Studies of mass modification of the η'(958) meson in nuclei in the LEPS2/BGOegg experiment

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Reimei workshop
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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

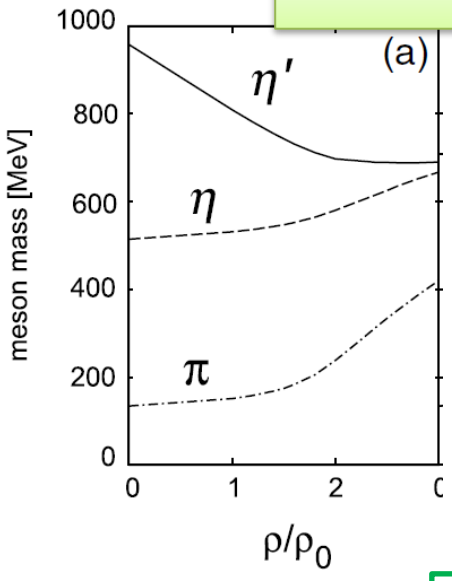
$U_A(1)$ anomaly

$U_A(1)$ 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

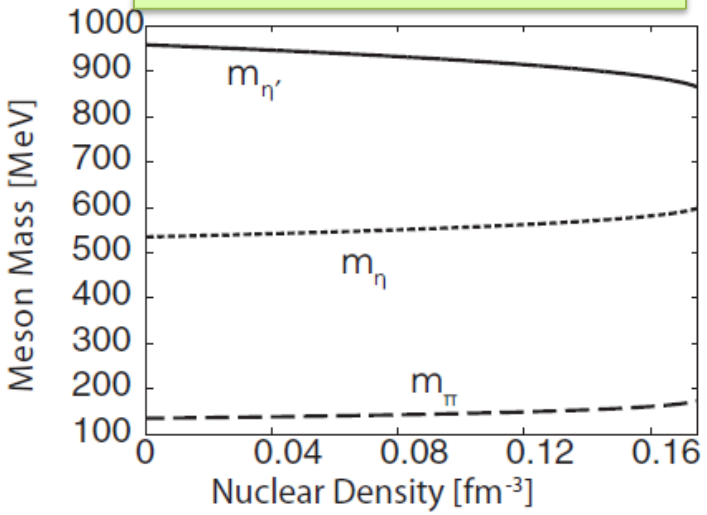
NJL model



$\Delta m(\rho_0)$ = -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

SPring-8/LEPS2 beam line

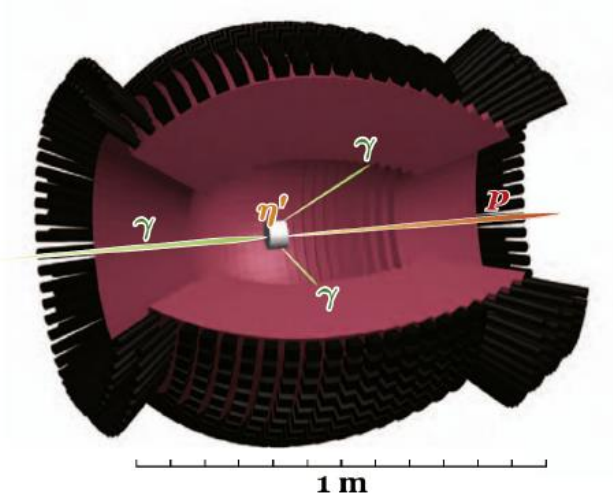
1.3-2.4 GeV γ beam

BGOegg calorimeter

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

$\eta' \rightarrow 2\gamma$, $\eta \rightarrow 2\gamma$

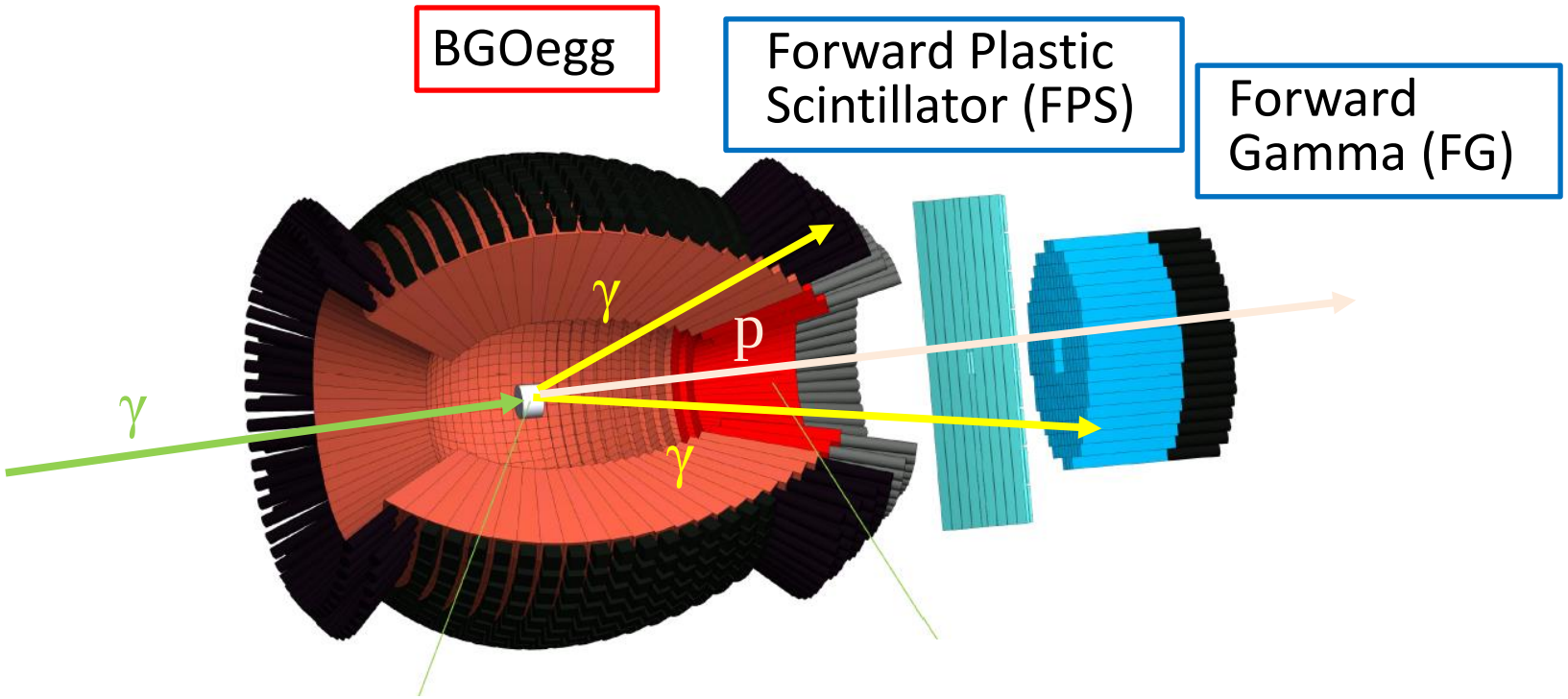
$\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$



Phase-I (2014-2016)

1. η'-nucleus bound state search N. Tomida *et al.*, PRL 124 (2020) 202501
2. Direct measurement of η' mass in nuclei Y. Matsumura , PhD thesis (2021)

BGOegg Phase-II experiment



- Additional calorimeters in the upstream hole

  ⇒ ~Full acceptance for γ rays

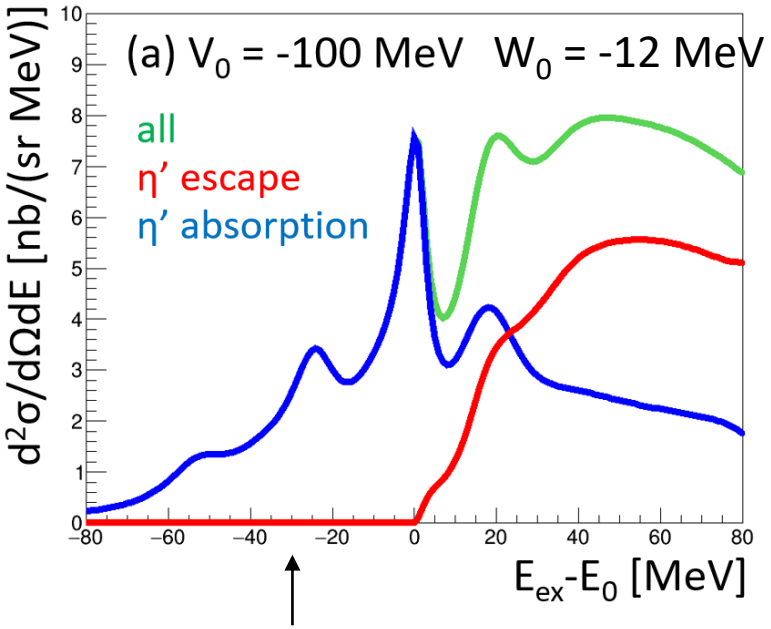
- 2022-

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

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

Our aim

Examine η'-nucleus potential

Search for a bound state

Calculation within Distorted Wave Impulse Approximation (DWIA)

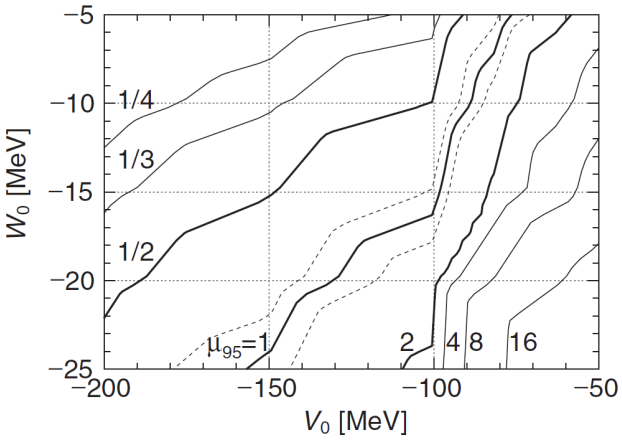
H.Nagahiro, JPS Conf. Proc. 13 (2017) 010010

Past experiments

η-PRiME@GSI

^{12}C(p,d)X

Inclusive missing mass spectroscopy



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

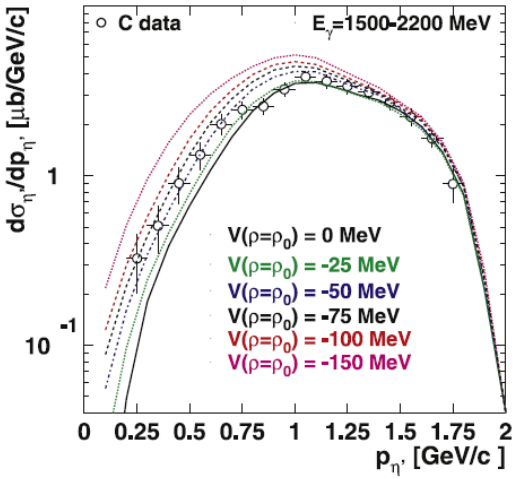
Y.K. Tanaka, PRC 97 (2018) 015202

- 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

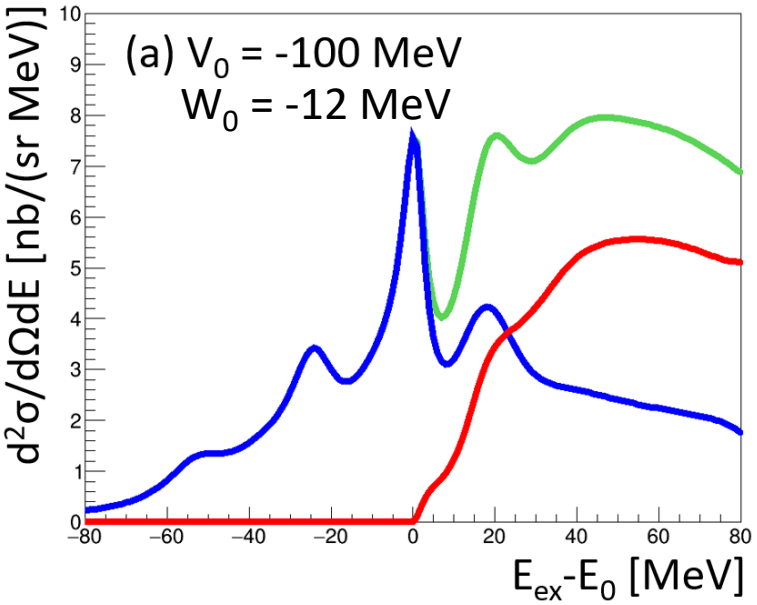
S. Friedrich et al., Eur. Phys. J A 52 (2016) 297

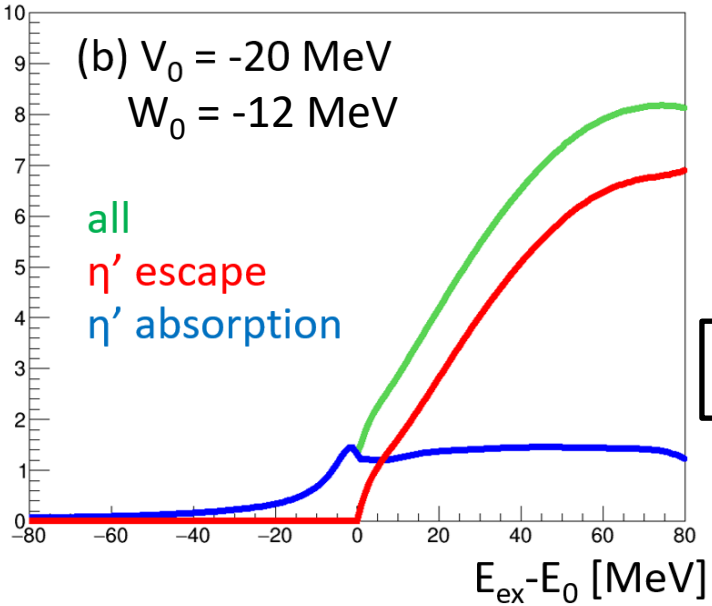
- V_0 = -(40±6(stat)±15(syst)) MeV from comparisons with **the collision model**
- W_0 = -(13±3(stat)±3(syst)) MeV from **the transparency measurement**

Present experiment

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

Tag decay products from η' in nucleus to reduce BG





DWIA calculation

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

E_{ex}-E_0<50 MeV

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

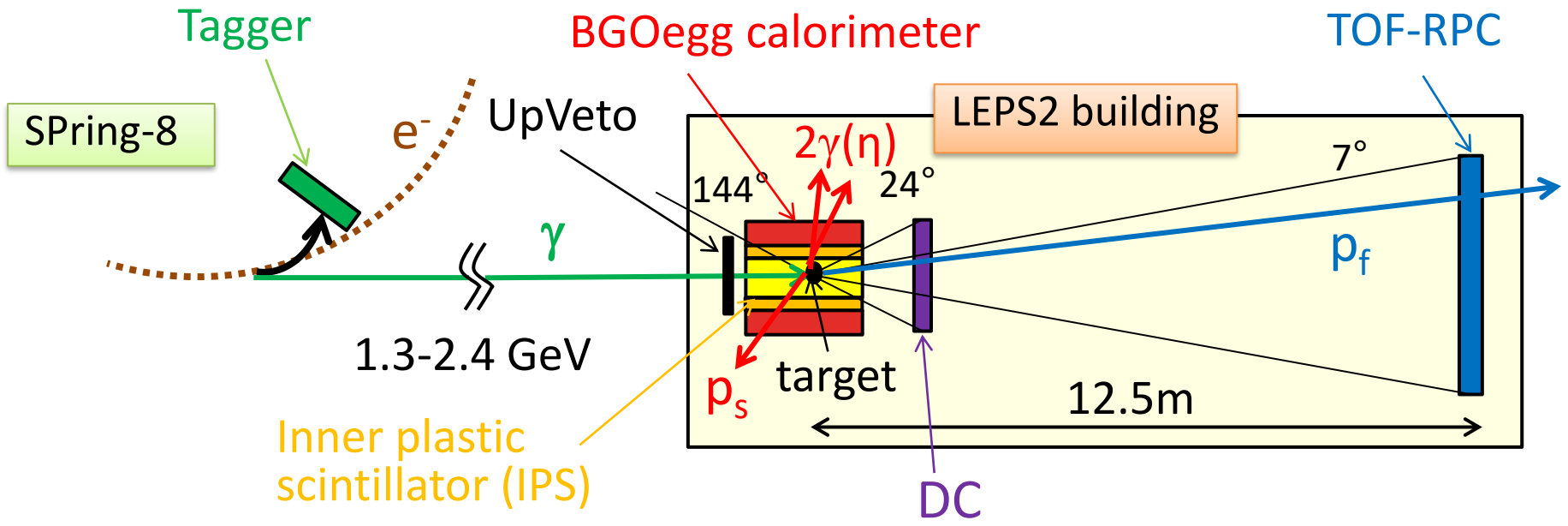
$$\gamma + {}^{12}\mathrm{C} \to p_f + \eta' \otimes {}^{11}\mathrm{B}$$
$$\hookrightarrow \eta' + p \to \eta + p_s$$

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

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

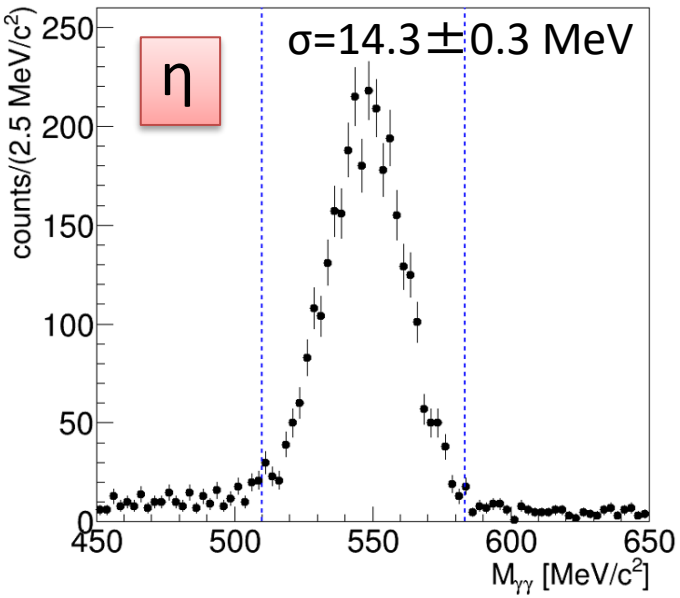
Experimental set up

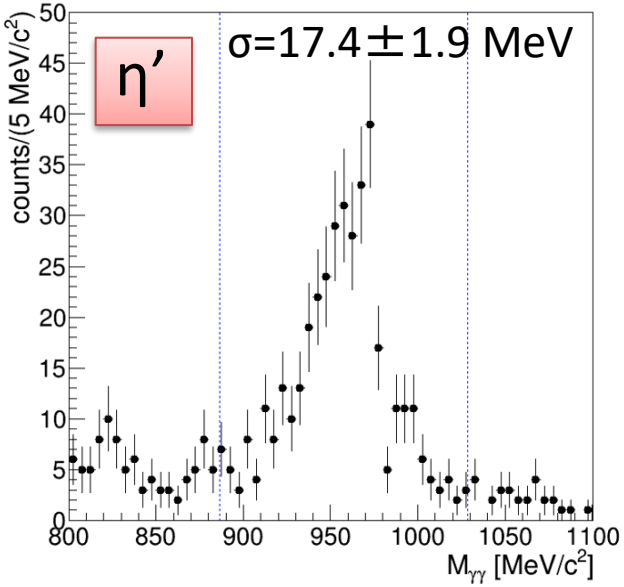
- LEPS2 beam line @ SPring-8
- 2015/Apr-Jul



- $\gamma + {}^{12}C \rightarrow p_f + (\eta + p_s) + X$: bound state search ($\eta'N \rightarrow \eta N$)
- $\gamma + {}^{12}C \rightarrow p_f + \eta' + X$: production rate of η'
  - Missing mass spectroscopy of ${}^{12}C(\gamma, p_f)$: Tagger, TOF-RPC
  - Decay products ($\eta + p_s$), η' : BGOegg, IPS
  - No other detected particles
- Trigger : Tagger × BGOegg 2 crystal hits
  => Simultaneous measurements of ($\eta + p_s$) and η' tag modes
  η' mass spectrum study

Particle identification



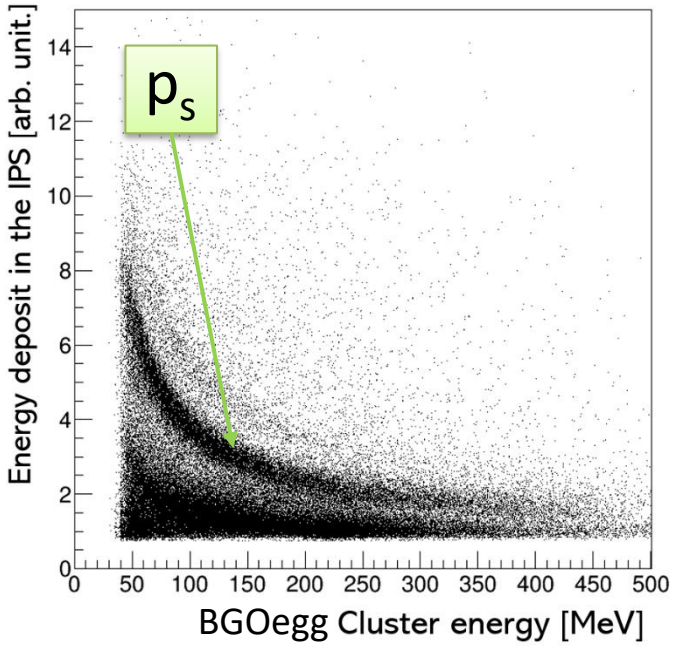


- 2γ invariant mass (BGOegg)

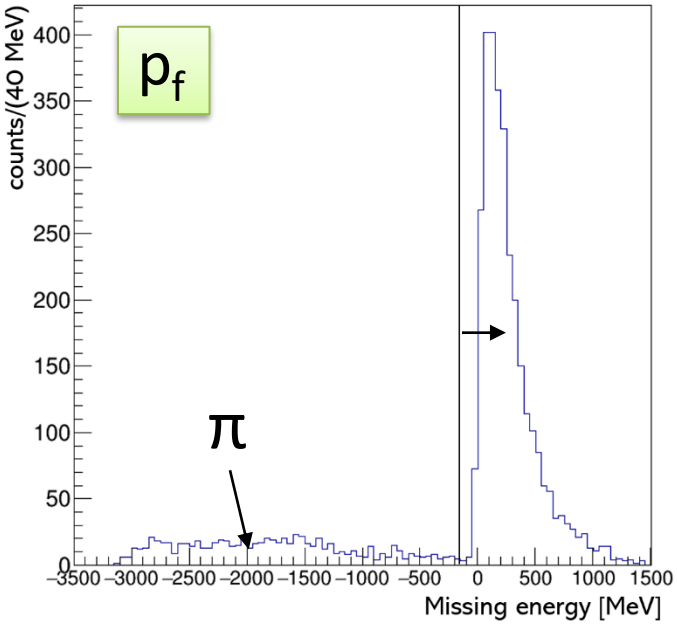
  η : Br=39%

  η' : Br=2.2%

- Small combinatorial BG



- dE-E (BGOegg, IPS)



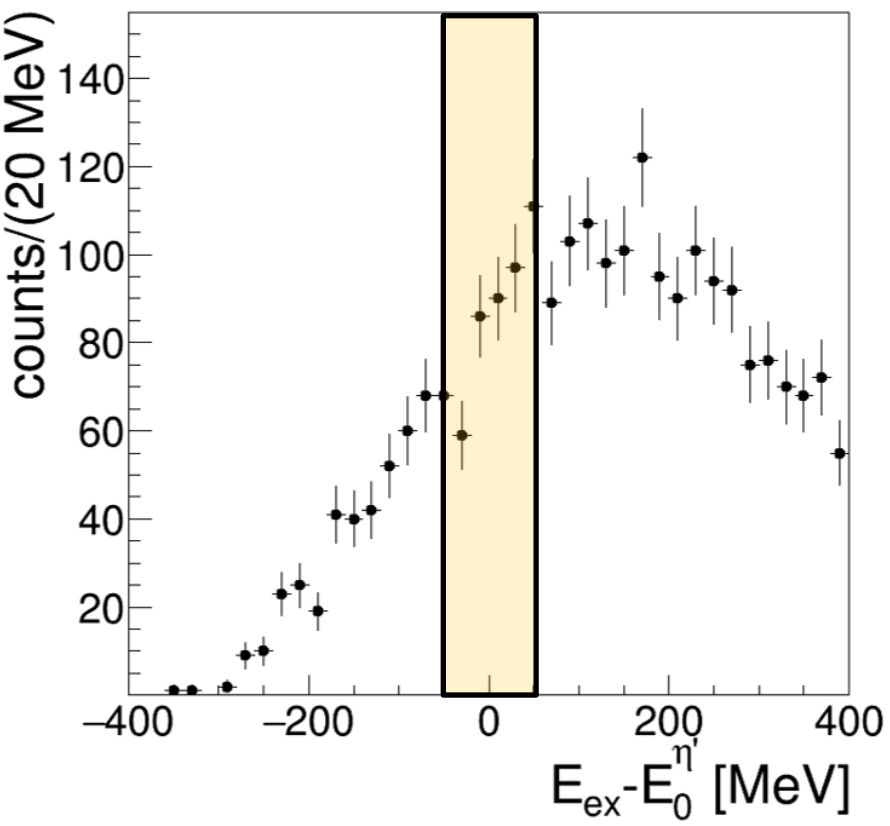
- missing energy E_i-E_f (no PID detector, assume it is a proton)

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)

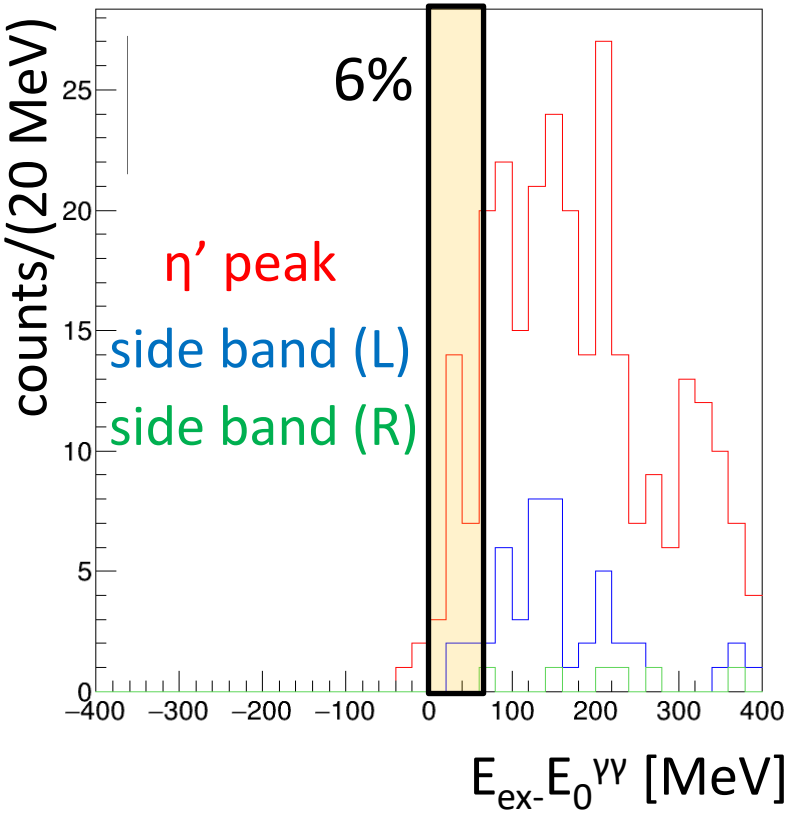


No signal enhancement

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 source

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

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

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

$$\gamma + {}^{12}\mathrm{C} \to p_f + \eta + \pi^- + {}^{11}\mathrm{C}$$
$$\hookrightarrow \pi^- + p + p \to p_s + n.$$

Forward-going η Undetected π

(η+p_s) kinematical cut

- Optimize to maximize S/N ratio & signal yield : Blind analysis
  - Signal : simulation (isotropic back-to-back ηp_s pair + FSI in nuclei (QMD))
  - BG : side-band data ($\cos(\eta p_s)<-0.9$, $100<|E_{ex}-E_0|<200$ MeV)

(a) **Opening angle $\cos(\eta p_s)<-0.9$** <= 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 $\cos(p_s)<0.5$**

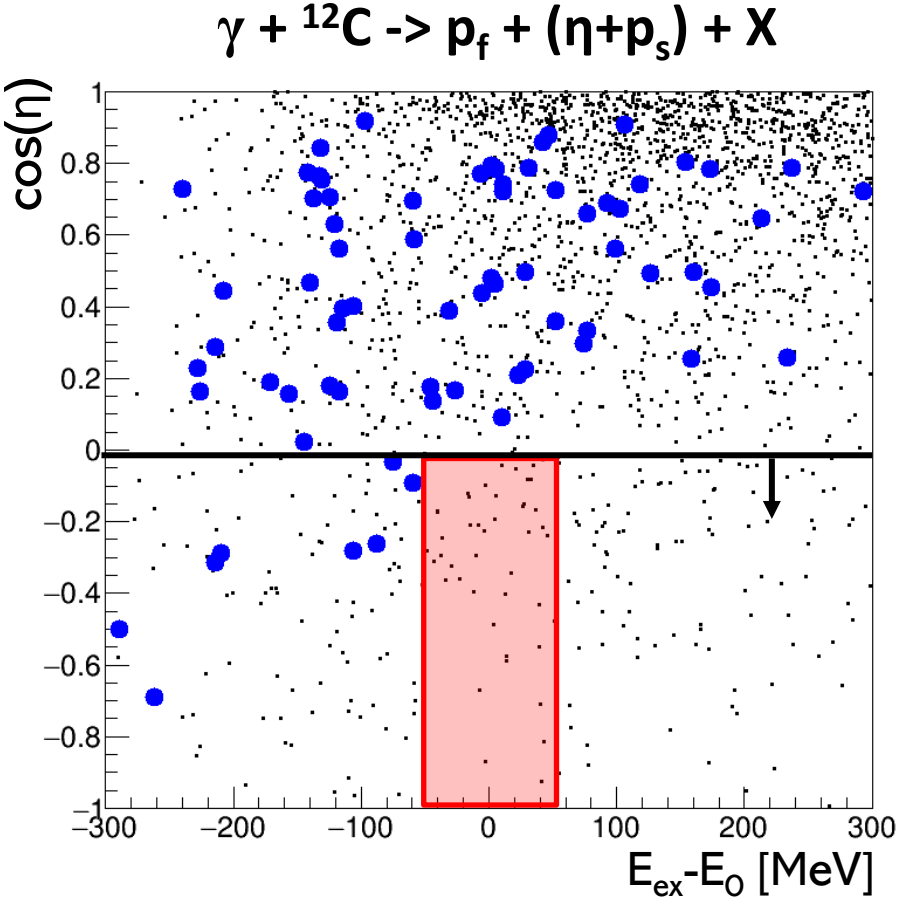
(d) **Polar angle $\cos(\eta)<0$**

<= signal : Isotropic distribution; BG : concentrate in forward

$E_{ex} - E_0^{\eta'}$ region [MeV]	Side band $[-300, -200]$	Side band $[-200, -100]$	(V_0 = -100 MeV) expected signal $[-50, 50]$	Side band $[100, 200]$	Side band $[200, 300]$
no cuts	67	188	$(58.4 \pm 14.7) \times \mathrm{Br}_{\eta' N \to \eta N}$	507	438
(a):$\cos\theta_{lab}^{\eta p_s} < -0.9$	11	26	$(43.8 \pm 11.0) \times \mathrm{Br}_{\eta' N \to \eta N}$	24	18
(a), (b):$\lvert E_{miss}^{\eta p_s p_f}\rvert < 150$ MeV	11	24	$(43.8 \pm 11.0) \times \mathrm{Br}_{\eta' N \to \eta N}$	9	4
(a), (b), (c):$\cos\theta_{lab}^{p_s} < 0.5$	9	18	$(35.7 \pm 9.0) \times \mathrm{Br}_{\eta' N \to \eta N}$	9	4
(a), (b), (c), (d):$\cos\theta_{lab}^{\eta} < 0$	4	1	$(13.1 \pm 3.3) \times \mathrm{Br}_{\eta' N \to \eta N}$	0	0

BG : Reduced to 0.4% Signal : Preserve 23%

η'-nucleus search result



- no $\eta+p_s$ kinematical cut
- $\eta+p_s$ cut **(a)-(c)**

No events satisfying cuts**(a)-(d)** in $-50<E_{ex}-E_0<50$ MeV

No $(\eta+p_s)$ signals from η' bound state are observed

Upper limit of the production cross section of η'-nucleus with $(\eta+p_s)$ emission : **2.2 nb/sr**
@$\cos(\eta p_s)<-0.9$
(E_γ=1.3-2.4 GeV average)

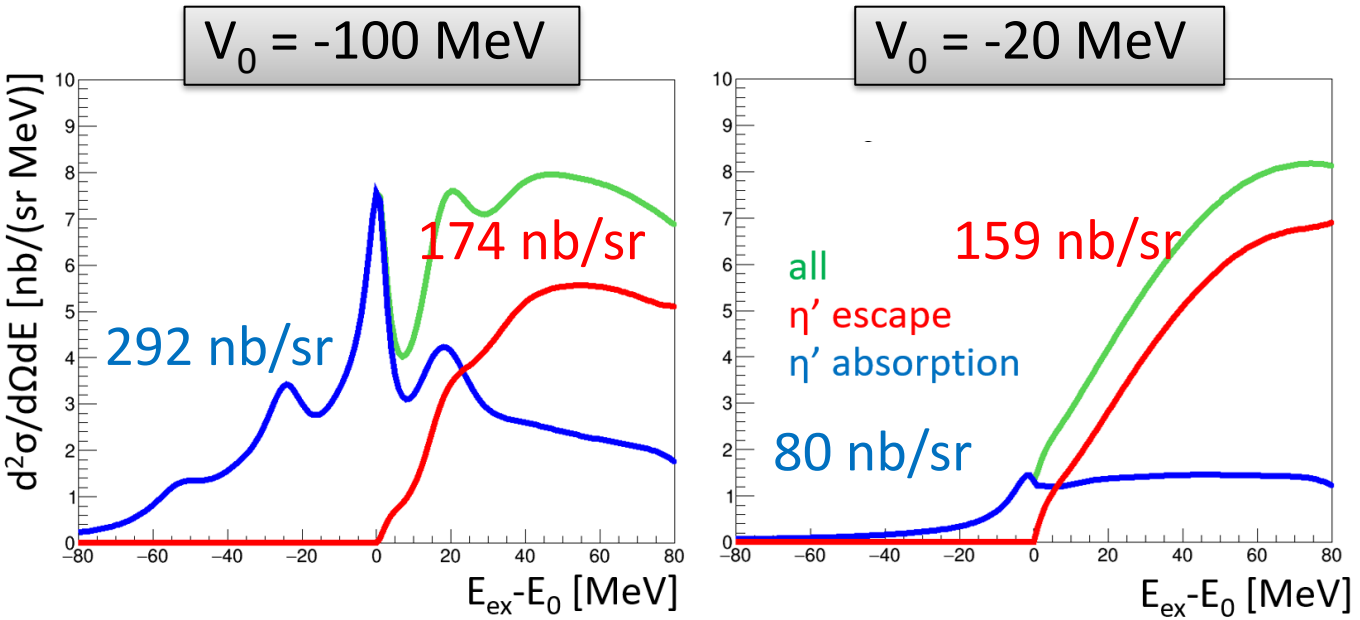
=> Compare with the DWIA calculation to discuss η'-nucleus potential

Comparison with theoretical calculation

DWIA calculation

Input : Fermi averaged γp→η'p elementary cross section <= CBELSA/LEPS data

W_0=-12 MeV



E_γ=1.3-2.4 GeV average

η' absorption : $-50<E_{ex}-E_0<50$ MeV

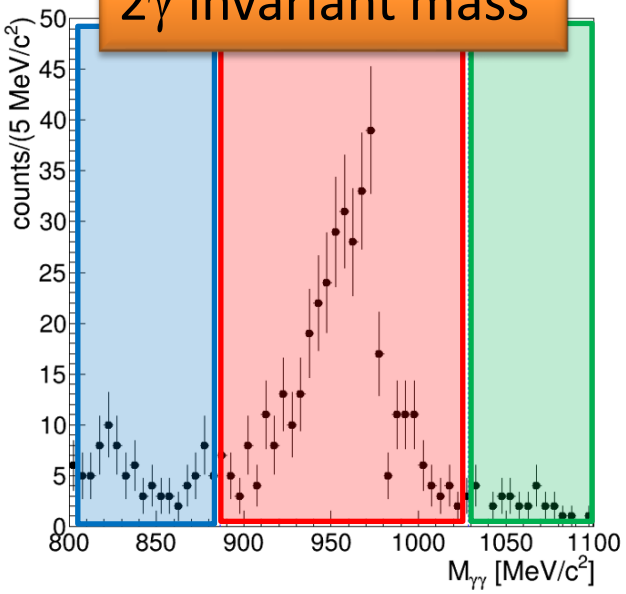
η' escape : $0<E_{ex}-E_0<50$ MeV

Experiment

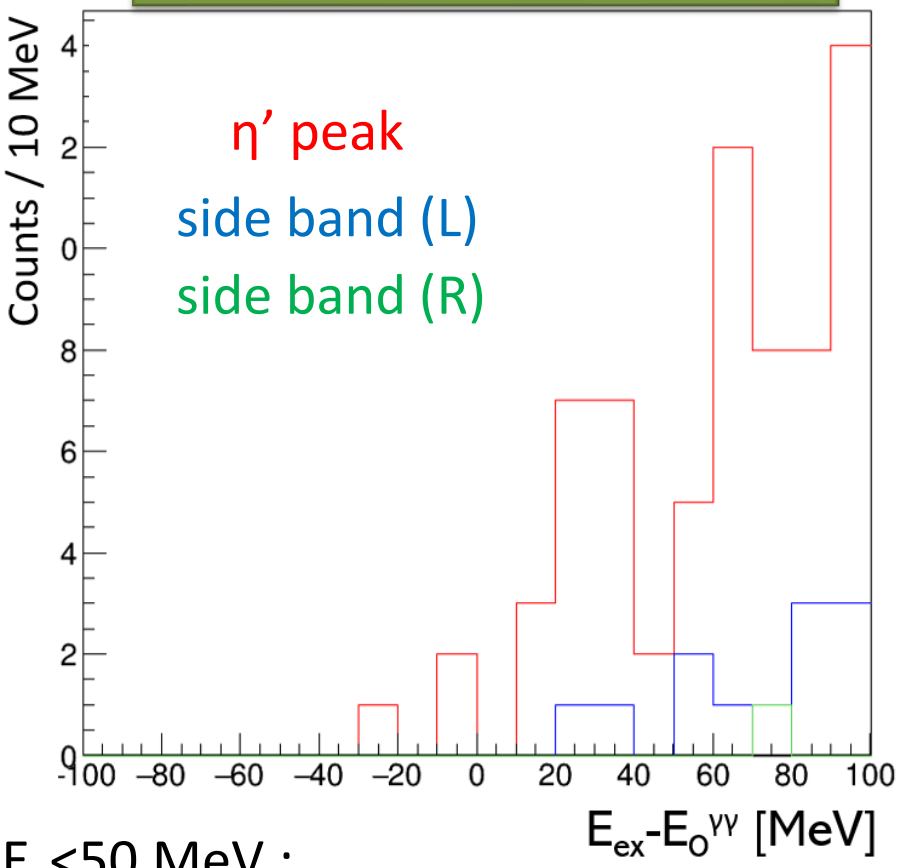
- η' absorption **($\eta+p_s$)**
  No events in $-50<E_{ex}-E_0<50$ MeV
  < 2.2 nb/sr
  => Small V_0 ?
  Small η'N->ηN branch ?
  Small η' production rate ?
- η' escape
  60.2±15.4(stat)±4.1(syst) nb/sr
  => Normalization factor of the DWIA calculation : ~1/3

η’ escape

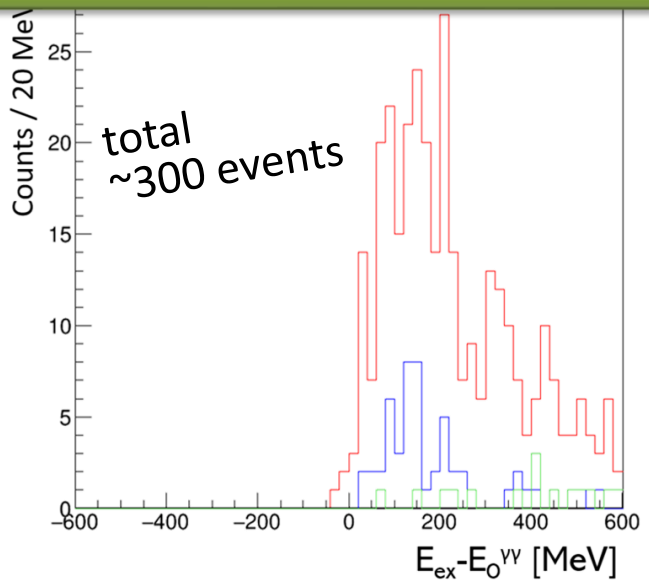
2γ invariant mass



Excitation energy spectrum



Wide excitation energy spectrum



$0<E_{ex}-E_0<50$ MeV :

17±4 events

60.2±15.4(stat)±4.1(syst) nb/sr

(E_γ=1.3-2.4 GeV average)

Theoretical $(\eta+p_s)$ cross section

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

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

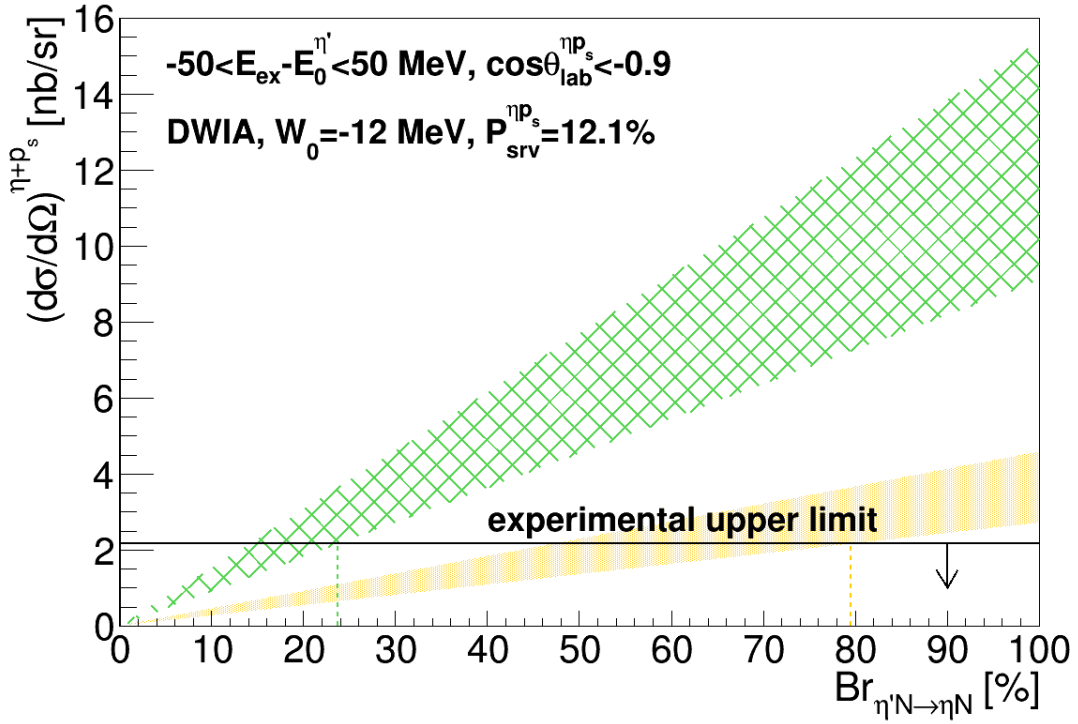
  E. Oset and A. Ramos PLB 704 (2011) 334

=> 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

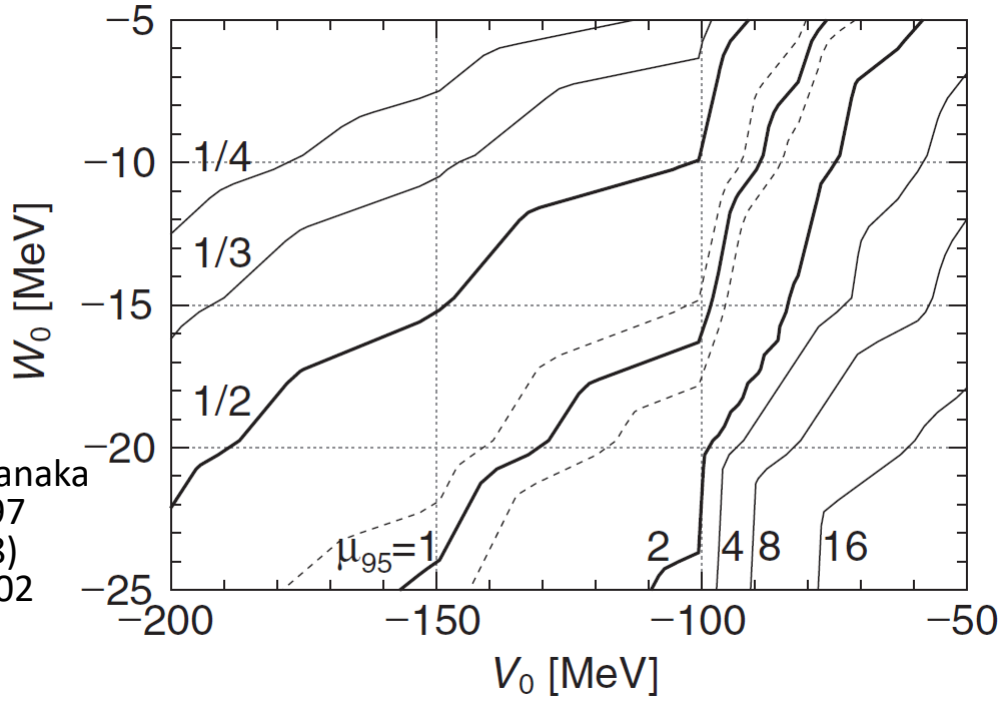
Comparison with past experiments

CBELSA/TAPS

V_0 = -40 ± 6(stat) ± 15(syst) MeV Consistent

Eta-PRiME/Super FRS

- Derived from the comparison with a similar DWIA calculation
- Uncertainty of the elementary n(p,d)η' cross section : ~2
- Uncertainty of the DWIA calculation : ~3 <- in our case



Y.K. Tanaka
PRC 97
(2018)
015202

Prospects of the η'-nucleus study

- New DWIA calculation
  - E_{ex}-E_0>50 MeV => Tighter upper limit
    Evaluation of potential using η' escape events
  - Different parameters (W_0, potential shape)

H. Fujioka *et al*., PRL 126 (2021) 019201

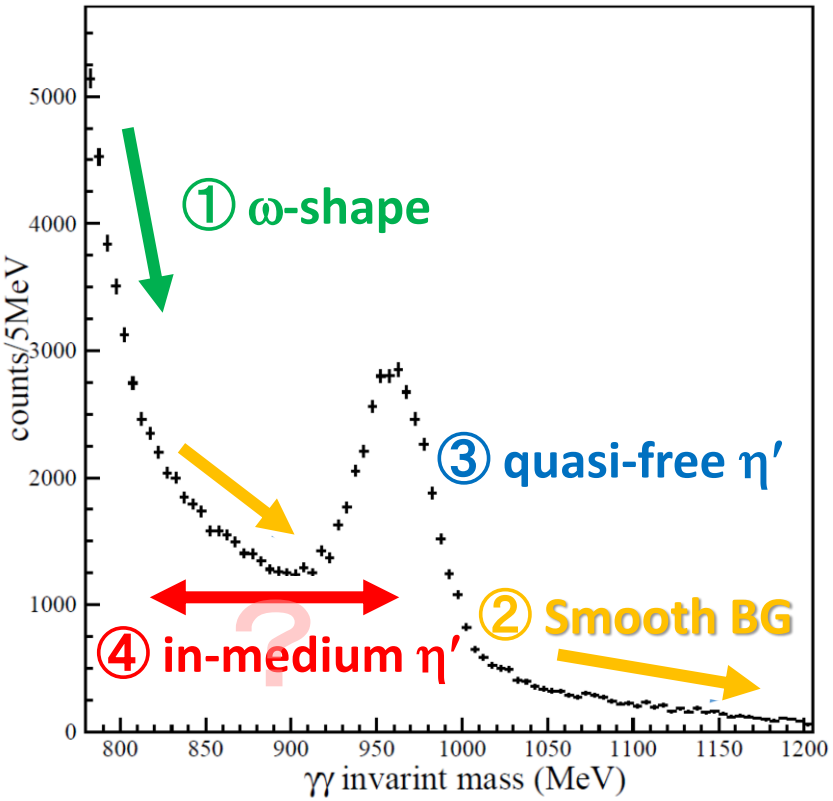
- Analysis of η'NN -> NN decay mode using existing BGOegg data
- Analysis of 2016 data

Direct measurement of η' mass spectrum

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

- 2 neutral BGOegg cluster (2γ)
- 1 or 0 charged BGOegg cluster (p)

2015 all data



Fitting function

① $\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$, 1γ missing

MC

② $2\pi^0 \rightarrow 4\gamma$ & $\pi^0\eta \rightarrow 4\gamma$, 2γ missing

$\exp(p_0 + p_1x + p_2x^2 + p_3x^3)$

③ quasi-free η'

gaussian with fixed σ

④ In-medium η'

MC

In-medium η’ spectrum

- Parameters of in-medium effect k_1 & k_2

$$m_{\eta'}(\rho) = m_0(1 - k_1\frac{\rho}{\rho_0})$$

$$\Gamma_{\eta'}(\rho) = \Gamma_0(1 + k_2\frac{\rho}{\rho_0})$$

$m_0 = 957.8\,\mathrm{MeV}$, $\Gamma_0 = 0.197\,\mathrm{MeV}$

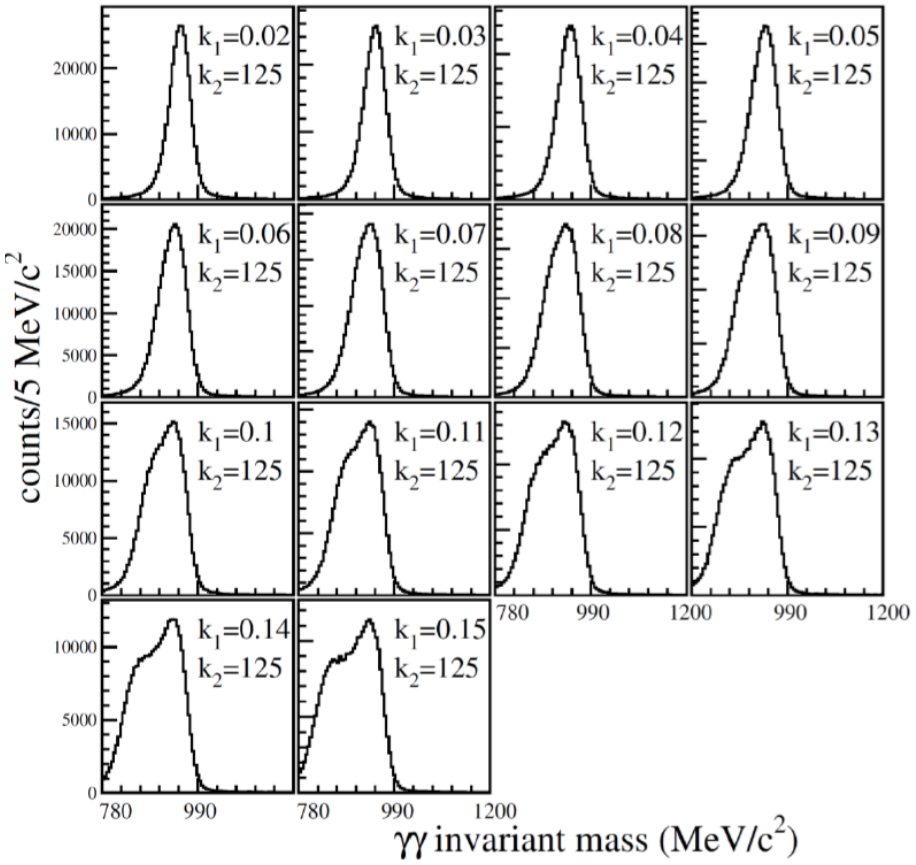
ρ_0 : nuclear saturation density

$\rho(r) \propto [1 + \exp\{(r - R)/d\}]^{-1}$

R=2.3 fm

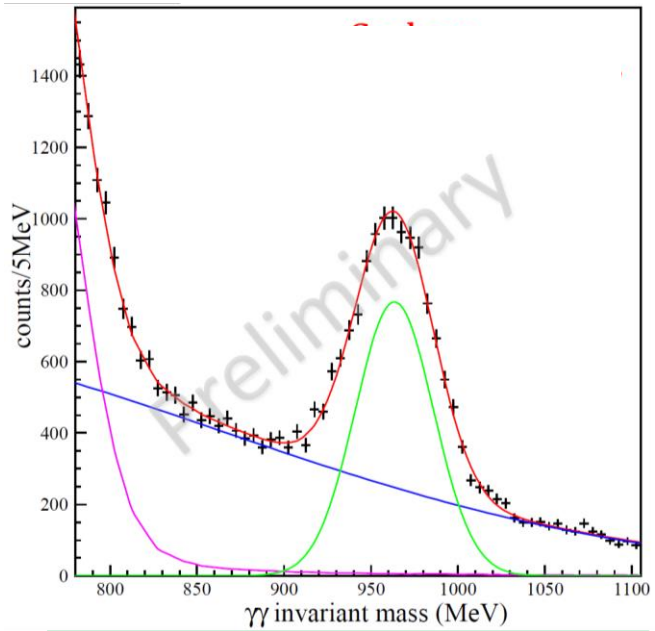
d=0.57 fm for C

- η’ propagation in nuclei and the mass distribution at the decay point
- Detector resolution



Fitting results

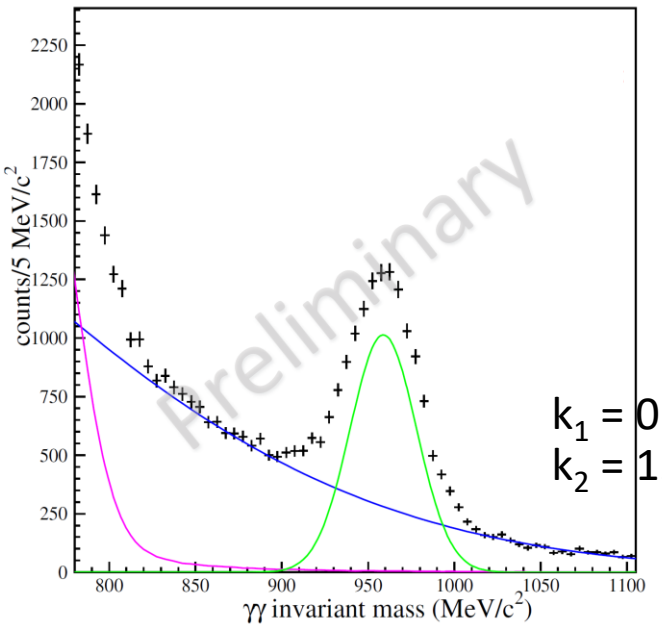
$p_{\eta'}$ >1000 MeV/c



χ^2 difference test

signal significance 0.9σ

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



k_1 = 0.06
k_2 = 125

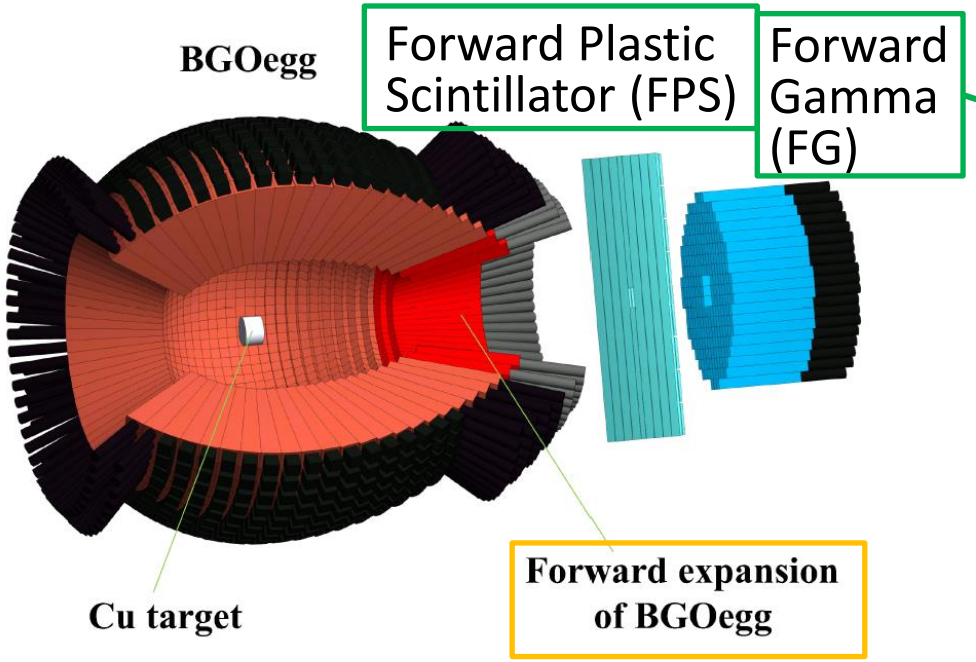
signal significance 3.7σ

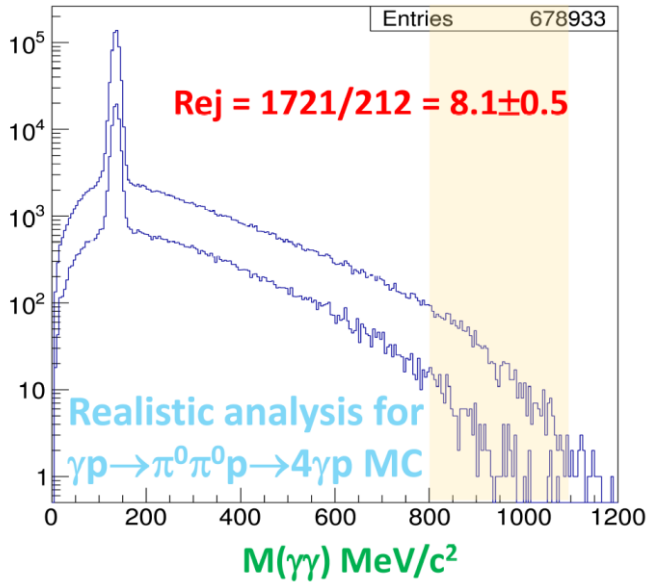
Next step

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

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, $\sigma(M_{\gamma\gamma})$ × 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

- Update DWIA calculation, Analysis of η'N→NN decay mode

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