Recent Progress and Prospects of the LEPS2/BGOegg experiment at SPring-8

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Contents

- Introduction of **Spring-8 LEPS2/BGOegg experiments**

  Photoproduction experiments by a **Laser Compton Scattering (LCS)** beam.

- Baryon resonance studies via **single meson photoproduction** off the proton

  Measurement of **differential cross section** & **photon beam asymmetry**

- Studies of **η' mass in nuclei**

  Two independent searches for **medium modification** & **mesic nuclei**

- **Near future Plan** of BGOegg experiment

  Detector upgrade & sensitivity for the η' medium modification search

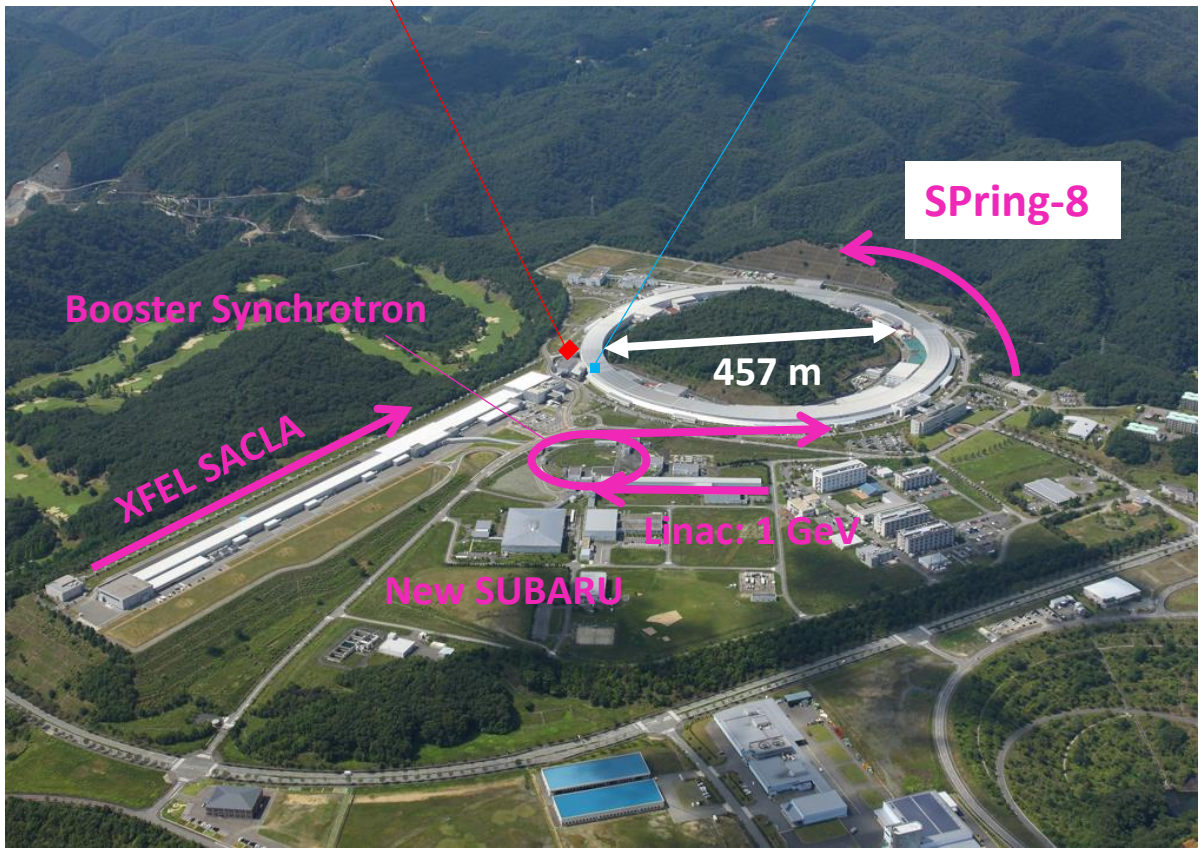
- **Summary**

SPring-8 LEPS2 Project

SPring-8 (Storage ring of 8 GeV e^- w/ 100 mA)

LEPS2 Experimental Building (2013 ~)

LEPS Experimental Hutch (1999 ~)



SPring-8 LEPS2 Project

Simultaneous injection of Max. 4-Lasers

355 nm UV laser ⇒ **$E_\gamma \leq 2.4$ GeV**

E_γ measurement by recoil electron tagging

Tagged photon intensity = **$1 - 5\times10^6$ cps**

e^- Beam Divergence

$<\sigma_{x'}>=58\ \mu rad$

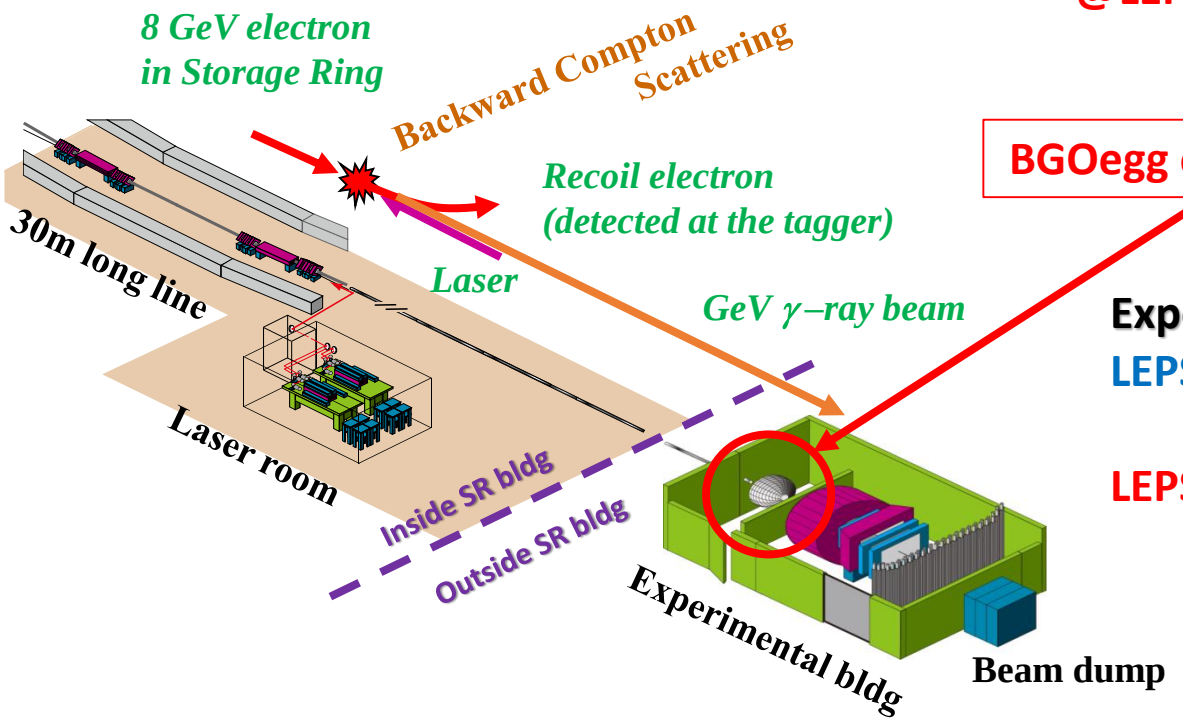
@LEPS 7.8m straight section

⇓

$<\sigma_{x'}>=12\ \mu rad$

@LEPS2 30m straight section

Only 4 of 62 beamlines



BGOegg experiment

Experimental Site (135m)

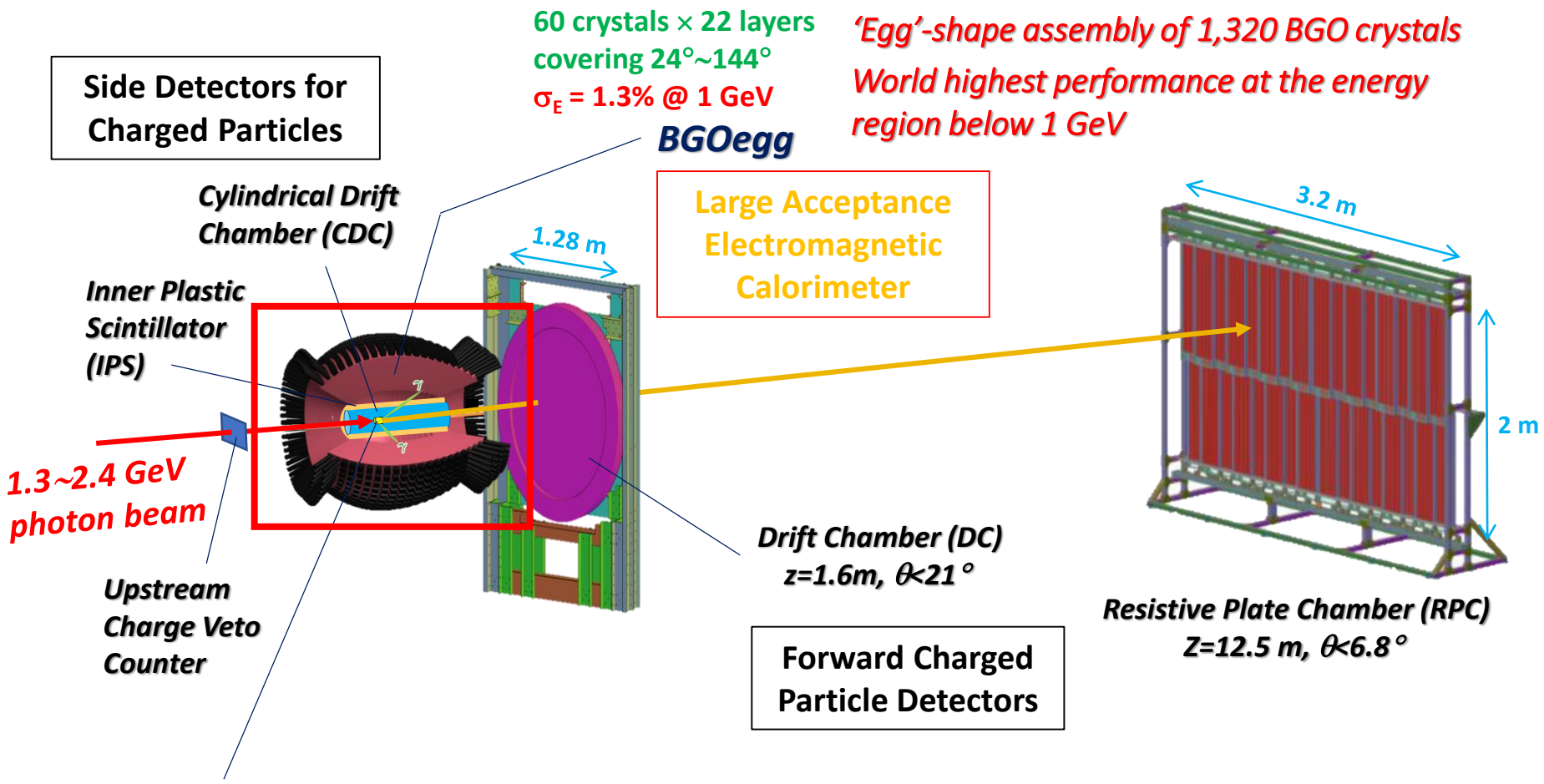
LEPS $42m^2$ (area) x $3m$ (high)

⇓

LEPS2 $198m^2$ (area) x $10m$ (high)

15 times in volume !

LEPS2/BGOegg Experimental Setup



Target LH_2 (t54 mm) : 2014 Nov - Feb, 2015 Sep - Dec
Carbon (t20 mm) : 2015 Apr - July, 2016 Apr – July
Cu : 2017 May (t1.5 mm), 2018 Jan – Feb (t7.5 mm)

- Introduction of Spring-8 LEPS2/BGOegg experiments
- **Baryon resonance studies via single meson photoproduction off the proton**
- Studies of η' mass in nuclei
- Near future Plan of BGOegg experiment
- Summary

Single π^0 / η / ω Meson Photoproduction

- The studies of **excited baryon resonances** are important for understanding the hadron structure which **has not been well explained by the constituent quark model and the lattice QCD**.
- **π^0 photoproduction** : 😟 I=1 $\Rightarrow$ Both **N^*** and **Δ^*** contribute at s-channel.
  - 👍 Traditional & Many existing data
    - $\Rightarrow$ **Check of analysis method & luminosity**.
  - 👍 Any hint for the discrepancy of **CLAS & CBELSA** **$d\sigma/d\Omega$** at low energies & backward angles.
- **single η / ω photoproduction** : I=0 $\Rightarrow$ Only couple with **nucleon resonances (N^*)**.
  - The η meson couples to **$s\bar{s}$ quarks**.
- The N^*s & Δ^*s have broad widths overlapping with each other. The measurement of the **photon beam asymmetry (Σ)** in addition to the **$d\sigma/d\Omega$** helps to **decompose the resonances** with the **interferences of helicity amplitudes**.

$$\sigma \propto |H_1|^2 + |H_2|^2 + |H_3|^2 + |H_4|^2$$

$$\Sigma \propto Re(H_1 H_4{}^* + H_2 H_3{}^*)$$

The photon beam asymmetries for $E_\gamma \gtrsim 2$ GeV are very scarce for all modes.

Analysis Procedure

Event Selection

E_γ meas. (1.3—2.4 GeV) at tagger.

2 or 3 neutral clusters at BGOegg.

$\pi^0 \rightarrow \gamma\gamma$ (Br=98.8%)

$\eta \rightarrow \gamma\gamma$ (Br=39.4%)

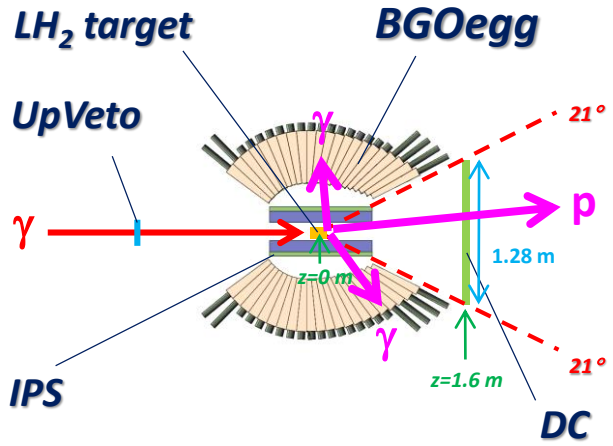
$\omega \rightarrow \pi^0\gamma \rightarrow \gamma\gamma\gamma$ (Br=8.40%)

Proton detection at DC or BGOegg.

Vertex is assumed to be variable on z-axis.

2 or 3 neutral clusters $\Rightarrow$ 4-momenta of each γ

Beam energy comes from tagger.

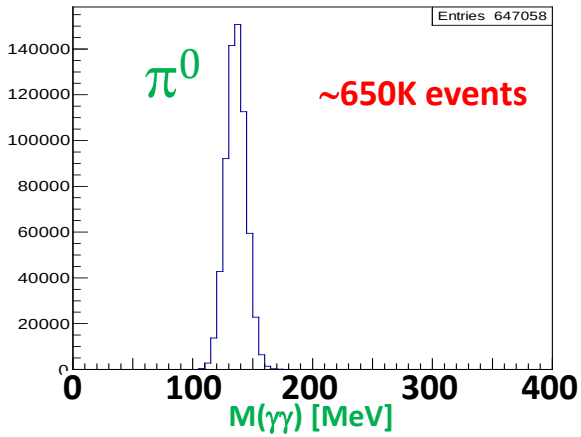


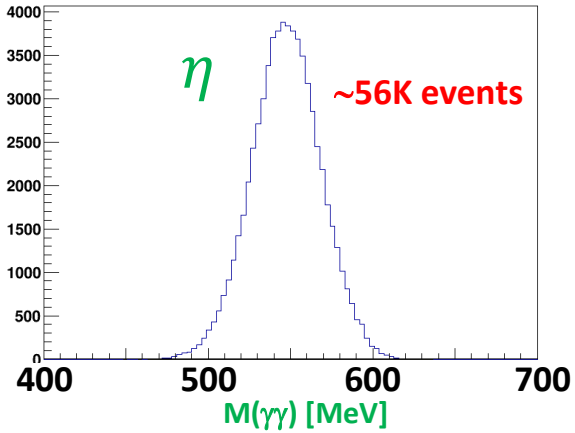
Only the proton direction is measured at DC or BGOegg.

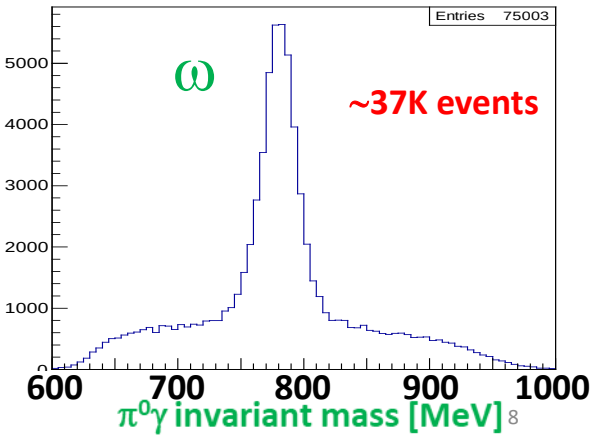
χ^2 probability cut with Kinematic Fit

Required **4-momentum conservation** & **π^0 / η mass** (PDG value).

Better S/N ratio & resolutions are expected.



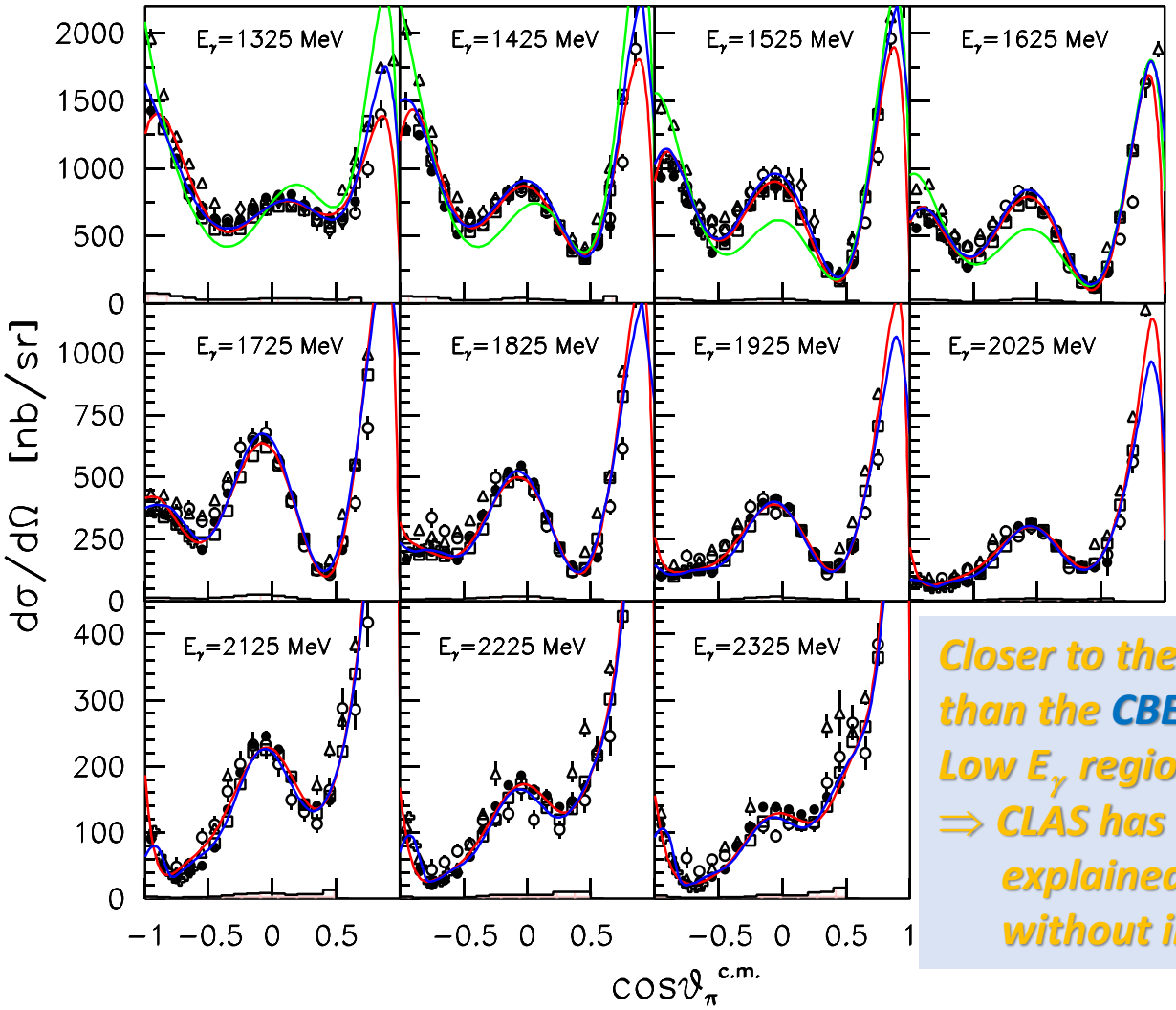




Differential Cross Section of $\gamma p \rightarrow \pi^0 p$

22 energy bins for $1300<E_\gamma<2400$ MeV & **17 polar angle bins** for $-1.0<\cos\theta_\pi^{CM}<0.7$

Being published.



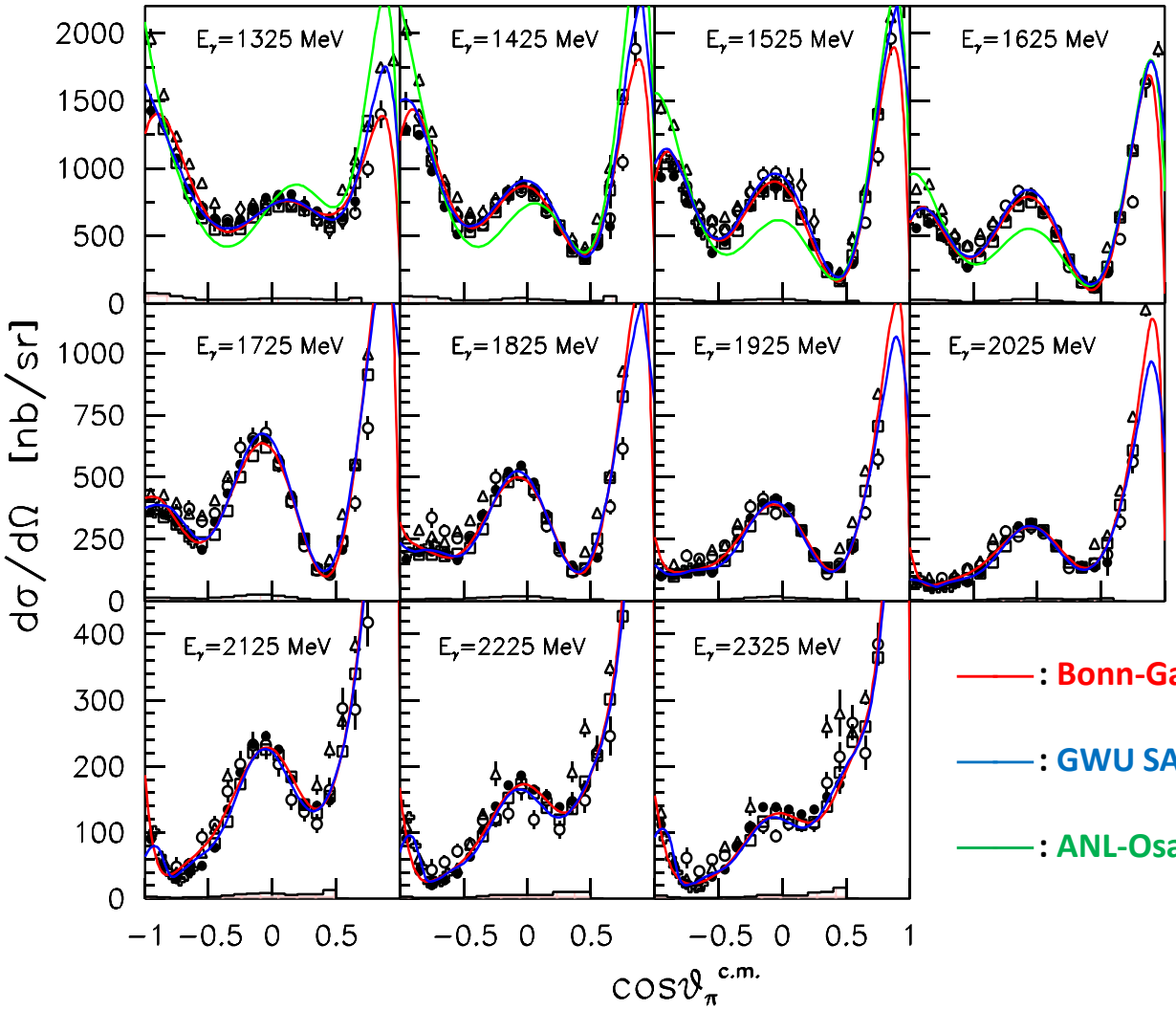
●: **this work (BGOegg)**
□: CLAS [PRC76 (2007) 025211]
○: CBELSA [PRL94 (2005) 012003]
△: CBELSA [PRC84 (2011) 055203]
◇: GRAAL [EPJA26 (2005) 399]
✞: LEPS [PLB657 (2007) 32]
Note: The histogram indicates the systematic error of the BGOegg meas.

Typically 4-5%

*Closer to the **CLAS**, **GRAAL**, and **LEPS** results than the **CBELSA** result at the backward & Low E_γ region.*
*⇒ CLAS has claimed the **$d\sigma/d\Omega$ data** can be explained by **"4-star" resonance states** without introducing new high spin states.*

Differential Cross Section of $\gamma p \rightarrow \pi^0 p$

22 energy bins for $1300 < E_\gamma < 2400$ MeV & **17 polar angle bins** for $-1.0 < \cos\theta_\pi^{CM} < 0.7$



More or less ***consistent with the existing PWA model calculations.***

⇒ *How about the* ***photon beam asymmetry ?***

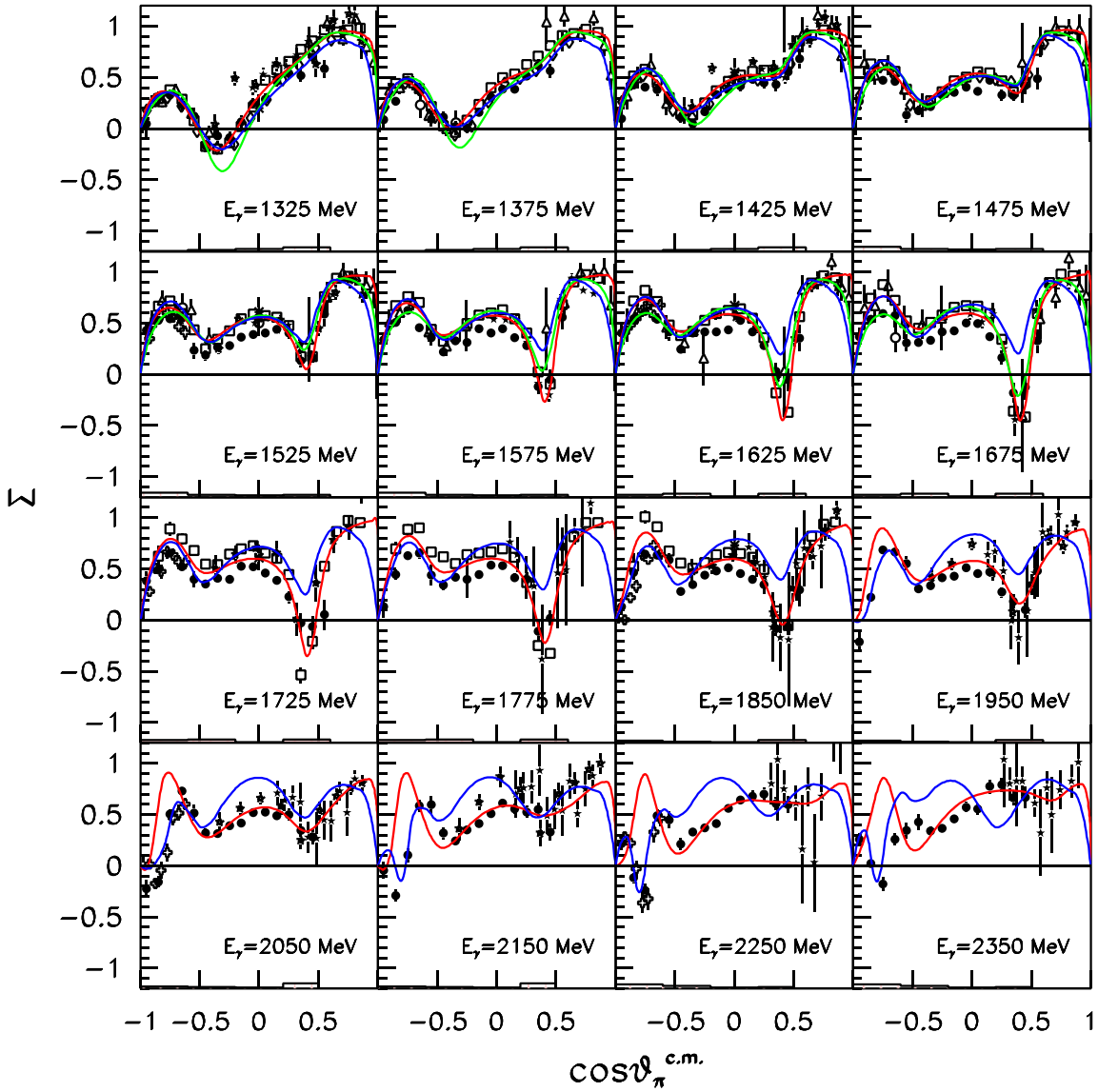
——: **Bonn-Gatchina** [https://pwa.hiskp.uni-bonn.de/BG2014_02_obs_int.htm]

——: **GWU SAID** [http://gwdac.phys.gwu.edu/analysis/pr_analysis.html]

——: **ANL-Osaka** [Private communication with Prof. Sato (Osaka Univ.)]

Photon Beam Asymmetry of $\gamma p \rightarrow \pi^0 p$

16 energy bins for 1300<E_γ<2400 MeV & **16 polar angle bins** for $-1.0<\cos\theta_\pi^{CM}<0.6$



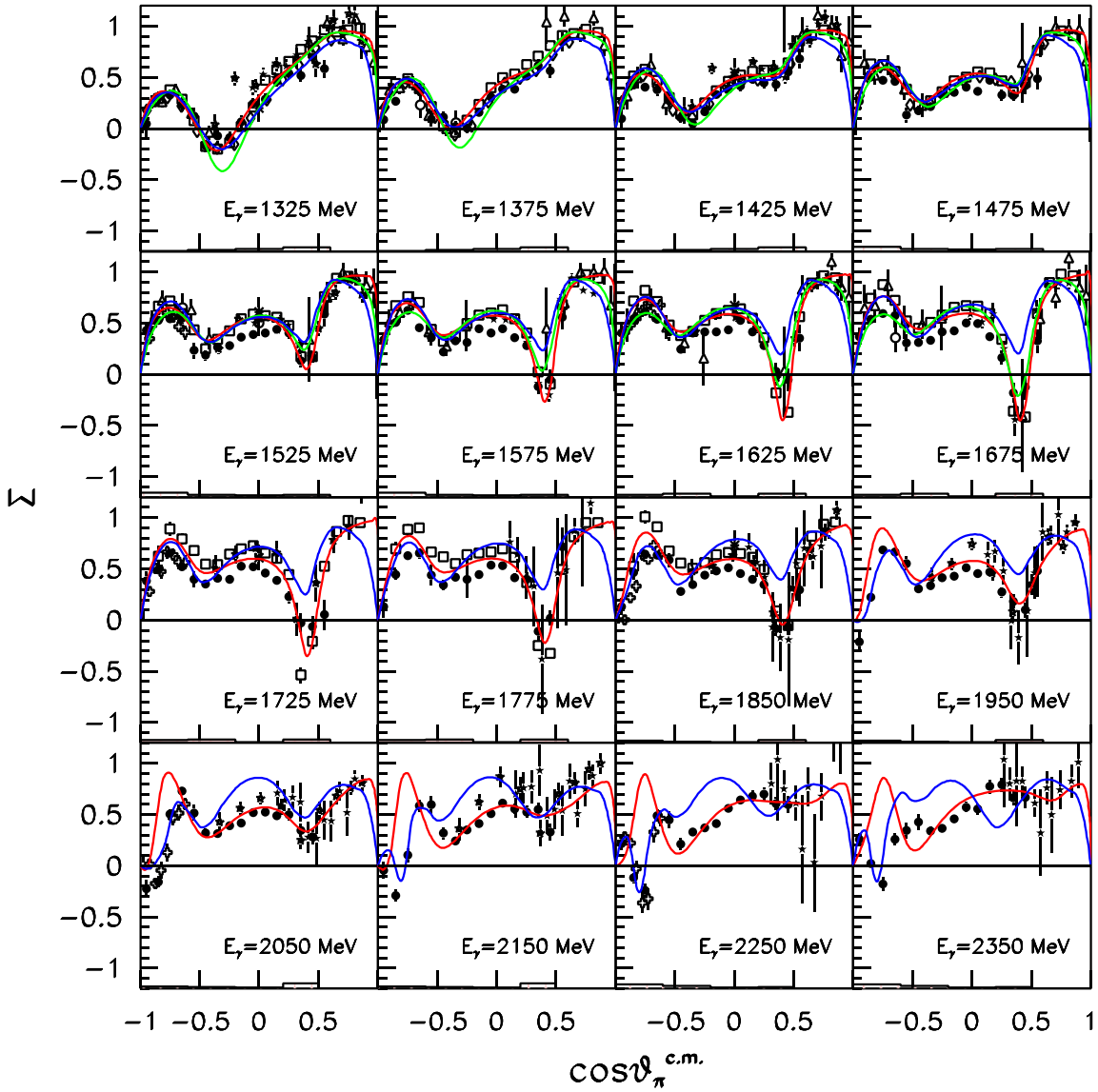
Being published.

●: **this work (BGOegg)**
□: CLAS [PRC88 (2013) 065203]
○: CBELSA [PRC81 (2010) 065210]
◇: GRAAL [EPJA26 (2005) 399]
✞: LEPS [PLB657 (2007) 32]
★: Daresbury [NPB104(1976)253]
☆: Daresbury [NPB154(1979)492]
∗: CEA [PRL28(1972)1403]
△: Yerevan [PLB48(1974)463]
Syst. error (hist) : **0.006 – 0.050**

- ***Angular behavior similar to the other experimental results at lower energies, indicating the contribution of higher spin states.***
- ***A wide angle measurement at $E_\gamma \gtrsim 2$ GeV is new.***

Photon Beam Asymmetry of $\gamma p \rightarrow \pi^0 p$

16 energy bins for $1300<E_\gamma<2400$ MeV & **16 polar angle bins** for $-1.0<\cos\theta_\pi^{CM}<0.6$



The existing PWA models deviate at the high energies where experimental data is scarce.

——: **Bonn-Gatchina**
[https://pwa.hiskp.uni-bonn.de/BG2014_02_obs_int.htm]

——: **GWU SAID**
[http://gwdac.phys.gwu.edu/analysis/pr_analysis.html]

——: **ANL-Osaka**
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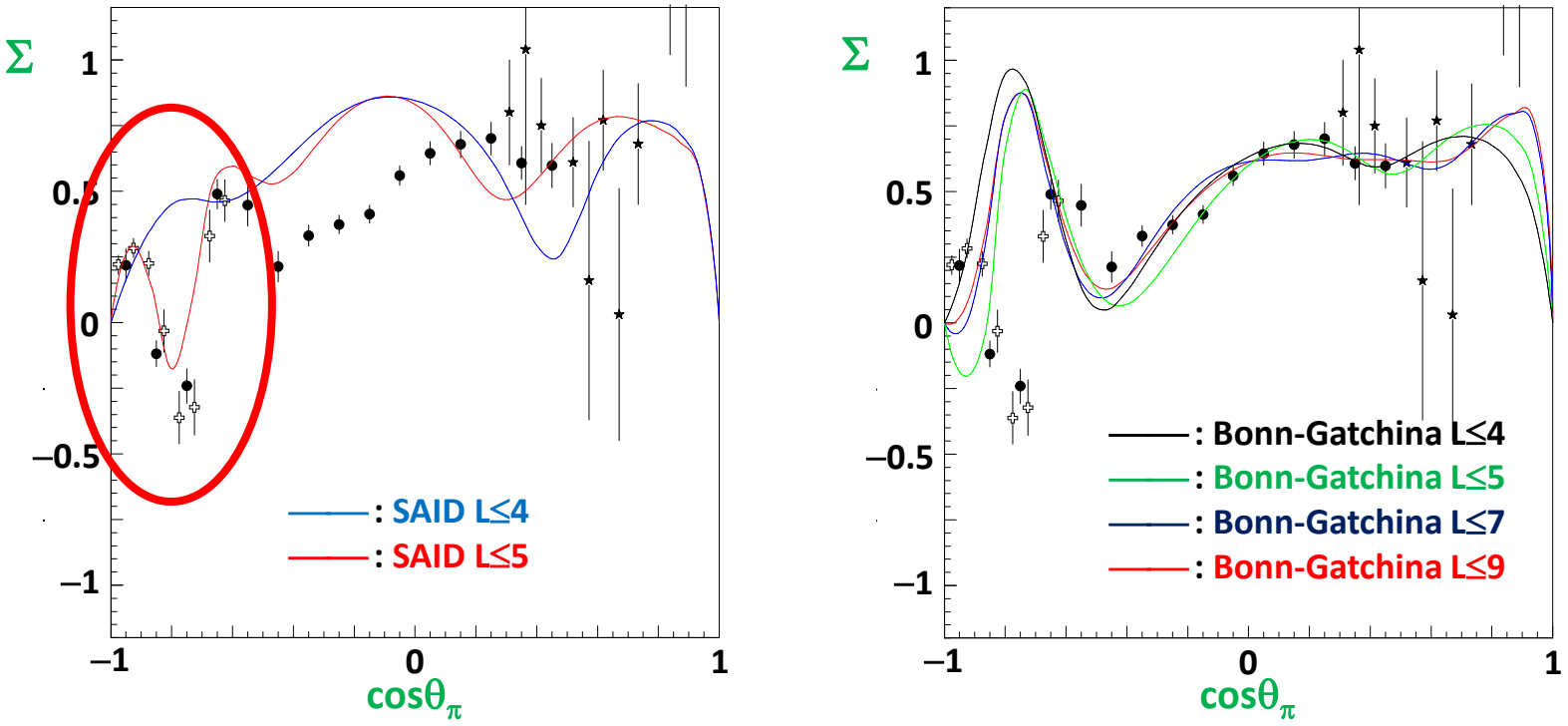
Comparison with PWA results at high energy region

Photon Beam Asymmetry (Σ) at 2200 < E_γ < 2300 GeV

●: this work (BGOegg), ✞ : LEPS [PLB657 (2007) 32], ★ : Daresbury [NPB104(1976)253]

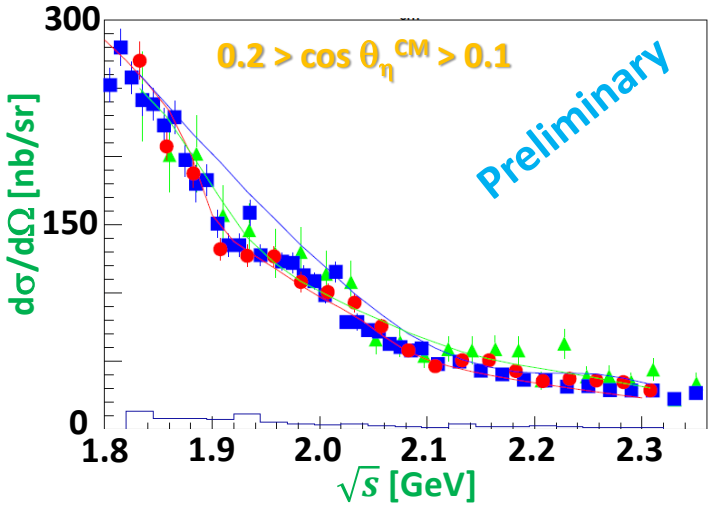


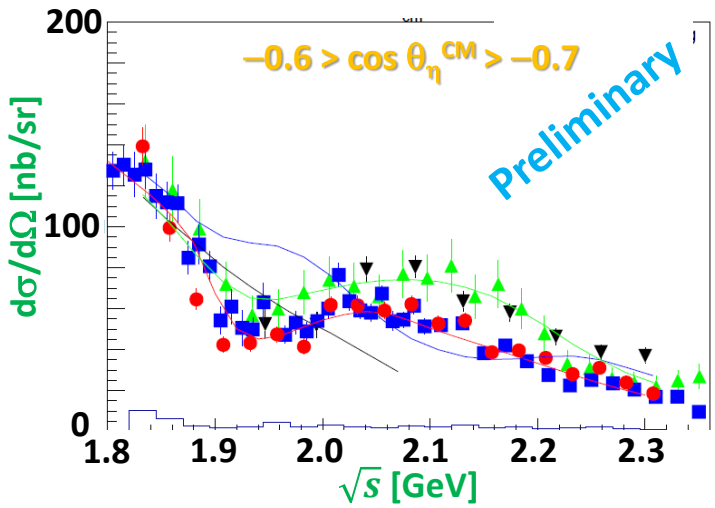
- SAID PWA reproduces the backward dip structure, while the middle & forward angle range can be explained only by Bonn-Gatchina PWA. The inconsistency of two PWA models tells **a large ambiguity in the amplitude solution** at E_γ > 2 GeV.
- The backward dip structure comes from **a higher multipole amplitude** (M_{5-}), which has the same quantum number as **high spin resonances** (H_{19} & H_{39} with $J^P=9/2^+$).

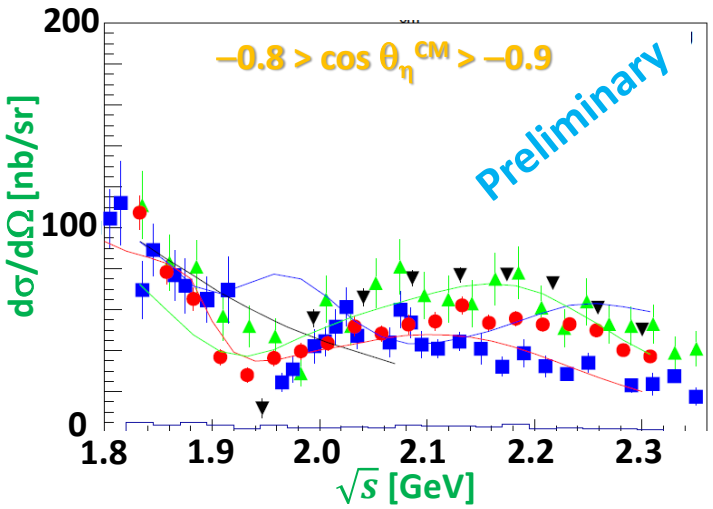
Differential Cross Section for γp→ηp

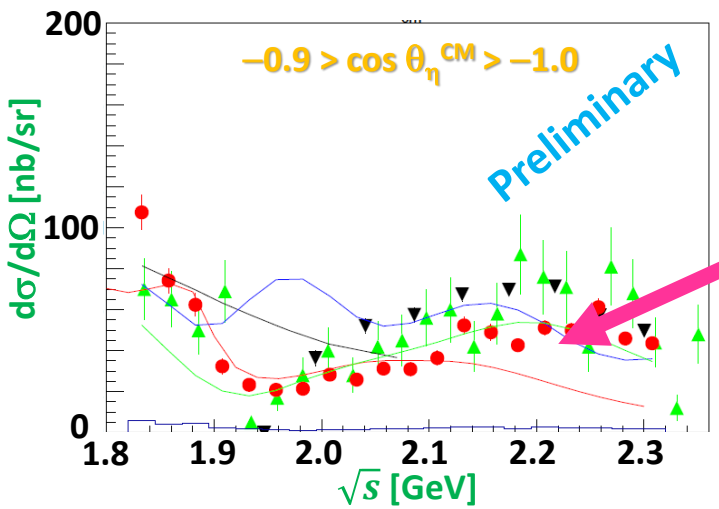
20 energy bins for 1820<$\sqrt{s}$<2320 MeV & **16 polar angle bins** for −1.0<cos θ_η^{CM}<0.6

dσ/dΩ : Closer to the CLAS result, but not well agree with the LEPS & CBELSA results at cosθ > −0.7.
At the most backward region, getting closer to the CBELSA result.
Variation in PWA results at backward angles because of the data inconsistencies.









● : BGOegg
▼ : LEPS [PRC80,052201]
▲ : CBELSA [PRC80,055202]
■ : CLAS [PRC80,045213]
Histogram : Syst. error

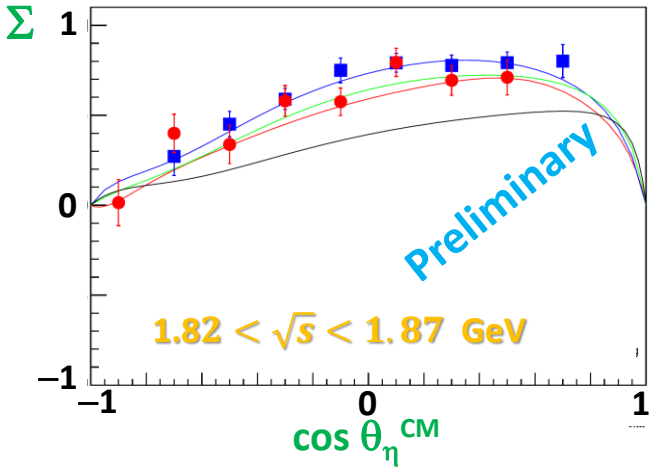
— ANL-Osaka
— Bonn-Gatchina
— GWU SAID
— eta-MAID2018

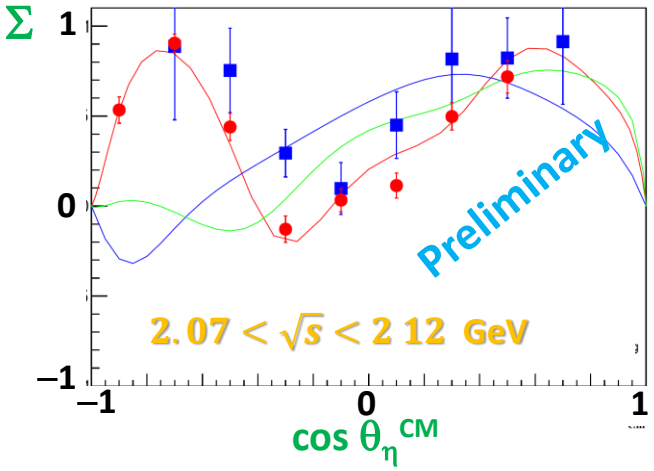
Enhancement at higher energies

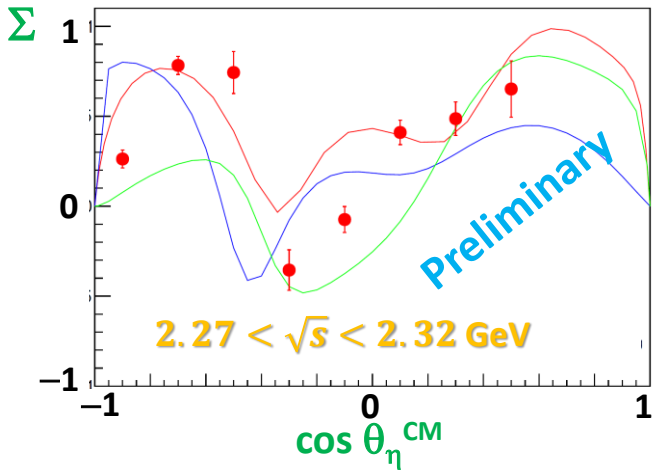
Photon Beam Asymmetry for γp→ηp

10 energy bins for 1820<$\sqrt{s}$<2320 MeV & **8 polar angle bins** for −1.0<cos θ_η^{CM}<0.6

Σ : The angle dependence is drastically changed above 1.9 GeV.
Measurement above 2.12 GeV is new.
⇒ None of PWA models reproduce the BGOegg result.







●: BGOegg
■: CLAS [PRC80,045213]

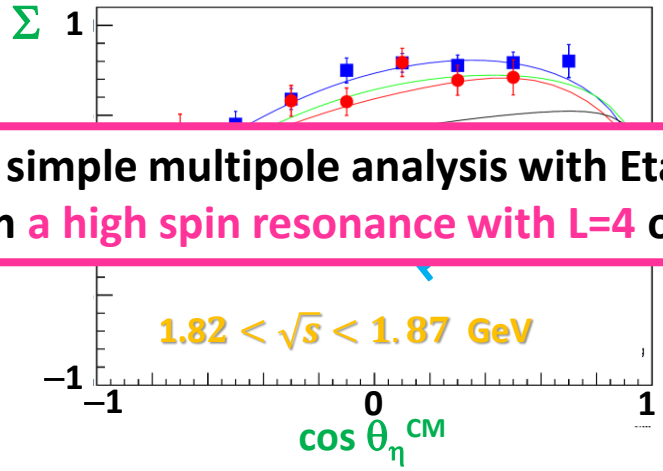
— **ANL-Osaka**
— **Bonn-Gatchina**
— **GWU SAID**
— **eta-MAID2018**

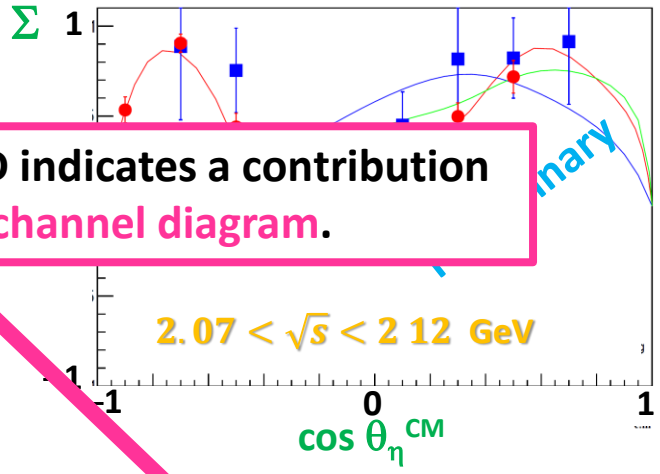
Photon Beam Asymmetry for γp→ηp

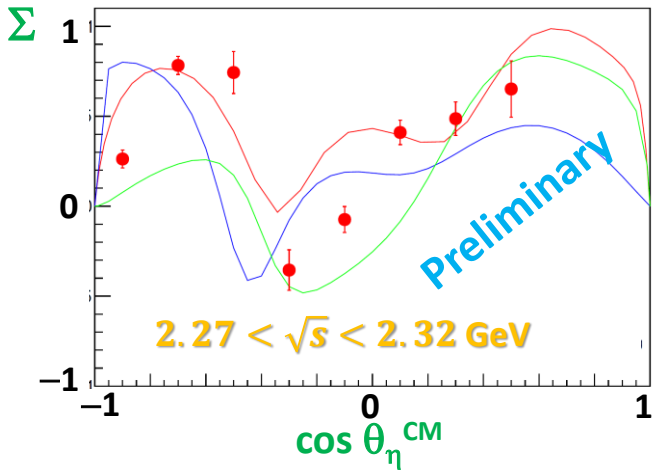
10 energy bins for 1820<$\sqrt{s}$<2320 MeV & **8 polar angle bins** for −1.0<cos θ_η^{CM}<0.6

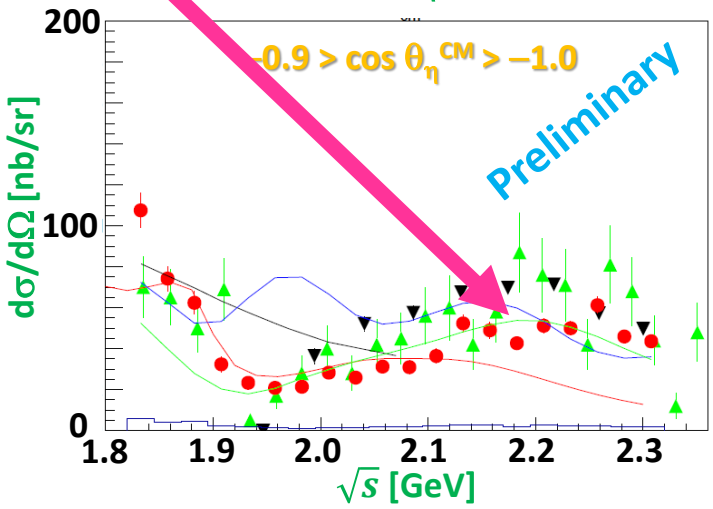
Σ : **The angle dependence is drastically changed above 1.9 GeV.**
Measurement above 2.12 GeV is new.
⇒ **None of PWA models reproduce the BGOegg result.**

Our simple multipole analysis with EtaMAID indicates a contribution from a high spin resonance with L=4 or a u-channel diagram.









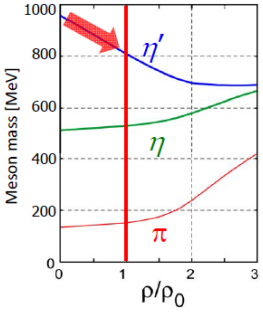
- Introduction of Spring-8 LEPS2/BGOegg experiments
- Baryon resonance studies via single meson photoproduction off the proton
- **Studies of η' mass in nuclei**
- Near future Plan of BGOegg experiment
- Summary

Studies of η' Mass in Nucleus

Large η' mass due to the $U_A(1)$ anomaly ⇒ A good place to examine the connection with $\langle q\bar{q}\rangle$.

Optical Potential

–150 MeV ***–100 MeV*** ***–50 MeV*** ***0 MeV***



Nagahiro et al.
PRC74 (2006) 045203

NJL : –150 MeV

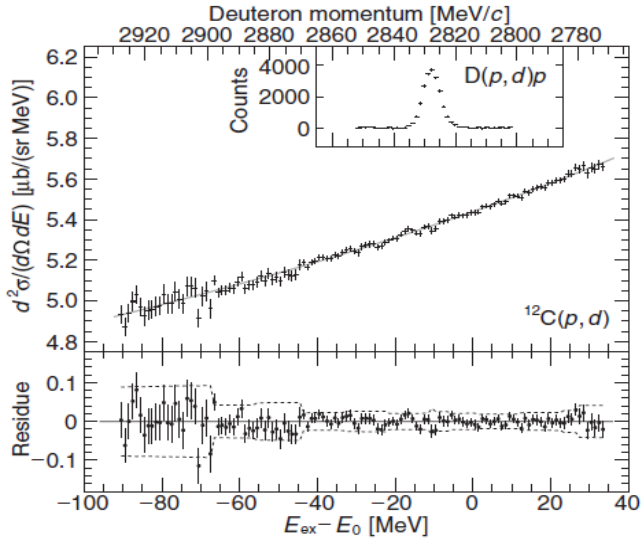
Linear σ model
–80 MeV

Sakai & Jido
PRC88(2013) 064906

CBELSA/TAPS
η'A interaction
≤–50 / –37 MeV

transparency ratio
Nanova et al.
PLB710 (2012) 600
sub-thr. cross section
Nanova et al.
PLB727 (2013) 417

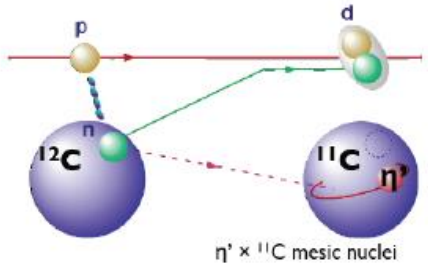
COSY-11
η'N scattering length in pp→ppη'
about –10 MeV
Moskal et al.
PLB482 (2000) 356



FRS@GSI

^{12}C(p,d) η'X @ 2.5 GeV

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



PRL117 (2016) 202501
Fist direct measurement, but large BG.

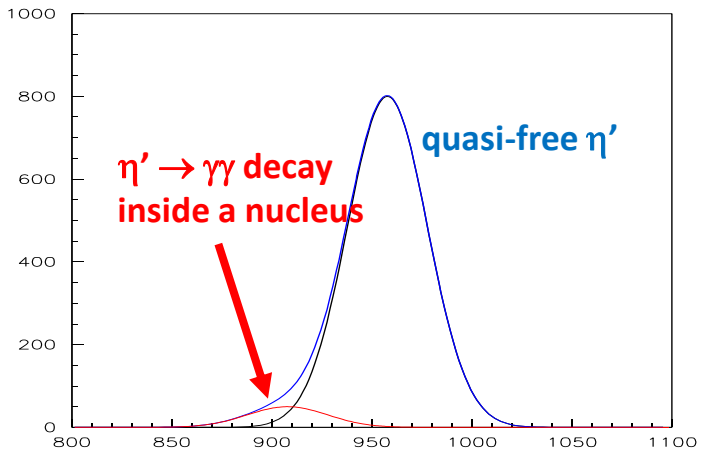
η' Mass Reduction Studies at BGOegg

High momentum proton detection at extremely forward angles.
⇒ TOF measurement at **RPC**

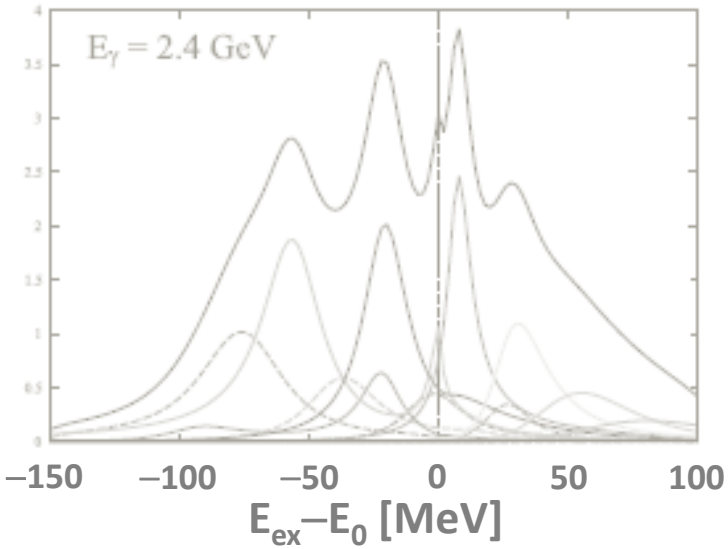
Search for the bound state in the **missing mass spectrum**.
&
Nuclear absorption signal for **a better S/N ratio**.
⇒ **η'p → ηp (back-to-back)** at **BGOegg**

$$\gamma\ ^{12}C \rightarrow \eta'\ ^{11}B + p$$
$$\text{or } \eta'\ ^{11}C + n$$

If nuclear absorption rate is low, a simple examination of the **η' → γγ mass spectrum** at **BGOegg** is effective.



Nagahiro's NJL calculation

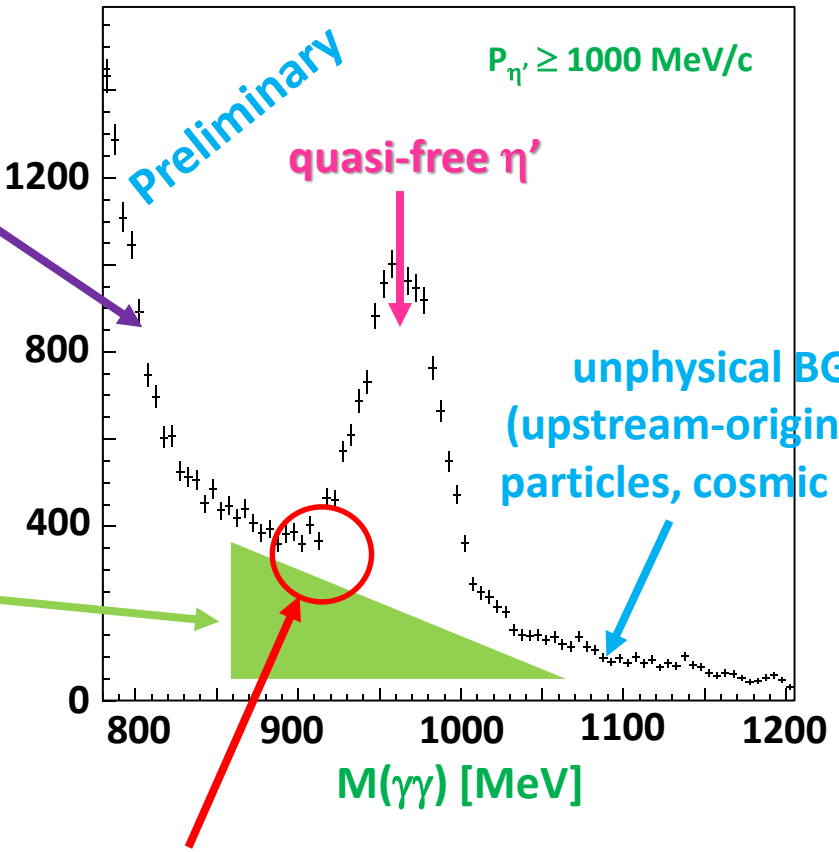


Masking **–100~100 MeV** region & **counting signal events** after fixing the event selection.

Search for η' Mass Medium Modification

C target data collected in 2015

ω photoproduction but 1γ is missing at BGOegg acc. hole



unphysical BG (upstream-originated particles, cosmic rays)

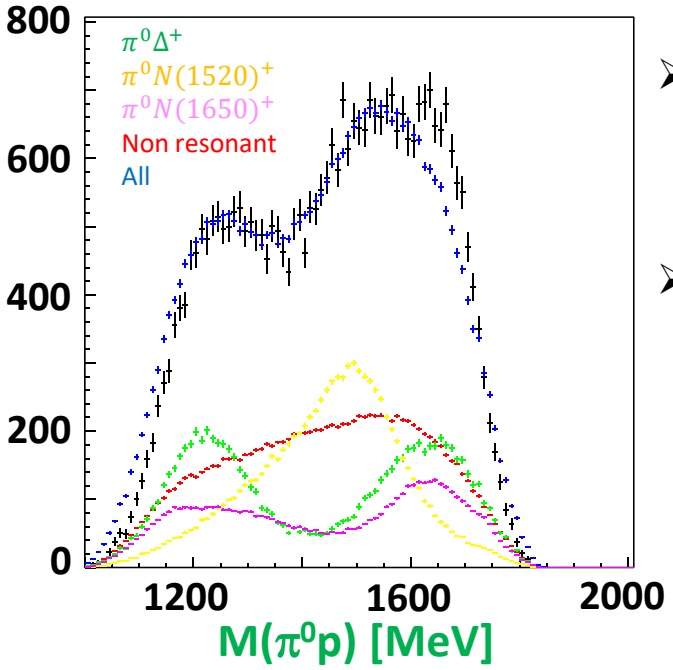
Photoproduction of $\pi^0\pi^0$, $\pi^0\pi^0\pi^0$, $\pi^0\eta$, etc. (Mostly $\pi^0\pi^0$)

Search for the medium modification signal by the fit with & without the signal function.

⇒ Significance will be discussed by χ^2 difference.

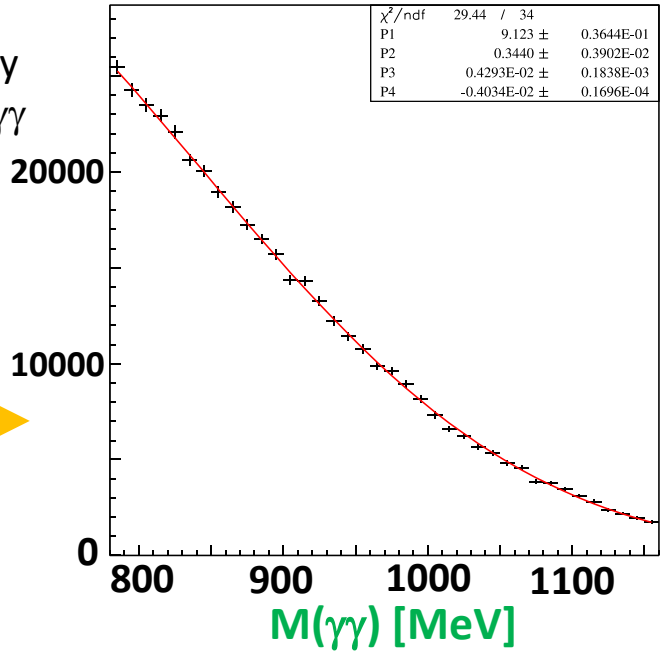
Smooth background

$\gamma p' \rightarrow \pi^0\pi^0 p'$



- $\pi^0\pi^0$p events are exclusively selected to **normalize** the $\gamma\gamma$ distribution.
- **Δ and N* resonances** are considered.

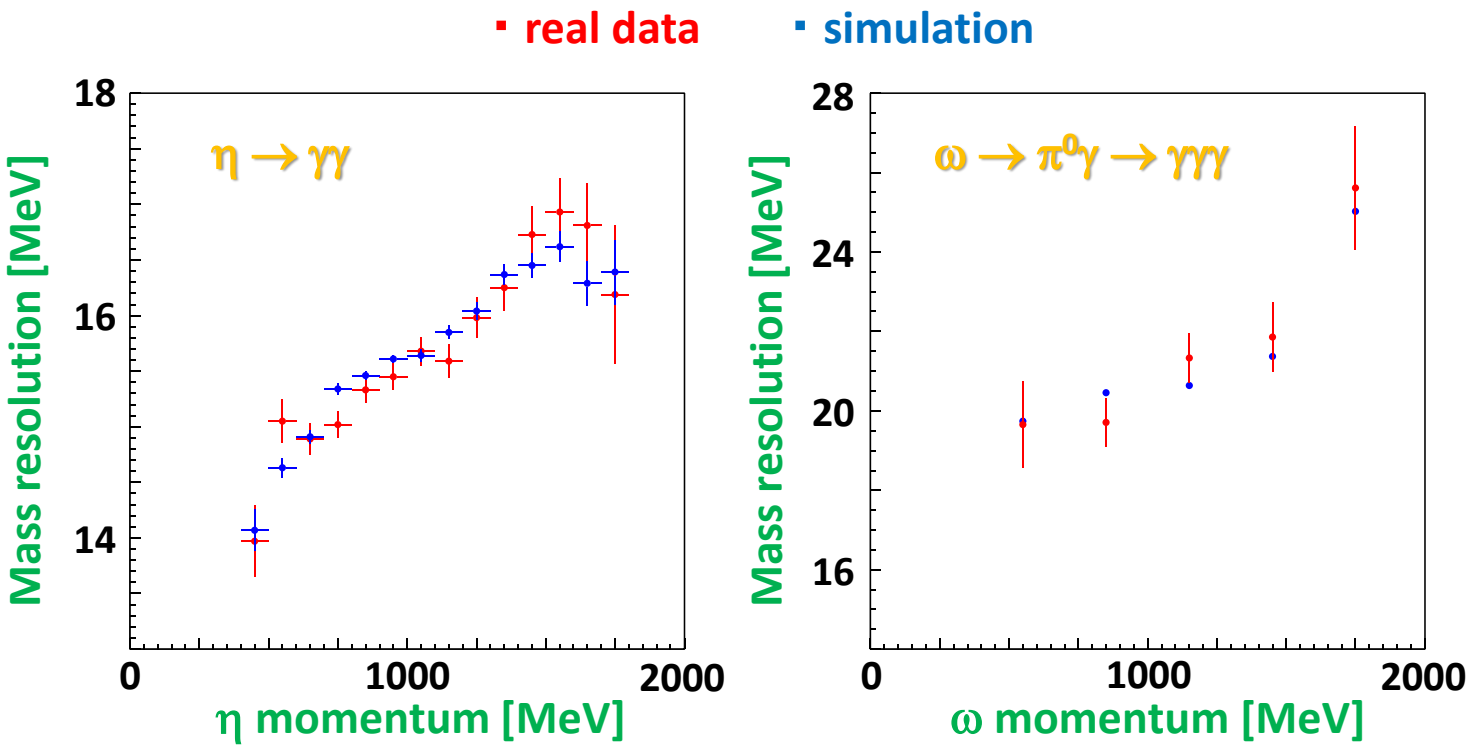
$\gamma\gamma$ invariant mass distribution of the normalized MC samples



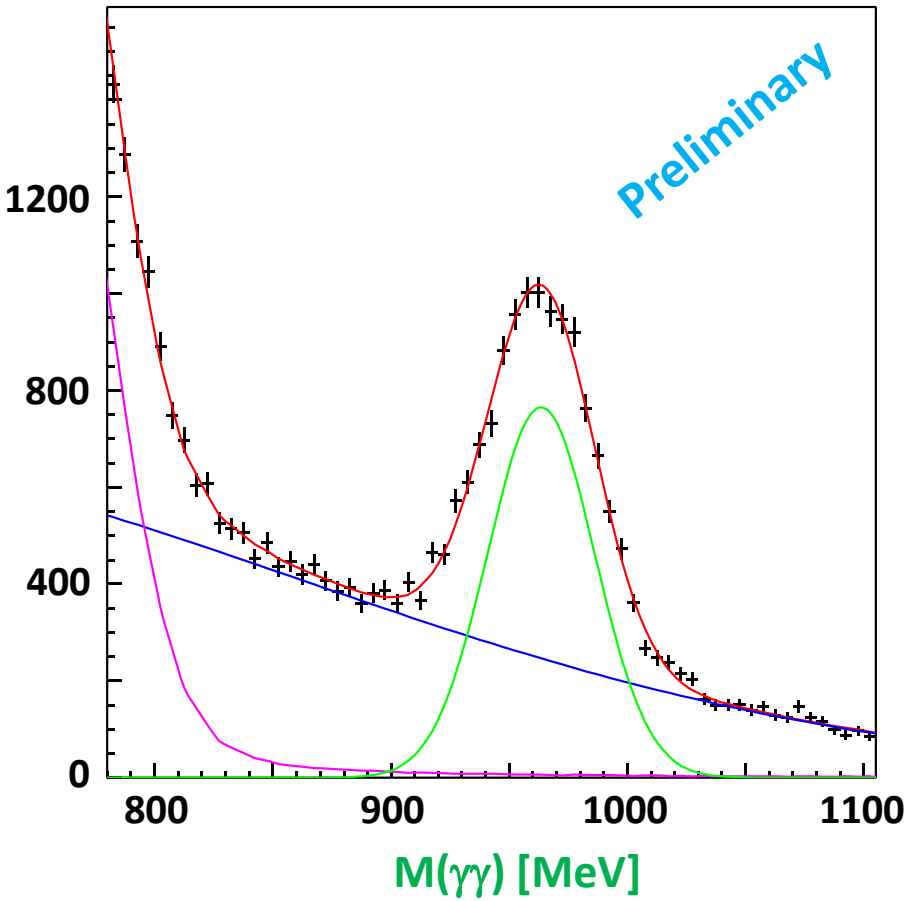
We confirmed the $\gamma\gamma$ distributions are **well expressed by a smooth BG function**, expressed by $\boldsymbol{exp(p_0 + p_1 x + p_2 x^2)}$ for **multiple π^0 or η photoproduction**, **neutral decay modes of η'**, **unphysical BGs**, and **their sum**.

Quasi-free η' Photoproduction

- The quasi-free η' peak is expressed by **a Gaussian function**, whose σ (mass resolution) is fixed to that from **a realistic MC simulation**.
- **The consistency of mass resolution** between the MC simulation and the real data is very good in the tests for $\eta \to \gamma\gamma$ and $\omega \to \pi^0\gamma \to \gamma\gamma\gamma$ events.



Fitting at High Recoil Momentum Region



$P_{\eta'} \geq 1000$ MeV/c for demonstration

Fit with BG components

- : quasi-free η'
- : smooth BG
- : ω (1γ missing)

χ^2/n.d.f. = 61.8/59

⇒ **No significant contribution from the medium modification signal.**

The low momentum region is under investigation as a function of binding energy and width.

Signal functions for mass reduction are also ready by taking into account **the Wood-Saxon type of the nuclear density distribution**.

η'-mesic nuclei search

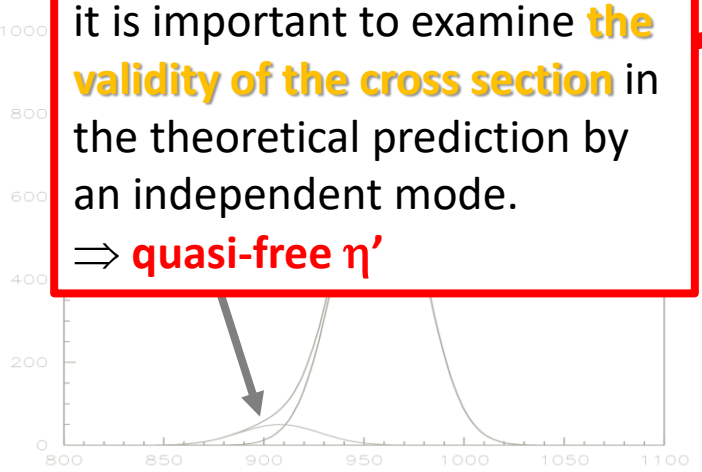
High momentum proton detection
at extremely forward angles.
⇒ TOF measurement at **RPC**

Search for the bound state in
the **missing mass spectrum**.
&
Nuclear absorption signal
for **a better S/N ratio**.
⇒ **η'p → ηp** (**back-to-back**)
at **BGOegg**

$$\gamma\ ^{12}C \rightarrow \eta'\ ^{11}B + p$$
$$\text{or } \eta'\ ^{11}C + n$$

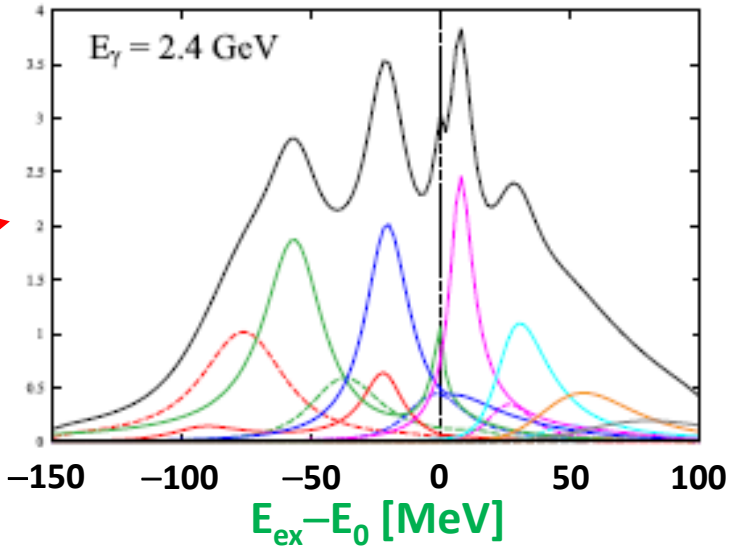
If nuclear absorption rate is low
a si
mas

For **a quantitative comparison**
with the experimental result,
it is important to examine **the validity of the cross section** in
the theoretical prediction by
an independent mode.
⇒ **quasi-free η'**



M(γγ) [MeV]

Nagahiro's NJL calculation

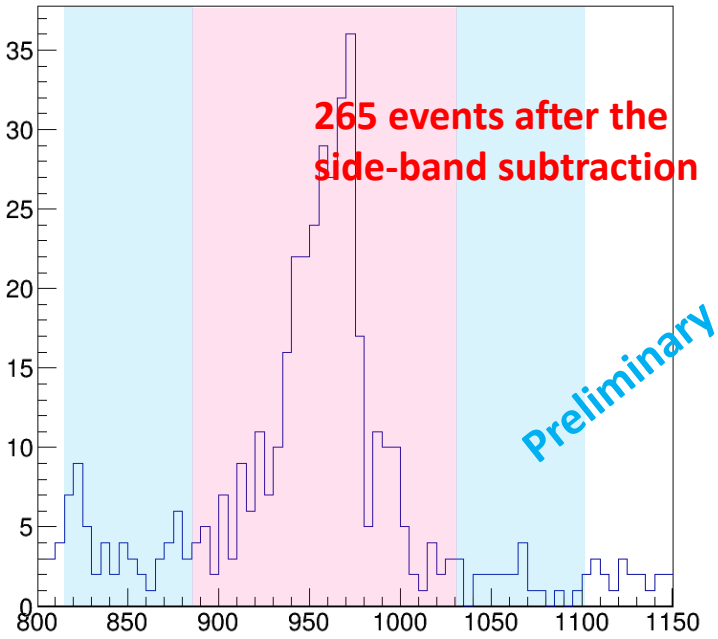


Masking **–100~100 MeV** region & **counting signal events** after fixing the event selection.

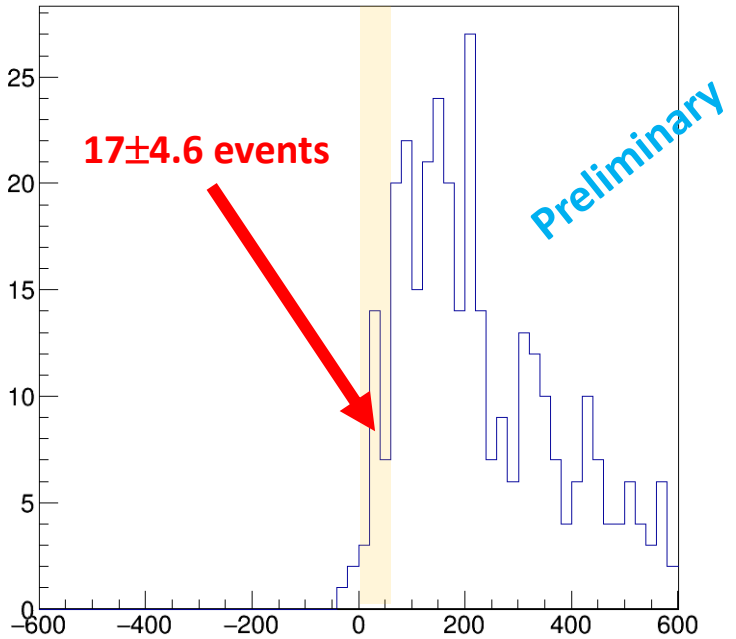
Normalization by quasi-free η' photoproduction

Selected η'→γγ with a proton detection at RPC. Then, events at 0<MM<50 MeV was inspected because the theoretical prediction was reliable only in this region.

2015 Carbon target data
Proton detected at RPC



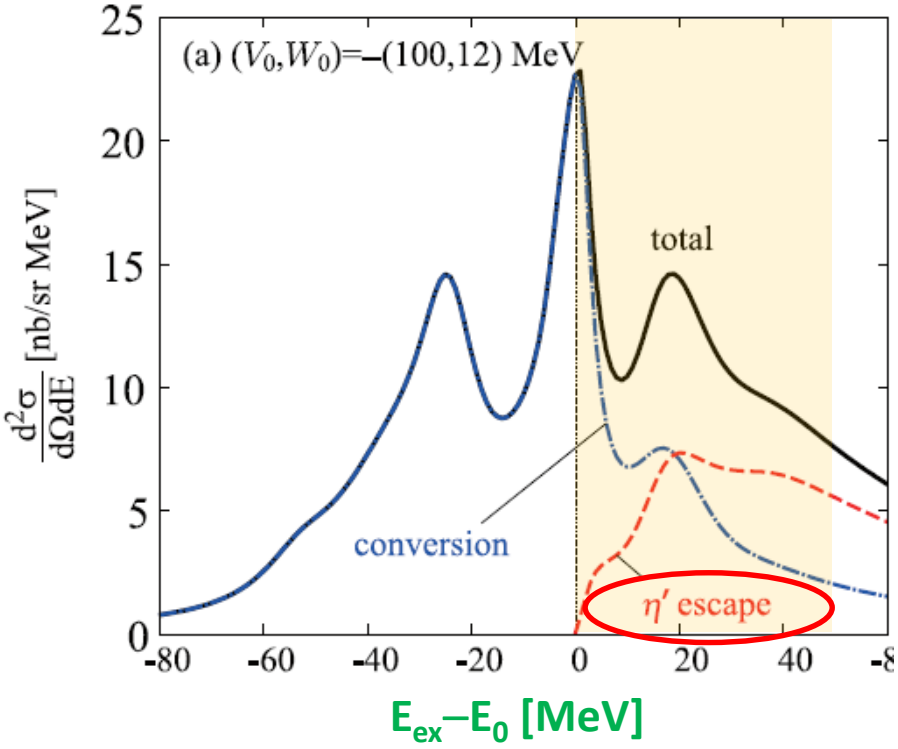
No contribution from higher orbits at
$0 < MM[^{12}C(\gamma,p)] - M[^{11}B] - M[\eta'] < 50$ MeV



Normalization by quasi-free η' photoproduction

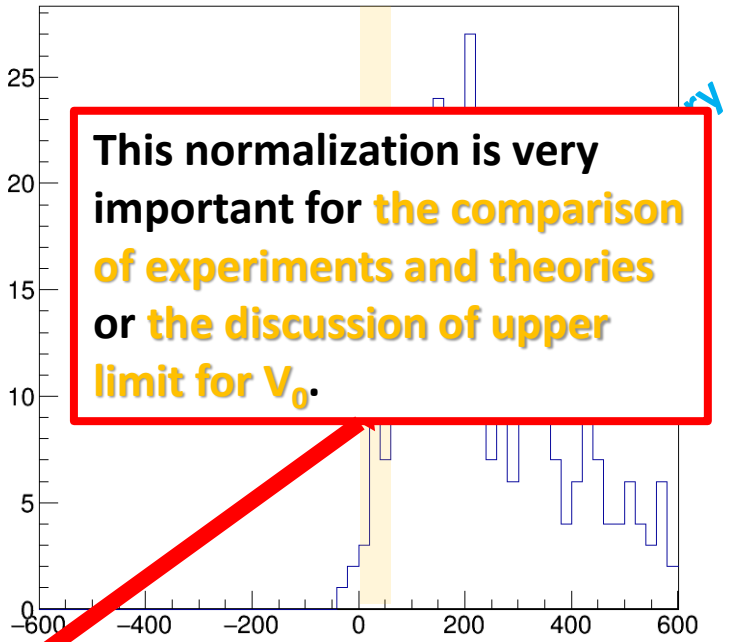
Selected η'→γγ with a proton detection at RPC. Then, events at 0<MM<50 MeV was inspected because the theoretical prediction was reliable only in this region.

H. Nagahiro, JPS Conf. Proc. 13 (2017) 0100010.



By taking into account **Fermi motion**,
172 nb/sr for V_0=100 MeV
⇒ **67.3 events** (Need **a scale of ~1/4**.)

No contribution from higher orbits at
$0 < MM[^{12}C(\gamma,p)] - M[^{11}B] - M[\eta'] < 50$ MeV

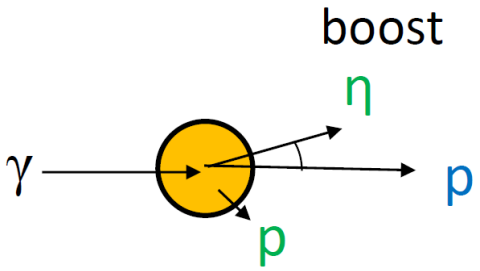


This normalization is very important for the comparison of experiments and theories or the discussion of upper limit for V_0.

Prospects for the η'-mesic nuclei search

Missing mass range	−100<MM<0 MeV	0<MM<50 MeV
BGOegg acceptance	0.50	
Branching fraction	0.39 (η→γγ) × Br(ηp)	
V_0 = 100 MeV	(196±53) × Br(ηp)	(204±55) × Br(ηp)

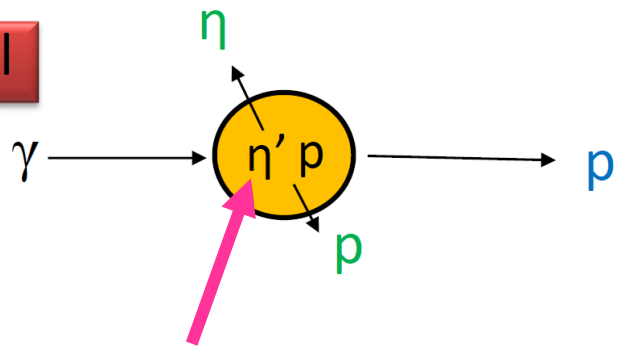
BG



- γp→ηp ; ηp'→ηp / pp'→pp
- γp→πηp ; πp'→πp / ηp'→ηp
- γp→ππp ; πp'→ηp

⇒ The η or p is **forward-peaked**.
The latter 2 modes have **an extra π**.

signal

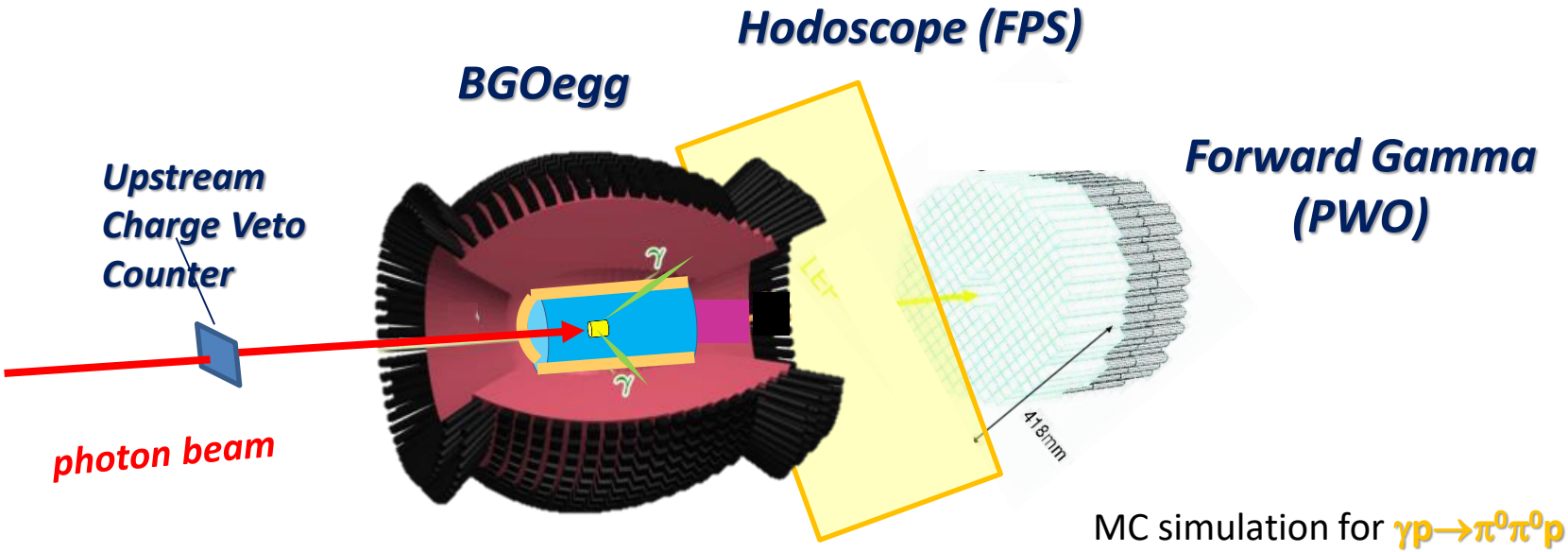


Absorption of **η' at rest**
⇒ **Isotropic & back-to-back** angular distribution. The kinetic energy of η & p is **monochromatic**.

Now the above kinematical cuts are being optimized.

- Introduction of Spring-8 LEPS2/BGOegg experiments
- Baryon resonance studies via single meson photoproduction off the proton
- Studies of η' mass in nuclei
- **Near future Plan of BGOegg experiment**
- Summary

Near Future Plan of BGOegg experiment

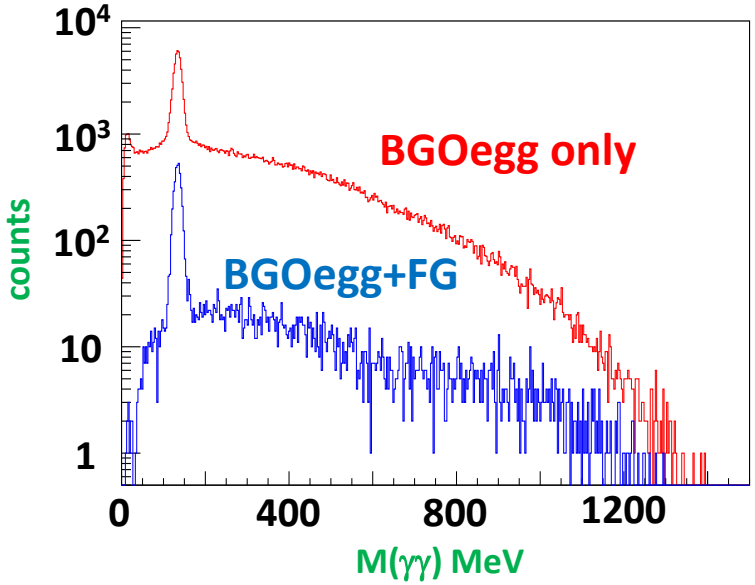


MC simulation for $\gamma p \rightarrow \pi^0\pi^0 p$.

BG can be reduced to 1/10 or less.

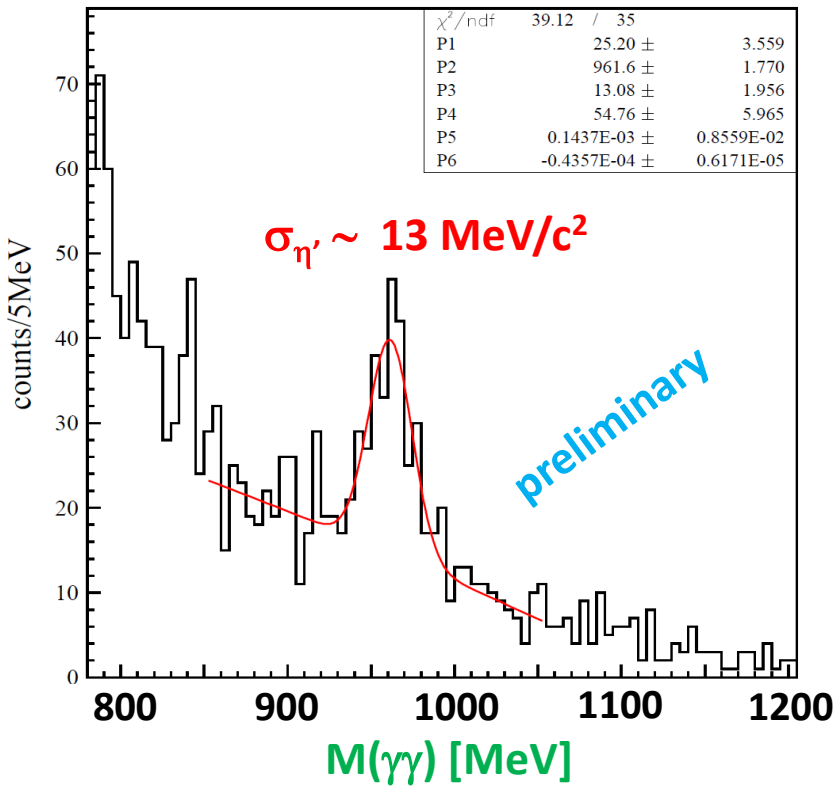
Forward DC & RPC were removed for the solenoid experiment. Instead, **Forward Gamma detector** & **Forward Plastic Scintillators** have been installed.

⇒ A new experiment to search for the **η' mass medium modification** with **a Cu target**.



Prospects with 0.5X_0 Cu target

2017 May test run w/ Cu target



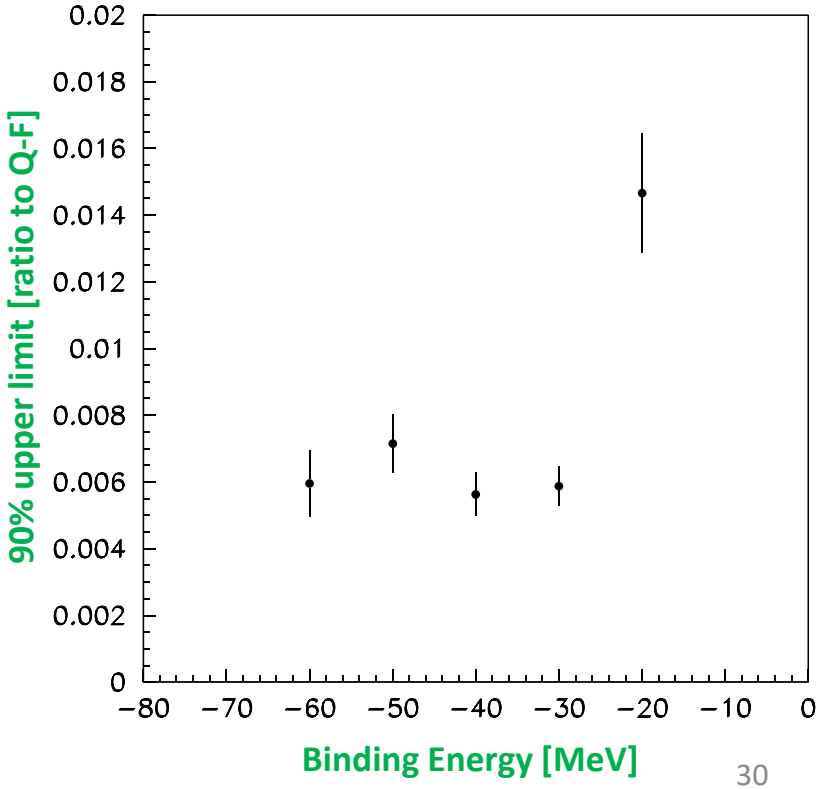
Toy MC generation of quasi-free η' & polynomial BG assuming :

(1) quasi-free η' yield of the 2017 run

(2) 1/10 BG reduction w/ FG detector

(3) 4 month run w/ 2 Mcps

⇒ **Upper limit to observe a signal with σ~13 MeV over the BG fluctuation.**



2017May : **Cu 1.5 mm (0.1X_0)**, <1 Mcps, ~1w

2018 Jan-Feb : **Cu 7.5 mm (0.5X_0)**, ~1 Mcps, ~4w

Aiming larger statistics & a better mass resolution.

c.f. 2015 Apr-July : **C [20 mm (~0.1X_0)]**

$\sigma_{\eta'}$ ~ 20 MeV/c²

Summary

- Activities of BGOegg collaboration so far
  - **N^* physics** with single meson photoproduction off the proton

    Photon beam asymmetry at higher energies are especially unique.
  - Studies for **η' mass reduction inside nuclei** (Carbon target)

    Both medium modification & mesic nuclei are searched for.
- Prospects of BGOegg experiment
  - Existing LH_2 data : **η' photoproduction**, **double meson photoproduction**
  - **Cu target data w/ the new setup** : Medium modification of the η' mass
    - Data collection using **a liquid deuteron target** (a neutron target) is suitable with the new detector setup.
    - If BGOegg is moved to **LEPS beamline**, further mesic nuclei searches are possible.

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