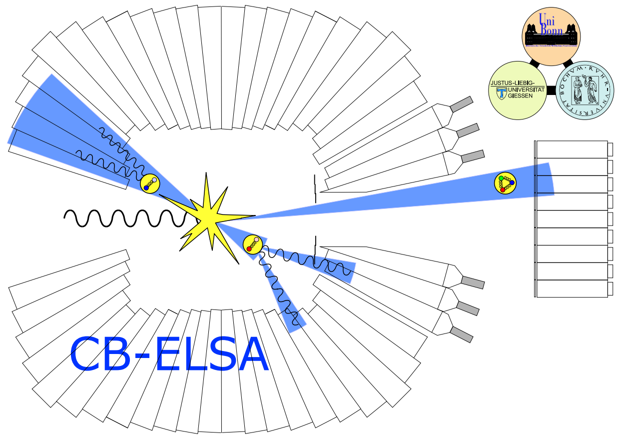
Hadrons in the medium - how properties of mesons are modified in nuclear matter

Volker Metag, Mariana Nanova
II. Physikalisches Institut
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

- theoretical predictions of in-medium modifications of meson properties
- <u>experimental approaches</u>:
  for short lived mesons: line shape analysis
  for longer-lived mesons: measurement of excitation functions, momentum distributions, transparency ratios
- summary of in-medium modifications reported by many groups worldwide
- outlook on search for meson-nucleus bound states

Experimental Physics II

60th International Winter Meeting
on Nuclear Physics
22.-26.01.2024, Bormio, Italy



hadrons in the medium

V. Bernard and U.-G. Meißner, NPA 489 (1988) 647
S. Klimt, M.Lutz and W.Weise, PLB 249 (1990) 386
G. E Brown and M. Rho, PRL 66 (1991)2720
T. Hatsuda and S. Lee, PRC 46 (1992) R34
T. Hatsuda and T. Kunihiro, Phys. Rep. 247 (1994) 221
S. Leupold and U. Mosel, PRC 58 (1998) 2939

what happens when you embed a composite particle with a dynamically generated mass into a strongly interacting medium ??

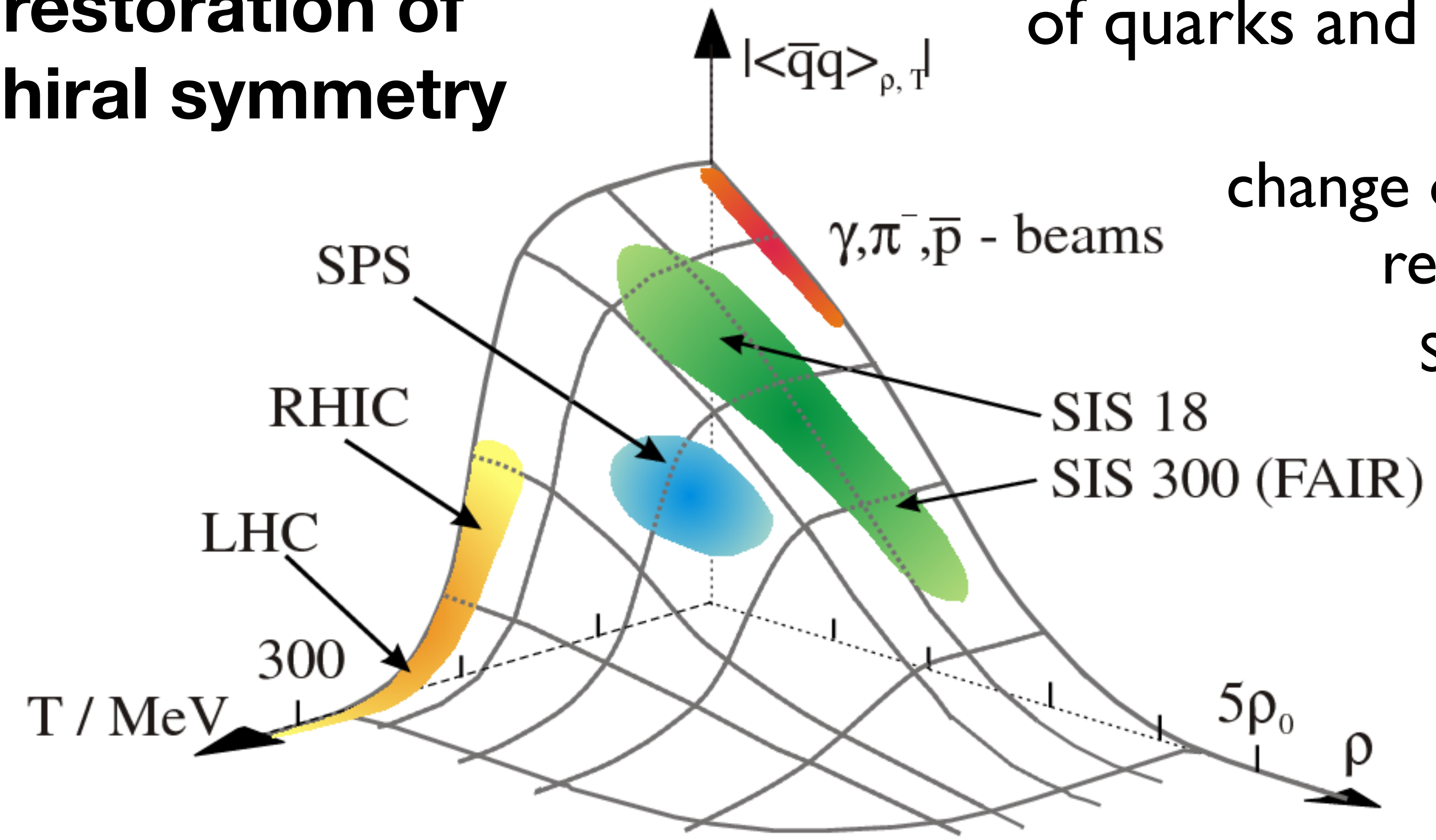
test case for non-perturbative QCD

nucleon mass generated dynamically

$\sum m_q \approx 10$ MeV $m_p = 938.3$ MeV

$m_p = E/c^2$ determined by kinetic energy of quarks and energy of the gluon fields

restoration of chiral symmetry



change of condensates due to partial restoration of chiral symmetry

S. Klimt et al., PLB 249 (1990) 386

chiral condensate linked to hadron masses (spectral functions) via QCD sum rules

the spectral function of mesons

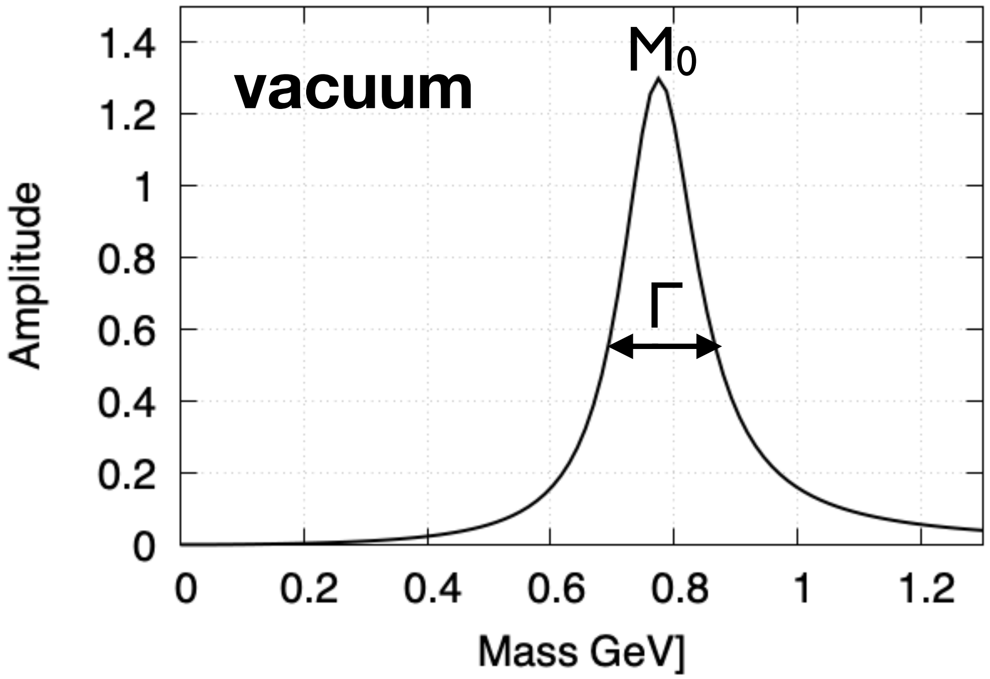
light mesons: $m \gg \Sigma_q m_q$, mass generated dynamically

mesons are unstable particles → additional property: width Γ

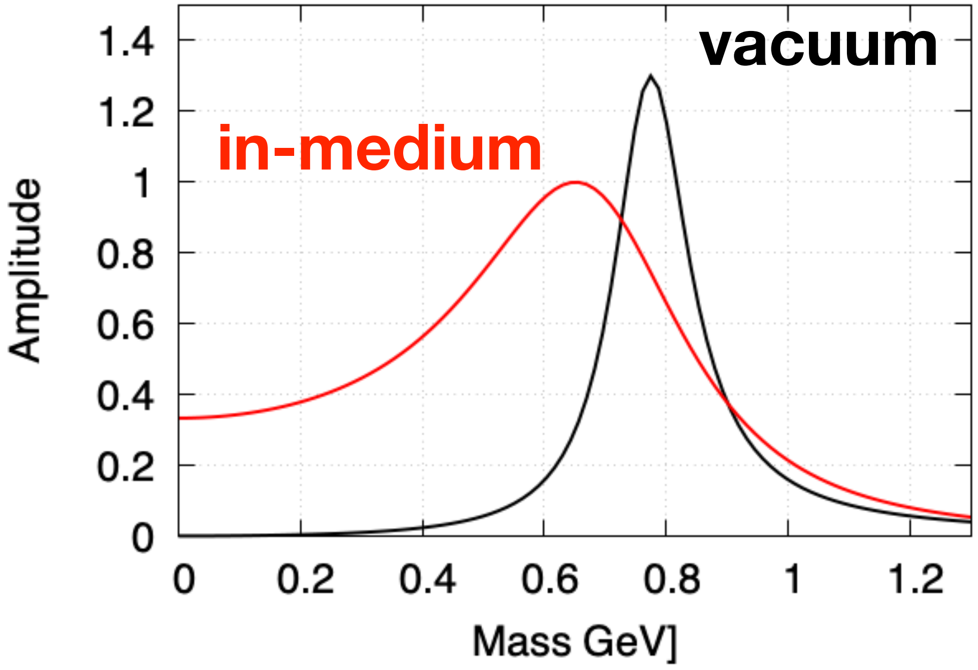
<u>spectral function:</u>

$$A(M) = \frac{M^2 \cdot \Gamma}{(M_0^2 - M^2)^2 + M^2 \cdot \Gamma^2(M)} \xrightarrow{\text{in the medium}} A(M) = \frac{\mathrm{Im}(\Sigma)}{(M_0^2 - M^2 - \mathrm{Re}(\Sigma))^2 + (\mathrm{Im}(\Sigma))^2}$$

Σ = in-medium meson self-energy describing the meson-nucleon interaction, allowing for changes of mass and width



in the medium →



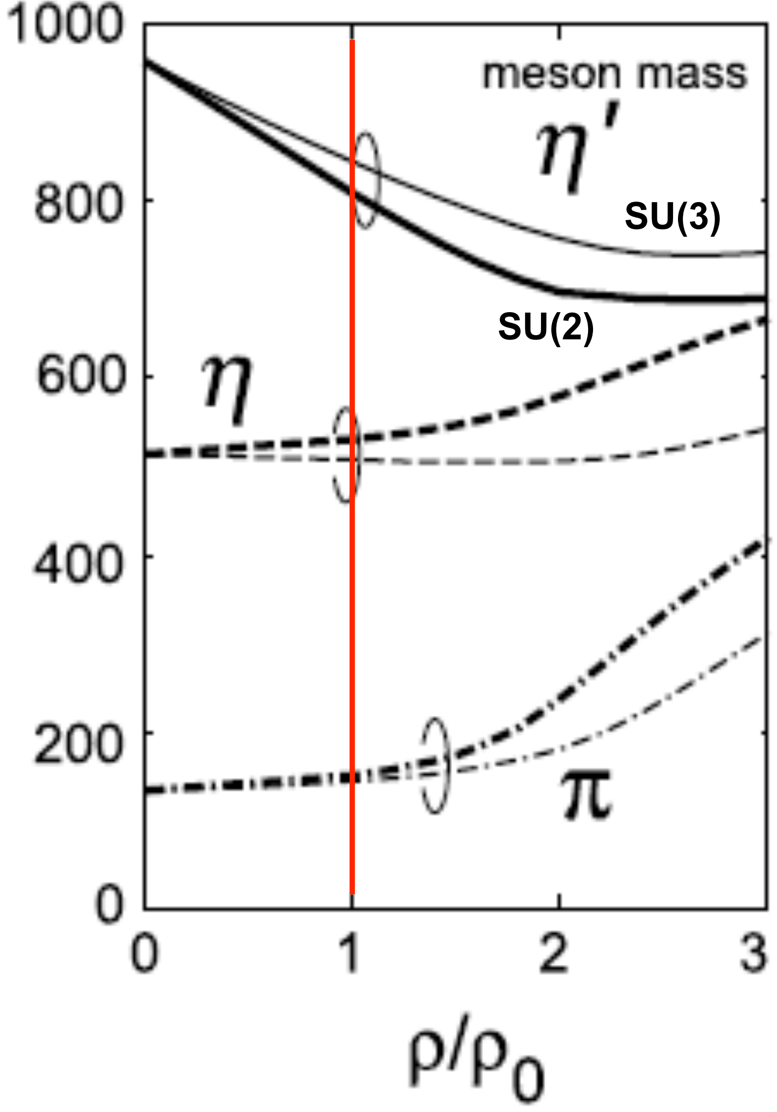
model calculations predict modification of meson properties:
NJL, QCD sum rules, chiral unitary, QMC, RMF, unitary coupled channel, chiral SU(3),…

predictions for in-medium changes

η,η'

NJL-model

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

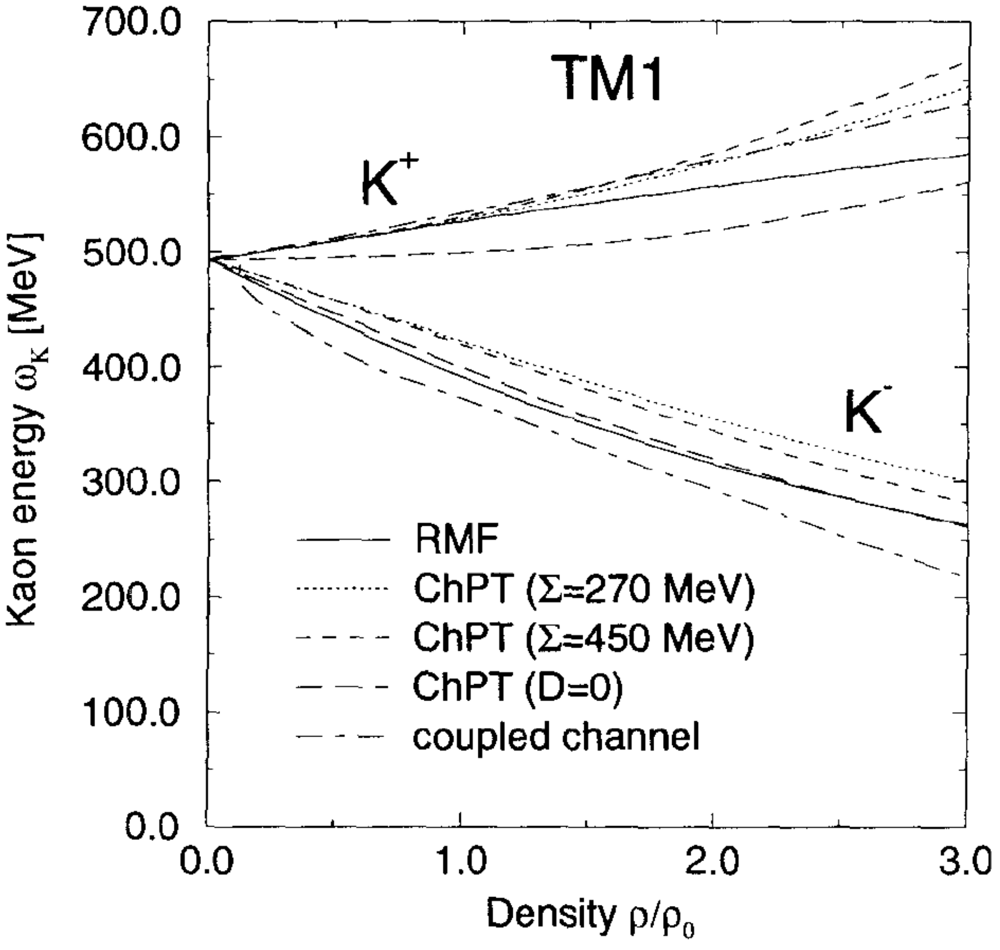


$\Delta m_{\eta'}(\rho_0)\approx$-150 MeV
$\Delta m_{\eta}(\rho_0)\approx$+20 MeV

K^+, K^-

RMF-approach

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

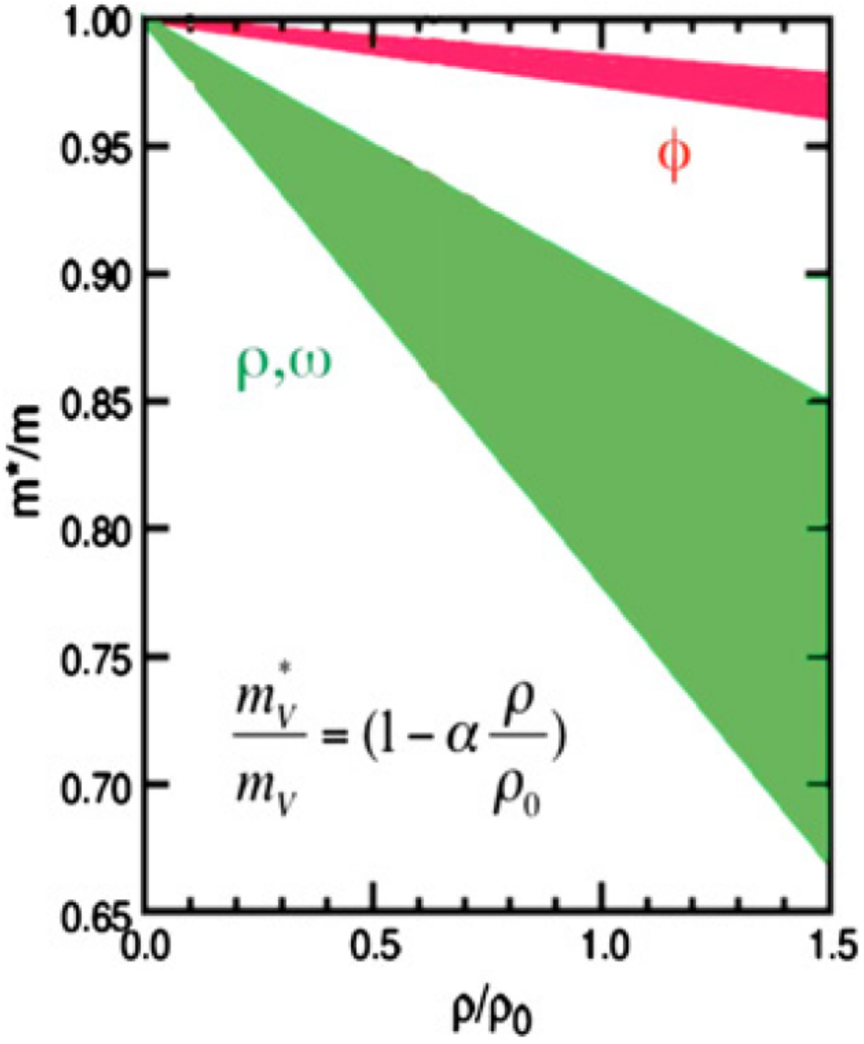


$\Delta m_{K^+}(\rho_0)\approx$ +30 MeV
$\Delta m_{K^-}(\rho_0)\approx$-100 MeV

ρ,ω,Φ

QCD sum rules

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

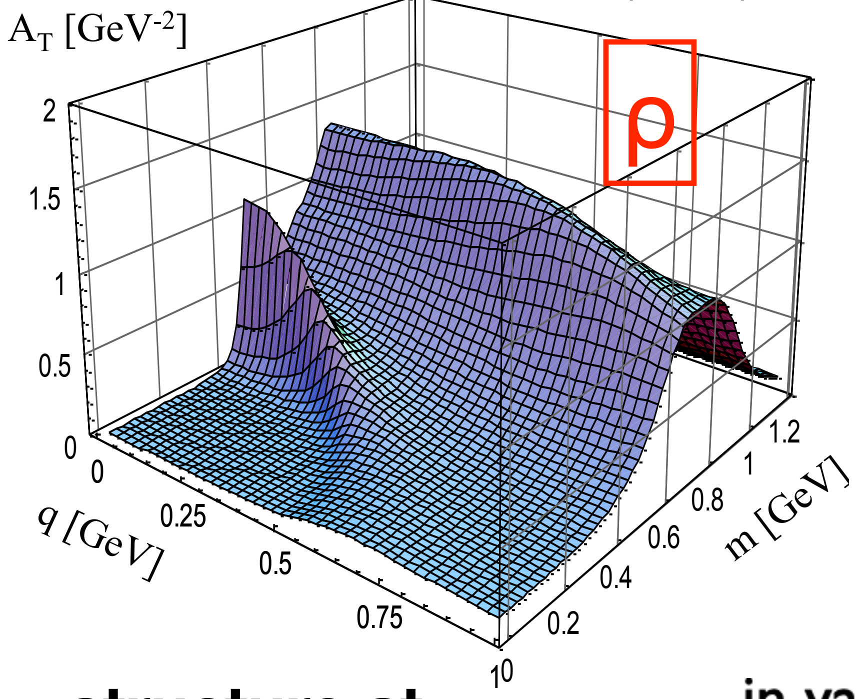


$\Delta m_{\rho}(\rho_0)\approx$ - (80-160) MeV
$\Delta m_{\omega}(\rho_0)\approx$ - (80-160) MeV
$\Delta m_{\Phi}(\rho_0)\approx$-(20-30) MeV

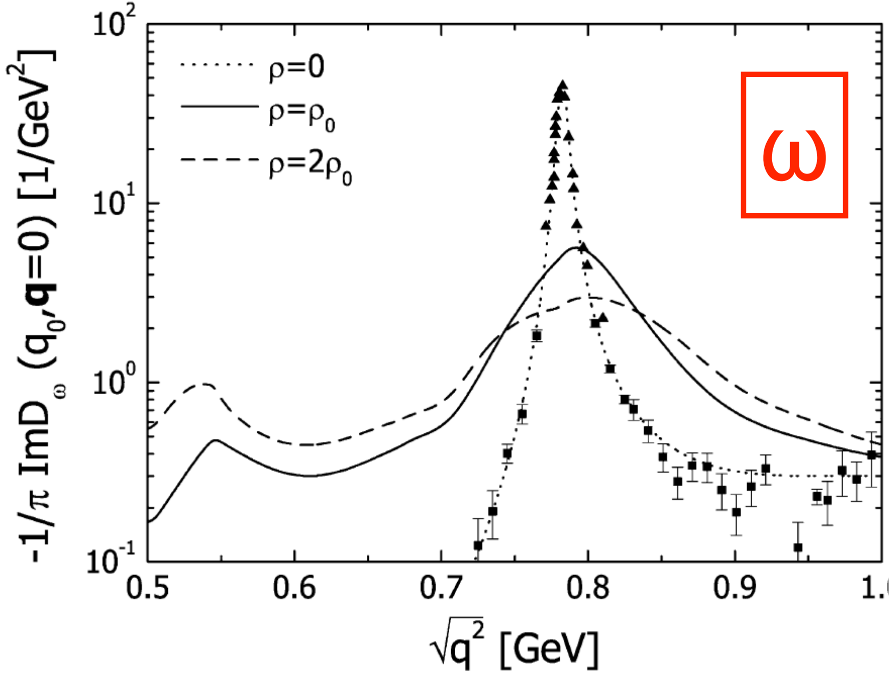
predictions for in-medium spectral functions

in the nuclear medium mesons have additional "decay"- options
they can be removed by inelastic reactions, e.g. ω N → π N
→shorter lifetime →larger in-medium width

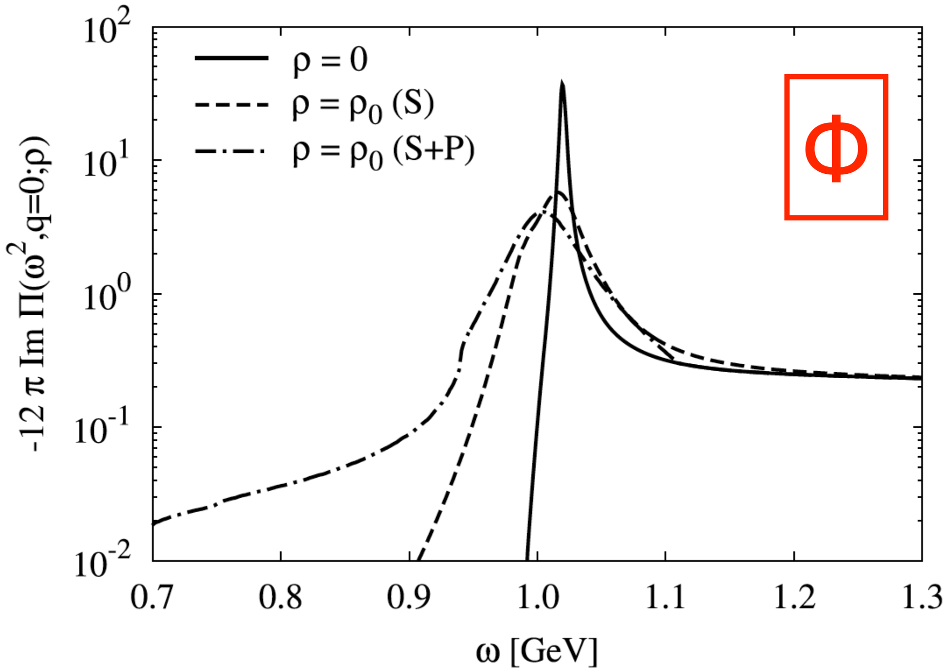
M. Post et al., NPA 741(2004) 84



P. Mühlich et al., NPA 780 (2006) 187



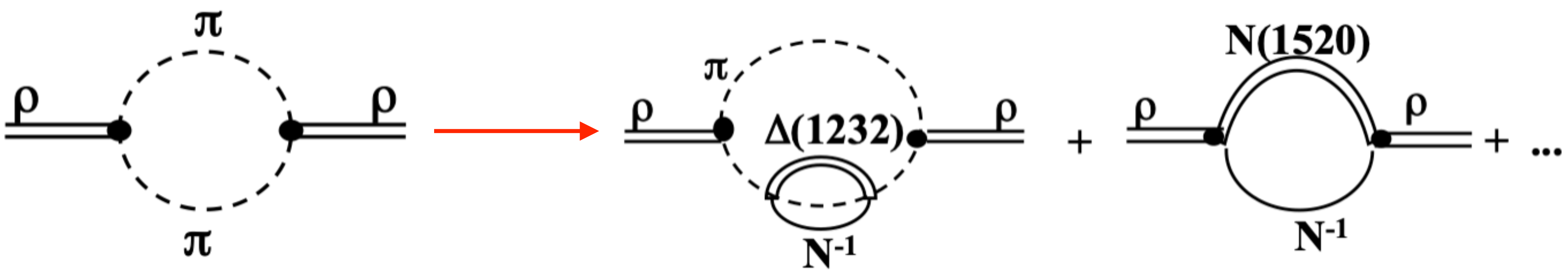
P. Gubler, W. Weise PLB 751 (2015) 396



structure at low momenta !

in vacuum:

in medium



in-medium vector meson spectral function modified due to coupling to resonance - holes states (modifications confined to small momenta)

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

from theoretical predictions to experimental observables

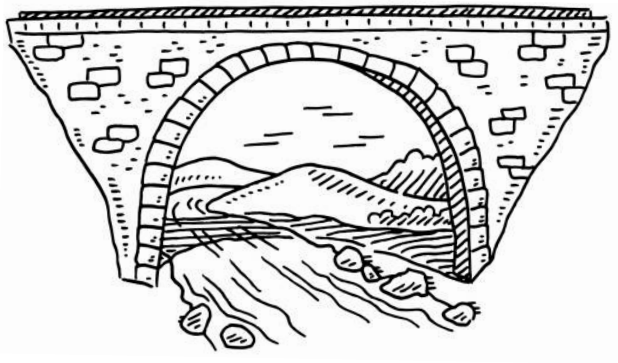
calculations of meson spectral functions assume:

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

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

theoretical predictions

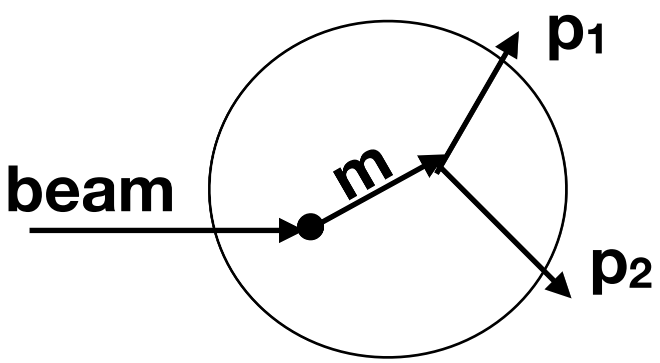
transport calculations



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
- fraction of decays inside of the nuclear environment
- final state interactions: distortion of momenta of decay products

measurement of mass and width of mesons



measure 4-momenta of decay products and reconstruct invariant mass distribution:

$$m_{1,2} = \sqrt{(p_1+p_2)^2}$$

- two conditions for the experimental observation of in-medium changes of mass and width:

1.) meson has to decay in the medium
→ very short-lived, very low recoil momentum: $p/m \bullet \tau < R_{nucleus}$

2.) no final state strong interaction (FSI) of meson decay products in the medium
→ dileptons (e+e-, μ+μ-)

only one meson ideally suited: ρ ($\tau \approx 1.3$ fm/c) → e^+e^- ($\mu^+\mu^-$)

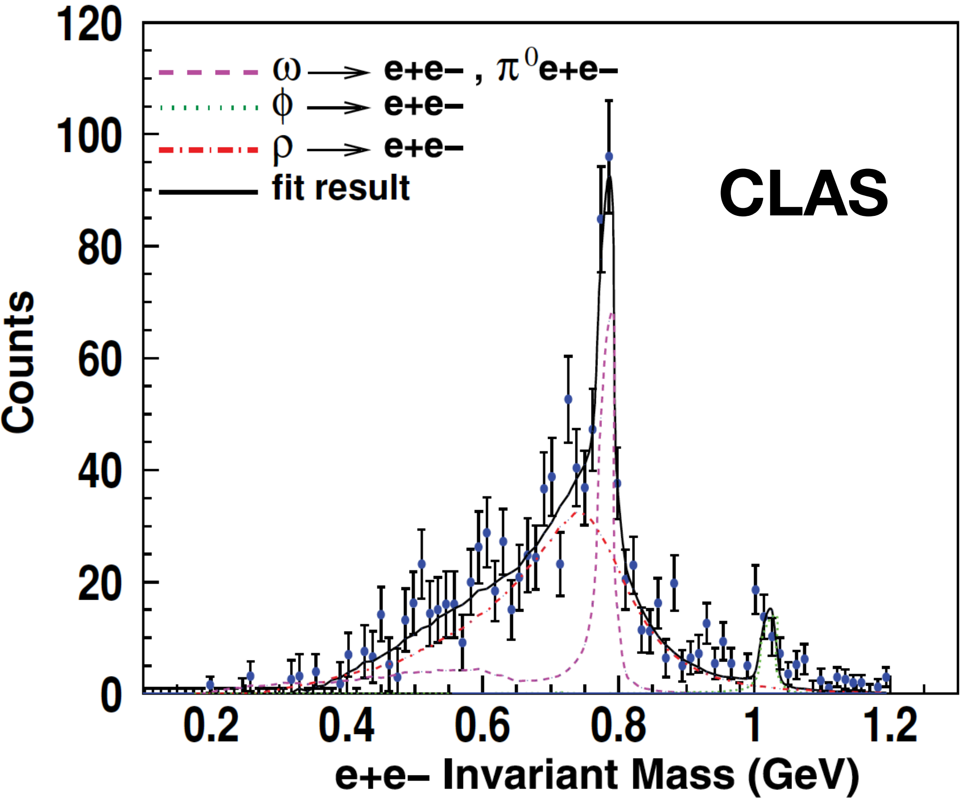
↓ short decay path ↓ no strong FSI

drawback and experimental challenge: small branching ratio $\rho \rightarrow e^+e^- \approx 5 \bullet 10^{-5}$

the in-medium spectral function of the ρ meson

for $p_\rho > 800$ MeV/c

at $\rho \leq \rho_0$; T = 0

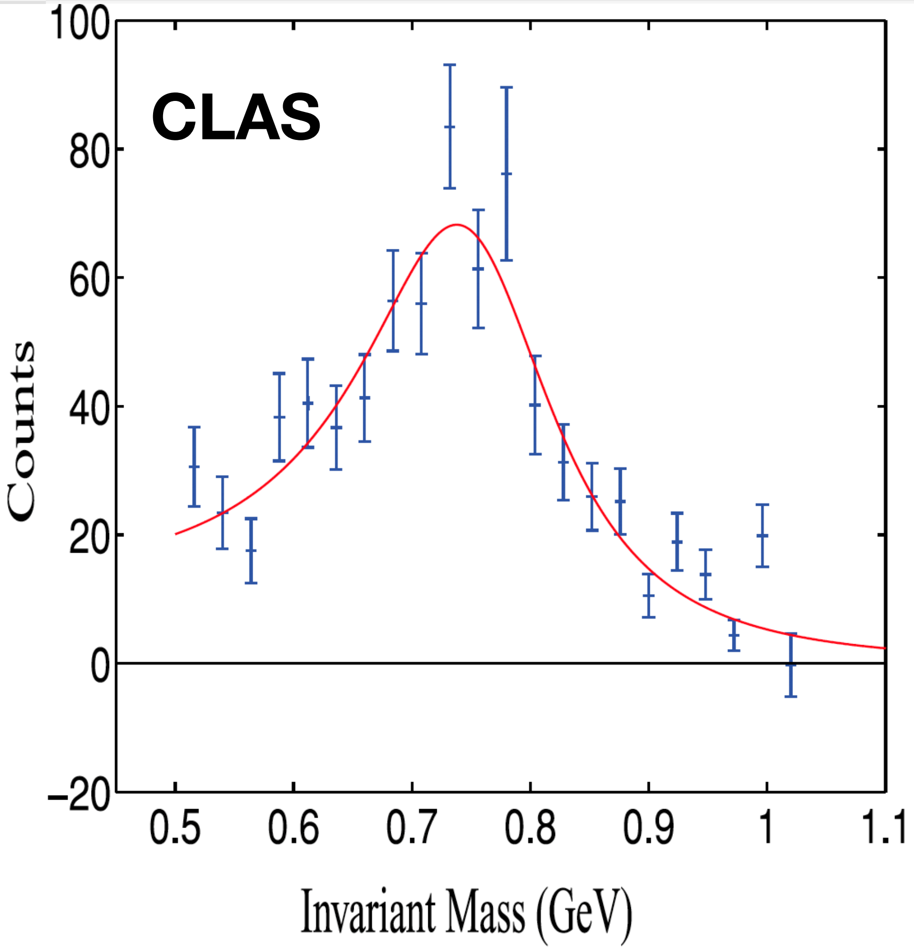


M.H.Wood et al., PRC 78 (2008) 015201

γ + Fe,Ti → ρ + X E_γ= 0.6 - 3.8 GeV

$\rho \rightarrow e^+e^-$

e^+e^- invariant mass spectrum showing ρ, ω, Φ peaks after subtraction of combinatorial background



after removing contributions from ω and Φ mesons

Fe,Ti: M_ρ = (779±5.7) MeV;   Γ= (217.7±14.5) MeV

^{2}H: M_ρ = (770±3.2) MeV;   Γ= (185.2±8.6) MeV

→ no mass shift but broadening !!

“golden” experiment,

but no acceptance for $q_{e+e-} < 800$ MeV/c

however conflicting result:
KEK325: M. Naruki et al., PRL (2006) 092301
problem with subtracting combinatorial background ?

the in-medium spectral function of the ρ meson

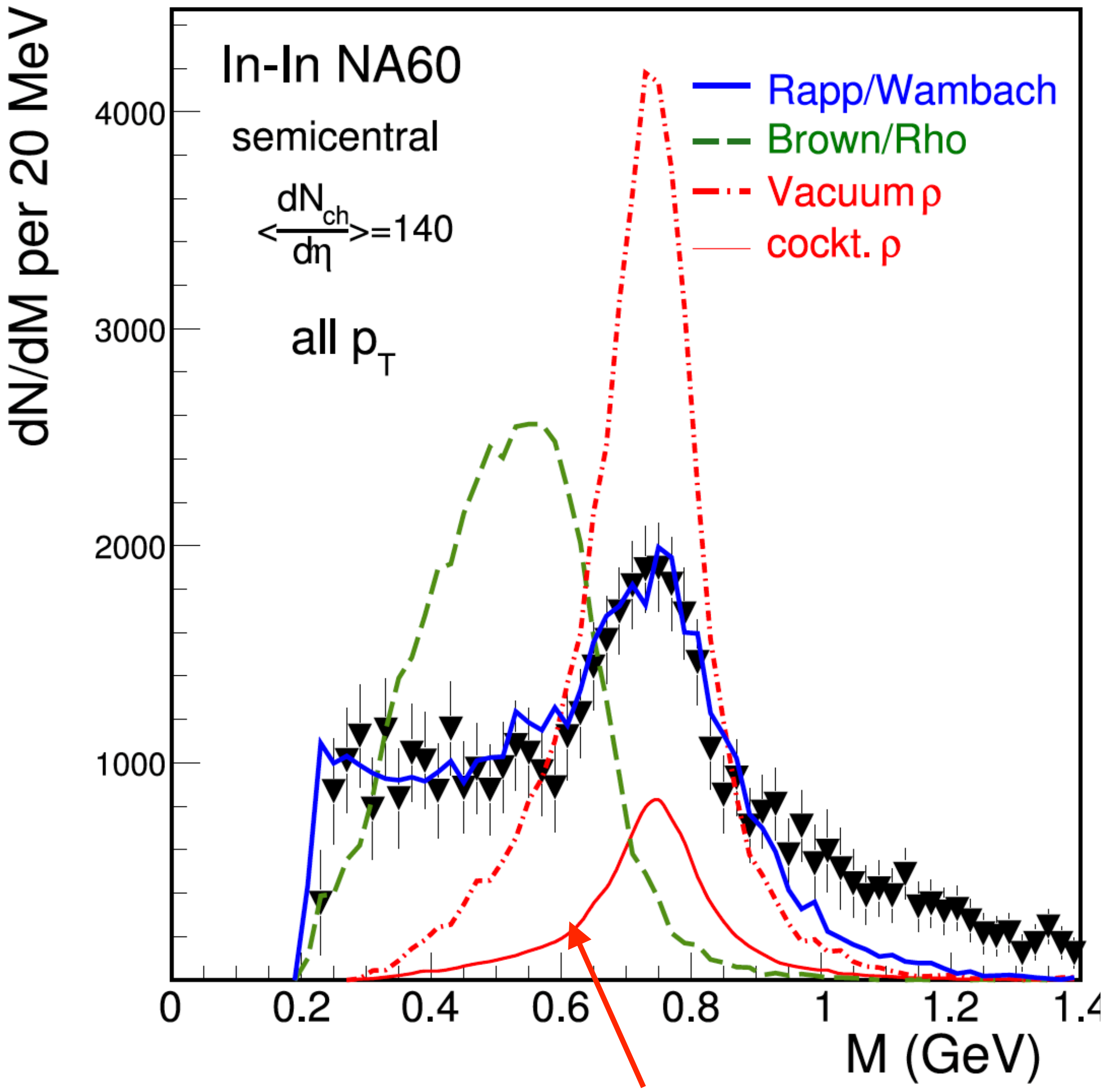
NA60 : In + In @ 158 GeV/c

at $\rho \approx (2\text{-}4)\ \rho_0$,;T ≈ 190 MeV

$\rho \to \mu^+\mu^-$

strong changes with centrality
(density, temperature)

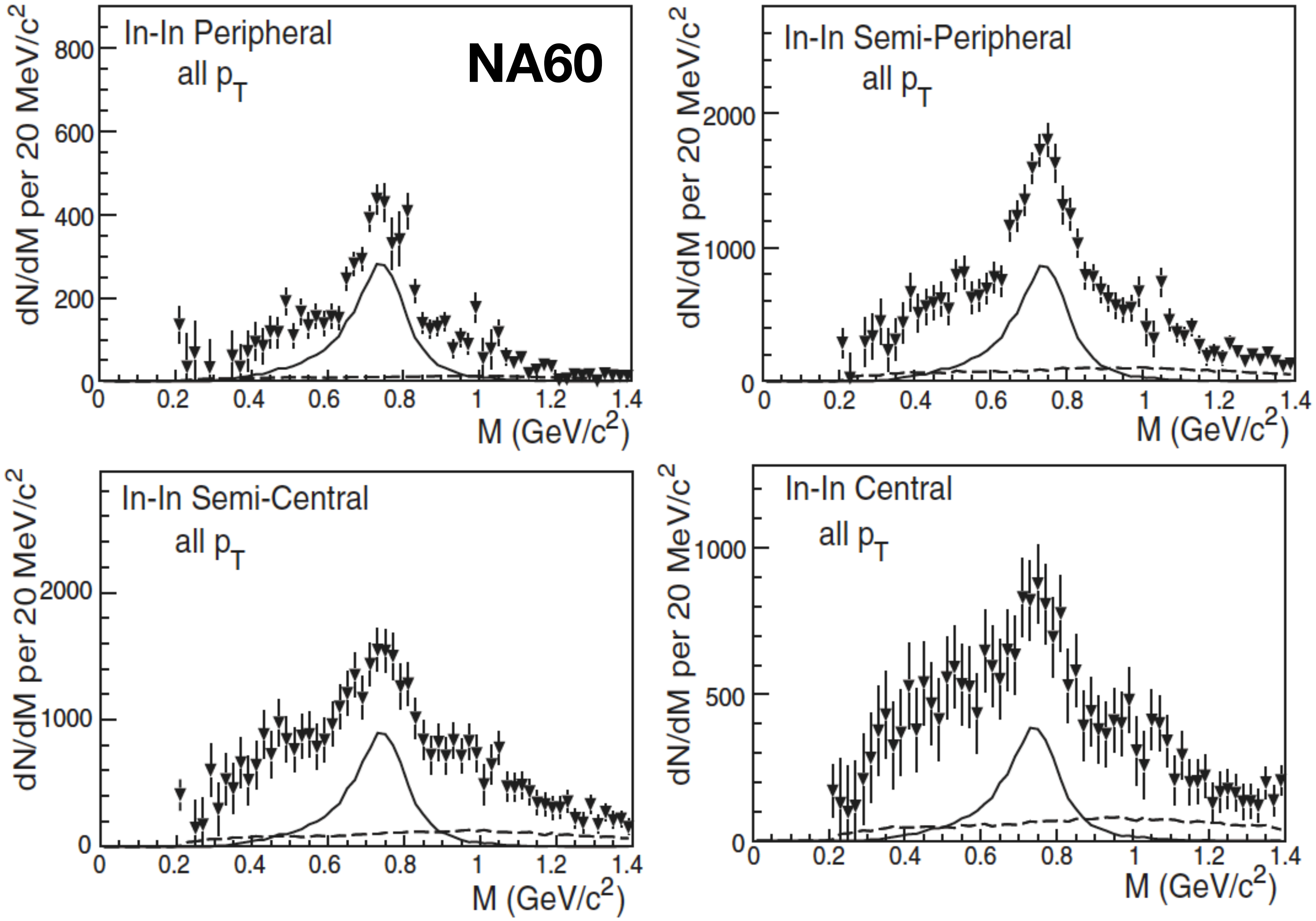
R. Arnaldi et al.,
EPJC 61 (2009) 711



ρ produced close to
or after freeze out

no mass shift but broadening !!

R. Arnaldi et al., PRL 96 (2006) 162302



melting of the ρ at the transition
to the quark-gluon plasma
→ chiral symmetry restoration

the in-medium spectral function of the ρ meson

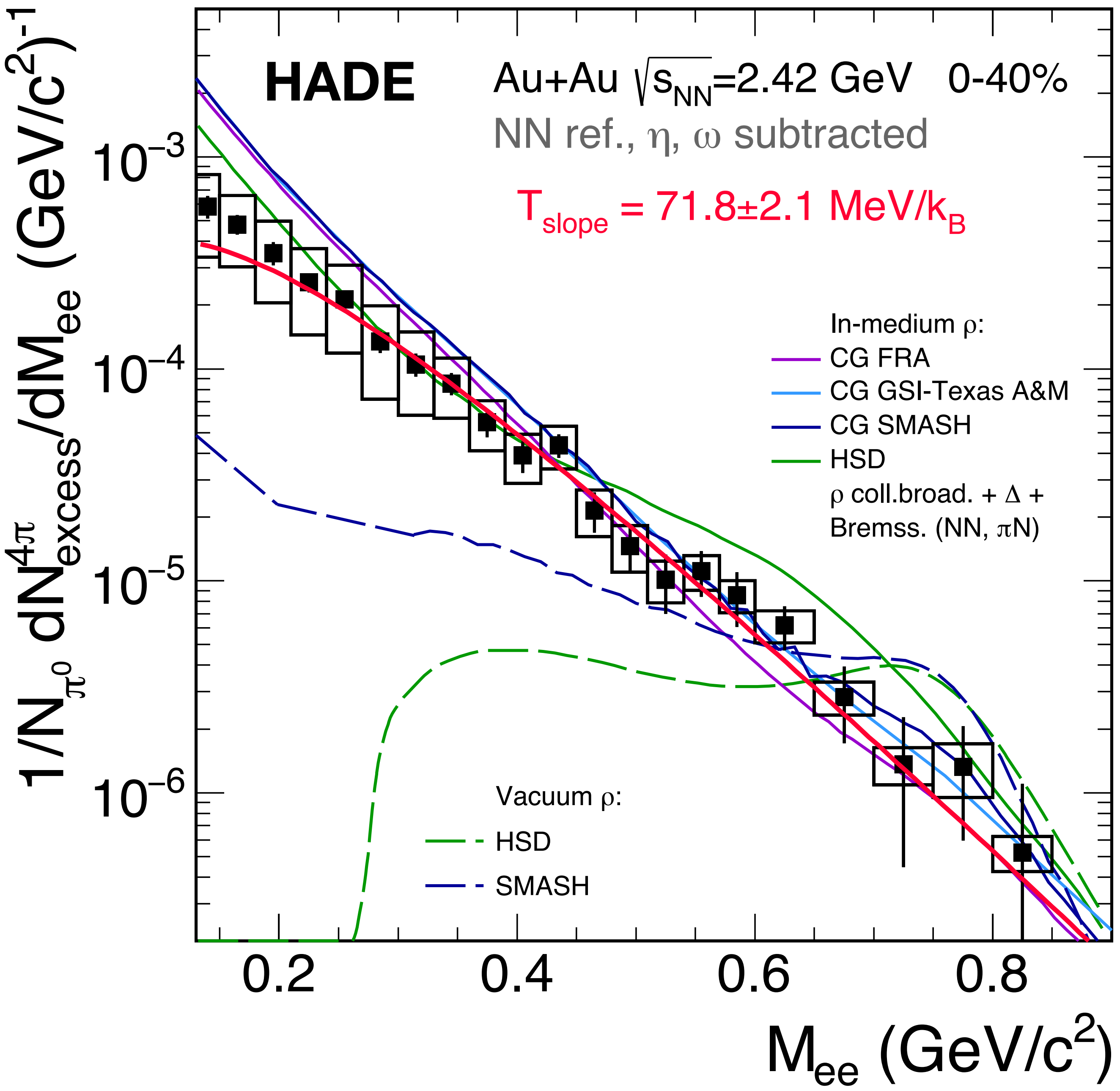
HADES: J.Adamczewski-Musch et al., Nature Physics 15 (2019) 1040

Au + Au @ $\sqrt{s_{NN}}$ = 2.42 GeV

at $\rho \approx (2\text{-}3)\ \rho_0$;
KT = (71±2.1) MeV

contributions from early NN collisions and final state particle decays subtracted

efficiency and acceptance corrected



virtual radiation from the fire ball after subtracting decays of long-lived mesons (π^0,η,ω,Φ)

calculations assuming a "free" ρ spectral function or collisional broadening overpredict data in the ρ-region

strong ρ broadening in the medium !!

ρ-meson dissolves by hadronic many-body effects

in-medium properties of the ρ meson

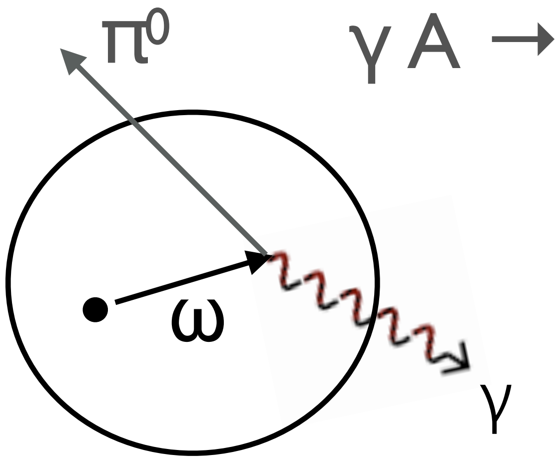
line shape analysis at nuclear density of the decay point

several independent experiment using different reactions show

- no mass shift
- broadening
- melting at high nuclear densities and temperatures

What about the in-medium properties of the many other mesons with longer lifetimes ?

problems in line shape analysis for longer-lived mesons



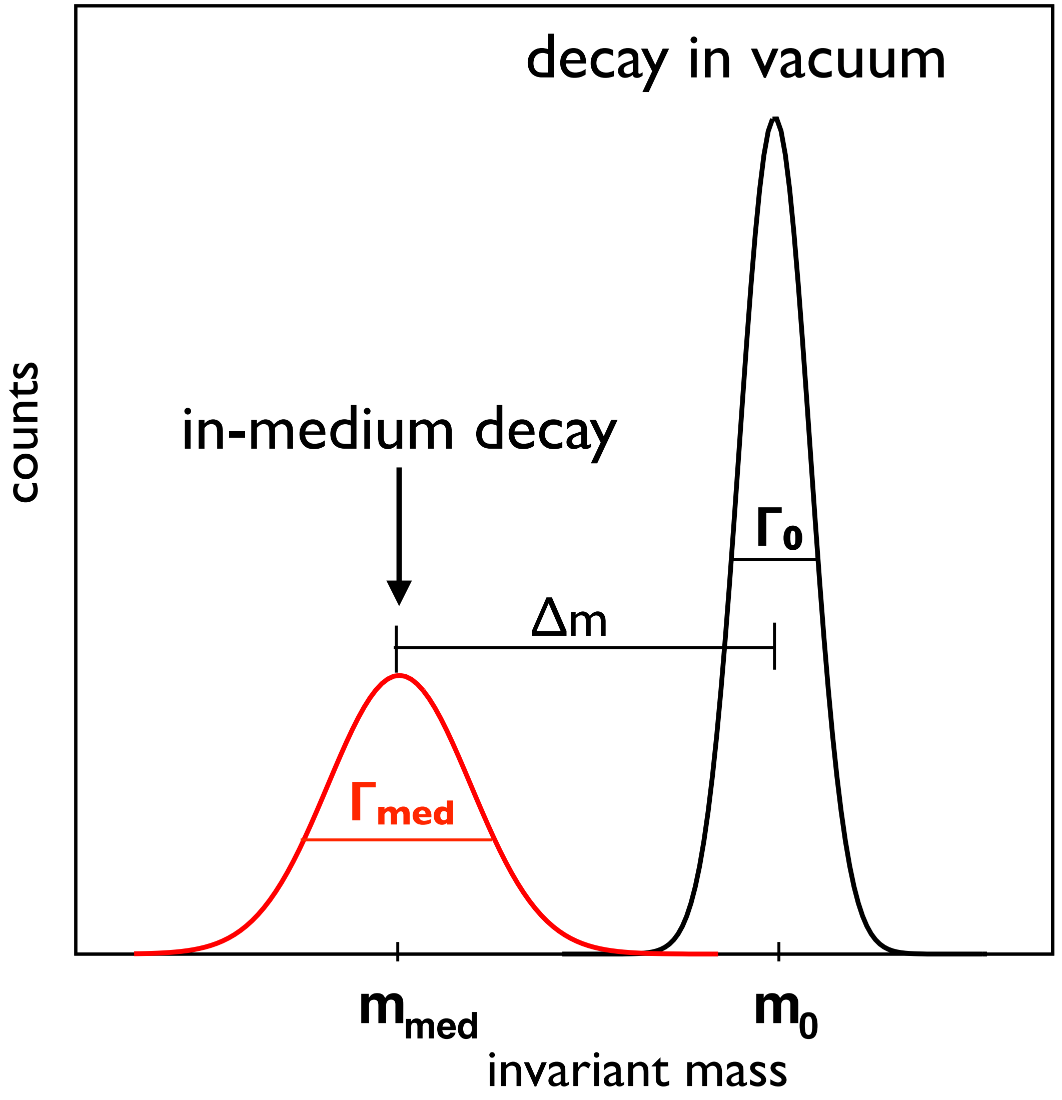
$\gamma A \rightarrow \omega X$

$\quad \hookrightarrow \pi^0 \gamma$

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

$\tau = 22$ fm/c; decay length $s = \gamma \cdot \beta\tau = \frac{p}{m} \cdot \tau$

for ω: $s \approx 22$ fm >> $R_A \approx 3\text{-}6$ fm



effects limiting the sensitivity:

1.) only fraction of decays occur within the nucleus → two-peak structure

2.) good mass resolution needed to separate the two peaks

3.) in-medium decays occur over wide range of nuclear densities (nuclear density profile) $\Delta m = \Delta m(\rho)$

4.) additional complication: hadronic decay products, e.g. $\omega \rightarrow \pi^0\gamma$
distortion of momenta and mass by final state interactions
absorption of decay products → reduced signal

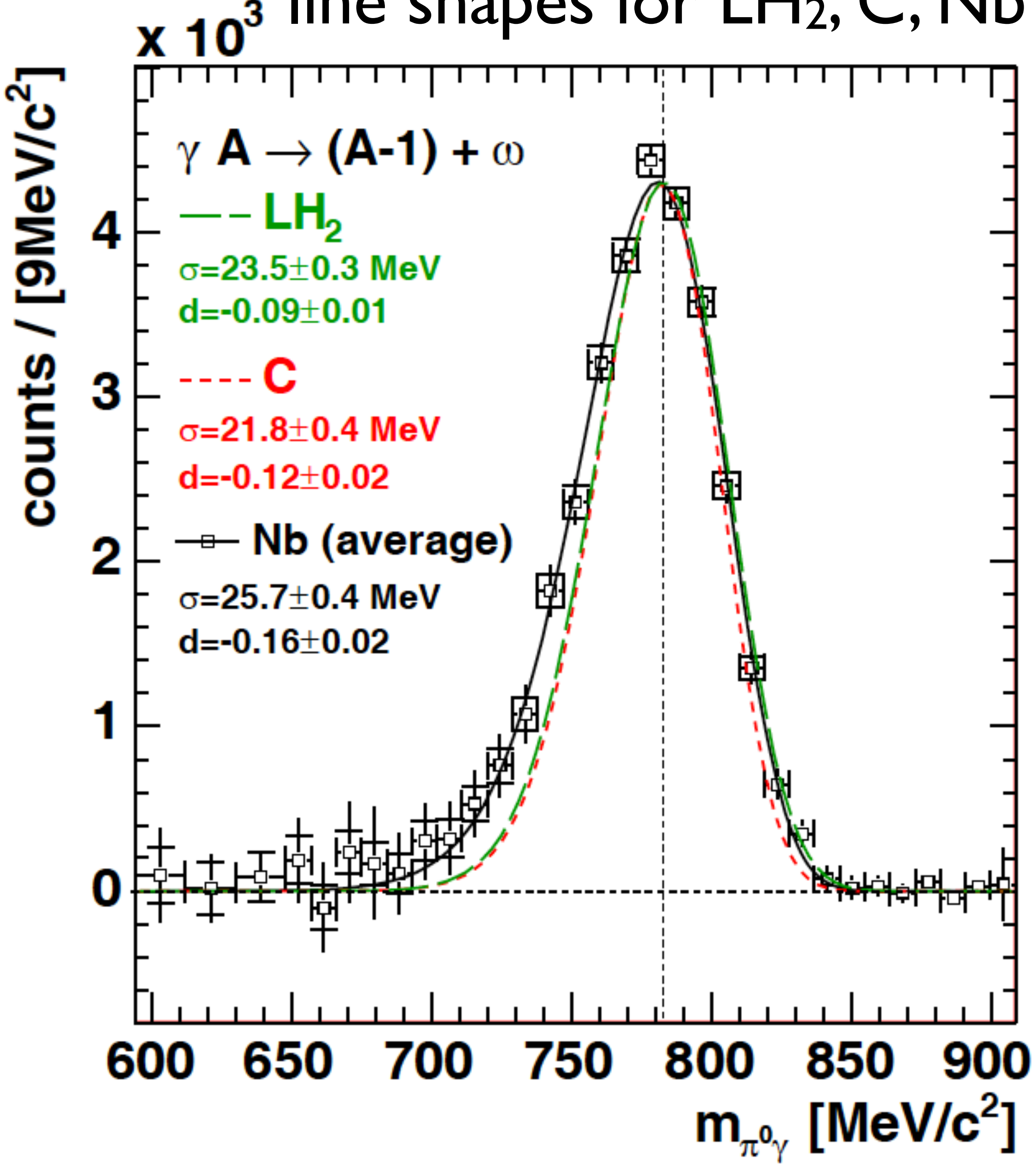
ω line shape in $\omega \rightarrow \pi^0\gamma$

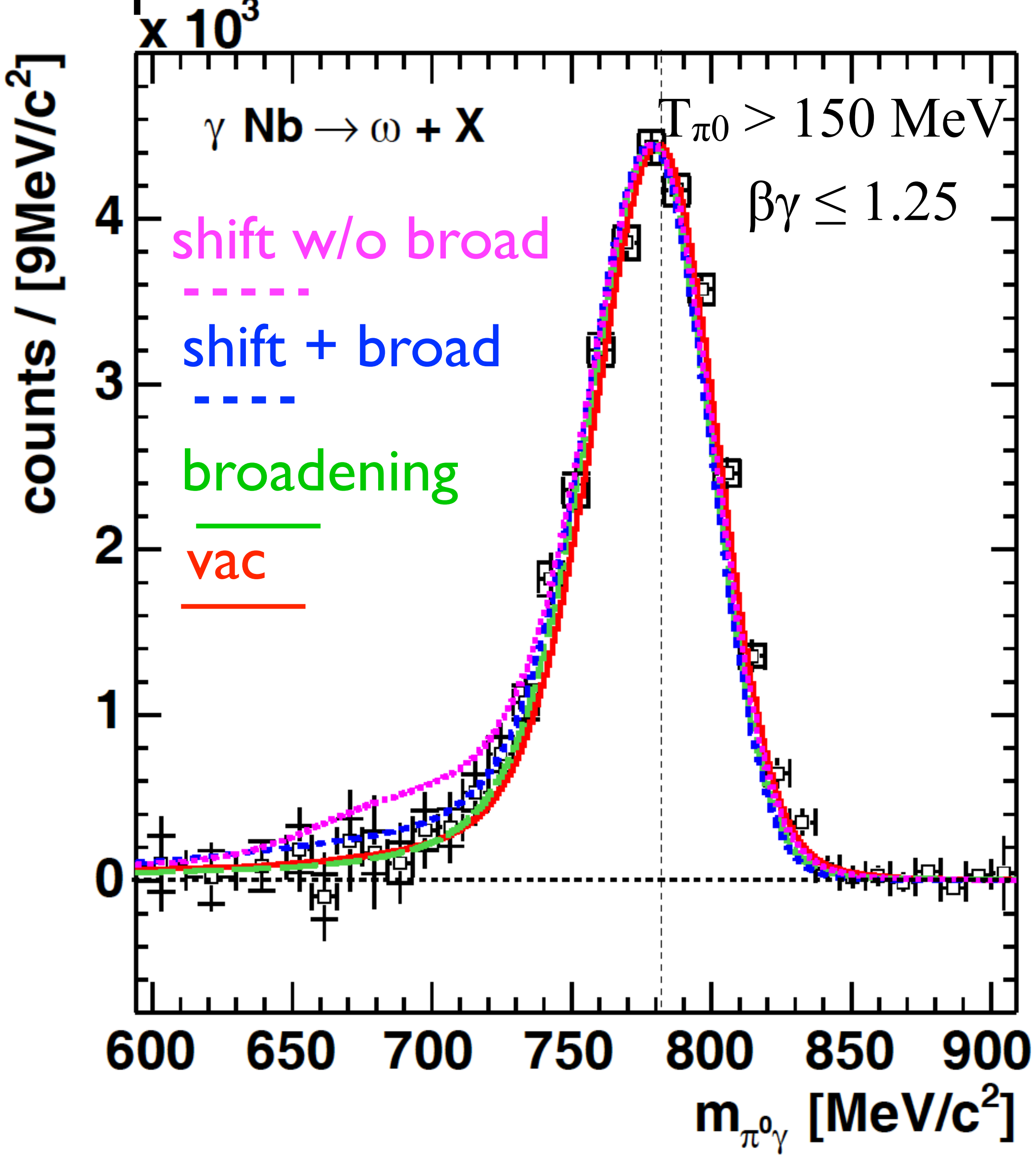
$\gamma A \rightarrow \omega X$; E_γ= 900-1300 MeV (MAMI)

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

line shapes for LH_2, C, Nb

comparison with GiBUU simulations





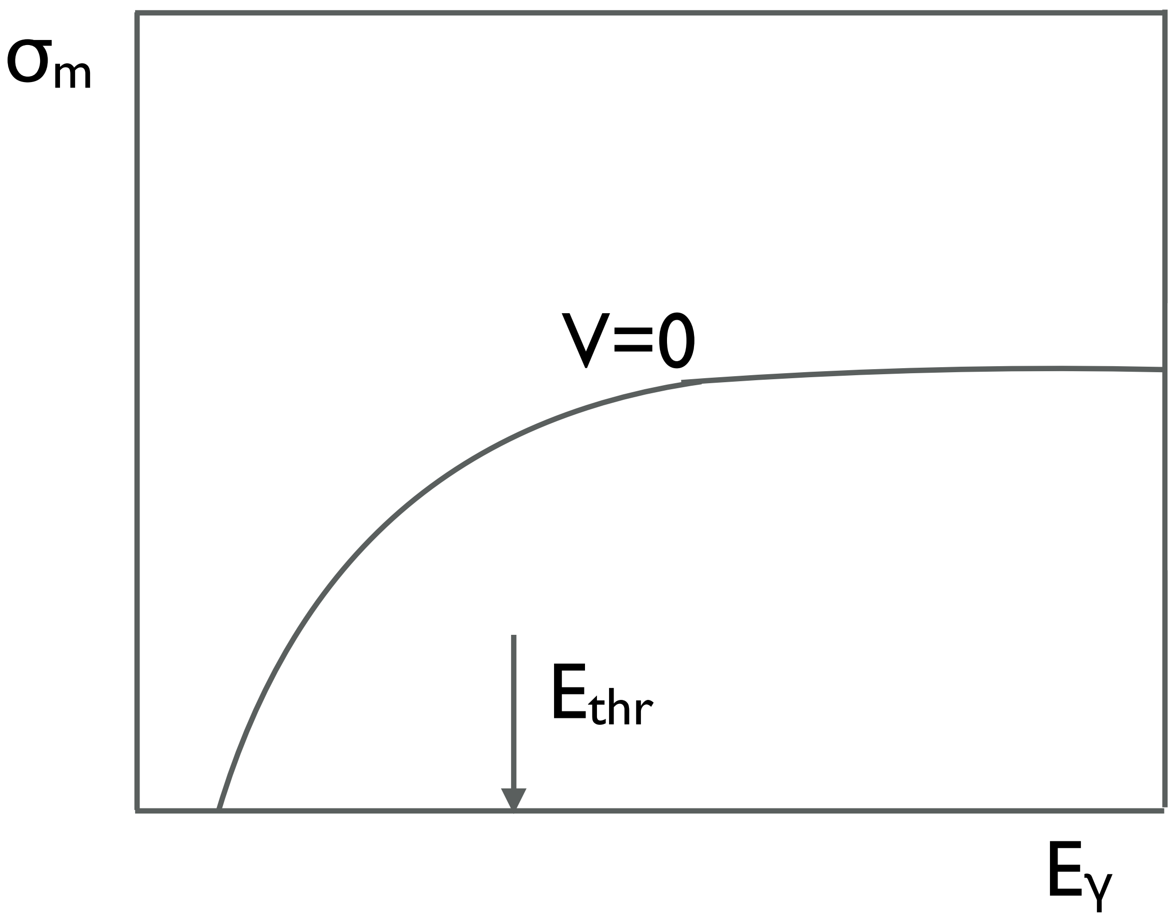
signal broader for Nb than for LH_2, C

different modification scenarios can not be distinguished

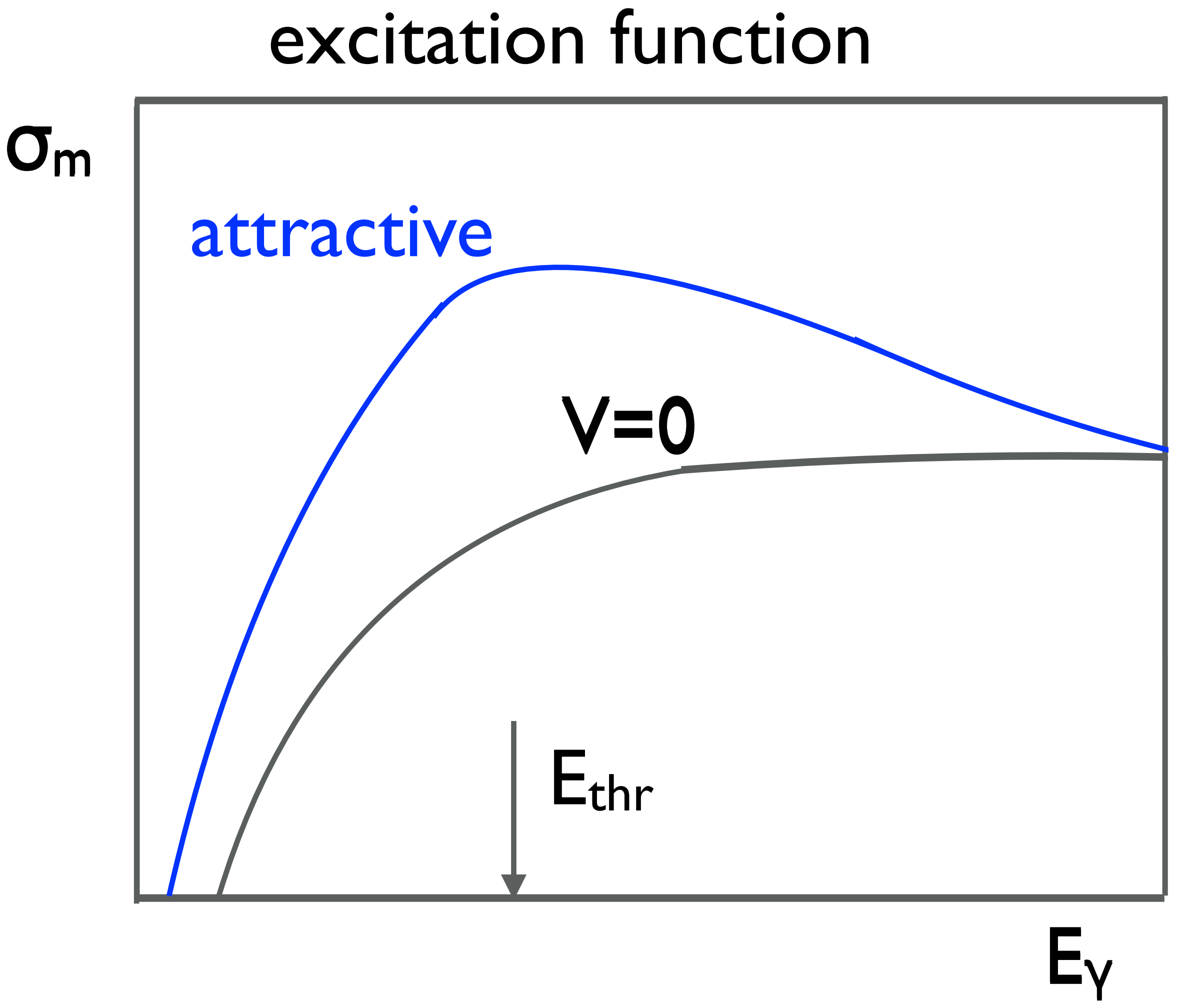
studying invariant masses of long-lived mesons at the decay point has only limited sensitivity to in-medium effects !!

studying meson properties at density of the production point

excitation function

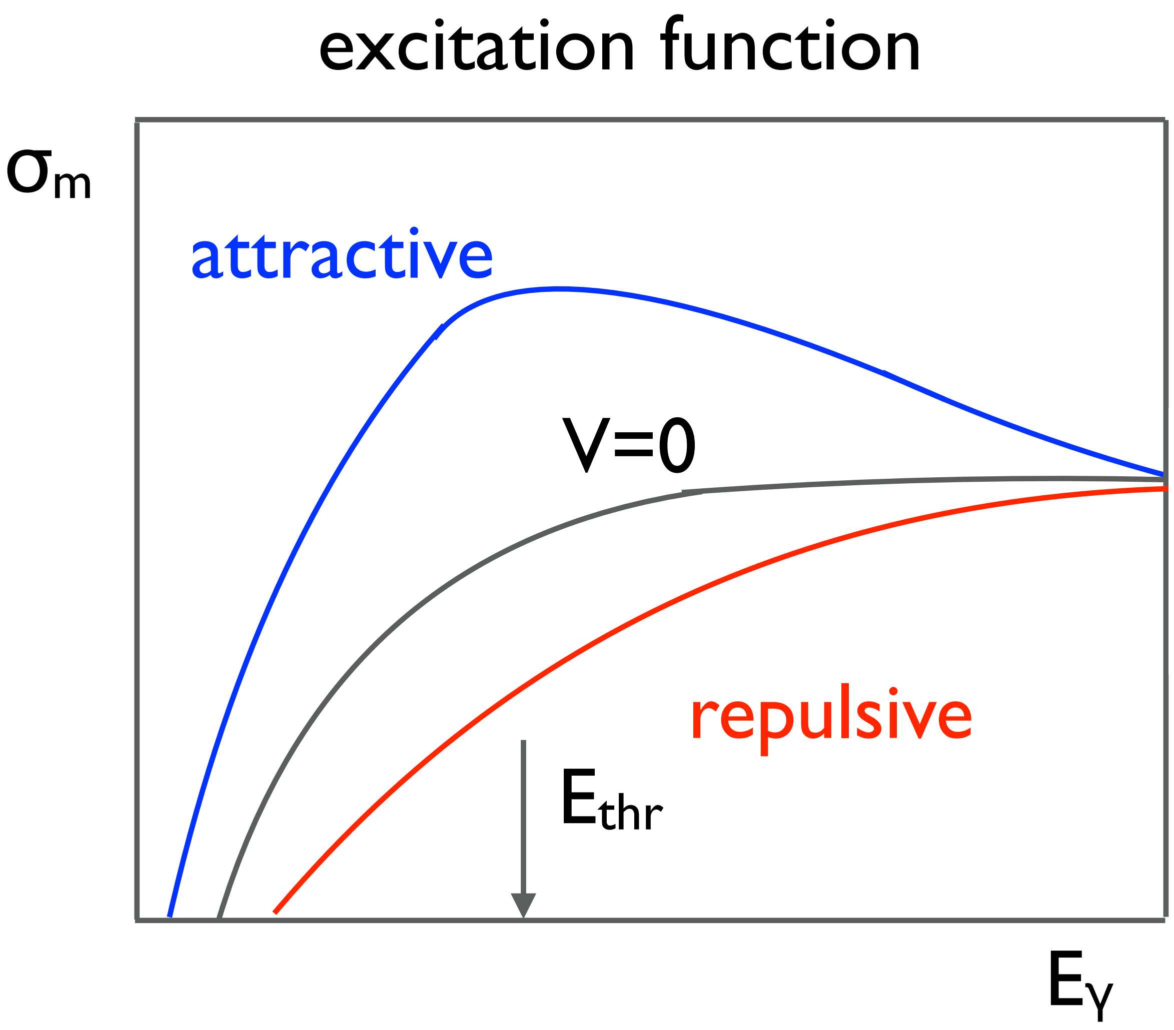


studying meson properties at density of the production point



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

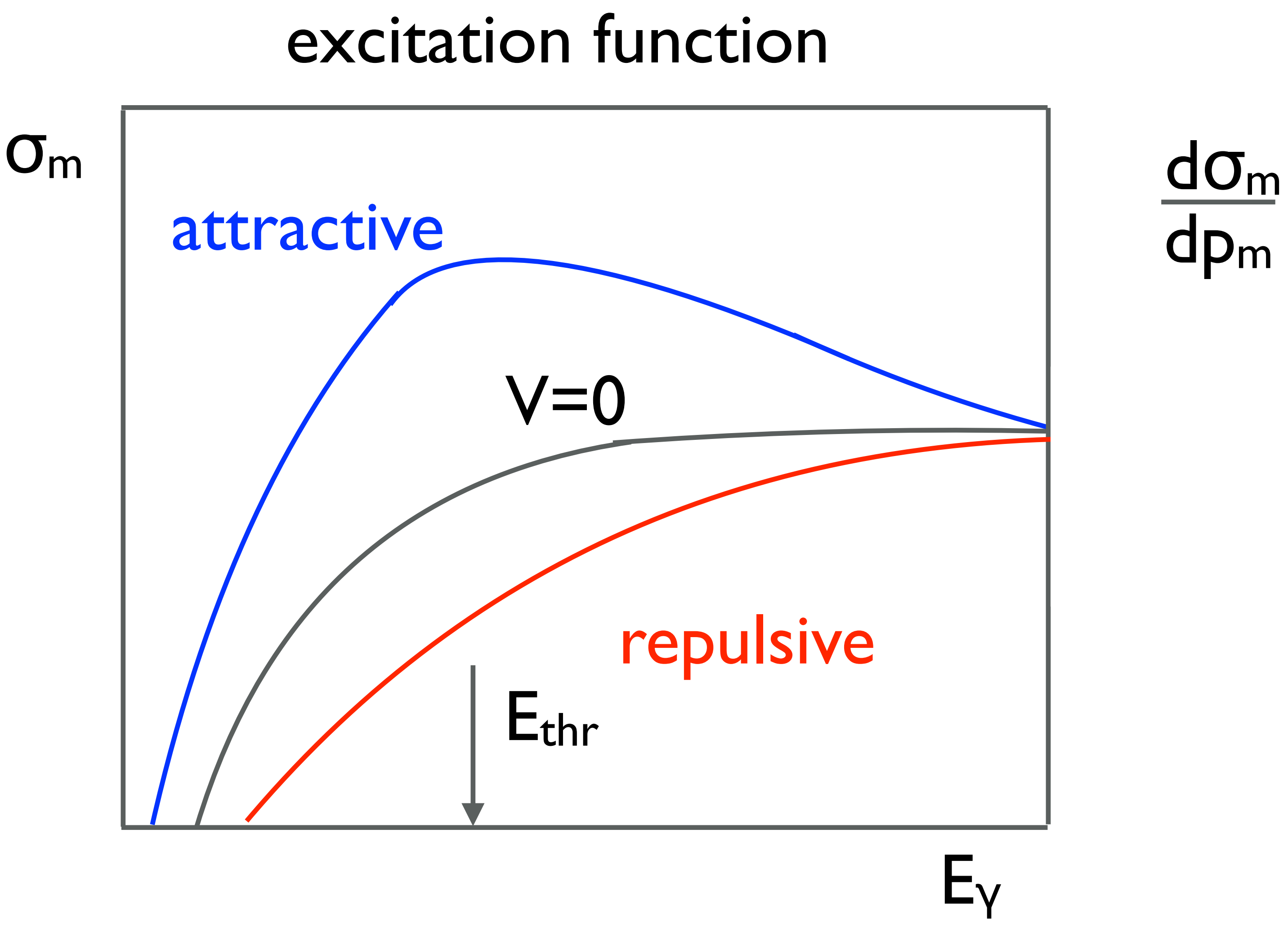
studying meson properties at density of the production point

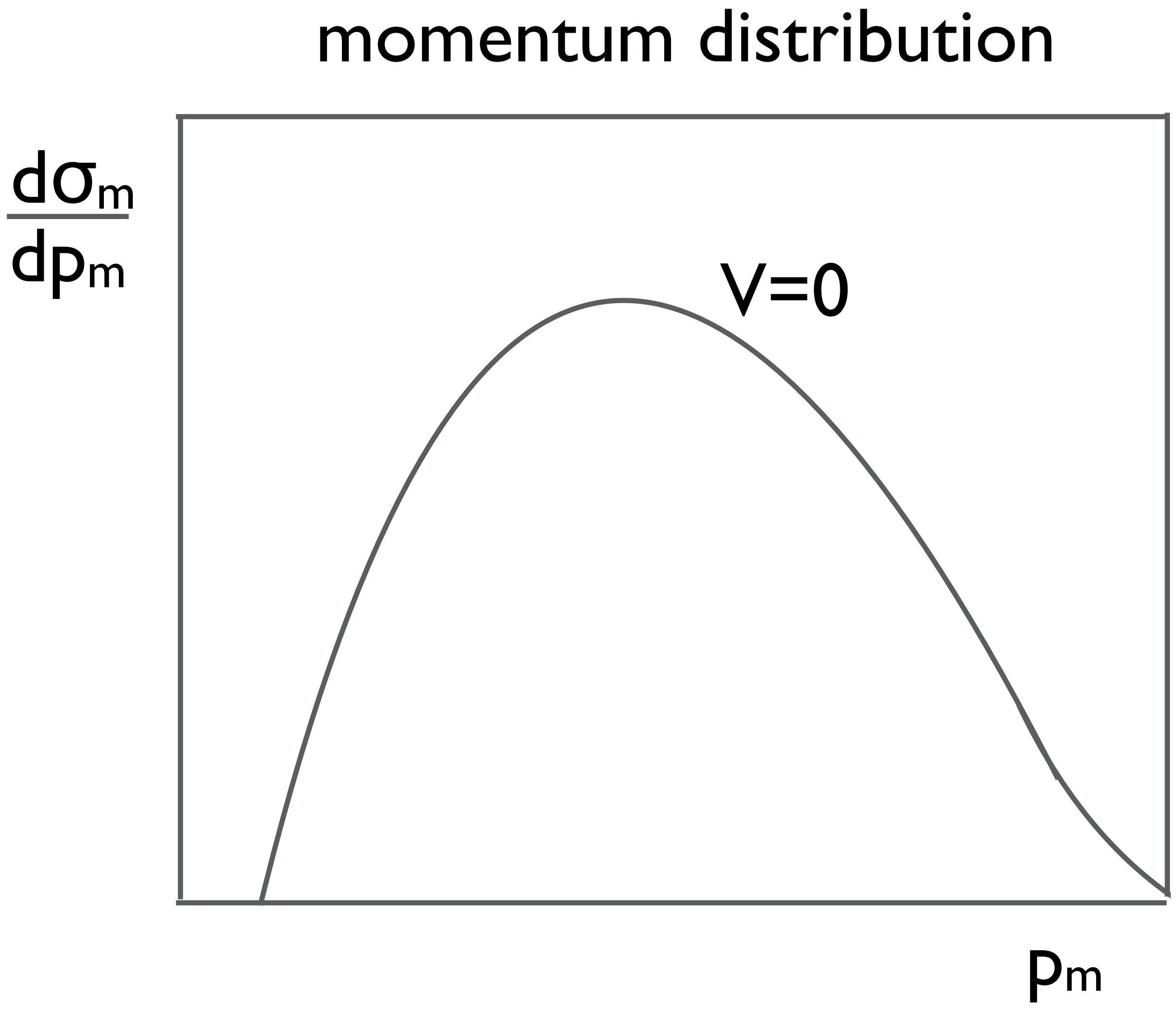


attractive interaction → mass drop
→ lower threshold → larger phase space
→ larger cross section

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

studying meson properties at density of the production point

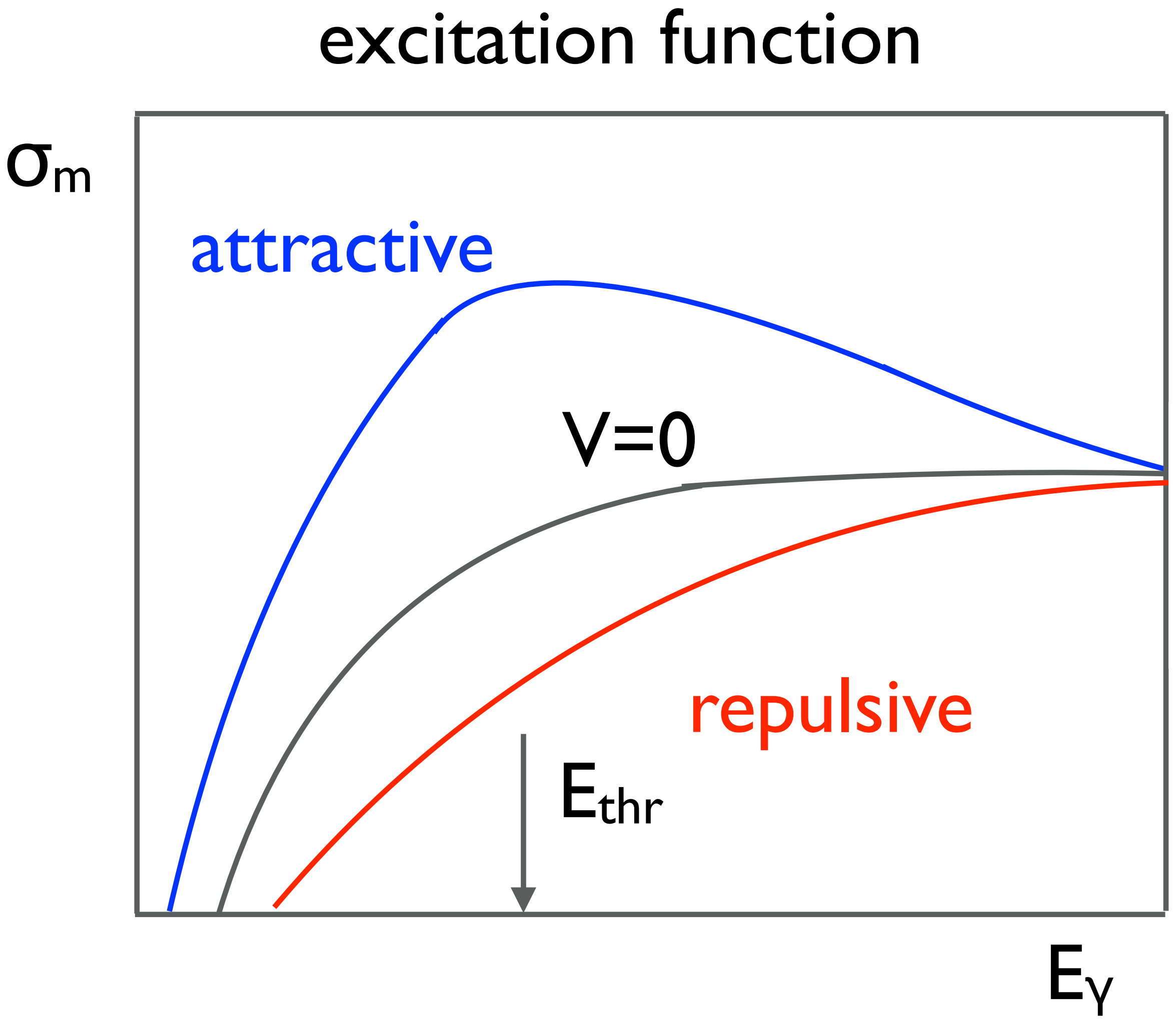


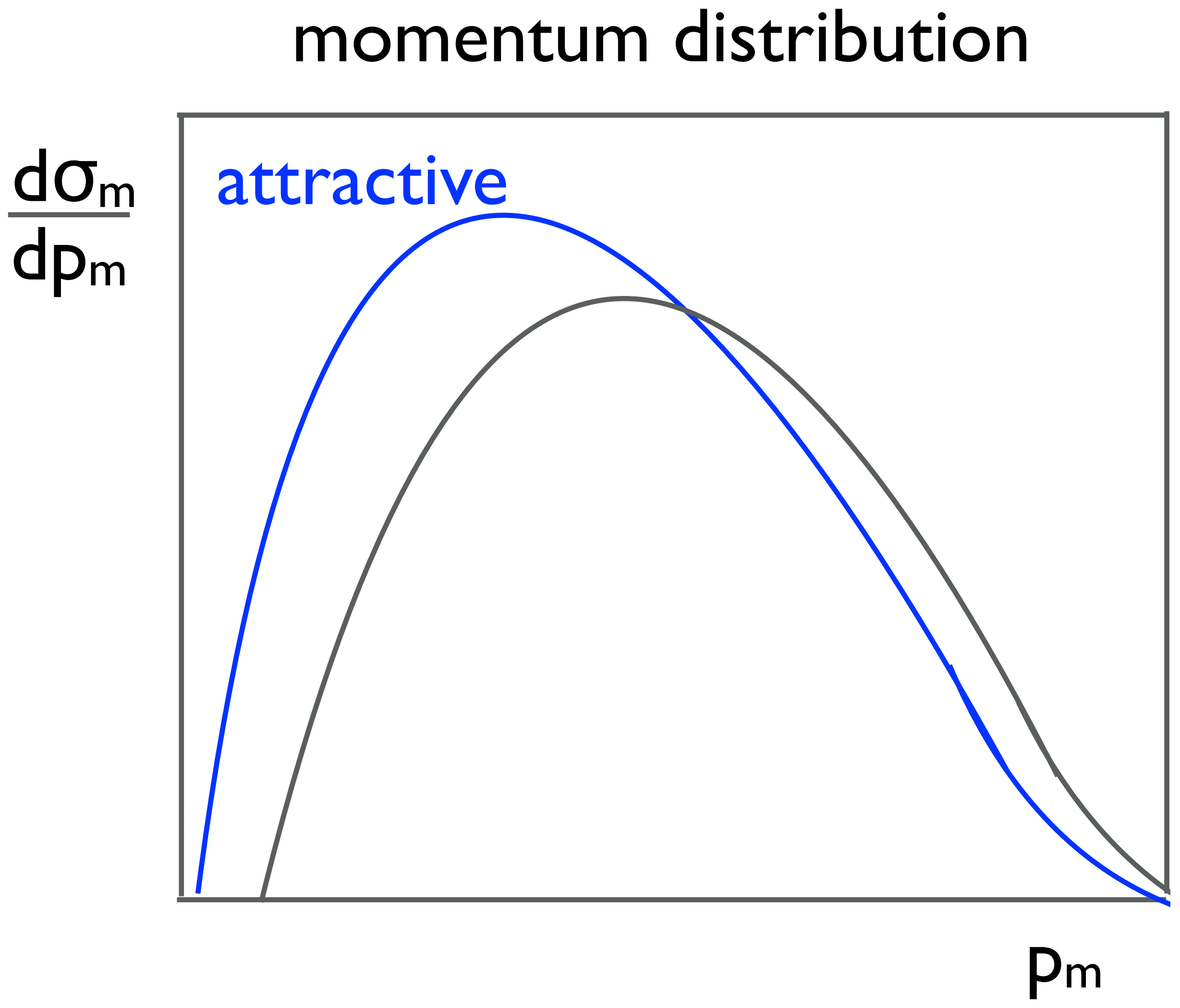


attractive interaction → mass drop
→ lower threshold → larger phase space
→ larger cross section

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

studying meson properties at density of the production point





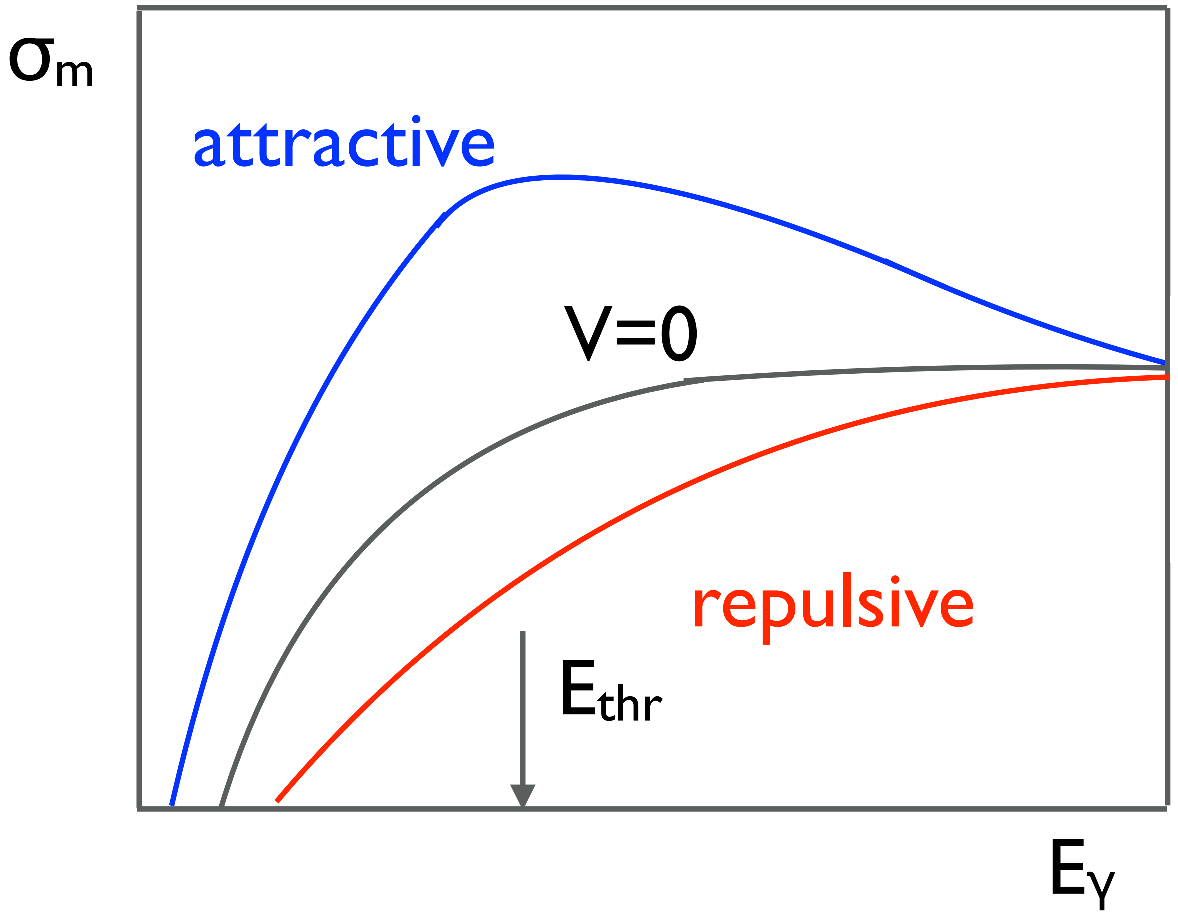
attractive interaction → mass drop
→ lower threshold → larger phase space
→ larger cross section

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

attractive interaction
→ meson slowed down
→ shift to lower momenta

studying meson properties at density of the production point

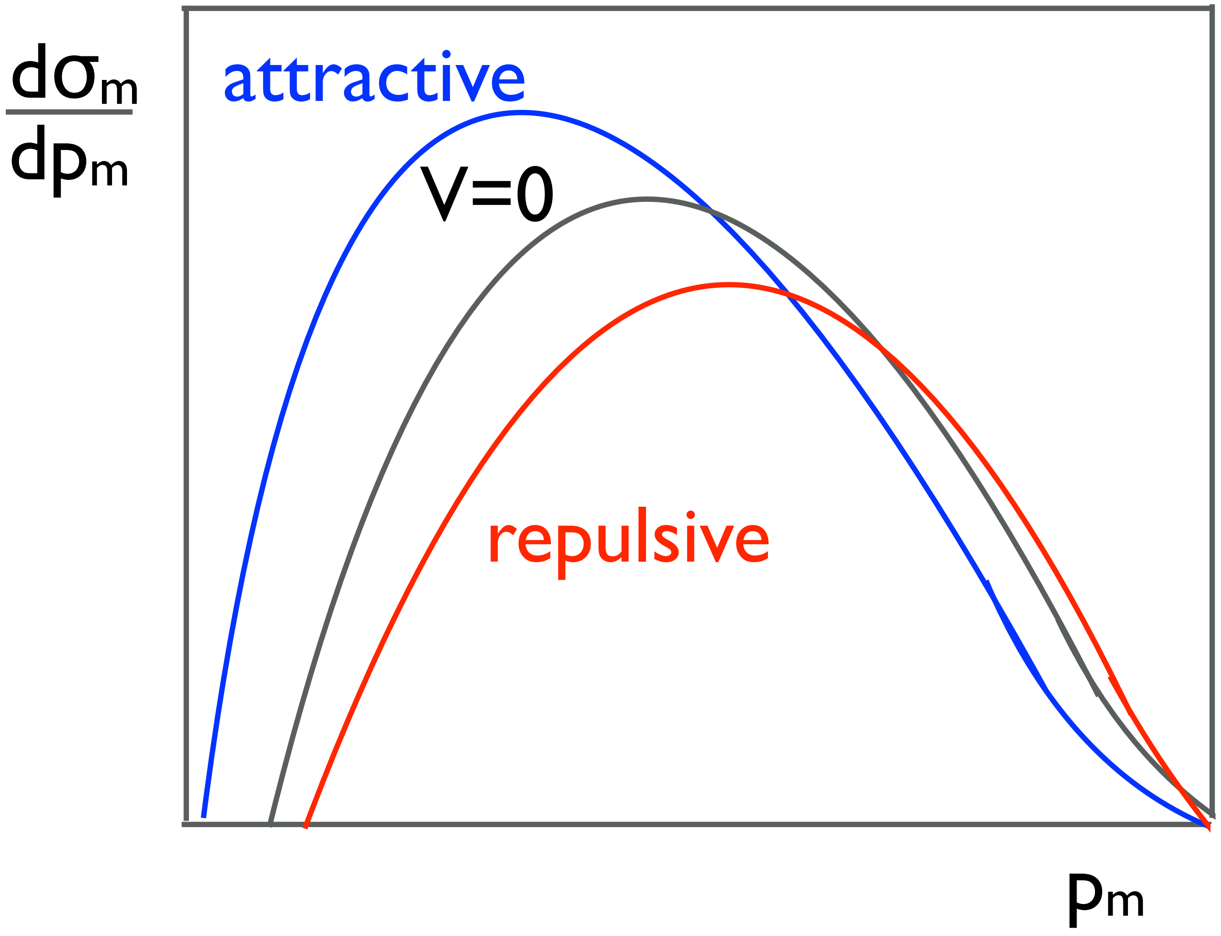
excitation function



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

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

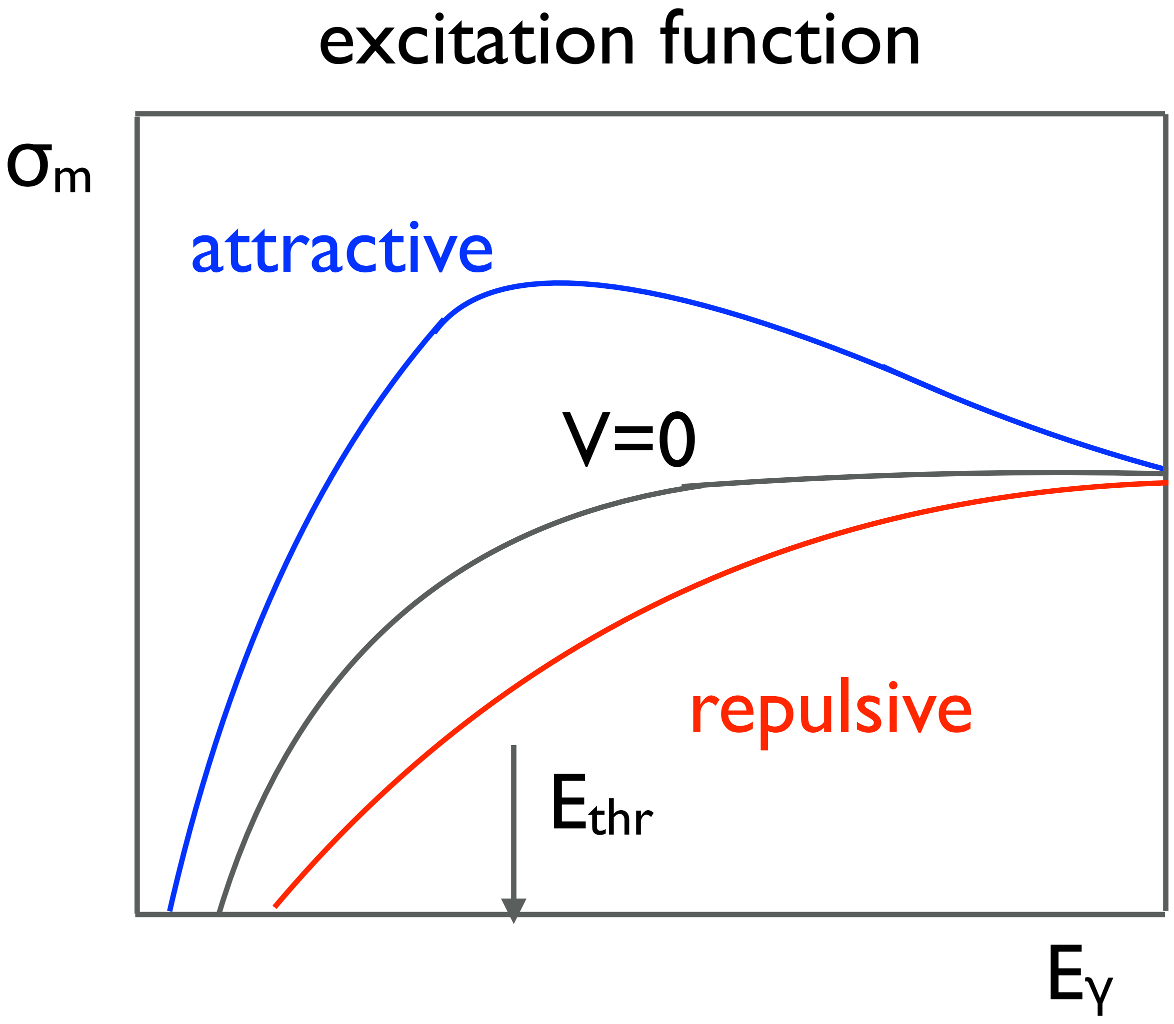
momentum distribution

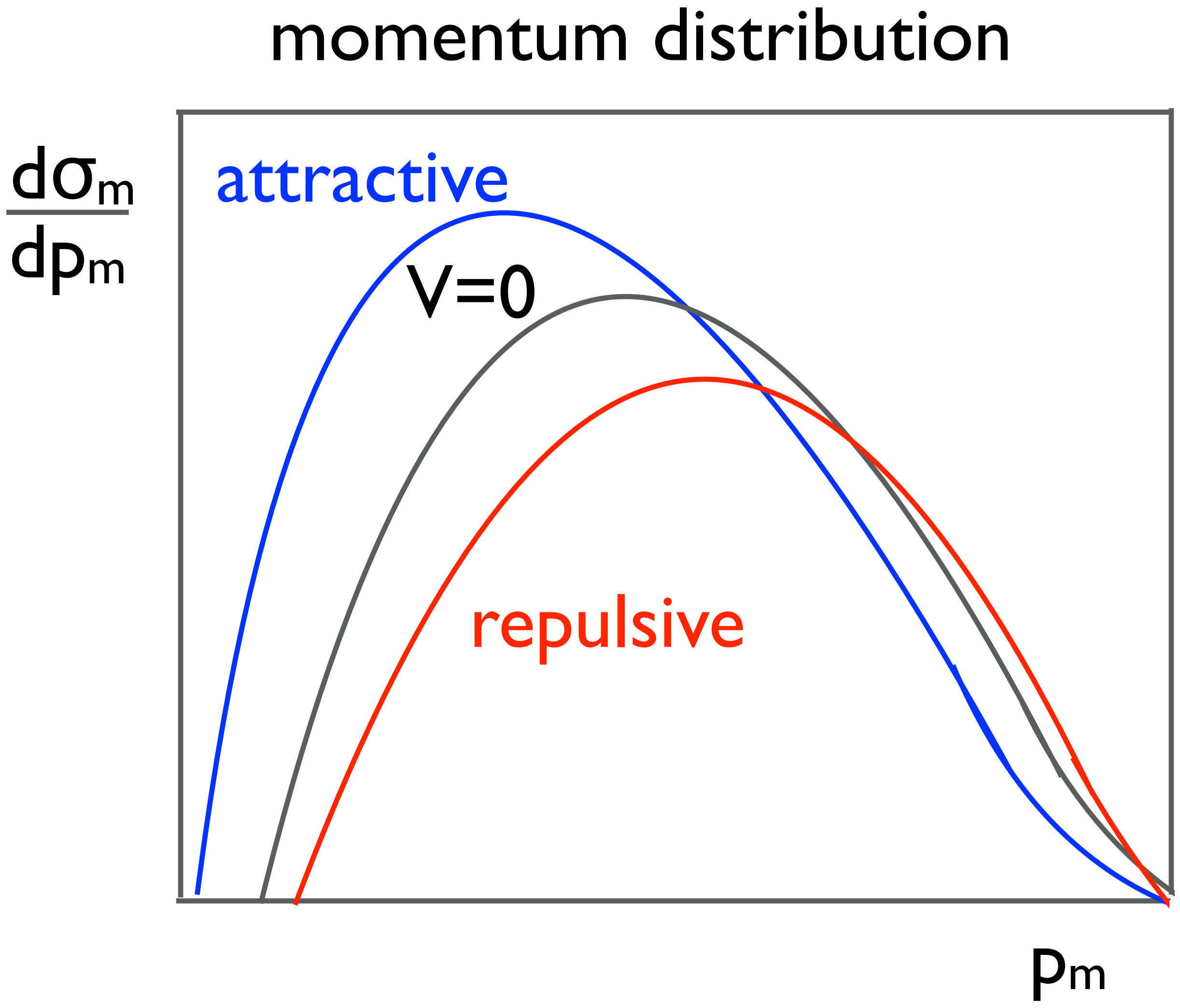


attractive interaction
→ meson slowed down
→ shift to lower momenta

repulsive interaction → extra kick
→ shift to higher momenta

studying meson properties at density of 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

attractive interaction
→ meson slowed down
→ shift to lower momenta

repulsive interaction → extra kick
→ shift to higher momenta

quantitative analysis requires comparison to transport- or collision models
→ model dependence !!!!

meson-nucleus potential

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

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

attractive ?
repulsive ?

absorption

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

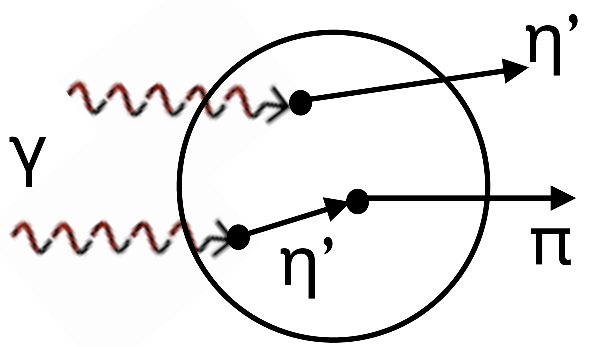
$$W(r) = -\Gamma_0/2\cdot\rho(r)/\rho_0$$
$$= -1/2\cdot\hbar c\cdot\rho(r)\cdot\sigma_{inel}\cdot\beta$$

- excitation function
- momentum distribution

- transparency ratio measurement

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

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



η’ N → π N

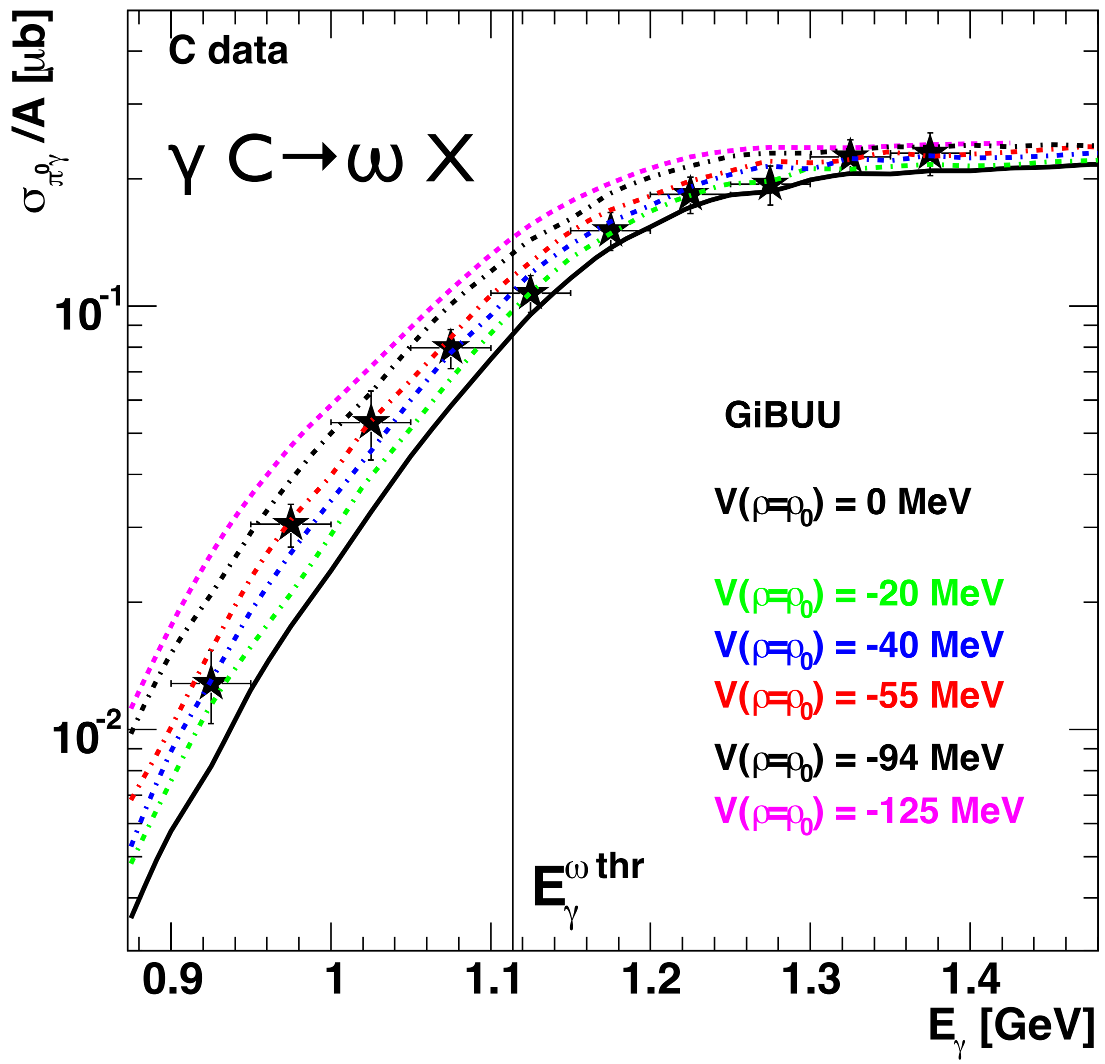
determining the real part and imaginary part of the ω-nucleus potential from measurement of excitation function and transparency ratio

ω $\tau \approx 22$ fm/c

A2@MAMI

real part from excitation function

V. Metag et al., Prog. Part. Nucl. Phys. 67 (2012) 530



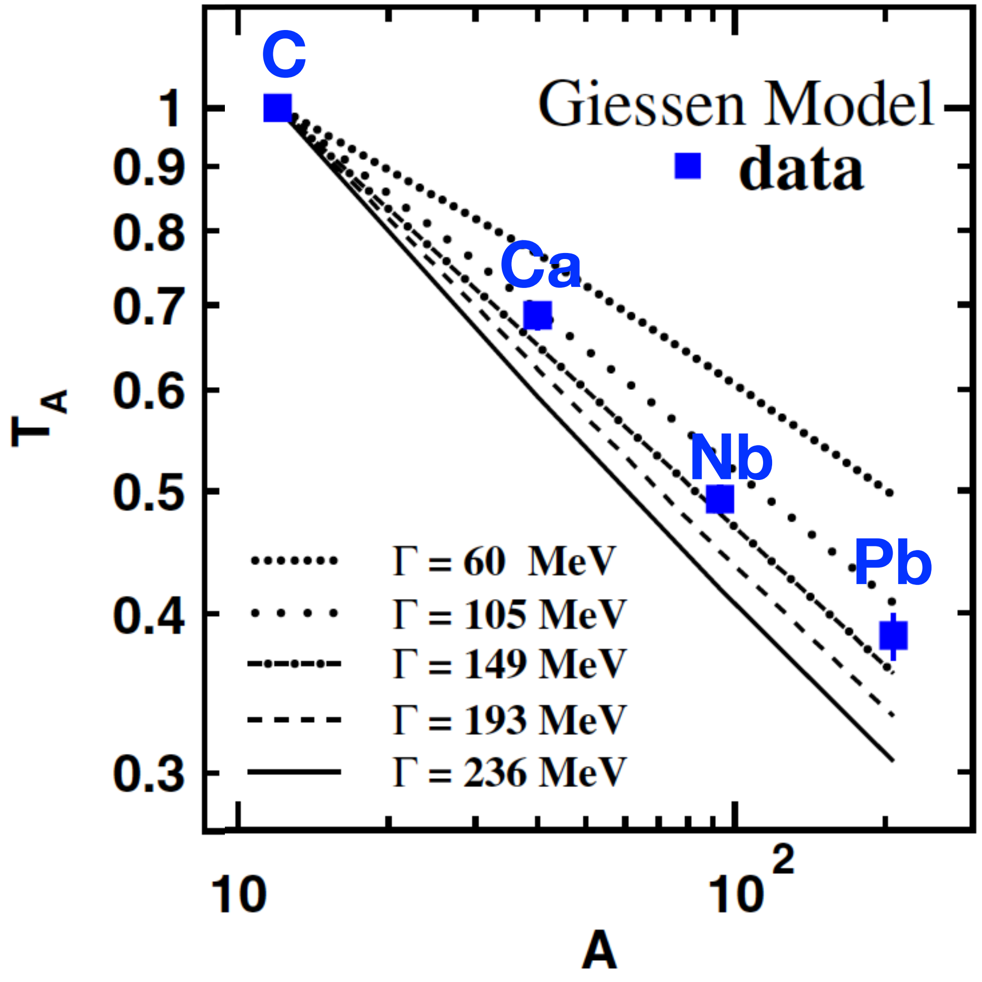
including information from momentum distributions (S. Friedrich et al. PLB 736 (2014) 26)

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

imaginary part from transparency ratio

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

M. Kotulla et al., PRL 100 (2008) 192302
PRL 114 (2015) 199903



$\Gamma(\rho=\rho_0) \approx 120$ MeV; $W_{\omega A} \approx 60$ MeV

including data from
S. Friedrich (EPJA 52 (2016)297)

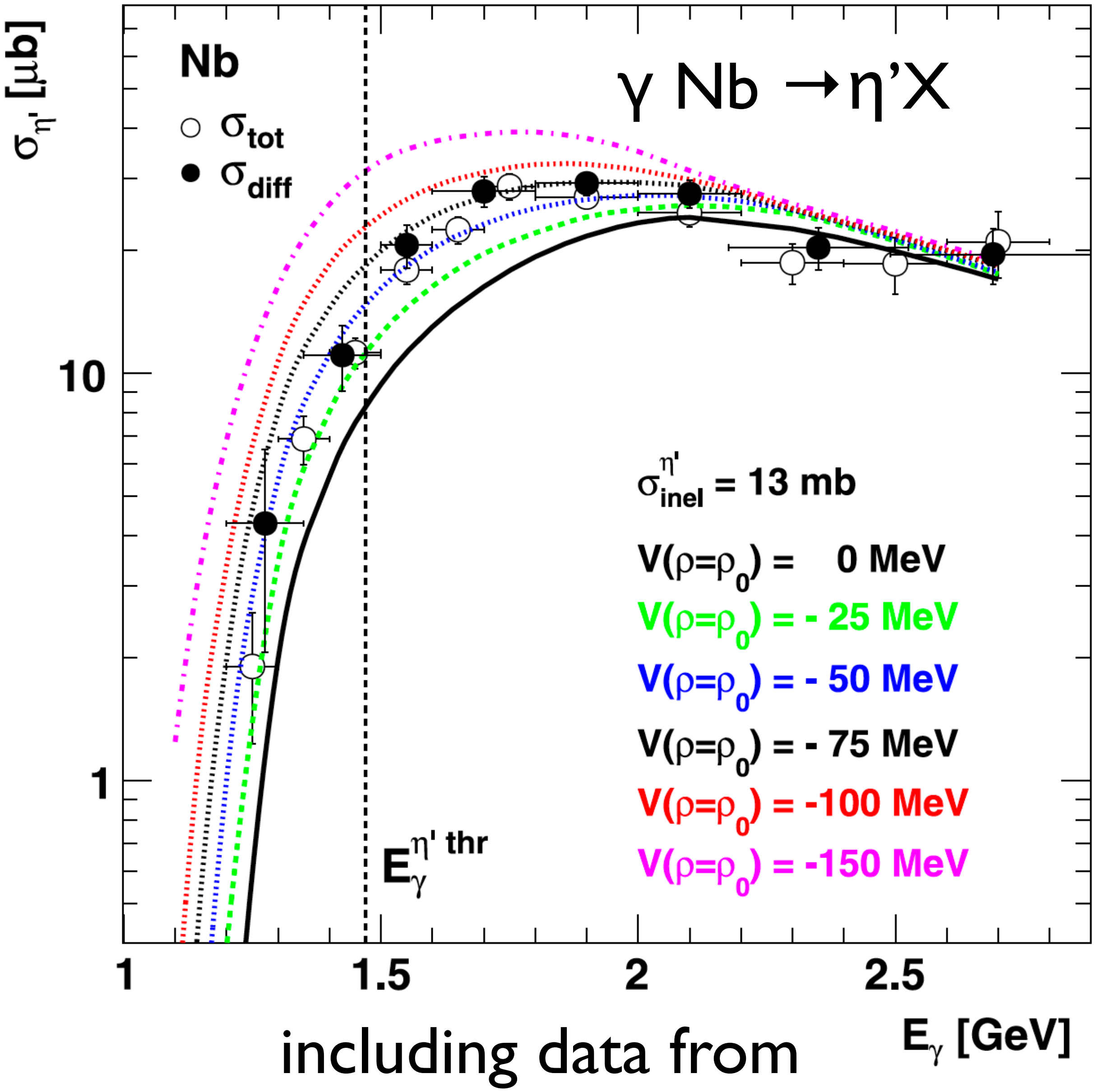
$W_{\omega A}(\rho=\rho_0)$ = -(48±12(stat)±9(syst)) MeV

determining the real part and imaginary part of the η'-nucleus potential from measurement of excitation function and transparency ratio

η' τ ≈ 1000 fm/c

CBELSA/TAPS @ ELSA

calc.: E. Paryev, J. Phys. G 40 (2013) 025201
data: M. Nanova et al., PRC 94 (2016) 025205



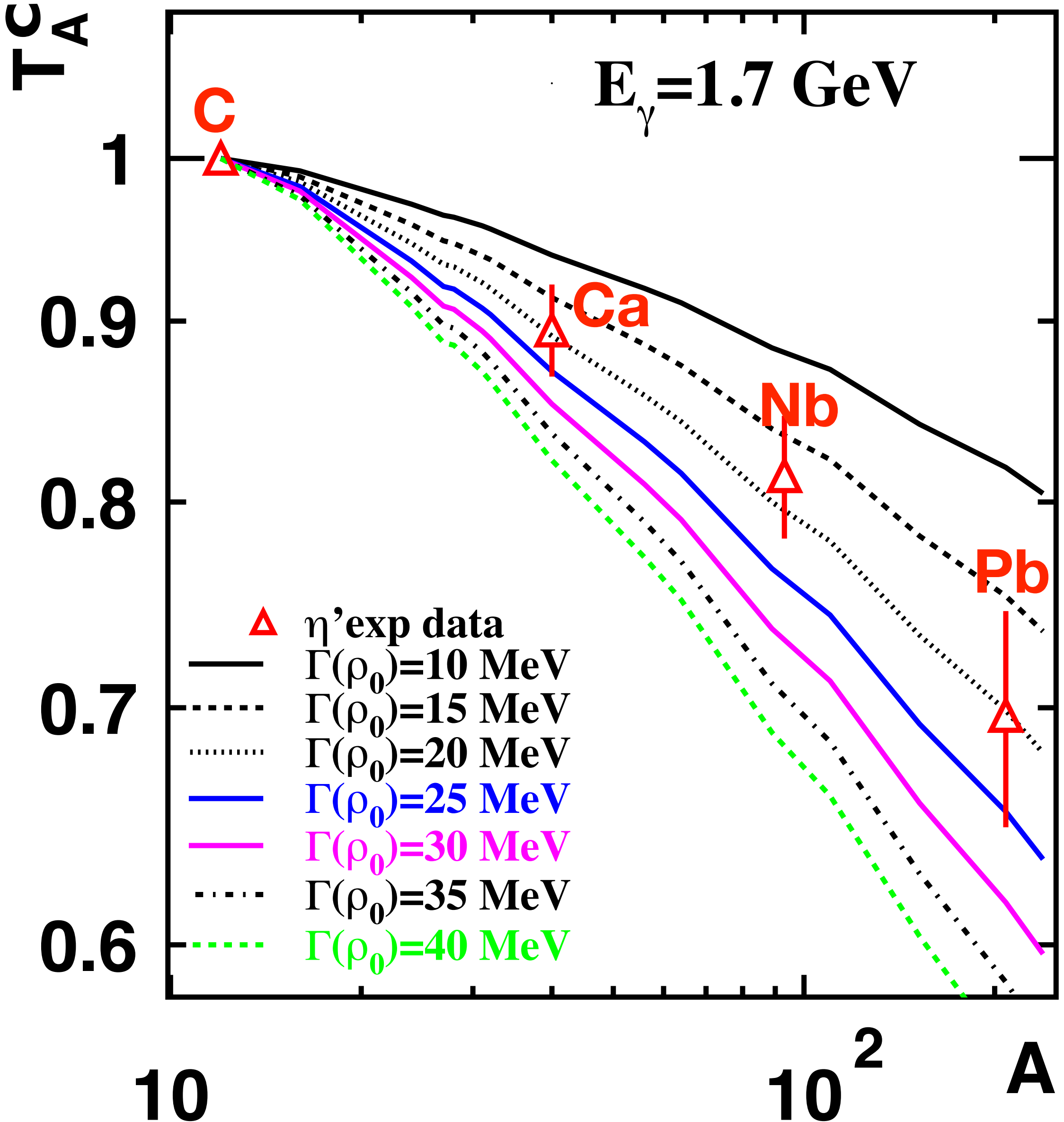
including data from
C: M. Nanova et al., PLB 727 (2013) 417

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

data disfavour strong mass shifts

mass dependence of T_A

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

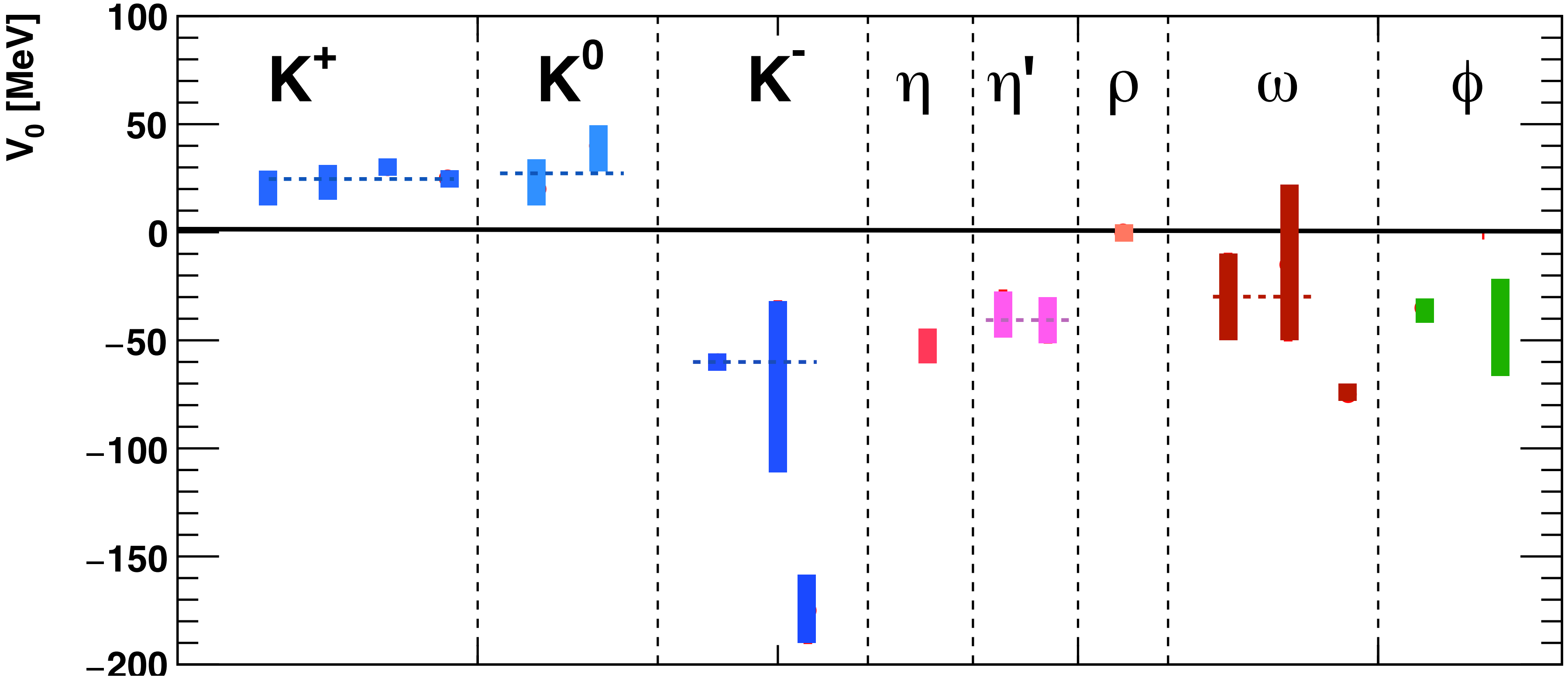


including data from
S. Friedrich et al. EPJA 52 (2016 297

$W_{\eta'A}(\rho=\rho_0)$ = -(13±3(stat)±3(syst)) MeV

the meson-nucleus potential $U(\rho_0) = V(\rho_0) + i\,W(\rho_0)$

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



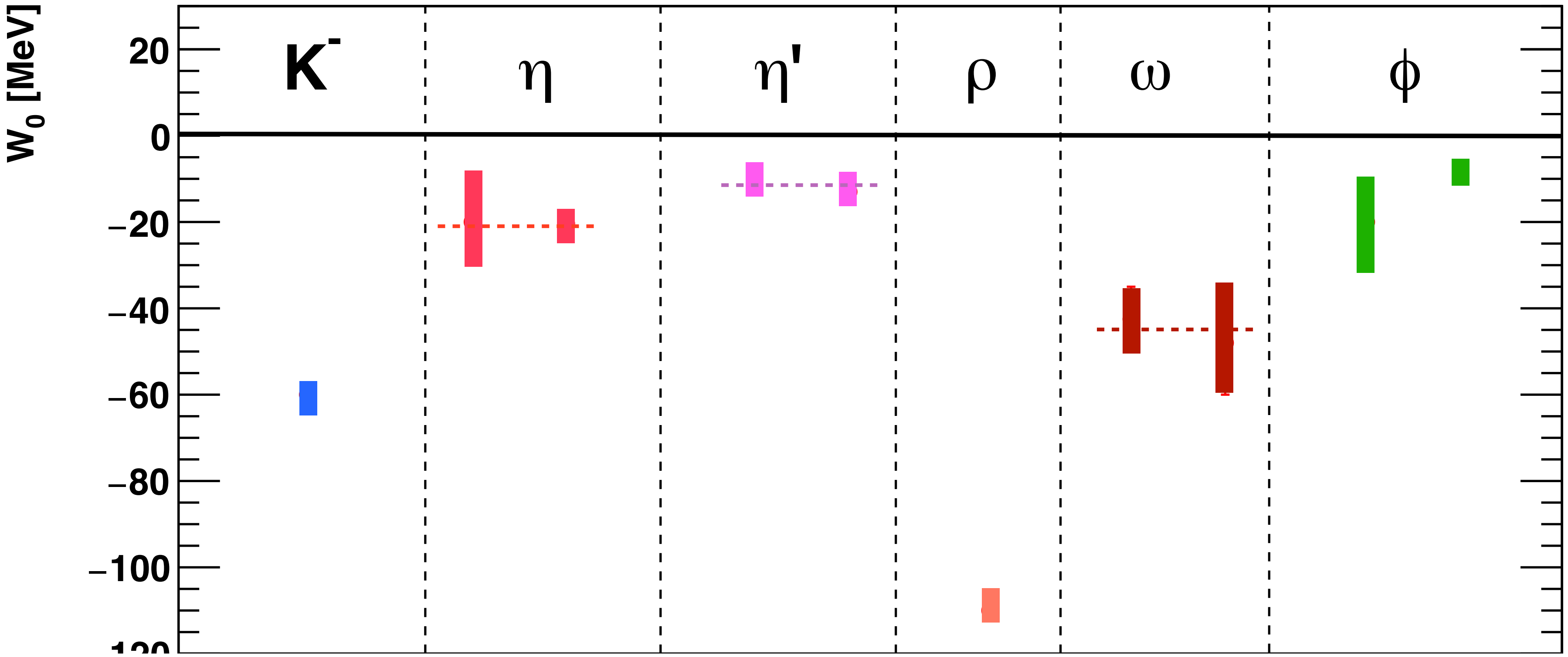
real potential $V(\rho_0)$

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

K^- : - (30 - 100) MeV

η, η’, ω, Φ : - (20 - 50) MeV

ρ: ≈ 0



imaginary potential $W(\rho_0)$

η’ : ≈ -10 MeV

η, Φ : ≈ - 20 MeV

ω : ≈ - 40 MeV quite broad

K^- : ≈ - 60 MeV very broad

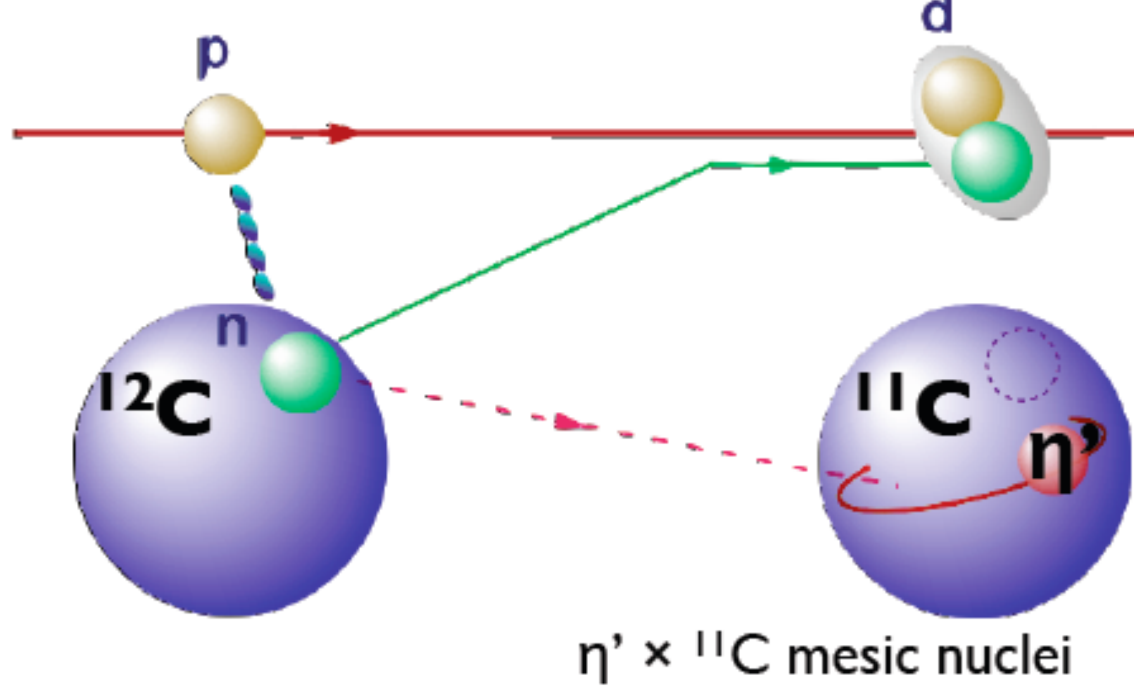
ρ: ≈ -110 MeV

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

search for η’ - nucleus bound states in ^{12}C(p,d)η’X

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

FRS@GSI: K. Itahashi et al., Exp. S 437



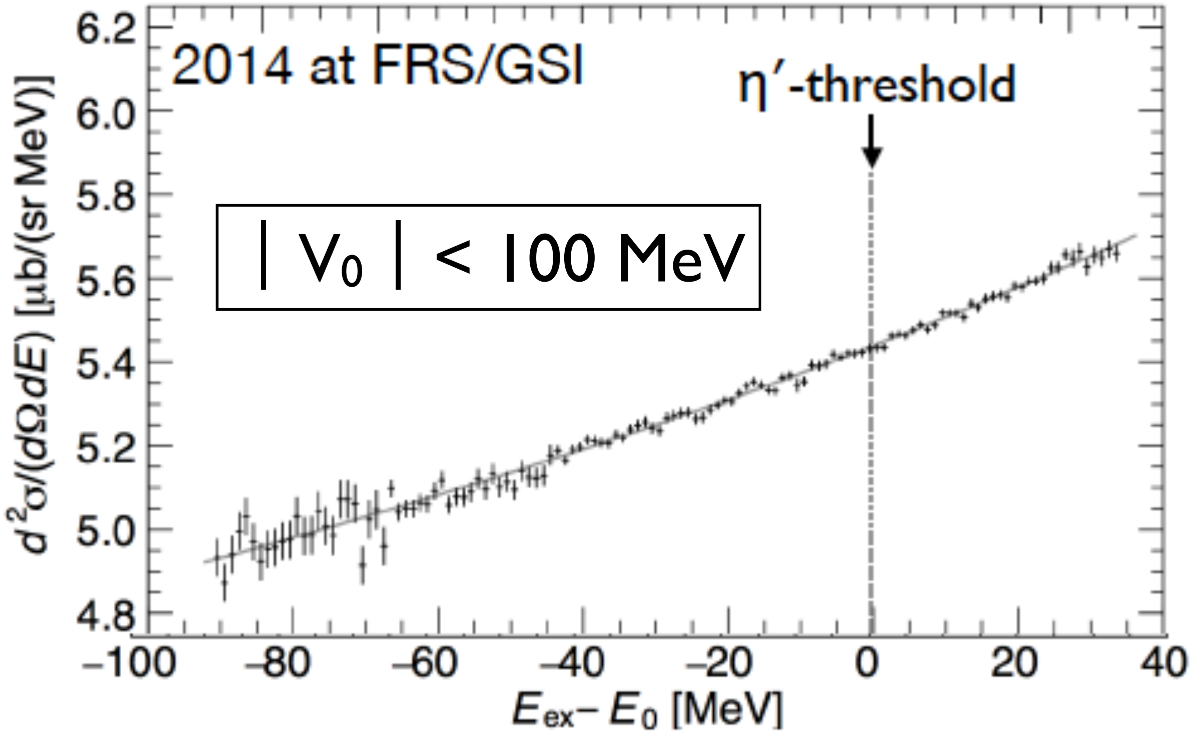
↓

η’NN→NN

K. Itahashi et al., Exp. S 490

measure forward going d in coincidence with decay products in WASA (high energy proton) of η’⊗^{11}C

Y.K. Tanaka et al., PRL 117 (2016) 202501
Y.K. Tanaka et al., arXiv:1705.10543 (2017)



WASA@FRS:

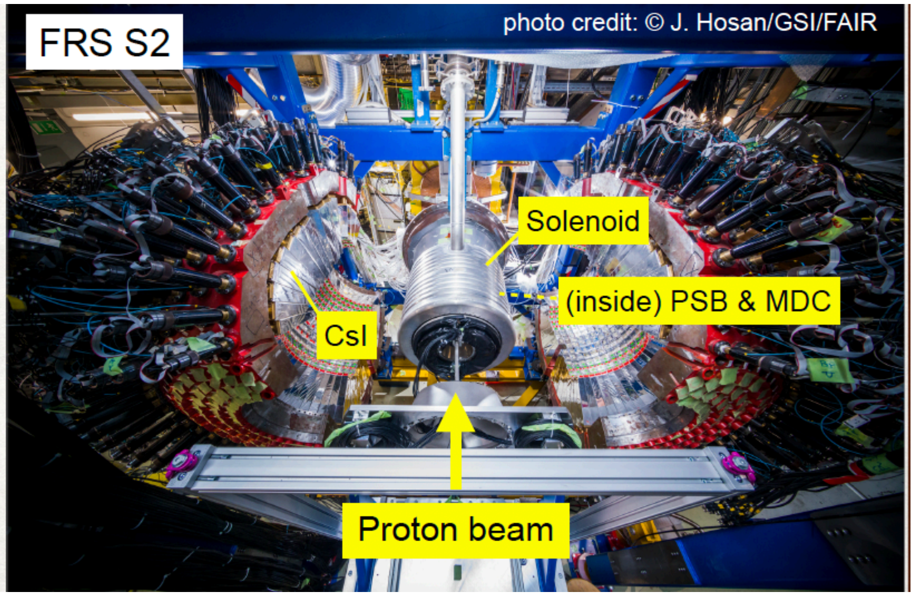
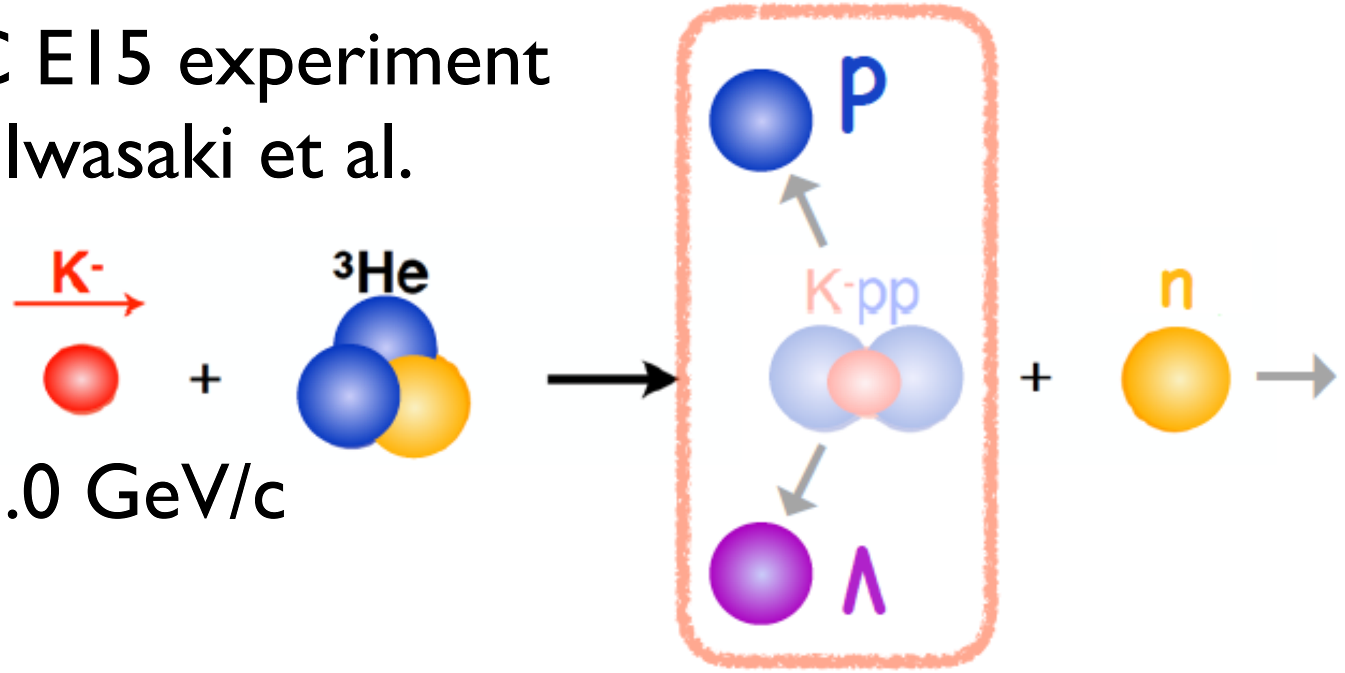


photo credit: © J. Hosan/GSI/FAIR

only upper limit from experiment at Spring8 looking for the η’ p → η p decay
Tomida et al., PRL PRL 124 (2020) 202501: $\gamma + {}^{12}C \rightarrow p_f + \eta' \otimes {}^{11}B$

observation of K^-pp clusters

J-PARC E15 experiment
M. Iwasaki et al.



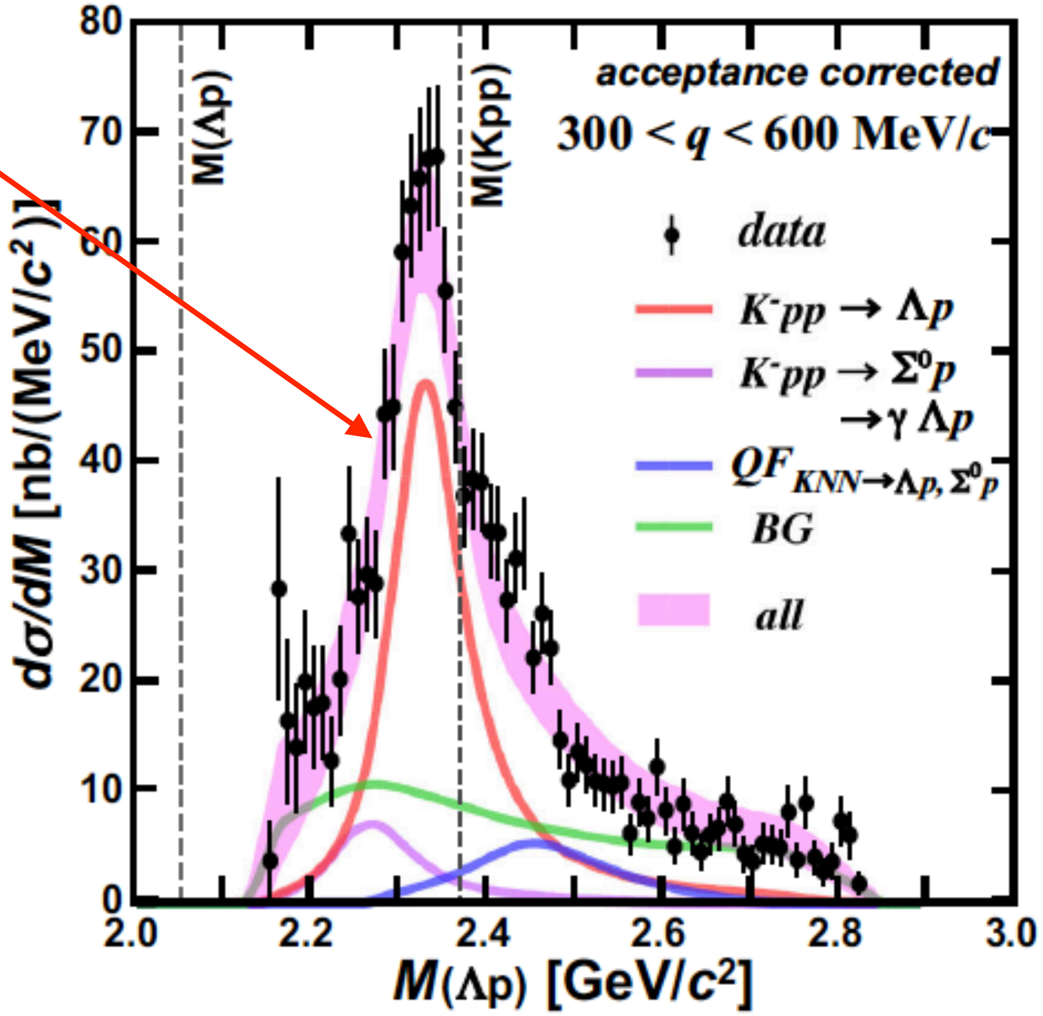
p_{K^-} = 1.0 GeV/c

strategy:
forward-going neutron takes up beam momentum; K^-pp bound states formed at low momenta decay into Λp pairs

K^-pp bound state formed decaying into Λp

$BE=(42\pm3(stat)^{+3}_{-2}(syst))MeV$

$\Gamma=(100\pm7(stat)^{+19}_{-9}(syst))MeV$



Y. Sada et al., PTEP 2016, 051D01

S. Ajimura et al. Phys. Lett. B 789 (2019) 620

T. Yamaga et al. PRC 102 (2020) 044002

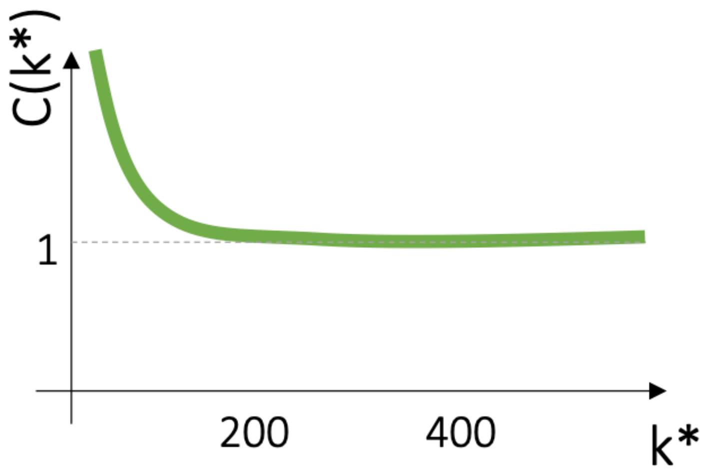
M. Iwasaki, Nucl. Phys. News 33 (2023)1

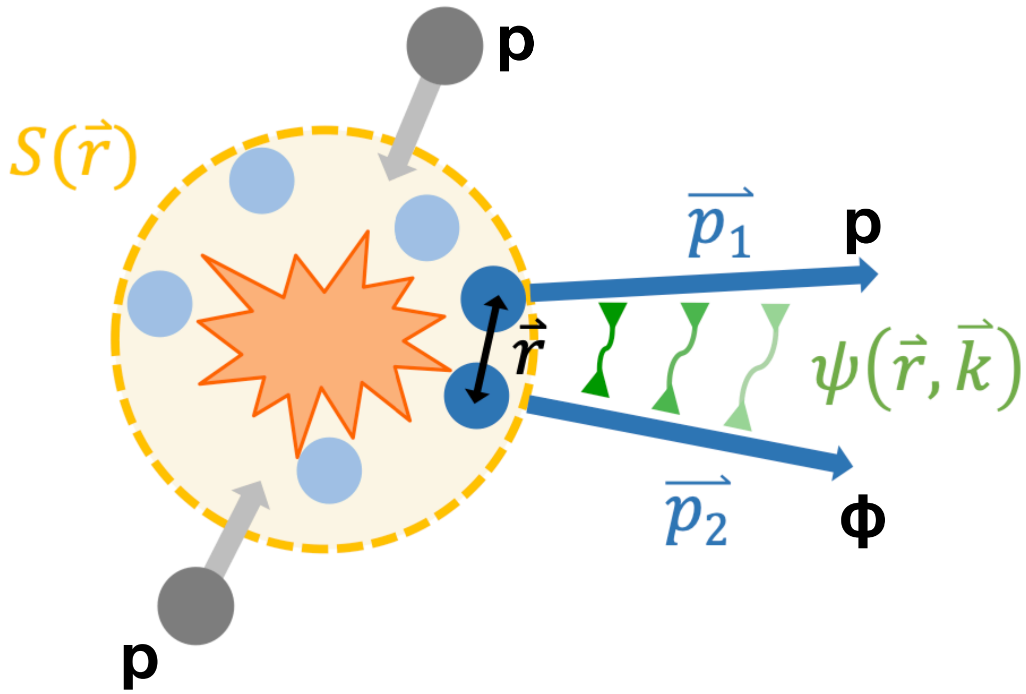
new era of studying
kaonic nuclei
in J-PARC E80

meson-nucleon interactions from particle correlations

p + p collisions at √s = 13 TeV (ALICE)

Emma Chizalli (TUM)





$$C(k^*) = \mathcal{N}\frac{\mathrm{N}_{same}(k^*)}{\mathrm{N}_{mixed}(k^*)} = \int S(\vec{r}^*)\left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^* > 1$$

attraction

correlation function: deviation from constant indicates repulsion or attraction

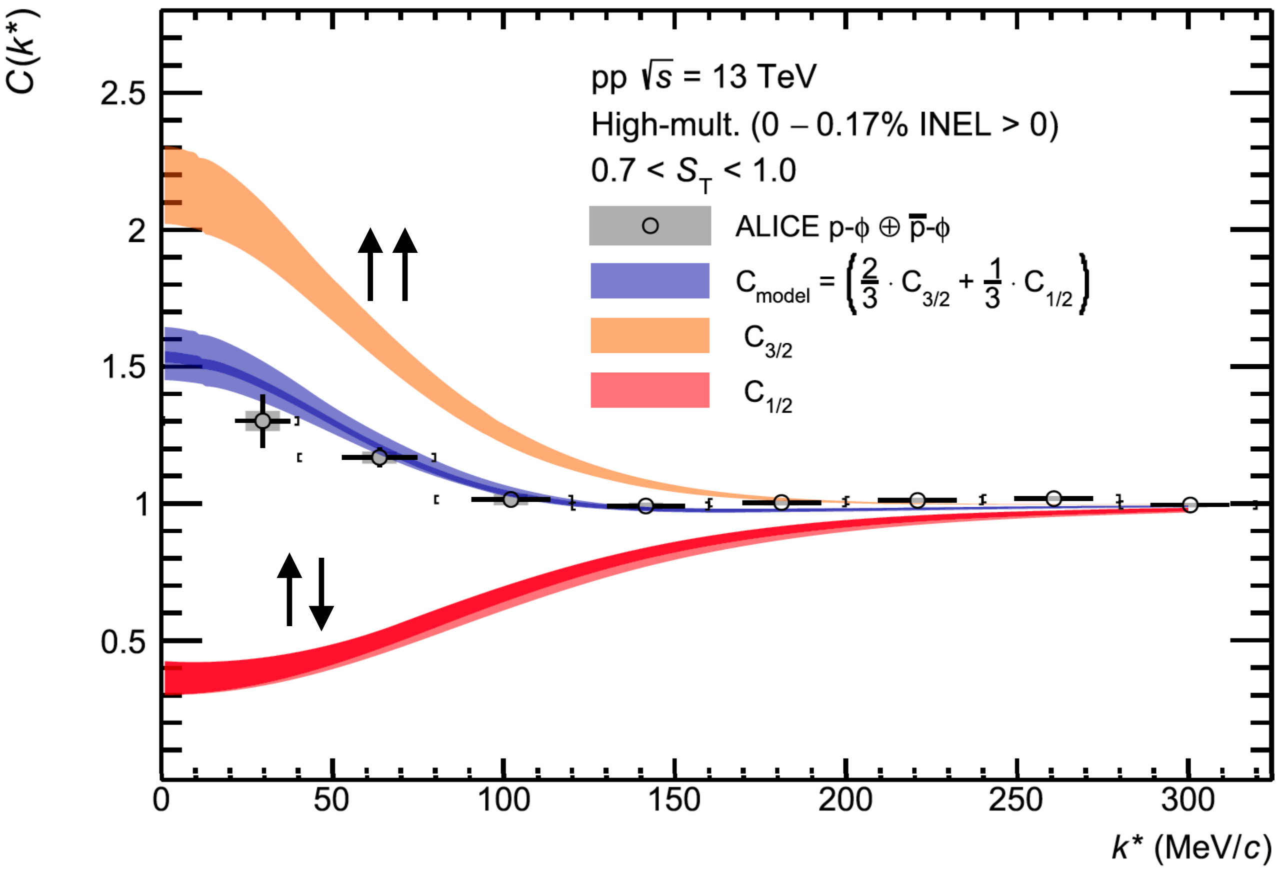
meson-nucleon interactions from particle correlations

p + p collisions at $\sqrt{s}$ = 13 TeV (ALICE)

p - Φ interaction

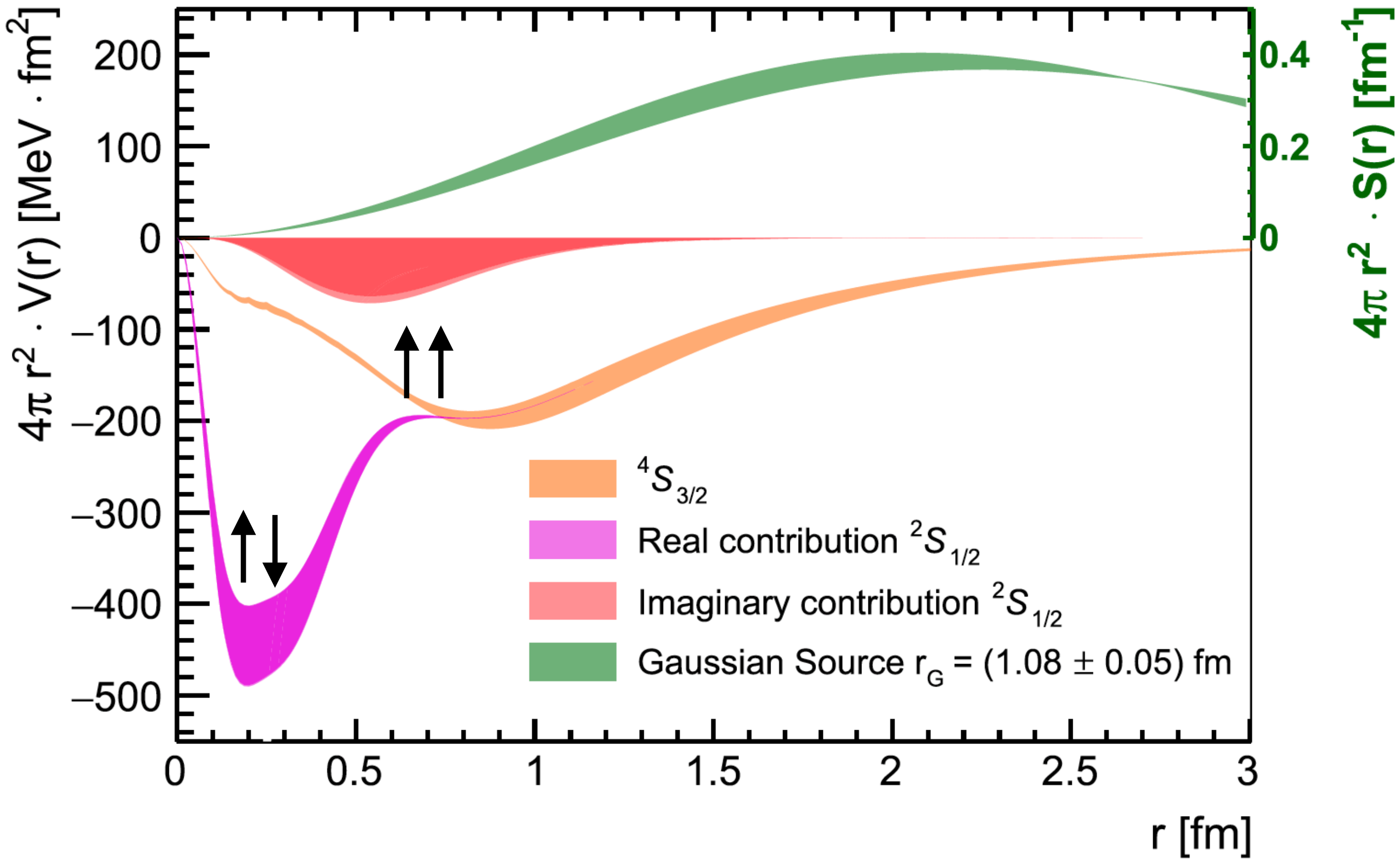
ALICE Collab. PRL 127 (2021) 172301

measured correlation function



E. Chizalli et al., PLB 848 (2024) 138358

deduced p - Φ potentials



attractive p - Φ interaction

indication of a bound p-Φ state in spin 1/2 channel
with binding energy BE ≈ -12 to -56 MeV

summary and conclusions

- mesons do change their properties in interactions with the nuclear medium !!
- at $\rho = \rho_0$ the effects are much smaller than theoretically predicted
- mesons masses are lowered for attractive and increased for repulsive meson-nucleus interactions: $\Delta m_\rho \approx 0$; $m_{K+,K0} \nearrow$; m_{K^-}, $m_{\eta'}$,m_ω, $m_\Phi \searrow$
- in-medium lifetimes are shortened by inelastic hadronic interactions within the nucleus → in-medium broadening of all mesons
- experimental approaches:
  - for short-lived mesons; e.g. ρ- meson line shape analysis (sensitive to nuclear density at decay point)
  - for longer-lived mesons: real and imaginary part of meson-nucleus potentials from excitation functions, momentum distributions and transparency ratios (sensitive to nuclear density at production point; model dependent !)
- outlook:
  - model independent information on meson-nucleus potential from observation of meson-nucleus bound states:
  - observation of bound K^-pp cluster and bound p-Φ state search for $\eta' \otimes A$ ongoing