

Studies of the eta- prime meson mass in nuclei with the BGOegg calorimeter

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EMMI WORKSHOP

Physics Motivation

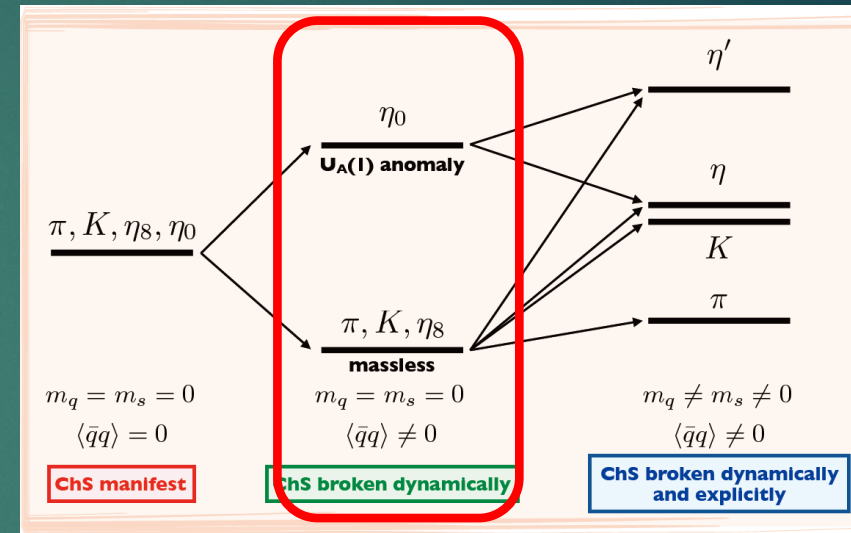
- ▶ We want to get a clue of evidence for partial restoration of spontaneously broken chiral symmetry.
- ▶ We pay attention to hadron(η') mass in a nucleus.
- ▶ The η' meson provides an attractive way to explore the relation between chiral symmetry and UA(1) anomaly.

- ▶ S. Kono et al., PTEP 2021 093D02.
- ▶ S.H. Lee and T. Hatsuda. PRD 54 (1996) R1871
- ▶ T.D. Cohen, PRD 54 (1996) R1867;

→ η' mesic nucleus search

η' (958) and $U_A(1)$ anomaly

- ▶ The η' mass measured is more than twice that theoretically expected value.
- ▶ Origin of large η' mass
 - ▶ Chiral symmetry breaking
 - ▶ $U_A(1)$ anomaly



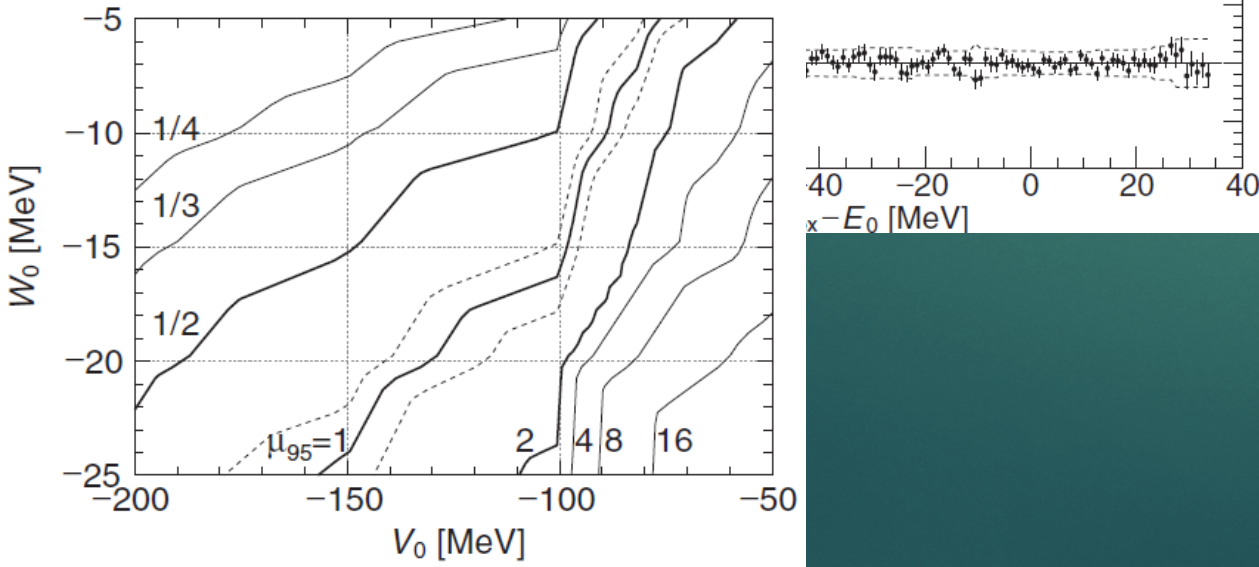
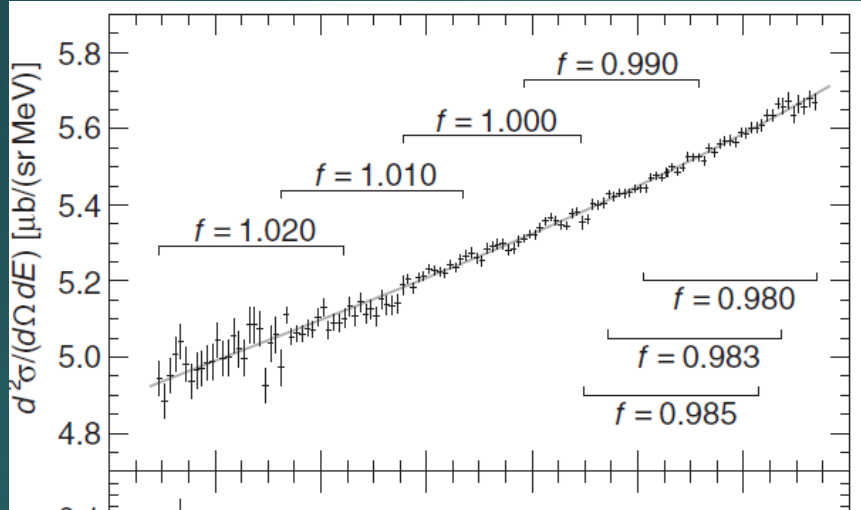
Daisuke Jido, Hideko Nagahiro, and Satoru Hirenzaki,
Phys. Rev. C 85 (2012) 032201 (R).

theoretical calculations predict a large amount of mass decrease in the nuclear medium: 150(NJL) and 80(LSM) MeV

η' mesic nuclei search

- ▶ In-direct measurement
 - ▶ Missing energy method
 - ▶ η -PRiME/Super-FRS @GSI : $^{12}\text{C}(p,d)$
 - ▶ LEPS2/BGOegg (phase-I) : $^{12}\text{C}(\gamma,p)$
 - ▶ Carbon target with proton missing energy spectrum
- ▶ Direct η' measurement from nuclei
 - ▶ Y. Matsumura (ELPH), Doctor thesis at Tohoku University.
 - ▶ $\gamma\gamma$ Invariant mass spectrum
- ▶ Study of $6\text{-}\gamma$ modes in a future experiment.
 - ▶ $\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$
 - ▶ $f_1(1285) \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$

Experimental results



▶ CBELSA/TAPS : η' A interaction

▶ transparency ratio /differential cross sections for low momentum η'

▶ $V_0 \sim -40$ MeV & $W_0 \sim -13$ MeV

- ▶ M. Nanovaet al., PLB 710 (2012) 600.
- ▶ M. Nanovaet al., PLB 727 (2013) 417.
- ▶ M. Nanovaet al., PRC 94 (2016) 025205.
- ▶ S. Friedrich et al., EPJA 52 (2016) 297.
- ▶ M. Nanovaet al., EPJA 54 (2018) 182.

▶ η -PRIME/Super-FRS @GSI : $^{12}\text{C}(p,d)$

▶ Missing mass spectroscopy w/o abs. tag

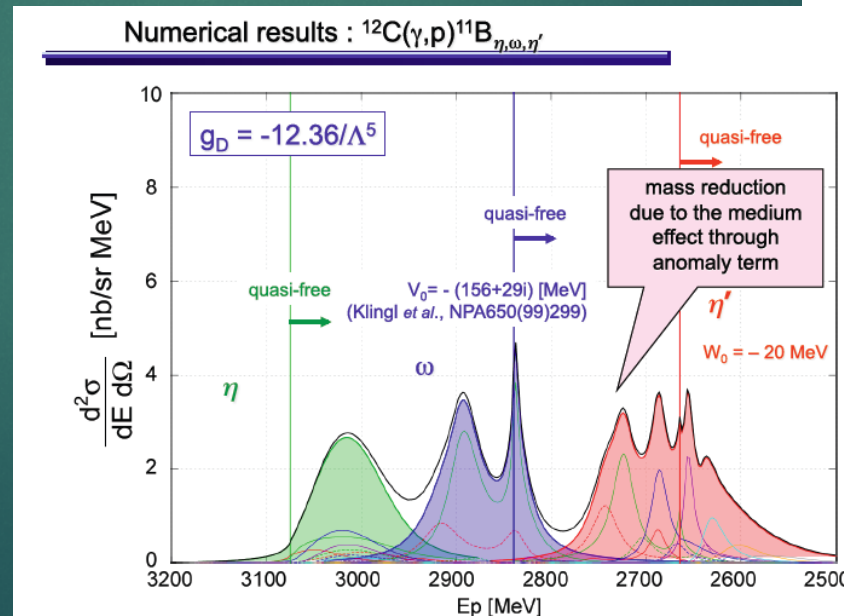
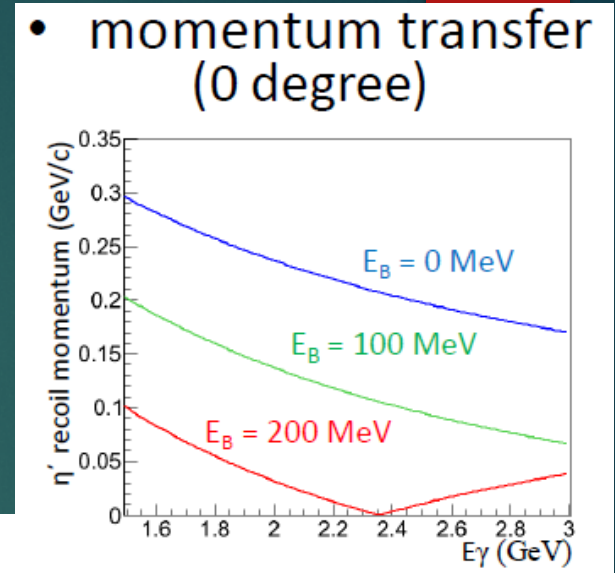
▶ Large $|V_0|$ (~ 150 MeV) is unfavored.

- ▶ Y.K. Tanaka et al., PRL 117 (2016) 202501.
- ▶ Y.K. Tanaka et al., PRC 97 (2018) 015202.

η' mesic nuclei in (γ, p) reaction

- ▶ Low recoil momentum of η'
- ▶ Experimental parameters
 - ▶ E_γ 1.6~2.9 GeV
 - ▶ Target C
 - ▶ Forward proton detection
- ▶ cf. $^{12}\text{C}(p, d)$ reaction

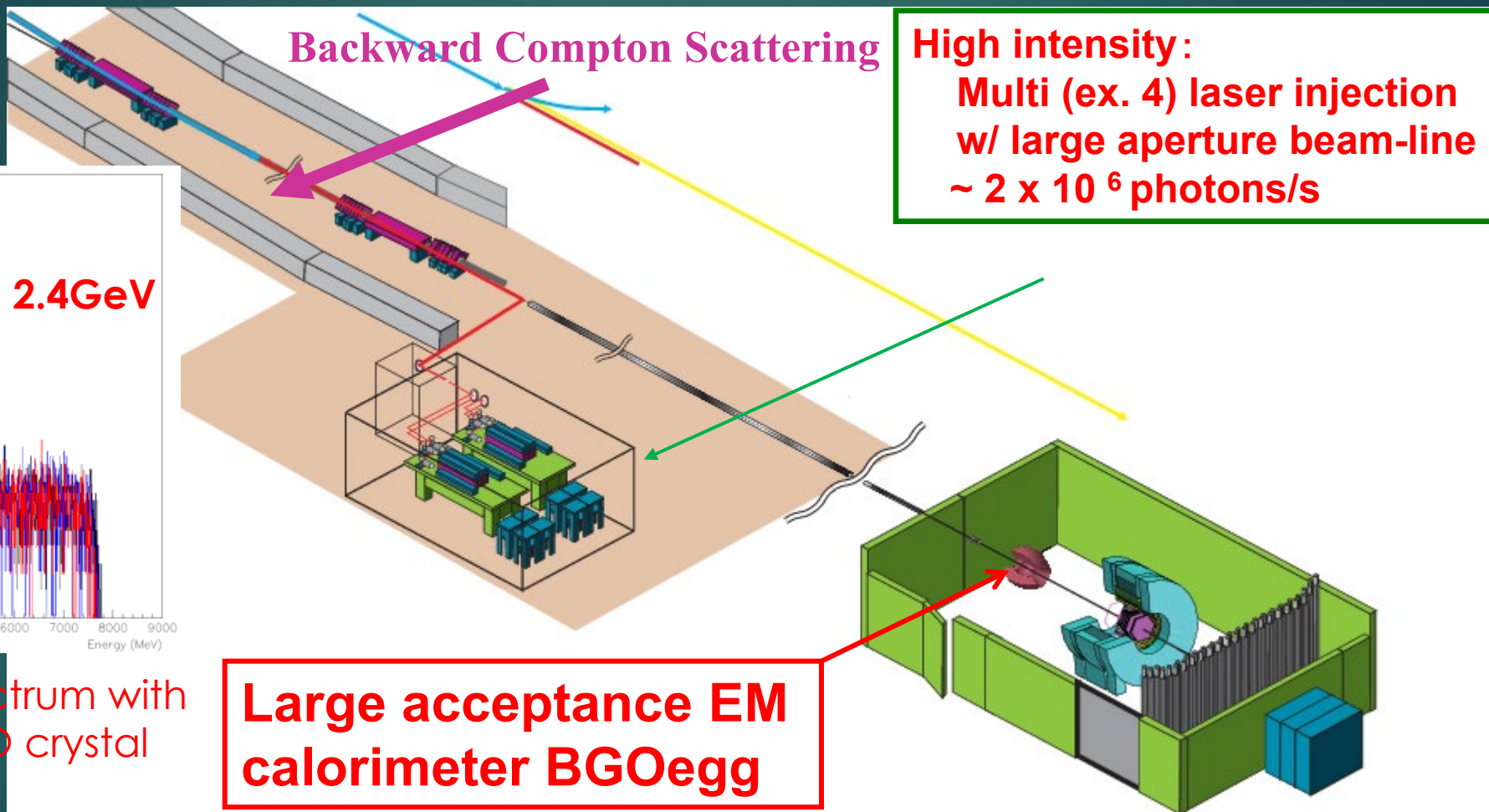
at η -PRiME/Super-FRS Collaboration



$\text{C}(\gamma, p)\text{X}$ missing mass
Hirenzaki@ELPH 2011

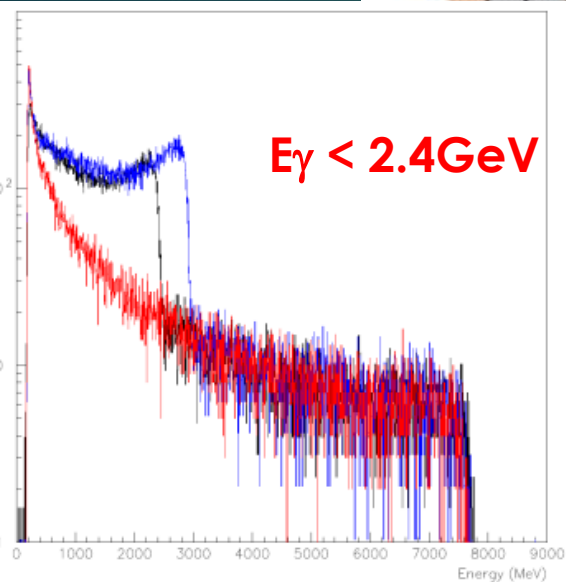
LEPS2/BGOegg experiment

LEP2 Project at SPring-8



High intensity:
Multi (ex. 4) laser injection
w/ large aperture beam-line
~ 2 x 10⁶ photons/s

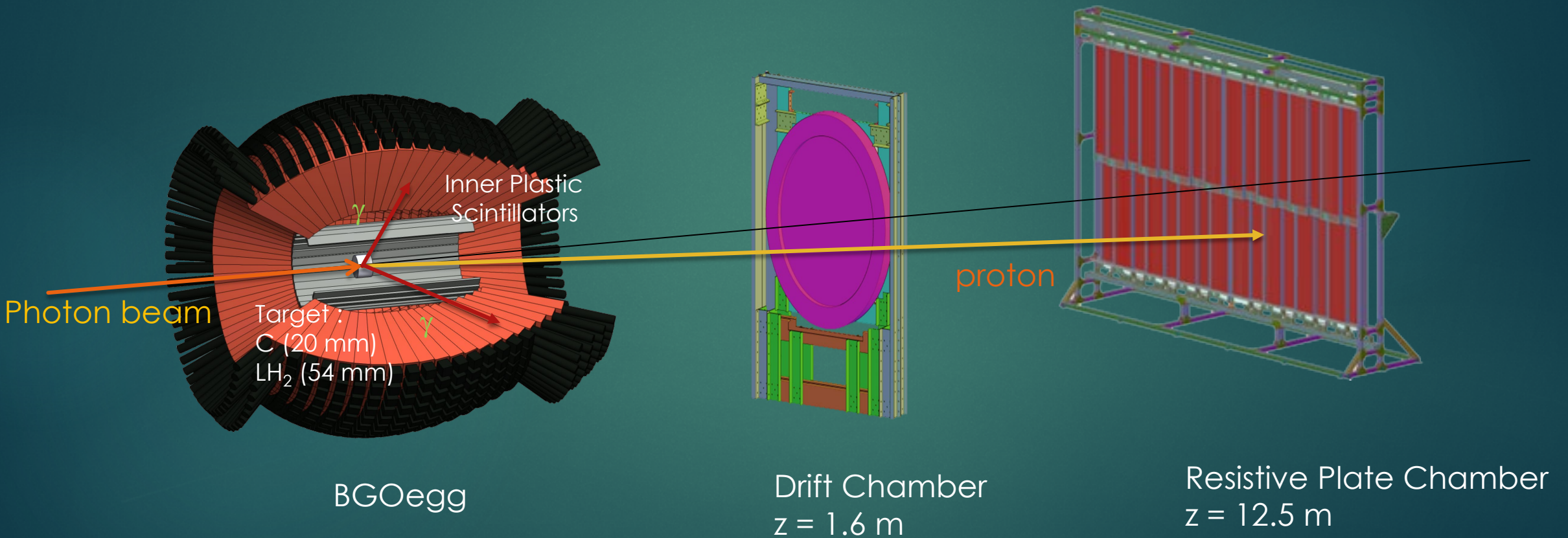
**Large acceptance EM
calorimeter BGOegg**



E_γ < 2.4 GeV

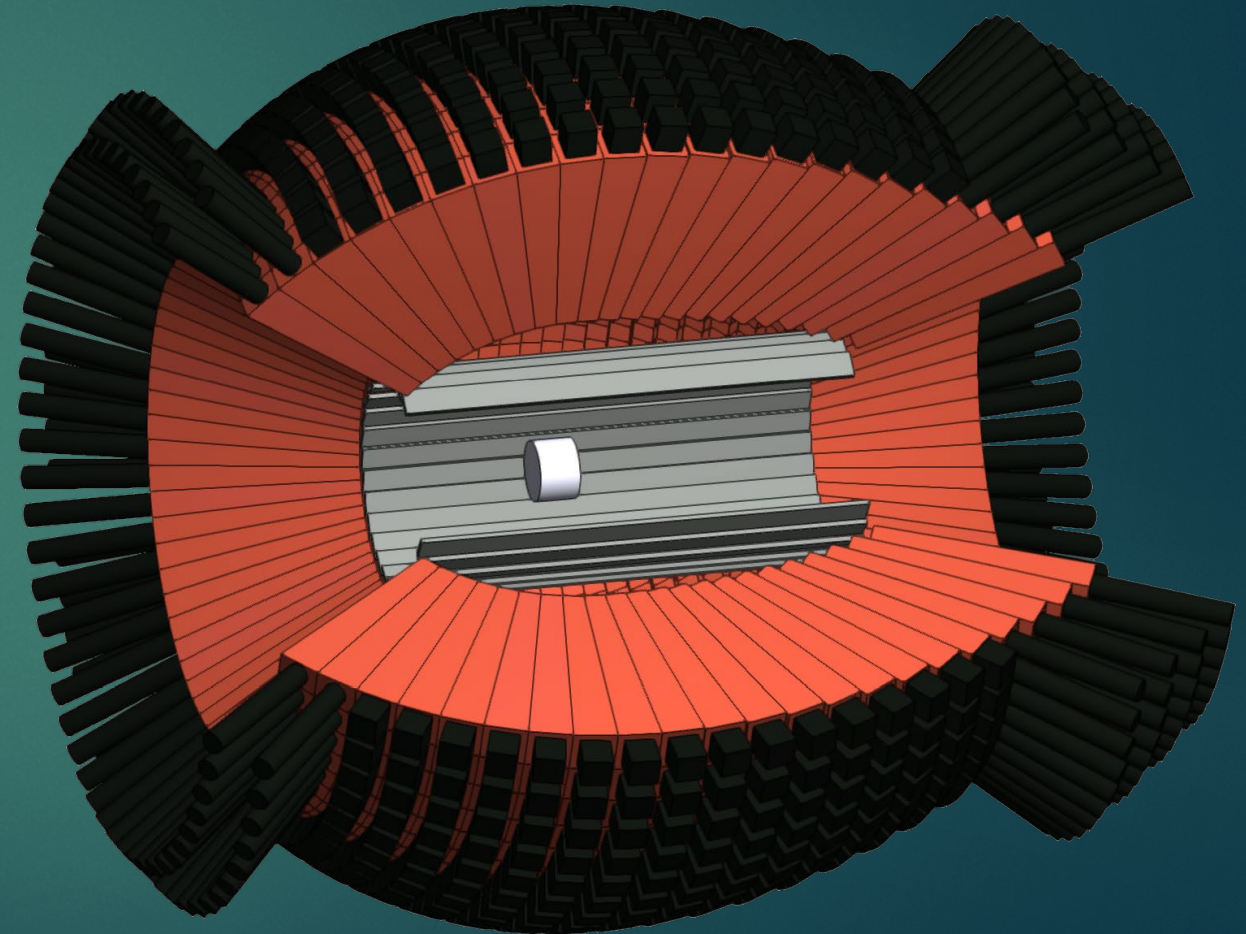
Energy spectrum with
a large BGO crystal

Spring-8 LEPS2/BGOegg experiment Phase-I (2014~2016)



Large acceptance EM calorimeter BGOegg

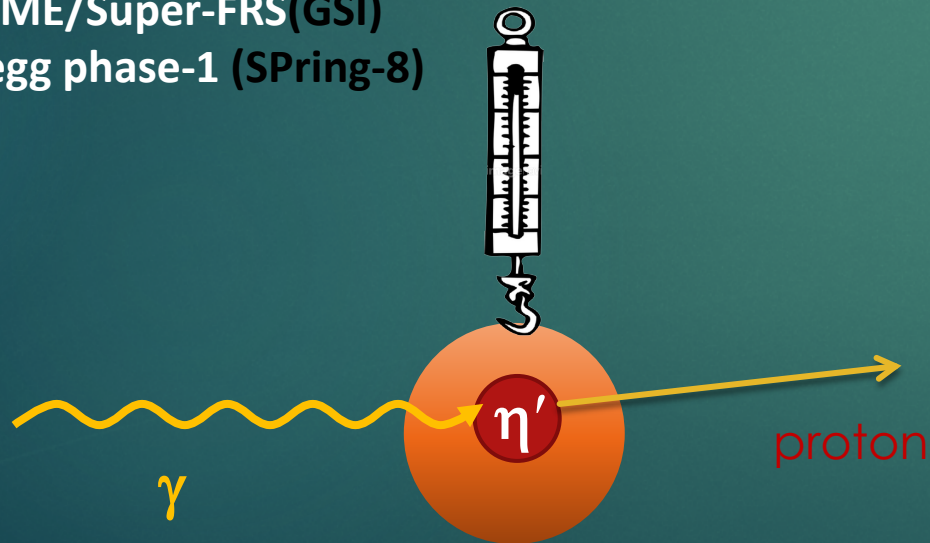
- ▶ Egg like shape
 - ▶ covering $24^\circ < \theta < 144^\circ$ by 1320 BGO crystals.
 - ▶ Total volume 264L
- ▶ Total weight 1.9t (crystal only)
- ▶ Two type photomultipliers
 - ▶ H11334 (metal package type)
 - ▶ H6524 (head on type)
- ▶ Very few dead-region
 - ▶ Without housing material
 - ▶ Only with 3M-Vikuity ESR film reflector.



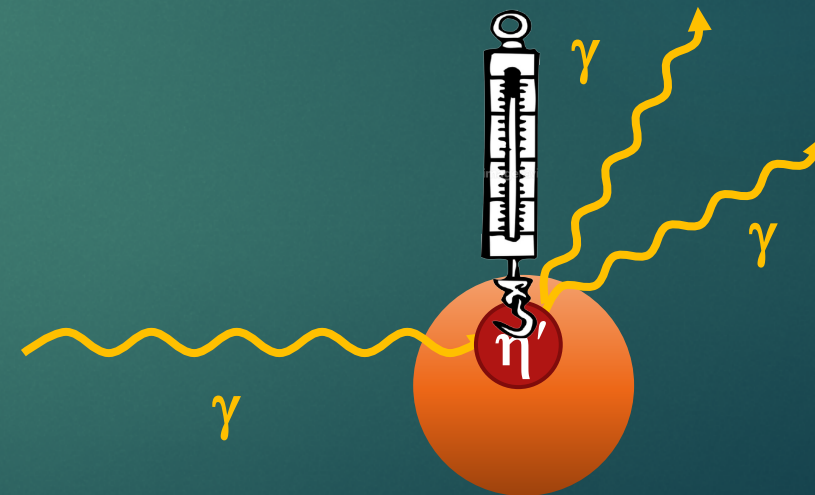
η' measurement from nuclei

- ▶ Indirect measurement ($m_{\eta'} + M_A$)
- ▶ Missing energy from forward hadron
- ▶ Need to know bound levels.
- ▶ Direct measurement by $M(\gamma\gamma)$
- ▶ **Need high-resolution calorimeter.**

η -PRiME/Super-FRS(GSI)
BGOegg phase-1 (SPring-8)

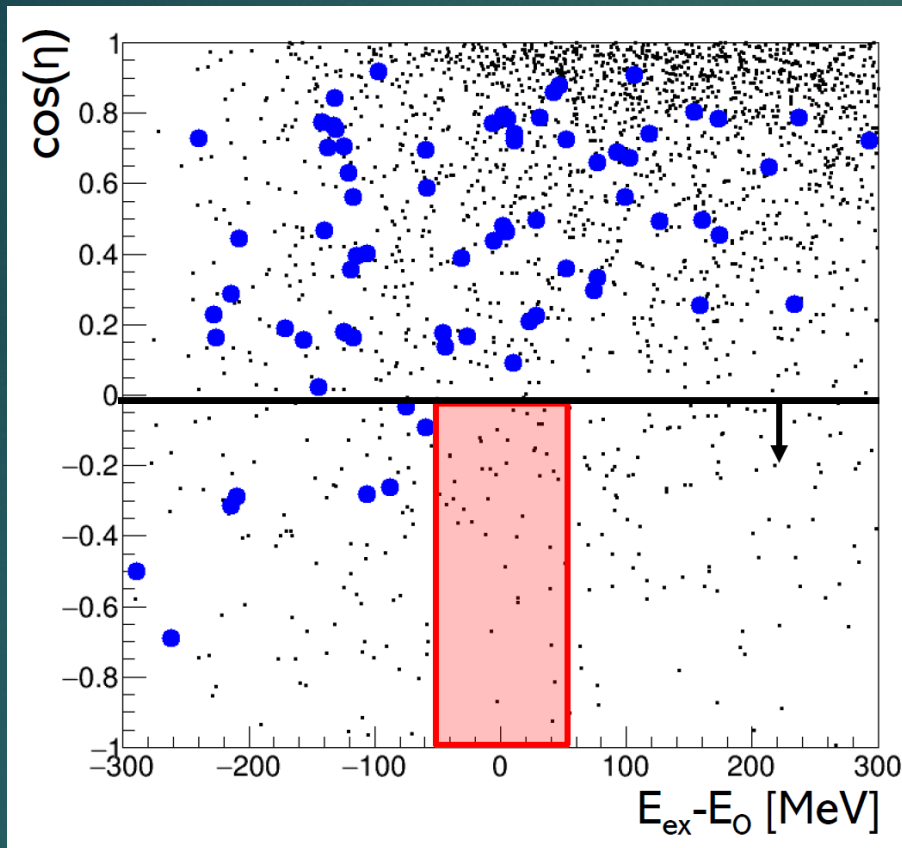


Nuclear target



Nuclear target

result of η' mesic nuclei



BG: $\gamma + {}^{12}\text{C} \rightarrow p_f + \eta + {}^{11}\text{B}$
 $\gamma + {}^{12}\text{C} \rightarrow p_f + \eta + \pi^0 + {}^{11}\text{B}$
 $\gamma + {}^{12}\text{C} \rightarrow p_f + \eta + \pi^- + {}^{11}\text{C}$
 w/ secondary interaction of $\eta/p_f/\pi^-$

- $\gamma + {}^{12}\text{C} \rightarrow \eta' \otimes {}^{11}\text{B} + p$
- Detection of 1N absorption ($\eta' p \rightarrow \eta p_s$)
- to improve S/N

Selection of η , p_s , and p_f

- After **kinematical cuts**

$$\cos \theta_{lab}^{\eta p_s} < -0.9$$

$$(\cos \theta_{lab}^{\eta} < 0)$$

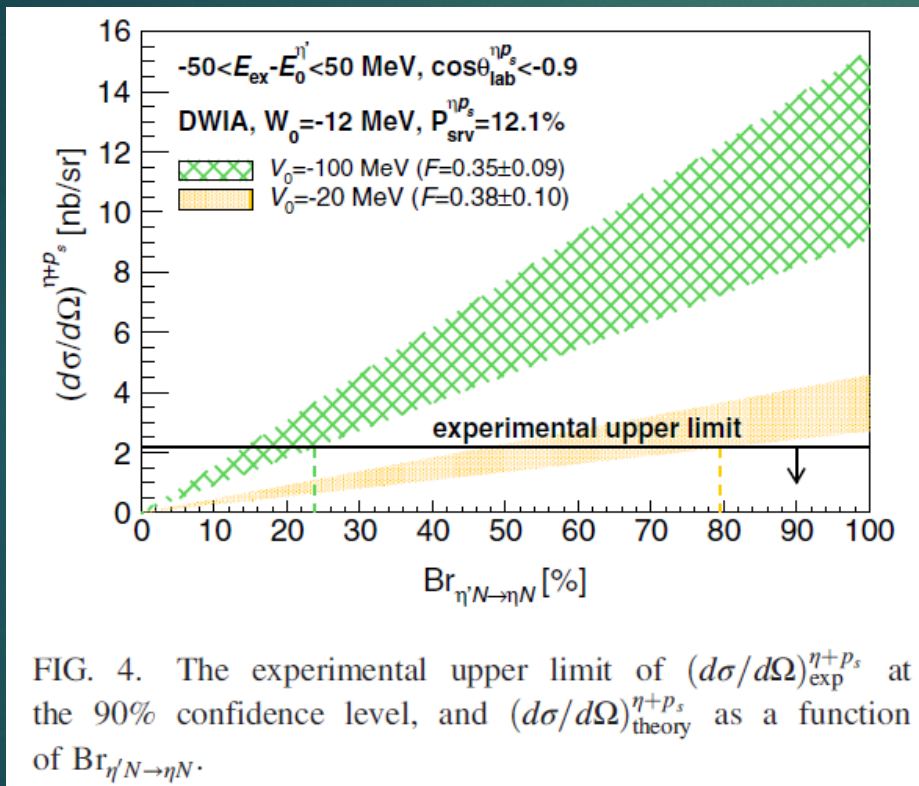
$$\cos \theta_{lab}^p < 0.5$$

$$|E_{miss}^{\eta p_s p_f}| < 150 \text{ MeV}$$

■ Signal search region
 $(-50 < E_{ex} - E_0 < 50 \text{ MeV})$

\Rightarrow **No 1N-absorption signal from η' bound state.**

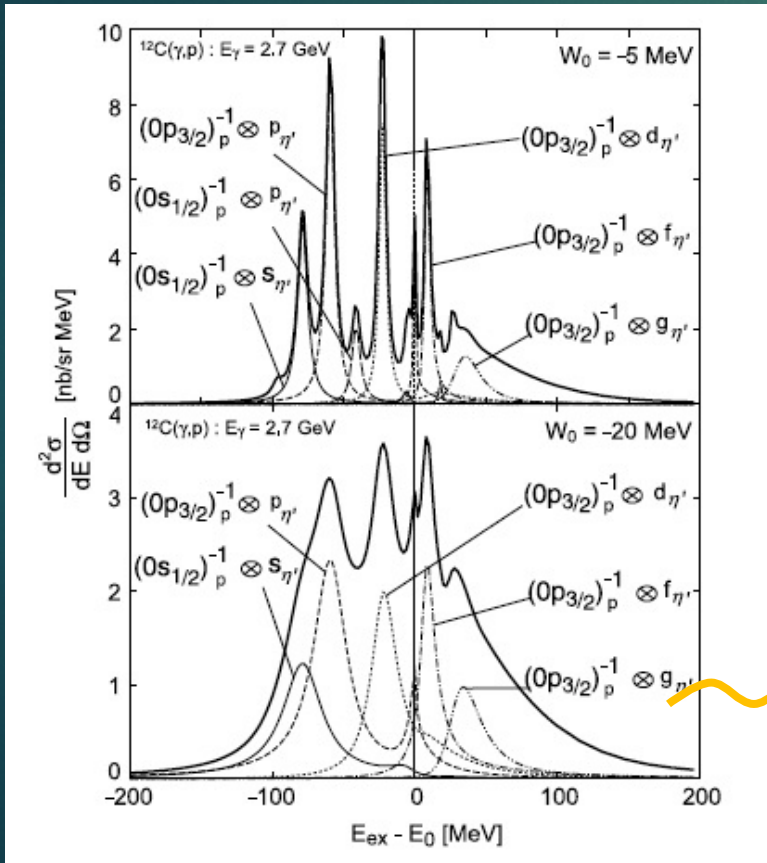
Results of Search for η' Bound Nuclei



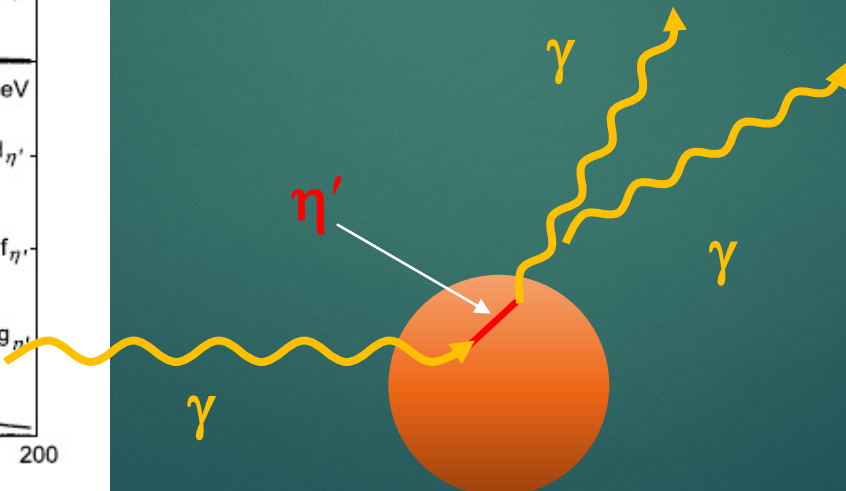
- ▶ We measured the $\gamma + {}^{12}\text{C} \rightarrow p_f + (\eta + p_s) + X$ reaction to search for η' -nucleus bound states.
- ▶ No signal events were observed
 - **Comparison** theoretical calculation
 - H. Nagahiro, JPS Conf. Proc. 13 (2017) 010010.
- ▶ **Indicate a small V_0**
 - ▶ 2.2 nb/sr in $\cos\theta_{\eta p_s} < -0.9$
- ▶ Analysis for **2-nucleon absorption tag ($\eta'NN \rightarrow NN$)** in preparation w/ a Doctor candidate.

Direct η' measurement from nuclei

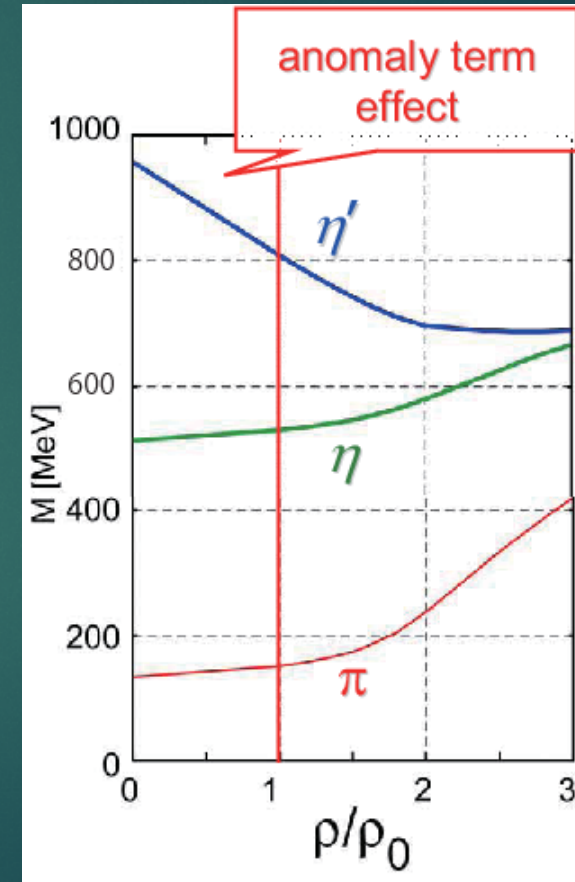
Missing Energy spectrum for Mesic nucleus search



Measurement a spectral function (line-shape) of η' mesons



Nuclear target



Mass spectrum

Spectrum line-shape analysis

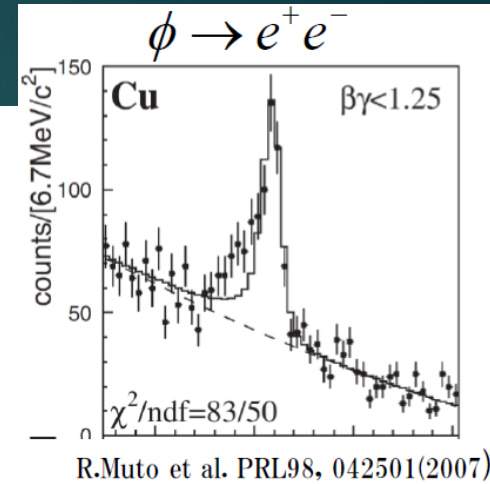
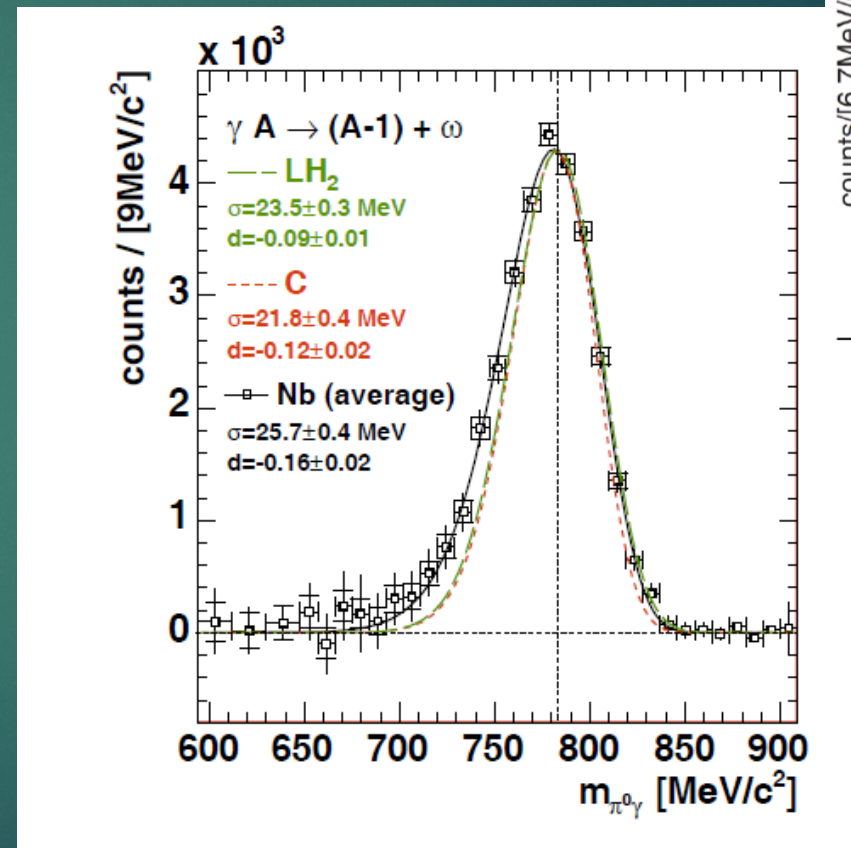
Eur. Phys. J. A (2013) **49**: 132

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

- ▶ ω line-shape for the different nuclei are compared and a broadening of the ω signal for the niobium target is observed in comparison to the liquid-hydrogen target.

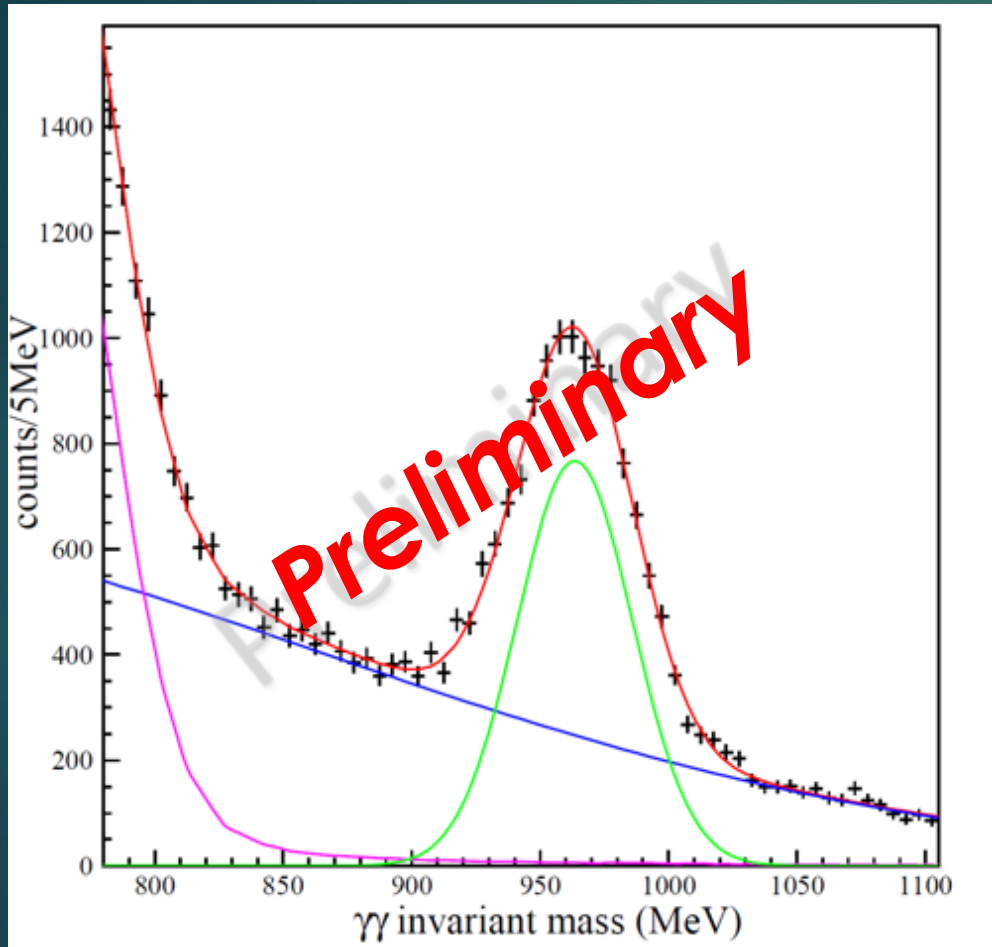
→ η' line-shapes study in heavy nuclei

Line-shape comparison for the three targets LH2 (dashed green), C (dotted red) and Nb (black)

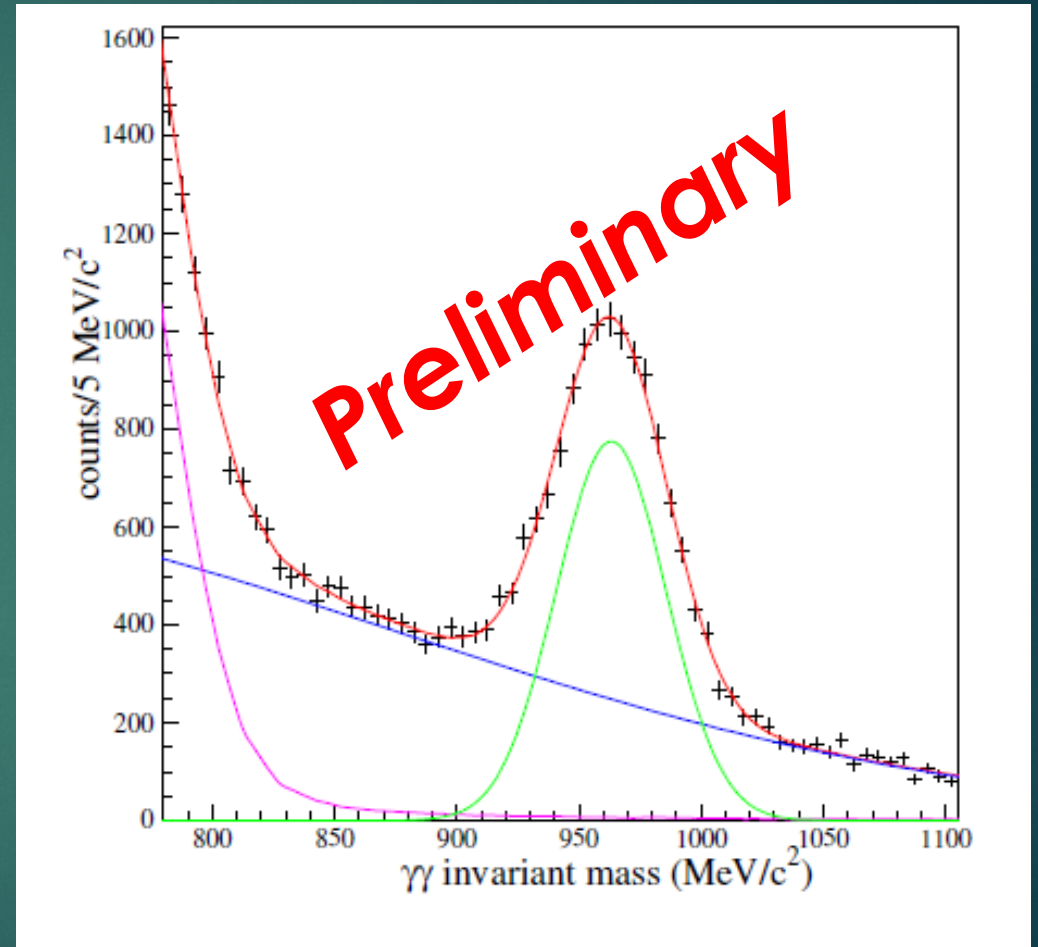


$\gamma\gamma$ invariant mass spectrum

Y. Matsumura, D-thesis



$P_{\gamma\gamma} < 1$ GeV

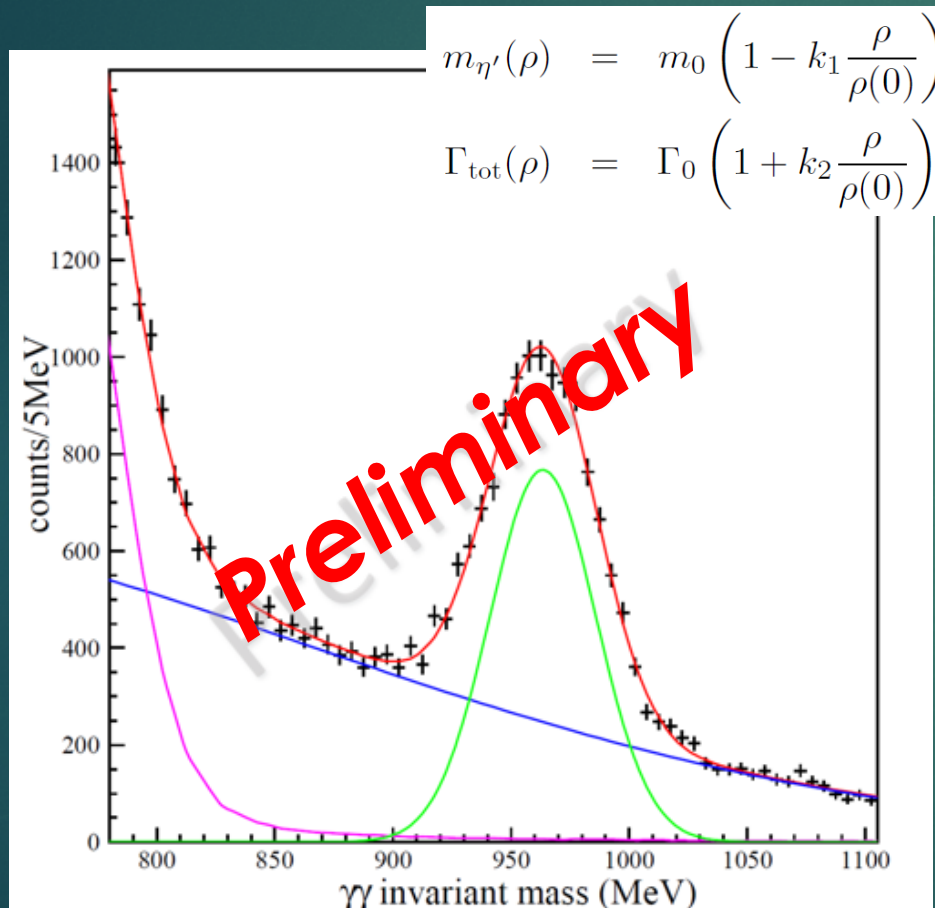


$P_{\gamma\gamma} \geq 1$ GeV

An enhancement in the low-mass region of the η' mass was obtained

Result of the Direct measurement

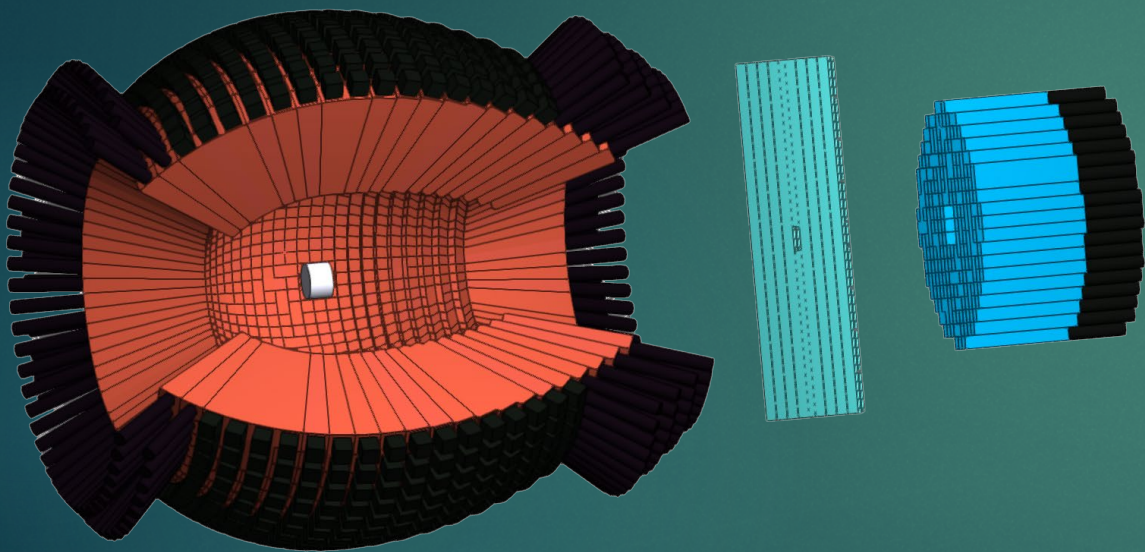
Y. Matsumura, D-thesis



2015A data only

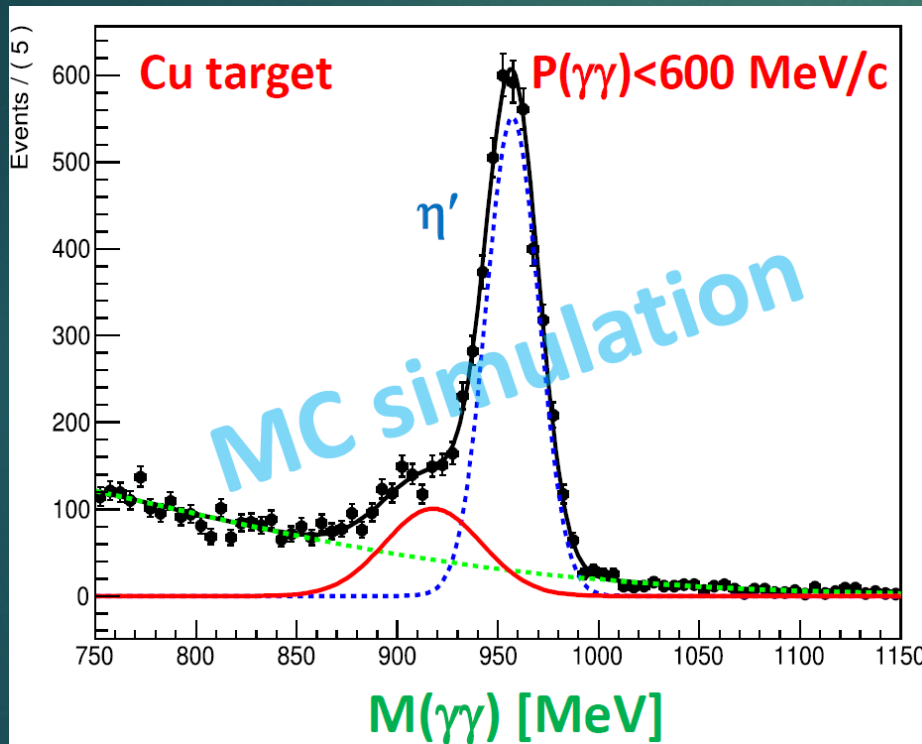
- ▶ Introduced the phenomenological parameters for mass and width of η' inside nucleus.
- ▶ The maximum significance of 3.7σ was obtained for the parameter corresponding to the mass reduction
- ▶ $\Delta m_{\eta'} = 40\text{-}70 \text{ MeV}/c^2$
- ▶ $\Delta \Gamma_{tot} < 60 \text{ MeV}$
- low-momentum sample
($P_{\eta'} < 1 \text{ GeV}/c$)
carbon target data.
- ▶ Preparing to publish with 2016A data.

LEPS2 BGOegg upgrade plan (Phase-II)



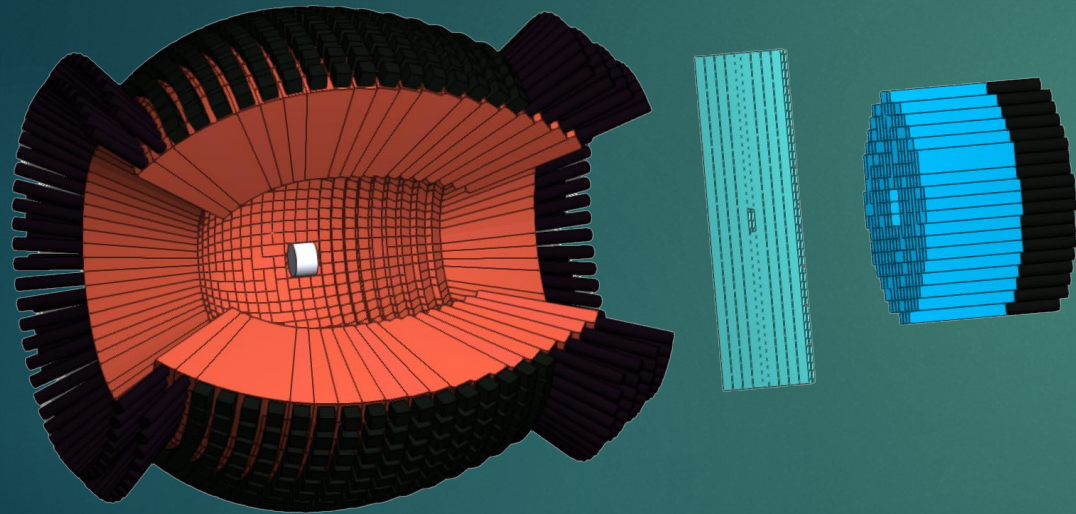
- ▶ Upgrade the detector setup.
 - ▶ Cover the most forward angle (6~16 deg)
 - ▶ Multi-meson BG ($\gamma p \rightarrow \pi^0 \pi^0 p$) $\sim 1/40$
- ▶ Change a target
 - ▶ from C [20 mm] to Cu [7 mm].
 - ▶ $R_{\text{nucleus}} \times 1.8$
 - ▶ # of nucleons $\times 1.8$
 - ▶ $\sigma(M\gamma\gamma) \times 0.6$
- ▶ Increase a photon beam intensity.
 - ▶ 24W pulse laser + existing 3 lasers \sim **5M cps**

Prospects of BGOegg upgrade



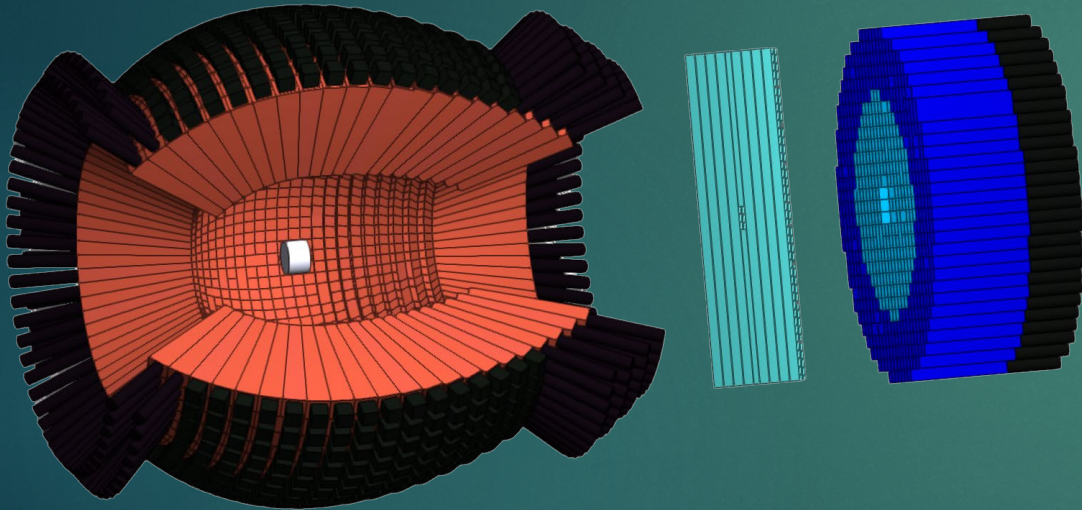
- ▶ Direct η' measurement from nuclei
 - ▶ $\eta' \rightarrow 2\gamma$
 - ▶ **28σ in a few months** if the Phase-1 result is assumed.
- ▶ Other physics possibilities via **multi-meson photoproduction**:
 - Spectral analysis of $f_1(1285)$**
 - ▶ $\eta'/f_1(1285) \rightarrow \pi\pi\eta \rightarrow 6\gamma$

From phase-II first stage to second stage



- ▶ Upgrade FG
 - ▶ Coverage of the forward angle
 - ▶ $< 16^\circ \rightarrow < 24^\circ$
- ▶ It becomes possible to capture events that produce more gamma rays in the final state.

From phase-II first stage to second stage



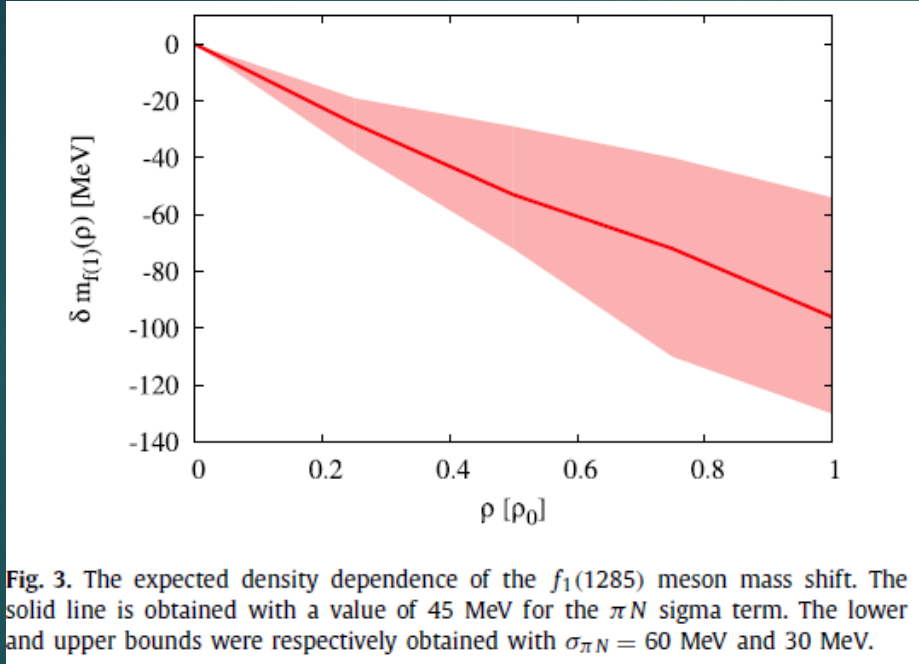
- ▶ Upgrade FG
 - ▶ Coverage of the forward angle
 - ▶ $< 16^\circ \rightarrow < 24^\circ$
- ▶ It becomes possible to capture events that produce more gamma rays in the final state.



$\eta' / f_1(1285)$ production in 6γ decay
mode

FURTHER FUTURE EXPERIMENTS

$f_1(1285)$ photo-production



- ▶ $f_1(1285)$
 - ▶ The CLAS collaboration was able to clearly identify a sharp peak
 - ▶ Feasibility of LEPS2/BGOegg
- ▶ The mass shift and width broadening of $f_1(1285)$ meson together with those of the ω .

$f_1(1285)$ photo-production (CLAS)

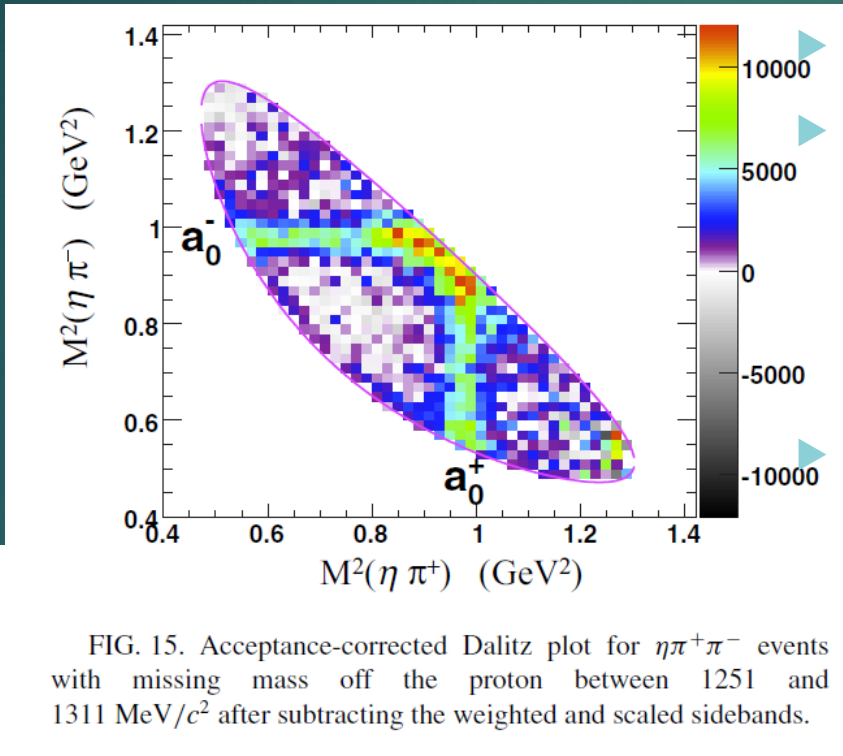


FIG. 15. Acceptance-corrected Dalitz plot for $\eta\pi^+\pi^-$ events with missing mass off the proton between 1251 and 1311 MeV/c^2 after subtracting the weighted and scaled sidebands.

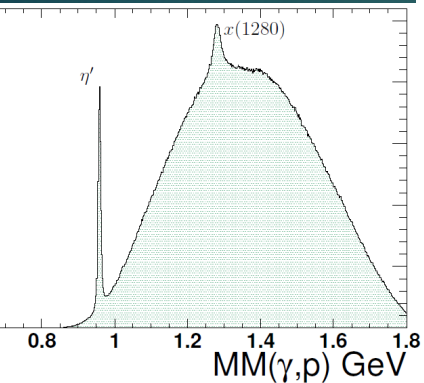
$f_1(1285)$ decay into $\pi\pi\eta$.

$f_1(1285)$ meson with

- ▶ mass $1281.0 \pm 0.8 \text{ MeV}$
- ▶ width $18.4 \pm 1.4 \text{ MeV}$

$\eta(1295)$

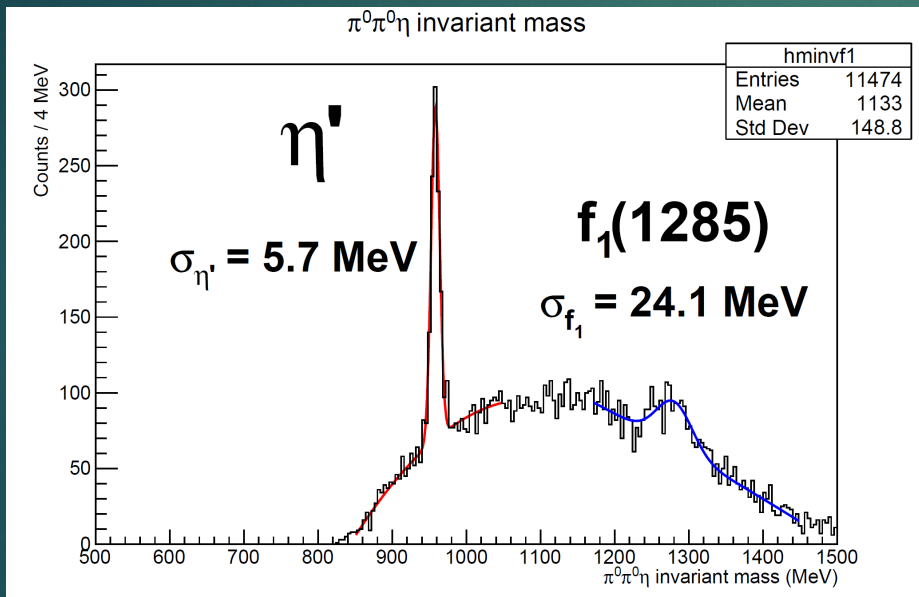
- ▶ Same decay mode
- ▶ first radial excitation of η ?
- ▶ $\eta(1405)$, $\eta(1475)$
- ▶ Glueball? Gluon component?



Missing mass off the proton for $\eta\pi^+\pi^-$ decay mode. The η' and $x(1280)$ mesons are visible above a substantial background.

$\gamma p \rightarrow \pi^+ \pi^- (\eta)$ reaction

$\pi^0\pi^0\eta$ study at LEPS2/BGOegg

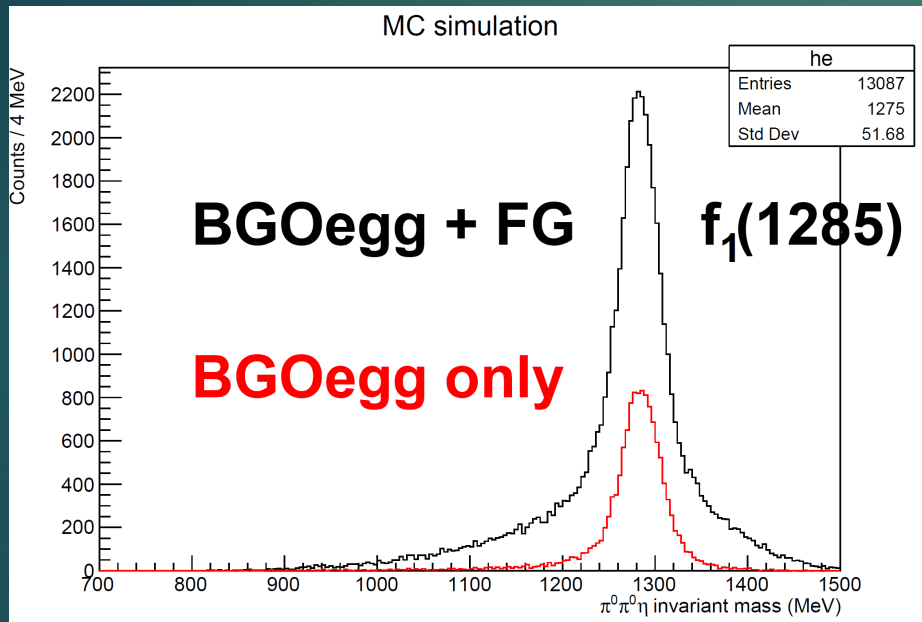


- ▶ Experimental period ~ 2015A
 - ▶ 3 months
 - ▶ Carbon target, $E_\gamma < 2.4$ GeV
 - ▶ 2 π^0 and η event are selected
 - ▶ Radius of all clusters < 20
- ▶ Kinematical fitting
 - ▶ Constraints
 - ▶ Invariant mass of $\gamma\gamma$ equal to M_π (2-pairs)
 - ▶ Invariant mass of $\gamma\gamma$ equal to M_η (1-pair)
- ▶ has the advantage of very good resolution

Estimation of feasibility for future experiment

Feasibility @ LEPS2/BGOegg Phase-

II



- ▶ $f_1(1285) \rightarrow \pi\pi\eta \rightarrow 6\gamma$
- ▶ Kinematical Fit
 - ▶ same as the real data
- ▶ 3.8 times statistics
- ▶ Estimated yield
 - ▶ $1.8 \times 1.8 \times 2.5 \times 3.8 = 31$
 - ▶ $\eta' \sim 800 \rightarrow 24500$ event
 - ▶ $f_1(1285) \sim 440 \rightarrow 13000$ event @ 3-month

Summary

- ▶ We perform the study of the media effect at LEPS2/BGOegg (phase-I).
 - ▶ Search for η' Bound Nuclei
 - ▶ Direct measurement of the in-medium η' mass
- ▶ We plan the direct measurement of in-medium mass spectrum of η' and $f_1(1285)$ meson with an electro-magnetic calorimeter BGOegg (and FG).
- ▶ We estimate the feasibility of the next stage BGOegg experiment (BGOegg phase-II).
- ▶ Data taking for 3 months or more was required with $0.5X_0$ copper target.
- ▶ Schedule
 - ▶ Preparation & test data-taking until FY2022. Then, start physics runs alternatively with the Solenoid exp.
 - ▶ At second stage of Phase-II, we will cover all the forward acceptance in a few years.