Overview on CLAS Baryon Results

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Florida State University
Tallahassee, FL

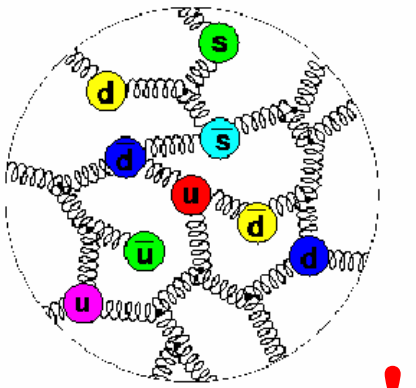
Hadron 2011

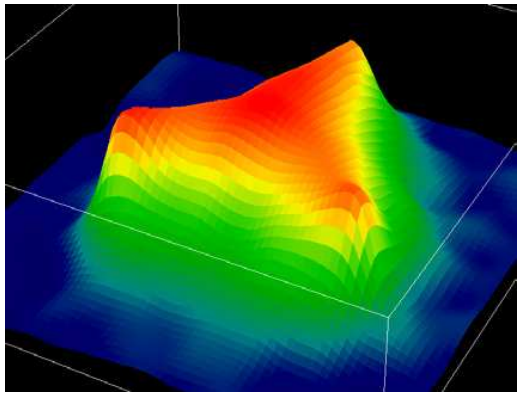
Munich, 06/13/2011

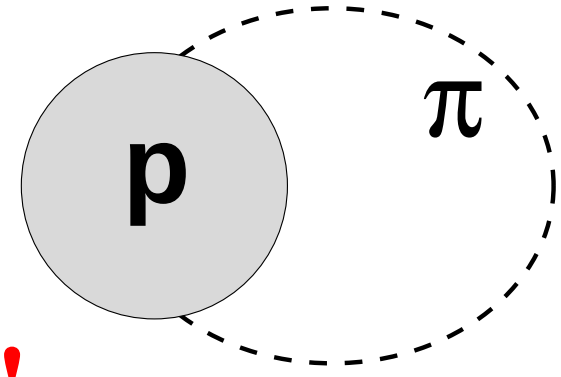
Outline

Outline

$\ll 0.1$fm | 0.1 – 1.0 fm | > 1.0 fm







pQCD
q, g, $q\bar{q}$

? ! ↔ ? !

Models
Quarks and Gluons
as Quasiparticles

? ! ↔ ! ?

ChPT
Nucleon and
Mesons

1. What are the relevant degrees of freedom?
2. What are the corresponding effective interactions responsible for hadronic phenomena?

One of the Goals of the N^* Program ...

... is the search for *missing* or yet unobserved baryon resonances.

Quark models predict many more baryons than have been observed.

	****	***	**	*
N Spektrum	11	3	6	2
Δ Spektrum	7	3	6	6

➜ Particle Data Group
(J. Phys. G **37**, 075021 (2010))

➜ little known
(many open questions left)

1. Are the states missing in the predicted spectra because our pictures do not capture the correct degrees of freedom?
2. Or have the resonances simply escaped detection?

One of the Goals of the N^* Program ...

... is the search for *missing* or yet unobserved baryon resonances.

Quark models predict many more baryons than have been observed.

	****	***	**	*
N Spektrum	11	3	6	2
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➜ Particle Data Group
(J. Phys. G **37**, 075021 (2010))

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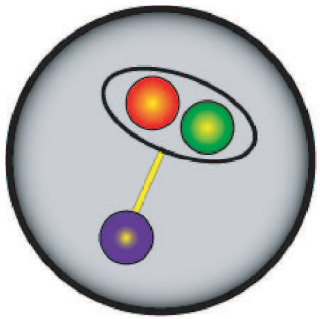
Possible solutions:

1. Quark-diquark structure



One of the internal degrees of freedom is frozen.

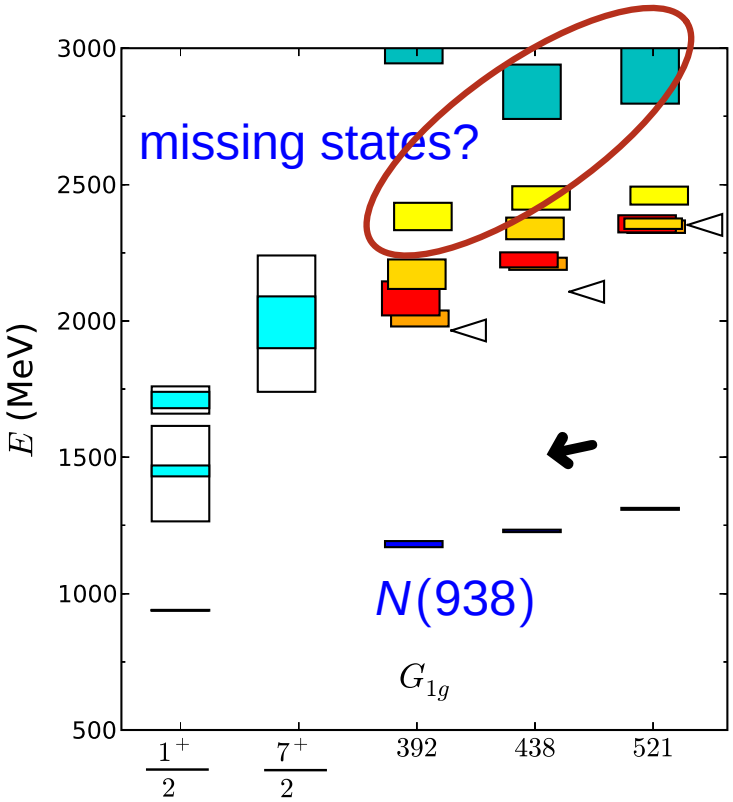
2. Have not been observed, yet.

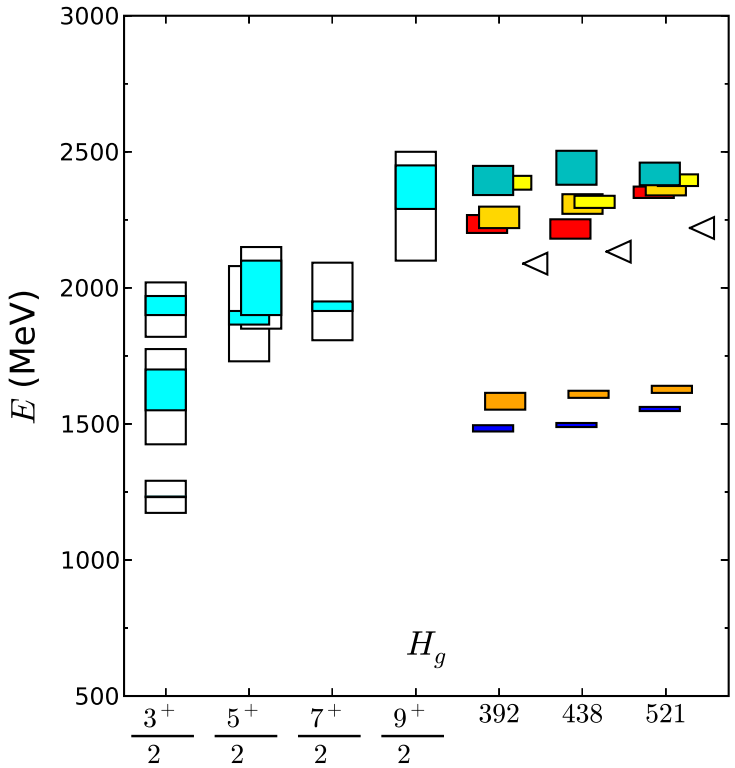
Nearly all existing data on baryons result from πN scattering experiments.

➜ If the resonances did not couple to πN, they would not have been discovered!!

First Lattice Calculations of Baryon Spectrum

J. Bulava *et al.*, Phys. Rev. D **82**, 014507 (2010) (➜ talk by R. Edwards, Thursday, Plenary 8)



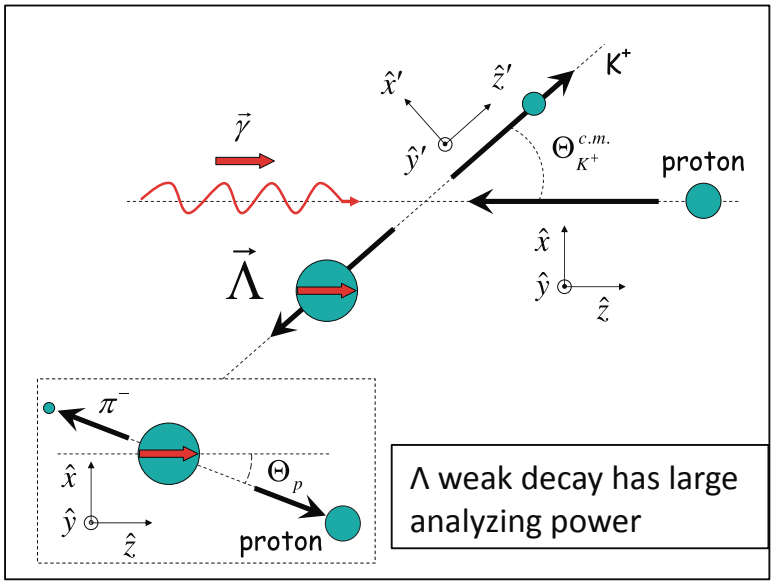


Δ(1600)
Δ(1232)

Many approximations, but efforts show what will be possible.

- Suggests spectrum at least as dense as quark model

Complete Experiments in Photoproduction



Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables.

Eight well-chosen measurements are needed to fully determine the amplitude

- 16 observables will be measured with CLAS
  ➜ Allows many cross checks

Photon beam		*Target*			*Recoil*			*Target - Recoil*								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly P_γ	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E		F	$L_{x'}$	$C_{x'}$	$T_{x'}$
circular P_γ		F		E	$C_{x'}$		$C_{z'}$		$O_{z'}$		G		H		$O_{x'}$	

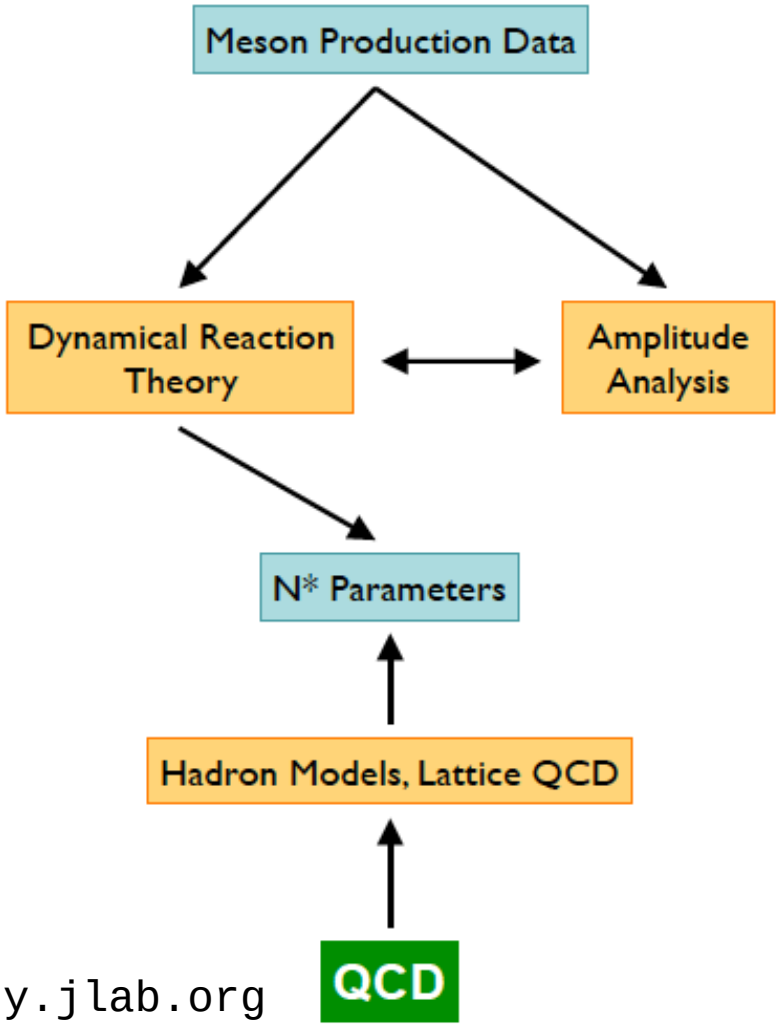
e.g. $\gamma p \to K\Lambda$

- ✓ published
- ✓ to be published
- ✓ data taken
- ✓ data taken, being analyzed

Extraction of Resonance Parameters

- Double-polarization measurements
- Measurements off neutron and proton to resolve isospin contributions:
  1. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=3/2} \iff \Delta^*$
  2. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=1/2} \iff N^*$
- Re-scattering effects: Large number of measurements (and reaction channels) needed to define full scattering amplitude.

Coupled Channels



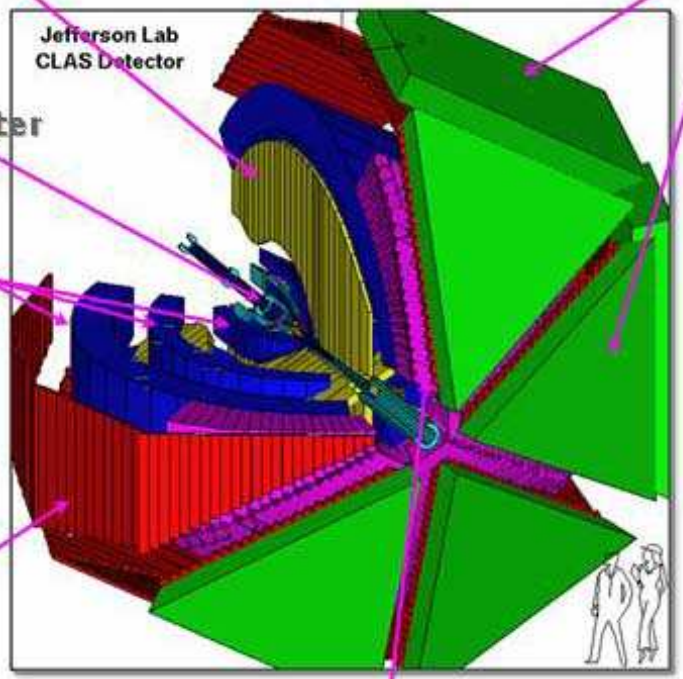
http://ebac-theory.jlab.org

Outline

CEBAF Large Acceptance Spectrometer (CLAS)

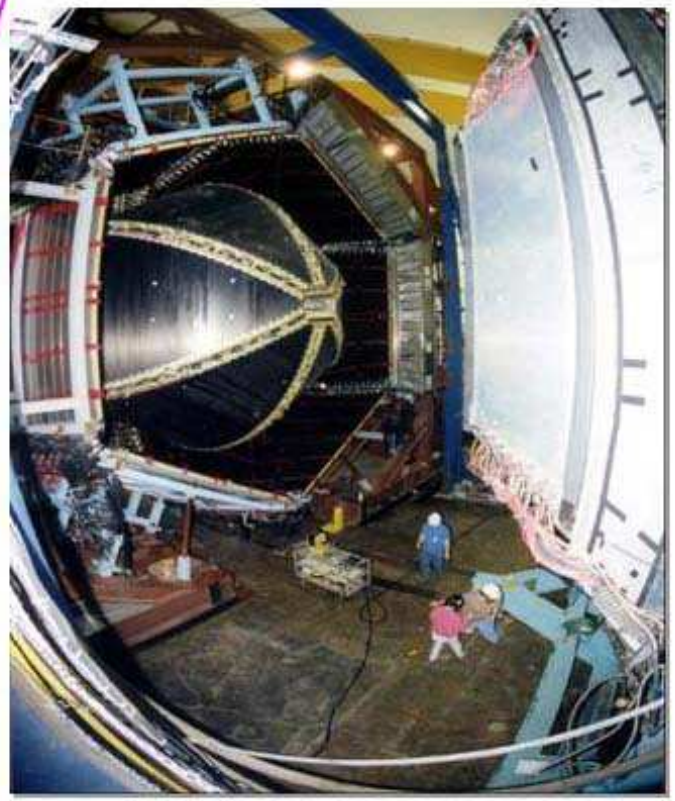
Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers



target + start counter

Drift chambers
argon/CO_2 gas, 35,000 cells



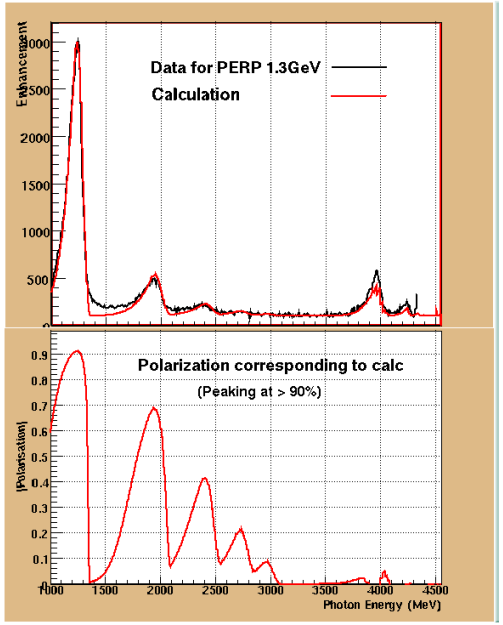
Time-of-flight counters
plastic scintillators, 684 photomultipliers

Gas Cherenkov counters

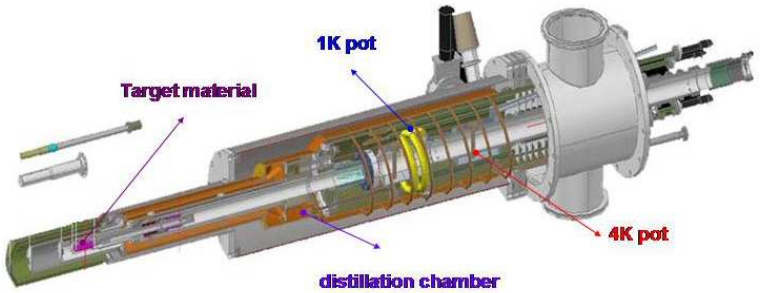
CLAS (Polarization) Run Periods: Photoproduction

- g1c: C_x and C_z, $I^{\odot}$ for $\gamma p \to p\pi^+\pi^-$
  (circ.-pol. beam, mostly published)
- g8b: Σ, I^s and I^c
  (lin.-pol. beam, H_2)
- FROST
  (double pol., C_4H_9OH)
- g13
  (lin.-pol. beam, D_2)
- HD-ICE
  ➜ future measurements
  (Fall 2011)

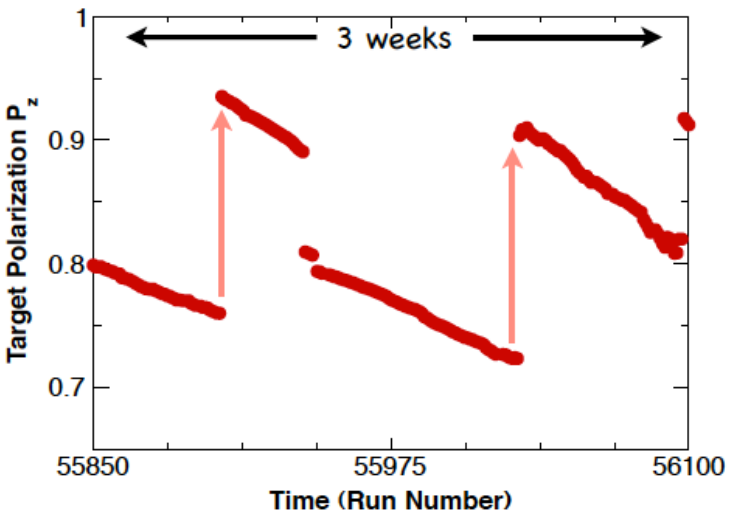
➜ g8b

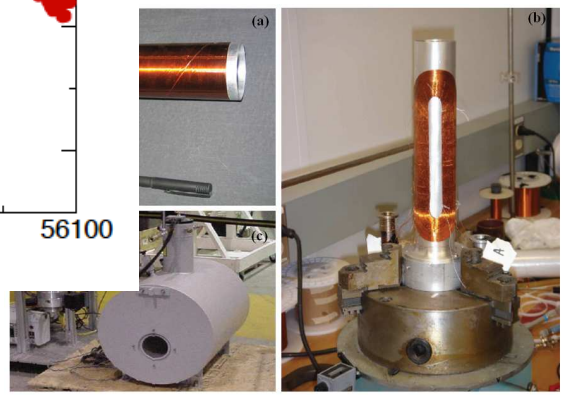


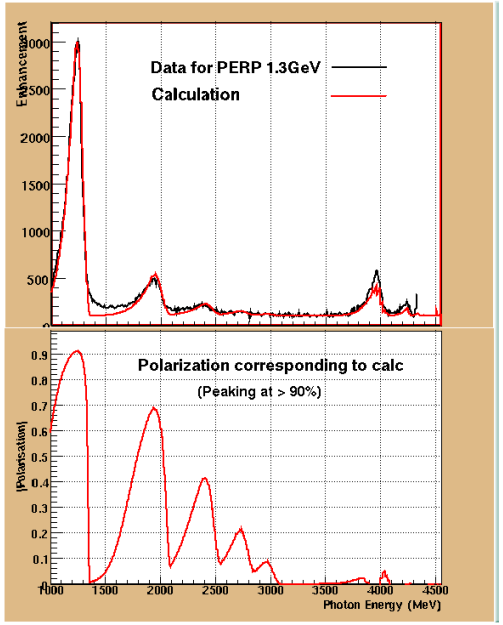
FROST ➜



Double-Polarization Measurements using FROST



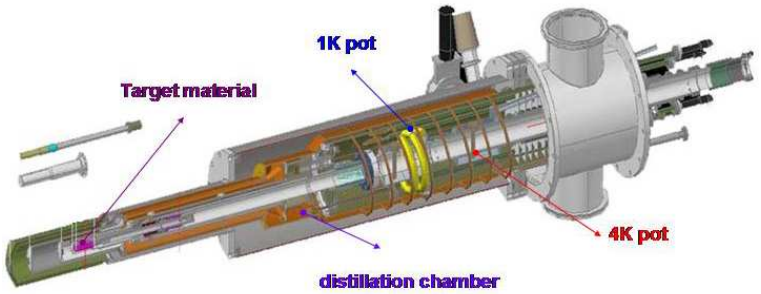




FROST

FRozen-Spin Target (FROST)

- $P_z \approx 80\,\%$
- Relaxation time $\sim$ 2,000 h
- Holding mode (0.5 T, $\approx$ 28 mK)



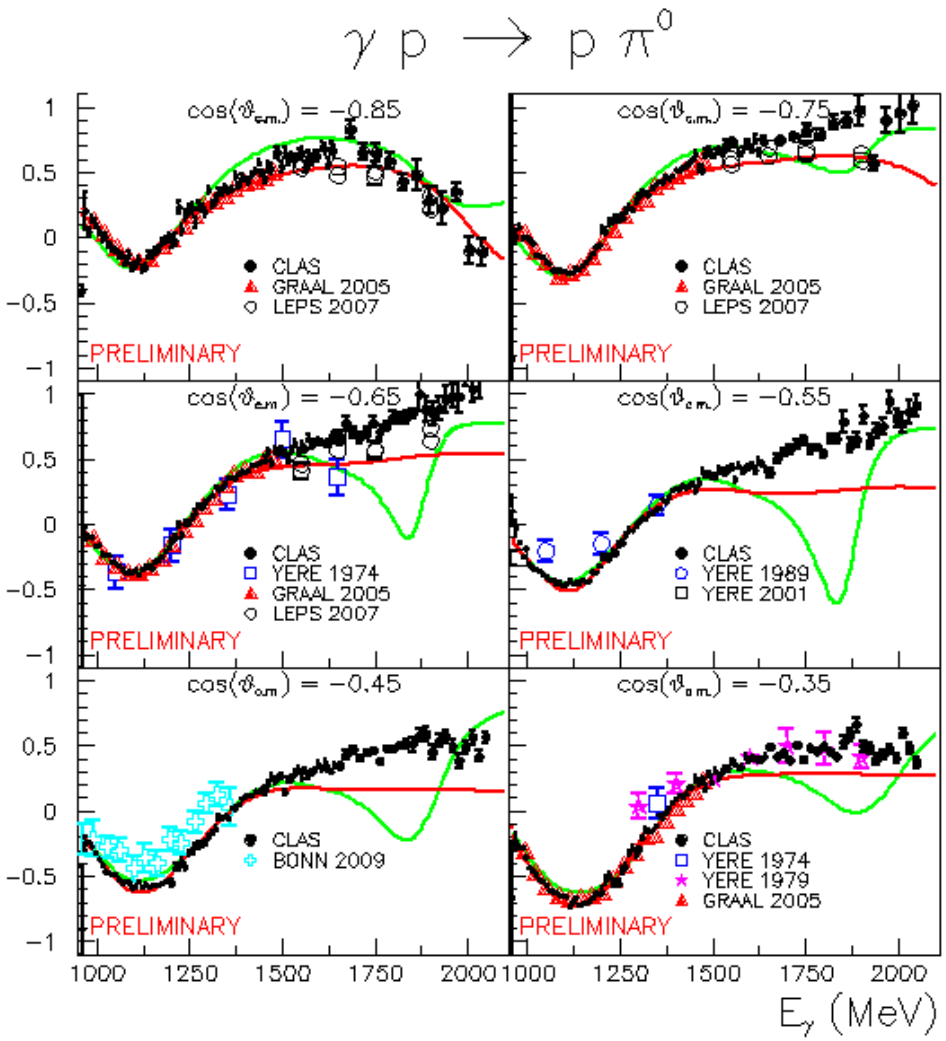
Outline

Beam Asymmetry Measurements: CLAS g8b

All analyses are about to be reviewed by the CLAS collaboration; held back by studies of the linear polarization.

- $\gamma p \to p\,\pi^0,\, n\,\pi^+$ (M. Dugger *et al.*) Arizona State University
- $\gamma p \to p\,\eta,\ \eta'$ (P. Collins *et al.*) Arizona State University
- $\gamma p \to p\,\omega$ (P. Collins *et al.*) Catholic University
- $\gamma p \to p\,\pi^+\pi^-$ (C. Hanretty *et al.*) Florida State University
- $\gamma p \to p\,\phi$ (J. Salamanca *et al.*) Idaho State University
- $\gamma p \to K^+ Y$ (C. Paterson *et al.*) University of Edinburgh, Glasgow

Beam Asymmetry Σ in $\gamma p \to p\,\pi^0$



$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l \mathbf{H} \sin 2\phi + \delta_\odot \mathbf{F}) - \Lambda_y (-\mathbf{T} + \delta_l \mathbf{P} \cos 2\phi) - \Lambda_z (-\delta_l \mathbf{G} \sin 2\phi + \delta_\odot \mathbf{E}) \}$$

— SAID — MAID • CLAS

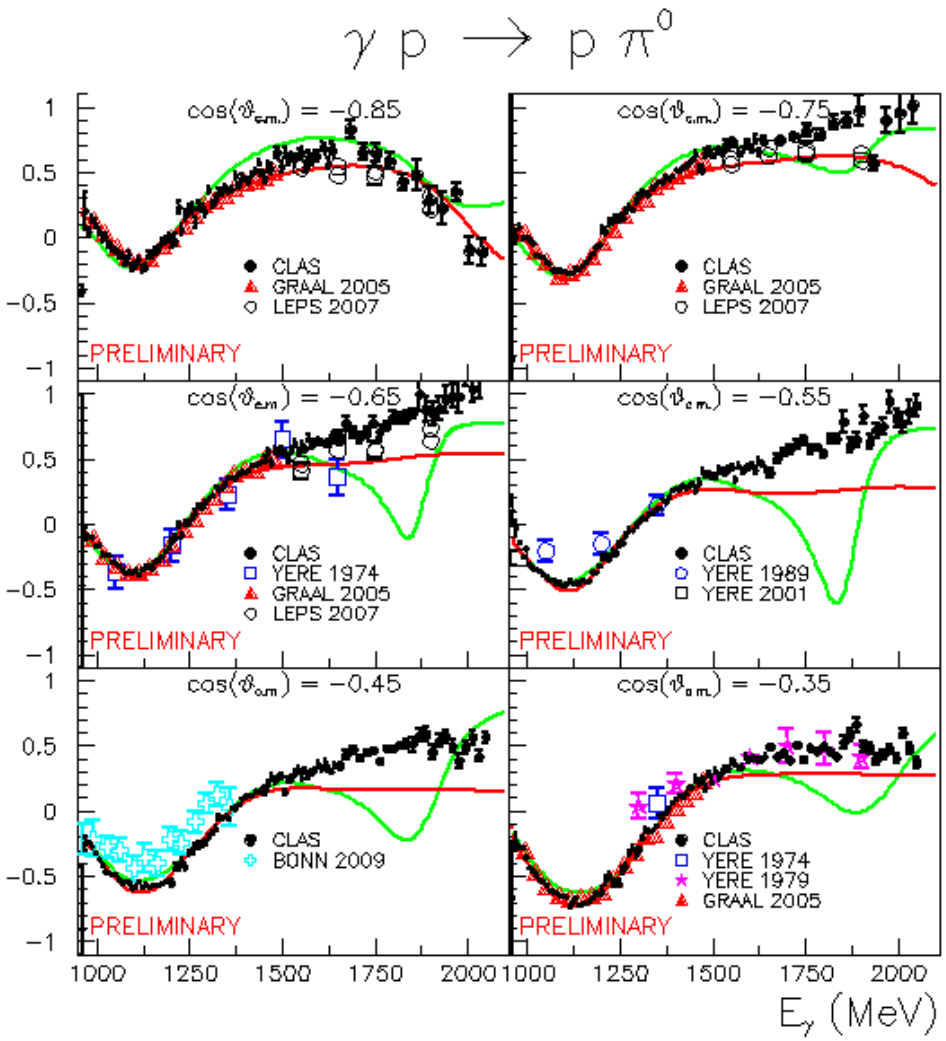
($E_\gamma < 2$ GeV, $-0.85 < \cos\theta_\pi < 0.85$)

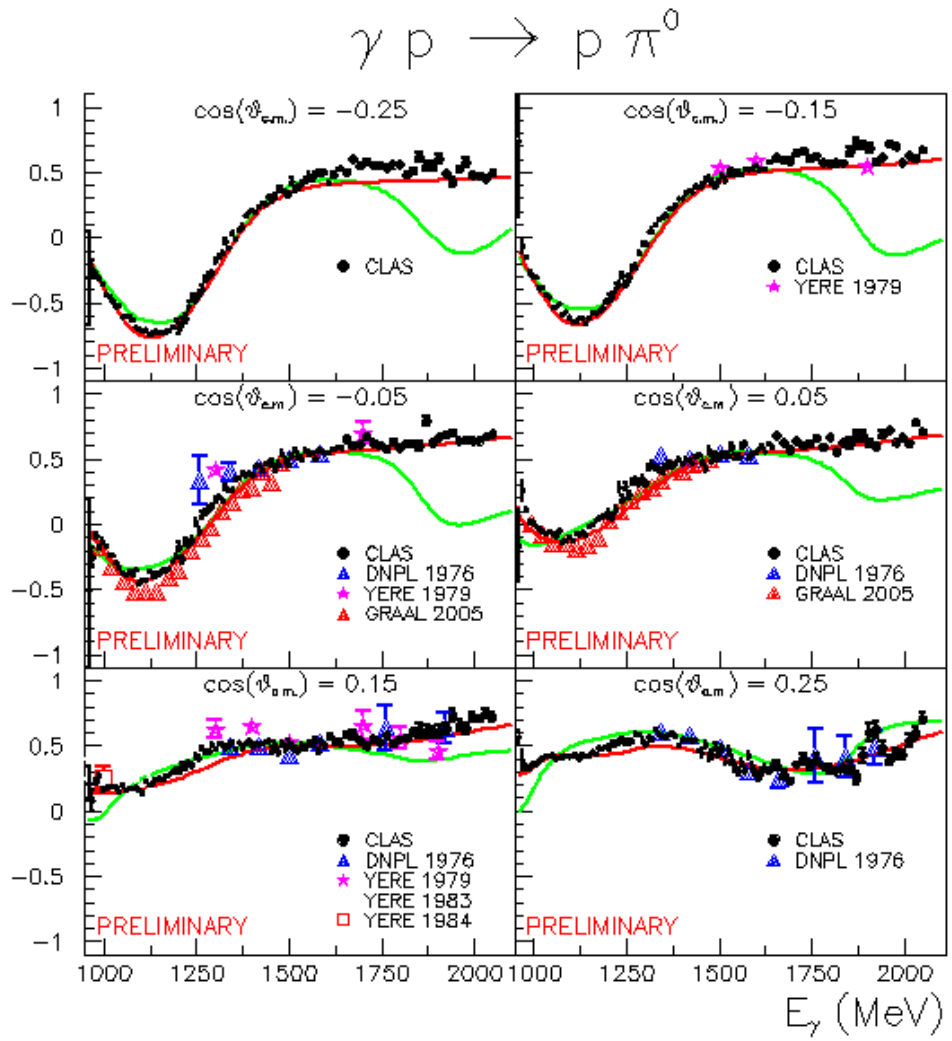
➜ Serious discrepancies between models and data.

M. Dugger (ASU), CLAS g8b run group, to be published

ASU Arizona State University

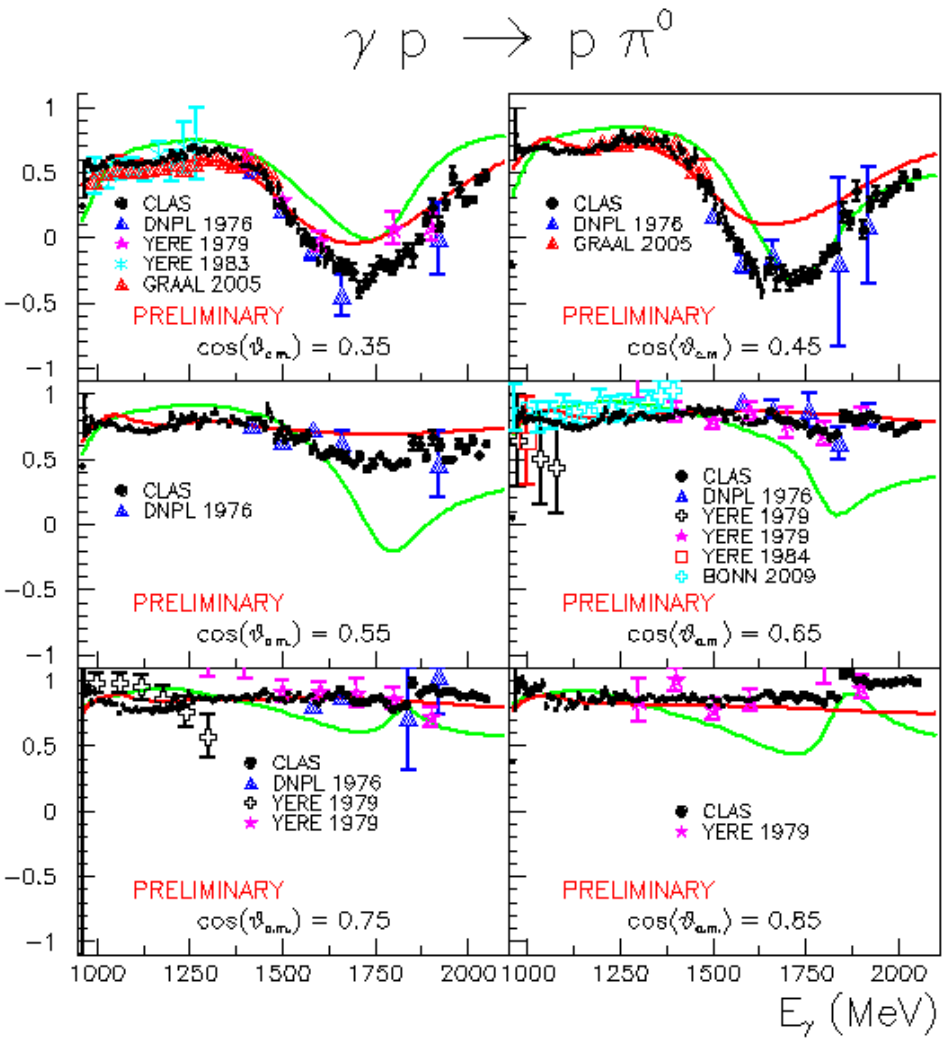
Beam Asymmetry Σ in $\gamma p \to p\,\pi^0$





M. Dugger (ASU), CLAS g8b run group, to be published

Beam Asymmetry Σ in $\gamma p \to p\,\pi^0$



Combination of $p\,\pi^0$ and $n\,\pi^+$ final states can help distinguish between Δ and N^* resonances:

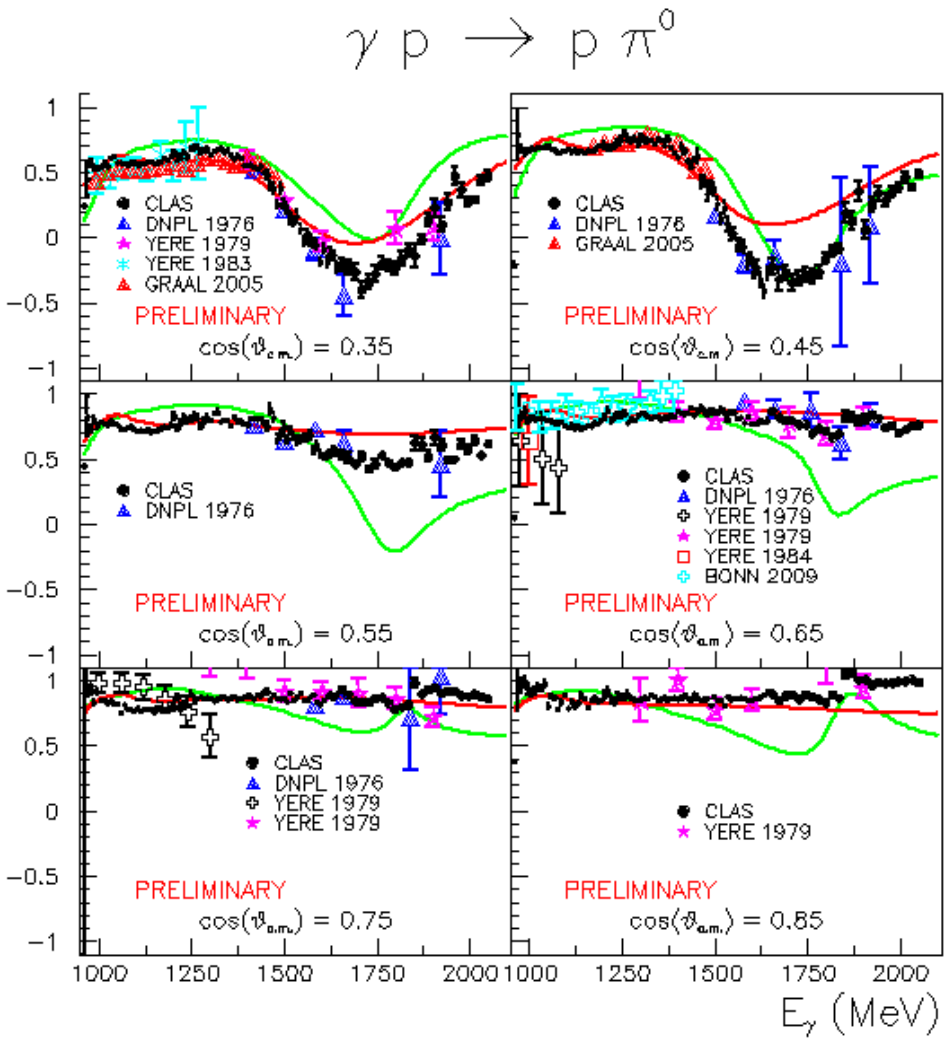
Δ^+ $\qquad$ N^*

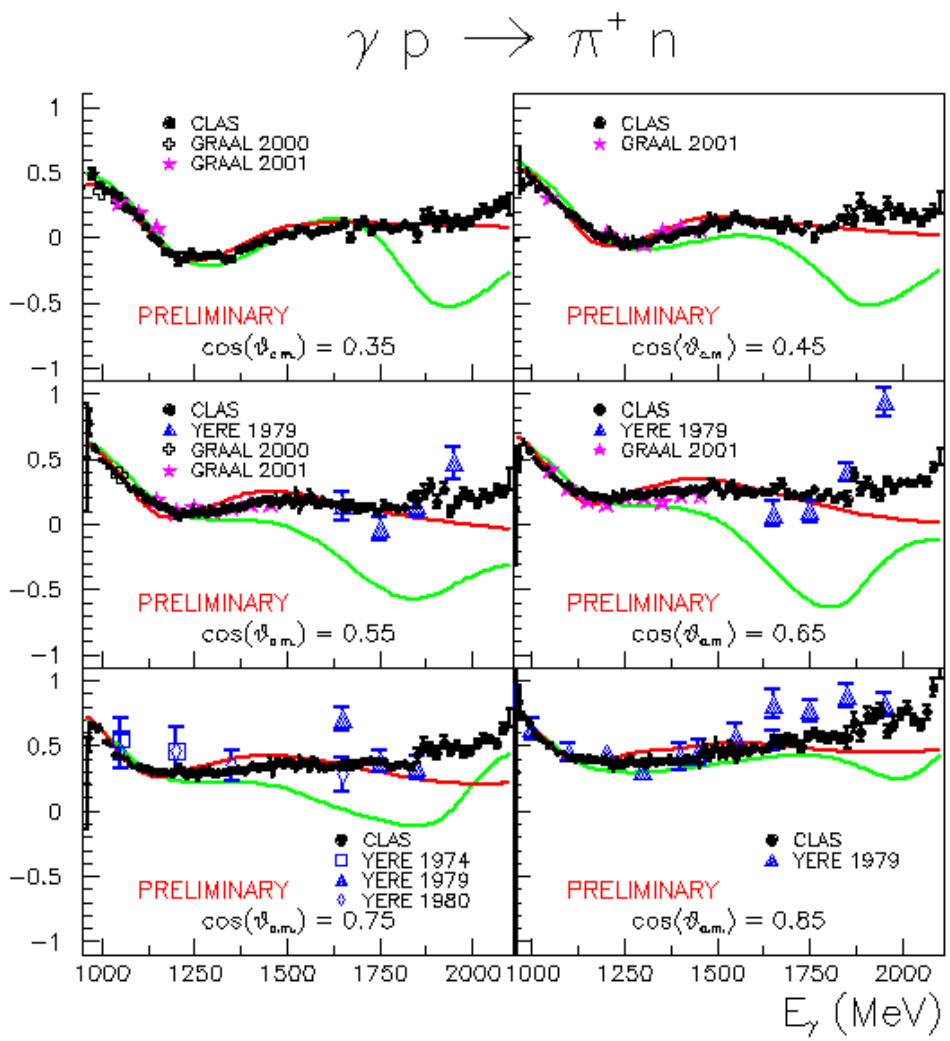
$$\pi^0 + p : \sqrt{2/3}\left|I=\tfrac{3}{2}, I_3=\tfrac{1}{2}\right\rangle - \sqrt{1/3}\left|I=\tfrac{1}{2}, I_3=\tfrac{1}{2}\right\rangle$$

$$\pi^+ + n : \sqrt{1/3}\left|I=\tfrac{3}{2}, I_3=\tfrac{1}{2}\right\rangle + \sqrt{2/3}\left|I=\tfrac{1}{2}, I_3=\tfrac{1}{2}\right\rangle$$

M. Dugger (ASU), CLAS g8b run group, to be published

Beam Asymmetry Σ in $\gamma p \to p\,\pi^0$ and $\gamma p \to n\,\pi^+$





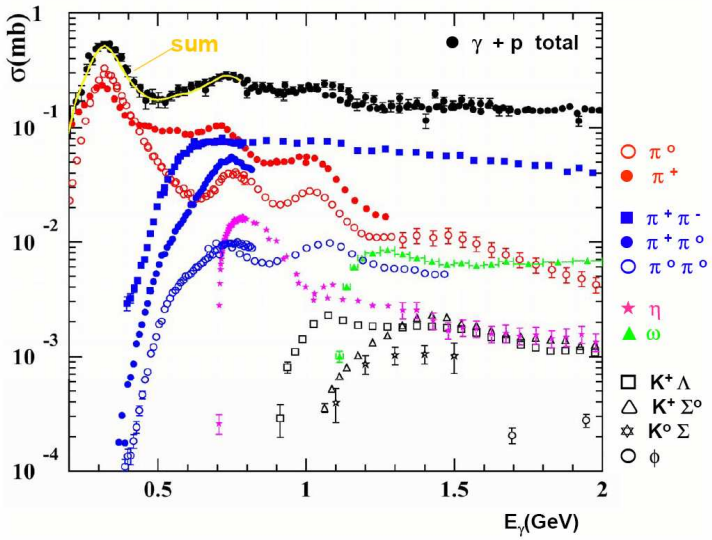
M. Dugger (ASU), CLAS g8b run group, to be published

Beam-Target Polarization Observables

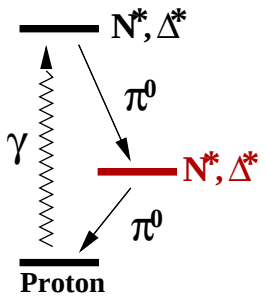
W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}$$

$\Leftarrow$ Double-Meson Final States (15 Observables)



At higher excitation energies:
Multi-meson final states play an increasingly important role.



➜ Search for states in cascades!

Photoproduction of $\pi^+\pi^-$ off the Proton: Kinematics

Two mesons in the final state require 5 independent variables!

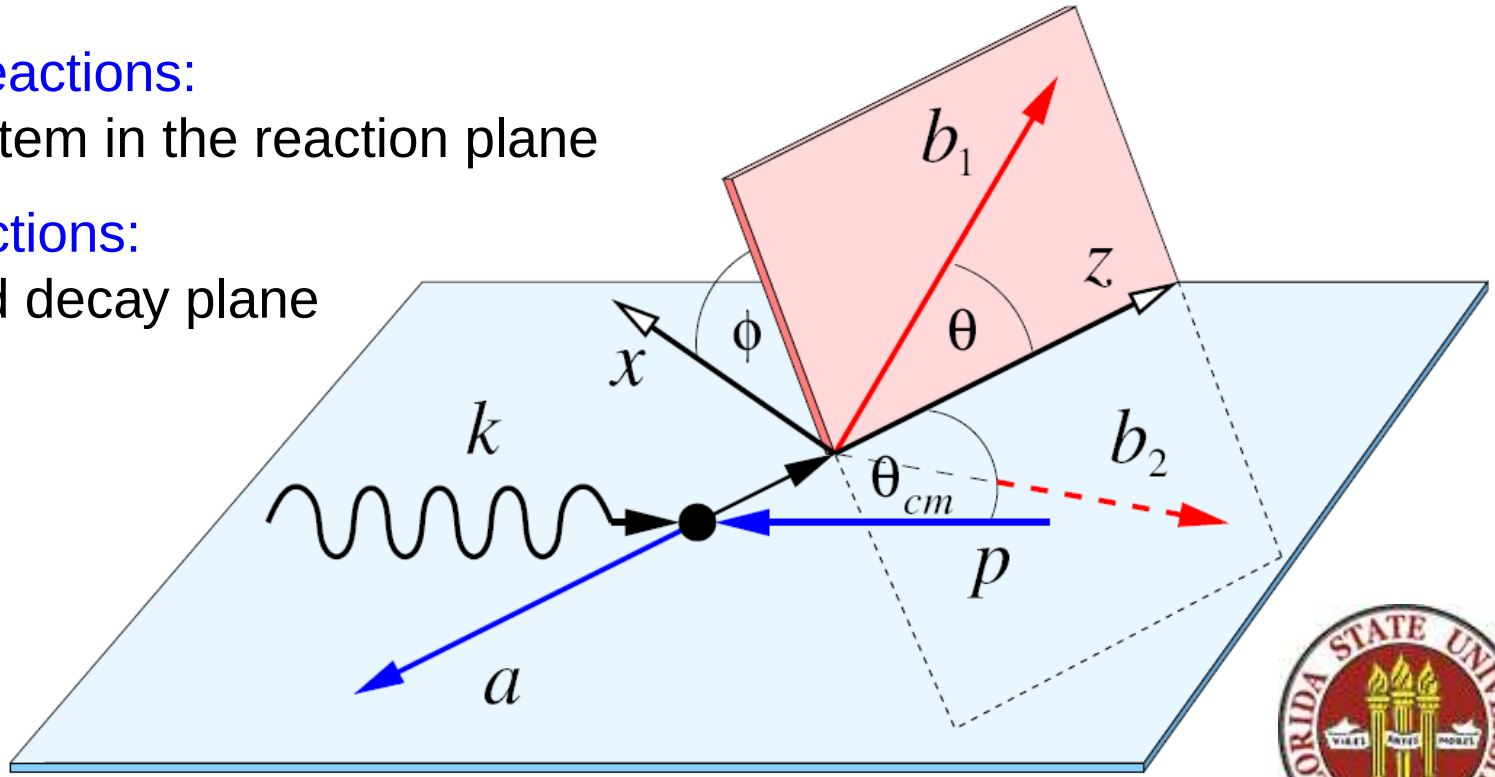
For example: E_γ, $\Theta_{\text{c.m.}}$, ϕ^*, θ^*, $M_{p+\text{meson}\,1}$

Single-meson reactions:

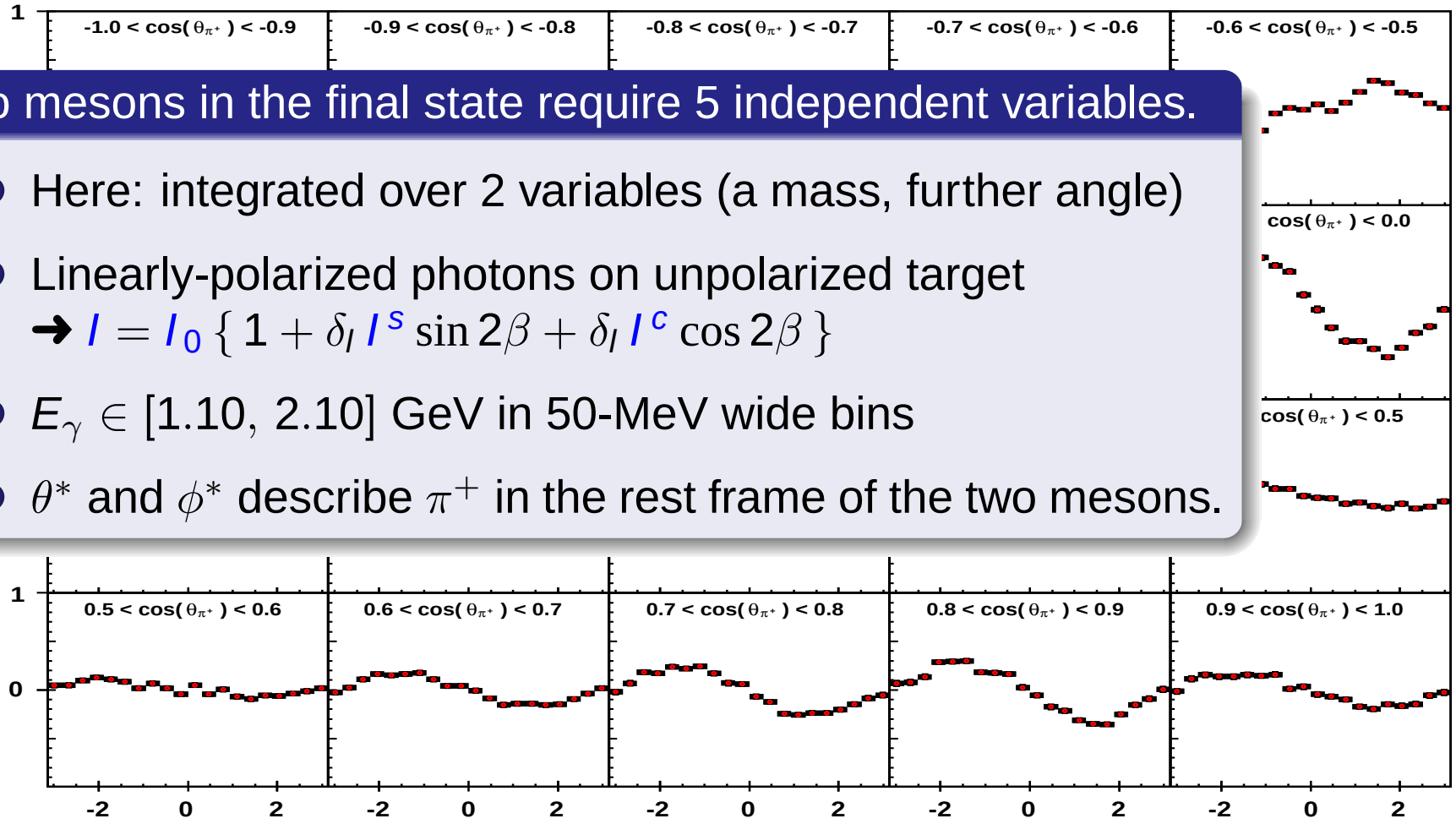
➜ p-meson system in the reaction plane

Two-meson reactions:

➜ Reaction and decay plane form angle ϕ



I^s in $\gamma p \to p\,\pi^+\pi^-$ $1100 < E_\gamma < 1150$ MeV

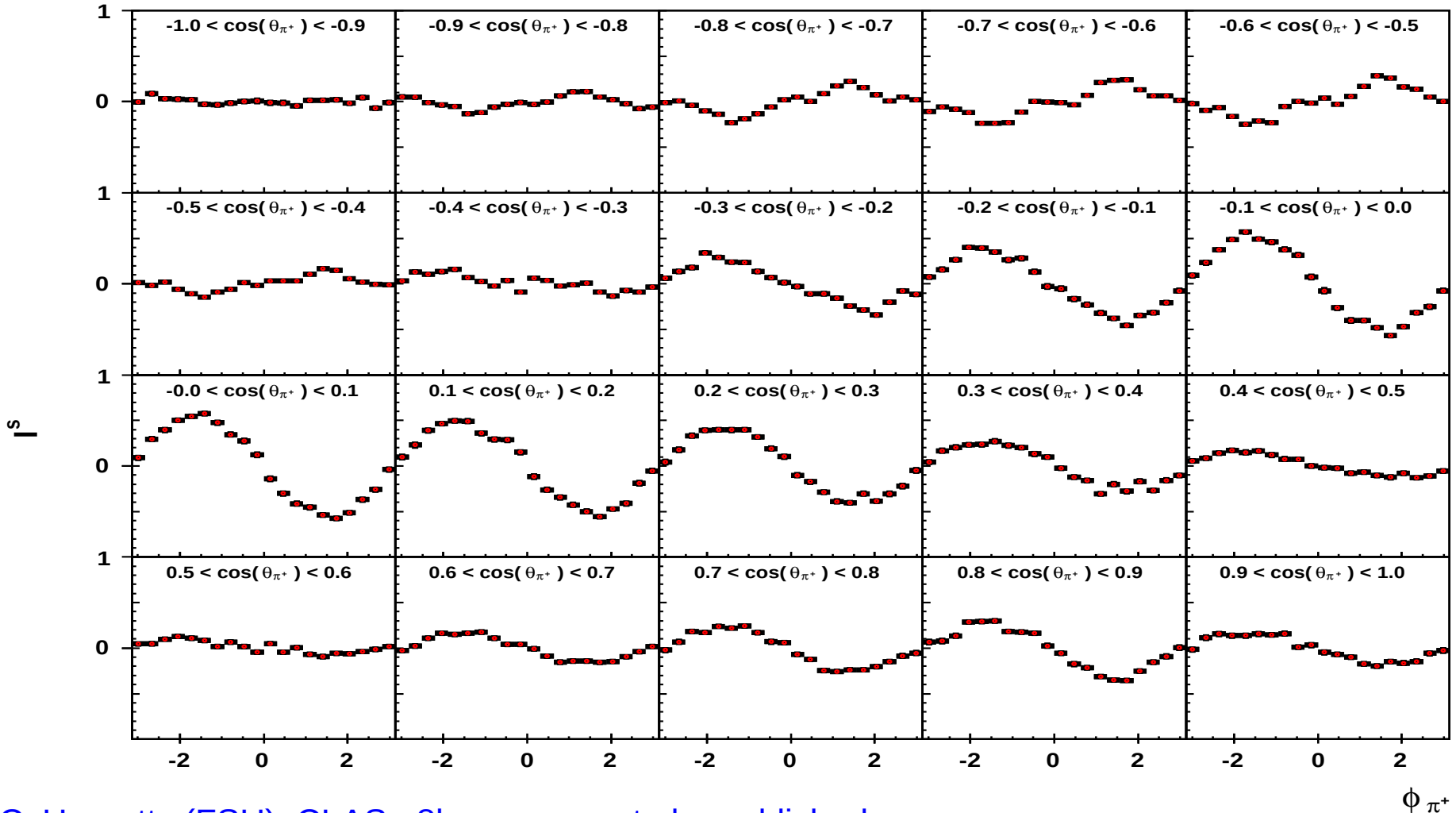


Two mesons in the final state require 5 independent variables.

- Here: integrated over 2 variables (a mass, further angle)
- Linearly-polarized photons on unpolarized target
  ➜ $I = I_0 \{ 1 + \delta_l I^s \sin 2\beta + \delta_l I^c \cos 2\beta \}$
- $E_\gamma \in [1.10, 2.10]$ GeV in 50-MeV wide bins
- θ^* and ϕ^* describe π^+ in the rest frame of the two mesons.

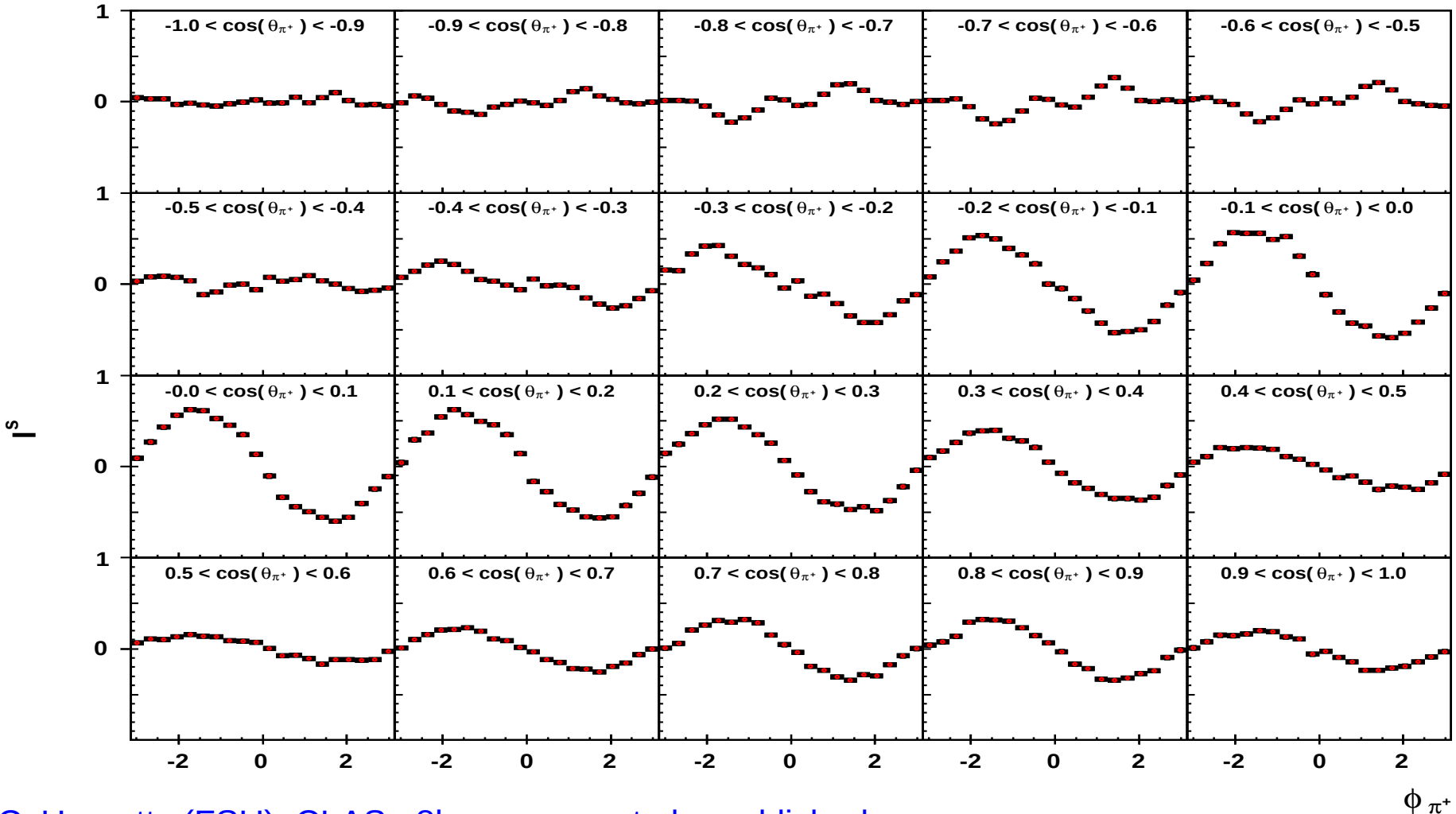
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1100 < E_\gamma < 1150$ MeV



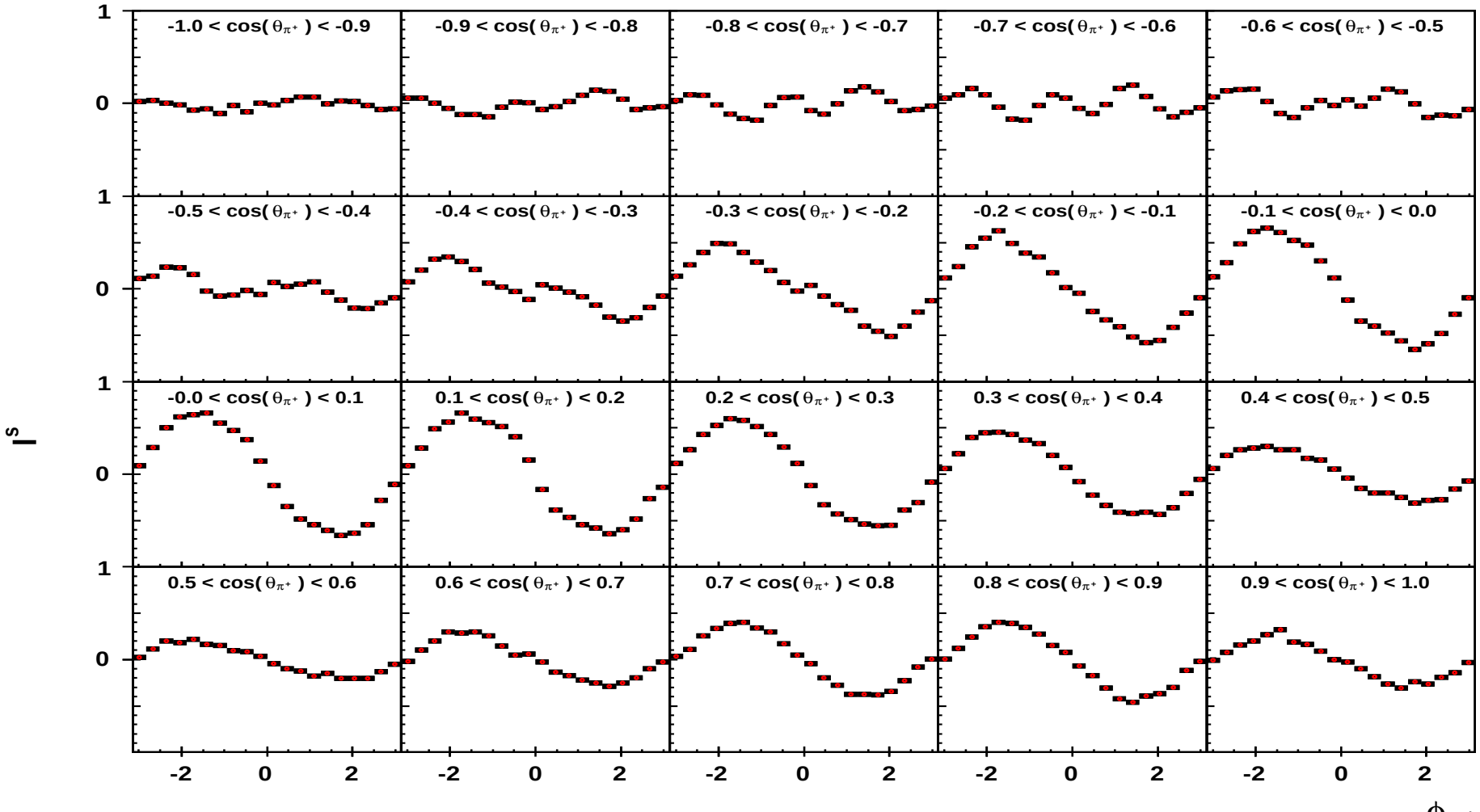
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1150 < E_\gamma < 1200$ MeV



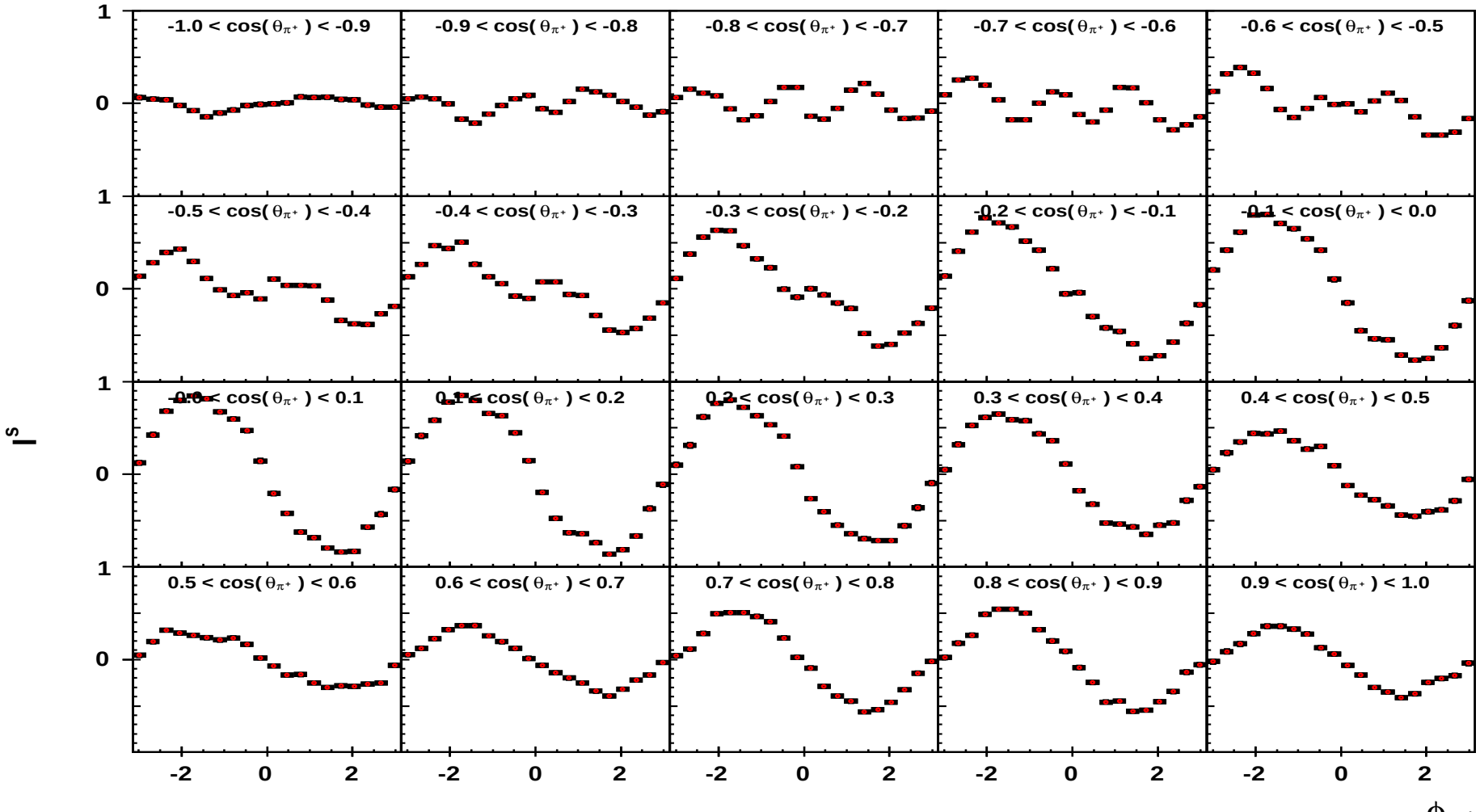
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1200 < E_\gamma < 1250$ MeV



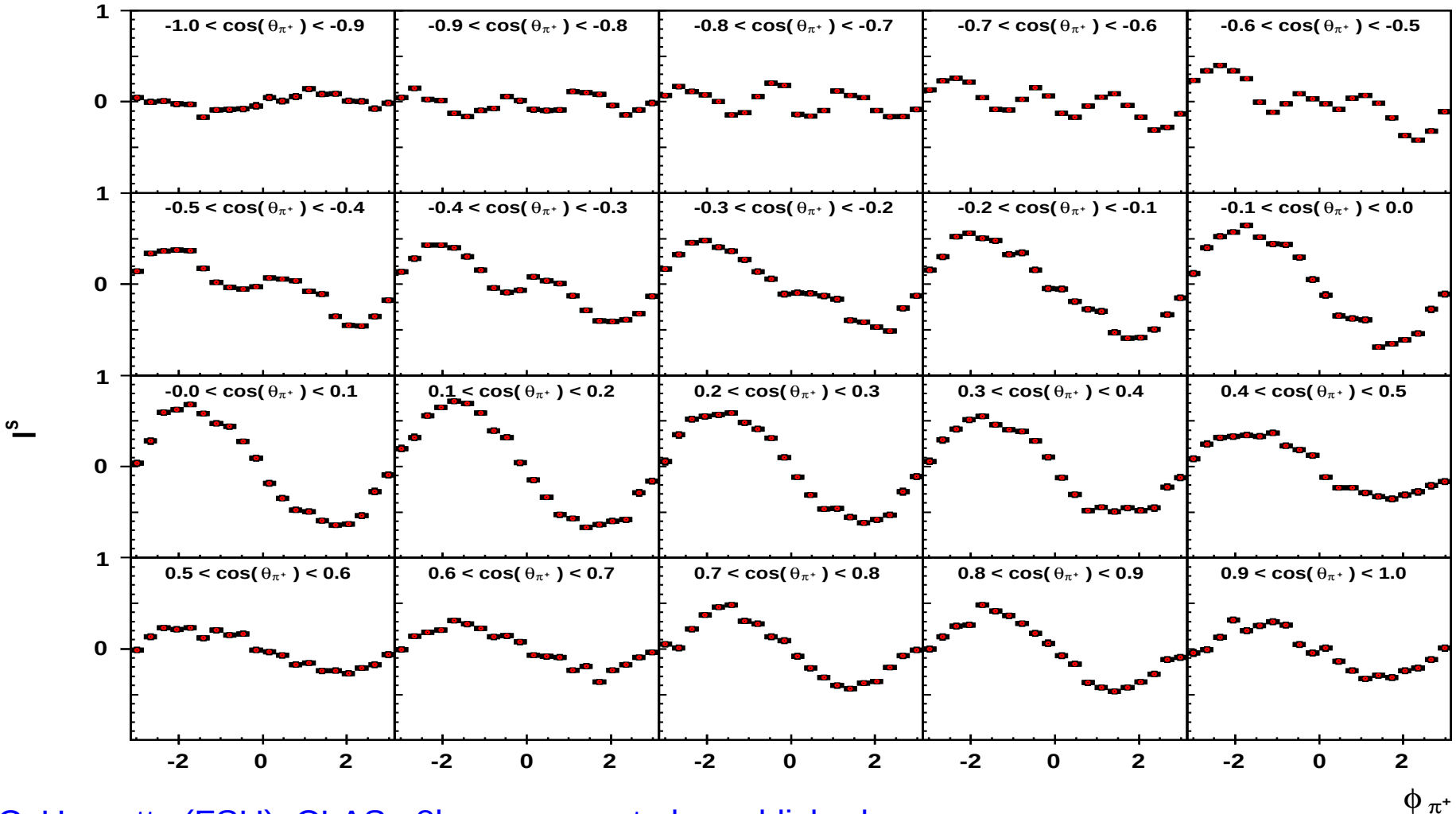
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1250 < E_\gamma < 1300$ MeV



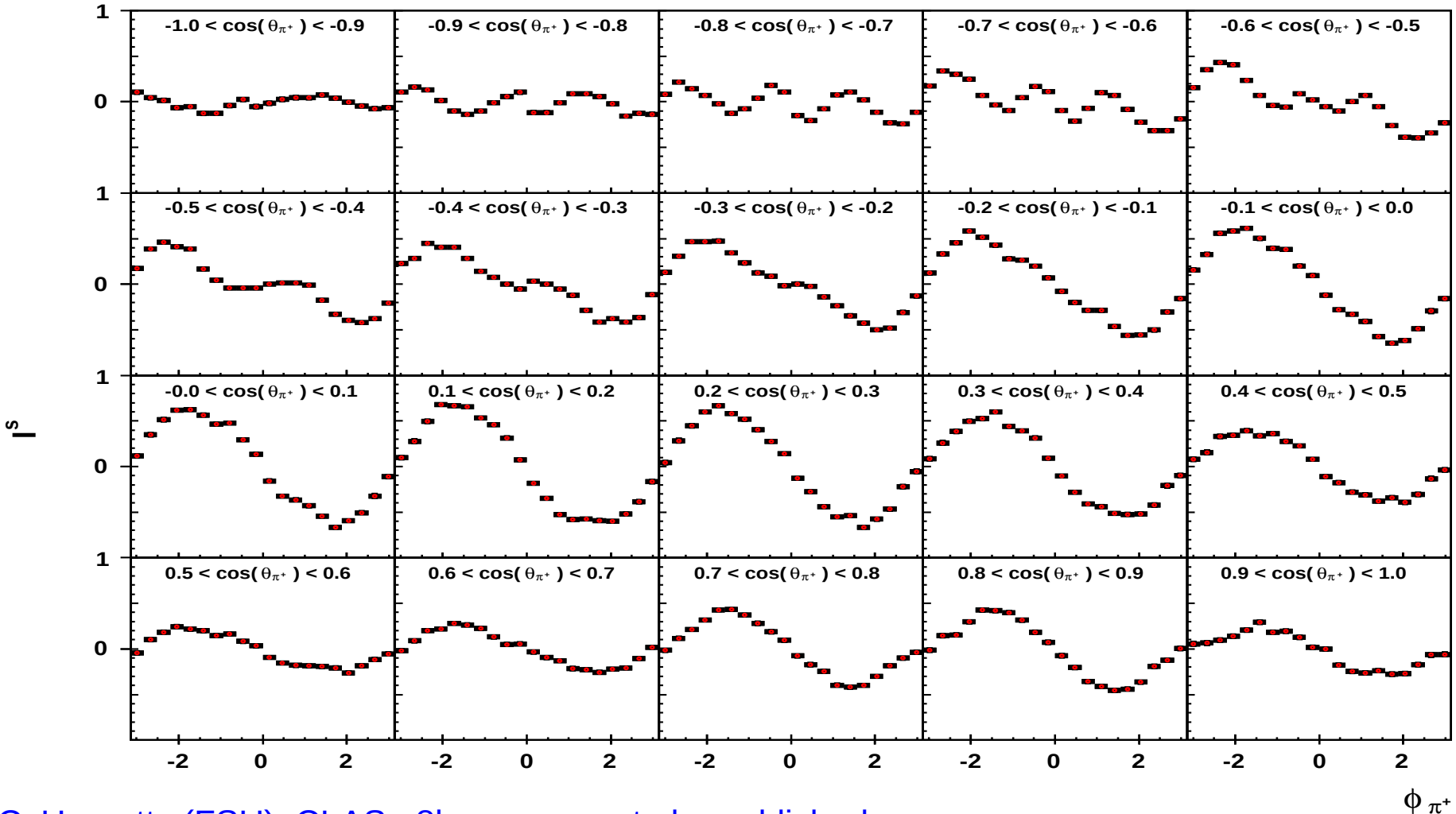
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1300 < E_\gamma < 1350$ MeV



C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1350 < E_\gamma < 1400$ MeV



C. Hanretty (FSU), CLAS g8b run group, to be published

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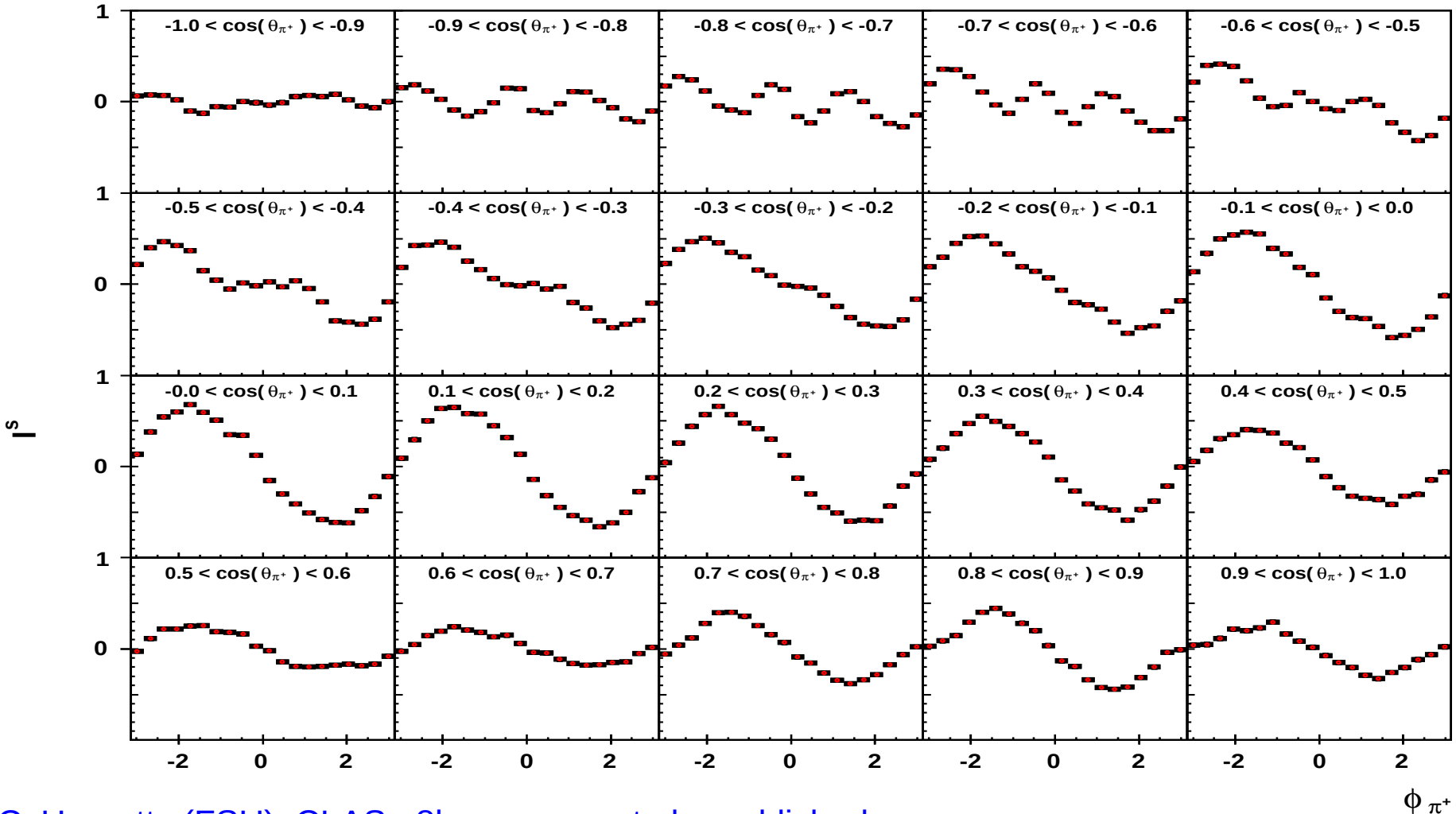
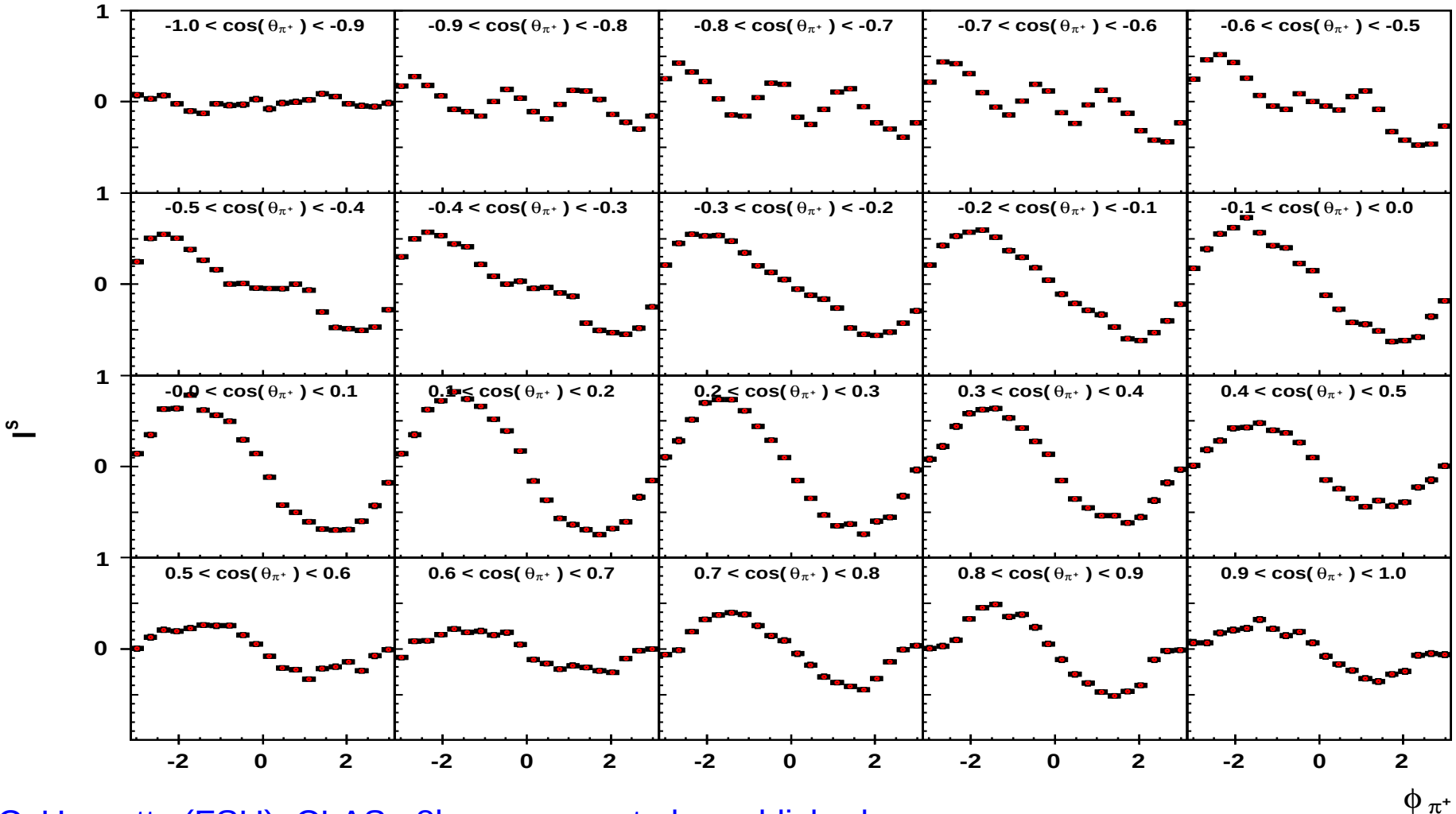


C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1450 < E_\gamma < 1500$ MeV



C. Hanretty (FSU), CLAS g8b run group, to be published

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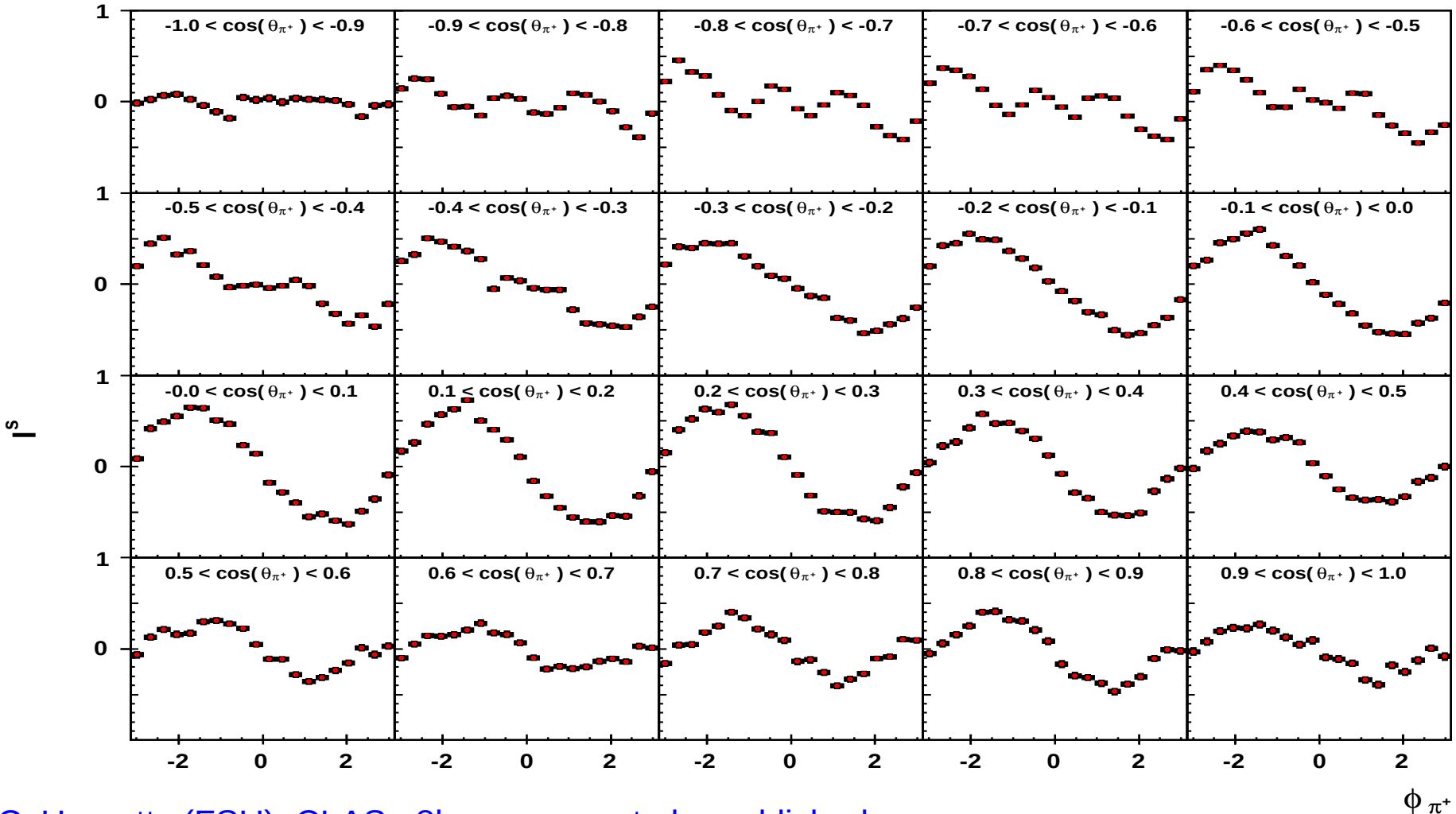
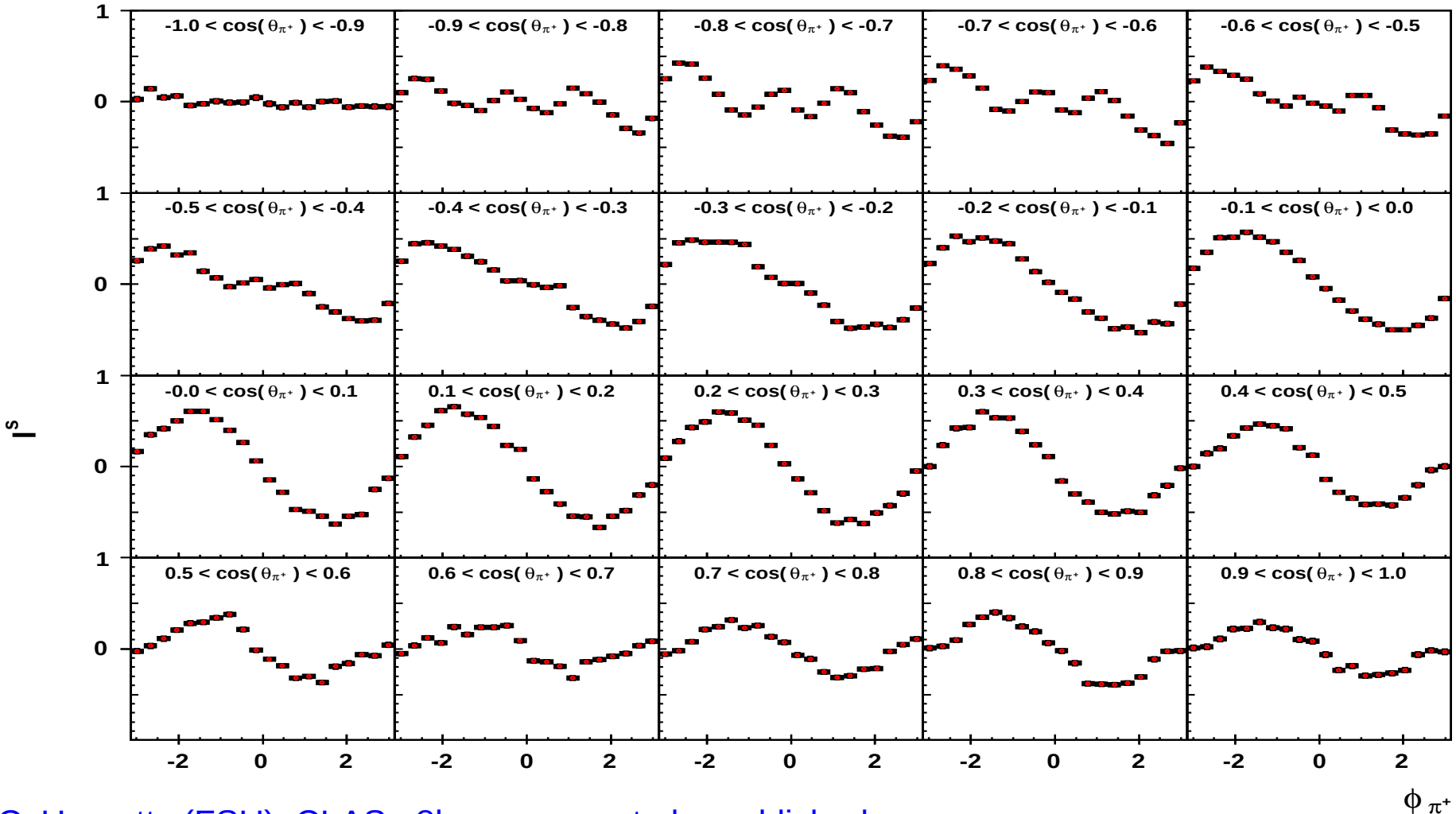


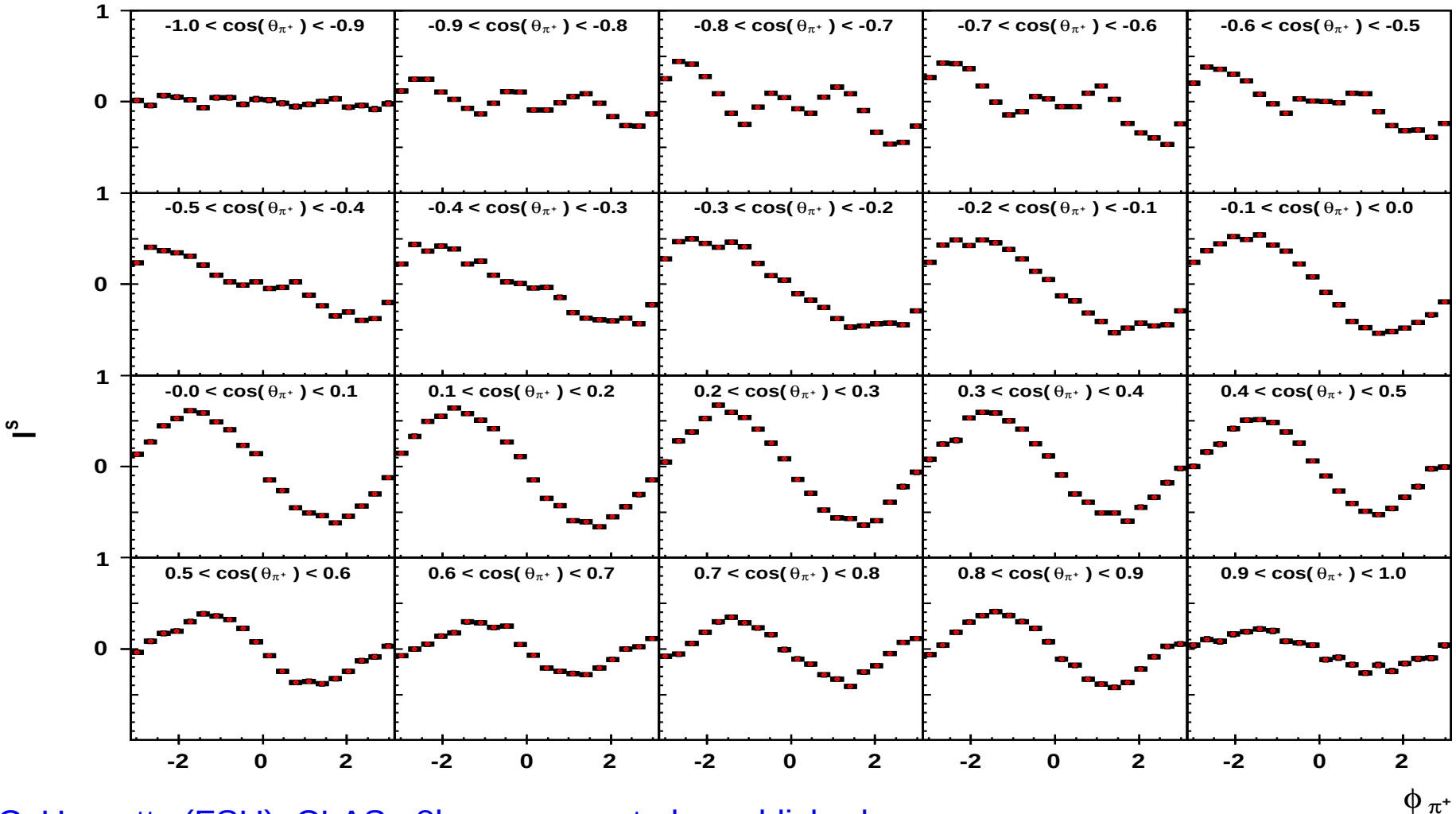
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1550 < E_\gamma < 1600$ MeV



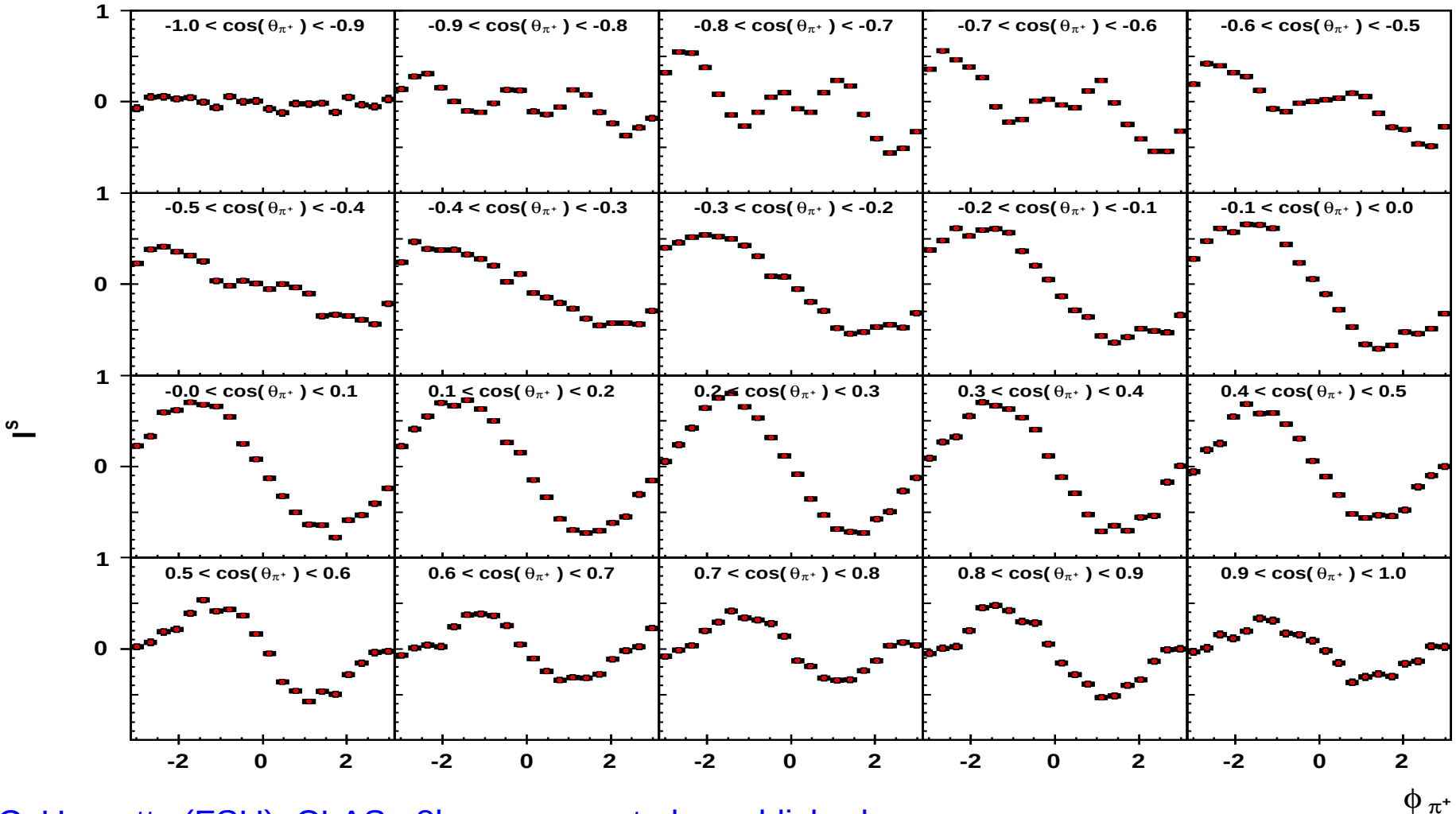
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1600 < E_\gamma < 1650$ MeV



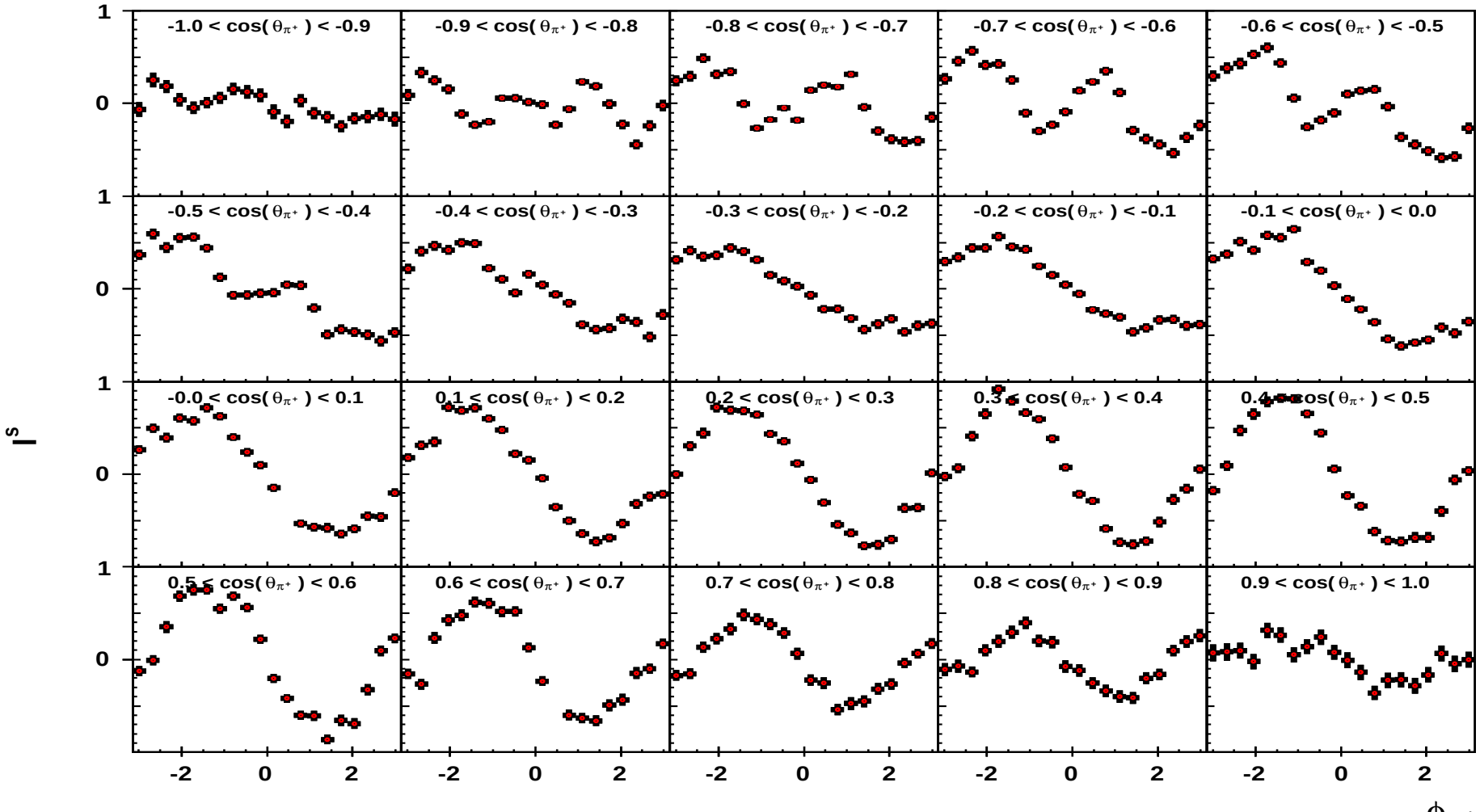
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1650 < E_\gamma < 1700$ MeV



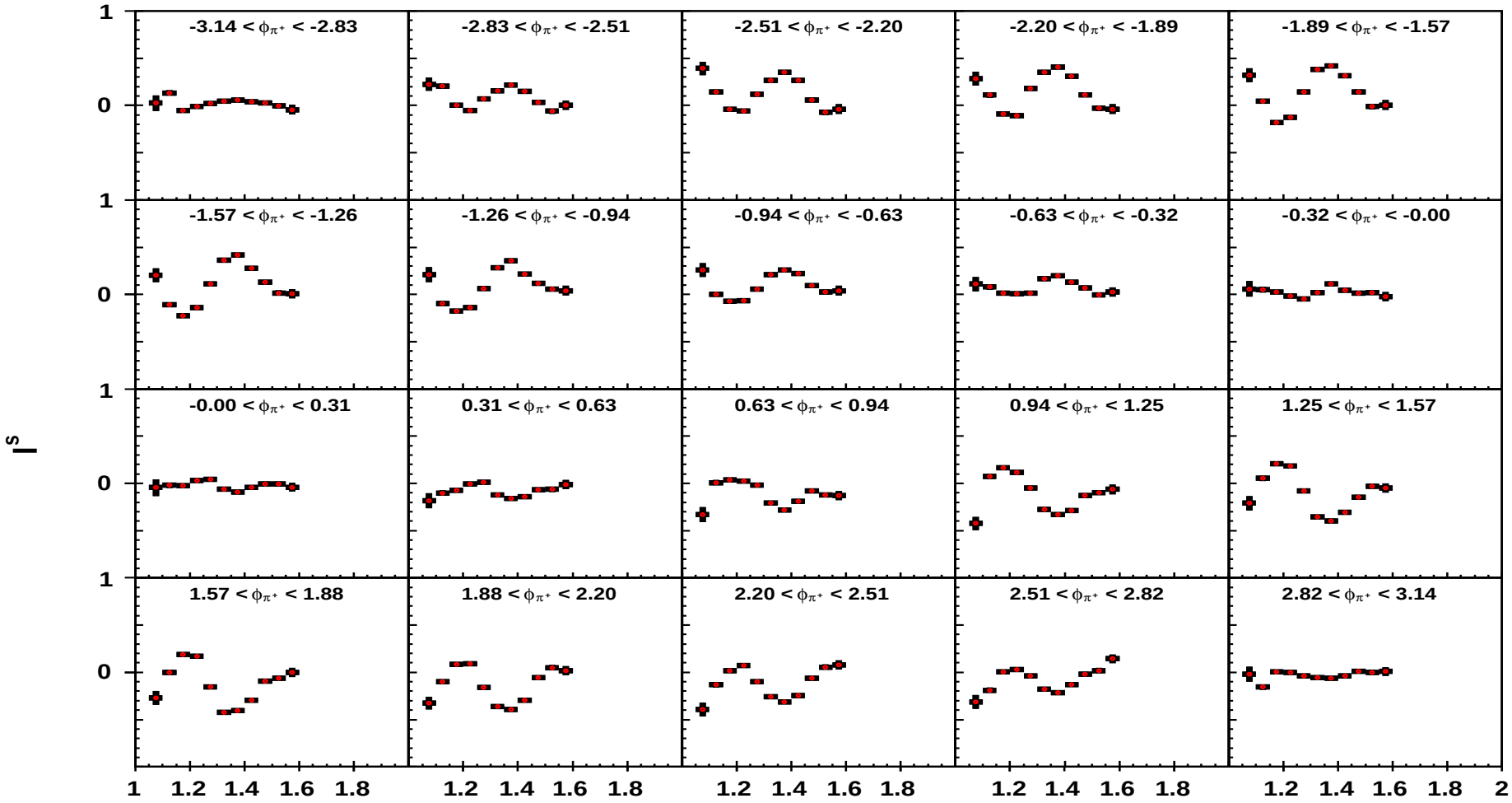
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $2050 < E_\gamma < 2100$ MeV



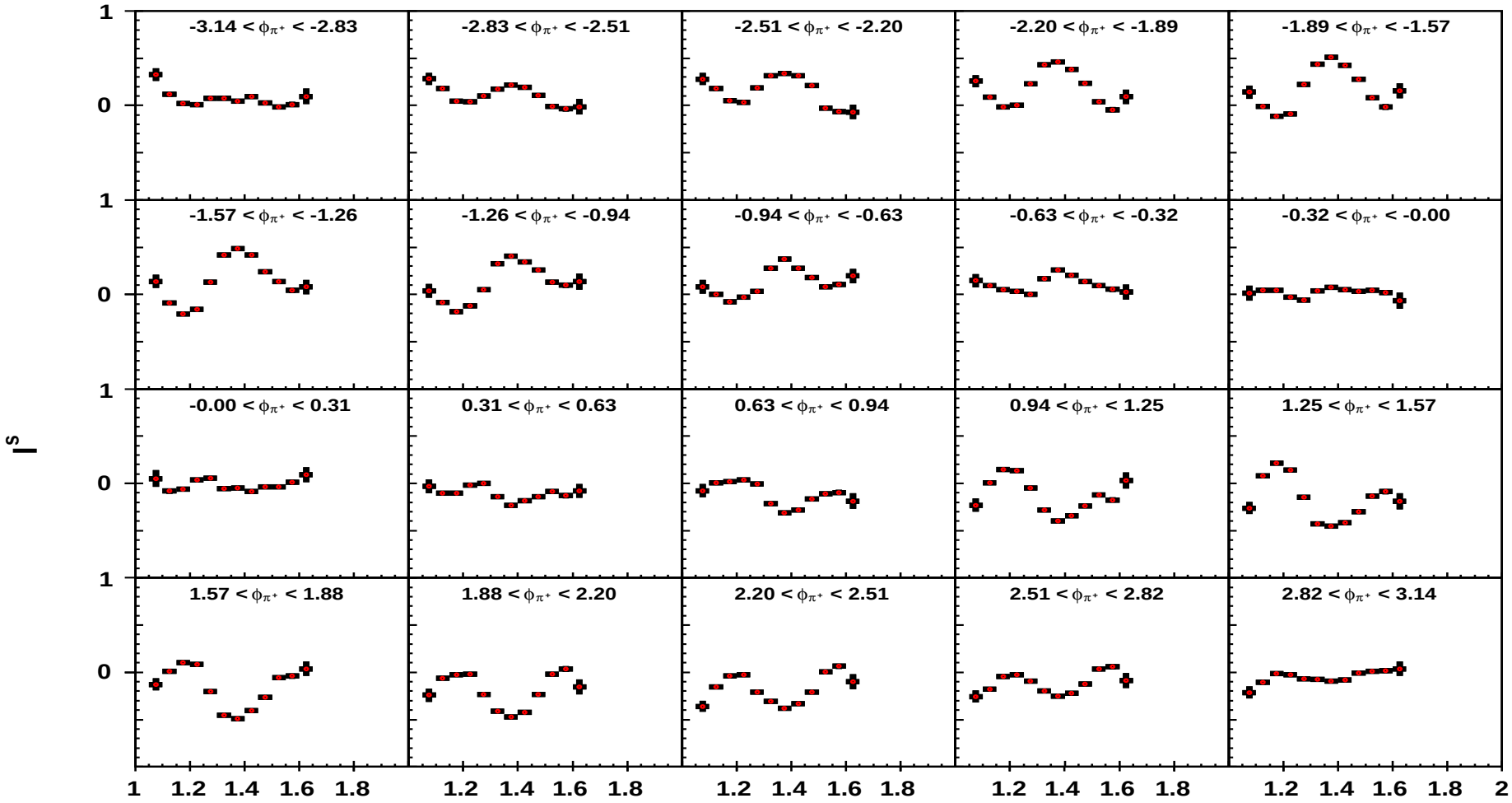
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1100 < E_\gamma < 1150$ MeV



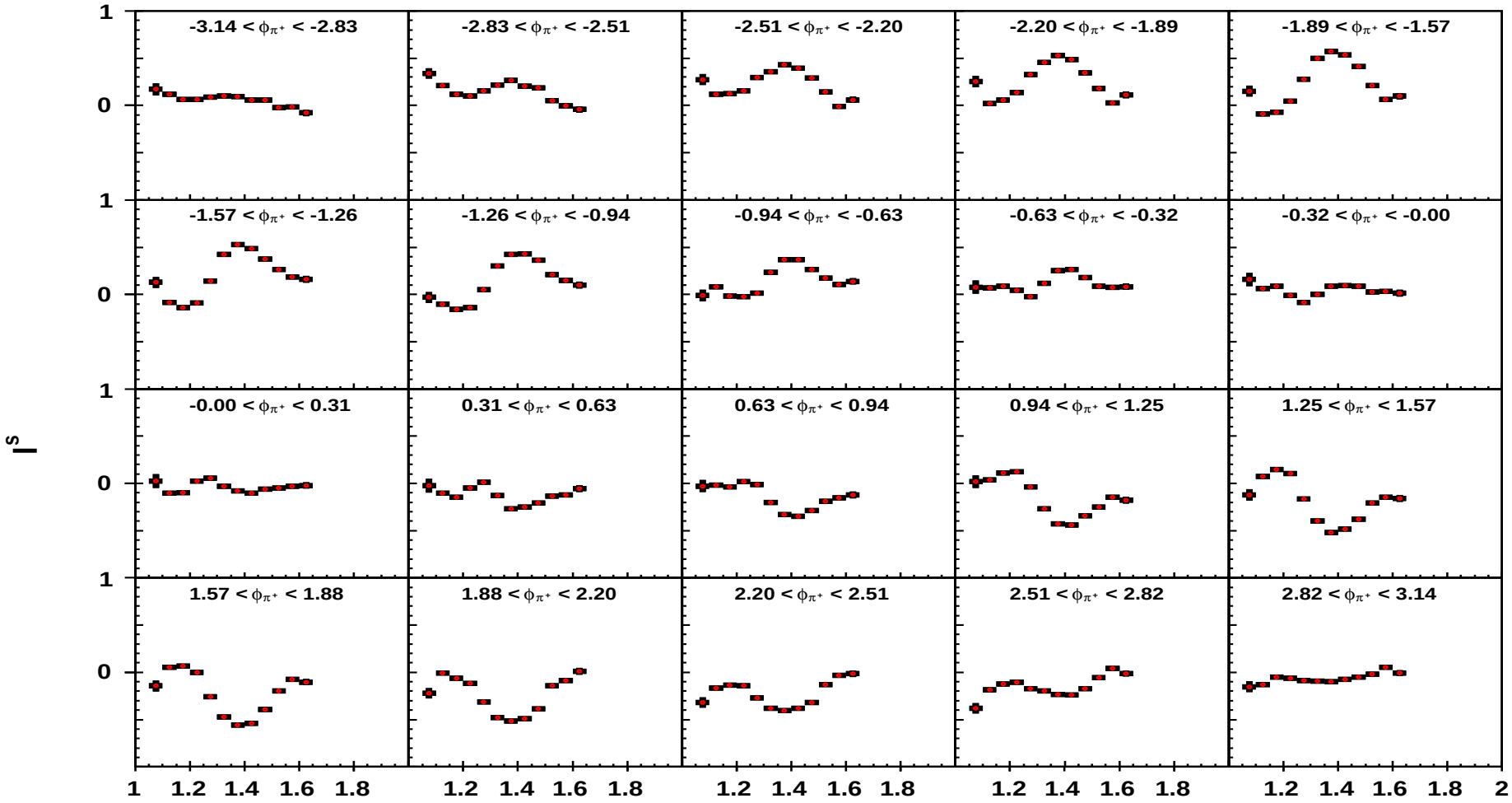
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1150 < E_\gamma < 1200$ MeV



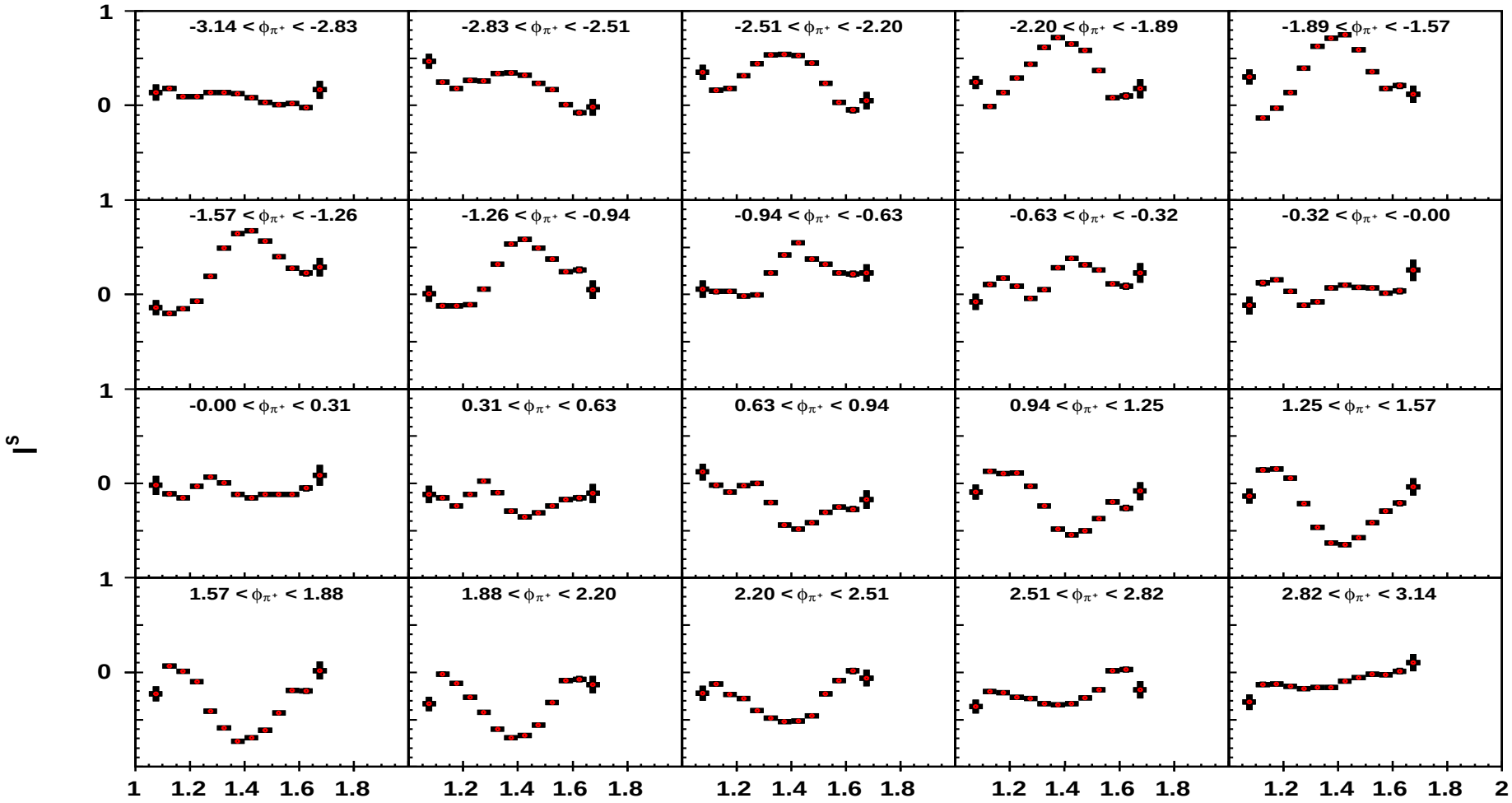
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1200 < E_\gamma < 1250$ MeV



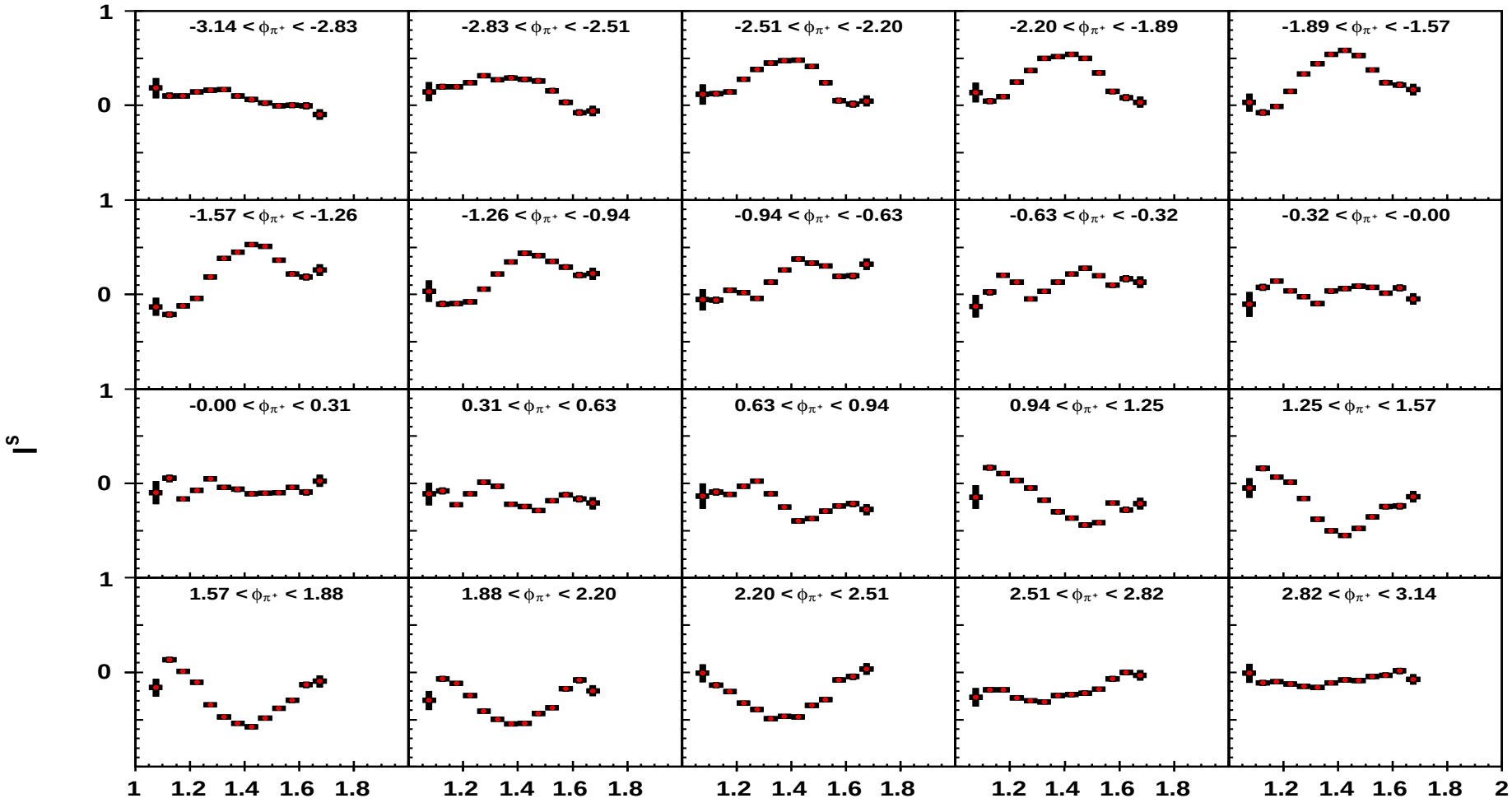
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1250 < E_\gamma < 1300$ MeV



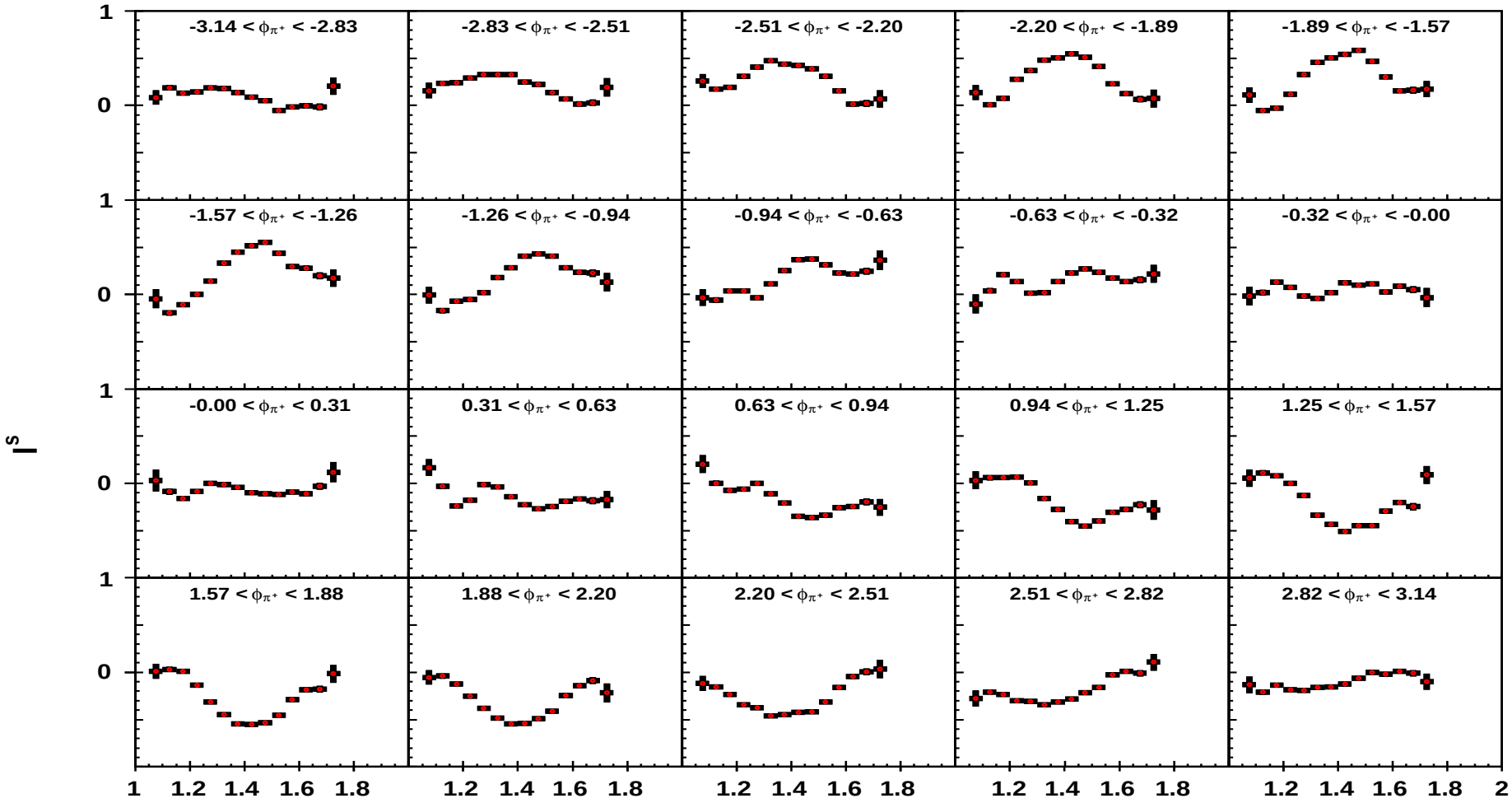
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1300 < E_\gamma < 1350$ MeV



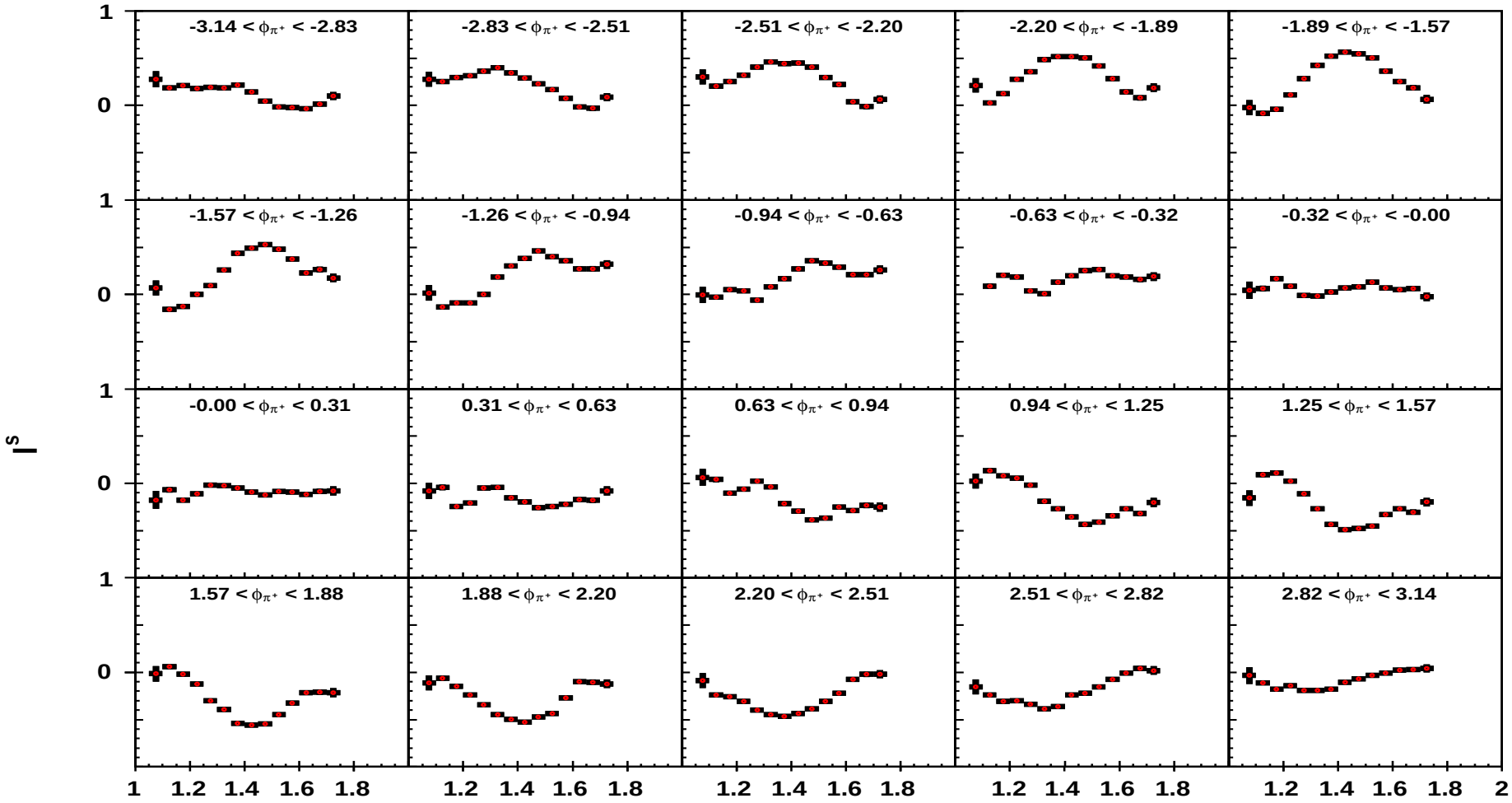
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1350 < E_\gamma < 1400$ MeV



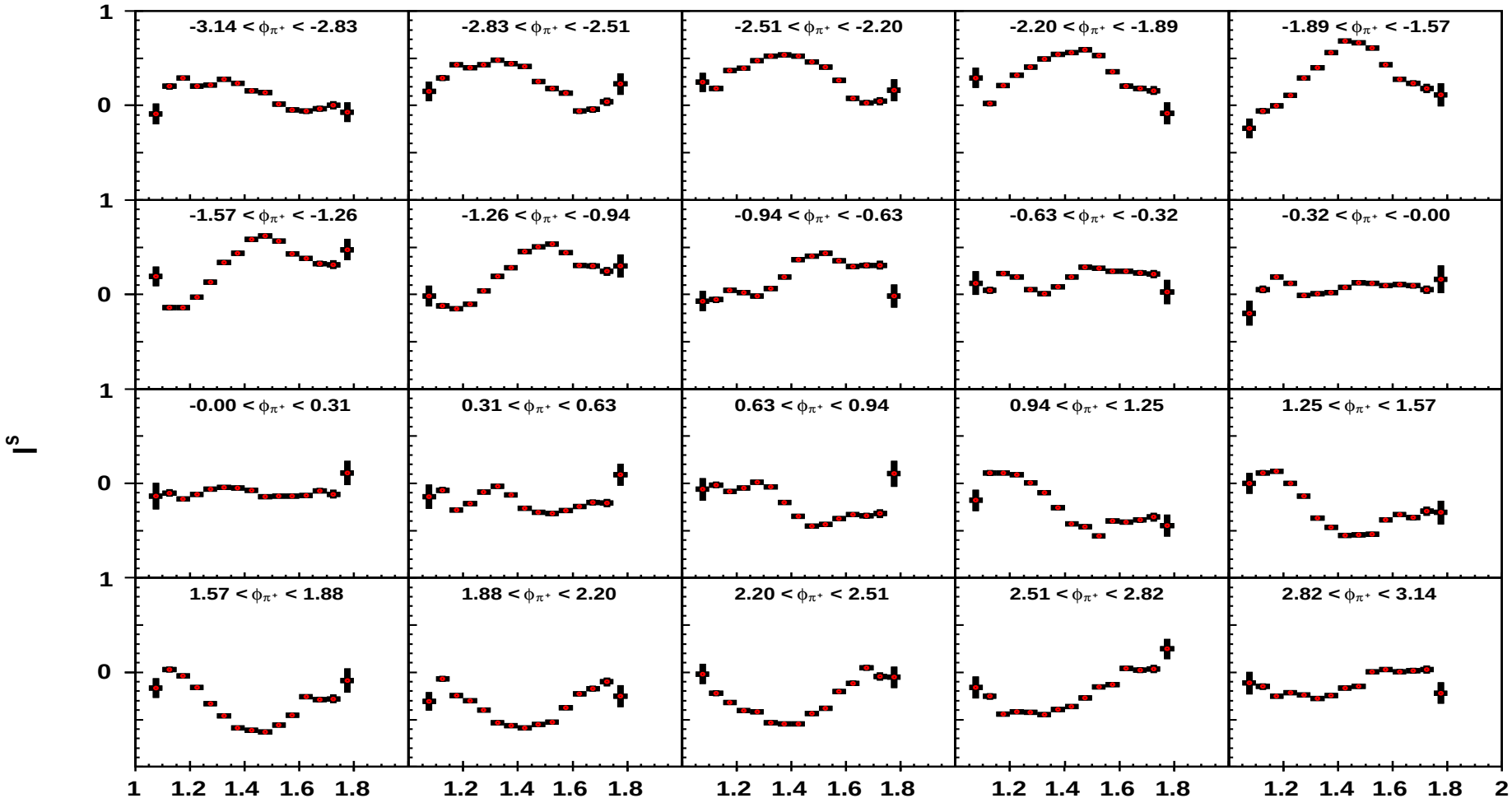
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1400 < E_\gamma < 1450$ MeV



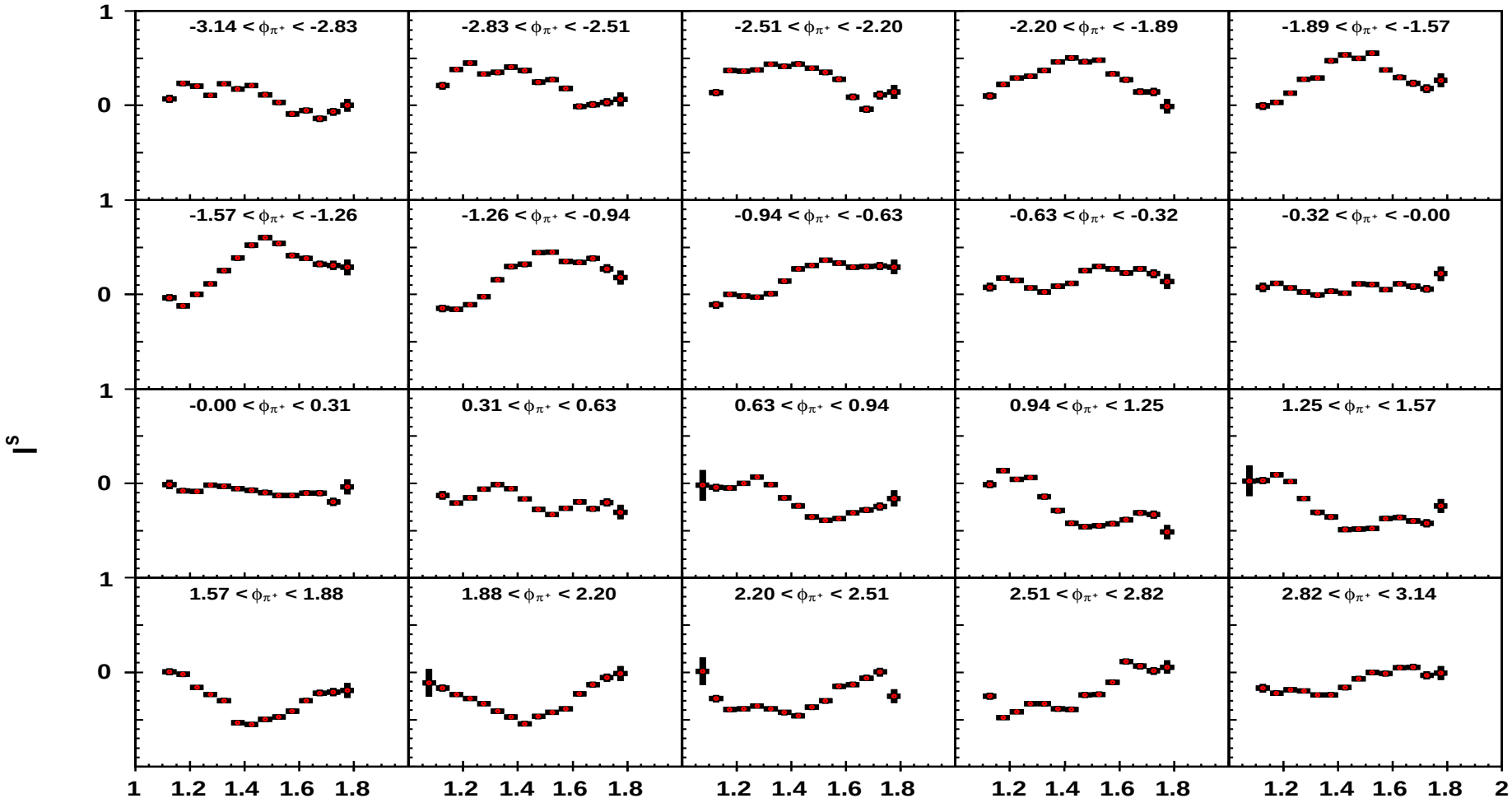
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1450 < E_\gamma < 1500$ MeV



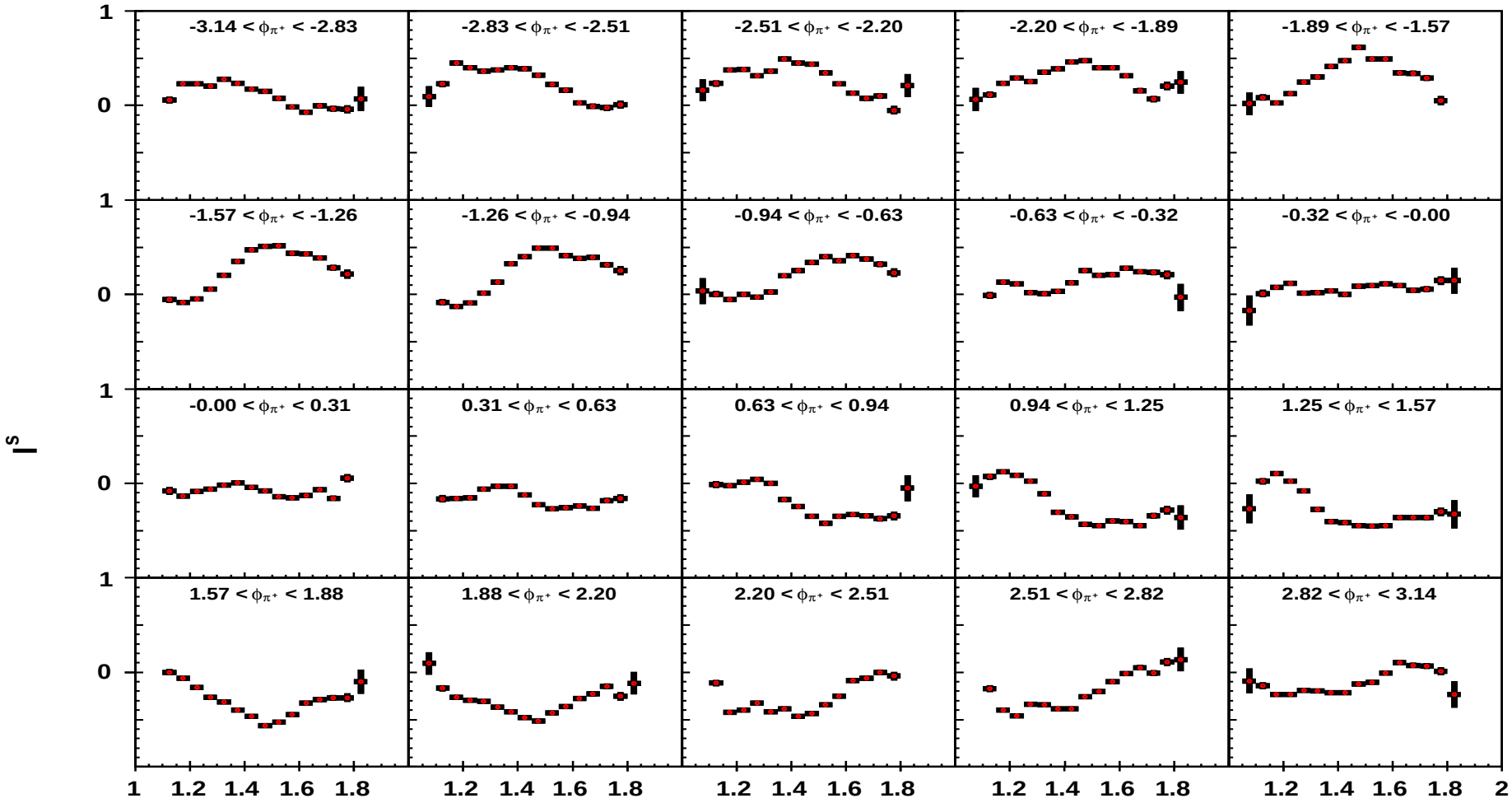
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1500 < E_\gamma < 1550$ MeV



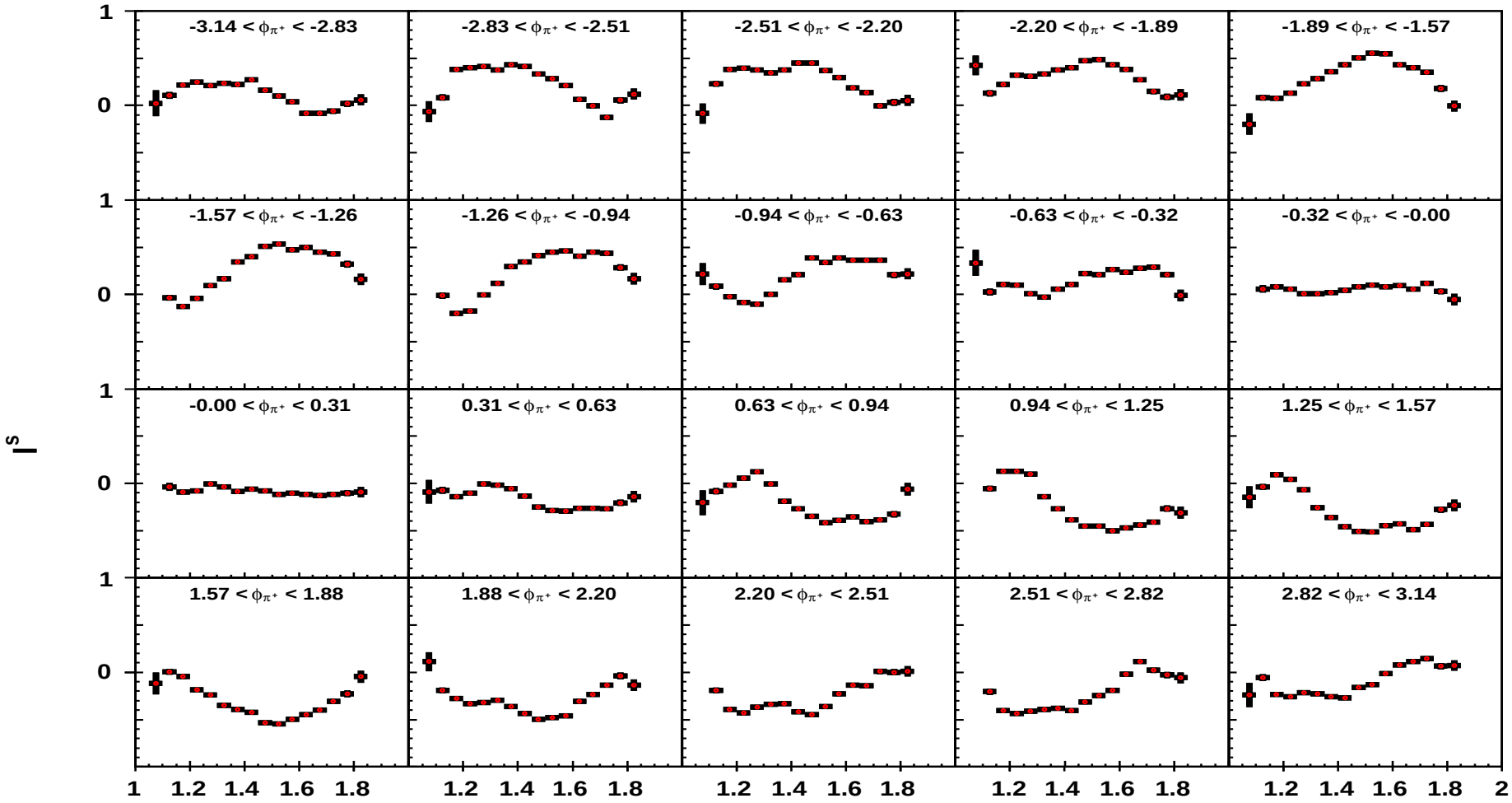
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1550 < E_\gamma < 1600$ MeV



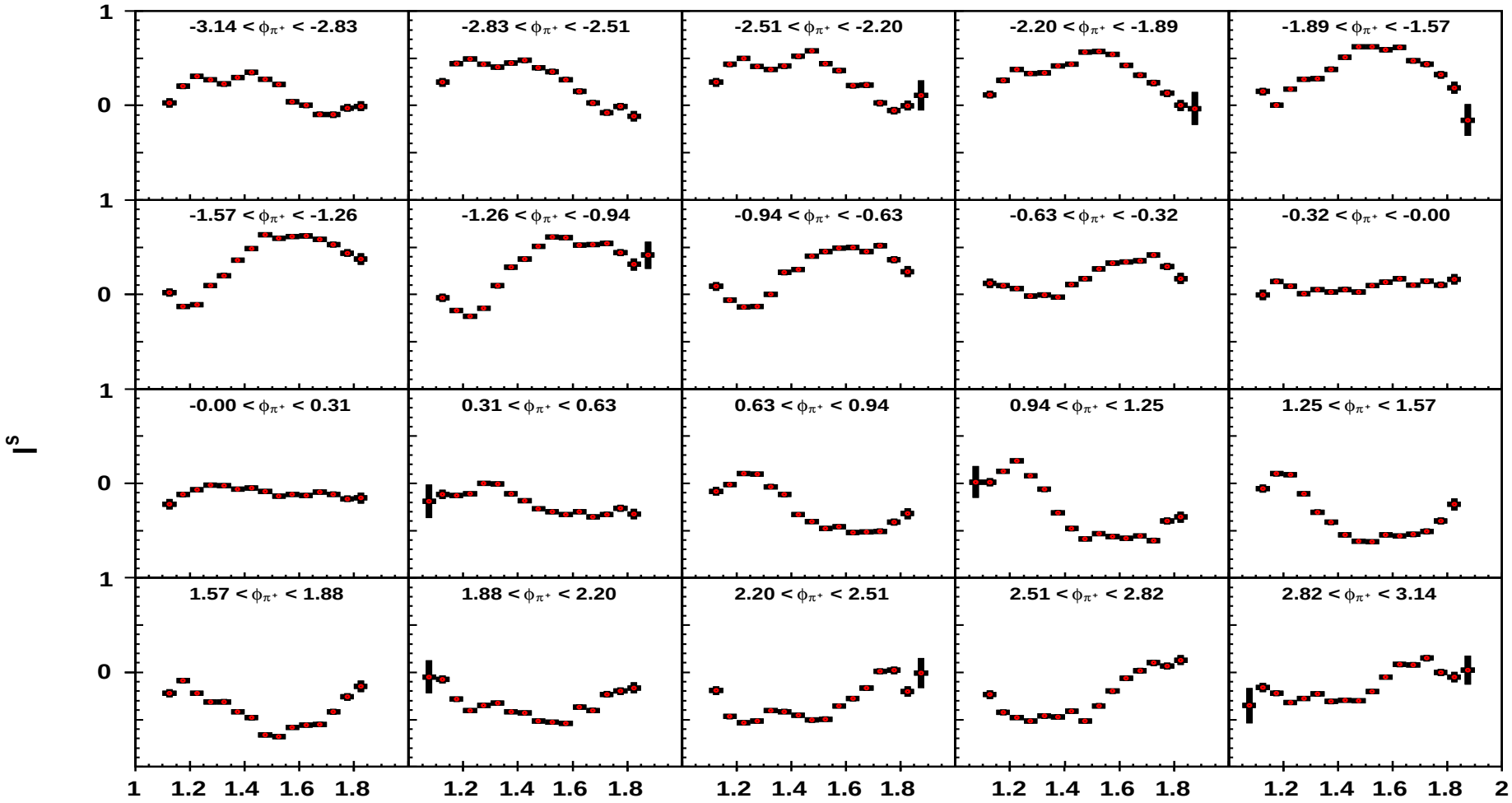
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1600 < E_\gamma < 1650$ MeV



C. Hanretty (FSU), CLAS g8b run group, to be published

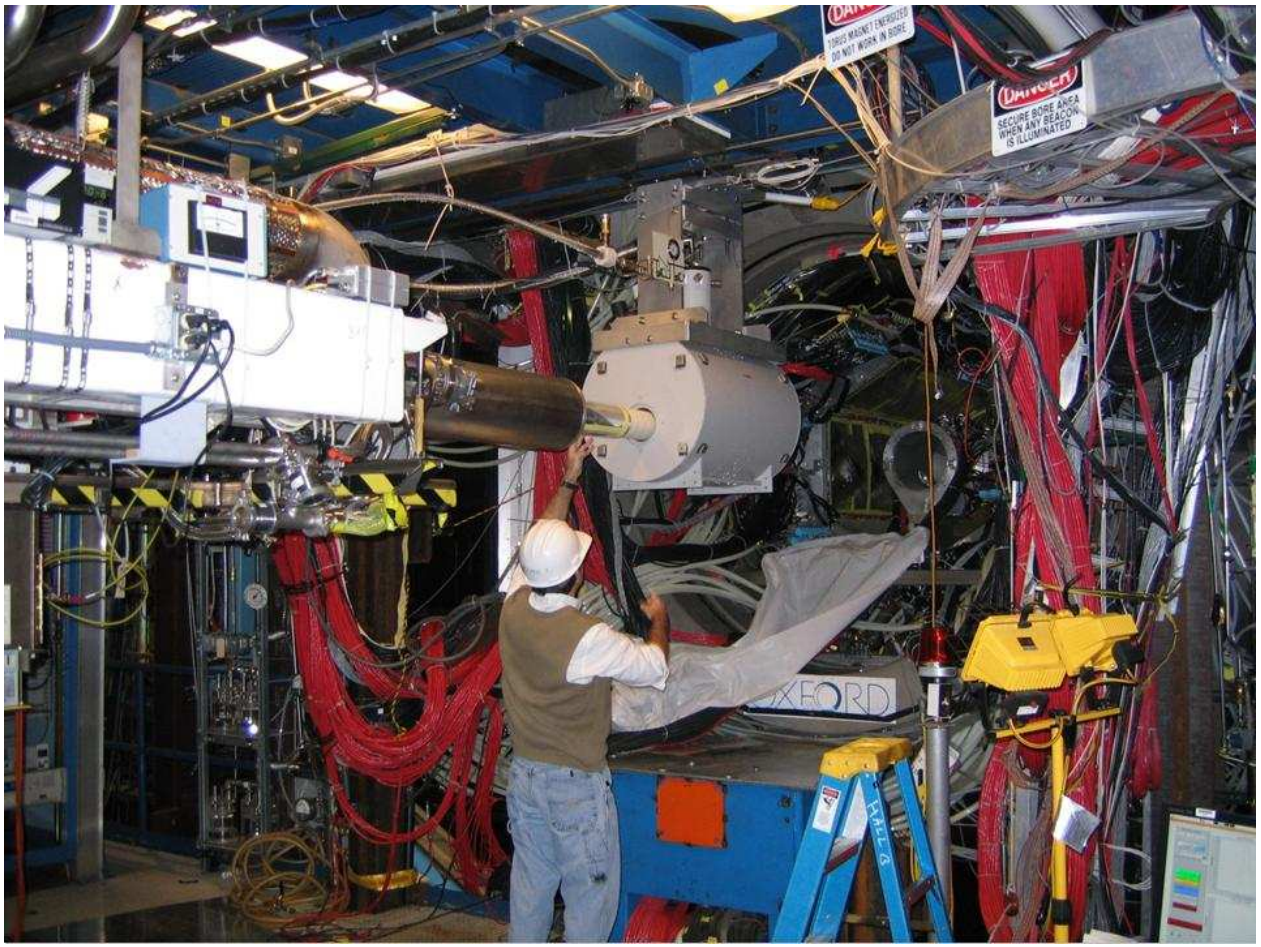
I^s in $\gamma p \to p\,\pi^+\pi^-$ $1650 < E_\gamma < 1700$ MeV



C. Hanretty (FSU), CLAS g8b run group, to be published

The CLAS FroST (g9a) Experiment

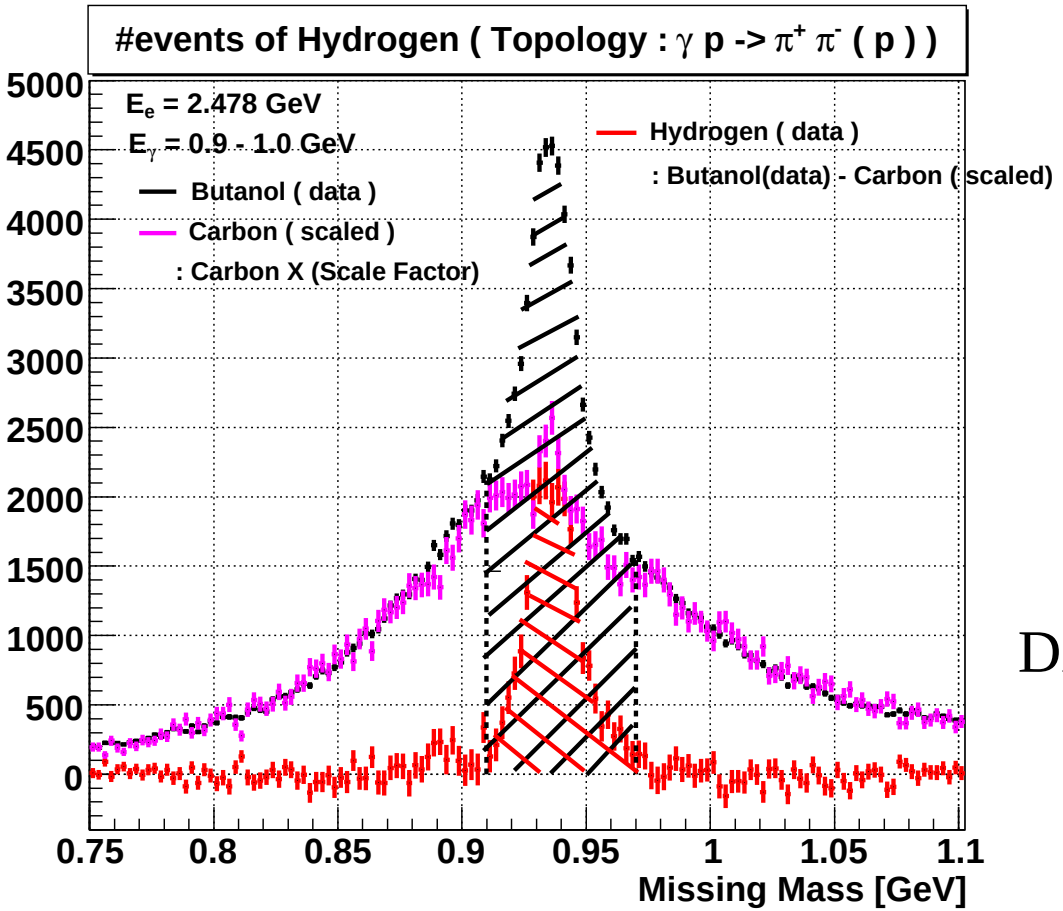
Data taking: 3 November, 2007 - 12 February, 2008

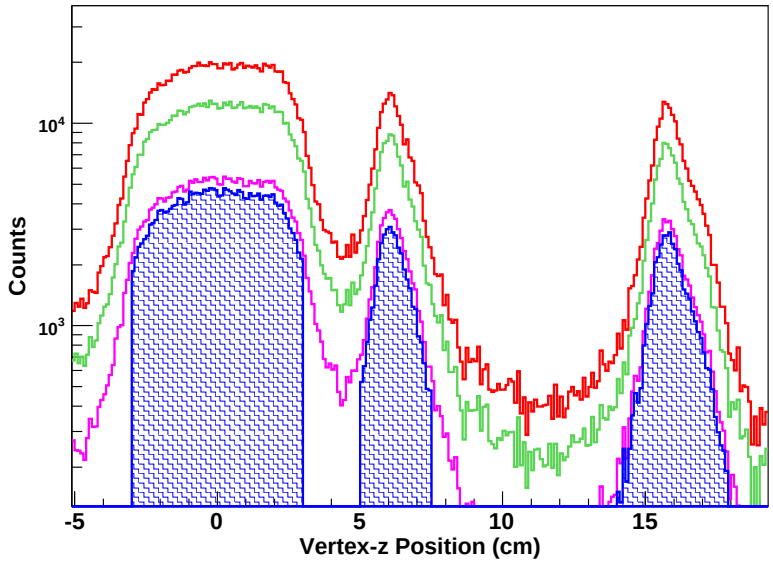


Double-Polarization Measurements: CLAS FroST

- $\gamma p \to p\,\eta$ (Dugger, Morrison *et al.*)
  Arizona State University
- $\gamma p \to p\,\omega$ (Collins, Vernarsky *et al.*)
  Catholic University, Carnegie Mellon
- $\gamma p \to n\,\pi^+$ (E) (S. Strauch *et al.*)
  University of South Carolina
- $\gamma p \to n\,\pi^+$ (G) (J. McAndrew *et al.*)
  University of Edinburgh
- $\gamma p \to p\,\pi^0$ (E) (H. Iwamoto *et al.*)
  George Washington University
- $\gamma p \to p\,\pi^+\pi^-$ $(P_z^{(\odot)})$ (S. Park *et al.*)
  Florida State University
- $\gamma p \to K^+ Y$ (S. Fegan *et al.*)
  University of Glasgow

Dilution Factor

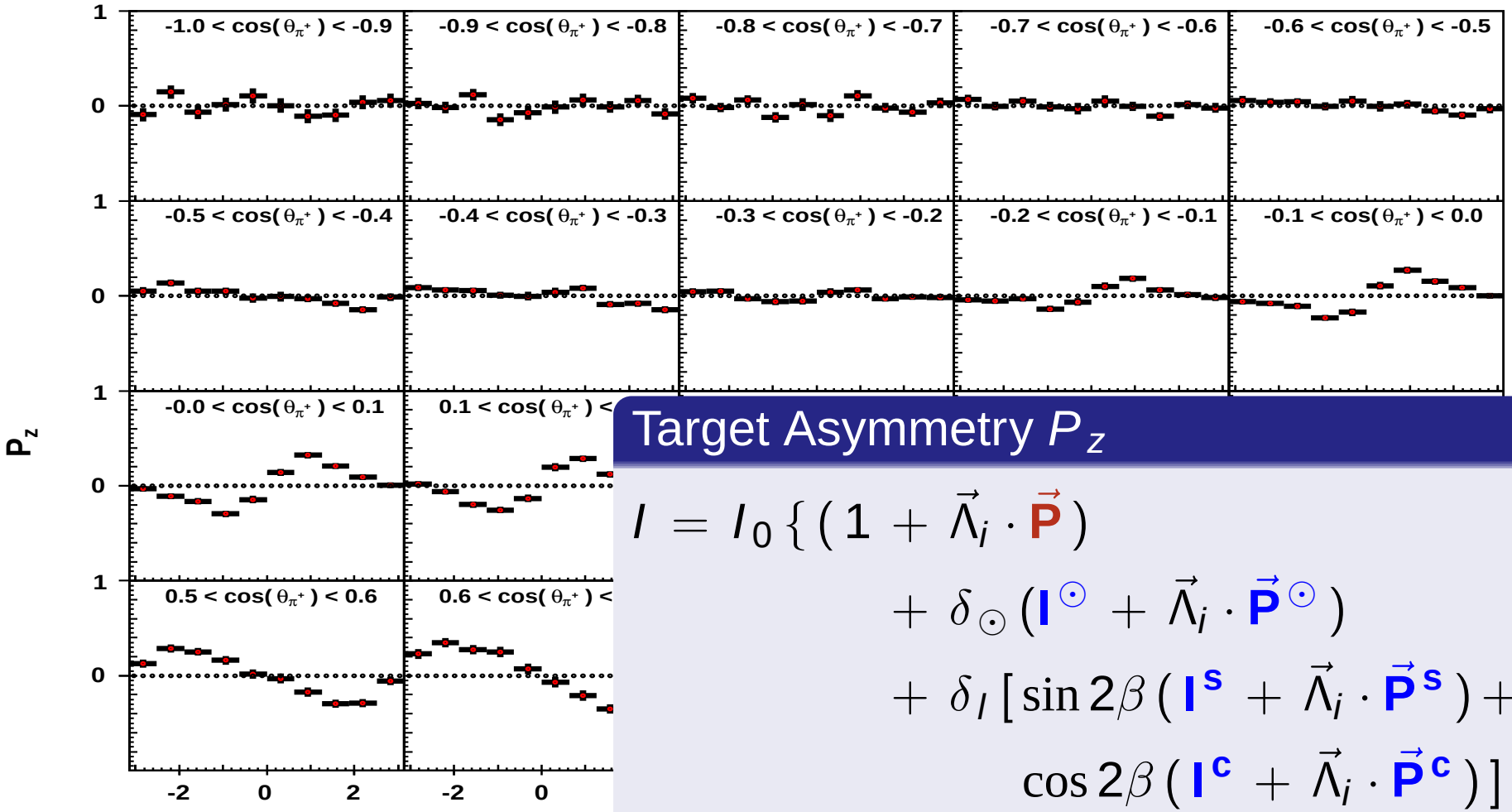




C_4H_9OH ^{12}C CH_2

$$\text{Dilution factor} = \frac{N_{\text{hydrogen}}}{N_{\text{butanol}}} = \frac{N_{C_4H_9OH} - N_C S}{N_{C_4H_9OH}}$$

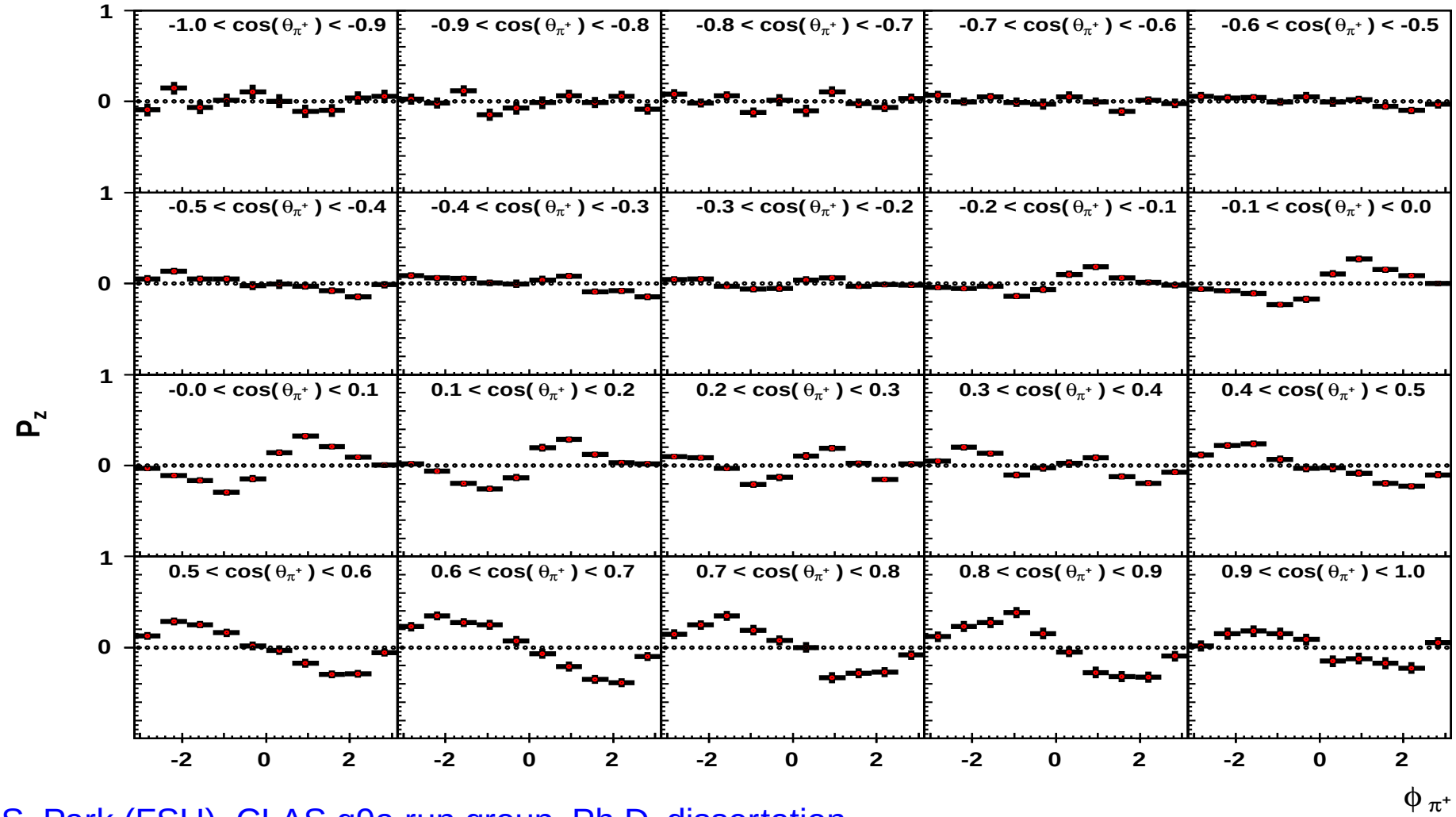
P_z in $\gamma p \to p\,\pi^+\pi^-$ $700 < E_\gamma < 800$ MeV



Target Asymmetry P_z

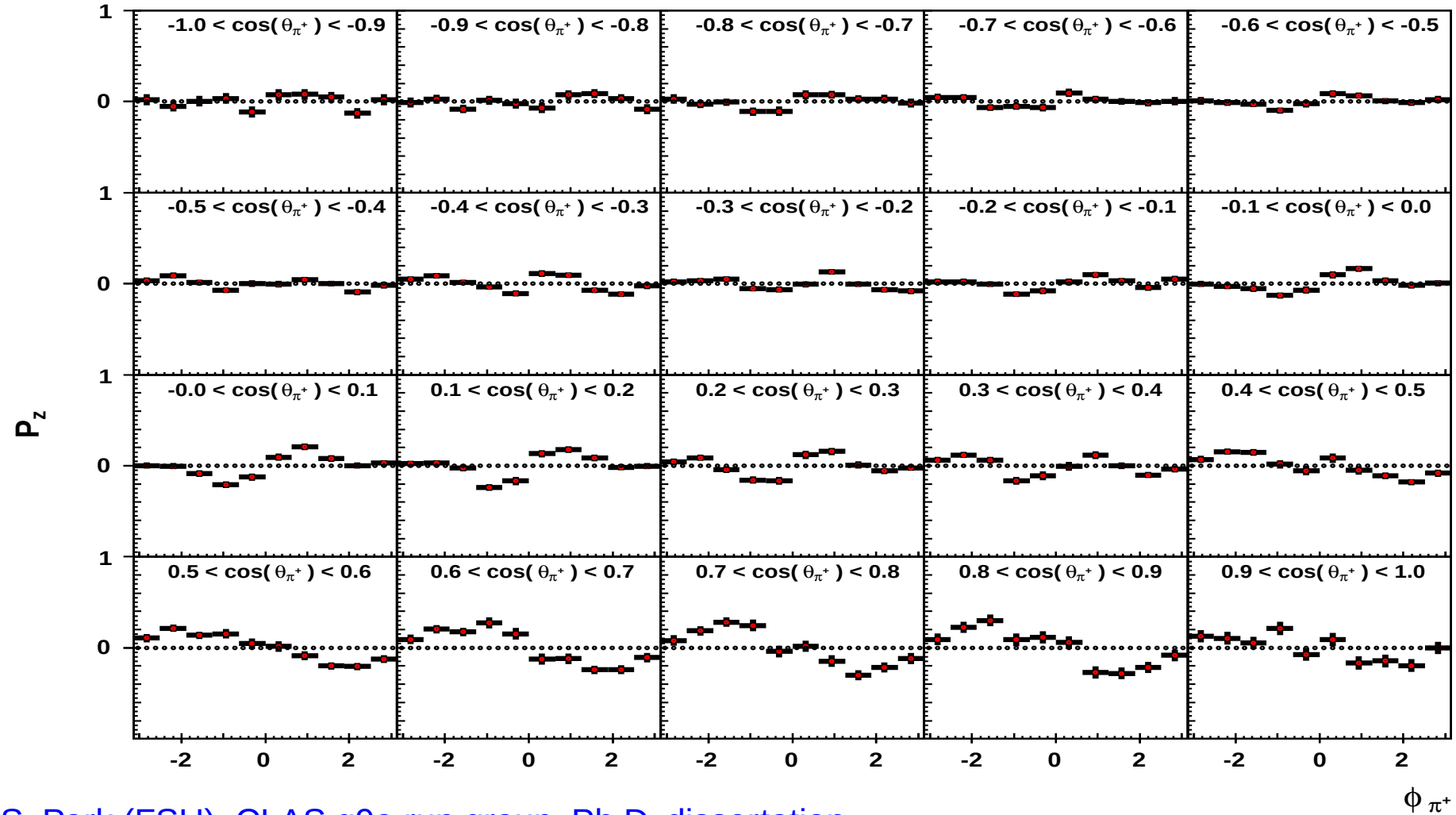
$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\odot) + \delta_l [\sin 2\beta (\mathbf{I}^s + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^s) + \cos 2\beta (\mathbf{I}^c + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^c)] \}$$

P_z in $\gamma p \to p\,\pi^+\pi^-$ $700 < E_\gamma < 800$ MeV



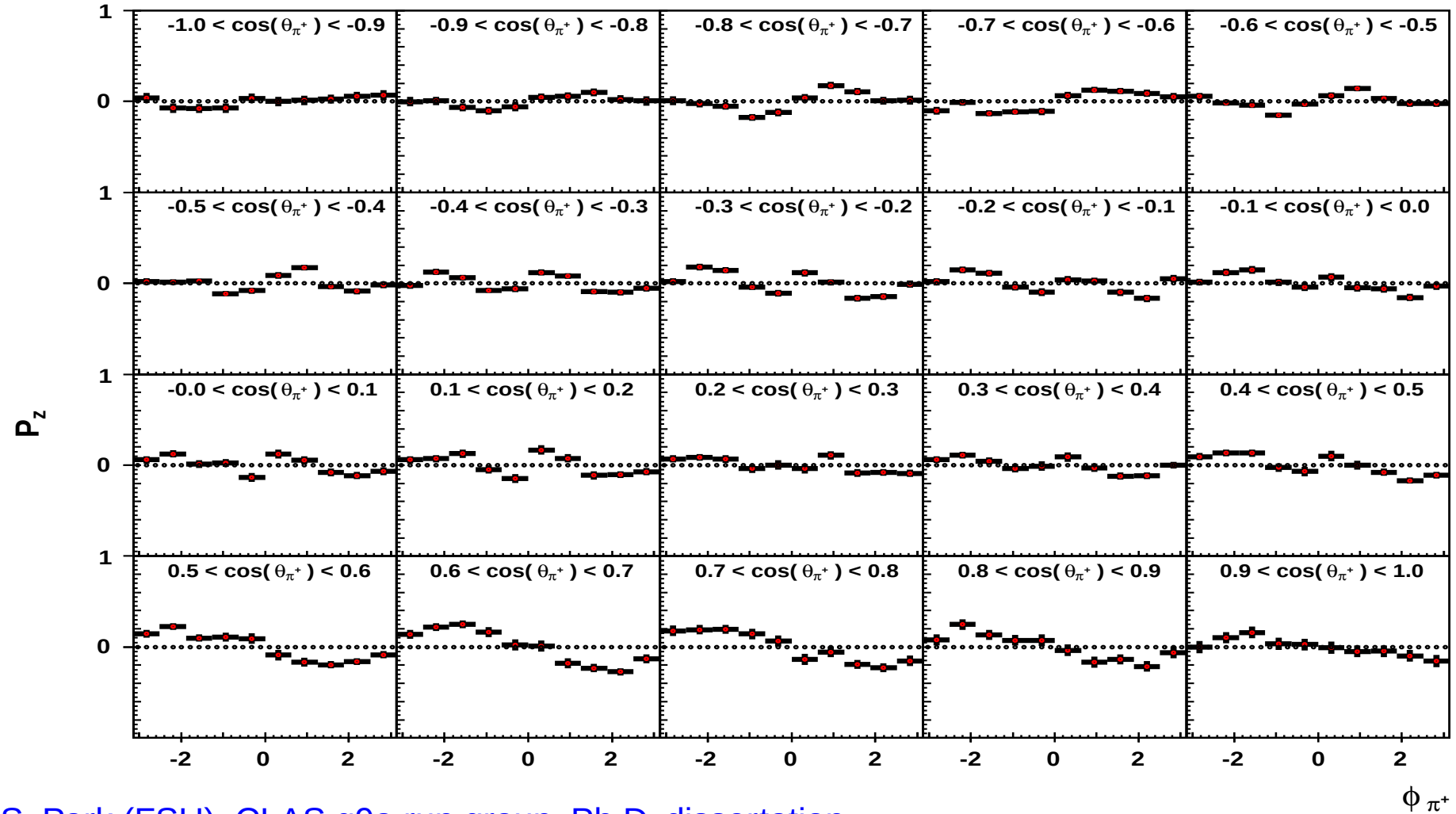
S. Park (FSU), CLAS g9a run group, Ph.D. dissertation

P_z in $\gamma p \to p\,\pi^+\pi^-$ $800 < E_\gamma < 900$ MeV



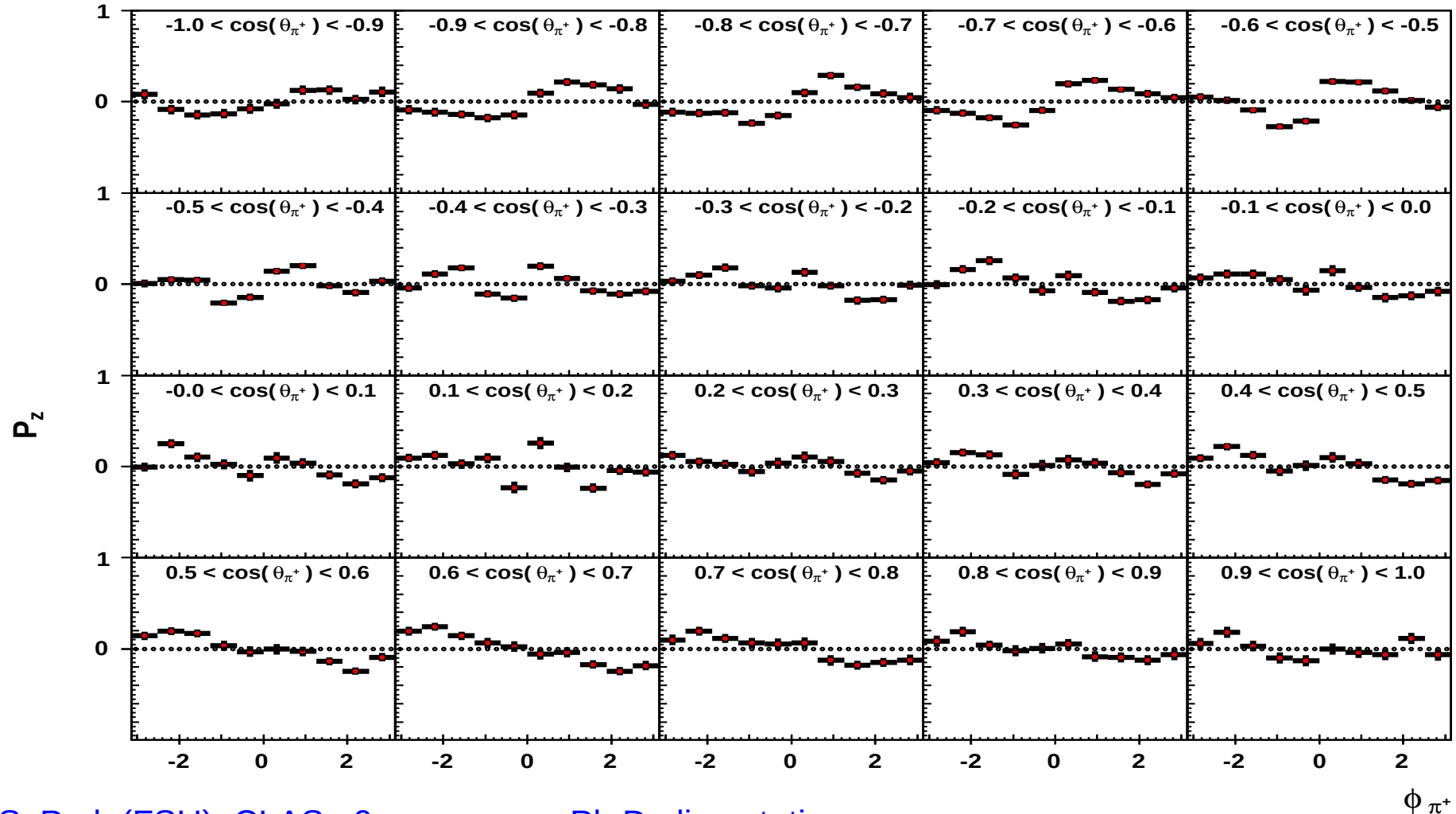
S. Park (FSU), CLAS g9a run group, Ph.D. dissertation

P_z in $\gamma p \to p\,\pi^+\pi^-$ $900 < E_\gamma < 1000$ MeV



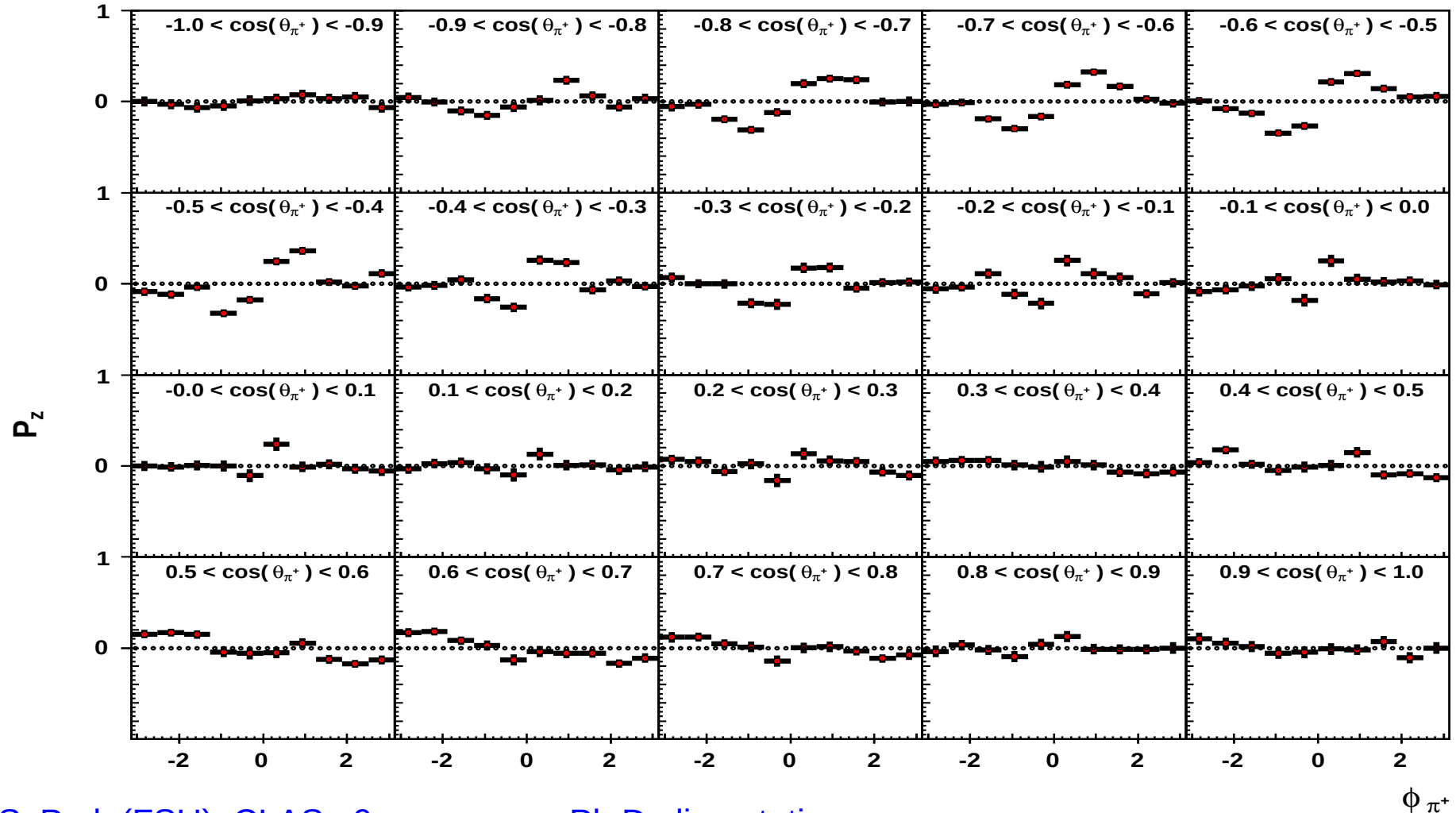
S. Park (FSU), CLAS g9a run group, Ph.D. dissertation

P_z in $\gamma p \to p\,\pi^+\pi^-$ $1000 < E_\gamma < 1100$ MeV



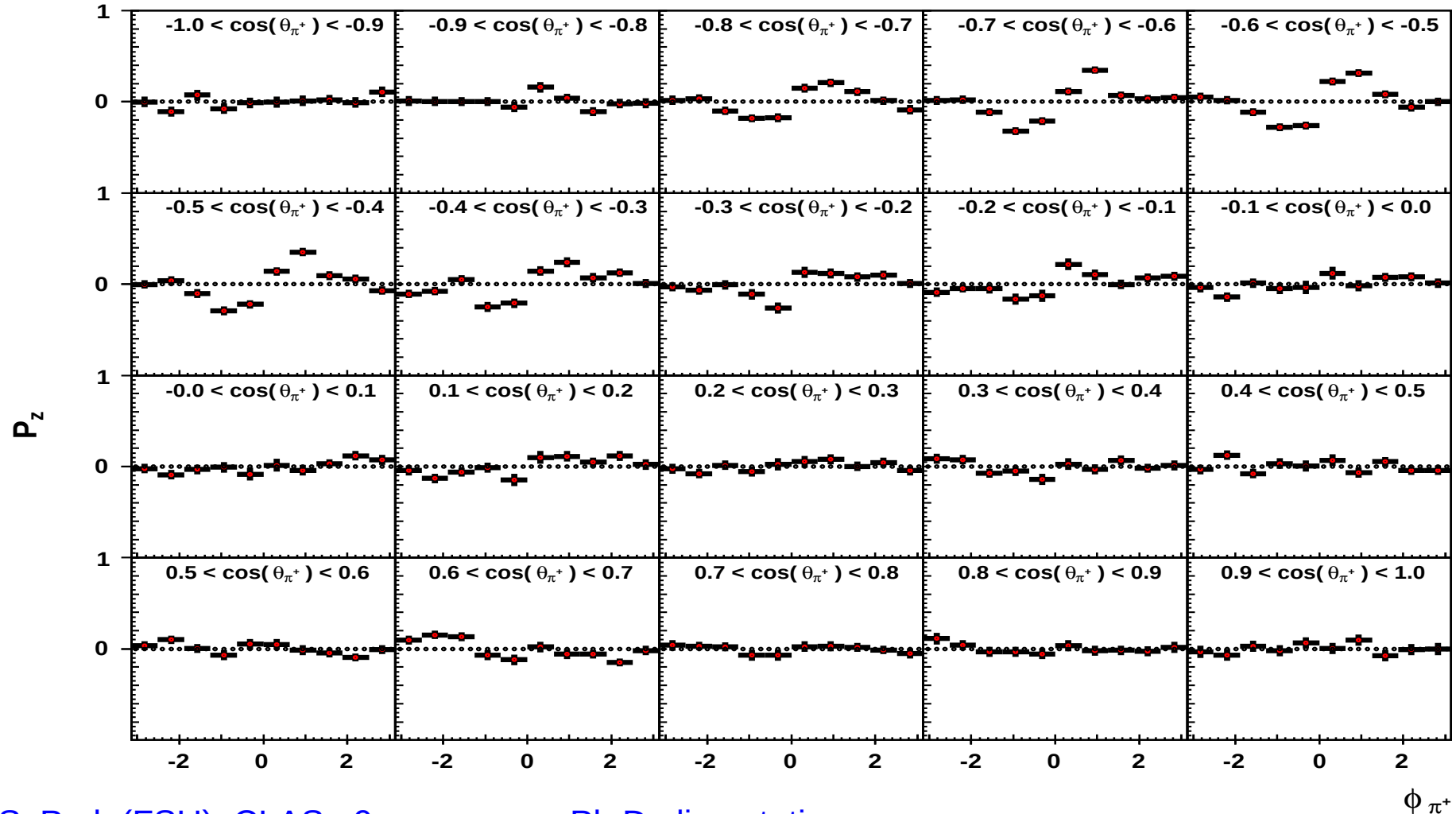
S. Park (FSU), CLAS g9a run group, Ph.D. dissertation

P_z in $\gamma p \to p\,\pi^+\pi^-$ $1100 < E_\gamma < 1200$ MeV



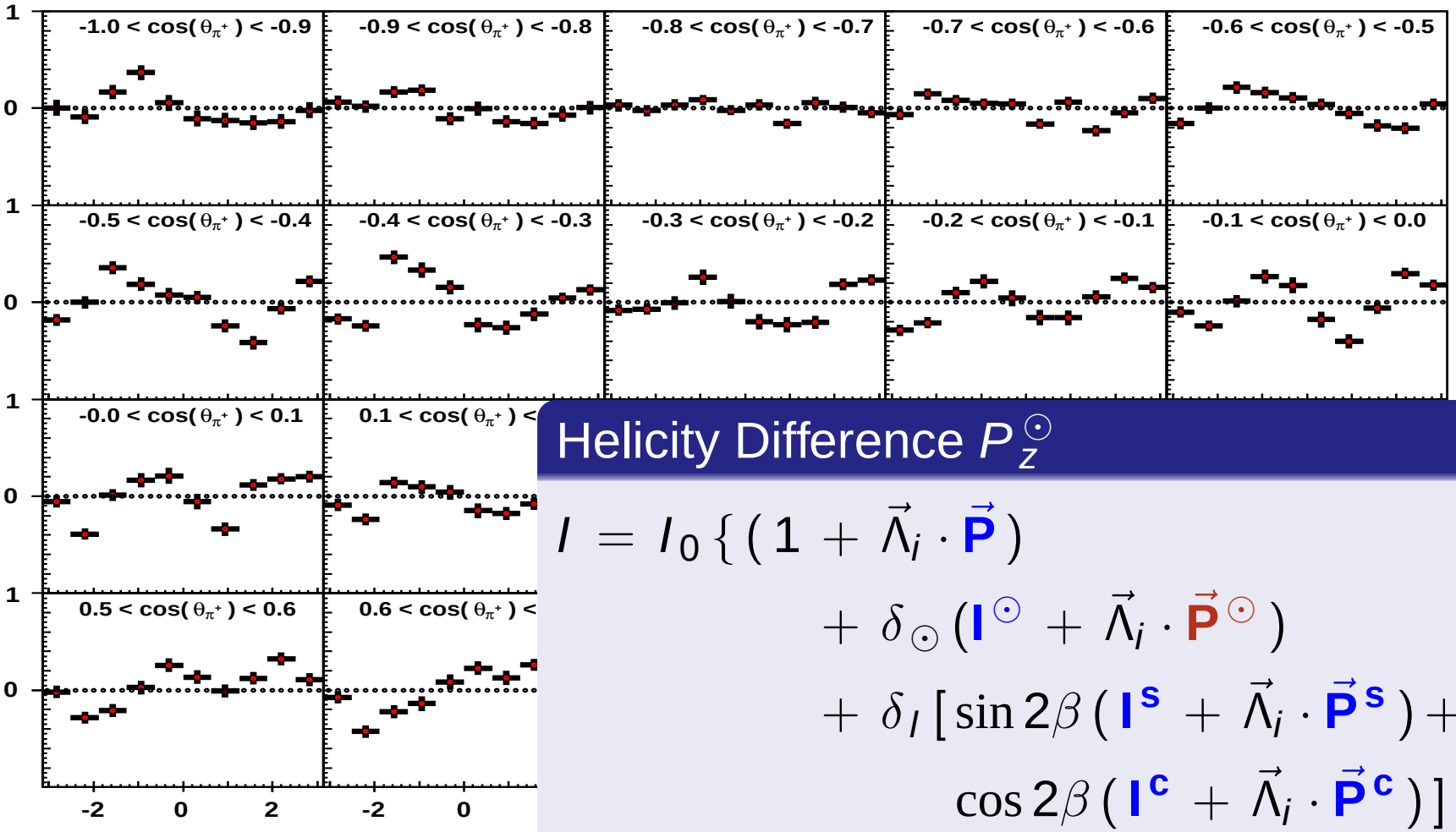
S. Park (FSU), CLAS g9a run group, Ph.D. dissertation

P_z in $\gamma p \to p\,\pi^+\pi^-$ $1200 < E_\gamma < 1300$ MeV



S. Park (FSU), CLAS g9a run group, Ph.D. dissertation

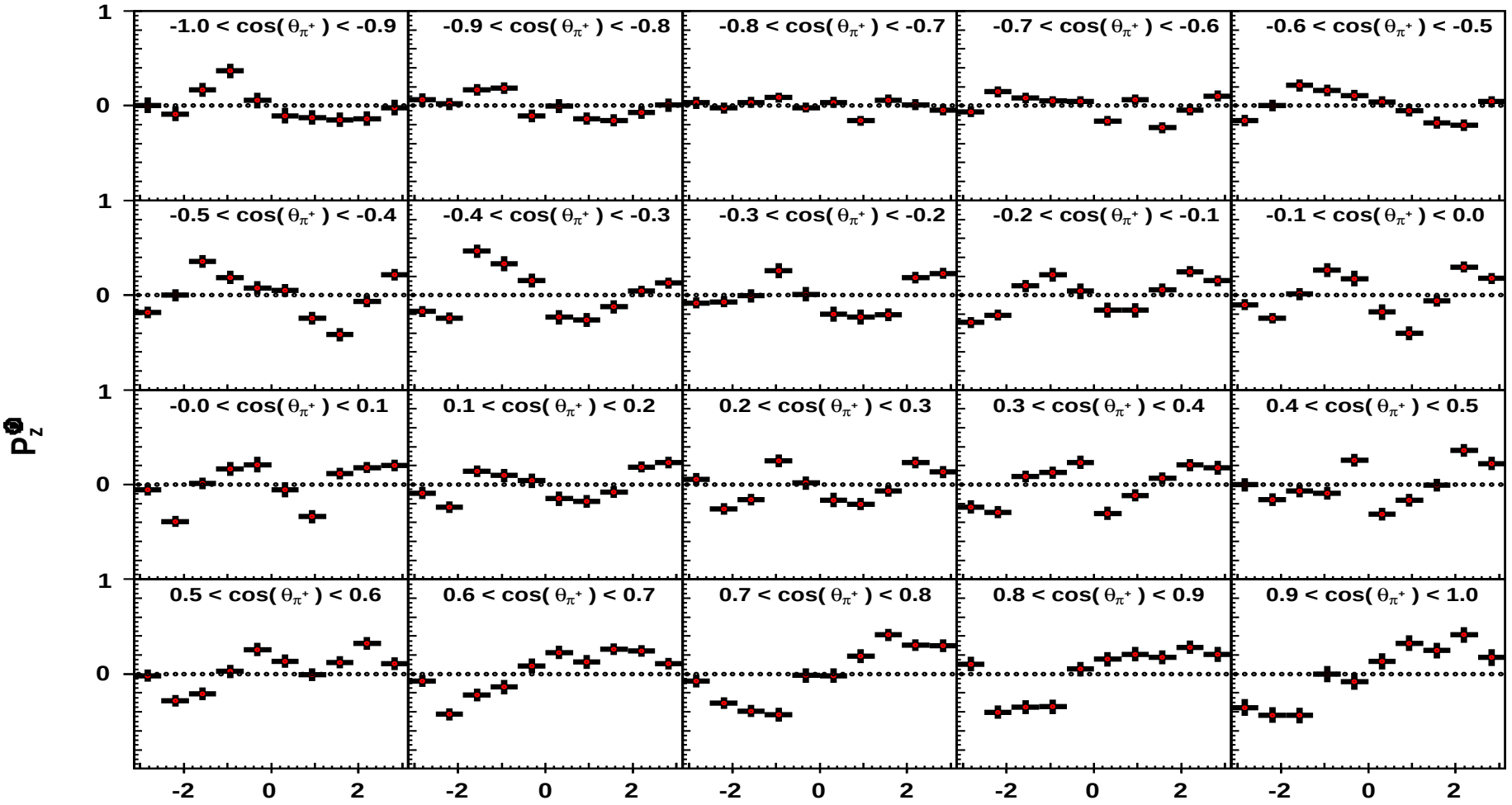
$P_z^{\odot}$ in $\gamma p \to p\,\pi^+\pi^-$ $1500 < E_\gamma < 1600$ MeV



Helicity Difference $P_z^{\odot}$

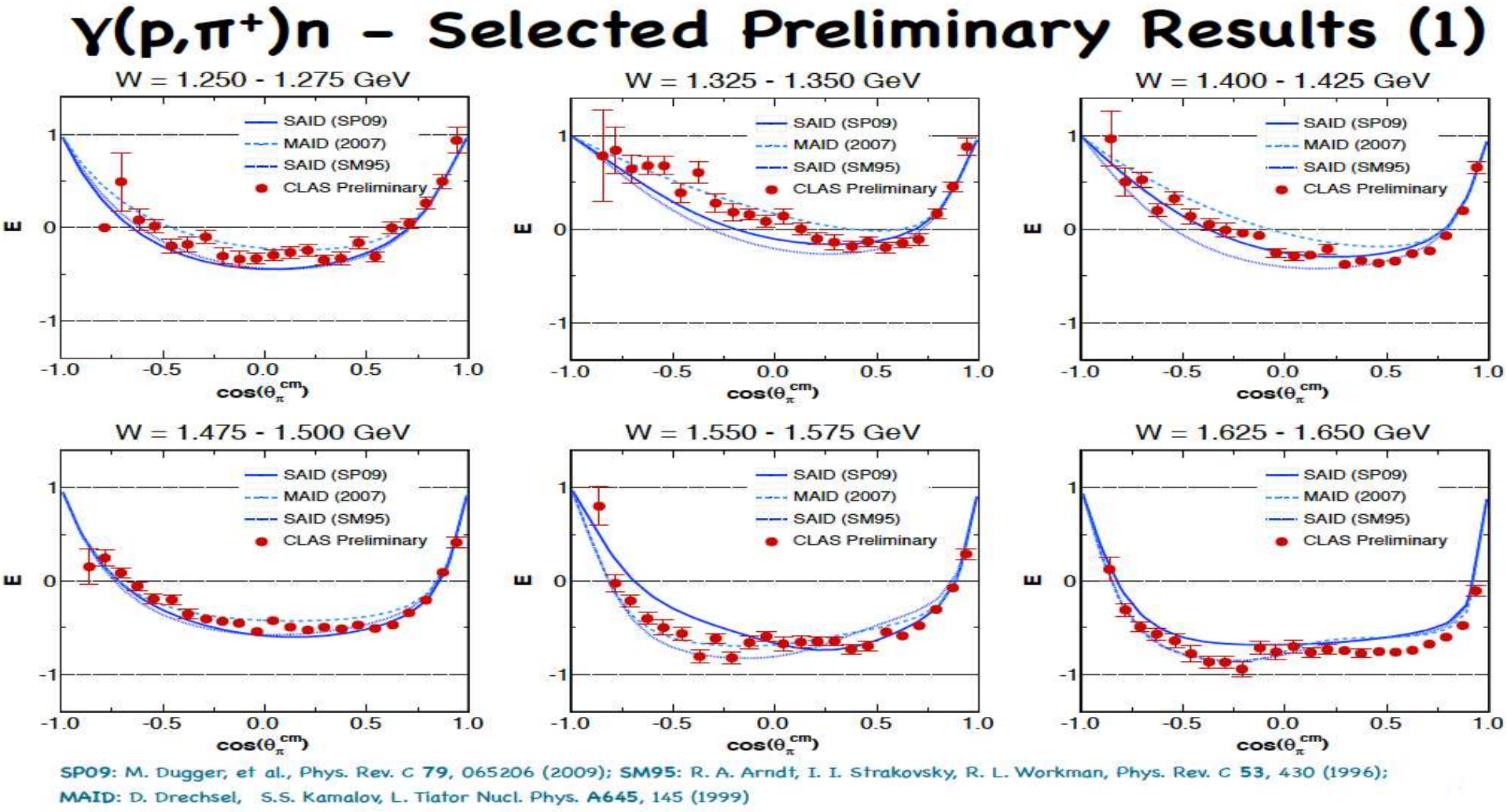
$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_{\odot} (\mathbf{I}^{\odot} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\odot}) + \delta_l [\sin 2\beta (\mathbf{I}^{\mathbf{s}} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\mathbf{s}}) + \cos 2\beta (\mathbf{I}^{\mathbf{c}} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\mathbf{c}})] \}$$

$P_z^{\odot}$ in $\gamma p \to p\,\pi^+\pi^-$ $1500 < E_\gamma < 1600$ MeV

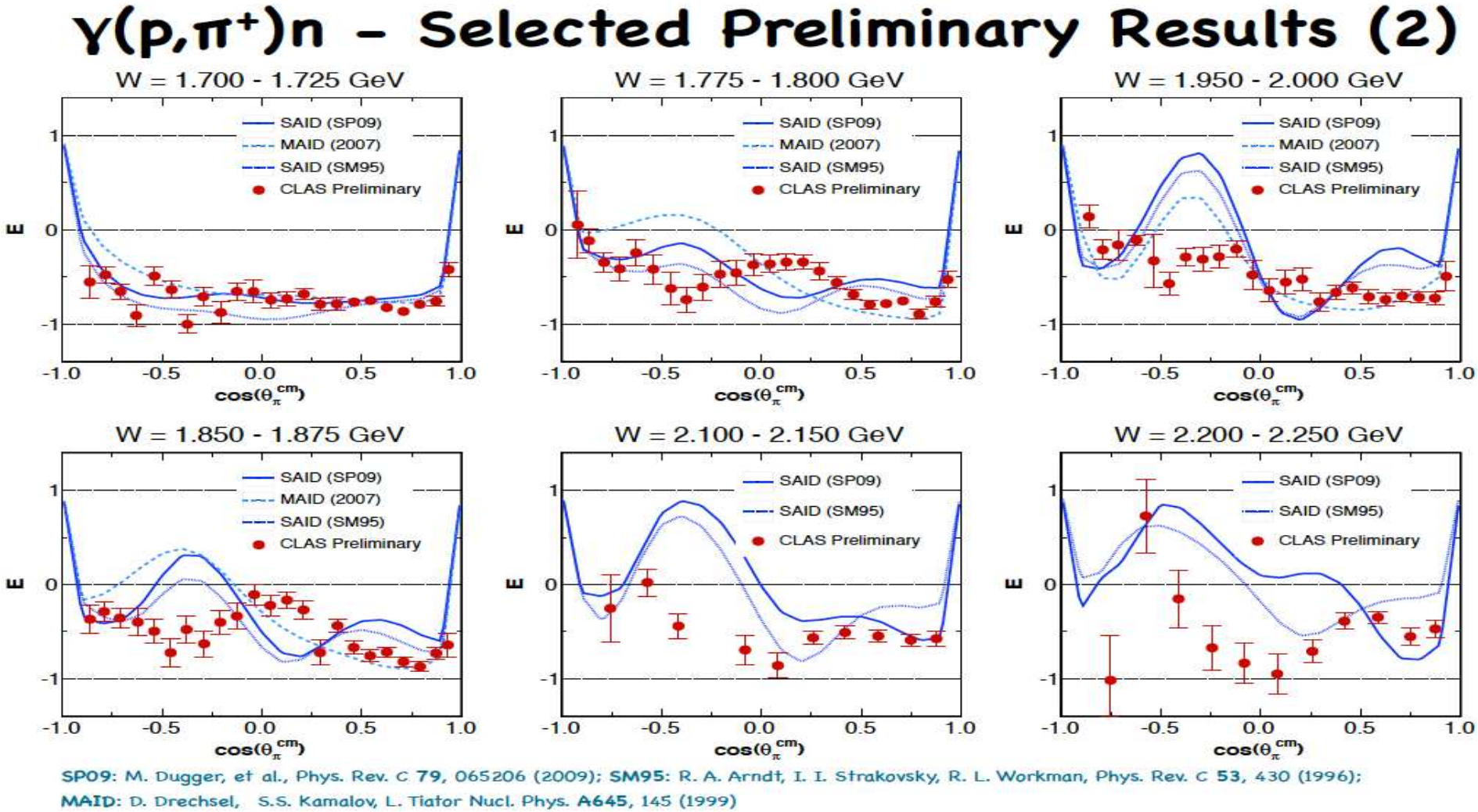


S. Park (FSU), CLAS g9a run group, Ph.D. dissertation

Helicity Difference in $\gamma p \to n \pi^+$

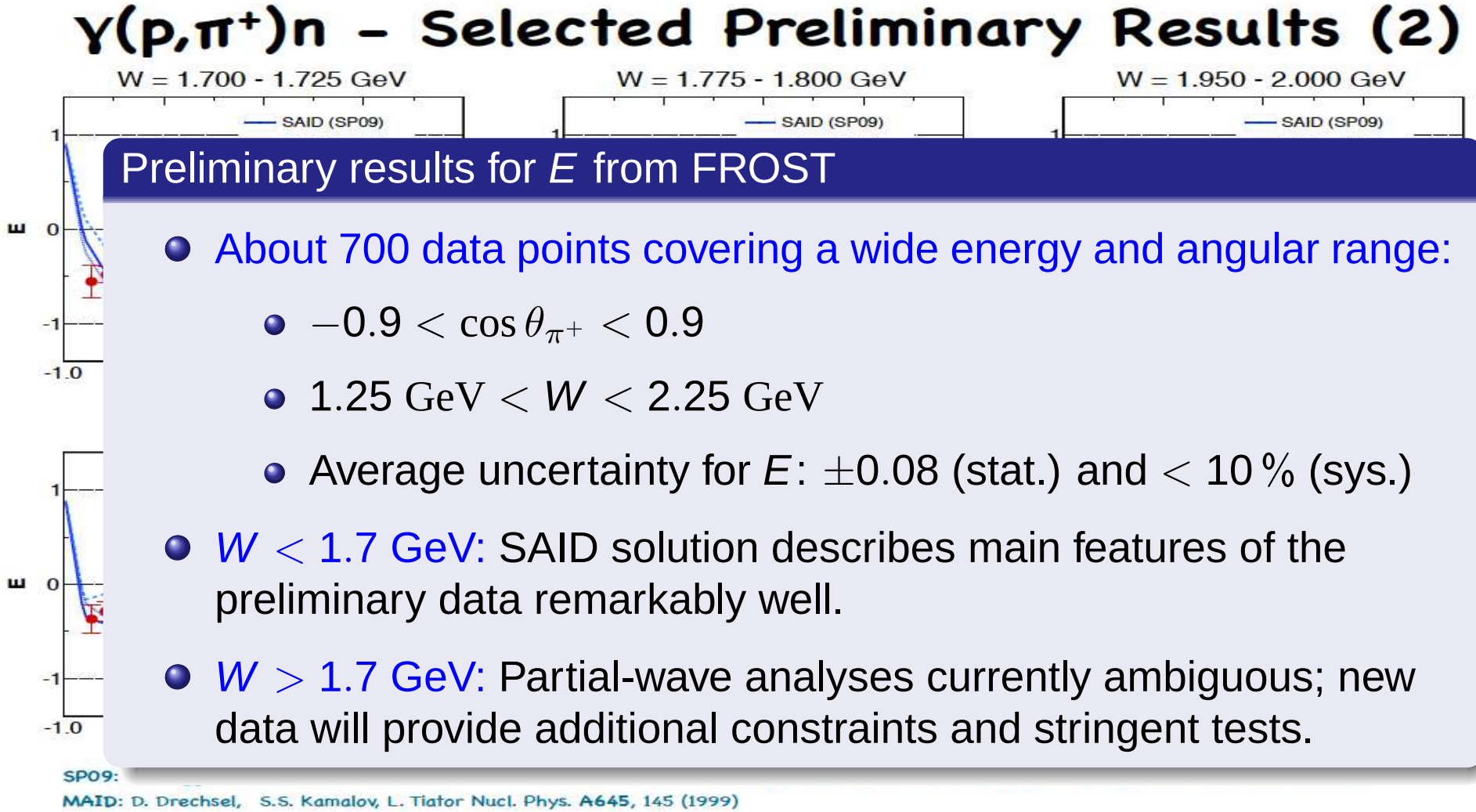


Helicity Difference E in $\gamma p \to n\pi^+$



S. Strauch (University of South Carolina)

Helicity Difference E in $\gamma p \to n\pi^+$

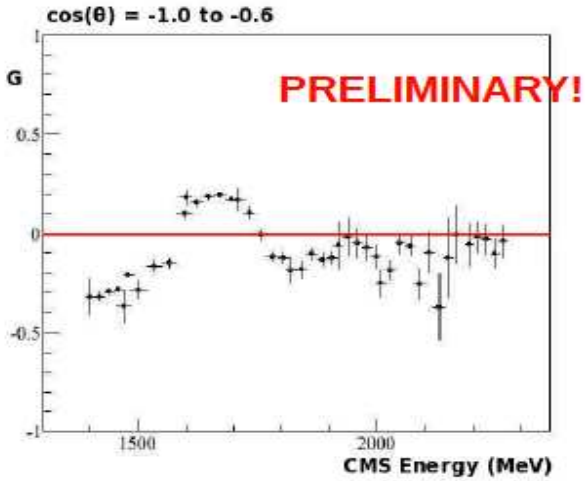


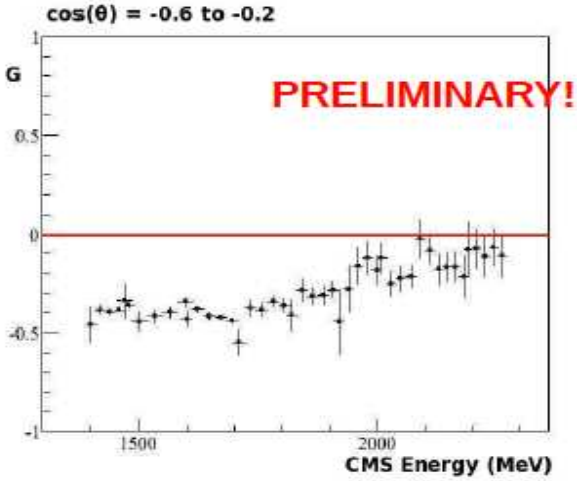
Preliminary results for E from FROST

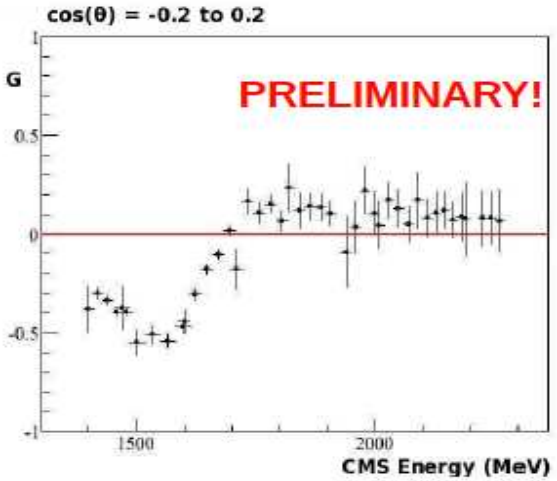
- About 700 data points covering a wide energy and angular range:
  - $-0.9 < \cos\theta_{\pi^+} < 0.9$
  - $1.25\ \text{GeV} < W < 2.25\ \text{GeV}$
  - Average uncertainty for E: ± 0.08 (stat.) and $< 10\,\%$ (sys.)
- $W < 1.7$ GeV: SAID solution describes main features of the preliminary data remarkably well.
- $W > 1.7$ GeV: Partial-wave analyses currently ambiguous; new data will provide additional constraints and stringent tests.

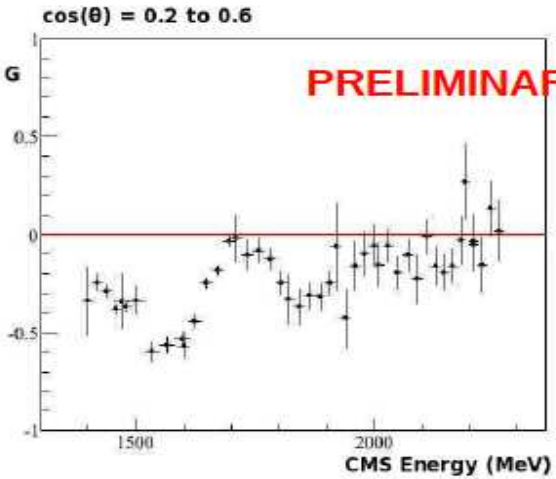
S. Strauch (University of South Carolina)

G Observable in $\gamma p \to n \pi^+$





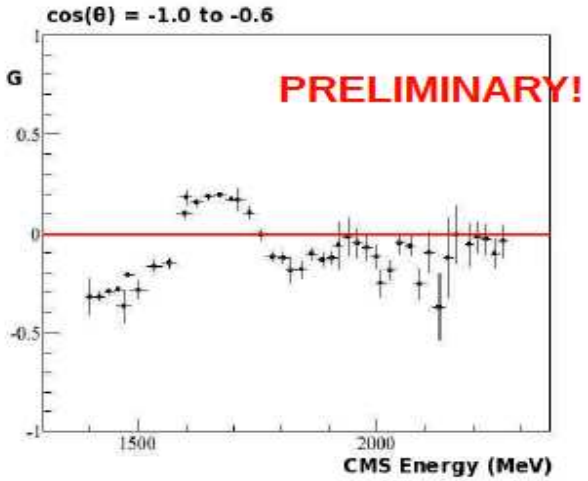


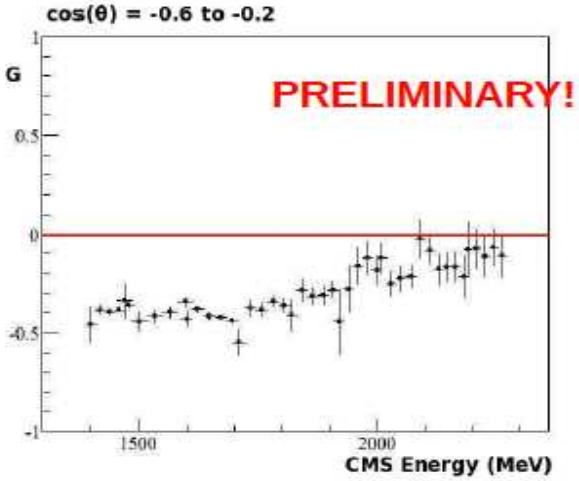


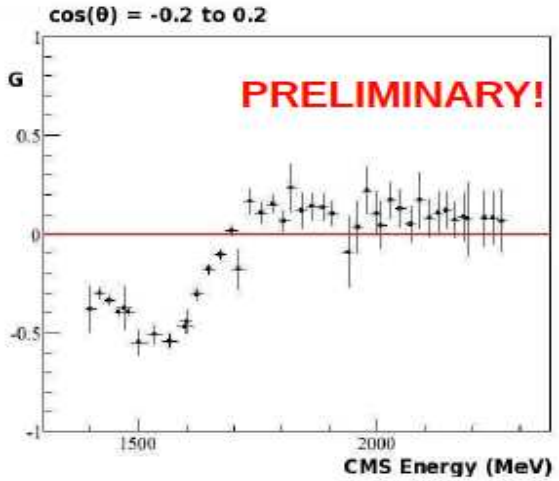
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \sigma_0 \{ 1 - \delta_l \, \Sigma \cos 2\phi + \Lambda_x (-\delta_l \, \mathbf{H} \sin 2\phi + \delta_\odot \, \mathbf{F}) - \Lambda_y (-\mathbf{T} + \delta_l \, \mathbf{P} \cos 2\phi) - \Lambda_z (-\delta_l \, \mathbf{G} \sin 2\phi + \delta_\odot \, \mathbf{E}) \}$$

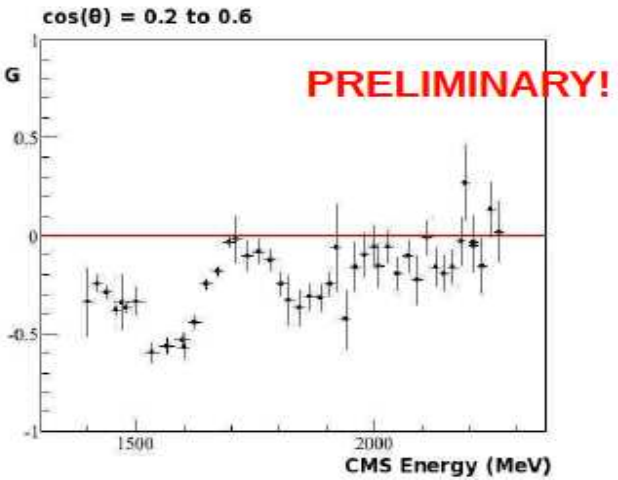
J. McAndrew (University of Edinburgh)

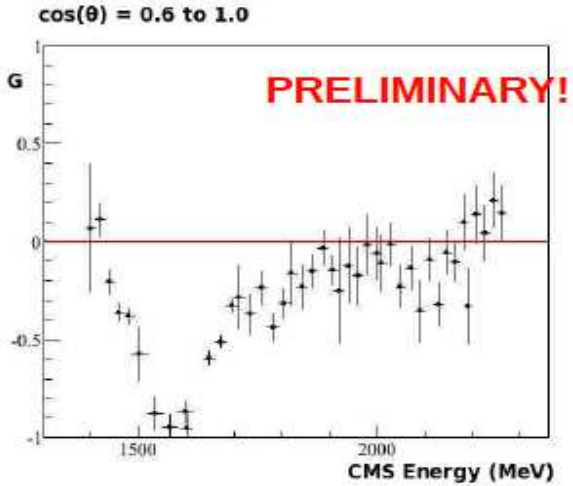
G Observable in $\gamma p \to n \pi^+$











Early stage results:

- 730 - 2300 MeV (fixed angular bins)

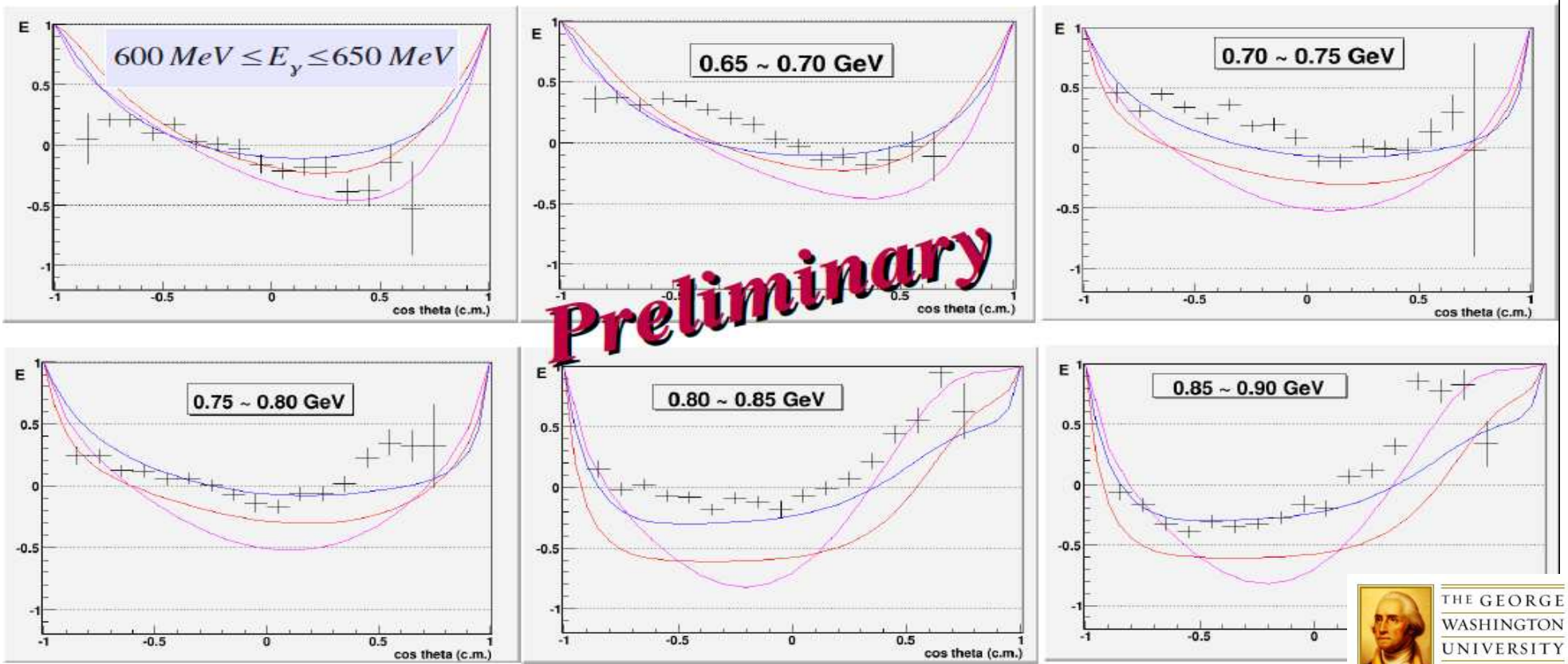
J. McAndrew (University of Edinburgh)

Helicity Difference E in $\gamma p \rightarrow p\,\pi^0$

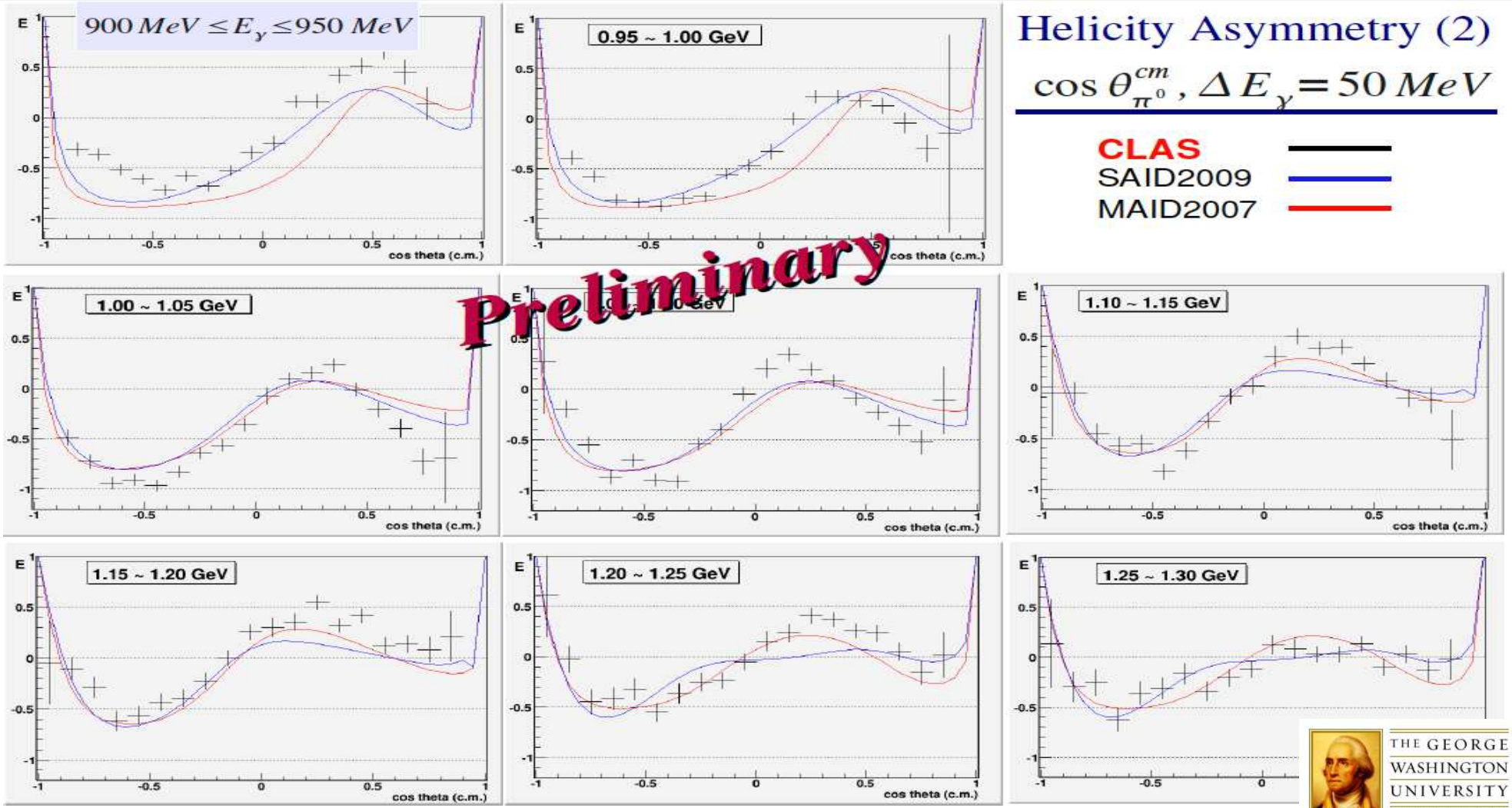
$$E = \frac{1}{D_f P_T P_\gamma} \frac{N_{3/2} - N_{1/2}}{N_{1/2} + N_{3/2}}$$

CLAS
SAID2009
MAID2007
EBAC

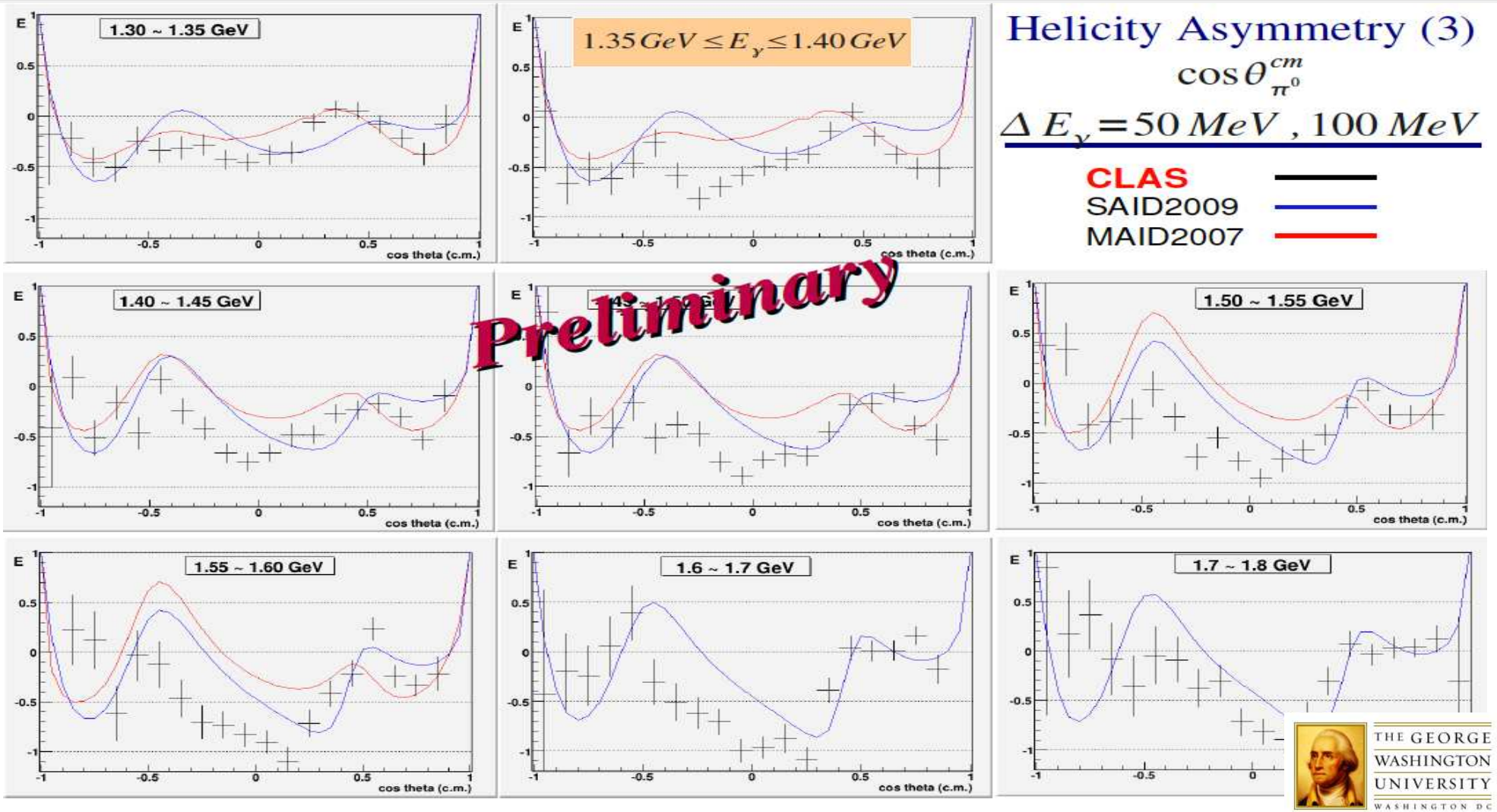
D_f : max ~ 0.35
P_T 0.78 ~ 0.92
Pe 0.79 ~ 0.87



Helicity Difference E in $\gamma p \to p\,\pi^0$



Helicity Difference E in $\gamma p \to p\,\pi^0$



Outline

Summary and Outlook

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton targets																
$p\pi^0$	✔	✓	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✓	✓		✓	✓	✓	✓								
$p\eta$	✔	✓	✓		✓	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$p\omega$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
Neutron targets																
$p\pi^-$	✔	✓	✓		✓	✓	✓	✓								
$p\rho^-$	✓	✓	✓		✓	✓	✓	✓								
$K^-\Sigma^+$	✓	✓	✓		✓	✓	✓	✓								
$K^0\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

✓ published

✓ acquired (being analyzed)

✓ acquired

✓ planned