First data with FROST

Michael Dugger*
Arizona State University

*Work at ASU is supported by the U.S. National Science Foundation

Outline

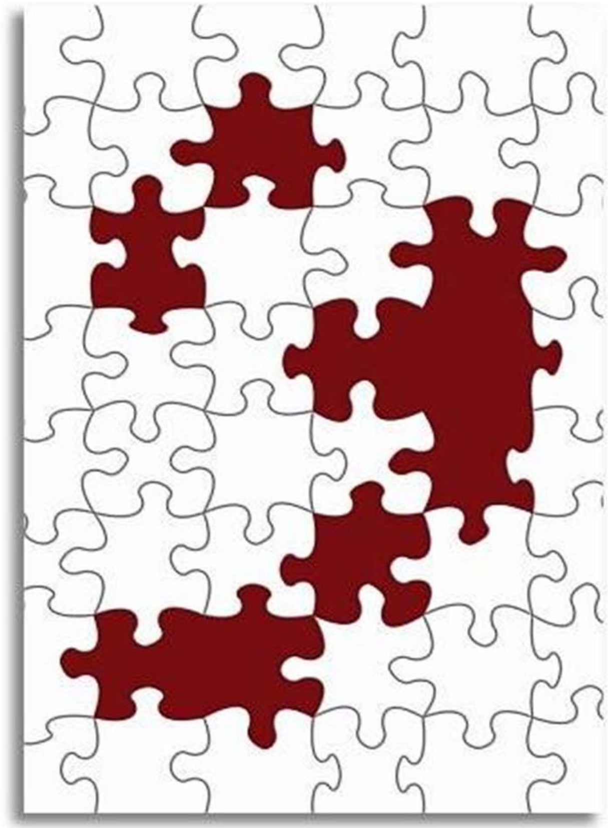
- **General motivations**
- Polarization observables to be discussed
- Experimental details
- Preliminary results for several polarization observables
- Conclusions

Motivation: Baryon resonances

• Masses, widths, and coupling constants not well known for many resonances

• Many models: relativised quark model, Goldstone-boson exchange, diquark and collective models, instanton-induced interactions, flux-tube models, lattice QCD…

• **Big Puzzle: Most models predict more resonance states than observed**



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Observables to be shown

- $\gamma\, p \rightarrow p\, \pi^0$ — E
- $\gamma\, p \rightarrow n\, \pi^+$ — $E,\ G$
- $\gamma\, p \rightarrow p\, \eta$ — E
- $\gamma\, p \rightarrow K^+ \Lambda$ — $E,\ \Sigma,\ G$
- $\gamma\, p \rightarrow K^+ \Sigma^0$ — E

→ Single pseudoscalar photoproduction

- $\gamma\, p \rightarrow p\, \pi^+ \pi^-$ — $I_s,\ P_z,\ P^{\circ}_z$

Photon		Target			Recoil			Target + Recoil			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

Isospin overlaps for reactions involving π^0 and π^+

- Differing isospin overlaps of N^* and Δ^+ for the $\pi^0\, p$ and $\pi^+\, n$ final states
- The $\pi^0\, p$ and $\pi^+\, n$ final states can help distinguish between the Δ and N^*

Δ^+ ↓ N^* ↓

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

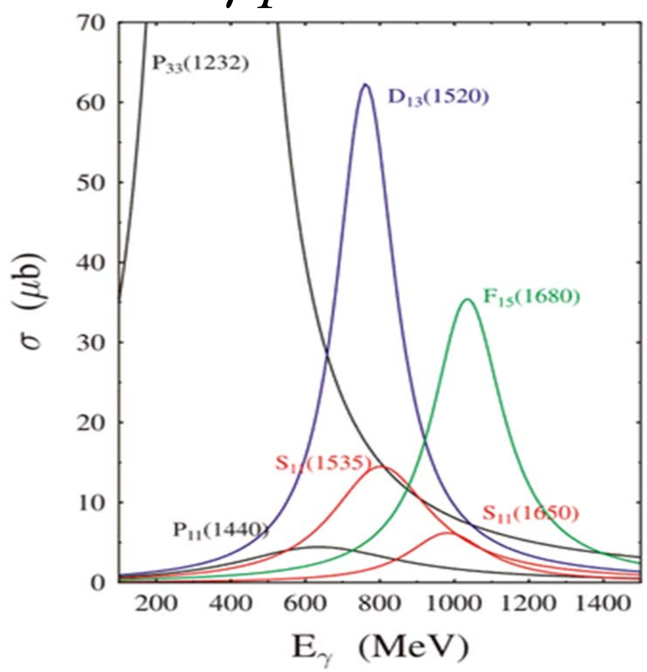
$$\pi^+ + n : \sqrt{1/3}\left|I = \tfrac{3}{2}, I_3 = \tfrac{1}{2}\right\rangle + \sqrt{2/3}\left|I = \tfrac{1}{2}, I_3 = \tfrac{1}{2}\right\rangle$$

“Isospin filters”

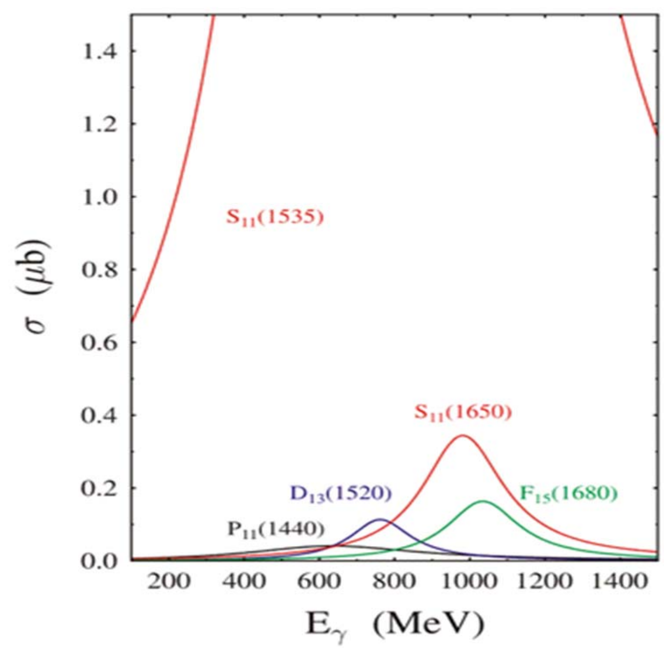
- Resonance spectrum has many broad overlapping states

- The ηp and $K^+\Lambda$ systems have isospin ½ and limit one-step excited states of the proton to be isospin ½. The final states ηp and $K^+\Lambda$ act as **isospin filters** to the resonance spectrum.

$\gamma\, p \rightarrow \pi^+\, n$



$\gamma\, p \rightarrow \eta\, p$



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Self-analyzing reaction $K^+ Y$ (hyperon)

• The weak decay of the hyperon allows the extraction of the hyperon polarization by looking at the proton decay distribution in the hyperon center of mass system:

$$I_i(\cos\theta_i) = \tfrac{1}{2}\left(1 + \alpha P_{Yi} \cos\theta_i\right)$$

where I_i is the decay distribution of the proton, α is the weak decay asymmetry ($\alpha_\Lambda = 0.642$ and $\alpha_{\Sigma 0} = -\tfrac{1}{3}\,\alpha_\Lambda$), and P_{Yi} is the hyperon polarization.

• We can obtain recoil polarization information without a recoil polarimeter and the reaction is said to be "self-analyzing"

Helicity amplitudes for $\gamma + p \rightarrow p + pseudoscalar$

- 8 helicity states: 4 initial, 2 final → 4·2 = 8
- Amplitudes are complex, but overall phase unobservable → 7 independent numbers
- **HOWEVER**, not all possible observables are linearly independent and it turns out that there must be a minimum of 8 observables / experiments

Initial helicity

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$$

Final helicity

helicity +1 photons (ε_+):

$$A_{\varepsilon_+} = \begin{array}{c|cc} & \frac{3}{2} & \frac{1}{2} \\ \hline \frac{1}{2} & H_1 & H_2 \\ \frac{-1}{2} & H_3 & H_4 \end{array}$$

$$\left(A_{-\mu,-\lambda} = -e^{(\lambda-\mu)\pi} A_{\mu,\lambda} \right)$$

Parity symmetry →

helicity -1 photons (ε_-):

$$A_{\varepsilon_-} = \begin{array}{c|cc} & \frac{-1}{2} & \frac{-3}{2} \\ \hline \frac{1}{2} & H_4 & -H_3 \\ \frac{-1}{2} & -H_2 & H_1 \end{array}$$

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Helicity amplitudes and observables for single pseudoscalar photoproduction

Spin observable	Helicity representation
$\check{\Omega}^1 \equiv \mathcal{I}(\theta)$	$\frac{1}{2}(\lvert H_1\rvert^2+\lvert H_2\rvert^2+\lvert H_3\rvert^2+\lvert H_4\rvert^2)$
$\check{\Omega}^4 \equiv \check{\Sigma}$	$\mathrm{Re}(-H_1H_4^*+H_2H_3^*)$
$\check{\Omega}^{10} \equiv -\check{T}$	$\mathrm{Im}(H_1H_2^*+H_3H_4^*)$
$\check{\Omega}^{12} \equiv \check{P}$	$\mathrm{Im}(-H_1H_3^*-H_2H_4^*)$
$\check{\Omega}^3 \equiv \check{G}$	$\mathrm{Im}(H_1H_4^*-H_3H_2^*)$
$\check{\Omega}^5 \equiv \check{H}$	$\mathrm{Im}(-H_2H_4^*+H_1H_3^*)$
$\check{\Omega}^9 \equiv \check{E}$	$\frac{1}{2}(\lvert H_1\rvert^2-\lvert H_2\rvert^2+\lvert H_3\rvert^2-\lvert H_4\rvert^2)$
$\check{\Omega}^{11} \equiv \check{F}$	$\mathrm{Re}(-H_2H_1^*-H_4H_3^*)$
$\check{\Omega}^{14} \equiv \check{O}_x$	$\mathrm{Im}(-H_2H_1^*+H_4H_3^*)$
$\check{\Omega}^7 \equiv -\check{O}_z$	$\mathrm{Im}(H_1H_4^*-H_2H_3^*)$
$\check{\Omega}^{16} \equiv -\check{C}_x$	$\mathrm{Re}(H_2H_4^*+H_1H_3^*)$
$\check{\Omega}^2 \equiv -\check{C}_z$	$\frac{1}{2}(\lvert H_1\rvert^2+\lvert H_2\rvert^2-\lvert H_3\rvert^2-\lvert H_4\rvert^2)$
$\check{\Omega}^6 \equiv -\check{T}_x$	$\mathrm{Re}(-H_1H_4^*-H_2H_3^*)$
$\check{\Omega}^{13} \equiv -\check{T}_z$	$\mathrm{Re}(-H_1H_2^*+H_4H_3^*)$
$\check{\Omega}^8 \equiv \check{L}_x$	$\mathrm{Re}(H_2H_4^*-H_1H_3^*)$
$\check{\Omega}^{15} \equiv \check{L}_z$	$\frac{1}{2}(-\lvert H_1\rvert^2+\lvert H_2\rvert^2+\lvert H_3\rvert^2-\lvert H_4\rvert^2)$

g9b

g9a

Differential cross section

Beam polarization

Target asymmetry

Recoil polarization

Double polarization observables

- Need **at least** 4 of the double observables from at least 2 groups for a "complete experiment"
- $\pi^0 p$, $\pi^+ n$, and $\eta\ p$ will be nearly complete
- $K^+ \Lambda$ will be complete!

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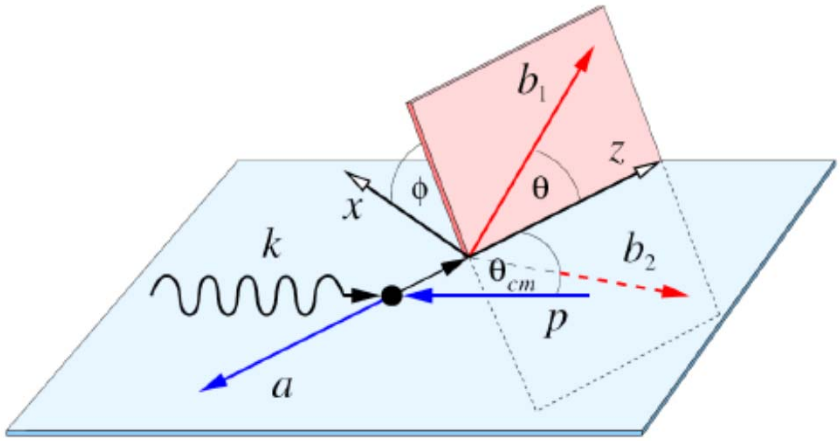
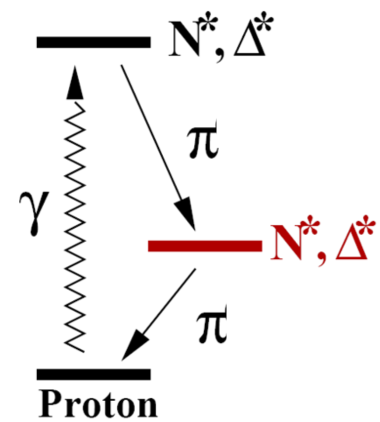
Photoproduction of $\pi^+ \pi^- p$ states

- 64 observables
- 28 independent relations related to helicity amplitude magnitudes
- 21 independent relations related to helicity amplitude phases
- Results in 15 independent numbers





Good for discovering resonances that decay into other resonances!

Finding missing resonances requires lots of different observables. Cross sections are not enough.

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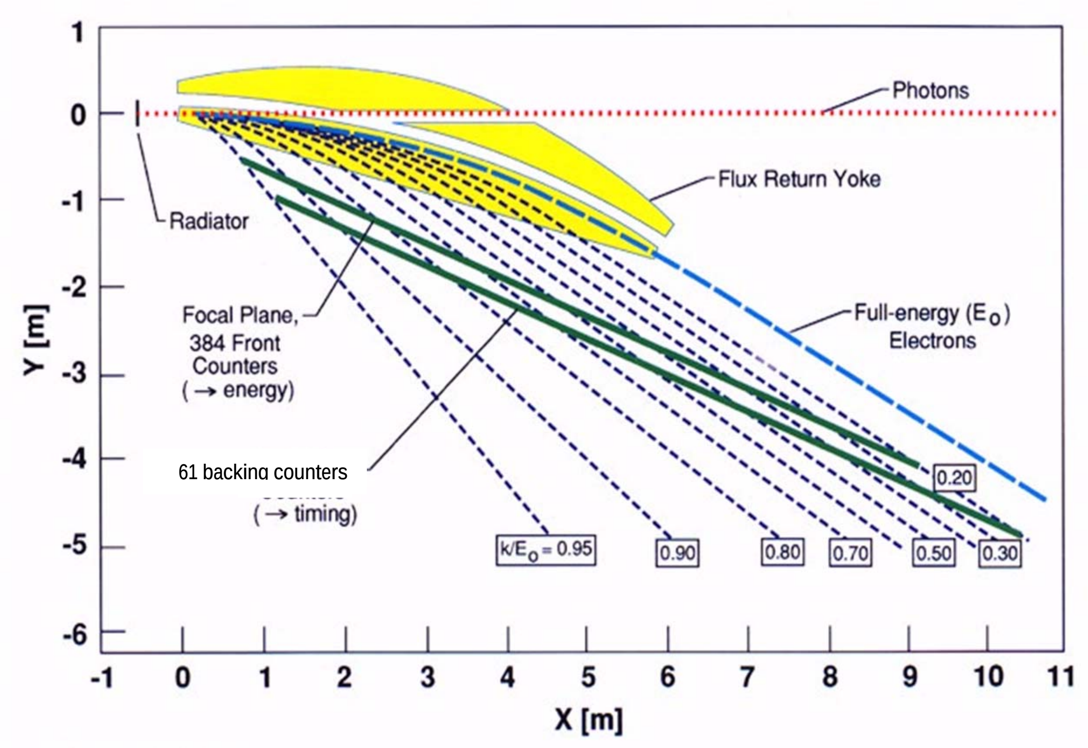
Bremsstrahlung photon tagger



- Jefferson Lab Hall B bremsstrahlung photon tagger
  - E_γ = 20-95% of E_0
  - E_γ up to ~5.5 GeV
  - **Circular polarized photons with longitudinally polarized electrons**
  - **Oriented diamond crystal for linearly polarized photons**

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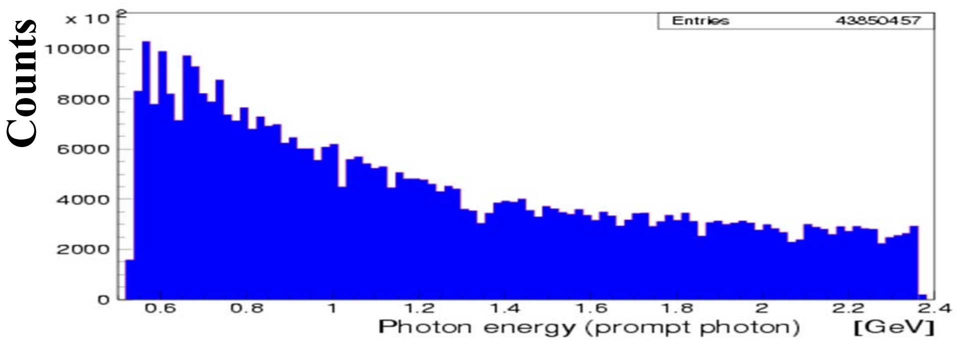
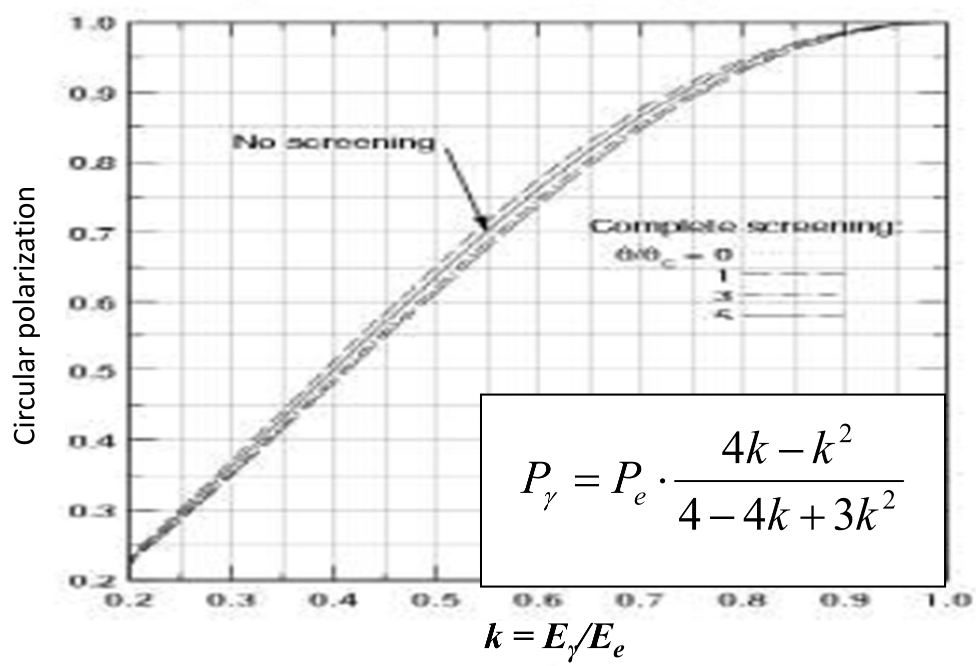
Circular beam polarization



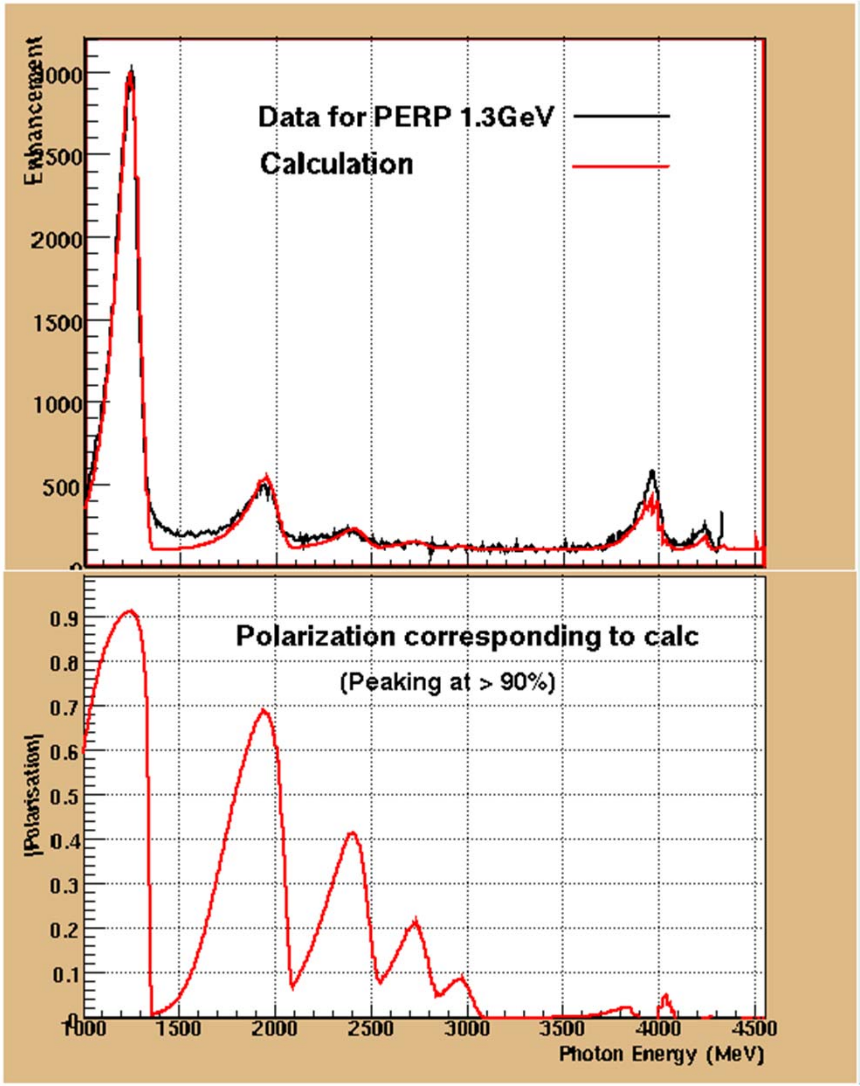
Circular polarization from 100% polarized electron beam



$$P_\gamma = P_e \cdot \frac{4k - k^2}{4 - 4k + 3k^2}$$

- Circular photon beam from longitudinally polarized electrons
- Electron beam polarization > 85%

Linearly polarized photons



- Coherent bremsstrahlung from 50 μ oriented diamond
- Two linear polarization states (vertical & horizontal)
- Analytical QED coherent bremsstrahlung calculation fit to actual spectrum (Livingston/Glasgow)
- Vertical 1.3 GeV edge shown
- Currently, only very preliminary values of P_γ

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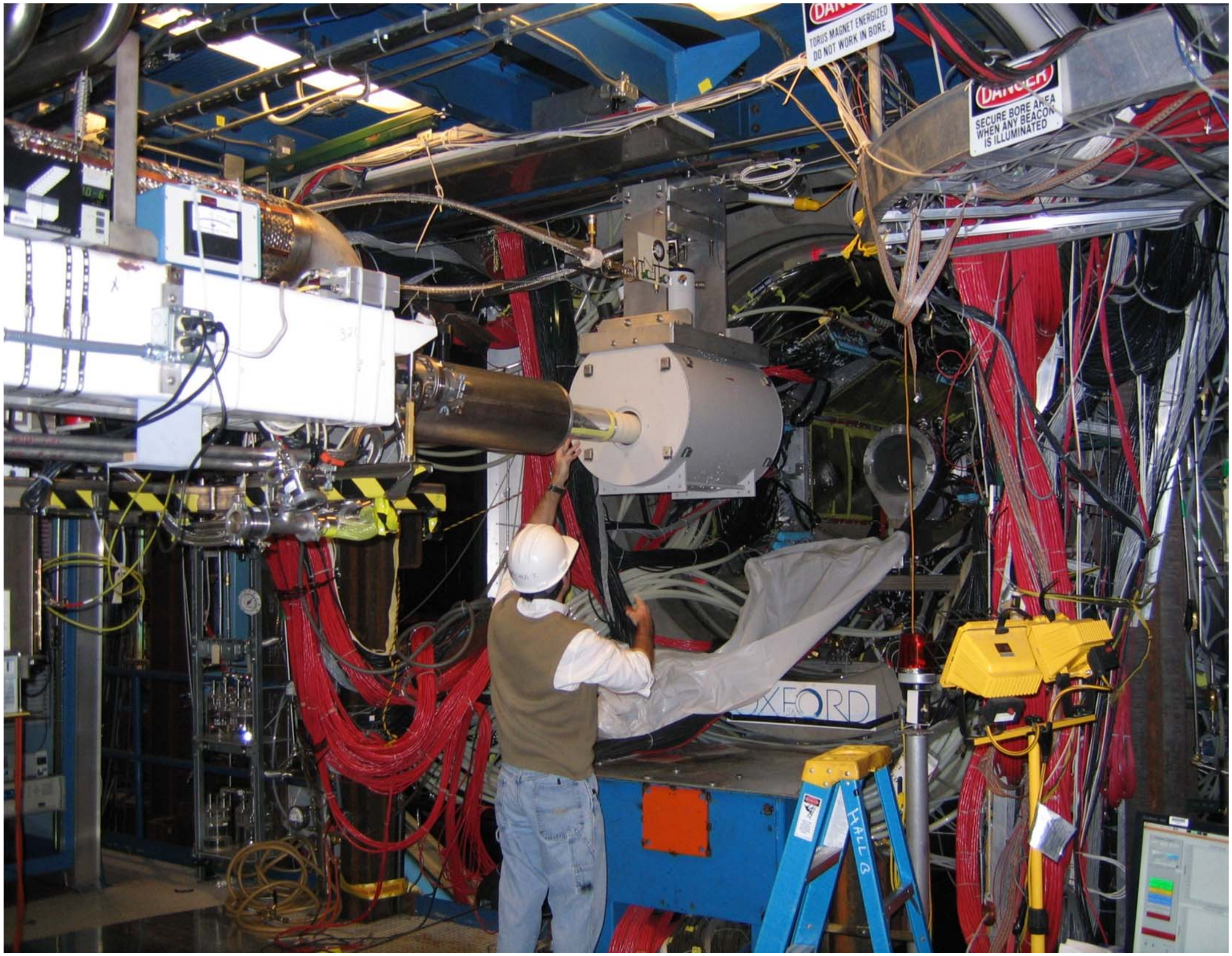
FROST in Hall B

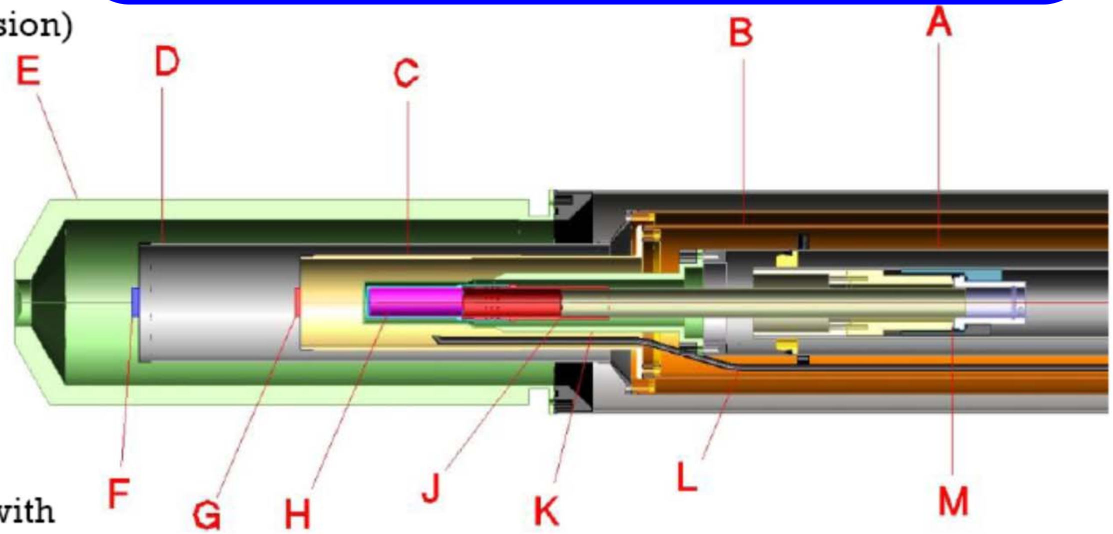


FROST target

- Butanol composition: C_4H_9OH
- Each bound proton is paired with a bound neutron → No polarization of the bound nucleons

The FroST target and its components:

A: Primary heat exchanger
B: 1 K heat shield
C: Holding coil
D: 20 K heat shield
E: Outer vacuum can (Rohacell extension)
F: CH2 target
G: Carbon target
H: Butanol target
J: Target insert
K: Mixing chamber
L: Microwave waveguide
M: Kapton coldseal

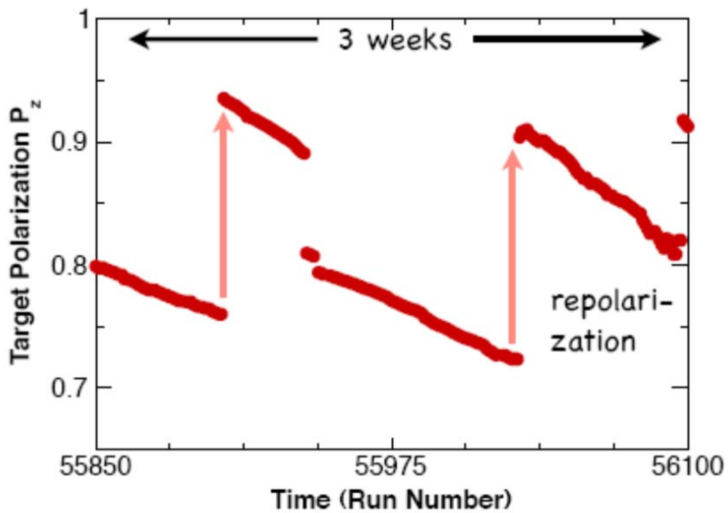


Performance Specs:

Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 μW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.

- Carbon target used to represent bound nucleon contribution of butanol

Target polarization



- Frozen spin butanol (C_4H_9OH)
- $P_z \approx 80\%$
- Target depolarization: $\tau \approx 100$ days

- For g9a (longitudinal orientation) 10% of allocated time was used polarizing target

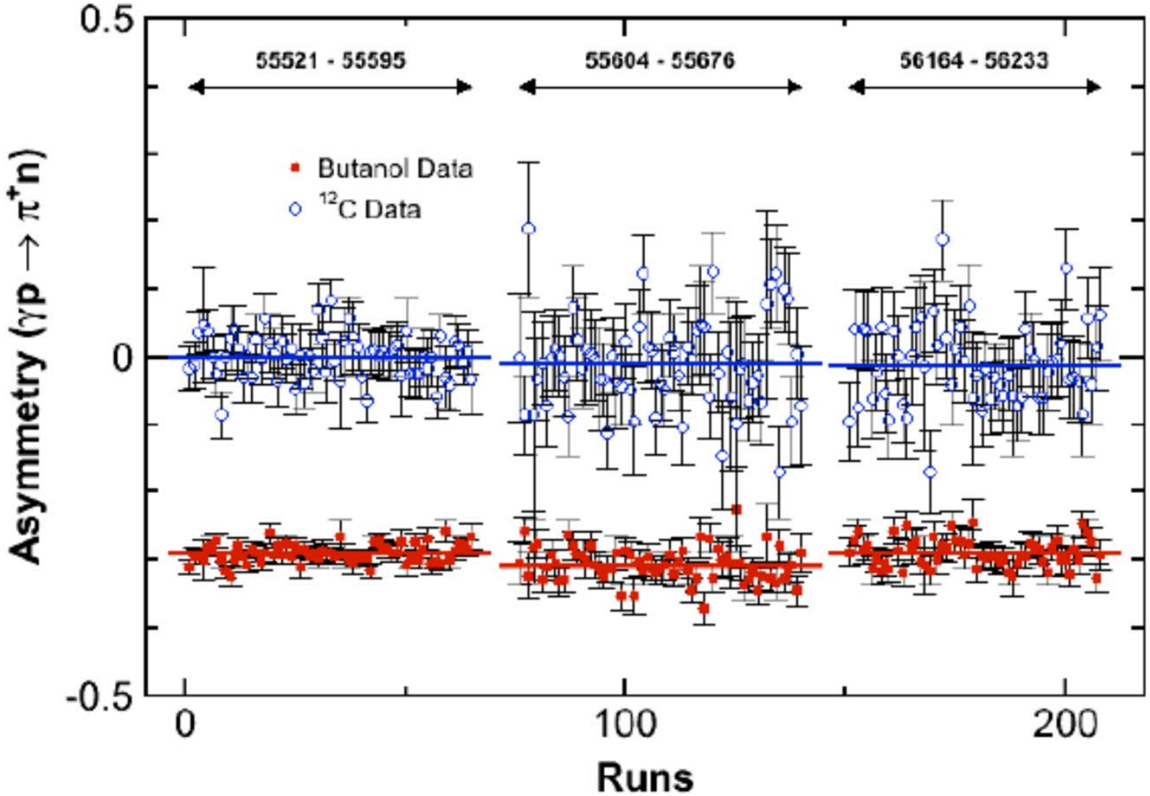
- For g9b (transverse orientation) 5% of allocated time was used polarizing target

Stability of Beam/Target Polarization

E_e = 1.65 GeV

1^{st} E_e = 2.48 GeV

2^{nd} E_e = 2.48 GeV



- Per-run sign of $P_Z P_\odot$ is understood
- Asymmetry of butanol data stepwise constant
- Target de- and re-polarizations under control
- Systematic uncertainty of $\sigma(P_Z P_\odot) \approx 5\%$.

S. Strauch

FROST running conditions

g9a: First running of FROST	g9b: Second running of FROST
• Longitudinally polarized target	• Transversely polarized target
• Circular and linear photon polarization	• Circular and linear photon polarization

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Dilution factor and helicity asymmetry *E*

Theoretically:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left(1 - P_z P_C E\right) \quad \longrightarrow \quad E = \frac{\sigma_{1/2} - \sigma_{3/2}}{P_z P_C\left(\sigma_{1/2} + \sigma_{3/2}\right)}$$

Experimentally: $$E = \frac{1}{P_Z P_C d}\left[\frac{Y_{1/2} - Y_{3/2}}{Y_{1/2} + Y_{3/2}}\right]$$

where Y represents yield and d is the dilution, which is the ratio of hydrogen events to total events:

$$d = \frac{Y_H}{Y_{bound} + Y_H}$$

Note: Bound nucleons have no polarization $\rightarrow E_{bound} = 0$

$\gamma p \rightarrow p \eta$

- Arizona State University
- Brian Morrison, Michael Dugger, and Barry Ritchie

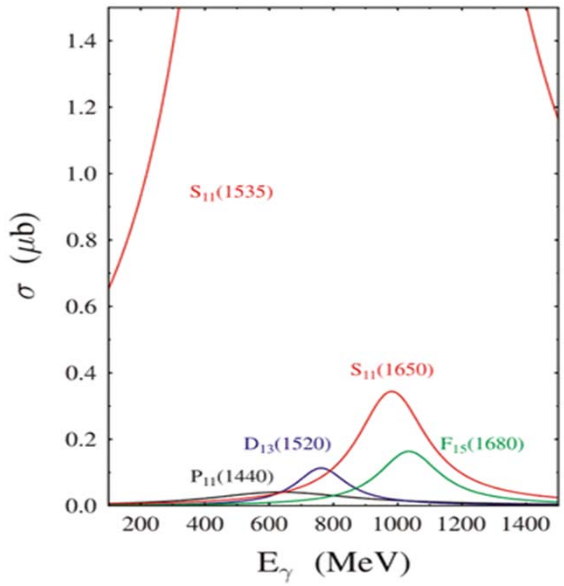
Helicity asymmetry for η photoproduction at threshold

- S_{11}(1535) dominates at threshold

- Since the S_{11}(1535) is an L=0, s = ½, resonance, this resonance can only couple to helicity = ½ initial state.

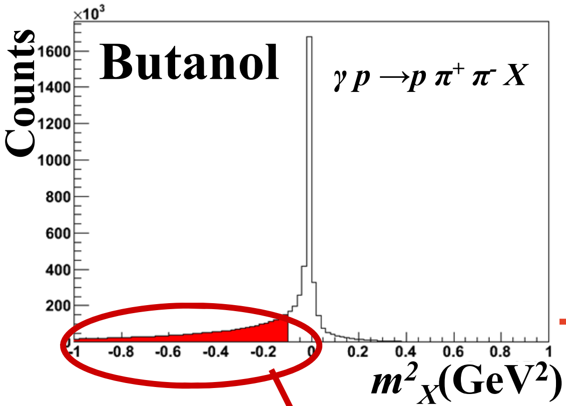
- S_{11} dominance forces $E \approx 1.0$ at, and near, threshold for all scattering angles

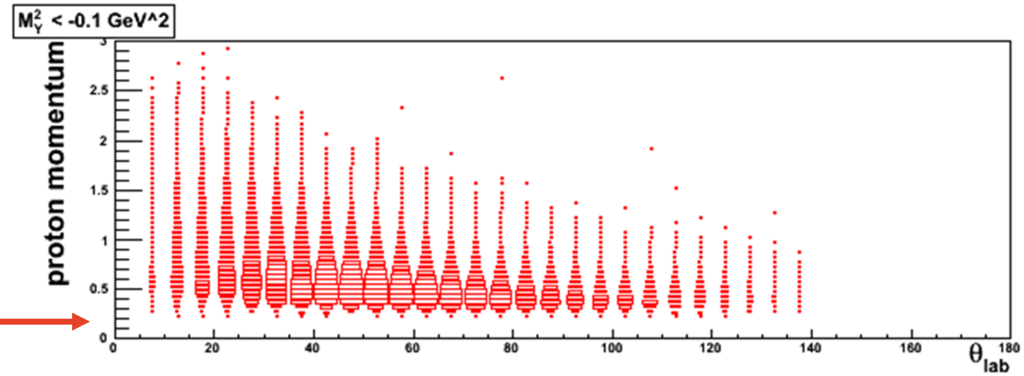
- Provides an analytic check



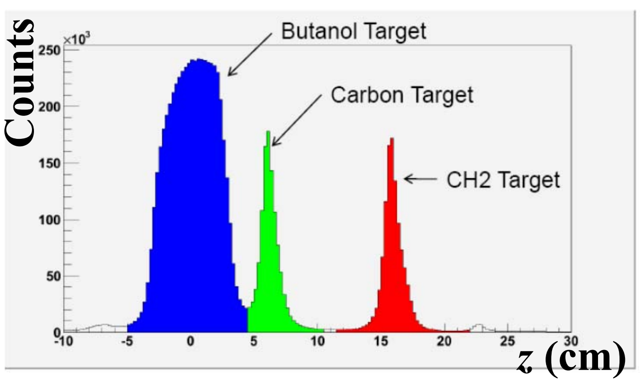
$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{P_z P_C \left(\sigma_{1/2} + \sigma_{3/2}\right)}$$

Scale factors



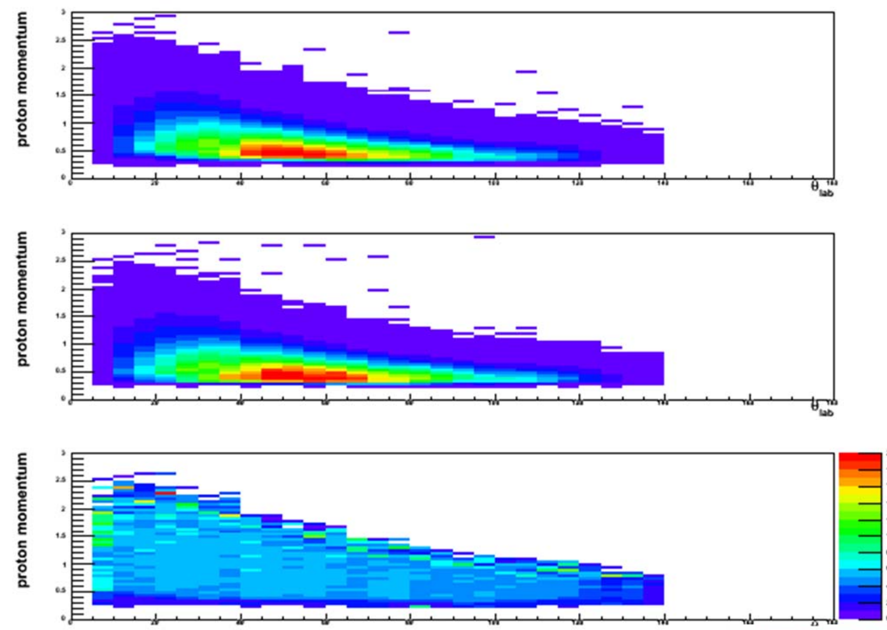


Bound nucleon events



Butanol

Carbon



Scale factors = Butanol/Carbon

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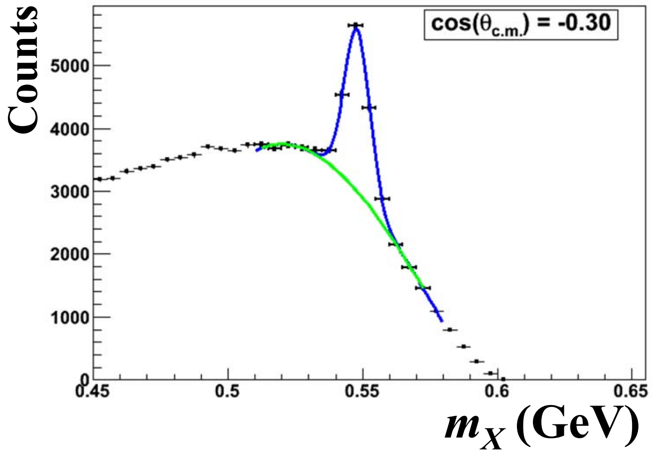
Arizona State University

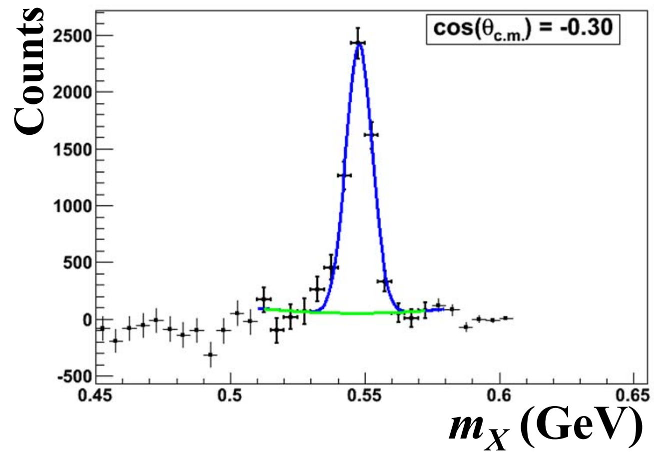
Sample η fits from $\gamma\, p \rightarrow p\, X$

- W = 1525 MeV
- $\cos(\theta_{c.m.}) = -0.3$

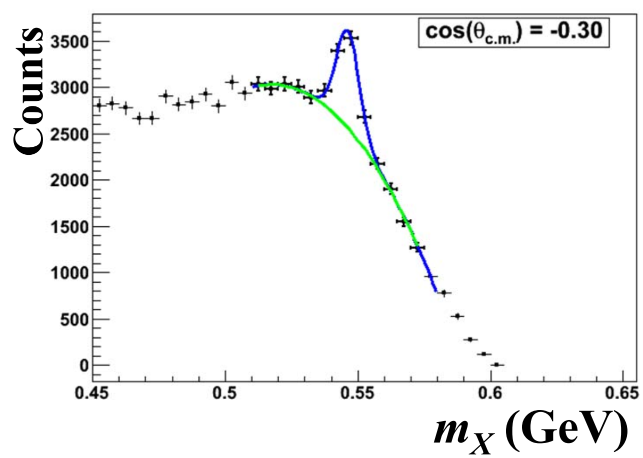
$N_{1/2} + N_{3/2}$



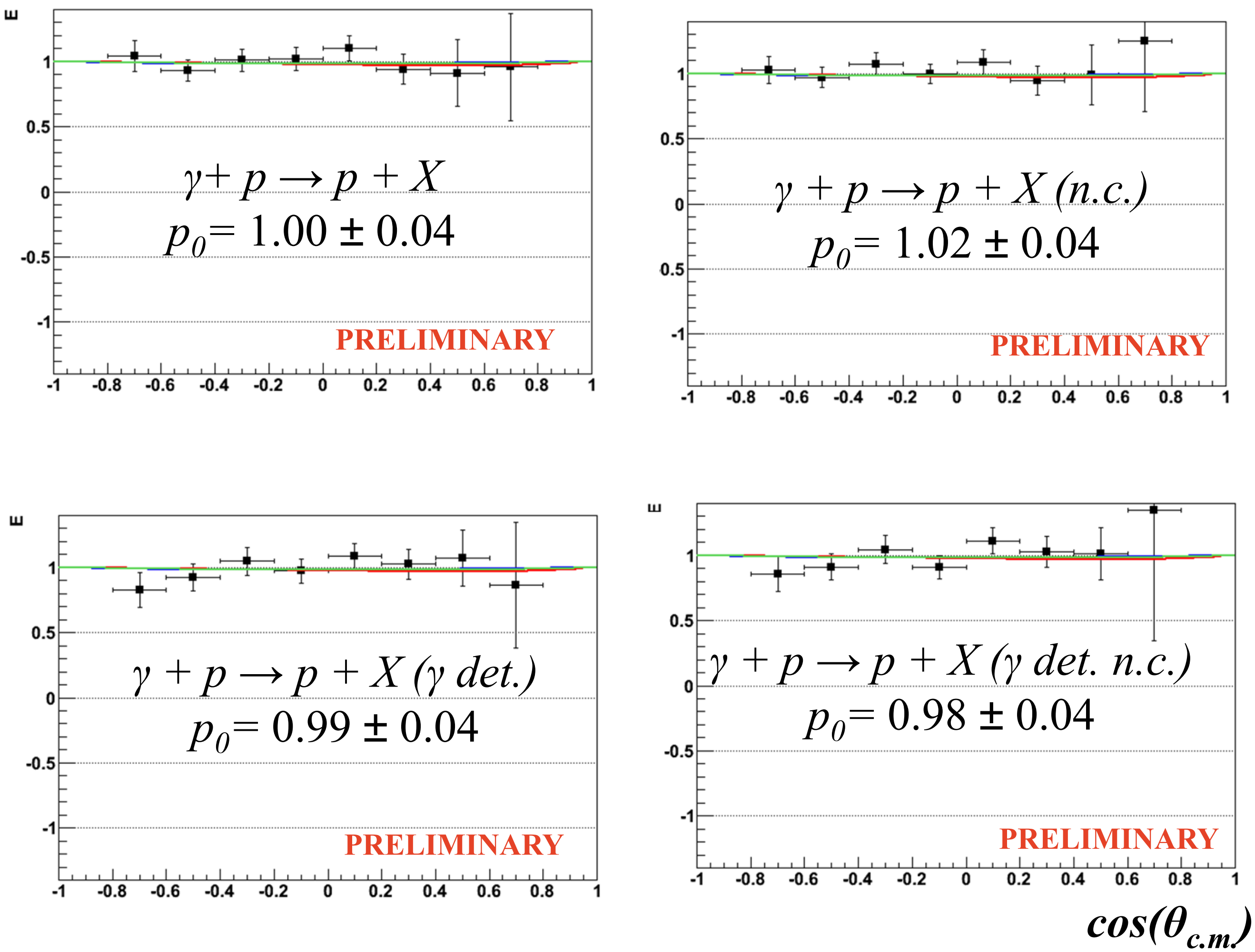
$N_{1/2} - N_{3/2}$



Scaled carbon



E at threshold for $p\ \eta$



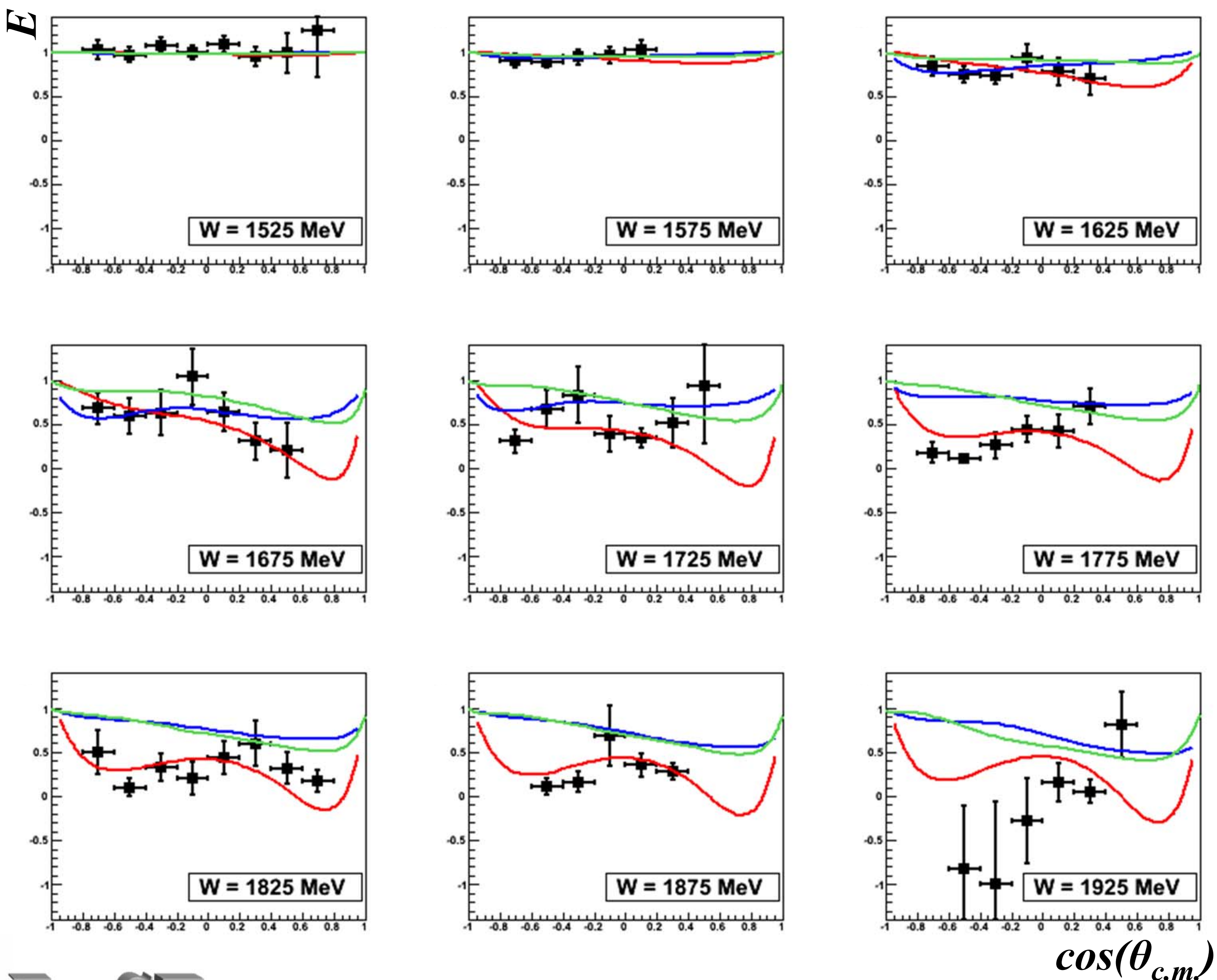
SAID
MAID
Bonn-Gatchina

- $W = 1525$ MeV
- All have E=1, within statistical uncertainties

☺

*n.c. implies no charged particles other than the proton.

Helicity asymmetry at fixed energies



SAID
MAID
Bonn-Gatchina

Preliminary data prefers SAID for W >1.75 GeV

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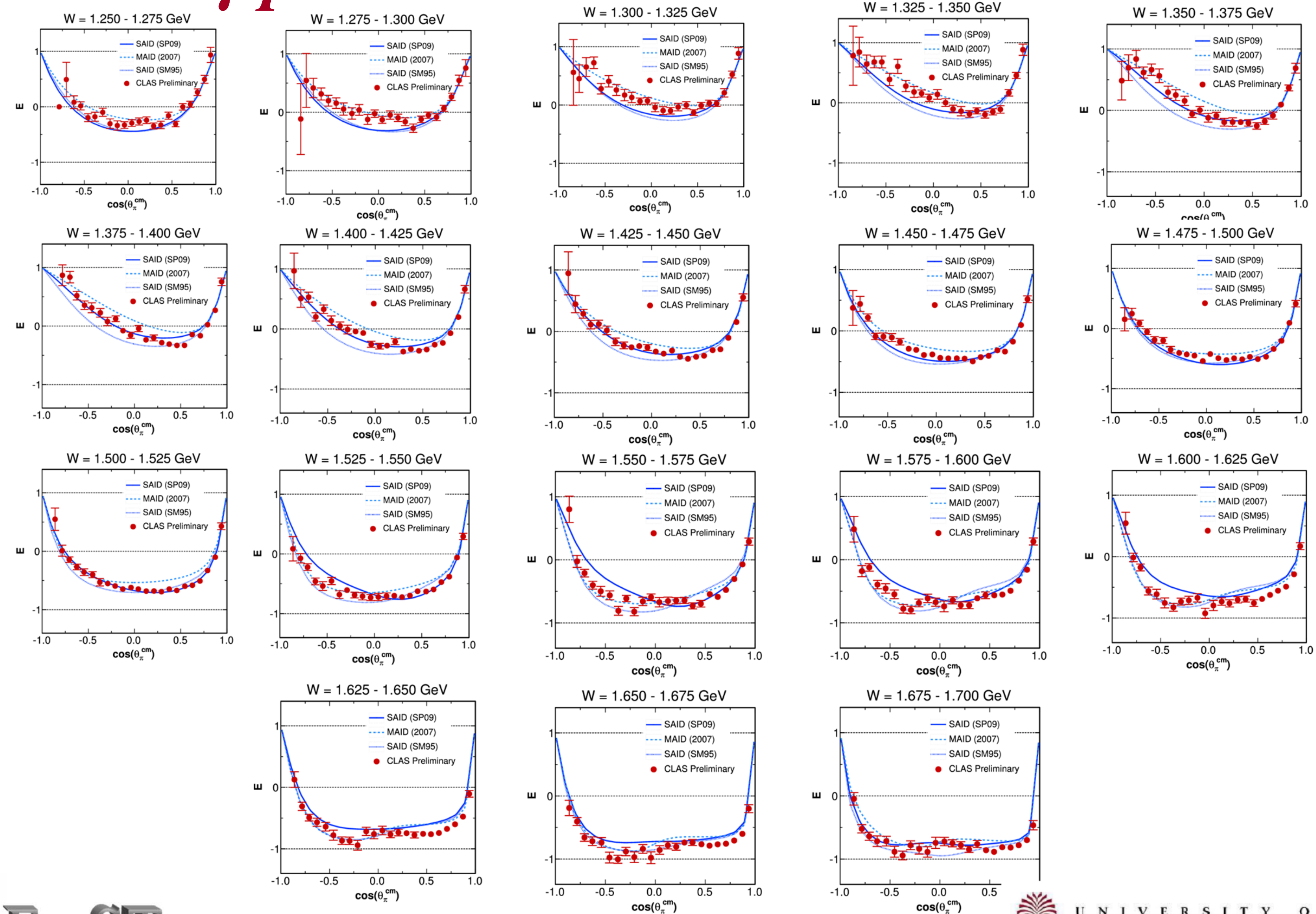
ASU Arizona State University

$\gamma p \rightarrow \pi^+ n$

- University of South Carolina
- Steffen Strauch

E: $\gamma\, p \rightarrow \pi^+ n$ for W = 1.25 to 1.70 GeV



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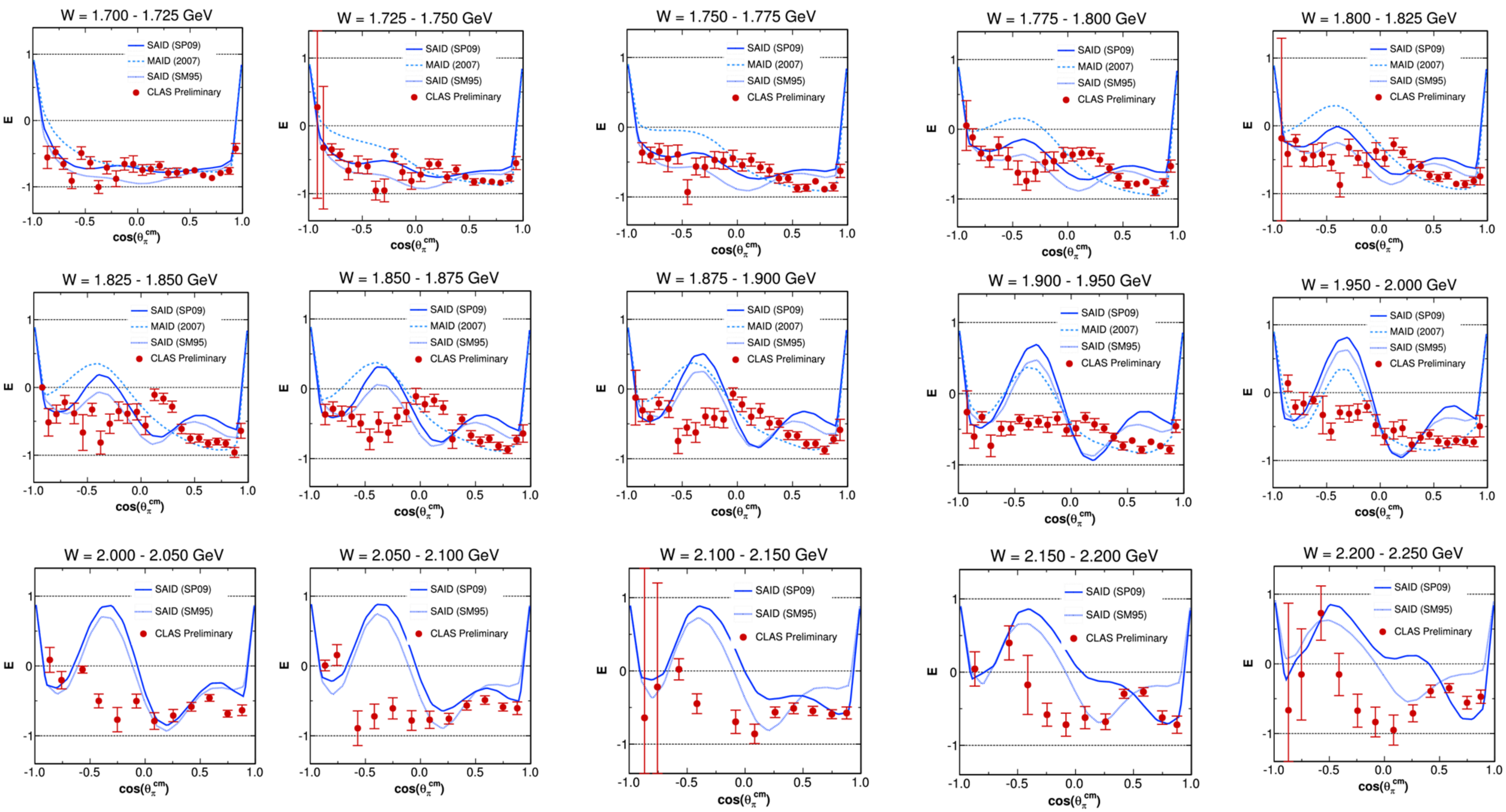
$E: \gamma p \rightarrow \pi^+ n$ for W = 1.70 to 2.25 GeV



For W< 1.75 GeV all of the models represent the data fairly well.

For W> 1.75 GeV none of the models represents the data well.

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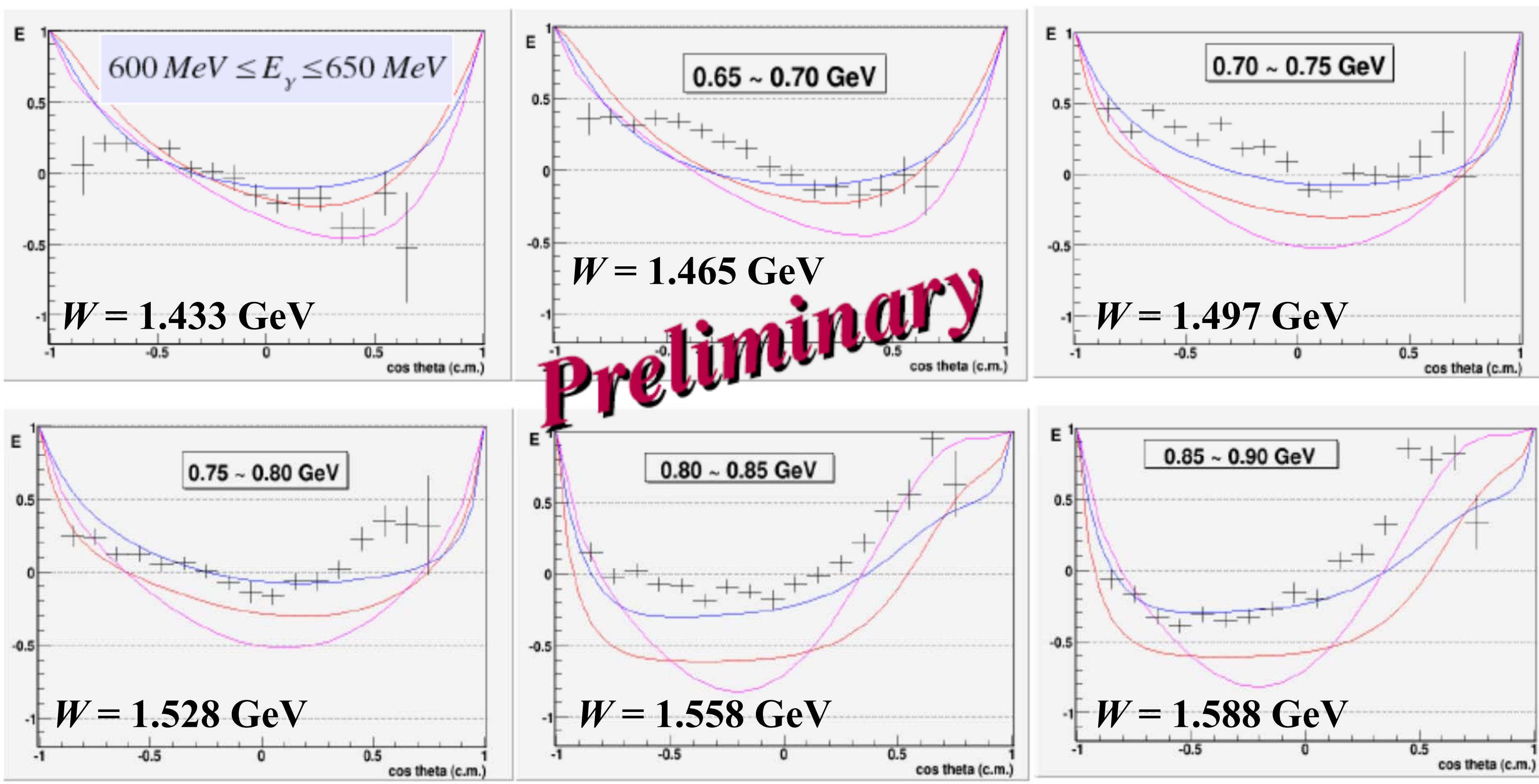
$\gamma\, p \rightarrow p\, \pi^0$

- The George Washington University
- Hideko Iwamoto and Bill Briscoe

Helicity asymmetry E for $\gamma p \rightarrow \pi^0 p$ $\Delta E_\gamma = 50\, MeV$

SAID2009
MAID2007
EBAC

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



Only statistical uncertainty of asymmetry is shown

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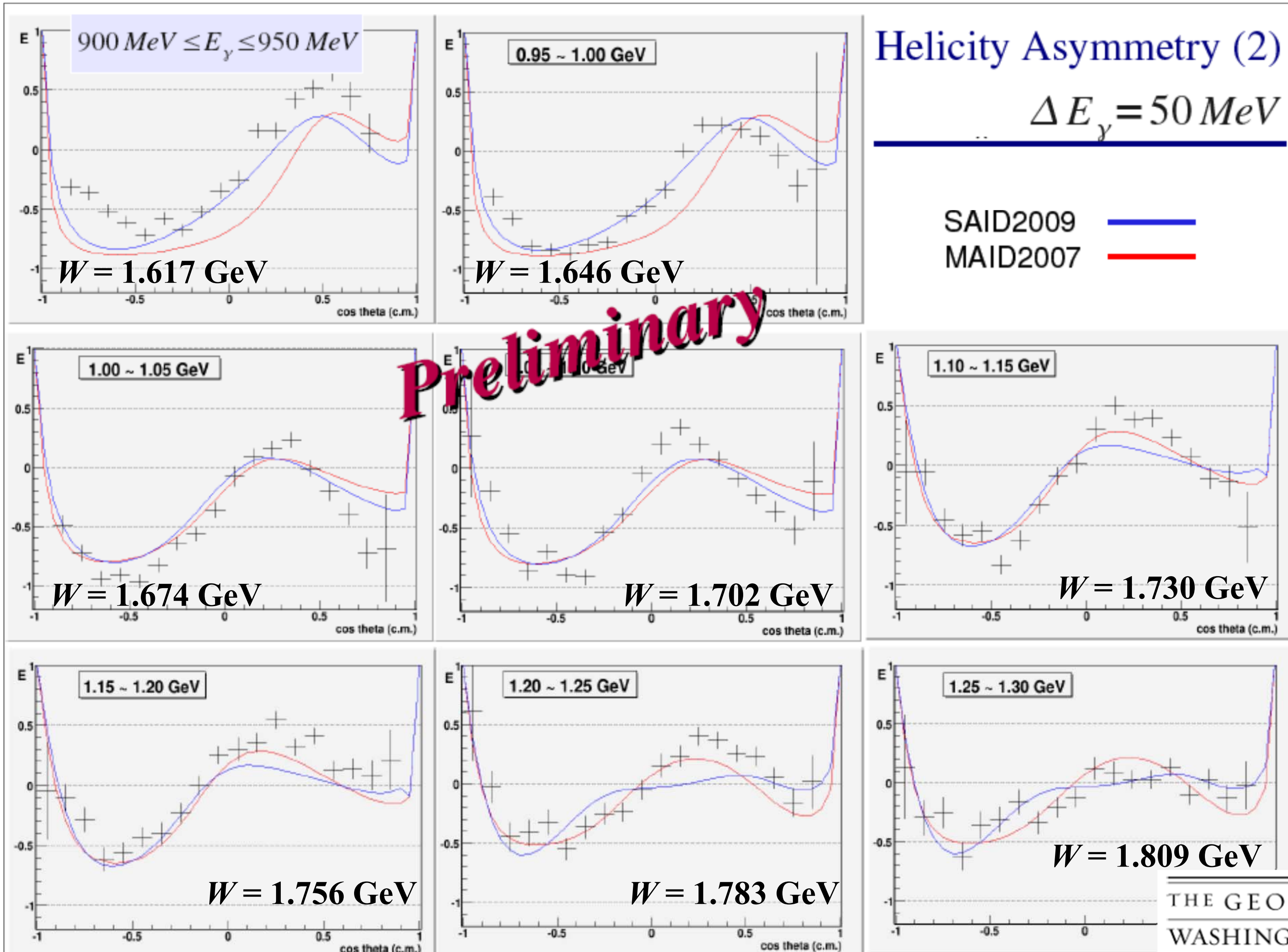
Helicity Asymmetry (2)

$\Delta E_\gamma = 50\ MeV$



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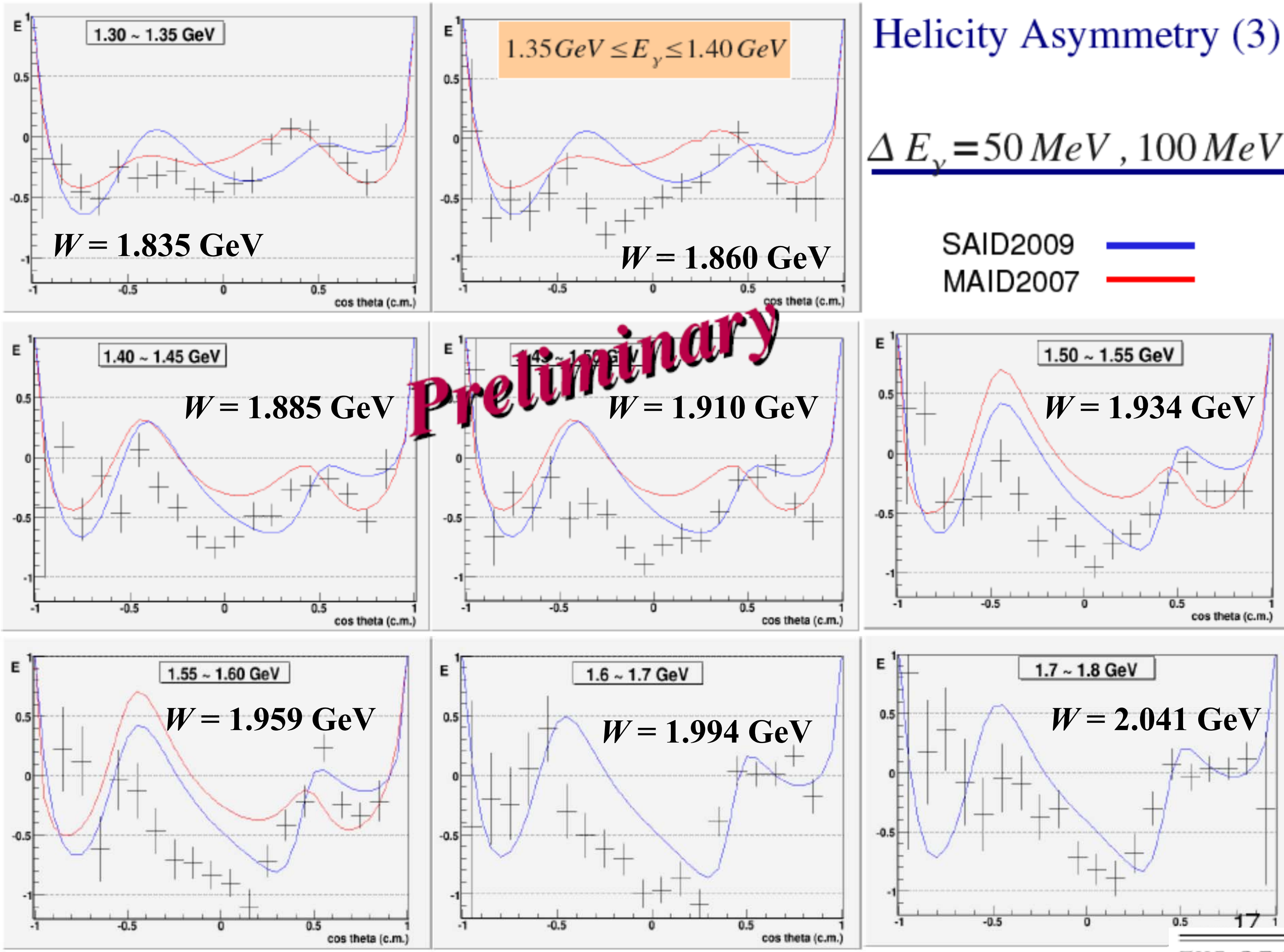
Helicity Asymmetry (3)



- **Agreement with models breaks down for *W* > 1850 MeV**

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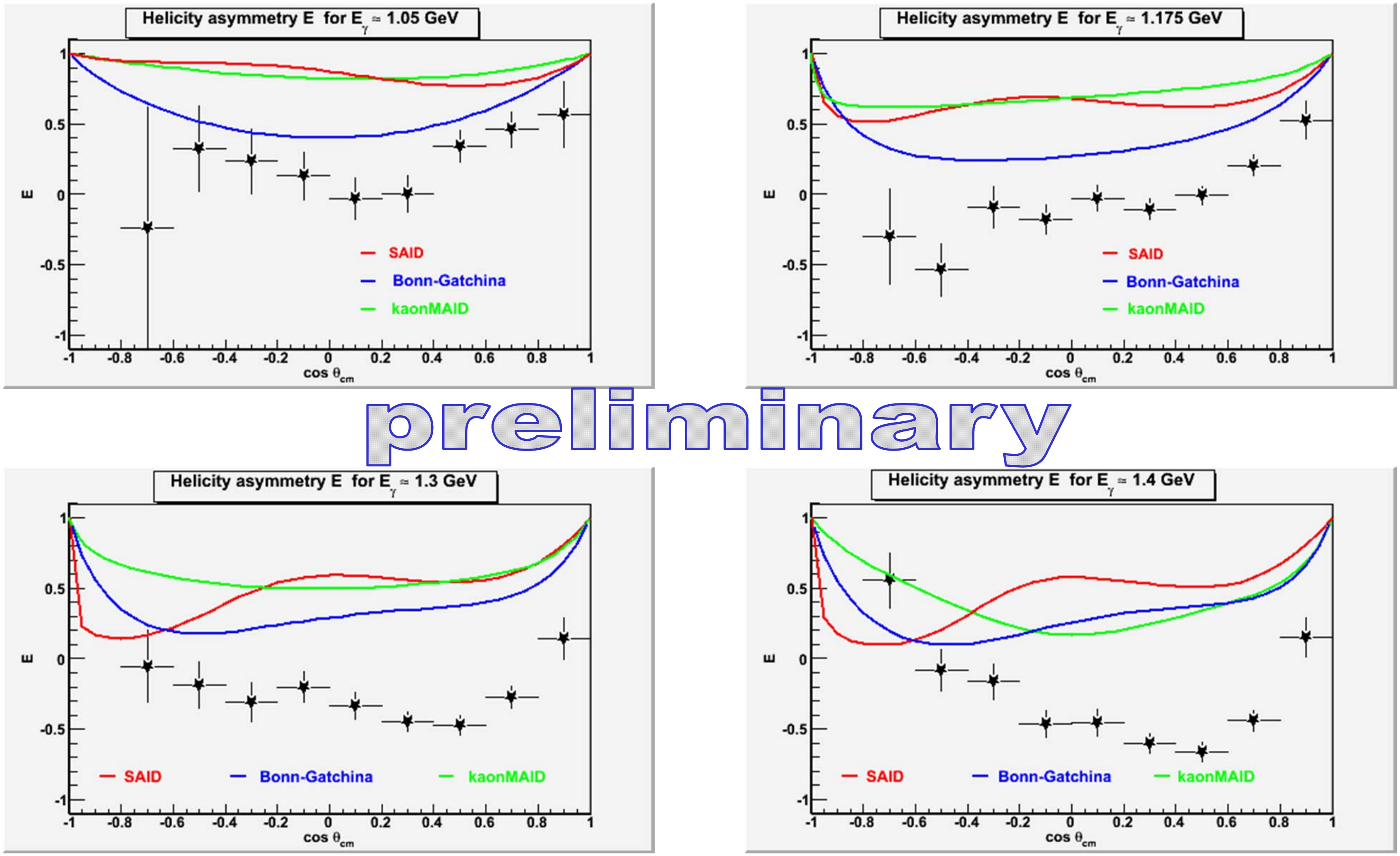
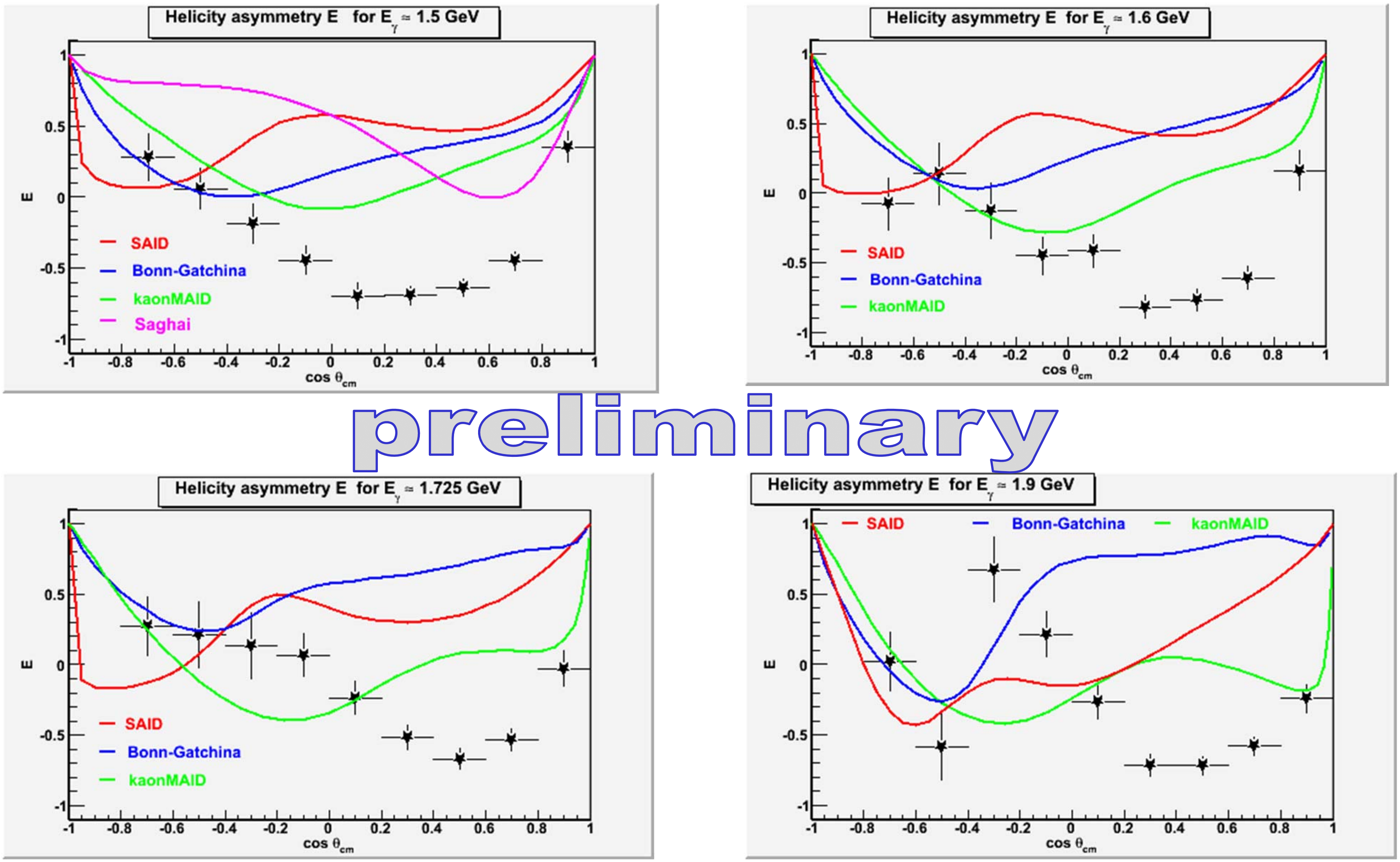
$\gamma\, p \rightarrow K^+ \Lambda$ and $\gamma\, p \rightarrow K^+ \Sigma^0$

- Catholic University of America
- Liam Casey and Franz Klein

Helicity asymmetry E for $K^+ \Lambda$



Helicity asymmetry for $K^+ \Lambda$



- **None of the models represents the data well**

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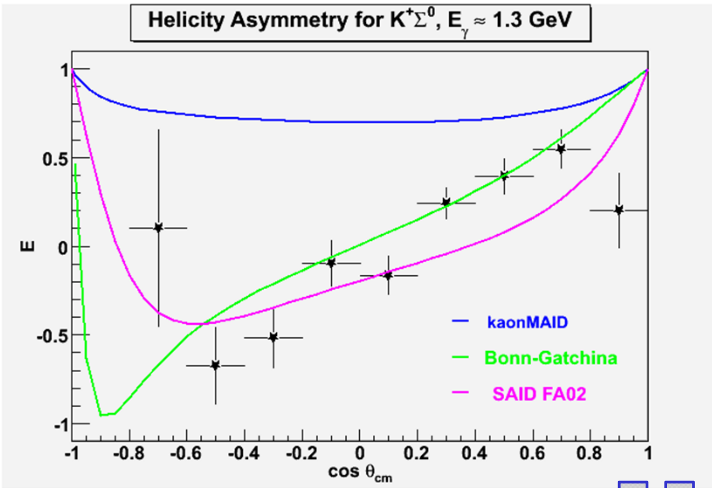
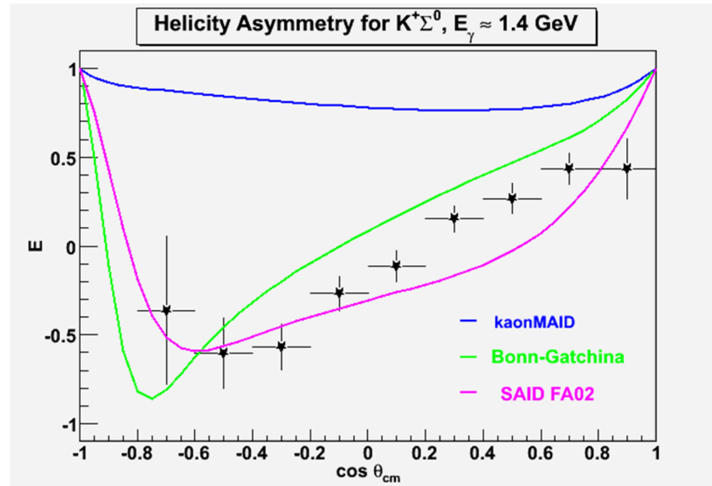
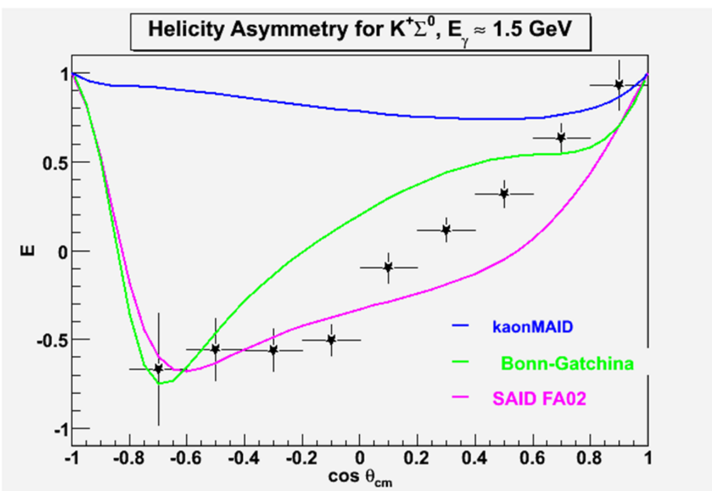
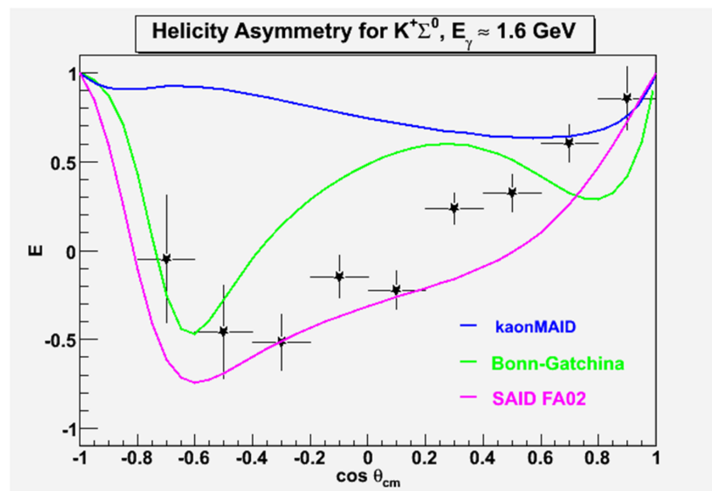
Helicity asymmetry for $K^+ \Sigma^0$





preliminary





- **Models represents the data better than for $K^+ \Lambda$**

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Σ and G observables

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left(1 - P_T \Sigma \cos(2\varphi) + P_T P_z G \sin(2\varphi)\right)$$

- Σ is a single polarization observable (beam asymmetry)
- G is a double polarization observable

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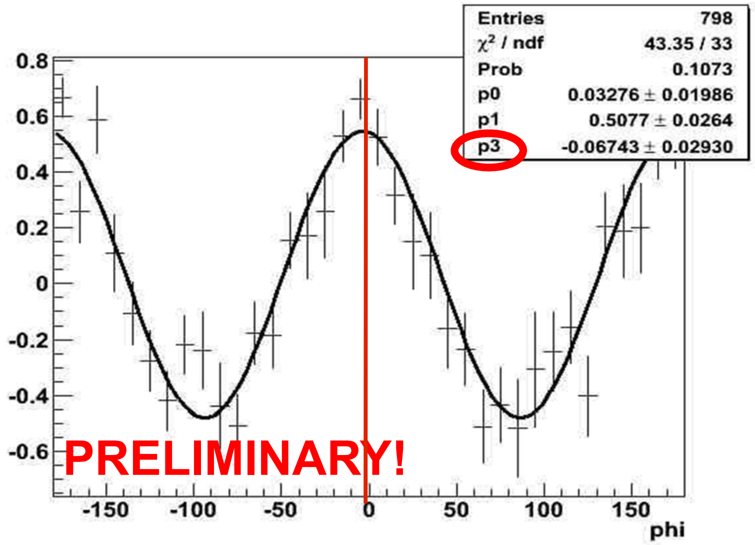
$\gamma p \rightarrow \pi^+ n$

- The University of Edinburgh
- Jo McAndrews and Dan Watts

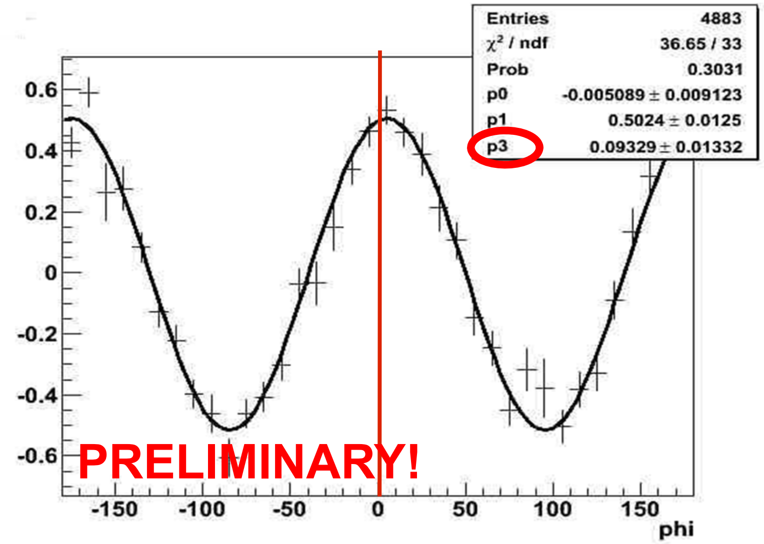
Example of extraction for G for $\pi^+ n$

$$f(\phi)_{||\perp} = P0 + P1\cos(2(\phi - P2)) + P3 sin(2(\phi - P2))$$

p3 = $p_\gamma p_z fG$



Asymmetry -ve polarised target



Asymmetry +ve polarised target

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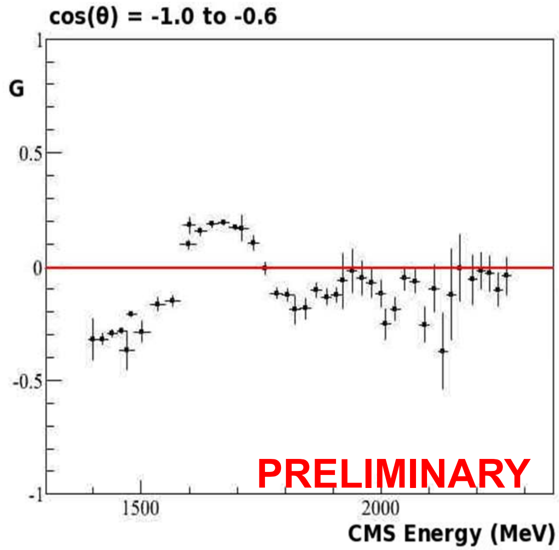
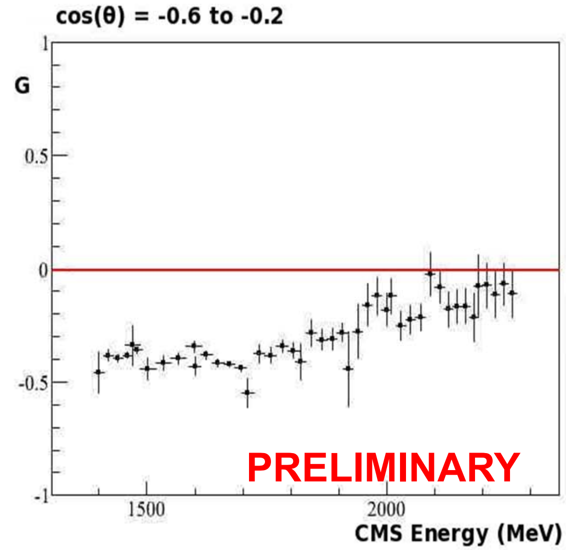
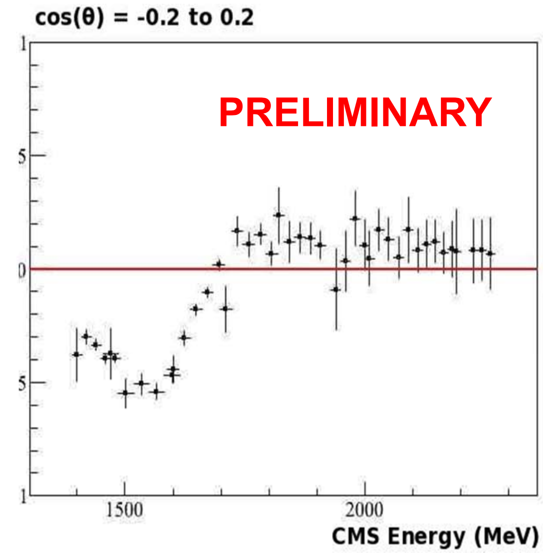
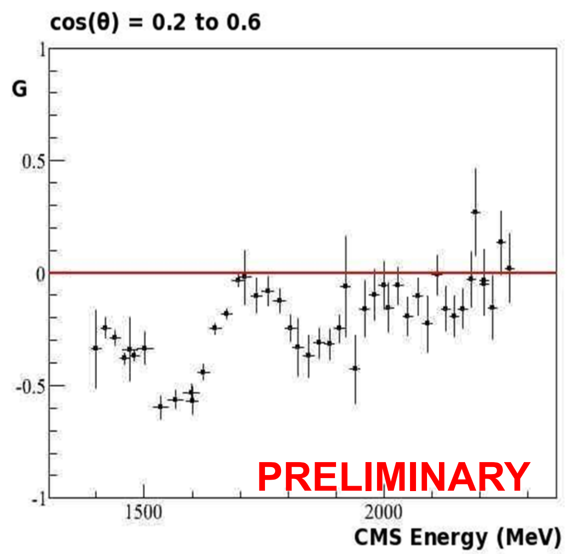
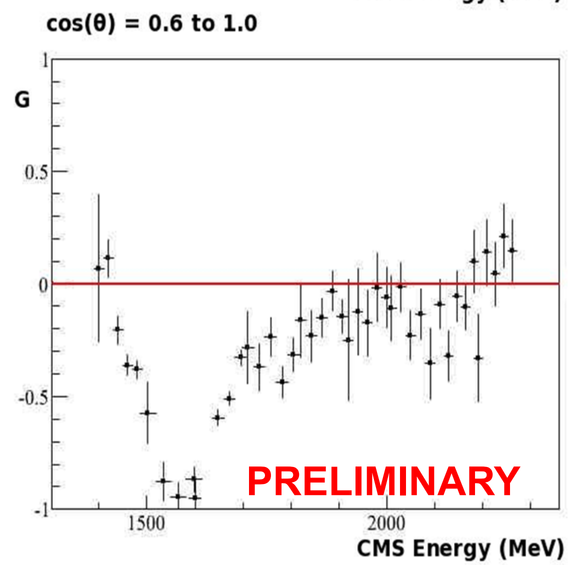
Preliminary results of *G* for $\pi^+ n$









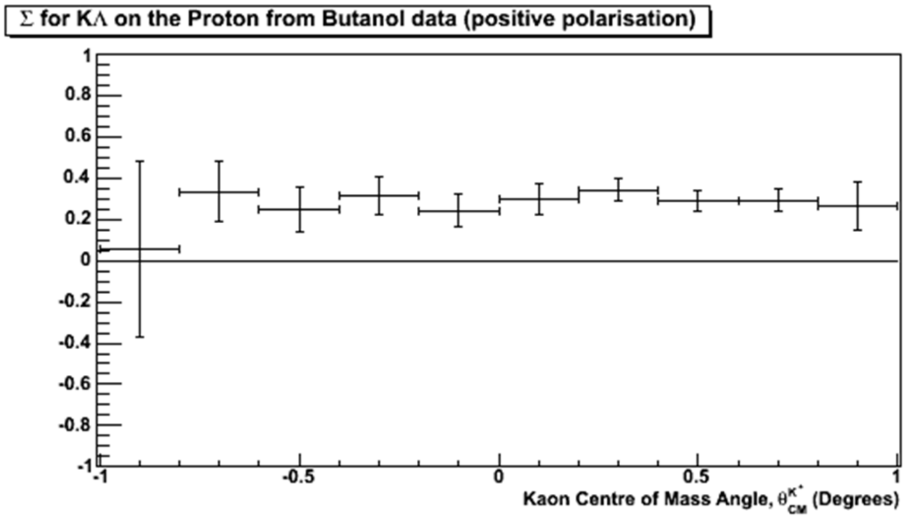


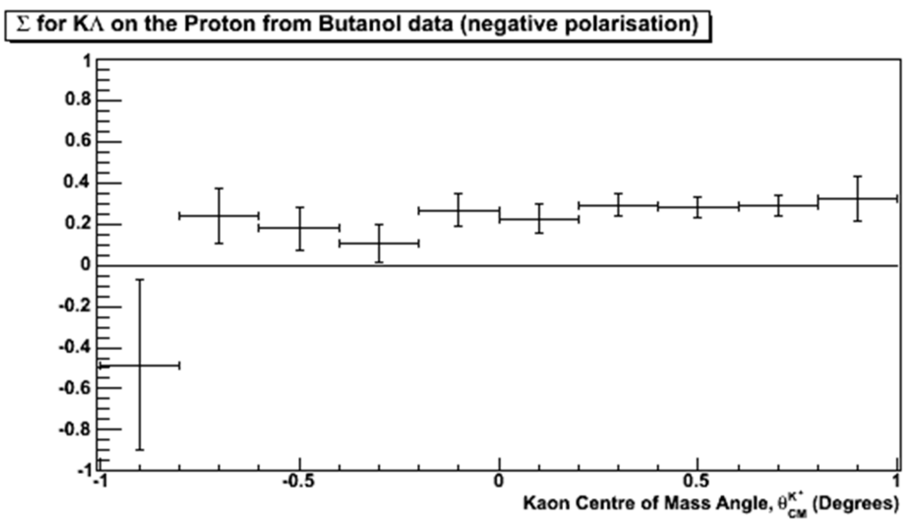
- Early stage results with very preliminary linear beam polarization values

$\gamma\, p \rightarrow K^{+} \Lambda$

- University of Glasgow
- Stuart Fegan and Ken Livingston

Σ for $K^+\Lambda$



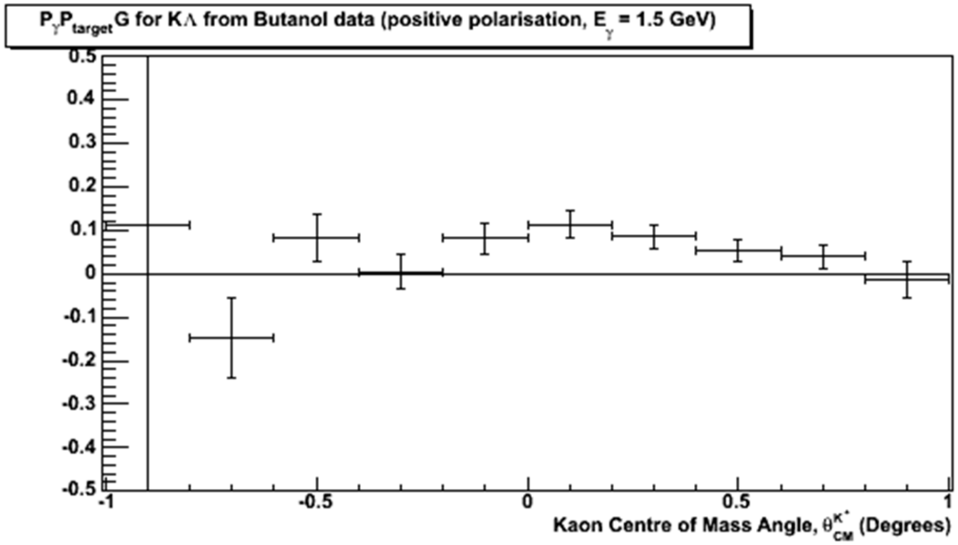


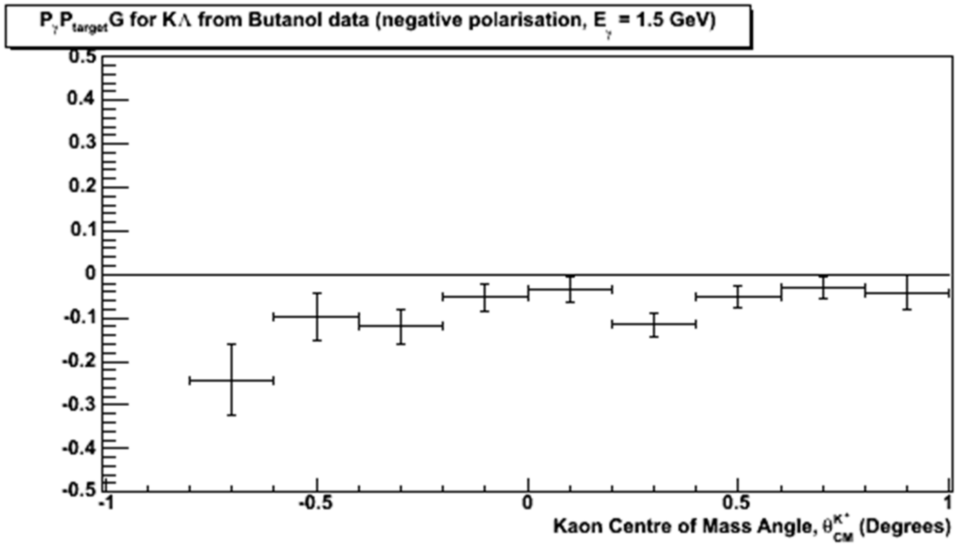
- Since the beam asymmetry Σ does not rely upon target polarization, bound nucleons can have $\Sigma \neq 0$

- Dilution must be carefully determined

- The beam asymmetry is used only for purposes of checking data consistency

$P_\gamma P_z G$ for $K^+\Lambda$





- E_γ = 1.5 GeV
- Can clearly see sign change between +z and –z target polarization data

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University of Glasgow

$\gamma p \rightarrow p \pi^{+} \pi^{-}$

- Florida State University

- Sung Park and Volker Crede

$\gamma p \rightarrow p \pi^+ \pi^-$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$

(without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_{\odot} (\mathbf{I}^{\odot} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\odot})$$

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

- σ_0: The unpolarized cross section
- β: The angle between the direction of polarization and the x-axis
- $\delta_{\odot, l}$: The degree of polarizaton of the photon beam $\Rightarrow \delta_{\odot}$, and δ_l
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $\mathbf{I}^{\odot, \mathbf{s}, \mathbf{c}}$: The observable arising from use of polarized photons $\Rightarrow \mathbf{I}^{\odot}, \mathbf{I}^{\mathbf{s}}, \mathbf{I}^{\mathbf{c}}$
- $\vec{\mathbf{P}}$: The polarization observable $\Rightarrow (\mathbf{P_x}, \mathbf{P_y}, \mathbf{P_z})$ $(\mathbf{P}_x^{\odot}, \mathbf{P}_y^{\odot}, \mathbf{P}_z^{\odot})$ $(\mathbf{P}_x^s, \mathbf{P}_y^s, \mathbf{P}_z^s)$ $(\mathbf{P_x^c}, \mathbf{P_y^c}, \mathbf{P_z^c})$

15 Observables

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$\gamma p \rightarrow p \pi^+ \pi^-$

The circularly-polarized beam $\rightarrow \delta_l = 0$

The longitudinally-polarized target $\rightarrow \Lambda_x = \Lambda_y = 0$

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot (\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P}_z^\odot)\}$$

3 Observables

$\mathbf{I}^\odot$ only is published and small and sensitive

The linearly-polarized beam $\rightarrow \delta_\odot = 0$

The longitudinally-polarized target $\rightarrow \Lambda_x = \Lambda_y = 0$

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \vec{\Lambda}_z \cdot \vec{\mathbf{P}}_z)$$

$$+ \delta_l [\sin 2\beta (\mathbf{I}^s + \vec{\Lambda}_z \cdot \vec{\mathbf{P}}_z^s) + \cos 2\beta (\mathbf{I}^c + \vec{\Lambda}_z \cdot \vec{\mathbf{P}}_z^c)]\}$$

5 Observables

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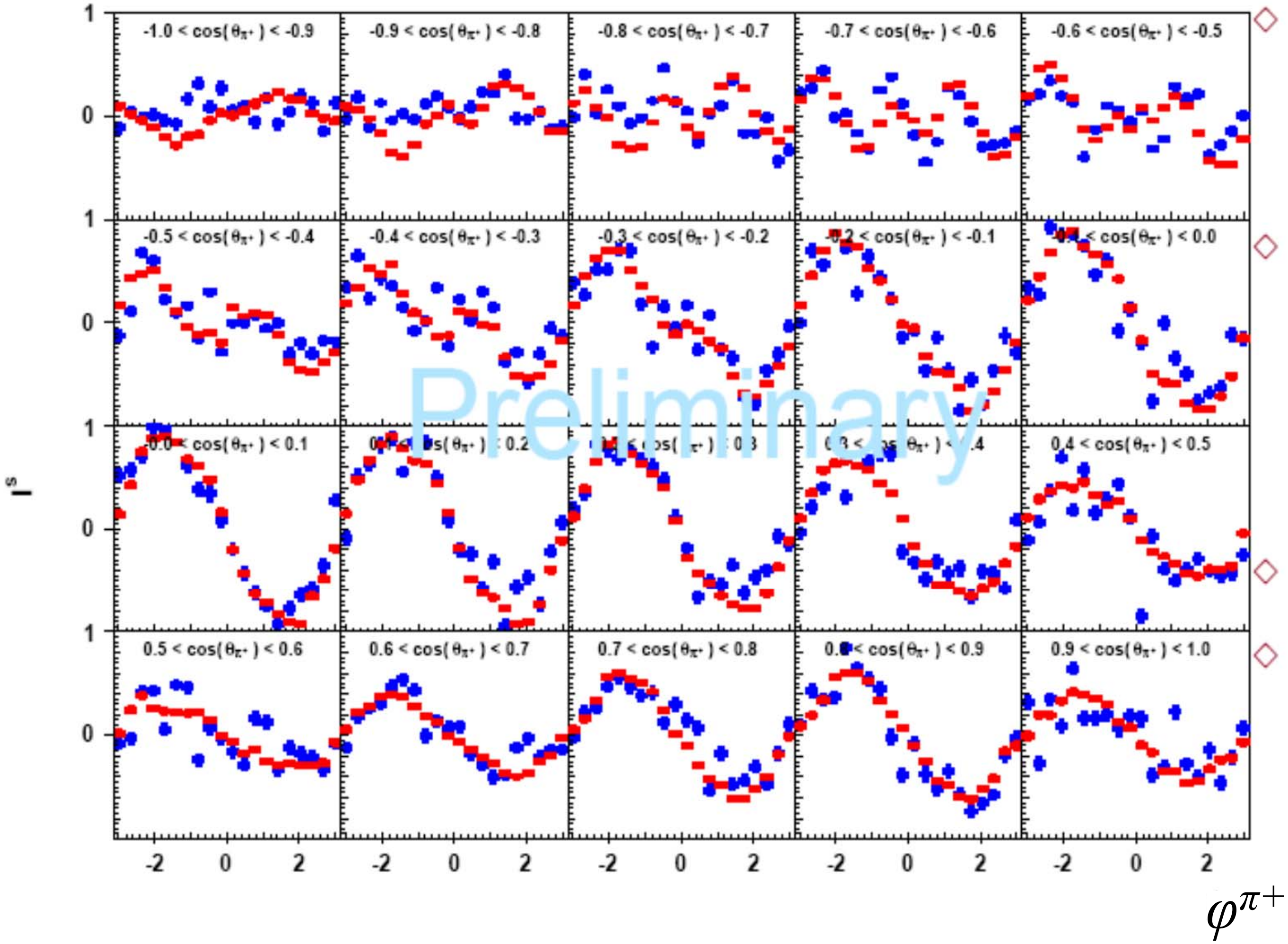
I^S for $p\ \pi^+\ \pi^-$

E_γ : 1250 - 1300 MeV (comparison with g8b data)



◇ g9a (FROST)
polarized beam
polarized target
(butanol)

◇ g8b
polarized beam
unpolarized target
(liquid hydrogen)

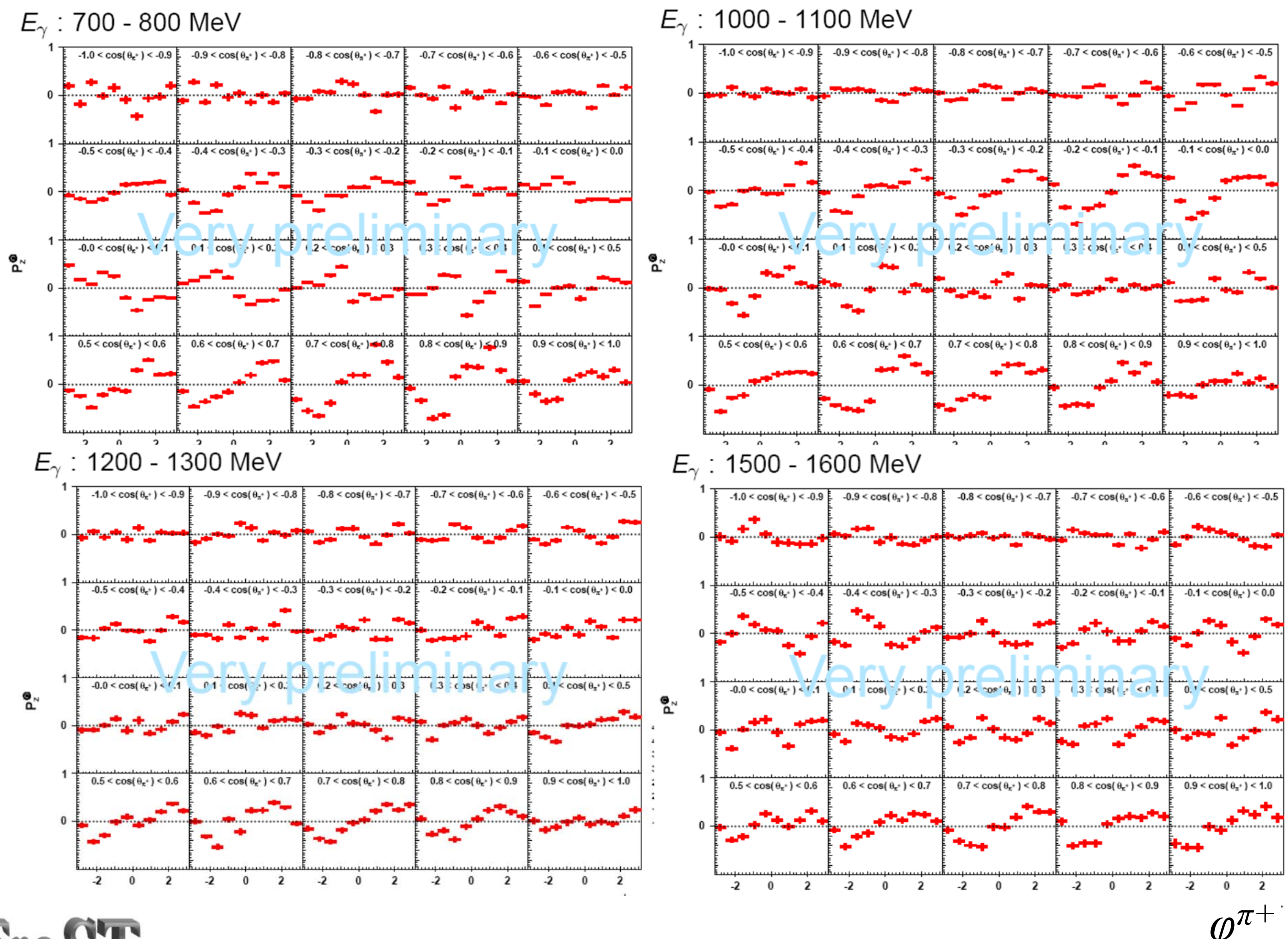
- previous presentation

◇ $\phi_{\pi+}$: the π^+ azimuthal angle

◇ $\theta_{\pi+}$: the π^+ polar angle

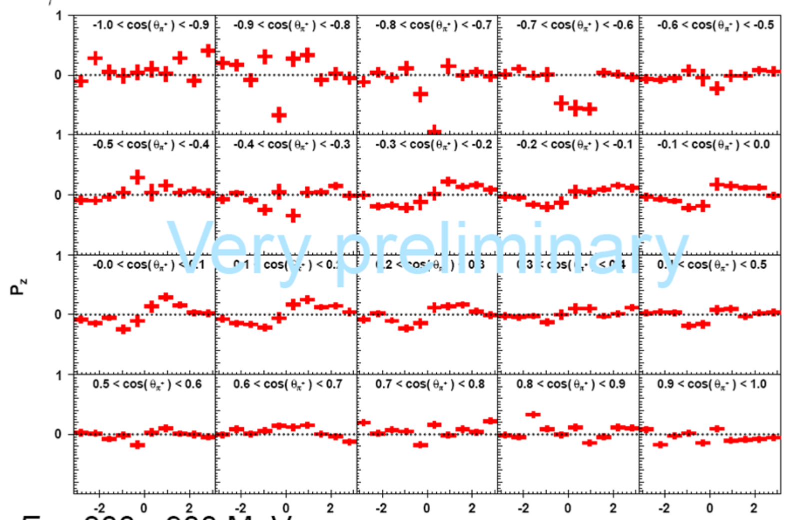
(in the rest frame of the $\pi^+\ \pi^-$ system)

$P^{\odot}_z$ for $p\,\pi^+\,\pi^-$

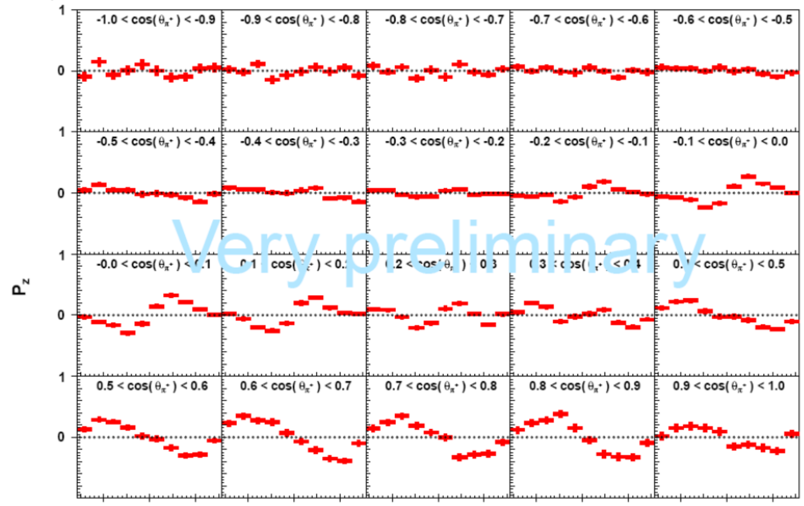


P_z for $p\ \pi^+\ \pi^-$

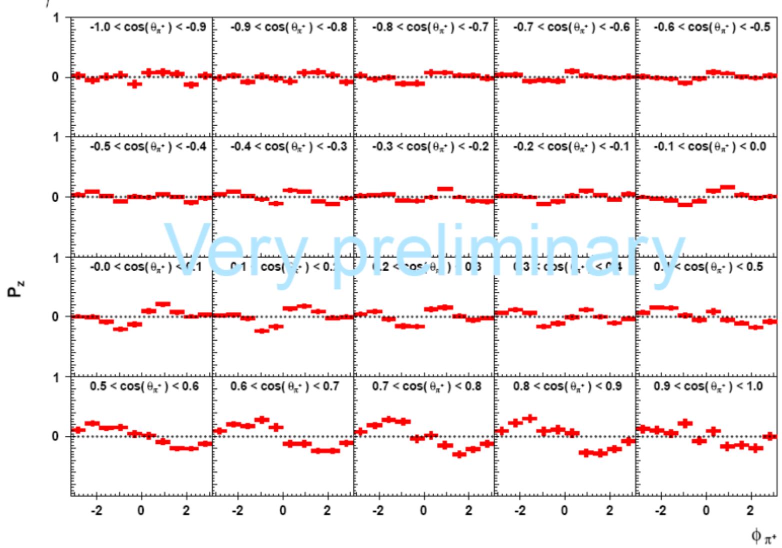
E_γ : 500 - 600 MeV



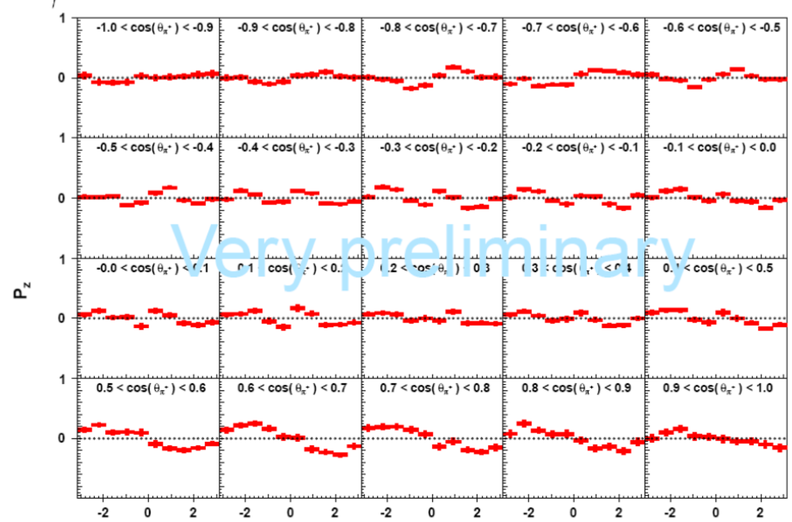
E_γ : 700 - 800 MeV



E_γ : 800 - 900 MeV



E_γ : 900 - 1000 MeV



$\varphi^{\pi+}$

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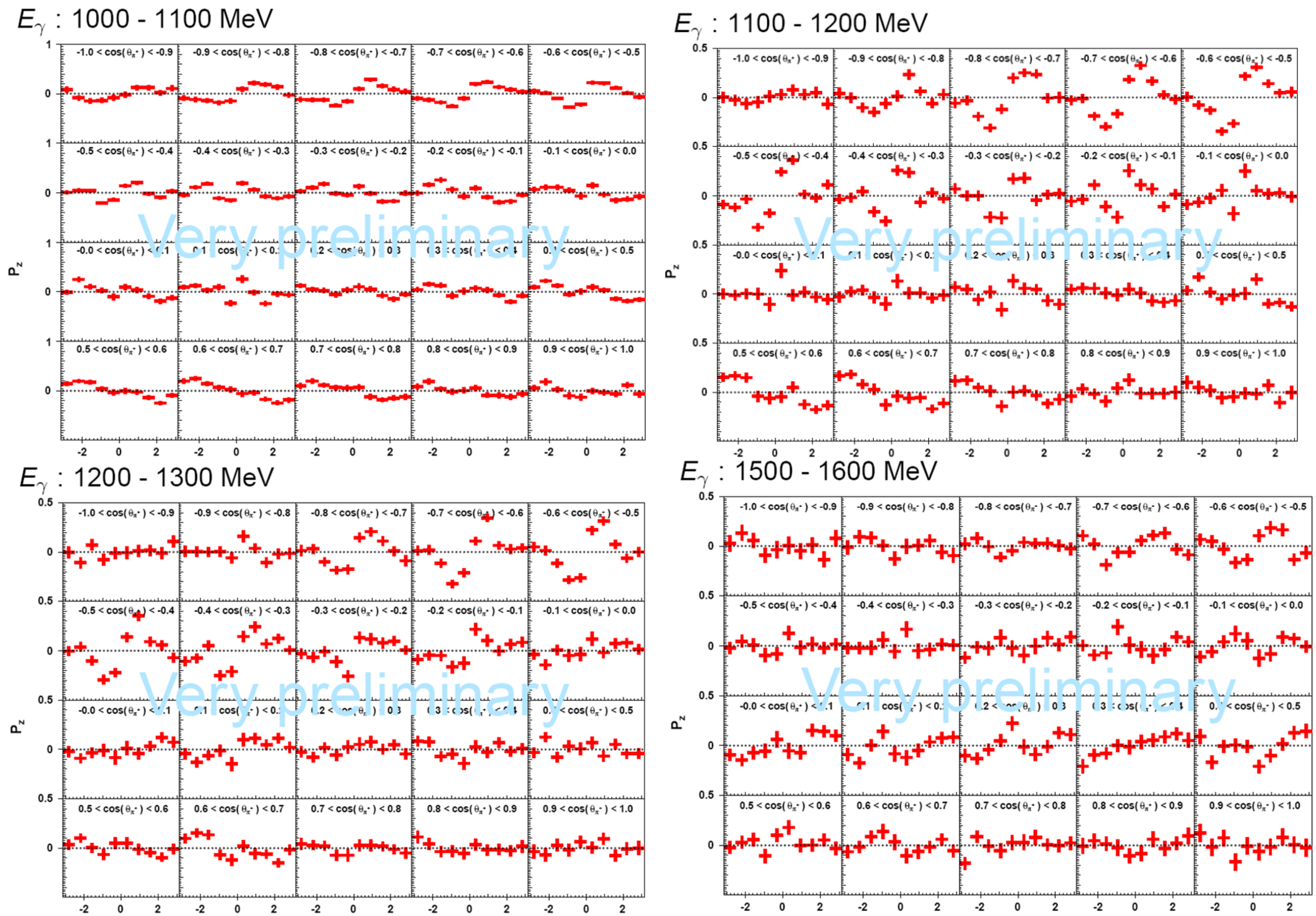
P_z for $p\,\pi^+\,\pi^-$



$\varphi^{\pi+}$

FROzen Spin Target "FROST" (g9b)

➢ Transversely polarized target

- **Beam: Circular polarization; Linear polarization; Un-polarized**
- **Data obtained for *Σ*, *F*, *H*, *P* and *T* (for pseudoscalars)**
- **Data is in calibration phase right now**

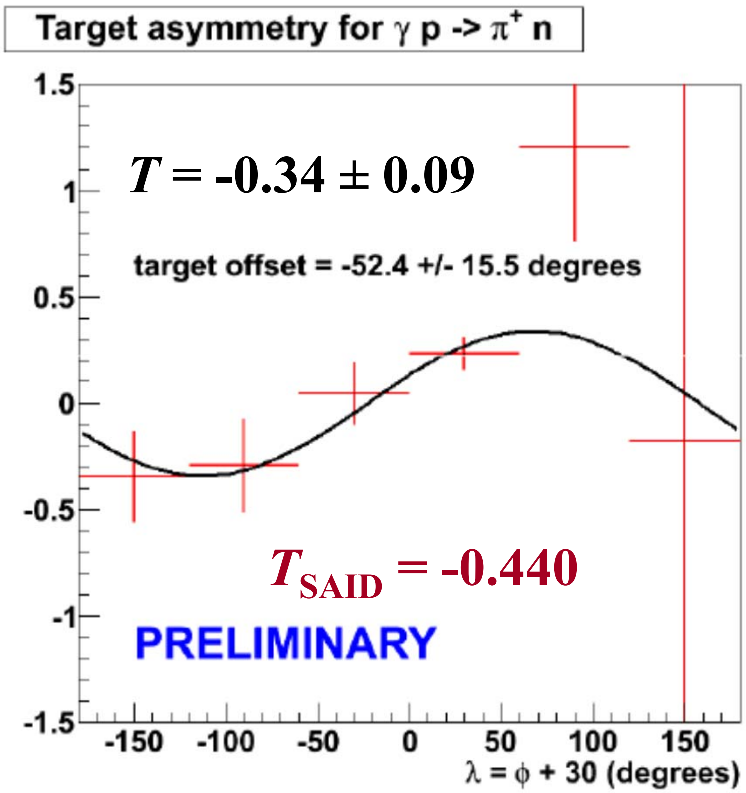
Beam	Target	Observable
Circular	Transverse	$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left[1 - P_{xy}^{lab} P_{\odot} F \cos(\beta - \varphi) + P_{xy}^{lab} T \sin(\beta - \varphi)\right]$
Linear	Transverse	$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left[1 - P_T \Sigma \cos(2\varphi) + P_{xy}^{lab} P_T H \cos(\beta - \varphi)\sin(2\varphi) + P_{xy}^{lab} T \sin(\beta - \varphi) - P_{xy}^{lab} P_T P \sin(\beta - \varphi)\cos(2\varphi)\right]$

σ_0 = unpolarized cross section, P_T = transverse beam polarization
P_0= circular polarization, P_z= longitudinal target polarizaion

A very early look at T for $\gamma p \rightarrow \pi^{+} n$

- Arizona State University
- Michael Dugger and Barry Ritchie

A quick attempt at *T* from uncalibrated CLAS data



- Used only 2 uncalibrated runs
- E_γ from 0.65 to 1.2 GeV
- $cos(\theta^{\pi}_{c.m.}) = 0.95$
- Target offset (in φ) is within one standard deviation of the set value (-60 degrees)
- The measured value of *T* is within 1.14 standard deviations of SAID

Conclusion

• Models fit preliminary FROST pion helicity asymmetry data best when $W < 1.75$ GeV

• Preliminary FROST helicity asymmetry data for $\eta\, p$ favors SAID for $W > 1.75$ GeV

• None of the models shown represents the $K^+ \Lambda$ data well but do much better for $K^+ \Sigma^0$

• Σ and G measurements are at an early stage of analysis and use very preliminary linear beam polarization values, but are progressing nicely

• There is **lots** of data for the $\pi^+ \pi^- p$ channel, and the preliminary I^S observable from FROST compares well with g8b

• Very preliminary looks at data from the second running of FROST (transverse target) are promising

Acknowledgements

- ✦ NSF
- ✦ DOE
- ✦ CLAS Collaboration

ASU
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University of South Carolina

The University of Edinburgh

Jefferson Lab

The George Washington University
Washington DC

Florida State University 1851

University of Glasgow

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Status of meson photoproduction

	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 target																
$p\pi^0$	✔ (red)	✔ (green)	✔ (green)	✔ (grey)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$n\pi^+$	✔ (red)	✔ (green)	✔ (green)	✔ (grey)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\eta$	✔ (red)	✔ (green)	✔ (green)	✔ (grey)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\eta'$	✔ (red)	✔ (green)	✔ (green)	✔ (grey)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\omega$	✔ (red)	✔ (green)	✔ (green)	✔ (grey)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$K^+\Lambda$	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)
$K^+\Sigma^0$	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)
$K^{0*}\Sigma^+$	✔ (red)	✔ (green)									✔ (green)	✔ (green)				
Neutron target																
$p\pi^-$	✔ (red)	✔ (green)	✔ (blue)		✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)								
$p\rho^-$	✔ (green)	✔ (green)	✔ (blue)		✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)								
$K^-\Sigma^+$	✔ (red)	✔ (green)	✔ (blue)		✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)								
$K^0\Lambda$	✔ (green)	✔ (green)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)
$K^0\Sigma^0$	✔ (green)	✔ (green)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)	✔ (blue)
$K^{0*}\Sigma^0$	✔ (green)	✔ (green)														

✔ (red) - published, ✔ (green) - acquired, ✔ (blue) - planned

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