# in-medium properties of mesons - experimental results and perspectives

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<u>Outline</u>:

- theoretical predictions for in-medium modifications of hadron properties
- exp. approaches and results on the real part of the ω, η'- nucleus potential
- exp. approaches and results on the imaginary part of the ω, η'- nucleus potential
- search for meson-nucleus bound states
- summary & outlook

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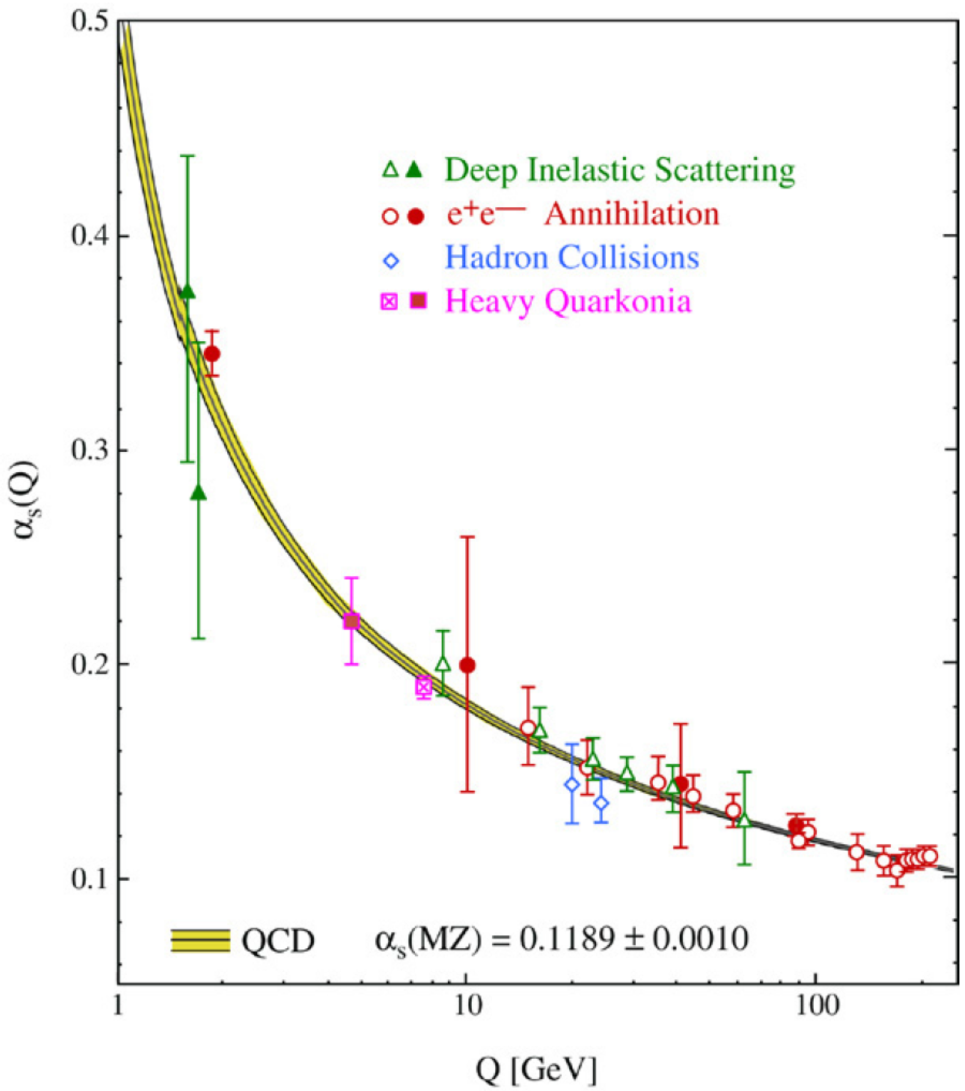
GlueX workshop,
Jlab, Newport News, USA
April 28/29, 2016

HIC for FAIR
Helmholtz International Center

# how strong is the strong interaction ??

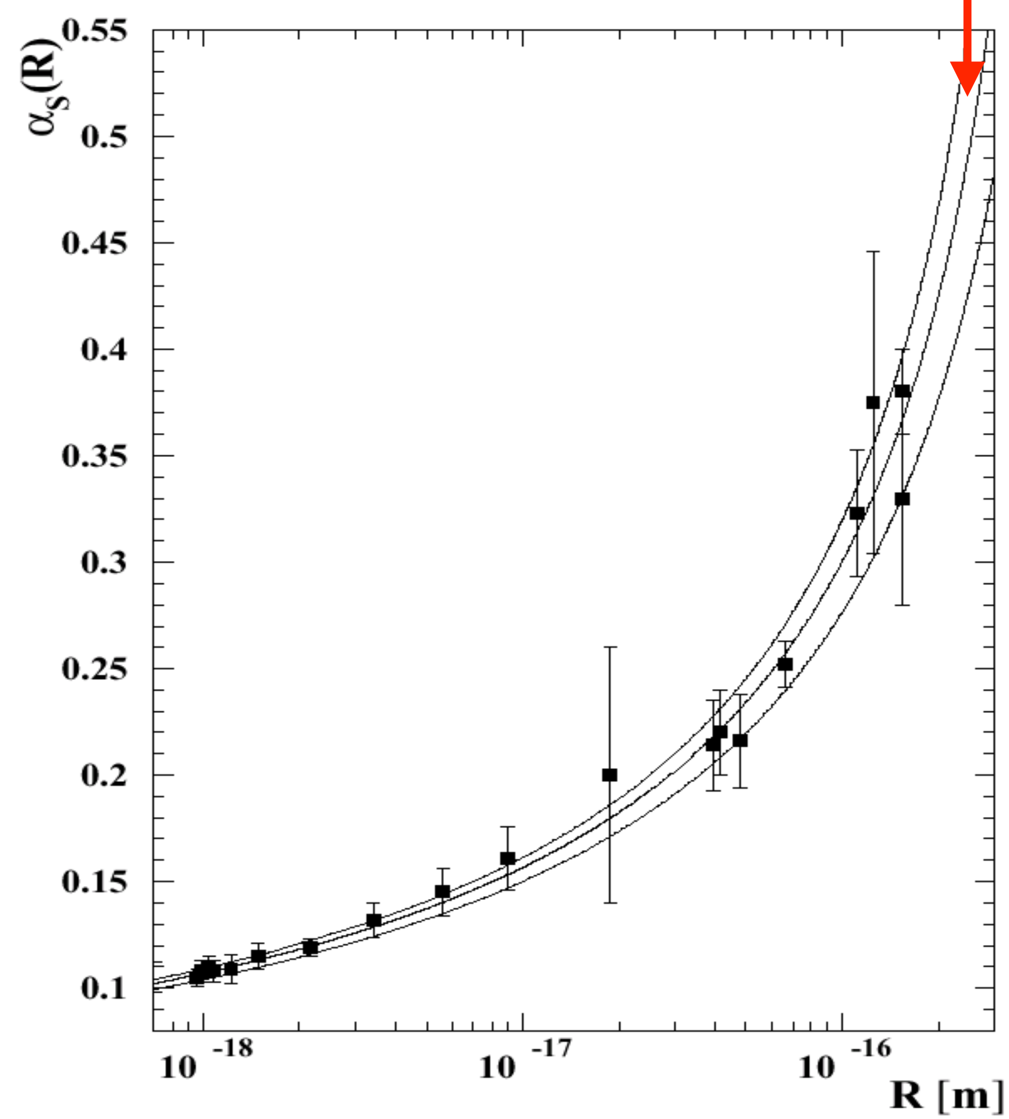
the running coupling strength: $\alpha_s$ (Q)

S. Bethge,
Prog. Part. Nucl. Phys. 58 (2007) 351




$p \bullet q \approx \hbar$

**strong QCD**




for high momenta $\alpha_s \ll 1$:
asymptotic freedom;
⇒ **perturbative QCD**

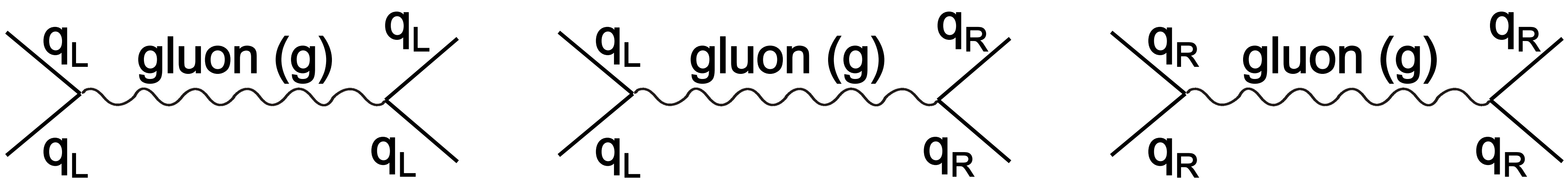
for low momenta $\alpha_s \lesssim 1$
(large distances: ≈ Rp ≈0.8 fm)

⇒ 1.) lattice QCD
2.) QCD inspired models

# QCD inspired models

models exploiting the symmetries of QCD

- chiral symmetry = fundamental symmetry of QCD for massless quarks ($m_q \rightarrow 0$)




- if chiral symmetry were to hold also in the hadronic sector, chiral partners (same spin; opposite parity) should be degenerate in mass: $m(J^+) = m(J^-)$

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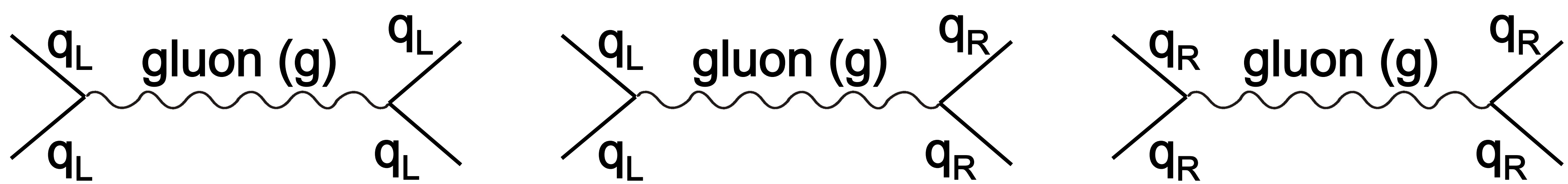


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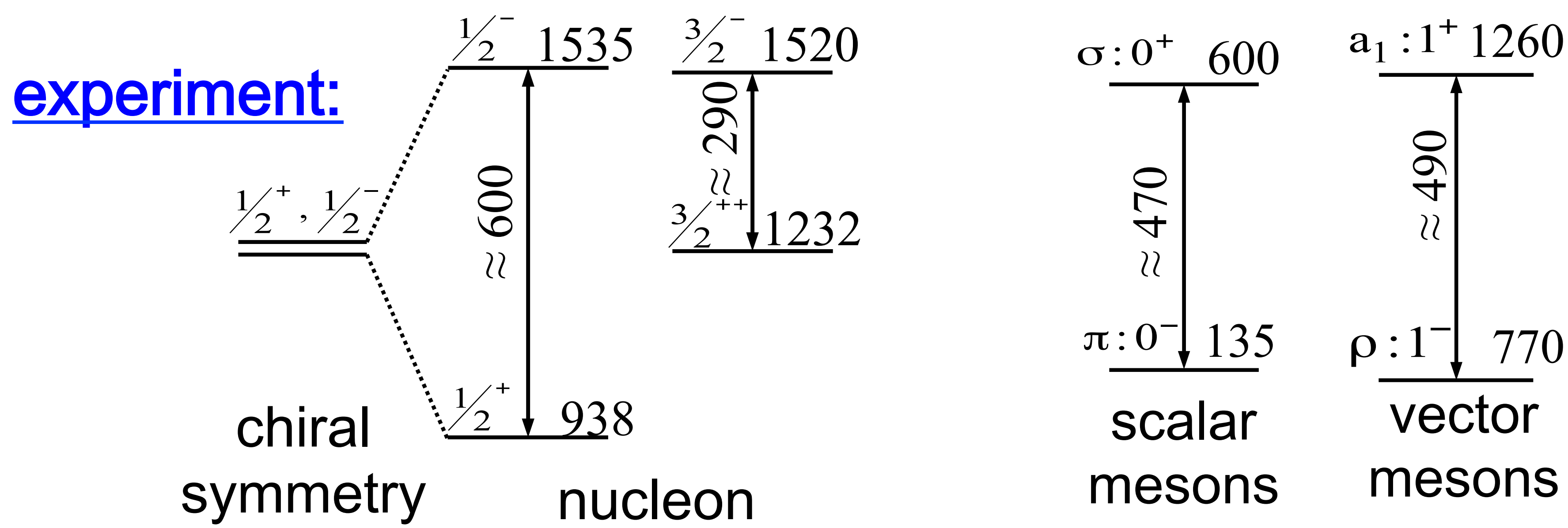


- chiral symmetry broken in the hadronic sector
  mass split $\Delta m \approx 300\text{-}600$ MeV, almost comparable to hadron masses !!

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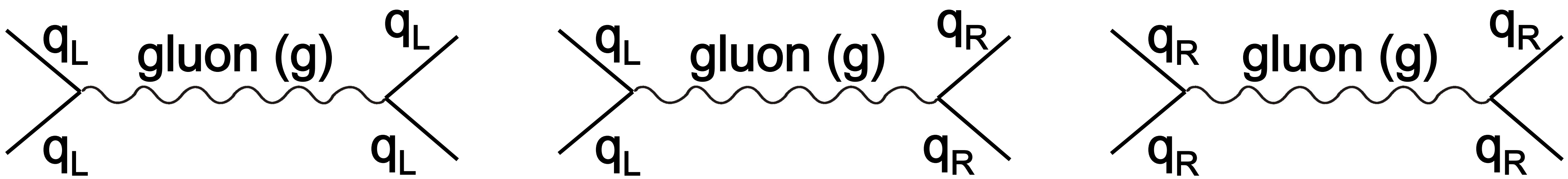


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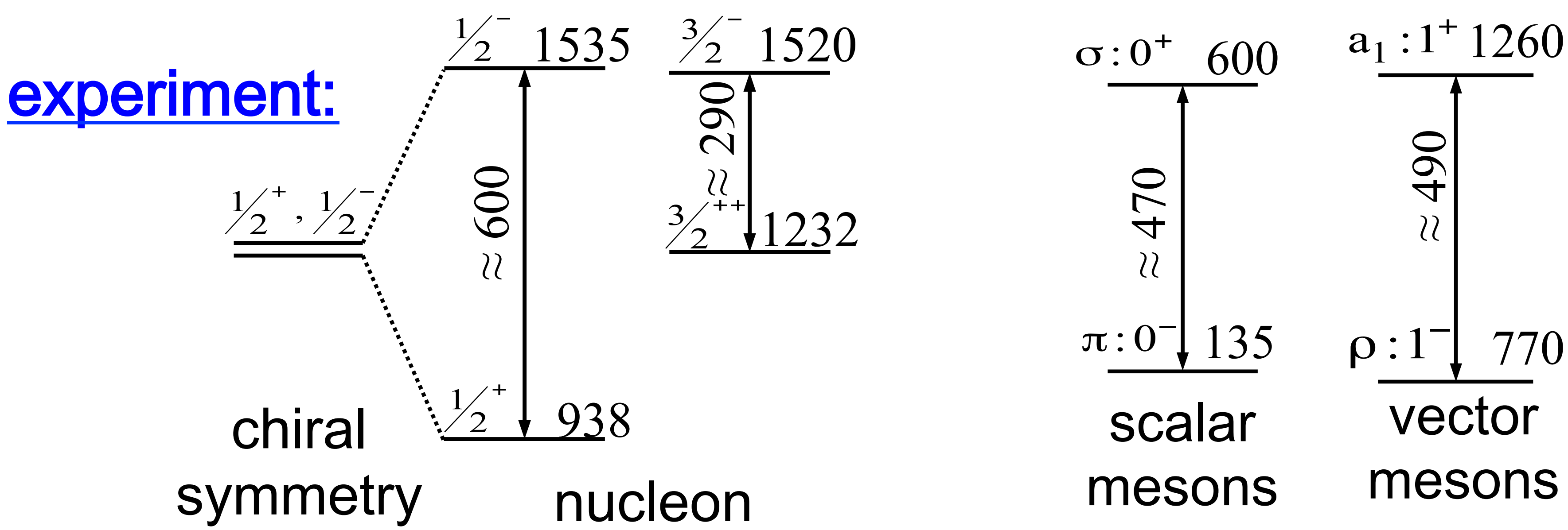


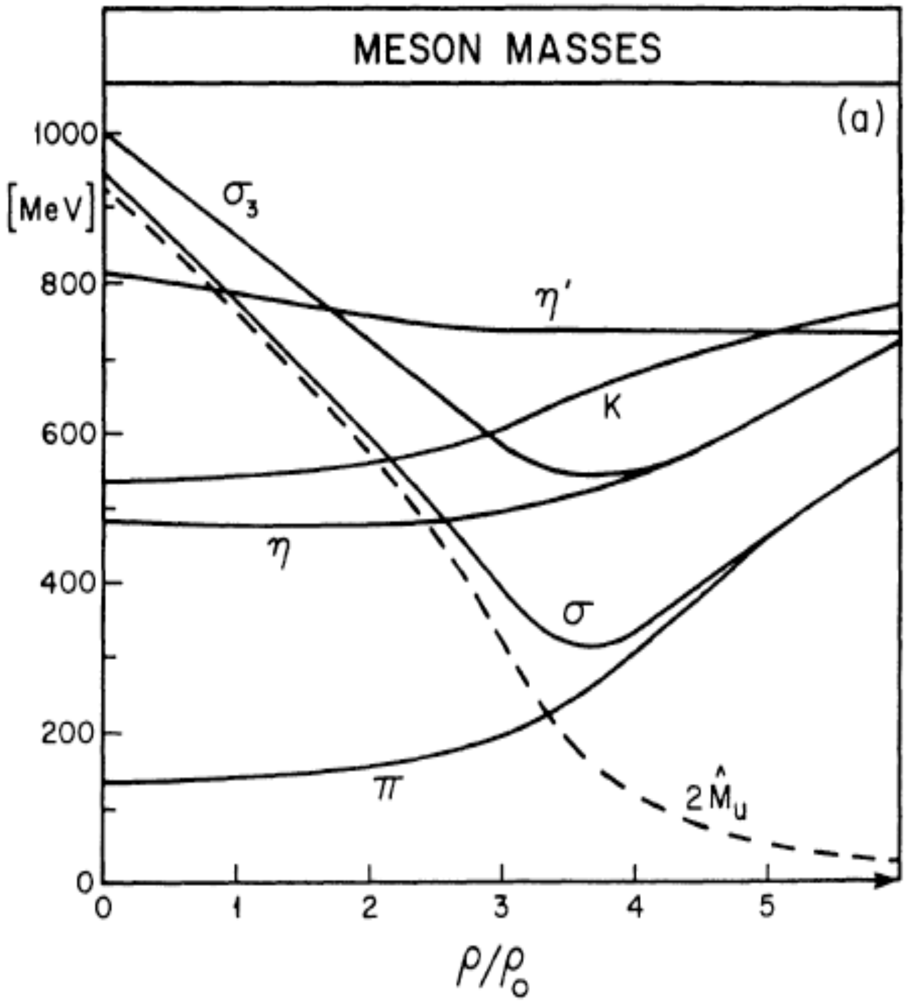

- chiral symmetry broken in the hadronic sector
  mass split $\Delta m \approx 300\text{-}600$ MeV, almost comparable to hadron masses !!

- if chiral symmetry were at least partially restored in the nuclear medium
  - as predicted in several theoretical approaches -
  $\Delta m \rightarrow 0$, **hadron mass distributions in the medium should change !!**

# model predictions for in-medium mass/width of the η’,ω,Φ meson

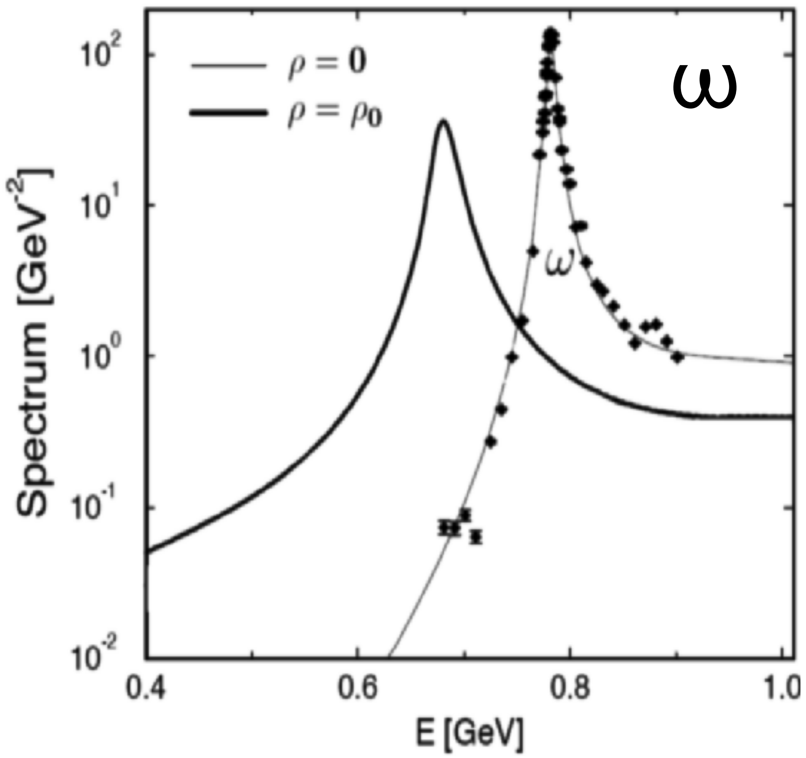
NJL-model

V. Bernard and U.-G. Meissner, Phys. Rev.D 38 (1988) 1551




almost no dependence of η’ mass on density

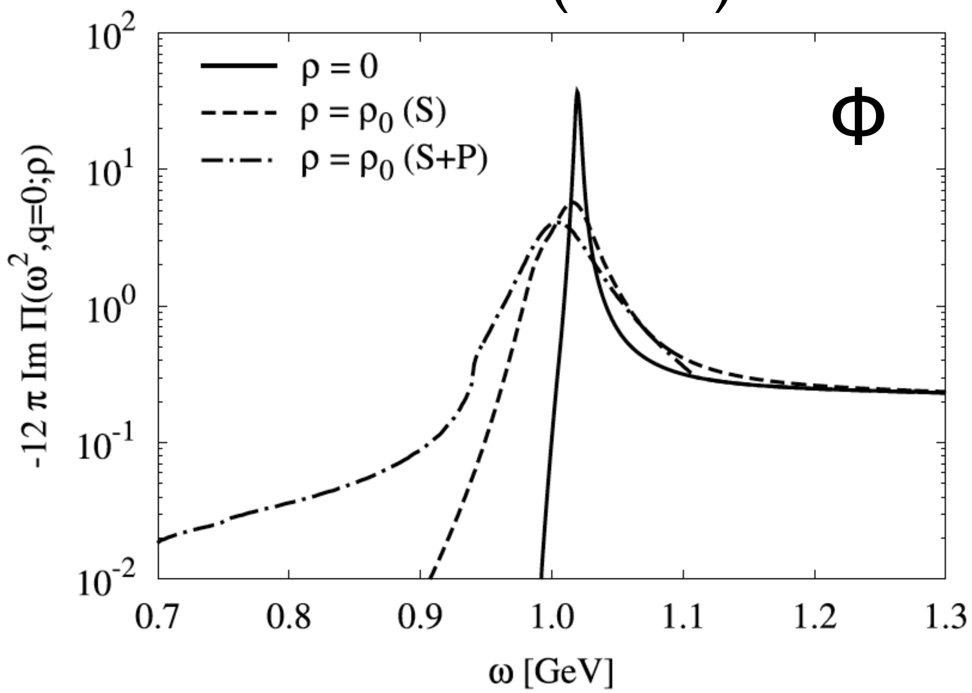
F. Klingl et al., NPA 610 (1997) 297; NPA 650 (1999) 299




with increasing nuclear density

- lowering of in-medium mass
- broadening of resonance

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



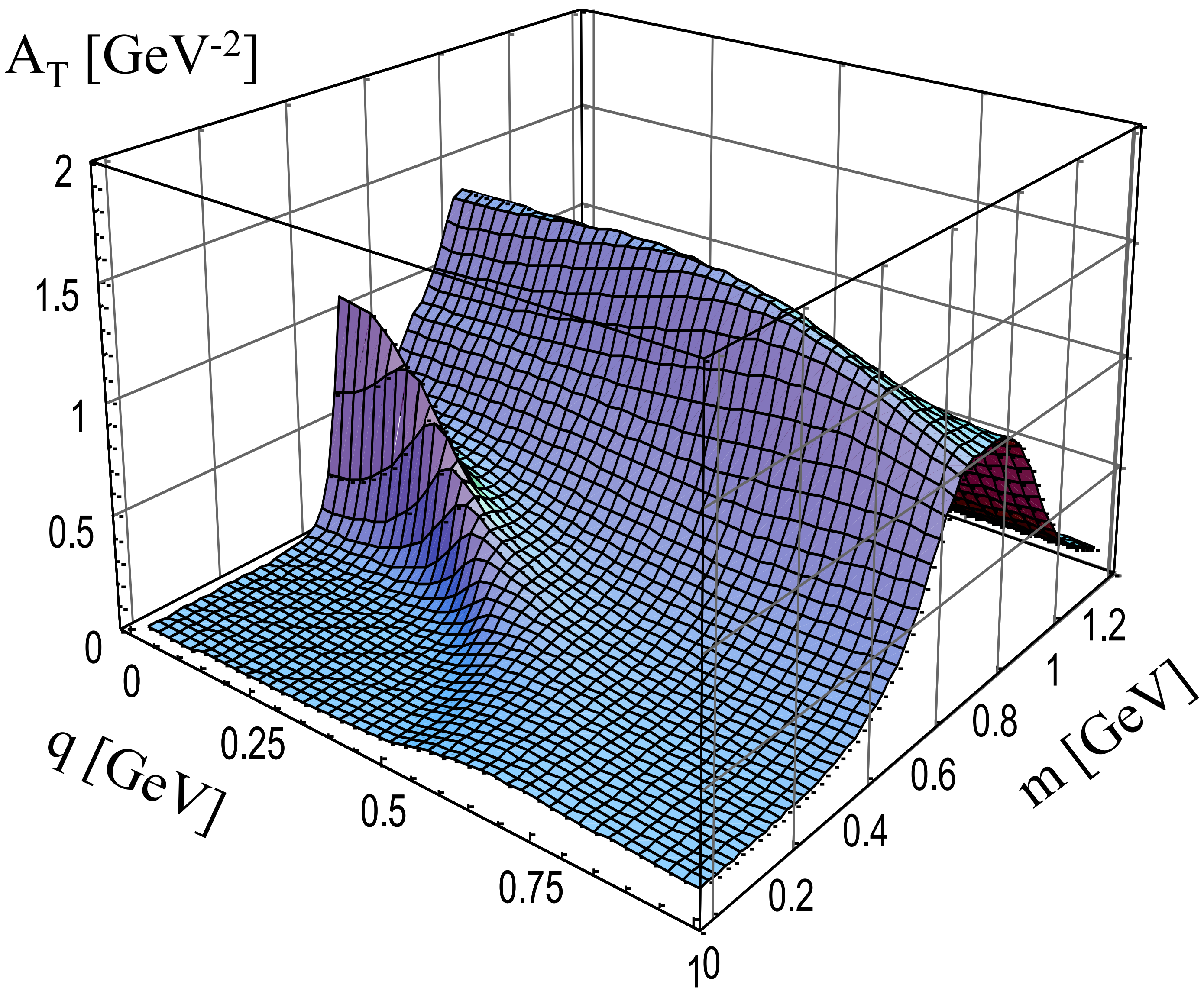

$\Delta m/m < 2\%$

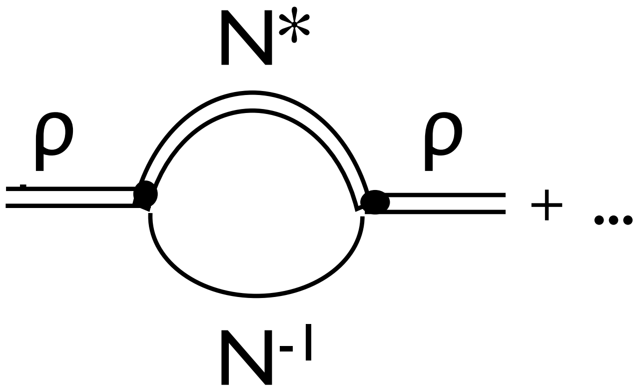
asymmetric broadening

$\Gamma(\rho_0) \approx 45$ MeV

# model predictions for the in-medium ρ spectral function

M. Post et al., NPA 741 (2004) 81




- structure in ρ spectral function: splitting into ρ-like and $N^*N^{-1}$ mode due to coupling to baryon resonances
- strong momentum dependence of spectral function
- modifications most pronounced at small momenta

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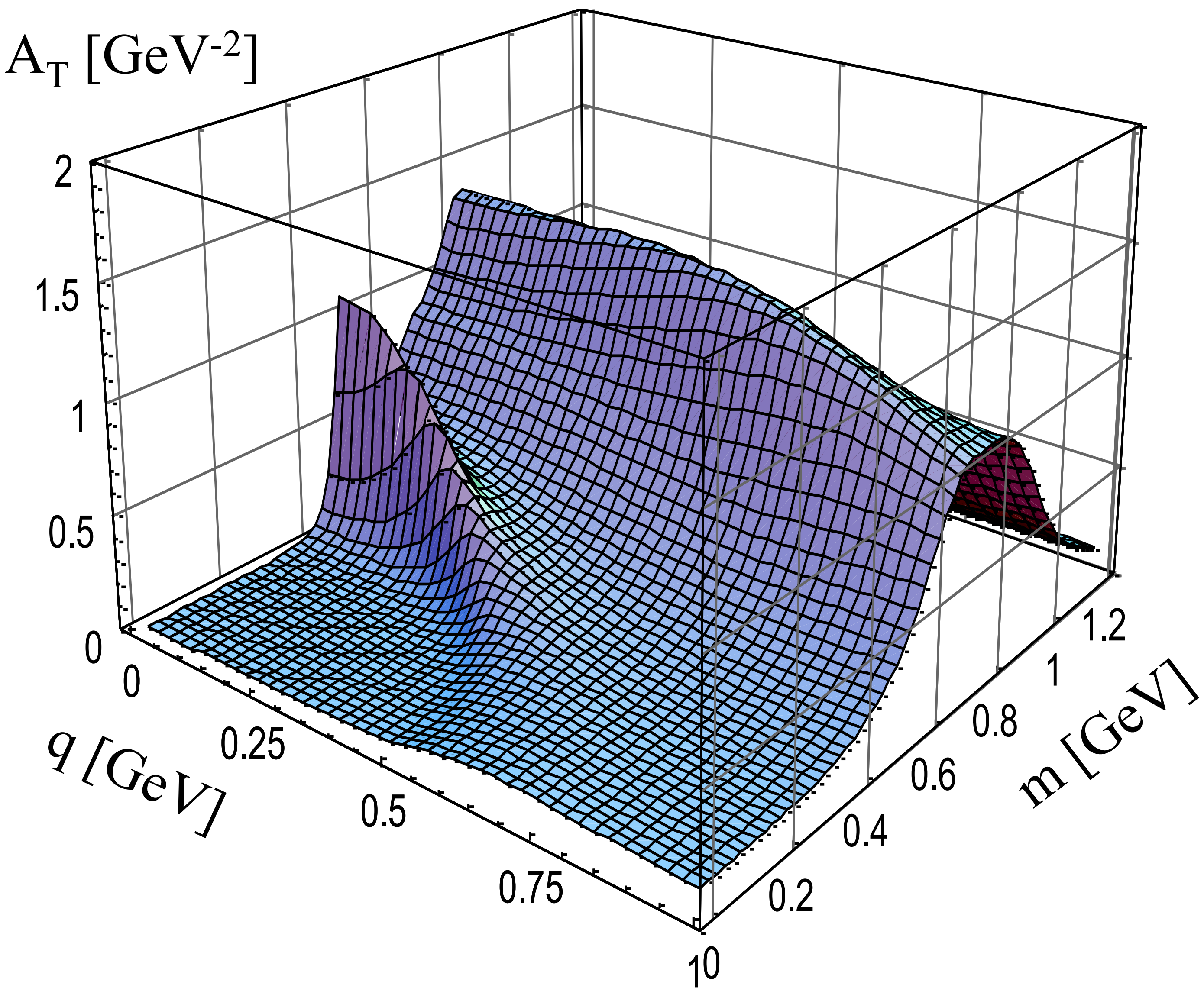


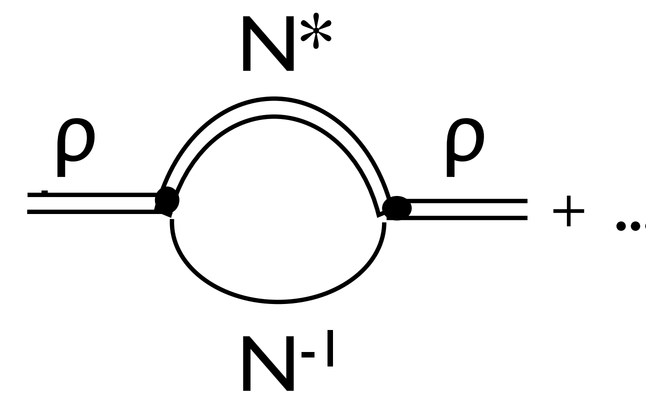


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experimental task: search for { mass shift ? broadening? structures? } of hadronic spectral functions

detector acceptance down to very small meson momenta needed !!!

# from theoretical predictions to experimental observables

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calculations of meson spectral functions assume:

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

theoretical predictions

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theoretical predictions

⇨

experimental observables

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- meson at rest in nuclear medium

**transport calculations (GiBUU, HSD, UrQMD, ...)**
**are needed for comparison with experiment !!!**

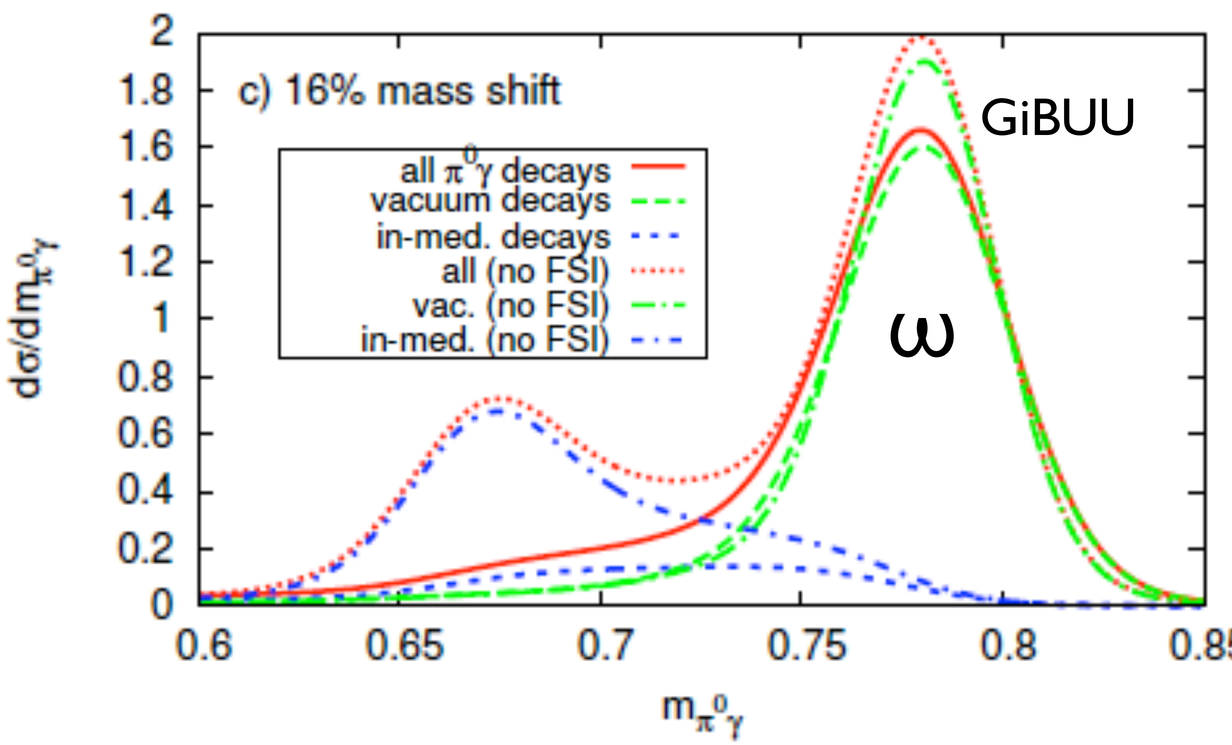
theoretical predictions ⇨ transport calculations ⇨ experimental observables

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

# sensitivity of the ω line shape measurement to in-medium modifications of the ω meson

$$m(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

J. Weil, U. Mosel, V. Metag, PLB 723 (2013) 120




$\omega \rightarrow e^+e^-$ br: $7.3 \cdot 10^{-5}$

$\omega \rightarrow \pi^0\gamma$ br: 8.3%

- only 20-30 % of the ω decays occur within the nuclear medium;
  $< d > = \beta\gamma c\tau \approx 17$ fm
- a density dependent mass shift is smeared out due to the nuclear density profile

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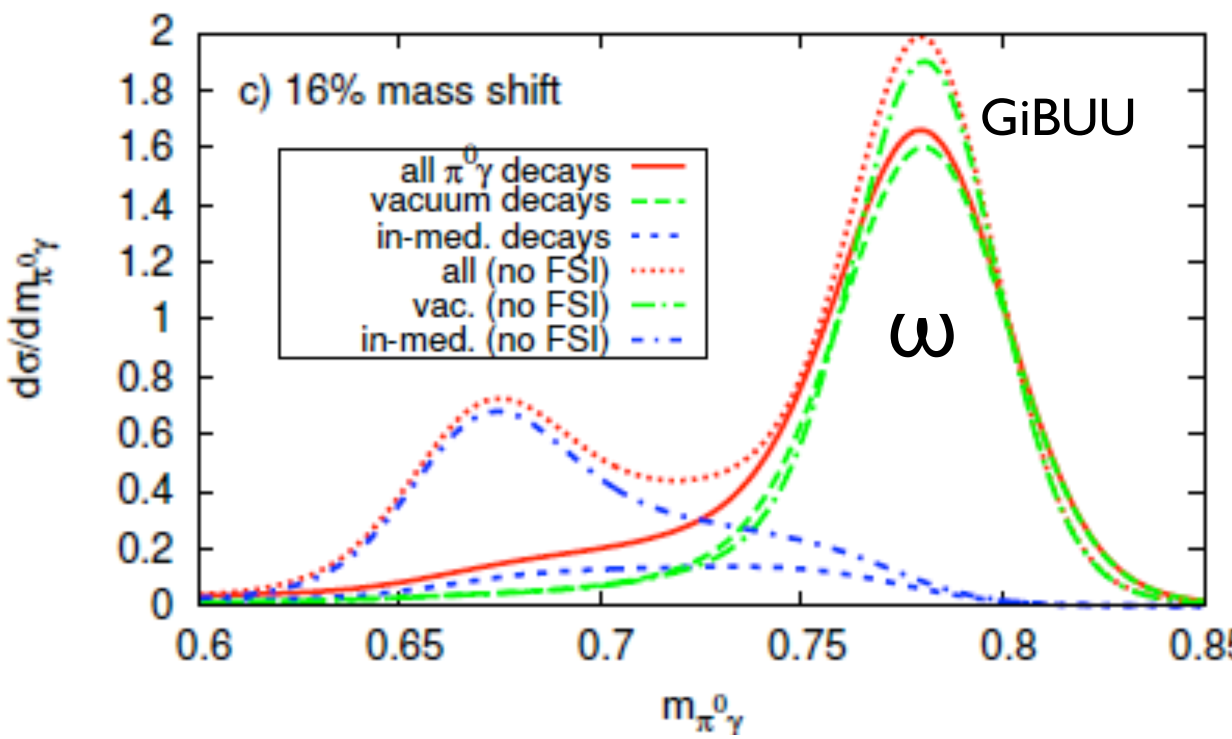


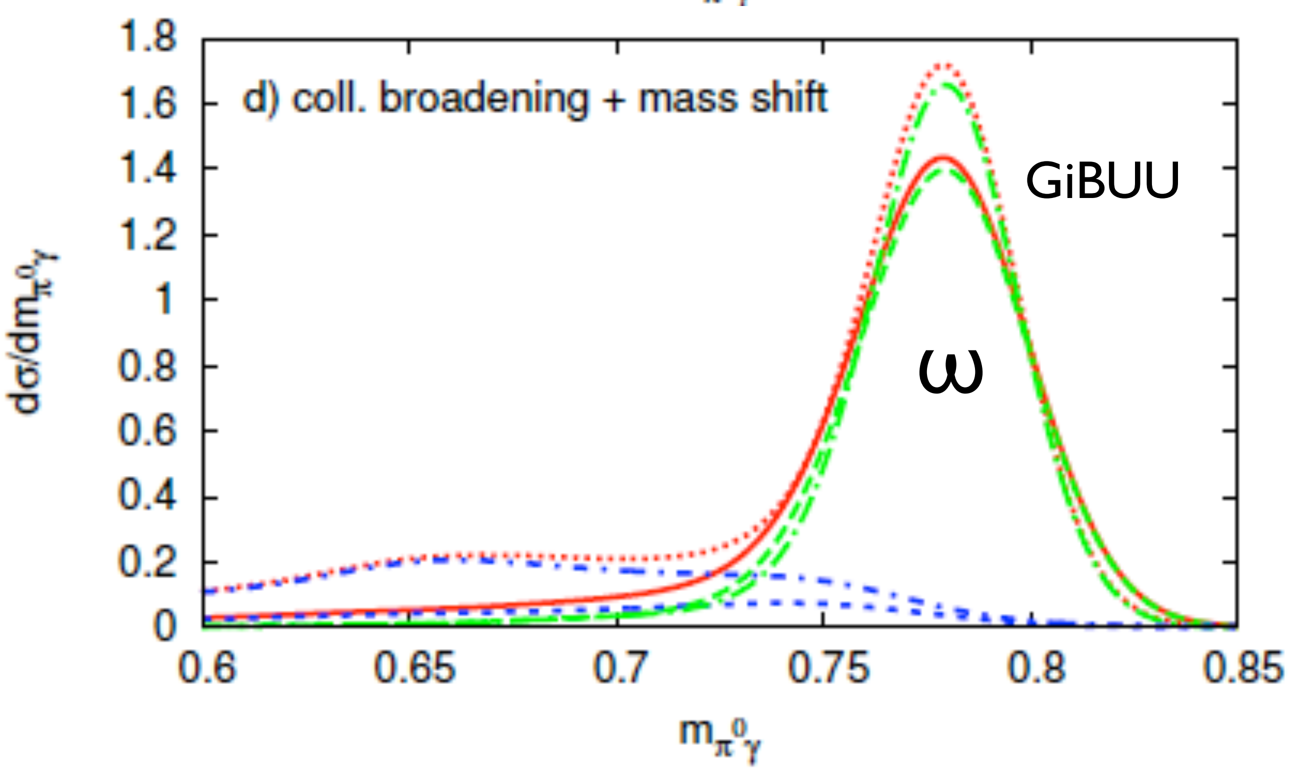


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- a density dependent mass shift is smeared out due to the nuclear density profile
- a density dependent mass shift is smeared out due to the in-medium collisional broadening of the ω-signal: $\Gamma(\rho_0) \approx 130$ - $150$ MeV
- due to $\pi^0$ absorption ($\pi^0$-FSI) $\omega \rightarrow \pi^0\gamma$ decays in the center of the nucleus are suppressed; only $\omega \rightarrow \pi^0\gamma$ decays in the surface region can be reconstructed

# meson-nucleus optical potential

H. Nagahiro and S. Hirenzaki, PRL 84 (2005) 232503

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

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

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

real part

⇕

**in-medium mass modification**

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

real part

⇕

**in-medium mass modification**

imaginary part

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**lifetime shortened**

in-medium width

inelastic cross section

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real part

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**in-medium mass modification**

imaginary part

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**lifetime shortened**

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inelastic cross section

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

# experimental approaches to determine the meson-nucleus optical potential

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

real part

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

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

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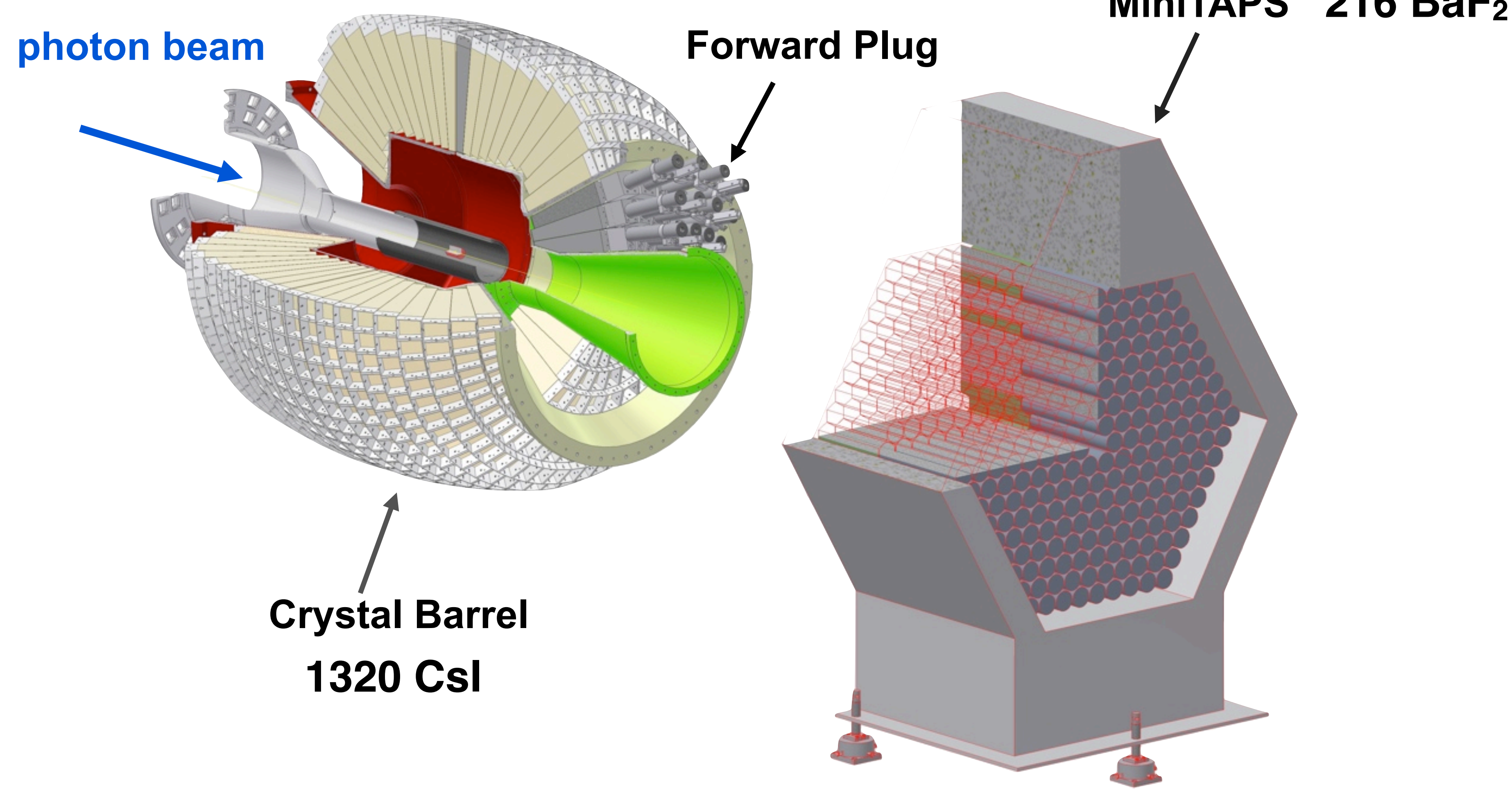
- transparency ratio measurement

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

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

# CBELSA/TAPS experiment

$E_\gamma$=1.2 - 2.9 GeV



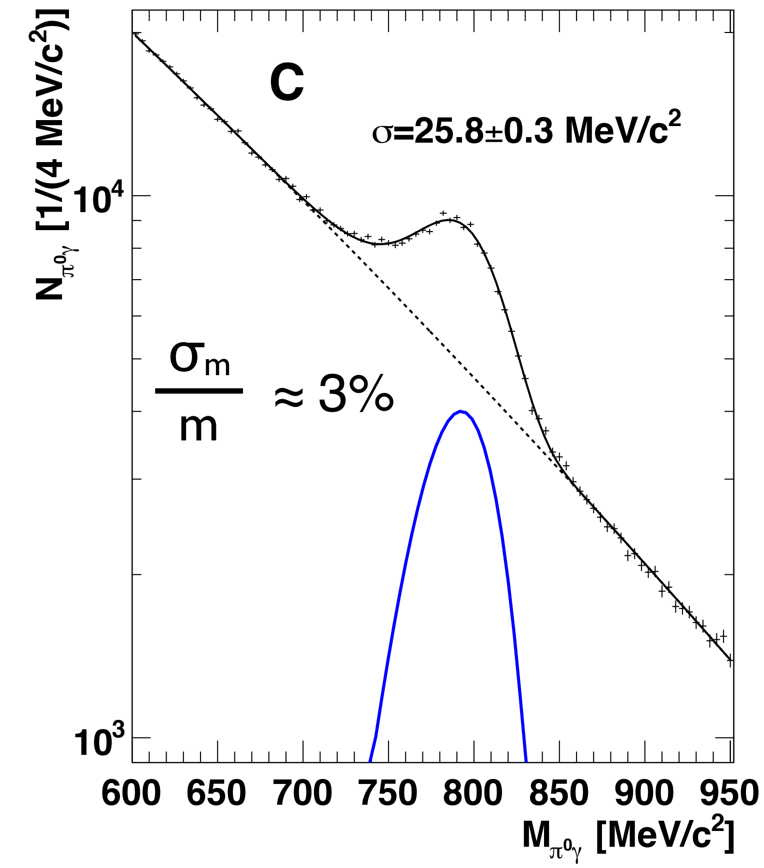

solid target: $^{12}C$ and $^{93}Nb$

$4\pi$ photon detector: ideally suited for identification of multi-photon final states

$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$ BR 8.5%

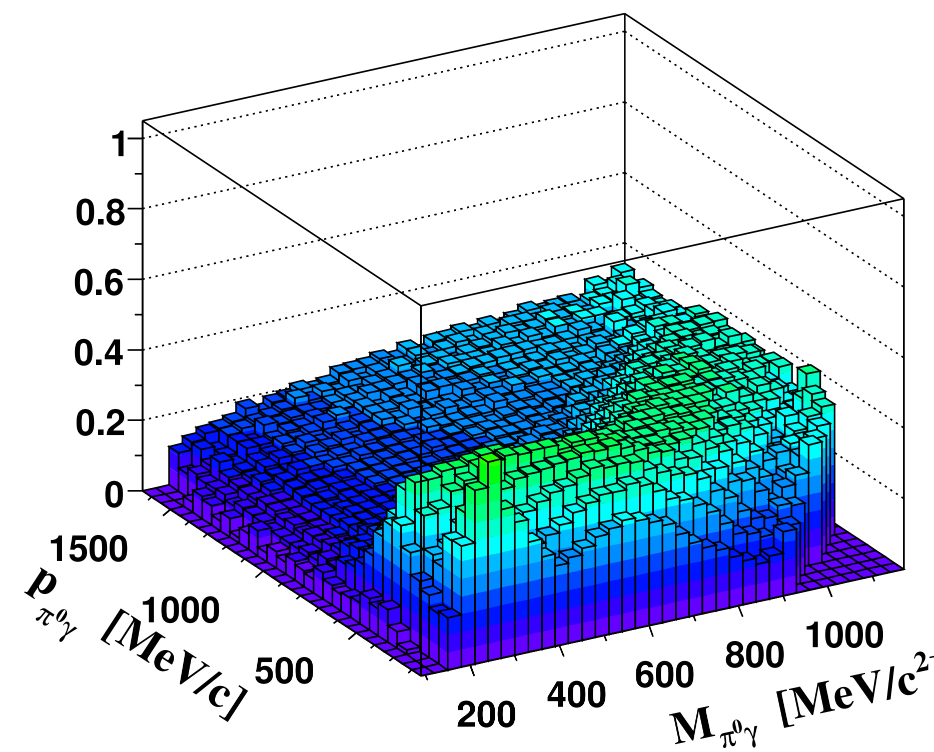
$\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ BR 8.5%

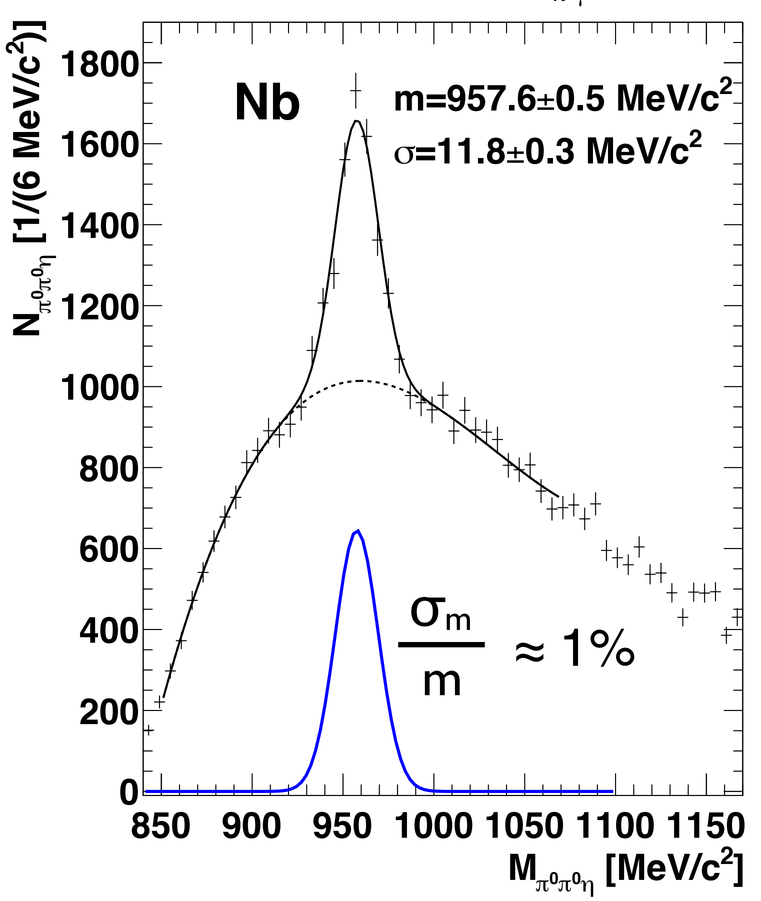
# detector performance: invariant mass spectra; acceptances




**acceptance over full momentum range !!**

$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$

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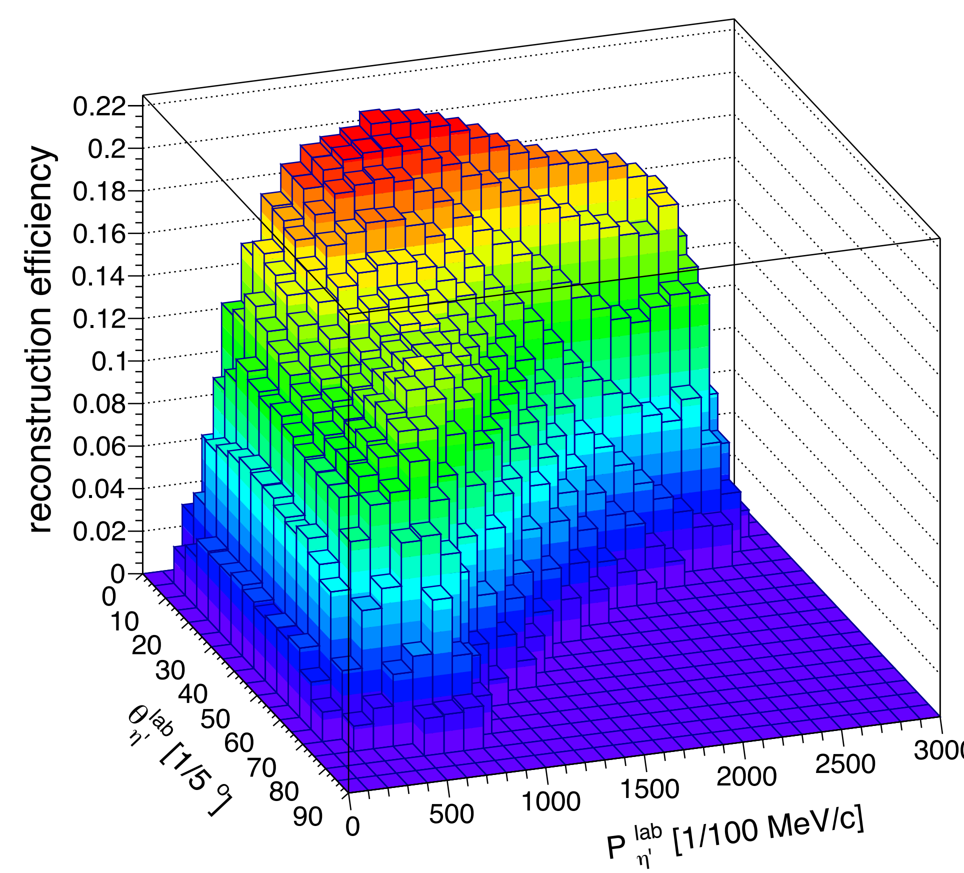
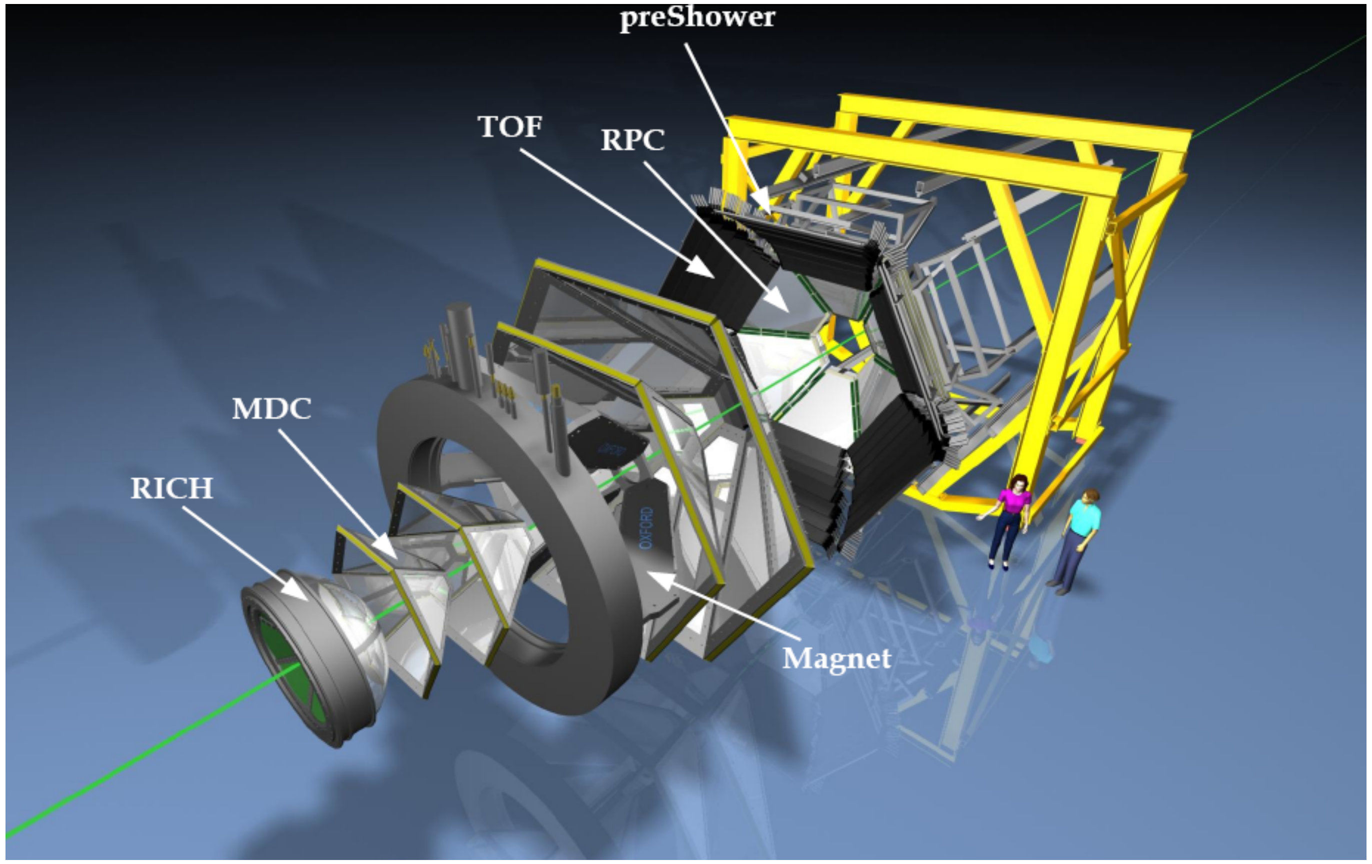
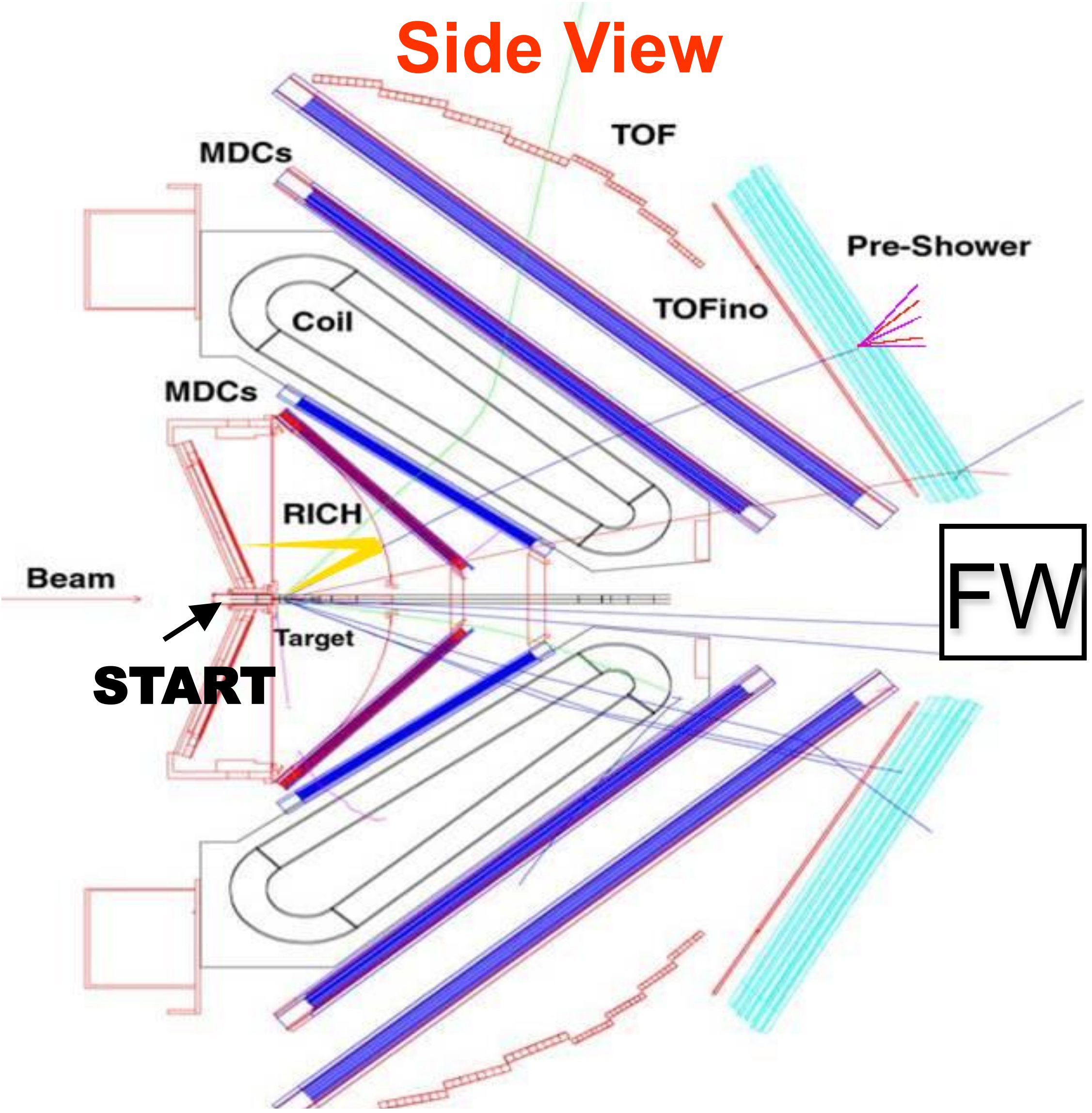


# High acceptance Dielectron spectrometer (HADES@GSI)

beams from SIS18: protons, nuclei, pions
$2.0 \text{ GeV} < \sqrt{s} < 3.2 \text{ GeV}$



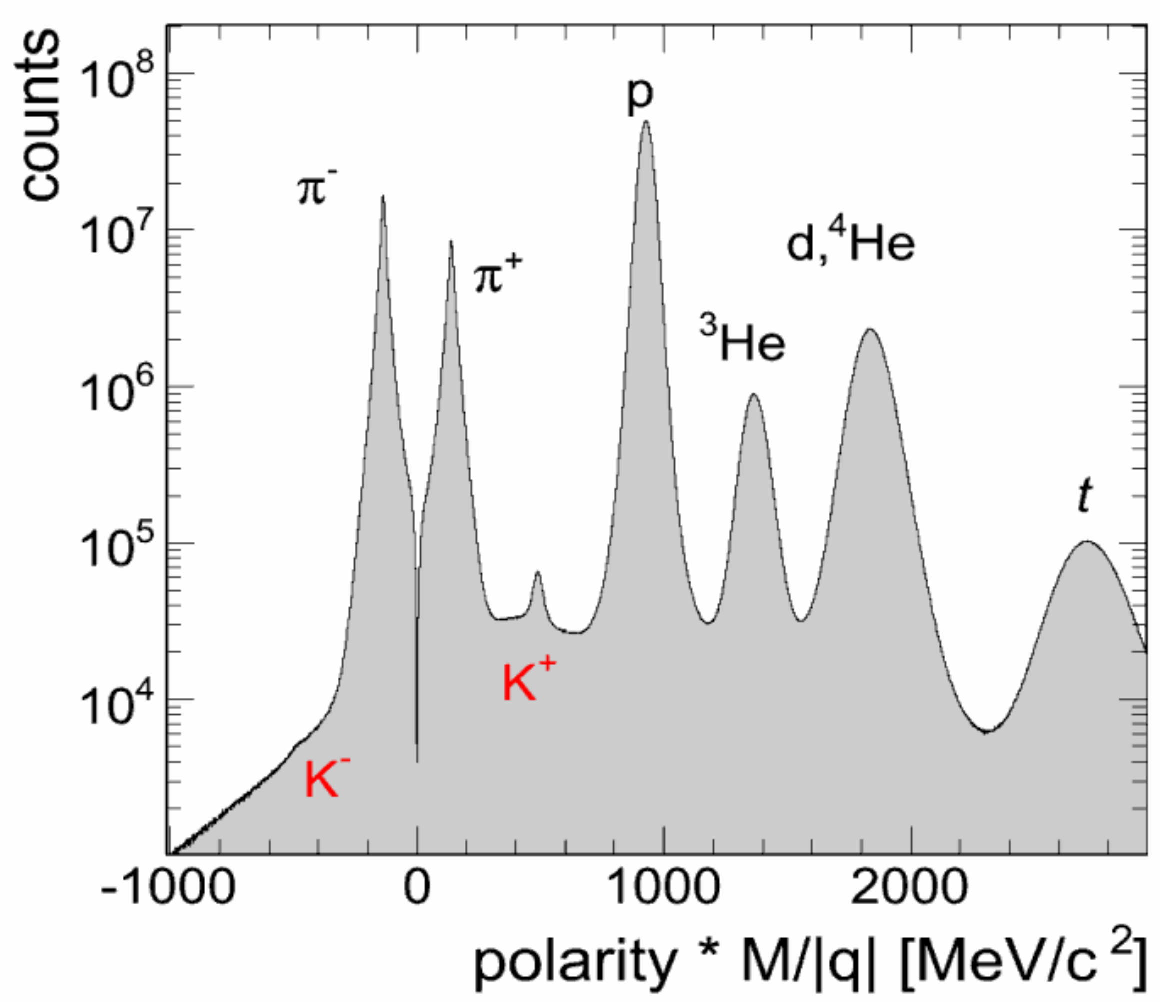




spectrometer with good particle identification and high invariant mass resolution: ≈2% at $\rho/\omega$

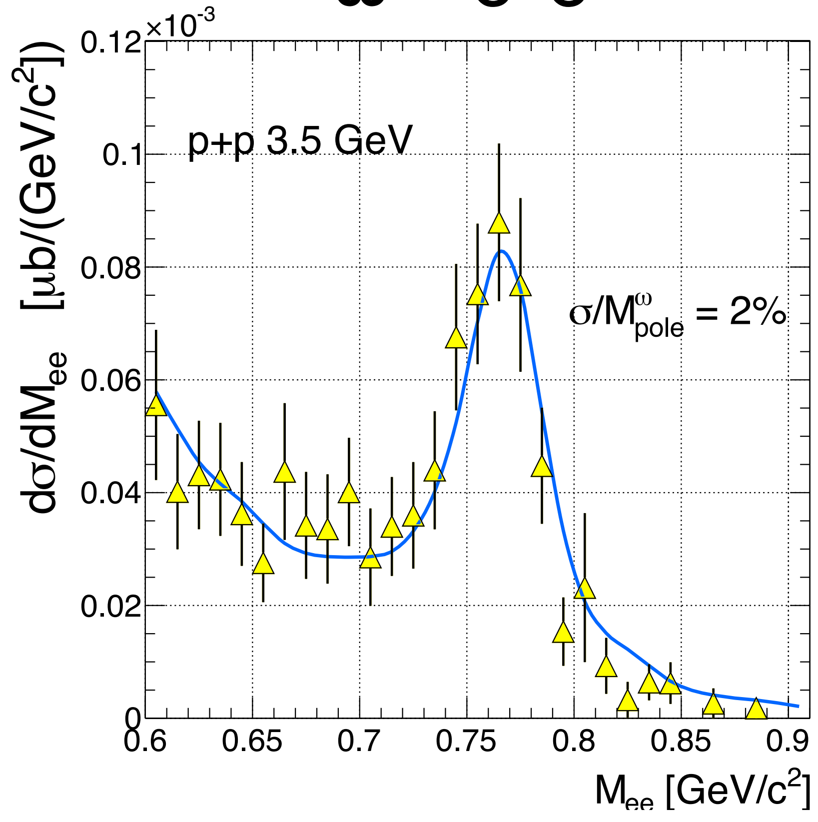
versatile detector for rare probes:
- dielectrons $e^+e^-$
- strangeness: $\Lambda$ , $K\pm$ , $\Sigma$ , $\Xi$, $\Phi$

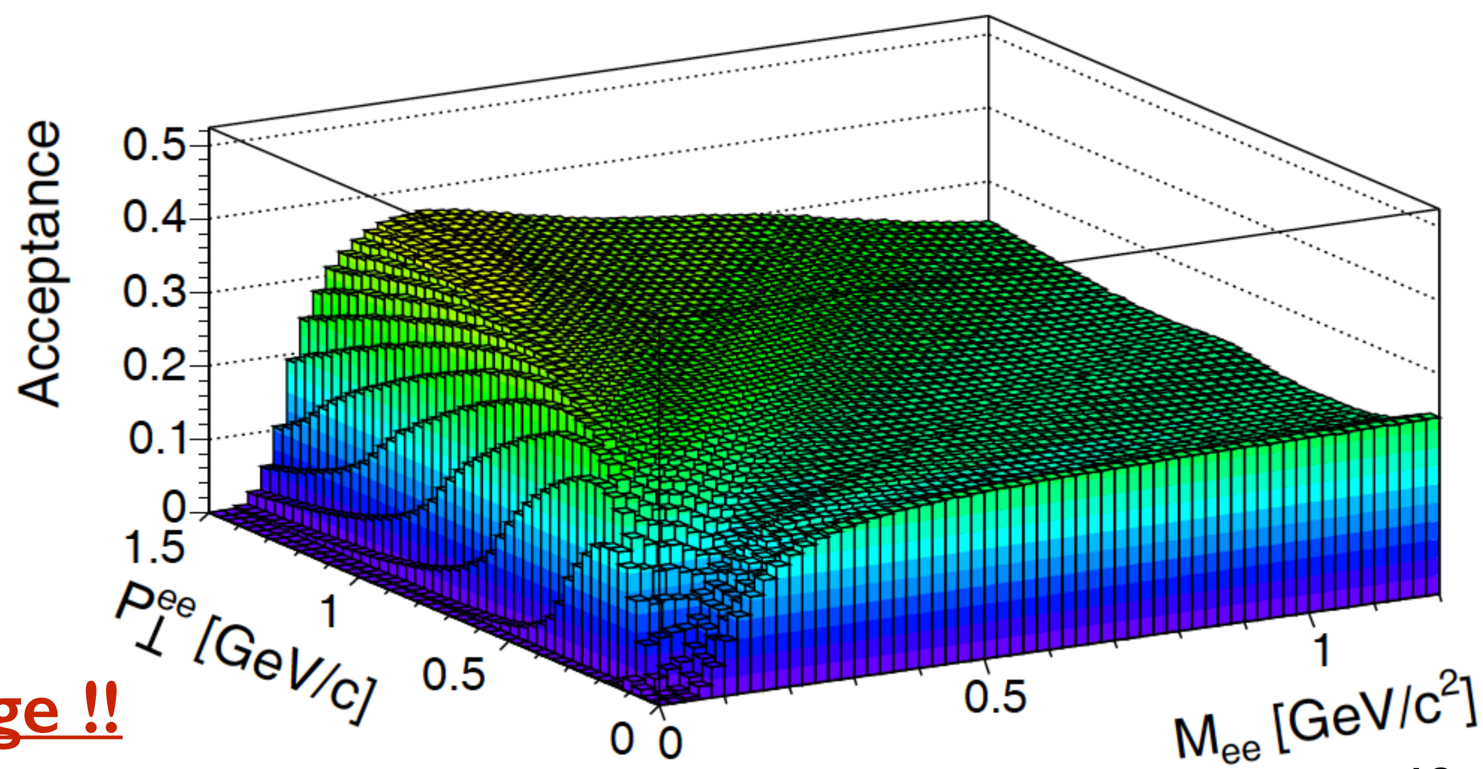
# detector performance:
# particle identification; invariant mass spectra; acceptances

particle identification




ω→e+e-




**acceptance over full momentum range !!**

## the real part of the meson-nucleus optical potential

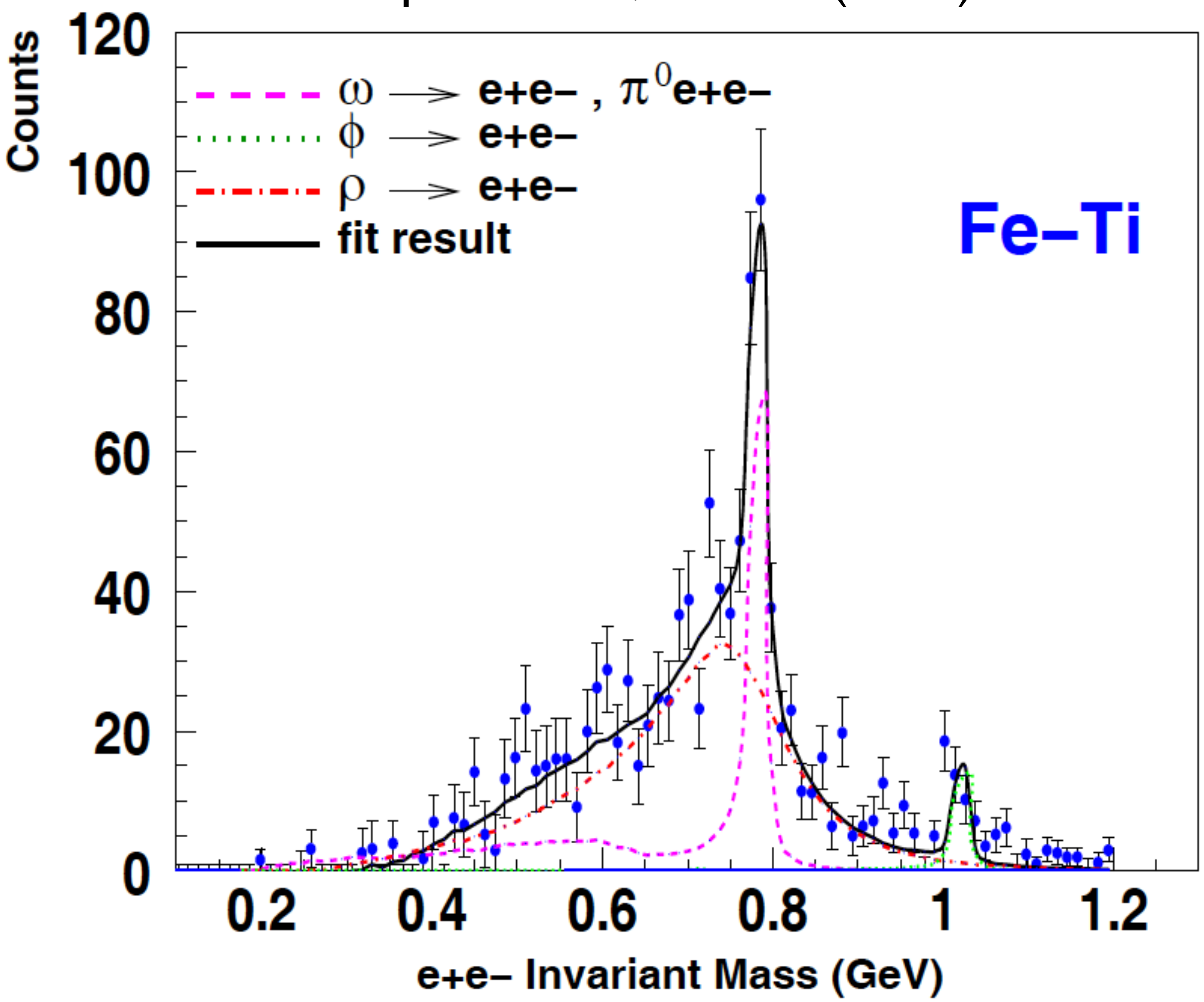
# in-medium ρ-spectral function from $\rho \to e^+e^-$

$$m(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

**JLAB-CLAS**: $\gamma A \to e^+e^-X$;

$E_\gamma$= 0.6-3.8 GeV

R. Nasseripour et al., PRL 99 (2007) 262302




ρ broadened; no mass shift

$\Delta\Gamma(\rho=\rho_0) \approx 70$ MeV

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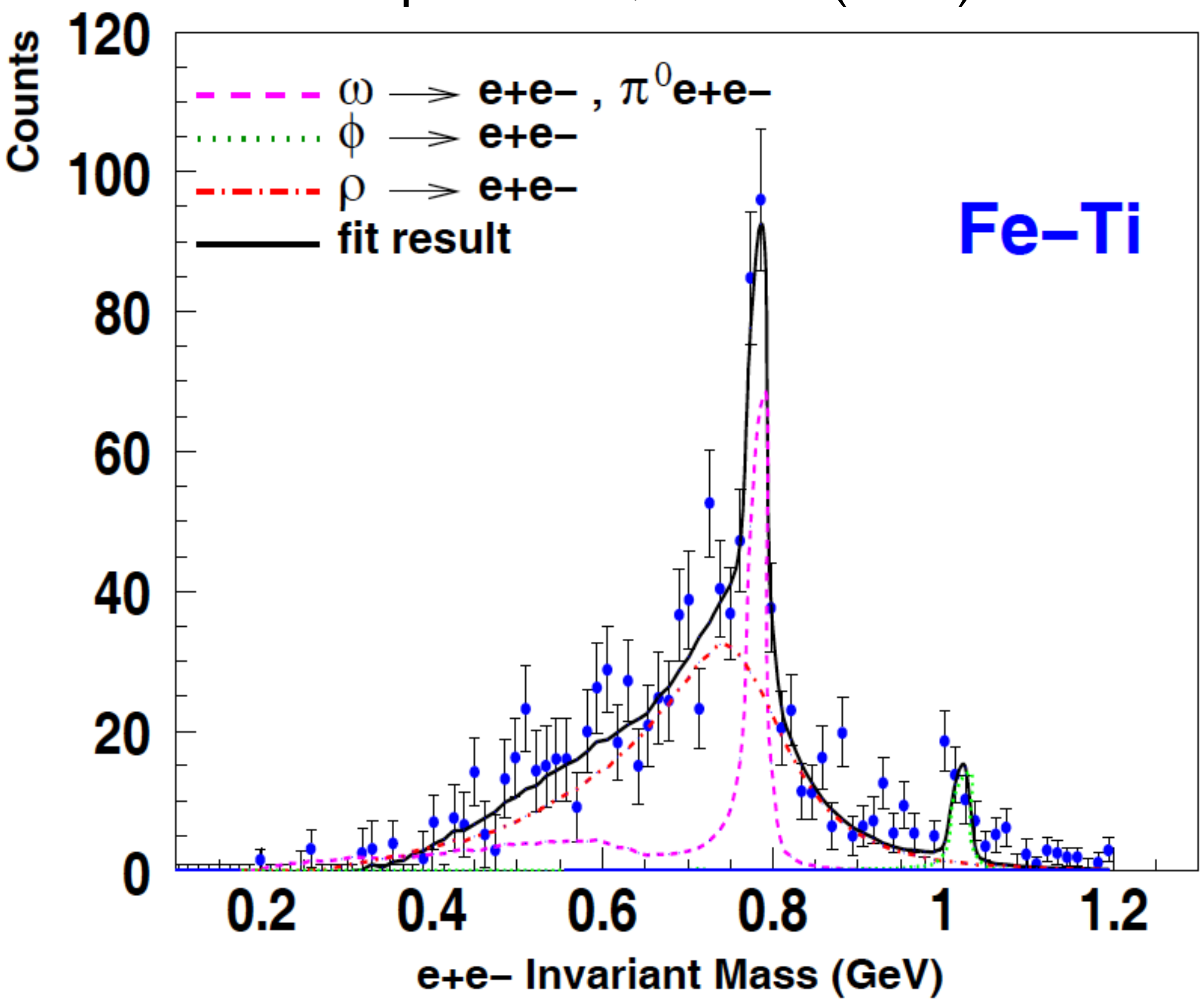


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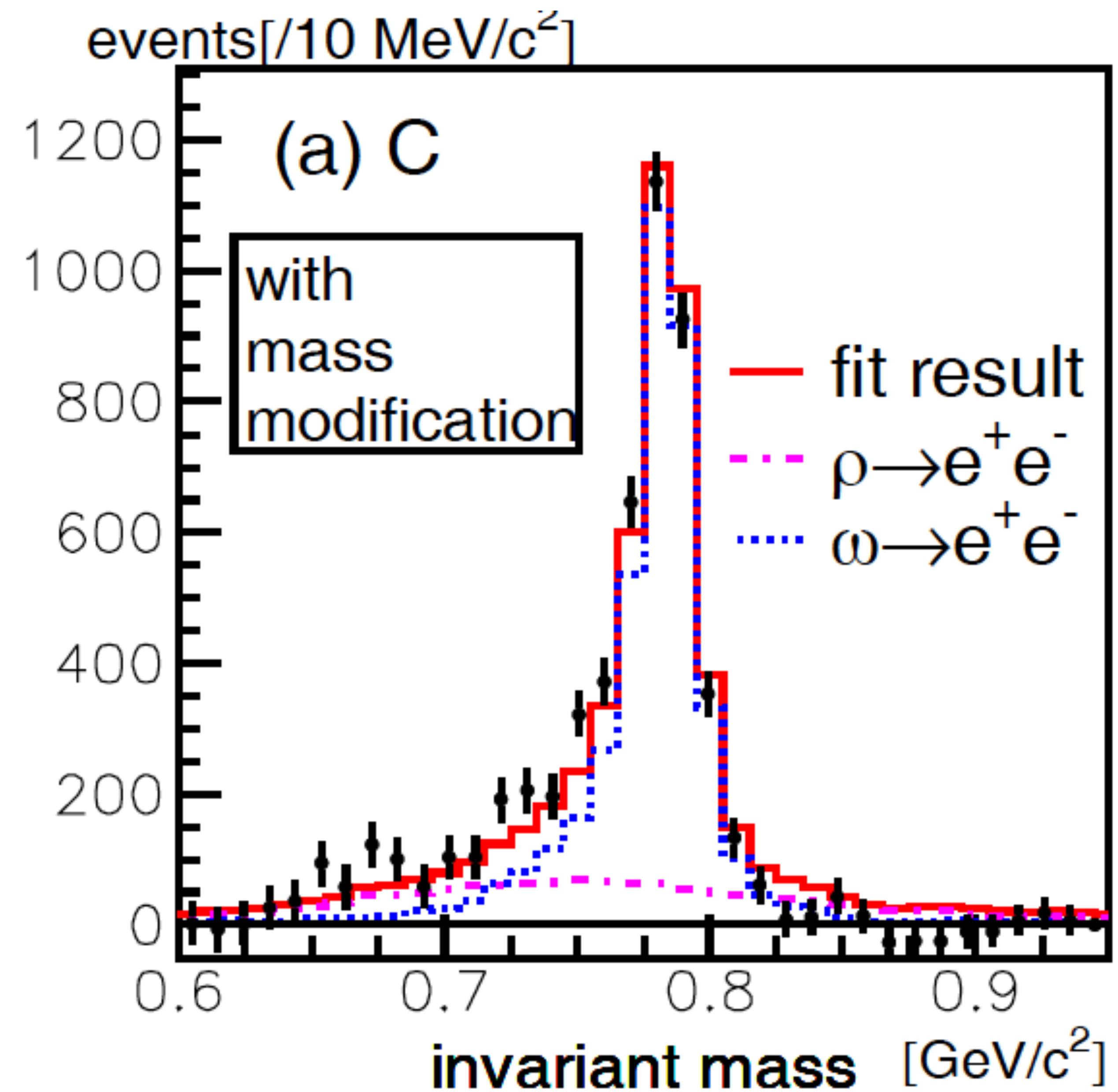
**KEK-E325:** p(12 GeV) A $\to e^+e^-X$;
M. Naruki et al., PRL96 (2006) 092301

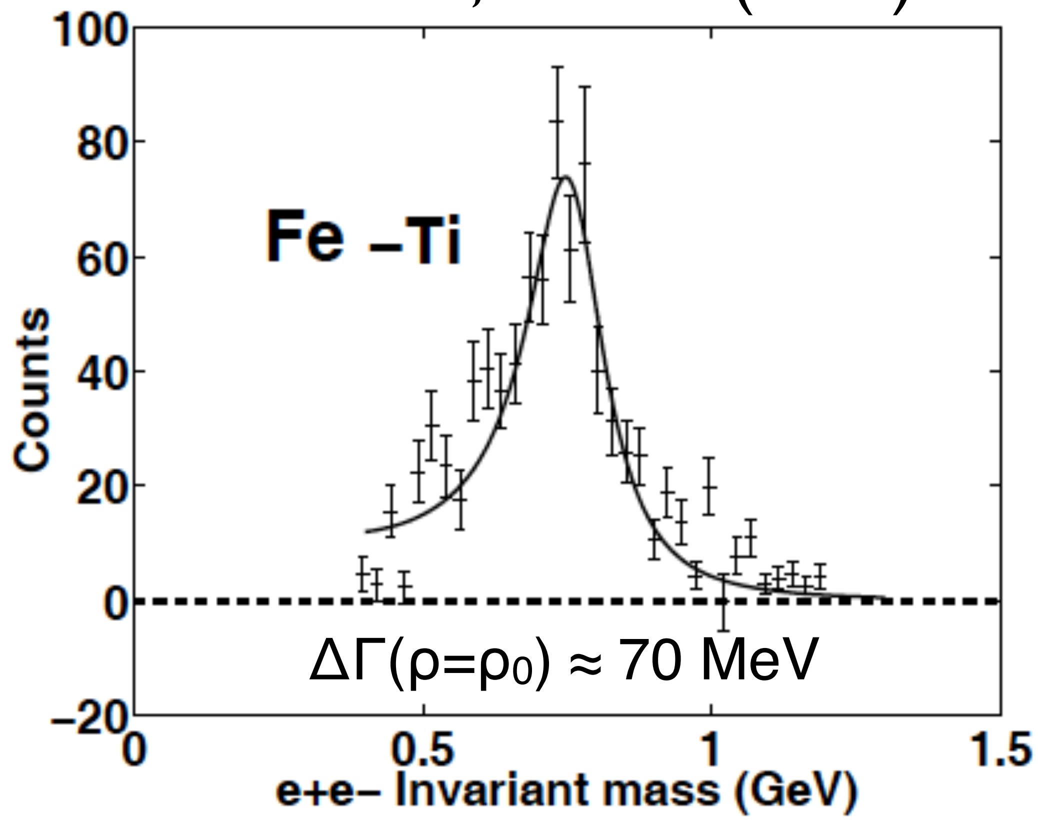



ρ shifted in mass; no broadening !!

$$m_\rho(\rho) = m_0 \cdot (1 - 0.092\frac{\rho}{\rho_0})$$

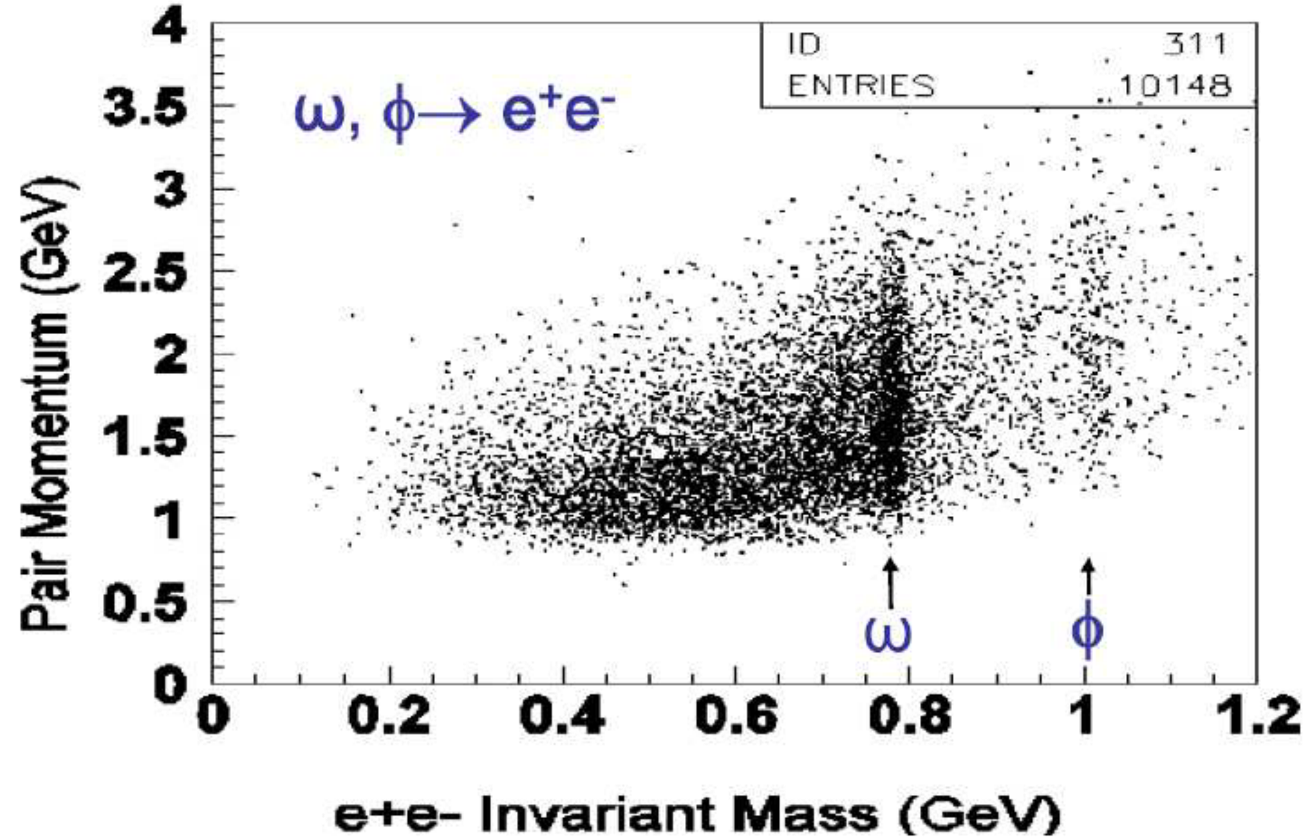
# detector performance: acceptance

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

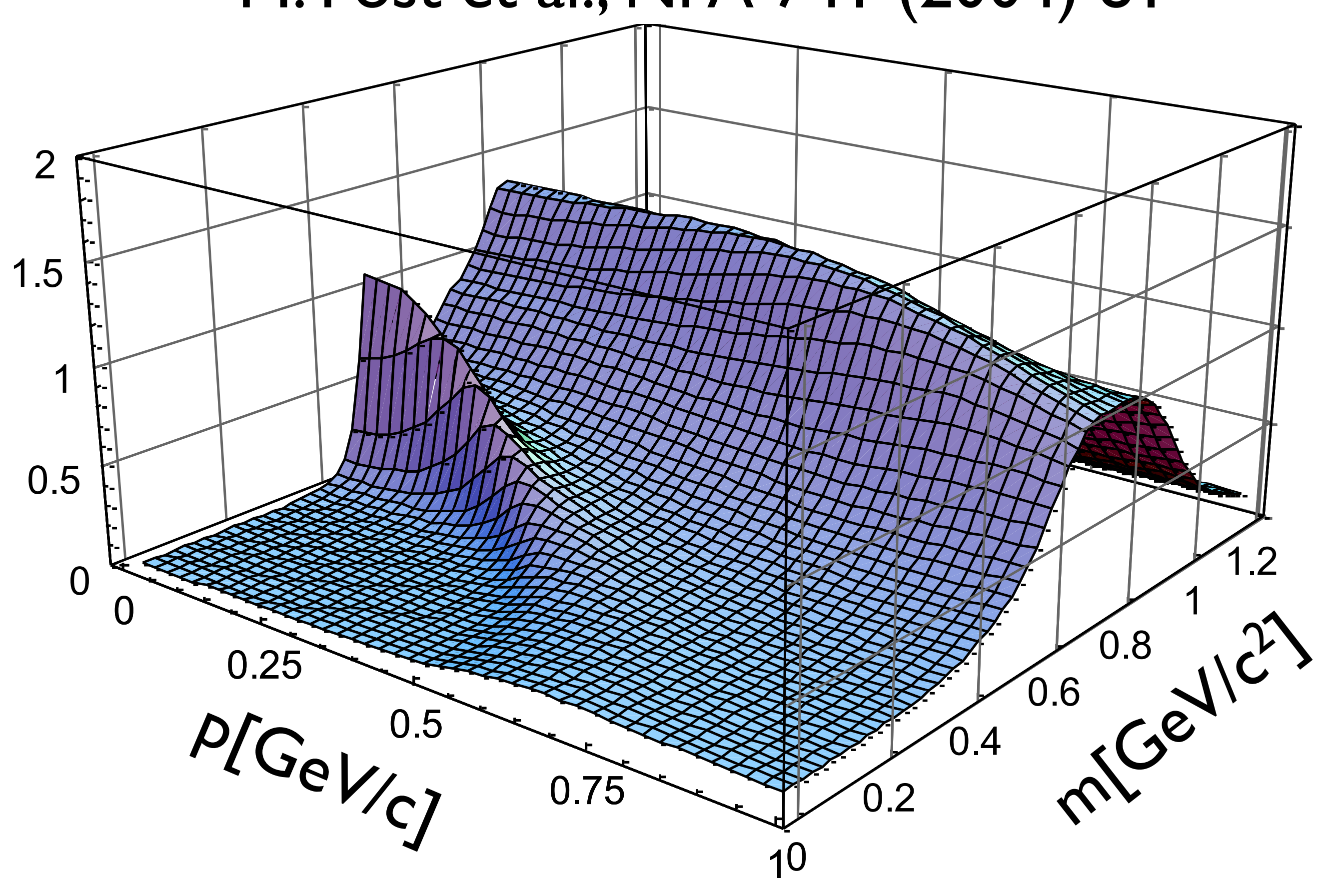



CLAS

$e^+e^-/\pi^+\pi^-$ misidentification $\approx 10^{-7}$




M. Post et al., NPA 741 (2004) 81




no acceptance for $p_{ee}$ < 800 MeV/c
reduced acceptance for low $m_{e+e-}$

predicted structures at
$p_{e+e-}$ < 500 MeV/c not observable !!

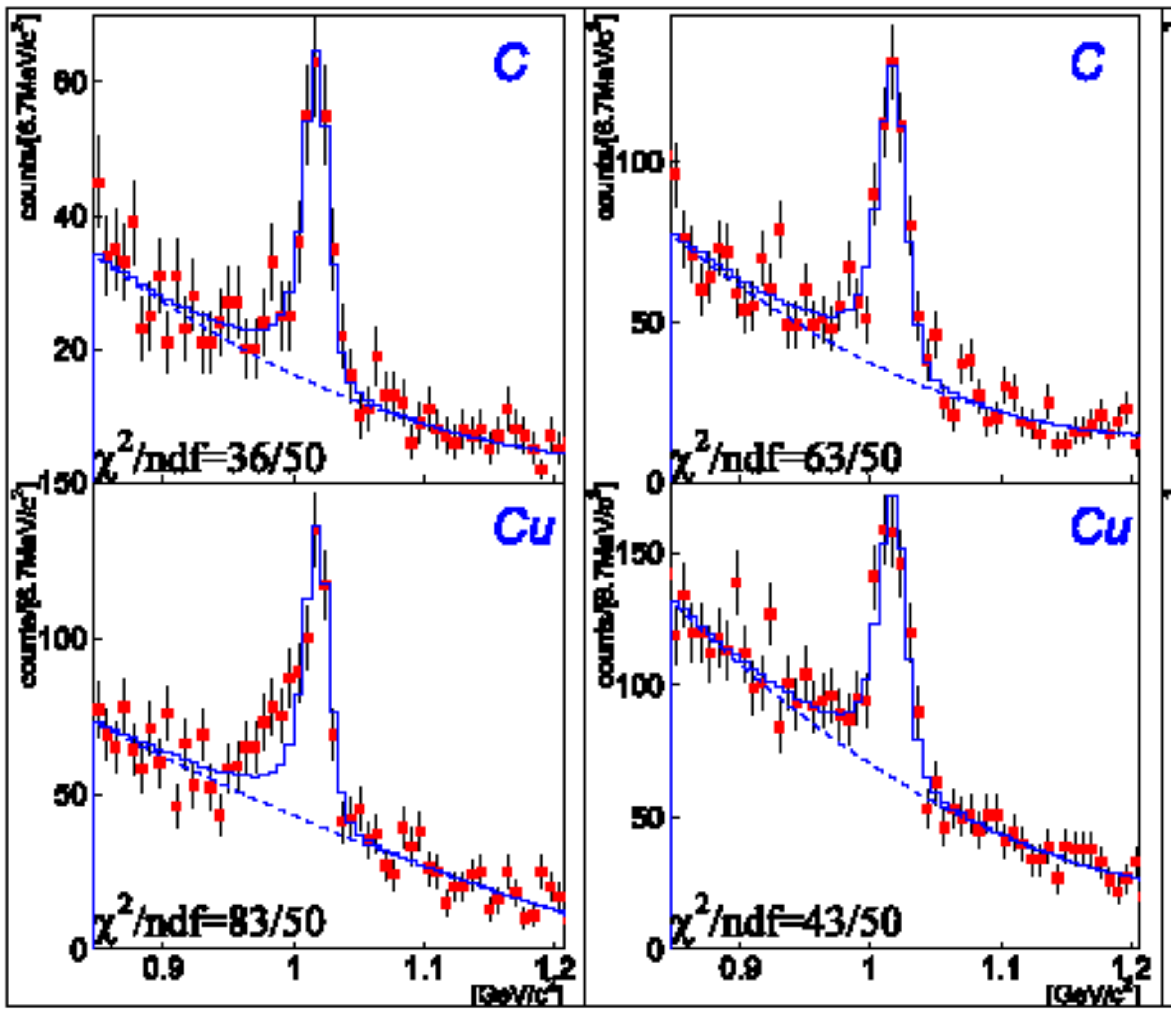
# in-medium Φ-spectral function from $\Phi \rightarrow e^+e^-$

$$m(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

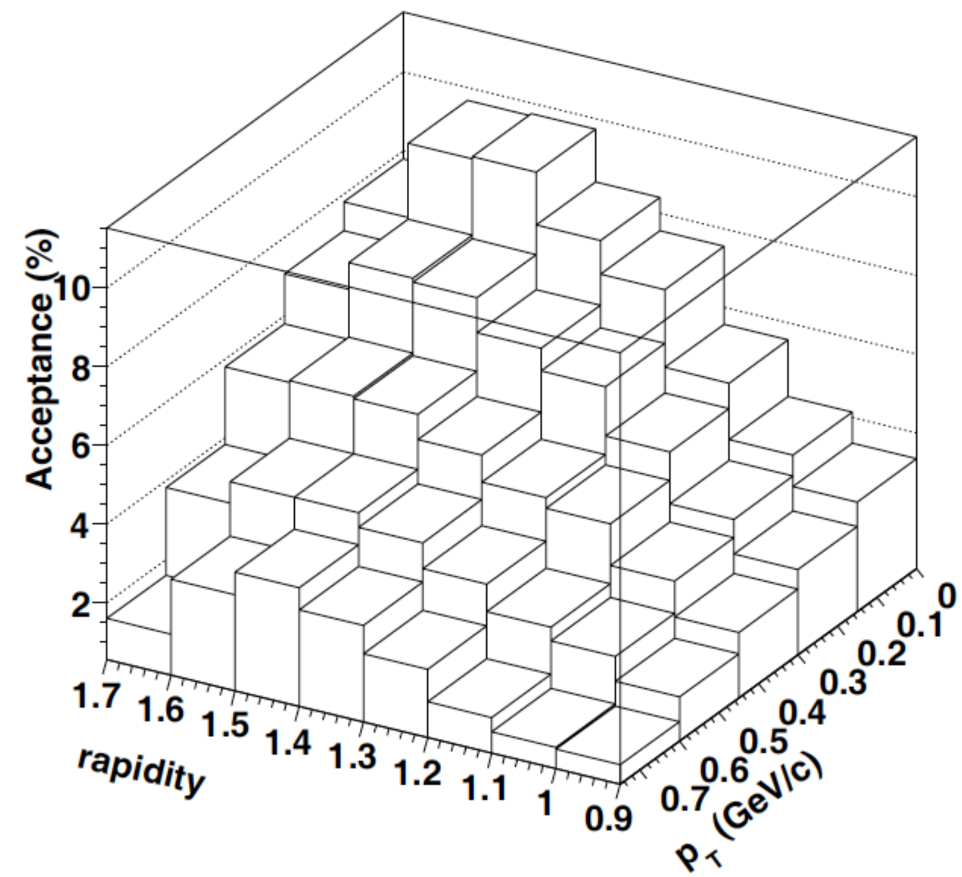
KEK-E325: p (12 GeV) A→ ρ, ω +X; $\Phi \rightarrow e^+e^-$

$\phi$: $c\tau \approx 46$ fm

$\beta\gamma \leq 1.25$ (slow)   $1.25 \leq \beta\gamma \leq 1.75$ (fast)




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




mass shift of Φ meson for low recoil momenta in Cu: $m_\Phi = m_0\,(1-0.04\,\rho/\rho_0)$

increase in width by a factor 3.6; $\Gamma_\Phi(\rho=\rho_0) \approx 15$ MeV

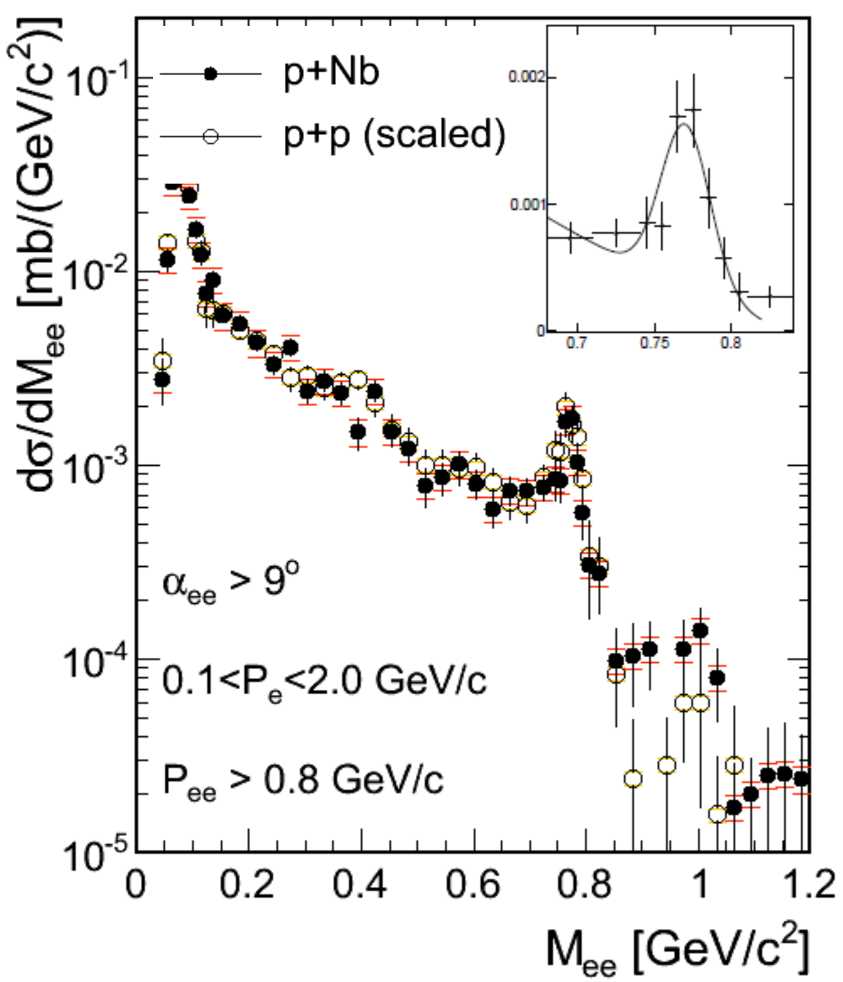
improved experiment (E16) in preparation at JPARC

# dilepton invariant mass spectra

**HADES@GSI** p + p, Nb 3.5 GeV $m(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$

G. Agakishiev et al., Phys. Lett. B 715 (2012) 304

$p_{ee}$ > 800 MeV/c




shape of $m_{ee}$ spectrum in p+Nb identical to reference spectrum in p+p

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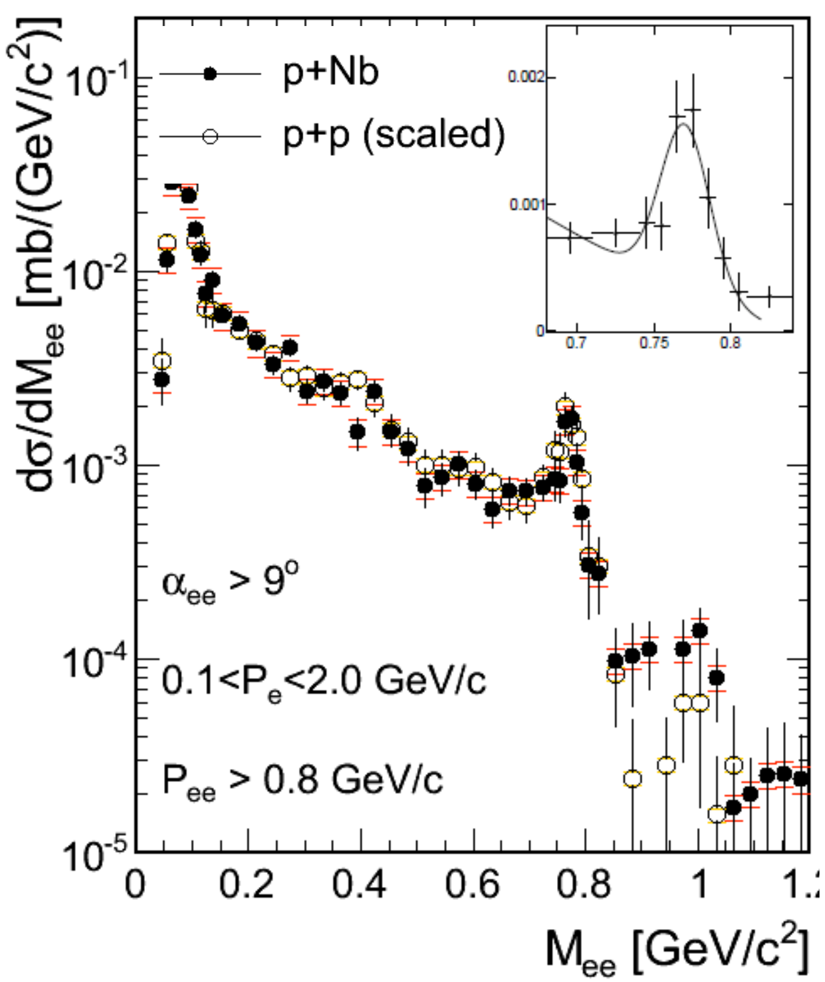


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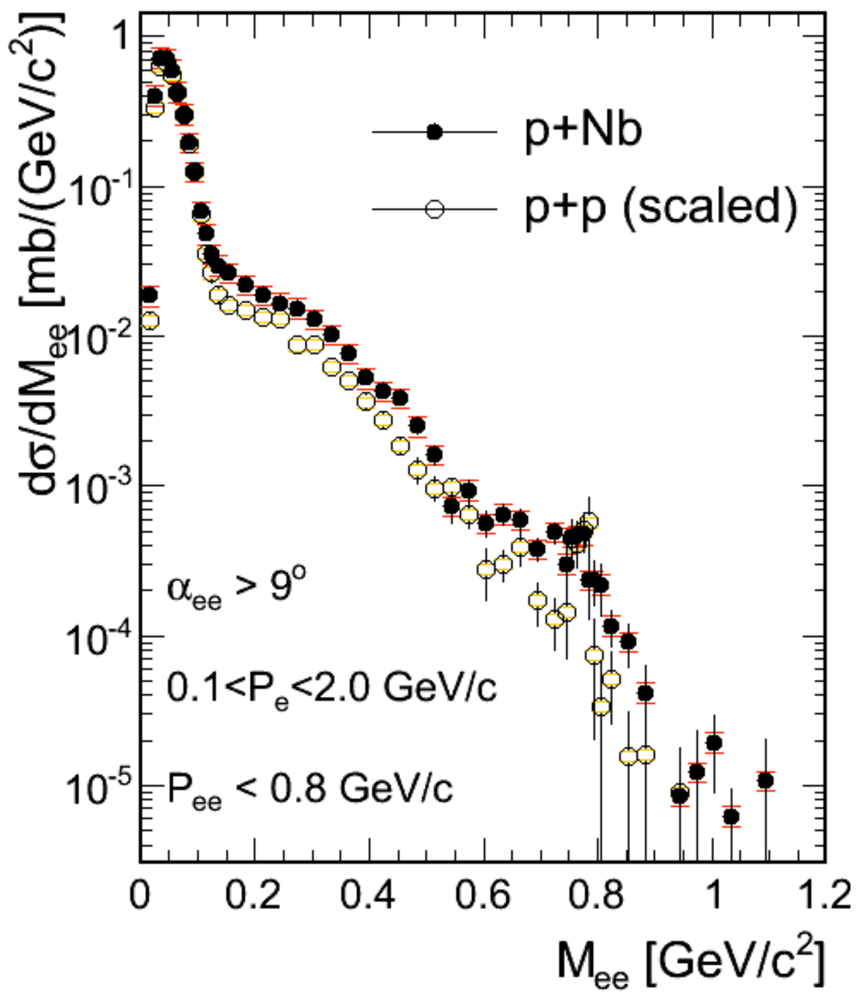


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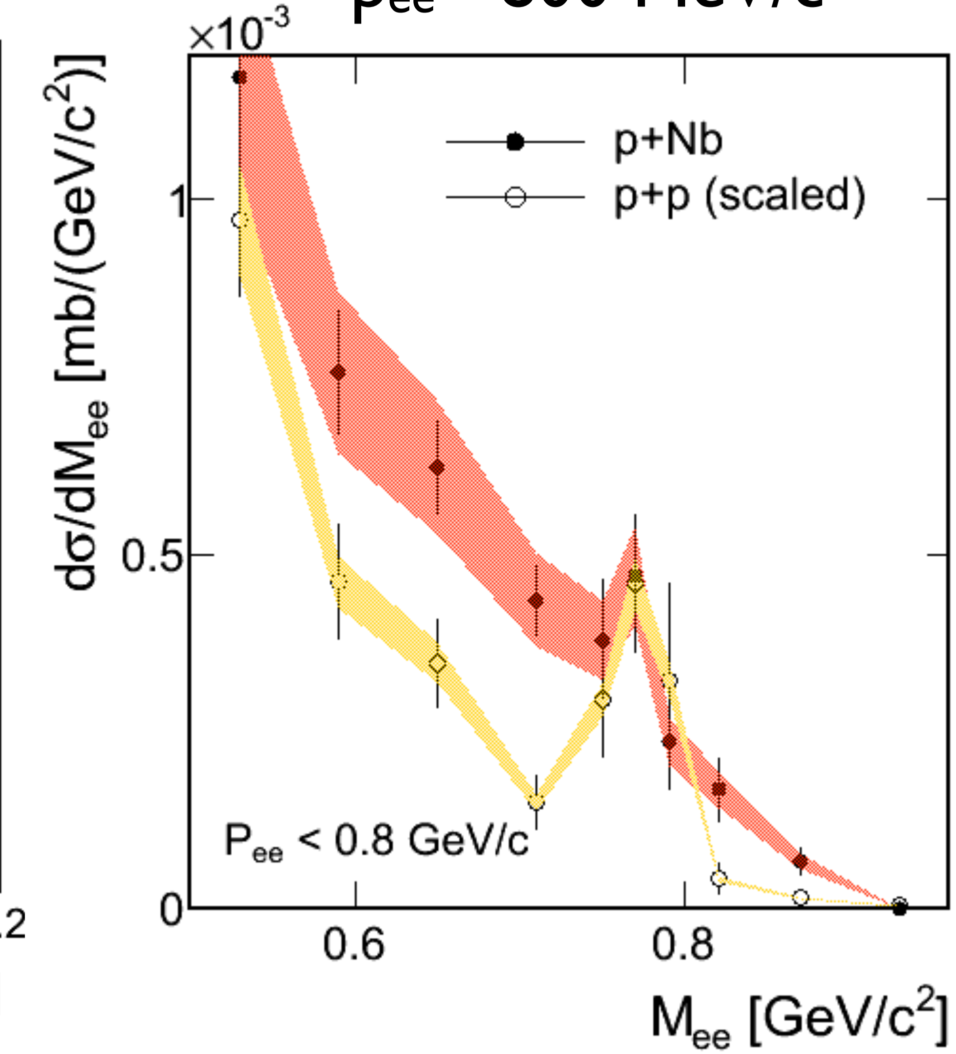
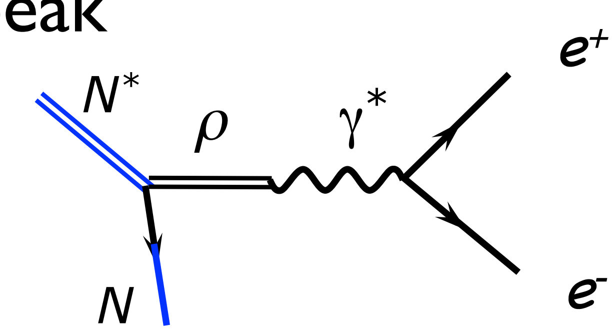



shape of $m_{ee}$ spectrum in p+Nb identical to reference spectrum in p+p

- strong $e^+e^-$ excess yield below ω peak attributed to ρ-like channels;
- no hint for change in ω line shape;
- strong ω absorption

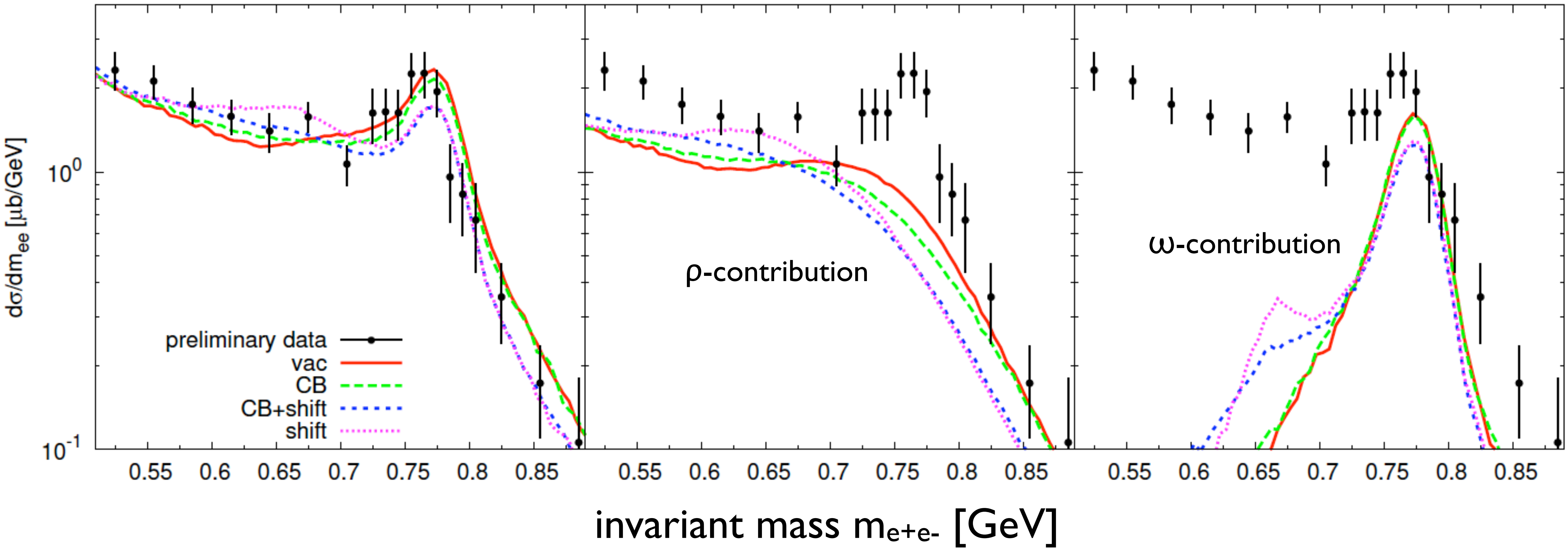


# comparison to GiBUU simulations

J. Weil, H. van Hees, U. Mosel; EPJA 48 (2012) 111

comparison to different in-medium modification scenarios

HADES data G. Agakishiev et al., Phys. Lett. B 715 (2012) 304
p+Nb at 3.5 GeV




- difficult to distinguish between different in-medium scenarios:
- difficult to disentangle ρ, ω contributions and to extract individual in-medium properties

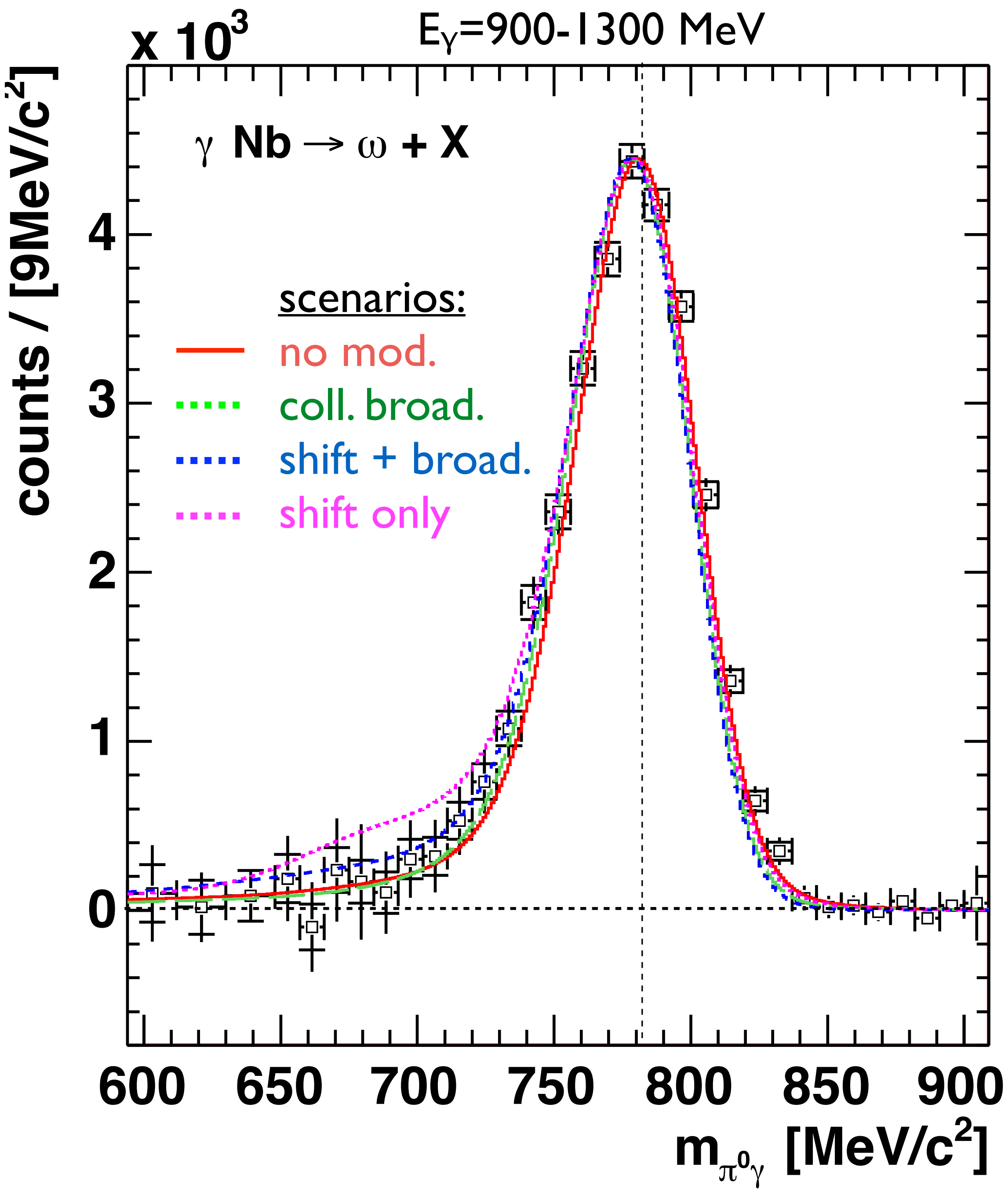
# ω line shape from ω→π⁰γ in photo-nuclear reaction

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

advantage: no $\rho \to \pi^0\gamma$
$\omega\to\pi^0\gamma$ br: 8.3%

- line shape analysis: $m(\rho,\vec{p}) = \sqrt{(p_1+p_2)^2}$

comparison with GiBUU calculations
for different in-medium scenarios




- sensitivity limited by 5 effects:

1) mass resolution $\sigma \approx 3\%$;
only mass shifts ≫ 3% observable

2) only 30% of all $\omega\to\pi^0\gamma$ decays occur within the Nb nucleus

3) ω decays occur over a wide range of densities, thereby smearing out any density-dependent signal

4) $\omega\to\pi^0\gamma$ signal smeared out and reduced due to large in-medium width ($\Gamma_{med} \approx 16 \cdot \Gamma_{vac}$)

5.) due to $\pi^0$ absorption ($\pi^0$-FSI) $\omega\to\pi^0\gamma$ decays in the center of the nucleus are suppressed

# the real part of the ω-nucleus potential

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

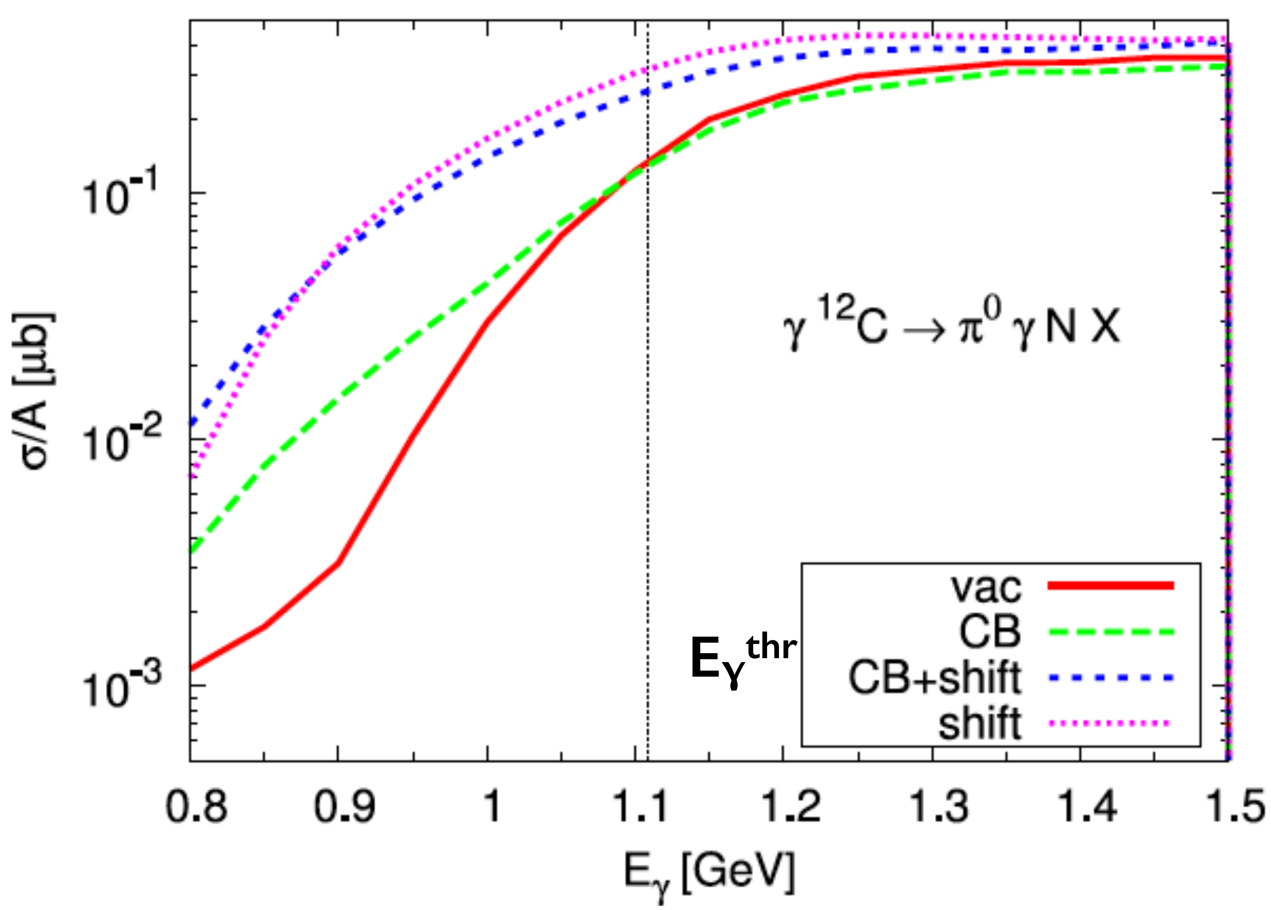
sensitive to nuclear density at production point

- 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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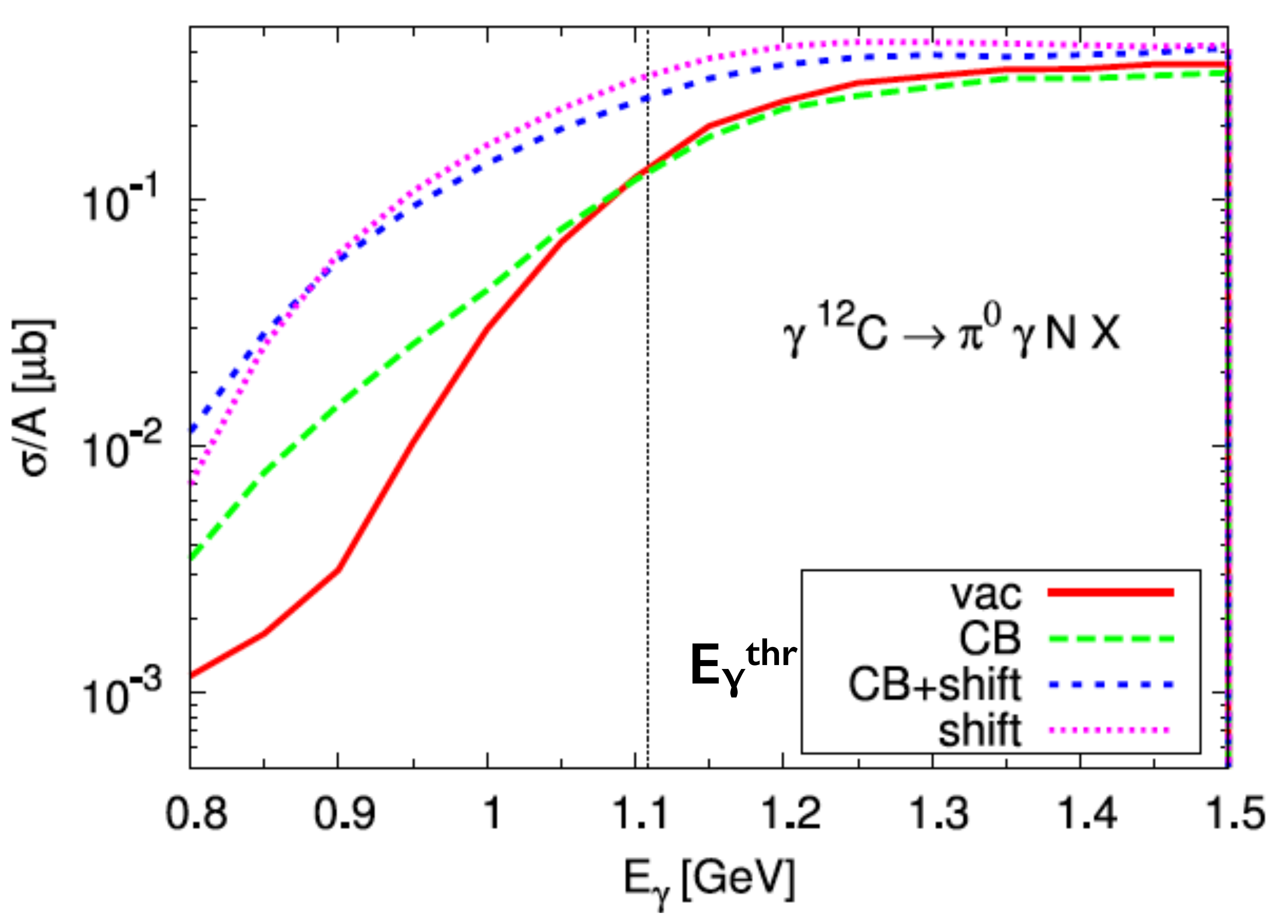
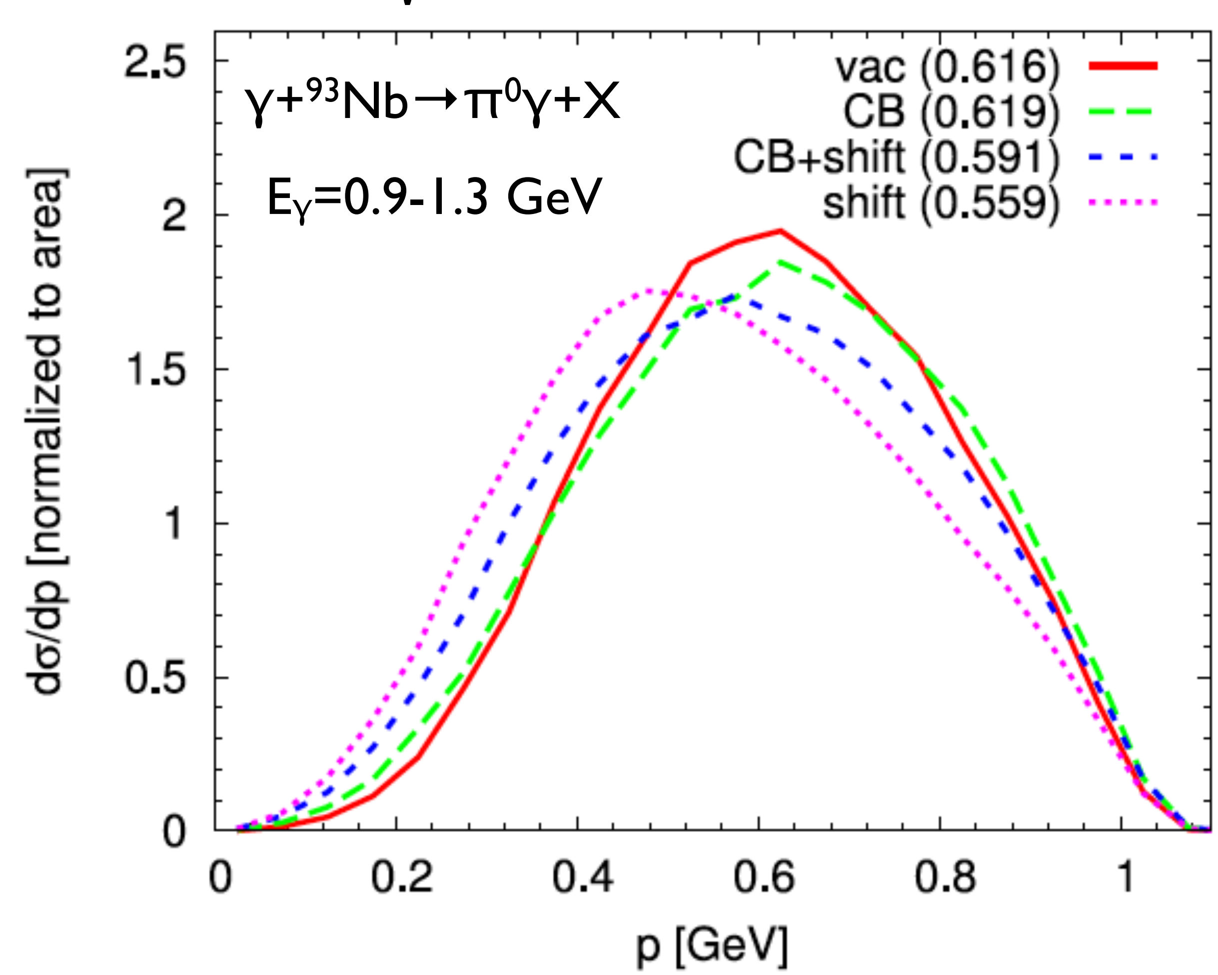



- momentum distribution of the meson:

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



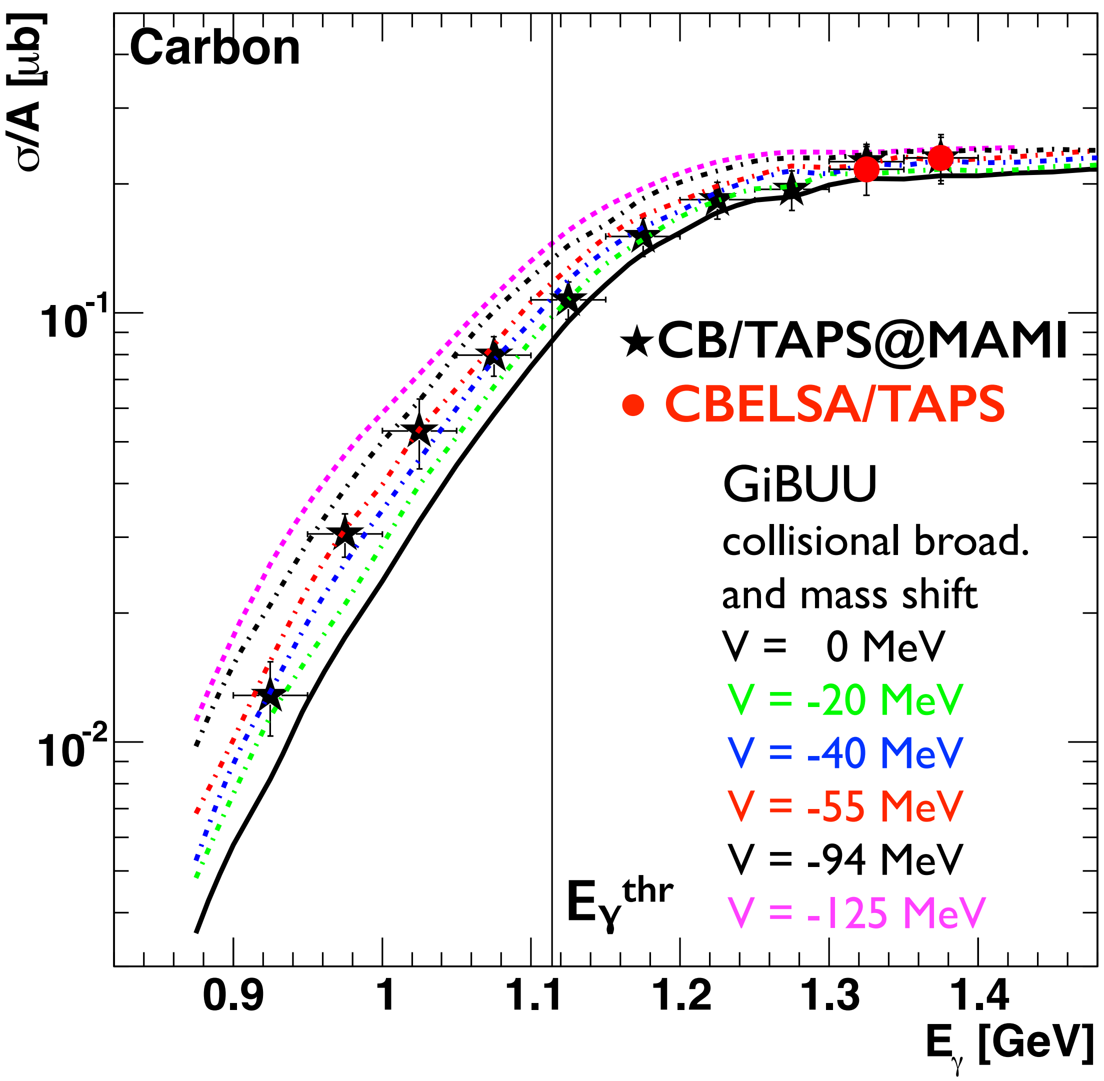
# excitation function for ω photoproduction off C comparison with GiBUU calculation

CB/TAPS @ MAMI

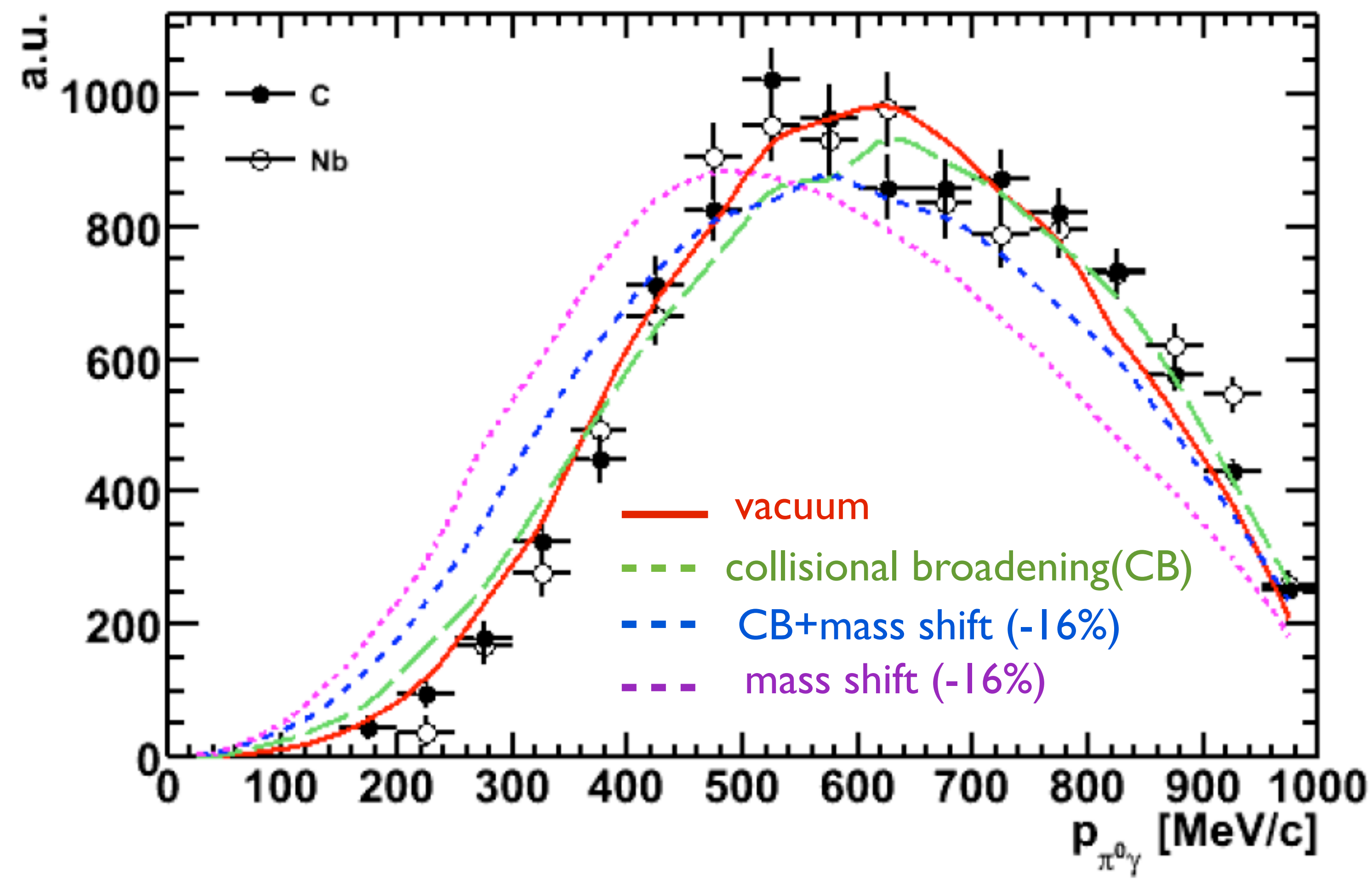
V. Metag et al., PPNP, 67 (2012) 530

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

excitation function




momentum distribution




V(ρ=ρ0) = -(42±17(stat)±20(syst)) MeV

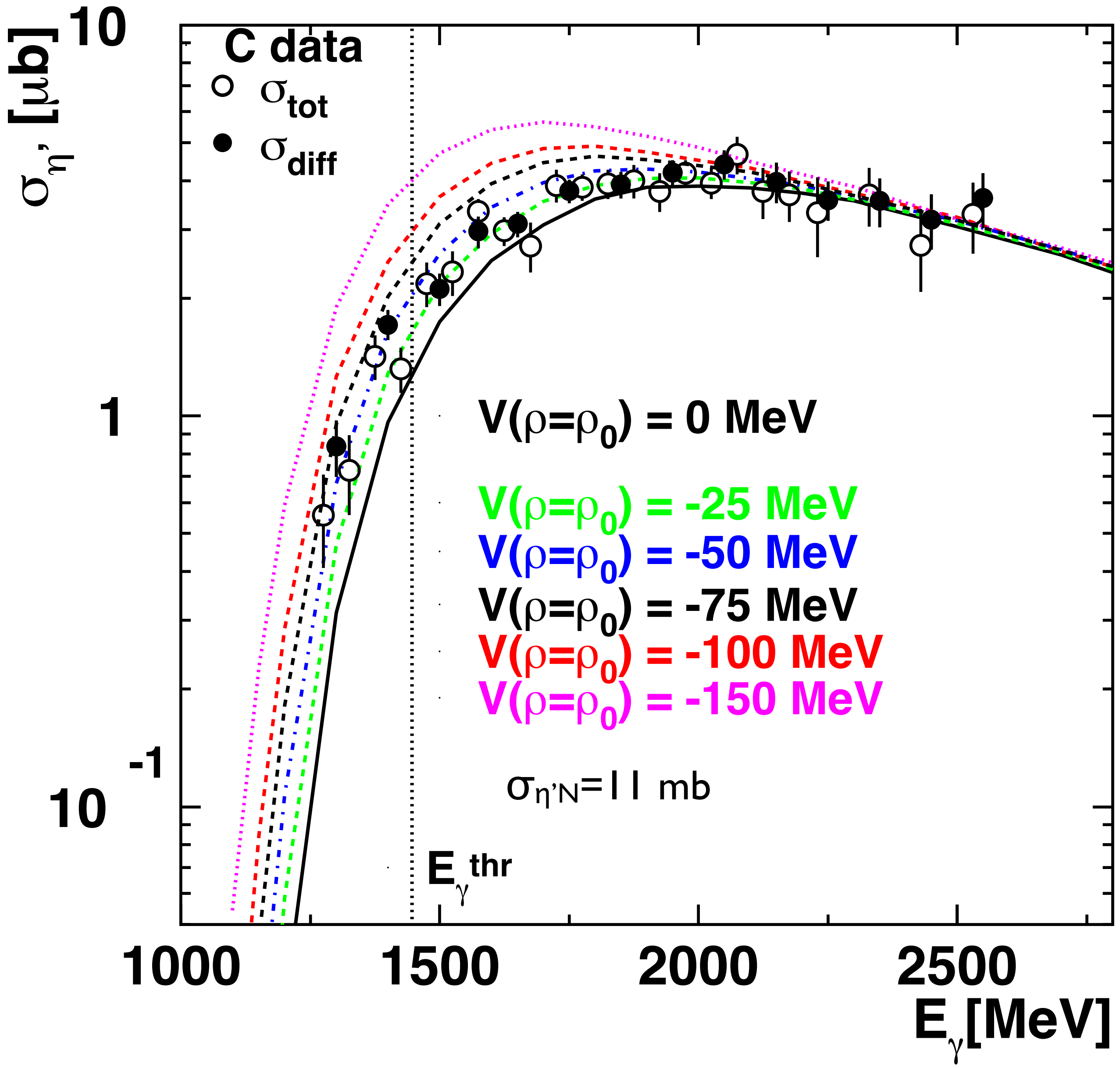
data not consistent with strong mass shift scenario (Δm/m≈-16%)

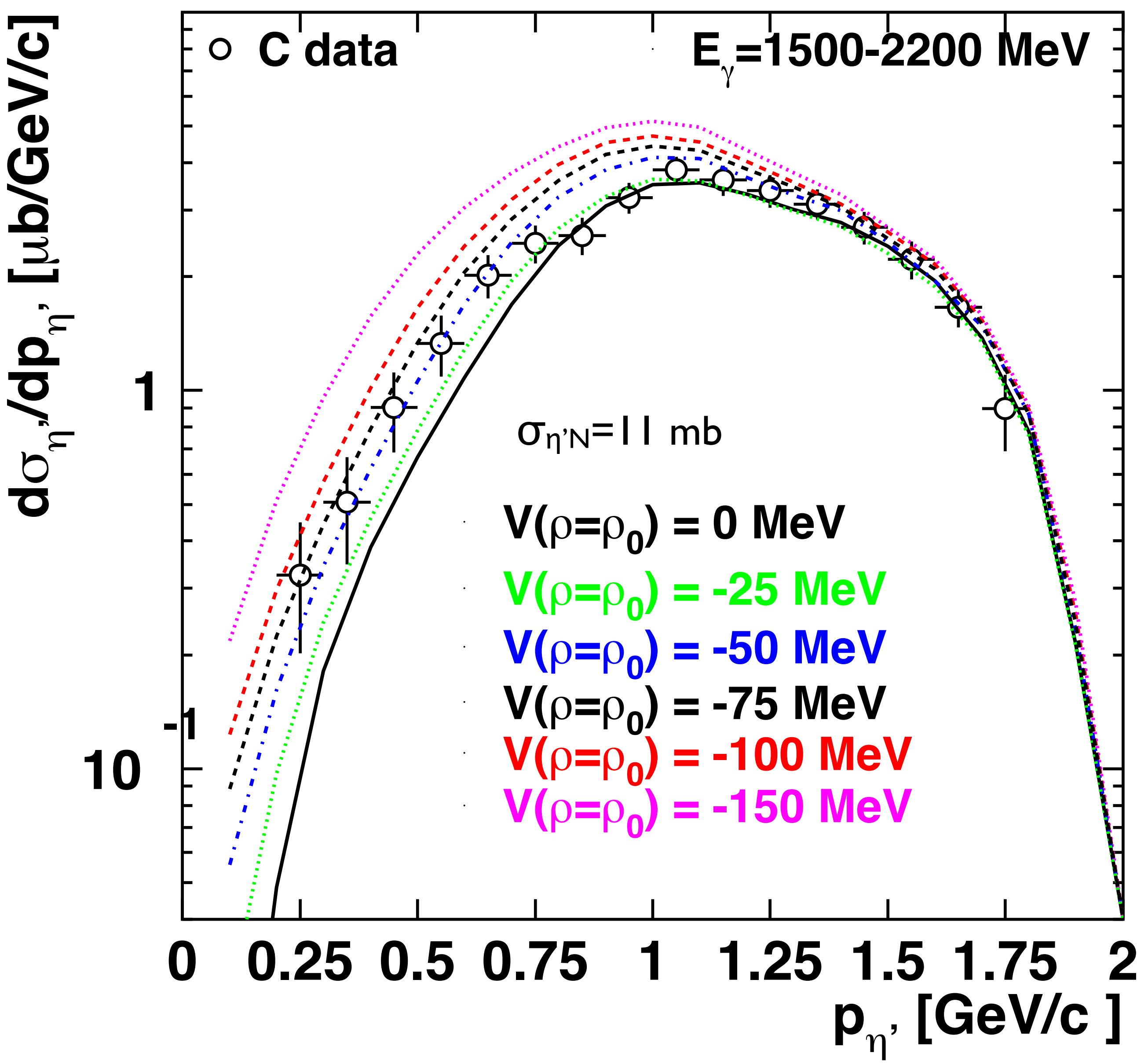
# excitation function and momentum distribution for η' photoproduction off C

CBELSA/TAPS @ ELSA

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

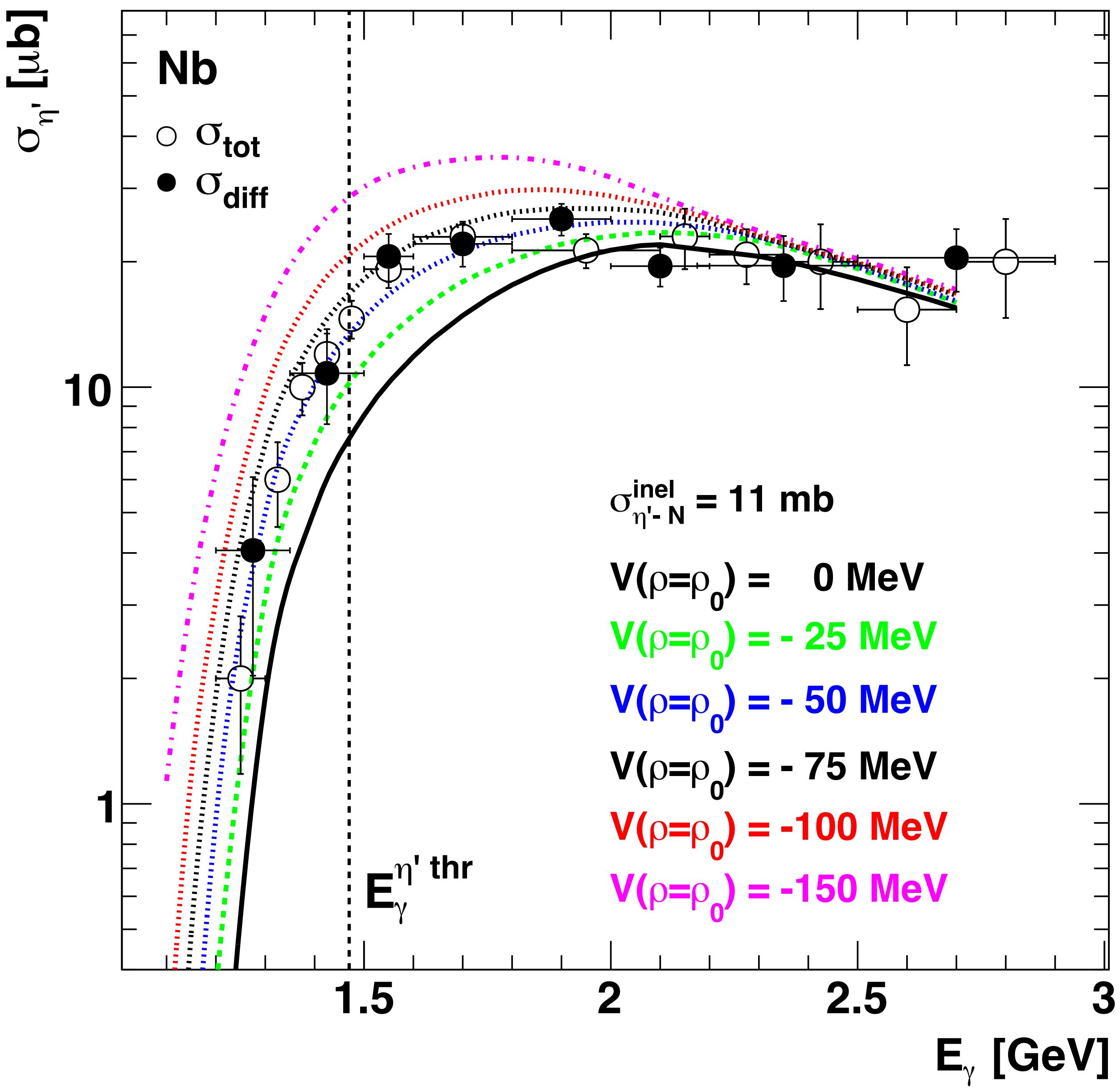
# excitation function and momentum distribution for η' photoproduction off Nb

PRELIMINARY

CBELSA/TAPS @ ELSA

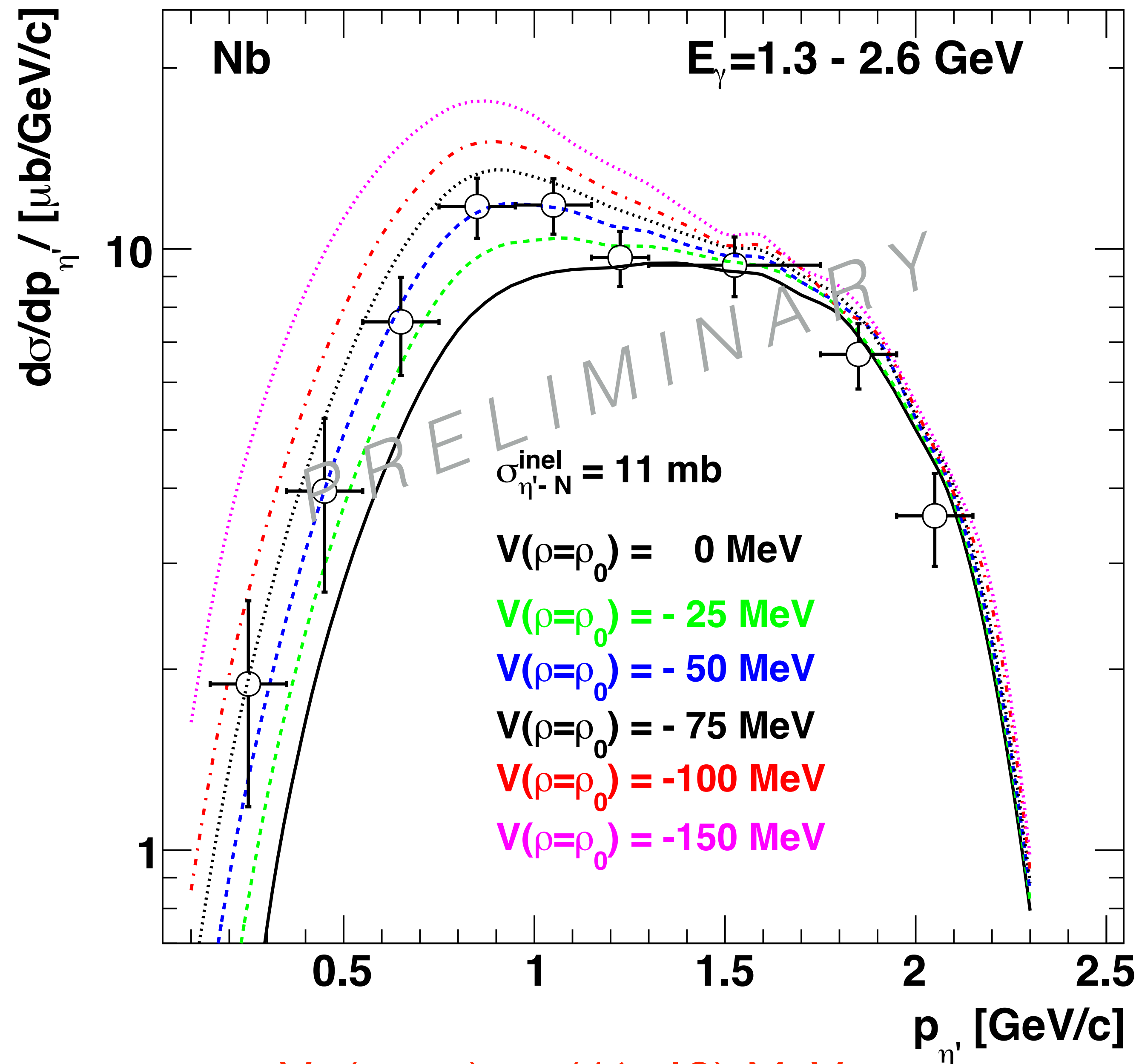
calc.: E. Paryev, priv. communication

excitation function




$V_{\eta'}(\rho=\rho_0) = -(46\pm16)$ MeV

momentum distribution



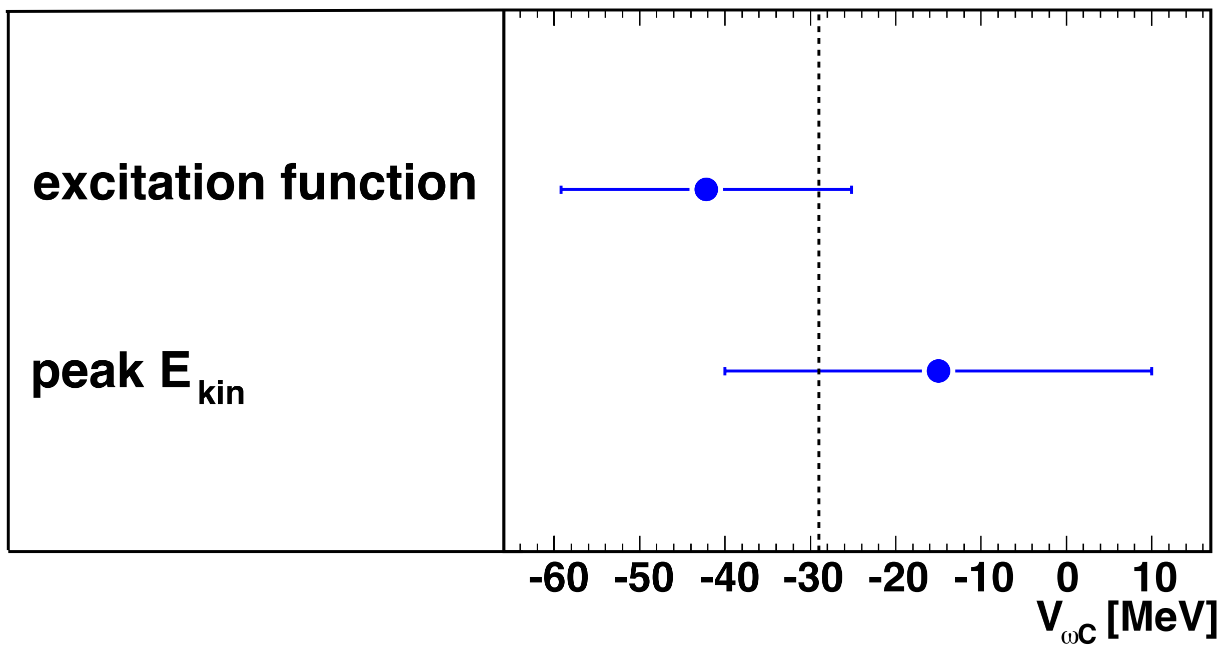

$V_{\eta'}(\rho=\rho_0) = -(46\pm13)$ MeV

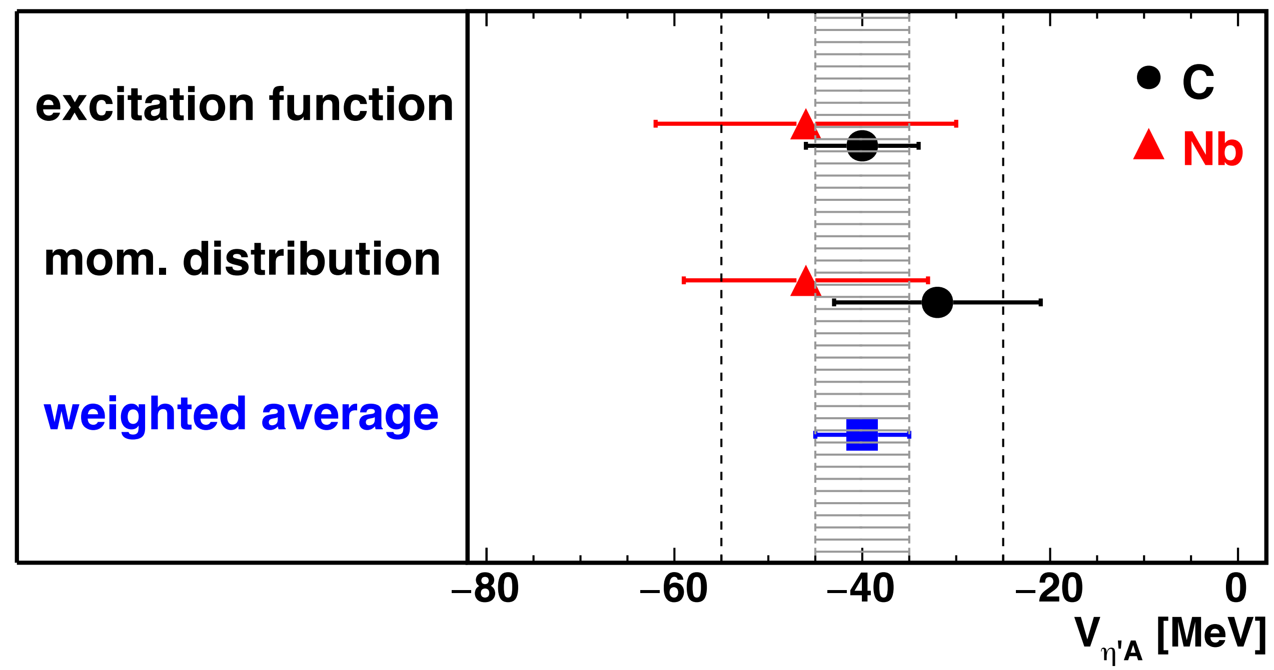
data disfavour strong mass shifts

# compilation of results for the real part of the ω- and η'-nucleus optical potential

ω

η'




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

$V_{\eta' A}(\rho=\rho_0)$ = -(40±5(stat)±15(syst)) MeV

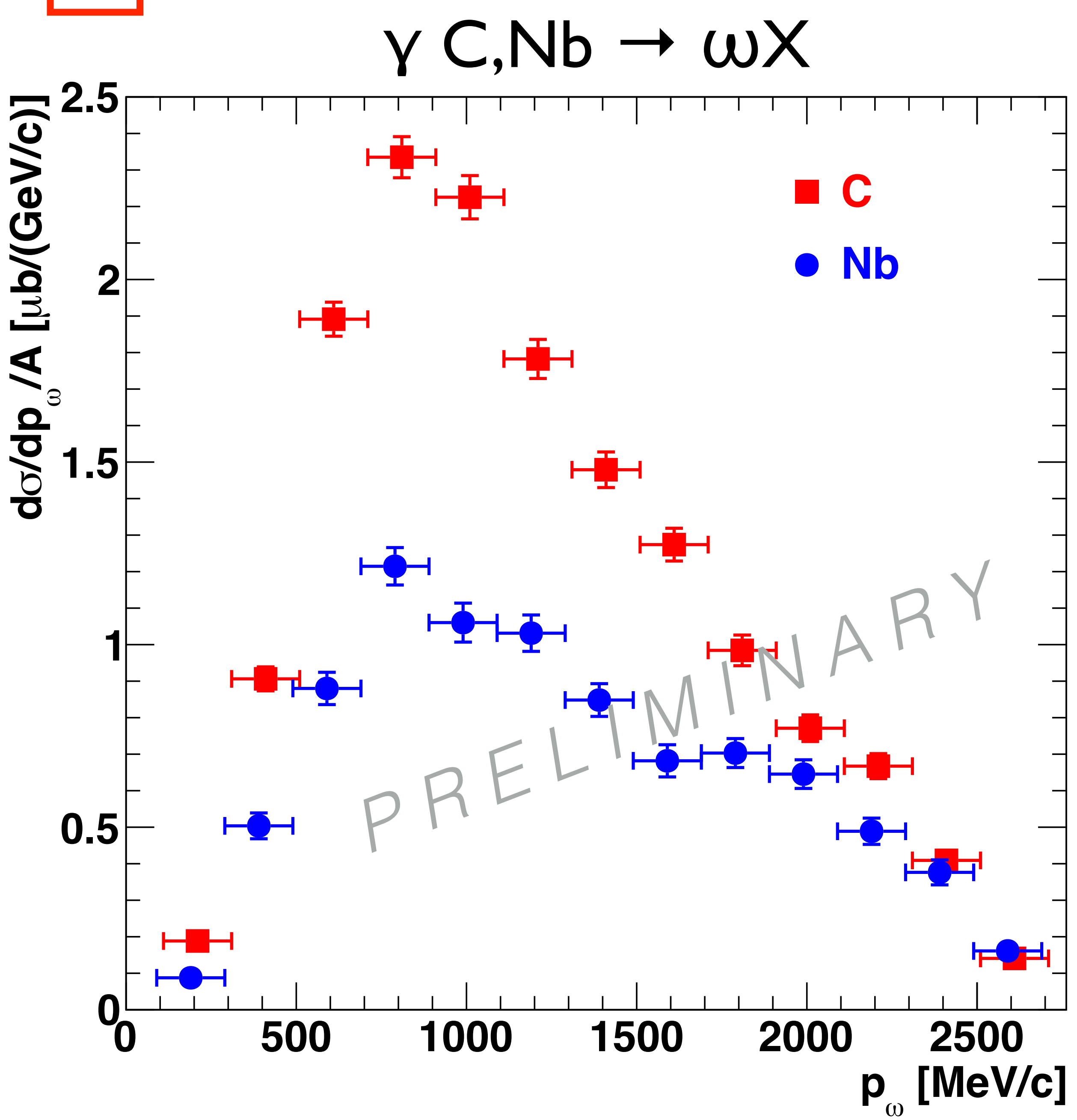
## the imaginary part of the meson-nucleus optical potential: momentum dependence

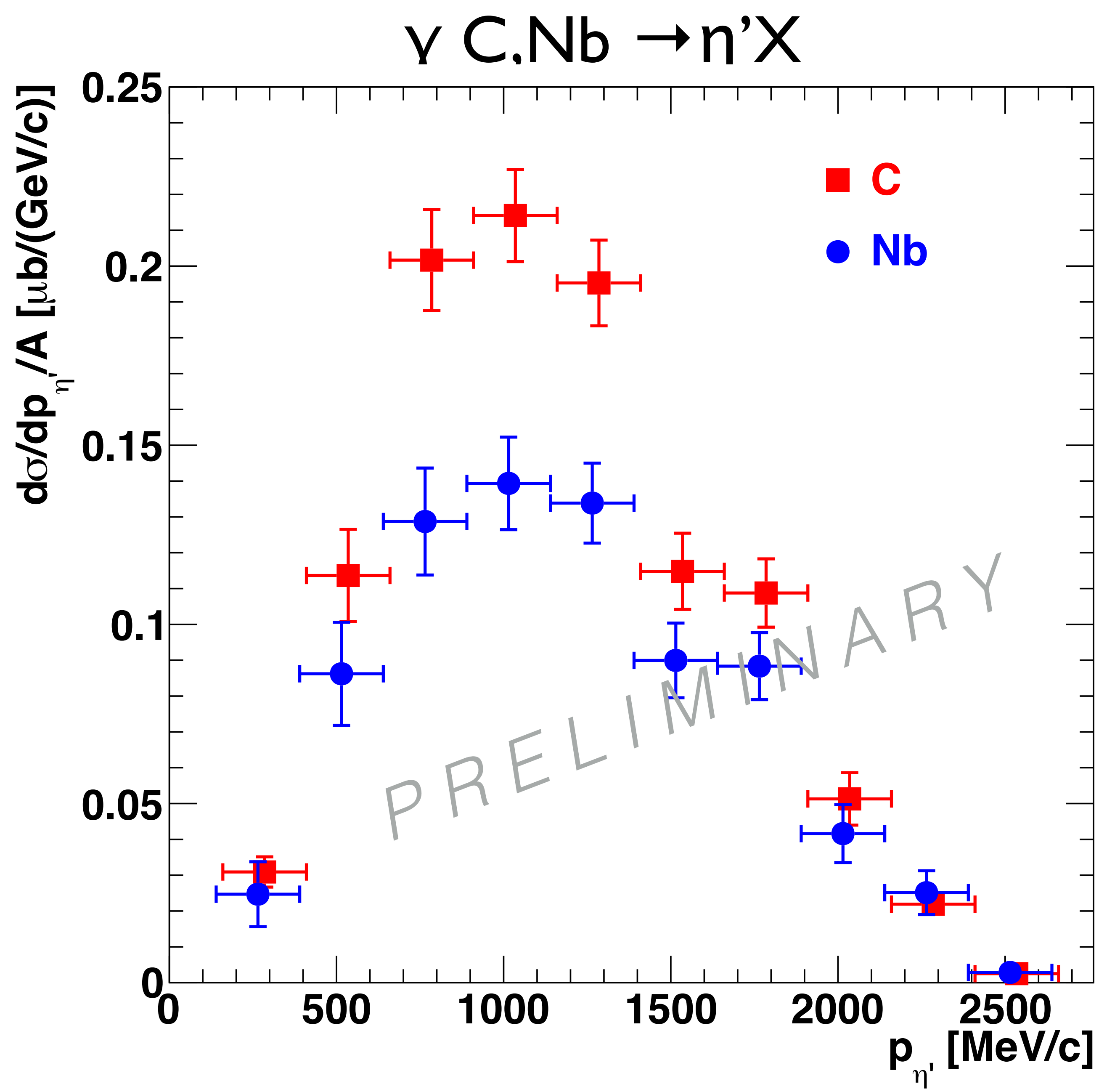
# momentum differential cross section for ω, η' produced off C, Nb

ω

$E_\gamma$ = 1.2- 2.9 GeV

η'



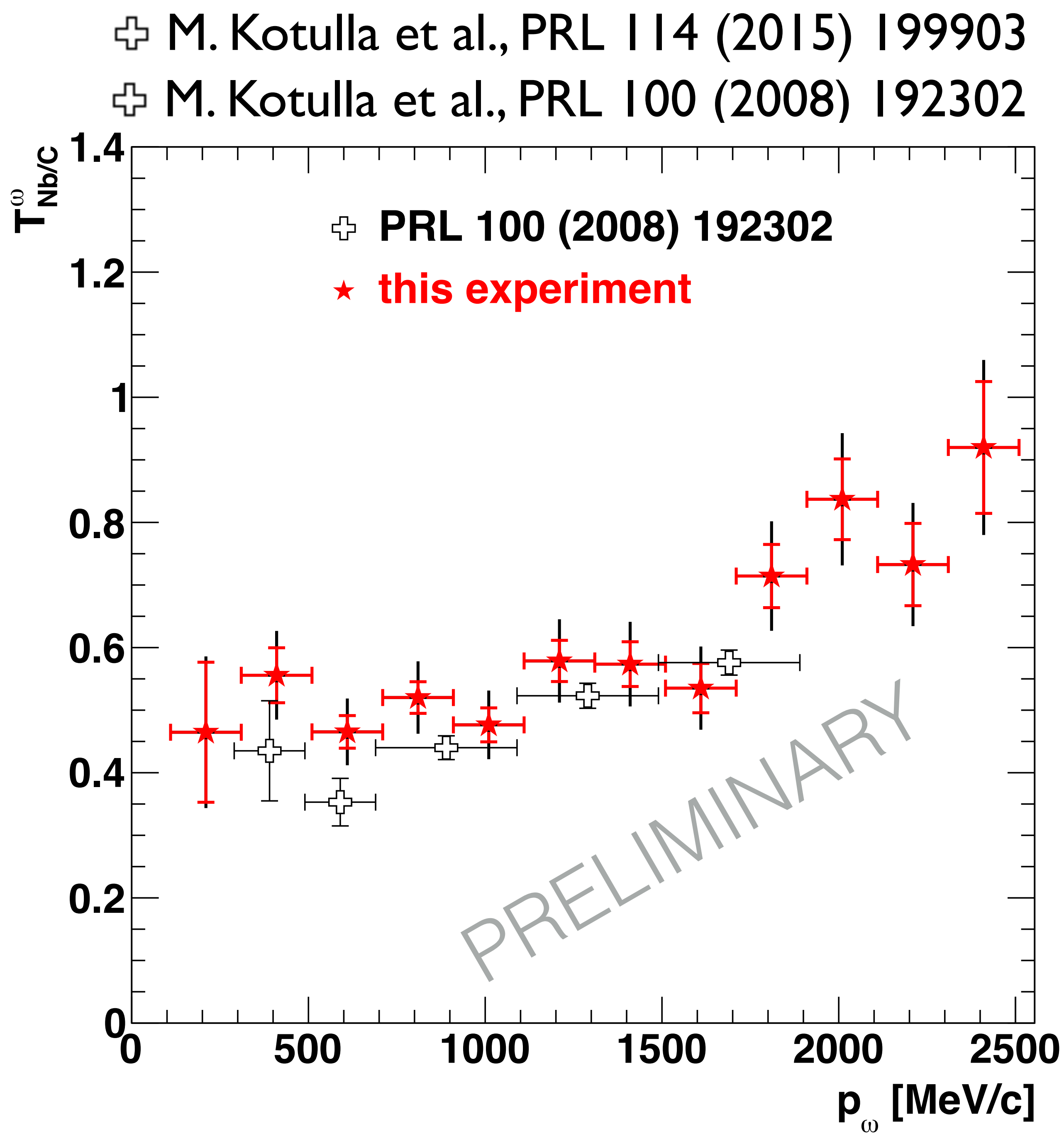

momentum differential cross sections ⇒ $T^{m}_{Nb/C}(p_m) = \frac{12 \cdot \sigma_{\gamma Nb \rightarrow mX}(p_m)}{93 \cdot \sigma_{\gamma C \rightarrow mX}(p_m)}$

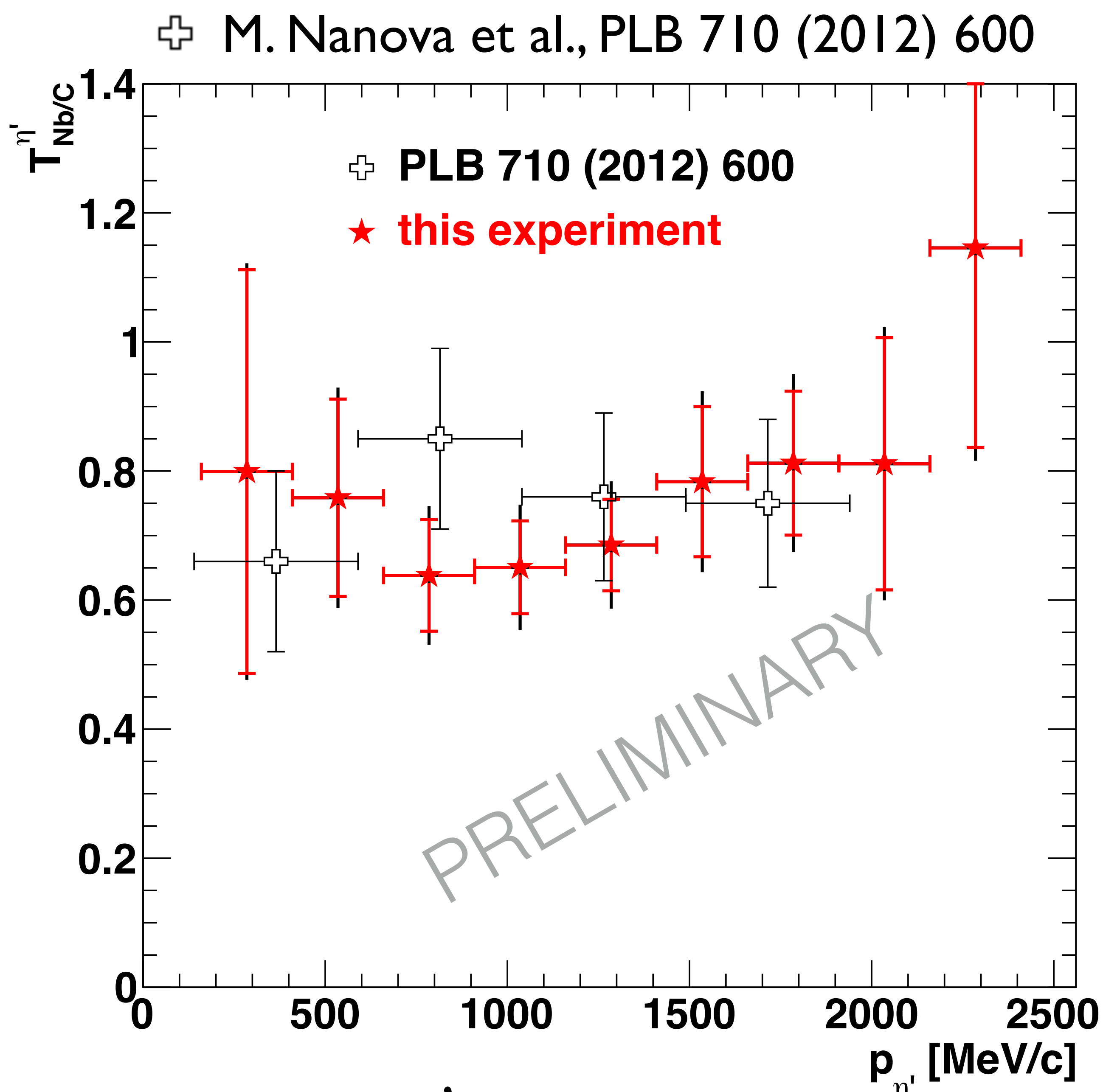
# momentum dependence of transparency ratio for ω, η'

$$T^{m}_{Nb/C}(p_m) = \frac{12 \cdot \sigma_{\gamma Nb \to mX}(p_m)}{93 \cdot \sigma_{\gamma C \to mX}(p_m)}$$

ω

η'




$T^{\omega}_{Nb/C} \approx 0.4\text{-}0.6$

$T^{\eta'}_{Nb/C} \approx 0.7\text{-}0.8$

absorption of η' mesons much weaker than for ω mesons !!

# momentum dependence of imaginary potential for ω, η'

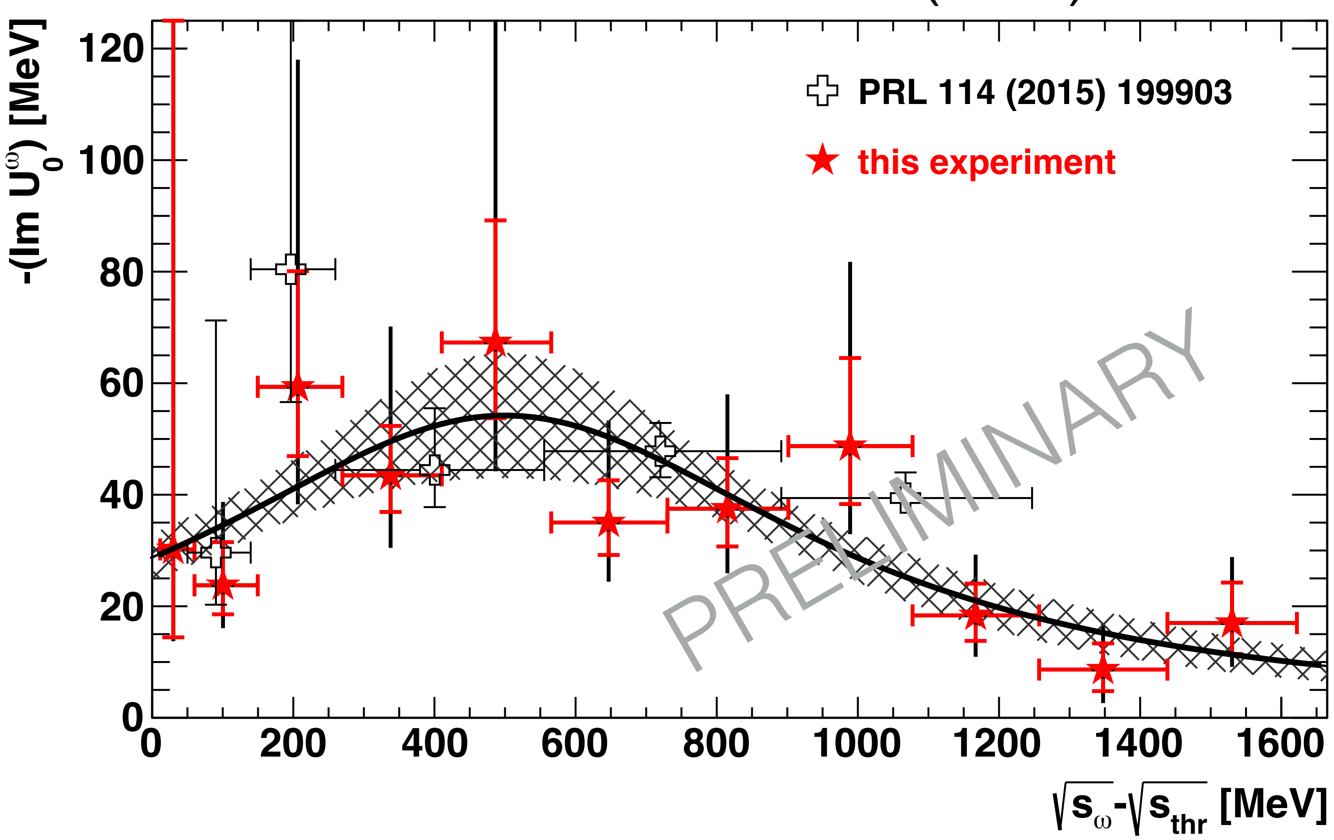
Glauber model: high energy Eikonal approximation

ω

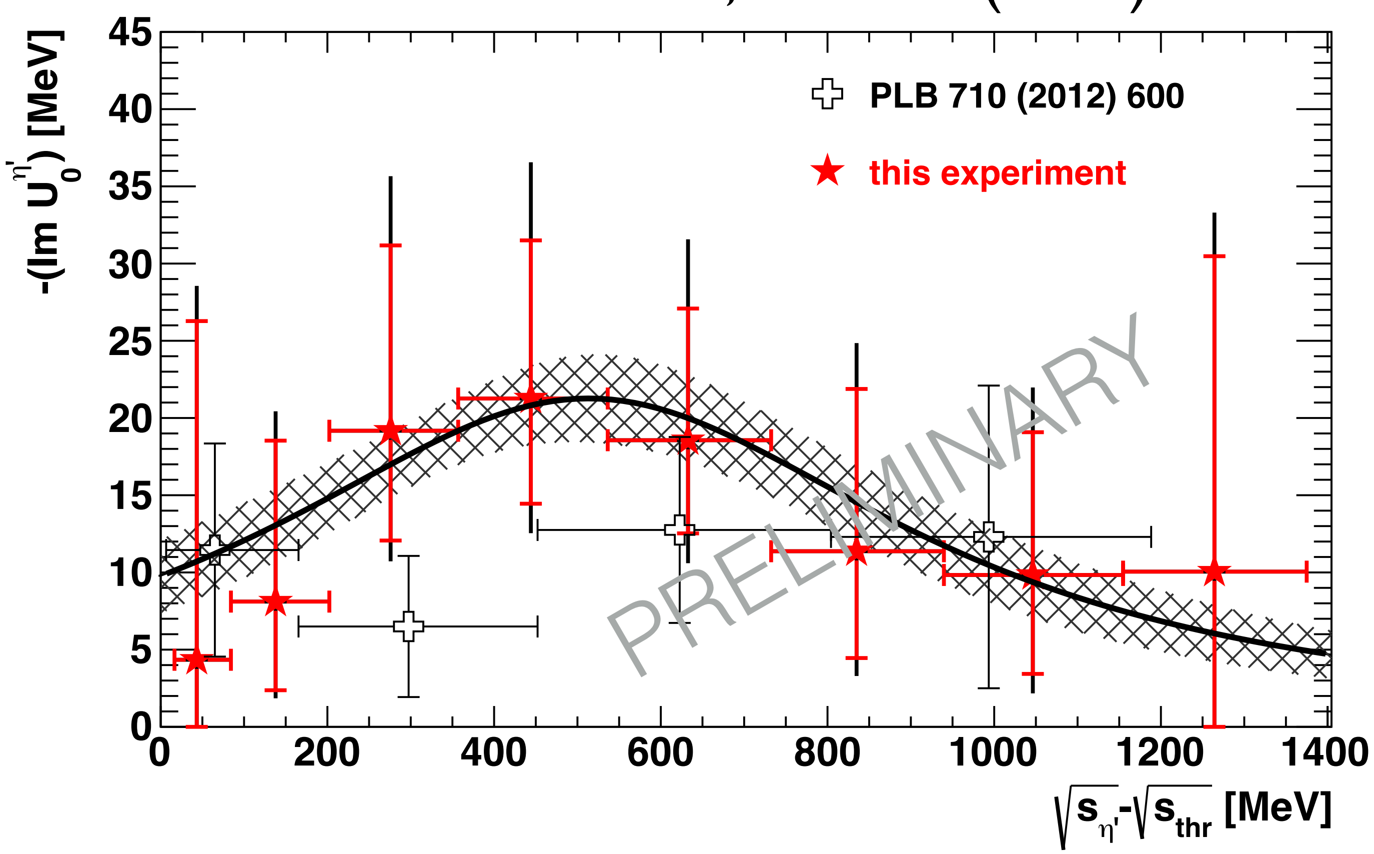
η'

$$T^{m}_{Nb/C}(p_m) \Rightarrow \Gamma^{m}_{0}(\rho=\rho_0)\,(p_m) = -\,2\,\mathrm{Im}\,U^{m}_{0}(p_m)$$

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




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




- extrapolation to production threshold:

$$\mathrm{Im}\,U^{\omega}_{0}(\rho=\rho_0,p_\omega=0) = (29\pm5)\ \mathrm{MeV} \qquad \mathrm{Im}\,U^{\eta'}_{0}(\rho=\rho_0,p_{\eta'}=0) = (10\pm3)\ \mathrm{MeV}$$

- extension to high moment allows for dispersion relation analysis, providing link between real and imaginary part of potential

# compilation of results for real and imaginary part of the ω, η' -nucleus optical potential

ω

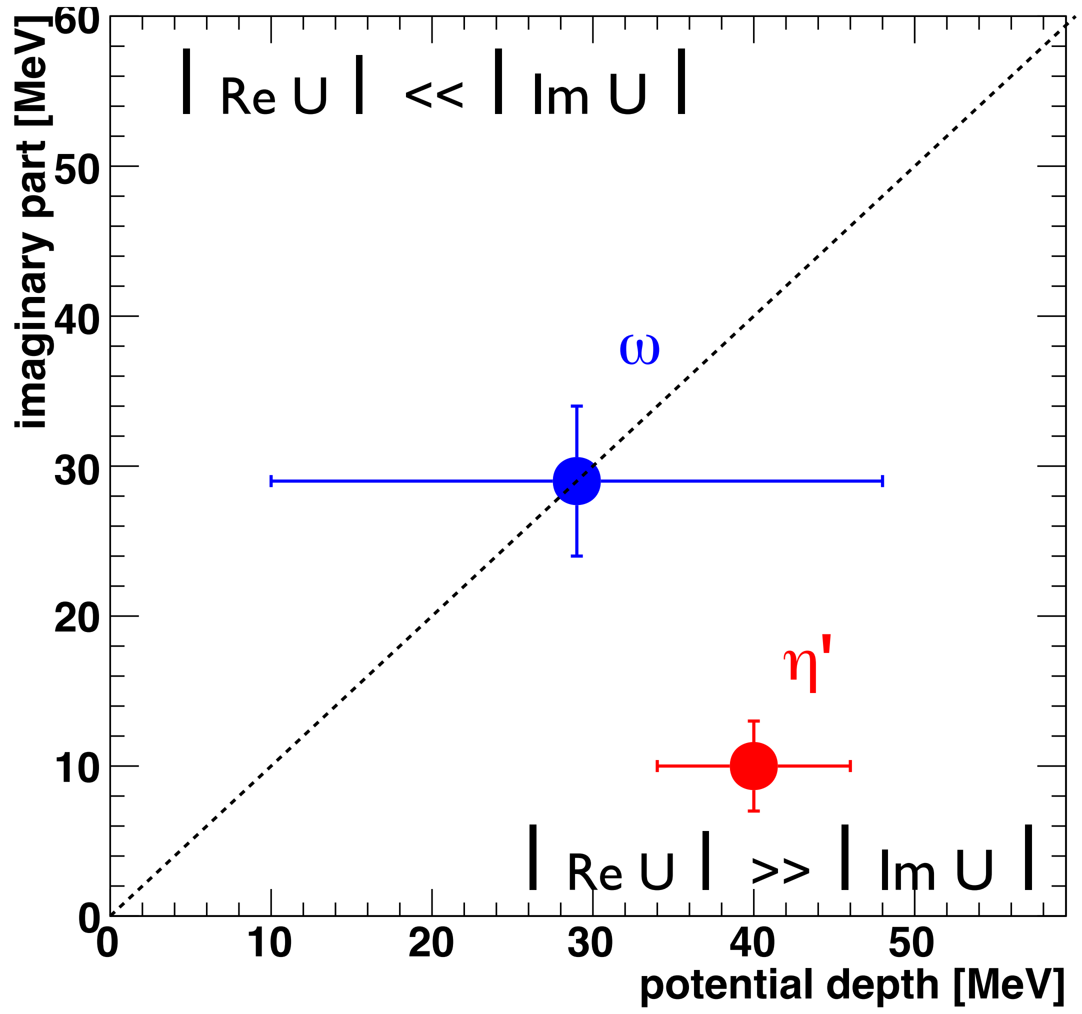
$U_{\omega A}(\rho=\rho_0)=$

$-((29\pm19(stat)\pm20(syst) + i(29\pm5))$ MeV

η'

$U_{\eta' A}(\rho=\rho_0)=$

$-((40\pm5(stat)\pm15(syst) + i(10\pm3))$ MeV




V. Metag
Hyp.Int. 234 (2015) 25

| Im U | ≈ | Re U | ; ⇨ ω <u>not a good candidate</u> to search for meson-nucleus bound states!

| Re U | >> | Im U | ; ⇨ η' <u>promising candidate</u> to search for mesic !!

first (indirect) observation of in-medium mass shift of η' at $\rho=\rho_0$ and T=0
in good agreement with QMC model predictions (S. Bass et al. , PLB 634 (2006) 368)

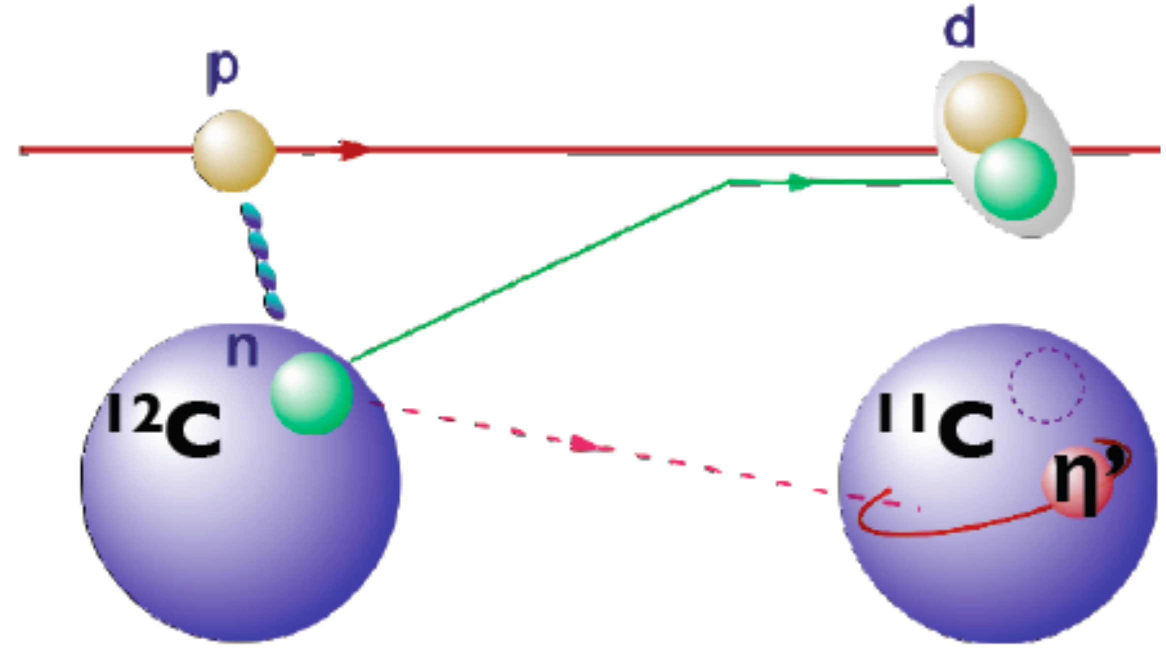
# search for η’-mesic states in hadronic reactions

**FRS@GSI:** PRiME

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

K. Itahashi et al., PETP 128 (2012) 601

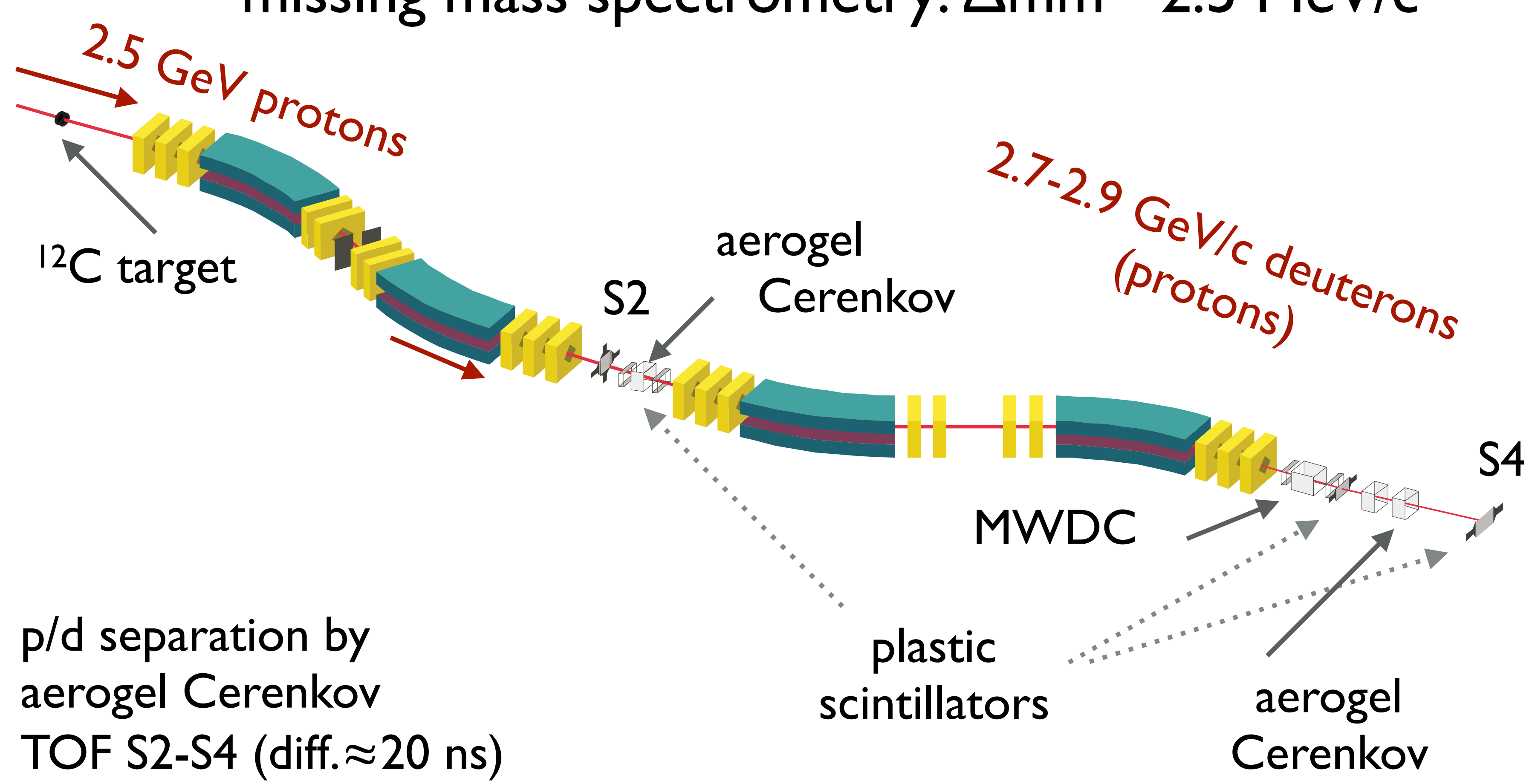
H. Nagahiro et al., PRC 87 (2013) 045201




η’ × $^{11}$C mesic nuclei

particle identification by time-of-flight

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




p/d separation by aerogel Cerenkov
TOF S2-S4 (diff.≈20 ns)

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K. Itahashi et al., PETP 128 (2012) 601
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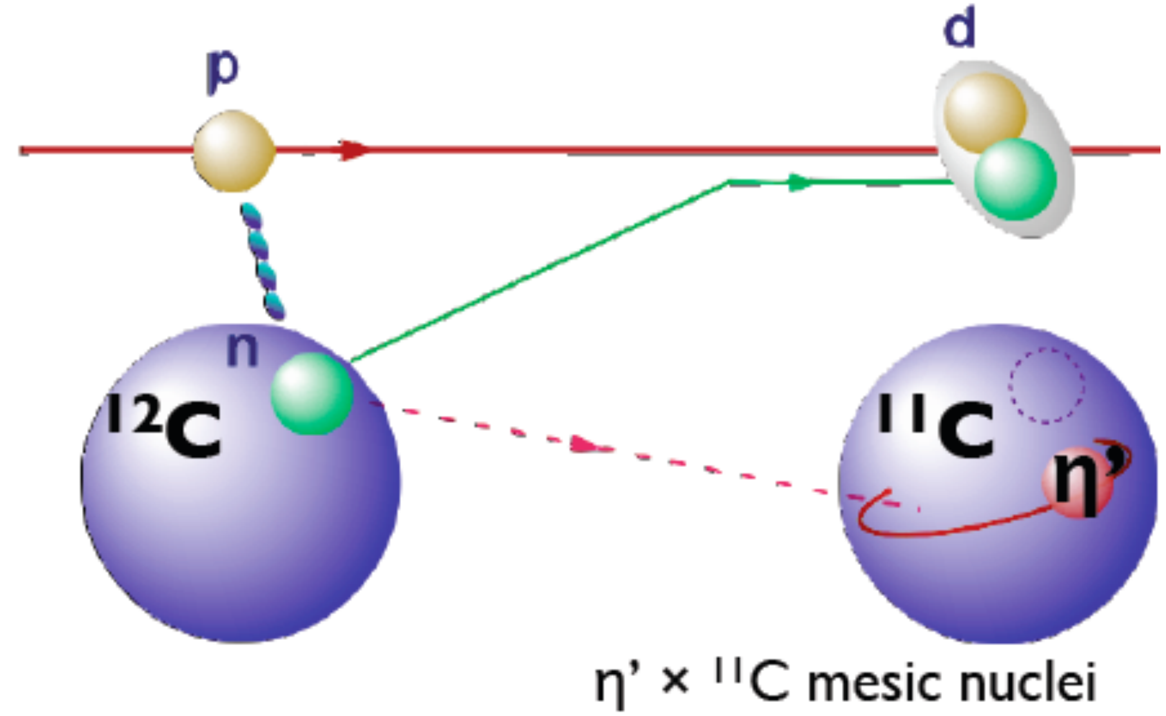
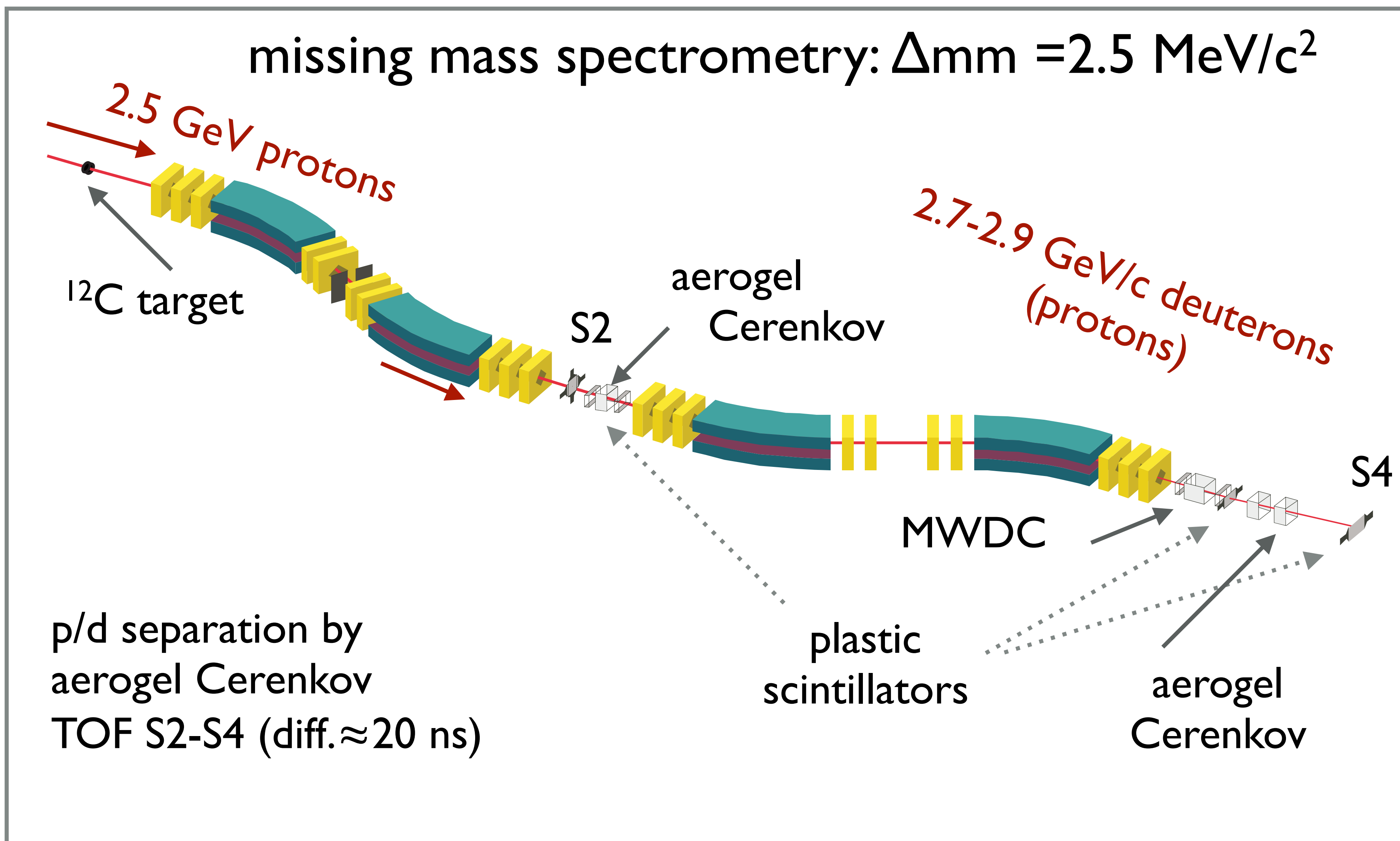



particle identification by time-of-flight

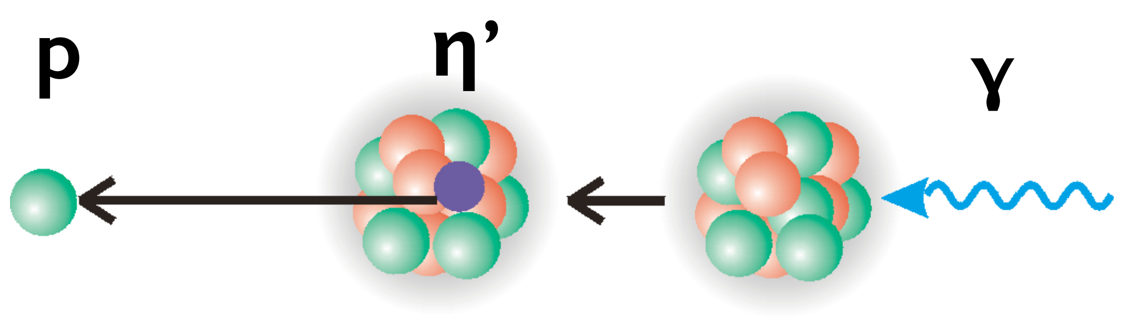
no structures in bound state region observed;
deep potentials with $|V_0| > 100$ MeV excluded



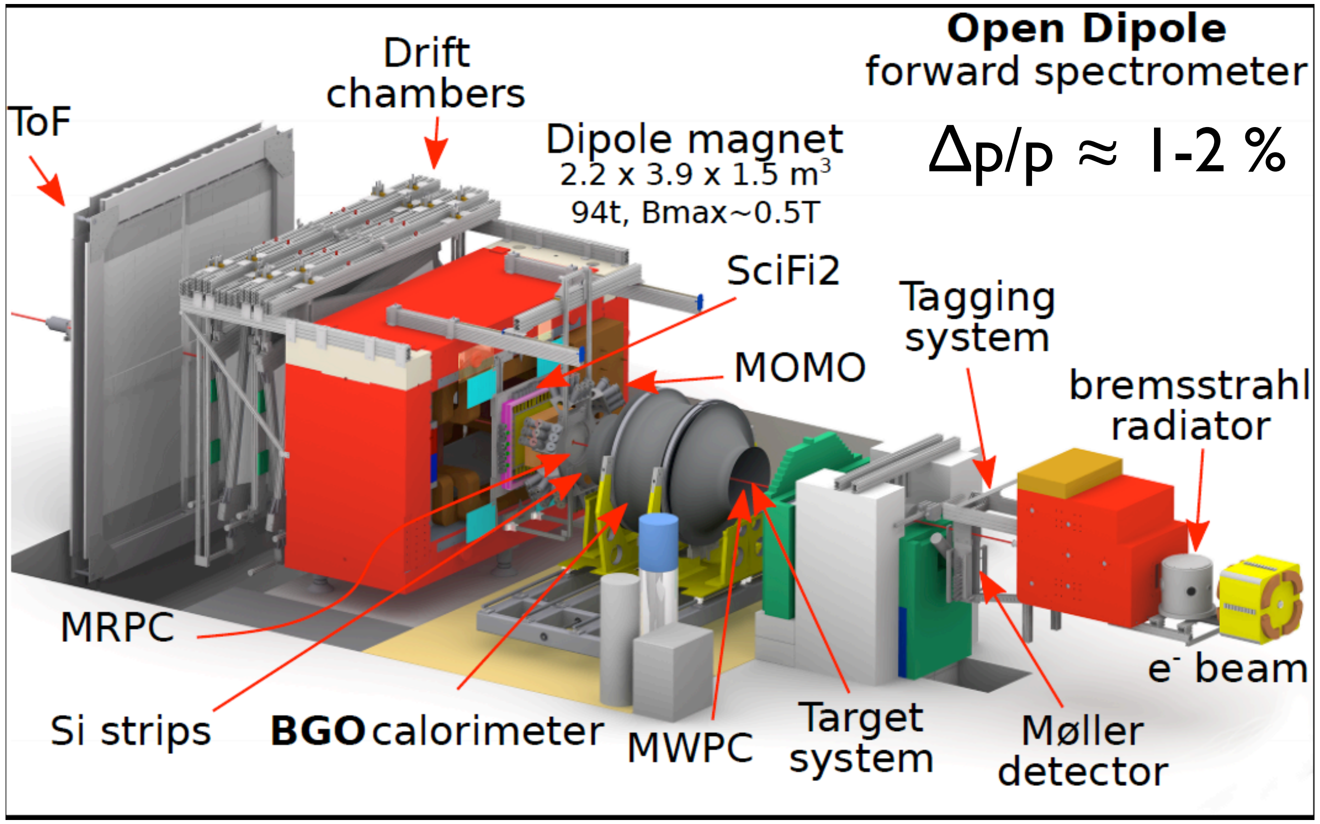
# outlook: search for η'-mesic states in photo-nuclear reactions

## BGO-OD@ELSA

$^{12}C(\gamma,p)\ \eta' X$ @ 1.5-2.8 GeV




formation and decay of η'-mesic state




BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

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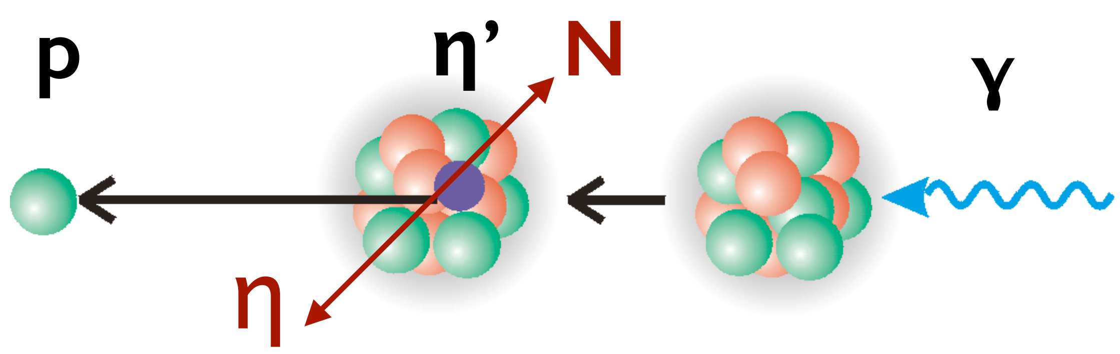


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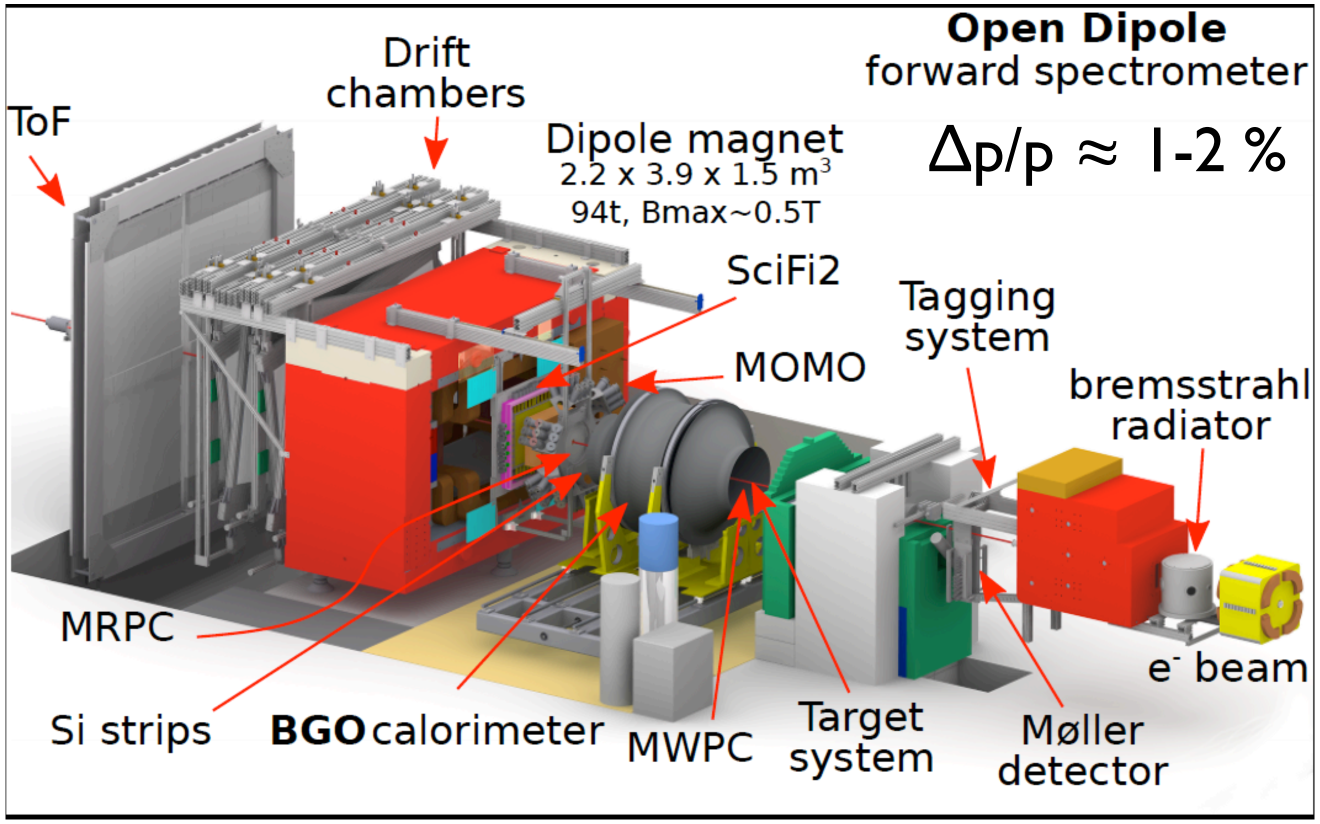


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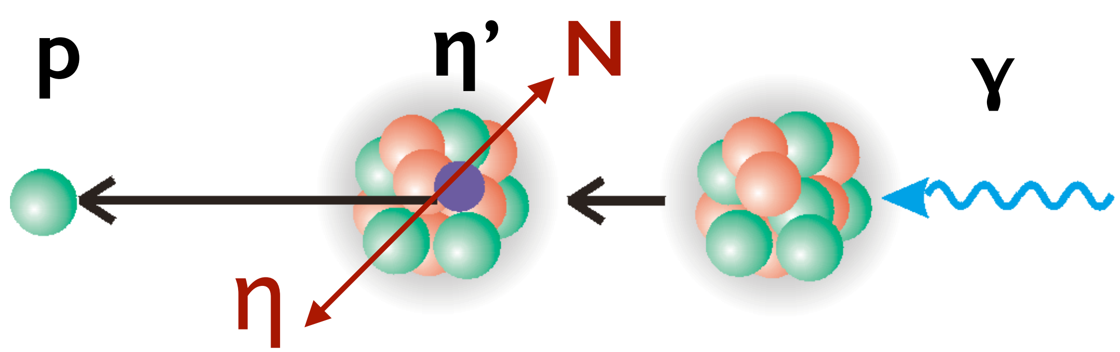


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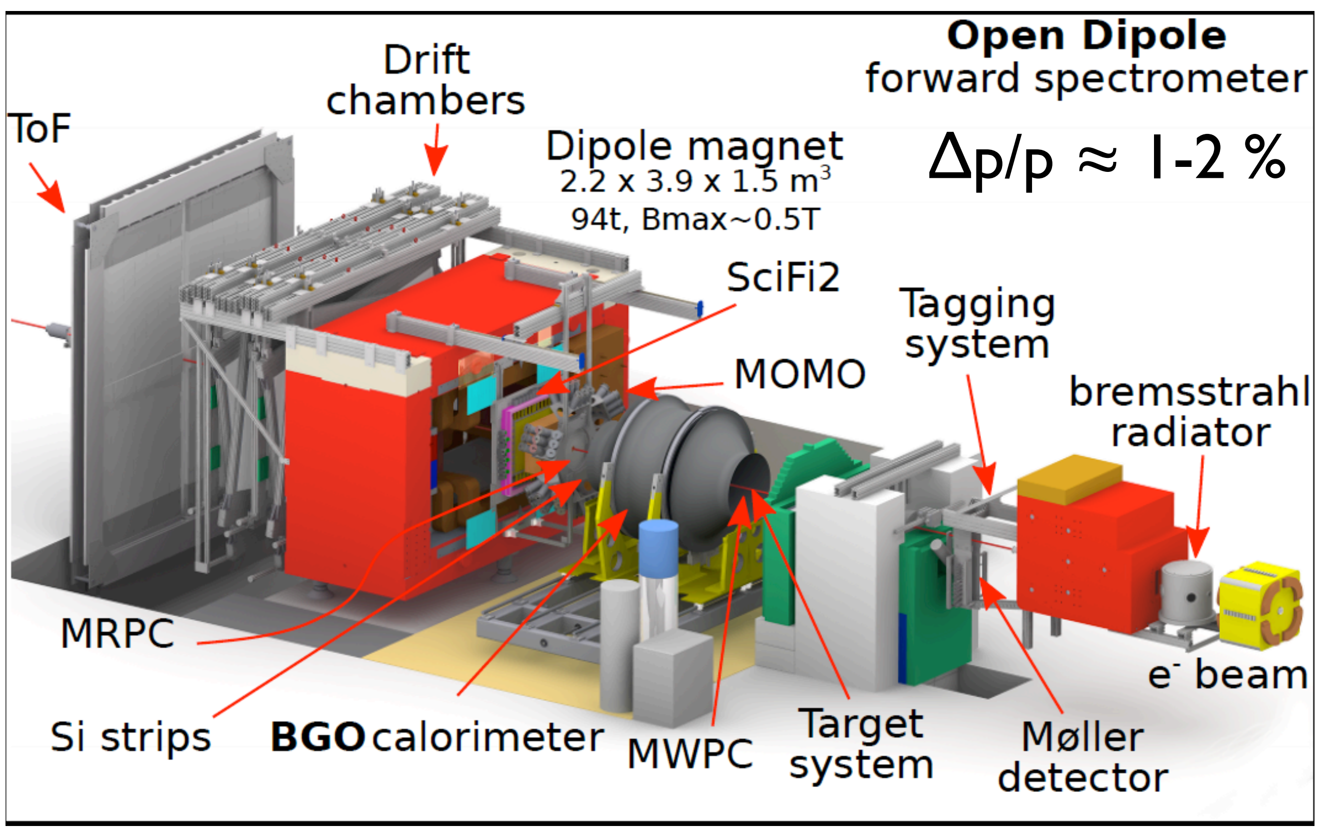
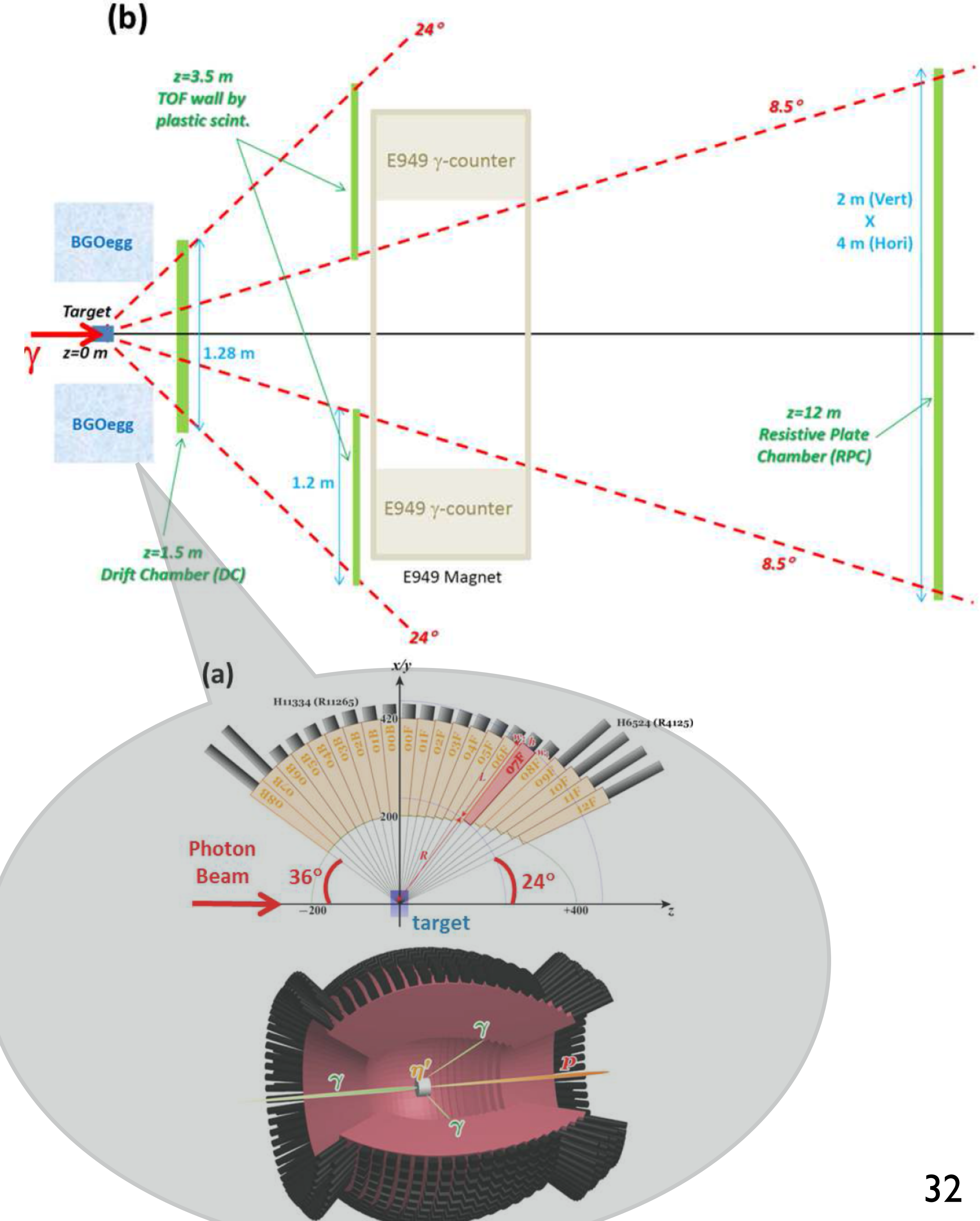



BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

## LEPS2@SPring-8

$^{12}$C(γ,p) η’X @ 1.5-2.4 GeV



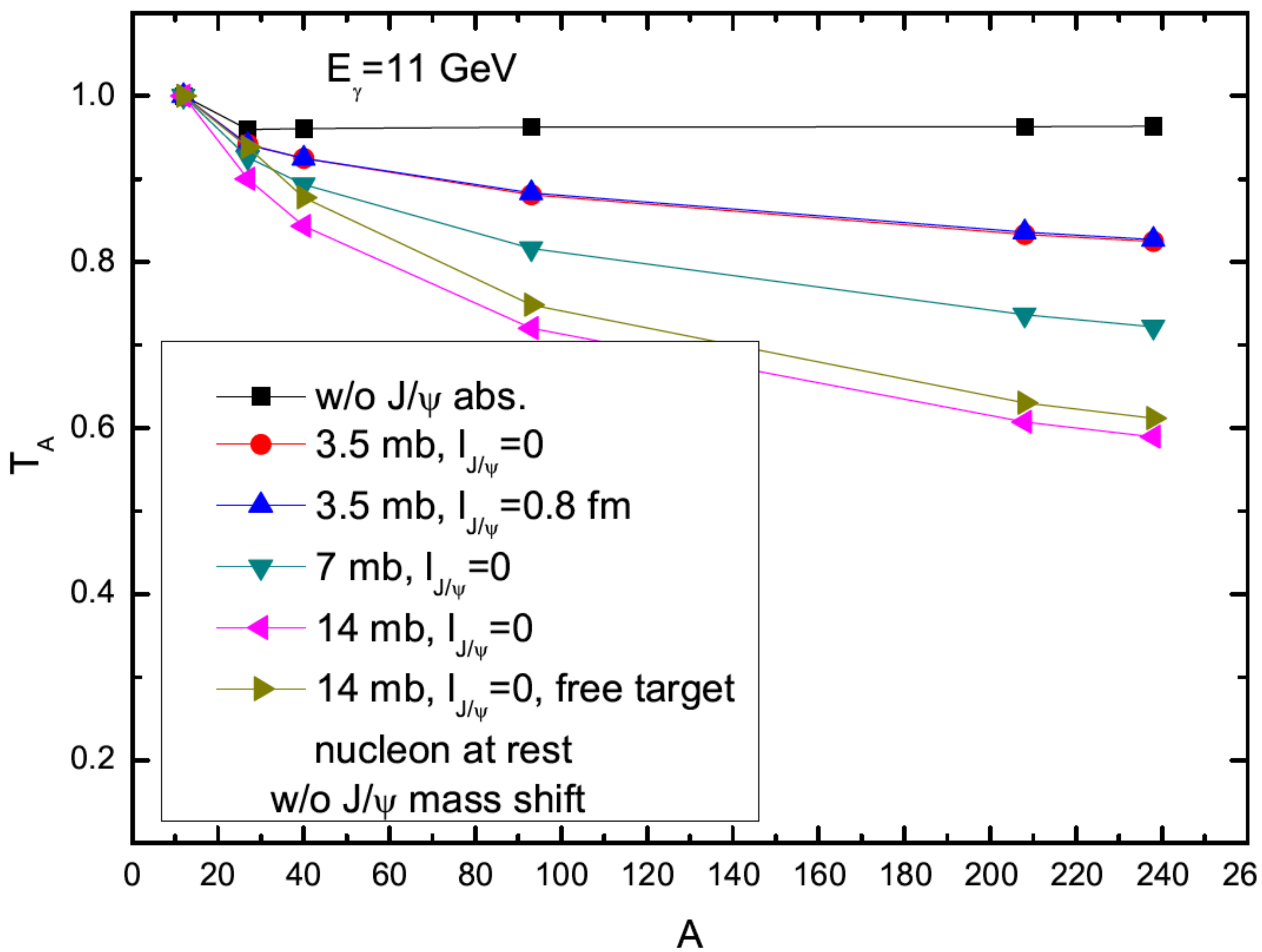
# outlook: charmonium properties in cold nuclear matter

E. Ya. Paryev and Yu. T. Kiselev, arXiv: 1510.00155

$E_\gamma$ = 6 - 11 GeV

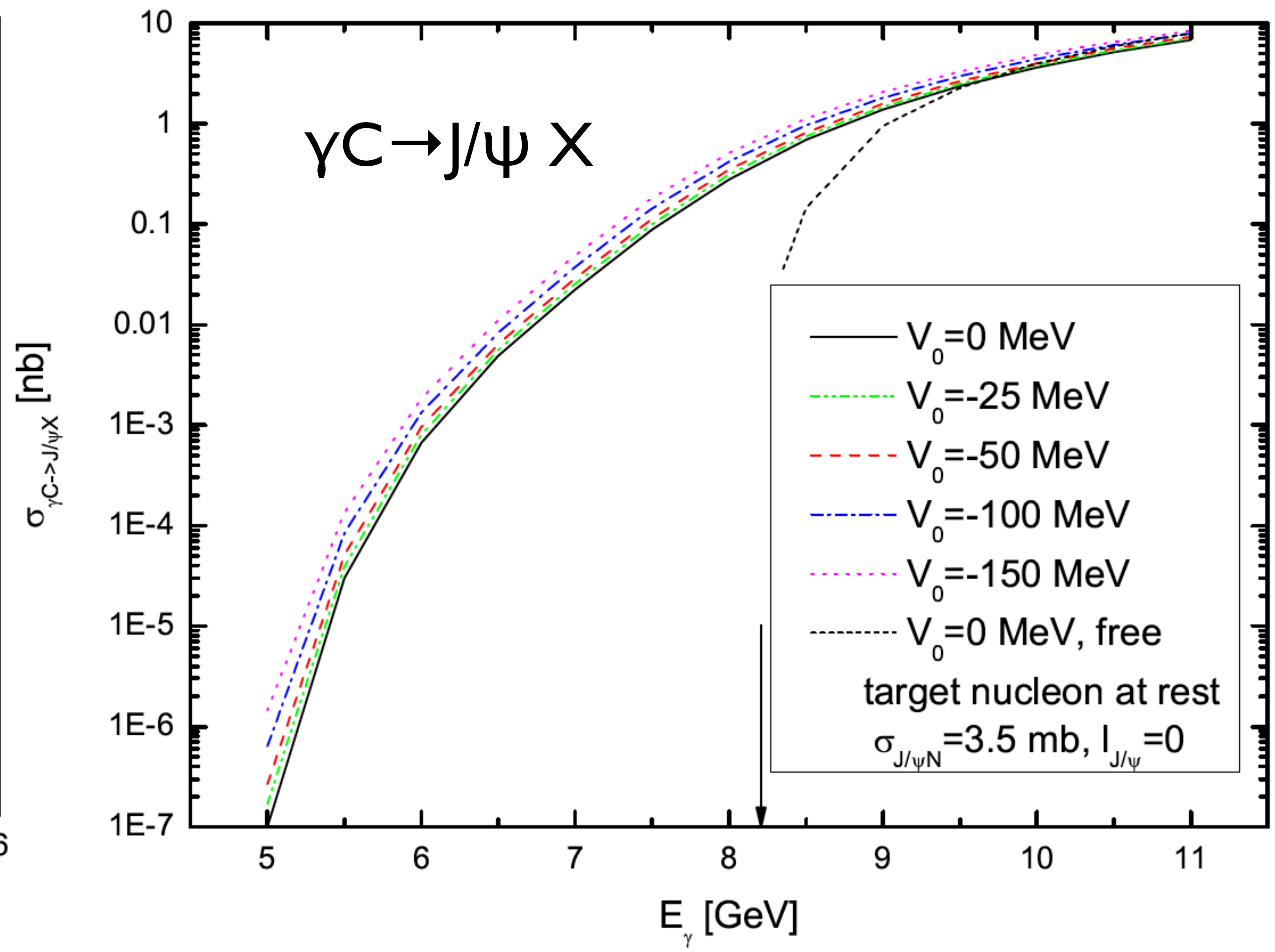
$$T_A = \frac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}}$$

transparency ratio ⇒ Γ (ρ=ρ₀) ⇒ Im U




⇒ J/ψ - N absorption cross section

excitation function ⇒ in-medium mass




mass shifts Δm ≳ 50 MeV appear measurable

# Summary & Outlook

**how does the intrinsic structure of hadrons change in a nuclear medium ??**

meson properties do change in a strongly interacting medium !!

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- for $\eta'$ meson in-medium mass drop of $\Delta m\ (\rho=\rho_0) \approx -40$ MeV determined

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- study in-medium properties (mass, width) of the J/ψ meson ??

# status of experiments in 2016

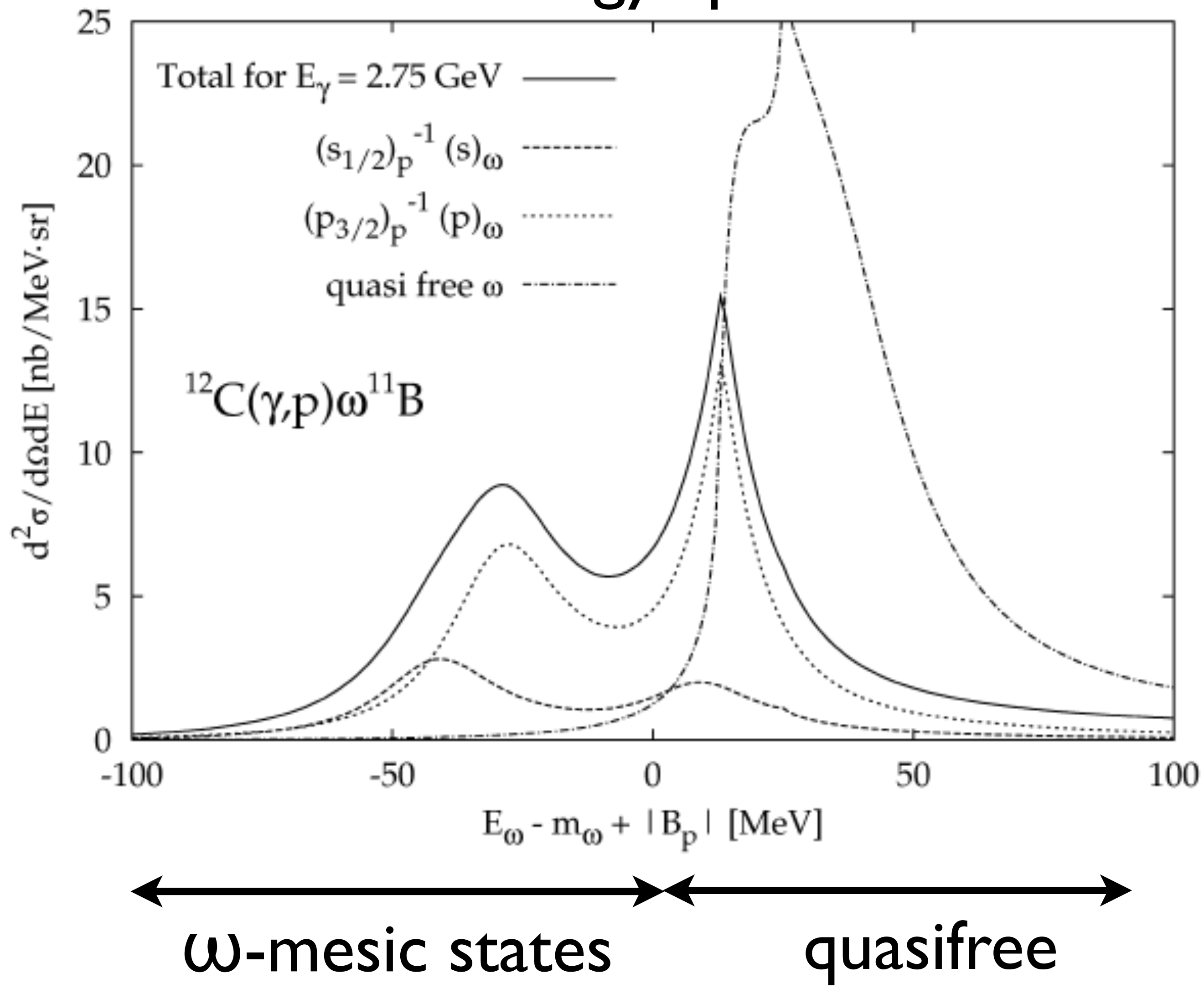
| | LEPS@ SPring-8 | CLAS @JLAB | CBELSA/ TAPS | E-325 @KEK | ANKE @COSY | CERES @CERN | NA60 @CERN |
|---|---|---|---|---|---|---|---|
| reaction | $\gamma$A 1.5-2.4 GeV | $\gamma$A 1.5-2.4 GeV | $\gamma$A 0.7-2.9 GeV | pA 12 GeV | pA 2.8 GeV | Au+Au 158 AGeV | In+ In 158 AGeV |
| momentum acceptance | $p > 1.0$ GeV/c | $p > 0.8$ GeV/c | $p > 0.0$ GeV/c | $p > 0.5$ GeV/c | $p > 0.6$ GeV/c | $p_t > 0.0$ GeV/c | $p_t > 0.0$ GeV/c |
| $\rho$ | | $\Delta m \approx 0$ $\Gamma(\rho_0/2) \approx 220$ MeV | | $\Delta m/m = -9\%$ $\Delta\Gamma \approx 0$ | | $\Delta m \approx 0$ broadening | $\Delta m \approx 0$ broadening |
| $\omega$ | | $\Gamma(\rho_0) > 200$ MeV | $\Delta m \approx -30$ MeV $\Gamma(\rho_0, p=0) \approx 60$ MeV | $\Delta m/m = -9\%$ $\Delta\Gamma \approx 0$ | | | |
| $\eta'$ | | | $\Delta m \approx -40$ MeV $\Gamma(\rho_0, p=0) \approx 20$ MeV | | | | |
| $\phi$ | $\Gamma(\rho_0) \approx 100$ MeV | $\Gamma(\rho_0) \approx$ 40-200 MeV | | $\Delta m/m \approx -3.4\%$ $\Gamma(\rho_0/2) \approx 15$ MeV | $\Gamma(\rho_0) \approx$ 30-60 MeV | | |

despite of enormous progress in experiments no fully consistent picture reached as yet

# search for ω-mesic states

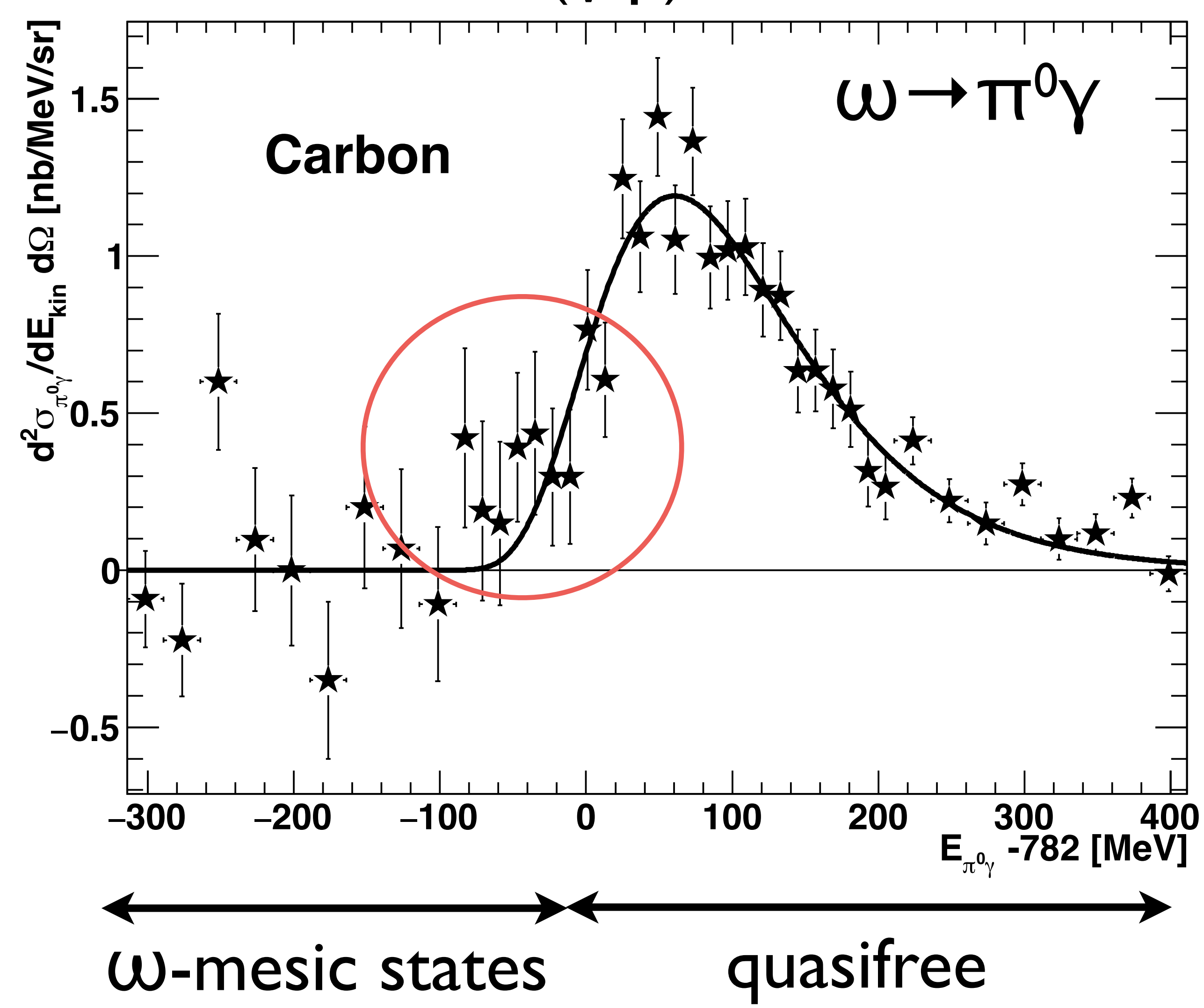
E. Marco and W. Weise, PLB 502 (2001) 59

excitation energy spectrum of $^{11}$B




S. Friedrich et al., PLB 736 (2014) 26

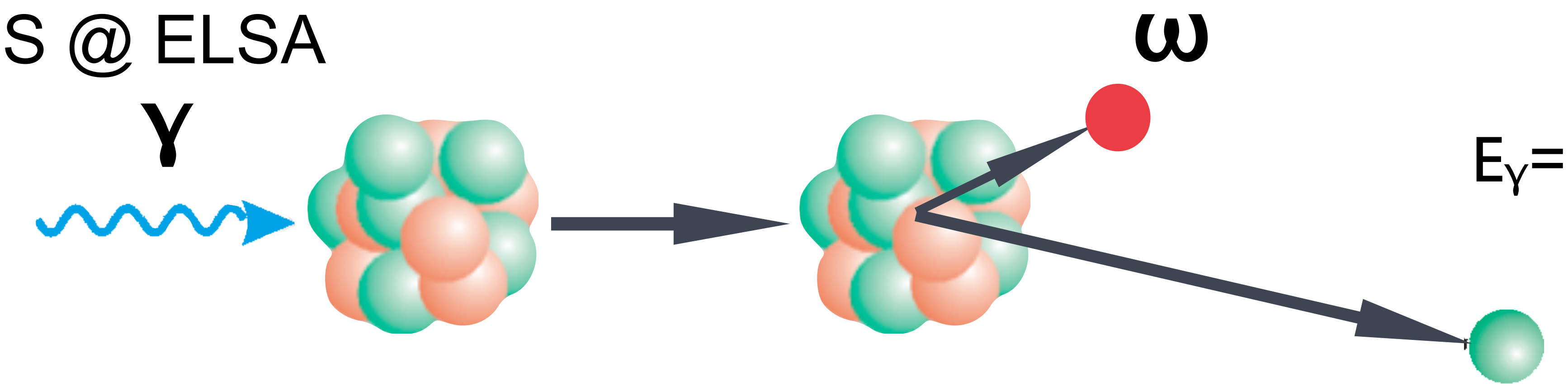
$^{12}C(\gamma,p)\omega$ X




intensity in bound state region consistent with tail due to large imaginary part

# real part of ω-nucleus potential from ω kinetic energy

CBELSA/TAPS @ ELSA

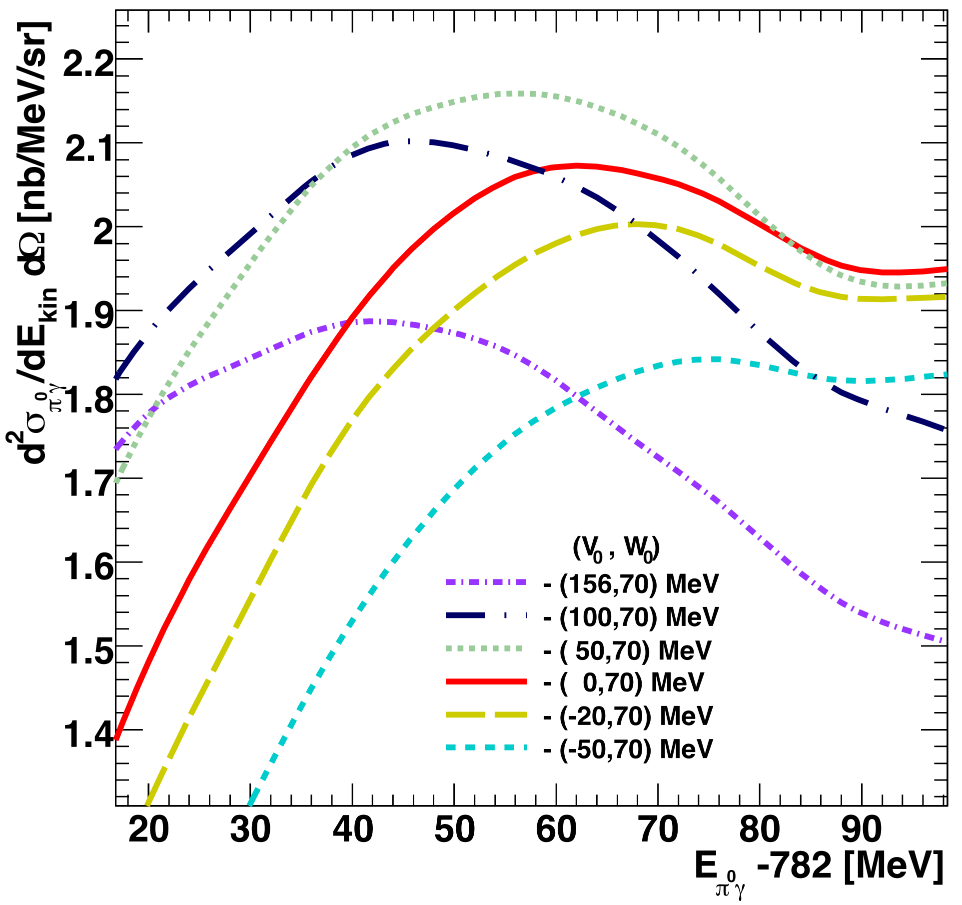



$E_\gamma$=1.25-3.1 GeV

$1^0 \leq \theta_p \leq 11^0$

the higher the attraction the lower the kinetic energy of the ω meson

H. Nagahiro, priv. com.



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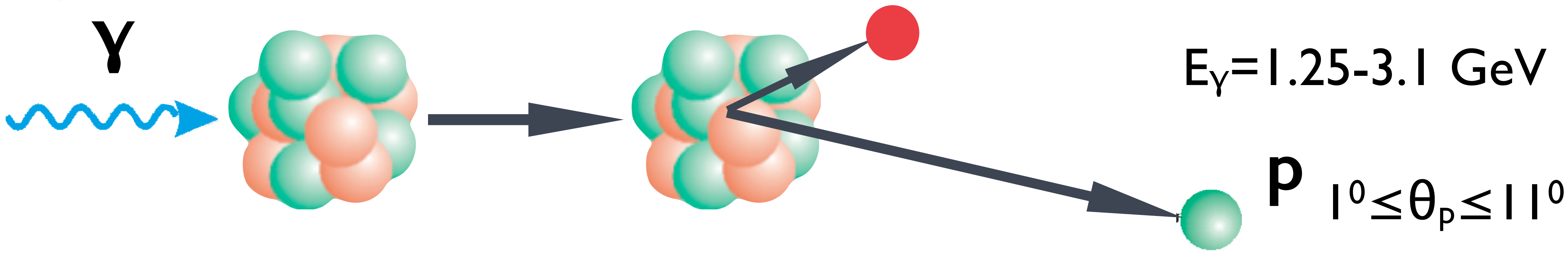
CBELSA/TAPS @ ELSA




the higher the attraction the lower the kinetic energy of the ω meson

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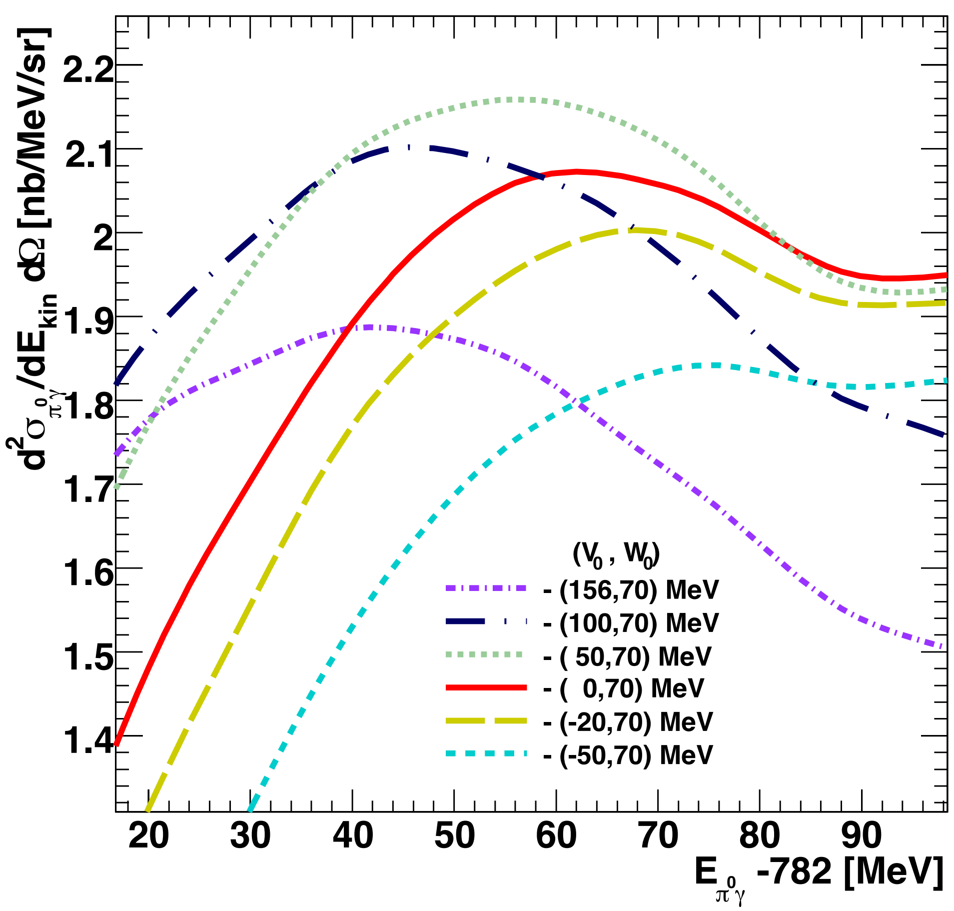
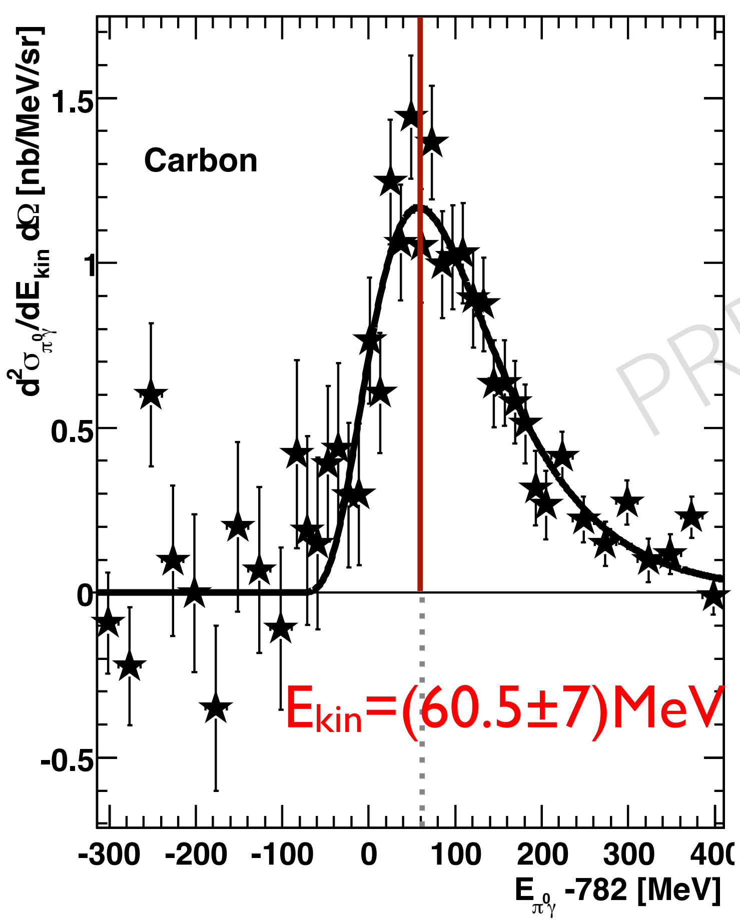
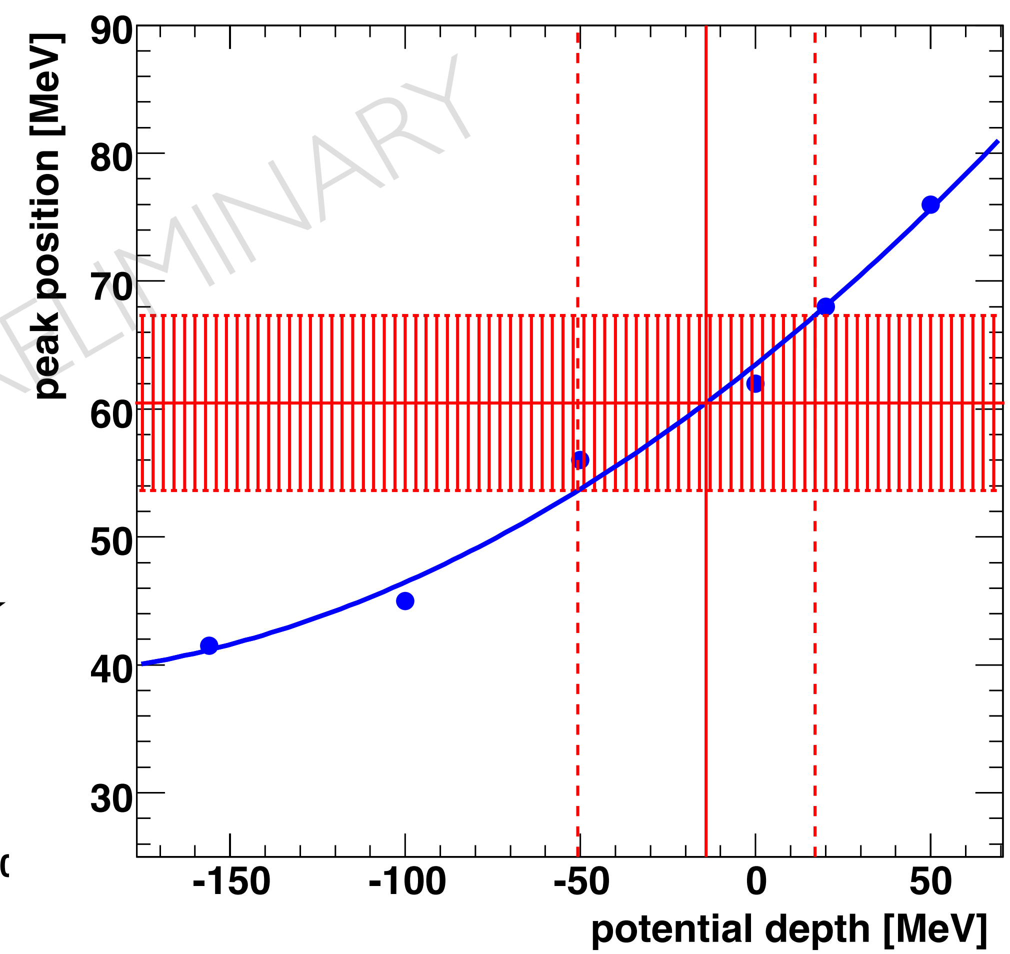



S. Friedrich, PhD thesis (Univ. Giessen)




$W_\omega(\rho=\rho_0) = -\Gamma_0/2 = -(70\pm10)$ MeV

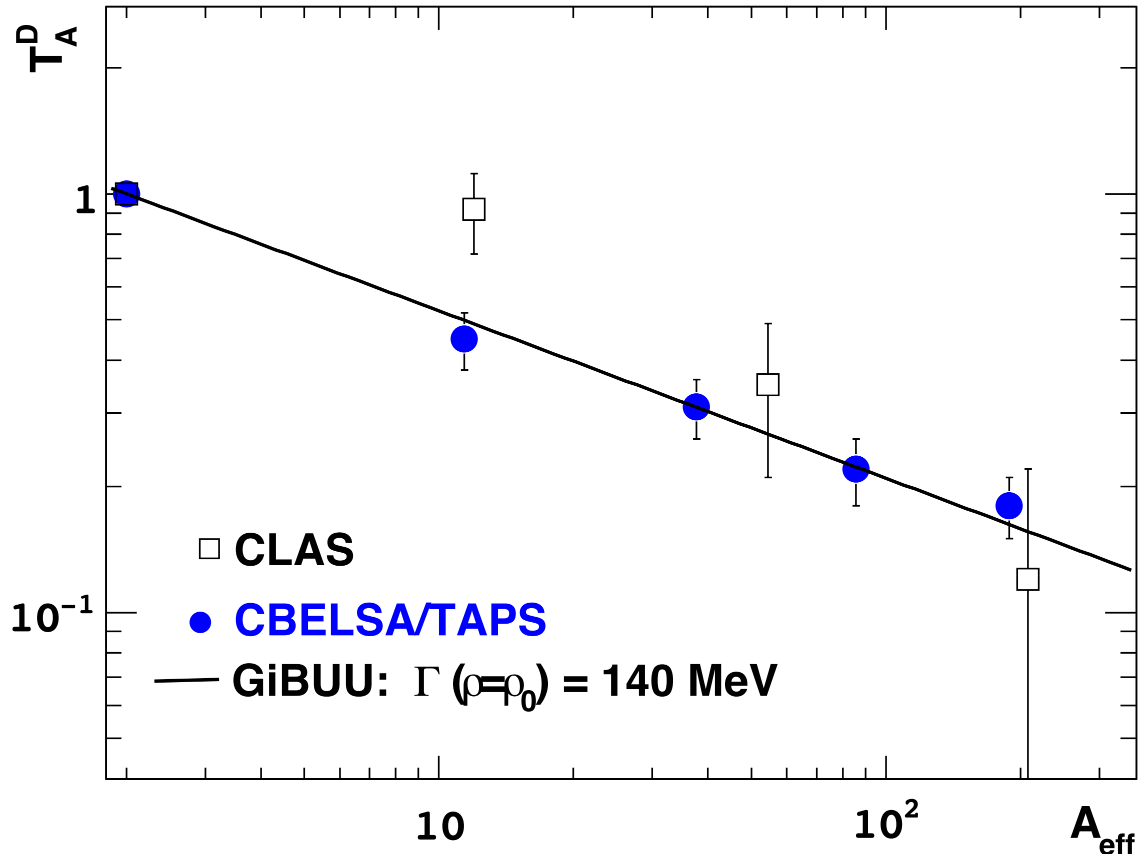
$V_\omega(\rho=\rho_0) = -(15\pm35)$ MeV

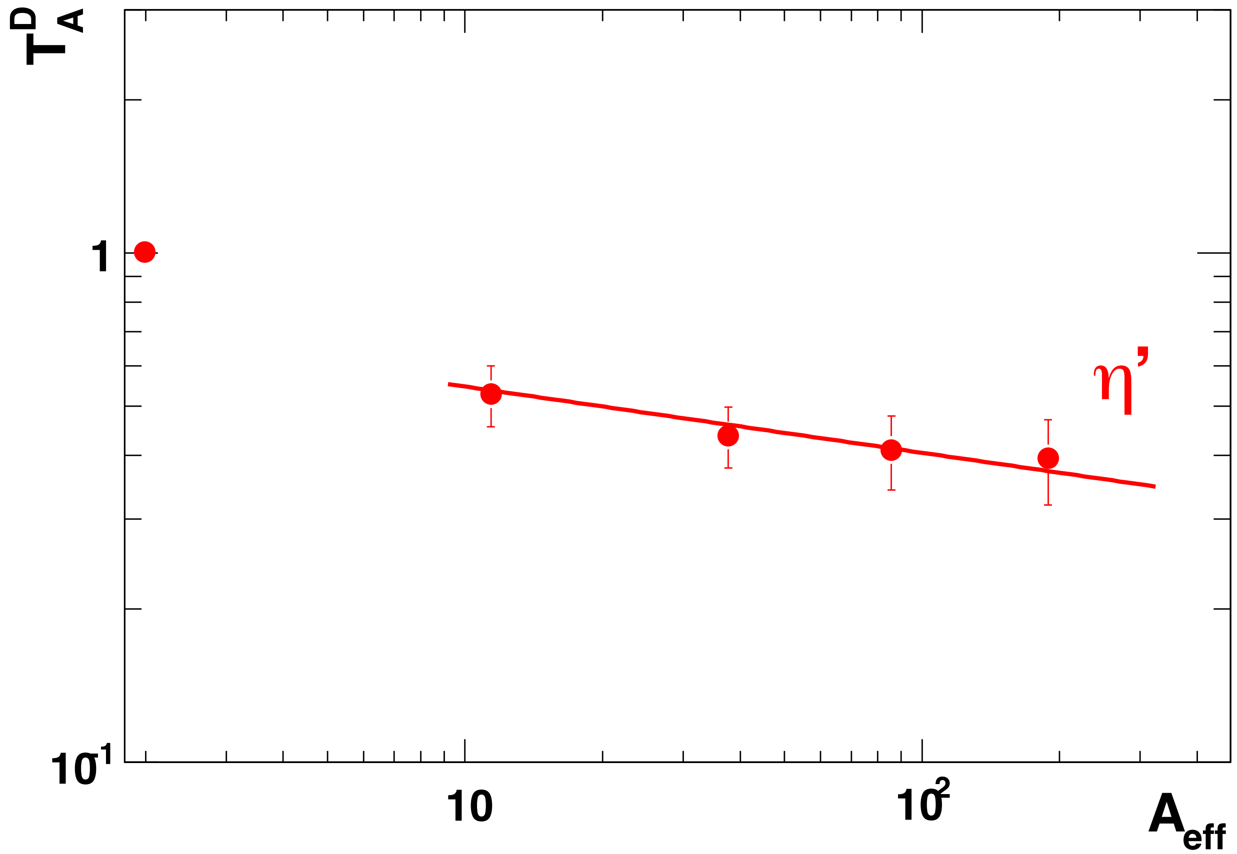
# transparency ratio for ω and η' mesons for different nuclei

$$T = \frac{\sigma_{\gamma A \to \omega X}}{Z_{eff} \cdot \sigma_{(\gamma p_{bound} \to \omega p)} + N_{eff} \cdot \sigma_{(\gamma n_{bound} \to \omega n)}}$$

data on photo production cross sections off bound proton and neutron from

**ω**: F. Dietz et al., EPJA 51(2015) 6 **η'**: I. Jaegle et al., EPJA 47 (2011) 11




$\Gamma_\omega(<p_\omega> = 1.1$ GeV/c; $\rho=\rho_0) \approx 140$ MeV $\Gamma_{\eta'}(<p_{\eta'}> = 1.05$ GeV/c; $\rho=\rho_0) \approx 20$ MeV

low density approximation: $\Gamma(\rho_0) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}$

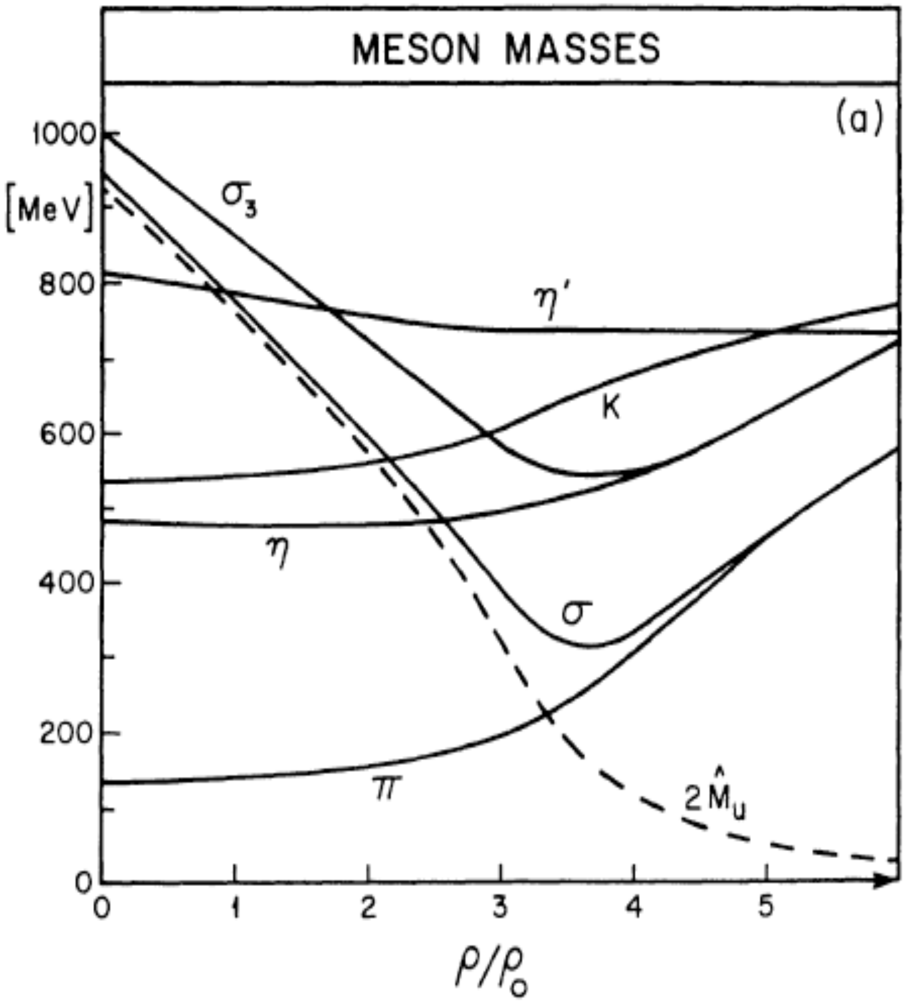
$\sigma_{\omega N}^{inel} = (65 \pm 25)$ mb $\sigma_{\eta' N}^{inel} = (10.3 \pm 1.4)$ mb

ω: $W(\rho=\rho_0) = -\Gamma_0/2 \approx -70$ MeV η': $W(\rho=\rho_0) = -\Gamma_0/2 = -(10 \pm 2.5)$ MeV

# model predictions for in-medium mass/width of the η' meson

## NJL-model

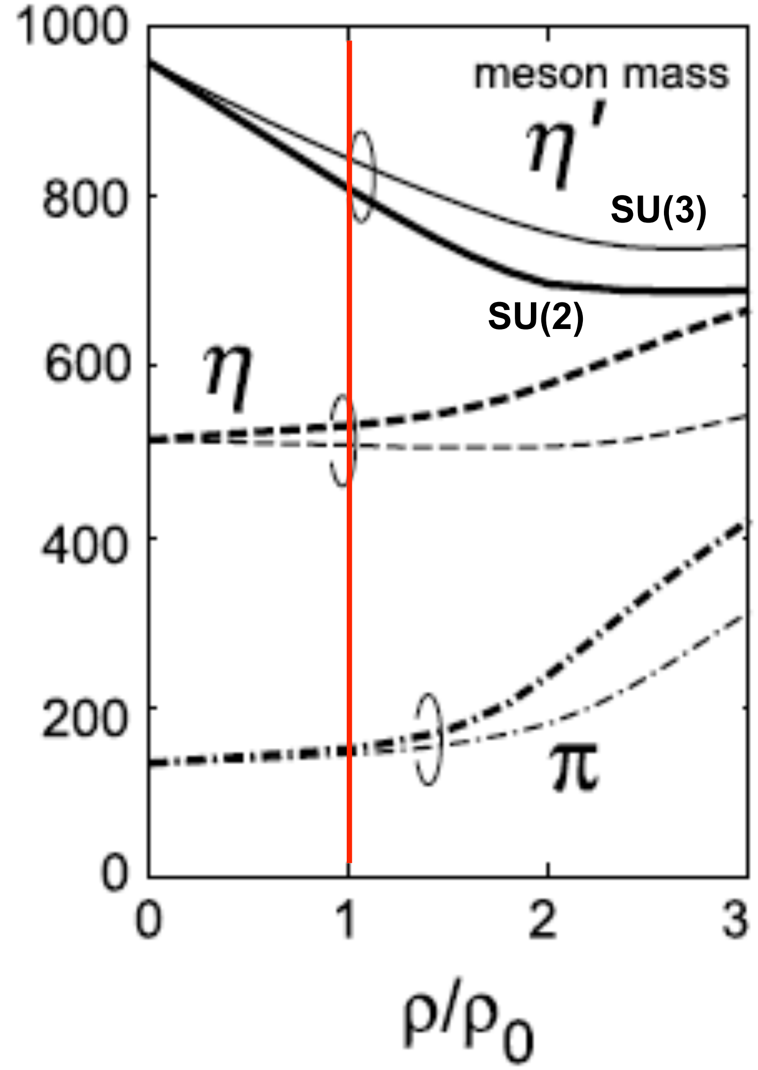
V. Bernard and U.-G. Meissner,
Phys. Rev.D 38 (1988) 1551




almost no dependence of η' mass on density

## NJL-model

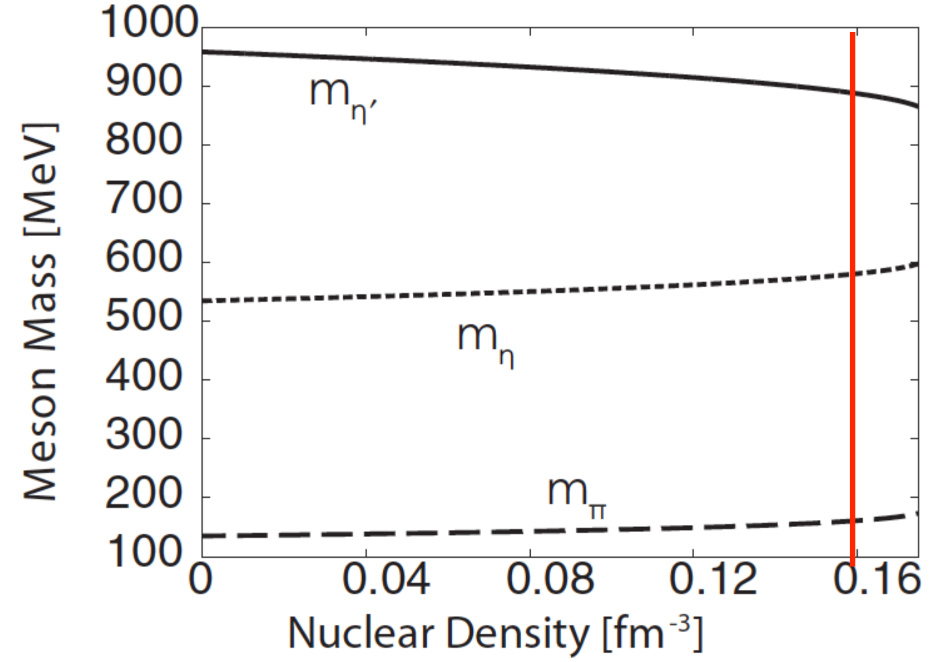
H. Nagahiro, M. Takizawa and S. Hirenzaki,
Phys. Rev. C 74 (2006) 045203




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

## linear σ model

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




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

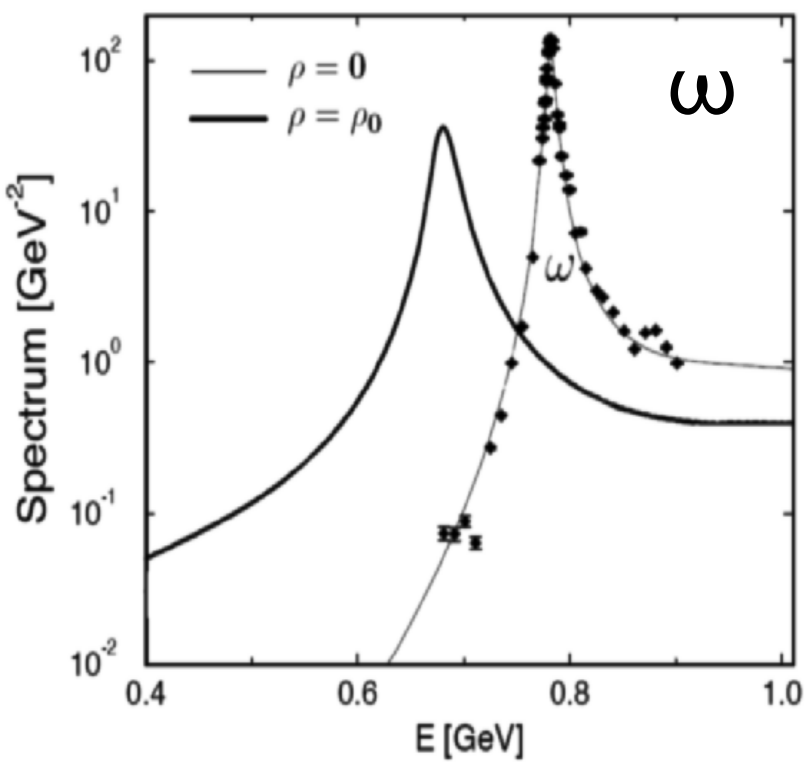
## QMC-model

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

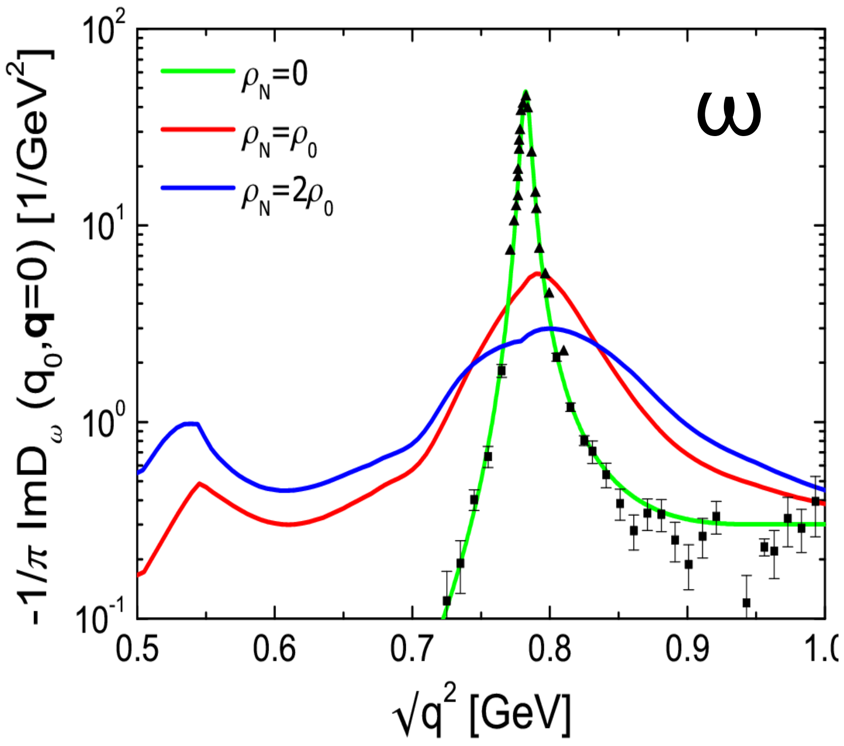
$\Delta m_{\eta'}(\rho_0) \approx -40$ MeV
for $\theta_{\eta\eta'} = -20^0$

# model predictions for in-medium mass/width of the ω, Φ meson

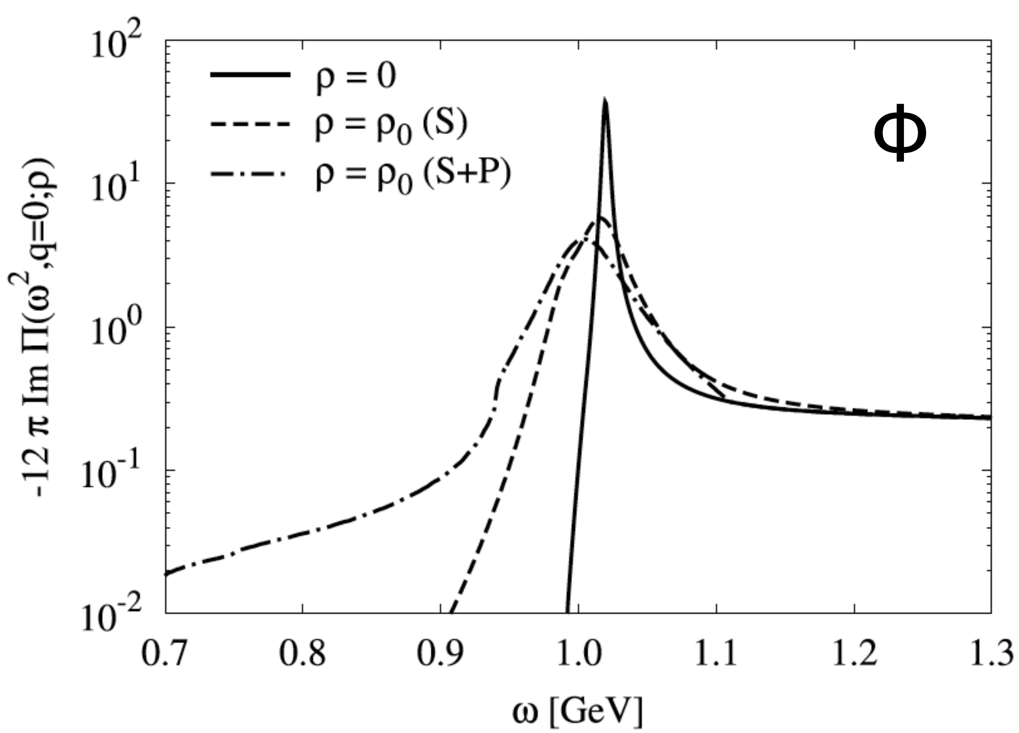
F. Klingl et al.,
NPA 610 (1997) 297;
NPA 650 (1999) 299




P. Mühlich et al.,
NPA 780 (2006) 187




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




with increasing nuclear density
- lowering of in-medium mass
- broadening of resonance

spectral function for ω at rest:
- almost no mass shift;
- strong in-medium broadening

$\Delta m/m < 2\%$

asymmetric broadening

$\Gamma(\rho_0) \approx 45$ MeV

# transparency ratio for ω and η' mesons for different nuclei

$$T = \frac{\sigma_{\gamma A \to \omega X}}{Z_{eff} \cdot \sigma_{(\gamma p_{bound} \to \omega p)} + N_{eff} \cdot \sigma_{(\gamma n_{bound} \to \omega n)}}$$

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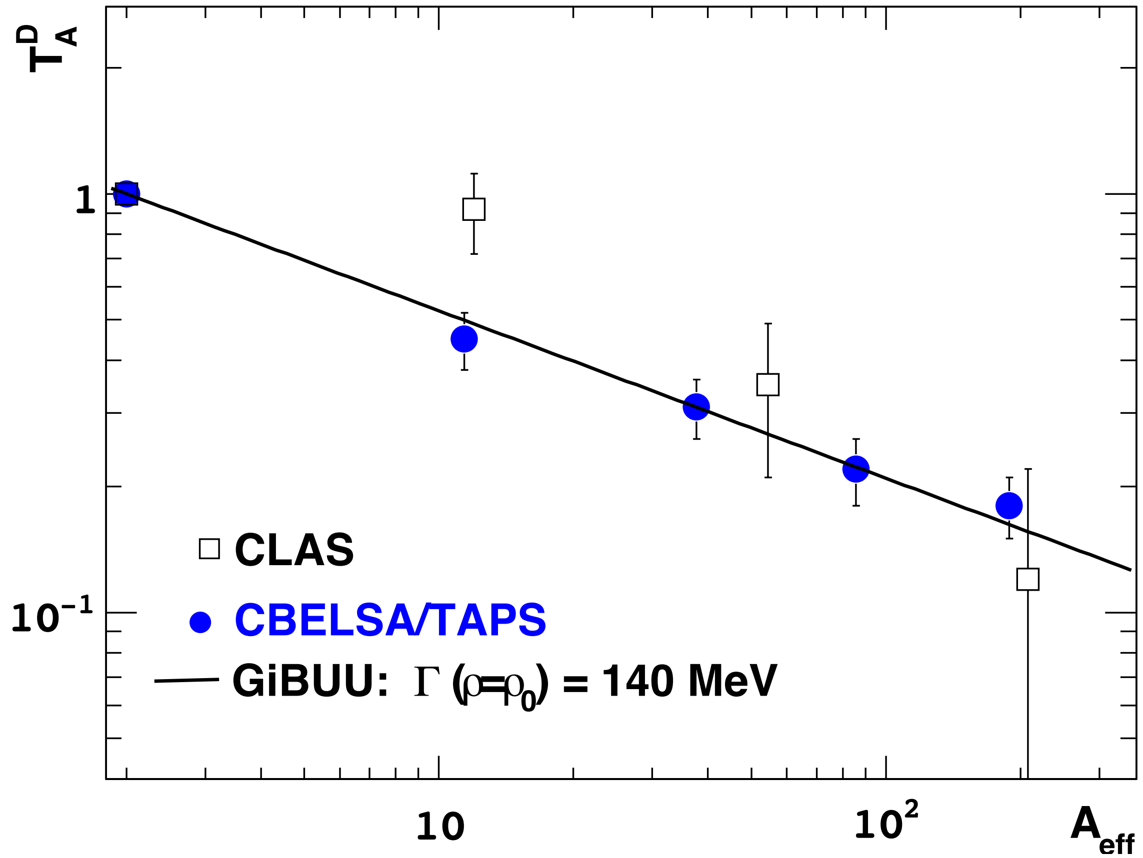


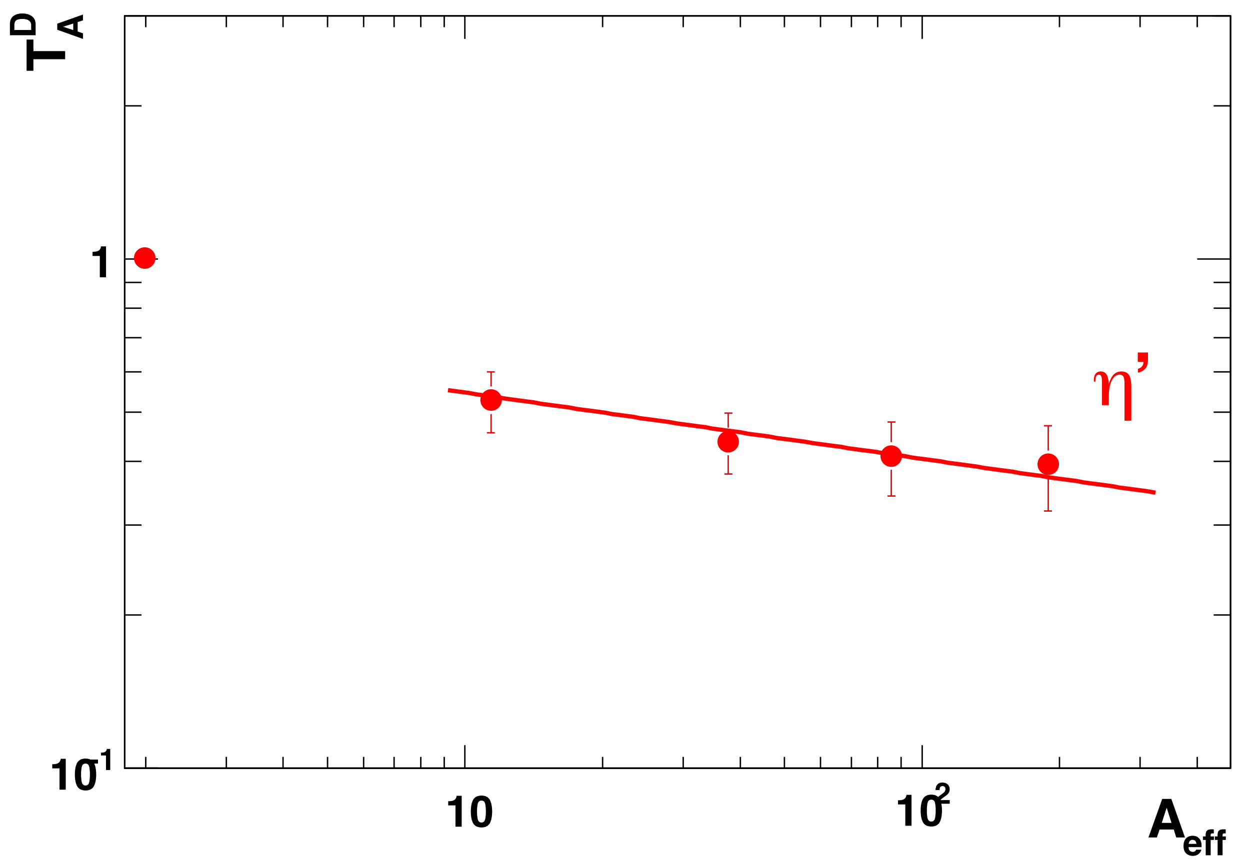


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ω: $W(\rho=\rho_0) = -\Gamma_0/2 \approx -70$ MeV η': $W(\rho=\rho_0) = -\Gamma_0/2 = -(10 \pm 2.5)$ MeV

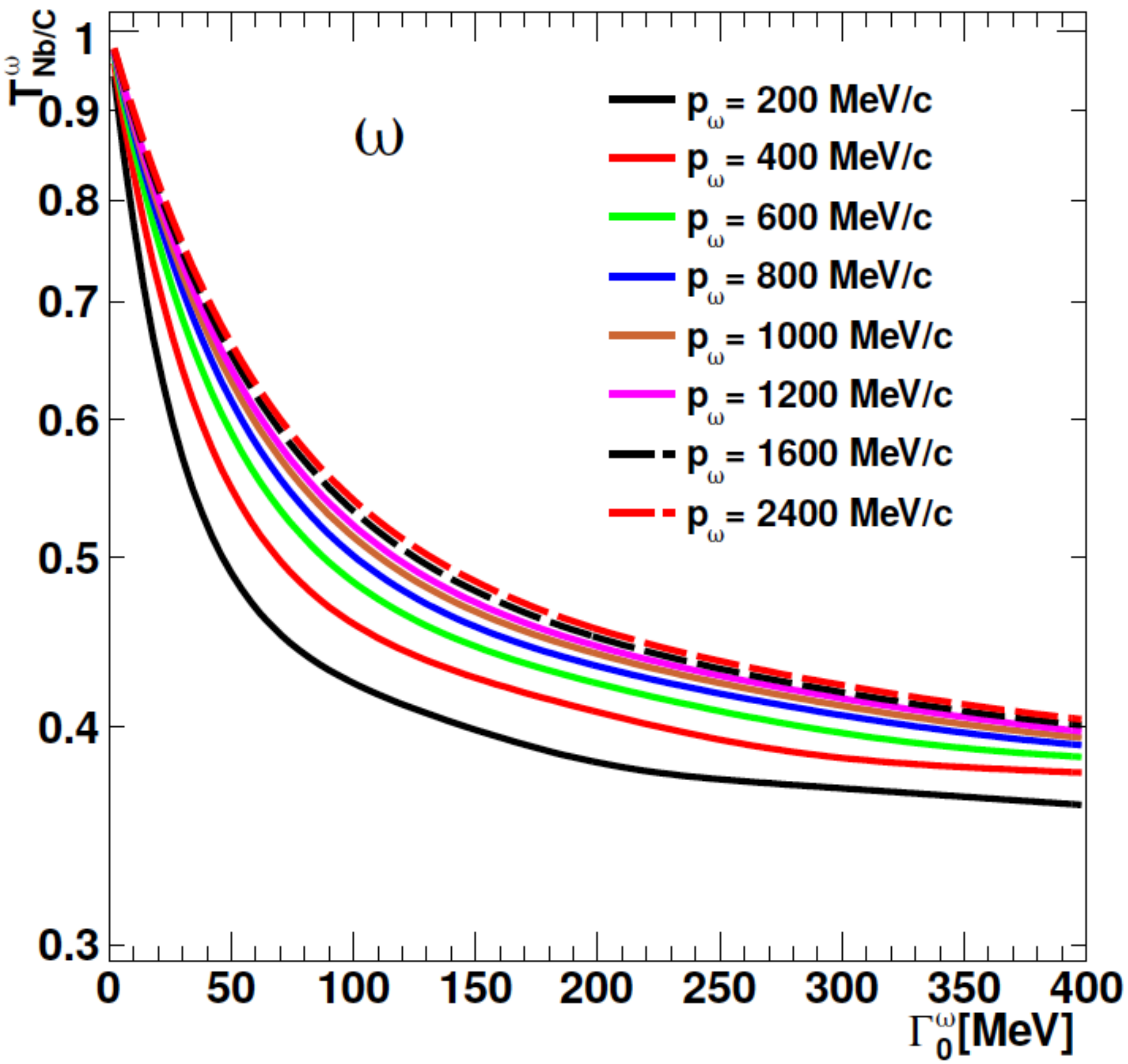
# in-medium width from transparency ratio

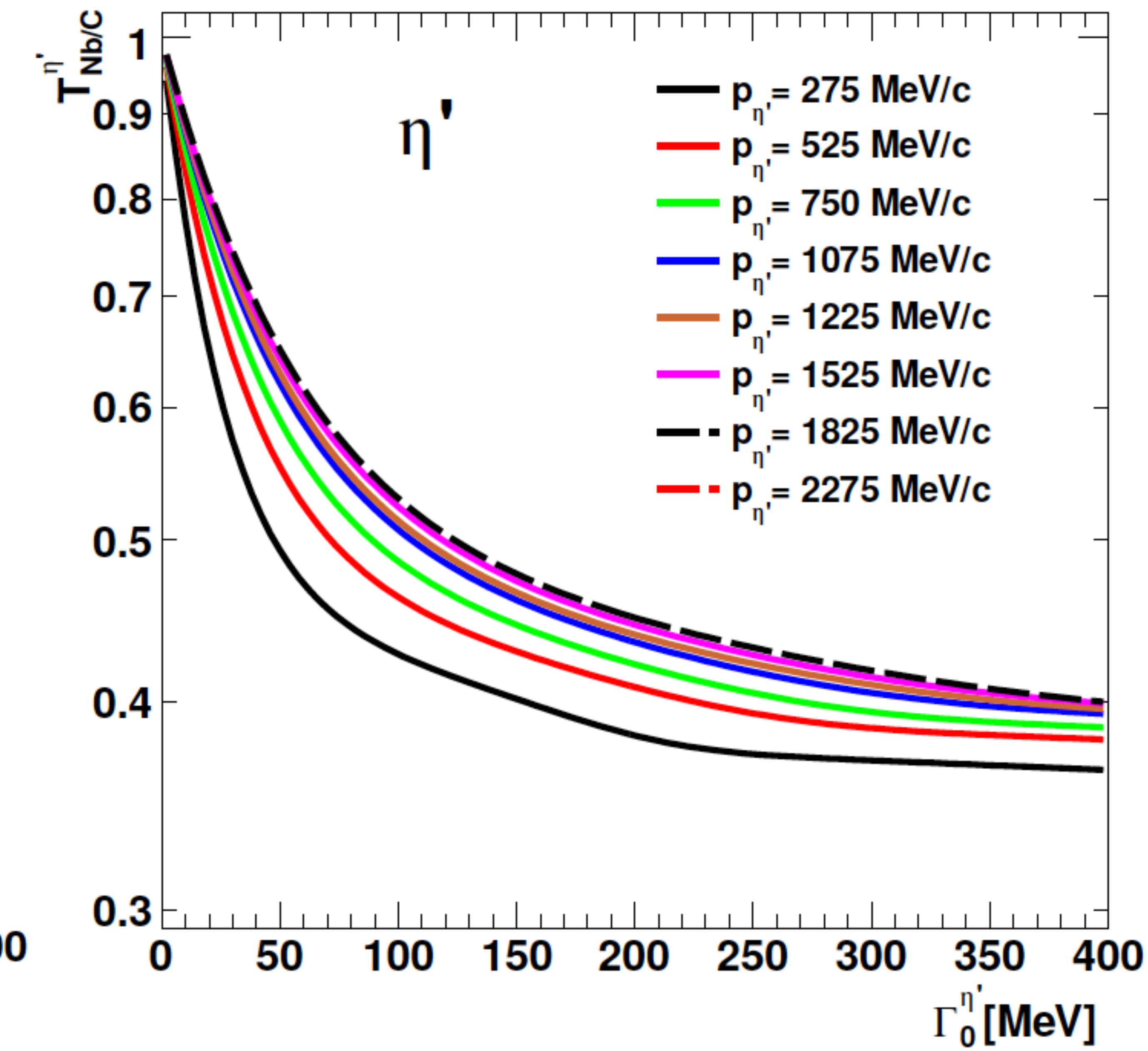
Glauber model analysis in high energy eikonal approximation

ω

η'

$$T^{m}_{Nb/C}(p_m) \Rightarrow \Gamma^{m}_{0}(\rho=\rho_0)\ (p_m)$$



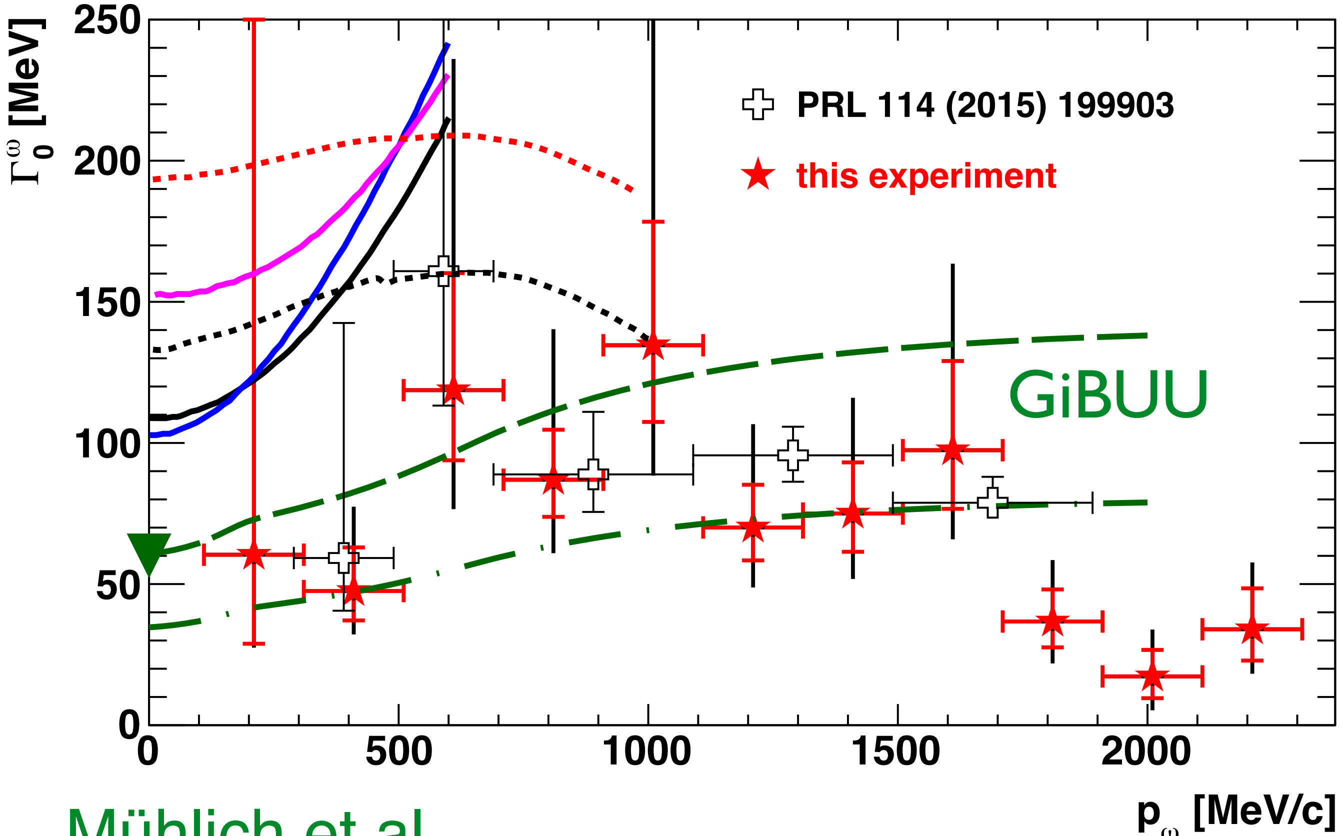



# momentum dependence of in-medium width $\Gamma_0(\rho=\rho_0)$

ω

η’

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

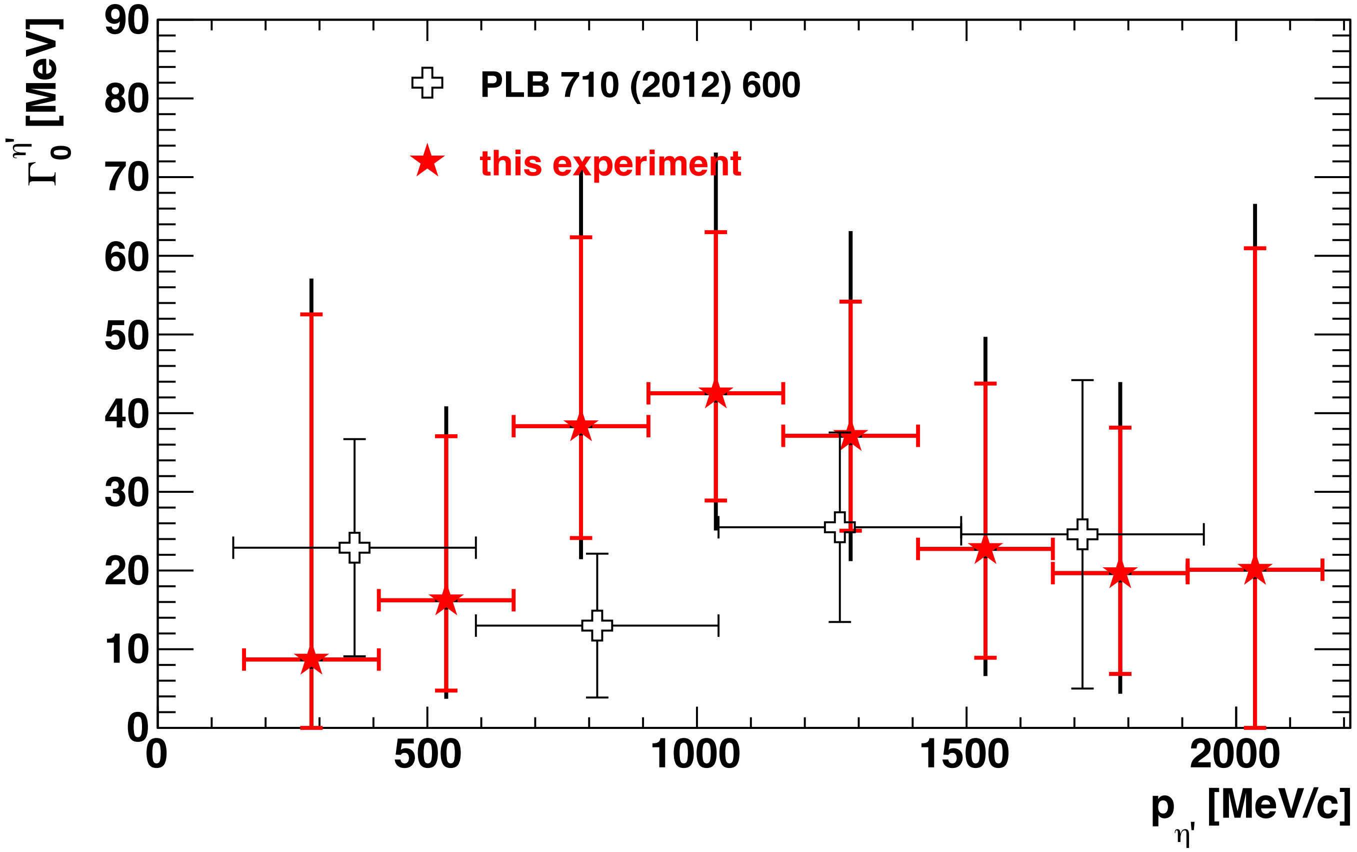



Mühlich et al. NPA 780

Cabrera & Rapp, PLB 729

Ramos et al. EPJA 49

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



# inelastic absorption cross section $\sigma_{inel}(p)$

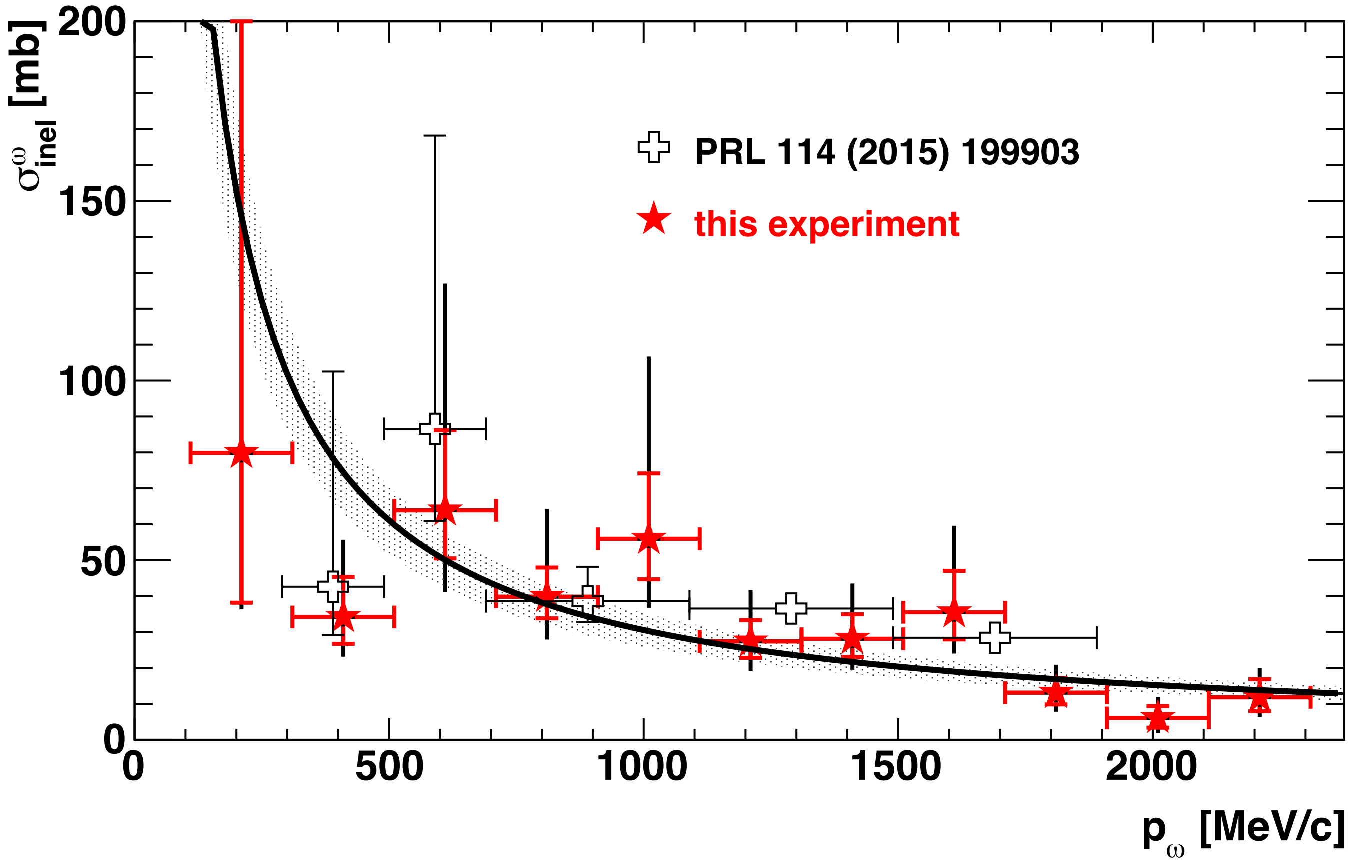
low density approximation

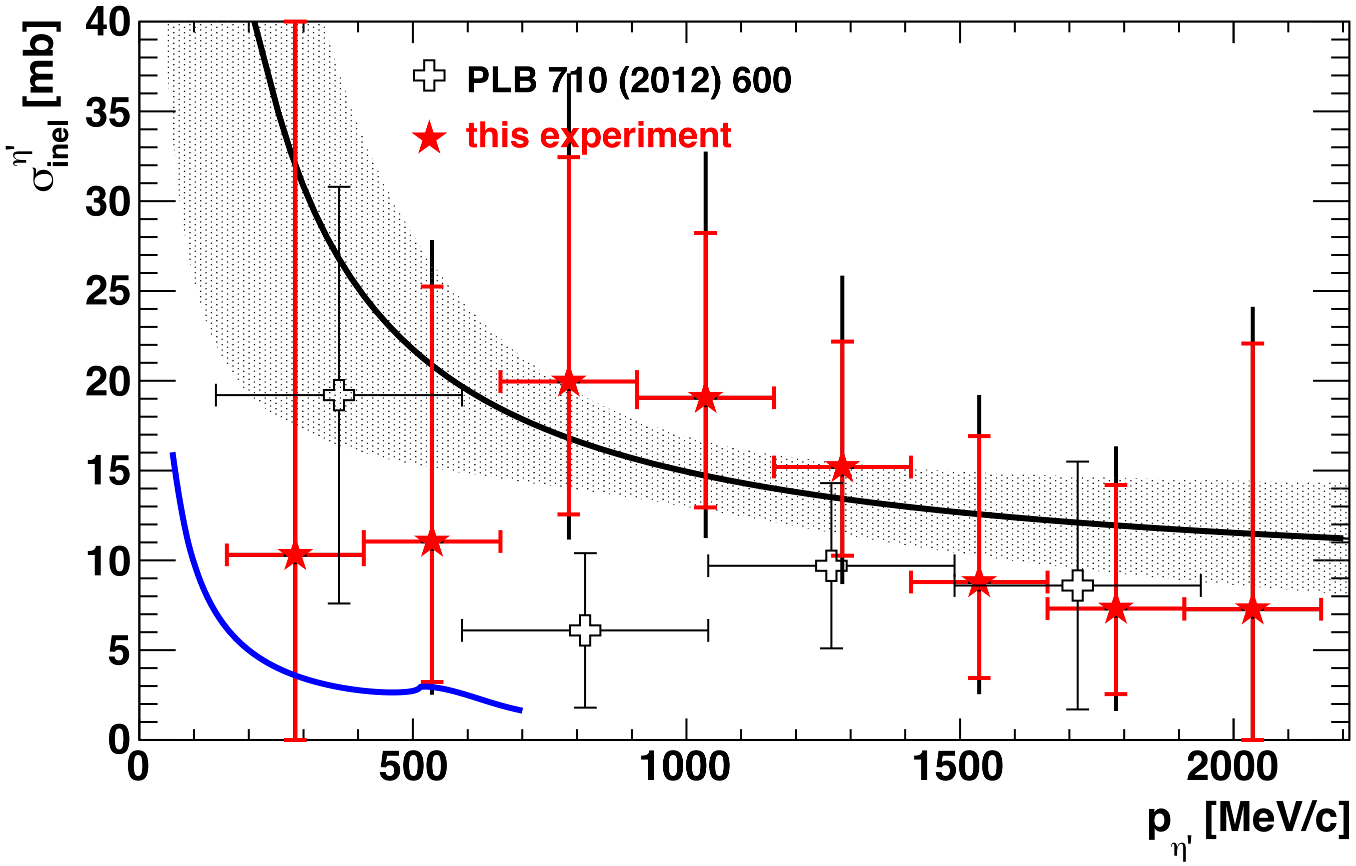
ω

η'

$$\Gamma_0(p) = \hbar c \bullet \rho_0 \bullet \beta \bullet \sigma_{inel}(p) \Rightarrow \sigma_{inel}(p) = \frac{\Gamma_0(p)}{\hbar c \bullet \rho_0 \bullet \beta}$$

$$\sigma_{inel}(p)[mb] = a + \frac{b}{p[GeV/c]}$$




a = 0.0±6.3

b = 35.5±4.3

a = 8.1±10

b = 6.8±10.4

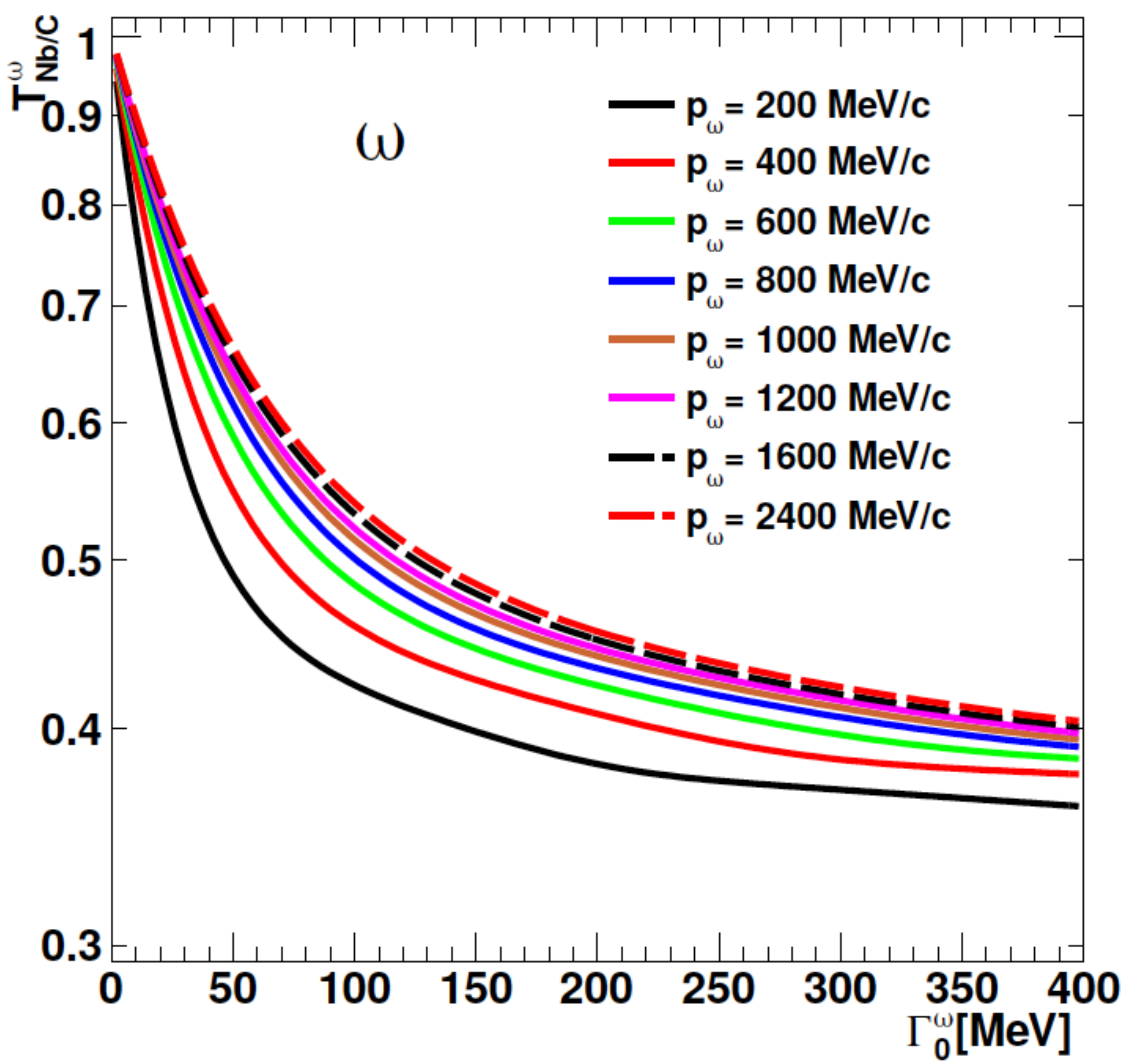
# in-medium width from transparency ratio

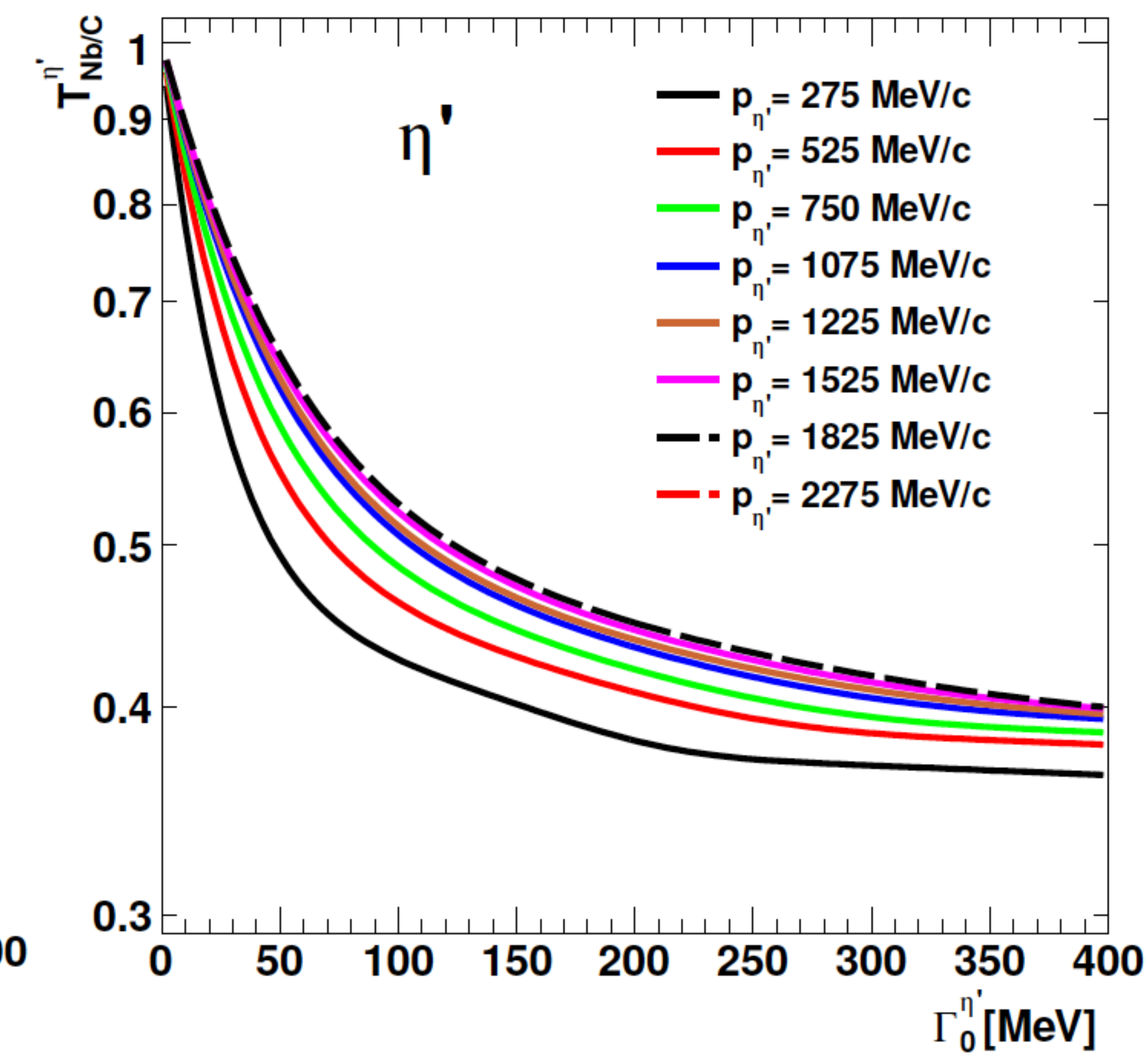
Glauber model analysis in high energy eikonal approximation

ω

η'

$$T^{m}_{Nb/C}\,(p_m) \Rightarrow \Gamma^{m}_{0}(\rho=\rho_0)\ (p_m)$$

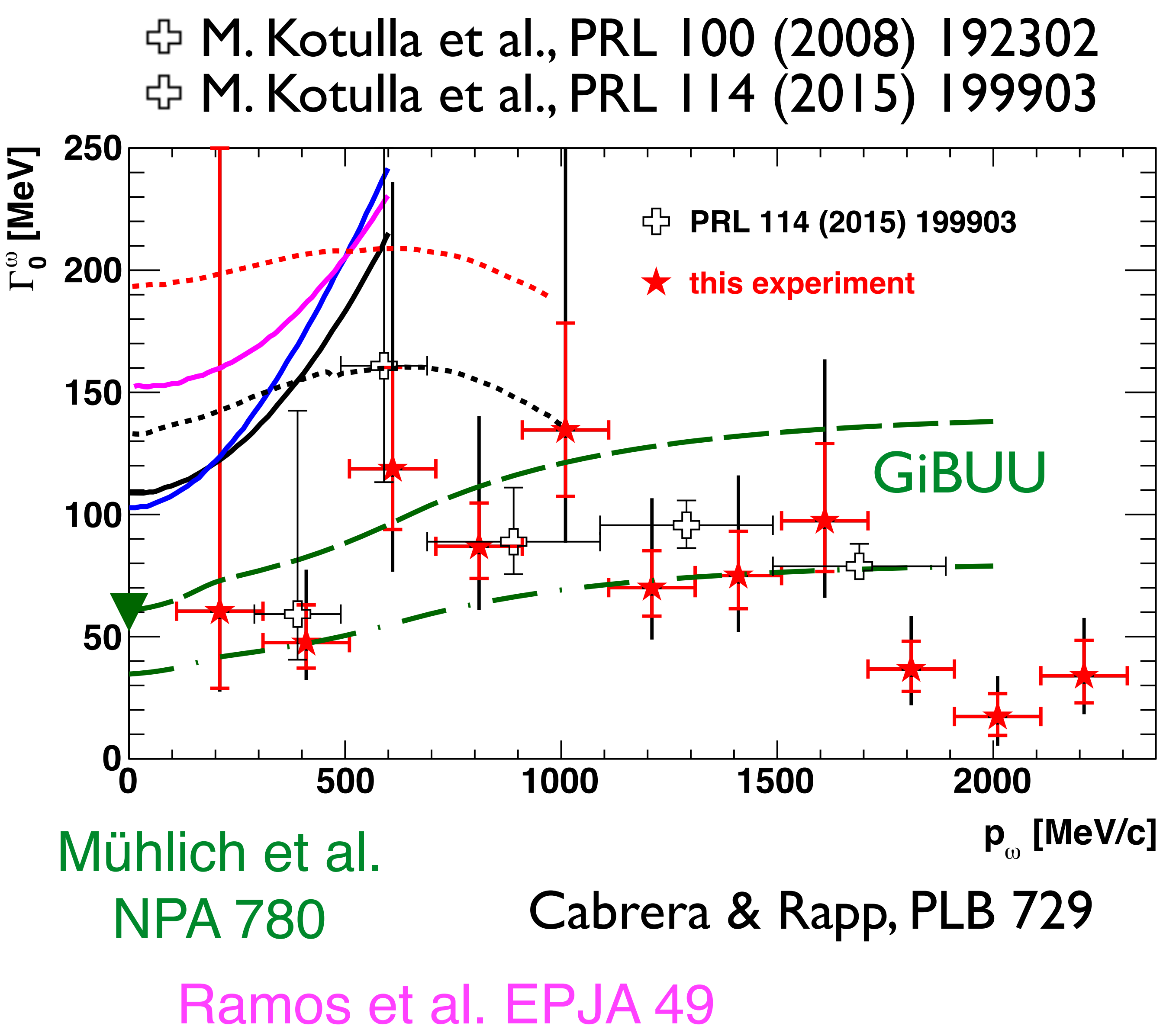


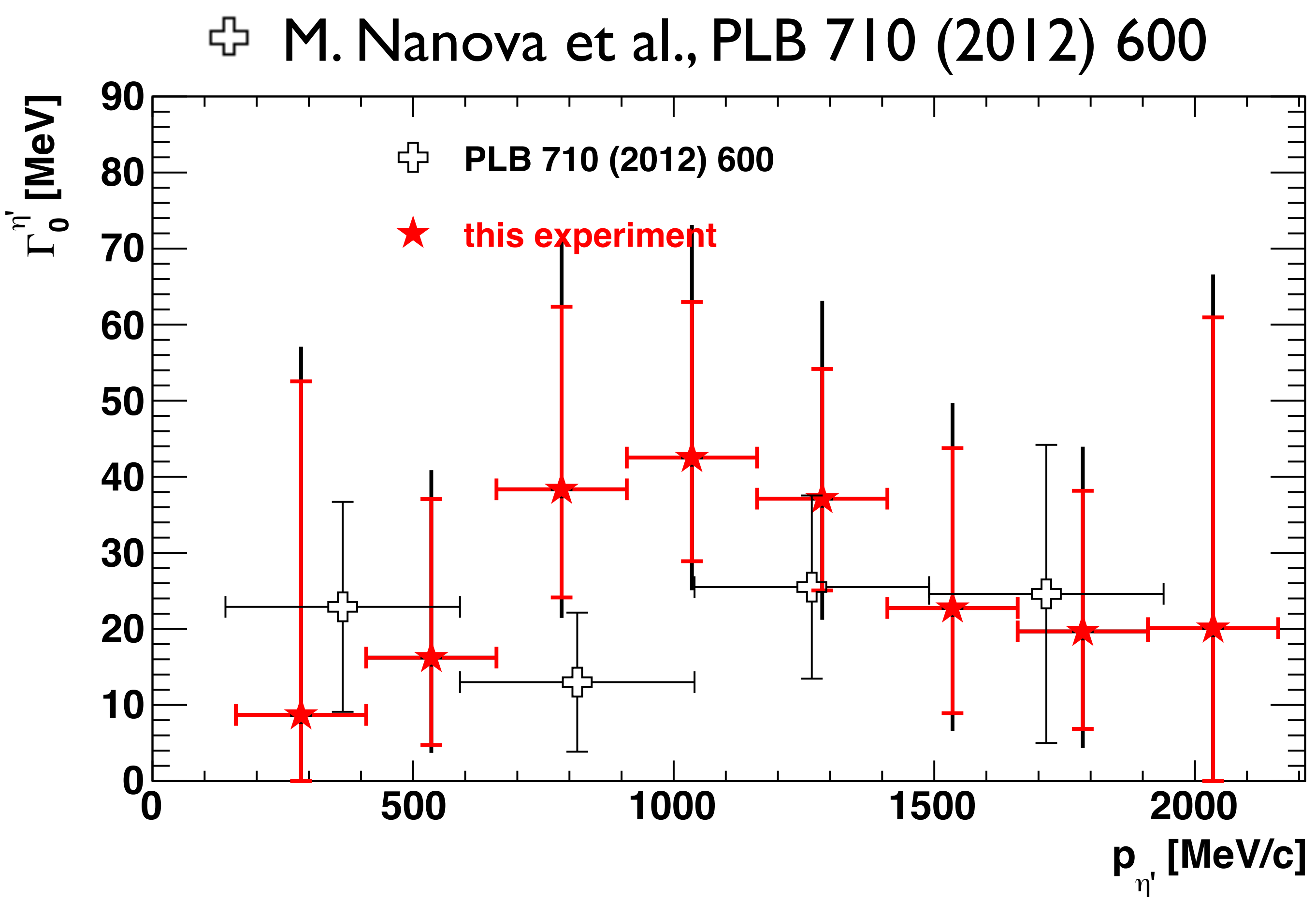



# momentum dependence of in-medium width $\Gamma_0(\rho=\rho_0)$

ω

η’



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low density approximation

ω

η’

$$\Gamma_0(p) = \hbar c \bullet \rho_0 \bullet \beta \bullet \sigma_{inel}(p) \Rightarrow \sigma_{inel}(p) = \frac{\Gamma_0(p)}{\hbar c \bullet \rho_0 \bullet \beta}$$

$$\sigma_{inel}(p)[mb] = a + \frac{b}{p[GeV/c]}$$