PWA10/ATHOS5 @IHEP, Beijing on 19 July, 2018

Light meson photoproduction at SPring-8 LEPS2/BGOegg experiments

Norihito Muramatsu (ELPH, Tohoku University)

for the BGOegg Collaboration

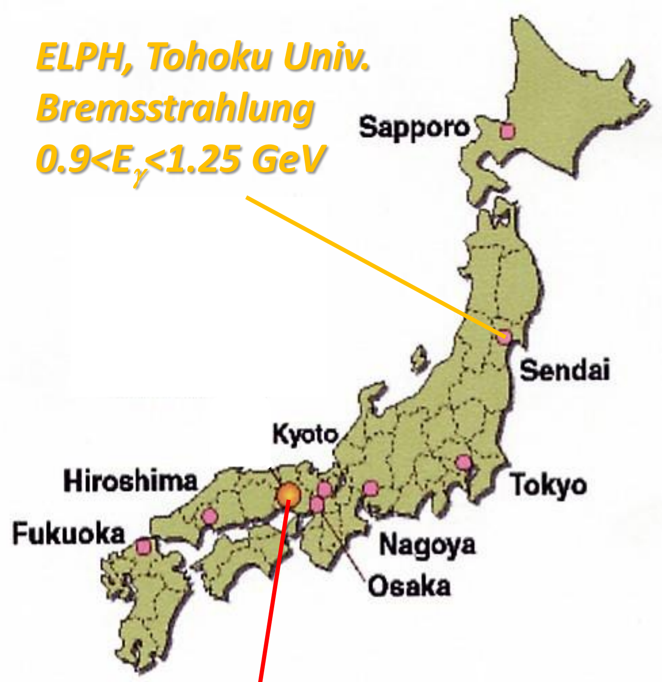
Contents

Today's Aim : Providing **new input data** for the PWA model calculations to study **baryon resonances** (N^*, Δ^*). PWA itself is not used to extract this "input" data.

- Introduction of **Spring-8 LEPS2/BGOegg experiments**
  Photoproduction experiments by a **Laser Compton Scattering (LCS)** beam.
- **Differential cross sections** & **Photon beam asymmetry**
  Especially, the beam asymmetries at $E_\gamma \gtrsim 2$ GeV are new.
  ☞ π^0 photoproduction off proton
  ☞ η photoproduction off proton
  ☞ ω photoproduction off proton

Photon Beam Facilities in Japan

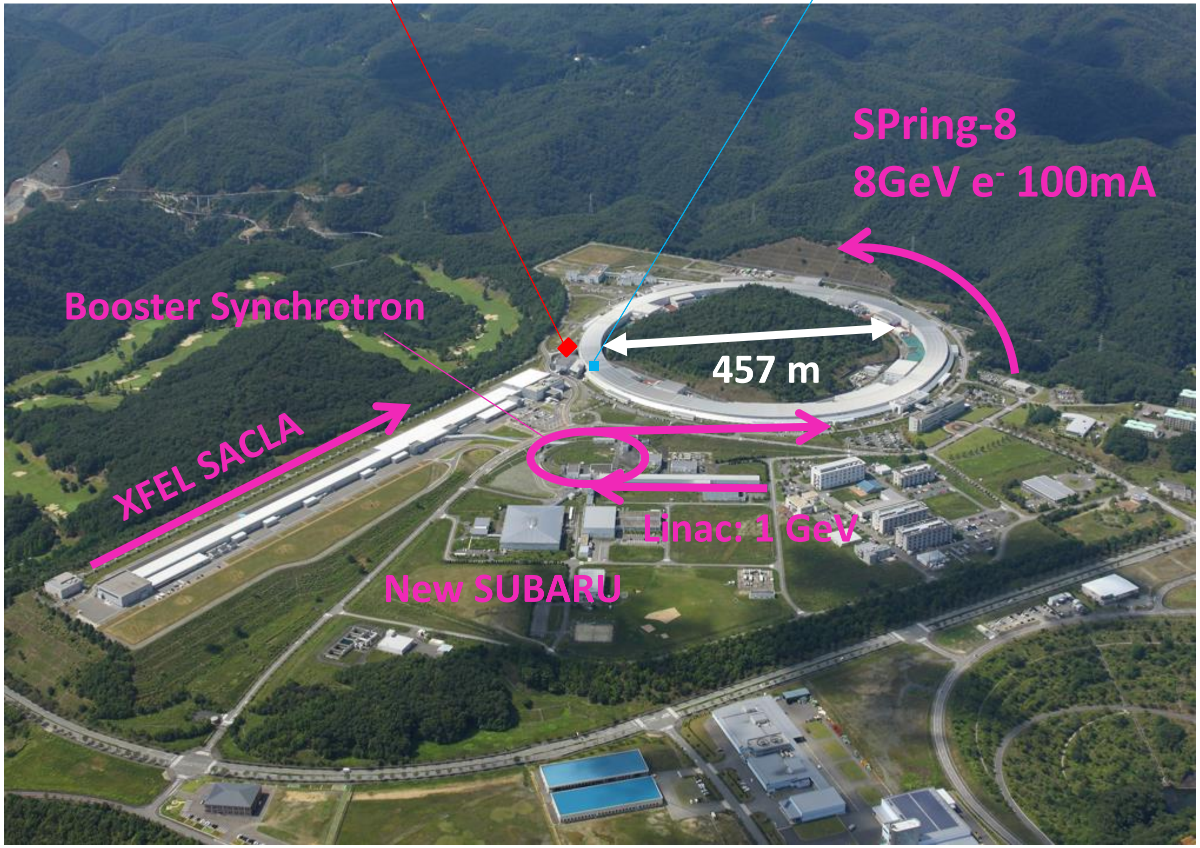
ELPH, Tohoku Univ.
Bremsstrahlung
$0.9<E_\gamma<1.25$ GeV



Spring-8
Laser Compton Scattering
LEPS : $1.5<E_\gamma<2.9$ GeV
LEPS2 : $1.3<E_\gamma<2.4$ GeV

LEPS2 Experimental Building (2013 ~)

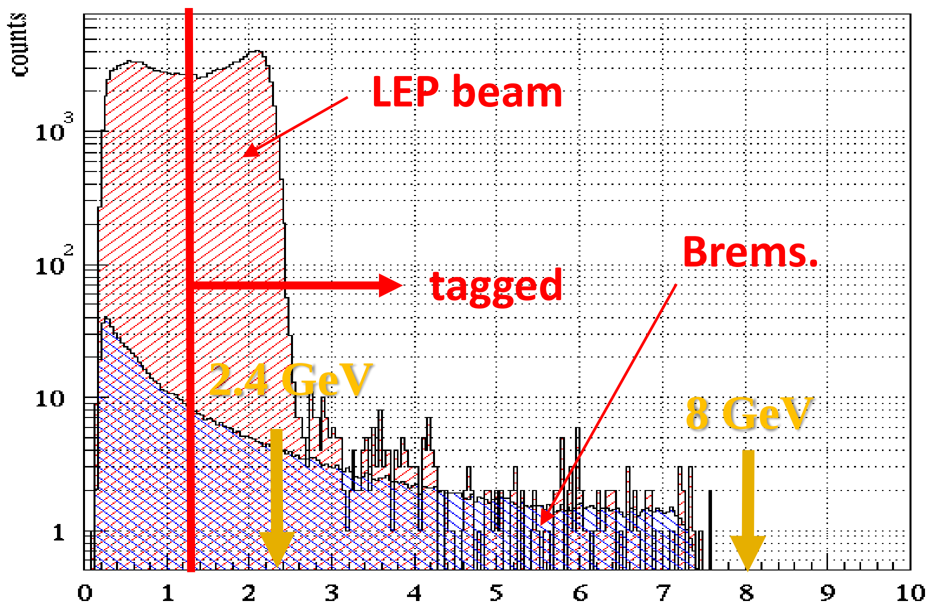
LEPS Experimental Hutch (1999 ~)



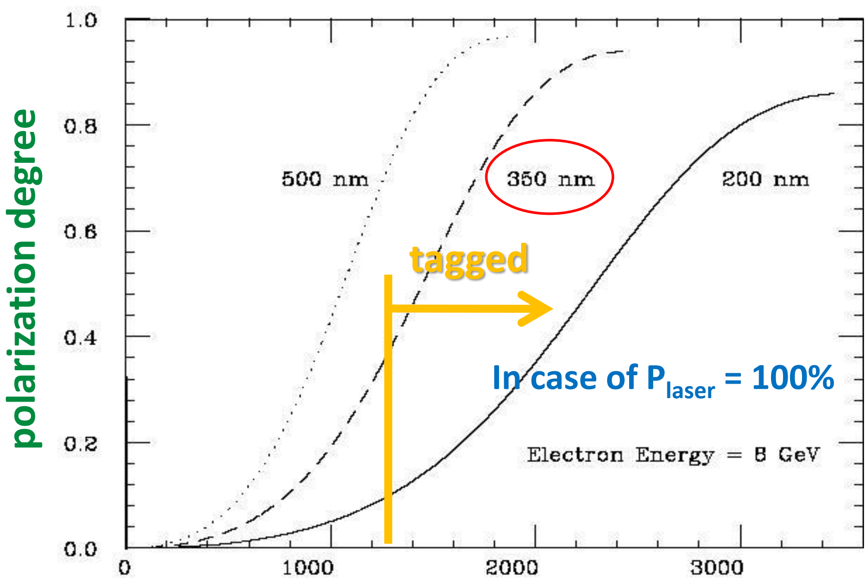
Laser Compton Scattering

- LEP (Laser Electron Photon) beam has nearly flat spectrum up to Compton edge. $k_{\max} = \frac{(E_e + P_e)k_{laser}}{E_e - P_e + 2k_{laser}} \simeq \frac{4E_e^2 k_{laser}}{m_e^2 + 4E_e k_{laser}} = \boxed{2.38GeV(355nm)}$
- LEP intensity is 3-order higher than Bremsstrahlung radiation by residual gas.
- LEP beam polarization ~95% at maximum energy.

LEP spectrum (PWO calorimeter)



Linear polarization



LEPS2 Beamline

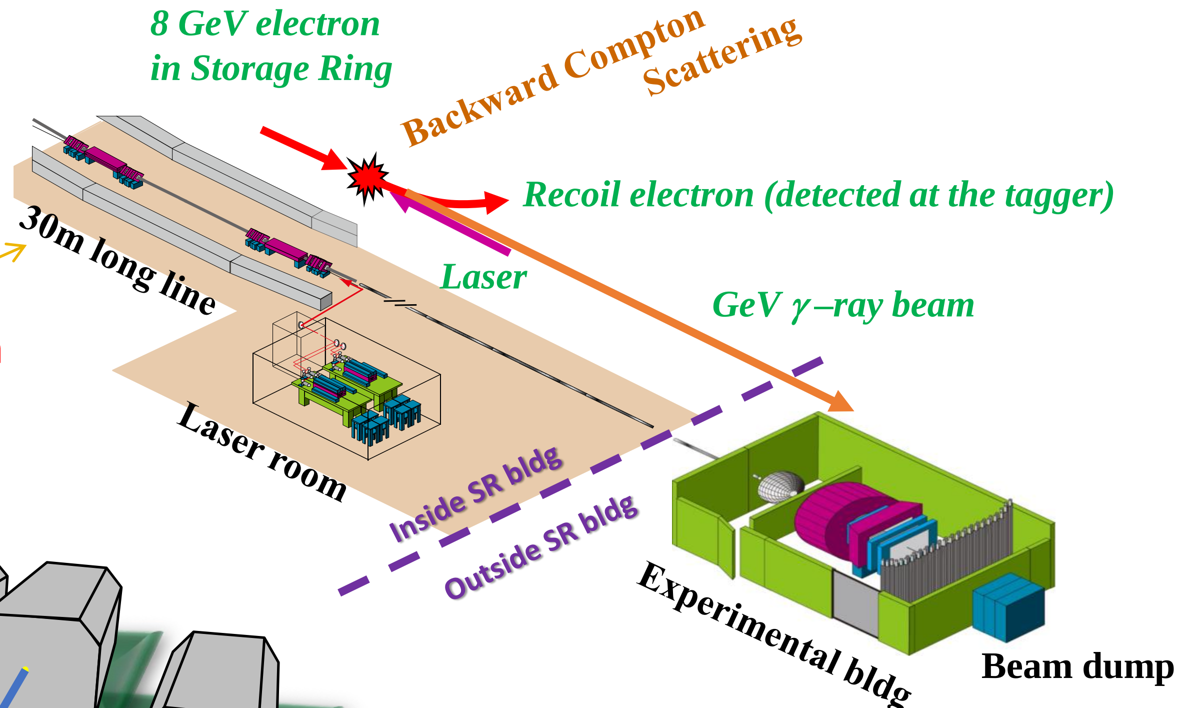
e⁻ Beam Divergence

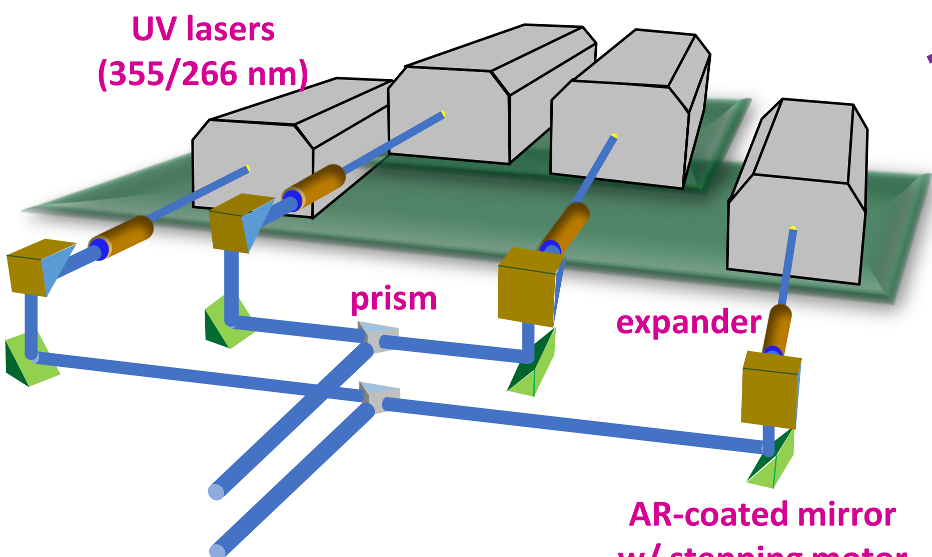
$<\sigma_{x'}>$=58 μrad
@LEPS 7.8m straight section

⇓

$<\sigma_{x'}>$=12 μrad
@LEPS2 30m straight section

Only 4 of 62 beamlines





Experimental Site (135m)

LEPS *42m²* (area) x *3m* (high)

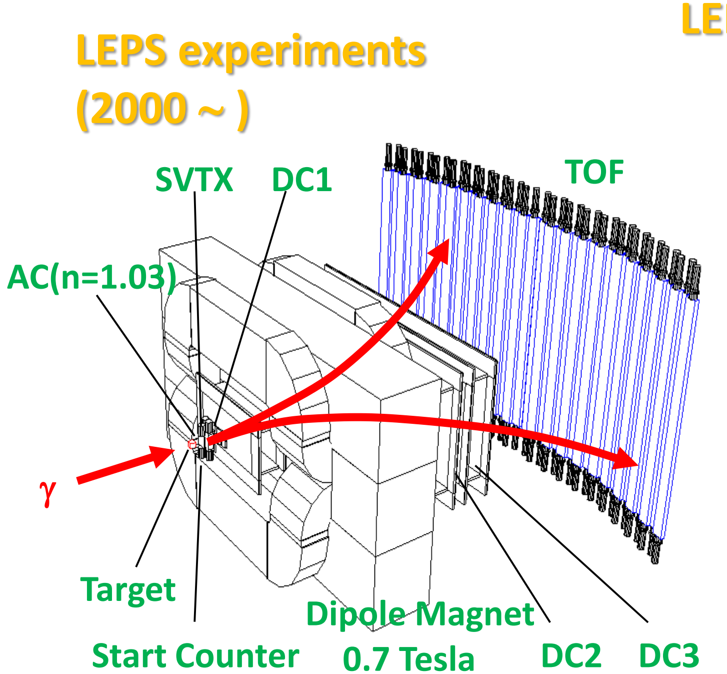
⇓

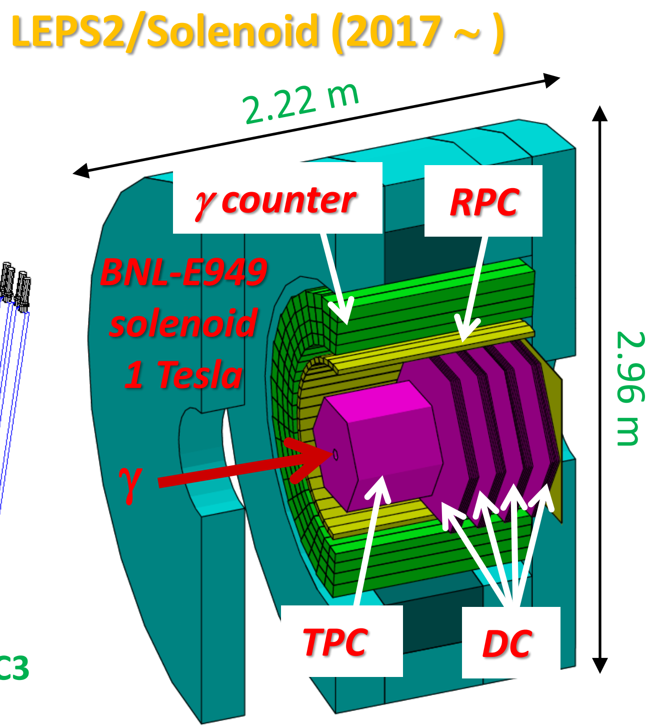
LEPS2 *198m²* (area) x *10m* (high)

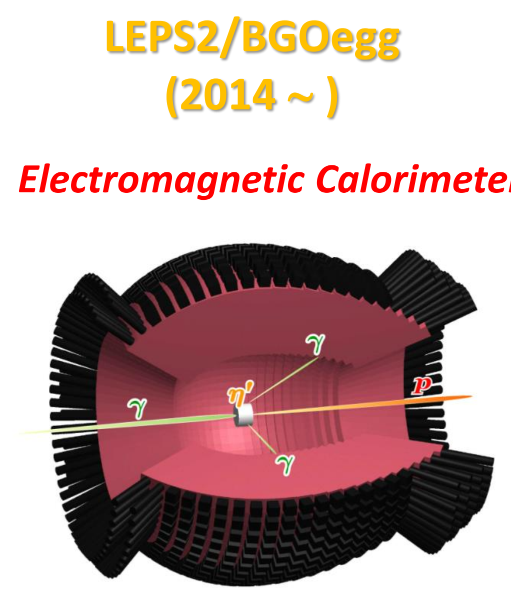
15 times in volume !

Three Detector Setups at SPring-8

	LEPS (BL33LEP)	LEPS2 (BL31LEP)
Tagged γ Energy	E_γ>1.5 GeV	E_γ>1.3 GeV
	Max. E_γ is 2.4/2.9 GeV. (UV/DUV Laser Injection)	
Tagged γ Beam Intensity	2-Laser Injection 2×10^6 cps	Max. 4-Laser Injection $\lesssim 10^7$ cps
Detector System	Charged Spectrometer with **Forward Acceptance**	**Covering Large Solid Angles** BGOegg / Solenoid







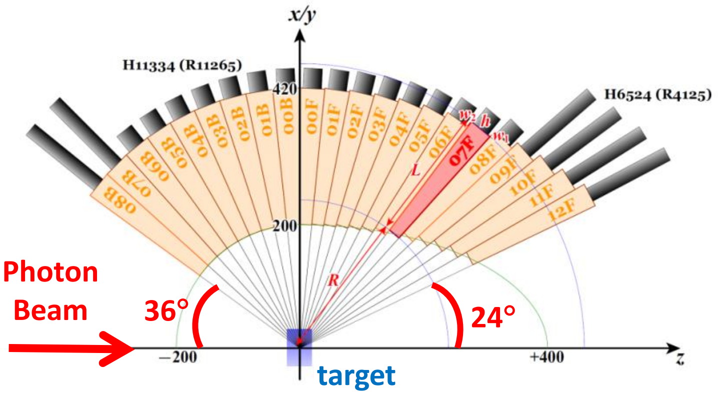
LEPS2/BGOegg Eexperimental Setup

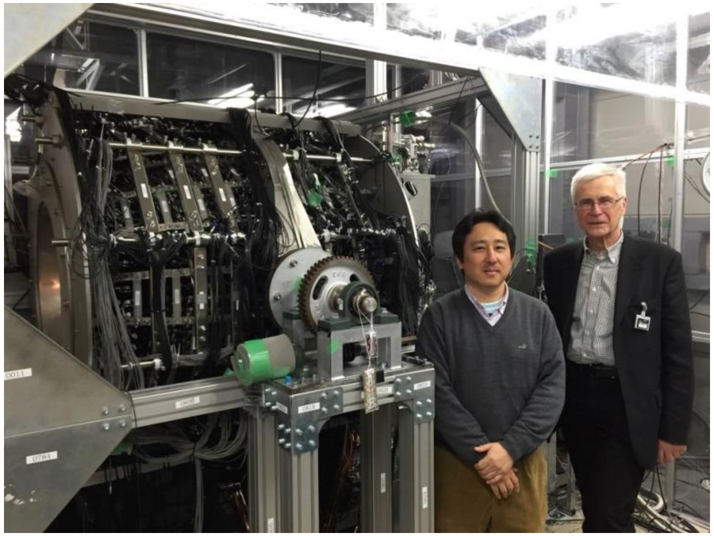
Target Carbon (20 mm) ⇒ Searches for η'-mesic nuclei or medium modification

LH_2 (54 mm) ⇒ Photoproduction of π^0, η, ω, etc (baryon resonance)

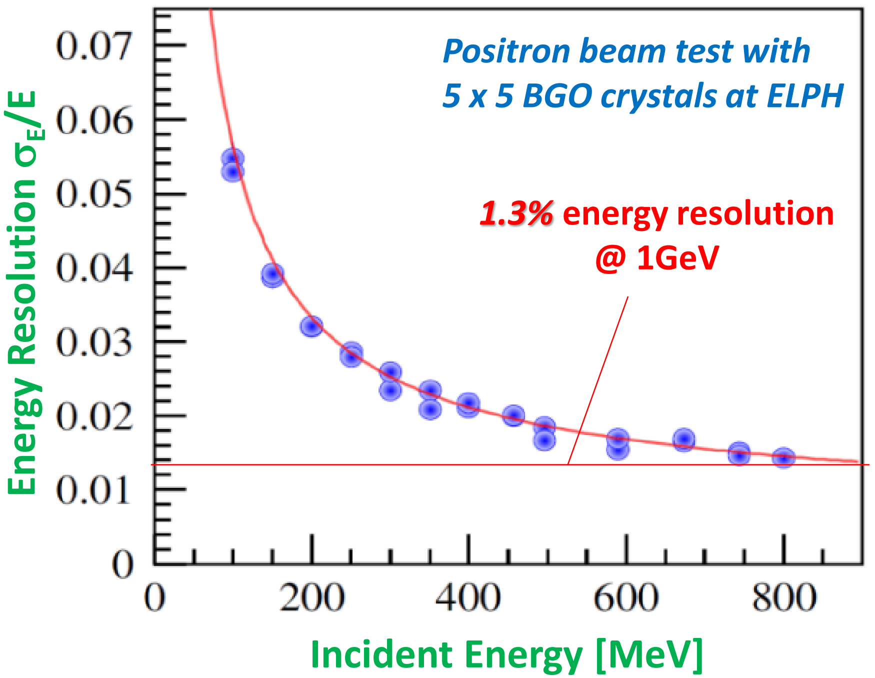
Large Acceptance EM calorimeter BGOegg

- *'Egg'-shape assembly of 1320 $Bi_4Ge_3O_{12}$ crystals* without supporting structures b/w crystals.
- Each BGO covers *~6°* in (θ,ϕ) with $L_{crystal}$ = 220 mm (*$20X_0$*). There are *22 layers*.
- World-highest energy resolution in the energy region below 1 GeV. (1.3% @ 1 GeV)





Crystal Barrel with CsI(Tl) : *σ_{E_γ}=2.5% @ 1 GeV*
BGO-OD with BGO : *σ_{M_π}=14 MeV* & *σ_{M_η}=24 MeV*



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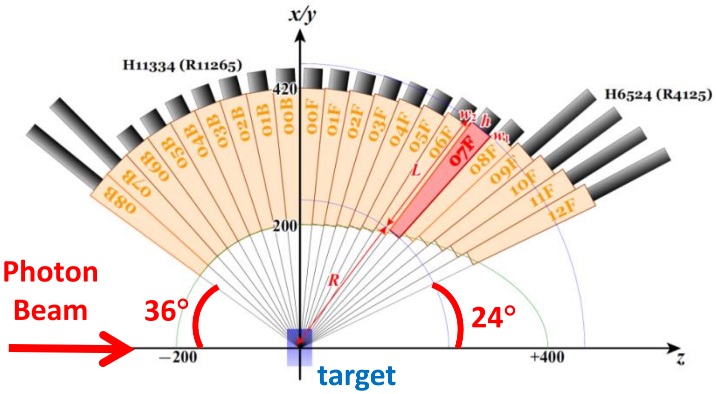

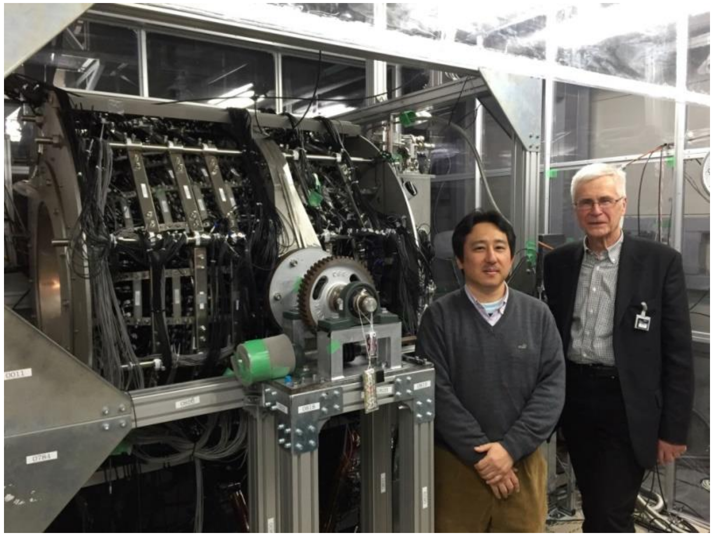

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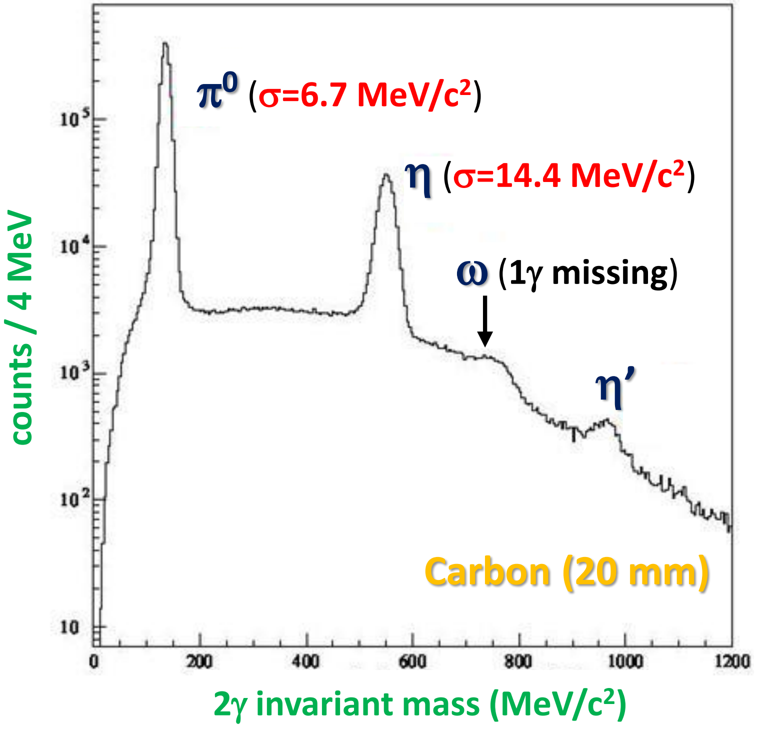

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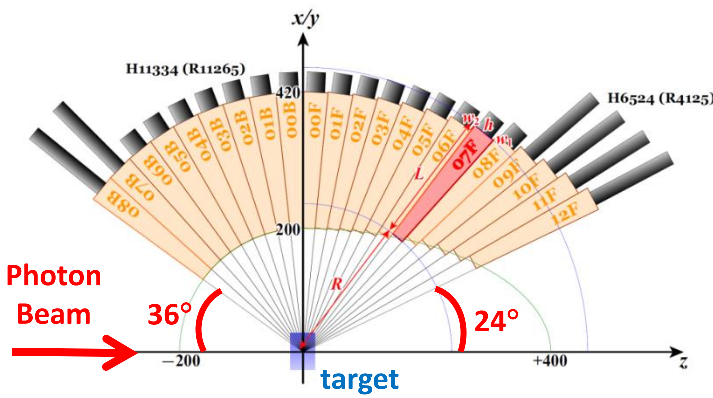

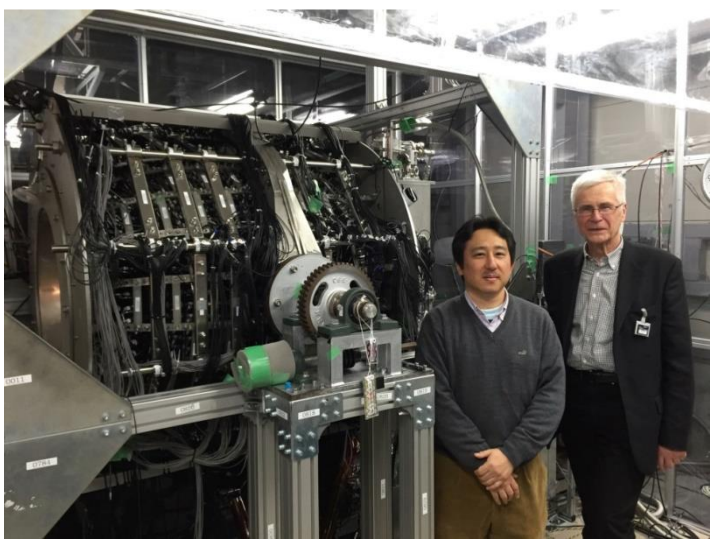

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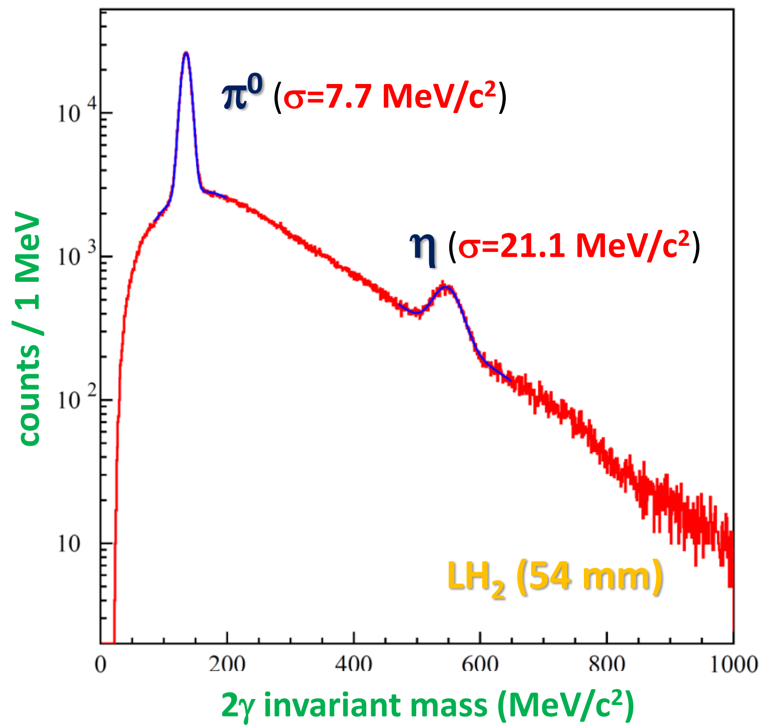


Summary of Data Collection

Period	Target	Integrated # of γ's (tagged E_γ region)
2014A (Apr.~July)	**Carbon/CH_2** [20 mm]	**C: 1.31×10^{12}, CH_2: 1.58×10^{12} with RPC** (In total, C: 4.29×10^{12}, CH_2: 2.56×10^{12}) ***Test sample for η'-mesic nuclei search & γp analyses***
2014B (Nov.~Feb.)	**LH_2** [40 mm]	**Hori: 2.24×10^{12} , Vert: 2.01×10^{12}** ***N^* physics, etc (with spin observable)***
2015A (Apr.~July)	**Carbon** [20 mm]	**9.77×10^{12} (Vert: 8.97×10^{12})** ***η'-mesic nuclei search***
2015B (Sep.~Dec.)	**LH_2** [40 mm]	**Hori: 2.87×10^{12} , Vert: 2.92×10^{12}** ***Additional data for γp reactions***
2016A (Apr.~July)	**LH_2** [40 mm] **Carbon** [20 mm]	**C: 7.04×10^{12} (LH_2: 1.44×10^{12})** ***Additional data for η'-mesic nuclei search***
2017A (May)	**Cu** [1.5 mm]	**0.41×10^{12}** (all horizontal) ***Test sample by 1-week data taking***
2017B (Jan.~Feb.)	**Cu** [7.5 mm]	**1.43×10^{12}** (all horizontal) ***Forward gamma detector was installed.***

BGOegg Physics Program 1 : η’-mesic nuclei search

2015A $\gamma + {}^{12}C \rightarrow \eta' \otimes {}^{11}B + p$

Tagger

photon beam energy (σ~12 MeV)

RPC-TOF (σ~80 ps)

forward proton momentum (σ~1%)

Missing mass

Search for a bound state in $M_{12C(\gamma,p)} - M_{11B} - M_{\eta'}$

Nucleon absorption signal of η’ at BGOegg ⇒ S/N improvement

η’p -> ηp

(back-to-back)

BGOegg

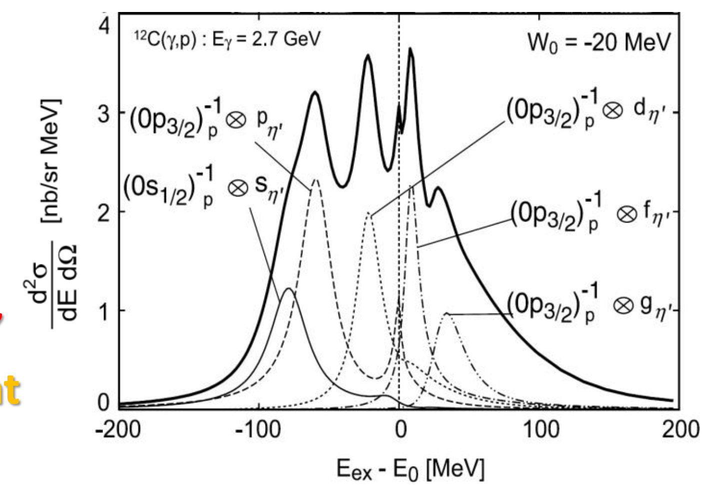
IPS

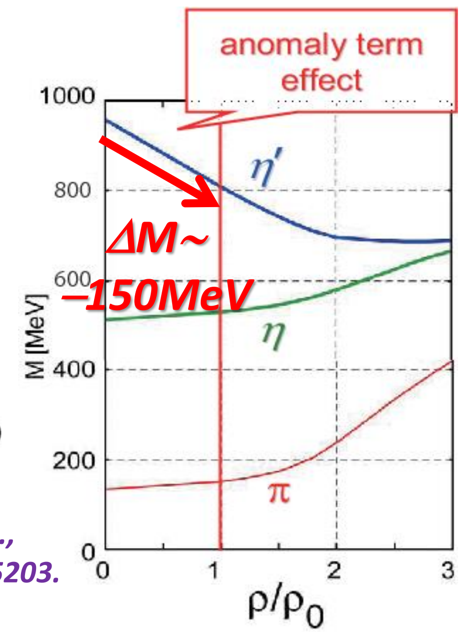
η tag in M(γγ)

proton PID (dE-E)

NJL model calculation

150MeV shift



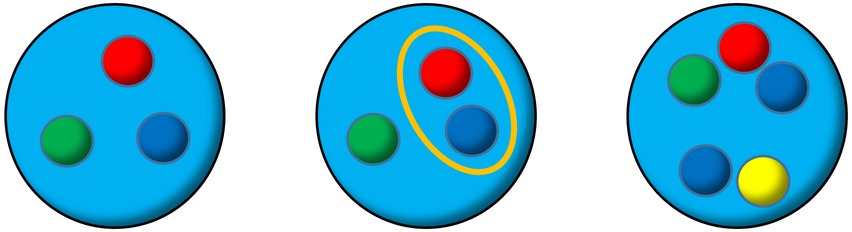


H. Nagahiro et al., PRC74 (2006) 045203.

BGOegg Physics Program 2 : Baryon Resonance

- The studies of **excited baryon resonances at 1.5—2.5 GeV/c^2** are important for understanding **the constituent quark model and beyond**.

  ex. **missing resonance**,
  diquark correlation,
  exotic baryon, …..



- At first, we start from the studies of **nucleon resonances (N^*)** via **η / ω / η' (isoscalar meson) photoproduction** for simplicity. Especially, the η & η' mesons couple with the N^*s including **$s\bar{s}$ quarks**.)
- The N^*s have broad widths overlapping with each other. The measurement of the **photon beam asymmetry** in addition to the **differential cross section** helps to **decompose the N^*s** 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.

BGOegg Physics Program 2 : Baryon Resonance

- **π^0 photoproduction** : I=1 $\Rightarrow$ Both **N^*** and **Δ^*** contribute at s-channel.

  Traditional & Many existing data

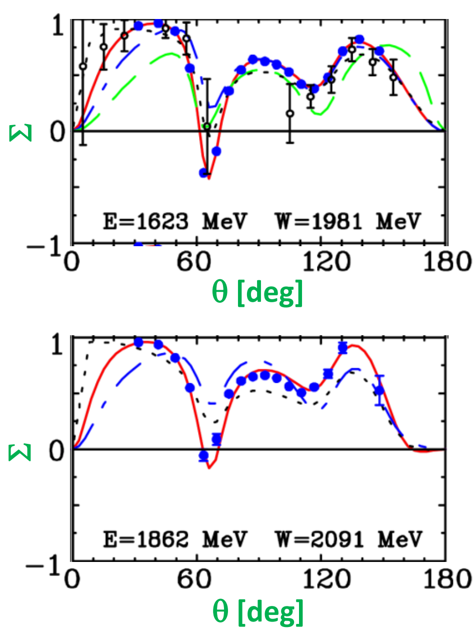
  $\Rightarrow$ **Check of analysis method & luminosity**.

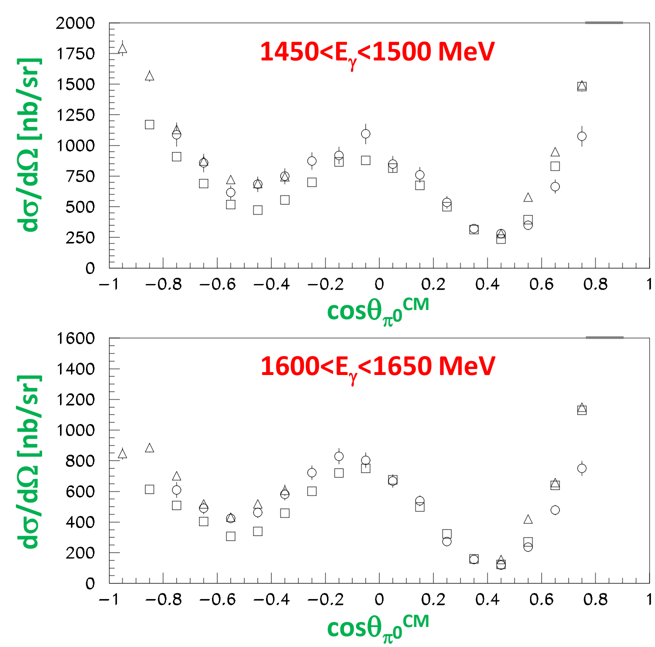
Can we expect **any new knowledge** from the π^0 photoproduction ?

- **Photon beam asymmetry above 2 GeV**.
- Discrepancy of **CLAS & CBELSA differential cross sections** at low energies & backward angles.

●: CLAS [PRC 88 (2013) 065203]

○: CBELSA [EPJA 39 (2009) 373, PRC 81 (2010) 065210]





□: CLAS [PRC76 (2007) 025211]

○: CBELSA [PRL94 (2005) 012003]

△: CBELSA [PRC84 (2011) 055203]

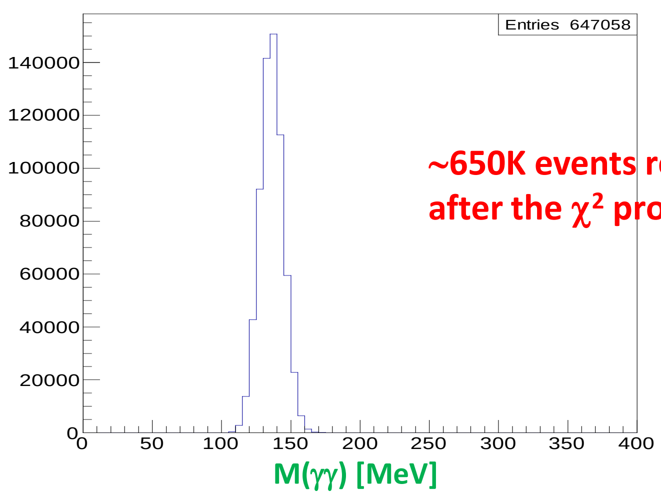
π^0 Photoproduction Analysis

Event Selection

E_γ meas. (1.3—2.4 GeV) at tagger.
No e^+e^- contamination at UpVeto.
2 neutral clusters at BGOegg.
$\pi^0 \to \gamma\gamma$ (Br=98.8%)
Proton detection at DC or BGOegg.

Kinematic Fit

Better S/N ratio & resolutions.
χ^2 probability cut at 2%.

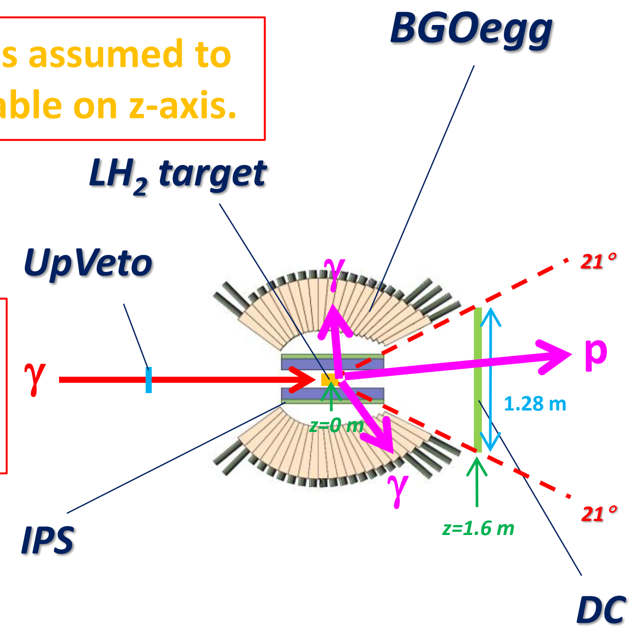


~650K events remains after the χ^2 prob. cut.

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

Vertex is assumed to be variable on z-axis.

Beam energy comes from tagger.

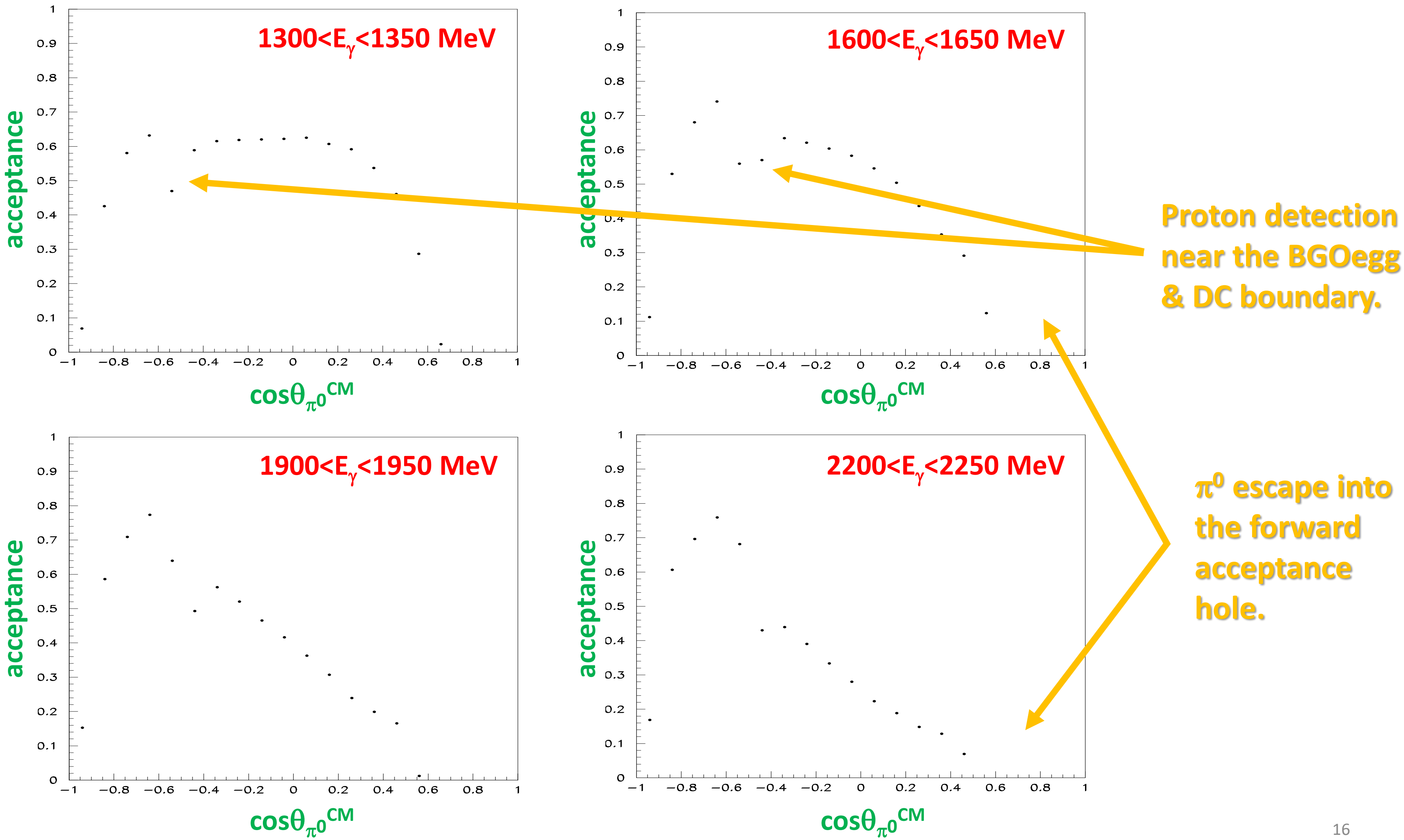


Only the proton direction is measured at DC or BGOegg.

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

Acceptance for the $\gamma p \to \pi^0 p$ reaction

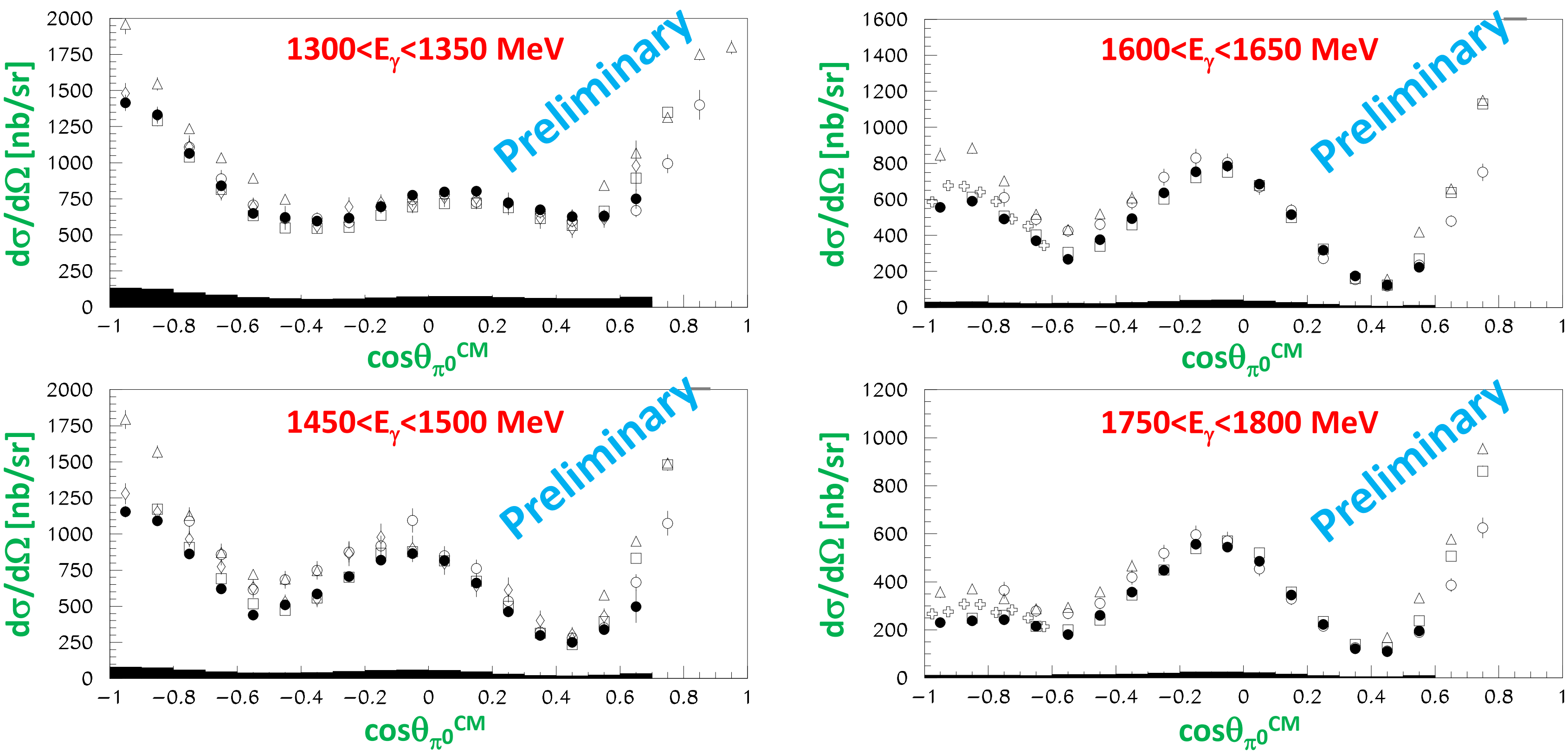
Acceptance measurement was **iterated** by using the MC sample of the $\gamma p \to \pi^0 p$ reaction.
Started from the phase space and took into account the **differential cross sections** in MC.



Differential Cross Section of $\gamma p \rightarrow \pi^0 p$ below 1.9 GeV

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

●: **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.



Differential Cross Section of $\gamma p \to \pi^0 p$ above 1.9 GeV

*Closer to the **CLAS**, **GRAAL**, and **LEPS** results than the **CBELSA** result at the low E_γ range.*

●: **this work (BGOegg)**, □: CLAS [PRC76 (2007) 025211],
○: CBELSA [PRL94 (2005) 012003], △: CBELSA [PRC84 (2011) 055203]
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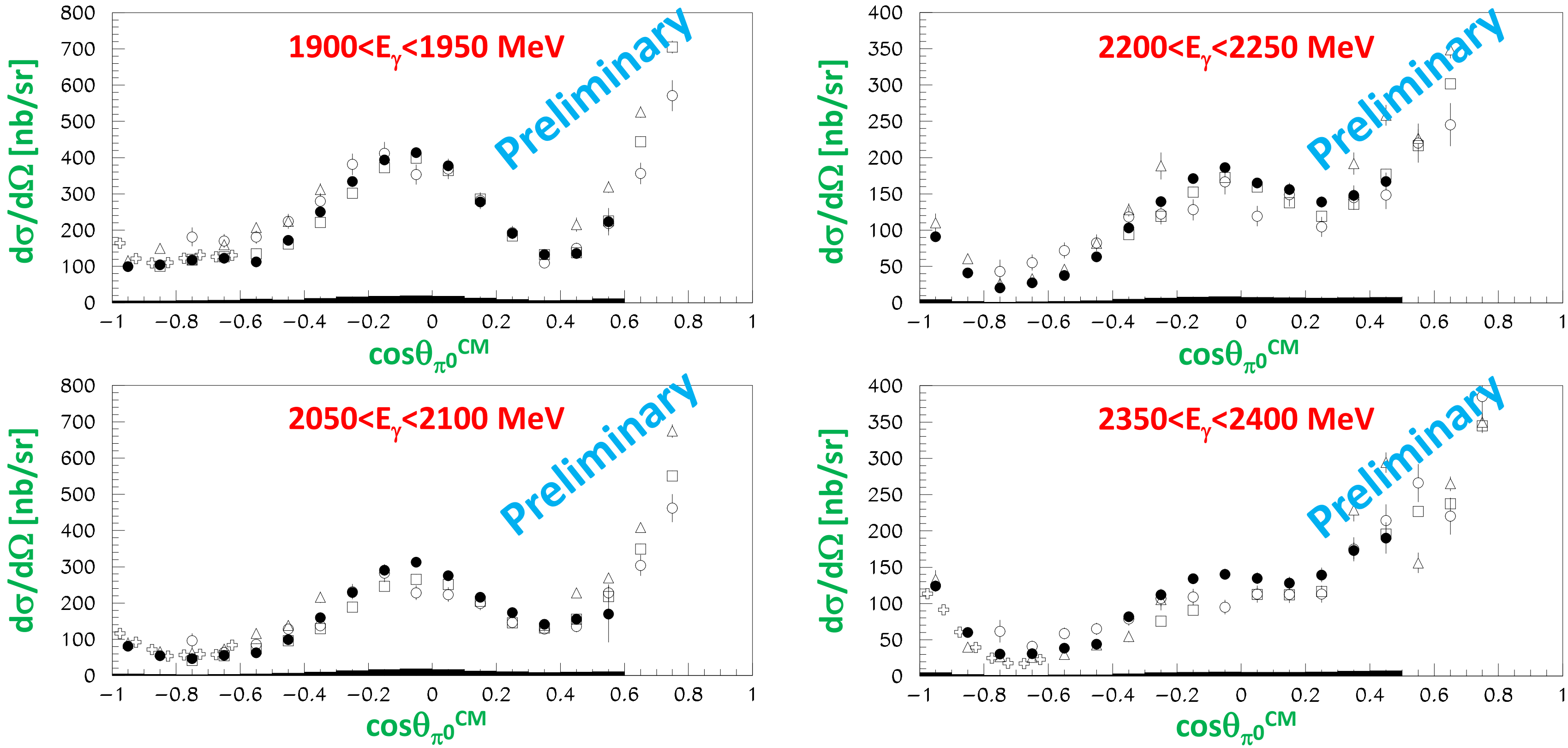


Comparison with Model Calculations (π^0 cross section)

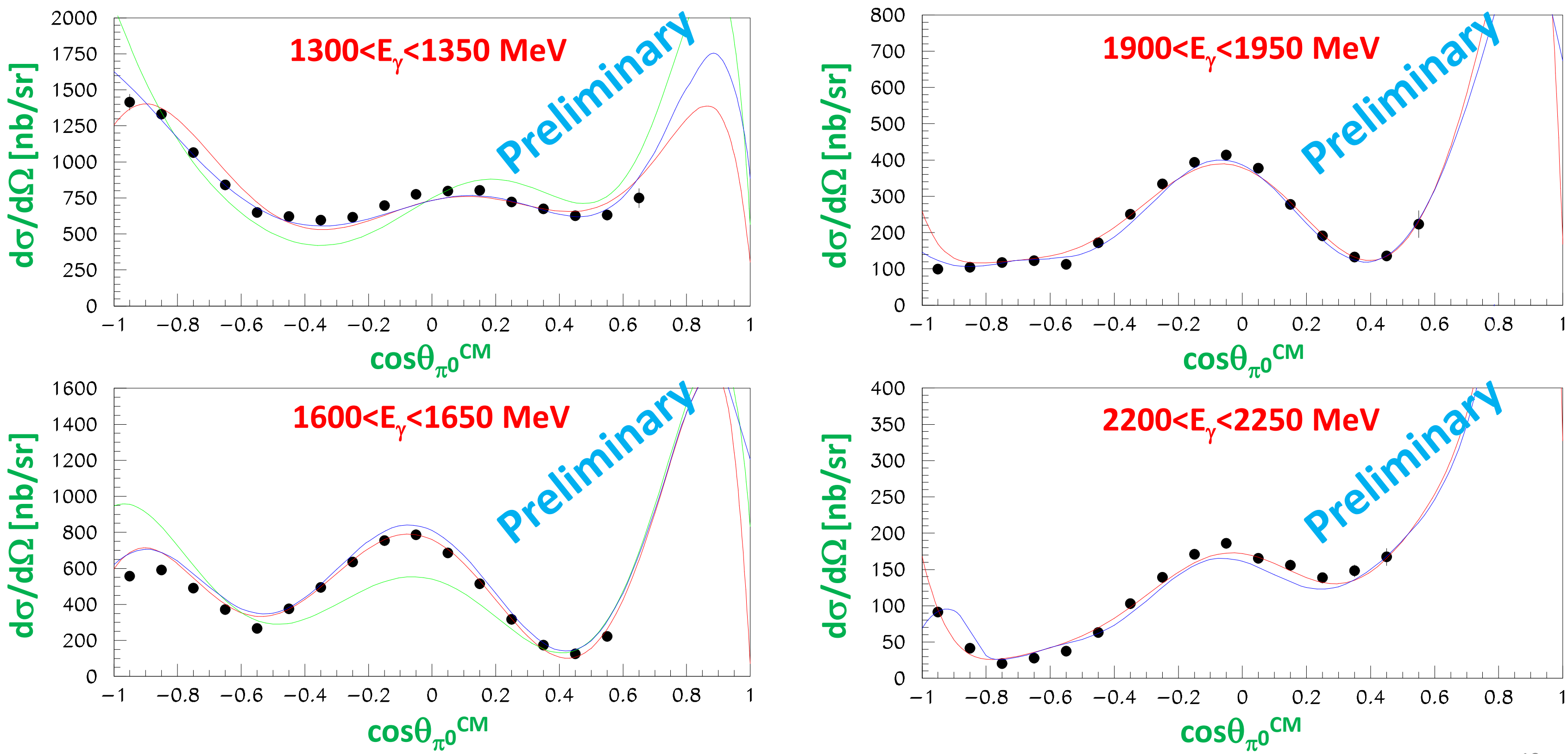
●: **this work (BGOegg)**

——: **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.)]

More or less consistent with the model calculations because the differential cross sections are well defined by the existing data.



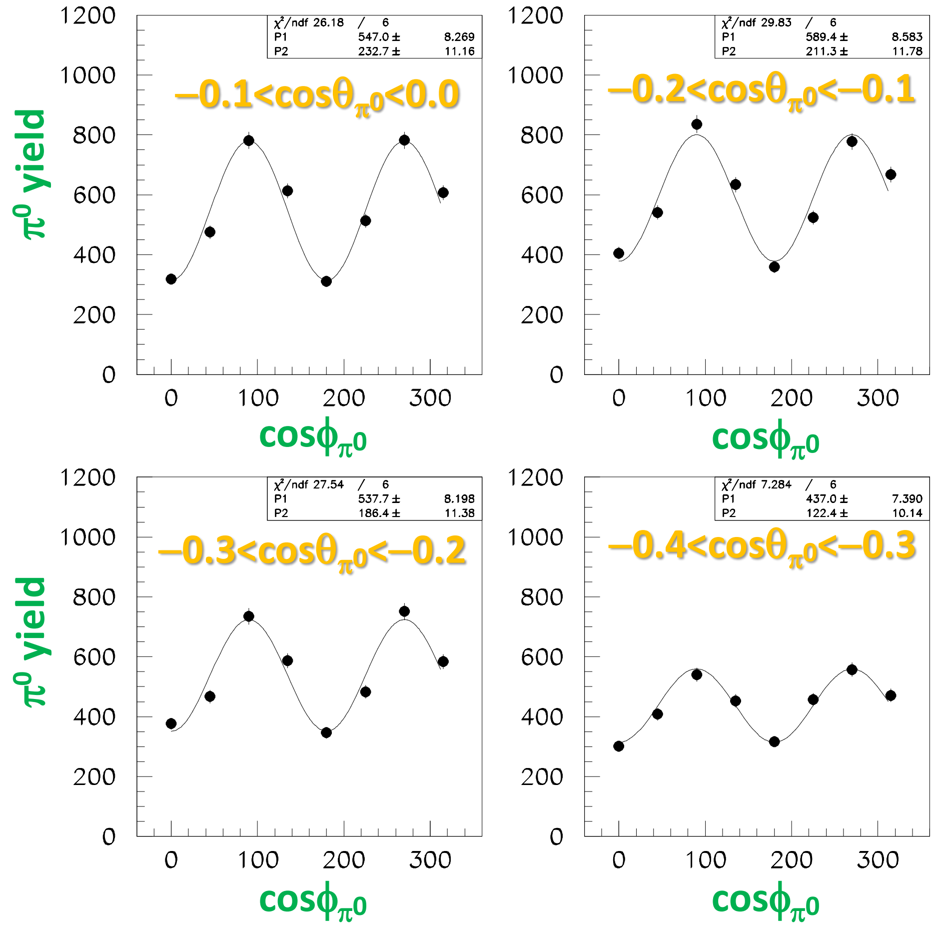
Photon Beam Asymmetry Measurement

- **Vertical & horizontal data** were summed by adjusting the linear polarization directions with rotations.
- **No acceptance correction** is necessary.
- Fit **$A\,(1+\Sigma'\cos 2\phi)$** .
- The beam asymmetry Σ was obtained by multiplying the **polarization degree P_γ** to the fitted Σ'.

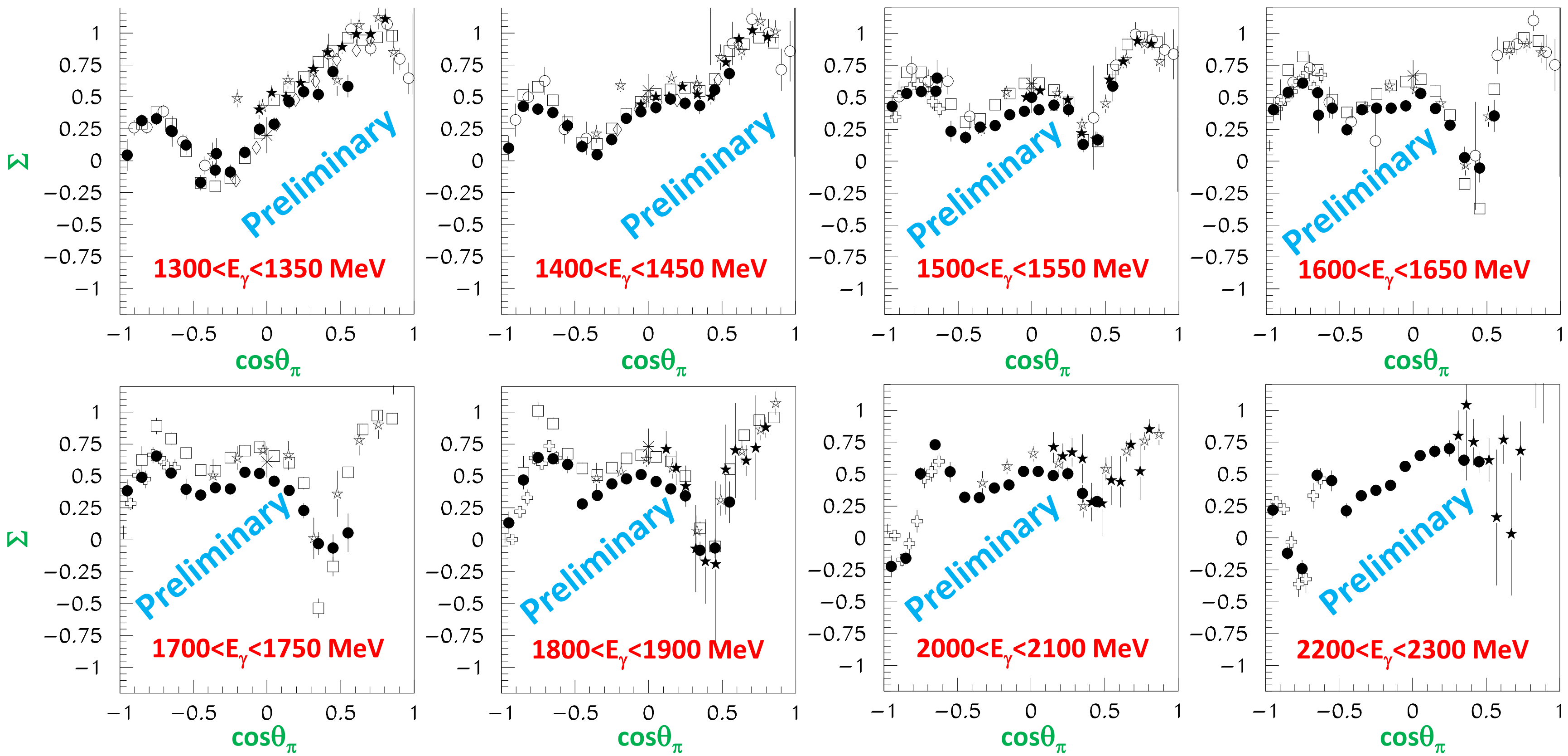
$$P_\gamma = P_{\mathrm{laser}} \frac{(1-\cos\alpha)^2}{2(\chi + 1 + \cos\alpha^2)}$$

Eq.16 of NIM A 455 (2000) 1.

Fit examples for $1900<E_\gamma<2000$ MeV

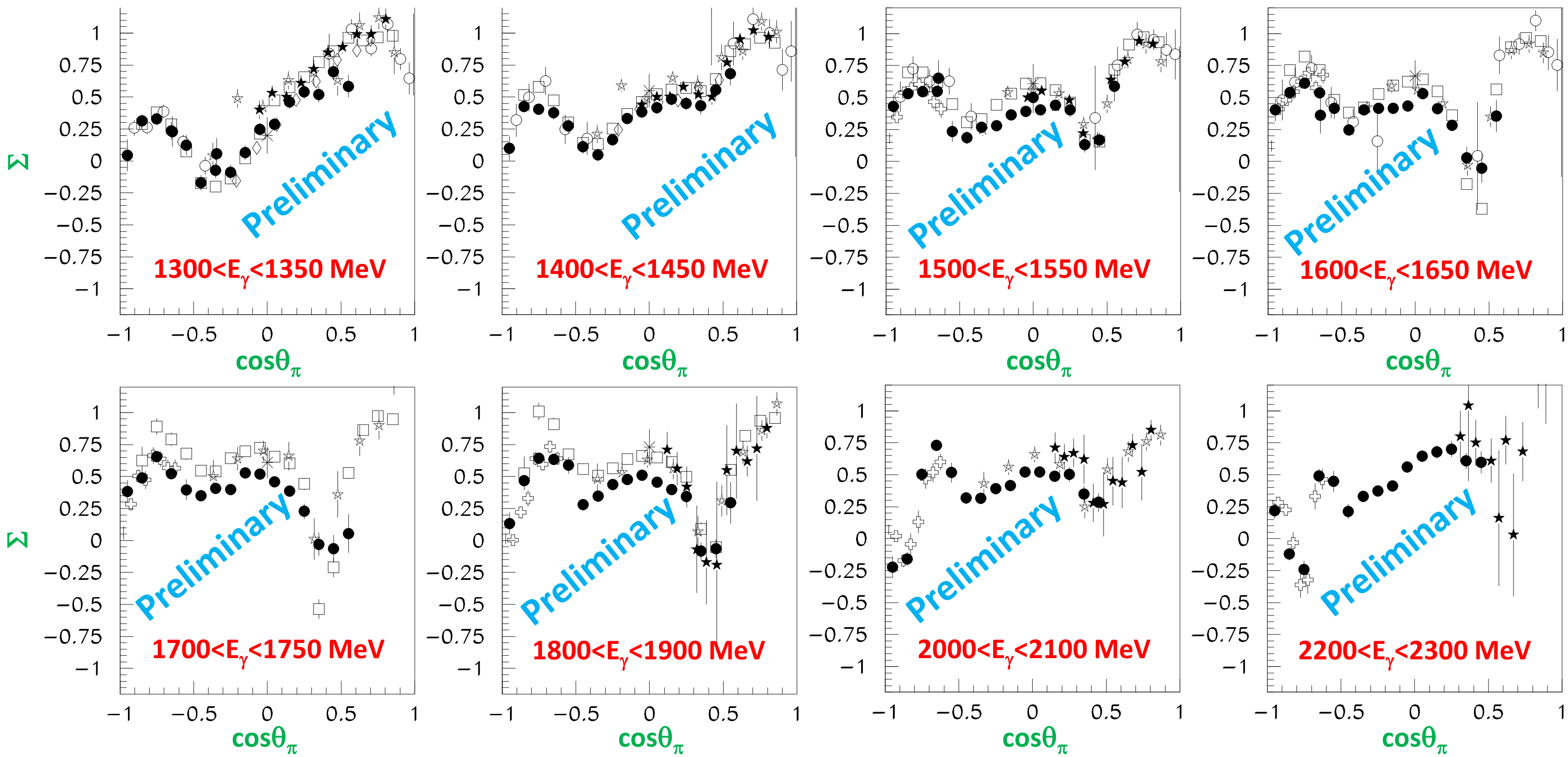


Photon Beam Asymmetry of $\gamma p \to \pi^0 p$



●: 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]

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



- ➢ The wide angle measurement at $E_\gamma \gtrsim 2$ GeV is **new.**
- ➢ **Very similar** to the other experimental results.
- ➢ The LCS results (BGOegg, LEPS, GRAAL) may be a bit smaller than the bremsstrahlung beam results at higher energies.

Comparison with Model Calculations (Σ_{π^0})

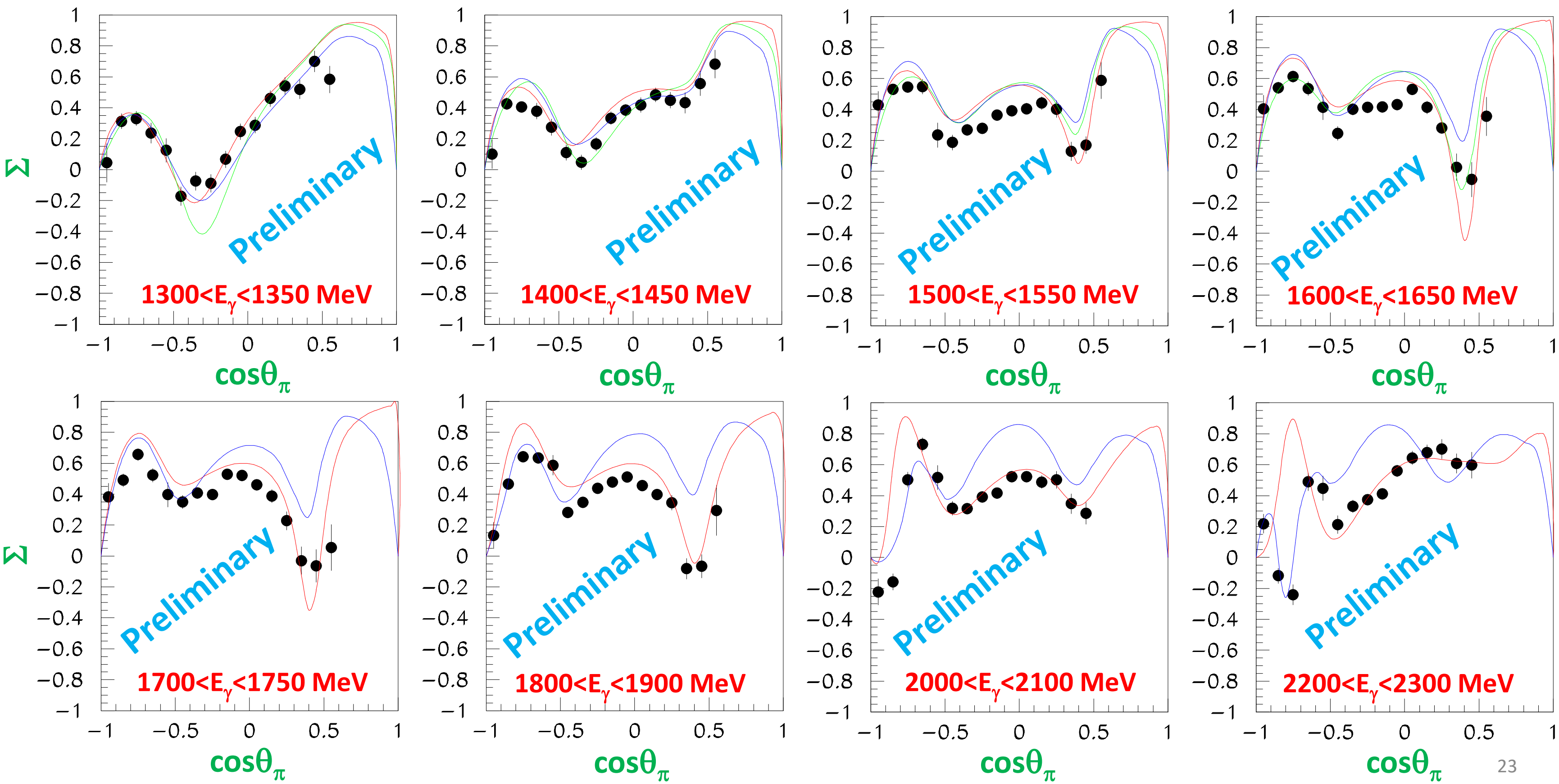
●: this work (BGOegg)

——: **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.)]

*There are **discrepancies at the high energies** where exp. data are scarce.*



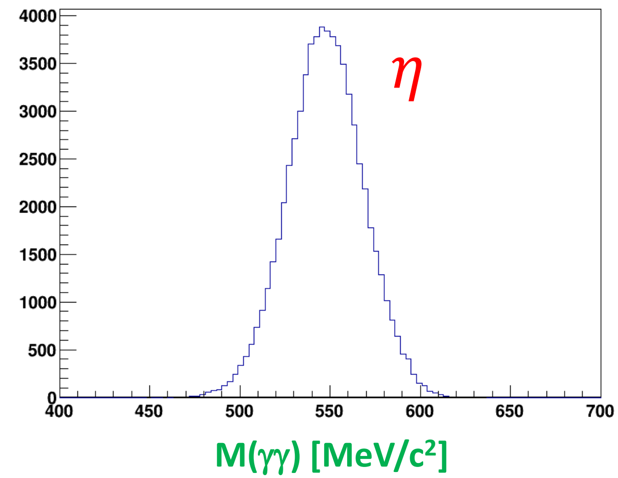
η Photoproduction

$\gamma p \rightarrow \eta p$

$\rightarrow \boxed{\gamma\,\gamma}\; p$

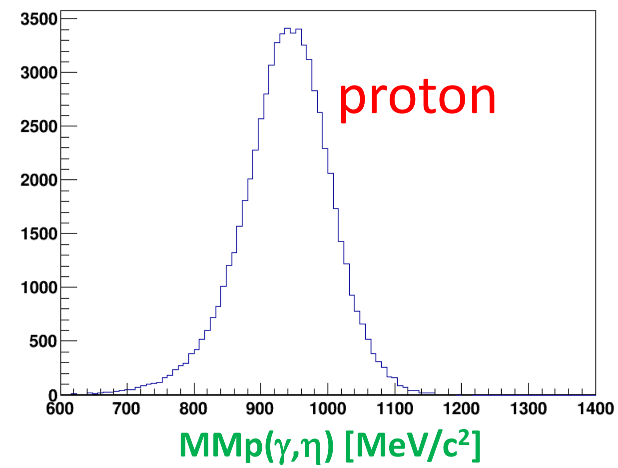
Detected at BGOegg (Br = 0.394)

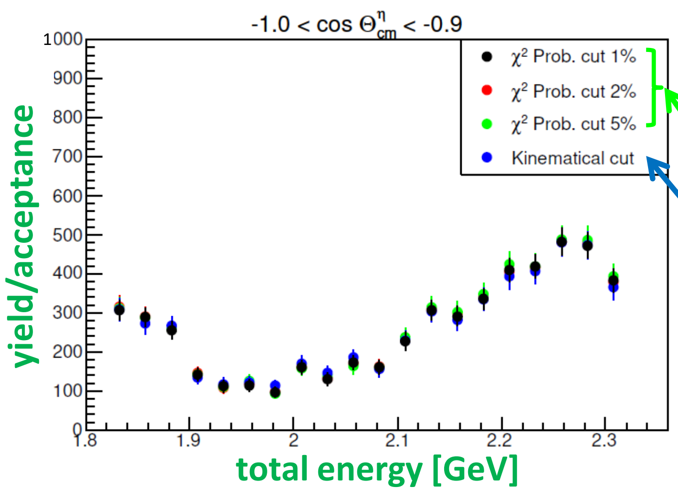
A charged track at DC or BGOegg (Only direction was measured.)



Kinematic fit (11 variables) was done in the same way as the π^0 analysis. There are **5 constraints** (4-momentum conservation and η mass)

~56K events after requiring χ^2 prob.>0.01

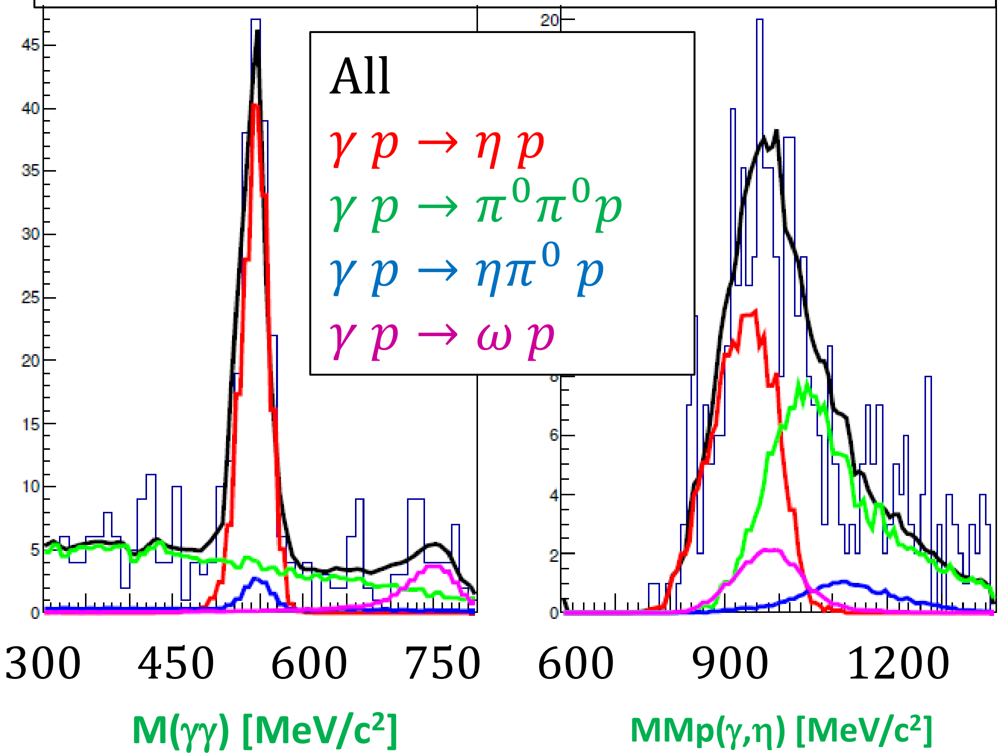




The "yield/acceptance" is unchanged even by
- varying the χ^2 prob. cut point
- using tight kinematical cuts instead of the KF

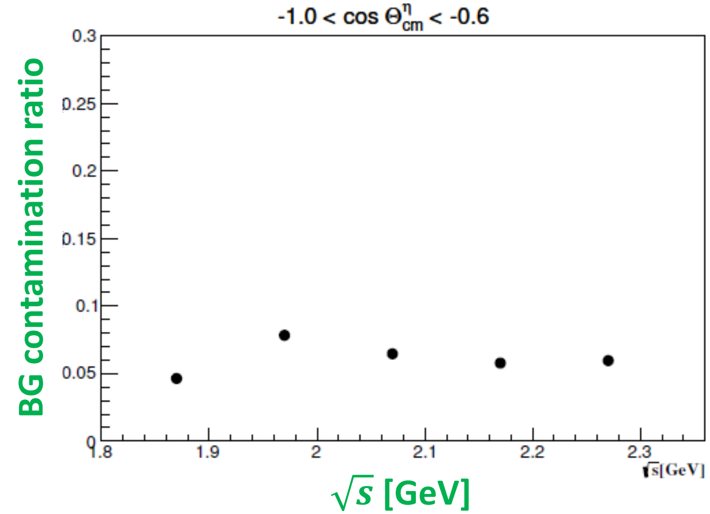
Backgrounds in η Photoproduction

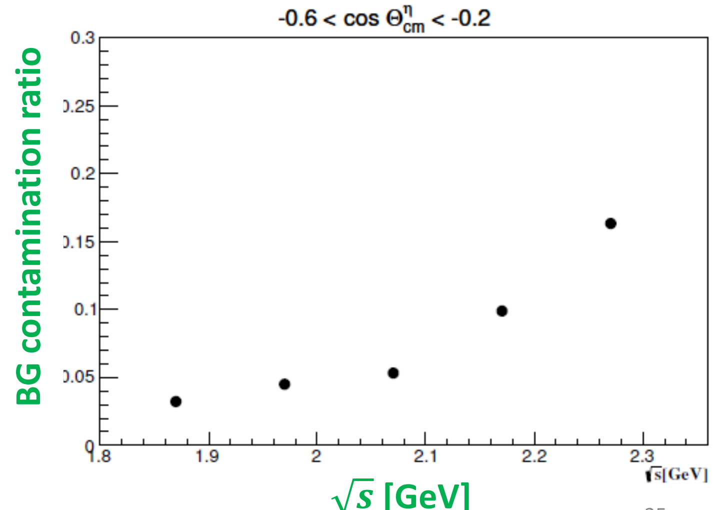
$1.82 < \sqrt{s} < 1.92$ GeV, $-1 < \cos\theta_\eta^{CM} < -0.6$
$-180° < \phi_\eta < -135°$



The invariant mass and missing mass are simultaneously fitted with the **template BG shapes**, which have specific mass distributions respectively.

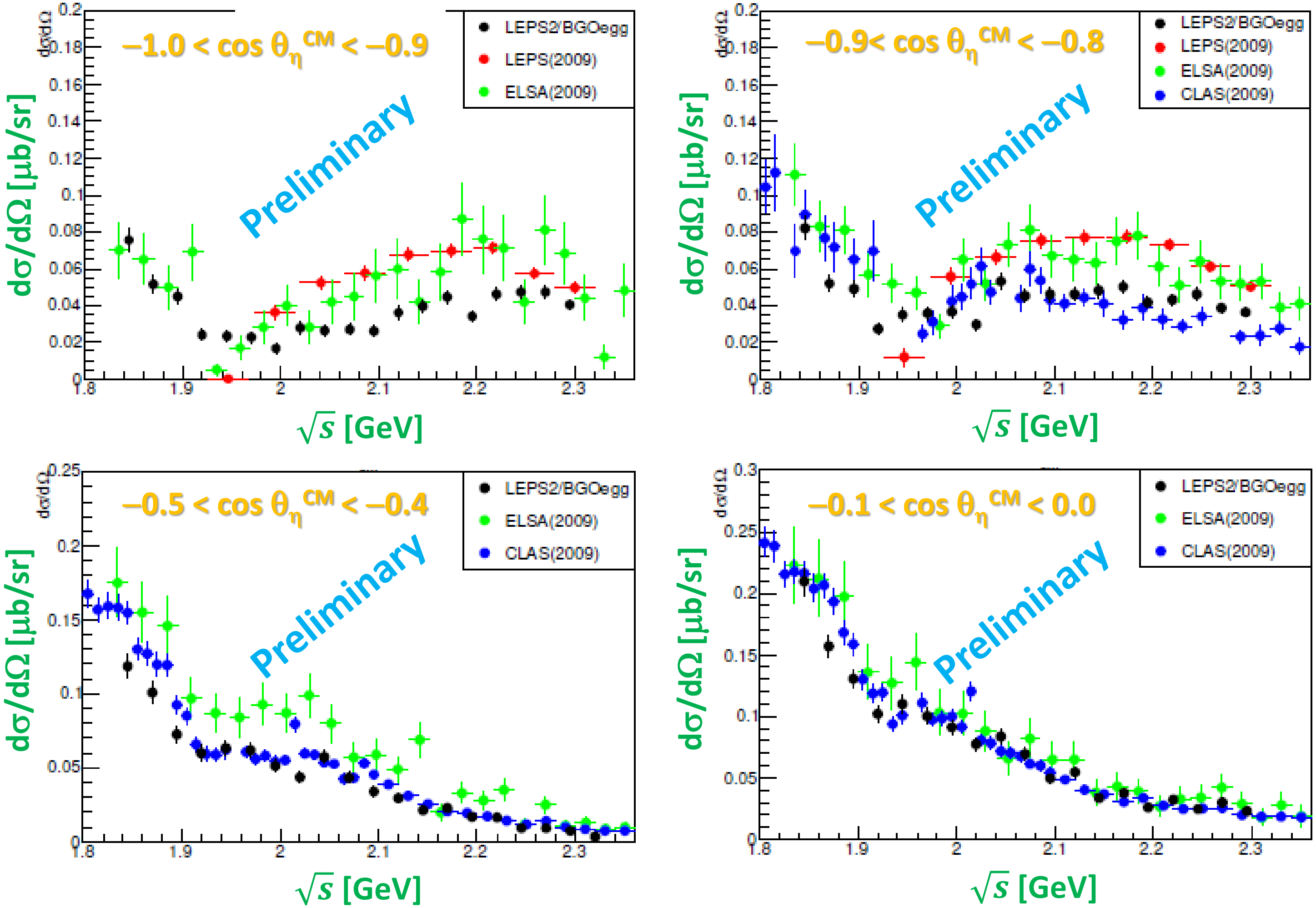
Typical BG contamination is about **5%** and subtracted after the χ^2 prob. cut.





Differential Cross Section of γp→ηp

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

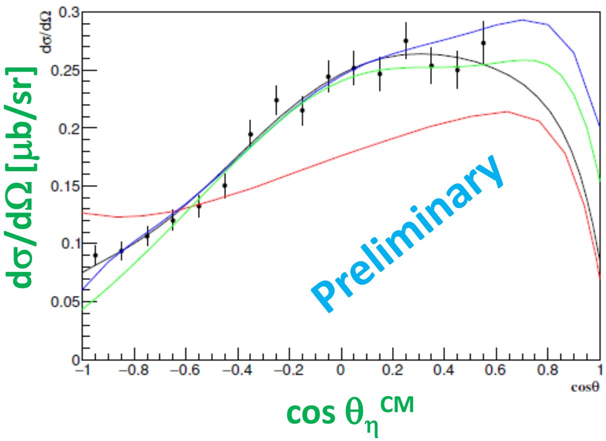


LEPS : PRC80,052201
CBELSA : PRC80,055202
CLAS : PRC80,045213

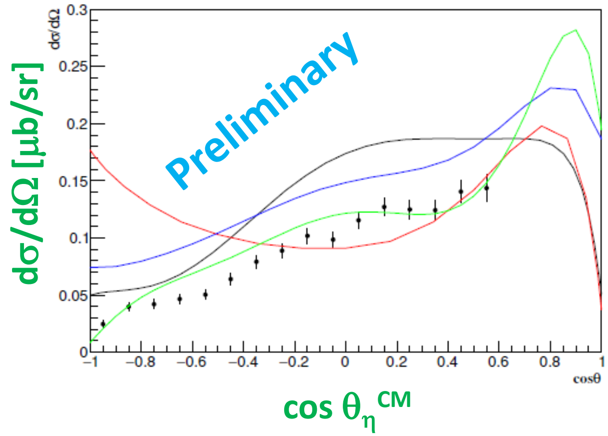
More or less **consistent with the CLAS result**, but **not in good agreement with the LEPS & CBELSA results**.

Comparison with Model Calculations (η cross section)

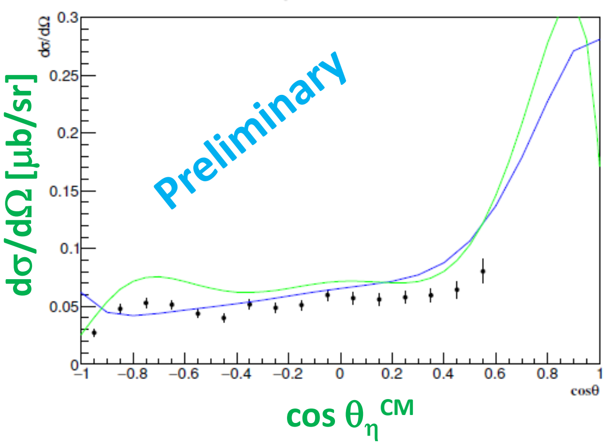
$1.820 < \sqrt{s} < 1.845$ GeV



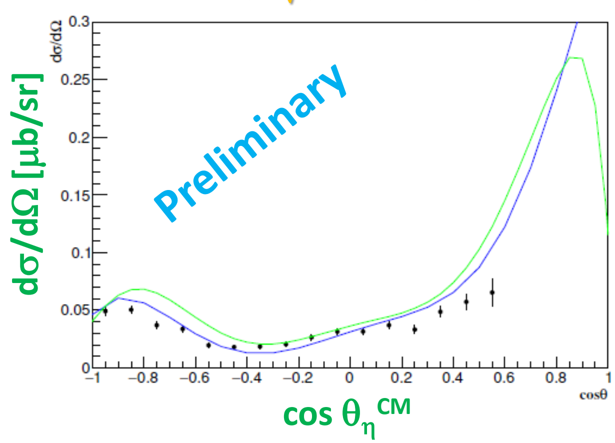
$1.945 < \sqrt{s} < 1.970$ GeV



$2.070 < \sqrt{s} < 2.095$ GeV



$2.195 < \sqrt{s} < 2.220$ GeV



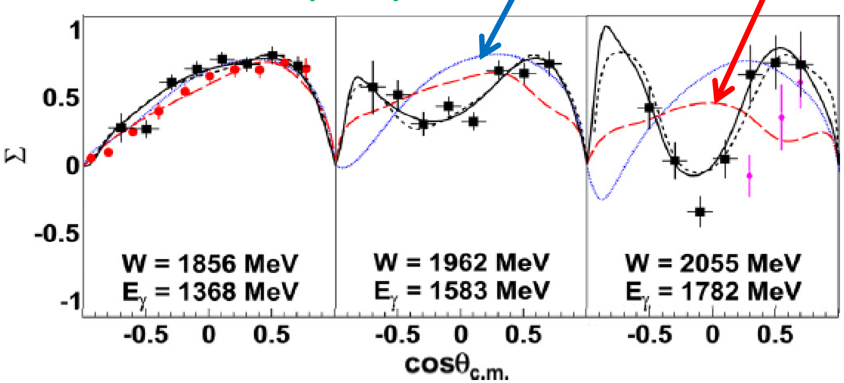
—— : ANL-Osaka
—— : Bonn-Gatchina
—— : GW SAID
—— : eta-MAID

Cross sections have been used for the fit by model calculations.

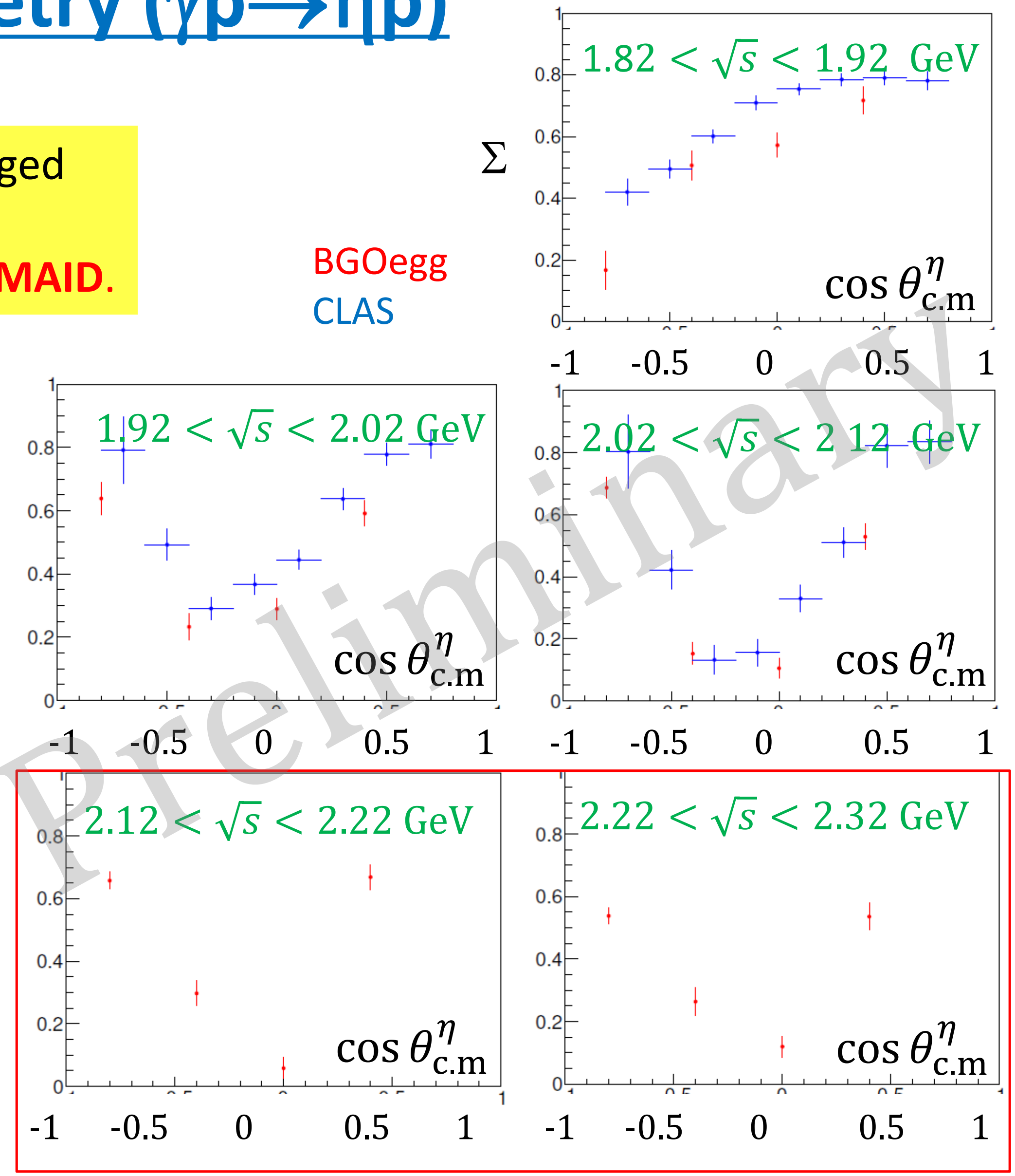
Photon Beam Asymmetry (γp→ηp)

The angle dependence is drastically changed above 1.9 GeV.
⇒ It had not predicted by **SAID** and **ETA-MAID**.

CLAS: PLB 771 (2017) 213.

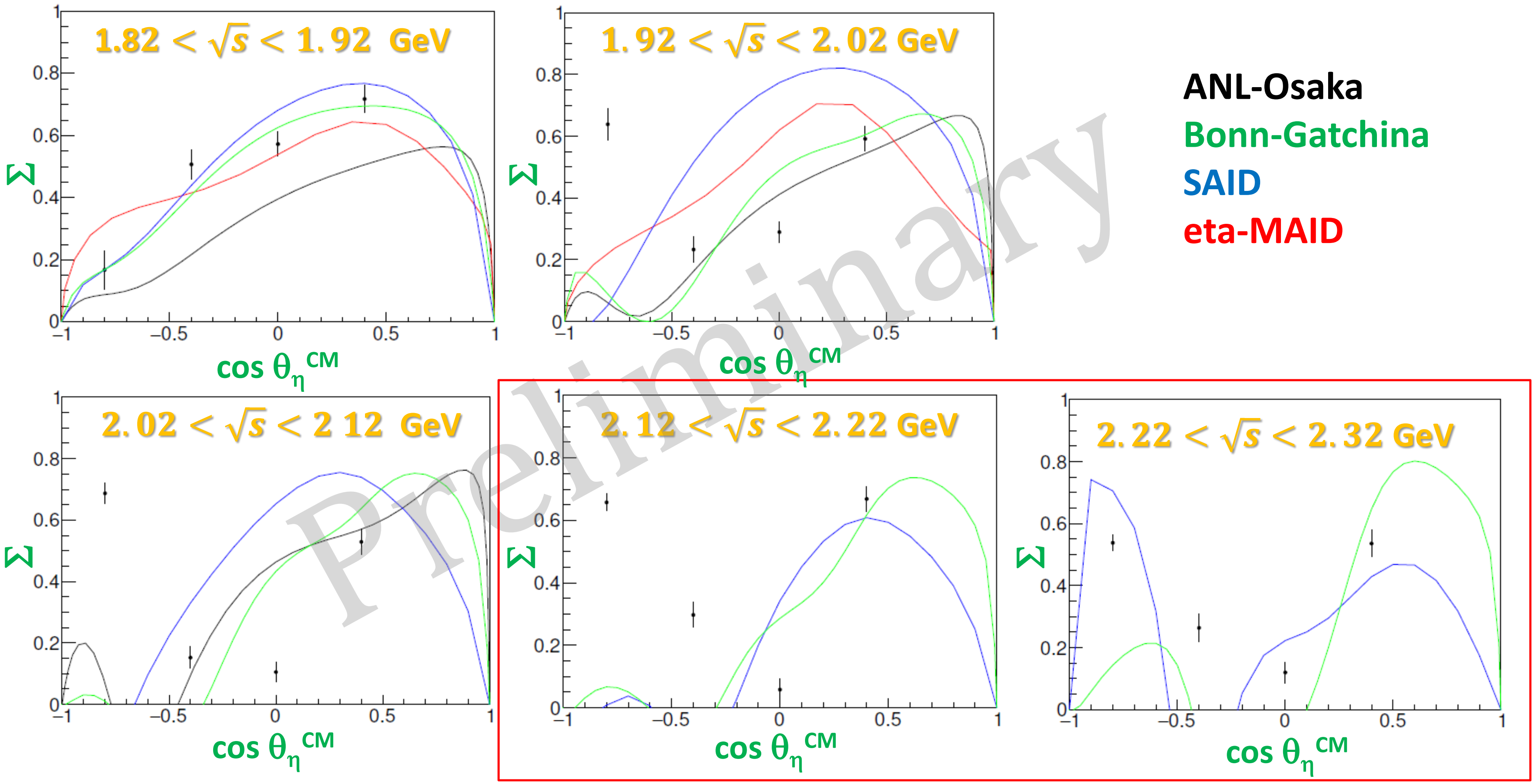


Large interference effect by $N(1720)\frac{3}{2}^+$ and partially by $N(1900)\frac{3}{2}^+$



new measurement

Comparison with Model Calculations (Σ_η)



new measurement

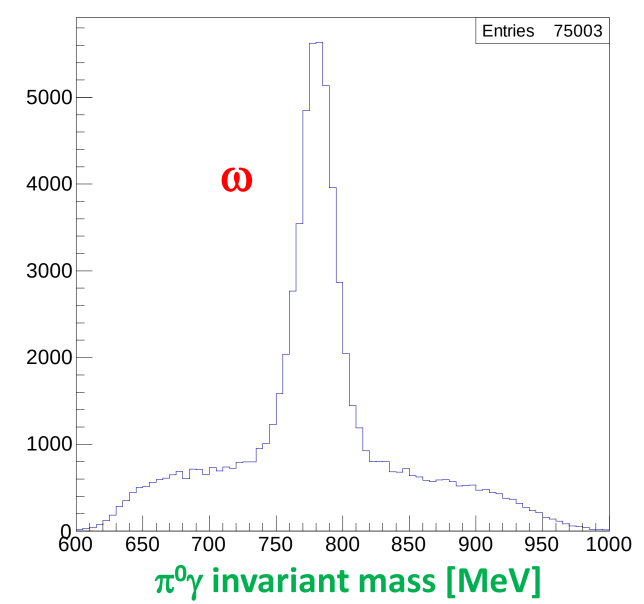
ω Photoproduction off Proton

$\omega \to \pi^0\gamma \to 3\gamma$ **@BGOegg** (Br=8.40±0.22%)
Proton direction meas. @ DC or BGOegg

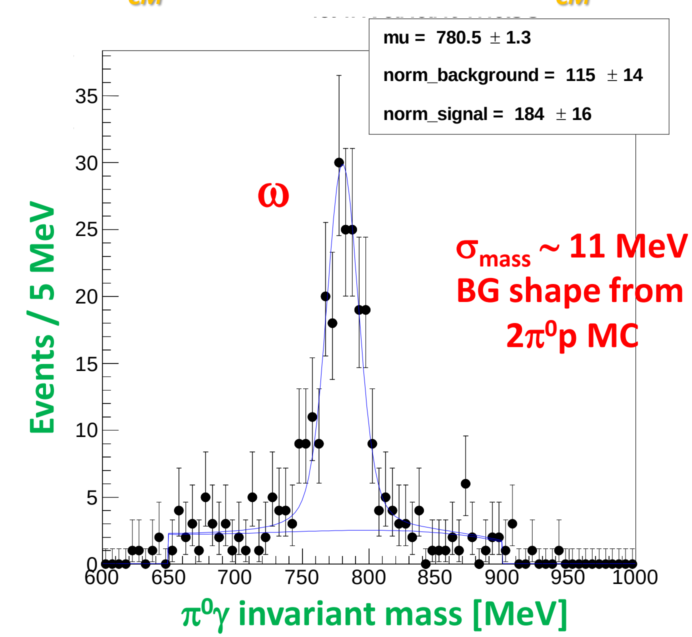
⇒ **Kinematic fit** (CL cut @2%, Required 4-momentum conservation & π^0 mass.) :
About 75K events remain finally.

⇒ Fit a **signal + BG function**. : # of signals : **~37K events**

Differential cross section measurement was done at
17 energy bins for $1810<E_{CM}<2320$ MeV & **18 polar angle bins** for $-1<\cos\theta^{\omega}_{CM}<0.8$.

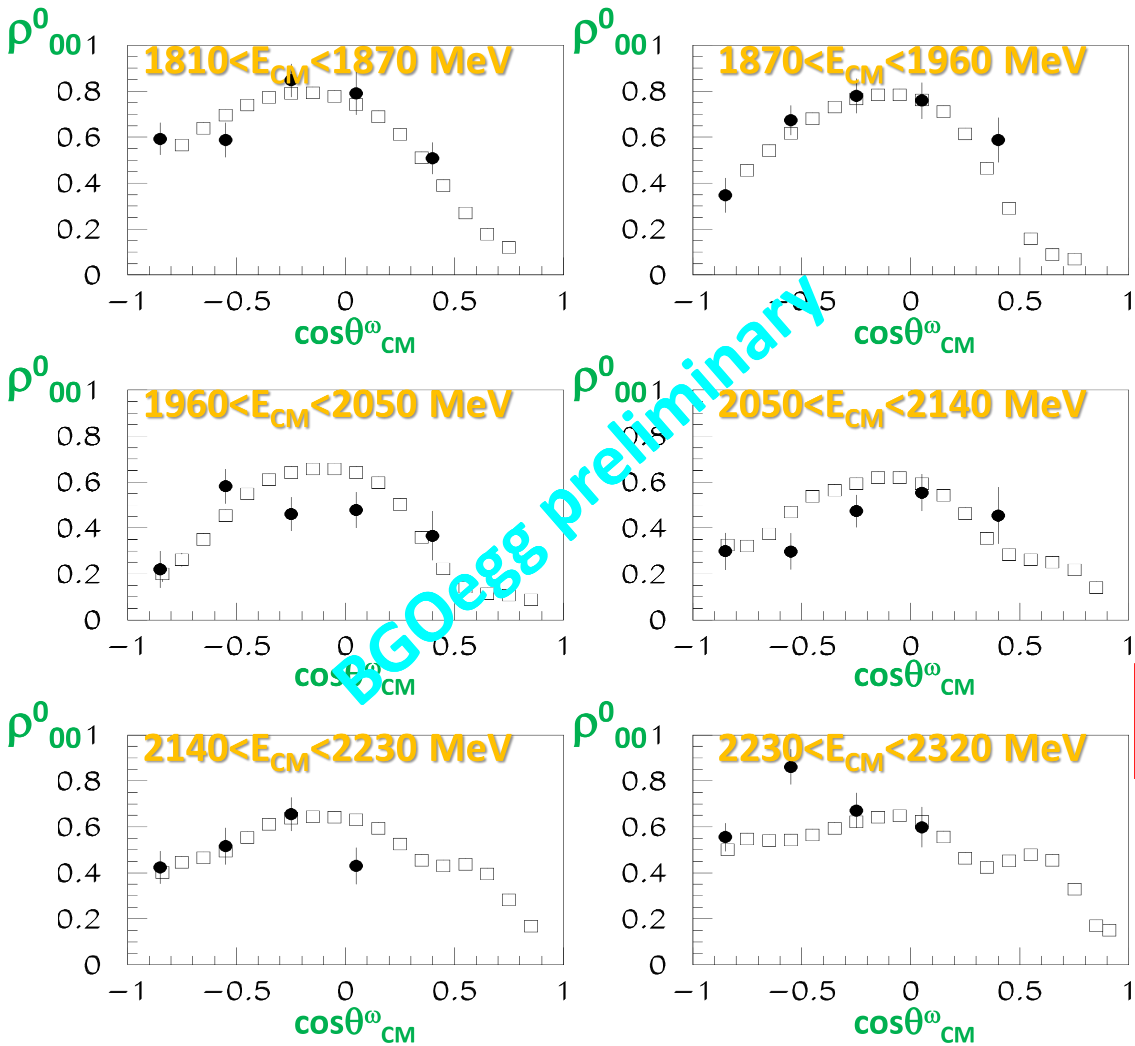


$1870<E_{CM}<1900$ MeV & $-0.5<\cos\theta^{\omega}_{CM}<-0.4$



ω spin density matrix element (Adair frame)

● : BGOegg, □ : CLAS



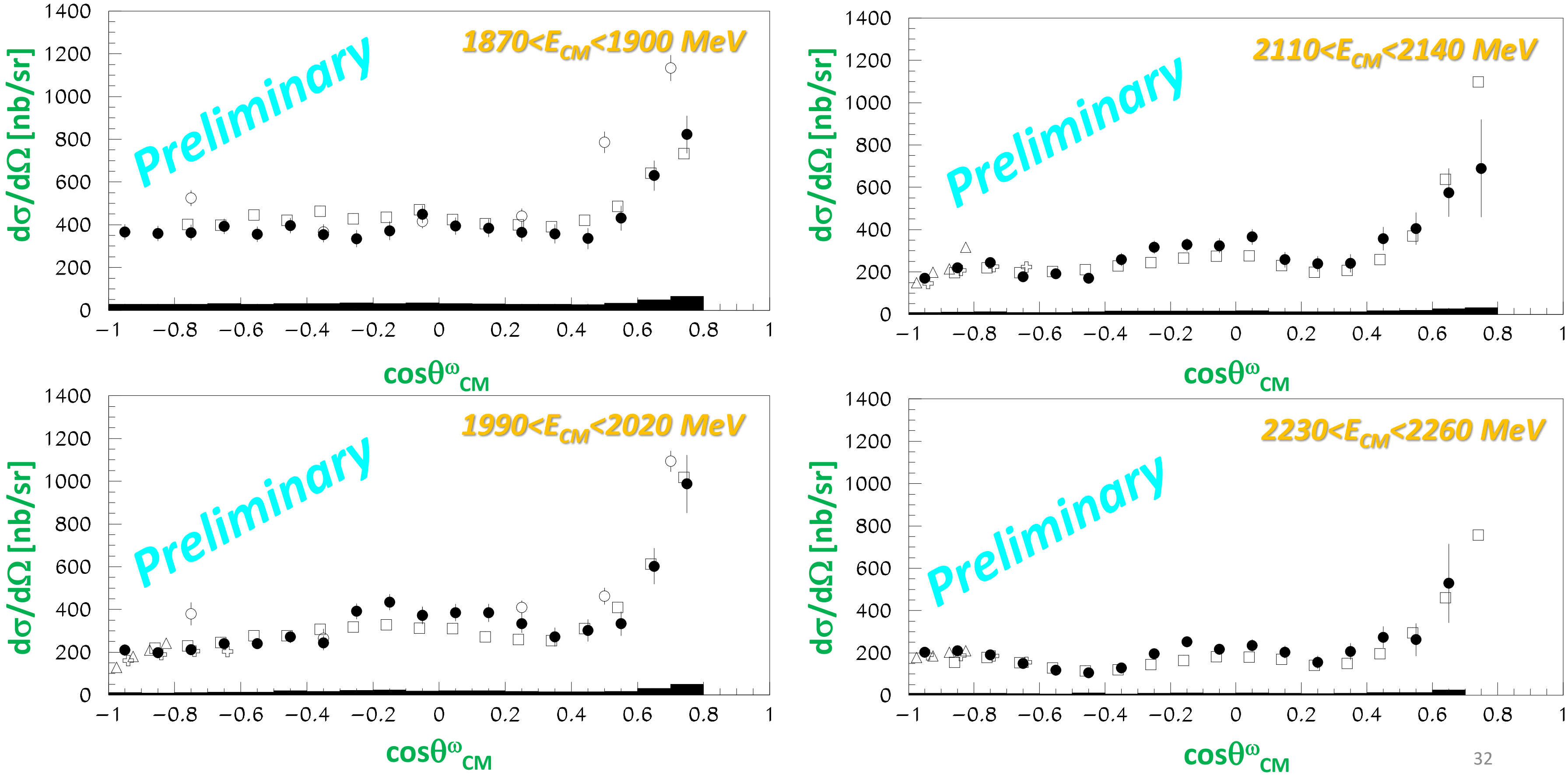
Acceptance measurement was iterated by adjusting the kinematics of MC sample simultaneously following the measured ρ^0_{00} and $d\sigma/d\Omega$.

PRC 78 (2008) 038201

$$W^{\pi^0\gamma}(\Theta) = \frac{3}{8}\left(1 + \cos^2\Theta + \rho^0_{00}(1 - 3\cos^2\Theta)\right)$$

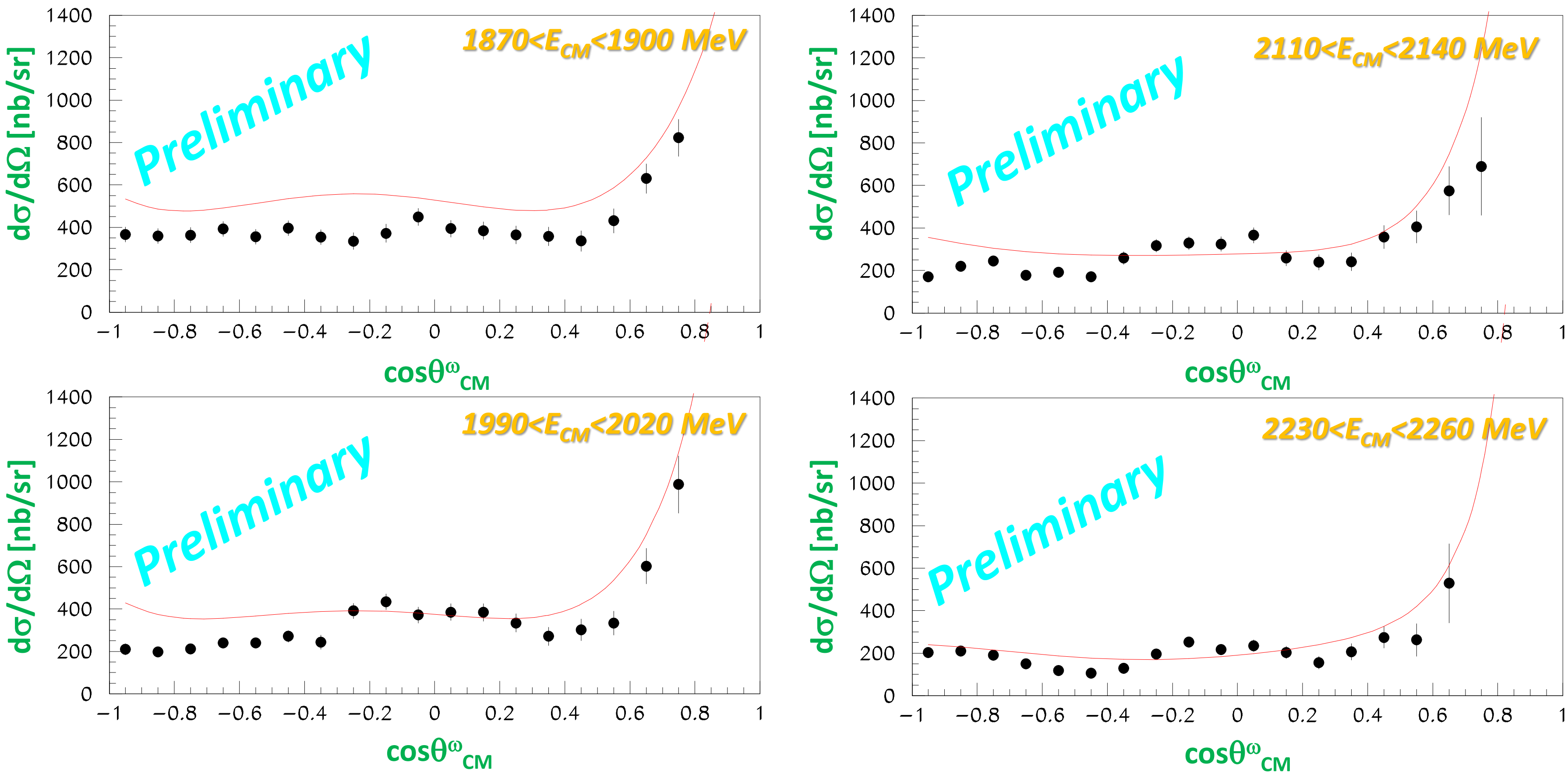
Differential Cross Section of γp→ωp

●: **this work (BGOegg)**, □: CLAS [PRC80 (2009) 065208],
○: CBELSA [EPJA 51(2015) 6], ✞ : LEPS [PRC80 (2009) 052201R],
△: LEPS-TPC [PTEP2015 013D01]
Note: The histogram indicates the **systematic error** of the BGOegg meas.



Comparison with Model Calculations (ω cross section)

●: **this work (BGOegg),** ——— : **Bonn-Gatchina** [Private communication]

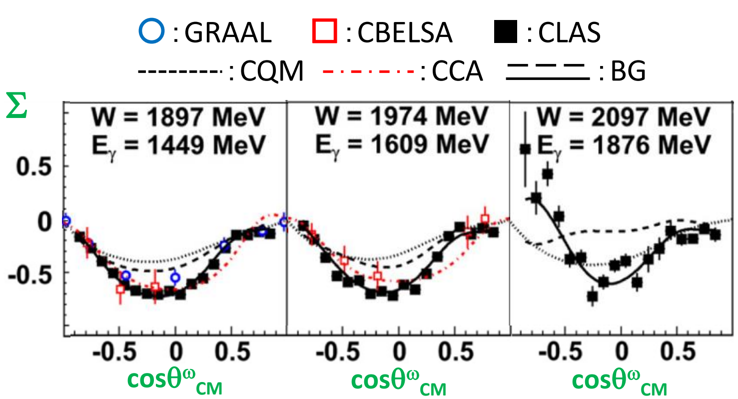


More or less similar but there may be some structure.

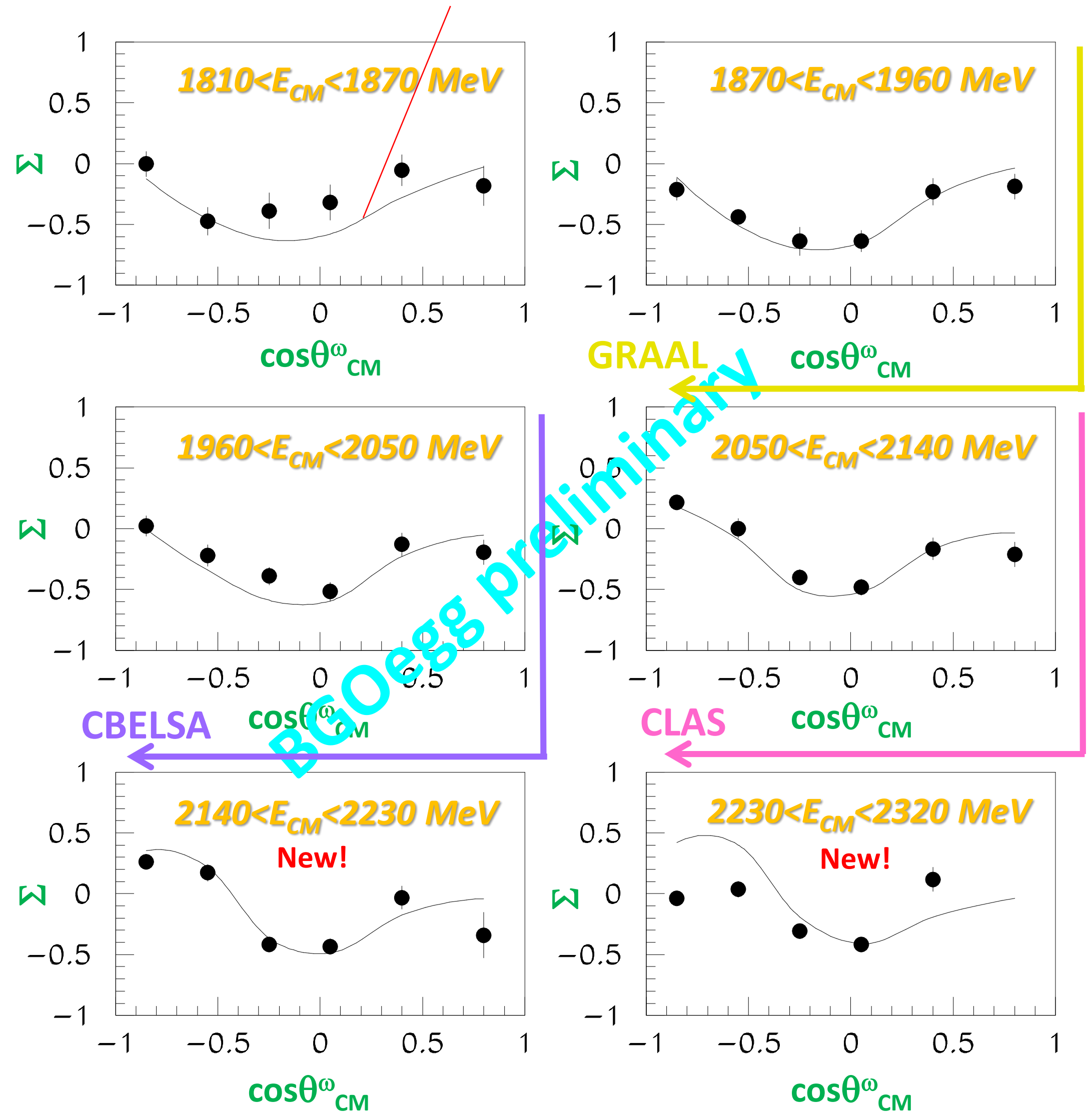
Photon Beam Asymmetry (ω photoproduction)

Photon Beam Asymmetry
represents **interferences** b/w
t-channels (pomeron, π^0) &
s- / u-channels (**N^*s as ωN**).

Interpretation **[PLB 773 (2017) 112]**
Low E_{CM}: **P_{13}** [N(1720)] in **CQM**
D_{15}@~1.9 GeV/c^2 in **CCA**
High E_{CM}: **P_{13}, S_{11}, D_{13}, F_{15}**
in **Bonn-Gatchina model**



Bonn-Gatchina model [private communication, PRC97(2018)055202]



Summary & Prospect

- At the highest energy region, the measured photon beam asymmetries of π^0, η, ω photoproduction **deviate from the existing PWA model calculations**.
  $\Rightarrow$ There is **room to update model parameters**.

- By using the already collected data, we can explore **double-meson photo-production** to study highly excited baryons and heavier mesons. At this stage, PWA would be really necessary.
- We are going to cover the forward acceptance hole of BGOegg by **another calorimeter (PWO)**. At this stage, the experiments with a **liquid deuterium target** (neutron) would be possible.