in-medium properties of hadrons

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JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
for the CBELSA/TAPS Collaboration

Outline

- motivation
- experimental approaches for studying in-medium properties of hadrons
- in-medium properties of ρ, ω, Φ and η' meson
- summary and outlook

*funded by the DFG within SFB/TR16

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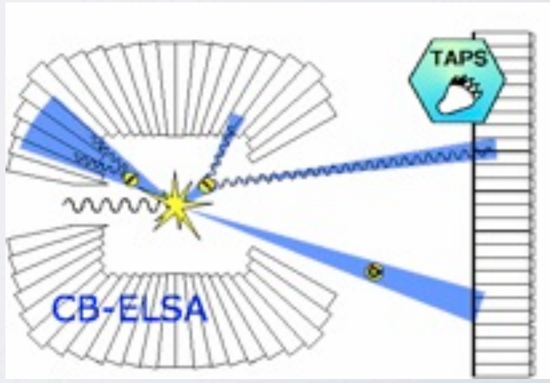
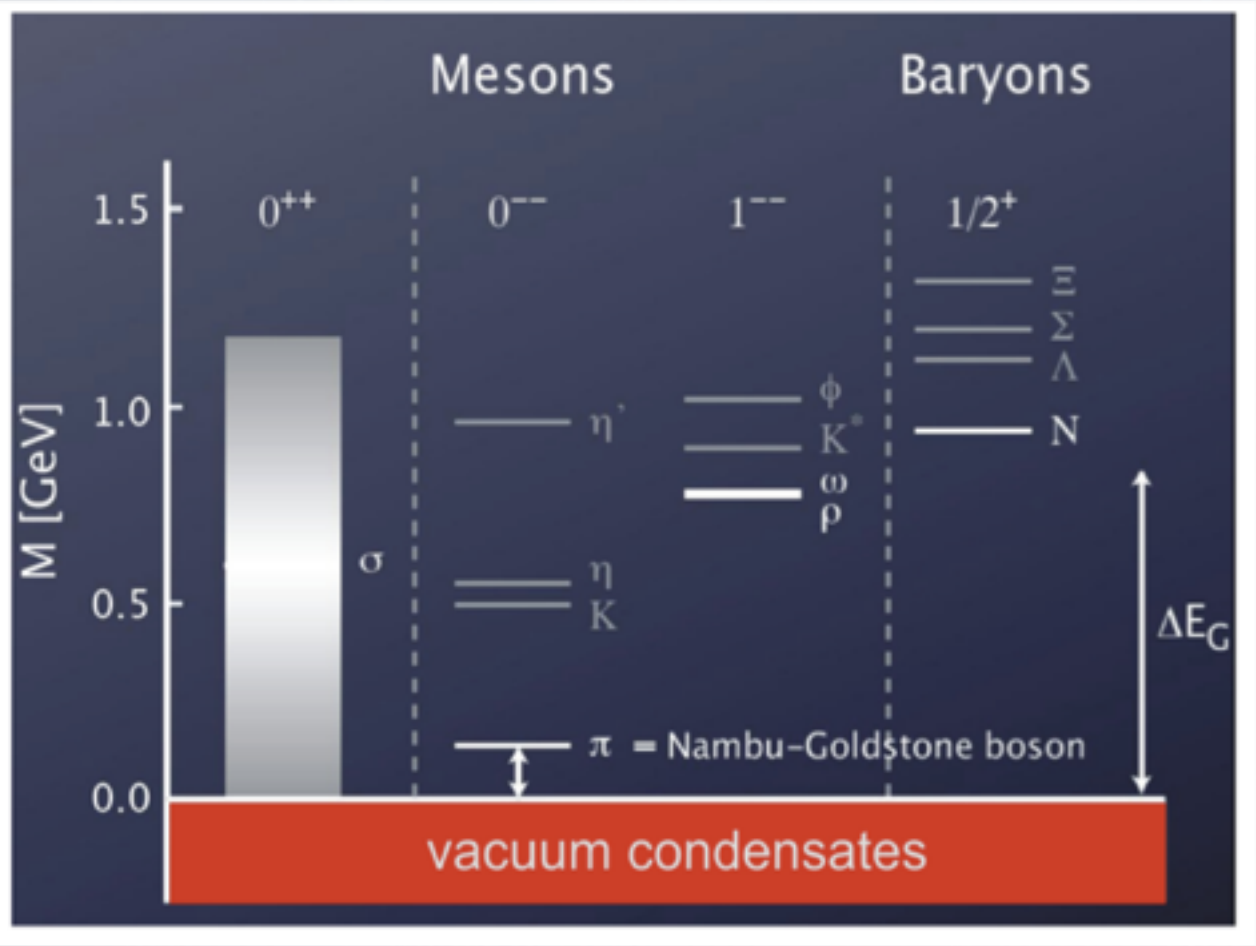
Krakow, Poland



hadron masses

J. Wambach



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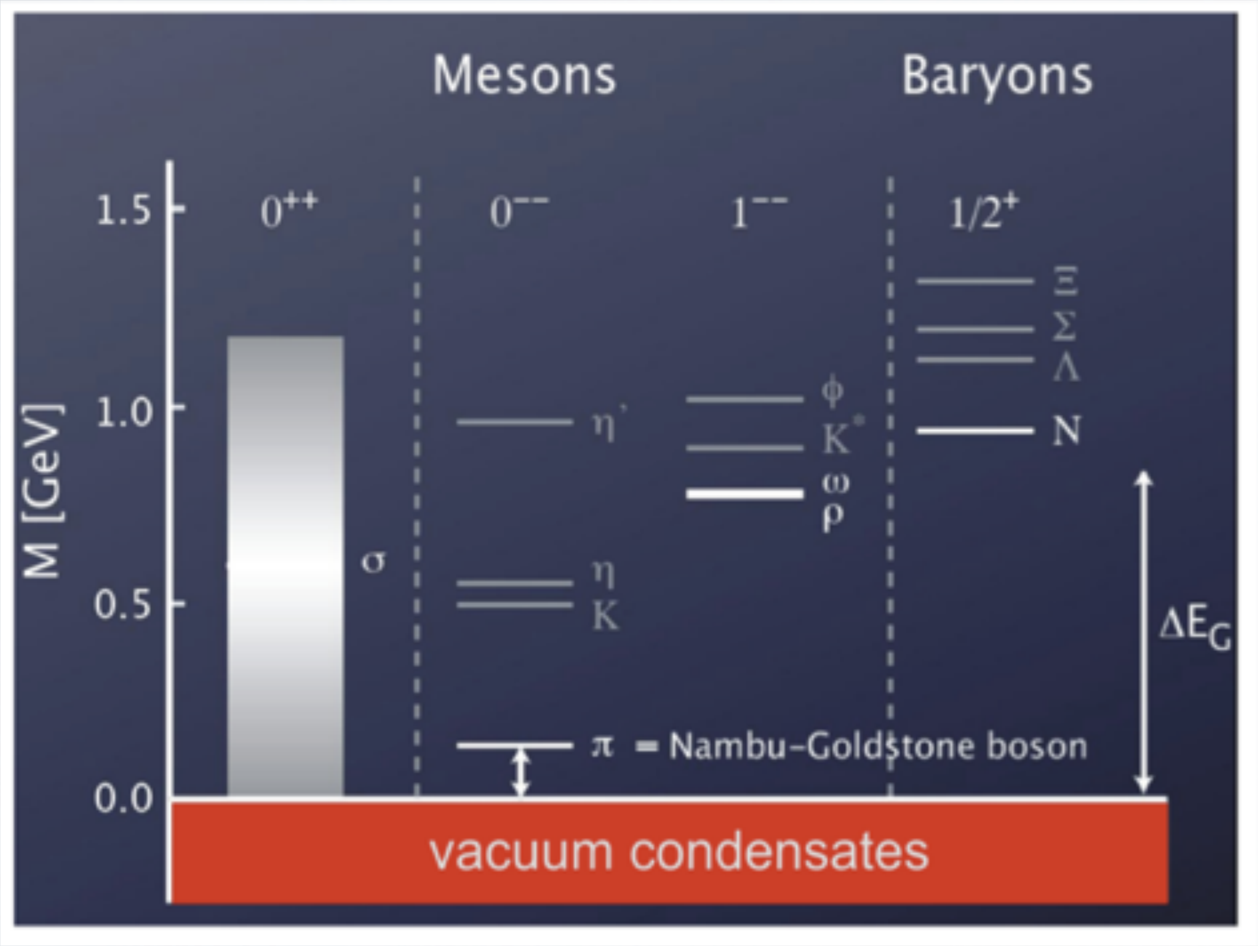

- hadrons = excitations of the QCD vacuum
- QCD vacuum: complicated structure characterized by condensates
- in the nuclear medium: condensates are changed

⇨ change of the hadronic excitation energy spectrum

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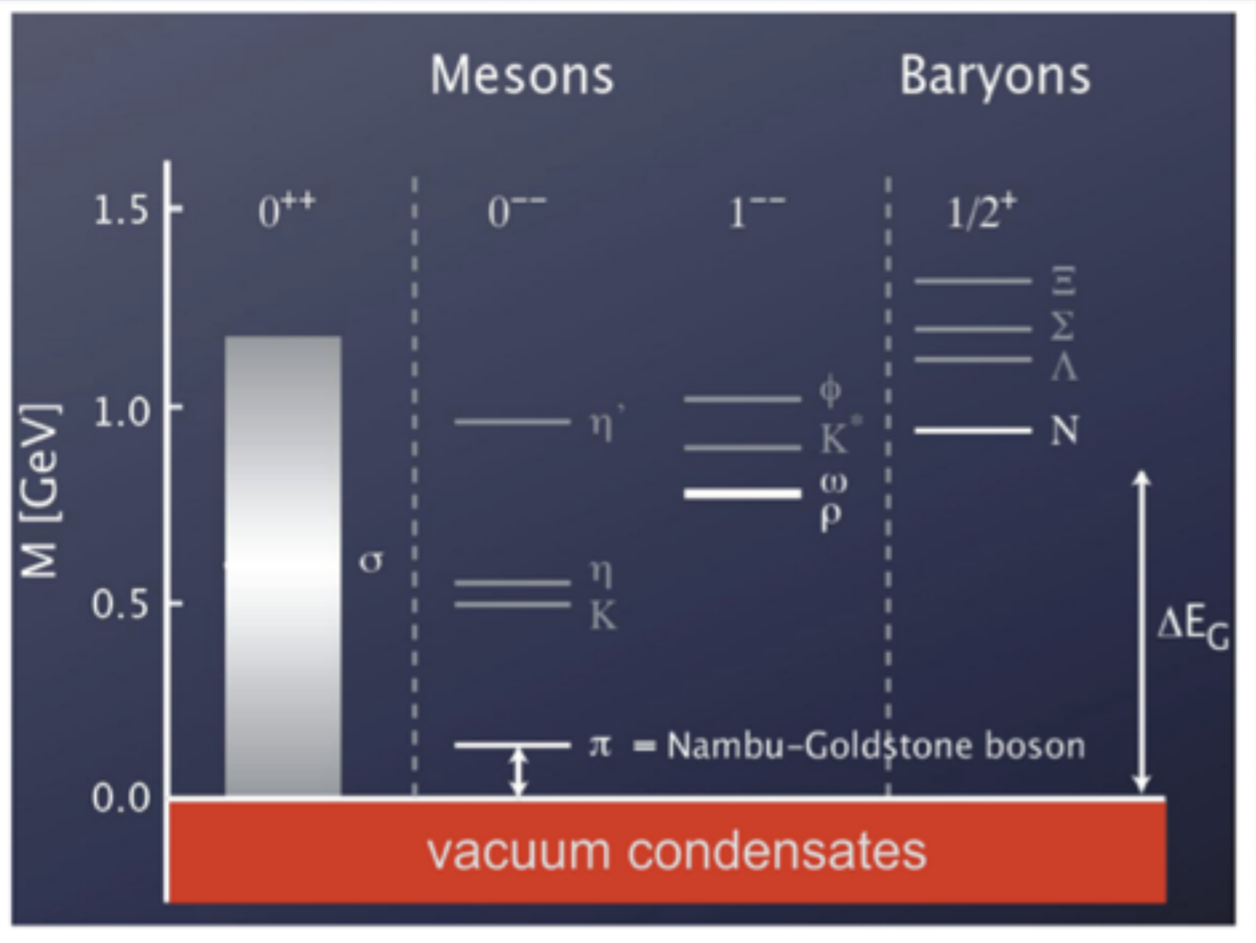

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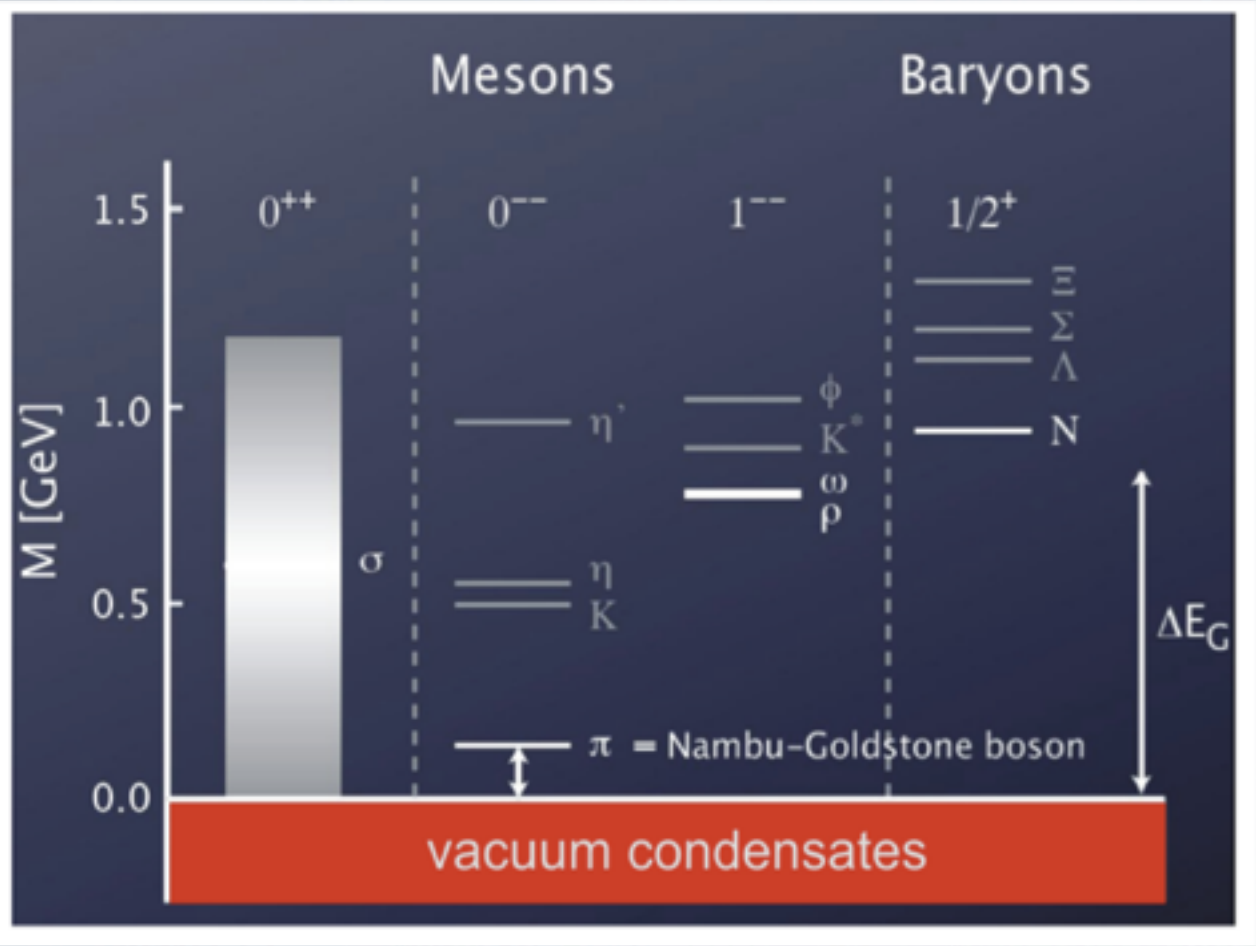

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widespread theoretical and experimental activities to search for in-medium modifications of hadrons

model predictions for in-medium masses of mesons

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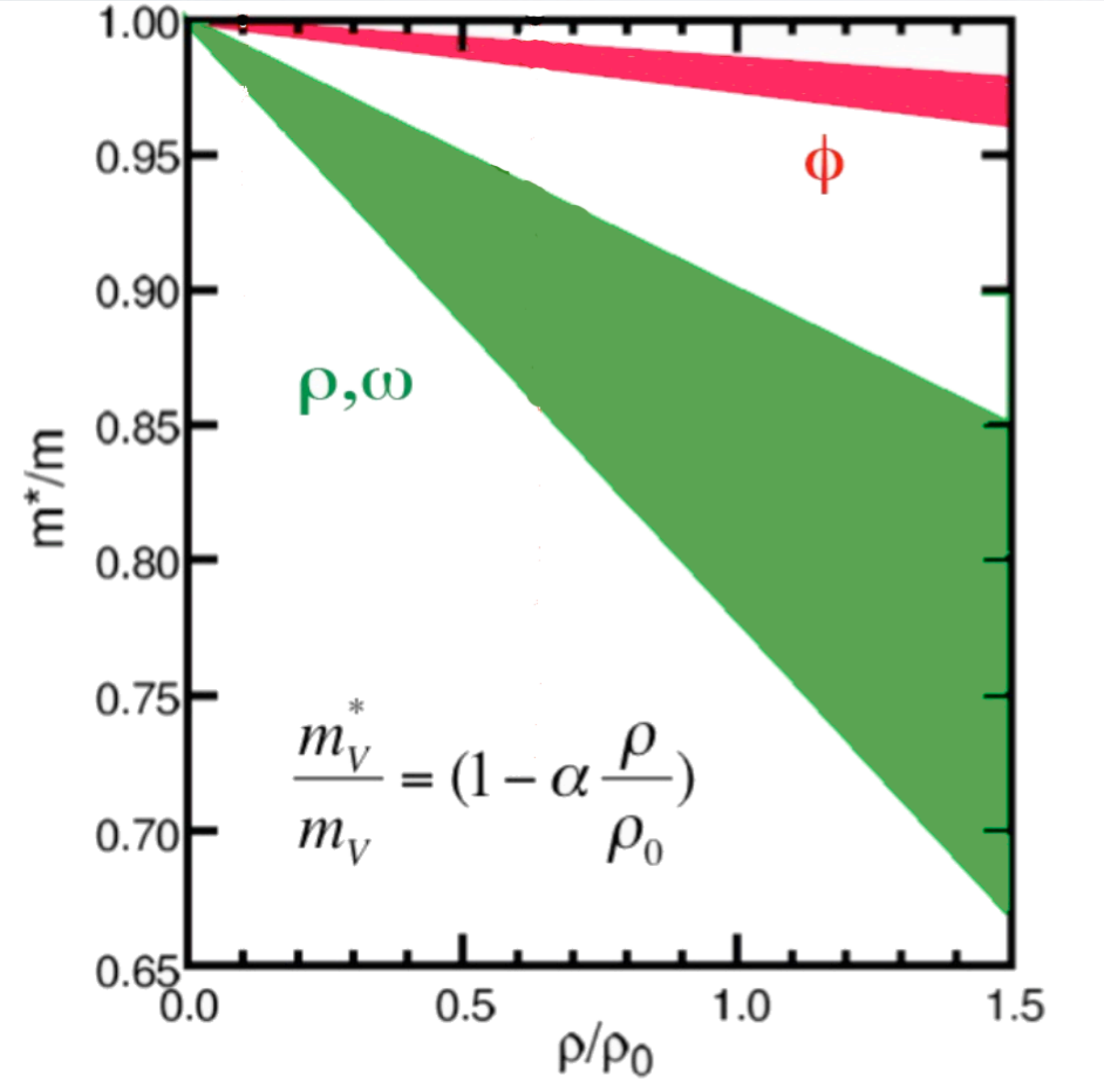

QCD sum rule approach: drop of ρ, ω mass by about 10% at average nuclear density of 0.6 ρ

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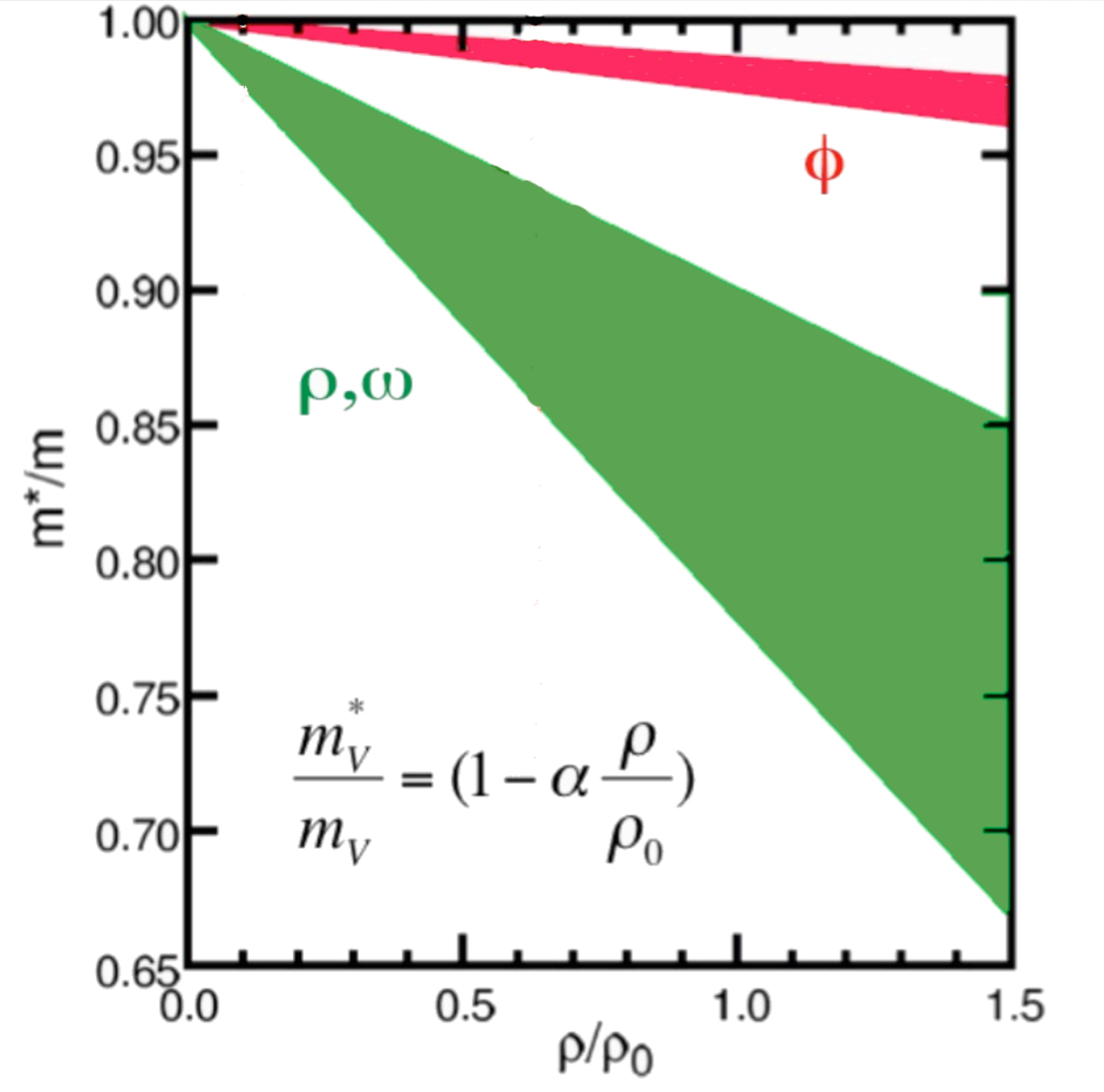
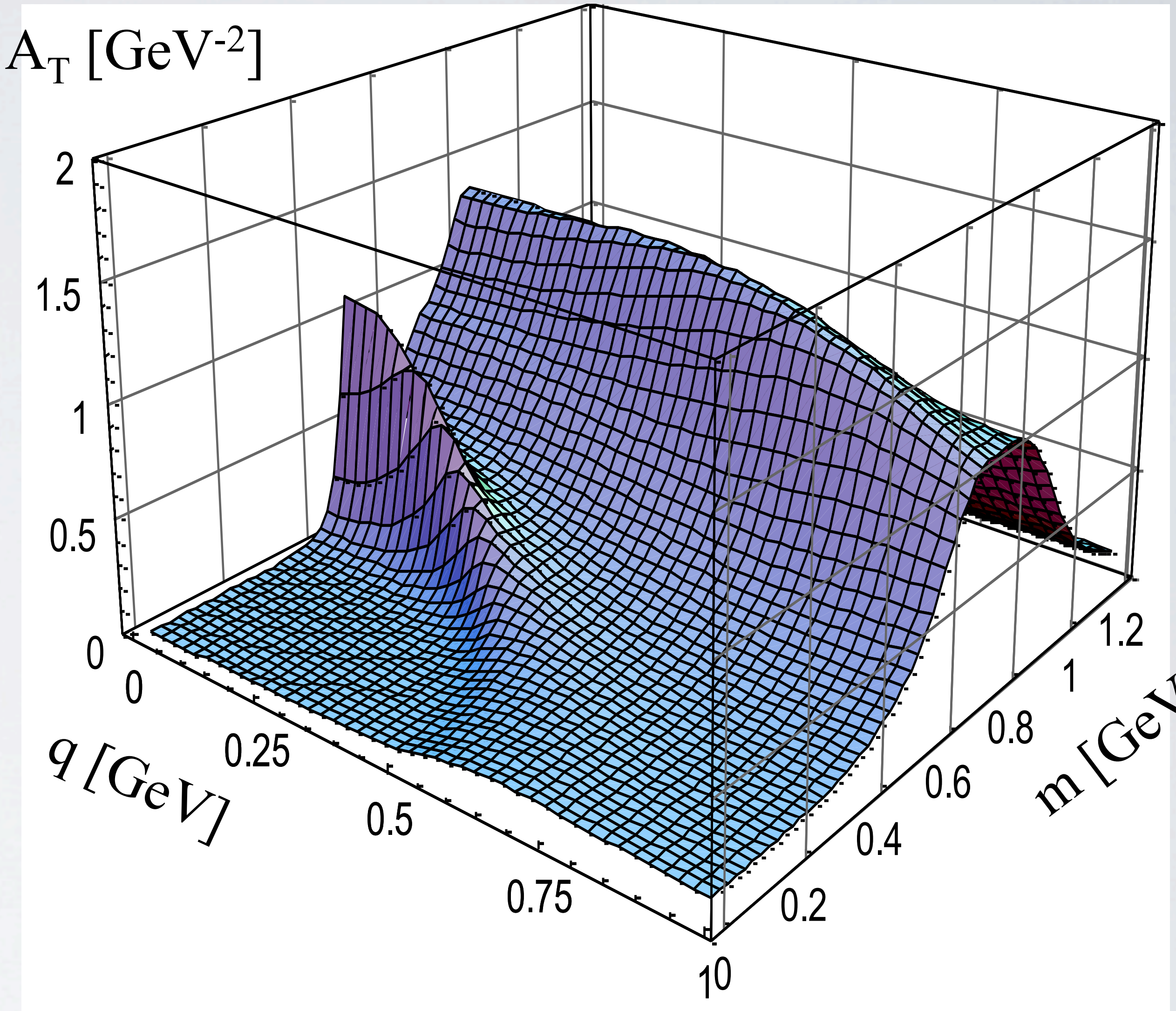


M. Post et al, NPA 741 (2004) 81



QCD sum rule approach: drop of ρ, ω mass by about 10% at average nuclear density of 0.6 ρ

- structure in ρ spectral function due to coupling to baryon resonances
- strong momentum dependence
- modifications most pronounced at small momenta

model predictions for spectral function of the ω meson

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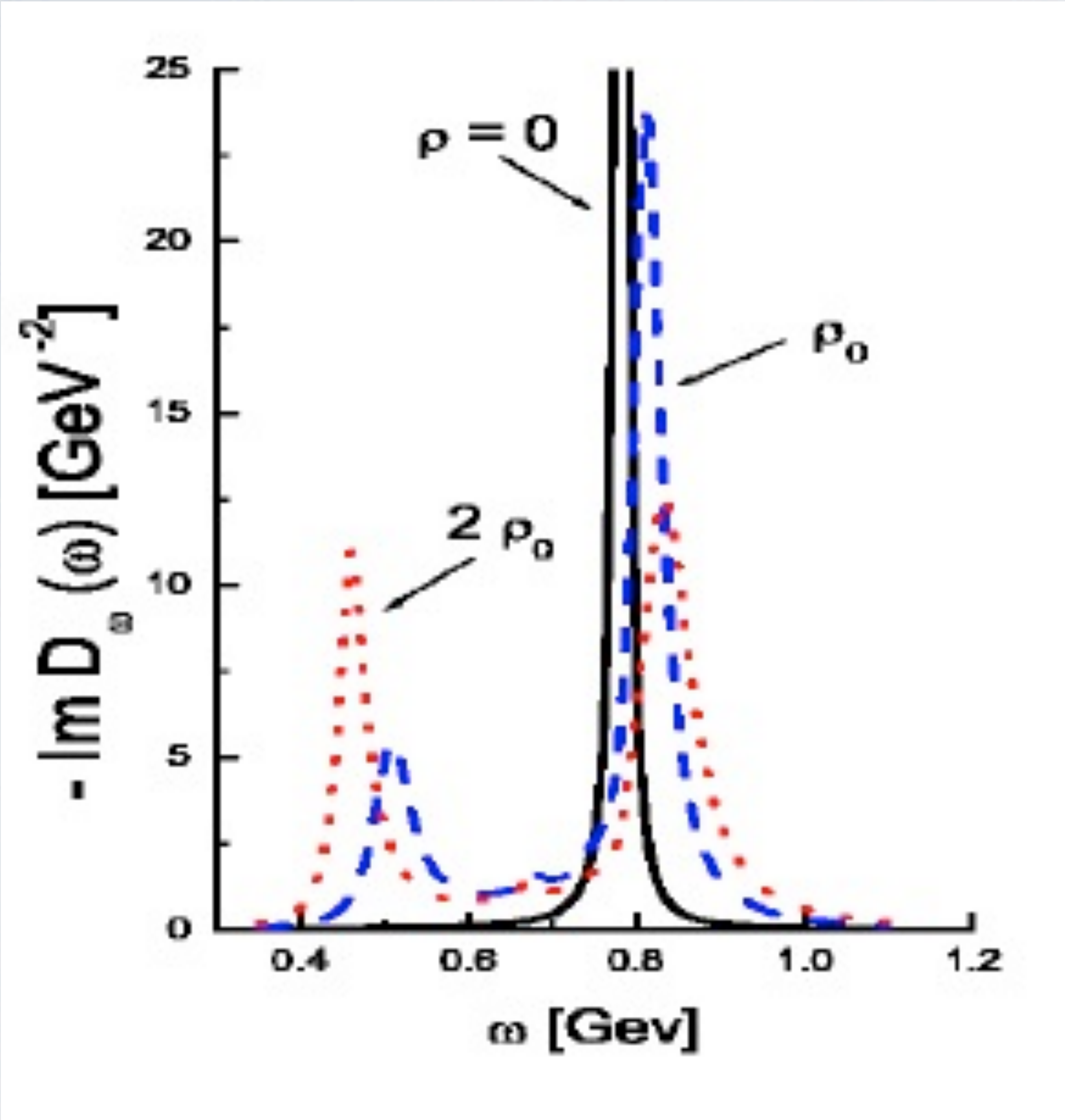
M. Lutz et al., NPA 706 (2002) 431



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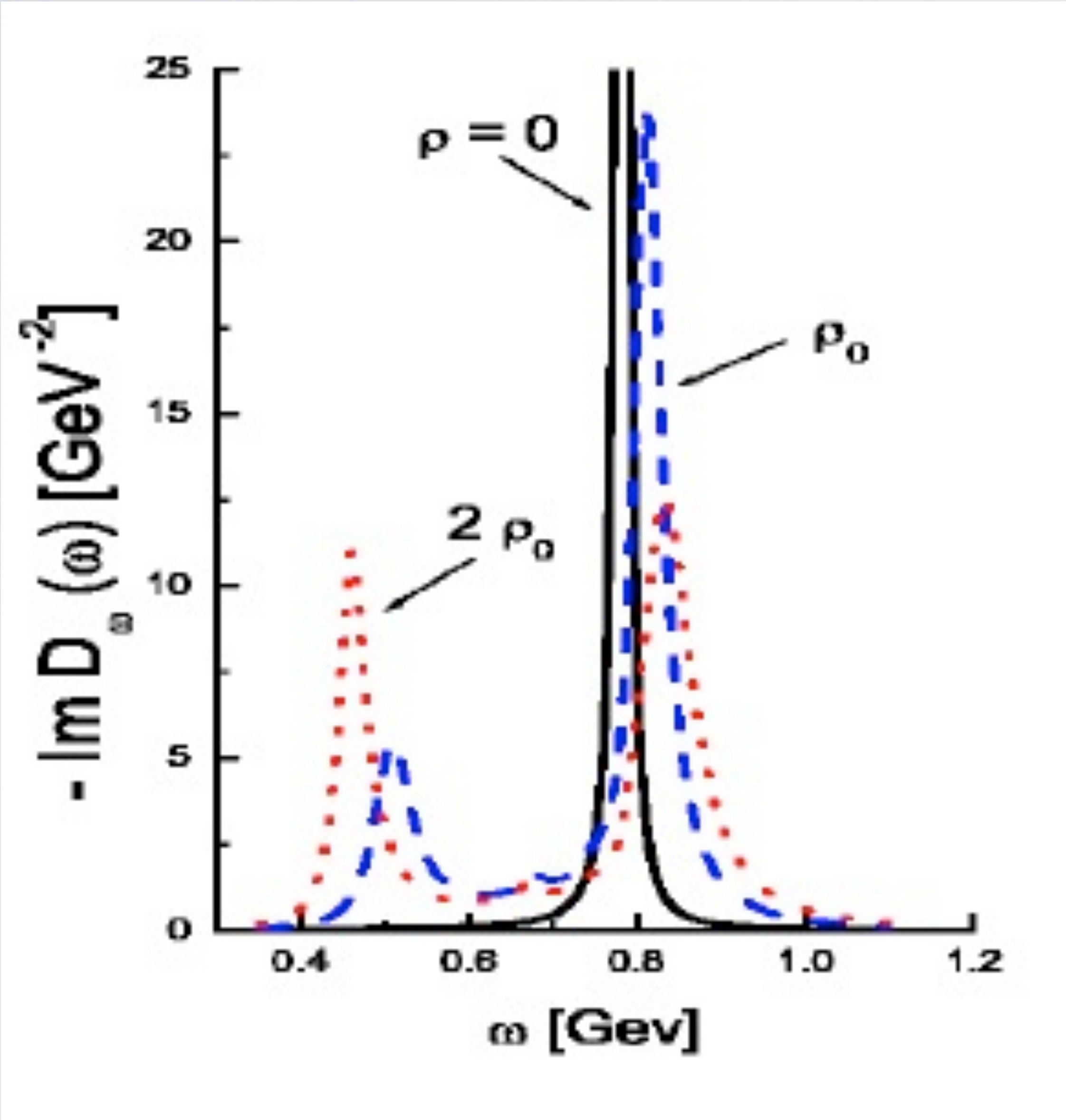
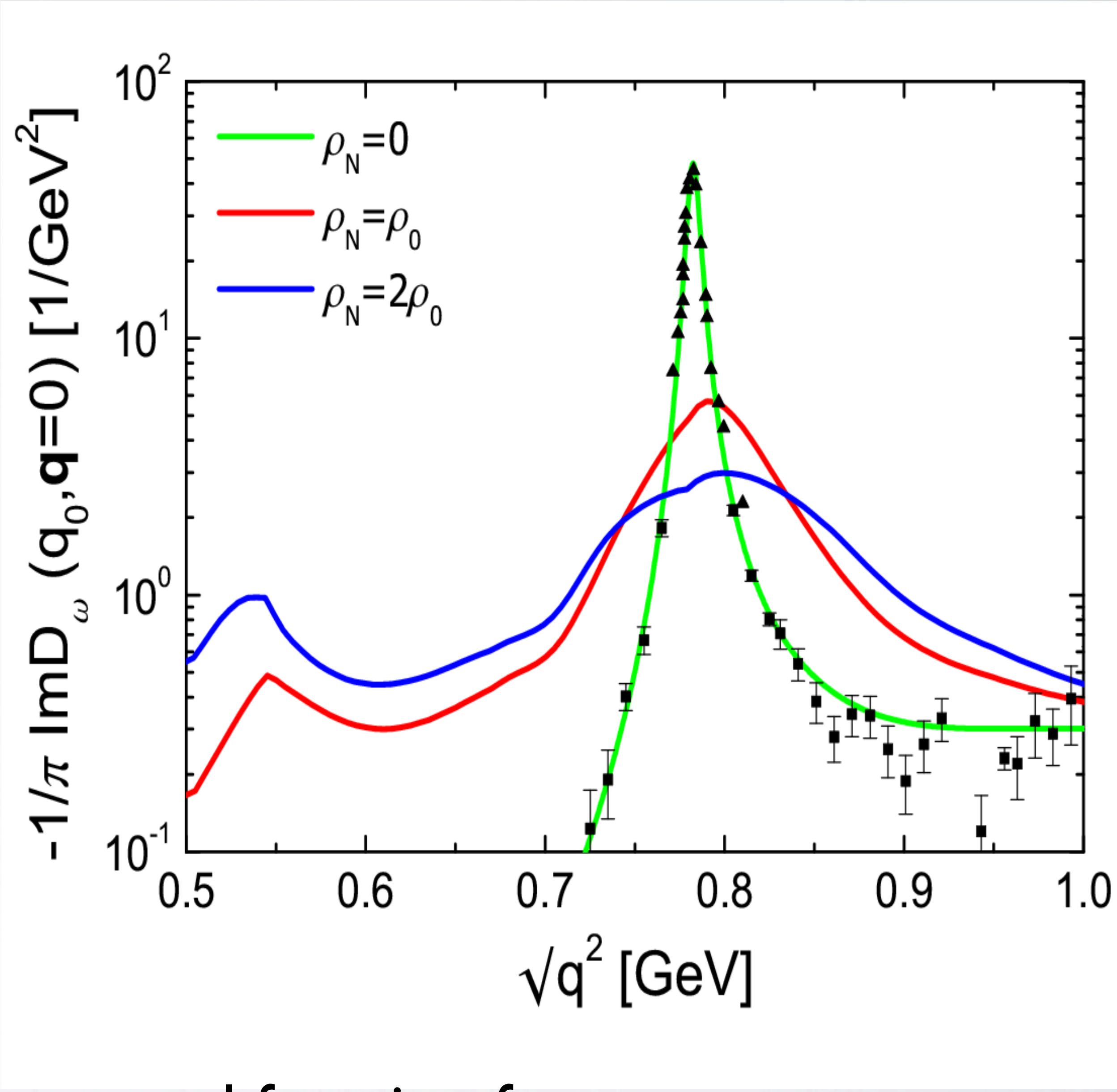


P Mühlich et al., NPA 780 (2006) 187



structure in spectral function due to coupling to baryon resonances: N(1520), N(1535), N(1650)

spectral function for ω meson at rest: splitting into ω-like and N^*N^{-1} mode due to coupling to S_{11} resonance

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V. Bernard and U.-G. Meissner,
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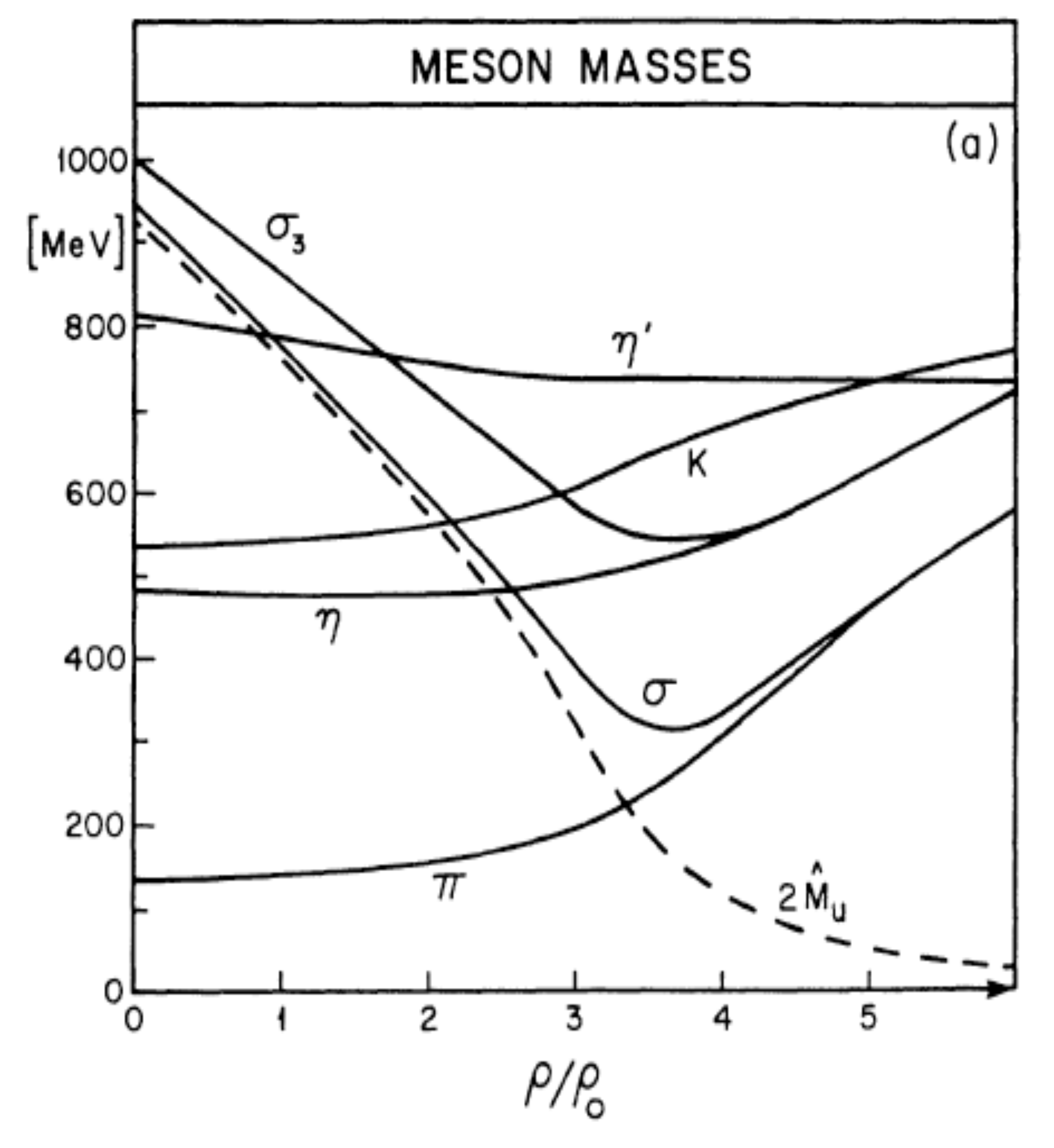

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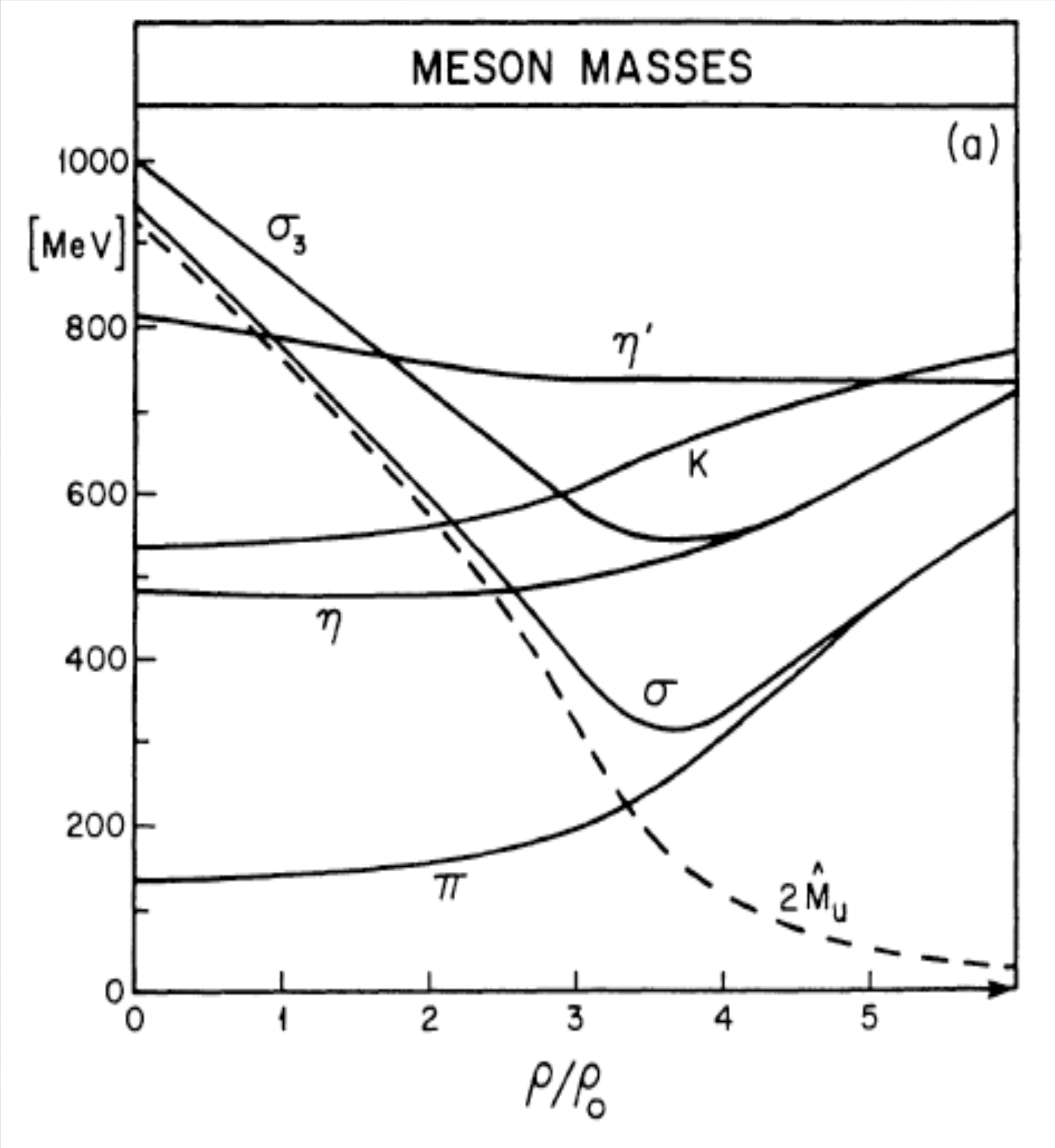

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M. Nagahiro, M.Takizawa and S. Hirenzaki,
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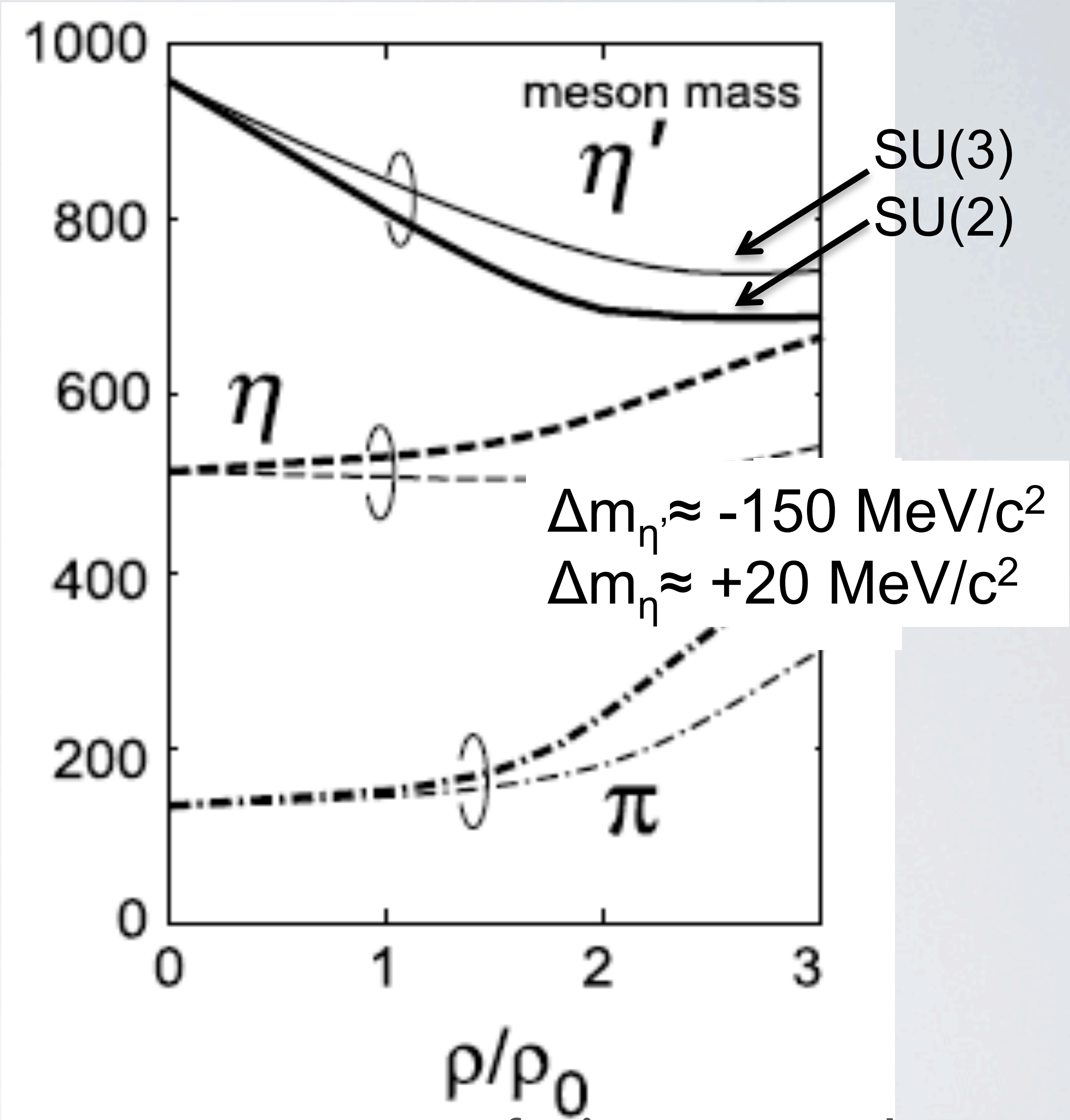

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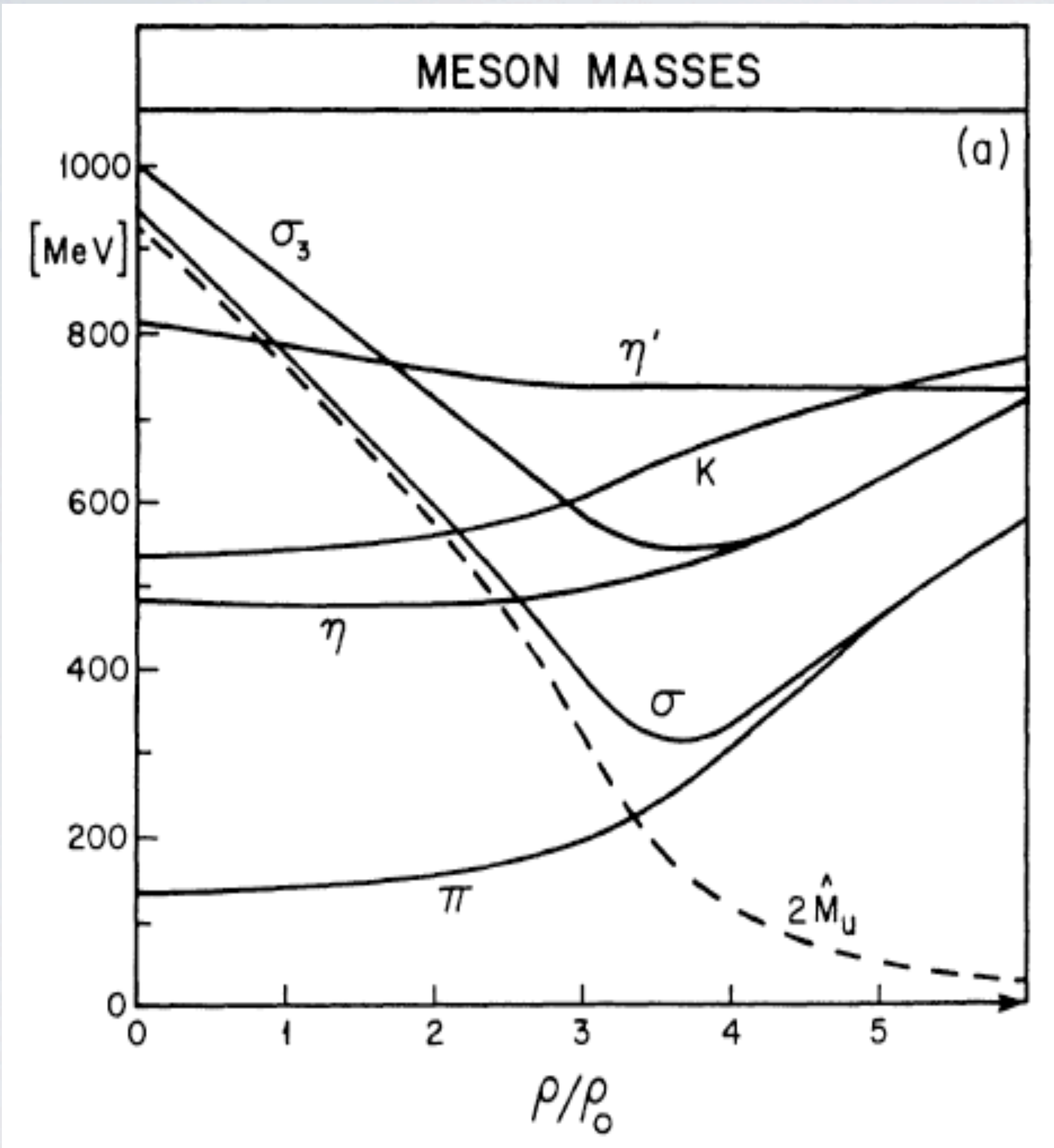

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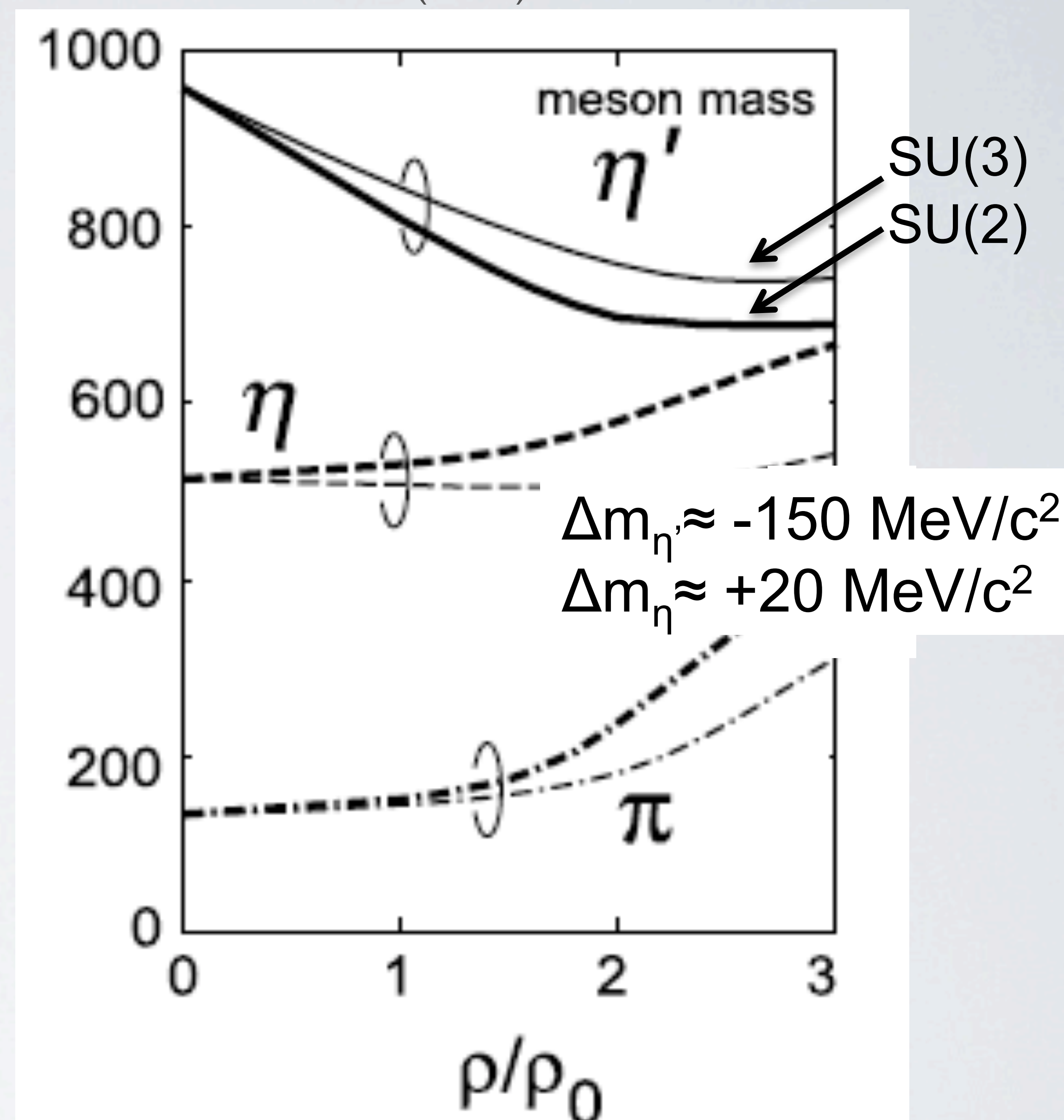

strong variation of η' mass on density

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

ensure acceptance for low meson momenta

From theoretical predictions to experimental observables

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calculations of meson spectral functions assume:

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

transport calculations calculations are needed for comparison with experiment !!!

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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

status of experiments in 2008/09

	M.Naruki et al., PRL 96 (2006) R. Muto et al., PRL 98 (2007)	T. Ishikawa et al., PLB608 (2005)	R.Nasseripour et al., PRL 99 (2007)	D. Trnka et al, PRL 94 (2005) M. Kotulla et al. PRL 100 (2008)	D. Adamova et al., PLB 666 (2008)	R. Arnaldi et al., PRL 96 (2006)
	KEK	Spring8	Jlab	CBELSA TAPS	CERES	NA60
reaction	p A 12 GeV	γ A 1.5-2.4 GeV	γ A 0.6-3.8 GeV	γ A 0.7-2.5 GeV	Au+Au 158 AGeV	In+In 158 AGeV
momentum acceptance	p > 0.5 GeV/c	p > 1.0 GeV/c	p > 0.8 GeV/c	p > 0.0 GeV/c	p_t > 0.0 GeV/c	p_t > 0.0 GeV/c
ρ	$\frac{\Delta m}{m} = -9\%$ $\Delta\Gamma \approx 0$		$\Delta m \approx 0$ $\Delta\Gamma \approx 70\,\text{MeV}$ $(\rho \approx \frac{\rho_0}{2})$		broadening favoured over density dependent mass shift	$\Delta m \approx 0$ strong broadening
ω				$\Delta m \approx 0$ $\Delta\Gamma \approx 130\,\text{MeV}$ $(\rho \approx \rho_0)$		
ϕ	$\frac{\Delta m}{m} = -3.4\%$ $\frac{\Gamma_\phi(\rho_0)}{\Gamma_\phi} = 3.6$	$\Delta\Gamma \approx 60\text{MeV}$ $(\rho \approx \rho_0)$				

experimental approaches for studying in-medium effects of mesons in photon- and proton- induced reactions

Reviews:

- R.S. Hayano and T. Hatsuda, Rev. Mod. Phys. 82 (2010) 2949
- R. Rapp, J. Wambach, H. van Hees, ArXiv:0901.3289, Landolt-Börnstein vol/23, 4-1 (2010)
- S. Leupold, V. Metag, and U. Mosel, Int. J. Mod. Phys. E19 (2010) 147

1.) measurement of transparency ratio: $T_A = \dfrac{\sigma_{\gamma A \to V X}}{A \cdot \sigma_{\gamma N \to V X}}$

2.) lineshape analysis: $M \to X_1 + X_2; \quad m_V(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$

3.) search for meson-nucleus bound states

measurement of the transparency ratio

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

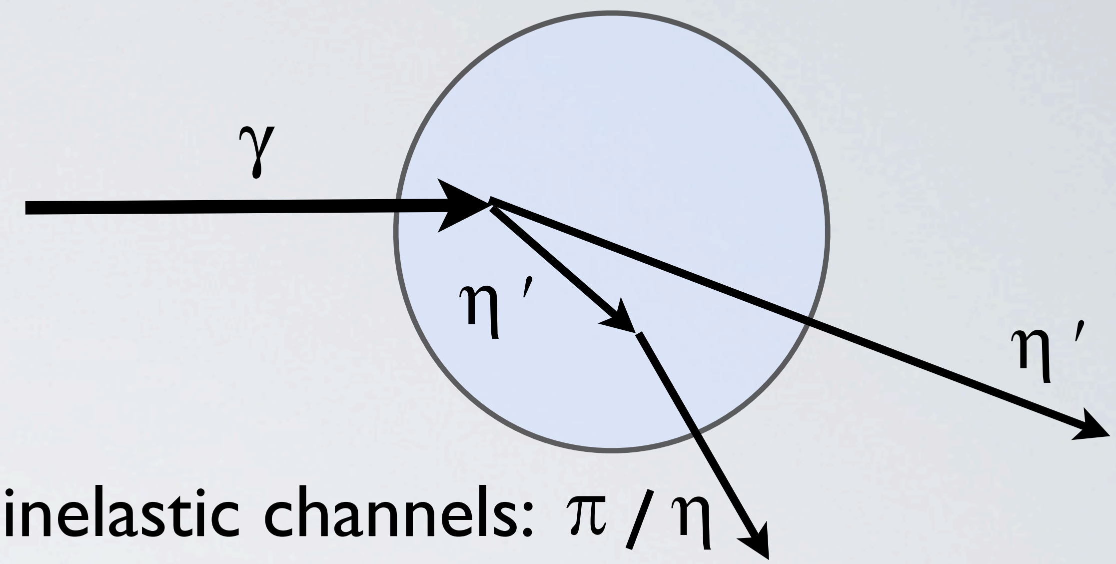
transparency ratio measurement

transparency ratio measurement

attenuation measurement of meson flux:

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

production probability per nucleon within the nucleus compared to production probability on the free nucleon



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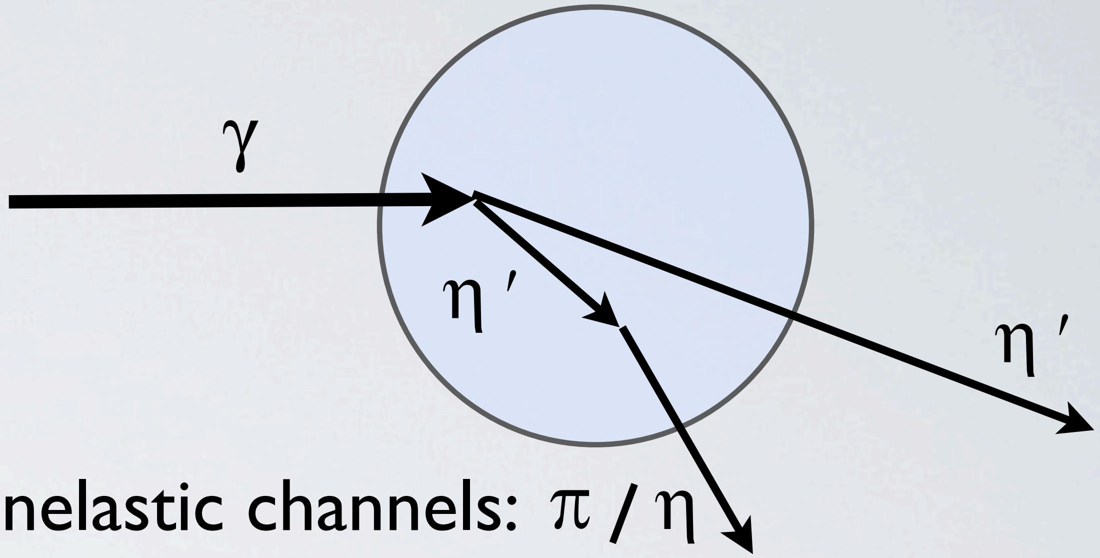

production probability per nucleon within the nucleus compared to production probability on the free nucleon

inelastic reactions remove ω, η' mesons, e.g. ω, η' N → π N
shortening of ω, η' lifetime in the medium ⇒ increase in width

low density approximation: $\Gamma(\rho) = -\frac{Im\Pi(\rho)}{E} \sim \rho v \sigma_{inel}$; $\Gamma(\rho) = \Gamma(\rho_0)\frac{\rho}{\rho_0}$

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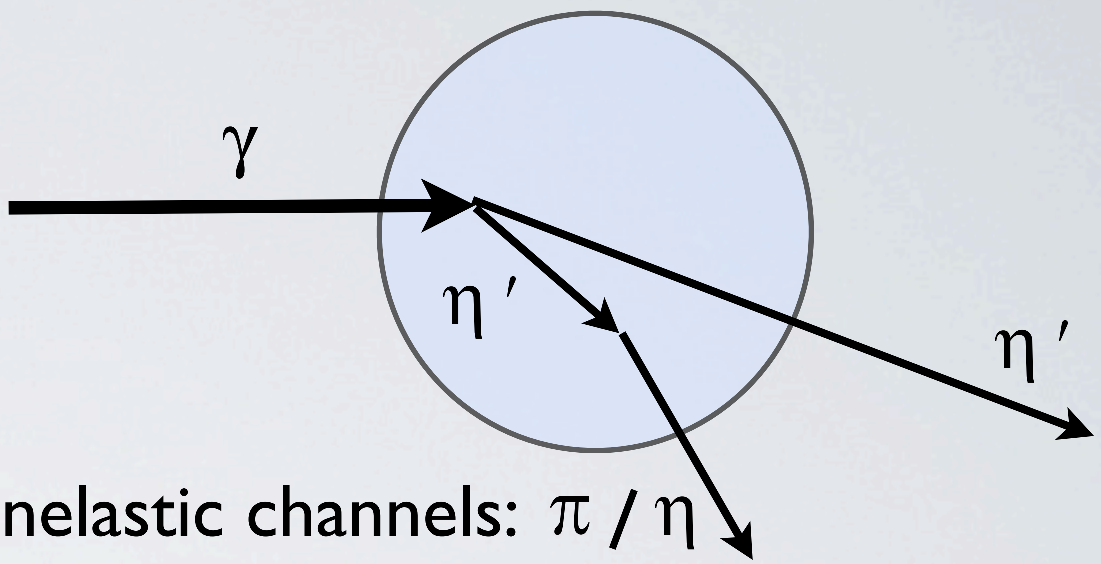

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in-medium ω, η' = quasi-particles with properties reflecting the interaction with the medium

applicable to any meson lifetime !!

information on in-medium properties of mesons from measurement of their decay outside of the nucleus

systematic uncertainties in transparency ratio measurements

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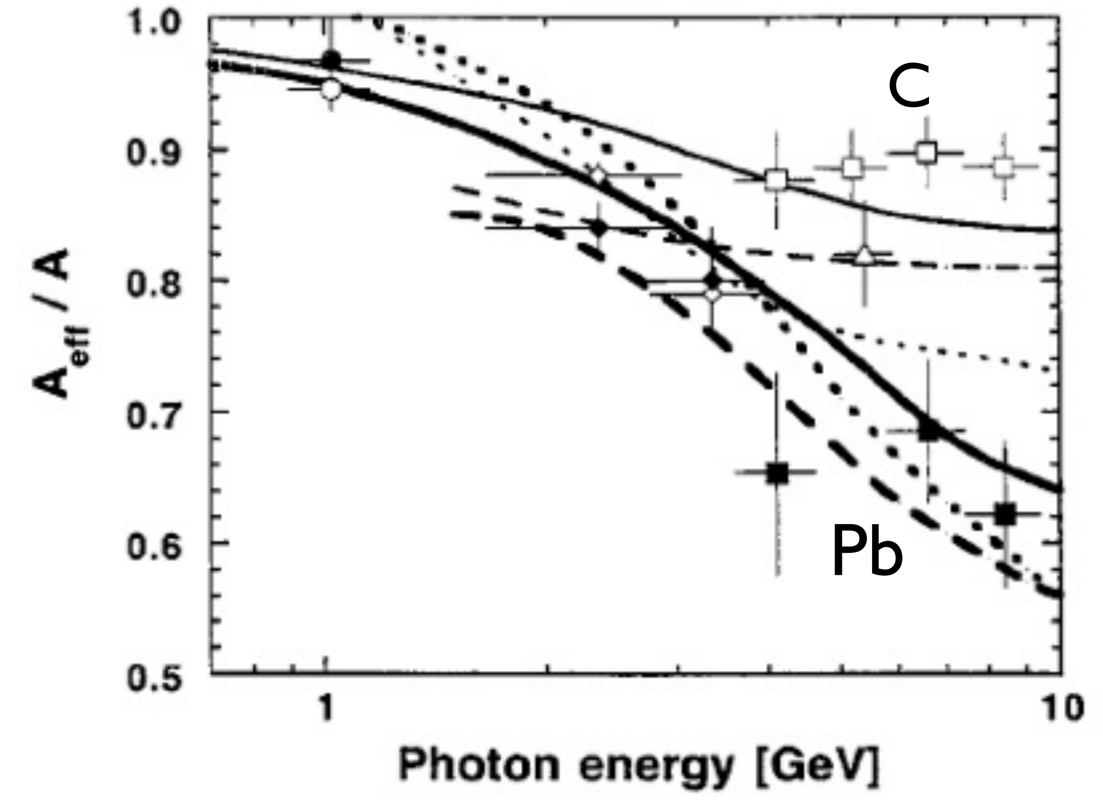
1.) photon shadowing:

due to hadronic fluctuations photons do not reach all nucleons
⇒ apparent reduction of transparency ratio

N. Bianchi et al., Phys. Rev. C 54 (1996)1688



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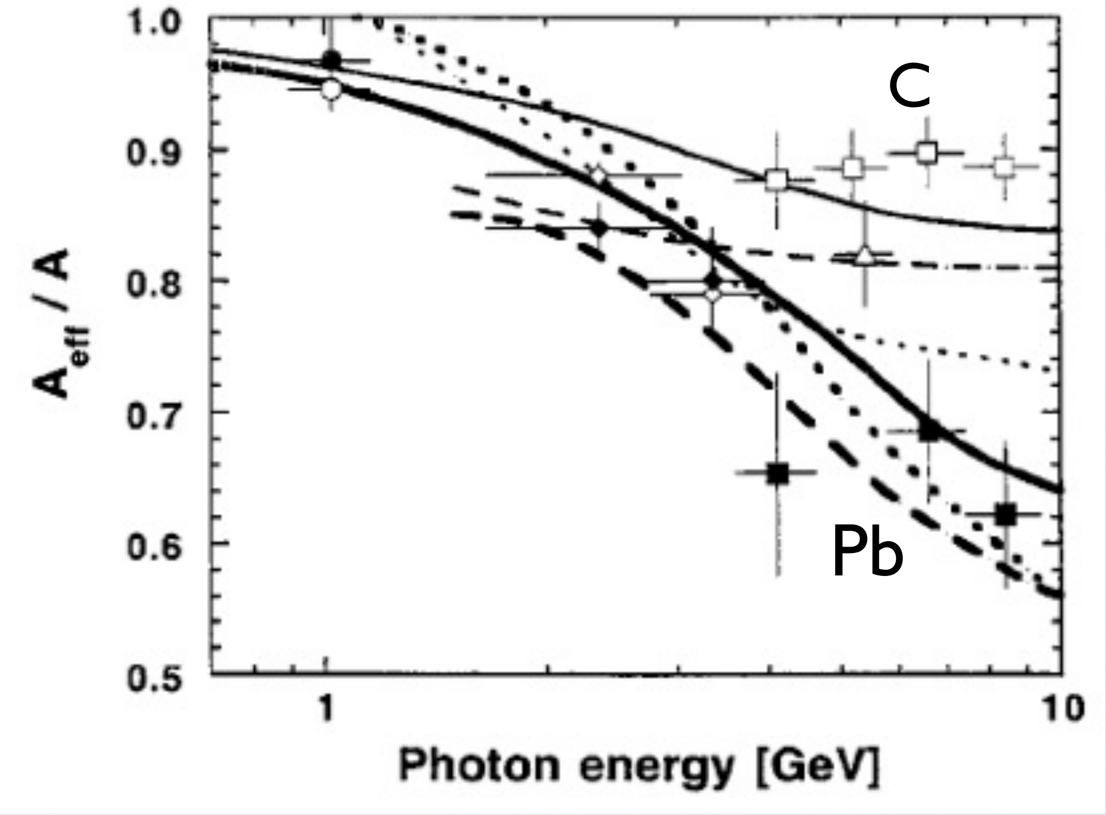
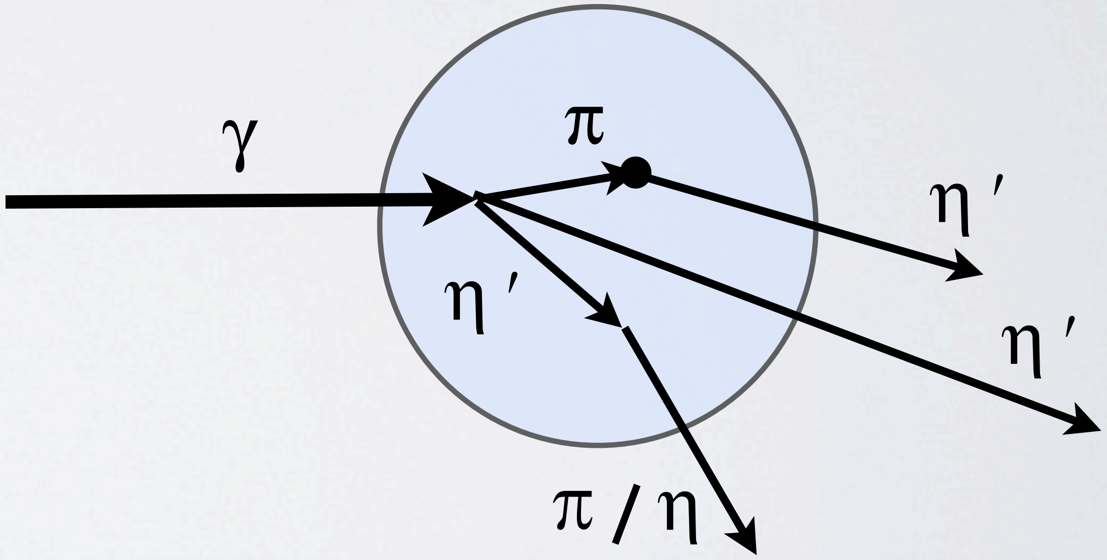


2.) multi-step processes:

e.g. $\gamma N_1 \rightarrow \pi N_1$
$\pi N_2 \rightarrow \omega, \eta' N_2$

⇒ apparent increase of transparency ratio at low meson momenta

second generation particles have on average lower momenta
⇒ momentum dependence of transparency ratio



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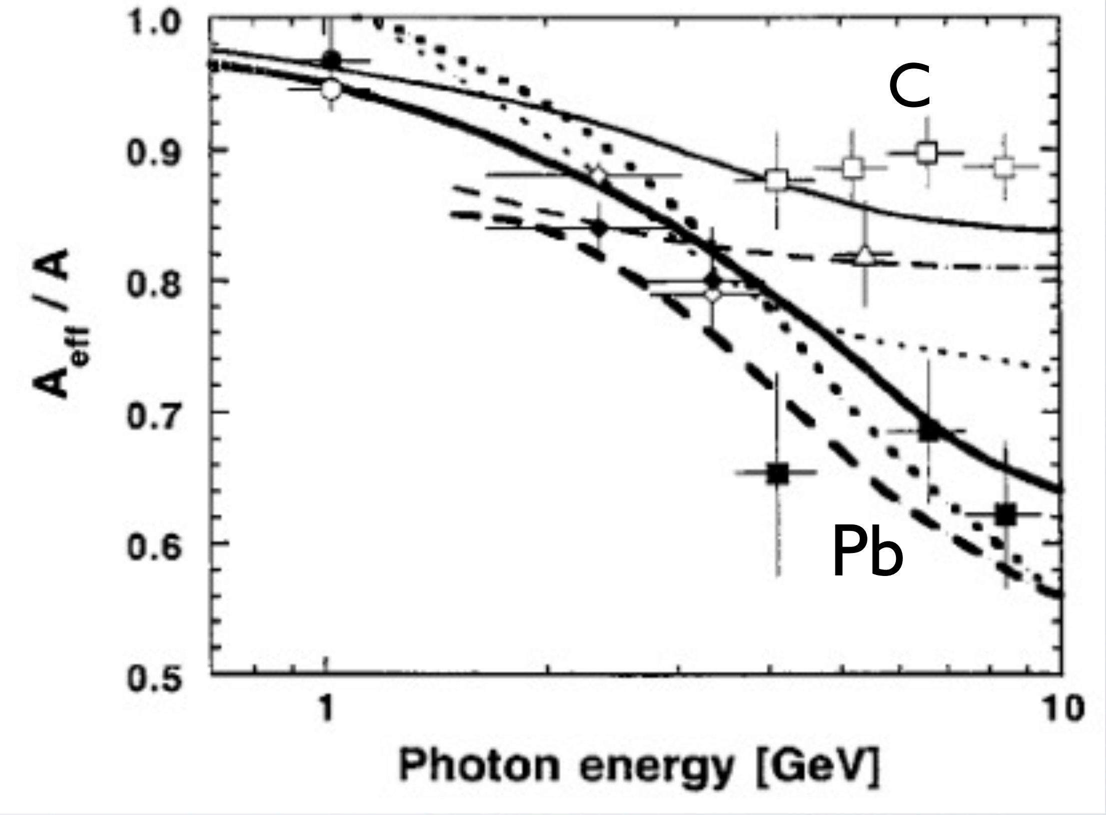

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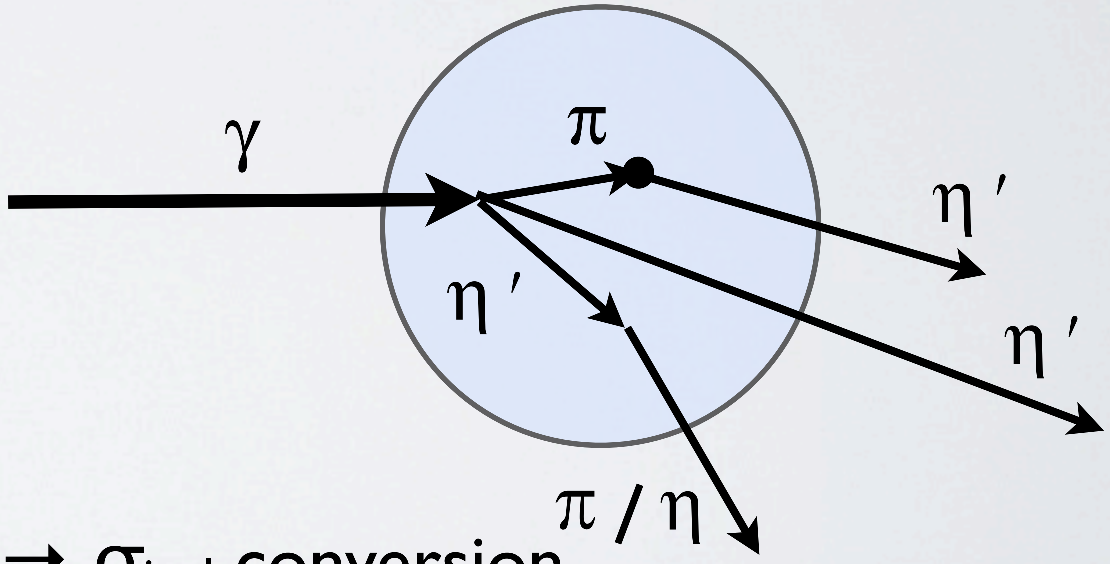

3.) two-body absorption processes:

absorption processs involving 2 nucleons distort $\Gamma \rightarrow \sigma_{inel}$ conversion

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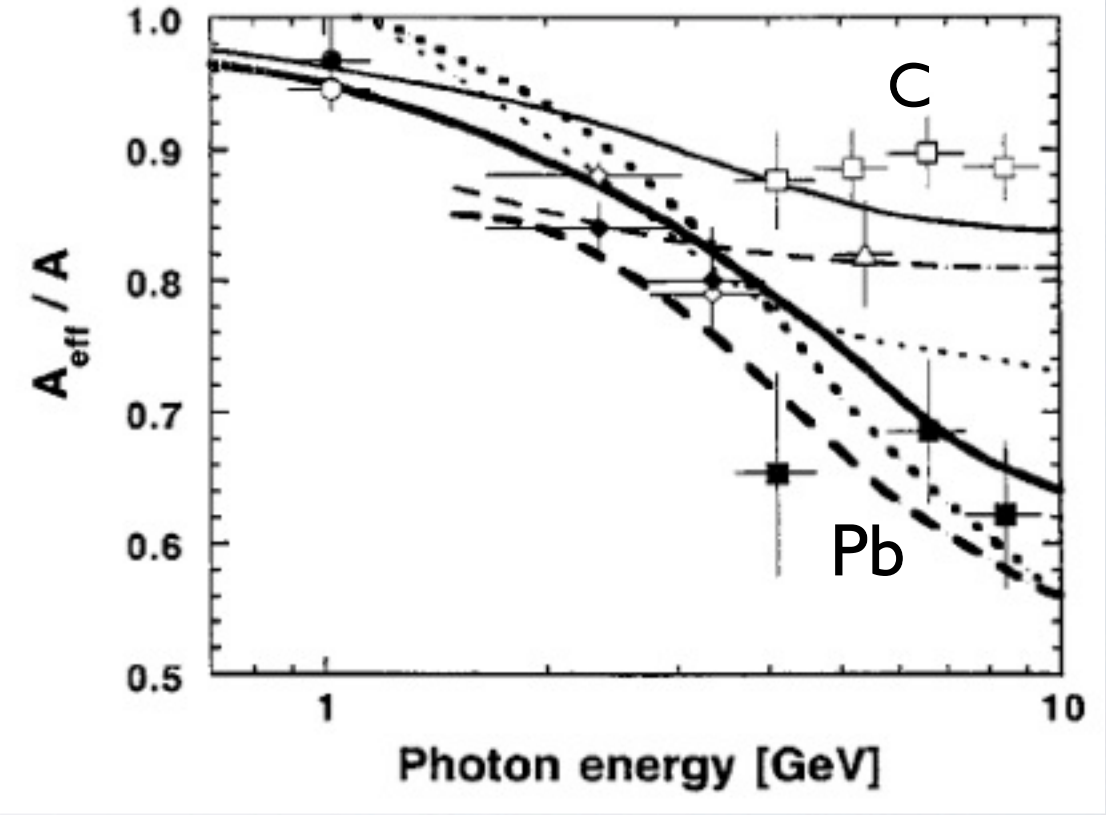

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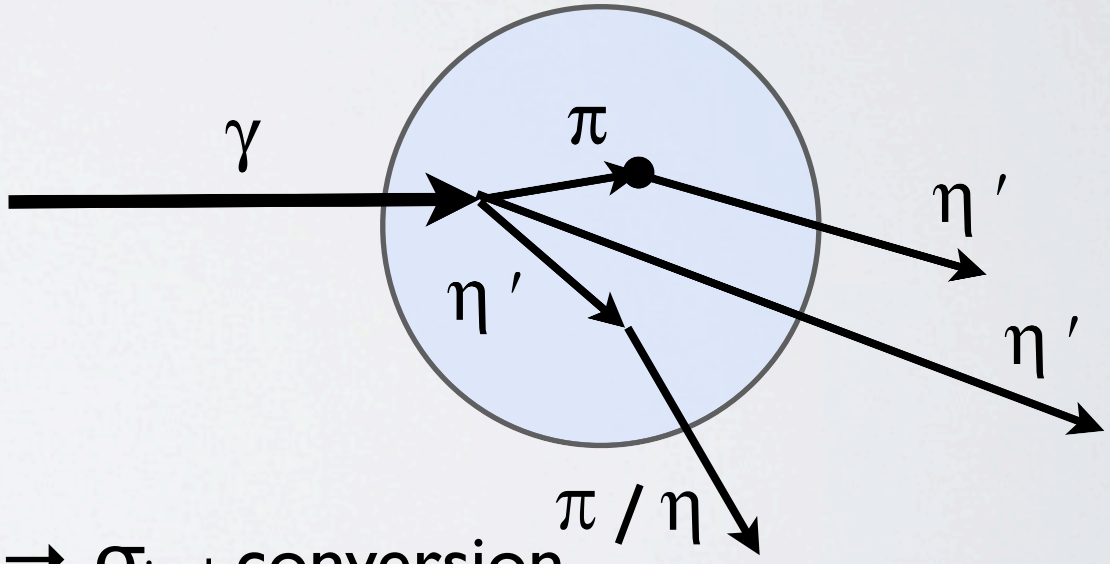

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distortions can be reduced by taking light nucleus like C as reference:

$$T_A^C = \frac{11 \cdot \sigma_{\gamma A \rightarrow \omega, \eta' X}}{A_{eff} \cdot \sigma_{\gamma C \rightarrow \omega, \eta' X}}$$

photoproduction of ω and η' mesons off C, Ca, Nb, Pb

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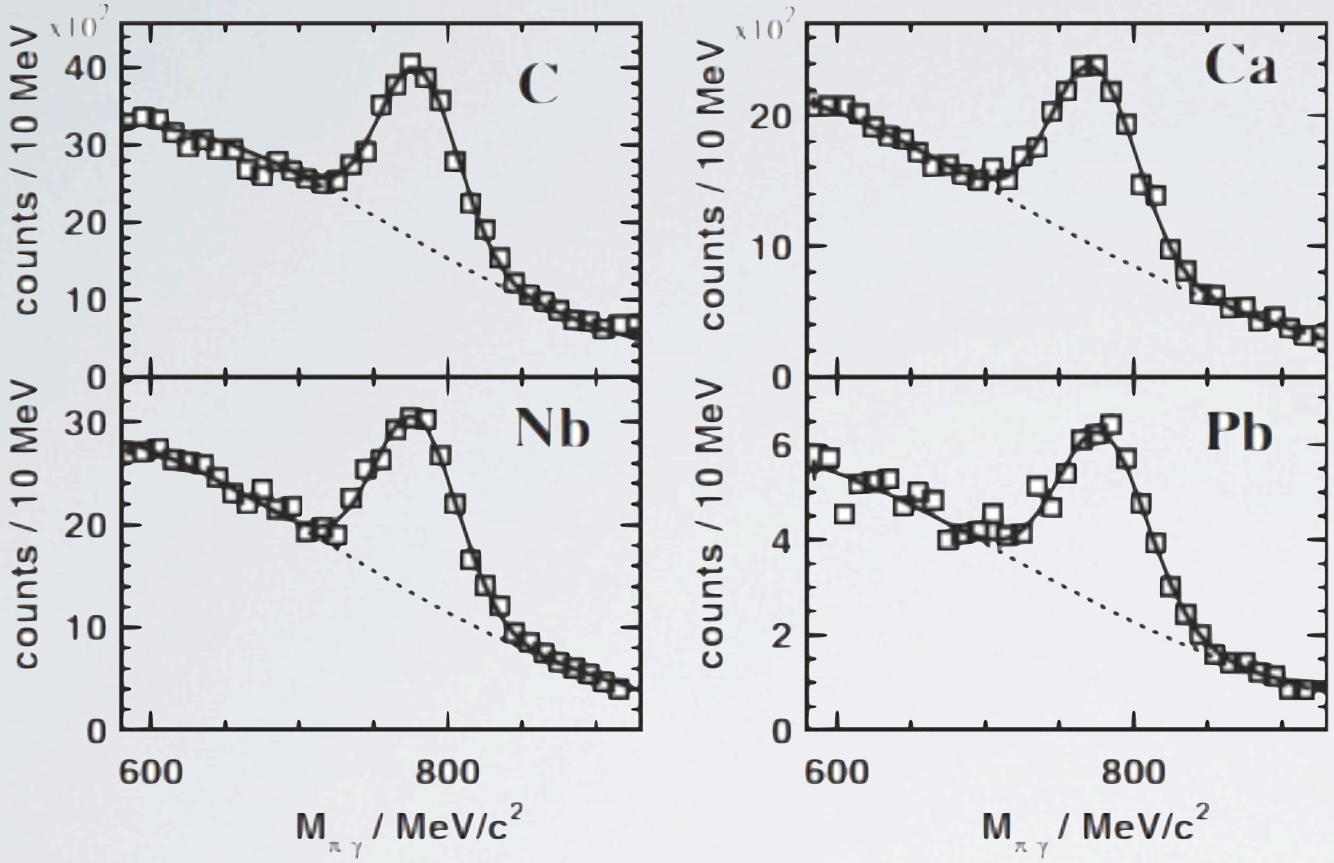

M. Kotulla et al,
PRL 100 (2008) 192302

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

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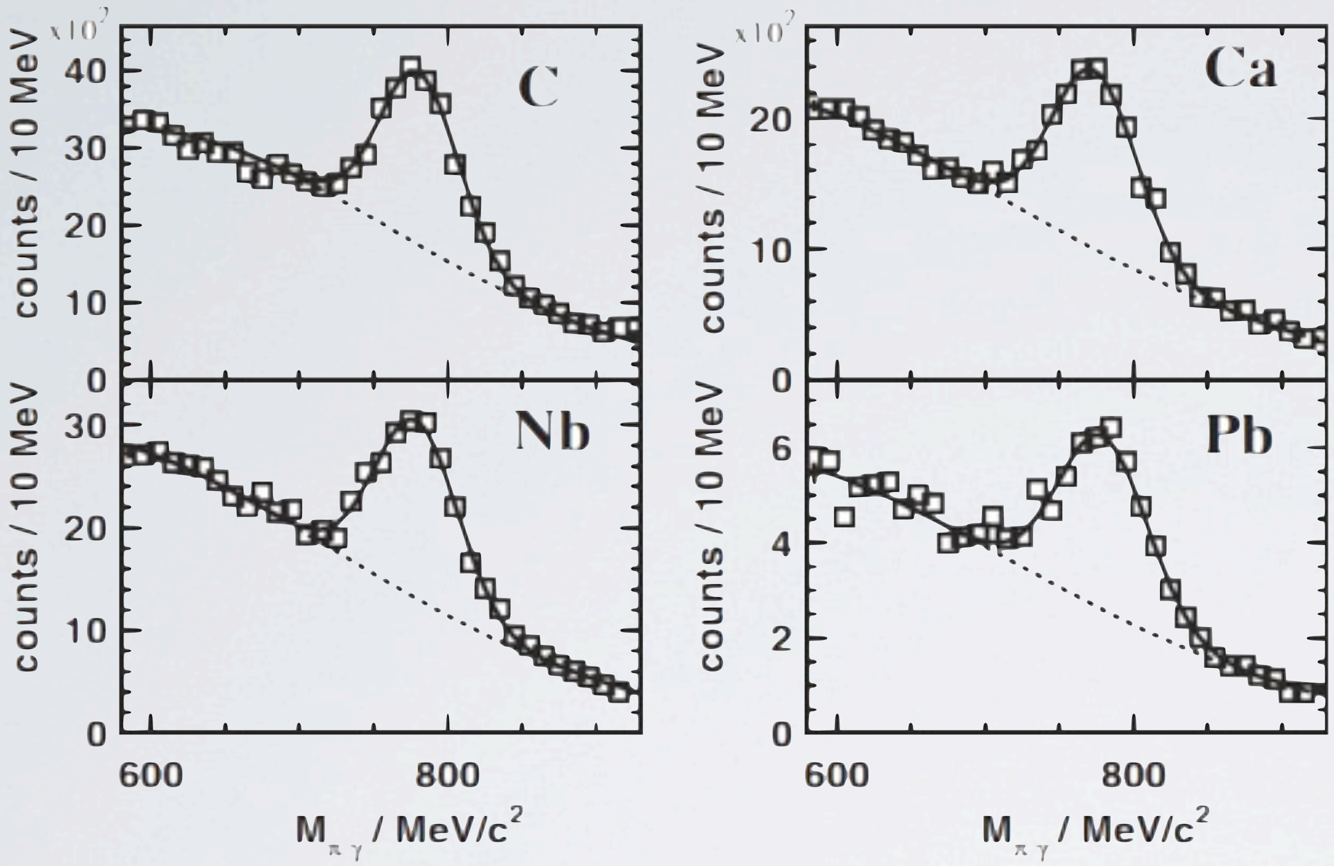

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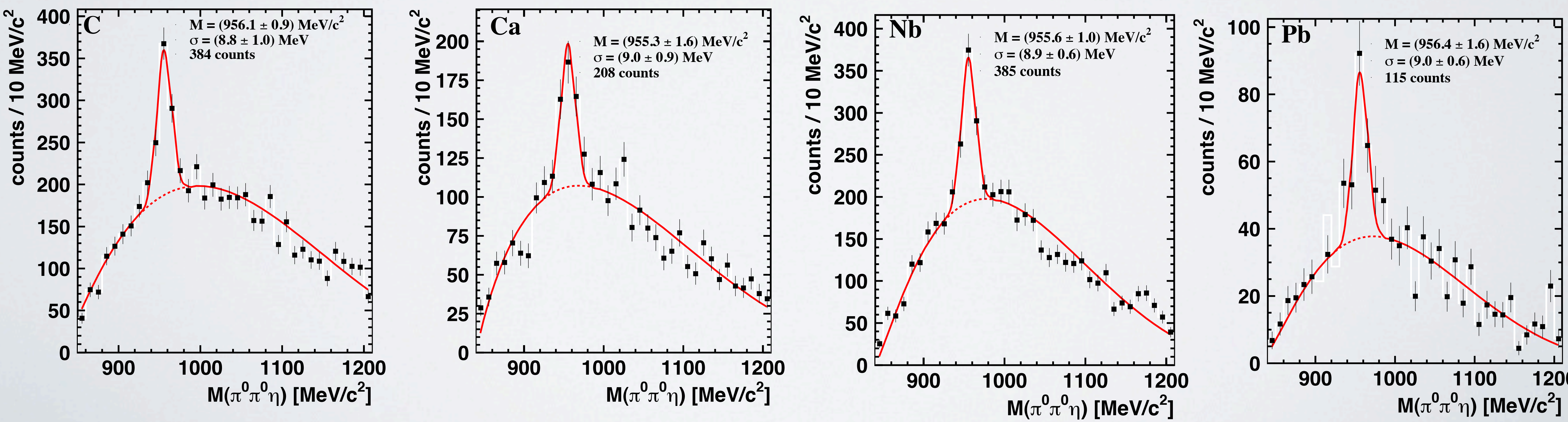
$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$

M. Nanova session C4

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

$\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$



extraction of in-medium width and inelastic cross section from T_A

transparency ratio normalized to C: $T_A^C = \frac{11 \cdot \sigma_{\gamma A \to \omega, \eta' X}}{A_{eff} \cdot \sigma_{\gamma C \to \omega, \eta' X}}$

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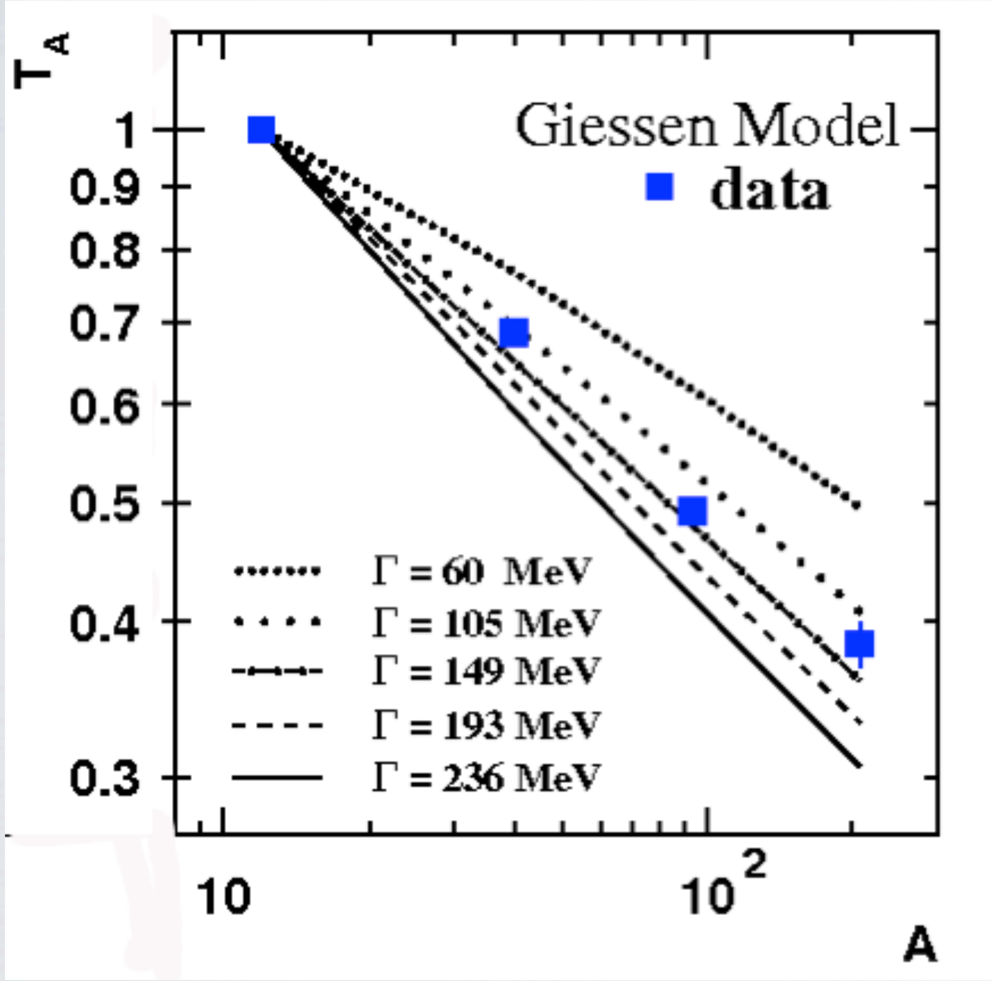
ω-meson



$\Gamma_\omega(\langle p_\omega \rangle = 1.1$ GeV/c; $\rho = \rho_0)$
$\approx$ 130-150 MeV
$\sigma_{\omega N}^{inel} \approx 60$ mb

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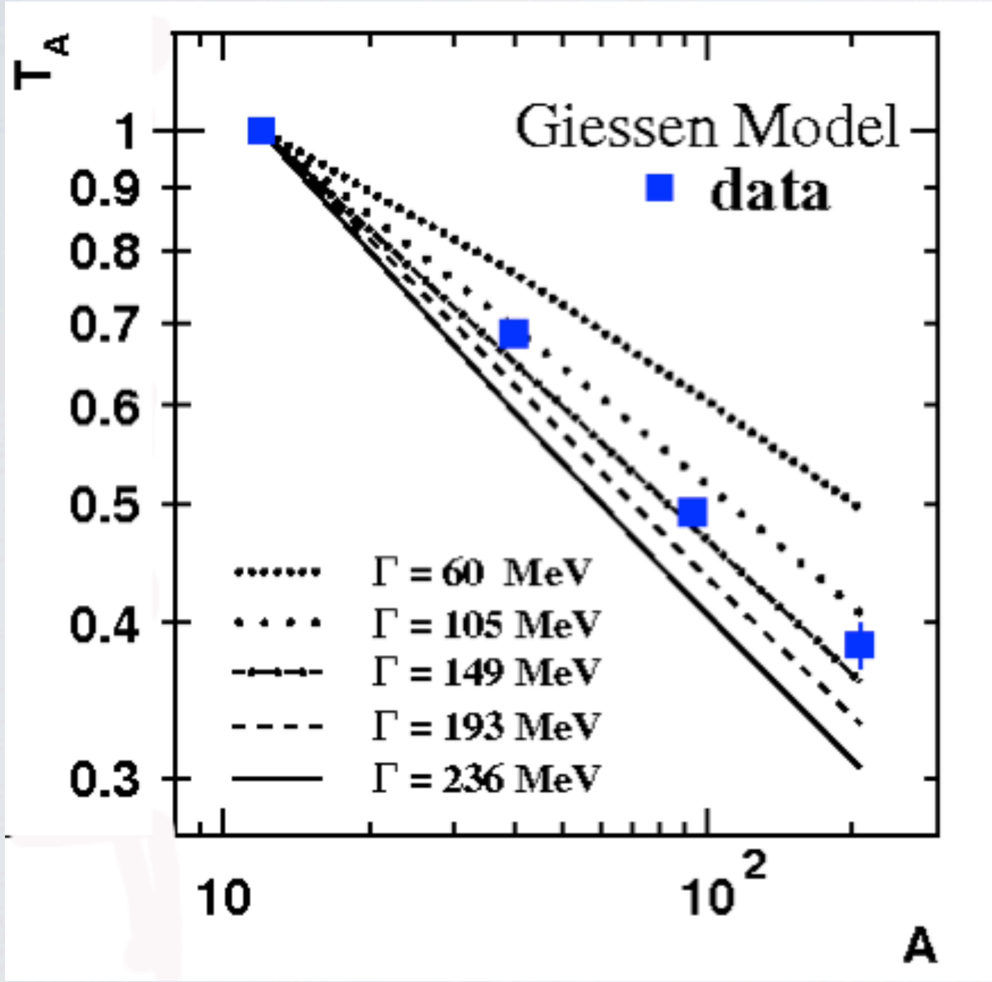

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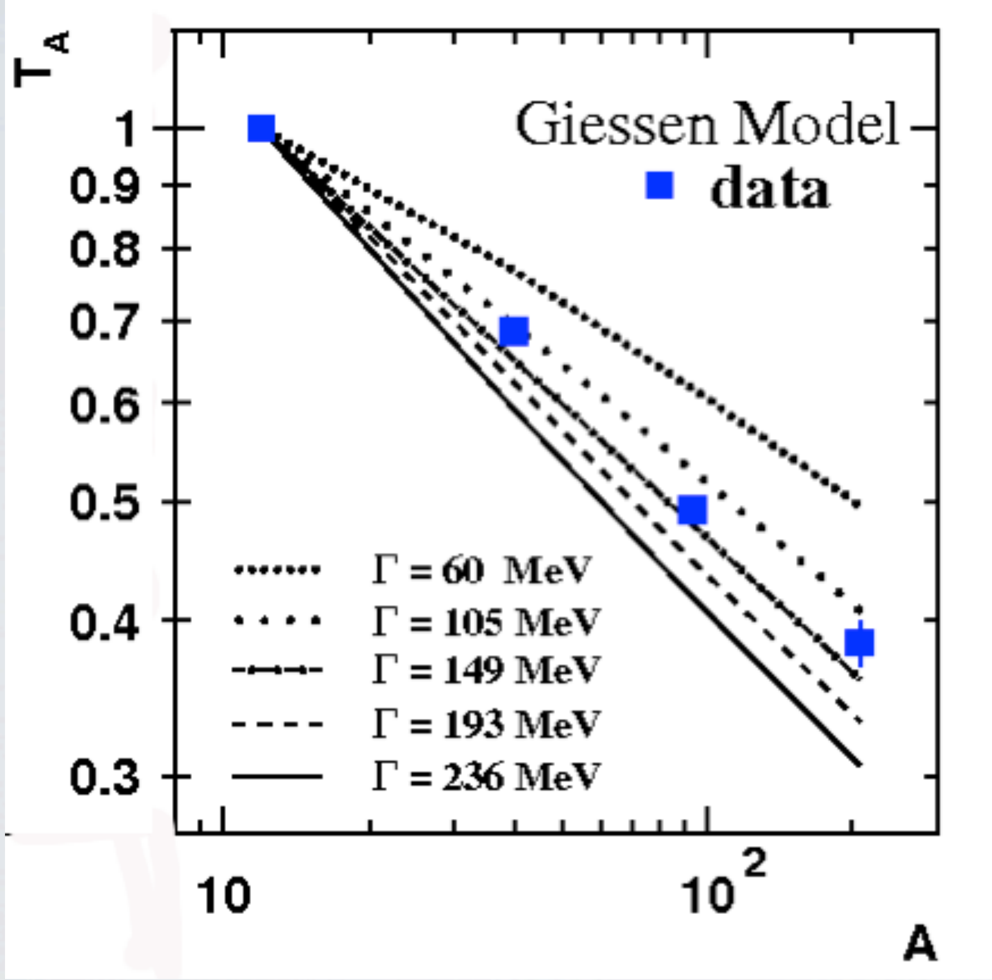

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PLB 710 (2012) 600

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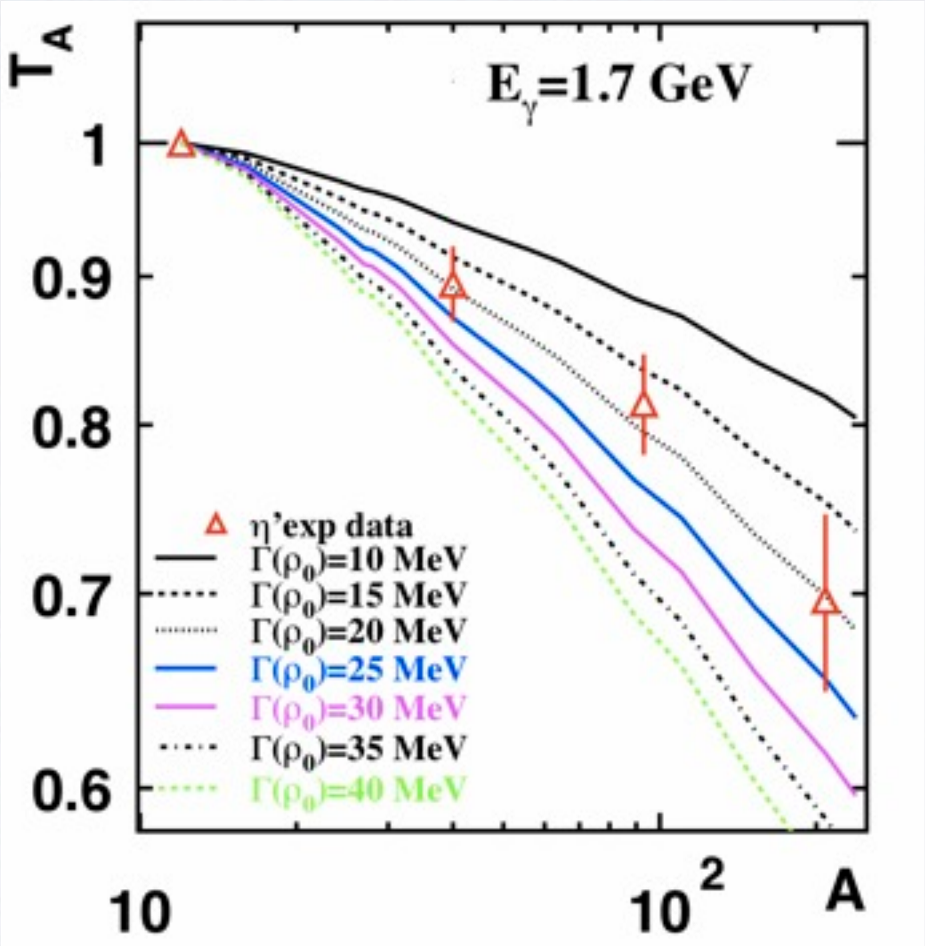

$\Gamma_{\eta'}(<p_{\eta'}> = 1.1$ GeV/c; $\rho=\rho_0)$
$\approx$ 15-25 MeV
$\sigma_{\eta' N}^{inel} \approx 3$-10 mb

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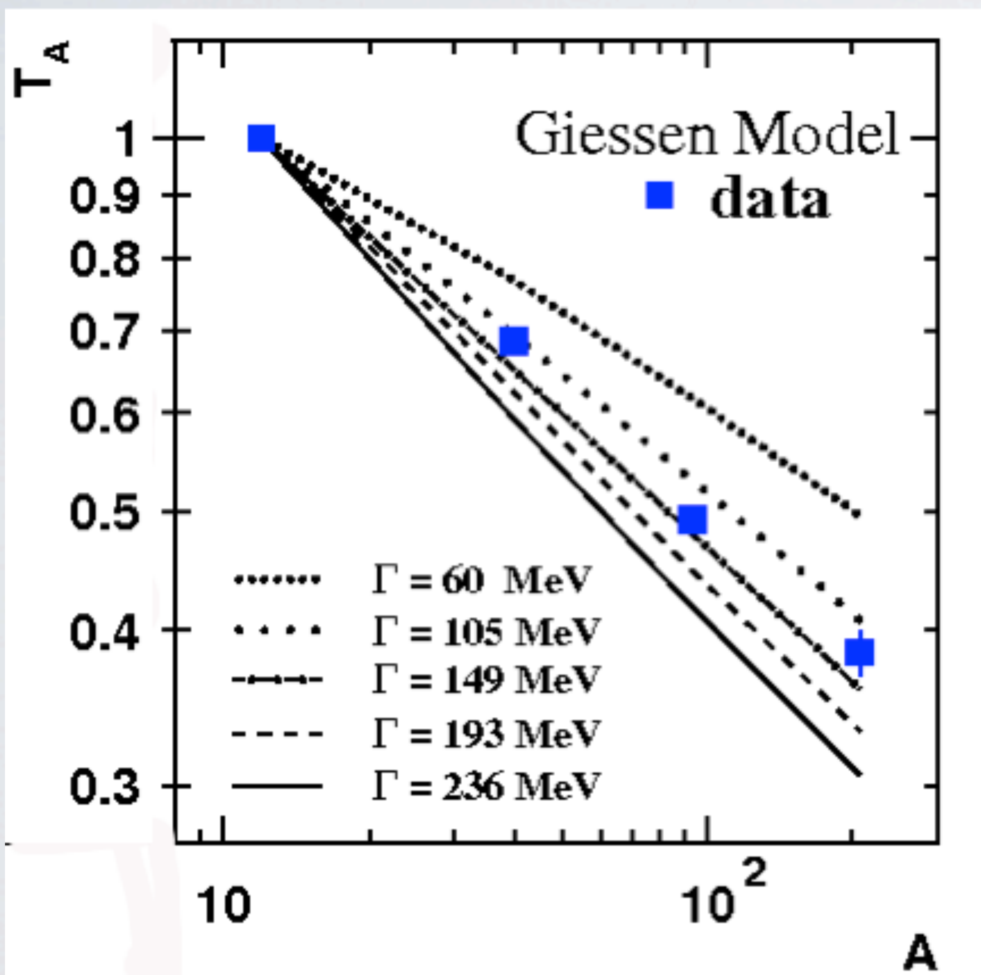

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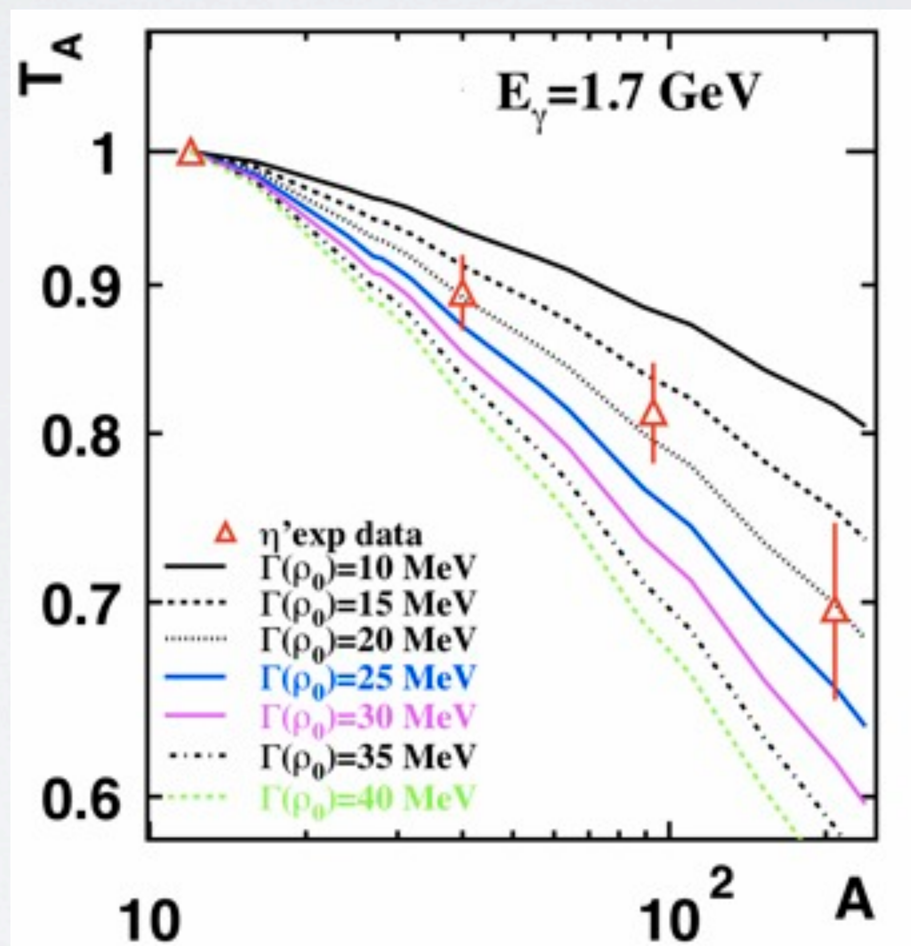
η' meson



$\Gamma_{\eta'}(<p_{\eta'}> = 1.1$ GeV/c; $\rho=\rho_0)$
$\approx$ 15-25 MeV
$\sigma_{\eta' N}^{inel} \approx 3$-10 mb

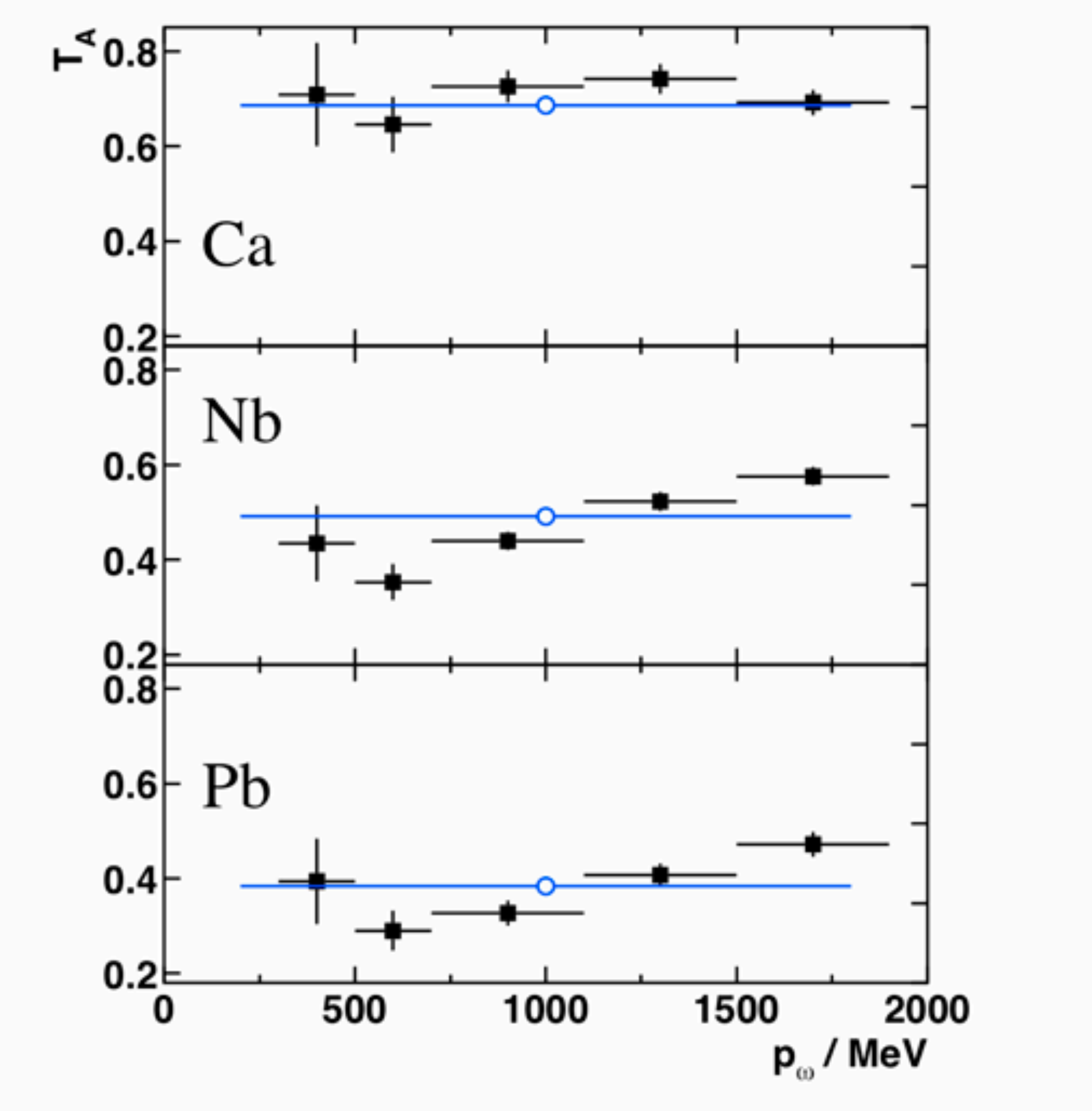
⇒ η' interaction with nuclear matter much weaker than for ω meson

momentum dependence of transparency ratio

momentum dependence of transparency ratio

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

ω meson



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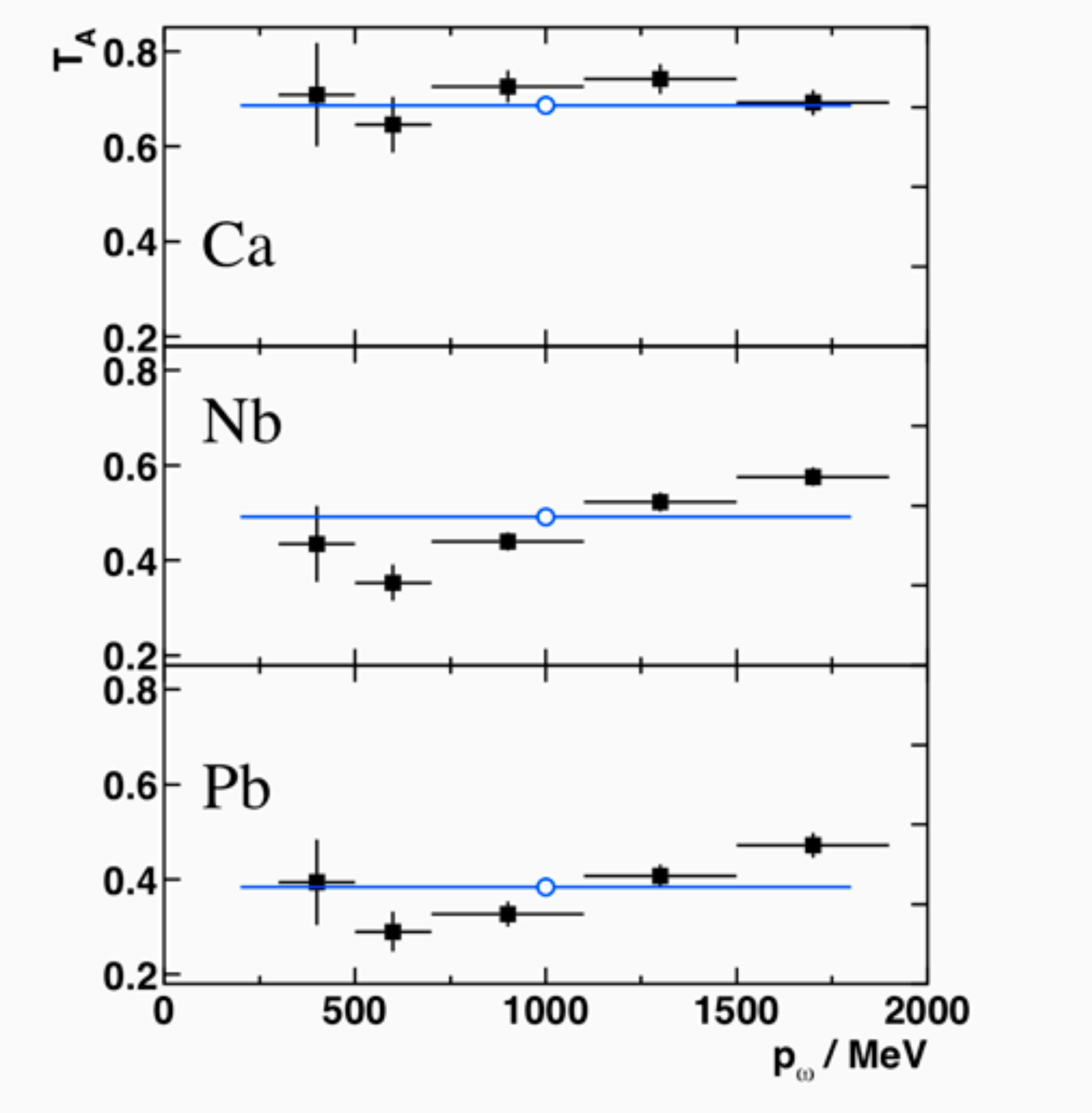
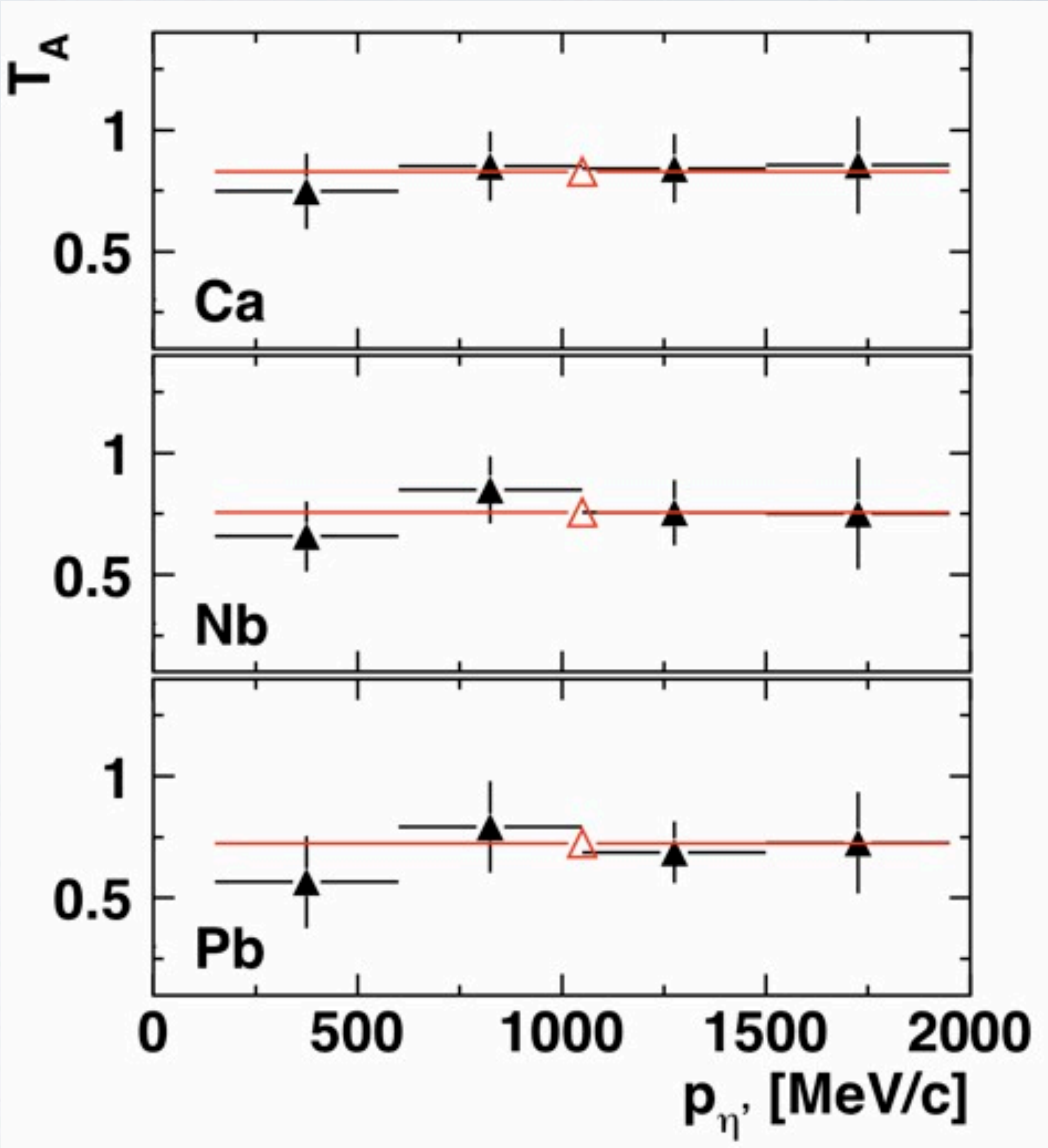
M. Kotulla et al.,
PRL 100 (2008) 192302

ω meson



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

η' meson

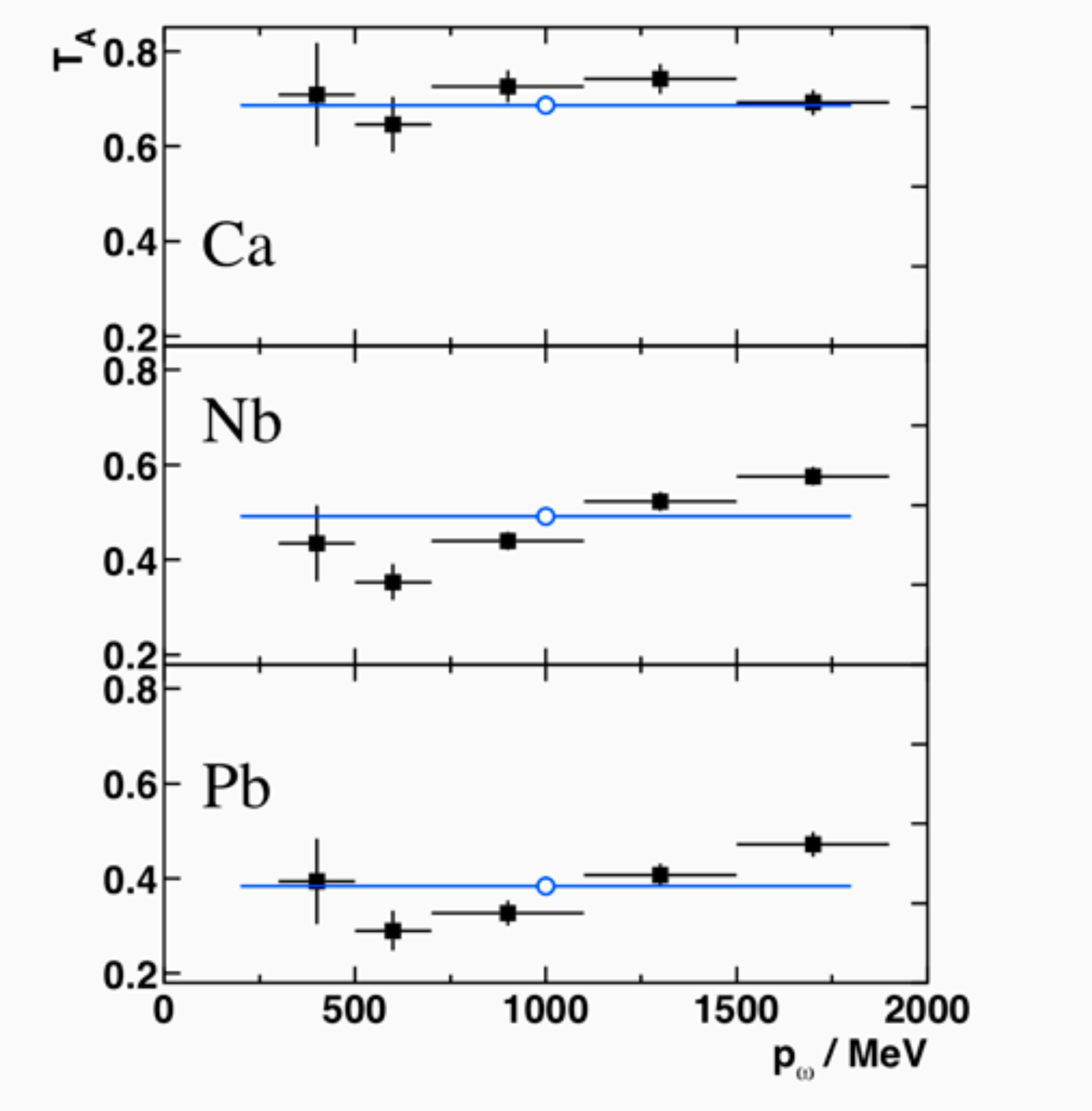


momentum dependence of transparency ratio

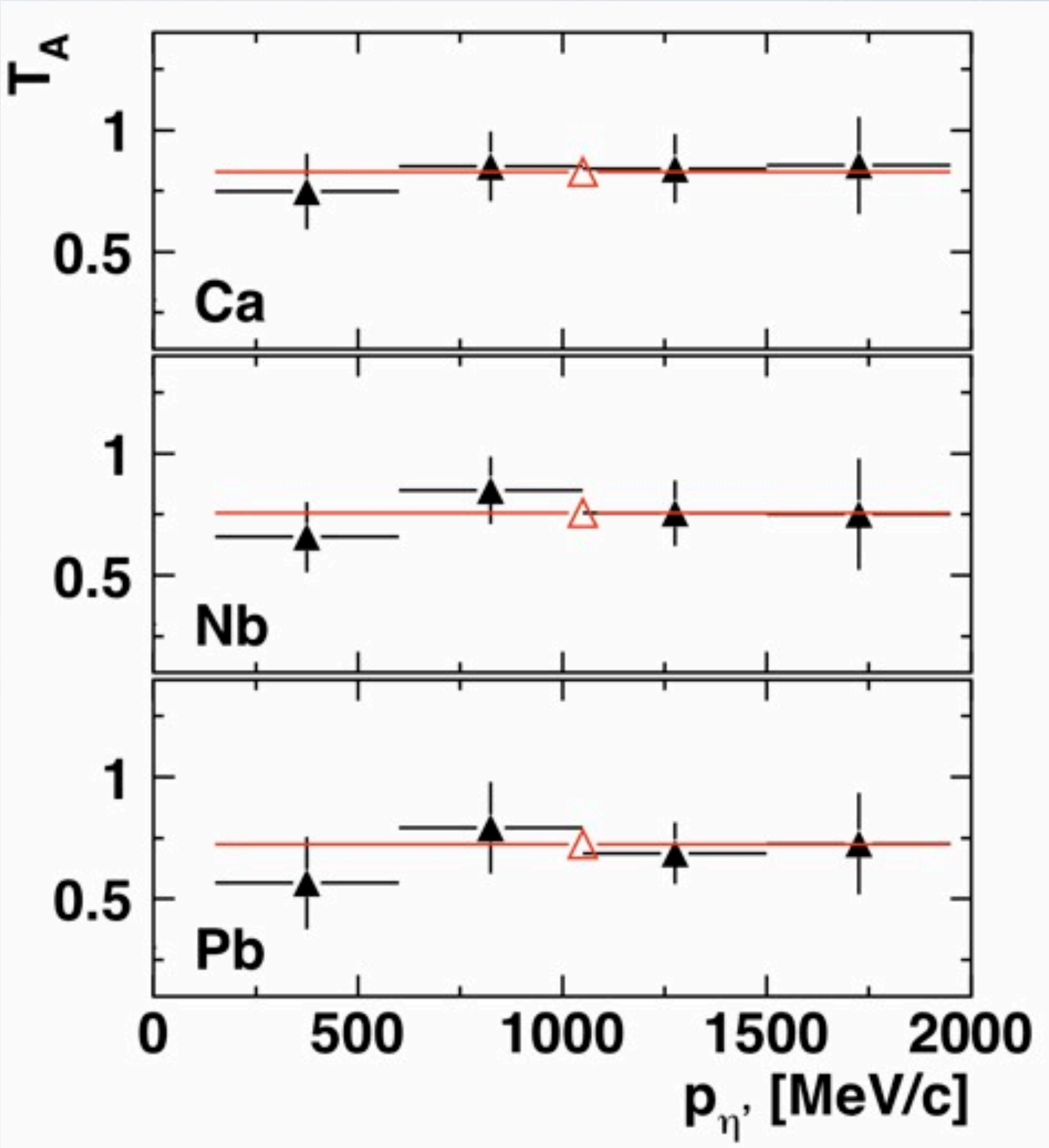
M. Kotulla et al.,
PRL 100 (2008) 192302

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

ω meson



η' meson



no strong variation of transparency ratio with meson momentum;
⇒ no evidence for two-step processes

momentum dependence of in-medium width Γ and σ_{inel}

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

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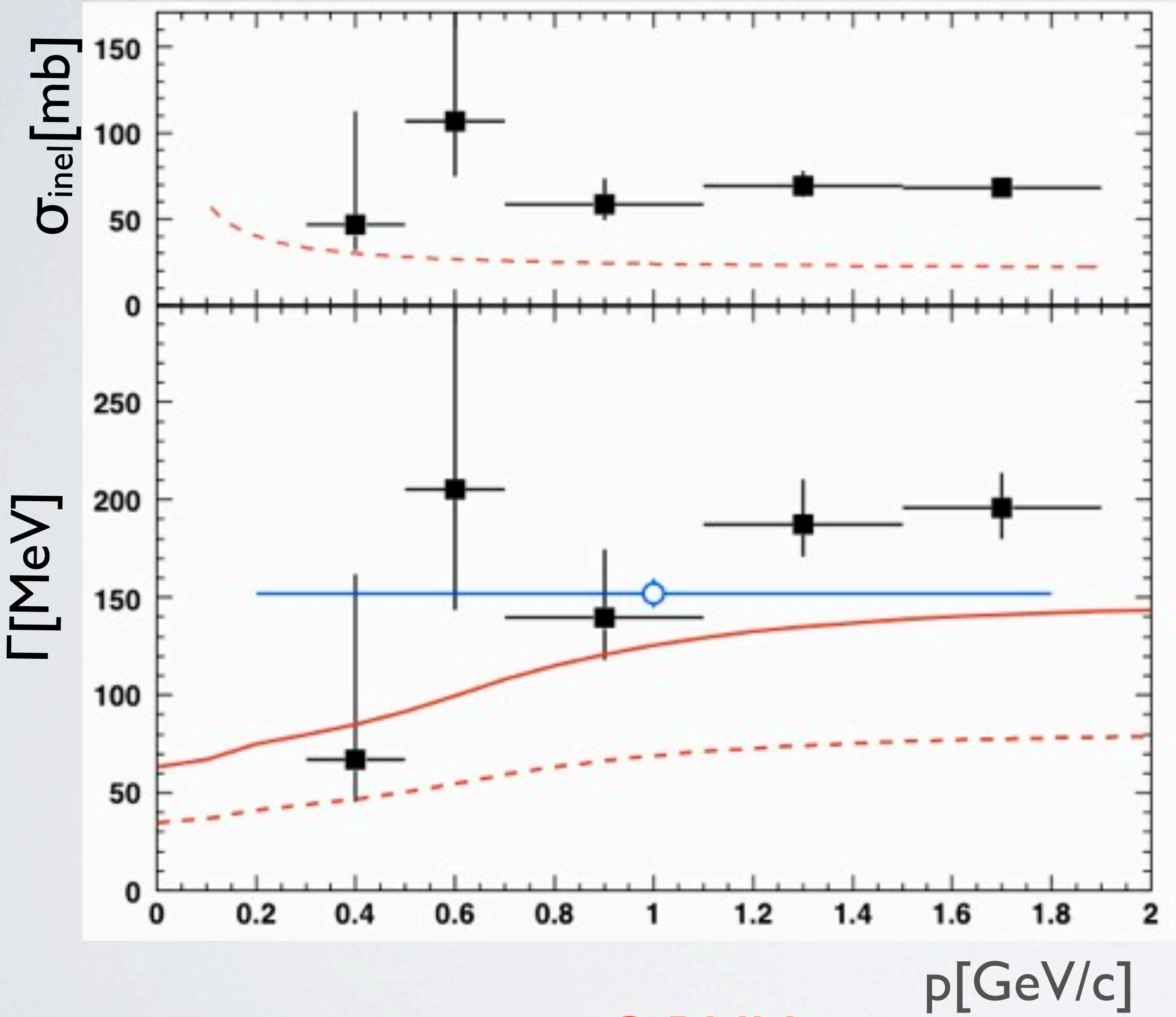

curves: GiBUU

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

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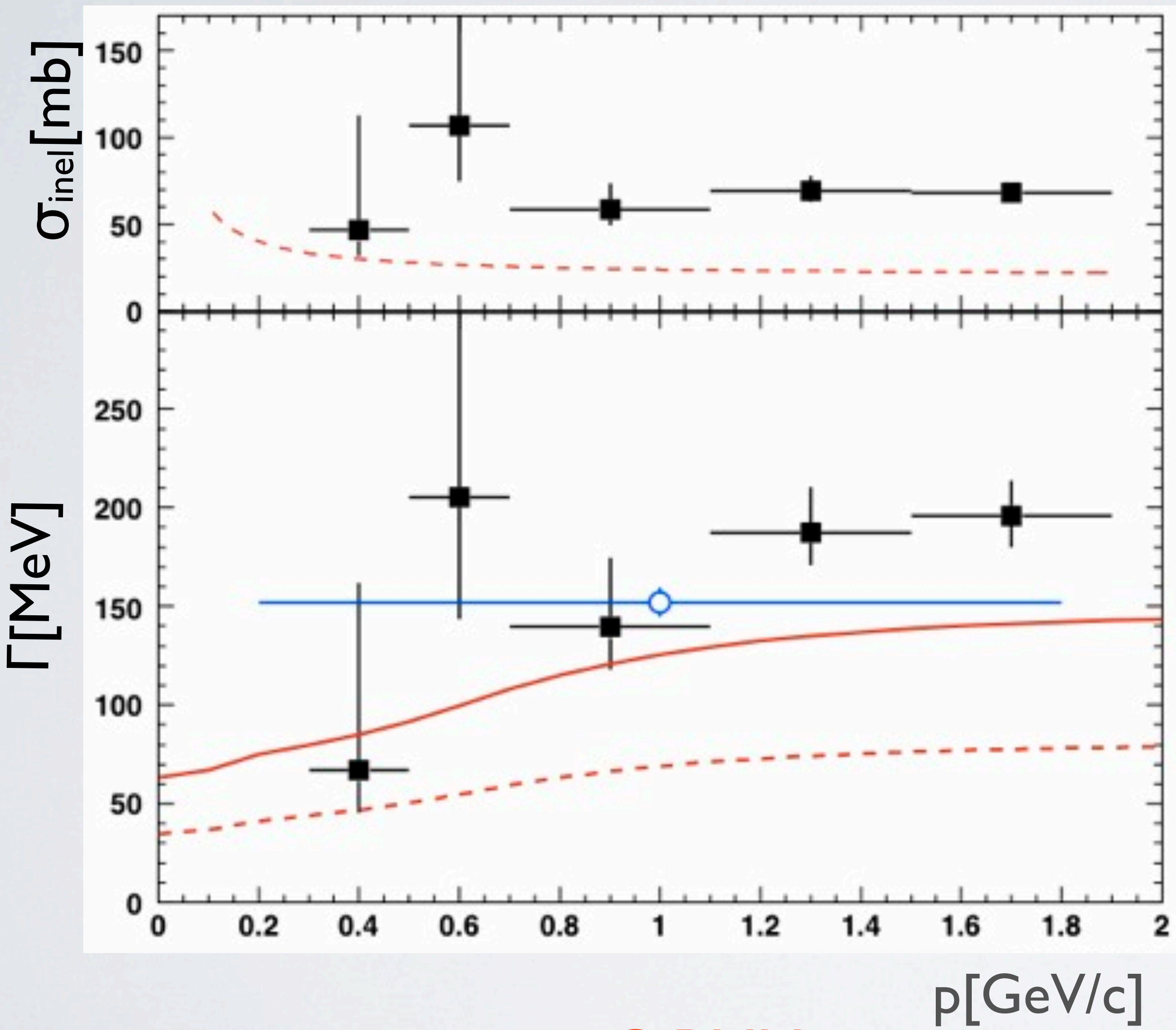

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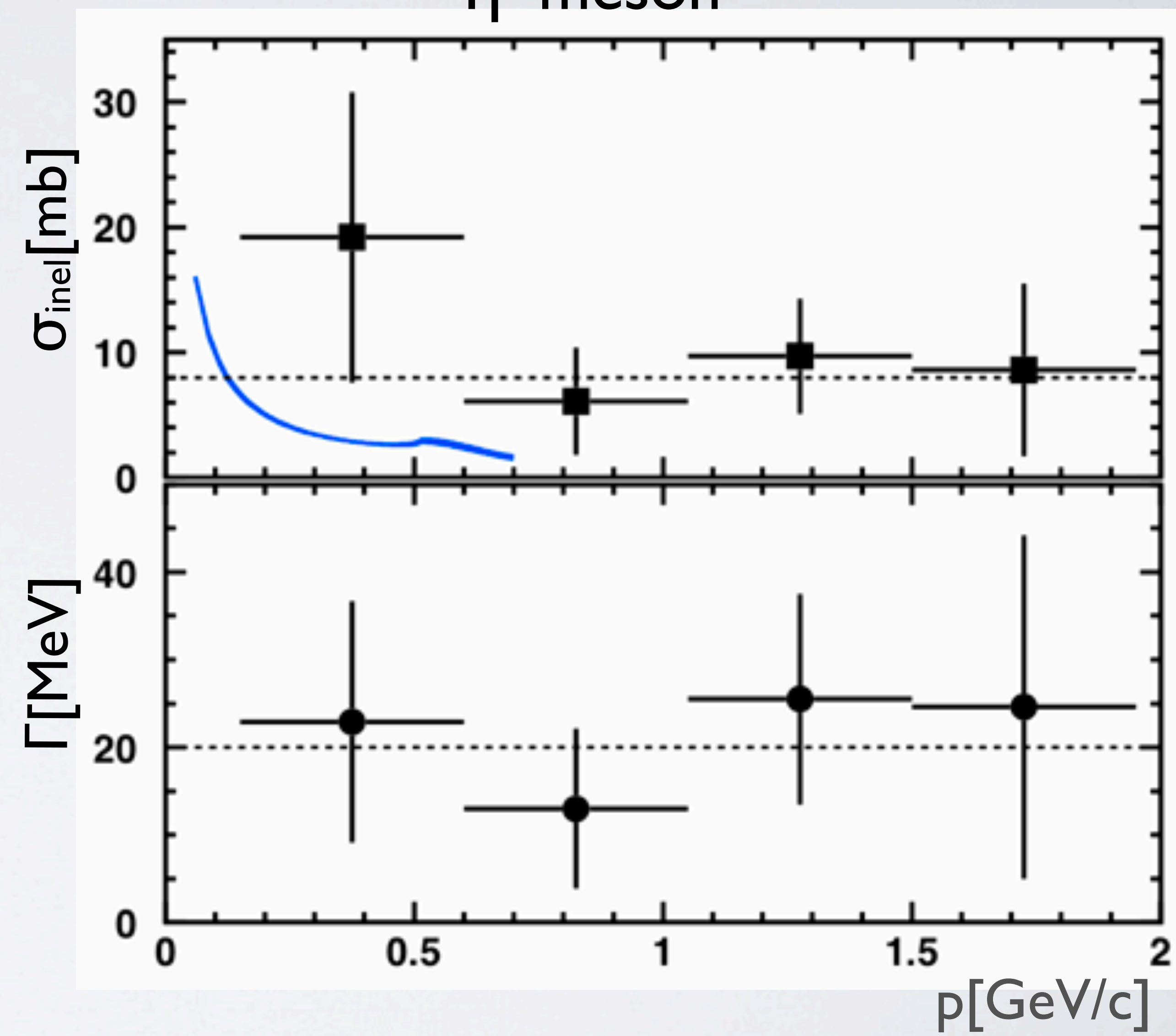
M. Nanova et al.,
PLB 710 (2012) 600

η' meson

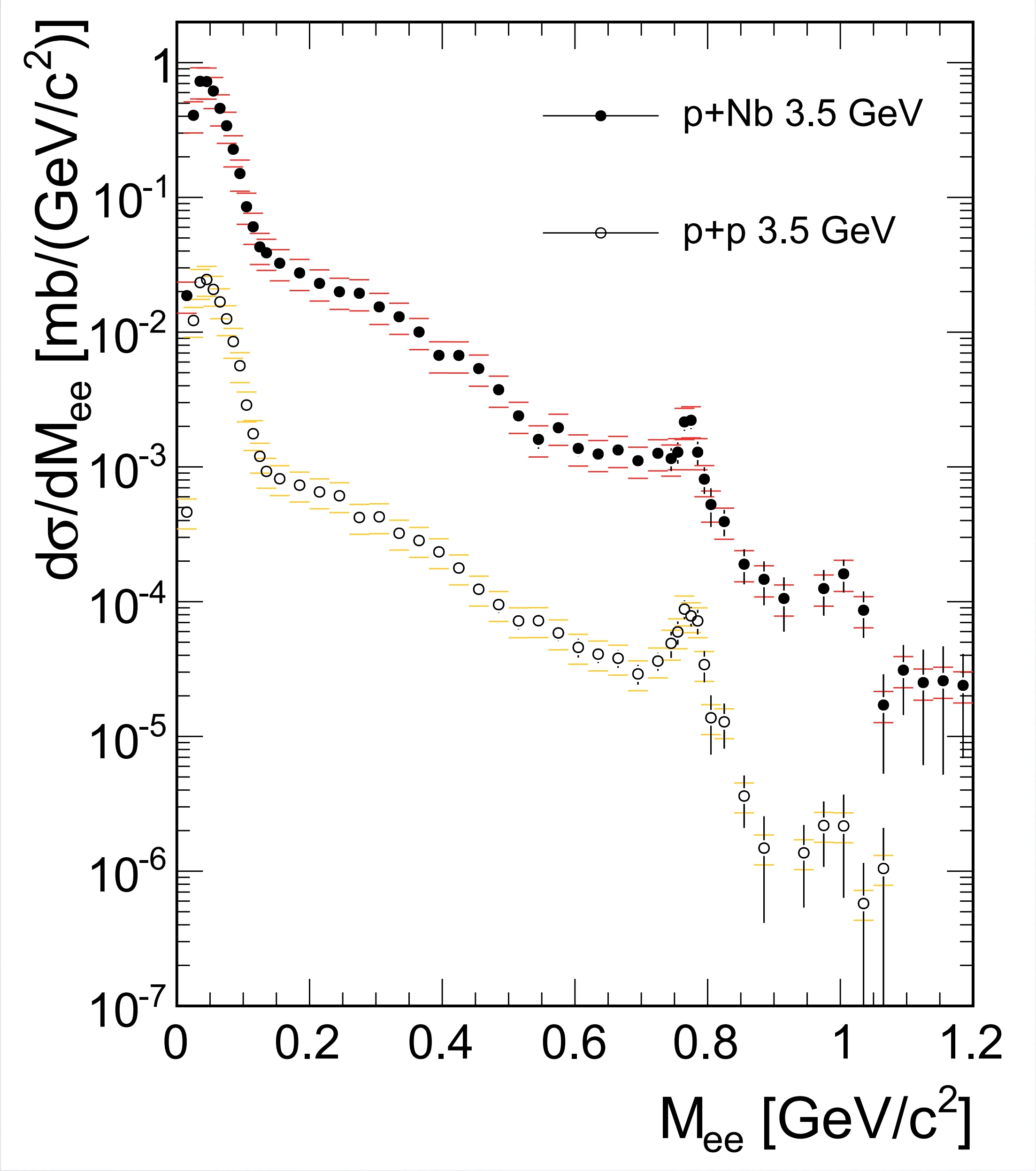


curve: E. Oset and A. Ramos,
PLB 704 (2011) 334

momentum dependence in transparency ratio: dilepton production

HADES M. Lorenz: A2; L. Fabietti arXiv:1205.1918

$\pi^0, \eta \rightarrow \gamma e^+e^-$; $\omega \rightarrow \pi^0 e^+e^-$;
$\Delta, N^* \rightarrow N e^+e^-$; $\rho, \omega \rightarrow e^+e^-$



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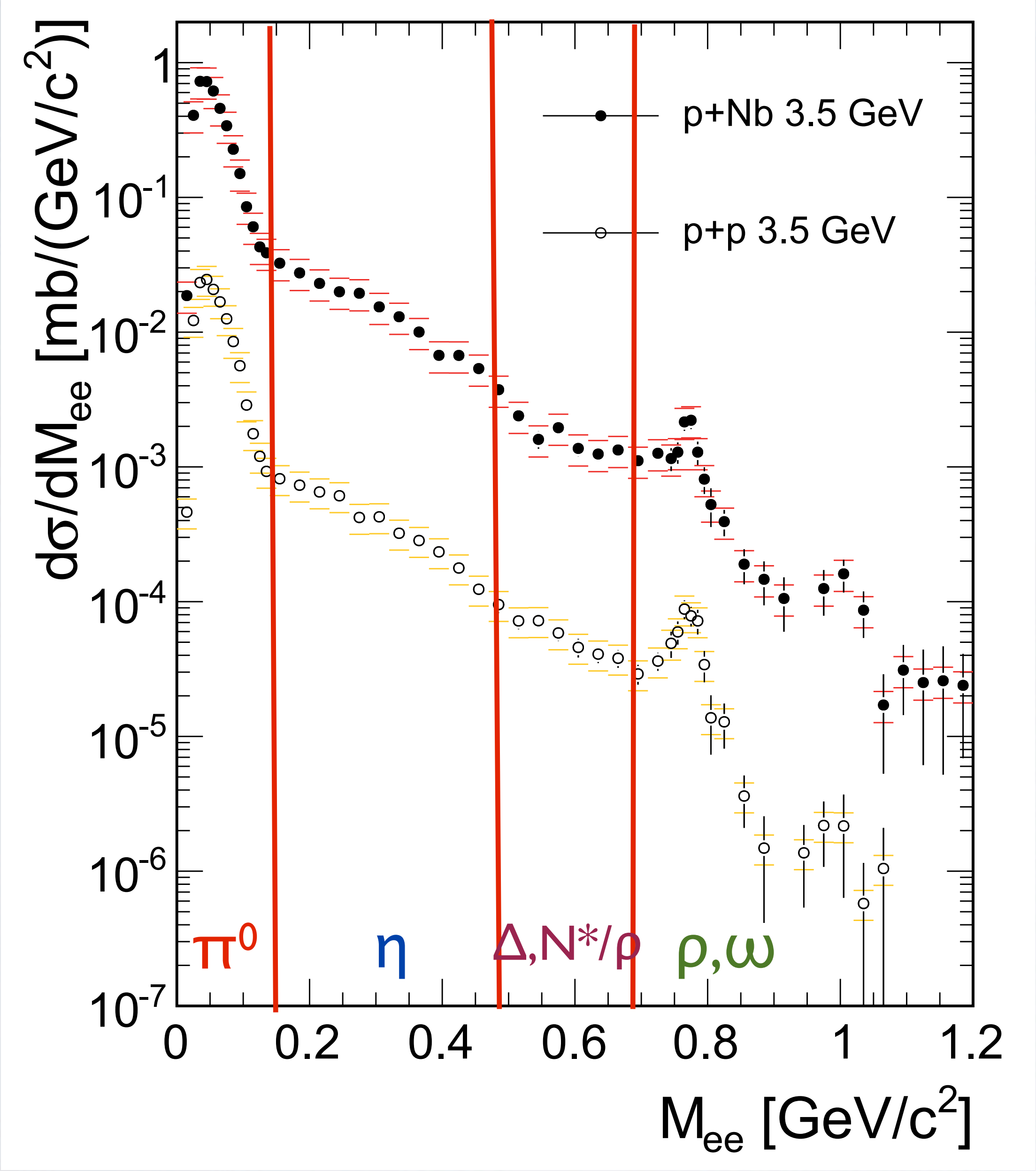

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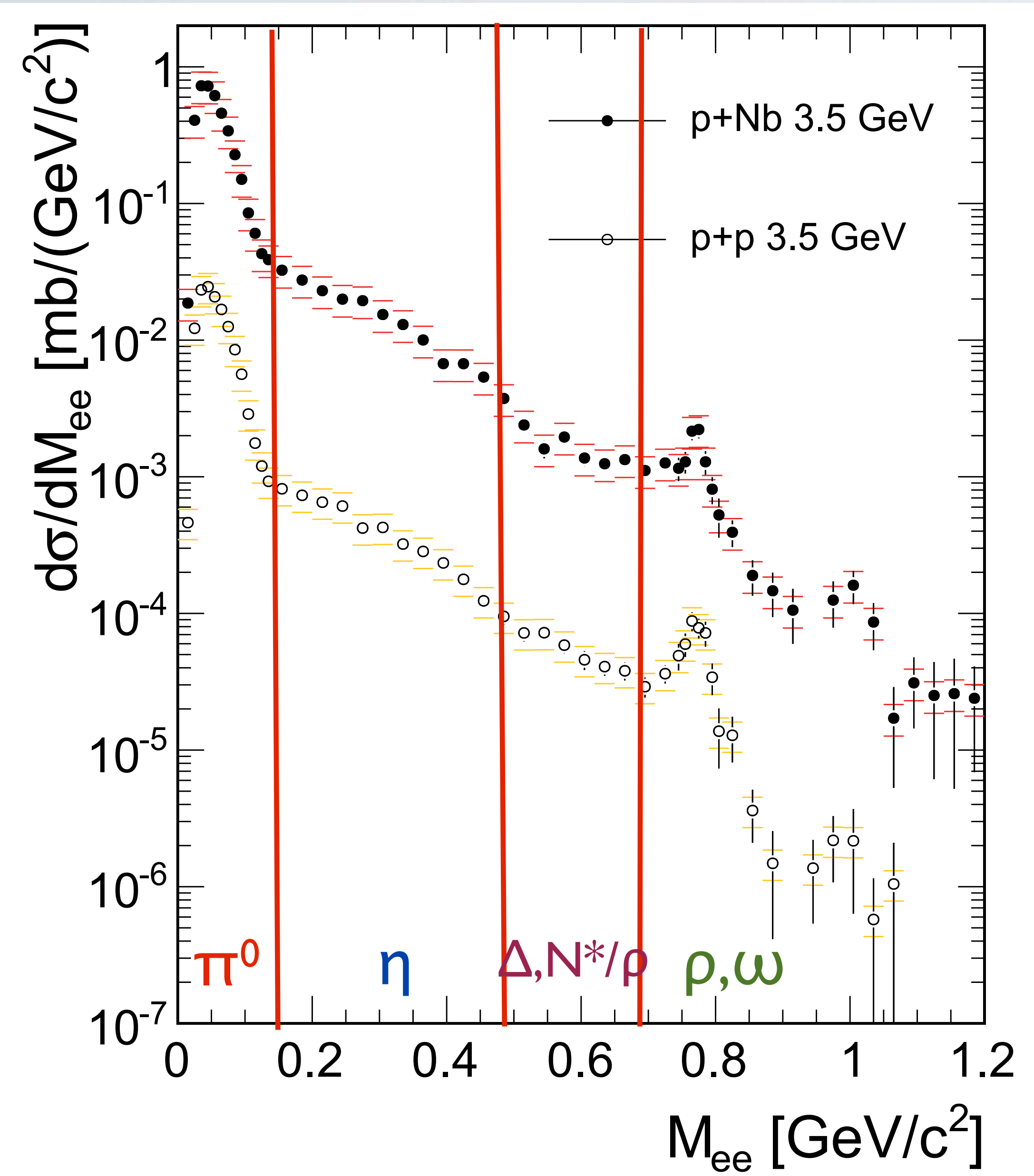
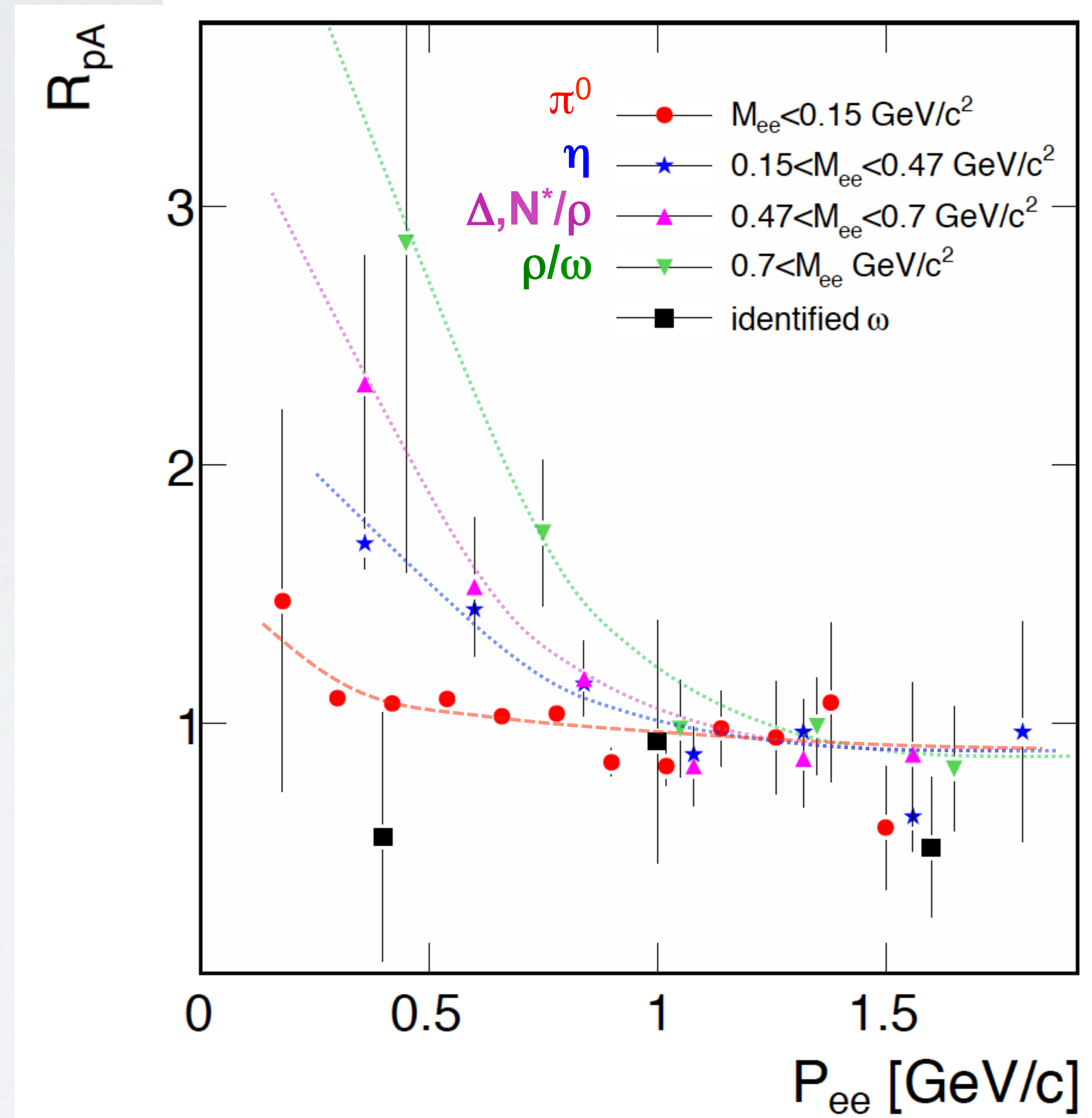
$$R_{pA} = \frac{d\sigma/dp^{pNb}}{d\sigma/dp^{pp}} \cdot \frac{A^{pp}_{part}}{A^{pNb}_{part}} \cdot \frac{\sigma^{pp}_{reaction}}{\sigma^{pNb}_{reaction}}$$





momentum dependence of dilepton spectra; ⇒ two-step production processes

the higher the e+e- invariant mass the stronger the momentum dependence;

no momentum dependence for transparency ratio of identified ω

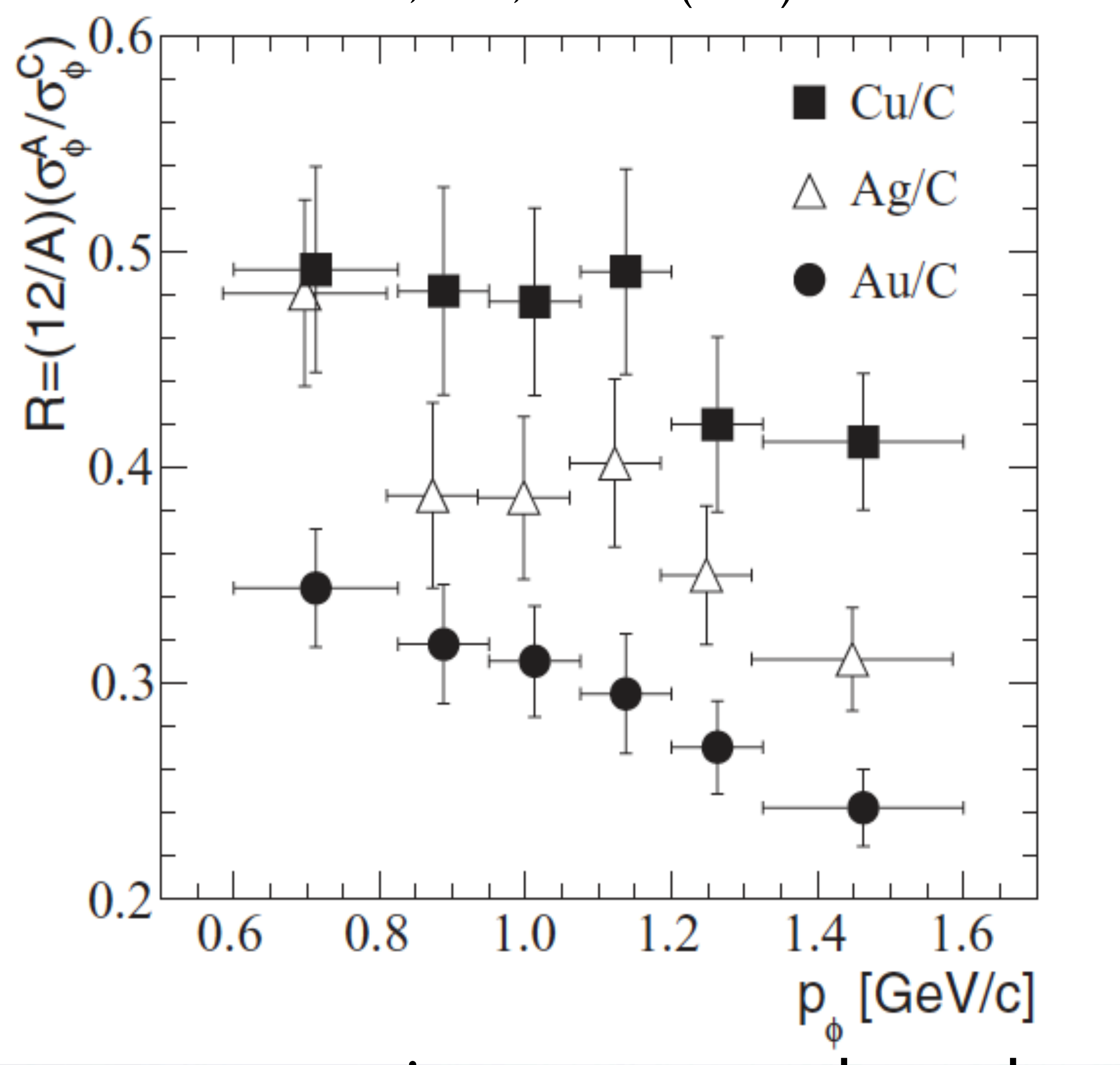
momentum dependence of Φ meson transparency ratio

ANKE @COSY: p (2.83 GeV)→ C, Cu, Ag, Au

$\Phi \rightarrow K^+K^-$

A.Polyanskiy: session A2

A. Polyanski et al., PLB 695 (2011) 74
M. Hartmann, et al., PRC 85 (2012) 935206



transparency ratio momentum dependent:
⇒ two-step production processes important

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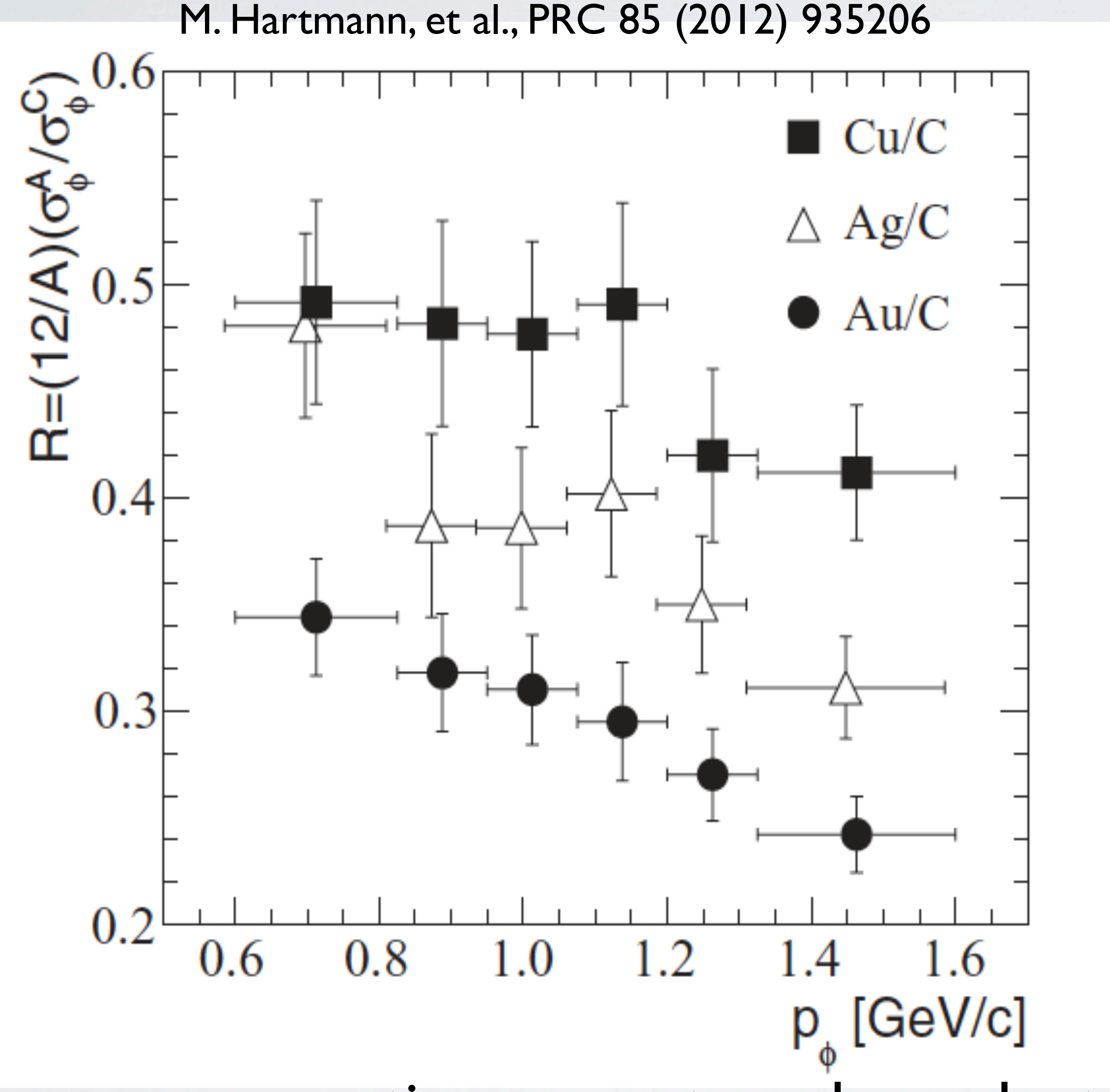

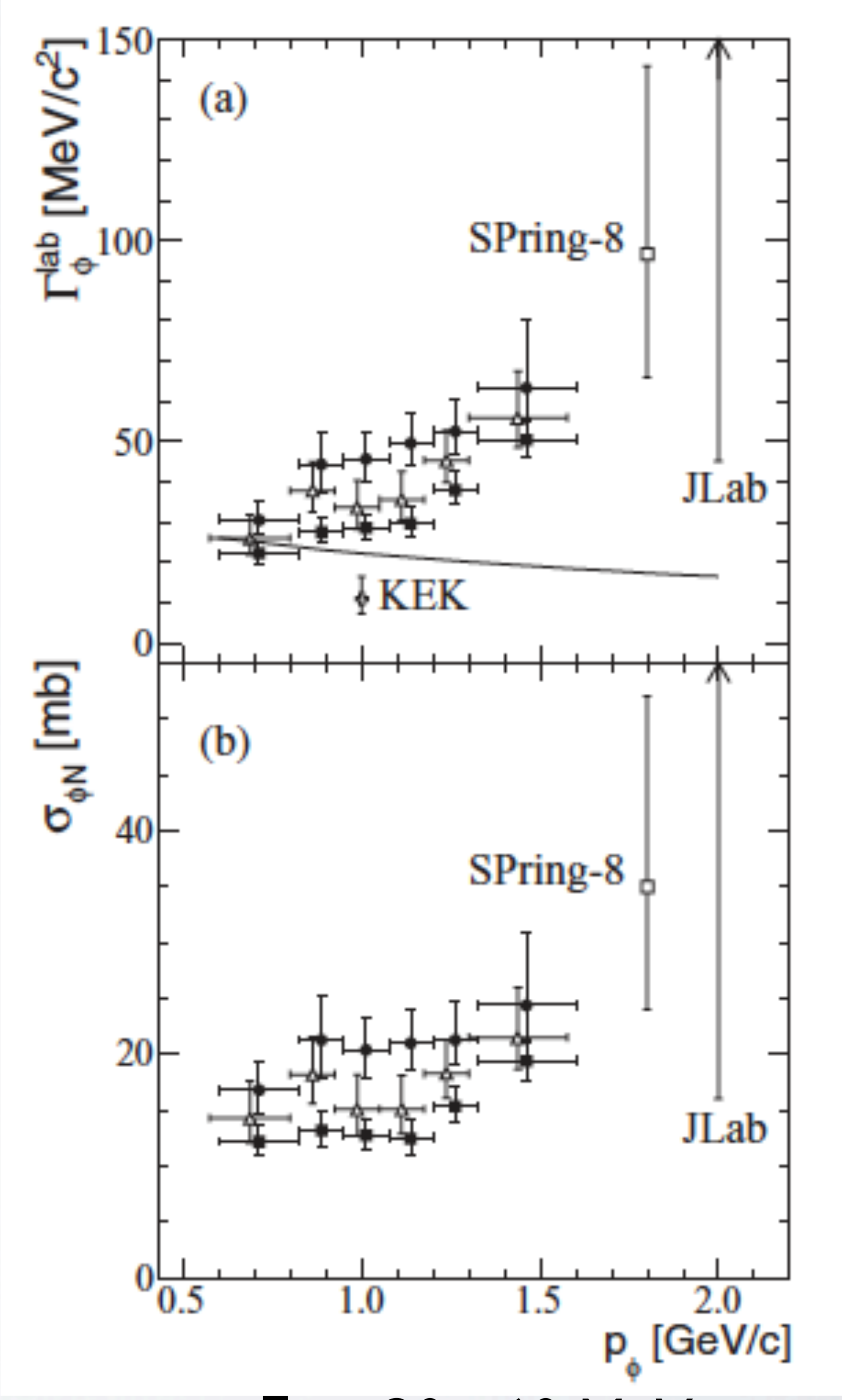

transparency ratio momentum dependent:
⇒ two-step production processes important

$\Gamma_\Phi \approx 30$ - 60 MeV
$\sigma_{\Phi N} \approx 14$-21 mb
for $p_\Phi \approx 0.6$-1.6 GeV/c

evidence for increase of Φ meson width with momentum, consistent with earlier Spring8 and JLab measurements

line shape analysis

$$M \to X_1 + X_2; \qquad m(\rho, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

sensitive to nuclear density at decay point

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1.) ensure sizable fraction of decays in the nuclear medium:
⇒ select short lived mesons or cut on recoil momentum

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2.) avoid distortion of 4-momentum vectors by final state interactions ⇒ dilepton spectroscopy: $\rho, \omega, \Phi \to e^+e^-$

disadvantage: small branching ratio $\approx 10^{-4}$ - 10^{-5}
$\omega \to \pi^0\gamma \to 3\gamma$; br=8.3% ; disadvantage: π^0-FSI

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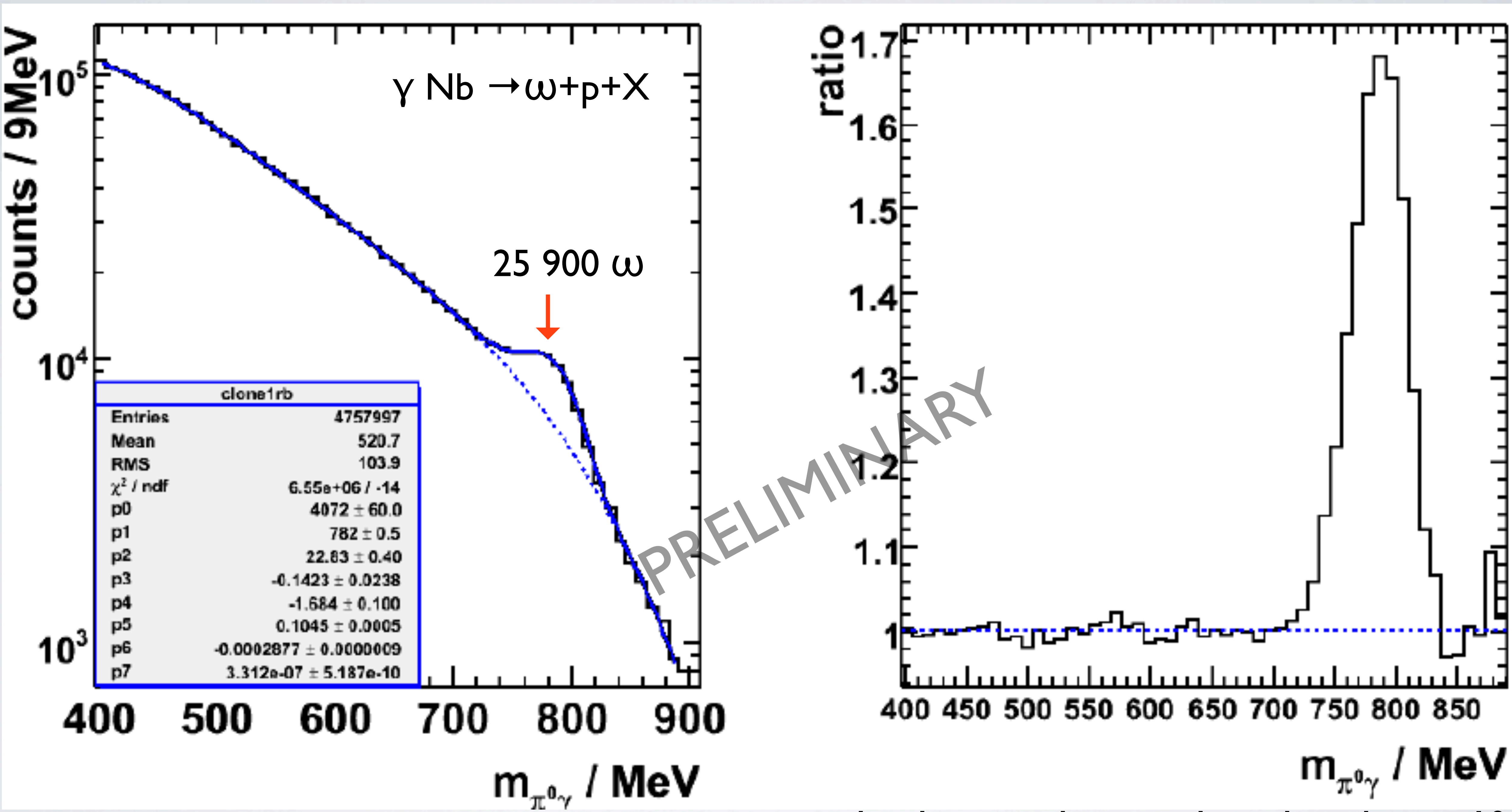
3.) measured mass distribution = convolution of spectral function with branching ratio into final state: $\frac{d\sigma}{dm} \sim A(m,p) \cdot \frac{\Gamma_{M \rightarrow X_1 + X_2}}{\Gamma_{tot}}$

$\omega \to \pi^0\gamma$ lineshape analysis

E_γ=900 -1300 MeV

main problem: background subtraction
$\pi^0\pi^0$, $\pi^0\eta \to 3\gamma(\gamma)$

M. Thiel



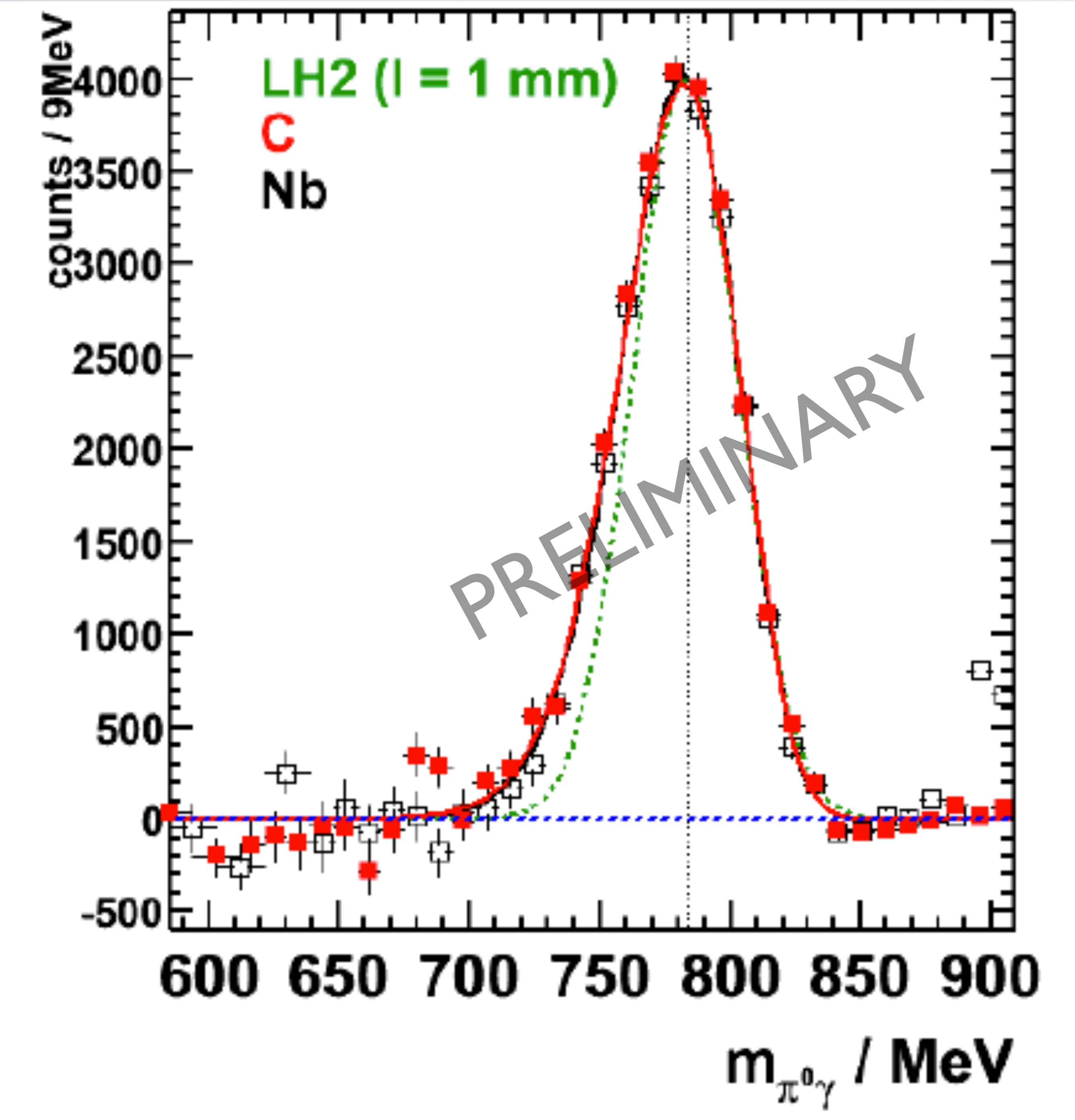
background reproduced within < 1%

systematic uncertainties due to different background subtraction techniques
M. Nanova et al. PRC 82 (2010) 035209

$\omega \to \pi^0\gamma$ lineshape analysis

M. Thiel

comparison with reference measurement on LH_2



no significant structure in spectral function; signal on Nb,C slightly broader than on LH_2

$\omega \rightarrow \pi^0 \gamma$ lineshape analysis

M. Thiel

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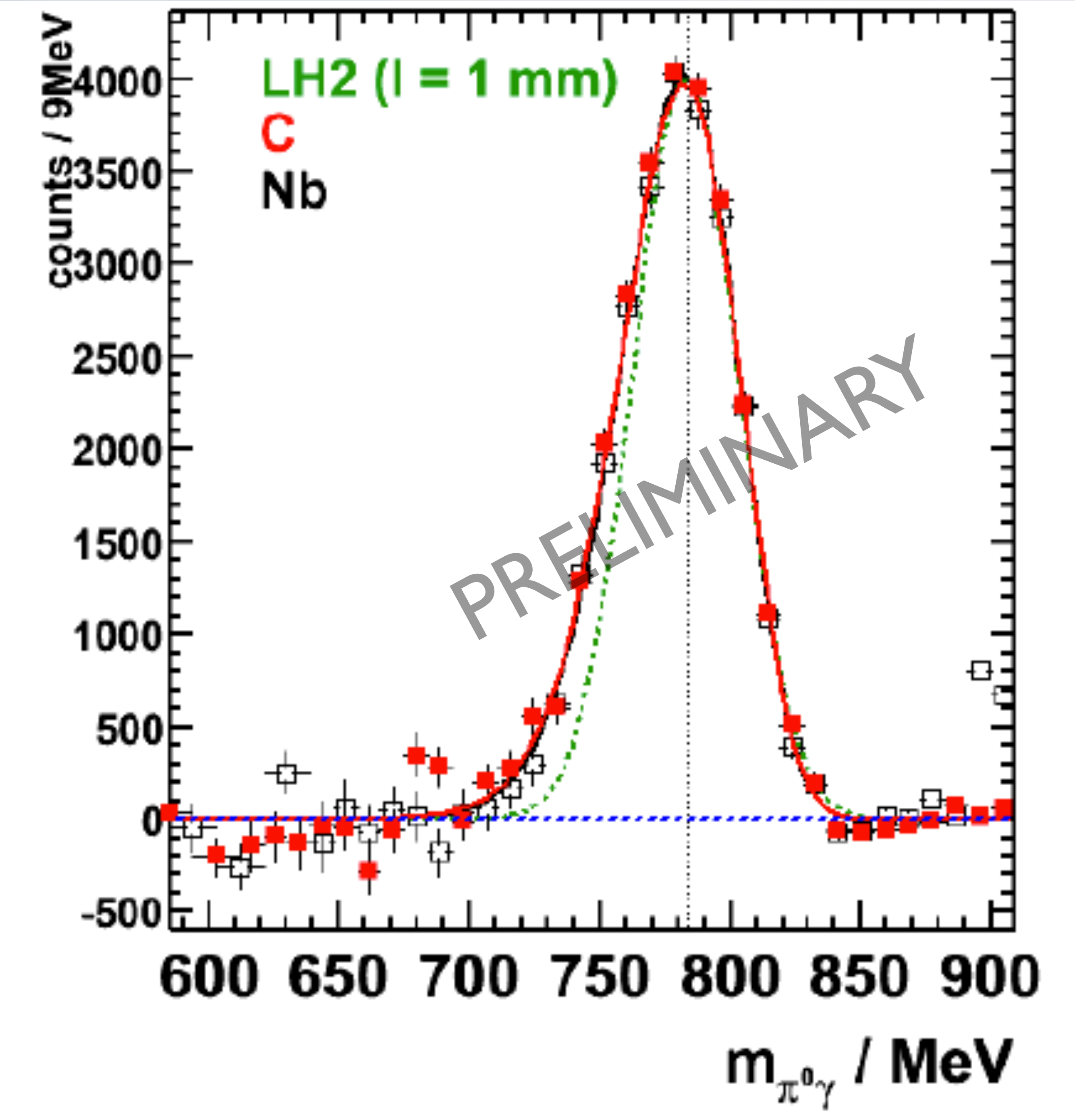

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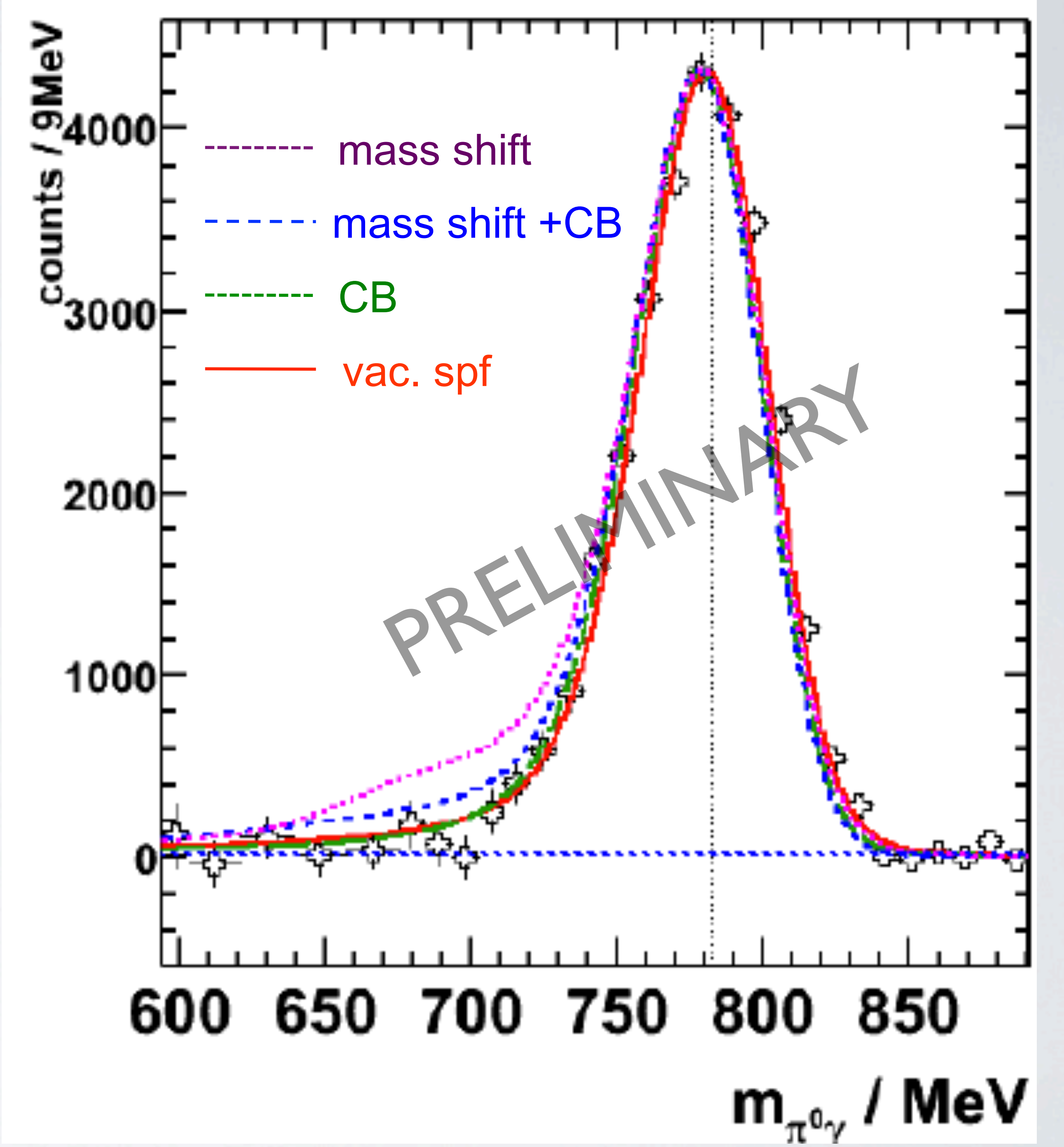
comparison with GiBUU calculations for different in-medium scenarios (J. Weil, U. Mosel)

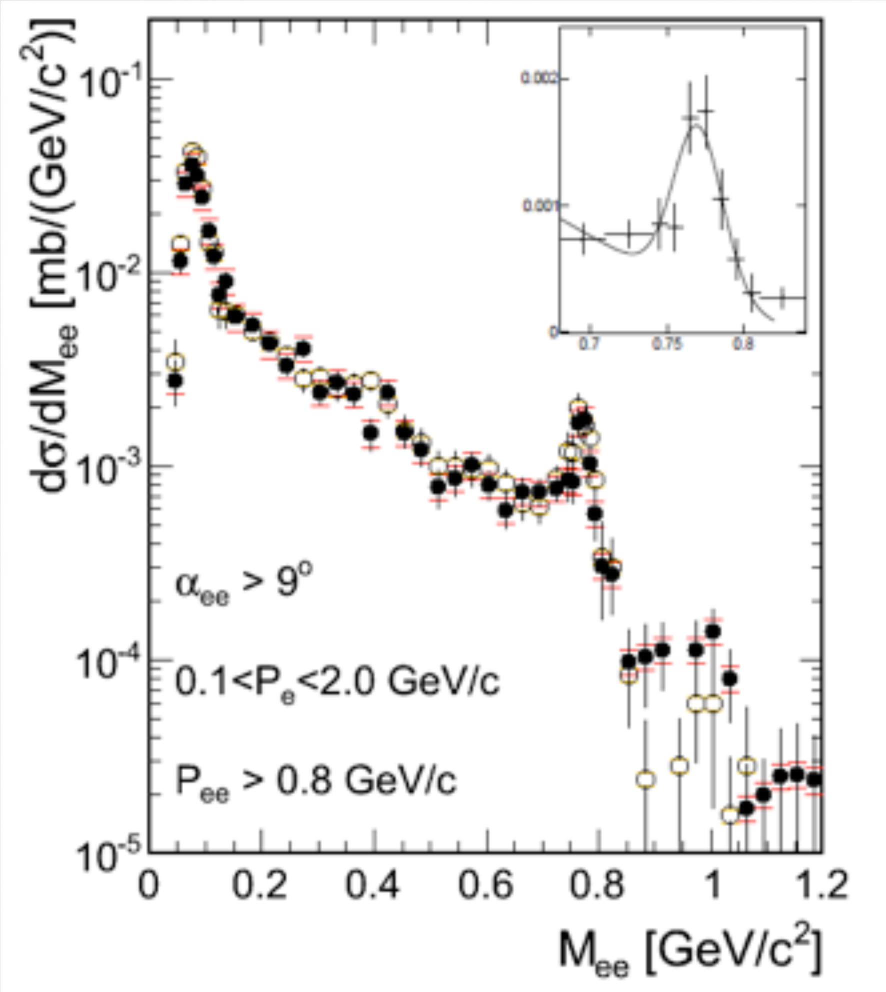


data consistent with collisional broadening scenario; mass shift less likely

dilepton invariant mass spectra

HADES arXiv:1205.1918 M. Lorenz: A2; L. Fabietti

p_{ee} > 800 MeV/c



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

dilepton invariant mass spectra

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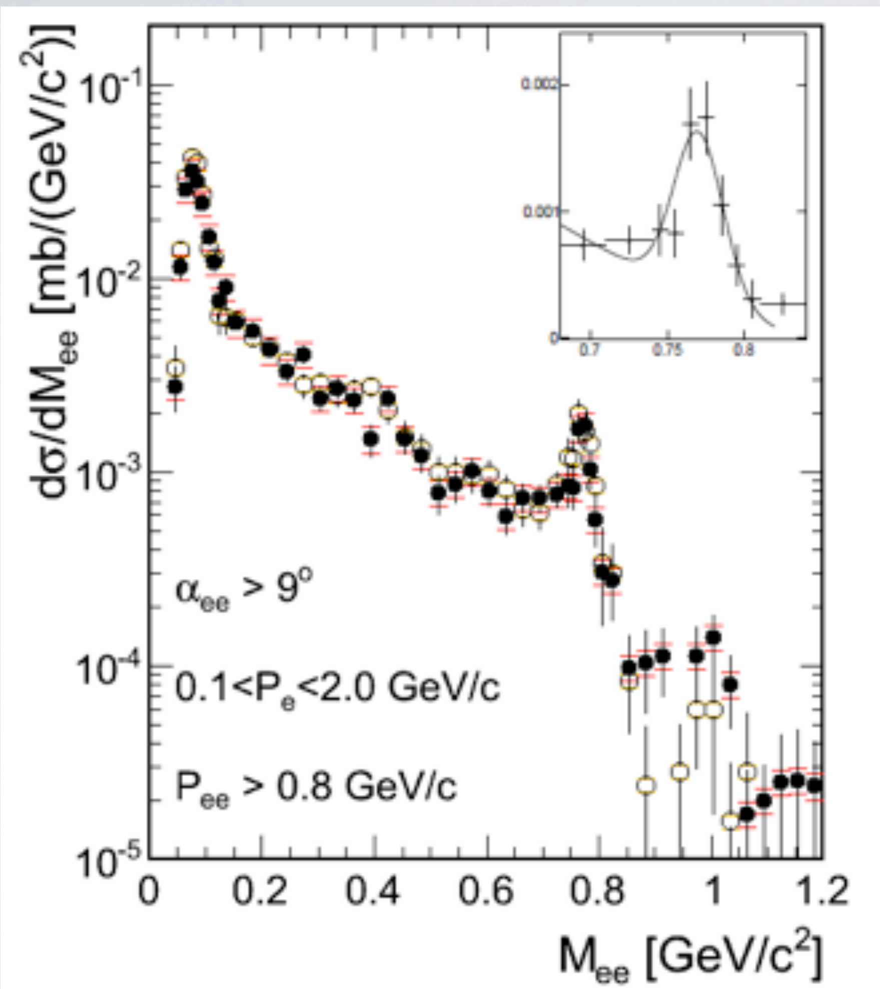

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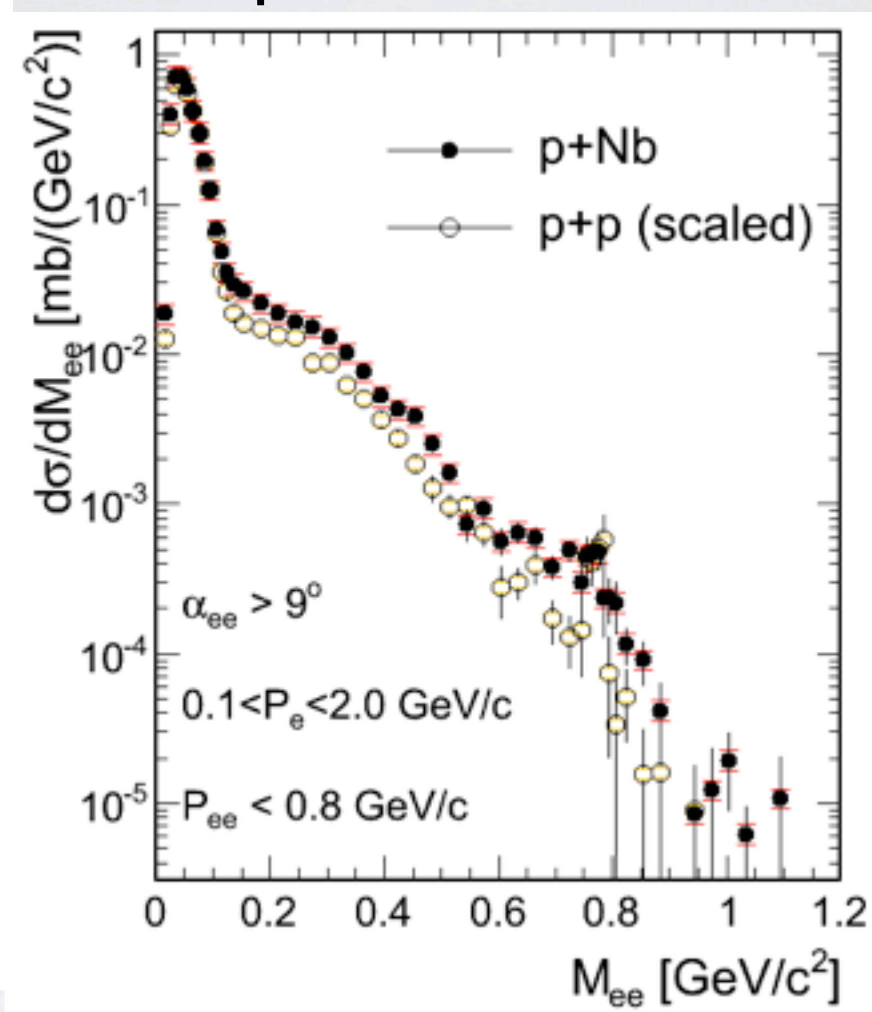

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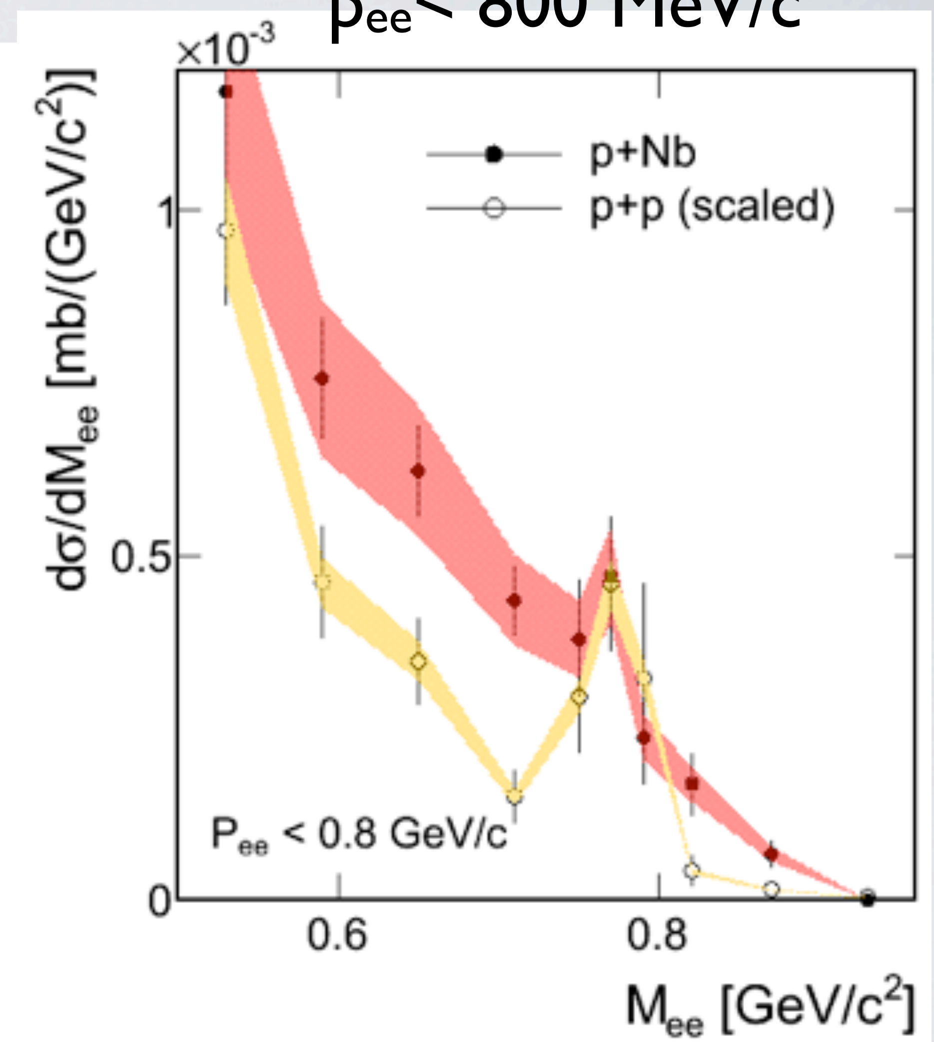


shape of m_{ee} spectrum in p+Nb identical to reference spectrum in p+p

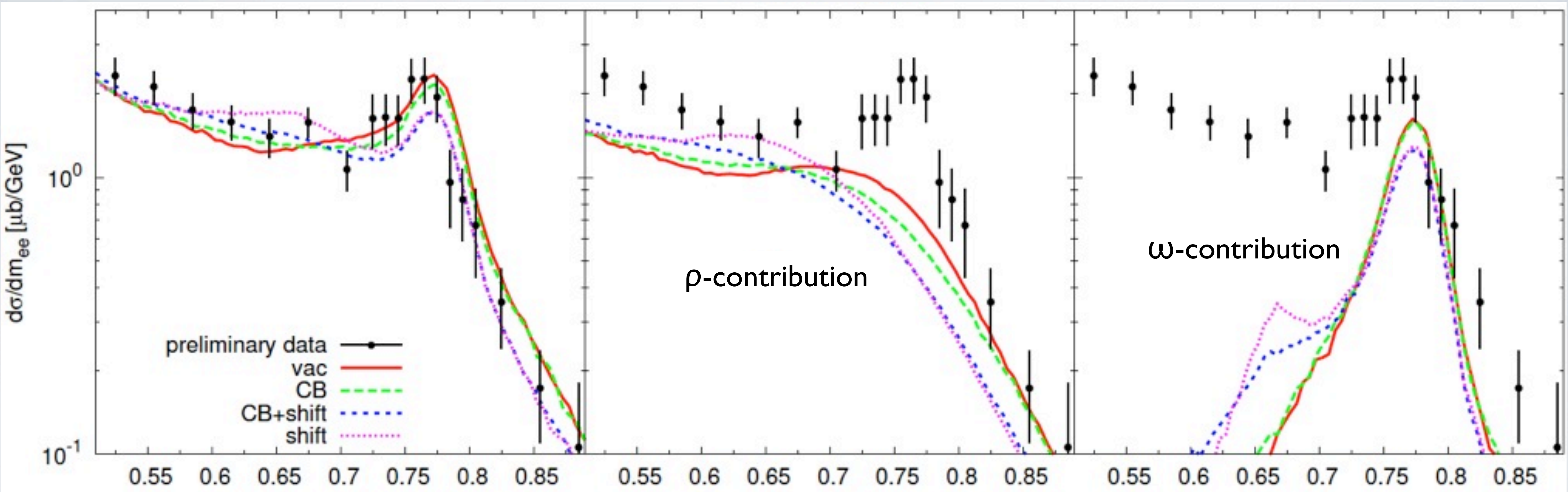
- strong e^+e^- excess yield below ω peak attributed to ρ-like channels;
- no hint for change in ω line shape;
- strong ω absorption confirmed

comparison to Gi BUU simulations

J. Weil, H. van Hees, U. Mosel; arXiv:1203.3557

comparison to different in-medium modification scenarios

p+Nb at 3.5 GeV



invariant mass m_{e+e-} [GeV]

- difficult to distinguish between different in-medium scenarios:
  ⇒ best agreement with data for collisional broadening scenario
  ⇒ mass shift tends to deteriorate agreement with data
  ⇒ difficult to disentangle ρ, ω contributions and to extract individual in-medium properties

Search for meson-nucleus bound states

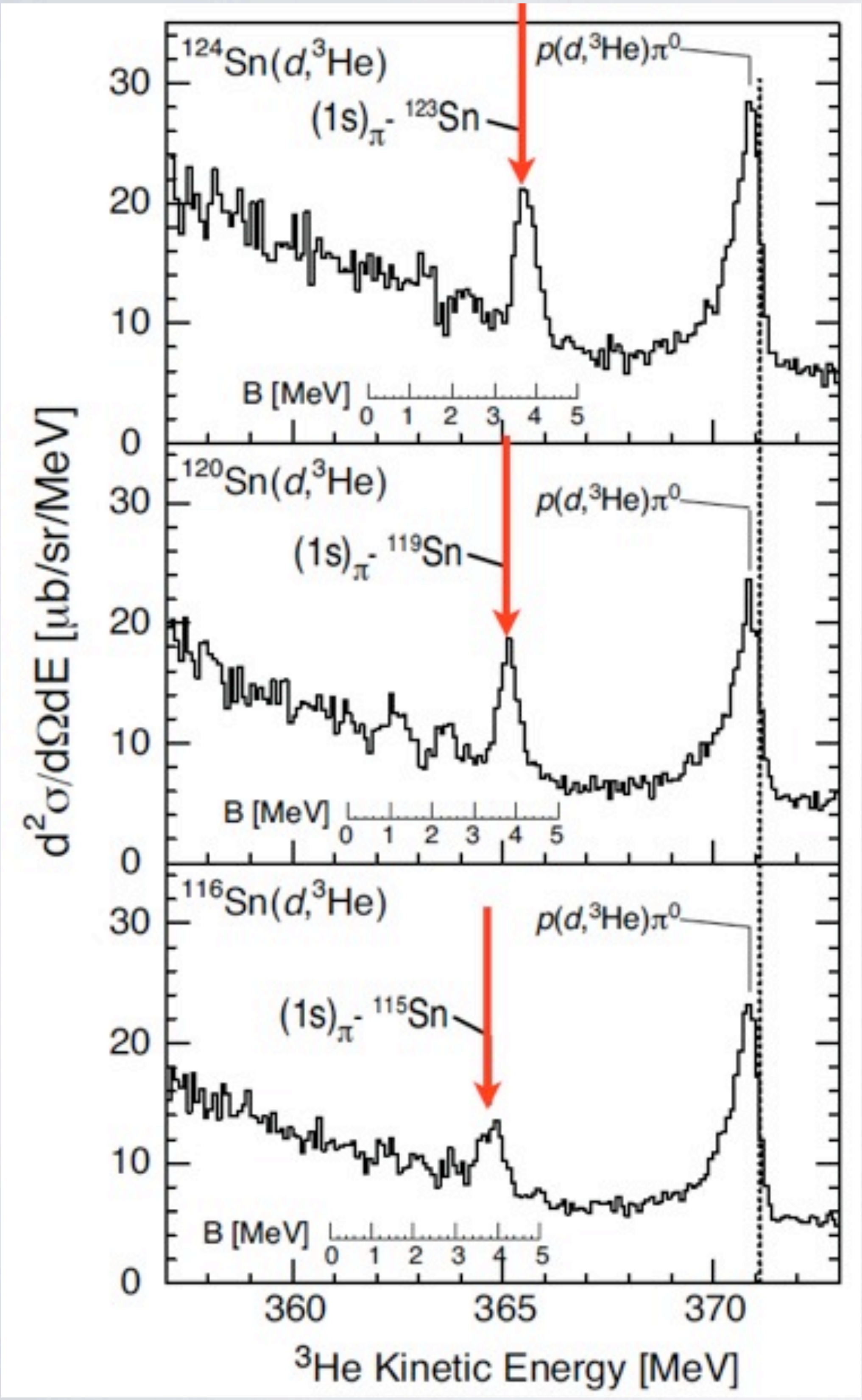
deeply bound pionic states

recoil free production in (d,^{3}He) reaction

deeply bound pionic states

recoil free production in (d,^{3}He) reaction

Suzuki et al., PRL 92 (20004) 072302

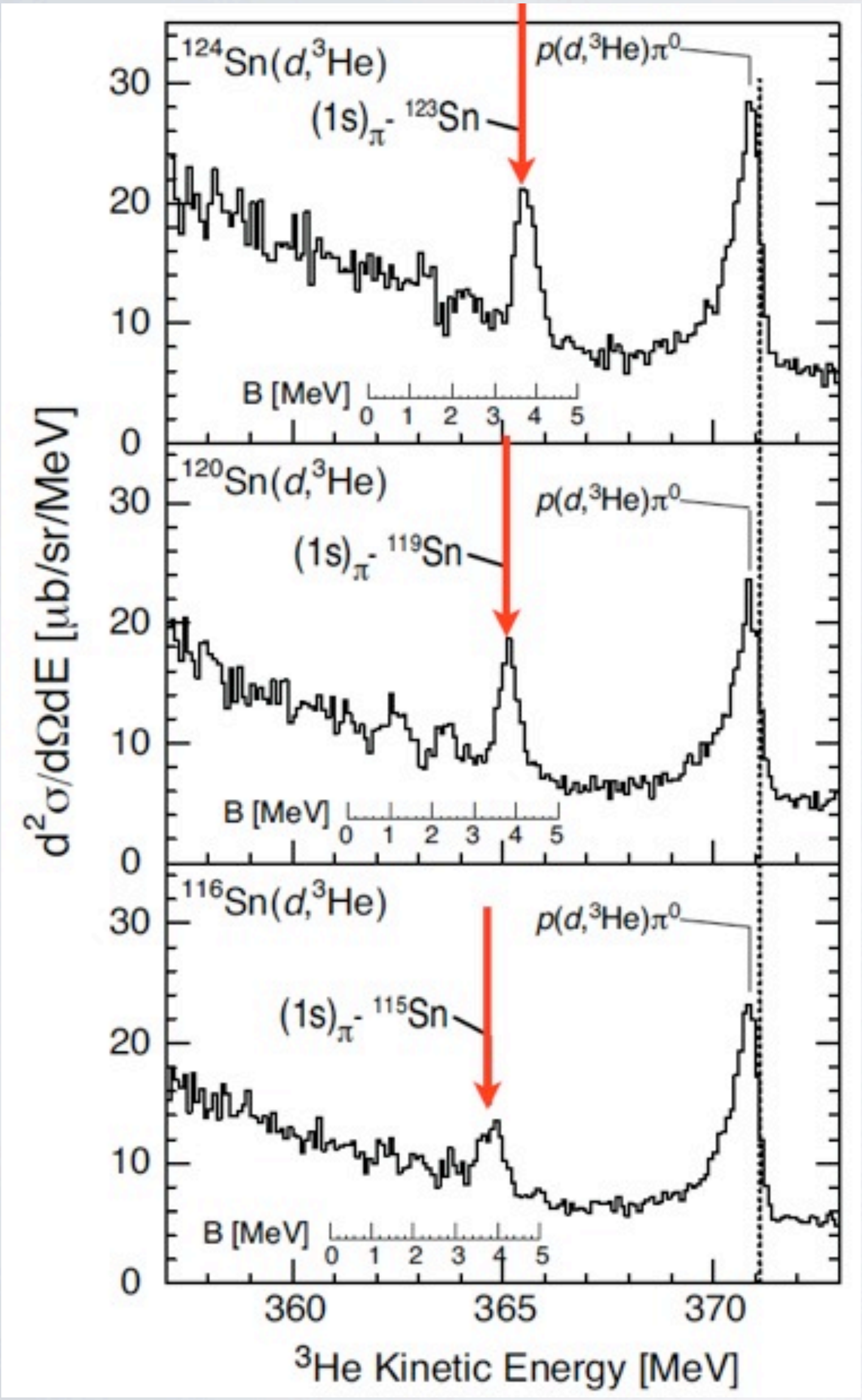


GSI

deeply bound pionic states

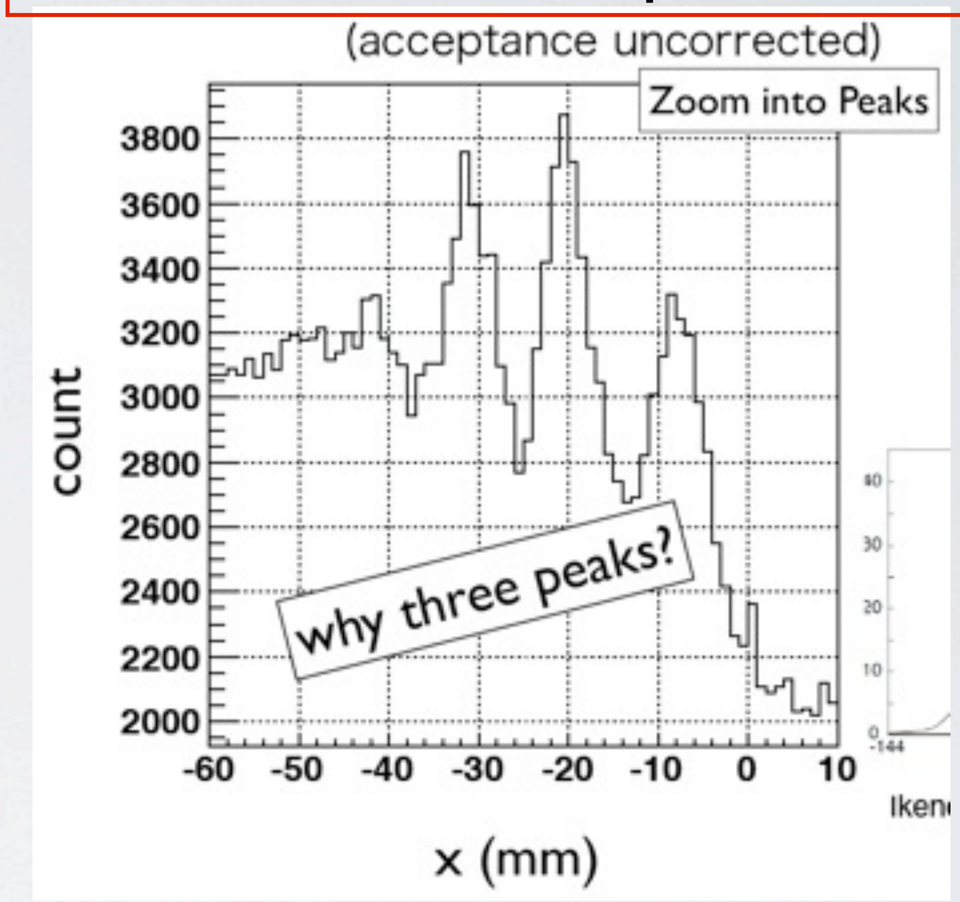
recoil free production in (d,^{3}He) reaction

Suzuki et al., PRL 92 (20004) 072302



GSI

K. Itahashi, N. Ikeno: poster #22

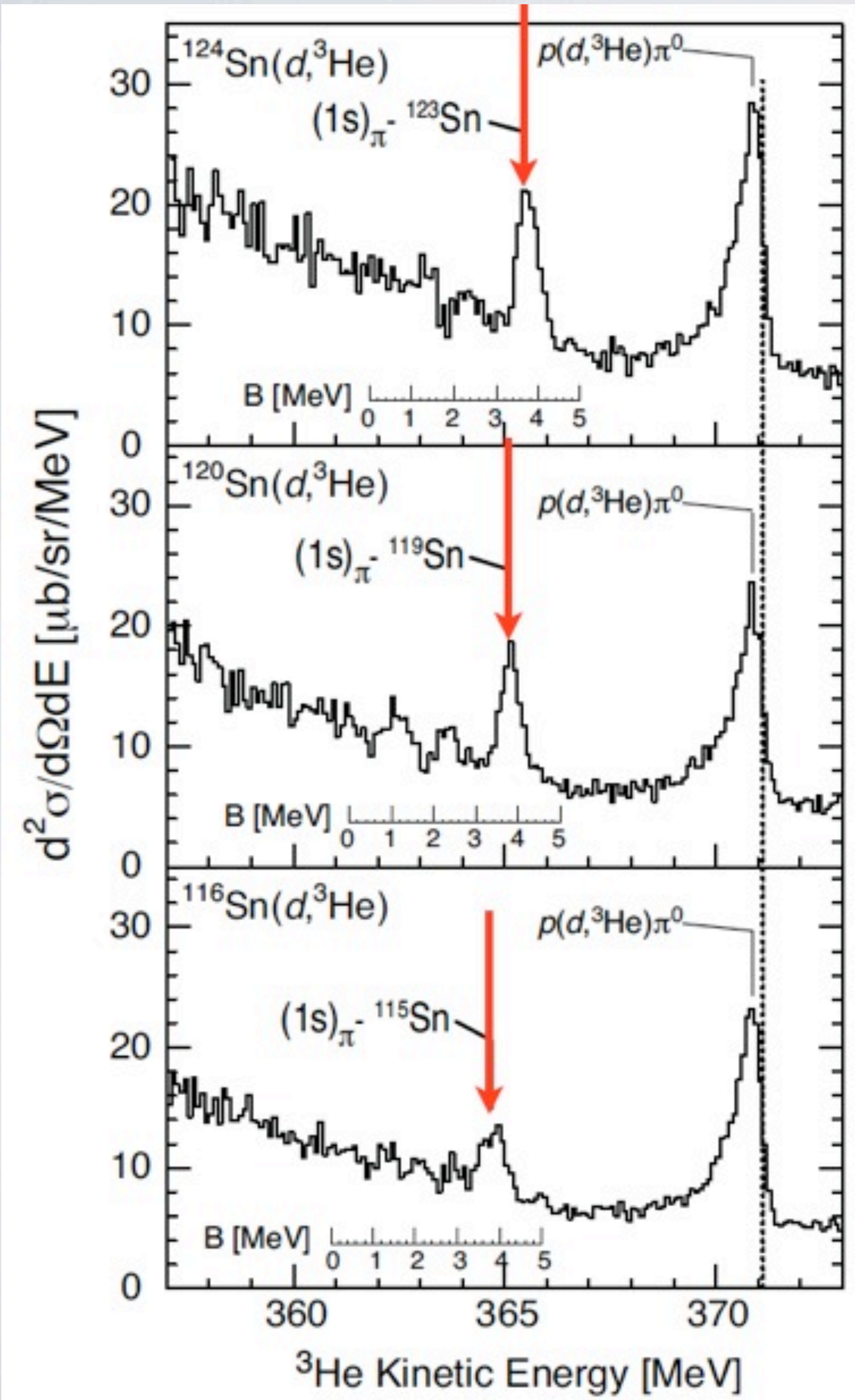


RIKEN RIBF

deeply bound pionic states

recoil free production in (d,^{3}He) reaction

Suzuki et al., PRL 92 (20004) 072302



GSI

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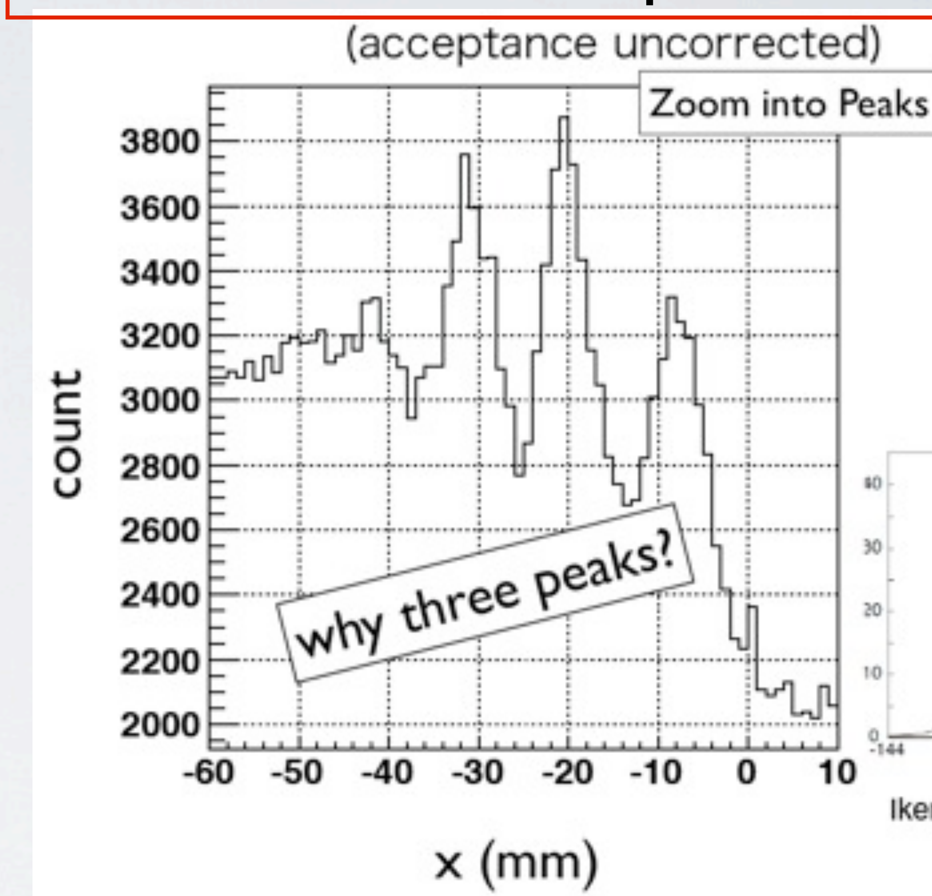


RIKEN RIBF

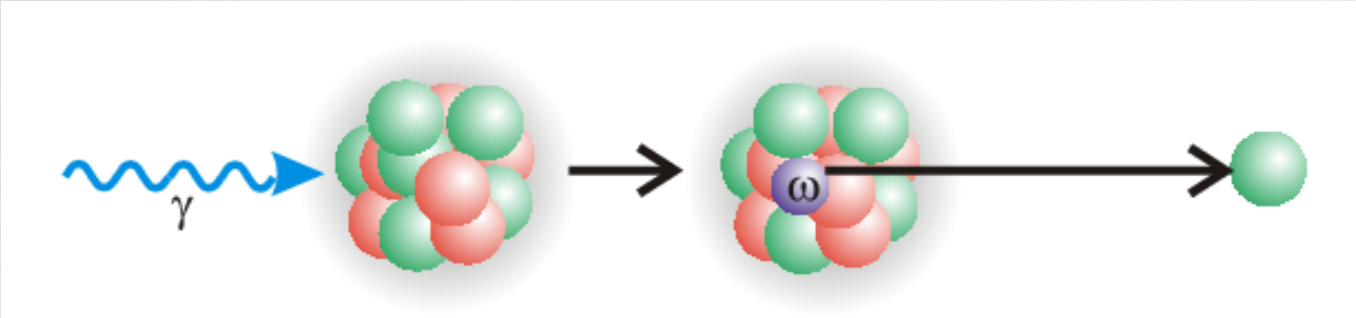
optical model parameters determined from energy and width of bound $(1s)_{\pi^-}$ states

$$\frac{< q\bar{q} >_\rho}{< q\bar{q} >_{\rho_0}} \approx 0.67$$

remaining systematic uncertainty in $< r_n^2 >^{1/2} - < r_p^2 >^{1/2}$ for odd A nuclei

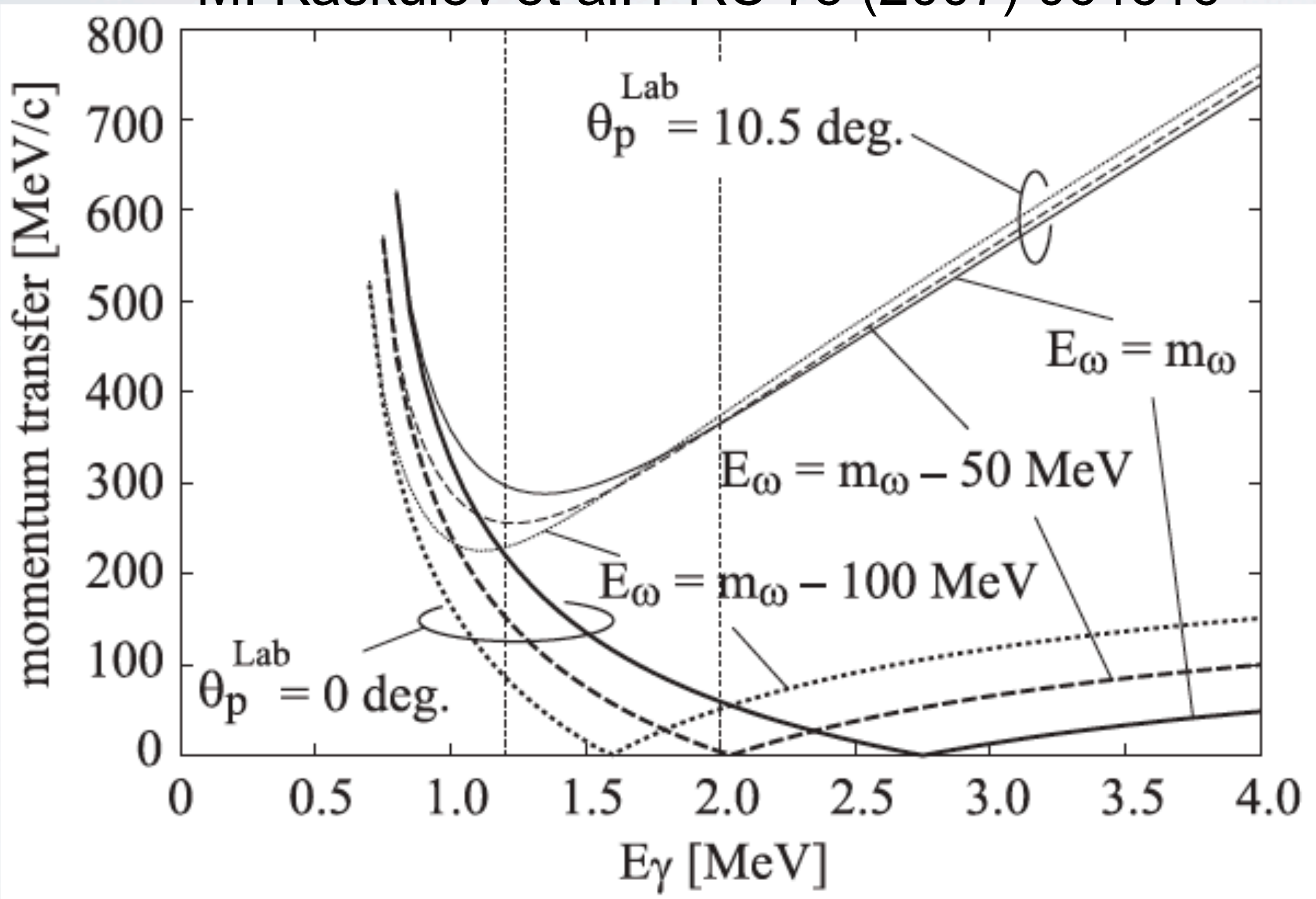
population of meson-nucleus bound states in recoil-less kinematics

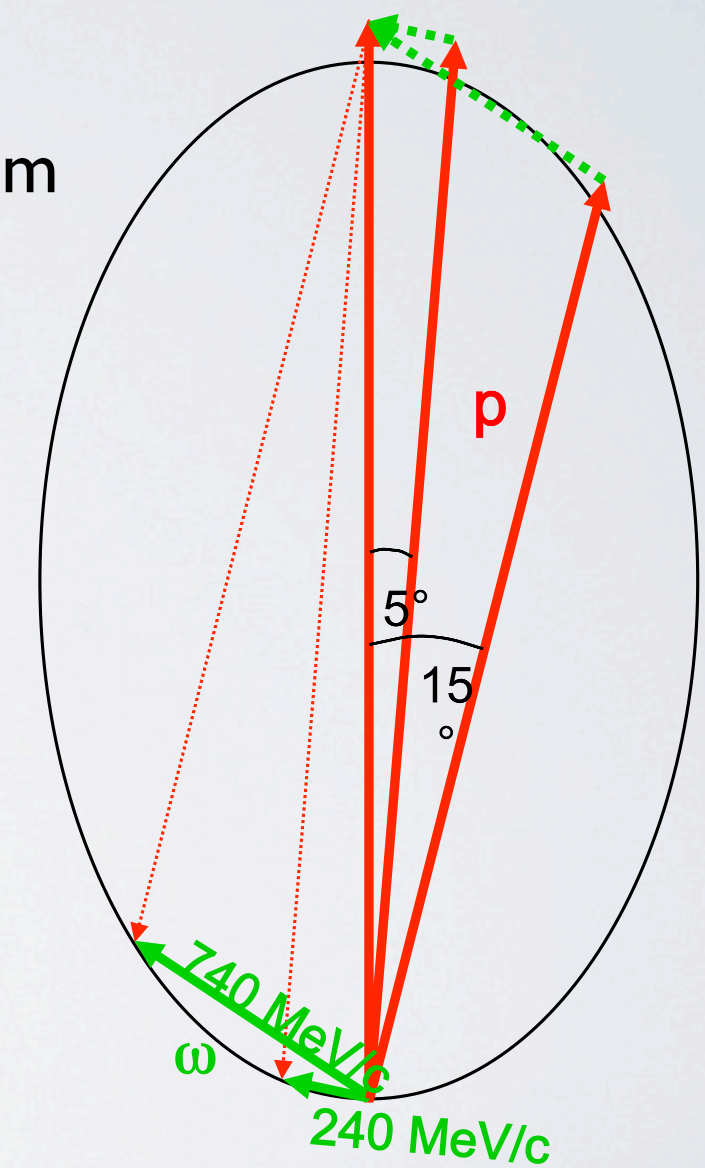
is ω A attraction strong enough to allow for ω-nucleus bound states ??



forward going nucleon takes over incident photon momentum

M. Kaskulov et al. PRC 75 (2007) 064616



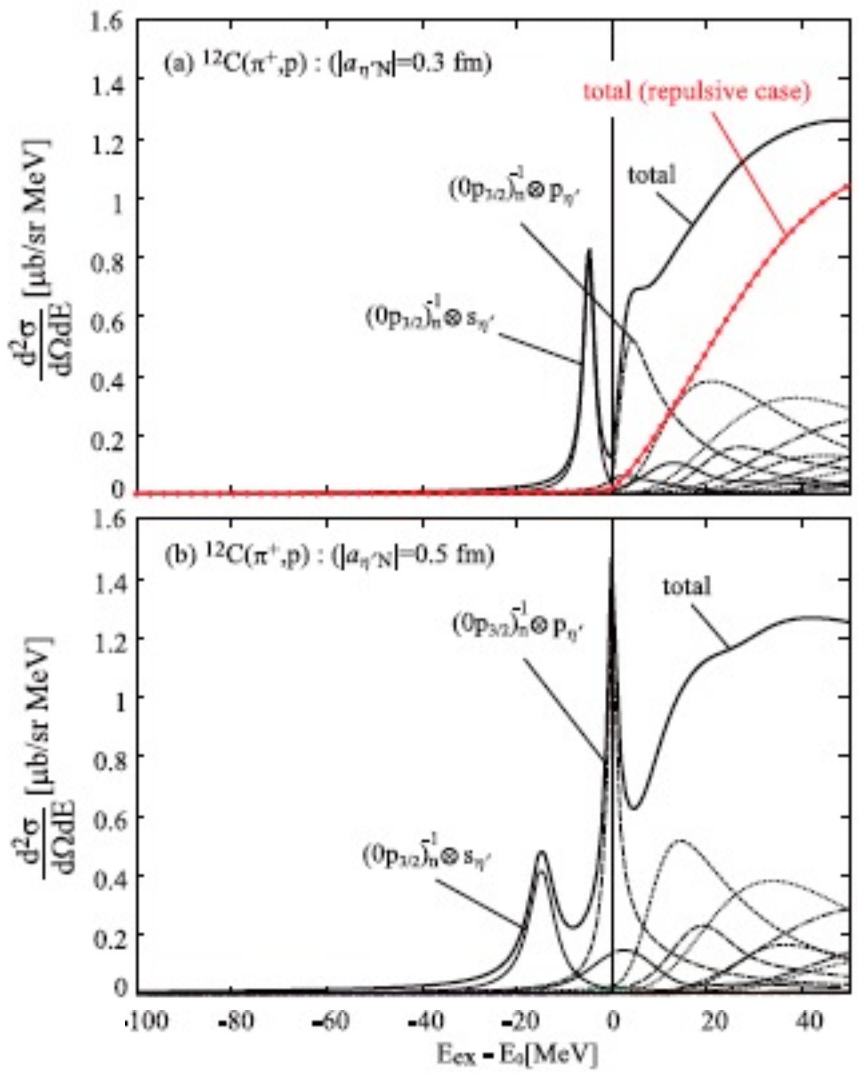


outlook : search for η' mesic states

J-PARC

$^{12}C(\pi^+,p)$ η'X @ 1.8 GeV/c

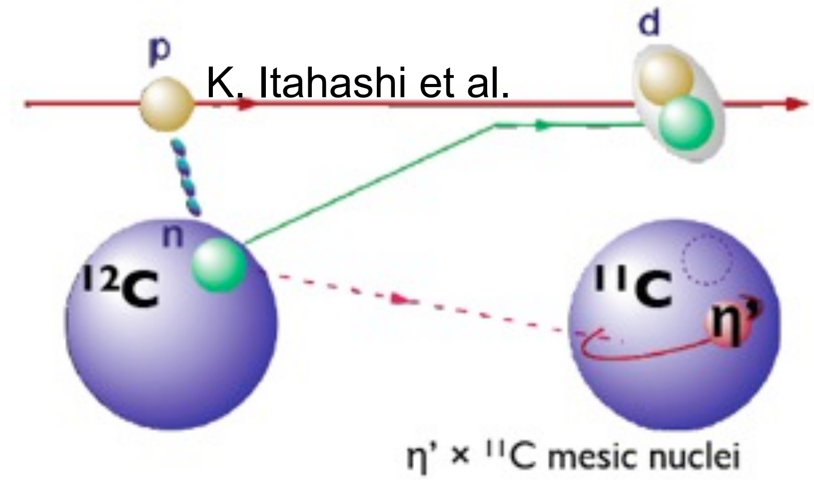
H. Nagahiro, S. Hirenzaki, E. Oset and A. Ramos
PLB 709 (2012) 87

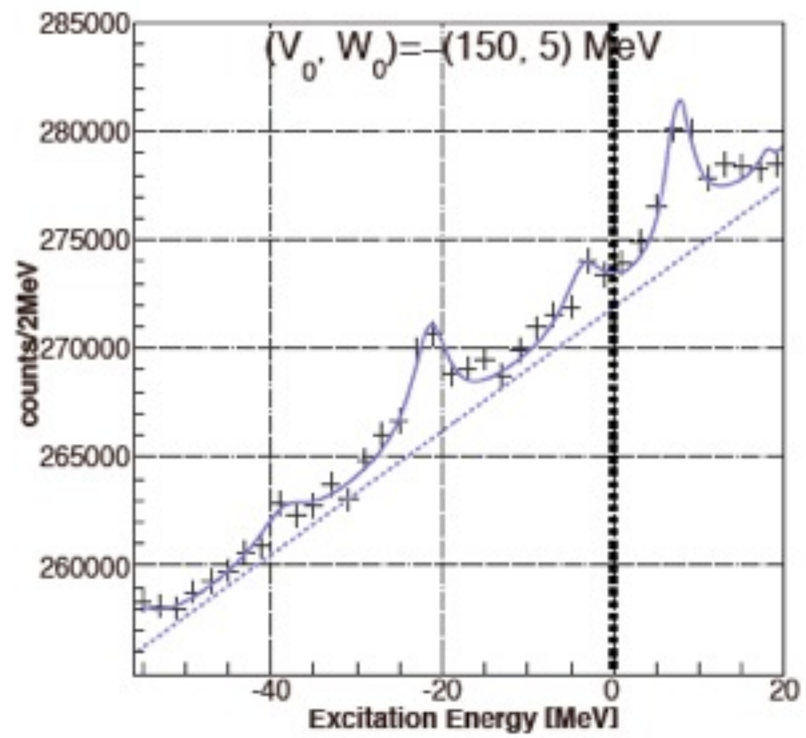


S. Hirenzaki: session B

GSI

$^{12}C(p,d)$ η'X @ 2.5 GeV



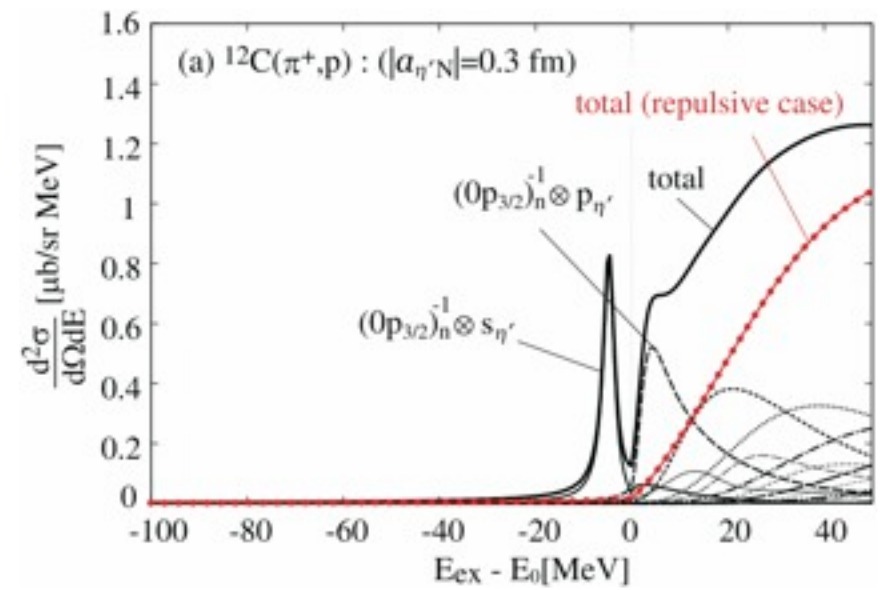


H. Fujioka: session B2

ELSA

$^{12}C(\gamma,\eta')X$ @ 1.5-2.9 GeV

H. Nagahiro, S. Hirenzaki, E. Oset and A. Ramos
PLB 709 (2012) 87



M. Nanova: session C4

narrow peaks for η' mesic states predicted

Summary

- observables for extracting in-medium properties of mesons:

- transparency ratio: (CBELSA/TAPS, ANKE, CLAS, LEPS)
  in-medium broadening of ω, η', Φ mesons;

	$\Gamma(\rho_0)$ [MeV]	$<p>$[GeV/c]	σ_{inel} [mb]
ω	130-150	1,1	≈ 60
η'	15-25	1,1	3-10
Φ	30-60	0.6-1.4	14-21

- ρ,ω-line shape analysis: (CB@MAMI, HADES)
  no evidence for structures or mass shifts;
  limited sensitivity due to strong in-medium broadening and small fraction of in-medium decays; π-FSI for $\omega \rightarrow \pi^0\gamma$

- meson-nucleus bound states: (GSI, RIKEN, CBELSA/TAPS, JPARC)
  deeply bound pionic states: drop of chiral condensate in the medium
  search for ω mesic states ongoing
  search for η' mesic states planned

meson spectral functions do change in the nuclear environment !!

experiments

experiments

- heavy-ion collisions:

  CERN SPS: HELIOS-3, CERES, NA60, $\sqrt{s}$ = 17 GeV;

  BNL RHIC: PHENIX, STAR, $\sqrt{s}$ = 200 GeV;

  probes: e^+e^-, $\mu^+\mu^-$, acceptance for $p_t > 0$ MeV/c

experiments

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  probes: e^+e^-, $\mu^+\mu^-$, acceptance for p_t> 0 MeV/c

- proton induced reactions:

  KEK: 12 GeV p;

  probes: e^+e^-, K^+K^- ; acceptnace for meson momenta > 800 MeV/c

  COSY ANKE: p 1.0 - 3.5 GeV/c;

  probes : K^+K^- ; acceptance for meson momenta 0.6-1.6 GeV/c

experiments

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  COSY ANKE: p 1.0 - 3.5 GeV/c;

  probes : K^+K^- ; acceptance for meson momenta 0.6-1.6 GeV/c

- photon induced reactions:

  SPRING8: 1.4-2.5 GeV

  probes K^+K^-; acceptance for meson momenta > 1.2 GeV/c

  JLab CLAS: 0.6-3.5 GeV

  probes: e+e-; acceptance for meson momenta > 0.8 GeV/c

  CBELSA/TAPS: 0.9-2.5 GeV

  probes: photons; acceptance for meson momenta > 0 MeV/c

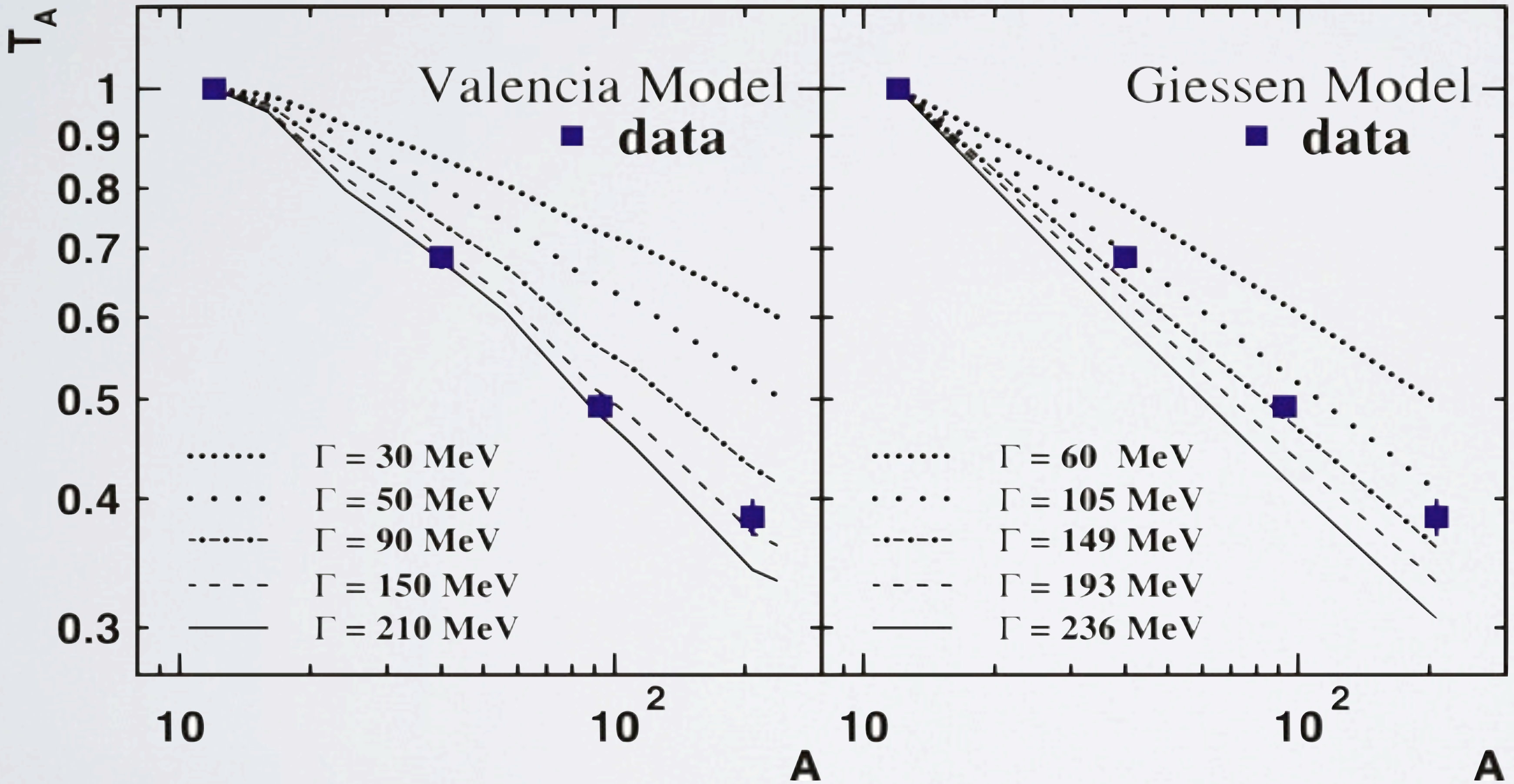
  CB/TAPS@MAMI: 0.9-1.4 GeV

  probes: photons; acceptance for meson momenta > 0 MeV/c

transparency ratio measurement for ω and η' mesons

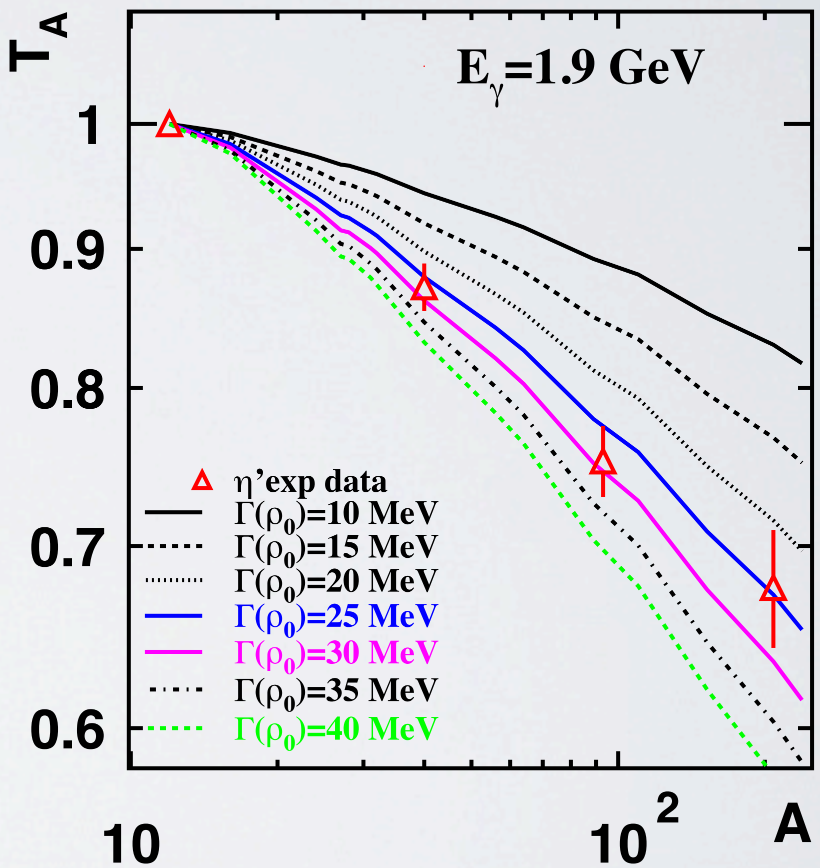
M. Kaskulov, E. Hernandez, E. Oset
EPJ A 31 (2007) 245

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



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

M. Nanova et al.



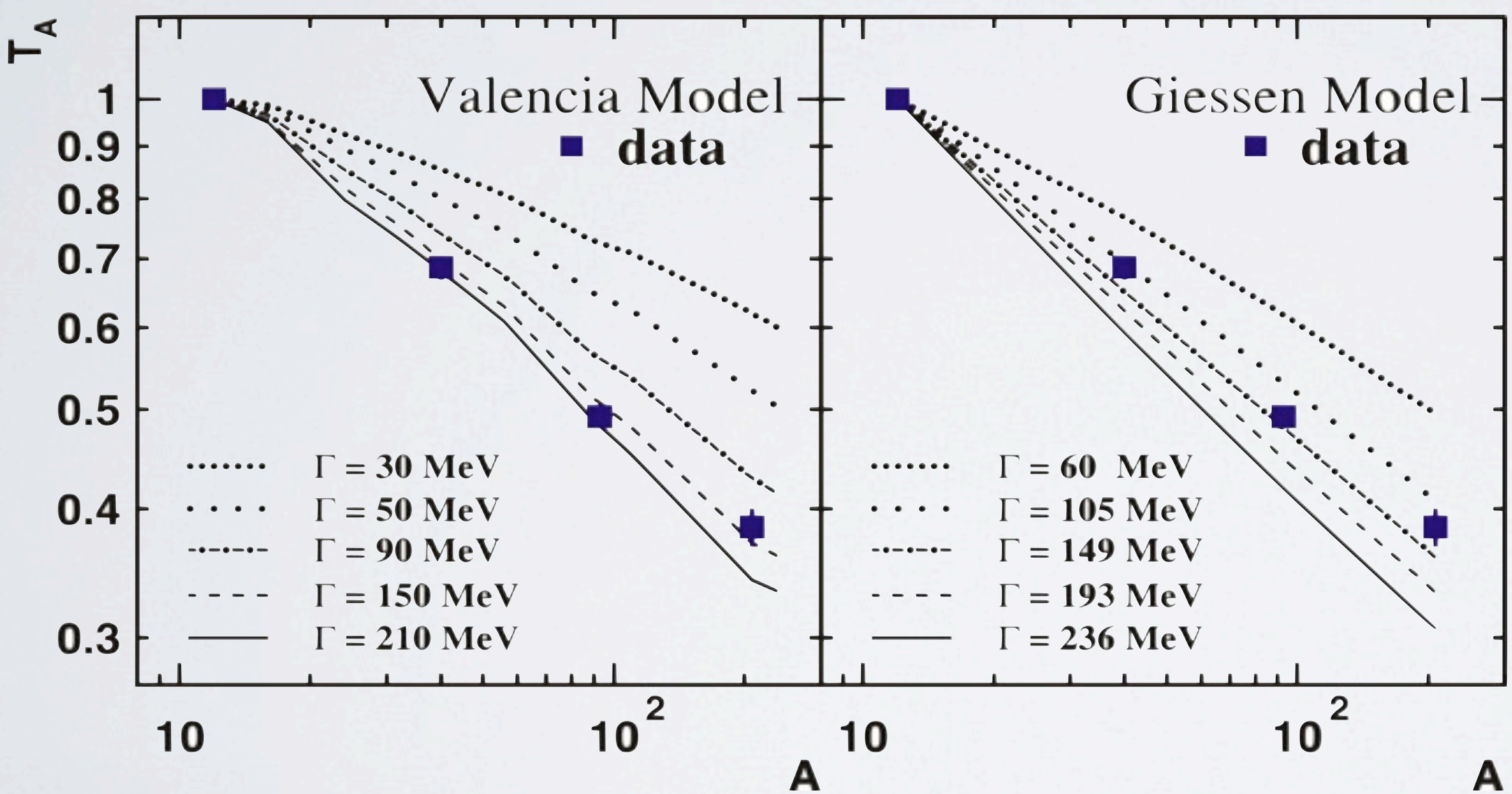
transparency ratio measurement for ω and η' mesons

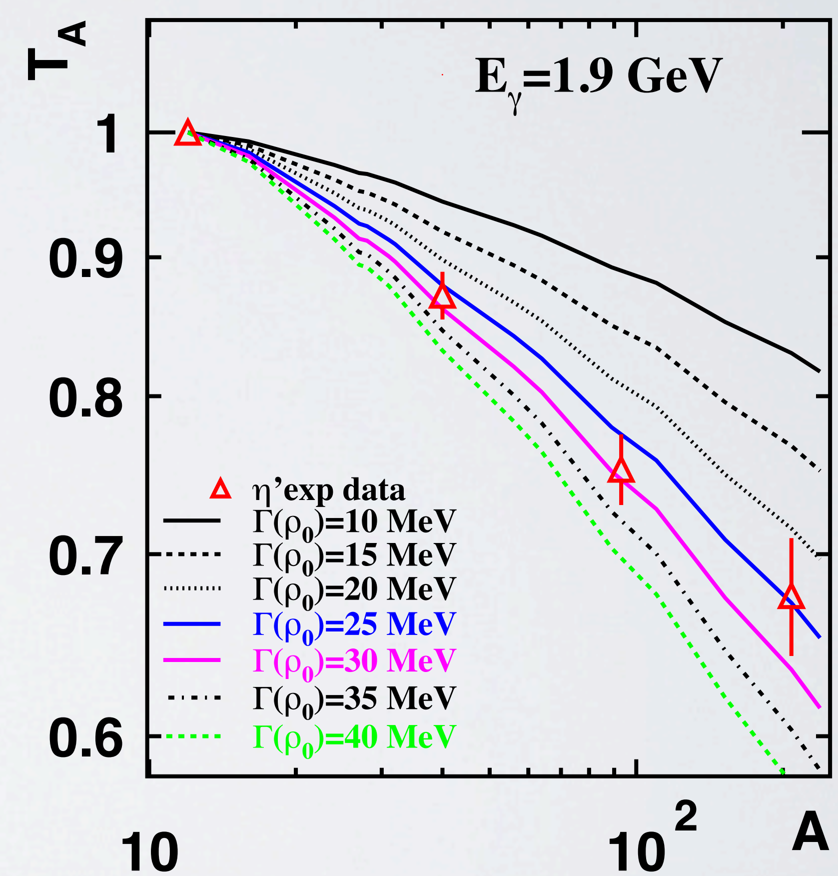
$$\sigma_{\gamma A\to\eta' A'} = C\int d^3r\rho(\vec{r})\int_0^{2\pi} d(\phi^{\eta'}_{\mathrm{c.m.}})\int_{-1}^{1} d(\cos\theta^{\eta'}_{\mathrm{c.m.}})\frac{d\sigma}{d\Omega}(\gamma p\to\eta' p)P_s(\vec{k}_{\eta'},\vec{r})$$

M. Kaskulov, E. Hernandez, E. Oset
EPJ A 31 (2007) 245

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

M. Nanova et al.





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transparency ratio measurement for ω and η' mesons

$$\sigma_{\gamma A\to\eta' A'} = C\int d^3r\rho(\vec{r})\int_0^{2\pi} d(\phi^{\eta'}_{\mathrm{c.m.}})\int_{-1}^{1} d(\cos\theta^{\eta'}_{\mathrm{c.m.}})\frac{d\sigma}{d\Omega}(\gamma p\to\eta' p)P_s(\vec{k}_{\eta'},\vec{r})$$

where $P_s(\vec{r})$ is the survival probabiliy $P_s(\vec{k}_{\eta'},\vec{r}) = \exp\left[\int_0^\infty dl\,\frac{\mathrm{Im}\,\Pi_{\eta'}(\rho(\vec{r}\,'))}{|\vec{k}_{\eta'}|}\right]$ with $\vec{r}\,' = \vec{r} + l\frac{\vec{k}_{\eta'}}{|\vec{k}_{\eta'}|}$

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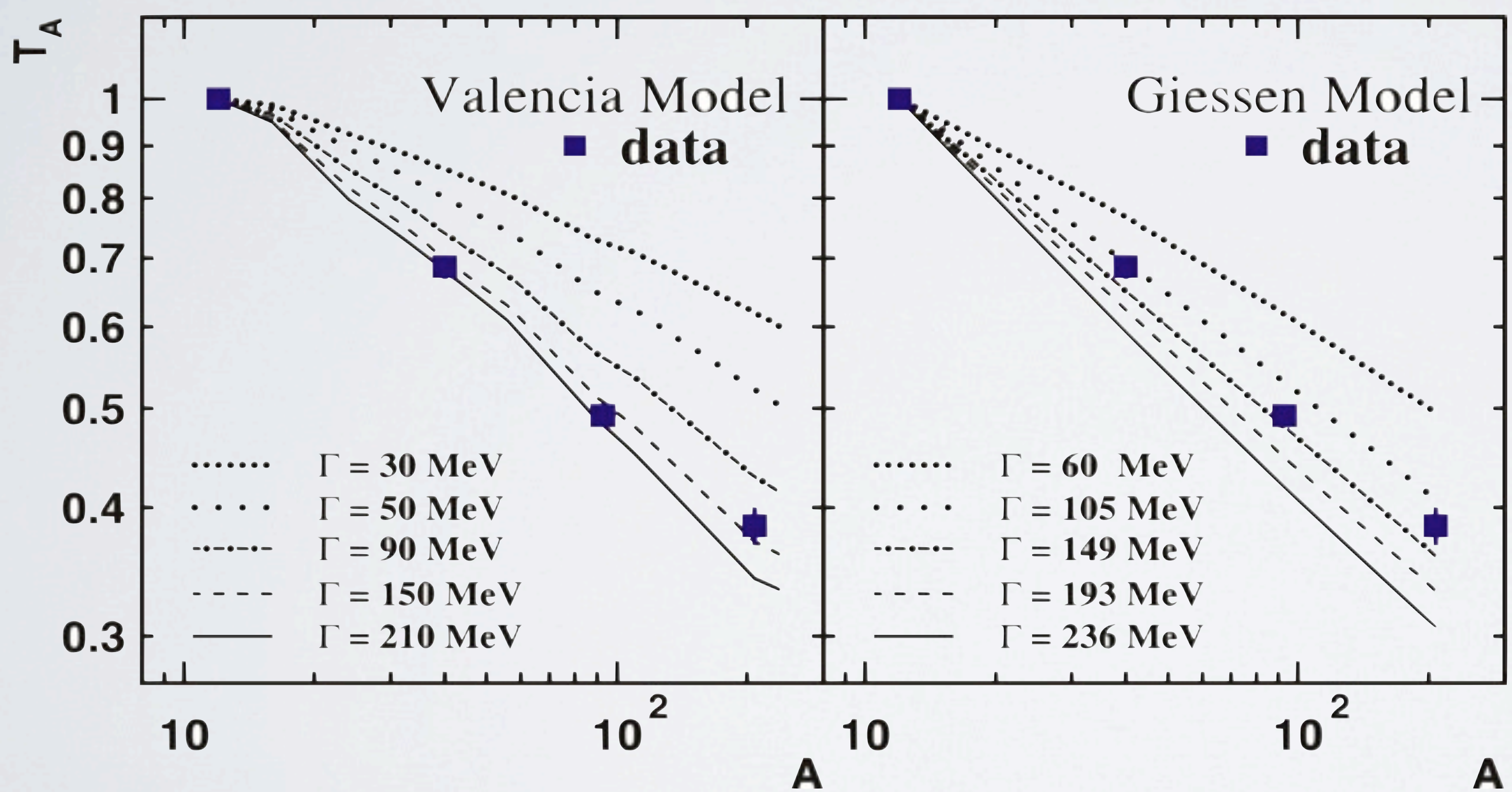

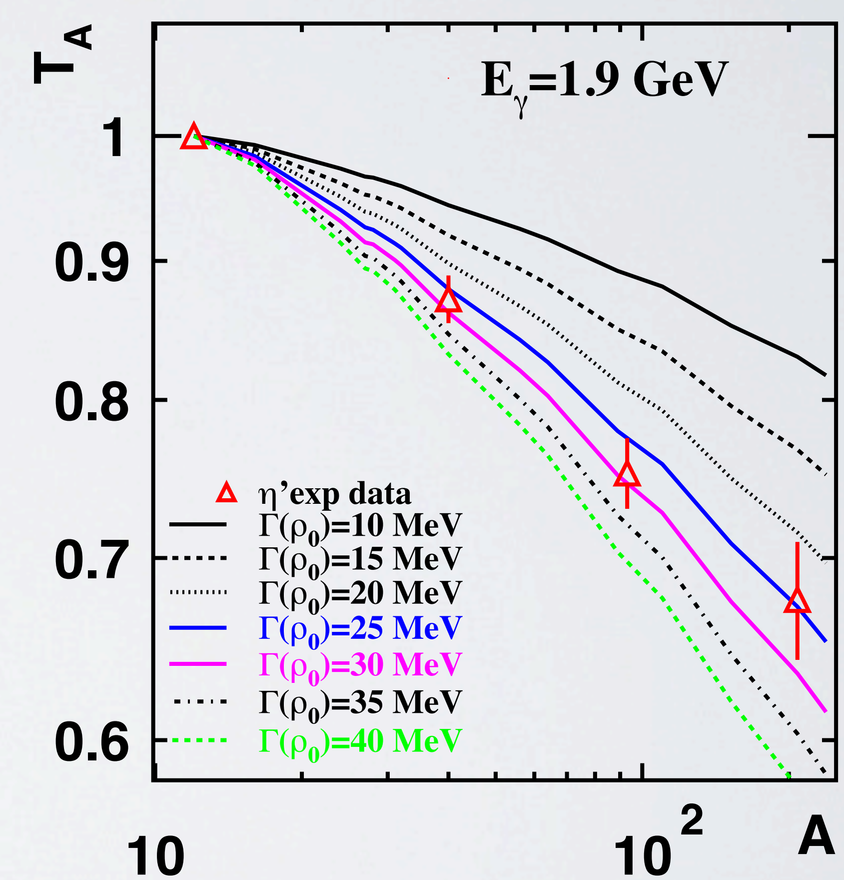

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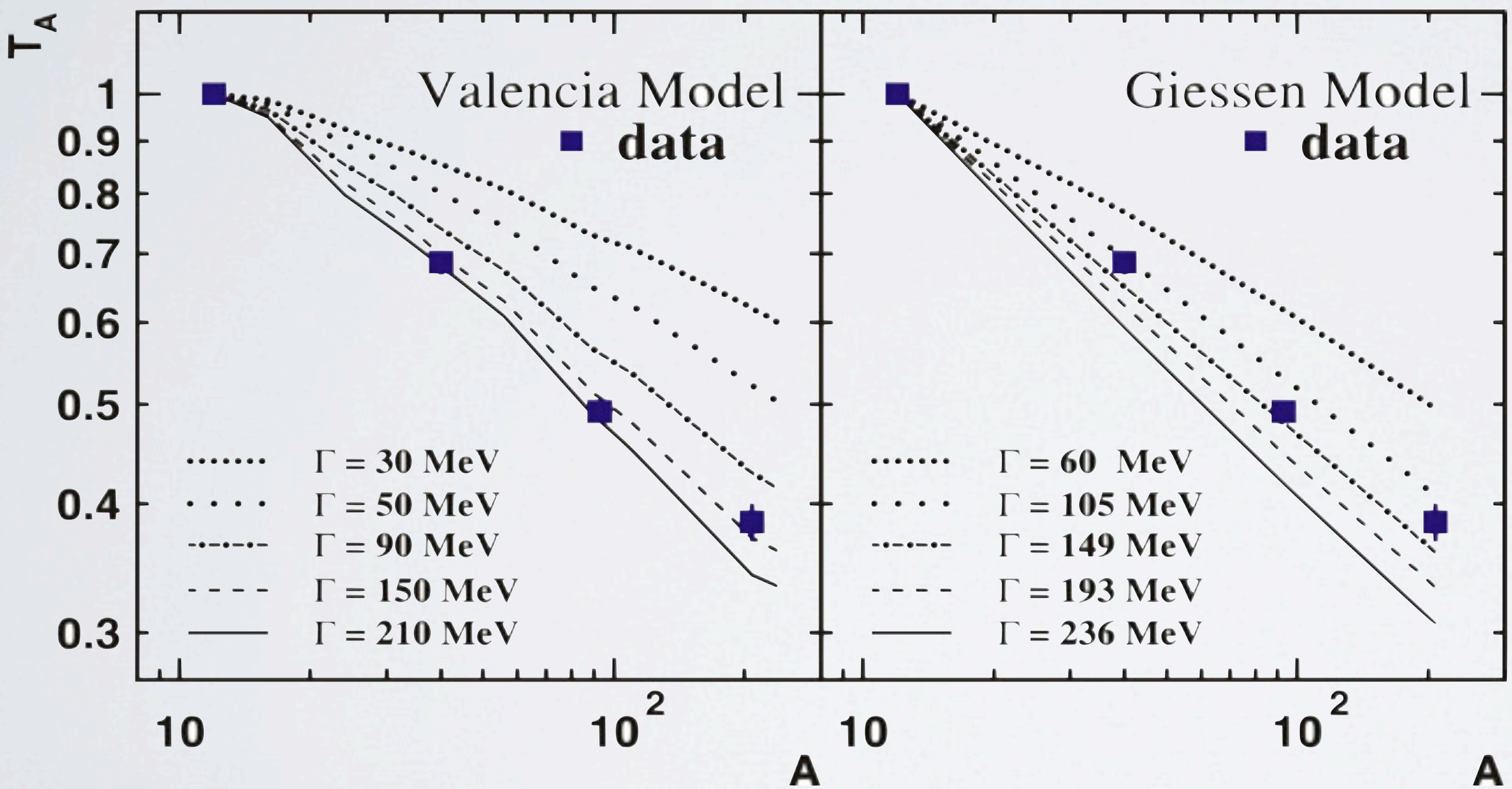

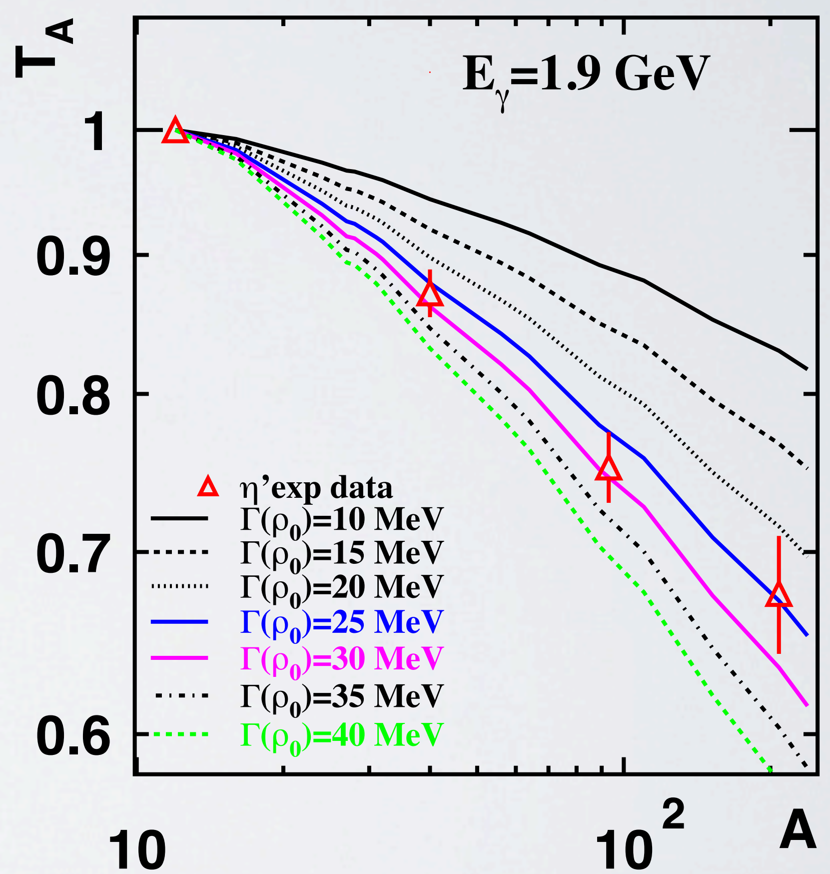

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$\Gamma_\omega(\langle p_\omega \rangle \approx 1.1$ GeV/c $) \approx 130\text{-}150$ MeV;
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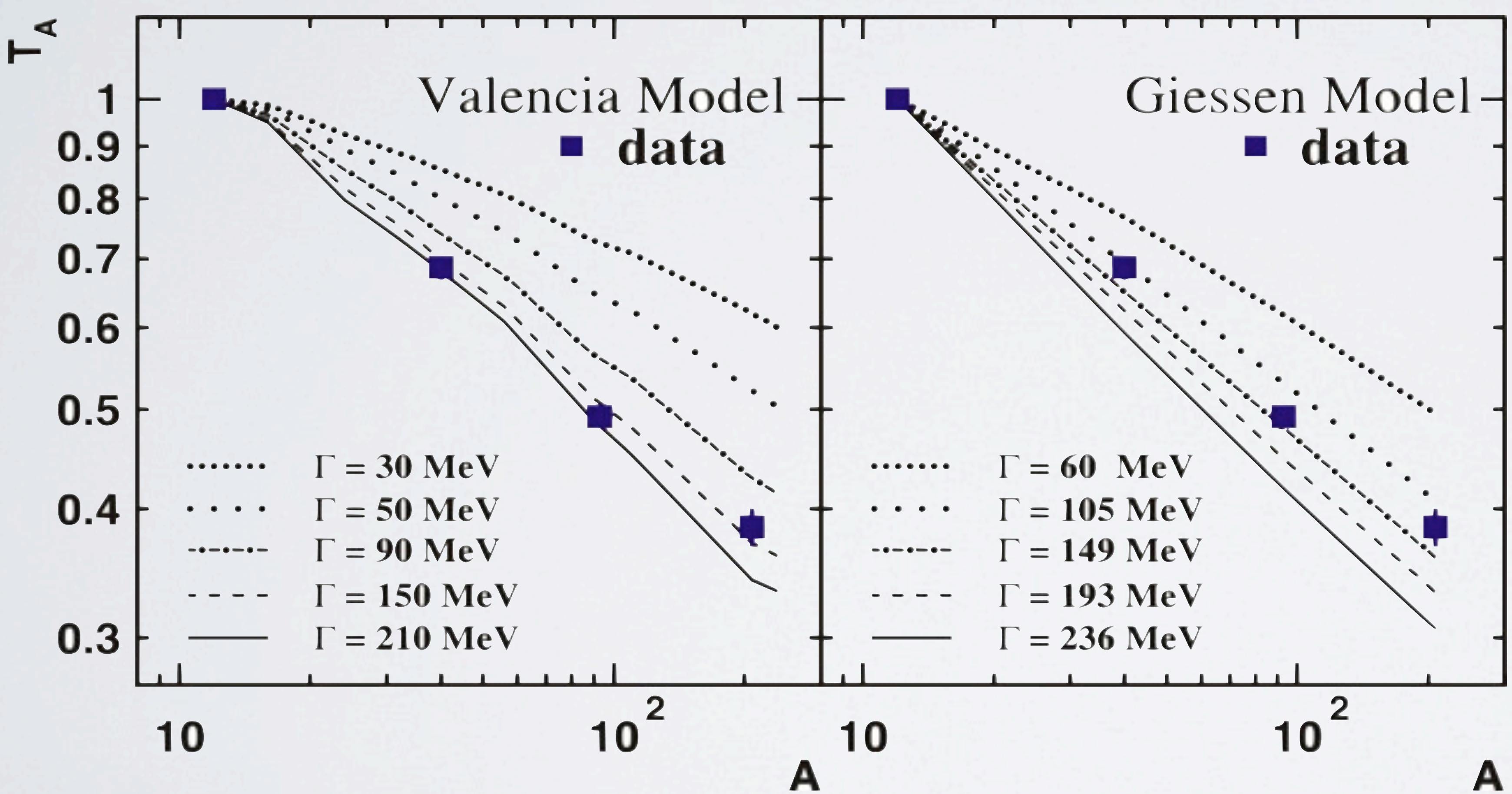

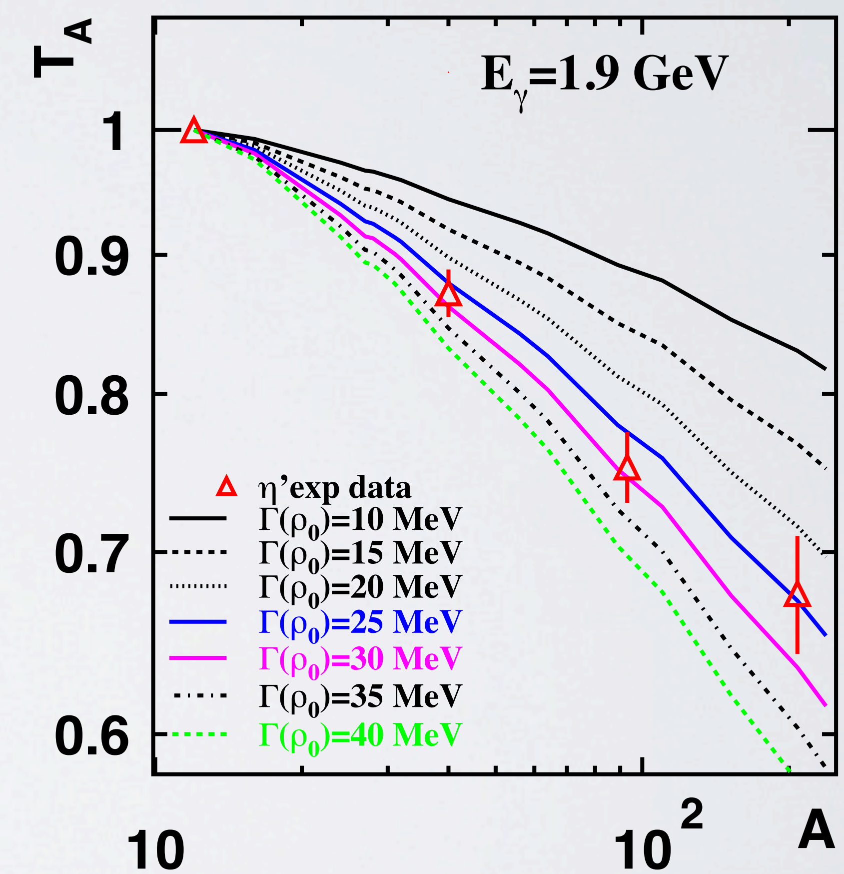

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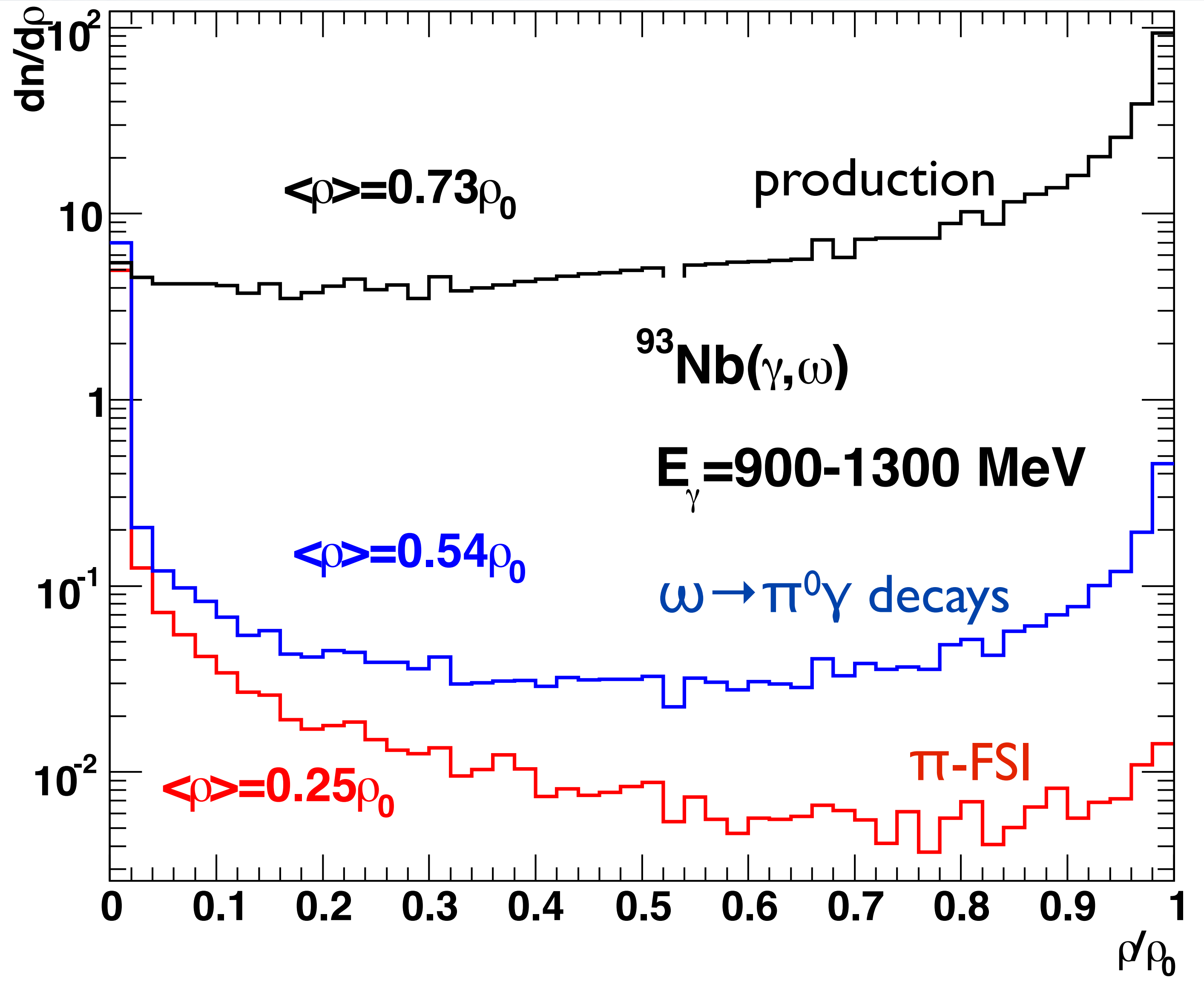
$\Gamma_{\eta'}(\langle p_{\eta'} \rangle \approx 1.05$ GeV/c $) \approx 25$ MeV;
$\sigma_{\eta'}^{inel} \approx 11$ mb

study of ω in-medum signal in GiBUU simulations

study of ω in-medum signal in GiBUU simulations

S. Friedrich: density distributions



average density finally probed only $\langle\rho\rangle \approx 1/4\ \rho_0$

study of ω in-medum signal in GiBUU simulations

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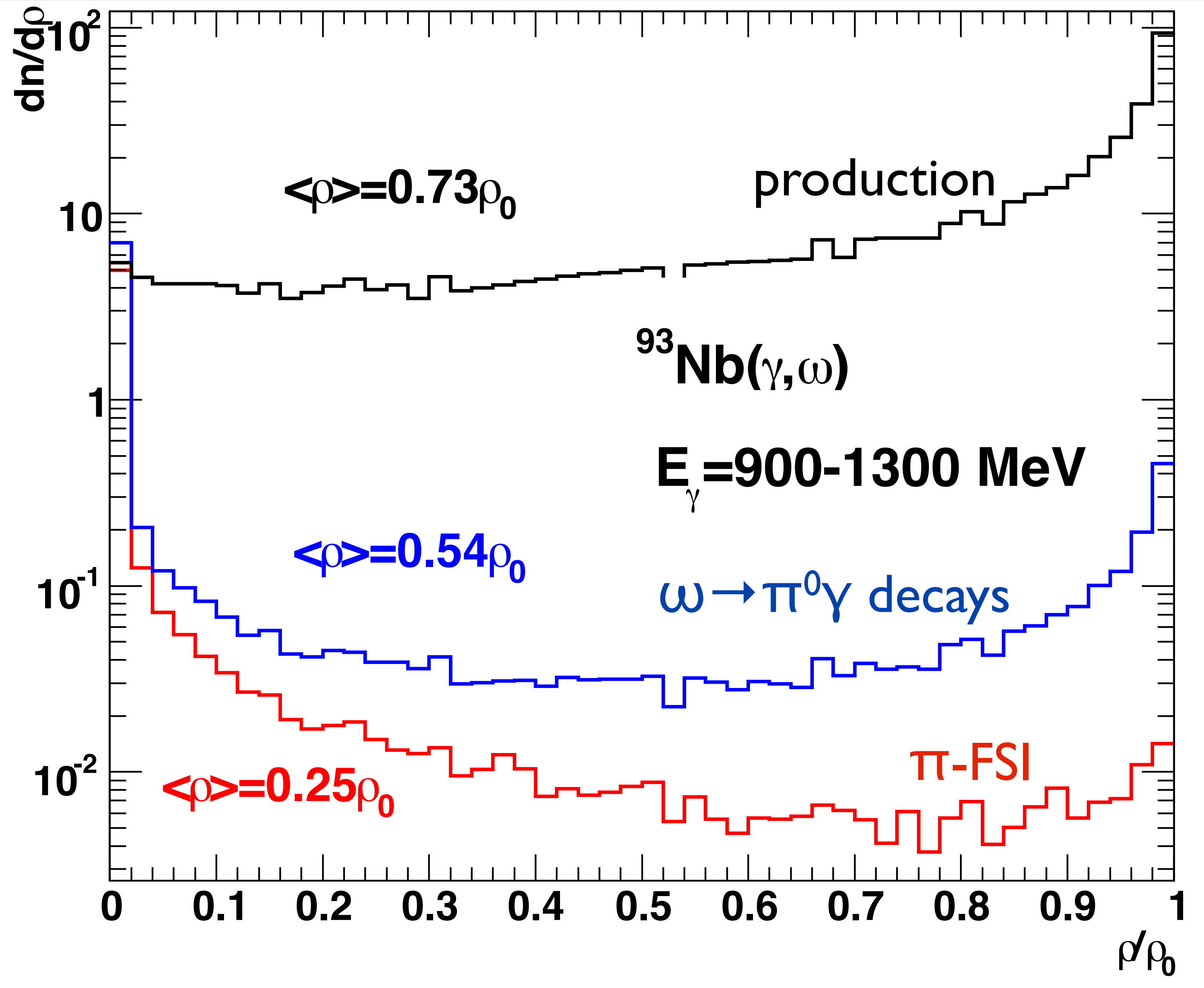

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10 000 ω produced

220 $\omega \rightarrow \pi^0\gamma$ decays

125 $\omega \rightarrow \pi^0\gamma$ decays reconstructed

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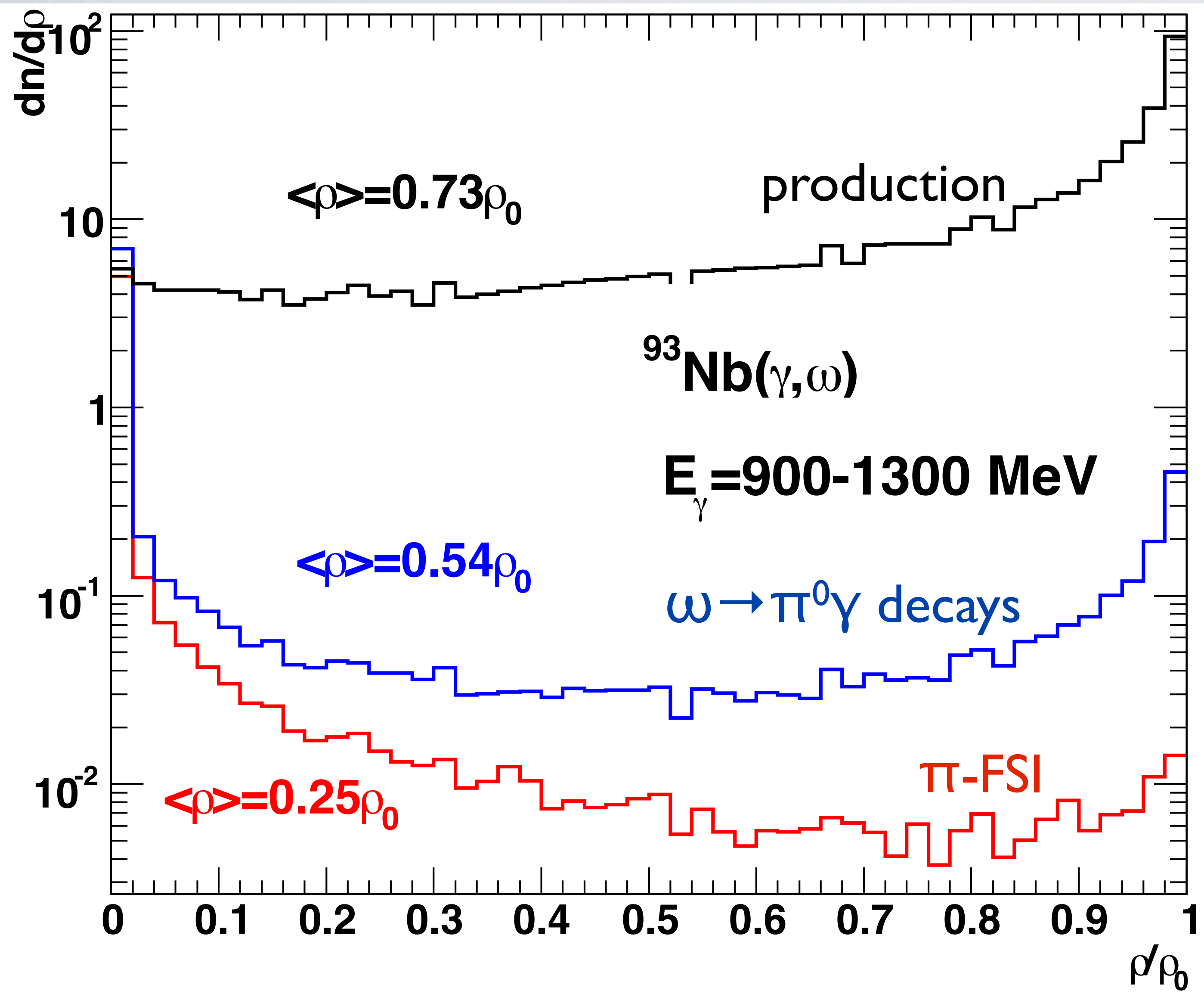
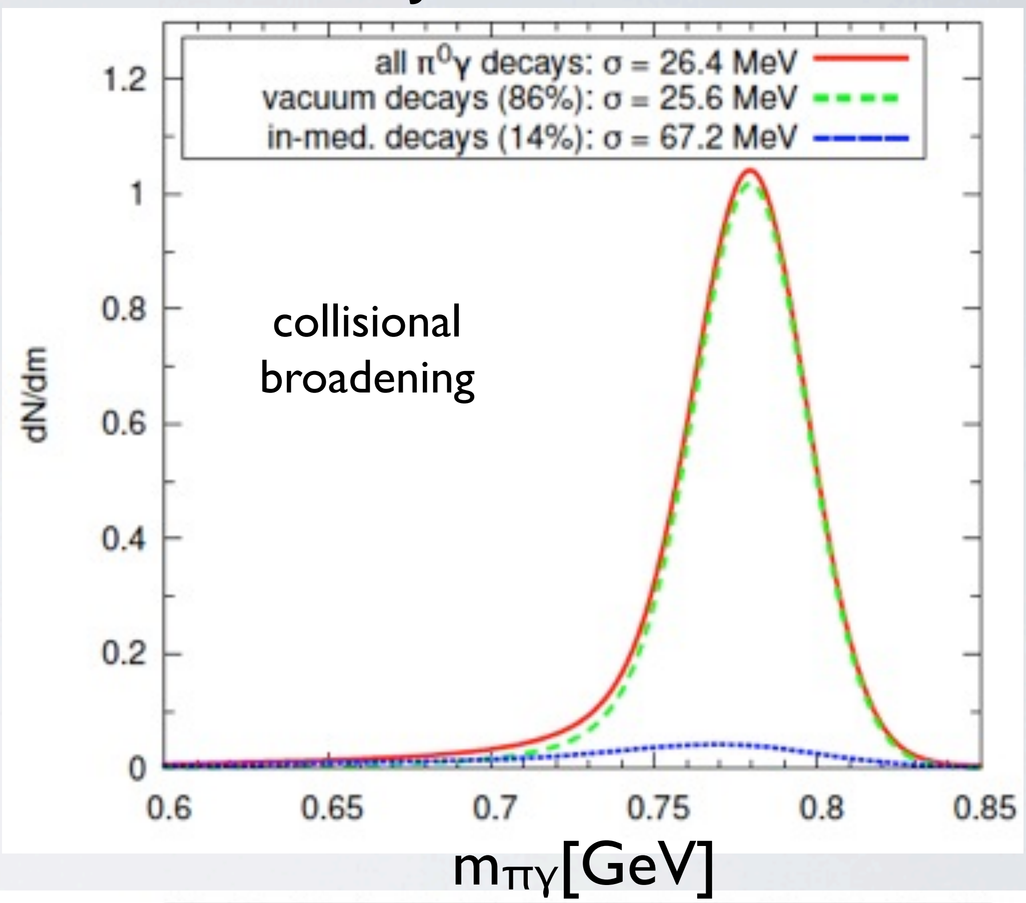
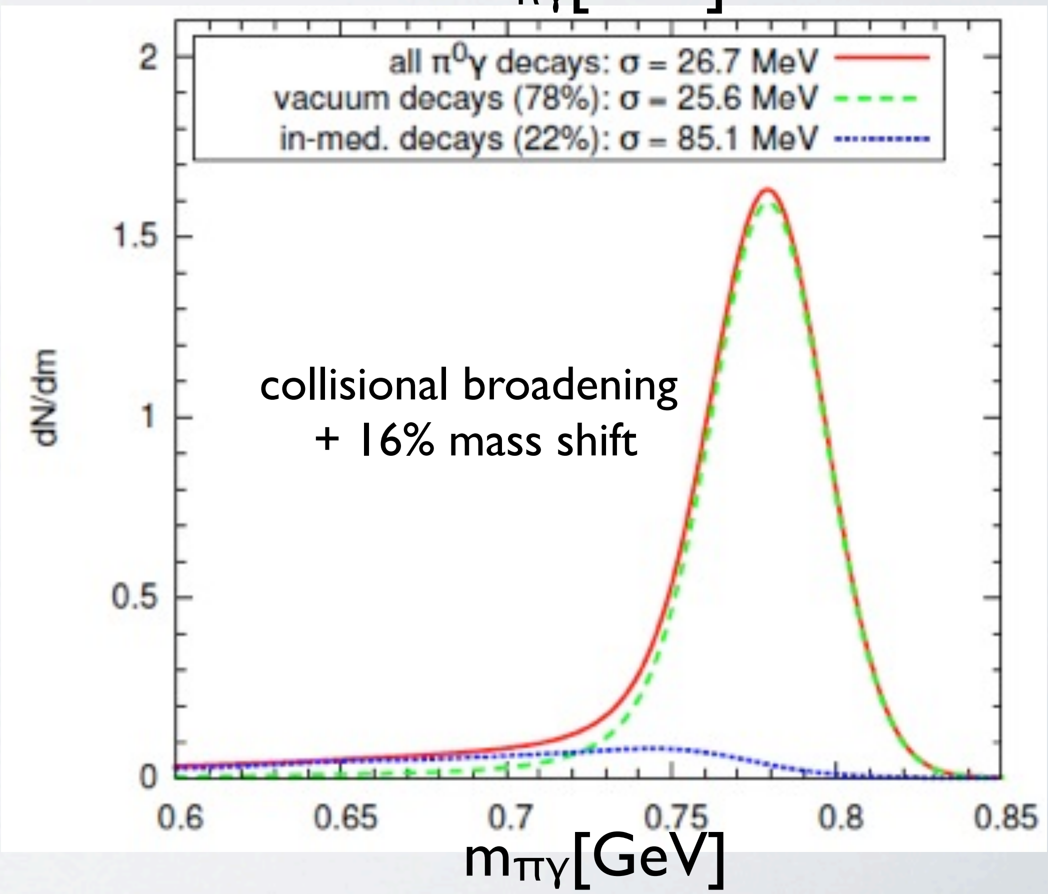


Janus Weil





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only marginal differences in ω lineshape
for different in-medium modification scenarios