

The quest for chiral symmetry restoration: experimental determination of meson-nucleus potentials and the search for meson-nucleus bound states

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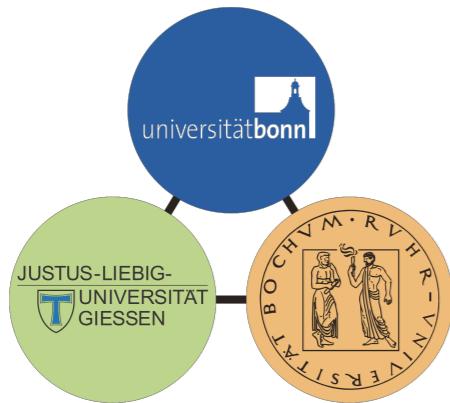


and

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*funded by the DFG within SFB/TR16



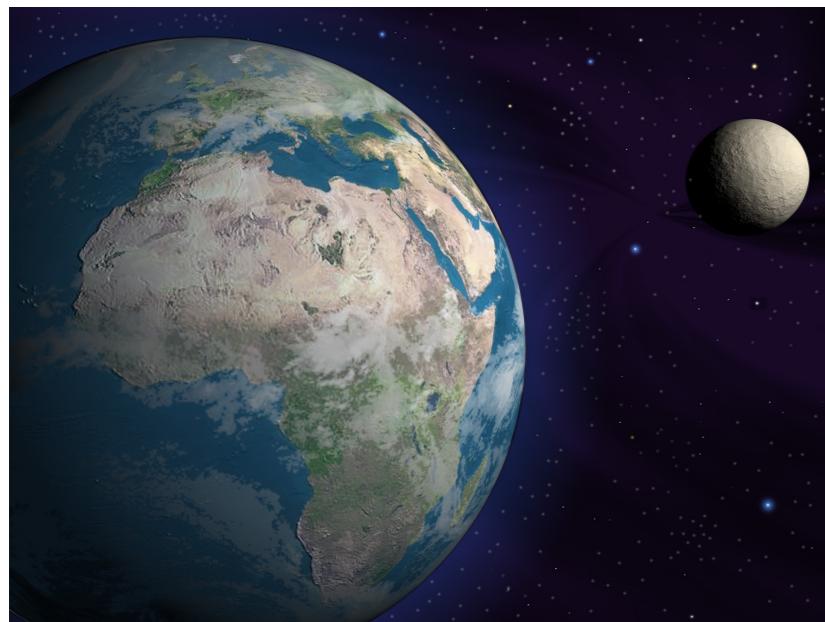
Humboldt Kolleg
Discoveries and Open Puzzles
in Particle Physics and Gravitation
23.6.-28.6.2019; Kitzbühel, Austria

HIC | FAIR
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Bound systems

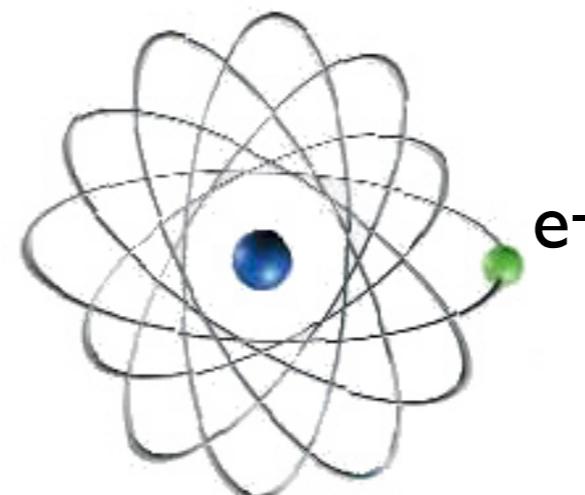
bound by

gravitation

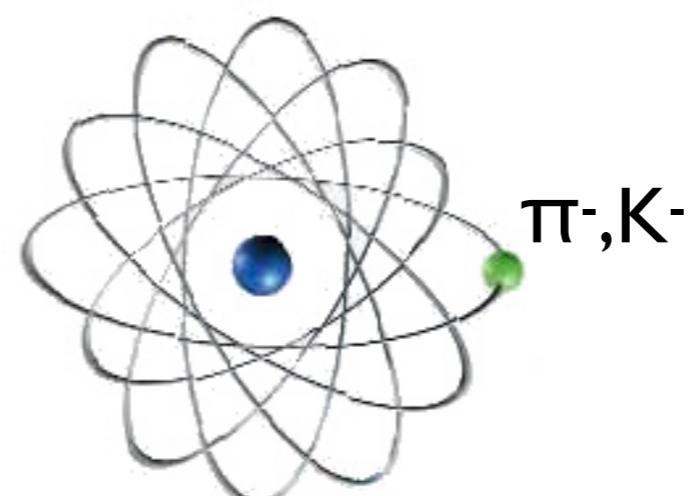


earth-moon system

electromagnetic interaction

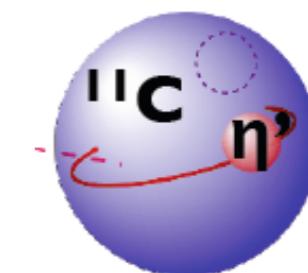


atom

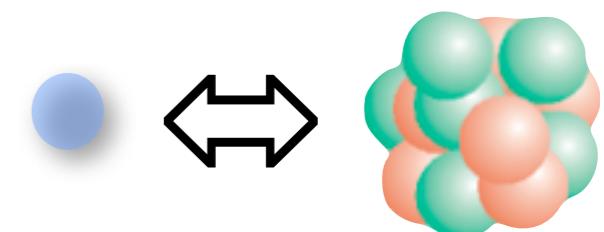


π^-, K^- - atoms

strong interaction



η' mesic state

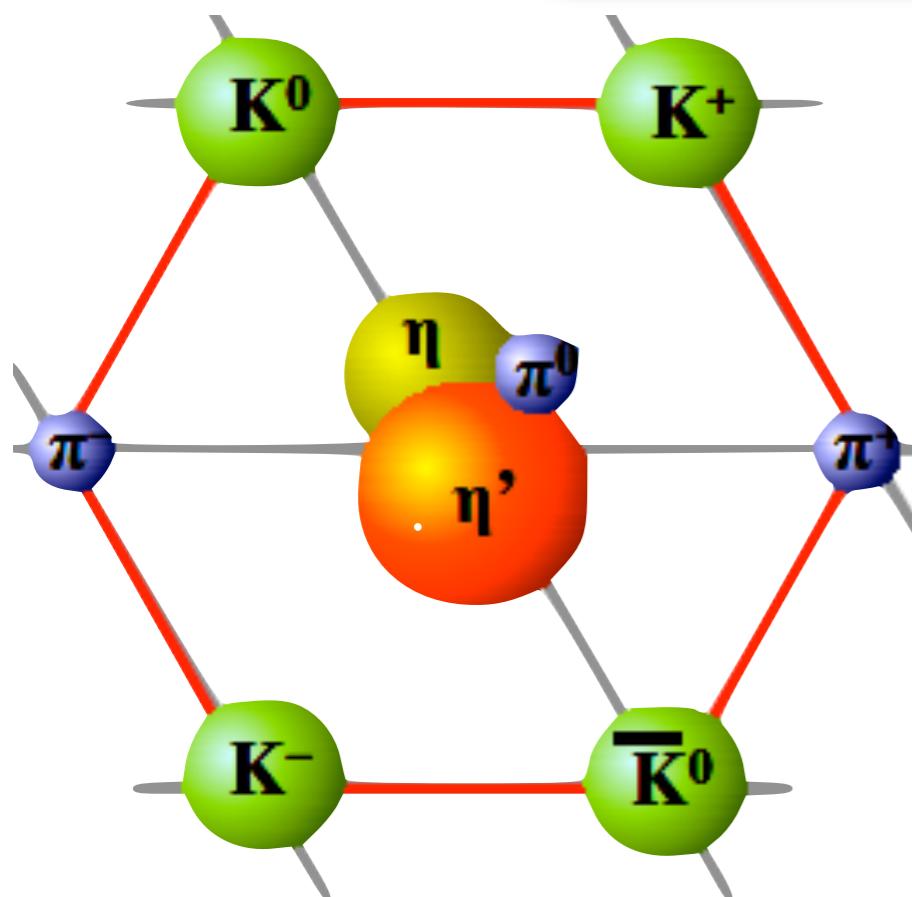


meson - nucleus
interaction
attractive?
repulsive?
→ meson-nucleus
potential

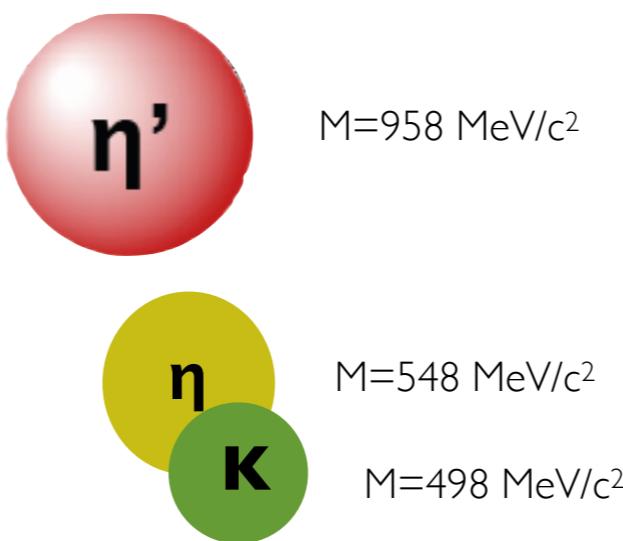
Outline

- ◆ introduction: meson-nucleus interactions
- ◆ methods for determining meson-nucleus potentials
- ◆ potential parameters for $K^+, K^0, K^-, \eta, \eta'\omega, \Phi$ - A interaction
- ◆ search for meson-nucleus bound states
- ◆ summary & outlook

Masses of pseudoscalar mesons



nonet of pseudoscalar mesons



η' has a surprisingly large mass:
 $m_\eta > m_p$



$M=140 \text{ MeV}/c^2$

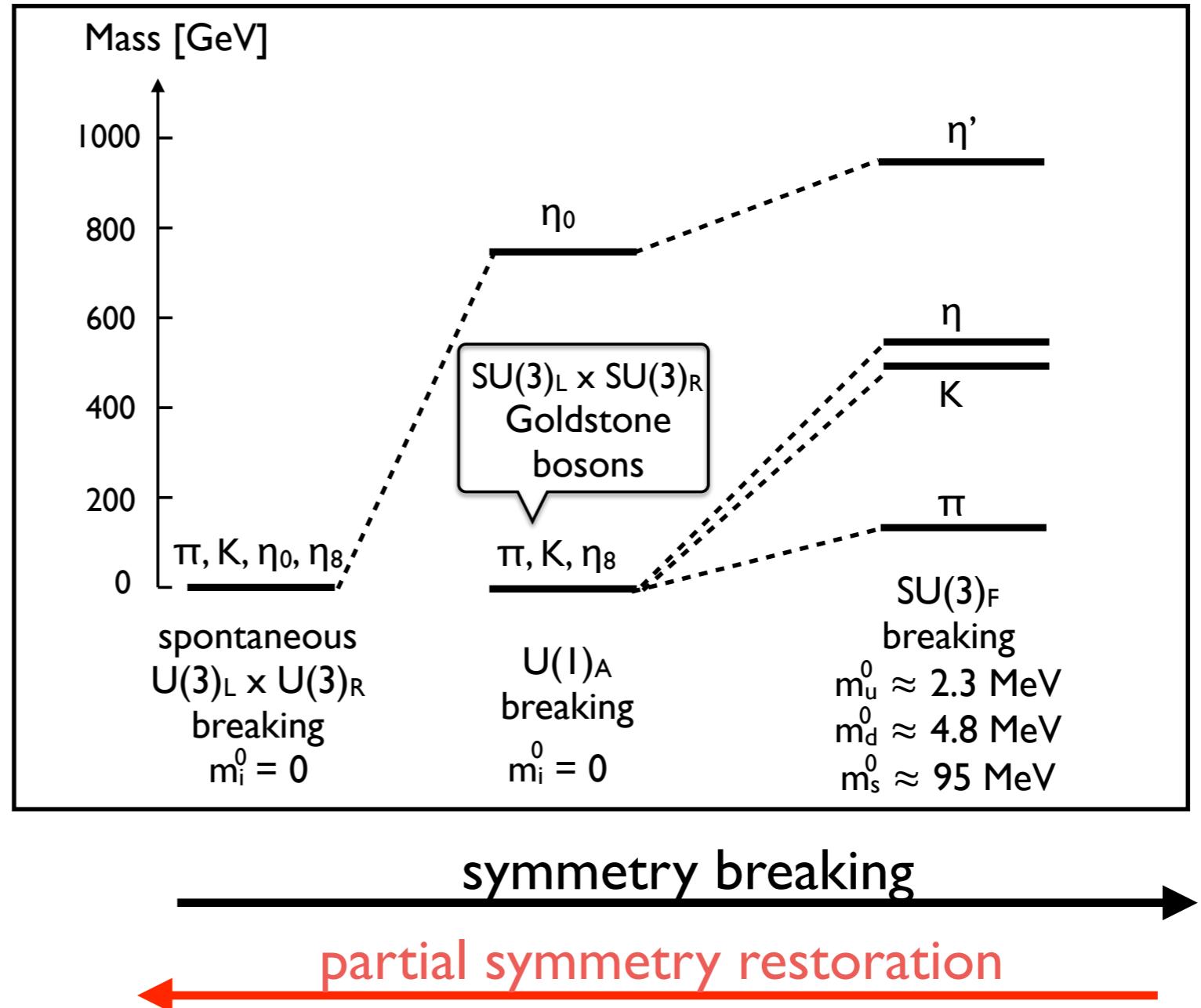
Chiral symmetry breaking in the hadronic sector

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 \Rightarrow impact on meson masses ??



S. D. Bass and P. Moskal (Rev. Mod. Phys. 91 (2019) 015003):

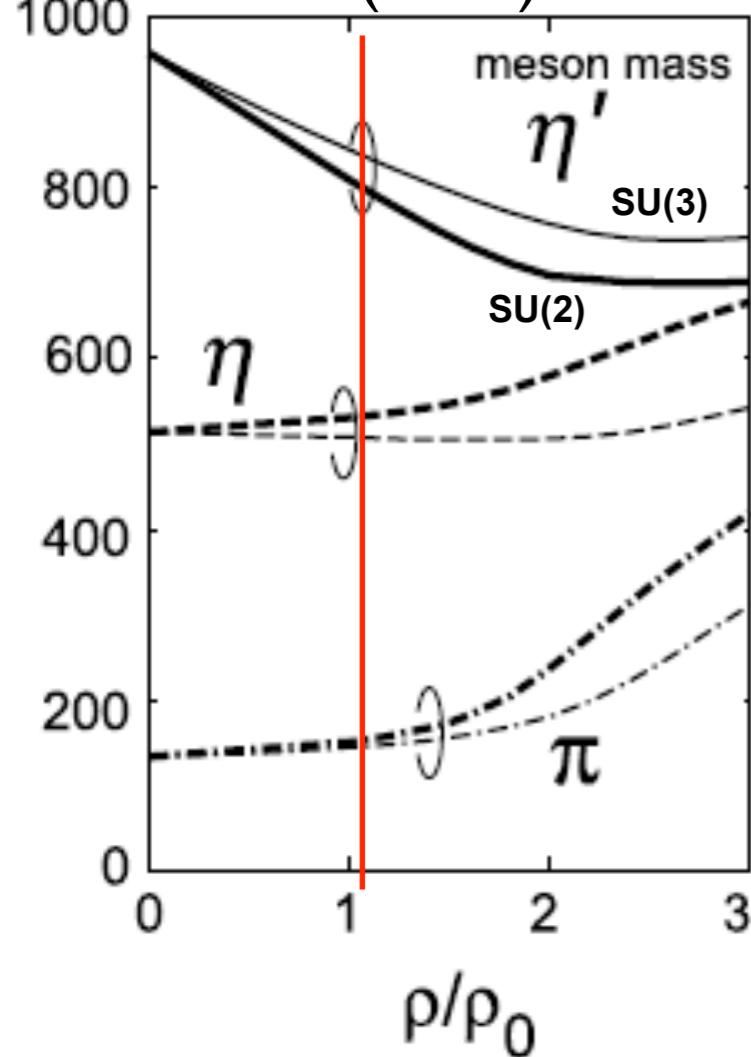
“the medium acts to partially neutralize axial $U(1)$ symmetry breaking by gluons effects”

Predictions for in-medium mass changes

η, η'

NJL-model

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



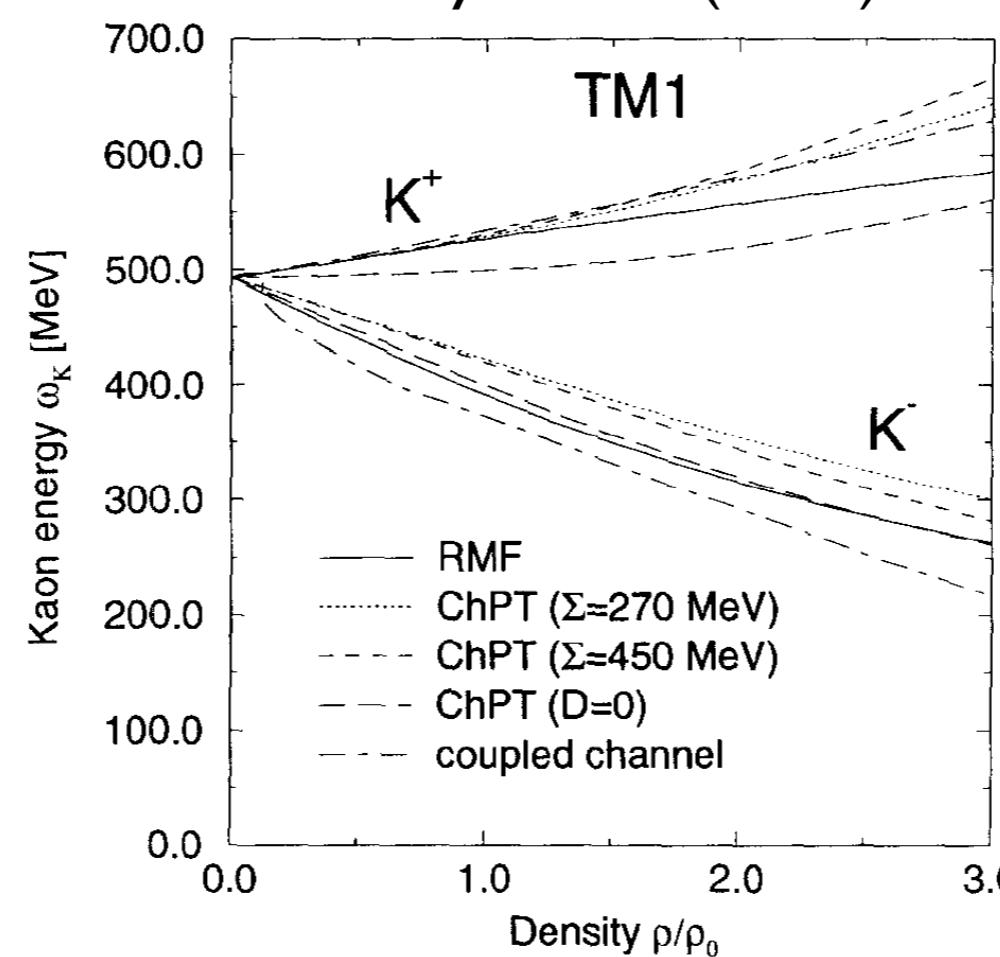
$$\begin{aligned}\Delta m_{\eta'}(\rho_0) &\approx -150 \text{ MeV} \\ \Delta m_\eta(\rho_0) &\approx +20 \text{ MeV} \\ \Delta m_\eta(\rho_0) &\approx -40 \text{ MeV}\end{aligned}$$

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

K^+, K^-

RMF-approach

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

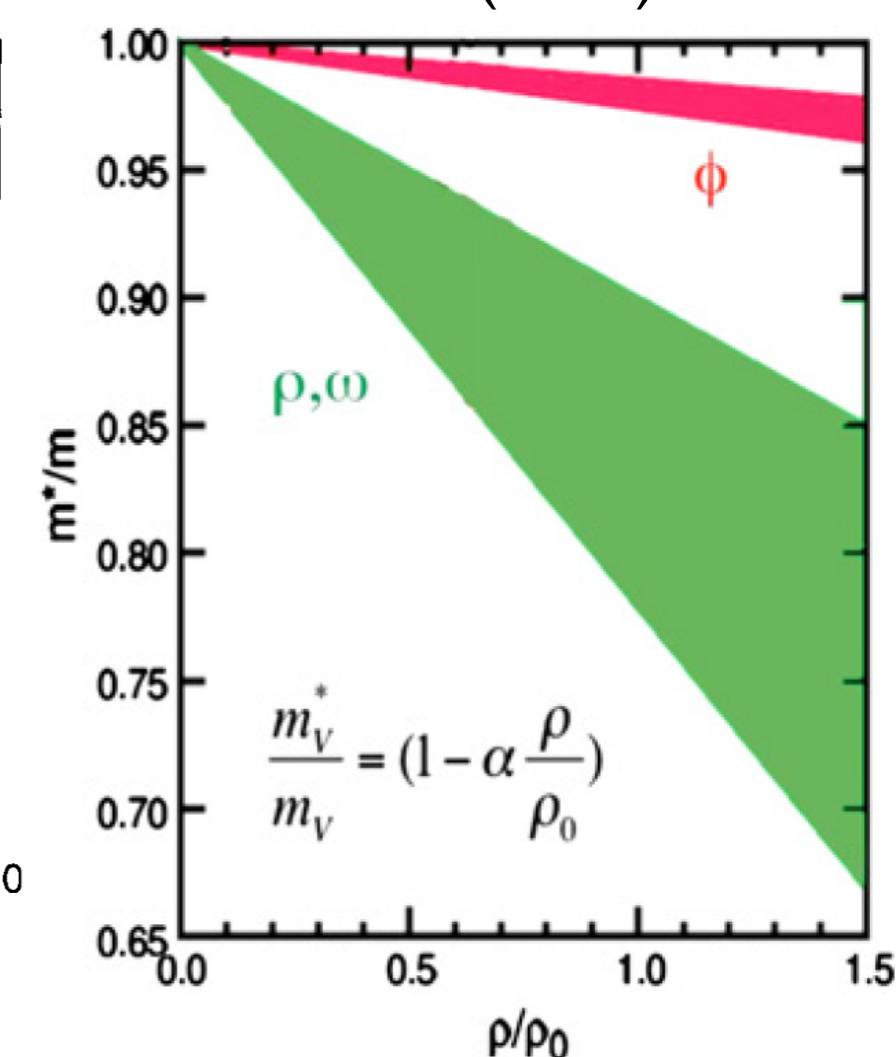


$$\begin{aligned}\Delta m_{K^+}(\rho_0) &\approx +30 \text{ MeV} \\ \Delta m_{K^-}(\rho_0) &\approx -100 \text{ MeV}\end{aligned}$$

ρ, ω, ϕ

QCD sum rules

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



$$\begin{aligned}\Delta m_\rho(\rho_0) &\approx - (80-160) \text{ MeV} \\ \Delta m_\omega(\rho_0) &\approx - (80-160) \text{ MeV} \\ \Delta m_\phi(\rho_0) &\approx - (20-30) \text{ MeV}\end{aligned}$$

Predictions for in-medium broadening by inelastic collisions

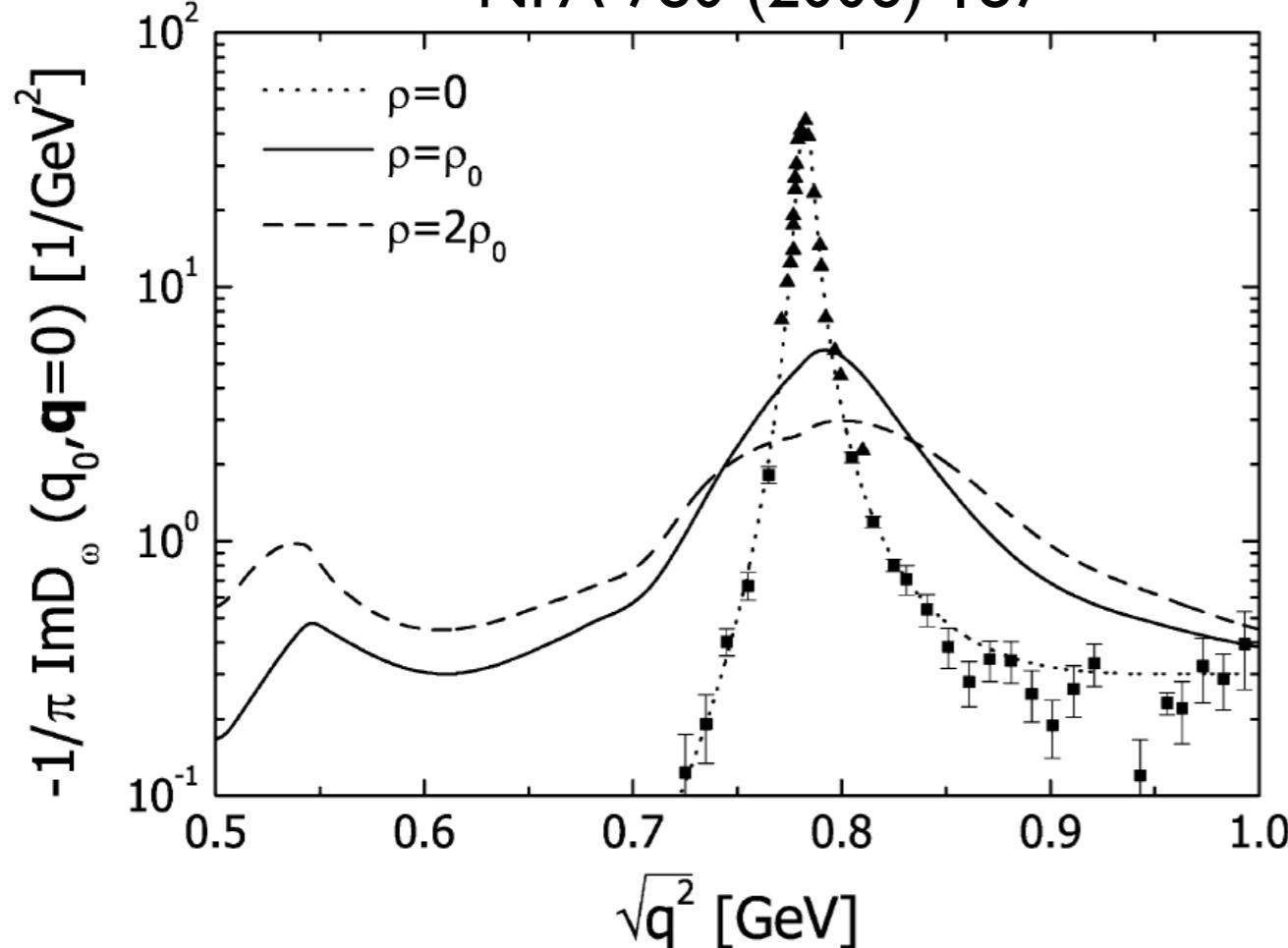


e.g. $\omega N \rightarrow \pi N$



unitary coupled channel
effective Lagrangian model

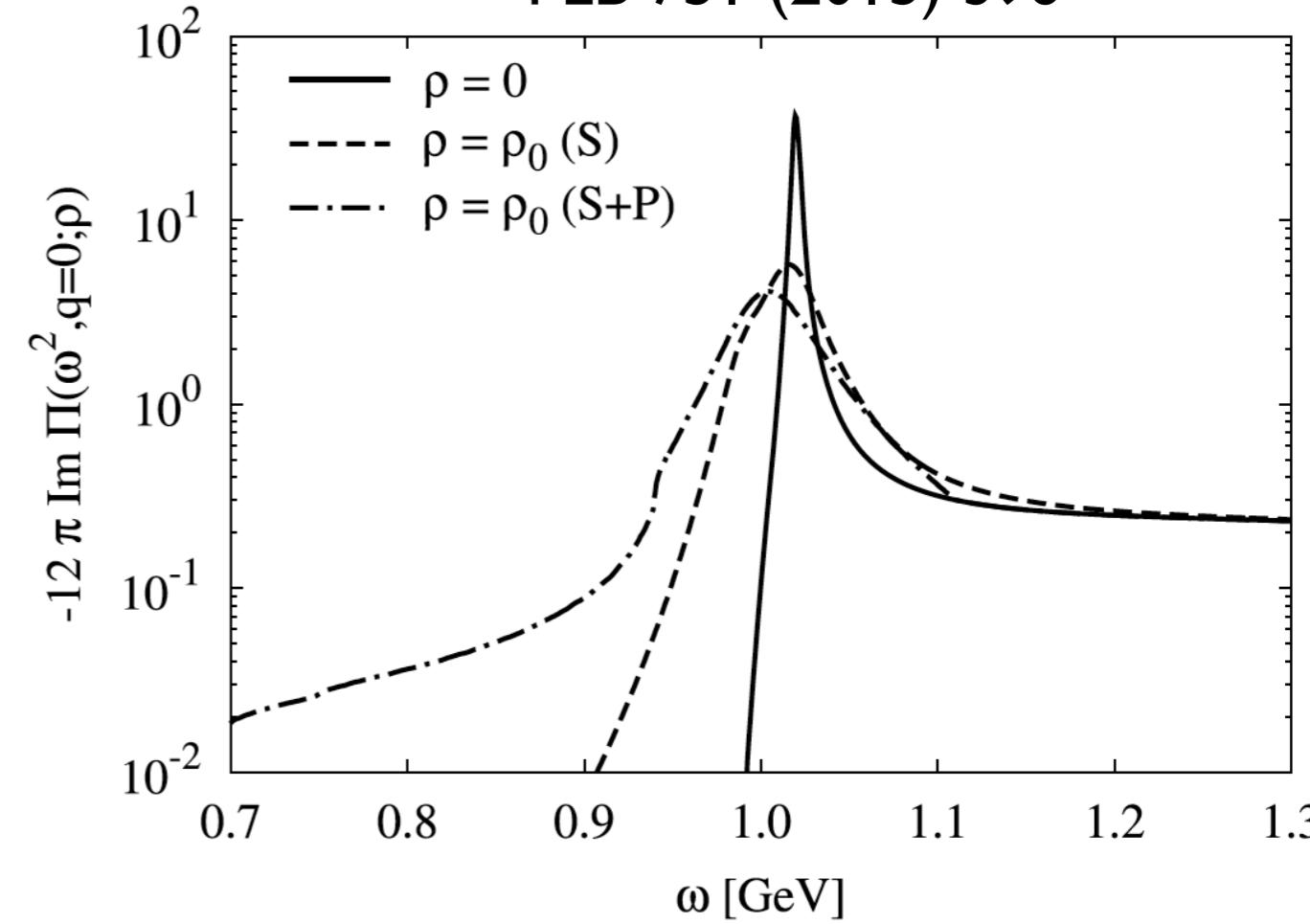
P. Mühlich et al.,
 NPA 780 (2006) 187



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

chiral-SU(3)
effective field theory

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



$$\Gamma_\phi(\rho=\rho_0) \approx 45 \text{ MeV}$$

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

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

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

- excitation function
- momentum distribution

- transparency ratio measurement

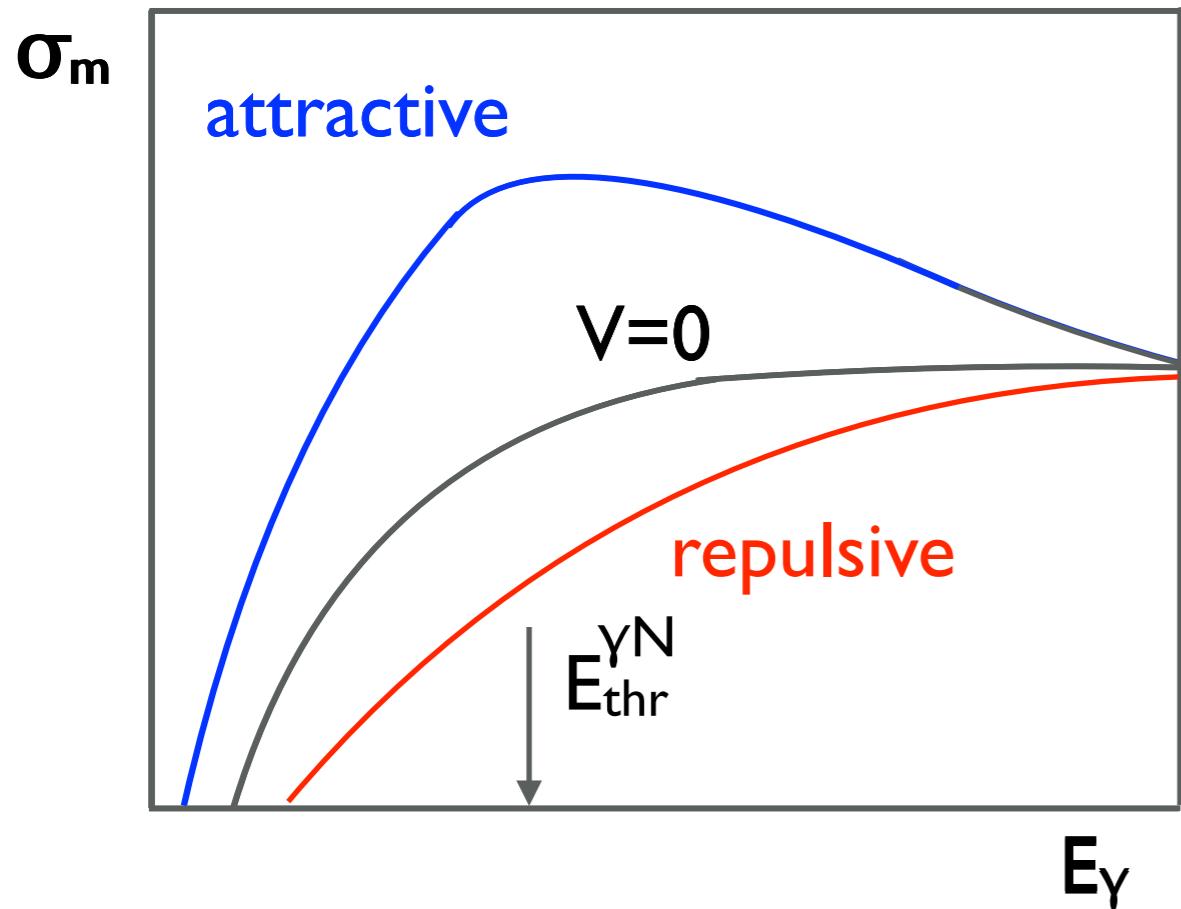
$$T_A = \frac{\sigma_{\gamma A \rightarrow \eta' X}}{A \cdot \sigma_{\gamma N \rightarrow \eta' X}}$$

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

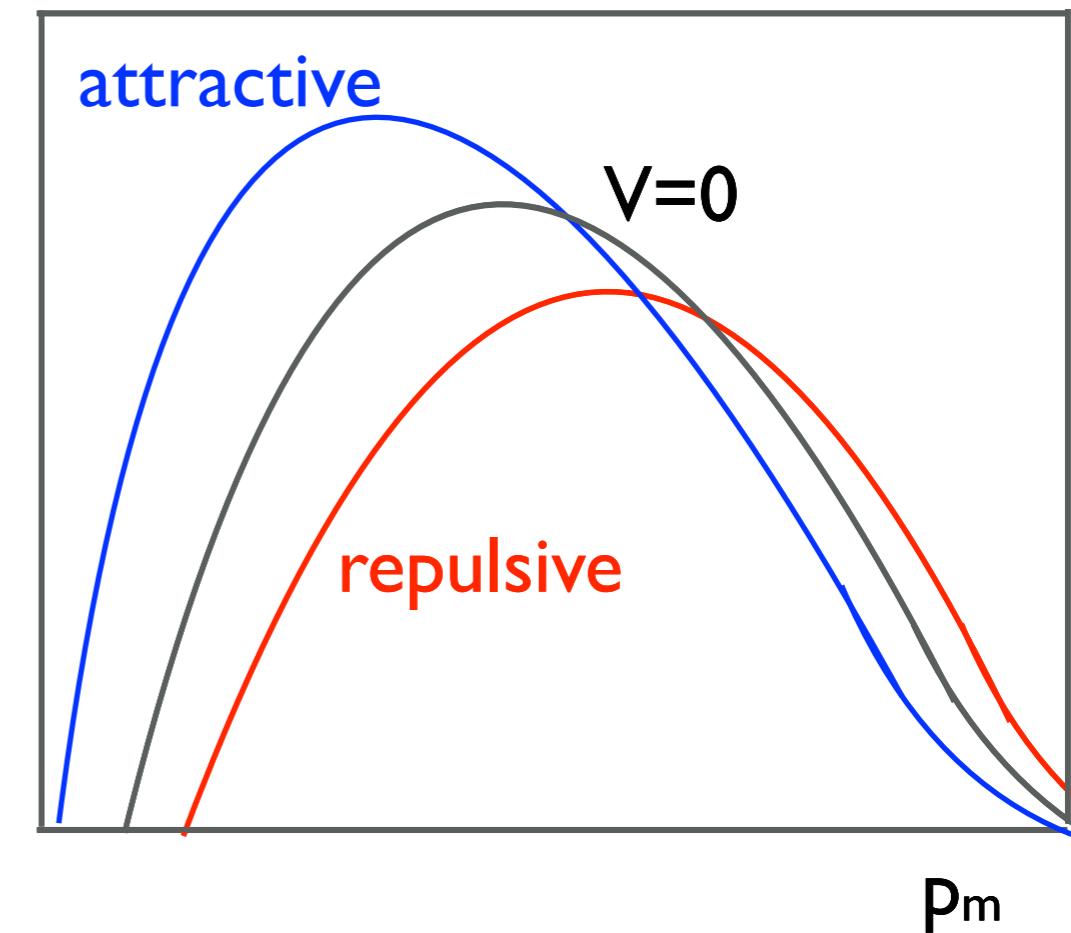
excitation function



attractive interaction \rightarrow mass drop \rightarrow
lower threshold \rightarrow larger phase space \rightarrow
larger cross section

repulsive interaction \rightarrow mass increase \rightarrow
higher threshold \rightarrow smaller phase space \rightarrow
smaller cross section

momentum distribution

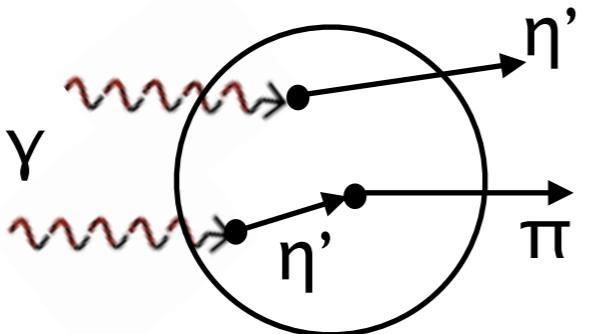


repulsive interaction \rightarrow extra kick \rightarrow
shift to higher momenta

attractive interaction \rightarrow
meson slowed down \rightarrow
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



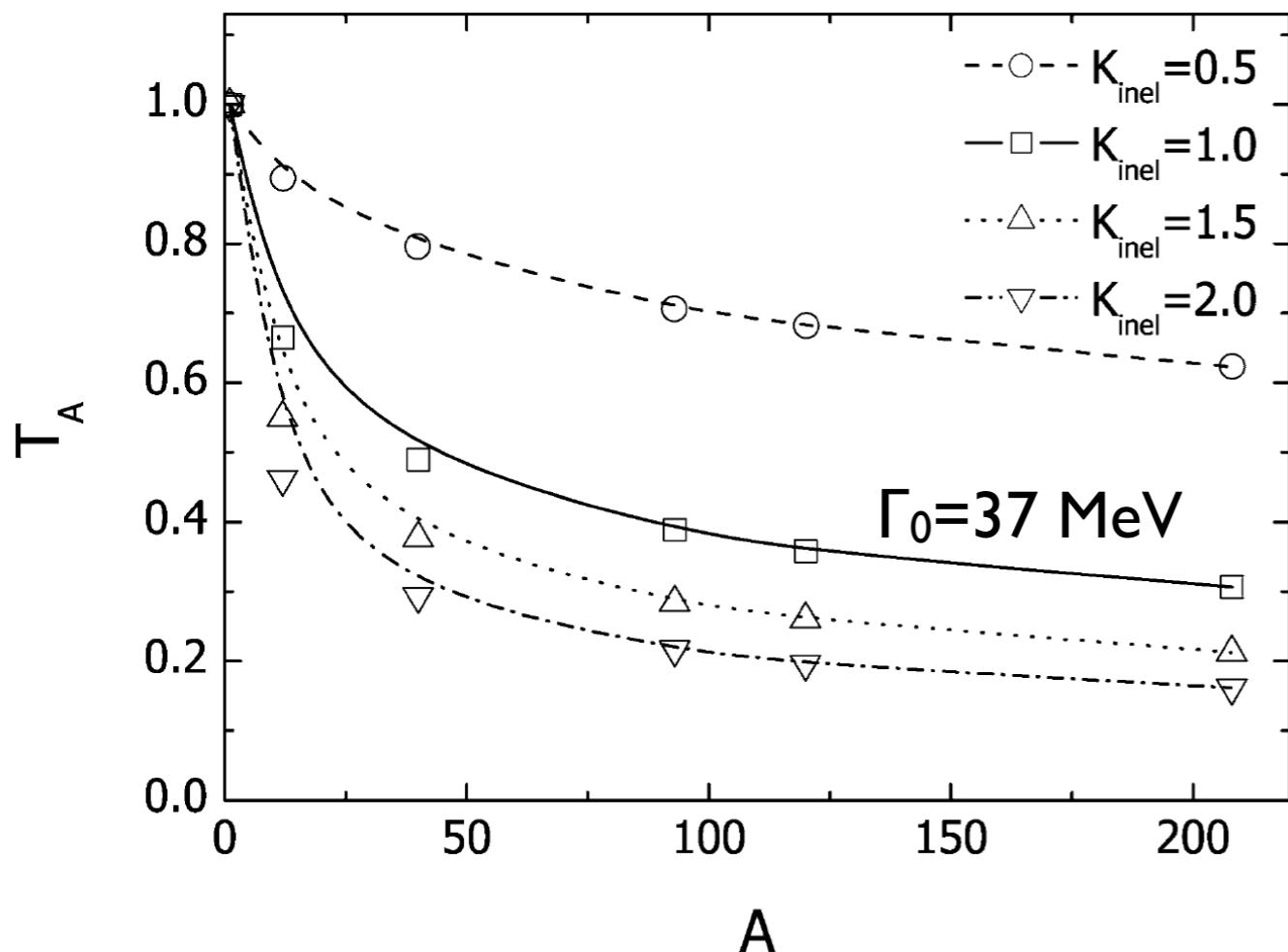
$$T_A = \frac{\sigma_{\gamma A \rightarrow \eta' X}}{A \cdot \sigma_{\gamma N \rightarrow \eta' X}}$$

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

transport model calculation: GiBUU

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

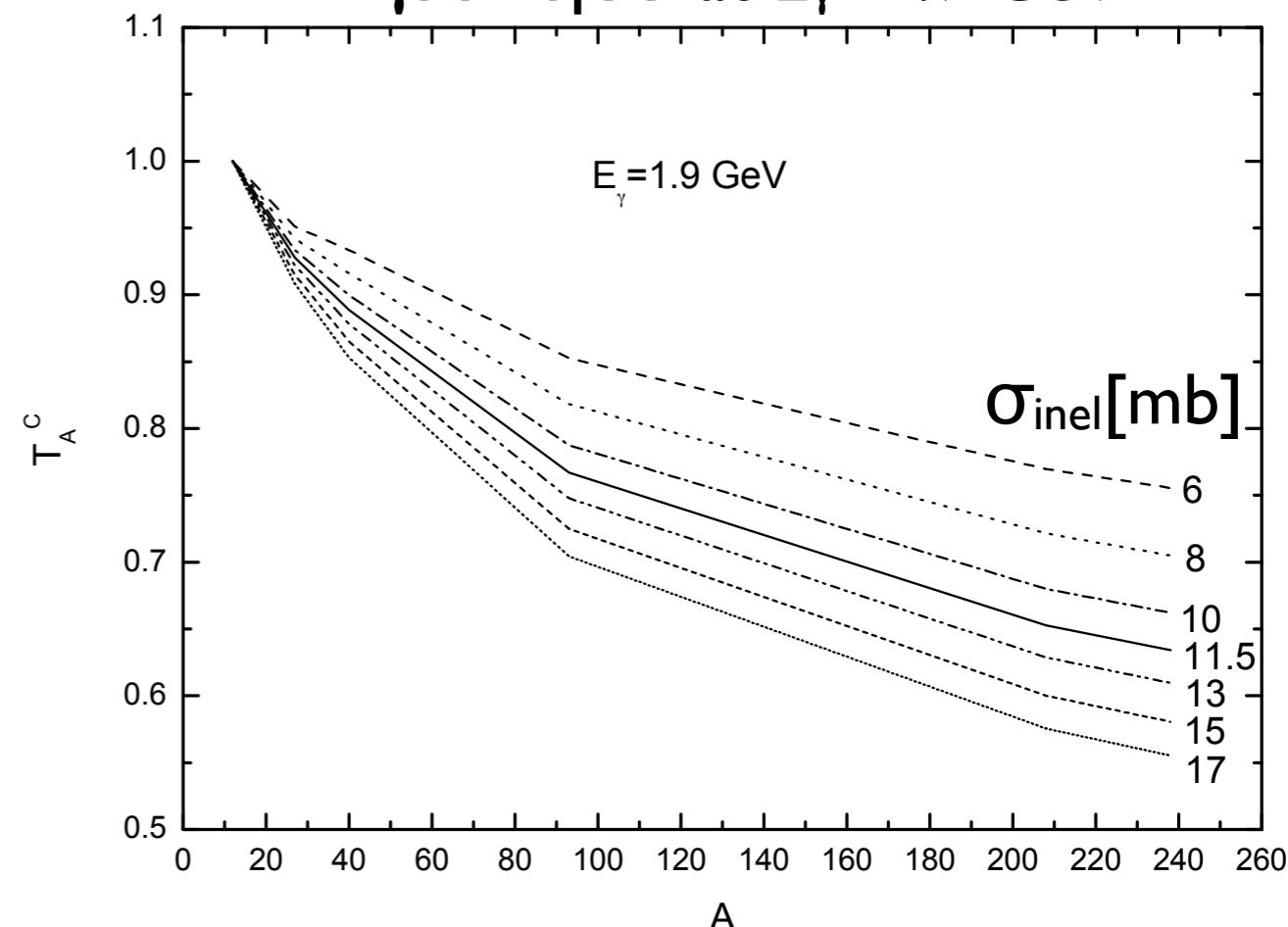
$\gamma A \rightarrow \omega X$ at $E_\gamma = 1.5$ GeV



collision model calculation

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

$\gamma A \rightarrow \eta' X$ at $E_\gamma = 1.9$ GeV



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

Strategy for determining potential parameters

real part of meson-nucleus potential

meson excitation functions and/or momentum distributions

→ comparison with transport / collision model calculations
for different sets of V_0 ;

$$\rightarrow V_0 = V(p=p_0)$$

imaginary part of meson-nucleus potential

transparency ratio $T_A(A,p)$

→ comparison with transport / collision model calculations
for different sets of $\Gamma_{\text{med}}, \sigma_{\text{inel}}$;

$$\rightarrow \Gamma_{\text{med}}, \sigma_{\text{inel}} \rightarrow W_0 = W(p=p_0; p=0)$$

$$U(p=p_0) = V_0 + iW_0$$

Review:

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

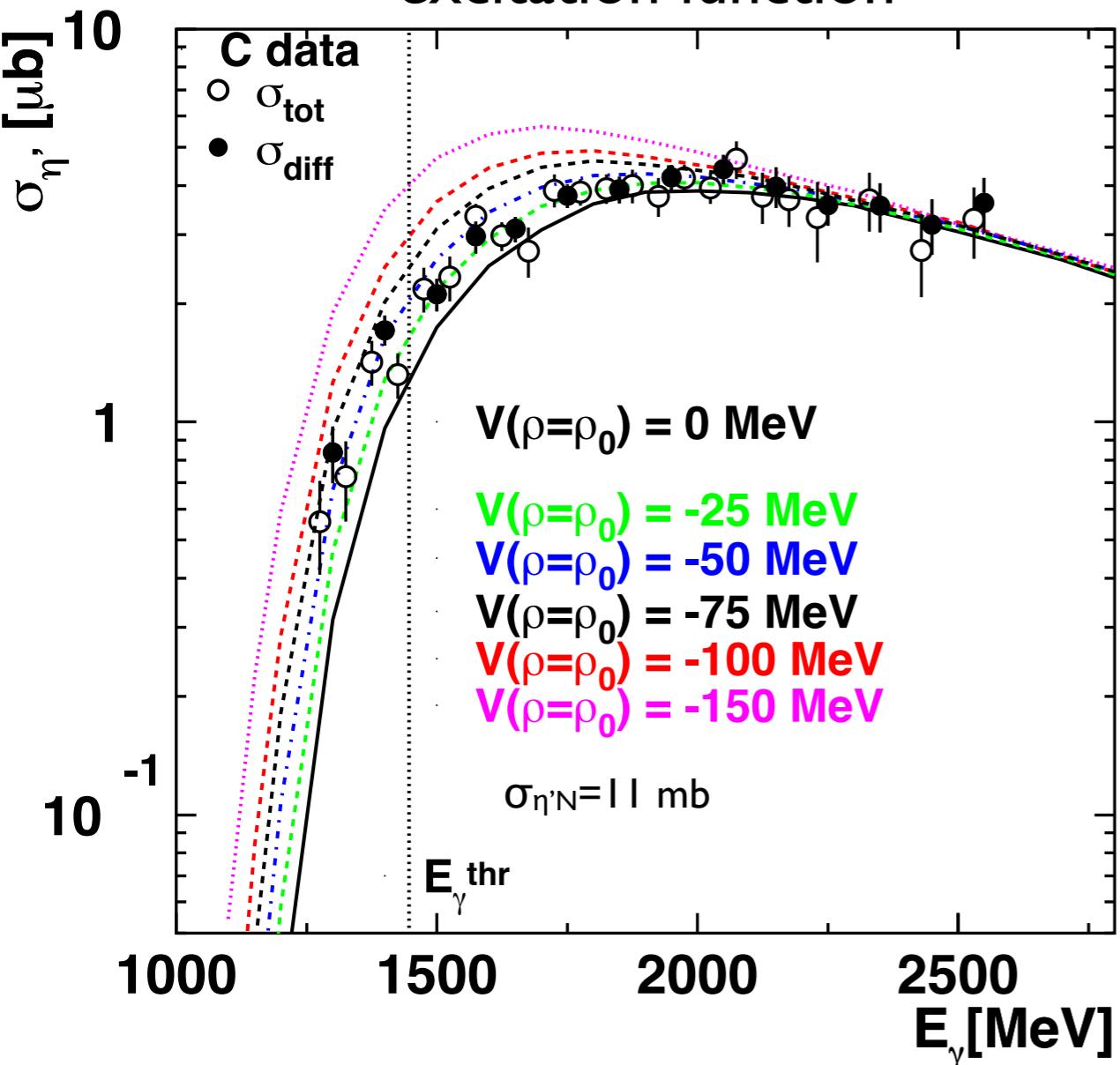
Excitation function and momentum distribution for η' photoproduction off C

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

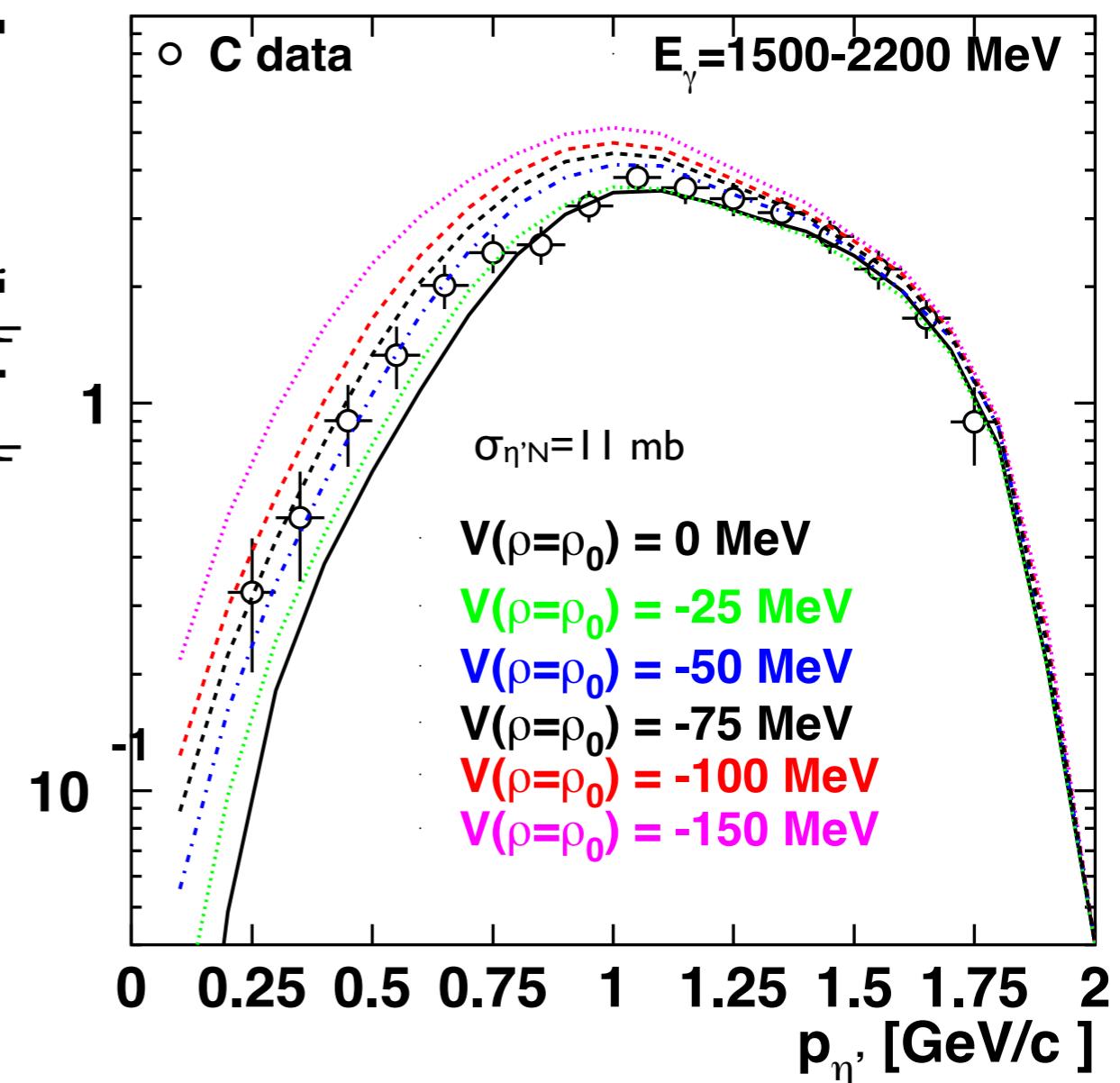
η'

excitation function



$$V_{\eta'}(\rho=\rho_0) = -(40 \pm 6) \text{ MeV}$$

momentum distribution



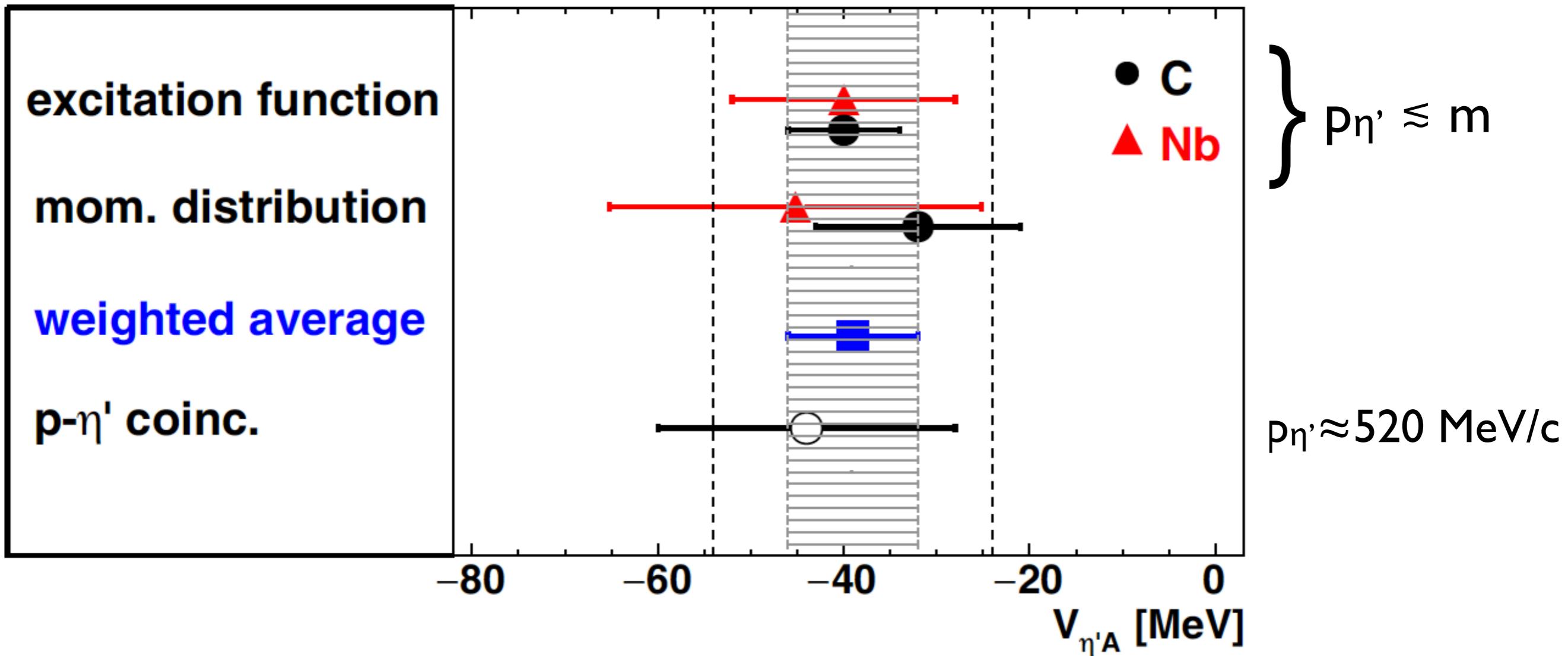
$$V_{\eta'}(< p_{\eta'} > \approx 1.1 \text{ GeV}/c; \rho=\rho_0) = -(32 \pm 11) \text{ MeV}$$

data disfavour strong mass shifts

Determining the real part of the η' -nucleus potential

M. Nanova et al., EPJA 54 (2018) 182

η'



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

observed mass shift in agreement with QMC model predictions

S. Bass and T. Thomas, PLB 634 (2006) 368: $V_{\eta'A}(\rho = \rho_0) = -40 \text{ MeV}$

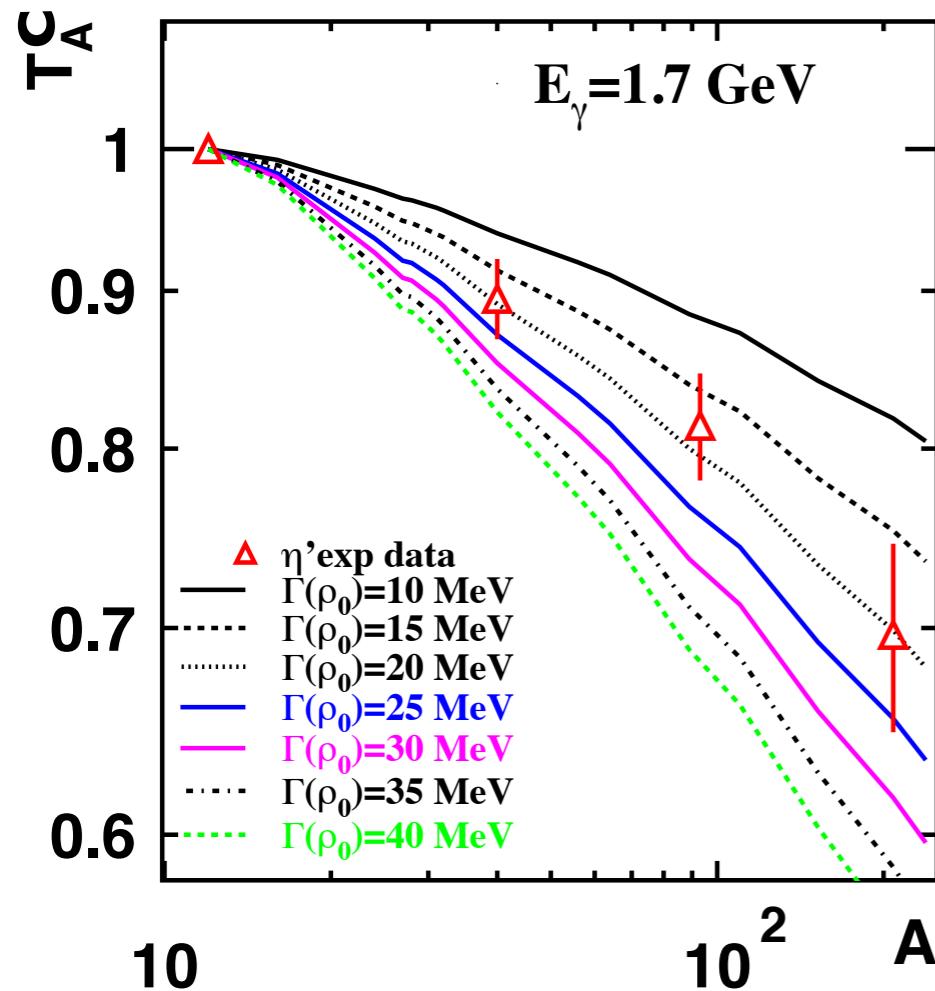
Determining the imaginary part of the η' -nucleus potential

η'

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

mass dependence of T_A

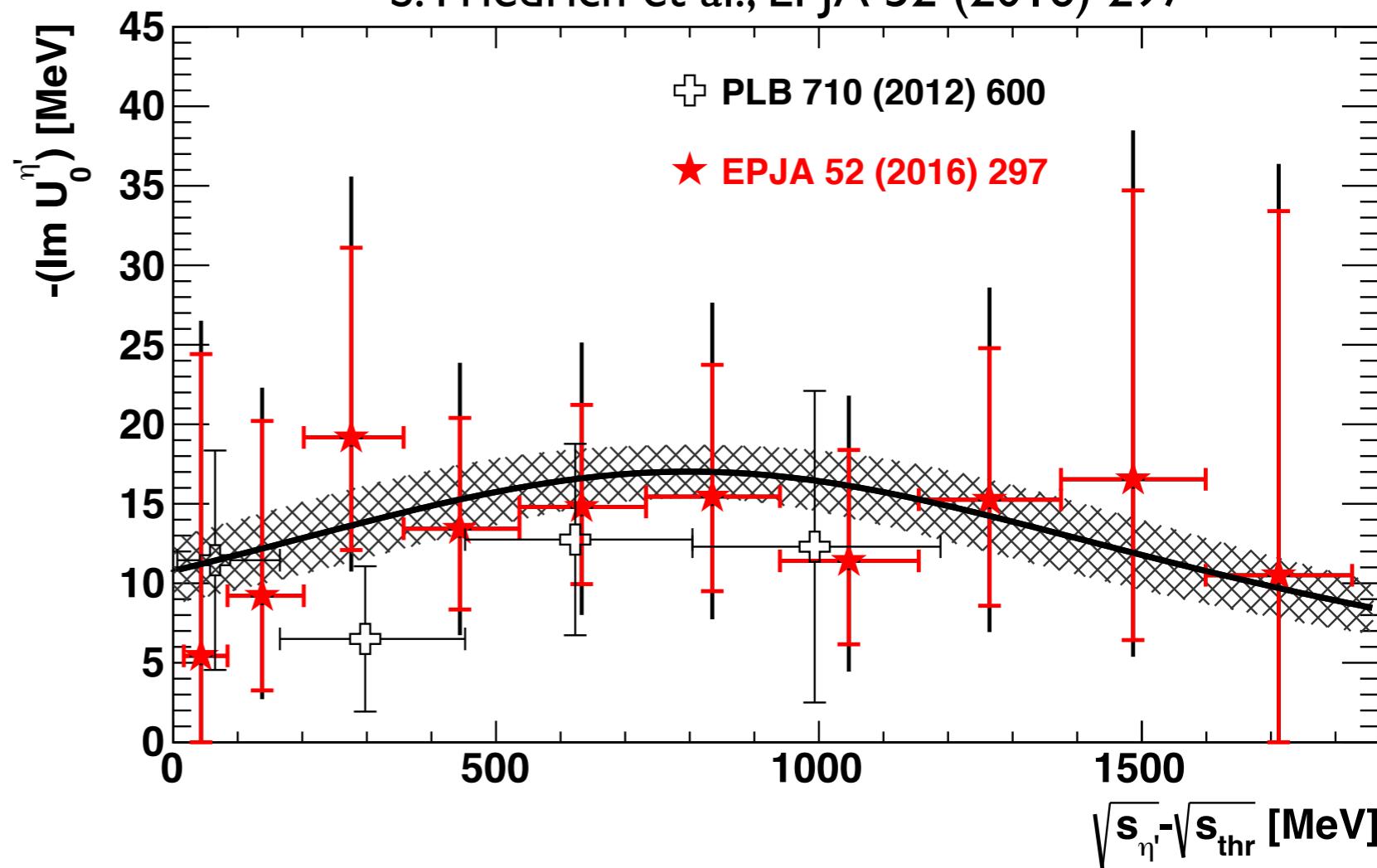
M. Nanova et al., PLB 710 (2012)



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

energy dependence of W_0

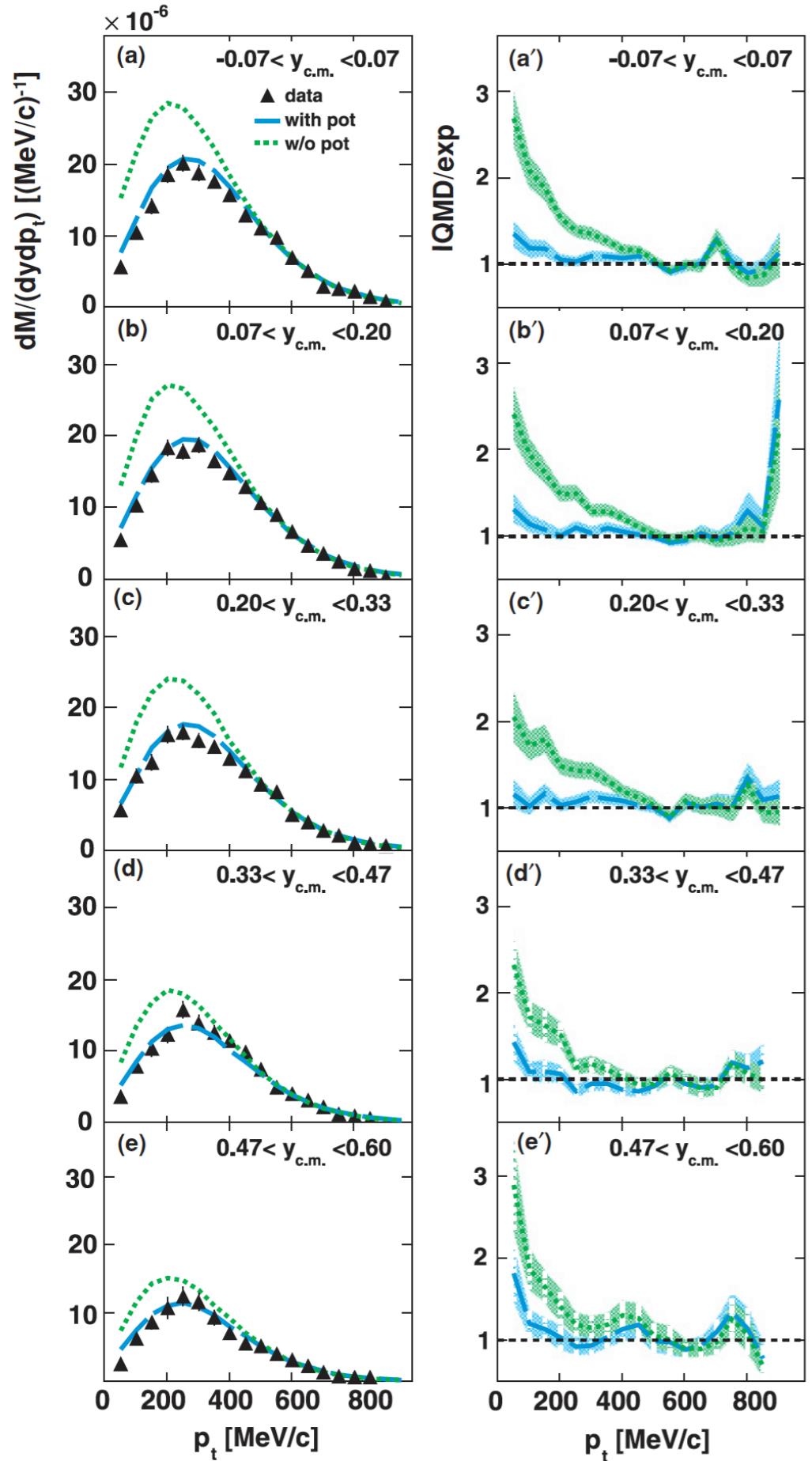
S. Friedrich et al., EPJA 52 (2016) 297



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

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)

$V \approx +40 \text{ MeV}$

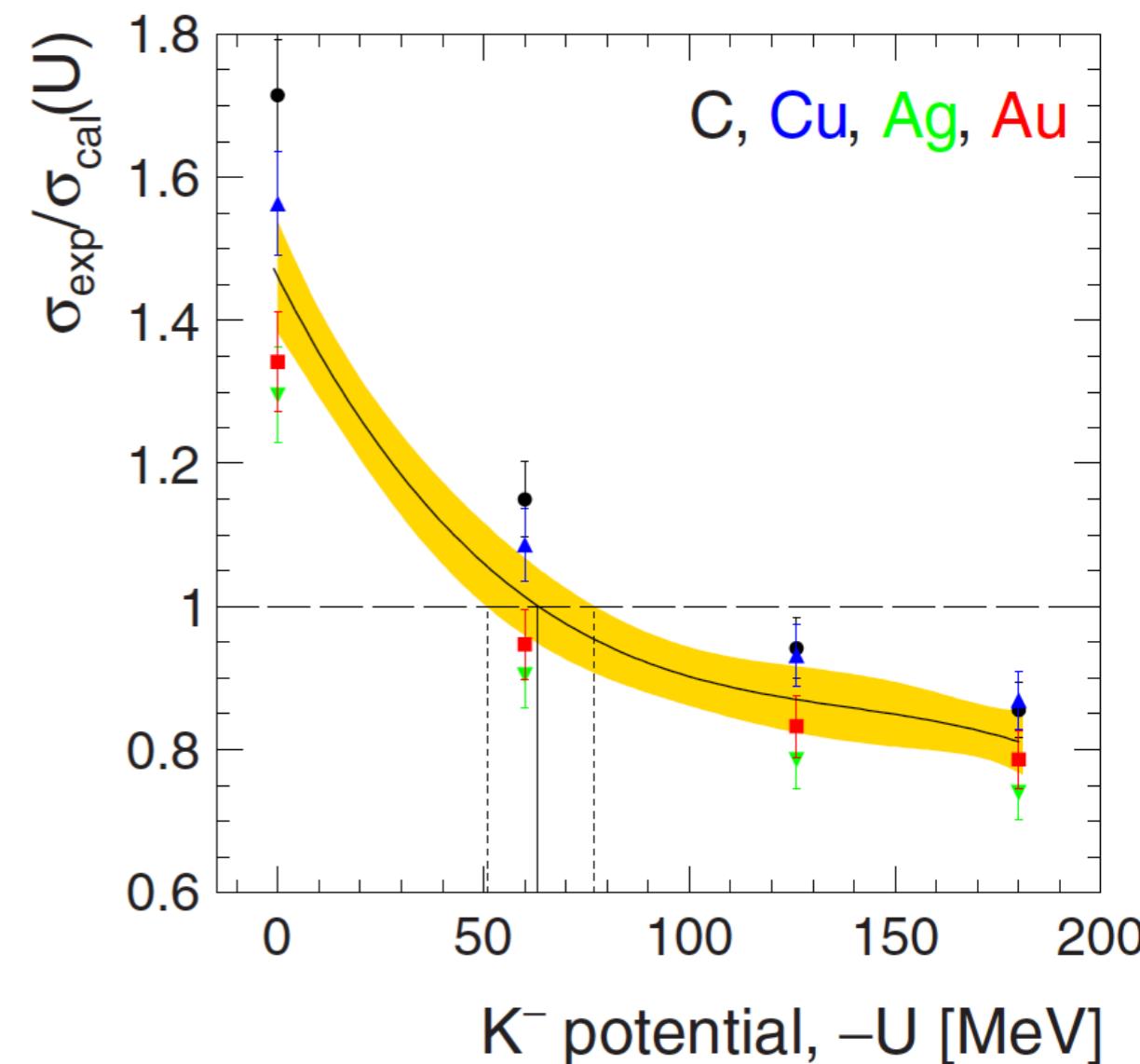
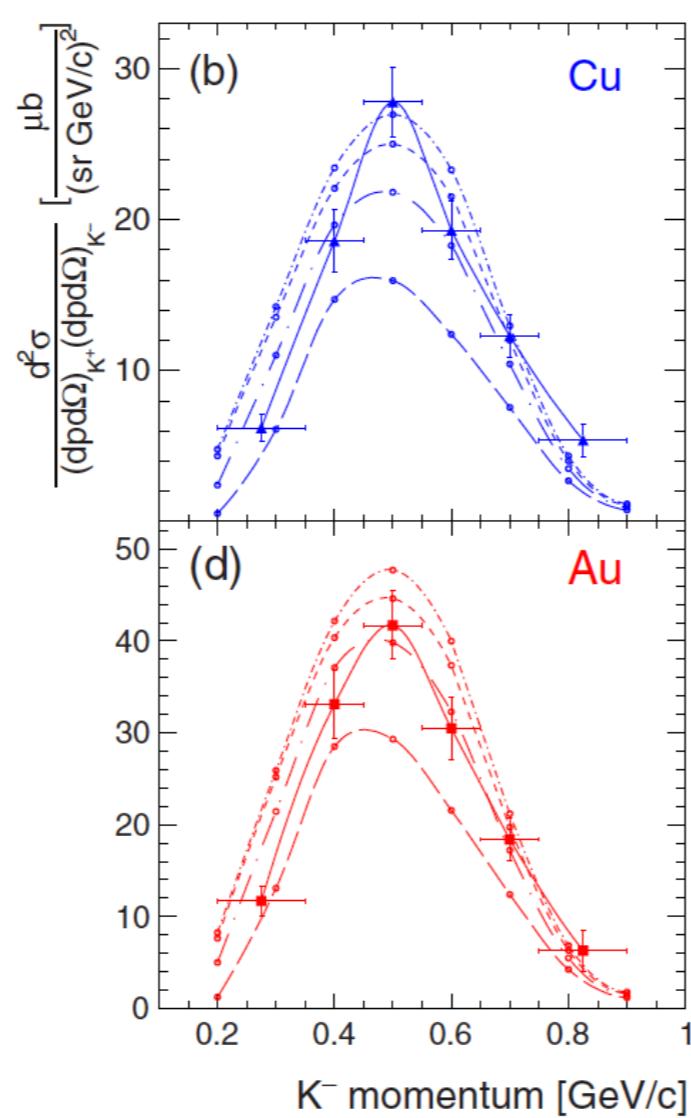
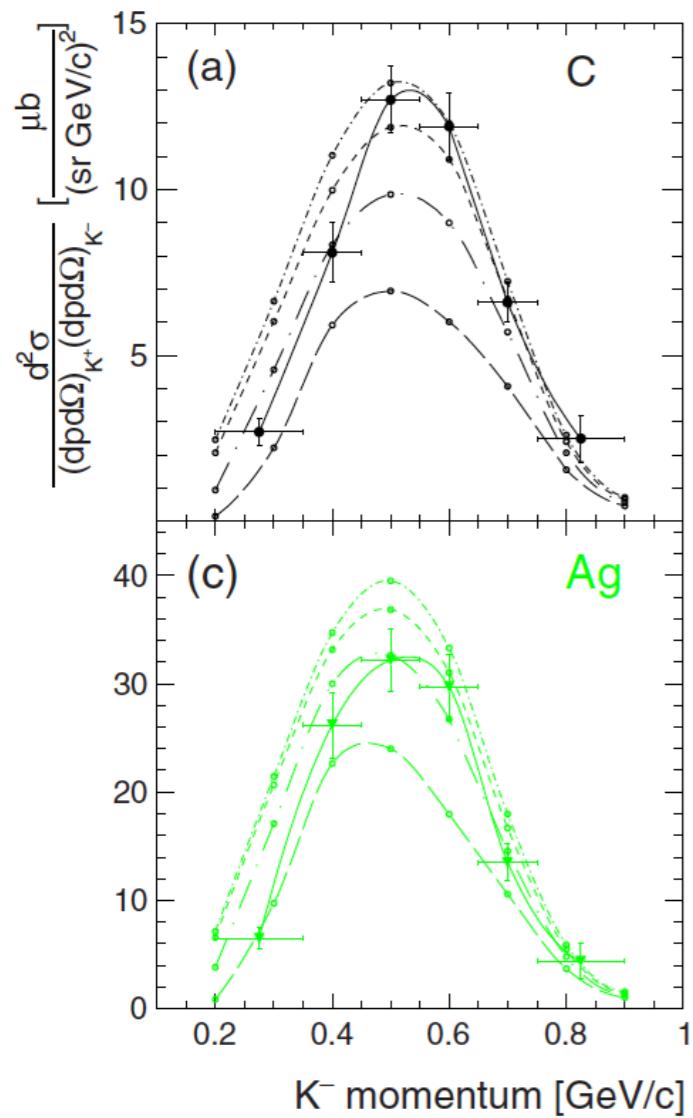
Determining the real part of the K⁻-nucleus potential

$p + C, Cu, Ag, Au \rightarrow K^+ K^- + X$

$K^+ K^-$ 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

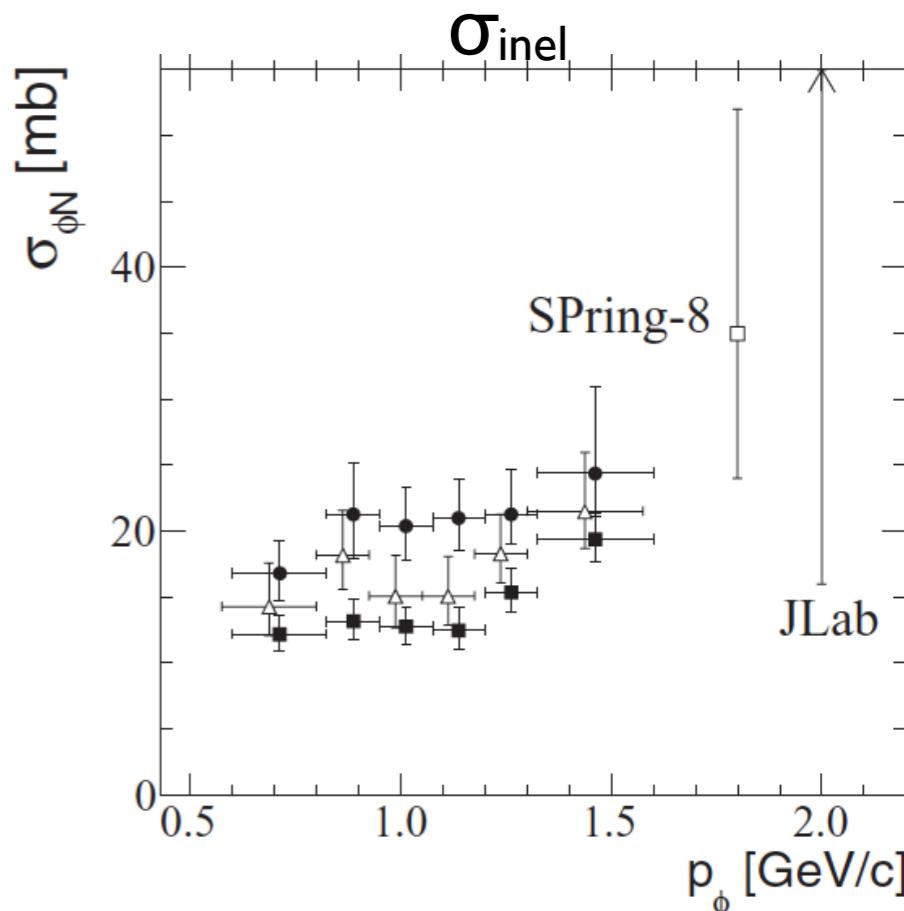
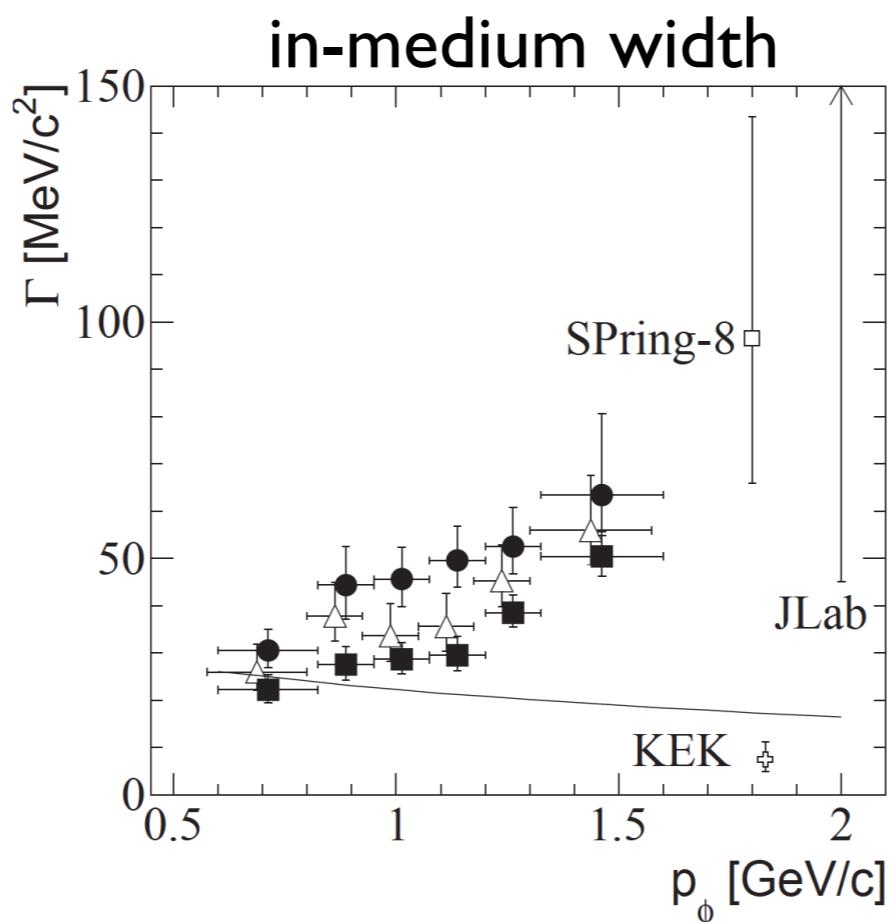
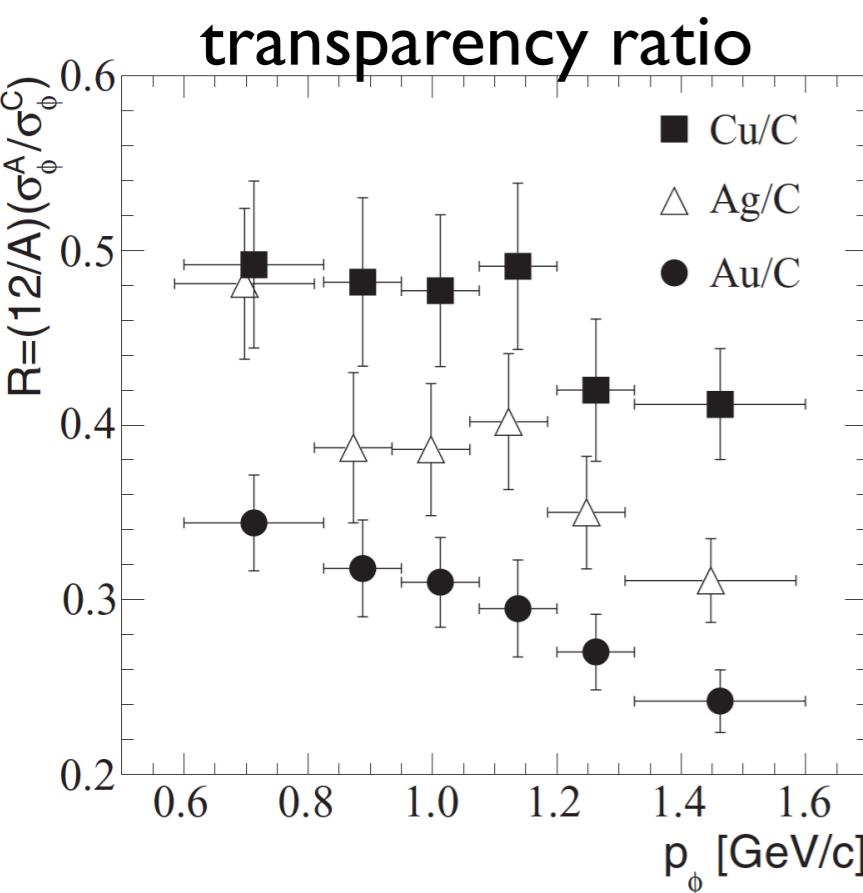
M. Hartmann et al., PRC85 (2012) 035206

ANKE: $p + C, Cu, Ag, Au \rightarrow \Phi + X$ at 2.83 GeV



momentum dependence of transparency ratio

$$T_A^C = \frac{\sigma_{\gamma A \rightarrow \Phi X}}{A \cdot \sigma_{\gamma N \rightarrow \Phi X}} / \frac{\sigma_{\gamma C \rightarrow \Phi X}}{12 \cdot \sigma_{\gamma N \rightarrow \Phi X}}$$



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

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

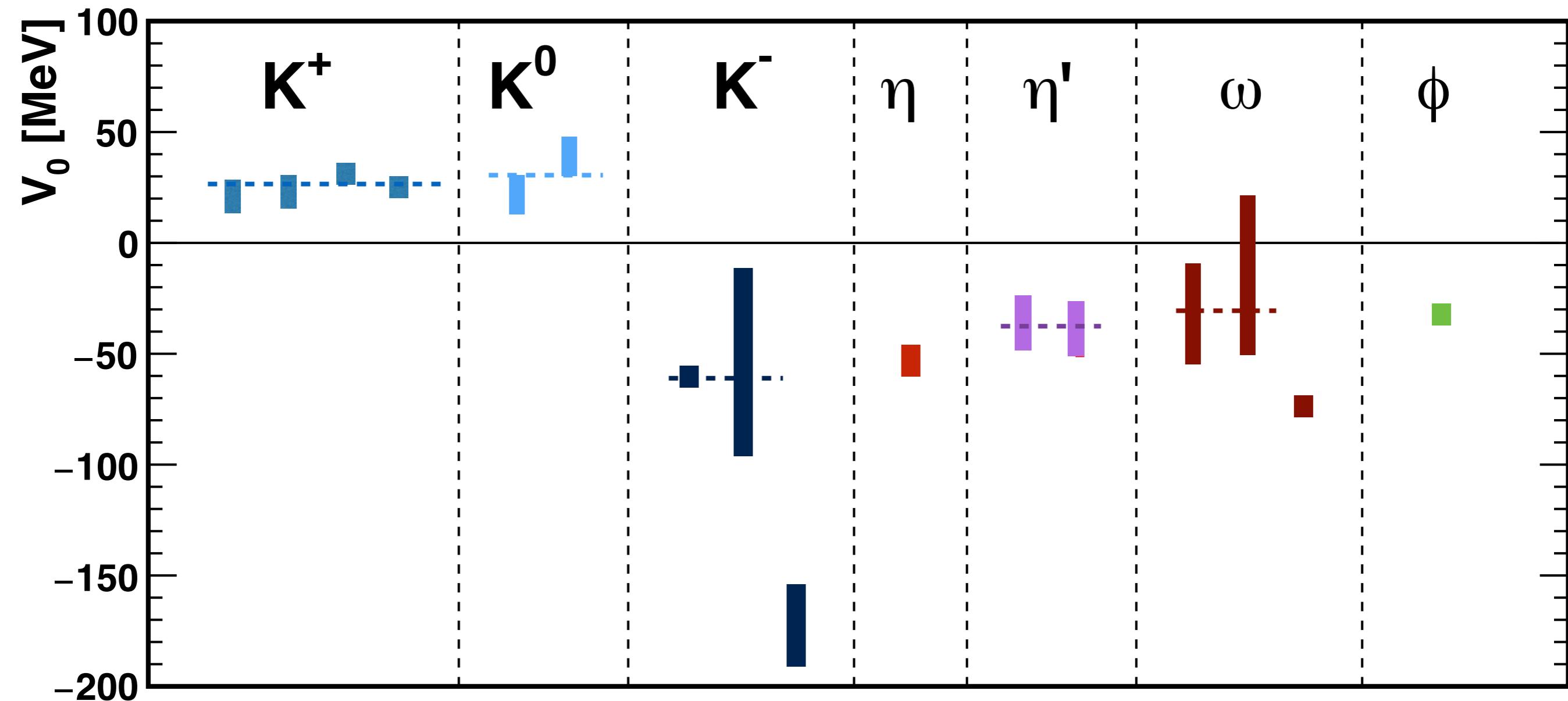
L. Fabbietti

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

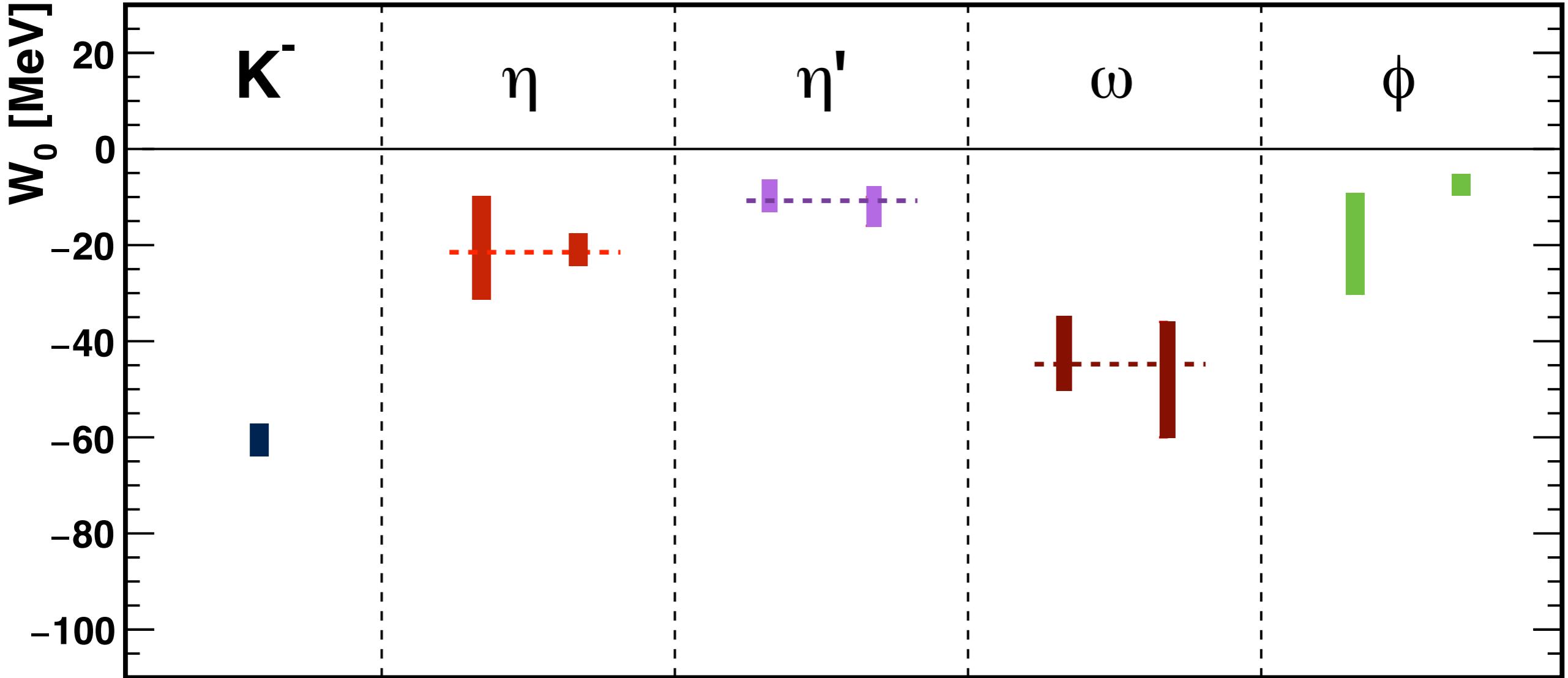
K^- strongest attraction: - (30 - 100) MeV

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

m_{K^+, K^0} ↗
 m_{K^-} ↘
 $m_{\eta'}$ ↘

Imaginary part of the meson-nucleus potential

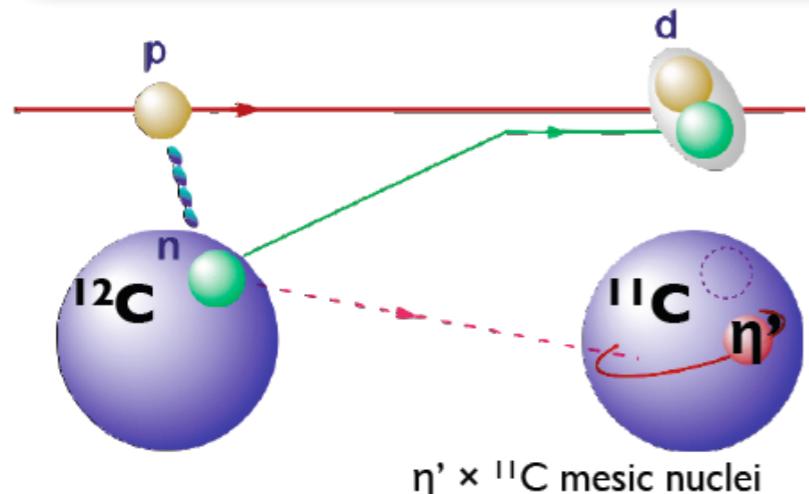
V. Metag, M. Nanova and E.Ya. Paryev, Prog. Part. Nucl. Phys. 97 (2017) 199



$\eta' : \approx -10 \text{ MeV}$
 $\eta, \Phi : \approx -20 \text{ MeV}$
 $\omega : \approx -40 \text{ MeV}$ quite broad
 $K^- : \approx -60 \text{ MeV}$ very broad

η' promising candidate for mesic state: $|W_0| \approx 10 \text{ MeV} \ll |V_0| \approx 40 \text{ MeV}$

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



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

K. Itahashi et al.

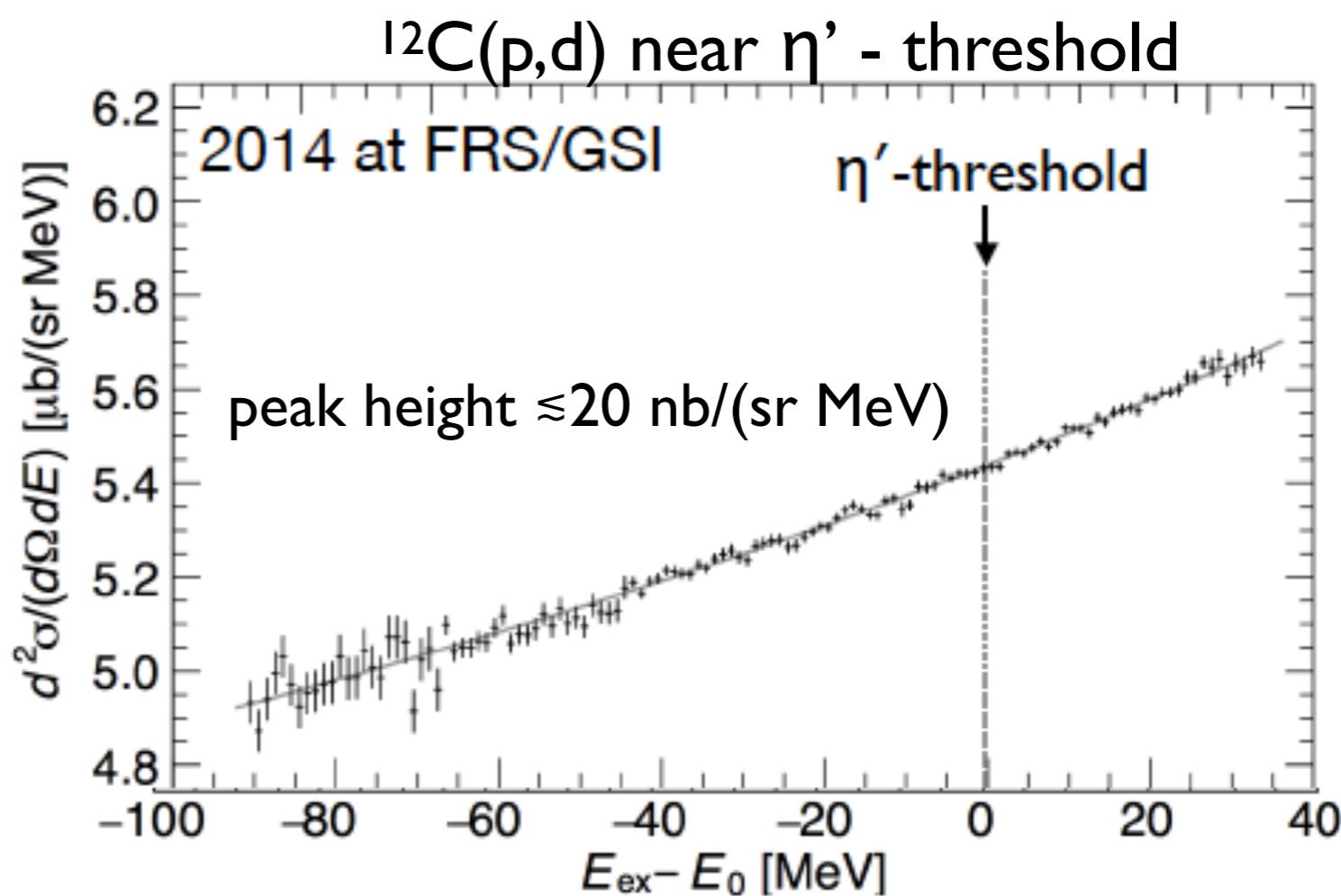
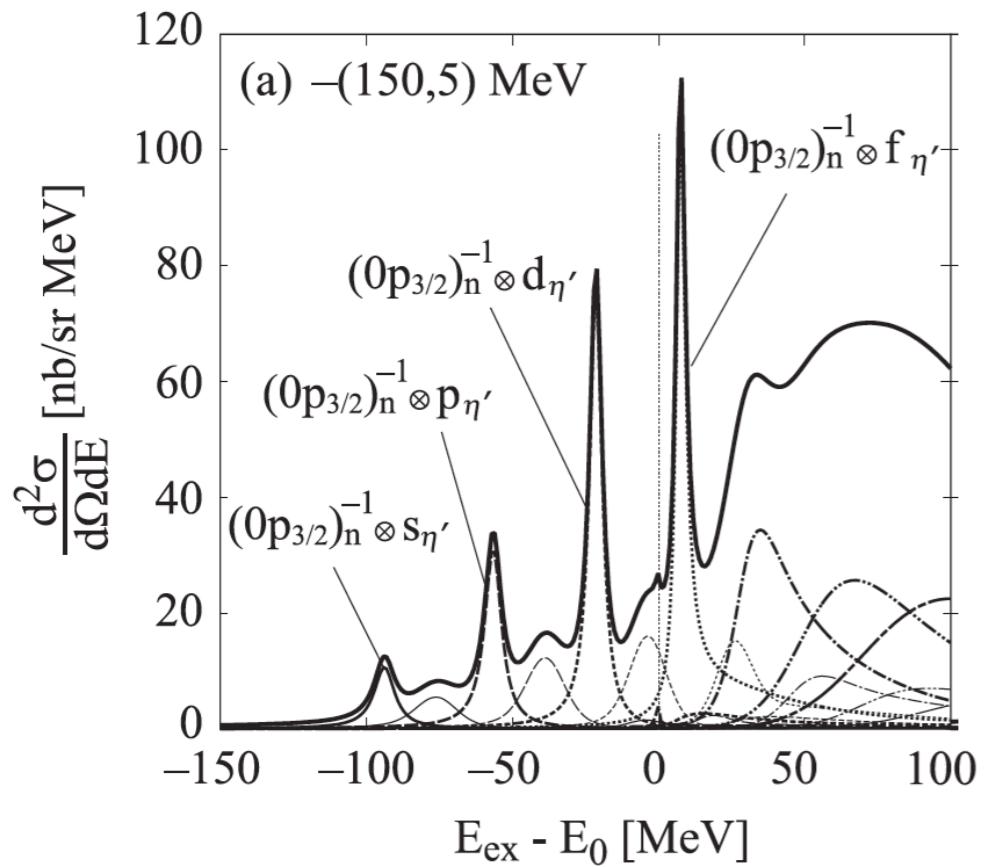
PRIME collaboration (2012)

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

Y.K. Tanaka et al., PRC 97 (2018) 015202

theoretical expectation

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

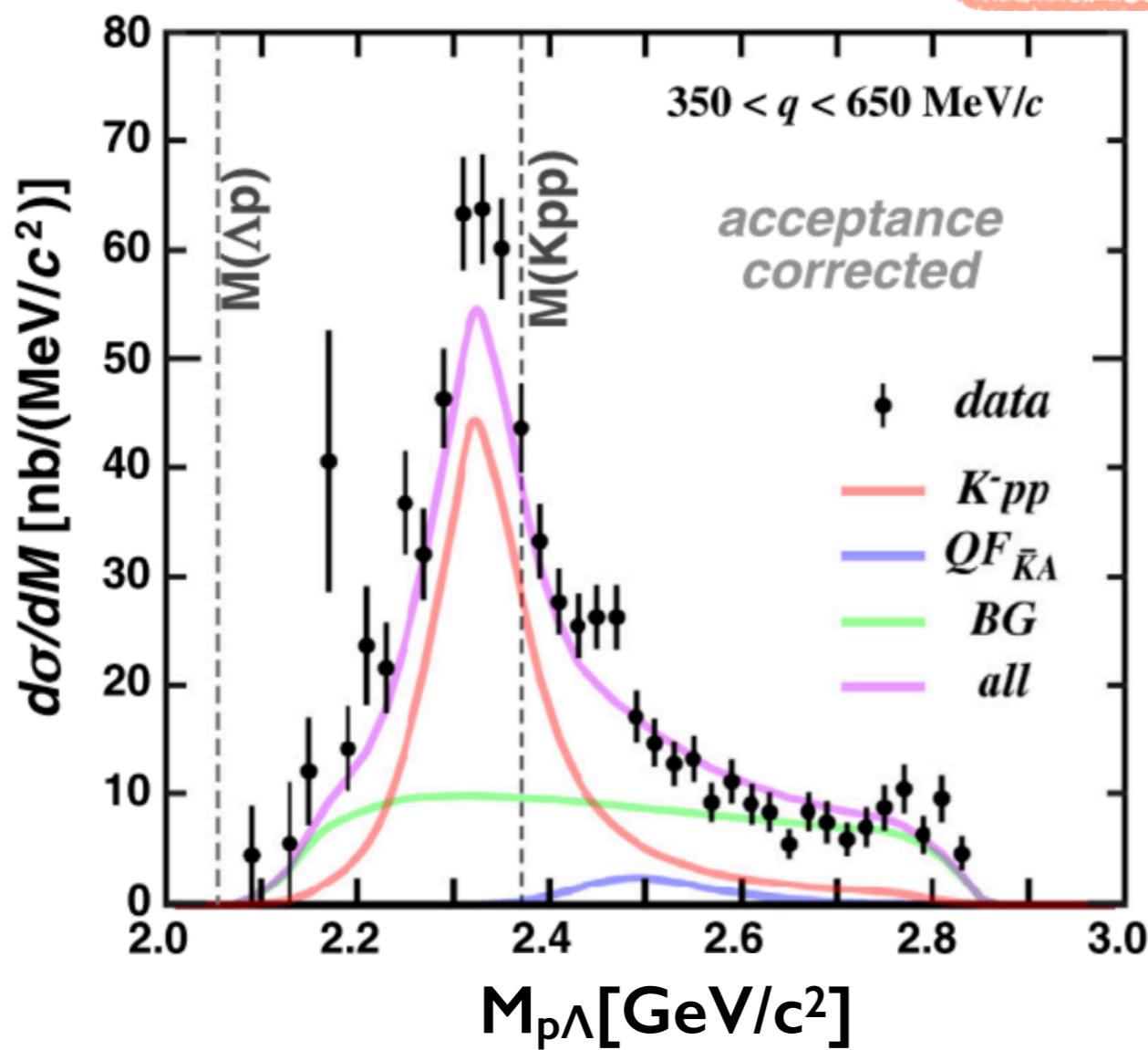
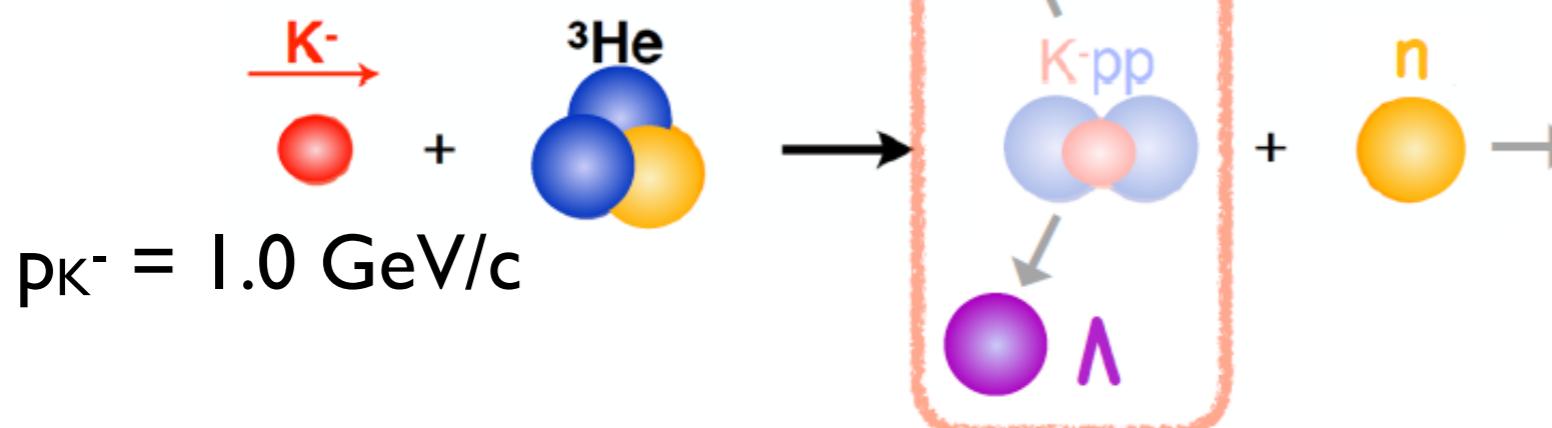


high statistical sensitivity sets constraints on η' - ${}^{11}\text{C}$ interaction: $| V_0 | < 100$ MeV
improved experiment detecting formation and decay of mesic state in preparation

First observation of a bound K-pp cluster

J-PARC E15 experiment

M. Iwasaki et al.



strategy:

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

M. Bragadireanu et al.,
Phys. Lett. B 789 (2019) 620

structure in $(p\Lambda)$ invariant mass below ppK^- threshold observed

K^-pp bound state formed decaying into Λp

$$B_{KPP} = 47 \pm 3(\text{stat})^{+3}_{-6}(\text{sys}) \text{ MeV}$$

$$\Gamma_{KPP} = 115 \pm 7(\text{stat})^{+10}_{-20} (\text{sys}) \text{ MeV}$$

strong attraction and large absorption of K^- confirmed

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 ($|V_0| \gg |W_0|$) for observing meson-nucleus quasi-bound states: promising candidate: 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
- **mesons do change their properties in the nuclear medium as predicted by chiral model calculations assuming partial restoration of chiral symmetry in a strongly interacting medium !!**