Overview over meson-nucleus interactions and mesic states

Volker Metag
II. Physikalisches Institut
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
and University of Bonn, Germany

Outline:
- meson-nucleon interactions: ω, η’
- meson-nucleus interactions: ω, η’ - A
- bound few body systems
- search for meson-nucleus bound states (π, η, ω, η’)
- summary & outlook

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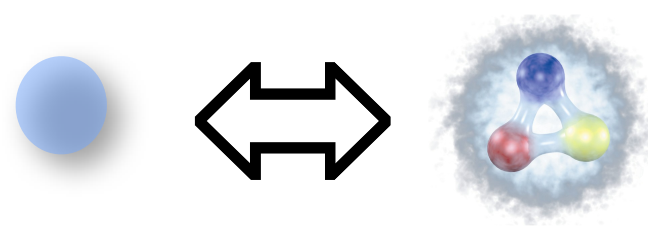
universitätbonn
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Symposium on Fundamental and Applied Subatomic Physics
Cracow, Poland, June 8-12, 2015

HIC for FAIR
Helmholtz International Center

meson-nucleon interactions

meson  nucleon

determination of the scattering length
from near-threshold meson production

meson-nucleon interaction

η'

COSY11

meson-nucleon interaction:

for short-lived mesons (η, ω, η', Φ)
no beams available; study of
meson-nucleon interaction
by final state interactions
in elementary reactions,
e.g. p + p ⇒ p + p + η'

$$|M_{pp\to pp\eta'}|^2 \approx |M_0|^2 |M_{FSI}|^2$$

$$M_{FSI} = M_{pp}(k_1) \times M_{p_1\eta'}(k_2) \times M_{p_2\eta'}(k_3).$$

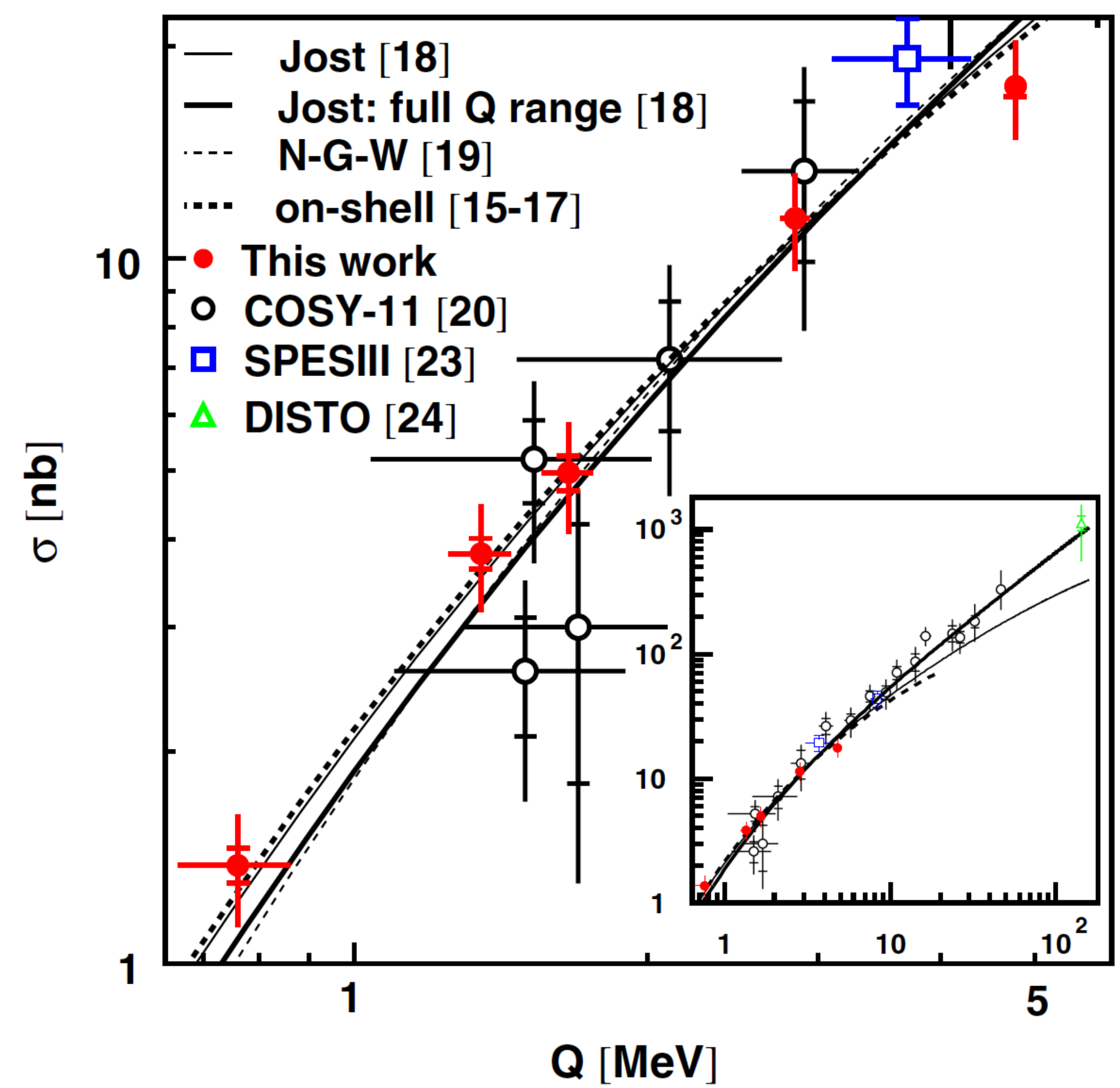
problem: pp FSI very strong

⇒ scattering length |a| (only modulus)

- interaction attractive or repulsive ?

E. Czerwinski et al., PRL 113 (2014) 062004

p + p ⇒ p + p + η'



$Re(a_{\eta' p}) = (0 \pm 0.43)$ fm;
$Im(a_{\eta' p}) = -(0.37^{+0.40}_{-0.16})$ fm

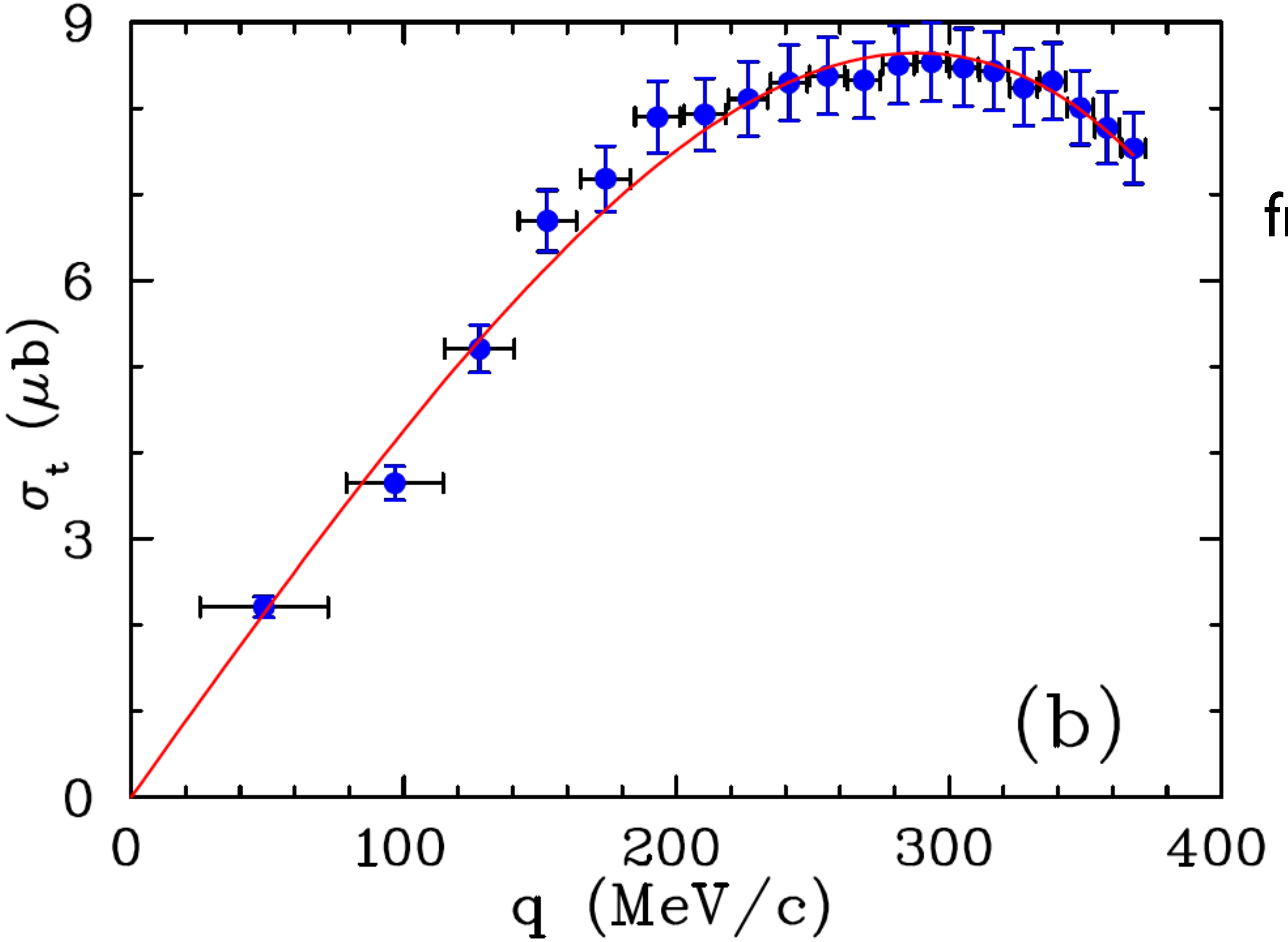
A2@MAMI

meson-nucleon interaction

ω

$\gamma p \rightarrow \omega p$ near threshold photo production

I. Strakowsky et al., PRC 91 (2015) 045207



Colin Wilkin

information on scattering length from cross section near threshold

$$\sigma_t = \frac{q}{k} \cdot \frac{4\alpha\pi^2}{\gamma^2} \cdot |a_{\omega p}|$$

$$|a_{\omega p}| = (0.82 \pm 0.03\ )\ \text{fm}$$

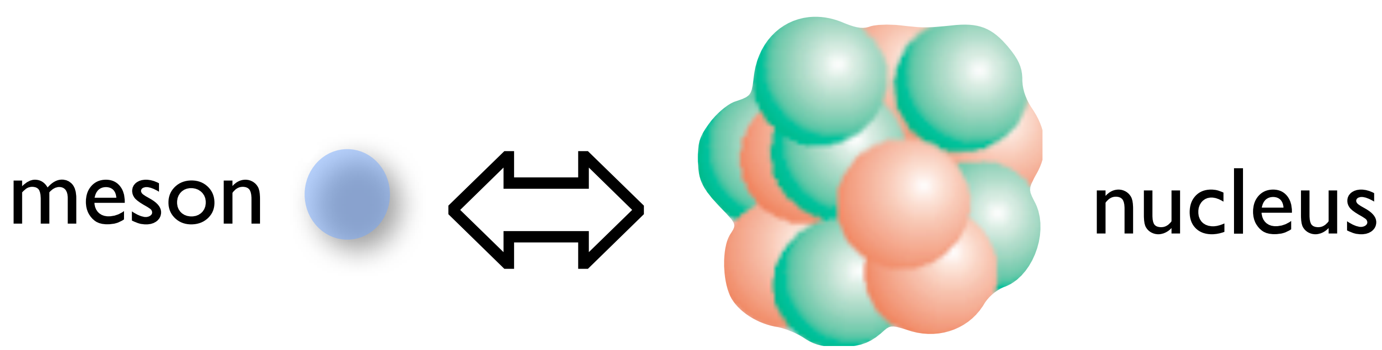
consistent with scattering amplitude deduced from ω-nucleus optical potential

(M. Kotulla et al., PRL 100 (2008) 192302; S. Friedrich et al., PLB 736 (2014) 26)

$$a_{\omega N} = -((0.17 \pm 0.40) + i\ (0.79 \pm 0.11))\ \text{fm}$$

$$|\ a_{\omega N}\ | = (0.81 \pm 0.41)\ \text{fm}$$

meson-nucleus interactions: real and imaginary part of the meson-nucleus optical potential



meson-nucleus optical potential

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

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

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

in-medium mass modification

real part

⇕

in-medium mass modification

reduction of lifetime

imaginary part

⇕

in-medium width
inelastic cross section

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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imaginary part

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

- transparency ratio measurement

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

imaginary part of the optical potential from transparency ratio measurements

Photoproduction of ω and η’ mesons on nuclei

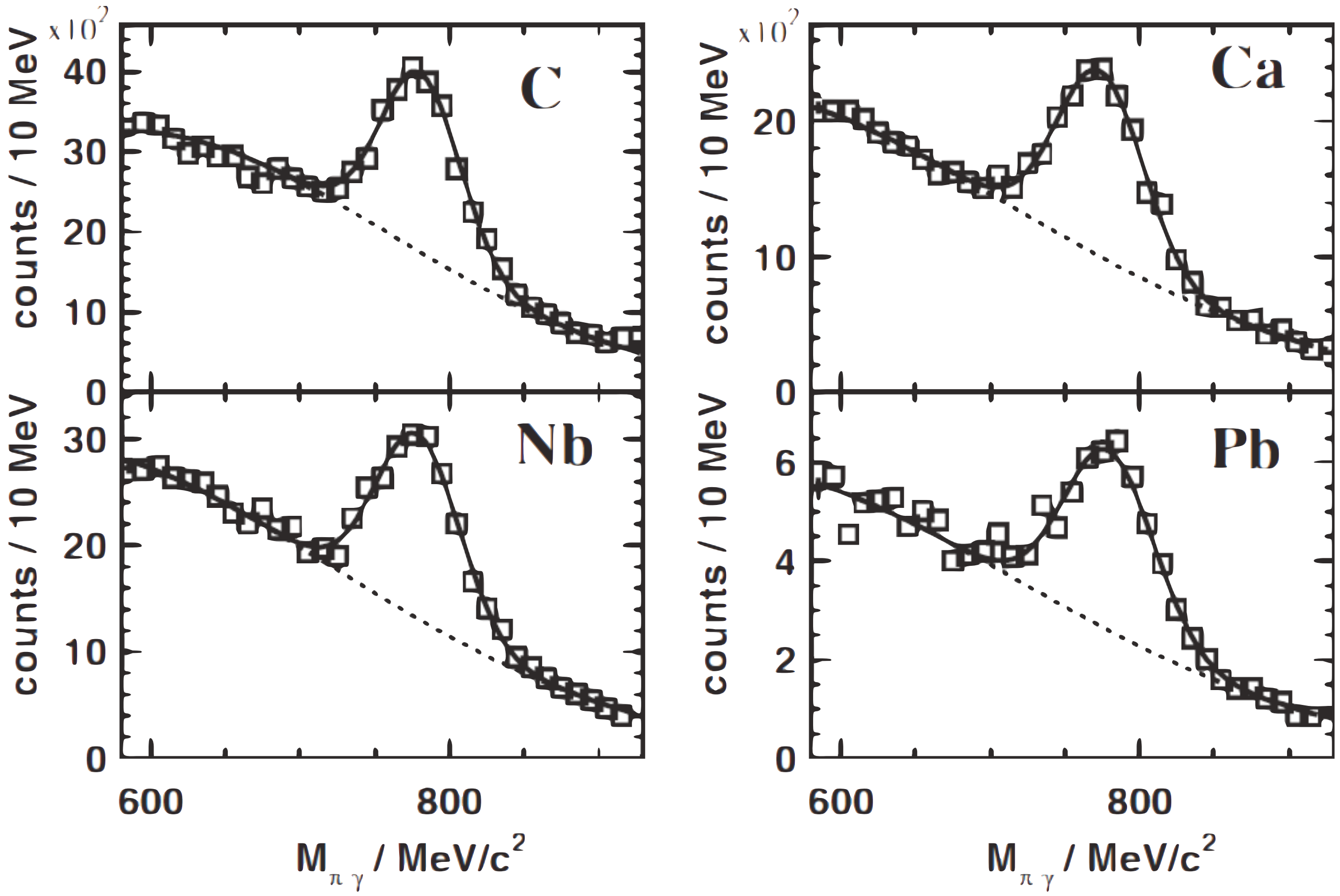
ω

experiments performed with the CBELSA/TAPS detector (Bonn)

η’

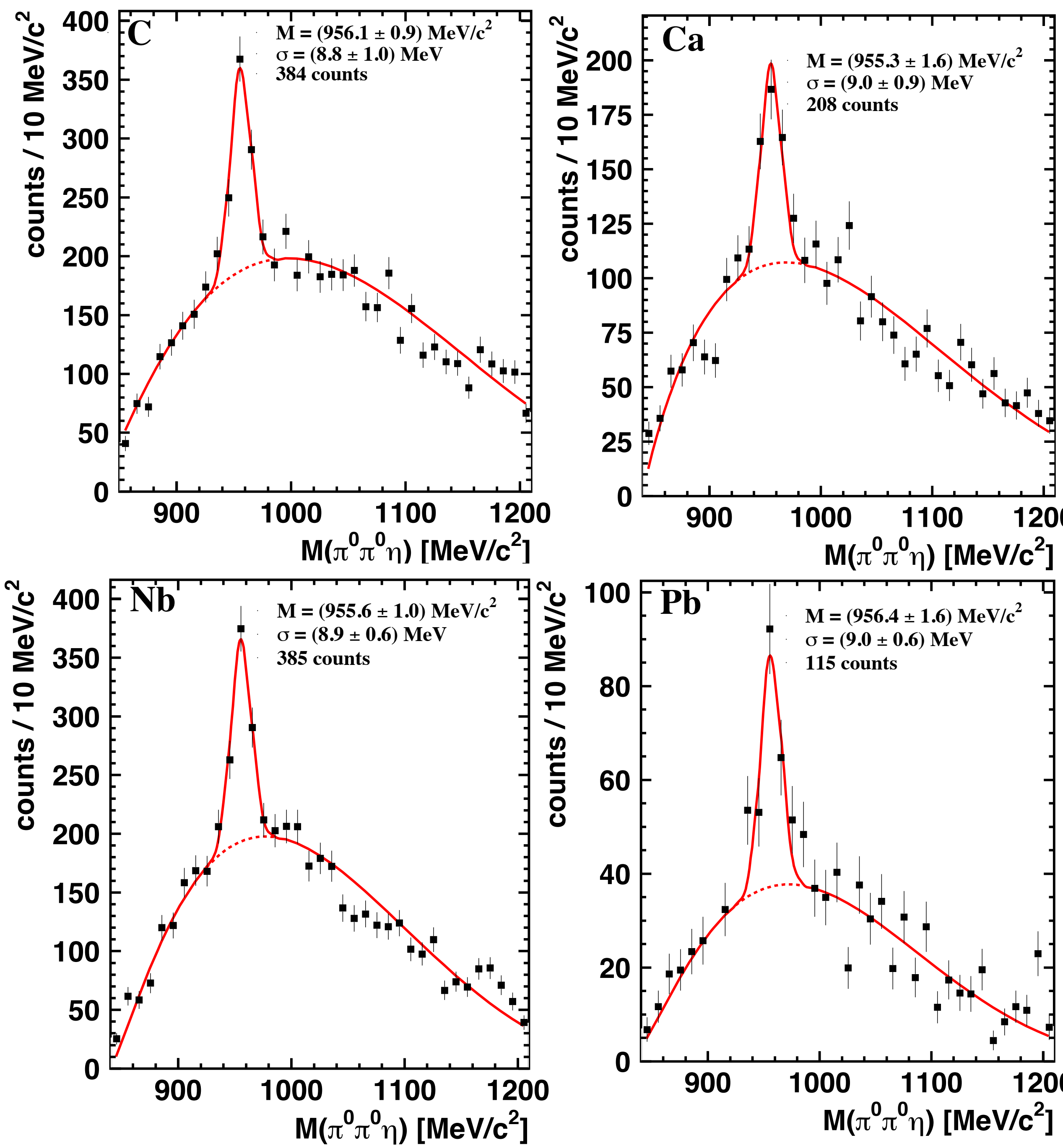
$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$

M. Kotulla et al, PRL 100 (2008) 19230



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

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



transparency ratio

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

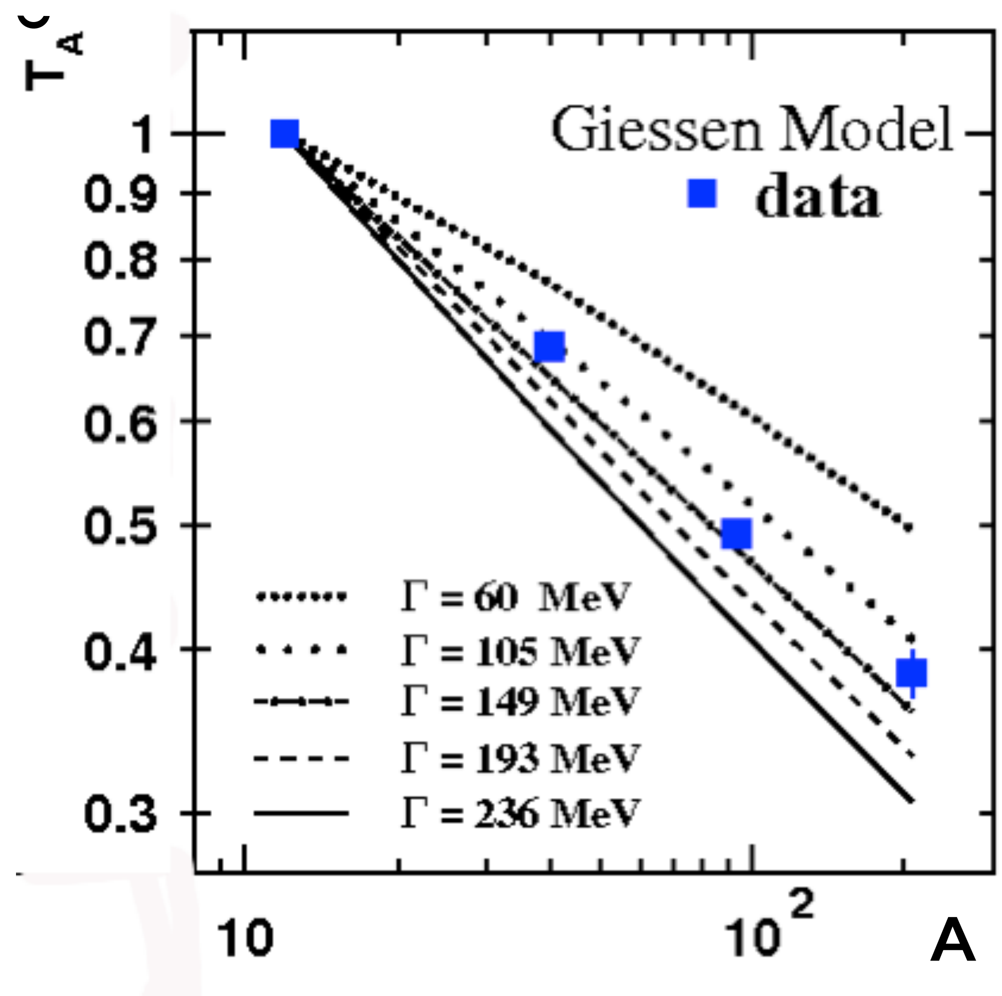
imaginary part of the ω- and η'-nucleus optical potential

ω

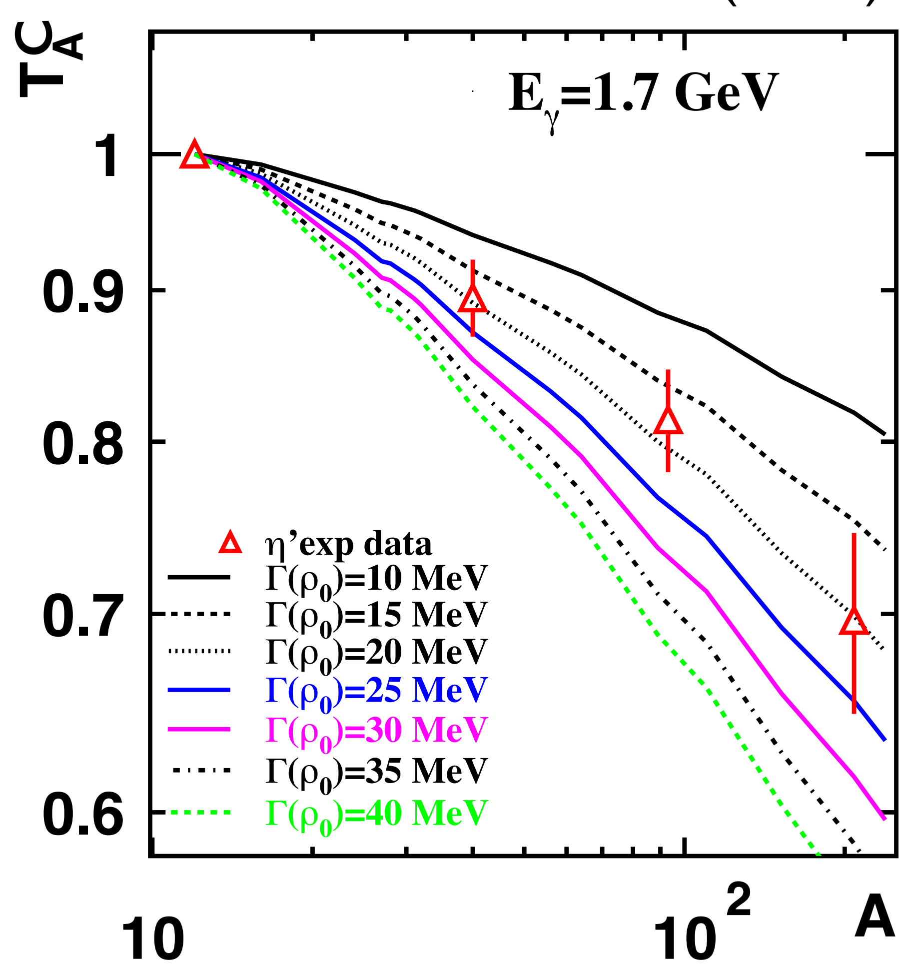
η'

$$T_A^C = \frac{12\cdot\sigma_{\gamma A\to\eta' X}}{A\cdot\sigma_{\gamma C\to\eta' X}}$$ normalized to carbon

M. Kotulla et al.,
PRL 100 (2008) 192302,
PRL 114 (2915) 199903



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



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

$\Gamma_\omega(\langle p_\omega\rangle = 1.1$ GeV/c; $\rho=\rho_0) \approx$ 130-150 MeV

$\sigma^{\omega}_{inel} \approx$ 60 mb

$\Gamma_{\eta'}(\langle p_{\eta'}\rangle \approx 1.05$ GeV/c $) \approx$ 15-25 MeV;

$\sigma^{\eta'}_{inel} \approx$ 3 -10 mb

ω: $W(\rho=\rho_0) = -\Gamma_0/2 = -(70\pm5)$ MeV

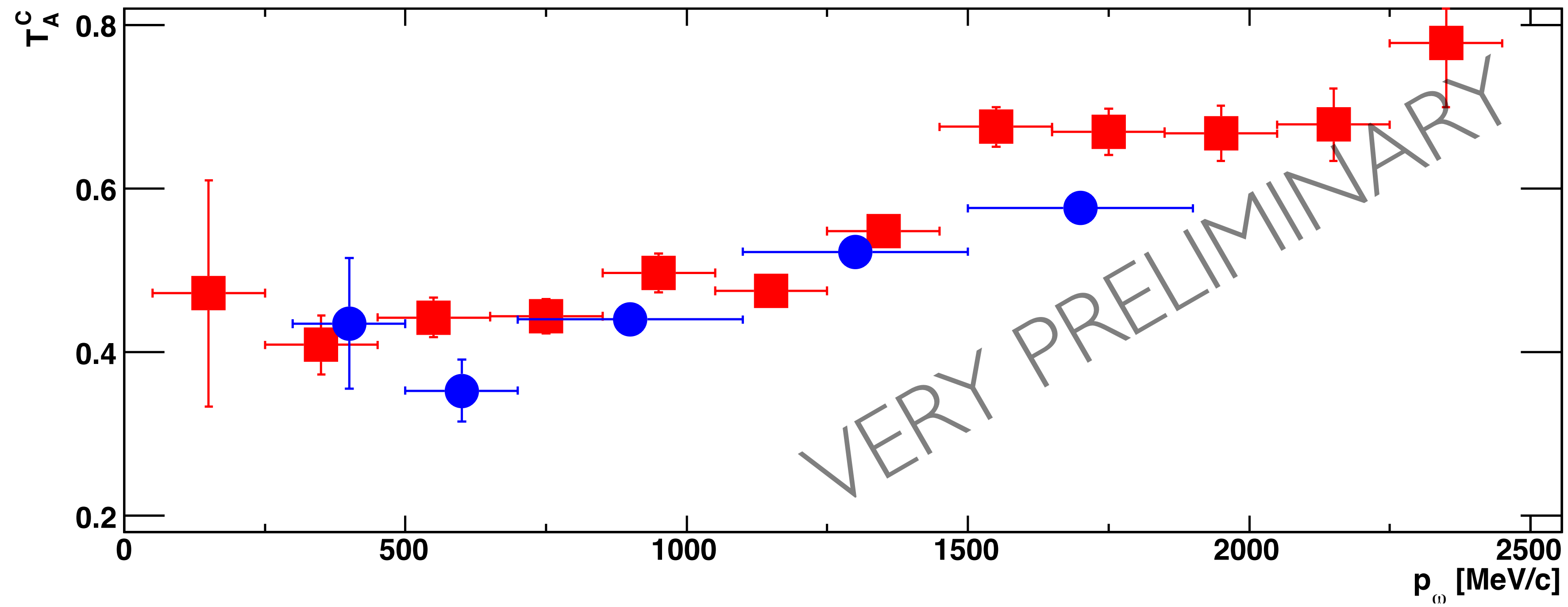
η': $W(\rho=\rho_0) = -\Gamma_0/2 = -(10\pm2.5)$ MeV

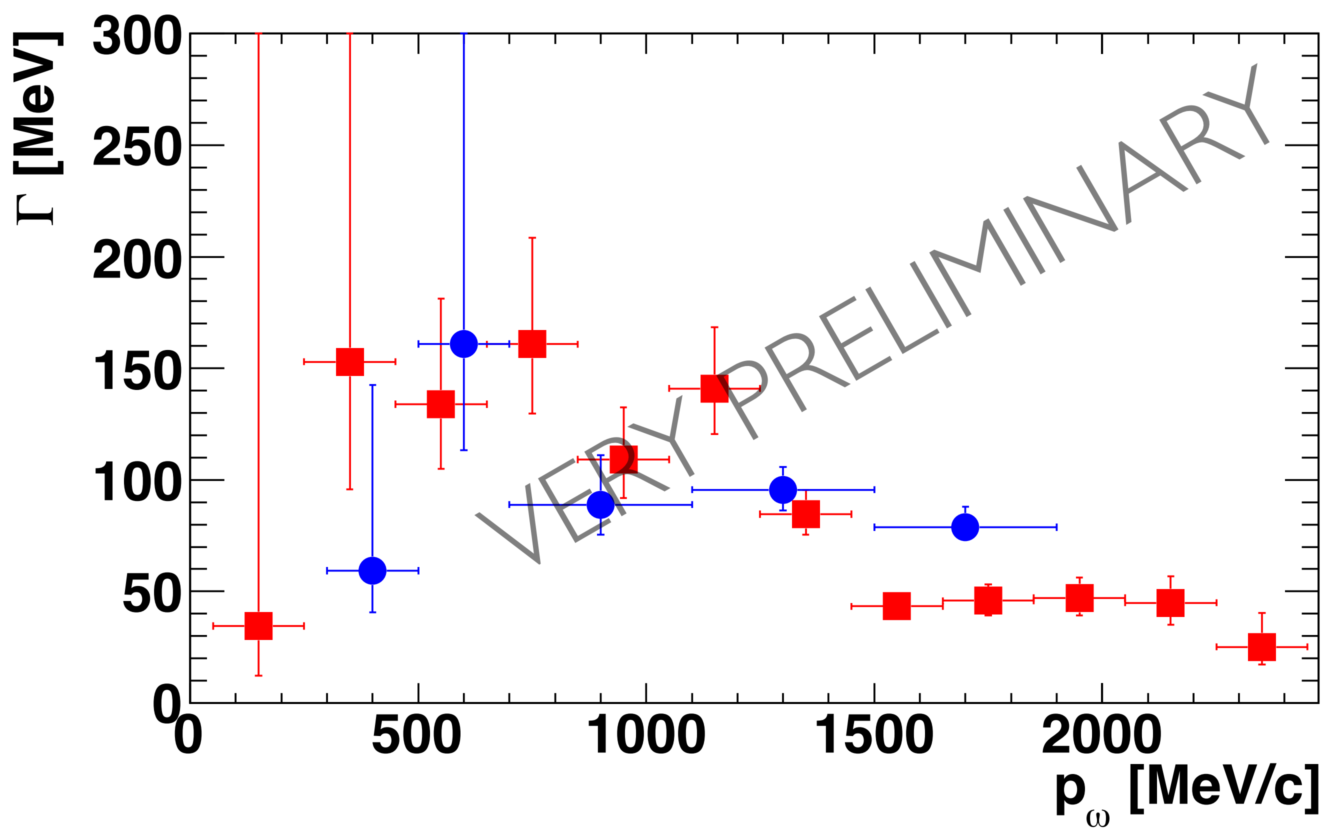
momentum dependence of $T_A{}^C$, Γ and σ_{inel} for ω mesons

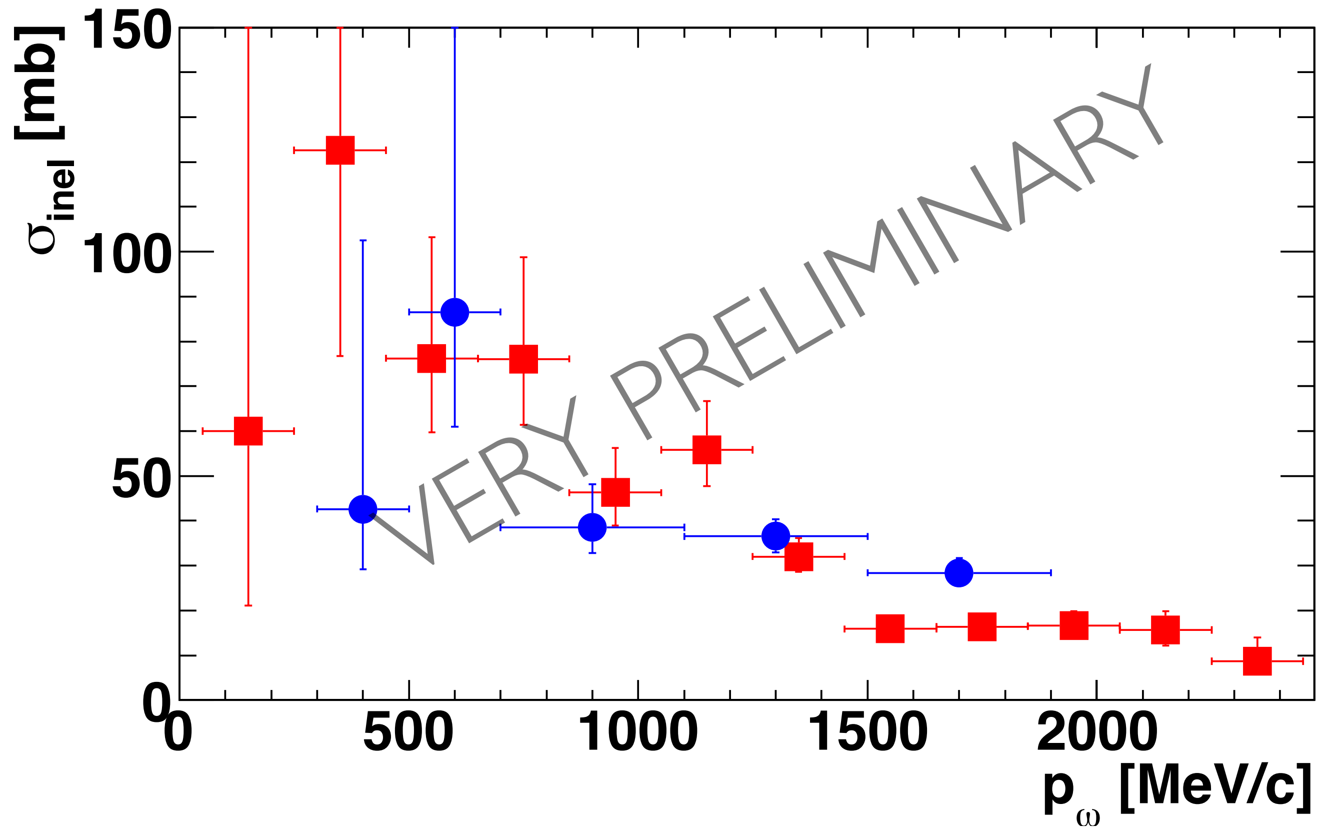
■ S. Friedrich et al.

● M. Kotulla et al.,
PRL 100 (2008) 192302
PRL 115 (2015) 199903

$$\Gamma(\rho_0) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}$$







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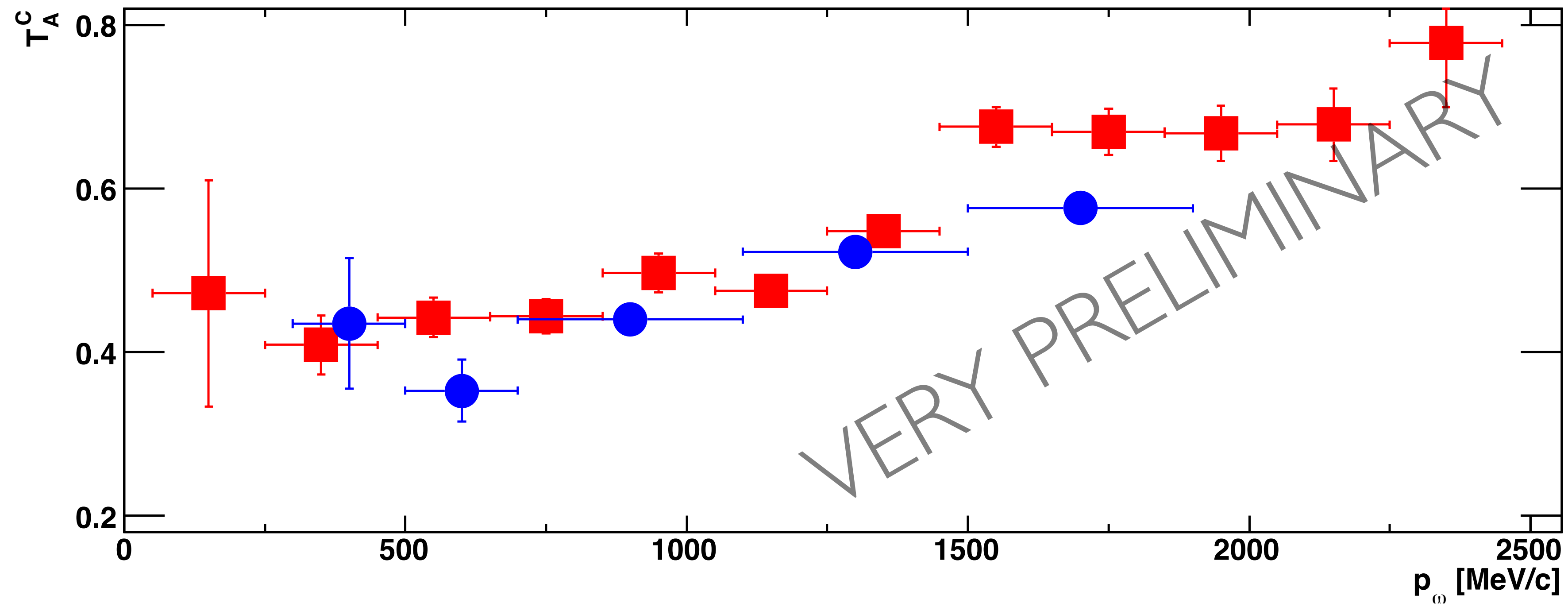

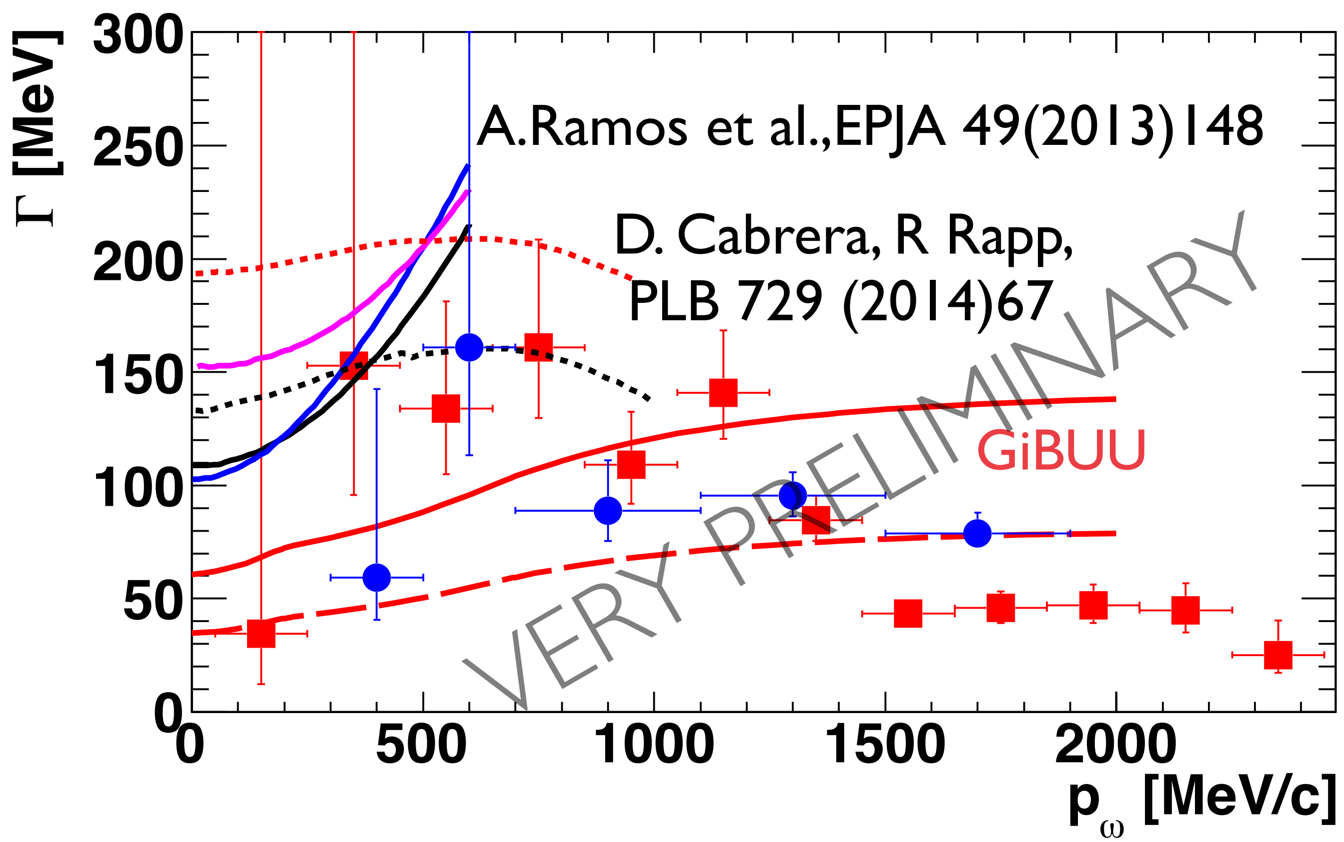

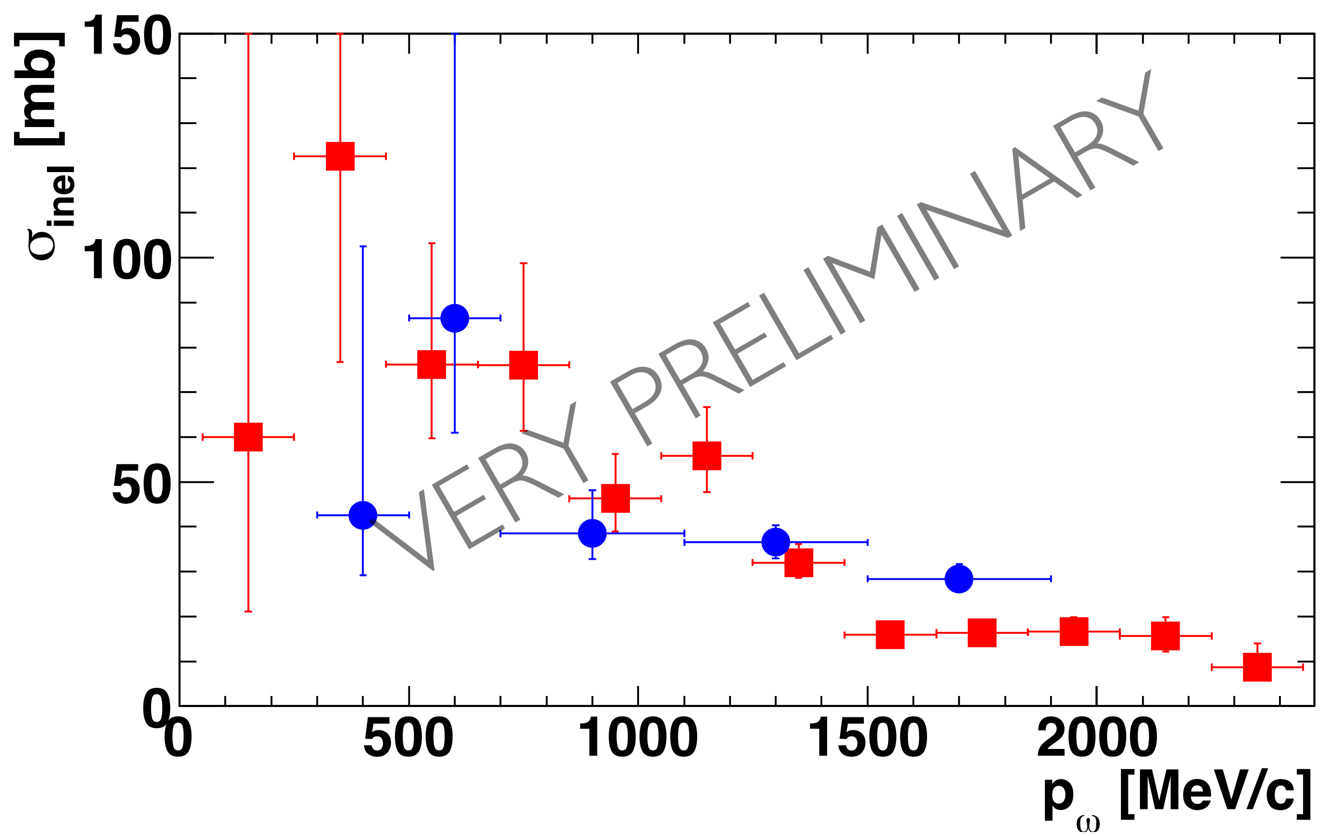

momentum dependence of T_A^C, Γ and σ_{inel} for ω mesons

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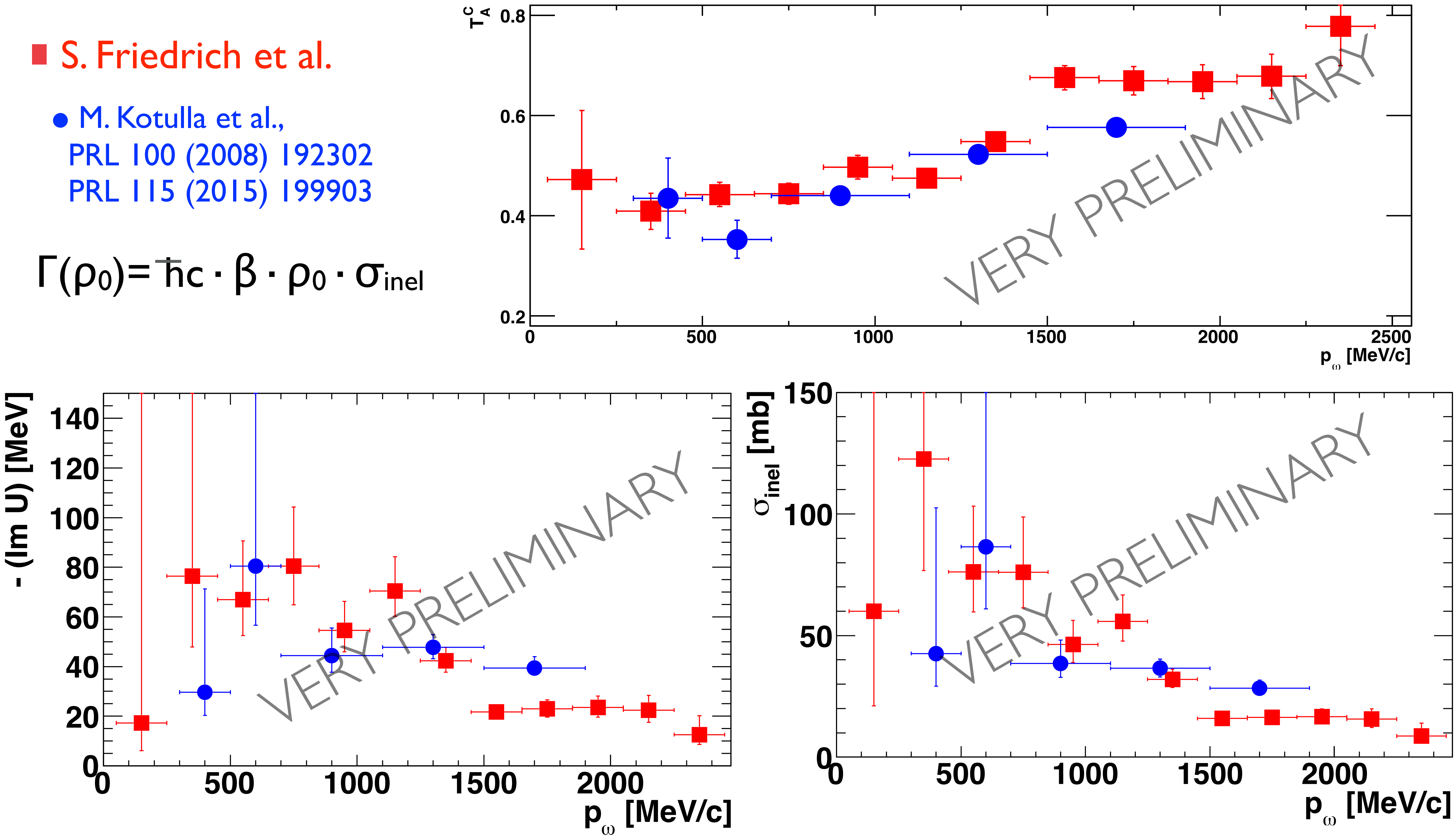


first information on momentum dependence of the imaginary part of the ω-nucleus optical potential; important for linking optical model parameters at high momenta to scattering length at production threshold

what have we learned from transparency ratio measurements ?

- transparency ratio measurements provide information on absorption of mesons in nuclei ⇒ imaginary part $W(\rho=\rho_0)$ of meson-nucleus potential; applicable for any meson lifetime

- **ω, η',Φ mesons show broadening in nuclei;** lifetime shortened (width increased) by inelastic processes

	$\Gamma(\rho_0)$ [MeV]	< p >[GeV/c]	$W(\rho=\rho_0)$ [MeV]	σ_{inel} [mb]	experiment
ω	130-150	1,1	65-75	≈ 60	CBELSA/ TAPS
η'	15-25	1,1	7.5-12.5	3-10	CBELSA/ TAPS
Φ	30-60	0,6-1,4	15-30	14-21	ANKE@ COSY
Φ	100^{+50}_{-30}	1,8	50^{+25}_{-15}	35^{+17}_{-11}	LEPS@ SPring-8

real part of the optical potential from excitation functions and momentum distributions

The real part of the ω-nucleus potential

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

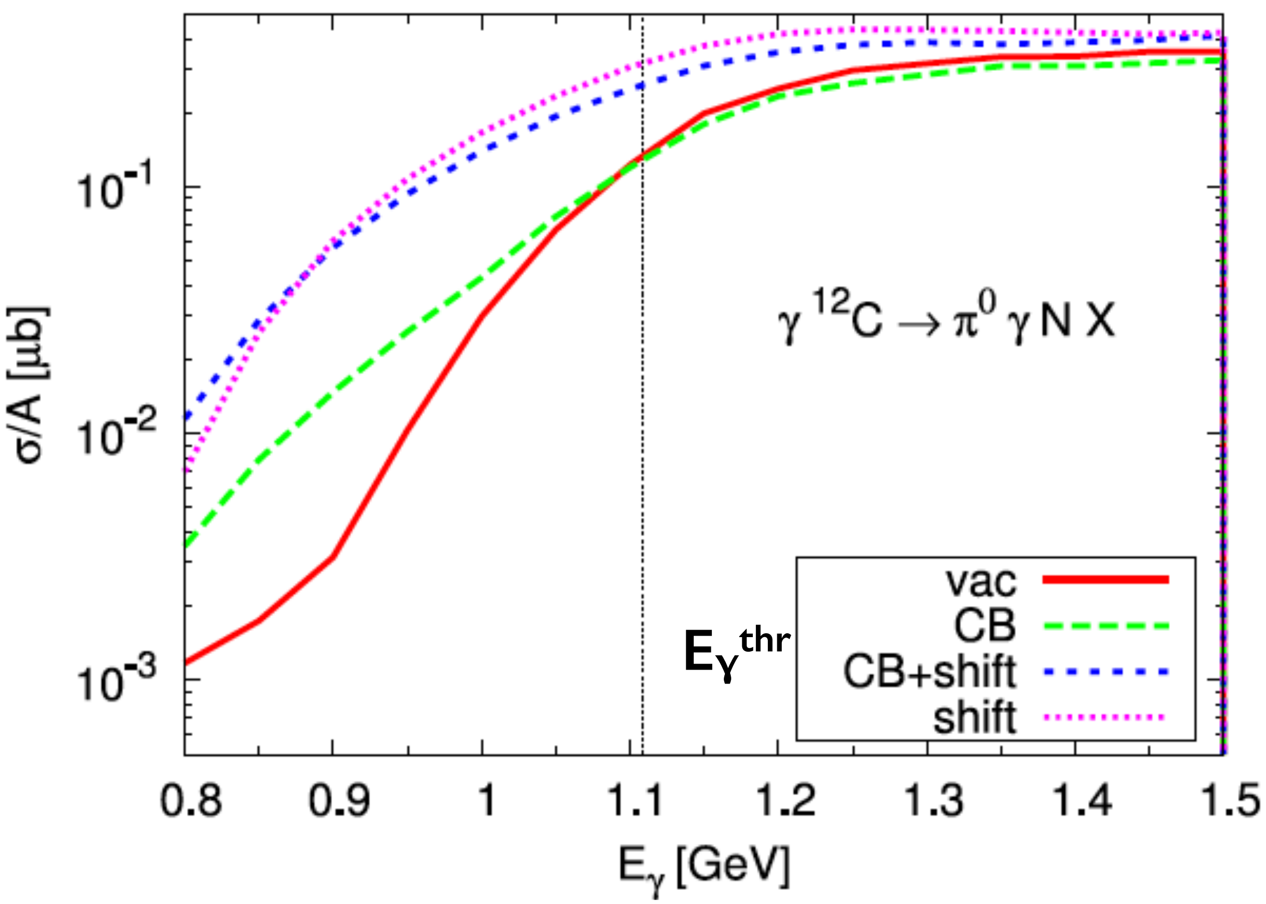
sensitive to nuclear density at production point

- 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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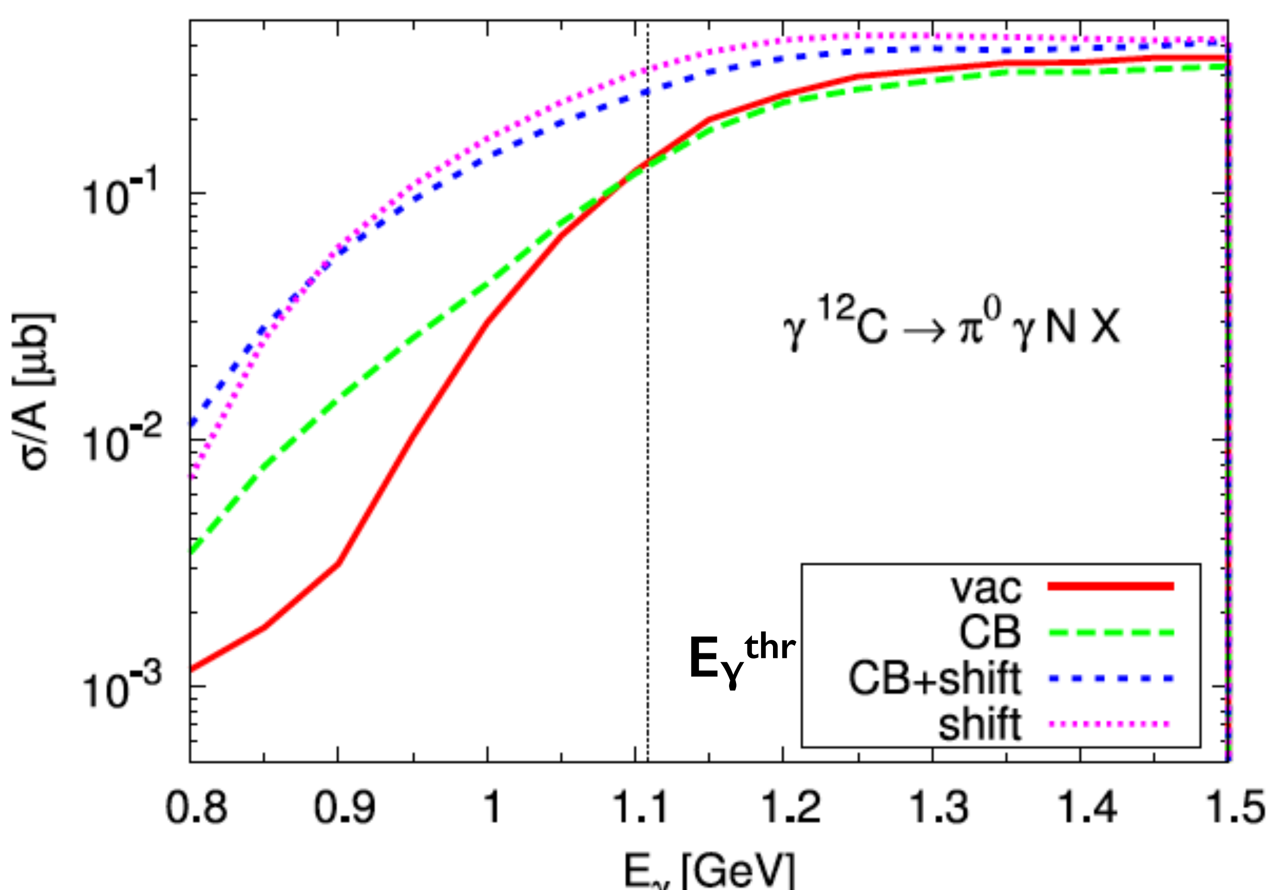
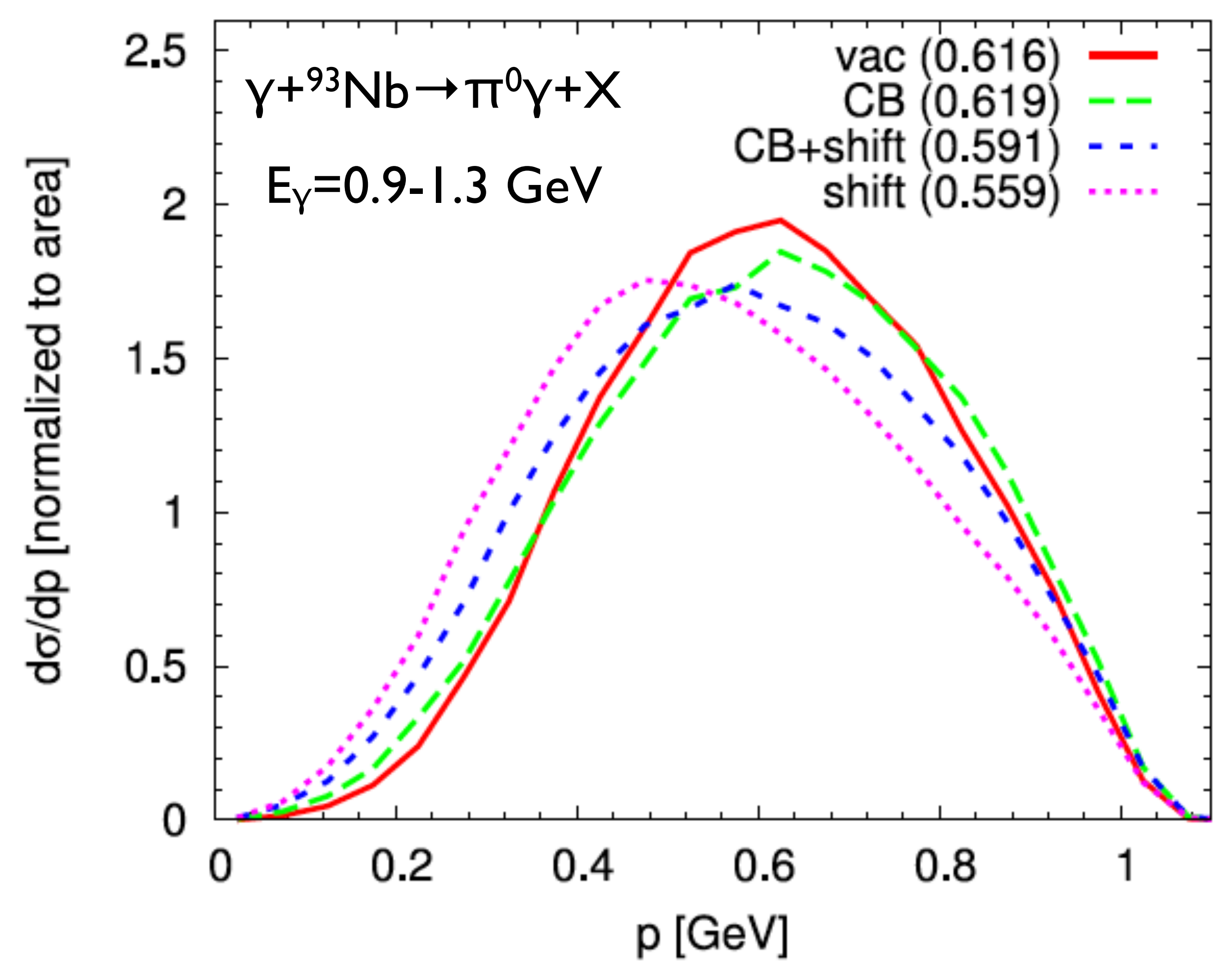


- momentum distribution of the meson:

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



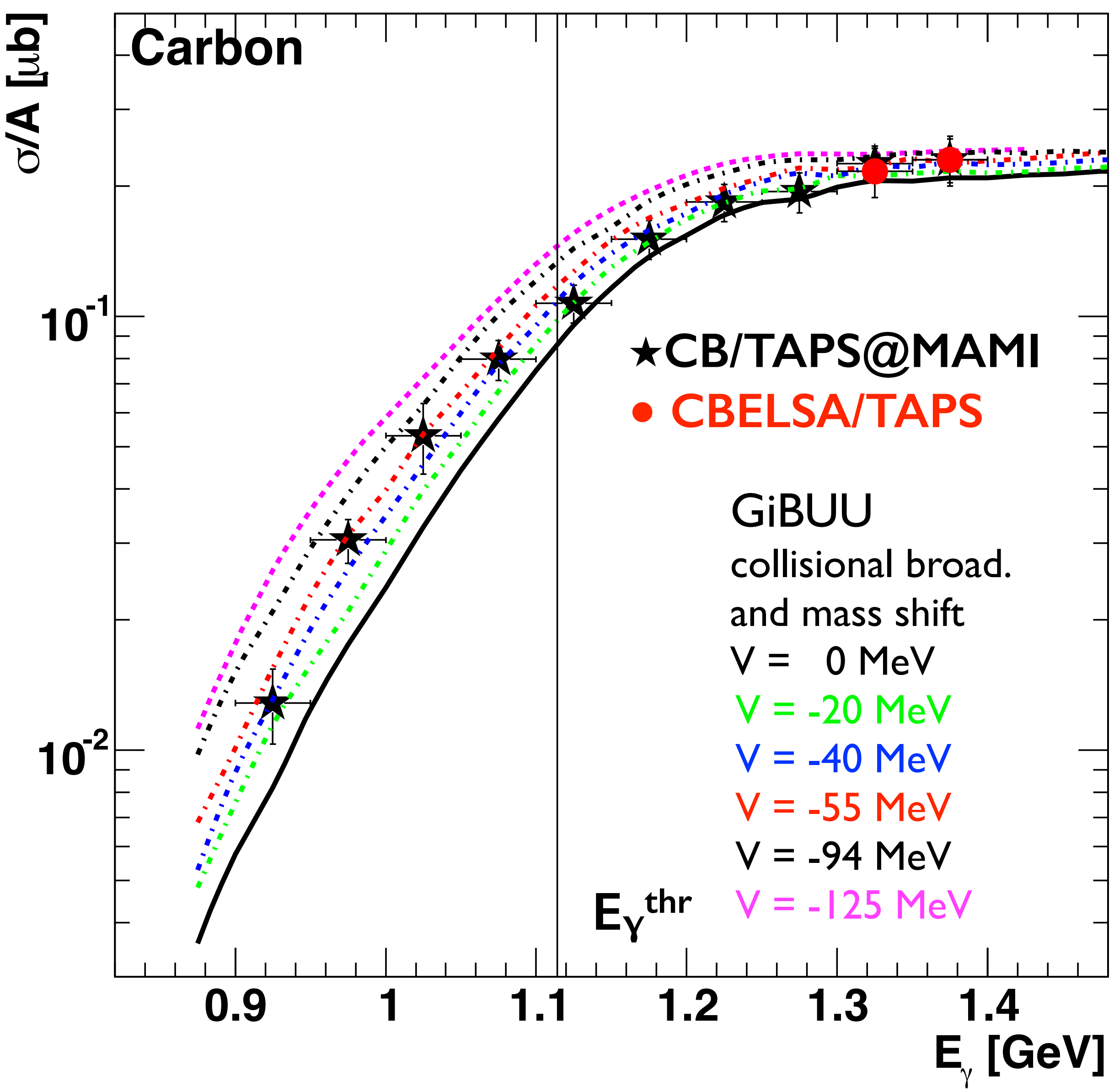
The real part of the ω-nucleus potential

ω

$\gamma A \to \omega X$

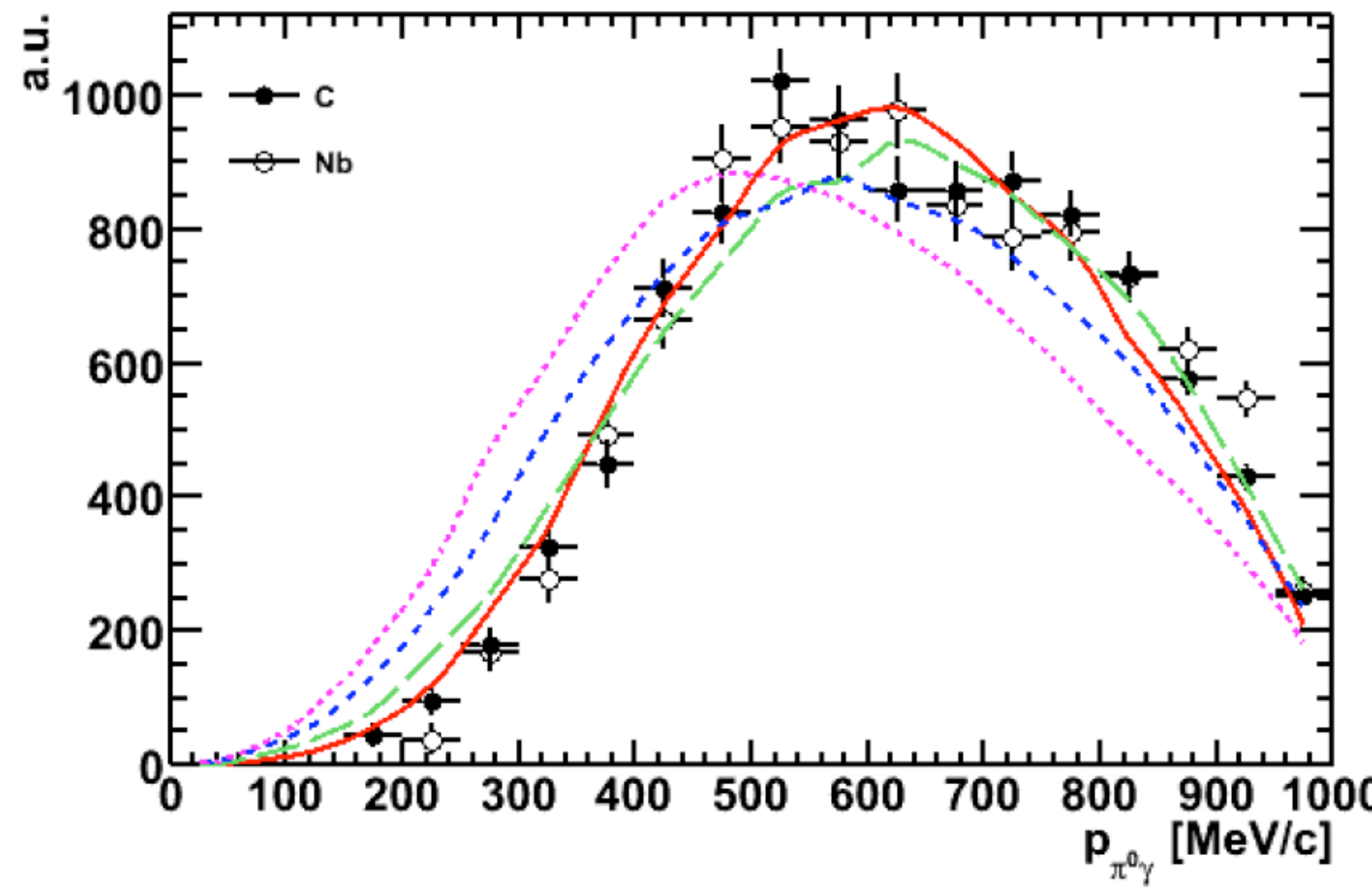
CB/TAPS @ MAMI

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



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

E_γ=900-1300 MeV



data not consistent with strong mass shift scenario ($\Delta m/m \approx$-16%)

$V_\omega(\rho=\rho_0)$ = -(42±17(stat)±20(syst)) MeV

The real part of the η'-nucleus potential

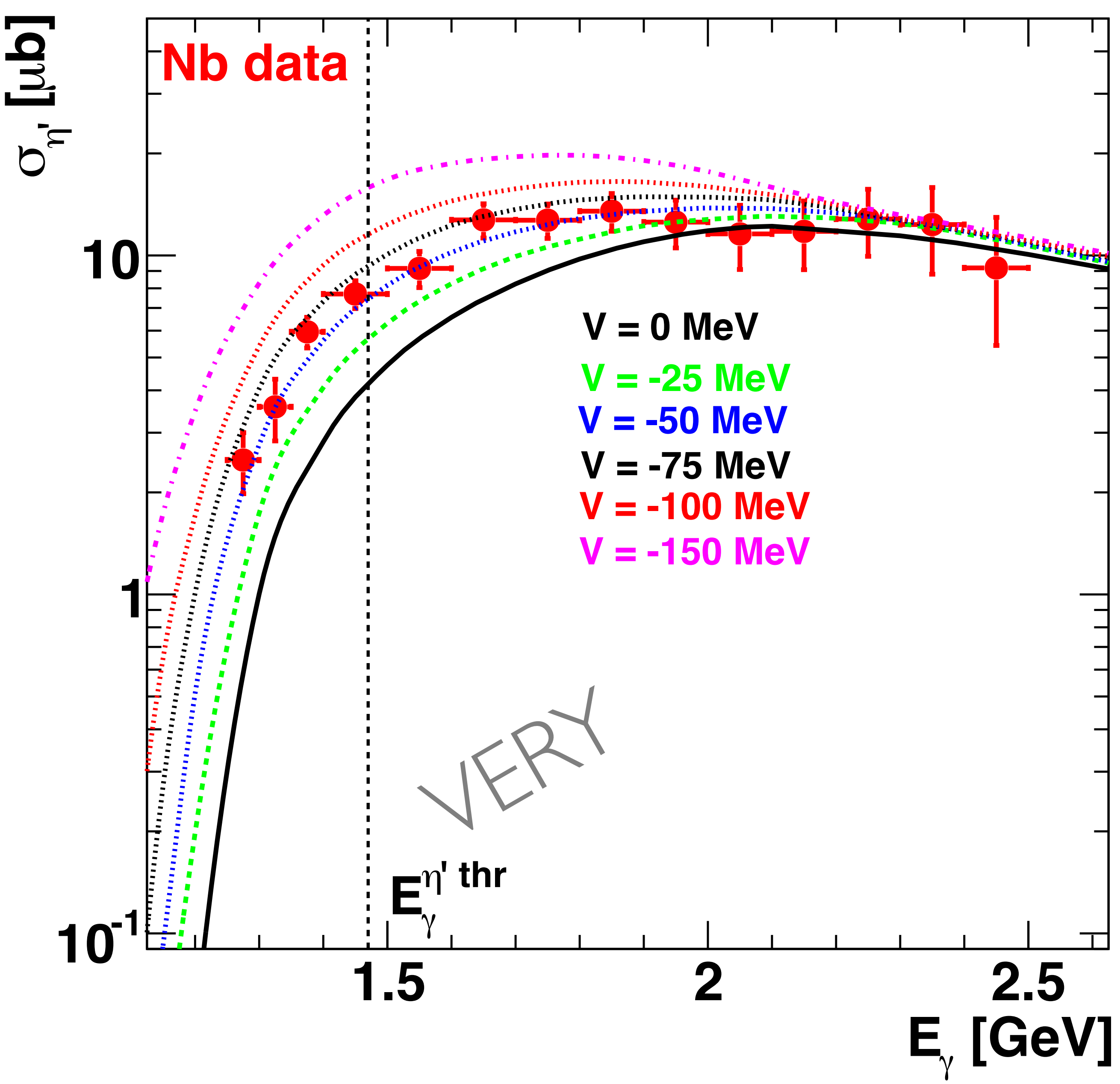
η'

Mariana Nanova

$\gamma A \rightarrow \eta' X$

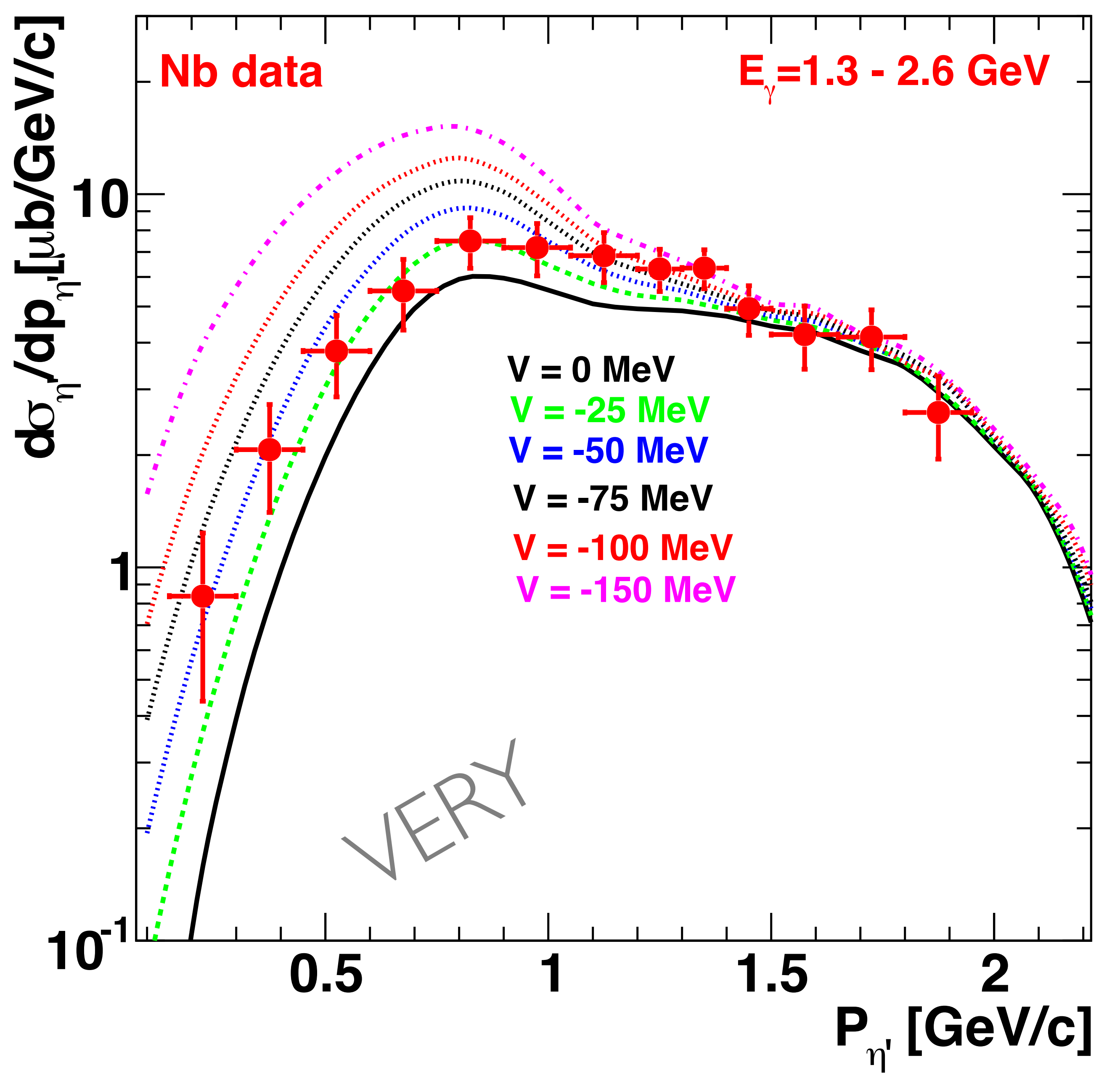
data compared to calculations by E. Paryev (priv. com.)

excitation function



$V_\eta(\rho=\rho_0) = -(57\pm8(stat)\pm15(syst))$ MeV

η' momentum distribution



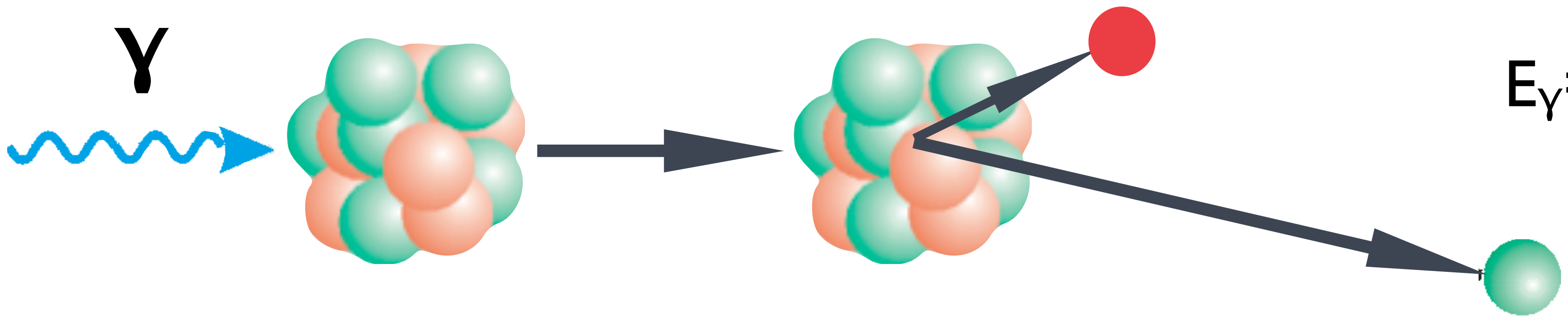
$V_\eta(\rho=\rho_0) = -(29\pm8(stat)\pm15(syst))$ MeV

$\langle p_{\eta'} \rangle \approx 1.1$ GeV/c

real part of η'-nucleus potential from η' kinetic energy

η'

CBELSA/TAPS @ ELSA

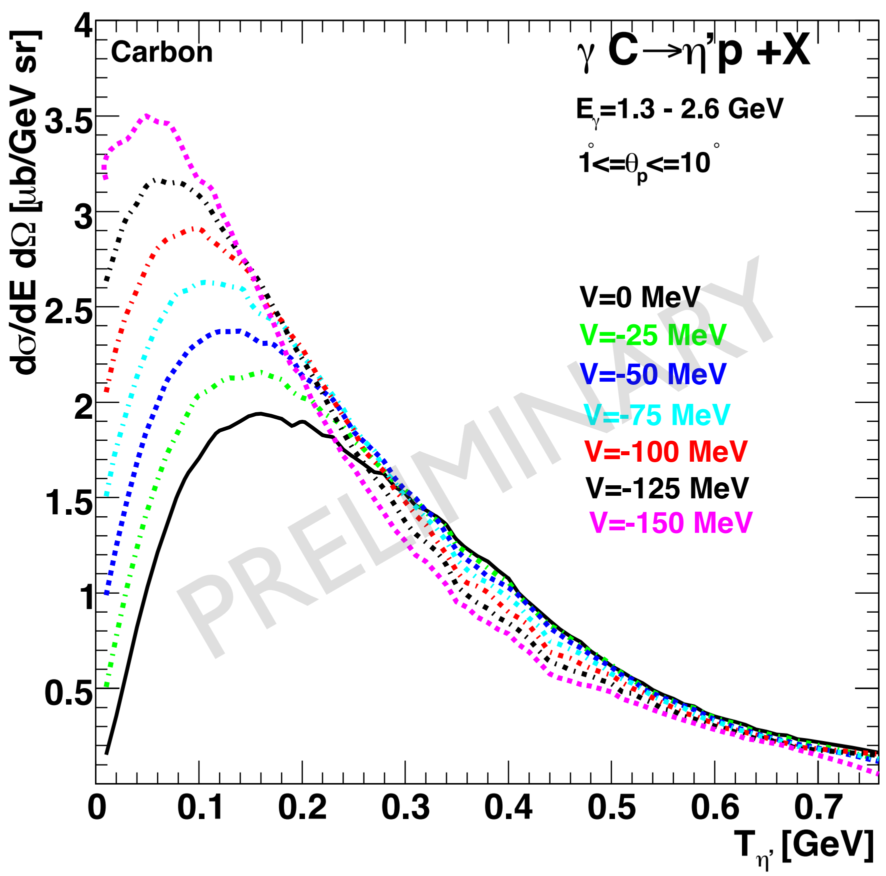


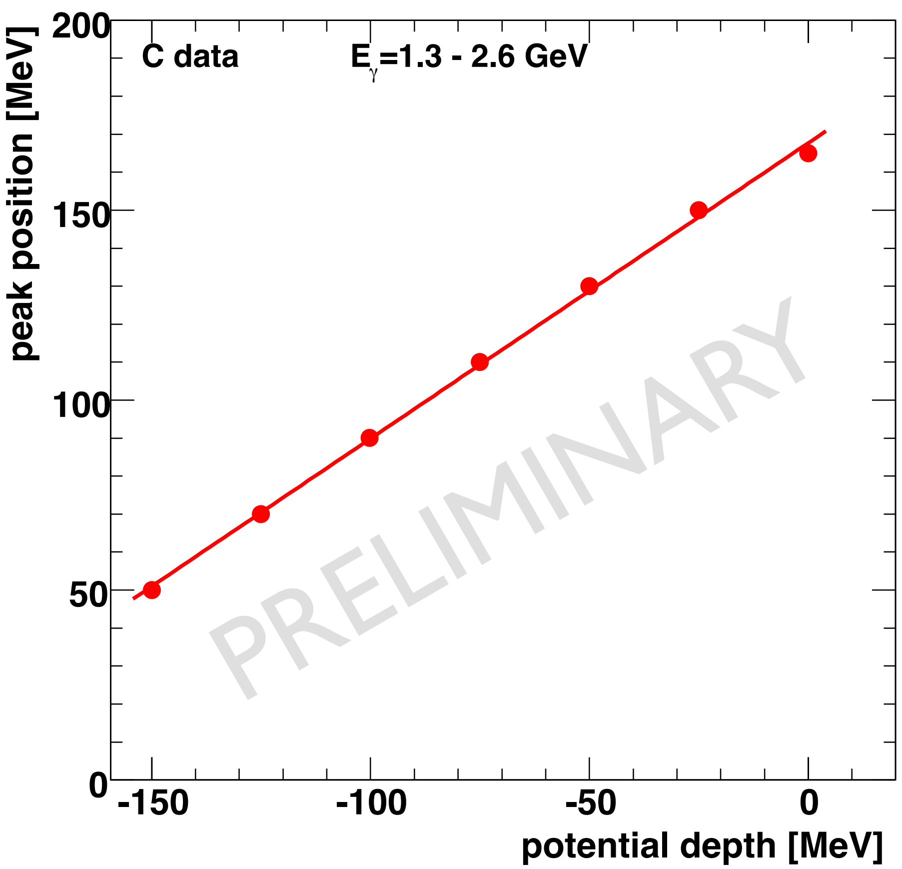
E_γ=1.3-2.6 GeV

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

the higher the attraction the lower the kinetic energy of the η' meson

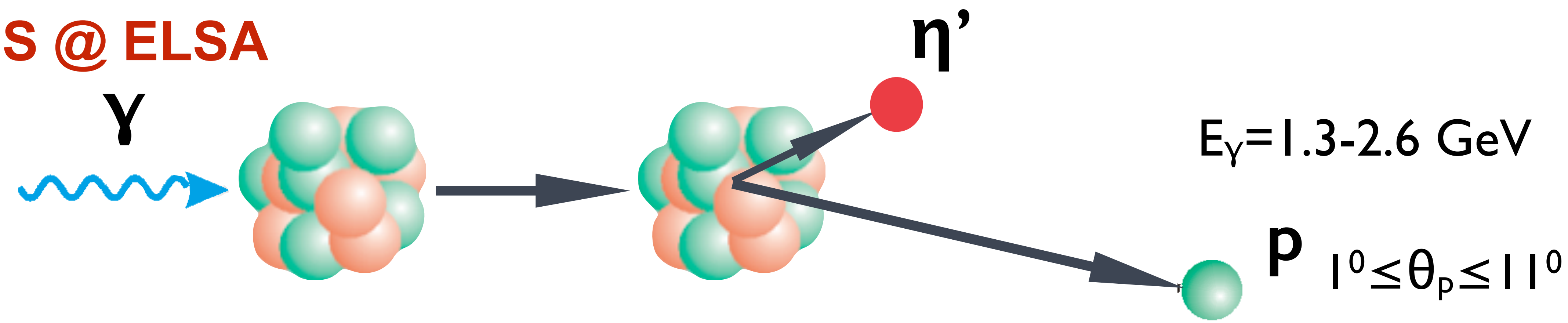
E. Paryev, arXiv:1503.09007





real part of η’-nucleus potential from η’ kinetic energy

CBELSA/TAPS @ ELSA



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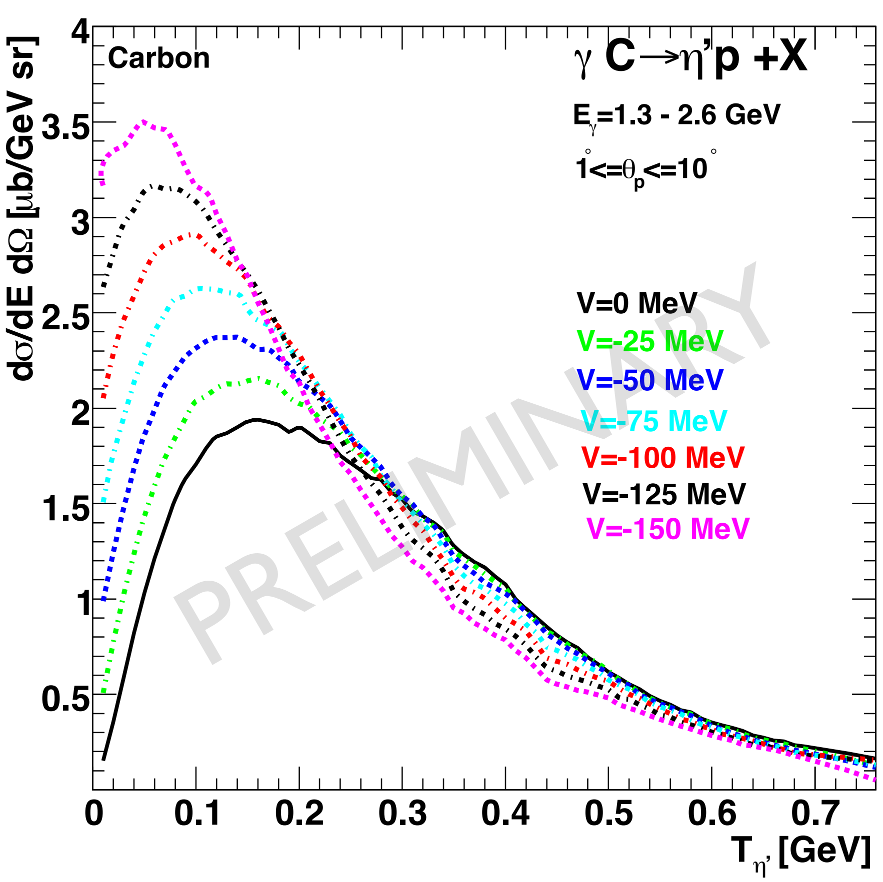
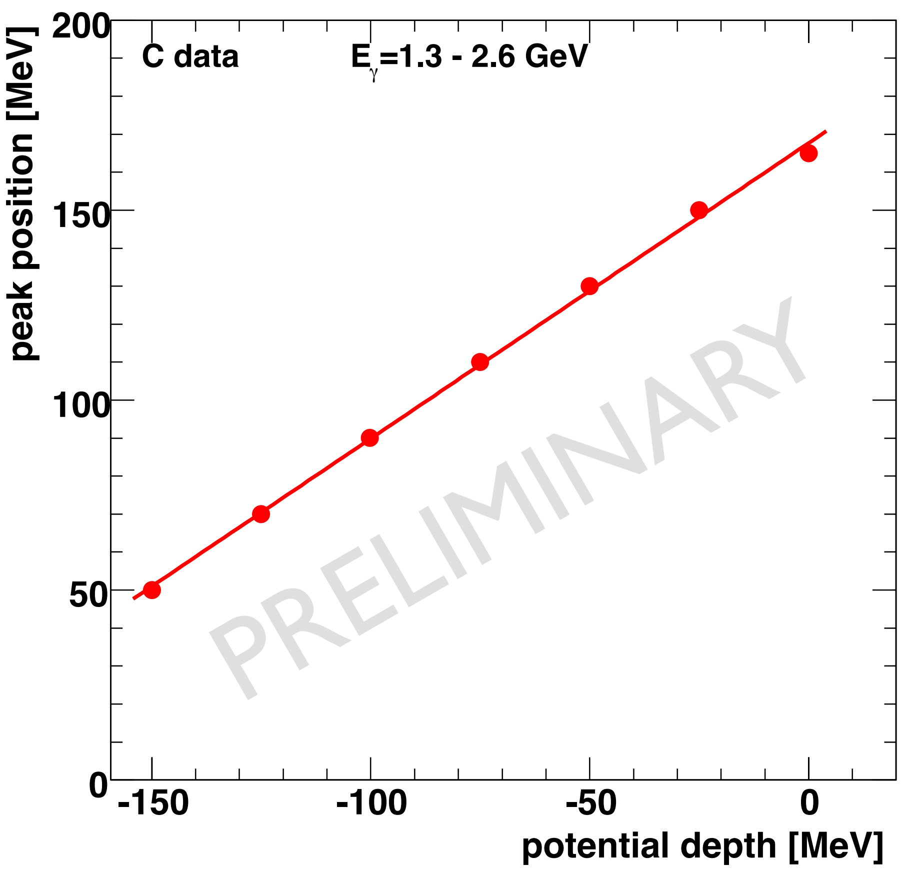
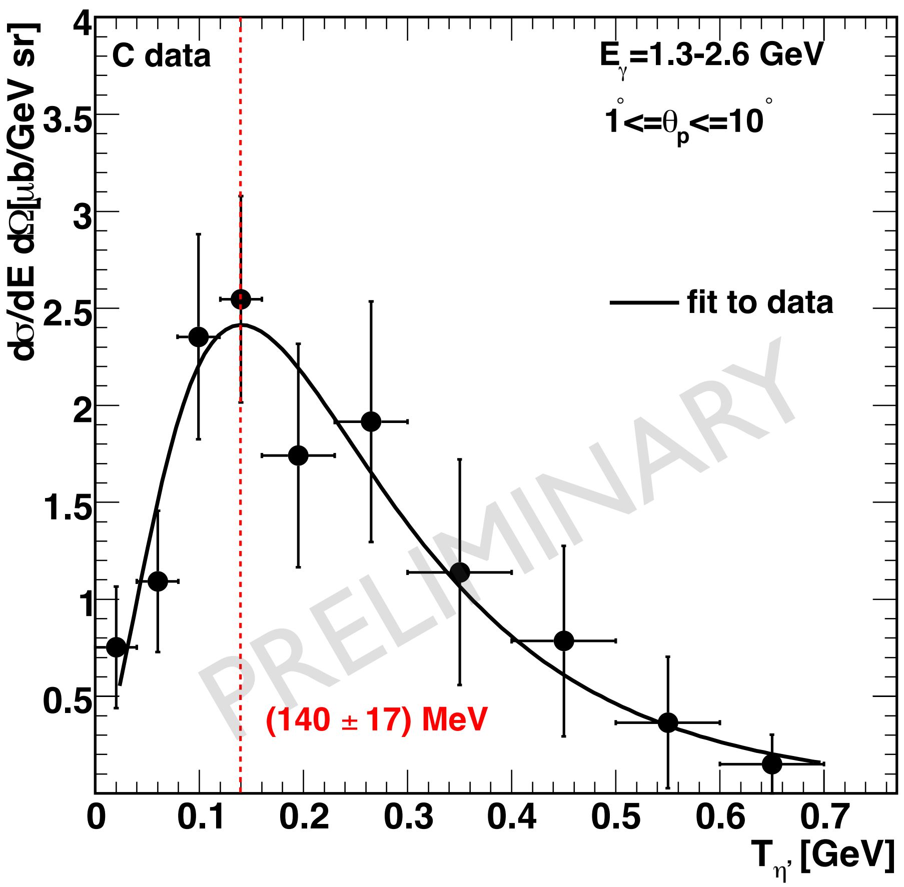


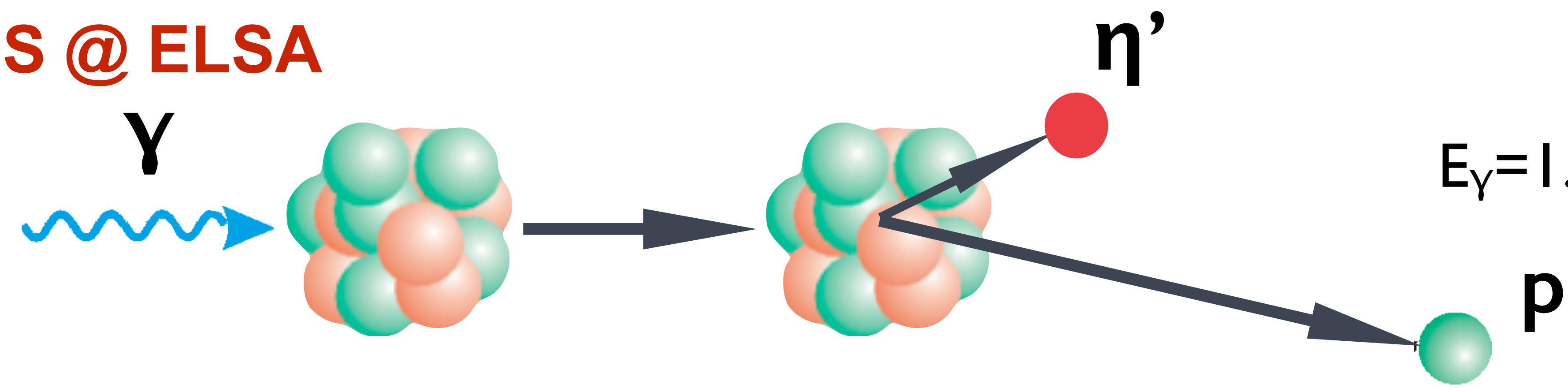




real part of η'-nucleus potential from η' kinetic energy

η'

CBELSA/TAPS @ ELSA



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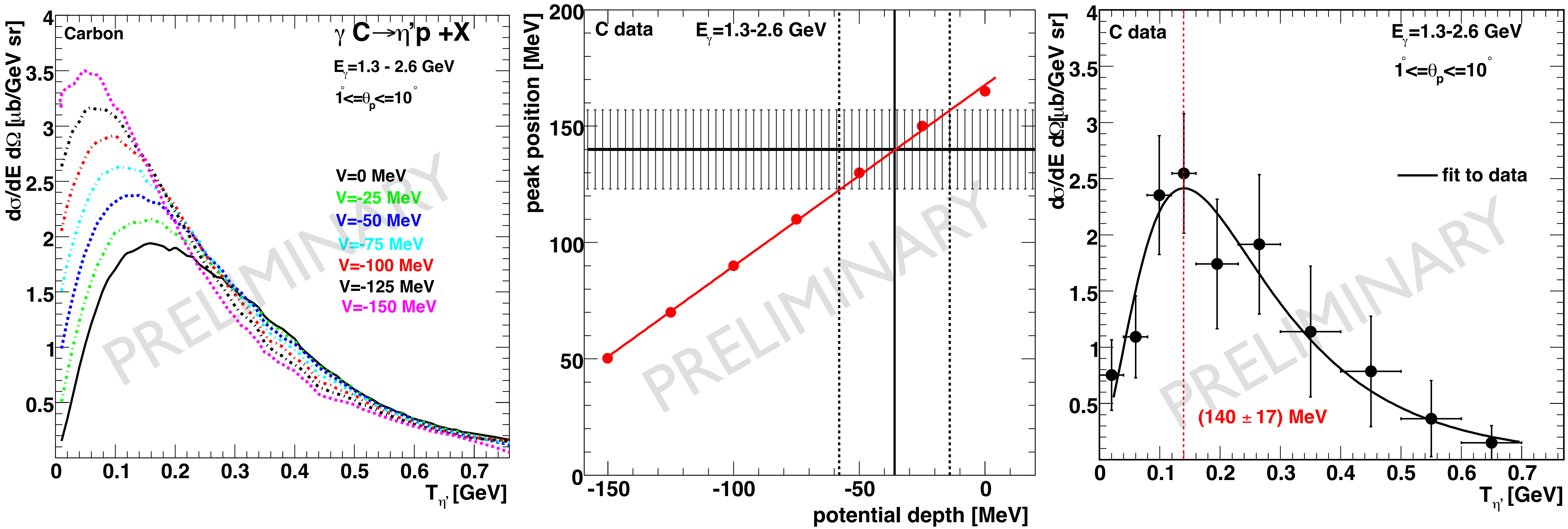
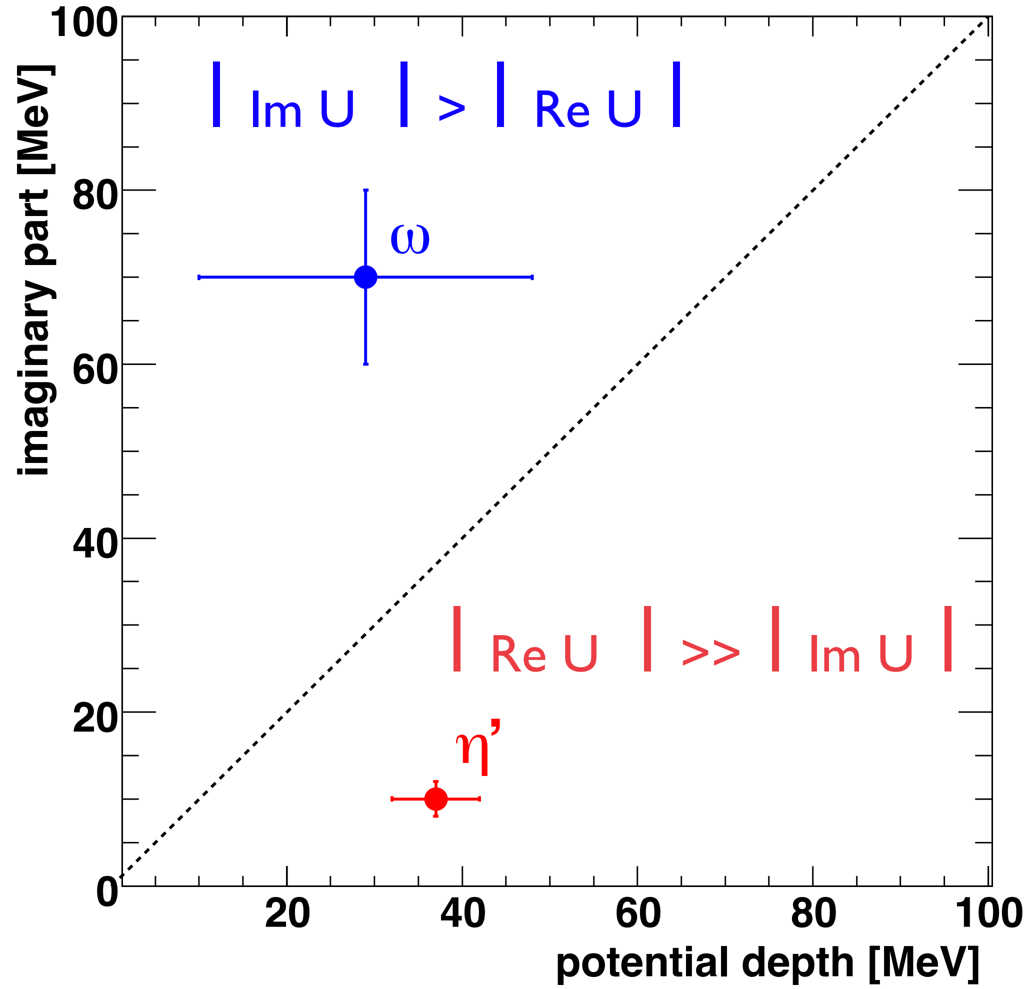


$V_{\eta'}(<p_{\eta'}> \approx 500 \text{ MeV/c};\ \rho=\rho_0) \approx -(36\pm22)$ MeV

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

$U_{\omega A}(\rho=\rho_0)=$
$-((29\pm19(stat)\pm20(syst) + i(70\pm10))$ MeV

$U_{\eta' A}(\rho=\rho_0)=$
$-((39\pm11(stat)\pm15(syst) + i(10\pm3))$ MeV

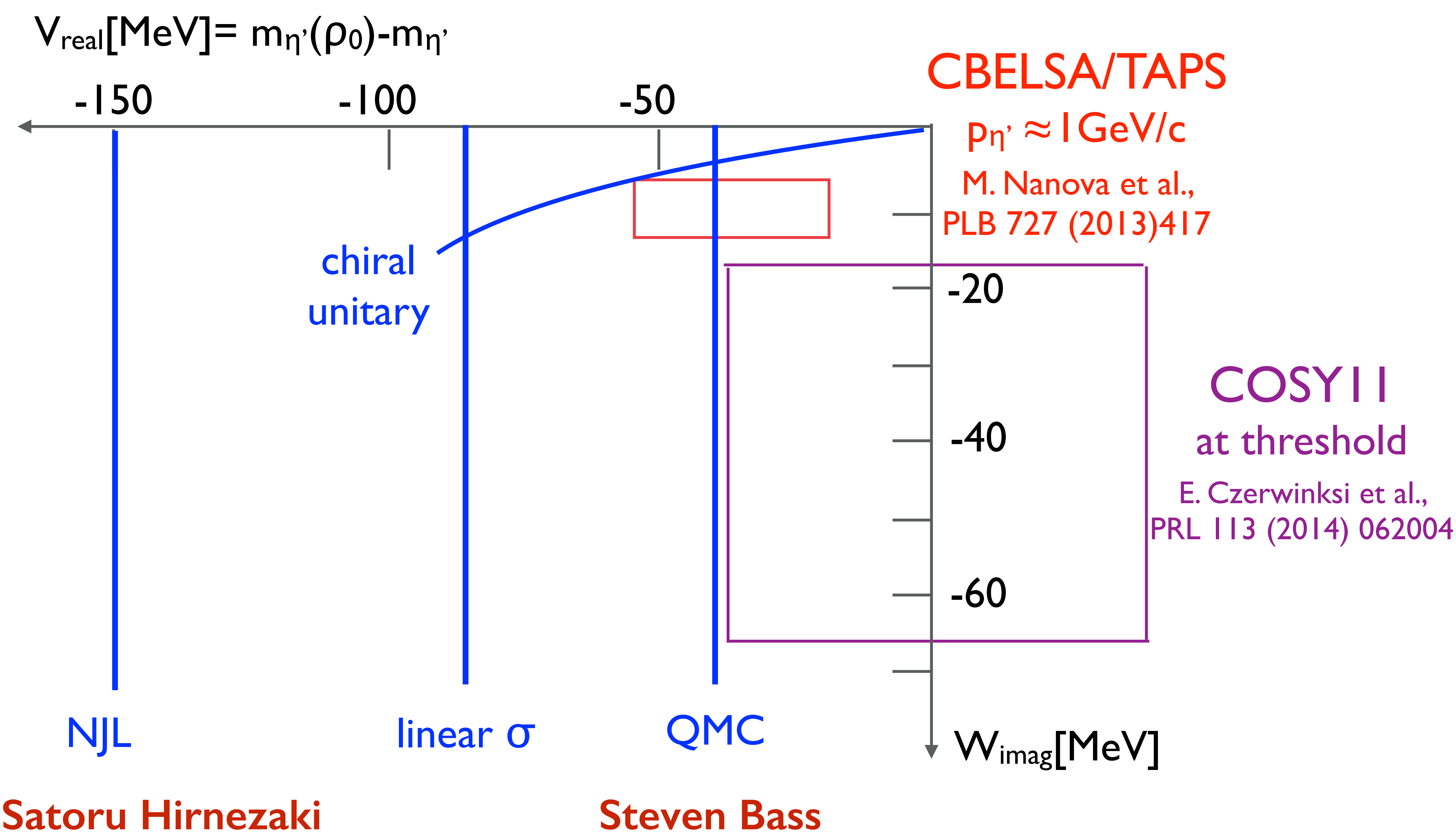


| Im U | > | Re U | ; ⇨ ω <u>not a good candidate</u> to search for meson-nucleus bound states!

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

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)

summary of theoretical predictions and experimental results on $U_{\eta'}(\rho_0)=V_{real}(\rho_0)+i\,W_{imag}(\rho_0)$



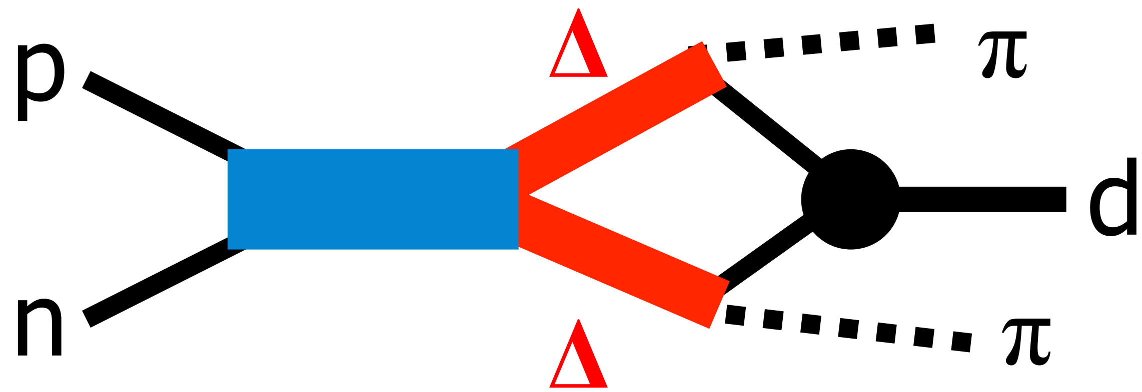
bound few body systems

Mikhail Baskanov:

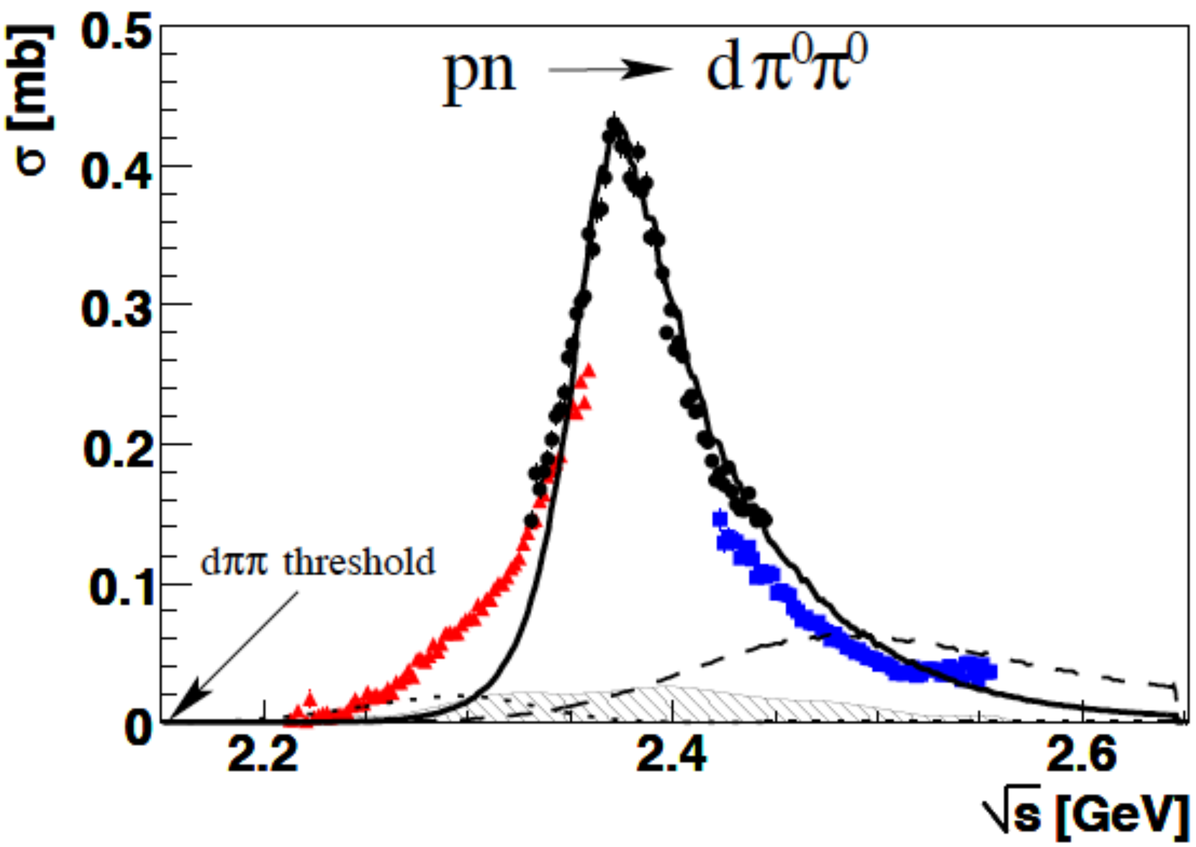
The dibaryon d*(2380) ; (deltaron)

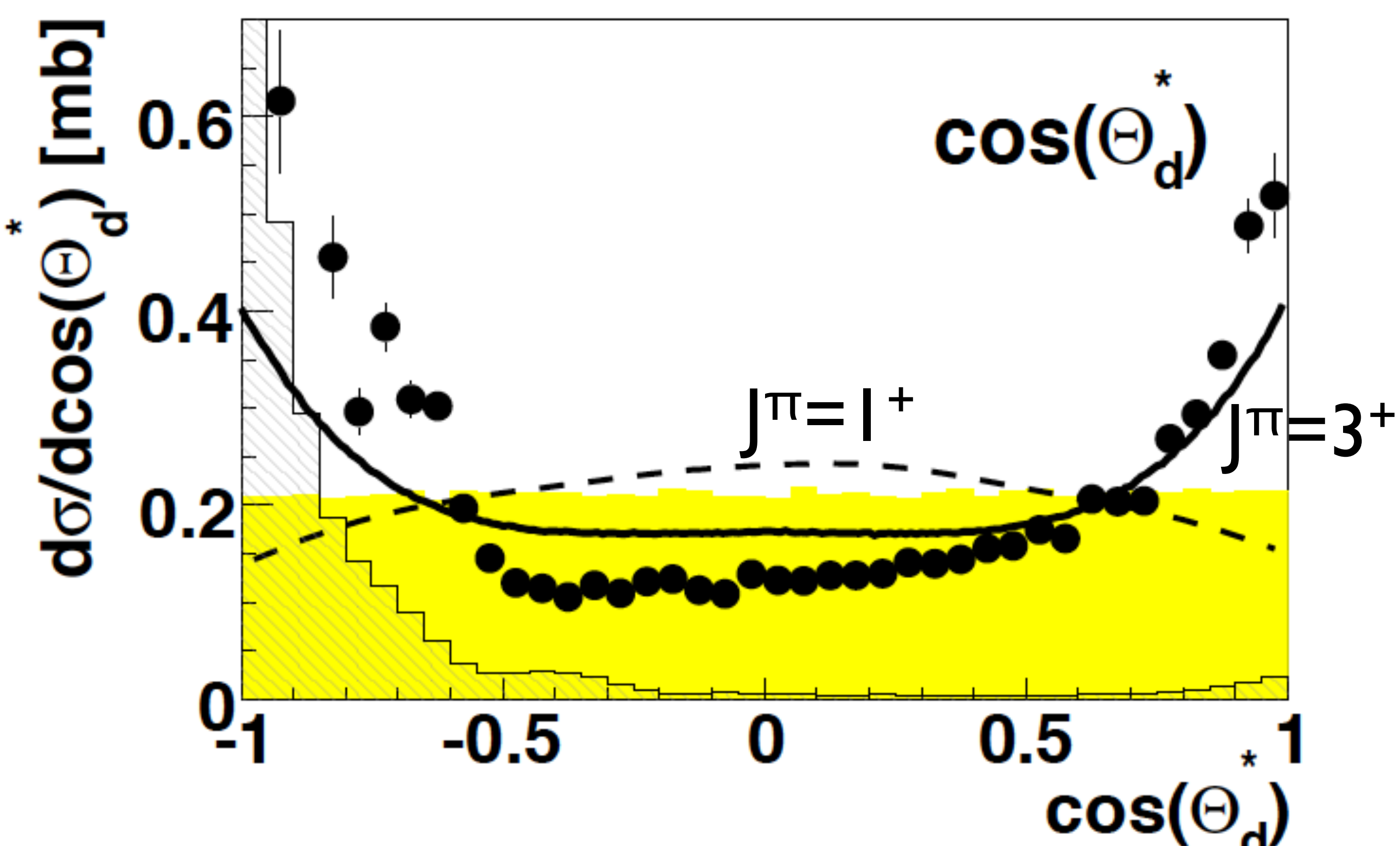
WASA@COSY: first observation in pn → d*(2380) →ΔΔ→dπ⁰π⁰

P.Adlarson et al,
PRL 106 (2011) 242302



M=2.38 GeV/c2; Γ= 70 MeV I(J^π)=0(3^+)

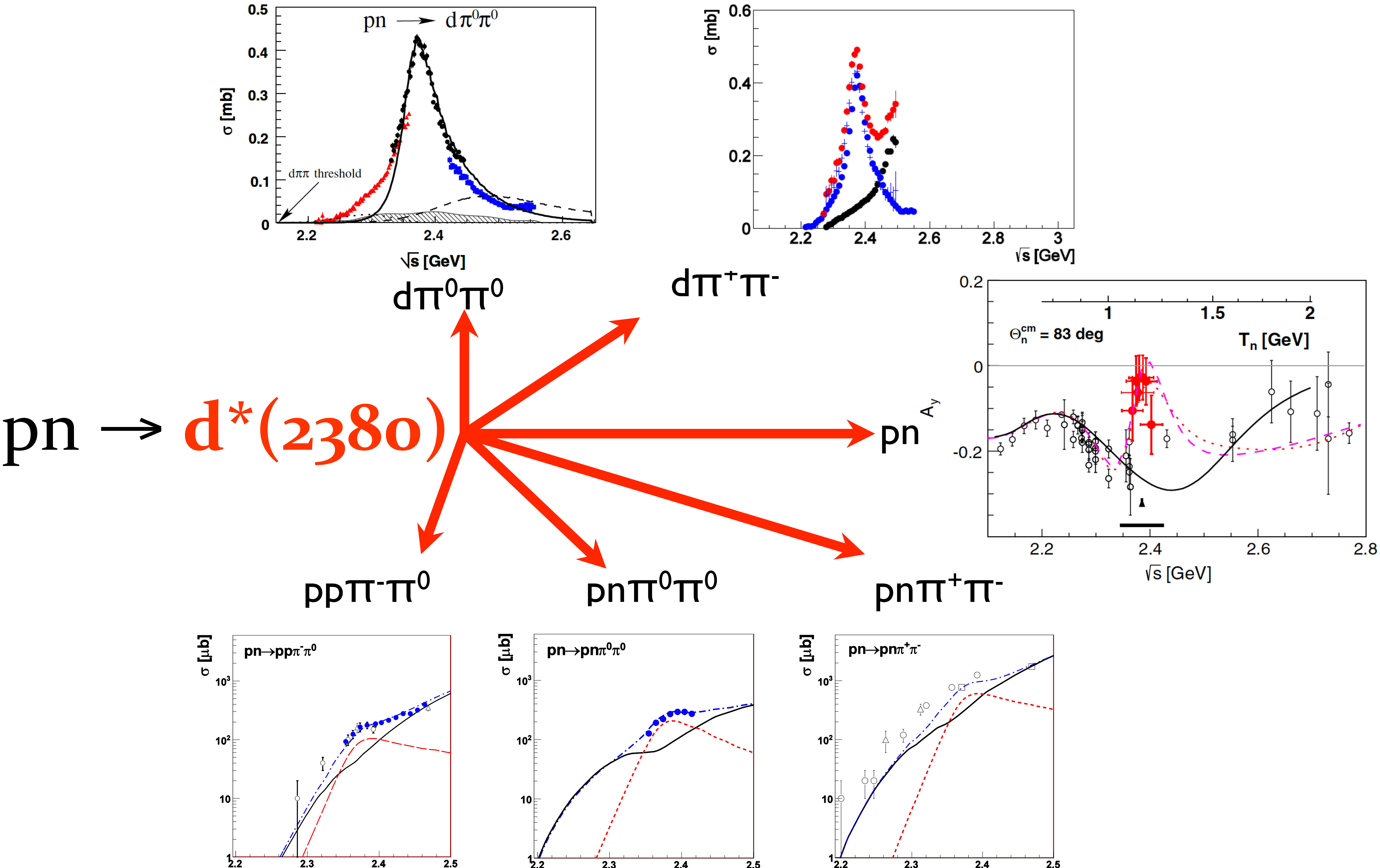




Avraham Gal: pion assisted dibaryons; also d*(2150) $(N\Delta)_{bound}$
quantitatively described by long range interaction among N, π, Δ

The dibaryon d*(2380)

established in various decay channels

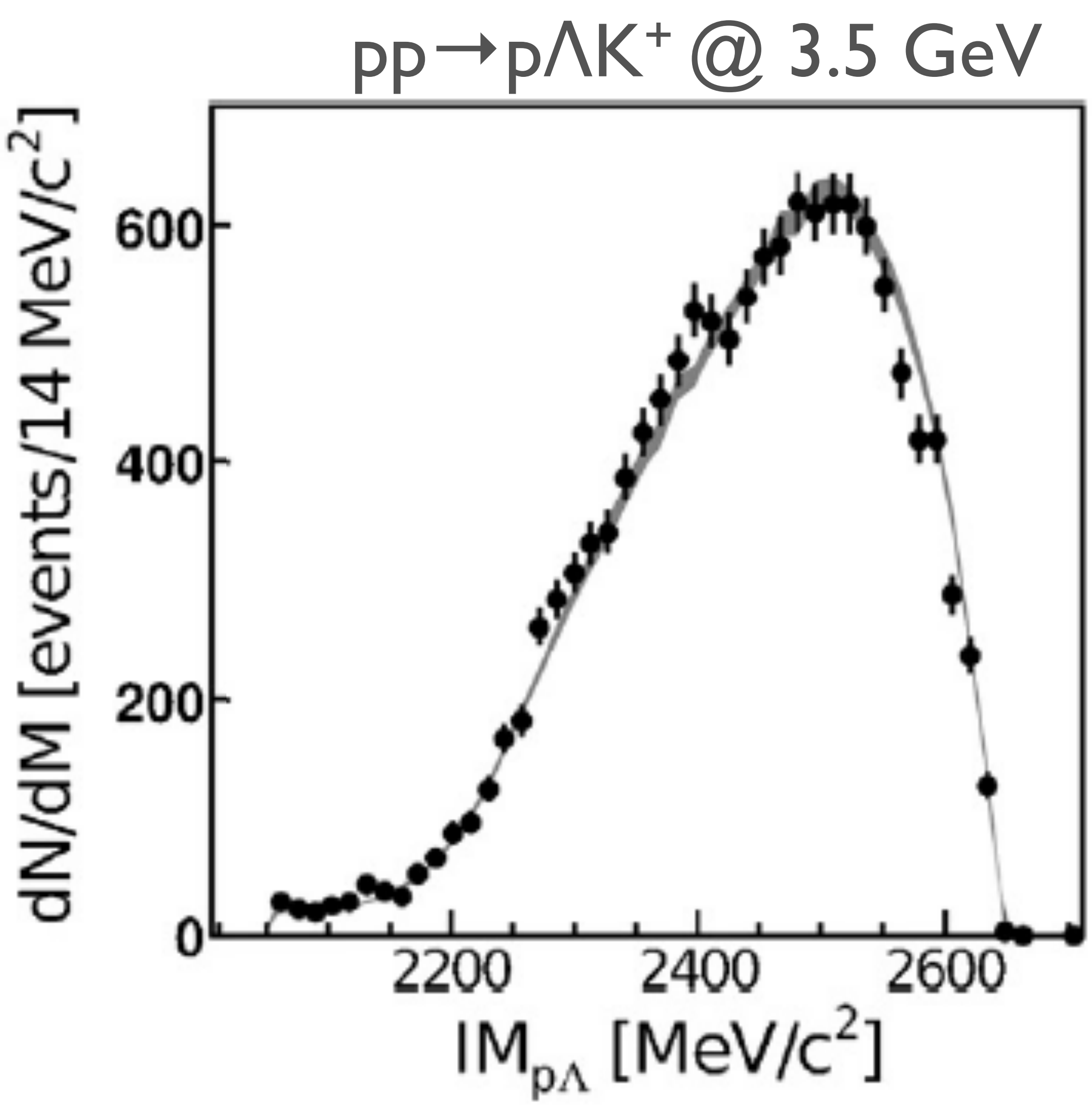


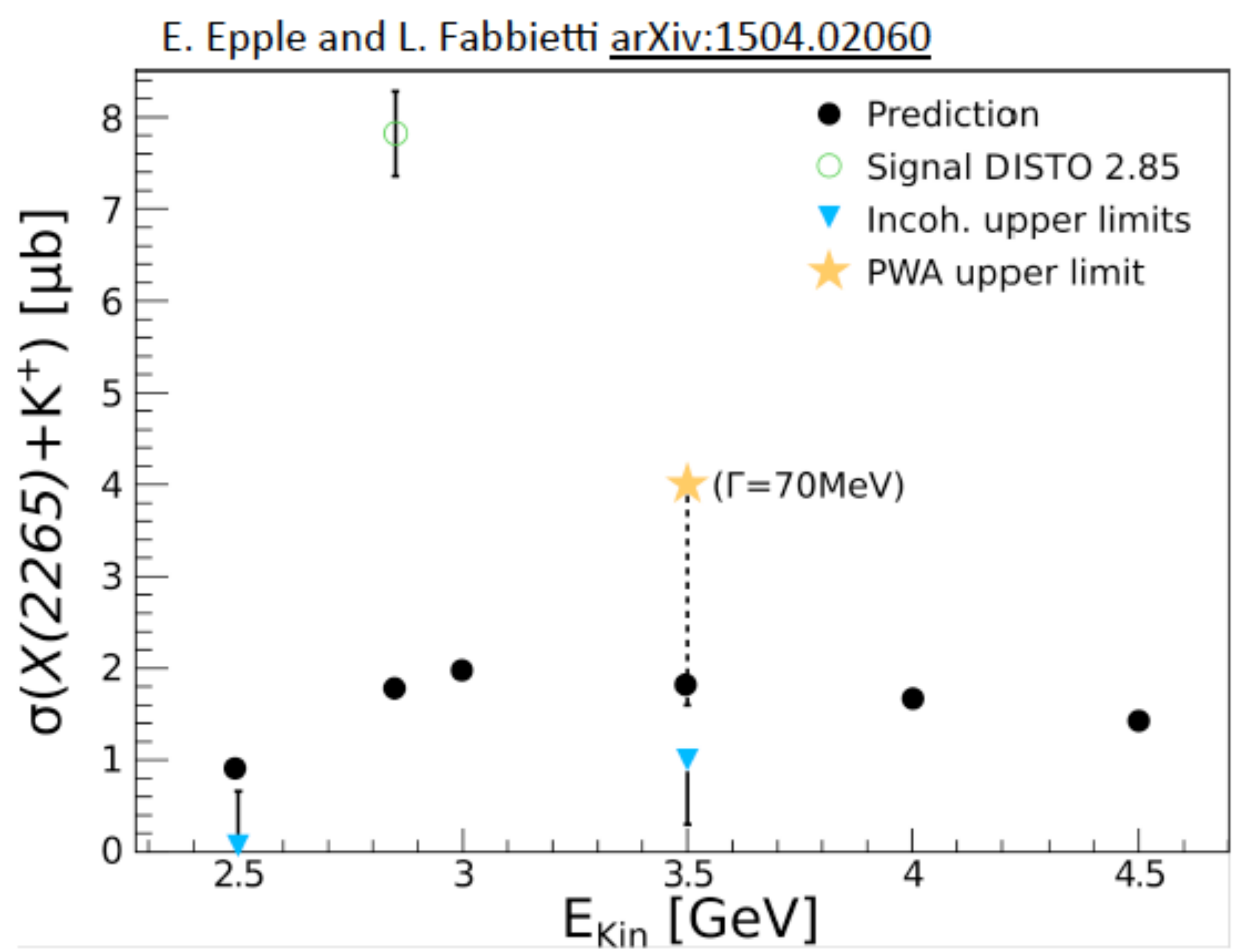
Search for kaonic clusters

SIDDHARTA:
x-ray spectroscopy of kaonic hydrogen: strong K^-N attraction in I=0 channel

FINUDA, DISTO: evidence for K^-pp cluster

Laura Fabbietti: HADES@GSI G. Agakishiev et al., PLB 742 (2015) 242





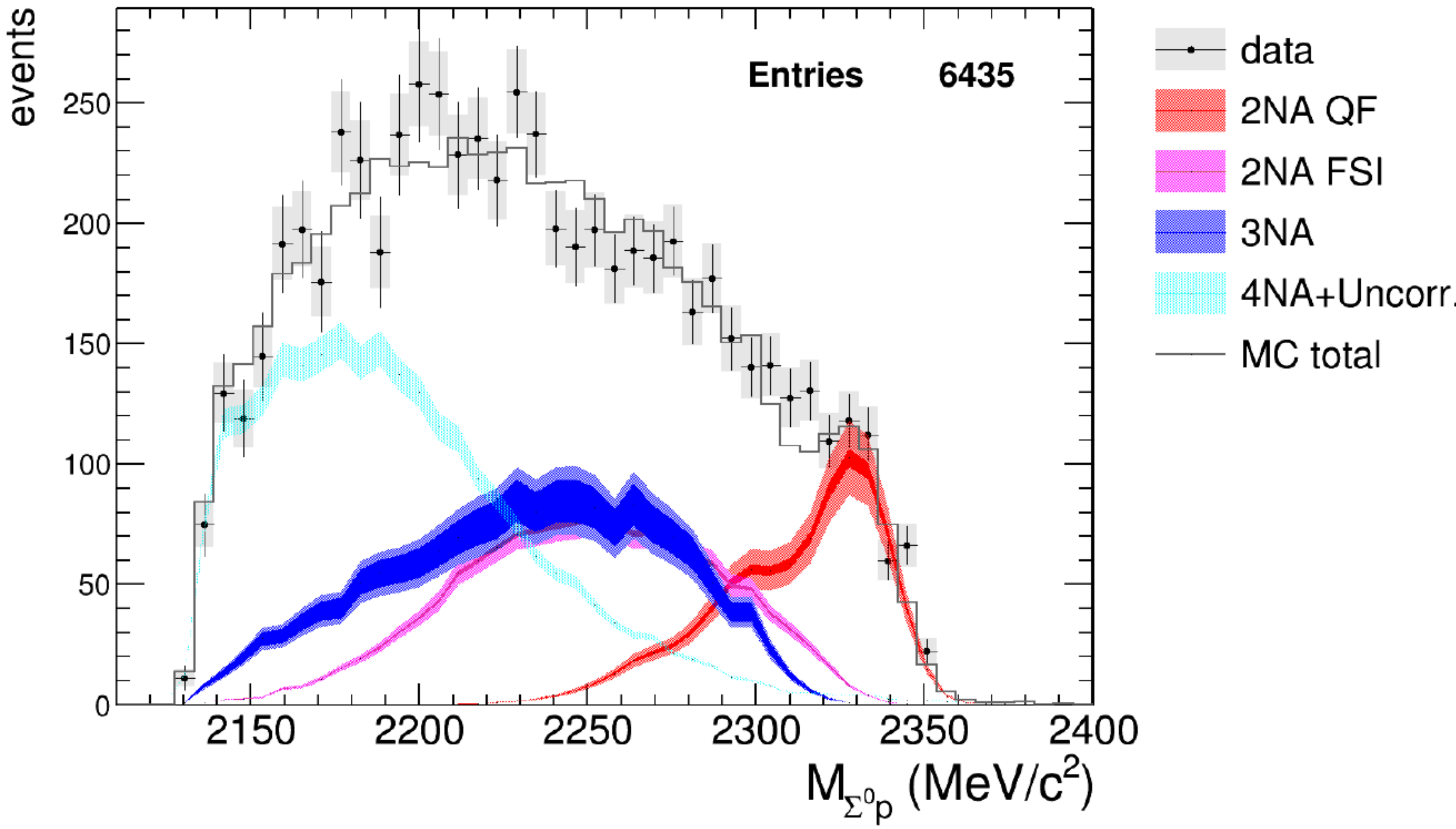
PWA analysis, using known sources:
no evidence for K^-pp cluster in mass range 2.20-2.37 GeV/c^2

KLOE@DAΦNE

Search for kaonic clusters

using low energy K^- from Φ decay

$K^- + C \rightarrow \Sigma^0 + p + X$; looking for $ppK^- \rightarrow \Sigma^0 + p$



statistical analysis including kaonic bound state with BE = 45MeV/c^2 and Γ= 30 MeV gives better χ^2 but only slightly better local p value

KLOE@DAΦNE

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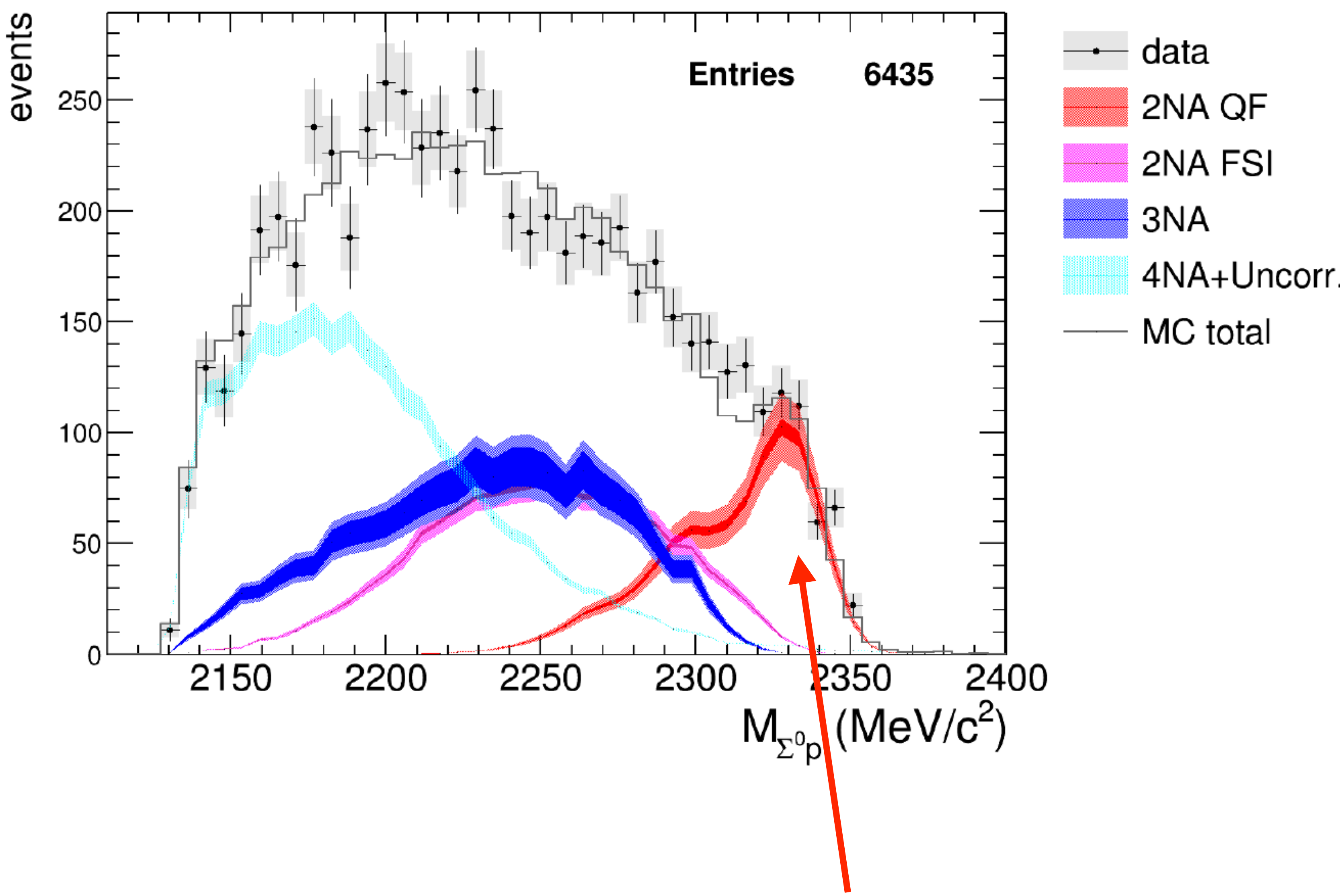

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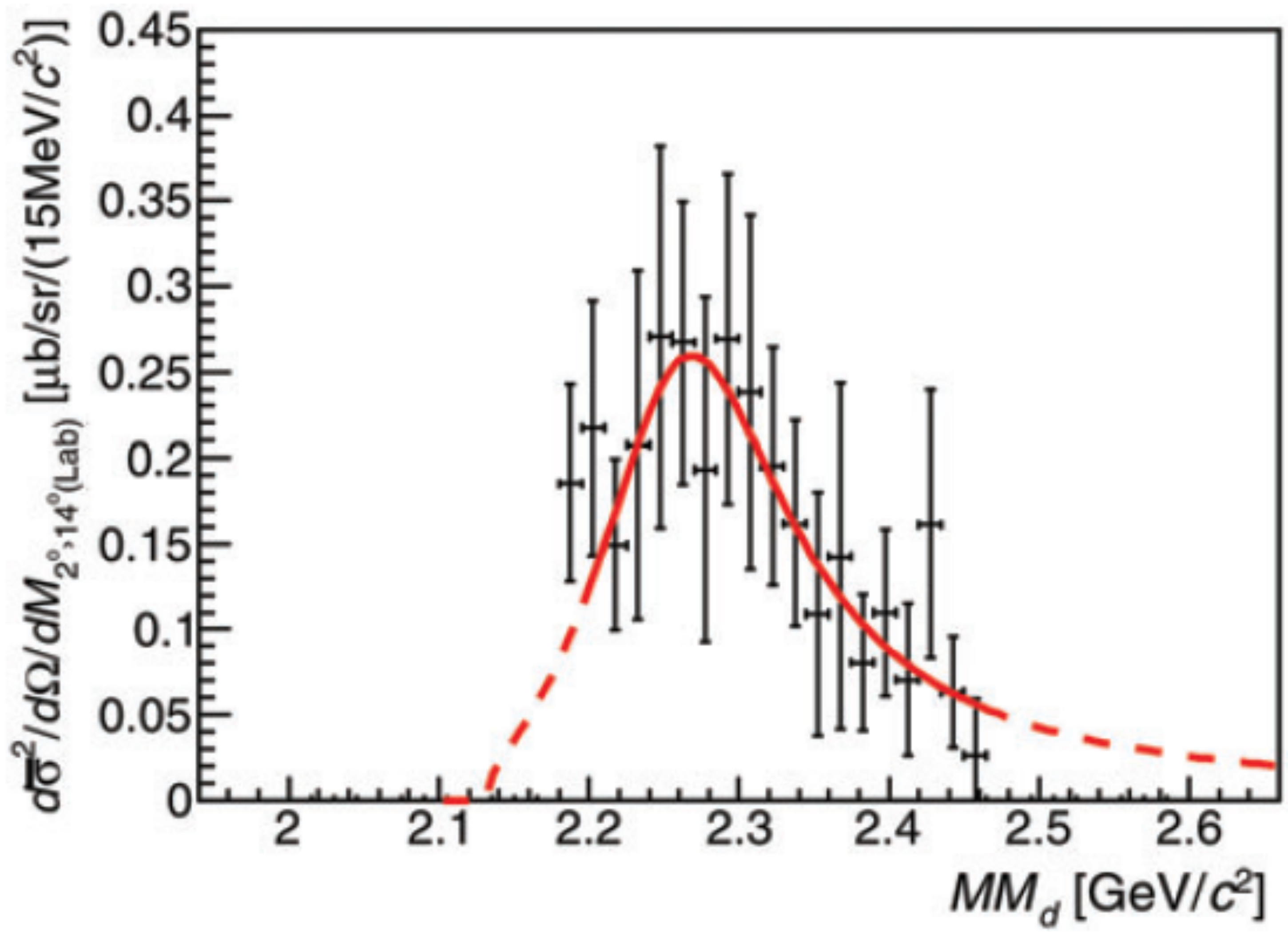
Slawomir Wycech: importance of multi-nucleon clusters in K^- capture

Search for kaonic clusters

E27@J-PARC Y. Ichikawa et al., Prog. Theor. Exp. Phys.(2015) 021D01

missing mass spectrum for $d(\pi^+,K^+)$ in coincidence with protons at $39^0 < \theta_p^{lab} < 122^0$



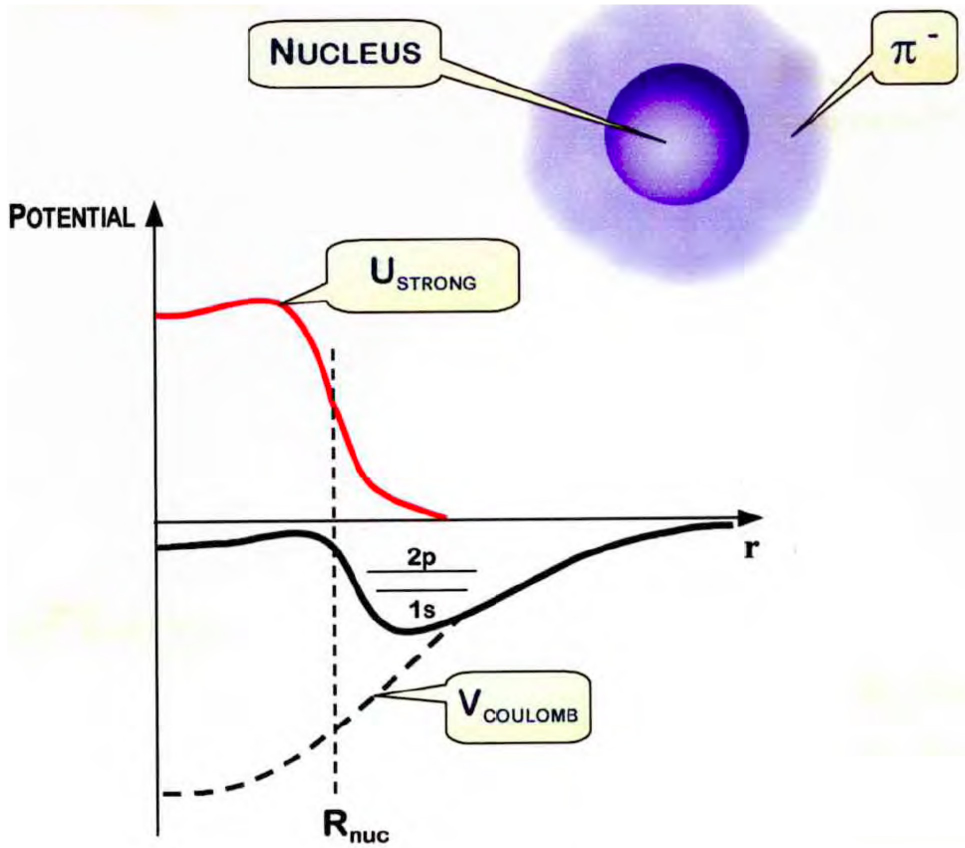
$B(\text{“}K^-pp\text{”}) = (95^{+18}_{-17}(\text{stat})^{+30}_{-21}(\text{syst}))$ MeV; $\Gamma(\text{“}K^-pp\text{”}) = (162^{+87}_{-45}(\text{stat})^{+66}_{-78}(\text{syst}))$ MeV

evidence for K^-pp - like structure

search for and study of meson-nucleus bound states

meson-nucleus interactions; mesic states

Electromagnetic (+Strong) interaction



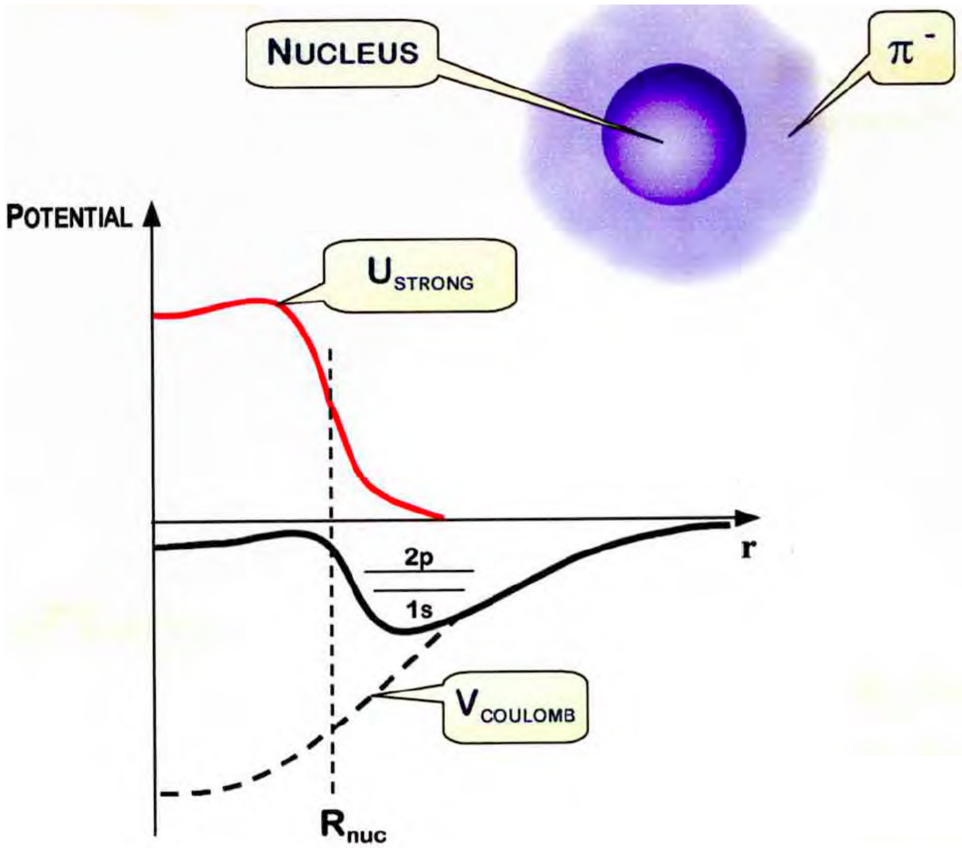
charged pion ⇔ nucleus

bound by superposition of attractive Coulomb- and repulsive strong interaction

Kenta Itahashi

meson-nucleus interactions; mesic states

Electromagnetic (+Strong) interaction



charged pion ⇔ nucleus

bound by superposition of attractive Coulomb- and repulsive strong interaction

Kenta Itahashi

ω, η, η' ↔ nucleus

bound solely by the strong interaction

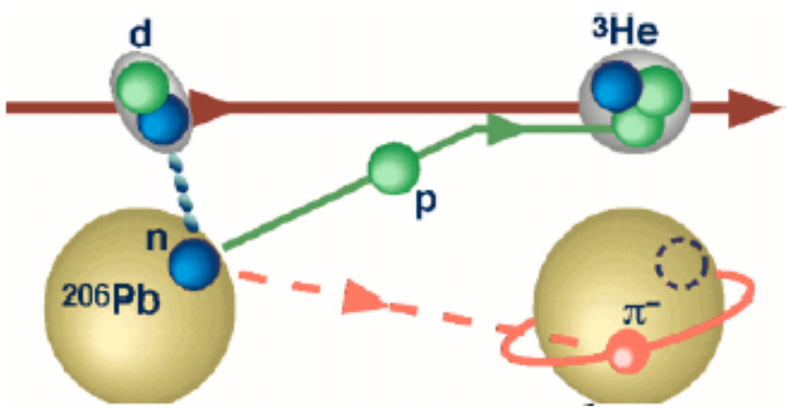
?

talks by

Kenta Itahashi
Magdalena Skurzok
Mariana Nanova

deeply bound pionic states

FRS@GSI

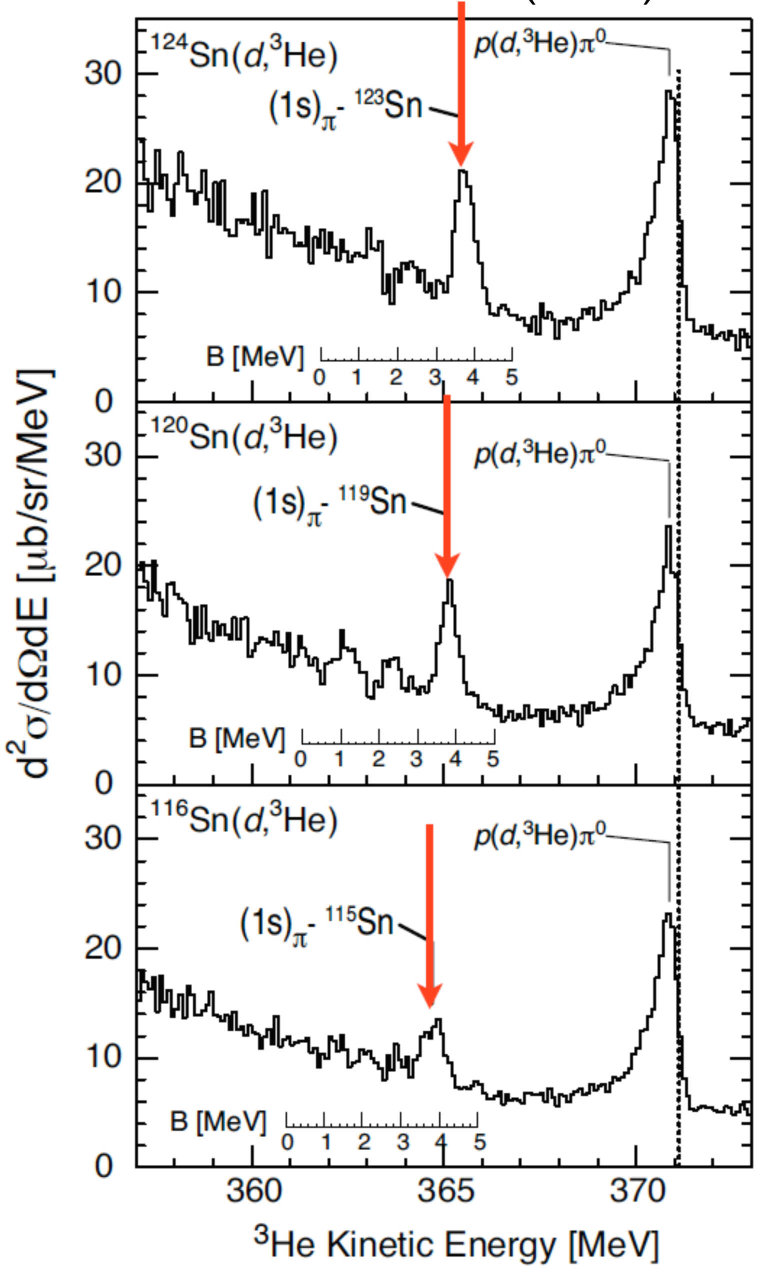


halo-like π⁻ distribution around nucleus

^{119}Sn: B_{1s} = (3.82±0.01) MeV; Γ_{1s}= (0.33±0.05) MeV

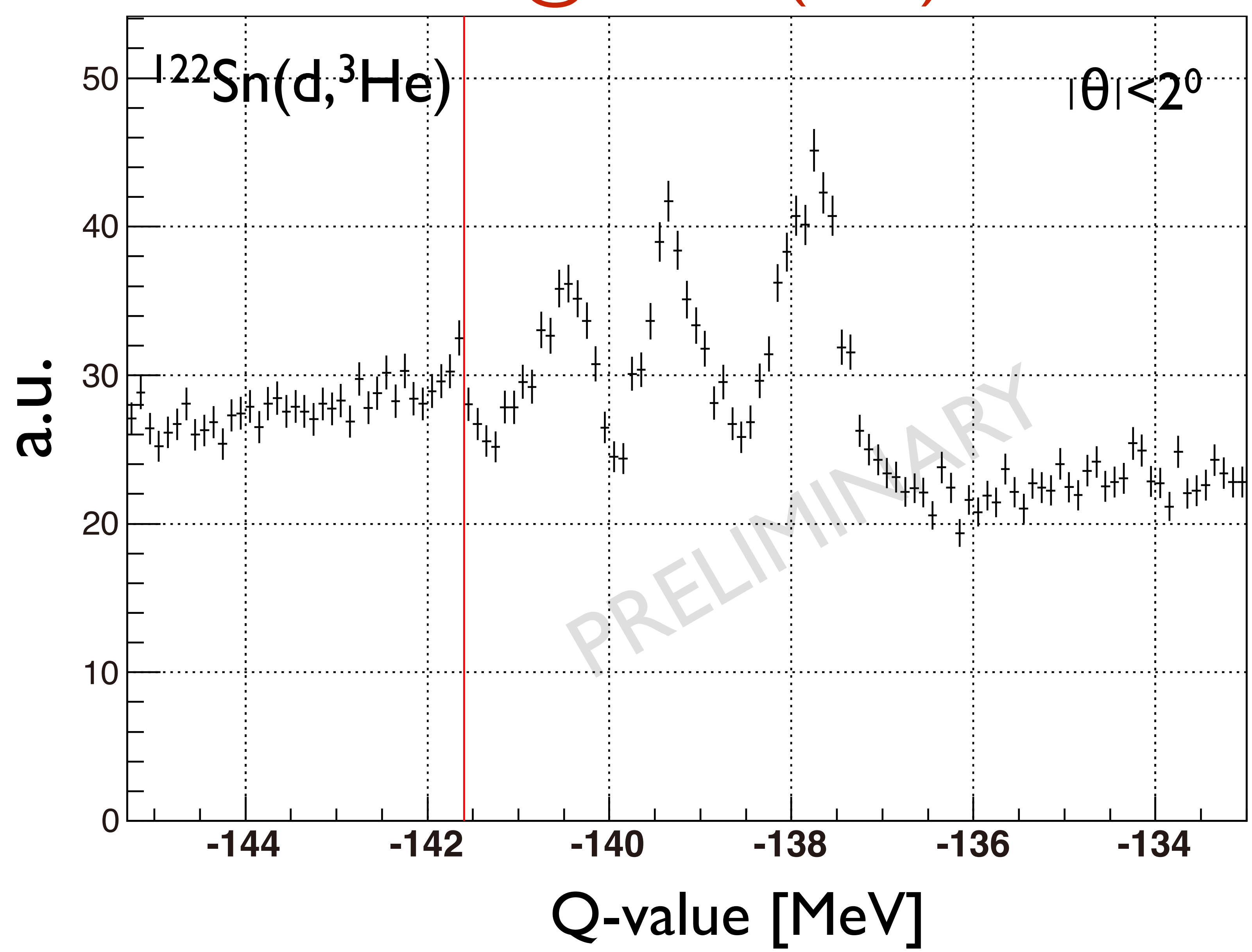
optical potential parameters (real and imaginary part) determined from binding energy and width of bound states

Suzuki et al., PRL 92 (2004) 072302



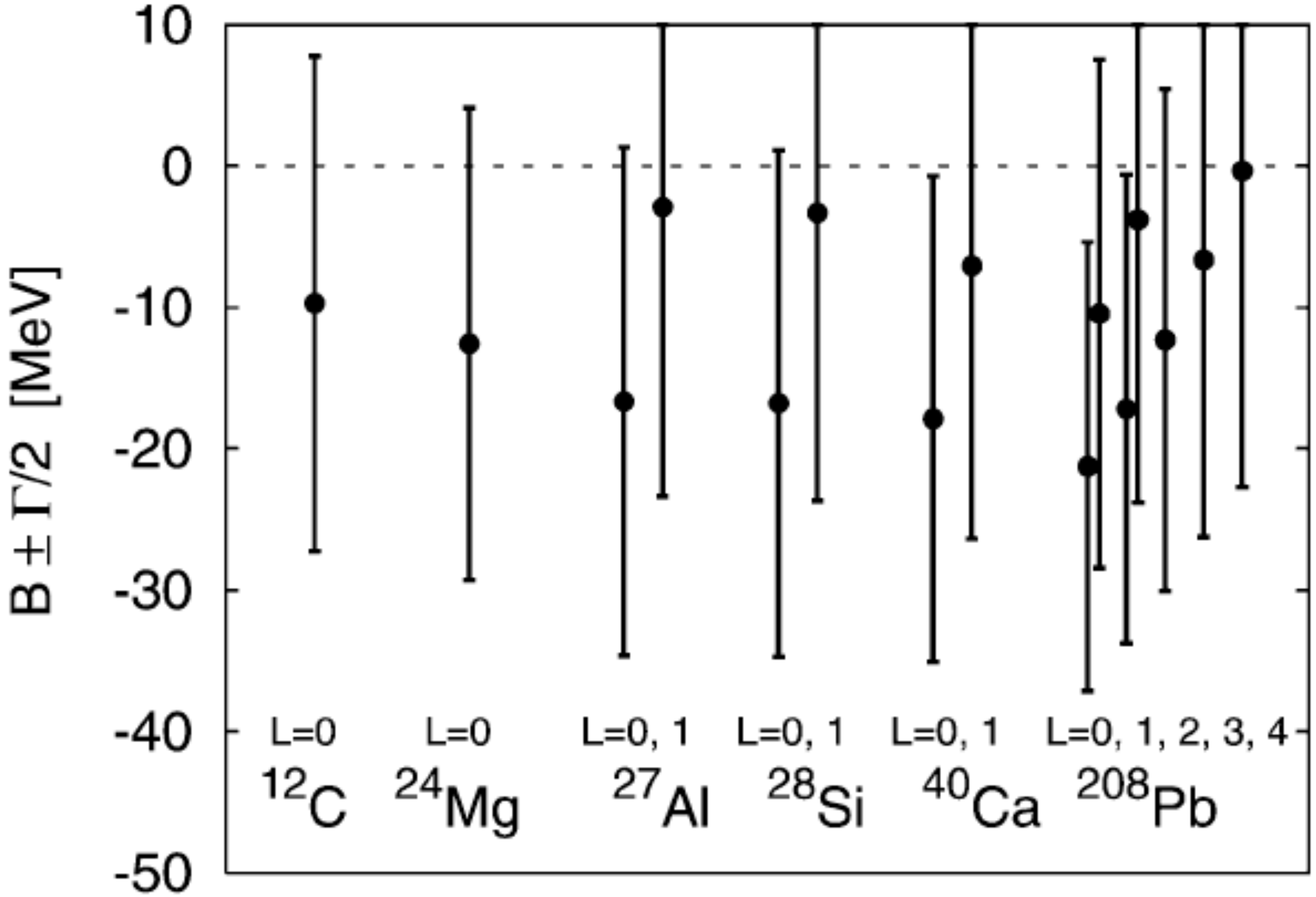
Kenta Itahashi

RIBF@RIKEN (2010)

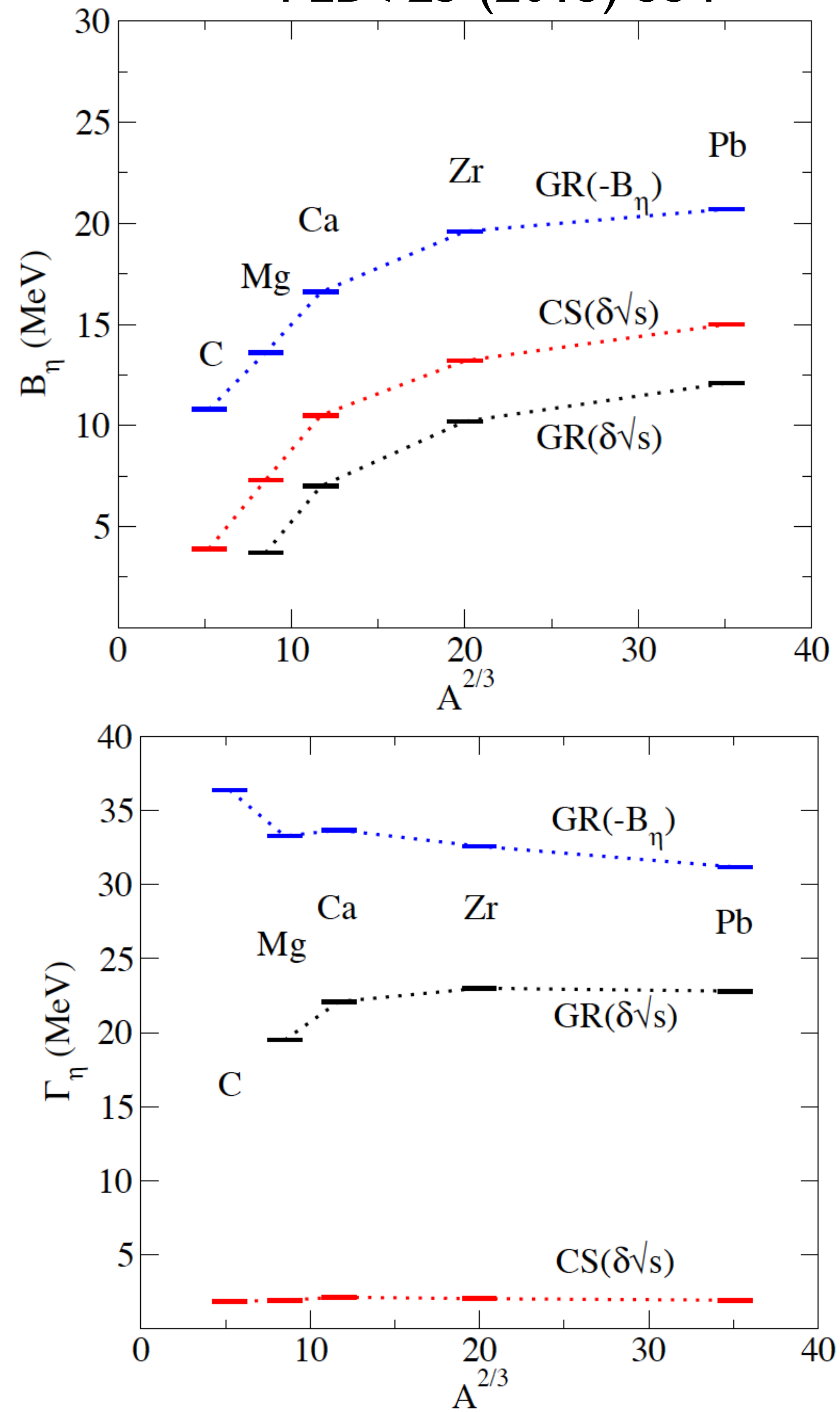


theoretical predictions for η-nucleus bound states

C. Garcia-Recio et al., PLB 550 (2002) 47



E. Friedman, A. Gal, J.Mares
PLB 725 (2013) 334

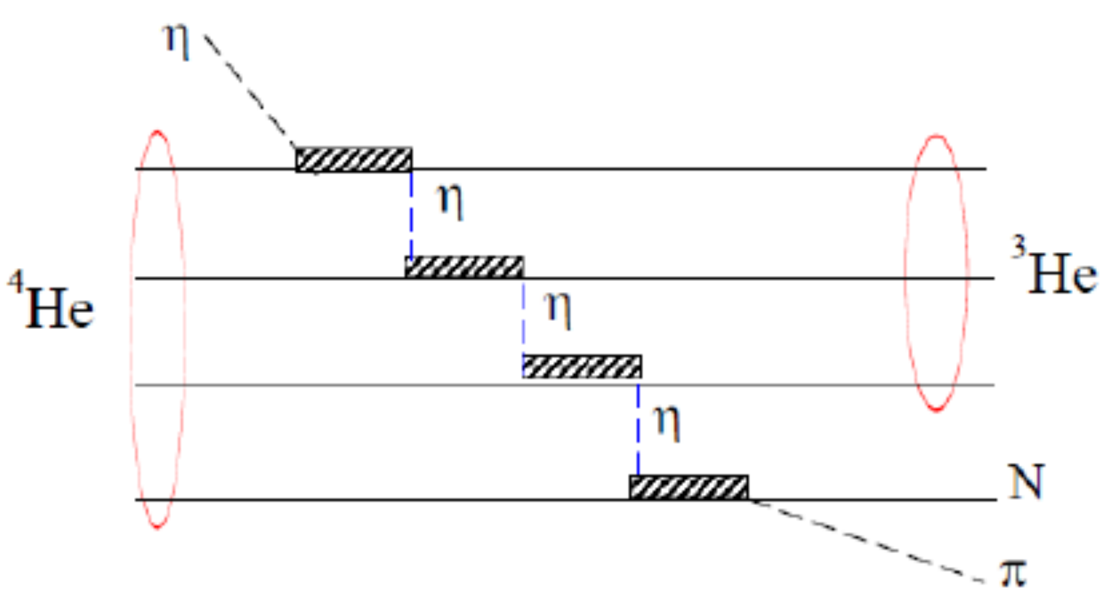


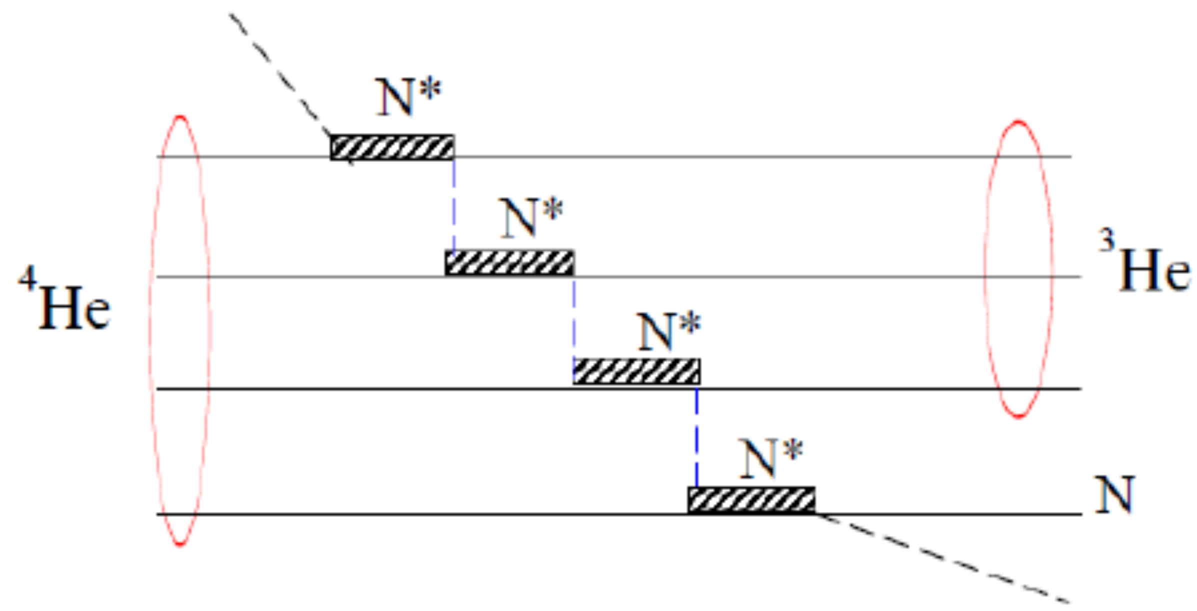
for most nuclei $B_\eta \lesssim \Gamma_\eta$

most states predicted to have tails into the continuum, allowing for η decays of bound states

η-nucleus or N*-nucleus bound states ?

Neelima Kelkar





$(^4He - \eta)_{bound}$ ⟺ $(^3He - N^*)_{bound}$??

N*-nucleus bound states may exist, however very broad:

$\Gamma \approx$ several 10 MeV

search for η-mesic states

A2@MAMI

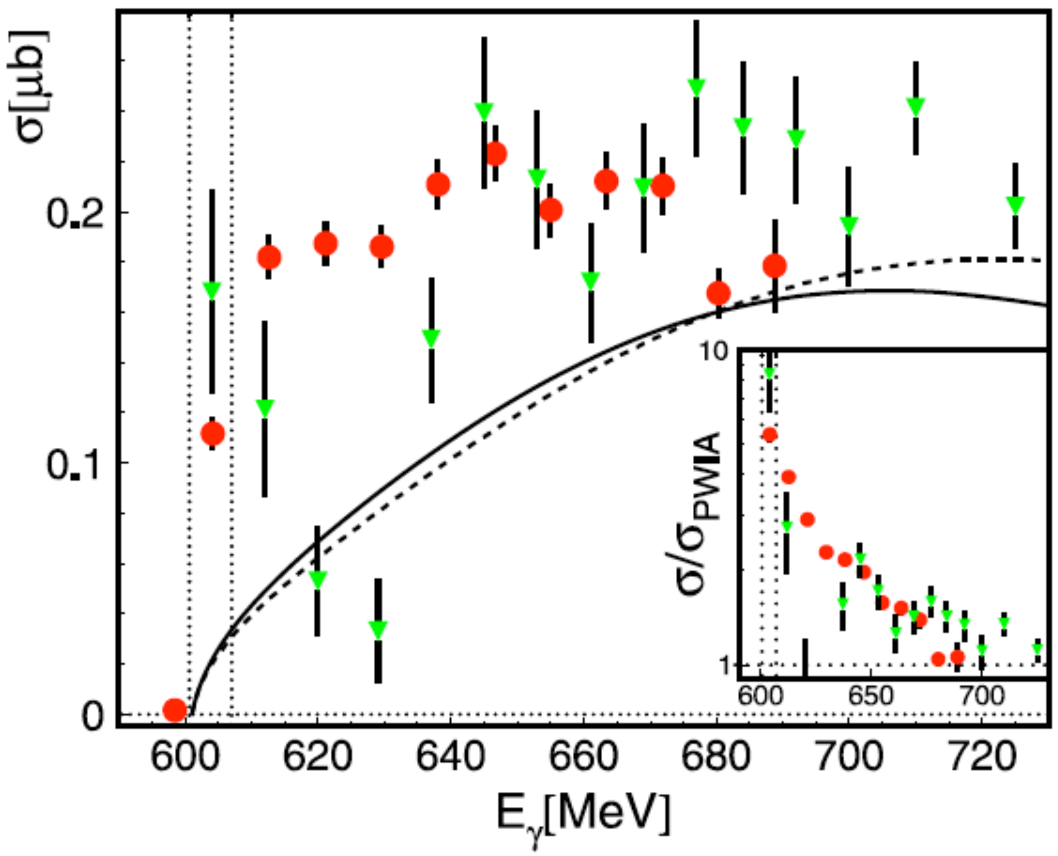
ANKE@COSY

coherent η photo production on ^{3}He

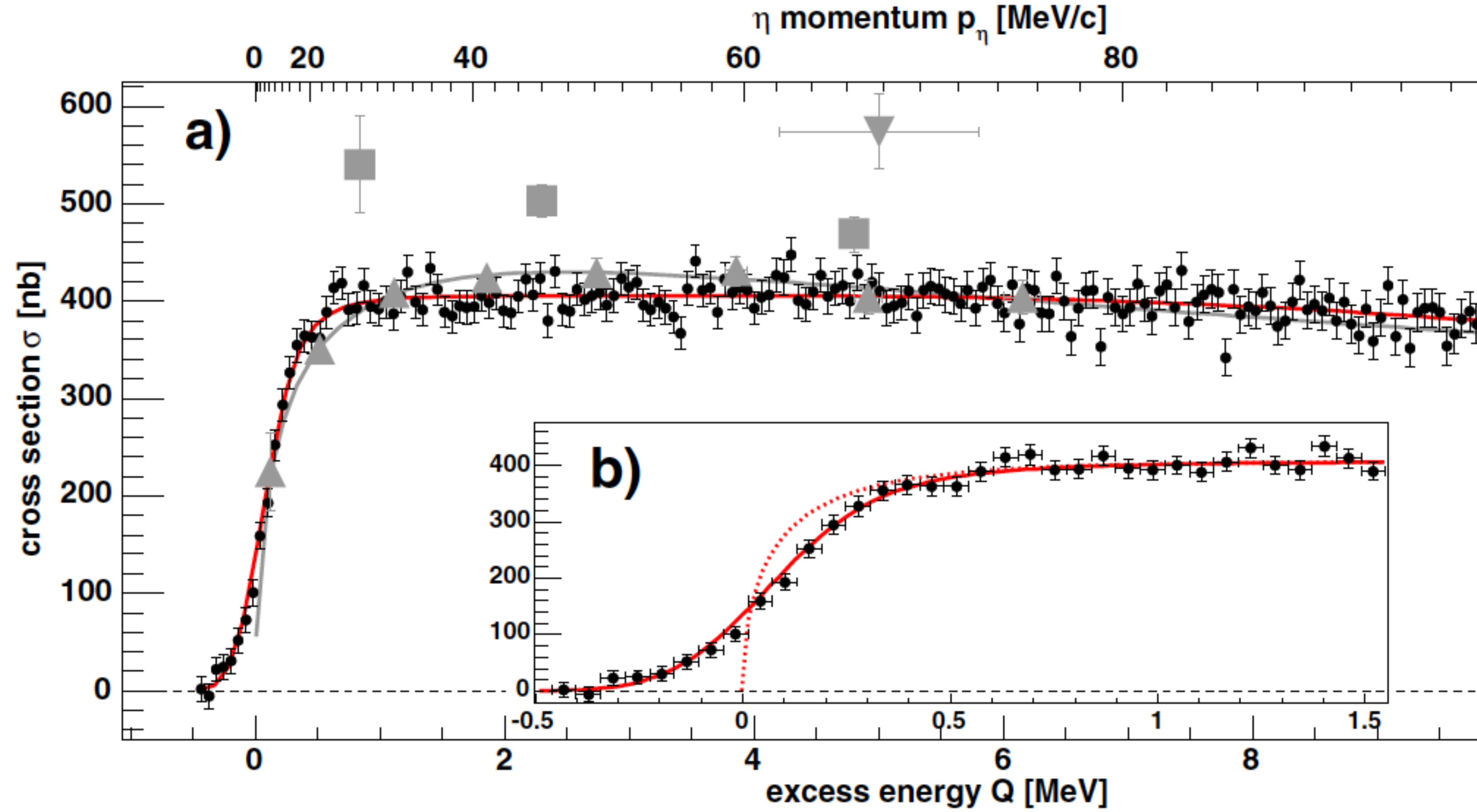
- M. Pfeiffer et al., PRL 92 (2004) 252001
  - F. Pheron et al., PLB 709 (2012) 21

T.Mersmann et al., PRL 98 (2007) 242301

$\gamma ^3He \rightarrow \eta ^3He$



$dp \rightarrow \eta ^3He$

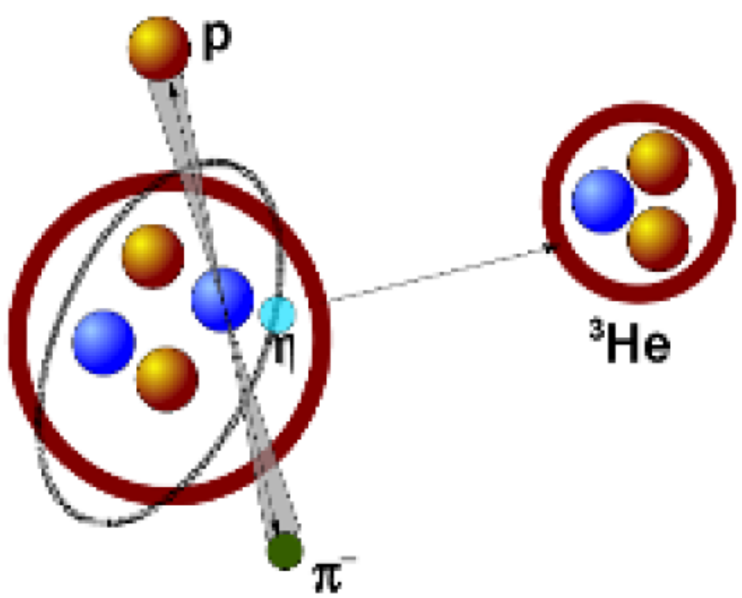


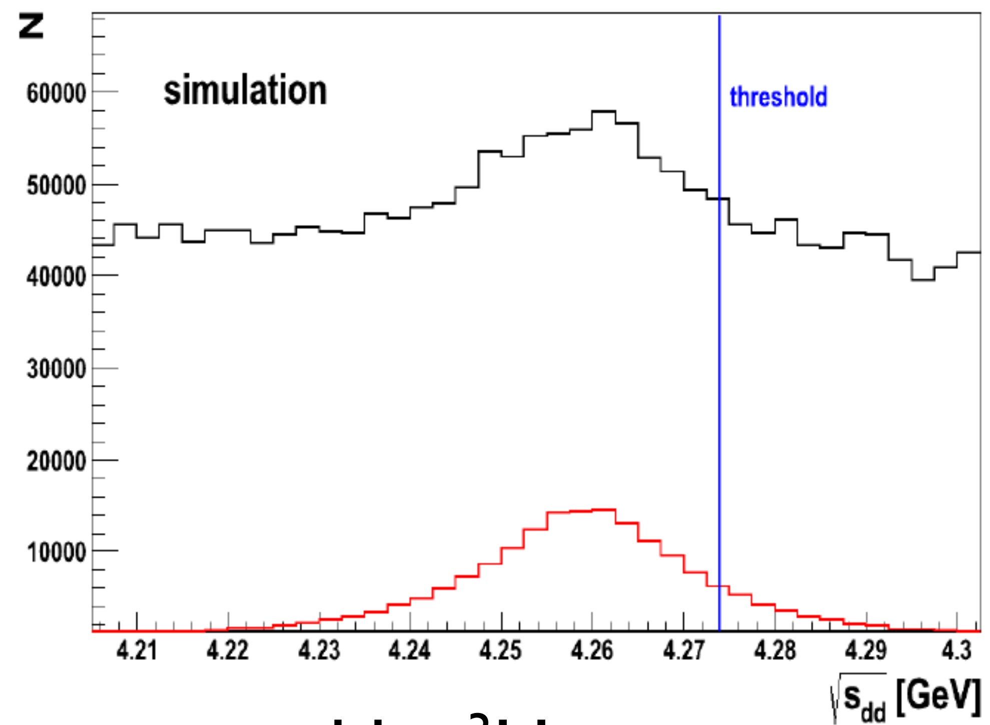
very strong rise of cross section directly at threshold
in contrast to phase-space expectations
⇒ strong ^{3}He-η FSI; quasi bound state close to threshold ??

search for η-mesic states: η⊗^{4}He

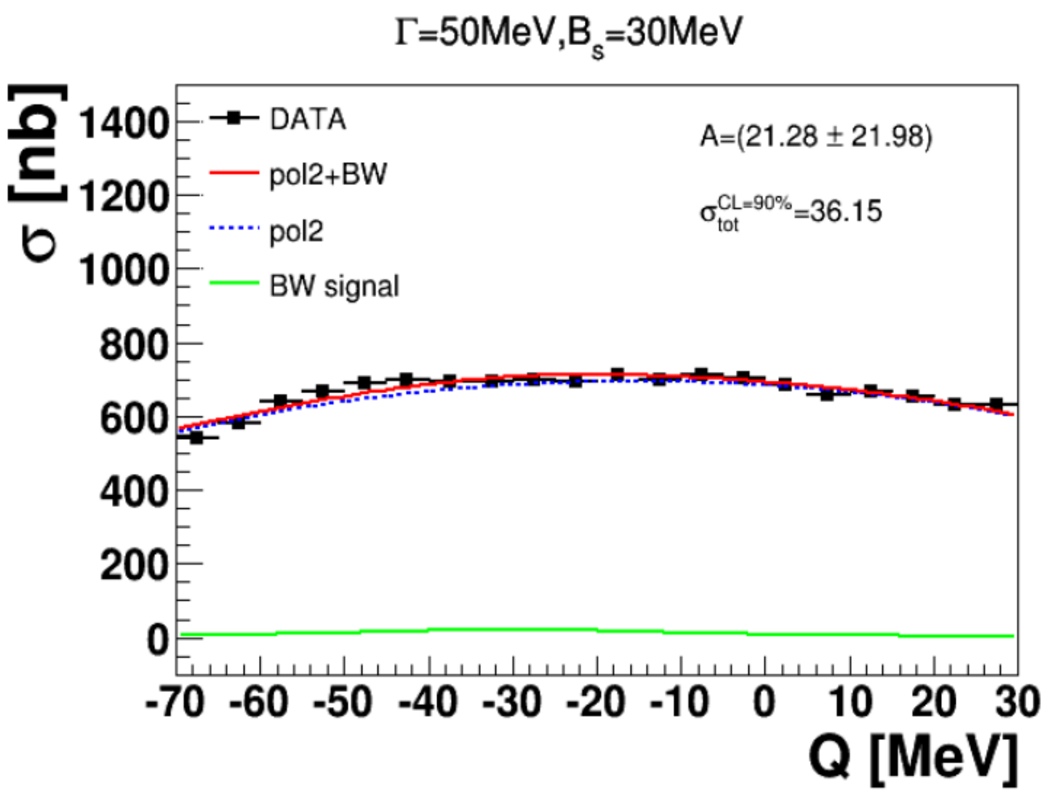
WASA@COSY
Magdalena Skurzok
W. Krzemien

dd→ η⊗^{4}He →^{3}He pπ$^-$, ^{3}He nπ^0

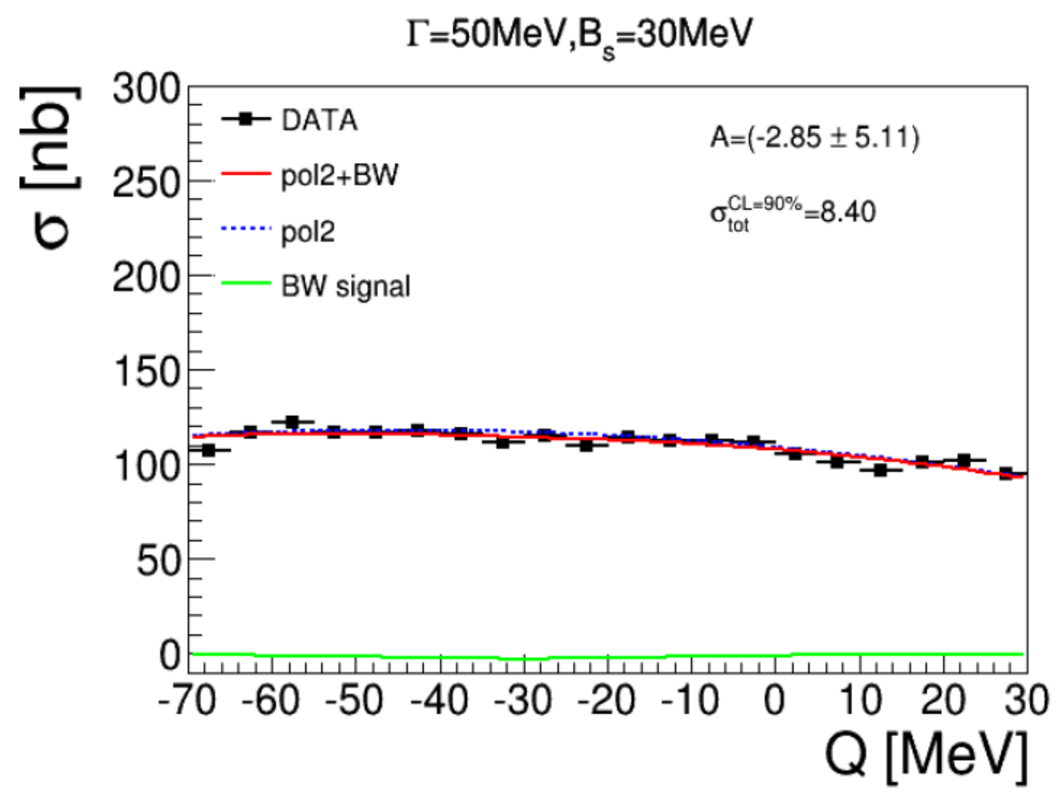




dd→^{3}He nπ^0



dd→^{3}He pπ$^-$



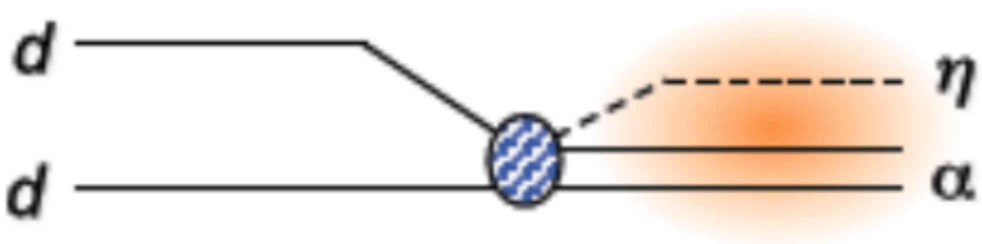
upper limit for bound state signal ≈ few nb

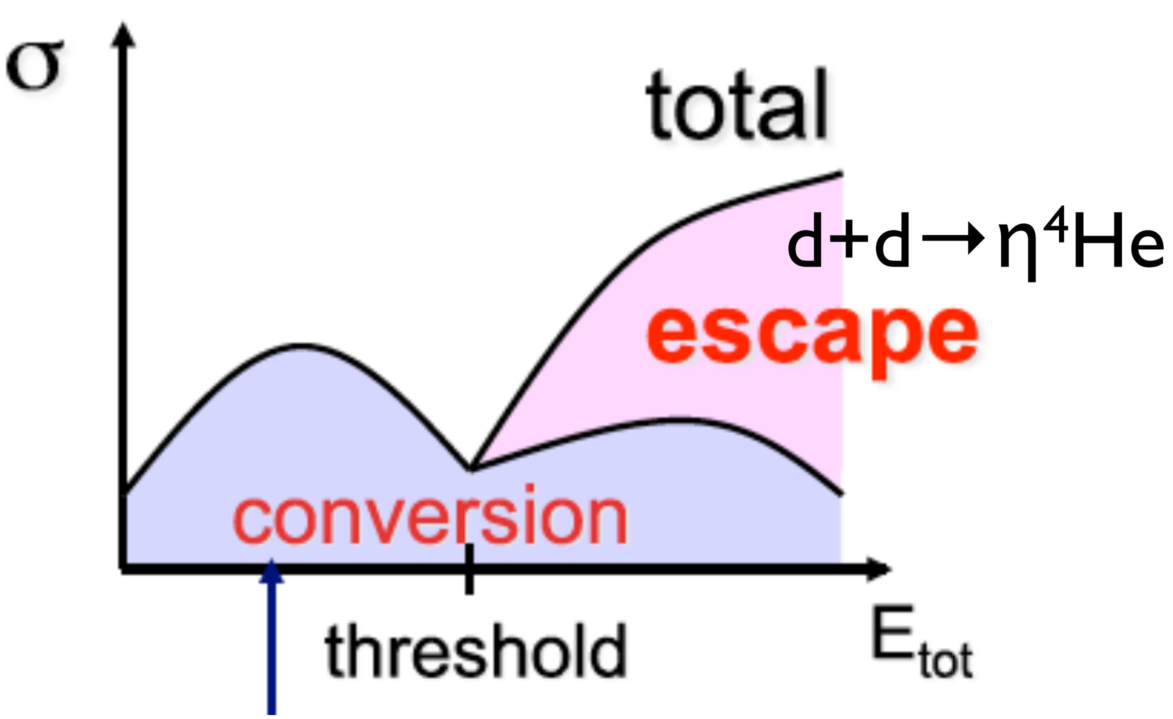
search for η-mesic states

η bound state formation in d+d fusion

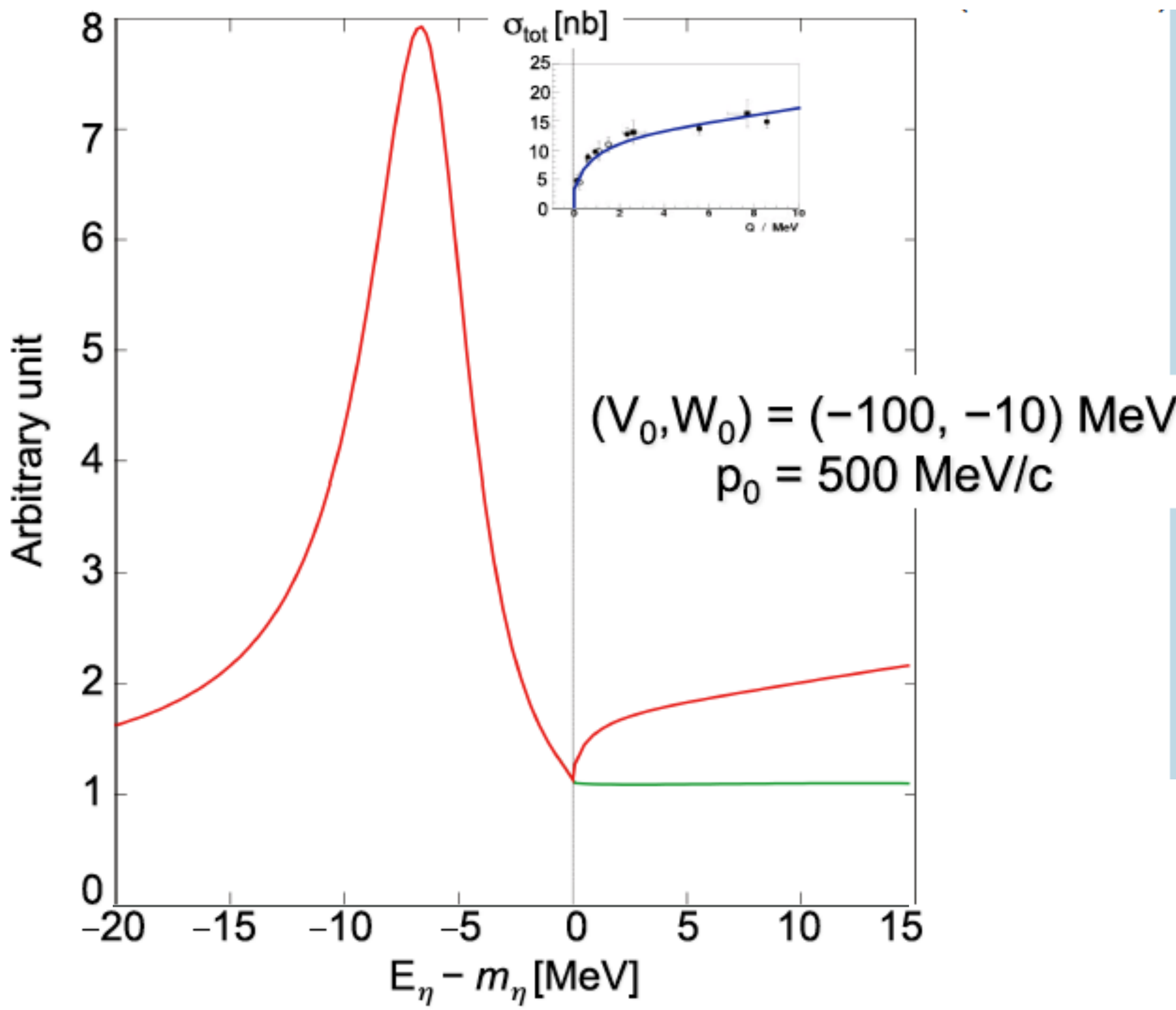
Satoru Hirenzaki

$dd \to \alpha \otimes \eta$





$d+d \to \eta \otimes {}^4He \to {}^3He\ \pi^-\ p;\ ({}^3He\ \pi^0\ n)$



formation of $\eta \otimes {}^4He$ bound states
with $\sigma \approx 80$ nb

ω-nucleus bound states

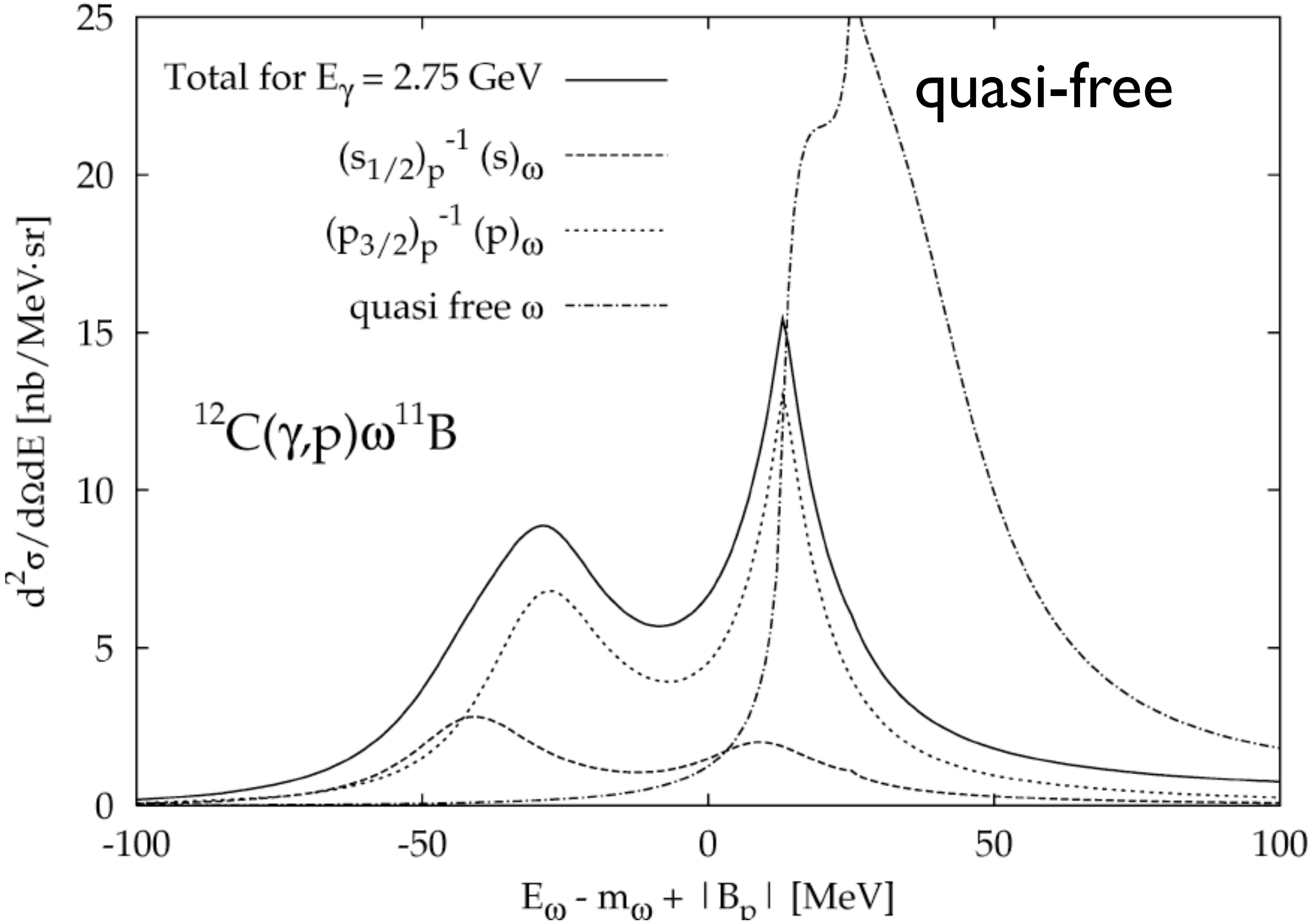
CBELSA/TAPS

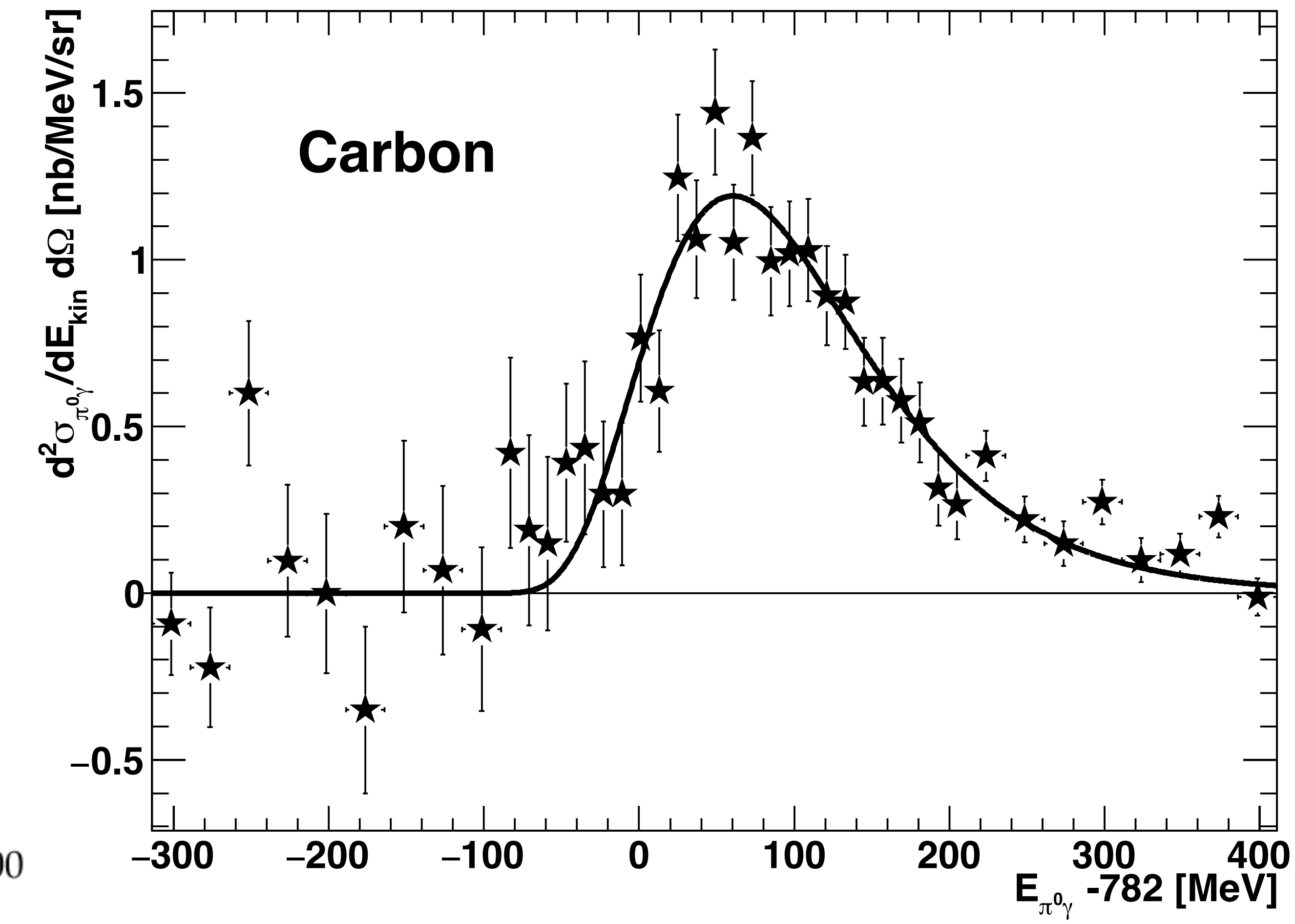
ω- mesic states

$^{12}C(\gamma,p)\omega\otimes^{11}B$

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

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



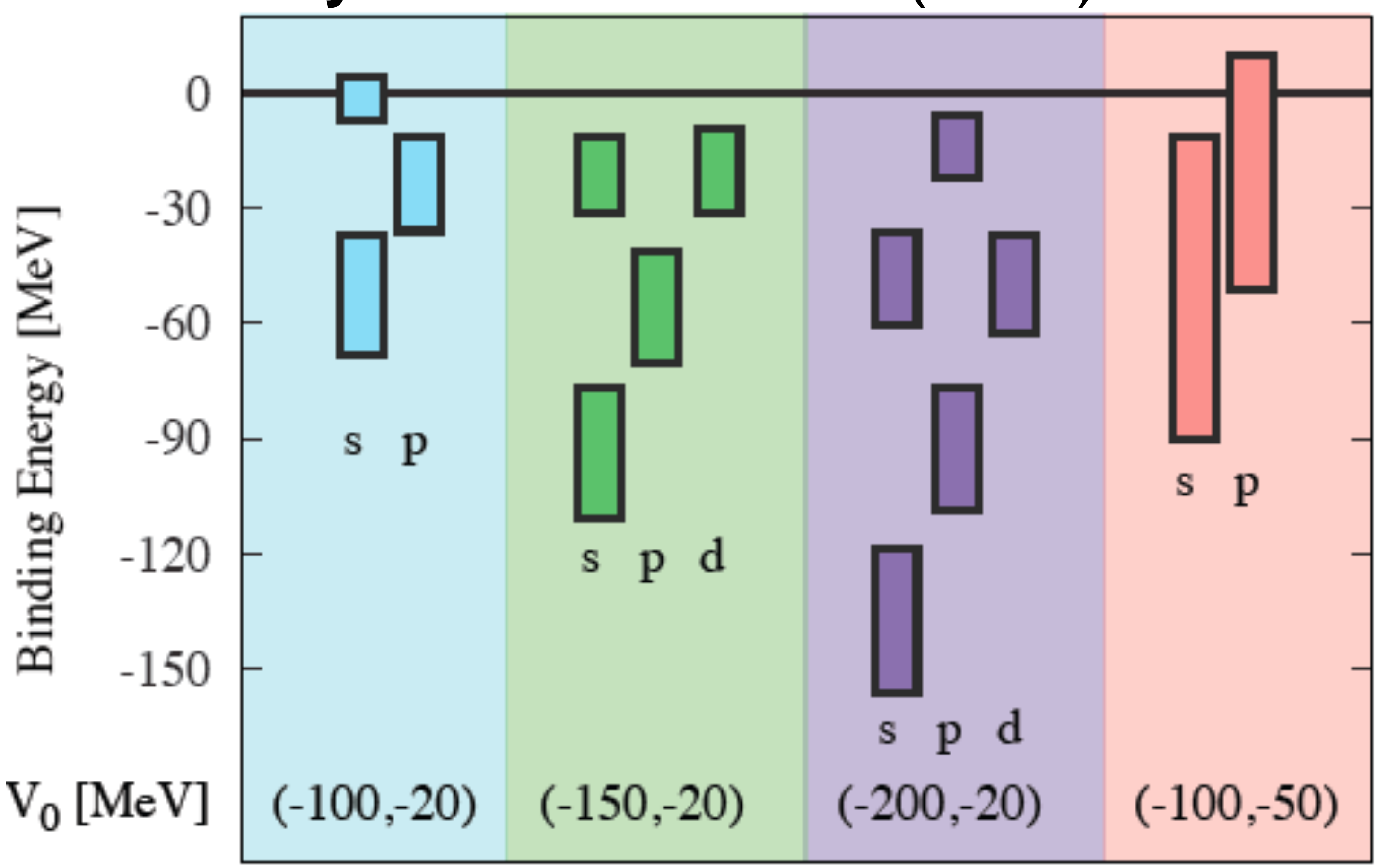


cross section in bound state region compatible with theoretical predictions, but no pronounced structure observed; consistent with tails extending into bound state region due to large imaginary part of the ω-nucleus optical potential

theoretical predictions for η’-nucleus bound states

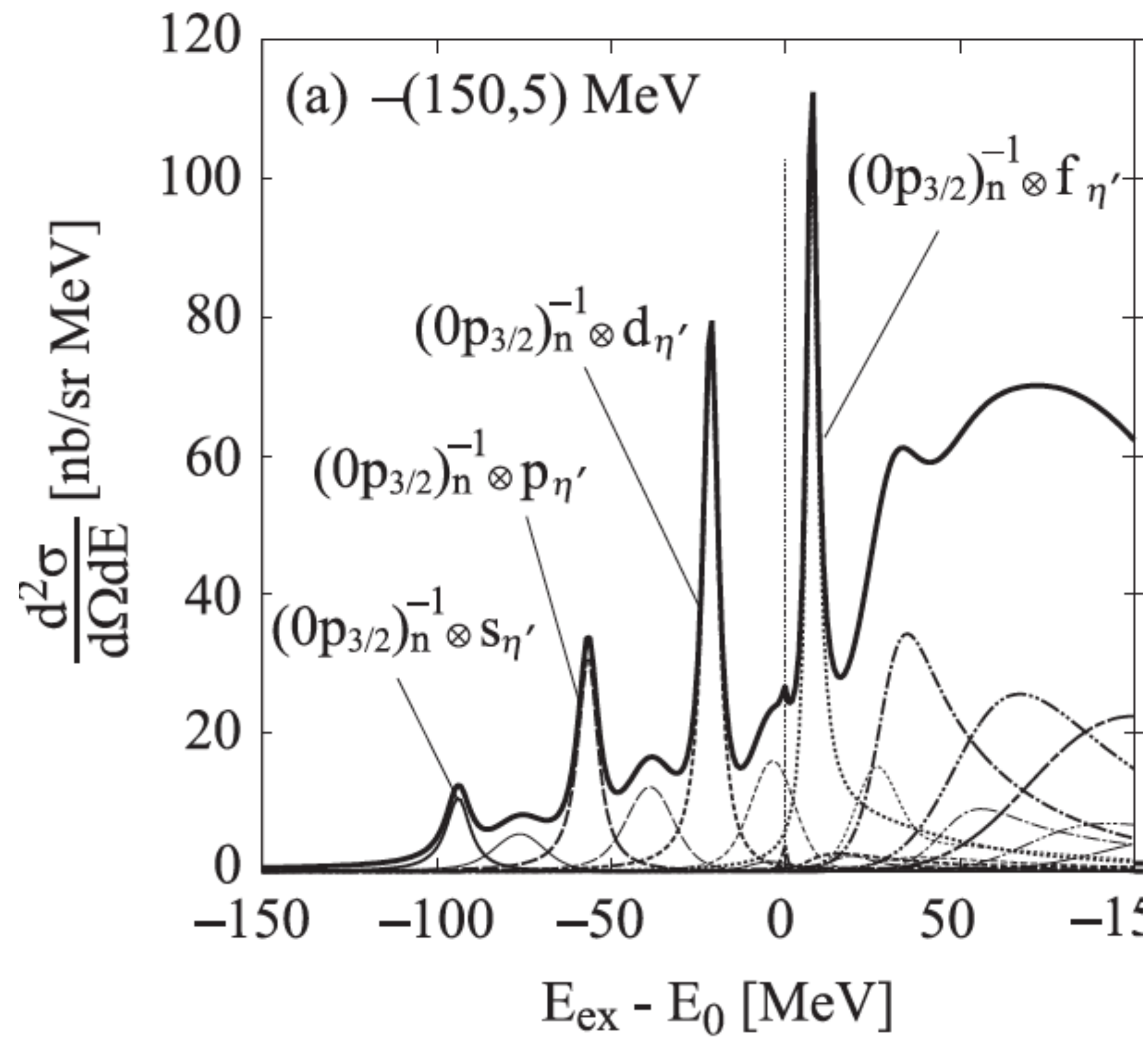
η’- mesic states: η’⊗^{12}C

D. Jido et al., PRC 85 (2012) 032201



most states with $\Gamma_{\eta'} \lesssim B_{\eta'}$

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

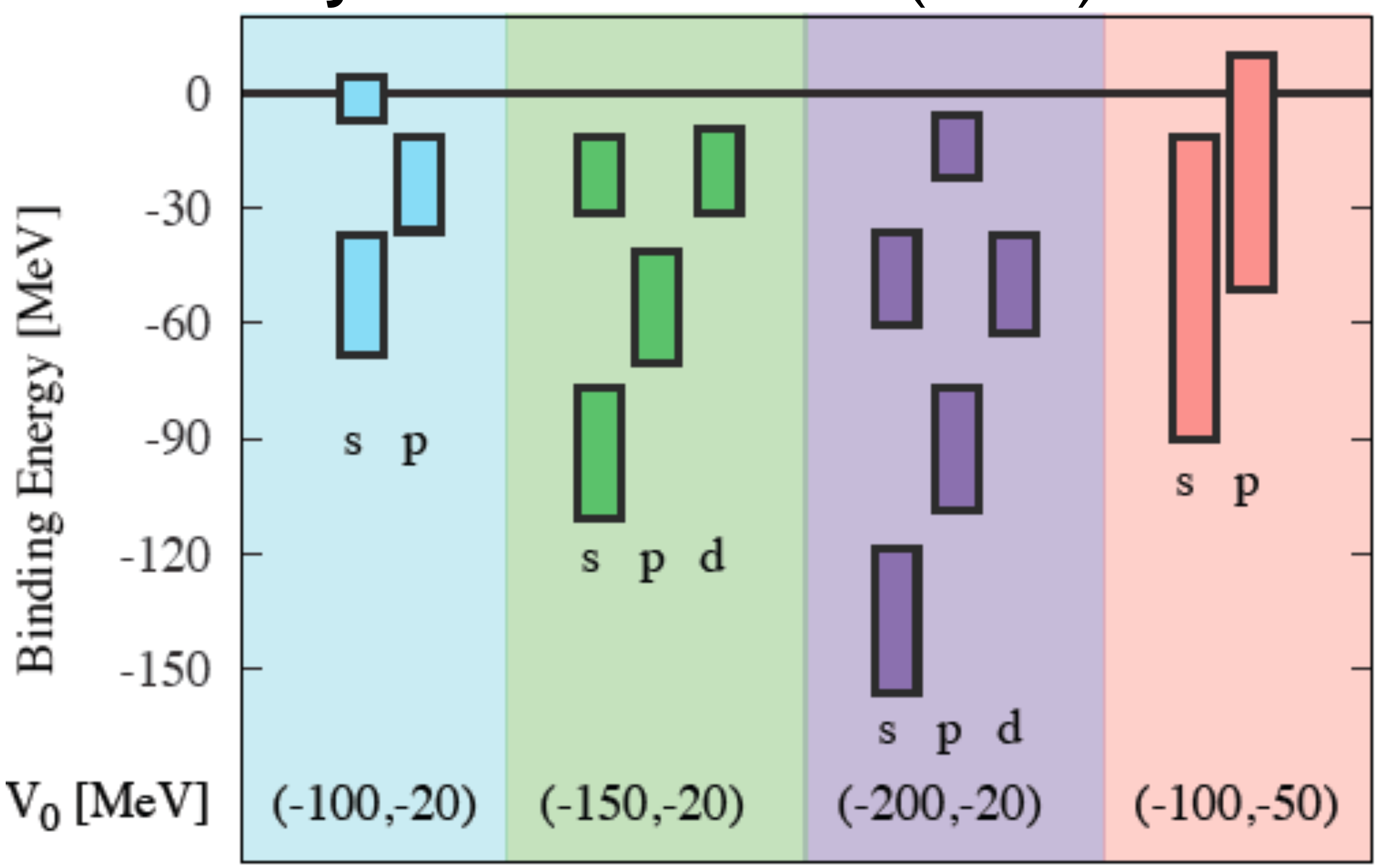


excitation energy spectrum
of the η’⊗^{12}C system

theoretical predictions for η'-nucleus bound states

η'- mesic states: η'⊗^{12}C

D. Jido et al., PRC 85 (2012) 032201



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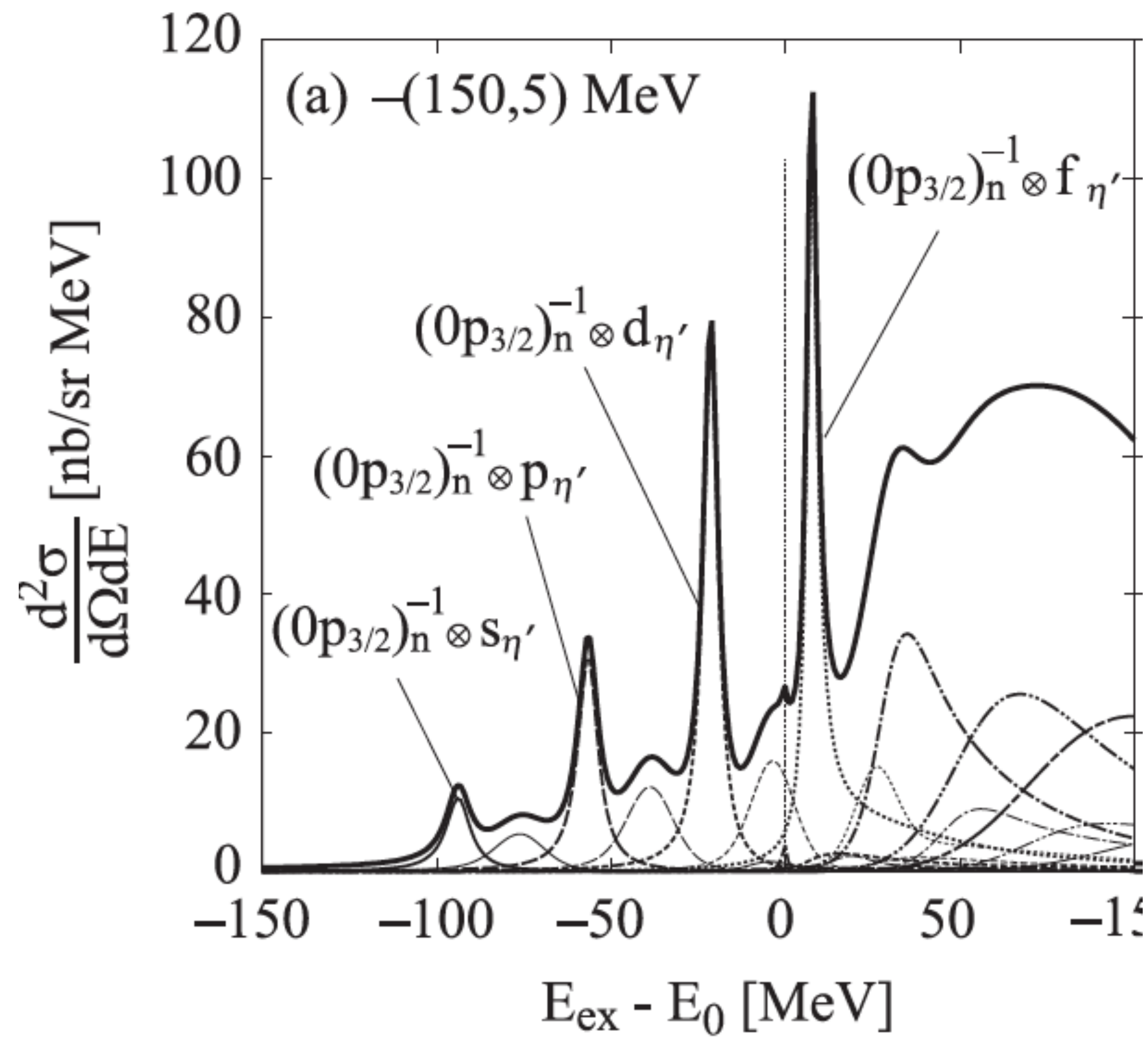
H. Nagahiro et al., PRC 87 (2013) 045201



excitation energy spectrum
of the η'⊗^{12}C system

Moeki Miyatani:

γ + ^{6}Li → d + α⊗η'

recoilless η' production off quasi deuteron in ^{6}Li ; $\frac{d^2\sigma}{dE\, d\Omega} \approx 10$ pb/(MeV sr)

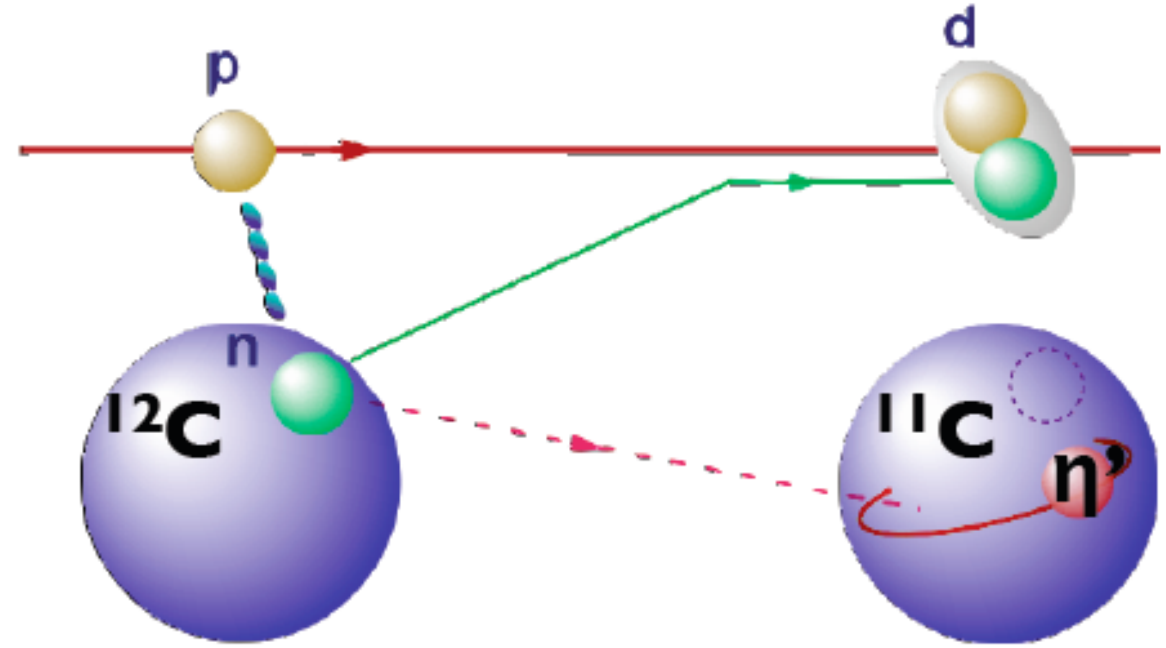
search for η'-mesic states in hadronic reactions

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



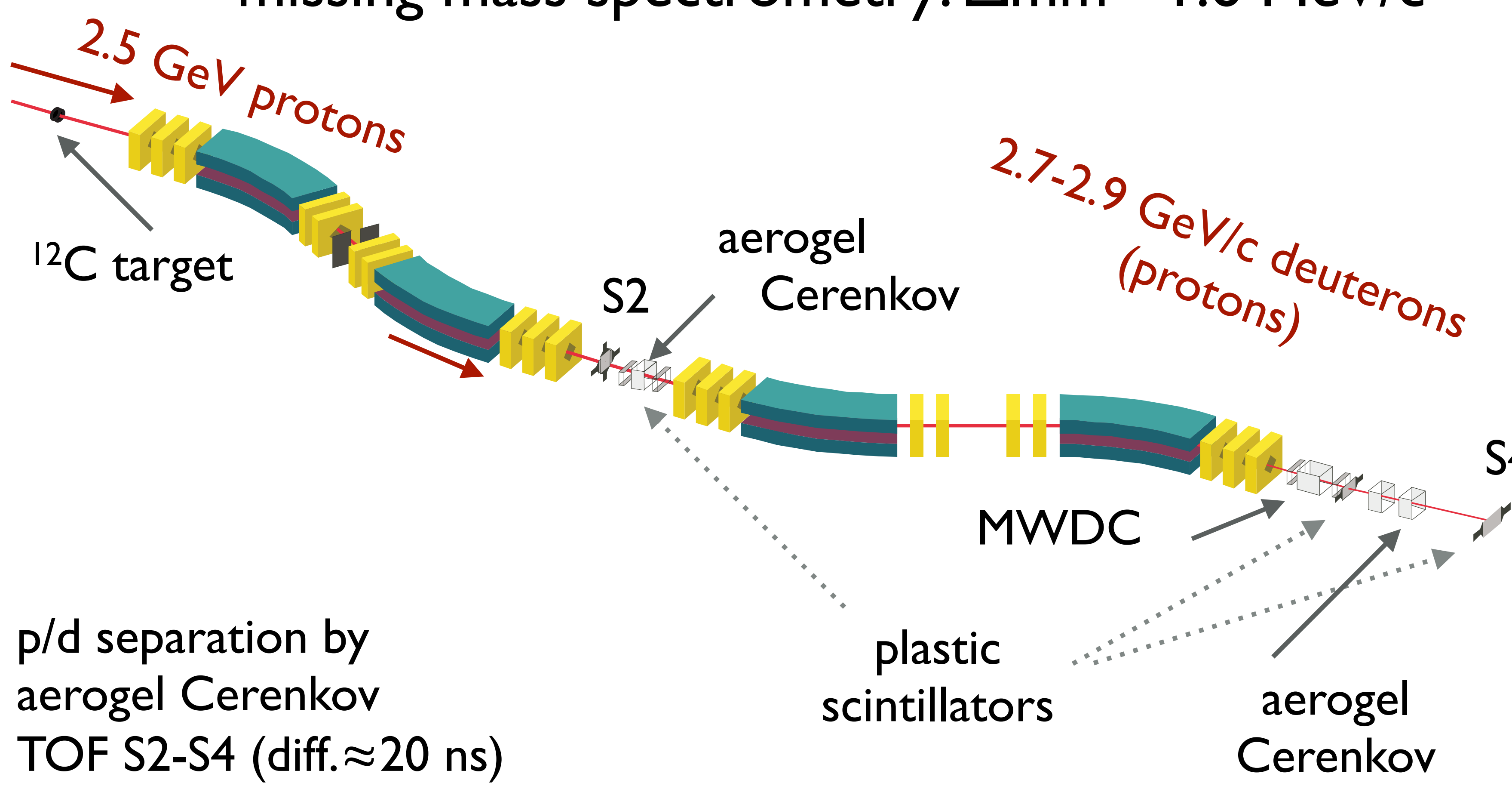
η' × 11C mesic nuclei

Kenta Itahashi

particle identification by time-of-flight

analysis ongoing

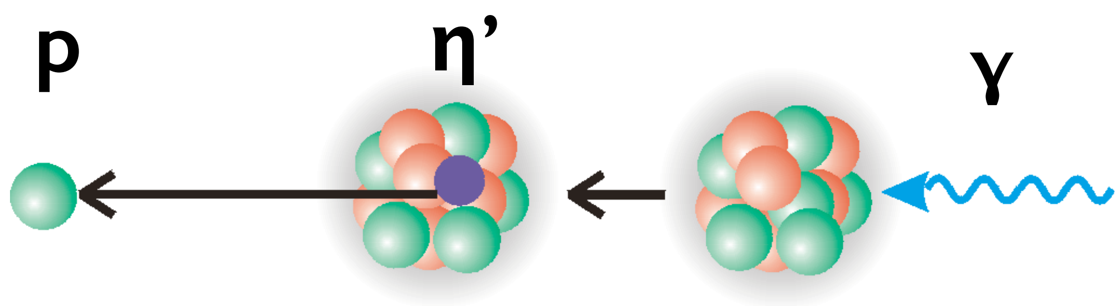
missing mass spectrometry: $\Delta mm = 1.6\ MeV/c^2$



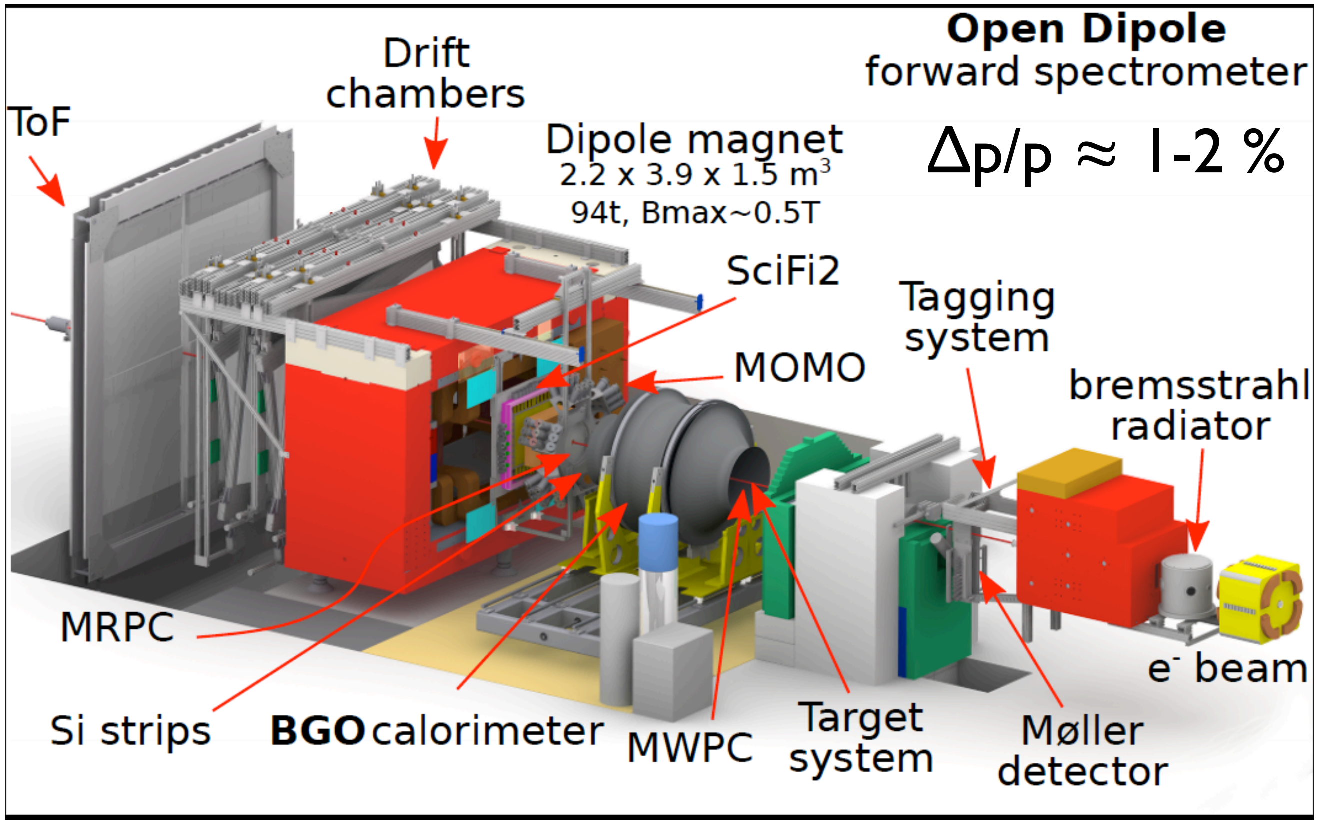
outlook: search for η'-mesic states in photo-nuclear reactions

BGO-OD@ELSA

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



formation and decay of η'-mesic state



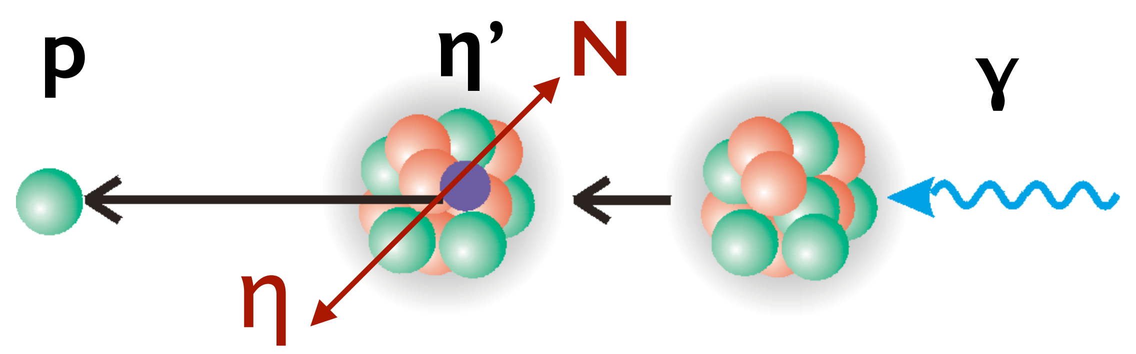
BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

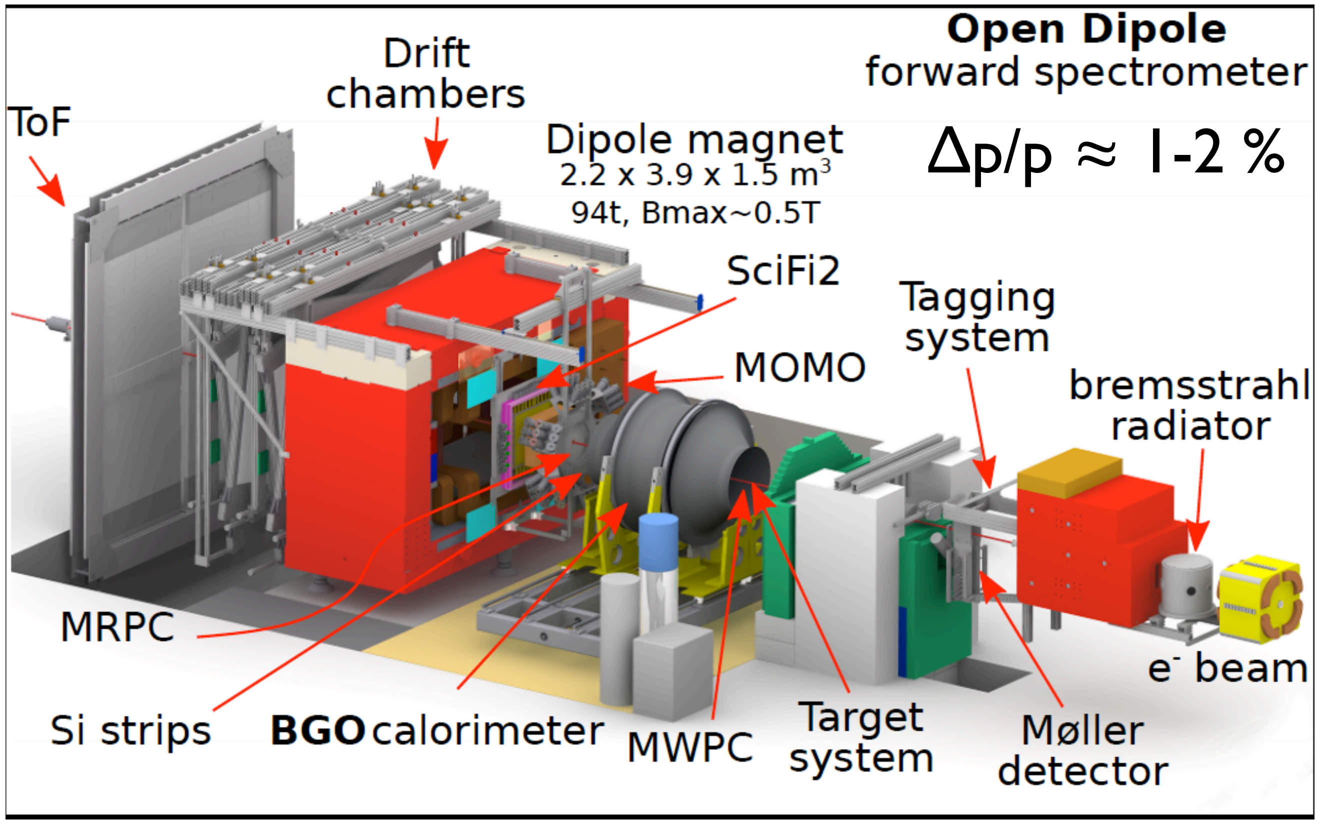
outlook: search for η’-mesic states in photo-nuclear reactions

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

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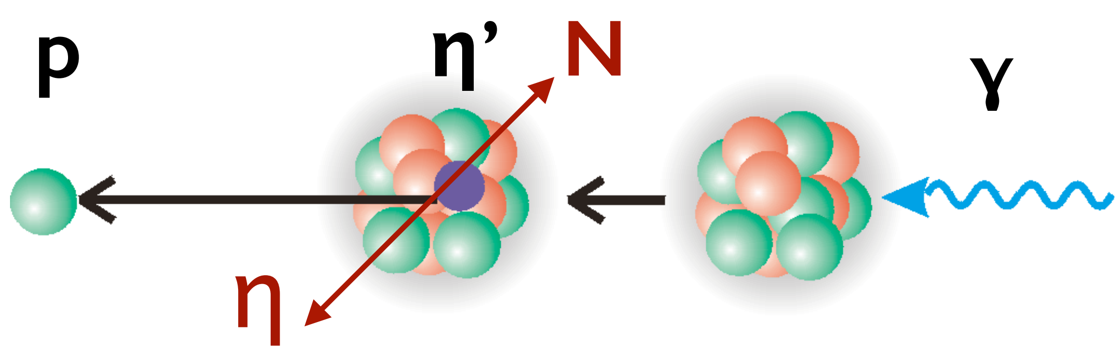
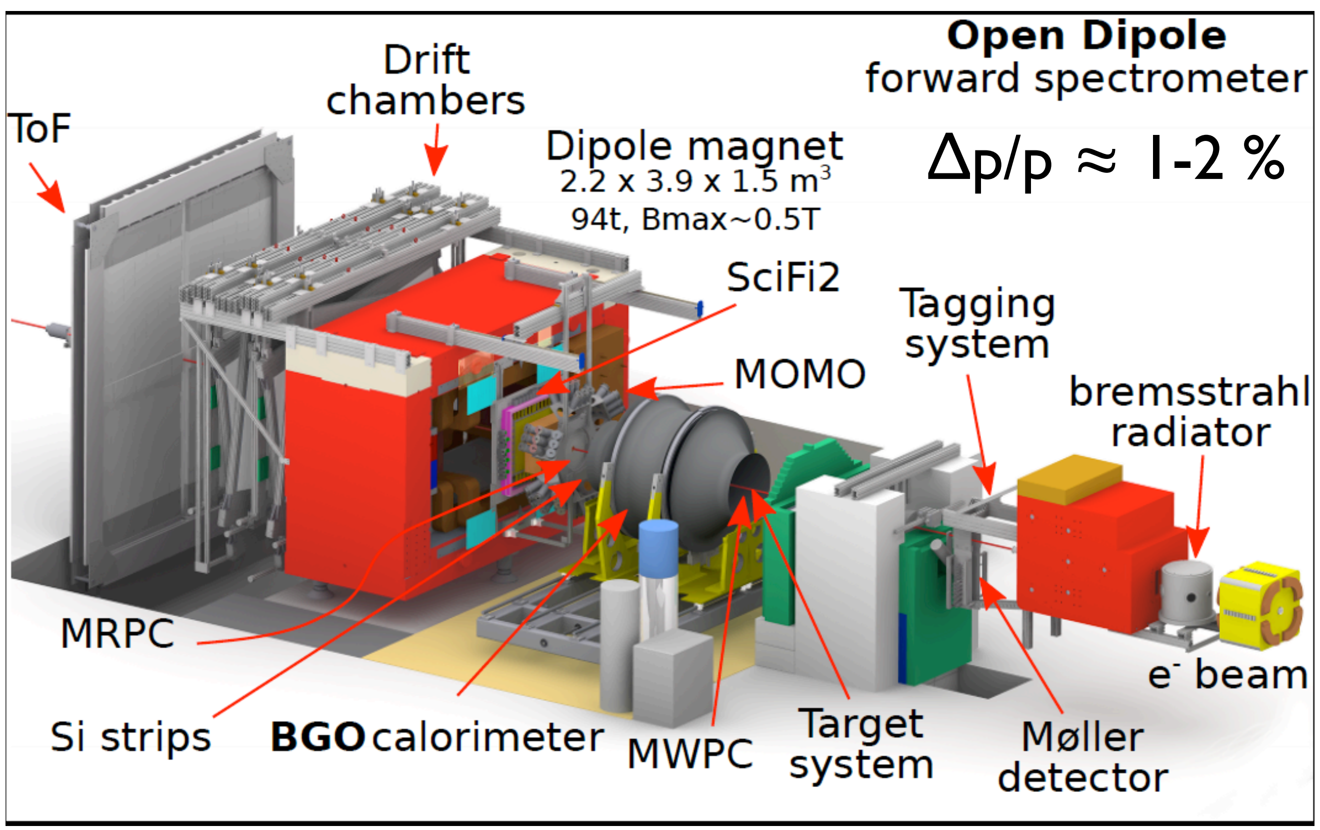
outlook: search for η'-mesic states in photo-nuclear reactions

BGO-OD@ELSA

^{12}C(γ,p) η'X @ 1.5-2.8 GeV



formation and decay of η'-mesic state

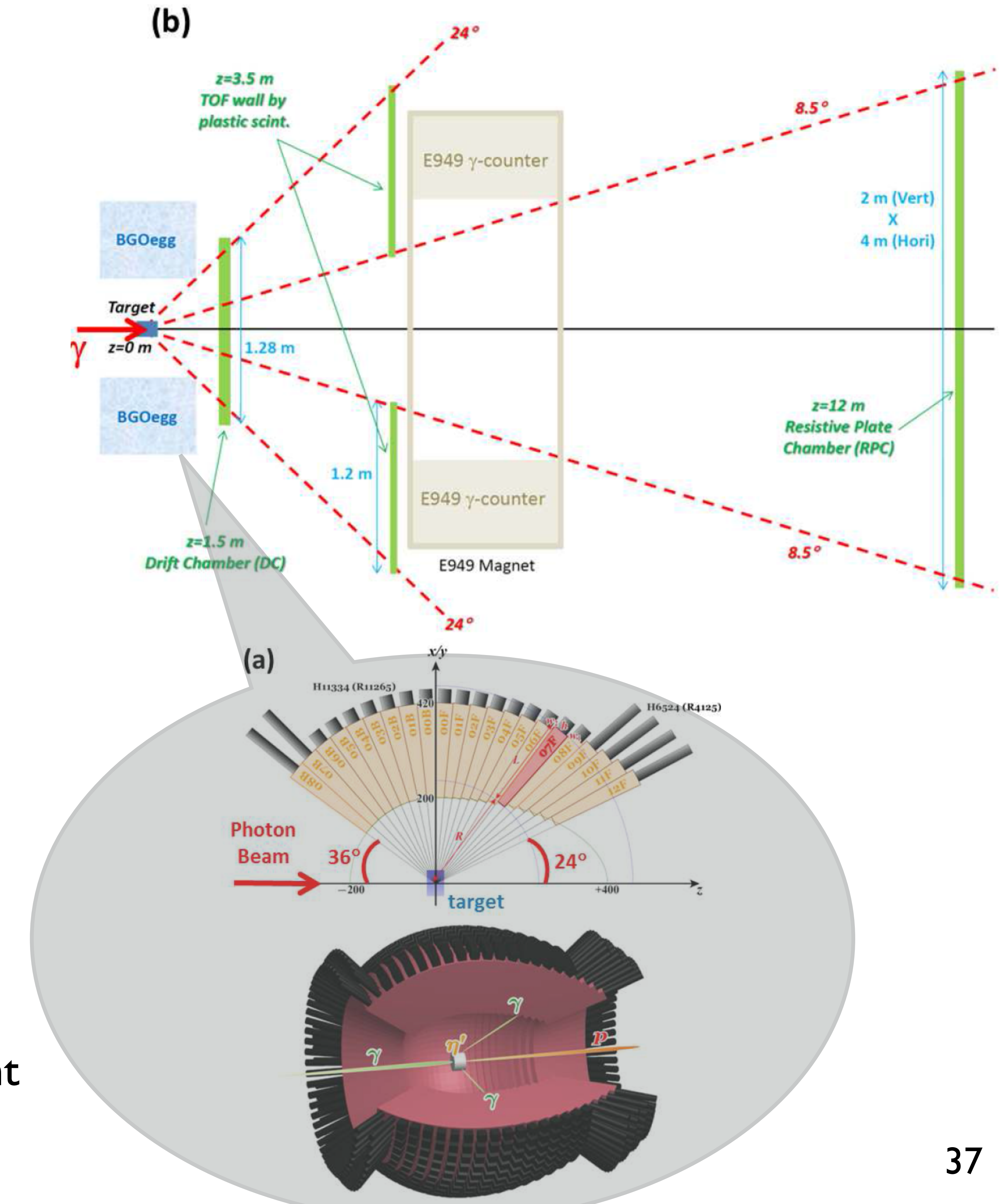


BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

LEPS2@SPring-8

^{12}C(γ,p) η'X @ 1.5-2.4 GeV



summary

meson-nucleus optical potential:

ω: weak attraction; strong absorption; $|V_{real}| << |V_{imag}|$

η': weak attraction, small absorption; $|V_{real}| > |V_{imag}|$

measure momentum dependence of potential parameters
to provide link to scattering length at production threshold

few body systems:

d*(2380) well established in various reactions and decay channels

existence of K^-pp clusters still controversial

search for mesic states:

π: deeply bound pionic states well established

η: indication for bound $\eta \otimes {}^4He$ state with large width ??

ω: no evidence for bound state due to large in-medium width

η': promising candidate for meson-nucleus bound state:
search ongoing at FRS@GSI, BGO-OD@ELSA, LEPS2@Spring8