Nobel prize for Eugene P. Wigner

Eugene P. Wigner
*17.11.1902, Budapest
✝ 1.1.1995, Princeton

Nobelprize in Physics 1963

"for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles"

together with Maria Göppert-Maier and J. Hans D. Jensen

Symmetries and in-medium effects

breaking and restoration of chiral symmetry and in-medium modifications of hadrons

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

Outline

- chiral symmetry breaking and restoration
- experimental approaches for studying in-medium properties of hadrons
- in-medium properties of the η' meson
- summary and outlook

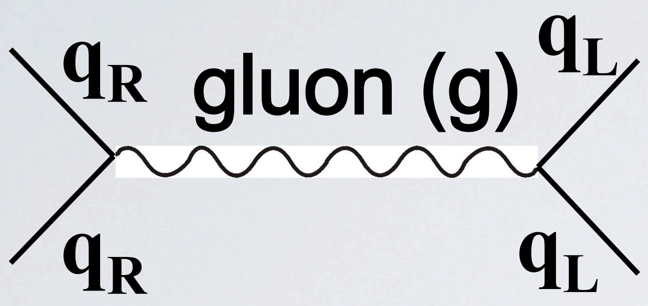
*funded by the DFG within SFB/TR16

Wigner 111 symposium
Nov. 11-14. 2013, Budapest, Hungary

HIC for FAIR
Helmholtz International Center

Chiral symmetry

- Chiral symmetry = fundamental symmetry of QCD for $m_q = 0$



in interaction by gluon exchange

q_R stays q_R; q_L stays q_L

chirality is conserved

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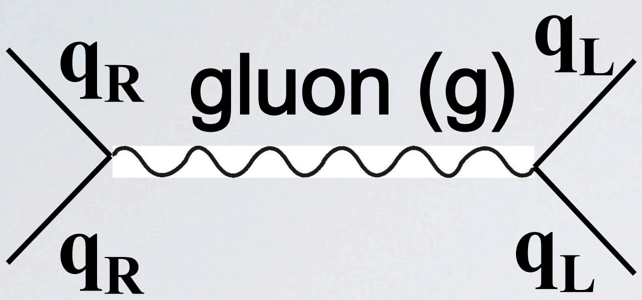

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$$L_{QCD}^{m=0} = \overline{\psi}(i\gamma_\mu D^\mu)\ \psi - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$

invariant under $SU(3)_L \otimes SU(3)_R$

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$$\psi_{L,R} \rightarrow exp(i\theta_{L,R}^a \frac{\lambda_a}{2})\psi_{L,R}$$

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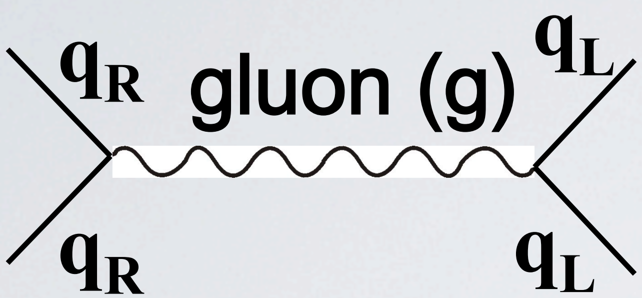

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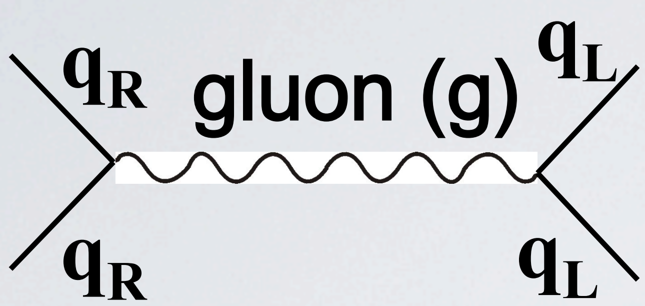

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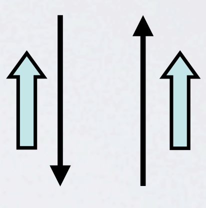

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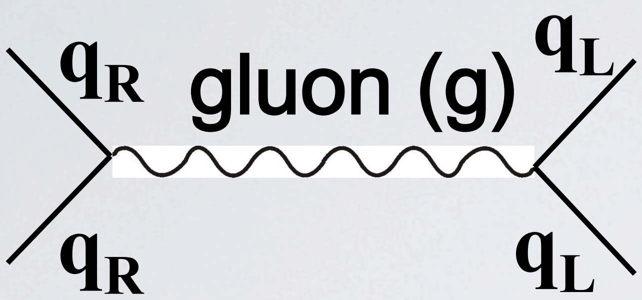

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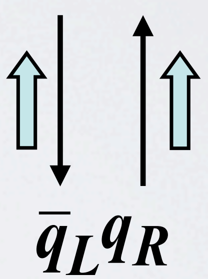

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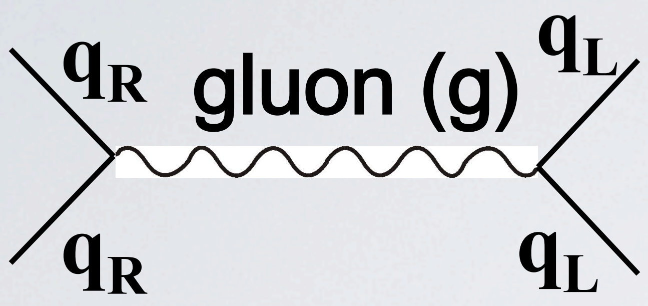

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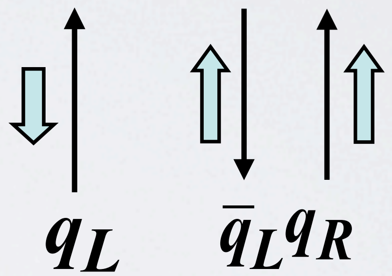

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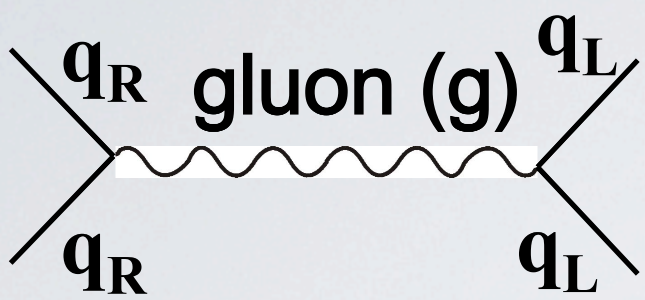

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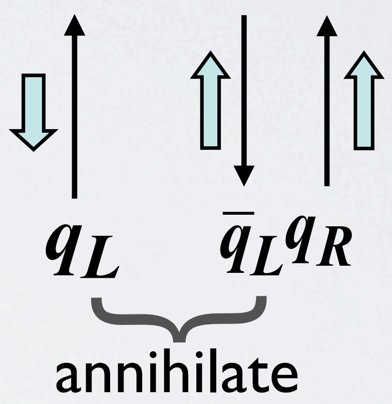

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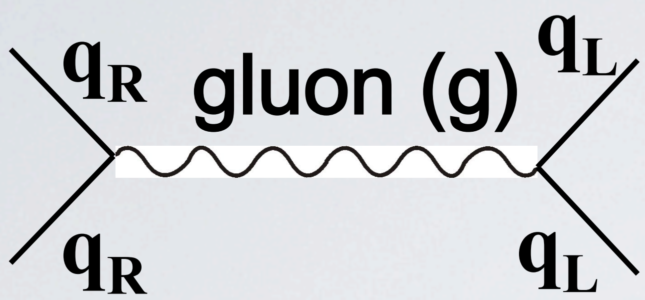

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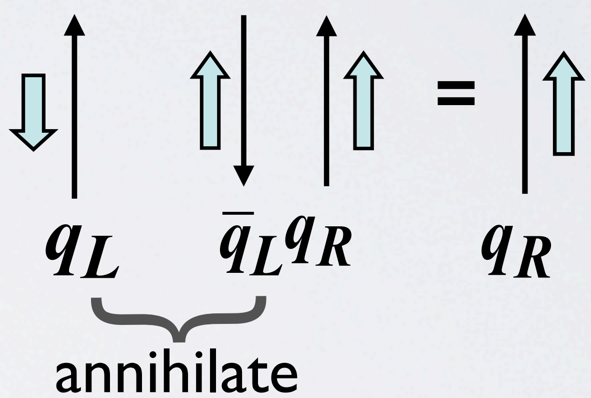

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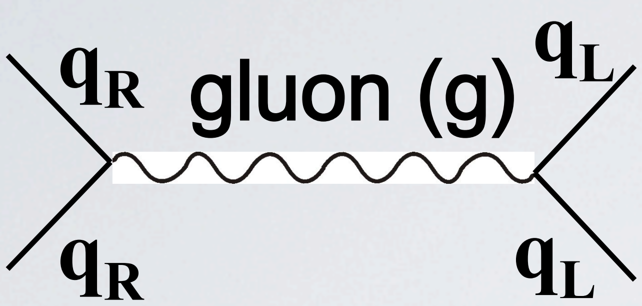

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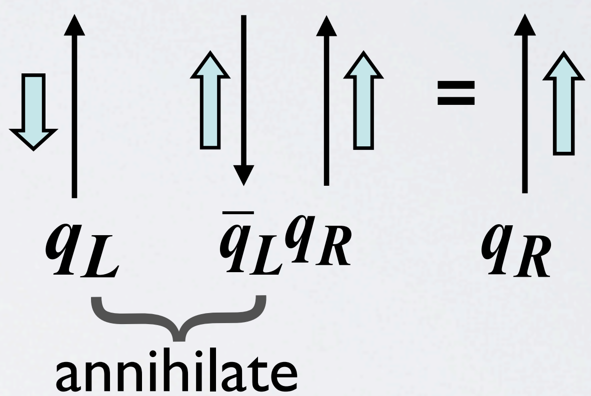


- $q_L \Rightarrow q_R$; χ symmetry broken
in presence of a chiral condensate

$<0|q\bar{q}|0>$ is order parameter for χ-symmetry

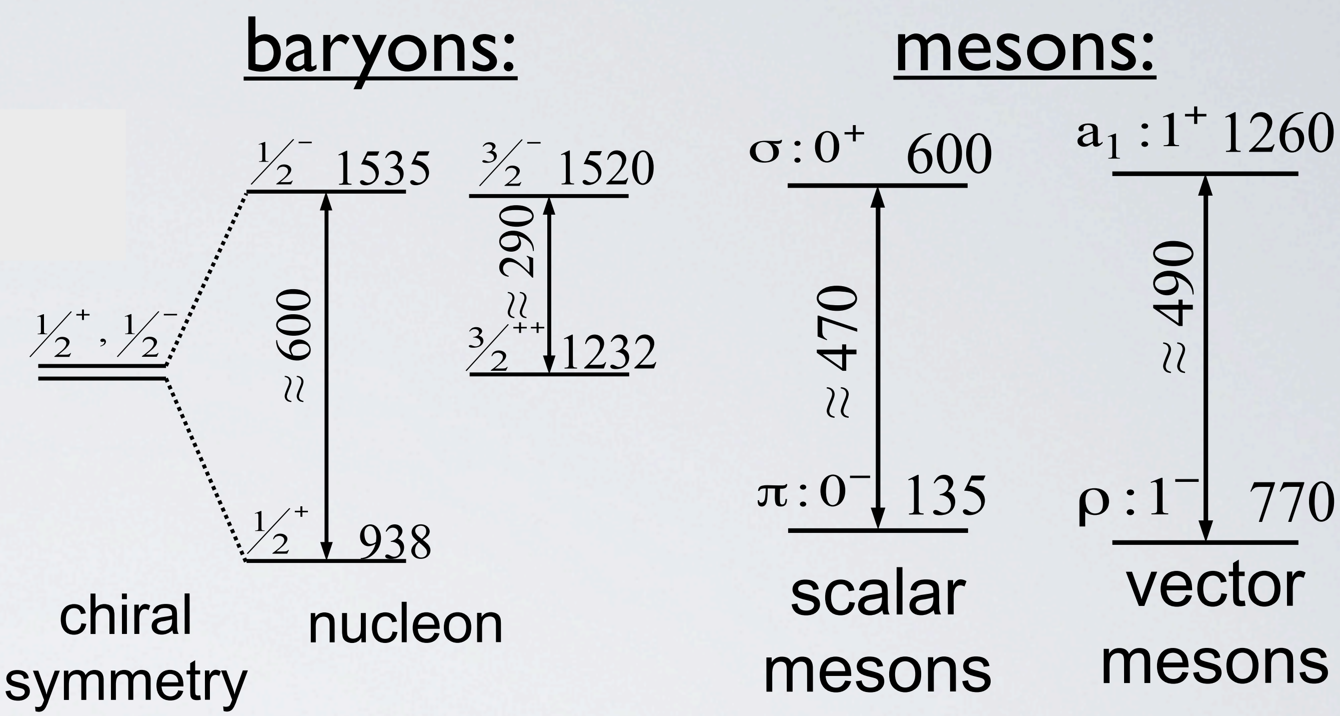
χ-symmetry restored for $<0|q\bar{q}|0> \rightarrow 0$

symmetry breaking in the hadronic sector

- for χ symmetry chiral partners (hadronic states with same spin but opposite parity) should be degenerate in mass: $m(J^{\pi}) = m(J^{-\pi})$

experiment: $\Delta m \neq 0$

➡ χ symmetry



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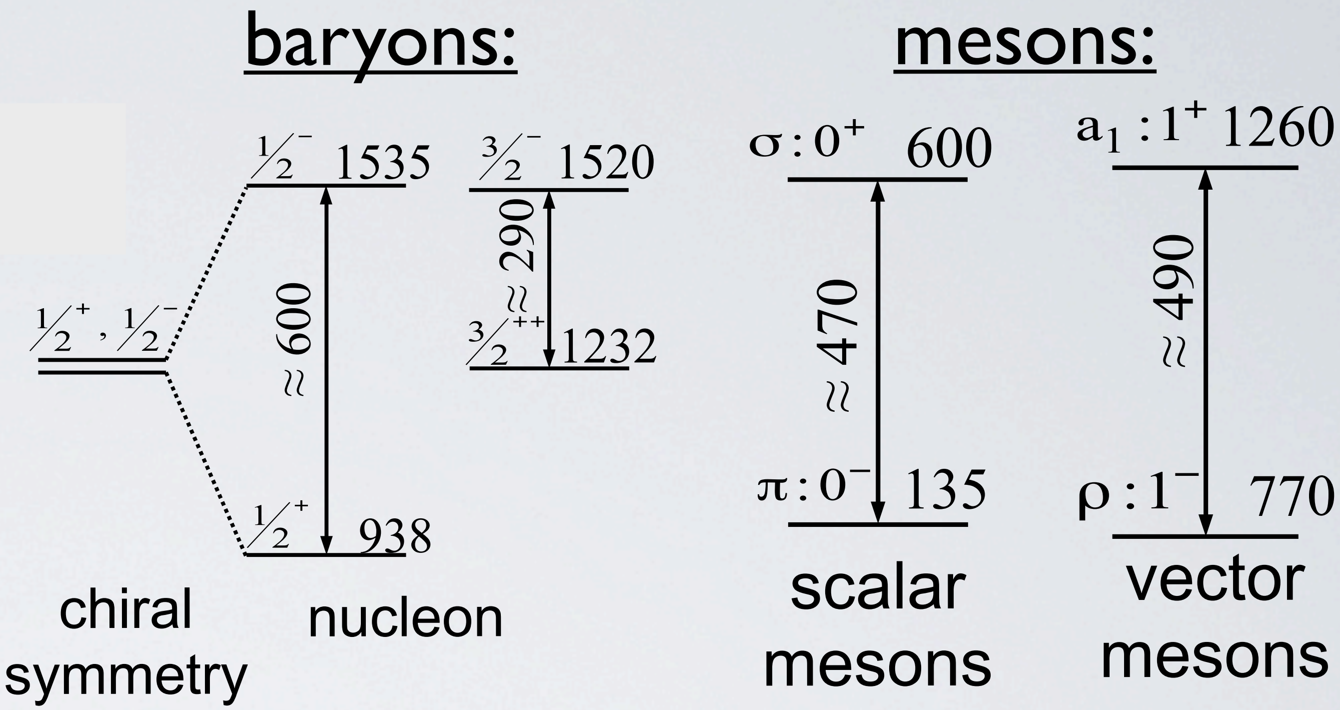
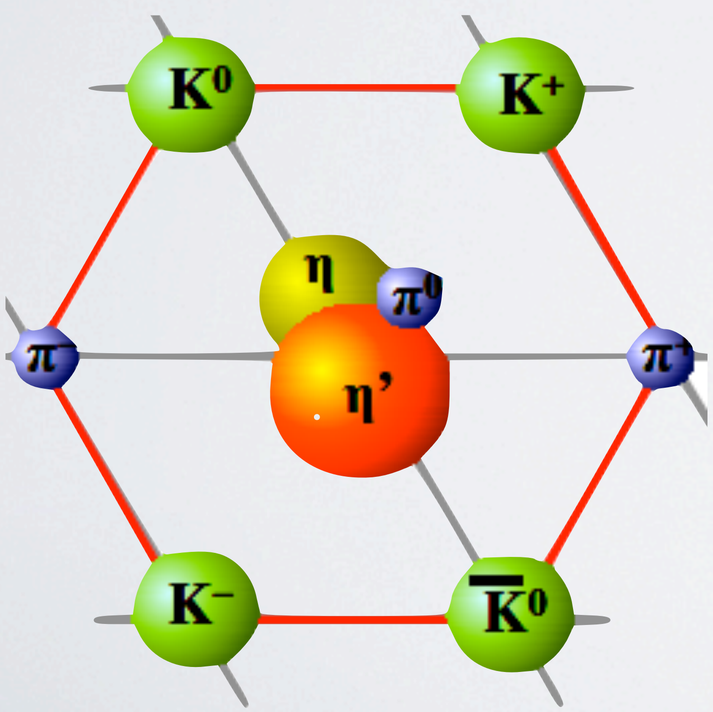
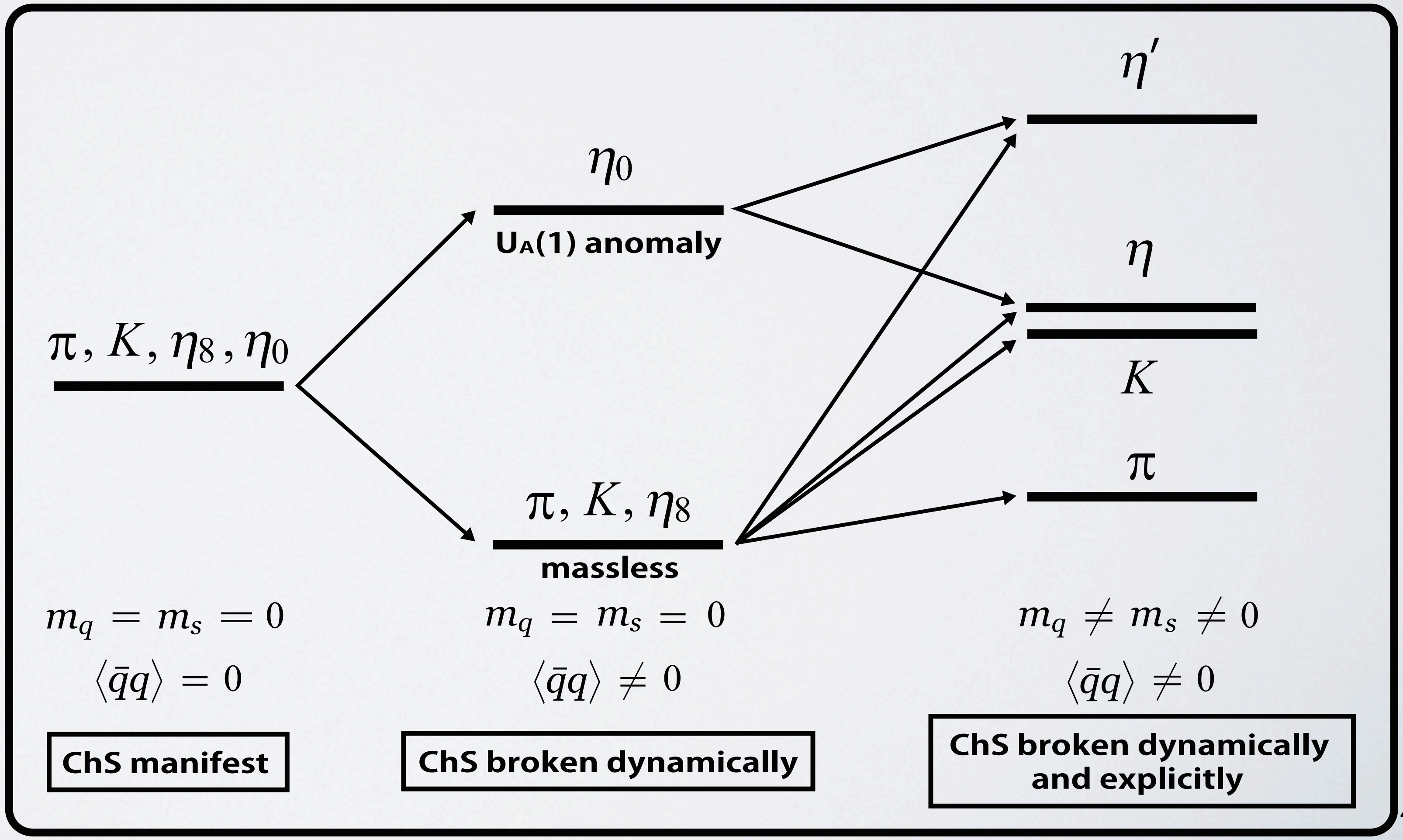


- mass as a result of symmetry breaking



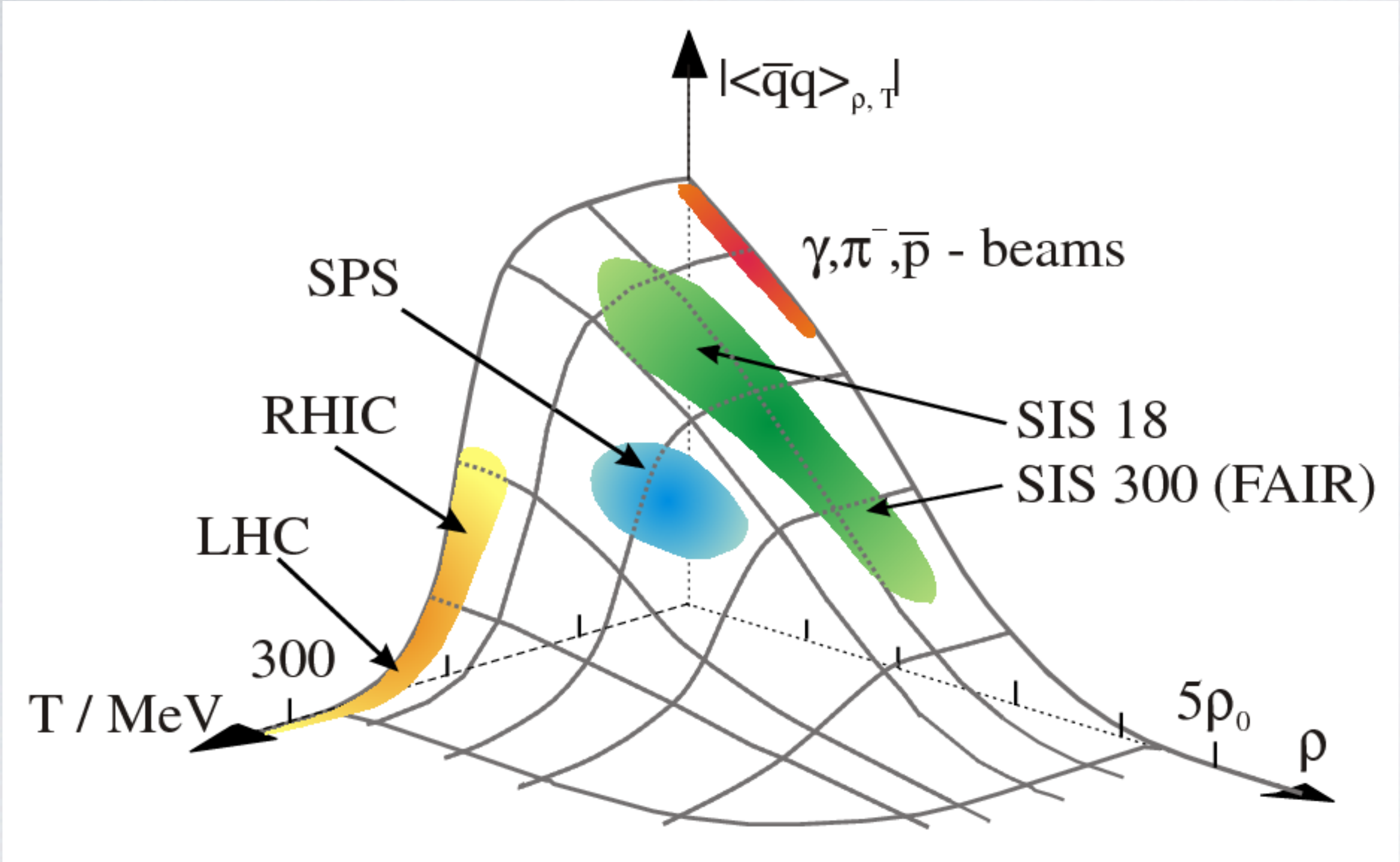
nonet of pseudoscalar mesons

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



Link between hadronic and QCD- descriptions

chiral condensate as function of
baryon density ρ_B and temperature T



partial restoration of chiral symmetry

$|\langle\bar{q}q\rangle_{\rho,T}| \rightarrow 0$ for ρ_B , T↗

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

parameter range (ρ_B,T) reached in reactions with heavy-ion, γ,π, p-beams

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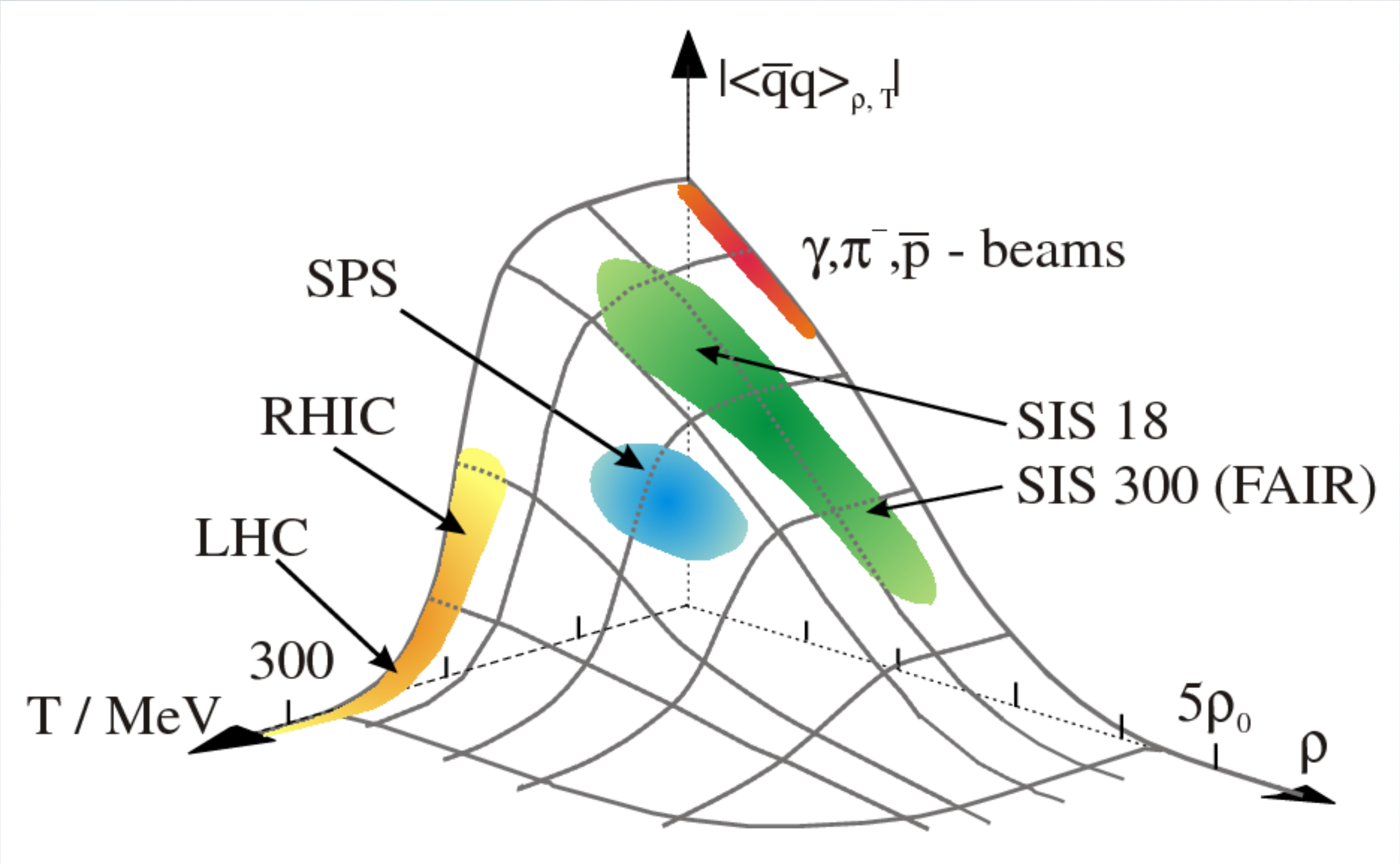

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QCD sum rules:

hadronic side — QCD side

$$\frac{Q^2}{\pi}\int_0^\infty ds\frac{Im\Pi(s)}{s(s+Q^2)} = -\frac{1}{8\pi^2}(1+\frac{\alpha_s}{\pi})ln\frac{Q^2}{\Lambda^2} + \frac{m_q\langle\bar{q}q\rangle}{Q^4} + \frac{1}{24}\frac{\langle\frac{\alpha_s}{\pi}G^2\rangle}{Q^4} - \frac{112}{81}\alpha_s\pi\frac{\langle\bar{q}q\rangle^2}{Q^6} + \ldots$$

no direct relation between in-medium properties of hadrons and QCD condensates

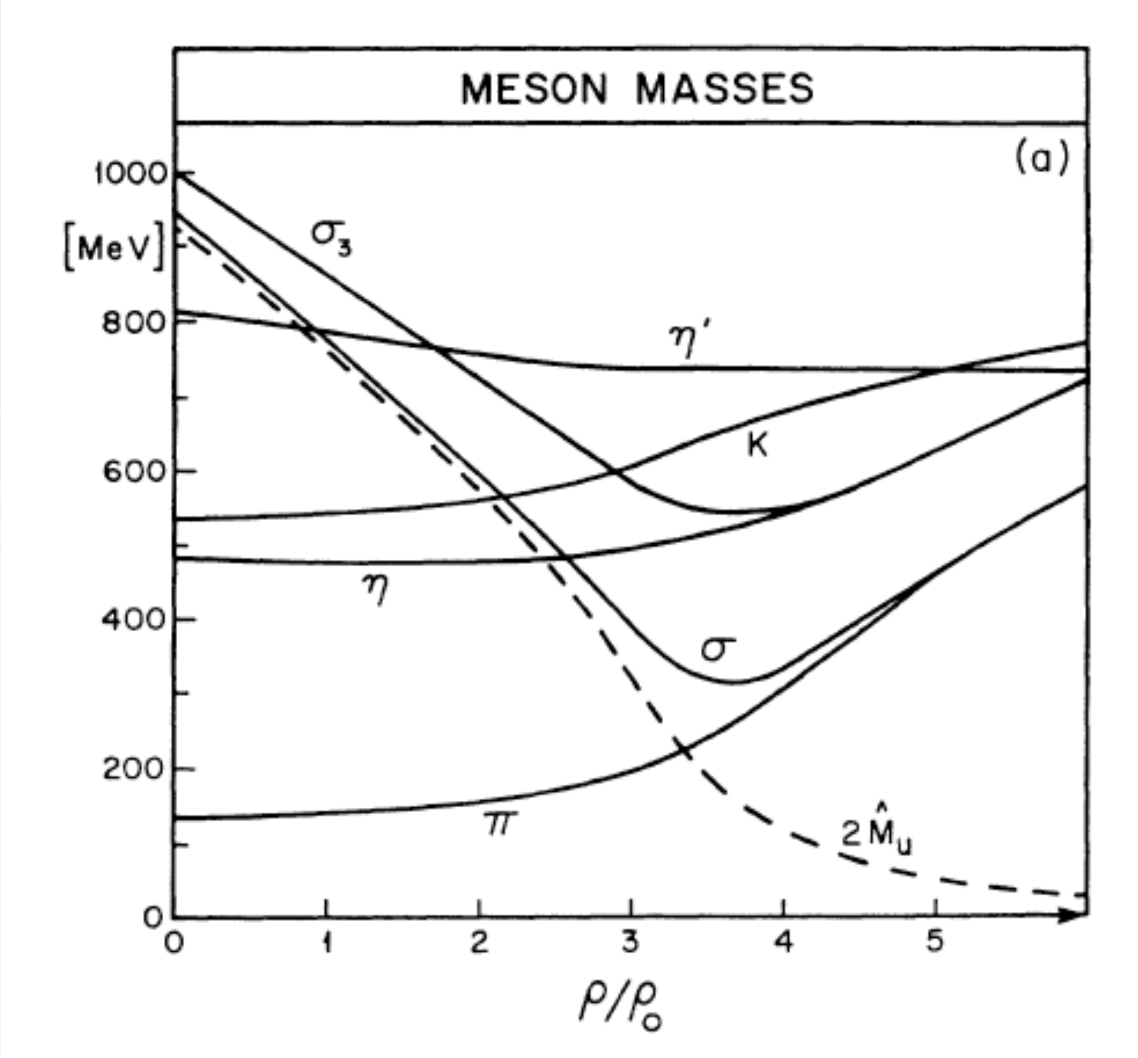
QCD sum rules provide important constraints for hadronic models

hadronic models needed for quantitative comparison to experiments

spectral function of the η' meson

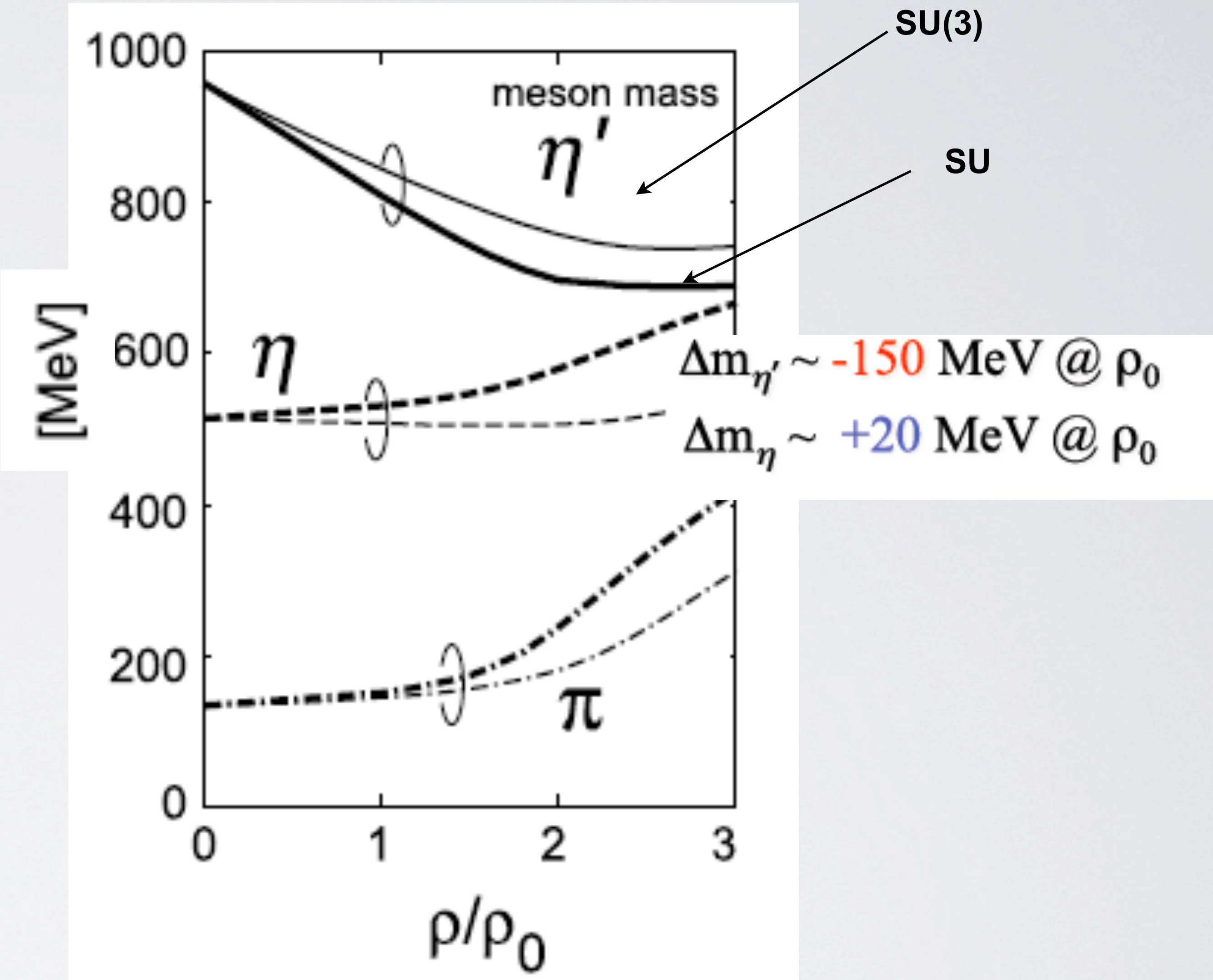
- model predictions - based on NJL

V. Bernard und U.-G. Meißner, Phys. Rev. D 38 (1988) 1551



the mass of the η' meson is almost independent of density

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



large medium effect could be seen even at normal nuclear density

Y. Kwon, S.H. Lee, K. Morita, and G. Wolf, PRD 86 (2012) 034014

$U_A(1)$ breaking part of η' mass (≈460 MeV) lowered by 20%: ➠ $\Delta m_{\eta'}(\rho_0) \approx -90$ MeV

discrepancy between theoretical predictions requires exprimental clarification !!

experimental results on η’ interactions

- $p\,p \rightarrow p\,p\,\eta'$ @ COSY (P. Moskal et al., PLB 482 (2000) 356)

analysis of final state interactions gives estimate of η’- proton scattering length

$|a_{\eta' p}| \approx 0.1$ fm ➡ weak η’- nucleon interaction

- ultra-relativistic heavy-ion collisions @RHIC (Csörgo et al., PRL 105 (2010) 182301)

two-pion Bose-Einstein correlation analysis of PHENIX and STAR data indicates massdrop of η’ meson in highly compressed and heated collision zone

$\Delta m_{\eta'} \approx -200$ MeV ➡ very strong η’- nucleon interaction

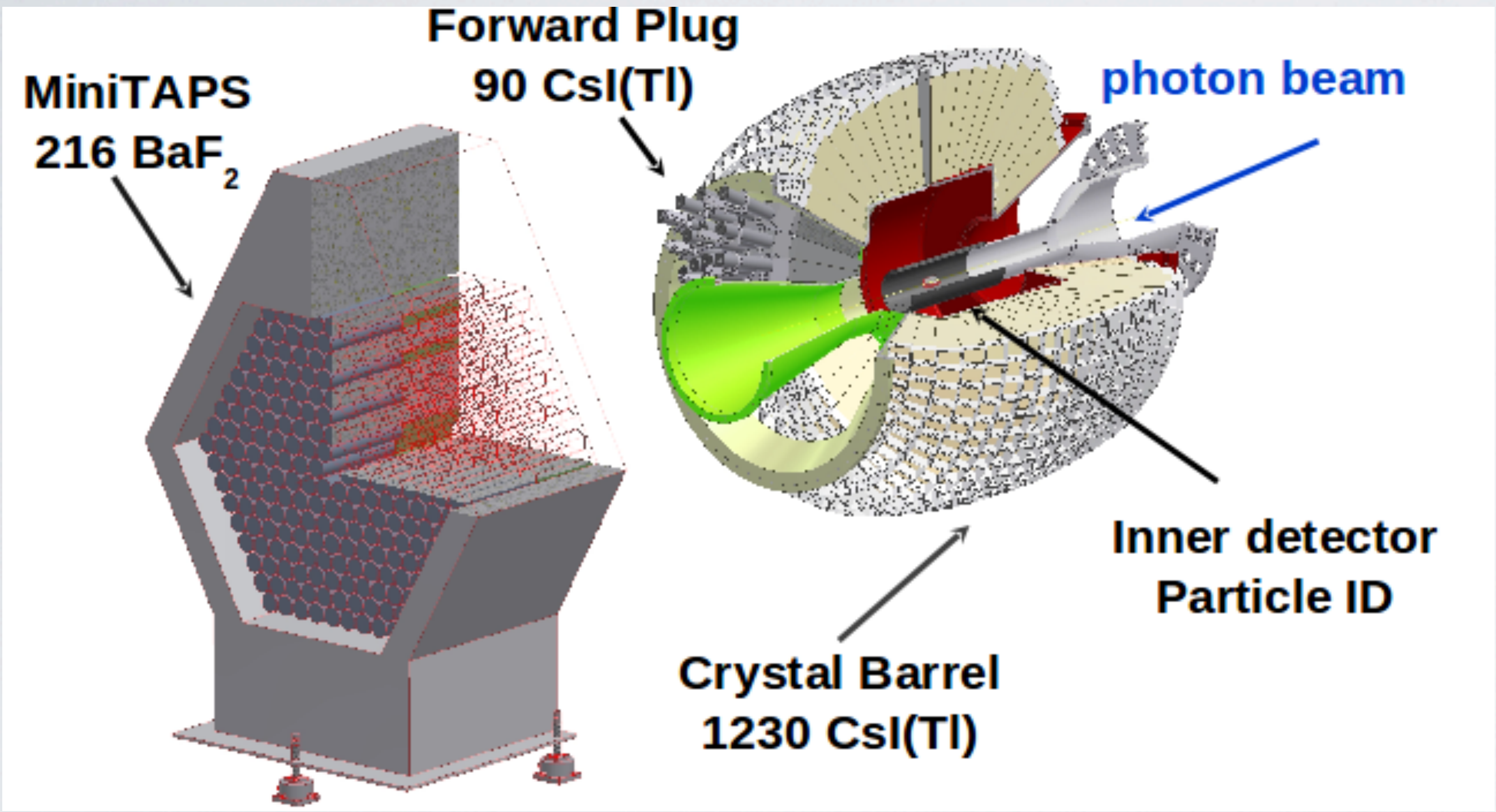
conflicting experimental evidence !!!
further experiments needed

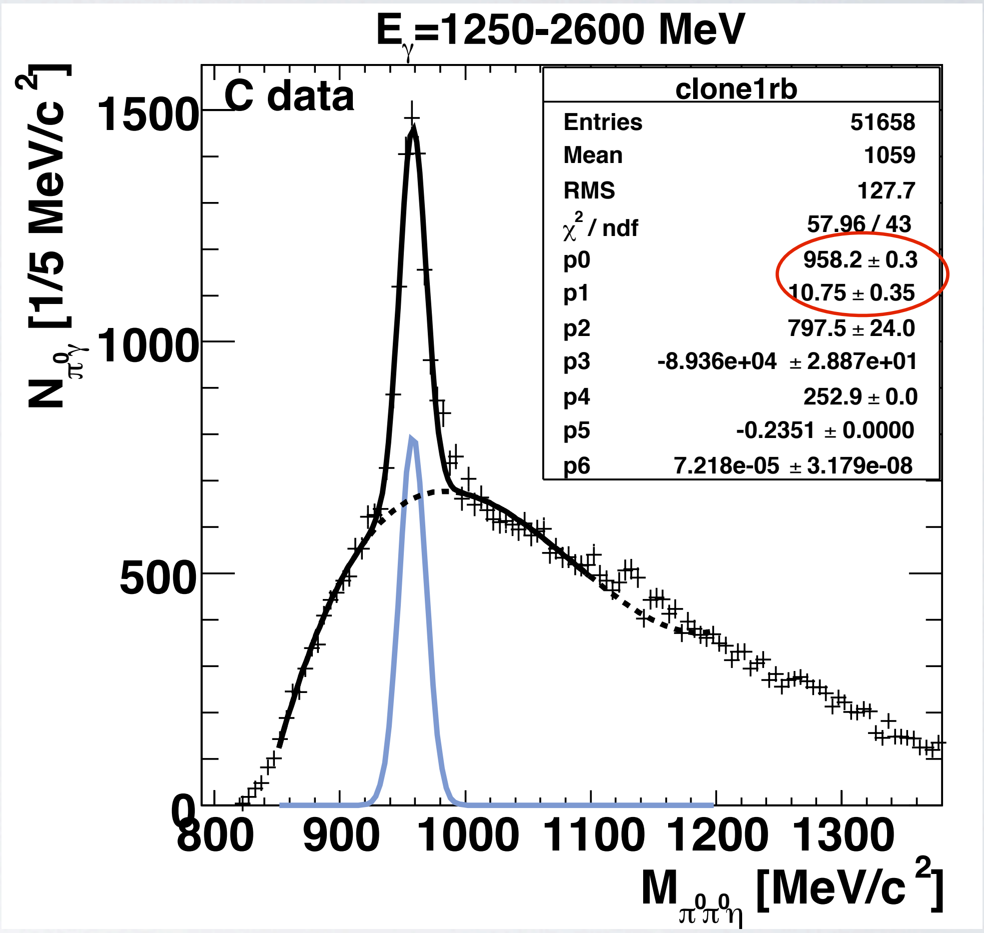
photoproduction of η' mesons off nuclei at ELSA

CBELSA/TAPS-detector system : ≈4π photon detector system

E_γ = 1.0- 2.8 GeV

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





m = 958 MeV/c^2

σ = 11 MeV

Δm/m = 1.1%

Experimental approaches to determine the meson-nucleus optical potential

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

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meson mass shift

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

line shape analysis:
direct determination of Δm

excitation function:
provides information about the depth of V(r)

meson momentum distribution:
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meson-nucleus-bound states:
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meson absorption

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

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Transparency ratio measurement

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

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

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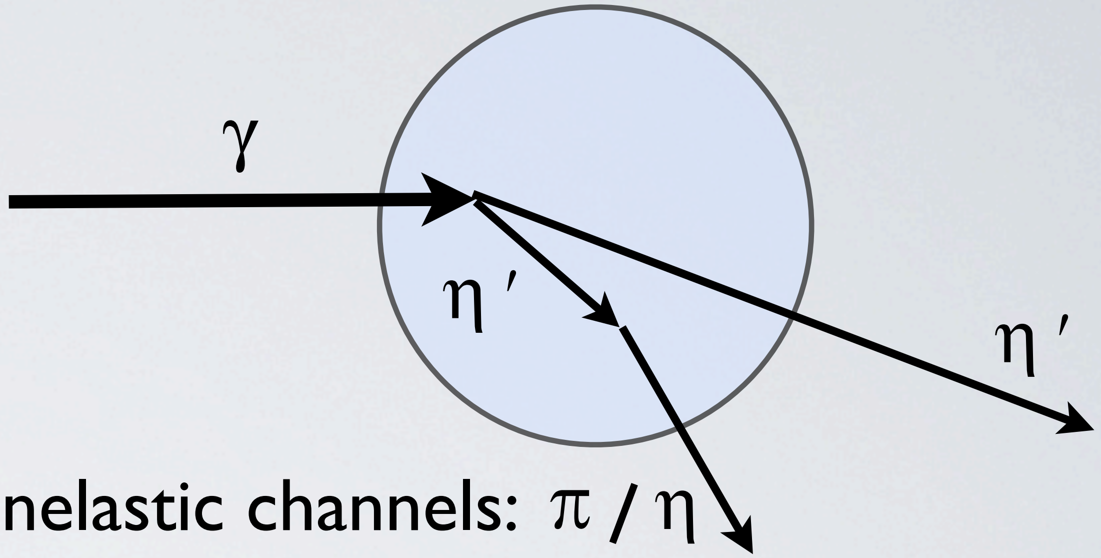

production probability per nucleon within the nucleus compared to production probability on the free nucleon;

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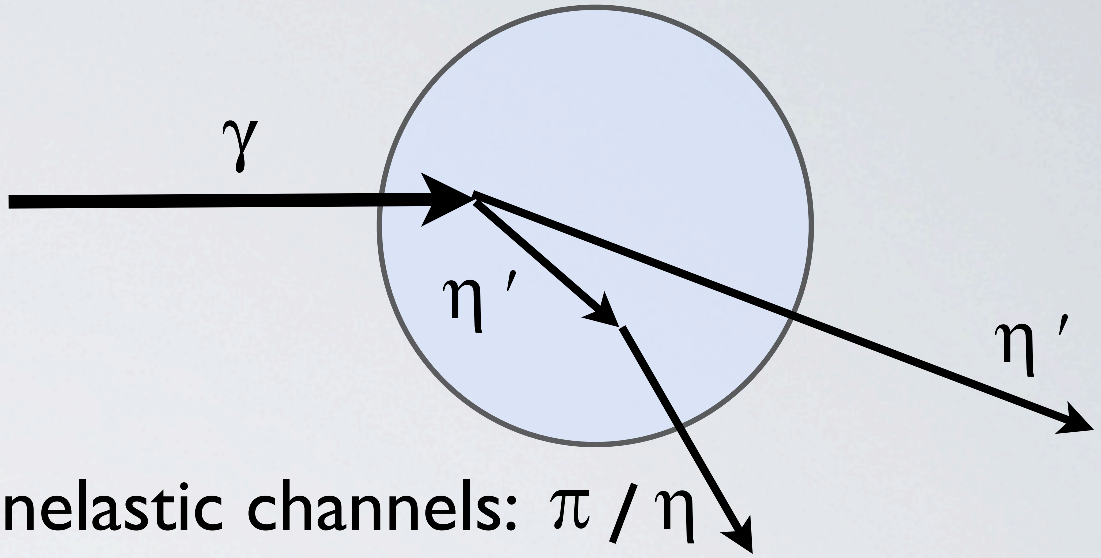

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inelastic reactions remove ω, η' mesons, e.g. ω, η' N → π N
shortening of ω, η' lifetime in the medium ⇒ increase in width

low density approximation: $\Gamma(\rho) = -\frac{Im\Pi(\rho)}{E} = \hbar c \cdot \rho \cdot \beta \cdot \sigma_{inel}$; $\Gamma(\rho) = \Gamma(\rho_0)\frac{\rho}{\rho_0}$

information on imaginary part of meson-nucleus potential

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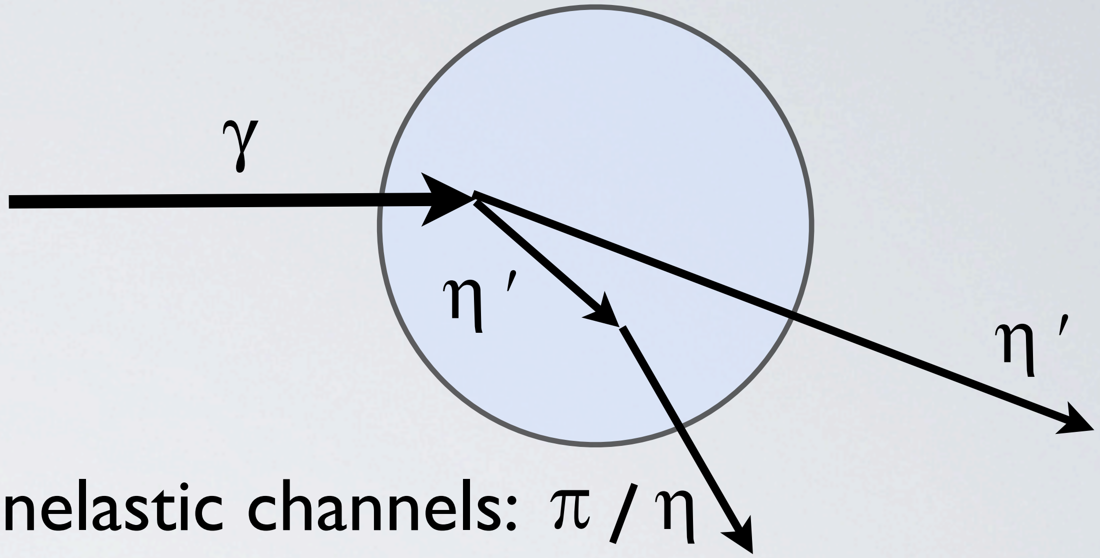

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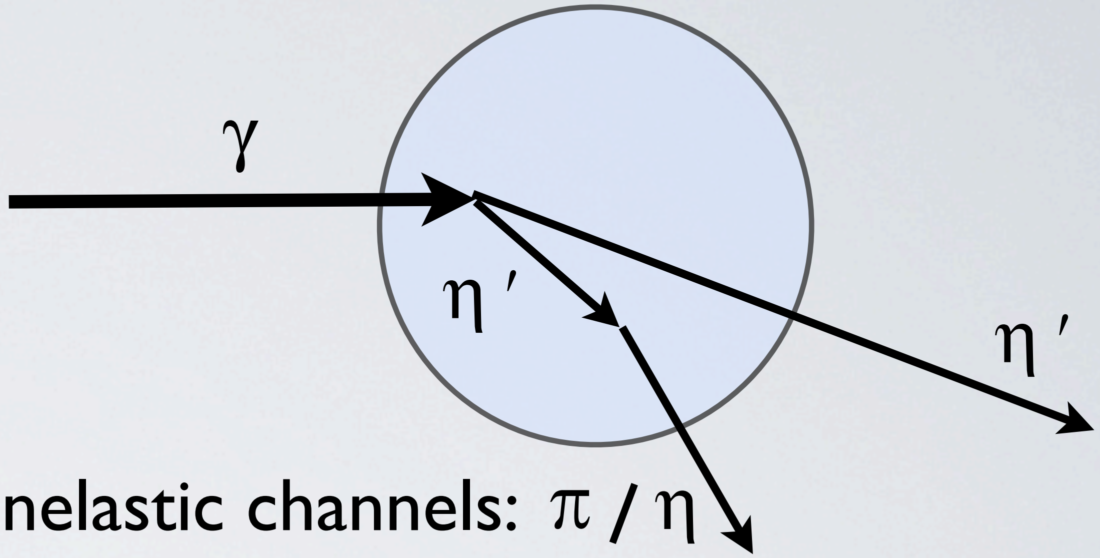

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information on imaginary part of meson-nucleus potential

applicable to any meson lifetime !!

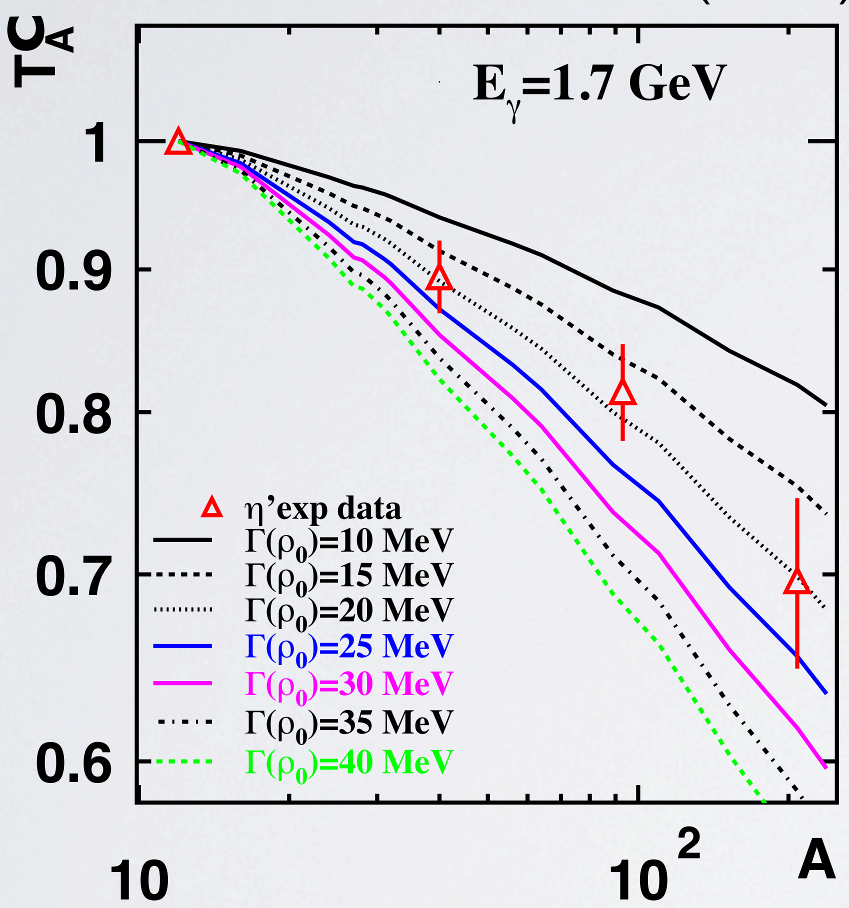
information on in-medium properties of mesons from measurement of their decay outside of the nucleus

The imaginary part of the η'-nucleus potential

E_γ = 1500 - 2200 MeV; photoproduction of η' meson off ^{12}C, ^{40}Ca, ^{93}Nb and ^{208}Pb

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

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



at low density approximation:

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

⇨ $\Gamma_{\eta'}(<p_{\eta'}> \approx 1.05$ GeV/c $) \approx 15\text{-}25$ MeV;

$\rho_0 = 0.17$ fm^{-3}; $\sigma^{\eta'}_{inel} \approx 3$ -10 mb

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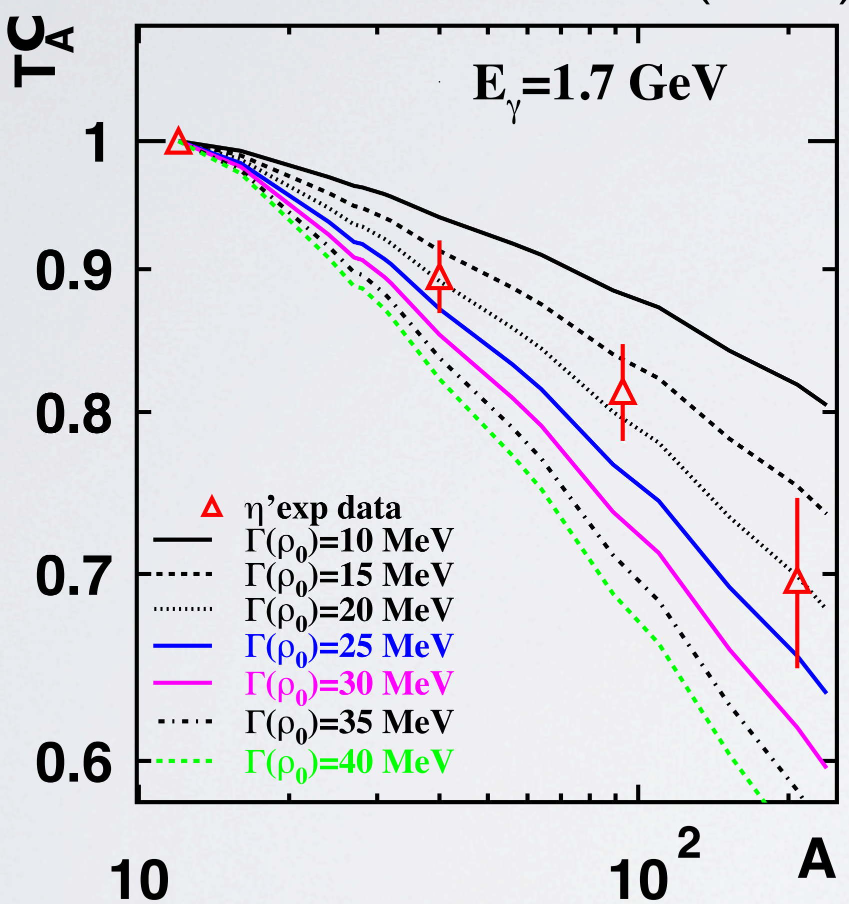


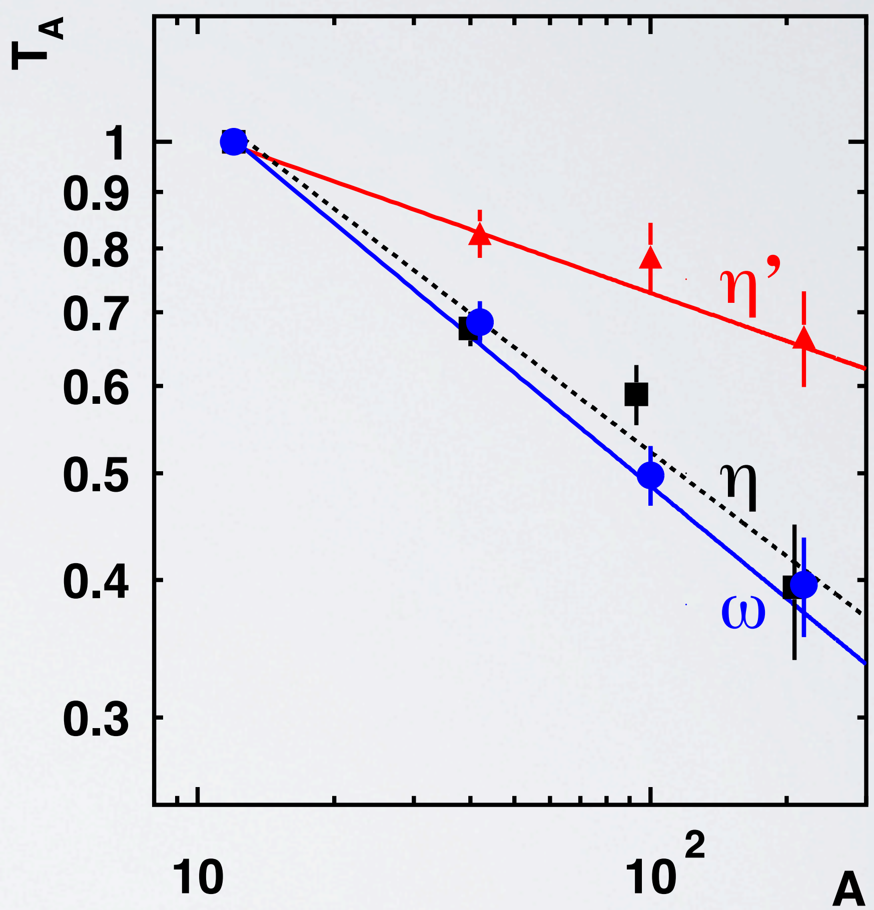
at low density approximation:

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

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

ρ_0=0.17 fm^{-3}; $\sigma^{\eta'}_{inel}$ ≈ 3 -10 mb

comparison with other mesons



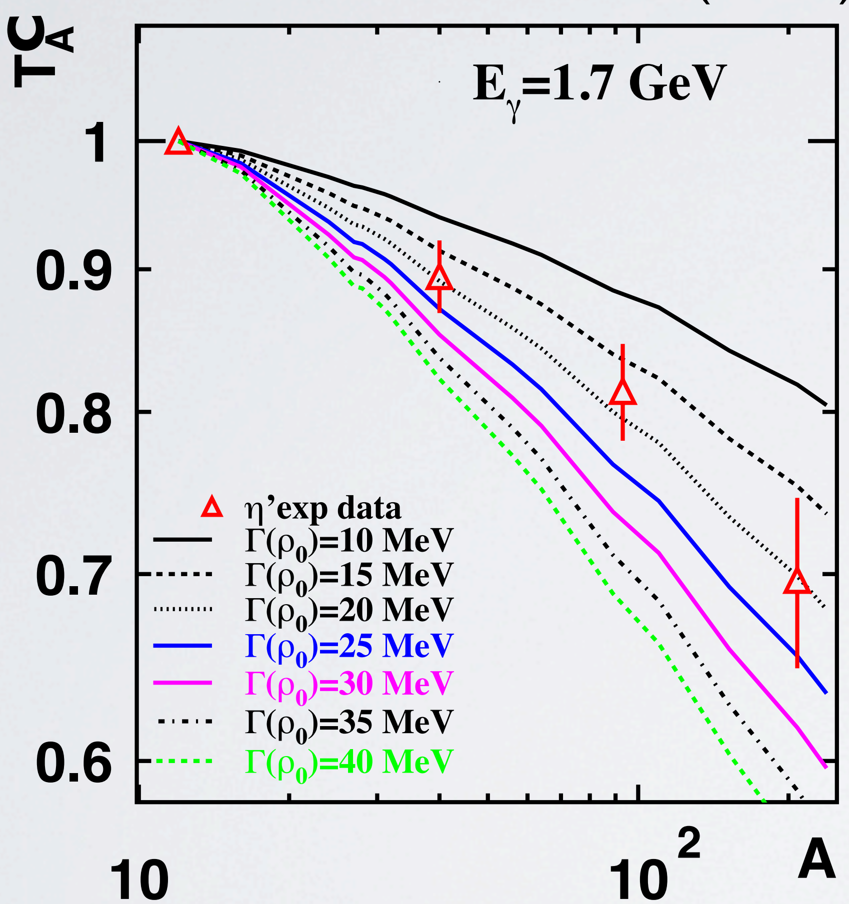
η' interaction with nuclear matter much weaker than for η, ω mesons

The imaginary part of the η'-nucleus potential

E_γ = 1500 - 2200 MeV; photoproduction of η' meson off ^{12}C, ^{40}Ca, ^{93}Nb and ^{208}Pb

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

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



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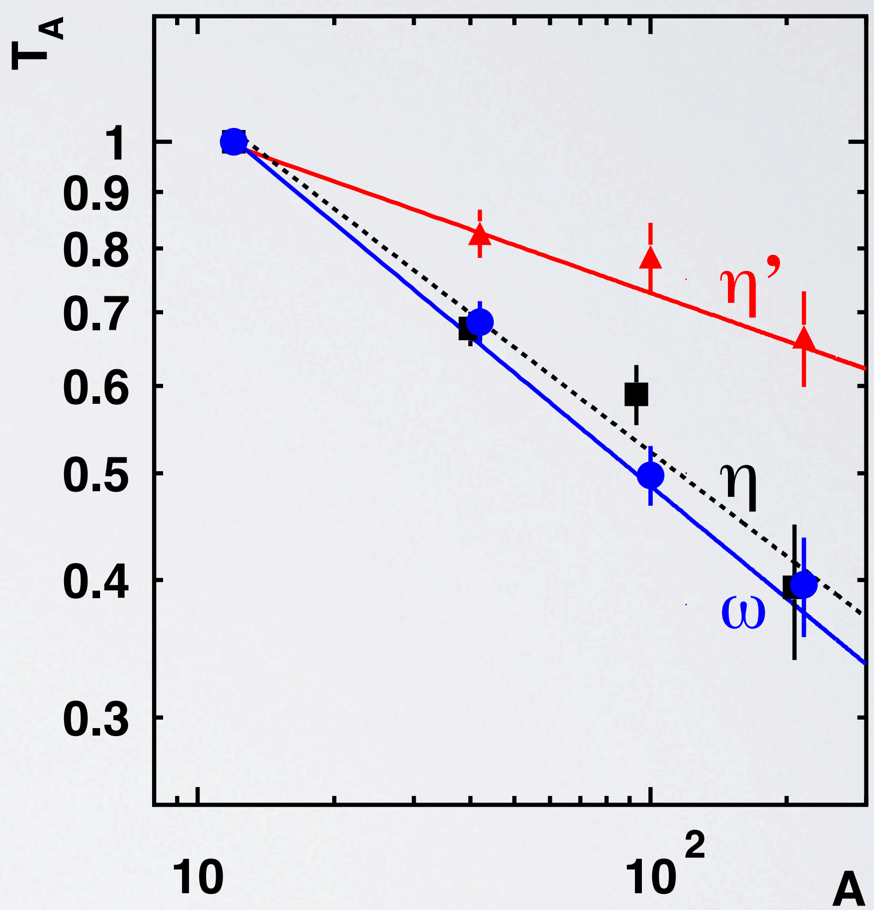

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η' interaction with nuclear matter much weaker than for η, ω mesons

$W_{\eta'}(\rho=\rho_0) = -\Gamma_0/2$ = - (7.5-12.5) MeV

Determination of the real part of the η'-nucleus potential

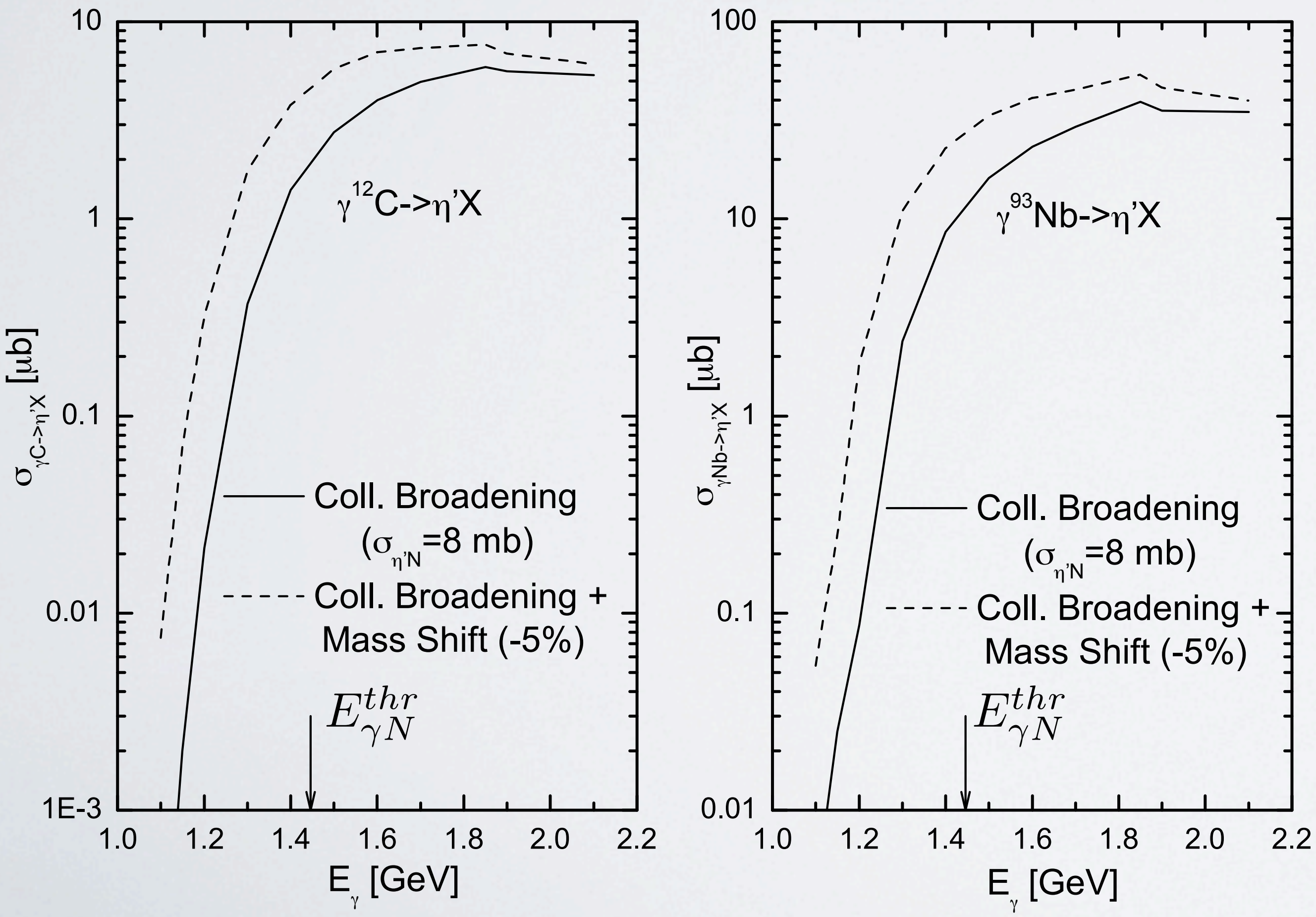
J. Weil, U. Mosel and V. Metag, PLB 723 (2013)120

E. Paryev, J. Phys. G: Nucl. Part. Phys. 40 (2013) 025201

- measurement of the excitation function:

in case of dropping mass - higher meson yield for given √s because of increased phase space due to lowering of the production threshold

η' excitation function



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- measurement of the excitation function:

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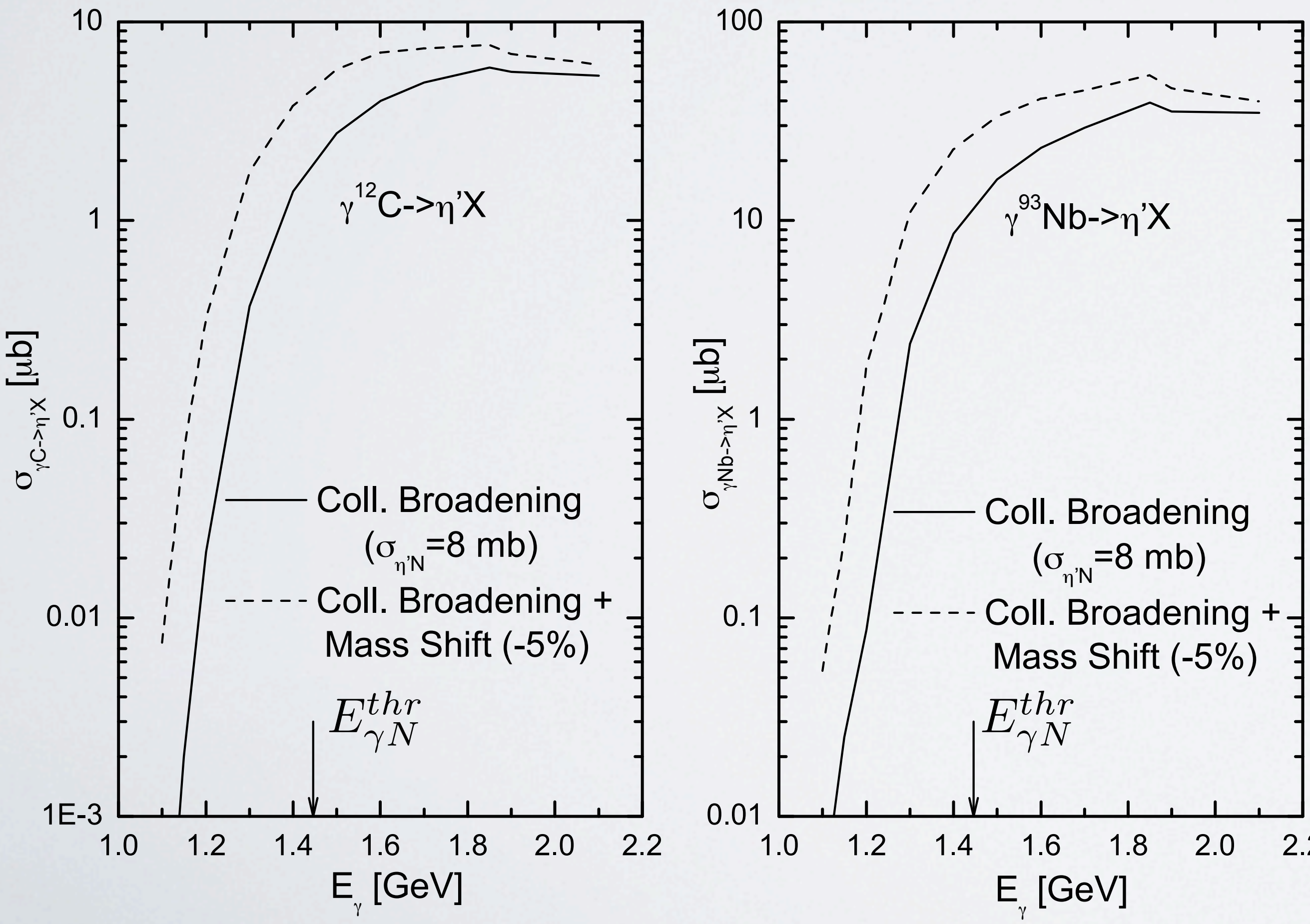
- measurement of the momentum distribution:

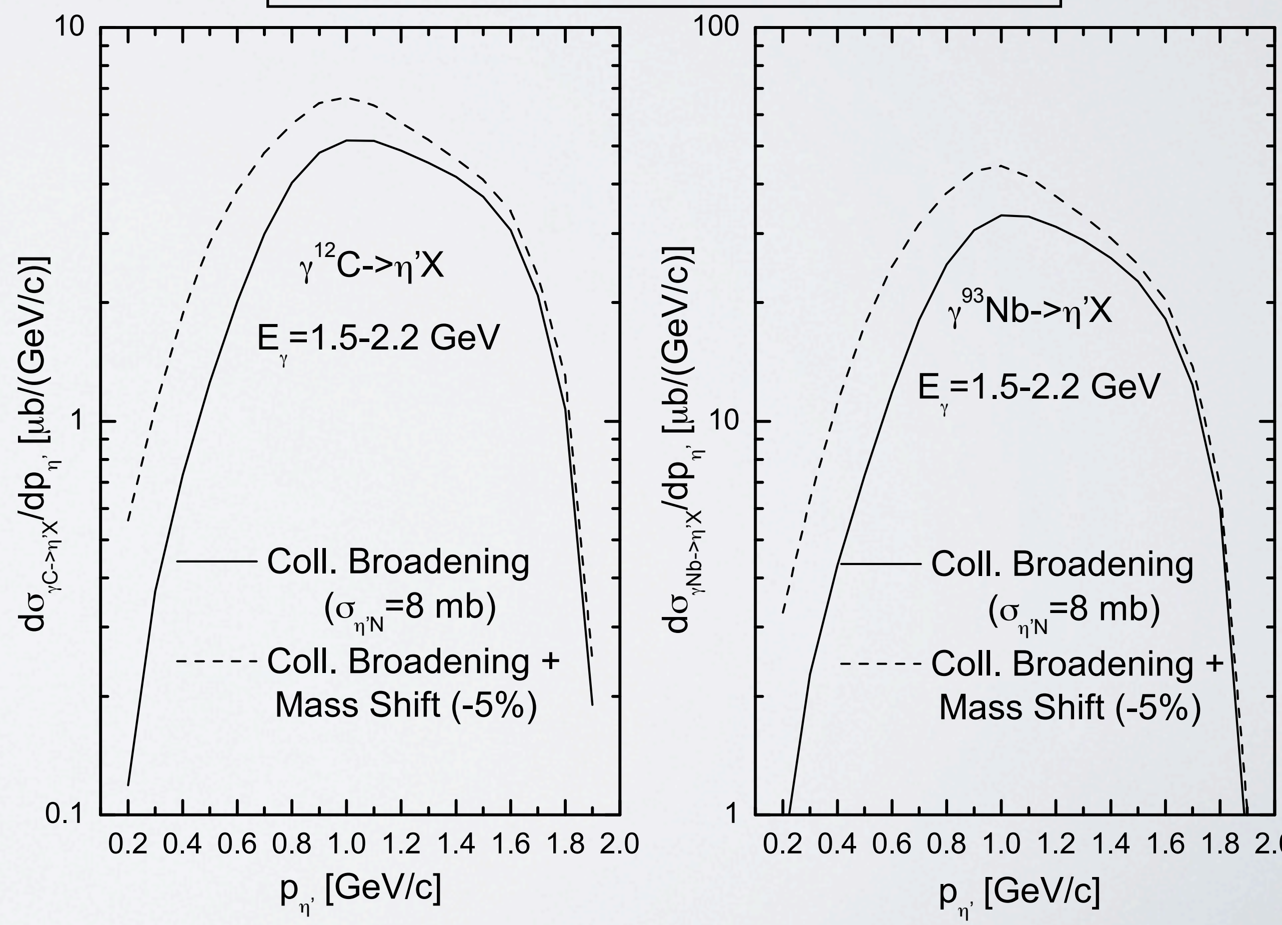
in case of dropping mass - when leaving the nucleus hadron has to become on-shell; mass generated at the expense of kinetic energy

⇨ downward shift of momentum distribution

η' excitation function

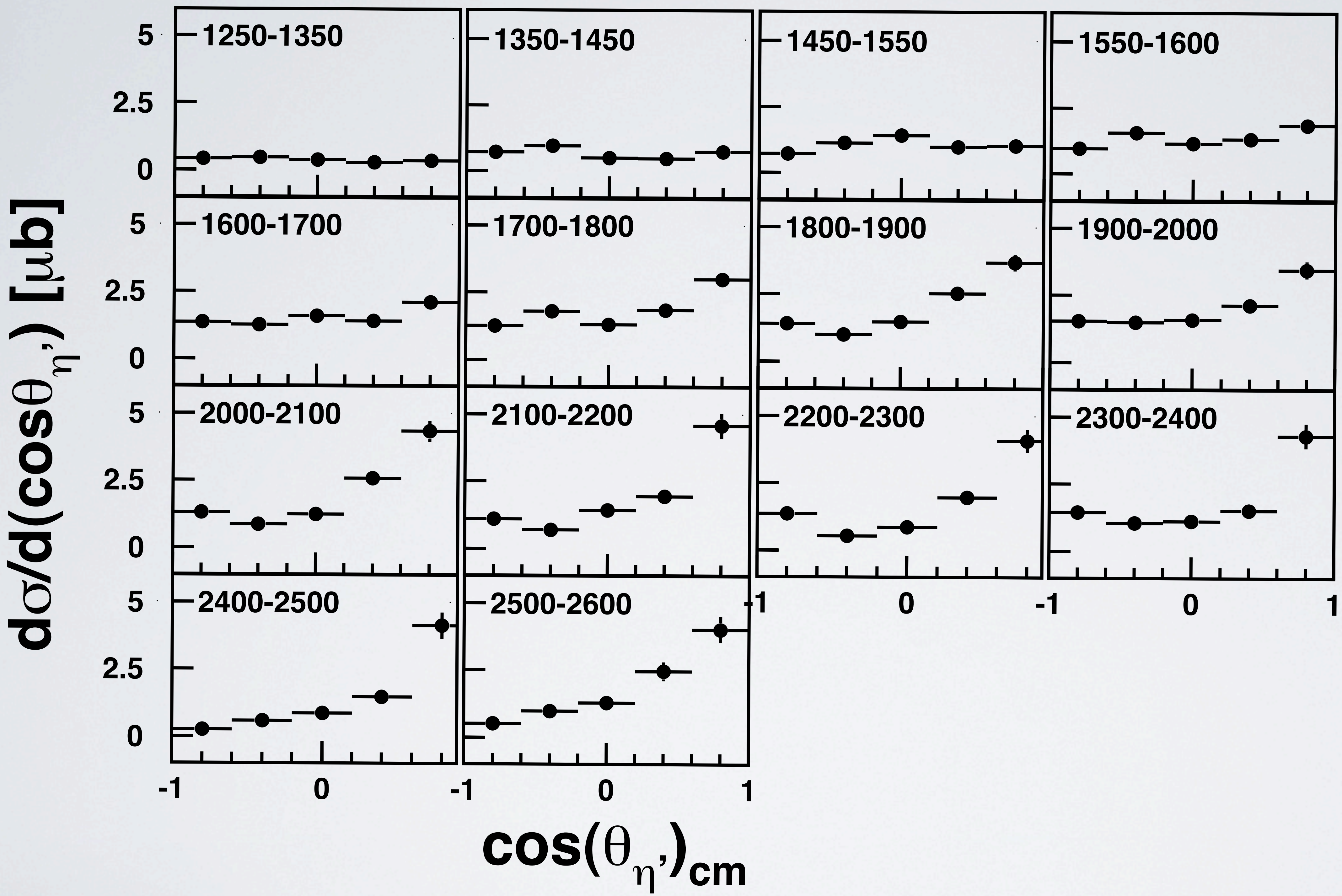


η' momentum distribution



differential cross sections for η’ photo production off carbon

M. Nanova et al., arXiv:1311.0122; accepted for publication in PLB



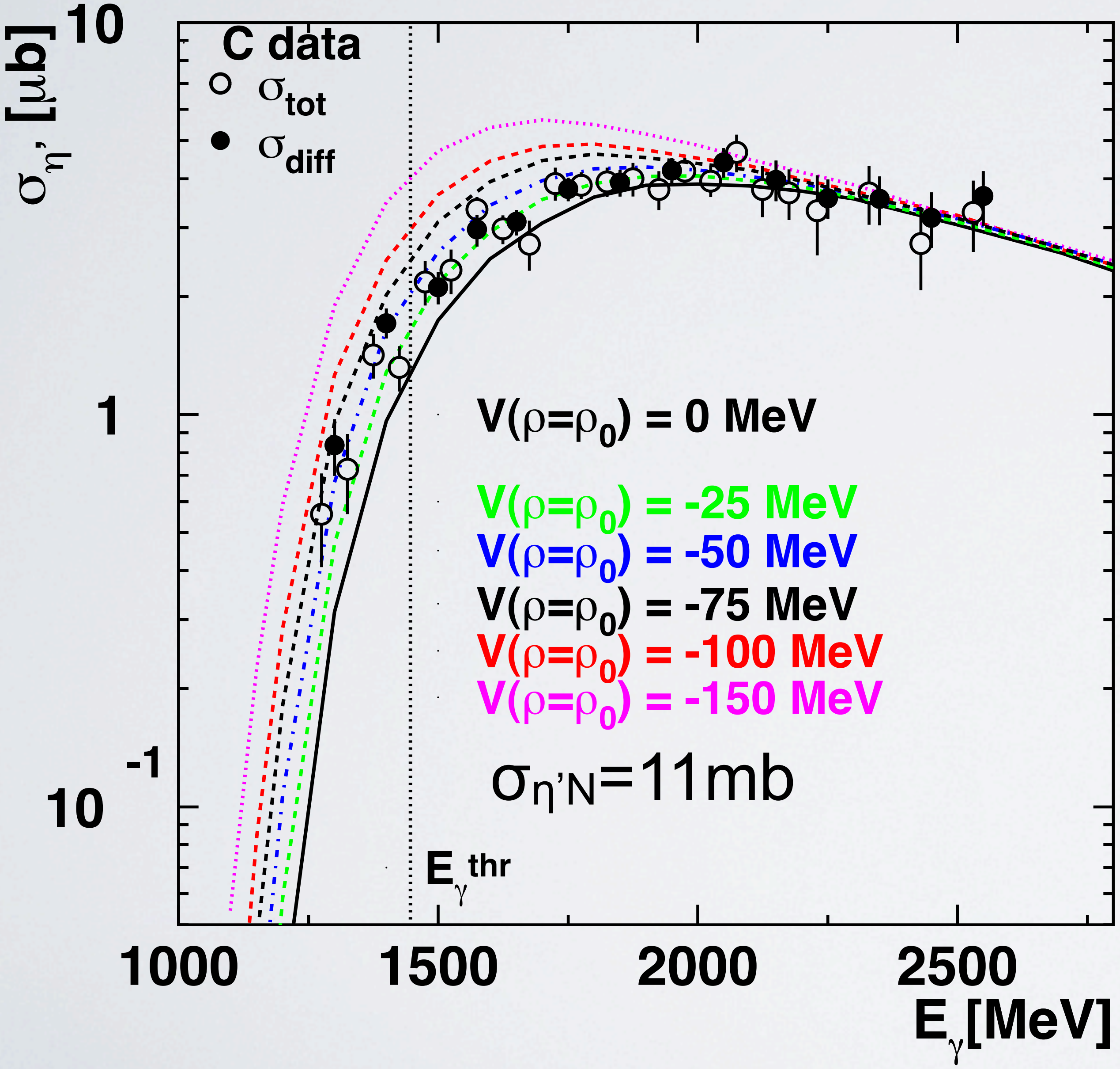
forward rise of cross section with increasing incident photon energy:
t-channel production mechanism

excitation function for η’ photoproduction off C

comparison of CBELSA/TAPS data with
calculations by E. Paryev, J. Phys. G: Nucl. Part. Phys. 40 (2013) 025201
and priv. communication

decay mode: $\eta' \rightarrow \pi^0\pi^0\eta$

excitation function



calculations normalized to data for
E_γ = 2000-2500 MeV; downscaled by 1.2

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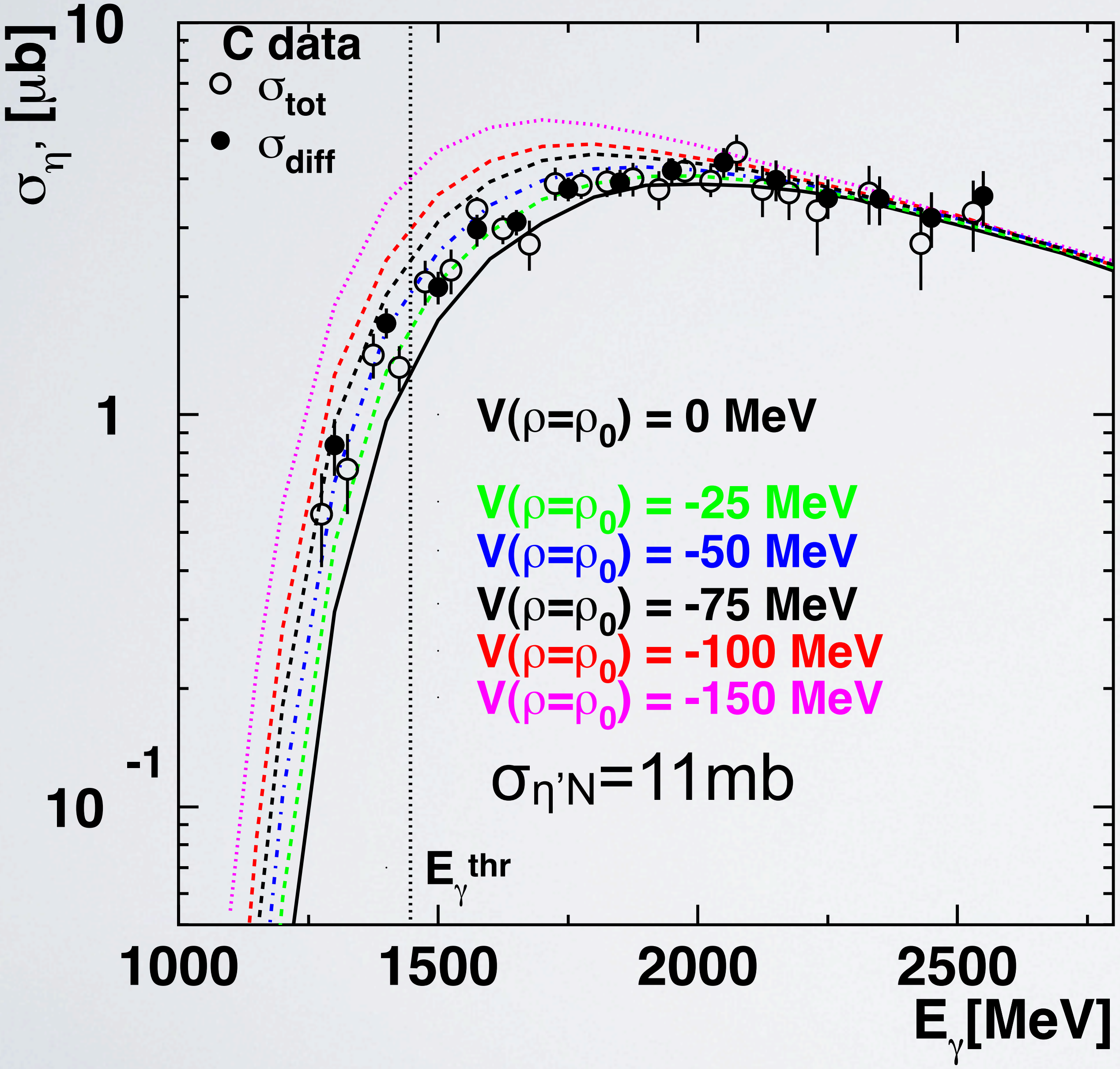

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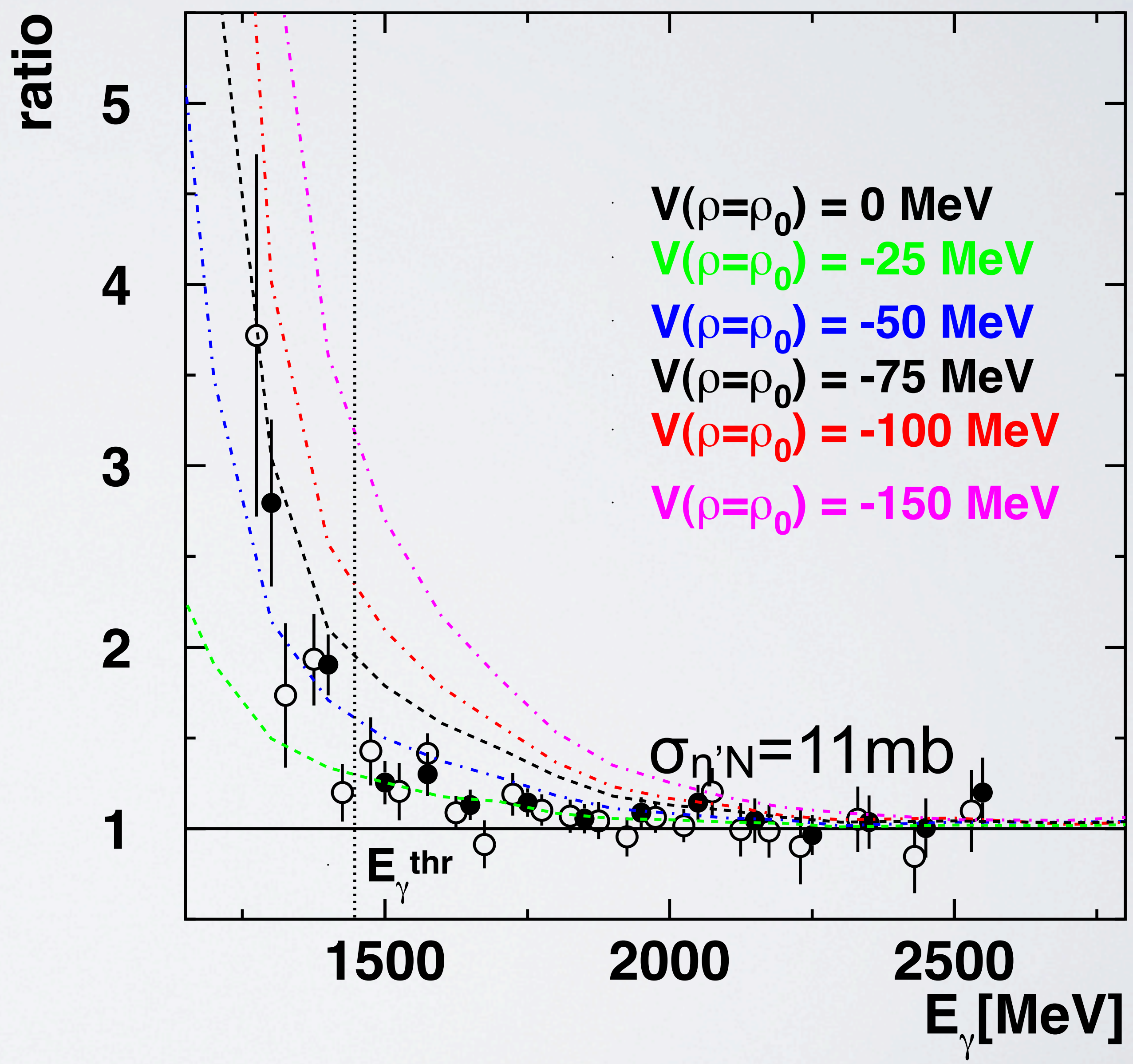
exp. data and the 5 scenarios divided by the calculation for scenario $V(\rho=\rho_0)$=0 MeV



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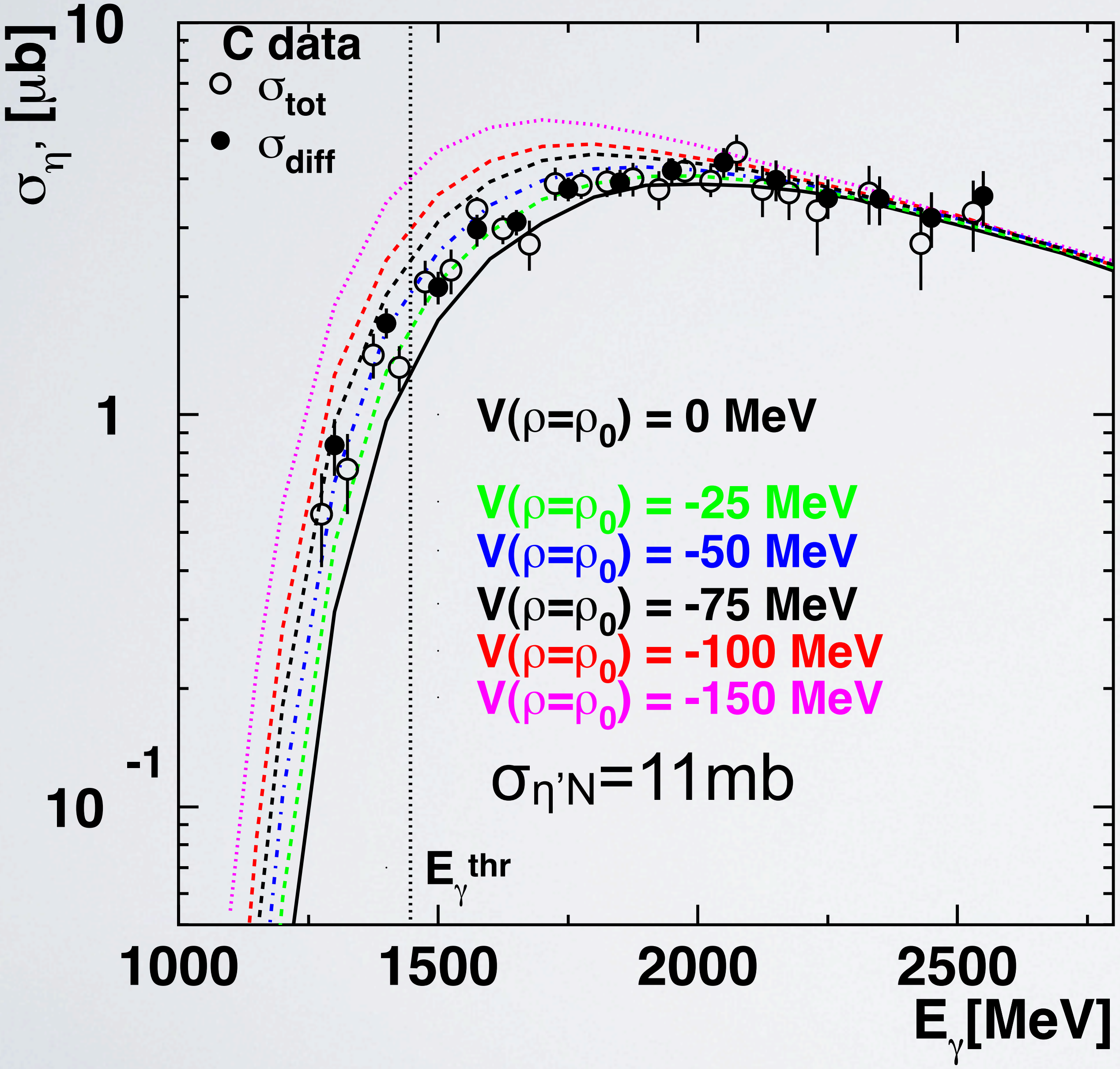

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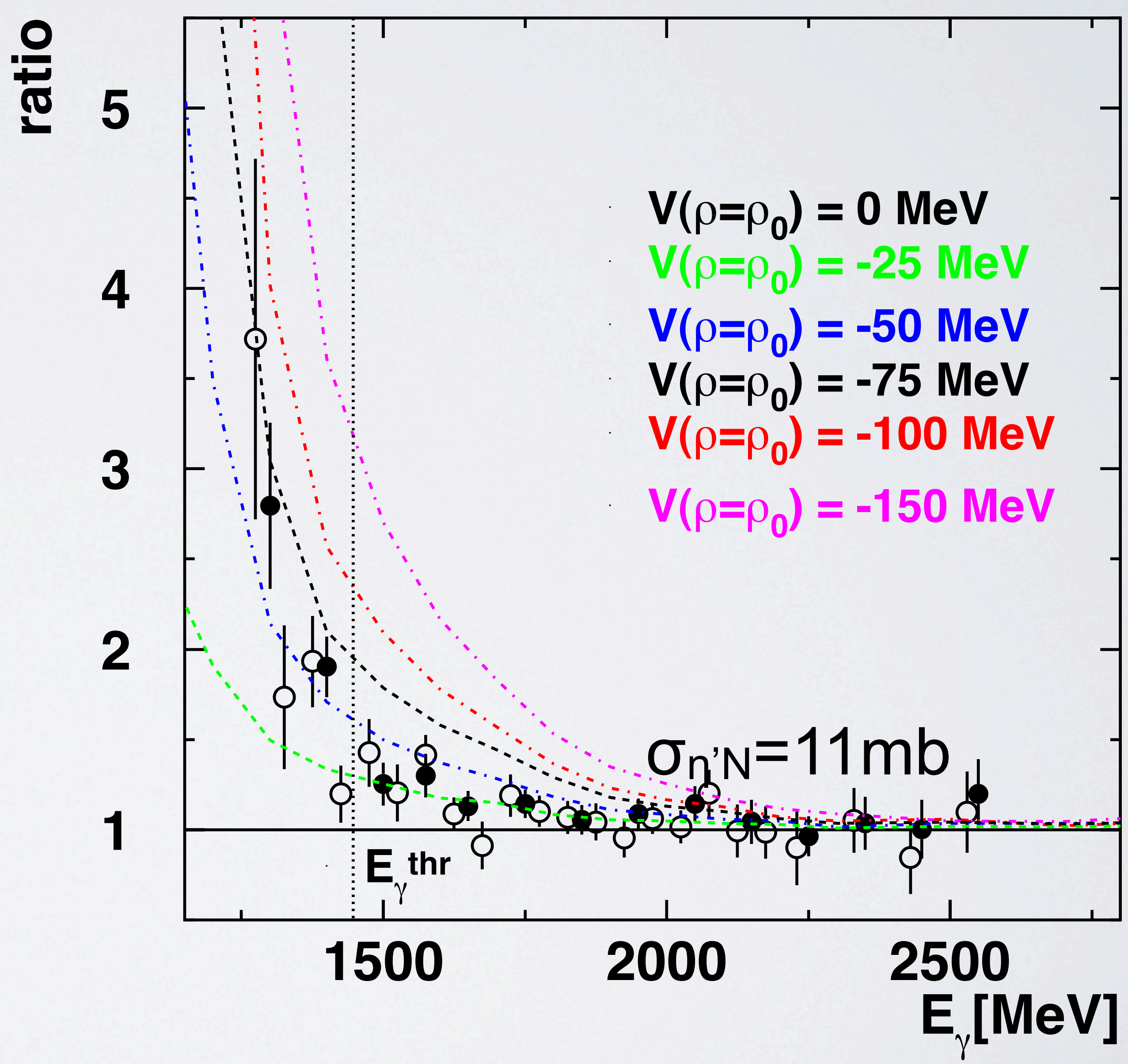
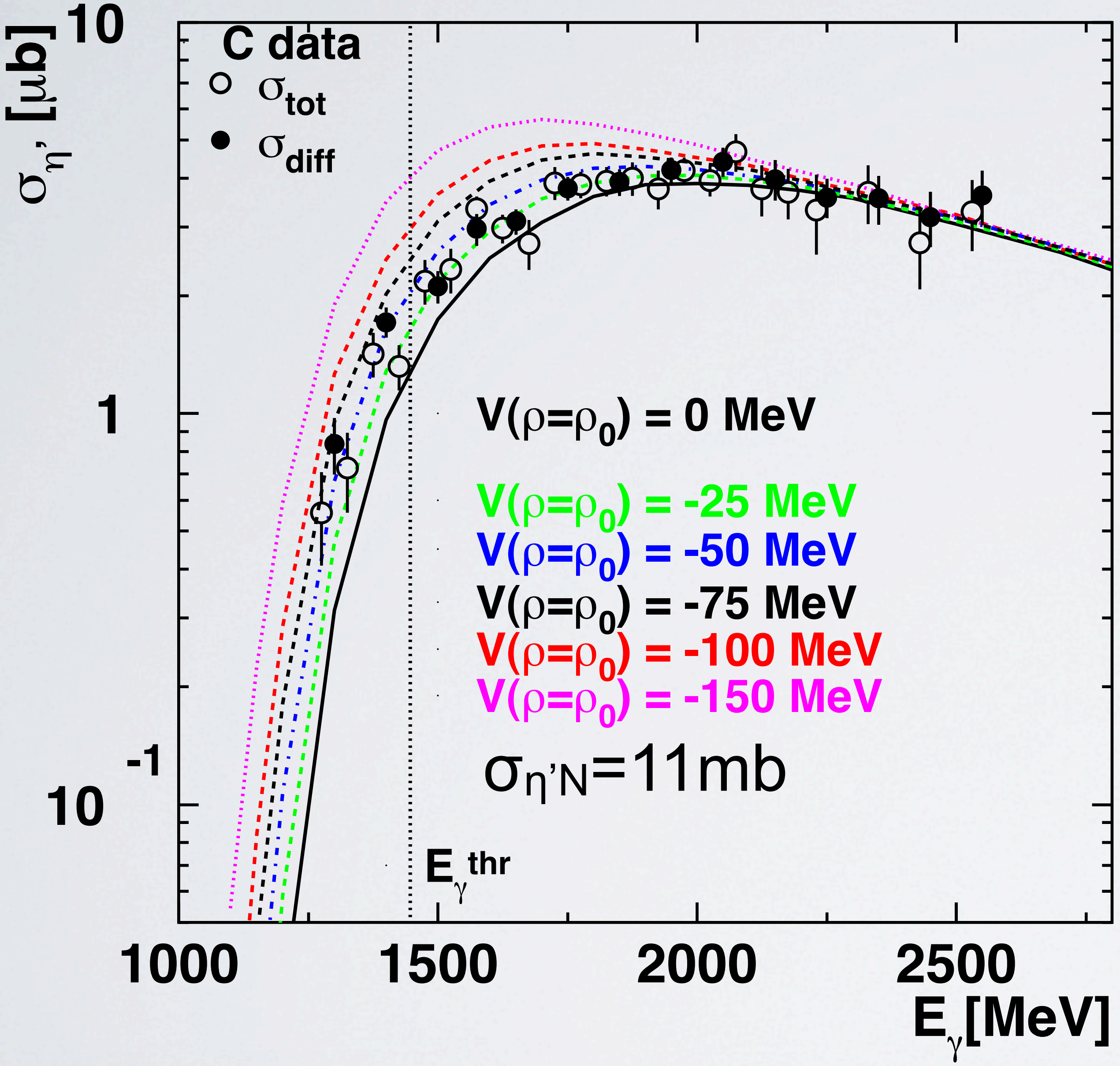


strong mass shift not supported by data

estimation of the real part of the η'-nucleus potential from the η' excitation function

excitation function



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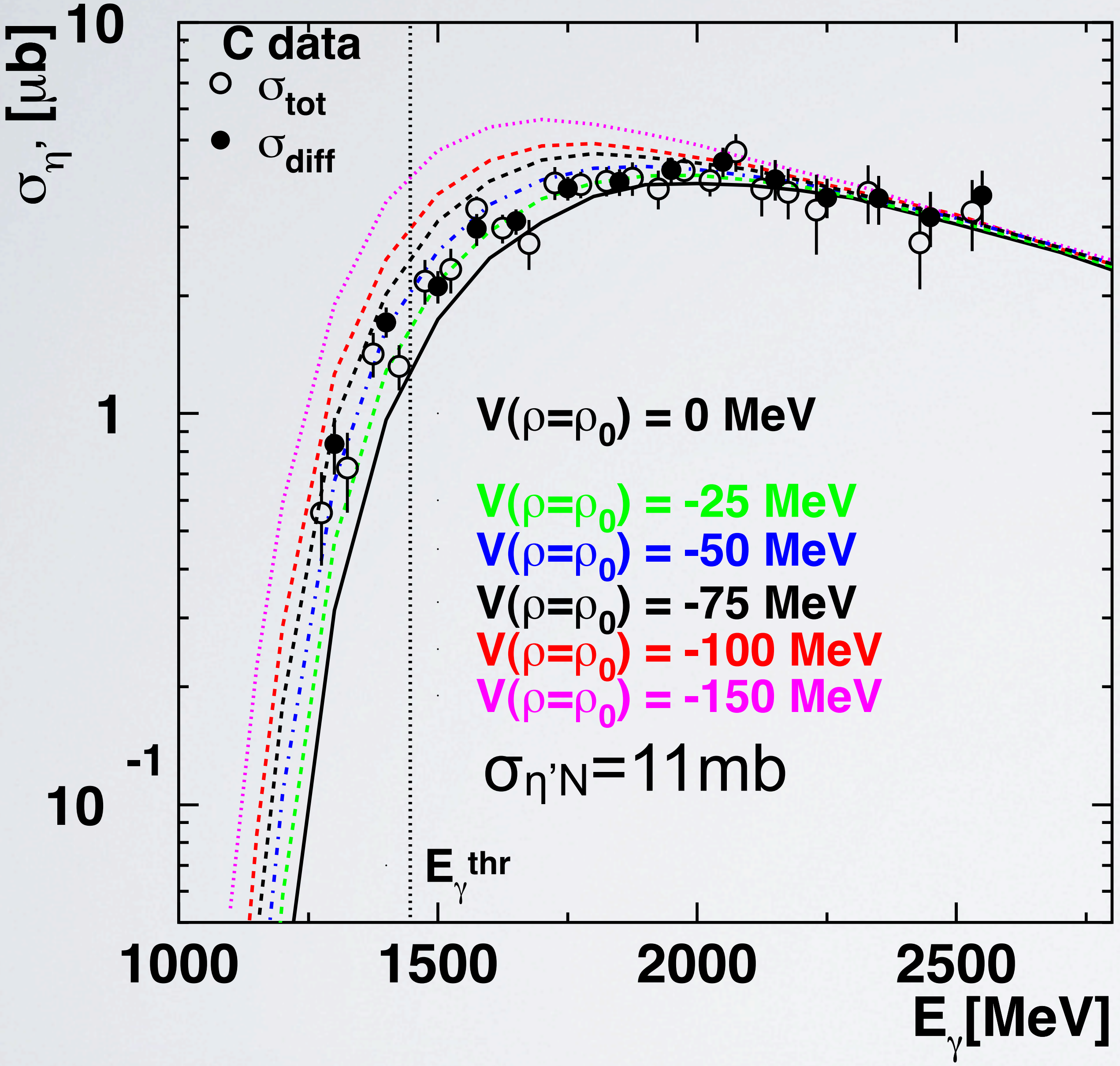
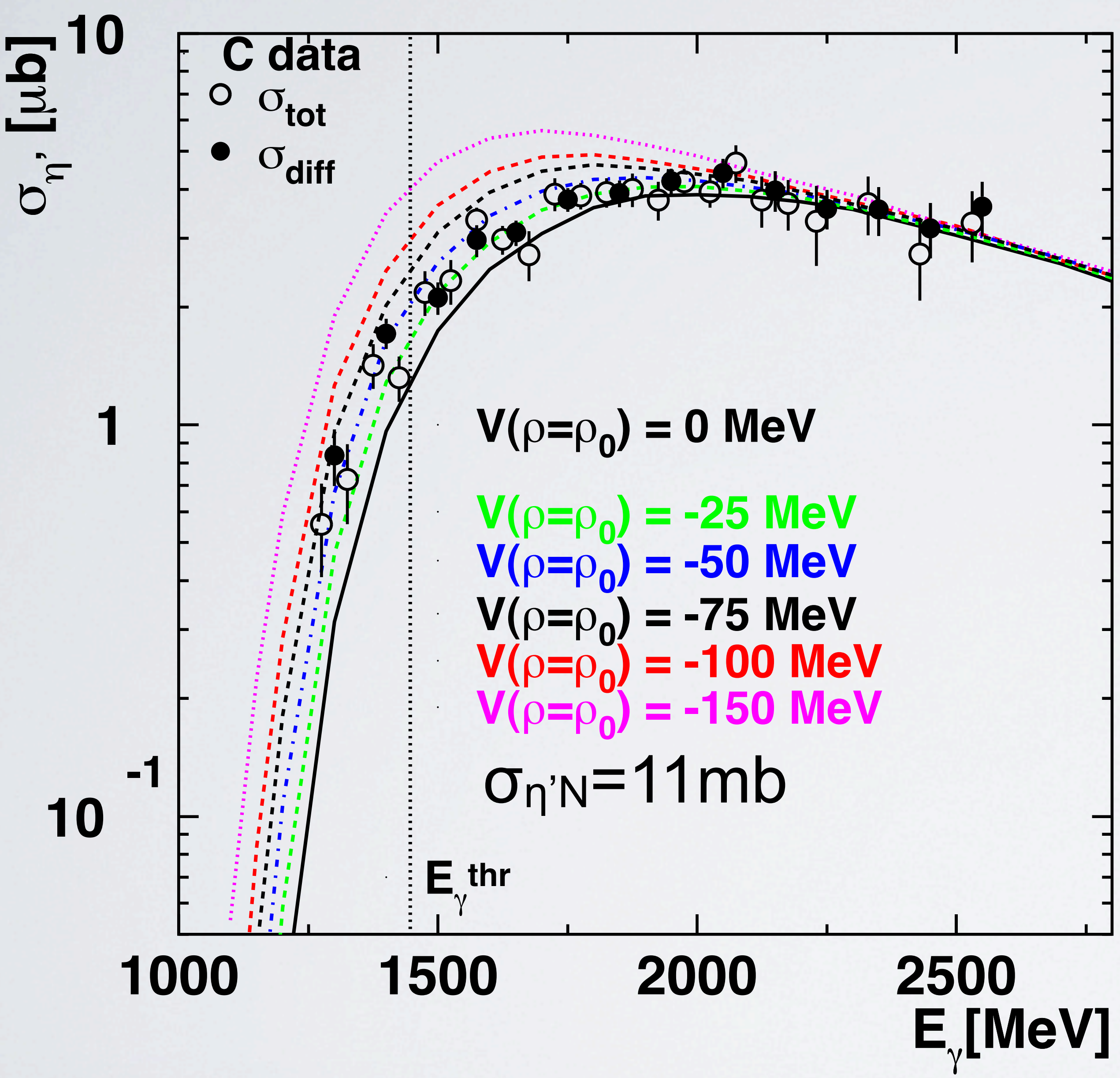


significance test

estimation of the real part of the η'-nucleus potential from the η' excitation function

excitation function



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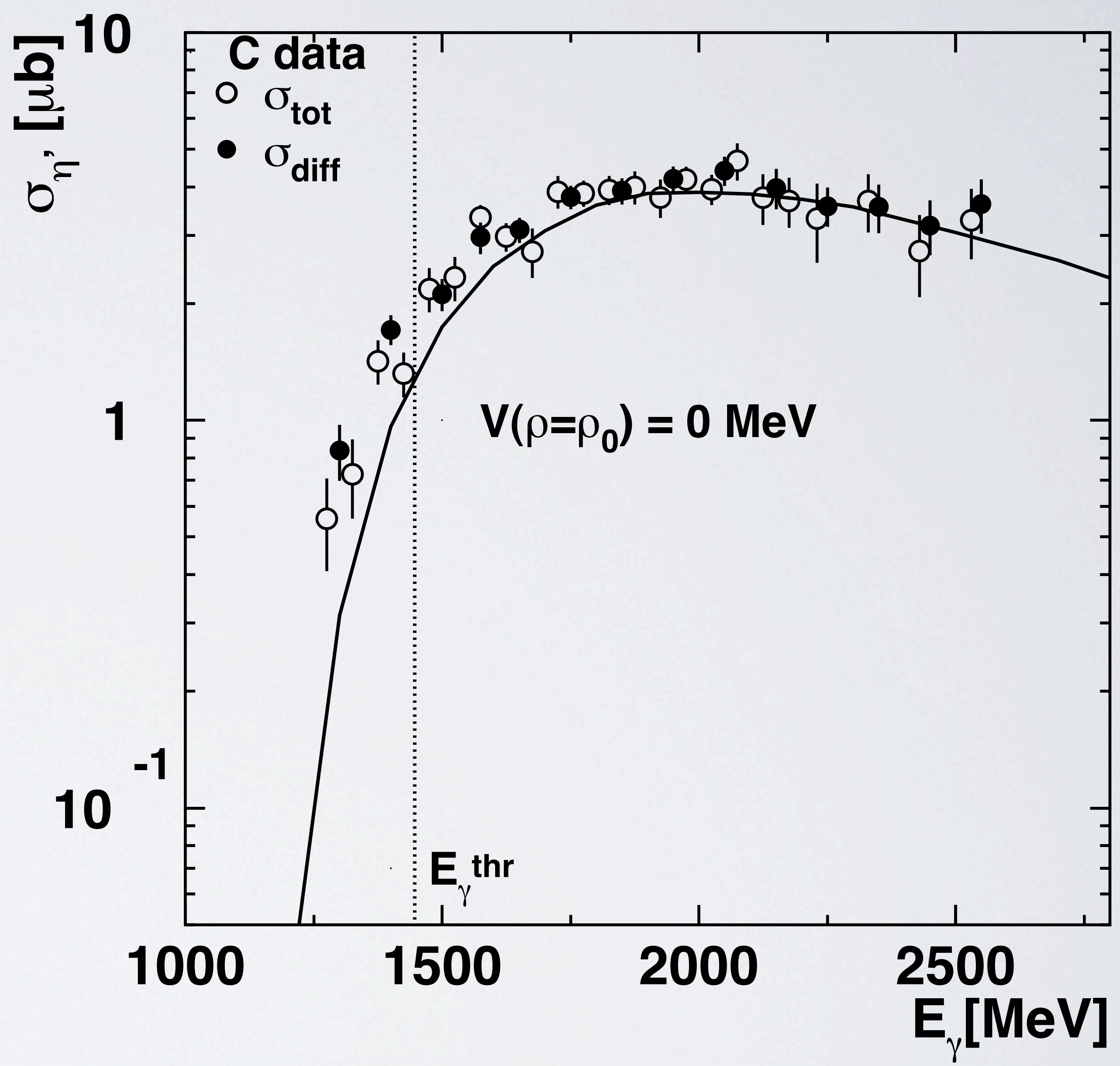

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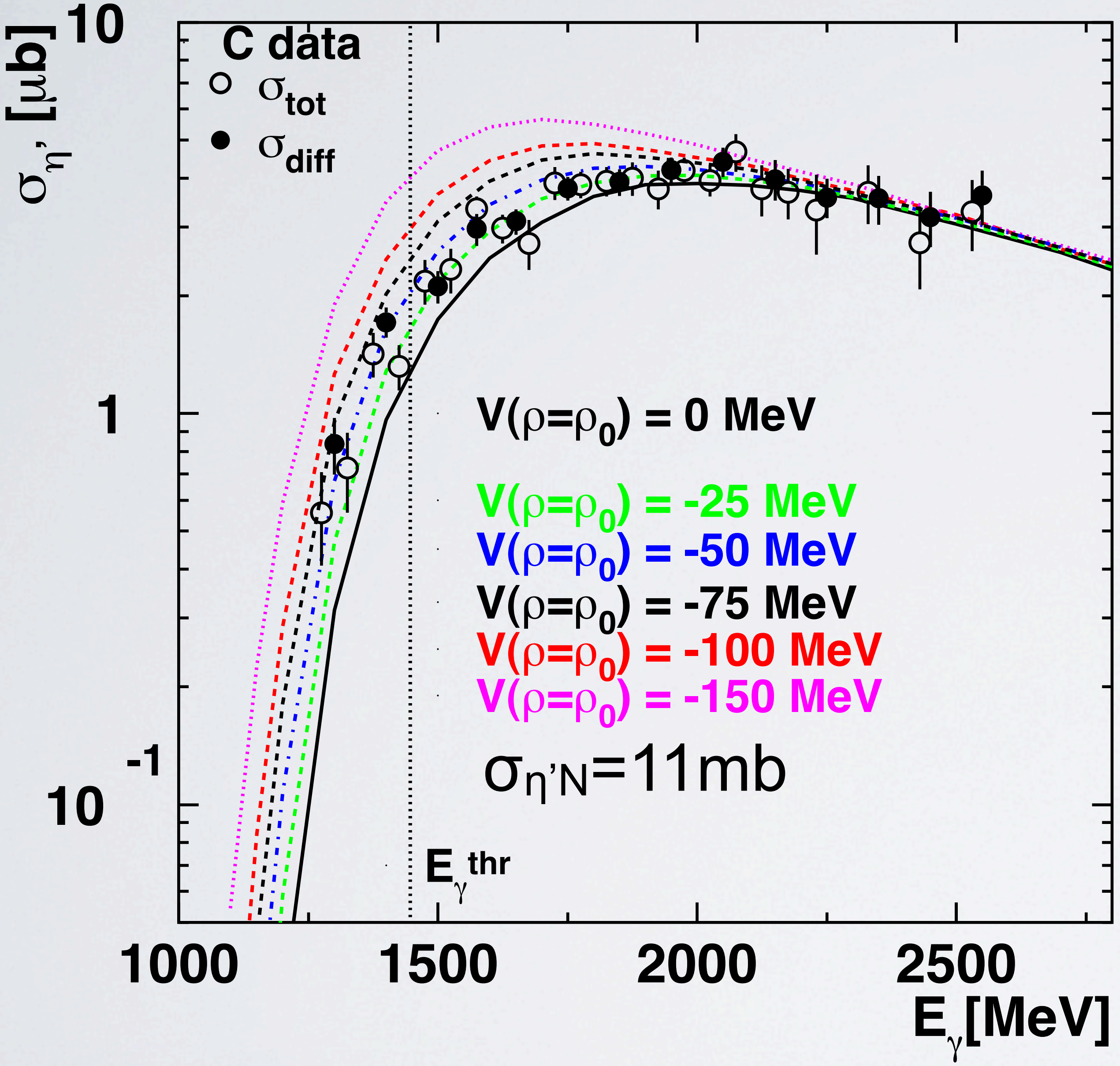

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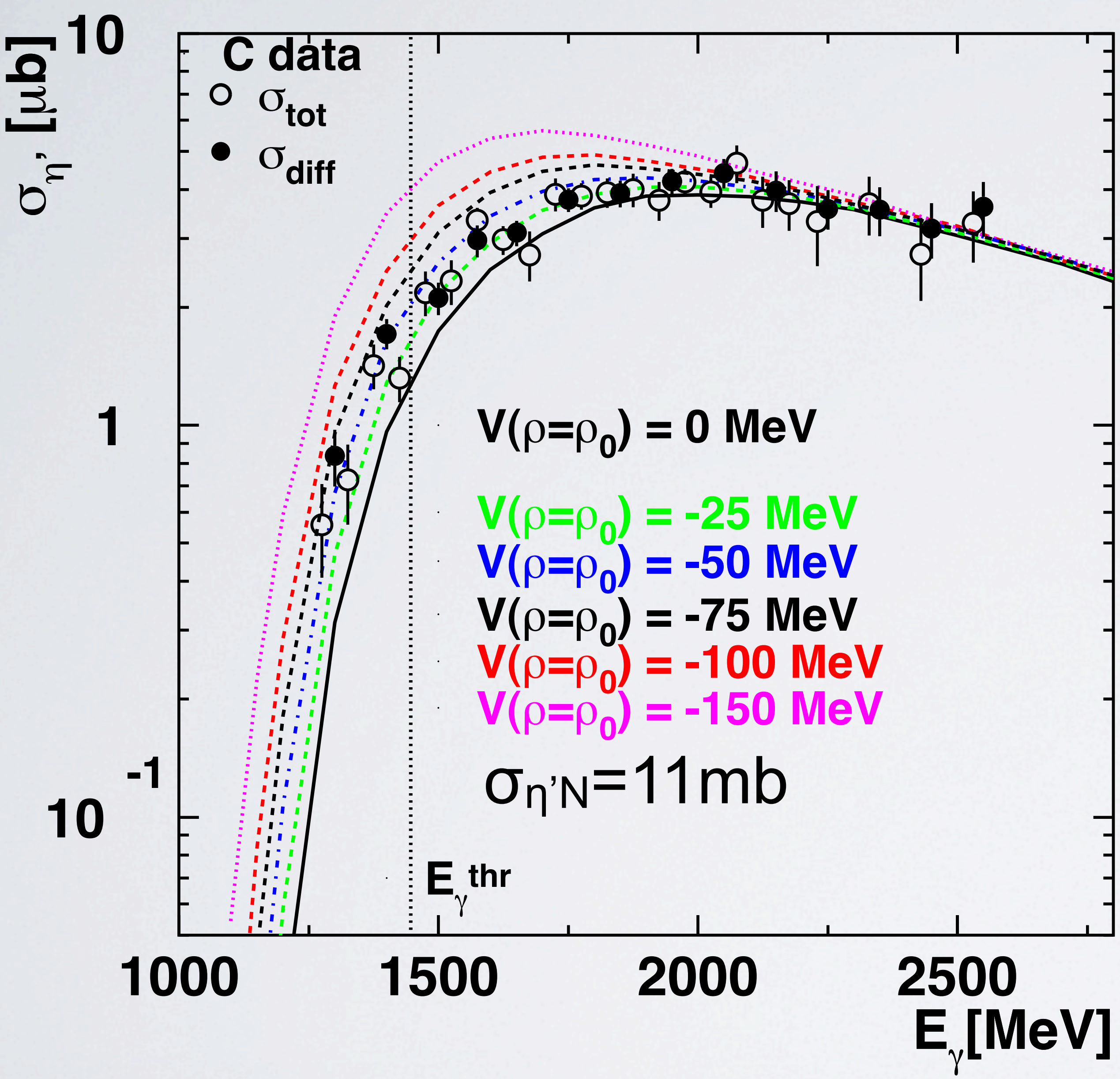

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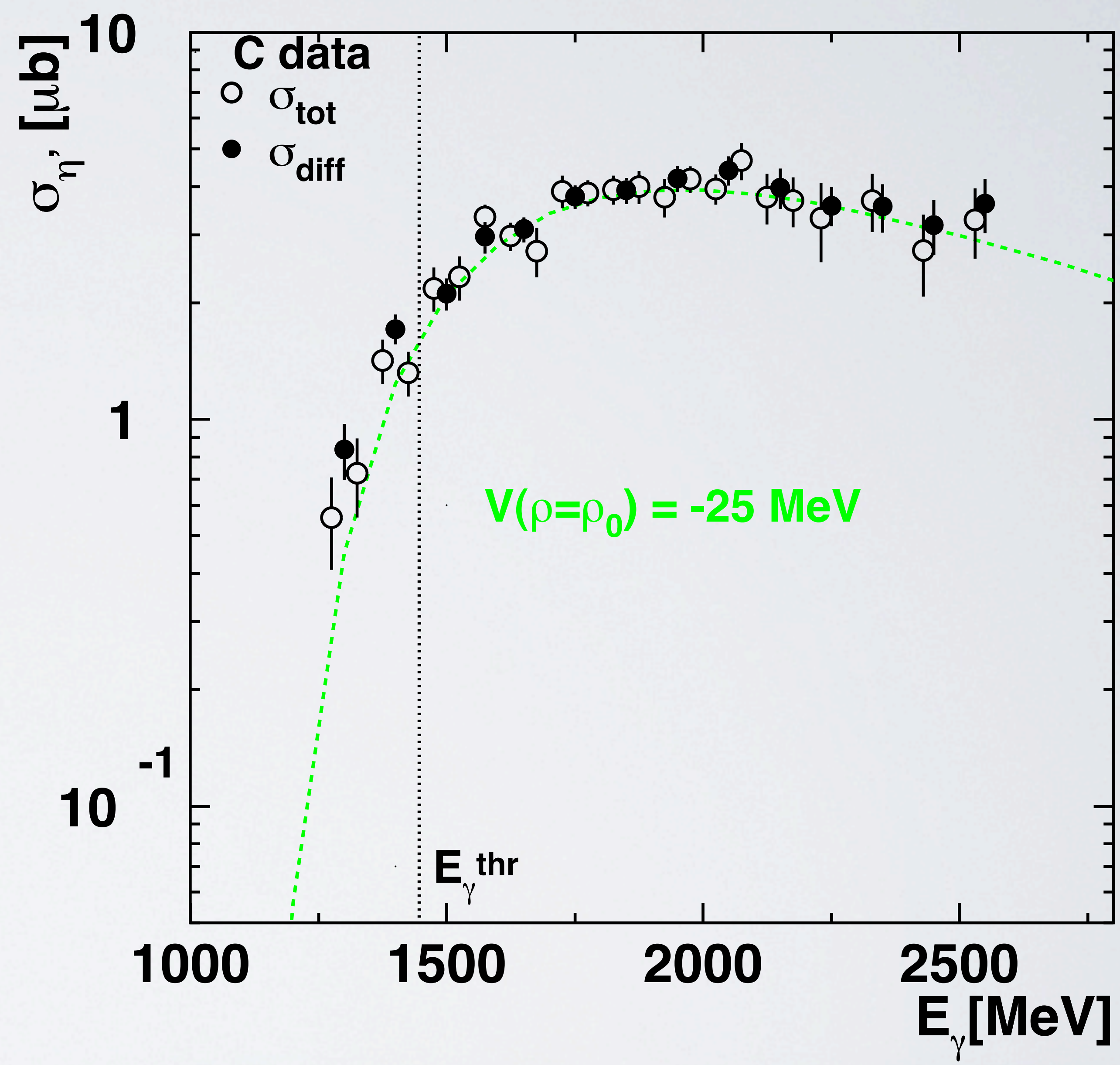

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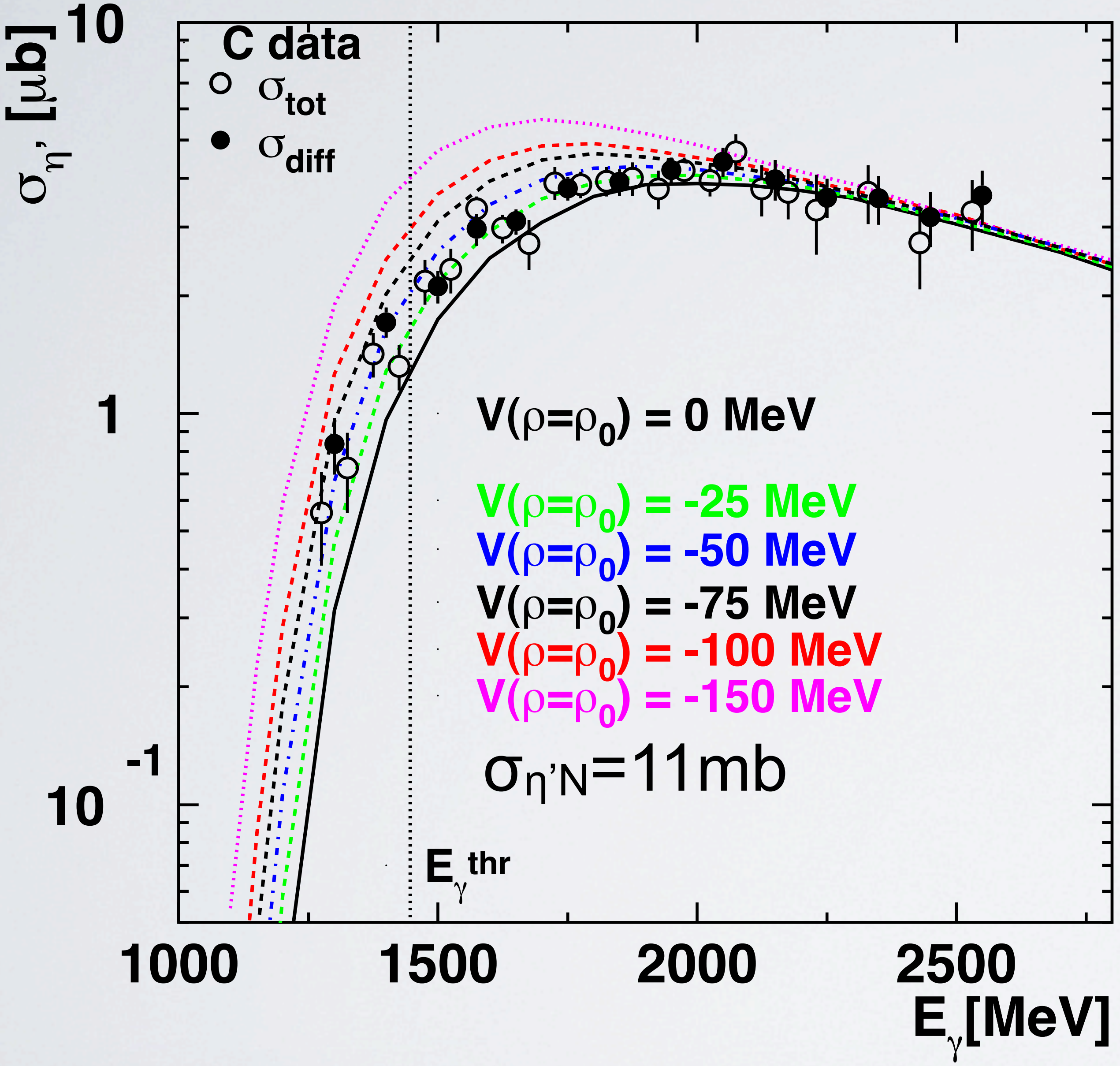

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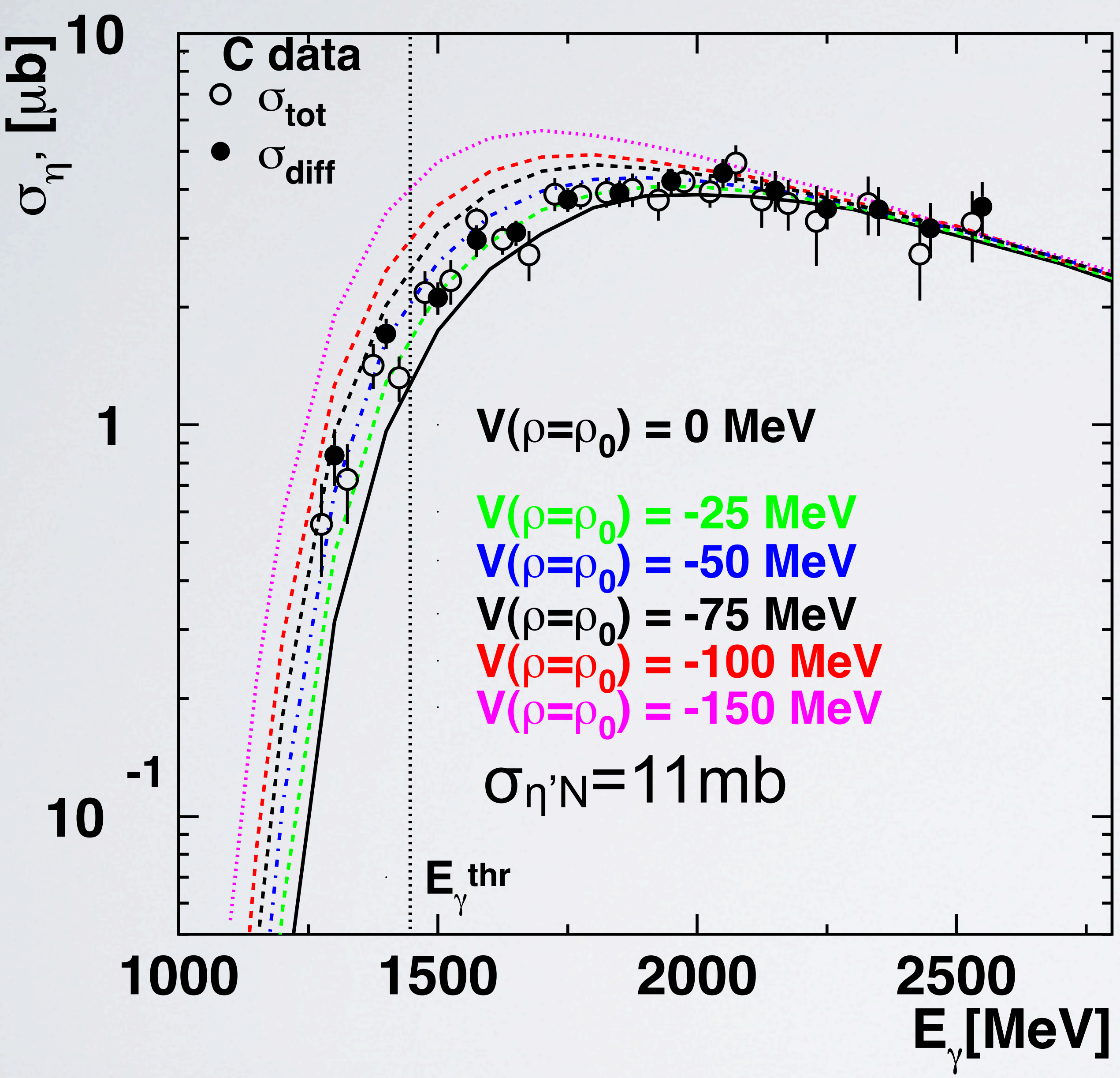

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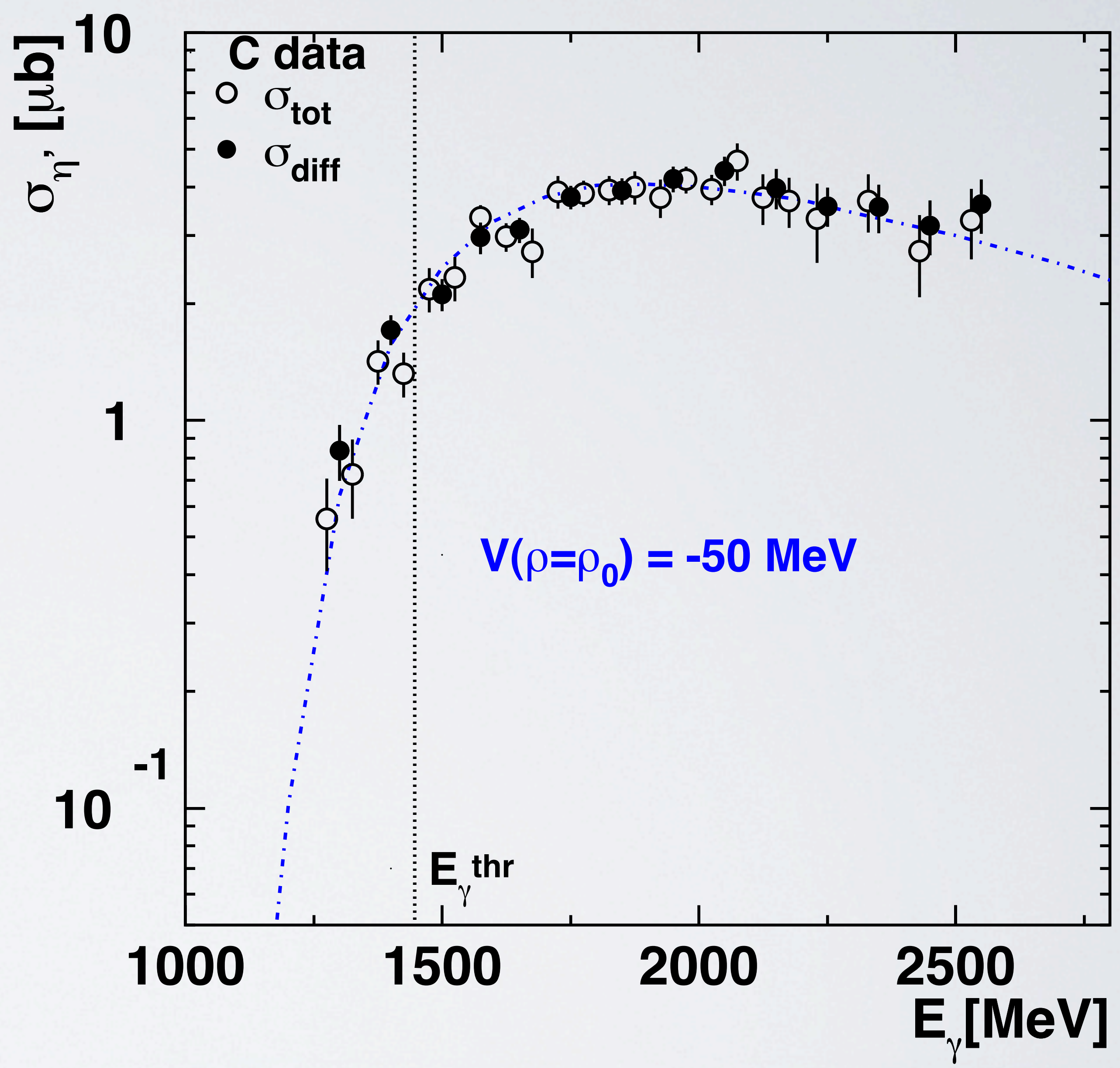

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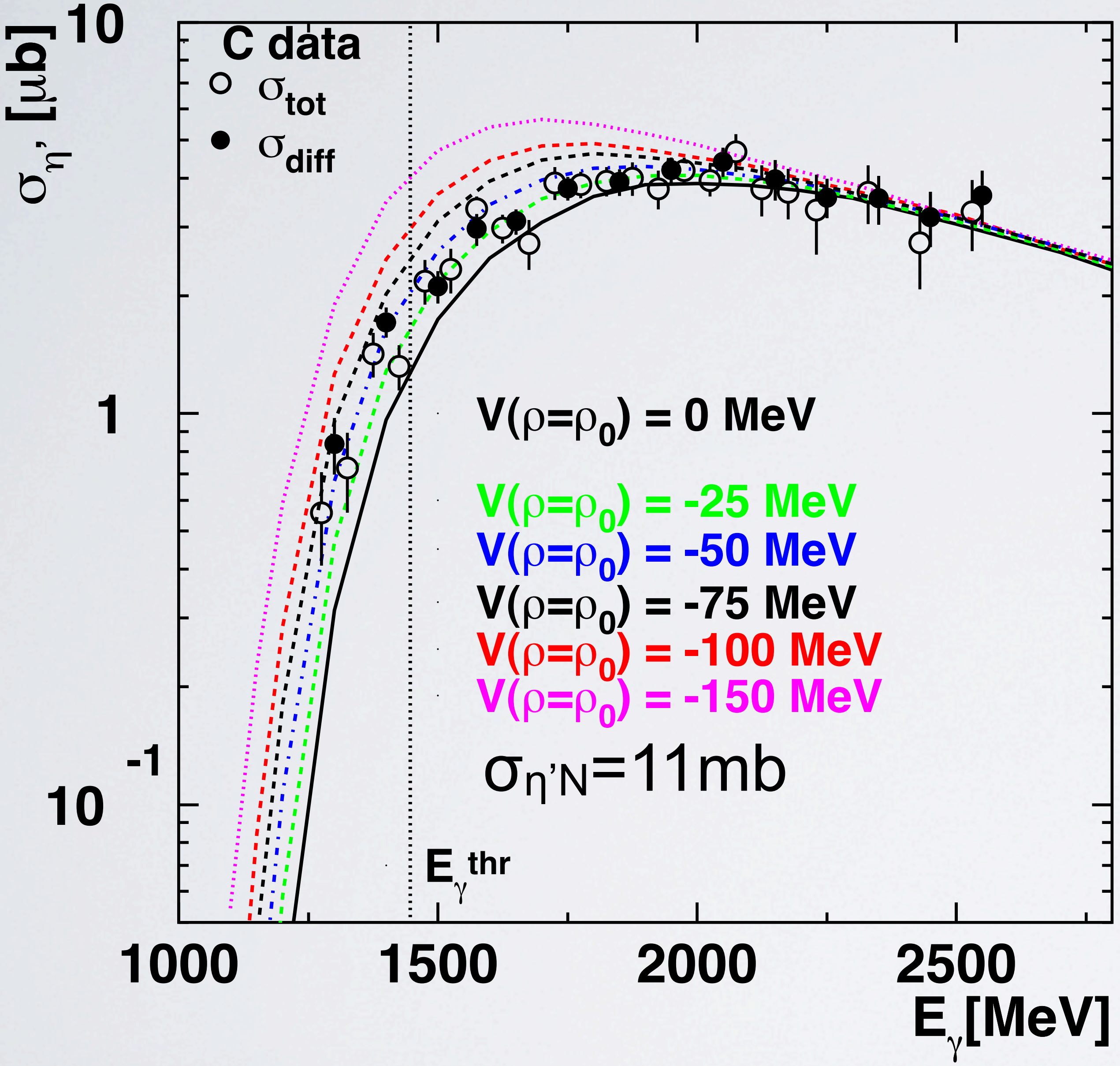

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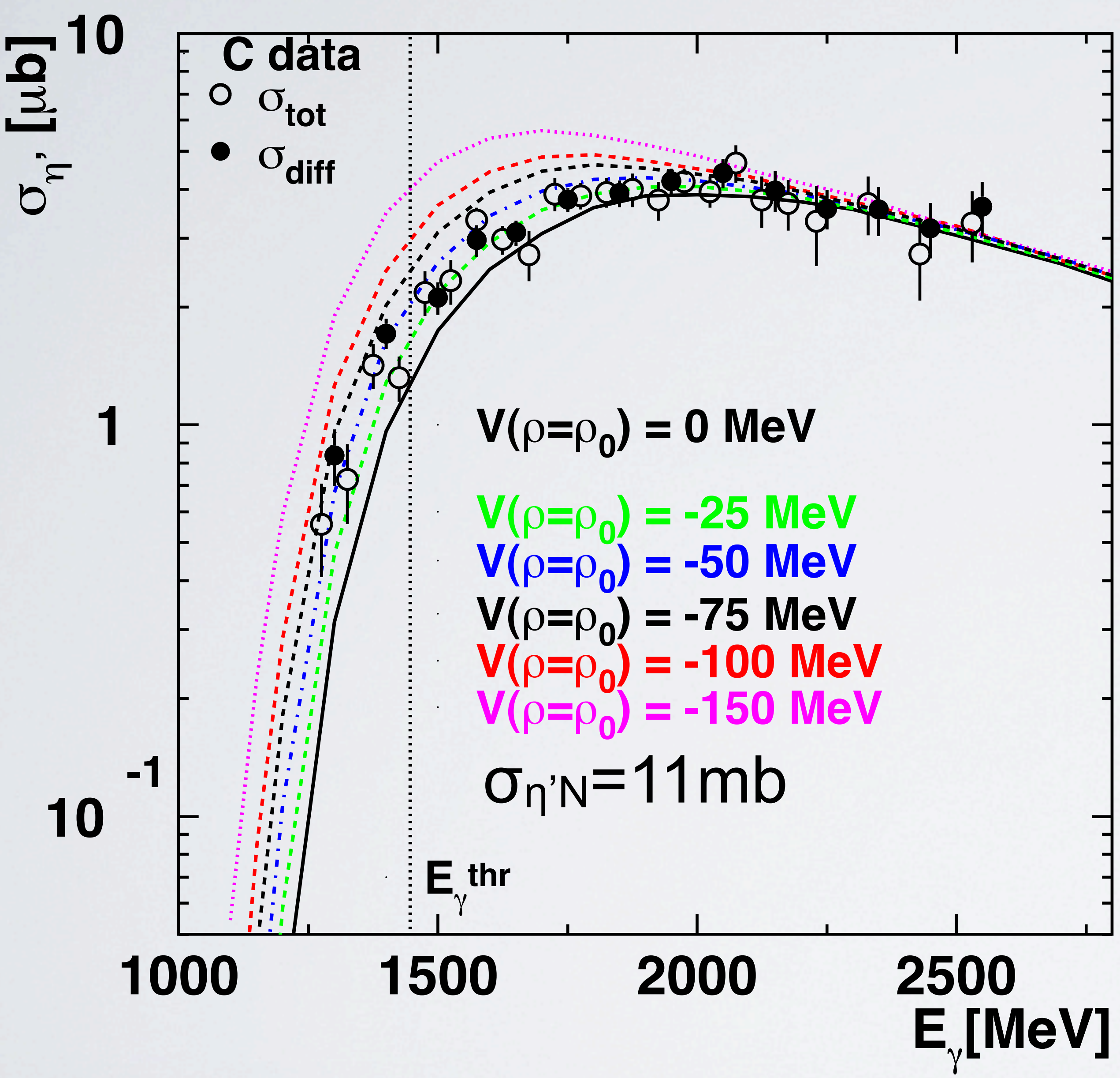

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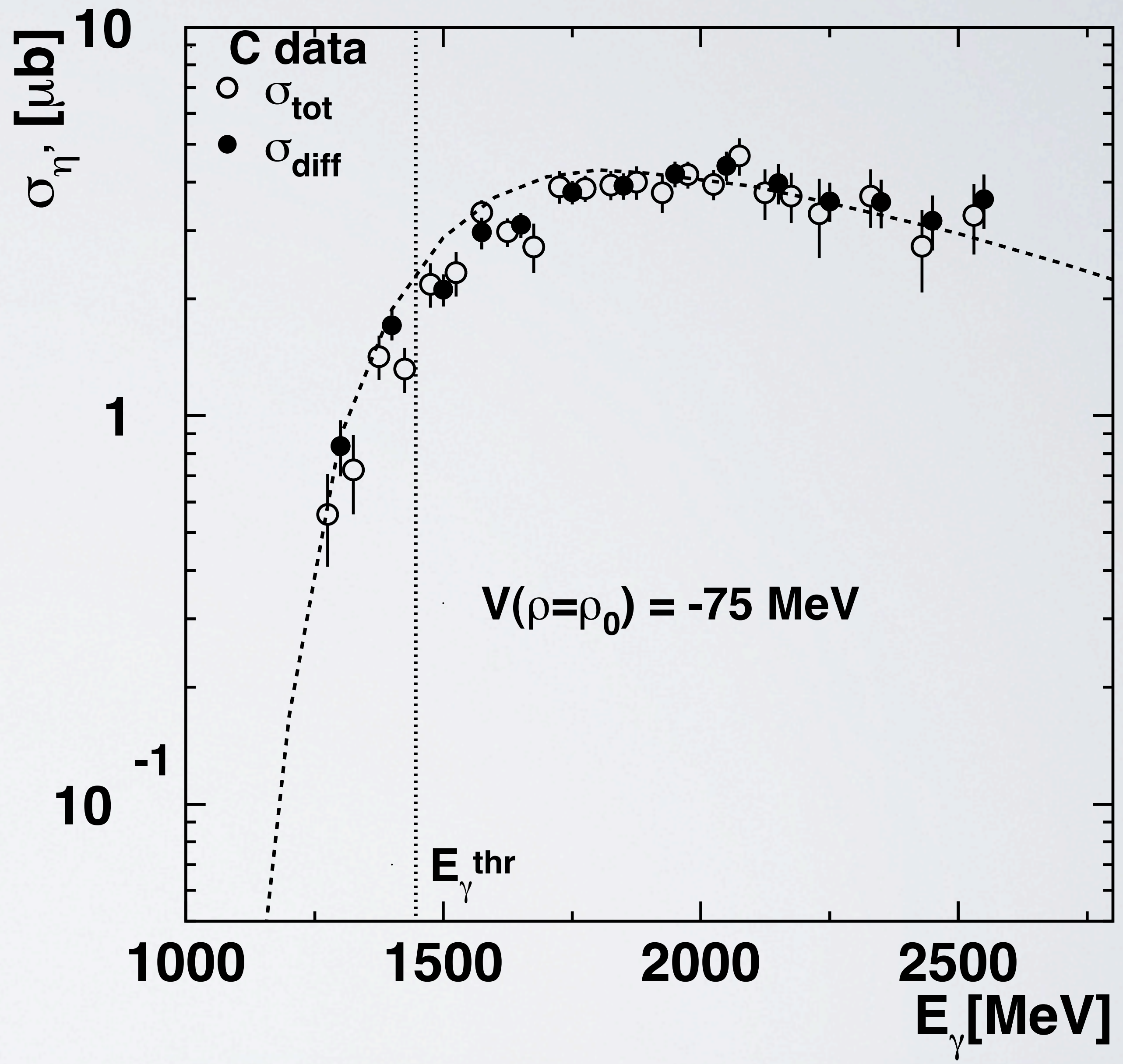

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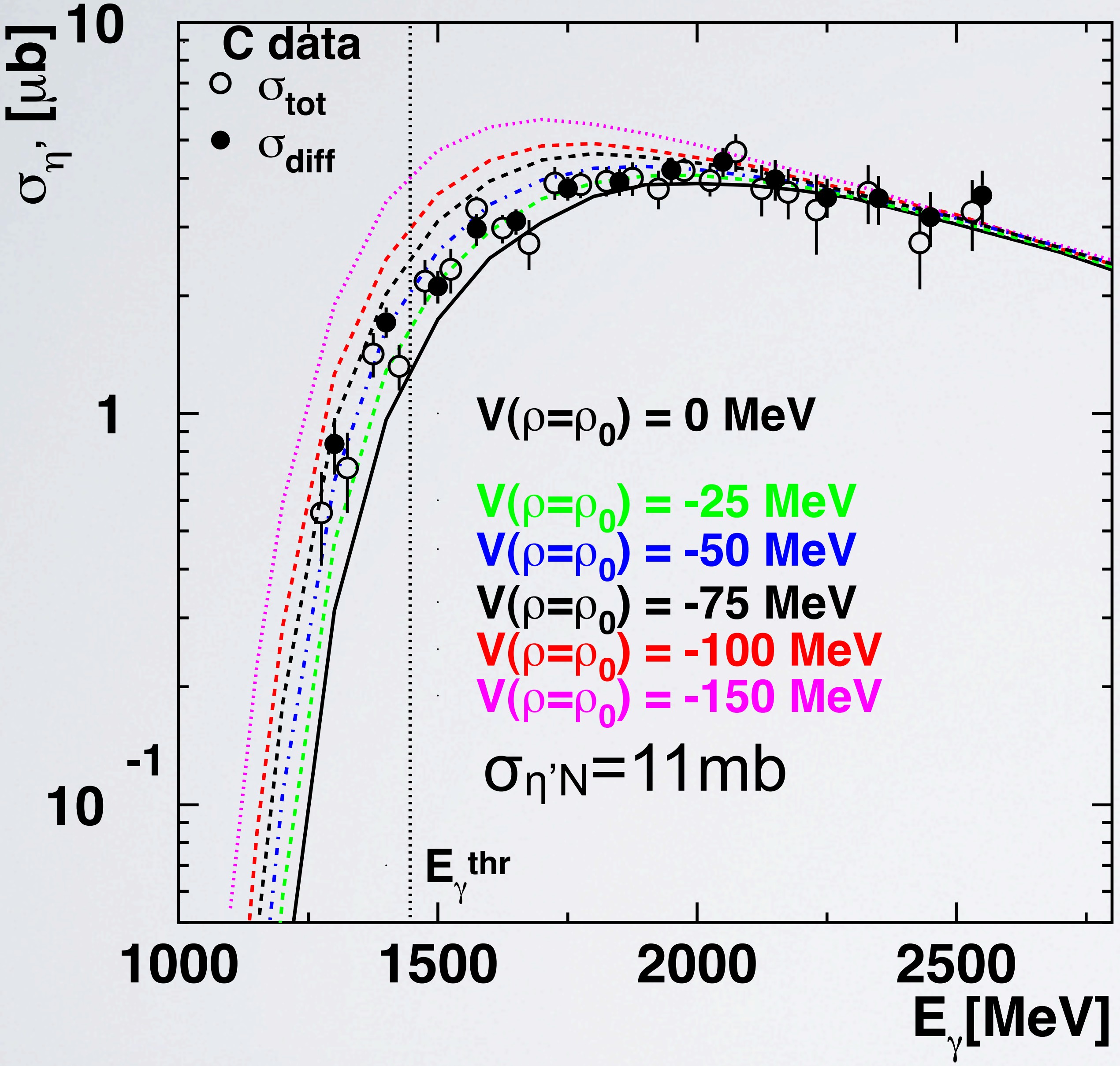

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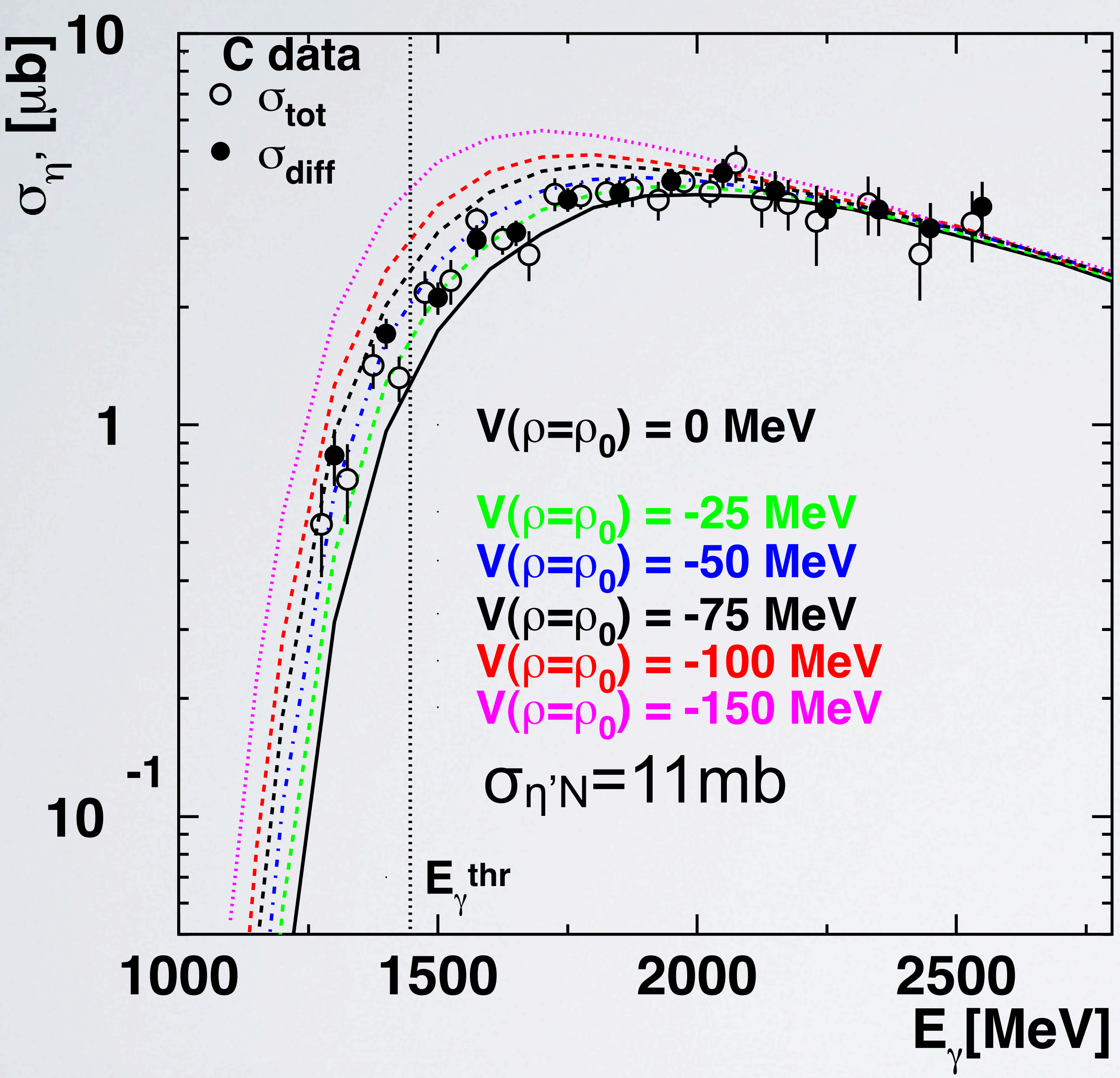

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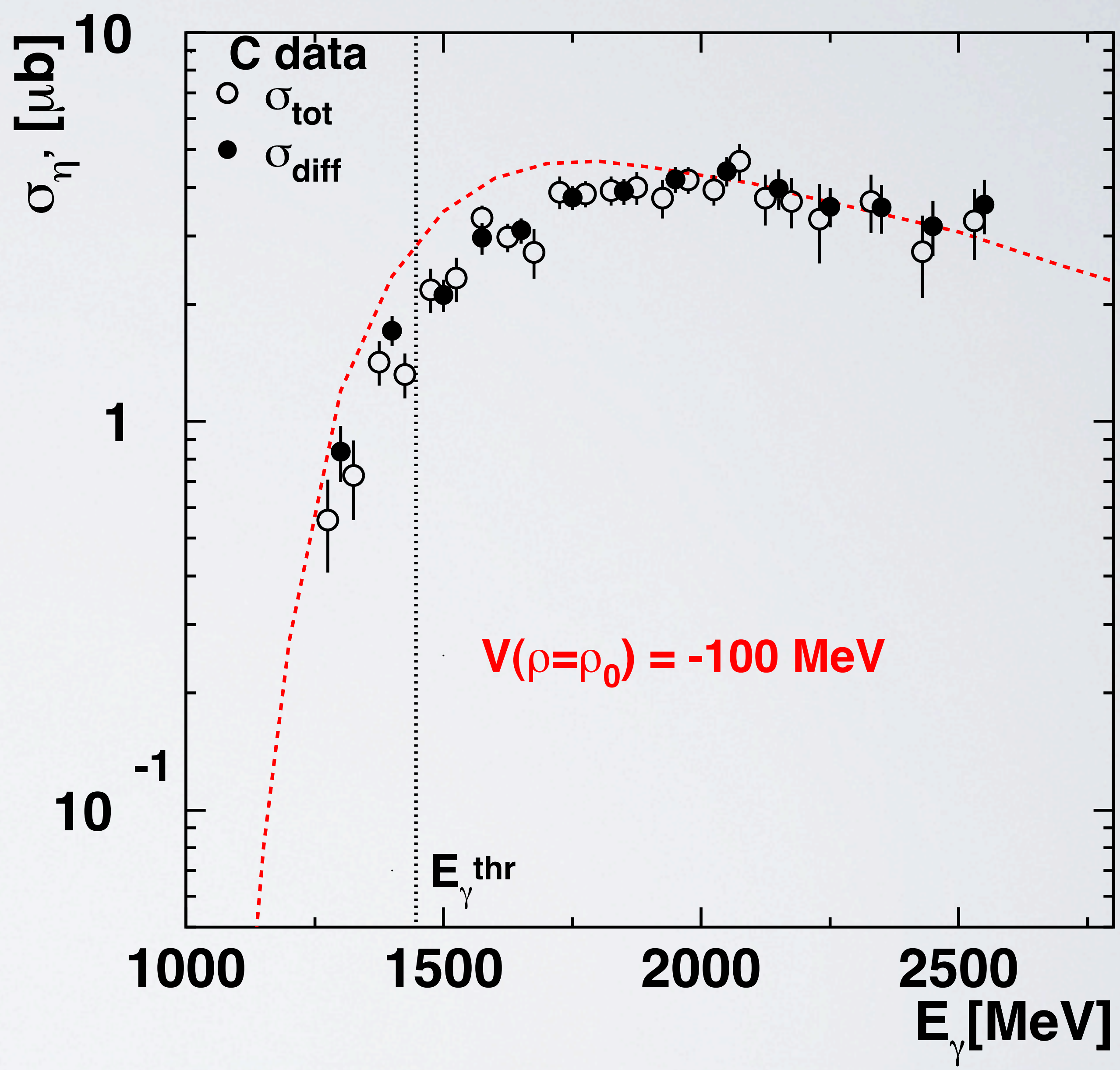

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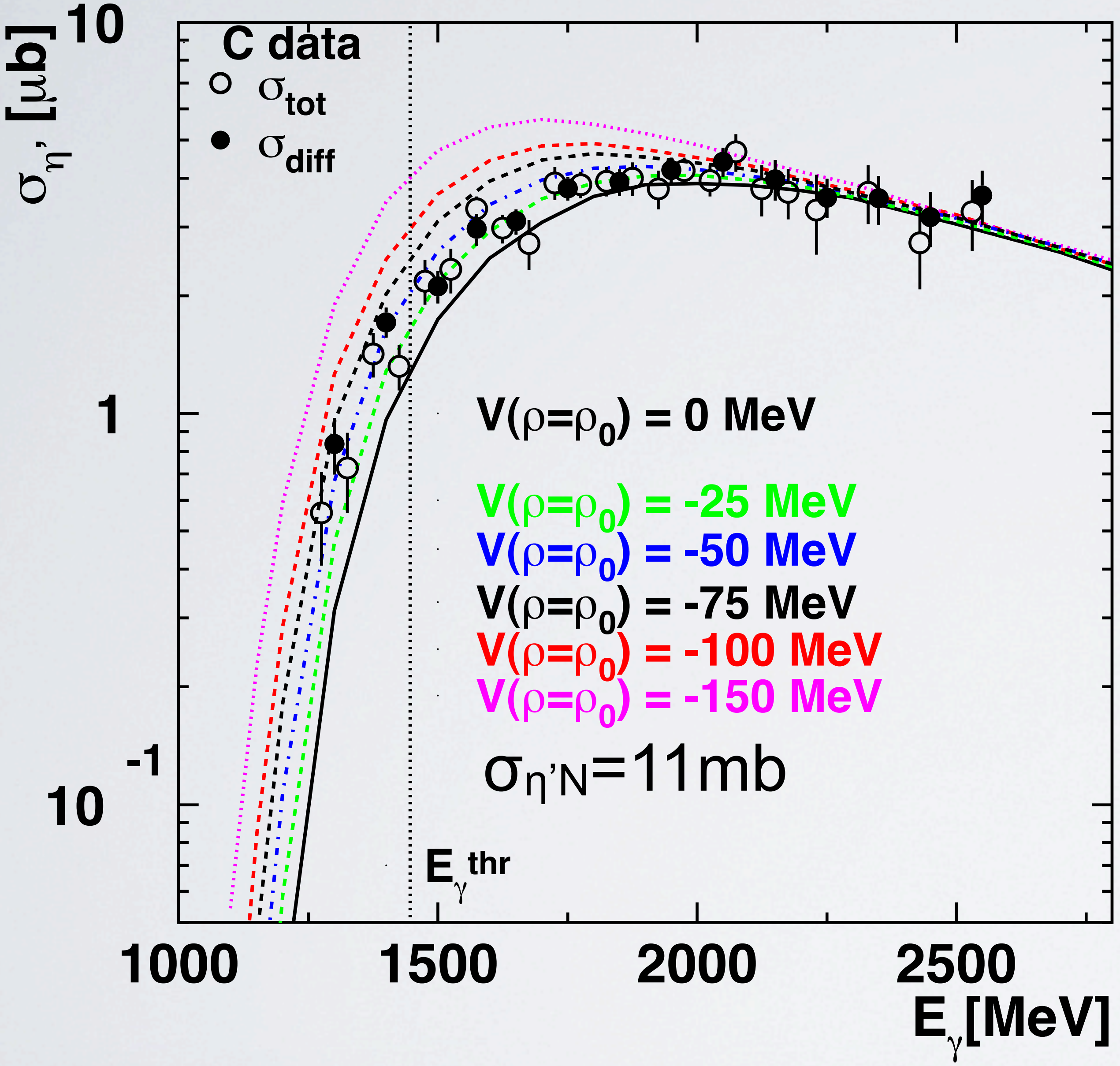

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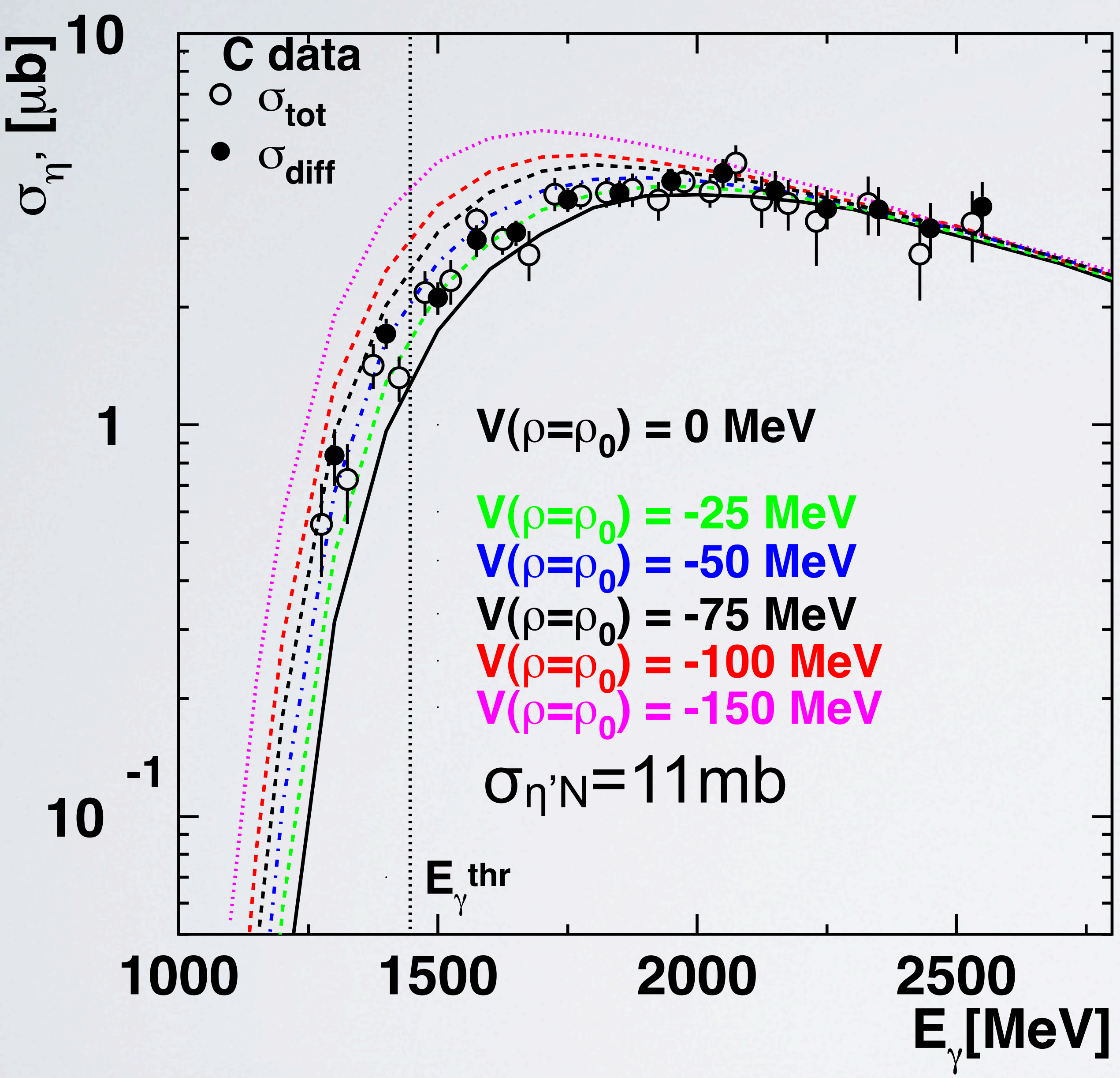

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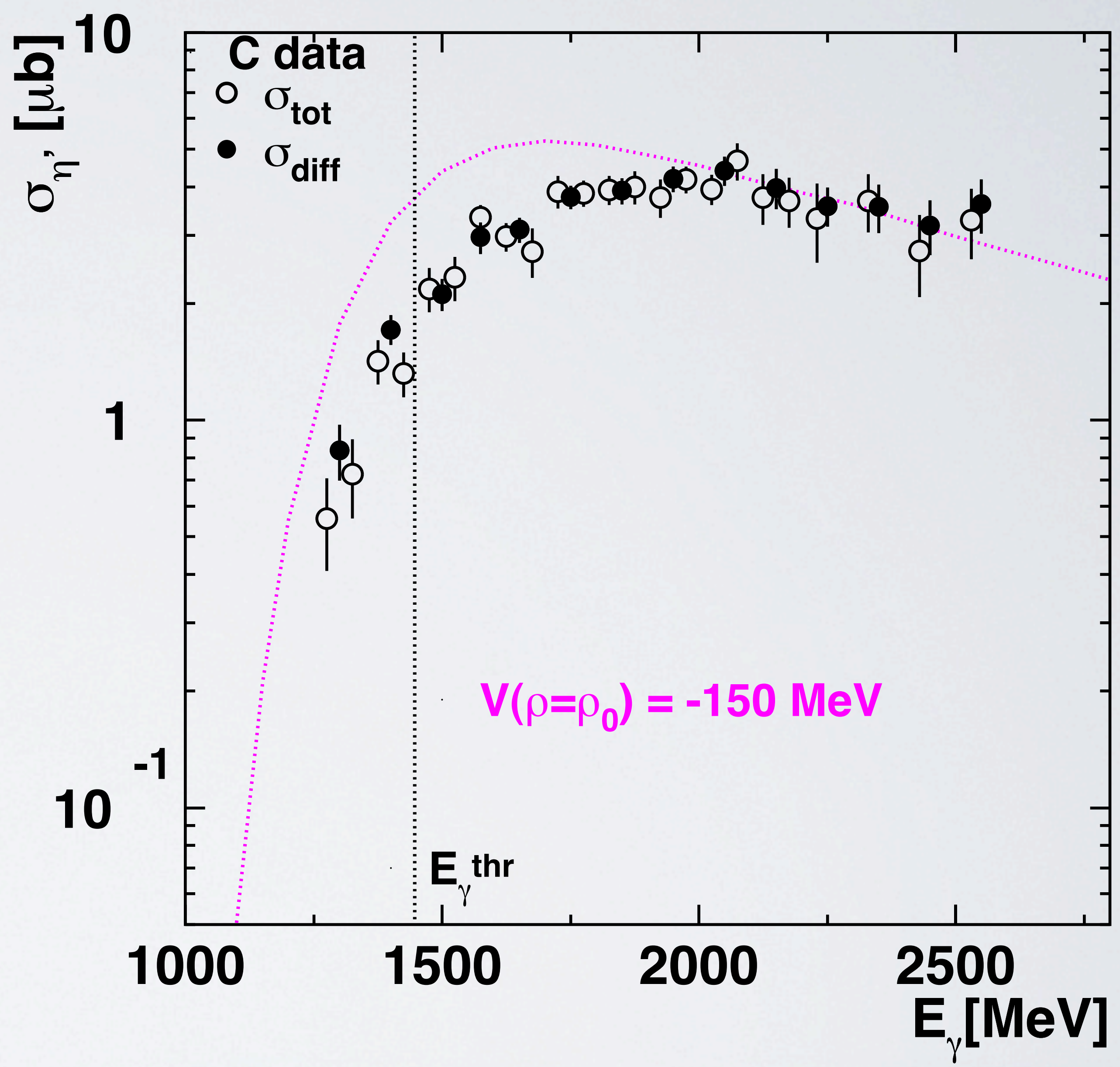

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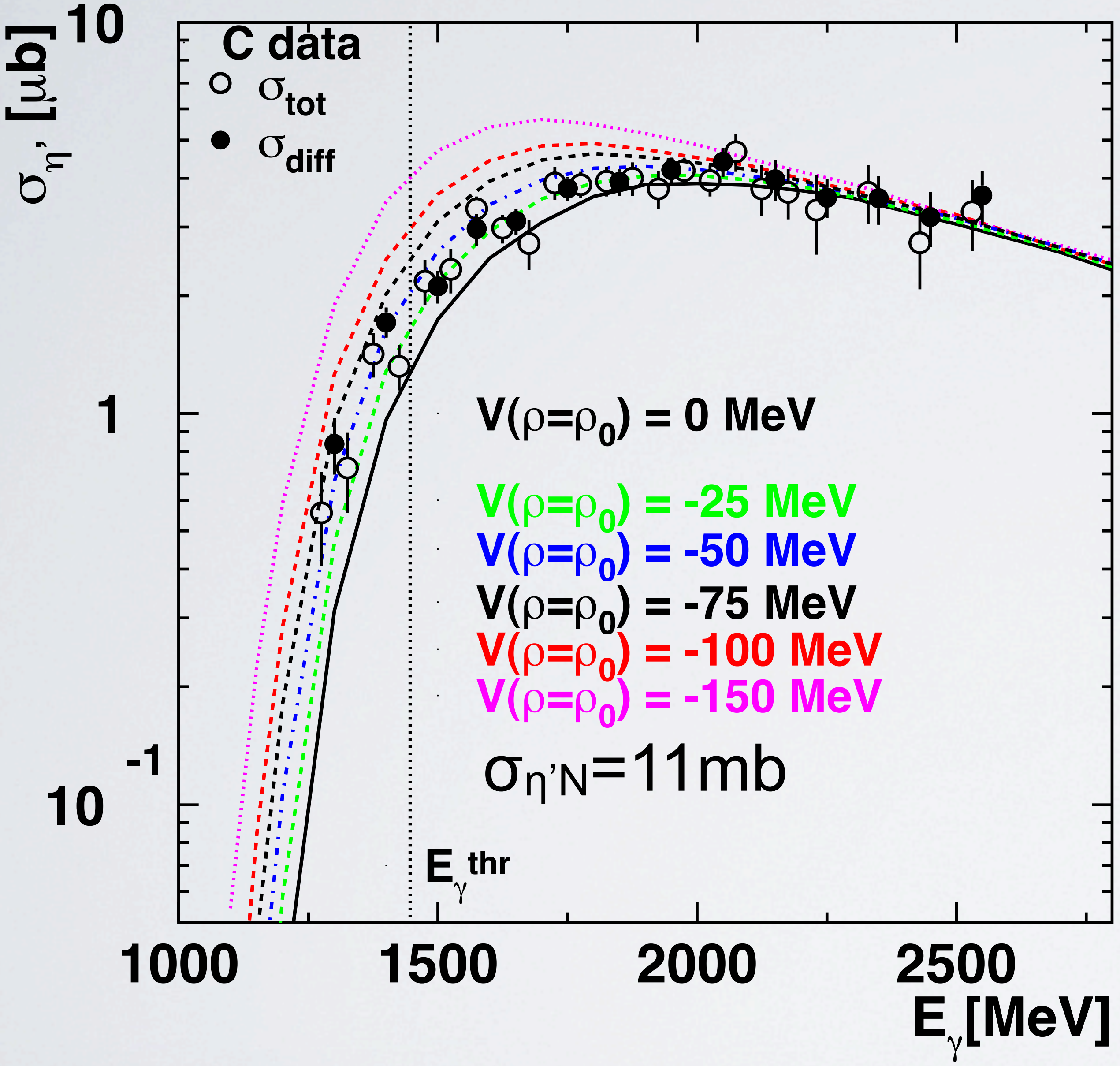

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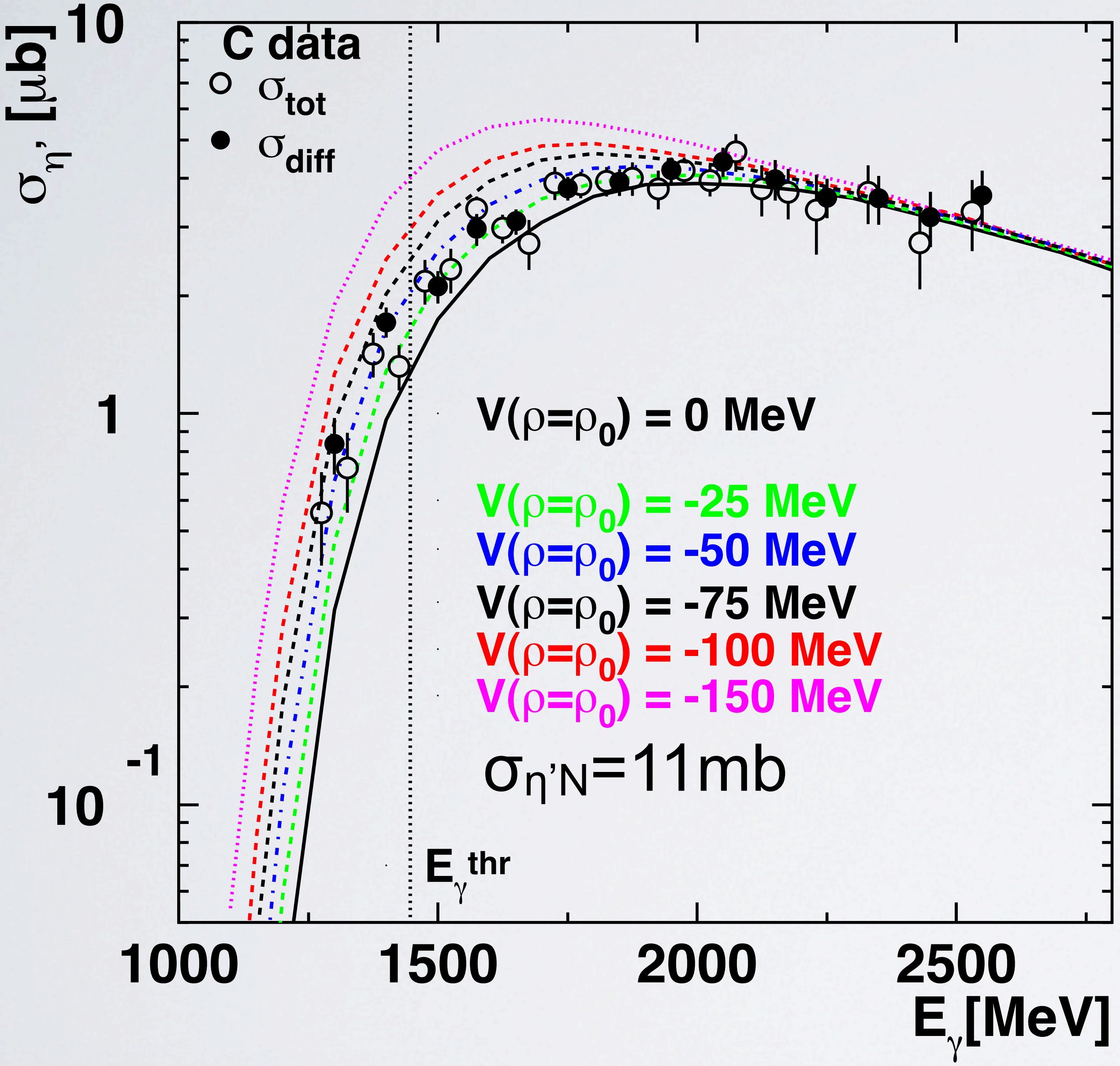

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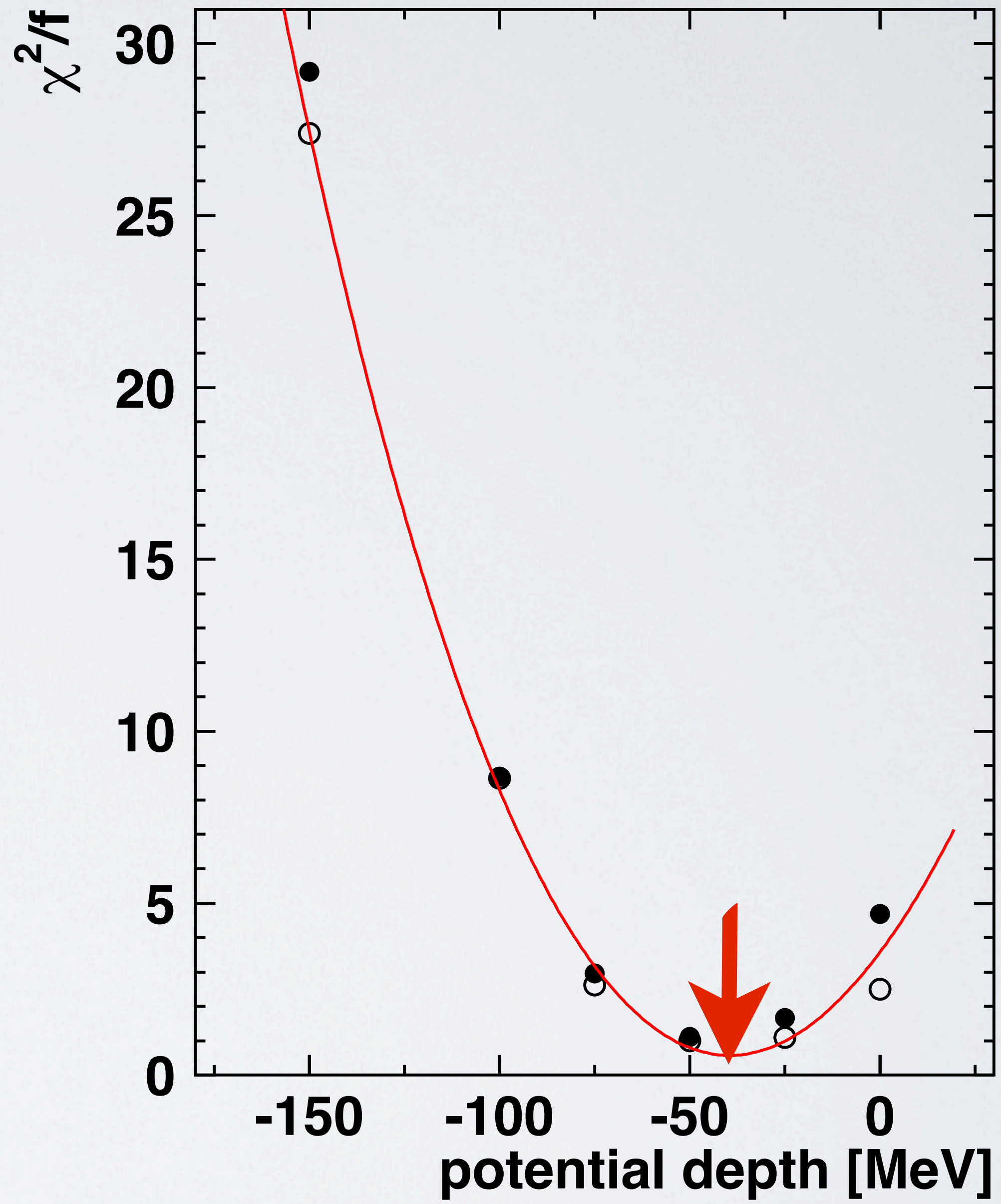
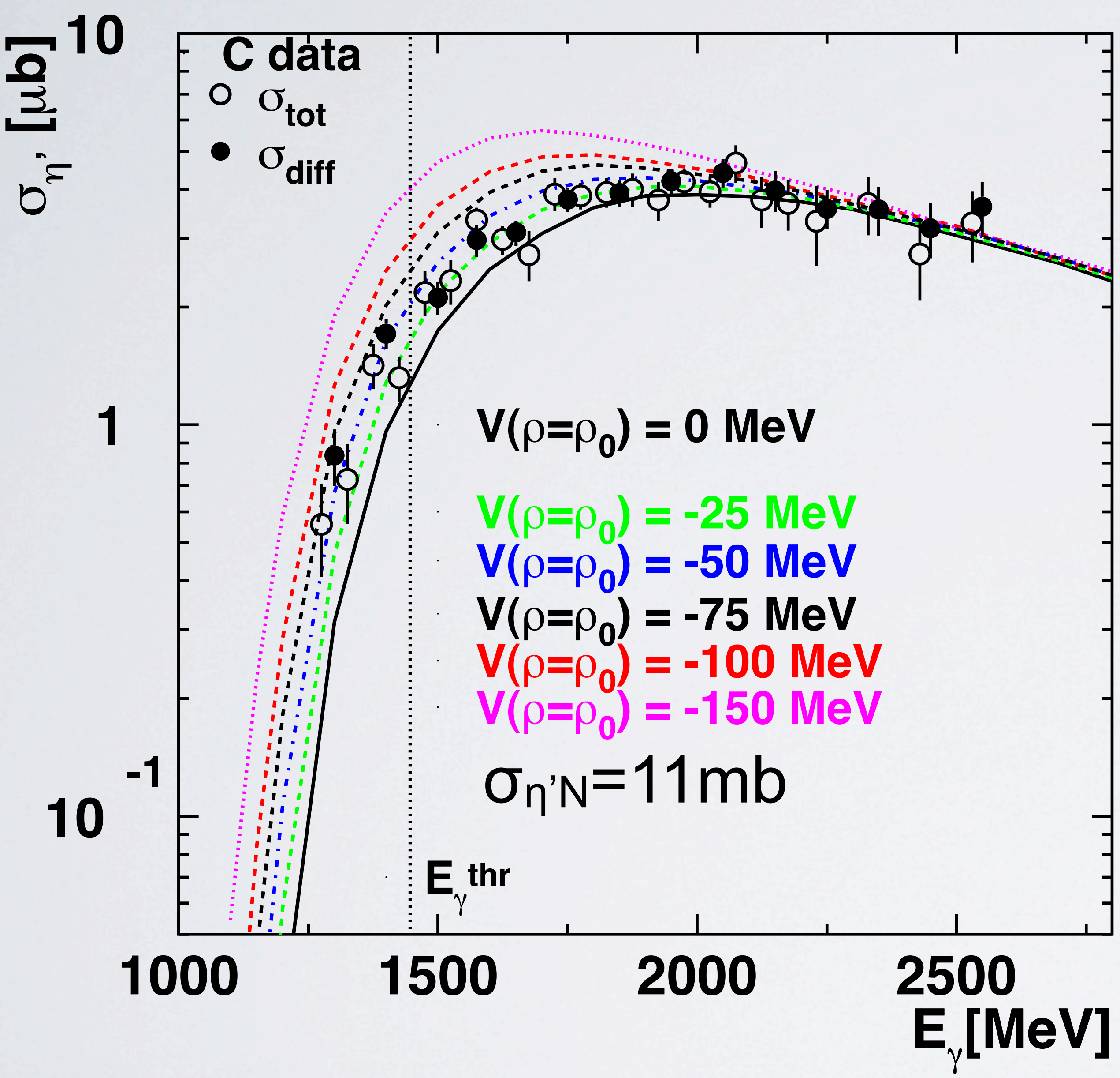


χ^2-fit of the data with the calculated excitation functions for the 6 scenarios

estimation of the real part of the η'-nucleus potential from the η' excitation function

excitation function



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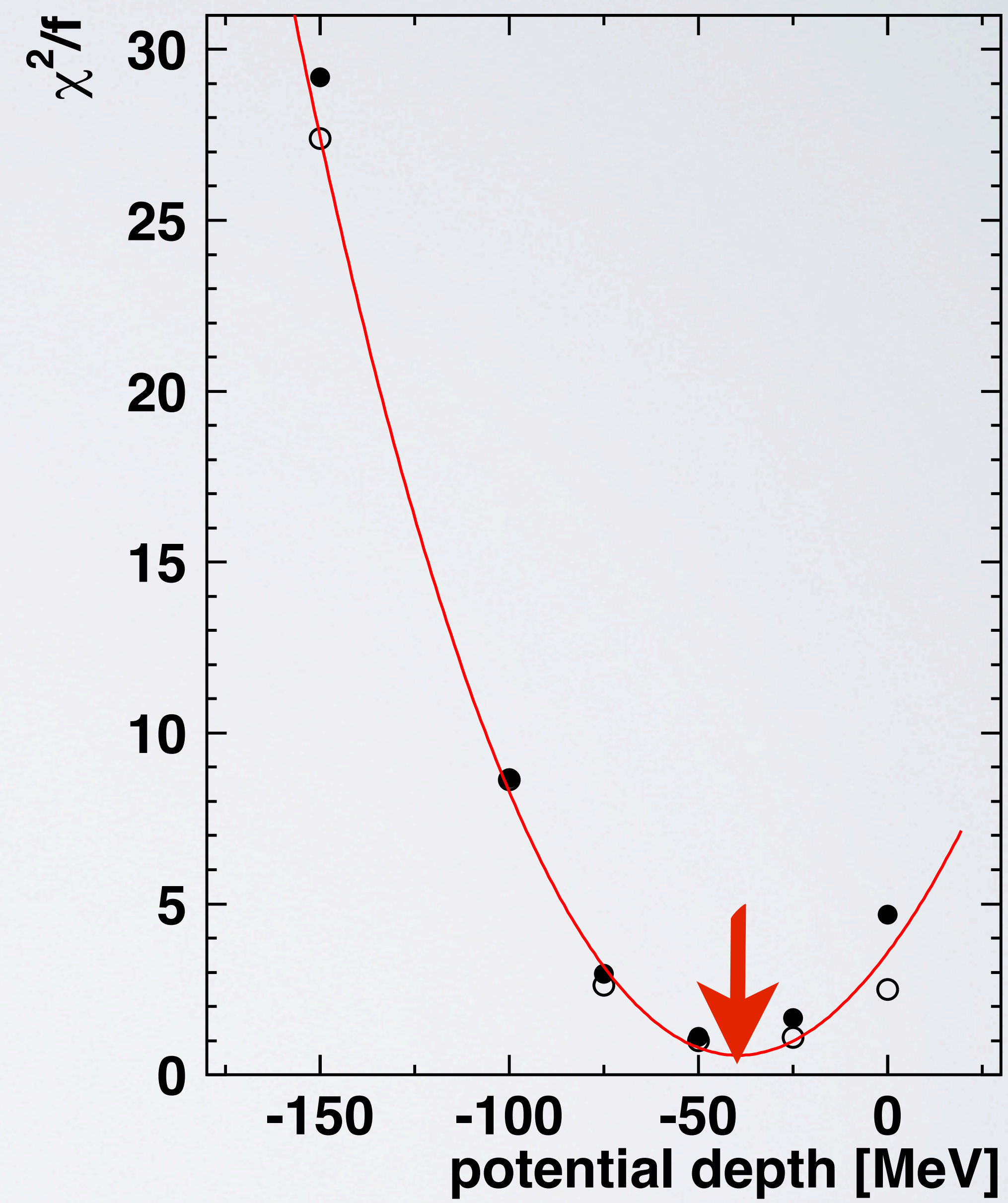


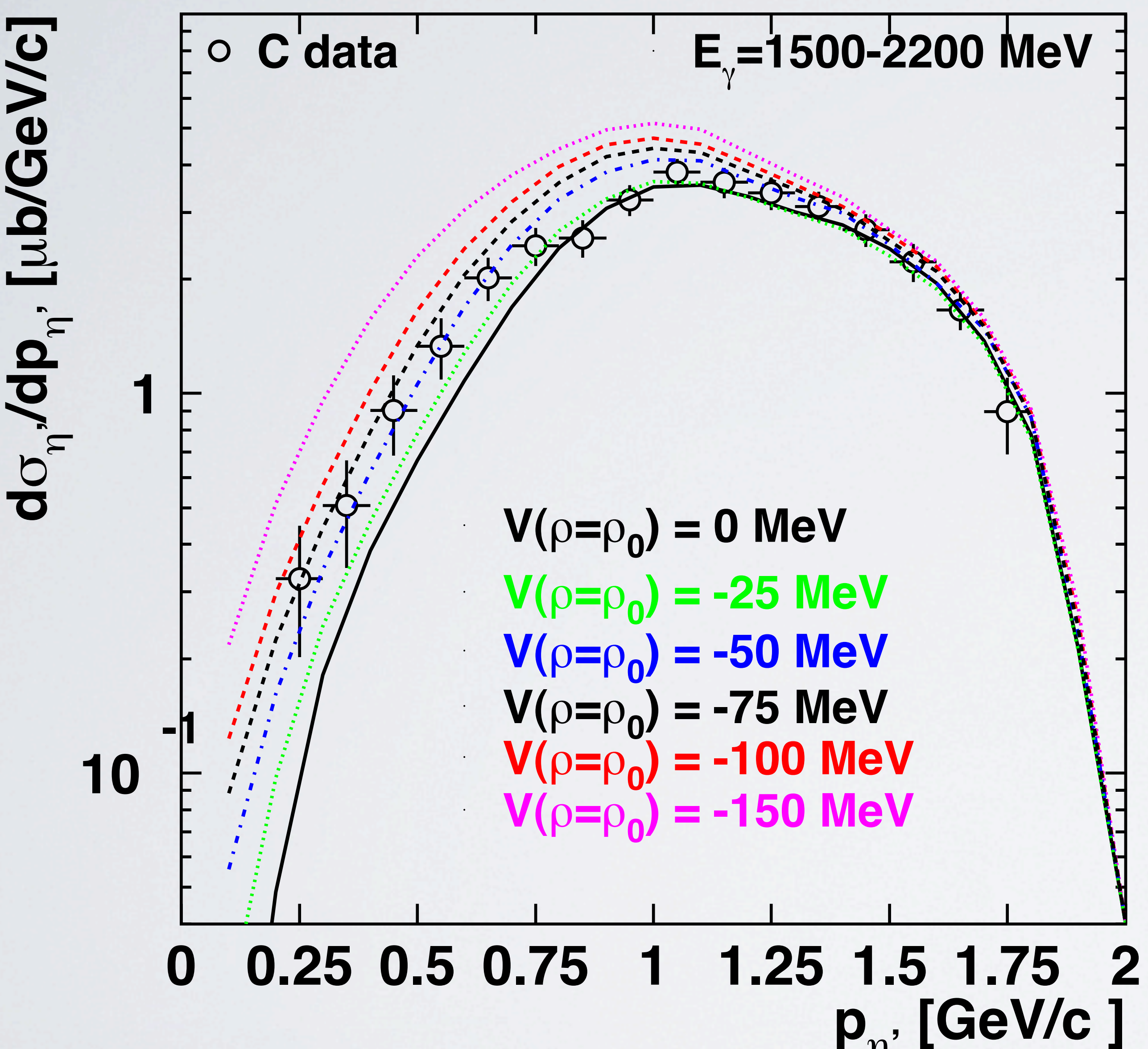
χ^2-fit of the data with the calculated excitation functions for the 6 scenarios

$V(\rho=\rho_0)$ = -40±6 MeV

η’ momentum distribution off C

comparison of CBELSA/TAPS data with calculations by
E. Paryev, J. Phys. G: Nucl. Part. Phys. 40 (2013) 025201 and priv. communication

momentum distribution



calculation normalized to data in p = 1.5-1.8 GeV/c,
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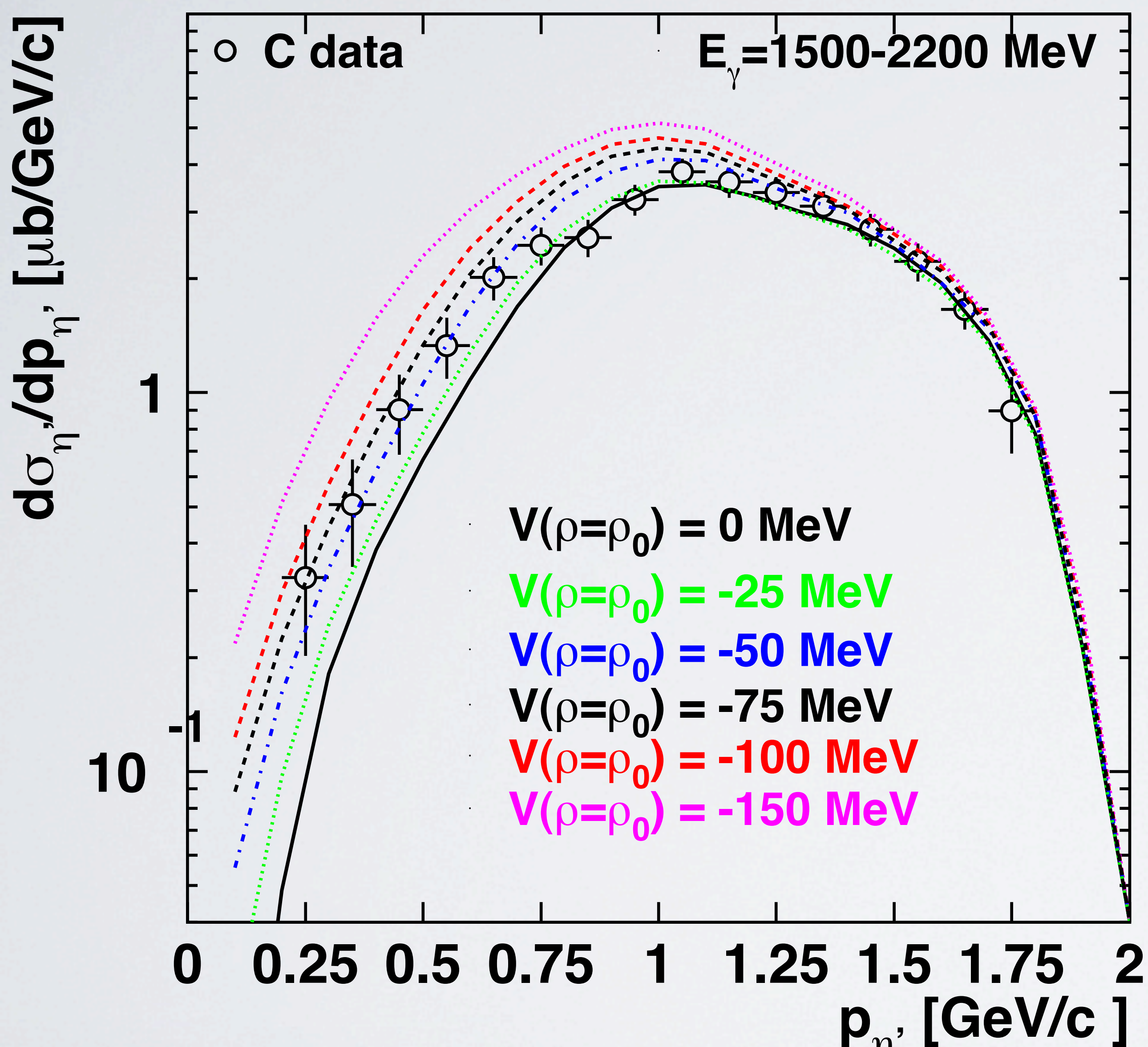

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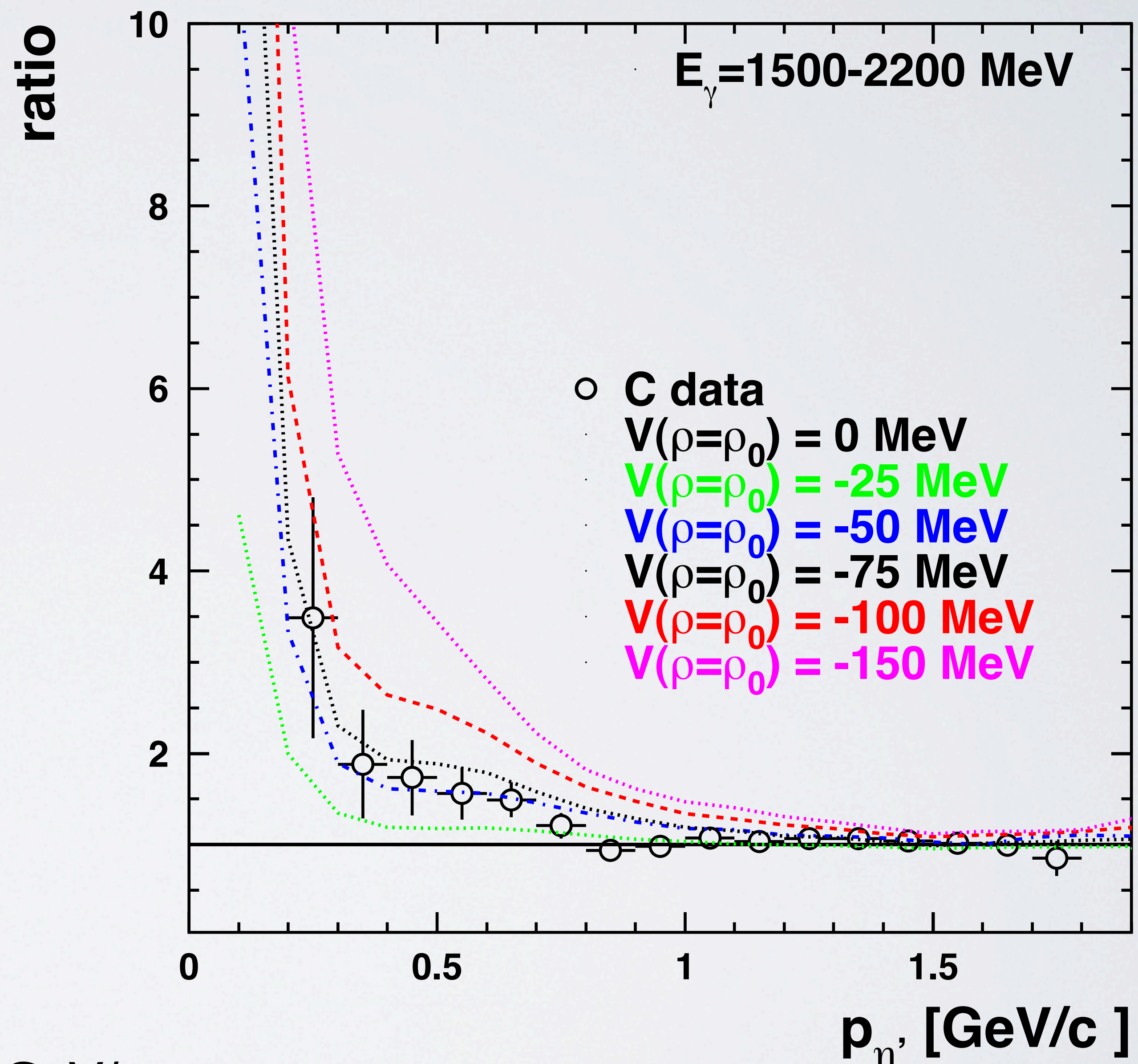
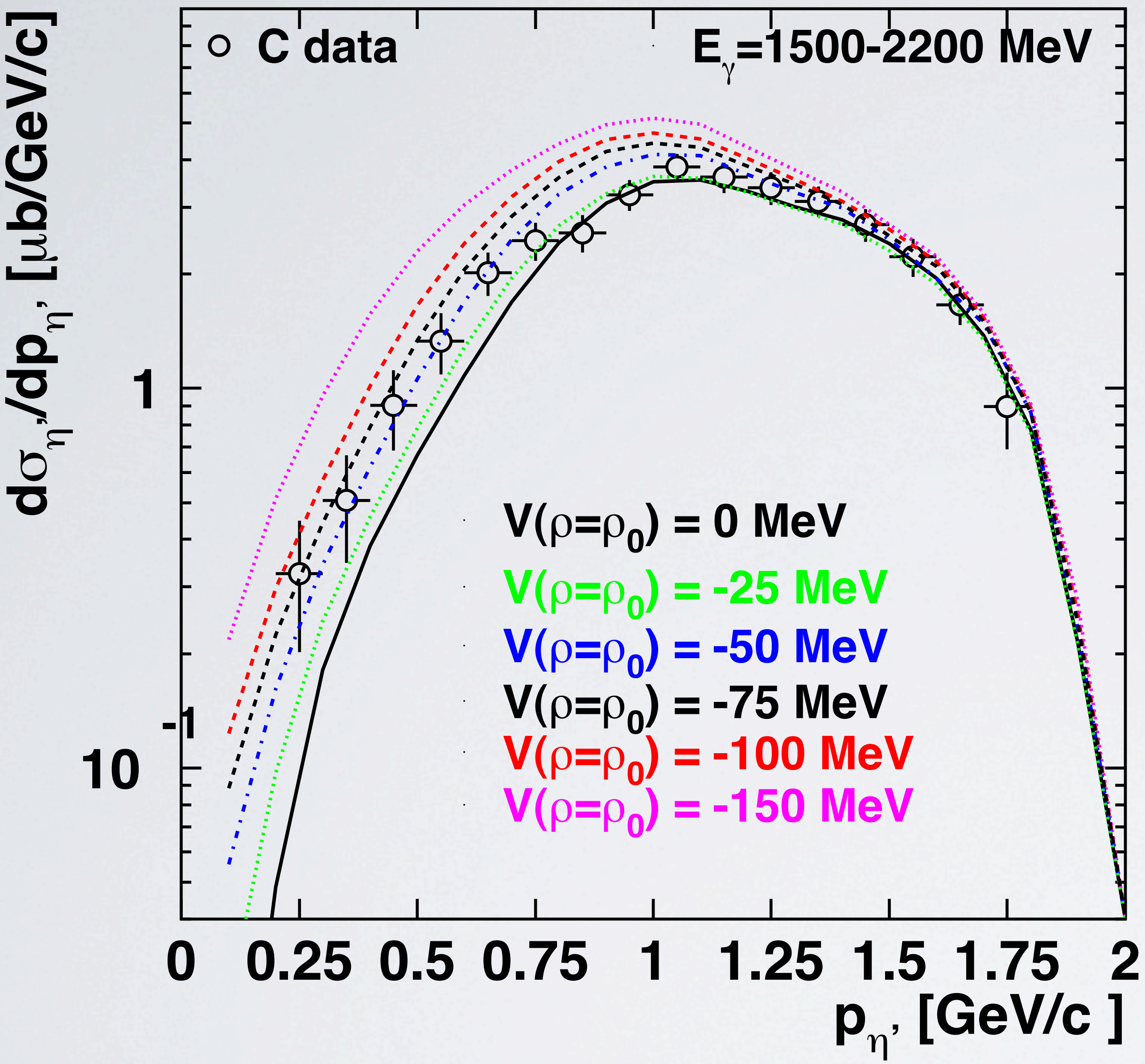


estimation of the of η'-nucleus potential depth from the η' momentum distribution



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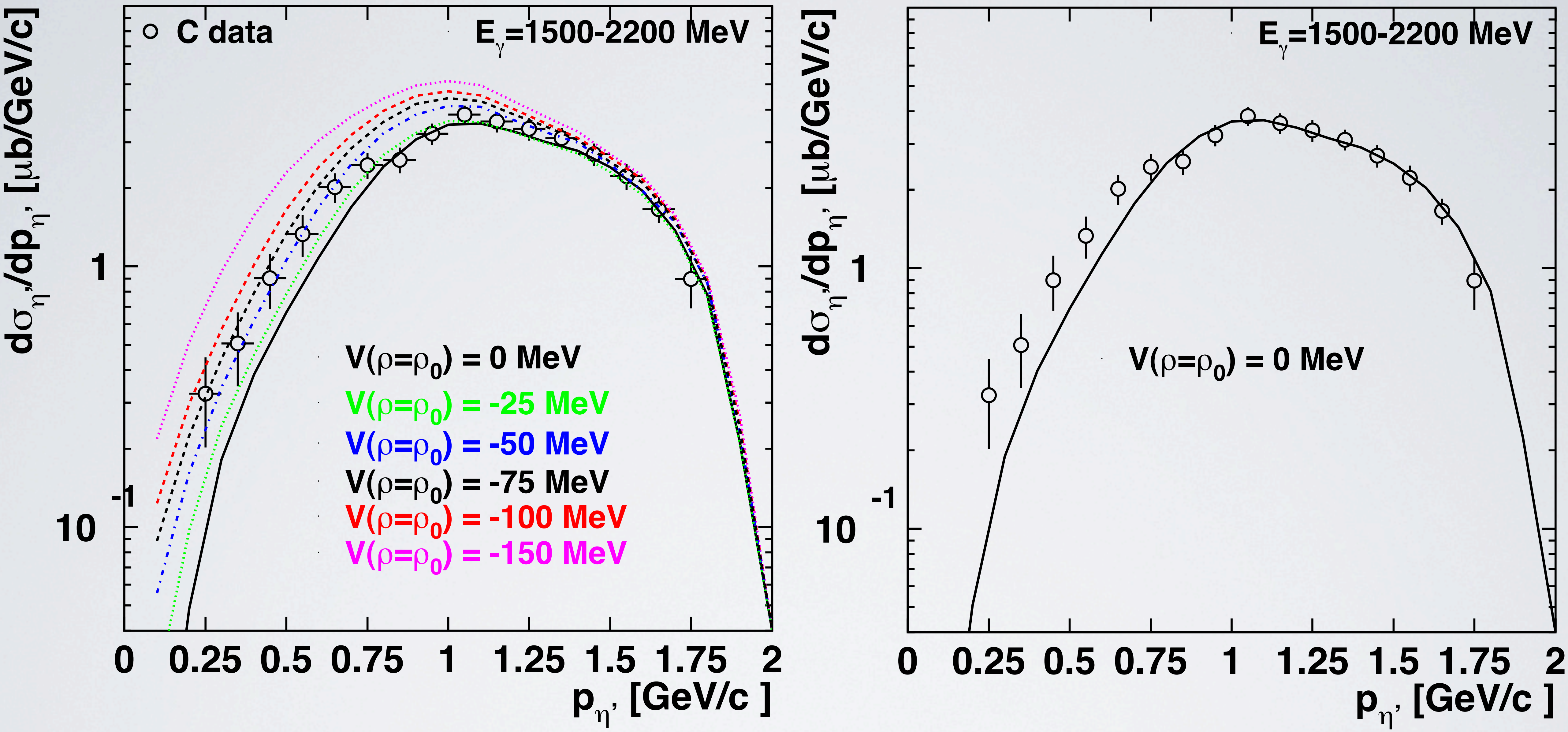

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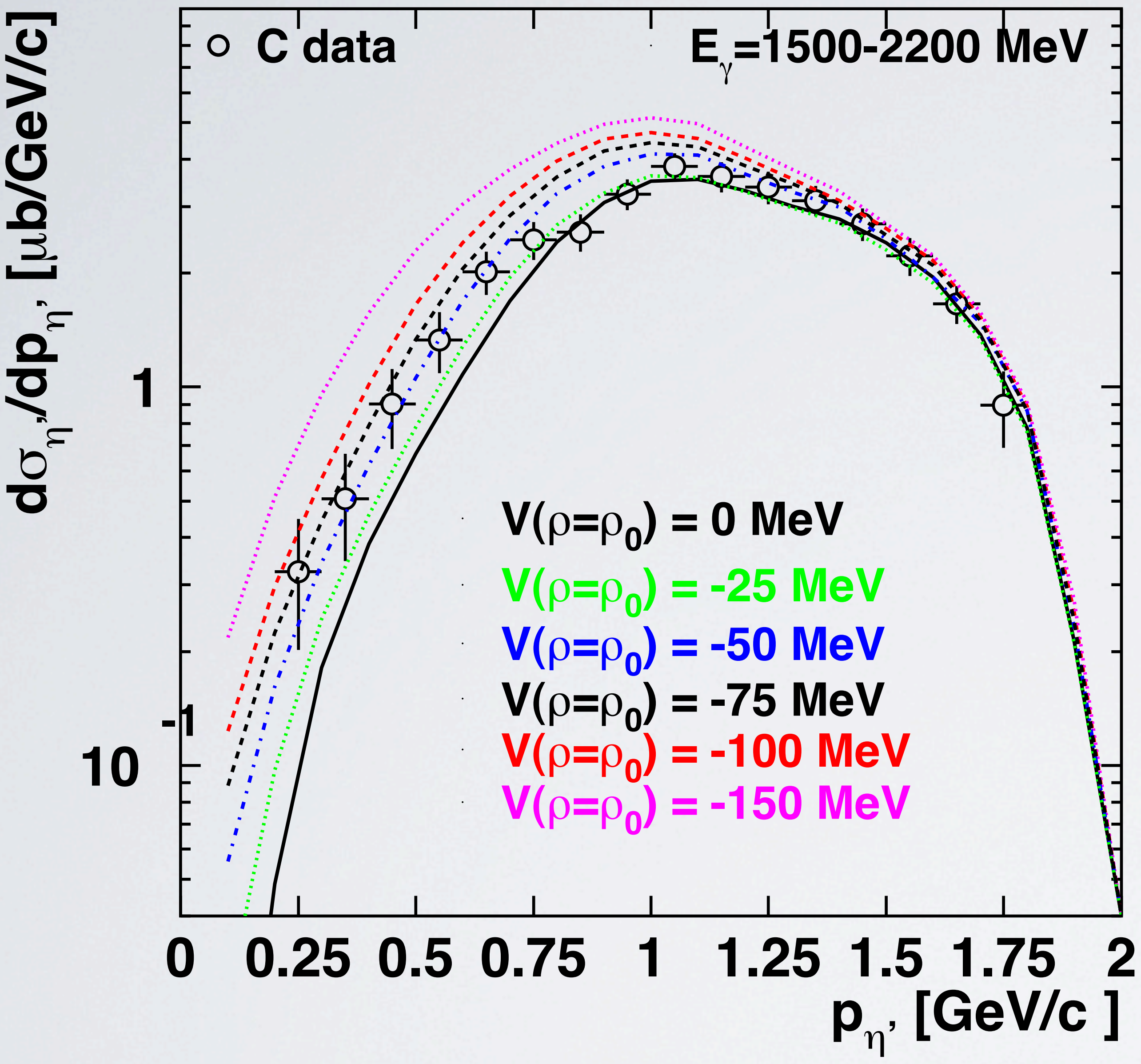

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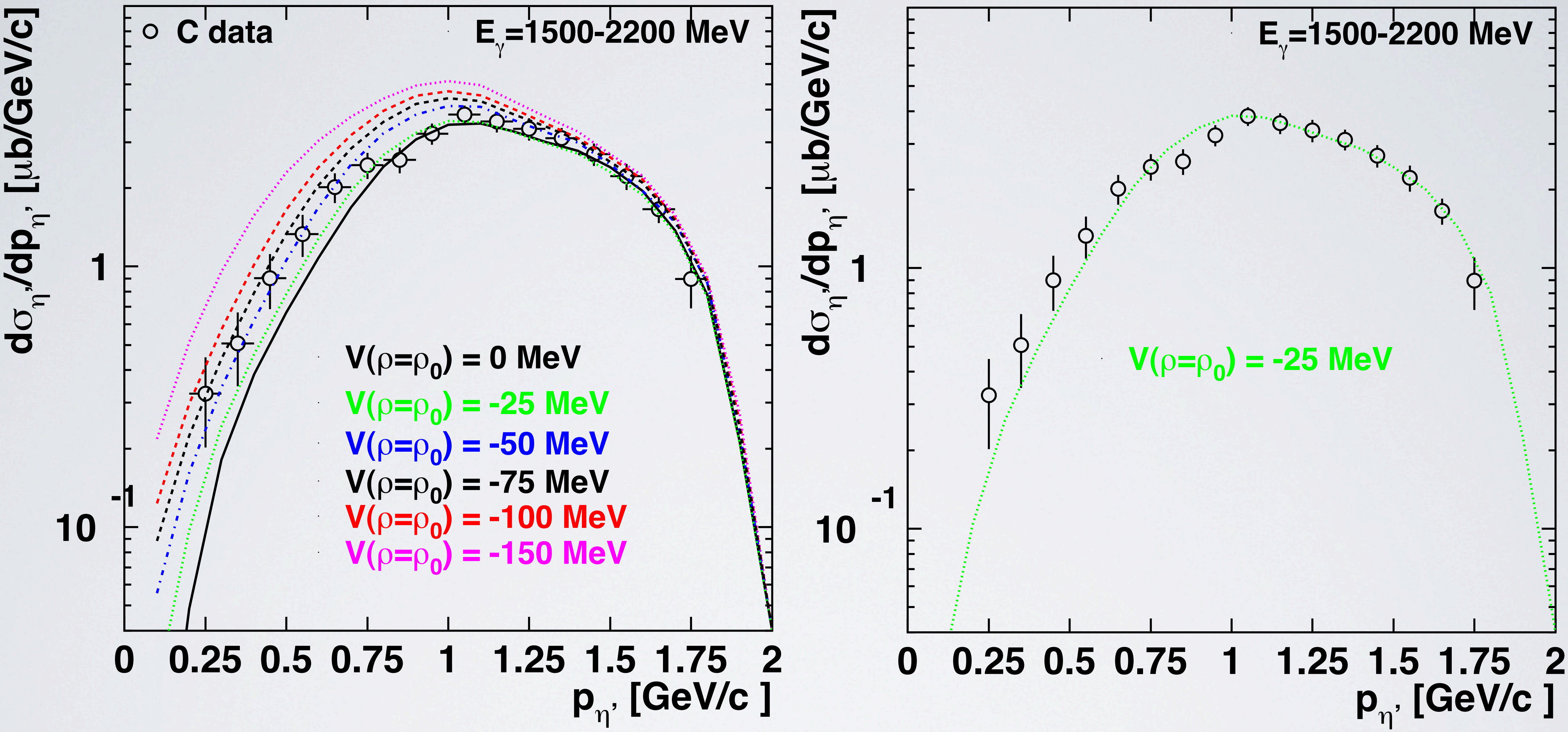

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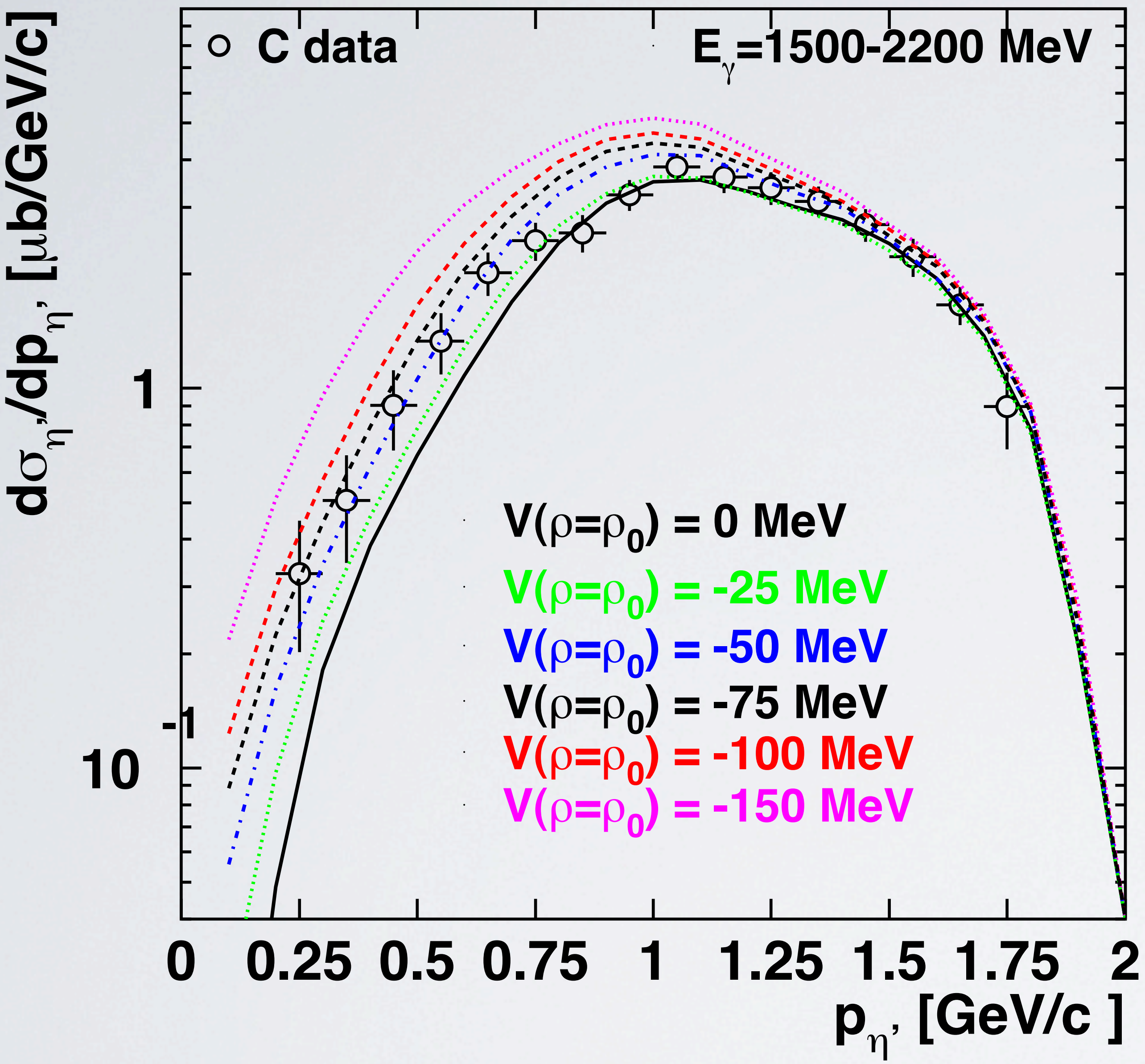

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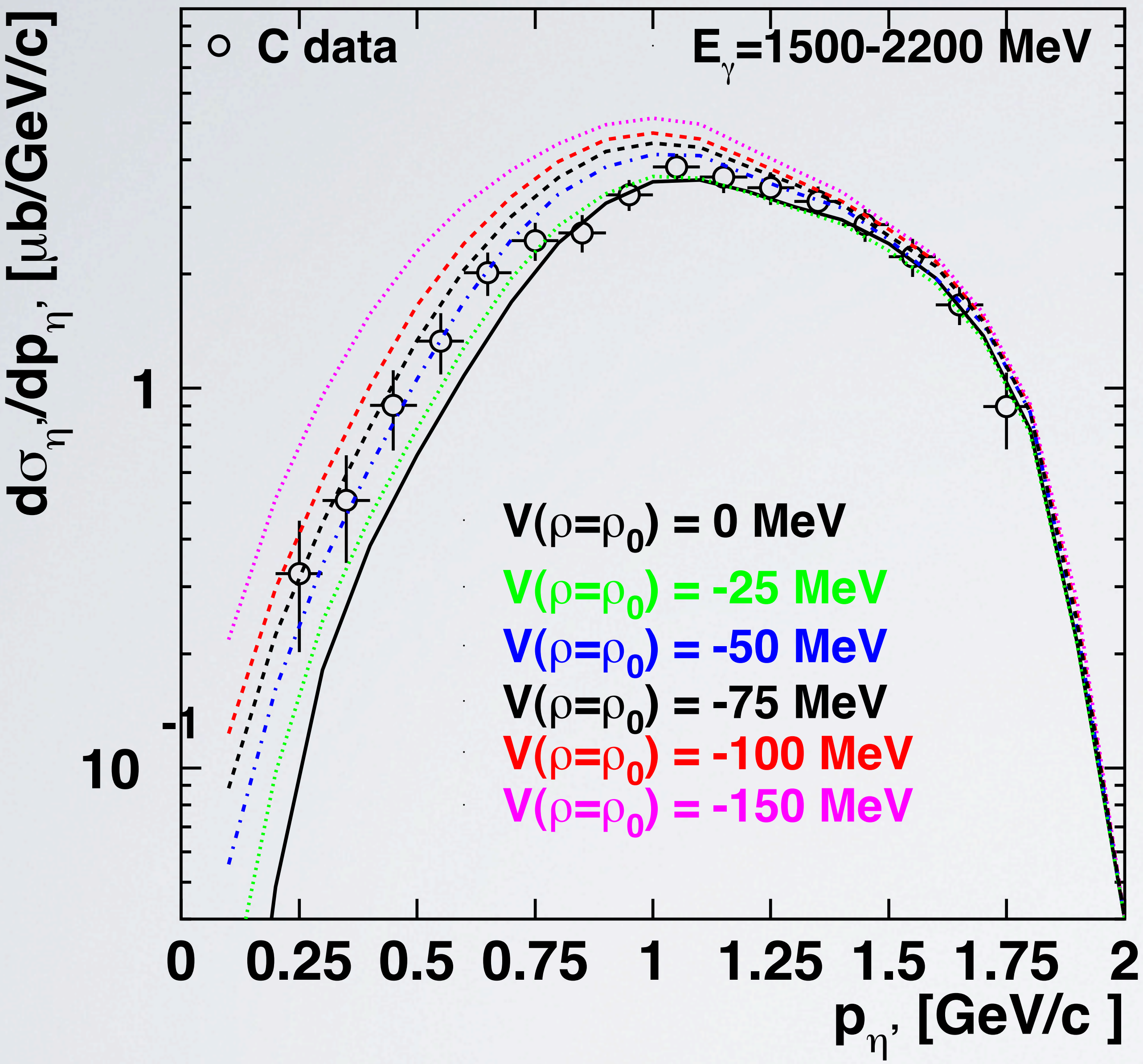

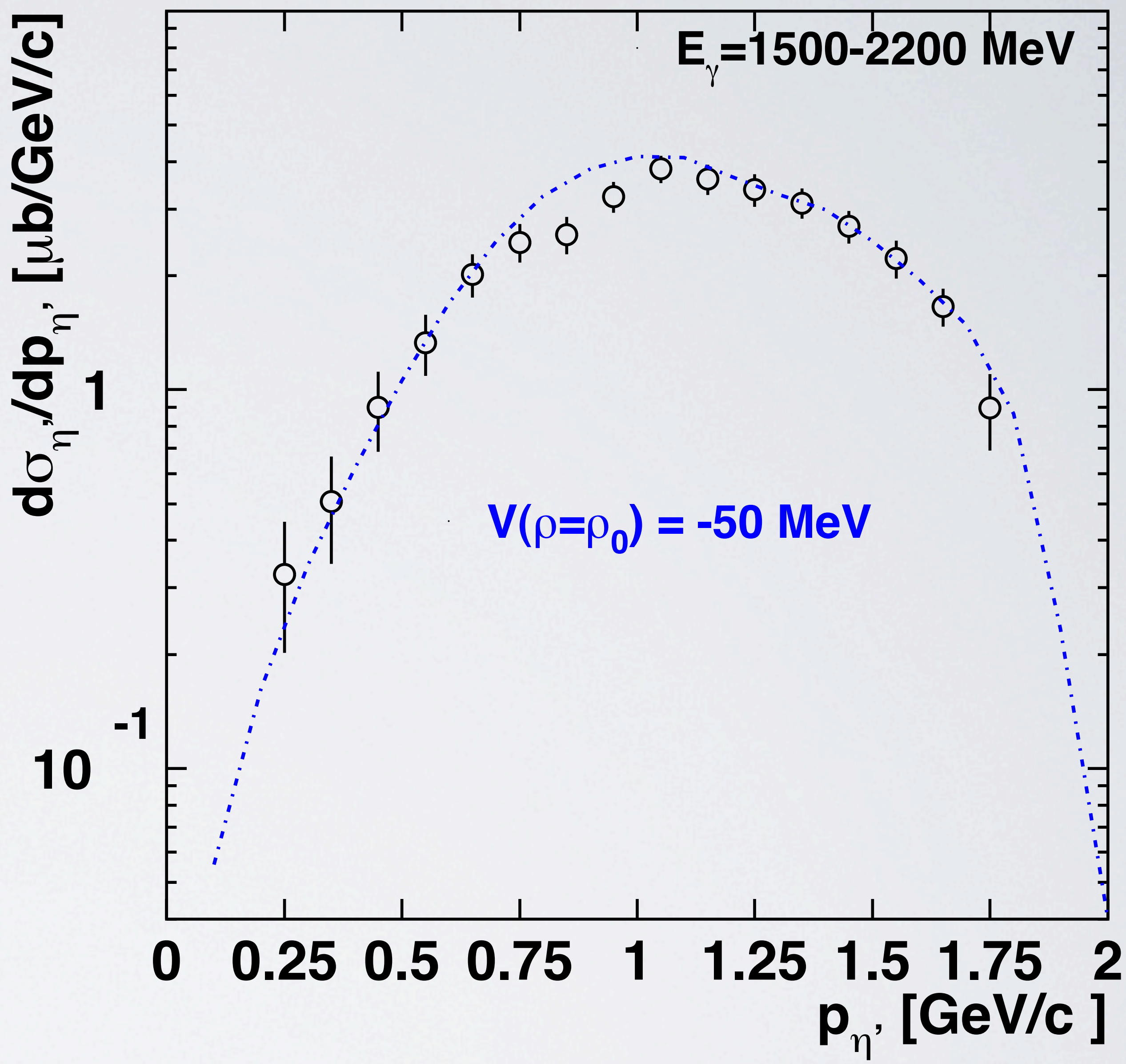

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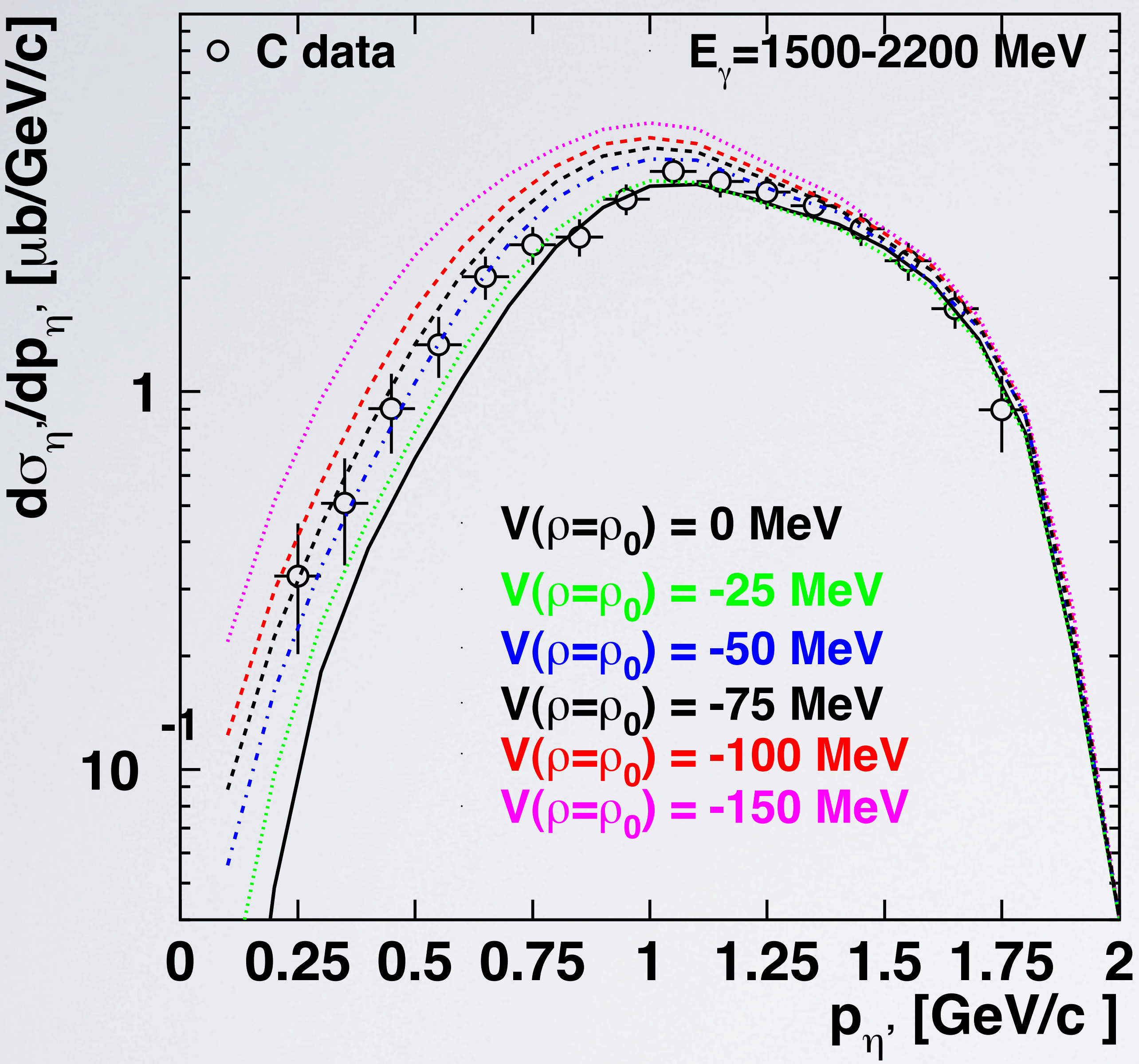

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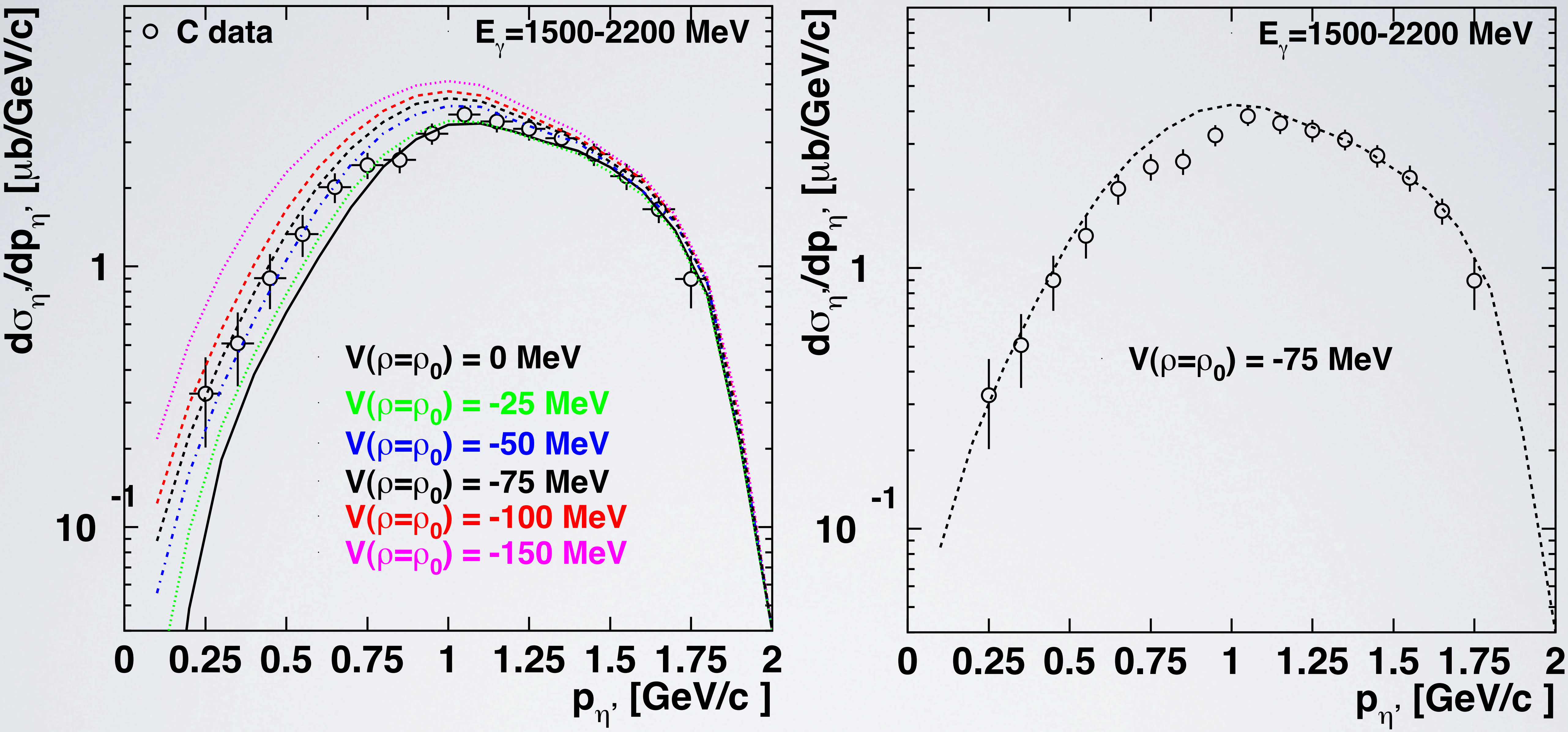

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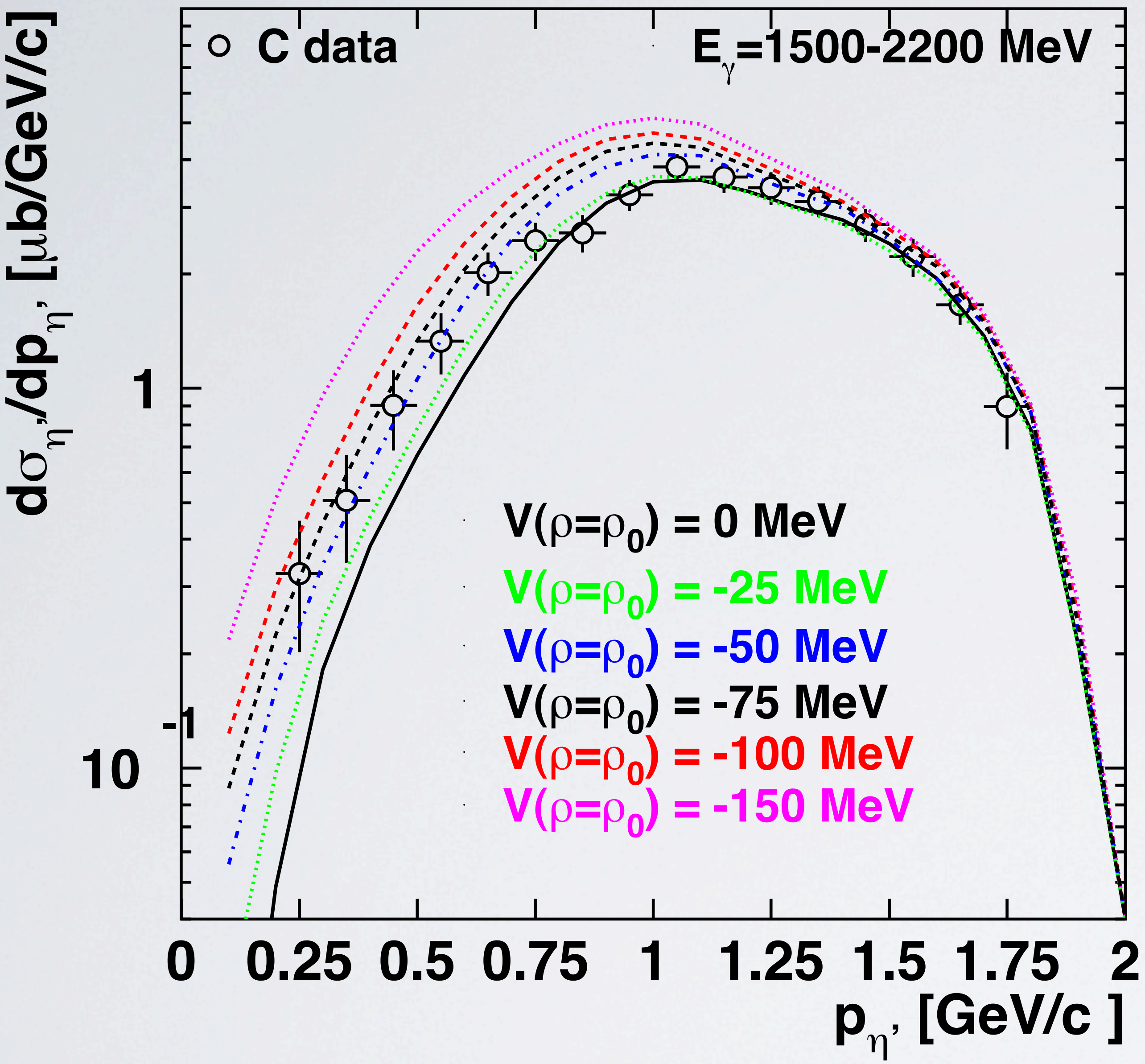

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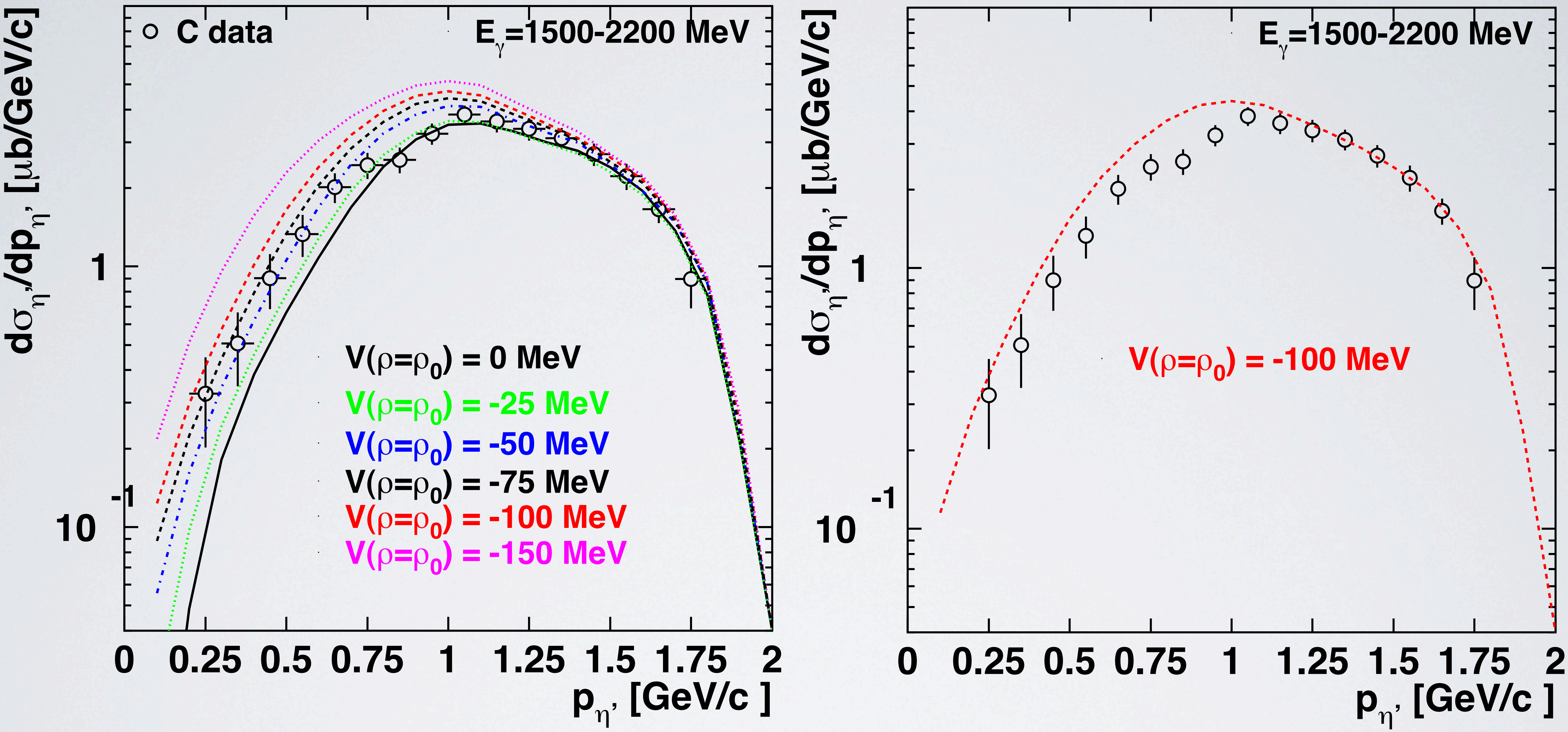

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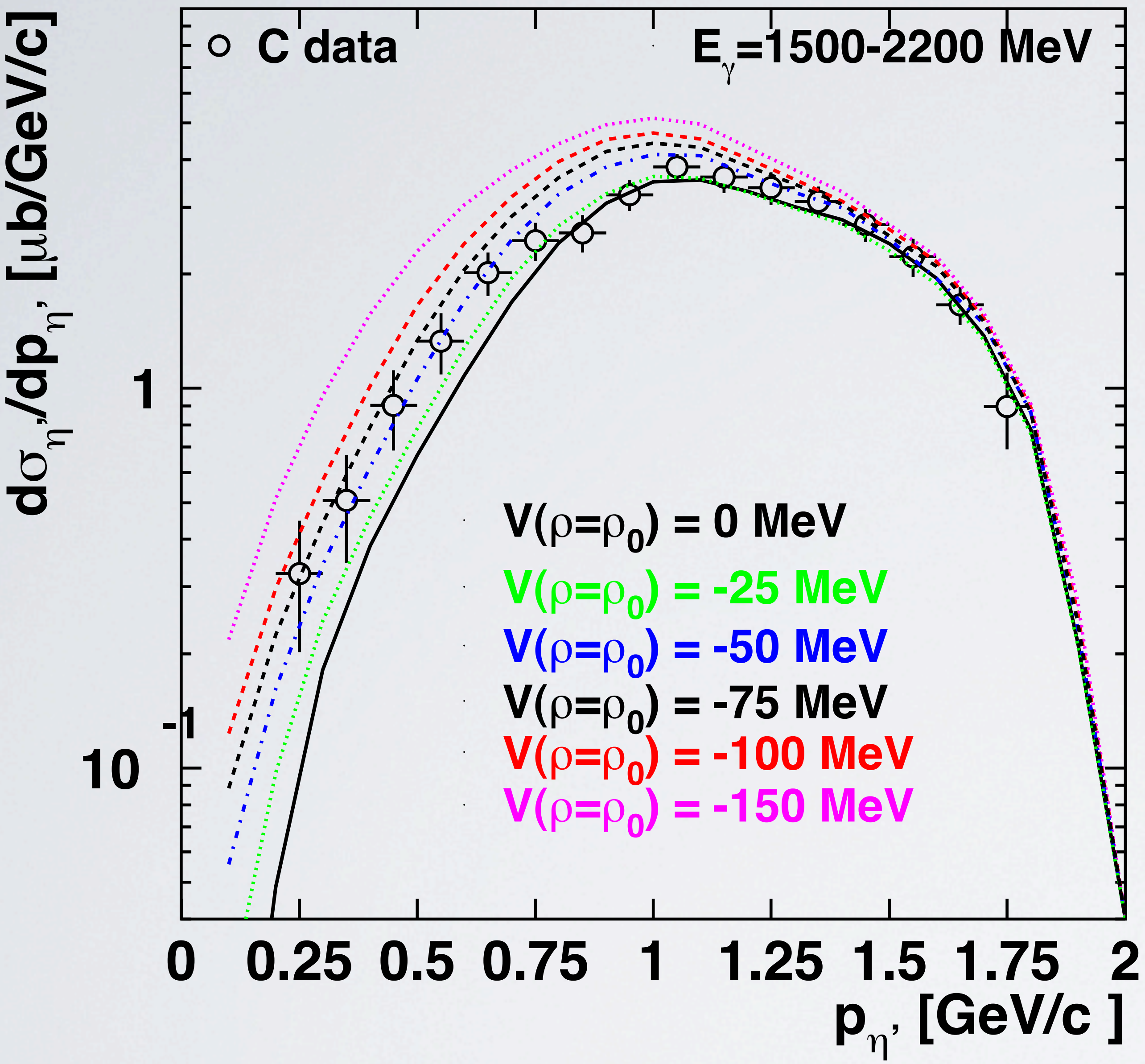

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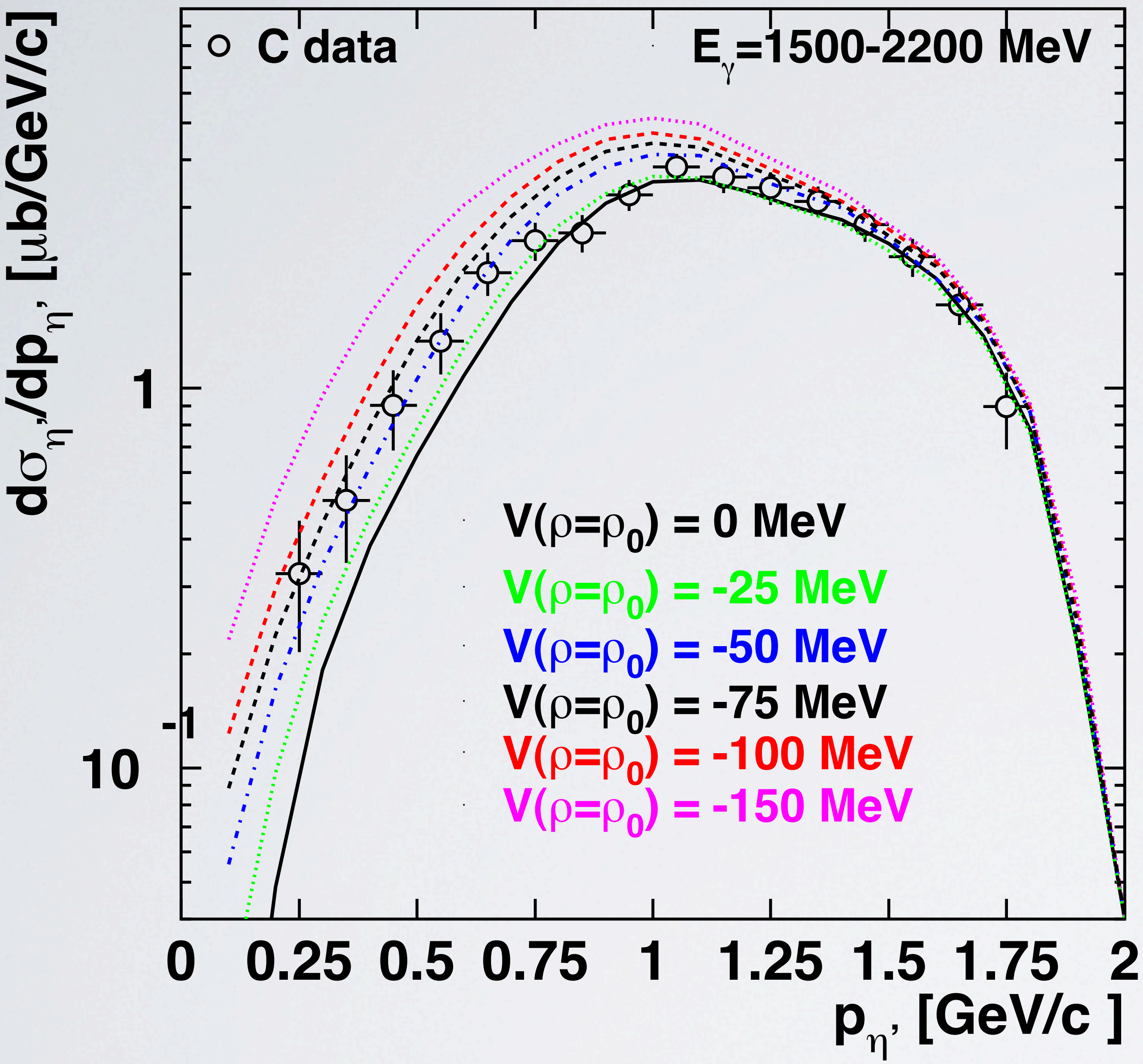

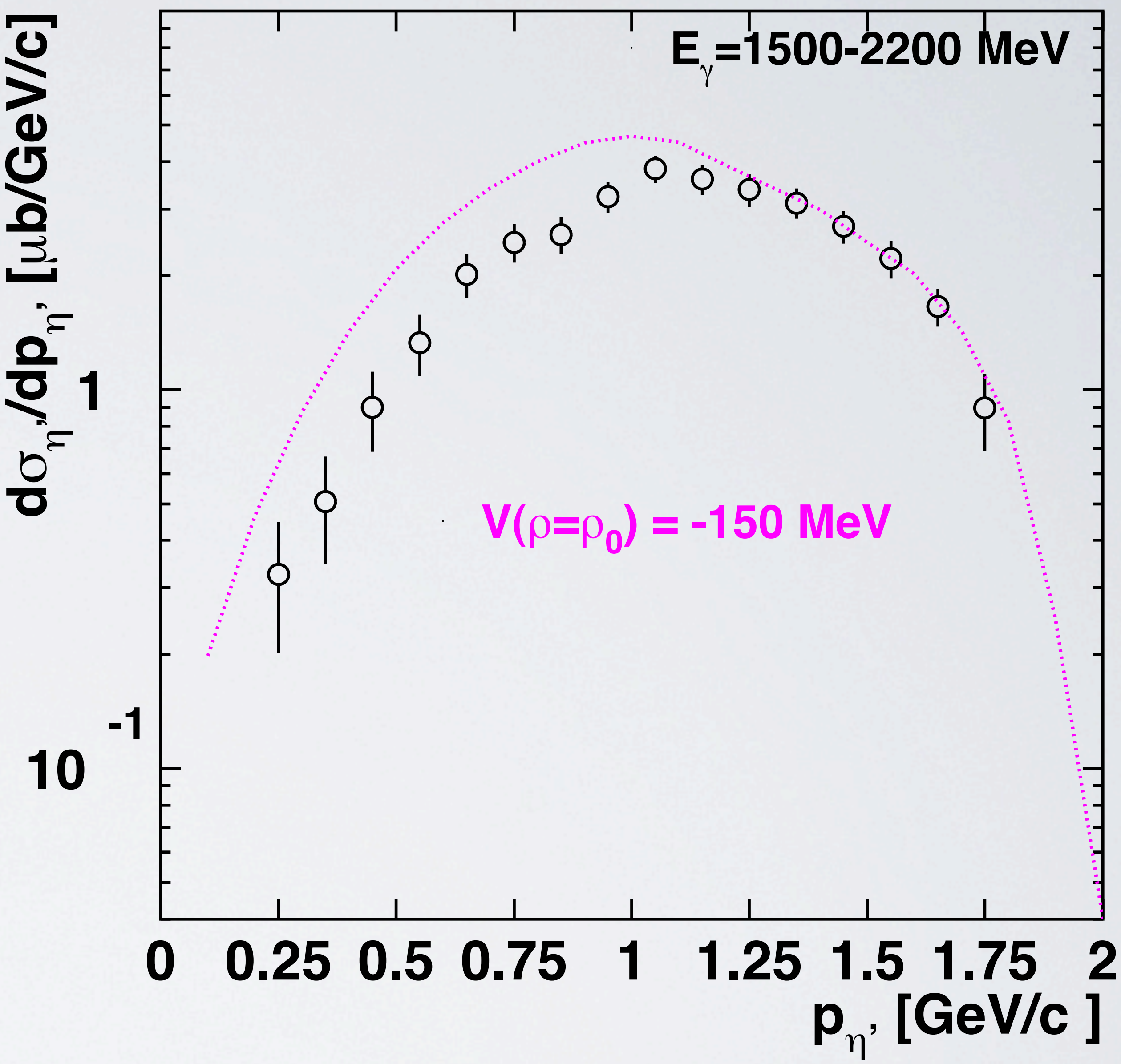

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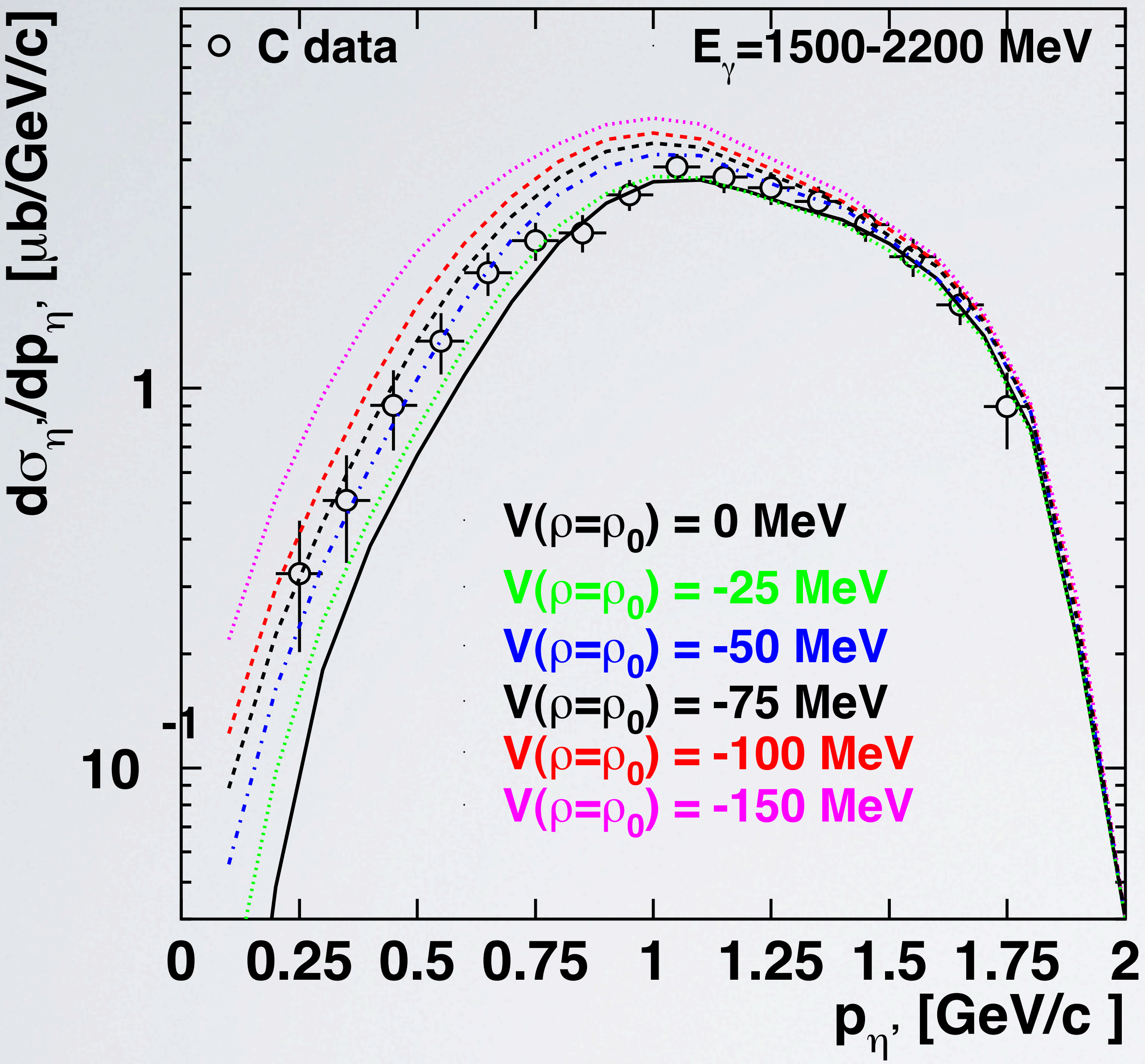

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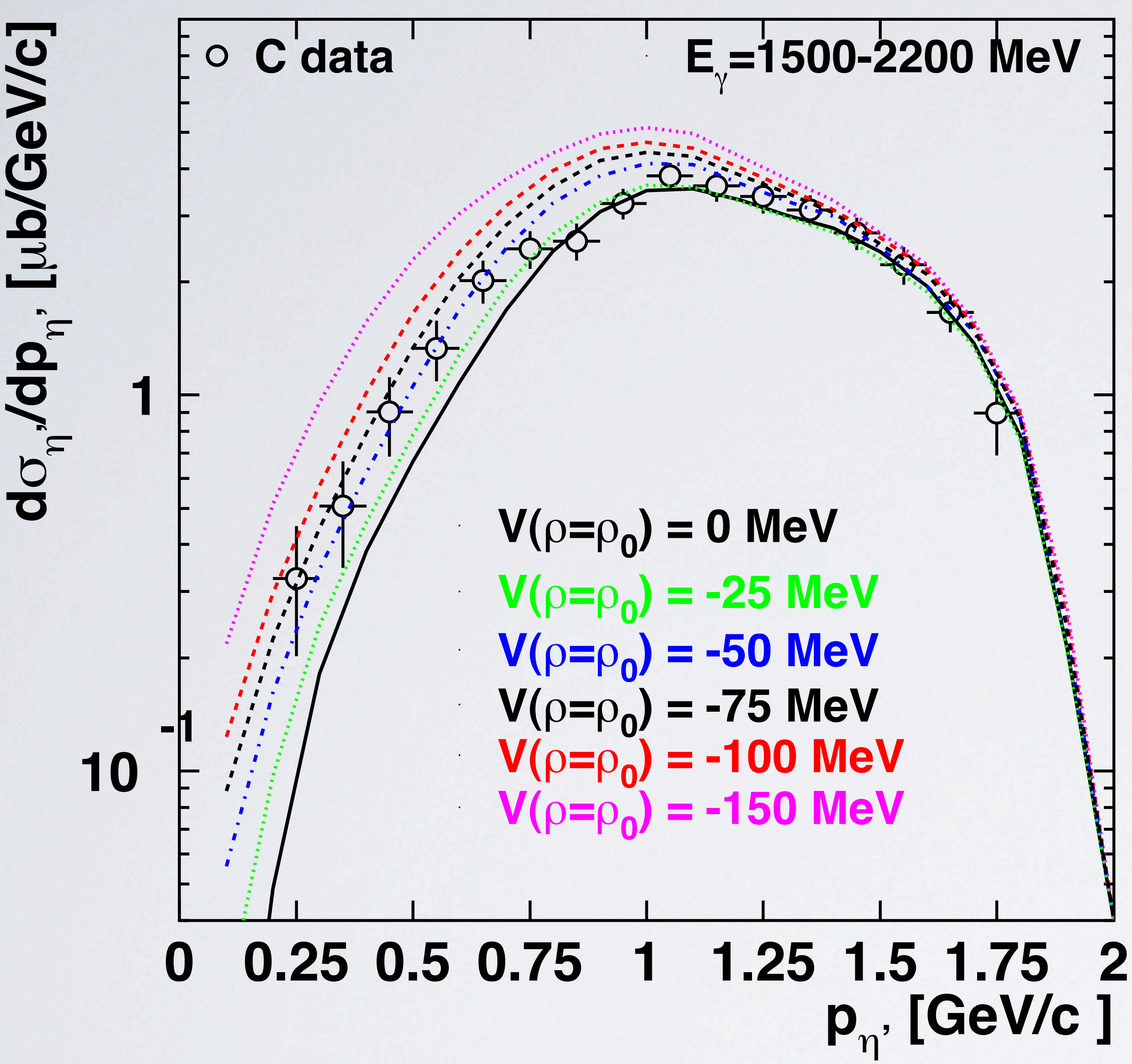
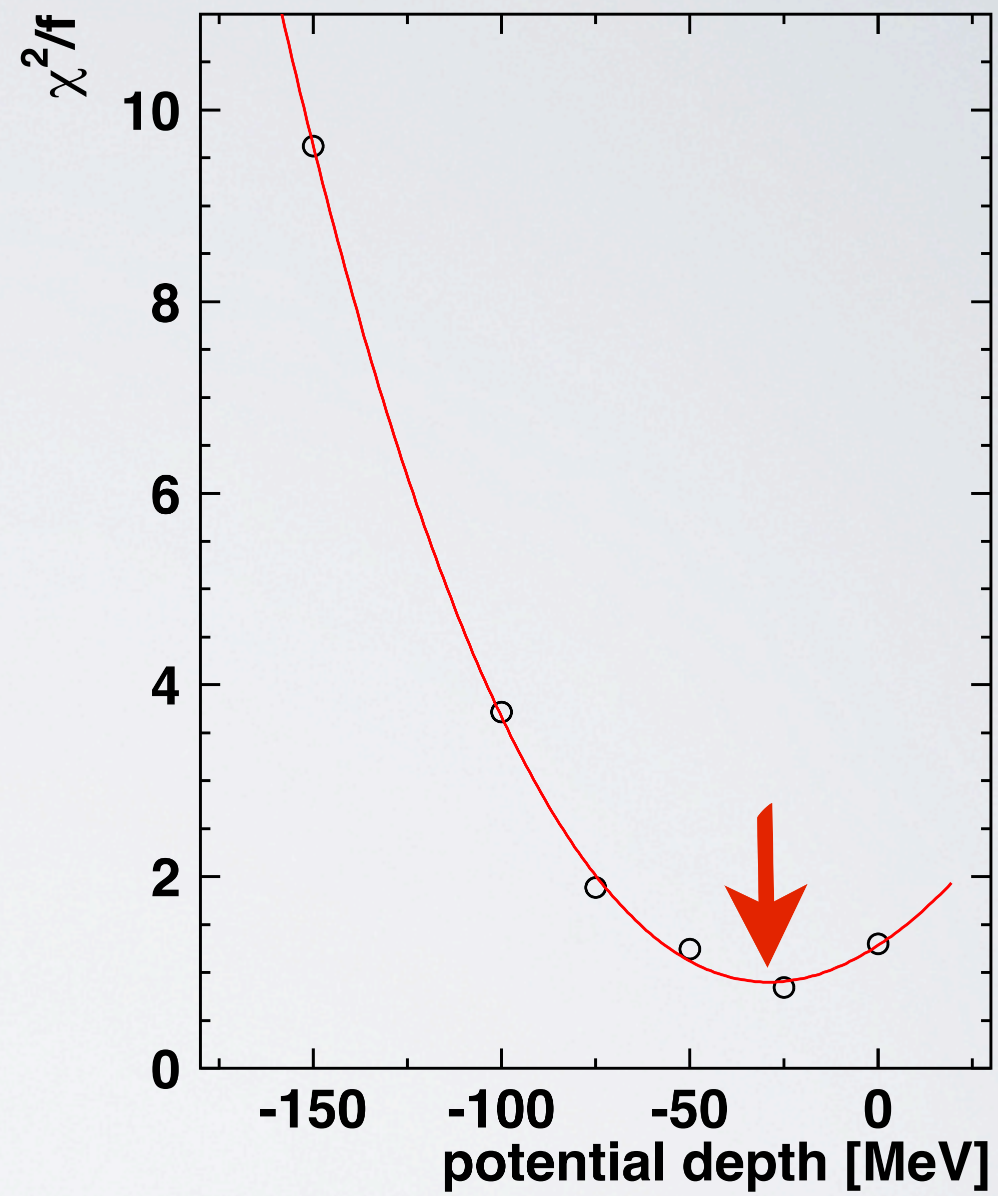
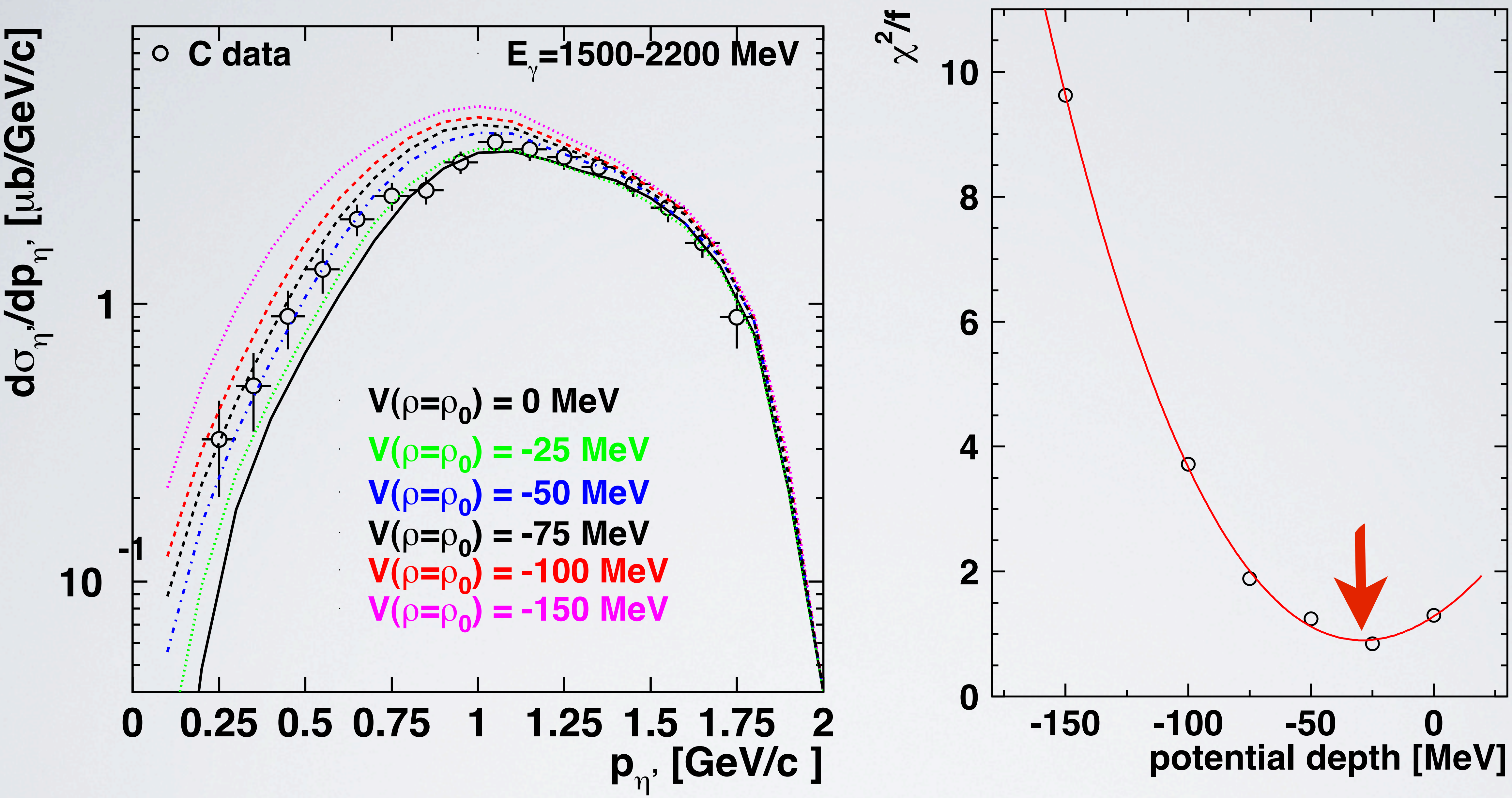


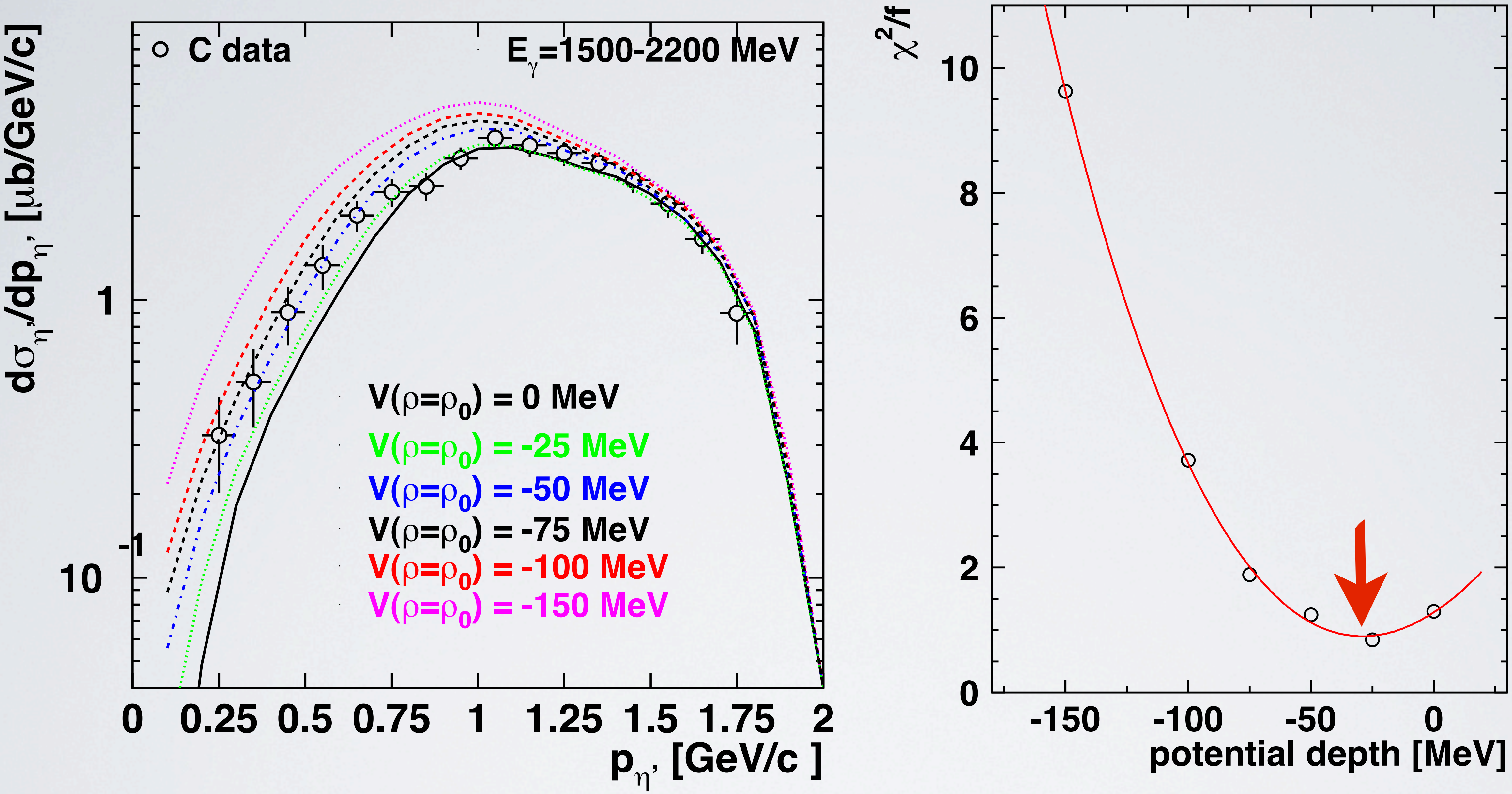


estimation of the of η'-nucleus potential depth from the η' momentum distribution



$V(\rho=\rho_0) = -32 \pm 11$ MeV

estimation of the of η'-nucleus potential depth from the η' momentum distribution



V(ρ=ρ₀) = -32±11 MeV

consistent with predictions by:

S. Bass and A.W.Thomas, Acta Phys. Pol. B 41 (2010) 2239

H. Nagahiro et al., PLB 709 (2012) 87.

Summary

1. Imaginary part of the η'- nucleus optical potential determined from transparency ratio measurements: $W(\rho=\rho_0)=-\Gamma_0/2$ = -10±2.5 MeV

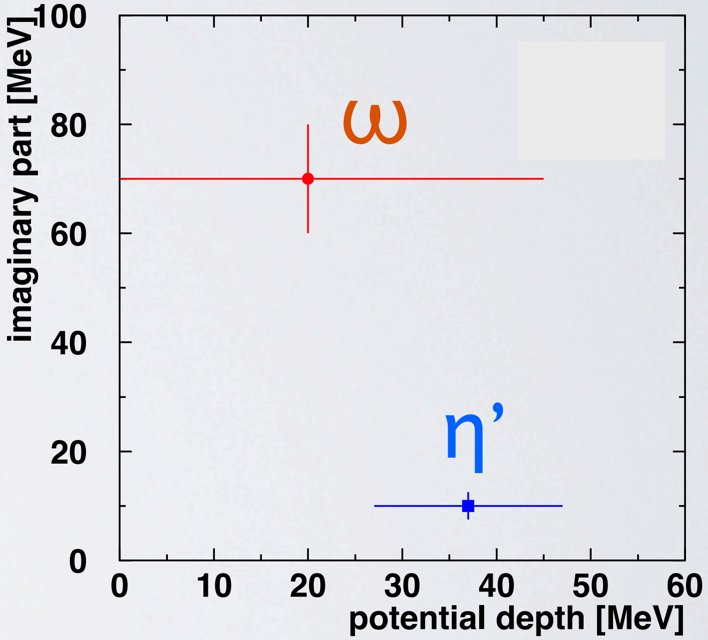
2. Real part of the η'- nucleus optical potential determined from:

a. measurement of the excitation function of the η'-meson

$V(\rho=\rho_0)$ = -40±6 MeV

b. measurement of the momentum distribution of the η'-meson:

$V(\rho=\rho_0)$ = -32±11 MeV



$U_{\eta' A}(\rho=\rho_0)$ = -(37±10(stat) ±10(syst) + i(10±2.5)) MeV

M. Nanova et al., arXiv:1311.0122; to be published in PLB

First (indirect) observation of a mass drop of a peusdoscalar meson in nuclear matter at normal conditions ($\rho=\rho_0$;T=0)

3. V >> W ! ⇨ η' promising candidate for mesic states

experiments searching for η' mesic states at FRS@GSI and BGO-OD@ELSA

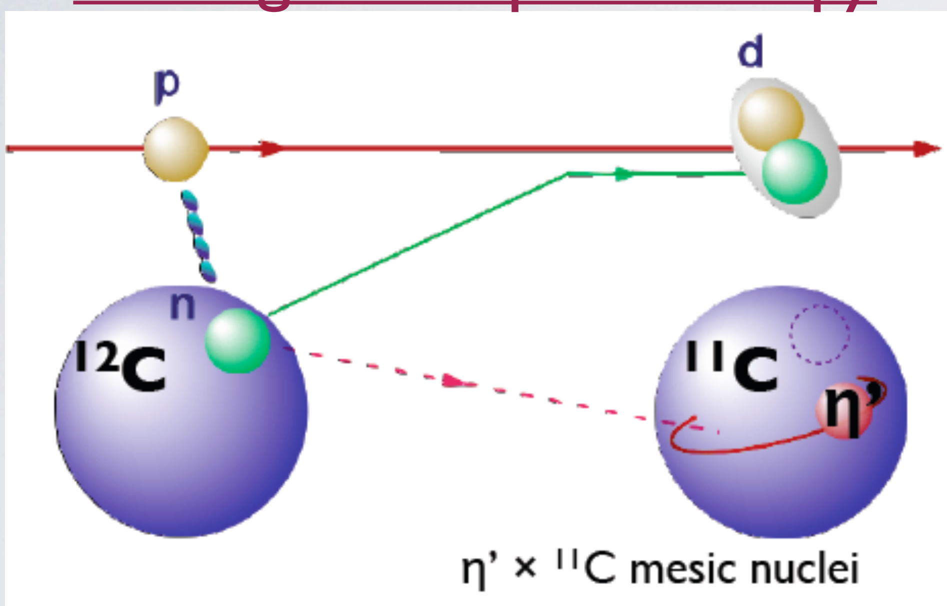
search for η' mesic states at FRS@GSI and BGO-OD@ELSA

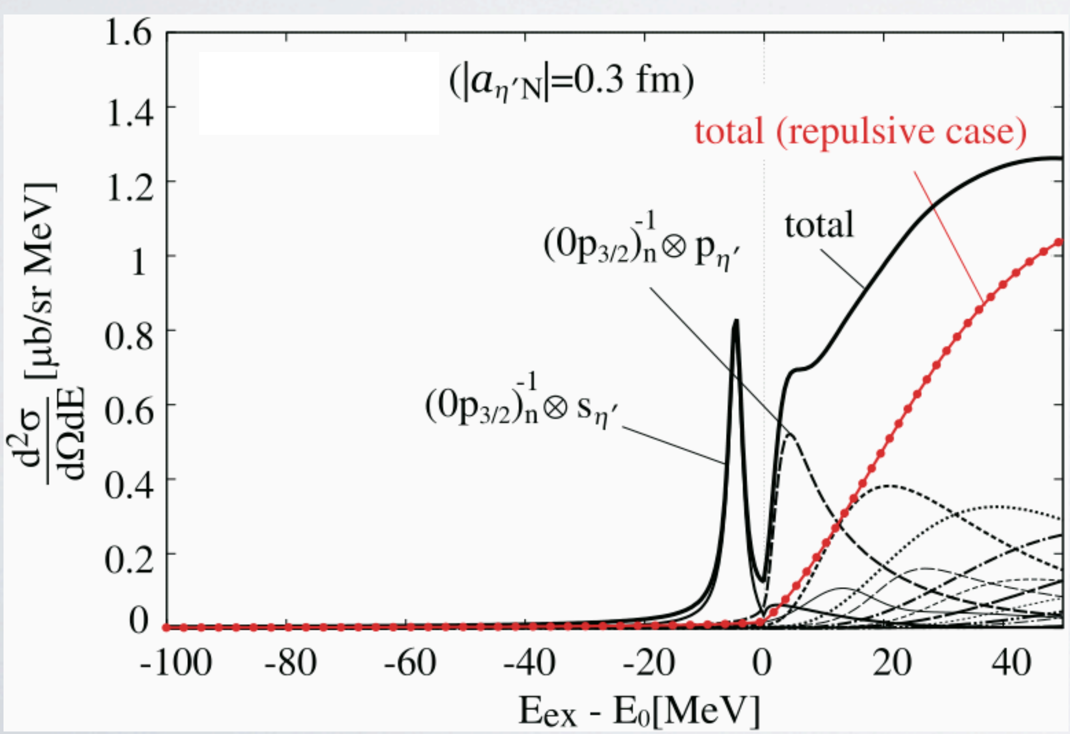
GSI $^{12}C(p,d)\,\eta' X$ @ 2.5 GeV

K. Itahashi et al.:FRS@GSI

K. Itahashi et al.,
Prog. Theo. Phys. 128 (2012) 601

missing mass spectroscopy

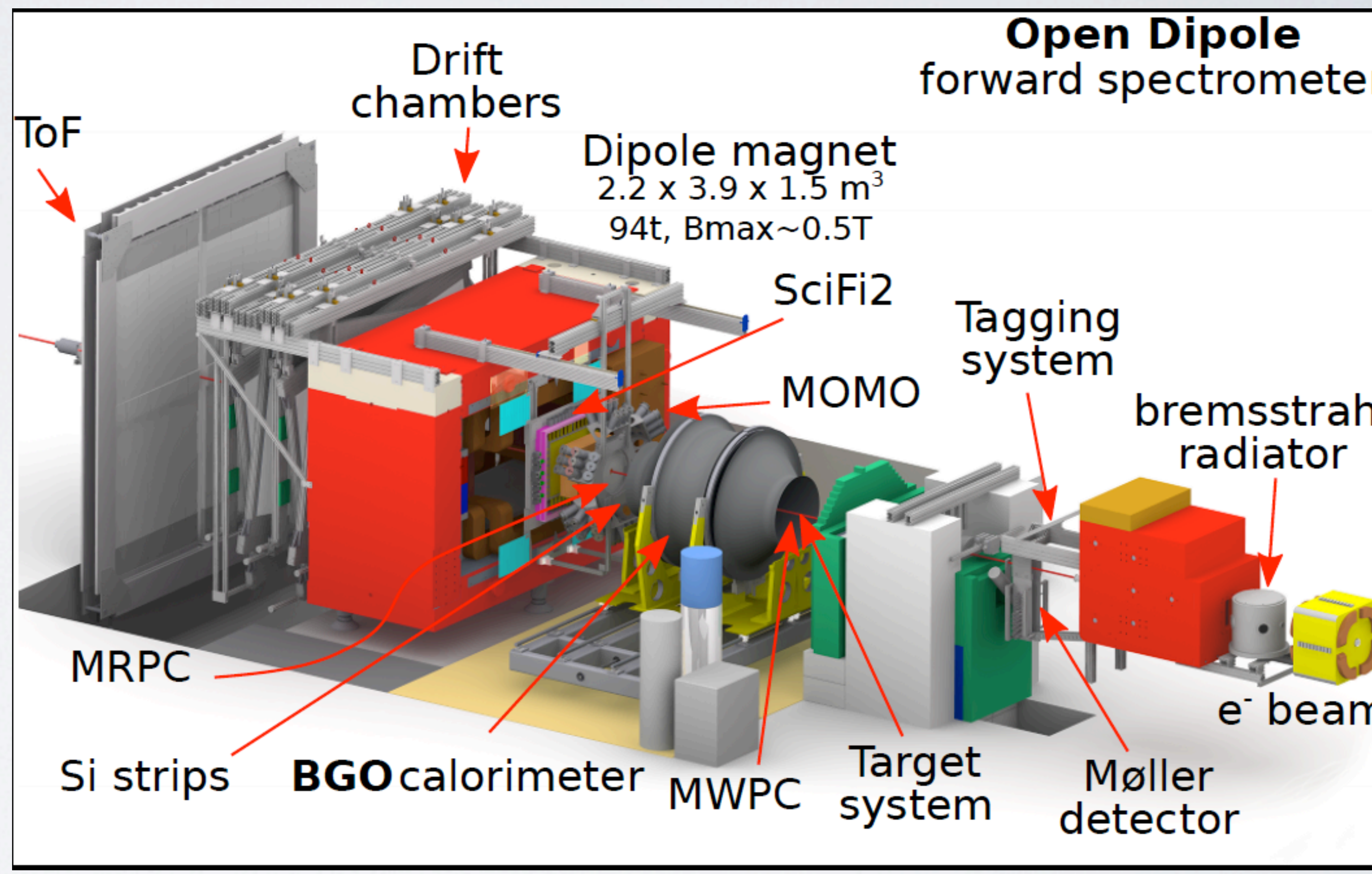




$\gamma + {}^{12}C \rightarrow \eta' \otimes {}^{11}B + p$ @2.2-2.8 GeV **ELSA**

semi-exclusive measurement:

coincident detection of forward going proton and decays of η' mesic states: $\eta' N \rightarrow \eta N$

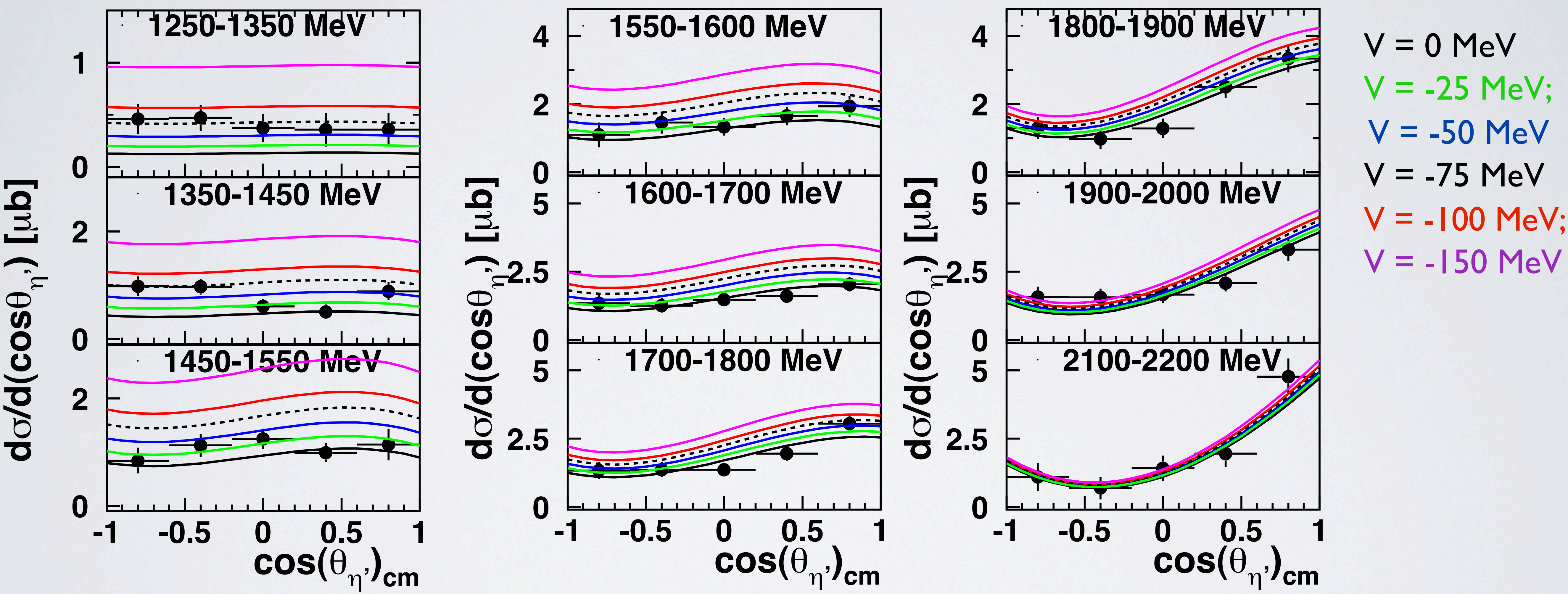


differential cross sections for η' photoproduction off ^{12}C

E_γ = 1250 - 2600 MeV $\eta' \to \pi^0\pi^0\eta \to 6\gamma$ BR: 8.1%

sensitivity to different scenarios   E. Ya. Paryev, priv. communication

below threshold   at threshold   above threshold



high sensitivity to different scenarios at threshold

strong mass shift not supported by data