Beam asymmetries of $\pi^0\eta$ photoproduction off protons

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Outline

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- § BGOegg experiments
- § Beam asymmetries of $\pi^0\eta$ photoproduction
  - Motivation
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Why photoproduction?

Hadron spectroscopy

-Still many quark models predicted resonances are missing for excited baryons (W>2 GeV)

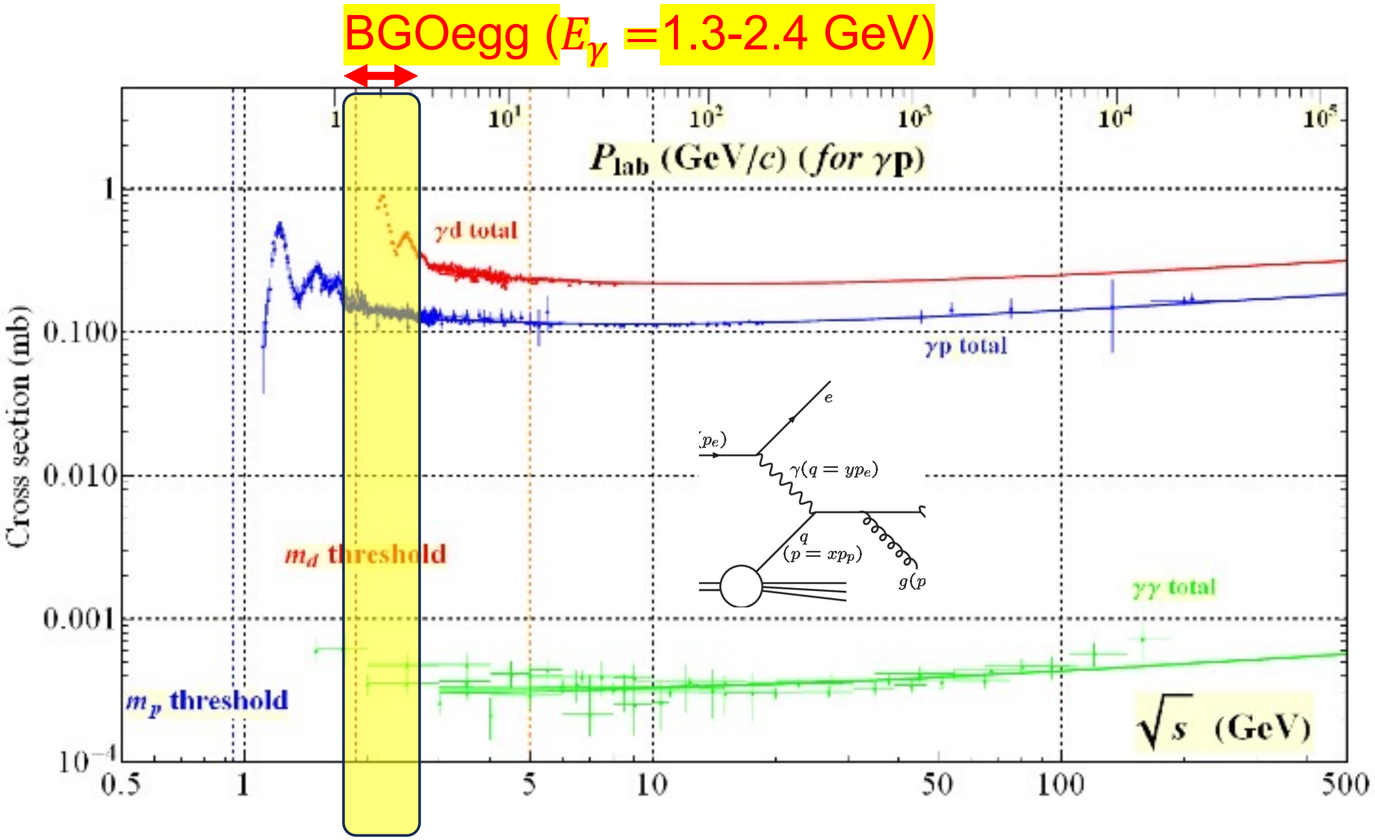
-Mass ordering problem (e.g. N(1440) and N(1535))

GeV Photon probe is promising for searching these missing resonances

Meson photoproduction

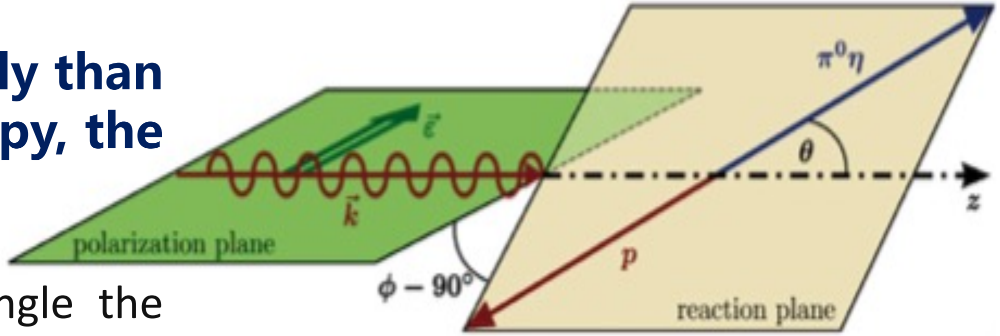
$\gamma N \to N^* or \Delta^* \to$ mesons N for light baryon spectroscopy

-Short-lived resonances are overlapped with each other



Beam asymmetries| Motivation

In meson spectroscopy, more states are found experimentally than are expected from a $q\bar{q}$ scheme. While in baryon spectroscopy, the situation is reverse (missing baryon resonances problem).



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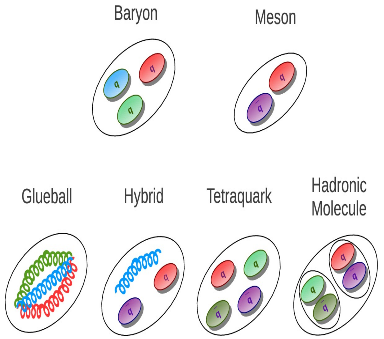
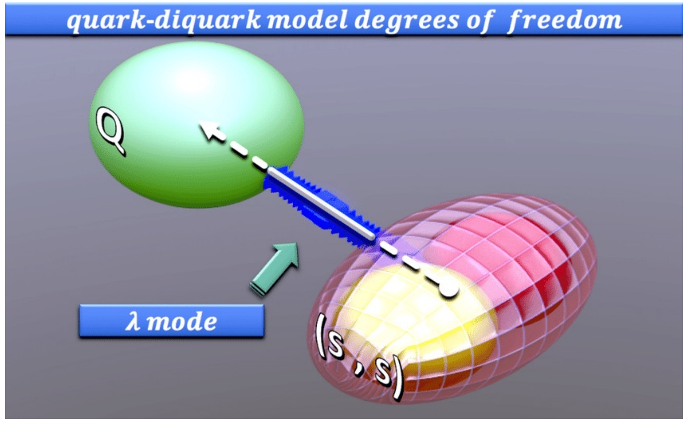
Polarization observables are important in photoproduction to disentangle the multitude of contributing resonances.



Linearly polarized photons induced photoproduction of single mesons shows a cos 2ϕ dependence. Three body polarization observables I^s, I^c **is highly sensitive** to the dynamics of the reaction (intermediate resonance decay properties).

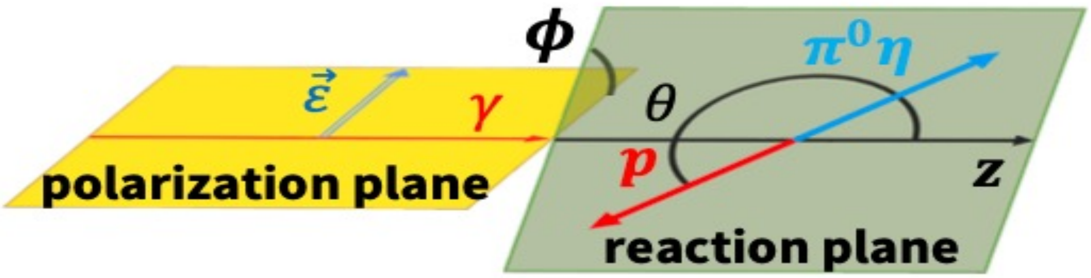
Baryon resonances can be **generated dynamically from** the interaction of pseudoscalar or vector **mesons** and ground- state octet or decuplet **baryons**.

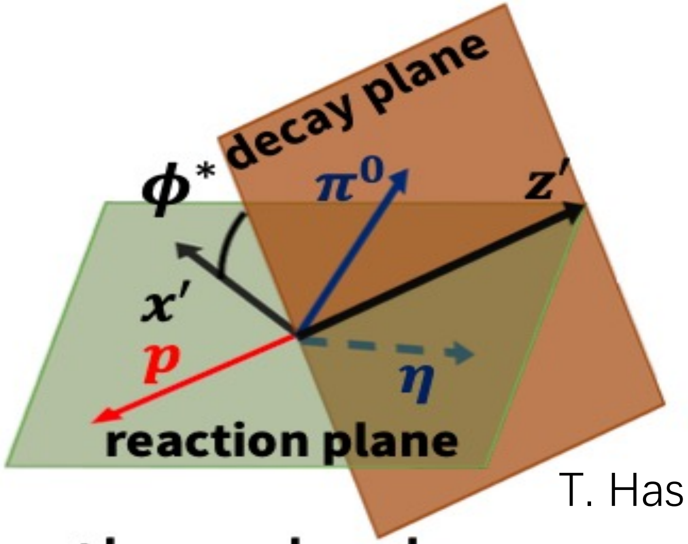
Three-body dynamics of a **full quark model** or a **quark-diquark** picture (one of the constituent particles of a baryon can be regarded as a quark and the other particle can be considered as a tightly bound state of two quarks, or diquark).



arXiv:1811.01799v2

$\gamma p \to \pi^0 \eta p$ beam asymmetries





T. Hashimoto, Baryons2025

Quasi two body approach: 1)p − ($\pi^0\eta$); 2) π^0 − (ηp); 3) η − (π^0p)

Cross section $\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 - P\Sigma cos2\phi)$

P: *degree of polarization of photon beam*

Fit: $f(\phi) = A + P \cdot B \cdot cos2\phi$

Beam Asymmetry: $\Sigma = B/A$

Three-body approach : I^c, I^s

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P(I^c(\phi^*)cos2\phi + I^s(\phi^*)sin2\phi)\right)$$

Fit: $f(\phi) = A - P(Bcos2\phi + Csin2\phi)$

$I^c(\phi^*) = I^c(2\pi - \phi^*)$ $I^s(\phi^*) = -I^s(2\pi - \phi^*)$

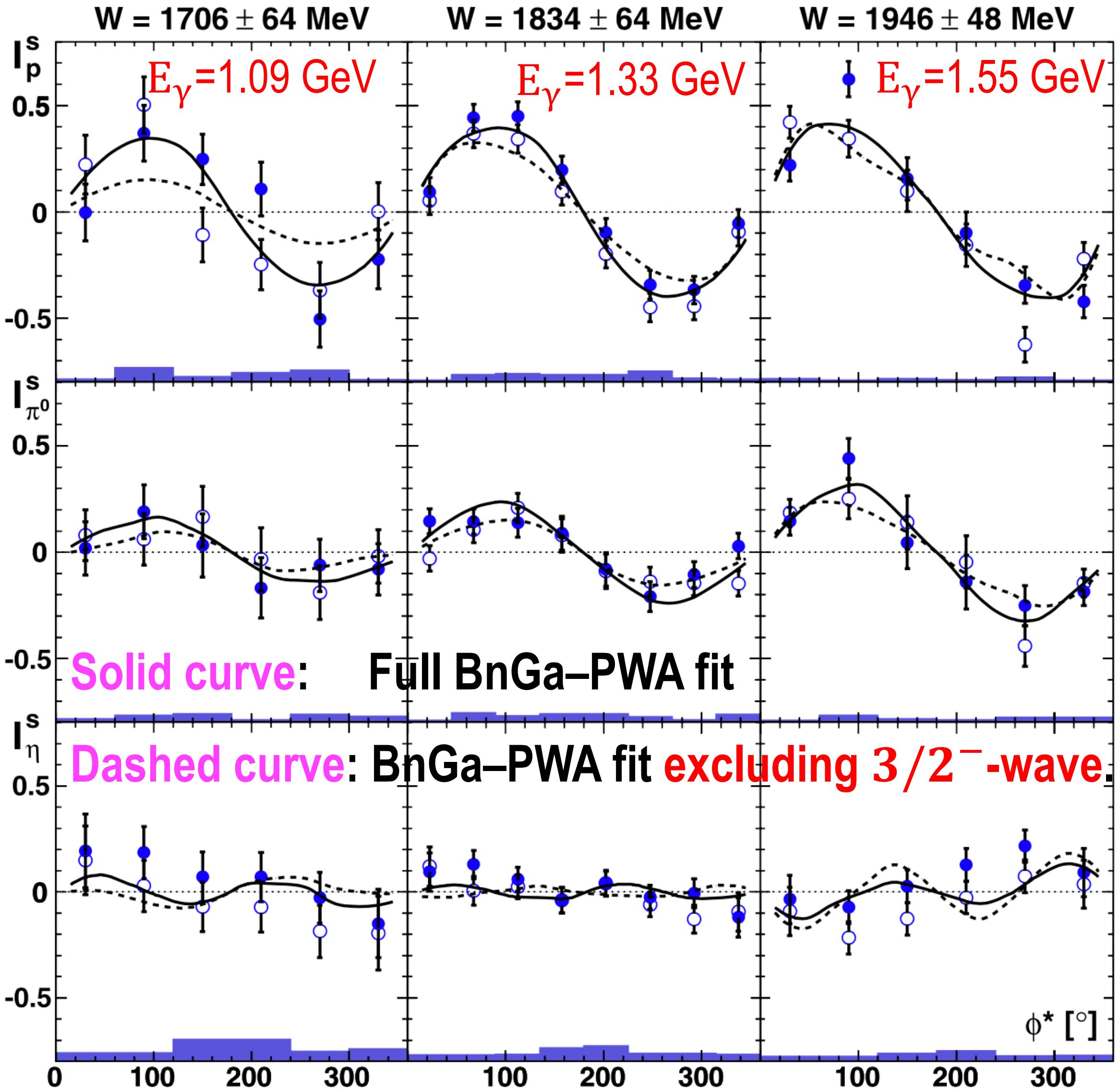
I^c =B/A I^s = C/A

I^s and I^c are sensitive to **interference effect**, and the relative phase of the amplitudes.

Beam asymmetries| Motivation

The CBELSA/TAPS Collaboration   Physics Letters B 687 (2010) 11–15

$\gamma p \rightarrow \pi^0 \eta p$ I^s and I^c observables



Excluding I^s and I^c in fitting:

Claimed evidence for contributions from negative- and positive-parity resonances with spin J = 3/2, the Δ(1700) and Δ(1940) (poorly established so far, one-star) resonances with $J^P = 3/2^-$, and the established Δ(1600) and Δ(1920) (three-star) resonances with $J^P = 3/2^+$.

***Including* I^s and I^c in fitting:**

Through comparing the $3/2^+$-wave and $3/2^-$-wave contributions to $\pi^0\eta p$, it is found removing the $3/2^-$-wave which includes the resonances Δ(1700) and Δ(1940) leads to noticeable discrepancies in the fits.

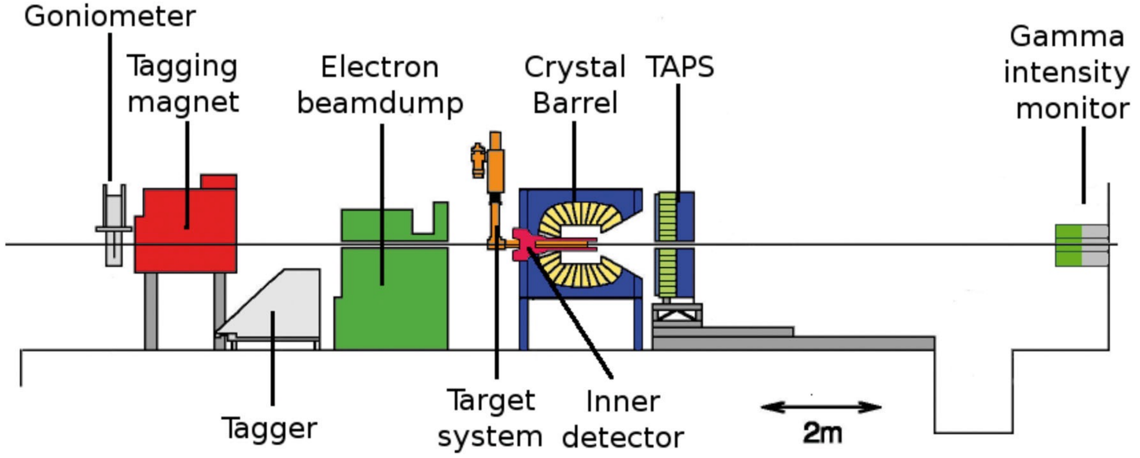
parity doublet? Δ(1940) and Δ(1920)

Beam asymmetries| Motivation

The CBELSA/TAPS Collaboration Eur. Phys. J. A (2014) 50: 74

High statistic study of the reaction $\gamma p \to p\pi^0\eta$

Polarized beam energy up to ~1.7 GeV



BnGa PWA confirms some nucleon and Δ resonances (only fair evidence so far)

Change in χ^2 of the multi-channel fit when the coupling of a resonance to different decay modes is set to zero and the data refitted.

	$\Delta(1232)\eta$	$N(1535)1/2^-\pi$	$pa_0(980)$
$N(1710)1/2^+$	–	656	–
$N(1880)1/2^+$	–	23	166
$N(1900)3/2^+$	–	883	108
$N(2100)1/2^+$	–	323	156
$N(2120)3/2^-$	–	169	–
$\Delta(1700)3/2^-$	1333	263	–
$\Delta(1900)1/2^-$	198	–	–
$\Delta(1905)5/2^+$	328	337	–
$\Delta(1910)1/2^+$	1195	–	–
$\Delta(1920)3/2^+$	273	–	204
$\Delta(1940)3/2^-$	1545	162	–
$\Delta(1950)7/2^+$	476	–	–
ρ/ω exchange	849	–	696
p exchange	299	–	189

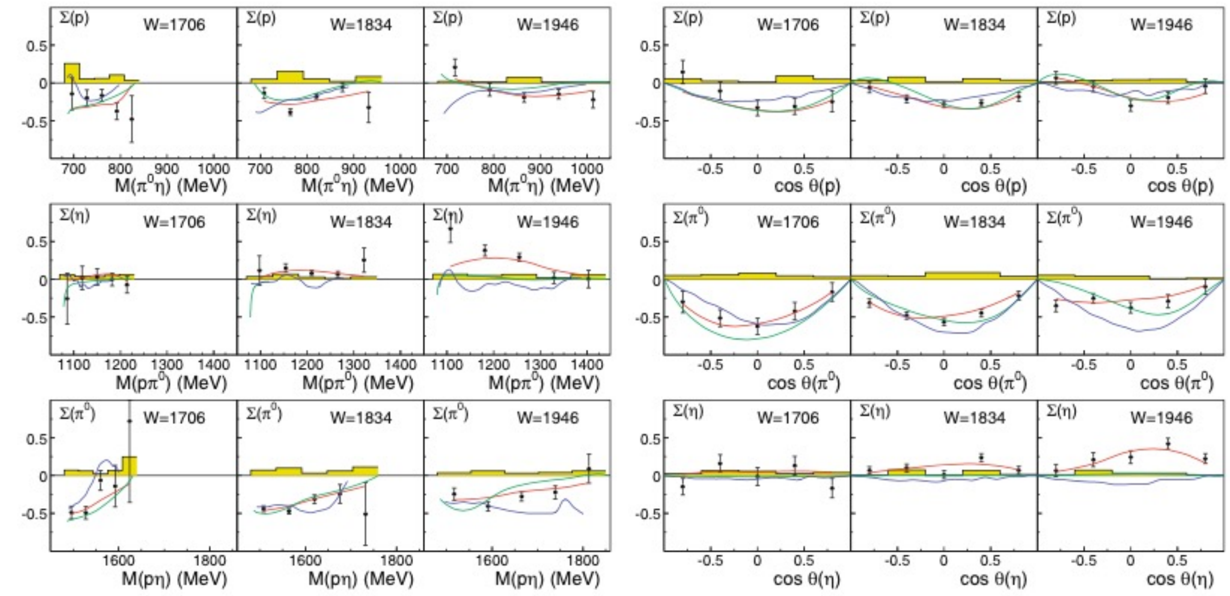


Fig. 31. Two-body beam asymmetry Σ for the reaction $\gamma p \to p\pi^0\eta$. Top to bottom: incoming photon energy ranges 1085 ± 115 MeV, 1325 ± 125 MeV, 1550 ± 100 MeV. Left: asymmetries obtained from the ϕ distributions of the recoiling (left to right) p, η, π^0 as function of the invariant mass of the other two particles [67]. Right: The same as function of the $\cos\theta$ of the recoiling particle. Systematic error estimate from acceptance studies (yellow). Curves: BnGa-PWA (red), Fix *et al.* [69] (green), Döring *et al.* [50] (blue).

At W=1706 and 1834 MeV， Σ(η) is almost 0:

The strongest contributions come from the Δ(1232)η isobar with Δ(1232) and η in a relative S-wave

Beam asymmetries| Motivation

Polarized beam energy up to ~1.7 GeV

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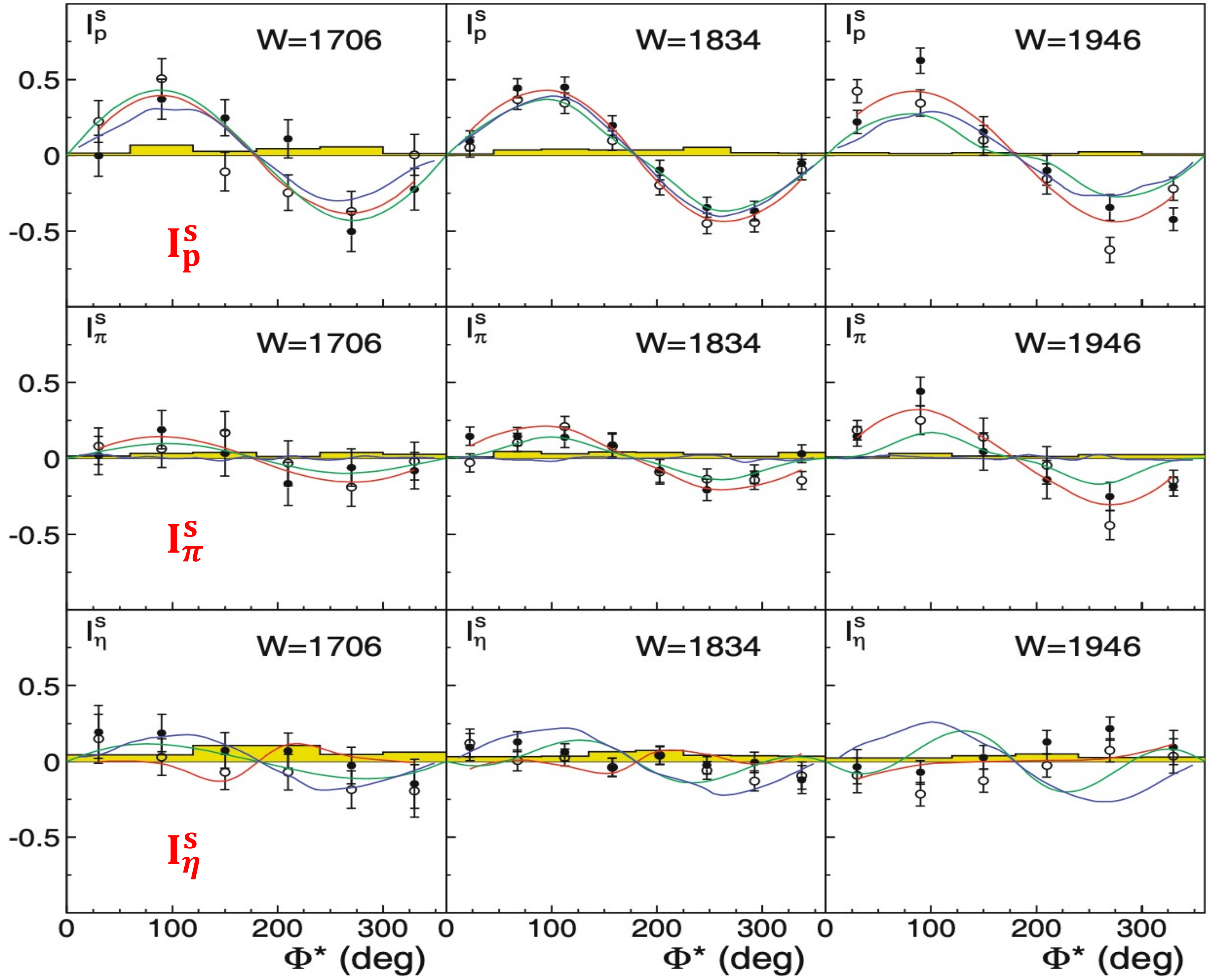


- I_p^s, I_π^s and I_η^s obviouly oscillate with ϕ^*, indicating interference effects.
- The magnitude of I_p^s is large (~0.5), indicating large spin-alignment of the intermediate states

BGOegg experiment | setup

LEPS2/BGOegg Experiments

A large acceptance electromagnetic (EM) calorimeter BGOegg (Fig.1) was constructed at ELPH, Tohoku University. This calorimeter system has been transferred to the new laser Compton scattering beamline LEPS2 at SPring-8, where a 1.3-2.9 GeV photon beam with high linear polarization is available. The phase-1 experiments have started from 2014 April with the EM calorimeter BGOegg and the additional detectors for charged particles. We are now upgrading the experimental setup by covering most of the solid angles with EM calorimeters to start new data collection in the phase-2 experiments.

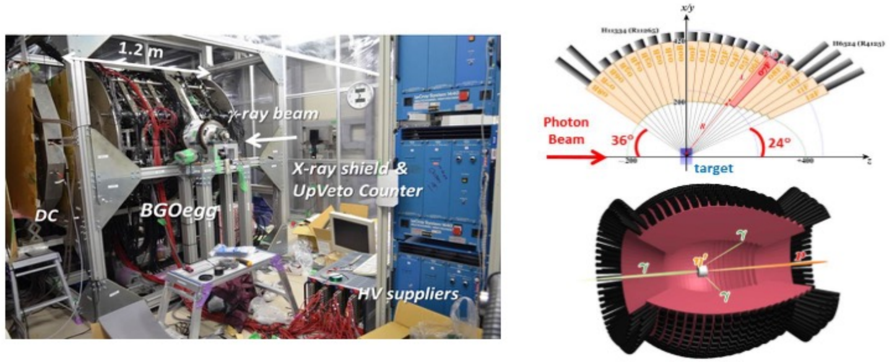


Fig.1 A picture of BGOegg inside the thermostatic booth (Left) and the drawings of BGOegg (Right).

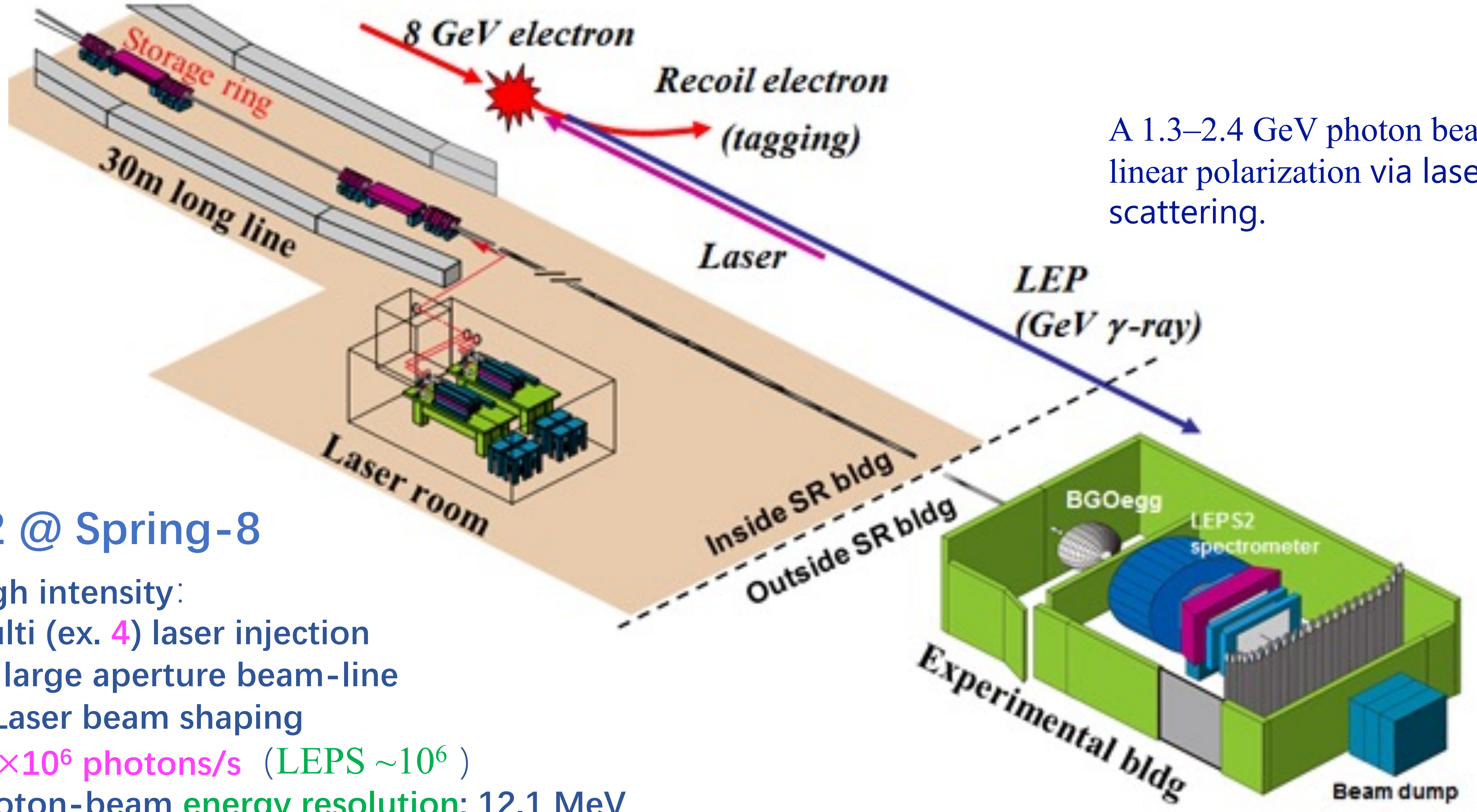
Physics

experiments, we are planning to upgrade the detector setup as shown in Fig.3. Instead of using DC and RPC, the forward acceptance hole of the BGOegg calorimeter will be covered by additional EM calorimeters. We install the "Forward Gamma" detector, which consists of 252 PWO crystals, in the polar angle range of 3 to 16 degrees. We are also considering to cover the gap region between the BGOegg calorimeter and the Forward Gamma detector. This configuration will significantly reduce backgrounds in the direct measurement of η'-mass spectral shape using a nuleus target.

Status

The LEPS2/BGOegg experiments are carried out under the collaboration of ELPH (Tohoku University), RCNP (Osaka University), Nanjing University of Aeronautics and Astronautics, Kyoto University, KEK, RIKEN, JASRI (SPring-8), and many other institutes in the world. ELPH and RCNP cooperate the LEPS2 facility.

BGOegg experiment | setup



A 1.3–2.4 GeV photon beam with high linear polarization via laser Compton scattering.

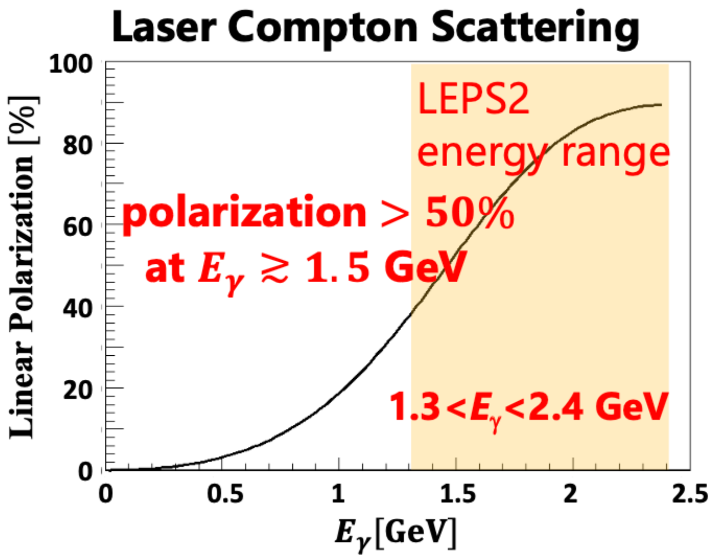
LEPS2 @ Spring-8

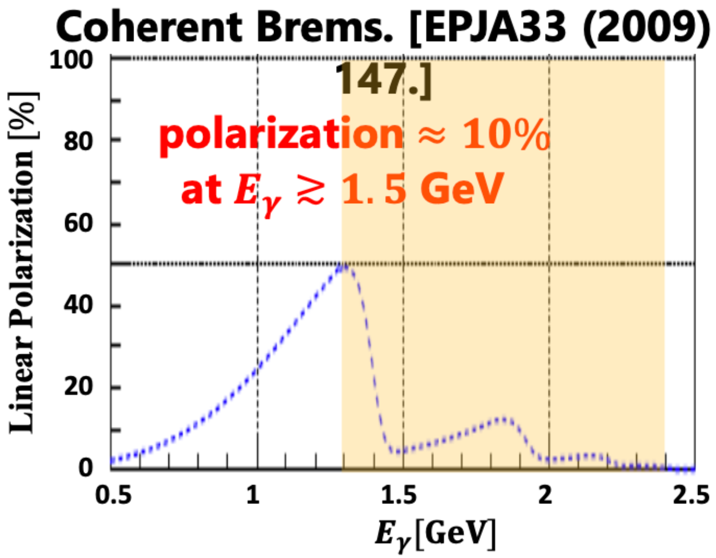
High intensity:
Multi (ex. 4) laser injection
w/ large aperture beam-line
& Laser beam shaping
~5×10^6 photons/s (LEPS ~10^6)
Photon-beam energy resolution: 12.1 MeV

BGOegg experiment | setup

A 1.3–2.4 GeV photon beam with high linear polarization via laser Compton scattering

- LEPS2 beam is generated via laser Compton scattering.
- Other experimental facilities(CLAS, ELSA...) use coherent bremsstrahlung as a photon beam.

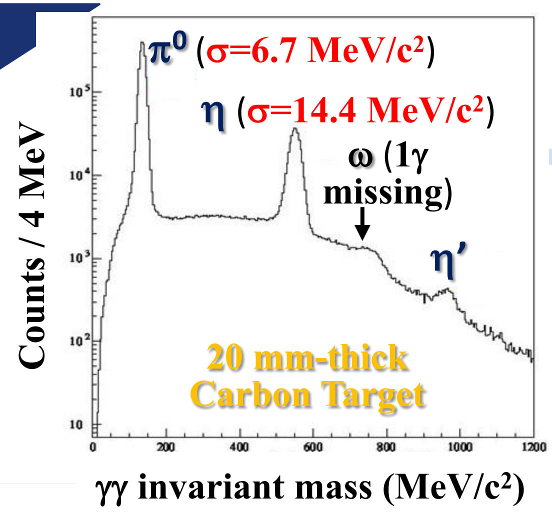


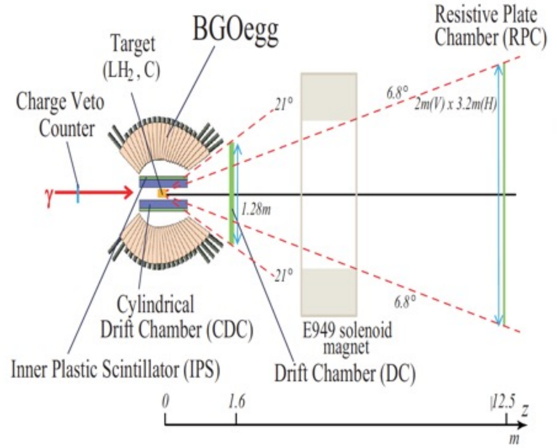


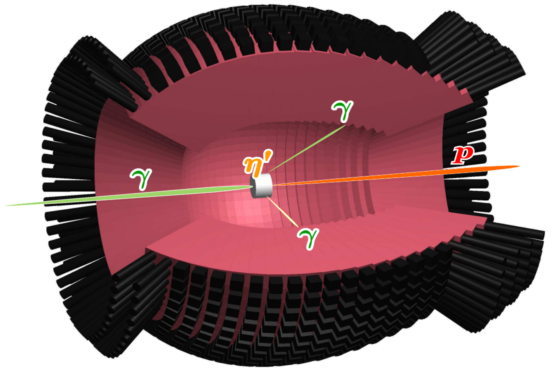
- LEPS2 beam polarization is **greater** than other experimental facilities at higher energies(**$E_\gamma \gtrsim 1.5$ GeV**).

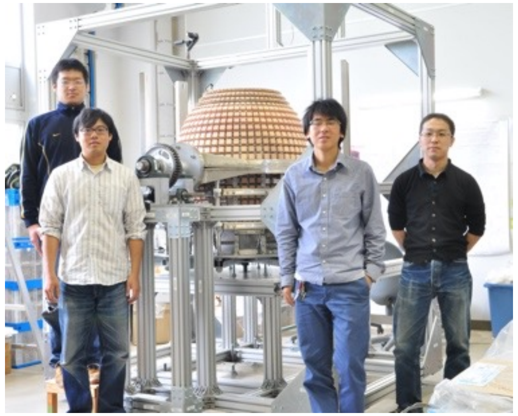
BGOegg experiment | setup

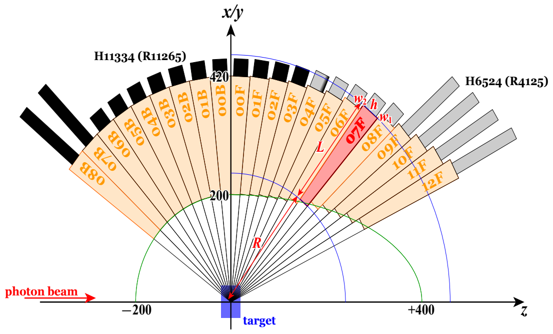
World leading energy resolution (carbon target)
π^0 mass resolution: 6.7 MeV/c^2;
η: 14.4 MeV/c^2)

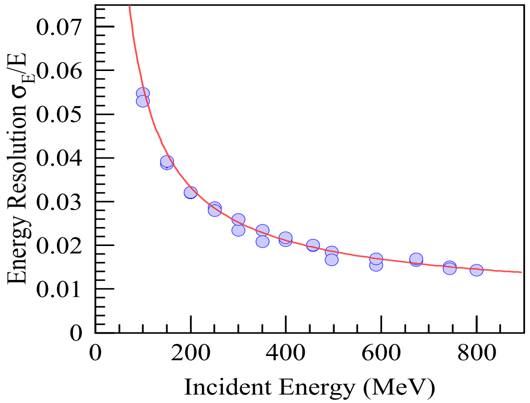


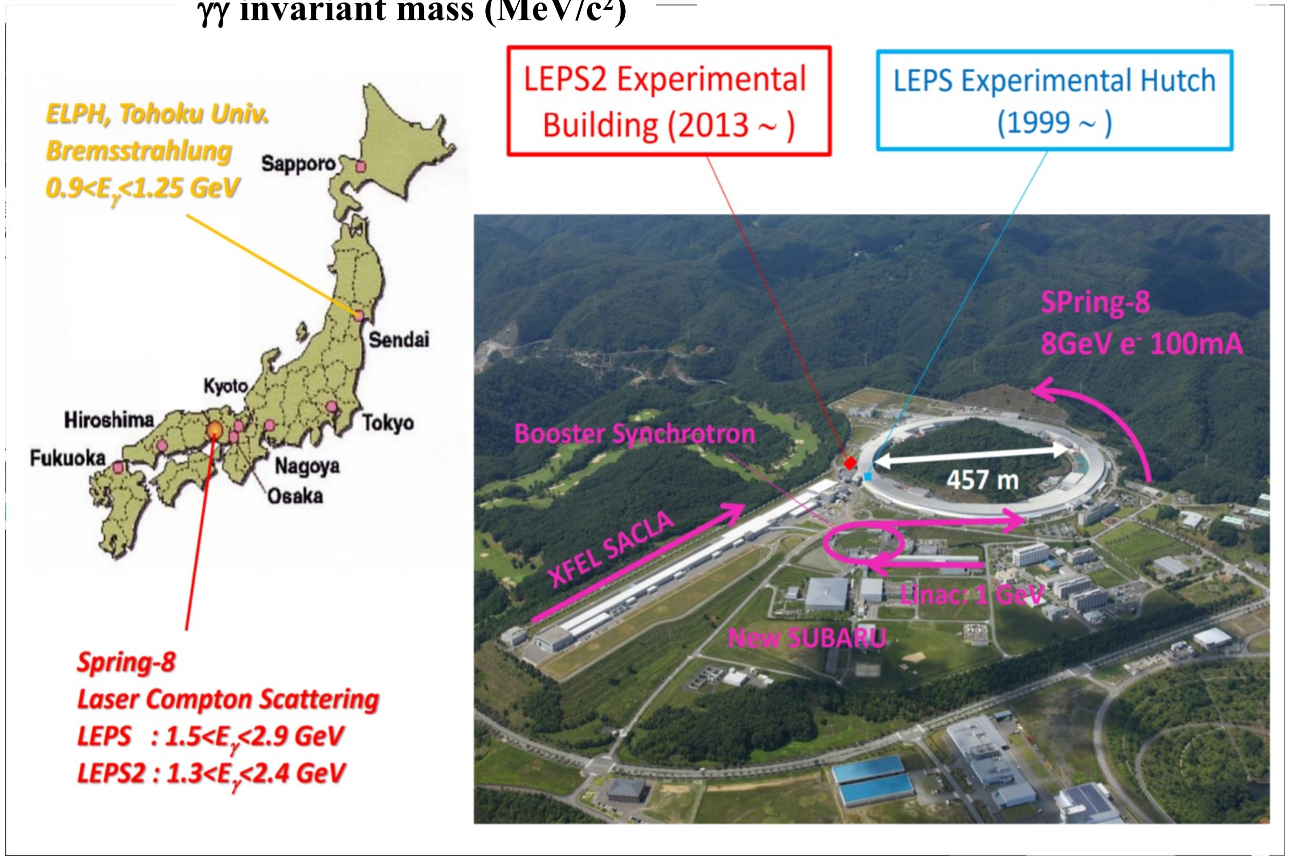












Target: LH2 (54mm) or Carbon (20 mm)

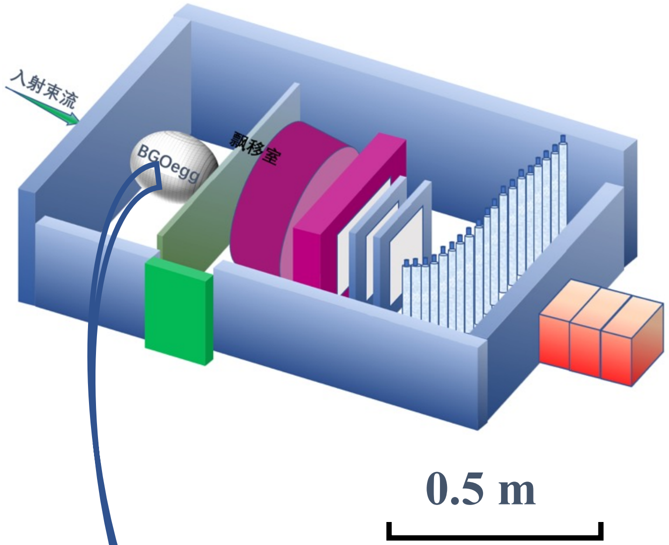
M. Miyabe, N. Muramatsu, H. Shimizu, et al., NIM paper in preparation.

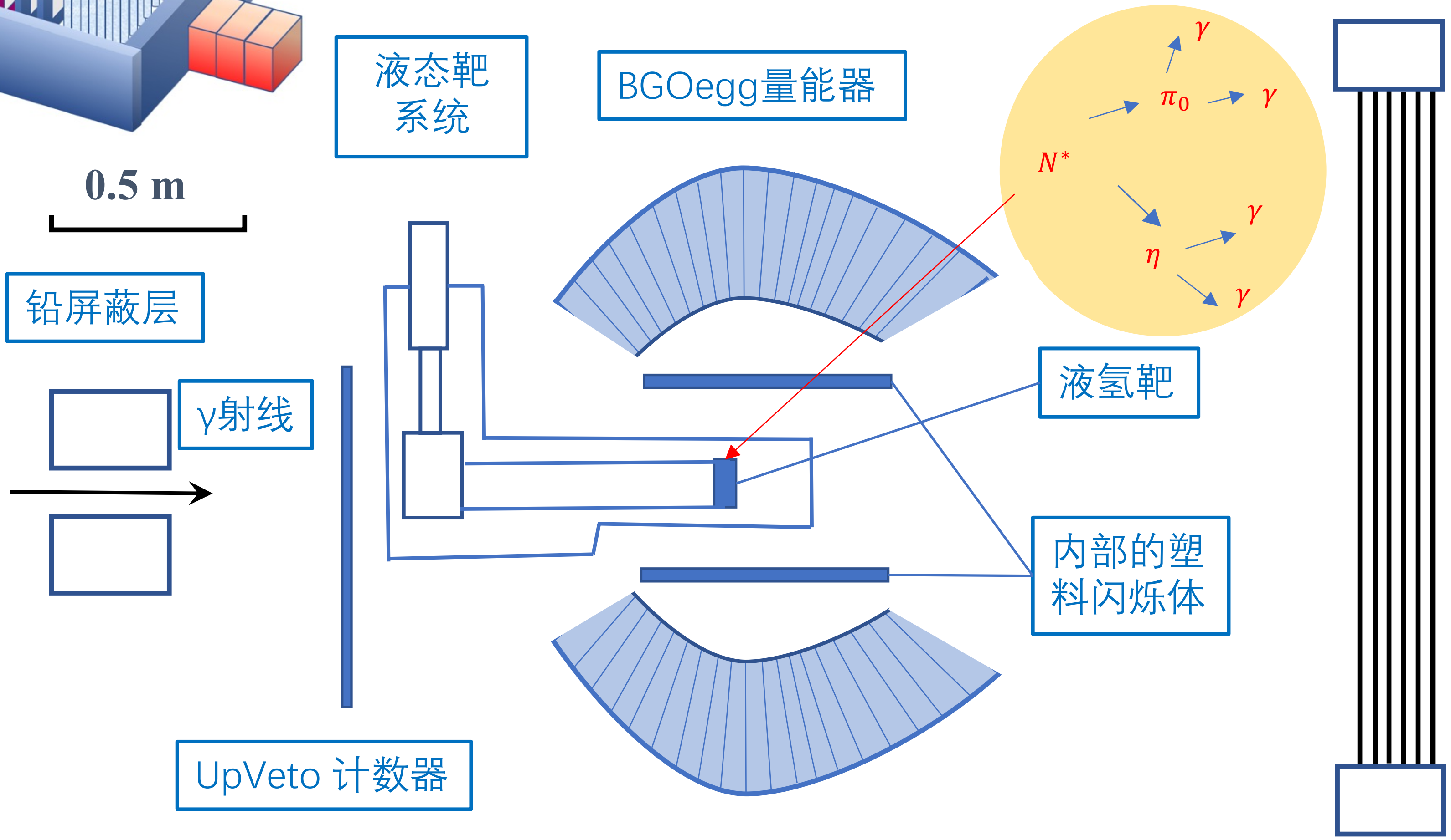
$\gamma p \rightarrow \pi^0 \eta p$ event selection

Polarized beam energy up to ~2.4 GeV

➢ $\pi^0\eta$光生反应实验

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





BGOegg

- 1320 BGOcrystals
- Polar coverage: 24°-144°
- EM cluster energy threshold: 30 MeV
- 2 hits $\Delta t < 2$ ns

Planner drift chamber

Polar coverage: $\theta < 21^\circ$

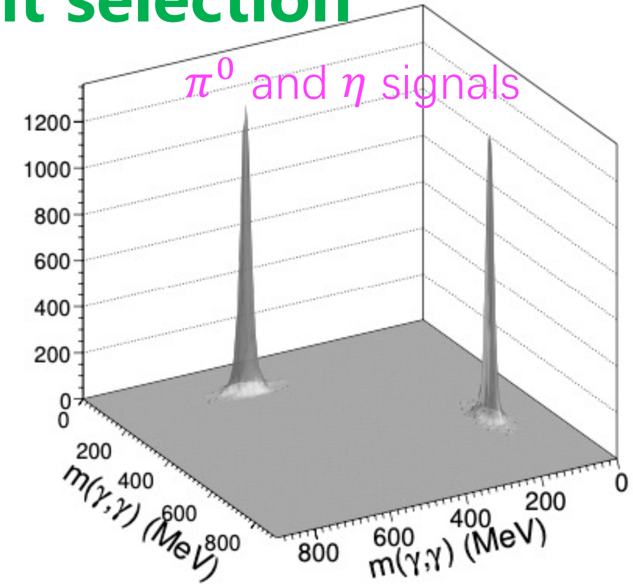
Tagged beam photons

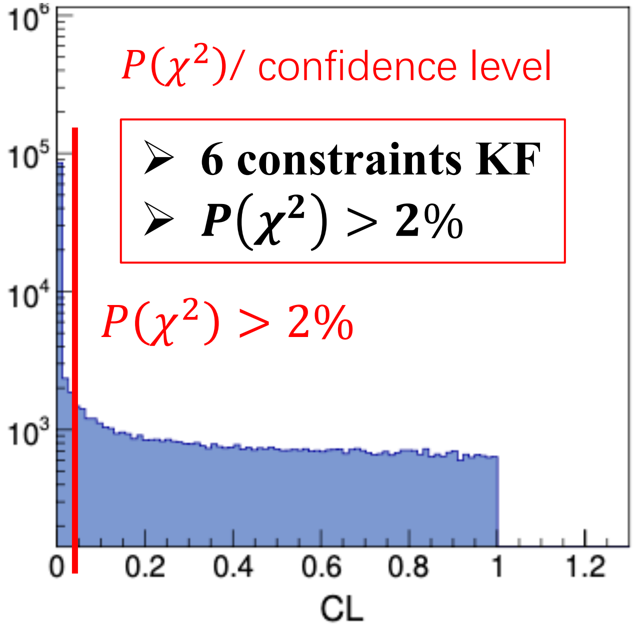
reaches 3.320×10^{12} with the correction for dead times.

4 neutral clusters

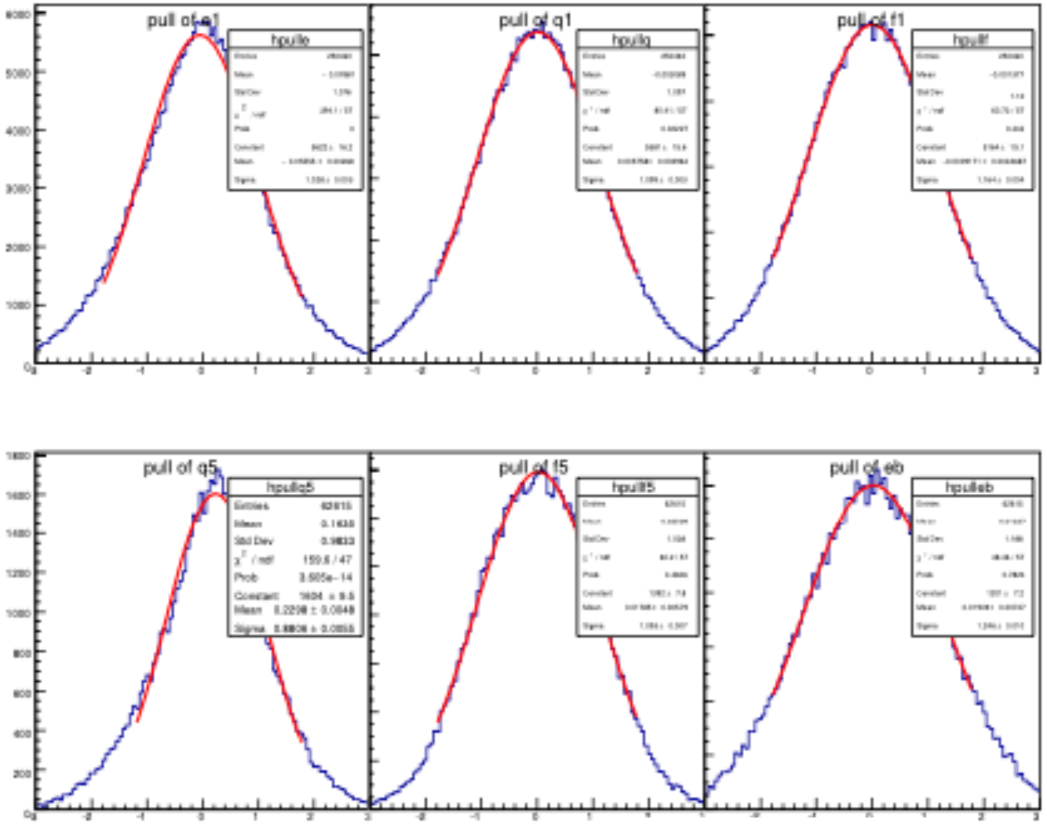
1 charged particle hit

Event selection





- **6 constraints KF**
- $P(\chi^2) > 2\%$



Kinematic fitting (6 constraints):

1-4: 4 momentum conservation

5: invariant mass of η

6: invariant mass of π^0

$$Pull_i = \frac{\epsilon_i}{\sigma(\epsilon_i)}$$

$$\epsilon_i = \eta_i - y_i$$

η_i: fit value

y_i: measued value

Background estimation ($\pi^0\pi^0\pi^0 p$)

Template fitting with constraints

Because the not full 4π coverage of the detector acceptance, $\pi^0\pi^0\pi^0 p$ will be mis-identified in the event selection.

To estimate the $\pi^0\pi^0\pi^0 p$ background, a template fitting with constraints is performed using the invariant mass spectra of $m(p,\pi)$, $m(p,\eta)$ and $m(\eta,\pi)$ in several kinematic bins:

(1)Constraints:

1)equality constraints: 1) normalitztion and 2) conservations in different quasi-two-body schemes

2)bound constraints: [0,1]

(2)Kinematic bins:

W: (1)W=1810-1980 MeV, (2) W=1980-2150 MeV, (3) W=2150-2320 MeV

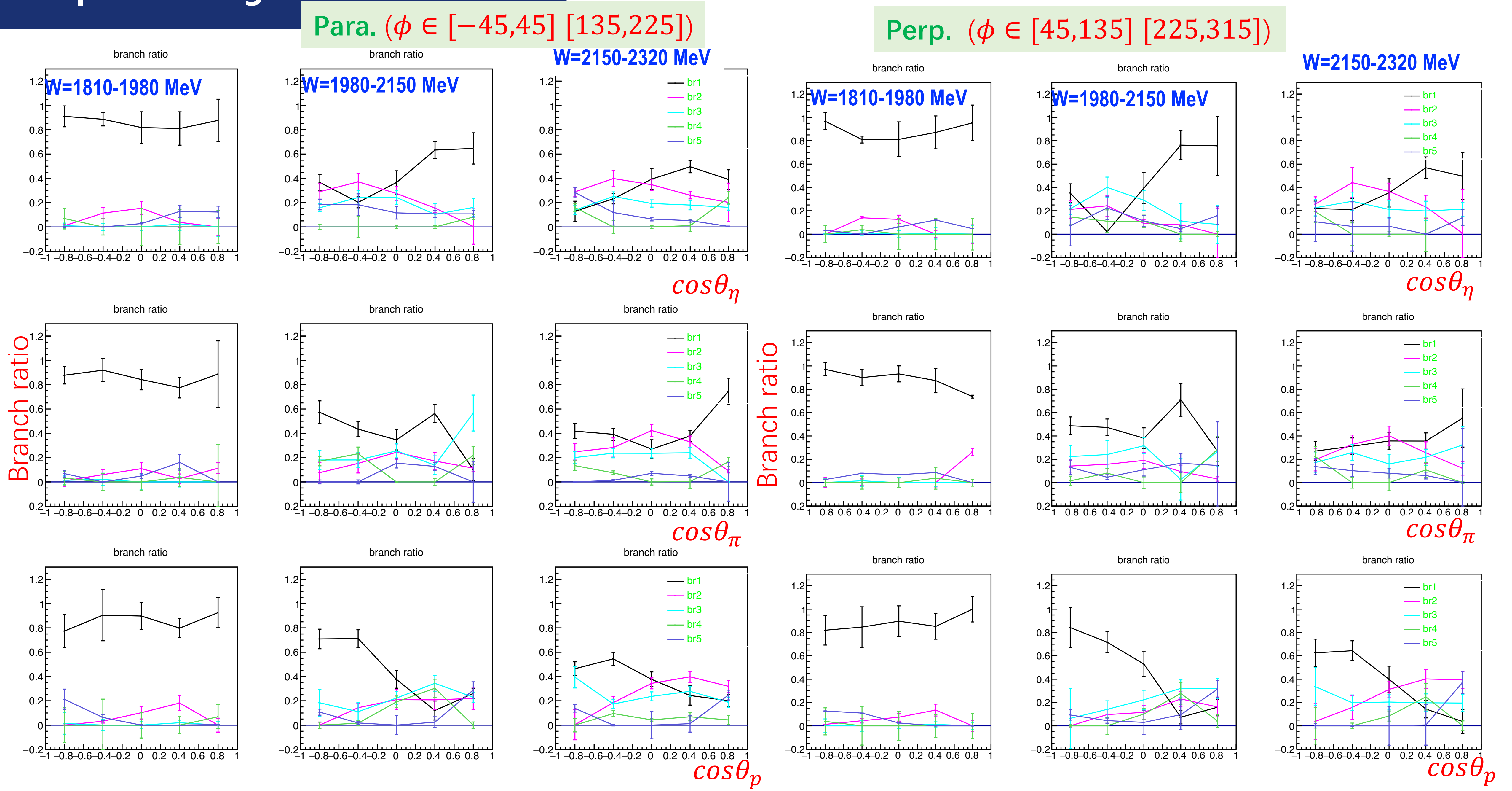
$\cos\theta$: 5 bins

(3) Branches:

br1) $\gamma p \to \eta\Delta$, br2) $\gamma p \to \pi^0 N(1535)$, br3) $\gamma p \to a_0(980)p$, br4)$\gamma p \to \pi^0\eta p$, br5) $\gamma p \to \pi^0\pi^0\pi^0 p$

Template fitting

br1) $\gamma p \to \eta\Delta$, **br2)** $\gamma p \to \pi^0 N(1535)$, **br3)** $\gamma p \to a_0(980)p$, **br4)** $\gamma p \to \pi^0\eta p$, **br5)** $\gamma p \to \pi^0\pi^0\pi^0$



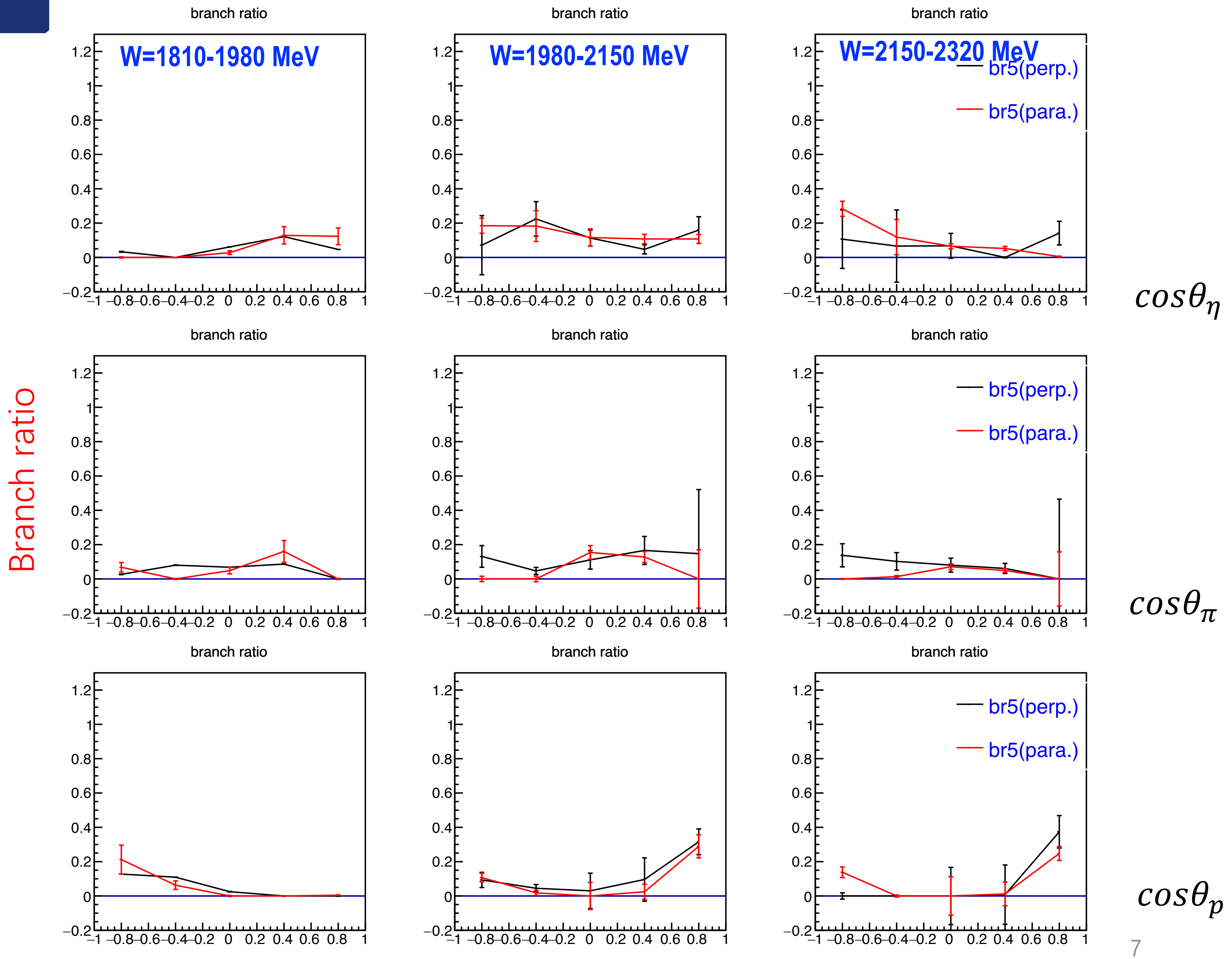
Template fitting

Difference in

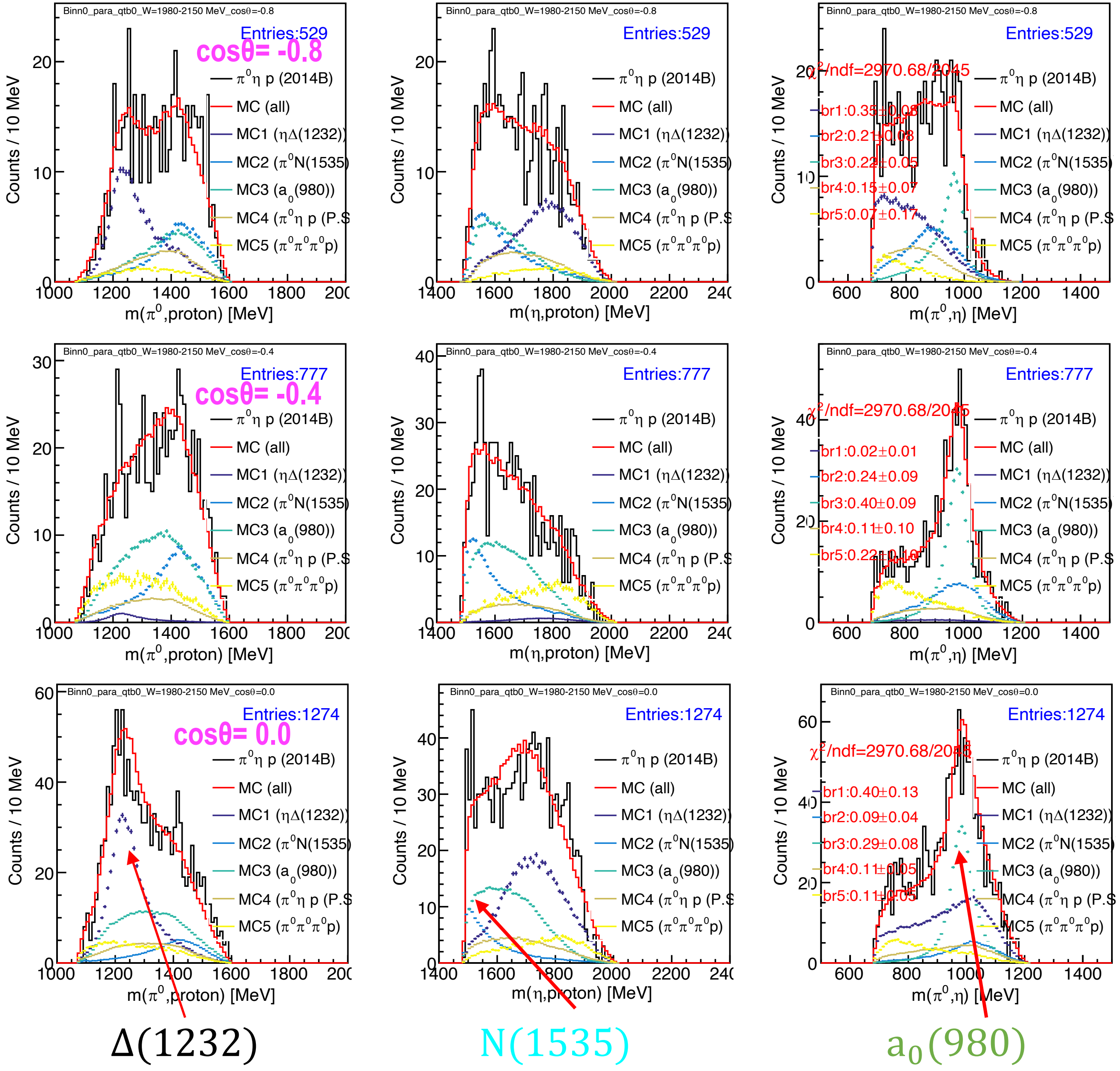
1) Para. ($\phi \in [-45,45]\ [135,225]$)
2) Perp. ($\phi \in [45,135]\ [225,315]$)

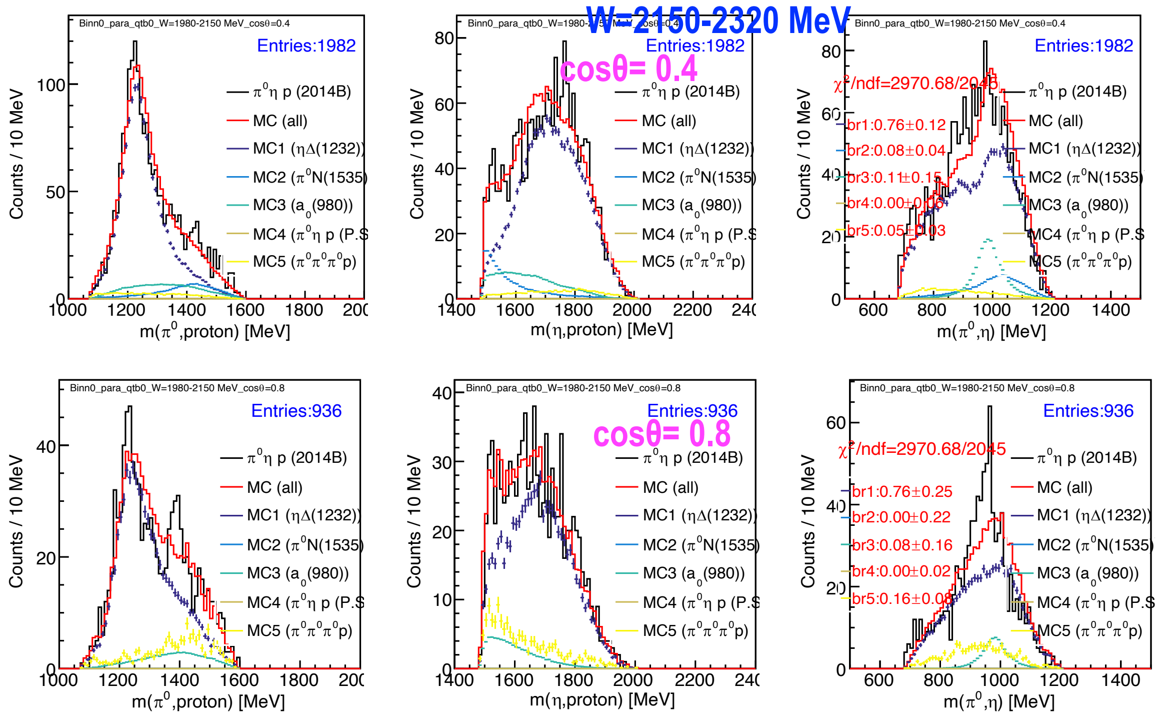
$\gamma p \rightarrow \pi^0\pi^0\pi^0 p$ background:

0%-20%



Template fitting



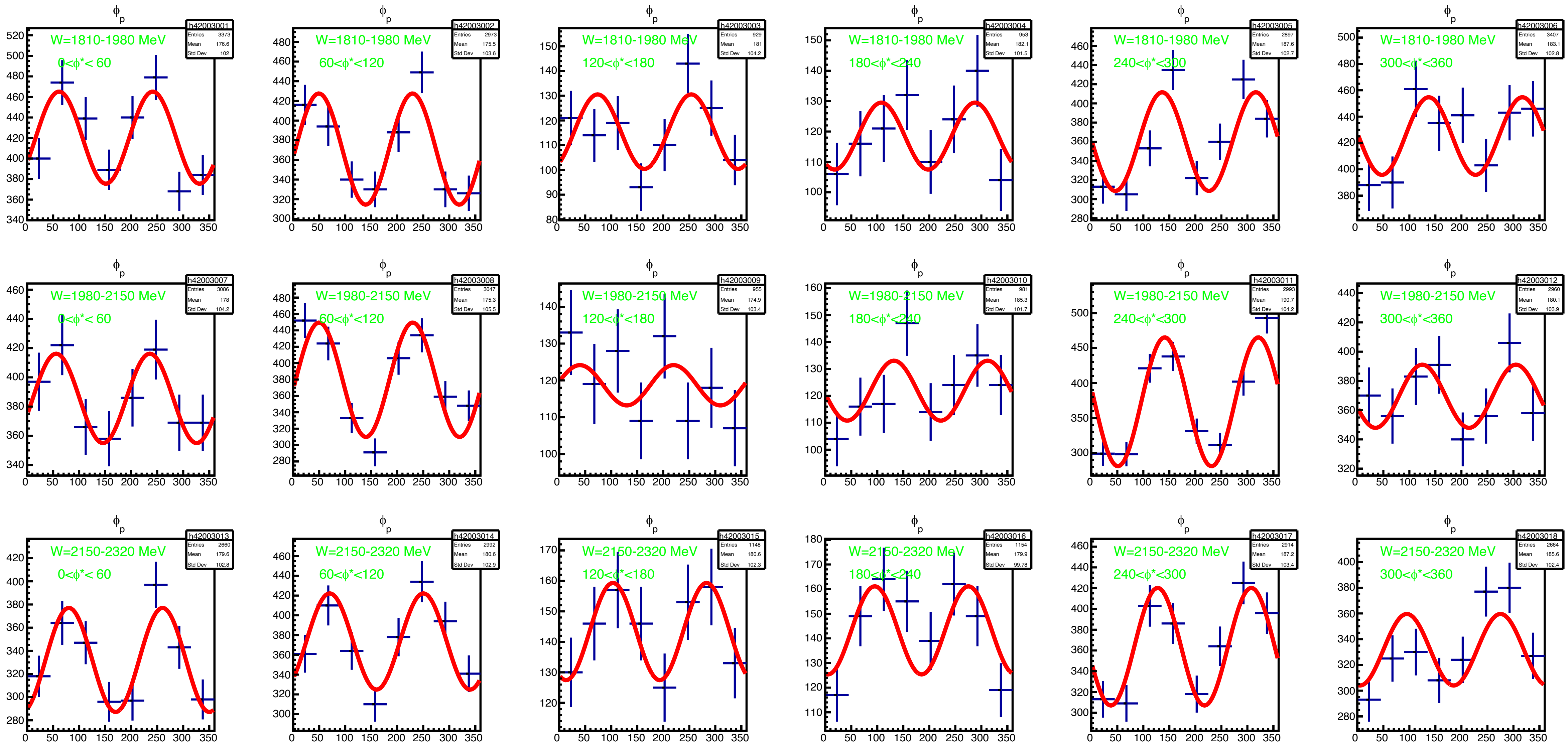


W=1980-2150 MeV
Para.
Quasi-two-body: eta-(pi0,proton)

$\gamma p \to \pi^0 \eta p$ beam asymmetries

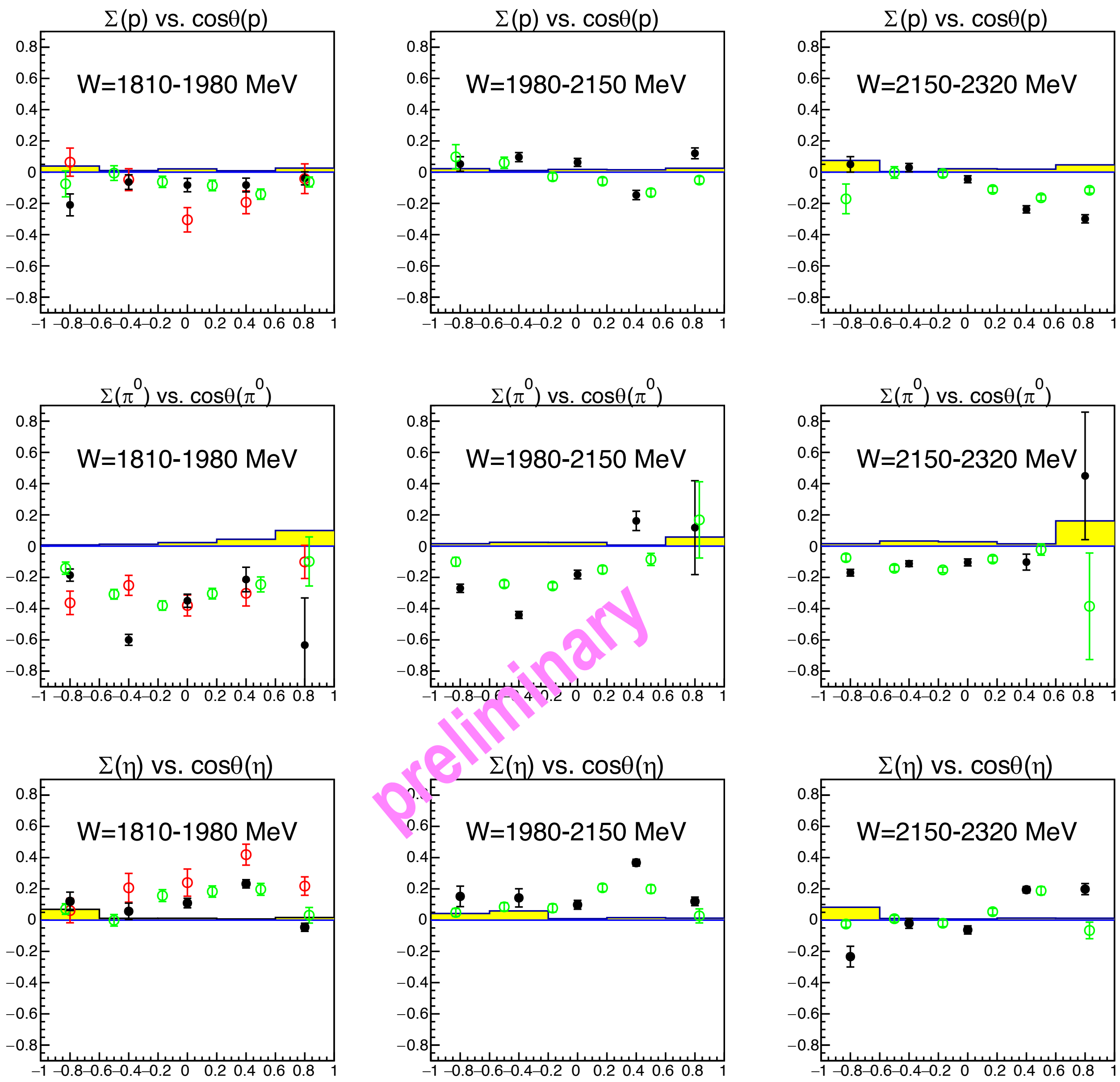
ϕ distributions binned in $\phi*$

Fit: $f(\phi) = A - P(B\cos2\phi + C\sin2\phi)$ I^c:B/A I^s: C/A



$\gamma p \rightarrow \pi^0 \eta p$ beam asymmetries

Two-body beam asymmetries $\Sigma(\cos\theta)$ of $\gamma p \rightarrow \pi^0 \eta p$



$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 - P\Sigma cos2\phi)$$

○ **CBELSA 2014** CBELSA: Eur. Phys. J. A (2014) 50: 74

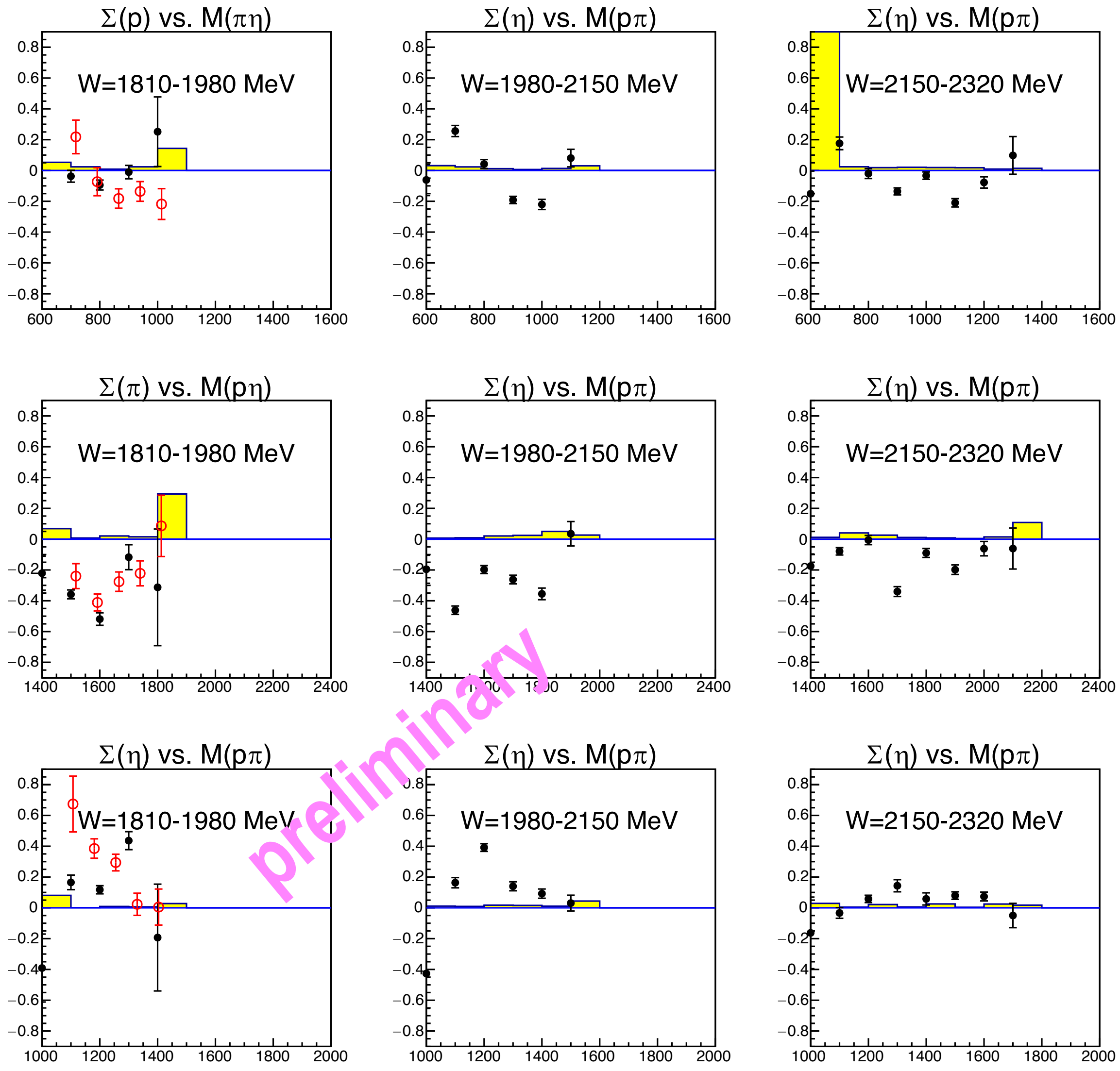
● **BGOegg 2014B**

Systematic error (acc. &CL)

- **$\Sigma(\mathrm{p})$: ~ 0**
- **$\Sigma(\pi)$: negative, Unnatural parity exchange (pseudoscalar meson exchange, π)**
- **$\Sigma(\eta)$: positive, Natural parity exchange (vector meson exchange, ρ)**
- **Σ data above W=1980 (E_γ~1.65 GeV) were measured for the first time**

$\gamma p \rightarrow \pi^0 \eta p$ beam asymmetries

Two-body beam asymmetries $\Sigma(\text{InvM})$ of $\gamma p \rightarrow \pi^0 \eta p$



○ **CBELSA 2014** CBELSA: Eur. Phys. J. A (2014) 50: 74

● **BGOegg 2014B**

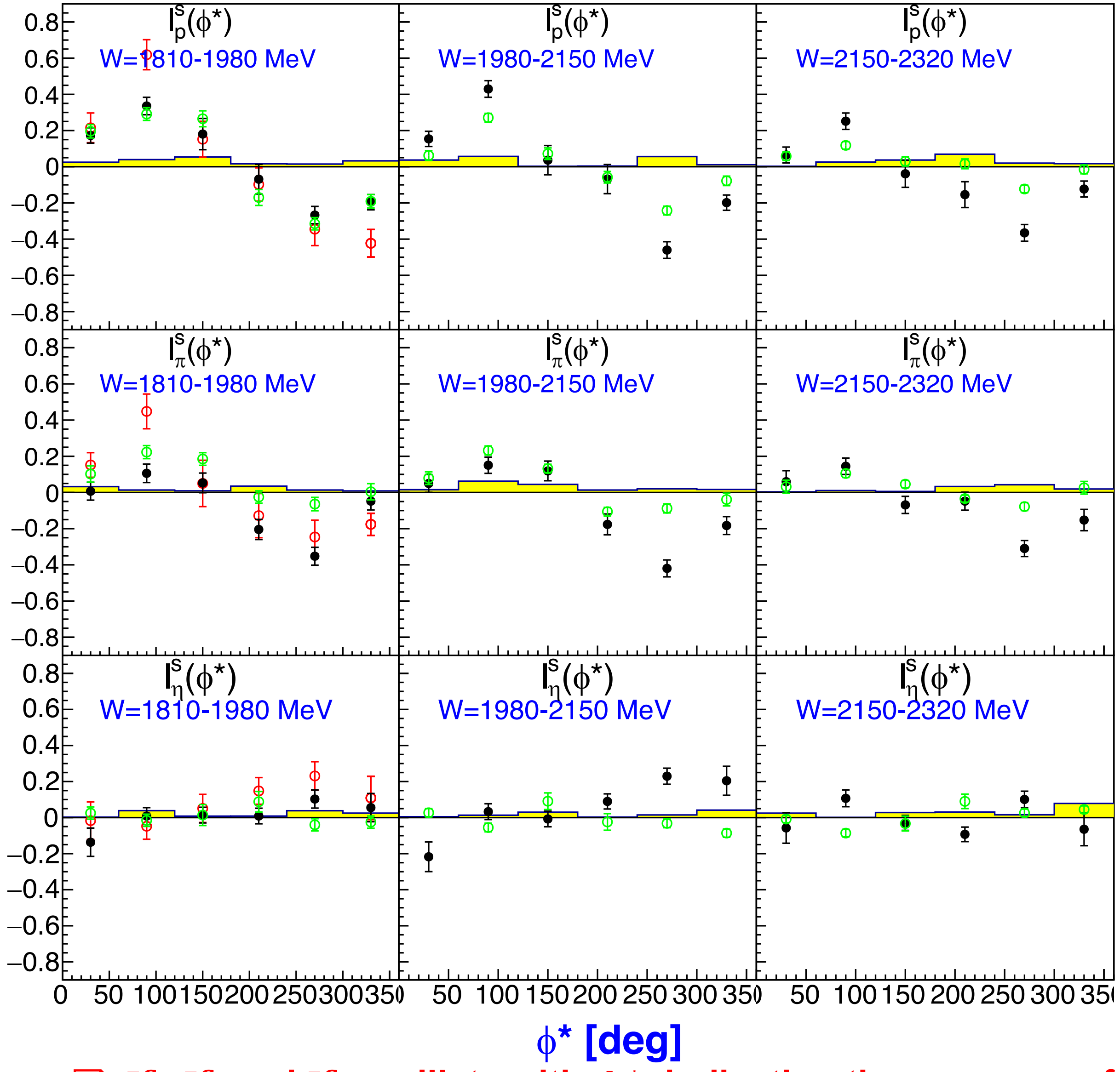
Systematic error (acc. &CL)

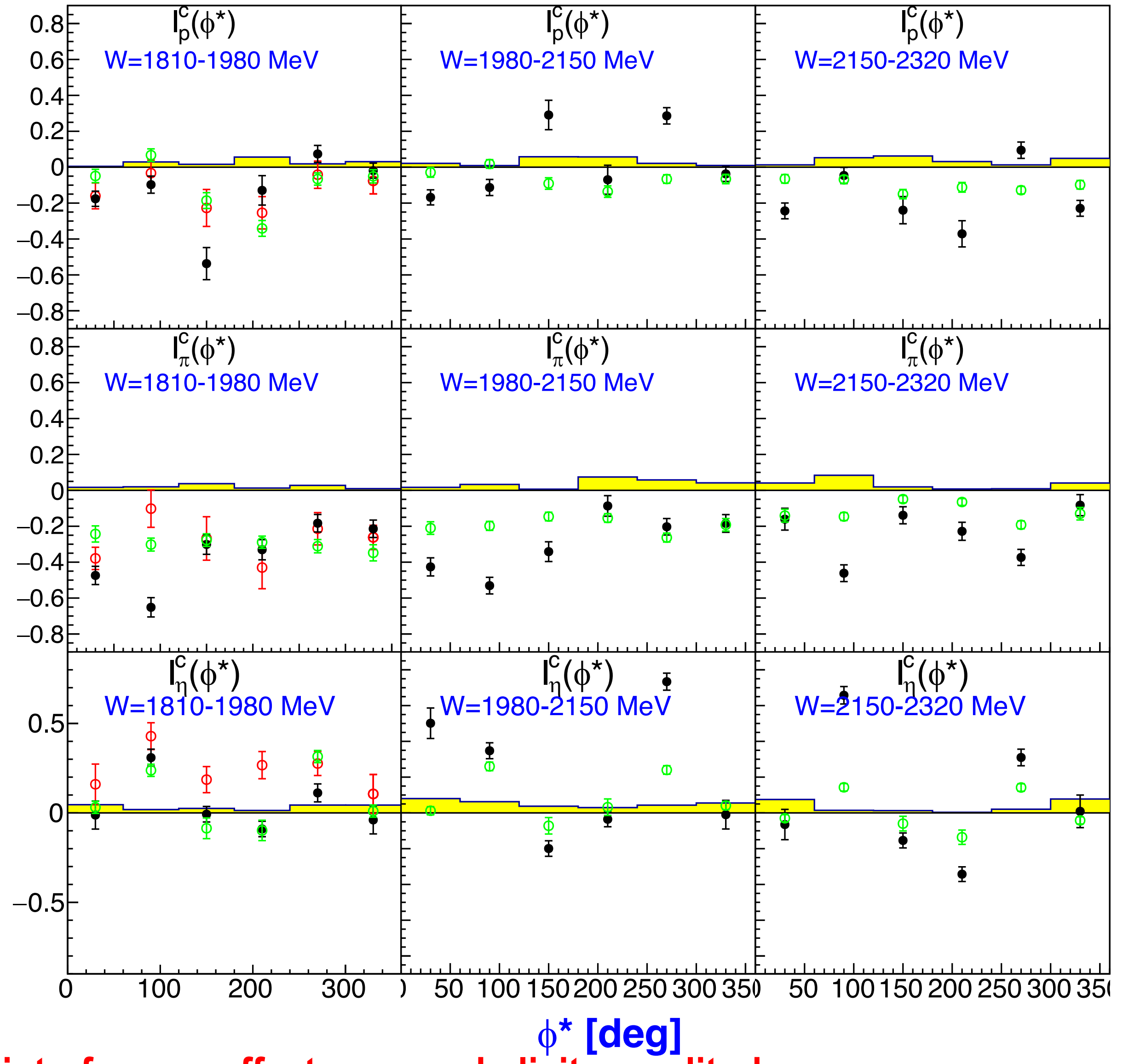
- **$\Sigma(p)$: ~ 0**
- **$\Sigma(\pi)$: negative, Unnatural parity exchange (pseudoscalar meson exchange, π)**
- **$\Sigma(\eta)$: positive, Natural parity exchange (vector meson exchange, ρ)**
- **Σ data above W=1980 ($E_\gamma \sim 1.65$ GeV) were measured for the first time**

$\gamma p \rightarrow \pi^0 \eta p$ beam asymmetries

I^s, I^c of $\gamma p \rightarrow \pi^0 \eta p$

CBELSA 2014
BGOegg 2014B
Systematic error (acc. &CL)





- ❑ I^s_p, I^s_π and I^s_η oscillate with ϕ^*, indicating the presence of interference effects among helicity amplitudes.
- ❑ PWA analysis will give more detailes

Discussion

The CBELSA/TAPS Collaboration   Eur. Phys. J. A (2014) 50: 74

Polarized beam energy up to **~1.7 GeV**

Abstract. Photoproduction off protons of the $p\pi^0\eta$ three-body final state was studied with the Crystal Barrel/TAPS detector, at the electron stretcher accelerator ELSA in Bonn, for incident energies from the $\pi^0\eta$ production threshold up to 2.5 GeV. Differential cross sections and the total cross sections are presented. The use of linearly polarized photons gives access to the polarization observables Σ, I^s, and I^c, the latter two characterize beam asymmetries in case of three-body final states. $\Delta(1232)\eta$, $N(1535)1/2^-\pi$, and $pa_0(980)$ are the dominant isobars contributing to the reaction. The partial wave analysis confirms the existence of some nucleon and Δ resonances, for which so far only fair evidence was reported. A large number of decay modes of known nucleon and Δ resonances is presented. It is shown that detailed investigations of decay branching ratios may provide a key to unravelling the structure of nucleon and Δ resonances.

Table 3. Branching ratios of nucleon and Δ resonances.

Resonance	πN	$N(1535)\pi$	$\Delta(1232)\eta$
$N(1710)1/2^+$	$5\pm3\%$	$15\pm6\%$	–
$N(1880)1/2^+$	$6\pm3\%$	$8\pm4\%$	–
$N(1900)3/2^+$	$3\pm3\%$	$7\pm3\%$	–
$N(2100)1/2^+$	$3\pm2\%$	$22\pm8\%$	–
$N(2120)3/2^-$	$5\pm3\%$	$15\pm8\%$	–
$\Delta(1700)3/2^-$	$22\pm4\%$	$1\pm0.5\%$	$5\pm2\%$
$\Delta(1900)1/2^-$	$7\pm2\%$	–	$1\pm1\%$
$\Delta(1905)5/2^+$	$13\pm2\%$	$\leq1\%$	$4\pm2\%$
$\Delta(1910)1/2^+$	$12\pm3\%$	$5\pm3\%$	$9\pm4\%$
$\Delta(1920)3/2^+$	$8\pm4\%$	$\leq2\%$	$11\pm6\%$
$\Delta(1940)3/2^-$	$2\pm1\%$	$8\pm6\%$	$10\pm6\%$
$\Delta(1950)7/2^+$	$46\pm2\%$		$\leq1\%$

$\Delta(1940)3/2^-$ **

$\Delta(1940)3/2^-$ decay modes			
$M_{\rm pole}$	2040 ± 50	$\Gamma_{\rm pole}$	450 ± 90
$A^{1/2}$	$0.170^{+0.120}_{-0.080}$	Phase	$-(10\pm30)^\circ$
$A^{3/2}$	0.150 ± 0.080	Phase	$-(10\pm30)^\circ$
$\Delta(1940)3/2^-$ transition residues			phase
$\pi N\to\pi N$		4 ± 3 (MeV)	$-(50\pm35)^\circ$
$2\,(\pi N\to\Delta(1232)\eta)/\Gamma$		$<1\%$	not defined
$2\,(\pi N\to N(1535))\pi/\Gamma$		$<3\%$	not defined
$(\gamma p)^{1/2}\to\Delta(1232)\eta$		$6.5\pm3\ 10^{-3}$	$-(110\pm55)^\circ$
$(\gamma p)^{3/2}\to\Delta(1232)\eta$		$4\pm2\ 10^{-3}$	$-(110\pm45)^\circ$
$(\gamma p)^{1/2}\to N(1535)\pi$		$16\pm6\ 10^{-3}$	$-(30\pm20)^\circ$
$(\gamma p)^{3/2}\to N(1535)\pi$		$11\pm4\ 10^{-3}$	$-(30\pm20)^\circ$
$\gamma p\to\Delta(1232)\eta$	E_{2-}	$6.7\pm3\ 10^{-3}$	$(65\pm55)^\circ$
$\gamma p\to\Delta(1232)\eta$	M_{2-}	$2\pm1\ 10^{-3}$	$-(110\pm55)^\circ$
$\gamma p\to N(1535)\pi$	E_{2-}	$18\pm6\ 10^{-3}$	$(150\pm15)^\circ$
$\gamma p\to N(1535)\pi$	M_{2-}	$6\pm3\ 10^{-3}$	$-(30\pm15)^\circ$
$\Delta(1940)3/2^-$ Breit-Wigner parameters			
M_{BW}	2050 ± 40	Γ_{BW}	450 ± 70
$\mathrm{Br}(\pi N)$	$2\pm1\%$	$\mathrm{BR}(\Delta(1232)\eta)$	$10\pm6\%$
$\mathrm{Br}(N(1535)\pi)$	$8\pm6\%$		
$A^{1/2}_{BW}$	$0.170^{+0.110}_{-0.080}$	$A^{3/2}_{BW}$	0.150 ± 0.080

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Polarized beam energy up to **~2.4 GeV**

(1) cascade processes of higher mass resonances into a resonance with intrinsic orbital angular momentum can be studied

(2) The comparison of these decay modes with decays into Nπ is very helpful for identifying mechanisms responsible for the decays of N and Δ resonances.

(3) More information about branching ratios for decays into Nπ, N(1535)π, and Δ(1232)η can be obtained.

Summary

- Preliminary results of beam asymmetries of $\gamma p \rightarrow \pi^0 \eta p$ in the beam energy region of 1.3-2.4 GeV were obtained.
- The quasi 2-body polarization observables Σ and 3-body observables I^s, I^c above ~1.7 GeV (E_γ) are new experimental data in the world.
- Our results are consistent with CBELSA's results in the beam energy region of 1.3-1.7 GeV within error bars
- Cooperation with PWA (Bonn-Gatchina) could provide more interesting information about cascade processes of higher mass resonances and branching ratios for decays into Nπ, N(1535)π, and Δ(1232)η

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