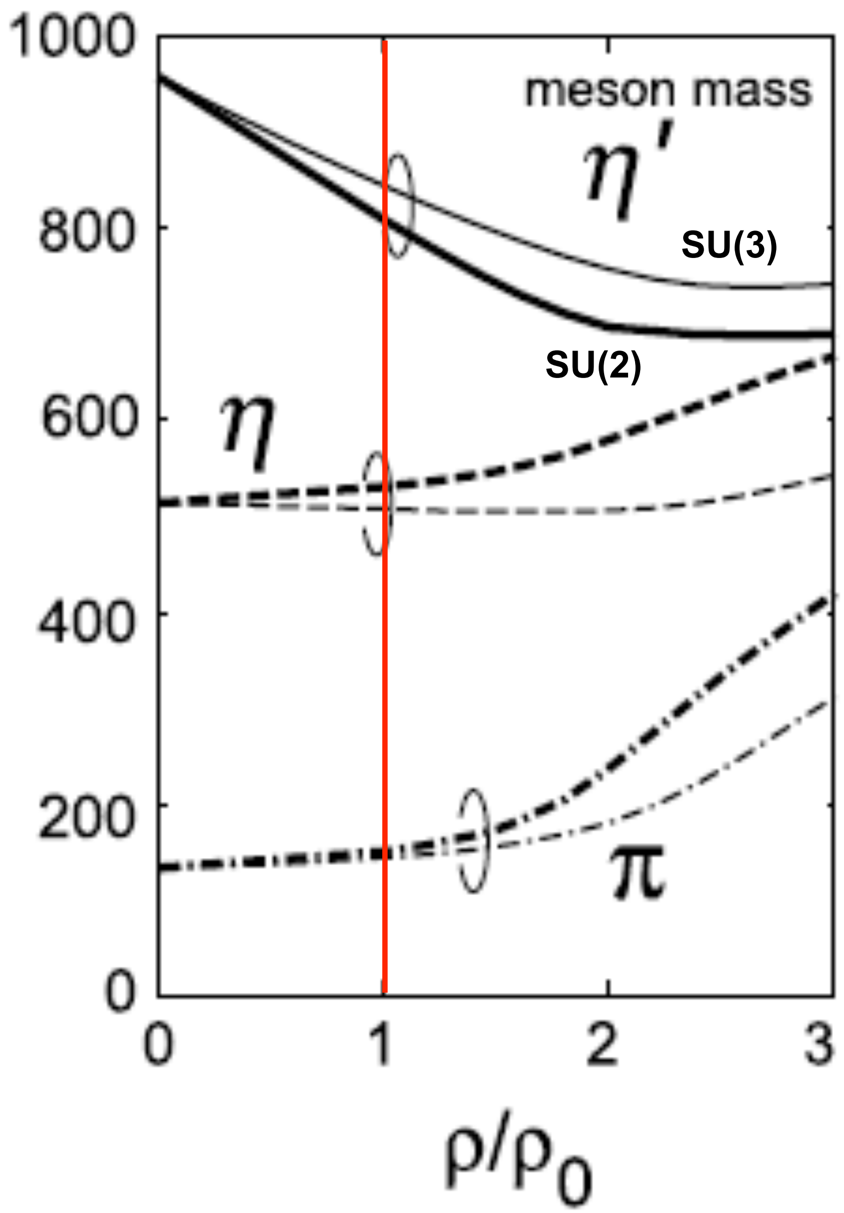
mass as a result of symmetry breaking

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

hadronic models: predictions for η' in-medium mass

<u>NJL-model</u>

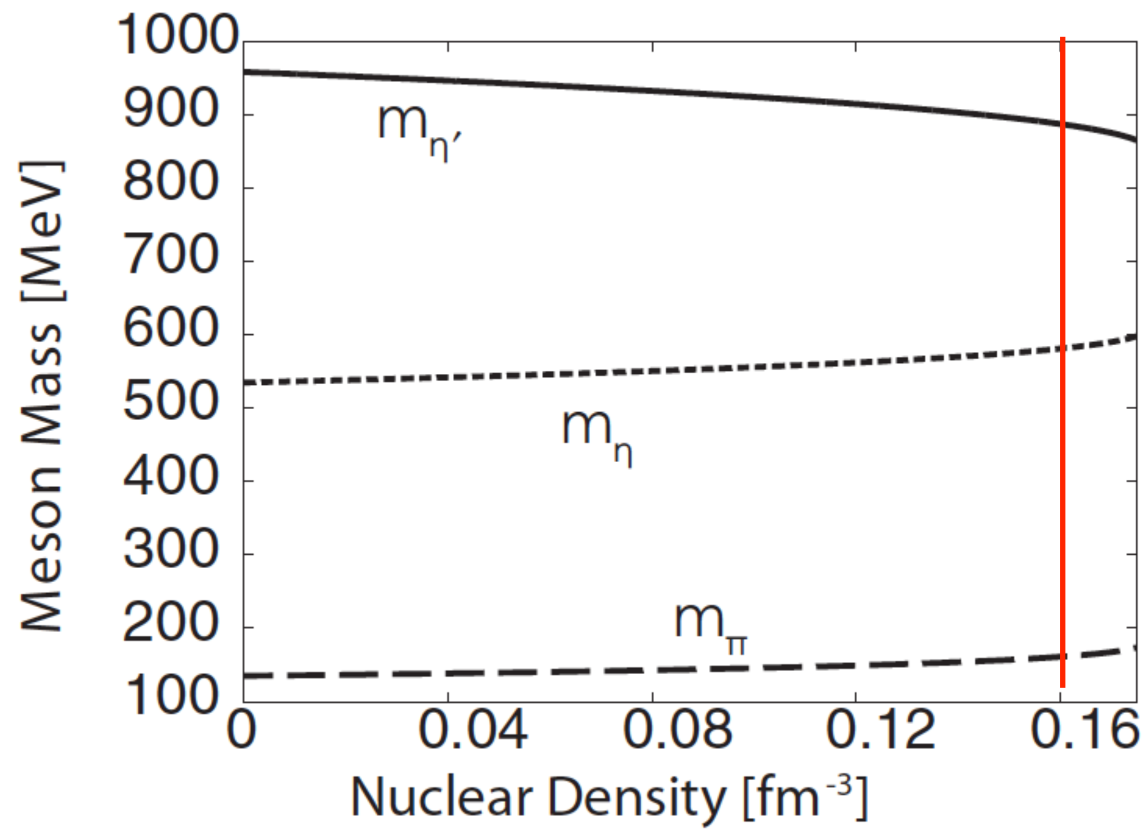
H. Nagahiro et. al,
Phys. Rev. C 74 (2006) 045203



$\Delta m_{\eta'}(\rho_0) \approx -150$ 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 $\theta_{\eta\eta'} = -20^0$

meson-nucleus optical potential

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

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

meson-nucleus optical potential

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

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

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

real part

$\Updownarrow$

in-medium mass modification

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

$\Updownarrow$

in-medium mass modification

imaginary part

$\Updownarrow$

lifetime shortened

in-medium width, absorption
inelastic cross section

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

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

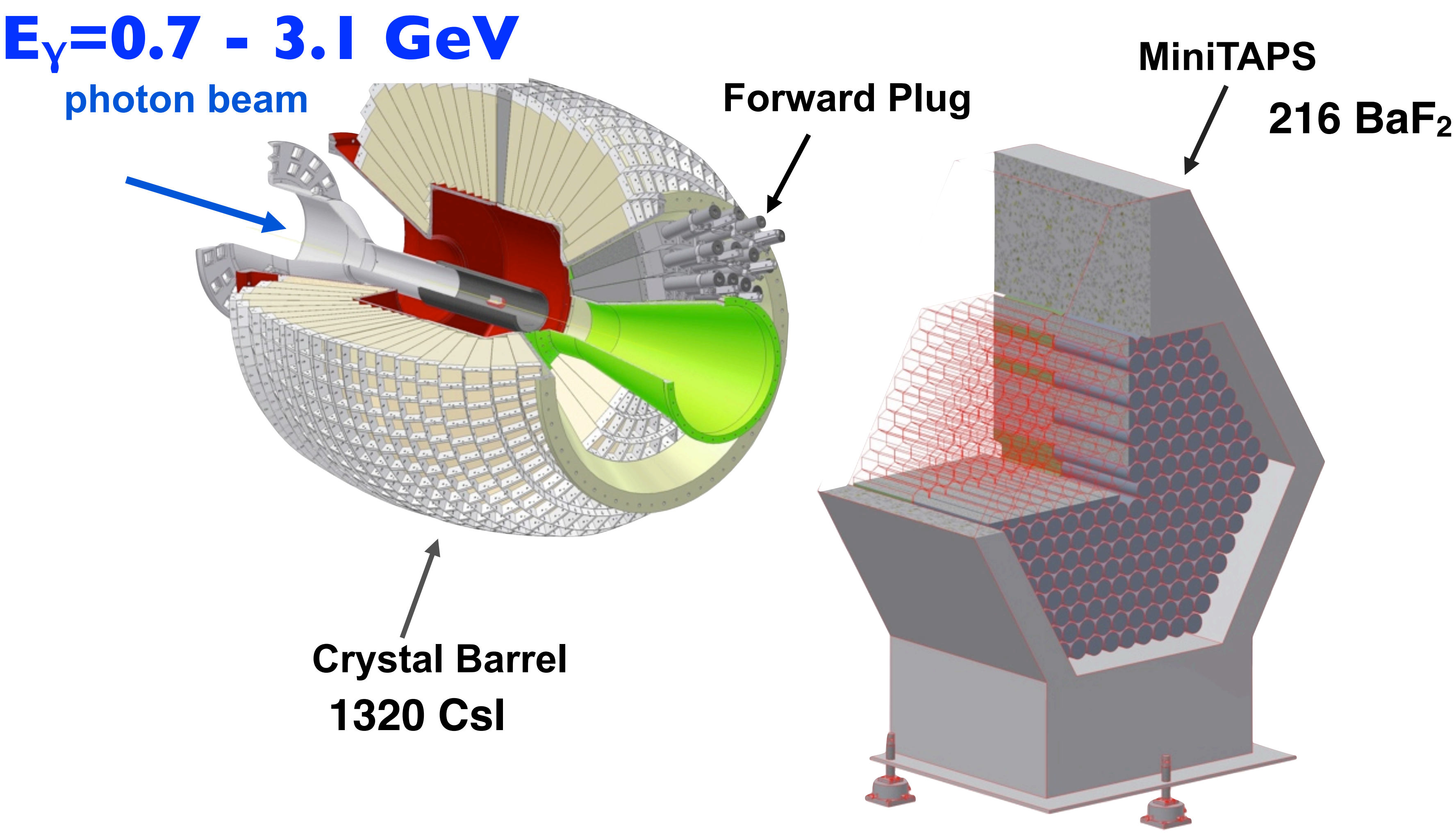
$$W(r) = -\Gamma_0/2 \cdot \frac{\rho(r)}{\rho_0}$$
$$= -\frac{1}{2} \cdot \hbar c \cdot \rho(r) \cdot \sigma_{inel} \cdot \beta$$

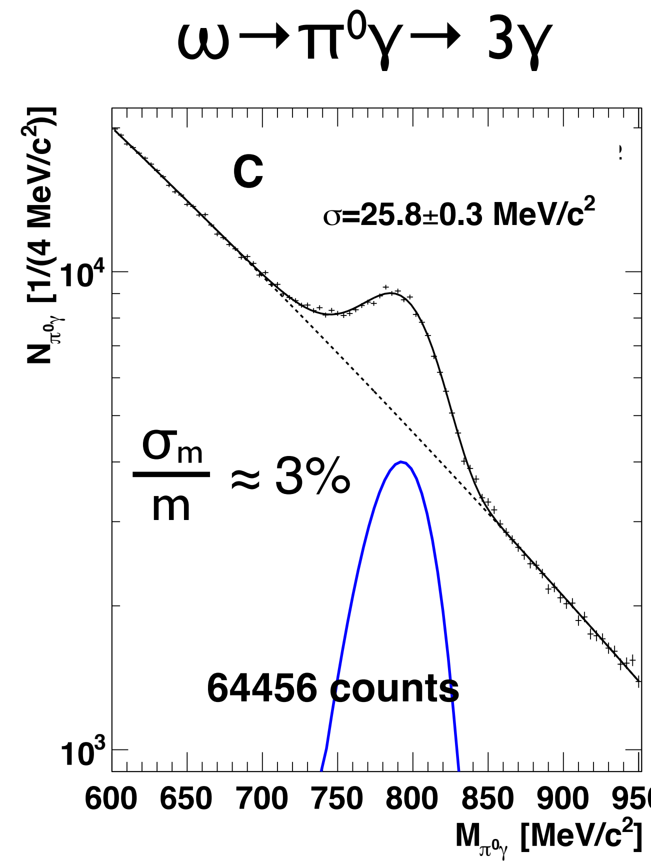
- transparency ratio measurement

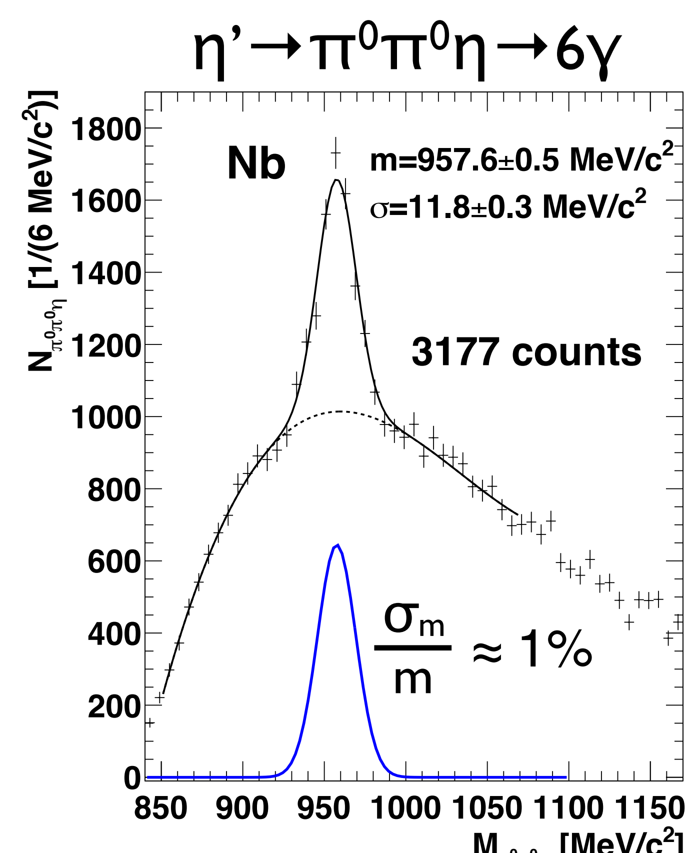
$$T_A = \frac{\sigma_{\gamma A \rightarrow \eta' X}}{A \cdot \sigma_{\gamma N \rightarrow \eta' X}}$$

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

CBELSA/TAPS experiment







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

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

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

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

The real part of the meson-nucleus optical potential

the real part of the meson-nucleus potential

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

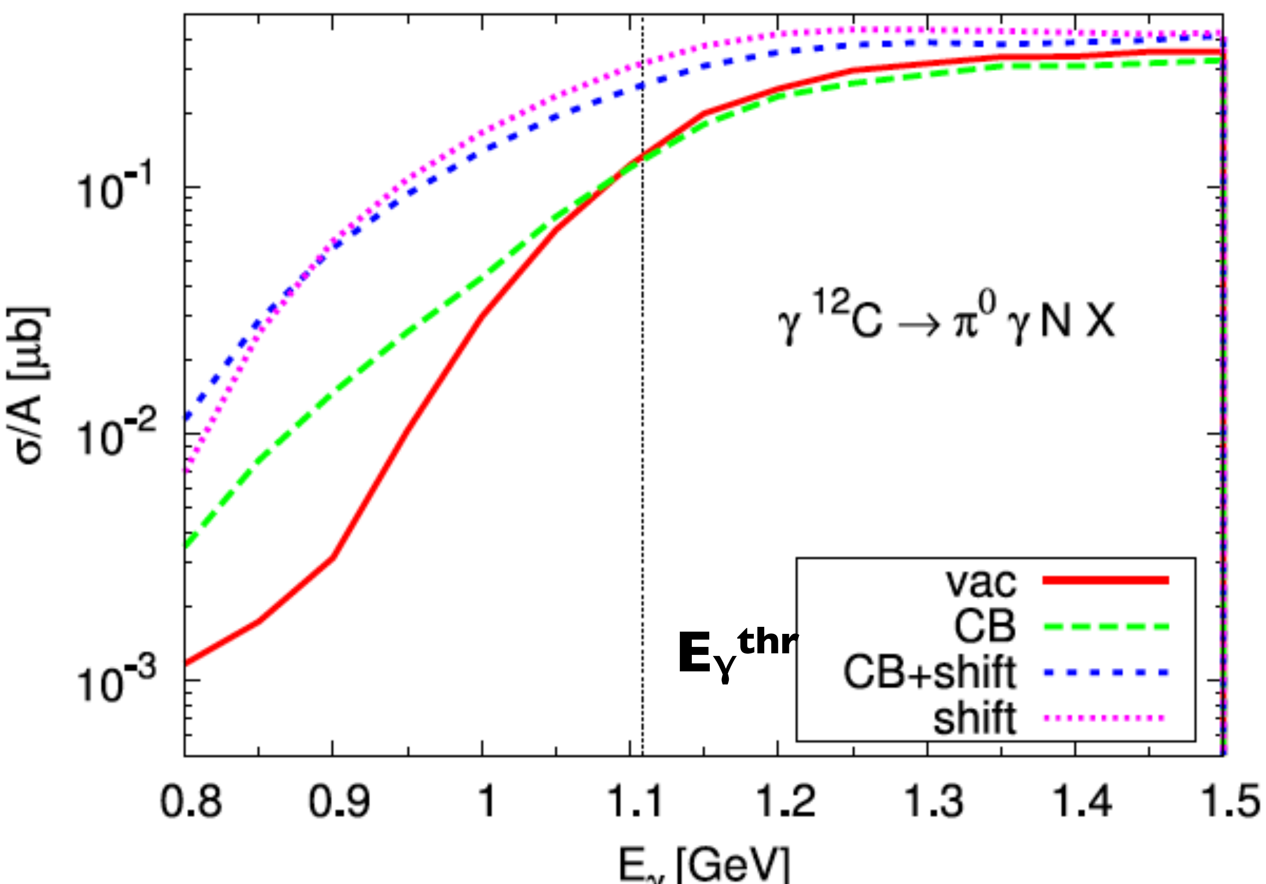
sensitive to nuclear density at production point and not at decay point

◆ 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

$\pi^0\gamma$ excitation function



the real part of the meson-nucleus potential

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

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

◆ measurement of the excitation function of the meson

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

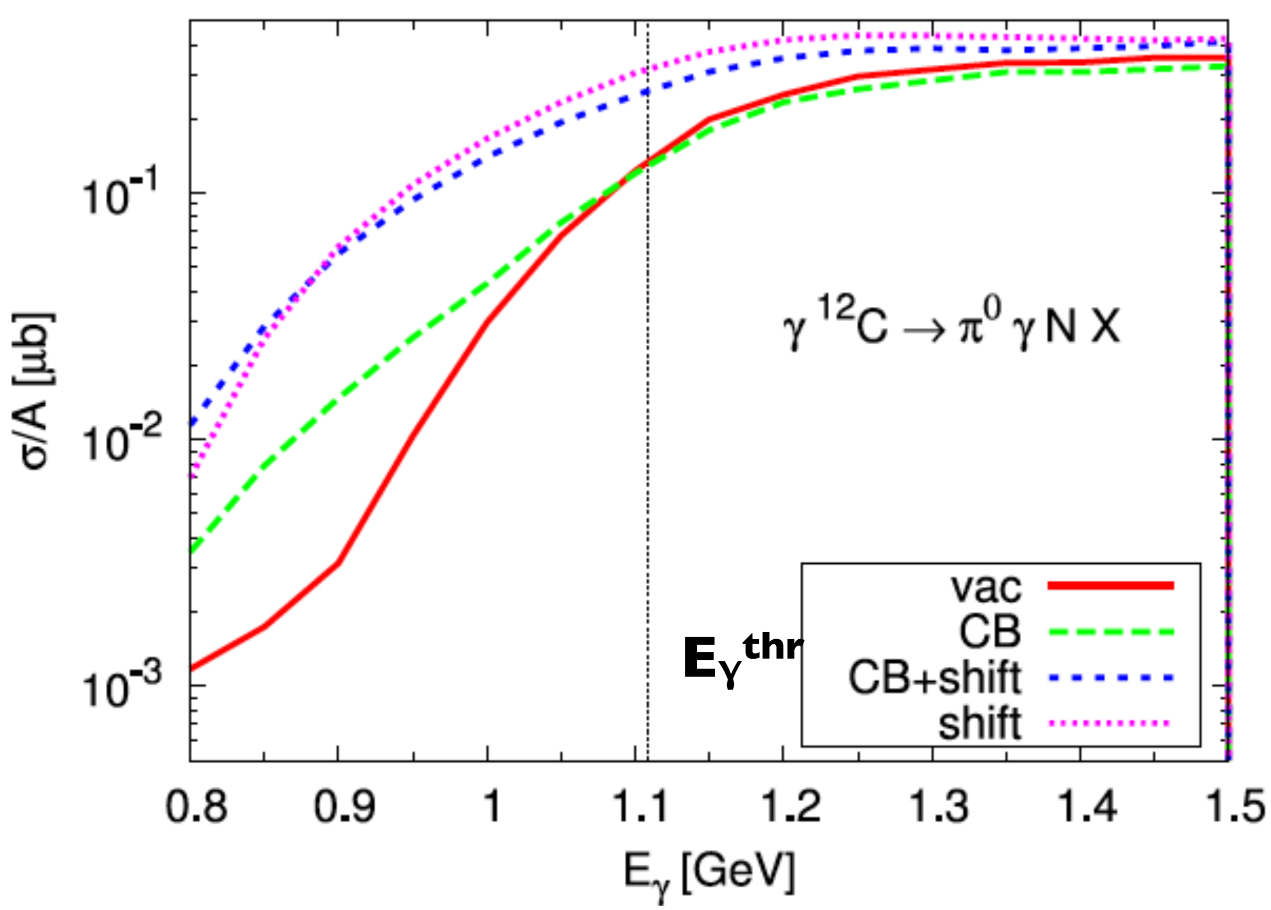
⇨ cross section enhancement

◆ momentum distribution of the meson:

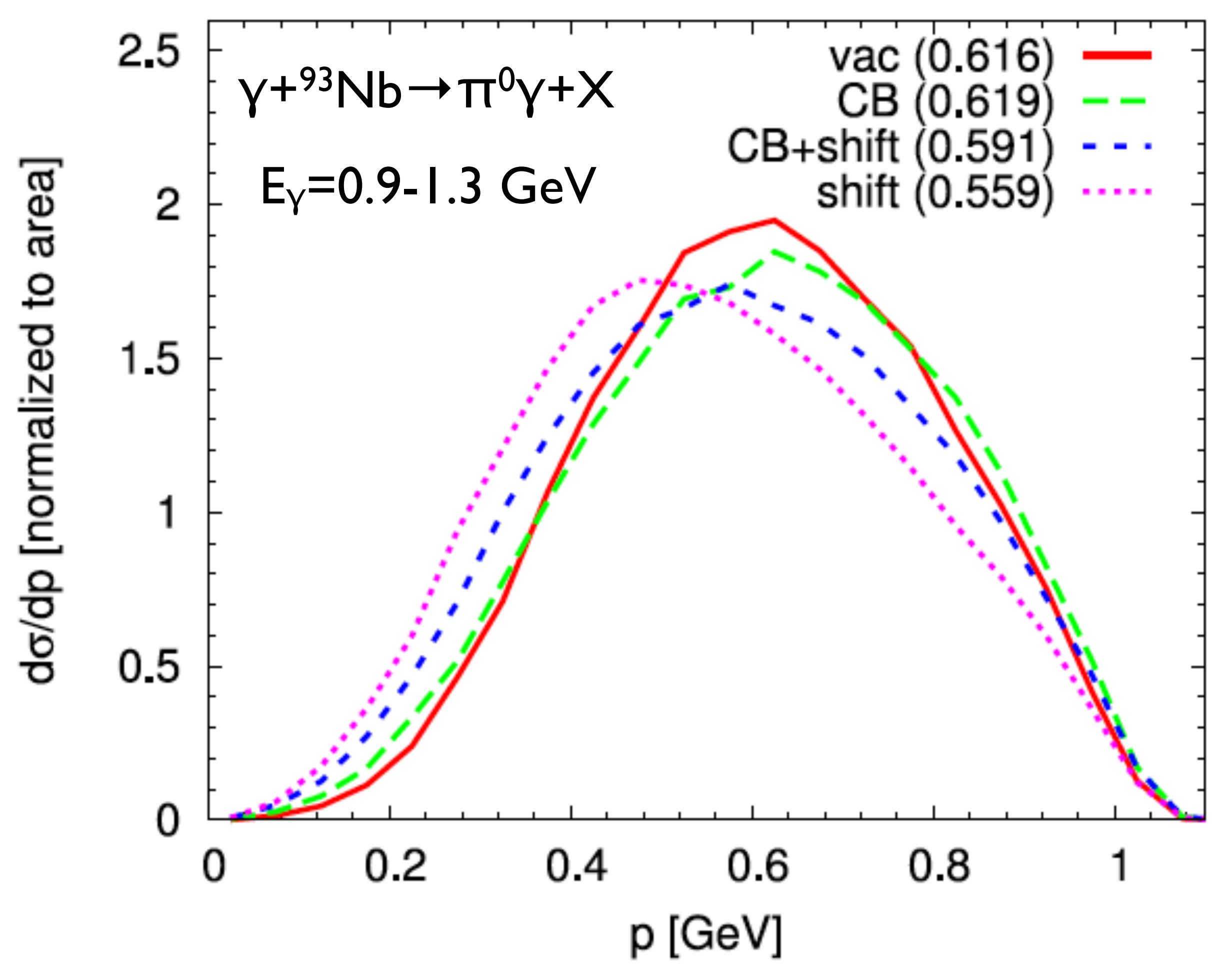
in case of dropping mass - when leaving the nucleus hadron has to become on-shell; mass generated at the expense of kinetic energy

⇨ downward shift of momentum distribution

$\pi^0\gamma$ excitation function



$\pi^0\gamma$ momentum distribution



excitation function and momentum distribution for η' photoproduction off C

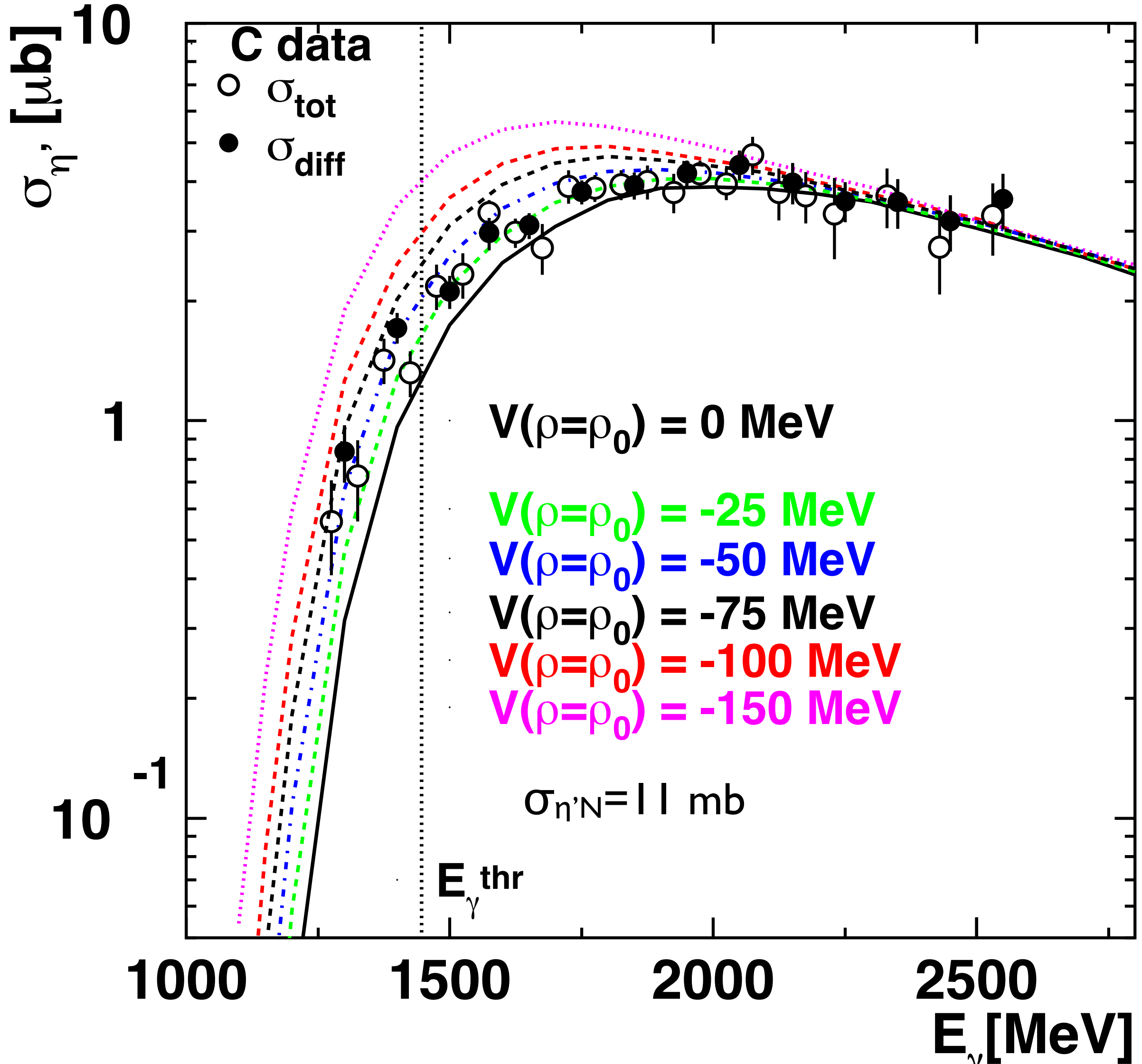
CBELSA/TAPS @ ELSA

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

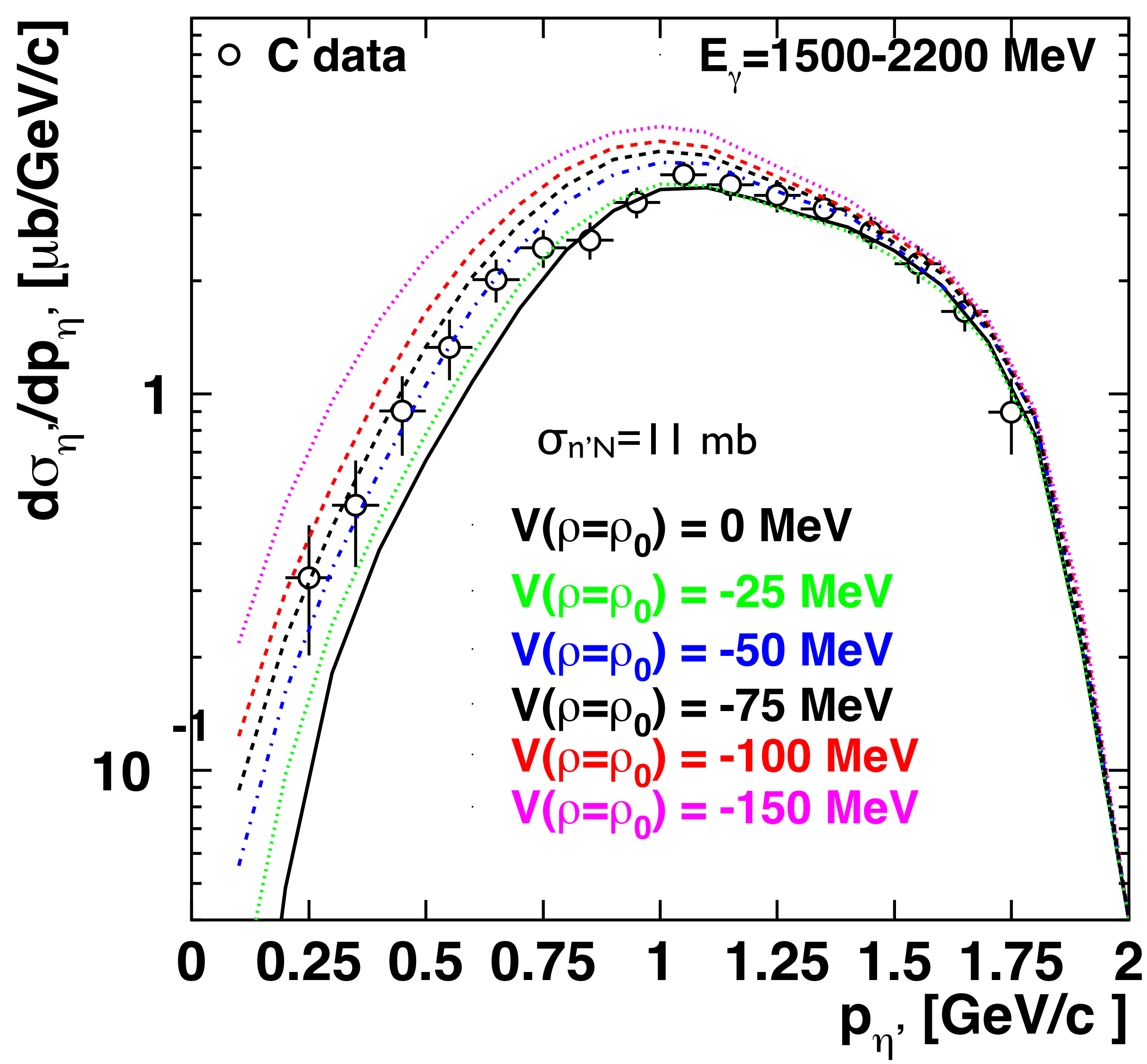
data: M. Nanova et al., PLB 727 (2013) 417

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

excitation function



momentum distribution



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

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

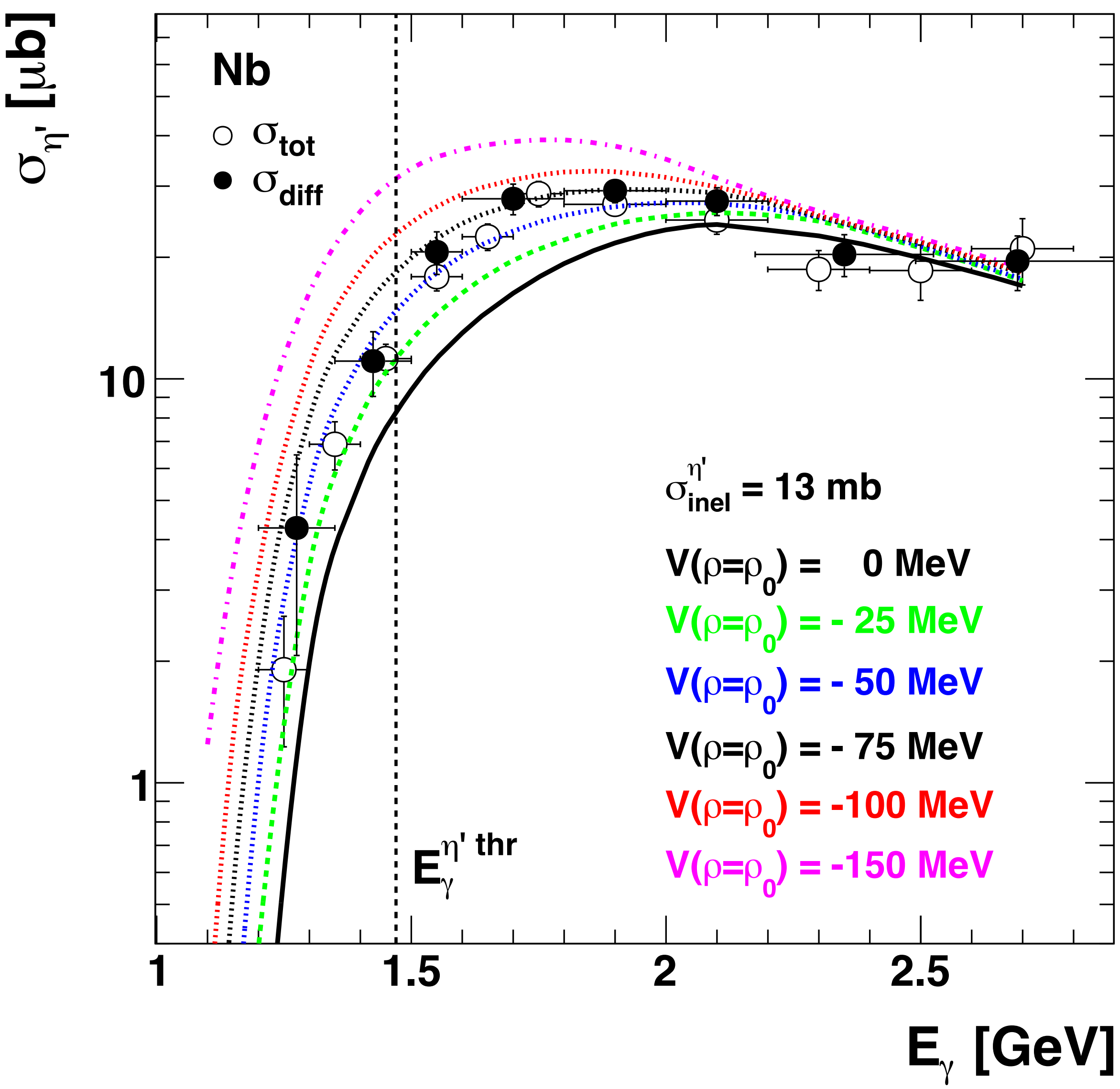
data disfavour strong mass shifts

excitation function and momentum distribution for η' photoproduction off Nb

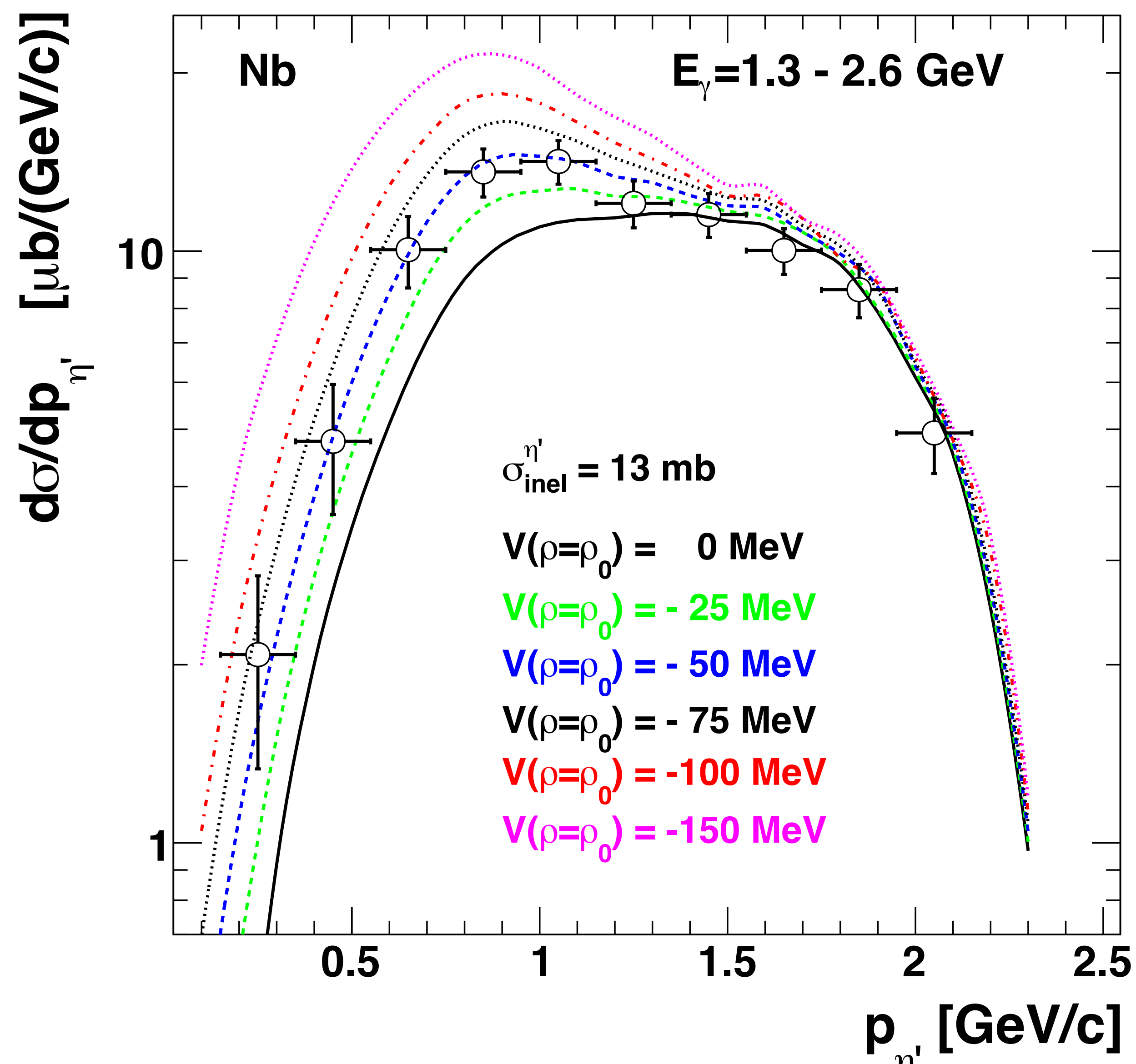
CBELSA/TAPS @ ELSA

γ Nb $\rightarrow \eta$'X M. Nanova et al., PRC 94 (2016) 025205

excitation function



momentum distribution

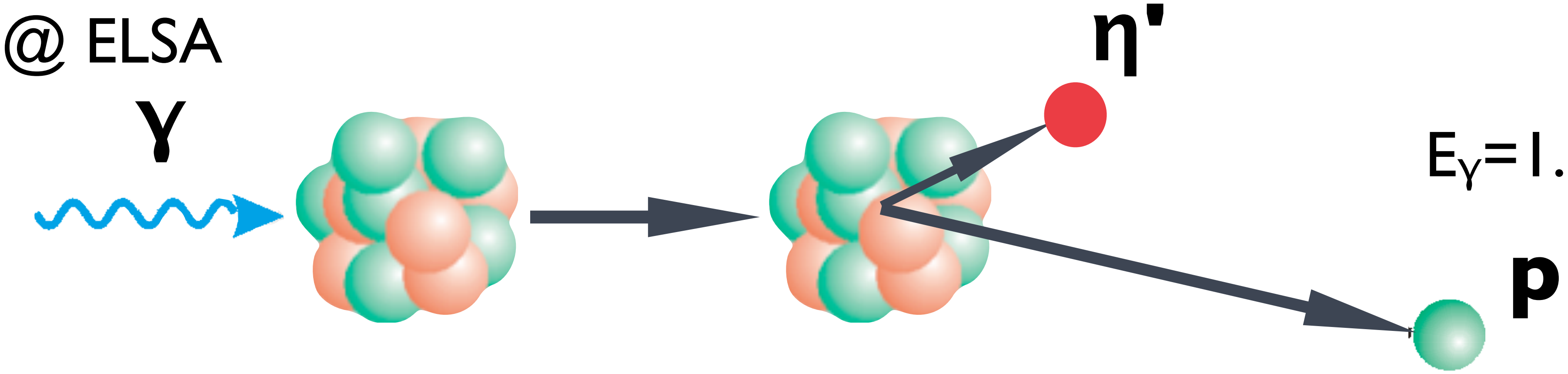


$V_{\eta'}(\rho=\rho_0) = -(40\pm12)$ MeV $V_{\eta'}(p_{\eta'}\approx 1.14$ GeV/c$;\rho=\rho_0) = -(45\pm20)$ MeV

data disfavour strong mass shifts

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

CBELSA/TAPS @ ELSA



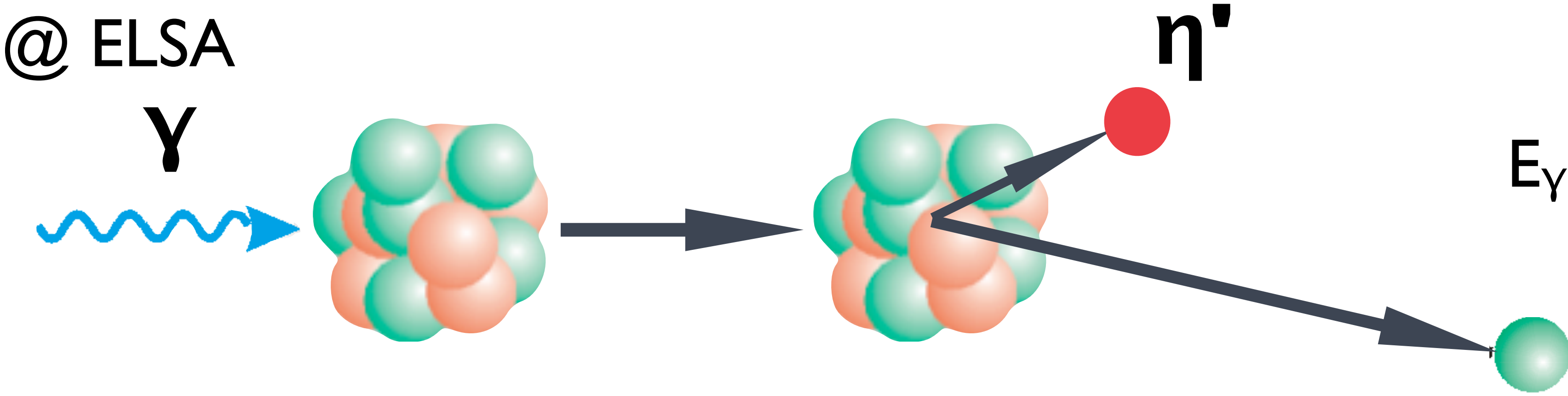
E_γ=1.3-2.6 GeV

$2^0 \leq \theta_p \leq 11^0$

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

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

CBELSA/TAPS @ ELSA



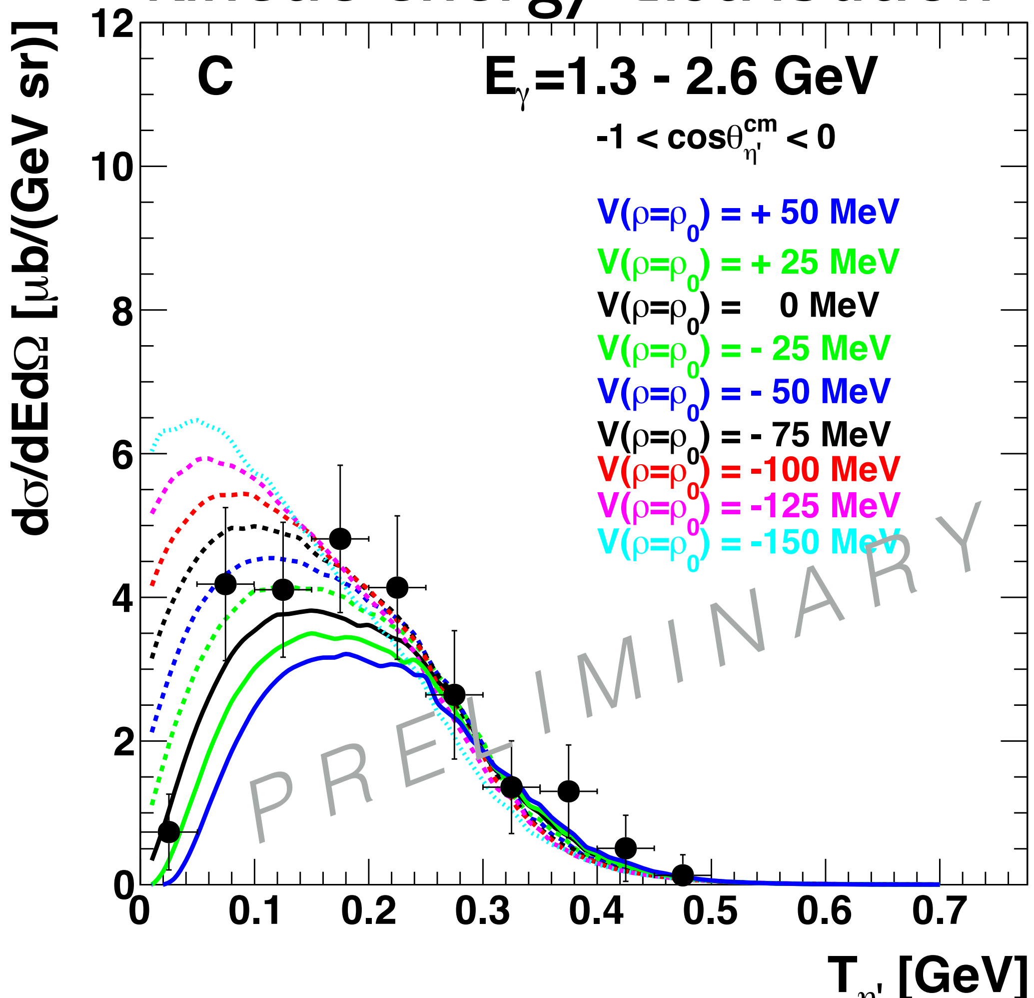
E_γ=1.3-2.6 GeV

$2^0 \leq \theta_p \leq 11^0$

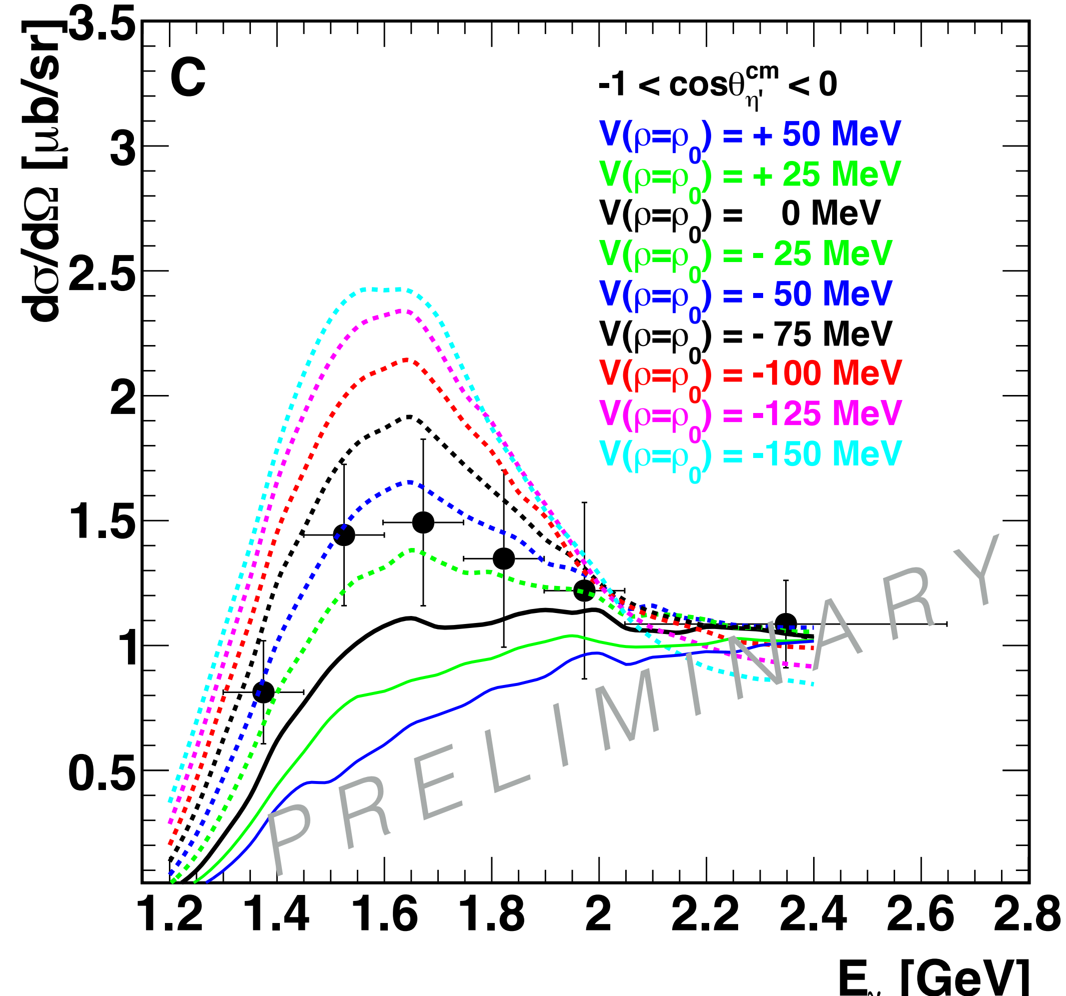
the higher the attraction the lower the kinetic energy of the η' meson

calc. by E.Ya. Paryev, JPG 43 (2016) 015106

kinetic energy distribution

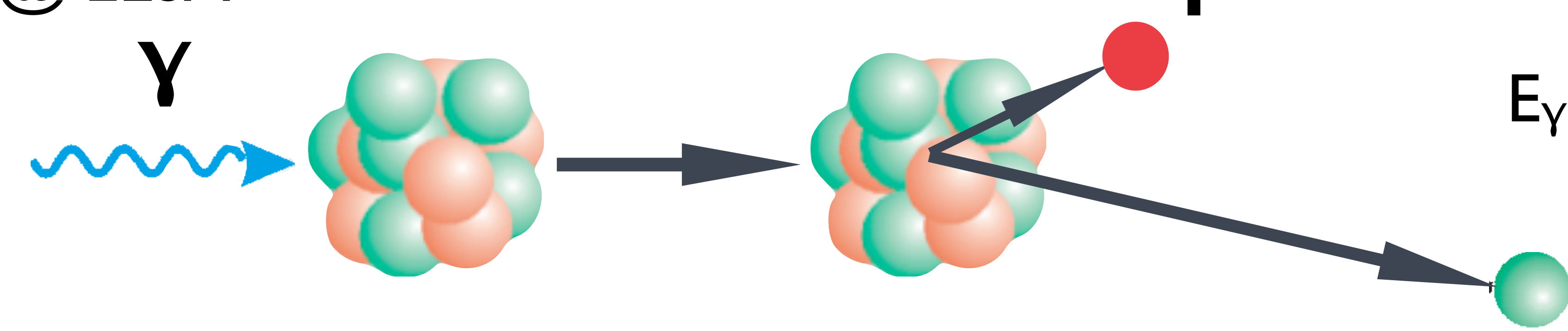


excitation function



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

CBELSA/TAPS @ ELSA



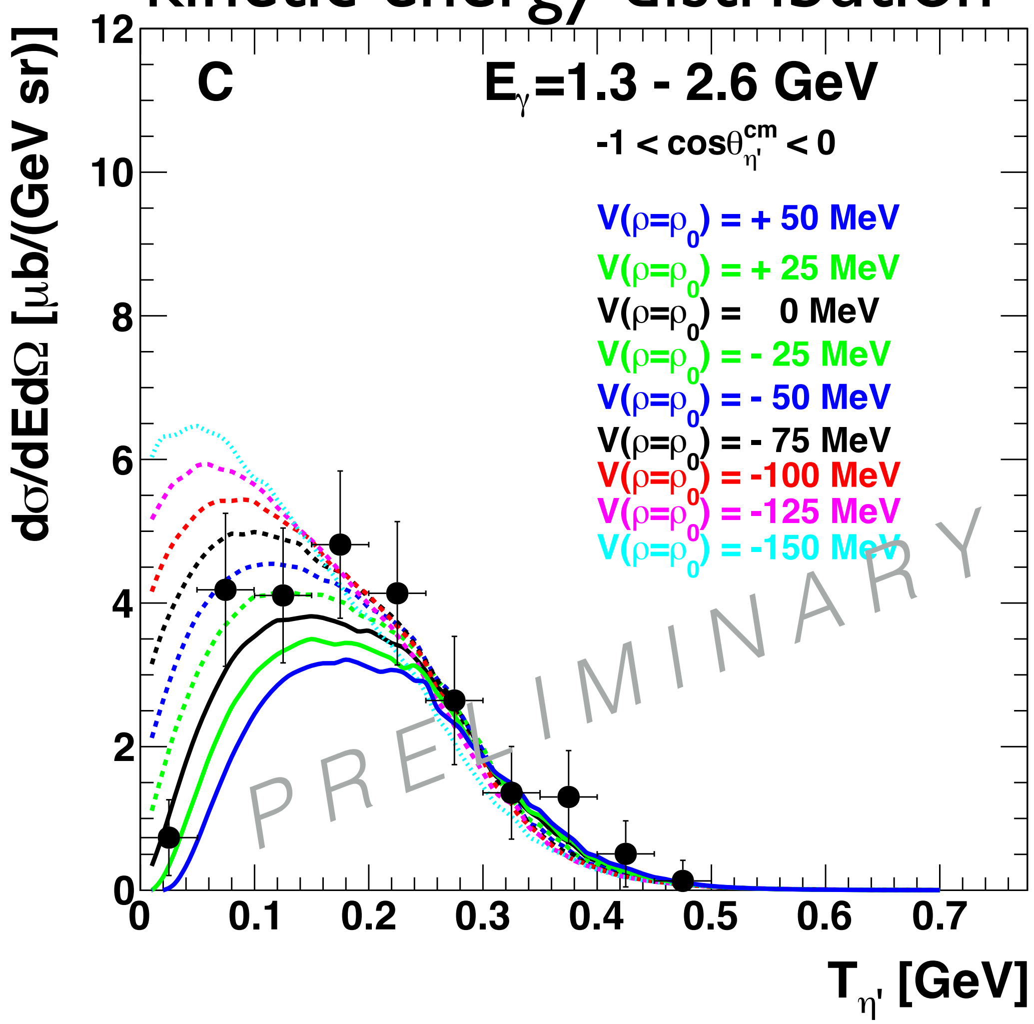
E_γ=1.3-2.6 GeV

$2^0 \leq \theta_p \leq 11^0$

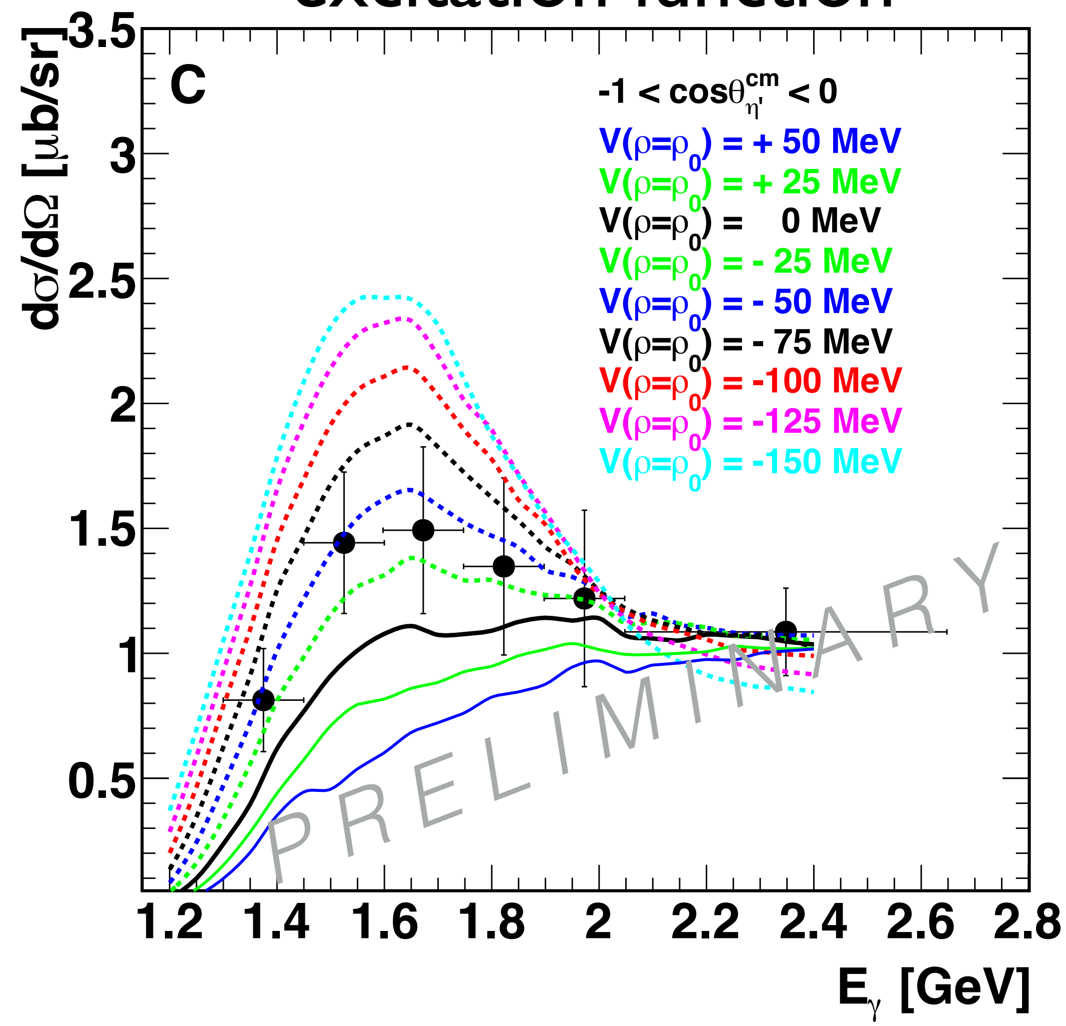
the higher the attraction the lower the kinetic energy of the η' meson

calc. by E. Ya. Paryev, JPG 43 (2016) 015106

kinetic energy distribution



excitation function



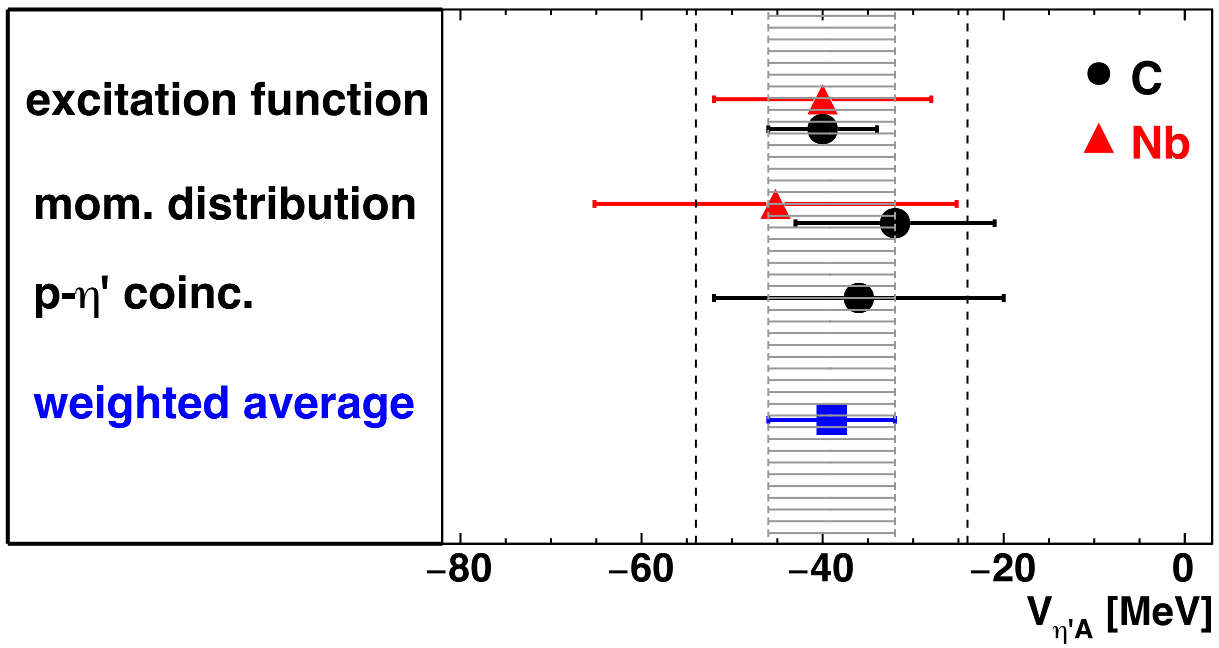
$V_{\eta'}(p_{\eta'} \approx 0.6\ \mathrm{GeV}/c;\ \rho=\rho_0) = -(36 \pm 16)$ MeV

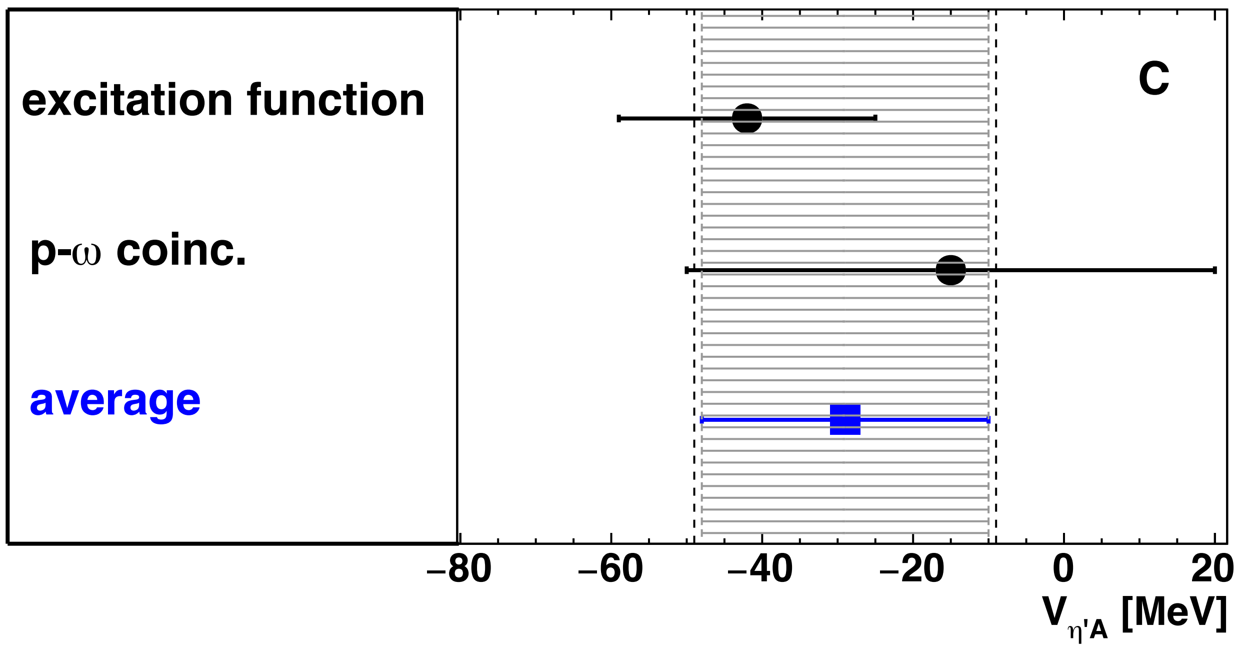
compilation of results for the real part of the η'- and ω-nucleus optical potential

η'

M. N. and V. Metag, EPJ Web of conf. 130 (2016) 02007

ω





$V_{\eta' A}(\rho=\rho_0) =$
$-(39 \pm 7(stat) \pm 15(syst))$ MeV

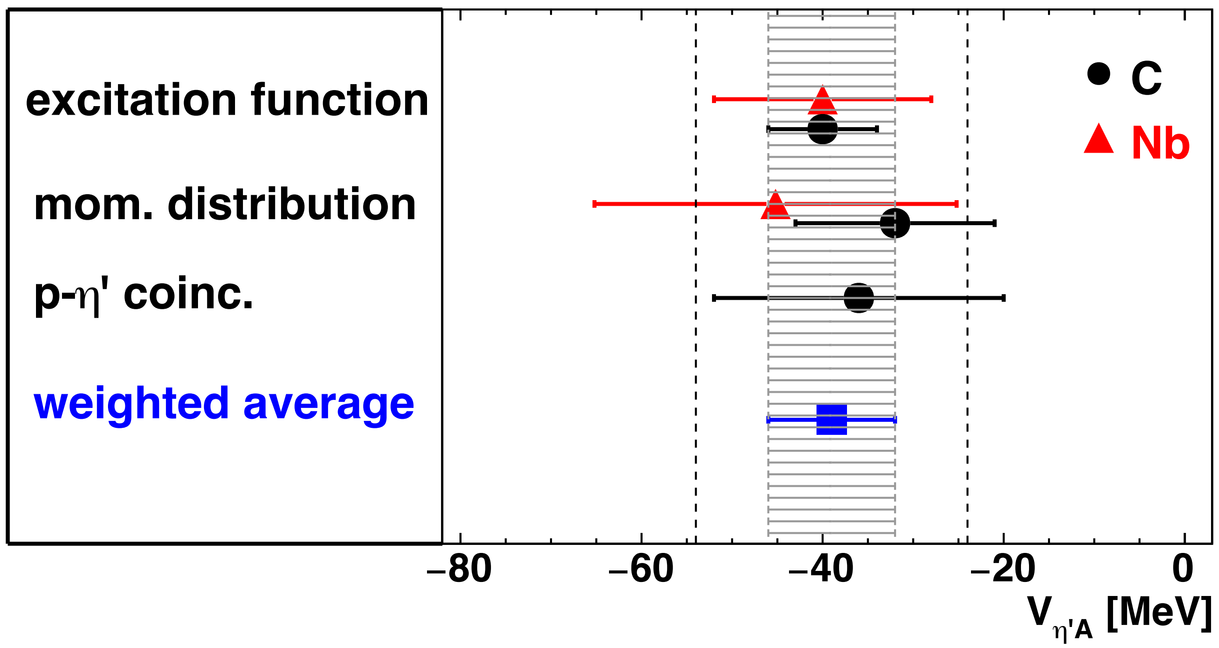
$V_{\omega A}(\rho=\rho_0) =$
$-(29 \pm 19(stat) \pm 20(syst))$ MeV

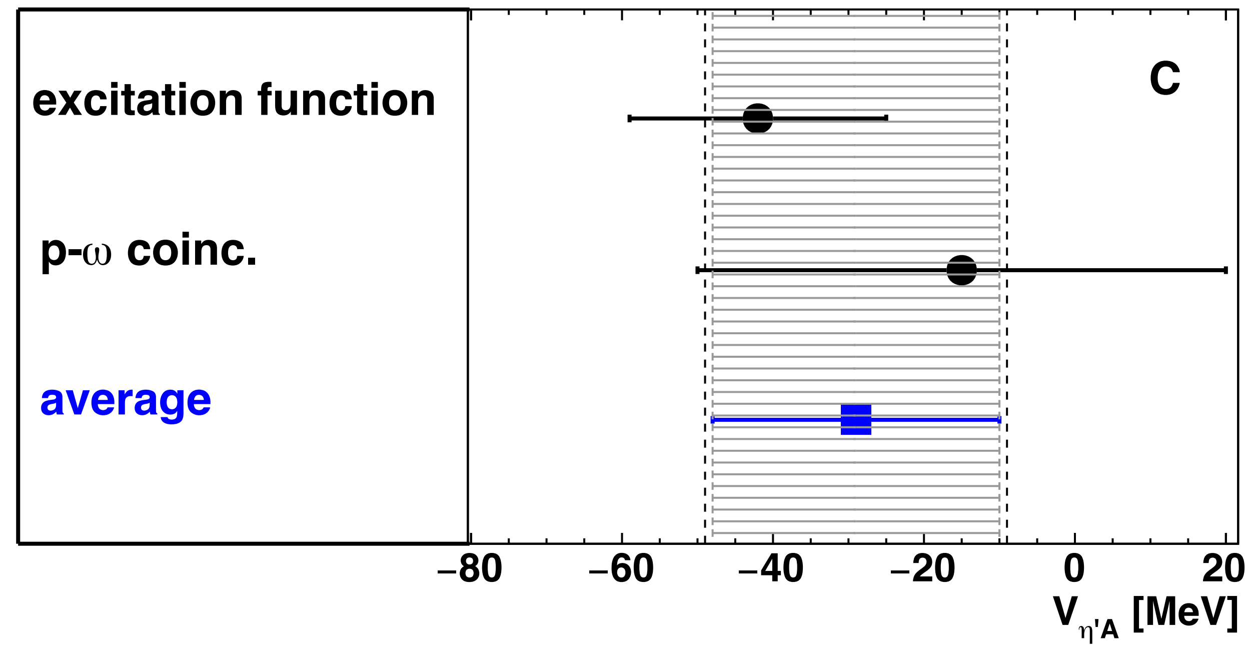
compilation of results for the real part of the η'- and ω-nucleus optical potential

η'

M. N. and V. Metag, EPJ Web of conf. 130 (2016) 02007

ω





$V_{\eta' A}(\rho=\rho_0)$ = −(39±7(stat)±15(syst)) MeV

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

for the η': in-medium mass drop of $\Delta m\ (\rho=\rho_0) \approx -\ 40$ MeV observed
in good agreement with QMC model predictions (S. Bass et al. , PLB 634 (2006) 368)
ω- and η'-nucleus interaction is attractive
formation of meson-nucleus bound states?

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

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

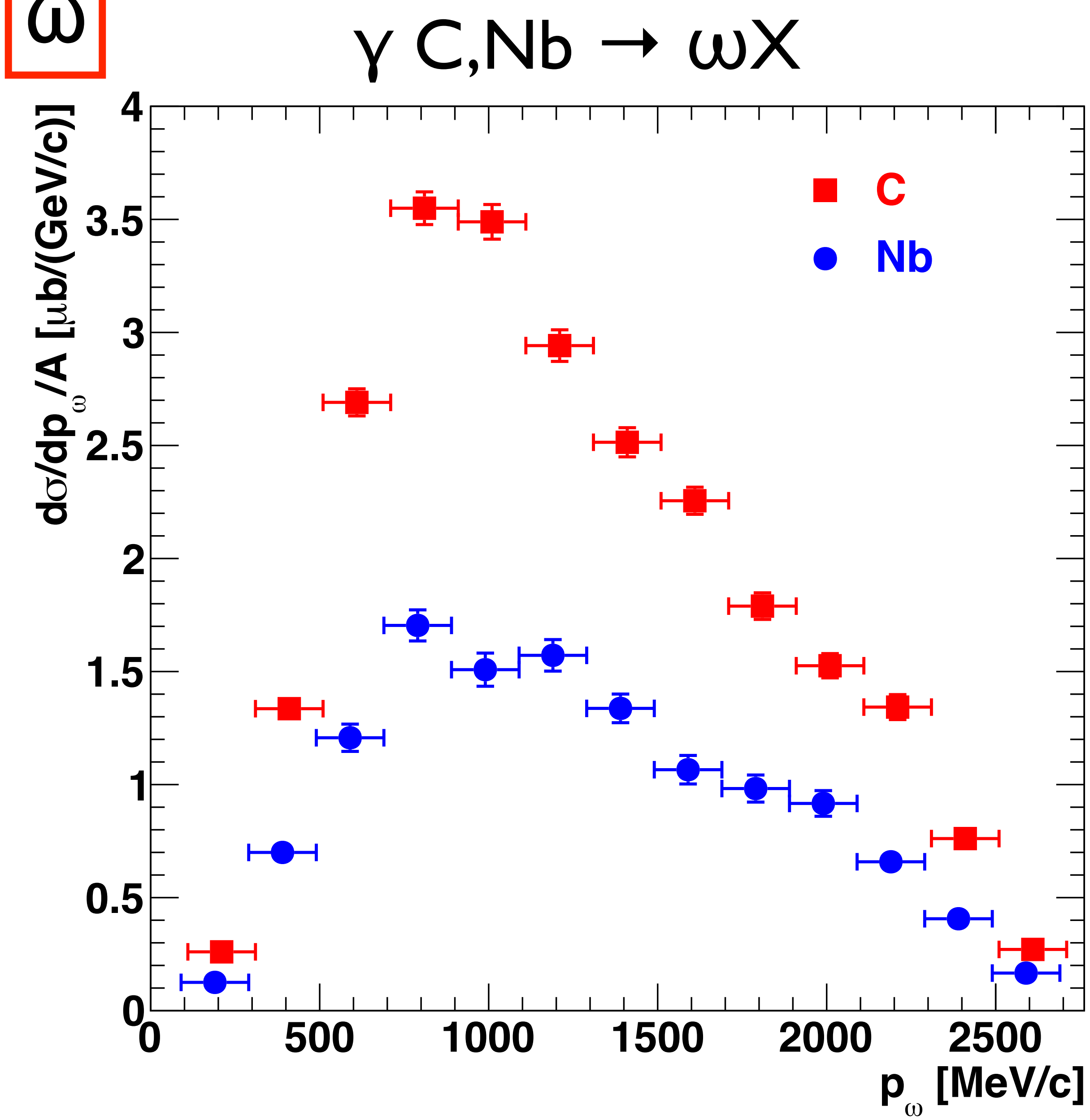
$$T_A = \frac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}}$$

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

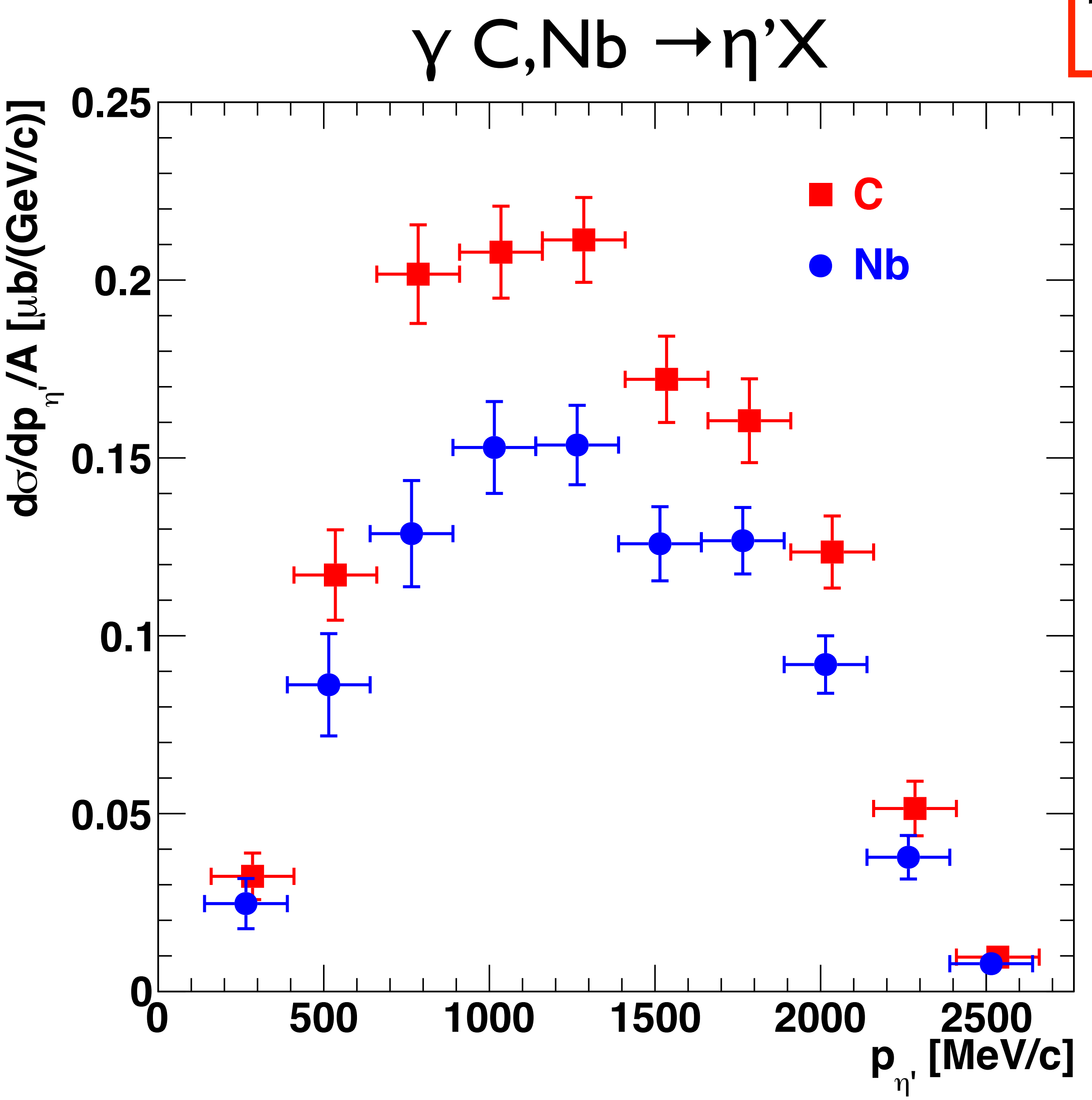
$$T_A = \frac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}}$$

E_γ = 1.2- 2.9 GeV

ω



η'



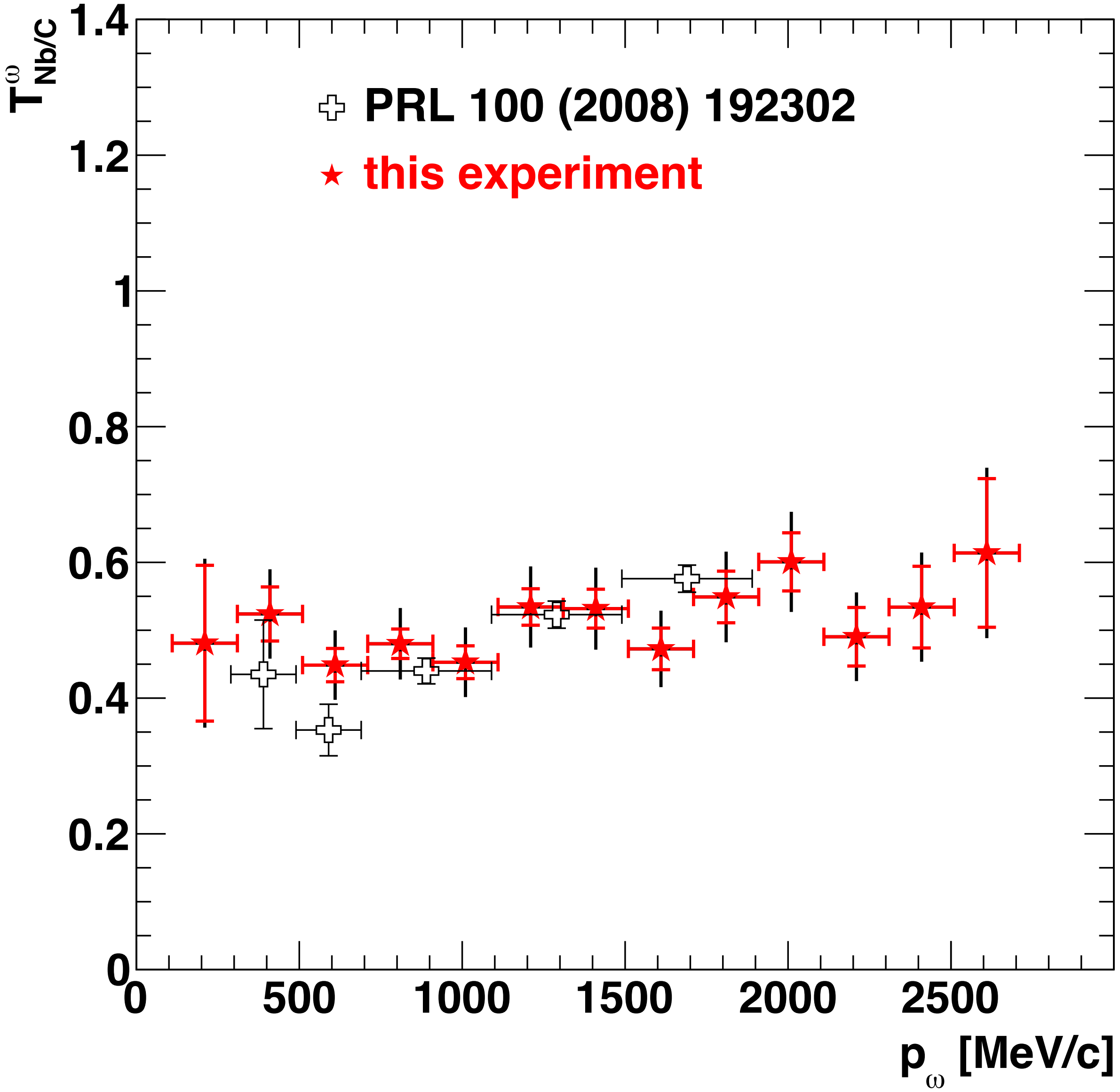
momentum differential cross sections ⇒ $T^{m}_{Nb/C}(p_m) = \dfrac{12 \cdot \sigma_{\gamma Nb \to mX}(p_m)}{93 \cdot \sigma_{\gamma C \to mX}(p_m)}$

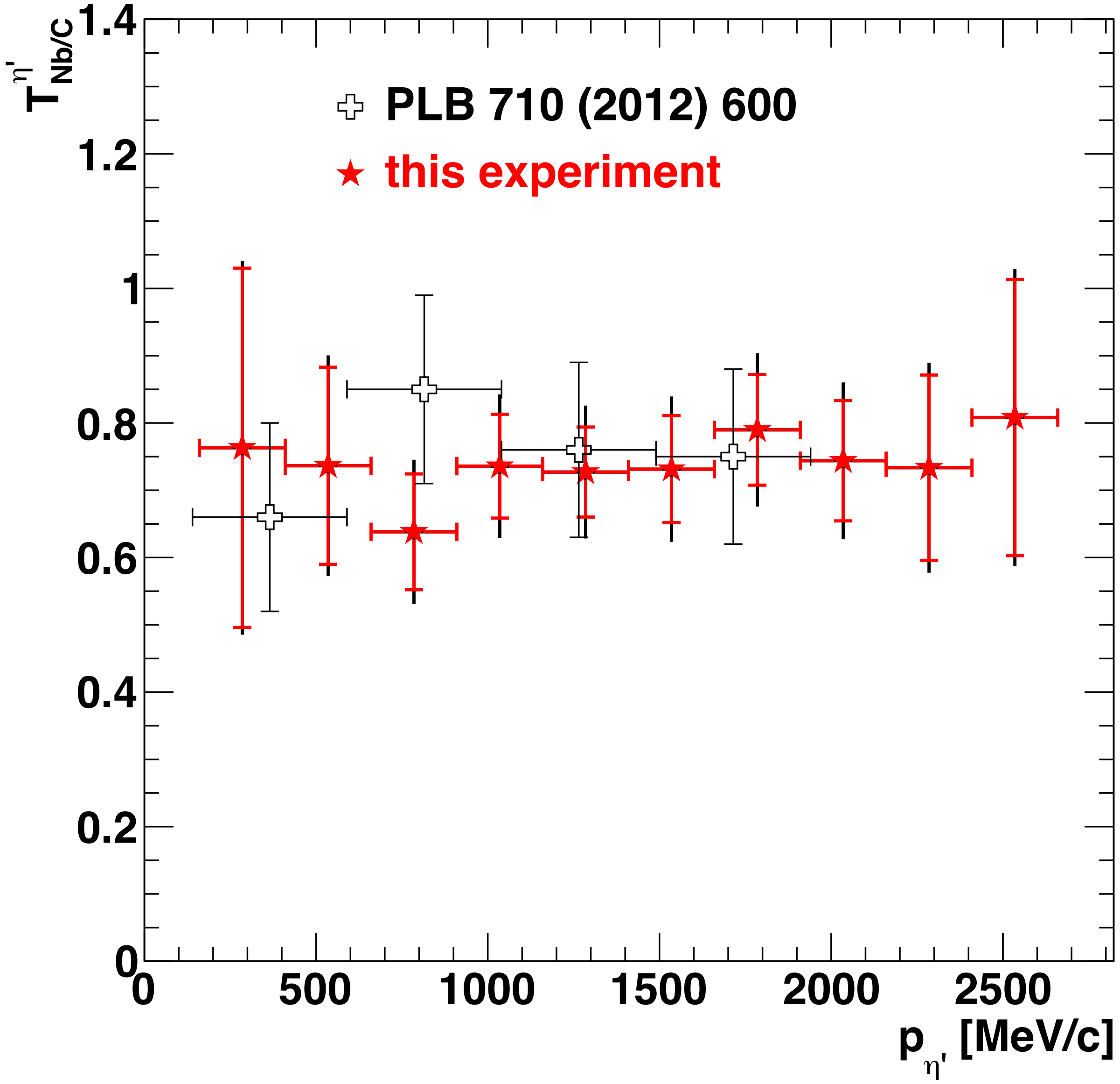
momentum dependence of transparency ratio for ω, η’

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

ω

η’





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

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

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

imaginary part of the potential for ω, η'

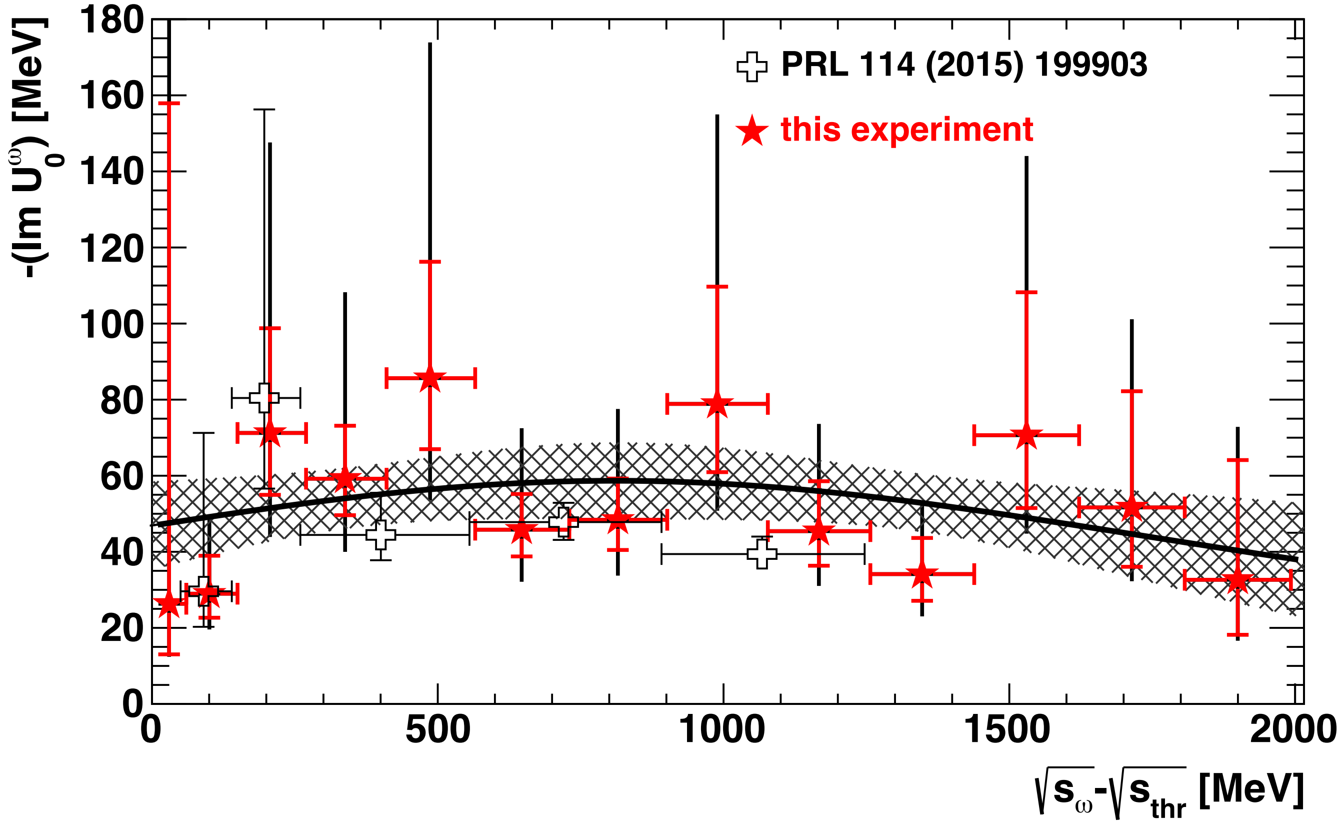
Glauber model: high energy Eikonal approximation

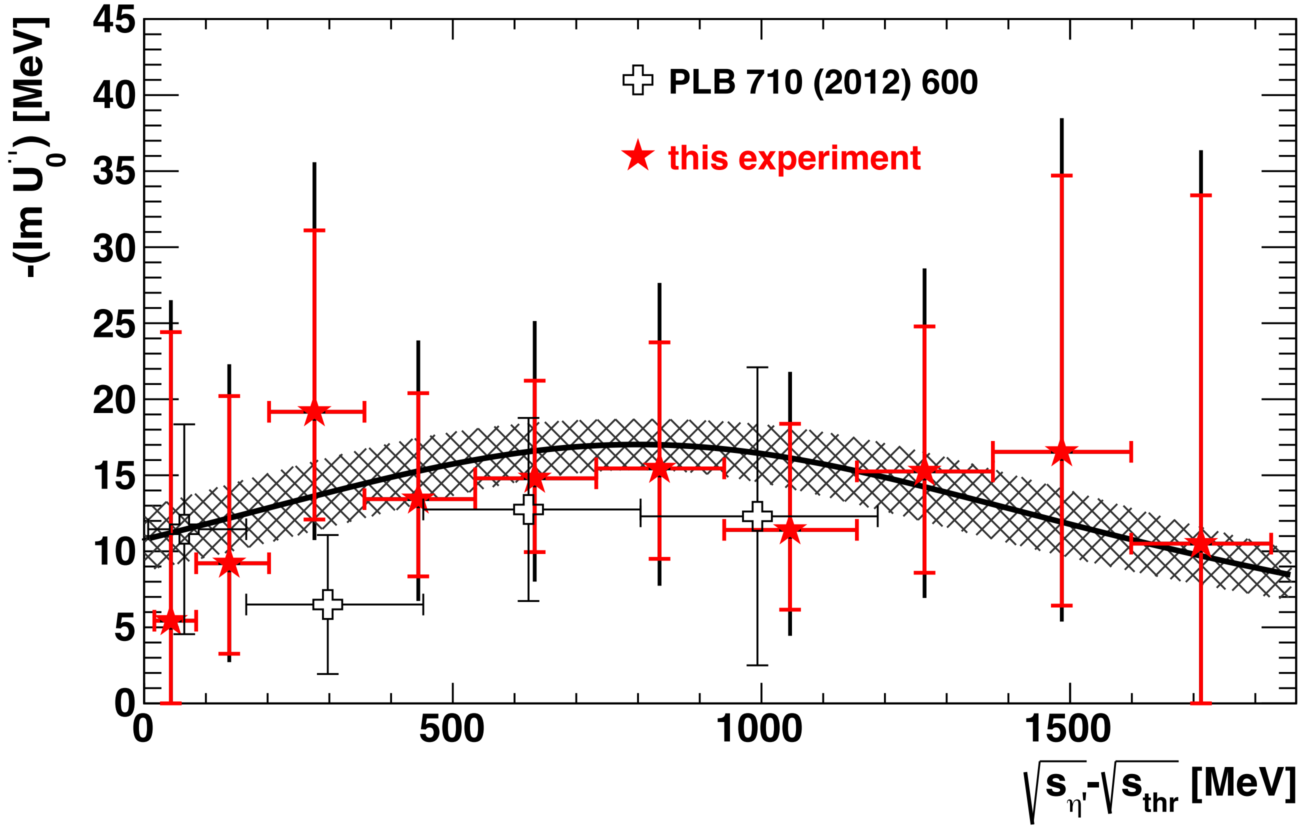
$$T^{m}_{Nb/C}\,(p_m) \Rightarrow \Gamma^{m}_{0}(\rho=\rho_0)\ (p_m) = -\,2\ \mathrm{Im}\ U^{m}_{0}(p_m)$$

ω

η'

S. Friedrich et al., EPJA 52 (2016) 297





- extrapolation to production threshold:

$$\mathrm{Im}\ U^{\omega}_{0}(\rho=\rho_0, p_\omega=0) = -(48\pm12)\ \mathrm{MeV} \qquad \mathrm{Im}\ U^{\eta'}_{0}(\rho=\rho_0, p_{\eta'}=0) = -(13\pm3)\ \mathrm{MeV}$$

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

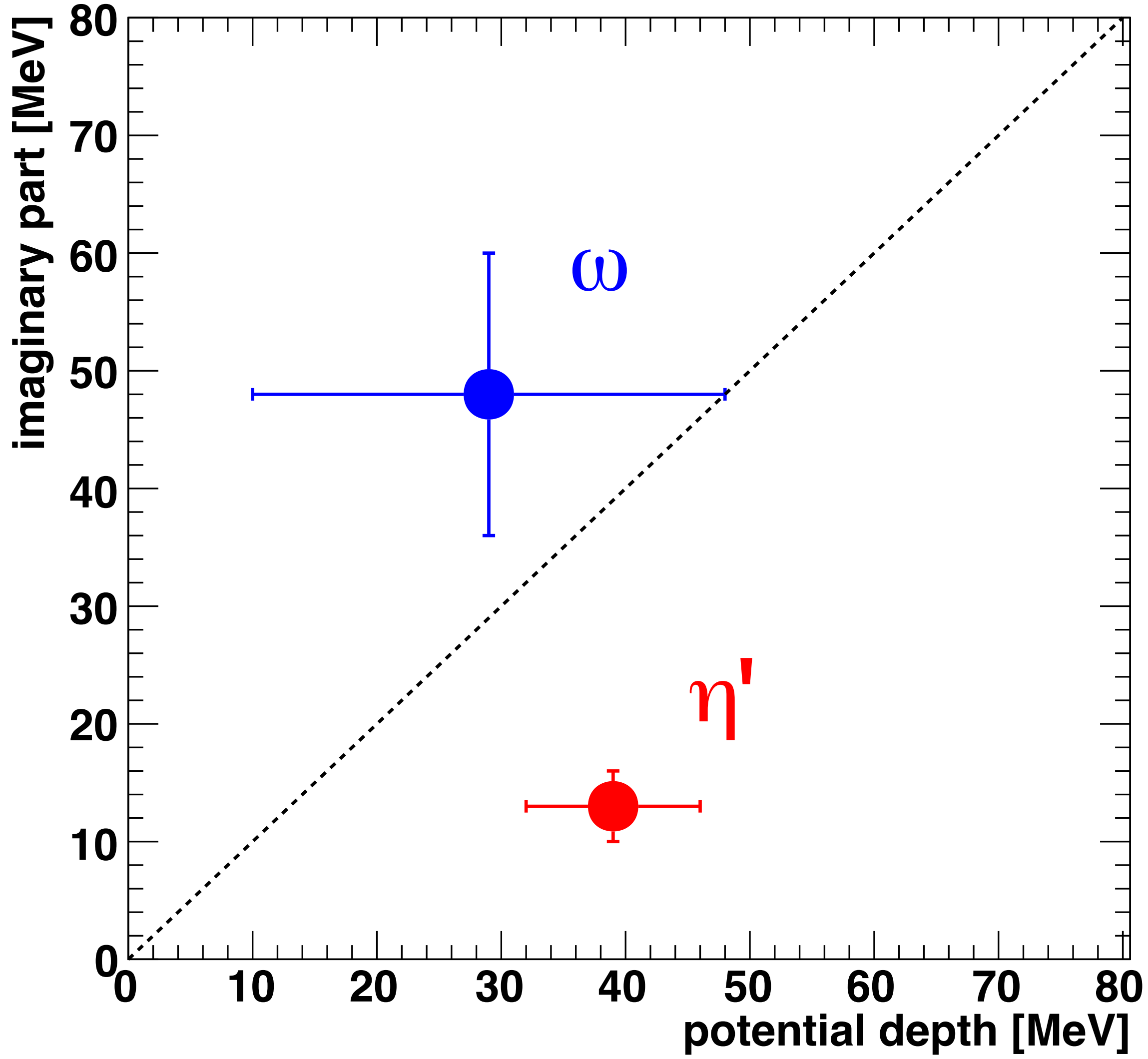
$\boxed{\omega}$ $\boxed{\eta'}$

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

$-((29\pm19(stat)\pm20(syst) + i(48\pm12))$ MeV

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

$-((39\pm7(stat)\pm15(syst) + i(13\pm3))$ MeV



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

ω

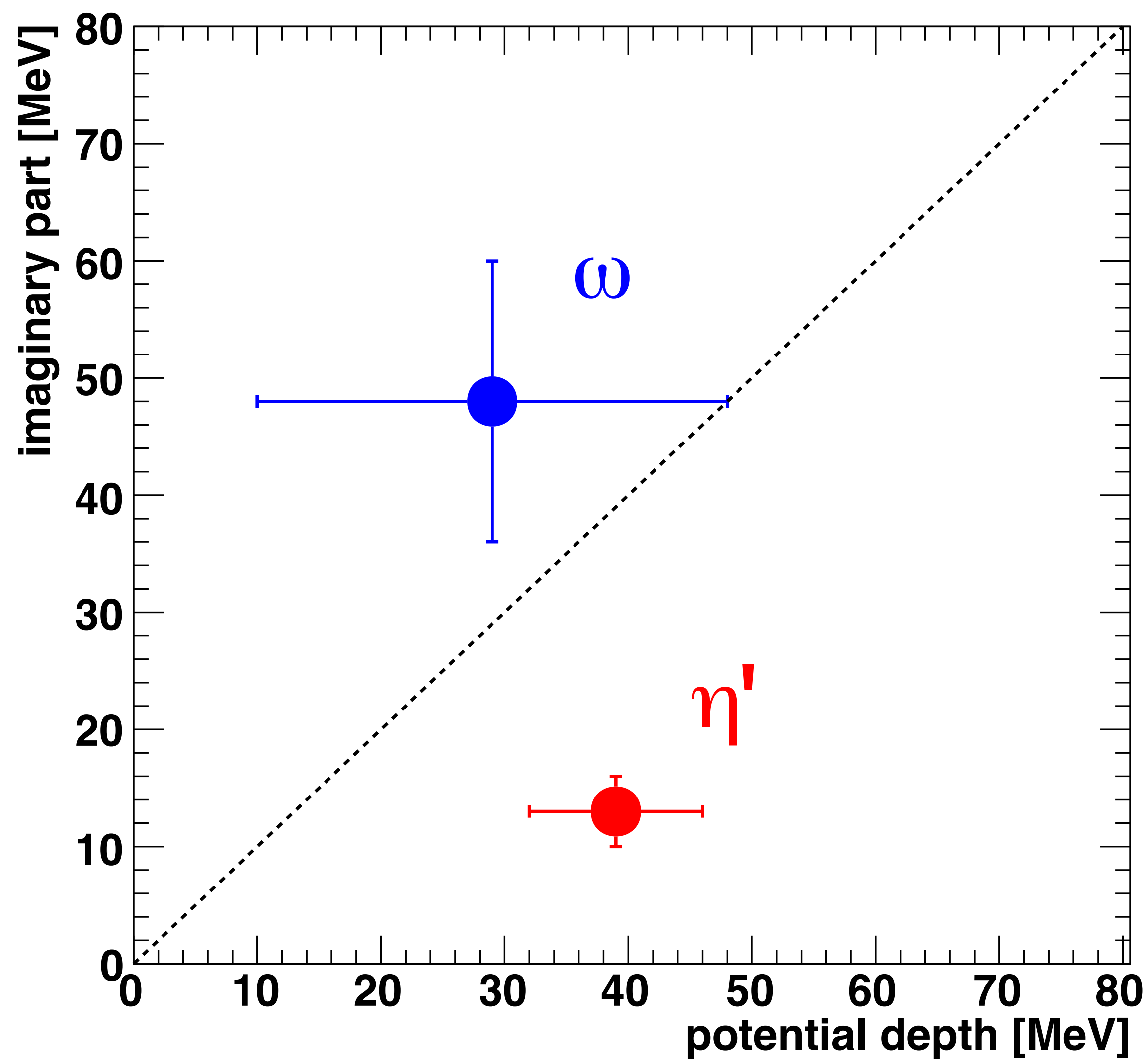
$U_{\omega A}(\rho=\rho_0)=$

$-((29\pm19(stat)\pm20(syst) + i(48\pm12))$ MeV

η'

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

$-((39\pm7(stat)\pm15(syst) + i(13\pm3))$ MeV



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

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

ω

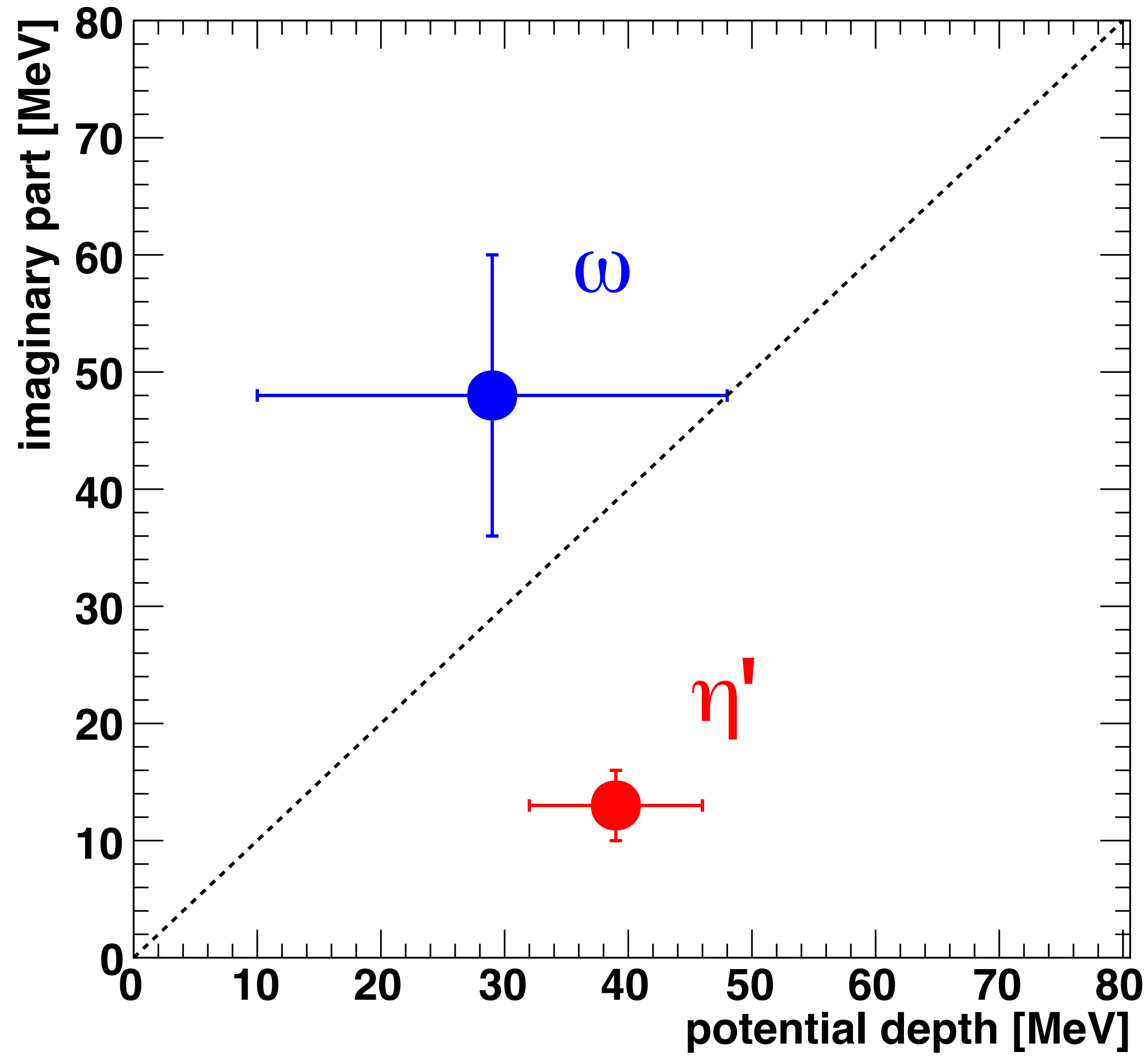
$U_{\omega A}(\rho=\rho_0)=$

$-((29\pm19(\text{stat})\pm20(\text{syst}) + i(48\pm12))$ MeV

η'

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

$-((39\pm7(\text{stat})\pm15(\text{syst}) + i(13\pm3))$ 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

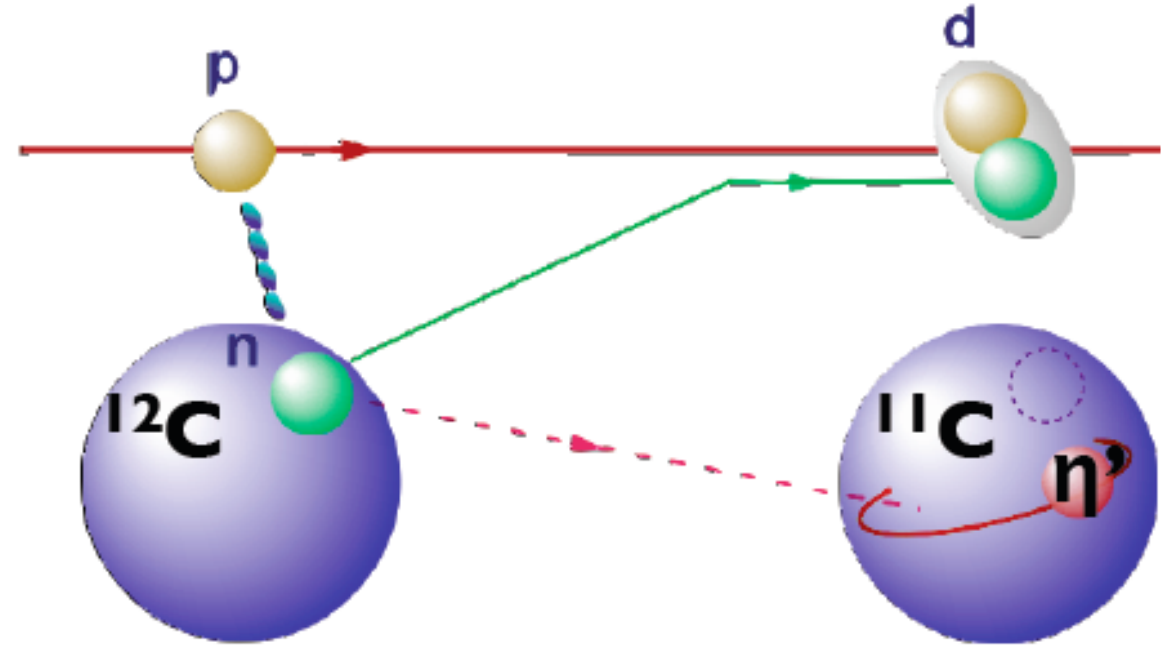
search for η'-mesic states in hadronic reactions

FRS@GSI: PRIME

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

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

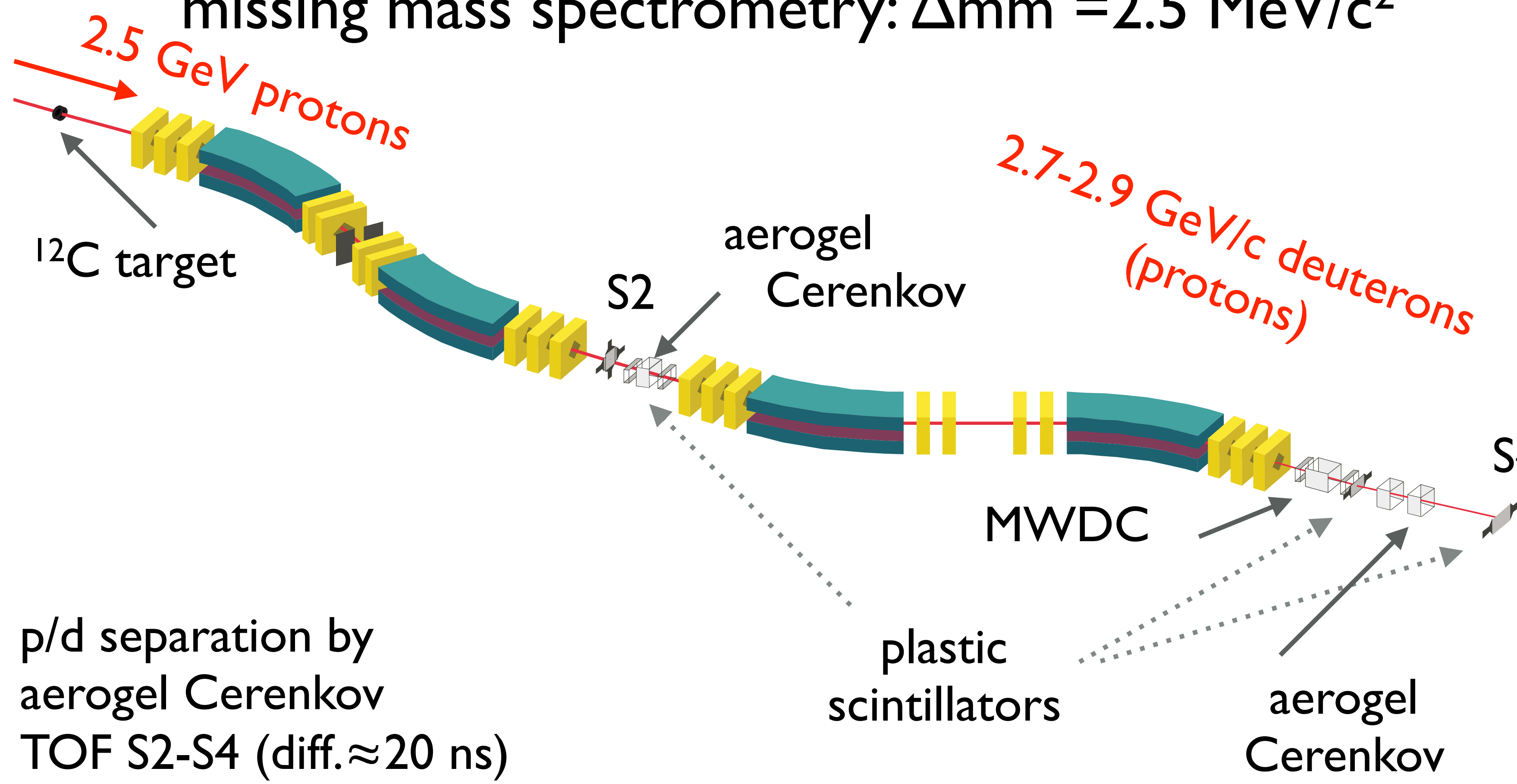
H. Nagahiro et al., PRC 87 (2013) 045201



η' × ^{11}C mesic nuclei

particle identification
by time-of-flight

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

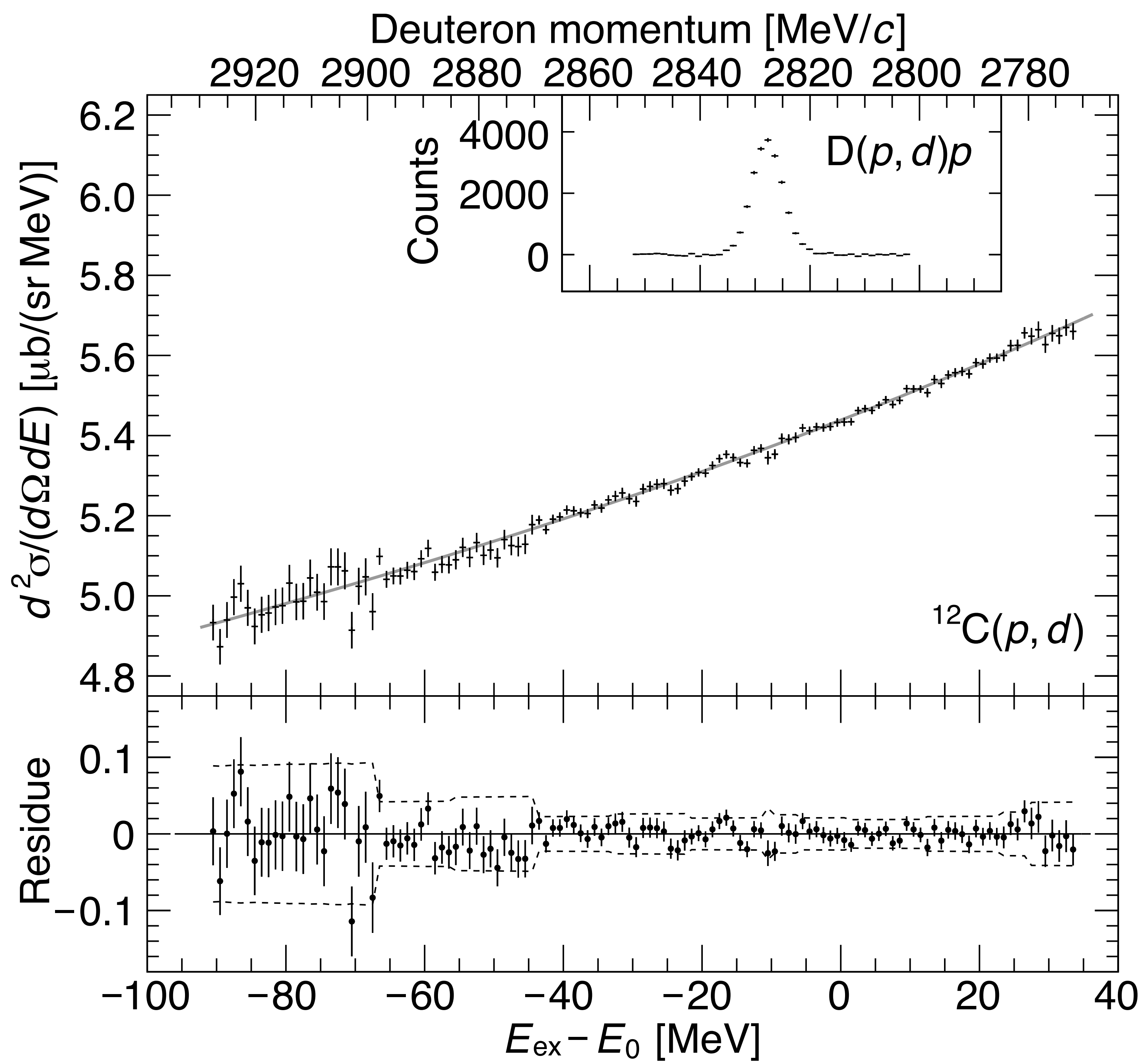


p/d separation by
aerogel Cerenkov
TOF S2-S4 (diff.≈20 ns)

FRS@GSI: PRiME

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

Y. K. Tanaka et al.,
PRL 117 (2016) 202501



no structure in
bound state region
observed
deep η’-nucleus potentials
|V|≥100 MeV excluded!

search for η’-mesic states in hadronic reactions

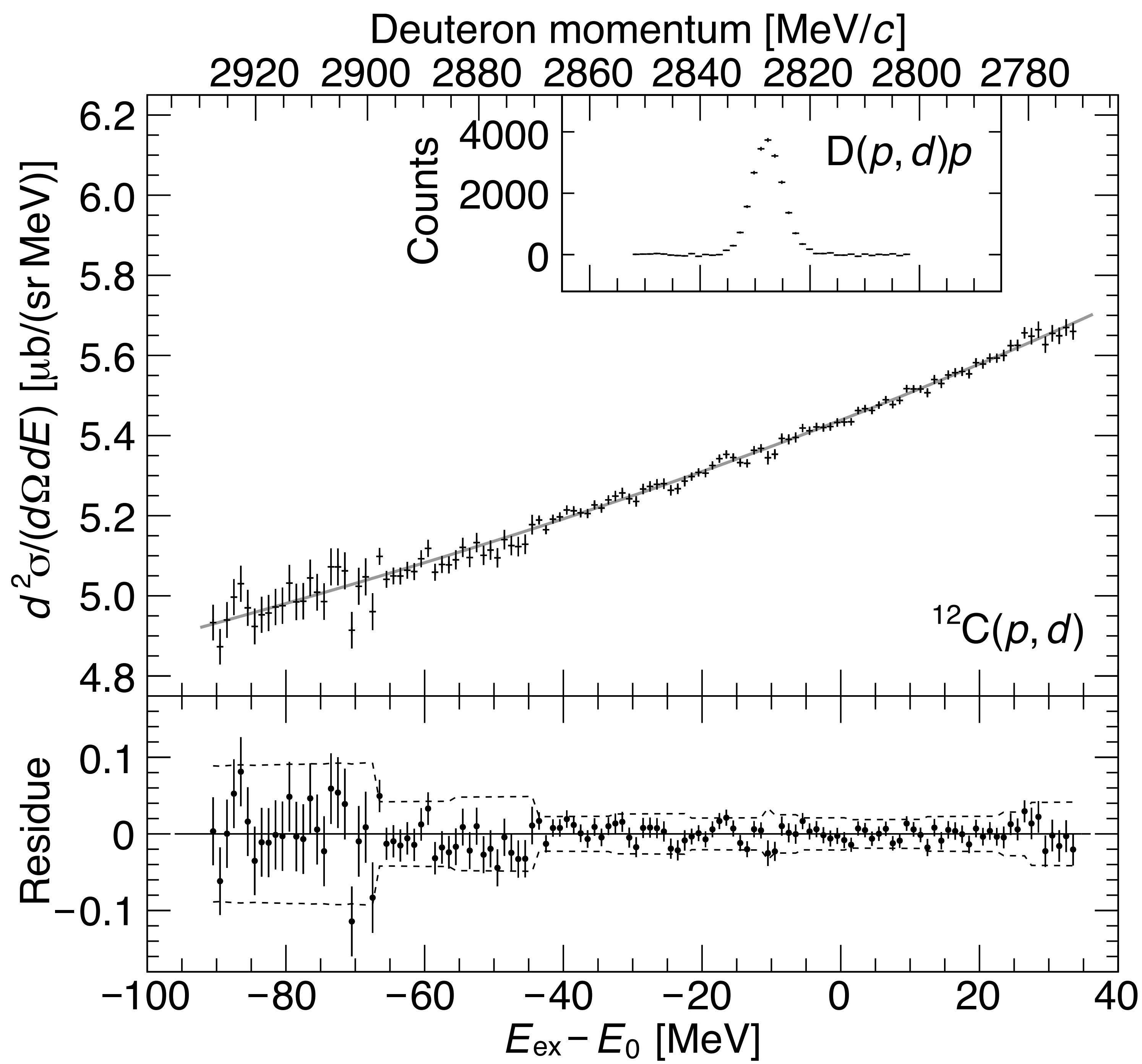
FRS@GSI: PRiME

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

Y. K. Tanaka et al.,
PRL 117 (2016) 202501

no structure in
bound state region
observed
deep η’-nucleus potentials
|V|≥100 MeV excluded!

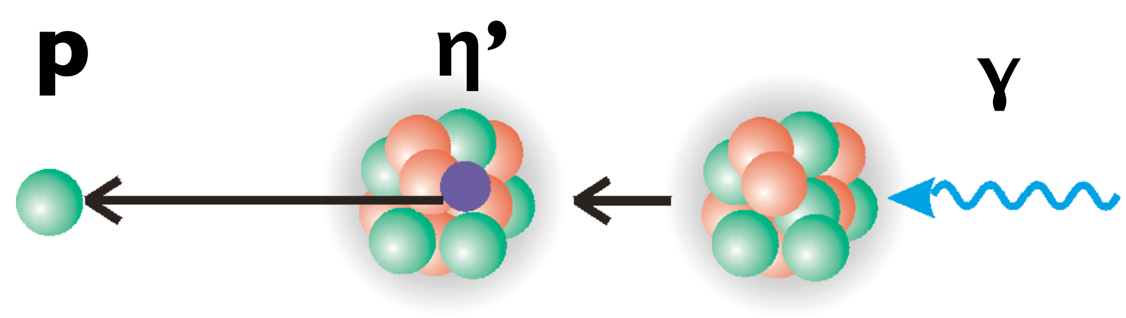
semi-exclusive experiment
in preparation
⟹ increased sensitivity
by studying formation AND
decay of η’-mesic states



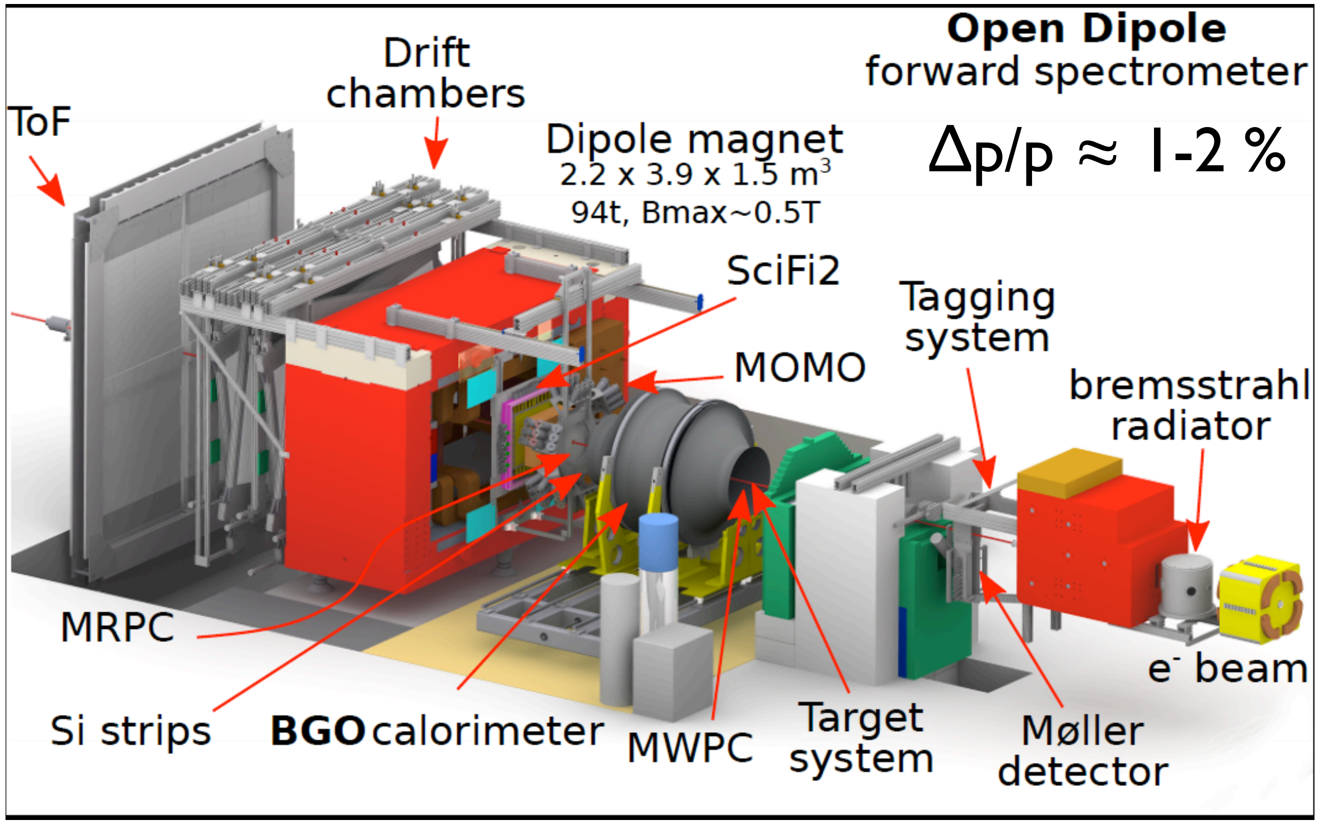
search for η’-mesic states in photo-nuclear reactions

B1: BGO-OD@ELSA

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



formation and decay of η’-mesic state



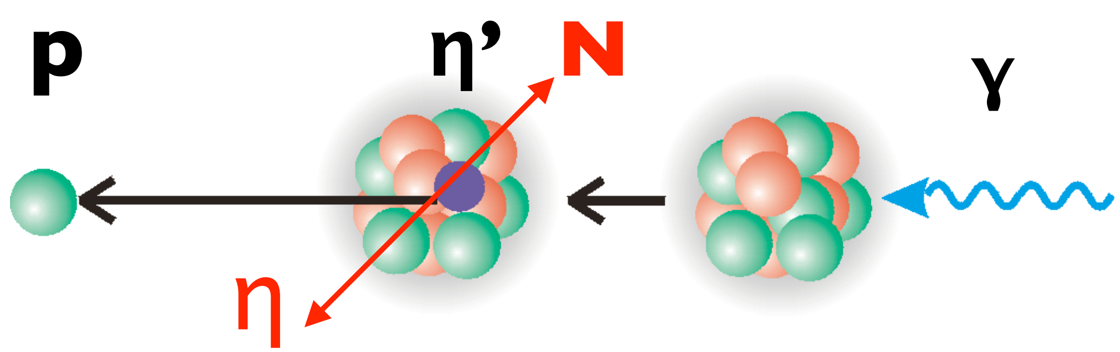
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

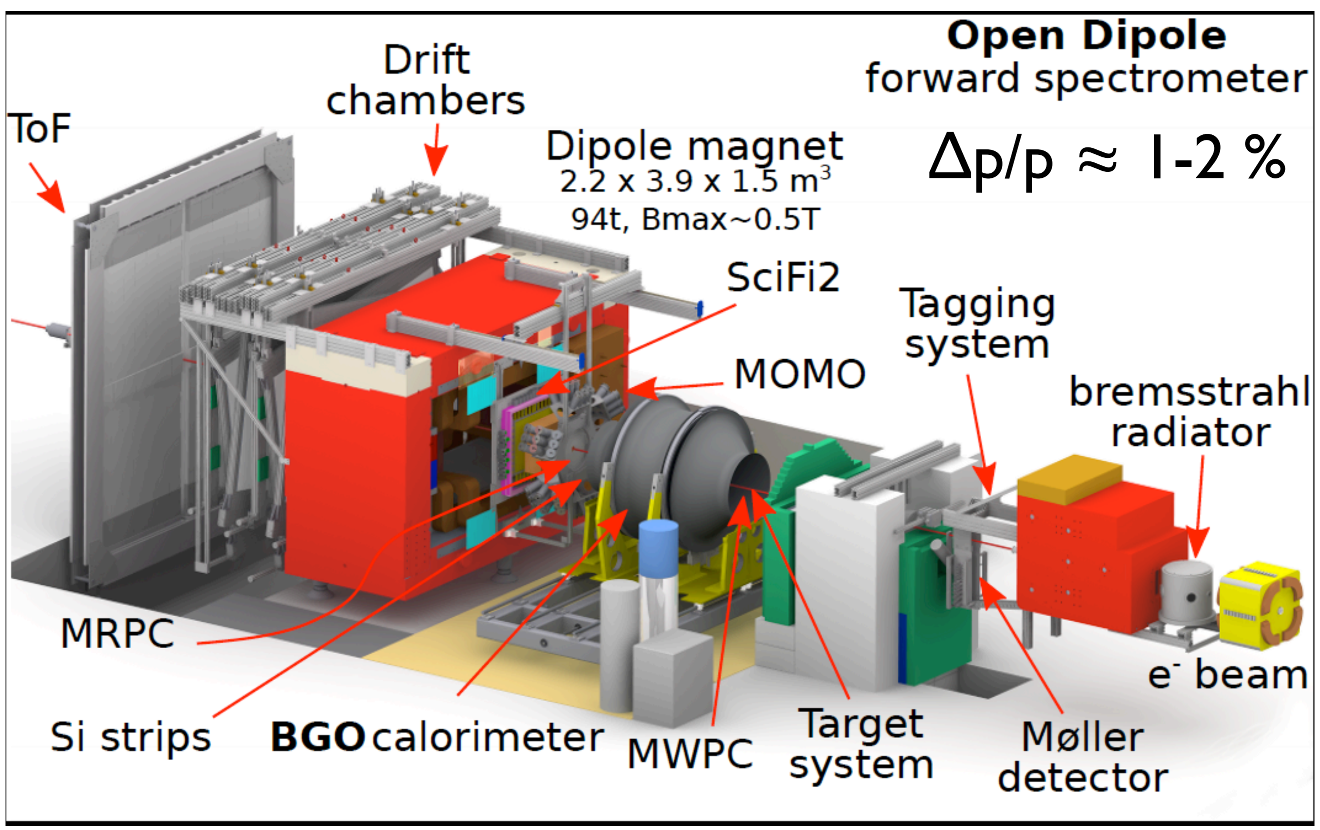
search for η'-mesic states in photo-nuclear reactions

B1: BGO-OD@ELSA

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



formation and decay of η'-mesic state



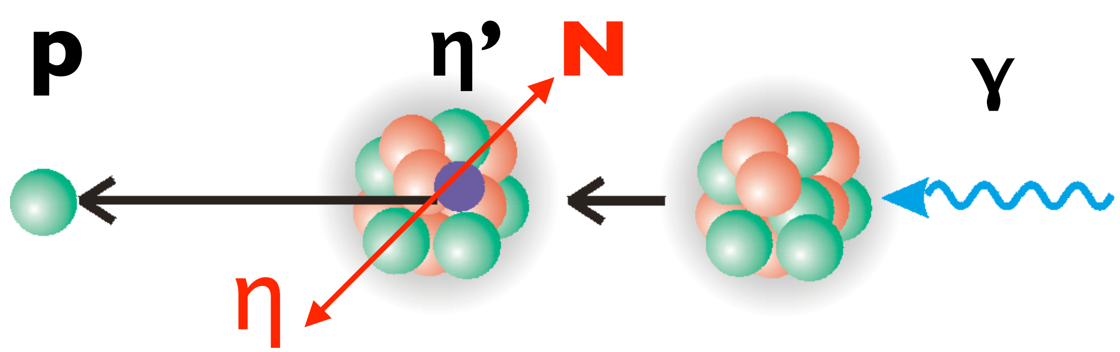
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

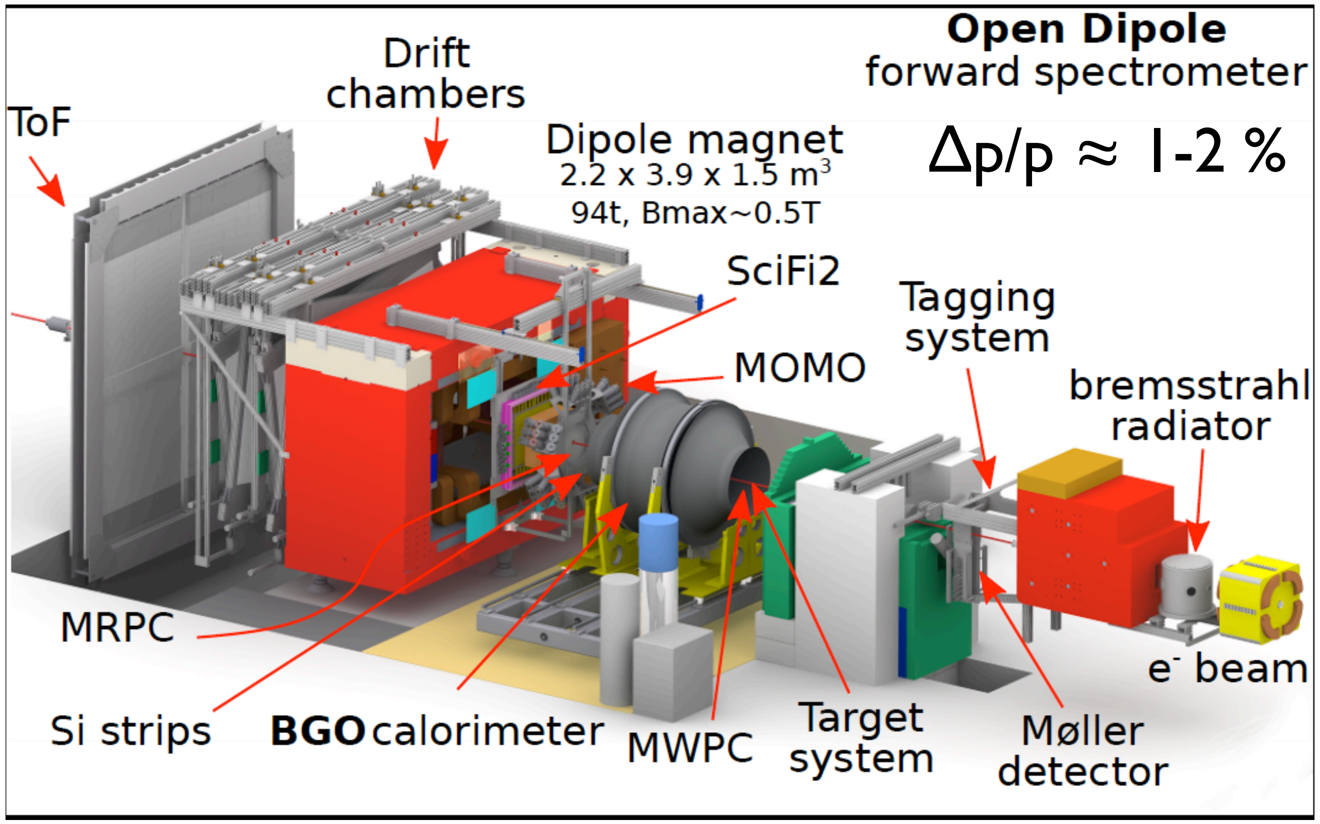
search for η'-mesic states in photo-nuclear reactions

B1: BGO-OD@ELSA

^{12}C(γ,p) η'X @ 1.5-2.8 GeV



formation and decay of η'-mesic state

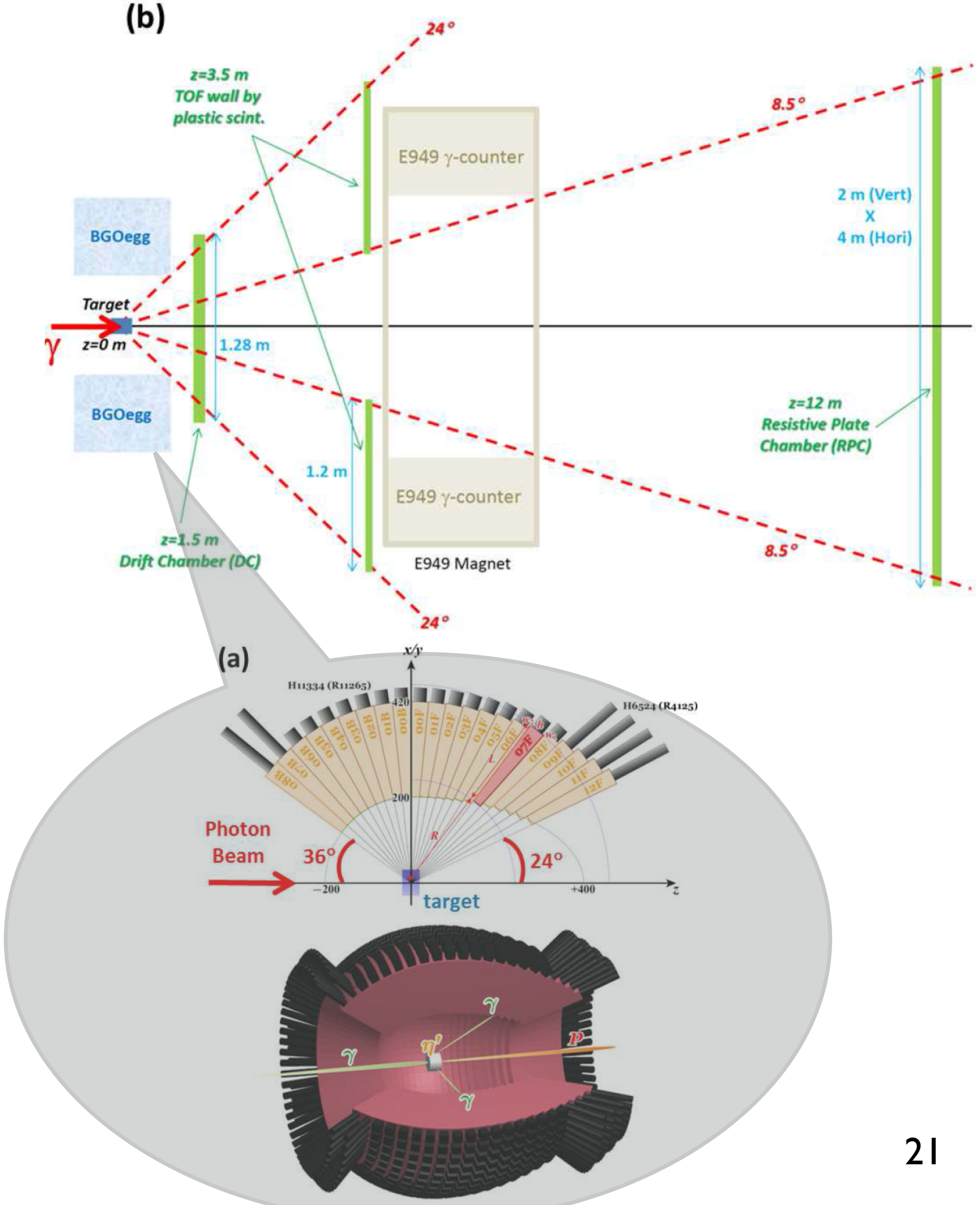


BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

LEPS2@SPring-8

^{12}C(γ,p) η'X @ 1.5-2.4 GeV



Summary

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

Summary

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

meson properties do change in a strongly interacting medium !!

Summary

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

meson properties do change in a strongly interacting medium !!

- all mesons are broadened; their lifetime is shortened through inelastic collisions

  $\Gamma_{\omega}(\rho=\rho_0; p=0) \approx 90$ MeV; $\Gamma_{\eta'}(\rho=\rho_0; p=0) \approx 25$ MeV;

Summary

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

meson properties do change in a strongly interacting medium !!

◆ all mesons are broadened; their lifetime is shortened through inelastic collisions

$\Gamma_{\omega}(\rho=\rho_0; p=0) \approx 90$ MeV; $\Gamma_{\eta'}(\rho=\rho_0; p=0) \approx 25$ MeV;

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

Summary

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

meson properties do change in a strongly interacting medium !!

◆ all mesons are broadened; their lifetime is shortened through inelastic collisions

$\Gamma_{\omega}(\rho=\rho_0; p=0) \approx 90$ MeV; $\Gamma_{\eta'}(\rho=\rho_0; p=0) \approx 25$ MeV;

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

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

Summary

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

meson properties do change in a strongly interacting medium !!

◆ all mesons are broadened; their lifetime is shortened through inelastic collisions

$\Gamma_{\omega}(\rho=\rho_0; p=0) \approx 90$ MeV; $\Gamma_{\eta'}(\rho=\rho_0; p=0) \approx 25$ MeV;

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

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

◆ in-medium effects described within meson-nucleus optical potential

Summary

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

meson properties do change in a strongly interacting medium !!

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

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

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

◆ in-medium effects described within meson-nucleus optical potential

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

Summary

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

meson properties do change in a strongly interacting medium !!

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

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

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

◆ in-medium effects described within meson-nucleus optical potential

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

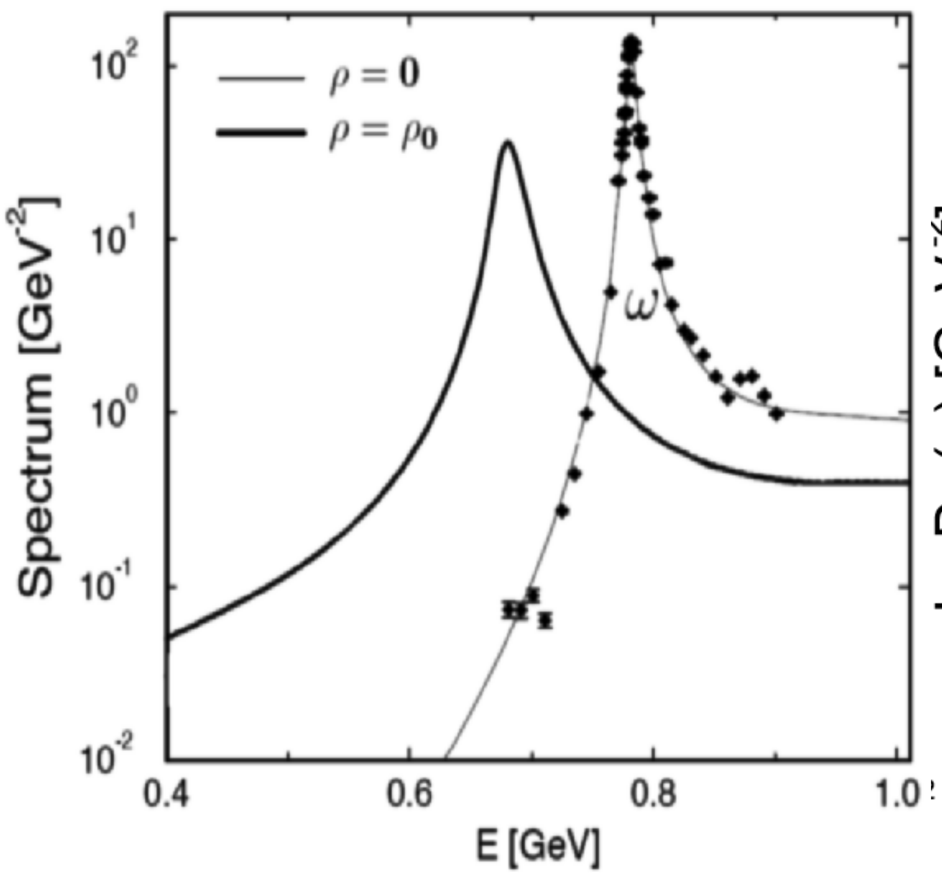
◆ search for η' mesic states ongoing

THANK YOU !

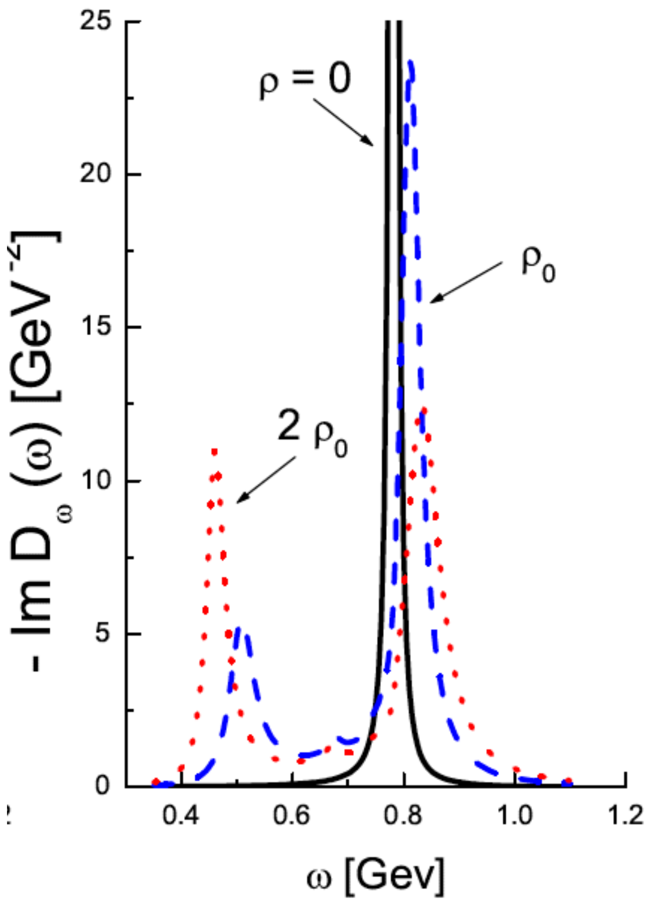
BACKUP

hadronic models: predictions for ω-spectral functions

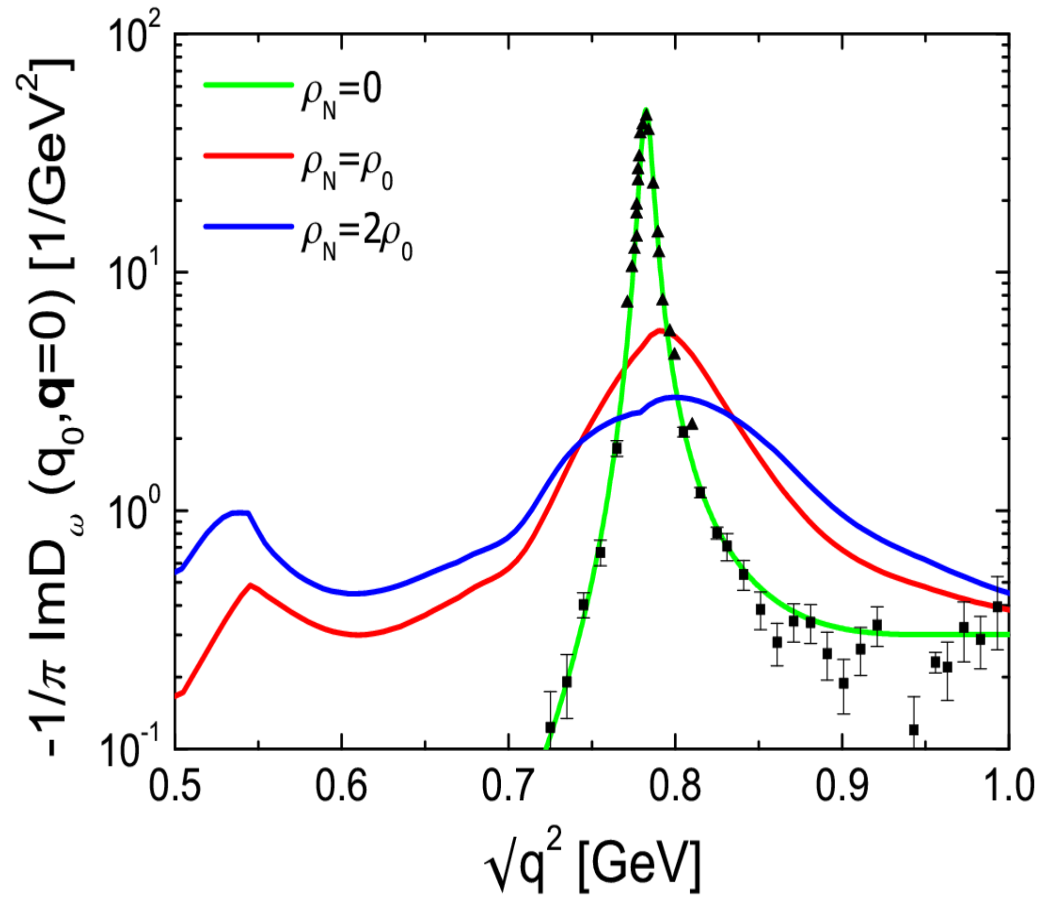
F. Klingl et al.,
NPA 610 (1997) 297;
NPA 650 (1999) 299



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



P. Mühlich et al., NPA 780 (2006) 187



- lowering of in-medium mass
- broadening of resonance

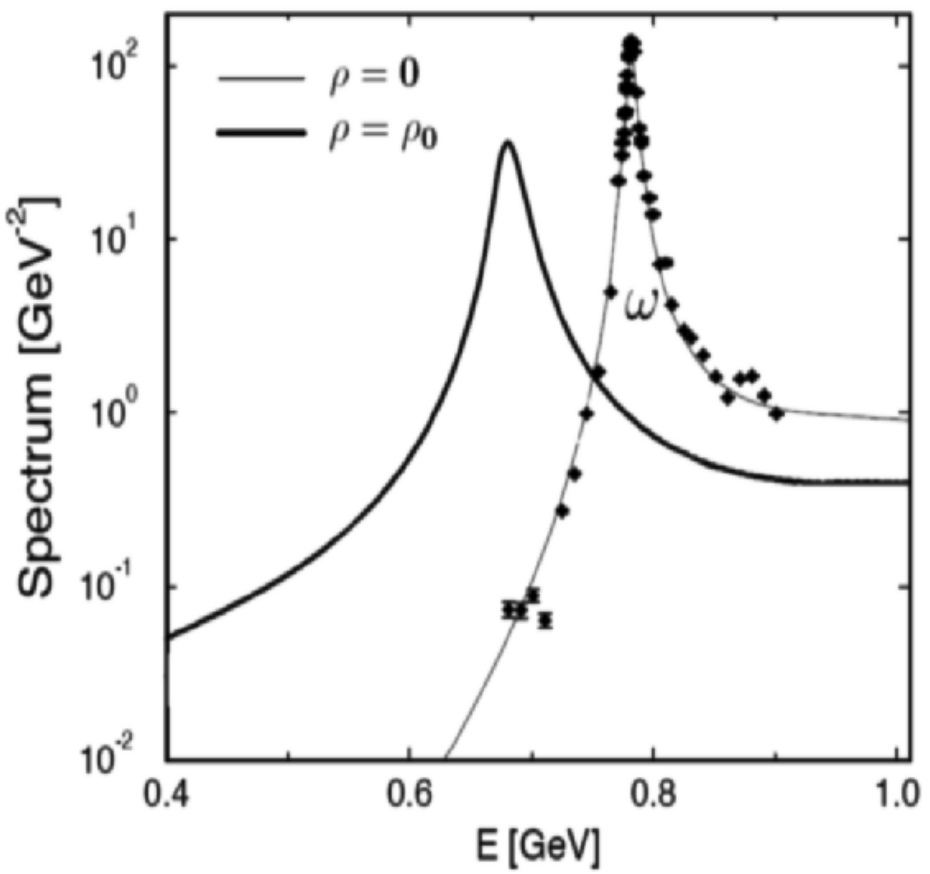
with increasing nuclear density
Re(U) ≠0; Im(U) ≠0

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

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

hadronic models: predictions for ω-spectral functions

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

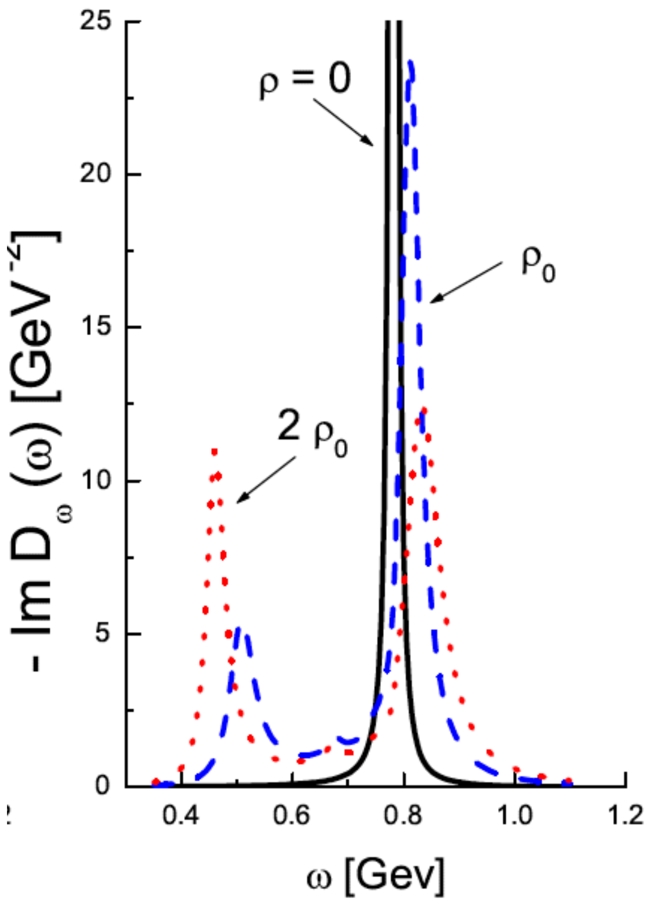


- lowering of in-medium mass
- broadening of resonance

with increasing nuclear density

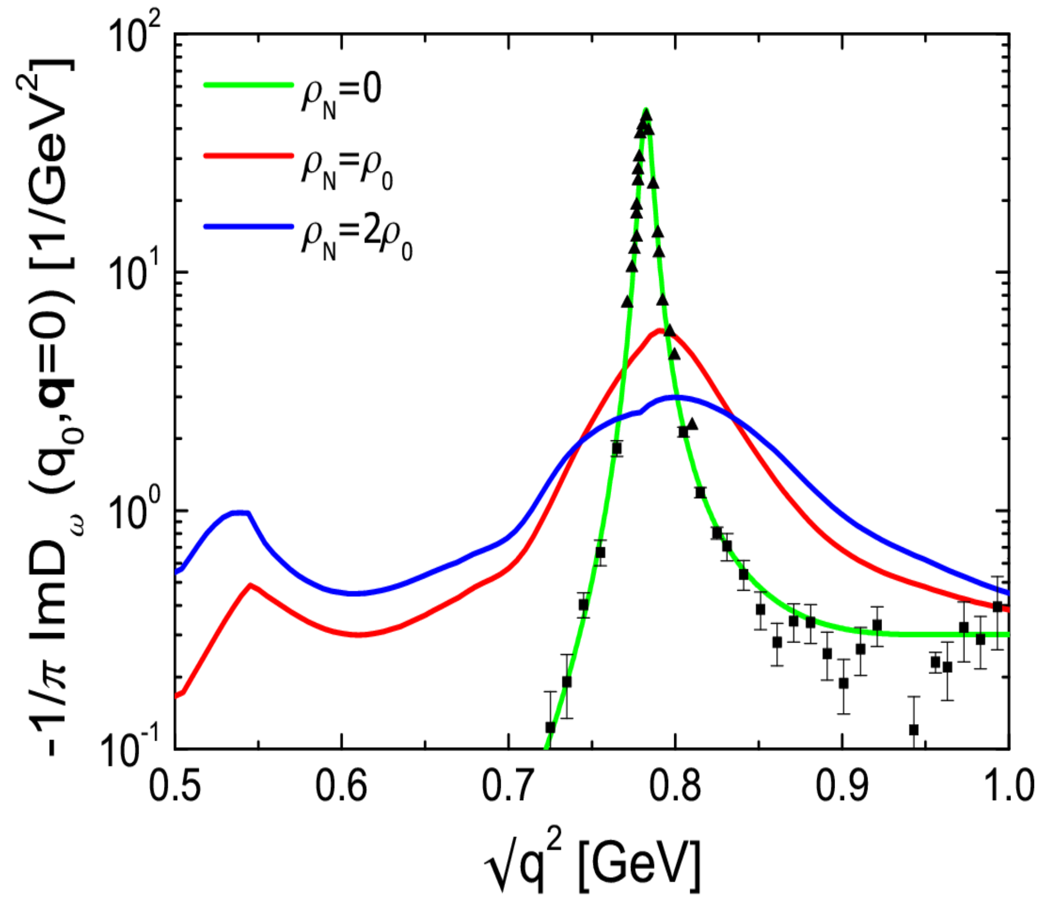
Re(U) ≠0; Im(U) ≠0

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

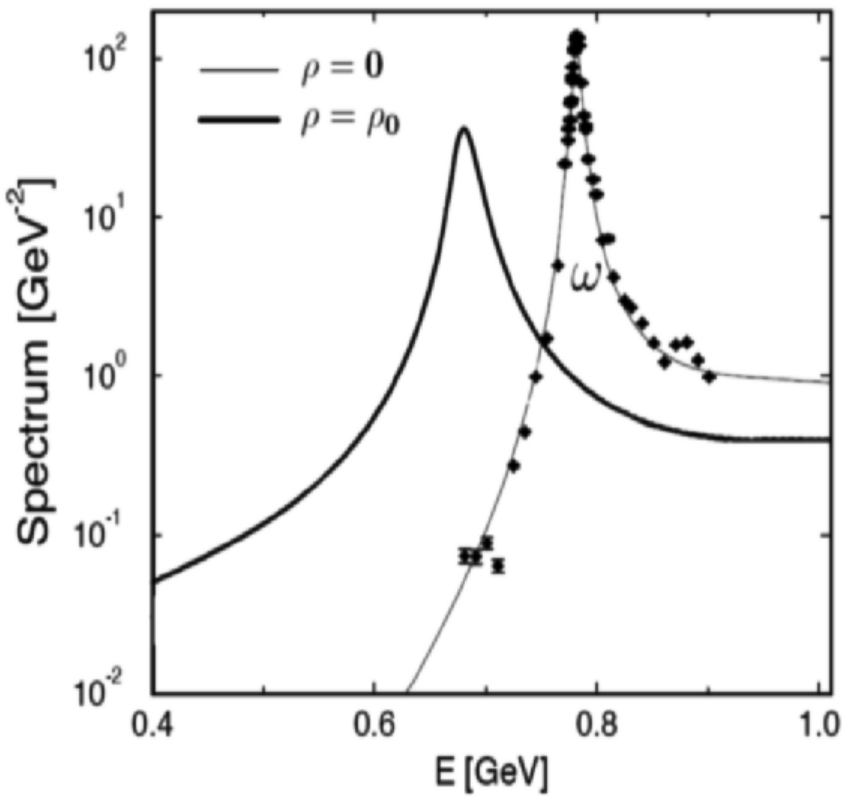
experimental task: search for { mass shift ? broadening? structures? } of hadronic spectral functions

in-medium mass shift and width from line shape measurements

$$m(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

reconstruction of meson mass distribution from 4-momenta of decay products

F. Klingl et al., NPA 610 (1997) 297



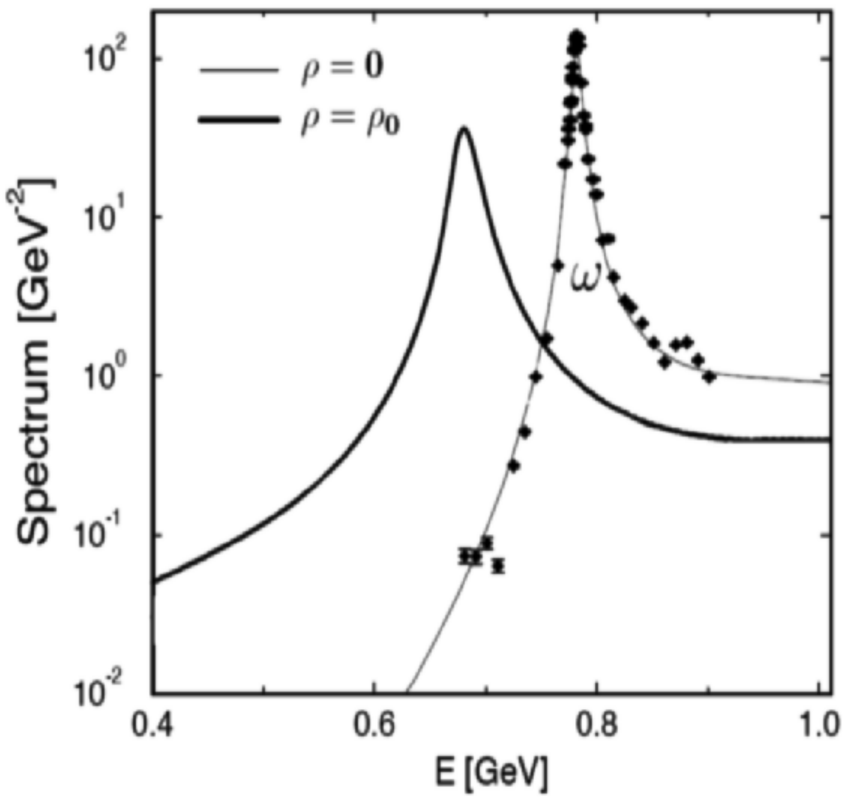
theoretical prediction for $\rho=\rho_0$ and meson at rest

in-medium mass shift and width from line shape measurements

$$m(\rho,\vec{p}) = \sqrt{(p_1+p_2)^2}$$

reconstruction of meson mass distribution from 4-momenta of decay products

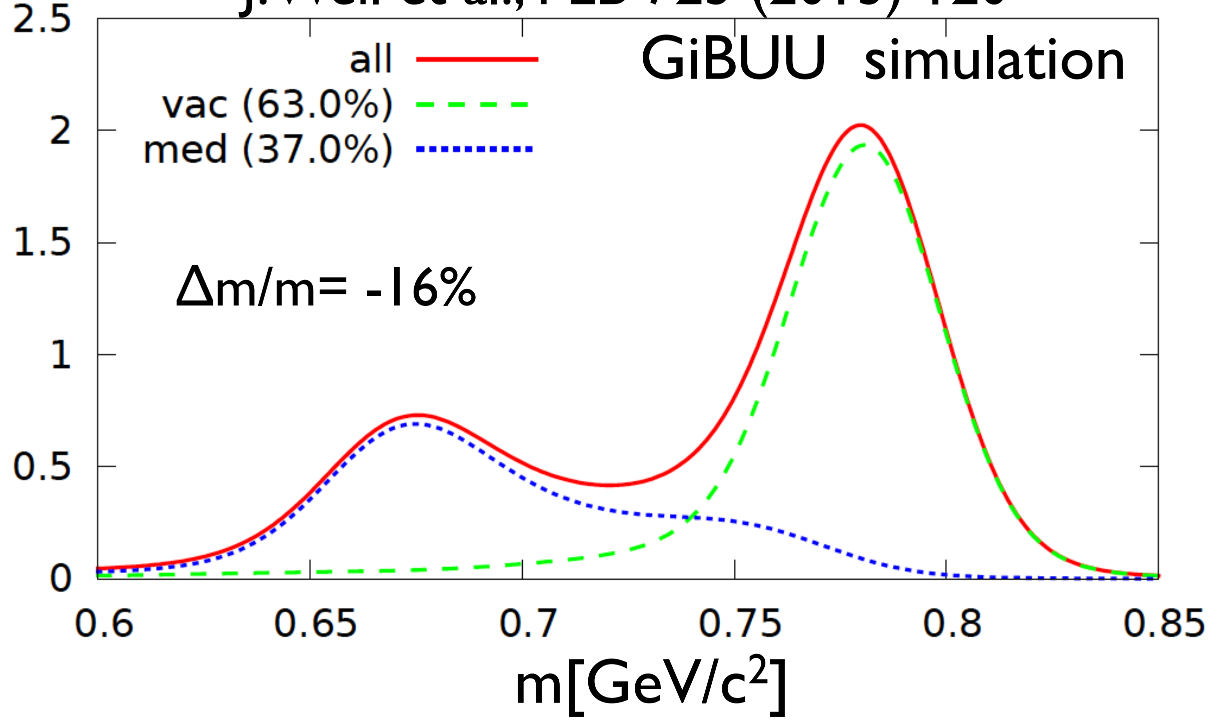
F. Klingl et al., NPA 610 (1997) 297



theoretical prediction for $\rho = \rho_0$ and meson at rest

in reality:
- mesons see nuclear density profile $\rho(r)$ ⇒ density dependent mass shift smeared out
- mesons have recoil momenta $p \approx m$; ⇒ only small fraction of decays occur inside nucleus since decay length $\beta\gamma c\tau > R$
- only mass shifts $\gg \sigma_m$ observable

J. Weil et al., PLB 723 (2013) 120

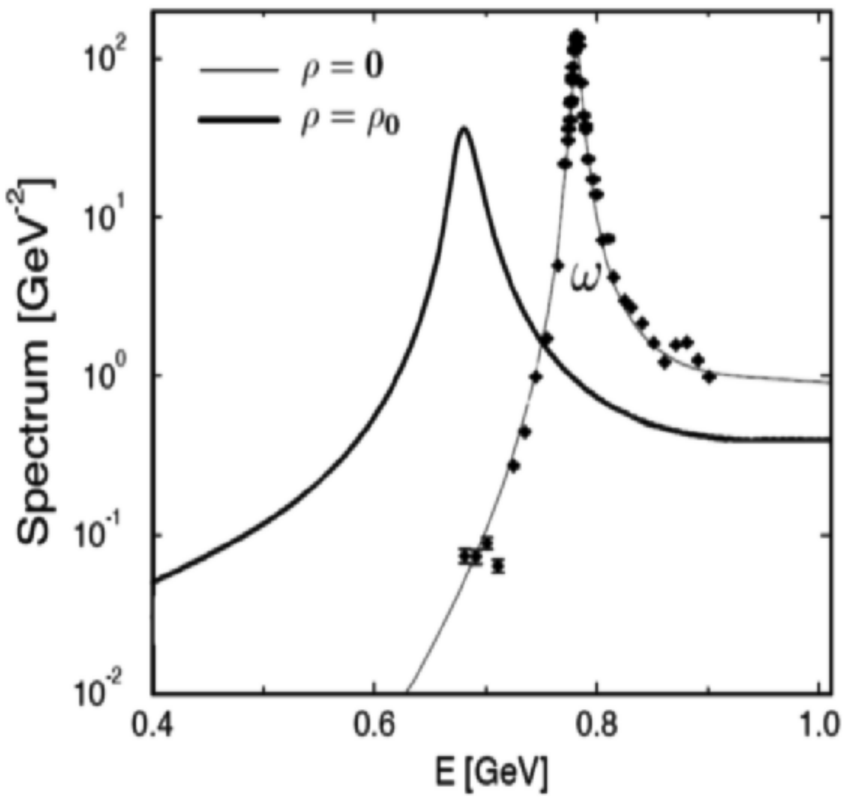


in-medium mass shift and width from line shape measurements

$$m(\rho,\vec{p}) = \sqrt{(p_1+p_2)^2}$$

reconstruction of meson mass distribution from 4-momenta of decay products

F. Klingl et al., NPA 610 (1997) 297

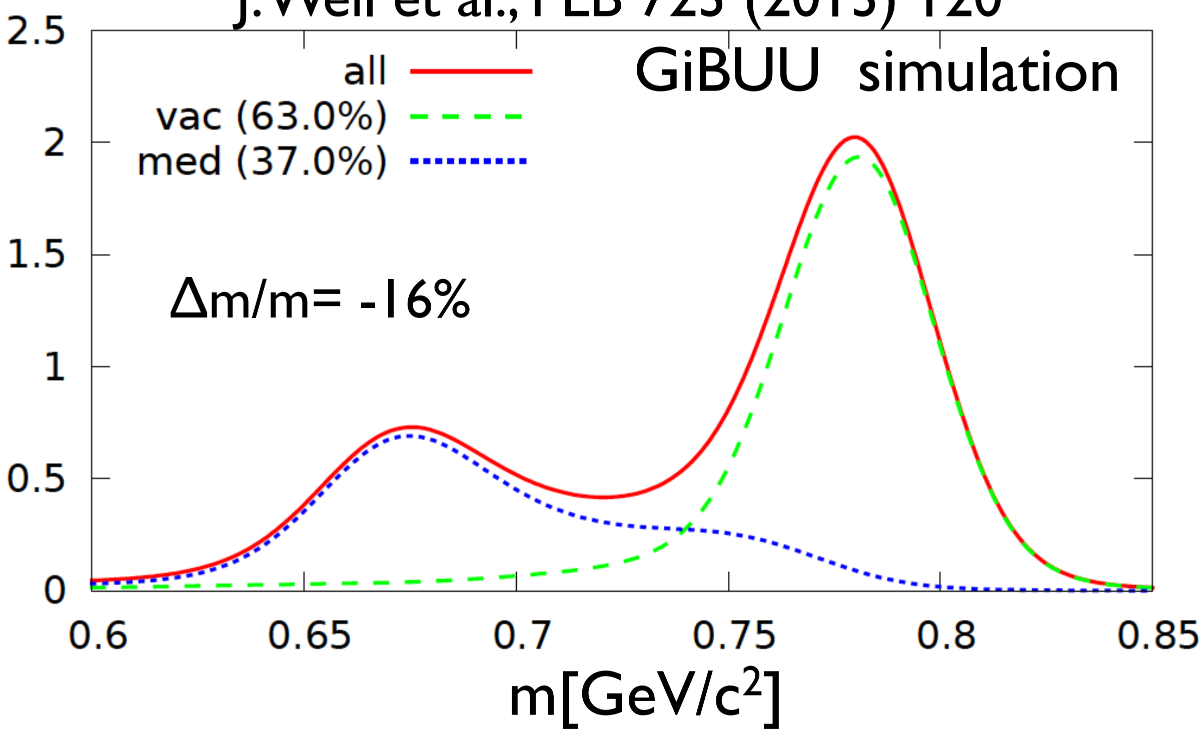


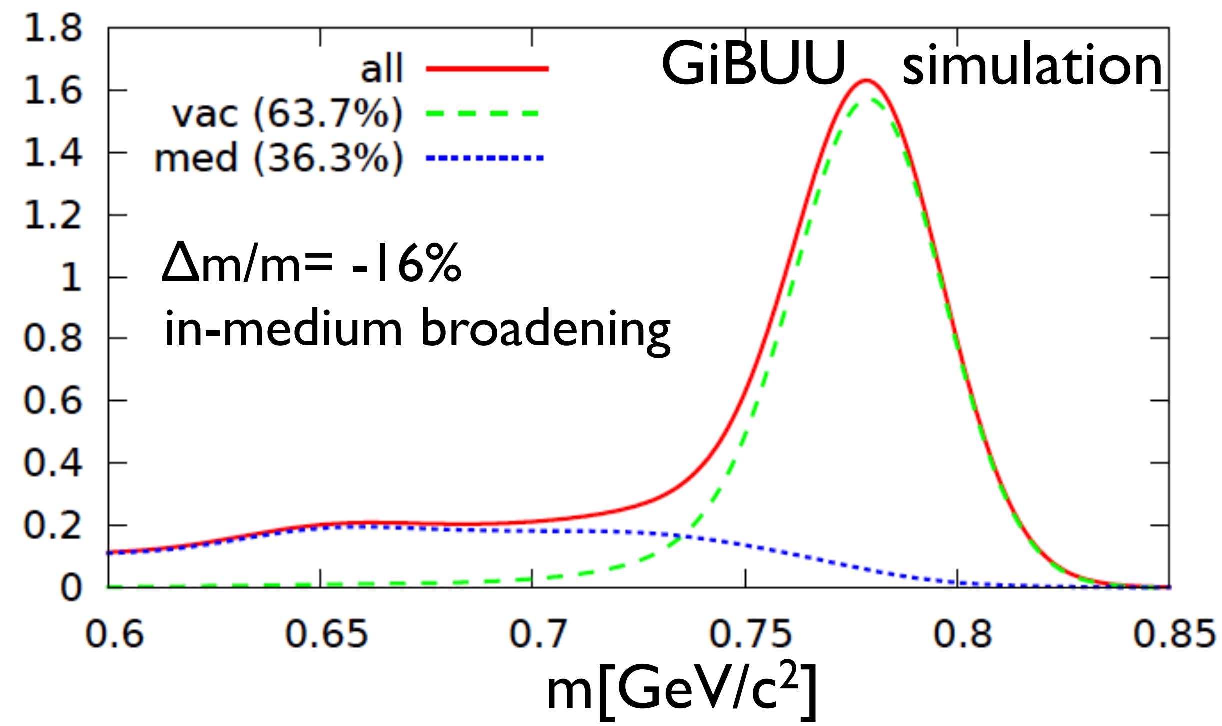
theoretical prediction for $\rho=\rho_0$ and meson at rest

in reality:

- mesons see nuclear density profile $\rho(r)$
  $\Rightarrow$ density dependent mass shift smeared out
- mesons have recoil momenta $p \approx m$;
  $\Rightarrow$ only small fraction of decays occur inside nucleus since decay length $\beta\gamma c\tau > R$
- only mass shifts $\gg \sigma_m$ observable
- mass distribution further smeared out by in-medium broadening

J.Weil et al., PLB 723 (2013) 120

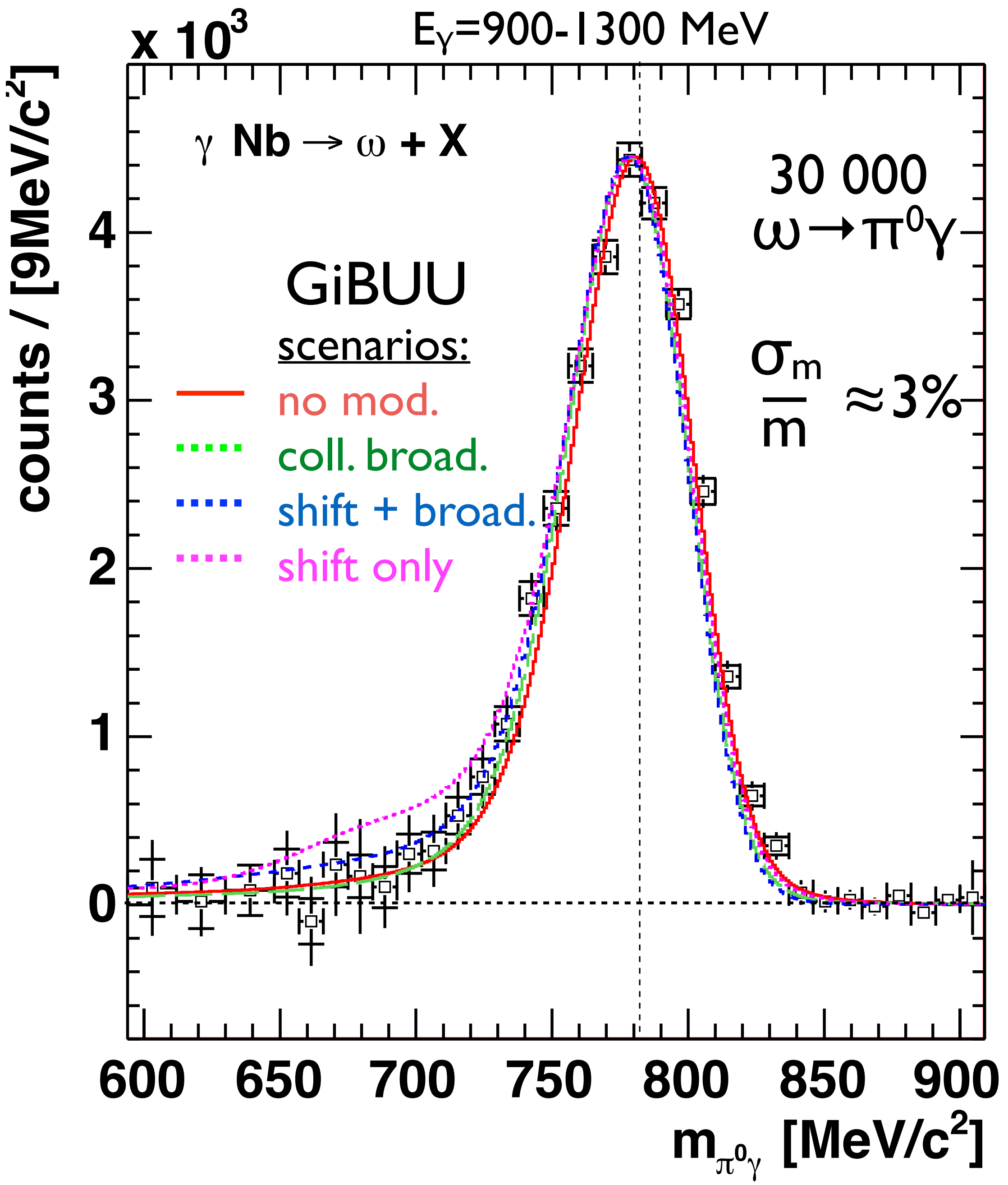




ω line shape from $\omega \to \pi^0\gamma$ in photo-nuclear reaction

CB/TAPS @ MAMI M. Thiel et al., EPJA 49 (2013) 132

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

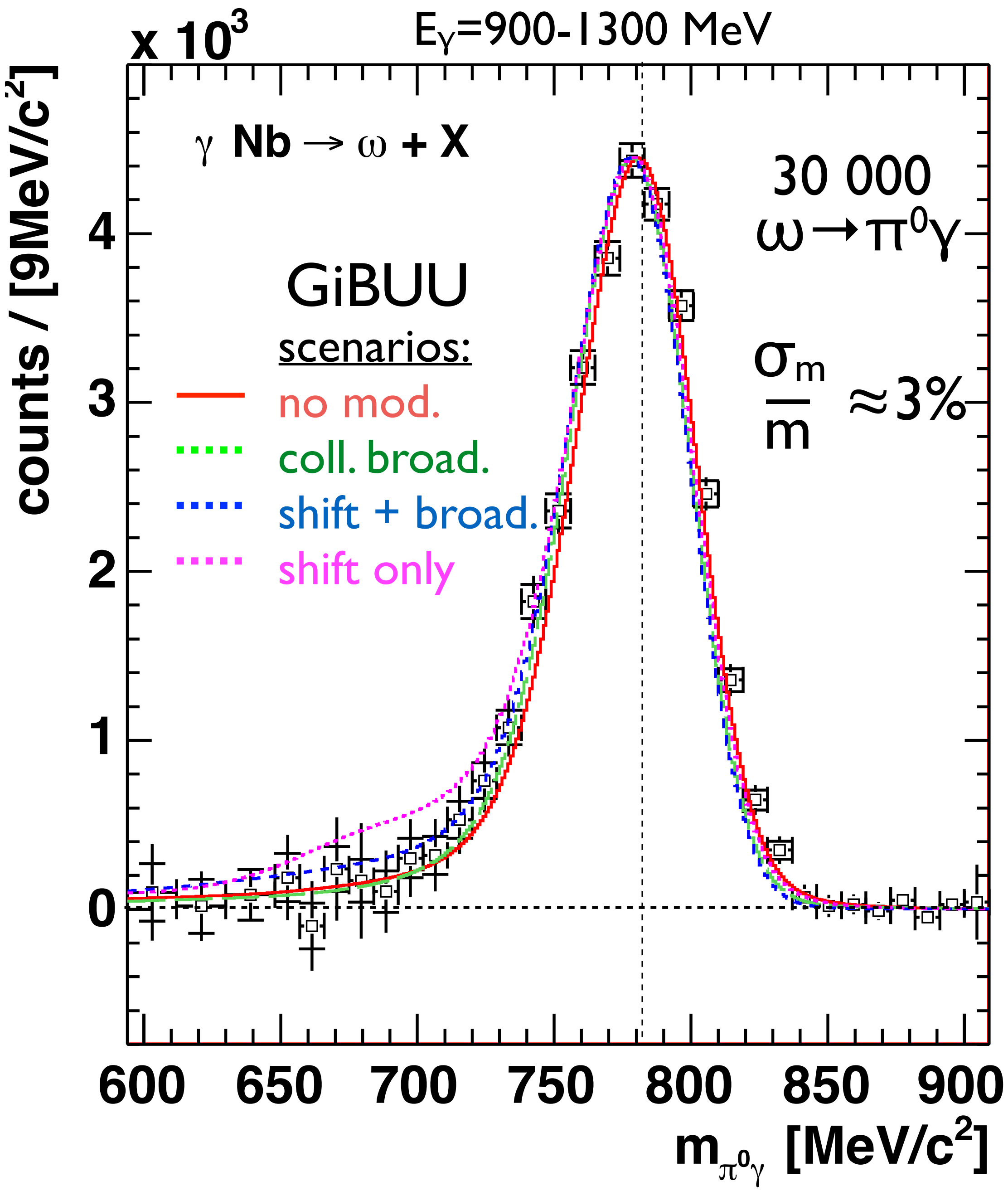


different in-medium modification scenarios almost indistinguishable

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

CB/TAPS @ MAMI M.Thiel et al., EPJA 49 (2013) 132

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



different in-medium modification scenarios almost indistinguishable

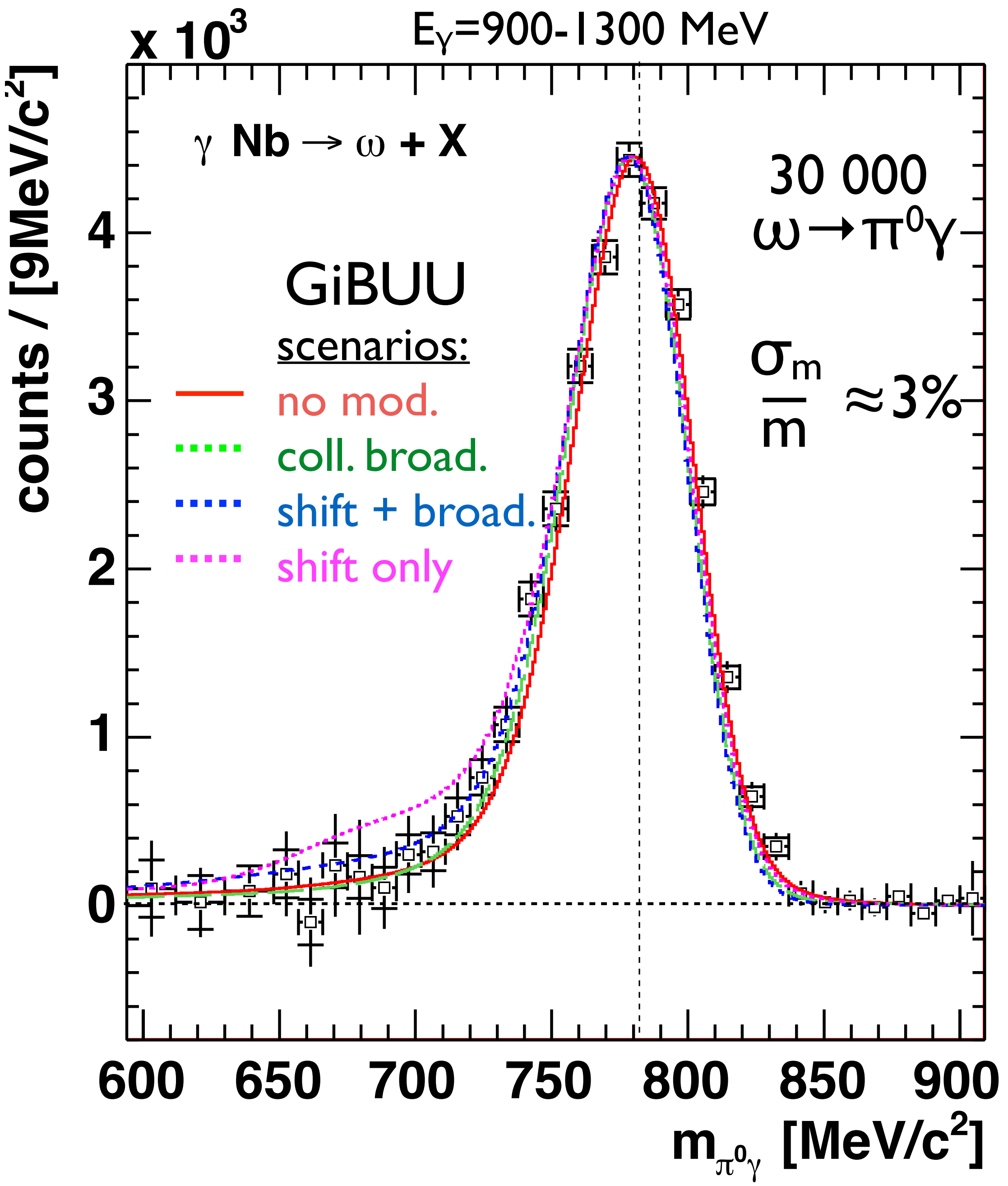
ω meson

- $c\tau$ = 22 fm
  for <p_ω>≈600 MeV/c: $\beta\gamma c\tau$ = 17 fm
  fraction of ω decays in Nb: ≈36%

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

CB/TAPS @ MAMI M. Thiel et al., EPJA 49 (2013) 132

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



different in-medium modification scenarios almost indistinguishable

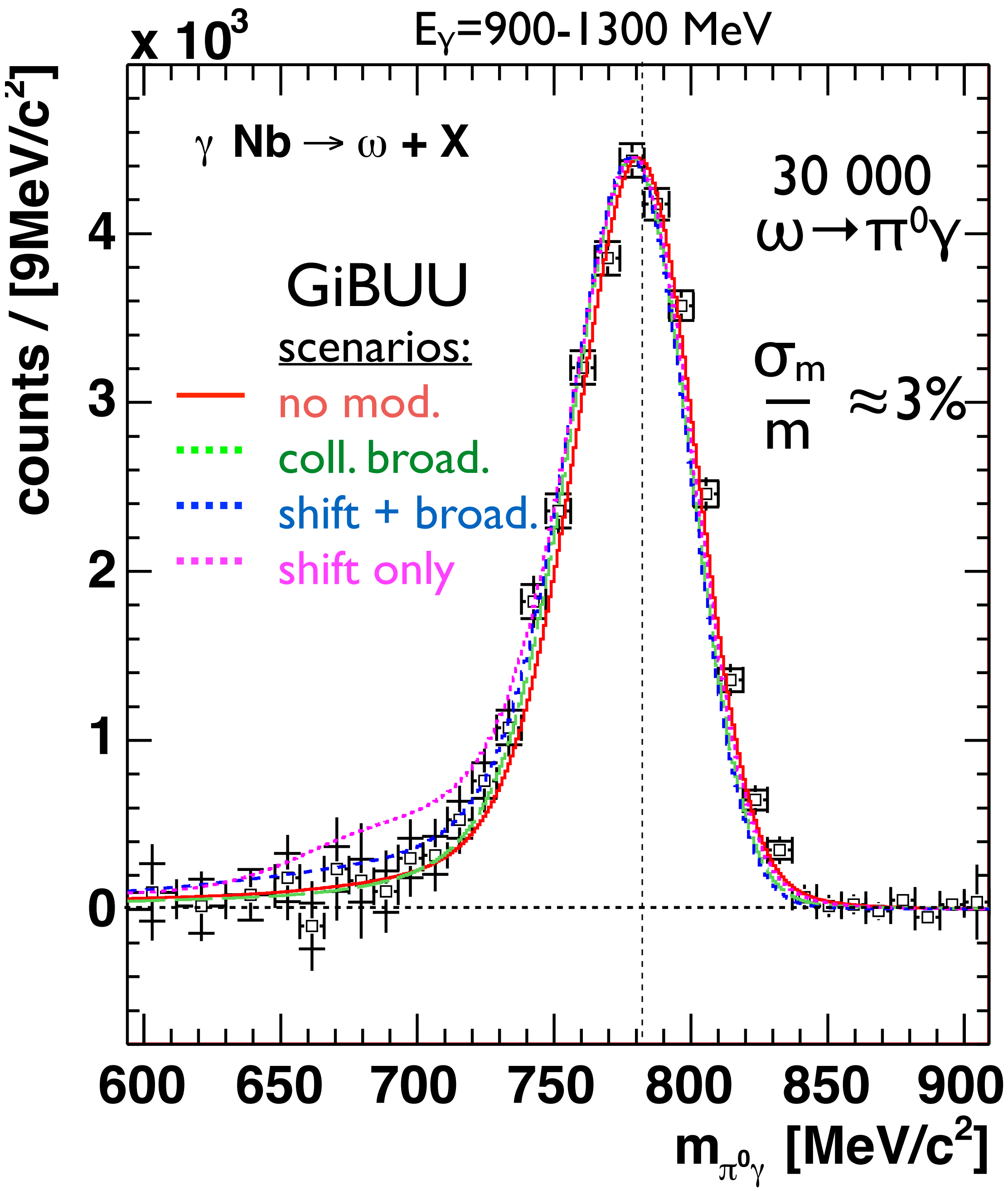
ω meson

- $c\tau$ = 22 fm
  for $\langle p_\omega \rangle \approx$ 600 MeV/c: $\beta\gamma c\tau$ = 17 fm
  fraction of ω decays in Nb: $\approx$36%
- only mass shifts $\gg$ σ=3% observable

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

CB/TAPS @ MAMI M. Thiel et al., EPJA 49 (2013) 132

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



different in-medium modification scenarios almost indistinguishable

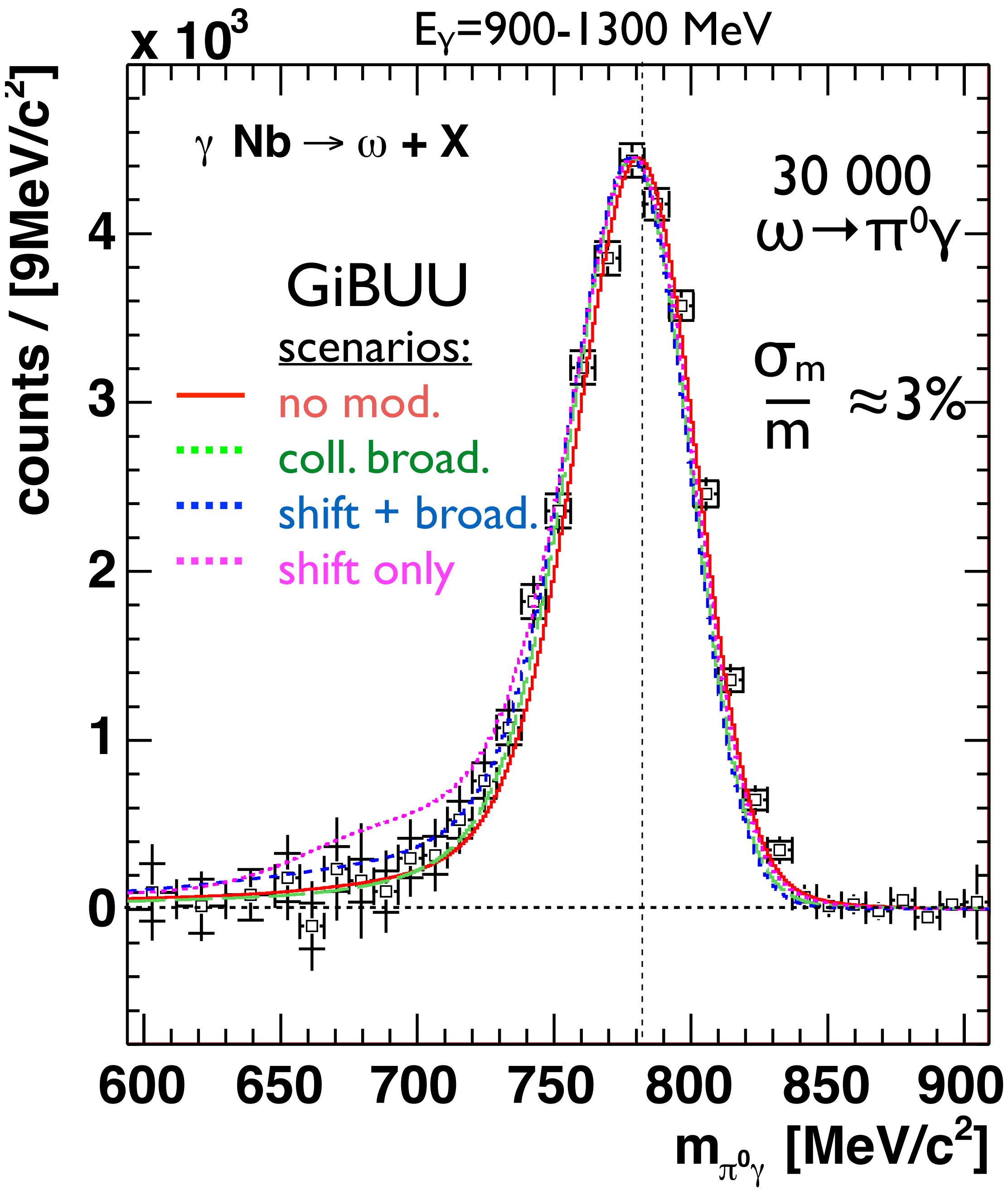
ω meson

- $c\tau$ = 22 fm
  for $\langle p_\omega \rangle \approx$ 600 MeV/c: $\beta\gamma c\tau$ = 17 fm
  fraction of ω decays in Nb: ≈36%
- only mass shifts ≫ σ=3% observable
- ω signal smeared out due to in-medium broadening (Γ≈140 MeV)

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

CB/TAPS @ MAMI M. Thiel et al., EPJA 49 (2013) 132

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



different in-medium modification scenarios almost indistinguishable

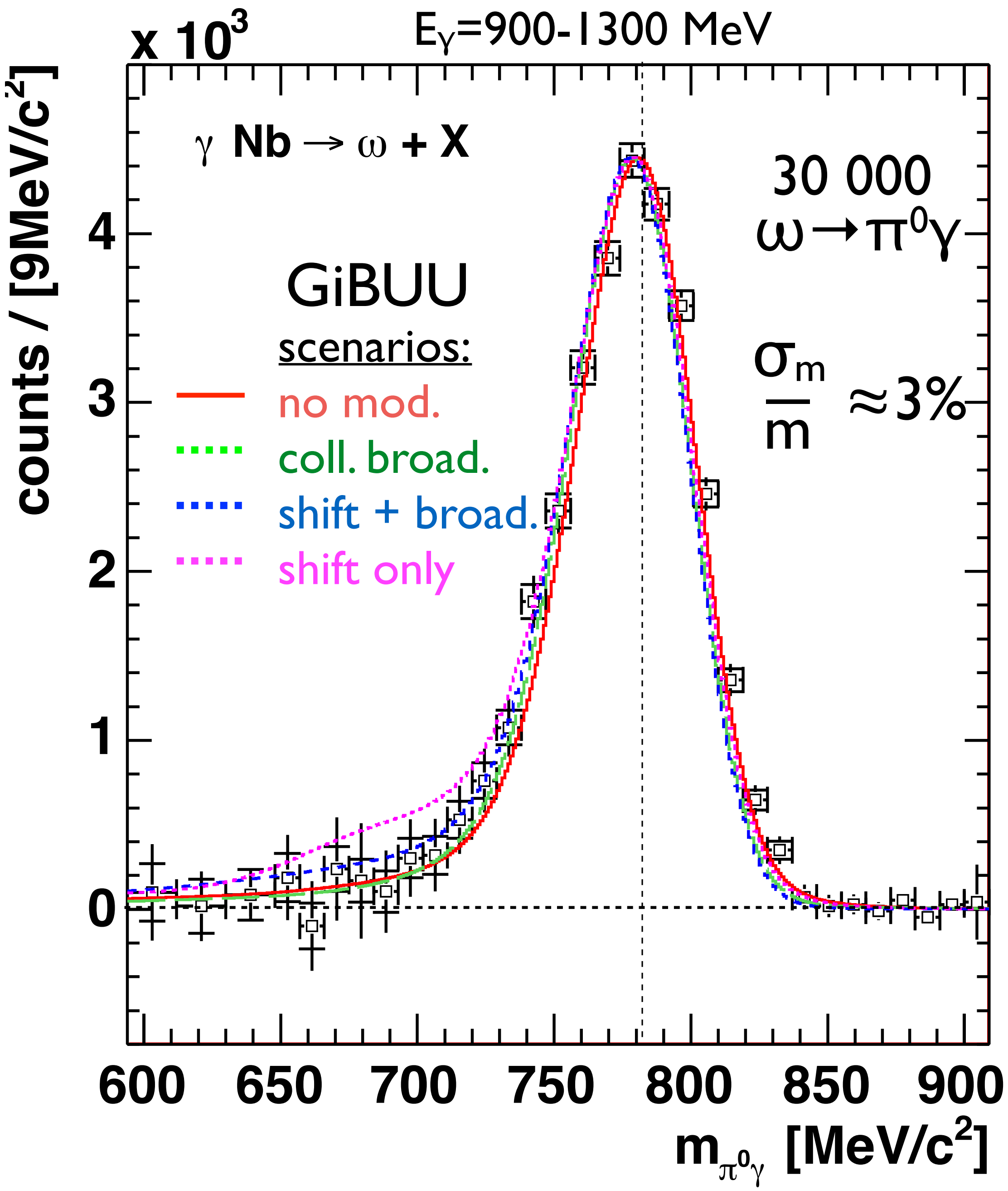
ω meson

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

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

CB/TAPS @ MAMI M.Thiel et al., EPJA 49 (2013) 132

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



different in-medium modification scenarios almost indistinguishable

ω meson

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

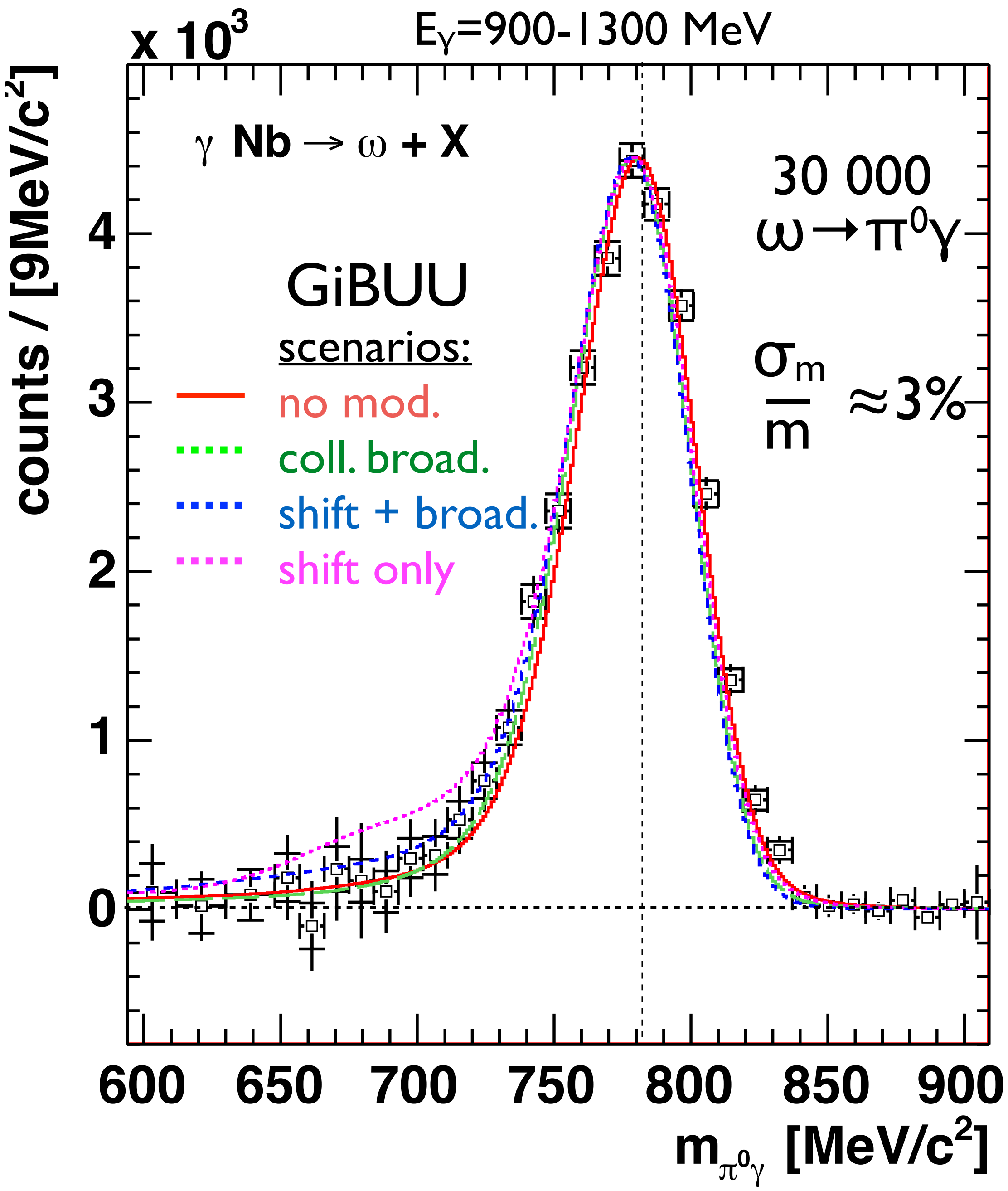
η' meson

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

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

CB/TAPS @ MAMI M.Thiel et al., EPJA 49 (2013) 132

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



different in-medium modification scenarios almost indistinguishable

ω meson

◆ $c\tau$ = 22 fm
for <p_ω>≈600 MeV/c: $\beta\gamma c\tau$ = 17 fm
fraction of ω decays in Nb: ≈36%

◆ only mass shifts ≫ σ=3% observable

◆ ω signal smeared out due to in-medium broadening (Γ≈140 MeV)

◆ due to π^0 absorption (π^0-FSI) ω→$\pi^0\gamma$ decays in the center of the nucleus are suppressed

η' meson

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

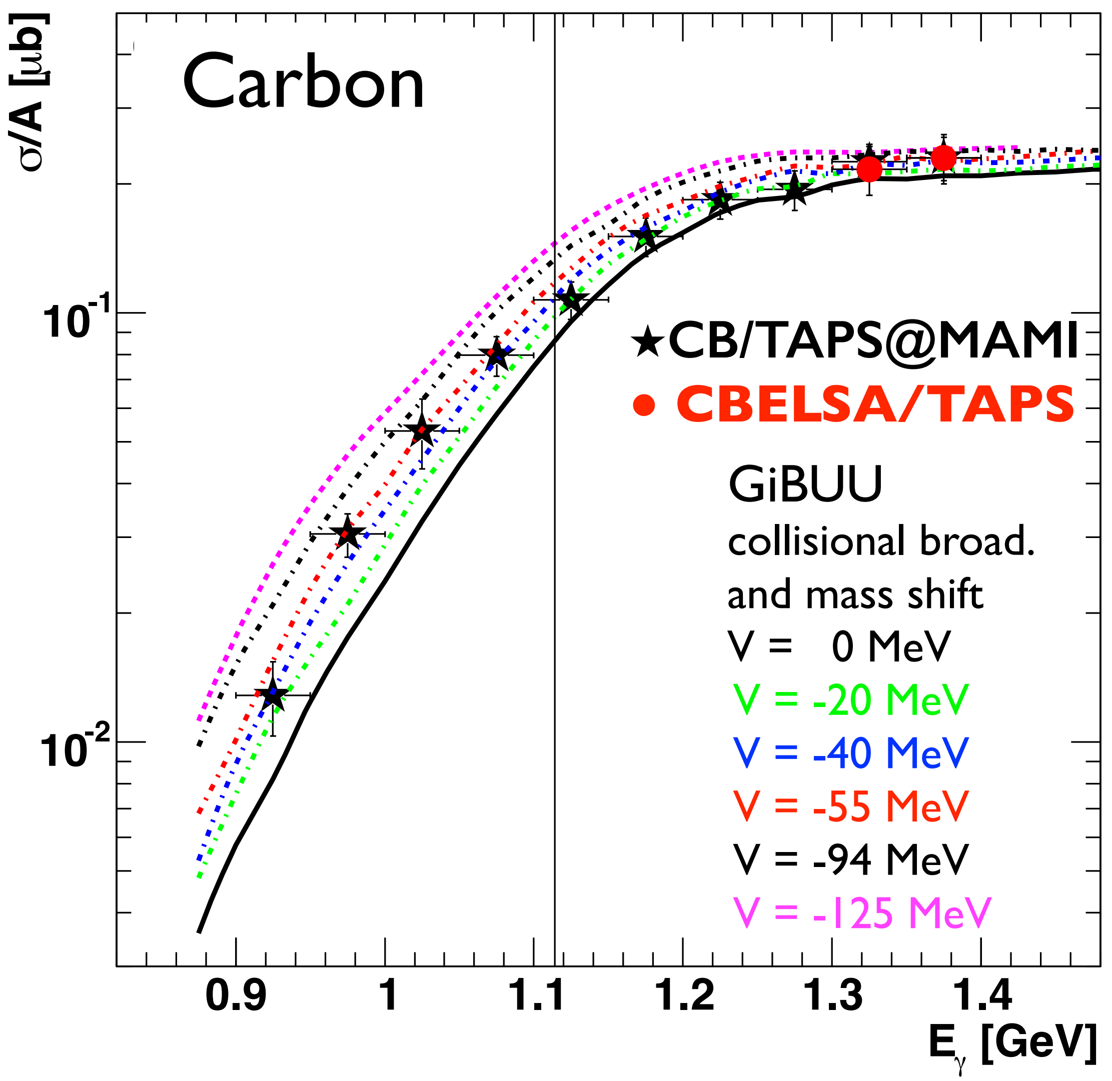
line shape analysis very difficult or even impossible

excitation function for ω photoproduction off C comparison with GiBUU calculation

CB/TAPS @ MAMI

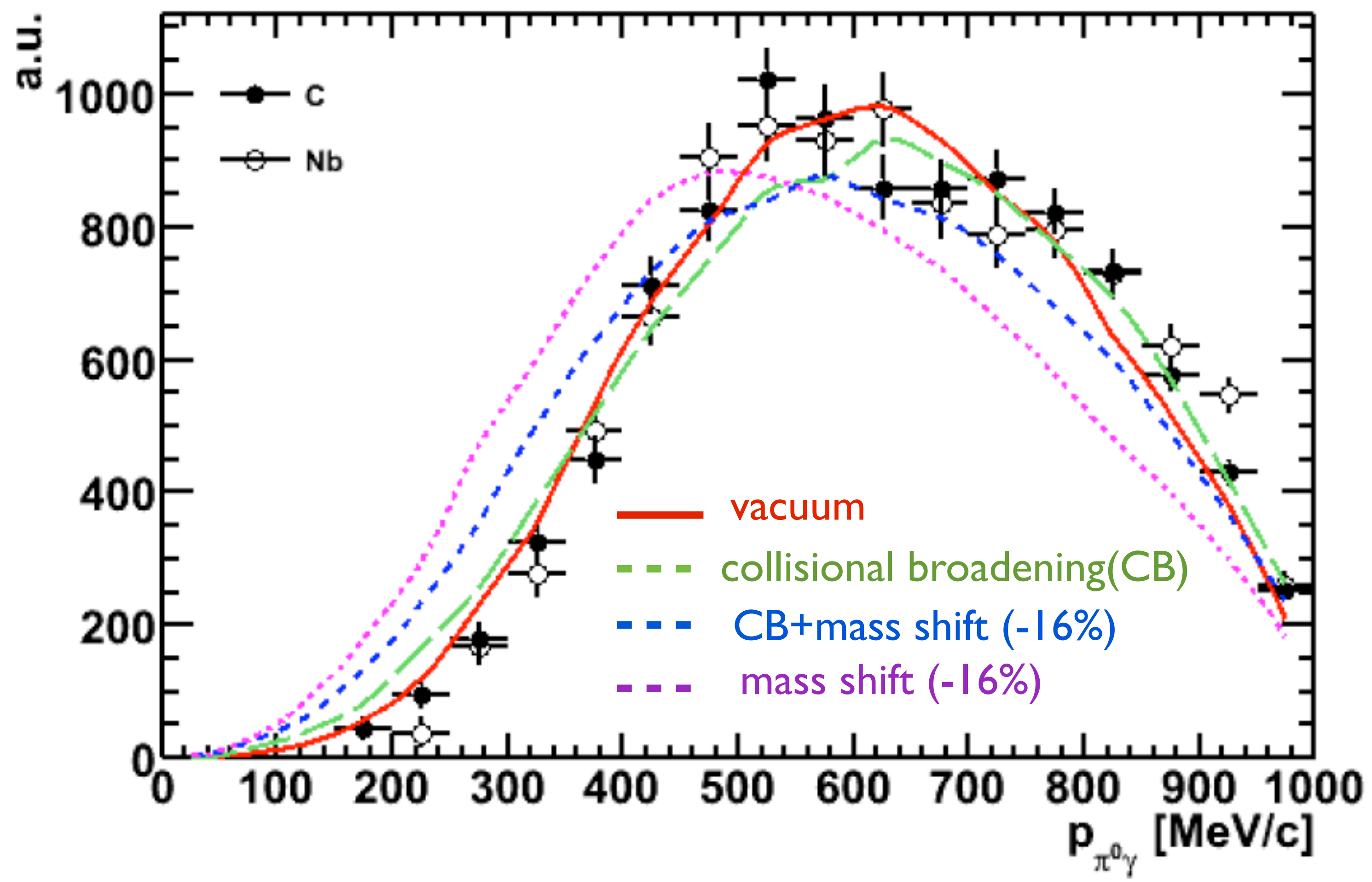
V. Metag et al., PPNP, 67 (2012) 530

excitation function



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

momentum distribution

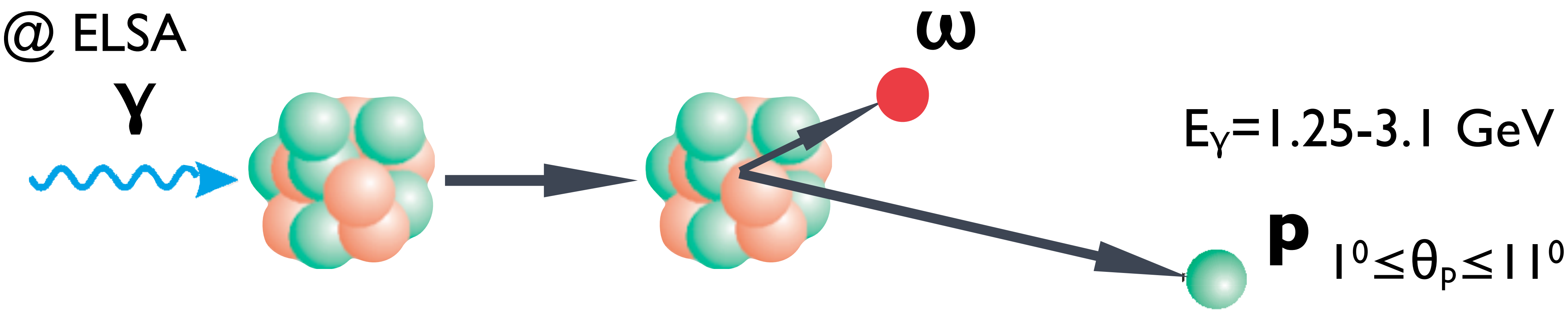


$V(\rho=\rho_0) = -(42\pm17(\mathrm{stat})\pm20(\mathrm{syst}))$ MeV

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

real part of ω-nucleus potential from ω kinetic energy

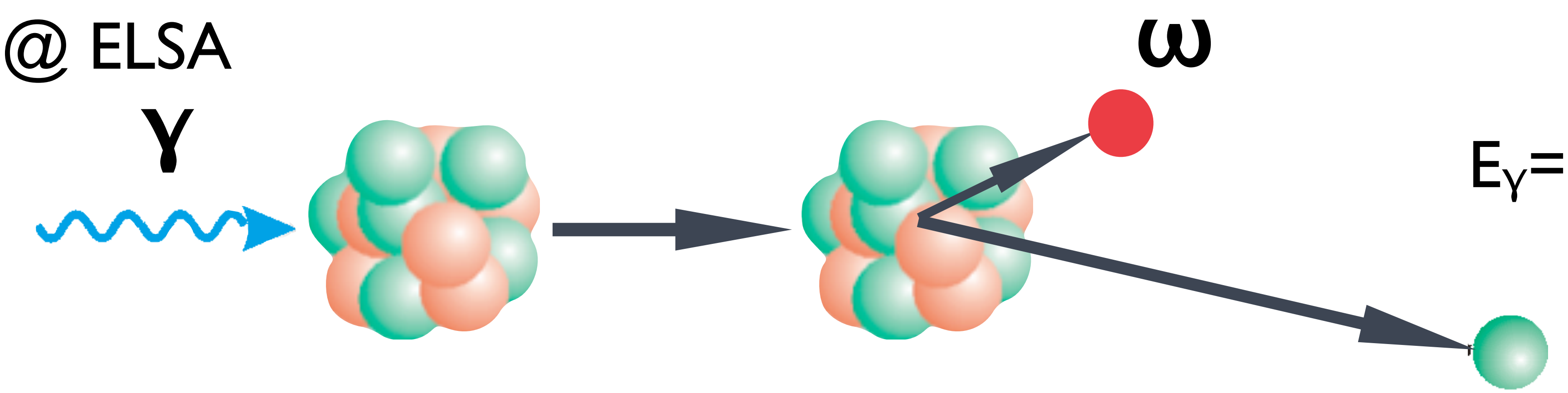
CBELSA/TAPS @ ELSA



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

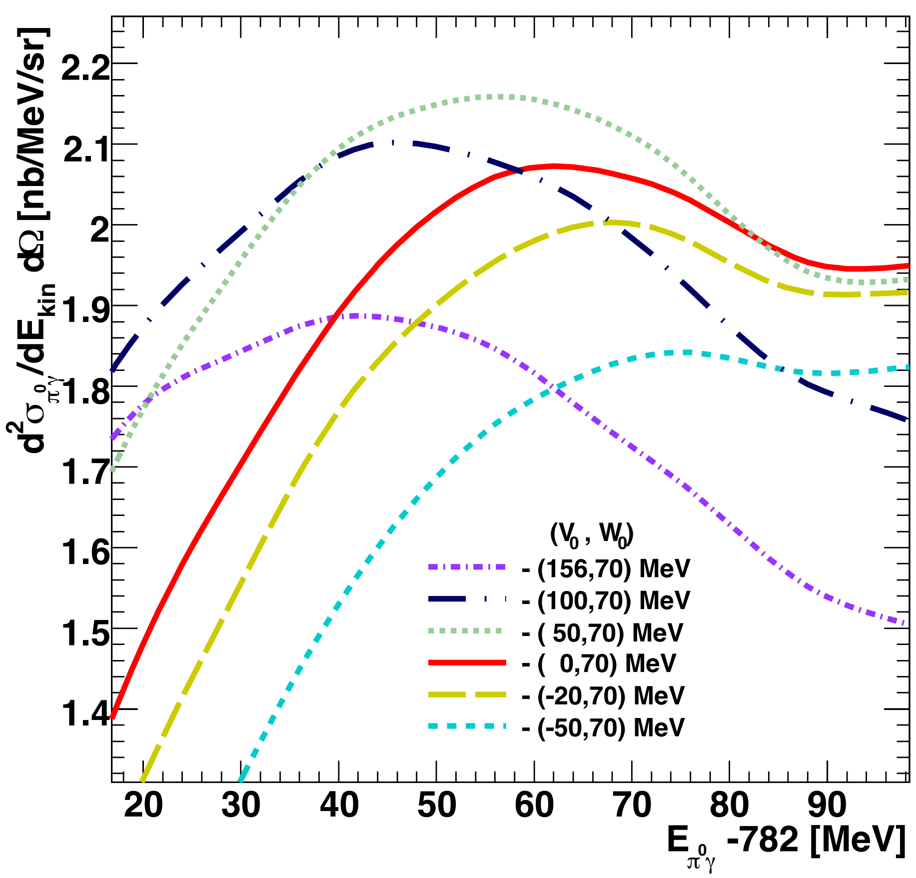


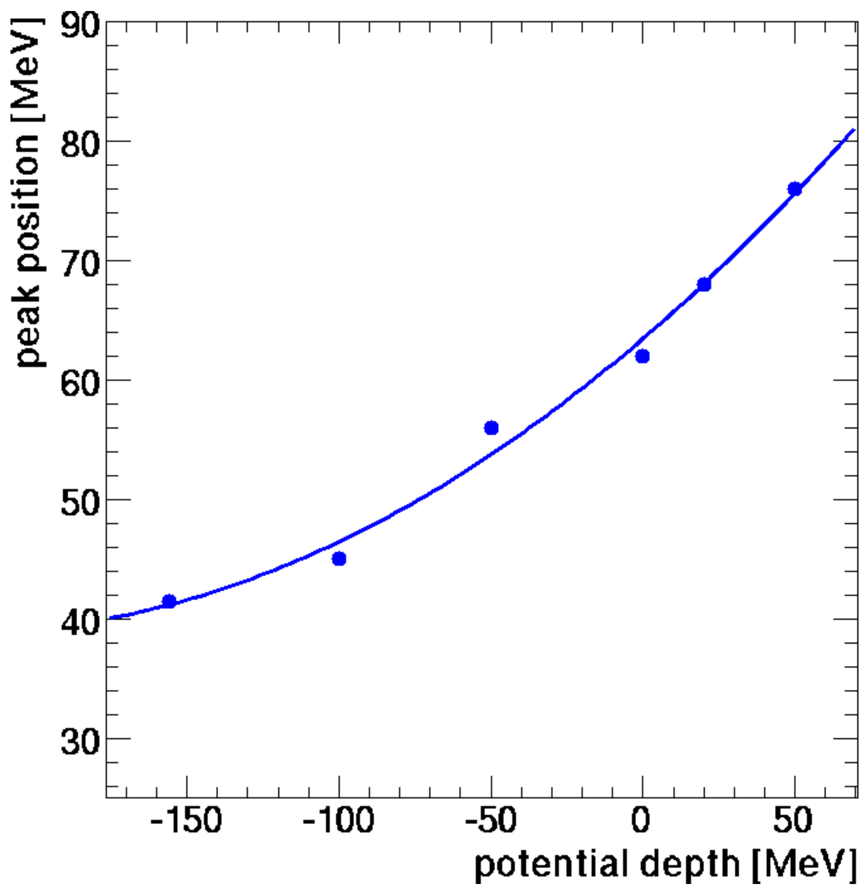
E_γ=1.25-3.1 GeV

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

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

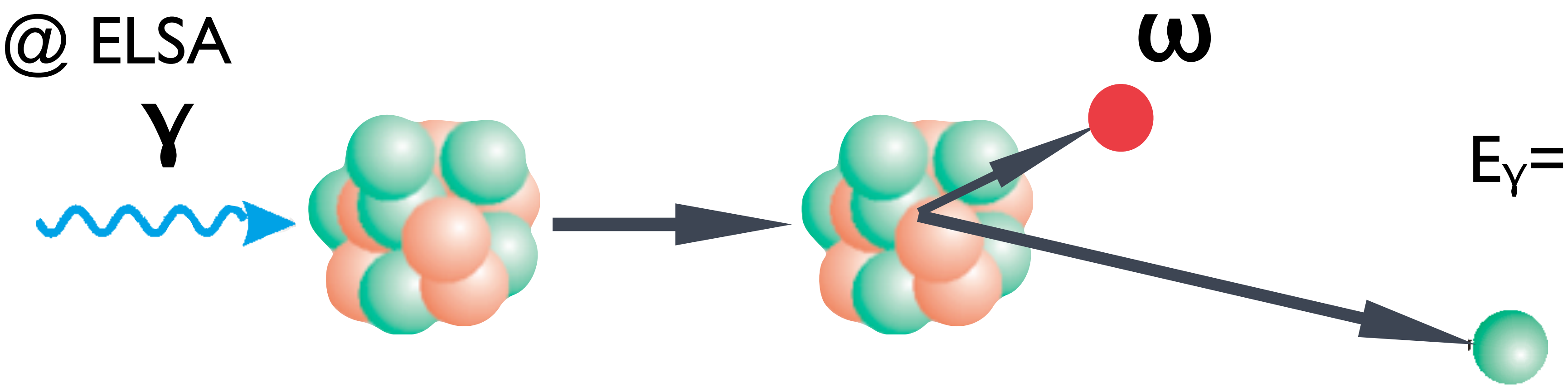
H. Nagahiro, priv. com.





real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA



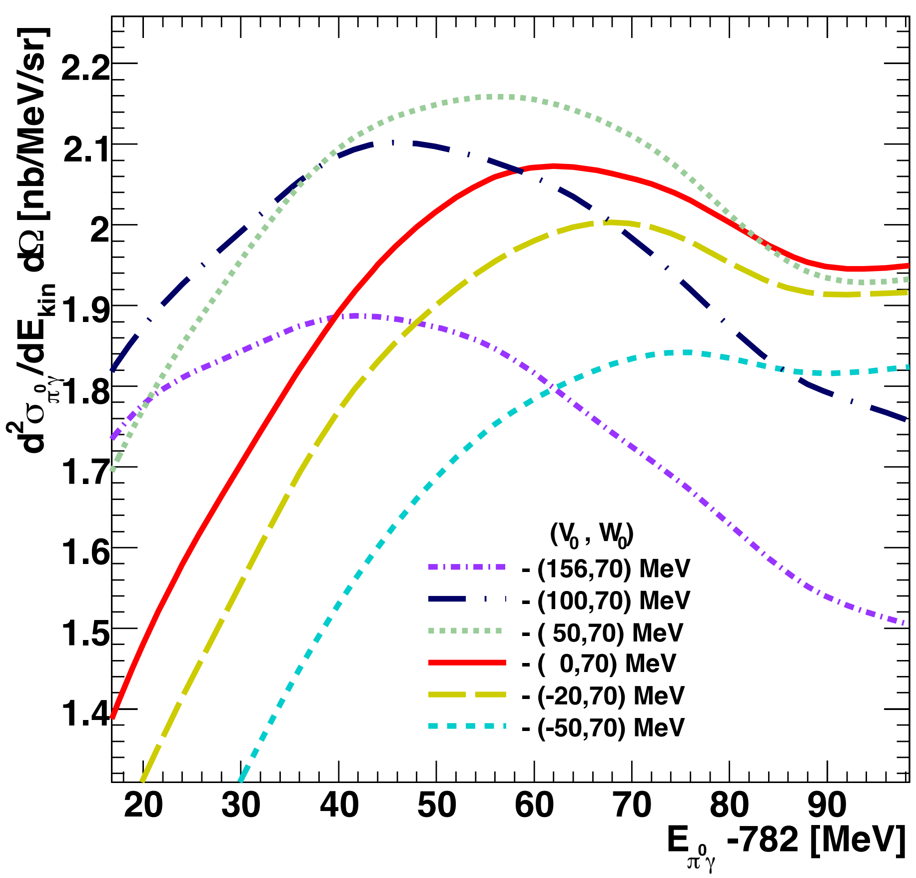
E_γ=1.25-3.1 GeV

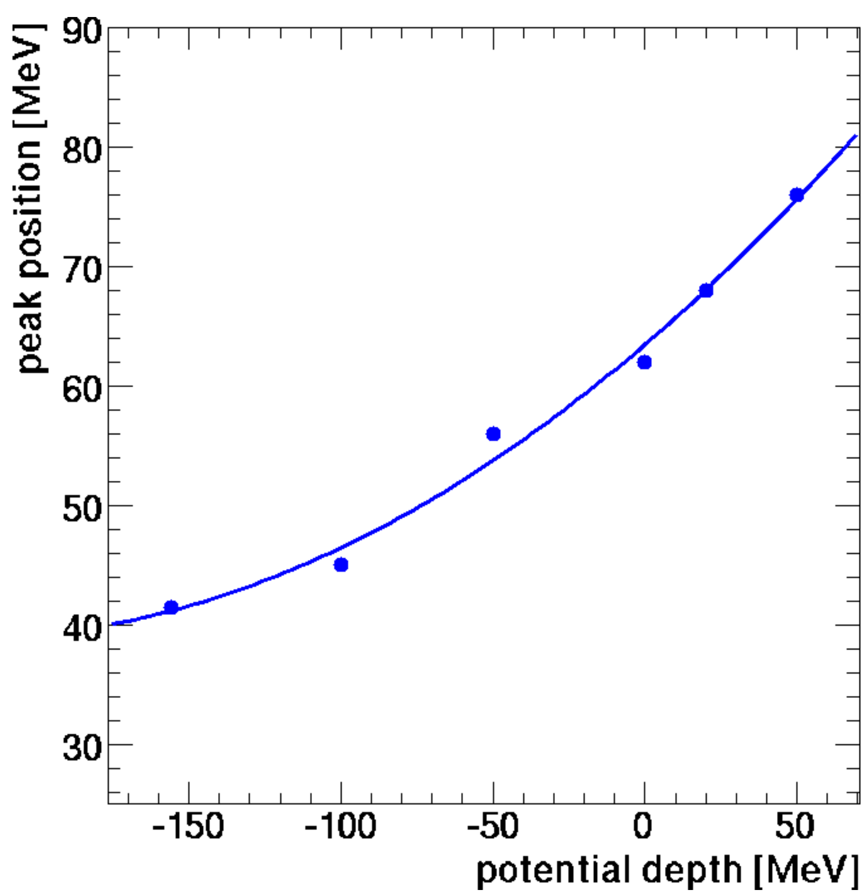
$1^0 \leq \theta_p \leq 11^0$

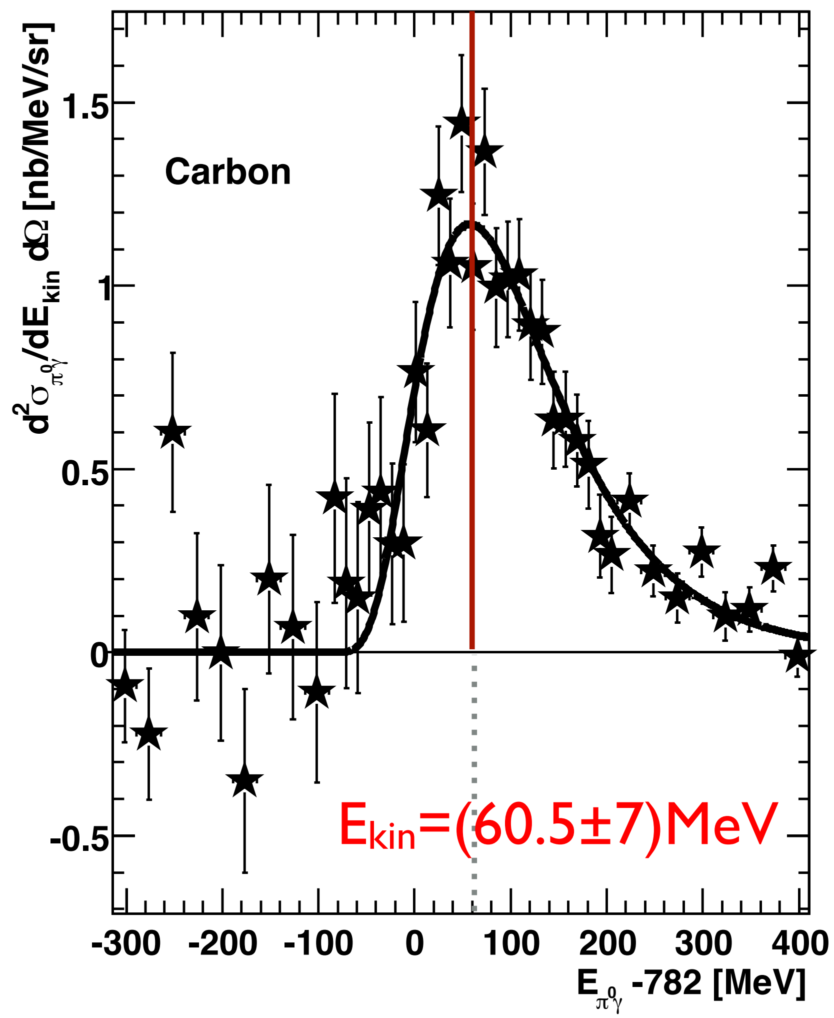
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.

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

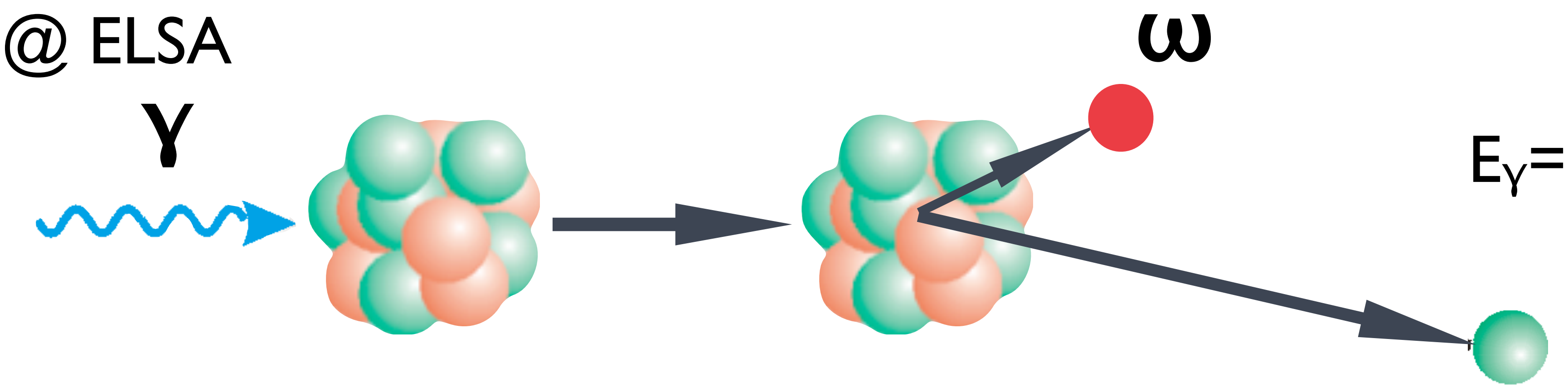






real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA

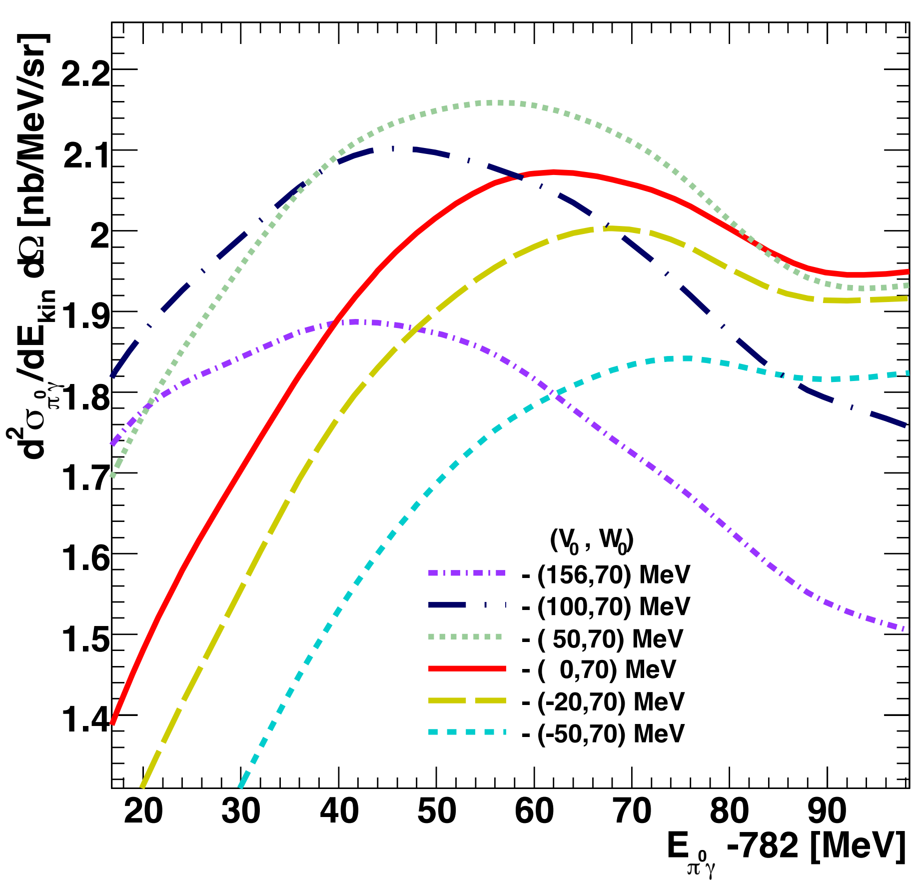


E_γ=1.25-3.1 GeV

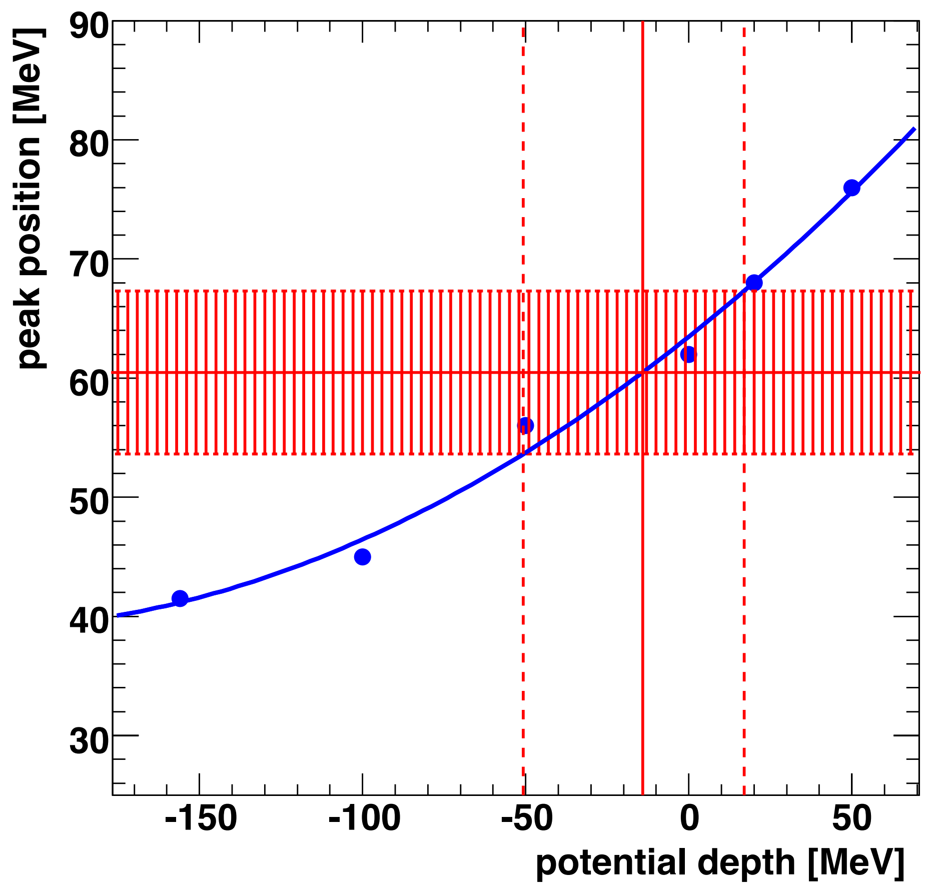
$1^0 \leq \theta_p \leq 11^0$

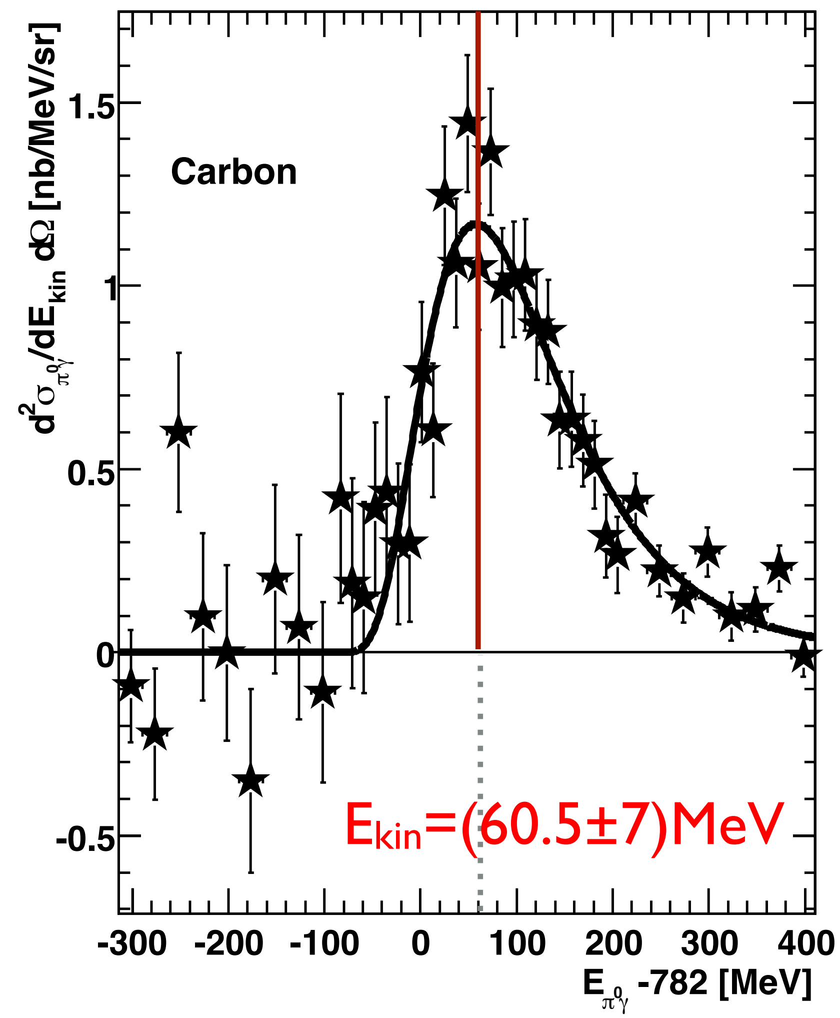
the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.



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





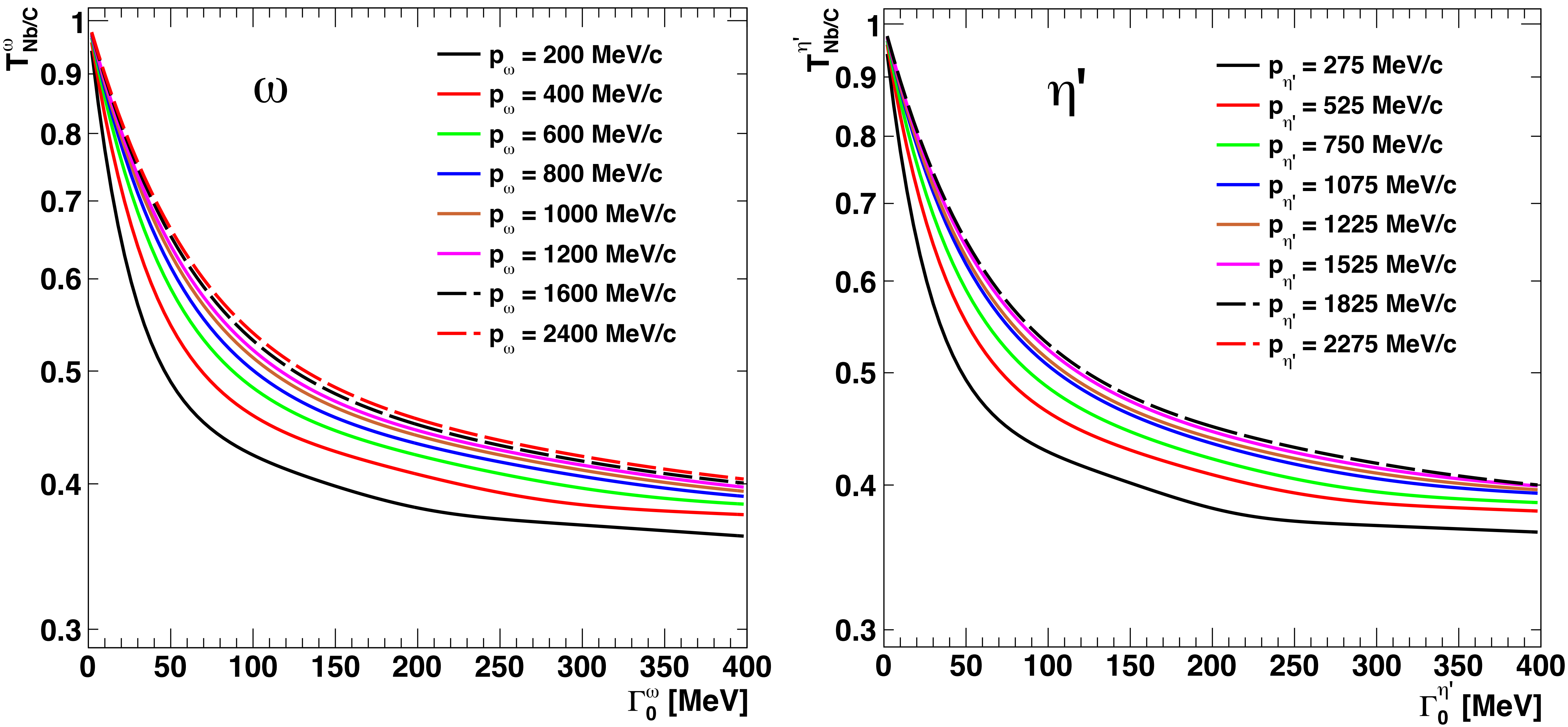
$V_\omega(p_\omega \approx 300\ \text{MeV/c};\ \rho=\rho_0) = -(15\pm35)$ MeV

in-medium width from transparency ratio

Glauber model

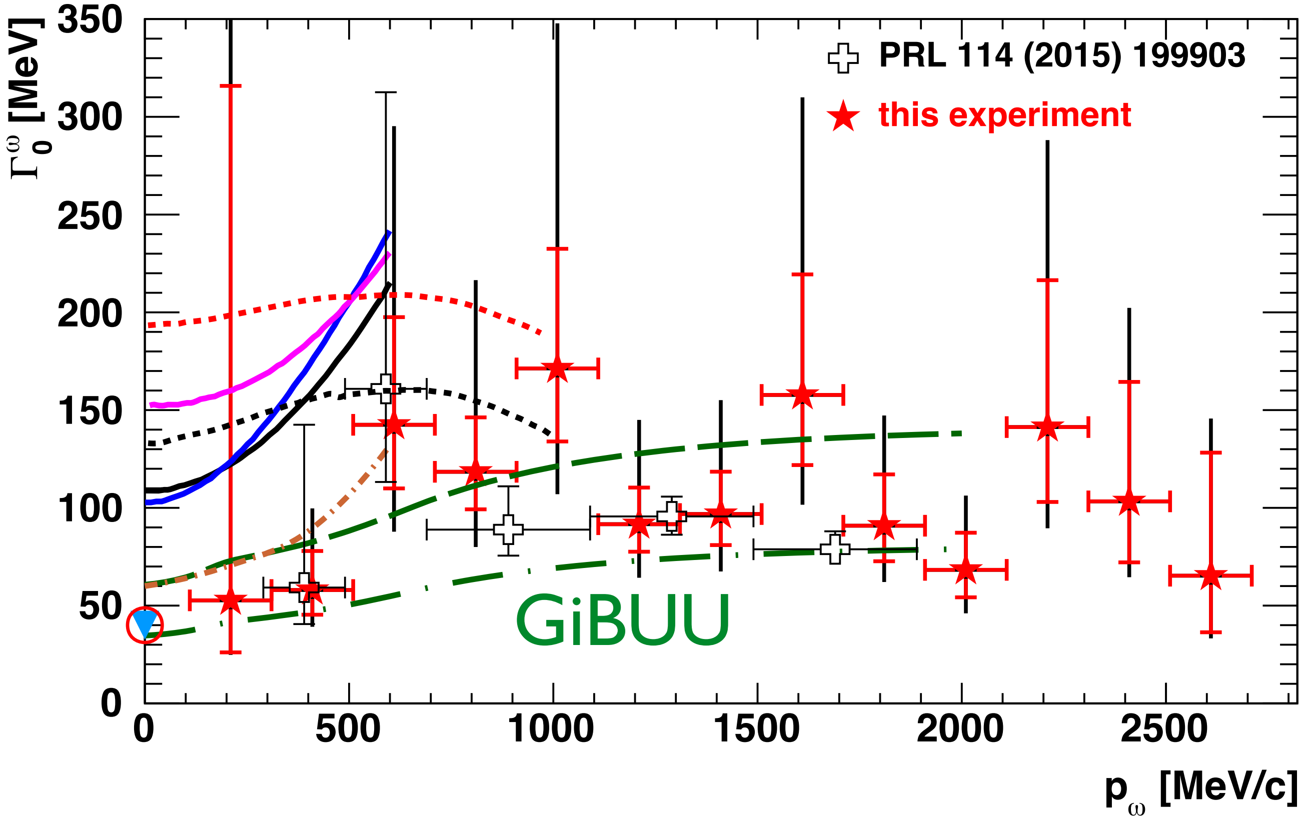
in high energy eikonal approximation

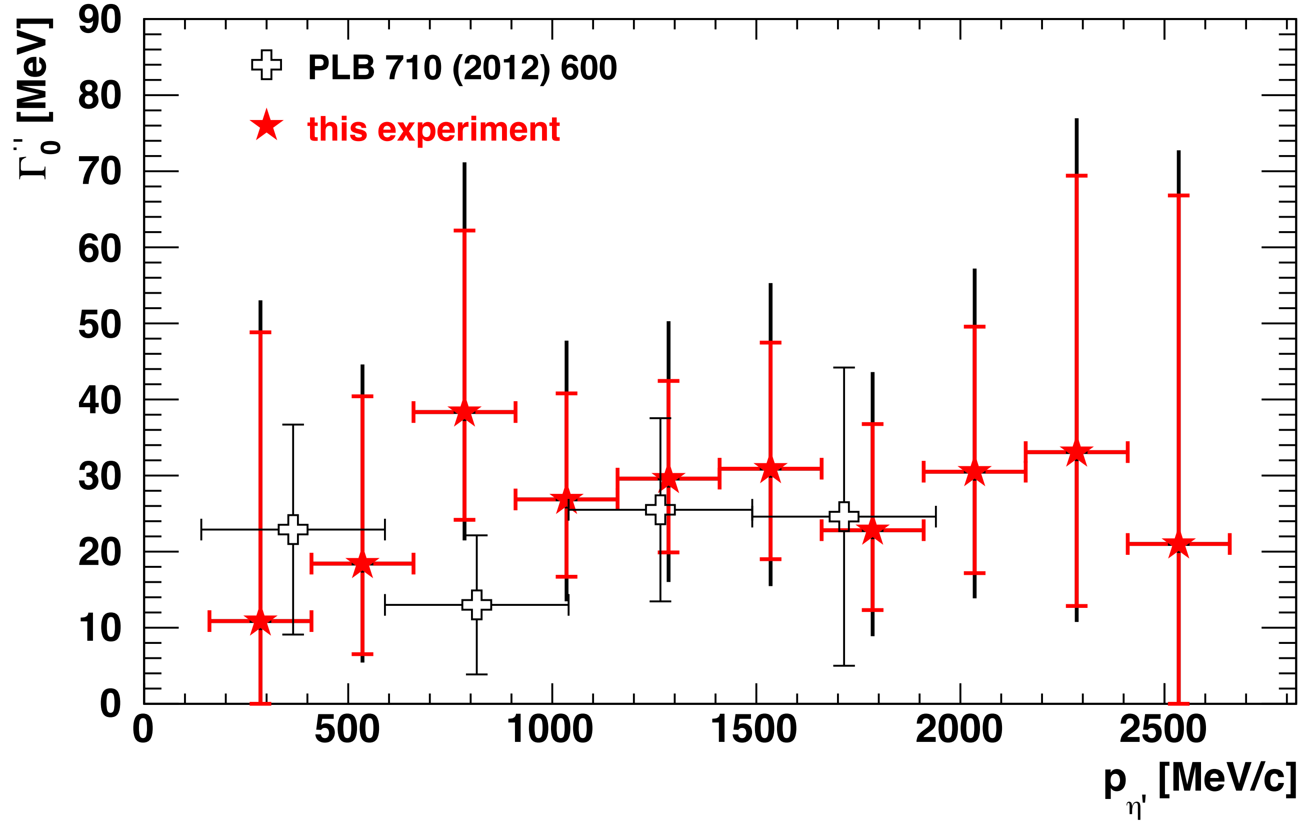
$T_{Nb/C}(p) \longleftrightarrow \Gamma_0(p)$



momentum dependence of ω, η' in-medium width

S. Friedrich et al., EPJA 52 (2016) 297





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

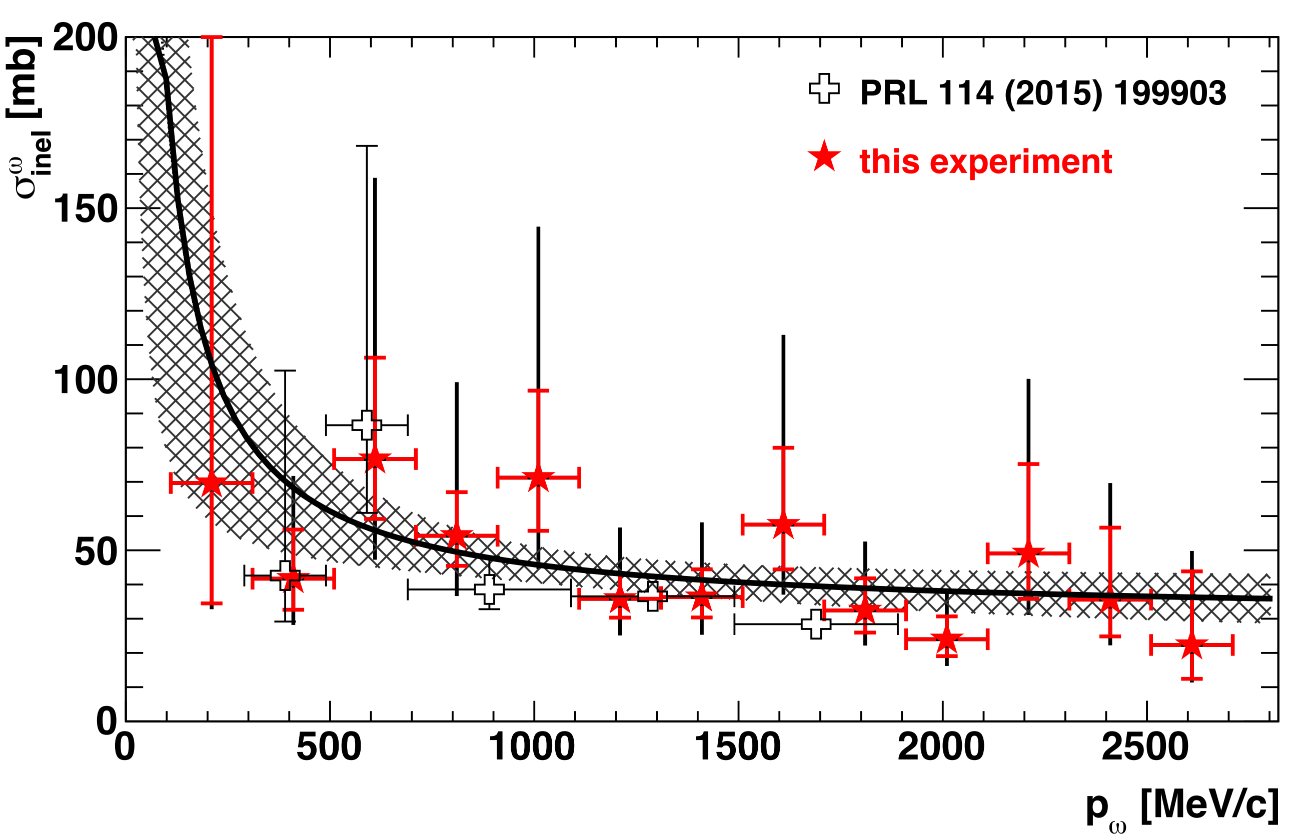
A. Ramos et al., EPJA 49 (2013)148

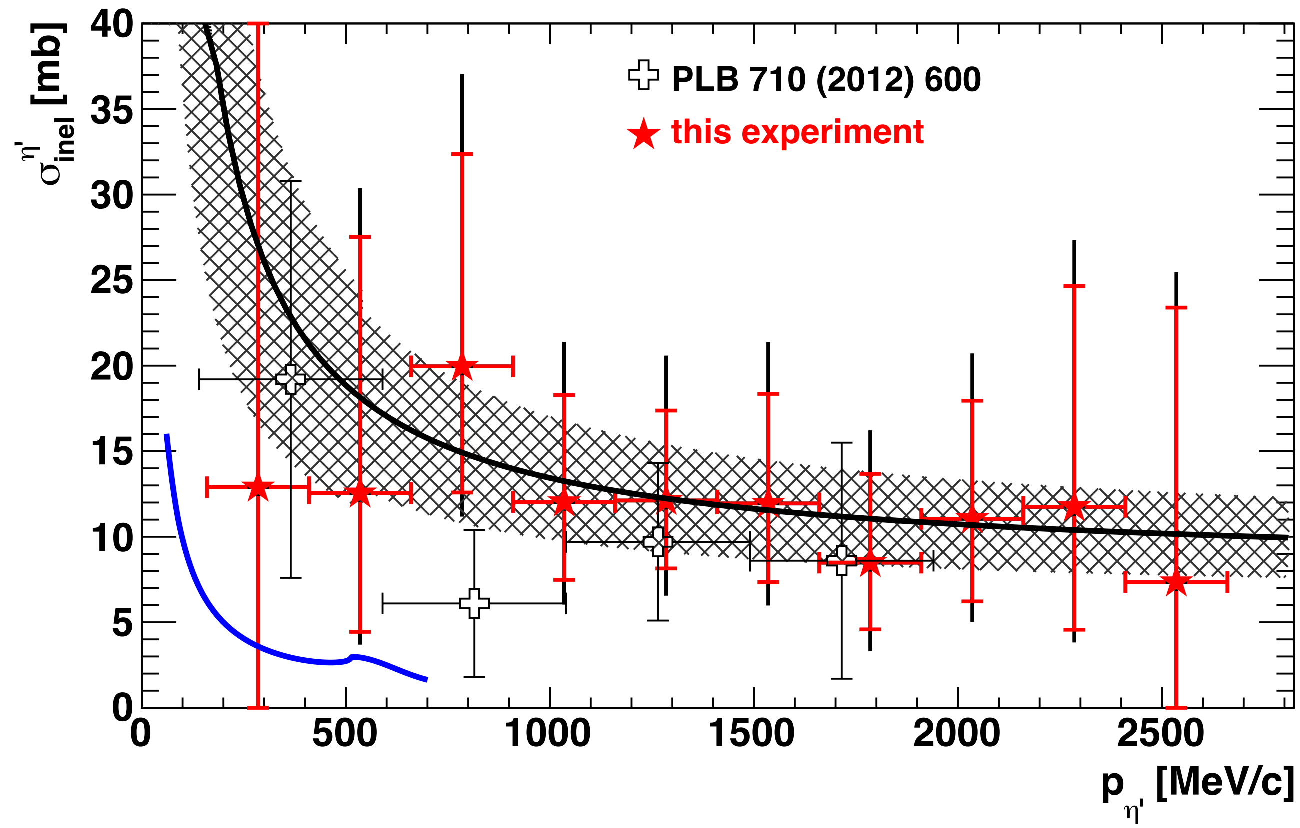
D. Cabrera and R. Rapp, PLB 729 (2014)67

inelastic absorption cross section σ_{inel}

low density approximation

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





E. Oset and A. Ramos, PLB 704 (2012) 334

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

a=15.5±15.1
b=30.3±13.8

a=5.4±8.1
b=8.0±7.0

$\langle \sigma_{inel}(p) \rangle$ = (13±3) mb