Beam-asymmetry measurement in pion photoproduction on the neutron at CLAS

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Resonance spectrum

- Most N*s and Δ^*s couple to the pion channel: still the biggest source of resonance information. Large cross-sections: precision data.

Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	ΣK	$N\rho$	$\Delta\eta$
$\Delta(1232)$	$3/2^+$	****	****	****				
$\Delta(1600)$	$3/2^+$	****	****	***	****			
$\Delta(1620)$	$1/2^-$	****	****	****	****			
$\Delta(1700)$	$3/2^-$	****	****	****	****	*	*	
$\Delta(1750)$	$1/2^+$	*	*	*		*		
$\Delta(1900)$	$1/2^-$	***	***	***	*	**	*	
$\Delta(1905)$	$5/2^+$	****	****	****	**	*	*	**
$\Delta(1910)$	$1/2^+$	****	***	****	**	**		*
$\Delta(1920)$	$3/2^+$	***	***	***	***	**		**
$\Delta(1930)$	$5/2^-$	***	*	***	*	*		
$\Delta(1940)$	$3/2^-$	**	*	**	*			*
$\Delta(1950)$	$7/2^+$	****	****	****	**	***		
$\Delta(2000)$	$5/2^+$	**	*	**	*		*	
$\Delta(2150)$	$1/2^-$	*		*				
$\Delta(2200)$	$7/2^-$	***	***	**	***	**		
$\Delta(2300)$	$9/2^+$	**		**				
$\Delta(2350)$	$5/2^-$	*		*				
$\Delta(2390)$	$7/2^+$	*		*				
$\Delta(2400)$	$9/2^-$	**	**	**				
$\Delta(2420)$	$11/2^+$	****	*	****				
$\Delta(2750)$	$13/2^-$	**		**				
$\Delta(2950)$	$15/2^+$	**		**				

PDG 2018

Meson photoproduction

- Pseudoscalar meson photoproduction is (up to an overall phase) completely described by four complex reaction amplitudes: functions of invariant mass (W) and meson-production angle, θ .

- Experimentally, 16 single- and double-polarisation observables:

Polarised:		Beam	Target	Recoil
	$\partial\sigma/\partial\Omega$	Σ	T	R
Beam		& 12 **double-polarisation** observables		
Target				
Recoil				

Required for a complete measurement

W.-T. Chiang and F. Tabakin, Phys. Rev. C **55**, 2054 (1997).

- Partial Wave Analysis (**PWA**) fits to observables are used to extract multipoles, which carry information on the resonance parameters (angular momenta, parity, etc).

- A number of different approaches: MAID, SAID, Bonn-Gatchina...

Neutrons as a target

- EM interaction does not conserve isospin, so multipole amplitides contain **isoscalar** and **isovector** contributions of EM current:

Proton

$$A_{\gamma p \to \pi^0 p} = -\left[\frac{1}{3}A^{(0)} - \frac{1}{3}A^{(1)}\right]^{I=1/2} + \frac{2}{3}A^{(I=2/3)}$$

$$A_{\gamma p \to \pi^+ n} = \frac{1}{\sqrt{2}}\left[\frac{1}{3}A^{(0)} - \frac{1}{3}A^{(1)}\right]^{I=1/2} + \frac{\sqrt{2}}{3}A^{(I=2/3)}$$

Neutron

$$A_{\gamma n \to \pi^0 n} = \left[\frac{1}{3}A^{(0)} + \frac{1}{3}A^{(1)}\right]^{I=1/2} + \frac{2}{3}A^{(I=2/3)}$$

$$A_{\gamma n \to \pi^- n} = \frac{1}{\sqrt{2}}\left[\frac{1}{3}A^{(0)} + \frac{1}{3}A^{(1)}\right]^{I=1/2} + \frac{\sqrt{2}}{3}A^{(I=2/3)}$$

- Proton data alone does not allow separation of the isoscalar, $A^{(0)}$, and isovector, $A^{(1)}$, components.

- Need data on both proton and **neutron**!

Pion Photoproduction

$$\rho_f \frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{unpol} \{1 - P_\gamma^{lin}\Sigma\cos 2\phi + P_x(P_\gamma^{circ}F + P_\gamma^{lin}H\sin 2\phi)$$

$$+P_y(T\text{-}\ P_\gamma^{lin}P\cos 2\phi) + P_z(P_\gamma^{circ}E + P_\gamma^{lin}G\sin 2\phi)$$

$$+\sigma'_x[P_\gamma^{circ}C_x + P_\gamma^{lin}O_x\sin 2\phi + P_x(T_x\text{-}\ P_\gamma^{lin}L_z\cos 2\phi)$$

$$+P_y(P_\gamma^{lin}C_z\sin 2\phi\text{-}P_\gamma^{circ}O_z) + P_z(L_x + P_\gamma^{lin}T_z\cos 2\phi]$$

$$+\sigma'_y[P + P_\gamma^{lin}T\cos 2\phi + P_x(P_\gamma^{circ}G\text{-}P_\gamma^{lin}E\sin 2\phi)$$

$$+P_y(\Sigma\text{-}P_\gamma^{lin}\cos 2\phi) + P_z(P_\gamma^{lin}F\sin 2\phi + P_\gamma^{circ}H)]$$

$$+\sigma'_z[P_\gamma^{circ}C_z + P_\gamma^{lin}O_z\sin 2\phi + P_x(T_z + P_\gamma^{lin}L_x\cos 2\phi)$$

$$+P_y(\text{-}\ P_\gamma^{lin}C_x\sin 2\phi\text{-}P_\gamma^{circ}O_z) + P_z(L_z + P_\gamma^{lin}T_x\cos 2\phi)]\}$$

Pion Photoproduction

$$
\begin{aligned}
\rho_f \frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{unpol} \{ 1 - P_\gamma^{lin}\Sigma\cos 2\phi + P_x(P_\gamma^{circ}F + P_\gamma^{lin}H\sin 2\phi) \\
+P_y(T - P_\gamma^{lin}P\cos 2\phi) + P_z(P_\gamma^{circ}E + P_\gamma^{lin}G\sin 2\phi) \\
+\sigma'_x[P_\gamma^{circ}C_x + P_\gamma^{lin}O_x\sin 2\phi + P_x(T_x - P_\gamma^{lin}L_z\cos 2\phi) \\
+P_y(P_\gamma^{lin}C_z\sin 2\phi - P_\gamma^{circ}O_z) + P_z(L_x + P_\gamma^{lin}T_z\cos 2\phi] \\
+\sigma'_y[P + P_\gamma^{lin}T\cos 2\phi + P_x(P_\gamma^{circ}G - P_\gamma^{lin}E\sin 2\phi) \\
+P_y(\Sigma - P_\gamma^{lin}\cos 2\phi) + P_z(P_\gamma^{lin}F\sin 2\phi + P_\gamma^{circ}H)] \\
+\sigma'_z[P_\gamma^{circ}C_z + P_\gamma^{lin}O_z\sin 2\phi + P_x(T_z + P_\gamma^{lin}L_x\cos 2\phi) \\
+P_y(-P_\gamma^{lin}C_x\sin 2\phi - P_\gamma^{circ}O_z) + P_z(L_z + P_\gamma^{lin}T_x\cos 2\phi)]\}
\end{aligned}
$$

- Beam-asymmetry Σ is a crucial observables to constrain PWAs.

- Experiment using CLAS @ JLab – exclusive measurement of Σ in 1.6 < W < 2.3 GeV, $25^\circ < \theta_{CM} < 145^\circ$ on a quasi-free neutron:

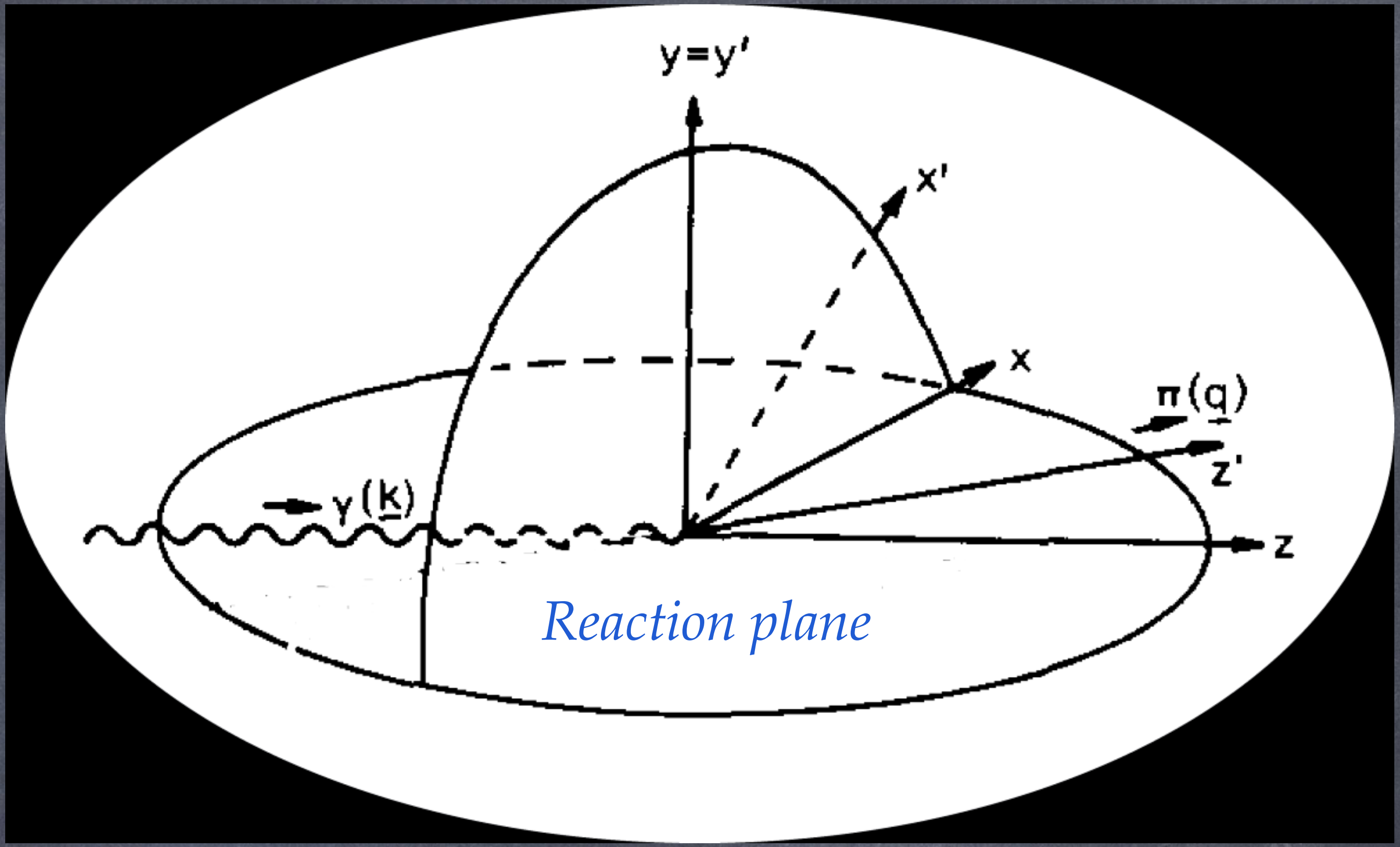
$$\gamma + d \to \pi^- + p + (p_{spectator})$$

Aside: axis conventions

Reaction **axes**:

$$z = \underline{p}_\gamma \Big/ p_\gamma$$

$$y = \underline{p}_\gamma \times \underline{p}_{\pi^-} \Big/ \left| \underline{p}_\gamma \times \underline{p}_{\pi^-} \right|$$

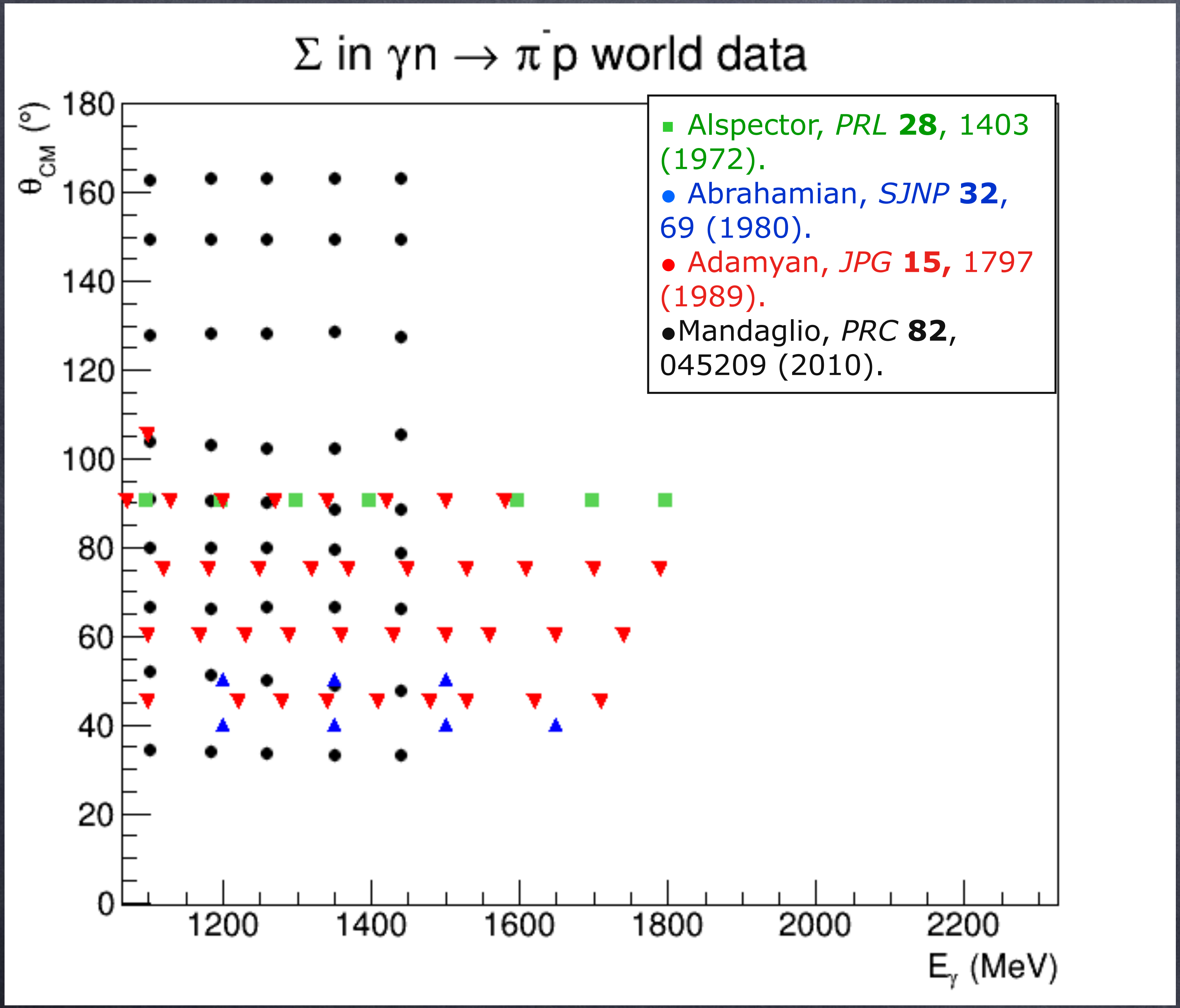


in the Centre of Momentum System (CMS)

- **φ**: angle of beam polarisation plane in CMS w.r.t. reaction plane.
- **Asymmetry** from cos(2φ) fit to the φ-distribution of pions:

$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 - P_{lin} \Sigma \cos 2\varphi)$$

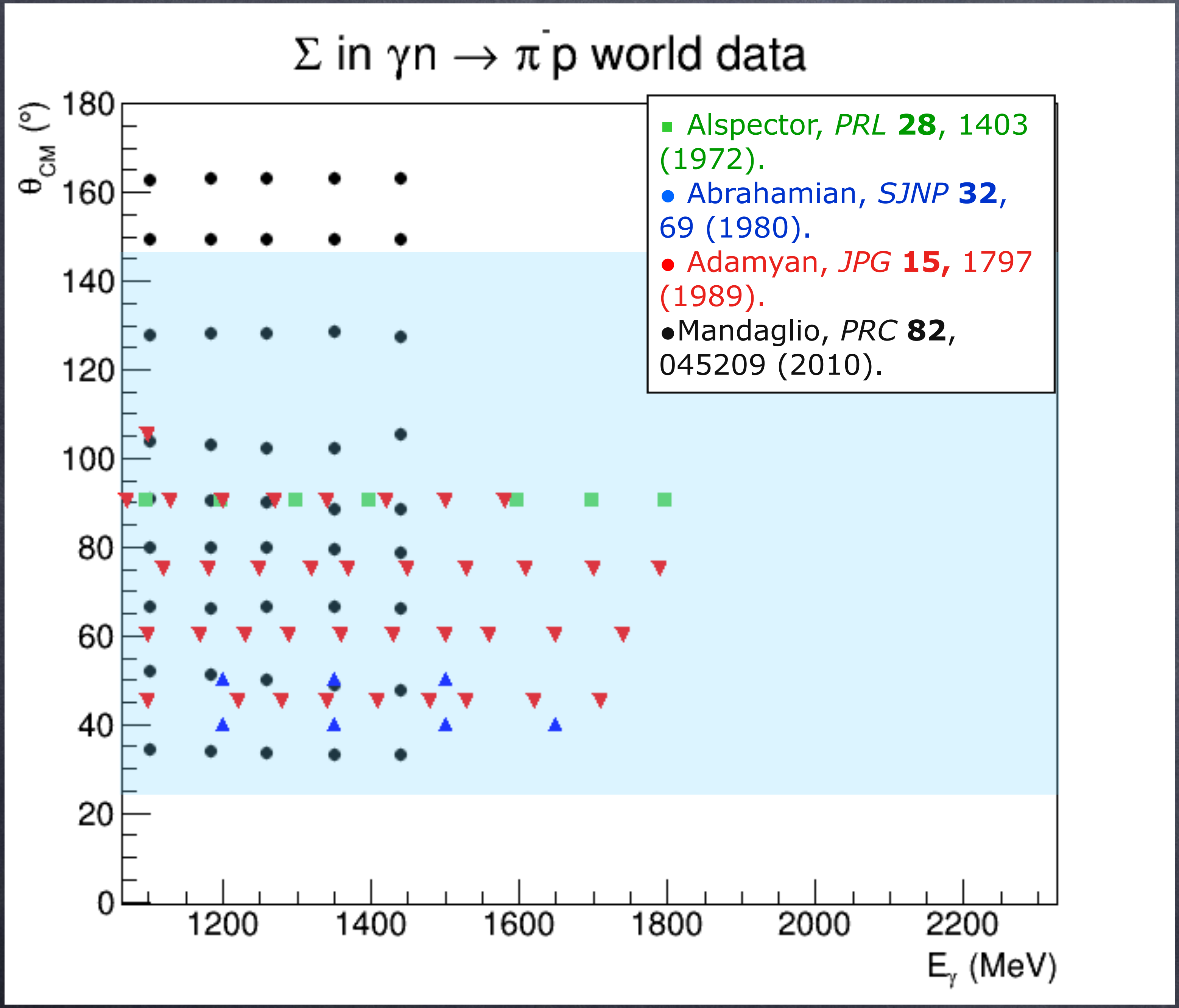
World dataset...



... has very **few points** from the neutron (most data is from proton).

... is in a **limited** polar-angle and energy range.

World dataset...



... has very **few points** from the neutron (most data is from proton).

... is in a **limited** polar-angle and energy range.

CLAS measurement has added **>1000 new data points** to the previous set of 166

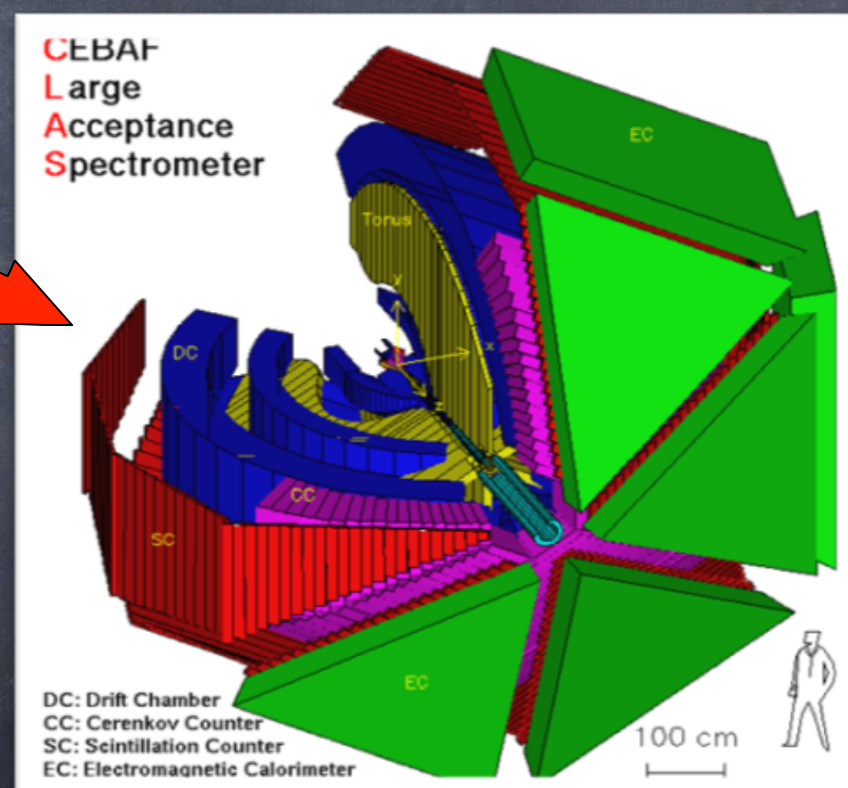
1.6 < W < 2.3 GeV

$25^\circ < \theta_{CM} < 145^\circ$

CLAS @ Jefferson Lab

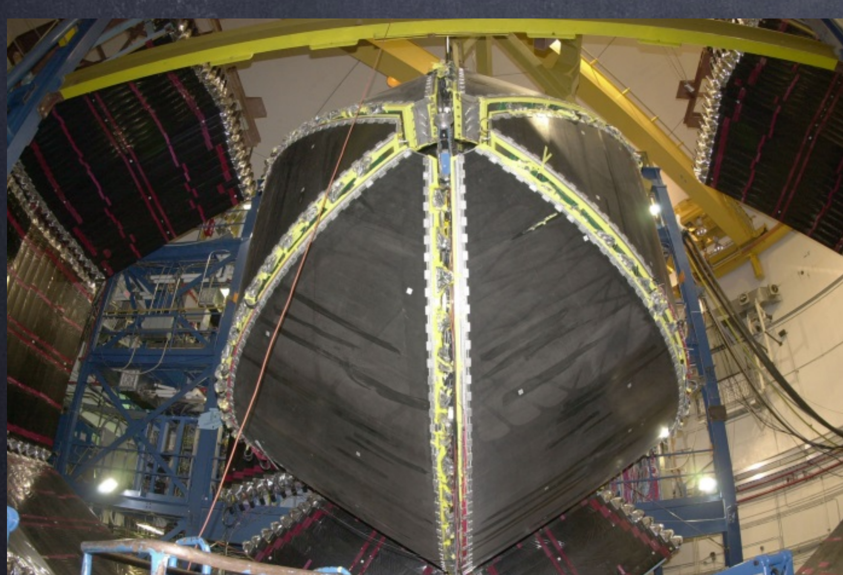
Continuous Electron Beam Accelerator Facility (CEBAF):

- Duty cycle: ~100%
- Energy up to ~6 GeV
- Electron polarisation up to ~ 85%



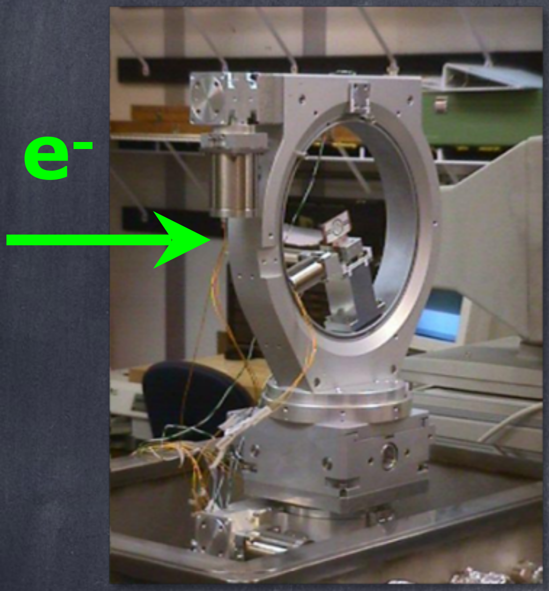
CLAS (CEBAF Large Acceptance Spectrometer) in Hall B:

- Drift chambers
- Toroidal magnetic field
- Cerenkov Counters
- Scintillator Time of Flight
- Electromagnetic Calorimeters



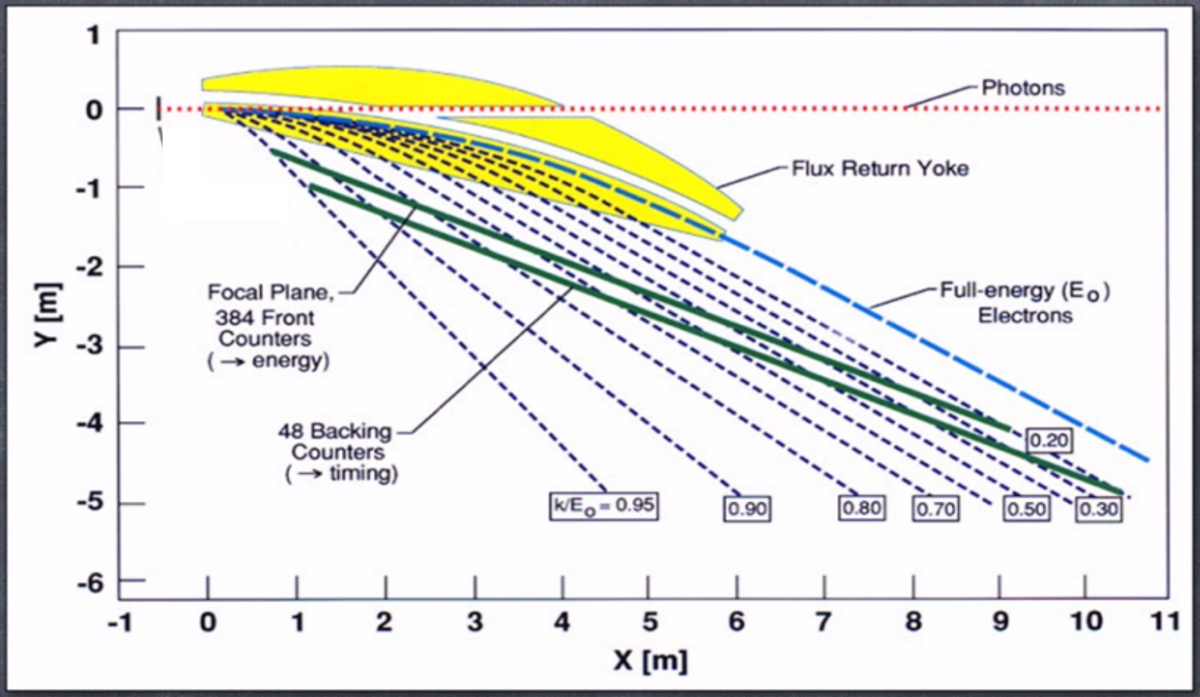
Very large angular coverage – near full azimuthal and 8° to 140° scattering angle (lab).

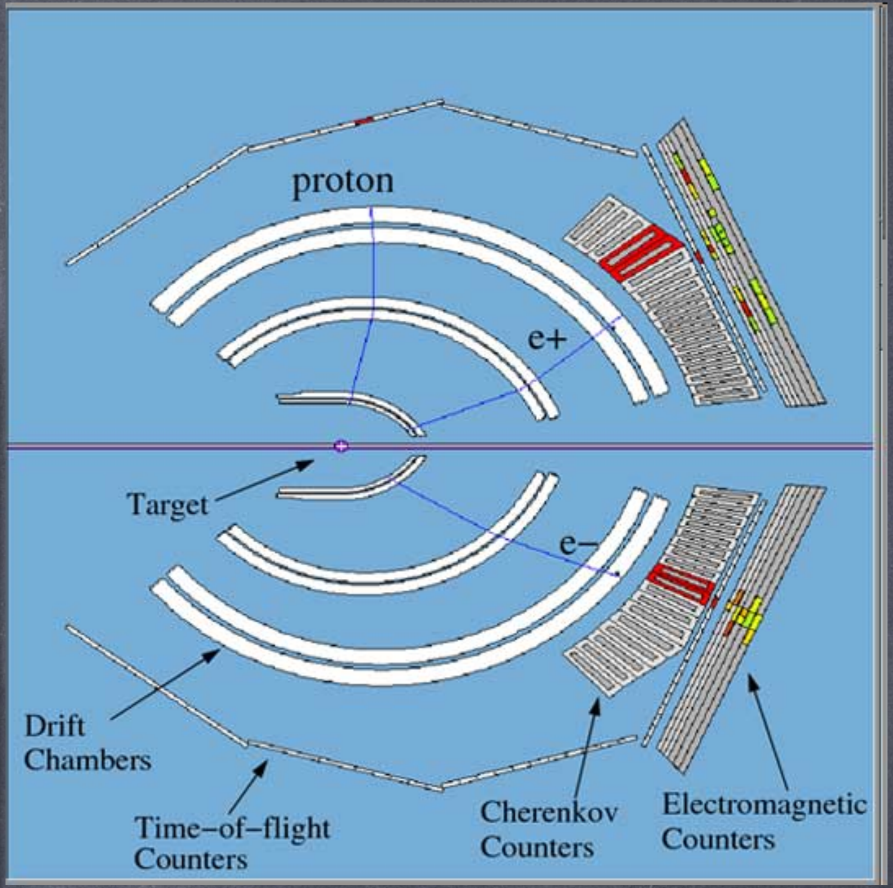
The photon beam



Goniometer for tilting radiator

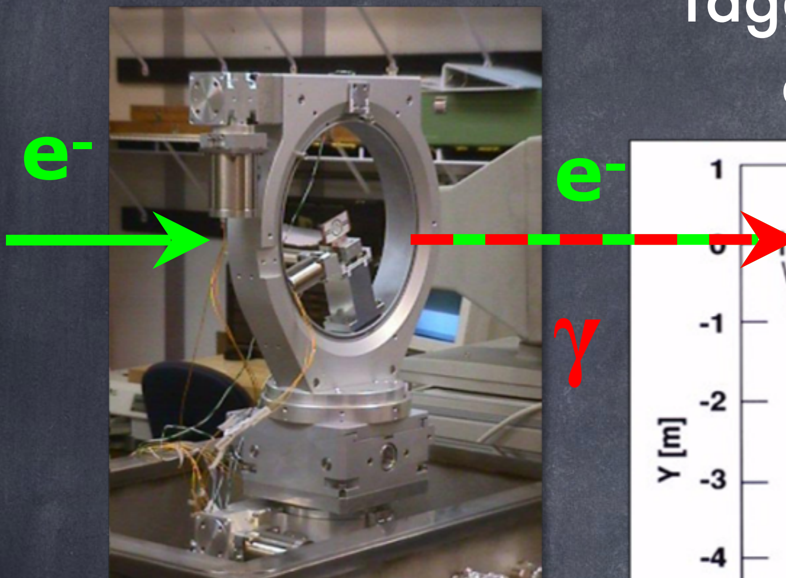
Tagging spectrometer – momentum analyses deflected electrons





Target within CLAS

The photon beam



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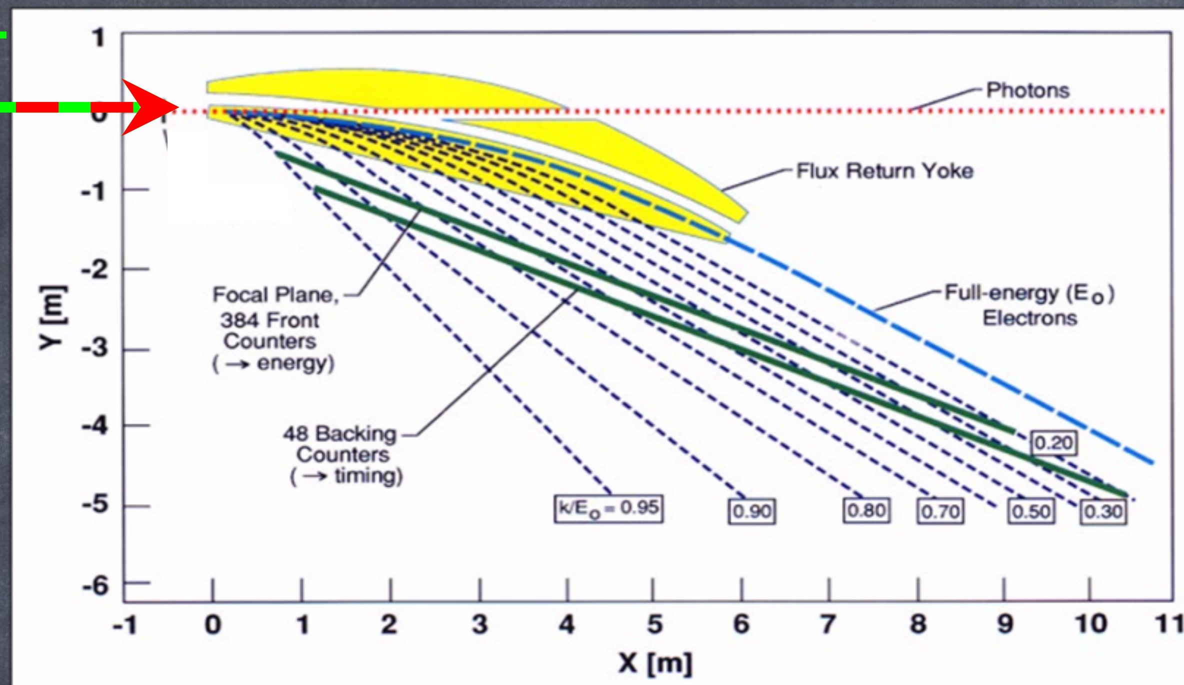
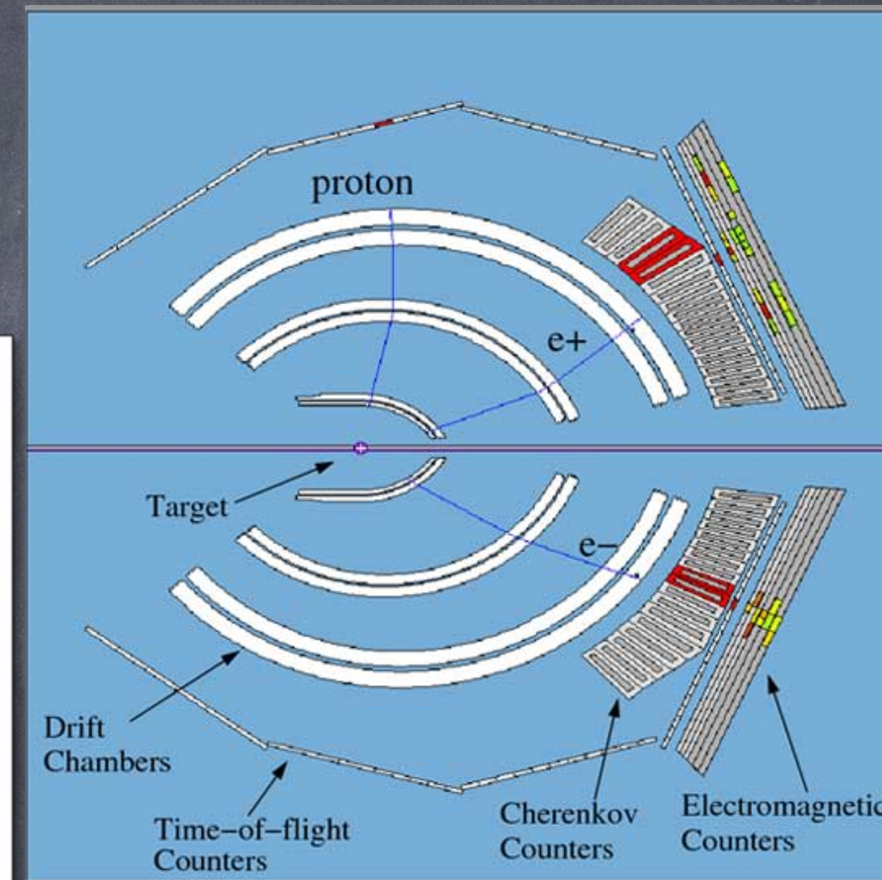
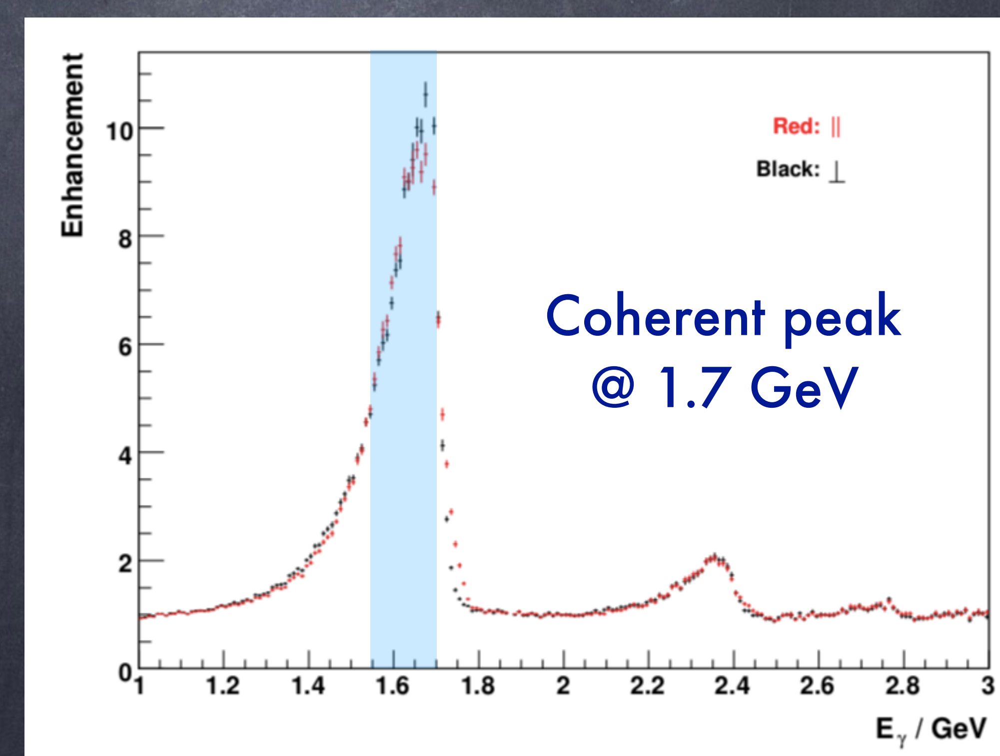




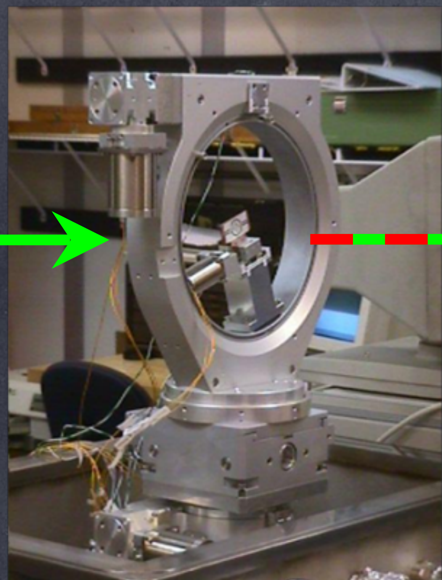
Target within CLAS

- **Linearly polarised** (up to > **90%**) photon beam: bremsstrahlung of unpolarised electrons in a highly ordered crystalline radiator, typically 20 – 50 μm diamond.

- Crystal orientation chosen to produce a "**coherent**" peak of polarised photons at the required energy.



The photon beam



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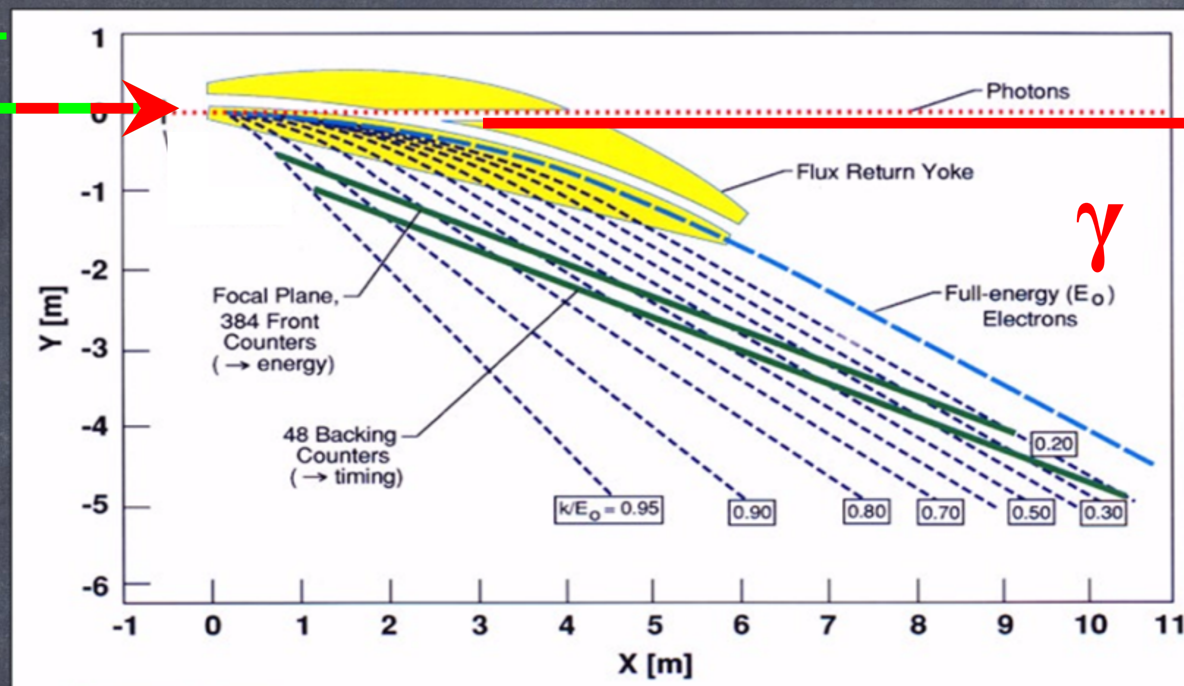

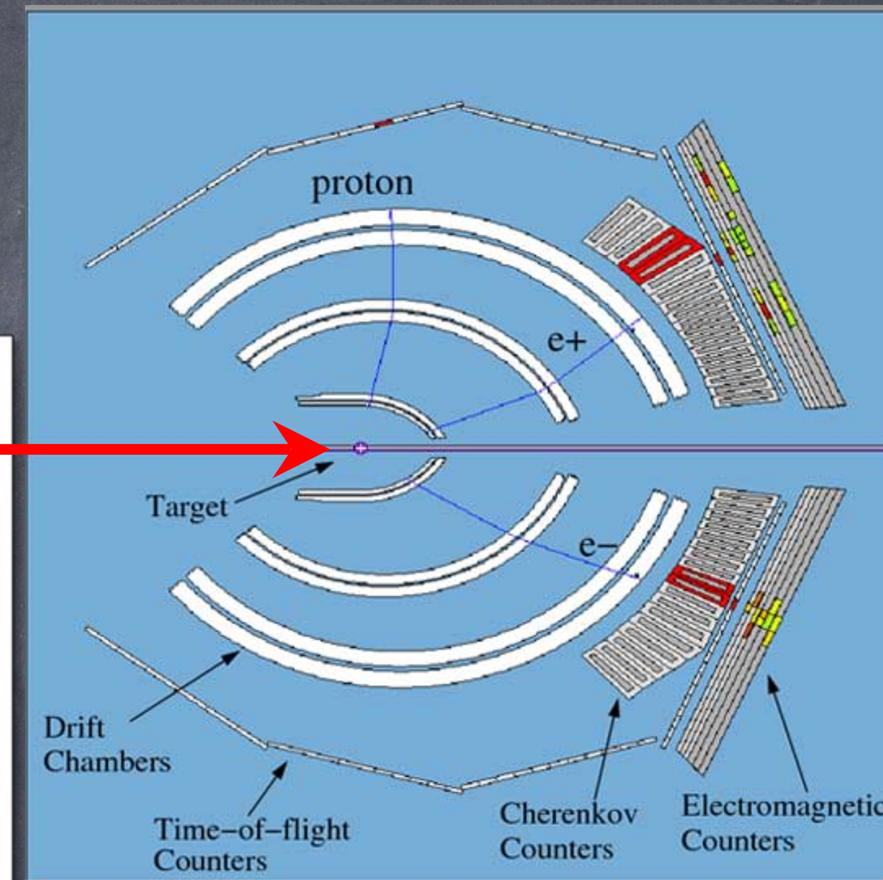

Target within CLAS

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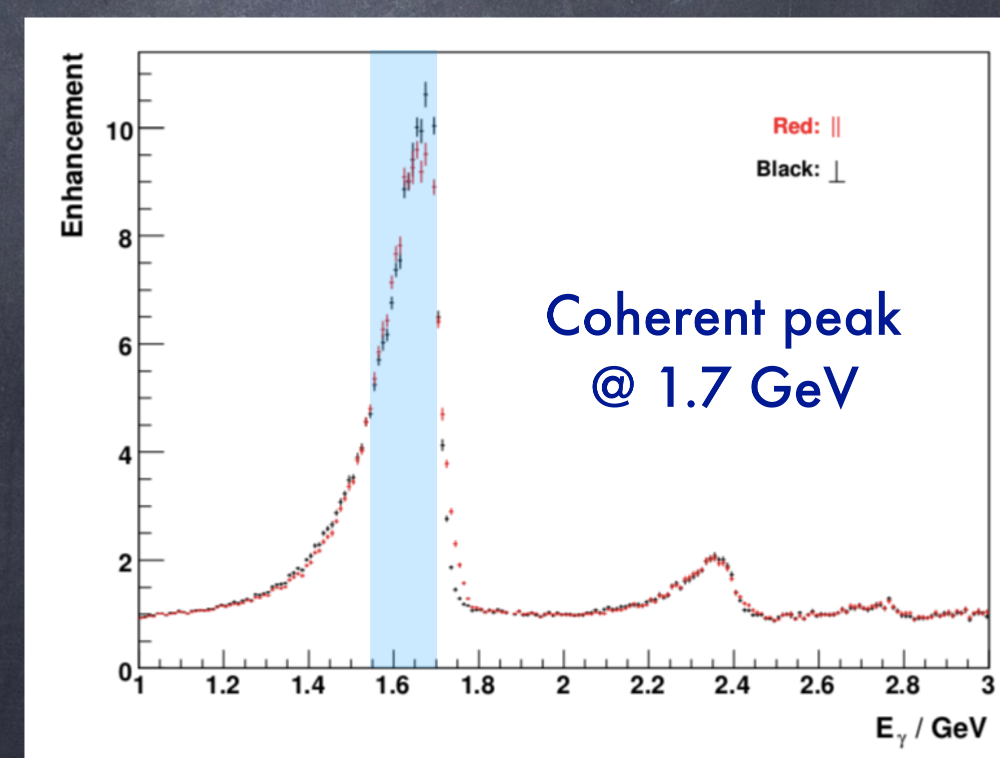
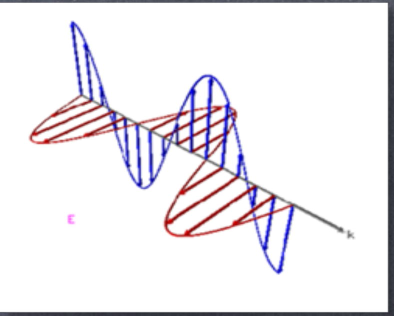
- ✶ Crystal orientation chosen to produce a "**coherent**" peak of polarised photons at the required energy.



The g13b experiment

- ✶ Liquid deuterium target: quasi-free neutrons
- ✶ Linearly-polarised photon beam from coherent bremsstrahlung
- ✶ Ten electron / photon energy settings



- ✶ Photon polarisation plane flipped frequently between two orthogonal orientations: PARA and PERP
- ✶ Single charged particle trigger: total of $3 \cdot 10^{10}$ events, of those 13.4 M remain in the final data-sample for the reaction channel:

$$\gamma + d \rightarrow \pi^- + p + (p_{spectator})$$

E_γ (GeV)	E_e (GeV)
1.3	3.3, 4.2
1.5	4.1, 4.5
1.7	4.1, 4.7
1.9	5.1
2.1	5.1, 5.2
2.3	5.2

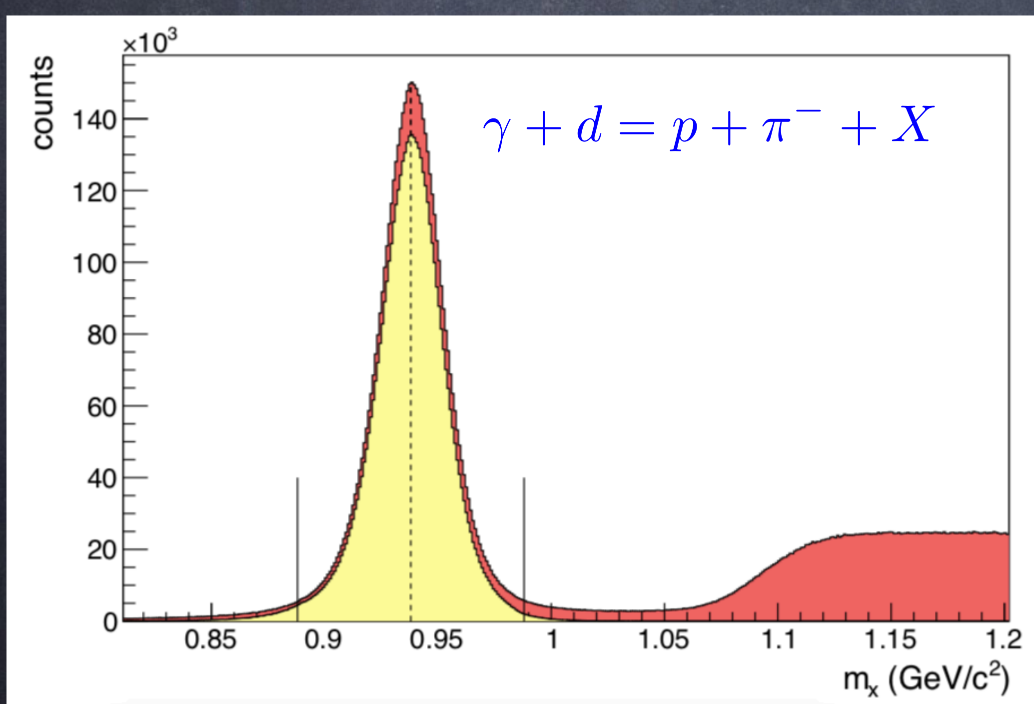
Reaction identification

Exact photon (and its energy) identified from timing coincidence with scattered electron in the "tagger"

Proton and pion detected and their momenta measured within CLAS

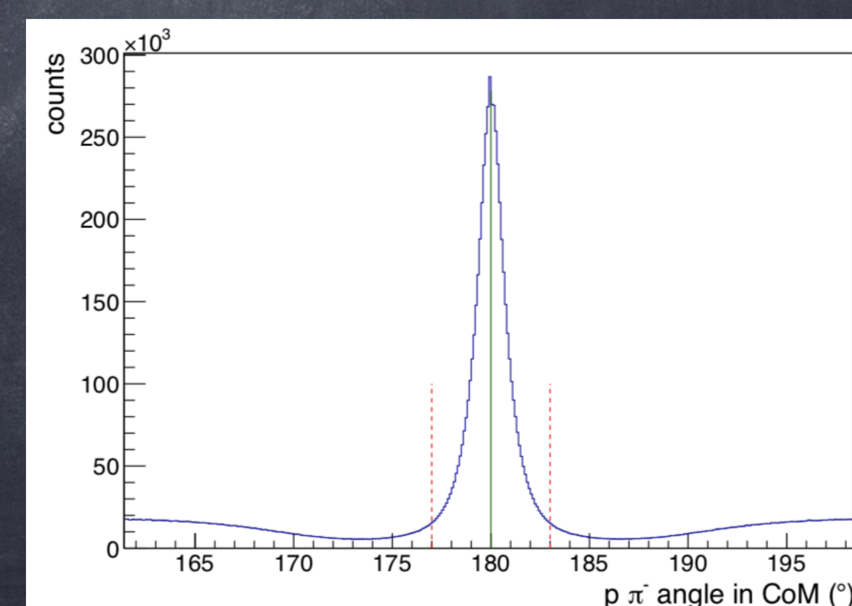
$$\gamma + d \to \pi^- + p + (p_{spectator})$$

Spectator proton reconstructed through the "missing" four-momentum, identified via its mass



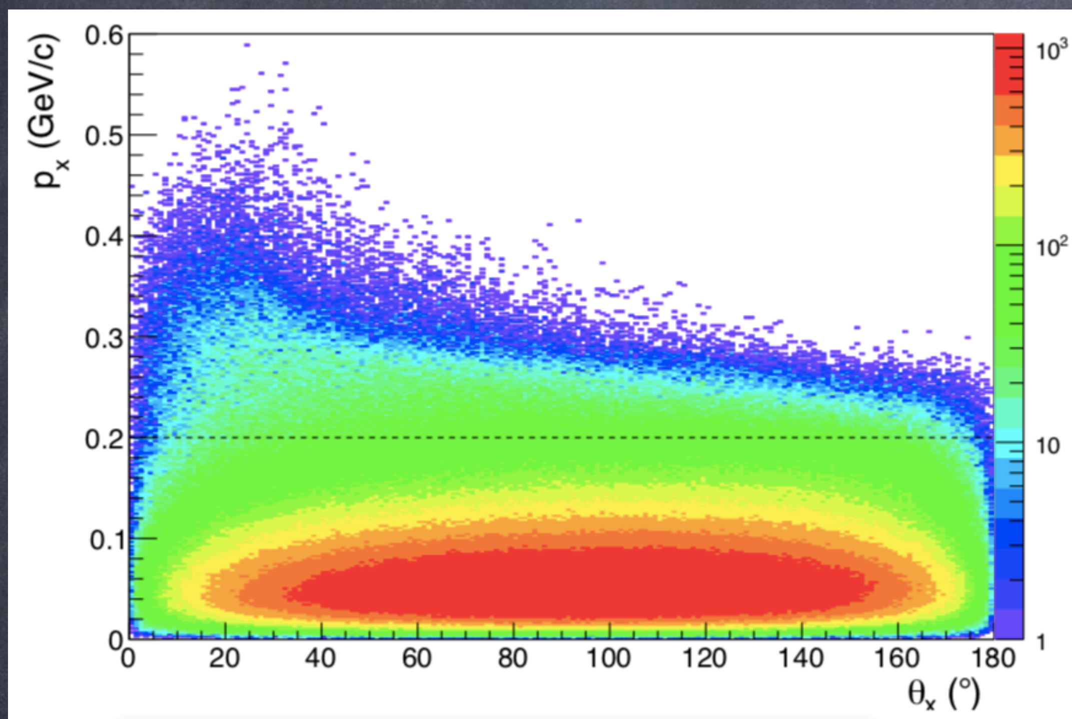
Assign the negative of the missing momentum to the target neutron.

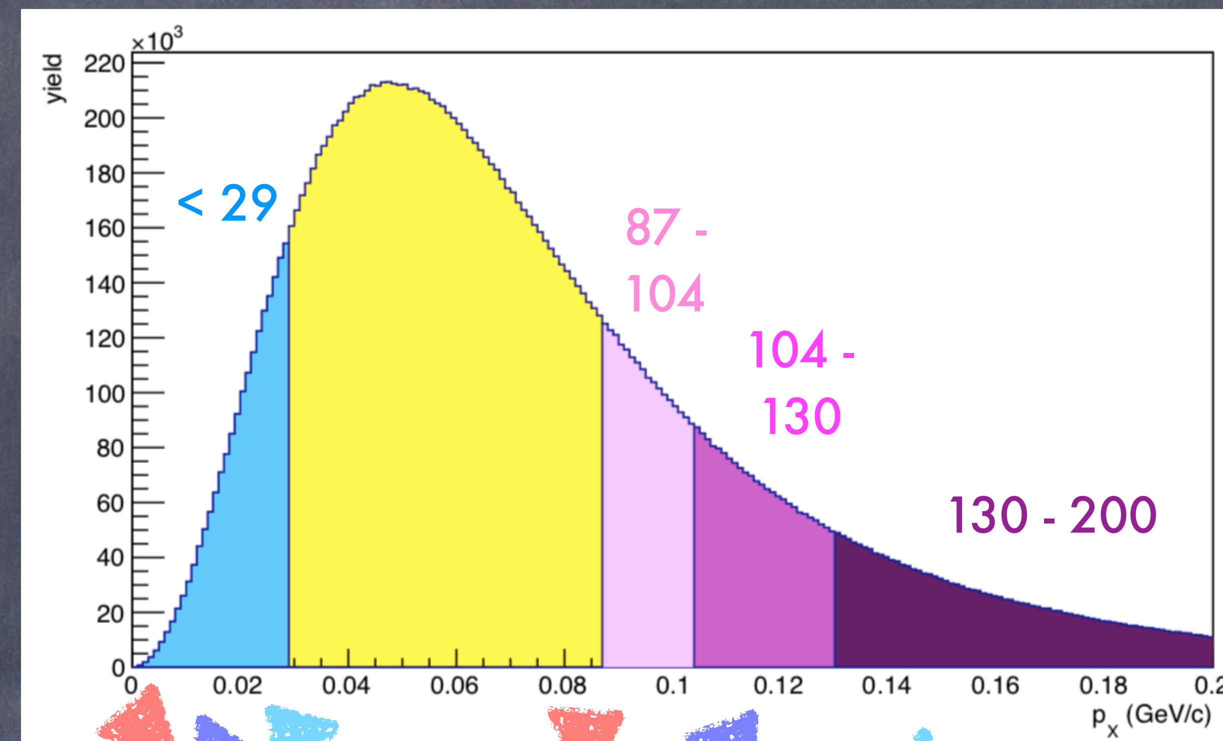
Exclusivity ensured by requiring the proton and pion to be back-to-back in the CoM frame of the photon and neutron.



Quasi-free kinematics

- Missing momentum from $\gamma + d = p + \pi^- + X$ assigned to spectator proton. Cut away p_x > 200 MeV/c.





Spectator momentum becomes forward-peaked for large values.

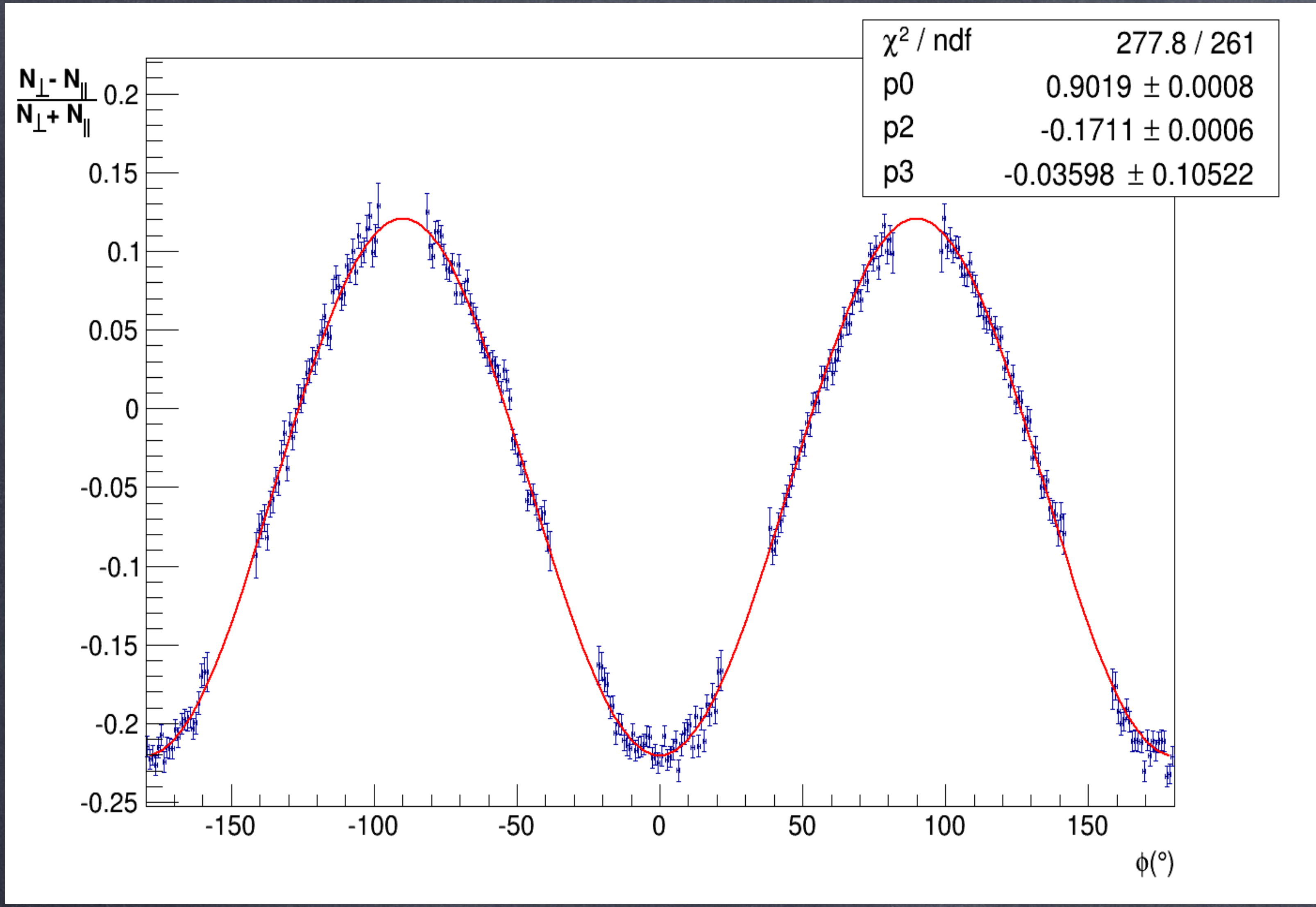
Mean weighted ratio of Σ: $0.8 \pm 1\%$

$2.4 \pm 1\%$

$9 \pm 1\%$

Small systematic shift observed between data with lowest and highest spectator momentum.

Asymmetry fits



$$N_\parallel = N_\theta(1 - P\Sigma cos2\phi)$$

$$N_\perp = N_\theta(1 + P\Sigma cos2\phi)$$

$$P\Sigma cos2\phi = \frac{N_\parallel - N_\perp}{N_\parallel + N_\perp}$$

At its simplest, fit with:

$$A + B\cos(2\phi + C)$$

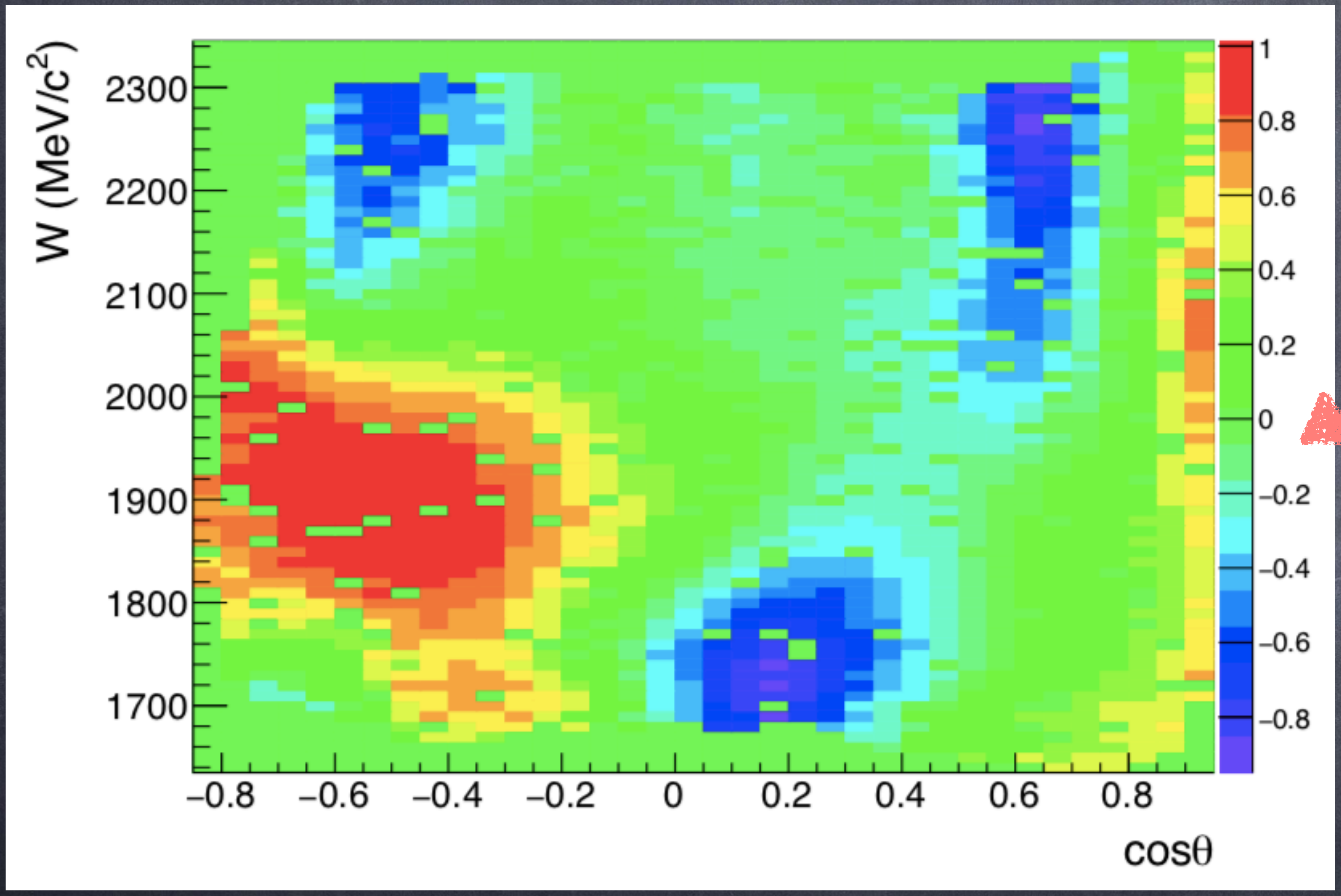
Where $B = P\Sigma$

Actual fit function allows flux ratio (N_R) and polarisation ratio (P_R) different from unity:

$$\frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{(N_R - 1) + \frac{N_R P_R + 1}{P_R + 1}\, 2\,\bar{P}\,\Sigma\,\cos\left(2(\phi + \phi_0)\right)}{(N_R + 1) + \frac{N_R P_R - 1}{P_R + 1}\, 2\,\bar{P}\,\Sigma\,\cos\left(2(\phi + \phi_0)\right)}$$

Results

- Data from all electron/photon energy settings, except the 1.3 GeV coherent peak setting, was found to be compatible and integrated. The1.3 GeV coherent peak data was kept separate, and showed systematic shifts of up to 10% in some bins.



For illustration only: binned in 10 MeV (W) and 0.05 ($\cos\theta_{cm}$), all data integrated.

Final bin width chosen was 10 MeV in W and 0.1 in $\cos\theta_{cm}$.

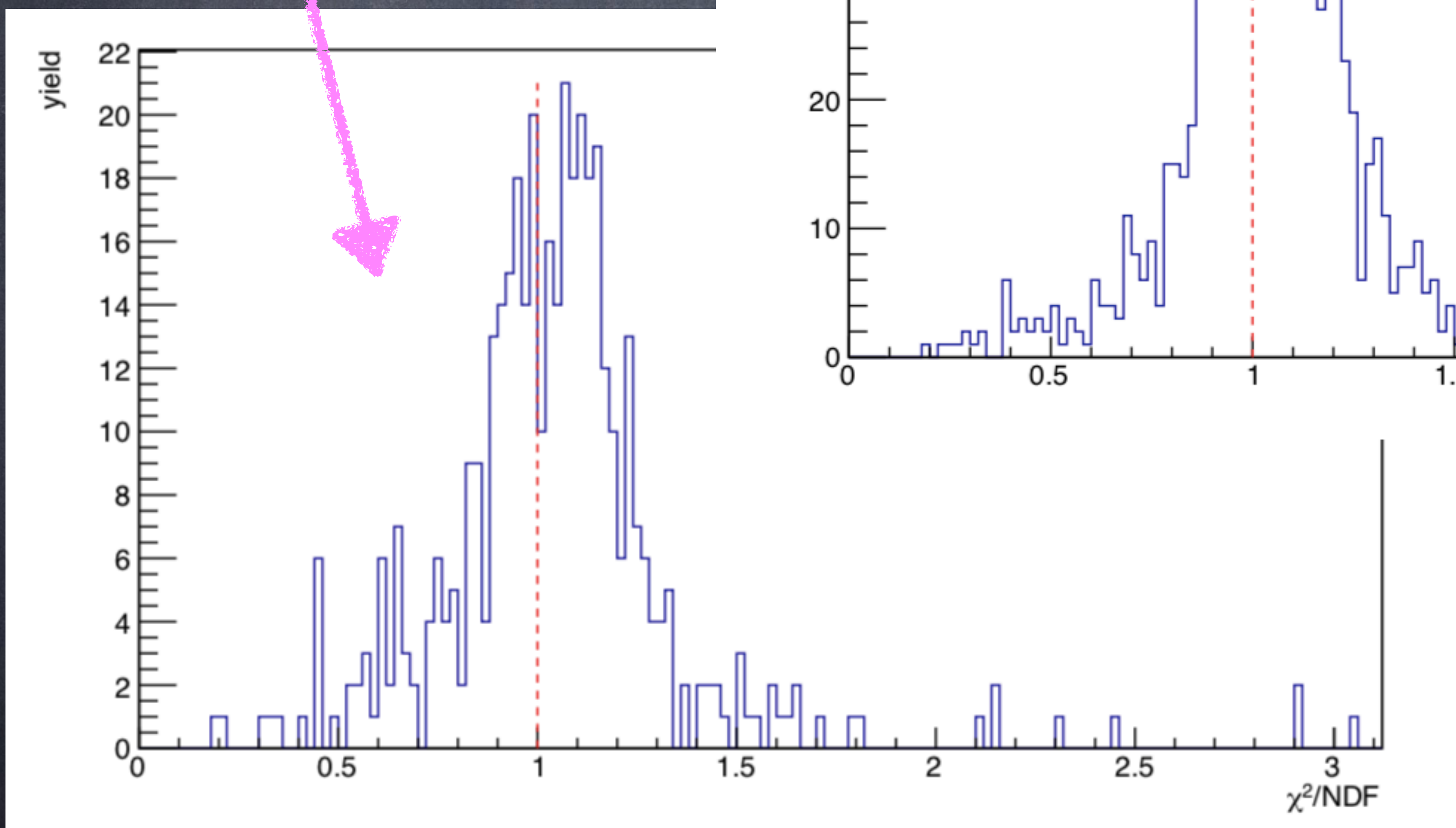
Systematic uncertainties:

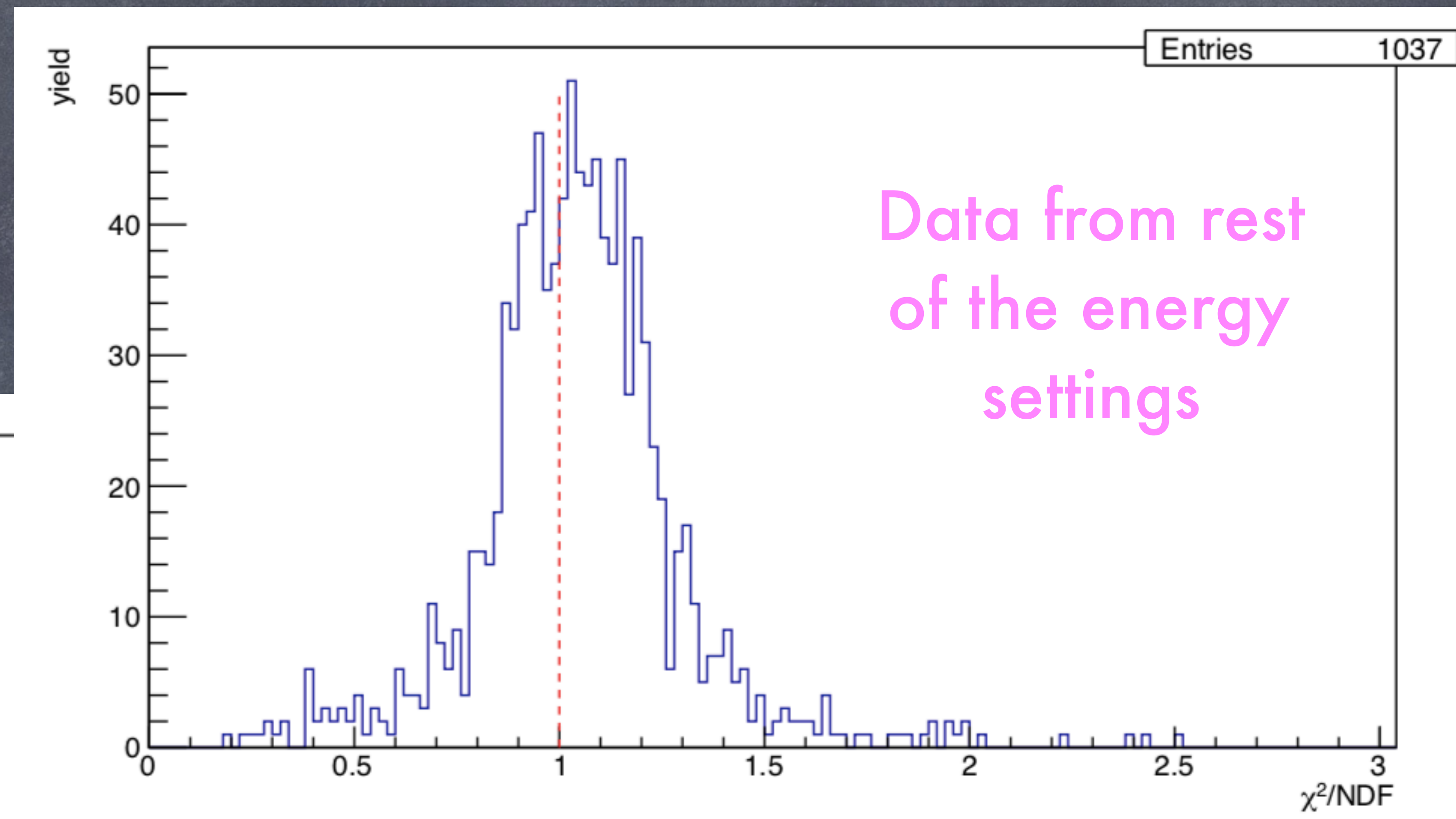
lower than statistical!

- Polarisation: 3%
- Bin and fit-related systematics: 0.5 - 2%
- For the 1.3 GeV coherent peak dataset: extra 10%

Fit quality: χ^2/NDF

Data from the 1.3 GeV coherent peak setting

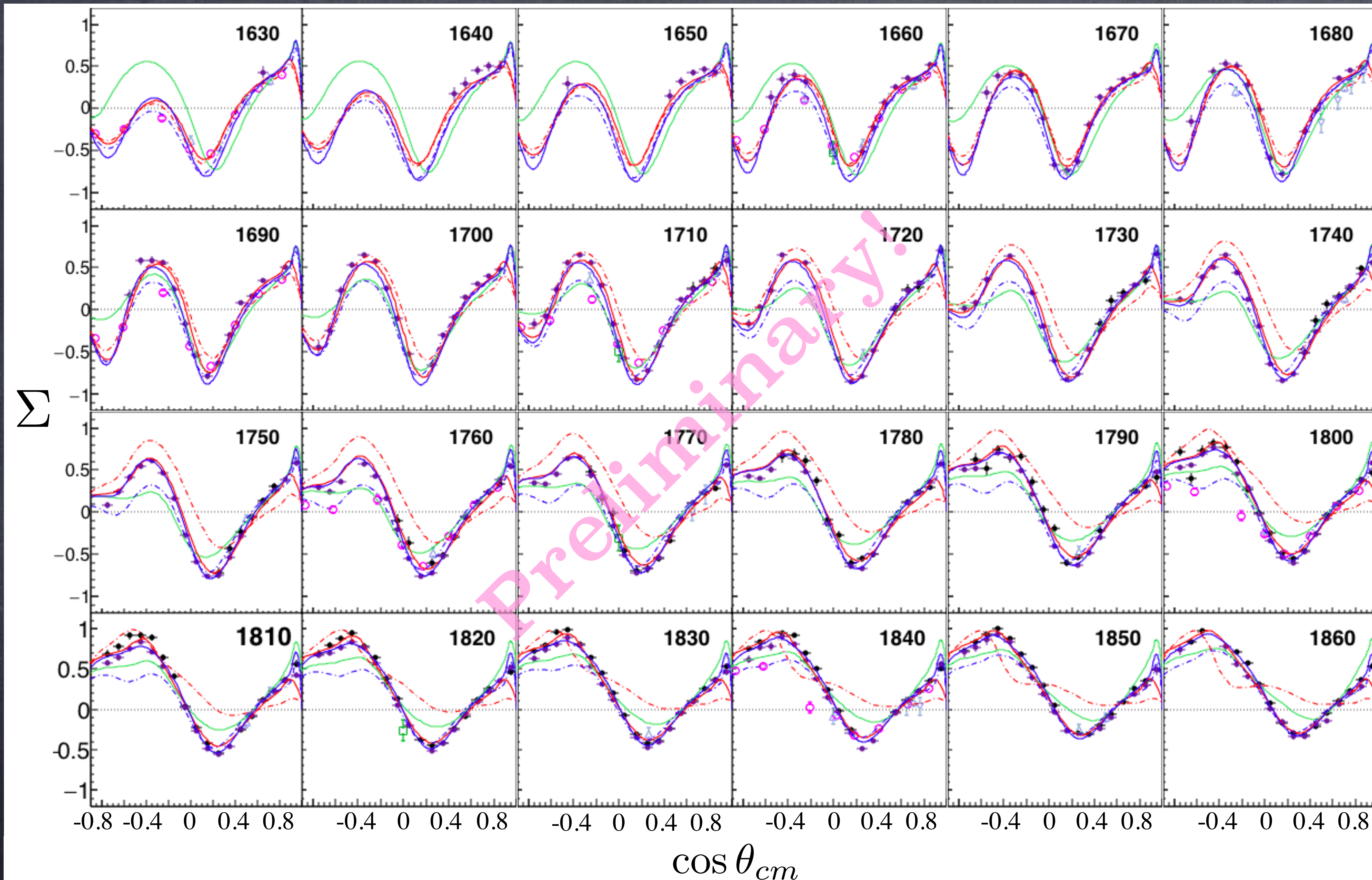




Data from rest of the energy settings

This includes "bad" fit results where the fit probability was < 0.05 (excluded from final data-set).

Results I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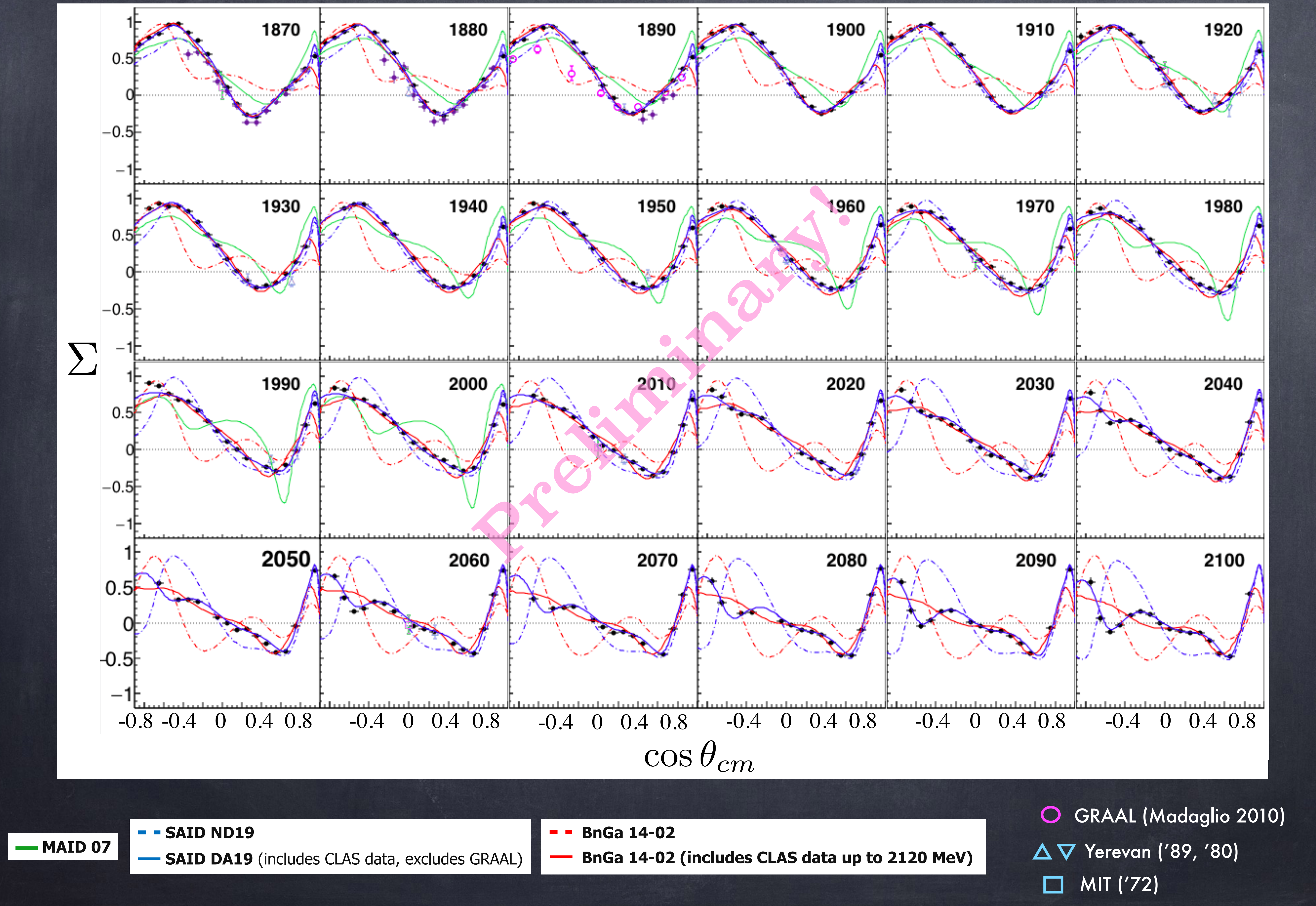
1860
Preliminary!
Σ
cos θ_cm
MAID 07
SAID ND19
SAID DA19 (includes CLAS data, excludes GRAAL)
BnGa 14-02
BnGa 14-02 (includes CLAS data up to 2120 MeV)
GRAAL (Madaglio 2010)
Yerevan ('89, '80)
MIT ('72)

Results II



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2090
2100
Preliminary!
Σ
cos θ_{cm}
MAID 07
SAID ND19
SAID DA19 (includes CLAS data, excludes GRAAL)
BnGa 14-02
BnGa 14-02 (includes CLAS data up to 2120 MeV)
GRAAL (Madaglio 2010)
Yerevan ('89, '80)
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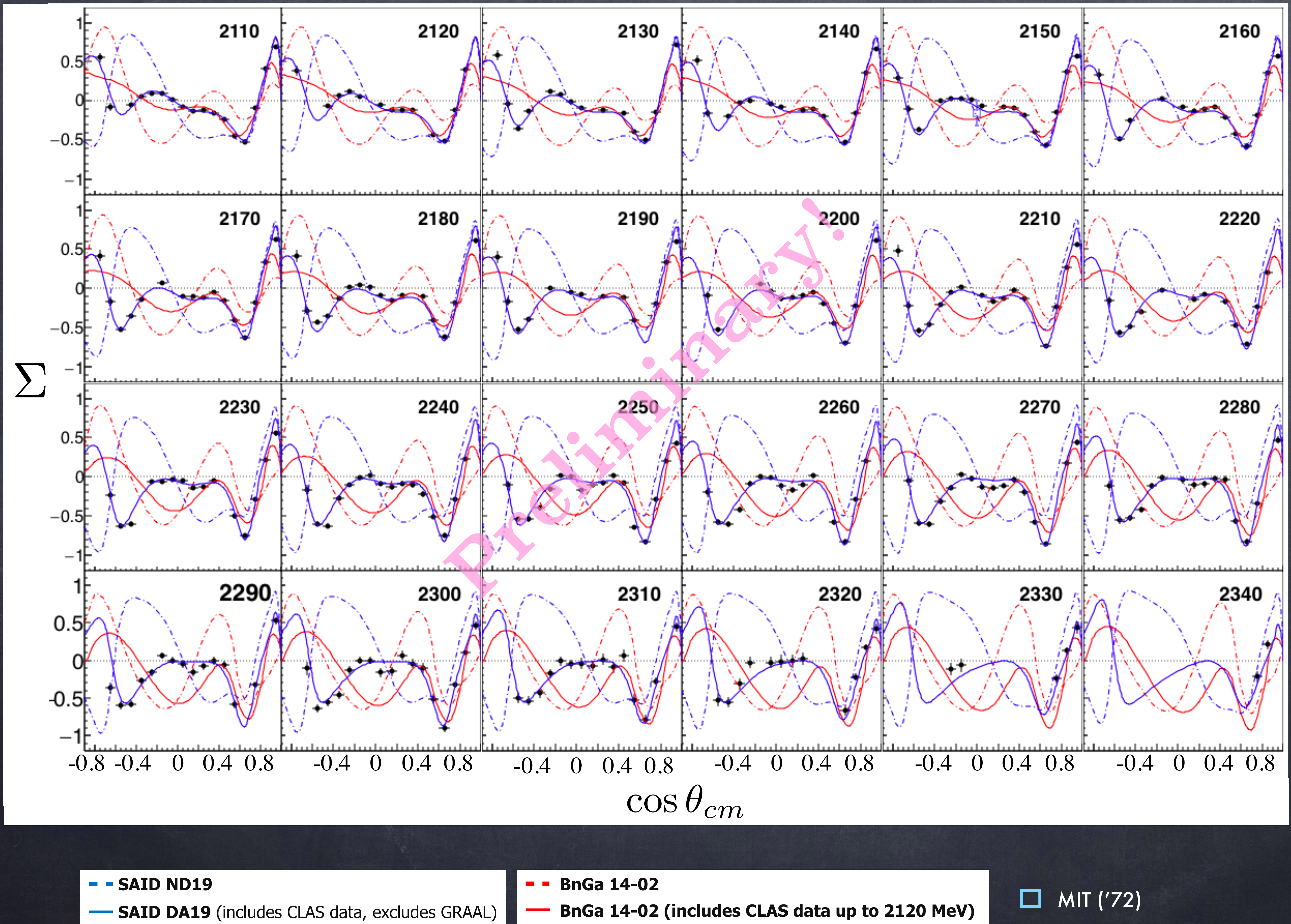
Results III



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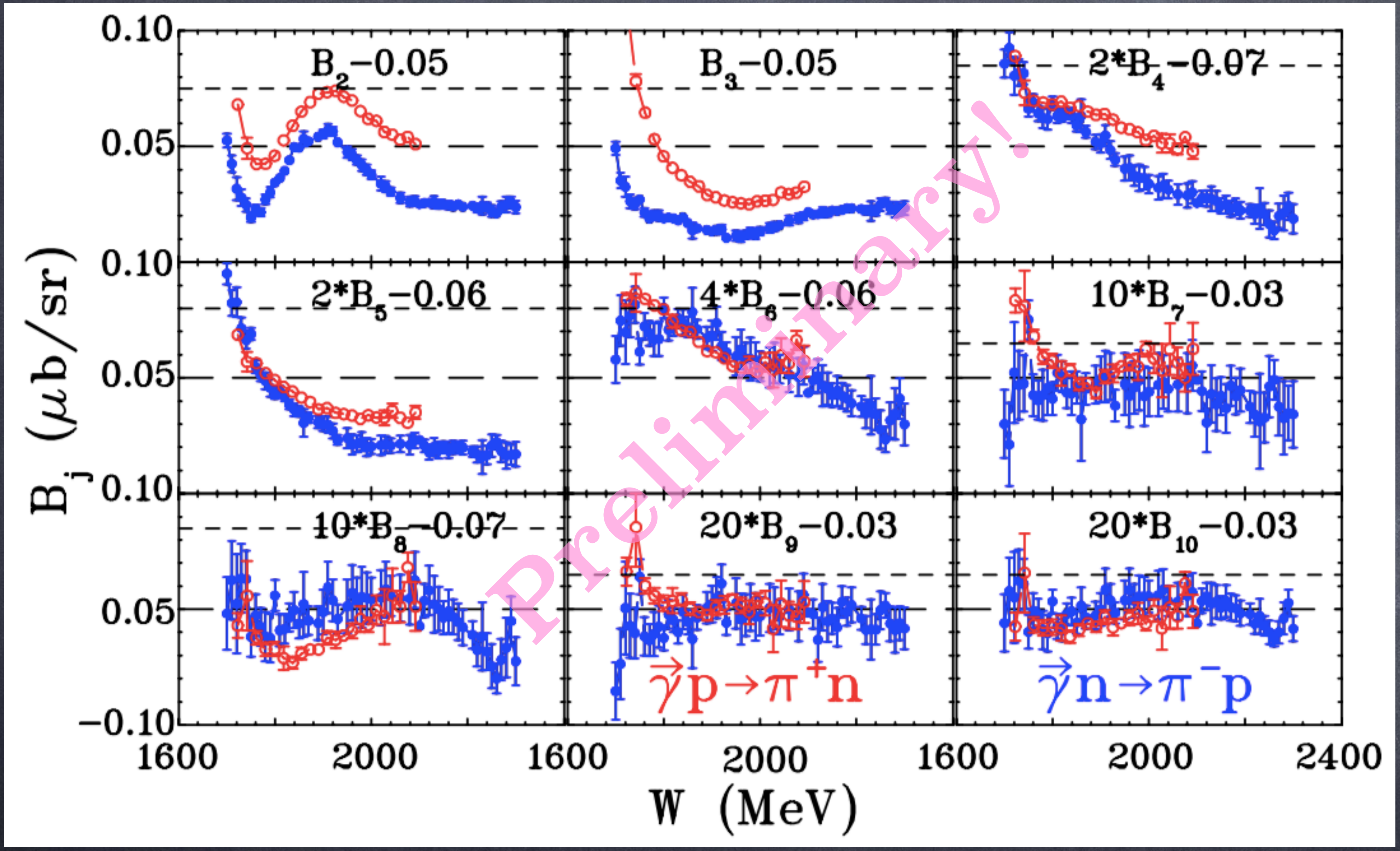
2340
Σ
cos θ_cm
Preliminary!
SAID ND19
SAID DA19 (includes CLAS data, excludes GRAAL)
BnGa 14-02
BnGa 14-02 (includes CLAS data up to 2120 MeV)
MIT ('72)

SAID PWA

Legendre expansion: model-independent approach but requires very high-statistics data. Ya. Azimov, I. Strakovsky, W. Briscoe and R. Workman, Phys. Rev. C **95**, 025205 (2017).



Coefficients of second order Legendre functions, scaled $nB_J + m$ to allow visualisation on a common abscissa. Only statistical errors were used in fits.

I. Strakovsky

Proton target data:
M. Dugger et al. (CLAS), PRC **88**, 065203 (2013).

Neutron target data:
This measurement

- B_J appears to reduce significantly by J ~ 10: sufficient to truncate the series.
- Will be used in phase shift analysis to better understand the resonant amplitudes.

Summary

- Very high-statistics measurement of beam asymmetry in the range 1.6 < W < 2.3 GeV, in charged pion photoproduction from the neutron:

$$\gamma + d \rightarrow \pi^- + p + (p_{spectator})$$

- Greatly expanded the sparse world data set on the neutron with > 1000 new data points.
- A sizeable asymmetry changing rapidly with both scattering angle and invariant mass can be observed.
- Comparison with the most recent PWA predictions shows significant differences, especially with the BnGa PWA and at W > 2 GeV.
- Inclusion of the data into the SAID PWA yields a very good fit.
- BnGa fit including the new CLAS data up to 2120 MeV shows a reasonably good fit. Addition of new states is required to fit the data above 2120 MeV → *in progress!*
- Extraction of multipoles in both SAID and BnGa PWAs in progress...

Thank you!

IOP Institute of Physics

International Nuclear Physics Conference 2019

29 July – 2 August 2019, Scottish Event Campus, Glasgow, UK

Key dates

Abstract submission deadline:

25 January 2019

Early registration deadline:

1 June 2019

Registration deadline:

19 July 2019

http://inpc2019.iopconfs.org/home

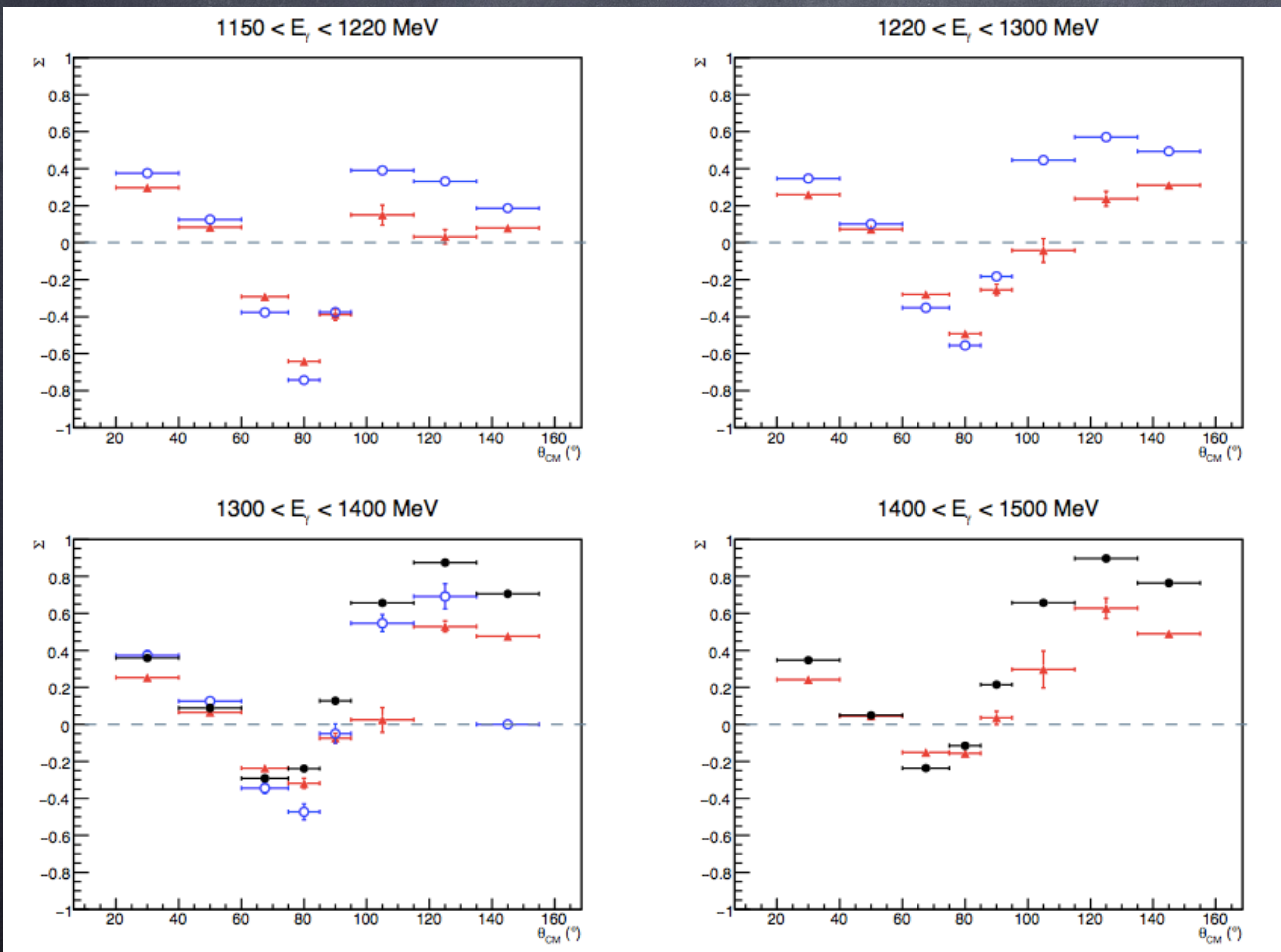
Come to Scotland!

Back-up

Discrepancy with GRAAL

- A discrepancy with GRAAL data is still observed in some bins, particularly at backward angles. This was investigated by binning in the same width bins as GRAAL:

● g13, all data except 1.3 GeV setting
○ g13, 1.3 GeV setting data
▲ GRAAL



The energy bins are very wide. Different acceptances and different parts of phase space contributing, so it's possible that the Sigmas cannot be directly compared.

GRAAL data does seem to give generally lower absolute Sigmas (possibly a polarisation systematic?)

Inconclusive!