Testing the conjecture of partial chiral symmetry restoration: meson-nucleus potentials and the search for mesic states

Volker Metag
II. Physikalisches Institut
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

*funded by the DFG within SFB/TR16

56th. Int. Winter Meeting on Nuclear Physics
Bormio, Italy, Jan. 22-26, 2018

HIC for FAIR
Helmholtz International Center

bound systems

bound by

gravitation

earth-moon system

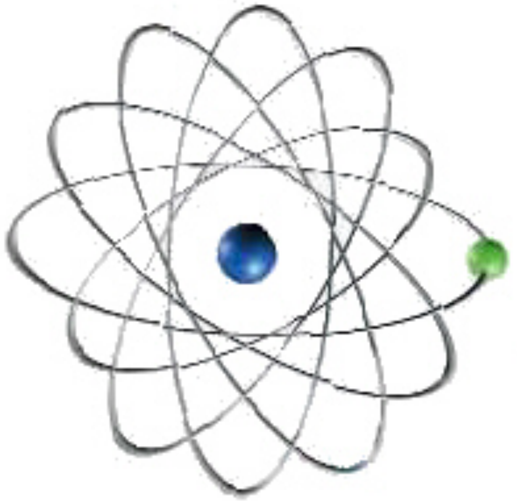
bound systems

bound by

gravitation

earth-moon system

electromagnetic interaction



atom

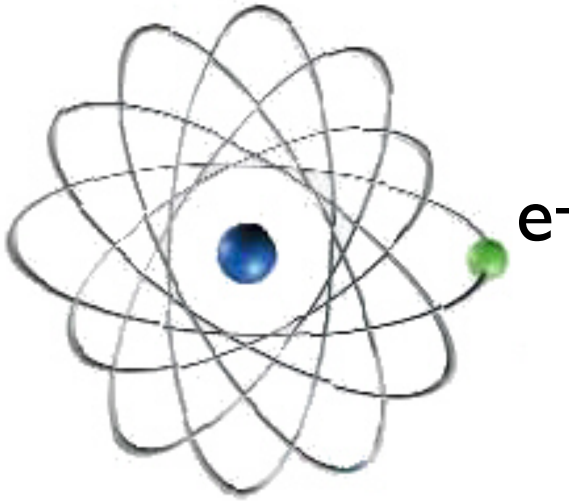
bound systems

bound by

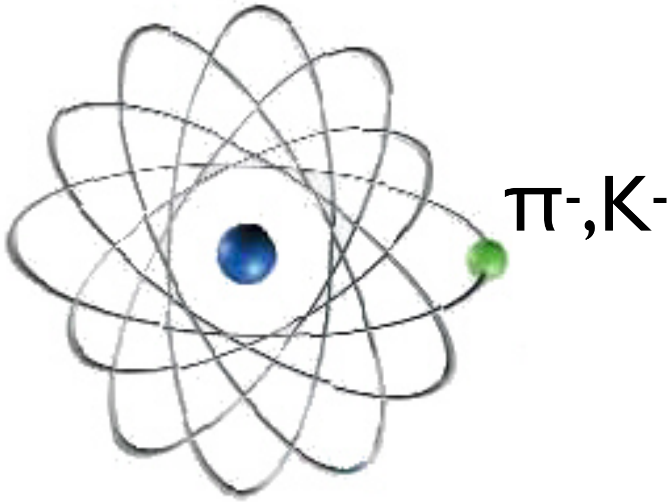
<u>gravitation</u>

earth-moon system

<u>electromagnetic interaction</u>



atom



π^-, K^- - atoms

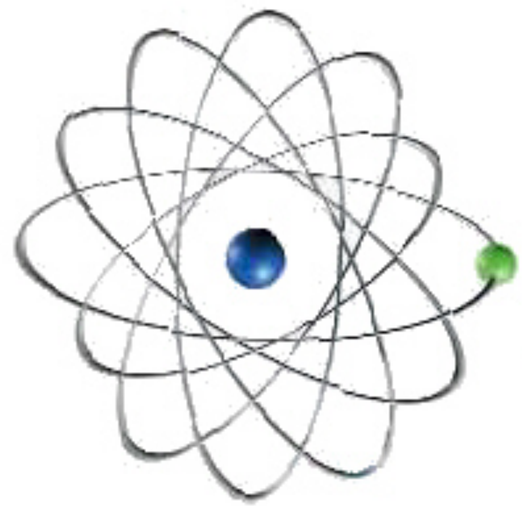
bound systems

bound by

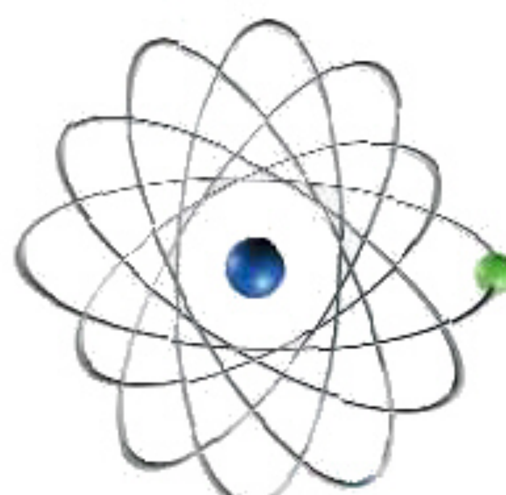
gravitation

earth-moon system

electromagnetic interaction

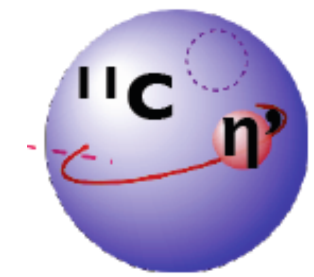


atom



π^-, K^- - atoms

strong interaction



η' mesic state

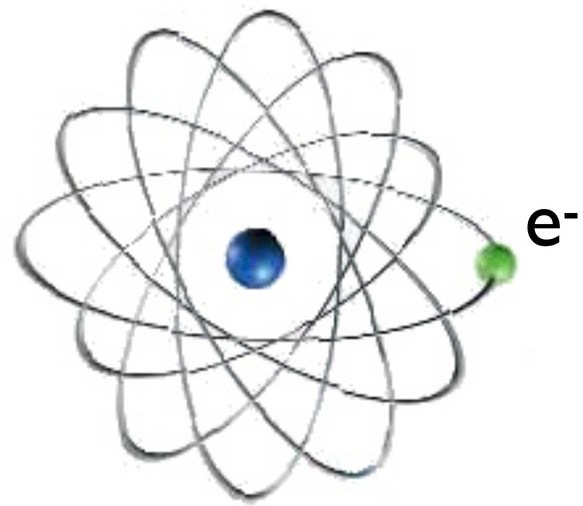
bound systems

bound by

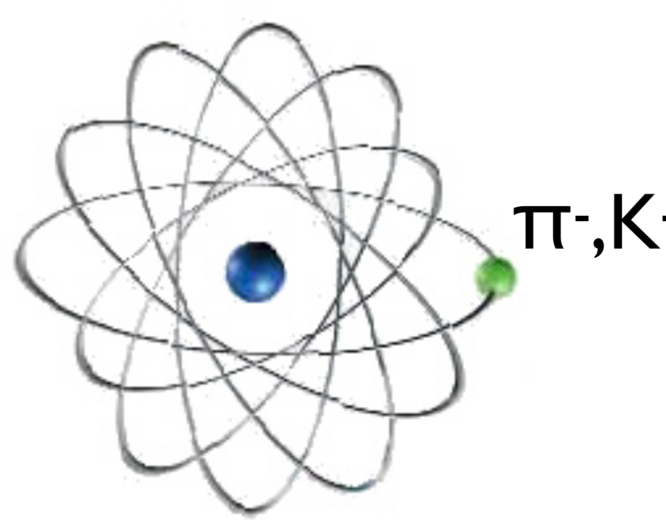
gravitation

earth-moon system

electromagnetic interaction

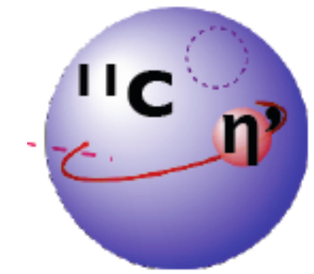


atom

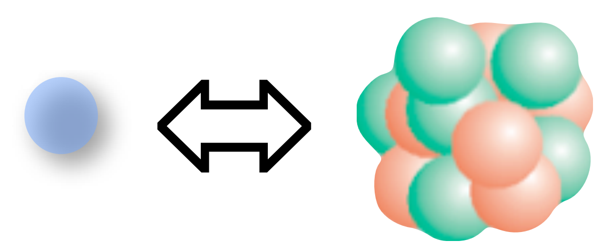


π^-, K^- - atoms

strong interaction



η' mesic state

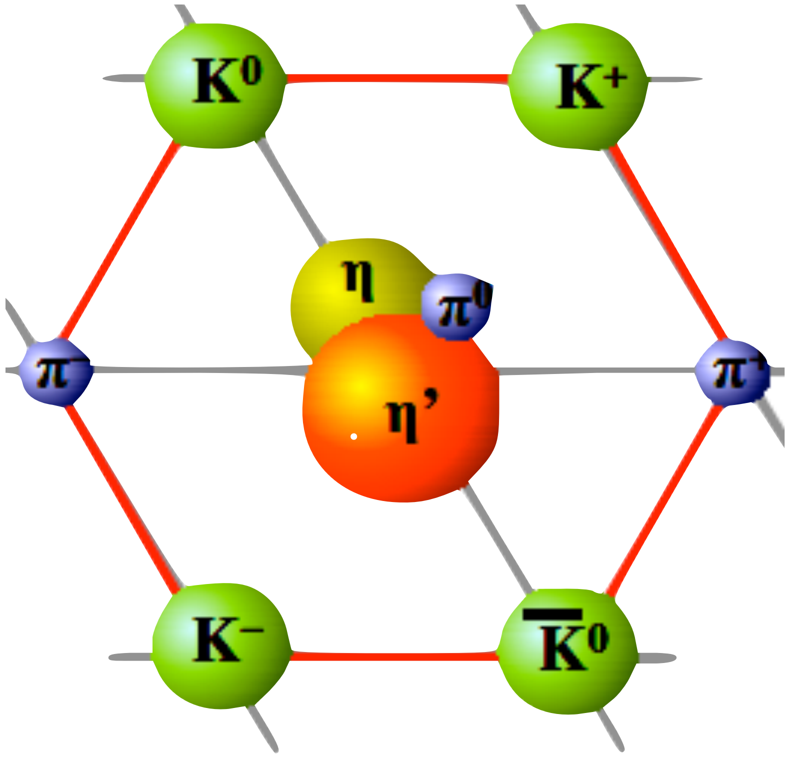


meson - nucleus interaction
attractive?
repulsive?
→ meson-nucleus potential

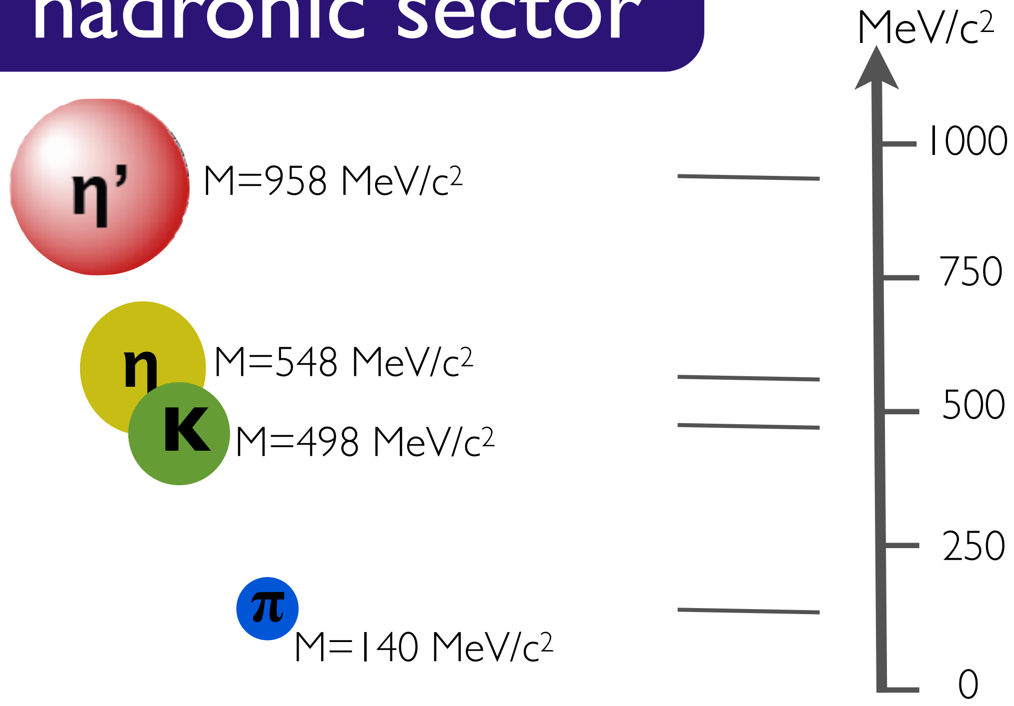
outline

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

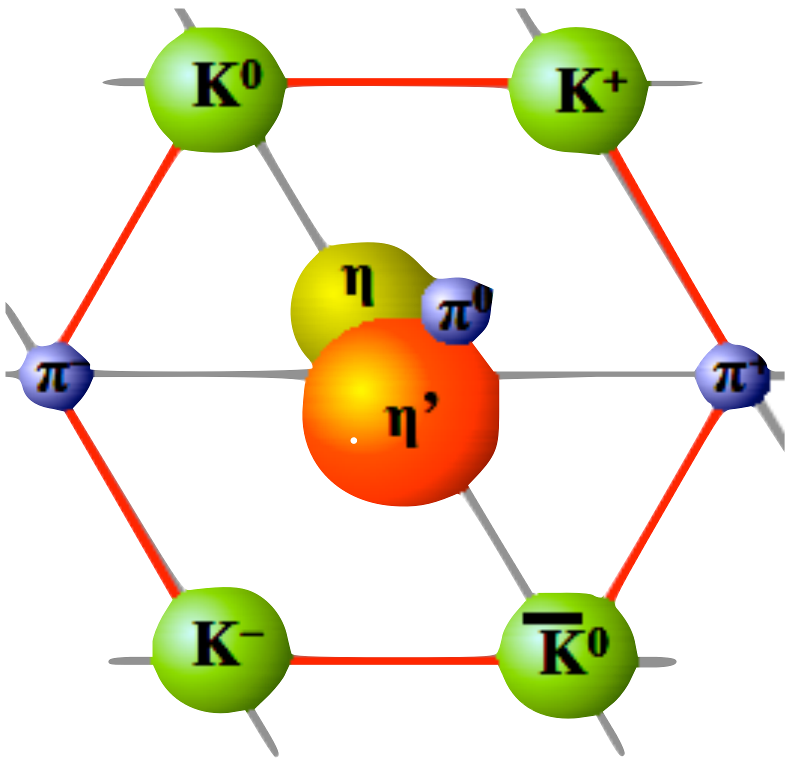
symmetry breaking in the hadronic sector



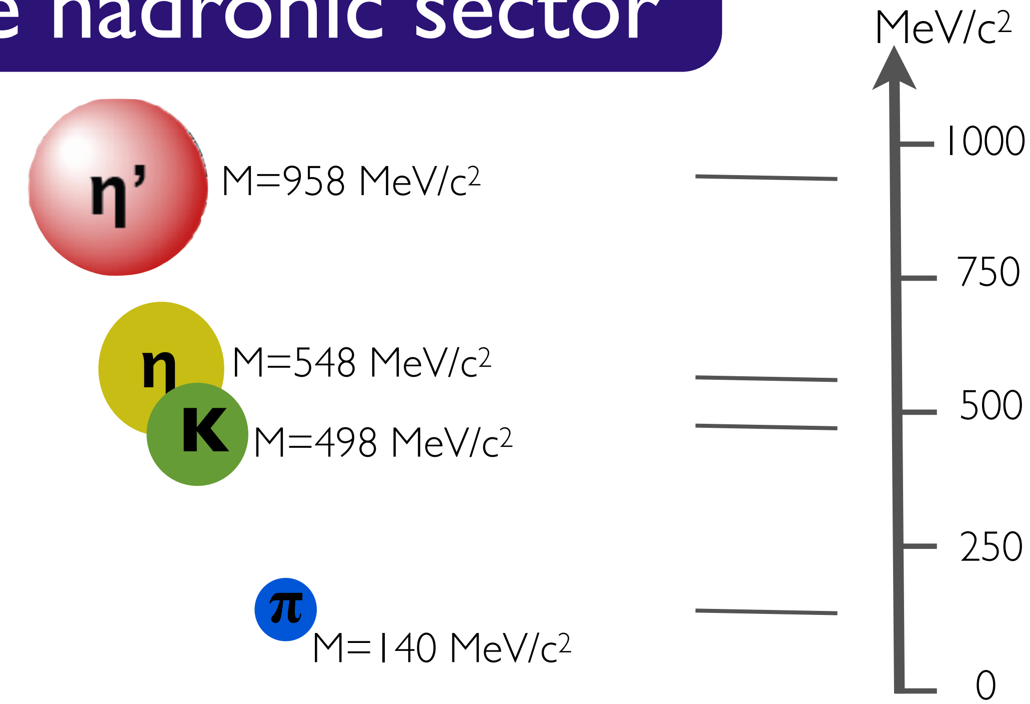
nonet of pseudoscalar mesons



symmetry breaking in the hadronic sector

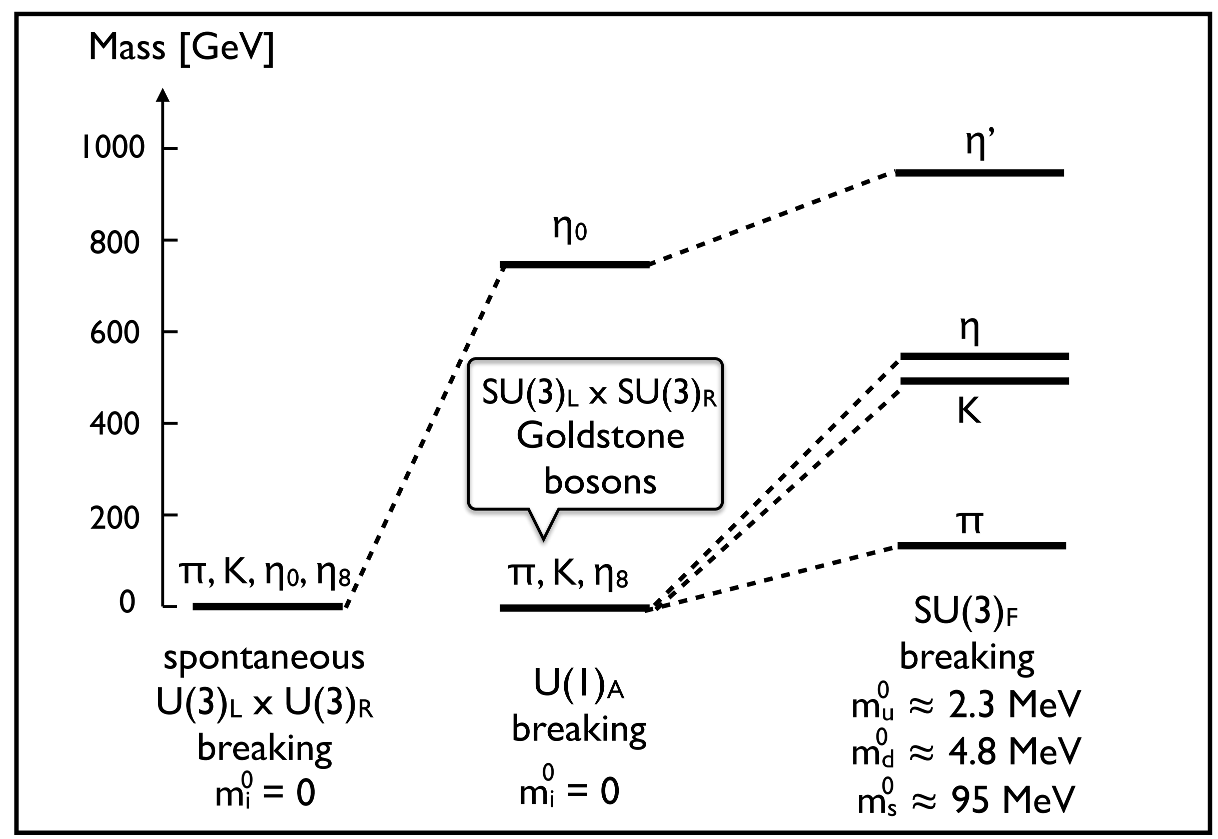


<u>nonet of pseudoscalar mesons</u>



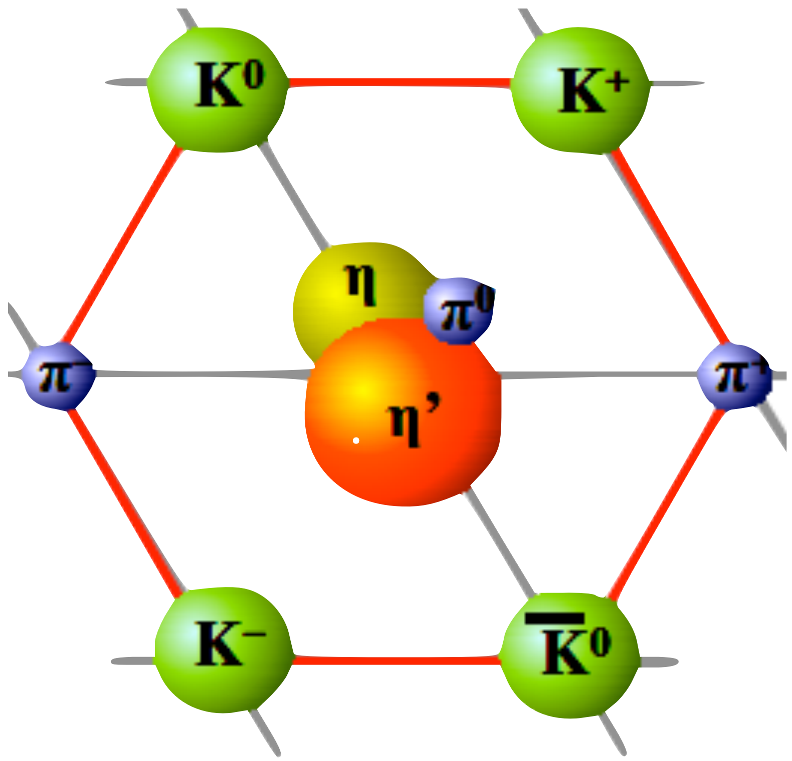
V. Bernard, R.L. Jaffe, U.-G. Meissner, NPB 308 (1988) 753
S. Klimt, M. Lutz, U. Vogel, W Weise, NPA 516 (1990) 429

mass as a result of symmetry breaking

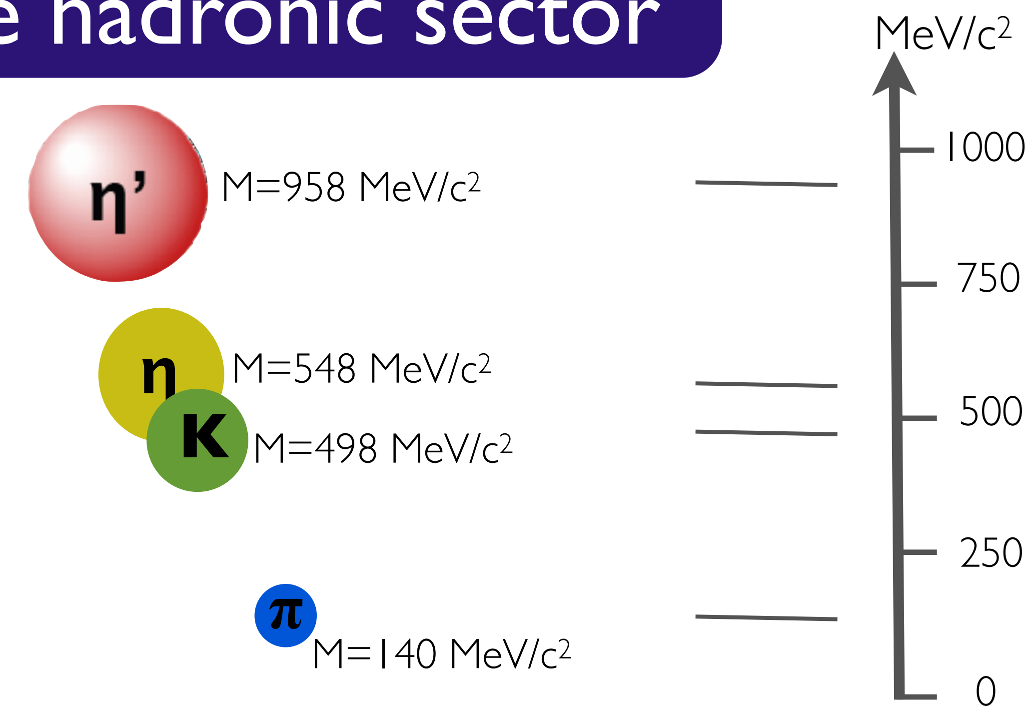


symmetry breaking →

symmetry breaking in the hadronic sector



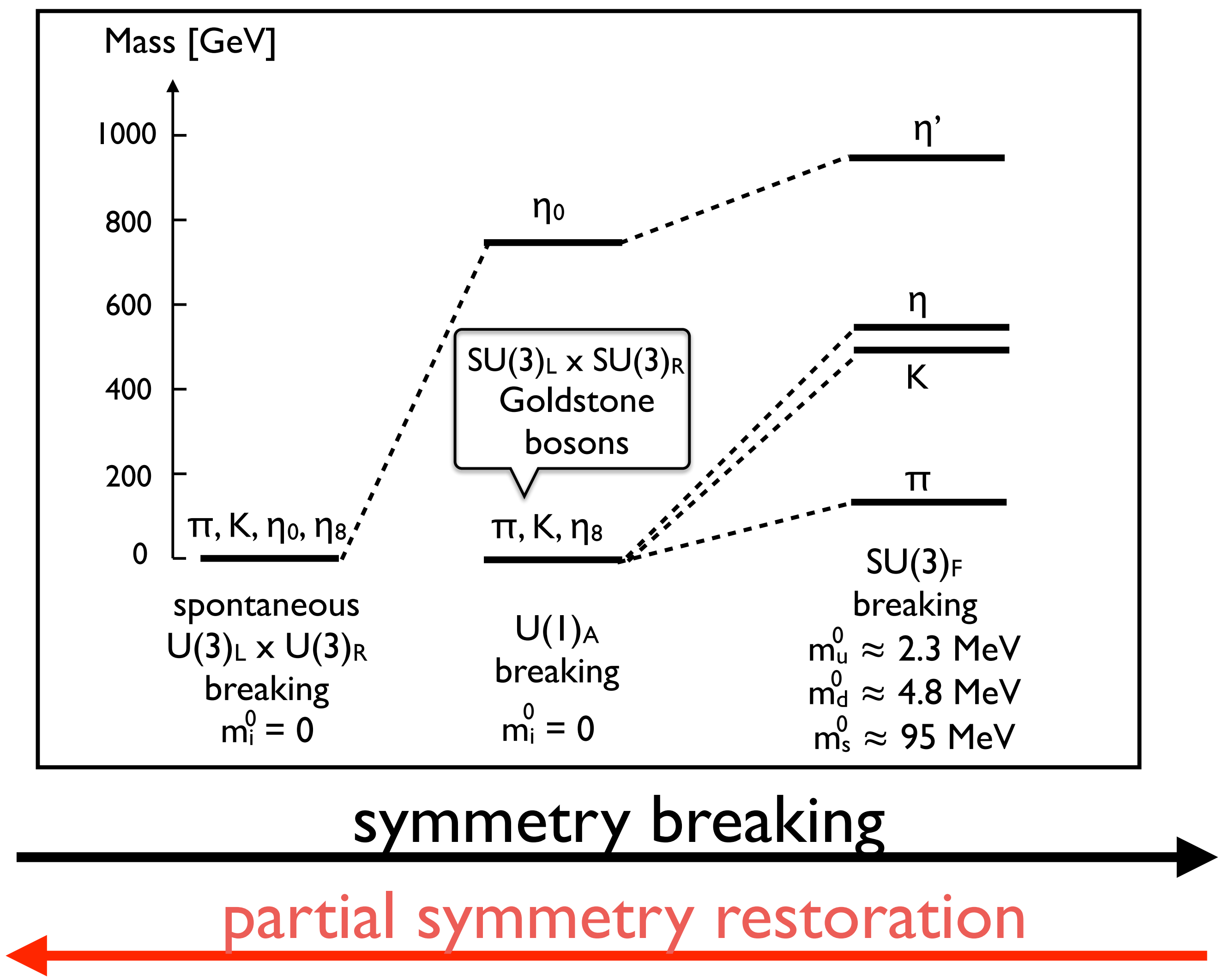
nonet of pseudoscalar mesons



V. Bernard, R.L. Jaffe, U.-G. Meissner, NPB 308 (1988) 753
S. Klimt, M. Lutz, U. Vogel, W Weise, NPA 516 (1990) 429

mass as a result of symmetry breaking

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

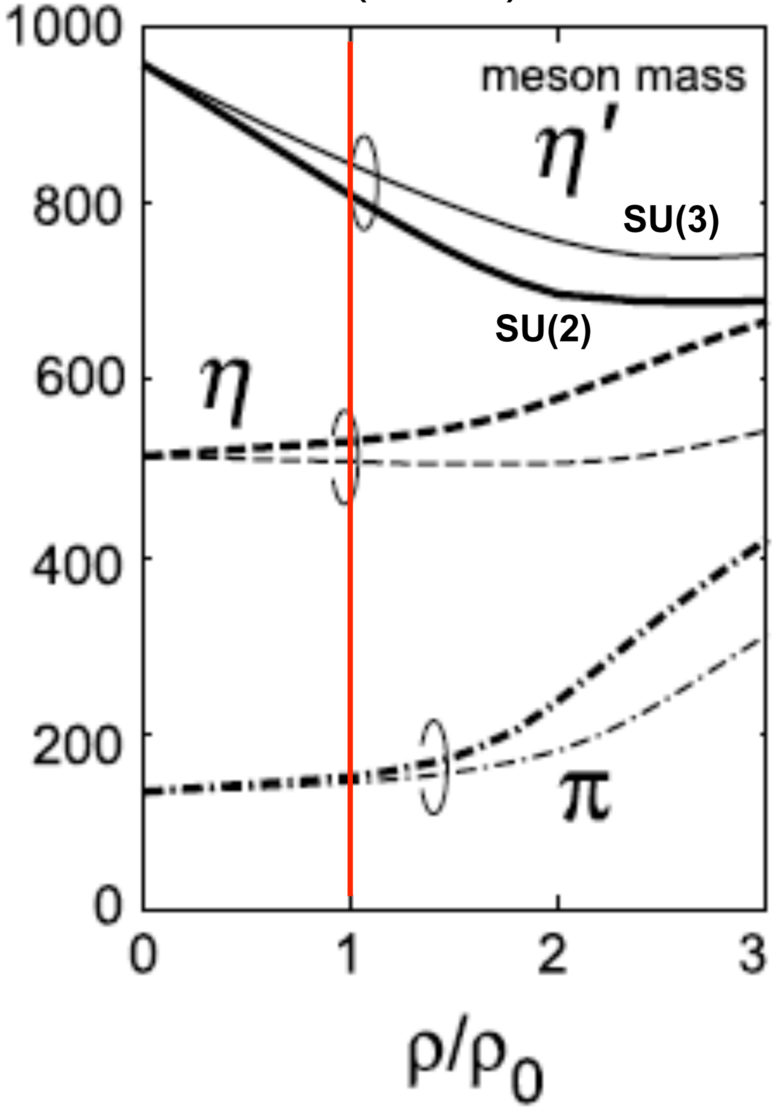


Predictions for in-medium mass changes

η,η'

NJL-model

H. Nagahiro et al., PRC 74 (2006) 045203



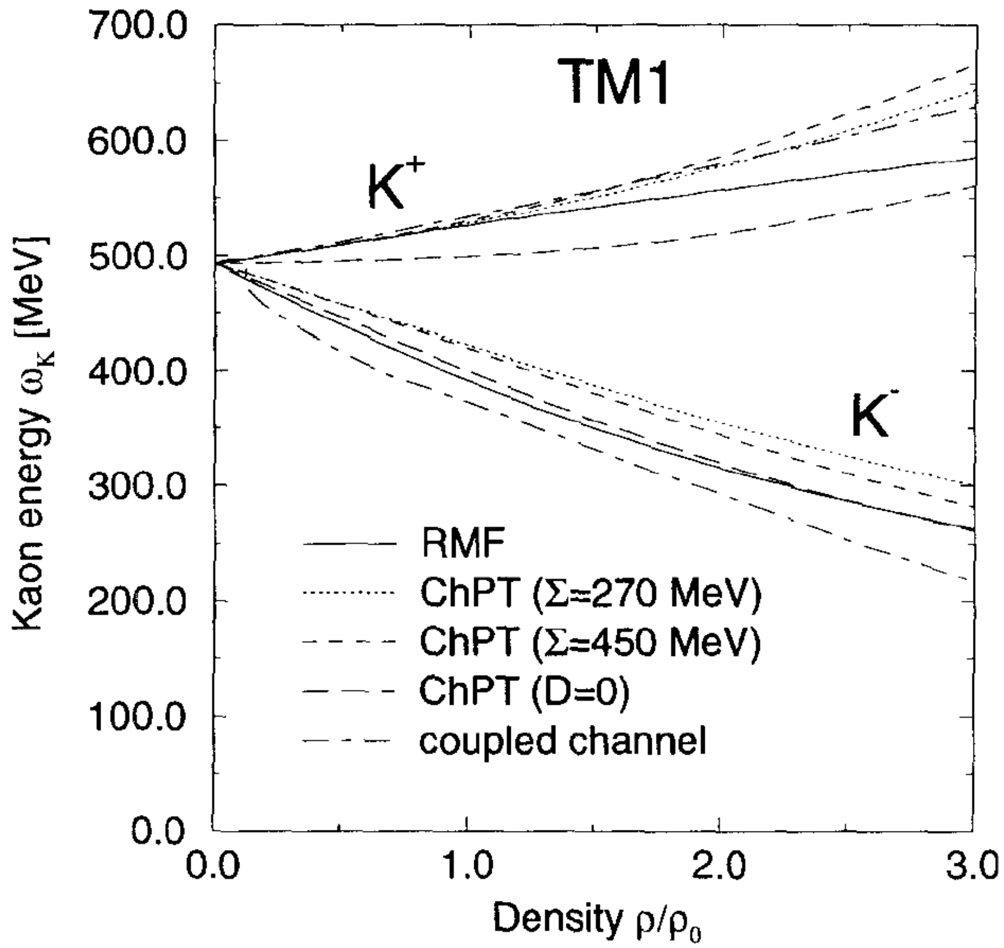
$\Delta m_{\eta'}(\rho_0) \approx -150$ MeV

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

K+, K-

RMF-approach

J.Schaffner-Bielich et al., Nucl. Phys. A625 (1997) 325



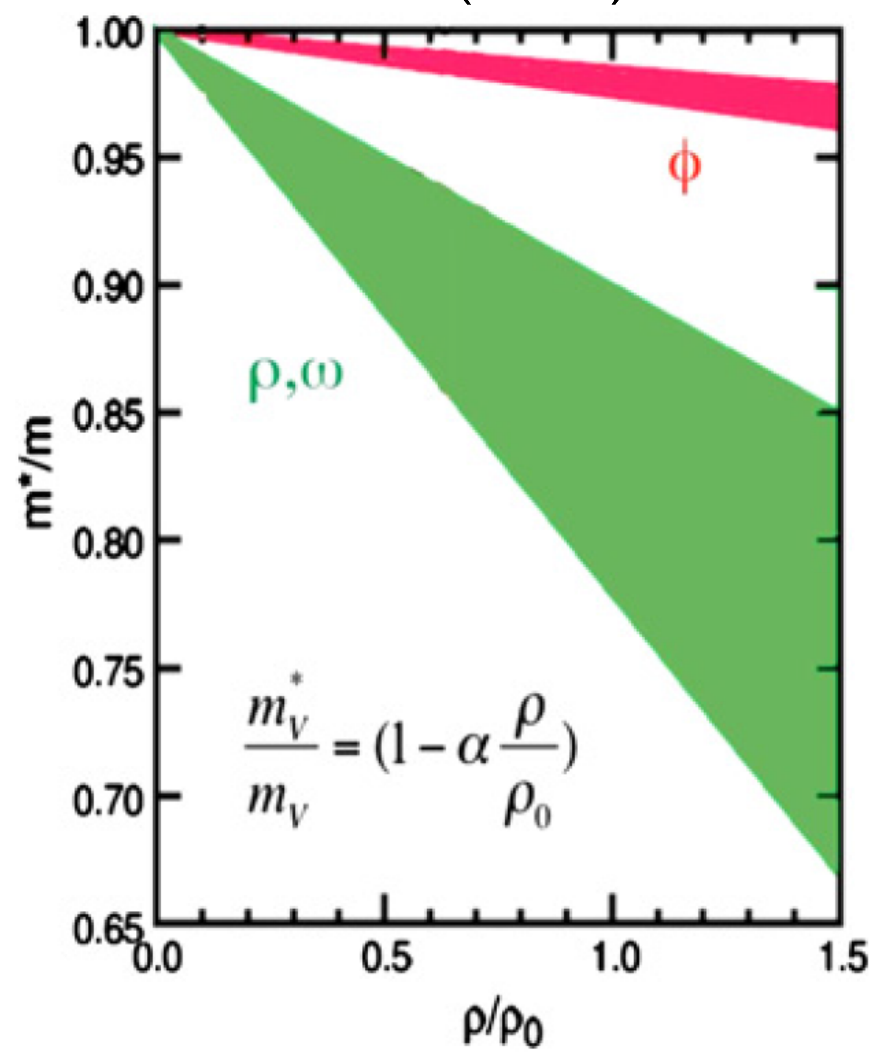
$\Delta m_{K^+}(\rho_0) \approx +30$ MeV

$\Delta m_{K^-}(\rho_0) \approx -100$ MeV

ρ,ω,Φ

QCD sum rules

T. Hatsuda, S. Lee PRC46 (1992)R34



$\Delta m_{\rho}(\rho_0) \approx$ - (80-160) MeV

$\Delta m_{\omega}(\rho_0) \approx$ - (80-160) MeV

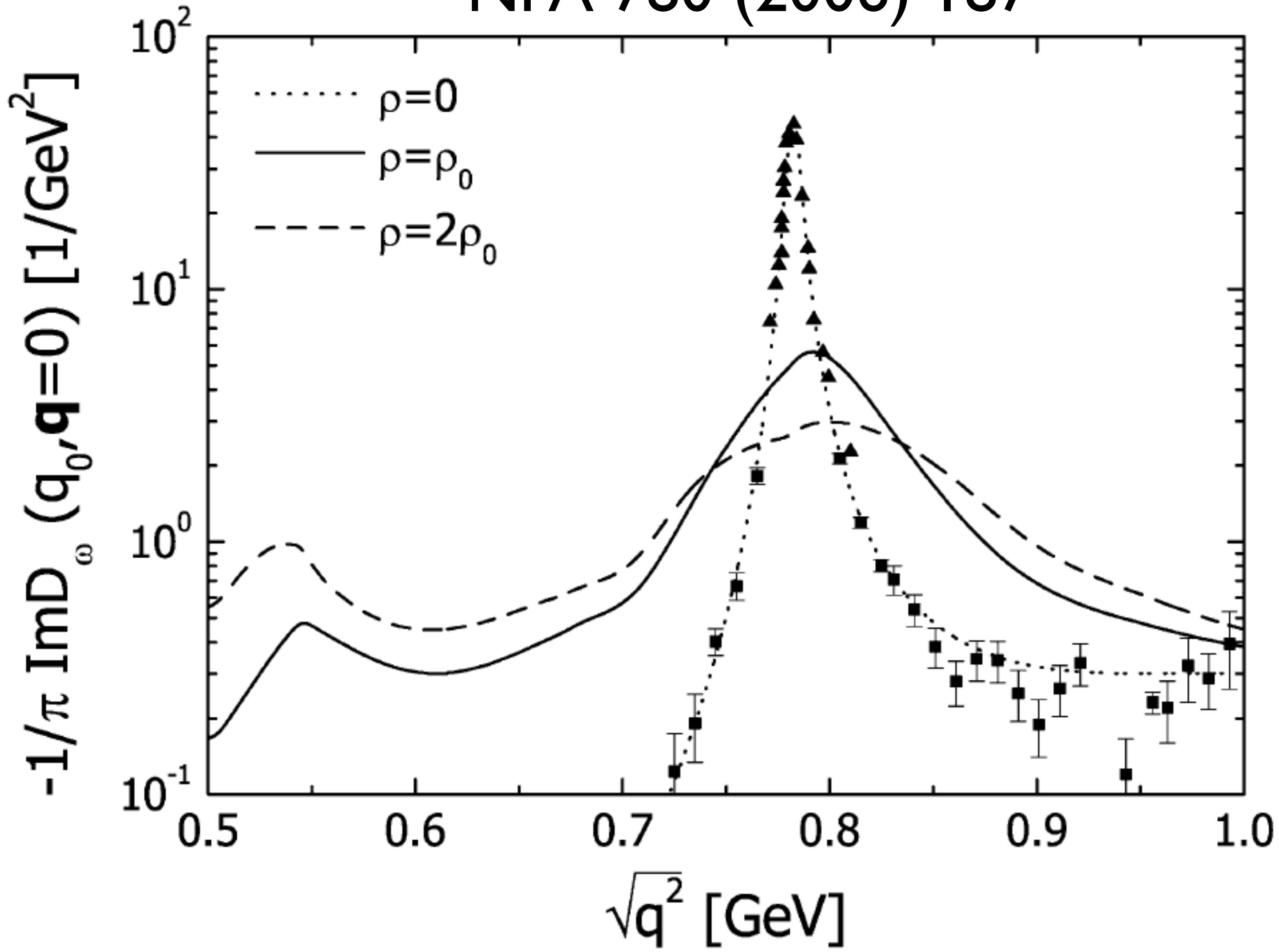
$\Delta m_{\Phi}(\rho_0) \approx$ -(20-30) MeV

Predictions for in-medium broadening

ω

unitary coupled channel
effective Lagrangian model

P. Mühlich et al.,
NPA 780 (2006) 187

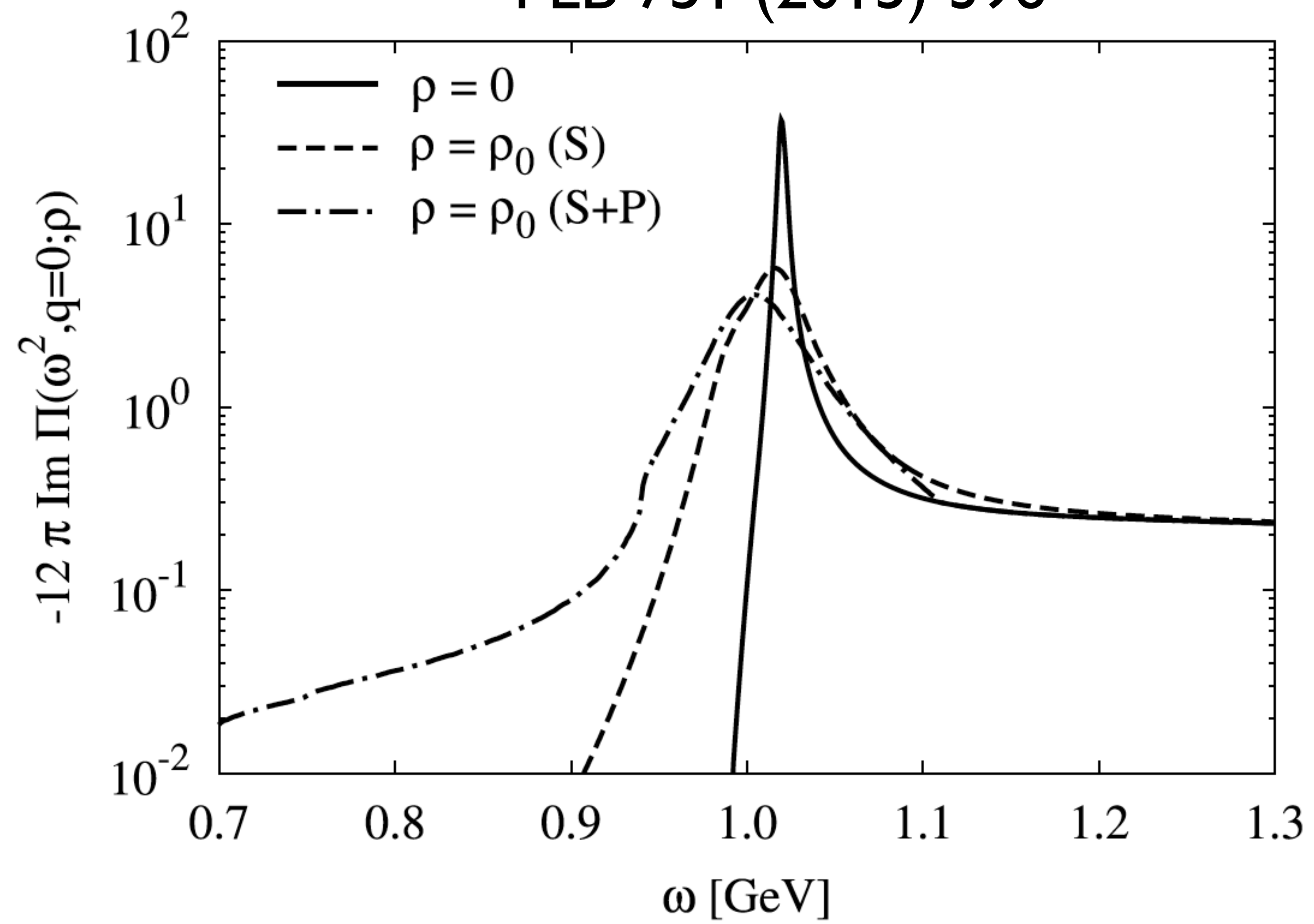


$\Gamma_\omega(\rho=\rho_0) \approx 60$ MeV

Φ

chiral-SU(3)
effective field theory

P. Gubler, W. Weise
PLB 751 (2015) 396



$\Gamma_\Phi(\rho=\rho_0) \approx 45$ MeV

in the nuclear medium: mesons removed by inelastic reactions
→shorter lifetime →larger in-medium width

meson-nucleus potential

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

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

attractive ?
repulsive ?

absorption

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

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

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

meson-nucleus potential

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

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

attractive ?
repulsive ?

absorption

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

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

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

- transparency ratio measurement

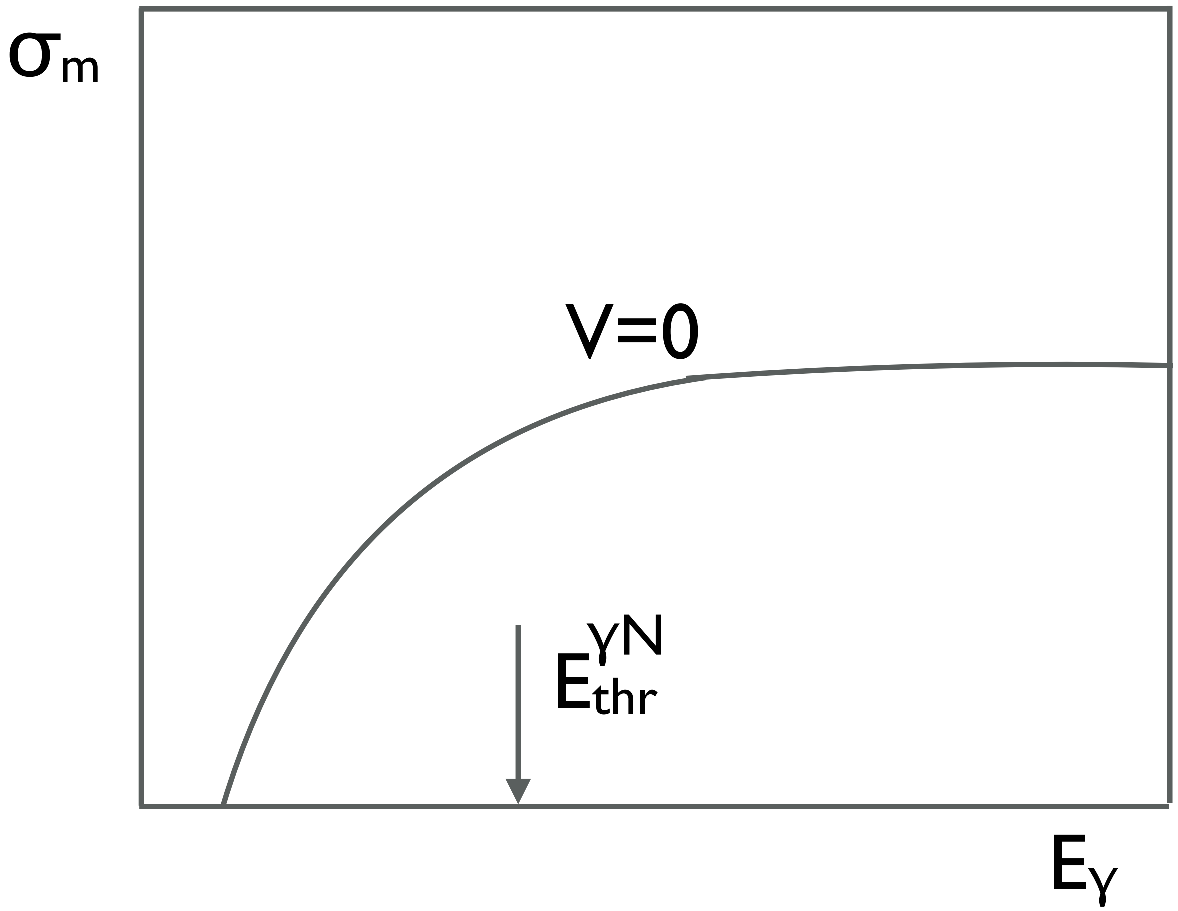
$$T_A = \frac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}}$$

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

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

sensitive to nuclear density at the production point

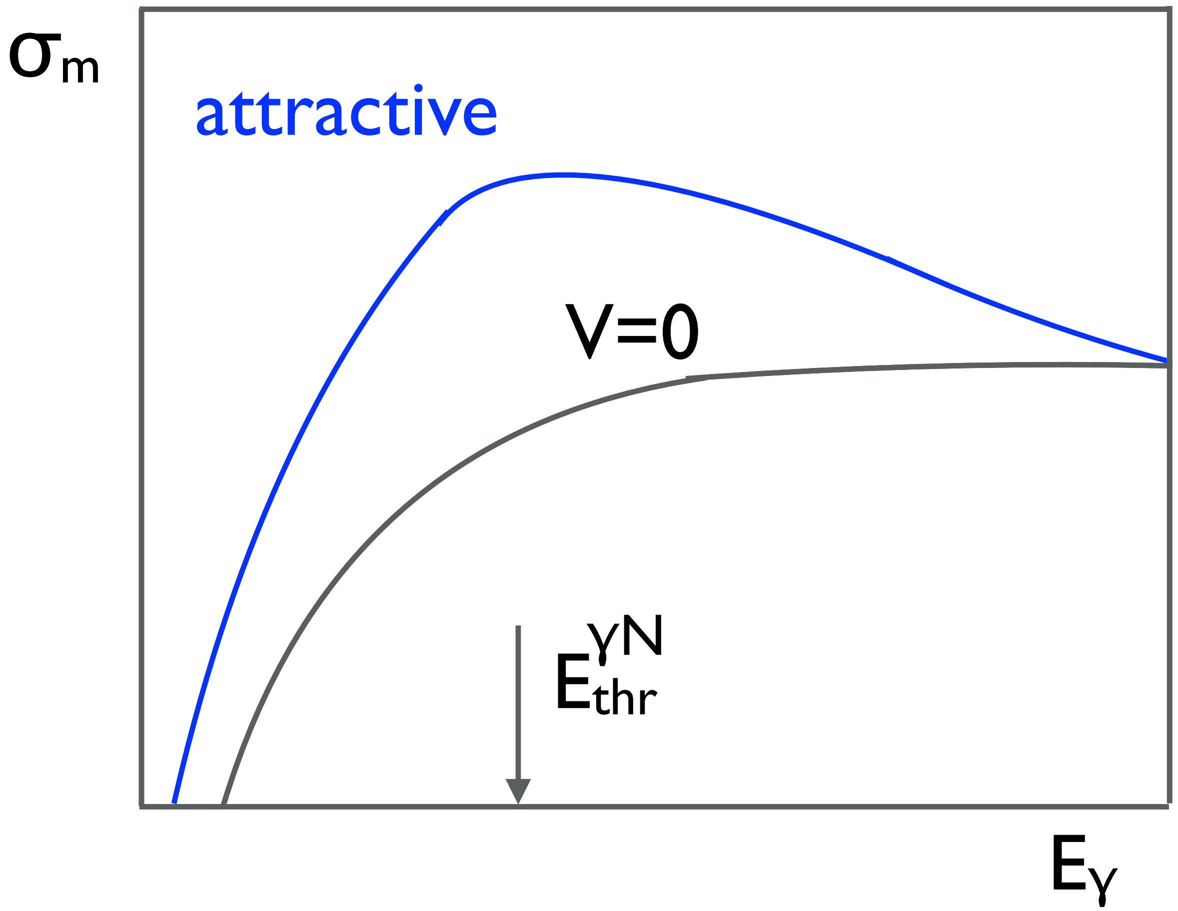
excitation function



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

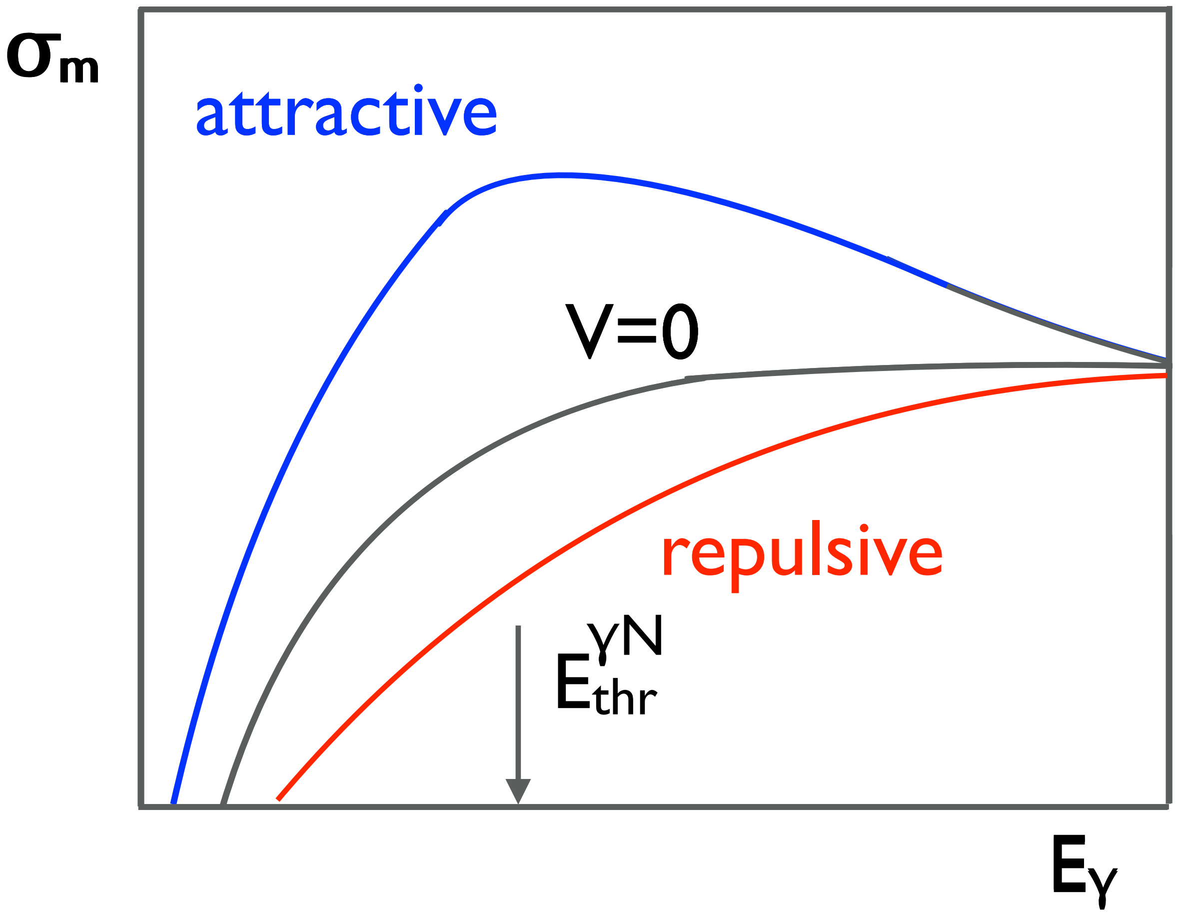


attractive interaction → mass drop → lower threshold → larger phase space→ larger cross section

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



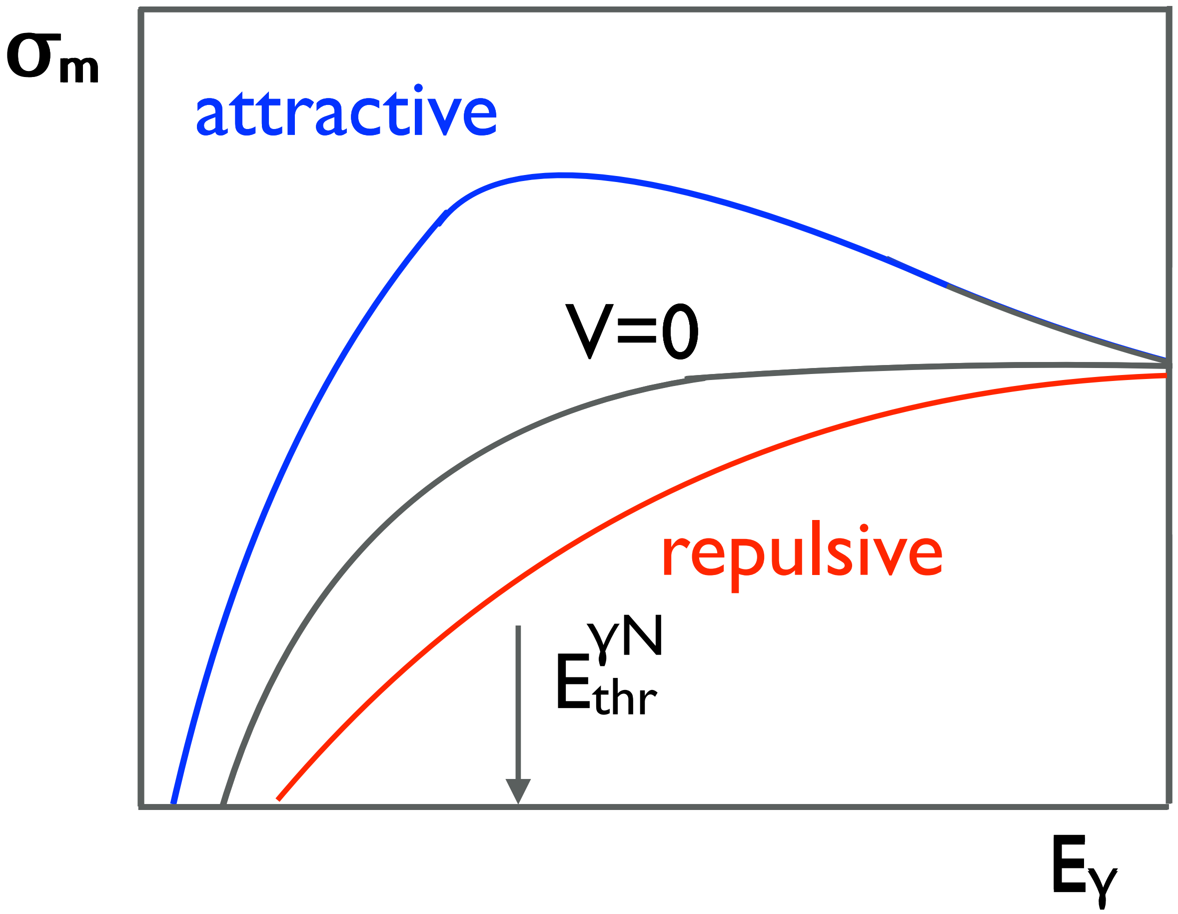
attractive interaction → mass drop → lower threshold → larger phase space→ larger cross section

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

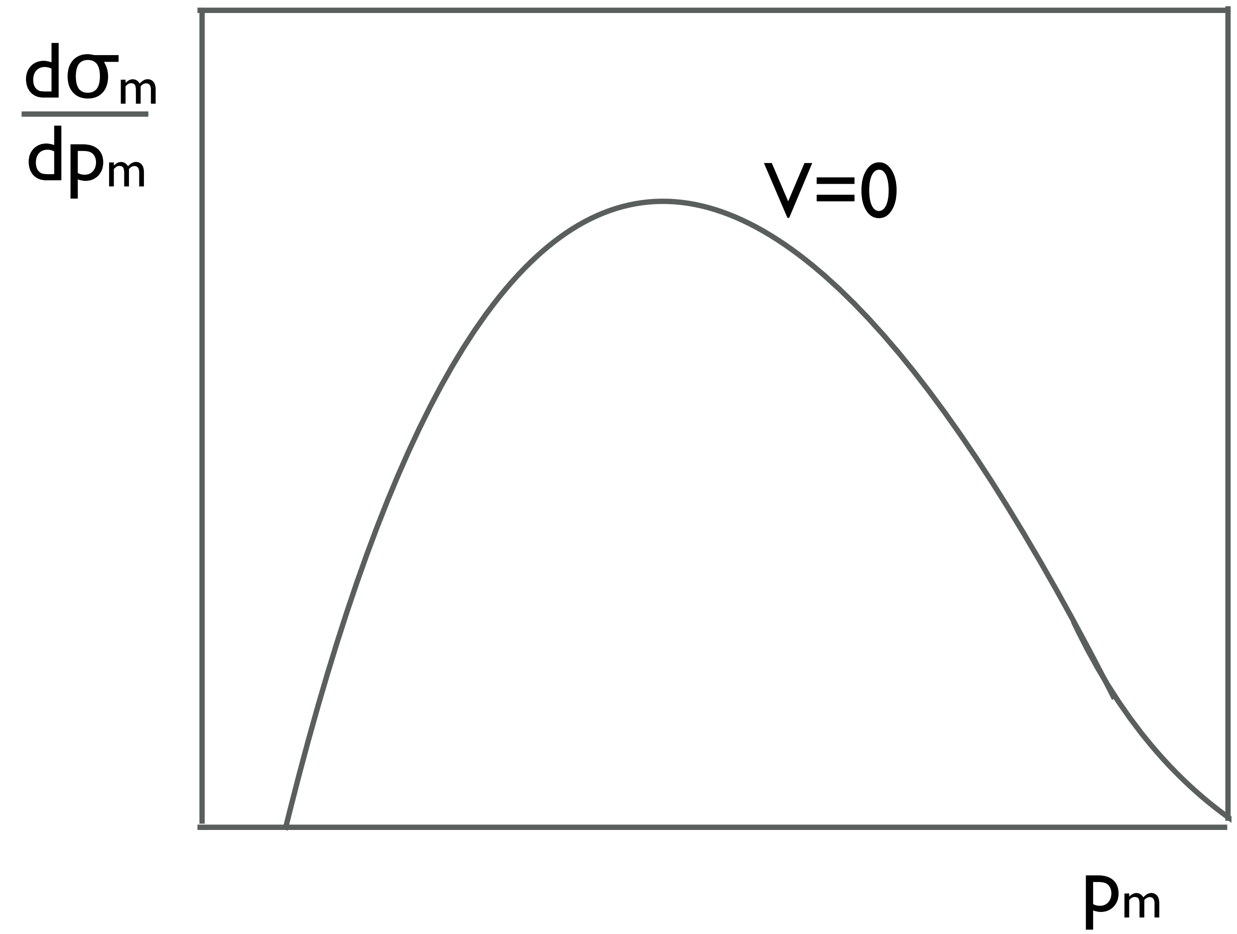
Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the production point

excitation function



momentum distribution



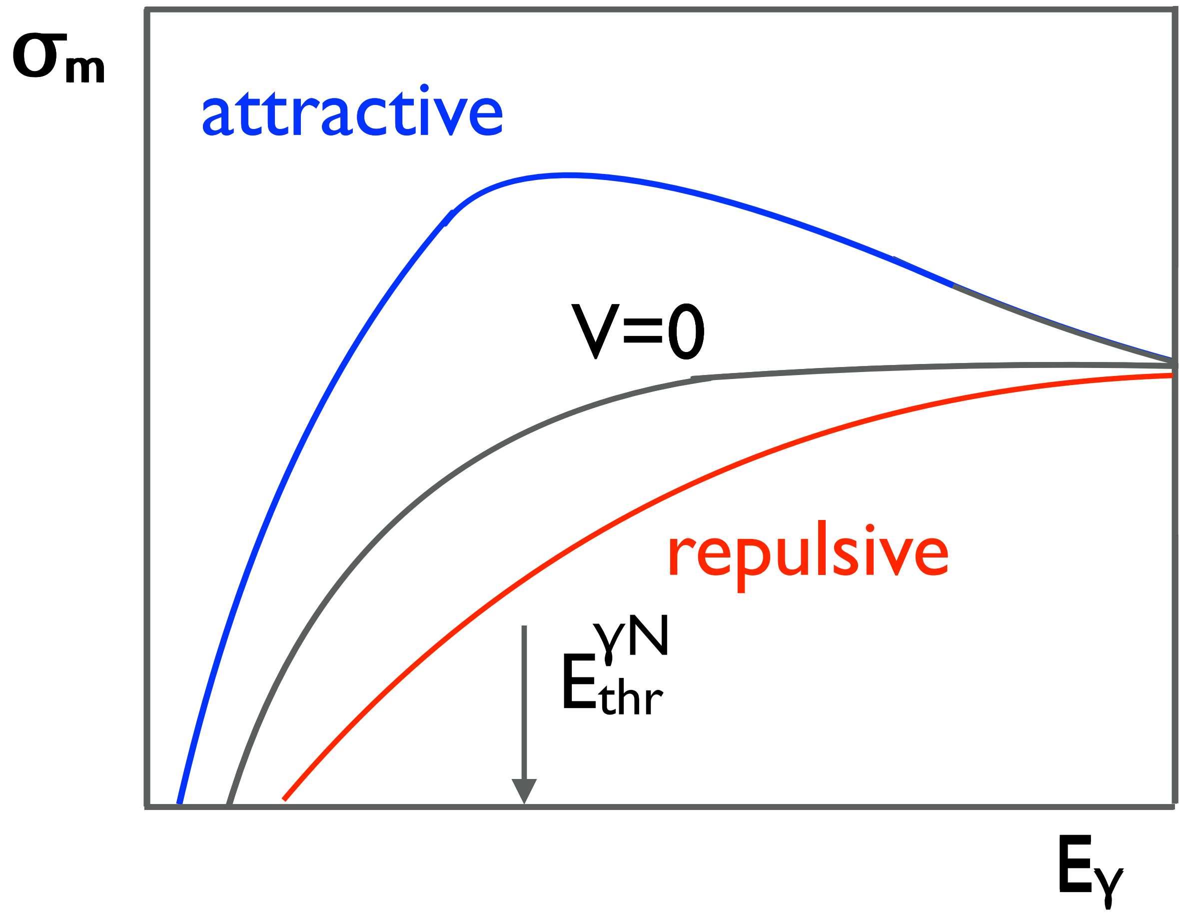
attractive interaction → mass drop → lower threshold → larger phase space→ larger cross section

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

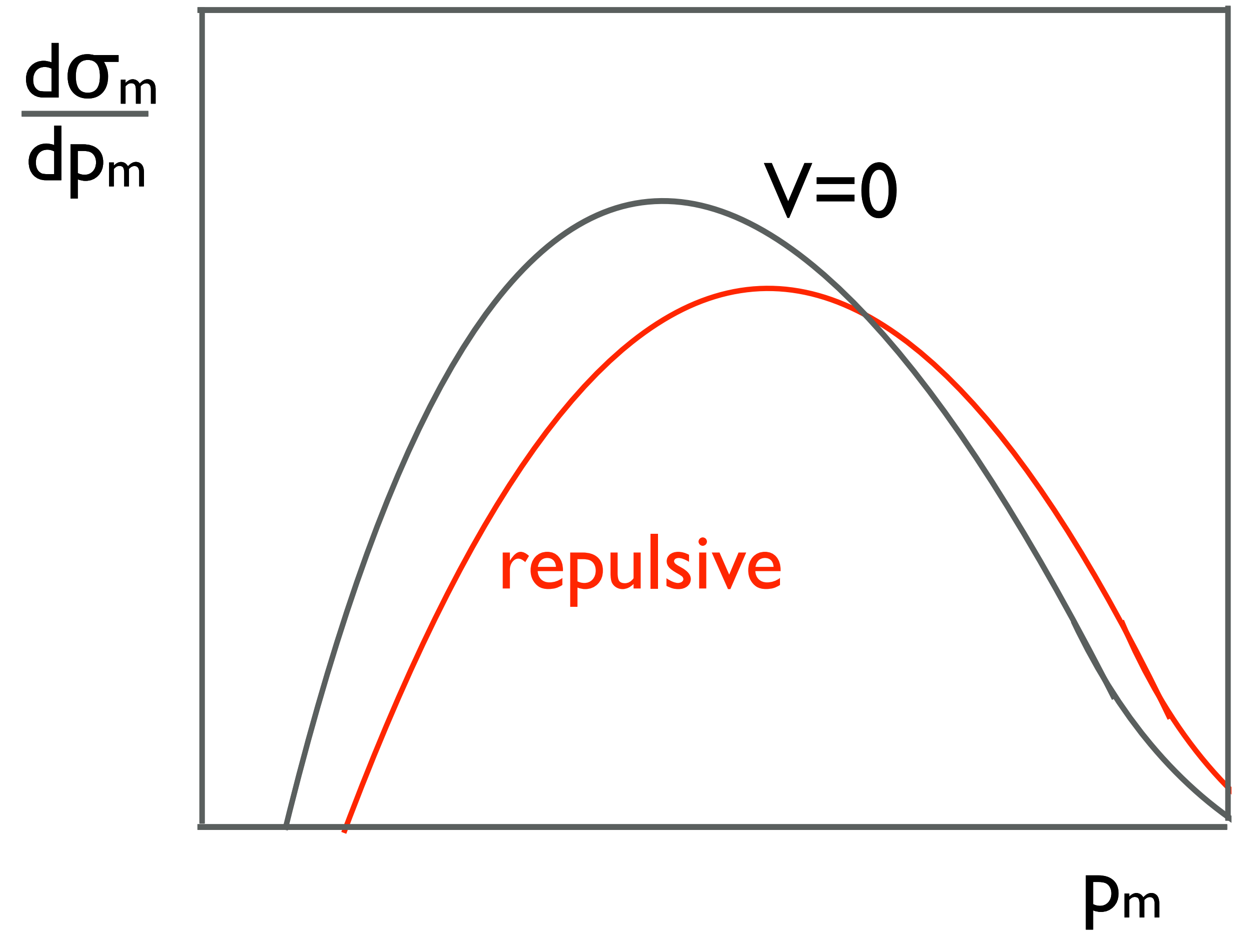
Determining the <u>real part</u> of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the production point

excitation function



momentum distribution



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

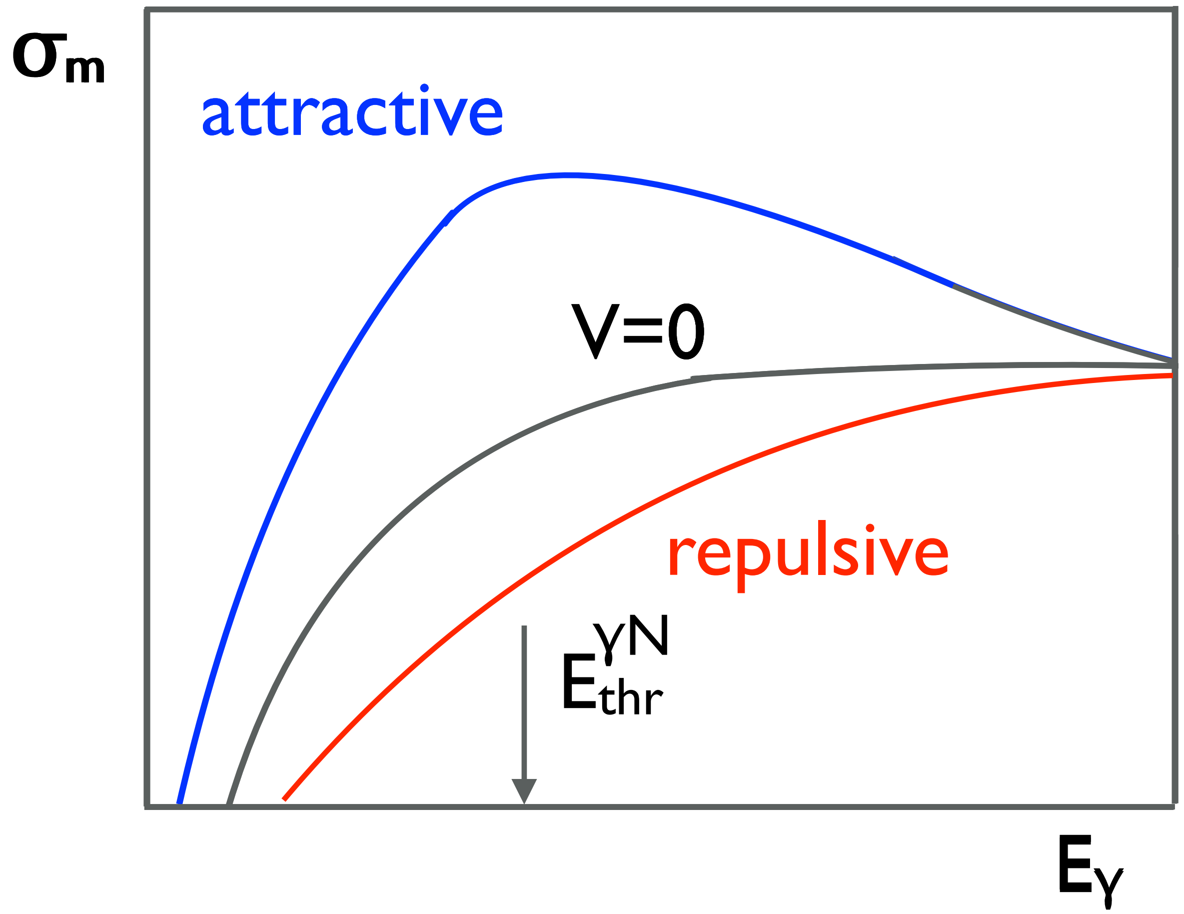
repulsive interaction → mass increase → higher threshold → smaller phase space→ smaller cross section

repulsive interaction → extra kick → shift to higher momenta

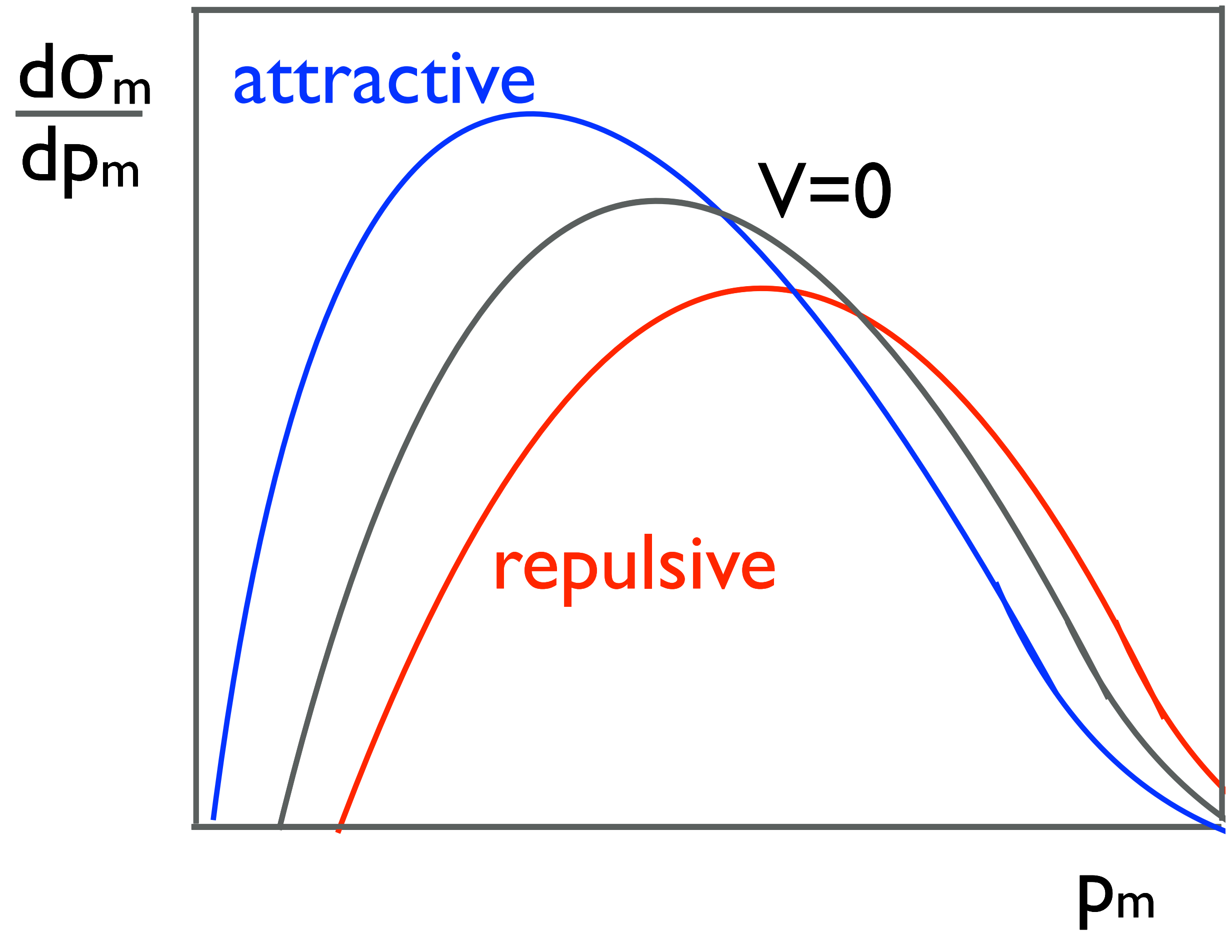
Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

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

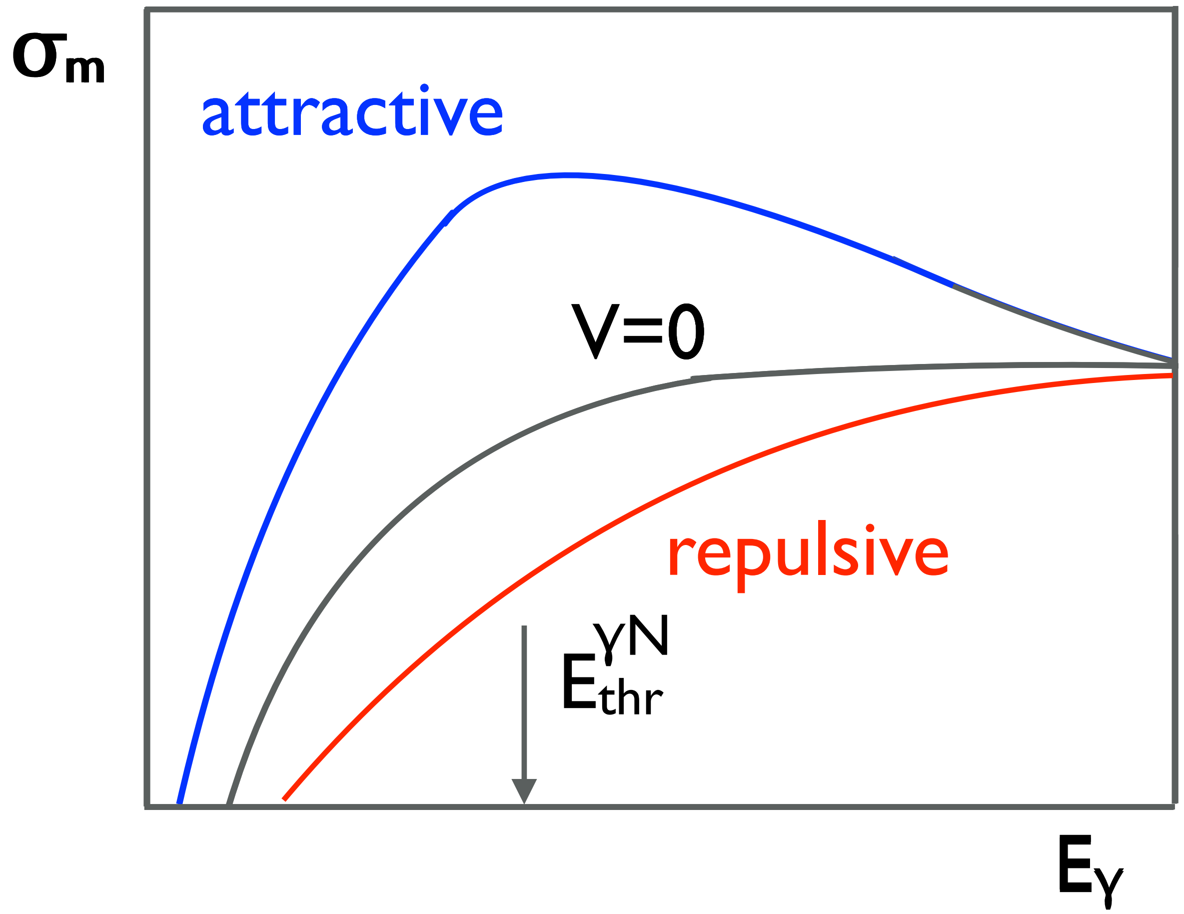
repulsive interaction → mass increase → higher threshold → smaller phase space→ smaller cross section

attractive interaction → meson slowed down → shift to lower momenta

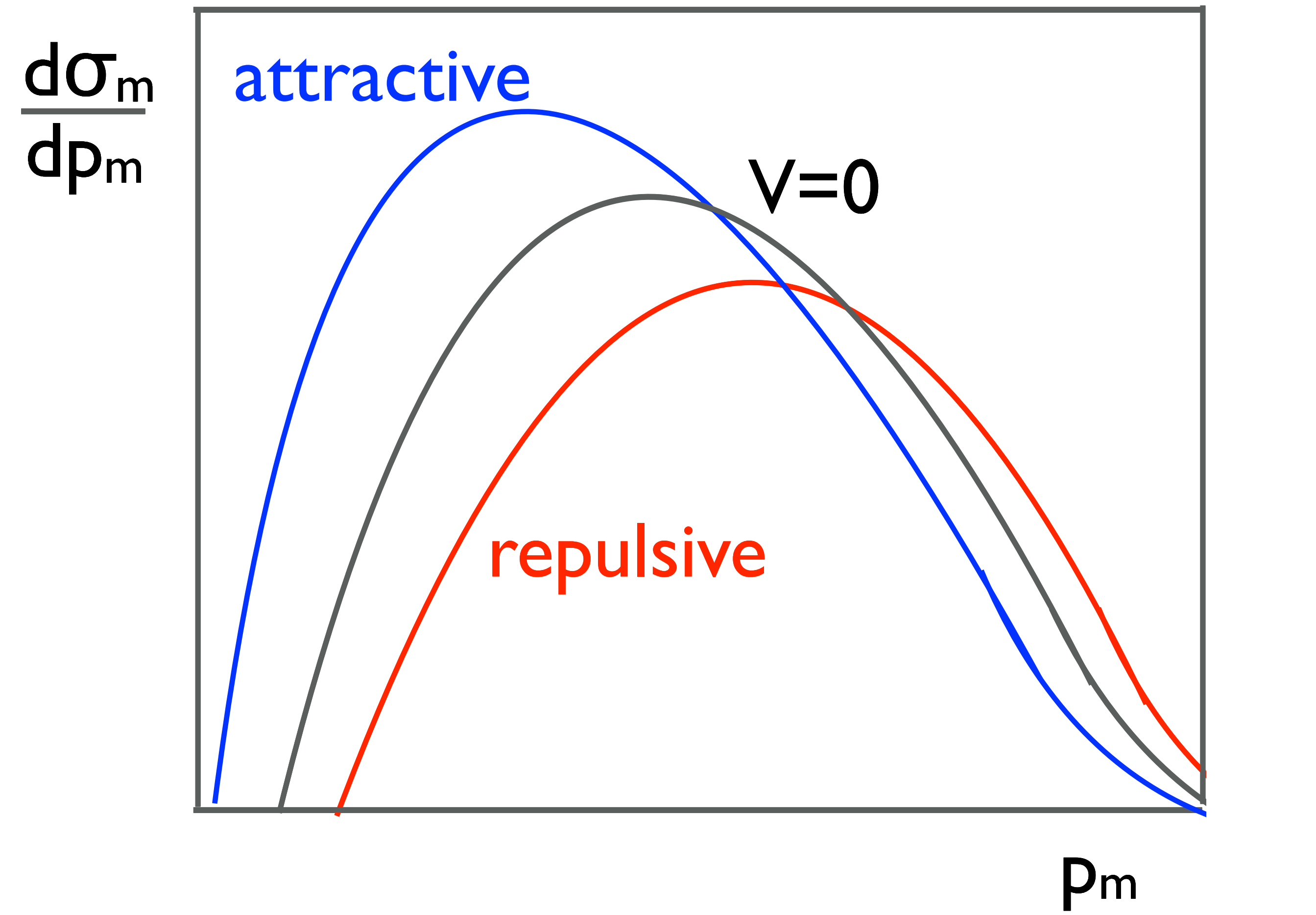
Determining the real part of the meson-nucleus potential from excitation functions and momentum distributions

sensitive to nuclear density at the production point

excitation function



momentum distribution



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

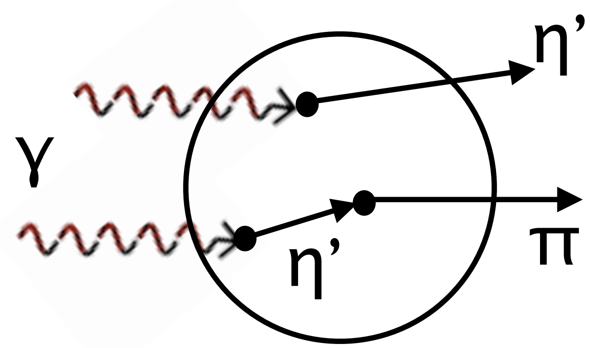
repulsive interaction → mass increase → higher threshold → smaller phase space→ smaller cross section

repulsive interaction → extra kick → shift to higher momenta

attractive interaction → meson slowed down → shift to lower momenta

quantitative analysis requires transport model or collision model calculations

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



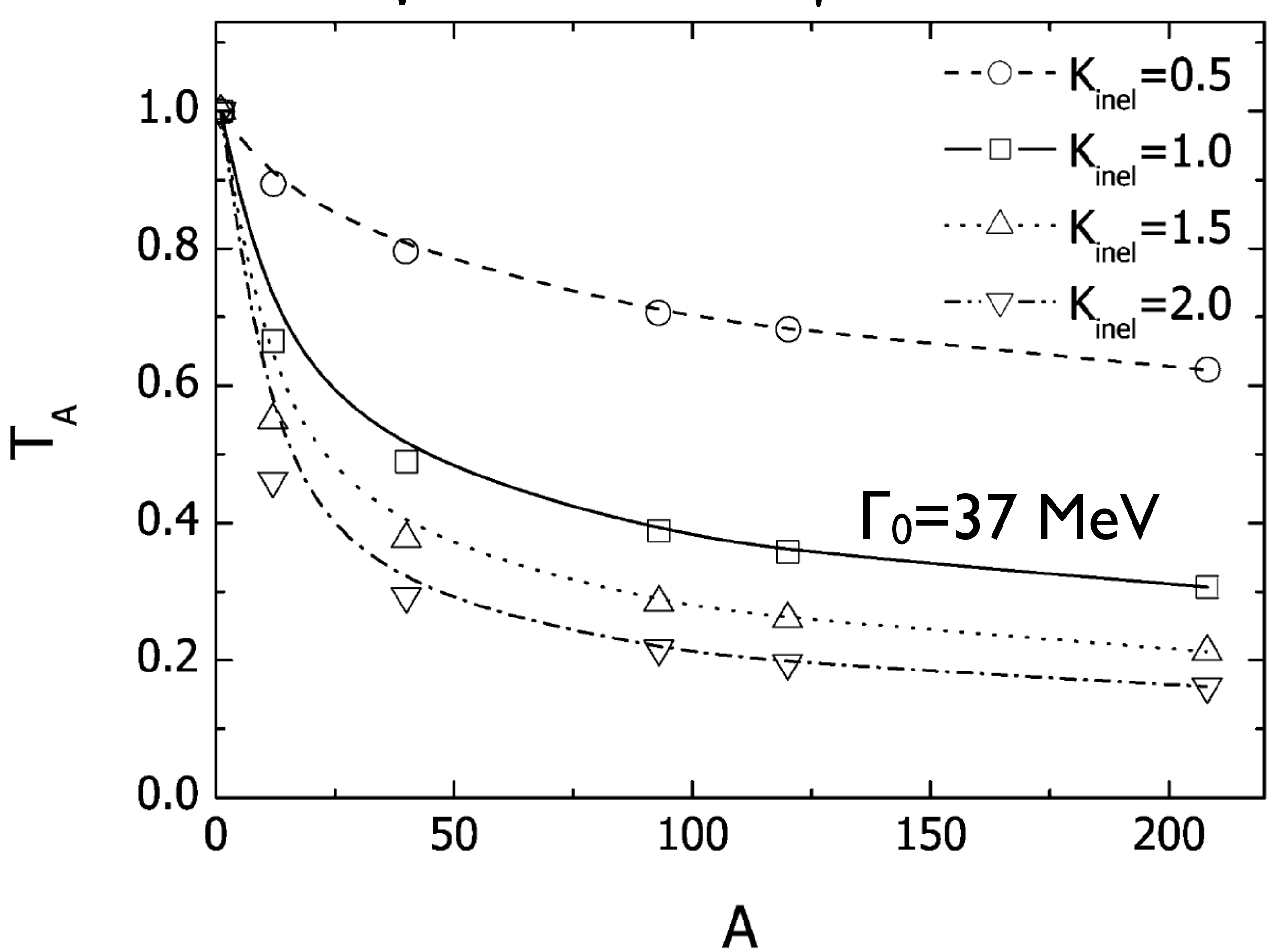
$$T_A = \frac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}}$$

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

transport model calculation: GiBUU

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

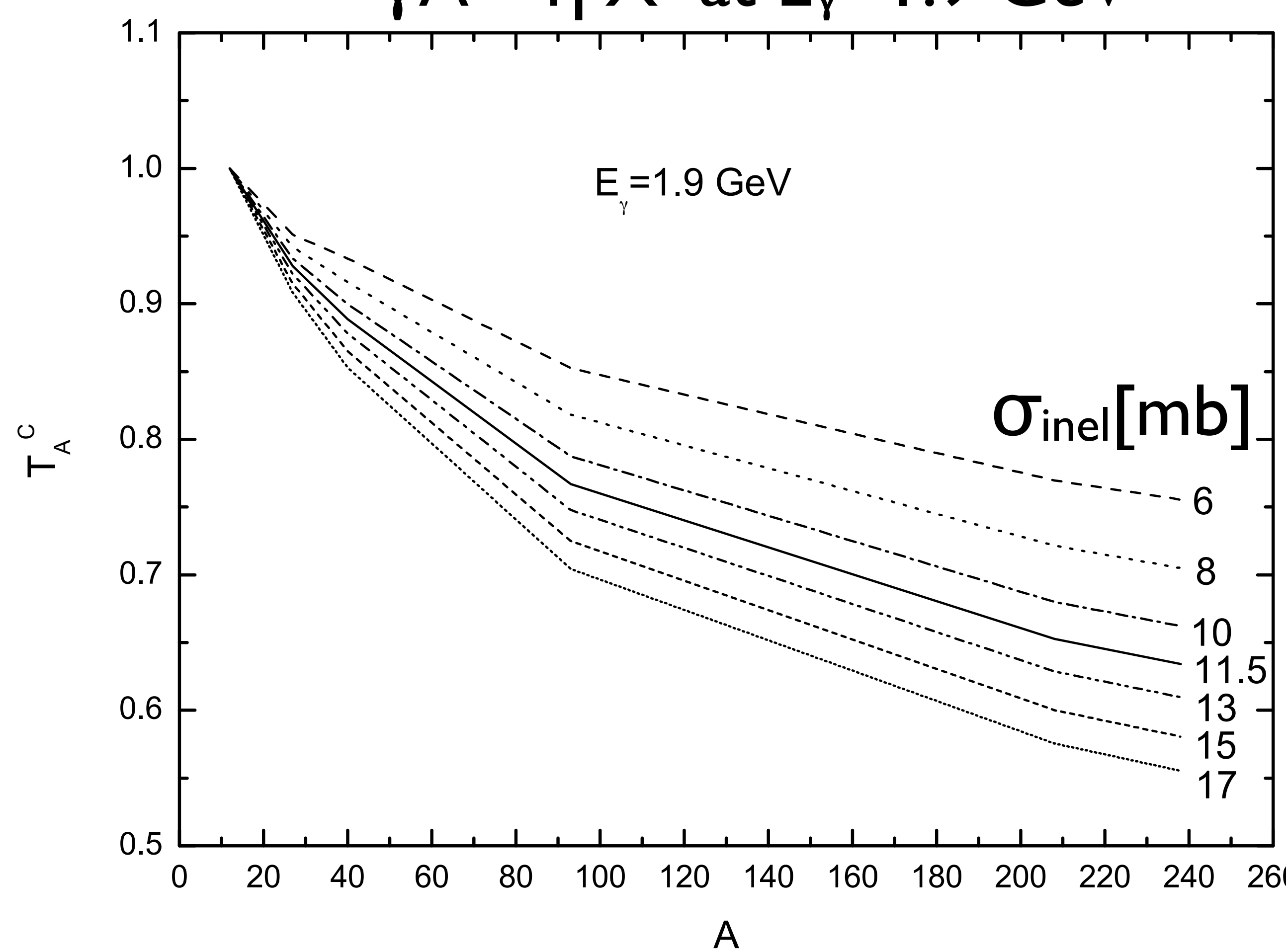
$\gamma A \to \omega X$ at E_γ=1.5 GeV



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}

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

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

Review:

V. Metag, M. Nanova and E. Ya. Paryev, Prog. Part. Nucl. Phys. 97 (2017) 199

excitation function and momentum distribution for η' photoproduction off C

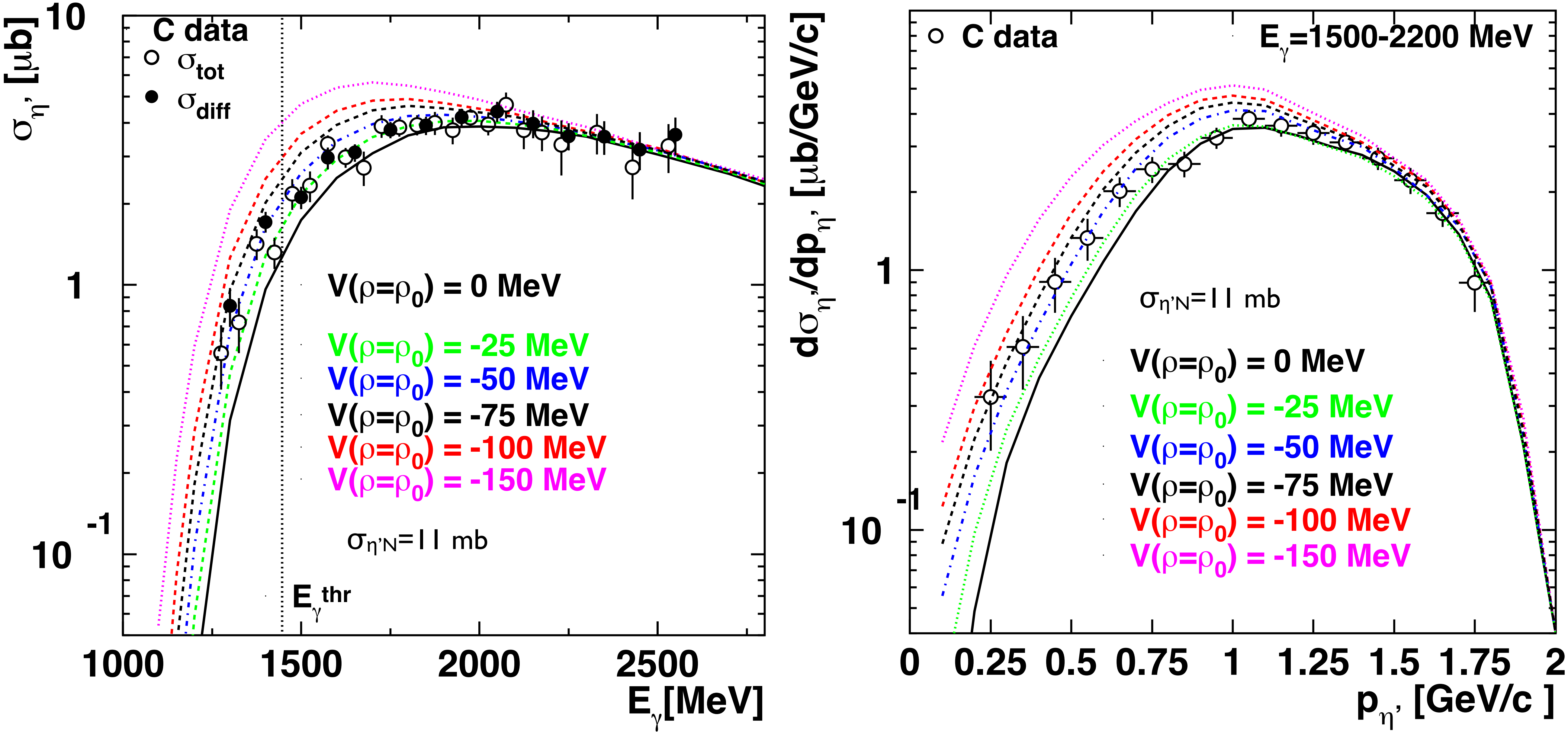
η'

CBELSA/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

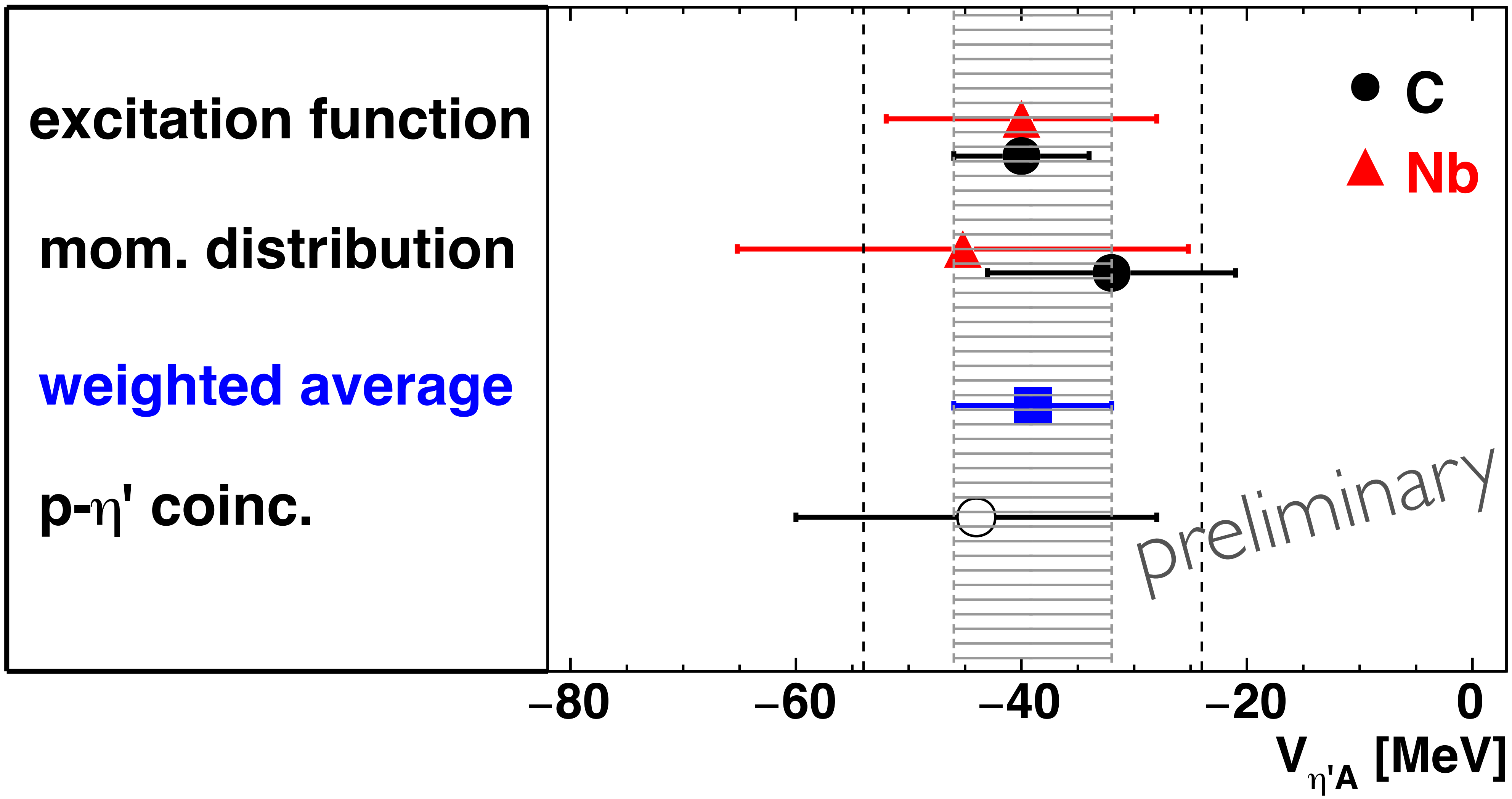
$V_{\eta'}(<p_{\eta'}>\approx 1.1$ GeV/c$;\rho=\rho_0) = -(32\pm11)$ MeV

data disfavour strong mass shifts

determining the real part of the η'-nucleus potential

η'

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



$p_{\eta'} \lesssim m$

$p_{\eta'} \approx 520$ MeV/c

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

observed mass shift in agreement with QMC model predictions

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

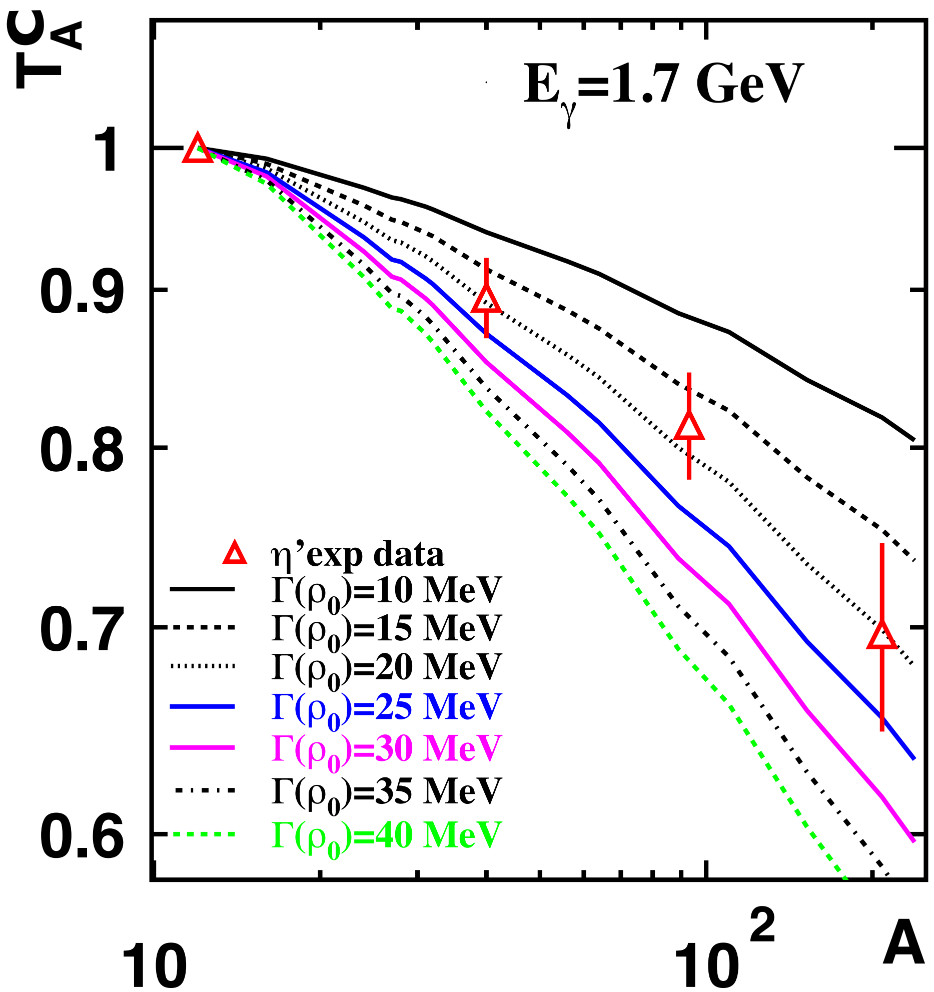
determining the imaginary part of the η'-nucleus potential

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

η'

mass dependence of T_A

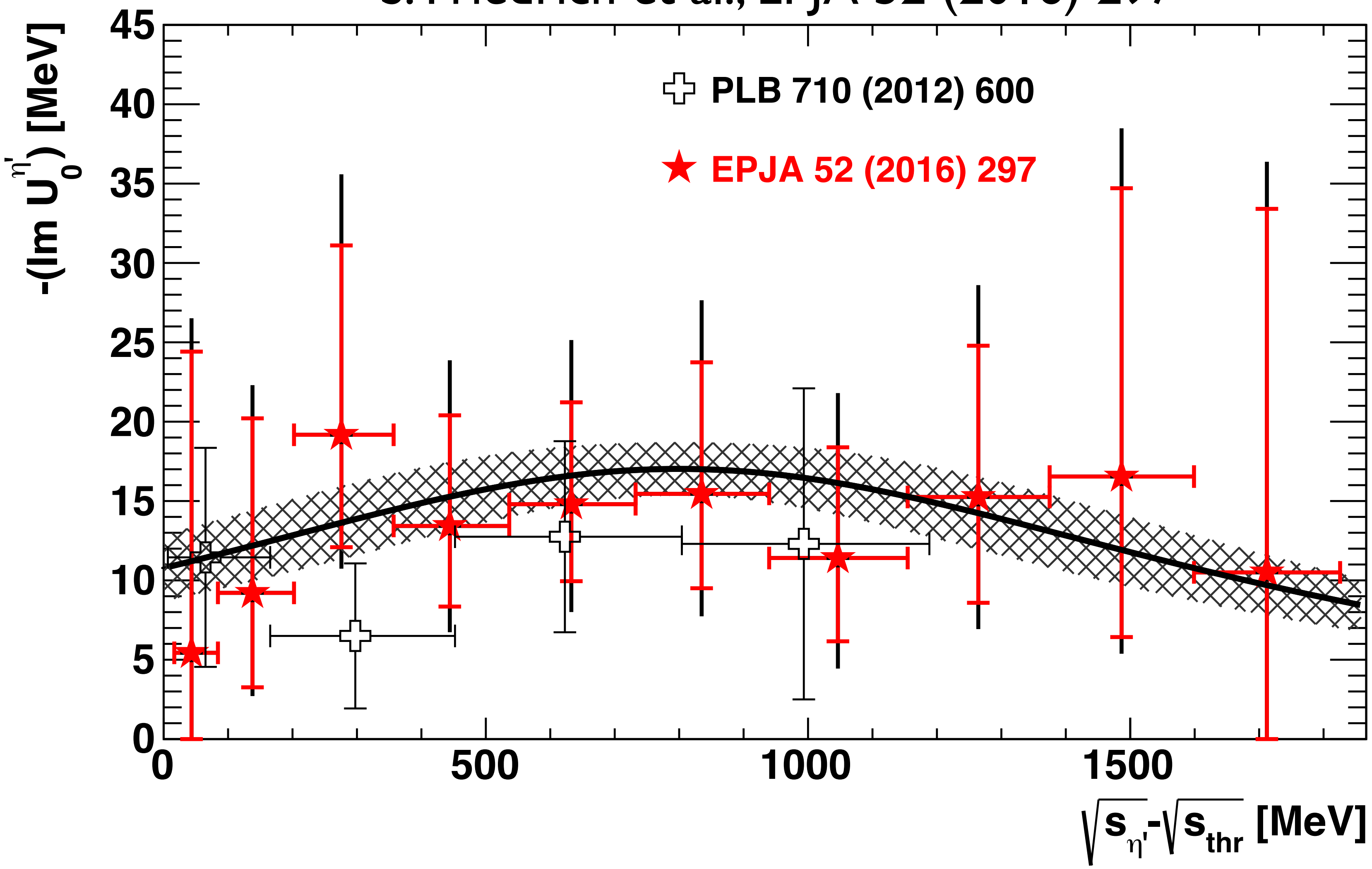
M. Nanova et al., PLB 710 (2012) 600



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

energy dependence of W_0

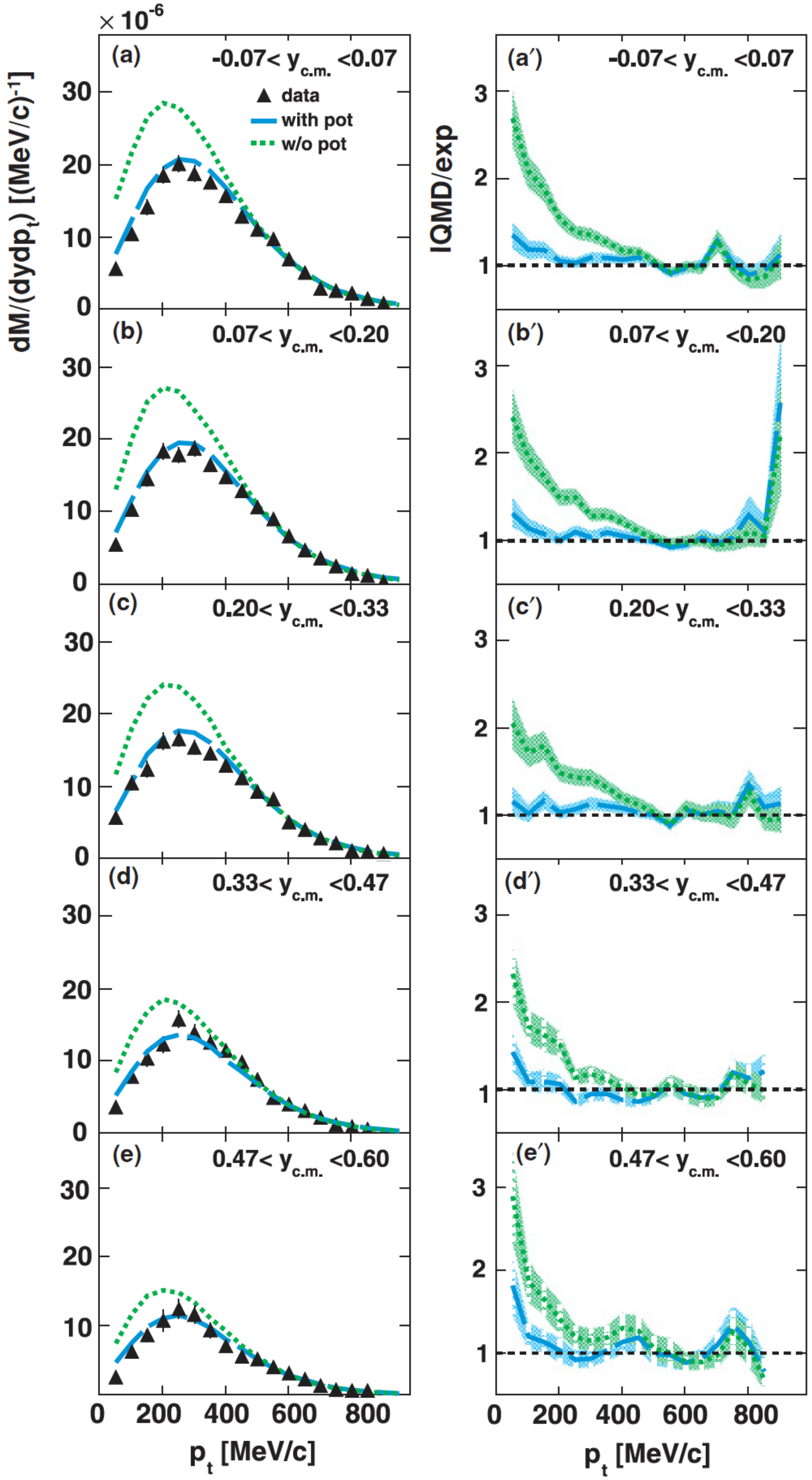
S. Friedrich et al., EPJA 52 (2016) 297



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

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

K^0



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 (green dotted)
and with repulsive potential
of +46 MeV (blue dashed curve)

$V \approx +40$ MeV

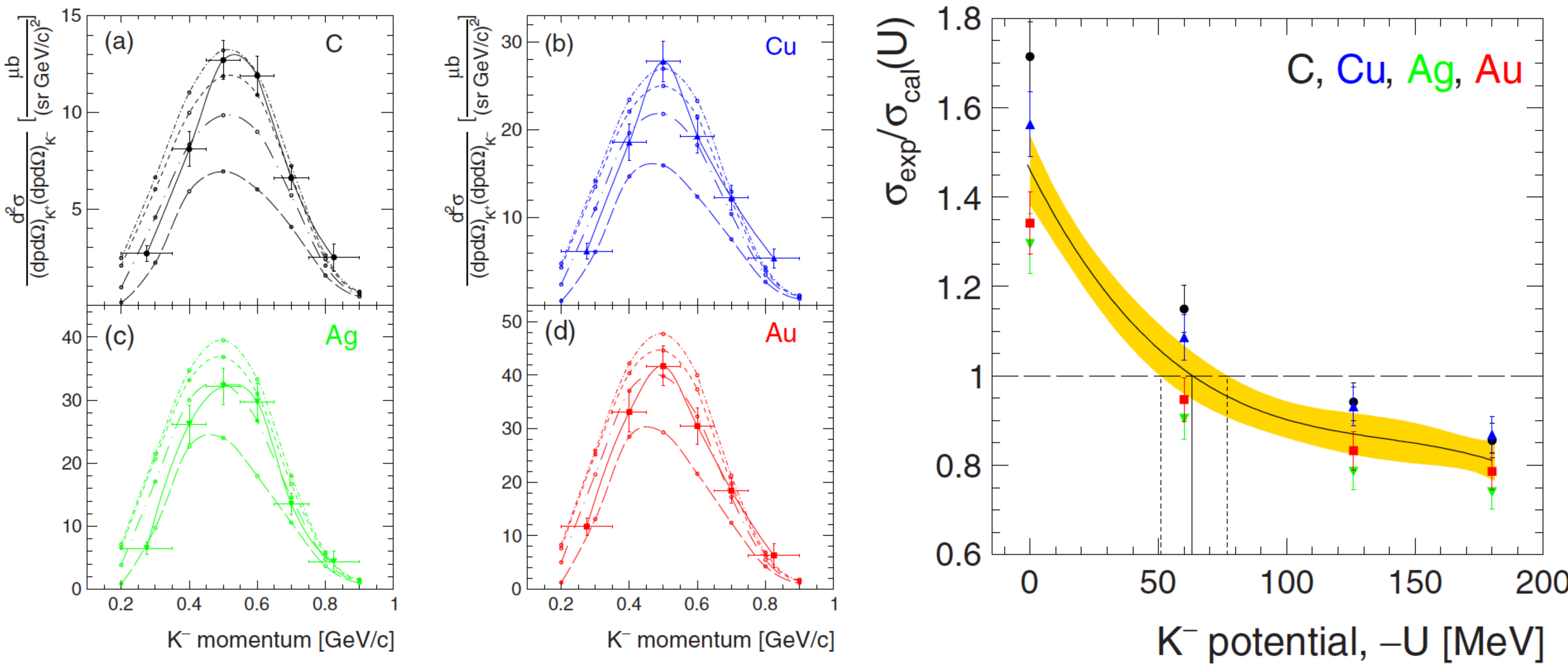
determining the real part of the K^--nucleus potential

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^-



K^--momentum spectra in coincidence with K^+ ($200 \leq p_{K+} \leq 600$ MeV/c) 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

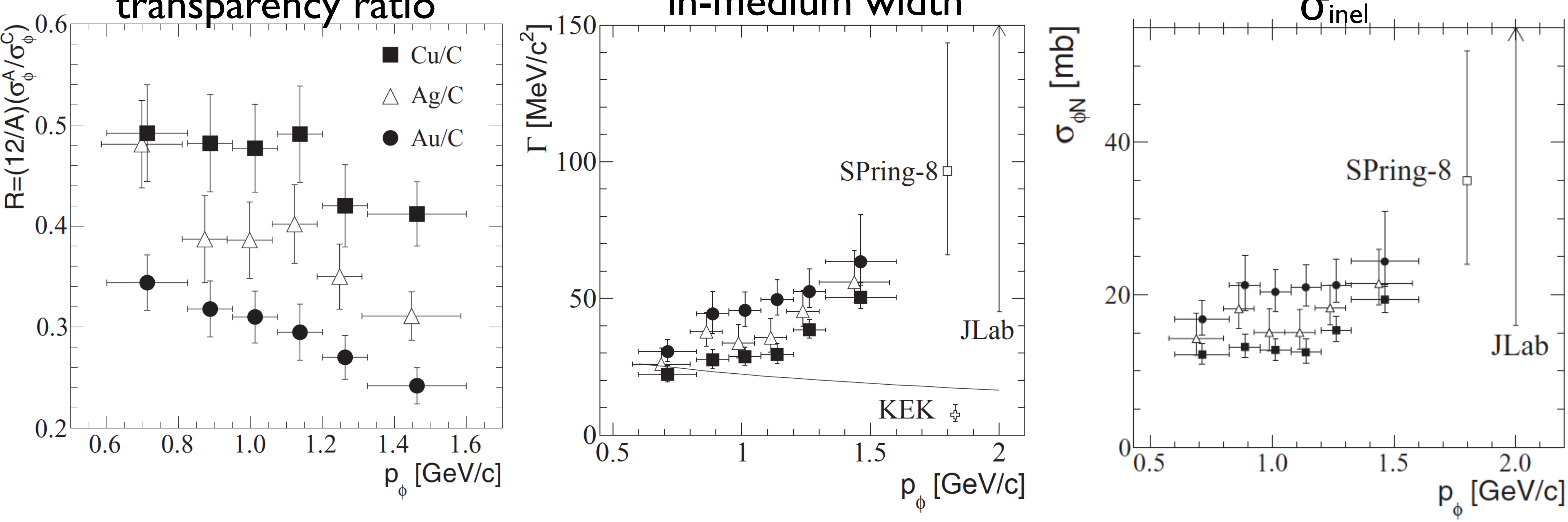
Determining the imaginary part of the Φ-nucleus potential

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

Φ

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

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



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

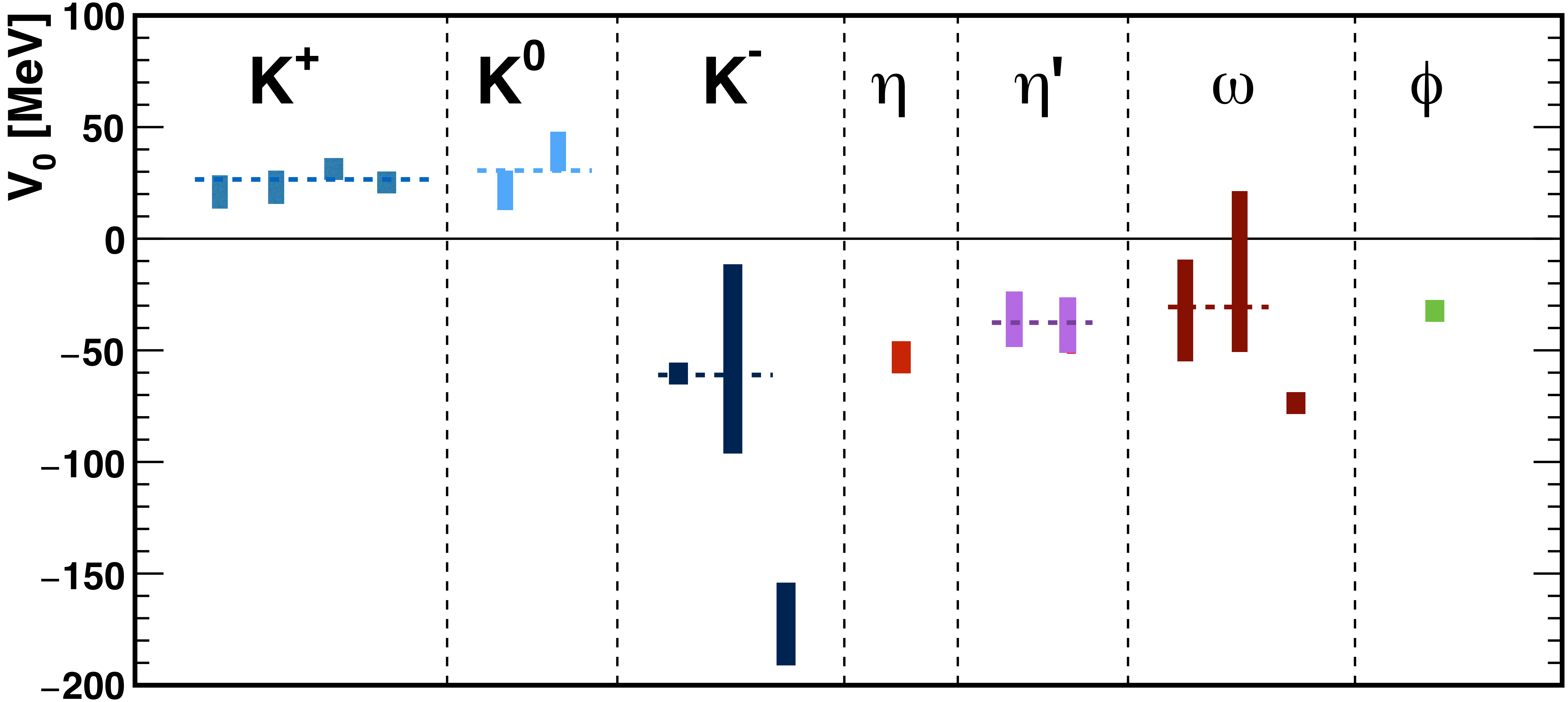
$W(\rho=\rho_0) = -$ (10-30) MeV for $0.7 < p_\Phi < 1.5$ GeV/c

L. Fabbietti
J.Wirth:
(HADES)

$\pi^- +$ C,W: $\Phi/K^-(C) \approx \Phi/K^-(W) \rightarrow \Phi, K^-$ experience similar absorption

Real part of the meson-nucleus potential

V. Metag, M. Nanova and E.Ya. Paryev, Prog. Part. Nucl. Phys.97 (2017) 199



meson-nucleus real potential:

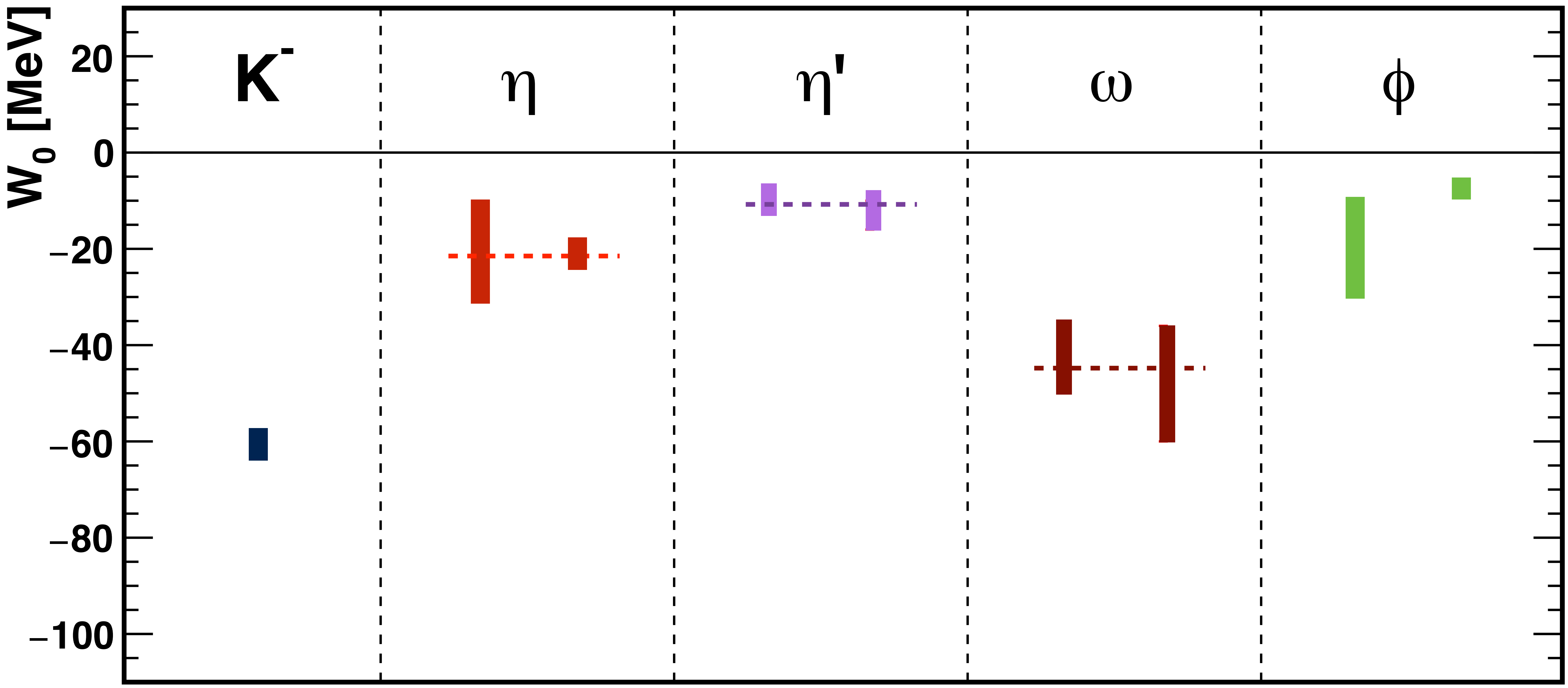
K^+, K^0 repulsive: 20-40 MeV — $m_{K+,K0}$ ↗

K^- strongest attraction: - (30 - 100) MeV — m_{K^-} ↘

η, η', ω, Φ weakly attractive: - (20 - 50) MeV — $m_{\eta'}$ ↘

Imaginary part of the meson-nucleus potential

V. Metag, M. Nanova and E.Ya. Paryev, Prog. Part. Nucl. Phys.97 (2017) 199



meson-nucleus imaginary potential:

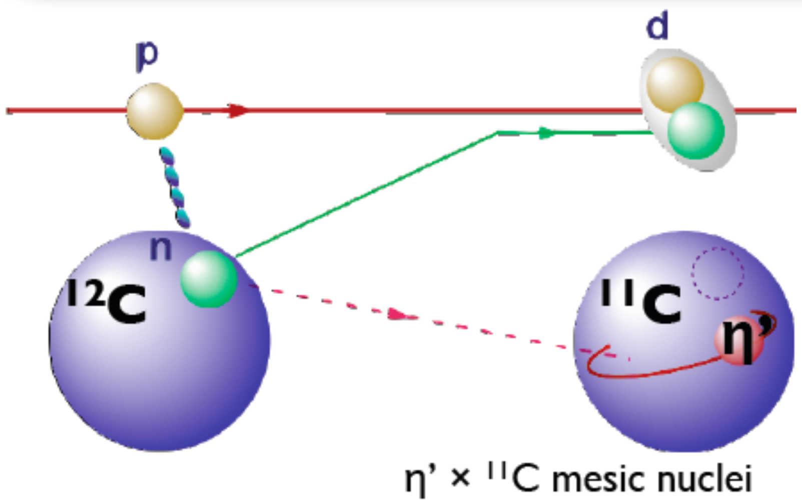
η' : ≈ -10 MeV

η, Φ : ≈ - 20 MeV

ω : ≈ - 40 MeV quite broad

K^- : ≈ - 60 MeV very broad

Search for η’ nucleus bound states in $^{12}C(p,d)\eta' X$



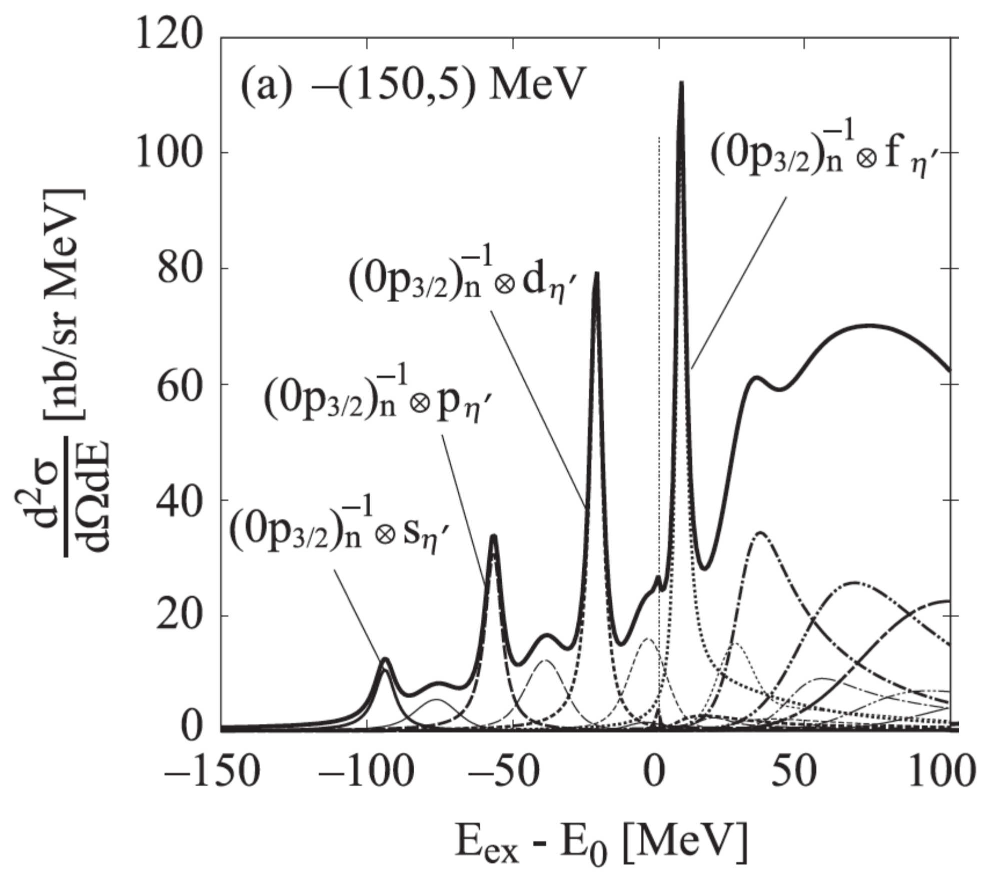
recoilless production in $^{12}C(p,d)$ reaction

PRiME collaboration (2012)

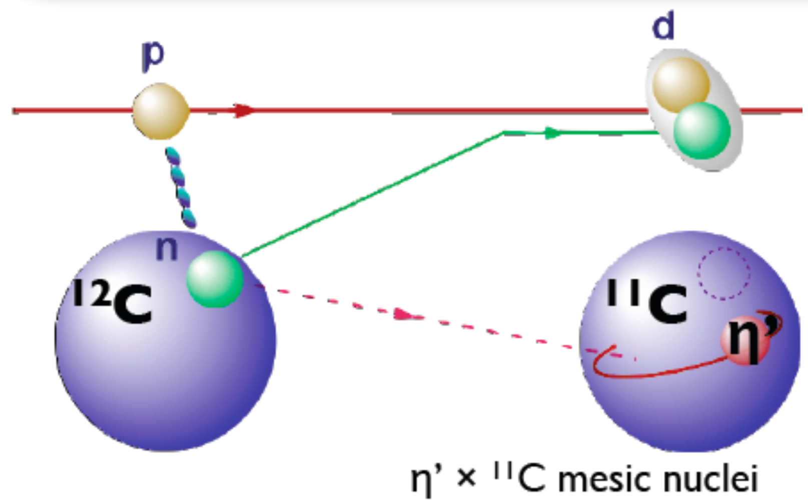
K. Itahashi et al., Exp. S 437

theoretical expectation

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



Search for η' nucleus bound states in $^{12}C(p,d)\eta' X$



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

PRiME collaboration (2012)

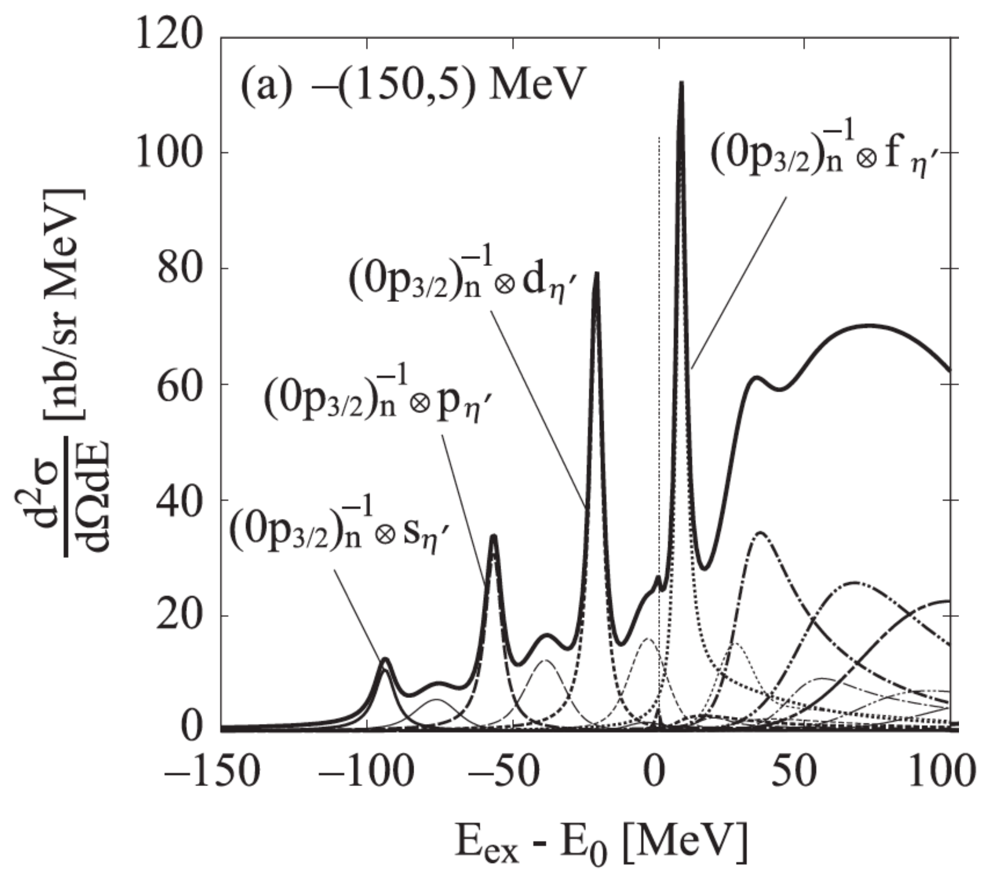
K. Itahashi et al., Exp. S 437

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

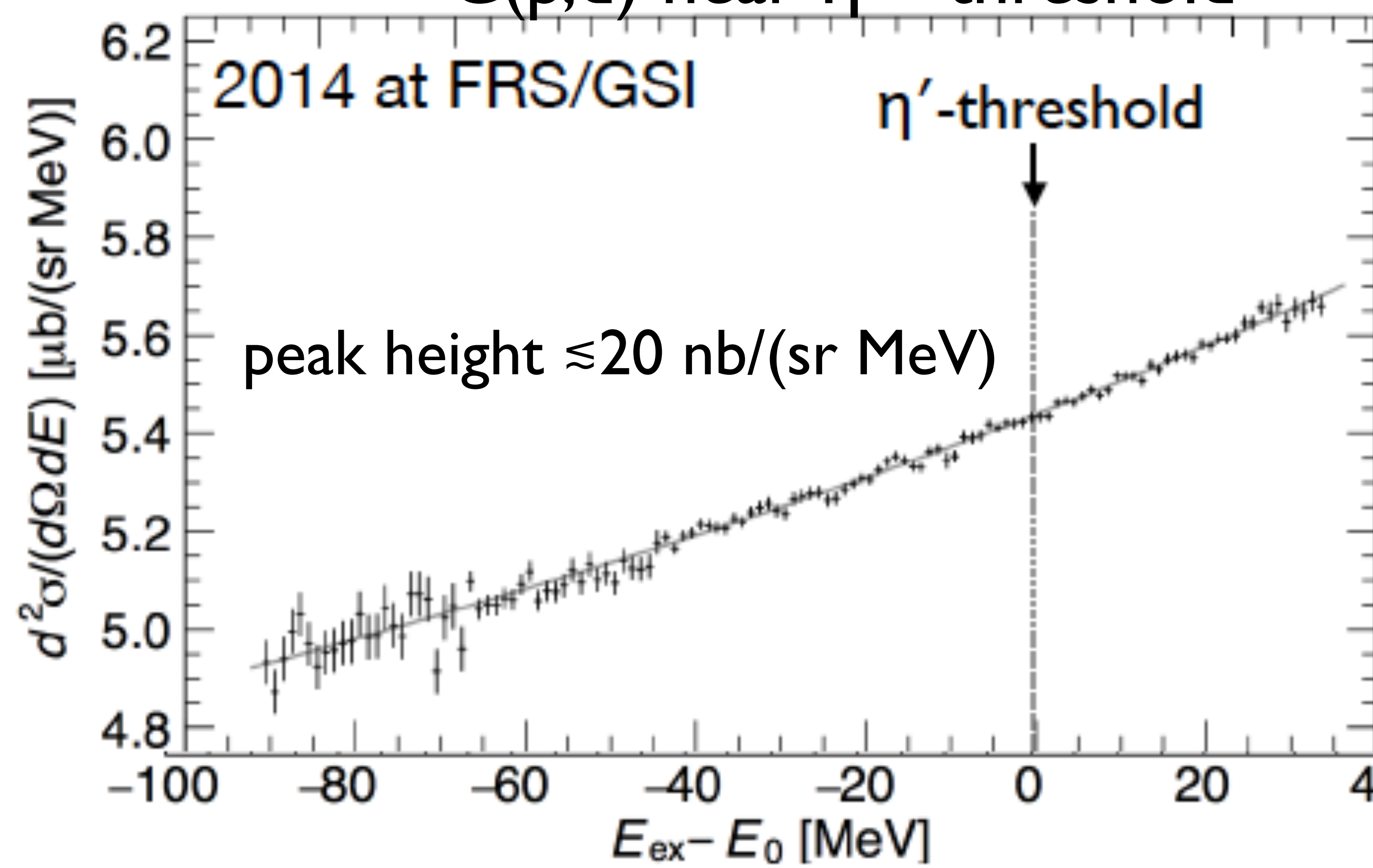
Y.K. Tanka et al., arXiv:1705.10543 (2017)

theoretical expectation

H. Nagahiro et al., PRC 87(2013) 04520



$^{12}C(p,d)$ near η' - threshold

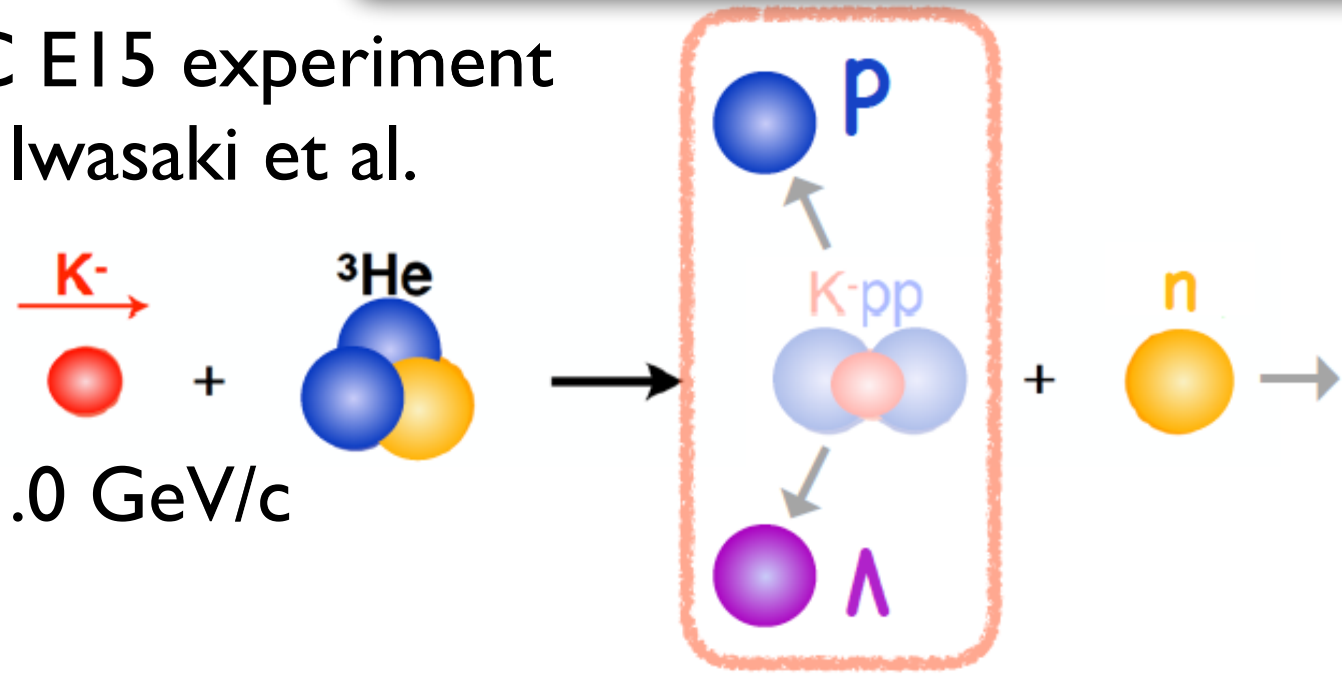


high statistical sensitivity sets constraints on η'-^{11}C interaction: $|V_0| < 100$ MeV

improved experiment detecting formation and decay of mesic state in preparation

Search for K^-pp clusters

J-PARC E15 experiment
M. Iwasaki et al.



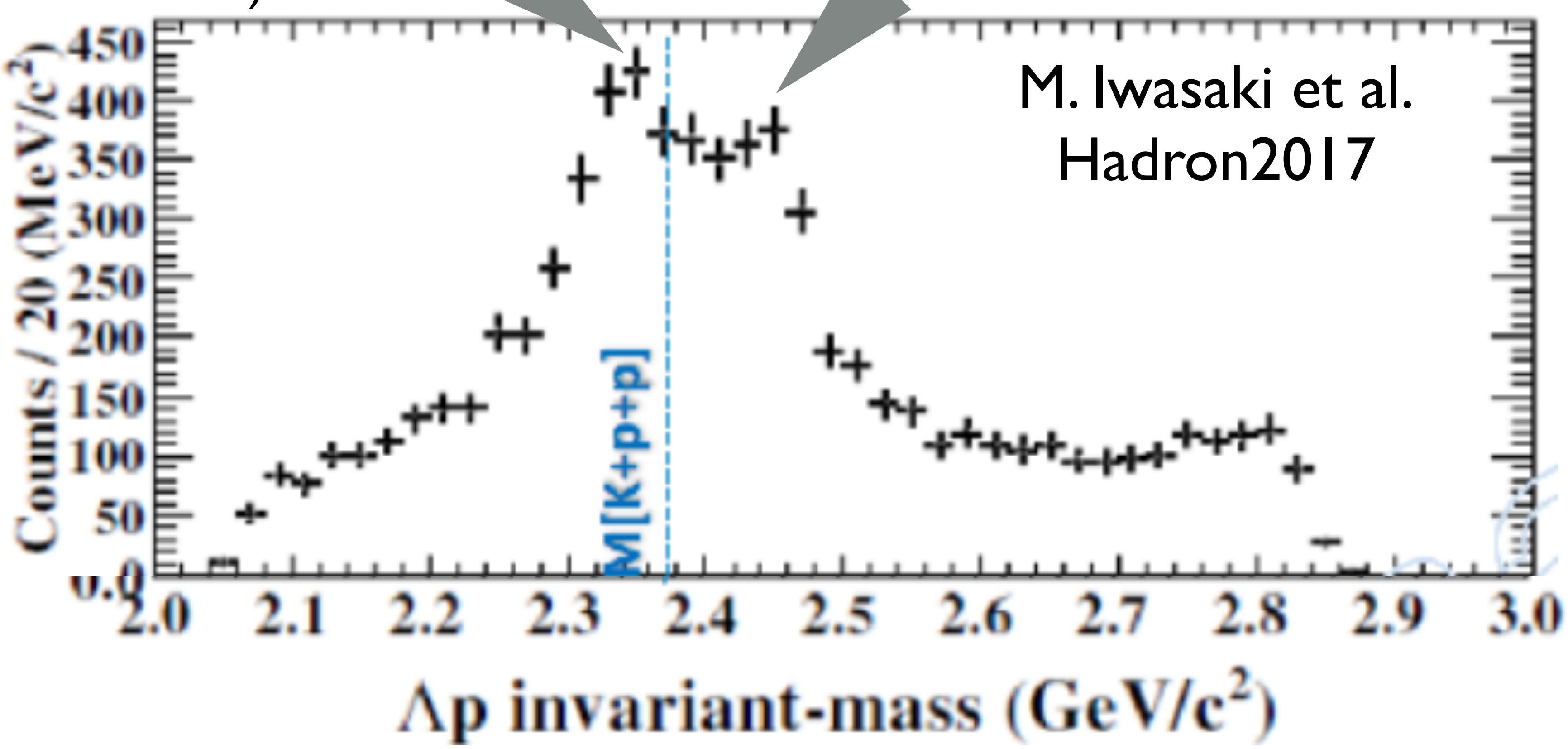
p_{K^-} = 1.0 GeV/c

strategy:
detect Λp pairs from K^-pp decay in coincidence with forward-going neutron

2 reaction mechanisms:

K^-pp bound state formed decaying into Λp (BE≈15 MeV)

quasi-free Λ(1405) production without forming bound state



two-peak structure in Λp invariant mass predicted by T. Sekihara et al., PTEP 2016 (2016)123D03

Summary and conclusions

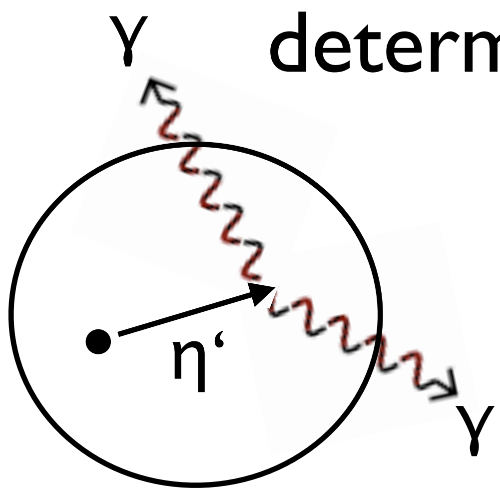
- mesons do change their properties in the nuclear medium as predicted by chiral model calculations: $m_{K+,K0}$ ↗; m_{K^-} ↘; $m_{\eta'}$ ↘
- meson-nucleus interaction described by complex potential

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

- 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 ($|V_0| \gg |W_0|$) for observing meson-nucleus quasi-bound states: promising candidate: η, η'
- pilot experiment searching for η' mesic states provides only upper limits; more sensitive semi-exclusive experiment in preparation
- evidence for existence of K^-pp cluster

backup slides

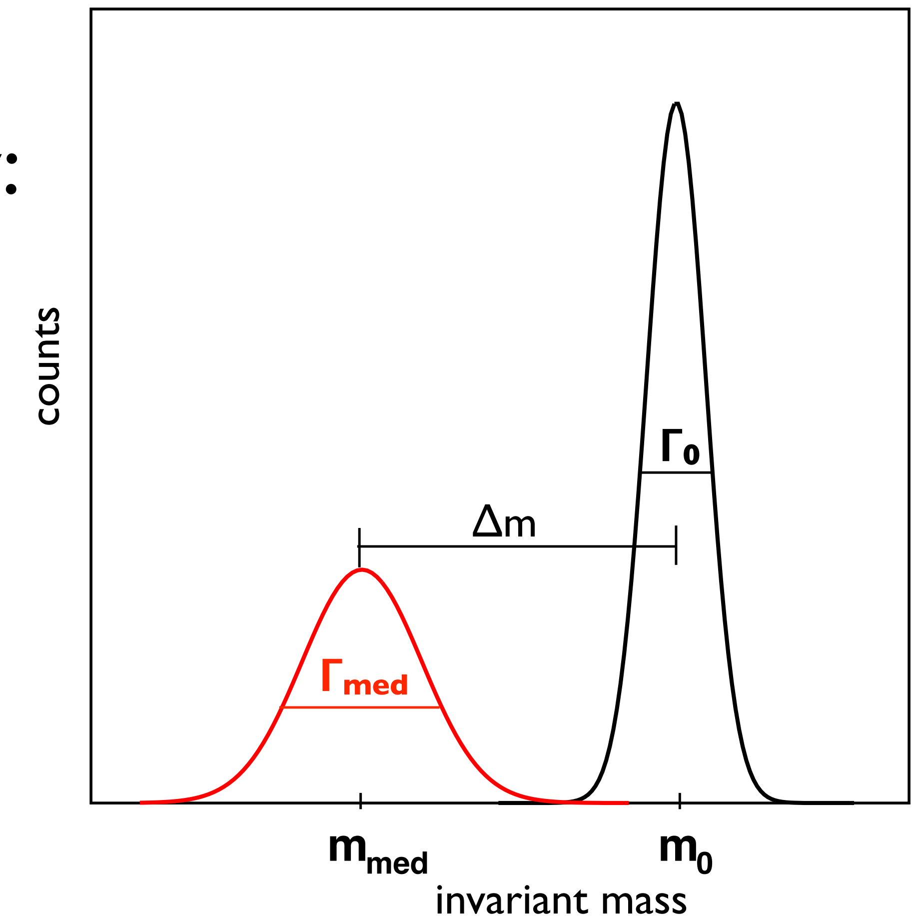
line shape analysis??



determine mass from in-medium decay:

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

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



probability for decay:

$$\frac{dP_{decay}}{dl} = \frac{mc}{p} \cdot \frac{1}{\hbar c} \cdot \Gamma_{decay} = 2.2 \cdot 10^{-5}\,/\text{fm}$$

$$\left(\text{for } \frac{mc}{p} \approx 1.0\right)$$

$$\Gamma_{\eta' \rightarrow \gamma\gamma} = 4.3 \cdot 10^{-3}\ \text{MeV}$$

probability for absorption:

$$\frac{dP_{abs}}{dl} = \sigma_{abs} \cdot \rho(r) = 0.22/\text{fm at } \rho=\rho_0$$

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

$$\frac{P_{decay}}{P_{abs}} = 10^{-4}$$

10 000 times more likely to get absorbed than to decay

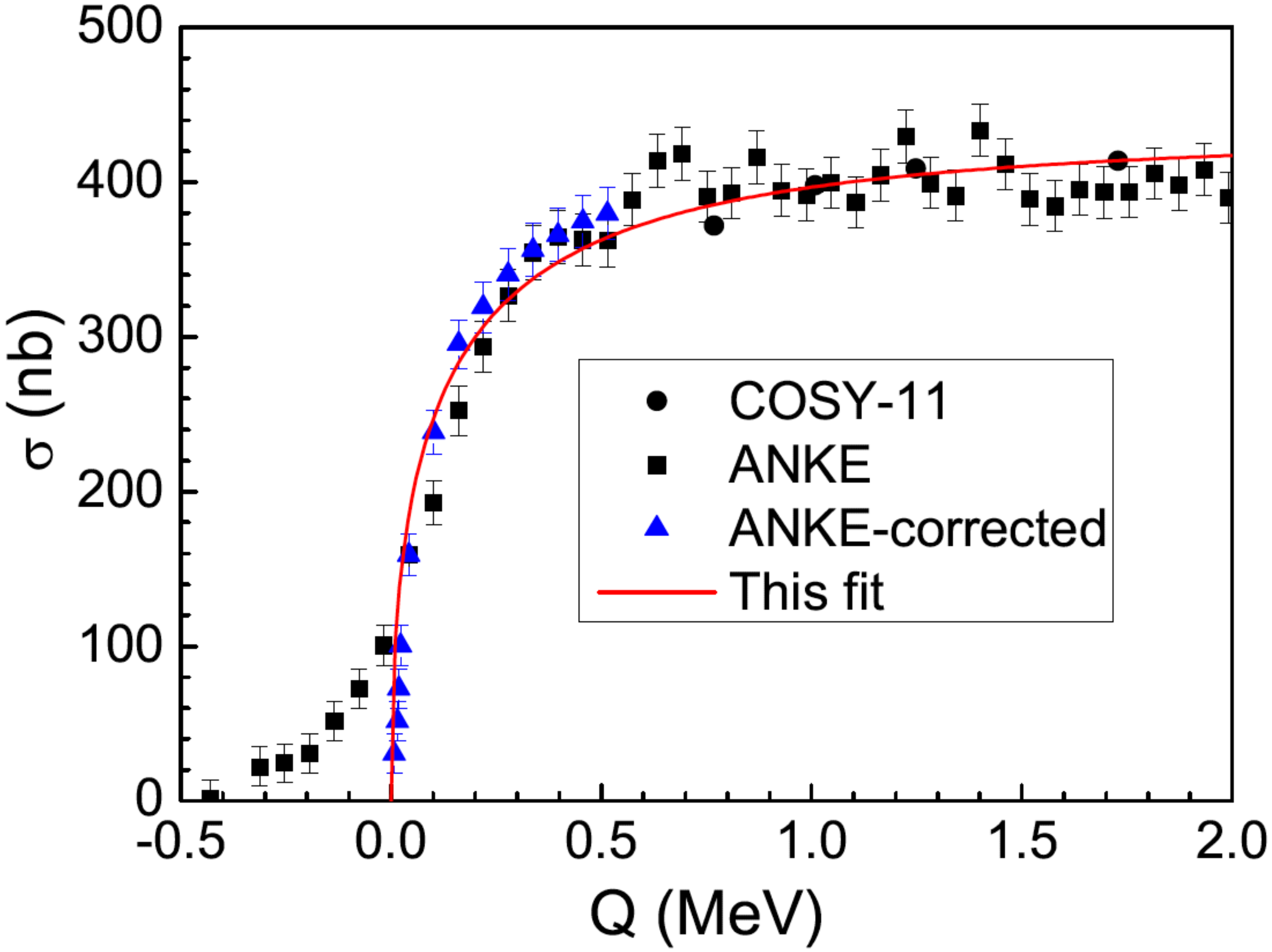
more favourable decay/absorption ratio only at lower densities near the surface where in-medium modifications are reduced

sensitive to nuclear density at decay point

real and imaginary part of the η-nucleus potential

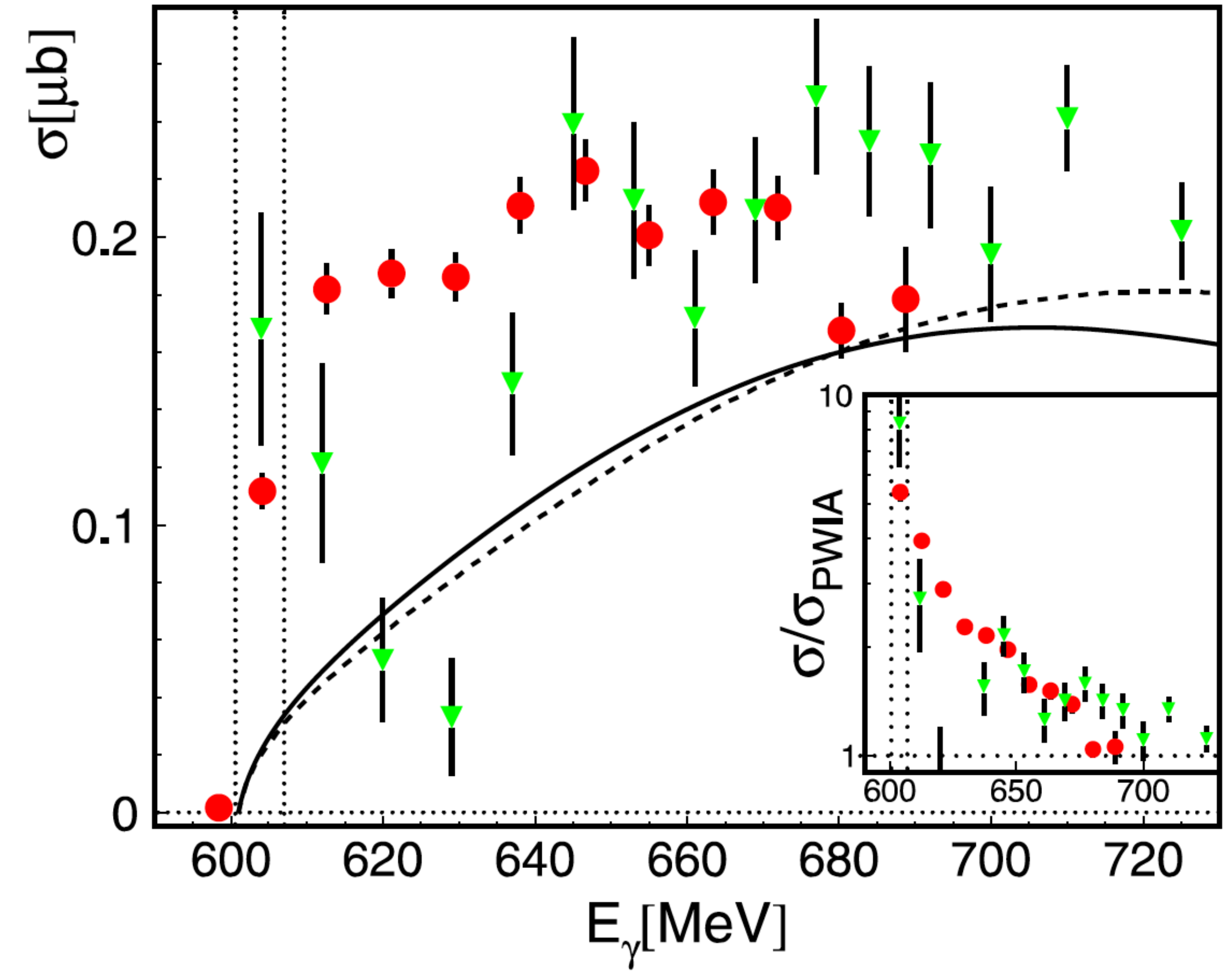
$p+d \rightarrow \eta+{}^3He$

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. PRC 95 (2017) 015202: BW structure at mass = -0.3 MeV; Γ = 3 MeV

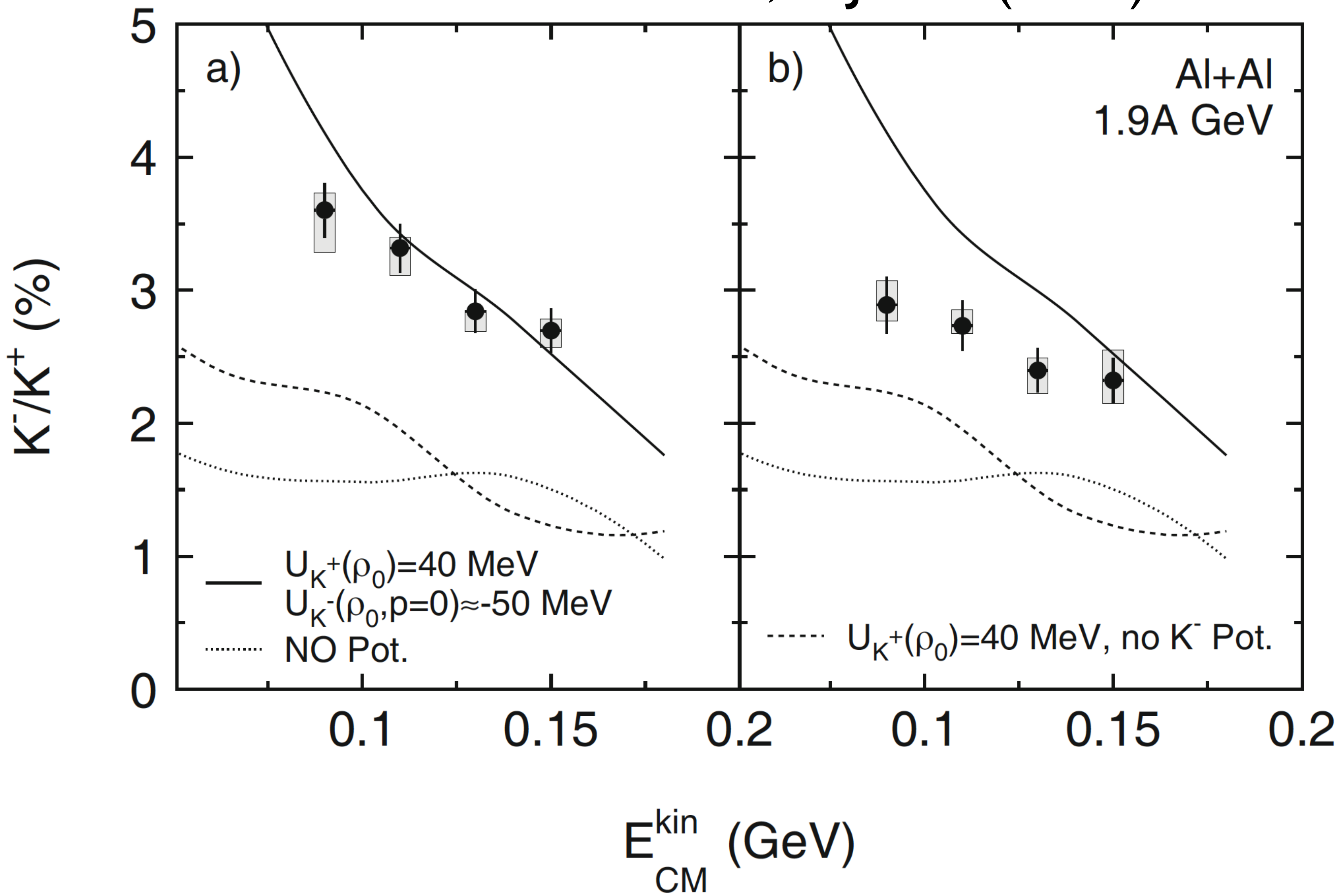
V_0 = -(54±6) MeV; W_0 = -(20±2) MeV

⇒ talks by A. Gal, E. Oset and S. Hirenzaki, M. Skurzok (WASA)

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

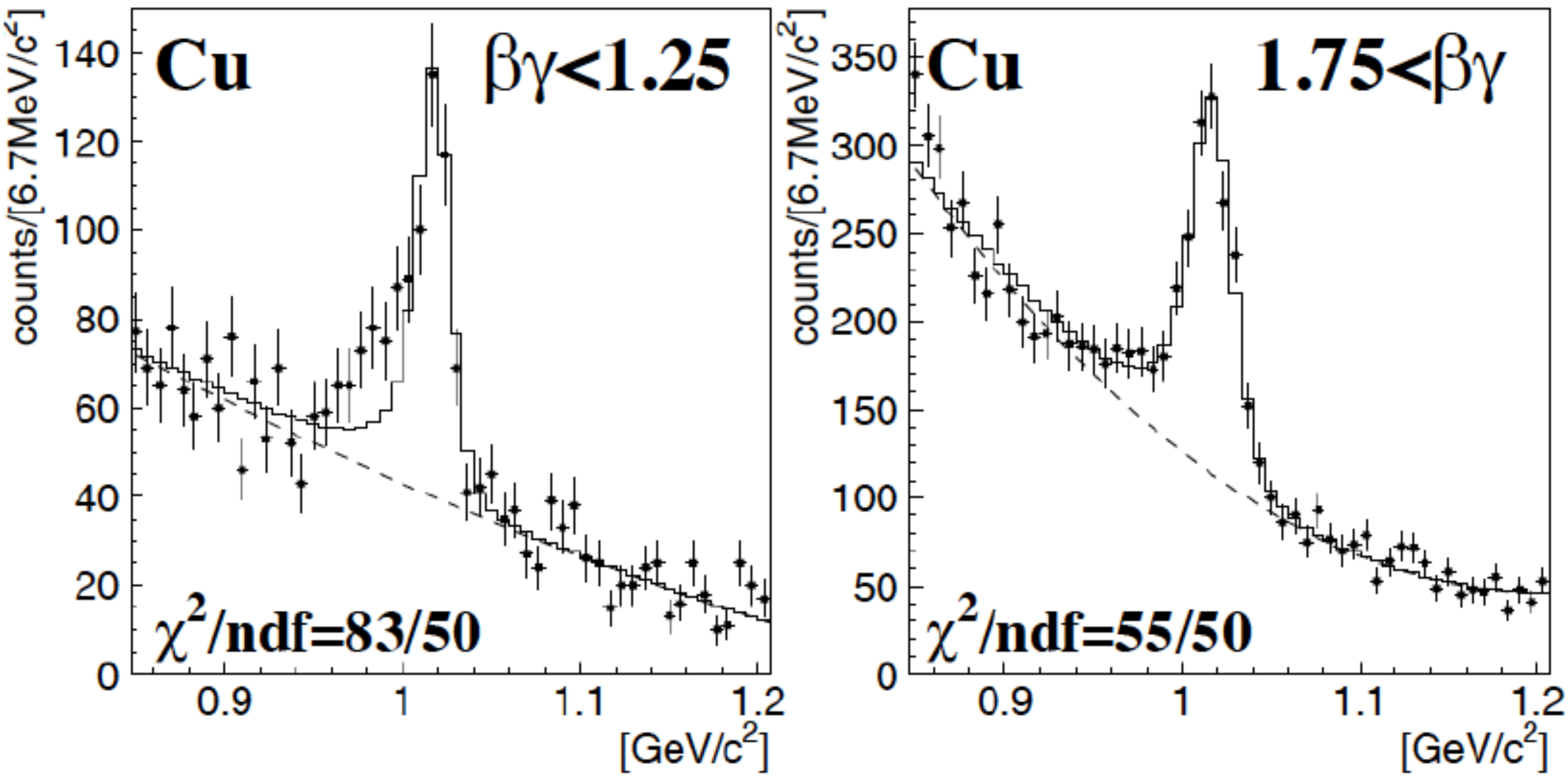
Φ/K⁻-ratio = 0.36±0.05 Ni+Ni at 1.9 AGeV (FOPI)
Φ/K⁻-ratio = 0.52±0.16 Au+Au at 1.23 AGeV (HADES)
} not reproduced in transport calculations

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

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 (βγ < 1.25) Φ mesons

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

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

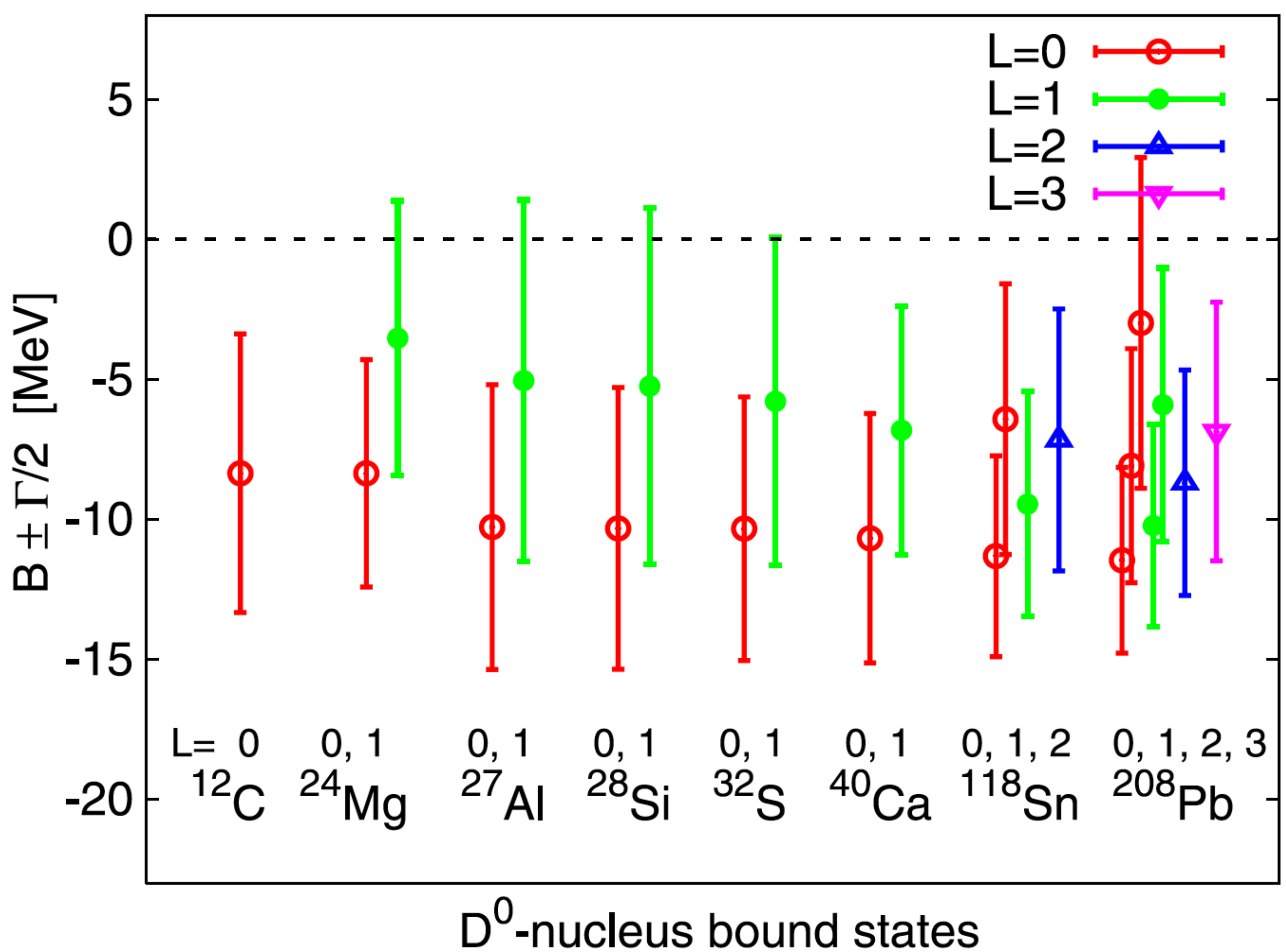
general experimental problem:

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 $\bar{p}\,p \to X\,Y$ 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 !!)



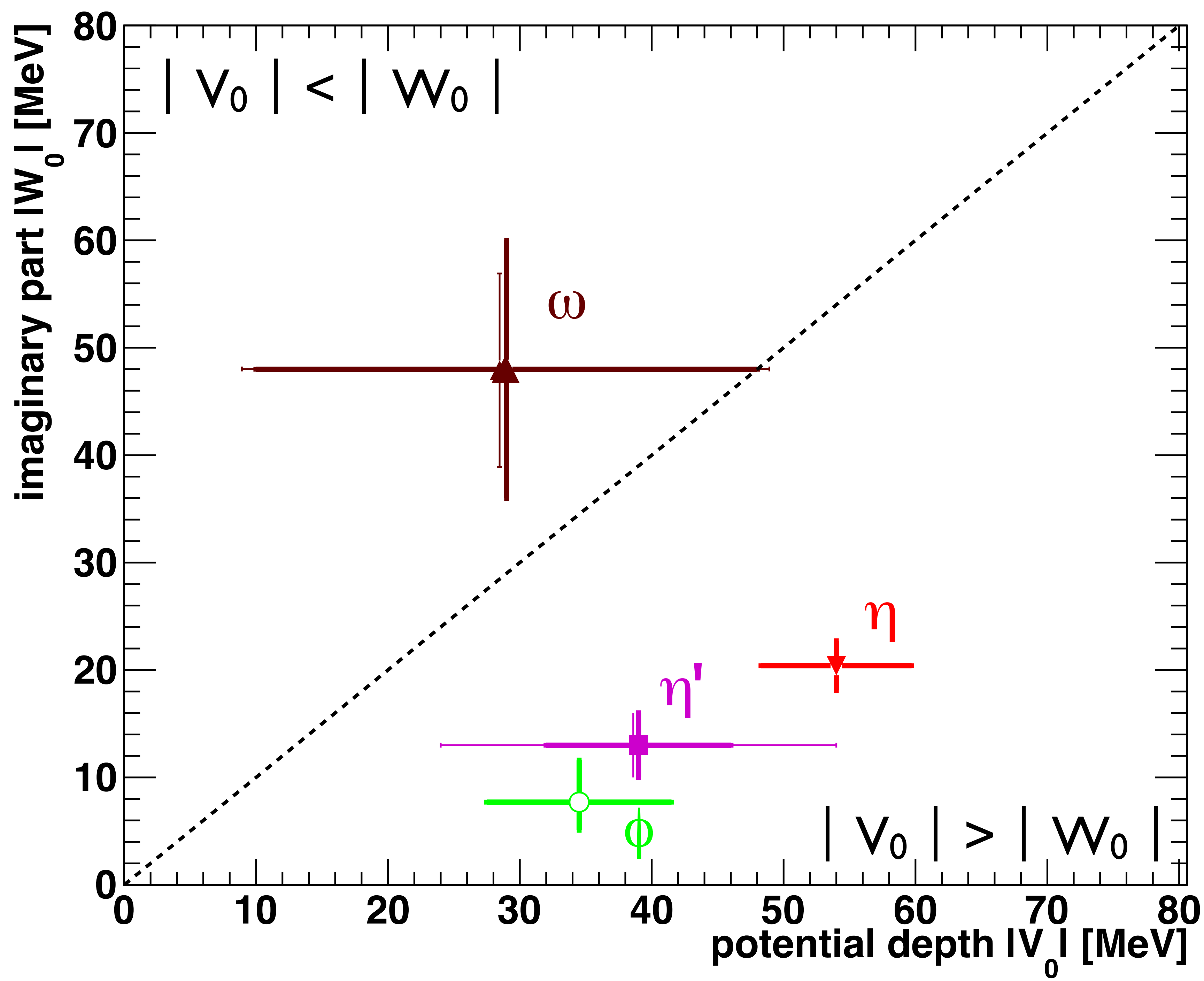
more favourable:
two step production

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

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

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

real vs. imaginary part of the meson-nucleus potential



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

meson-nucleus quasi-bound states

most favourable candidates: η, η'