Experimental tests of QCD as the theory of the strong interaction at the low energy frontier

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for the CBELSA/TAPS Collaboration

Outline:

- theo. predictions on hadron properties and their changes in a nuclear medium
- exp. approaches for studying the meson-nucleus interaction
- evidence for mass drop and broadening of the η' meson in nuclei
- search for η'-nucleus bound states
- summary & outlook

*funded by the DFG within SFB/TR16

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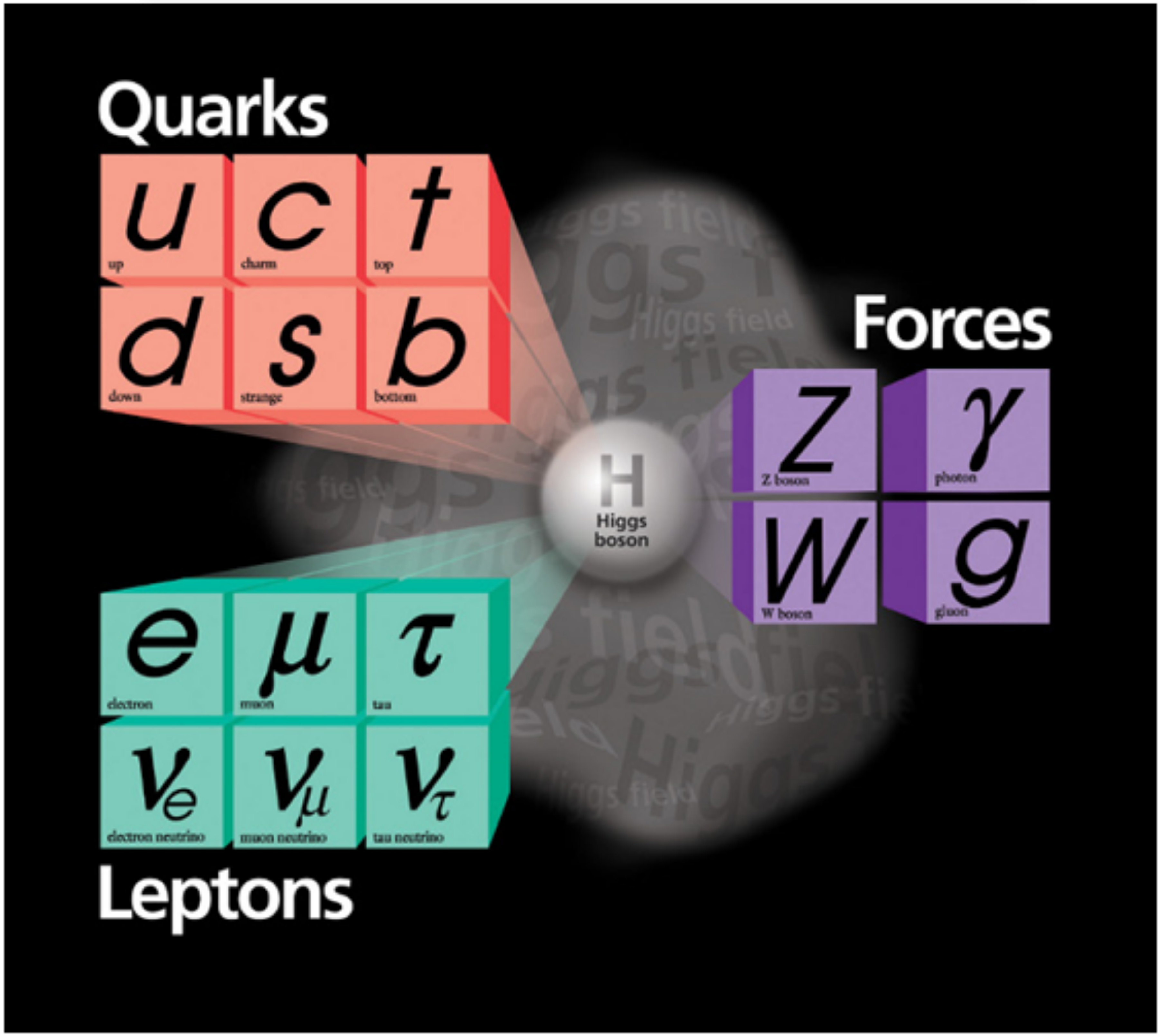
Humboldt Kolleg on Particle Physics
From the Vacuum to the Universe
26.6.-1.7.2016; Kitzbühel, Austria

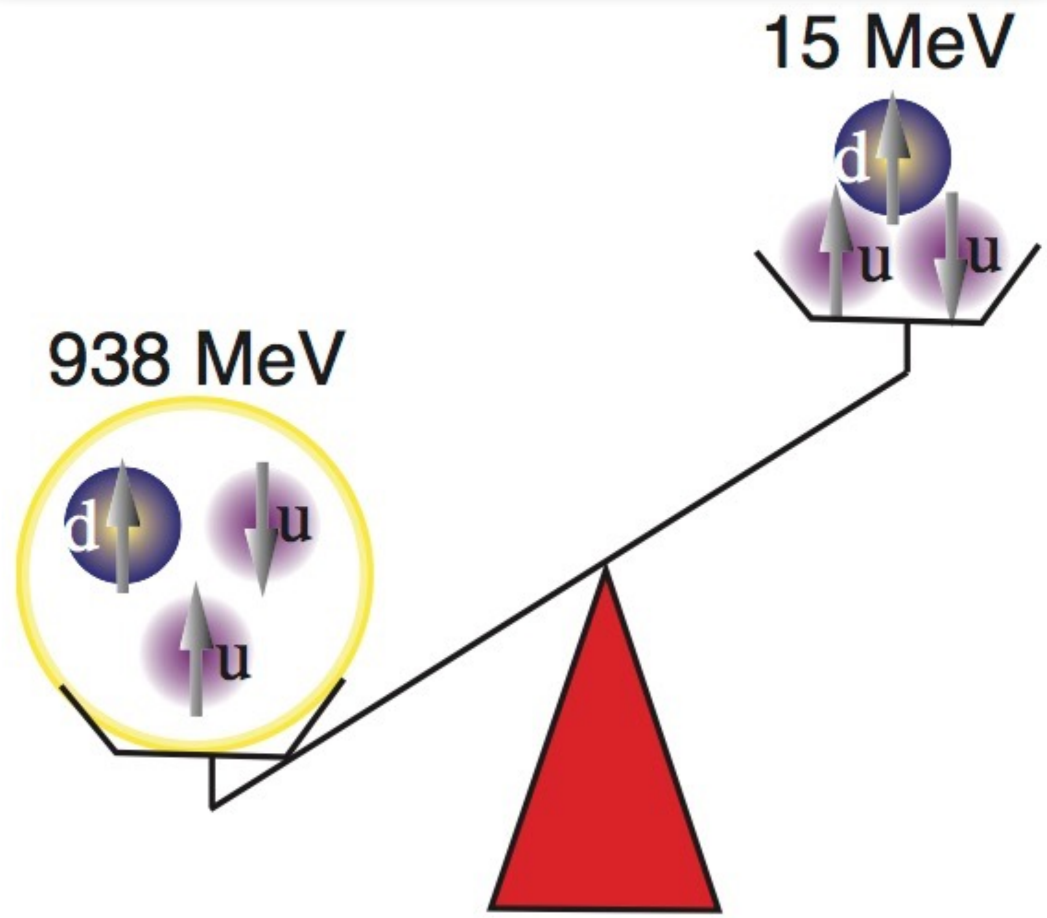
HIC for FAIR
Helmholtz International Center

The mass of elementary particles



mass of elementary particles generated by their interaction with the Higgs field

The mass of the nucleon



$m_N = 938\ \mathrm{MeV}/c^2 >> m_q \approx 5\text{-}10\ \mathrm{MeV}/c^2$

- how is it possible that massive protons and neutrons can be built from almost massless quarks ??

- $m = E/c^2$; mass without mass (Wheeler, Wilczek): mass given by energy stored in the motion of quarks (confined in the nucleon) and by energy stored in color gluon fields

how strong is the strong interaction ??

momentum dependence of the strong interaction coupling strength

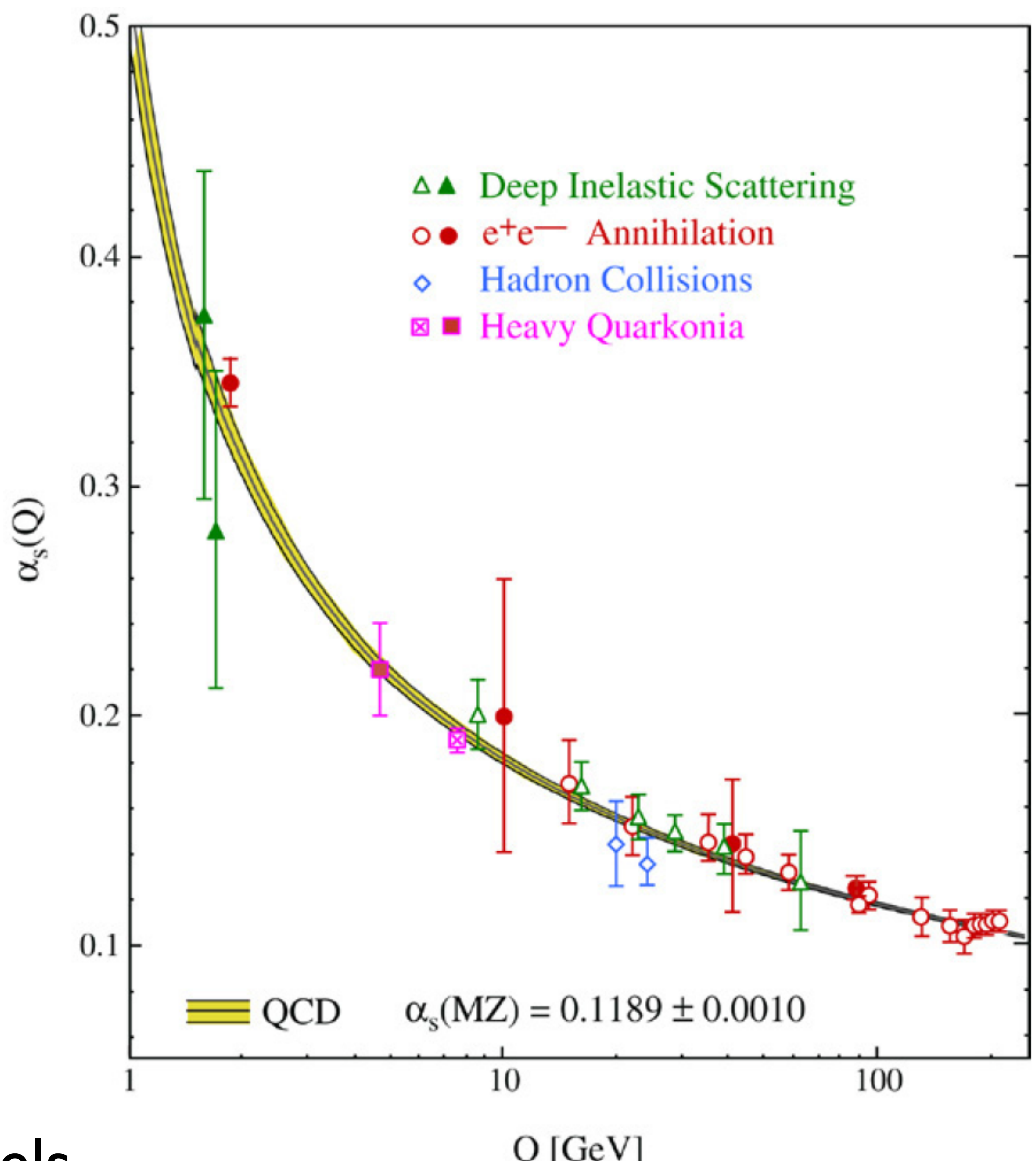
S. Bethge, Prog. Part. Nucl. Phys. 58 (2007) 351

for low momenta
$\alpha_s \lesssim 1$
⇒ **strong QCD**
confinement
infrared slavery

relevant degrees of freedom:

mesons, baryons

lattice QCD
QCD-inspired models



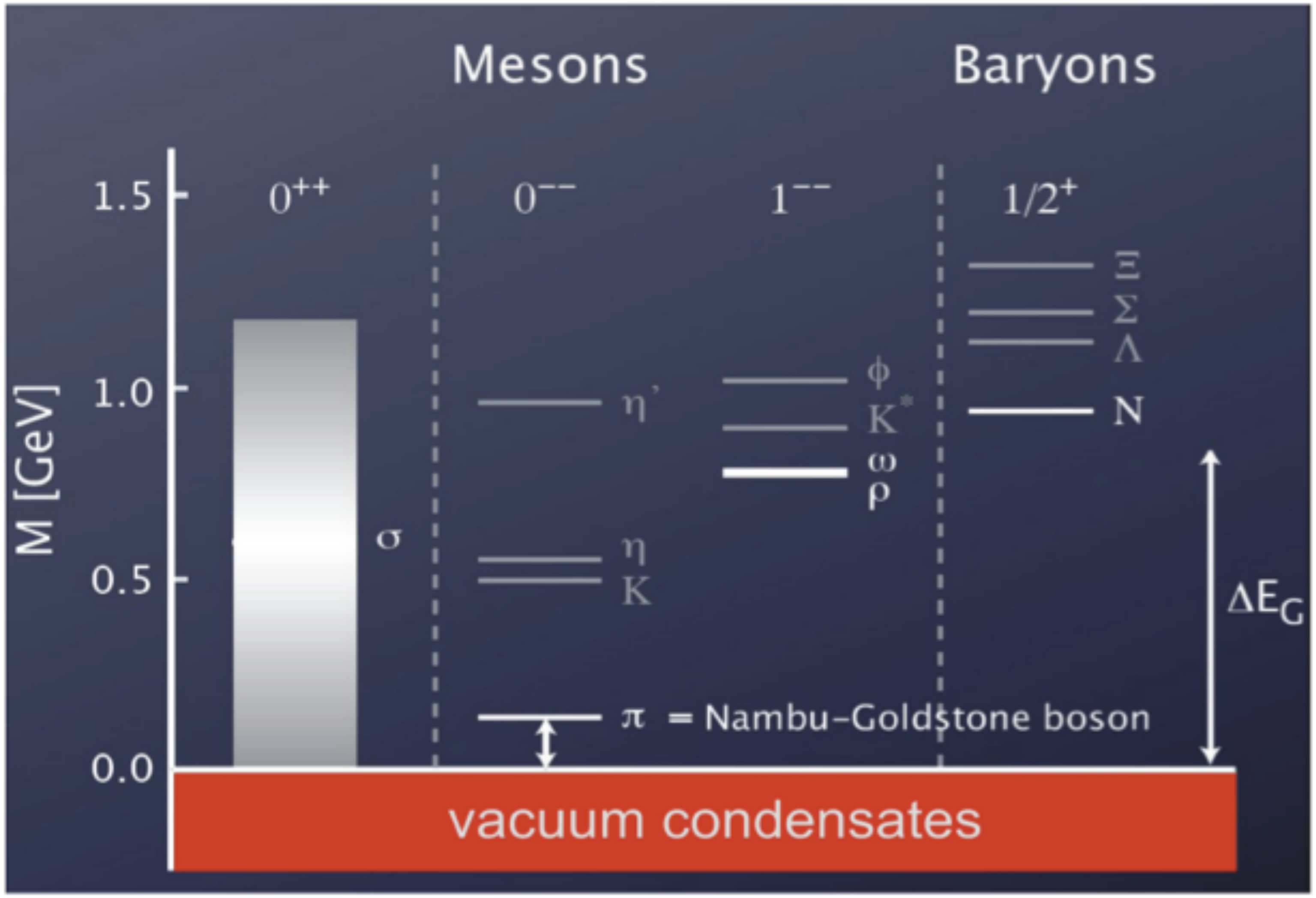
for high momenta
$\alpha_s \ll 1$:
⇒ **perturbative QCD**
asymptotic freedom;
(LO,NLO, NNLO)

relevant degrees of freedom:

quarks, gluons

How does one test QCD in the non-perturbative sector ??

our approach: study the mass spectrum of hadrons and their modification in a strongly interacting medium



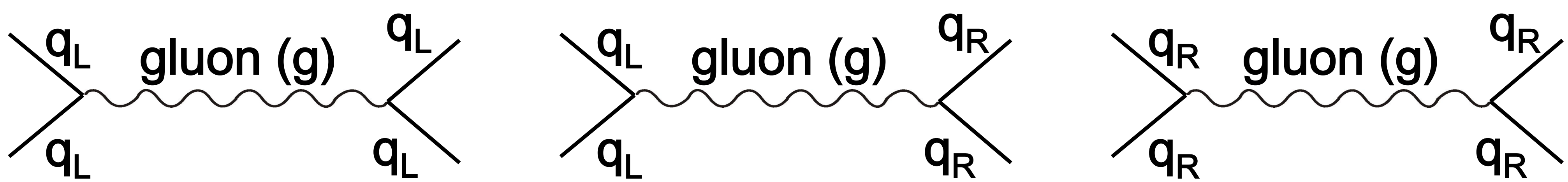
mesons ($q\bar{q}$) = excitations of the QCD vacuum

QCD vacuum has complex structure governed by condensates: chiral condensate, gluon condensate, higher order quark condensates

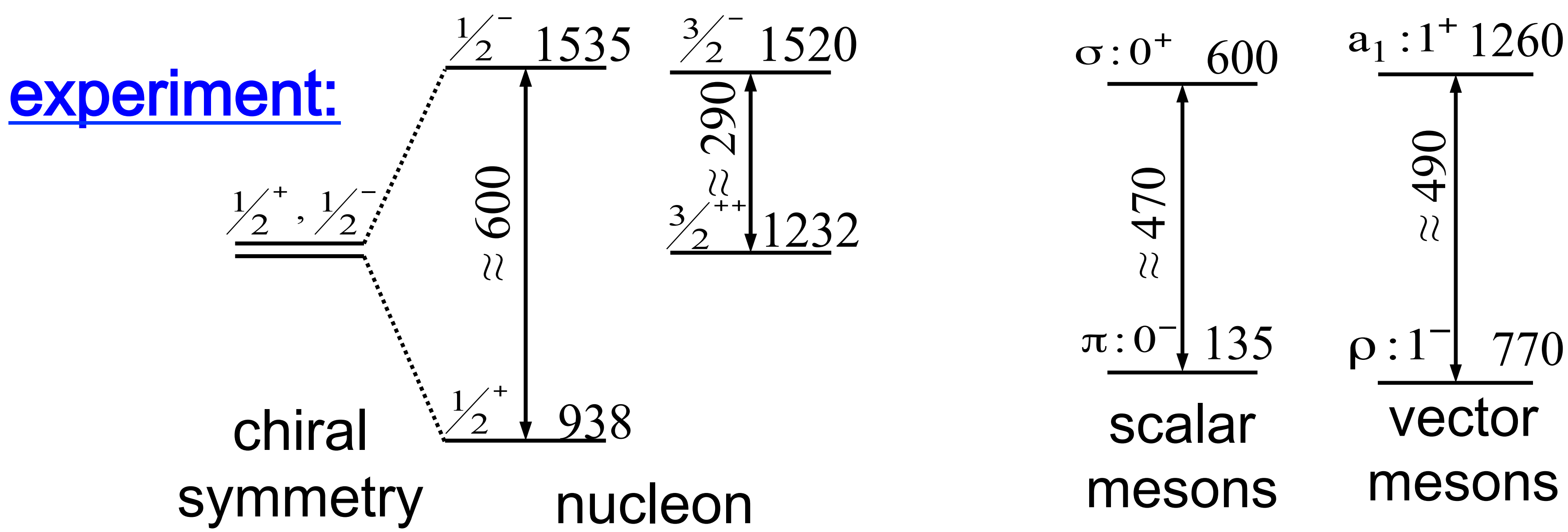
does this excitation energy spectrum reflect the symmetries of QCD ?

chiral symmetry and chiral symmetry breaking

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



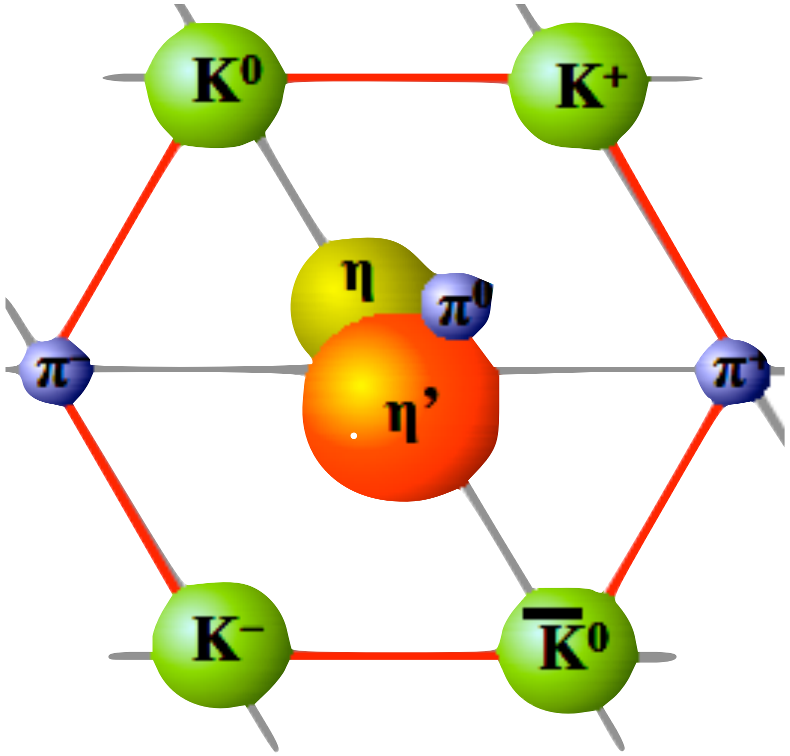
- if chiral symmetry were to hold also in the hadronic sector, chiral partners (same spin; opposite parity) should be degenerate in mass: $m(J^+) = m(J^-)$



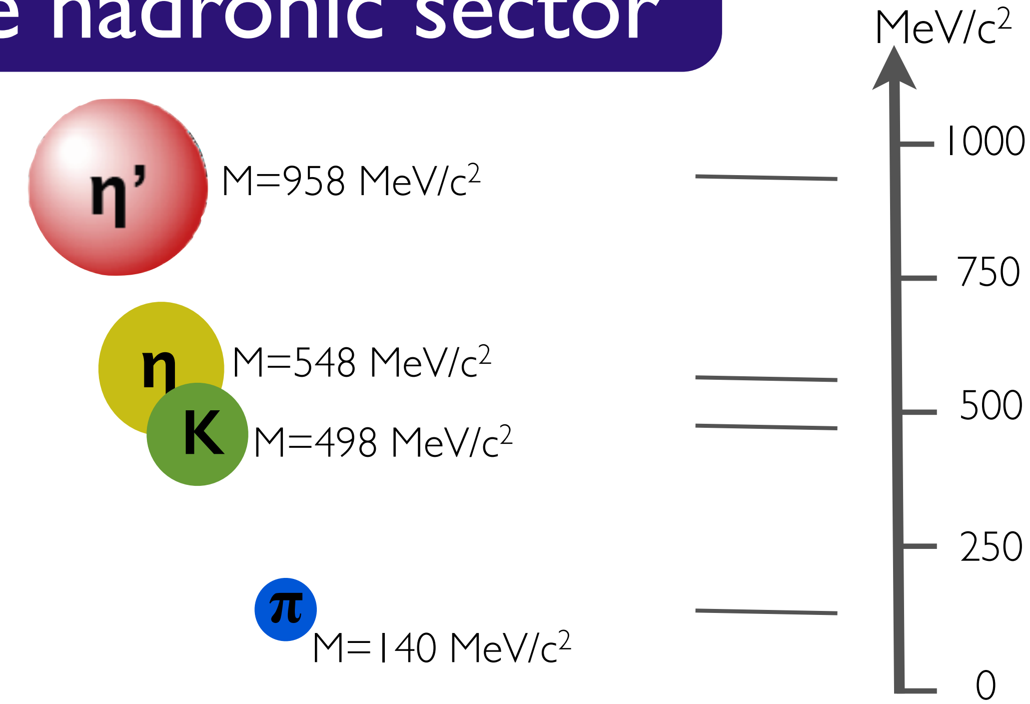
- chiral symmetry broken in the hadronic sector
  mass split $\Delta m \approx$ 300-600 MeV, almost comparable to hadron masses !!

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

symmetry breaking in the hadronic sector



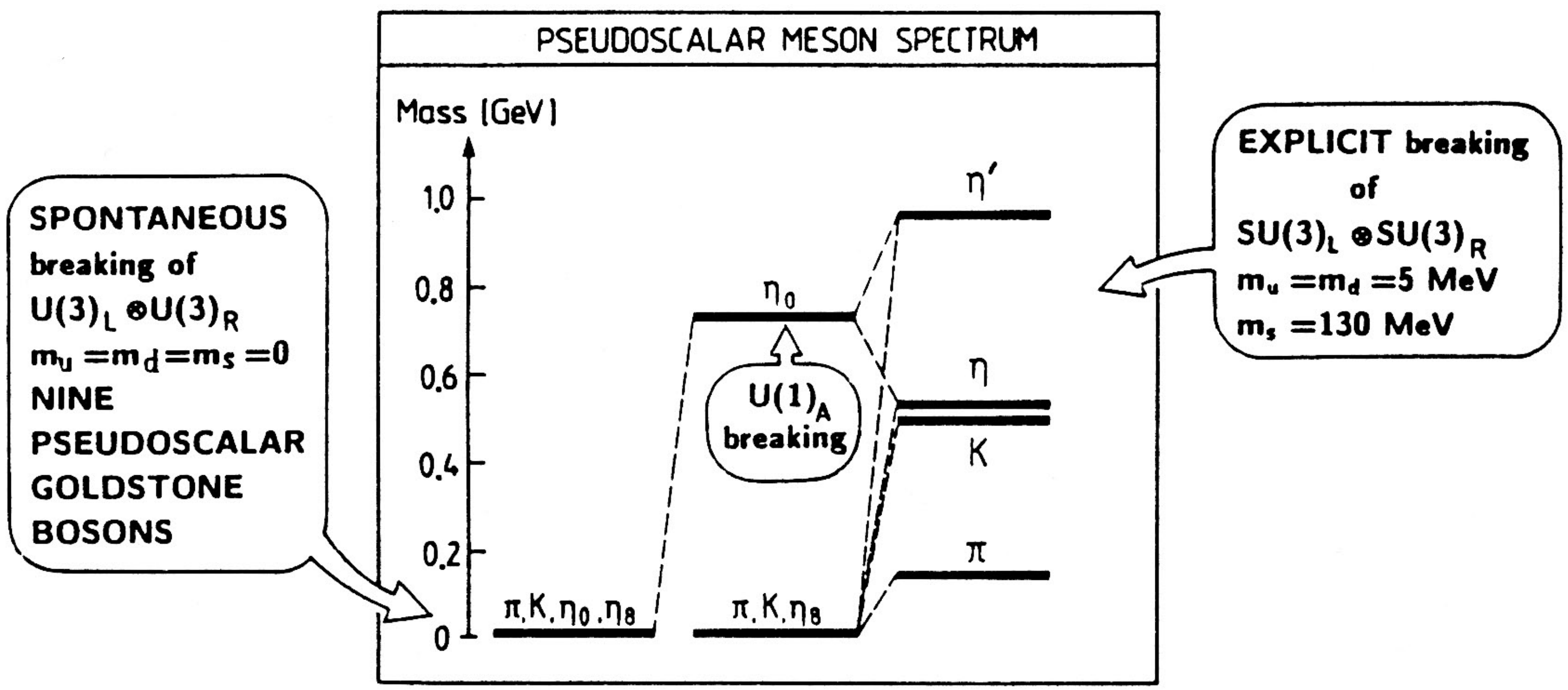
nonet of pseudoscalar mesons



V. Bernard, R.L. Jaffe, U.-G. Meissner, NPB 308 (1988) 753
S. Klimt, M. Lutz, U. Vogel, W Weise, NPA 516 (1990) 429
W. Weise, NBI Copenhagen, 1993

mass as a result of symmetry breaking

partial restoration of chiral symmetry predicted to occur in a nucleus ⟹ impact on meson masses ??



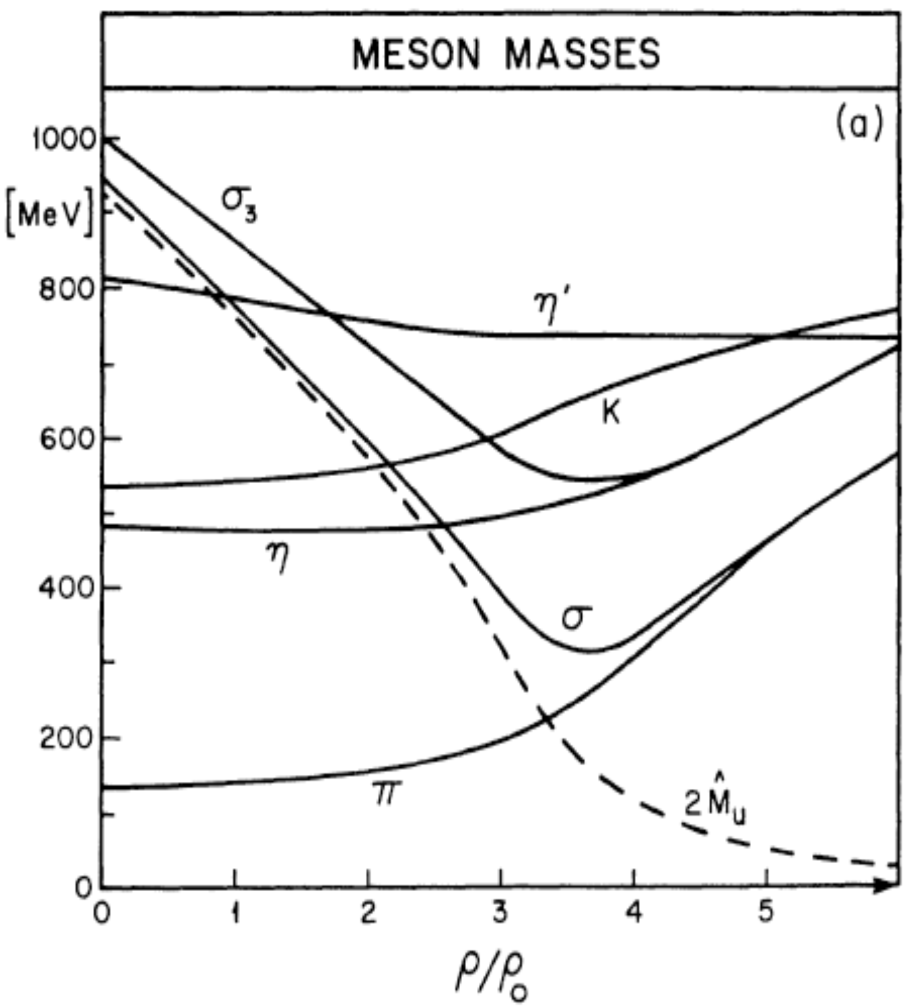
symmetry breaking →

← partial symmetry restoration

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

NJL-model

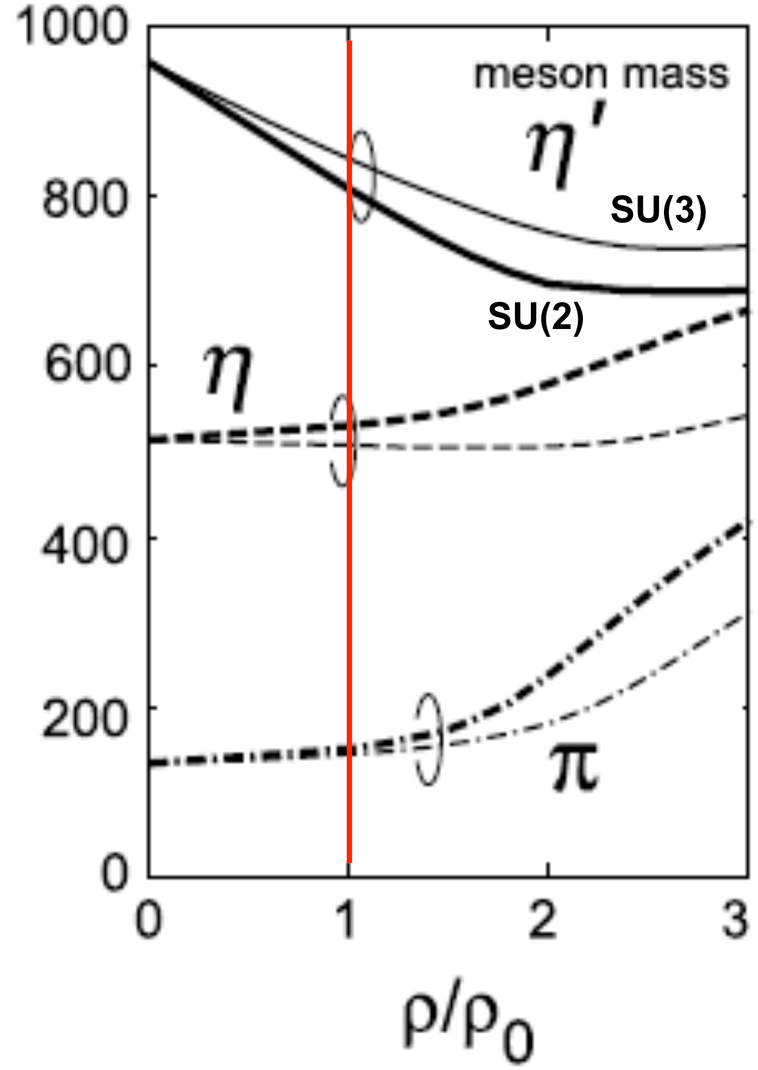
V. Bernard and U.-G. Meissner,
Phys. Rev.D 38 (1988) 1551



almost no dependence of
η' mass on density

NJL-model

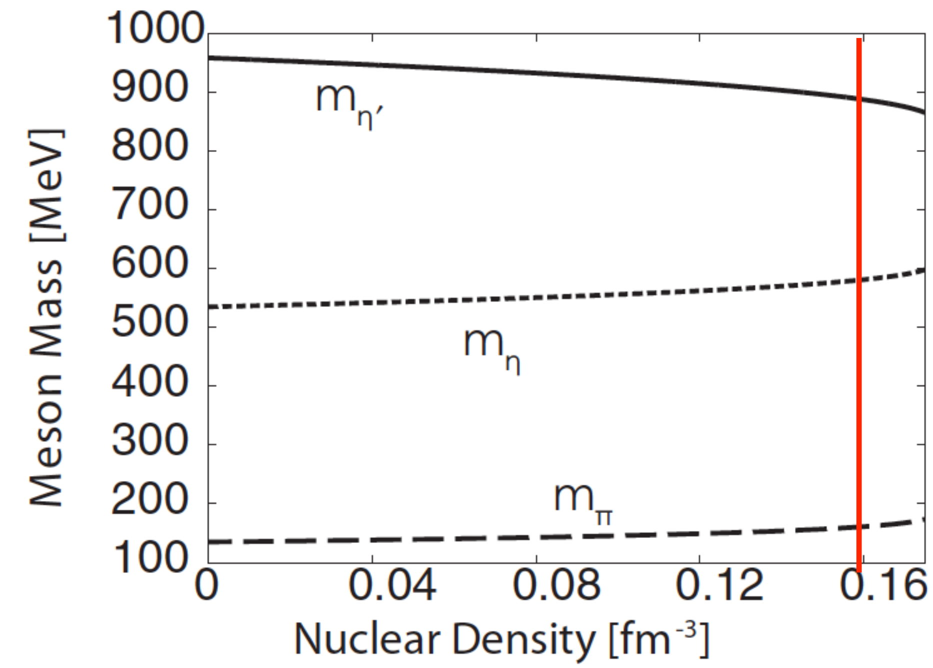
H. Nagahiro, M. Takizawa and S. Hirenzaki,
Phys. Rev. C 74 (2006) 045203



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

linear σ model

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



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

QMC-model

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

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

meson-nucleus optical potential

H. Nagahiro, M. Takizawa, S. Hirenzaki, PRC 74 (2006) 045203

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

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

real part

⇕

in-medium mass modification

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

imaginary part

⇕

lifetime shortened

in-medium width

inelastic cross section

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

experimental approaches to determine the meson-nucleus optical potential

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

real part

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

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

imaginary part

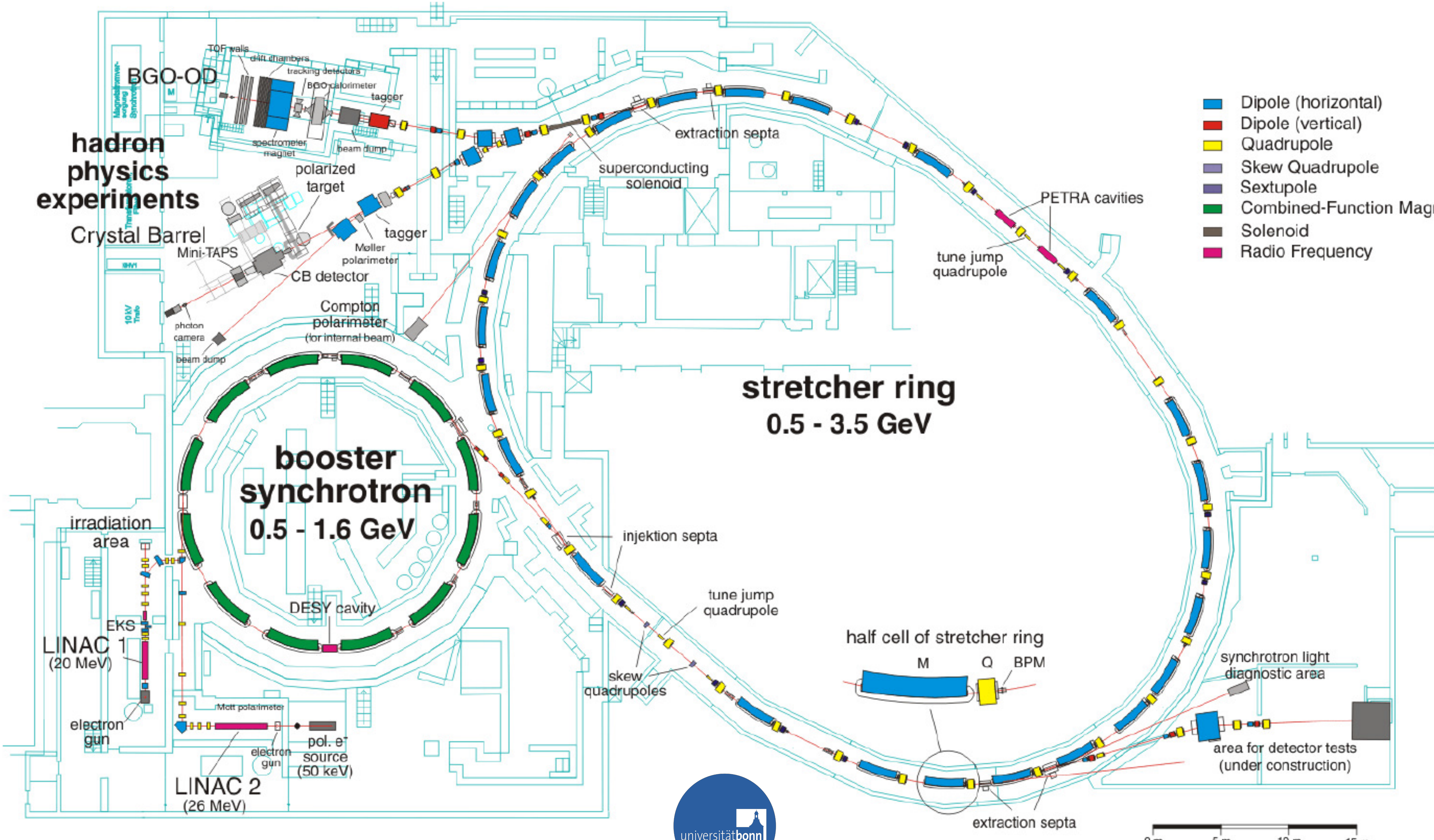
$$W(r) = -\Gamma_0/2 \cdot \frac{\rho(r)}{\rho_0}$$
$$= -\frac{1}{2} \cdot \hbar c \cdot \rho(r) \cdot \sigma_{inel} \cdot \beta$$

- transparency ratio measurement

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

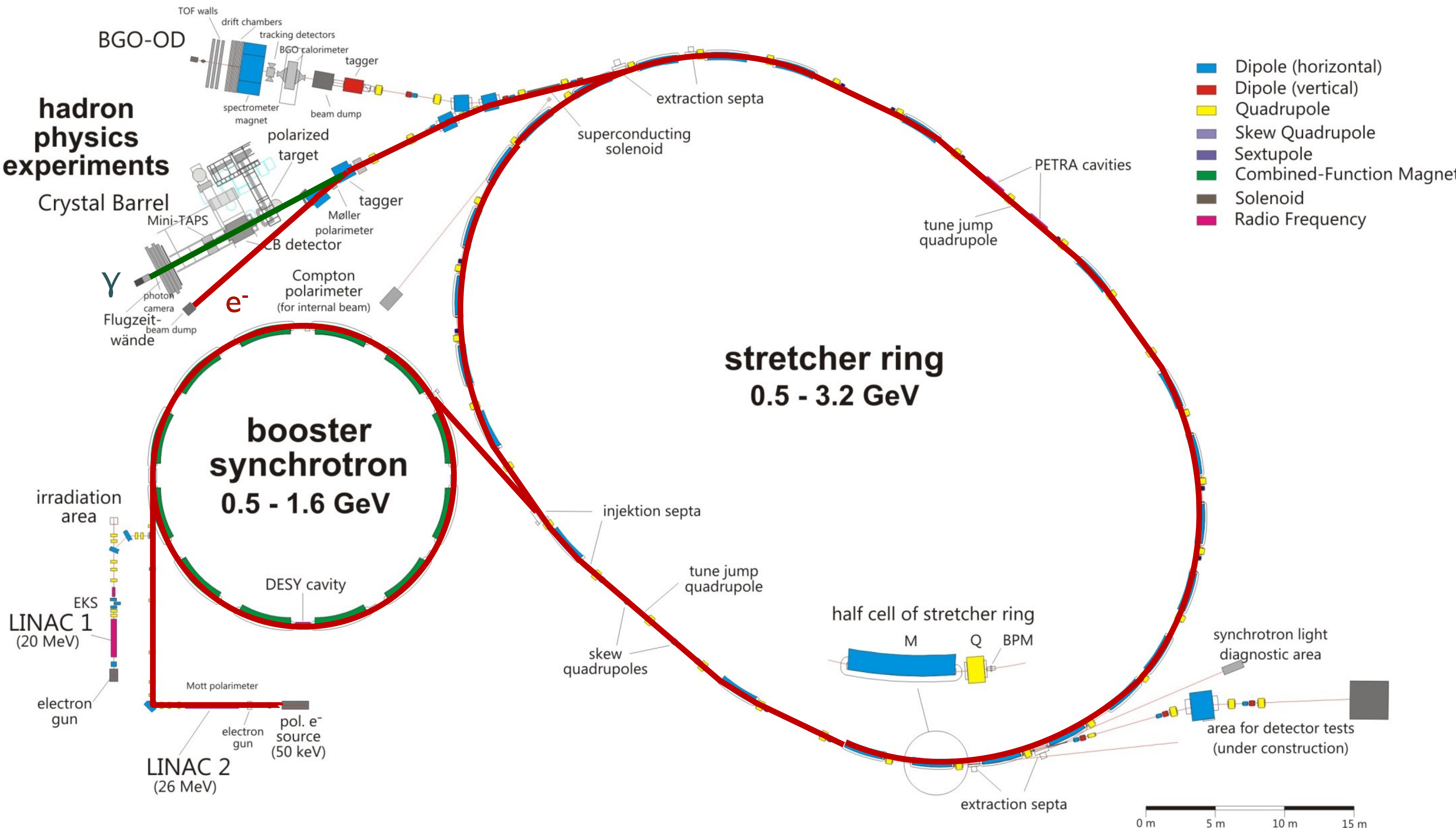
D. Cabrera et al., NPA 733 (2004)130

The Electron Stretcher Accelerator (ELSA), Univ. Bonn



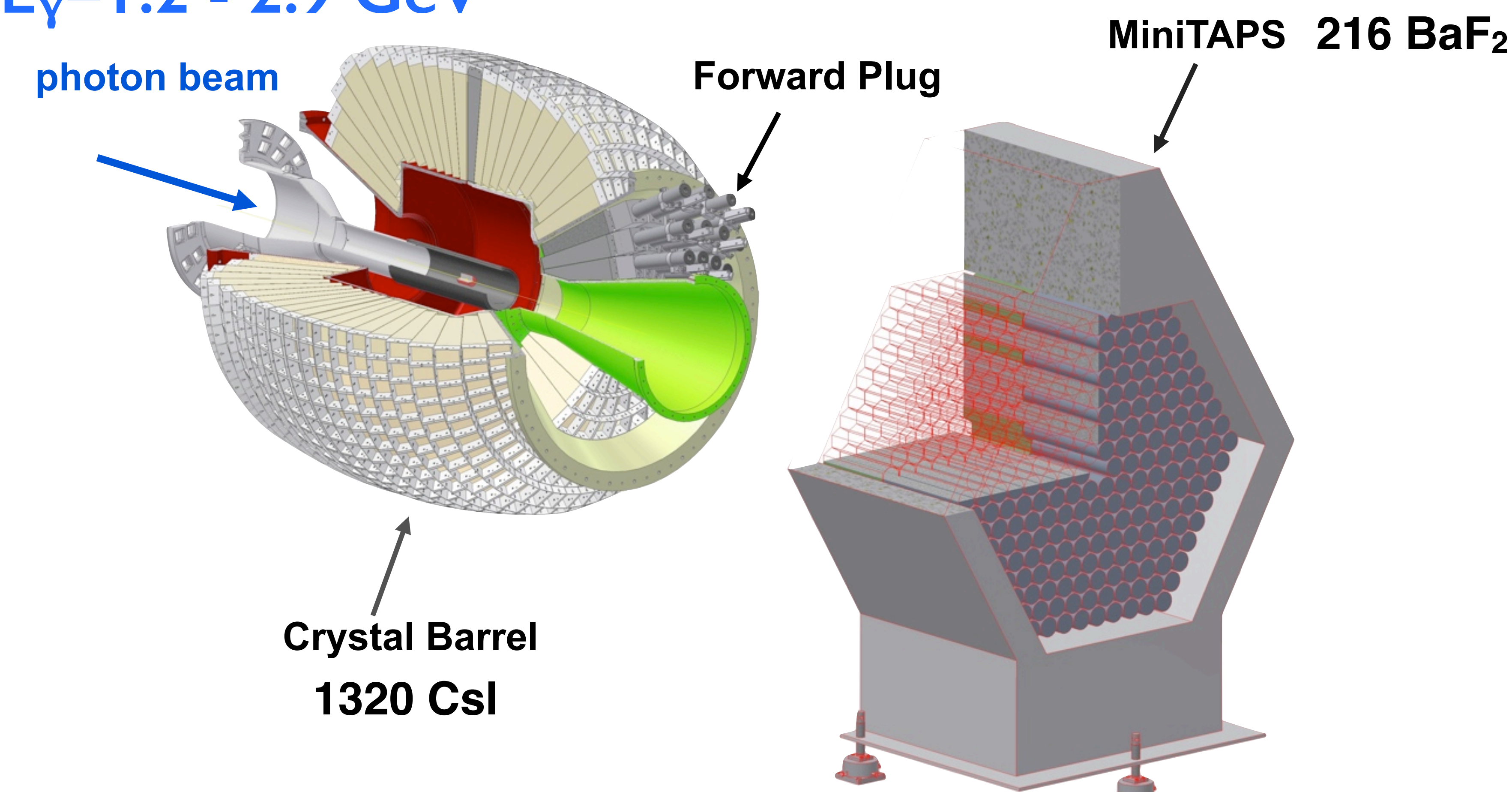
*funded by the DFG within SFB/TR16

The Electron Stretcher Accelerator (ELSA), Univ. Bonn



CBELSA/TAPS Experiment

E_γ=1.2 - 2.9 GeV



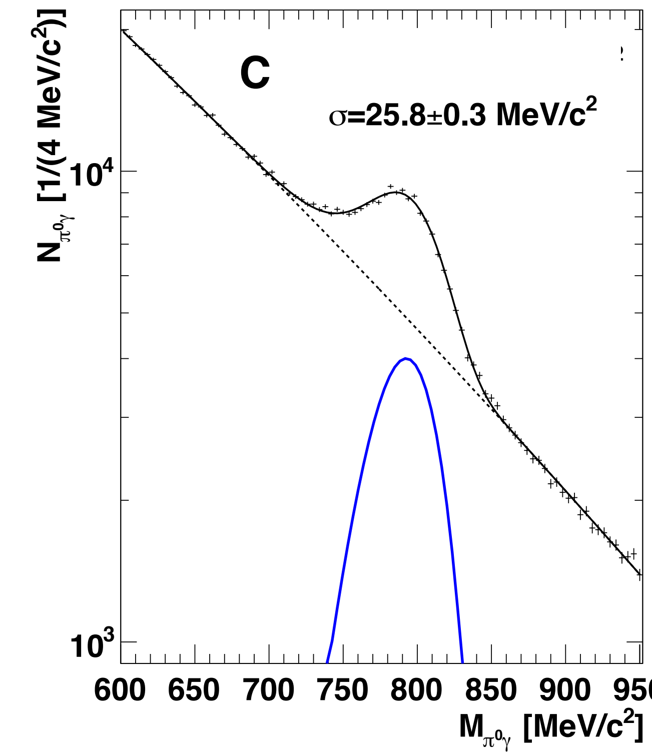
solid target: ^{12}C and ^{93}Nb

4π photon detector: ideally suited for identification of multi-photon final states

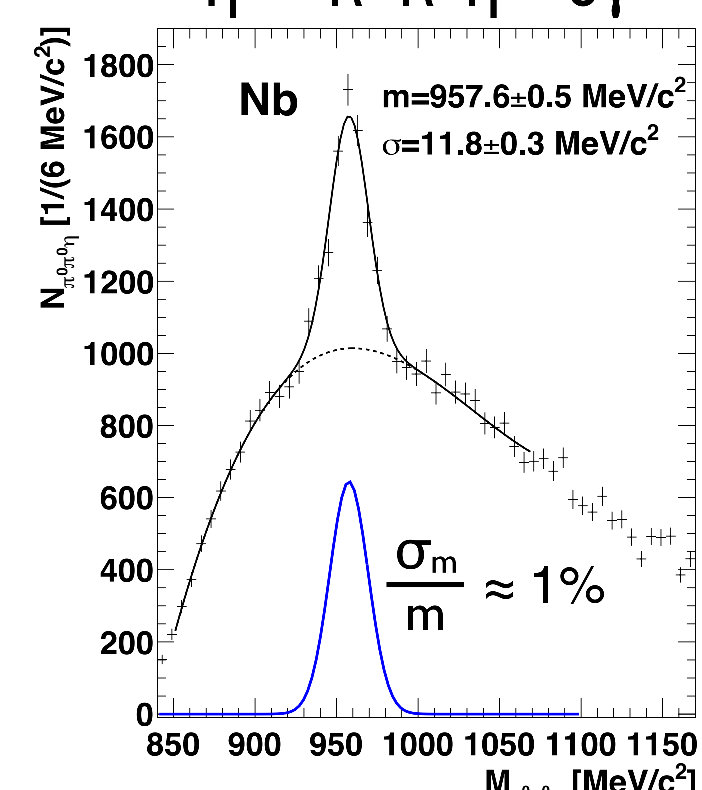
$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$ BR 8.2%

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

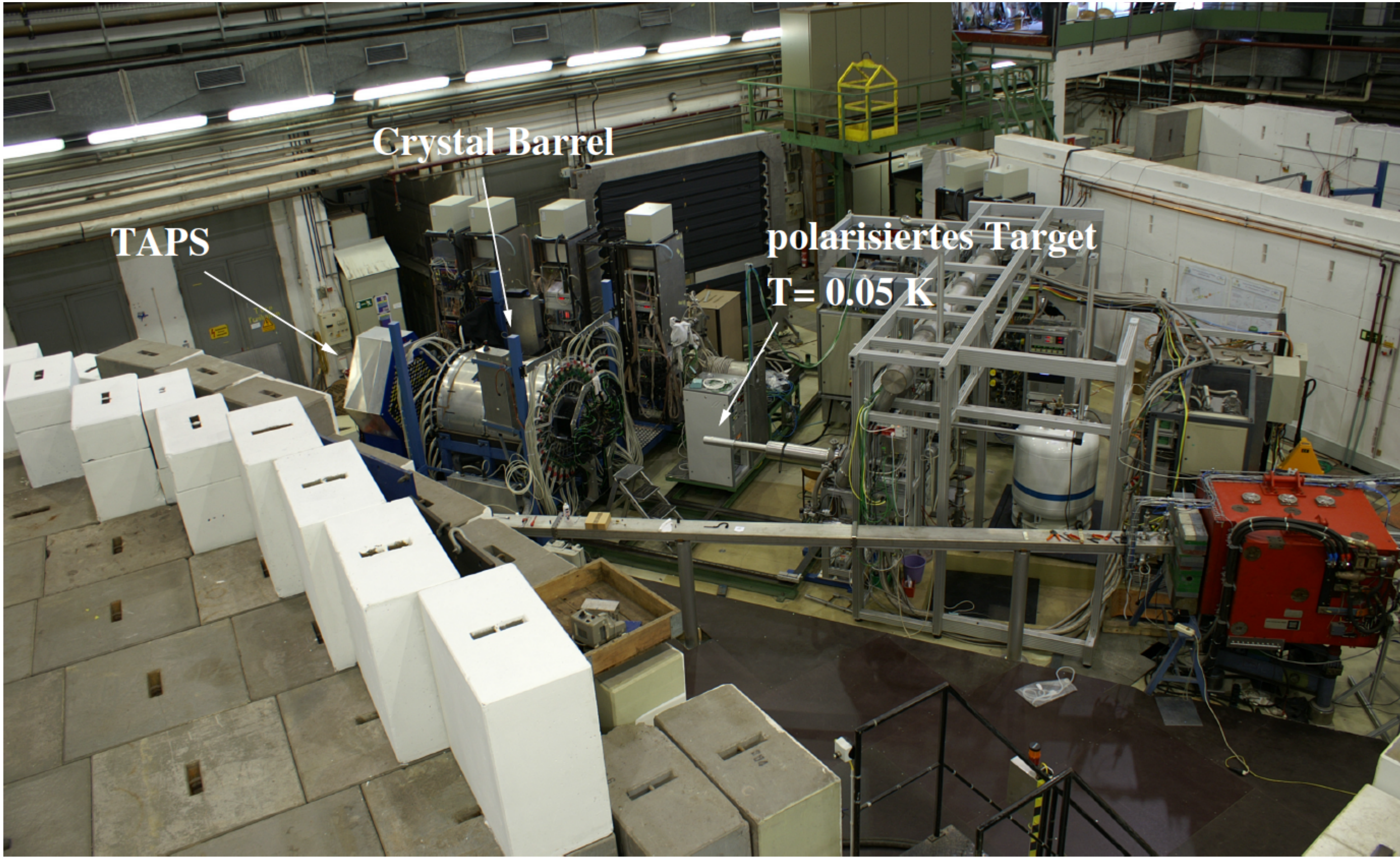
$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$



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



CBELSA/TAPS Experiment



The real part of the meson-nucleus optical potential

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

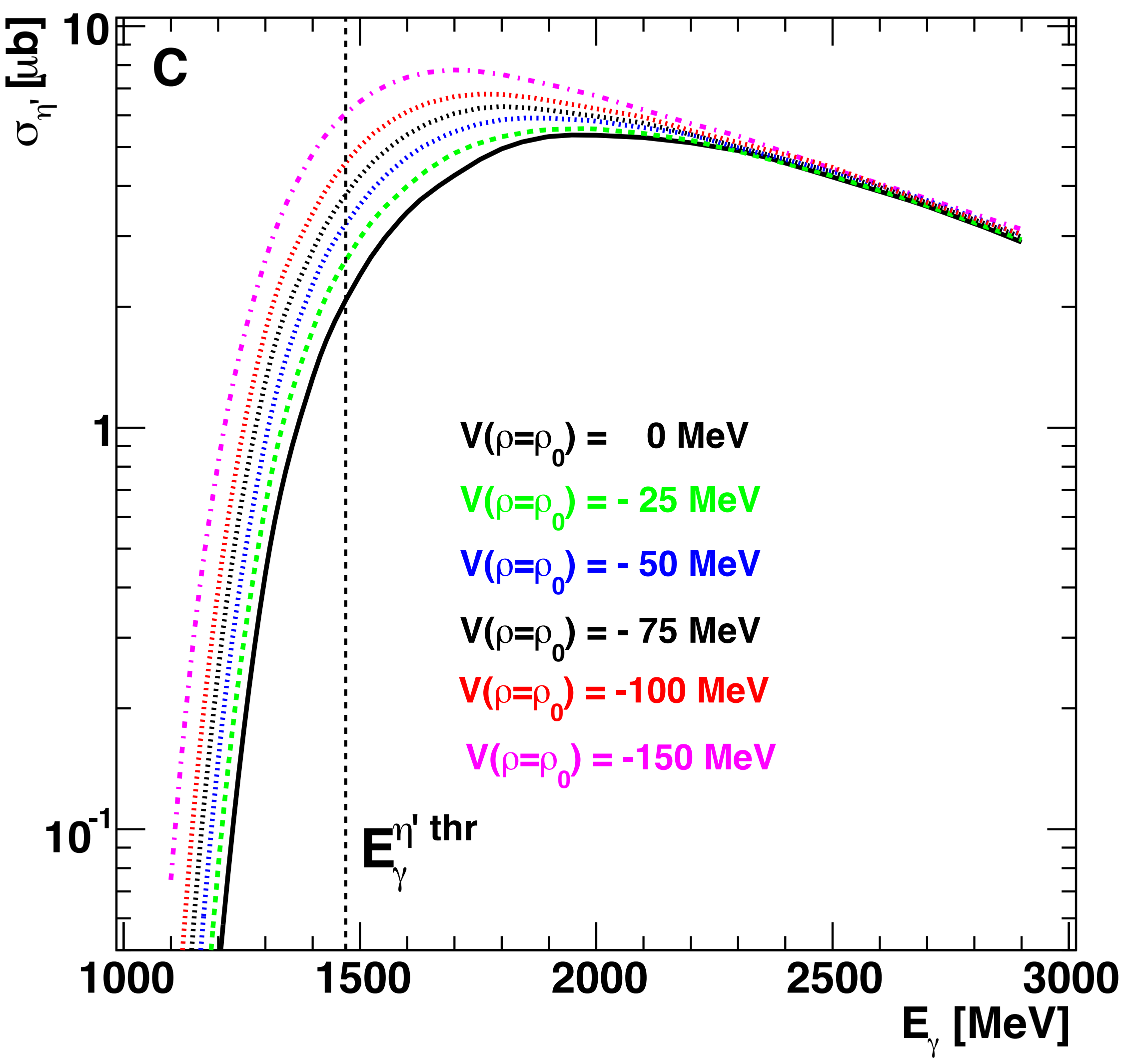
J. Weil, U. Mosel and V. Metag, PLB 723 (2013) 120
calc.: E. Paryev, J. Phys. G 40 (2013) 025201

based on σ_{exp} for γp →pη' and γn→nη' from I. Jaegle EPJA 47 (2011) 11

- measurement of the excitation function of the meson

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

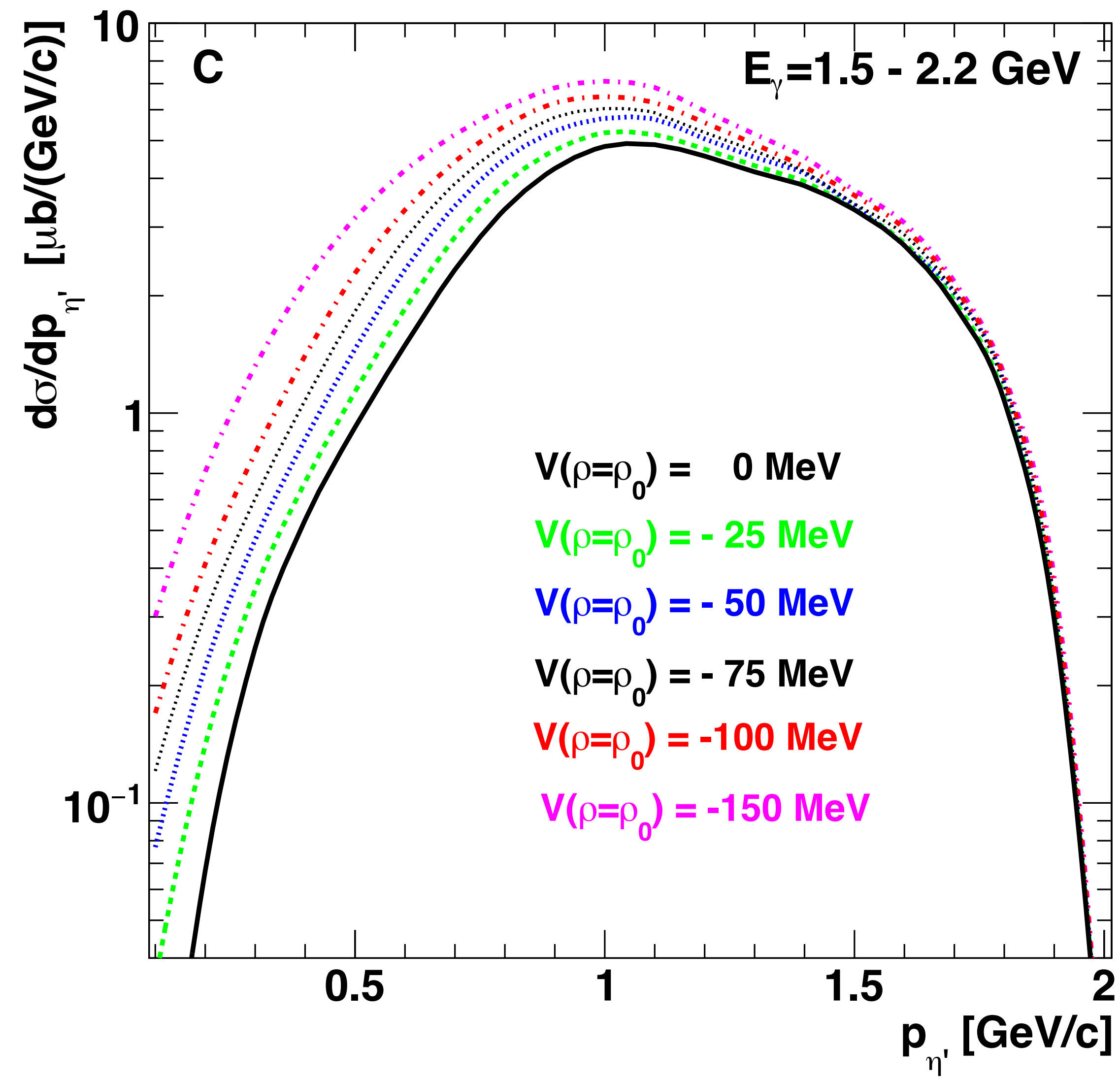
⇨ cross section enhancement



- 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



Excitation function and momentum distribution for η' photoproduction off C

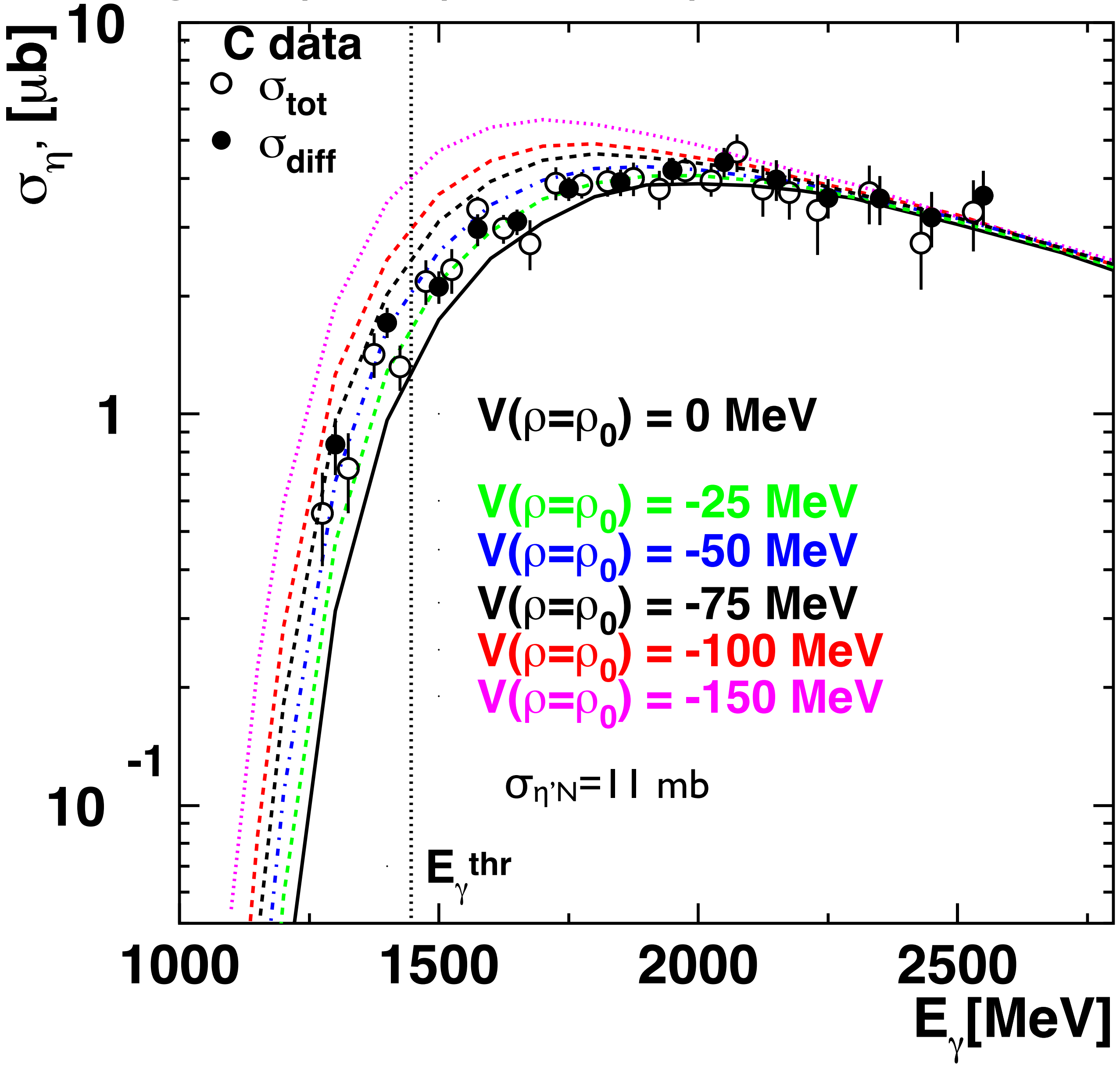
CBELSA/TAPS @ ELSA

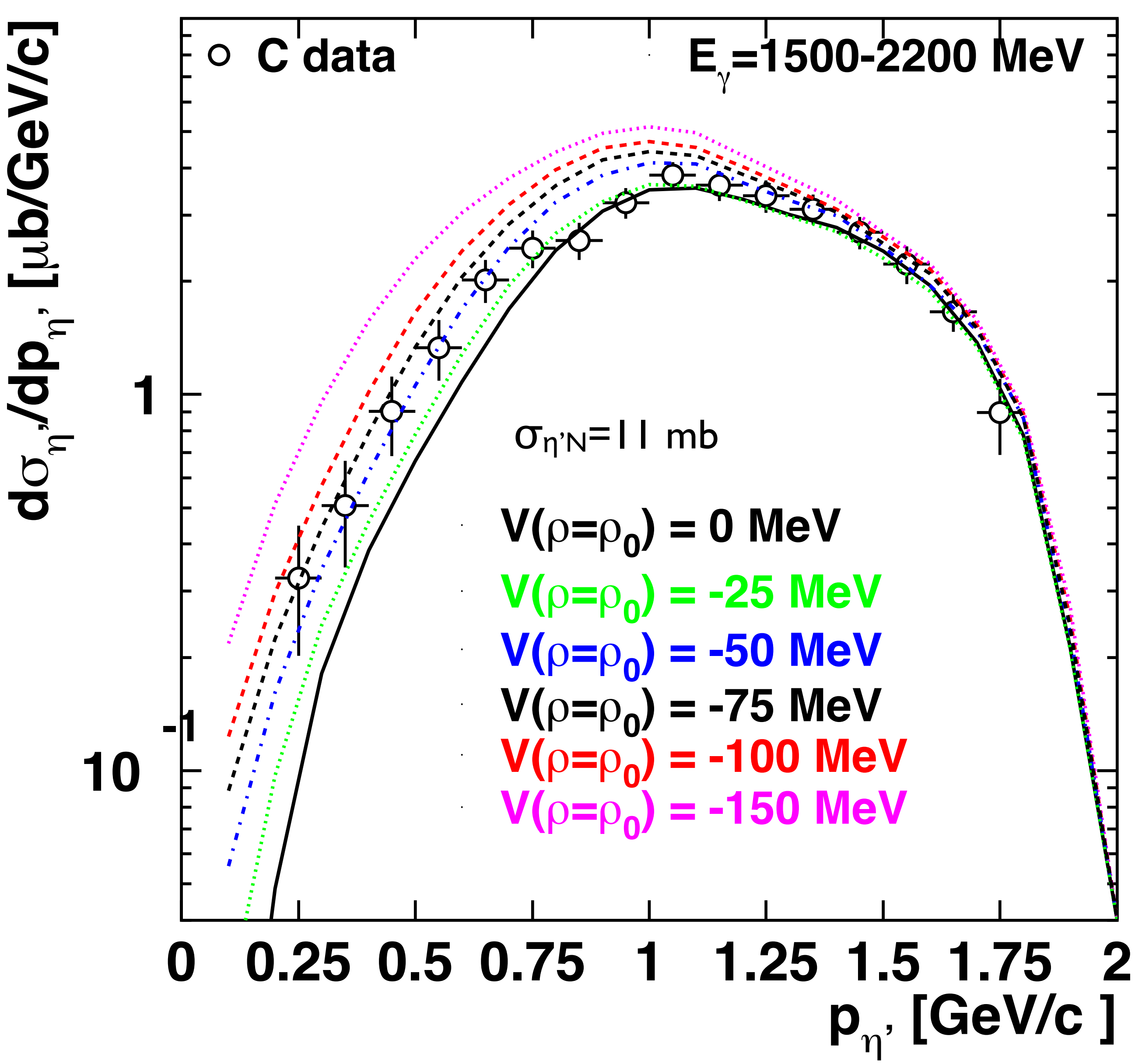
data: M. Nanova et al., PLB 727 (2013) 417

$\gamma\, C \rightarrow \eta' X$

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

using as input experimental production cross sections: $\gamma + p,n \rightarrow \eta' X$; I. Jaegle et al., EPJA 47 (2011) 11





$V_{\eta'}(\rho=\rho_0) = -(40 \pm 6)$ MeV

$V_{\eta'}(p_{\eta'} \approx 1.1$ GeV/c$;\rho=\rho_0) = -(32 \pm 11)$ MeV

data disfavour strong mass shifts

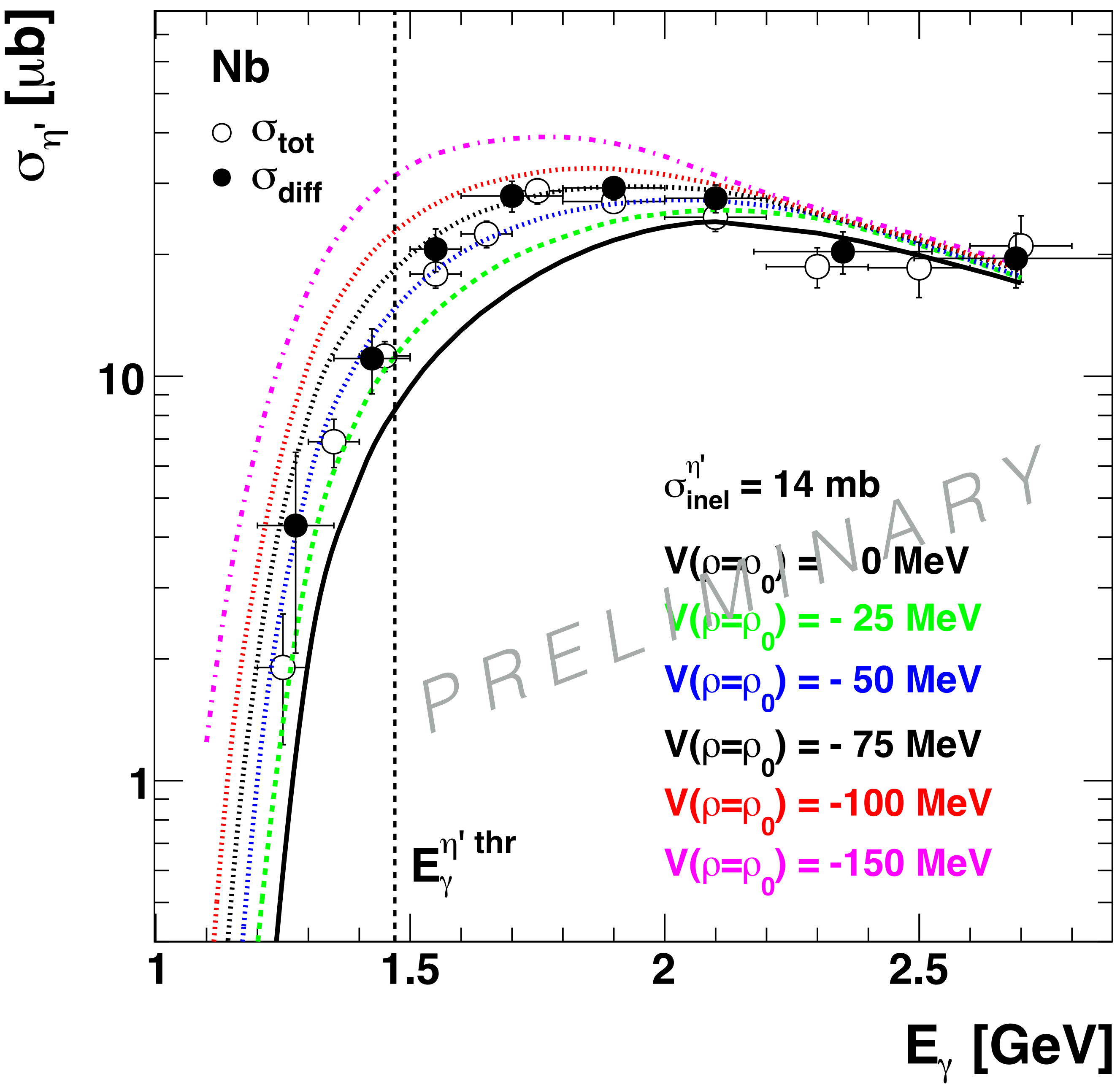
Excitation function and momentum distribution for η' photoproduction off Nb

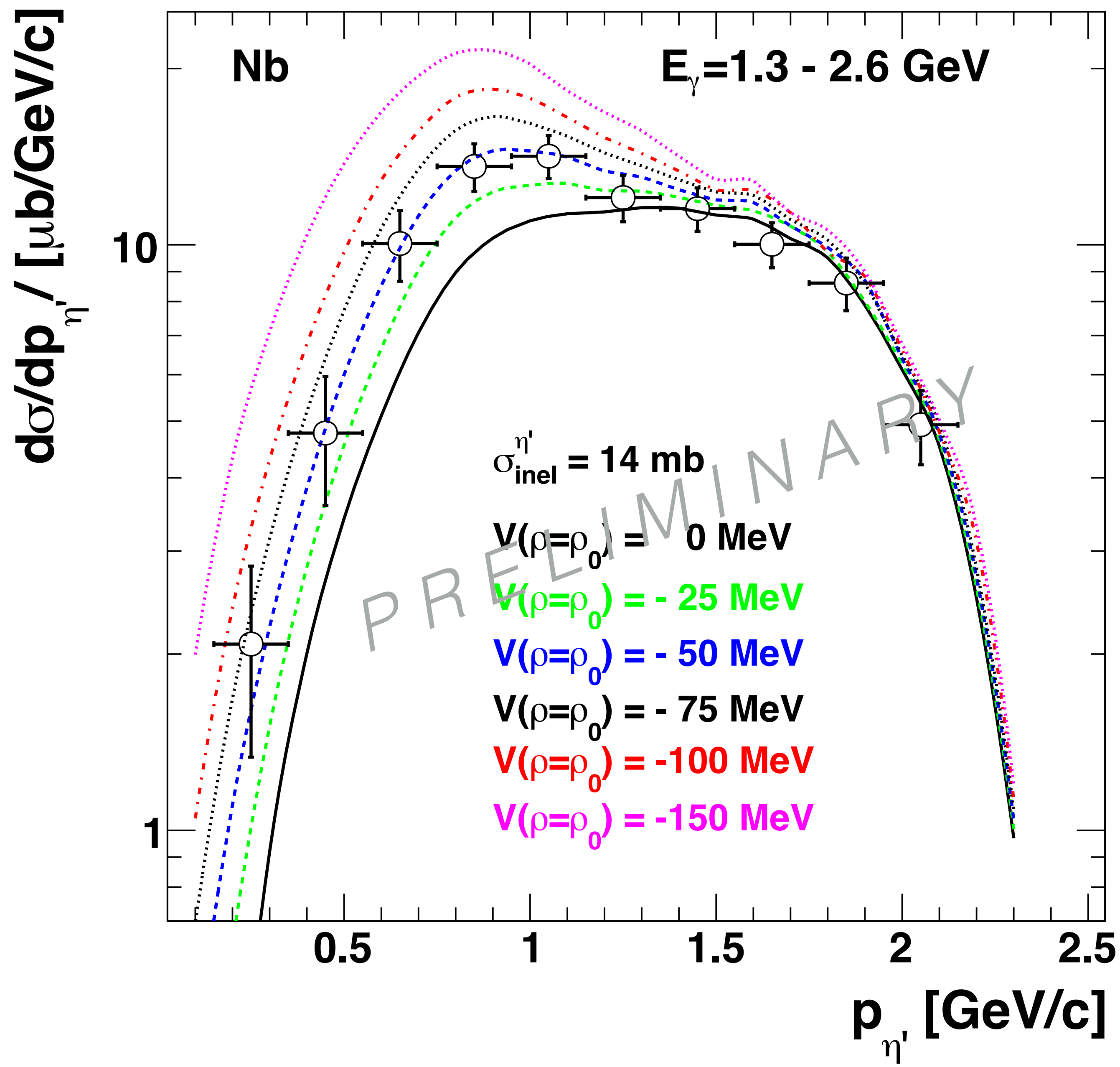
CBELSA/TAPS @ ELSA

M. Nanova et al., submitted to PRC for publication

calc.: E. Paryev, priv. communication

γ Nb $\rightarrow \eta'$X



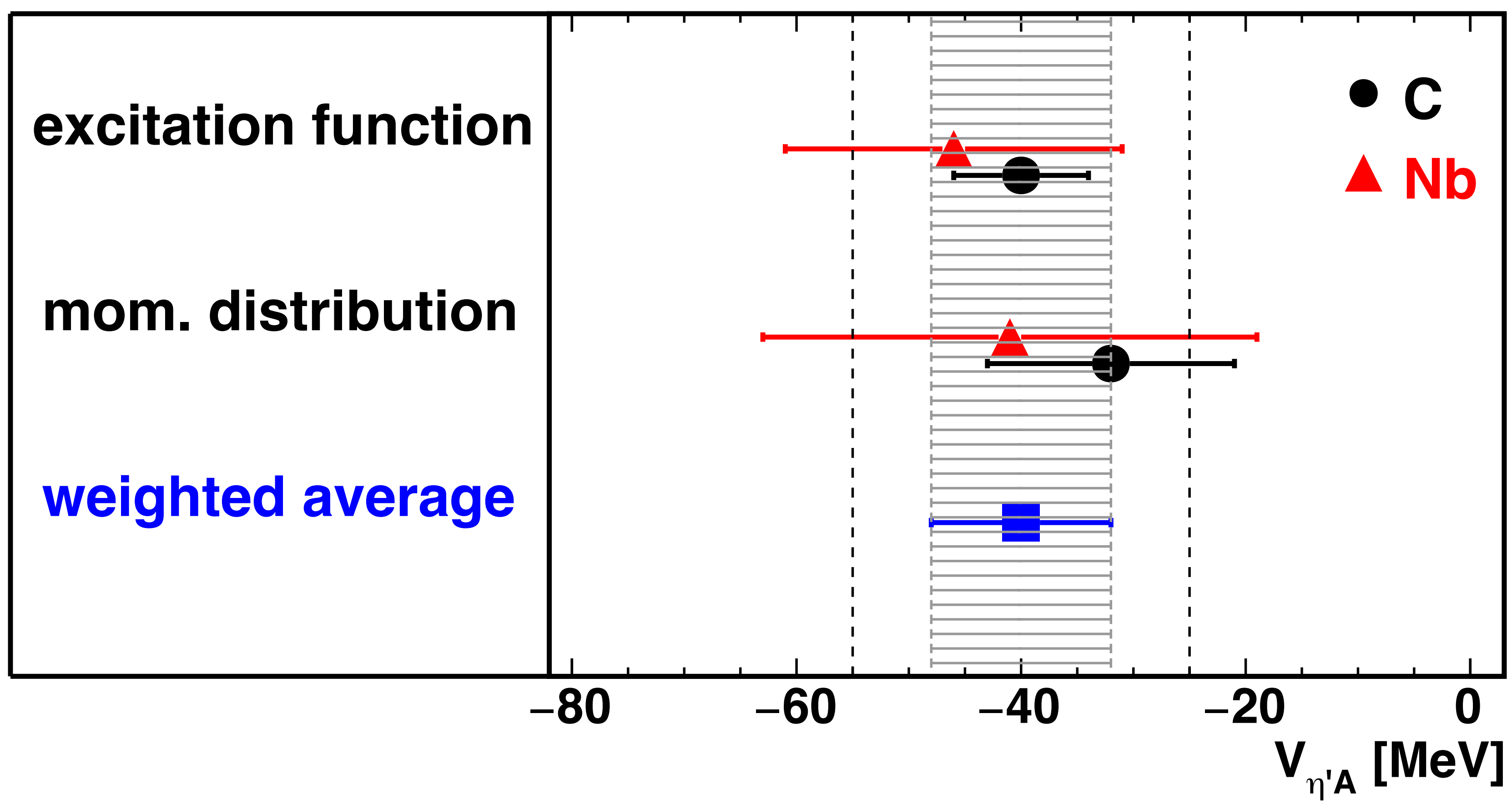


$V_{\eta'}(\rho=\rho_0)$ = -(47±15) MeV

$V_{\eta'}(p_{\eta'}\approx 1.14$ GeV/c;$\rho=\rho_0)$ = -(41±22) MeV

data disfavour strong mass shifts

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



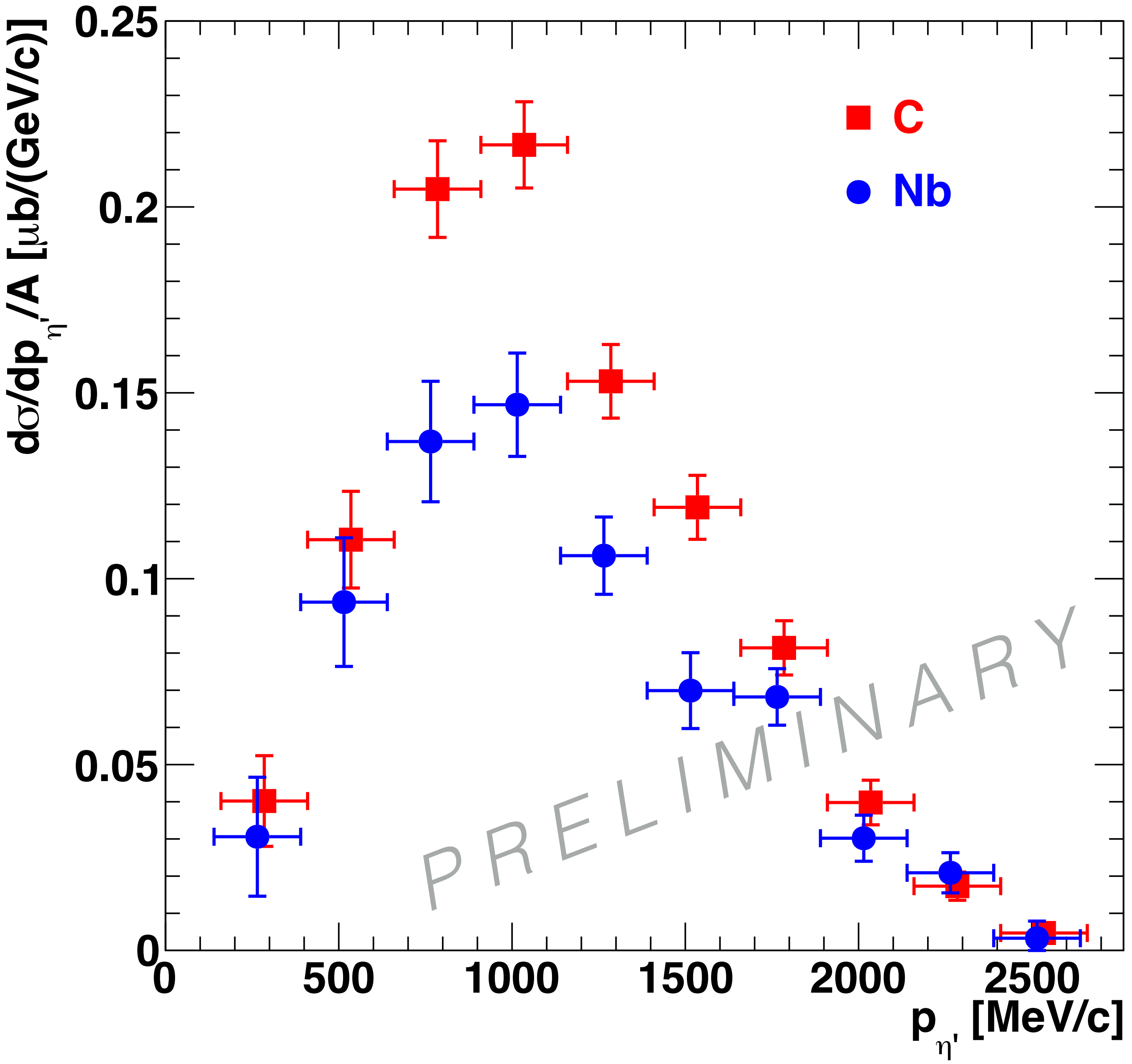
$V_{\eta' A}(\rho=\rho_0) = -(40\pm8(\mathrm{stat})\pm15(\mathrm{syst}))$ MeV

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)

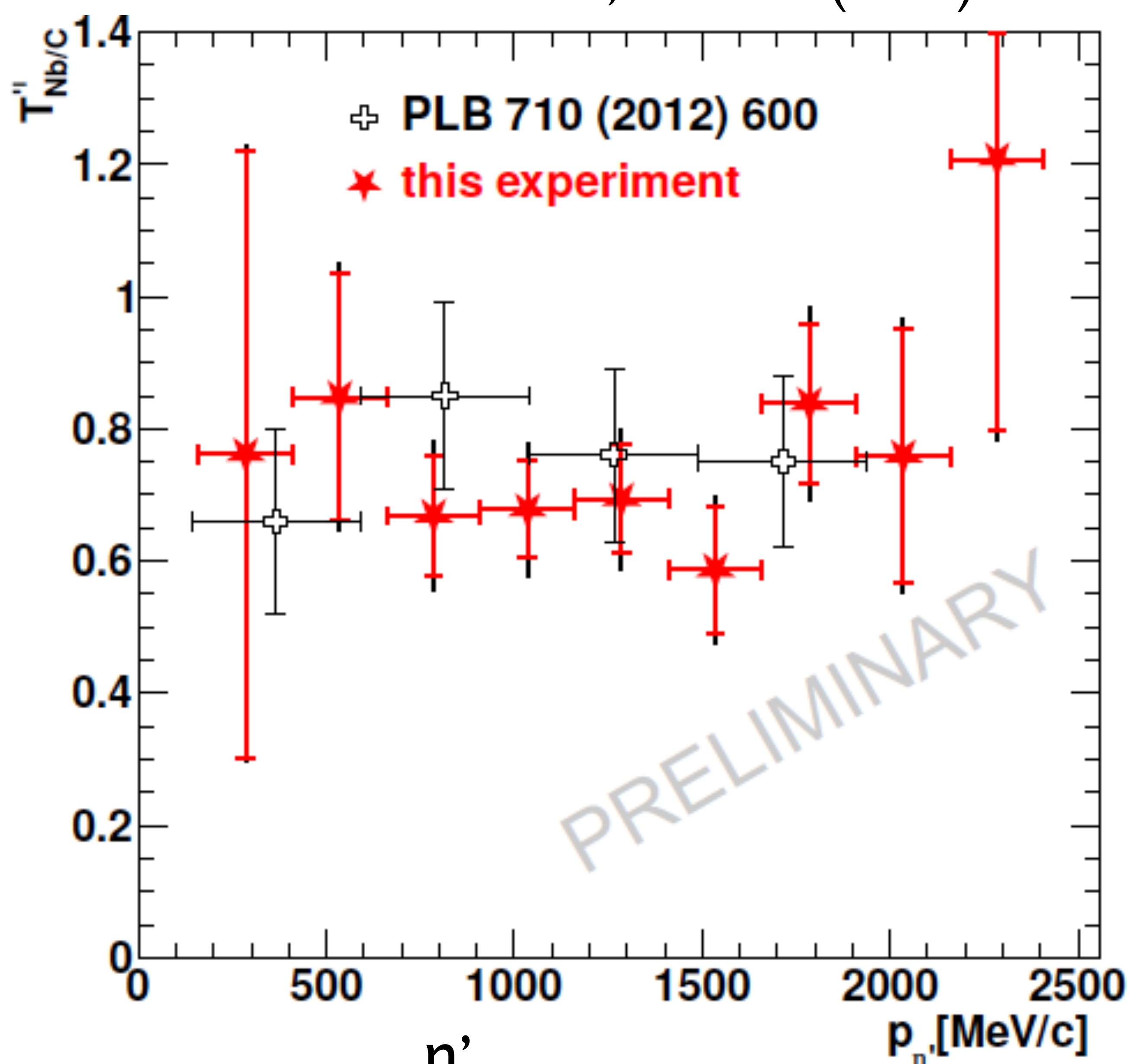
The imaginary part of the meson-nucleus optical potential: momentum dependence

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

E_γ = 1.2- 2.9 GeV



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



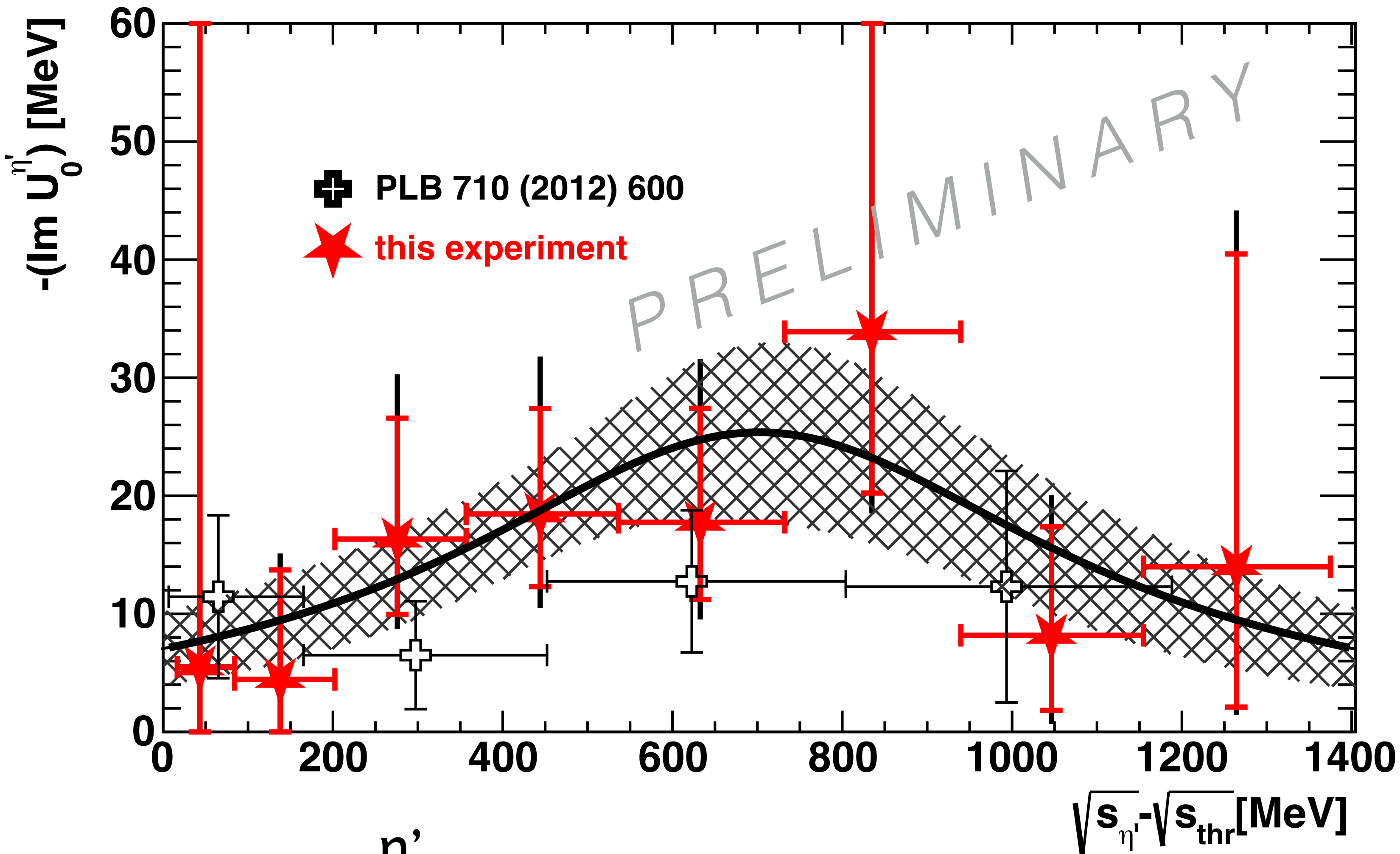
$T^{\eta'}_{Nb/C} \approx 0.6\text{-}0.8$

momentum differential cross sections $\Rightarrow T^{m}_{Nb/C}(p_m) = \dfrac{12 \bullet \sigma_{\gamma Nb \to mX}(p_m)}{93 \bullet \sigma_{\gamma C \to mX}(p_m)}$

momentum dependence of imaginary potential for ω, η'

Glauber model: high energy Eikonal approximation

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



$$\mathrm{Im}\ U^{\eta'}_{0}(\rho=\rho_0, p_{\eta'}=0) = (7\pm3)\ \mathrm{MeV}$$

$$U_{\eta' A}(\rho=\rho_0) = -((40\pm8(stat)\pm15(syst) + i(7\pm3))\ \mathrm{MeV}$$

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

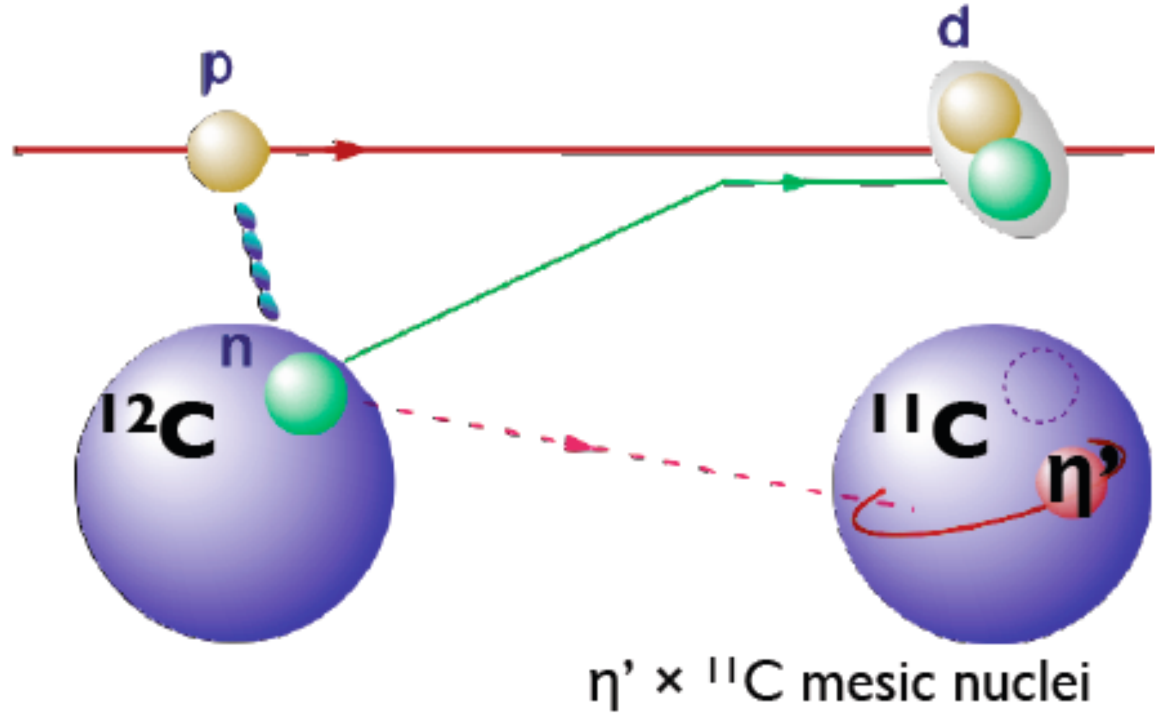
search for η'-mesic states in hadronic reactions

FRS@GSI: PRiME

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

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

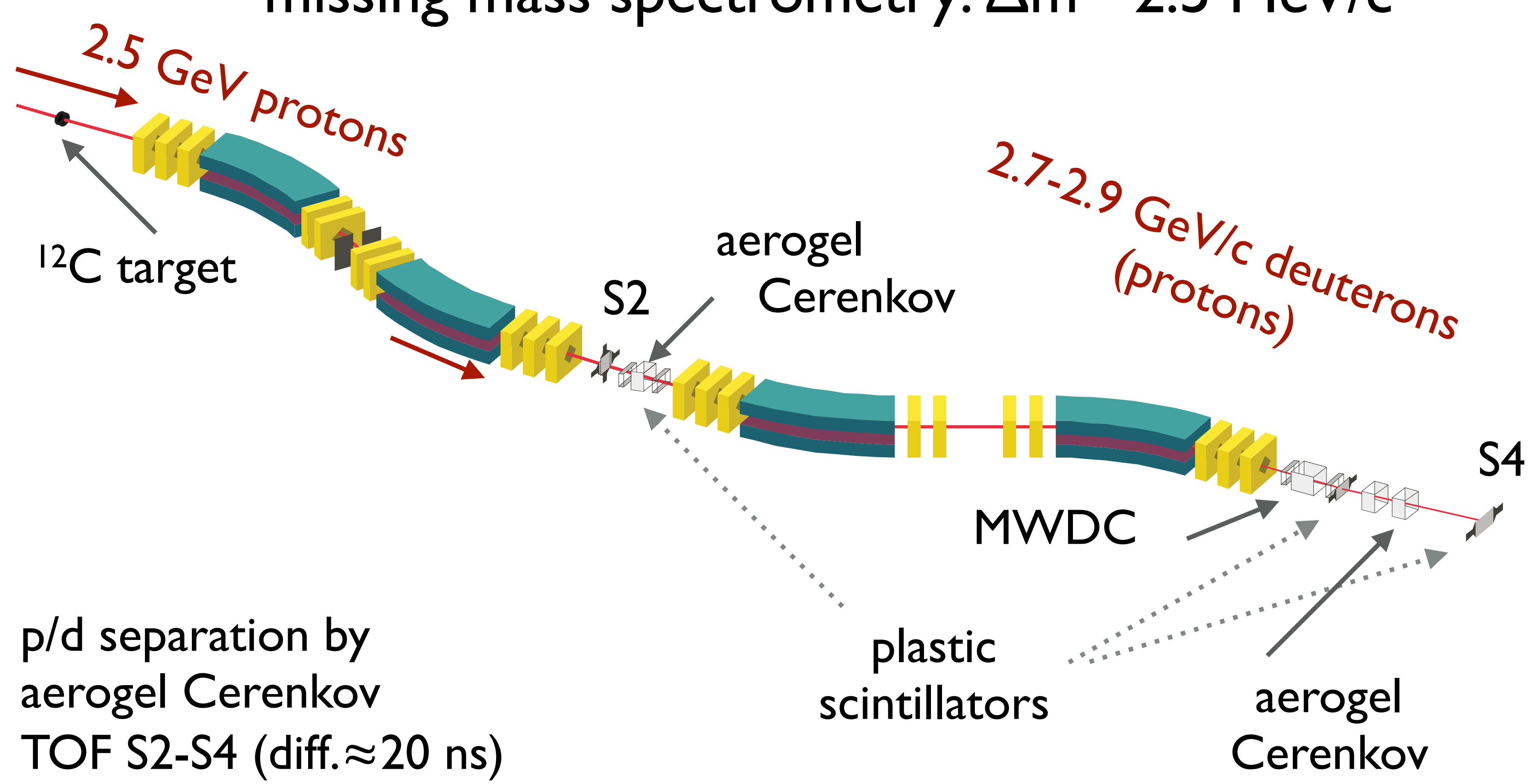
H. Nagahiro et al., PRC 87 (2013) 045201



particle identification by time-of-flight

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

missing mass spectrometry: $\Delta m = 2.5$ MeV/c^2

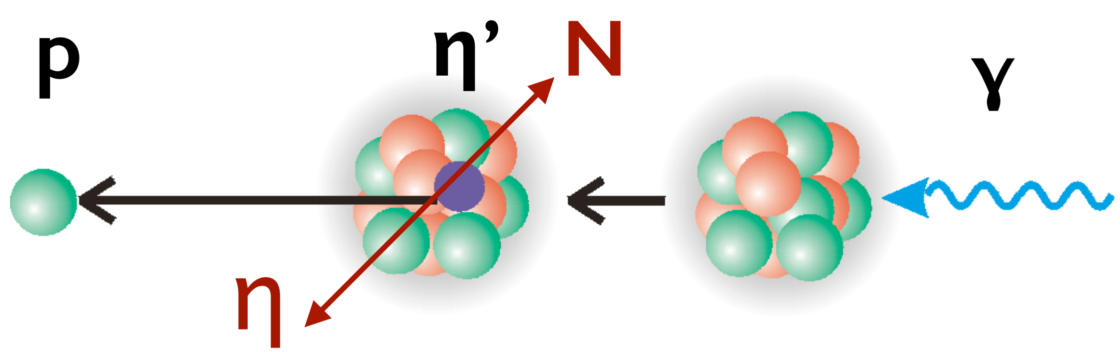


p/d separation by aerogel Cerenkov
TOF S2-S4 (diff.≈20 ns)

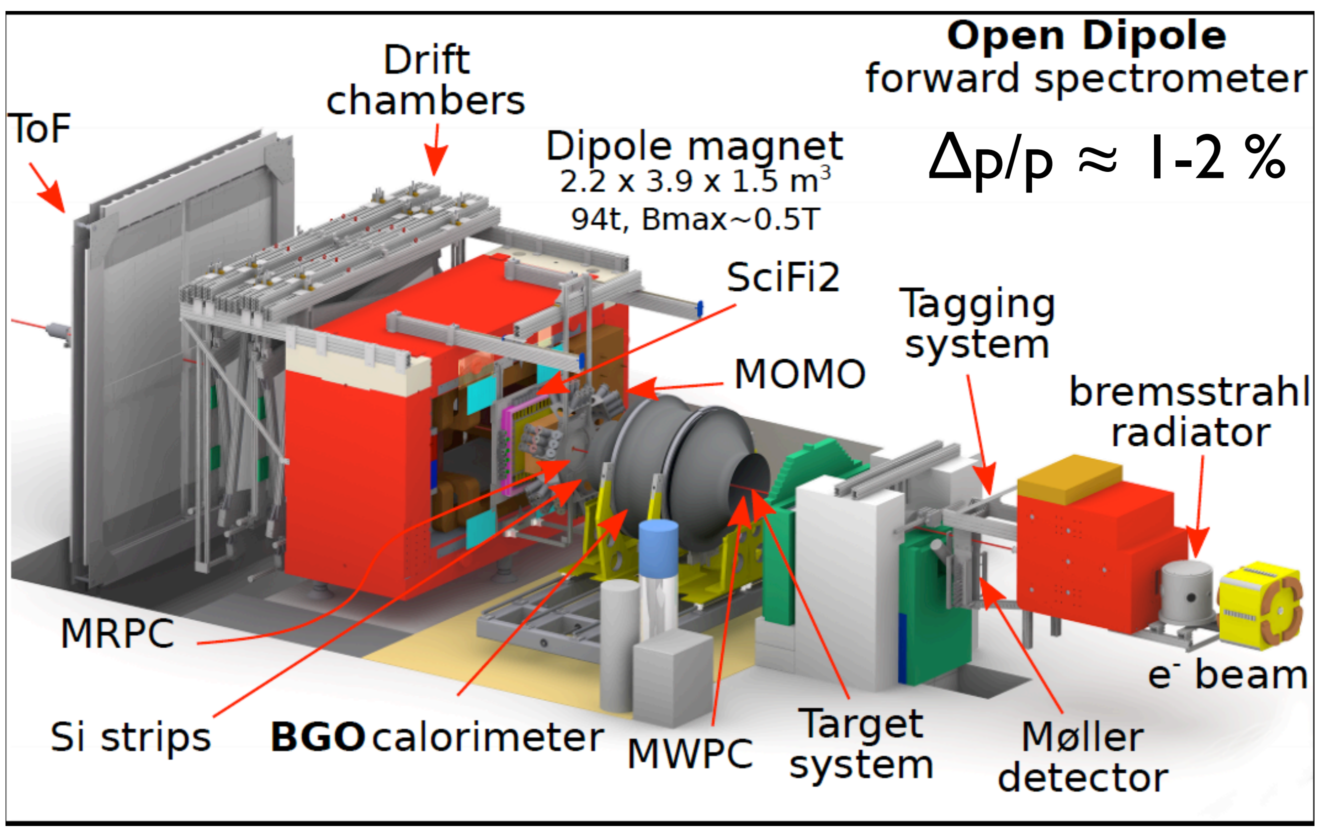
outlook: search for η'-mesic states in photo-nuclear reactions

BGO-OD@ELSA

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



formation and decay of η'-mesic state

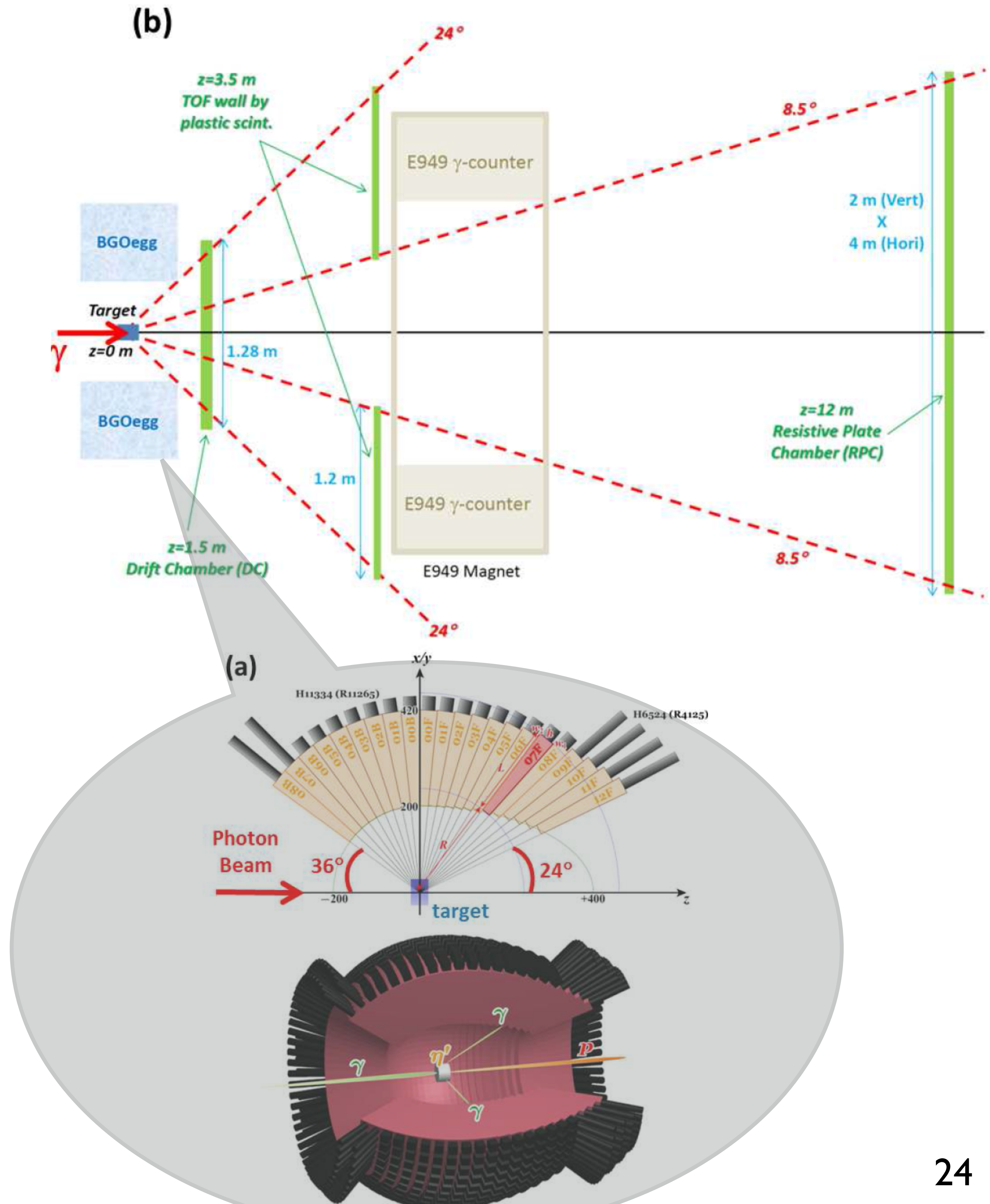


BGO-OD ideally suited for exclusive measurement

approved proposal: ELSA/3-2012-BGO

LEPS2@SPring-8

$^{12}C(\gamma,p)\ \eta' X$ @ 1.5-2.4 GeV



Summary & Outlook

how do meson properties (mass, width) change in a dense nuclear medium ??

meson properties do change in a strongly interacting medium !!

- mesons are broadened in the medium; their lifetime is shortened through inelastic collisions: **$\Gamma_{\eta'}(\rho=\rho_0; p_{\eta'}= 0) = (14\pm6)$ MeV**; ($\Gamma_{\eta'}^{vac}$ = 0.2 MeV)

- large mass modifications $|\Delta m| > 100$ MeV (as predicted by some calculations) have not been observed

- for the η' meson an in-medium mass drop of **$\Delta m\ (\rho=\rho_0) \approx -40$ MeV** has been determined

- in-medium effects described within meson-nucleus optical potential

- the η' meson is a good candidate for forming meson-nucleus bound states since $|\mathrm{Im}\ U| \ll |\mathrm{Re}\ U|$

- search for η' mesic states ongoing

status of experiments in 2016

	LEPS@ SPring-8	CLAS @JLAB	CBELSA/ TAPS	E-325 @KEK	ANKE @COSY	CERES @CERN	NA60 @CERN
reaction	γA 1.5-2.4 GeV	γA 1.5-2.4 GeV	γA 0.7-3.1 GeV	pA 12 GeV	pA 2.8 GeV	Au+Au 158 AGeV	In+ In 158 AGeV
momentum acceptance	p > 1.0 GeV/c	p > 0.8 GeV/c	p > 0.0 GeV/c	p > 0.5 GeV/c	p > 0.6 GeV/c	p_t> 0.0 GeV/c	p_t> 0.0 GeV/c
ρ		Δm≈0 Γ($ρ_0$/2) ≈ 220 MeV		Δm/m= -9% ΔΓ≈ 0		Δm≈0 broadening	Δm≈0 broadening
ω		Γ($ρ_0$) > 200 MeV	Δm≈-30 MeV Γ($ρ_0$, p=0) ≈ 60 MeV	Δm/m= -9% ΔΓ≈ 0			
η’			Δm≈-40 MeV Γ($ρ_0$,p=0) ≈15 MeV				
ϕ	Γ($ρ_0$)≈ 100 MeV	Γ($ρ_0$)≈ 40-200 MeV		Δm/m≈-3.4% Γ($ρ_0$/2)≈ 15 MeV	Γ($ρ_0$)≈ 30-60 MeV		