Study of the η’ meson in nuclei in the LEPS2/BGOegg experiment

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η’(958) meson

meson	mass [MeV/c^2]
π^0	134.97
$\pi^\pm$	139.57
$K^\pm$	493.68
$K^0, \overline{K}^0$	497.61
η	547.86
η'	957.78

Larger mass compared with other pseudo-scalar mesons

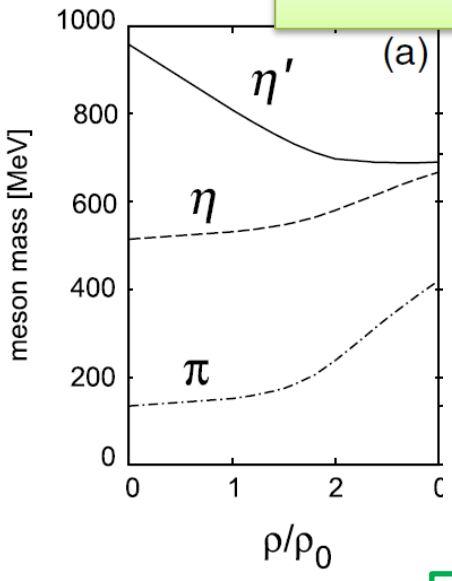
$U_A(1)$ anomaly

$U_A(1)$ anomaly effect is manifest under the breaking of chiral symmetry

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

Models with $U_A(1)$ anomaly term

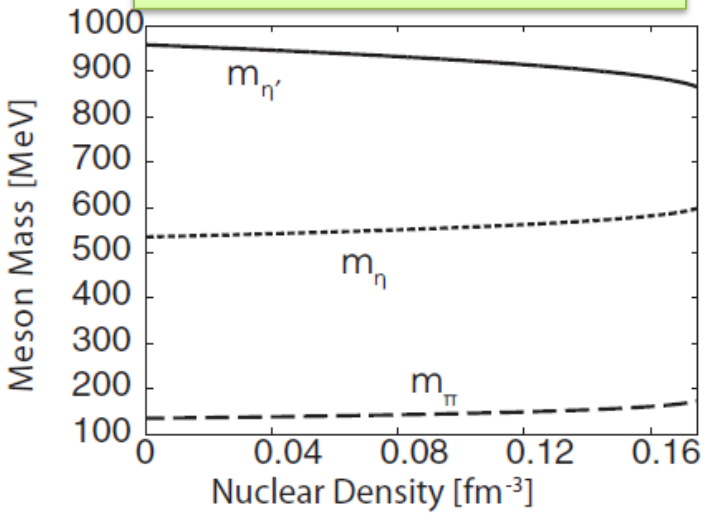
NJL model



$\Delta m(\rho_0)$ = -150 MeV

H. Nagahiro et al. PRC 74 (2006) 045293

Linear sigma model



$\Delta m(\rho_0)$ = -80 MeV

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

A large mass reduction is expected

Studies of η’(958) mass in medium in the LEPS2/BGOegg experiment

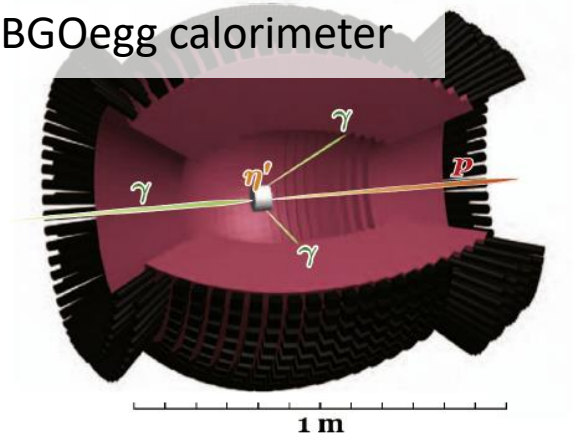
LEPS2/BGOegg experiment

- LEPS2 beamline @ SPring-8 in Japan
- 1.3-2.4 GeV γ beam from backward Compton scattering of laser and 8 GeV e

BGOegg experiment

T. Ishikawa, et al., NIM A 837 (2016) 109

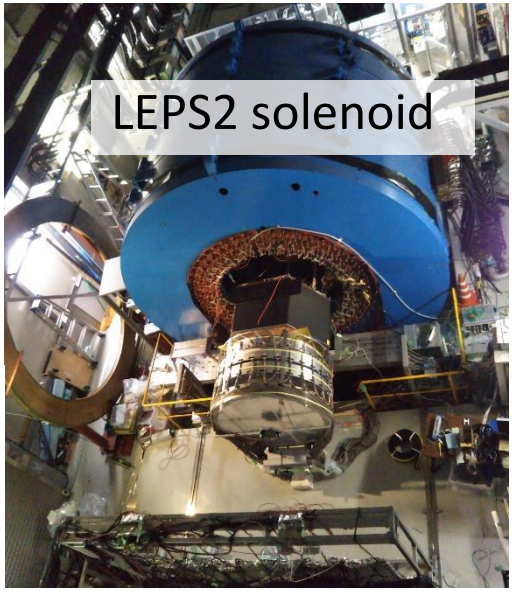
BGOegg calorimeter



- World's best energy resolution calorimeter for 1 GeV γ : 1.4%
- Large polar angle coverage : $24^\circ < \Theta^{lab} < 144^\circ$

$\eta' \rightarrow 2\gamma$, $\eta \rightarrow 2\gamma$ $\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$

- 2014-2016 : Phase-1 — N. Tomida *et al.*, PRL 124 (2020) 202501
  - η'-nucleus bound state search — Y. Matsumura , PhD thesis (2021)
  - Direct measurement of η' mass in nuclei
  - $\pi^0/\eta/\omega$ production off proton — N. Muramatsu *et al.,* PRC 100 (2019) 055202
- 2022- : Phase-2 — N. Muramatsu *et al.*, PRC 102 (2020) 025201



LEPS2 solenoid experiment

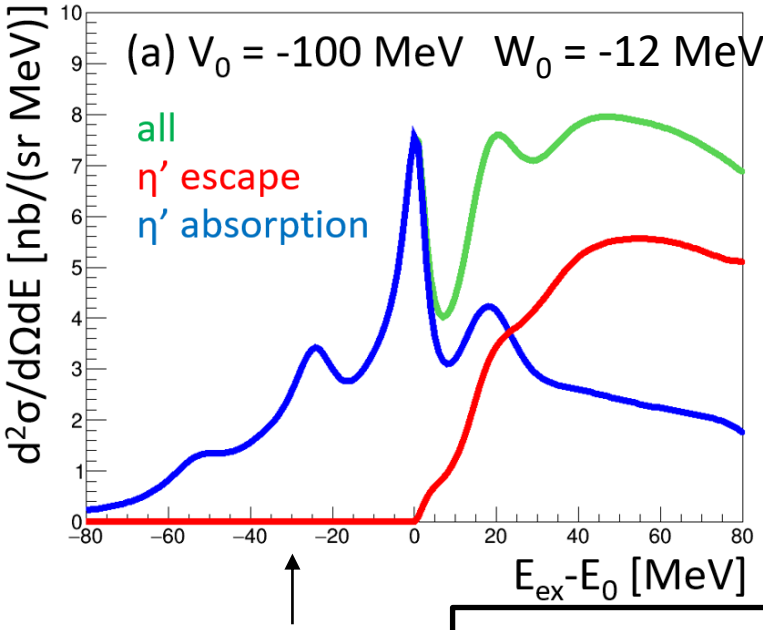
- Charged particles
- Exotic hadrons
- 2017- construction
- 2021- physics run

η'-nucleus bound state

η'-nucleus optical potential H. Nagahiro, S. Hirenzaki PRL 94 (2005) 232503

- $U(r) = (V_0+iW_0) \times \rho(r)/\rho_0$
- $V_0 = \Delta m(\rho_0)$: mass shift at the normal nuclear density
- $W_0 = -\Gamma(\rho_0)/2$: width at the normal nuclear density

- If V_0 is large and W_0 is small, η' and a nucleus may form a bound state



$$\gamma + {}^{12}\mathrm{C} \rightarrow p + \eta' \otimes {}^{11}\mathrm{B}$$

Excitation energy

$E_{ex}-E_0 = MM(^{12}C(\gamma,p))-M_{^{11}B}-M_{\eta'}$

Our aim

Examine η'-nucleus potential

Search for a bound state

Calculation within Distorted Wave Impulse Approximation (DWIA)

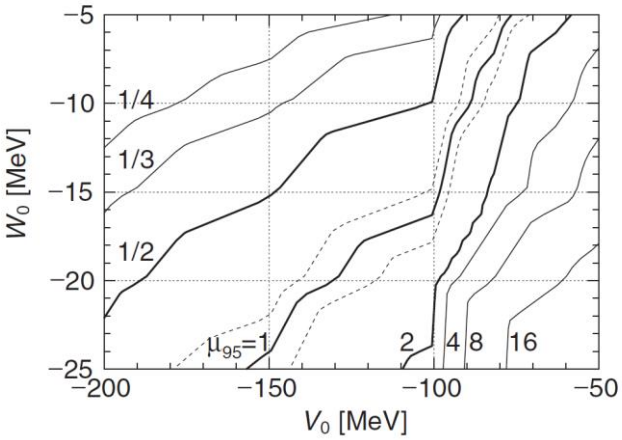
H.Nagahiro, JPS Conf. Proc. 13 (2017) 010010

Past experiments

η-PRiME@GSI

^{12}C(p,d)X

Inclusive missing mass spectroscopy



Y.K. Tanaka, PRL 117 (2016) 202501

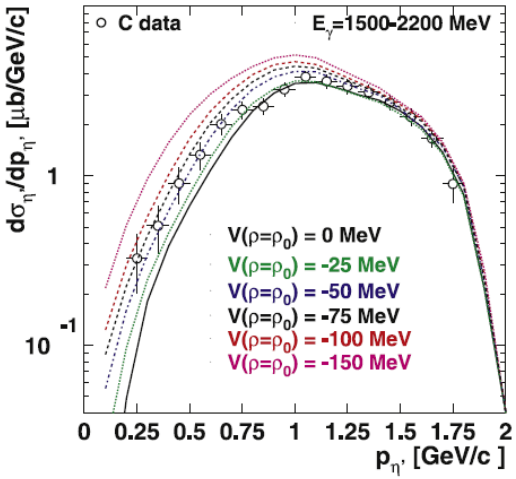
Y.K. Tanaka, PRC 97 (2018) 015202

- Large multi meson backgrounds → **No signal peak observed**
- Upper limit on V_0, W_0 depending on an unknown **scaling factor** of the DWIA cross section and the elementary cross section

CBELSA/TAPS

η' photoproduction off C, Nb

η' escaped from nuclei



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

M. Nanova et al., PRC 94 (2016) 025205

M. Nanova et al., Eur. Phys. J. A 54 (2018) 182

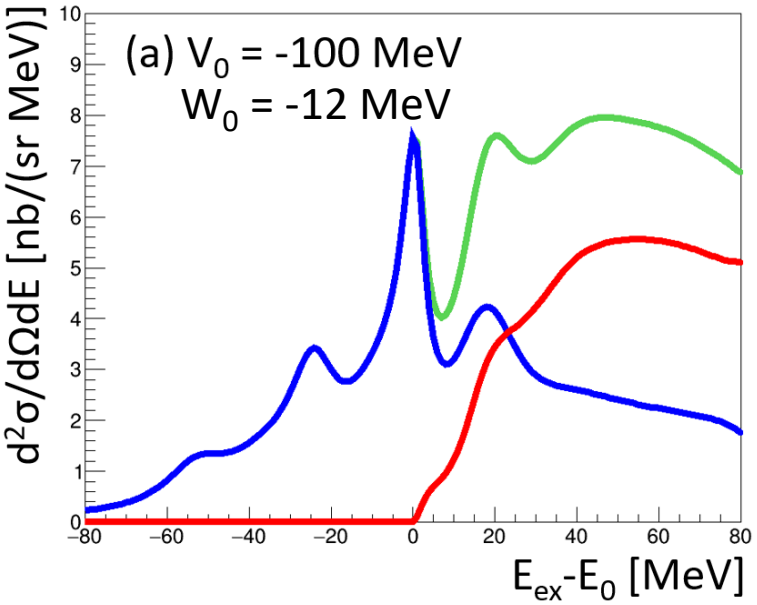
S. Friedrich et al., Eur. Phys. J A 52 (2016) 297

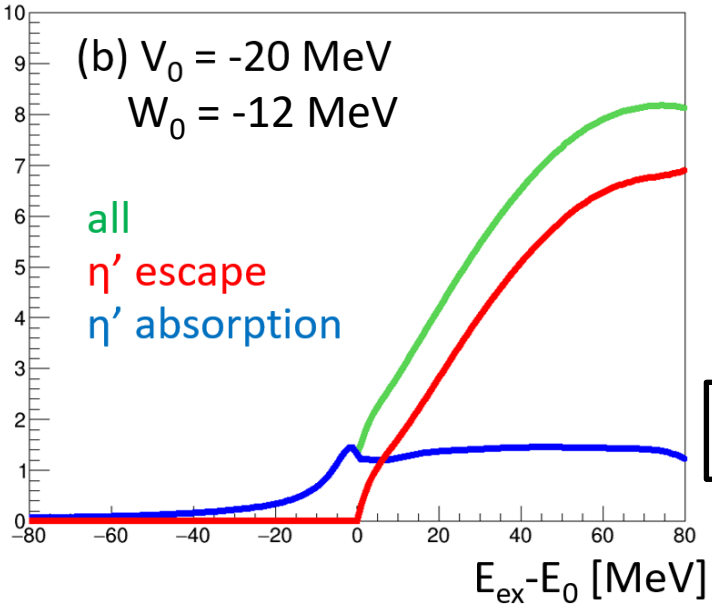
- V_0 = -(40±6(stat)±15(syst)) MeV from comparisons with **the collision model**
- W_0 = -(13±3(stat)±3(syst)) MeV from **the transparency measurement**

Present experiment

Missing mass spectroscopy of $^{12}C(\gamma,p)X$

Tag decay products from η' in nucleus to reduce BG





DWIA calculation in lab frame

$L_{\eta'} < 7$ =>

E_{ex}-E_0<50 MeV

- η' absorption : Search for bound states
  η'N->ηN large branch expected (>40%)

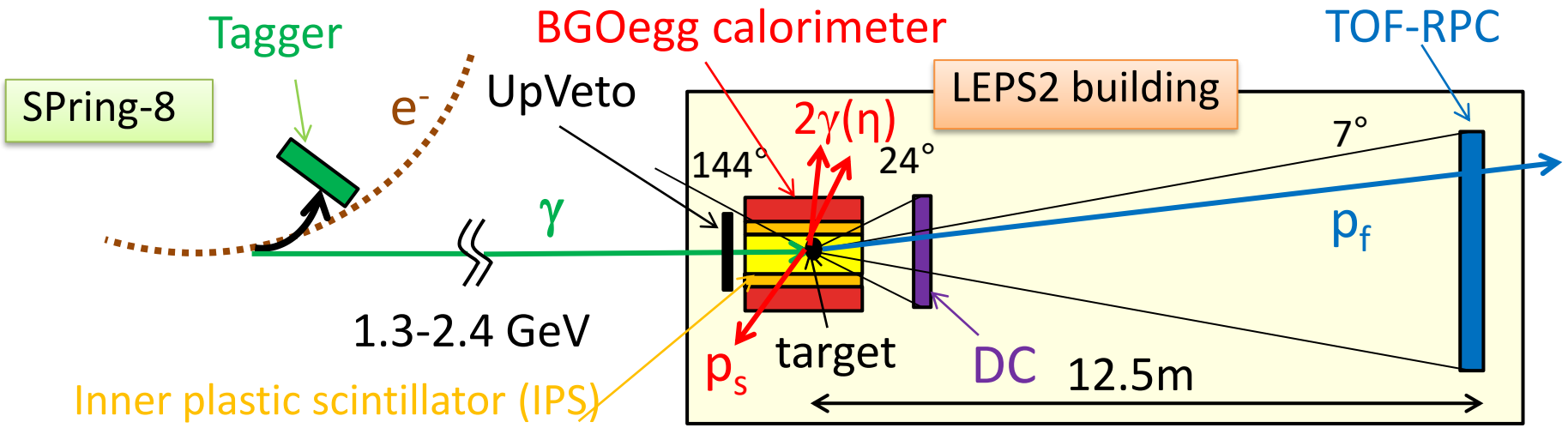
$$\gamma + {}^{12}\mathrm{C} \to p_f + \eta' \otimes {}^{11}\mathrm{B}$$
$$\hookrightarrow \eta' + p \to \eta + p_s$$

- η' escape => Evaluate production rate of η'
  (Normalization of the DWIA calculation)

$$\gamma + {}^{12}\mathrm{C} \to p_f + \eta' + {}^{11}\mathrm{B}$$
$$\hookrightarrow \eta' \to 2\gamma$$

Experimental set up

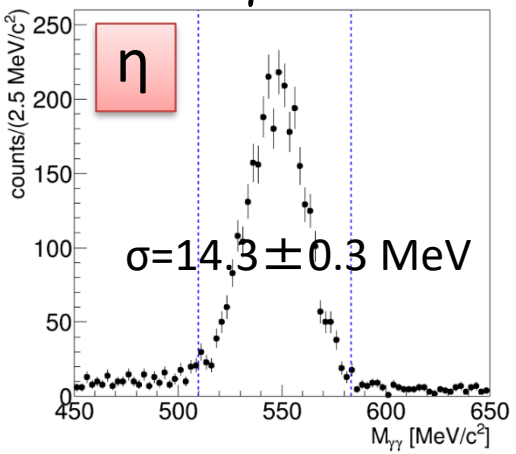
- LEPS2 beam line @ SPring-8
- 2015/Apr-Jul

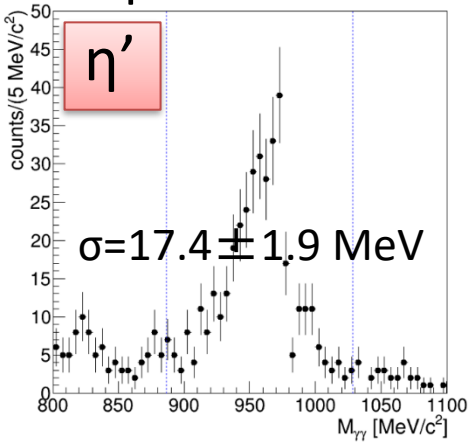


- Trigger : Tagger × BGOegg 2 crystal hits
  => Simultaneous measurements of (η+p_s) and η' tag modes

- Missing mass spectroscopy of $^{12}C(\gamma,p_f)$: Tagger, TOF-RPC
- Decay products (η+p_s), η' : BGOegg, IPS

2γ invariant mass spectra



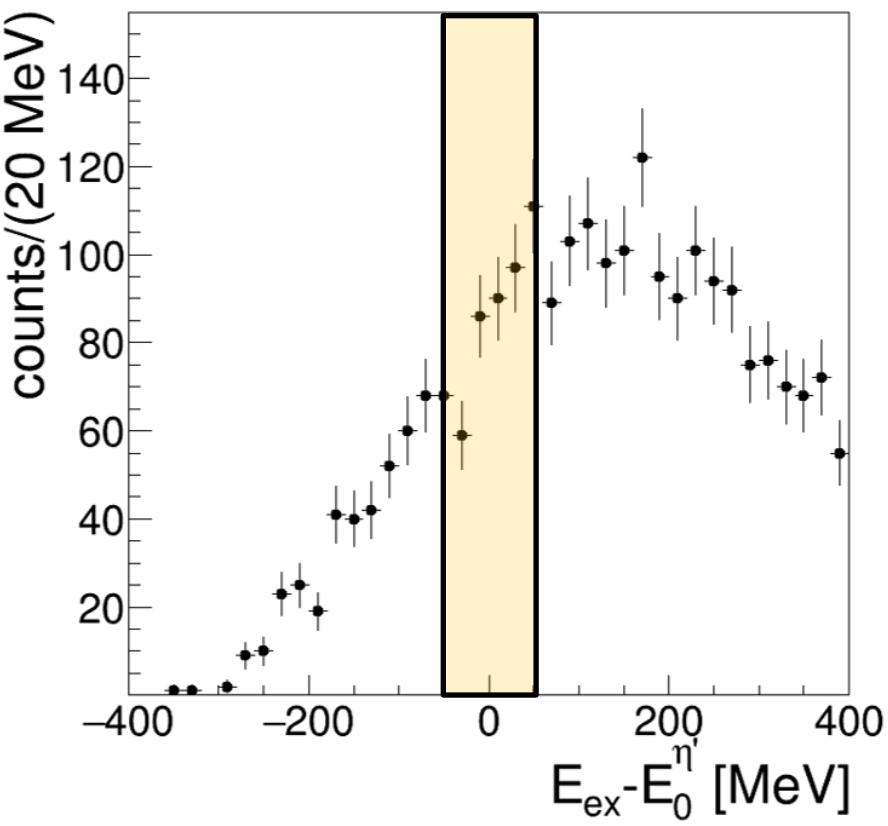


Excitation energy distribution

$$E_{ex}-E_0 = MM(^{12}C(\gamma,p))-M_{11B}-M_{\eta'}$$

$\gamma + {}^{12}C \rightarrow p_f + (\eta+p_s) + X$

(bound state search)

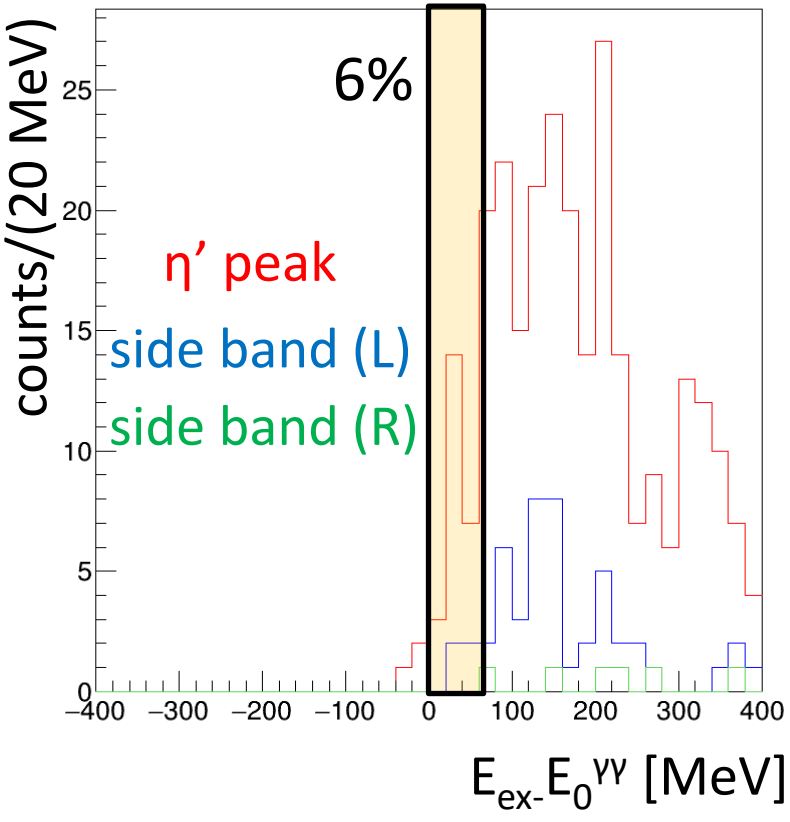


No signal enhancement

Need to suppress ($\eta+p_s$) BG

$\gamma + {}^{12}C \rightarrow p_f + \eta' + X$

(η' yield)



Rising from η' threshold

Few events in $0<E_{ex}-E_0<50$ MeV

(η+p_s) : background suppression

signal

secondary η

$$\gamma + {}^{12}\mathrm{C} \to p_f + \eta' \otimes {}^{11}\mathrm{B}$$
$$\hookrightarrow \eta' + p \to \eta + p_s$$

back-to-back ηp_s

isotropic angular distribution

BG

primary η

$$\gamma + {}^{12}\mathrm{C} \to p_f + \eta + {}^{11}\mathrm{B}$$
$$\hookrightarrow \eta + p \to \eta + p_s,$$
$$\text{or } p_f + p \to p_f + p_s.$$

Forward-going η

$$\gamma + {}^{12}\mathrm{C} \to p_f + \eta + \pi^0 + {}^{11}\mathrm{B}$$

Undetected π

Kinematical cut determined by blind analysis

(a) **Opening angle cos(ηp_s)<-0.9** <= signal : back-to-back ηp_s

(b) **|Missing energy| < 150 MeV** <= signal : no additional particle

missing energy = $E_\gamma + m_{12C} - E_\eta - E_{ps} - E_{pf} - m_{11B}$

(c) **Polar angle cos(p_s)<0.5**

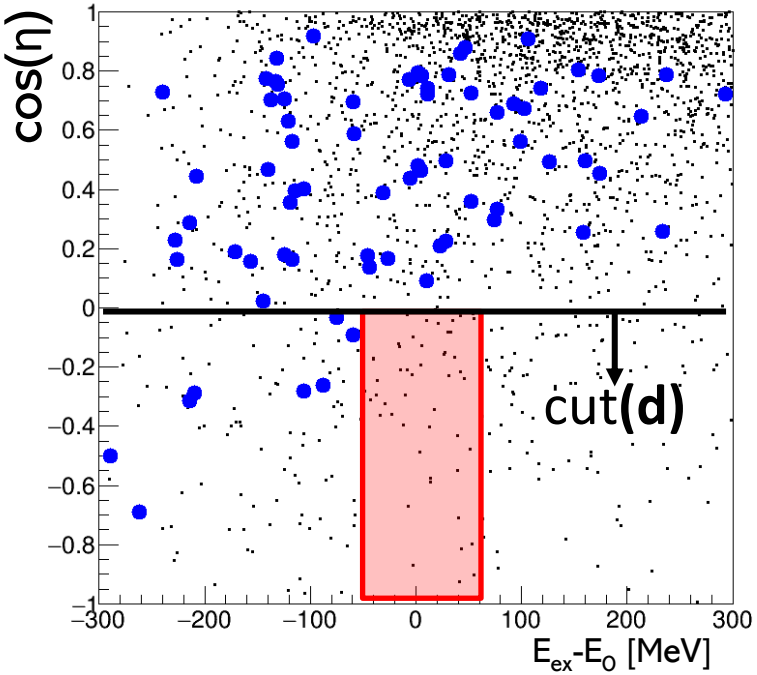
(d) **Polar angle cos(η)<0**

<= signal : Isotropic distribution

BG : concentrate in forward

BG : Reduced to 0.4% Signal : Preserve 23%

η'-nucleus search result



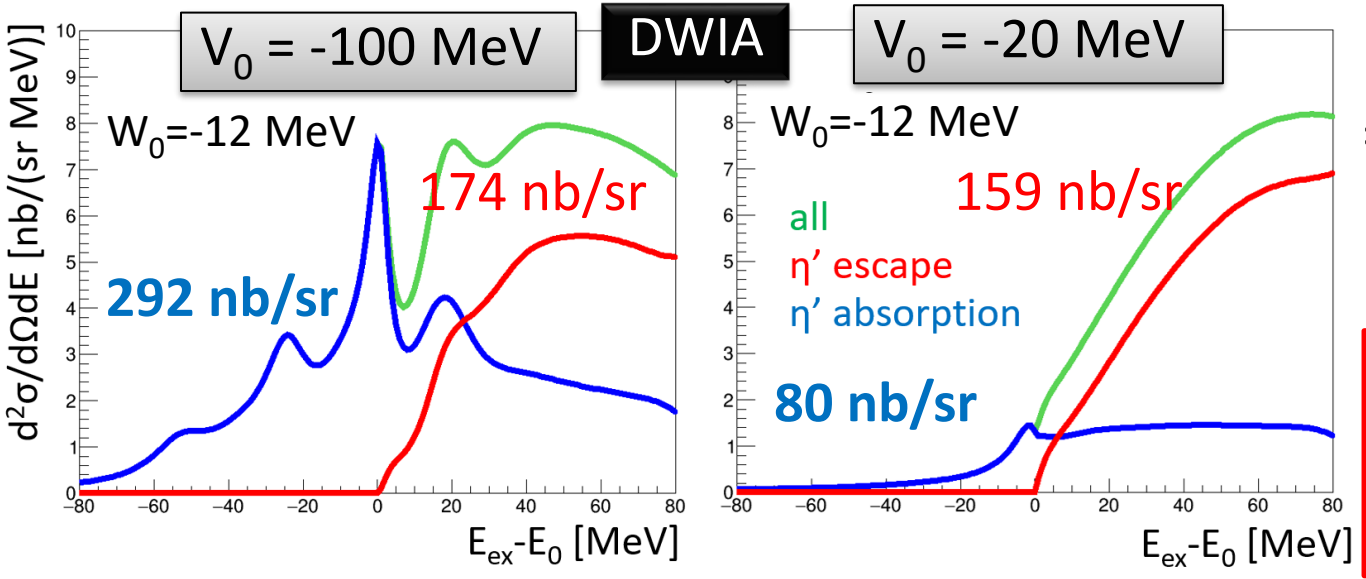
- no η+p_s kinematical cut
- η+p_s cut **(a)-(c)**

No (η+p_s) signals from η' bound state in -50<E_{ex}-E_0<50 MeV

Upper limit : **2.2 nb/sr** @cos(ηp_s)<-0.9
(E_γ=1.3-2.4 GeV average)

=> Compare with the DWIA calculation to discuss η'-nucleus potential

DWIA



=>
Small V_0 ?
Small η'N->ηN branch ?
Small η' production rate ?

η' escape :
60.2±15.4(stat) ±4.1(syst) nb/sr
(0<E_{ex}-E_0<50 MeV)

Theoretical **(η+p$_s$)** cross section

Decomposition

$$\left(\frac{d\sigma}{d\Omega_{p_f}}\right)^{\eta+p_s}_{theory} = F \times \left(\frac{d\sigma}{d\Omega_{p_f}}\right)^{\eta' abs}_{theory} \times \mathrm{Br}_{\eta' N \to \eta N} \times P^{\eta p_s}_{srv}$$

V_0	Normalization factor	total η' absorption cross section (DWIA)	η'N->ηN branch	Probability that ηp_s is emitted in $\cos(\eta p_s)<-0.9$
-100 MeV	0.35±0.09	292.2 nb/sr	unknown	12.1%
-20 MeV	0.38±0.10	79.7 nb/sr		

- 1 nucleon absorption (η'N->MB) ≧ multi nucleon absorption (η'NN->NN)

  H. Nagahiro *et al.*, PLB 709 (2012) 87
- η'N->ηN : ~80% of 1N abs

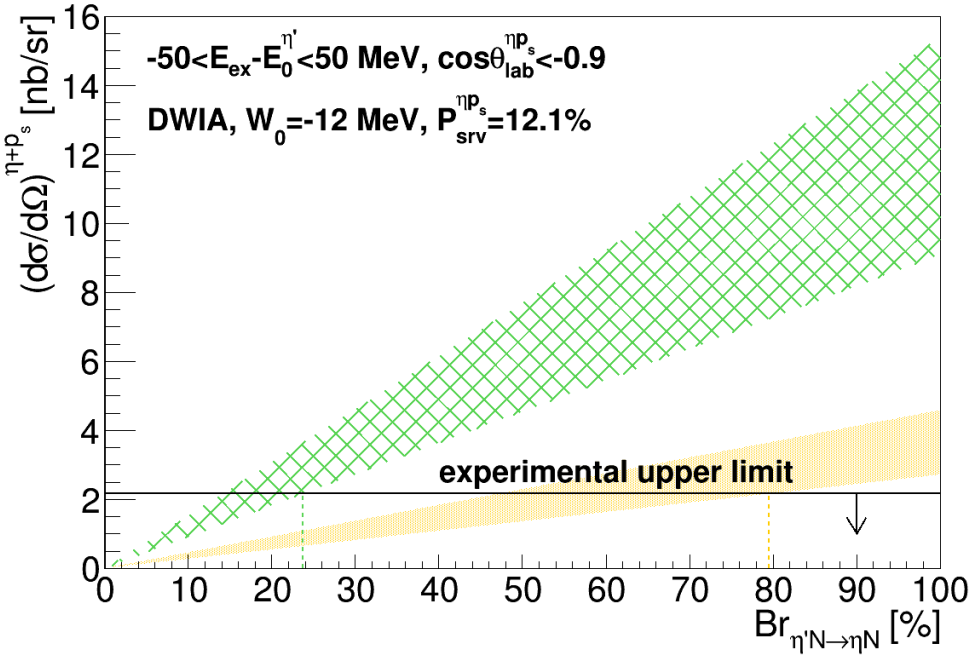
  E. Oset and A. Ramos PLB 704 (2011) 334

=> Expect $\mathrm{Br}_{\eta' N \to \eta N}$ ≧ 50% × 80% = 40%

- Including both η'p->ηp, η'n->ηn
- Evaluated using QMD
- Consistent with experimental data

Comparison

(η+p_s) cross section



DWIA V_0=-100 MeV

DWIA V_0=-20 MeV

Indicate

Small η'N->ηN branch

or/and

Small V_0

$\Leftrightarrow$ Expectation : $Br_{\eta'N->\eta N} > 40\%$

$\Leftrightarrow$ NJL model : V_0 = -150 MeV

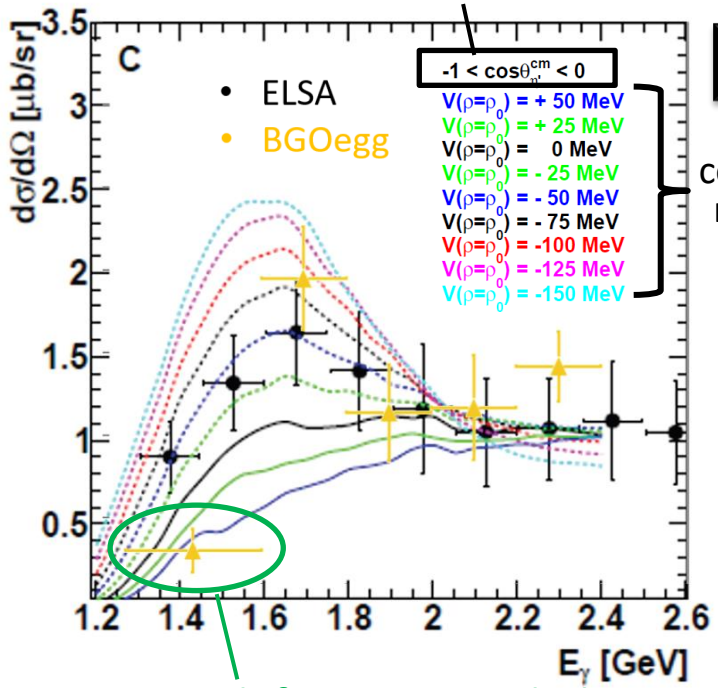
Linear sigma model = -80 MeV

Consistent with the CBELSA measurement
(V_0 = -(40±6(stat)±15(syst)) MeV)

η’ escape process

$\cos\Theta^{cm}_{\eta'}$: defined assuming a proton target (at rest)

$\gamma+^{12}C\rightarrow\eta'+p+X$



We cannot define $\cos\Theta^{cm}_{\eta'}$ below production threshold (1.447 GeV)

CBELSA (Θ_p~2~11° in lab) M. Nanova et al., Eur. Phys. J. A 54 (2018) 182

- Evaluated η’-nucleus potential from the comparison with the collision model calculation

⇒ Peak height around 1.7 GeV is important ?

- No momentum measurement of the proton, all excitation energy is included

BGOegg (Θ_p~0.9~6.8° in lab)

- Same cut conditions as CBELSA’s data ($E_{\eta'}$<500 MeV, $\cos\Theta^{cm}_{\eta'}$<0)
- Consistent cross sections except below the threshold where definition of $\cos\Theta^{cm}_{\eta'}$ is ambiguous

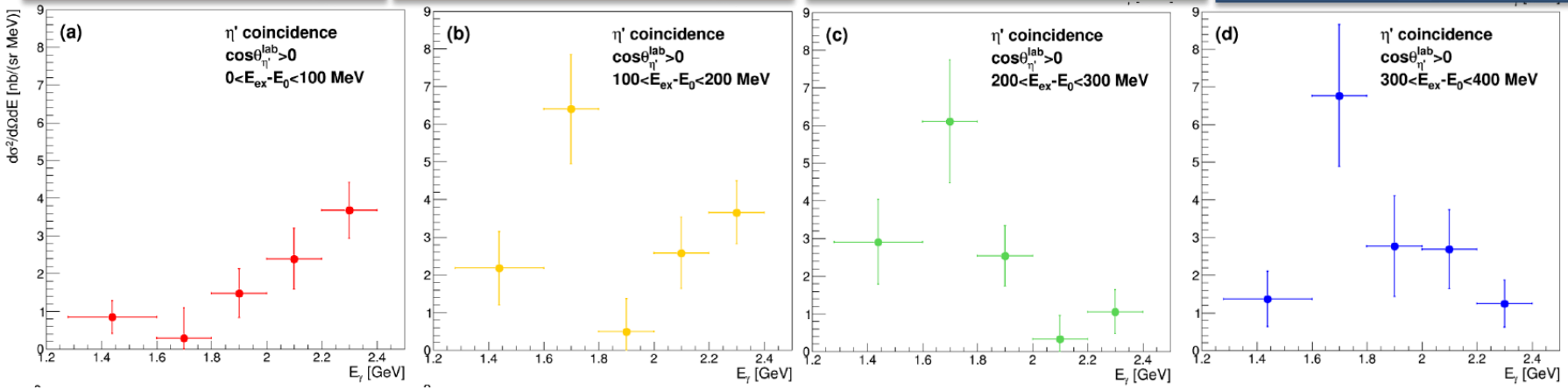
We can separate E_γ spectrum in different E_{ex}-E_0 region

$\gamma+^{12}C\rightarrow\eta'+p+X$

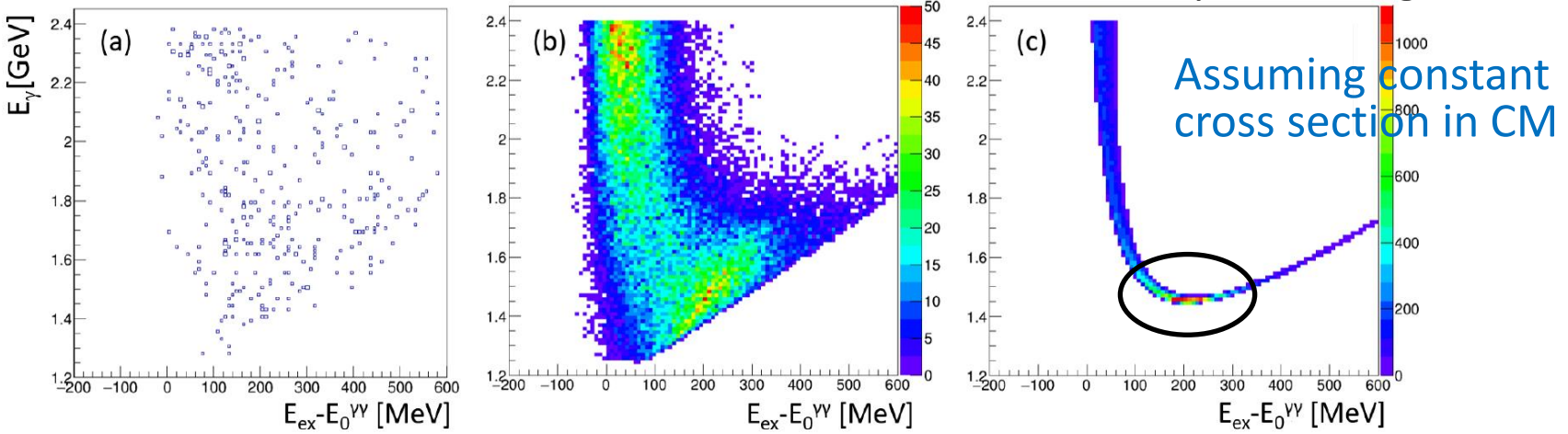
BGOegg

E_γ distribution in different E_{ex}-E_0 region

$0<E_{ex}-E_0<100$ MeV | $100<E_{ex}-E_0<200$ MeV | $200<E_{ex}-E_0<300$ MeV | $300<E_{ex}-E_0<400$ MeV



Data | MC with Fermi motion | MC with a proton target



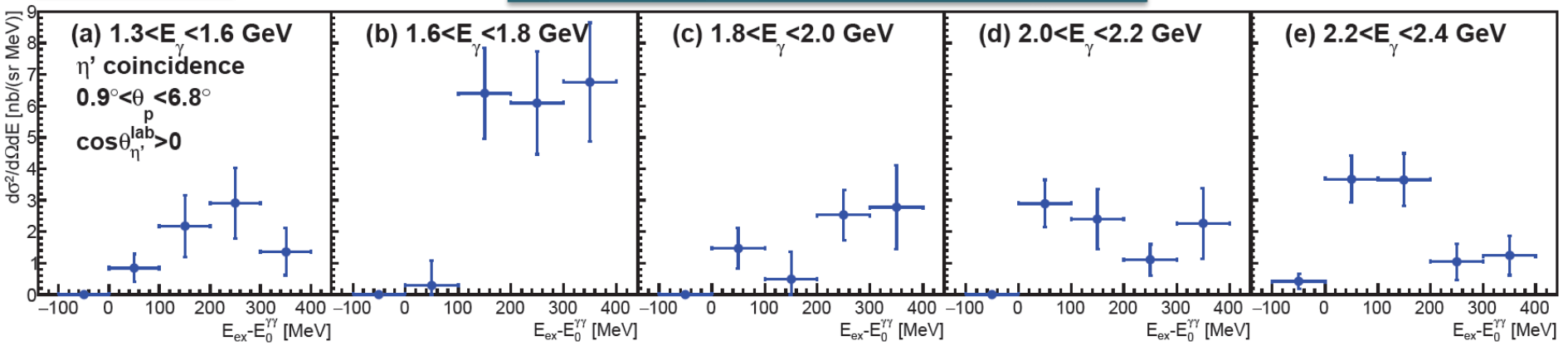
Peak comes from Large CM→Lab factor @ threshold

Collision model calculations in different E_{ex}-E_0 regions are desired

$\gamma + {}^{12}C \rightarrow \eta' + p + X$

BGOegg

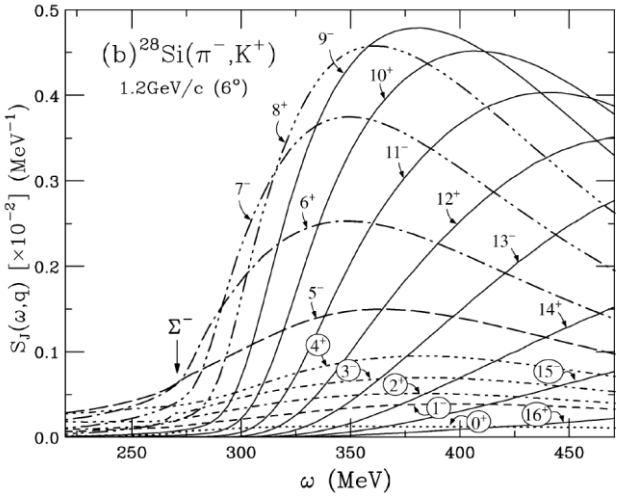
E_{ex}-E_0 distributions of different E_γ



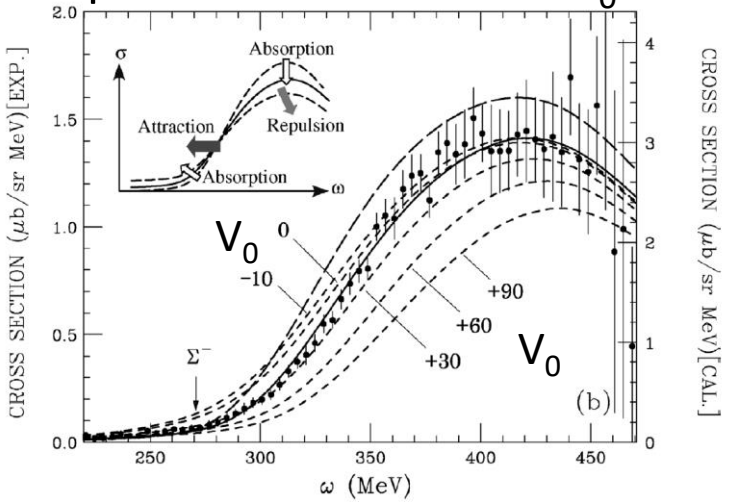
Can be compared with DWIA calculations with large η' orbit $L_{\eta'}$

cf) Σ-nucleus potential T.Harada and Y. Hirabayashi, Nucl. Phys. A 759 (2005) 143

Calculation up to L = 16



Comparison with different V_0 cases

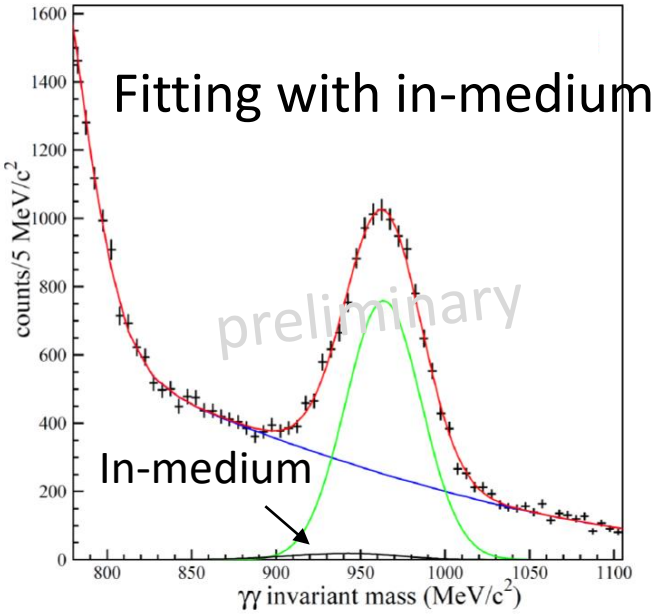


Direct measurement of η' mass spectrum

- $\gamma + {}^{12}C \rightarrow \eta' + X$, $\eta' \rightarrow 2\gamma$ (2.2%)

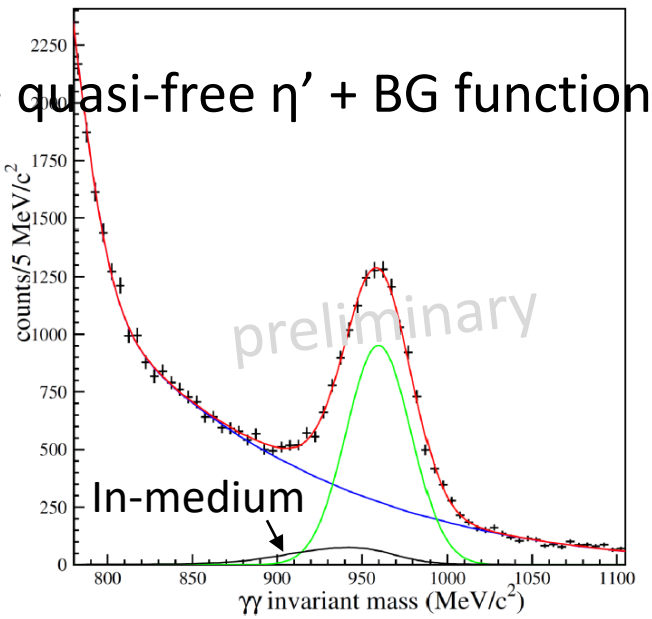
2γ invariant mass spectra (2015 data)

$p_{\eta'}$ >1000 MeV/c



Fitting with in-medium η' + quasi-free η' + BG functions

$p_{\eta'}$ <1000 MeV/c



χ^2 difference test

signal significance 0.9σ

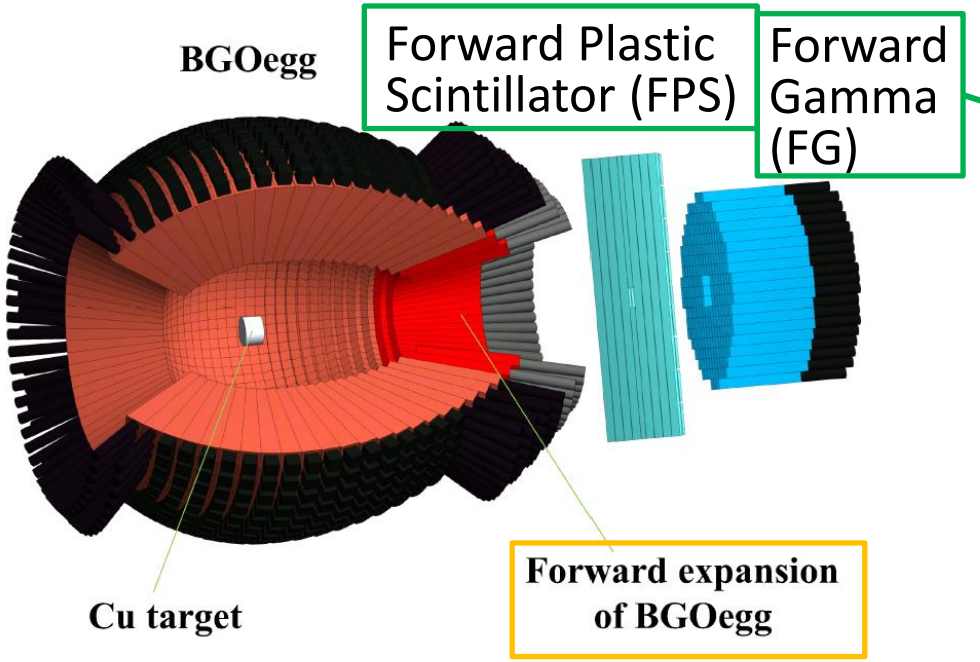
signal significance 3.7σ

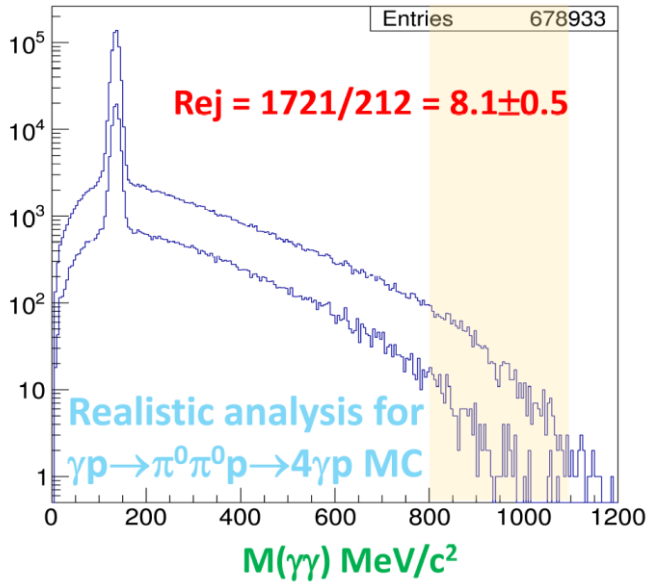
Next step

- Analysis of 2016 data → Increase statistics x2
- Phase-II experiment with reduced BG

Phase-II experiment

- Additional calorimeter in the forward hole of the BGOegg
  1. FPS, FG : BG × 1/8 2. Expansion of BGOegg : BG × 1/40
- Change the target : C(20 mm) → Cu(7 mm)
  $R_{nucleus}$ × 1.8, # of nucleons × 1.8, σ($M_{\gamma\gamma}$) × 0.6





- 2022 : Installation of readout system of FPS and FG
- 2023 : Data taking
- 2024 : Forward expansion of BGOegg

Summary

Study of η’ in medium in the LEPS2/BGOegg experiment

Phase-I (2014-2016)

1. η’-nucleus bound state search

- First simultaneous measurement of decay products (η-p)
- No signal events after kinematical selection
- Indicate small V_0 or small η’N→ηN branch
- Measurement of escaping η’ is also interesting

2. Direct measurement of η’ mass in nuclei

- Indication of in-medium modification

Phase-II (2022-)

- Additional calorimeters in the forward hole of the BGOegg
- Direct measurement of η’ mass with small background level