Experimental studies of the η'-nucleus interaction in photonuclear reactions

Mariana Nanova, Volker Metag

II. Physikalisches Institut

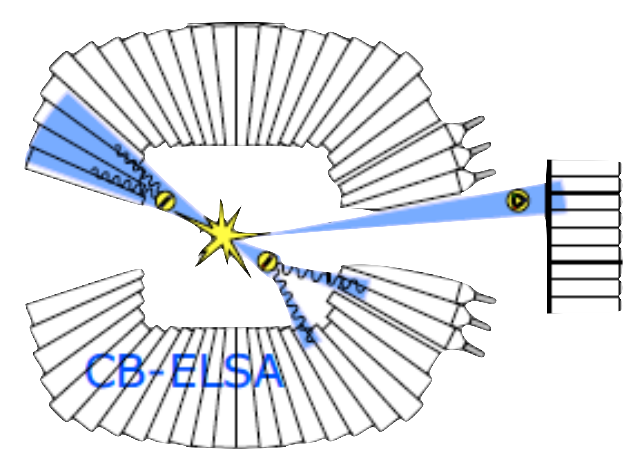
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

outline

- introduction
- scattering length
- complex meson-nucleus potentials
- theoretical predictions
- experimental approaches
- experimental results on the η'-nucleus potential
- search for η' mesic states
- summary and conclusion

Experimental Physics II

EMMI Workshop
“Meson and Hyperon Interaction with Nuclei”
Sep. 14-16 2022, Kitzbühel, Austria



Introduction: bound systems

earth ↔ moon

bound by gravitation

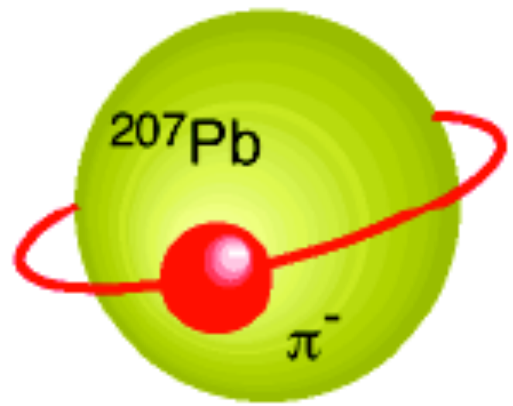
Introduction: bound systems

earth ↔ moon

bound by gravitation

charged meson

π^- ↔ nucleus



bound by superposition of attractive Coulomb- and repulsive strong interaction

talk by Kenta Itahashi

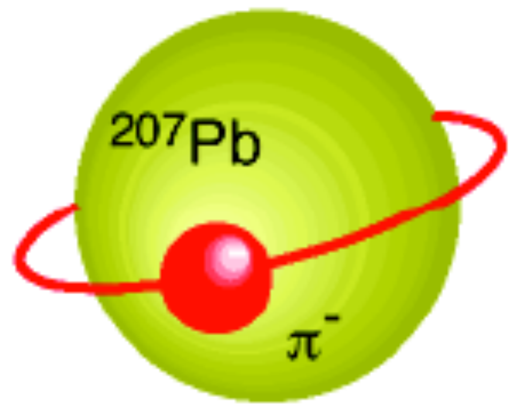
Introduction: bound systems

earth ↔ moon

bound by gravitation

charged meson

π^- ↔ nucleus



bound by superposition of attractive Coulomb- and repulsive strong interaction

talk by Kenta Itahashi

neutral meson

ω, η' ↔ nucleus

bound solely by the strong interaction

?

talk by Yoshiki Tanaka

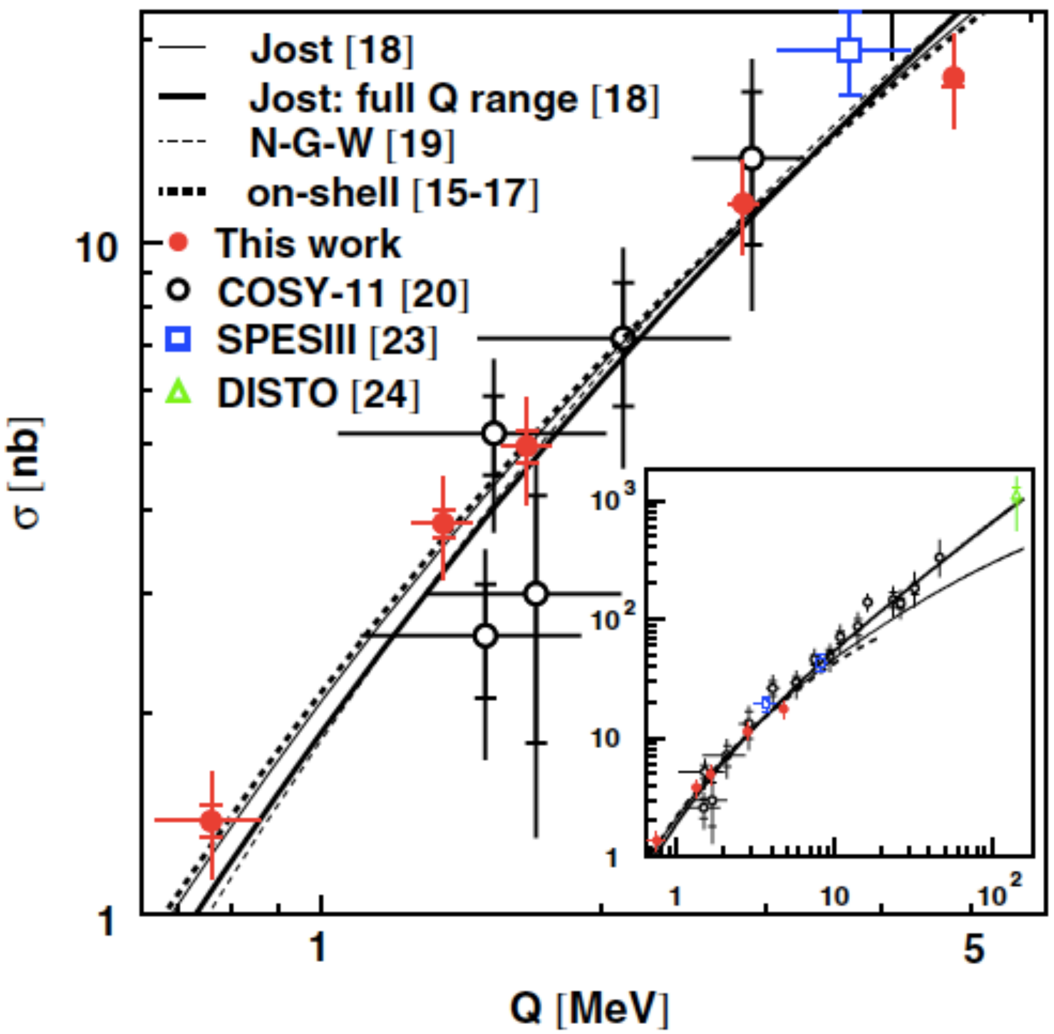
Determinations of the η' scattering length

p p → p p η'

γ p → p η'

near threshold measurement!!!

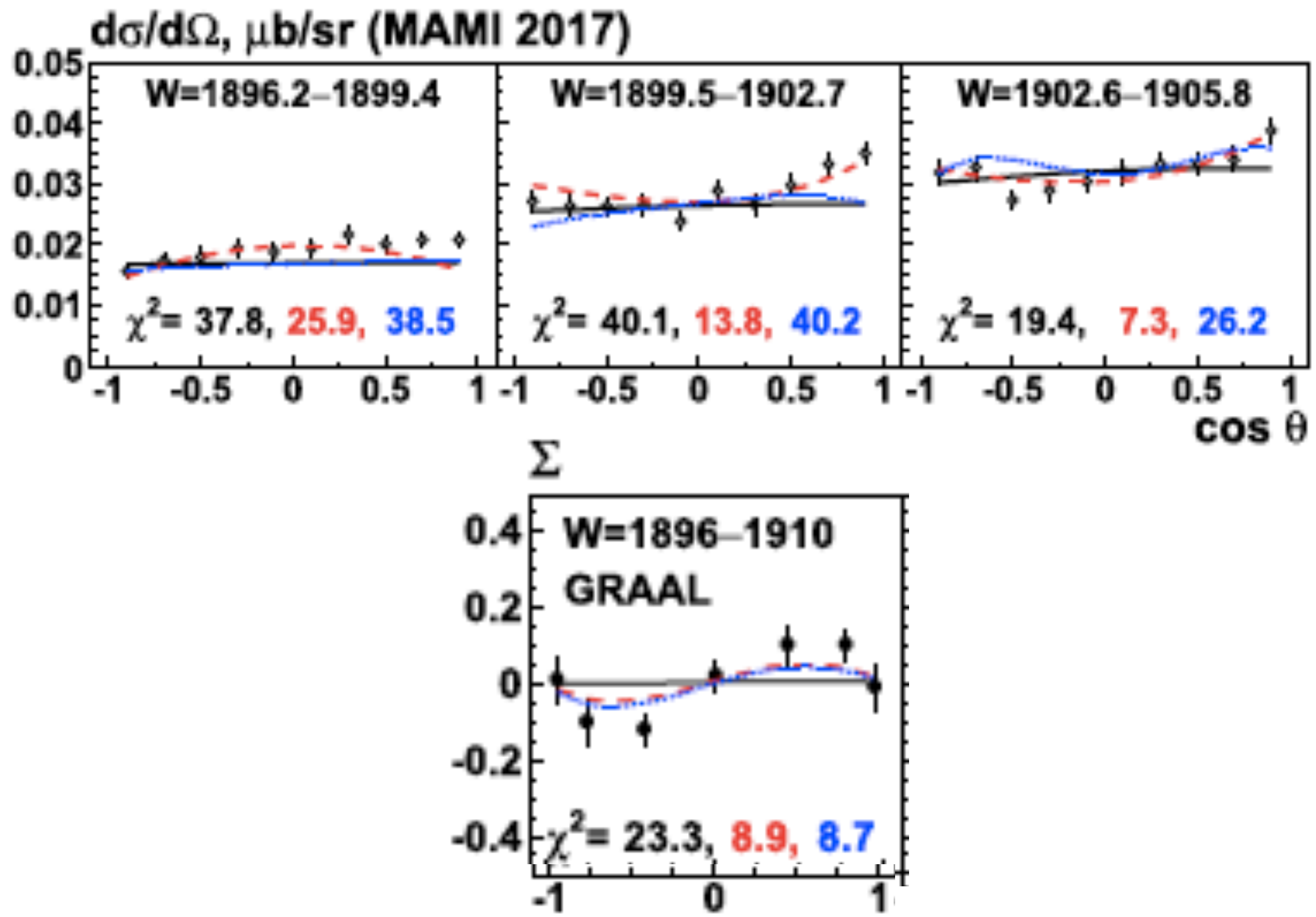
E. Czerwinski et al., PRL 113 (2014) 062004



$a_{\eta' p} = (0 \pm 0.43) + i(0.37^{+0.40}_{-0.16})\,\mathrm{fm}$

$|a_{\eta' p}| = 0.37^{+0.59}_{-0.46}$ fm

A. V. Anisovich et al. PLB 785 (2018) 626



$|a_{\eta' p}| = 0.403 \pm 0.015 \pm 0.06$ fm

$\delta_{\eta' p} = (87 \pm 2)^0$

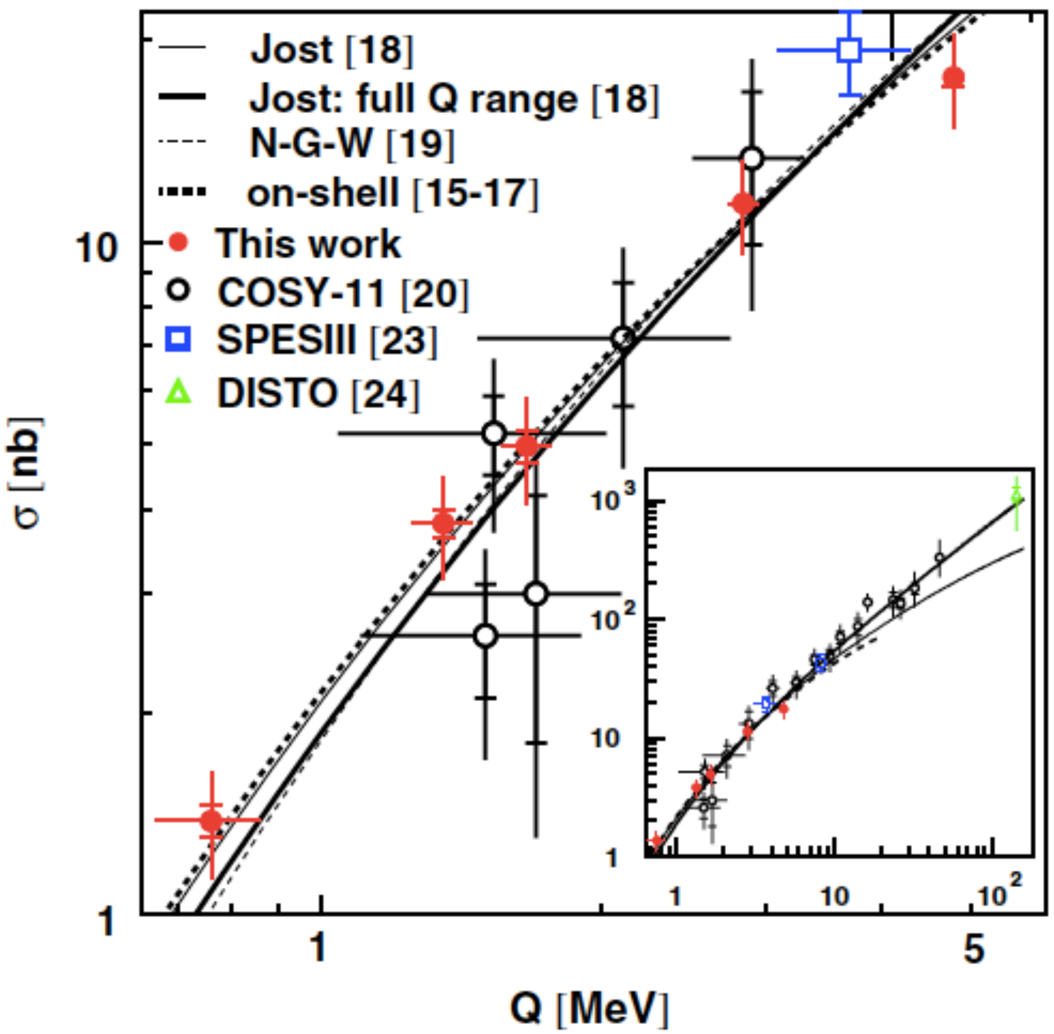
Determinations of the η’ scattering length

$p\,p \to p\,p\,\eta'$

$\gamma\,p \to p\,\eta'$

near threshold measurement!!!

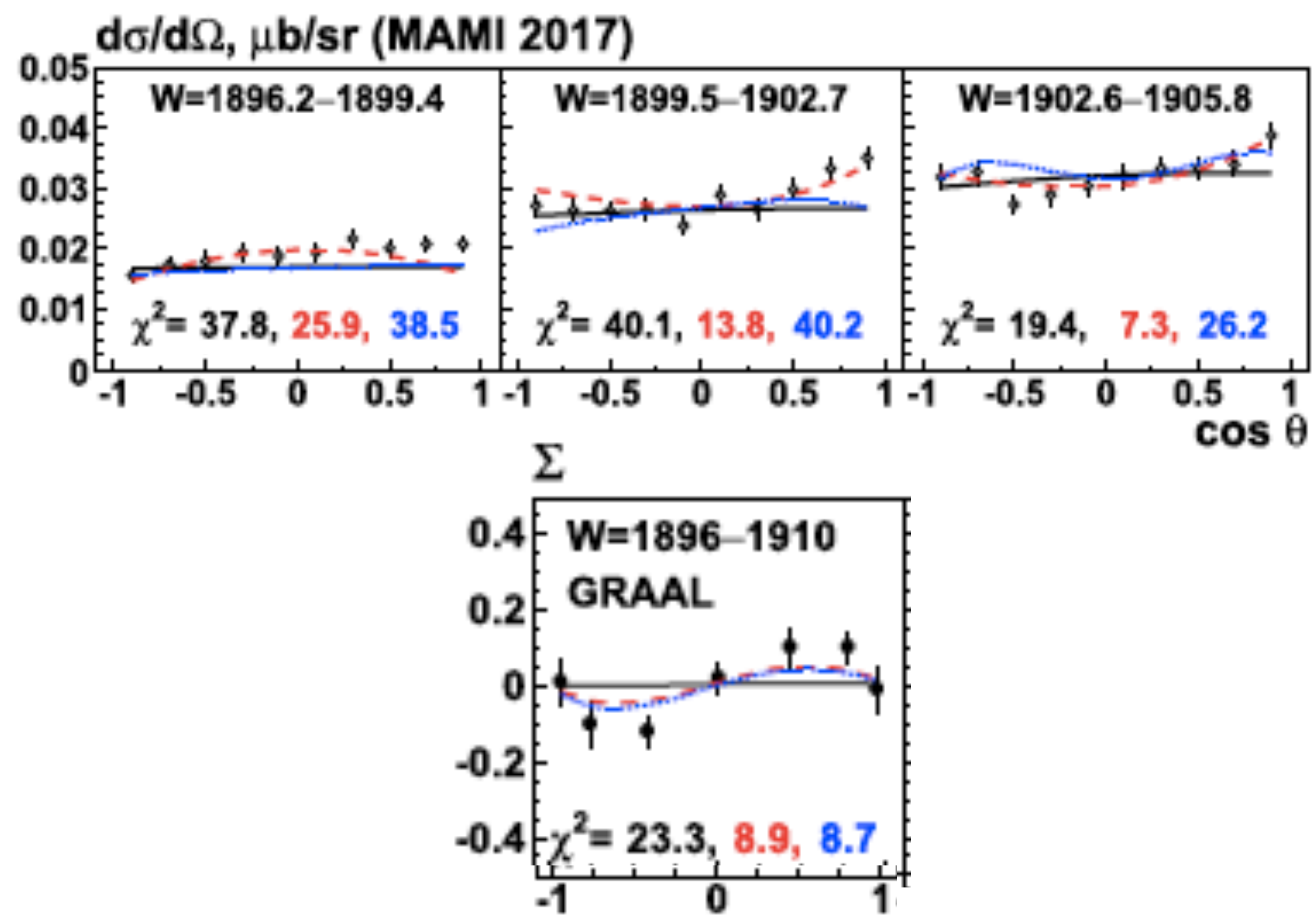
E. Czerwinski et al., PRL 113 (2014) 062004



$$a_{\eta' p} = (0\pm0.43) + i(0.37^{+0.40}_{-0.16})\,\mathrm{fm}$$

$$|a_{\eta' p}| = 0.37^{+0.59}_{-0.46}\ \mathrm{fm}$$

A. V. Anisovich et al. PLB 785 (2018) 626



$$|a_{\eta' p}| = 0.403\pm0.015\pm0.06\ \mathrm{fm}$$

$$\delta_{\eta' p} = (87\pm2)^0$$

modulus in agreement !

Meson-nucleus complex potential

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

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

Meson-nucleus complex potential

H. Nagahiro, 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

⇕

in-medium mass modification

Meson-nucleus complex potential

H. Nagahiro, 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

⇕

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

⇕

lifetime shortened

in-medium width

inelastic cross section

Meson-nucleus complex potential

H. Nagahiro, 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

⇳

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

⇳

lifetime shortened

in-medium width

inelastic cross section

mass and lifetime (width) may be changed in the medium

Meson-nucleus complex potential

H. Nagahiro, 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

⇕

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

⇕

lifetime shortened

in-medium width

inelastic cross section

mass and lifetime (width) may be changed in the medium

η' -nucleus potential derived from η'- p scattering length

E. Friedman and A. Gal, Phys. Rep. 452 (2007) 89

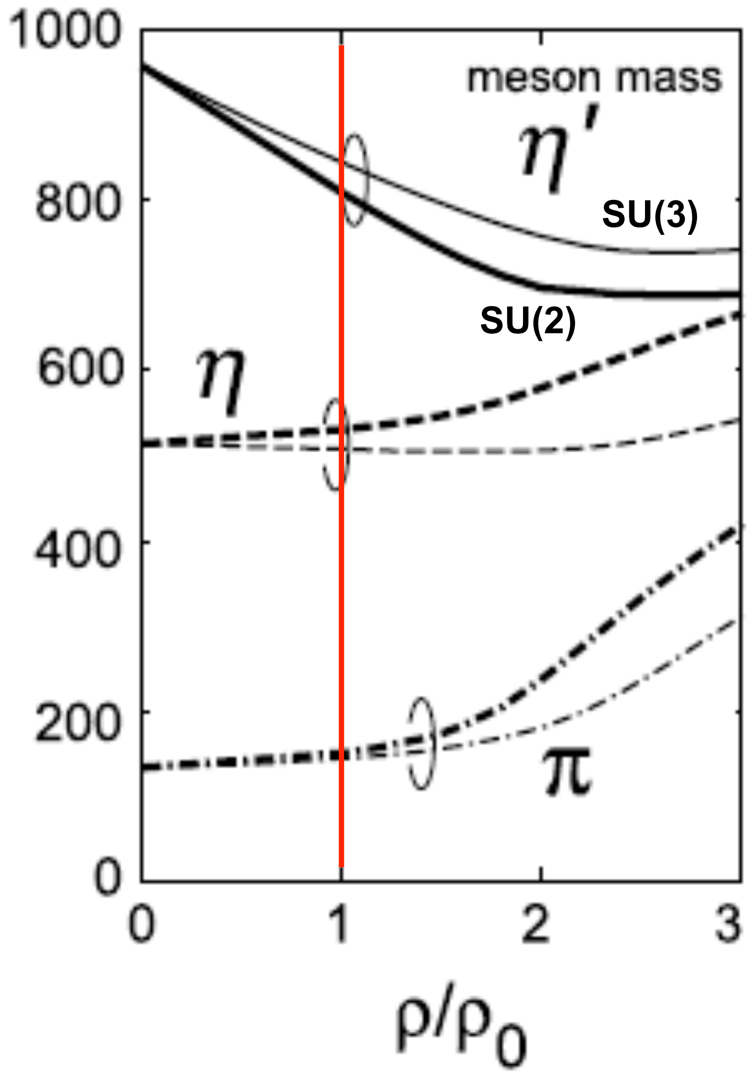
with $2\mu V_{opt} = -4\pi \left(1 + \frac{A-1}{A}\frac{\mu}{M_N}\right) a \rho \hbar^2$ and $\mu = \frac{M_{\eta'} \bullet M_A}{M_{\eta'} + M_A}$

$$U_0 = V_0 + i W_0 = -(0 \pm 37.9 + i \bullet 32.6^{+35.2}_{-14.1}) \text{ MeV}$$

Model predictions for the real part of the η'A interaction

NJL-model

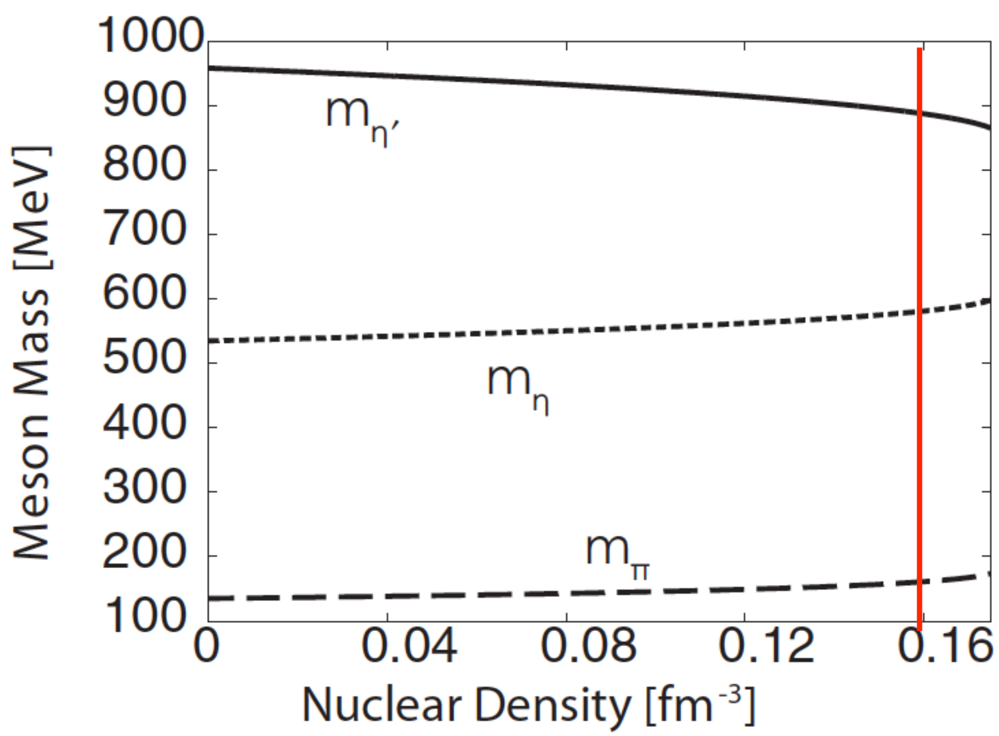
H. Nagahiro, M. Takizawa and S. Hirenzaki,
Phys. Rev. C 74 (2006) 045203



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

linear σ model

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



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

QMC-model

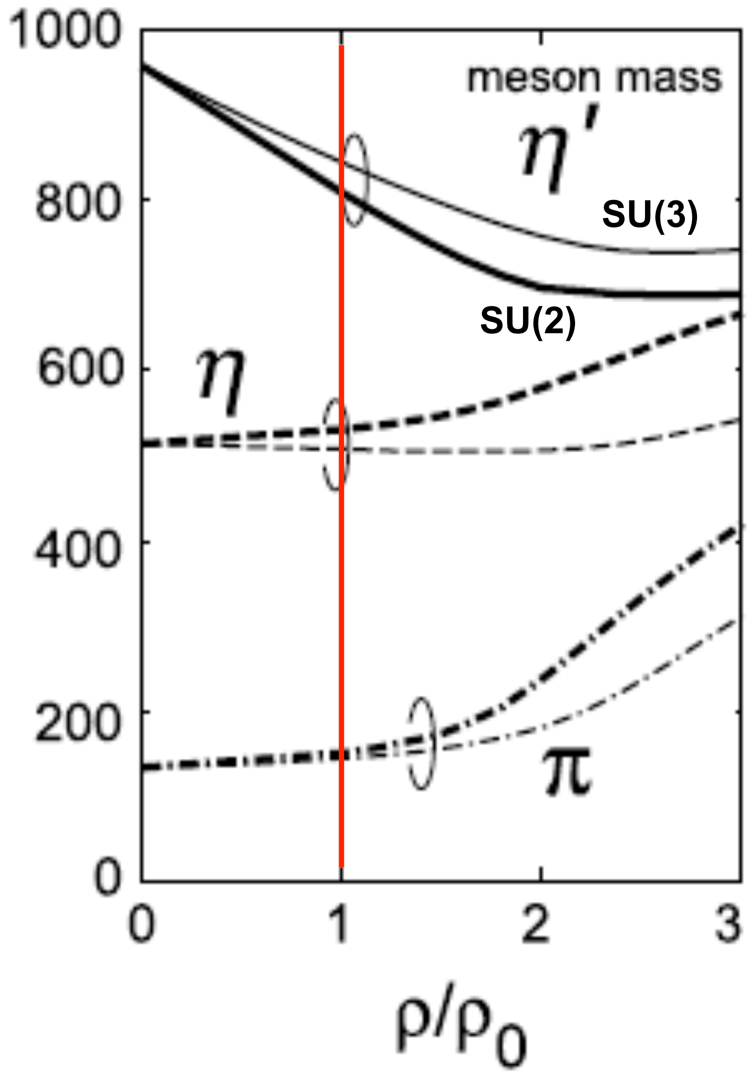
S. Bass and A. Thomas,
PLB 634 (2006) 368

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

Model predictions for the real part of the η'A interaction

NJL-model

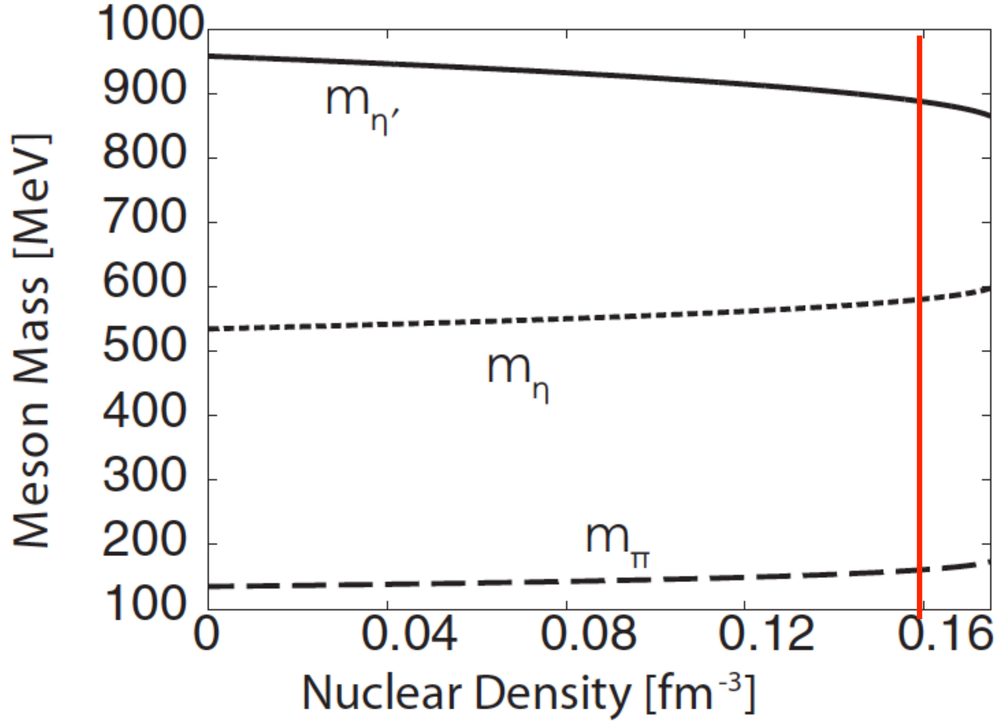
H. Nagahiro, M. Takizawa and S. Hirenzaki,
Phys. Rev. C 74 (2006) 045203



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

linear σ model

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



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

QMC-model

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

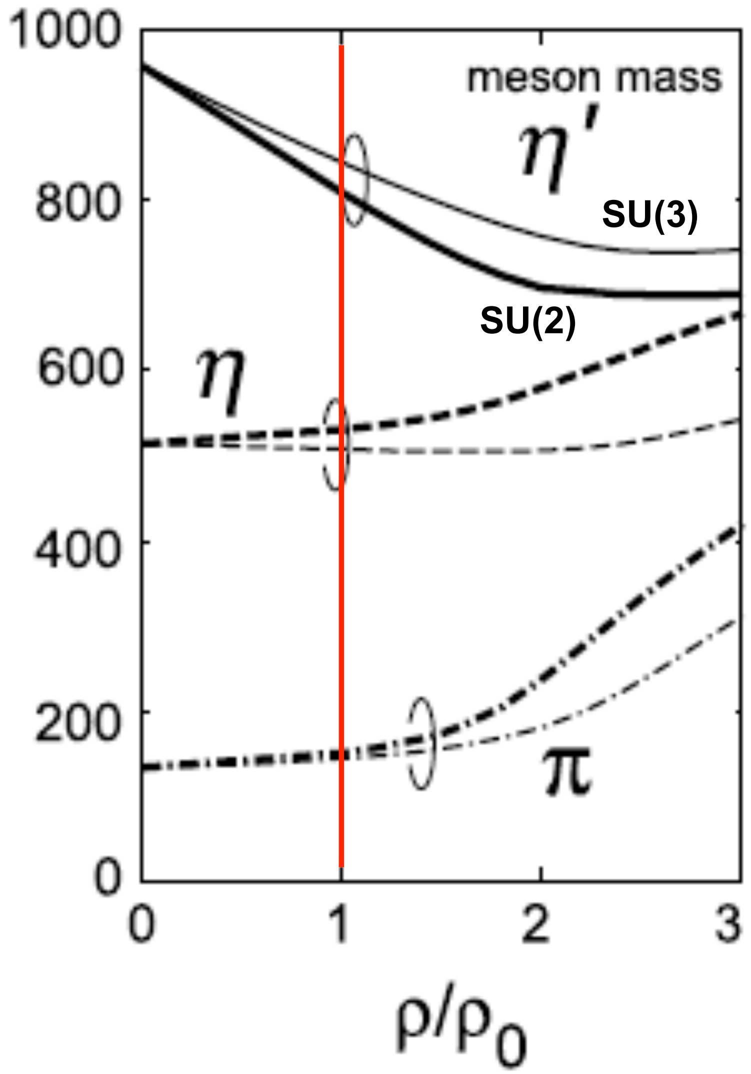
$\Delta m_{\eta'}(\rho_0) \approx -40$ MeV
for $\theta_{\eta\eta'} = -20^0$

throughout attractive potential predicted!
in
conflict with $a_{\eta' p}$?

Model predictions for the real part of the η'A interaction

NJL-model

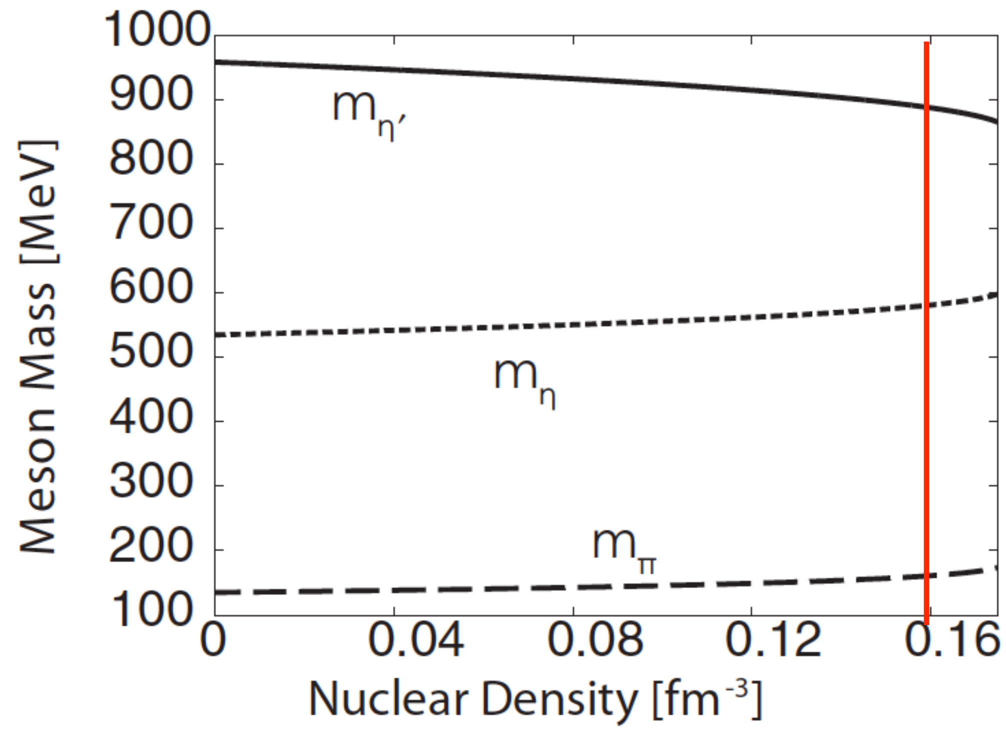
H. Nagahiro, M. Takizawa and S. Hirenzaki,
Phys. Rev. C 74 (2006) 045203



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

linear σ model

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



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

QMC-model

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

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

throughout attractive potential predicted!
in conflict with $a_{\eta' p}$?

experimental clarification needed!

From theoretical predictions to experimental observables

calculations of meson spectral functions assume:

- infinitely extended nuclear matter in equilibrium at ρ, T = const.;
- meson at rest in nuclear medium

From theoretical predictions to experimental observables

calculations of meson spectral functions assume:

- infinitely extended nuclear matter in equilibrium at ρ, T = const.;
- meson at rest in nuclear medium

theoretical predictions ⇨ experimental observables

From theoretical predictions to experimental observables

calculations of meson spectral functions assume:

- infinitely extended nuclear matter in equilibrium at ρ, T = const.;
- meson at rest in nuclear medium

transport calculations (GiBUU, HSD, UrQMD, JAM,…) or collision model calculations are needed for comparison with experiment !!!

theoretical predictions ⇨ transport/ collision model calculations ⇨ experimental observables

- initial state effects: absorption of incoming beam particles
- non equilibrium effects: varying density and temperature
- absorption and regeneration of mesons in the nuclear medium
- only fraction of decays inside of the nuclear environment
- final state interactions: distortion of momenta of decay products

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

*not applicable;

η' meson decays outside of nucleus;

$M_0 = 957.78$ MeV ; $\Gamma_0 = 0.194$ MeV;

$\lambda_{dec} = \hbar c/\Gamma_0 = 1000 fm >>> R_{nucl}$

Experimental approaches to determine the meson-nucleus optical potential

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

real part

imaginary part

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

- line shape analysis*
- excitation function
- momentum distribution
- meson-nucleus bound states

*not applicable;

η' meson decays outside of nucleus;

$M_0 = 957.78$ MeV ; $\Gamma_0 = 0.194$ MeV;

$$\lambda_{dec} = \hbar c/\Gamma_0 = 1000 fm >>> R_{nucl}$$

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

- transparency ratio measurement

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

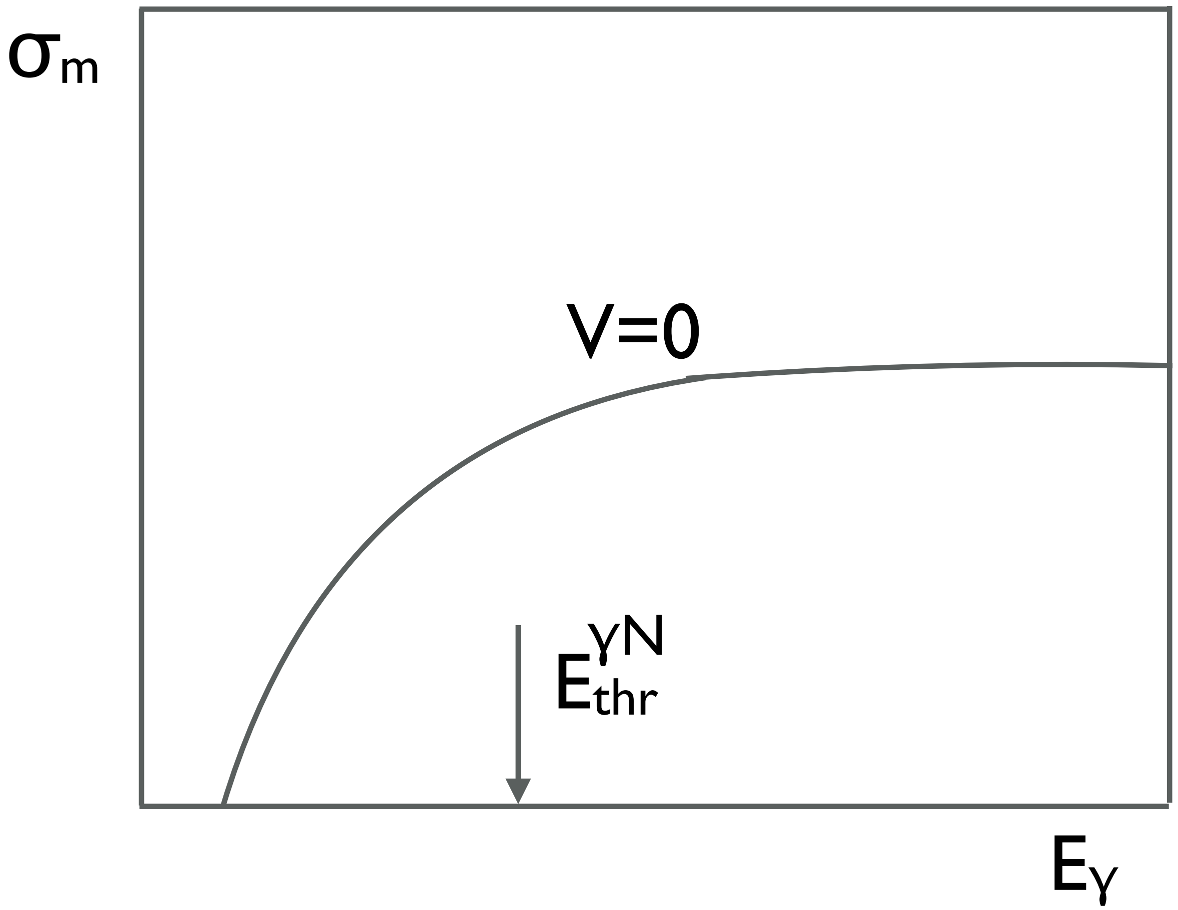
D. Cabrera et al., NPA 733 (2004)130

attenuation measurement of the η' meson flux

Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the **production point**

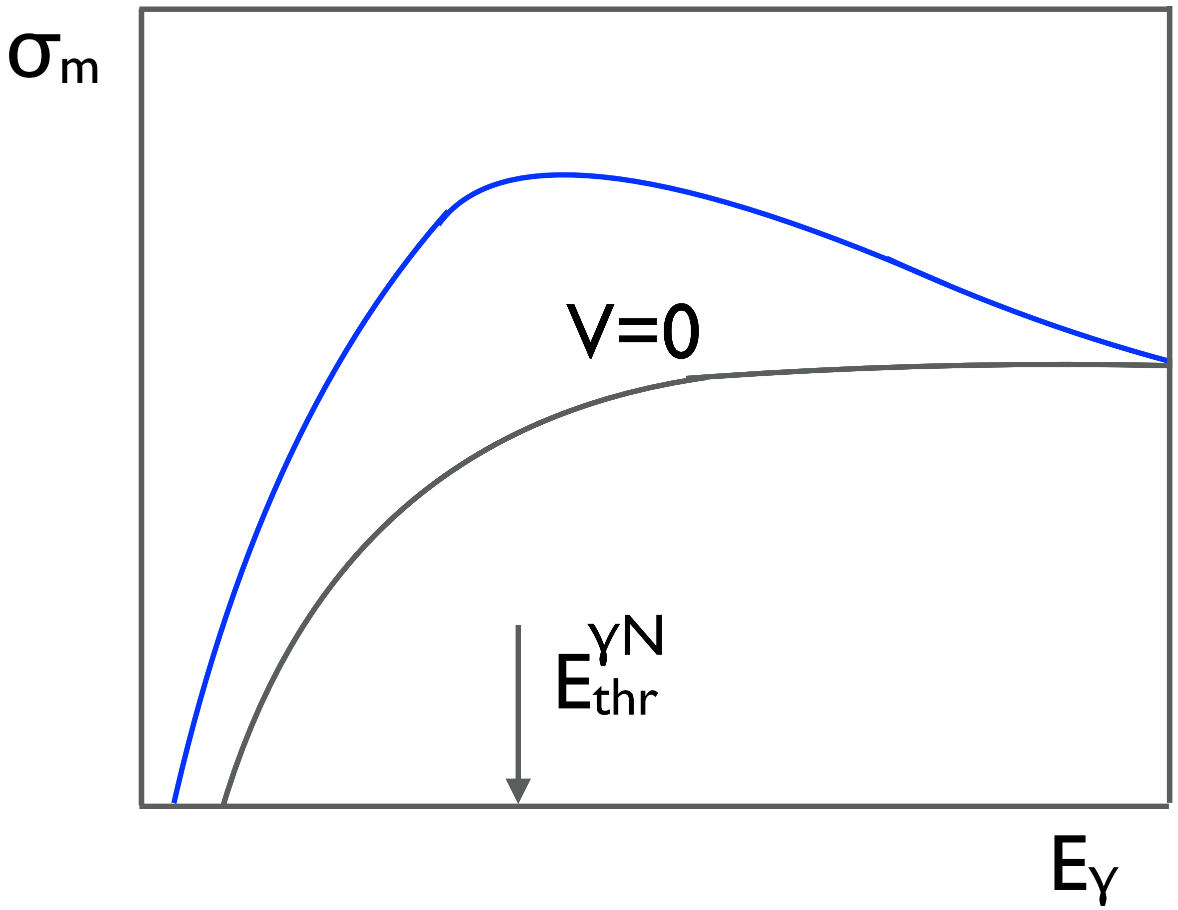
excitation function



Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the **production point**

excitation function

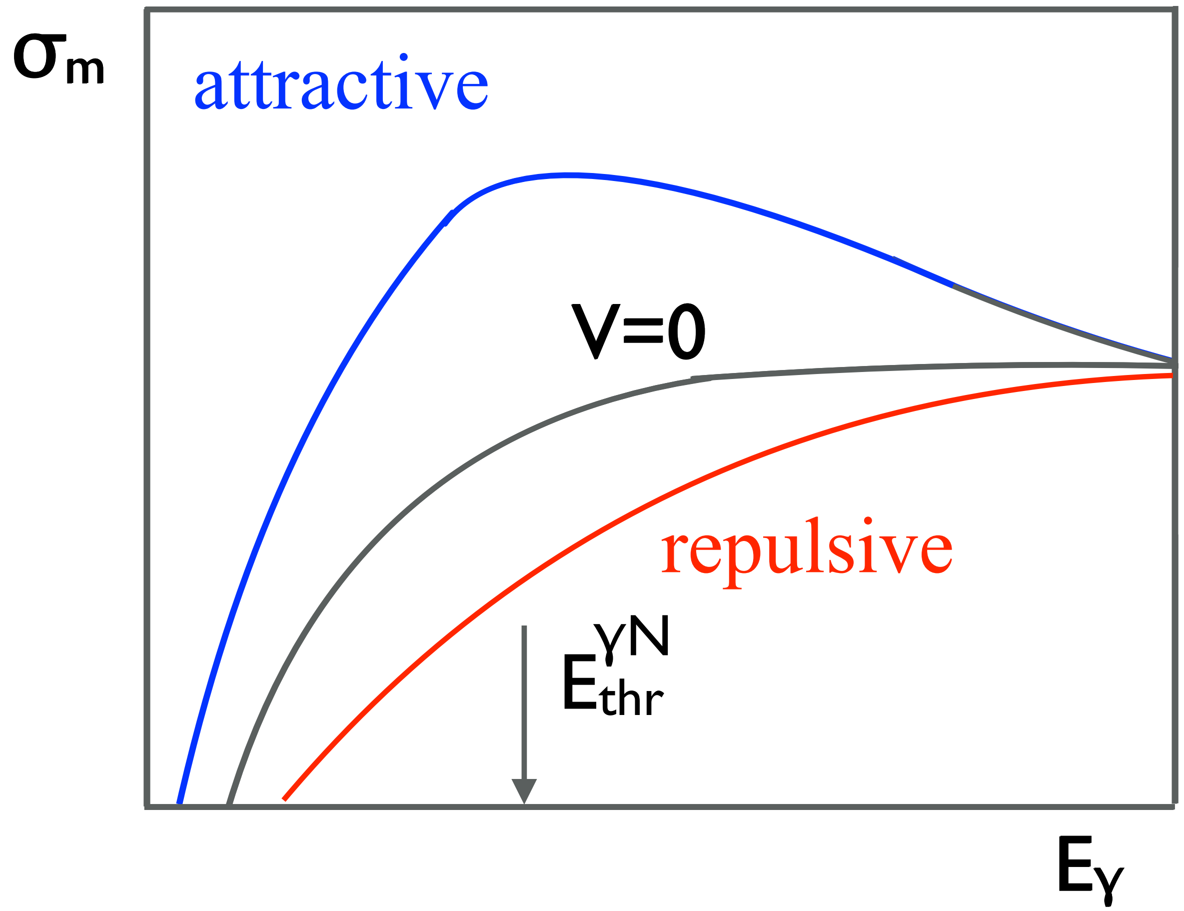


attractive interaction → mass drop →
lower threshold → larger phase space→
larger cross section

Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the **production point**

excitation function

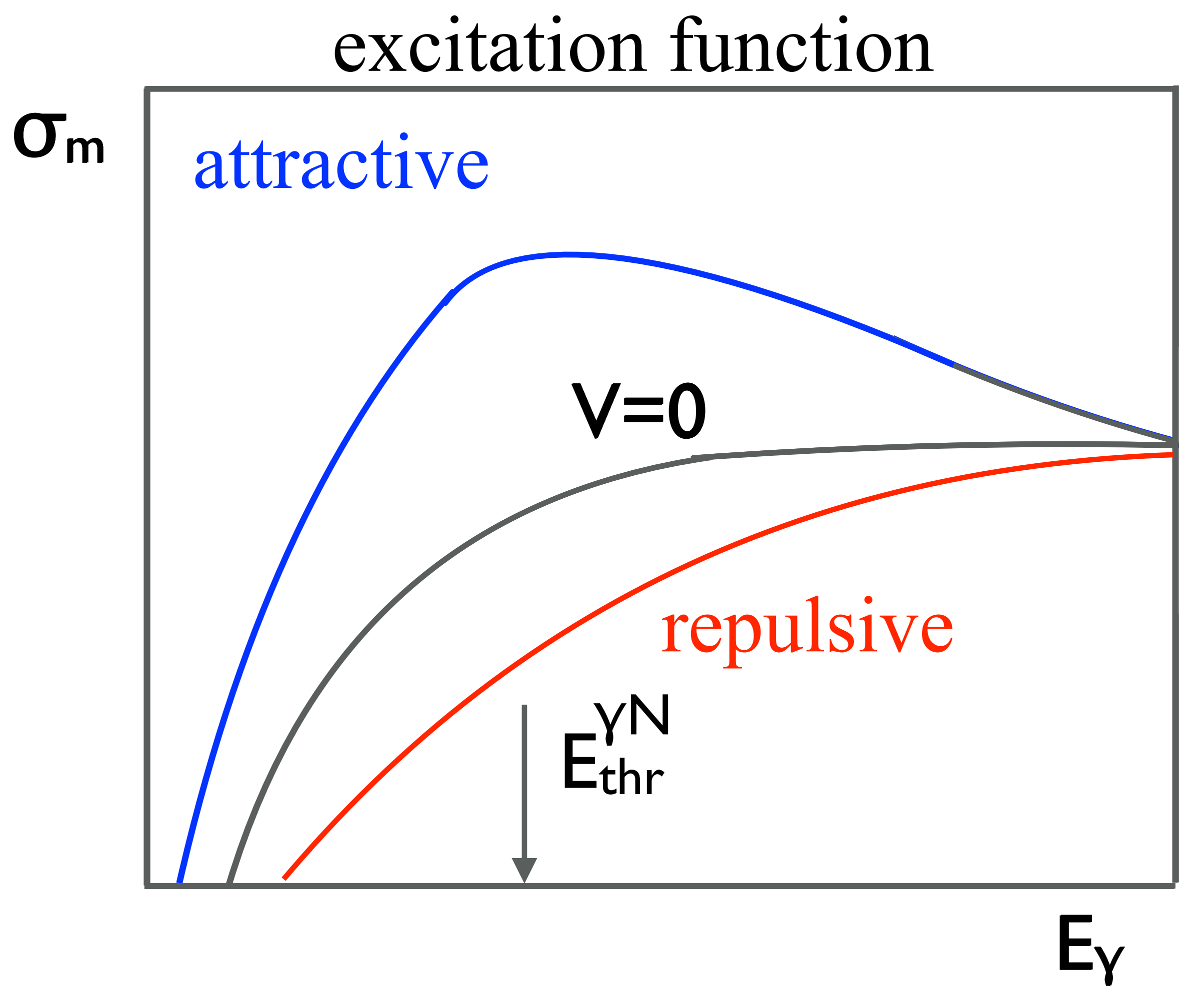


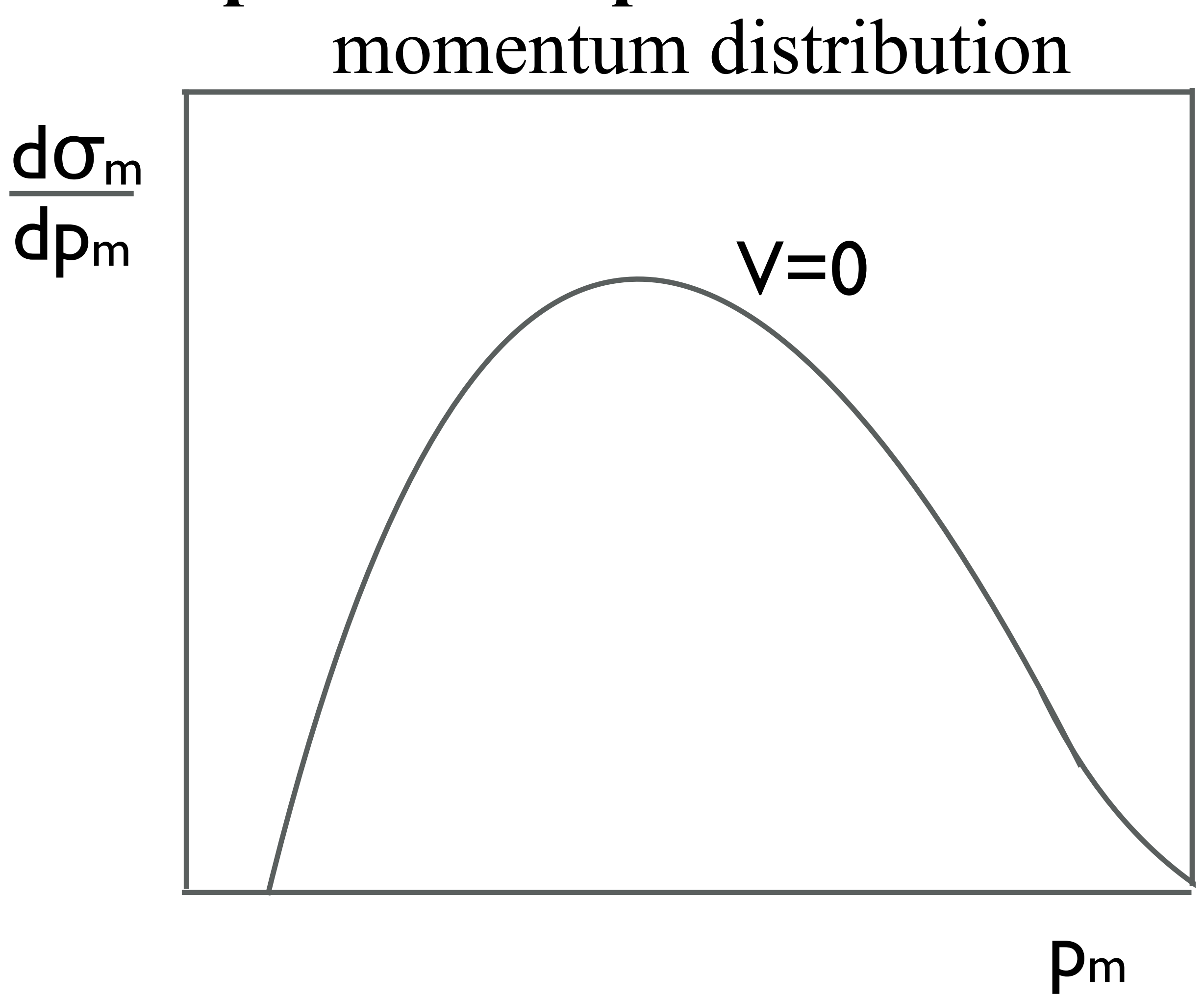
attractive interaction → mass drop → lower threshold → larger phase space→ larger cross section

repulsive interaction → mass increase → higher threshold → smaller phase space→ smaller cross section

Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the **production point**





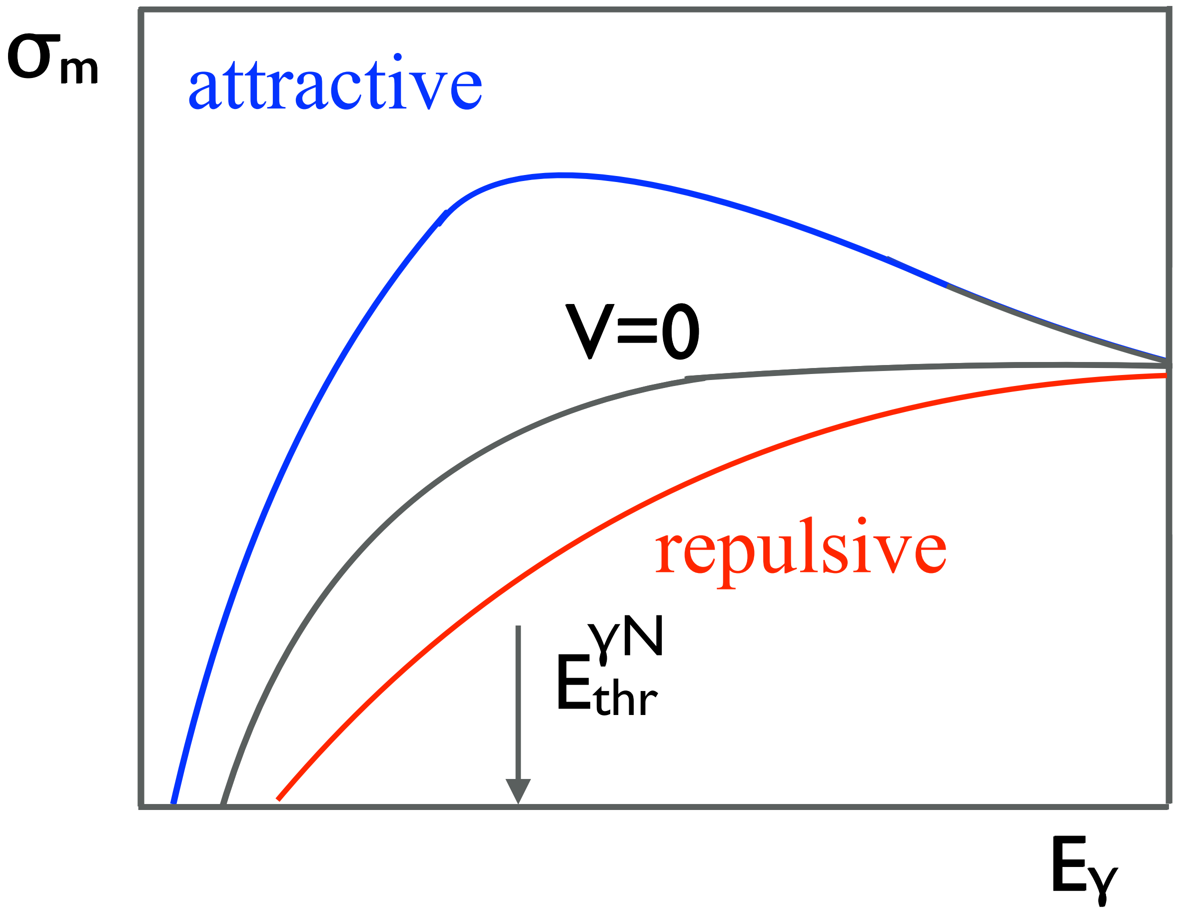
attractive interaction → mass drop → lower threshold → larger phase space→ larger cross section

repulsive interaction → mass increase → higher threshold → smaller phase space→ smaller cross section

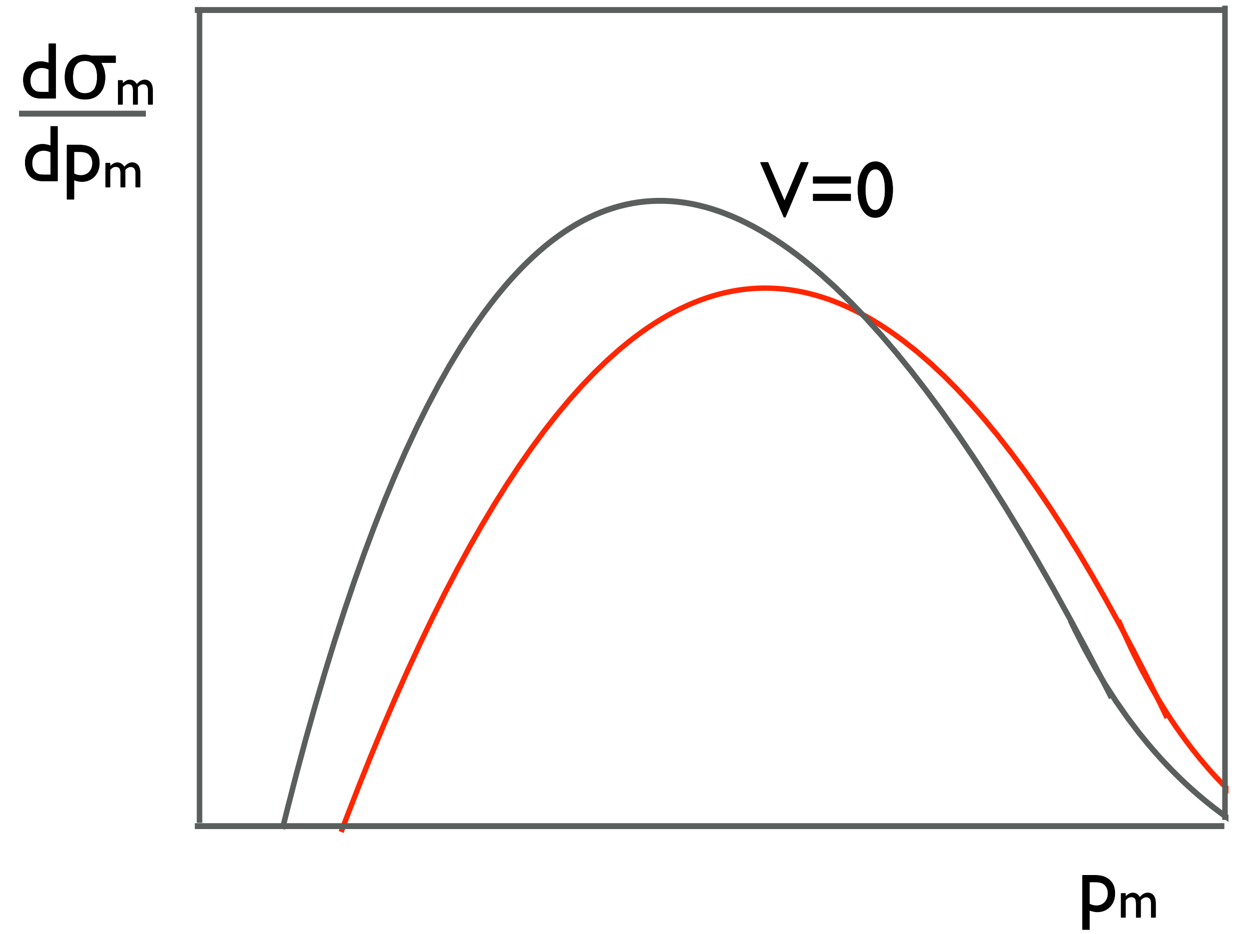
Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the **production point**

excitation function



momentum distribution



attractive interaction → mass drop → lower threshold → larger phase space→ larger cross section

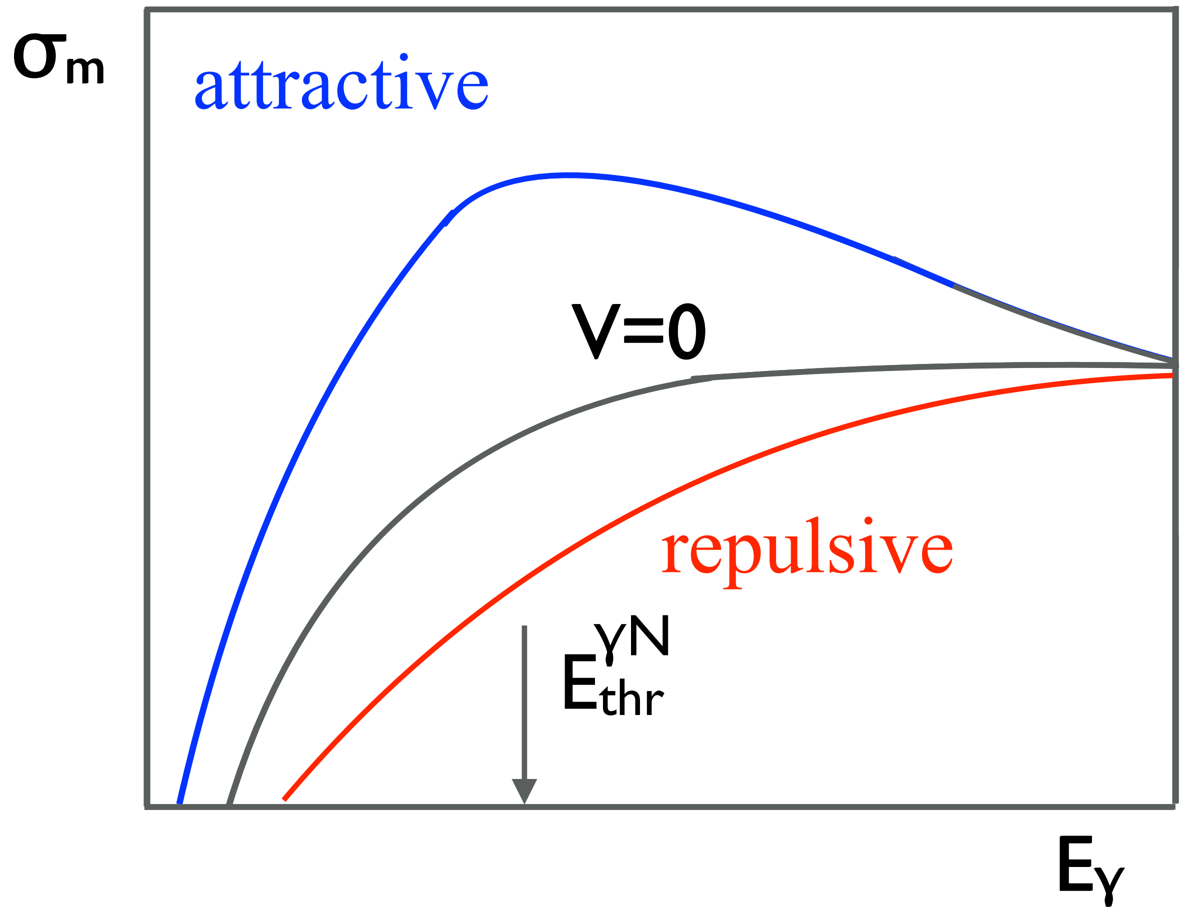
repulsive interaction → mass increase → higher threshold → smaller phase space→ smaller cross section

repulsive interaction → extra kick → shift to higher momenta

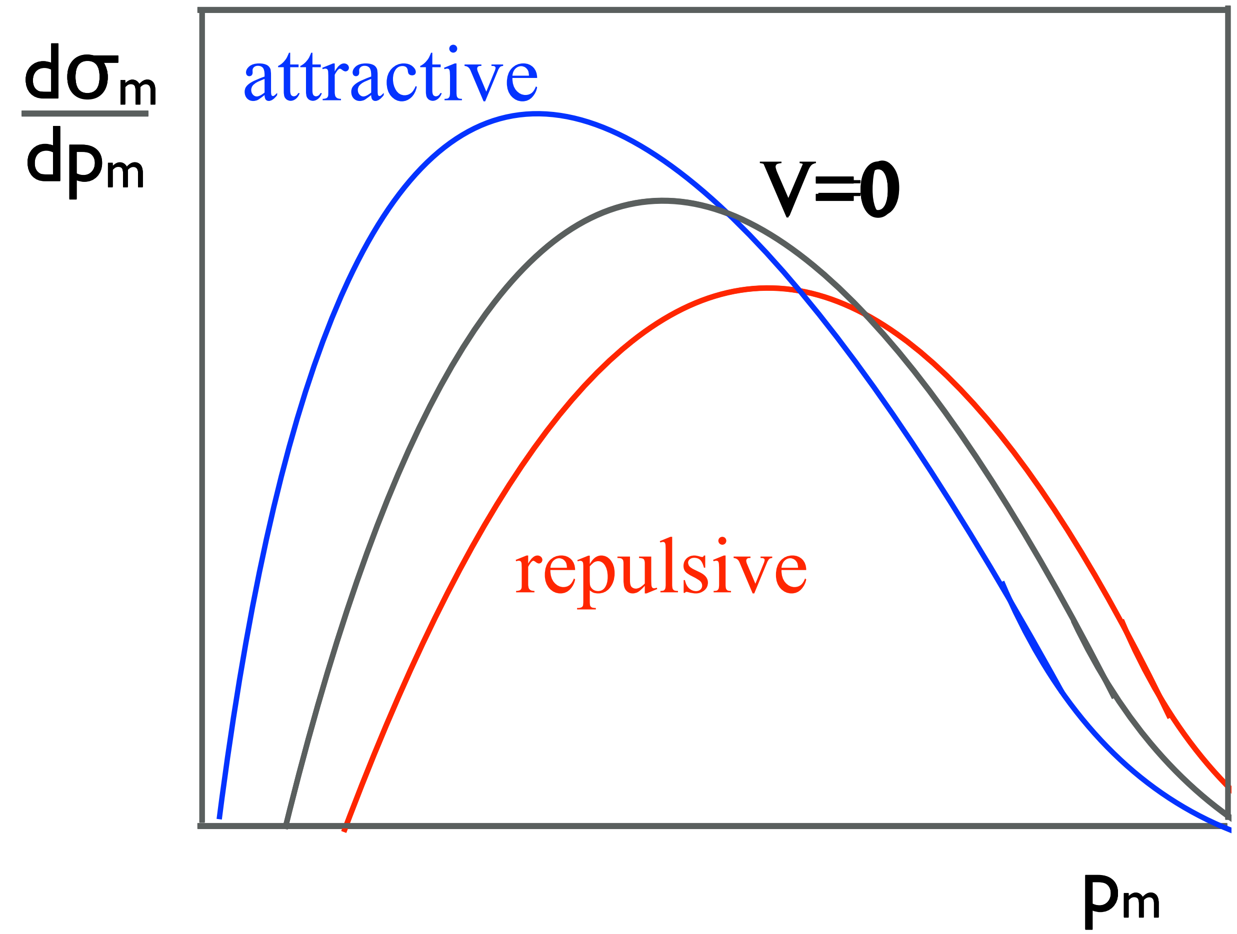
Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the **production point**

excitation function



momentum distribution



attractive interaction → mass drop → lower threshold → larger phase space→ larger cross section

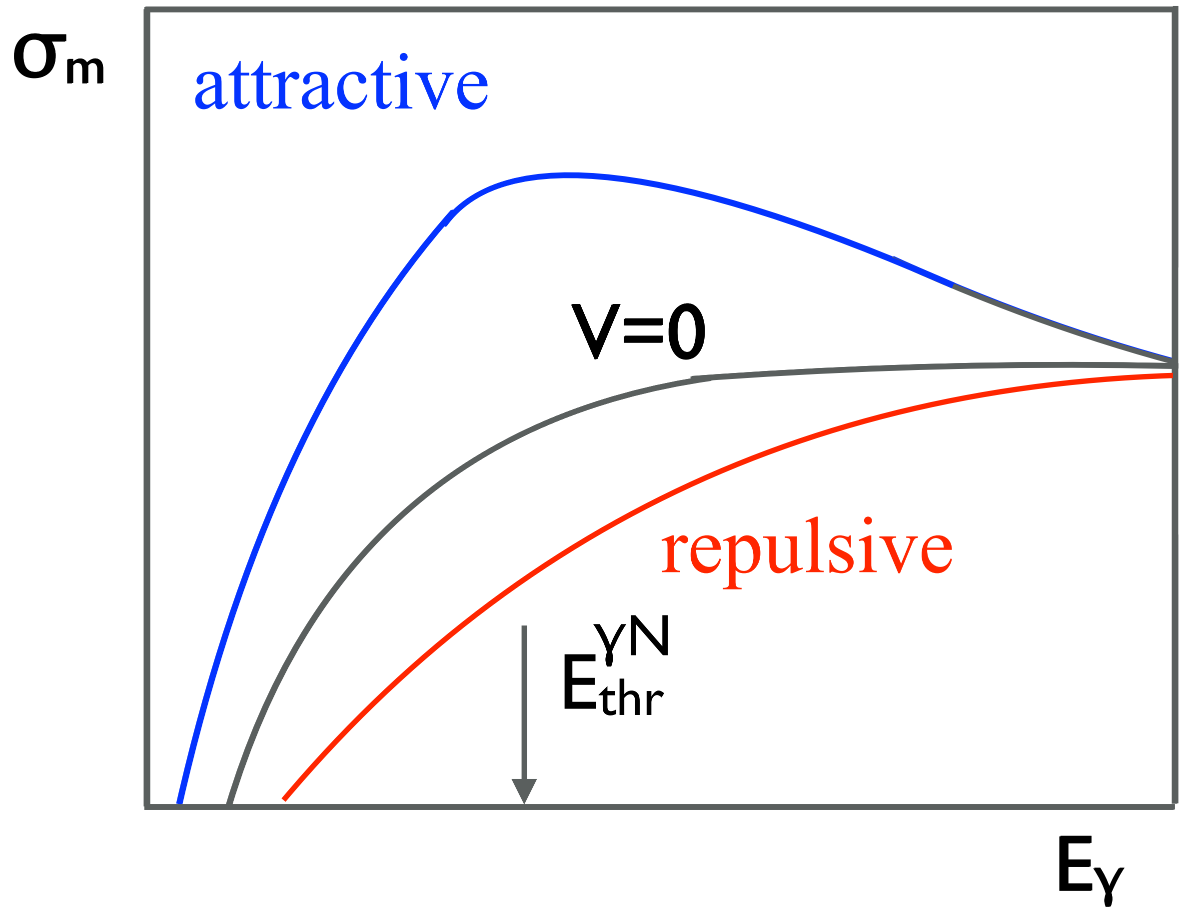
repulsive interaction → extra kick → shift to higher momenta

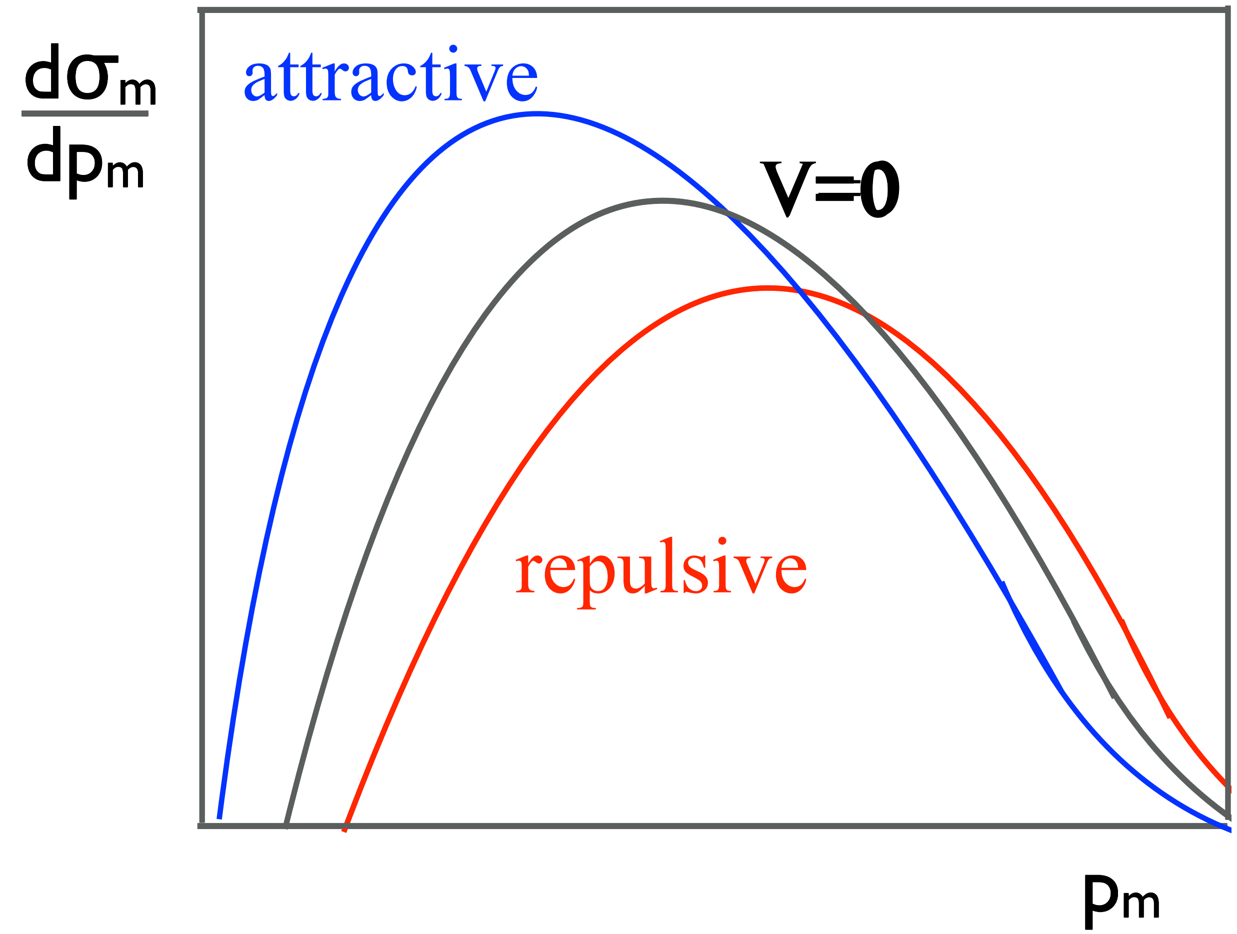
repulsive interaction → mass increase → higher threshold → smaller phase space→ smaller cross section

attractive interaction → meson slowed down → shift to lower momenta

Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the **production point**





attractive interaction → mass drop → lower threshold → larger phase space→ larger cross section

repulsive interaction → extra kick → shift to higher momenta

repulsive interaction → mass increase → higher threshold → smaller phase space→ smaller cross section

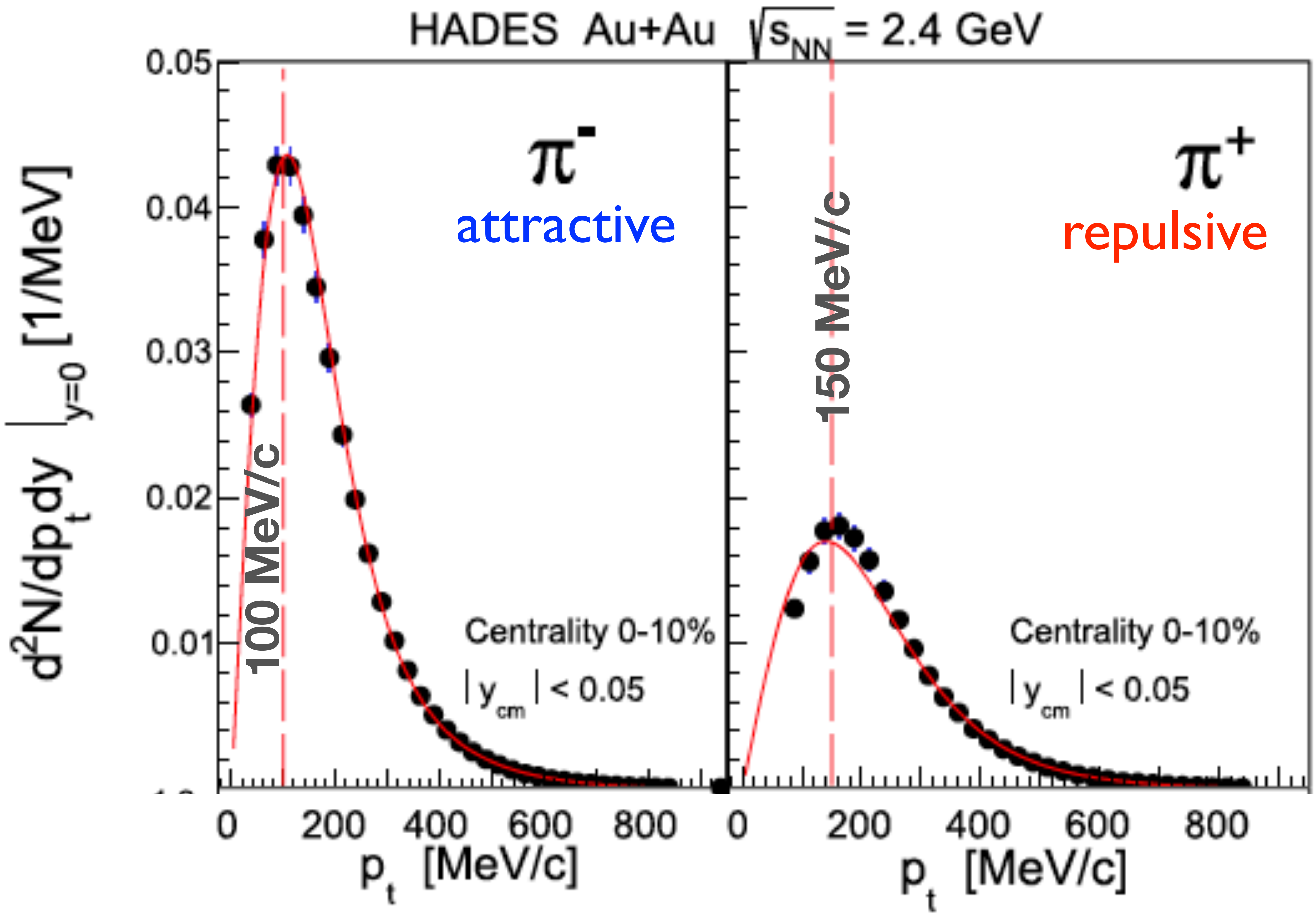
attractive interaction → meson slowed down → shift to lower momenta

quantitative analysis requires transport model or collision model calculations

Test of method

Coulomb interaction among charged pions and the fireball in heavy-ion collisions

Eur. Phys. J. A 56 (2020) 259

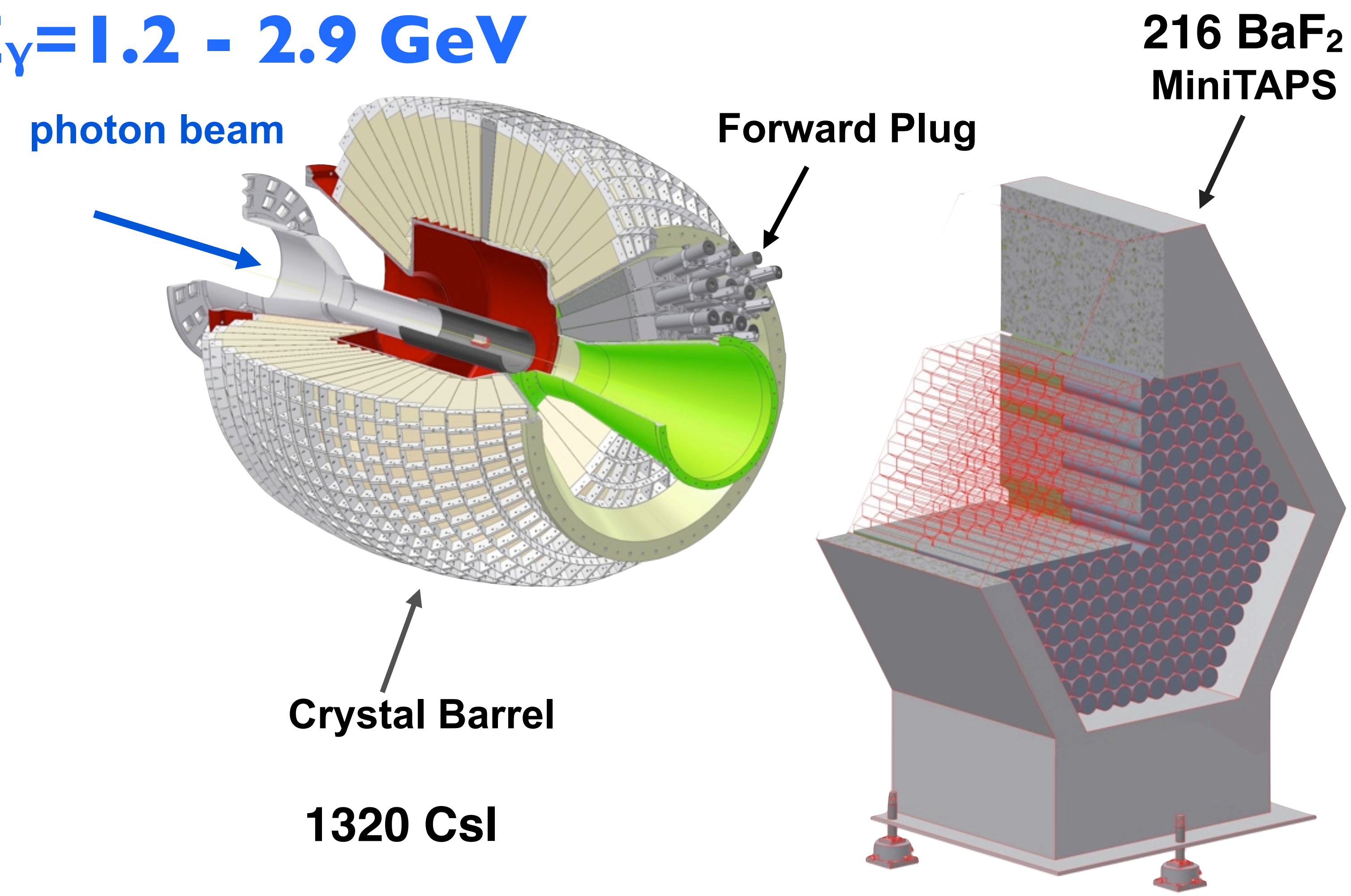


spectrum shifted to smaller (larger) momenta for π^- (π^+) mesons

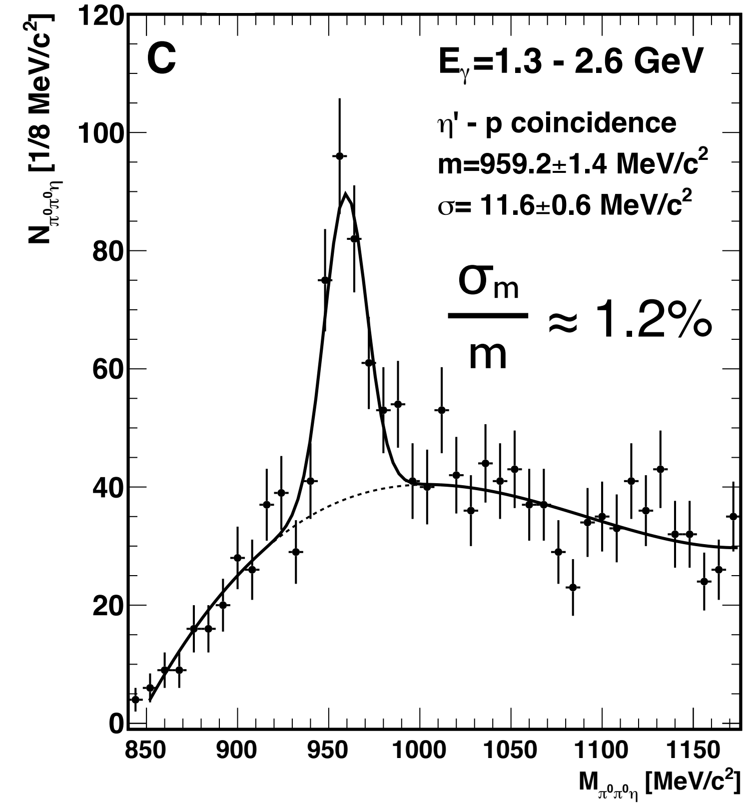
V_c = 13.6±0.6 MeV; HADES Collaboration, Eur. Phys. J. A 48 (2022) 9

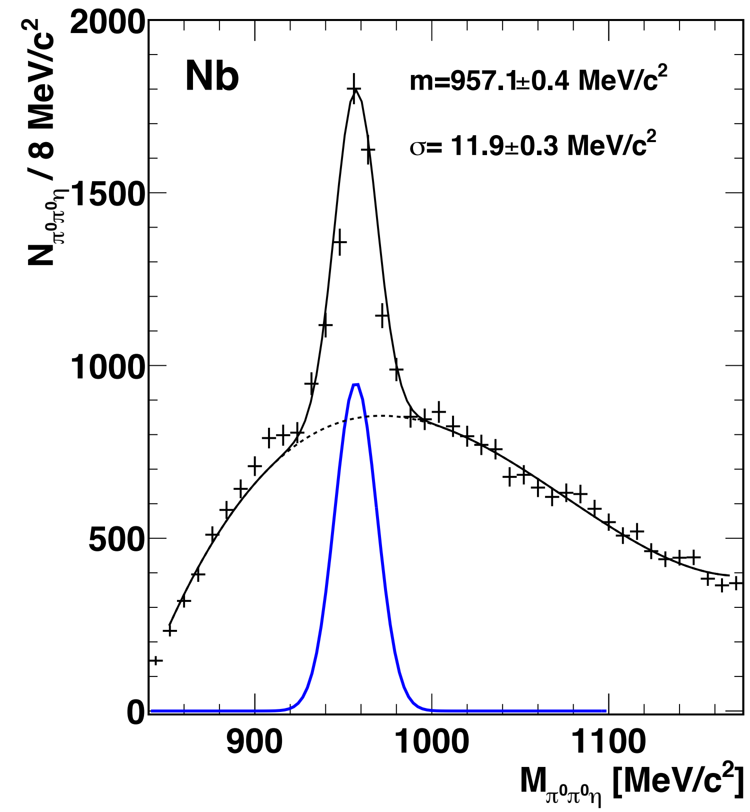
CBELSA/TAPS Experiment

E_γ=1.2 - 2.9 GeV



11°-156° 1°-11°





targets: LH_2, C, Ca, Nb, Pb

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

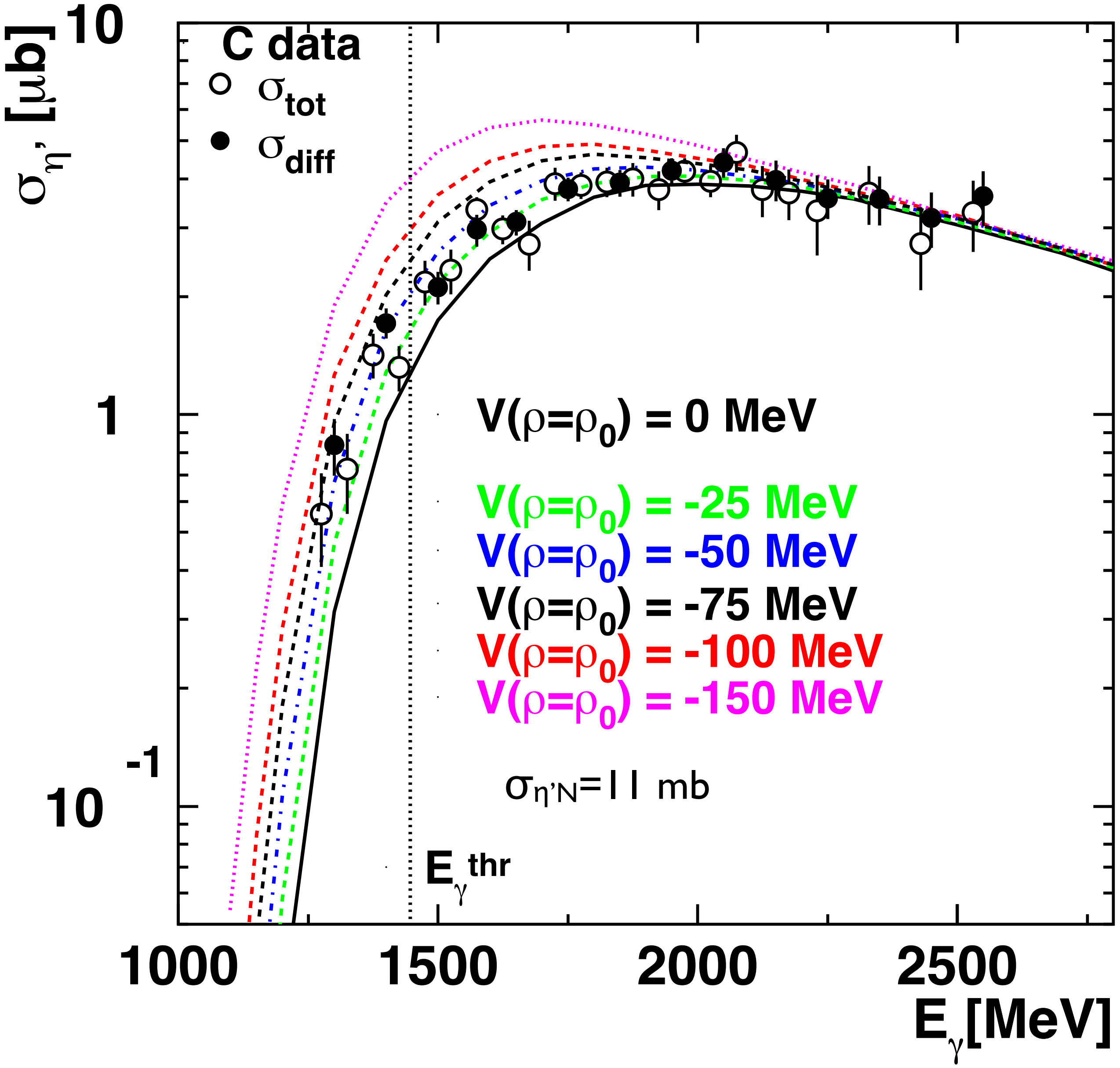
$\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ BR 8.5%

Determining the real part of the η' - nucleus potential from the excitation function

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

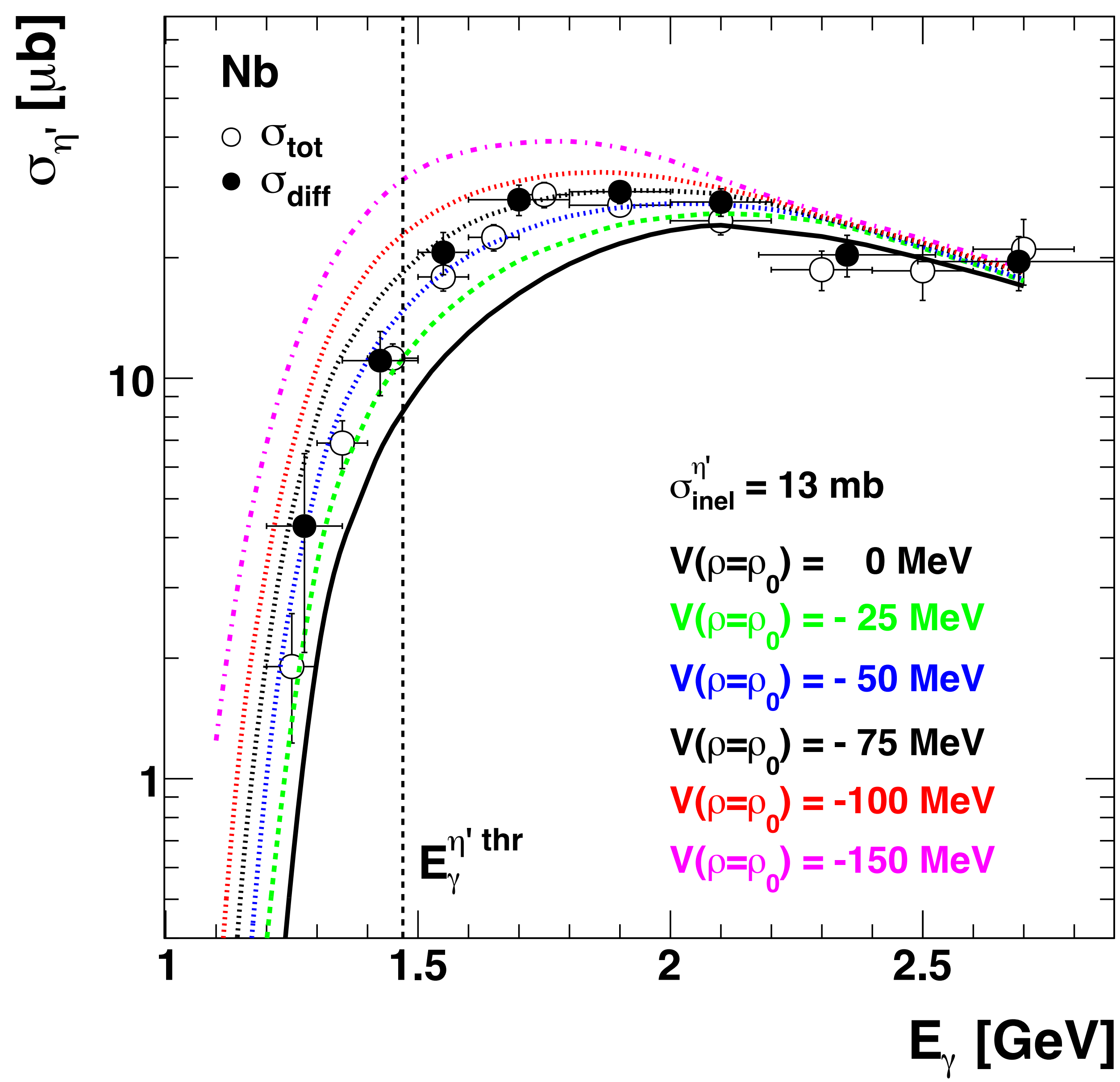
CBELSA/TAPS @ ELSA

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



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

M. Nanova et al., PRC 94 (2016) 025205



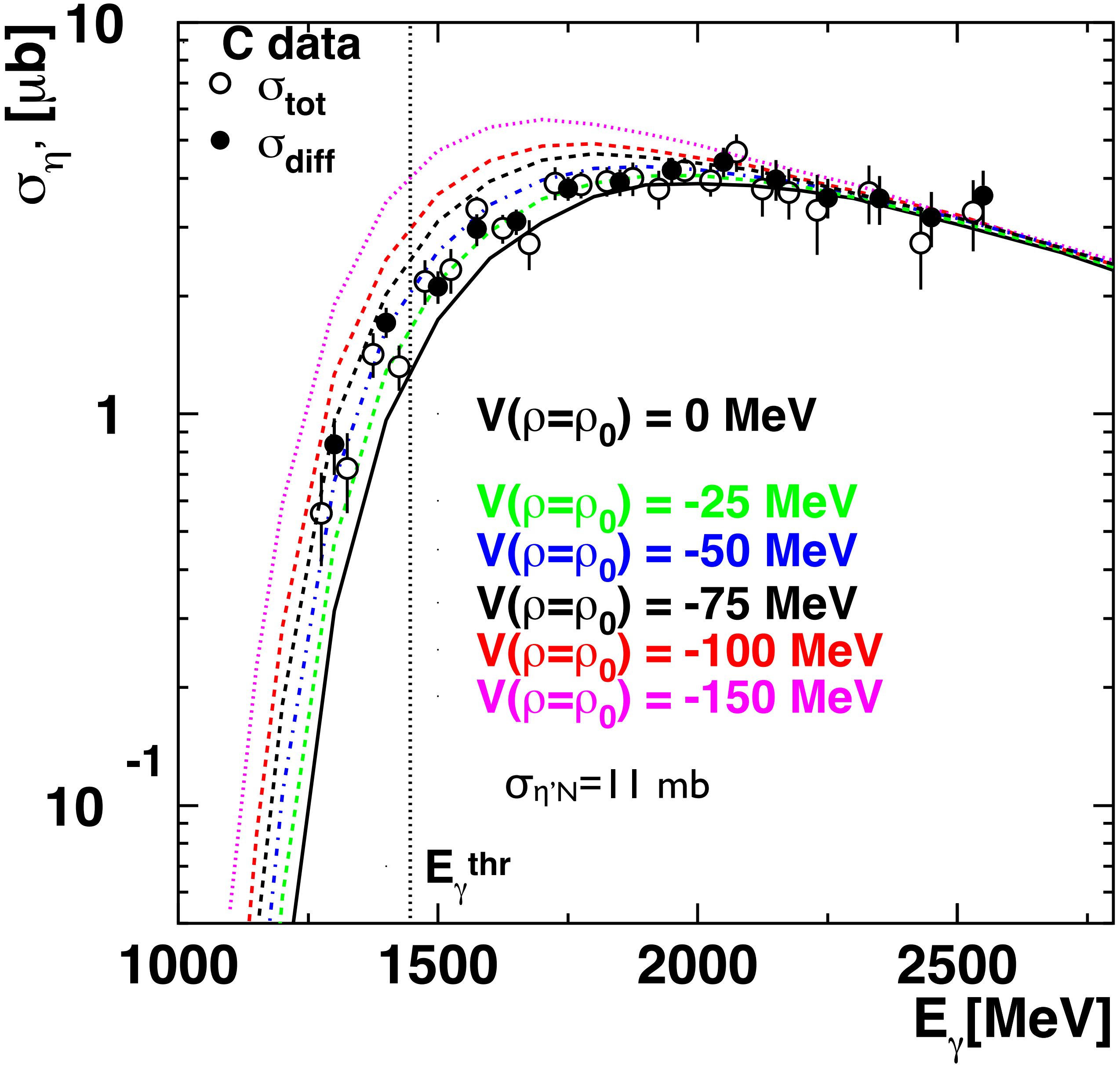
$V_{\eta'}(\rho=\rho_0) = -(40\pm12)$ MeV

Determining the real part of the η' - nucleus potential from the excitation function

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

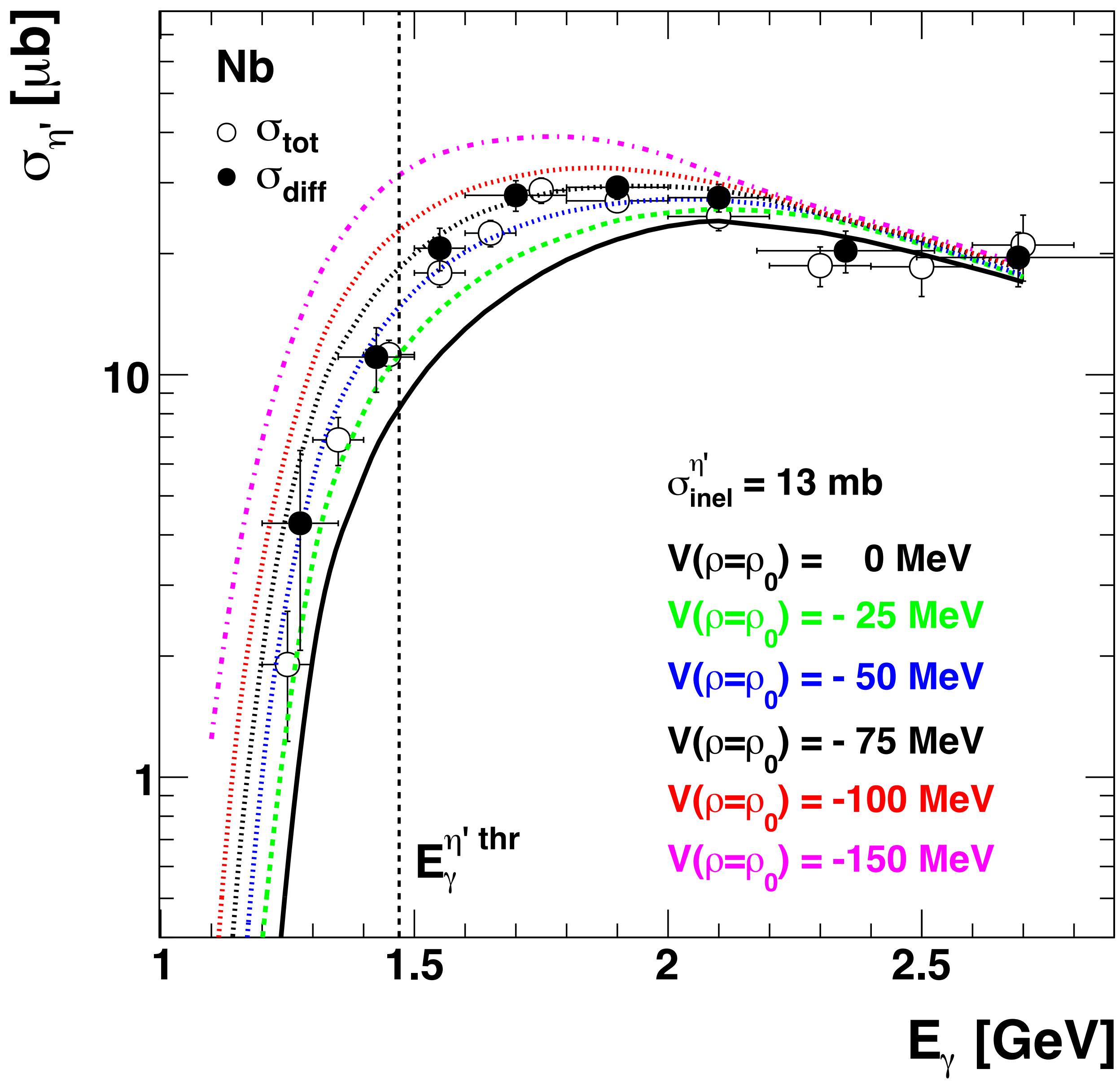
CBELSA/TAPS @ ELSA

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



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

M. Nanova et al., PRC 94 (2016) 025205



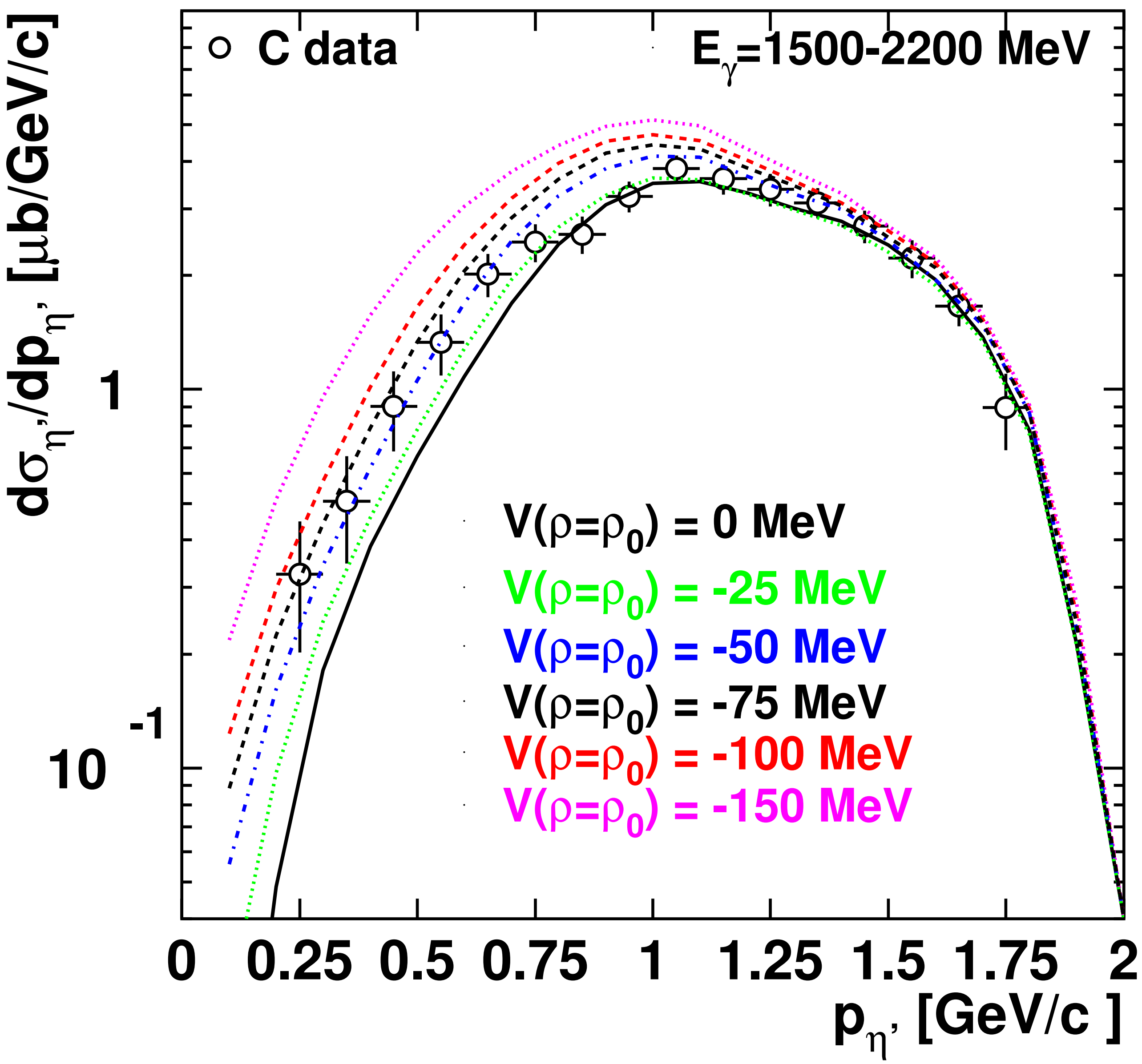
$V_{\eta'}(\rho=\rho_0) = -(40\pm12)$ MeV

data disfavour strong mass shifts

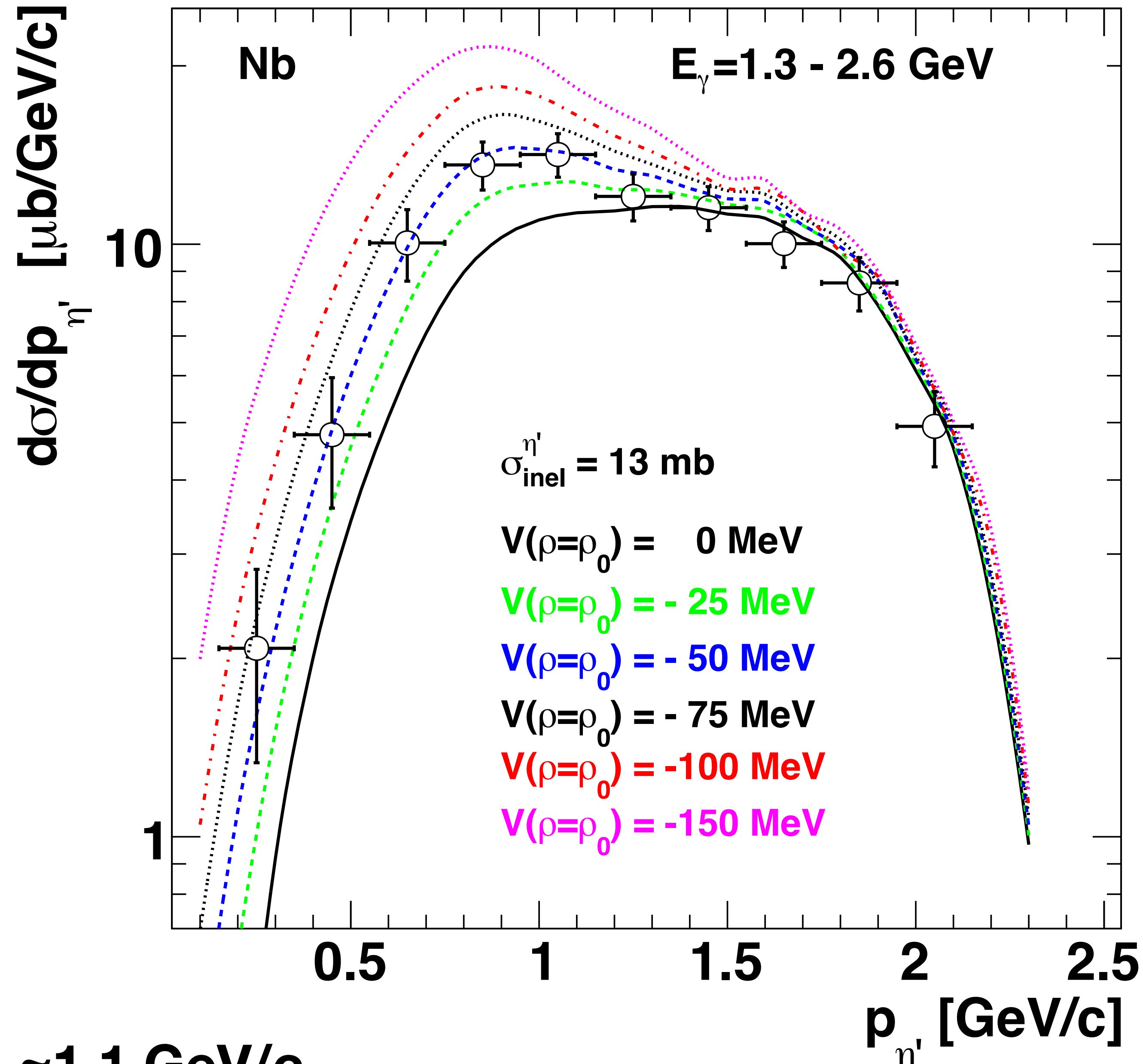
Determining the real part of the η' - nucleus potential from the momentum distribution

CBELSA/TAPS @ ELSA

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



M. Nanova et al., PRC 94 (2016) 025205



$< p > \approx 1.1$ GeV/c

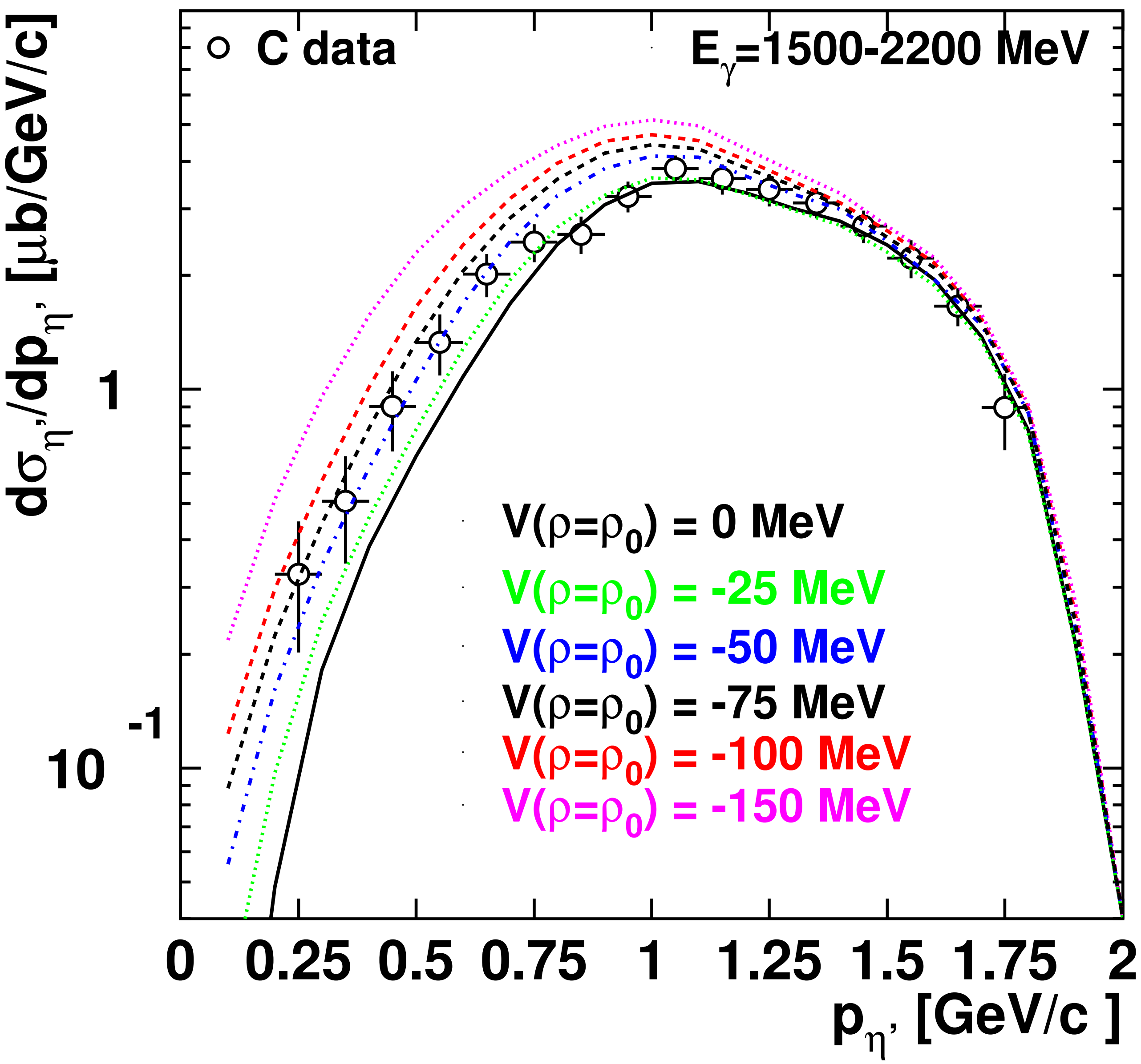
$V_{\eta'}(\rho=\rho_0) = -(32\pm11)$ MeV

$V_{\eta'}(\rho=\rho_0) = -(45\pm20)$ MeV

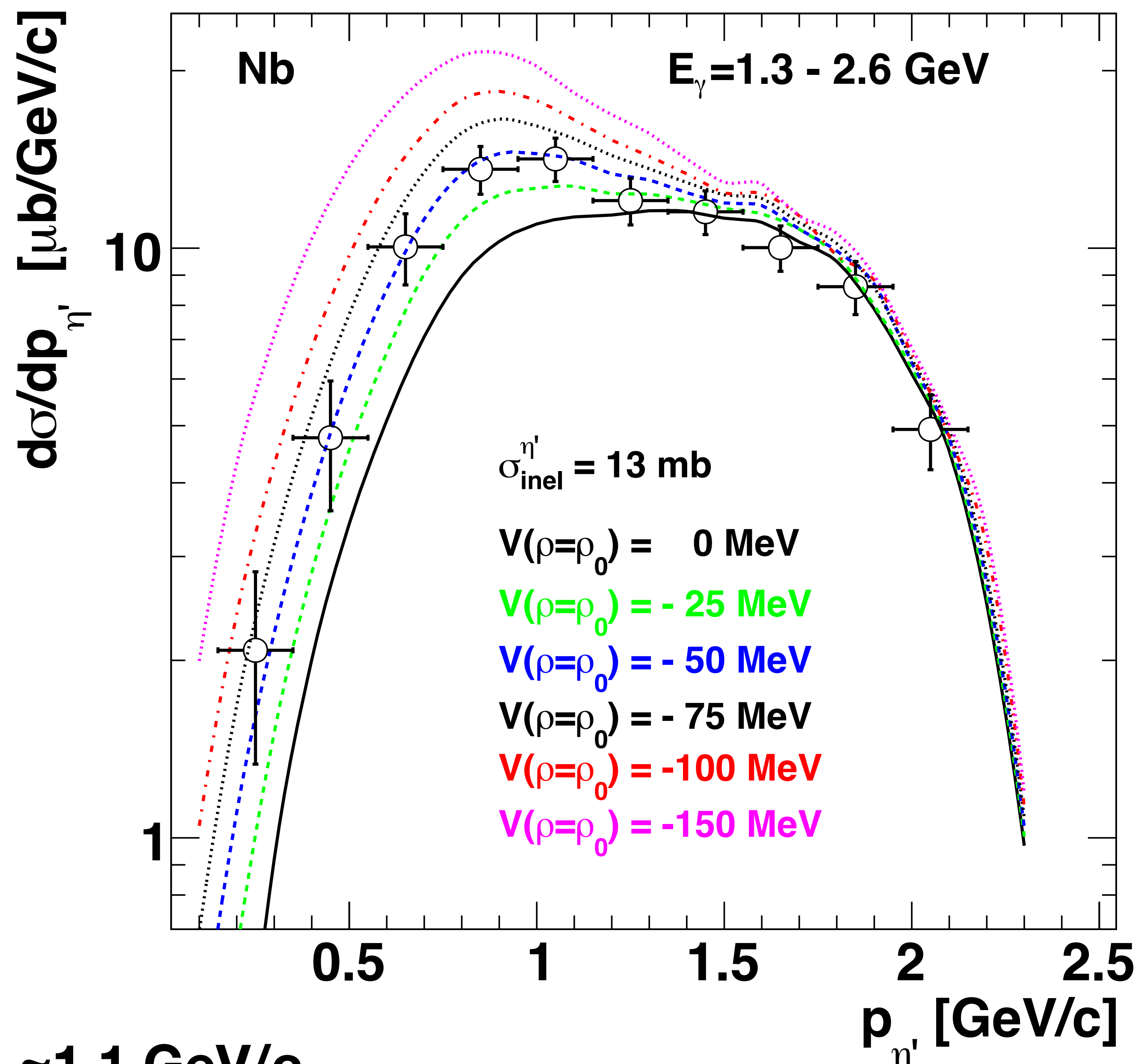
Determining the real part of the η' - nucleus potential from the momentum distribution

CBELSA/TAPS @ ELSA

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



M. Nanova et al., PRC 94 (2016) 025205



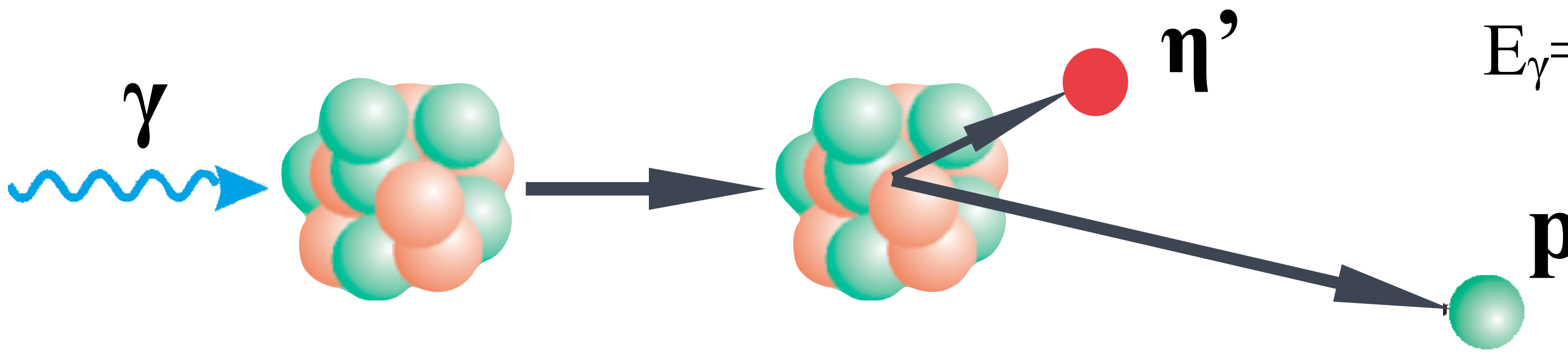
$\langle p \rangle \approx 1.1$ GeV/c

$V_{\eta'}(\rho=\rho_0) = -(32\pm11)$ MeV

$V_{\eta'}(\rho=\rho_0) = -(45\pm20)$ MeV

data disfavour strong mass shifts

Real part of the η'-nucleus potential at low momenta

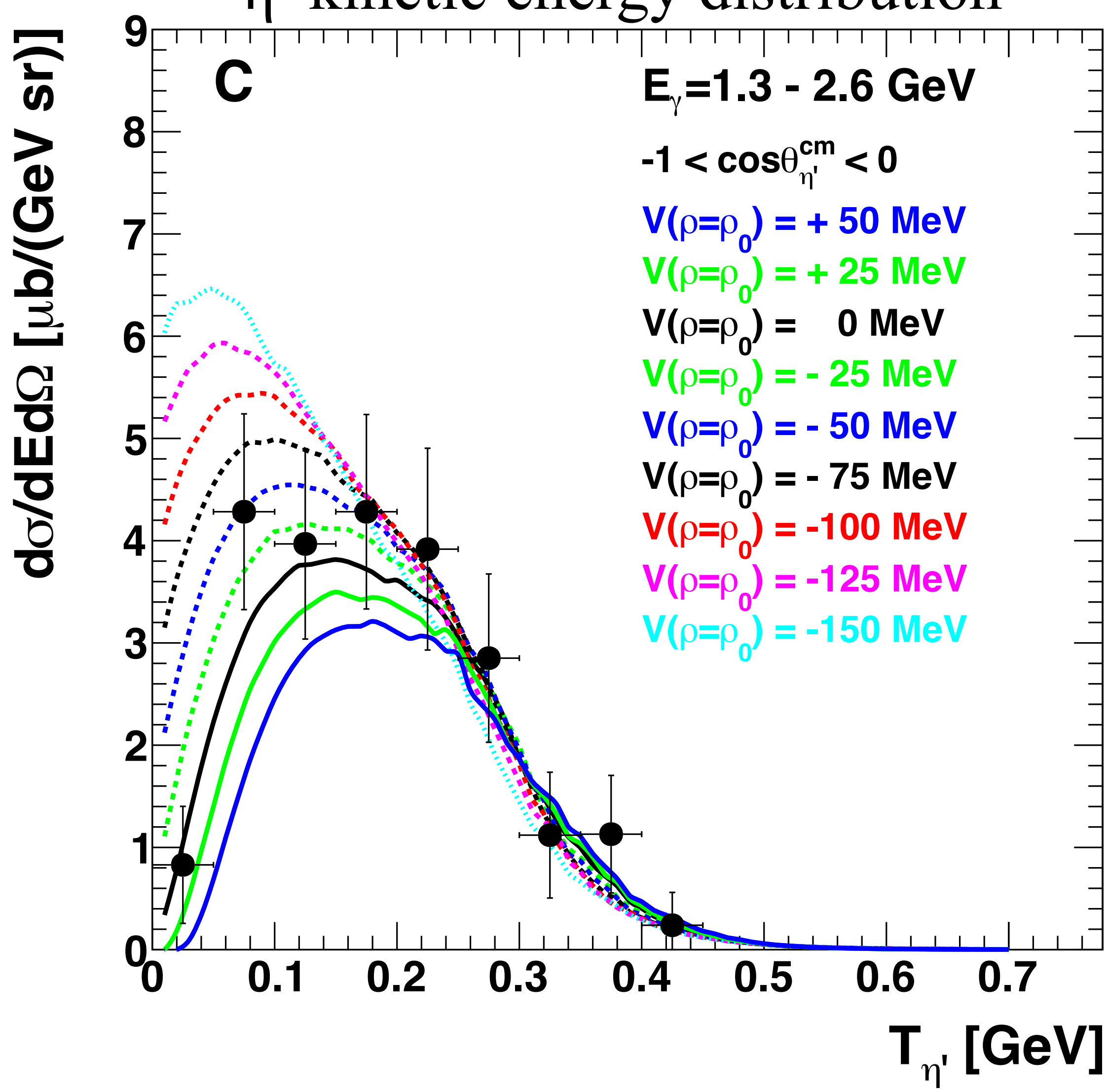


E_γ=1.3-2.6 GeV

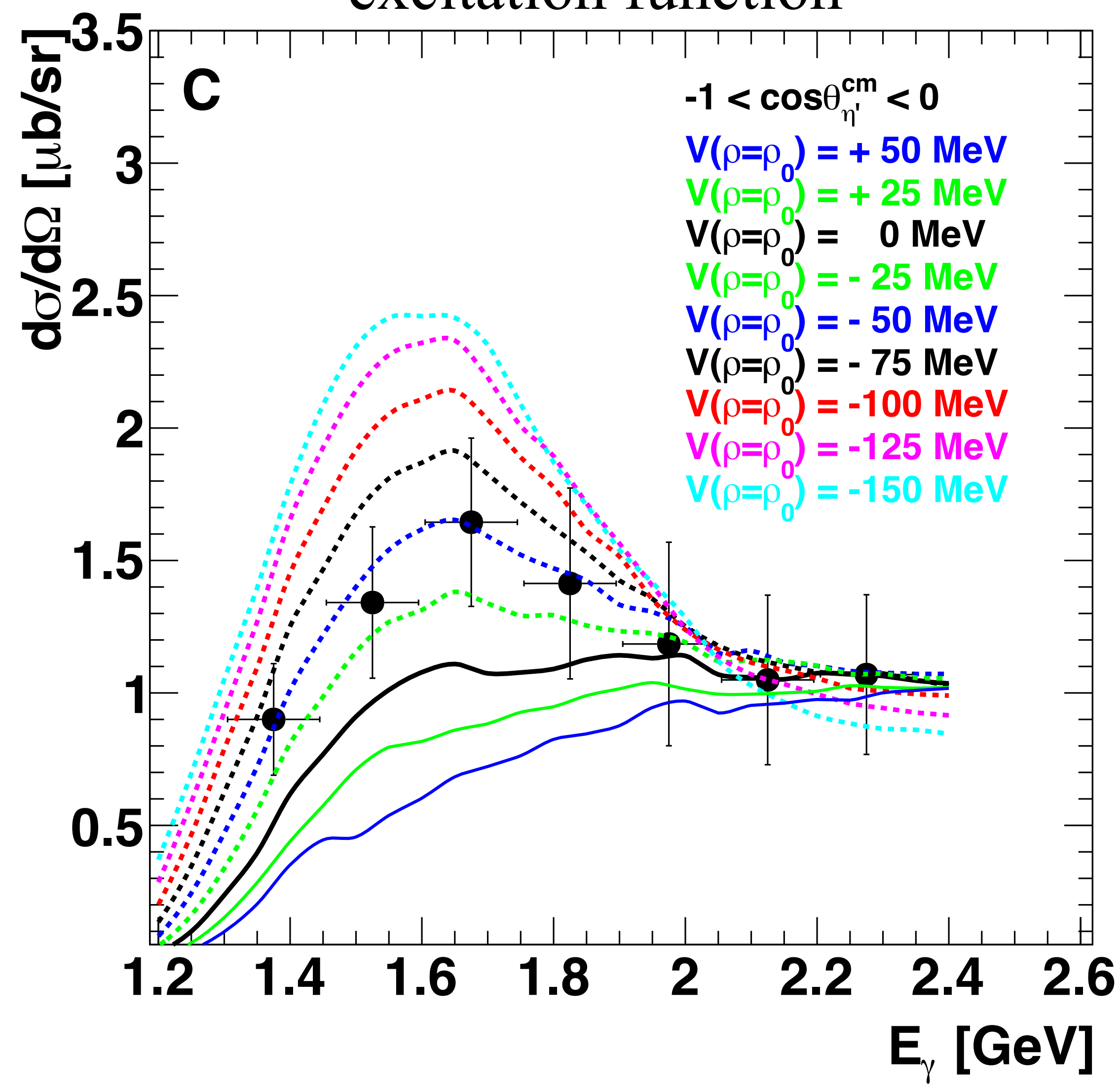
$2^0 \leq \theta_p \leq 11^0$

M. Nanova et al., EPJ A 54 (2018) 182

η' kinetic energy distribution

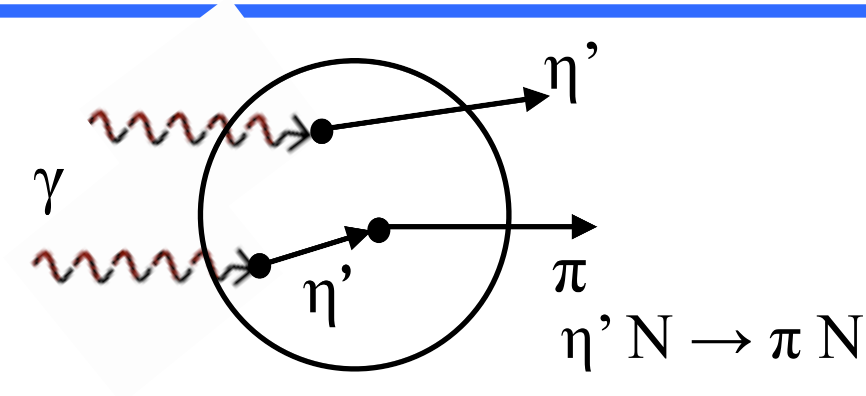


excitation function



best fit for $V(\rho=\rho_0)$= -[44±16(stat)±15(syst)] MeV

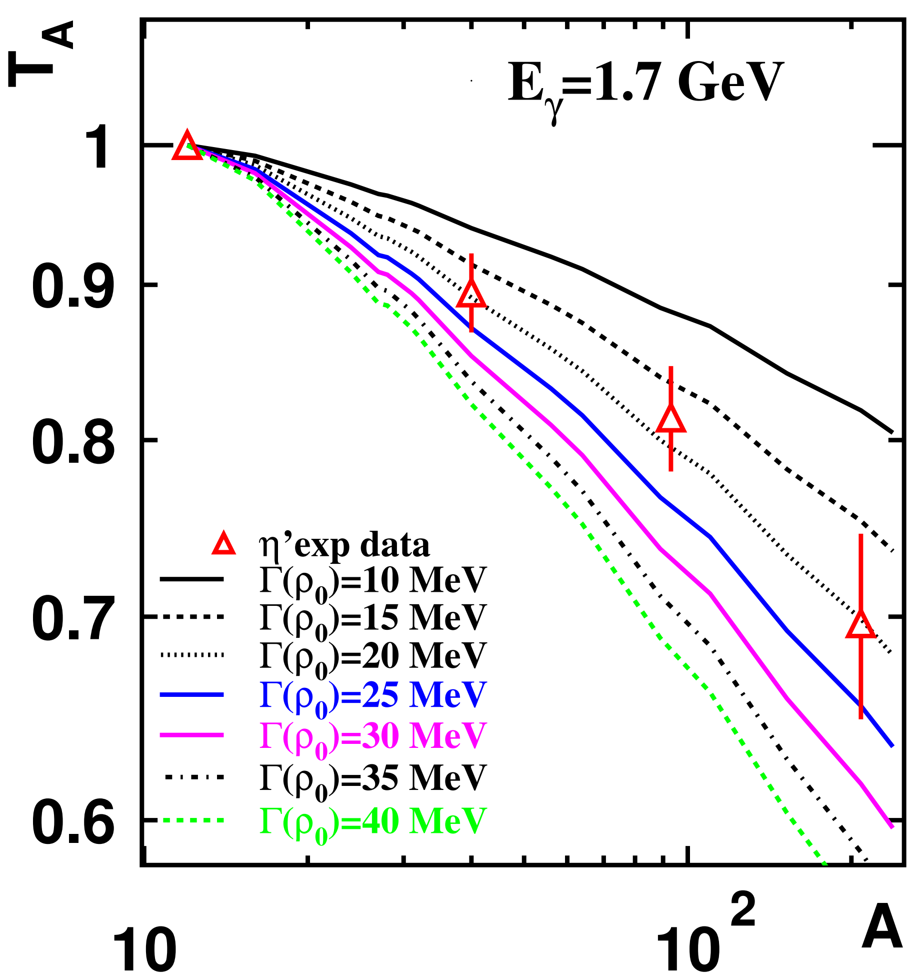
Determining the imaginary part of the η' - nucleus potential from transparency ratio measurements



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

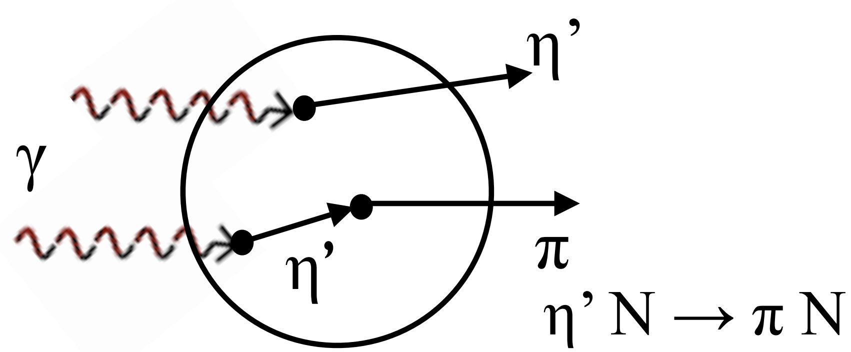
mass dependence of T_A

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



$\Gamma_{\eta'}(\rho=\rho0)$ =15-25 MeV

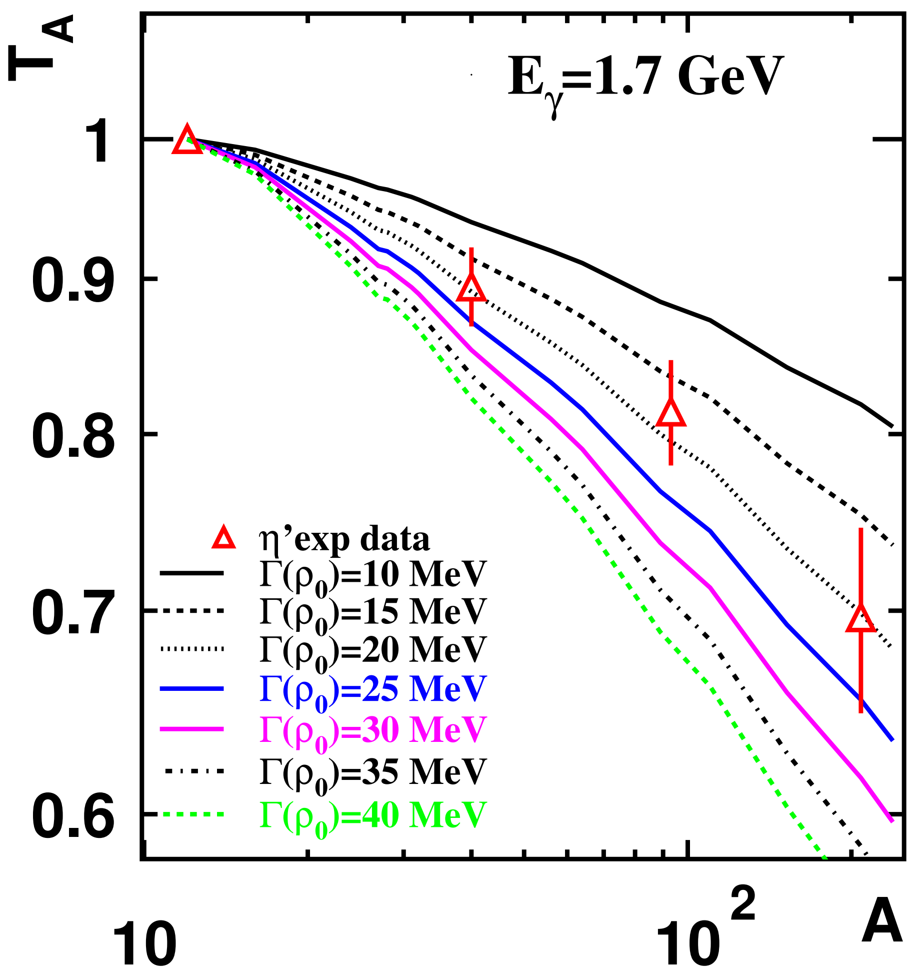
Determining the imaginary part of the η' - nucleus potential from transparency ratio measurements



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

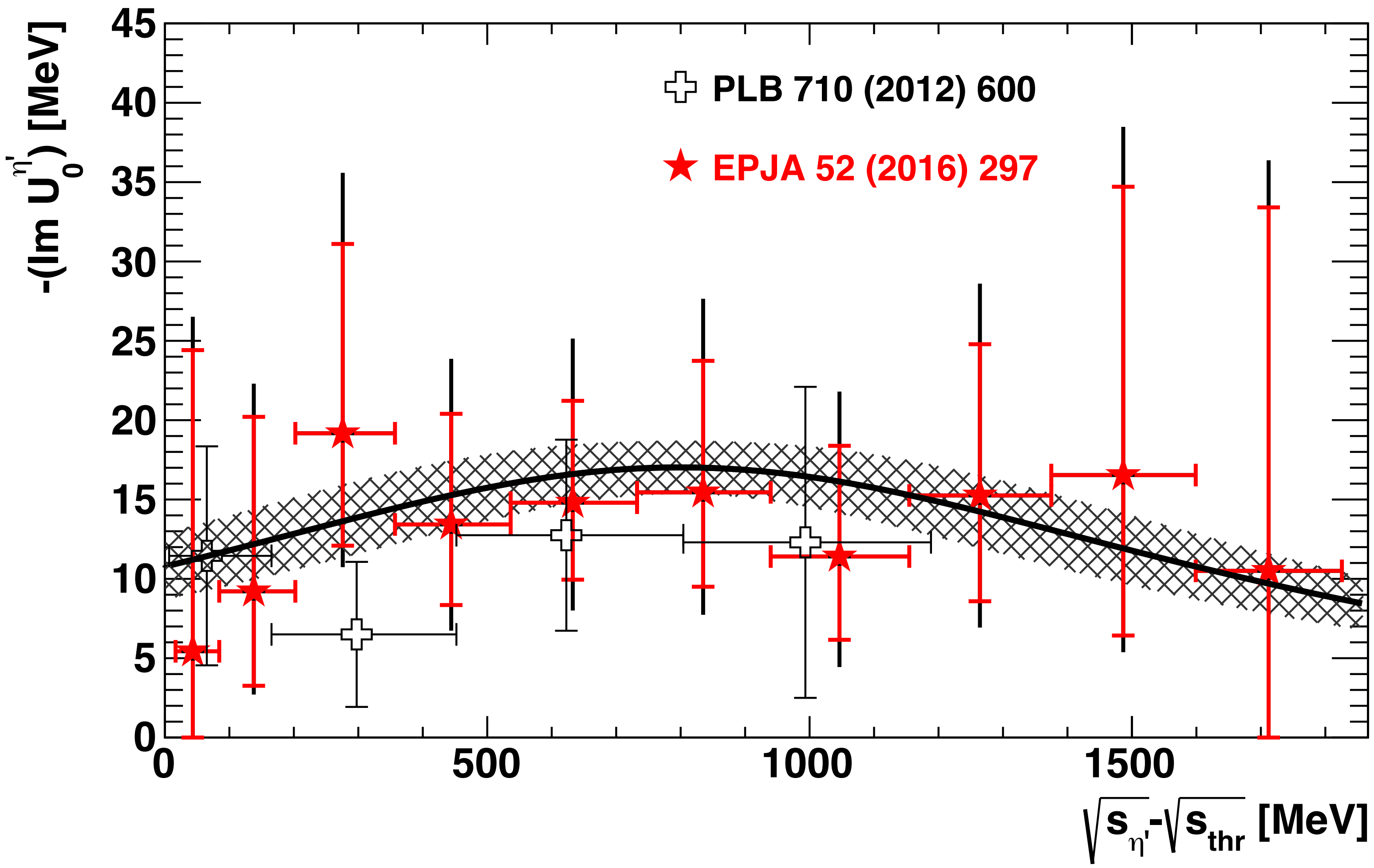
mass dependence of T_A

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



momentum dependence of W_0

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



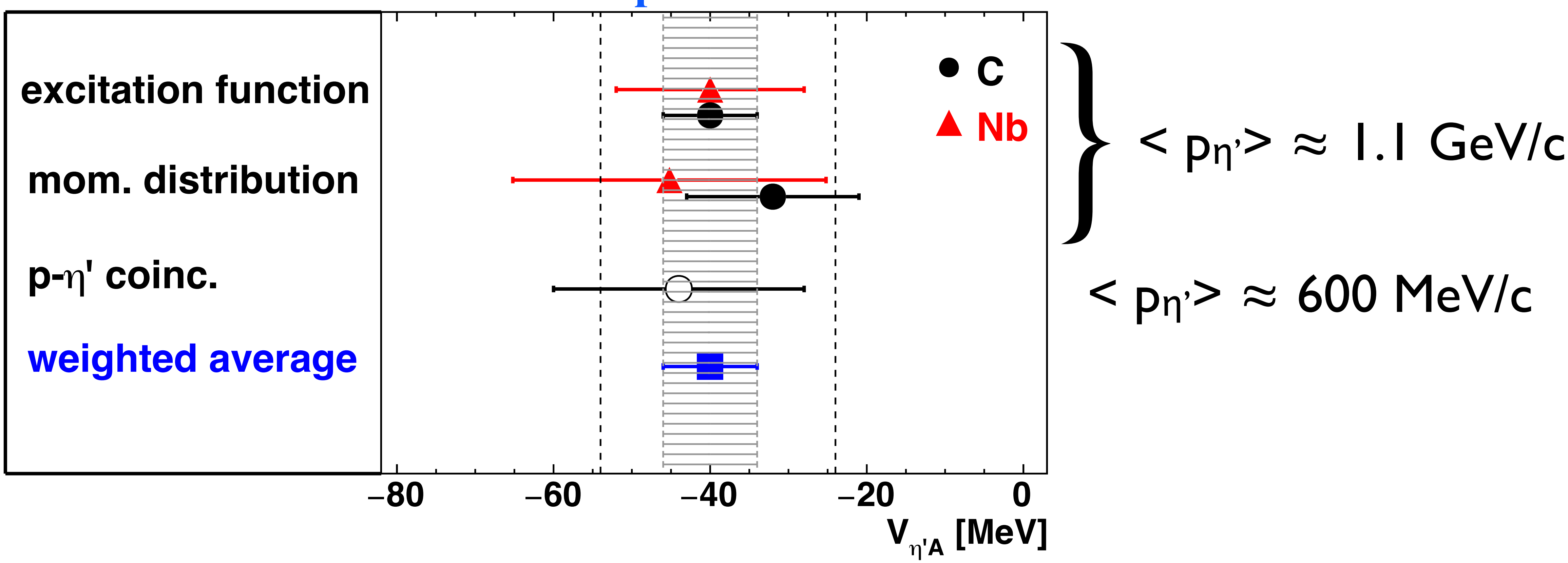
$\Gamma_{\eta'}(\rho=\rho 0)$ =15-25 MeV

$W(\rho=\rho_0, p_{\eta'}=0)$ =-[13±3(stat)±3(syst)] MeV

Real and imaginary part of the η'- nucleus potential

real part: M. Nanova et al., PRC 94 (2016) 025205
M. Nanova et al., EPJ A 54 (2018) 182
V. Metag, M. N. , E. Paryev , PPNP 97 (2017) 199

model dependend!



weighted average: $V_0=\Delta m(\rho=\rho_0)= -[39\pm7(stat)\pm15(syst)]$ MeV

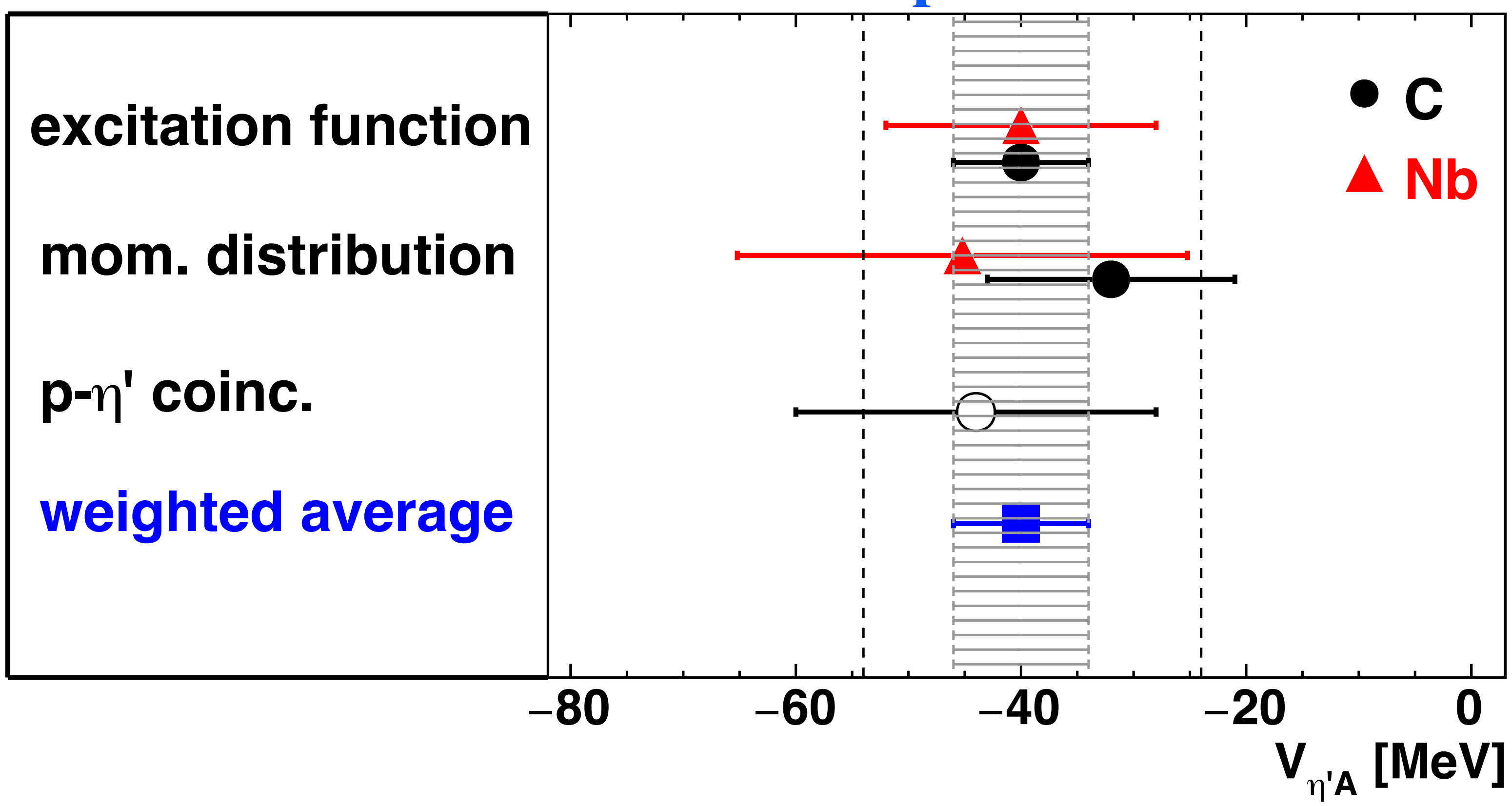
observed mass shift in agreement with QMC model predictions

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

Real and imaginary part of the η'- nucleus potential

real part: M. Nanova et al., PRC 94 (2016) 025205
M. Nanova et al., EPJ A 54 (2018) 182
V. Metag, M. N. , E. Paryev , PPNP 97 (2017) 199

model dependend!



$< p_{\eta'} > \approx 1.1$ GeV/c

$< p_{\eta'} > \approx 600$ MeV/c

weighted average: $V_0 = \Delta m(\rho=\rho_0) = -[39 \pm 7(stat) \pm 15(syst)]$ MeV

observed mass shift in agreement with QMC model predictions

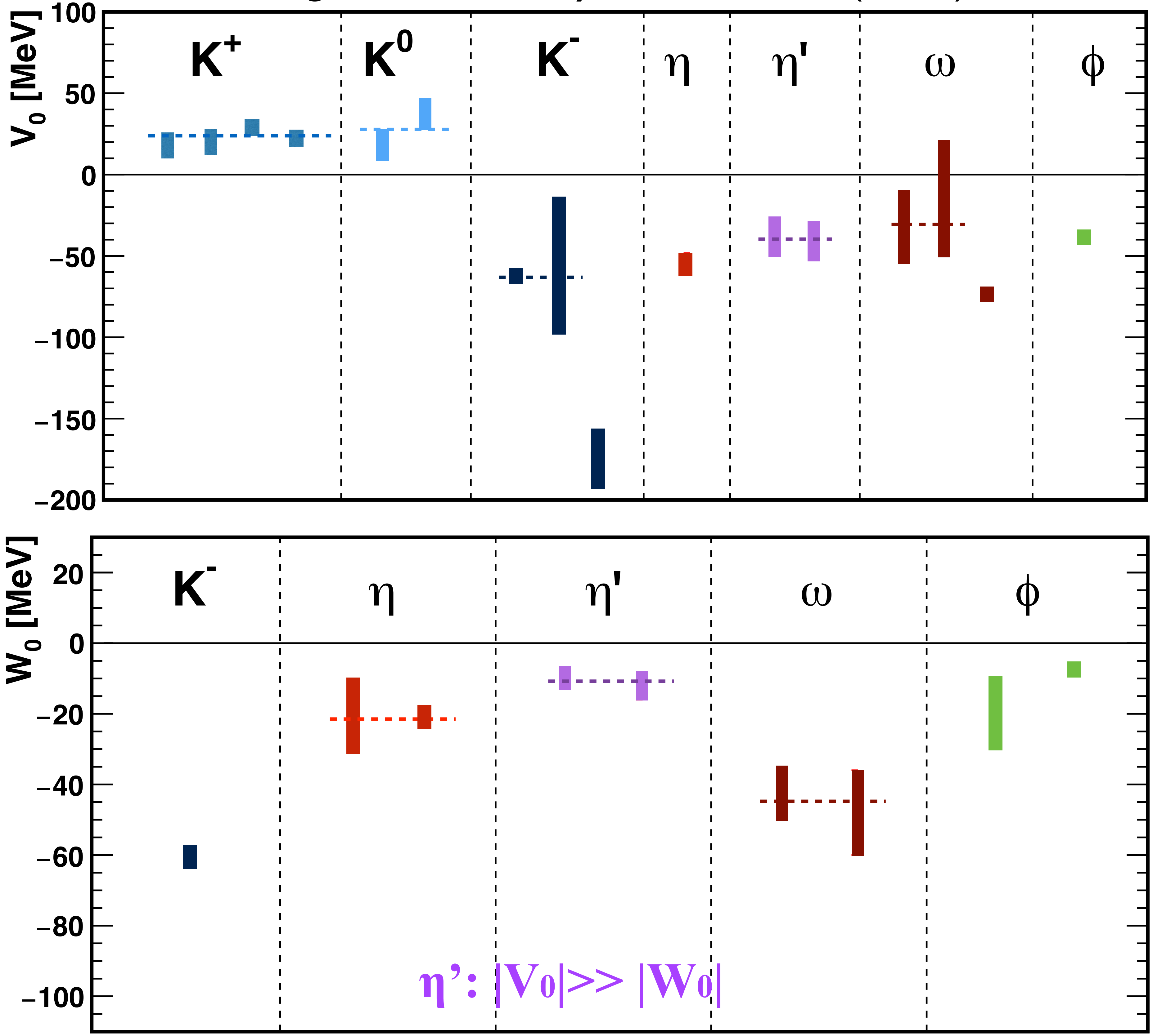
S. Bass and T. Thomas, PLB 634 (2006) 368

imaginary part: M. Nanova et al., PLB 727 (2013) 417
S. Friedrich et al., EPJA 52 (2016) 297

$$W_0 = \text{Im}\, U(\rho=\rho_0, p_{\eta'} \approx 0) = -[13 \pm 3(stat) \pm 3(syst)] \text{ MeV}$$

The meson-nucleus potential $U(\rho_0)=V(\rho_0)+iW(\rho_0)$

V. Metag, M. N. , E. Paryev , PPNP 97 (2017) 199



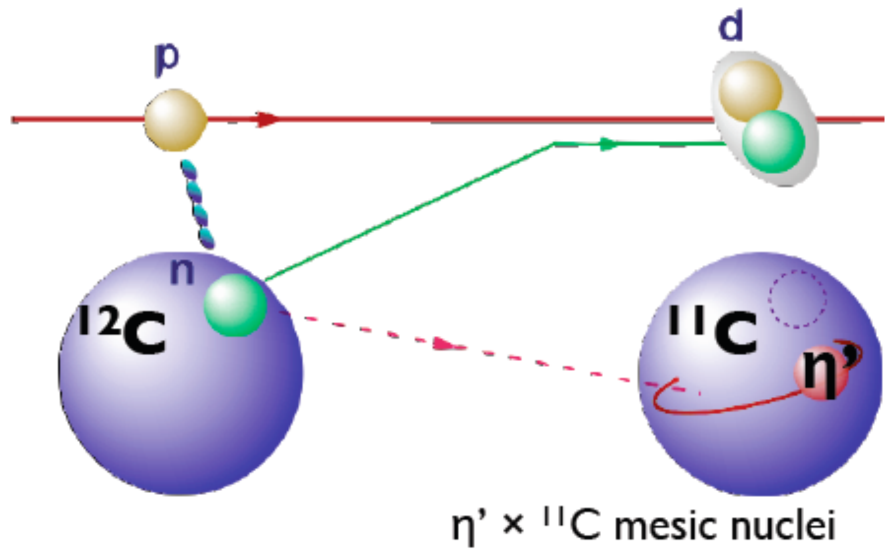
η' promising candidate for mesic state: $|W_0| \approx 13$ MeV $\ll |V_0| \approx 40$ MeV

Search for η’ - nucleus bound states I

recoilless production in $^{12}C(p,d)$ reaction

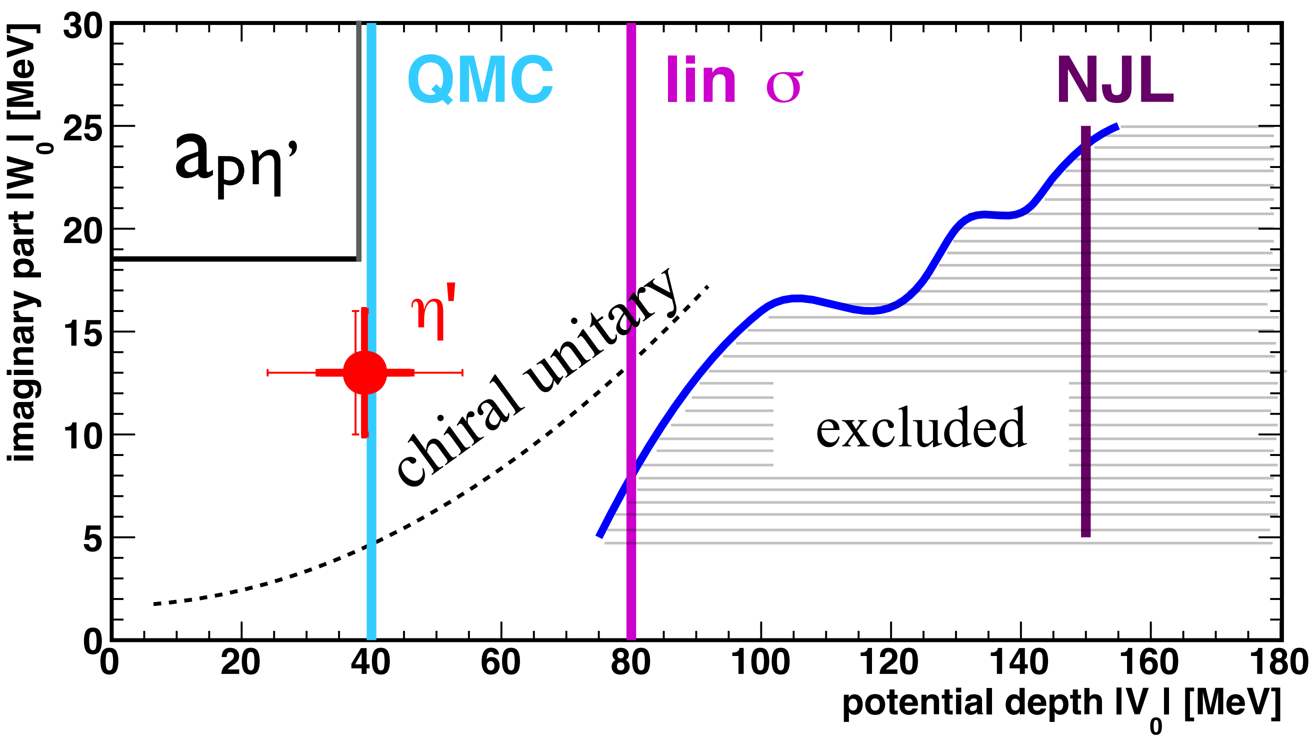
PRiME collaboration (2012)

K. Itahashi et al., Exp. S 437



FRS@GSI

Y.K. Tanaka et al., PRL 117 (2016) 202501
Y.K. Tanka et al., PRC 97 (2018) 015202

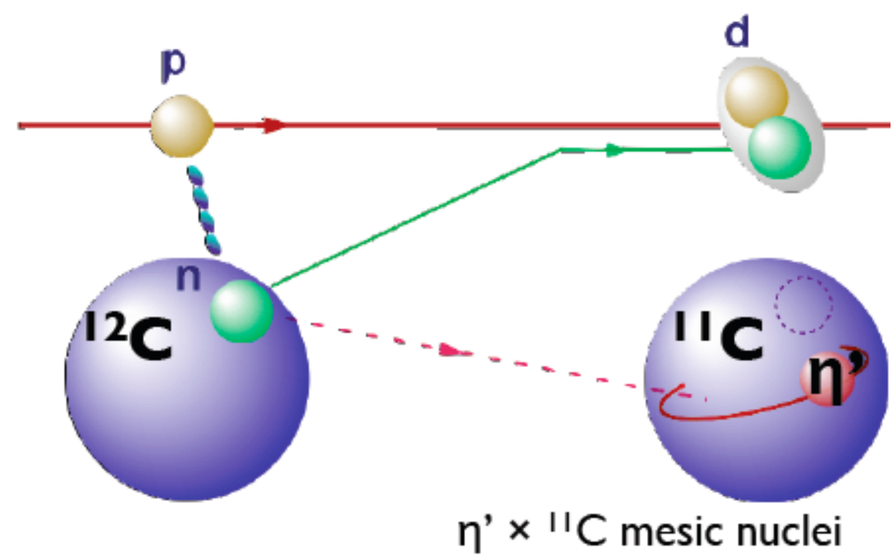


Search for η’ - nucleus bound states I

recoilless production in $^{12}C(p,d)$ reaction

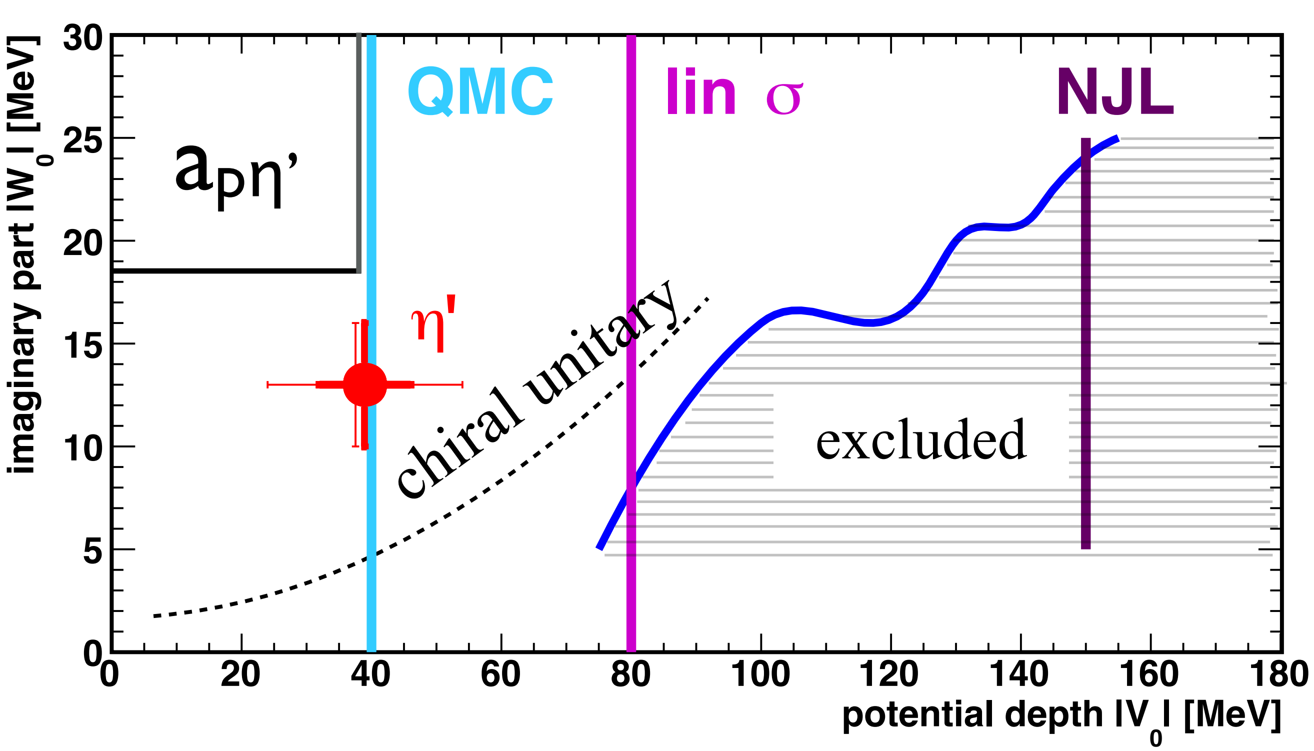
PRIME collaboration (2012)

K. Itahashi et al., Exp. S 437



FRS@GSI

Y.K. Tanaka et al., PRL 117 (2016) 202501
Y.K. Tanka et al., PRC 97 (2018) 015202



missing mass spectrometry with coincident detection of decay products

K. Itahashi, Y. Tanaka et al., Exp. S 490
Feb., 2022

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

↓

$\eta' + p\,N \rightarrow p\,N$

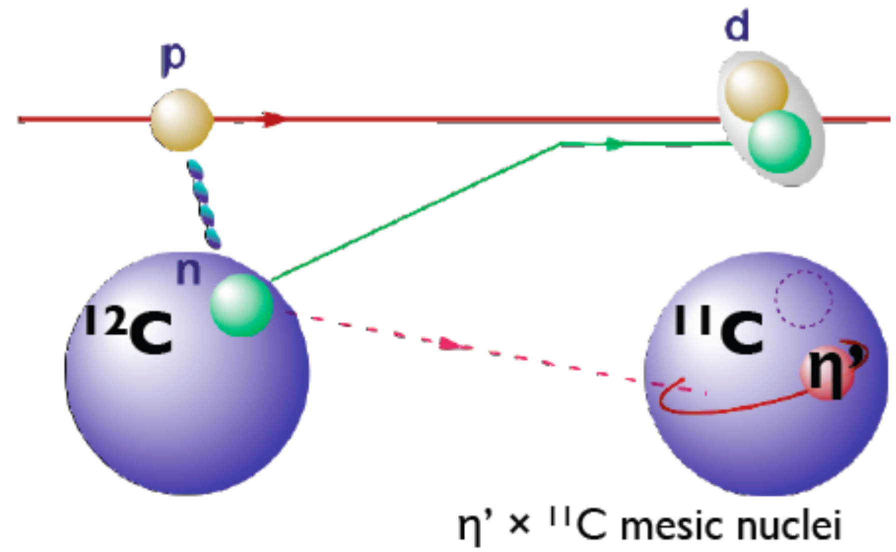
$\eta' + p \rightarrow \eta + p$

Search for η' - nucleus bound states I

recoilless production in $^{12}C(p,d)$ reaction

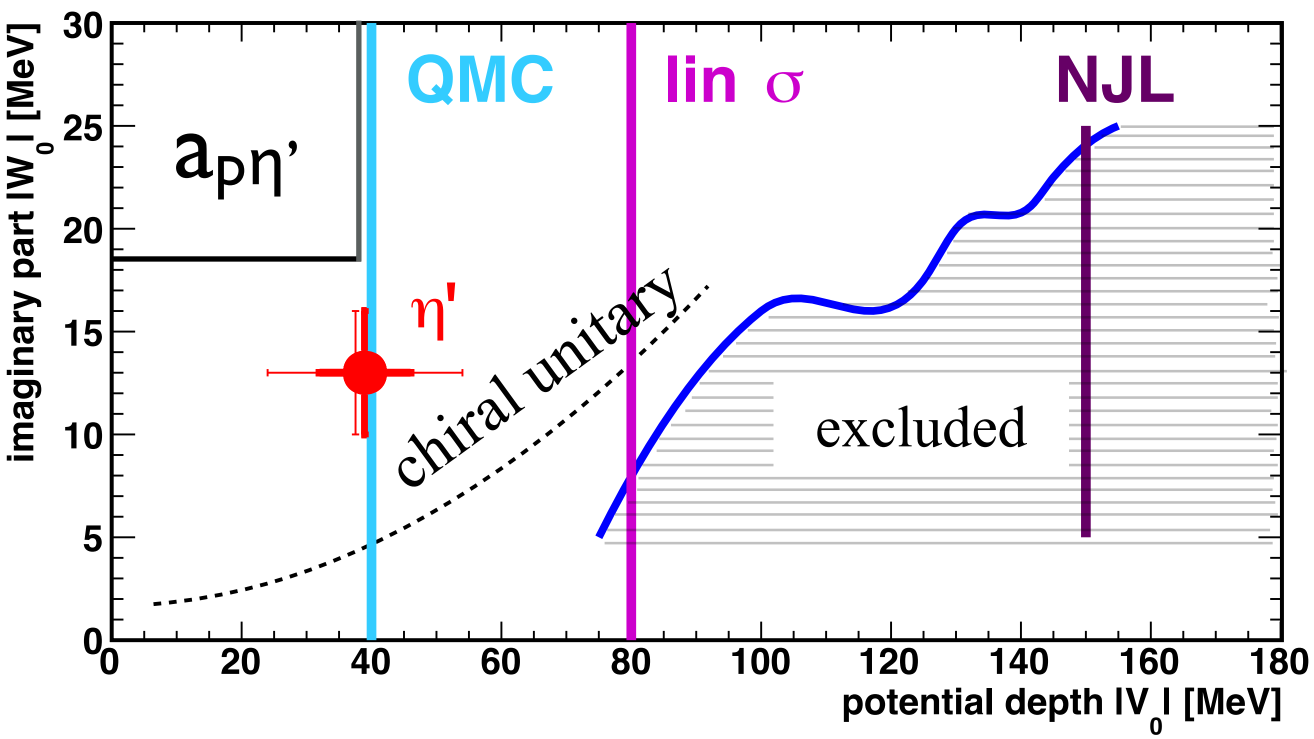
PRiME collaboration (2012)

K. Itahashi et al., Exp. S 437



FRS@GSI

Y.K. Tanaka et al., PRL 117 (2016) 202501
Y.K. Tanka et al., PRC 97 (2018) 015202



missing mass spectrometry with coincident detection of decay products

K. Itahashi, Y. Tanaka et al., Exp. S 490
Feb., 2022

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

↓

$\eta' + p\,N \rightarrow p\,N$

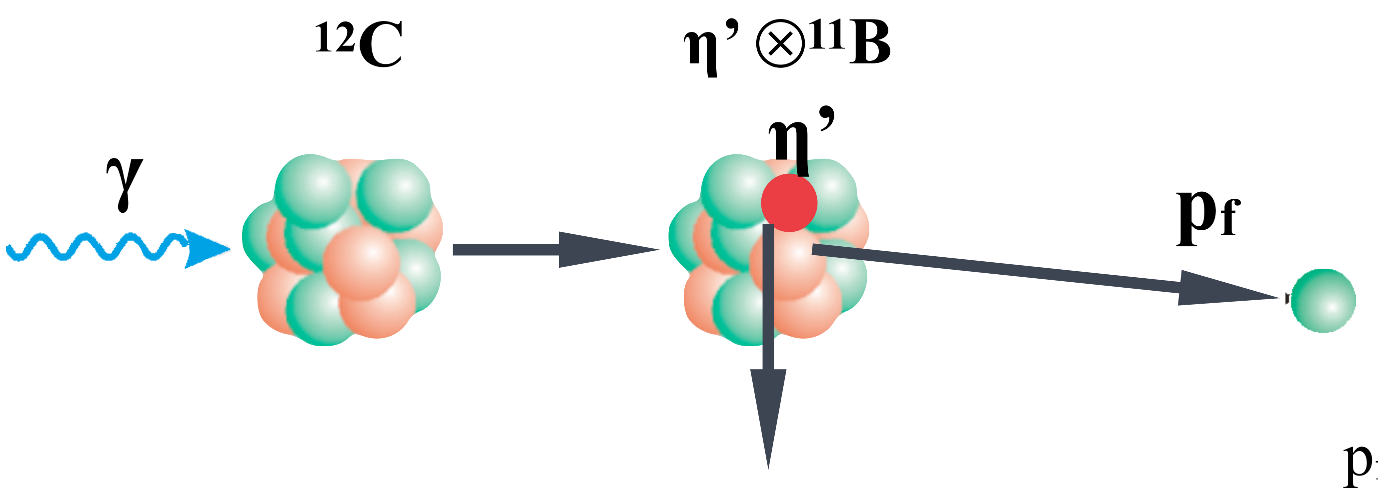
$\eta' + p \rightarrow \eta + p$

⟹ talk by Y. Tanaka about η'-mesic states

Search for η' - nucleus bound states II

N. Tomida et al. PRL 124 (2020) 202501

LEPS2/BGOegg@Spring-8



p_f = forward going proton
p_s= sideward going proton

$\eta' + p \rightarrow \eta + p_s$

missing mass spectrometry with
coincident detection of decay products

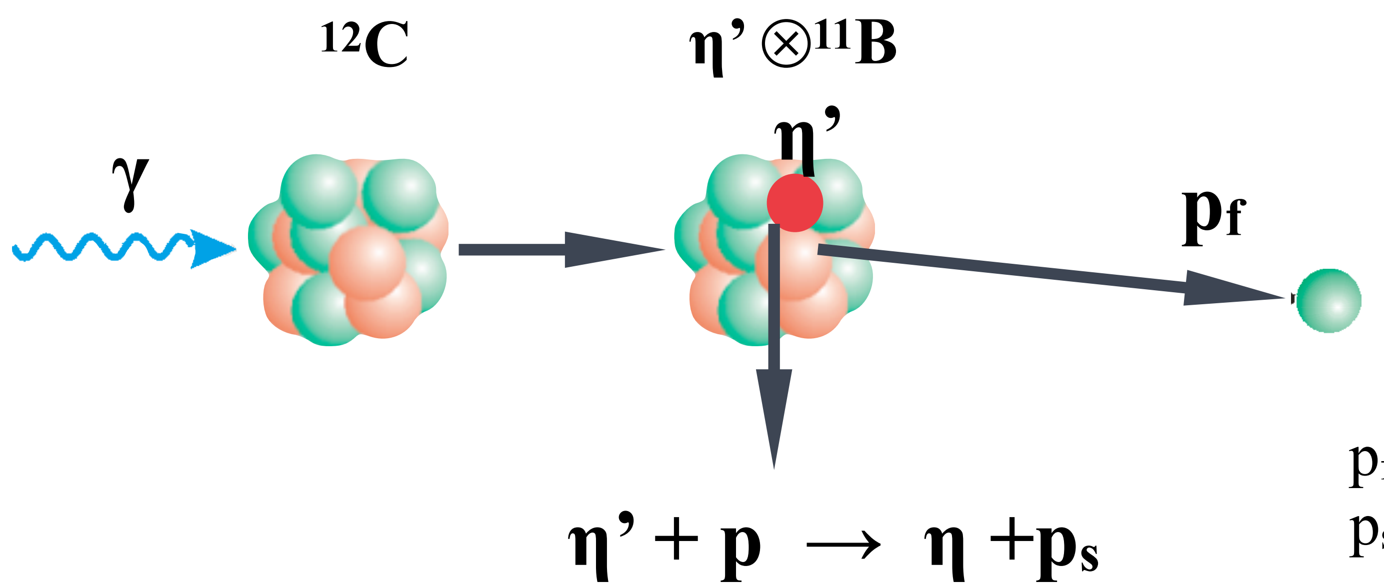
upper limit for branching
ratio BR($\eta' N \rightarrow \eta N$)
≈ 24% for V_0= -100 MeV
≈ 80% for V_0= -20 MeV

⟹ talk by M. Miyabe

Search for η’ - nucleus bound states II

N. Tomida et al. PRL 124 (2020) 202501

LEPS2/BGOegg@Spring-8



p_f = forward going proton
p_s= sideward going proton

missing mass spectrometry with
coincident detection of decay products

upper limit for branching
ratio BR(η’N→ηN)
≈ 24% for V_0= -100 MeV
≈ 80% for V_0= -20 MeV

⟹ talk by M. Miyabe

in both experiments so far only upper limits for production of η’ mesic states,
more to come at this workshop

Summary & Conclusion

meson properties do change in a strongly interacting medium !!

- η' is broadened; the lifetime is shortened through inelastic collisions
- large mass modifications $|\Delta m| > 100$ MeV (as predicted by some calculations) have not been observed
- in-medium effects described within meson-nucleus optical potential

$$V_0 = \Delta m(\rho=\rho_0) = -[39 \pm 7(stat) \pm 15(syst)] \text{ MeV}$$

$$W_0 = \text{Im } U(\rho=\rho_0, p_{\eta'} \approx 0) = -[13 \pm 3(stat) \pm 3(syst)] \text{ MeV}$$

(derived in comparison to model calculations!)

- the η' meson is a good candidate for forming meson-nucleus bound states since $|\text{Im } U| \ll |\text{Re } U|$
- search for η' mesic states ongoing; more at this workshop

Backup

Estimates of the imaginary part of the η'A interaction

based on analysis of $\gamma\, p \rightarrow p\, \eta'$ data: SAPHIR, CLAS, CBELSA

W = - 5 to -20 MeV H. Nagahiro, M. Takizawa, S. Hirenzaki , PRC 74 (2006) 045203

W = -2 to -30 MeV H. Nagahiro, et al., PLB 709 (2012) 87

based on analysis of $p\, p \rightarrow p\, p\, \eta'$ data: COSY-11

$W = -32^{+34}_{-14}$ MeV E. Czerwiński et al., PRL 113 (2014) 062004

theoretical estimate within chiral unitary approach:

$W \approx -1.8$ MeV E. Oset and A. Ramos PLB 704 (2011) 334