Mesons in the medium- what we have learned?

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

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Outline:

- introduction: meson-nucleus interactions
- methods for determining meson-nucleus potentials
- potential parameters for K^+, K^0, K^-, η', ω, Φ - A interaction
- search for meson-nucleus bound states
- summary & outlook

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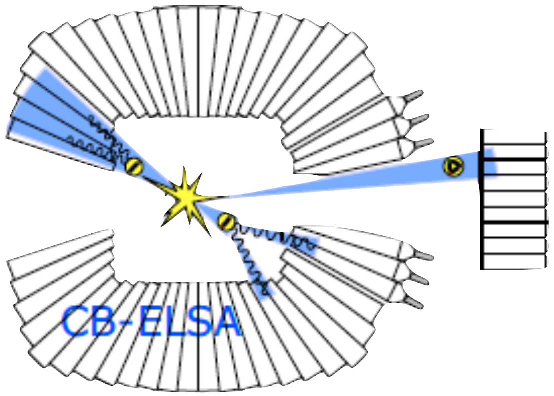
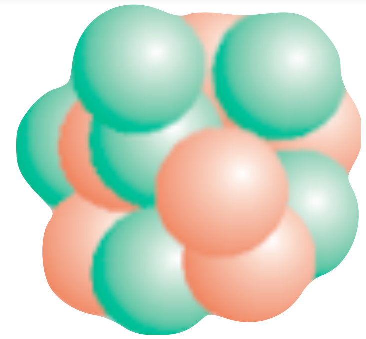
International Conference on Exotic Atoms and Related Topics - EXA 2017
Vienna, Austria, September 10-15, 2017



meson-nucleus interaction

meson ⟺  nucleus

1.) interaction attractive or repulsive ??

2.) if attractive, interaction strong enough
to form meson-nucleus bound state
exclusively bound by the strong interaction??

exotic nuclear configurations:

<u>nuclear physics:</u> states with excitation energies of several 100 MeV

<u>hadron physics:</u> investigate in-medium static properties of mesons

mesons investigated: K^+, K^0, K^-, η’, ω, Φ

meson-nucleus potential

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

$$U(r) = V(r) + i\,W(r)$$

attractive ?
repulsive ?

absorption

$$V(r) = \Delta m(\rho_0) \cdot \rho(r)/\rho_0$$

$$W(r) = -\Gamma_0/2 \cdot \rho(r)/\rho_0$$

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

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

- transparency ratio measurement

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

D. Cabrera et al., NPA733 (2004) 130

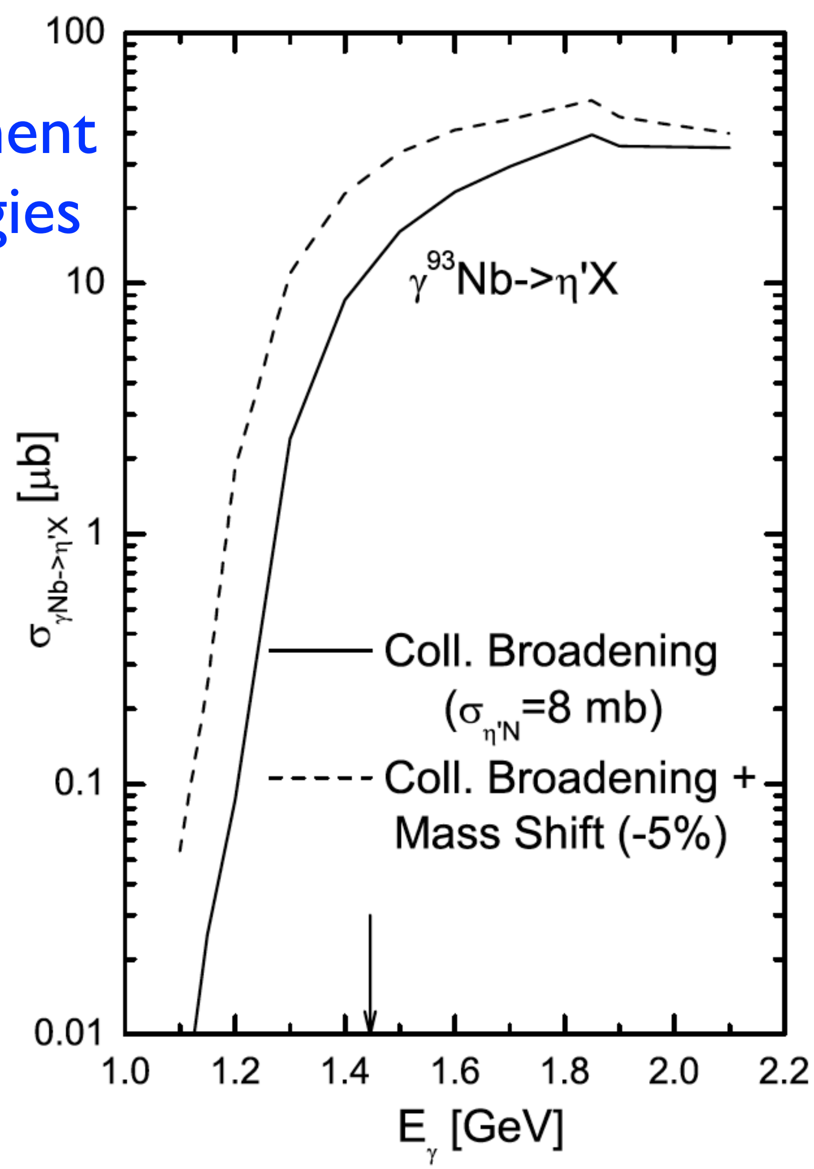
determining the real part of the η'-nucleus potential: comparison with collision/transport model calculations

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

- excitation function

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

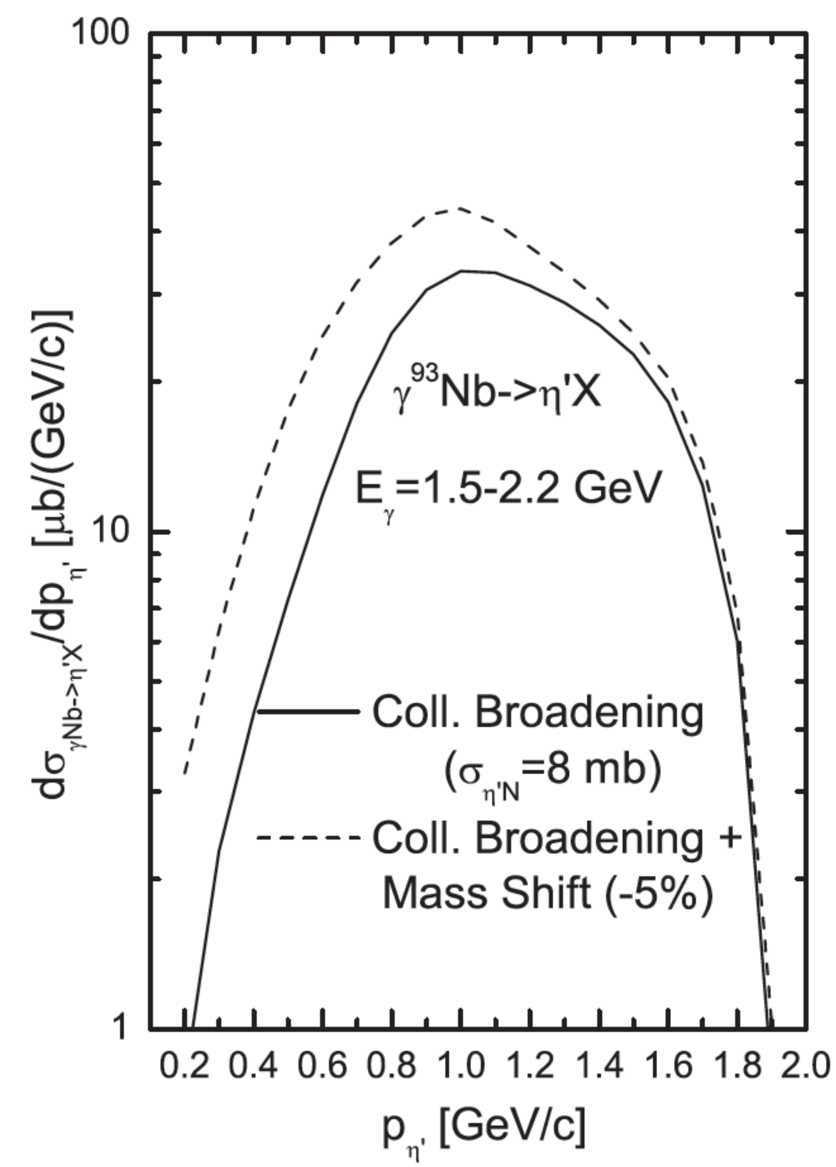
⇨ enhancement at low energies



- momentum distribution of the meson:

repulsion ⇒ higher η' kinetic energy

large attraction ⇒ low η' kinetic energy
⇨ downward shift of momentum distribution



for in-medium mass drop: $V(\rho=\rho_0) = -\Delta m\ (\rho=\rho_0)$

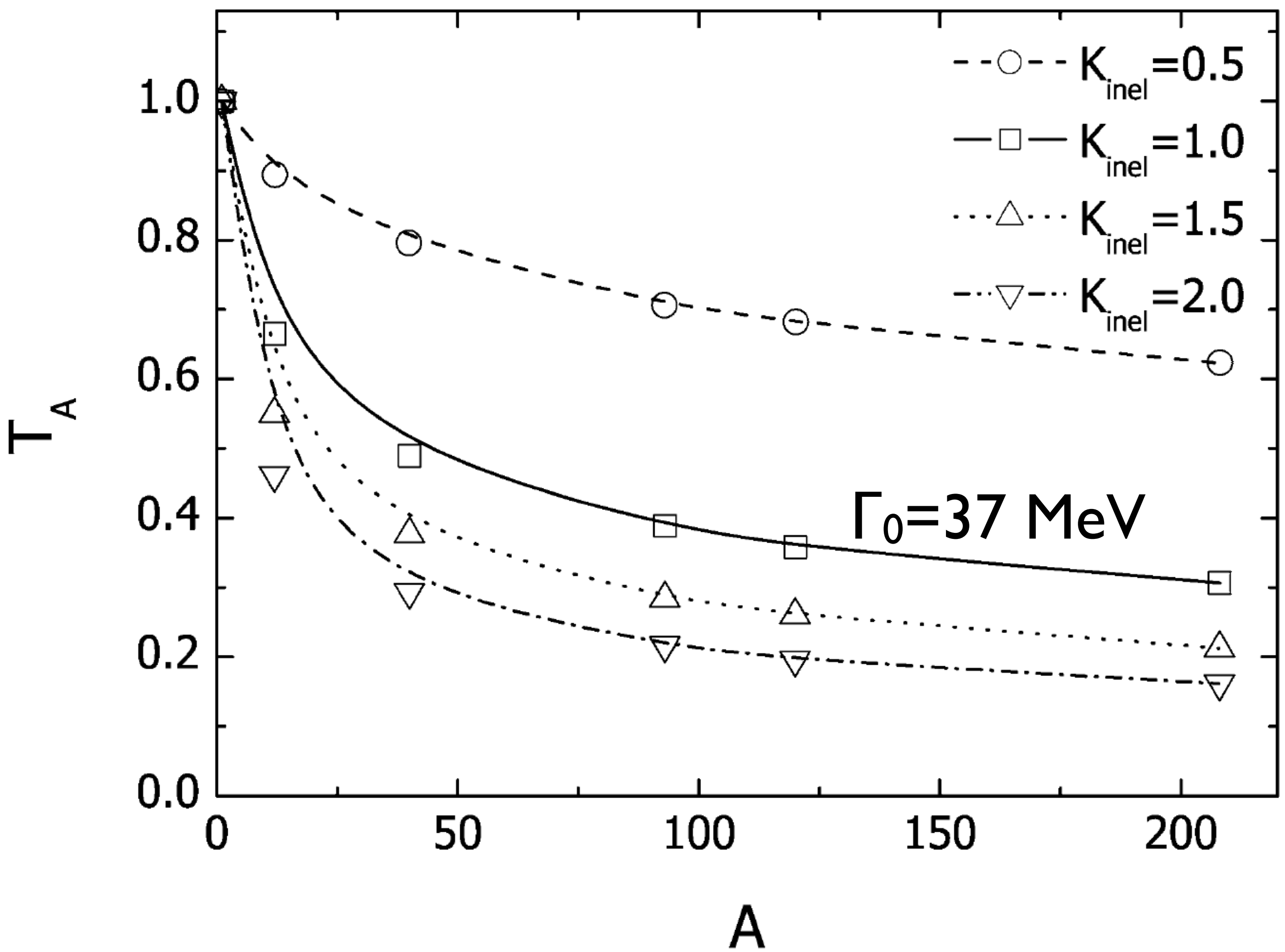
determining the imaginary part of the meson-nucleus potential from transparency ratio measurements

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

transport model calculation: GiBUU

P. Mühlich and U. Mosel, NPA 773 (2006) 156

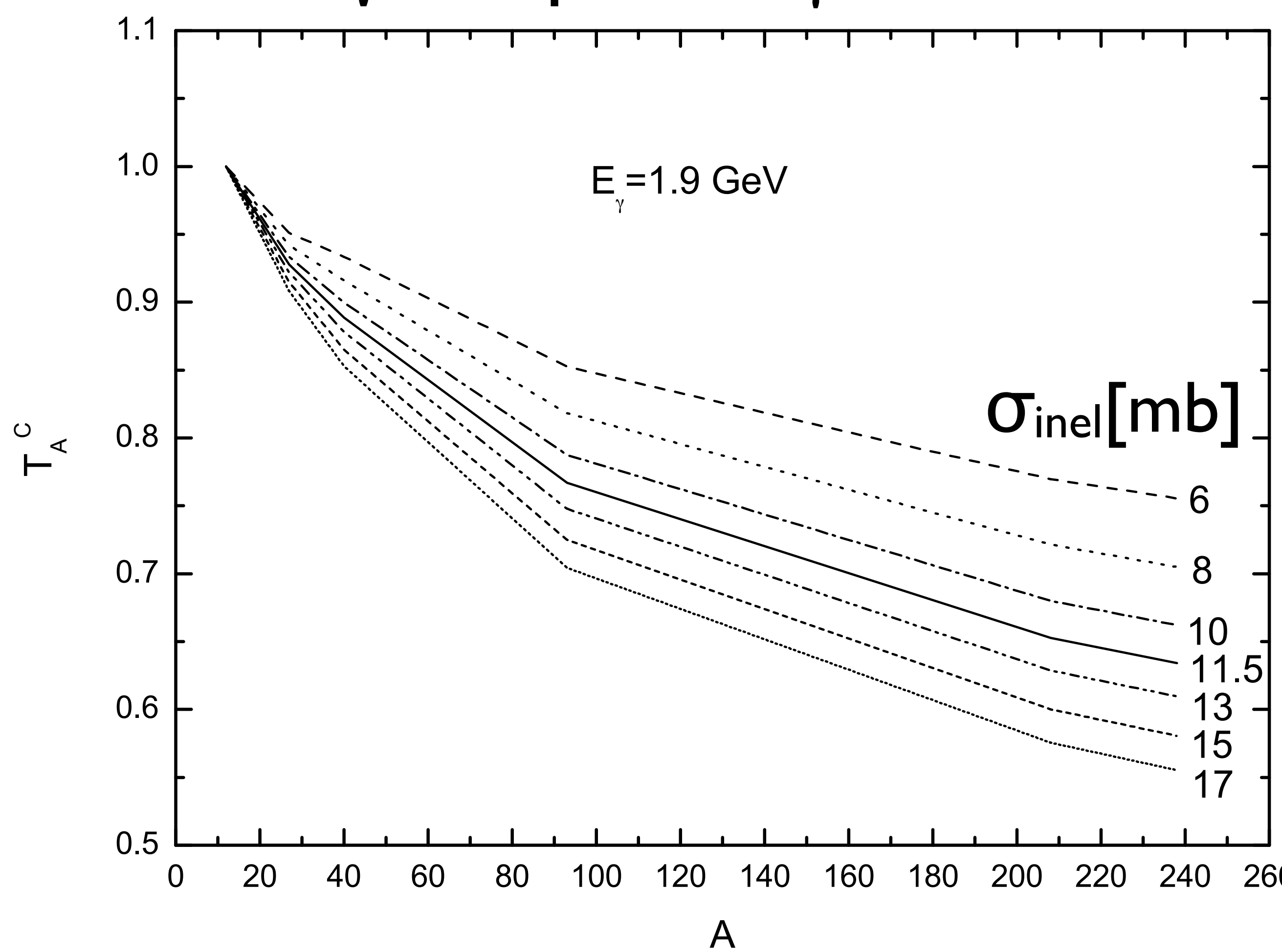
$\gamma A \to \omega X$ at E_γ=1.5 GeV



collision model calculation

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

$\gamma A \to \eta' X$ at E_γ=1.9 GeV



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

strategy for determining potential parameters

real part of meson-nucleus potential

- measure meson excitation functions and/or momentum distributions
- compare with transport and/or collision model calculations

for different sets of V_0

$$\rightarrow V_0 = V(\rho=\rho_0)$$

imaginary part of meson-nucleus potential

- measure transparency ratio $T_A(A,p)$
- compare with transport and/or collision model calculations

for different sets of Γ_{med}, σ_{inel}

$$\rightarrow \Gamma_{med}, \sigma_{inel} \rightarrow W_0 = W(\rho=\rho_{0;}\, p=0)$$

$$U(\rho=\rho_0) = V_0 + i\, W_0$$

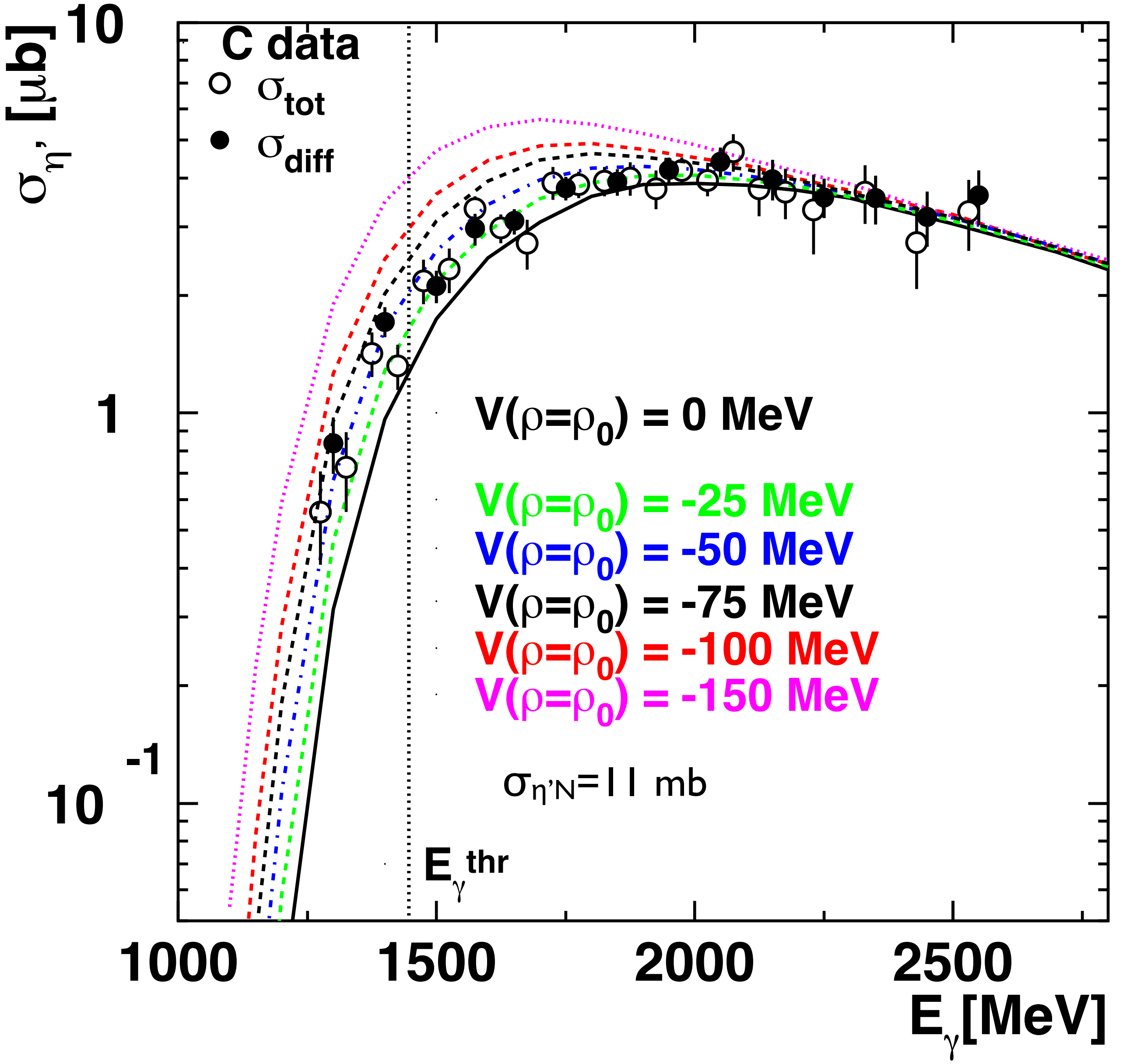
excitation function and momentum distribution for η' photoproduction off C

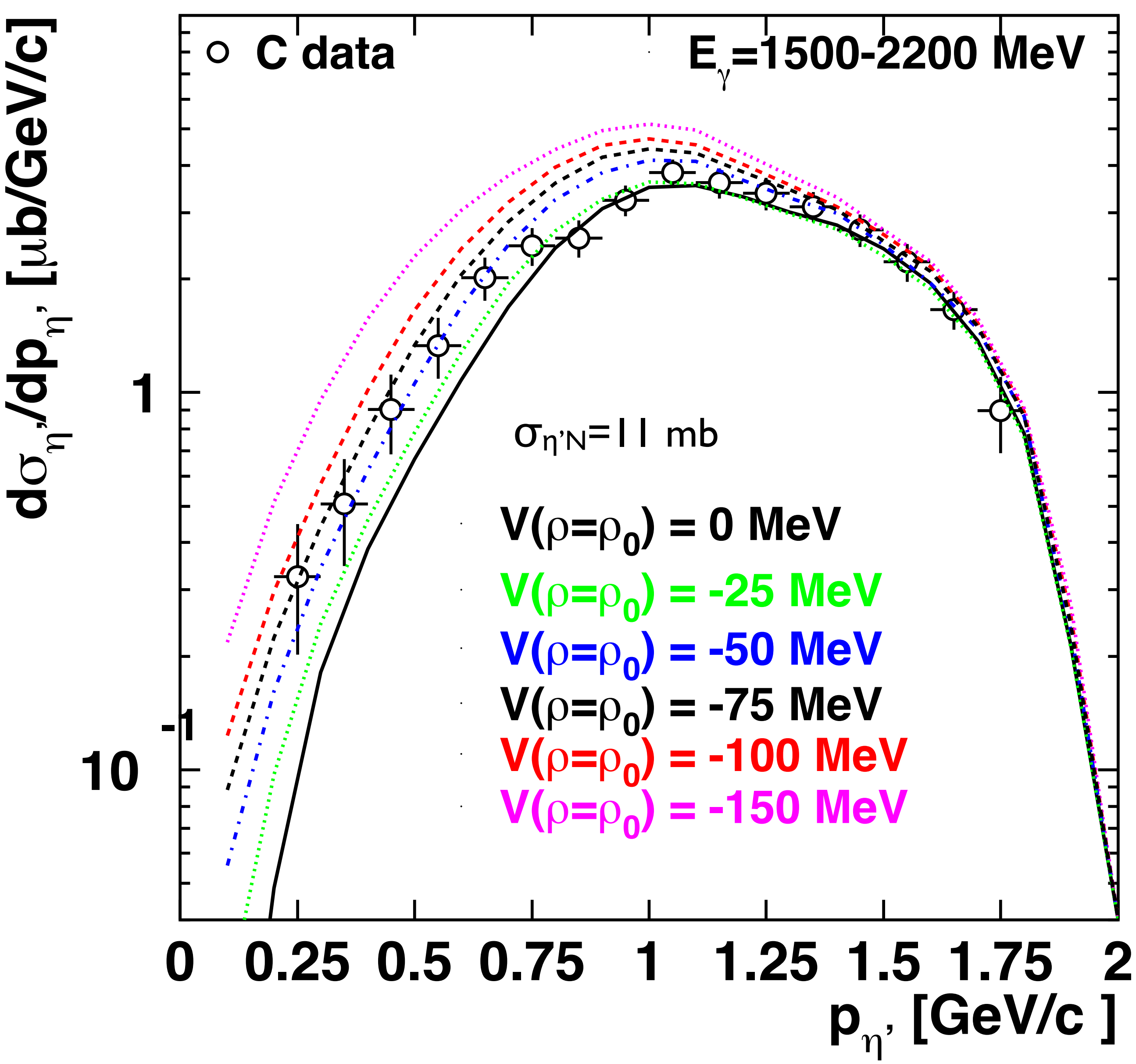
CB/TAPS @ ELSA

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

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

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





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

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

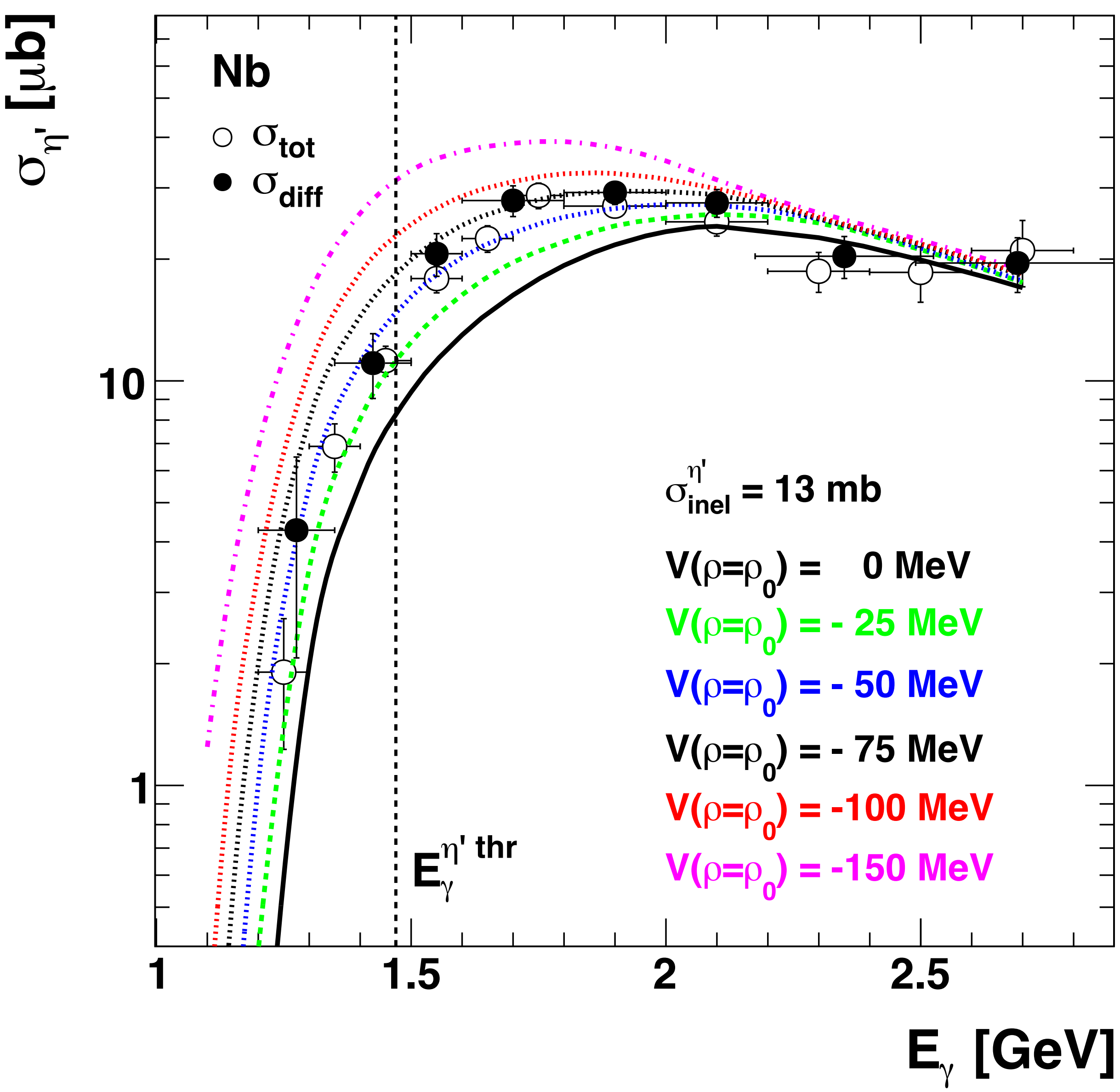
data disfavour strong mass shifts

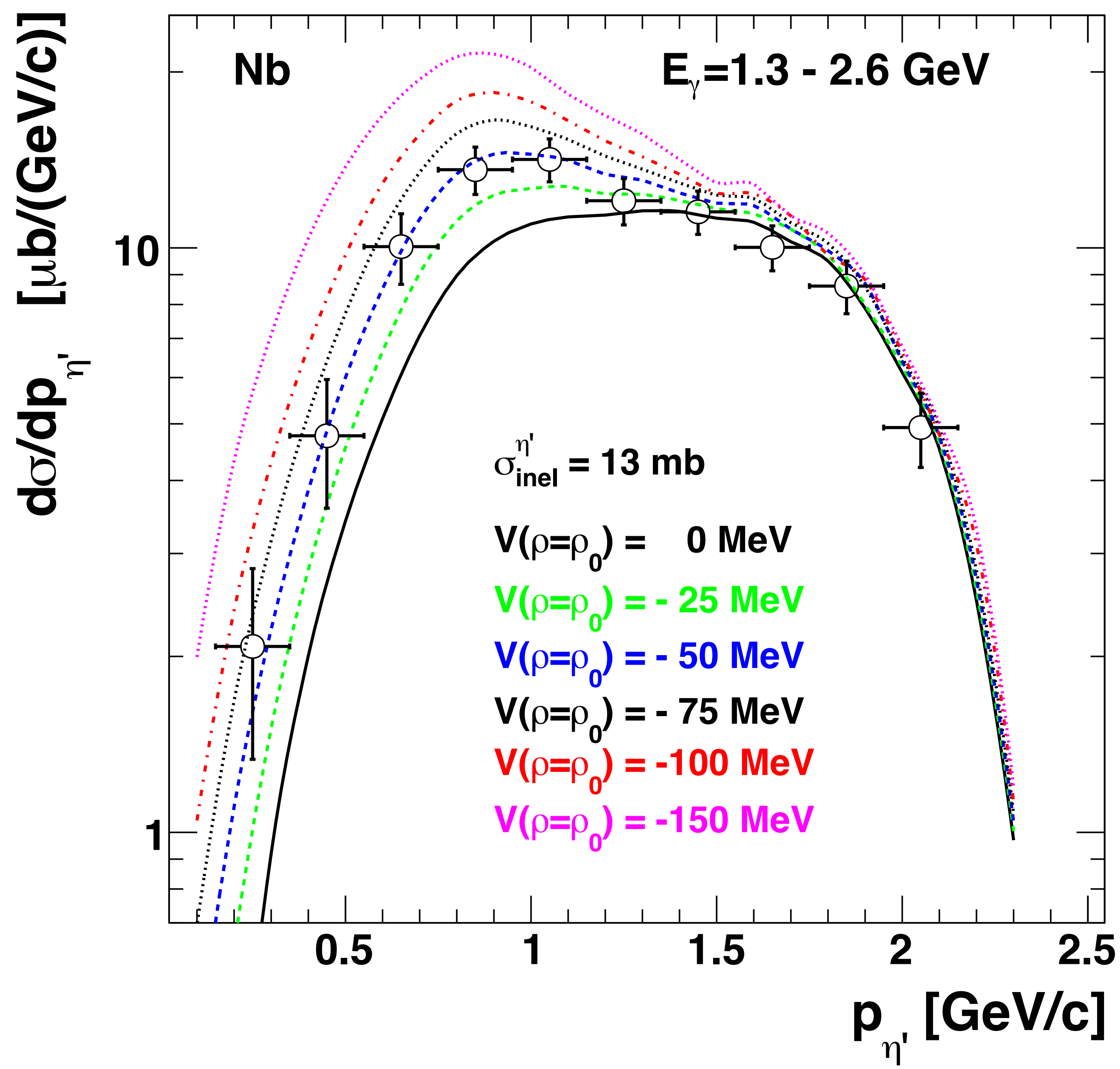
excitation function and momentum distribution for η' photoproduction off Nb

CB/TAPS @ ELSA

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

γ Nb $\rightarrow \eta' X$





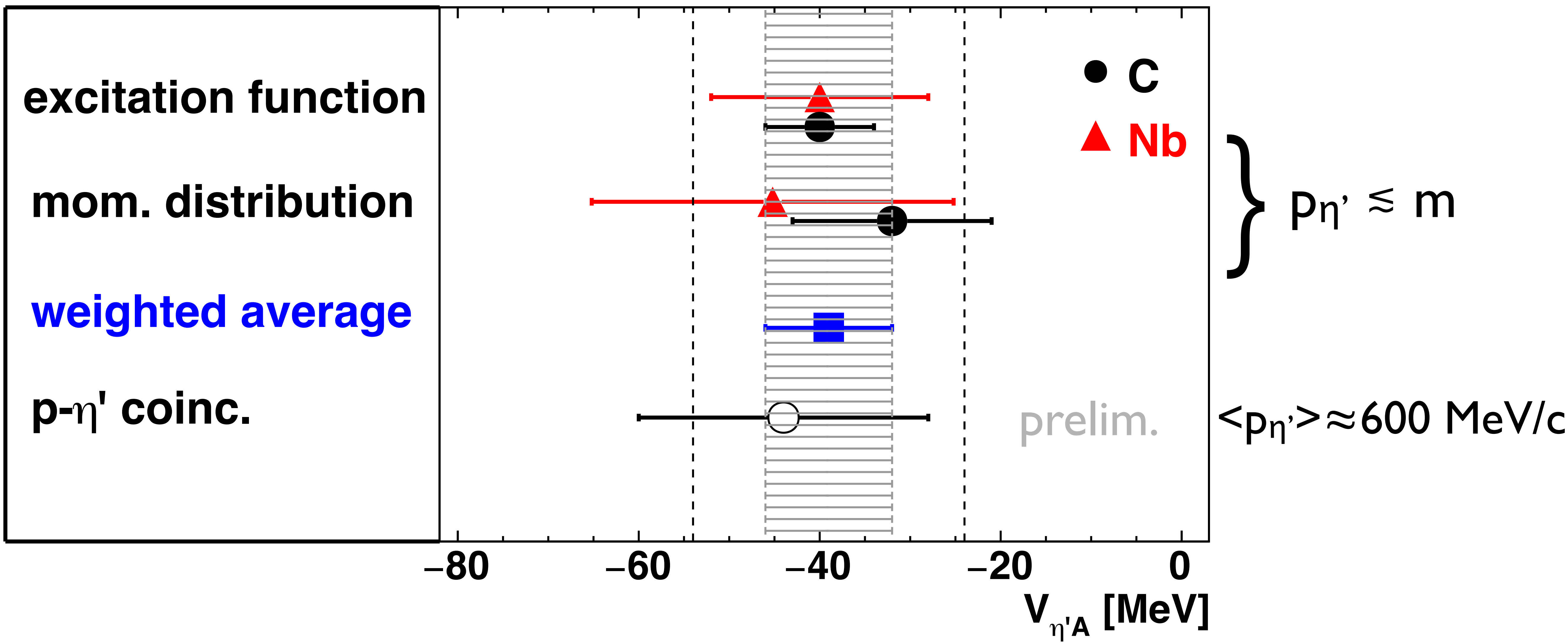
$V_{\eta'}(\rho=\rho_0) = -(40\pm12)$ MeV

$V_{\eta'}(<p_{\eta'}>\approx 1.1$ GeV/c$;\rho=\rho_0) = -(45\pm20)$ MeV

data disfavour strong mass shifts

determining the real part of the η'-nucleus potential

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



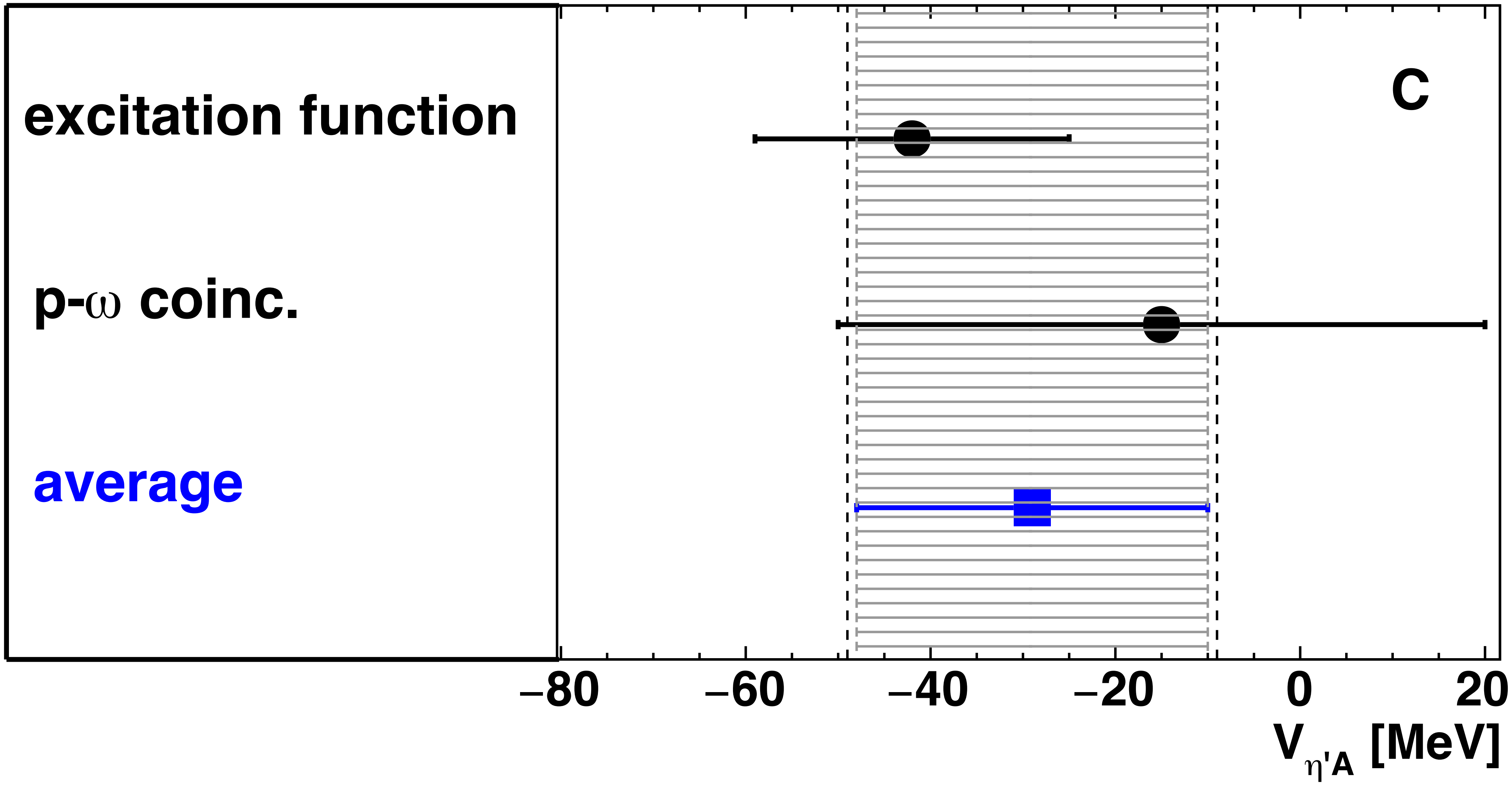
$V_0 = \Delta m(\rho=\rho_0) = -[39 \pm 7(stat) \pm 15(syst)]$ MeV

observed mass shift in agreement with QMC model predictions

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

determining the real part of the ω-nucleus potential

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



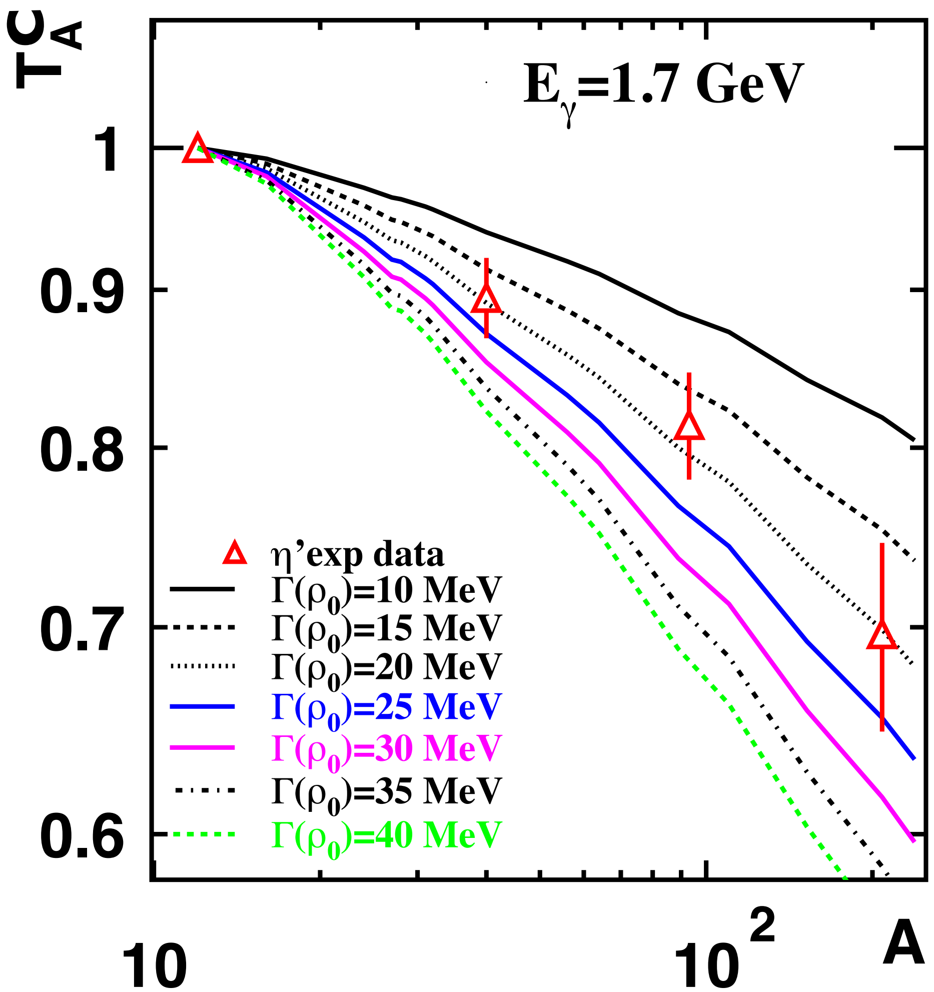
$V_0 = \Delta m(\rho=\rho_0) = -[29 \pm 19(stat) \pm 20(syst)]$ MeV

determining the imaginary part of the η'-nucleus potential

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

mass dependence of T_A

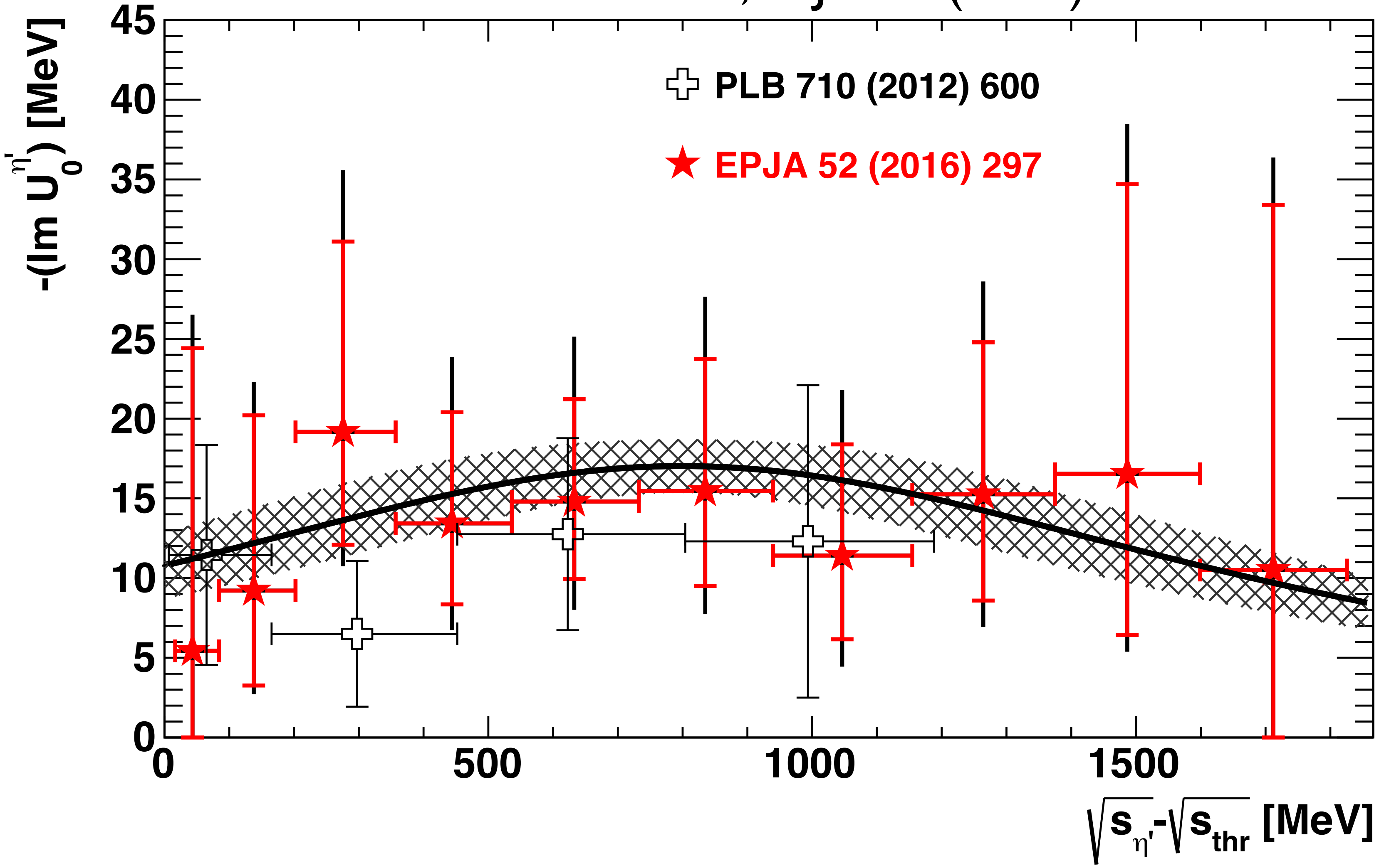
M. Nanova et al., PLB 710 (2012) 600



$\Gamma_{\eta'}(\rho=\rho_0)$ =15-25 MeV

momentum dependence of Γ_0, W_0

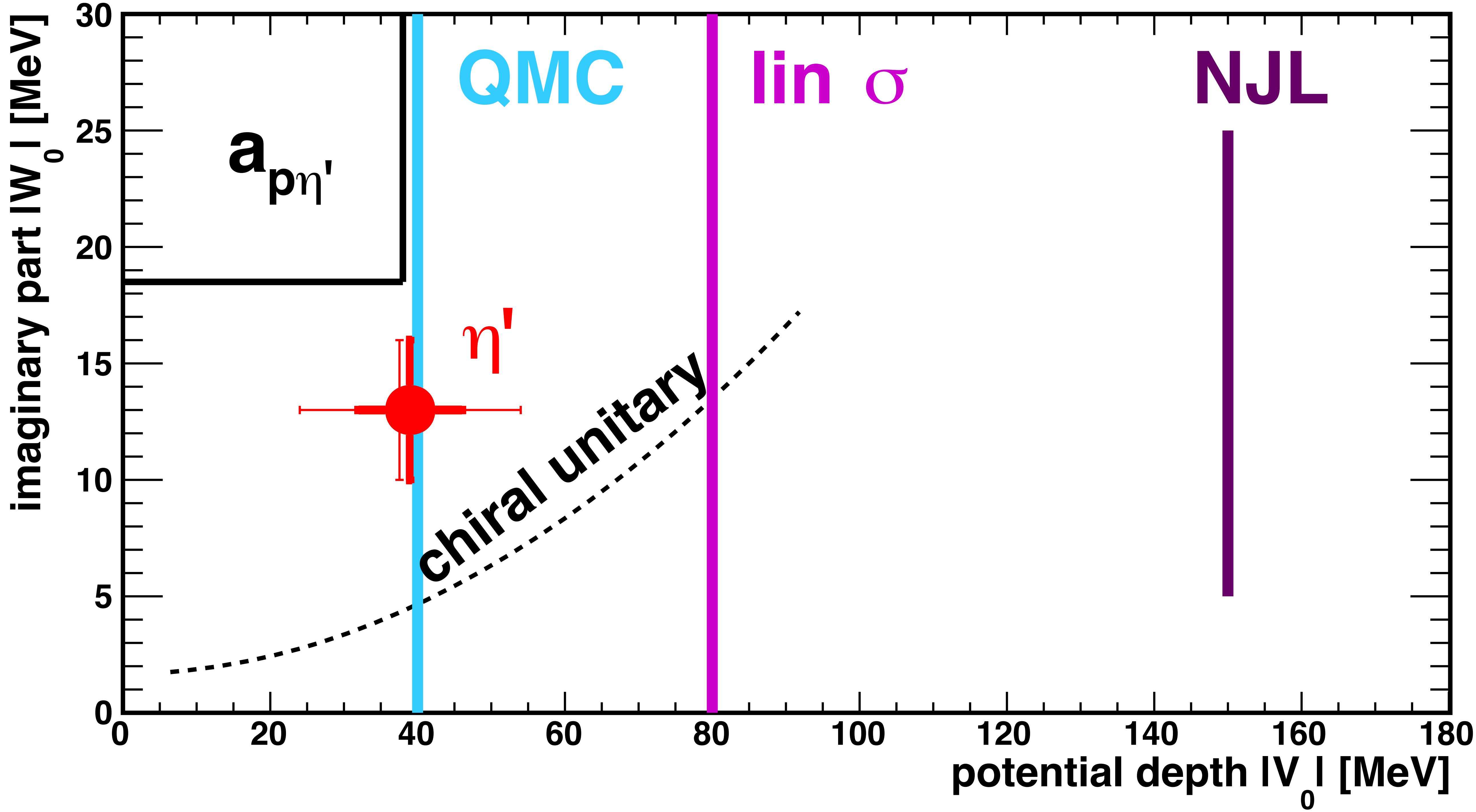
S. Friedrich et al., EPJA 52 (2016) 297



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

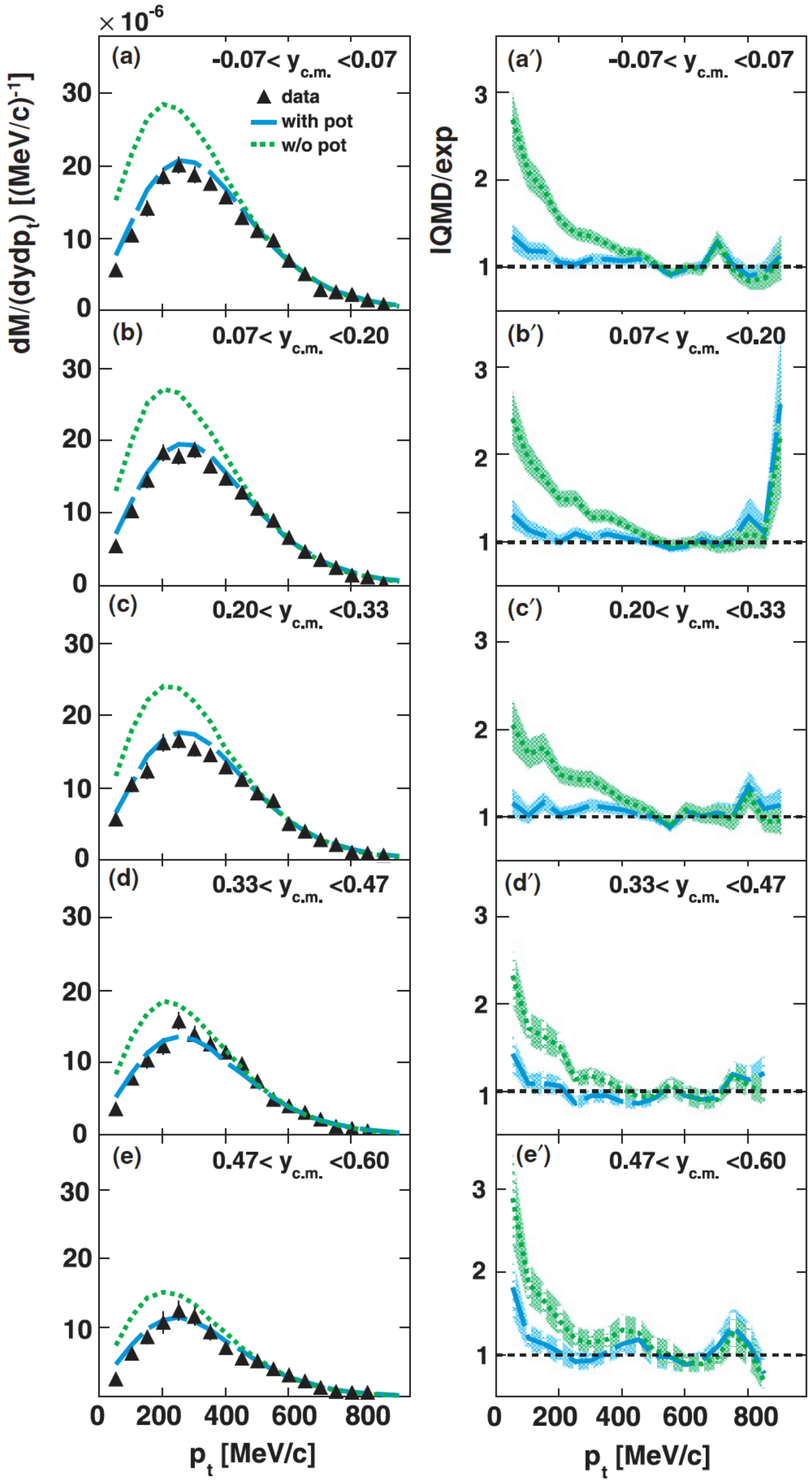
summary of information on the η’-nucleus potential

V. Metag, M. N. , E. Paryev , arXiv: 1706.09654, PPNP in press



$\mathbf{a_{p\eta'}}$ - potential parameters corresponding to the pη’ scattering length (Czerwinski et al. PRL 113 (2014) 062004)

determining the real part of the K^0 -nucleus potential



HADES: Ar + KCl at 1.756 AGeV

G. Agakishiev et al., PRC90 (2014) 054906

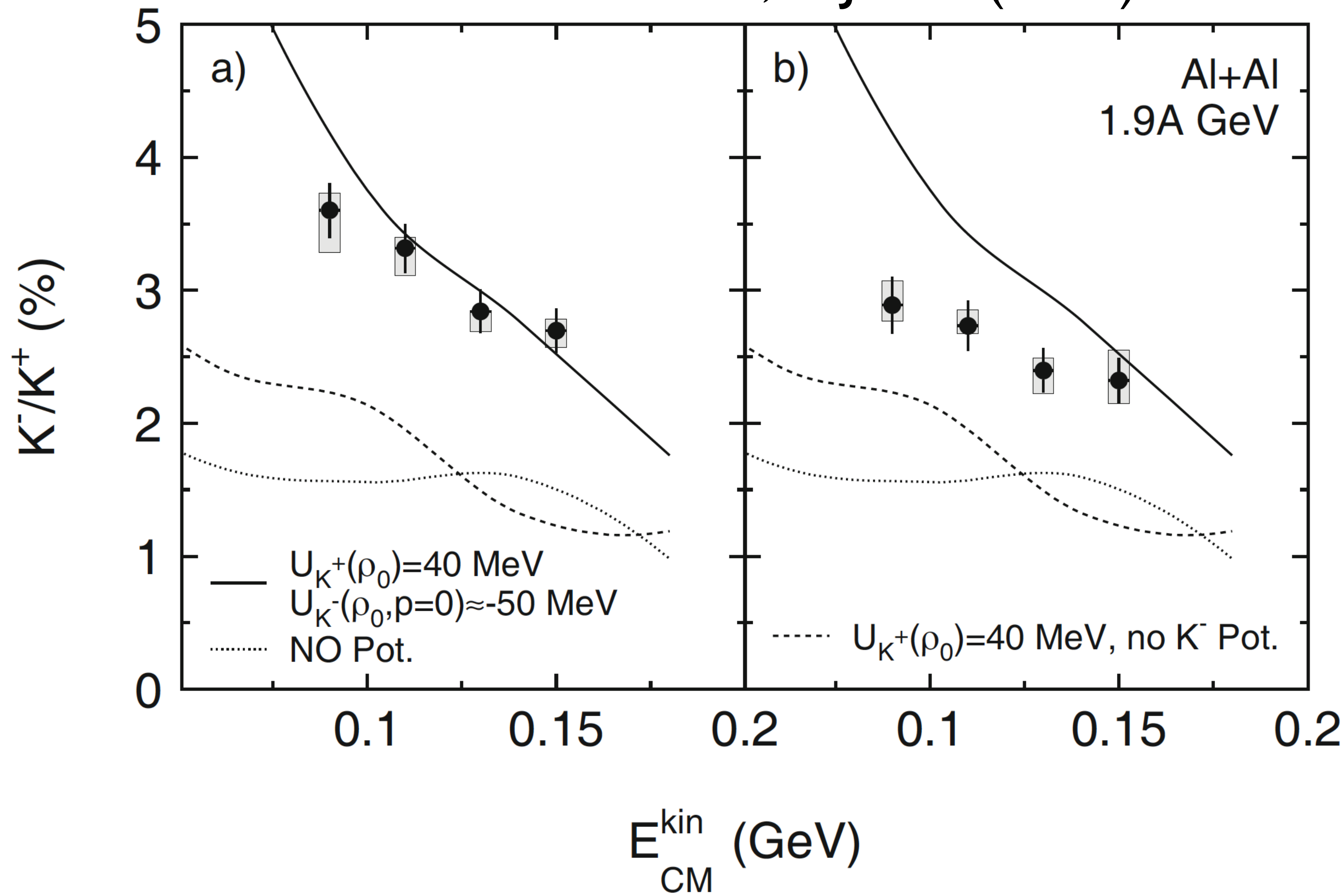
K^0 transverse momentum spectra
compared to IQMD transport calculations
without potential (dashed)
and with repulsive potential
of +46 MeV (solid curve)

V ≈+ 40 MeV

determining the real part of the K^--nucleus potential

K+ and K^- kinetic energy spectra from Al + Al at 1.94 AGeV

FOPI: P. Gasik et al., EPJA 52 (2016) 177



$V_{K^+} \approx$ +40 MeV

$V_{K^-} \approx$ -50 MeV ??

b.) corrected for feeding of K^- spectrum from decay $\Phi \rightarrow K^+K^-$ decays

Φ/K^--ratio = 0.36±0.05 Ni+Ni at 1.9 AGeV (FOPI)

Φ/K^--ratio = 0.52±0.16 Au + Au at 1.23 AGeV (HADES)

} not reproduced in transport calculations

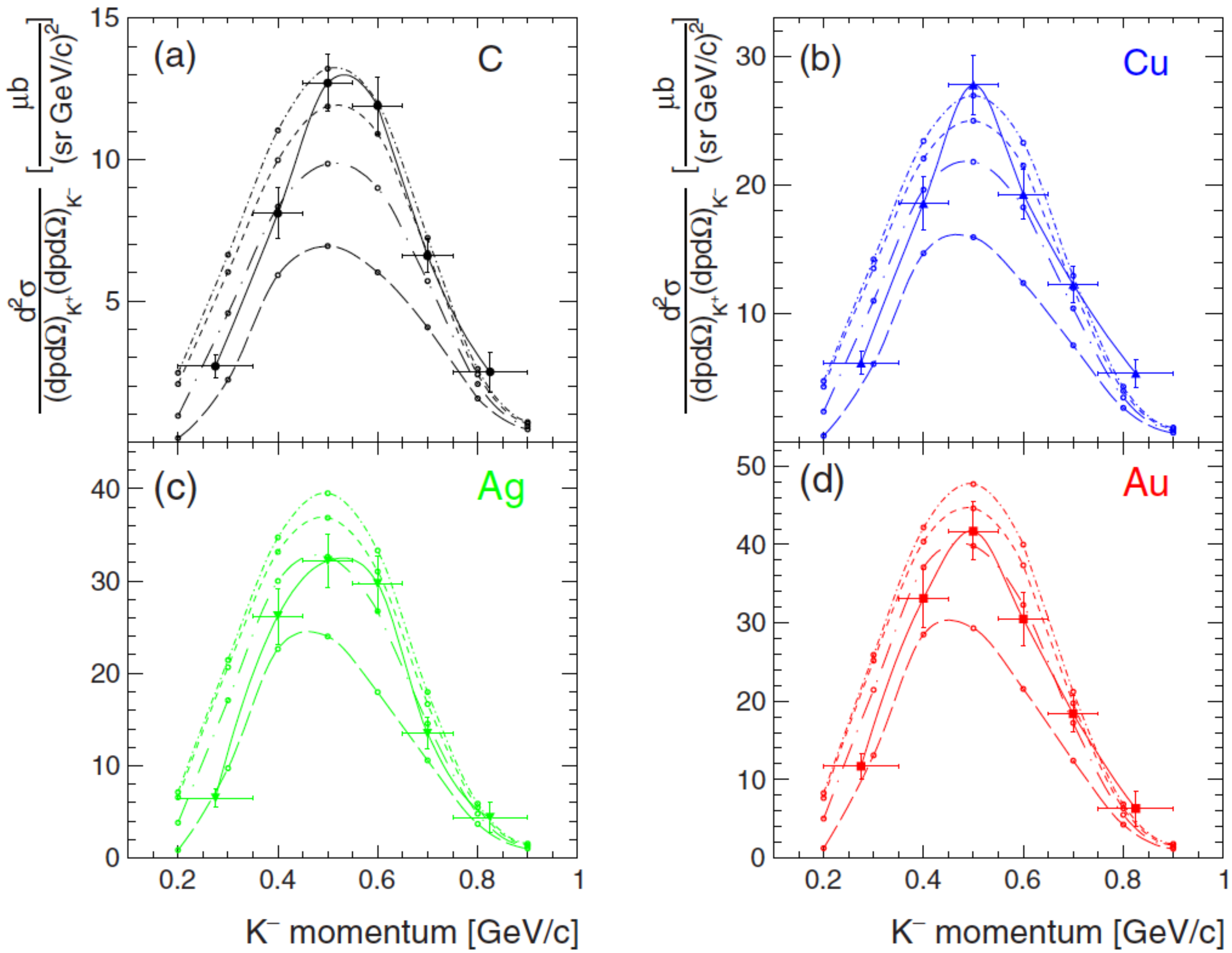
make sure other observables are reproduced before deducing potential parameters !!

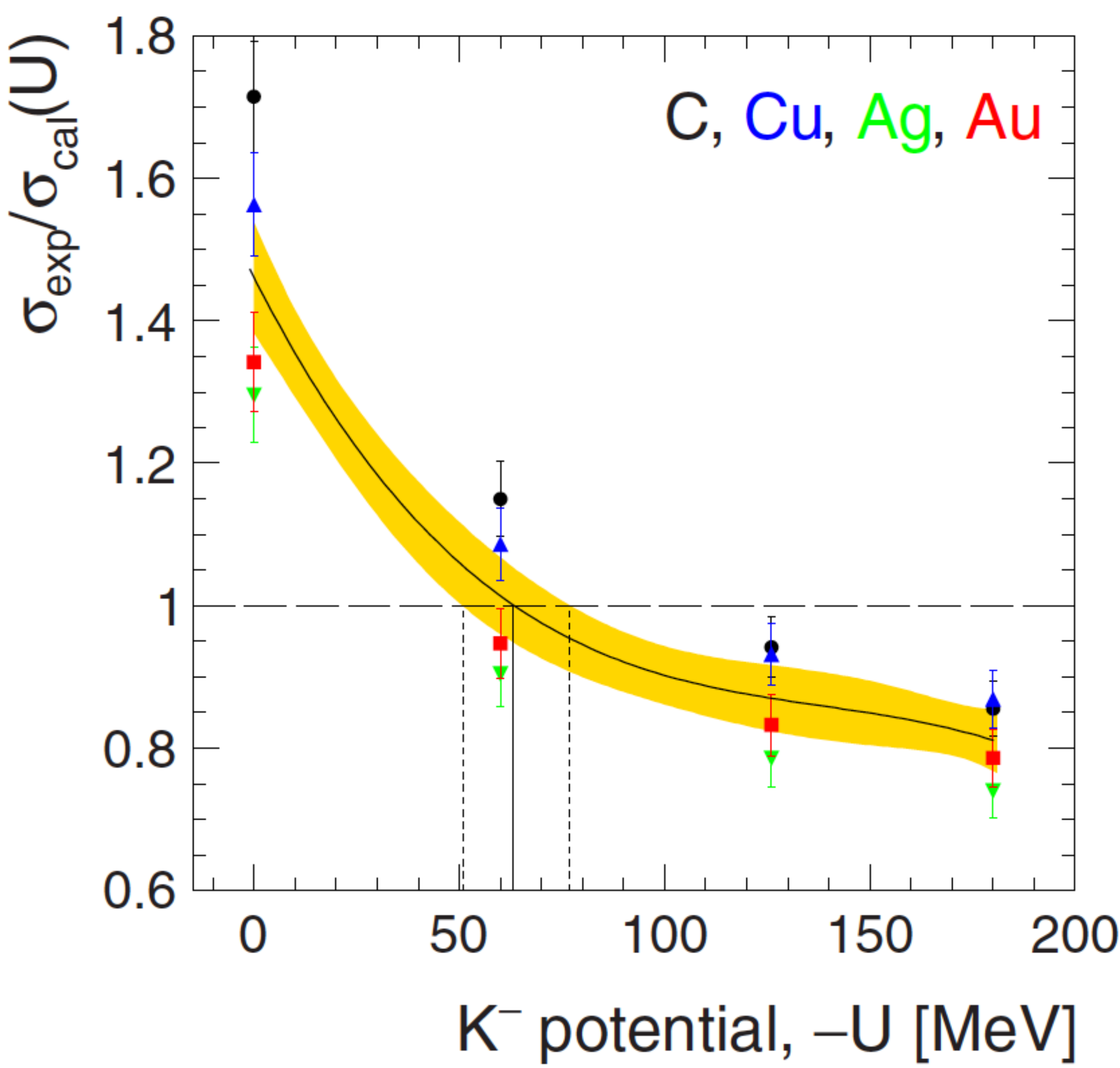
determining the real part of the K⁻ -nucleus potential

p + C, Cu, Ag, Au → $K^+ K^-$ +X

$K^+ K^-$ - pairs not from Φ decay

ANKE: Yu. T. Kiselev et al., PRC92 (2015) 065201





K^--momentum spectra compared to collision model calculations:

E. Paryev et al., J. Phys. G 42 (2015) 075107

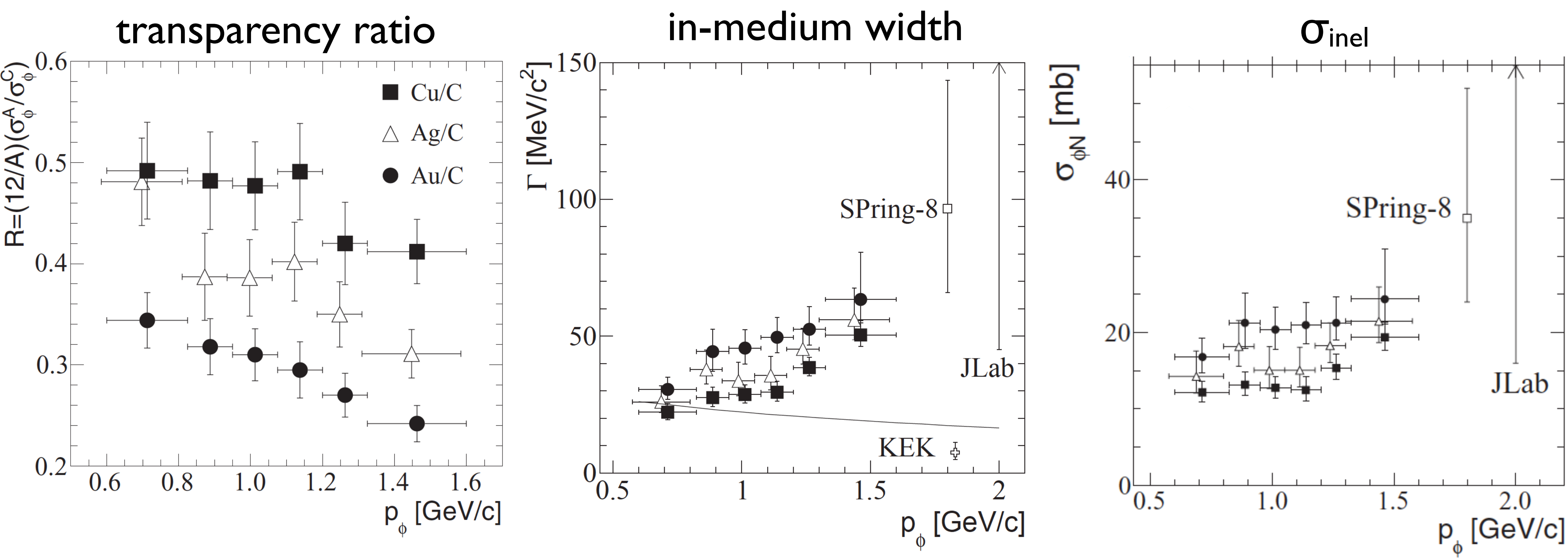
$V_{K^-} (\rho=\rho_0) = -63^{+50}_{-30}$ MeV accounting for systematic uncertainties

determining the imaginary part of the Φ-nucleus potential

M. Hartmann et al., PRC85 (2012)035206

ANKE: p + C, Cu, Ag, Au → Φ + X at 2.83 GeV

momentum dependence of transparency ratio $T_A^C = \dfrac{\sigma_{\gamma A\to\phi X}}{A\cdot\sigma_{\gamma N\to\phi X}} \Big/ \dfrac{\sigma_{\gamma C\to\phi X}}{12\cdot\sigma_{\gamma N\to\phi X}}$

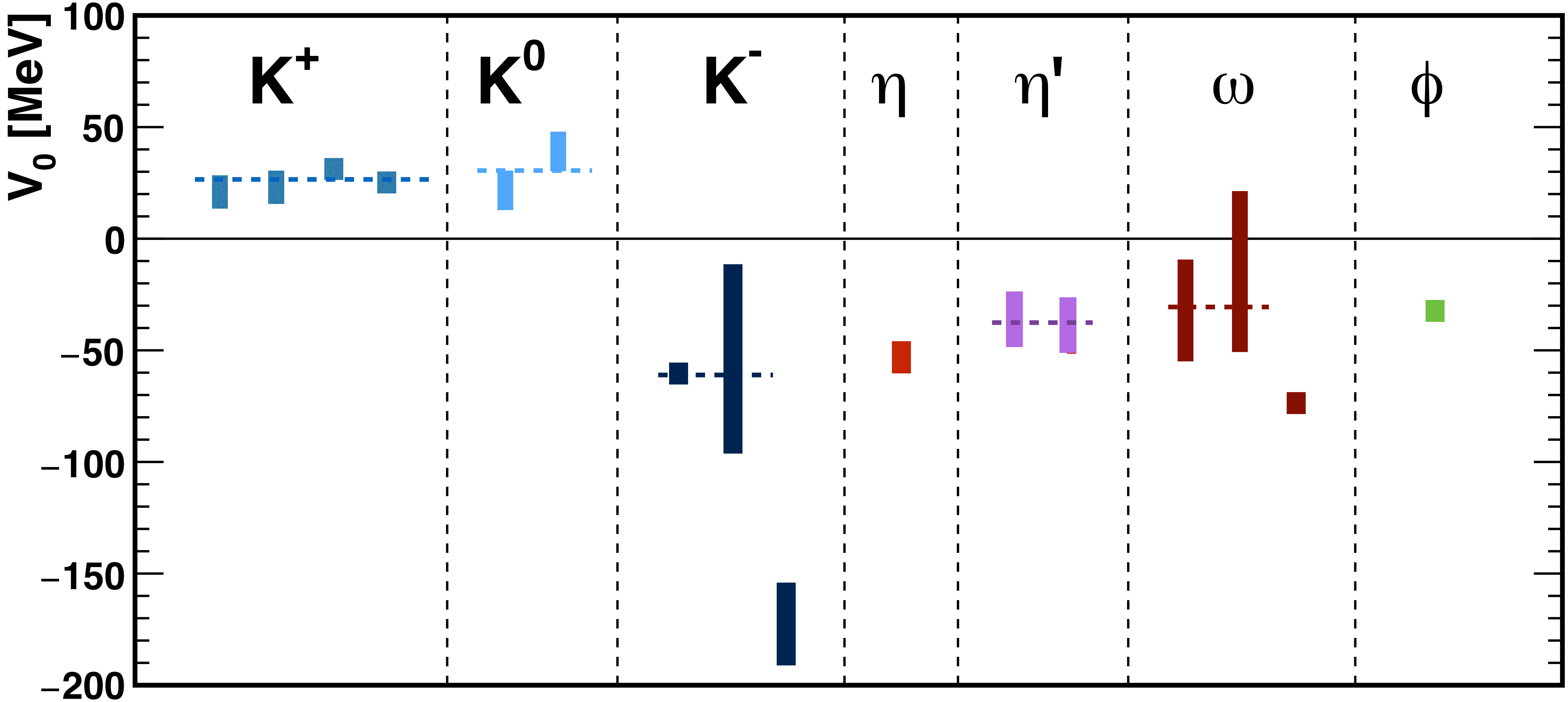


$W(\rho=\rho_0) = -\Gamma/2\ (\rho=\rho_0) = -1/2\cdot\hbar c\cdot\rho_0\cdot\sigma_{inel}\cdot\beta$

$W = -$ (10-30) MeV for $0.7 < p_\Phi < 1.5$ GeV/c

real part of the meson-nucleus potential

V. Metag, M. N. , E. Paryev , arXiv: 1706.09654, PPNP in press



meson-nucleus real potential:

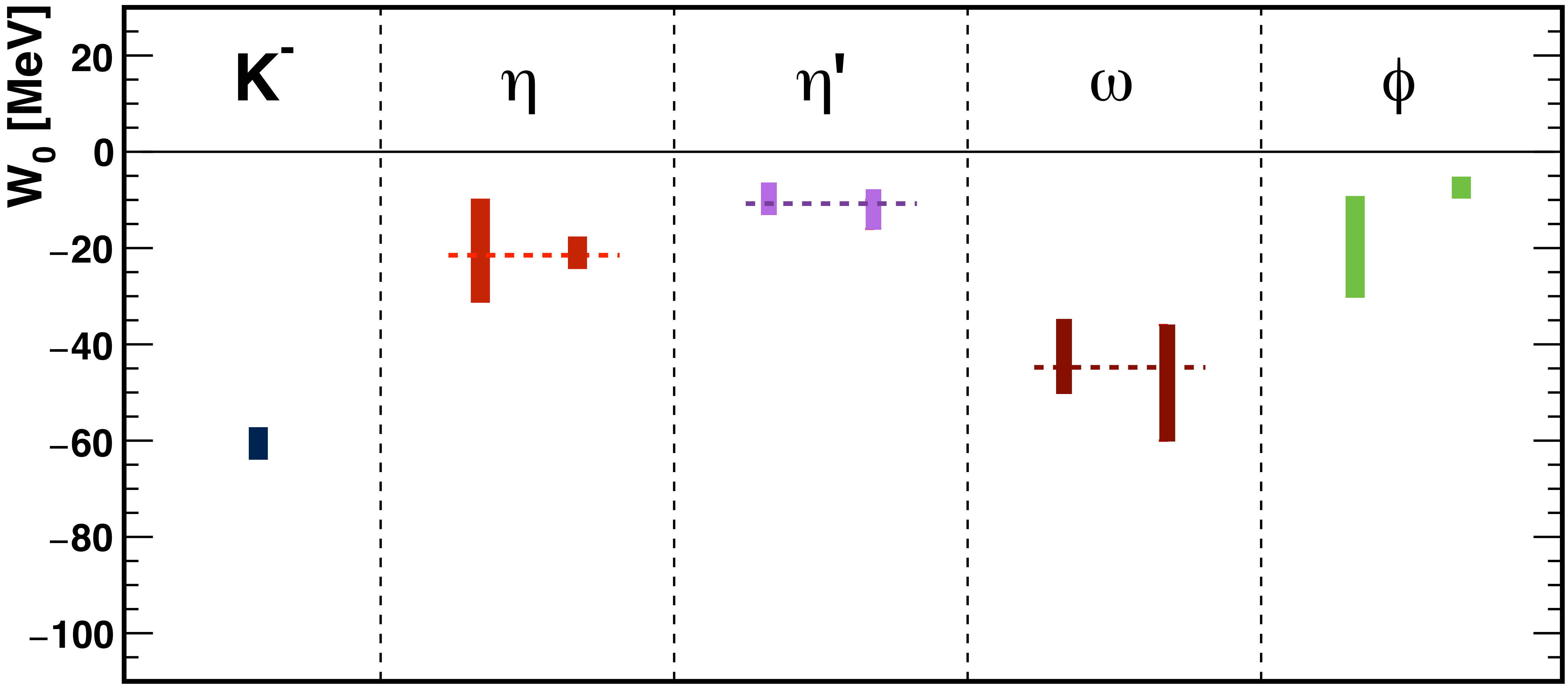
K^+, K^0 repulsive: 20-40 MeV

K^- strongest attraction: - (30 - 100) MeV

η, η', ω, Φ weakly attractive: - (20 - 50) MeV

imaginary part of the meson-nucleus potential

V. Metag, M. N. , E. Paryev , arXiv: 1706.09654, PPNP in press



meson-nucleus imaginary potential:

η' : ≈ -10 MeV

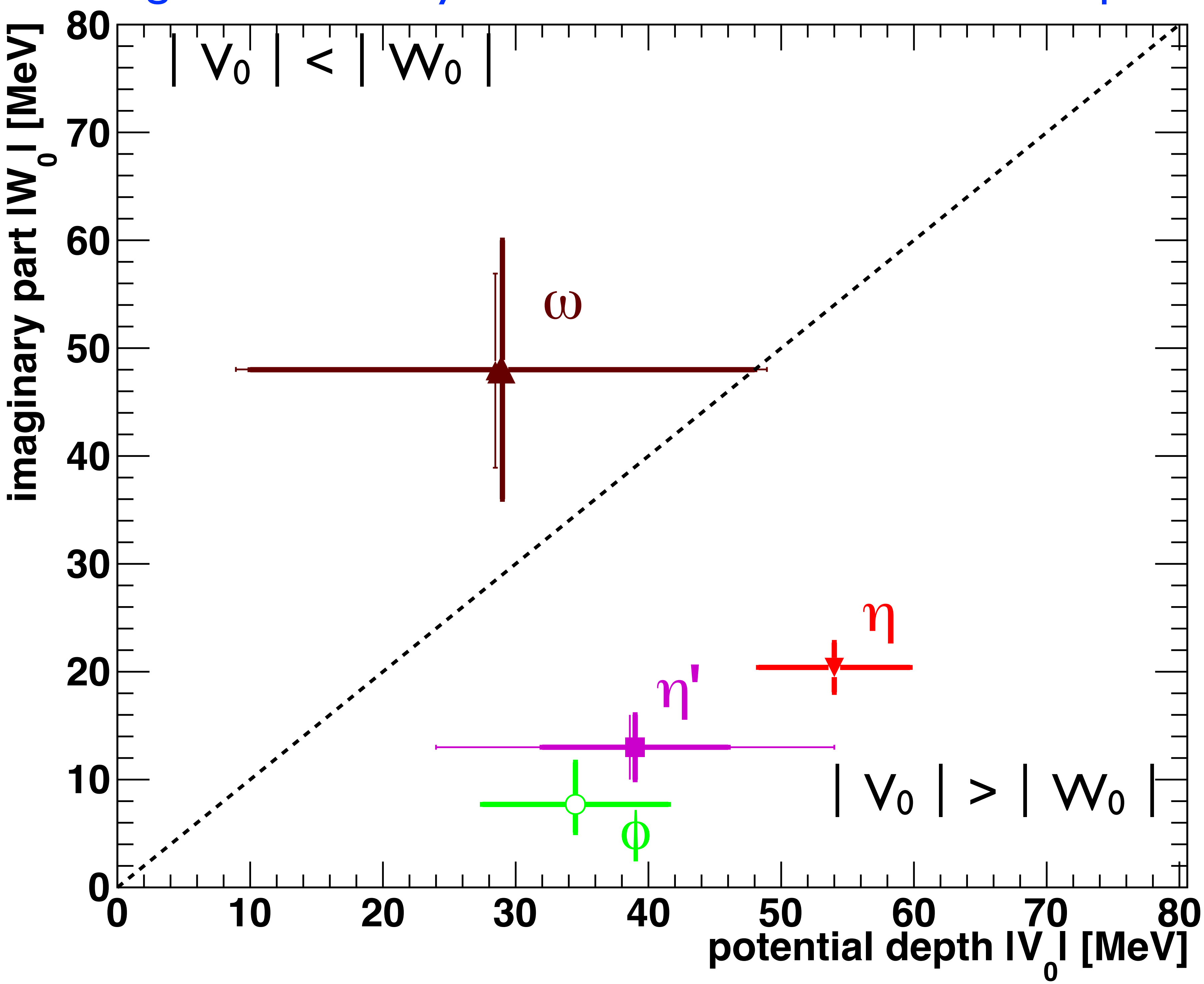
η, Φ : ≈ - 20 MeV

ω : ≈ - 40 MeV

K^- : ≈ - 60 MeV

real vs. imaginary part of the meson-nucleus potential

V. Metag, M. N. , E. Paryev , arXiv: 1706.09654, PPNP in press



meson with $|V_0| > |W_0|$ suitable for search

for meson-nucleus quasi-bound states

search for η’-mesic states in hadronic reactions

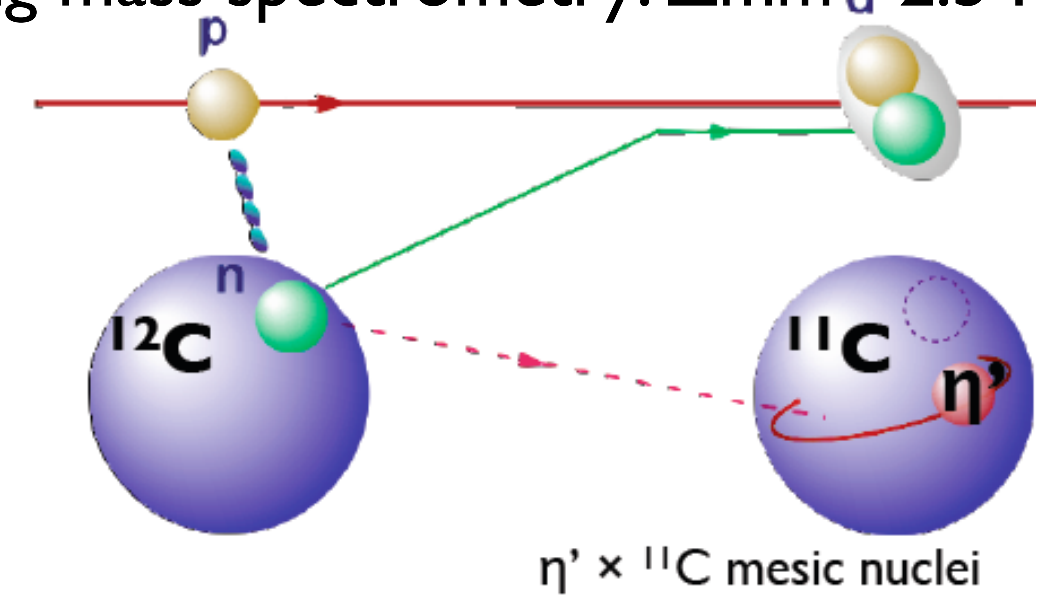
missing mass spectrometry: $\Delta mm = 2.5\ MeV/c^2$

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



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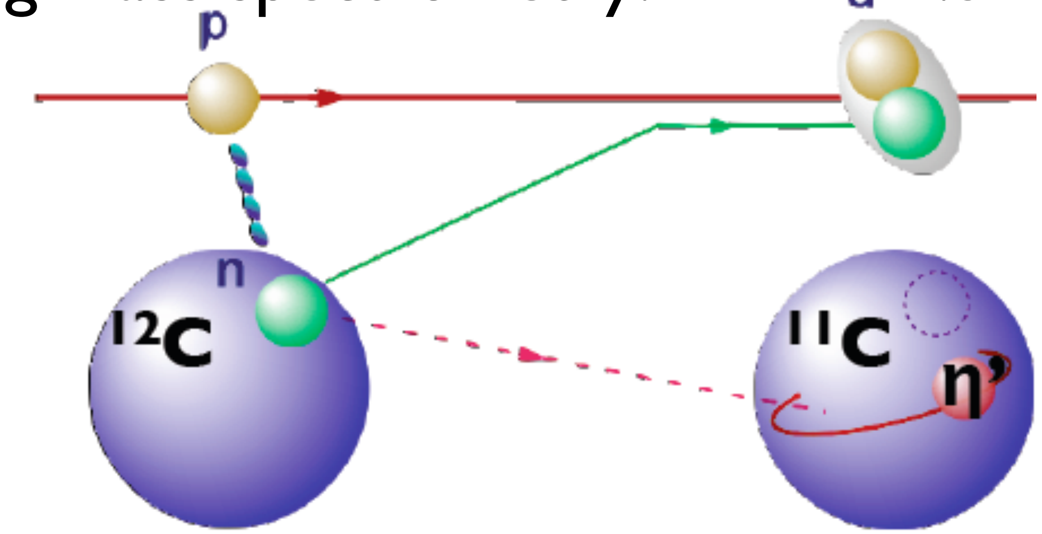
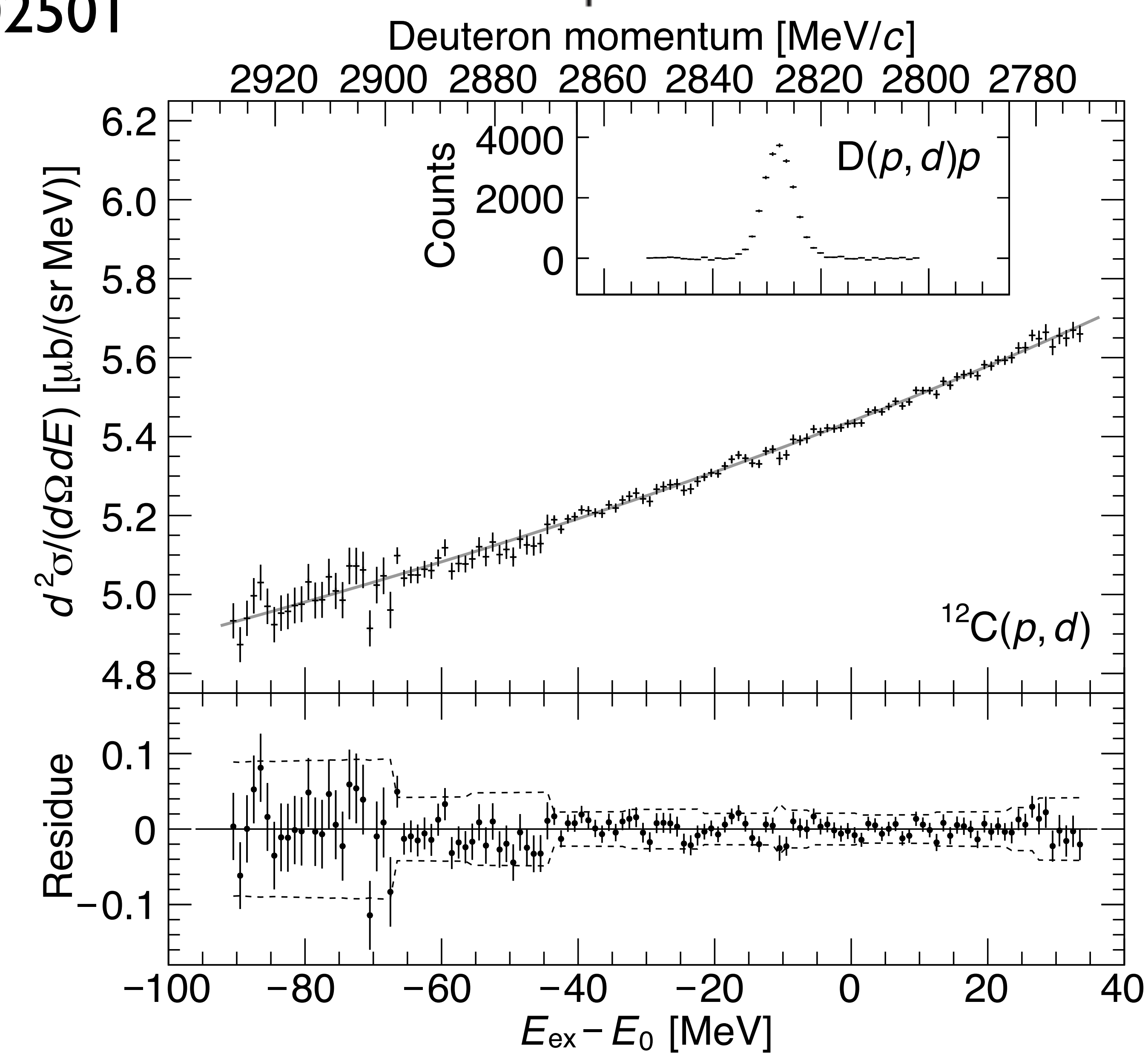


Y. K. Tanaka et al., PRL 117 (2016) 202501



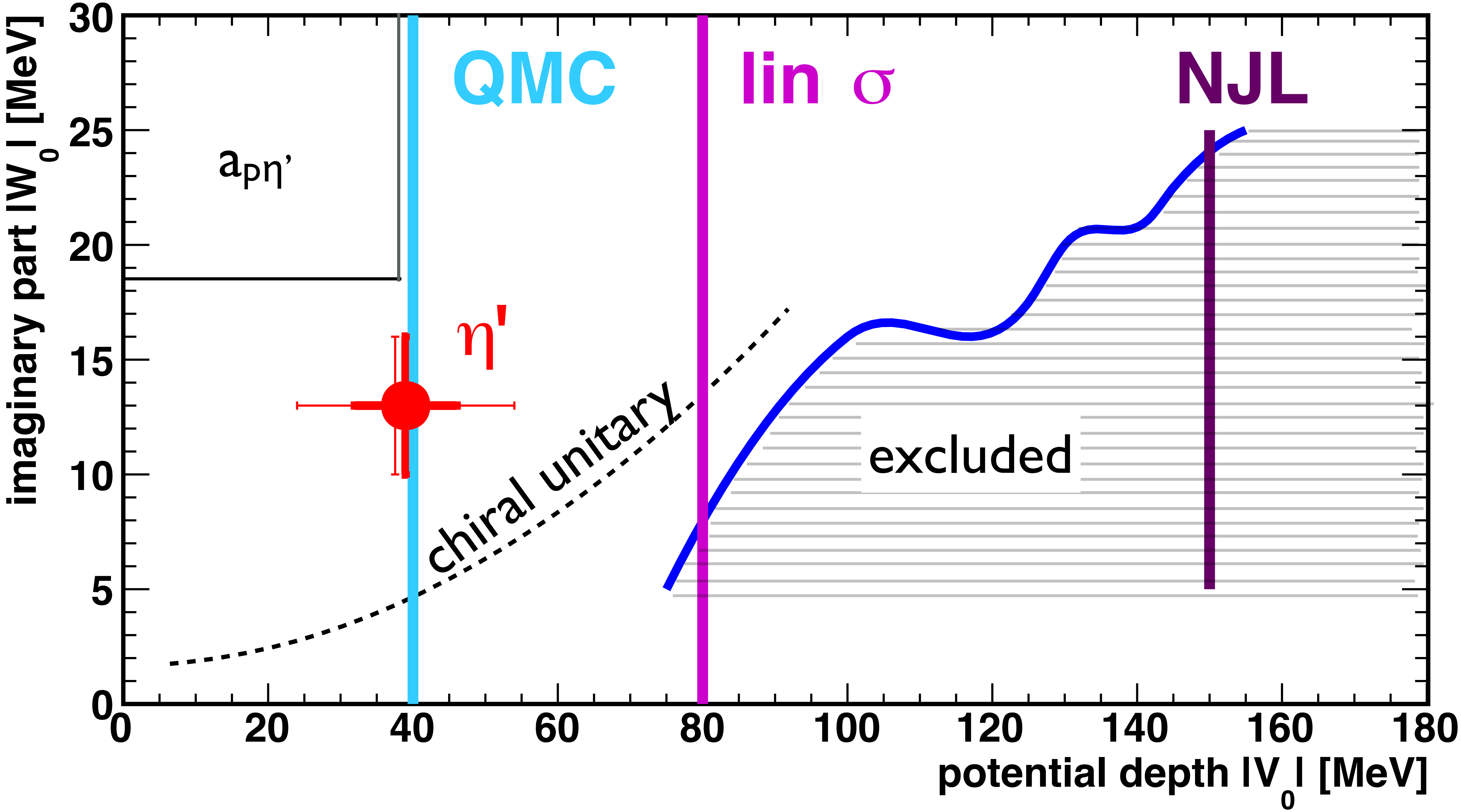
no structure in bound state region observed

⇒deep η'-nucleus potentials

|V|≥100 MeV excluded!

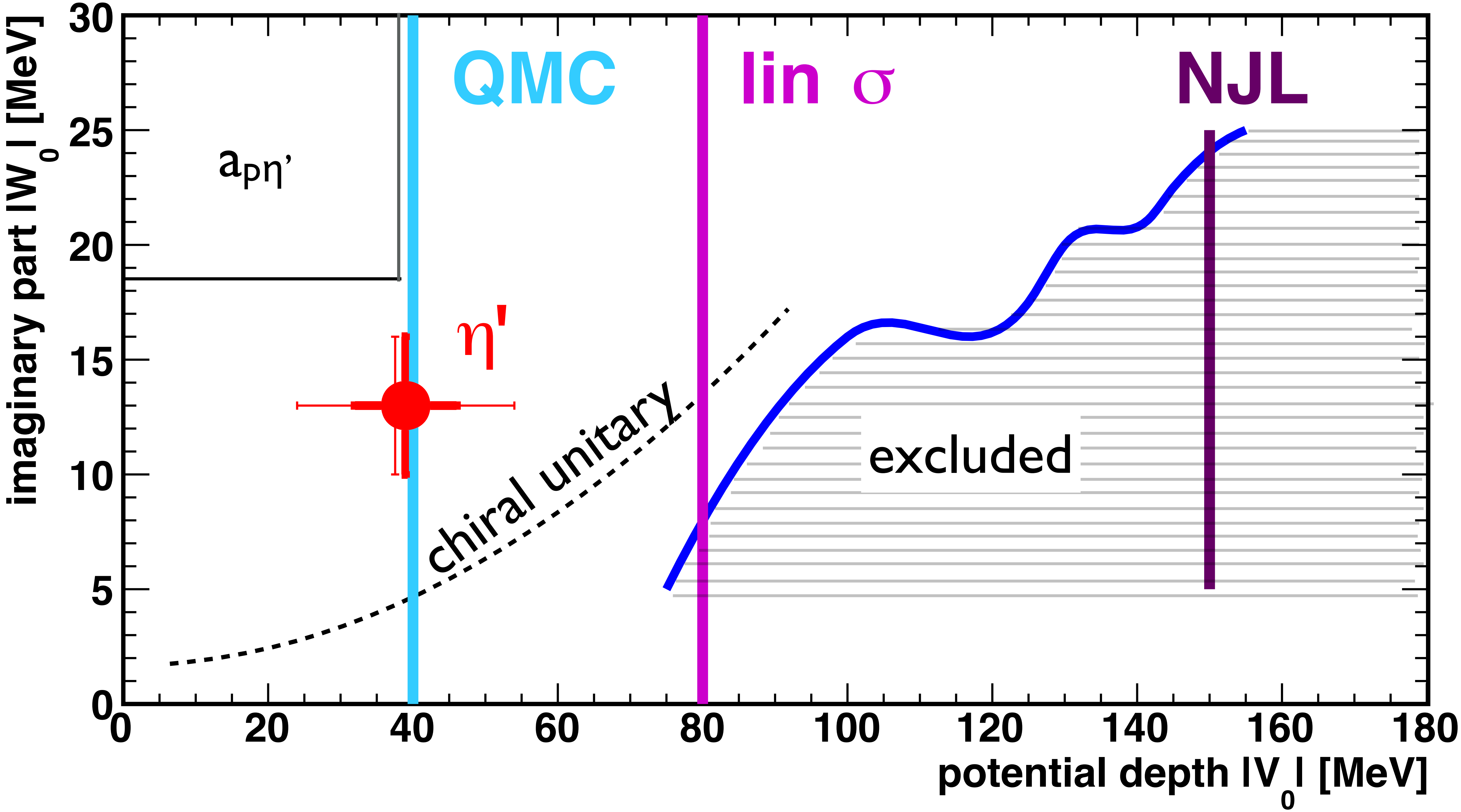
summary of information on the η'-nucleus potential

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



summary of information on the η’-nucleus potential

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



semi-exclusive experiment in preparation

$\Longrightarrow$ increased sensitivity by studying formation AND decay of η’-mesic states

summary and conclusions

- meson-nucleus interaction described by complex potential

$$U(r) = V(r) + i\,W(r)$$

- real part of meson-nucleus potential deduced from comparison of measured meson excitation functions or momentum distributions with transport and/or collision model calculations

- imaginary part of meson-nucleus potential deduced from comparison of measured transparency ratios with transport and/or collision model calculations

- measured potential parameters indicate favourable conditions ($|V_0| >> |W_0|$) for observing meson-nucleus quasi-bound states
  promising candidates: K^-, η, η'
  K^-pp clusters; η'⊗^{11}C mesic nuclei

- extension to charm sector difficult because of high momentum transfer

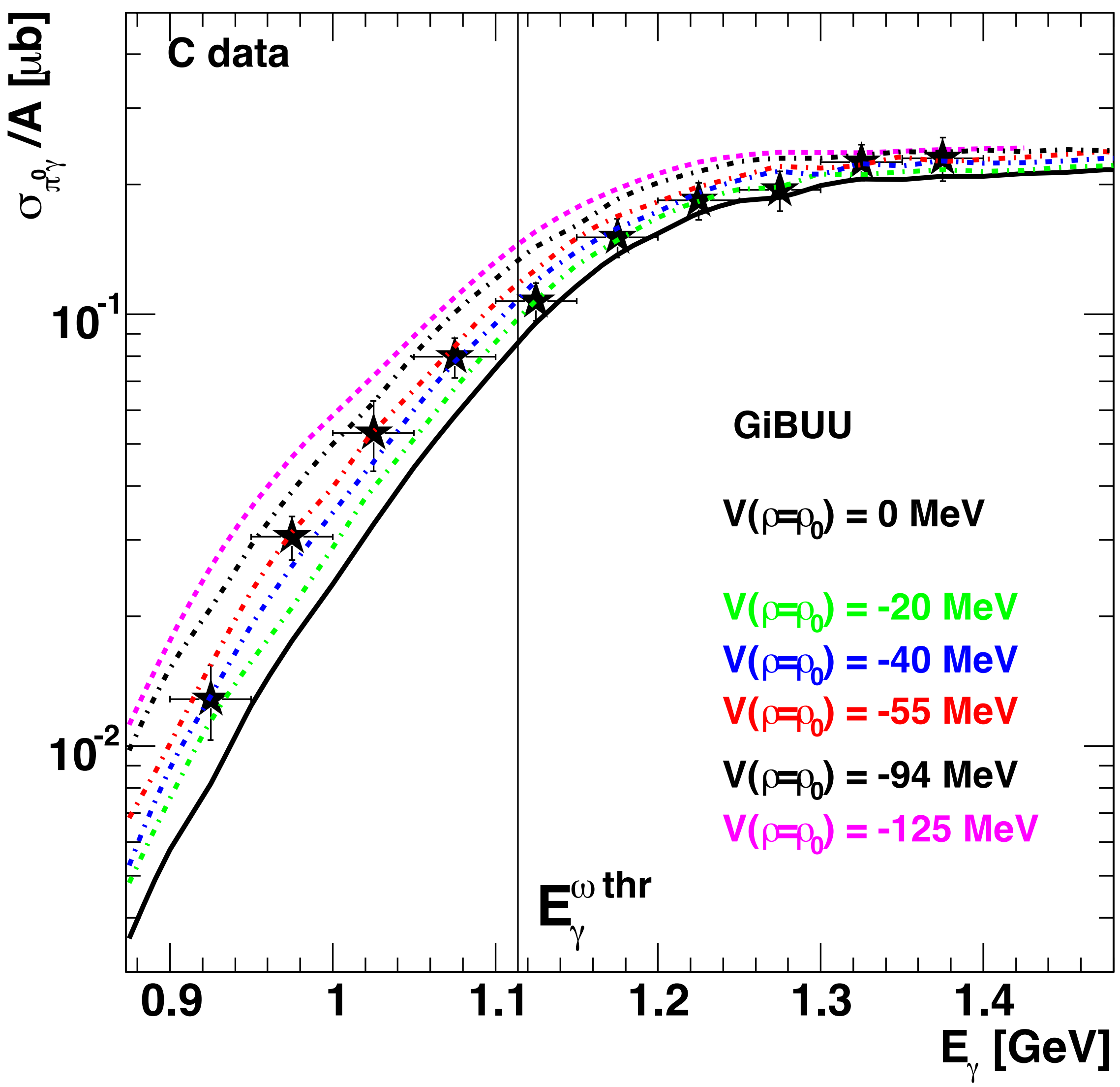
V. Metag, M. N. , E. Paryev , arXiv: 1706.09654, PPNP in press

Thank you!

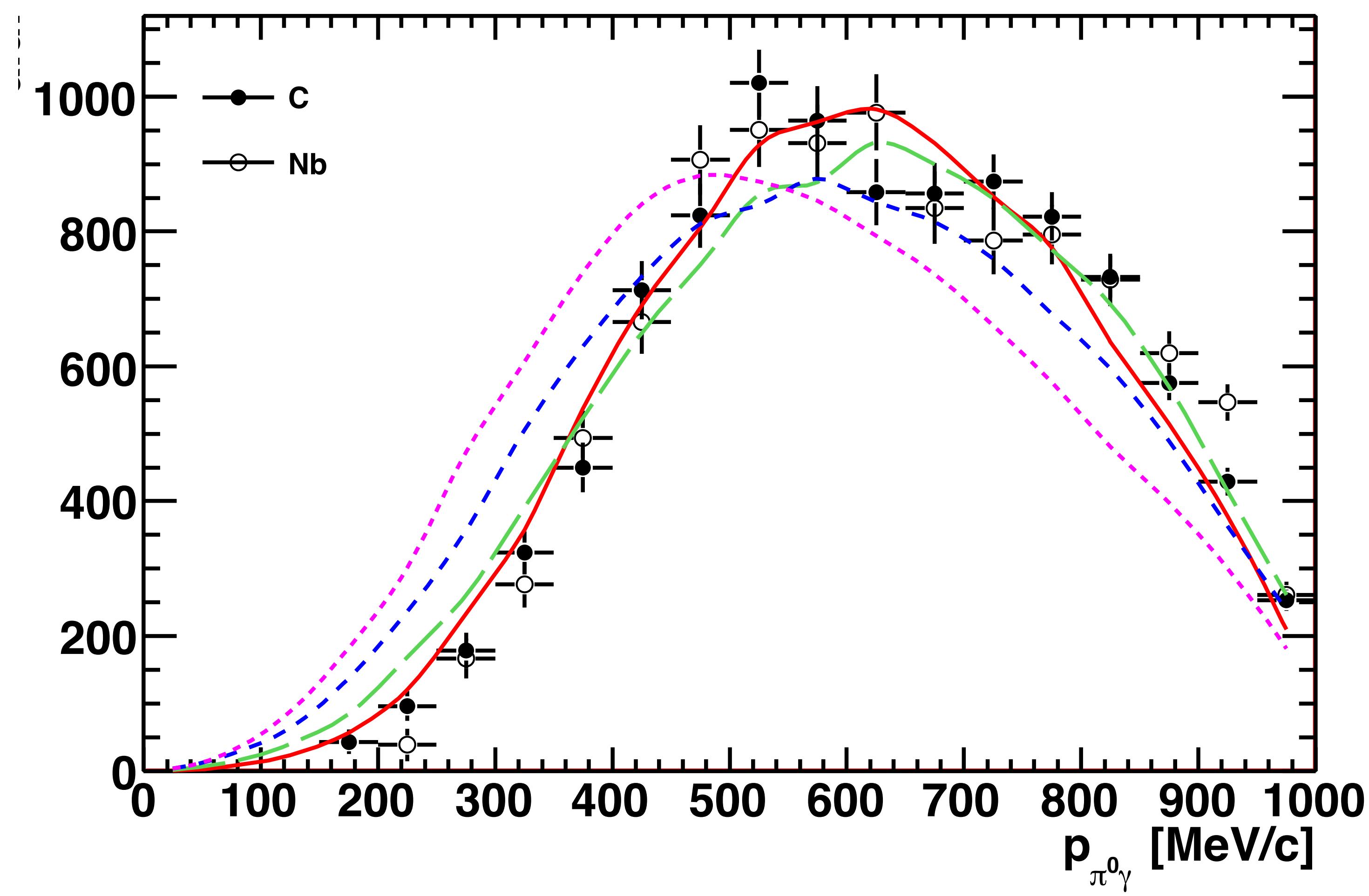
back-up slides

excitation function and momentum distribution for ω photoproduction off C, Nb

V. Metag et al., PPNP67 (2012)530



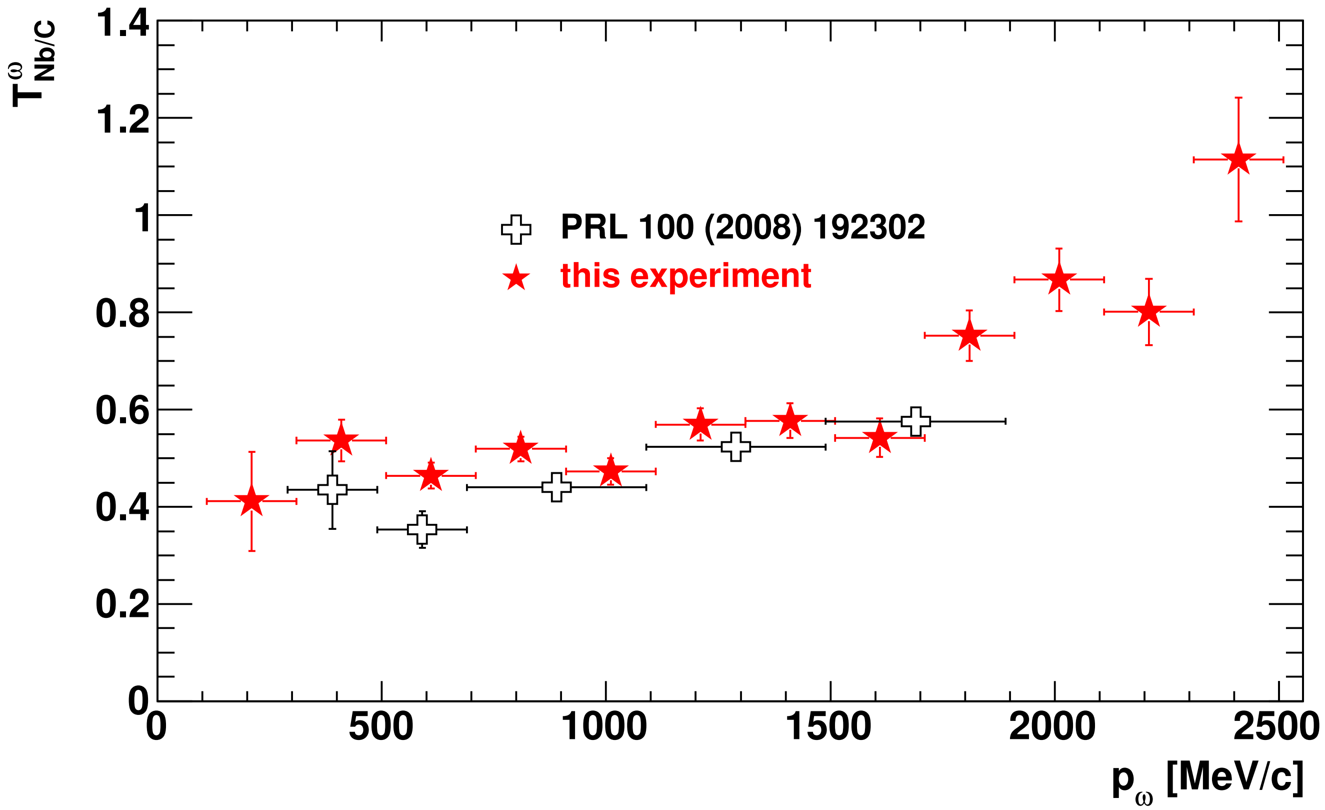
M. Thiel et al., EPJA 49 (23013) 132

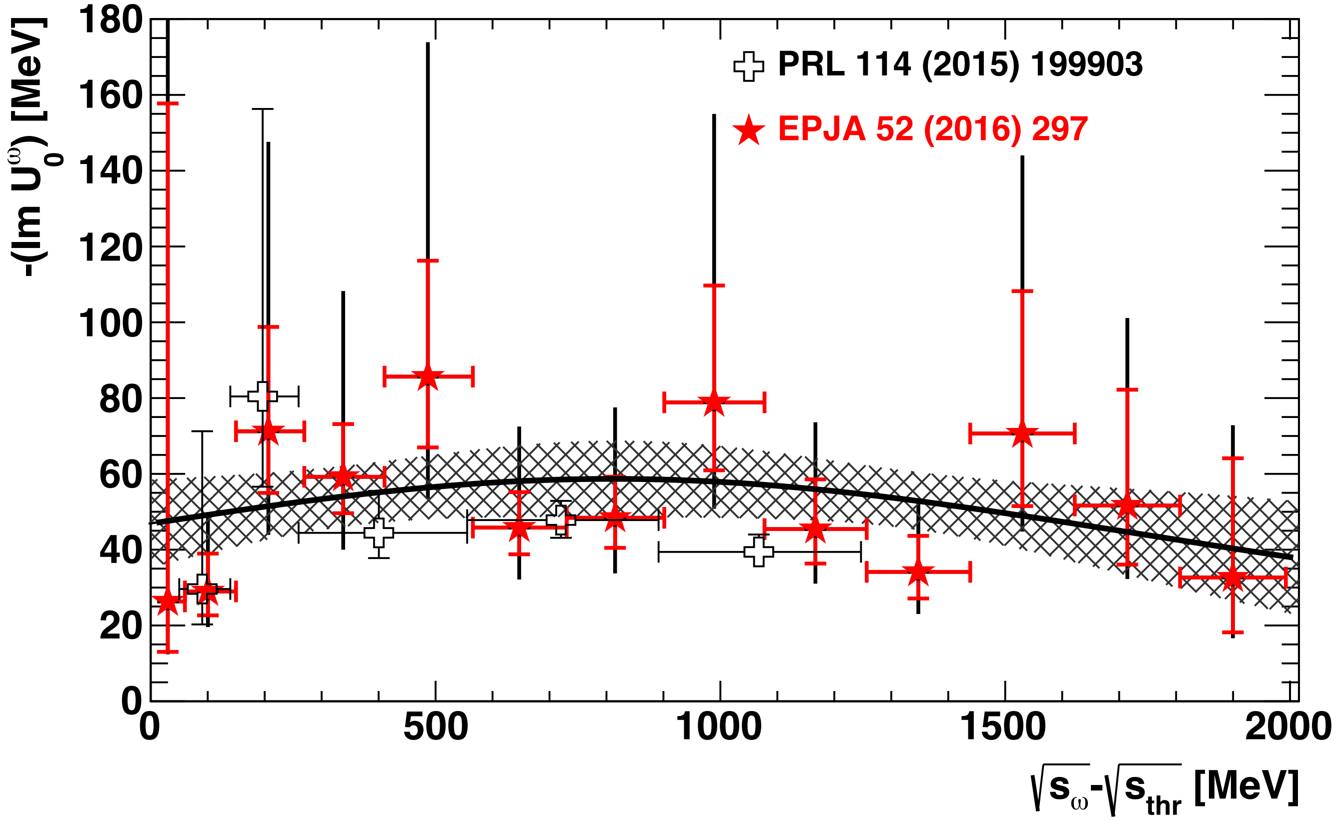


$V_0 = -[42 \pm 17(\text{stat}) \pm 20(\text{syst})]$ MeV

momentum dependence of ω transparency ratio: Nb/C

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





$W(\rho=\rho_0) = -[48\pm12(\text{stat})\pm9(\text{syst})]$ MeV

Determining the real part of the ω-nucleus potential: GiBUU transport model simulations

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

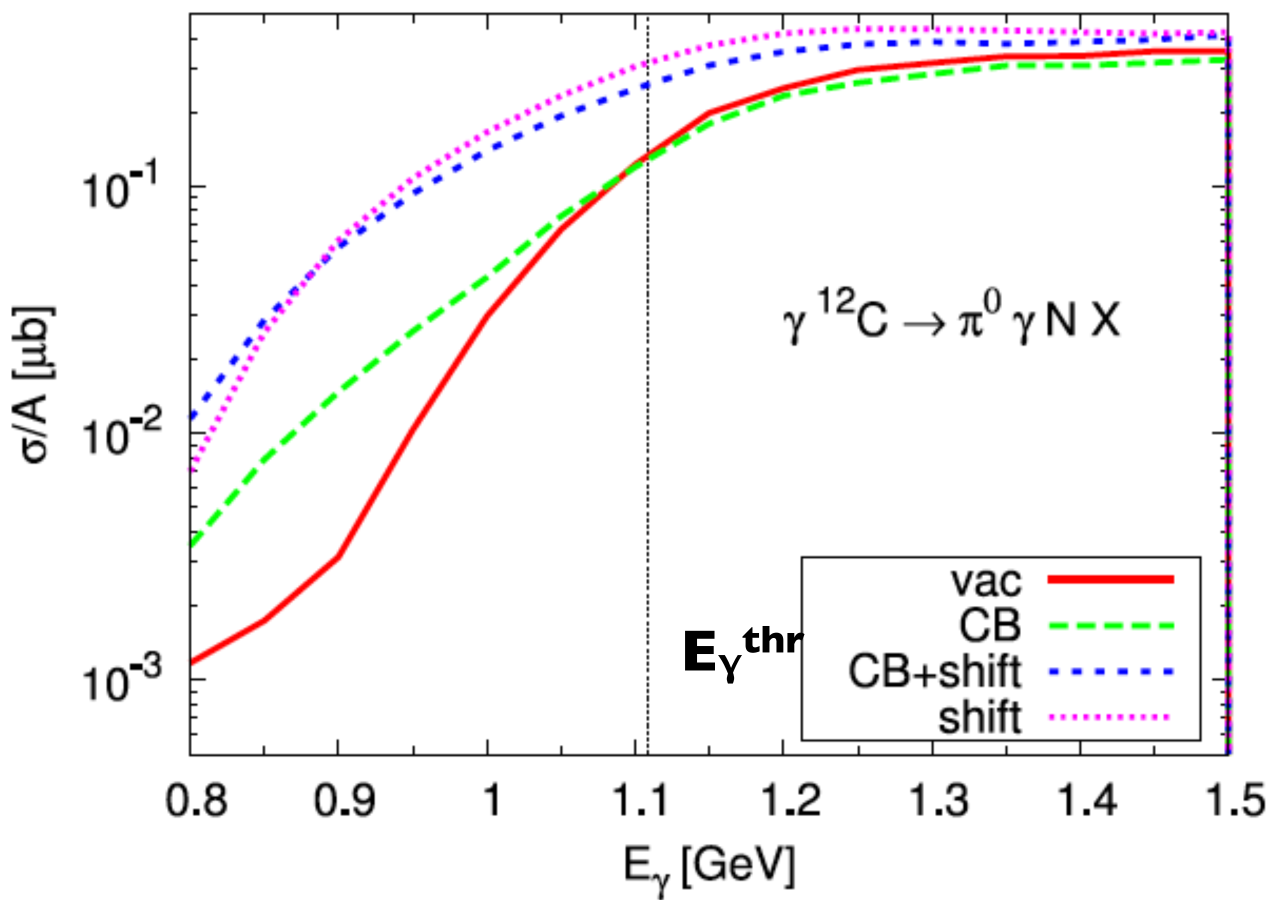
sensitive to nuclear density at production point

- 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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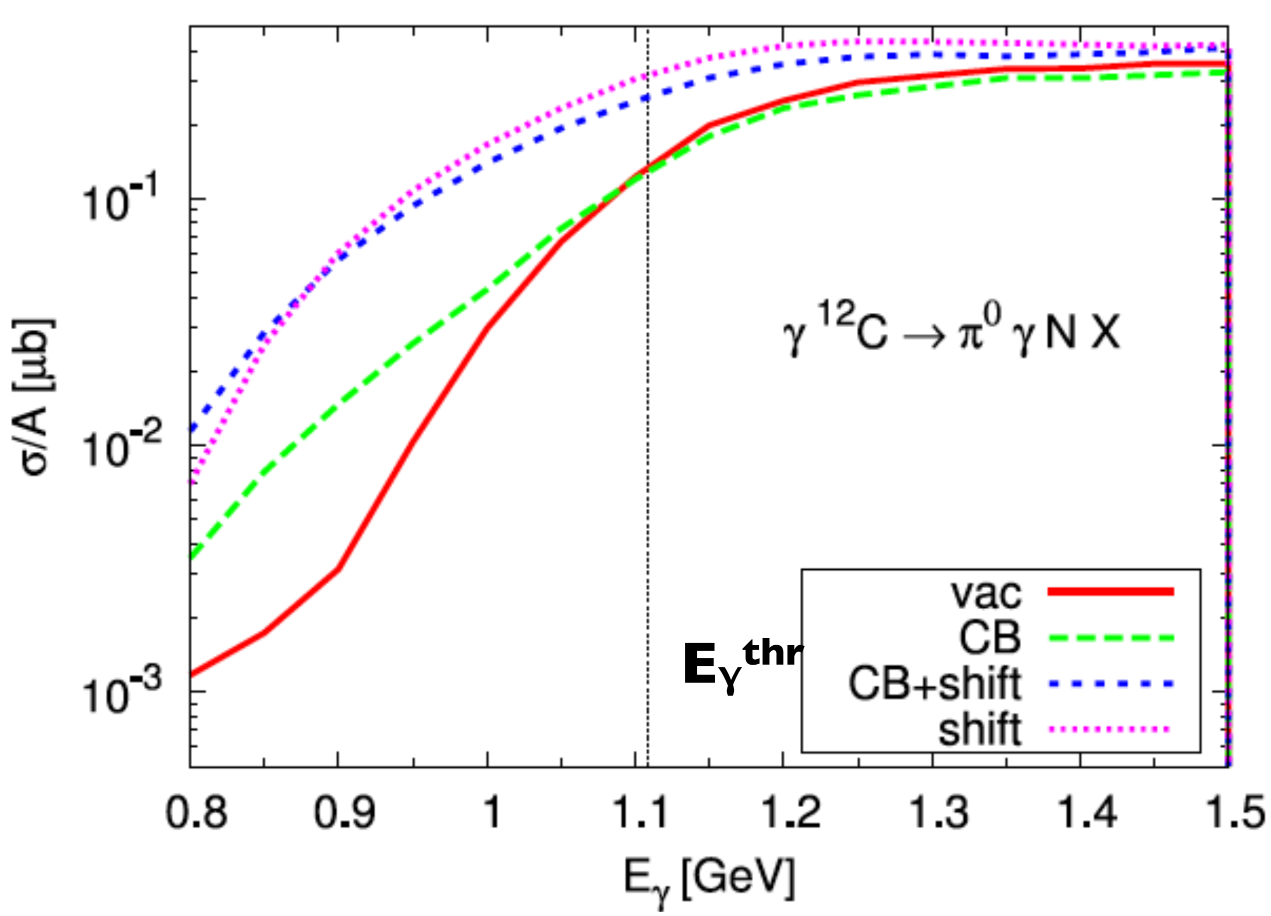
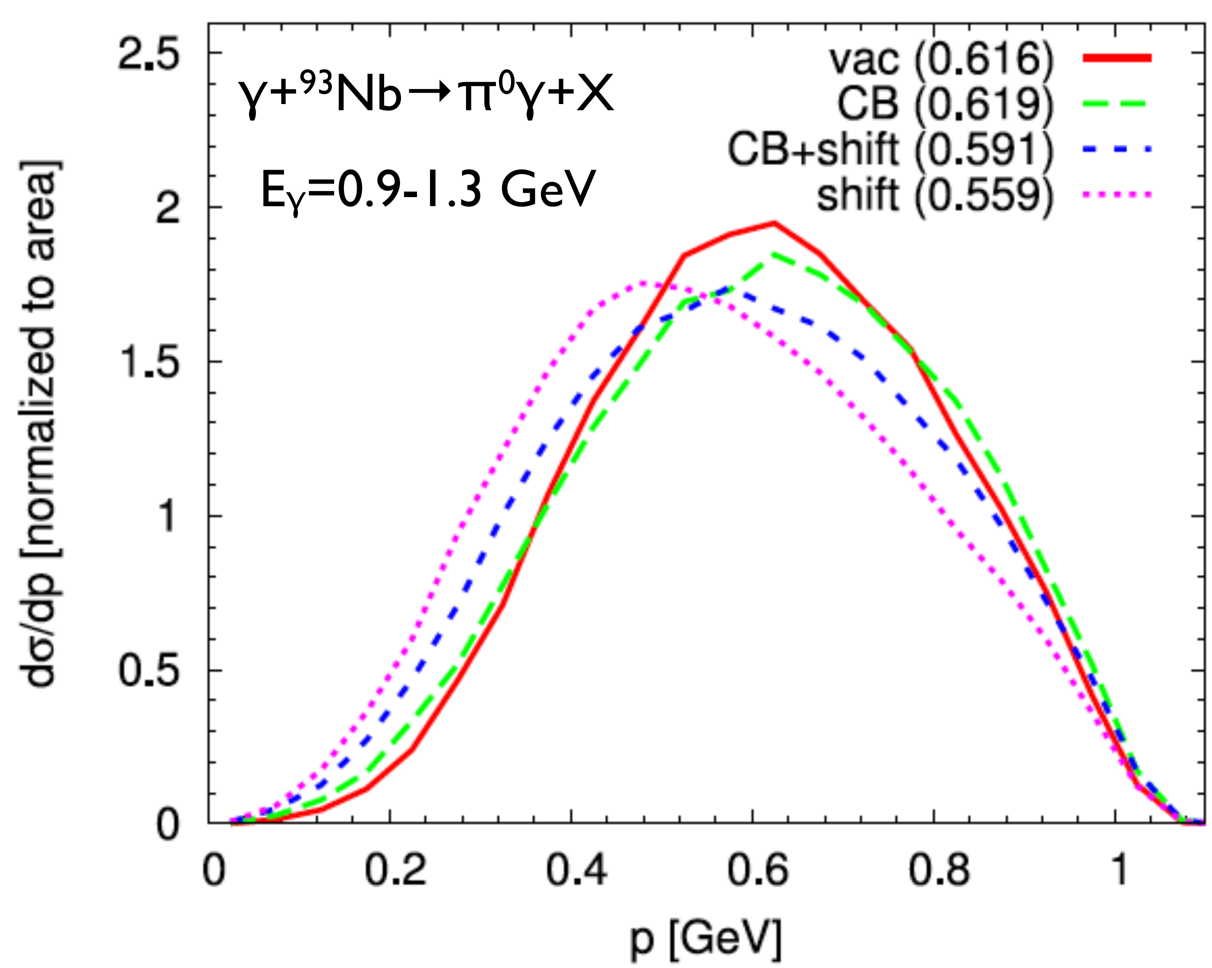


- momentum distribution of the meson:

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

⇨ downward shift of momentum distribution

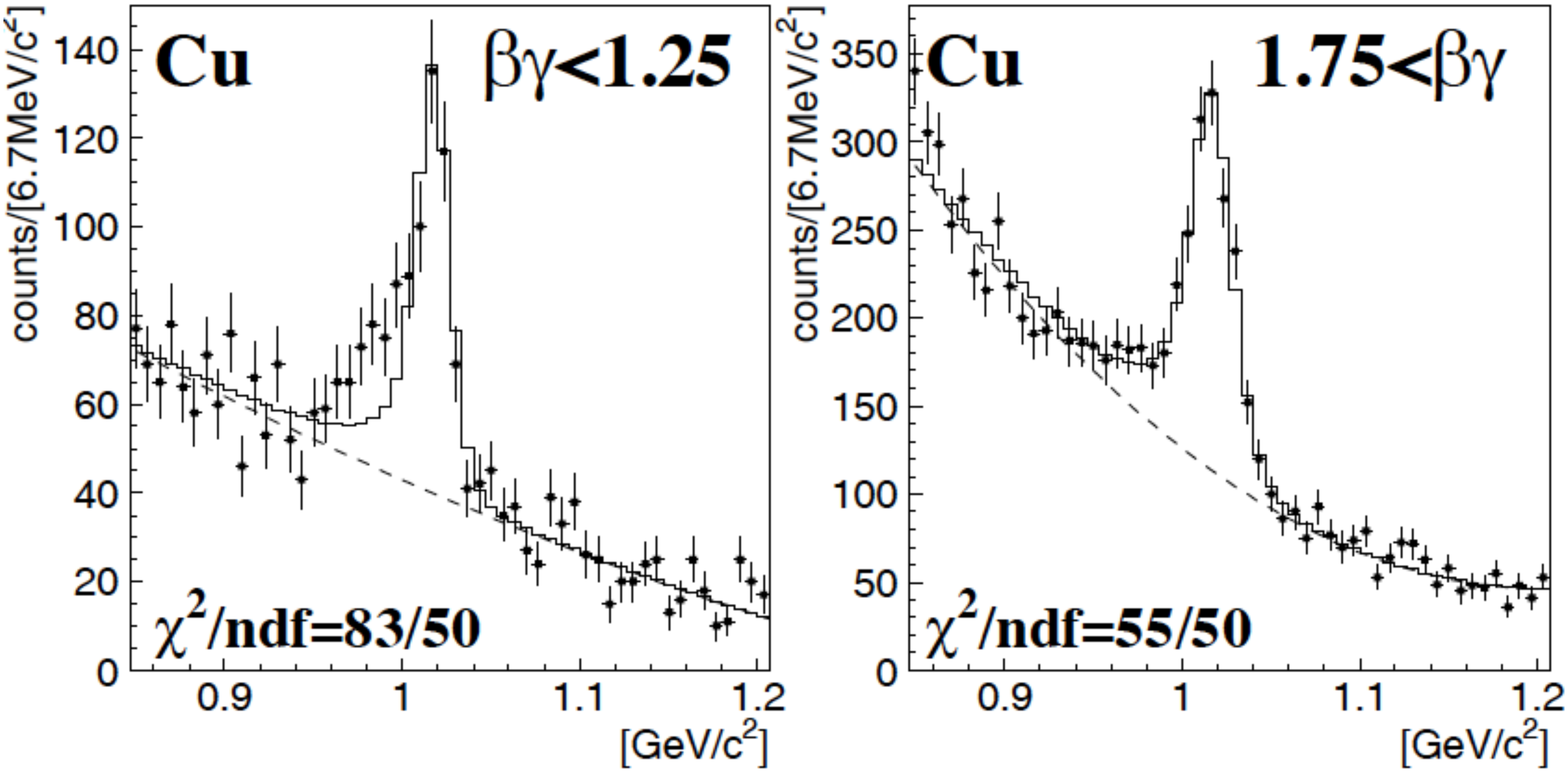
$\pi^0\gamma$ momentum distribution



line shape Analysis: Φ meson

p + C, Cu → Φ +X at 12 GeV

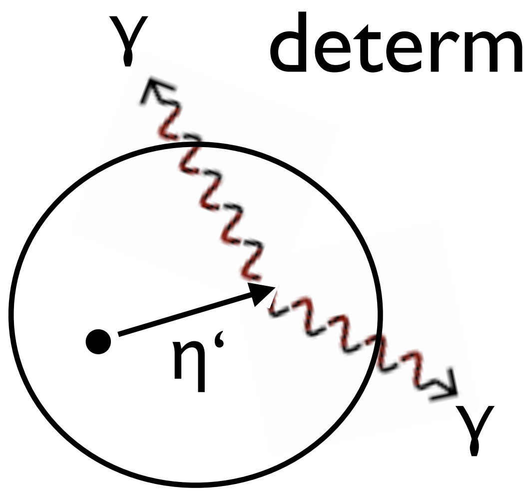
KEK E325: R. Muto et al., PRL 98 (2007) 042501



deviation from expected lines shape for slow ($\beta\gamma$ < 1.25) Φ mesons

$V_0 = \Delta m(\rho=\rho_0) = -35\pm7$ MeV; $W(\rho=\rho_0) = -7^{+4}_{-3}$ MeV

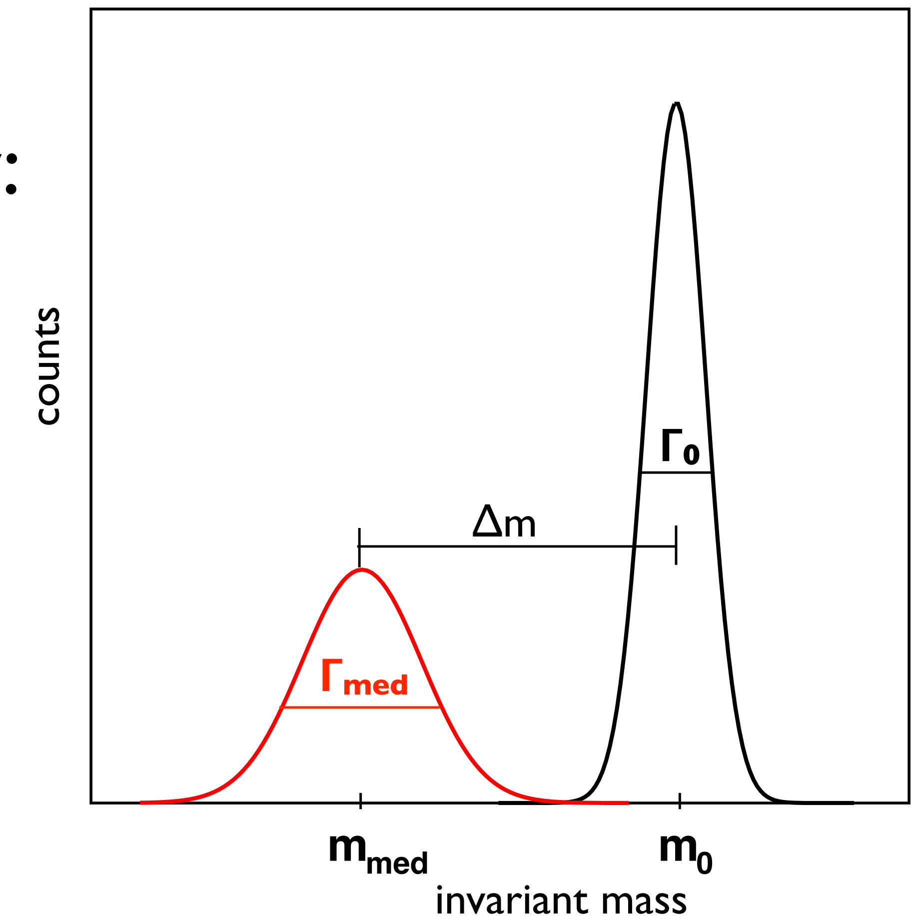
line shape analysis??



determine mass from in-medium decay:

e.g., $\eta' \rightarrow \gamma\gamma$

$$m = \sqrt{(p_1+p_2)^2}$$



probability for decay:

$$\frac{dP_{decay}}{dl} = \frac{mc}{p} \cdot \frac{1}{\hbar c} \cdot \Gamma_{decay} = 2.1 \cdot 10^{-5}\,/\mathrm{fm}$$

$$\Gamma_{\eta' \rightarrow \gamma\gamma} = 4.1 \cdot 10^{-2}\ \mathrm{MeV}$$

probability for absorption:

$$\frac{dP_{abs}}{dl} = \sigma_{abs} \cdot \rho(r) = 0.21/\mathrm{fm}\ \text{at}\ \rho=\rho_0$$

$$\sigma_{abs} = 13\ \mathrm{mb}$$

$$\frac{P_{decay}}{P_{abs}} = 10^{-4}\ \text{at}\ \rho=\rho_0$$

10 000 times more likely
to get absorbed than to decay

more favourable decay/absorption ratio only at lower densities near the surface where in-medium modifications are reduced

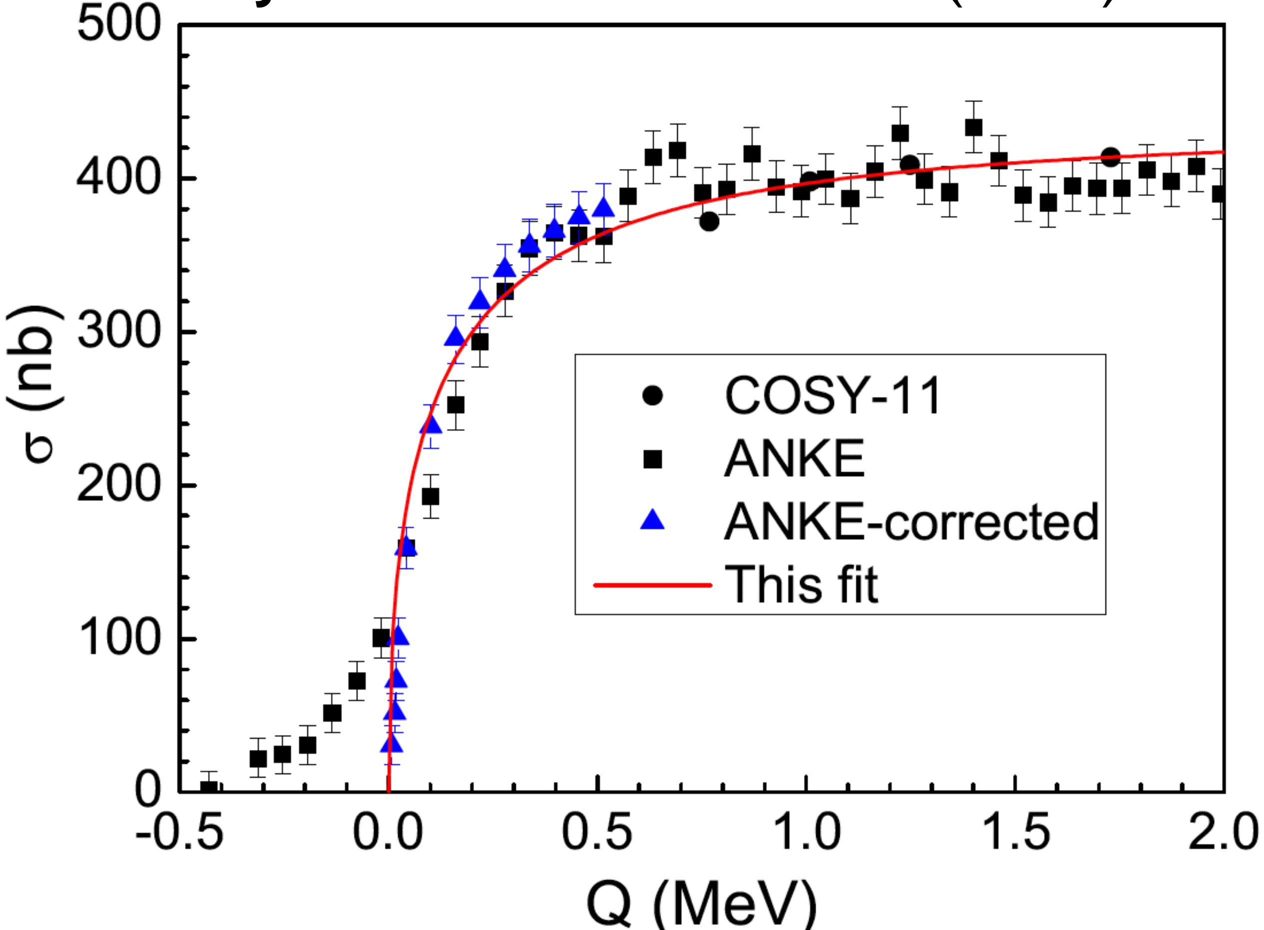
sensitive to nuclear density at decay point

real and imaginary part of the η-nucleus potential

$p+d \rightarrow \eta+{}^3He$

ANKE: T. Mersmann et al., PRL 98 (2007) 242301

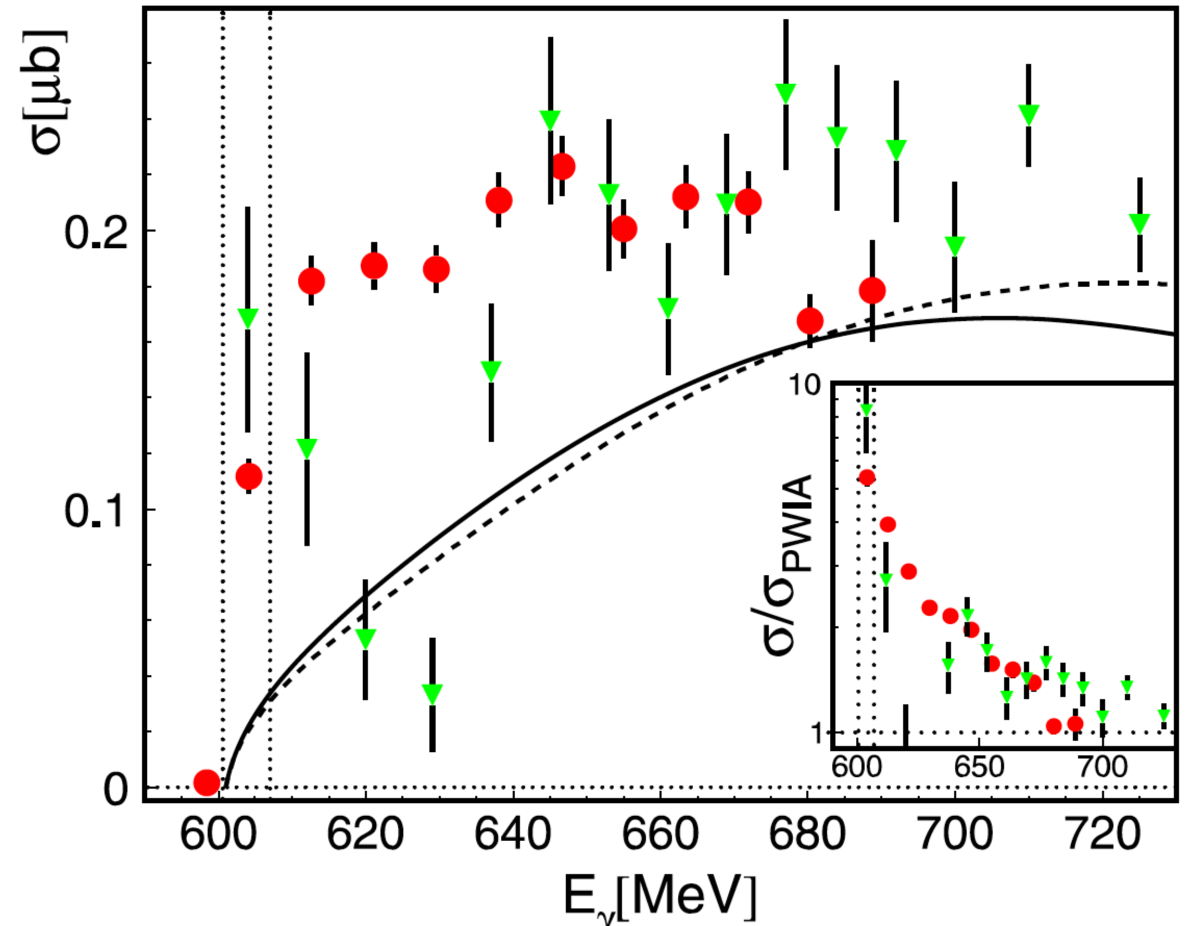
COSY-11: J. Smirski et al., PLB 649 (2007) 258



$\gamma+{}^3He \rightarrow \eta+{}^3He$

● M. Pfeiffer et al., PRL 92 (2004) 252001

● F. Pheron et al., PLB 709 (2012) 21



very steep rise of cross section near threshold !!

indication for a quasi-bound state near threshold ??

C. Wilkin et al. PLB 654 (2007) 92: pole at Q=-0.3 MeV; Γ = 0.3 MeV

J.J.Xie et al.,PRC95 (2017) 015202: BW structure at mass = -0.3 MeV; Γ = 3 MeV

$\Longrightarrow V_0 = -(54\pm6)$ MeV; $W_0 = -(20\pm2)$ MeV

η-meson binding in the He isotopes ⇒ talk yesterday by A. Gal

$(p)d+d \rightarrow \eta+{}^3He$ ⇒ talk yesterday by M. Skurzok (WASA)

information on the K^--nucleus potential from atomic X-rays

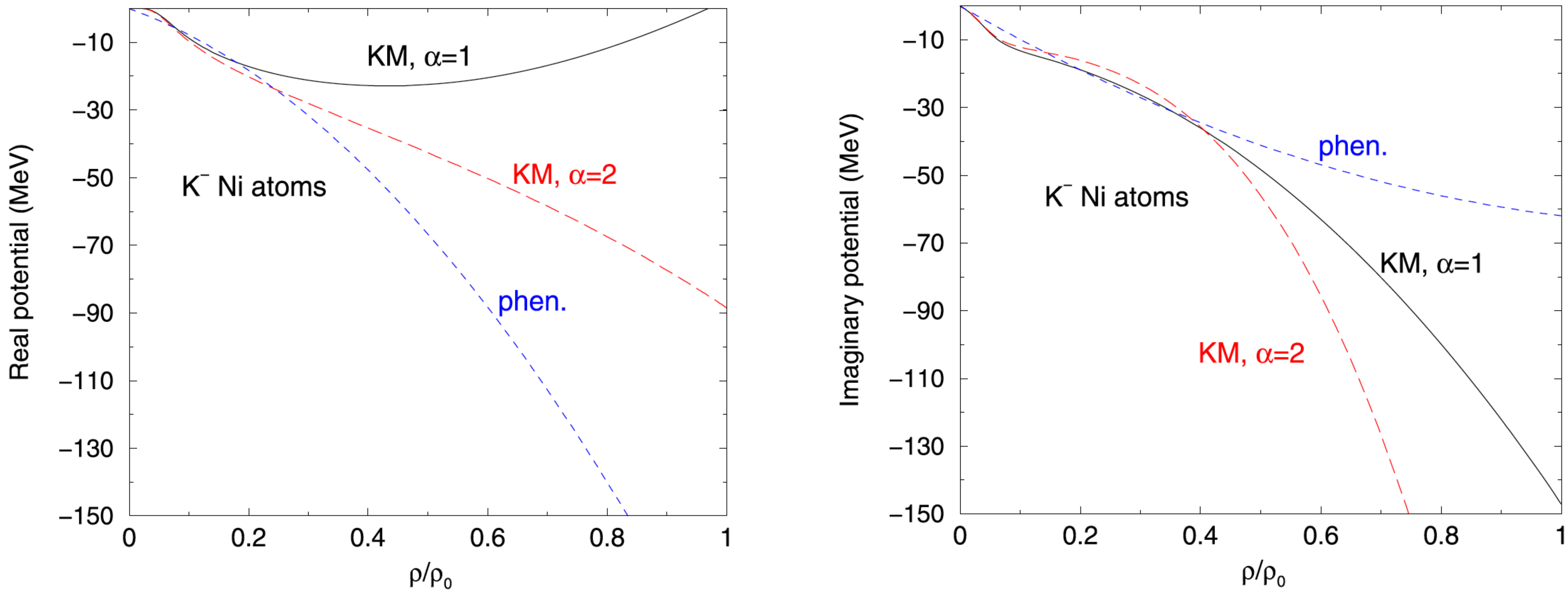
potential extracted from level shifts and widths of atomic states
arising from the strong interaction

E. Friedman, A. Gal, Phys. Rep. 452 (2007) 89 S. Hirenzaki et al., PRC 61 (2000) 055205

X-rays from kaonic atoms sensitive to the potential at low nuclear densities

K^- - multi nucleon interaction (talk by J. Mareš)

E. Friedman, A. Gal, NPA 959 (2017) 66



potentials can reliably be extracted up to 30% and 50% of normal nuclear matter density for real and imaginary part, respectively

other approaches needed to access $V(\rho=\rho_0), W(\rho=\rho_0)$ (talk yesterday by E. Friedman)

search for meson-nucleus bound states with Φ and heavier mesons (charm sector)

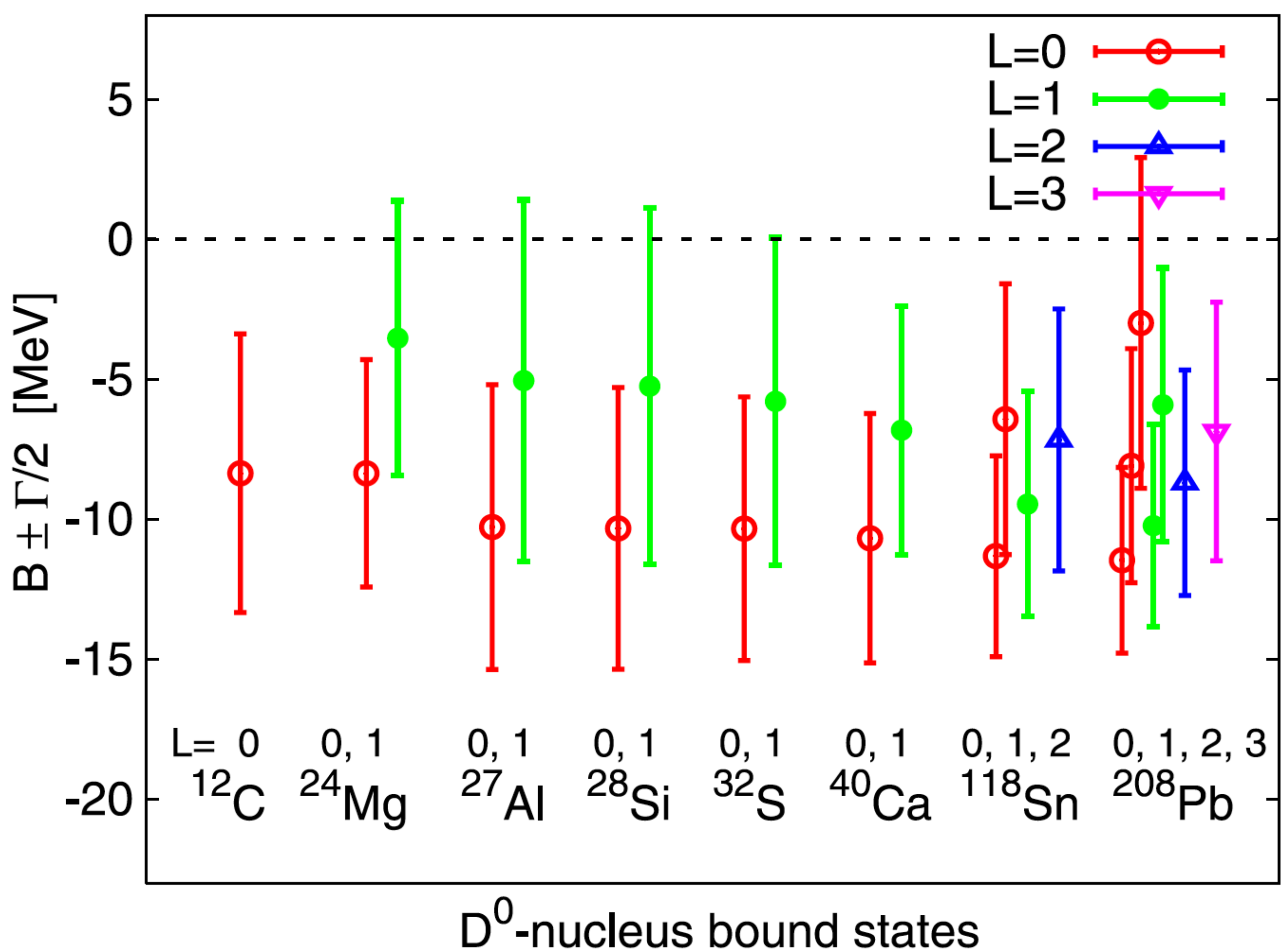
general experimental problem:

heavy meson production associated with high momentum transfer
probability for nucleus to stay intact ~ $F_A^2(q^2)$

minimising momentum transfer: M. Faessler, NPA 692 (2001) 104c

favourable reaction $\bar{p}\,p \rightarrow X\,Y$ with Y forward and X backward in cm

$$p_{min}(X) \approx \frac{m_X^2 - m_N^2}{2\,m_N}$$ (still 1.4 GeV/c for $\bar{D}D$ pairs !!)



more favourable:
two step production

$\bar{p}\,p \rightarrow D^{*-}\,D^{+}$

$D^{*-} + (Z,A) \rightarrow \pi^0 + D^{-} \otimes (Z,A)$

J. Yamagata-Sekihara et al., PLB 754 (1016) 26