NSTAR2024 @ York

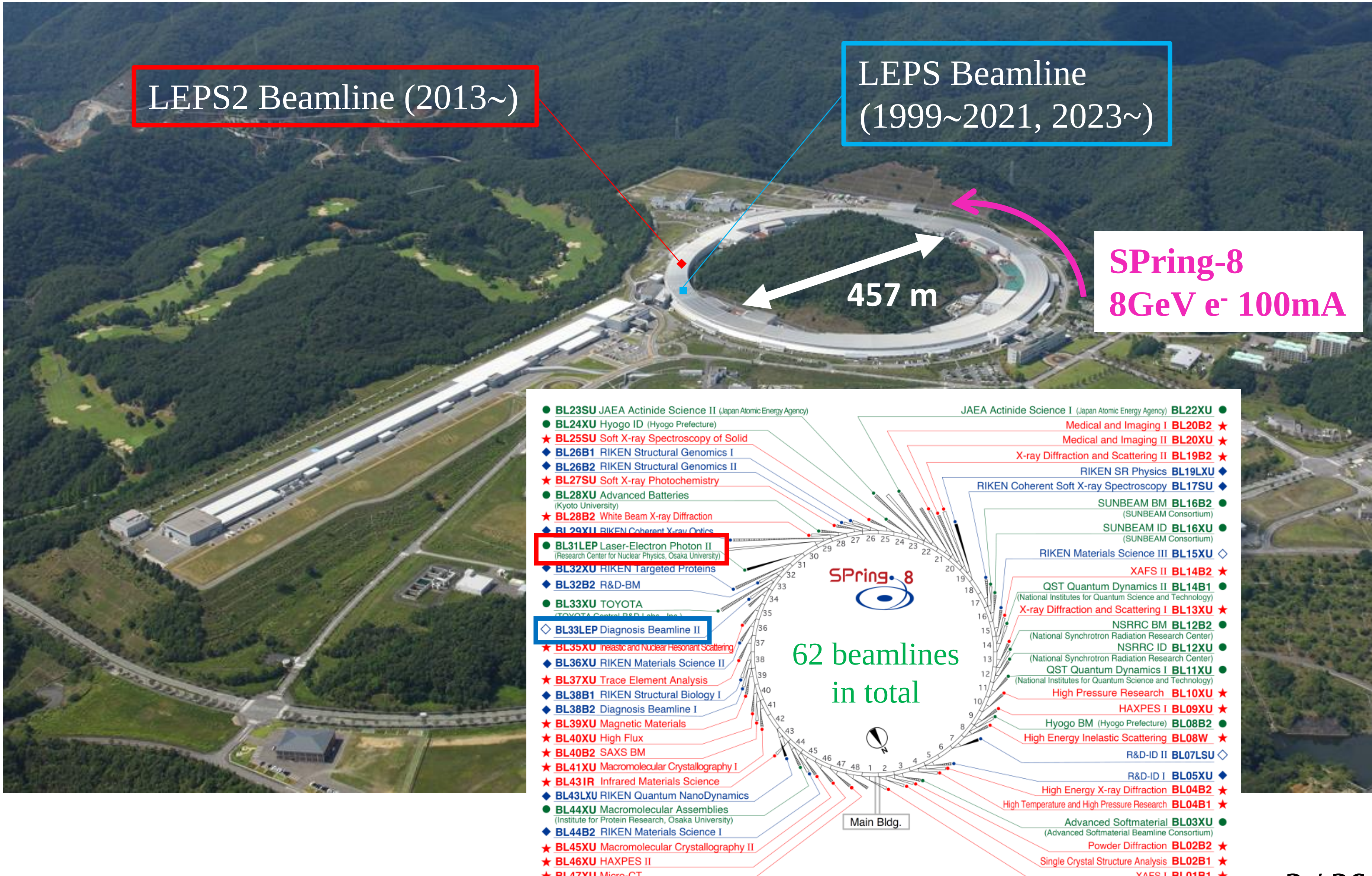
# Recent results from SPring-8 LEPS2

*Today I concentrate on light baryon spectroscopy in BGOegg experiment.*

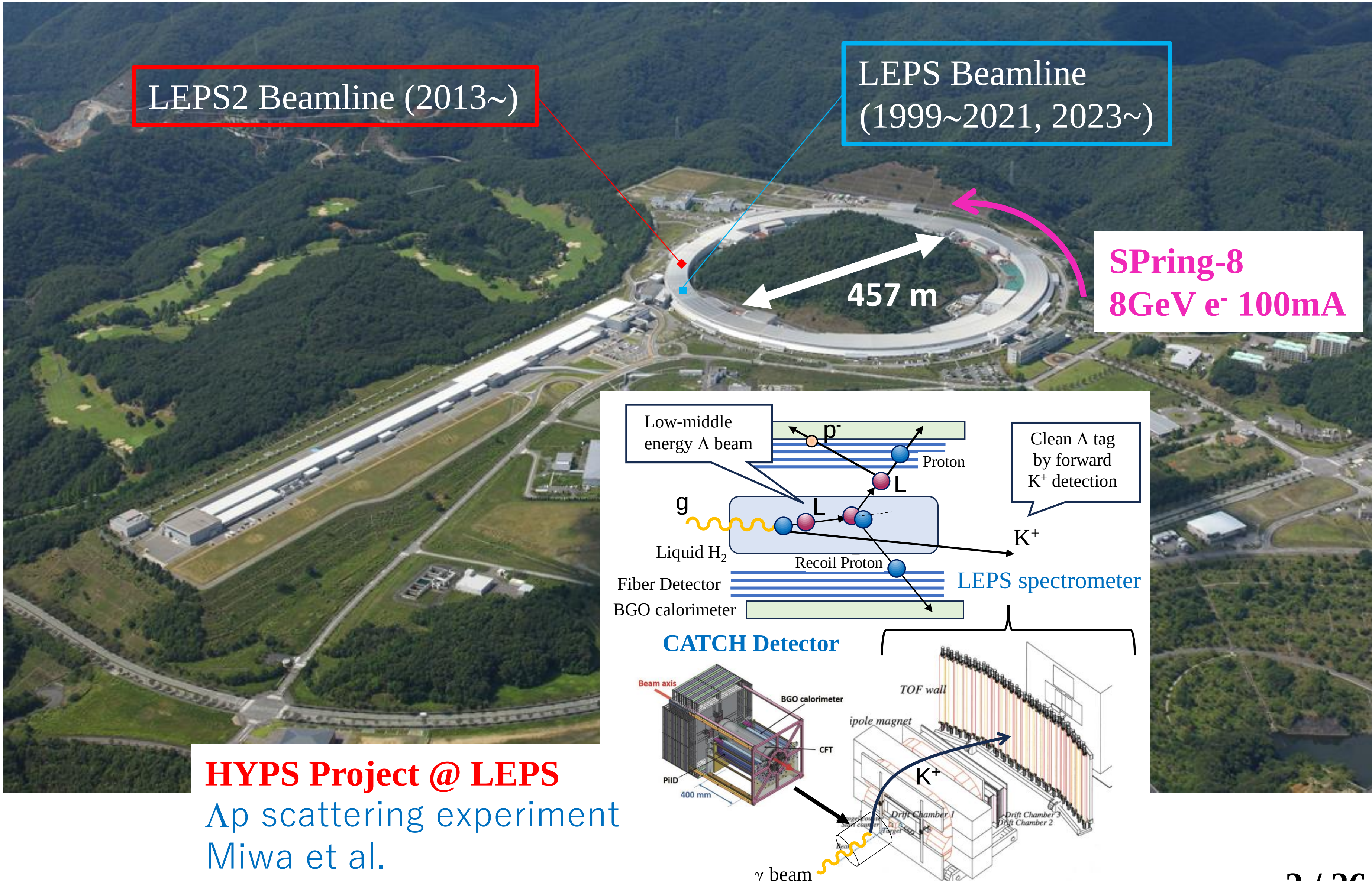
**Plenary session (20 June, 2024)**

**Norihito Muramatsu**
**RARIS, Tohoku University**

# SPring-8 LCS Beamlines



# SPring-8 LCS Beamlines

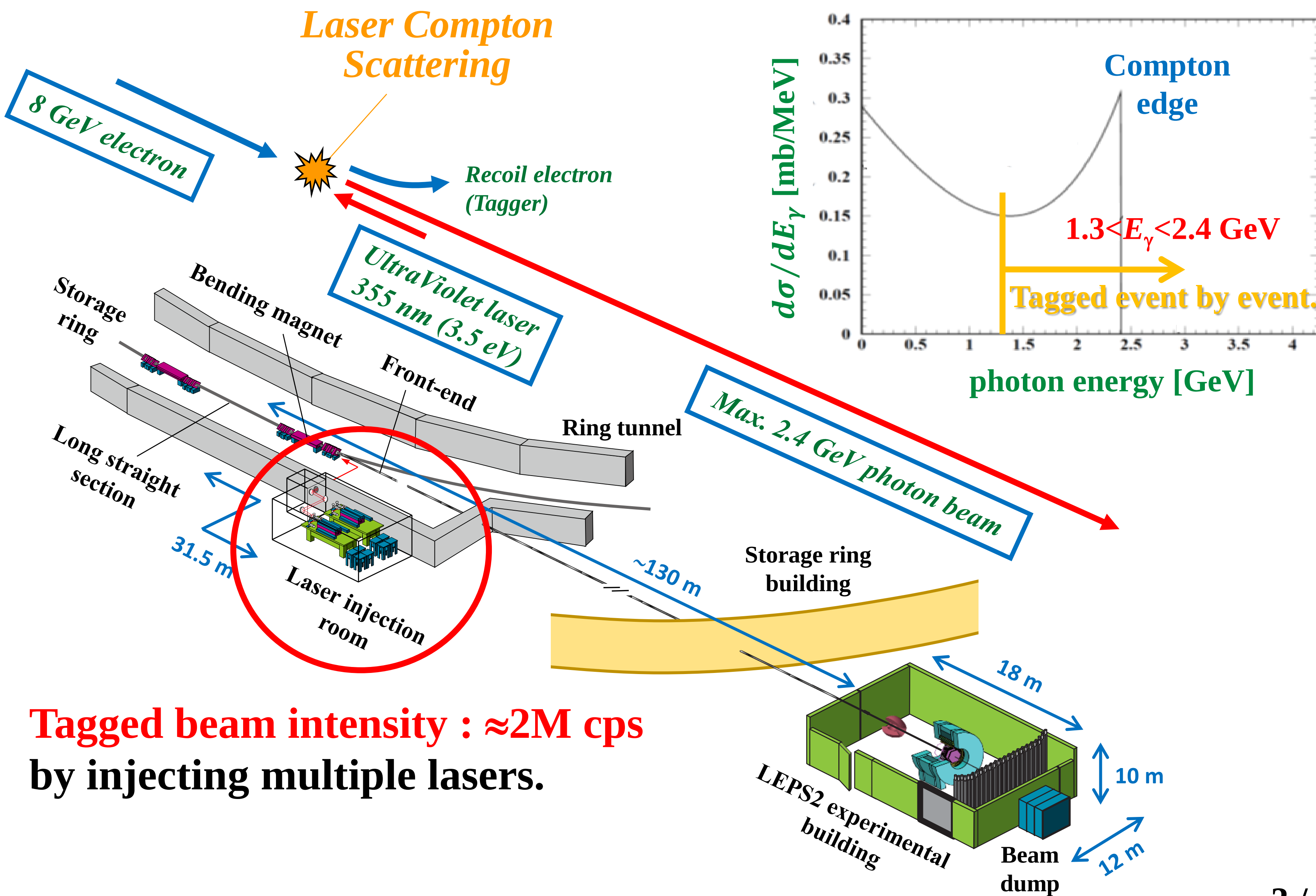



**HYPS Project @ LEPS**

Λp scattering experiment
Miwa et al.

# LEPS2 Beamline

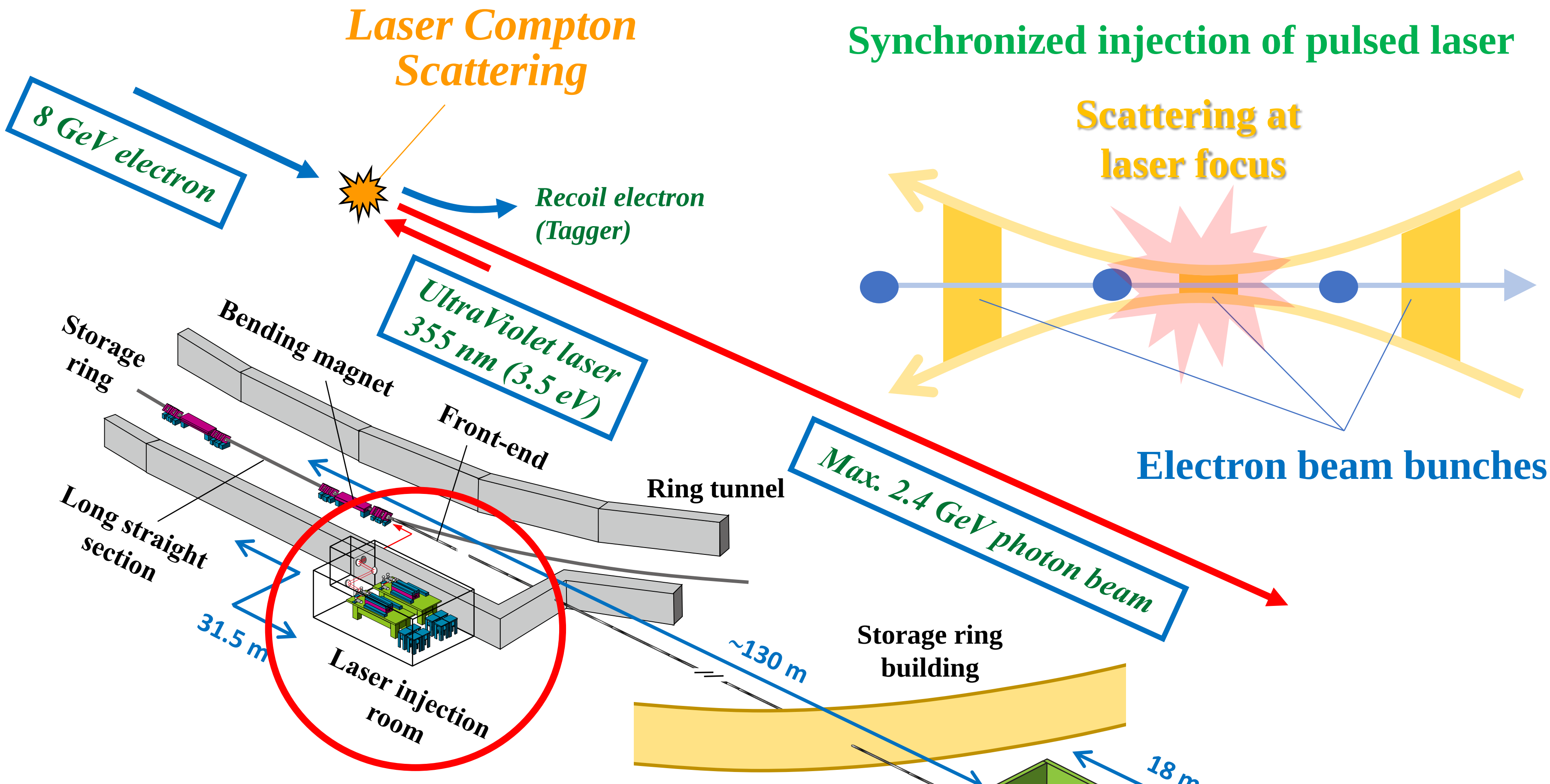
NIM A 1033 (2022) 166677

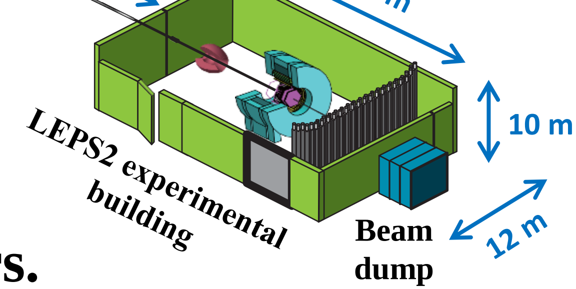



**Tagged beam intensity : ≈2M cps**
**by injecting multiple lasers.**

# LEPS2 Beamline

NIM A 1033 (2022) 166677



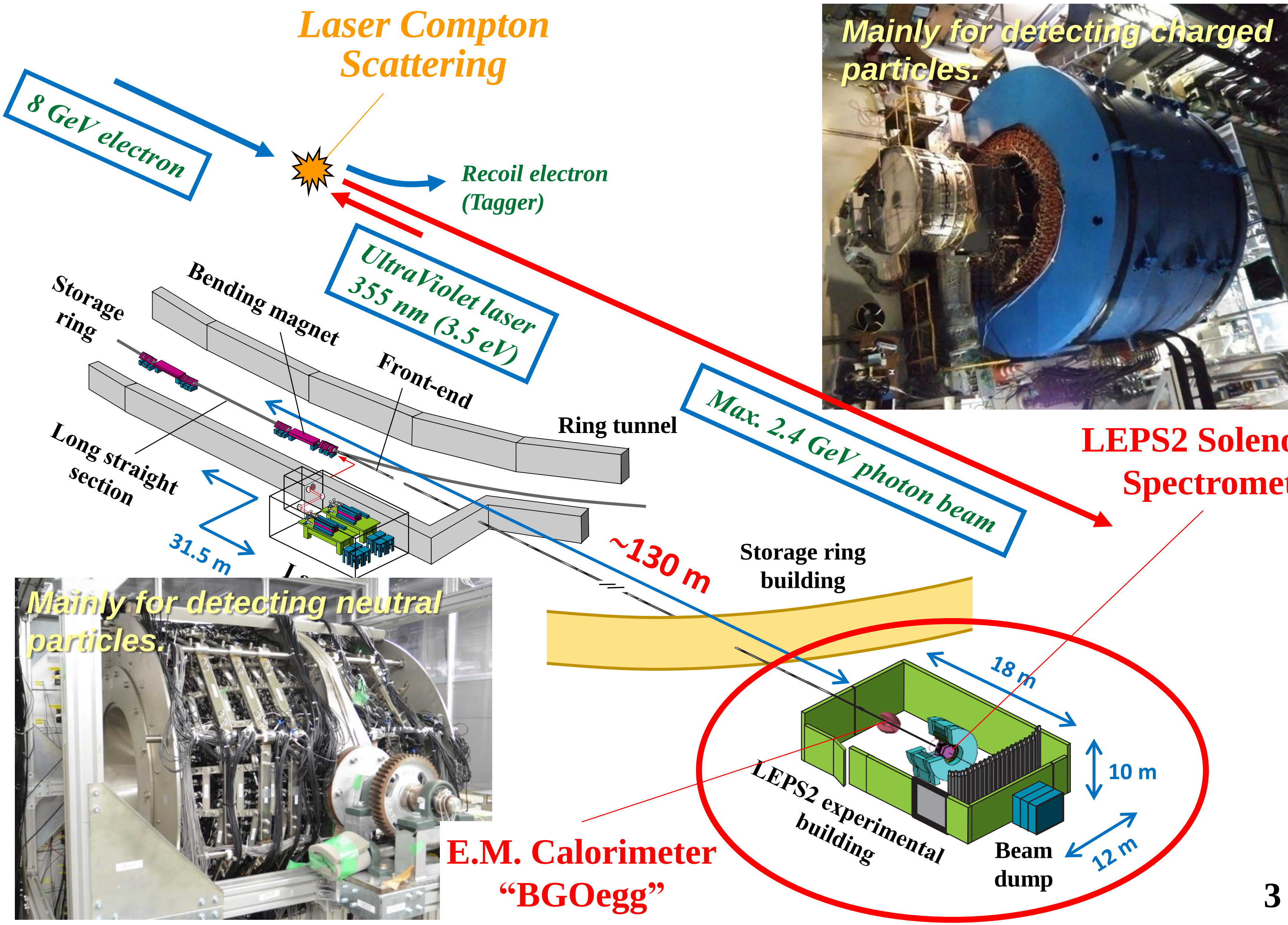




Tagged beam intensity : ≈2M cps
by injecting multiple lasers.

⇒ **Recently increased nearly up to 5M cps** by introducing pulsed lasers.

# LEPS2 Beamline

NIM A 1033 (2022) 166677



# Light Baryon Spectroscopy @ BGOegg

Now meson photoproduction data are the main input for PWA.

$\gamma N \rightarrow N^* \text{ or } \Delta^* \rightarrow MN$

A nucleon target is **excited** in the intermediate state.

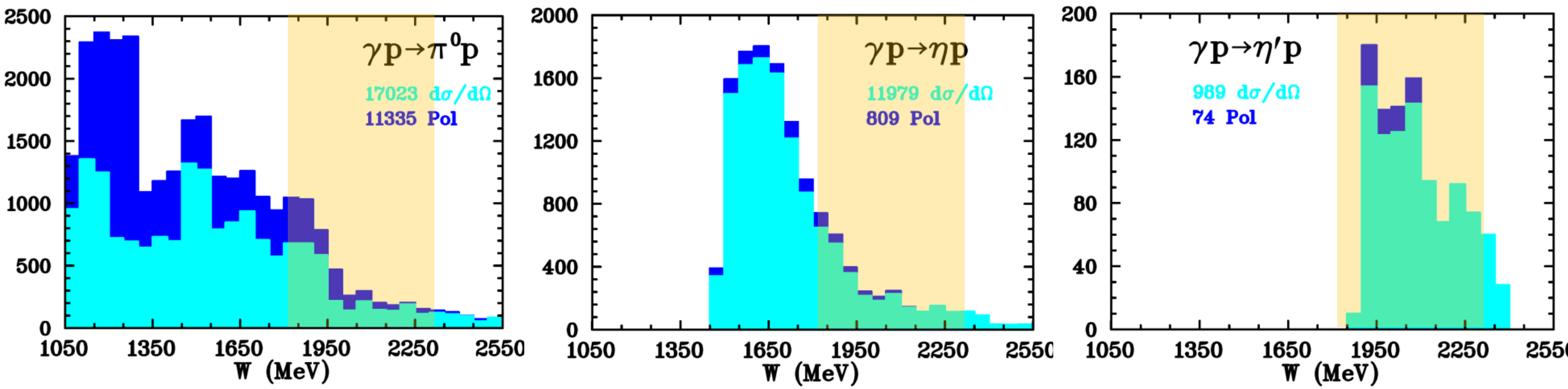
The type of a meson works as **"filters" for isospin & quark-flavor coupling.**

**Polarization observables** are useful to **decompose overlapping resonances.**

| | |
|---|---|
| $\gamma p \rightarrow \pi^0 p$ | **[PRC100 (2019) 055202]** |
| $\gamma p \rightarrow \omega p$ | **[PRC102 (2020) 025201]** |
| $\gamma p \rightarrow \eta p$ | **[PRC106 (2022) 035201]** |
| $\gamma p \rightarrow \eta' p$ | **In preparation for publication** <New results> |

# Importance of Polarization Data at W≈2 GeV

**# of existing data for PWA** [D. G. Ireland, et al., Prog. Part. Nucl. Phys. 111 (2020) 103752]

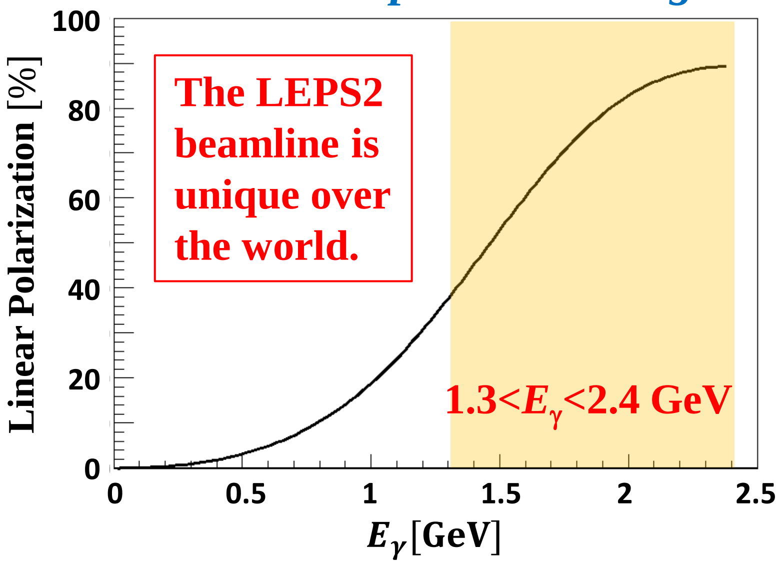



: **LEPS2/BGOegg energy region**

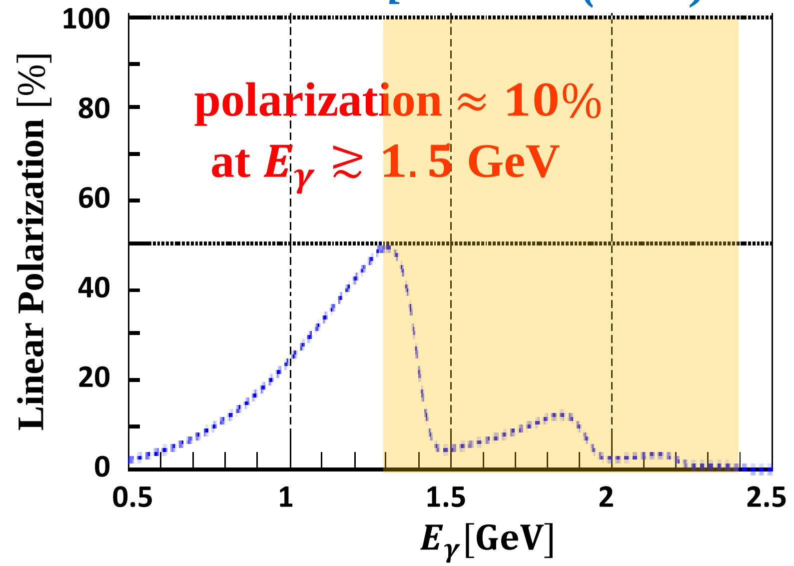
There are **missing resonances at $W \gtrsim 2$ GeV** in comparison with the spectra calculated by quark models & lattice QCD. But data amount is not enough yet especially for **polarization observables** and **heavier meson photoproduction**.

# Photon Beam Asymmetry Σ

*Laser Compton Scattering*



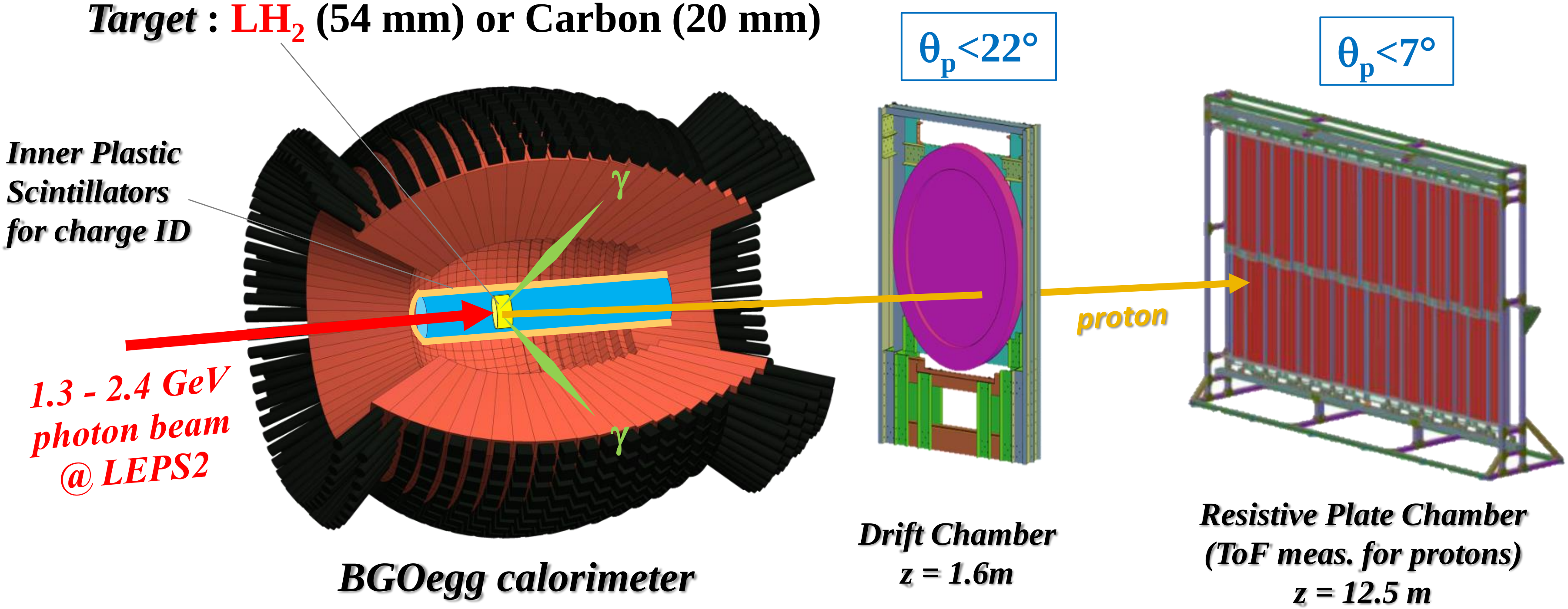

*Coherent Brems. [EPJA33 (2009) 147.]*




😄 High linear polarization at $W \approx 2$ GeV is important to measure **"Σ"** and solve spin amplitudes for the study of missing resonances. **High statistics data** are expected for a single polarization observable.

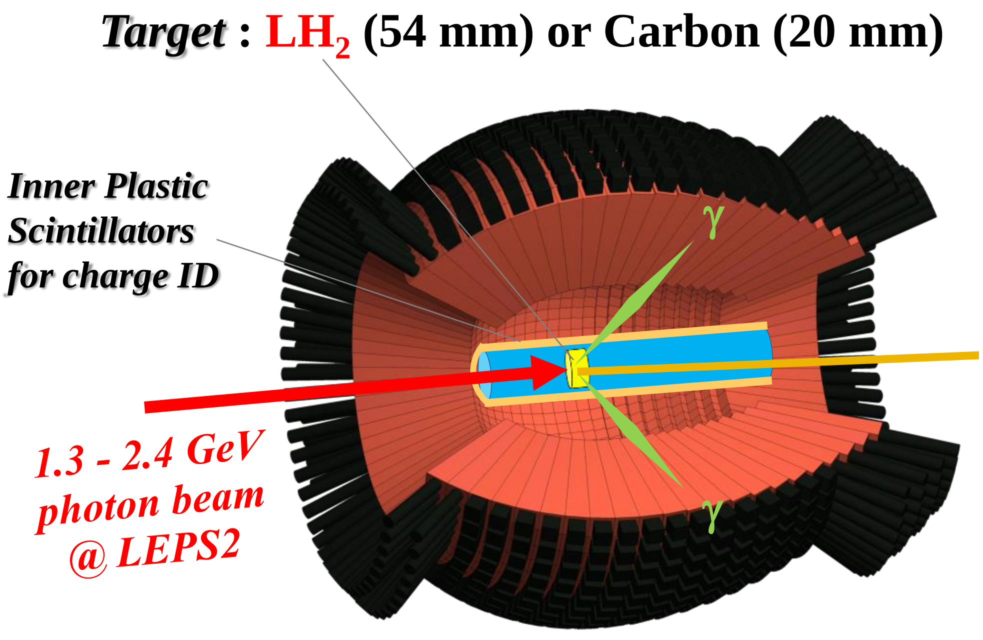
# BGOegg Experiment

***Target*** **:** **$LH_2$ (54 mm) or Carbon (20 mm)**



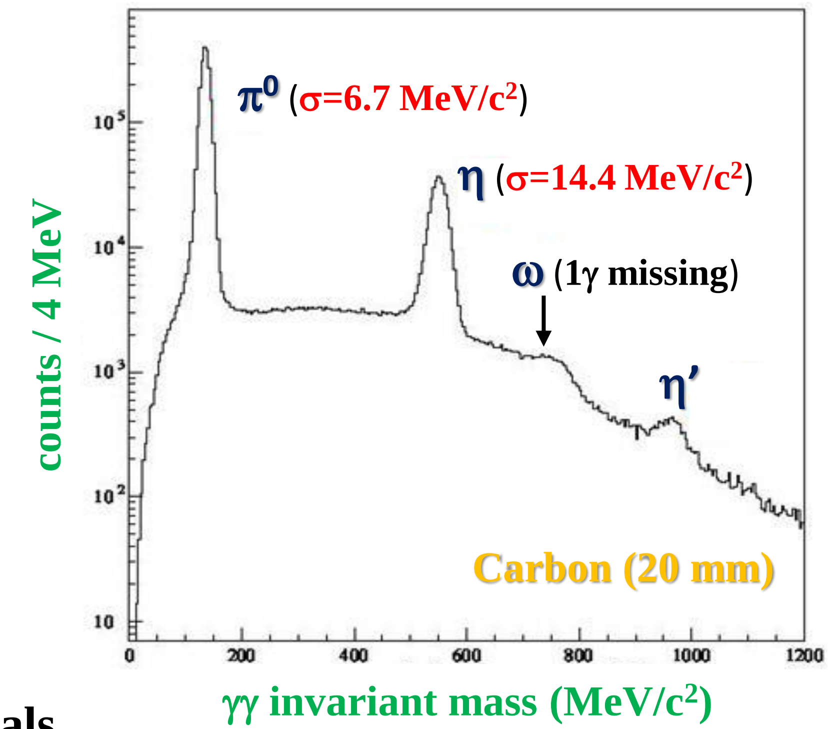

**Covering $24° < \theta_\gamma < 144°$ by 1320 BGO crystals.**

# BGOegg Experiment




***BGOegg calorimeter***

**Covering $24° < \theta_\gamma < 144°$ by 1320 BGO crystals.**




➢ **World's highest performance** for the energies of 1 GeV or less.

| Experiment | LEPS2/BGOegg | MAMI-A2 | | CBELSA/TAPS | | BGO-OD |
|---|---|---|---|---|---|---|
| Calorimeter | BGOegg | Crystal Ball | TAPS | | Crystal Barrel | BGO Rugby Ball |
| Scintillation crystal | BGO | NaI(Tl) | $BaF_2$ | | CsI(Tl) | BGO |
| Number of channels | 1320 | 672 | 384 | 528 | 1290 | 480 |
| Energy resolution ($\sigma$) at 1 GeV | 1.38% | 2.0% | 2.6% | | 2.5% | 1.3% |
| $\pi^0$ mass resolution (MeV/$c^2$) | 6.7 | 9 | | 10 | | 12* |
| $\eta$ mass resolution (MeV/$c^2$) | 14.4 | 21 | | 22 | | 15* |

# $\pi^0$ photoproduction

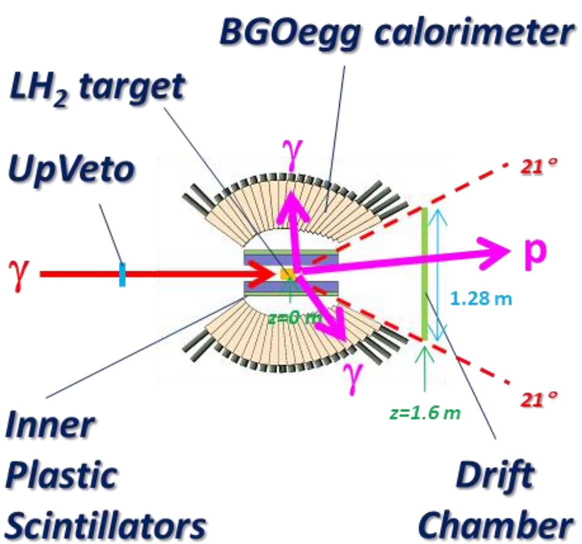
## Physics aspects

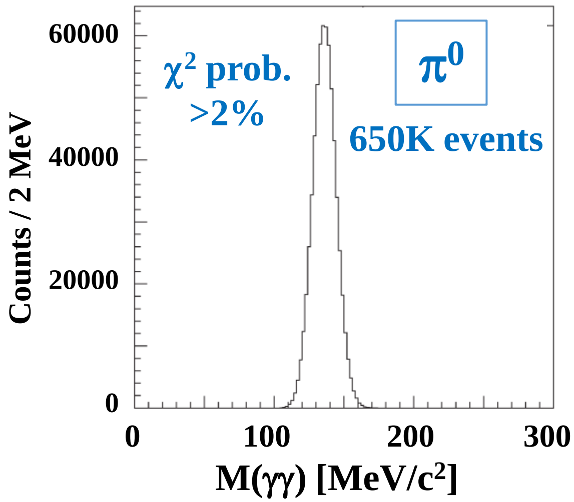
High precision data can be obtained thanks to its **larger $\sigma$**.

$I(\pi^0)=1 \Rightarrow$ Both $N^*(I=\frac{1}{2})$ and $\Delta^*(I=\frac{3}{2})$ contribute in the s-channel.

## BGOegg experiment

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



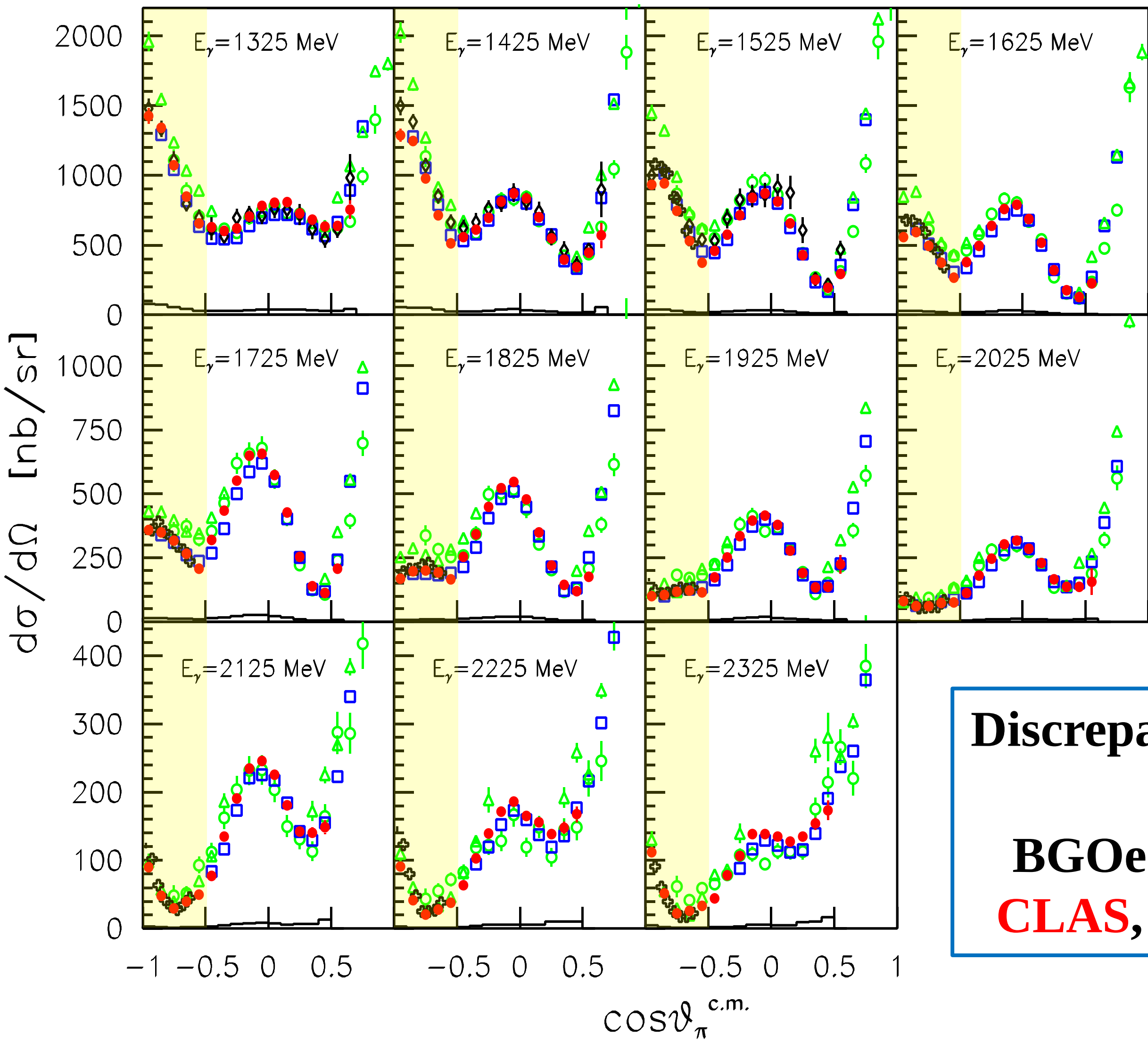




**Kinematic fit** with the constraints of **4-momentum cons.** & **$\pi^0$ mass**.

$\Rightarrow$ **$\frac{d\sigma}{d\Omega}$ and $\Sigma$ data at $-1<\cos\theta_M^{c.m.}<0.6$ & 1.82<W<2.32 GeV**

# Differential Cross Section of $\gamma p \to \pi^0 p$

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



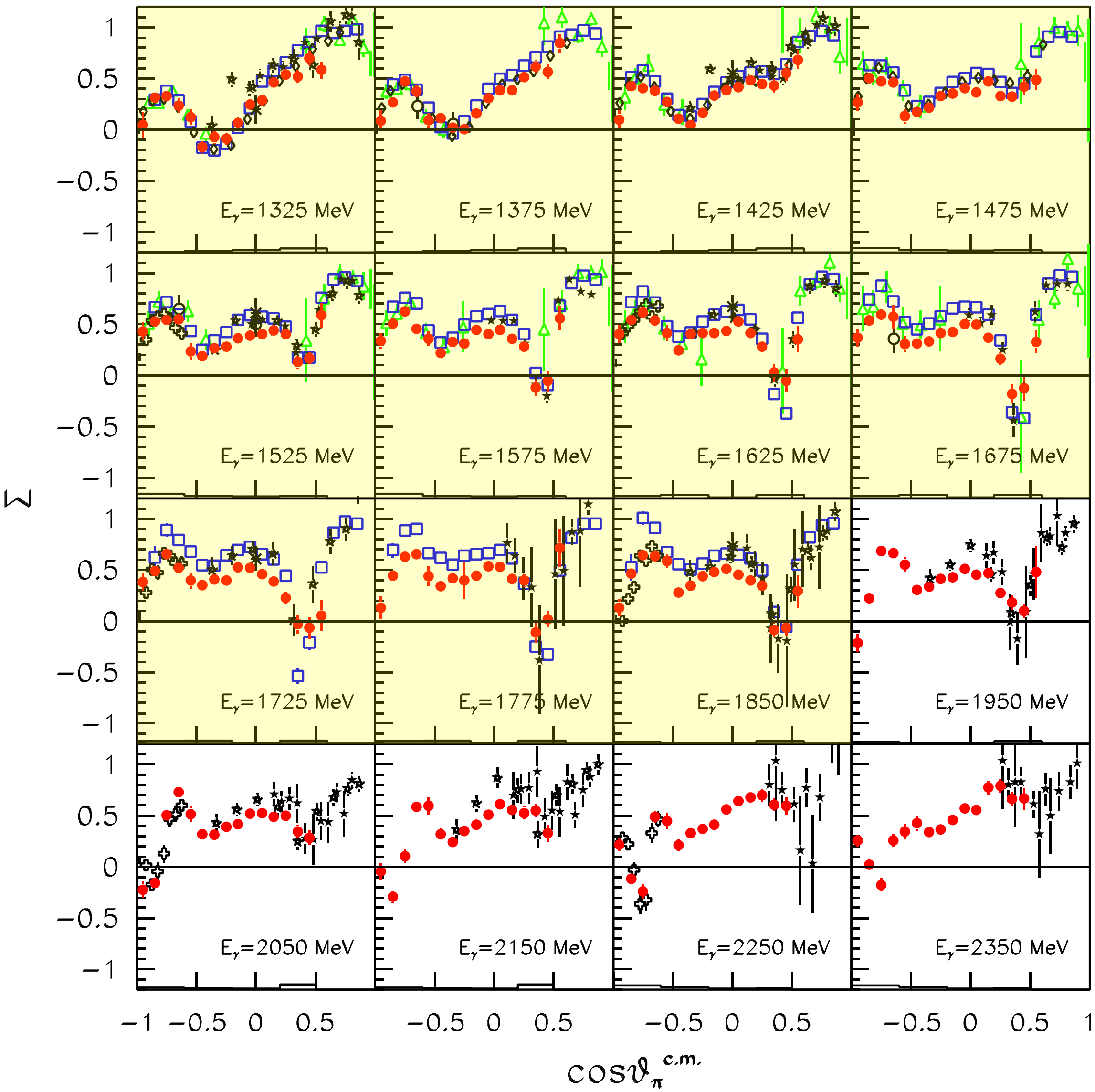

●: **BGOegg** [PRC100(2019)055202]
□: CLAS [PRC76 (2007) 025211]
○: CBELSA [PRL94 (2005) 012003]
△: CBELSA [PRC84 (2011) 055203]
◇: GRAAL [EPJA26 (2005) 399]
✞ : LEPS [PLB657 (2007) 32]

Note: BGOegg results are plotted in **every other energy bin**. Overlaid histograms indicate the systematic uncertainties of BGOegg results.

**Discrepancies at $\cos\theta_{\pi^0}^{c.m.} \lesssim -0.5$**
**⇓**
**BGOegg result is closer to the CLAS, GRAAL, & LEPS data.**

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

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



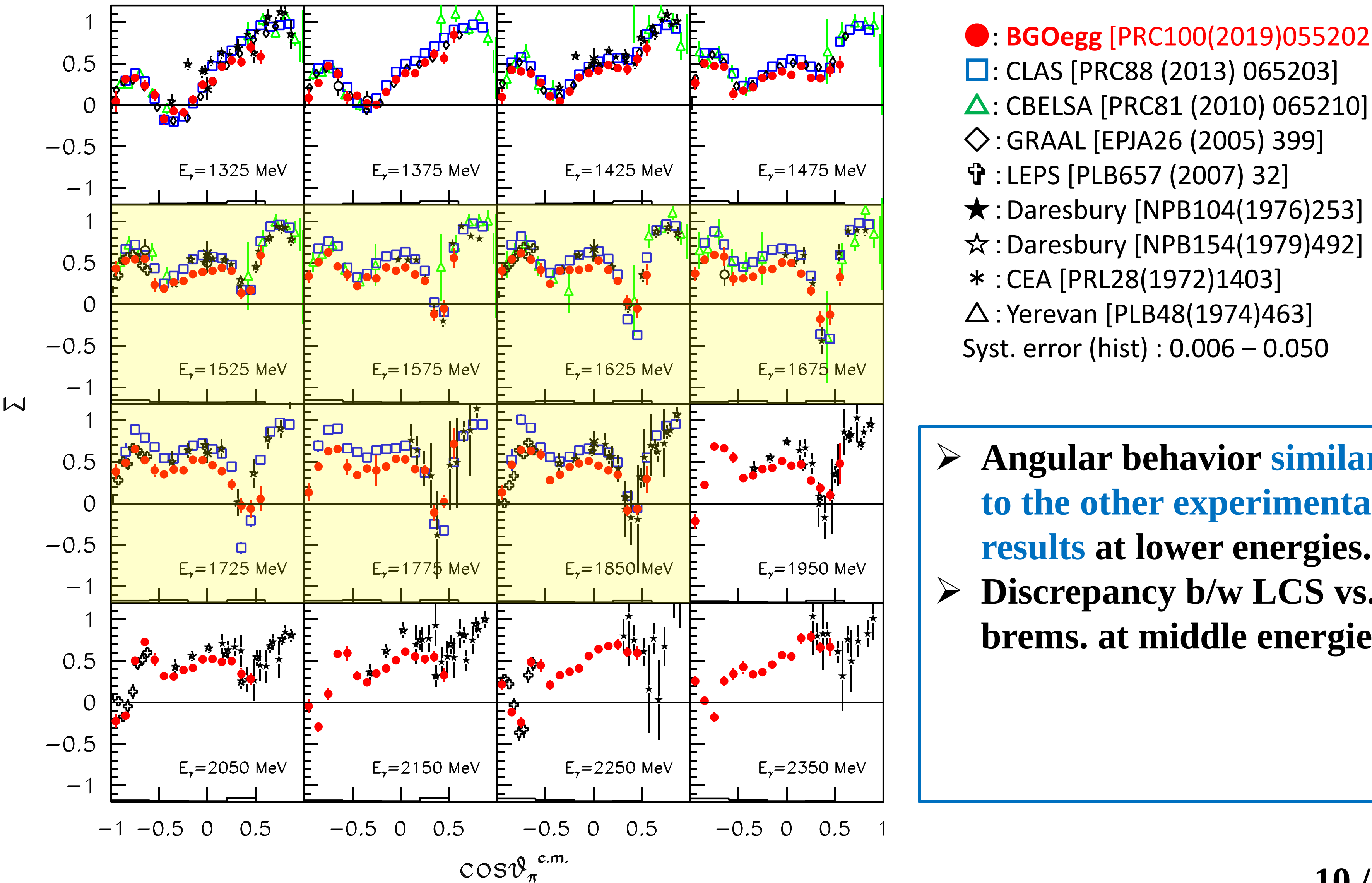

- ●: **BGOegg** [PRC100(2019)055202]
- □: CLAS [PRC88 (2013) 065203]
- △: CBELSA [PRC81 (2010) 065210]
- ◇: GRAAL [EPJA26 (2005) 399]
- ✞: LEPS [PLB657 (2007) 32]
- ★: Daresbury [NPB104(1976)253]
- ☆: Daresbury [NPB154(1979)492]
- ∗: CEA [PRL28(1972)1403]
- △: Yerevan [PLB48(1974)463]

Syst. error (hist) : 0.006 – 0.050

➢ **Angular behavior similar to the other experimental results at lower energies.**

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

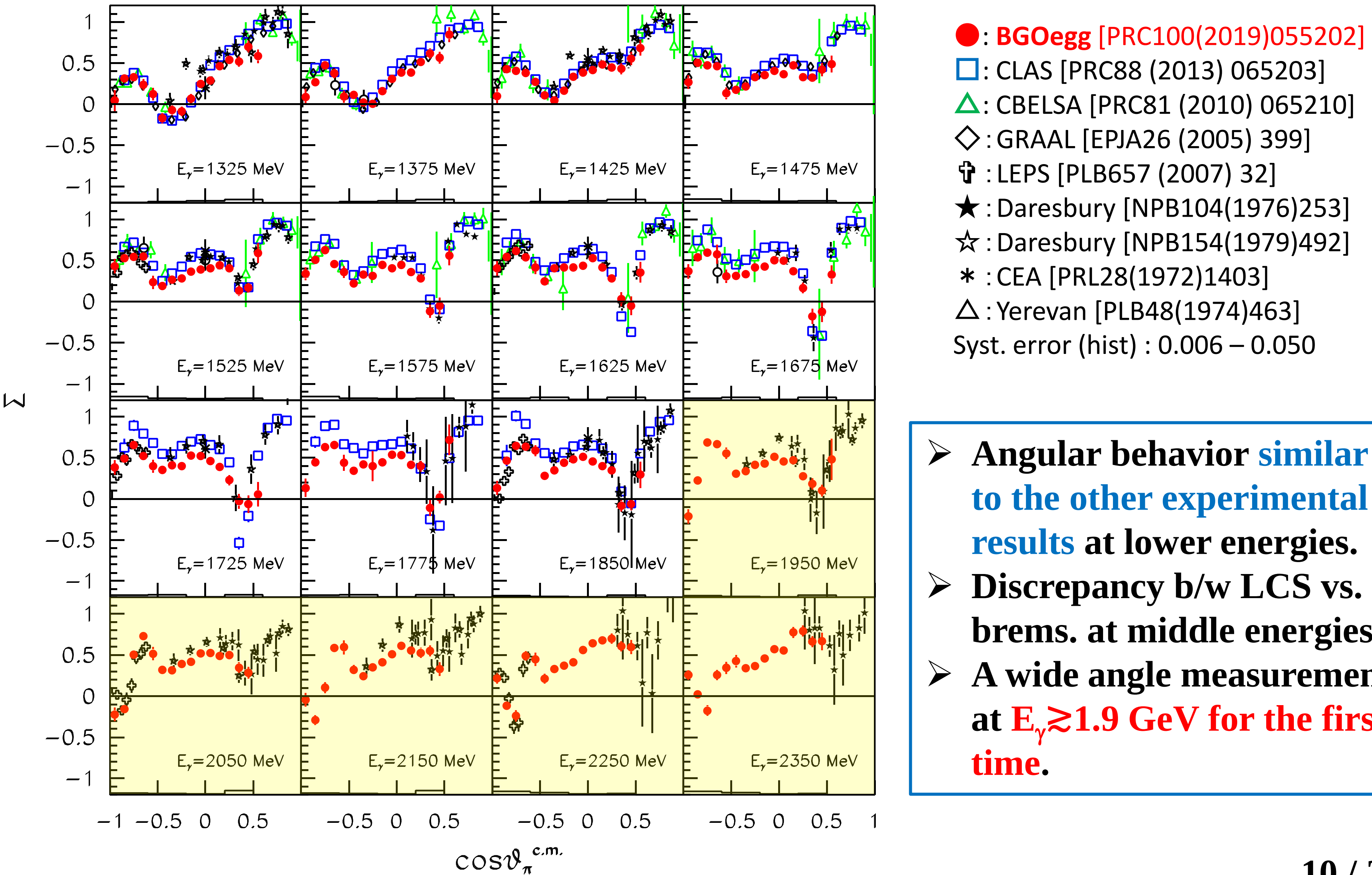
**16 energy bins** for 1300<$E_\gamma$<2400 MeV & **16 polar angle bins** for $-1.0<\cos\theta_\pi^{CM}<0.6$




- **Angular behavior similar to the other experimental results at lower energies.**
- **Discrepancy b/w LCS vs. brems. at middle energies.**

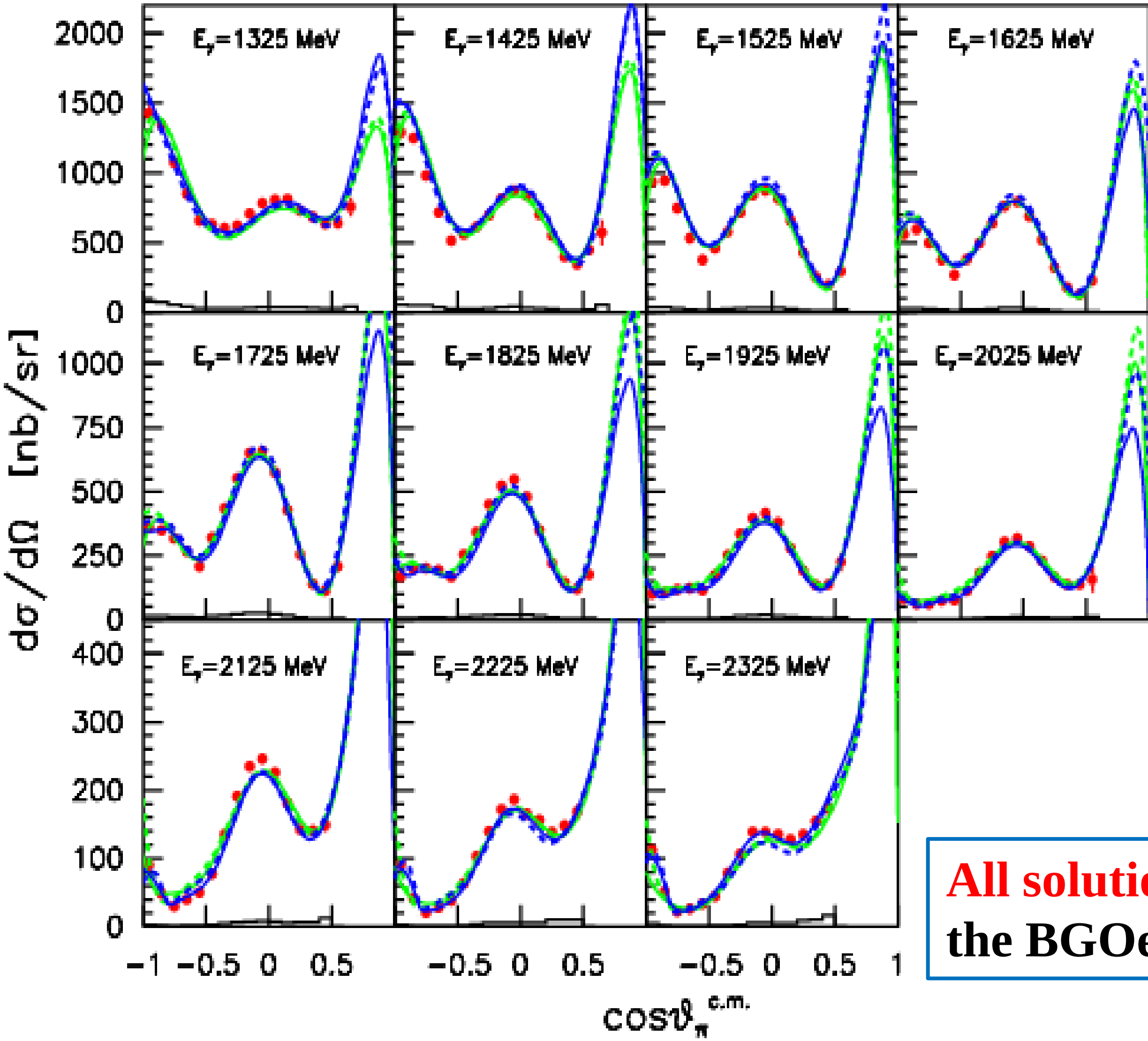
# Photon Beam Asymmetry of $\gamma p \rightarrow \pi^0 p$

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




- **Angular behavior similar to the other experimental results at lower energies.**
- **Discrepancy b/w LCS vs. brems. at middle energies.**
- **A wide angle measurement at $E_\gamma \gtrsim 1.9$ GeV for the first time.**

# Comparison with PWA: $d\sigma/d\Omega$ of $\gamma p \to \pi^0 p$




● : BGOegg data (2019)

**Bonn-Gatchina**

- - - - : BG2014

——— : BG2019

$\eta$ & $\pi^0\pi^0$ photoproduction data from CBELSA. [PLB 803 (2020) 135323, EPJA 51 (2015) 95]

**GW SAID**

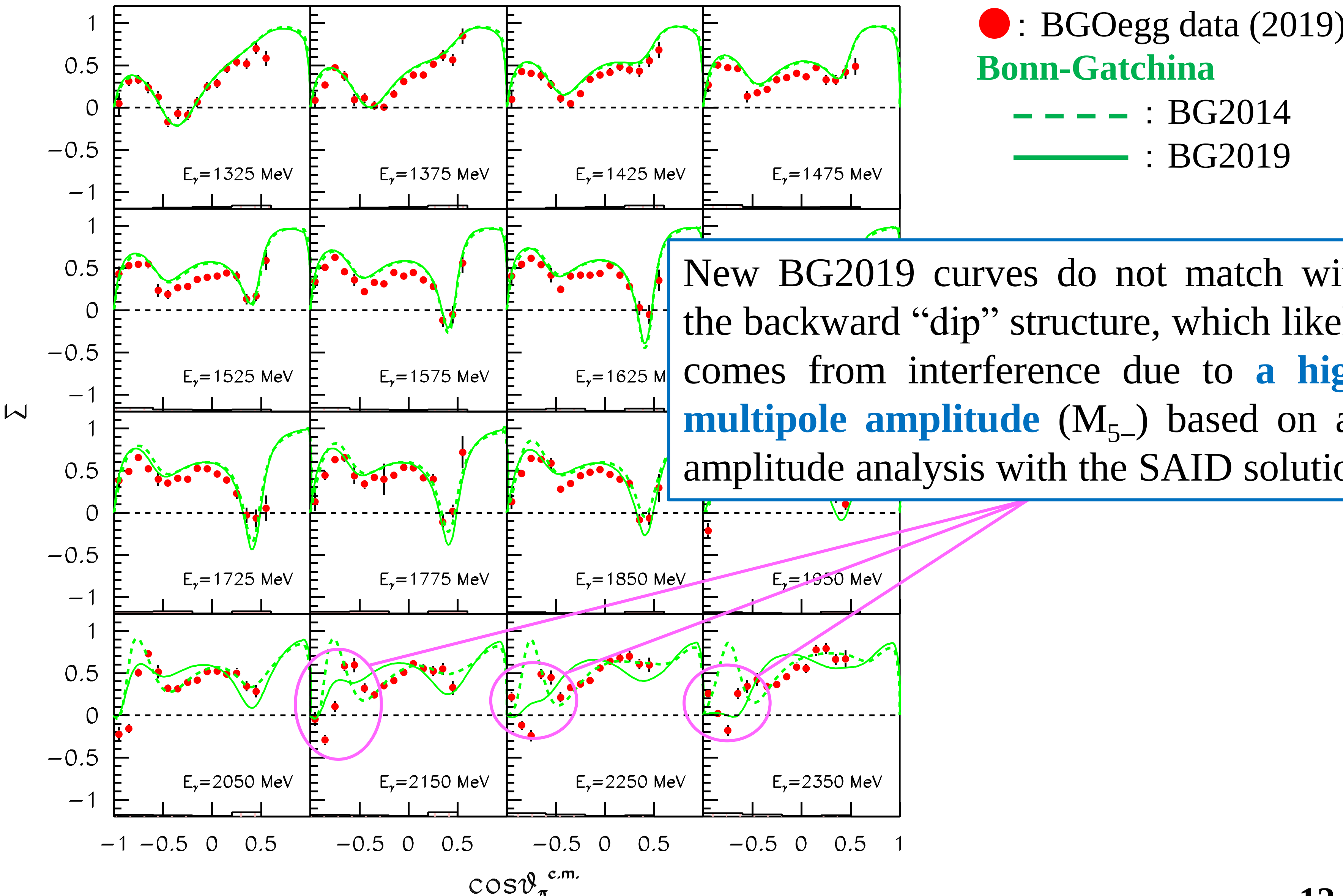
- - - - : CM12 (2012)

——— : SM22 (2022)

World-wide $\pi^0$ photoproduction data in 2011-2021. [PRC 108 (2023) 065205]

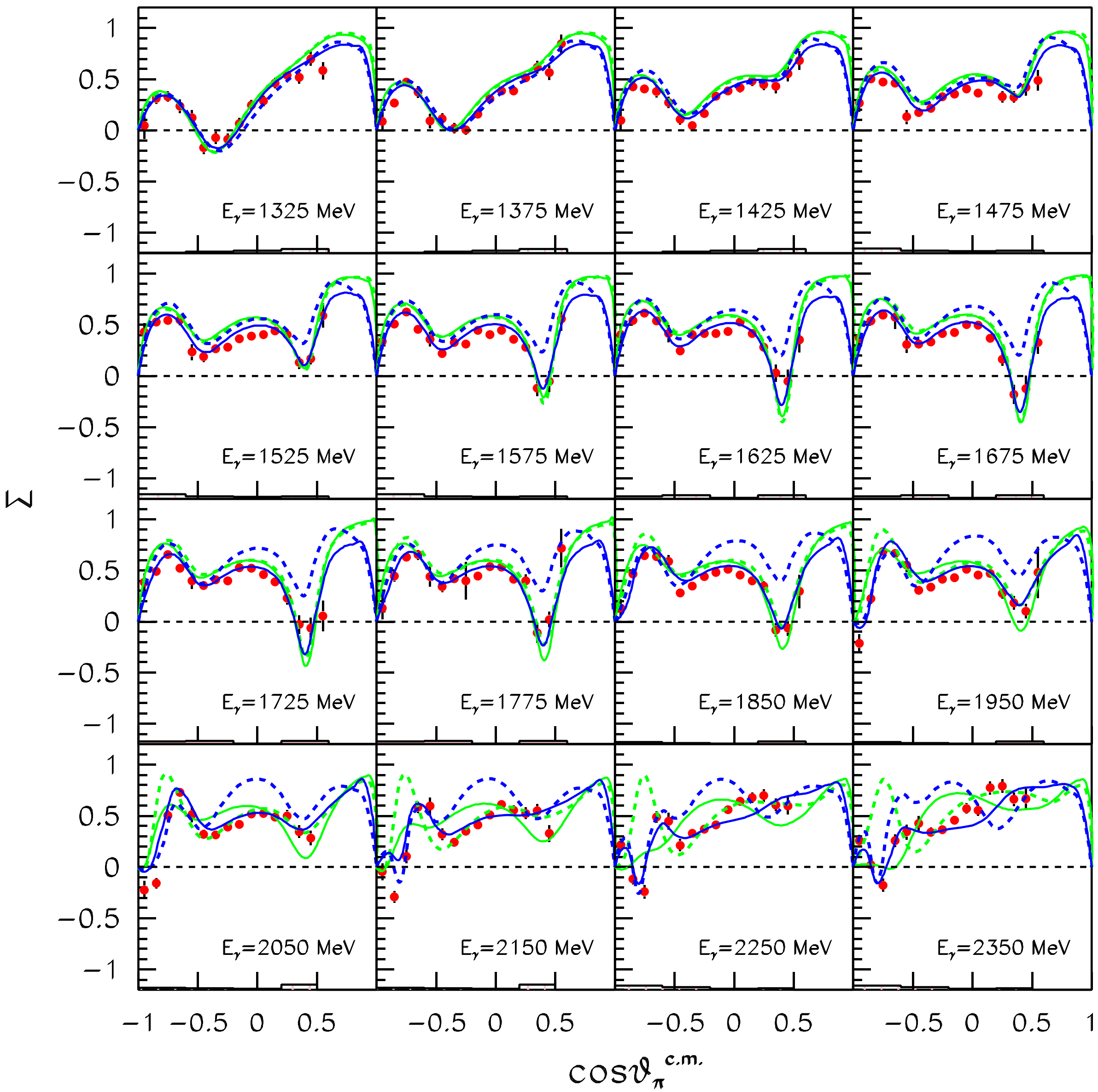
**All solutions more or less reproduce the BGOegg $d\sigma/d\Omega$ result.**

# Comparison with PWA: $\Sigma$ of $\gamma p \rightarrow \pi^0 p$




New BG2019 curves do not match with the backward "dip" structure, which likely comes from interference due to **a high multipole amplitude** ($M_{5-}$) based on an amplitude analysis with the SAID solution.

# Comparison with PWA: Σ of $\gamma p \to \pi^0 p$




●: BGOegg data (2019)

**Bonn-Gatchina**

- - - - : BG2014

——— : BG2019

**GW SAID**

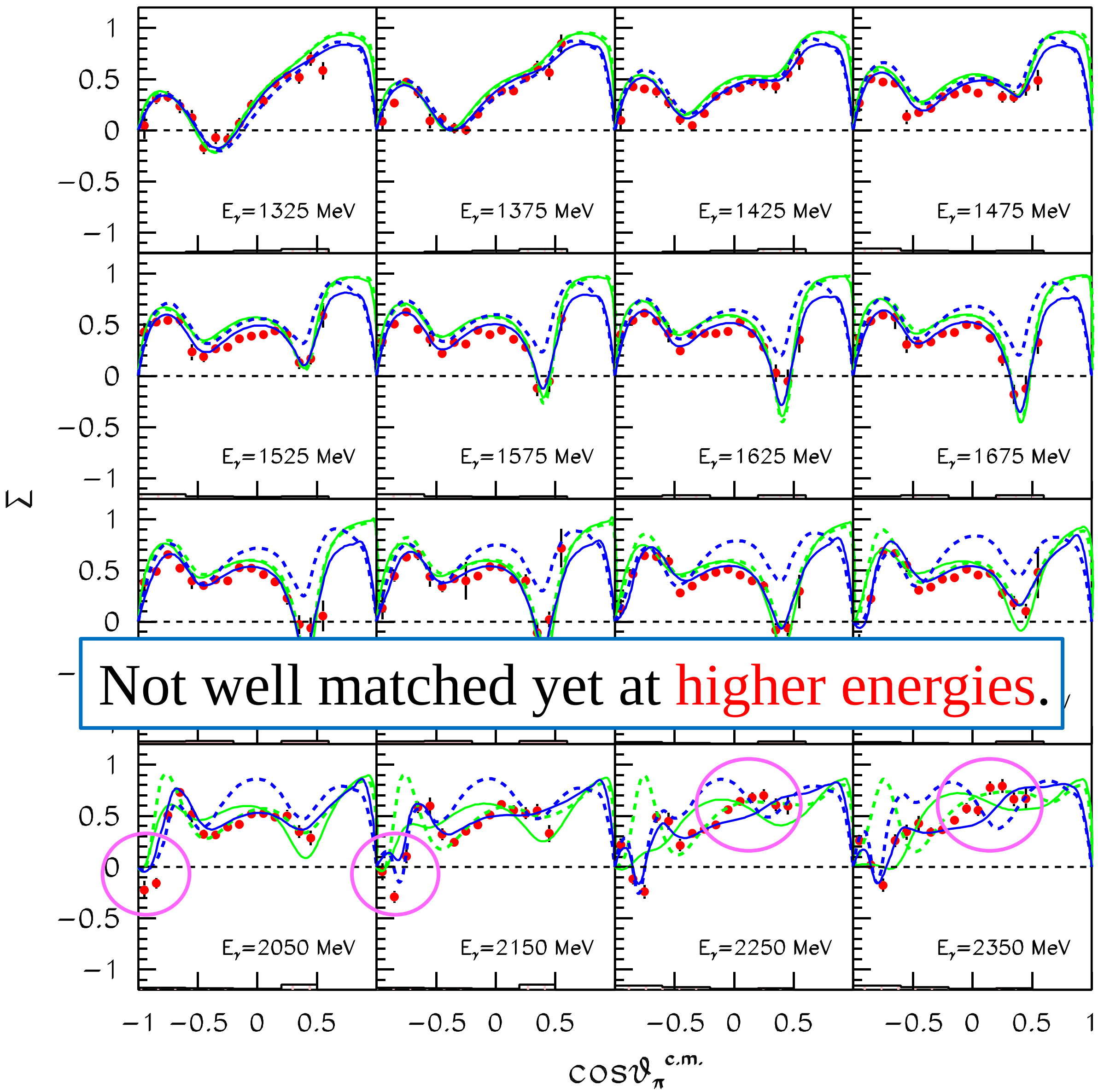
- - - - : CM12 (2012)

——— : SM22 (2022)

Only a limited number of resonances have significant contribution.
(PRC 108 (2023) 065205)

$E_{0+}$ : N(1535), N(1650)
$M_{1-}$ : N(1440)
$E_{1+}/M_{1+}$: N(1720), Δ(1232), Δ(1620)
$E_{2-}/M_{2-}$: N(1520), Δ(1700)
$E_{2+}/M_{2+}$: N(1675), Δ(1905), Δ(1910)
$E_{3-}/M_{3-}$: N(1680), Δ(1950)

# Comparison with PWA: Σ of $\gamma p \to \pi^0 p$




Not well matched yet at higher energies.

●: BGOegg data (2019)

**Bonn-Gatchina**

- - - - : BG2014

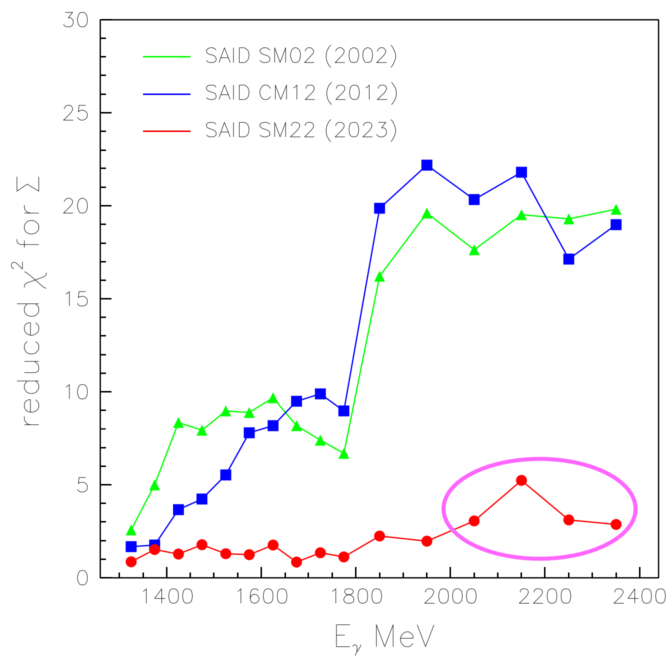
——— : BG2019

**GW SAID**

- - - - : CM12 (2012)

——— : SM22 (2022)

**I. Strakovsky, Private Communication**



# η & η′ photoproduction

## Physics aspects

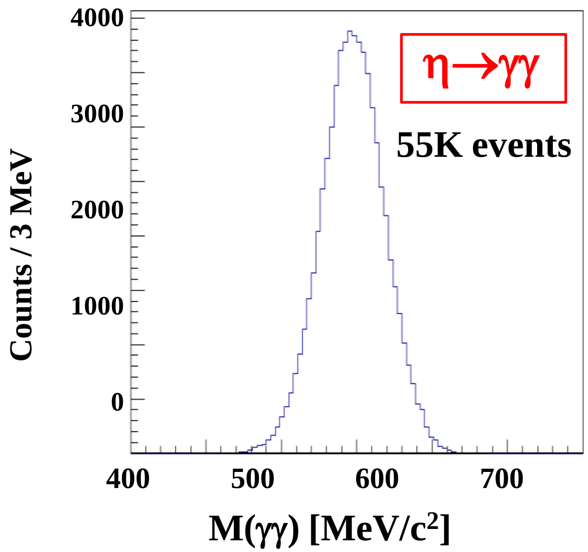
I(η/η′)=0 ⇒ Only contributions from ***N****(I=$\frac{1}{2}$) should exist.

Possible to investigate $N^*$s coupling with ***$s\bar{s}$***.

η′ : Useful to explore **higher mass resonances**, but experimental data are **scarce**, particularly for polarization observables.

## BGOegg experiment

$\gamma p \to \eta p$ ; $\eta \to \gamma\gamma$ **(Br=39.4%)**




*Kinematic fit w/*
*4-momentum conservation*
*& η mass constraint*

# η & η′ photoproduction

## Physics aspects

I(η/η′)=0 ⇒ Only contributions from $\boldsymbol{N^*}$(I=$\frac{1}{2}$) should exist.

Possible to investigate $N^*$s coupling with $\boldsymbol{s\bar{s}}$.

η′ : Useful to explore **higher mass resonances**, but experimental data are **scarce**, particularly for polarization observables.

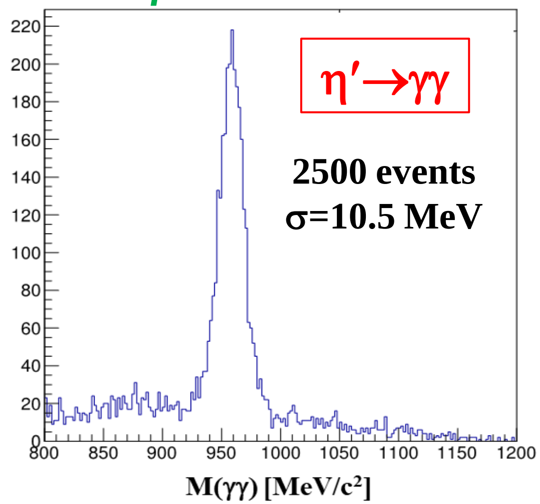
## BGOegg experiment

$\boldsymbol{\gamma p \to \eta p}$ ; $\boldsymbol{\eta \to \gamma\gamma}$ **(Br=39.4%)**

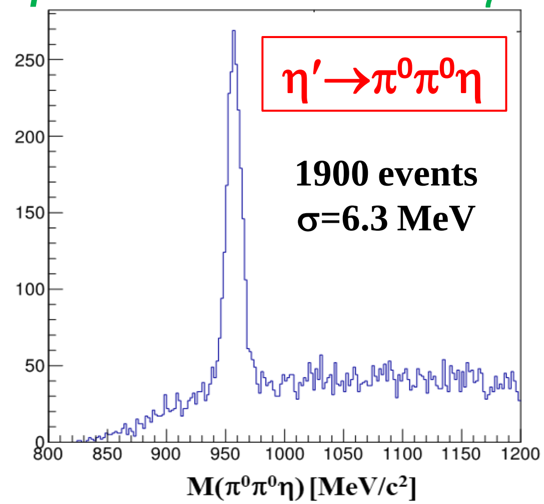
$\boldsymbol{\gamma p \to \eta' p}$ ; $\boldsymbol{\eta' \to \gamma\gamma}$ **(Br= 2.3%)**

**or** $\boldsymbol{\eta' \to \pi^0\pi^0\eta}$ **(Br=22.4%)** $\boldsymbol{\to 6\gamma}$

*Kin. fit w/ 4-mom. cons.*

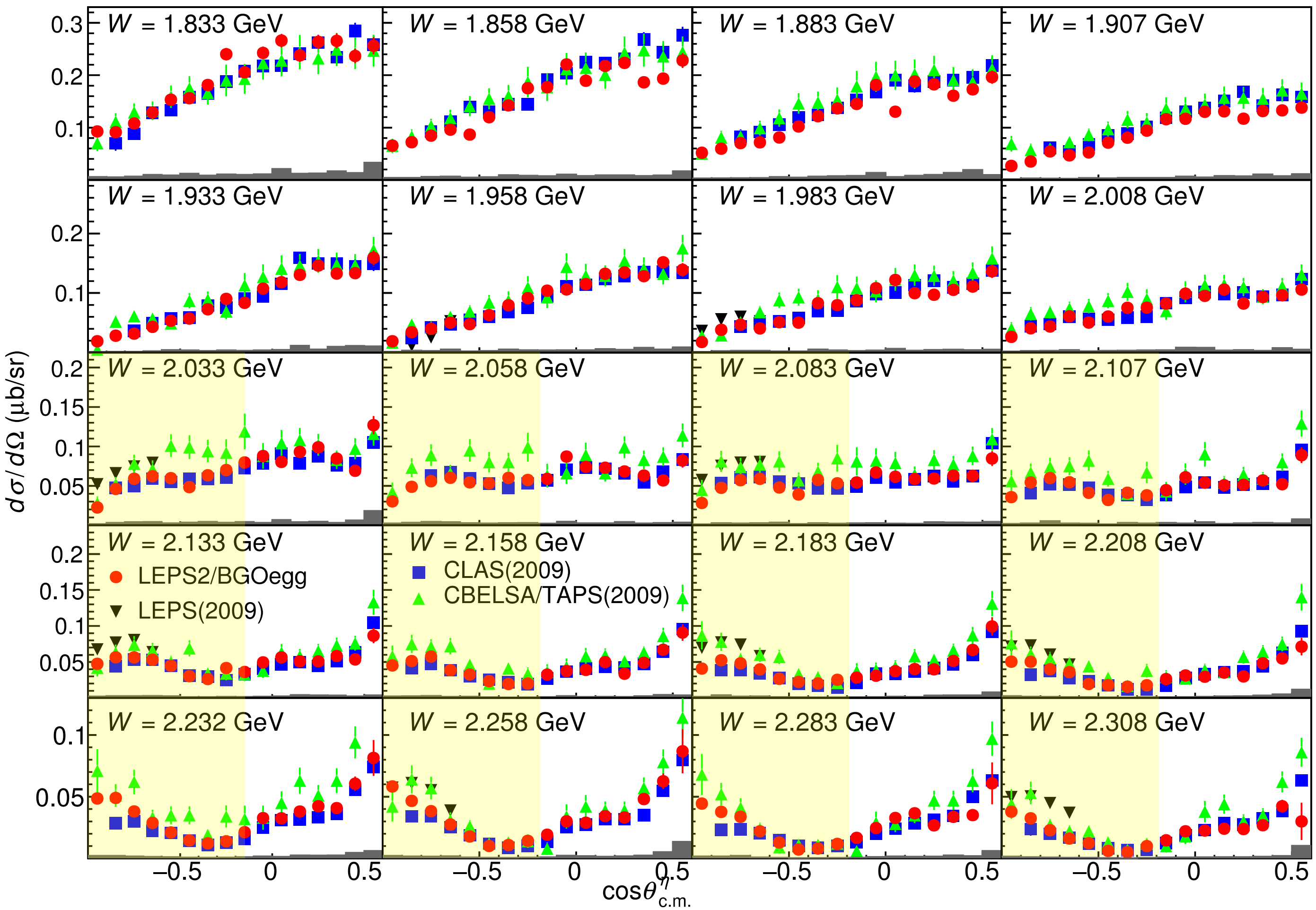



*Kin. fit w/ 4-mom. cons. & π⁰/η mass*



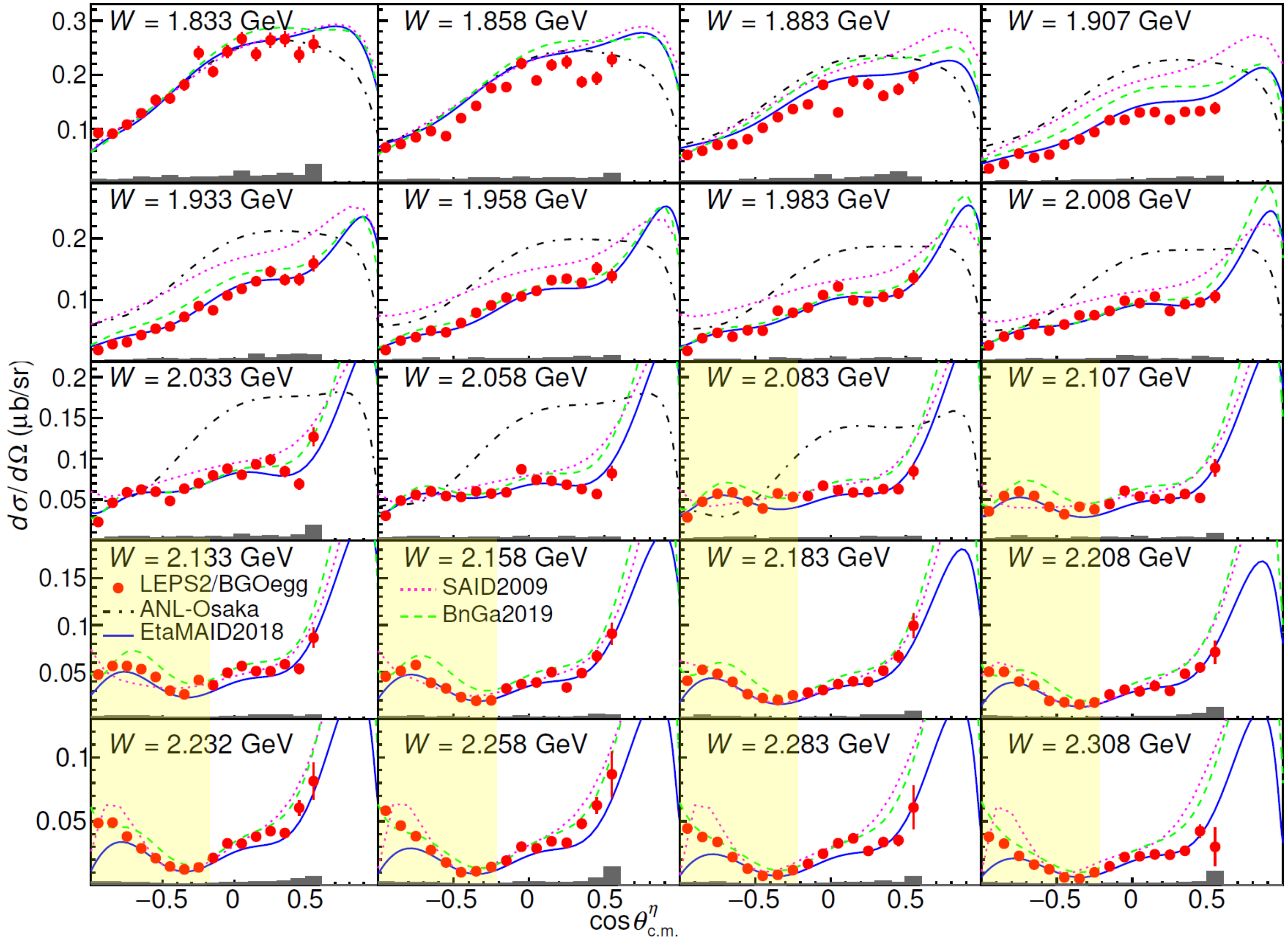
# Differential Cross Section of γp→ηp

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



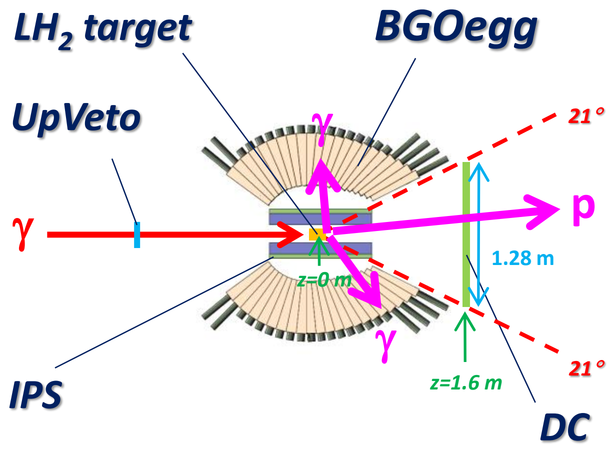

There are **inconsistencies at $\cos\theta_\eta^{c.m.} \lesssim -0.2$ & $W > 2$ GeV** among experiments.

# Comparison with PWA: $d\sigma/d\Omega$ of $\gamma p \to \eta p$




There are **ambiguities at backward angles & higher energies** reflecting the experimental situation.

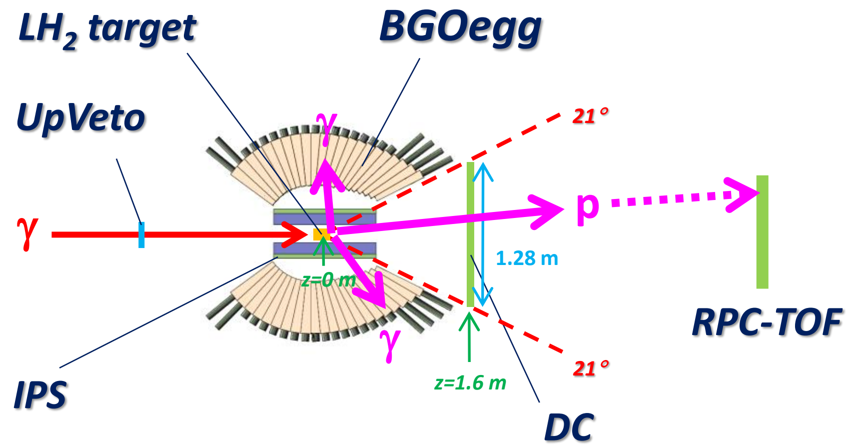
# Alternative method to measure $d\sigma/d\Omega$ of $\gamma p \to \eta p$

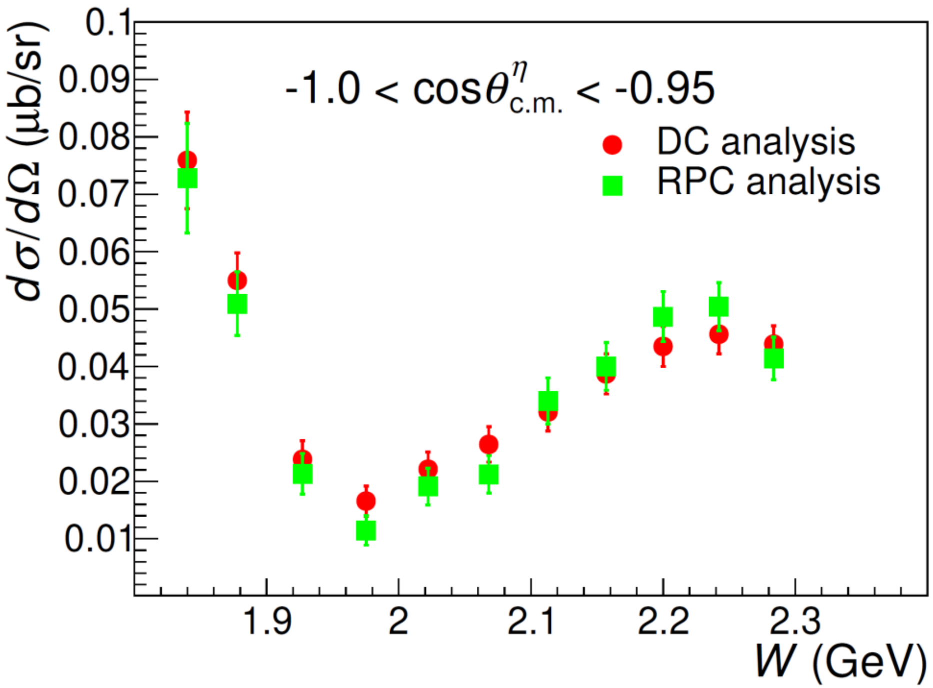



**BGOegg standard method**

**All the final-state particles** are detected, but **only direction** is measured for a proton.

# Alternative method to measure $d\sigma/d\Omega$ of γp→ηp




**BGOegg standard method**

**All the final-state particles** are detected, but **only direction** is measured for a proton.

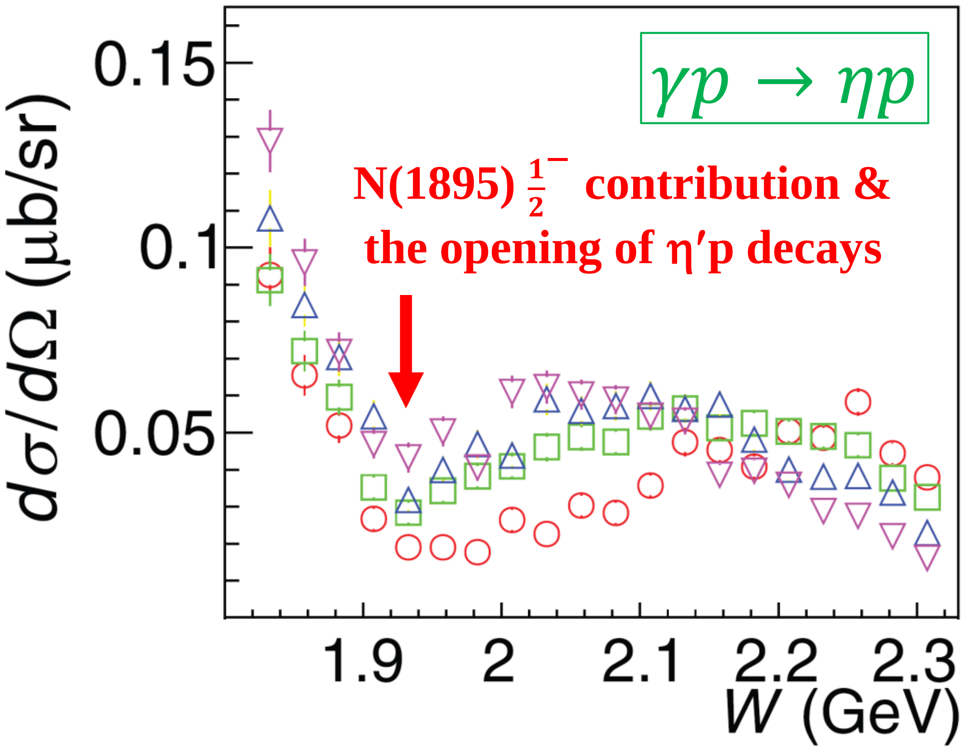
**Alternative analysis**

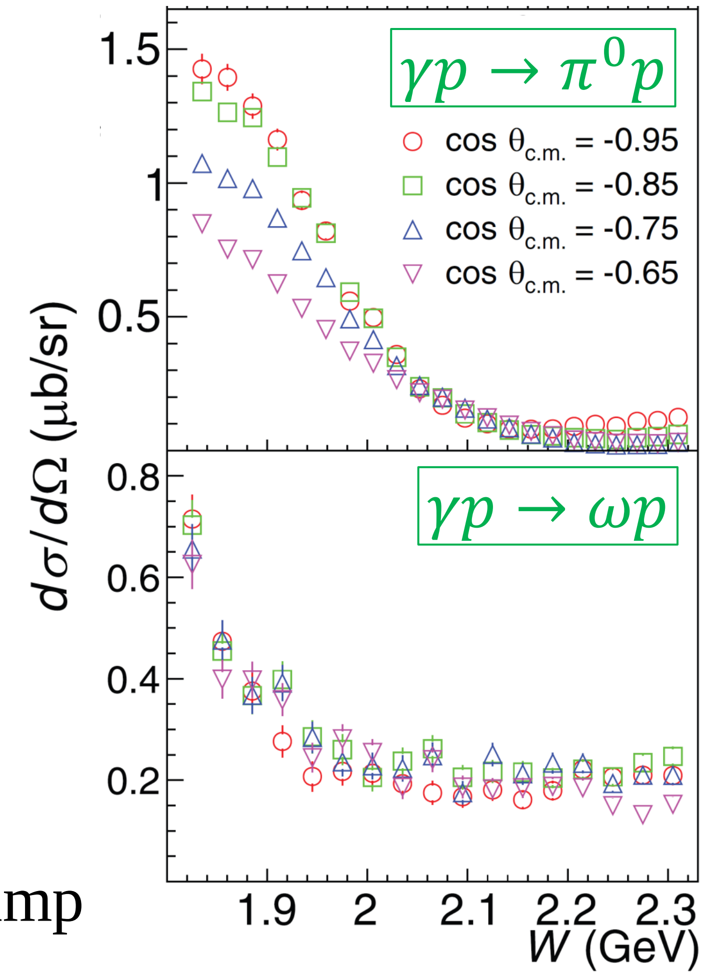
$|P_{proton}|$ is also measured at RPC-TOF in an extremely forward acceptance region. (Full kinematical information at the kinematic fit.)

⇓

**Two results are consistent** with each other.

# Bump structure in $d\sigma/d\Omega$ of $\gamma p \to \eta p$



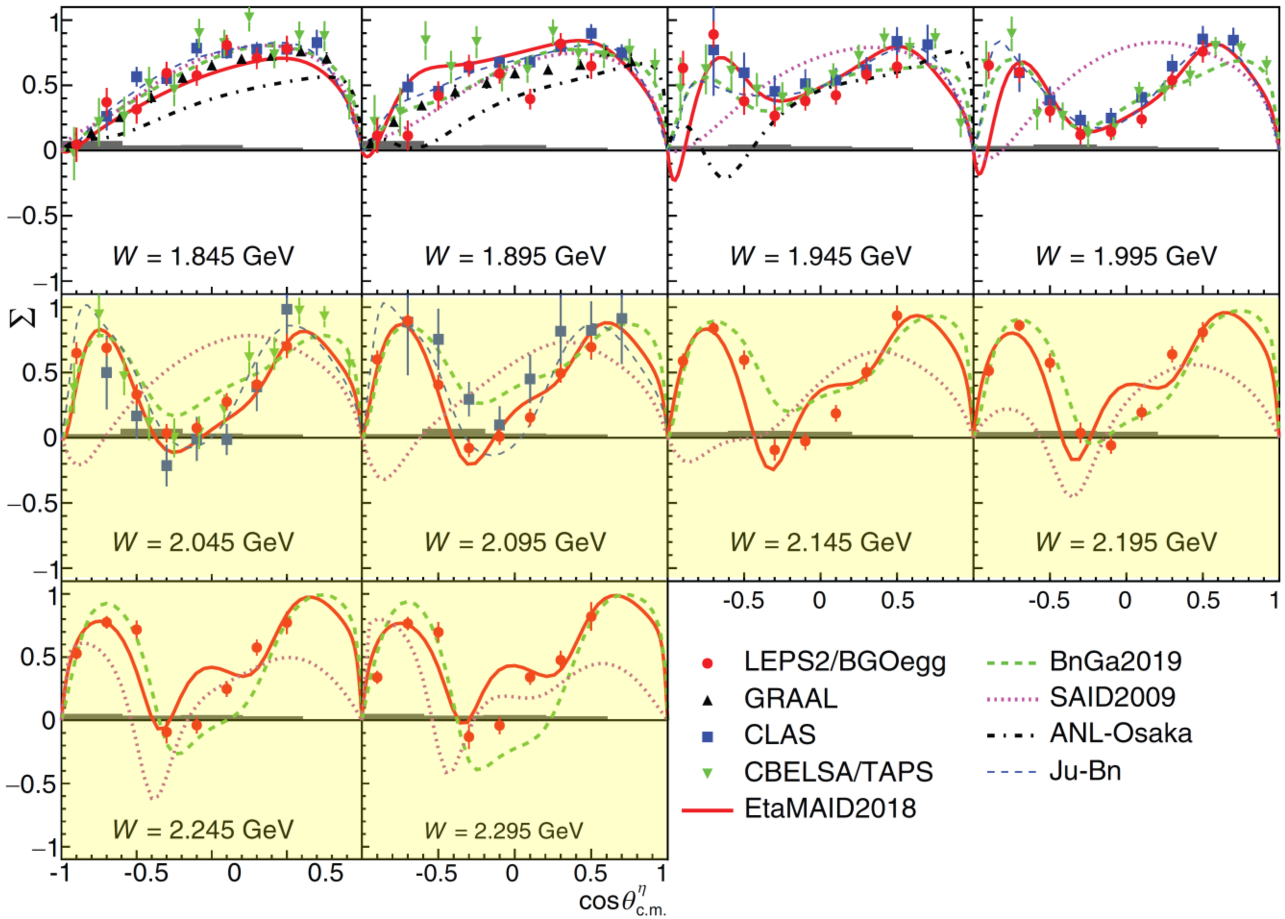




The shape & peak position of the bump structure strongly depend on $\cos\theta^{\eta}_{c.m.}$.

⇒ **Additional contributions from high-spin resonances ?**

# Photon Beam Asymmetry of $\gamma p \to \eta p$

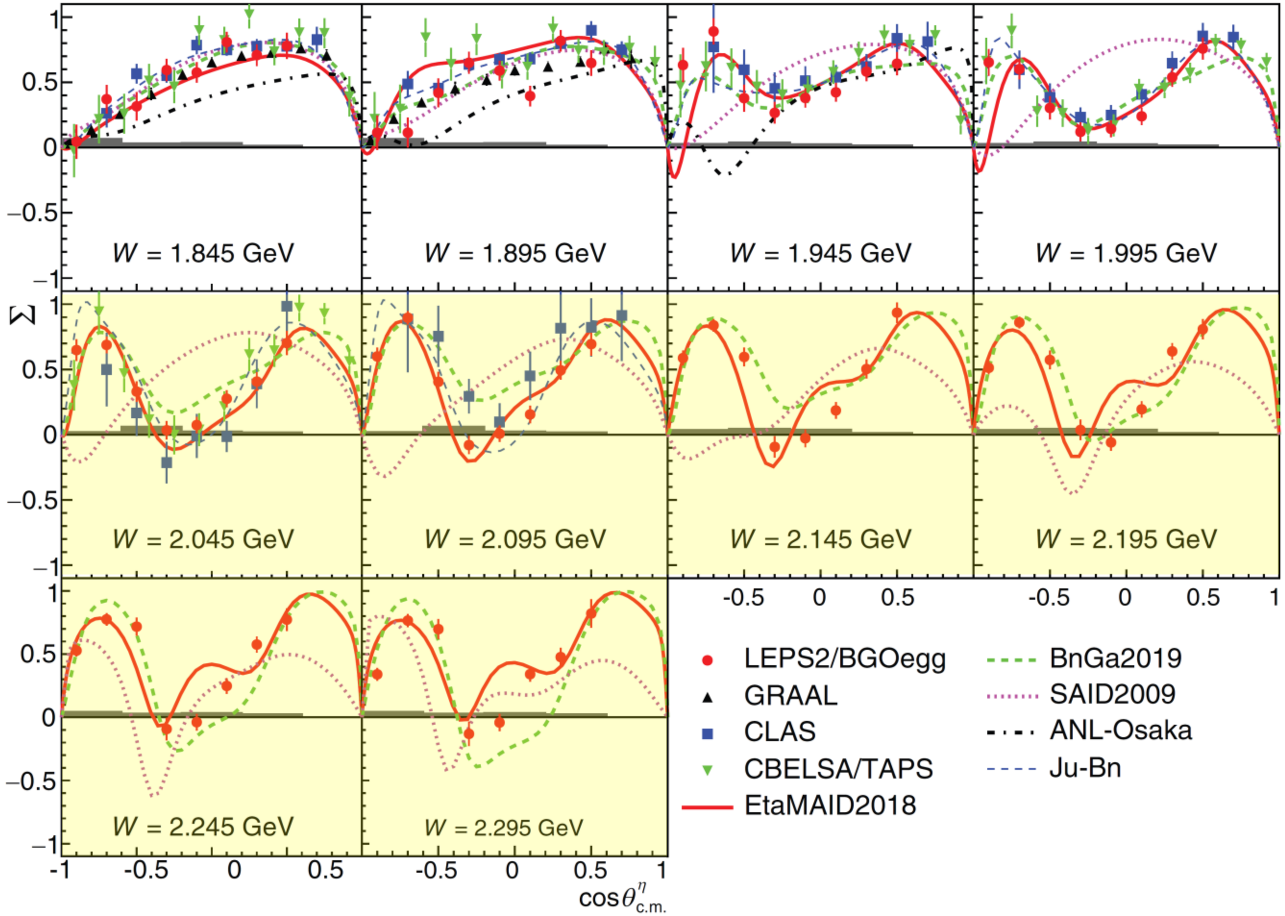
**10 energy bins** for $1820 < \sqrt{s} < 2320$ MeV & **8 polar angle bins** for $-1.0 < \cos\theta_\eta^{CM} < 0.6$




**New precise data for W>2.0 GeV & No PWA models reproduce our result.**

# Photon Beam Asymmetry of γp→ηp

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

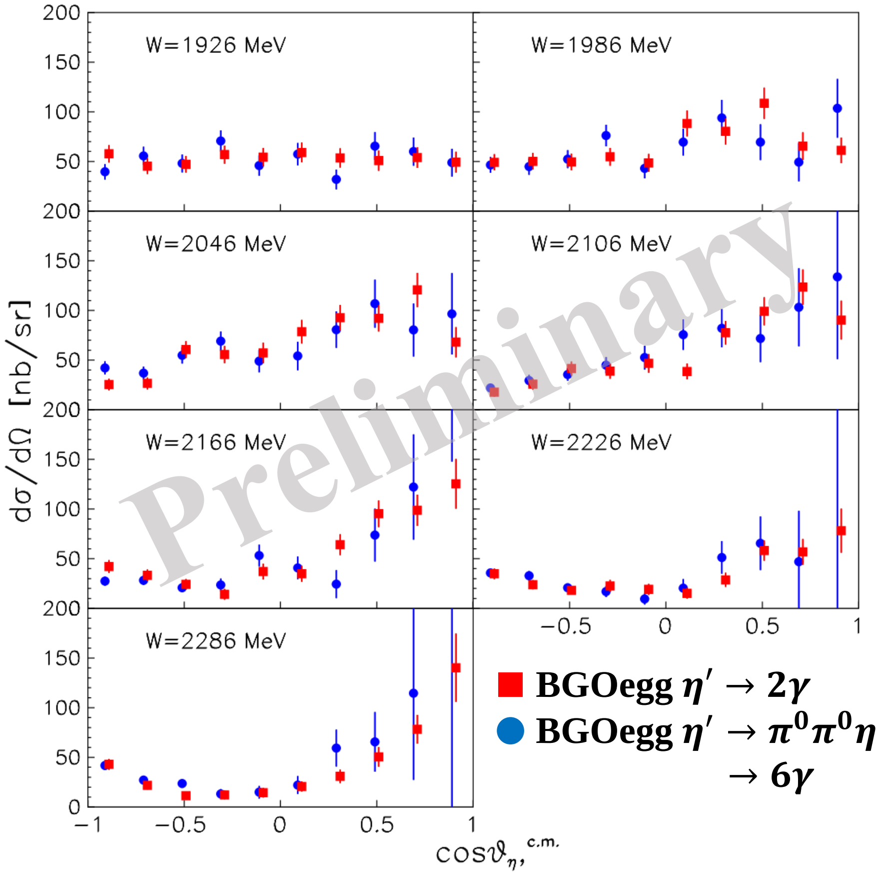



**New precise data for W>2.0 GeV & No PWA models reproduce our result. ⇒ Improved PWA solutions are required possibly with high-mass $N^*$ contributions.**

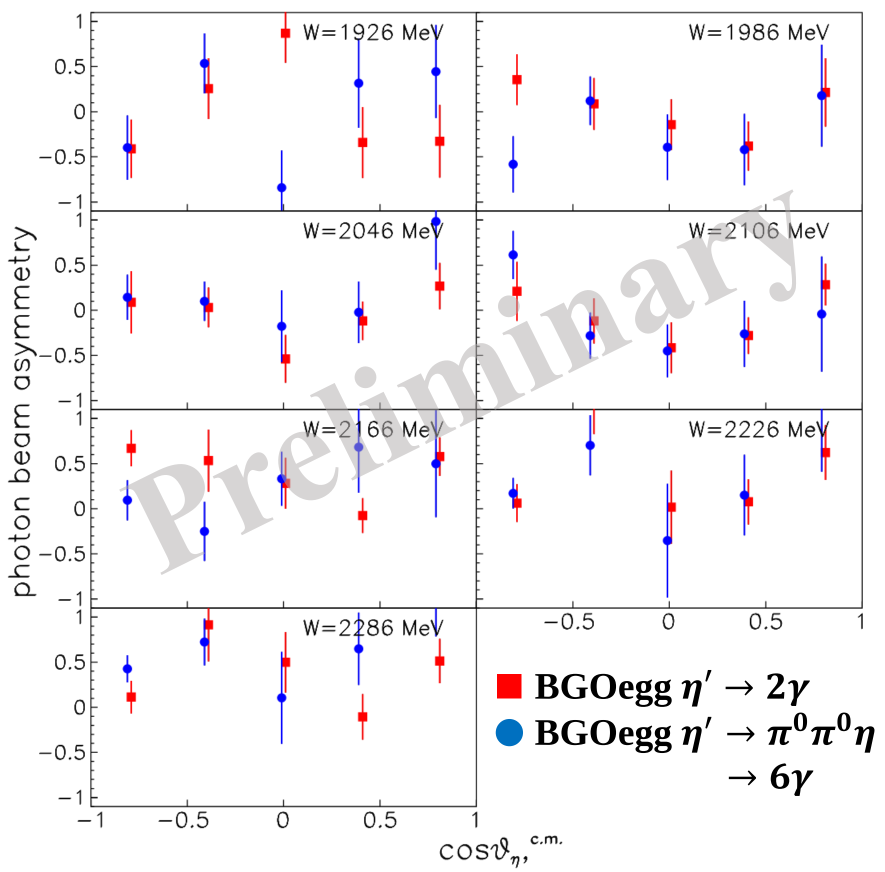
# A new analysis for $\gamma p \to \eta' p$

Opening angles in η′ decays are large enough to cover forward acceptance.

**Differential cross section $d\sigma/d\Omega$**




**Photon beam asymmetry Σ**

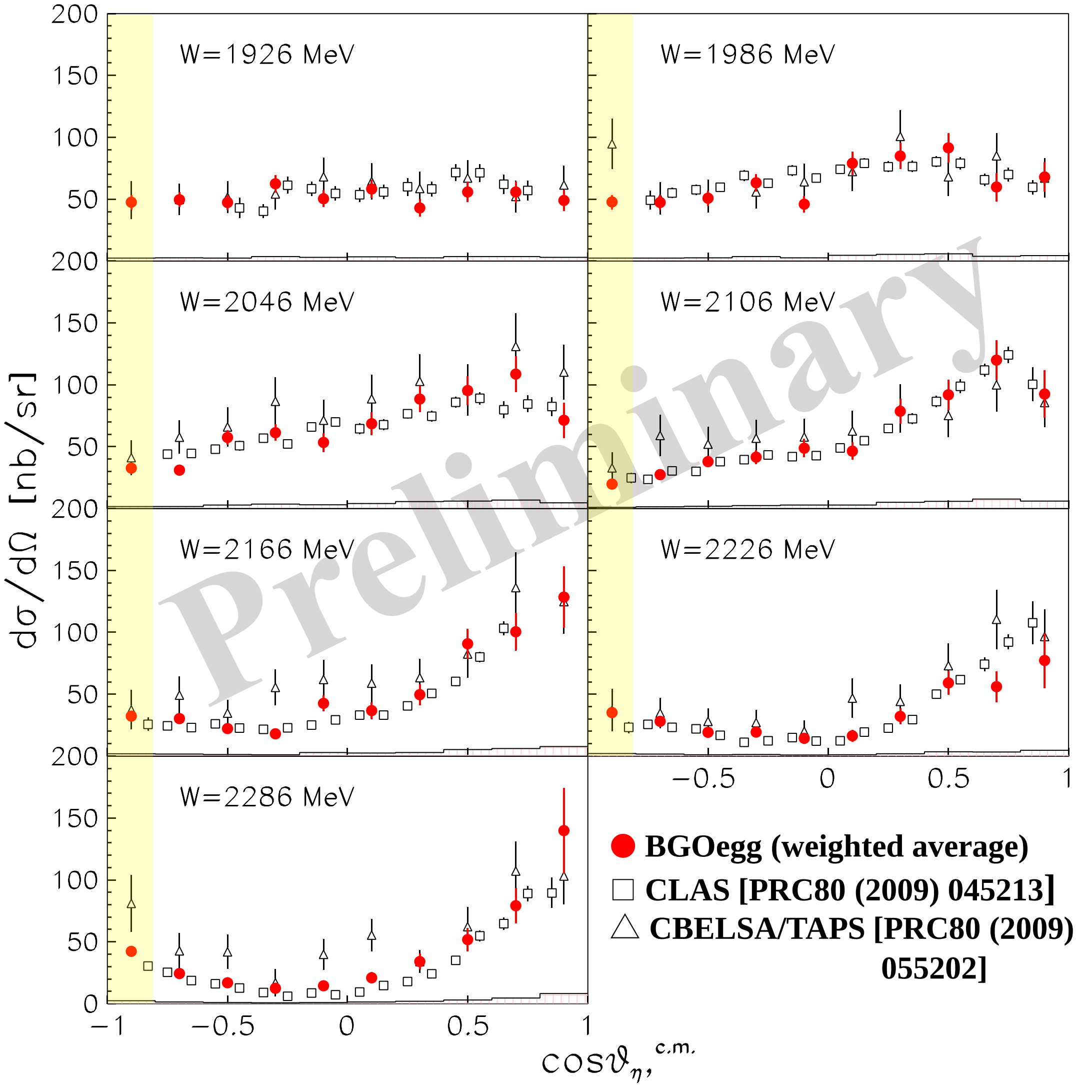



Results in the two decay modes agree with each other.

⇒ **Weighted averages** were taken as combined results.

# Differential cross section of $\gamma p \to \eta' p$

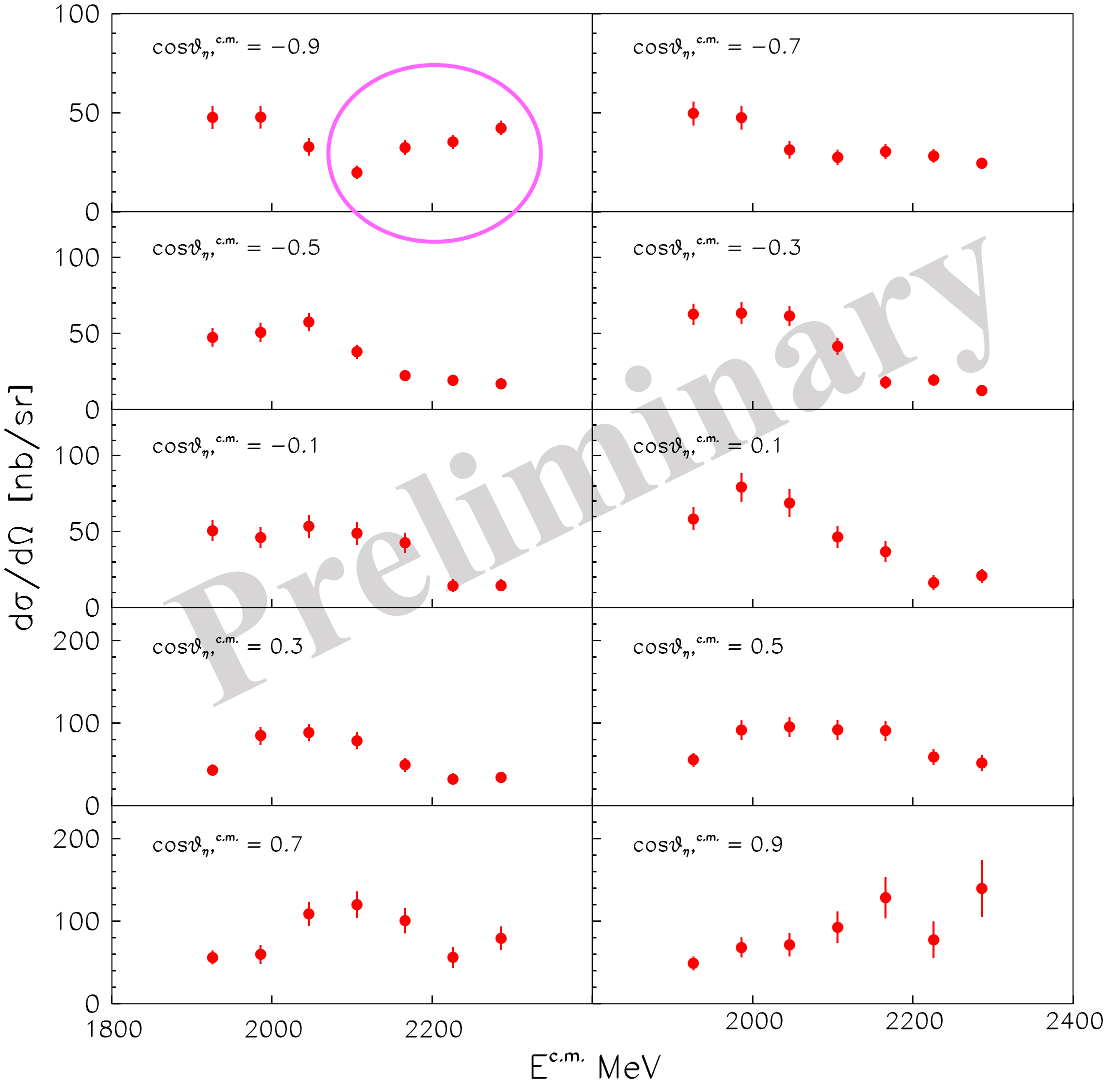
**60-MeV bins** for W & **0.2 bins** for $-1.0 < \cos\theta_{\eta'}^{CM} < 1.0$




- The BGOegg result is **statistically consistent** with the CLAS and CBELSA/TAPS data.
- High precision measurement is achieved at **the most backward angles**.

# Differential cross section of $\gamma p \to \eta' p$

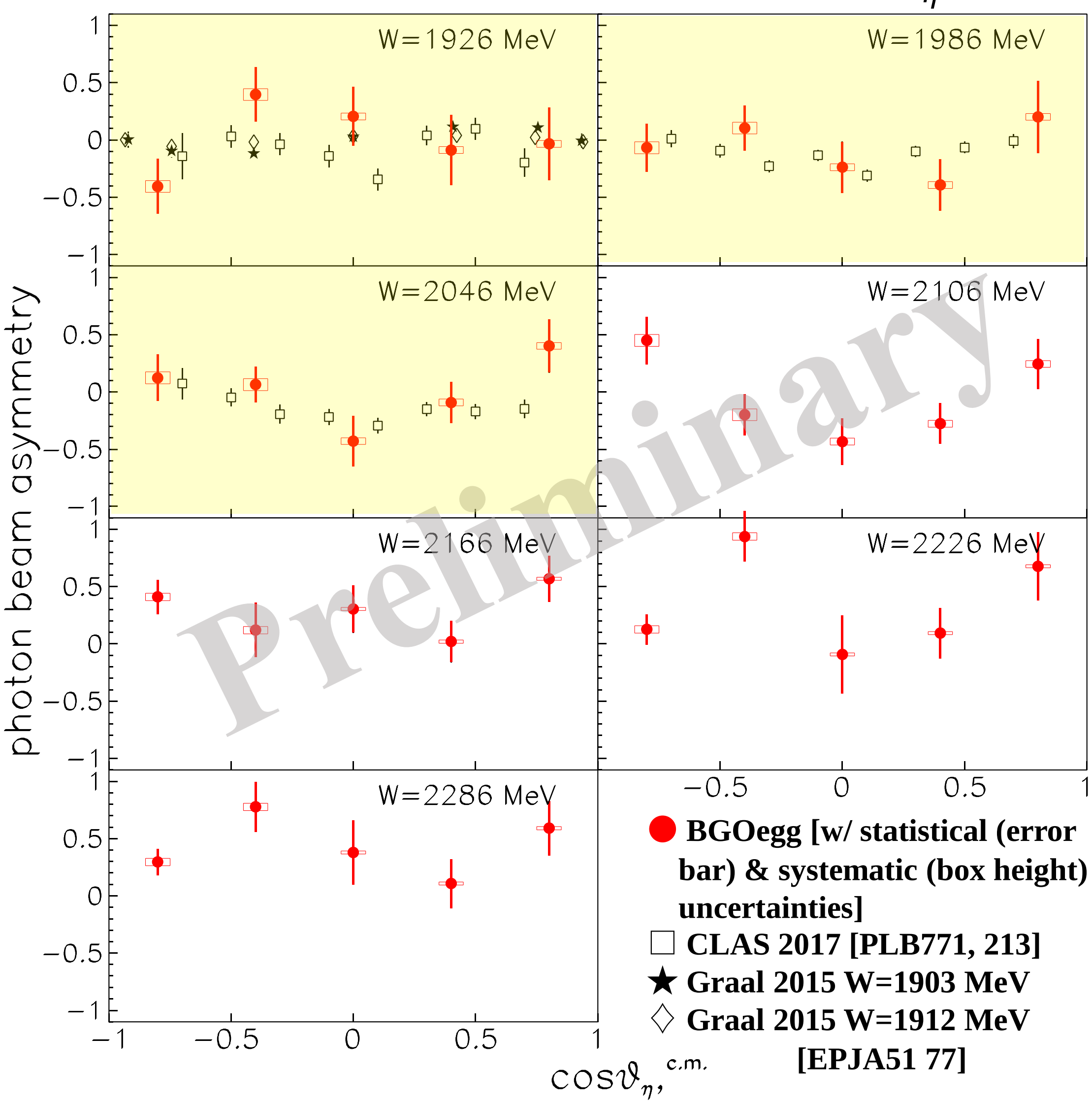
**60-MeV bins** for W & **0.2 bins** for $-1.0<\cos\theta_{\eta'}^{CM}<1.0$




- The BGOegg result is **statistically consistent** with the CLAS and CBELSA/TAPS data.
- High precision measurement is achieved at **the most backward angles**.
- **High energy enhancement** is seen at the most backward angles.

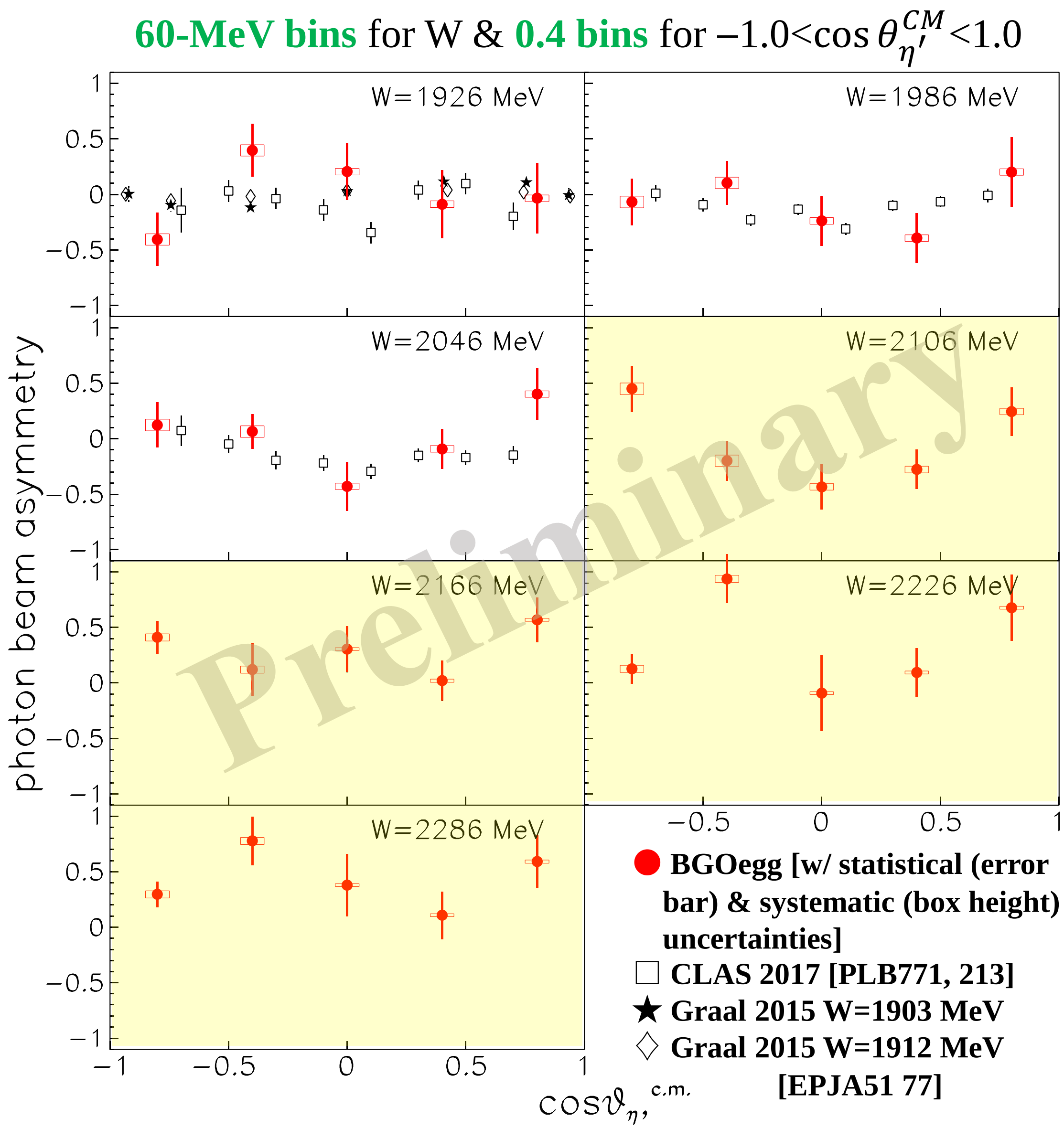
# Photon beam asymmetry of $\gamma p \to \eta' p$

60-MeV bins for W & 0.4 bins for $-1.0<\cos\theta_{\eta'}^{CM}<1.0$



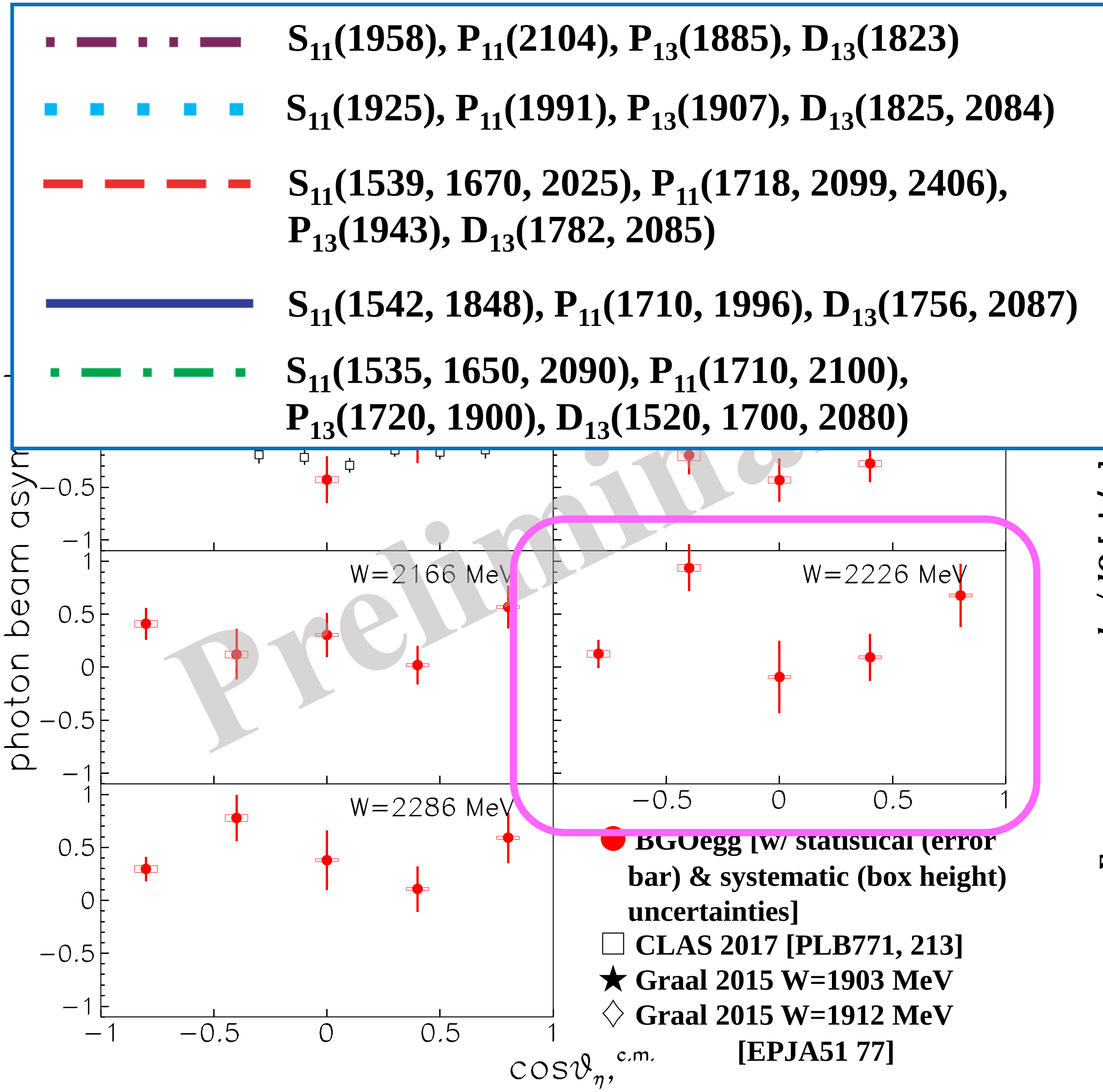

- **Statistically consistent** with the CLAS & Graal results at lower energies.

# Photon beam asymmetry of $\gamma p \rightarrow \eta' p$




- **Statistically consistent** with the CLAS & Graal results at lower energies.
- **New data** at W>2.1 GeV.

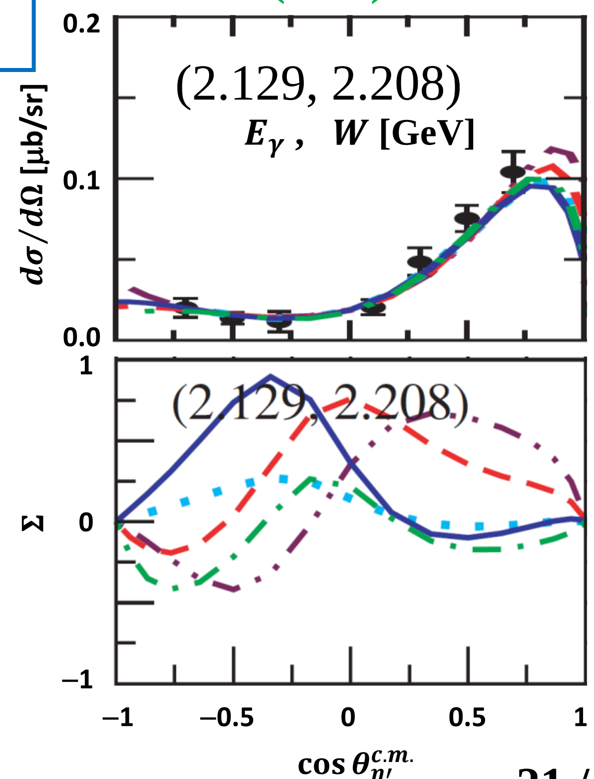
# Photon beam asymmetry of $\gamma p \to \eta' p$




**Statistically consistent** with the CLAS & Graal results at lower energies.

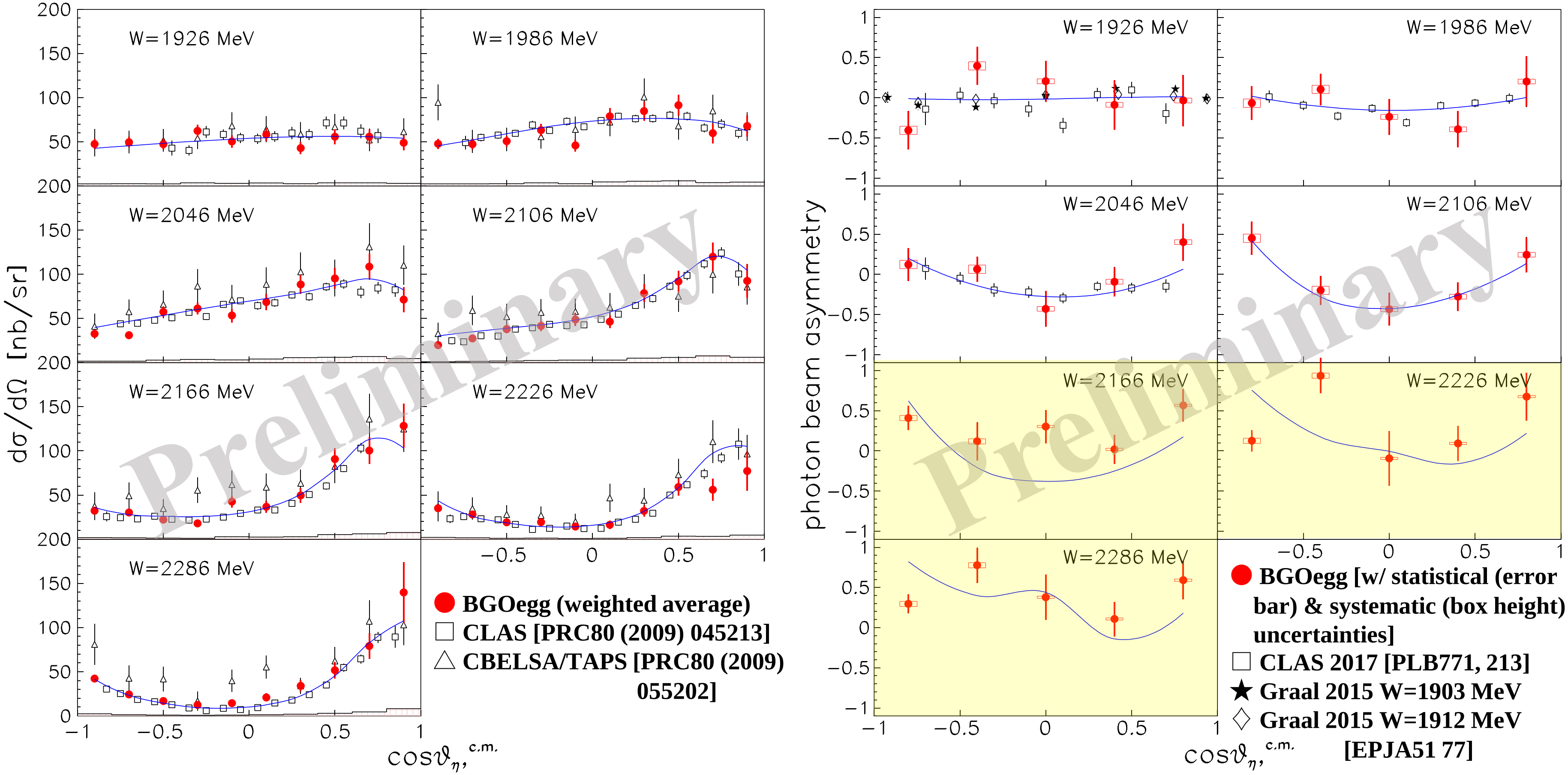
**New data** at W>2.1 GeV.

PRC73 (2006) 045211.



# Comparison with PWA: $d\sigma/d\Omega$ & Σ of γp→η′p

—— : **BG2019 predictions [K. Nikonov & A. Sarantsev, Private Communication; PLB 772 (2017) 247]**




There is room to improve the solution for reproducing
**$\Sigma$ at $W > 2140$ MeV**.

# ω photoproduction

**Physics aspects**

I(ω)=0 ⇒ Only $N^*$(I=$\frac{1}{2}$) contribution exists at *s*-channel.

Useful to investigate **higher mass resonances**.

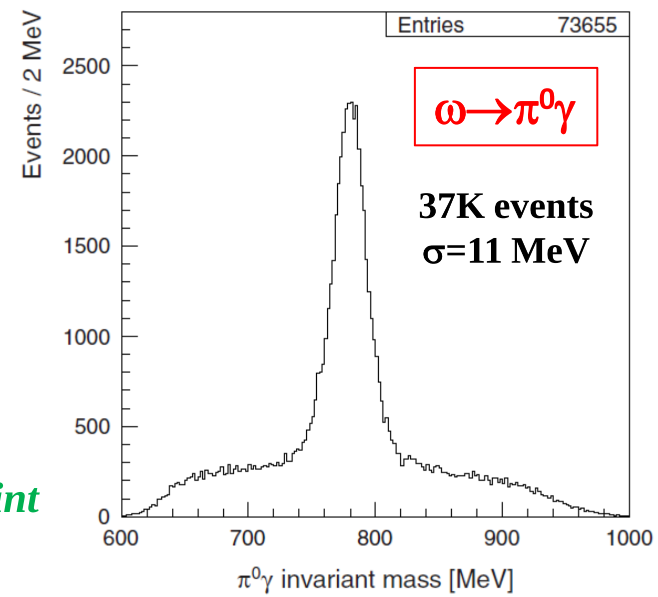
12 spin amplitudes ⇒ Many observables ($d\sigma/d\Omega$, $\Sigma$, $\rho_{\lambda_V\lambda'_V}$, …)

**BGOegg experiment**

$\gamma p \to \omega p$

$\omega \to \pi^0\gamma$ (Br=8.35%)

$\to 3\gamma$

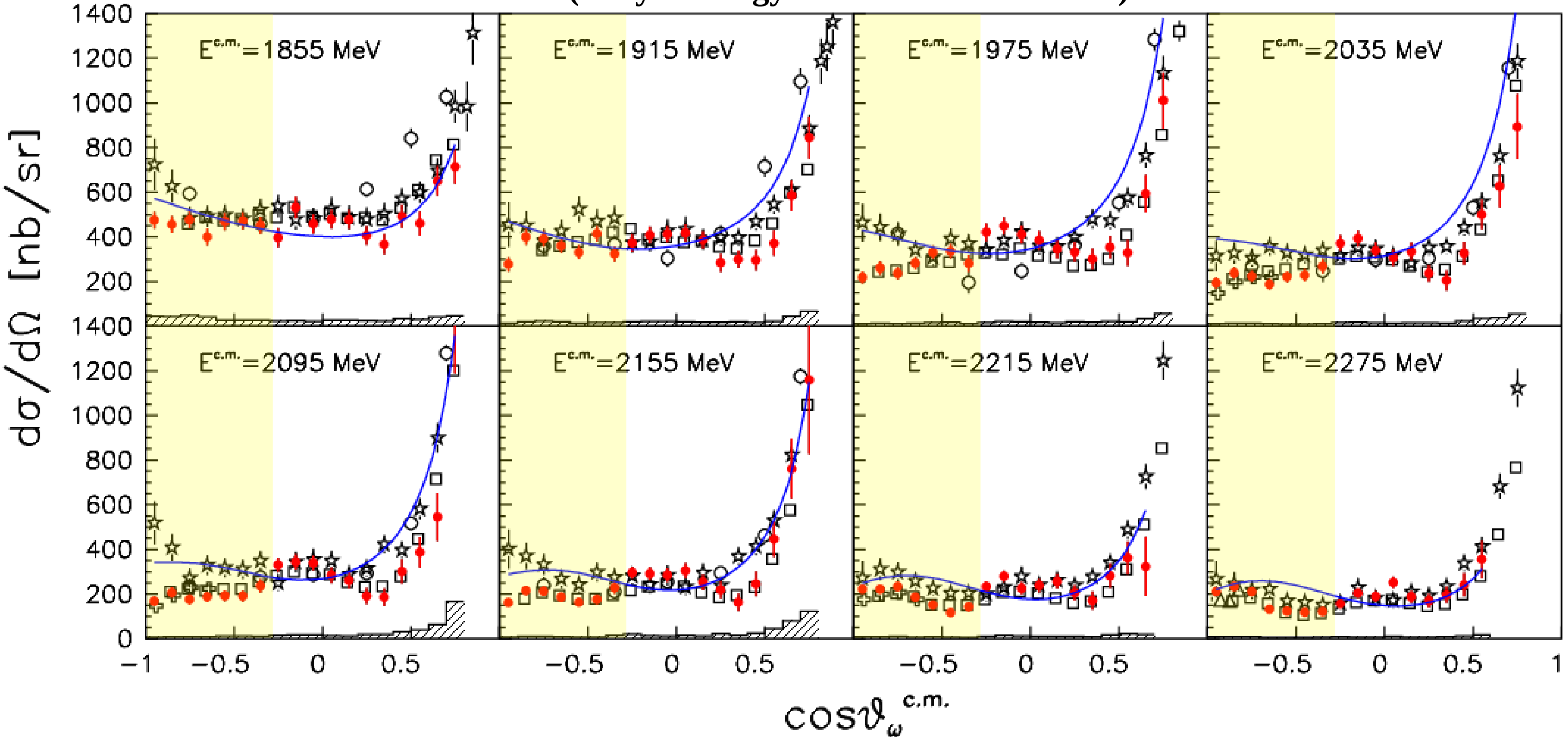



*Kinematic fit w/ 4-momentum conservation & $\pi^0$ mass constraint*

# Differential Cross Section of γp→ωp

**17 energy bins** for $1810<\sqrt{s}<2320$ MeV & **18 polar angle bins** for $-1.0<\cos\theta_{\omega}^{CM}<0.8$

**(Only 8 energy bins are shown below.)**

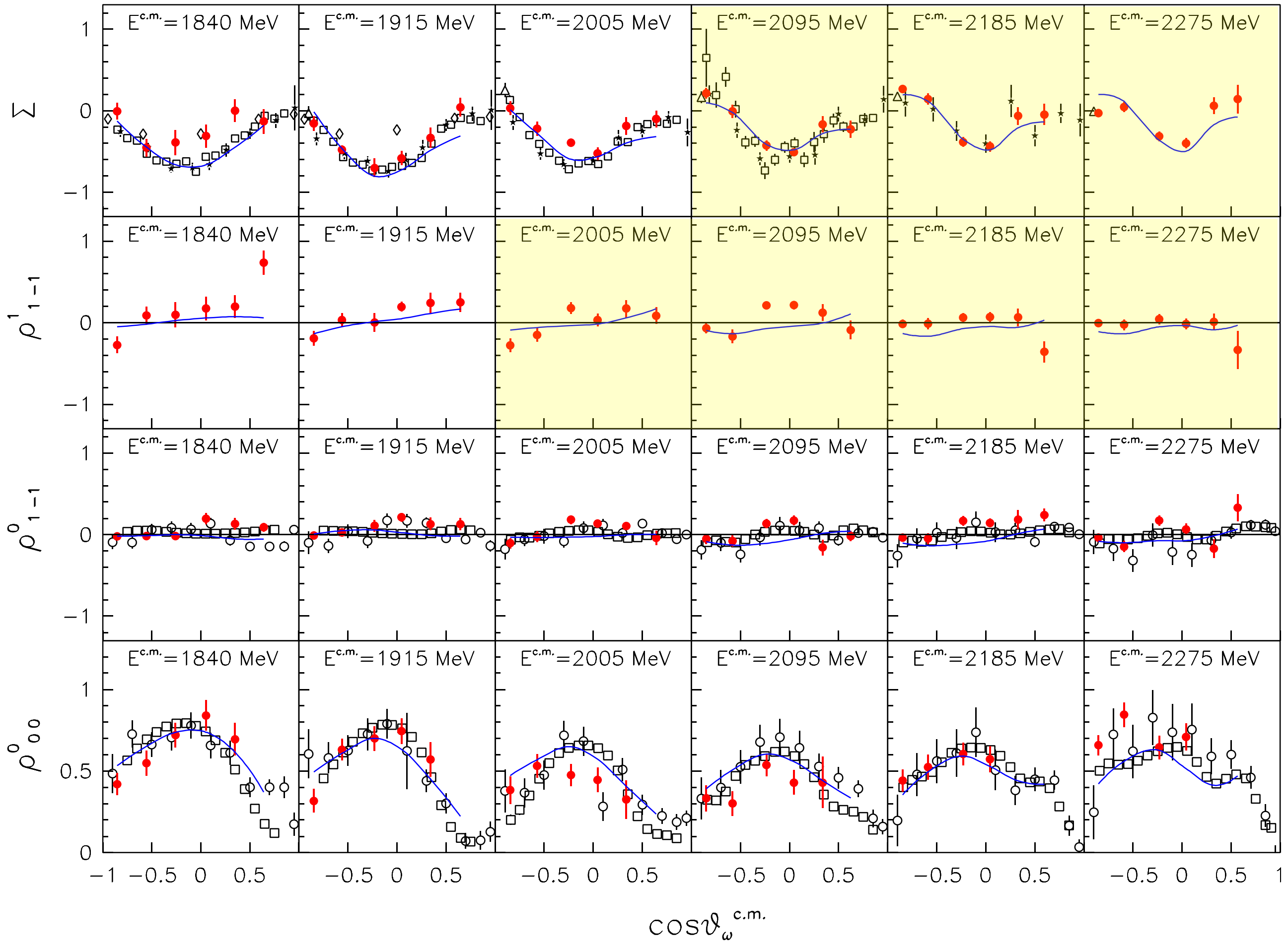



● **BGOegg [PRC102 (2020) 025201]**
○ **CBELSA [EPJA 51(2015) 6]**
✞ **LEPS [PRC80 (2009) 052201R]**
□ **CLAS [PRC80 (2009) 065208]**
☆ **CBELSA [PLB749 (2015) 407]**
△ **LEPS-TPC [PTEP2015 013D01]**
— **BG2019 [K. Nikonov & A Sarantsev, Private communication; PLB 755 (2016) 97]**

**Inconsistencies at backward angles** among experiments, affecting the existing PWA solution.

# $\Sigma$ and SDME of $\gamma p \to \omega p$

**6 energy bins** for $1810<\sqrt{s}<2320$ MeV & **6 polar angle bins** for $-1.0<\cos\theta_{\omega}^{CM}<0.8$




**For $\Sigma$**

- ● **BGOegg [PRC102 (2020) 025201]**
- □ CLAS [PLB 773 (2017) 112]
- ★ CLAS-FROST [PRC 97 (2018) 055202]
- ◇ GRAAL [PRC 91 (2015) 065207]
- △ LEPS-NTPC [PTEP2015 013D01]

— **Bonn-Gatchina (BG2019)**
[K. Nikonov & A. Sarantsev, Private communication; PLB 755 (2016) 97]

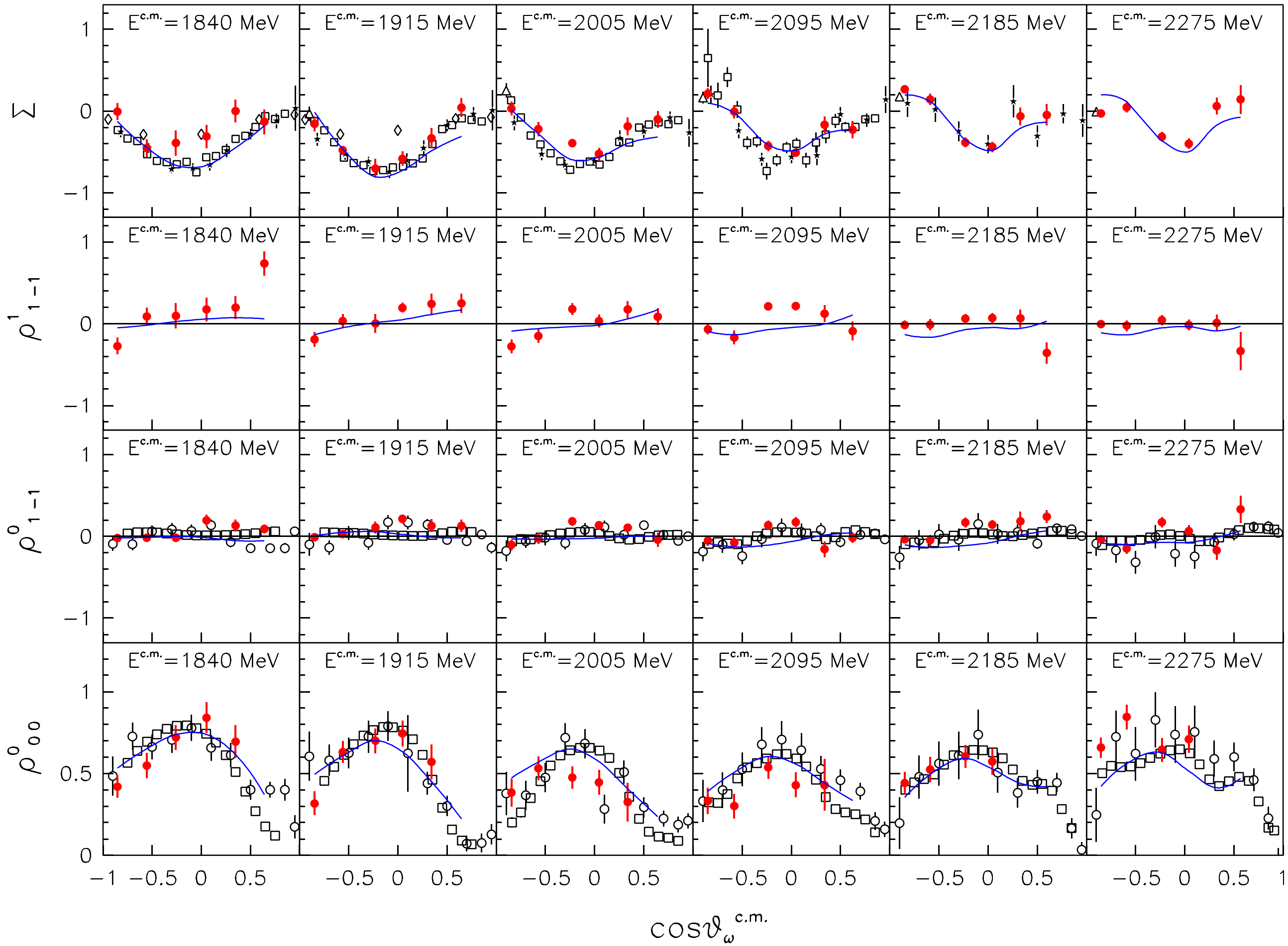
**For SDME**

- ● **BGOegg [PRC102 (2020) 025201]**
- □ CLAS [PRC 80 (2009) 065208]
- ○ CBELSA [PLB749 (2015) 407]

New measurements for **$\Sigma$ (W>2.1 GeV)** & **$\rho^1_{1-1}$ (W>2.0 GeV).**
Small values of $|\rho^1_{1-1}|$ indicate **stronger contributions of *s*-channel**.

# Σ and SDME of $\gamma p \to \omega p$

**6 energy bins** for $1810<\sqrt{s}<2320$ MeV & **6 polar angle bins** for $-1.0<\cos\theta_{\omega}^{CM}<0.8$




**For Σ**

- ● **BGOegg [PRC102 (2020) 025201]**
- □ CLAS [PLB 773 (2017) 112]
- ★ CLAS-FROST [PRC 97 (2018) 055202]
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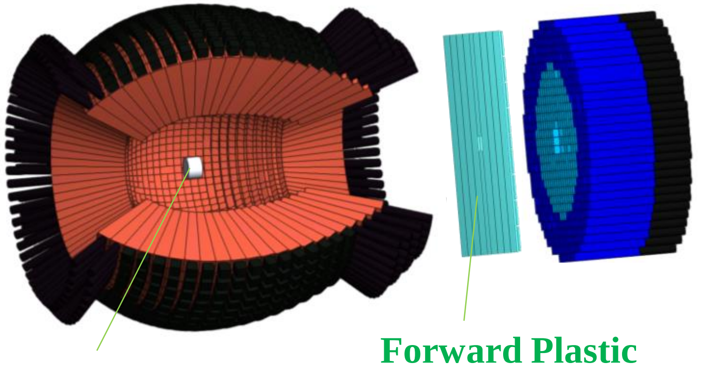
New measurements for **Σ (W>2.1 GeV)** & **$\rho^1_{1-1}$ (W>2.0 GeV).**
Small values of $|\rho^1_{1-1}|$ indicate **stronger contributions of *s*-channel**.
A current PWA solution more or less reproduces data points.

# Summary & Prospects

- Spring-8 LEPS2/BGOegg experiment is unique for the spectroscopy of light baryon resonances because of the **high linear polarization** of a photon beam at **$1.3 < E_\gamma < 2.4$ ($1.82 < W < 2.32$) GeV**. In addition, precise data are newly given for **extremely backward angles**.
- The $d\sigma/d\Omega$, $\Sigma$, and SDME for the reactions $\gamma p \to \pi^0 p$, $\eta p$, $\eta' p$, $\omega p$ have been measured as shown today. The statistics is being **twice** by using unanalyzed data.
- **Phase-II experiment** has just started. (In-medium $\eta'$ mass study)




(1) **Liquid deuterium (neutron) target** : Isospin structure of baryon resonances.

(2) **Double-meson photoproduction** : High-mass resonance search. Require polarization observables in 3-body kinematics. [cf. **EPJA50 (2014) 74**.]