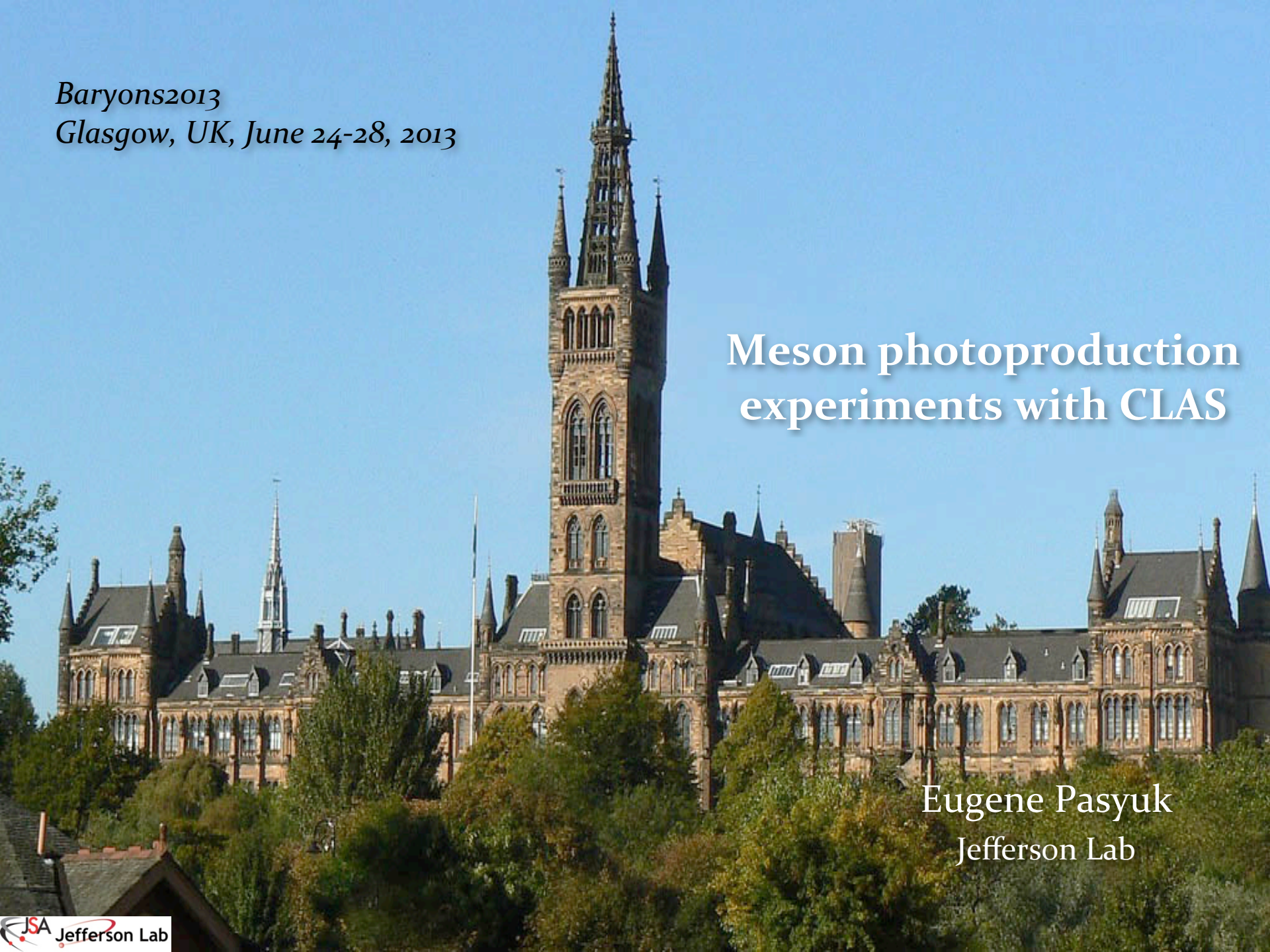


Baryons2013
Glasgow, UK, June 24-28, 2013

Meson photoproduction experiments with CLAS

Eugene Pasyuk
Jefferson Lab

JSA Jefferson Lab

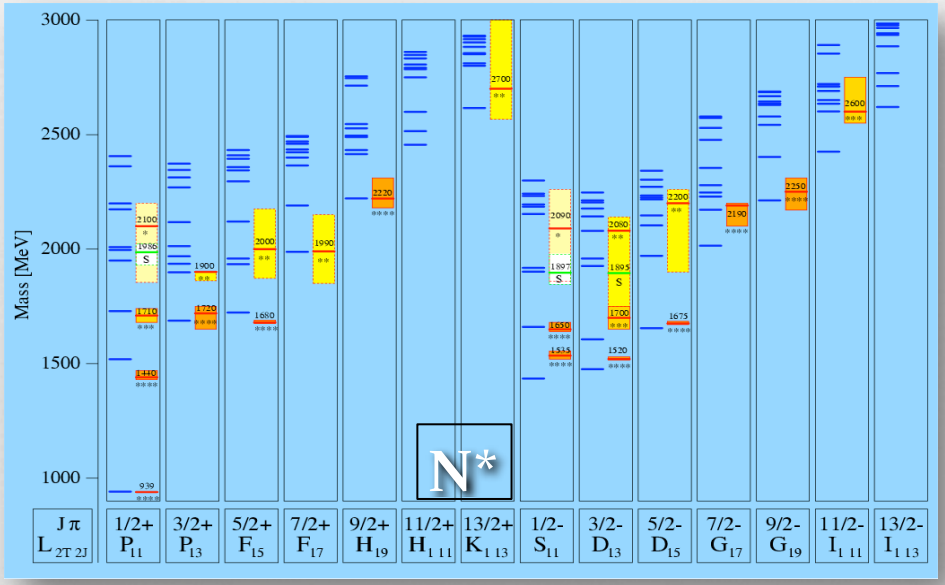
Resonance status for N^* and Δ^*

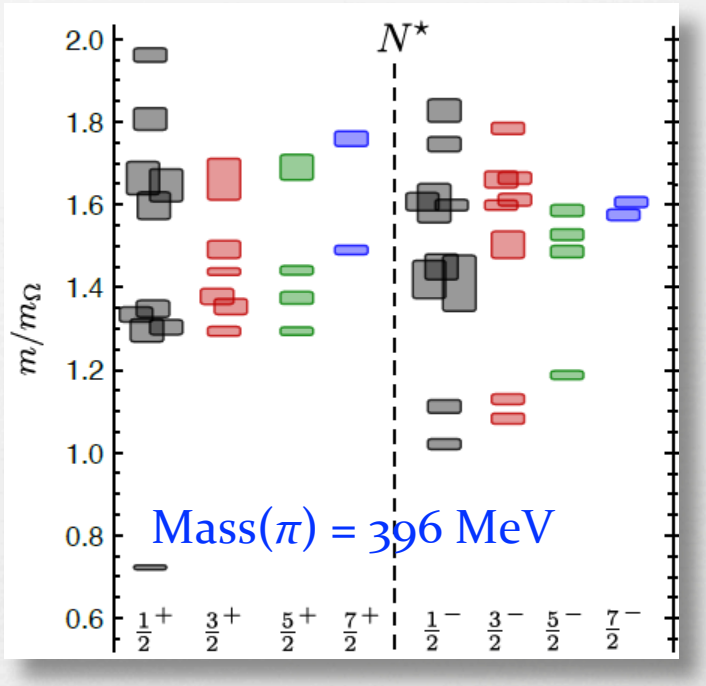
Particle	J^P	Status overall	Status as seen in — $N\pi$	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	***	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1685)$	$?^?$	*									
$N(1700)$	$3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
$N(1875)$	$3/2^-$	***	*	***			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	*	**	**			**	*		
$N(1900)$	$3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	*	**	**			**	*	**	
$N(2040)$	$3/2^+$	*									
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*									
$N(2150)$	$3/2^-$	**	**	**				**			**
$N(2190)$	$7/2^-$	****	****	***			*	**		*	
$N(2220)$	$9/2^+$	****	****								
$N(2250)$	$9/2^-$	****	****								
$N(2600)$	$11/2^-$	***	***								
$N(2700)$	$13/2^+$	**	**								

Particle	J^P	Status overall	Status as seen in — $N\pi$	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$\Delta(1232)$	$3/2^+$	****	****	****	F						
$\Delta(1600)$	$3/2^+$	***	***	***	o					*	***
$\Delta(1620)$	$1/2^-$	****	****	***	r					***	***
$\Delta(1700)$	$3/2^-$	****	****	****	b					**	***
$\Delta(1750)$	$1/2^+$	*	*		i						
$\Delta(1900)$	$1/2^-$	**	**	**		d			**	**	**
$\Delta(1905)$	$5/2^+$	****	****	****		d			***	**	**
$\Delta(1910)$	$1/2^+$	****	****	**			e		*	*	**
$\Delta(1920)$	$3/2^+$	***	***	**				n	***		**
$\Delta(1930)$	$5/2^-$	***	***								
$\Delta(1940)$	$3/2^-$	**	*	**	F				(seen	in	$\Delta\eta$)
$\Delta(1950)$	$7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$	$5/2^+$	**			r						**
$\Delta(2150)$	$1/2^-$	*	*		b						
$\Delta(2200)$	$7/2^-$	*	*		i						
$\Delta(2300)$	$9/2^+$	**	**			d					
$\Delta(2350)$	$5/2^-$	*	*			d					
$\Delta(2390)$	$7/2^+$	*	*				e				
$\Delta(2400)$	$9/2^-$	**	**					n			
$\Delta(2420)$	$11/2^+$	****	****	*							
$\Delta(2750)$	$13/2^-$	**	**								
$\Delta(2950)$	$15/2^+$	**	**								

- **Nearly half the states have only fair or poor evidence!**
- **Most states need more work to learn details**
- **Are there missing states?**

Baryon Resonance Spectrum

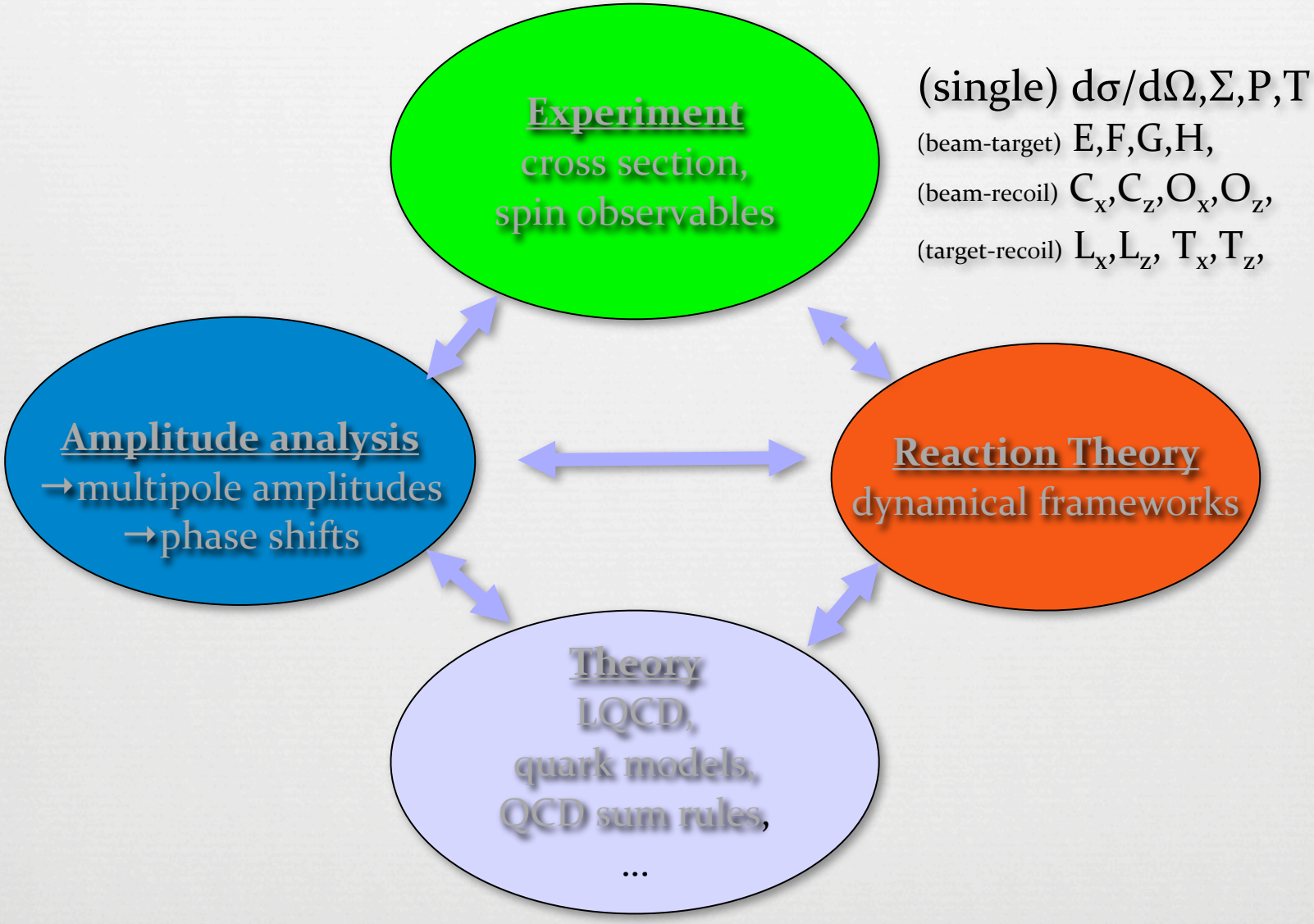




R.G. Edwards *et al.* Phys. Rev. D84 074508 (2011)

- Masses, widths, and coupling constants not well known for many resonances
- Most models predict more resonance states than observed

From the Experiment to Theory



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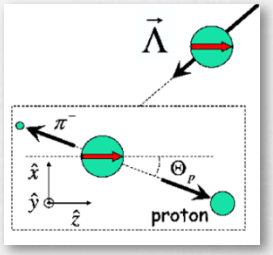

Symbol	Transversity representation	Experiment required	Type
$d\sigma/dt$	$\|b_1\|^2+\|b_2\|^2+\|b_3\|^2+\|b_4\|^2$	$\{-;-;-\}$	S
$\Sigma d\sigma/dt$	$\|b_1\|^2+\|b_2\|^2-\|b_3\|^2-\|b_4\|^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$	
$Td\sigma/dt$	$\|b_1\|^2-\|b_2\|^2-\|b_3\|^2+\|b_4\|^2$	$\{-;y;-\}$	
$Pd\sigma/dt$	$\|b_1\|^2-\|b_2\|^2+\|b_3\|^2-\|b_4\|^2$	$\{-;-;y\}$	
$Gd\sigma/dt$	$2\ \mathrm{Im}(b_1b_3^*+b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$Hd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_3^*-b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$Ed\sigma/dt$	$-2\ \mathrm{Re}(b_1b_3^*+b_2b_4^*)$	$\{C;z;-\}$	
$Fd\sigma/dt$	$2\ \mathrm{Im}(b_1b_3^*-b_2b_4^*)$	$\{C;x;-\}$	
$O_xd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_4^*-b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_zd\sigma/dt$	$-2\ \mathrm{Im}(b_1b_4^*+b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
$C_xd\sigma/dt$	$2\ \mathrm{Im}(b_1b_4^*-b_2b_3^*)$	$\{C;-;x'\}$	
$C_zd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_4^*+b_2b_3^*)$	$\{C;-;z'\}$	
$T_xd\sigma/dt$	$2\ \mathrm{Re}(b_1b_2^*-b_3b_4^*)$	$\{-;x;x'\}$	TR
$T_zd\sigma/dt$	$2\ \mathrm{Im}(b_1b_2^*-b_3b_4^*)$	$\{-;x;z'\}$	
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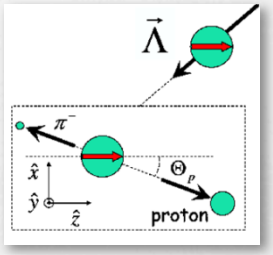

πN

recoil targ γ

KY

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$P d\sigma/dt$	$\|b_1\|^2-\|b_2\|^2+\|b_3\|^2-\|b_4\|^2$	$\{-;-;y\}$	
$G d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$H d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_3^* - b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$E d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$	$\{C;z;-\}$	
$F d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$	$\{C;x;-\}$	
$O_x d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_z d\sigma/dt$	$-2\ \mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
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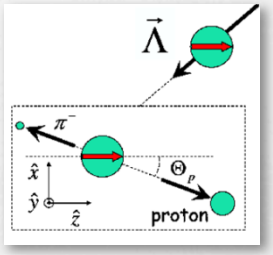

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$T_x d\sigma/dt$	$2\,\mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;x'\}$	TR
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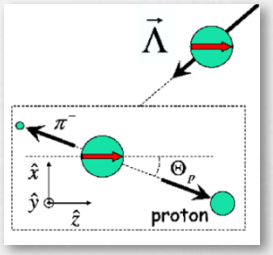

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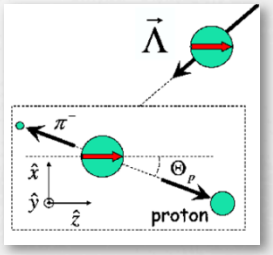

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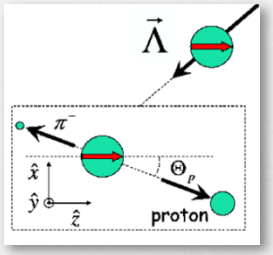

πN

recoil targ γ

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$G d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$H d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_3^* - b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$E d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$	$\{C;z;-\}$	
$F d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$	$\{C;x;-\}$	
$O_x d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_z d\sigma/dt$	$-2\ \mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
$C_x d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_4^* - b_2 b_3^*)$	$\{C;-;x'\}$	
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$T_x d\sigma/dt$	$2\ \mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;x'\}$	TR
$T_z d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;z'\}$	
$L_x d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_2^* + b_3 b_4^*)$	$\{-;z;x'\}$	
$L_x d\sigma/dt$	$2\ \mathrm{Re}(b_1 b_2^* + b_3 b_4^*)$	$\{-;z;z'\}$	

I. S. Barker, A. Donnachie, J. K. Storrow, Nucl. Phys. B95 347 (1975).

KY

γ targ recoil

circ polarized photons

linearly polarized photons

longitudinally polarized target

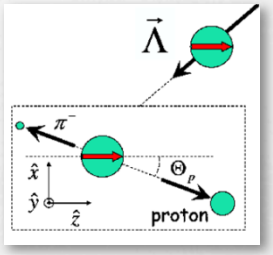
transversely polarized target

Polarization observables in pseudoscalar meson production

4 Complex amplitudes: **16** real polarization observables.

Complete measurement from **8** carefully chosen observables.

πN has large cross section but in **KY** recoil is **self-analysing**



πN

recoil targ γ

Symbol	Transversity representation	Experiment required	Type
$d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2+\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;-;-\}$	S
$\Sigma d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2-\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$	
$T d\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2-\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;y;-\}$	
$P d\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2+\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{-;-;y\}$	
$G d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$H d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_3^* - b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$E d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$	$\{C;z;-\}$	
$F d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$	$\{C;x;-\}$	
$O_x d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
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$T_x d\sigma/dt$	$2\ \mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;x'\}$	TR
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I. S. Barker, A. Donnachie, J. K. Storrow, Nucl. Phys. B95 347 (1975).

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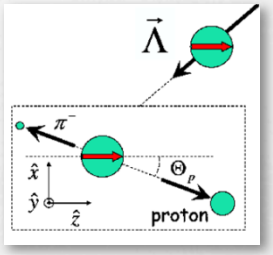

πN

recoil targ γ

KY

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$T_x d\sigma/dt$	$2\ \mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;x'\}$	TR
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$L_x d\sigma/dt$	$2\ \mathrm{Re}(b_1 b_2^* + b_3 b_4^*)$	$\{-;z;z'\}$	

I. S. Barker, A. Donnachie, J. K. Storrow, Nucl. Phys. B95 347 (1975).

circ polarized photons

linearly polarized photons

longitudinally polarized target

transversely polarized target

Complete, and over-determined

CEBAF Large Acceptance Spectrometer

1997-2012

Torus magnet

6 superconducting coils

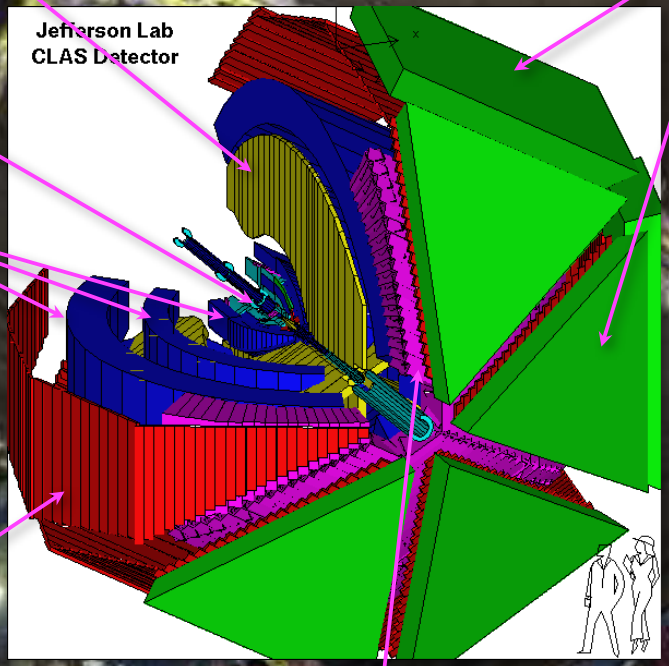
Electromagnetic calorimeters

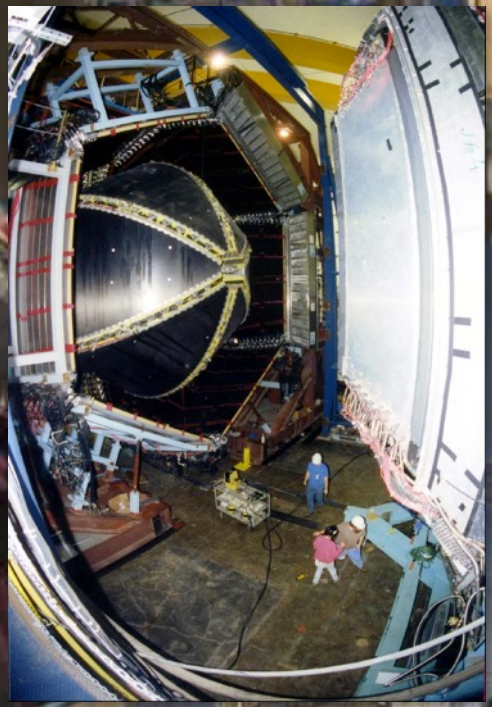
Lead/scintillator, 1296 photomultipliers

target + start counter

Drift chambers

35,000 cells





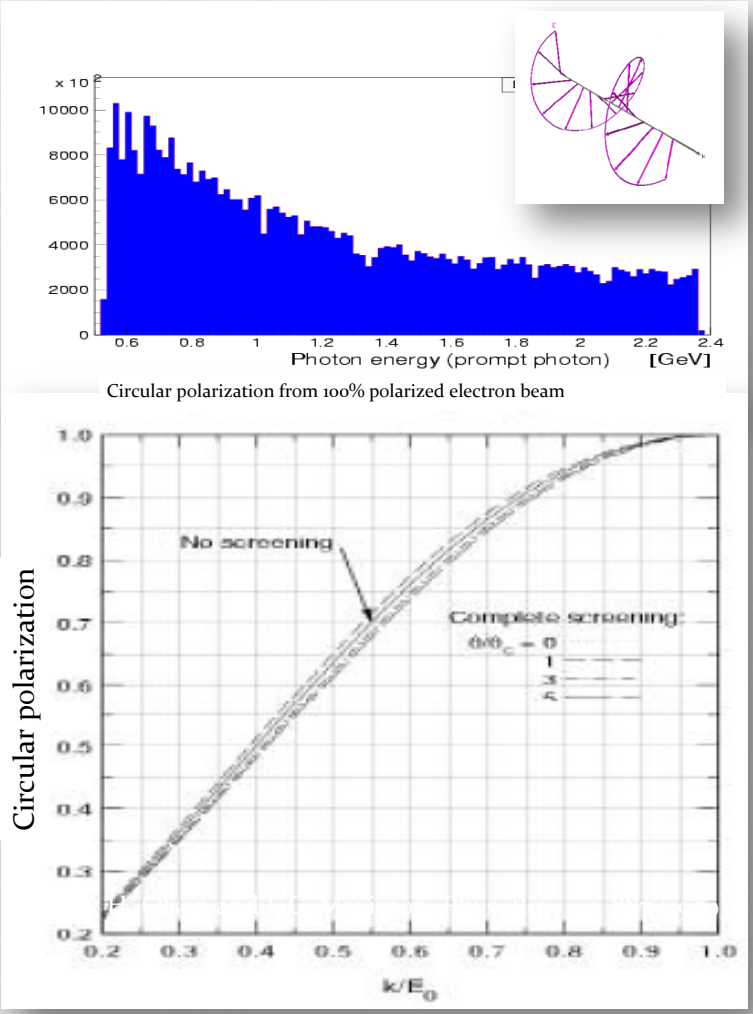
Time-of-flight counters

plastic scintillators, 684 photomultipliers

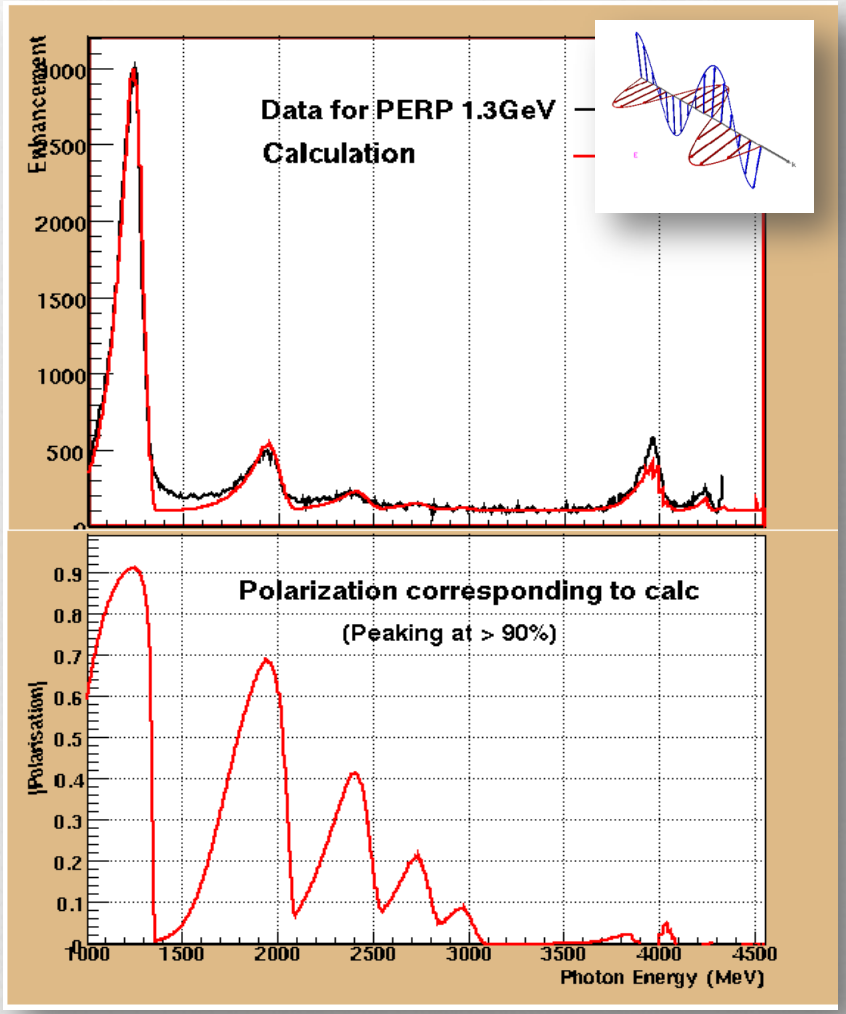
Gas Cherenkov counters

e/π separation, 256 PMTs

Polarized pohoton beam

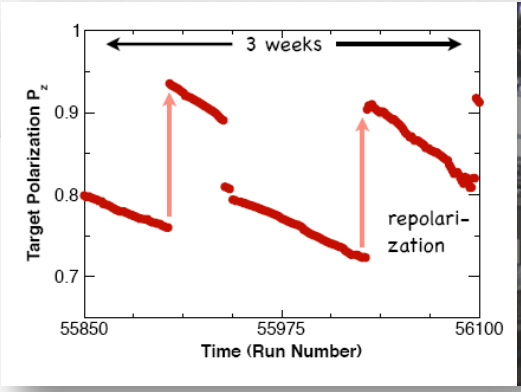


Circularly polarized beam produced by longitudinally polarized electrons



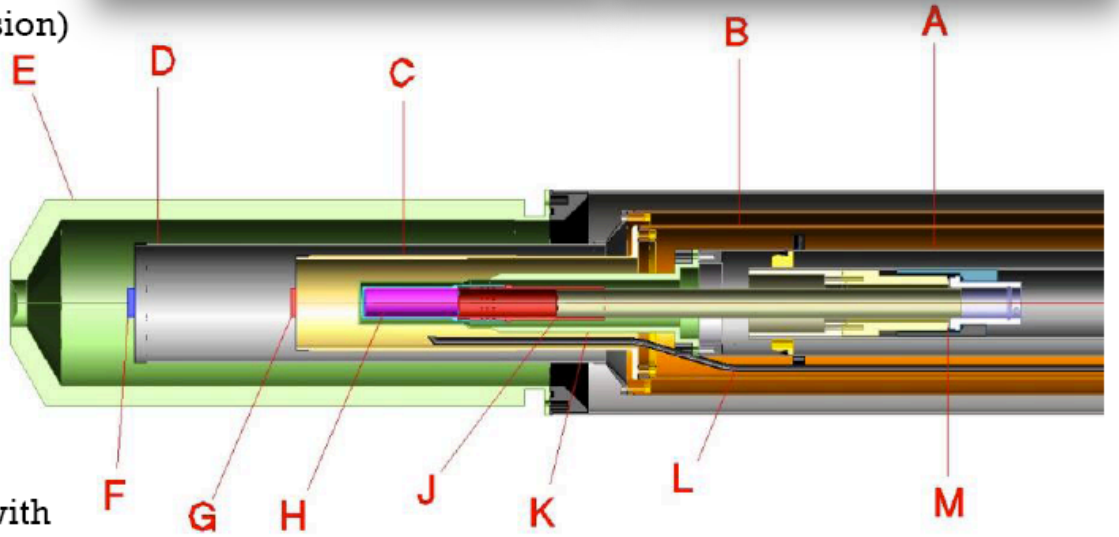
Linearly polarized photons: coherent bremsstrahlung on oriented diamond crystal

FROST



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

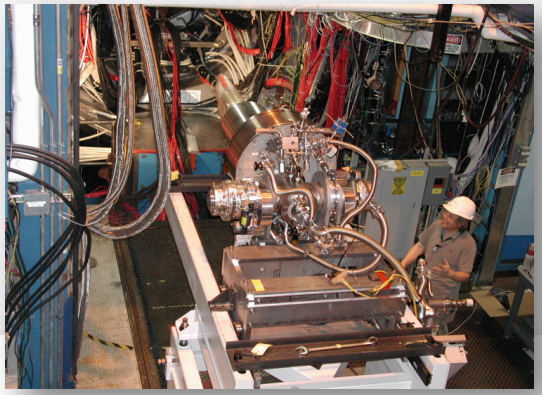


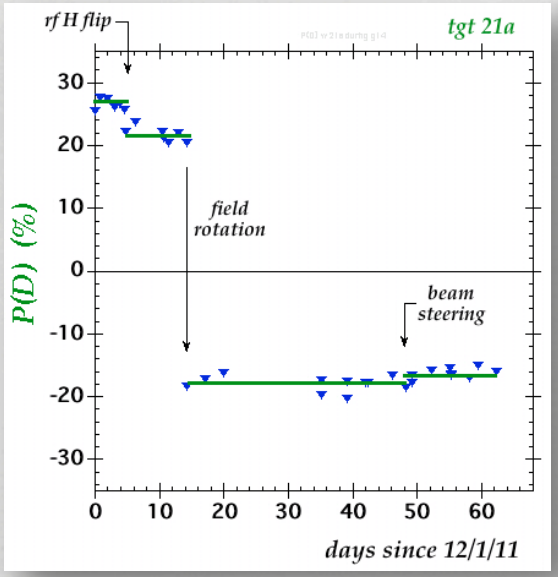
Performance Specs:

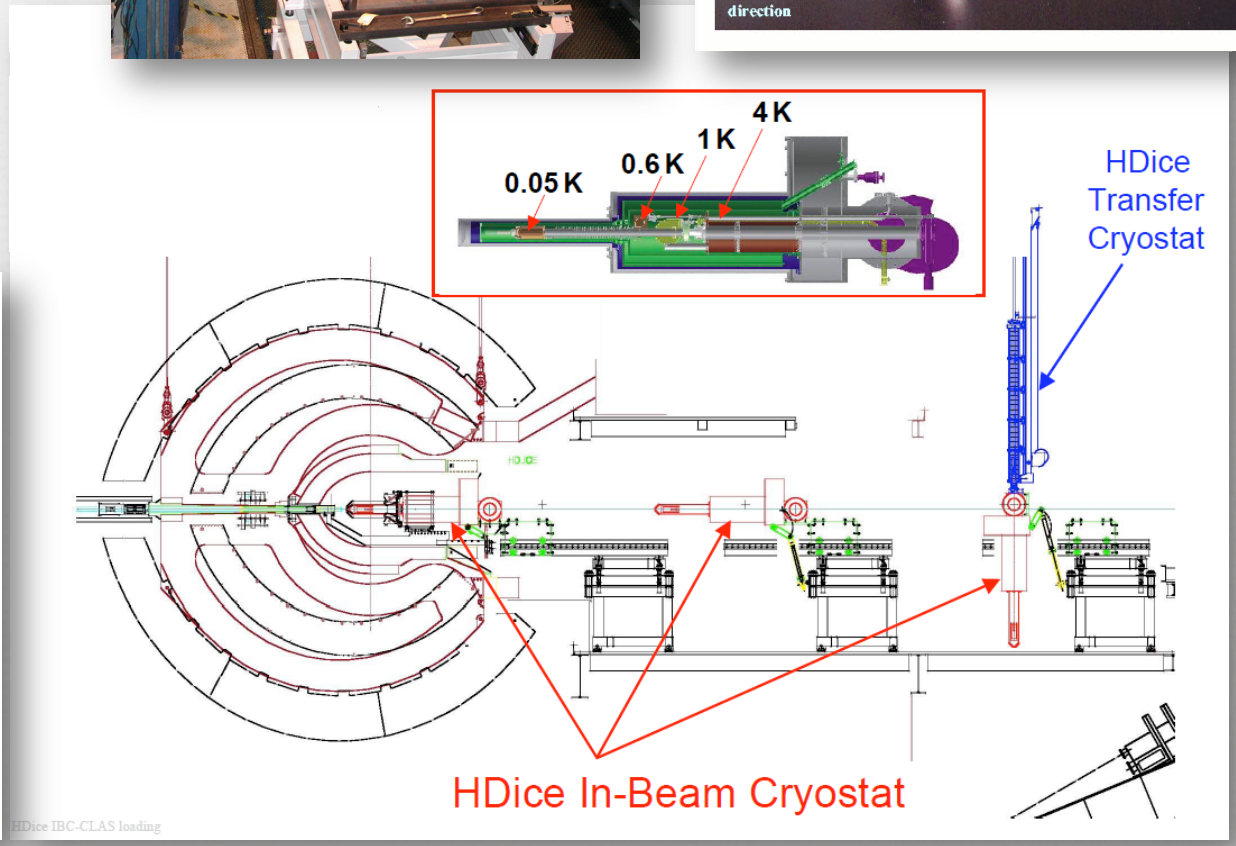
Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 μW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.

HDIce polarized target

- Polarized at very high magnetic field and very low temperature
- Transferred to in-beam cryostat
- Spin can be moved between H and D with RF transitions
- All material can be polarized with small background







What we measure with CLAS

- $\gamma p \rightarrow \pi^o p,\ \pi^+ n$
- $\gamma p \rightarrow \eta p$
- $\gamma p \rightarrow \eta' p$
- $\gamma p \rightarrow KY\ (K^+\Lambda,\ K^+\Sigma^o,\ K^o\Sigma^+)$
- $\gamma p \rightarrow \pi^+\pi^- p\ \omega p,\ \rho p,\ \phi p$
- ....

- $\gamma n \rightarrow \pi^- p$
- $\gamma n \rightarrow \pi^+\pi^- n$
- $\gamma n \rightarrow \Sigma^- K^+\ ,\ \Lambda K^o$
- .....

What we measure with CLAS

- $\gamma p \rightarrow \pi^o p,\ \pi^+ n$
- $\gamma p \rightarrow \eta p$
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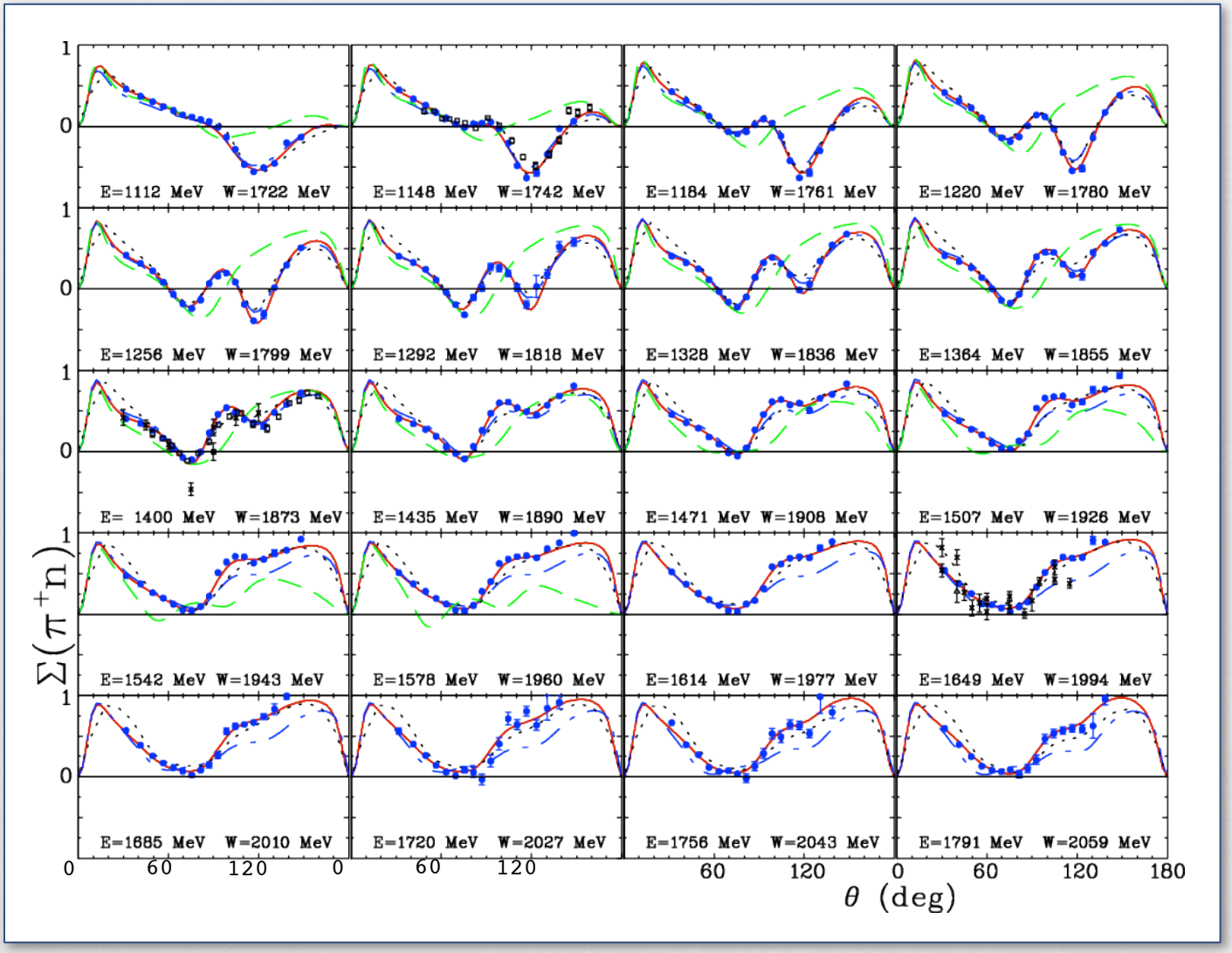
- ....

- $\gamma n \rightarrow \pi^- p$
- $\gamma n \rightarrow \pi^+\pi^- n$
- $\gamma n \rightarrow \Sigma^- K^+\ ,\ \Lambda K^o$
- .....

Single pion production

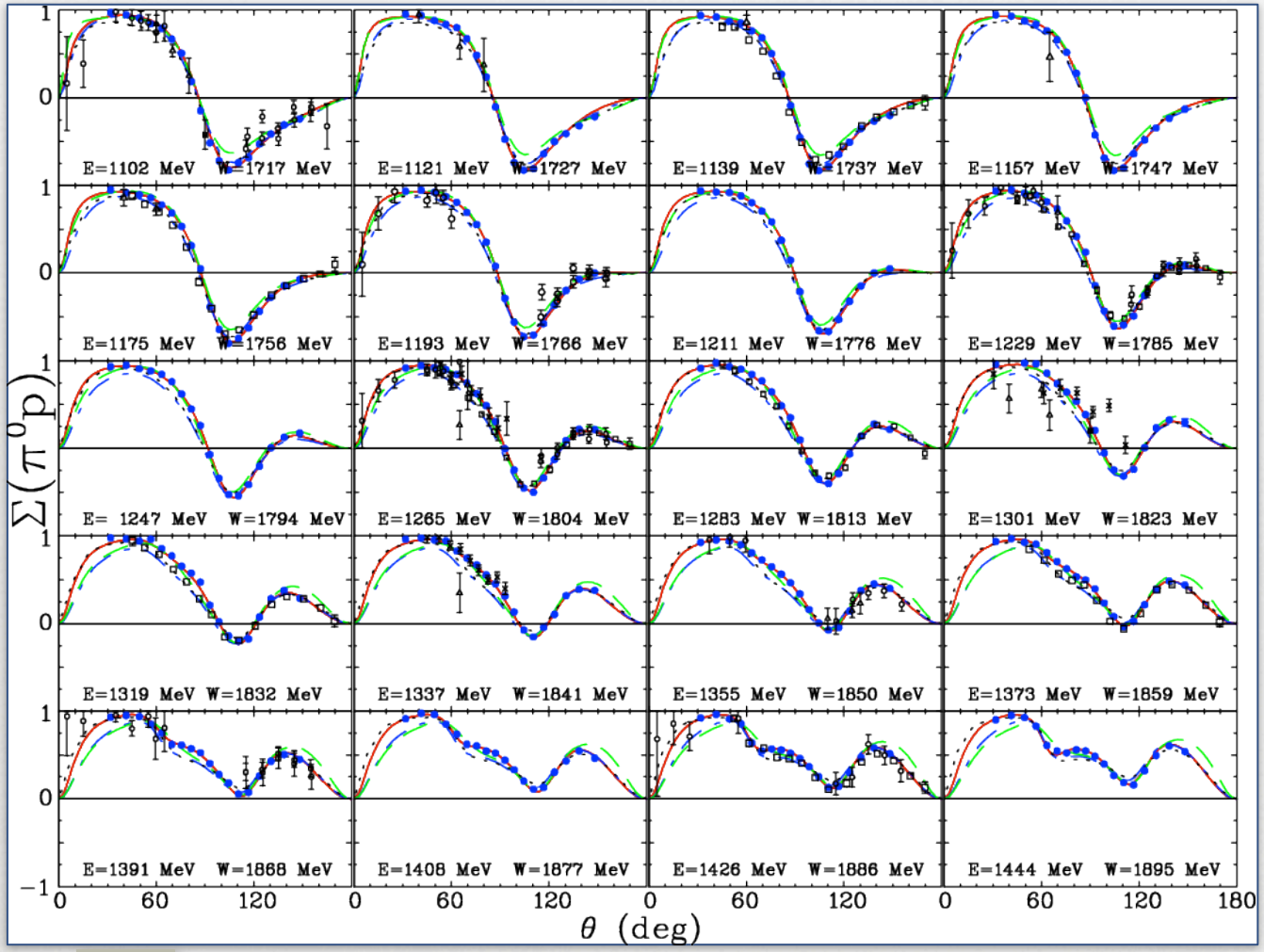
Σ for $\gamma p \rightarrow n\pi^+$



DU12
CM12
MAID
BbGa

M. Dugger et al.

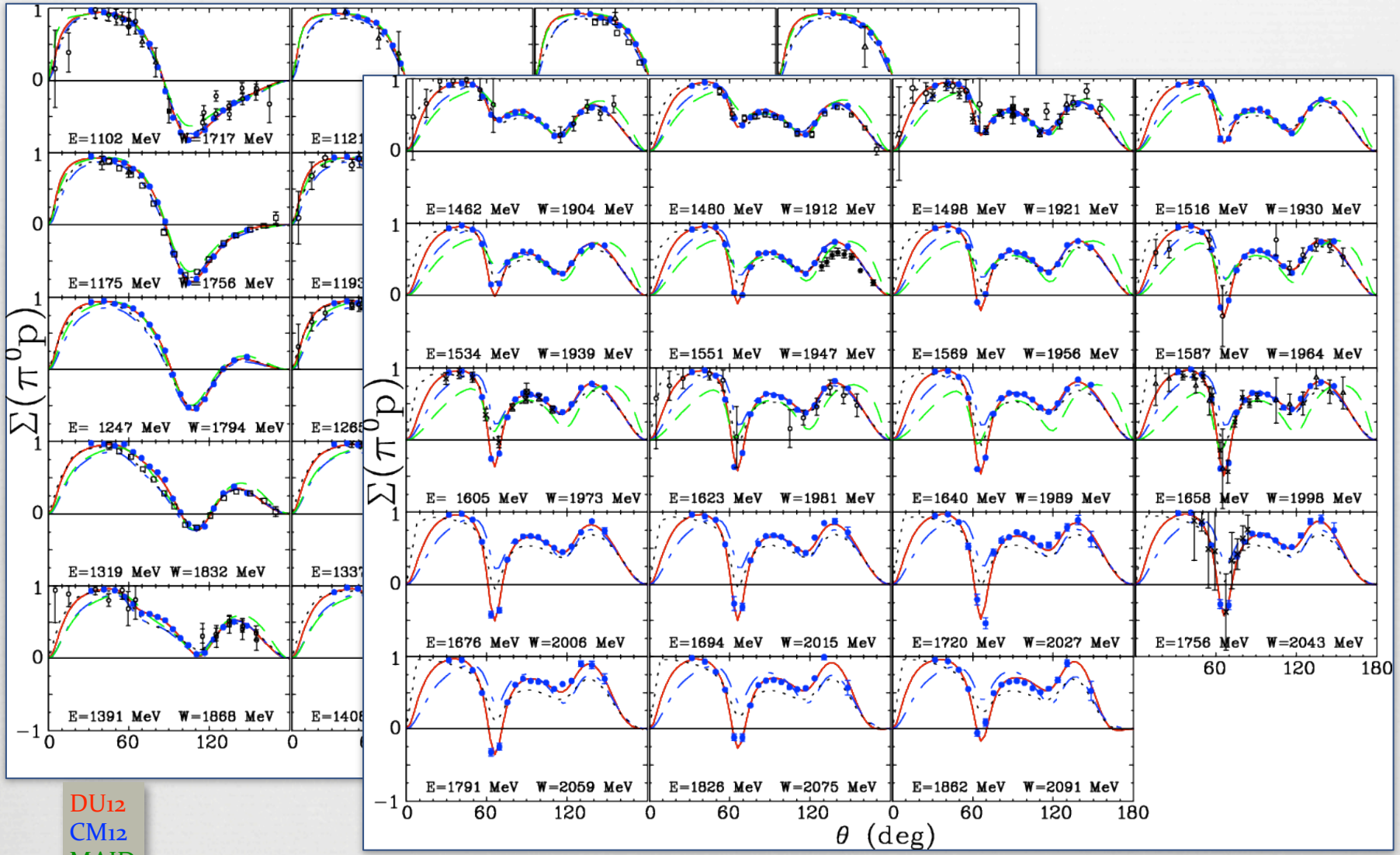
Σ for γ p → p π°



DU12
CM12
MAID
BbGa

M. Dugger et al.

Σ for $\gamma p \rightarrow p \pi^0$



DU12
CM12
MAID
BbGa

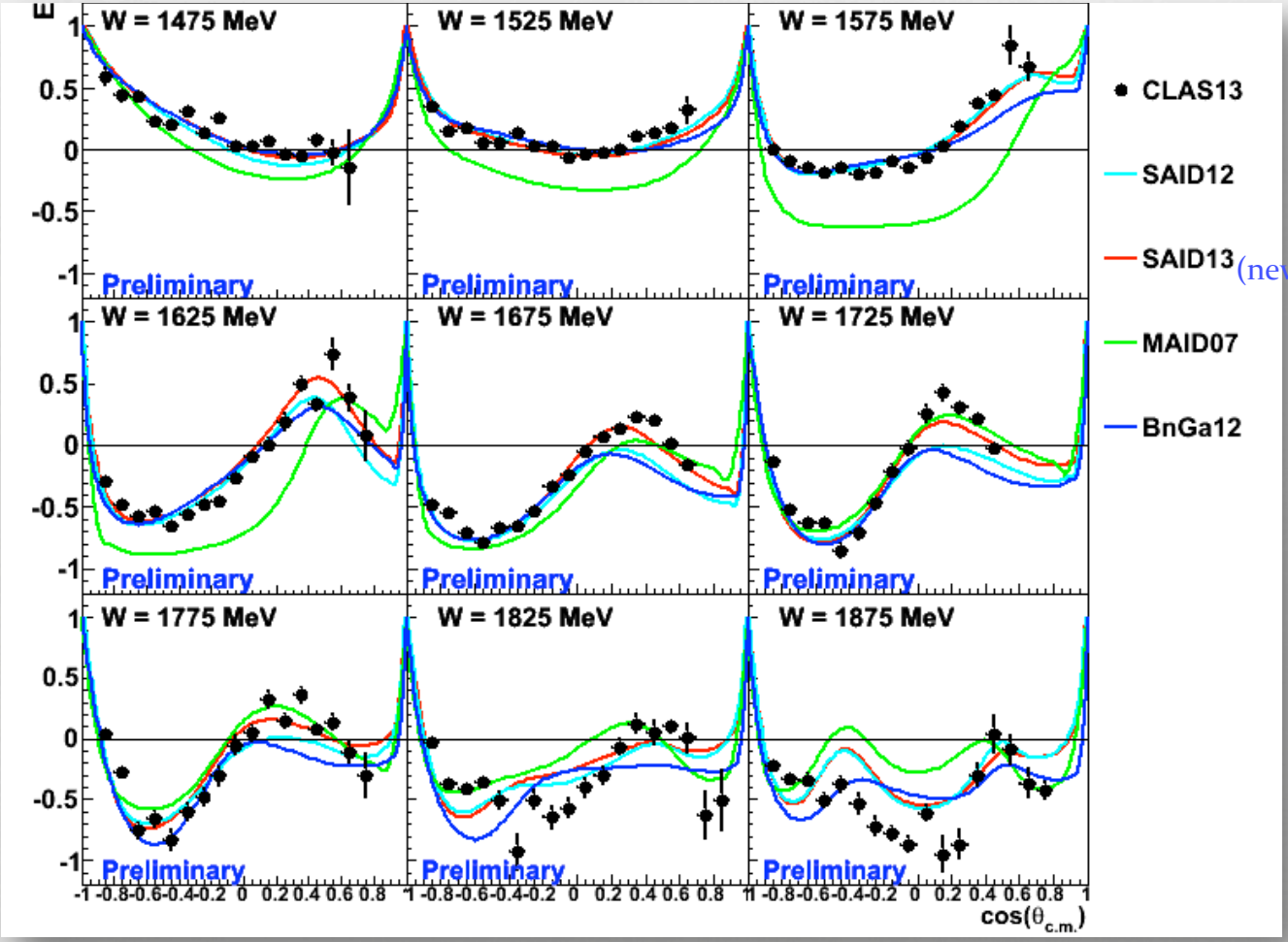
M. Dugger et al.

Changes in couplings

	Solution	$A_{1/2}$	$A_{3/2}$
$\Delta(1700)3/2^-$	DU12	132 ± 5	108 ± 5
	CM12	105 ± 5	92 ± 4
	BnGa	160 ± 20	165 ± 25
	MD07	226	210
	PDG12	104 ± 15	85 ± 22
$\Delta(1905)5/2^+$	DU12	20 ± 2	-49 ± 5
	CM12	19 ± 2	-38 ± 4
	BnGa	25 ± 5	-49 ± 4
	MD07	18	-28
	PDG12	26 ± 11	-45 ± 20

Those are both **** states!

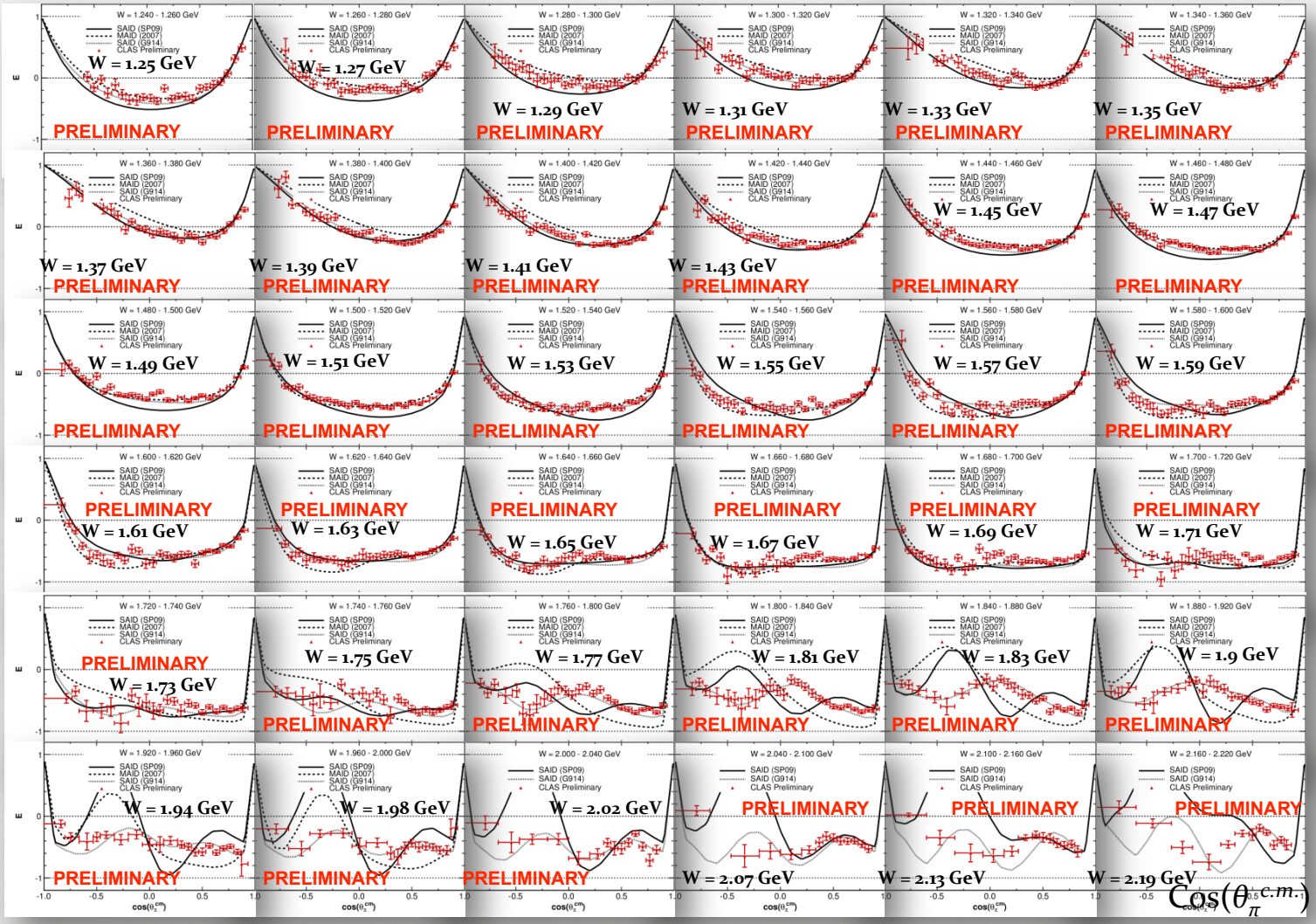
E for γ p → p π°



- Early stage results
- Predictions agree better at lower energies

M. Dugger et al.

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



SAID

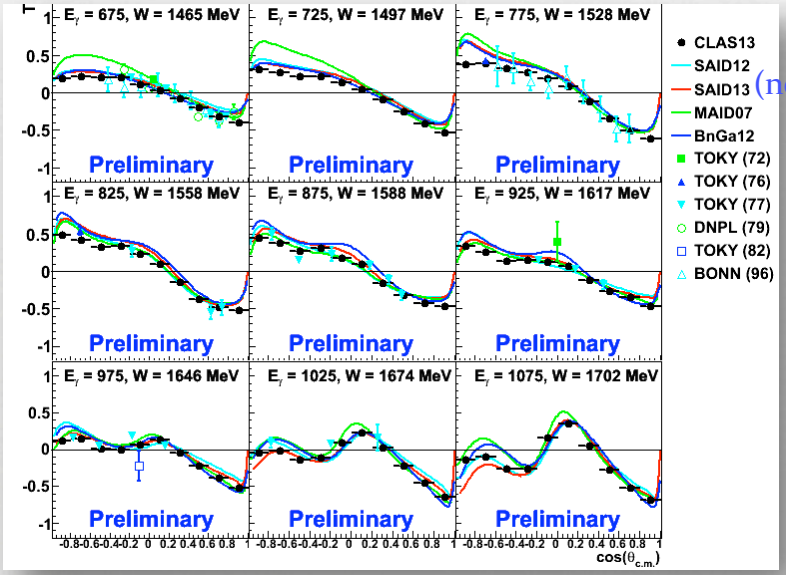
SAID (new fit)

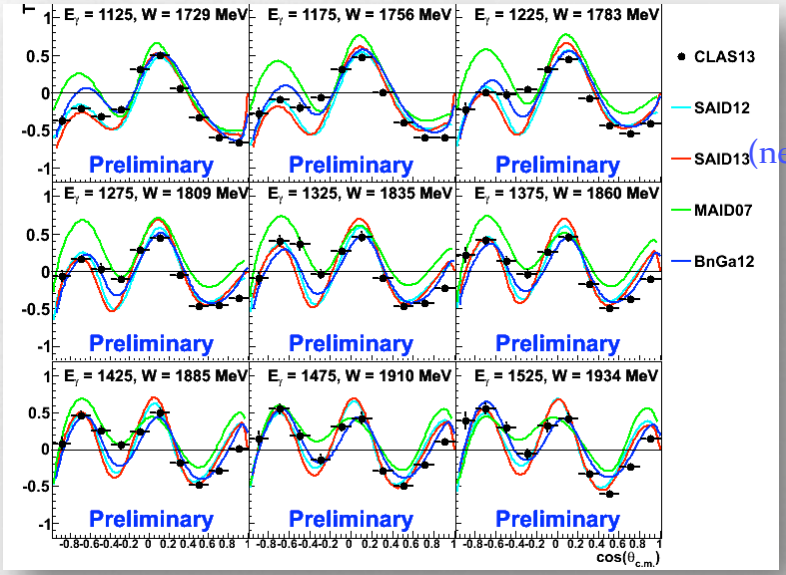
MAID

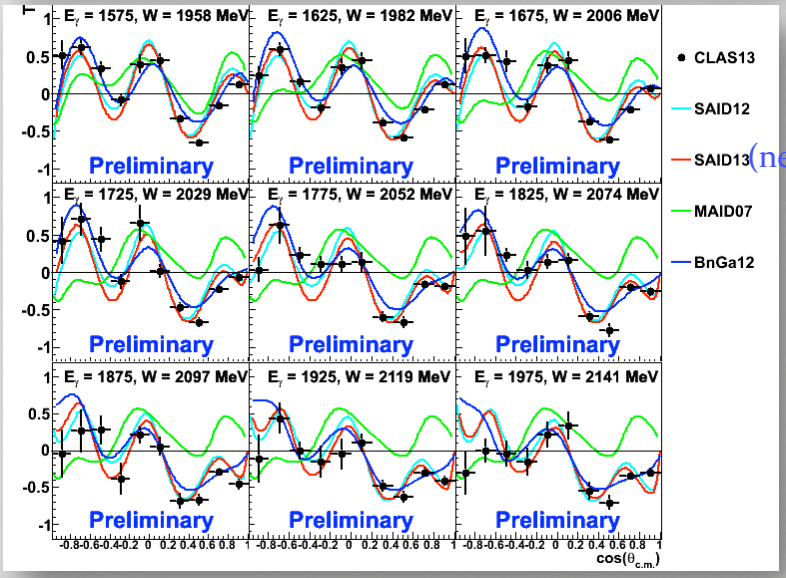
Agriment with predictions is getting worse at higher energies above 1.7 GeV

S. Strauch

T for γ p → n π^+

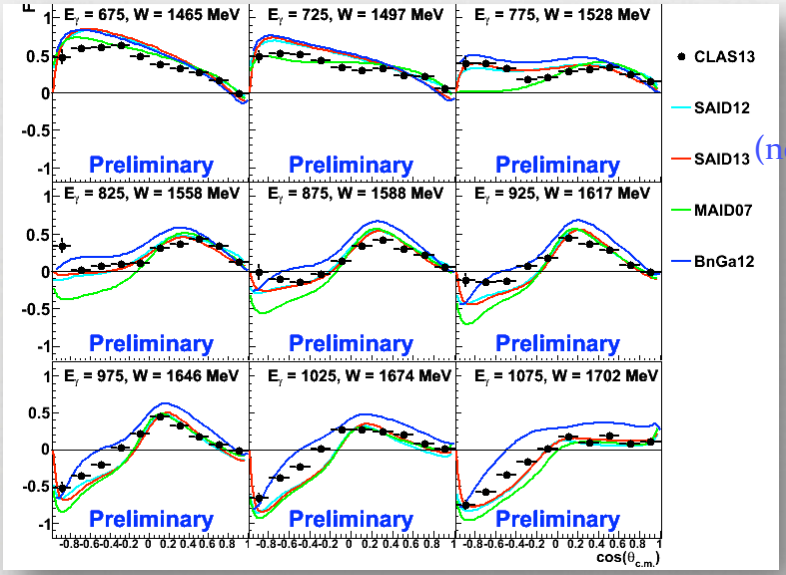


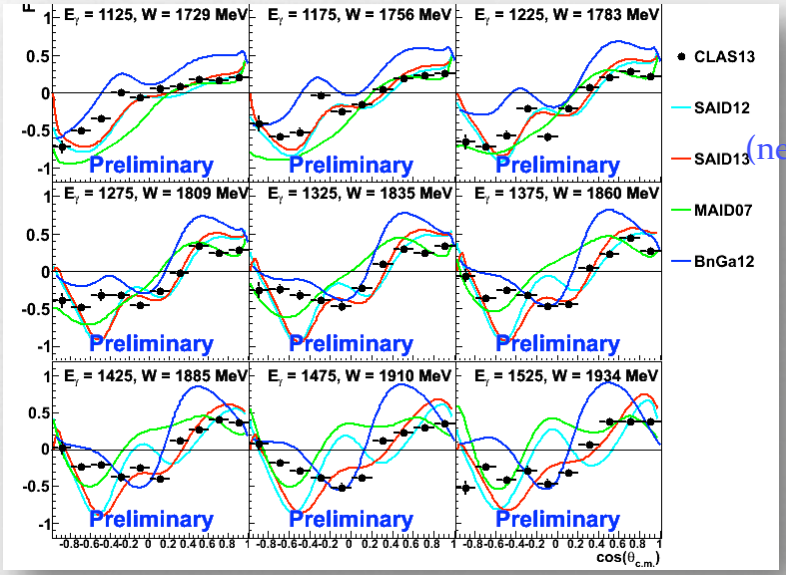


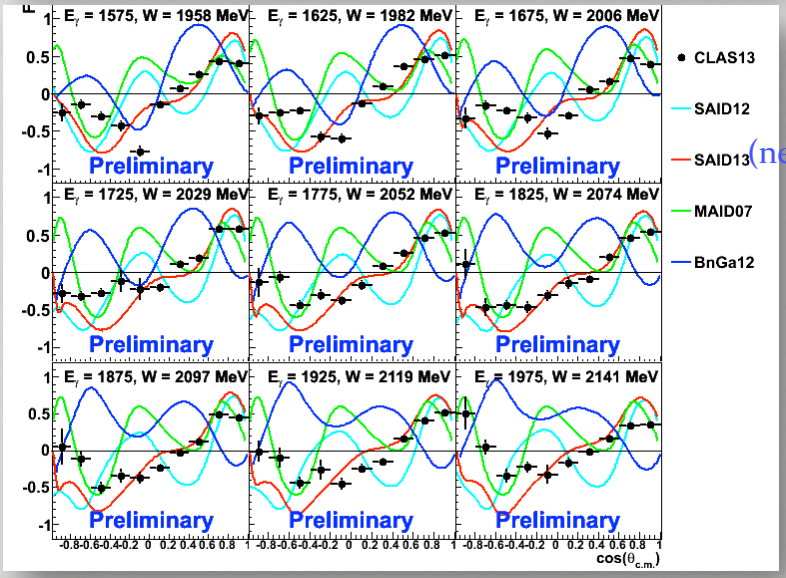


M. Dugger et al.

F for γ p → n π⁺



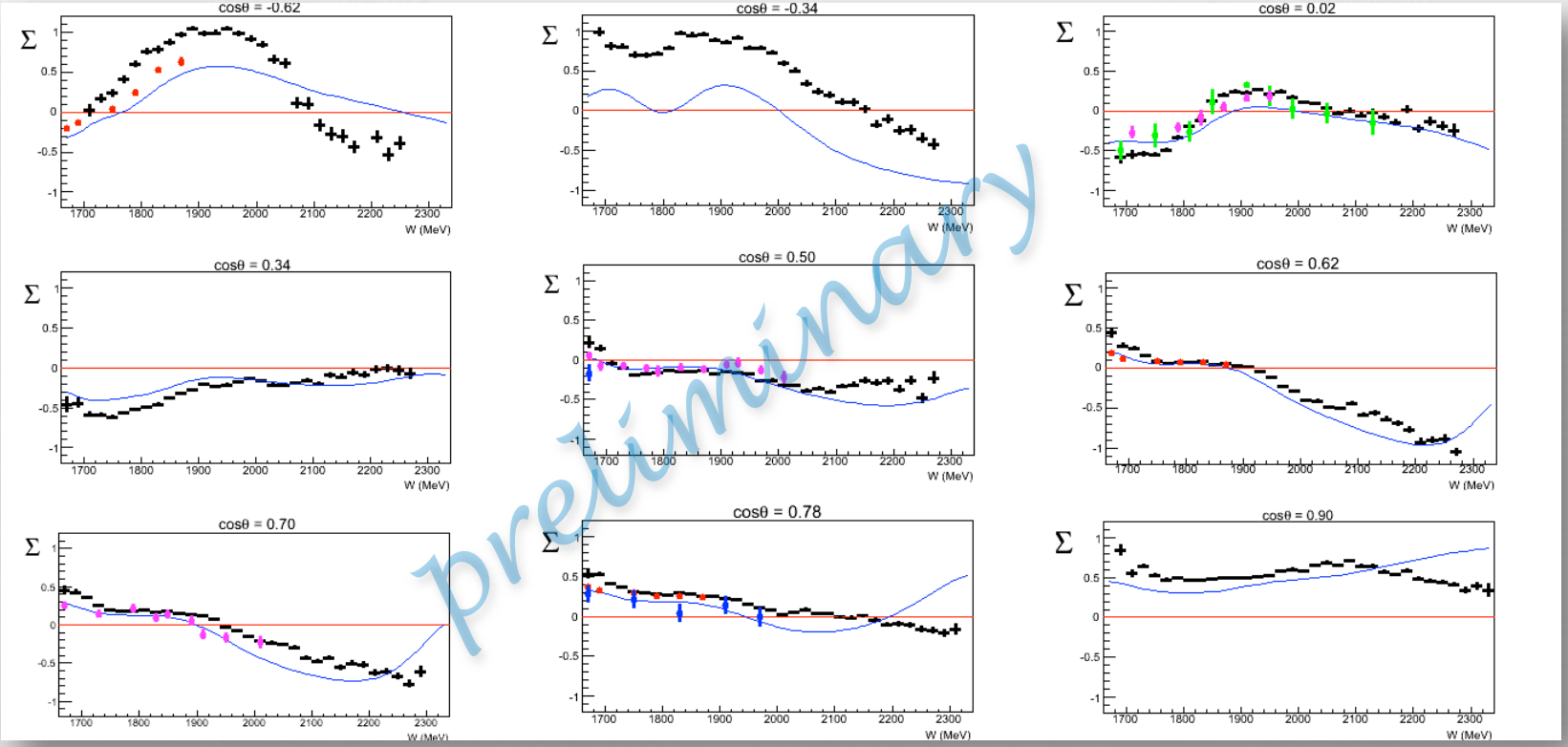




- Agreement with predictions get much worse at higher energies
- SAID13 are predictions based on preliminary fits to CLAS pion Σ measurements

M. Dugger et al.

Σ for γ n $\rightarrow$ p π^-



D. Sokhan

Curve - SAID
Red GRAAL
Magenta and Blue - Erevan

9 out of 40 angular bins are shown
Bins 0.04 in cos and 20 MeV in W

E for γn(p) → pπ⁻(p)

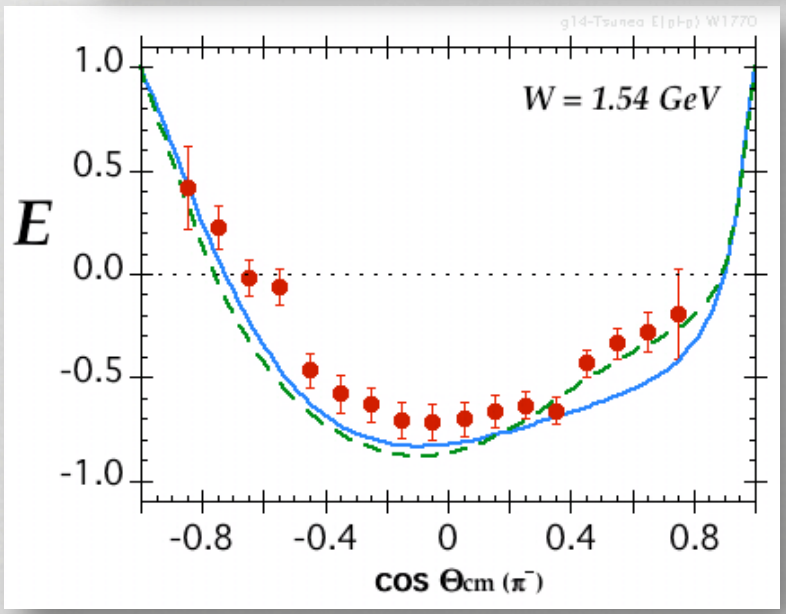
$\vec{\gamma}\,\vec{D} \rightarrow \pi^- p\,(p)$

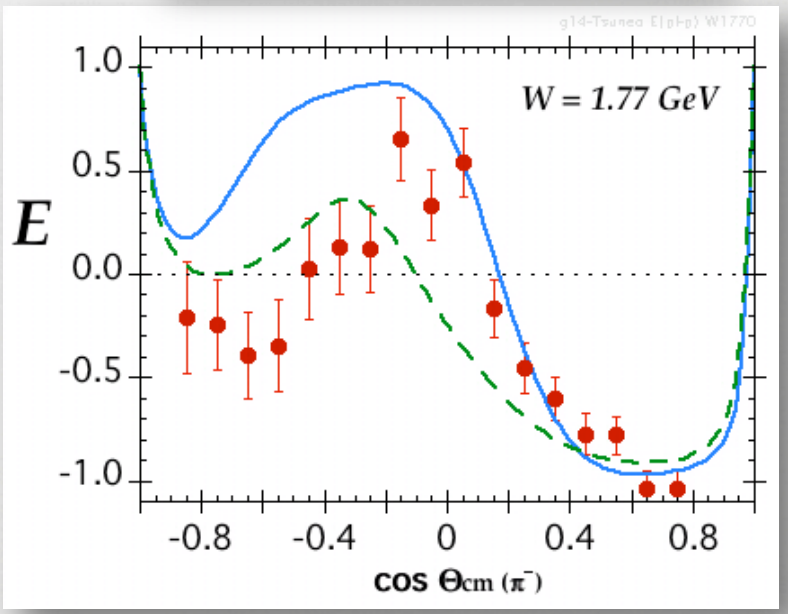
- *with cuts to restrict to quasi-free neutron kinematics*
- *~ 10% of data set analyzed*

$\vec{\gamma}\,\vec{n} \rightarrow \pi^- p$

SAID [SN11]

MAID [2007]



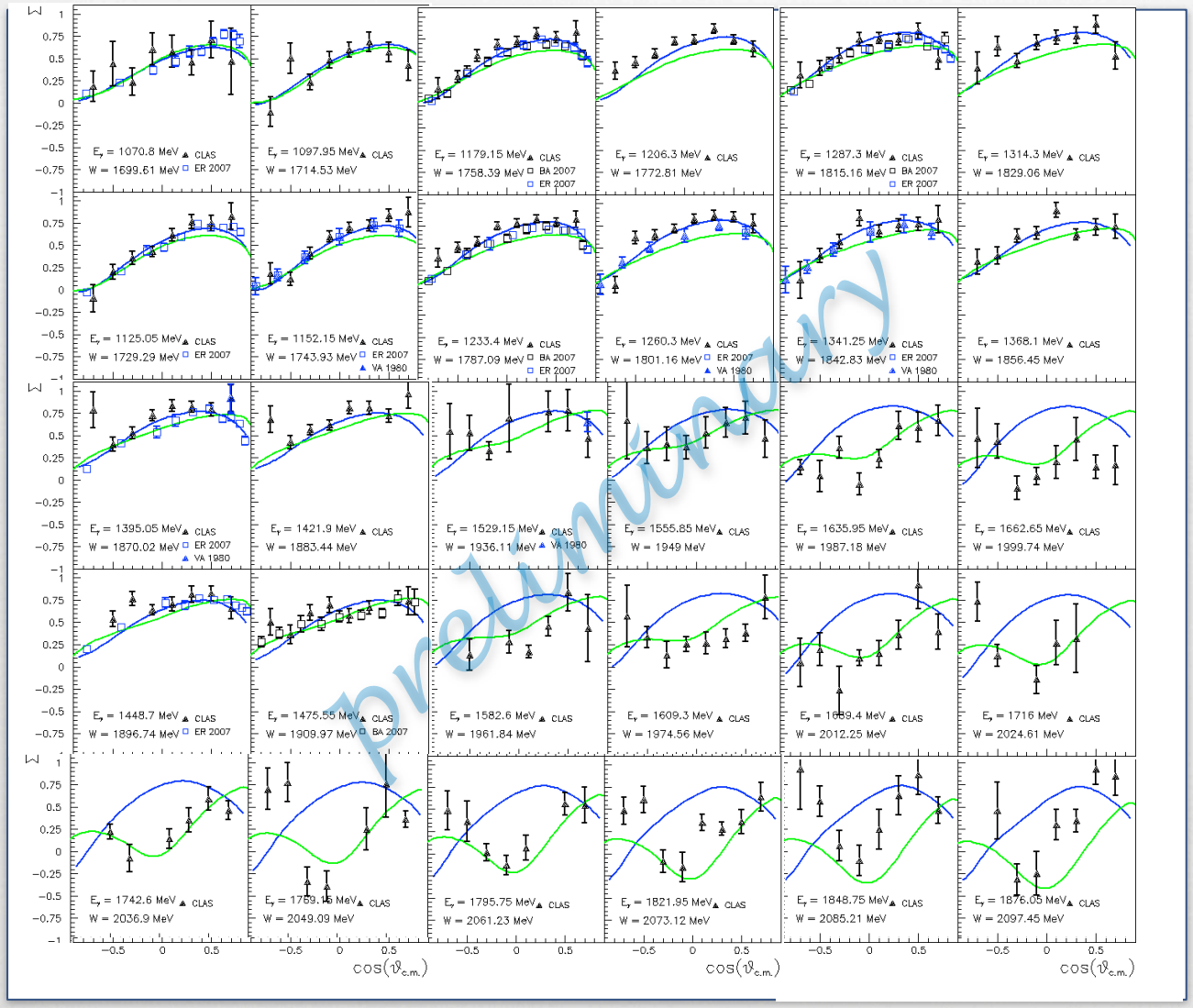


T. Kagea

η photoproduction

Σ for γp → pη

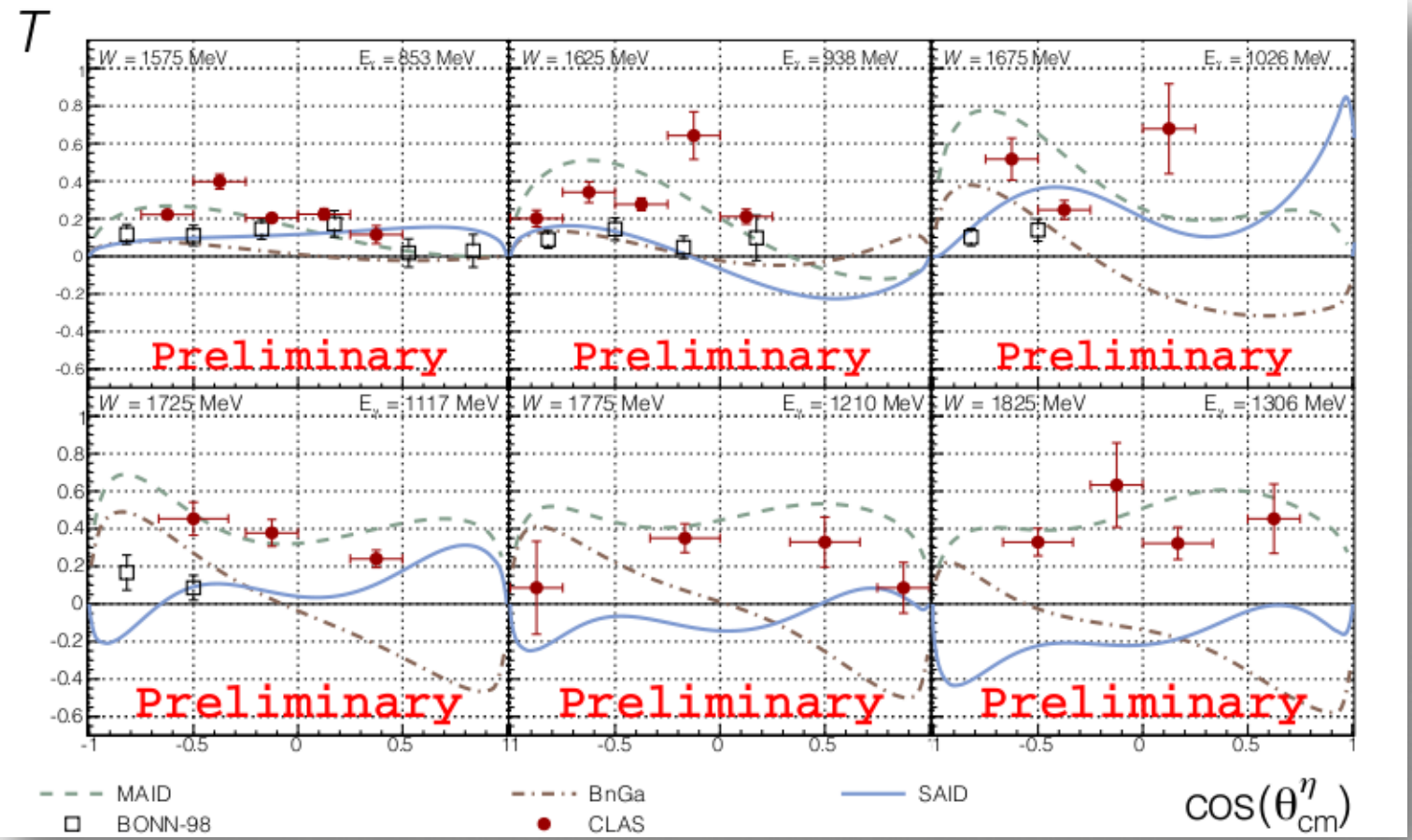
g8b



P. Collins

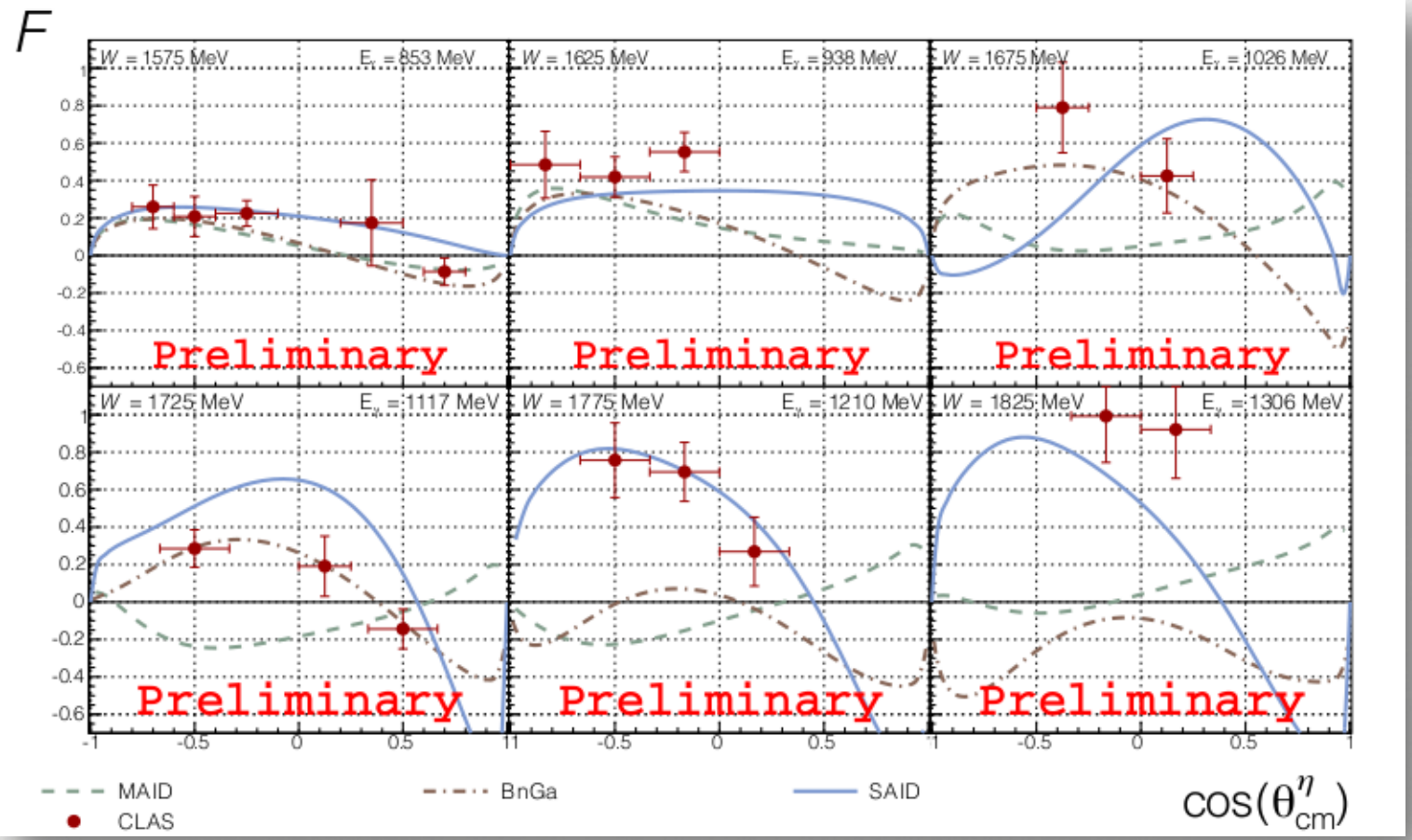
Analysis under working group review

T for for γp → pη



R. Tucker

F for for γp → pη

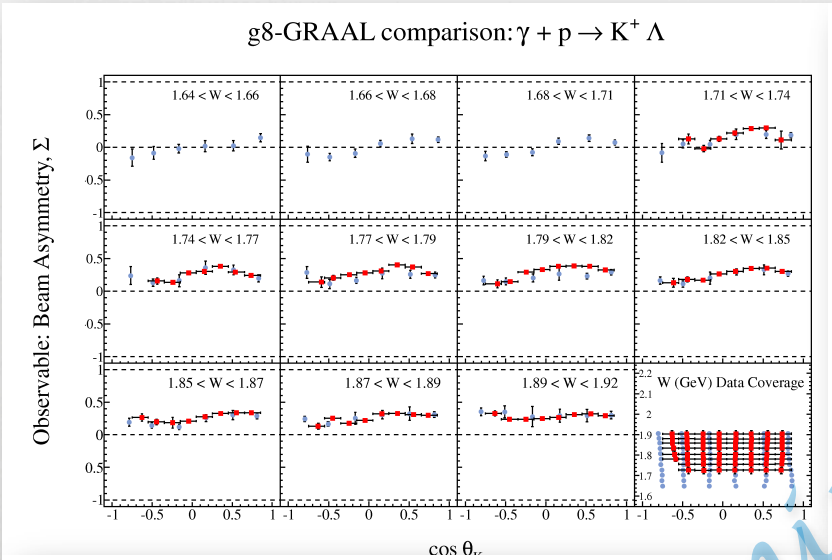


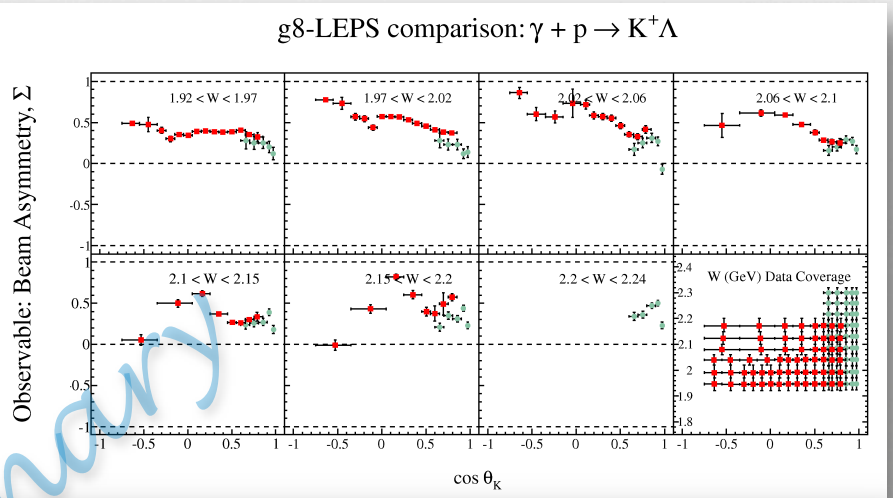
I. Senderovich later this session

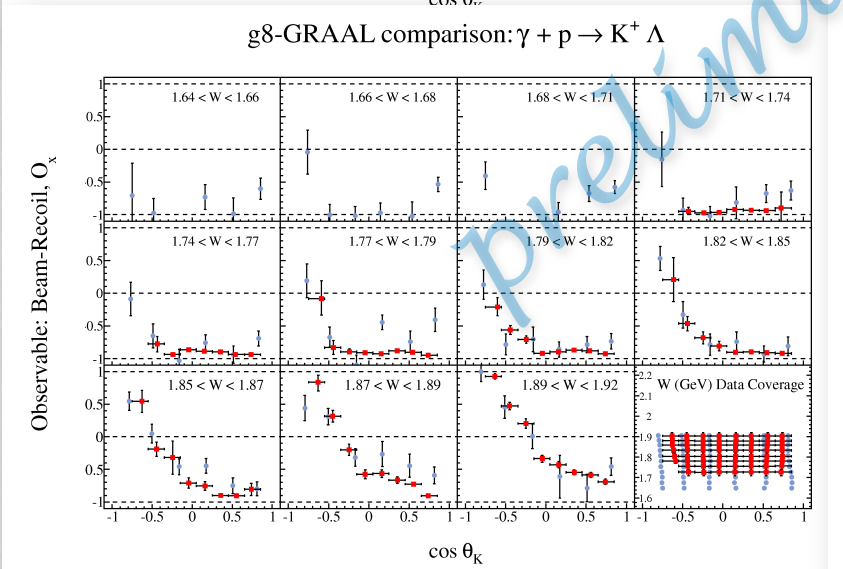
R. Tucker

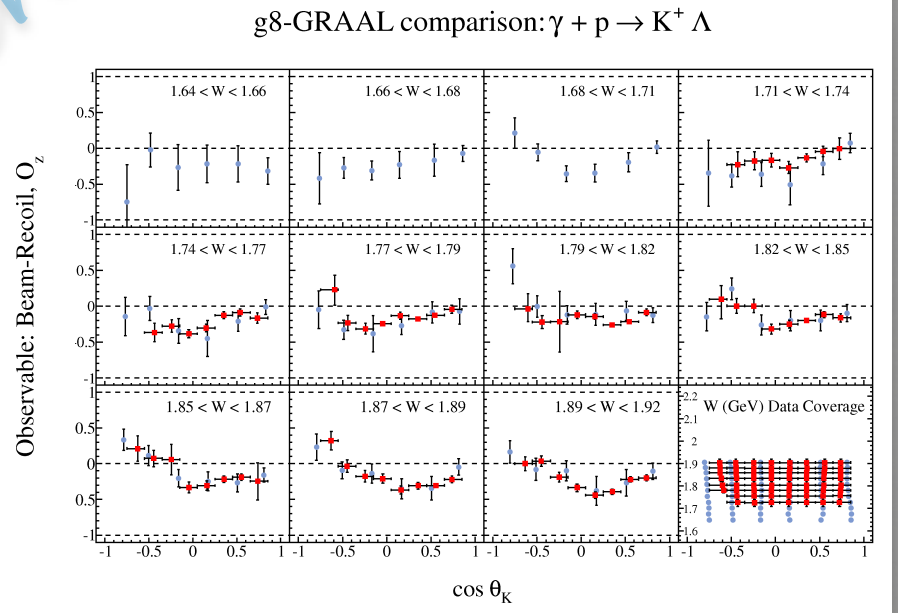
KY production

Σ , O_x , O_z for $\gamma p \rightarrow K^+ \Lambda$









preliminary

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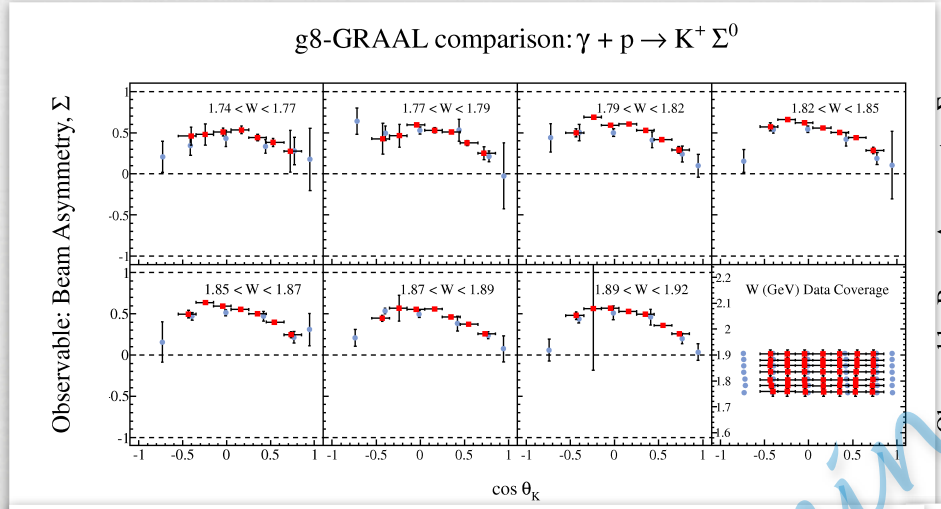
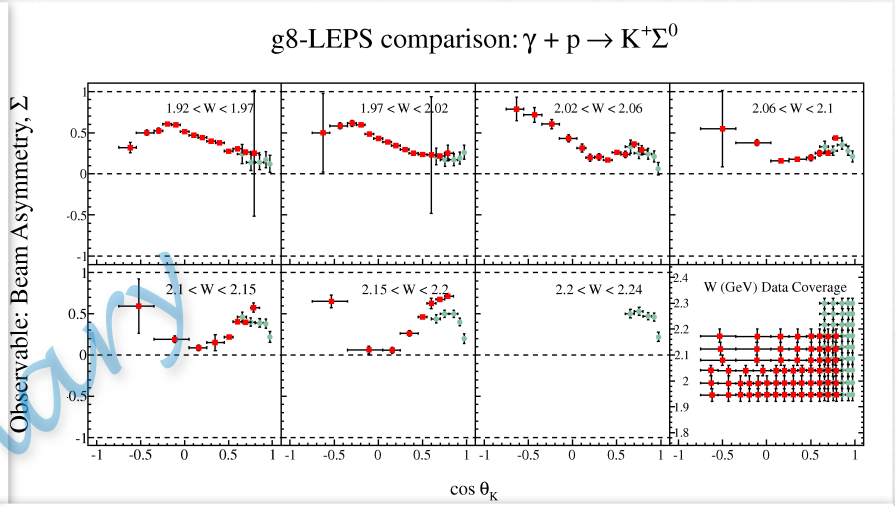
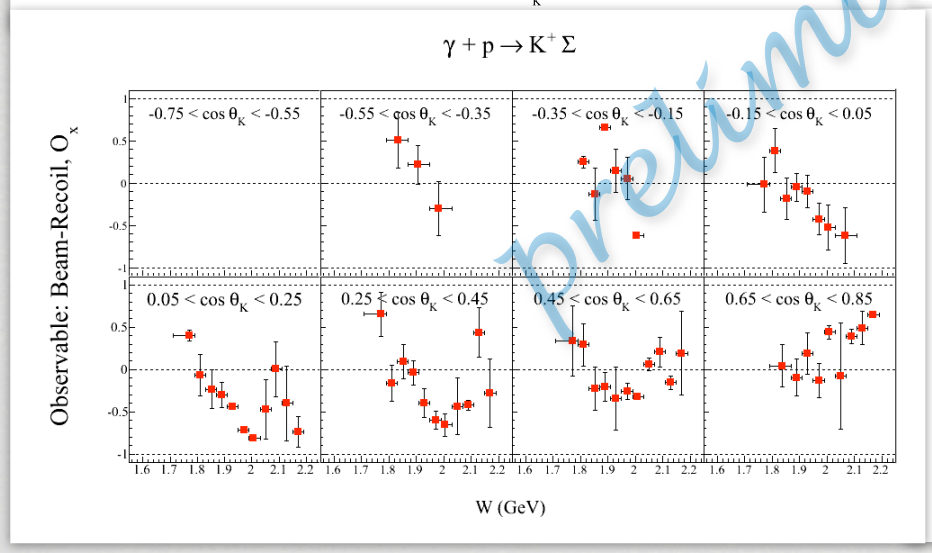
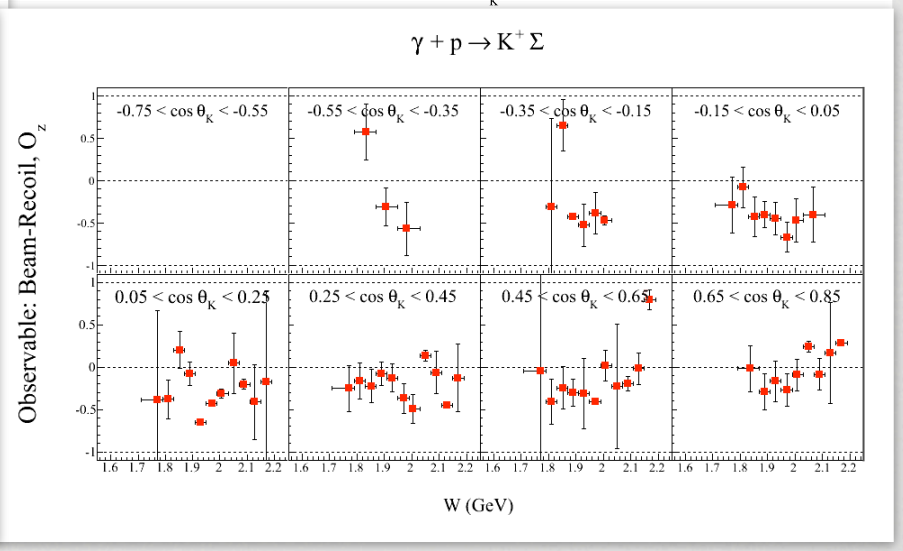
Σ , O_x , O_z for $\gamma p \rightarrow K^+ \Sigma^o$









preliminary

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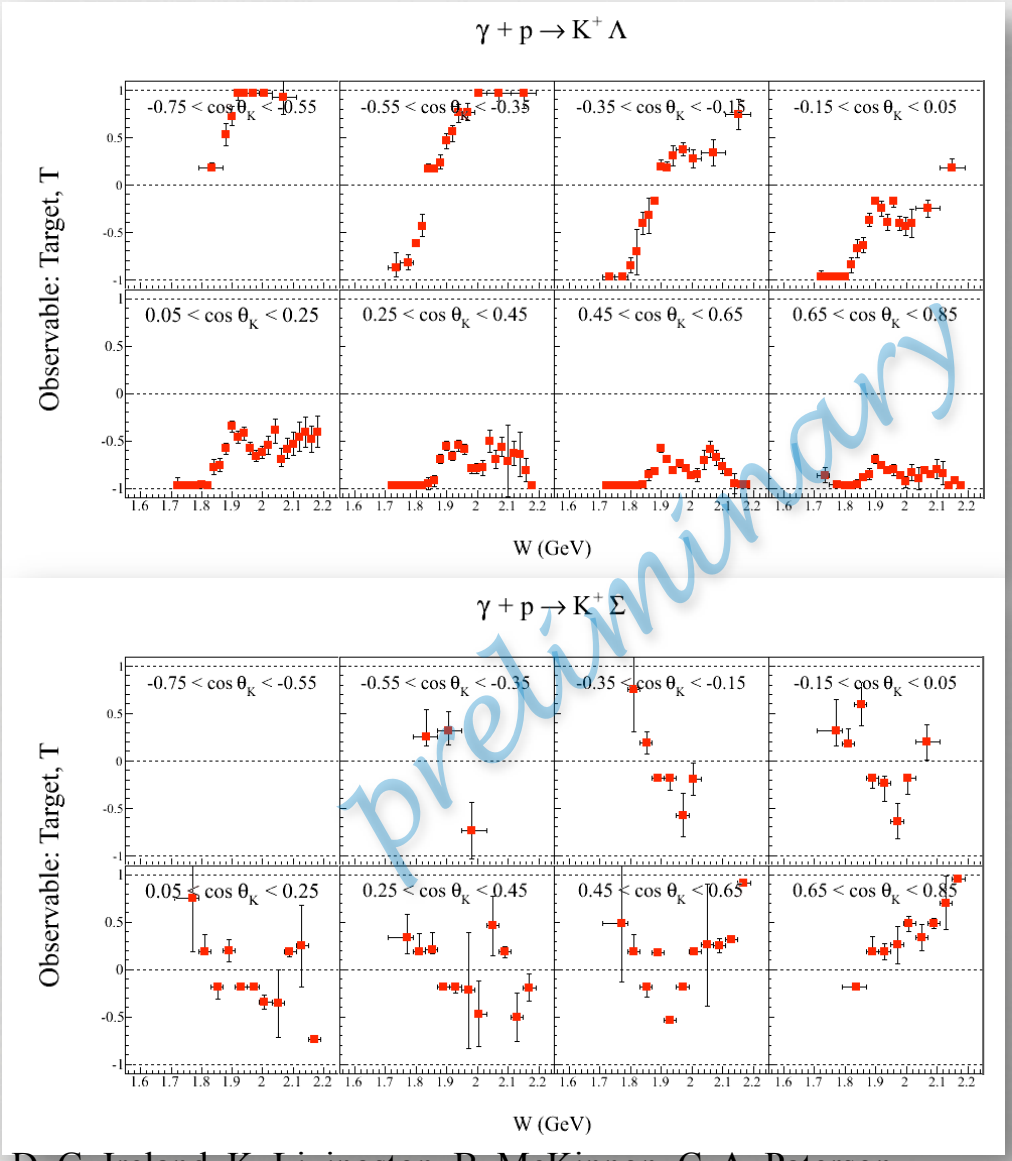
University of Glasgow

T for γ p → K⁺ Λ and γ p → K⁺Σ⁰

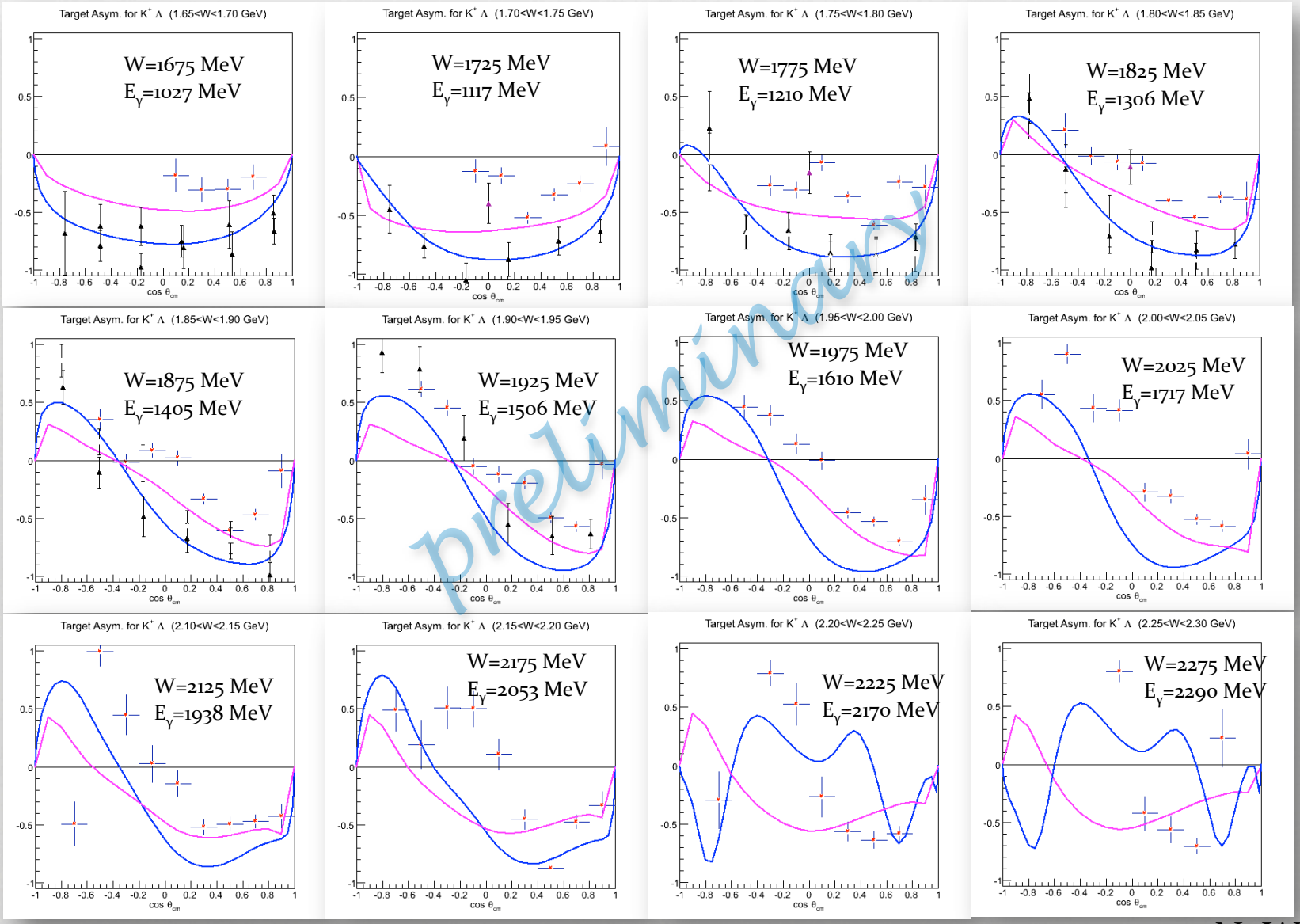


Due to the self-analyzing nature of the , determine many observables using only a linearly polarized beam

D. G. Ireland, K. Livingston, B. McKinnon, C. A. Paterson

University of Glasgow

T for γp→K⁺Λ



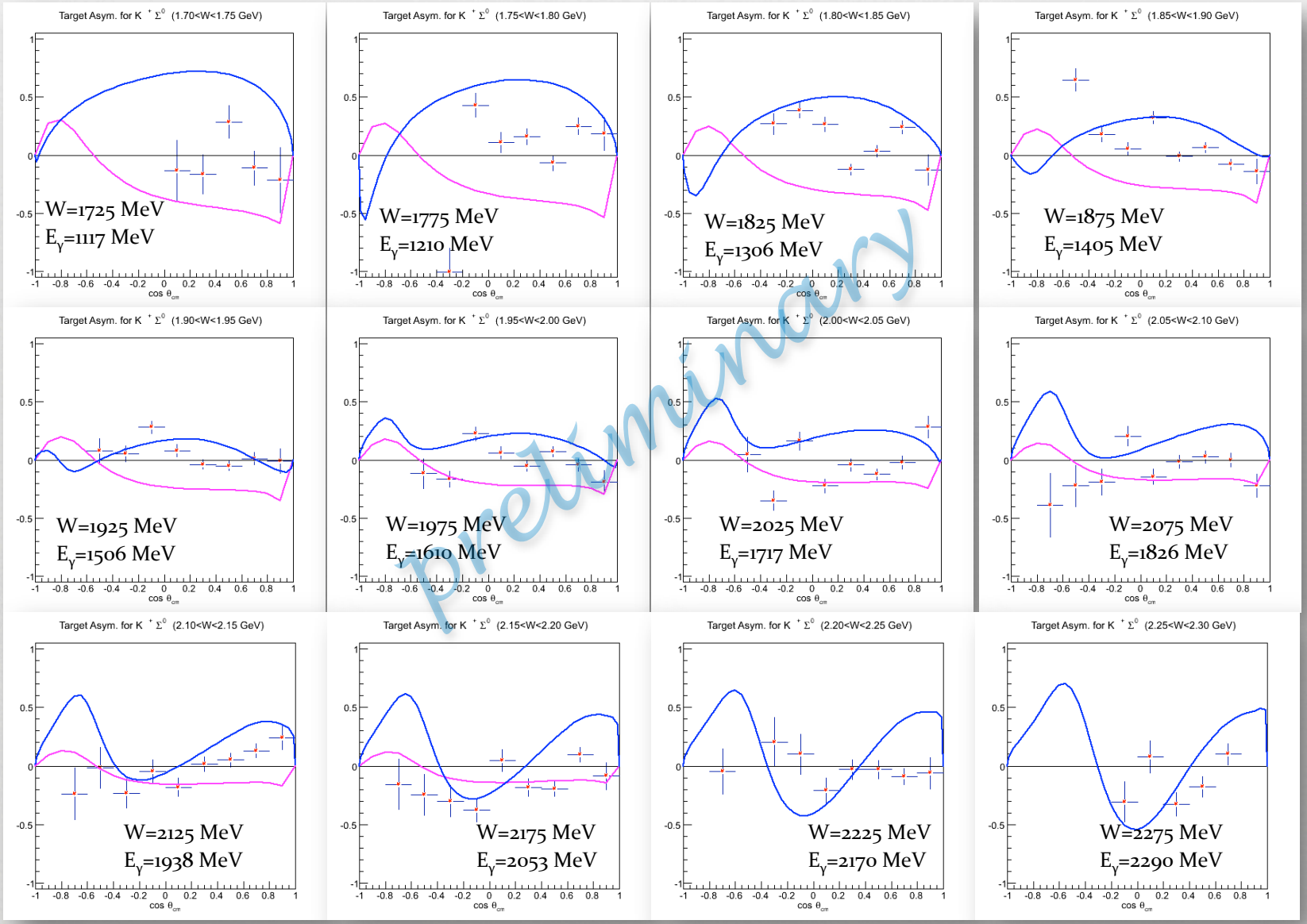
★-CLAS

BnGa

kaonMAID

N. Walford

T for γp → K+Σ0



★-CLAS

BnGa

kaonMAID

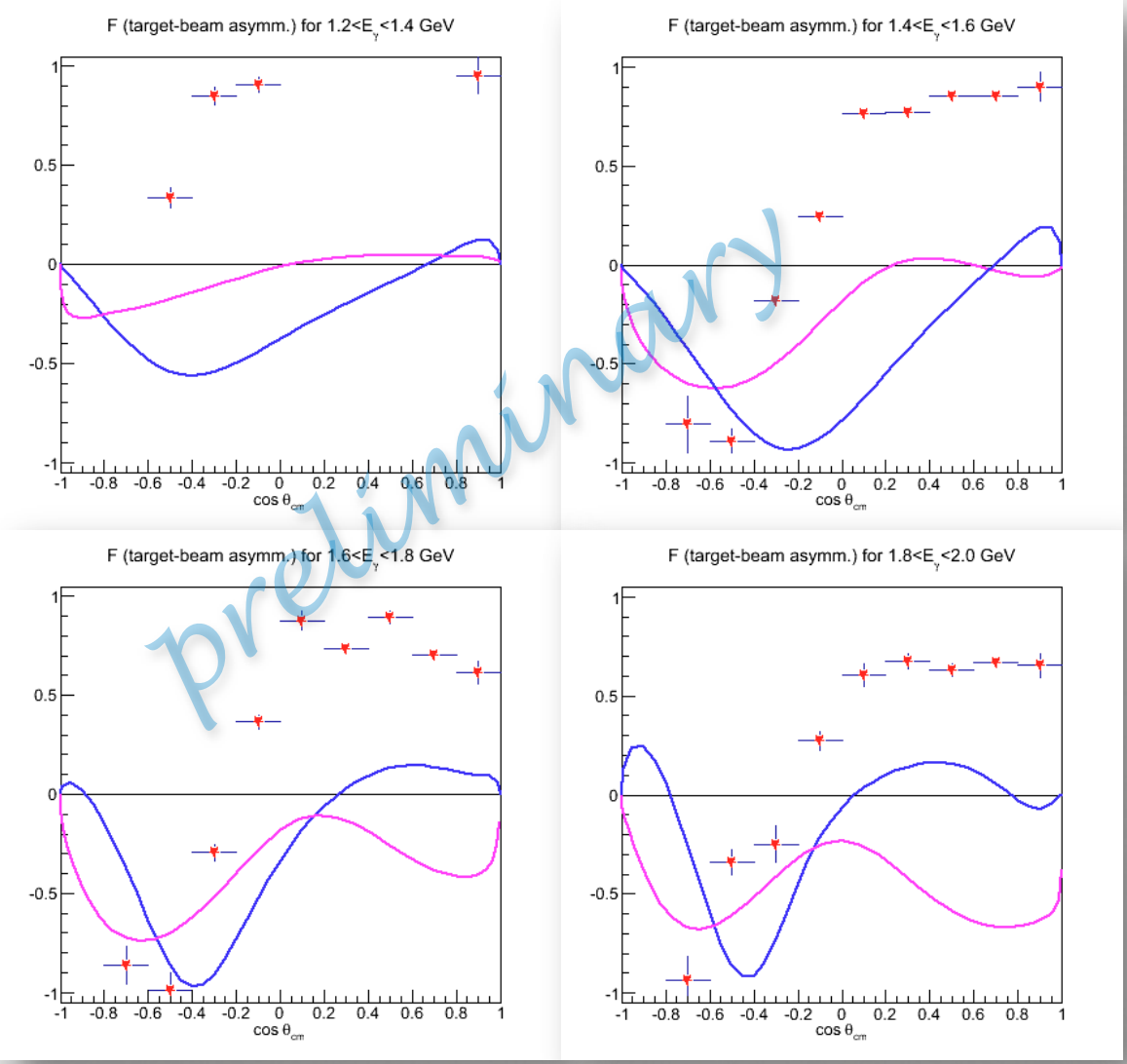
N. Walford

F for $\gamma p \rightarrow K^+\Lambda$

★-CLAS

BnGa

kaonMAID



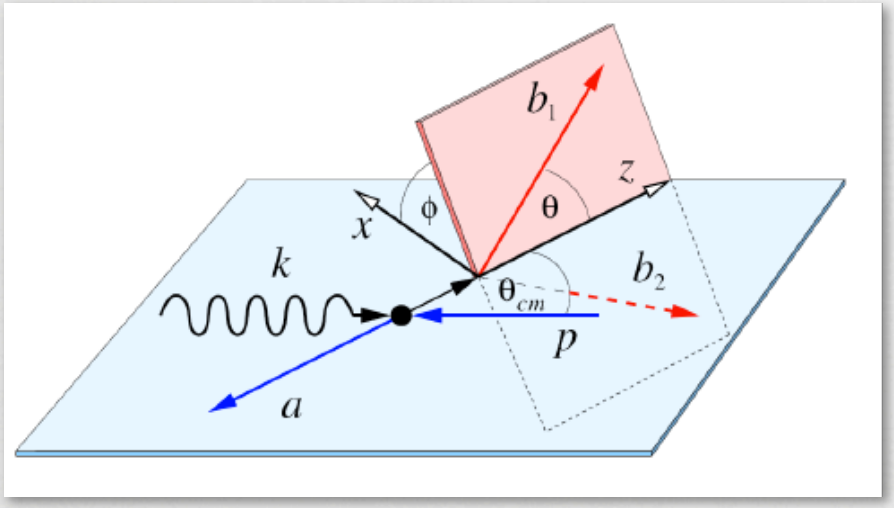
S. Fegan later this session

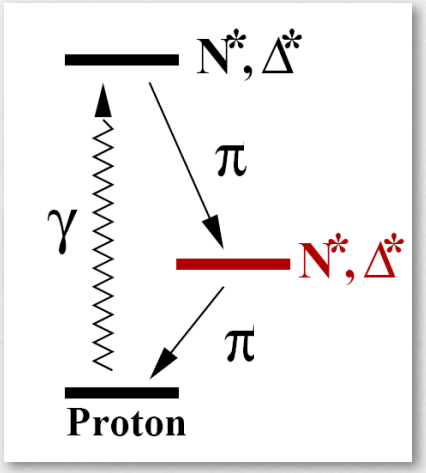
N. Walford

$\pi^+\pi^-$ photoproduction

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

- Dominates photoproduction cross section for W >1.6 GeV
- 64 observables
- 28 independent relations related to helicity amplitude magnitudes
- 21 independent relations related to helicity amplitude phases
- Results in 15 independent numbers





Could be used for search of resonances that decay into other resonances

Cross section for $\gamma p \rightarrow p\pi^+\pi^-$

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

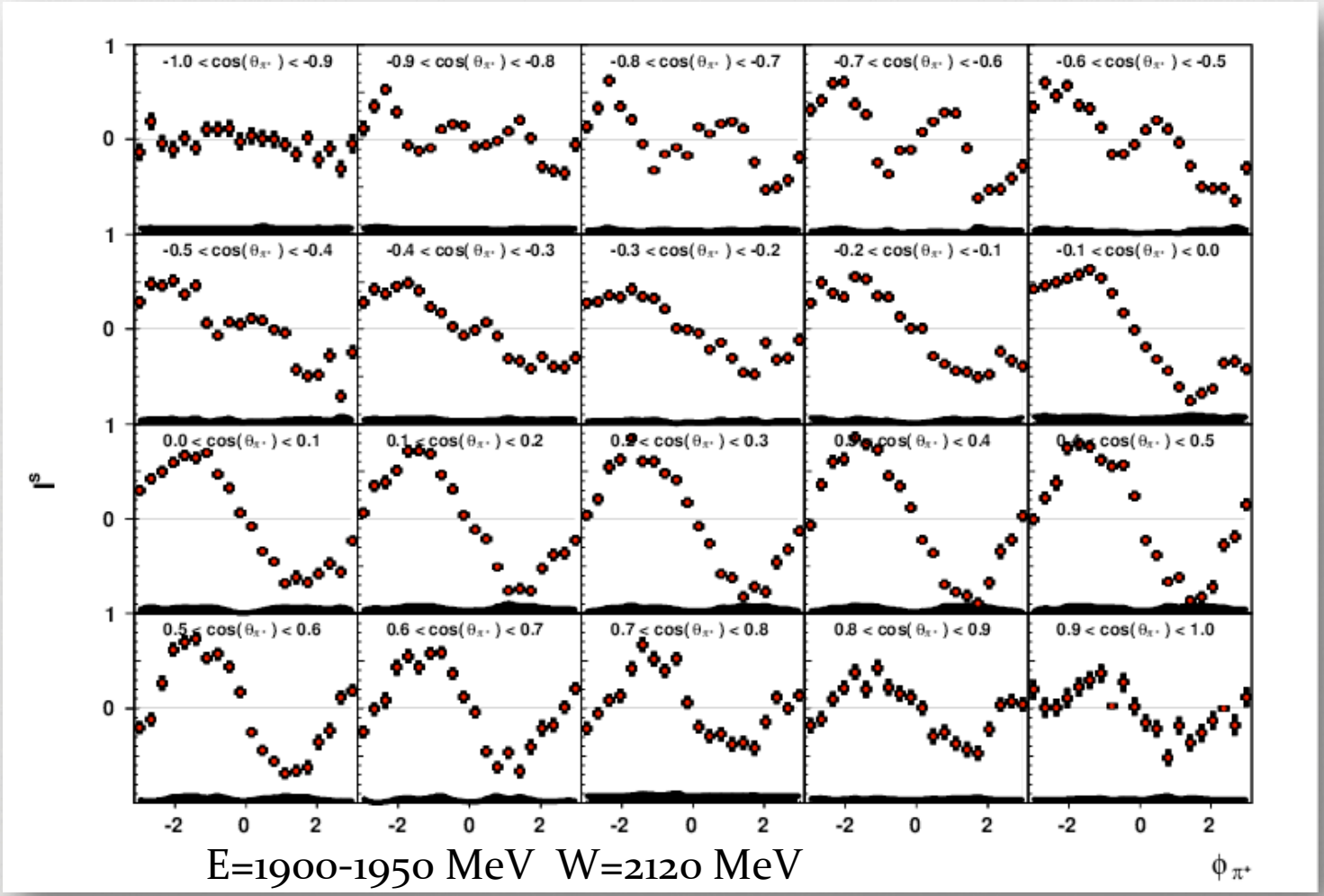
(without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}$$

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

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

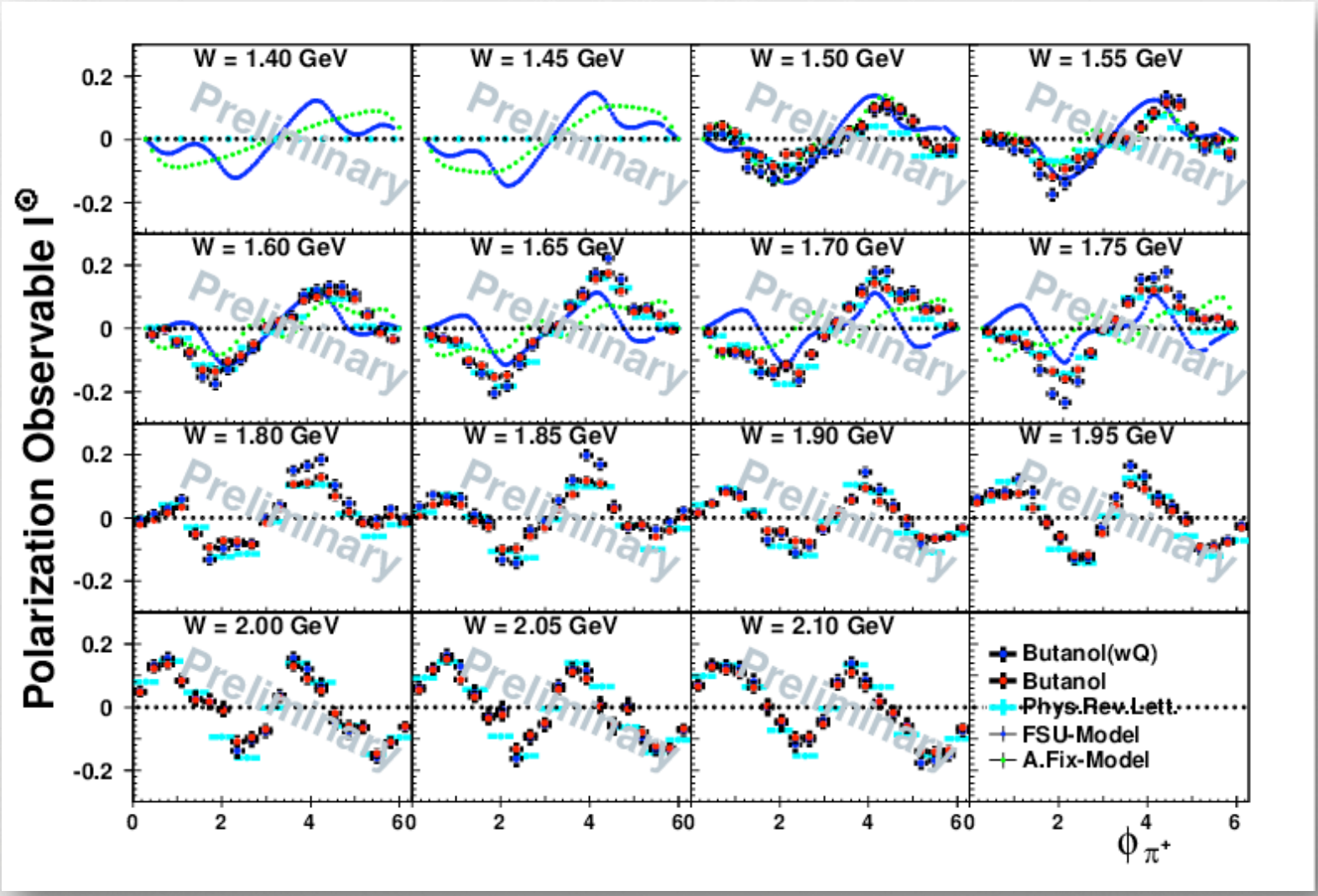
Linearly polarized photons, unpolarized target



One of 20 energy bins

Charles Hanretty

I⊙ for $p\pi^+\pi^-$



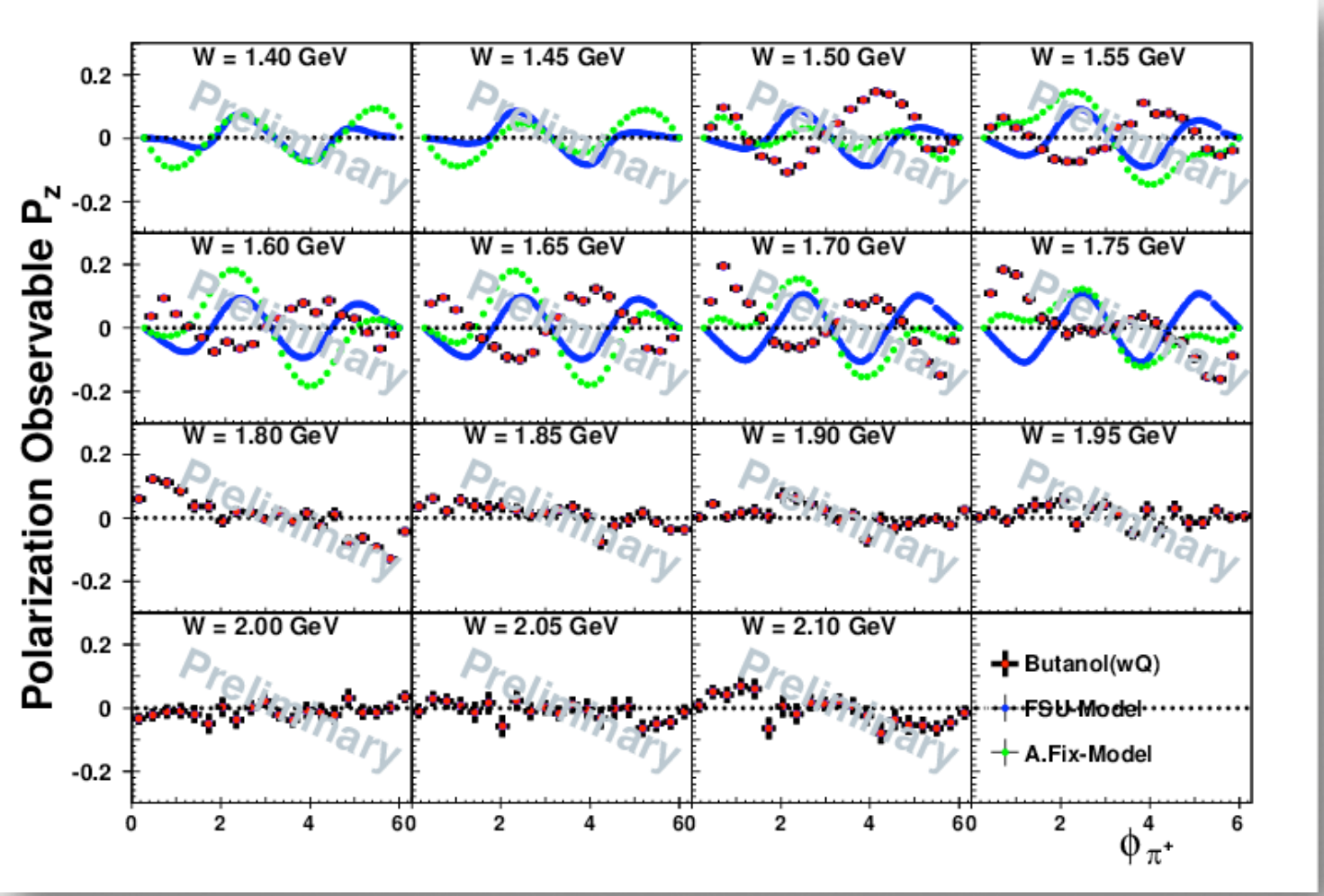
S. Strauch et al., PRL. 95, 162003 (2005)

W. Roberts and T. Oed, PRC 71, 055201 (2005)

A. Fix and H. Arenhovel, EPJA 25, 115 (2005)

S. Park

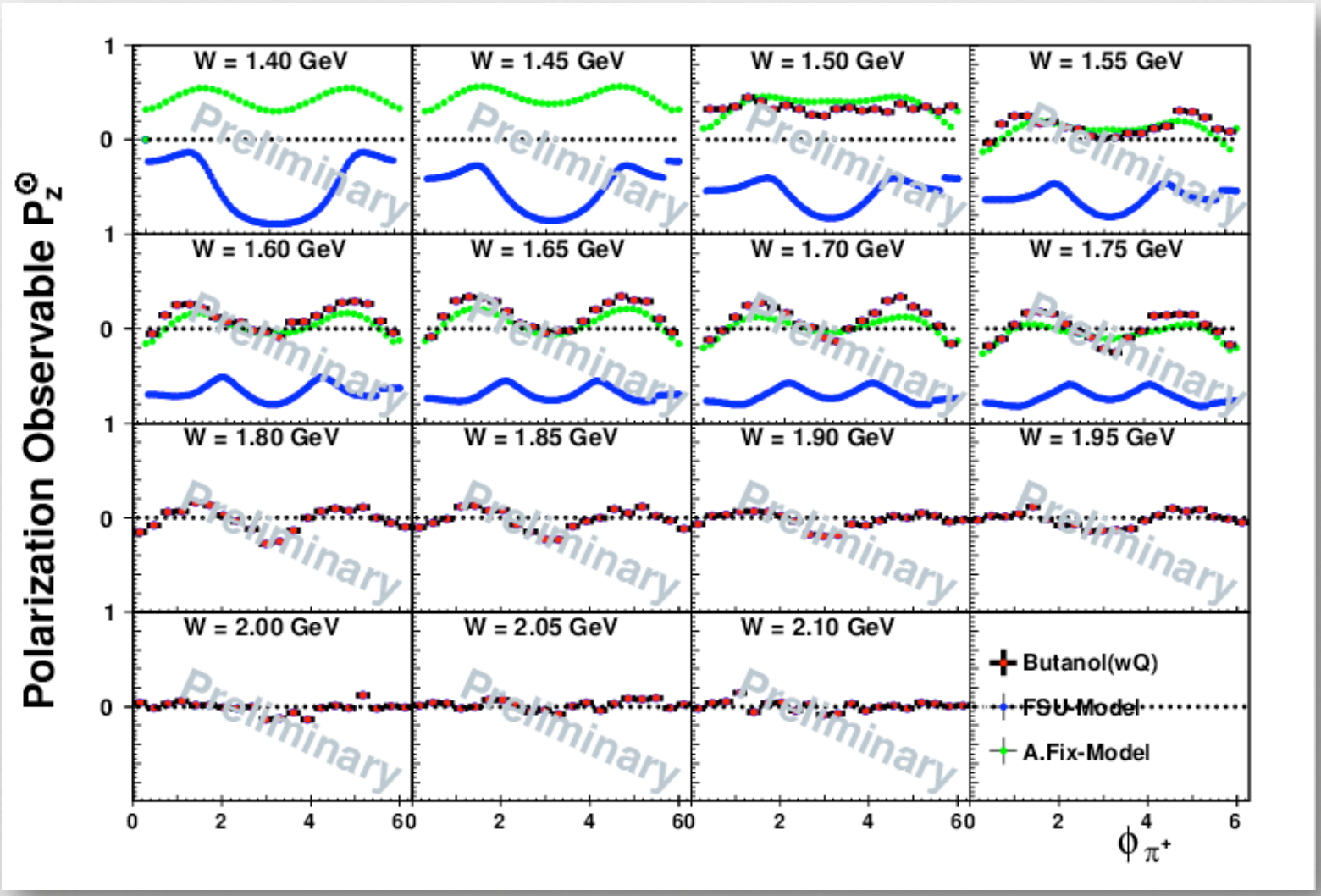
P_z for $p\pi^+\pi^-$



W. Roberts and T. Oed, PRC 71, 055201 (2005)
A. Fix and H. Arenhovel, EPJA 25, 115 (2005)

S. Park

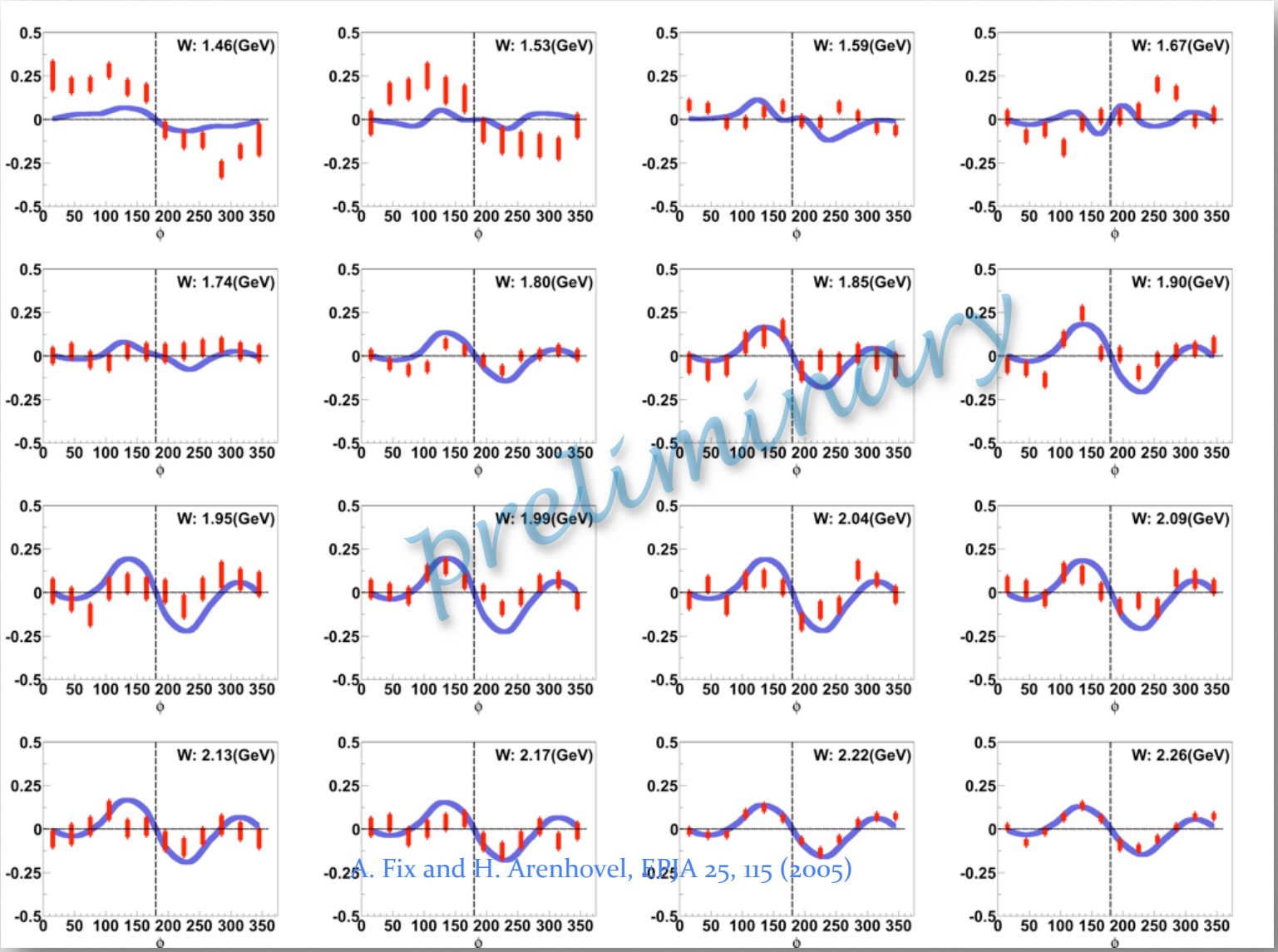
$P_z^{\odot}$ for $p\pi^+\pi^-$



W. Roberts and T. Oed, PRC 71, 055201 (2005)
A. Fix and H. Arenhovel, EPJA 25, 115 (2005)

S. Park

Comparison with model: P^c_z

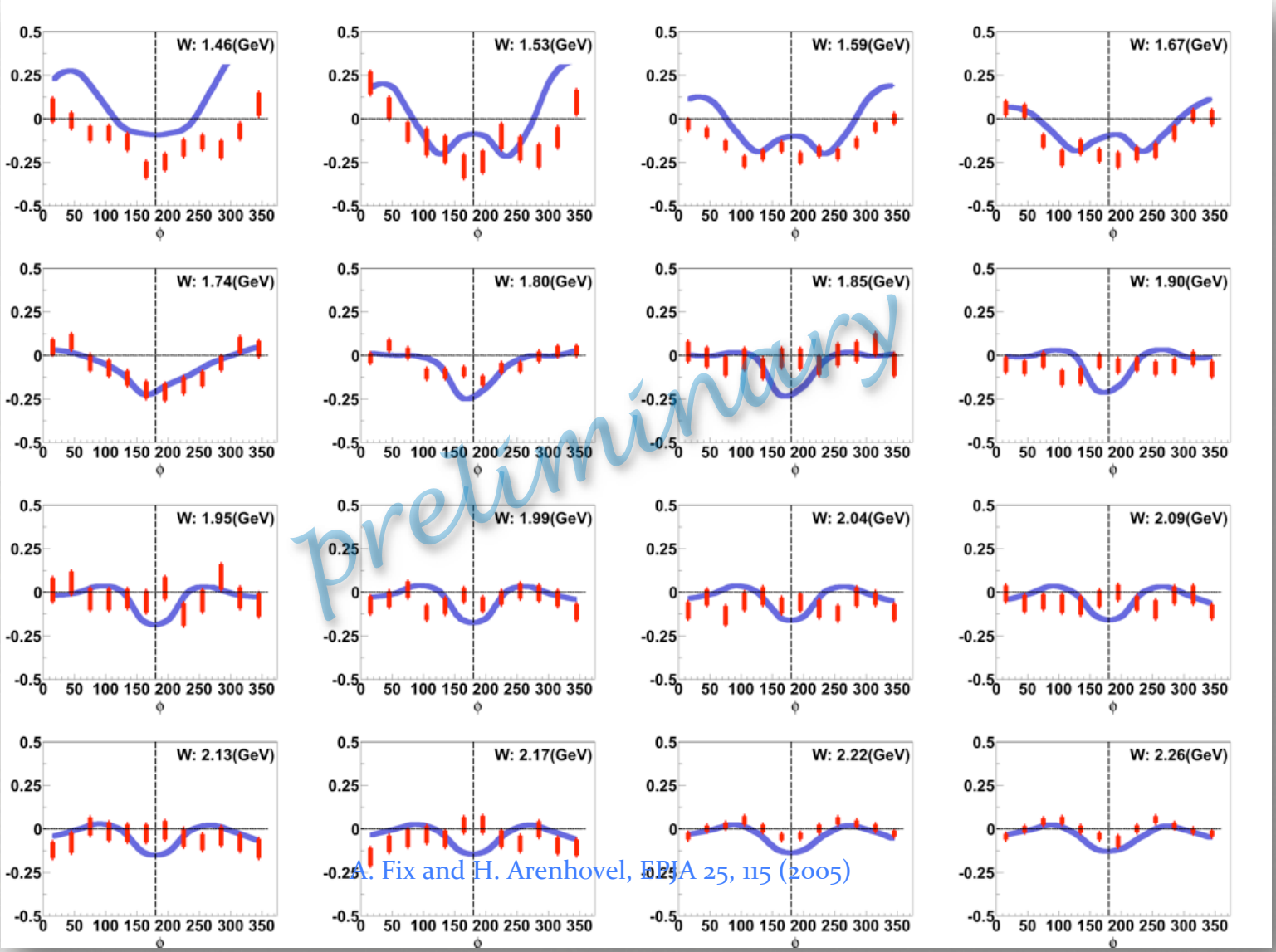


preliminary

A. Fix and H. Arenhovel, EPJA 25, 115 (2005)

Y. Mao

Comparison with model: P^s_z



A. Fix and H. Arenhovel, EPJA 25, 115 (2005)

Y. Mao

Summary 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																
$p\pi^o$	✔	✓	✓	✓	✓	✓	✓	✓								
$n\pi^+$	✔	✓	✓	✓	✓	✓	✓	✓								
$p\eta$	✔	✓	✓	✓	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	✓	✓	✓	✓	✓								
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^o$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{o*}\Sigma^+$	✔	✓	✓	✓	✓	✓	✓	✓								
"Neutron" target																
$p\pi^-$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Sigma^-$	✓	✓	✓		✓	✓	✓	✓								
$K^o\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^o\Sigma^o$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✔ - published ✔ - acquired

Summary

- Data collection with proton and deuteron targets is complete
- "*complete (or nearly complete) measurement*" in pseudoscalar meson photoproduction is in the can
- In many cases these are the first measurements.
- In most cases model predictions do not agree with the data at higher energies
- Phenomenological and theoretical analyses will have to deal with tenths of thousands of data points for various observables in different final states.

Extras

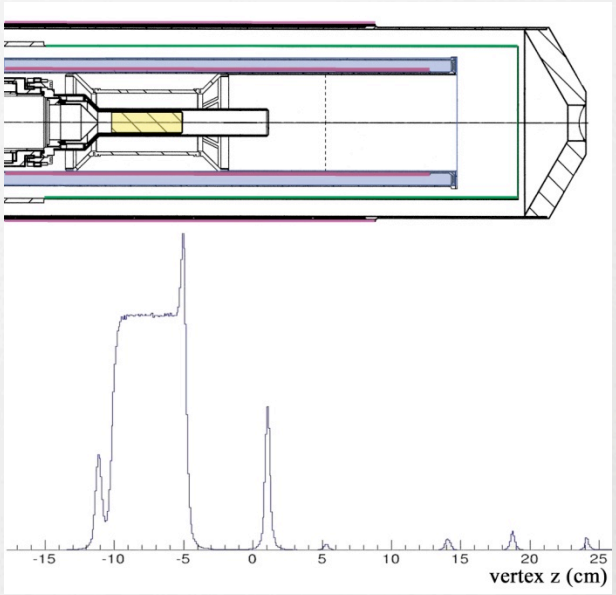
Polarization observables in pseudoscalar meson production

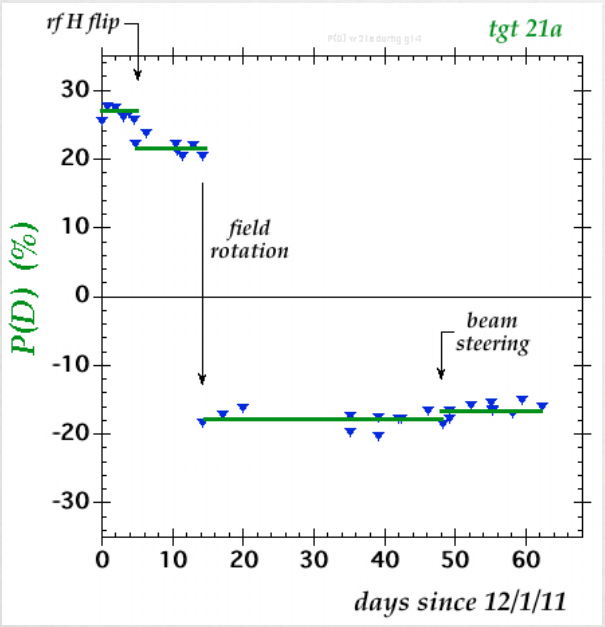
$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{unpol}\{1 - P_\gamma^{lin}\Sigma\cos 2\phi + P_x(P_\gamma^{circ}F + P_\gamma^{lin}H\sin 2\phi) + P_y(T - P_\gamma^{lin}P\cos 2\phi) + P_z(P_\gamma^{circ}E + P_\gamma^{lin}G\sin 2\phi) + \sigma'_x[P_\gamma^{circ}C_x + P_\gamma^{lin}O_x\sin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

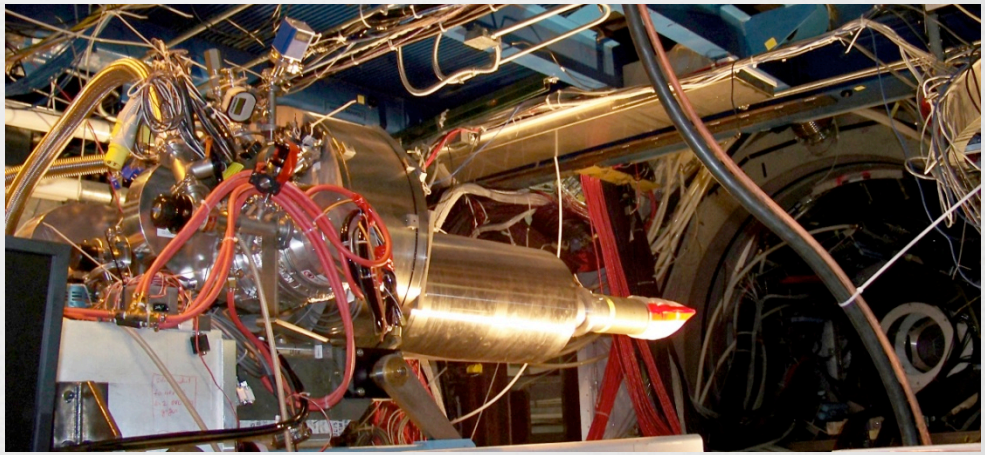
Photon		Target			Recoil			Target + Recoil			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular pol.	0	F	0	$-E$	$-C_{x'}$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

g14 – E06-101: polarized gamma beams on polarized HD

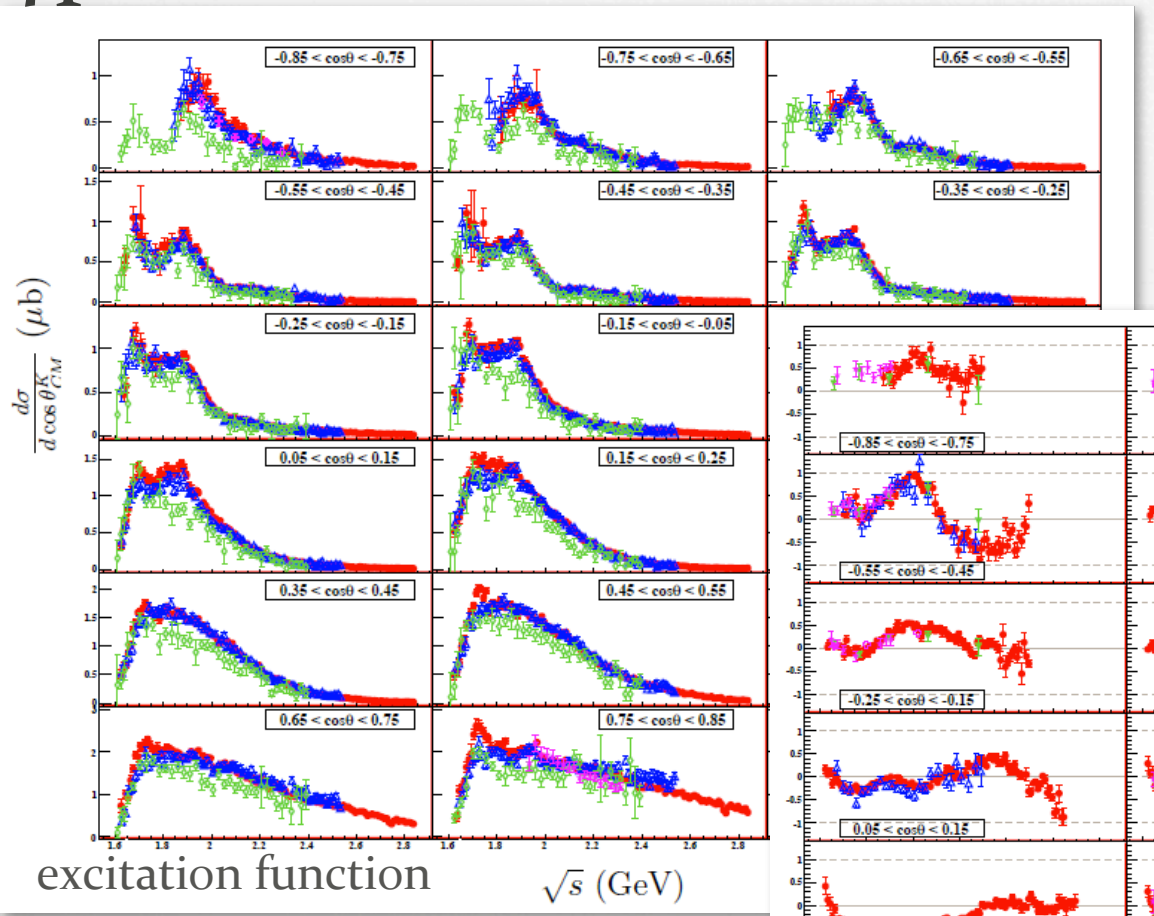
- Circular and Linear polarized photons
- flux up to 10^8 s^{-1} tagged (low bkg)
- Longitudinally polarized solid HD
- P(D) ~ 22%; lifetimes ~ 2 yr
- Nov/11 – May/12: 14 billion triggers





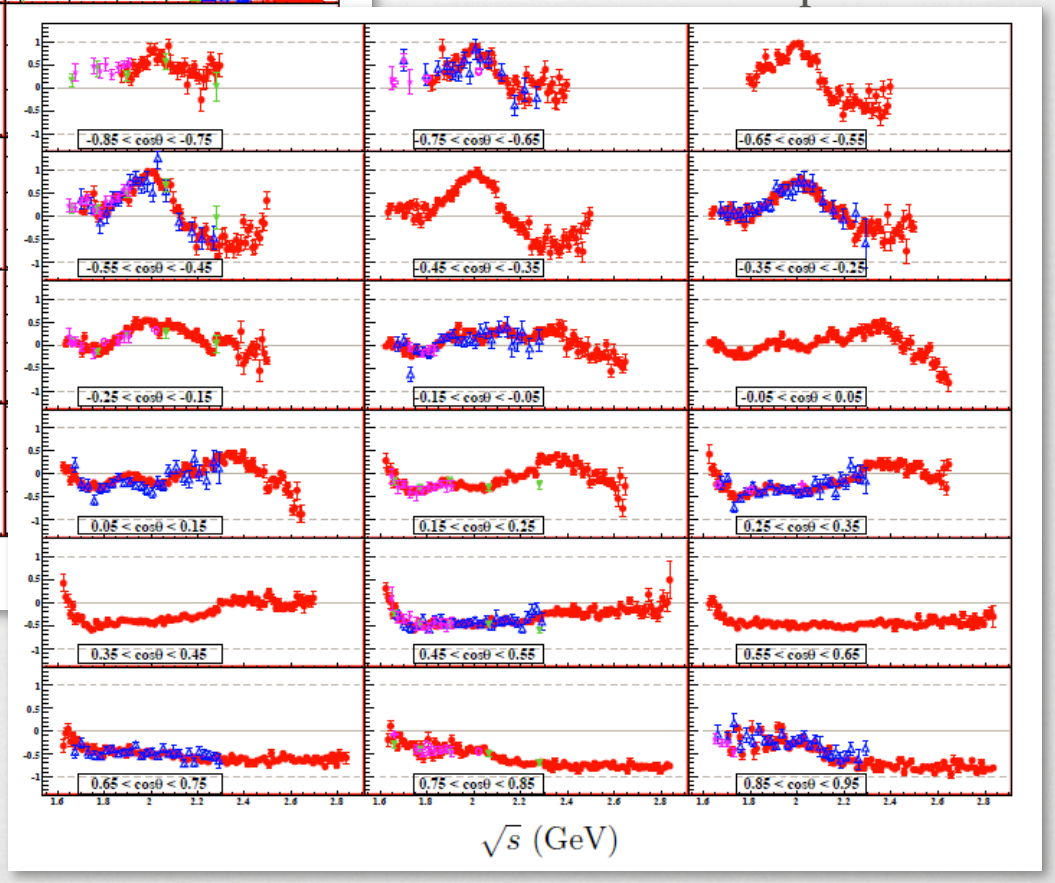


γp→K⁺Λ: cross section and P



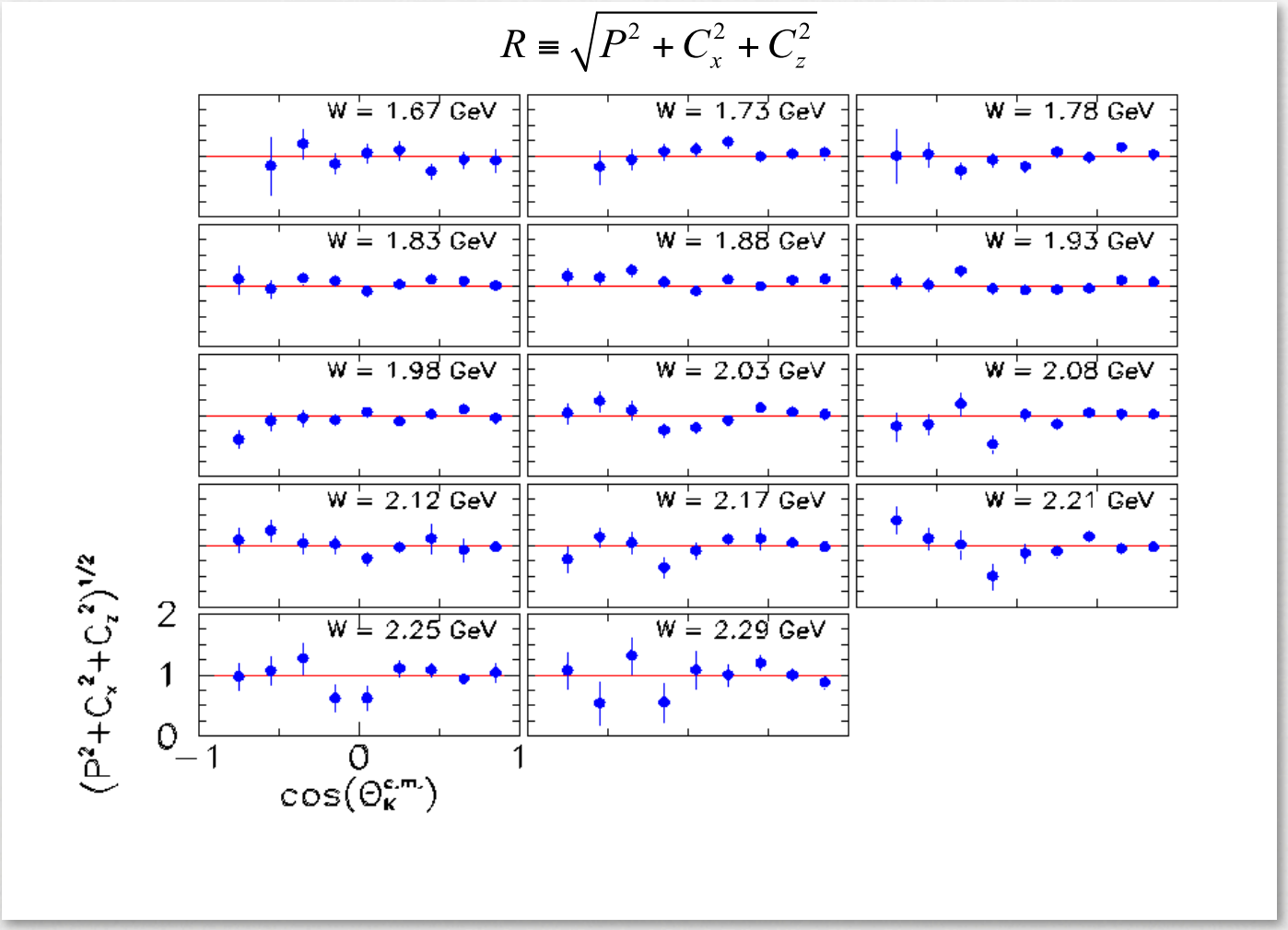
g11: W=1.7 – 2.8 GeV
(unpolarized beam & target)

recoil polarization *P*



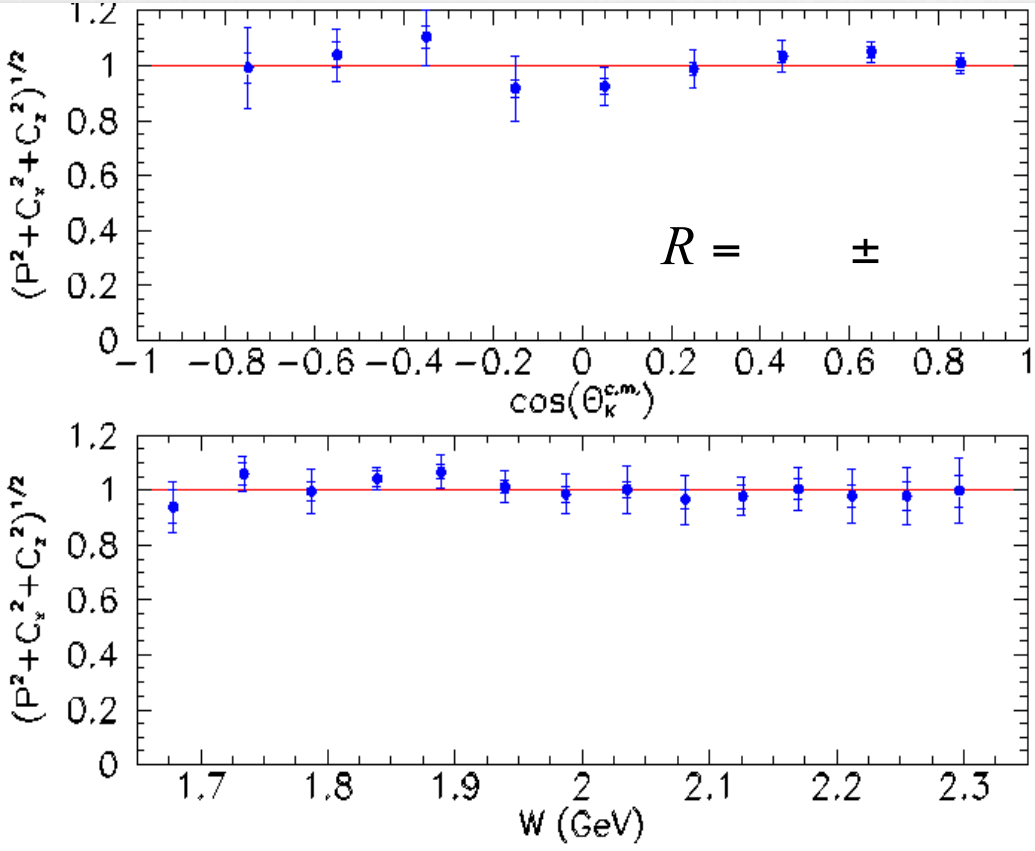
M.E. McCracken et al., PRC 81, 025201 (2010)

R Values for the Λ



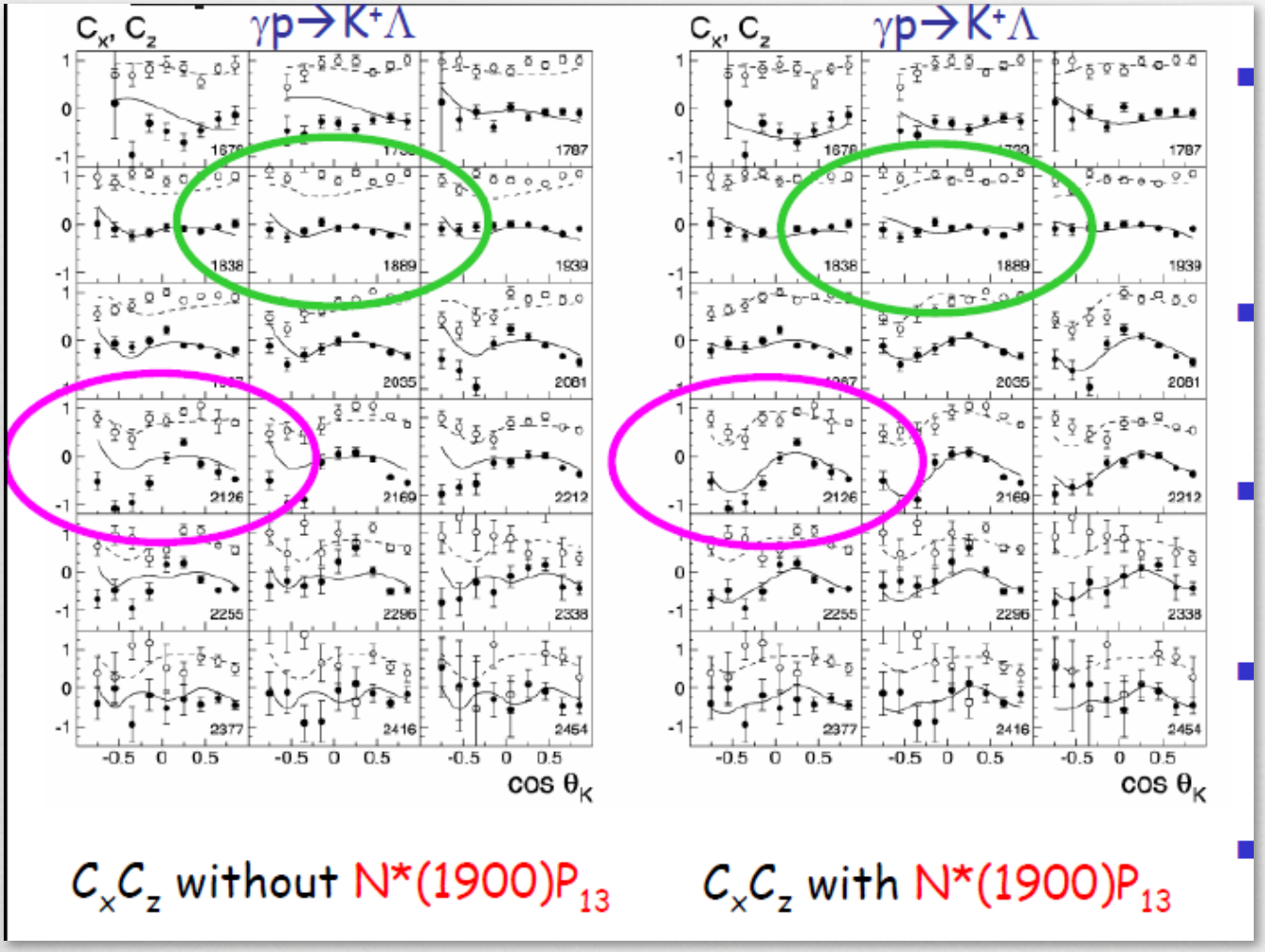
The Λ appears 100% polarized when created with a fully polarized beam.

Average R values



- Energy and angle averages are consistent with unity.
- No model predicted this CLAS result.

$\gamma p \rightarrow K^+\Lambda$: Cx/Cz

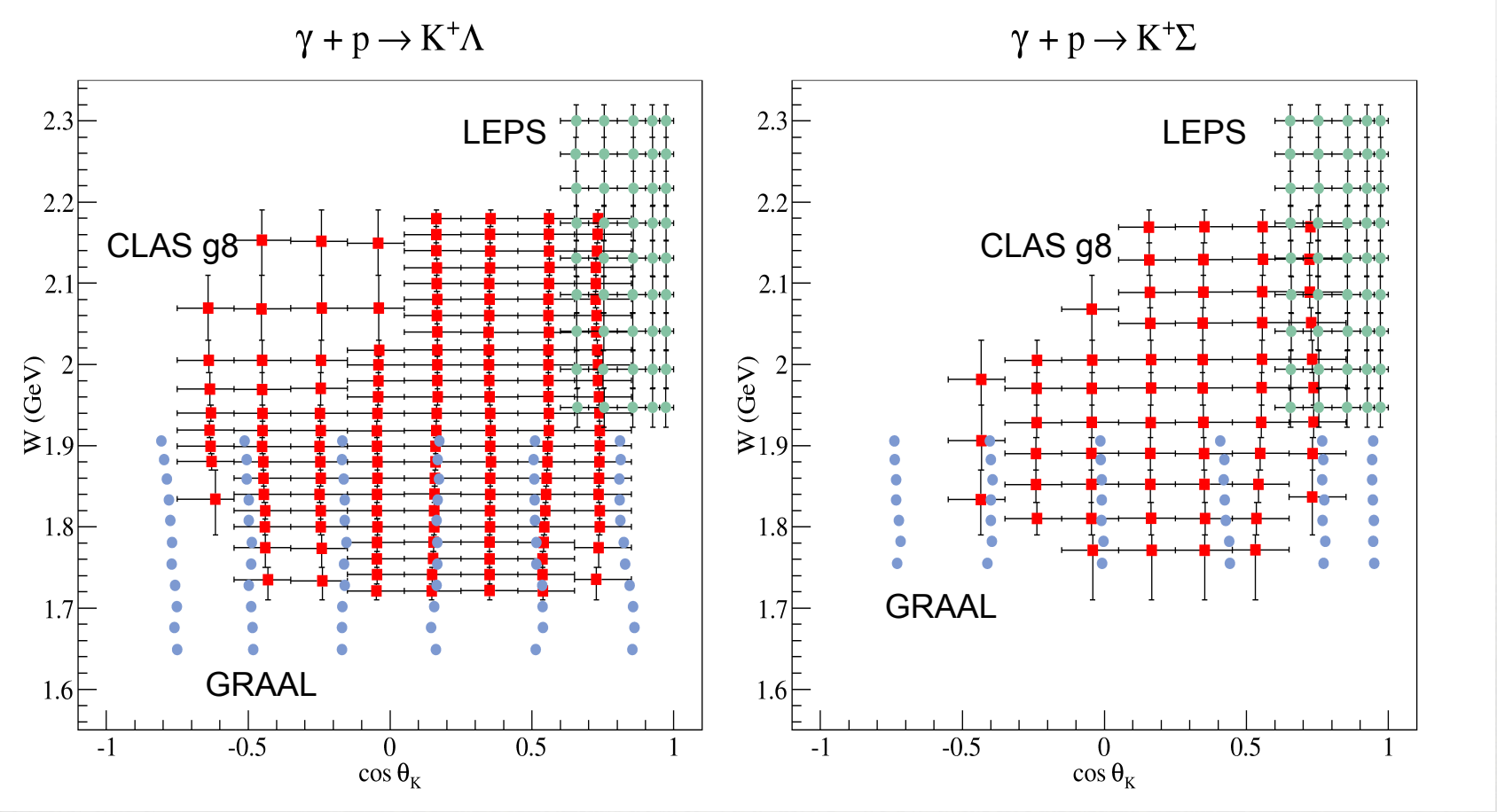


Bradford et al. PRC 75, 035205 (2007),

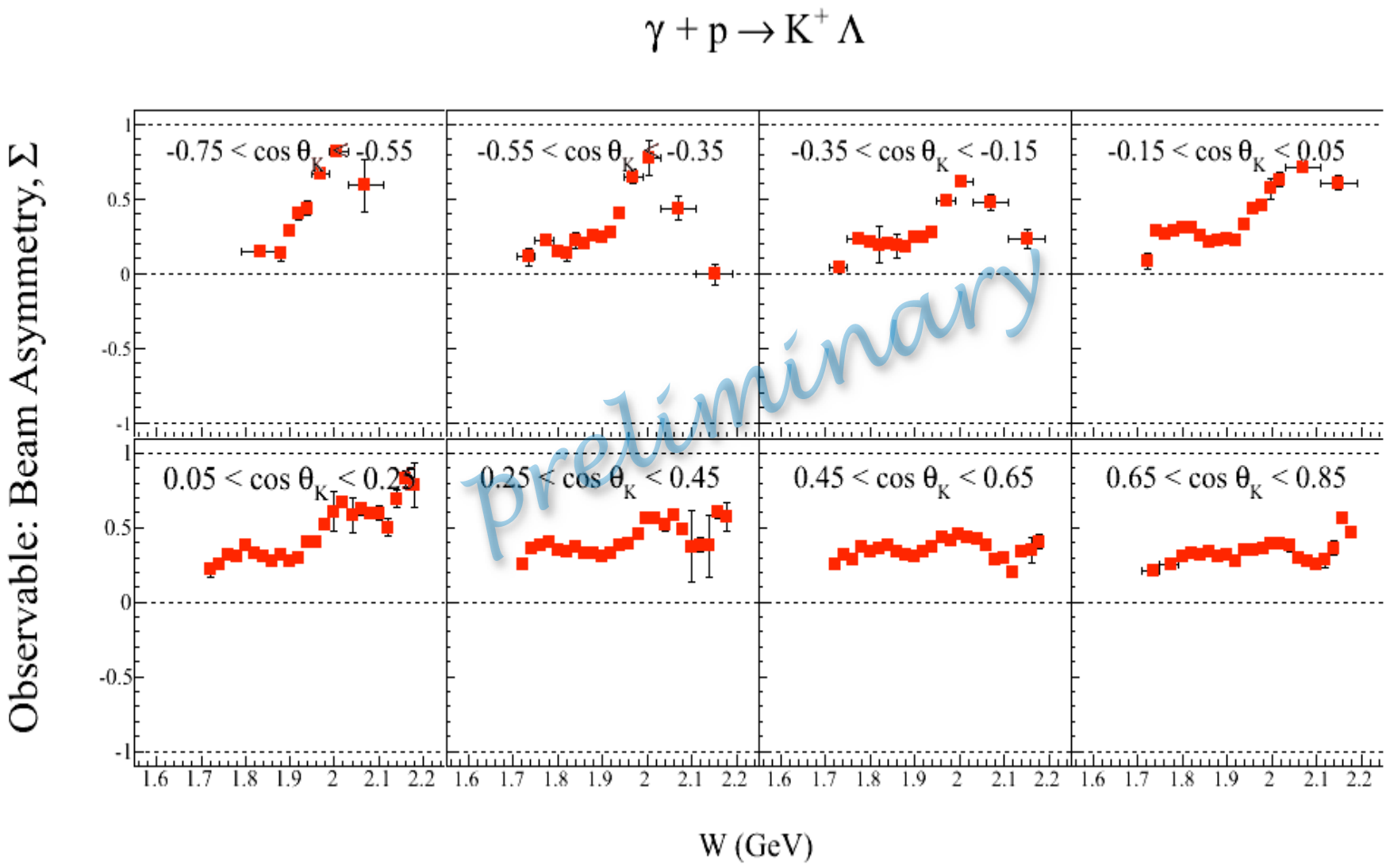
Comparison with other measurements

Experiment	Final State	W range	Σ	P	T	Ox	Oz
CLAS g11	KΛ	1.62 – 2.84	N	Y	N	N	N
	KΣ	1.69 – 2.84	N	Y	N	N	N
LEPS	KΛ	1.94 – 2.30	Y	N	N	N	N
	KΣ	1.94 – 2.30	Y	N	N	N	N
GRAAL	KΛ	1.64 – 1.92	Y	Y	Y	Y	Y
	KΣ	1.74 – 1.92	Y	Y	N	N	N
CLAS g8	KΛ	1.71 – 2.19	Y	Y	Y	Y	Y
	KΣ	1.75 – 2.19	Y	Y	Y	Y	Y

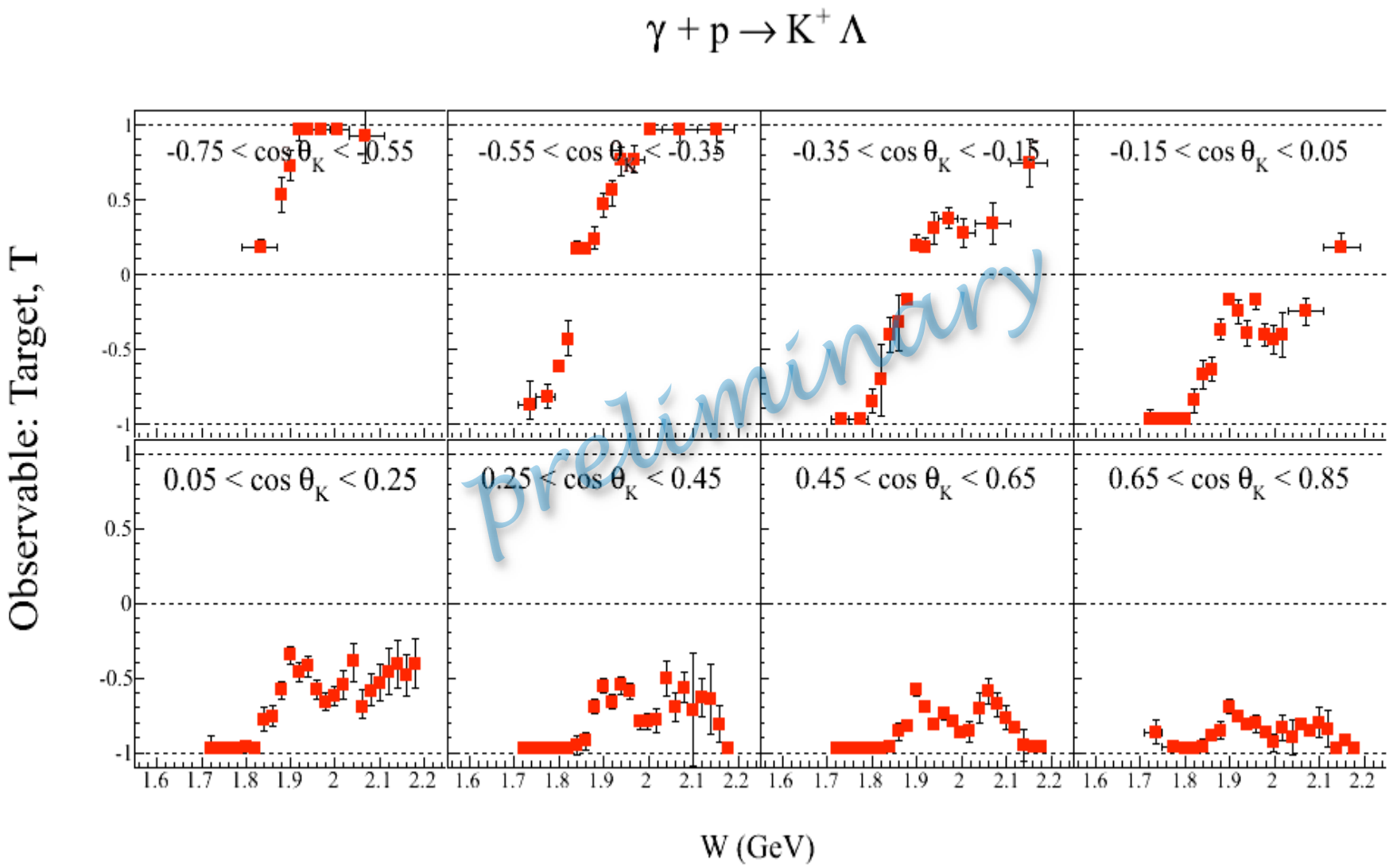
Comparison with other measurements



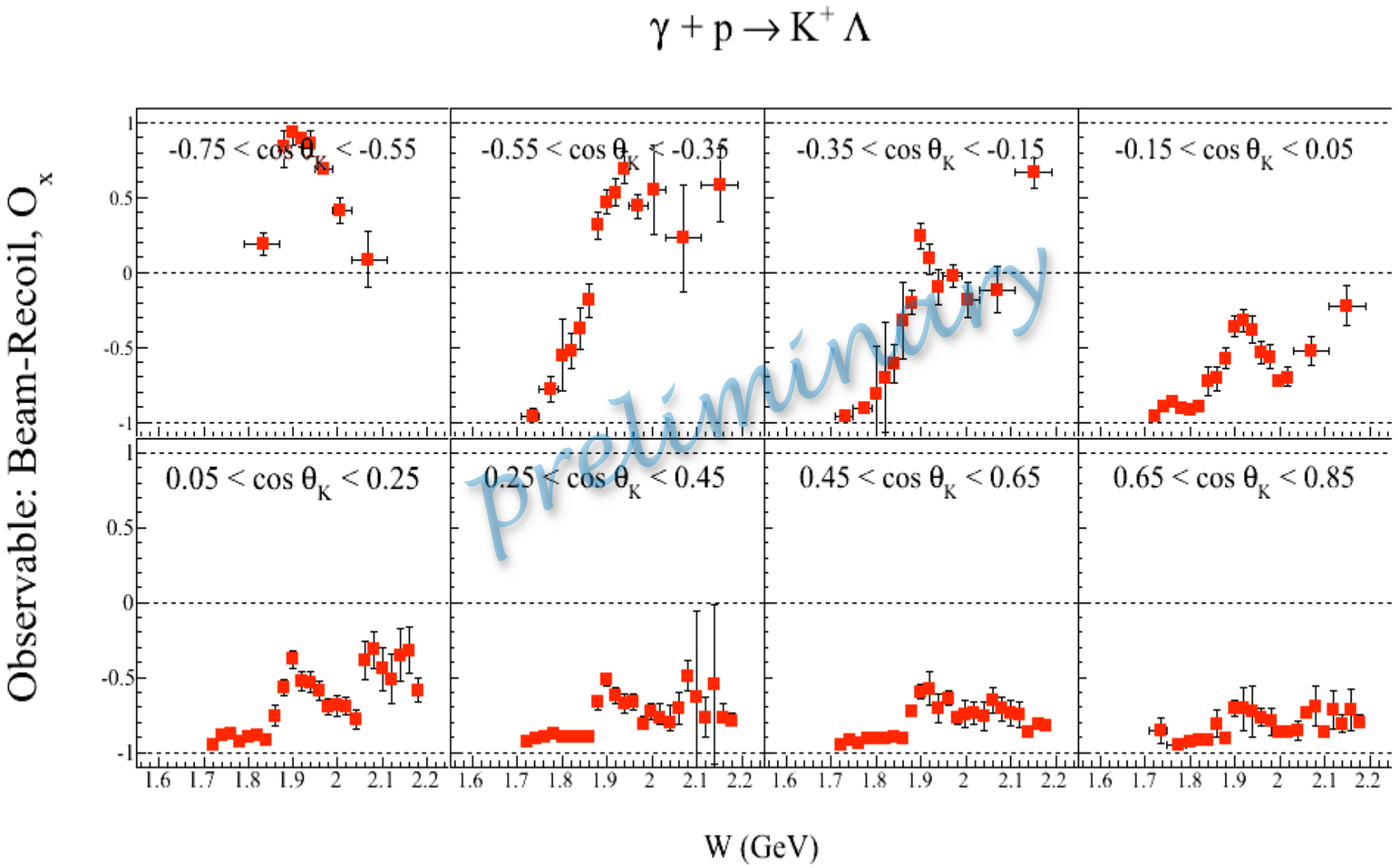
Beam Asymmetry



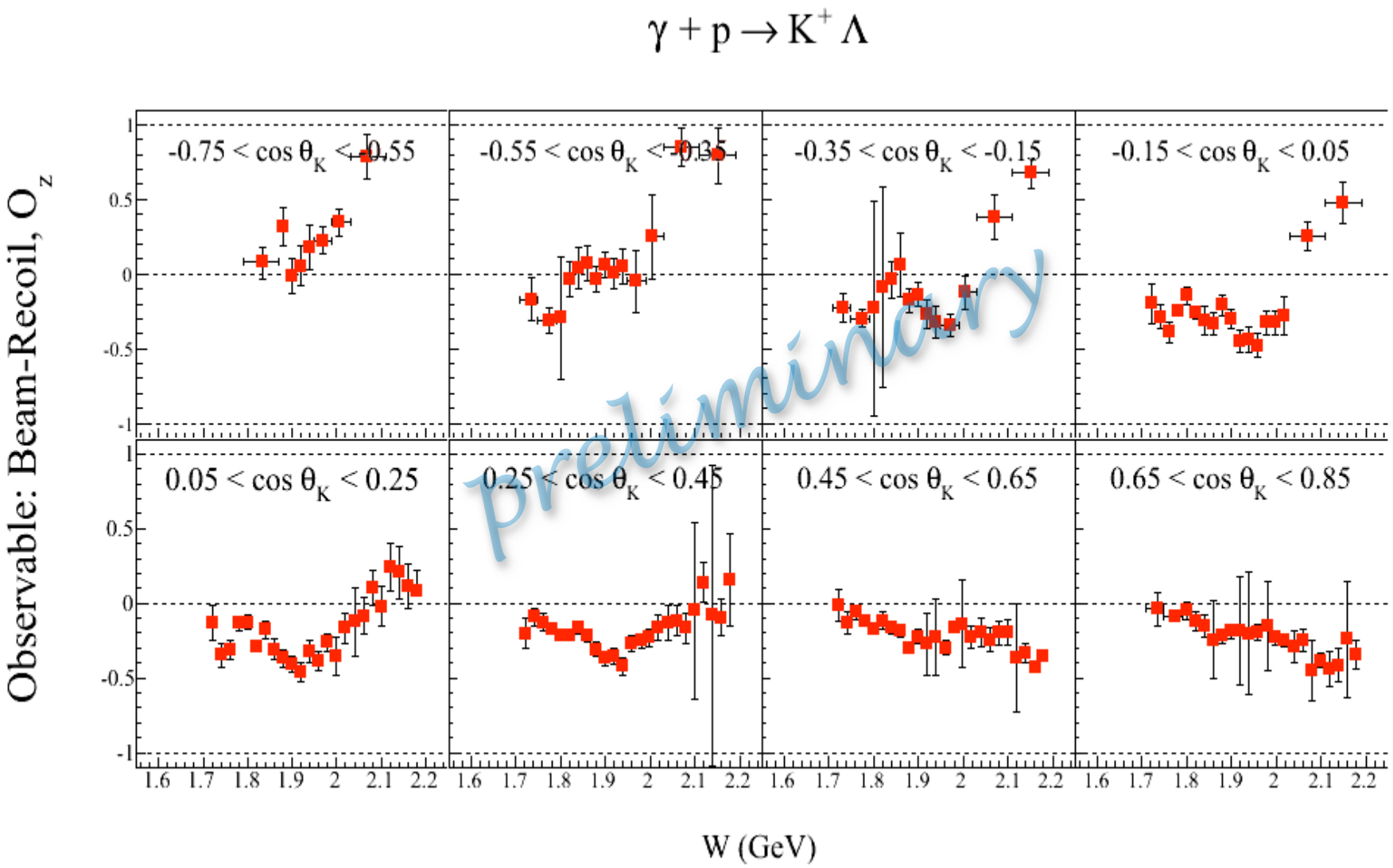
Target Asymmetry



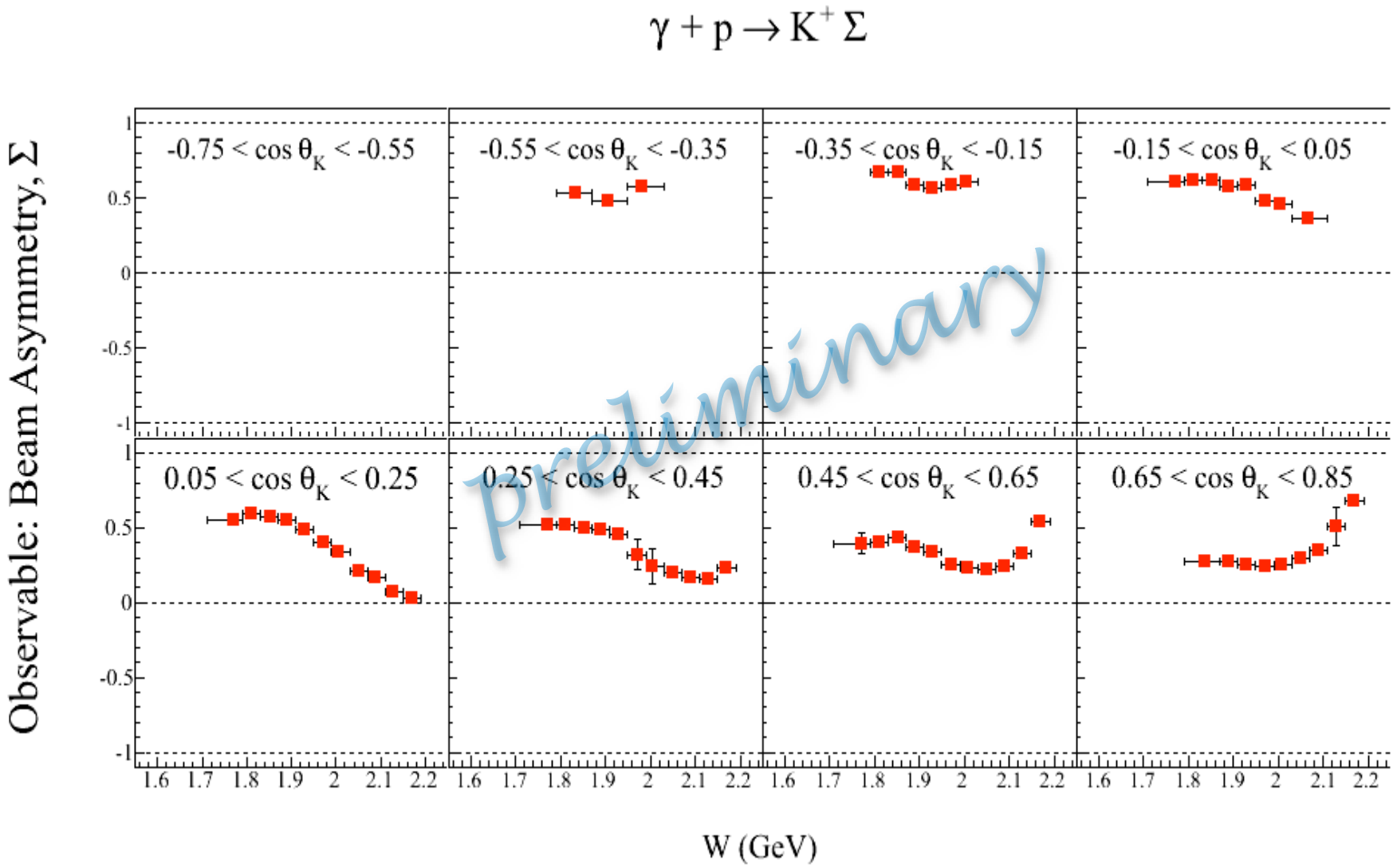
Beam-Recoil, Ox



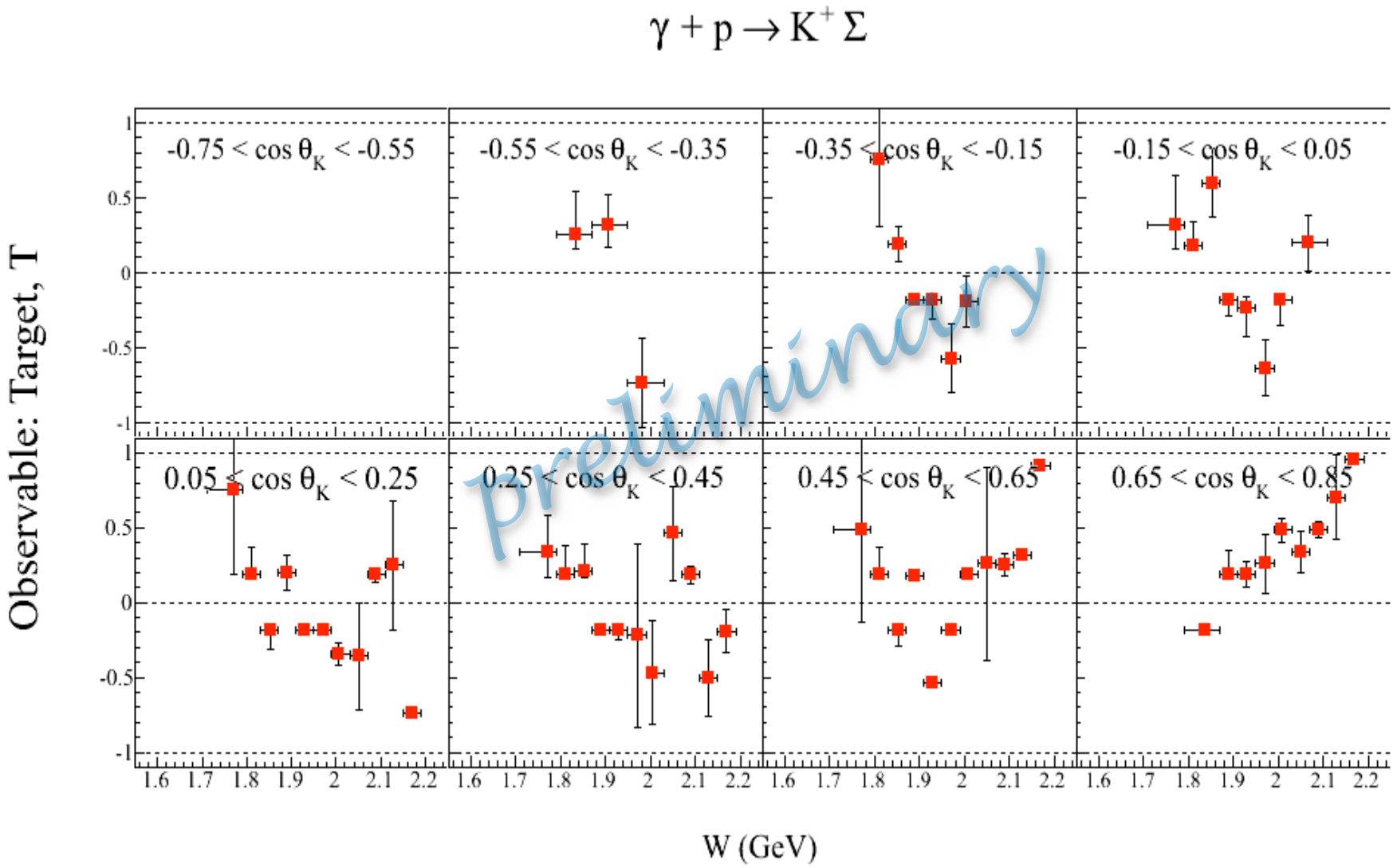
Beam-Recoil, Oz



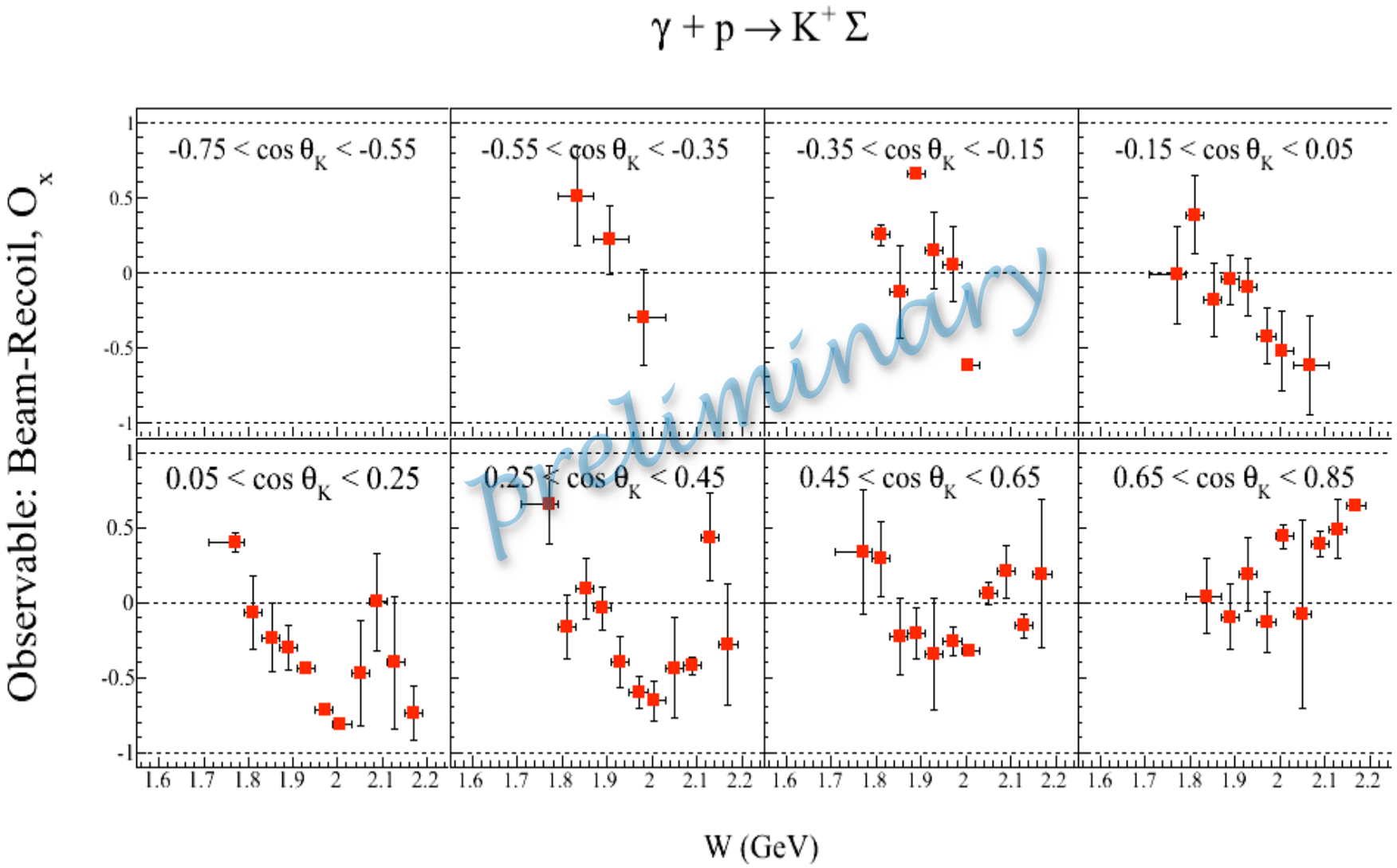
Beam Asymmetry



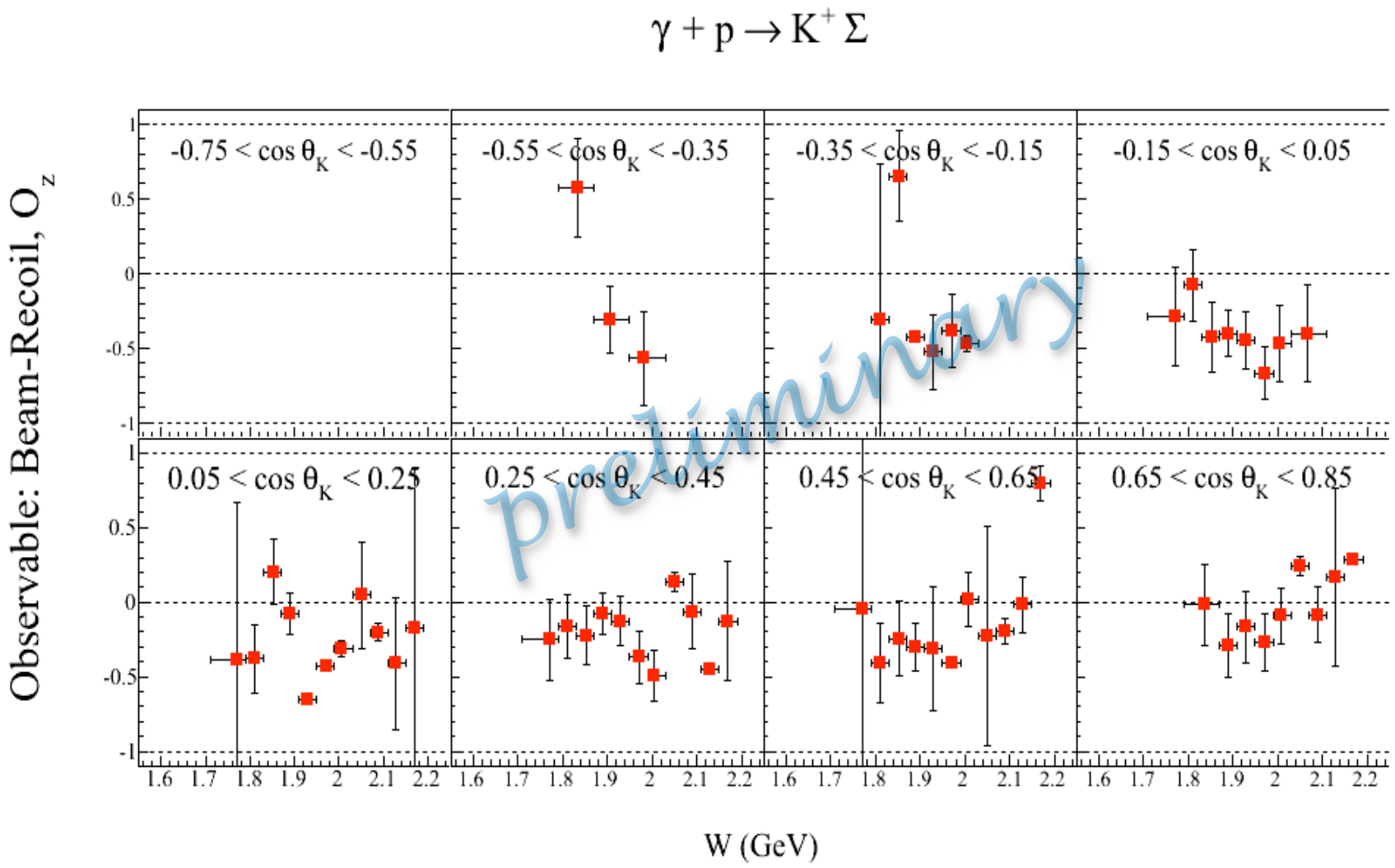
Target Asymmetry

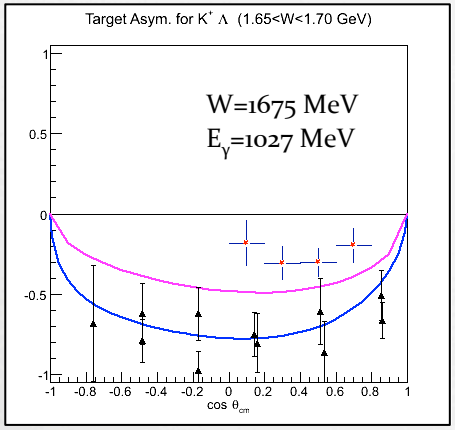


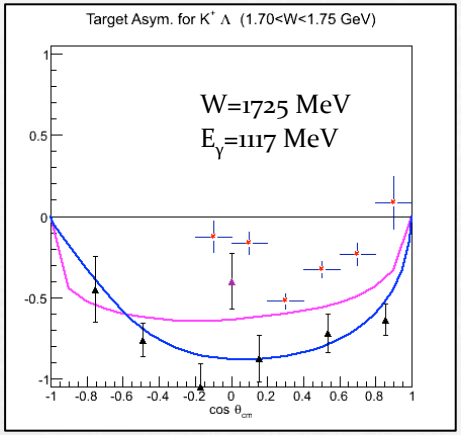
Beam-Recoil, Ox

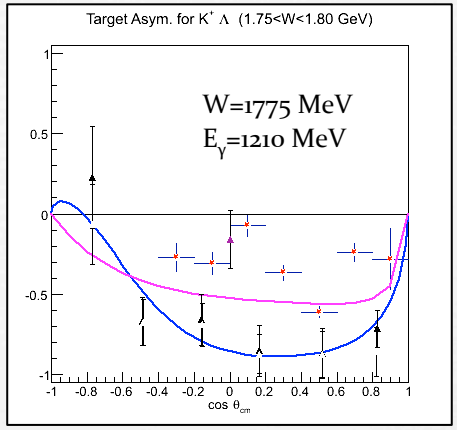


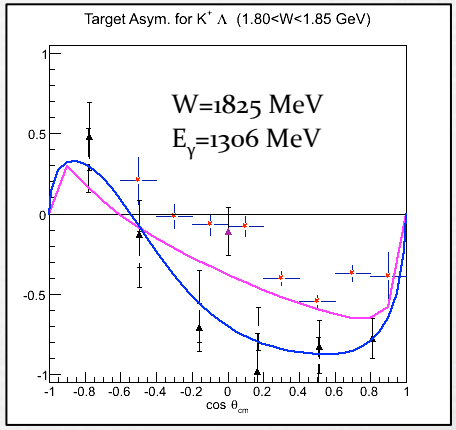
Beam-Recoil, Oz

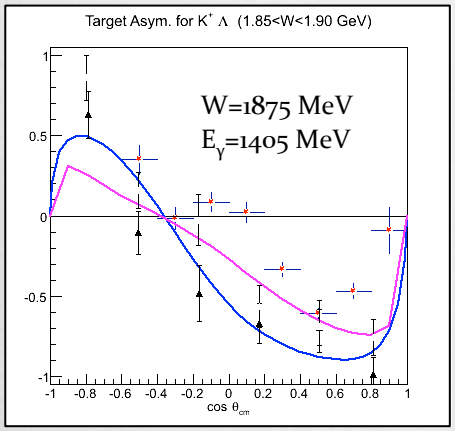


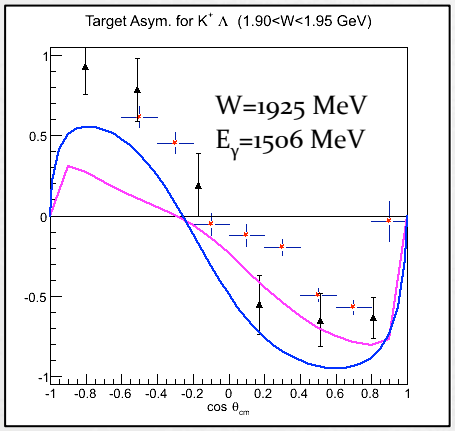

Target Asym. for K⁺ Λ (1.65<W<1.70 GeV)
W=1675 MeV
Eγ=1027 MeV
cos θcm

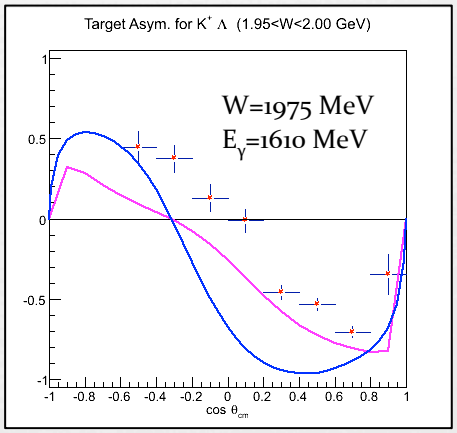

Target Asym. for K⁺ Λ (1.70<W<1.75 GeV)
W=1725 MeV
Eγ=1117 MeV
cos θcm

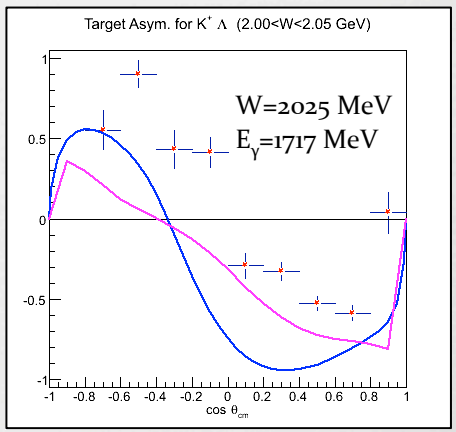

Target Asym. for K⁺ Λ (1.75<W<1.80 GeV)
W=1775 MeV
Eγ=1210 MeV
cos θcm

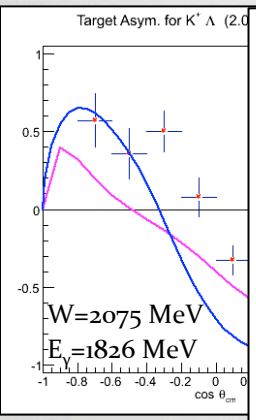

Target Asym. for K⁺ Λ (1.80<W<1.85 GeV)
W=1825 MeV
Eγ=1306 MeV
cos θcm

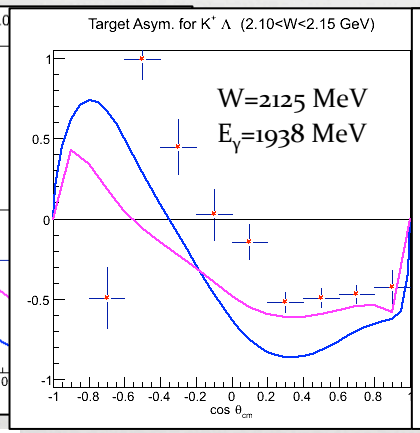

Target Asym. for K⁺ Λ (1.85<W<1.90 GeV)
W=1875 MeV
Eγ=1405 MeV
cos θcm

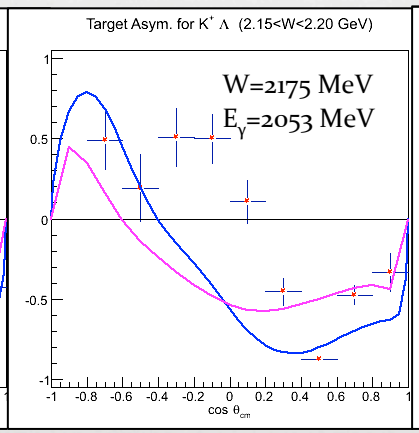

Target Asym. for K⁺ Λ (1.90<W<1.95 GeV)
W=1925 MeV
Eγ=1506 MeV
cos θcm

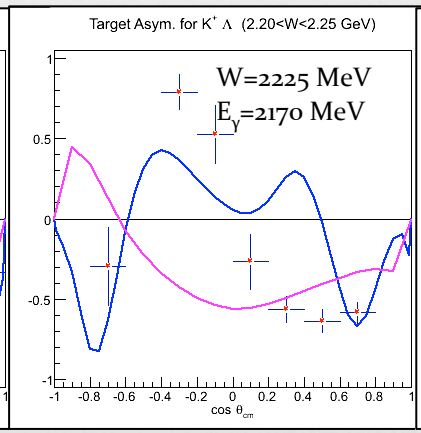

Target Asym. for K⁺ Λ (1.95<W<2.00 GeV)
W=1975 MeV
Eγ=1610 MeV
cos θcm

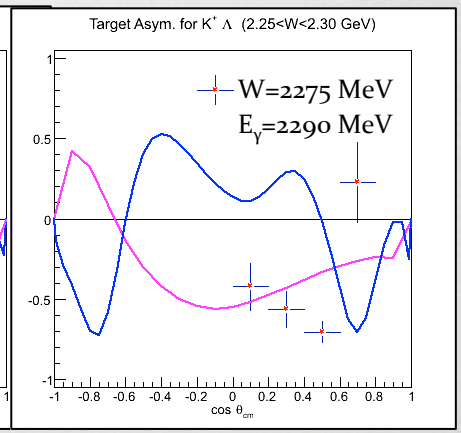

Target Asym. for K⁺ Λ (2.00<W<2.05 GeV)
W=2025 MeV
Eγ=1717 MeV
cos θcm


Target Asym. for K⁺ Λ (2.0
W=2075 MeV
Eγ=1826 MeV
cos θcm


Target Asym. for K⁺ Λ (2.10<W<2.15 GeV)
W=2125 MeV
Eγ=1938 MeV
cos θcm

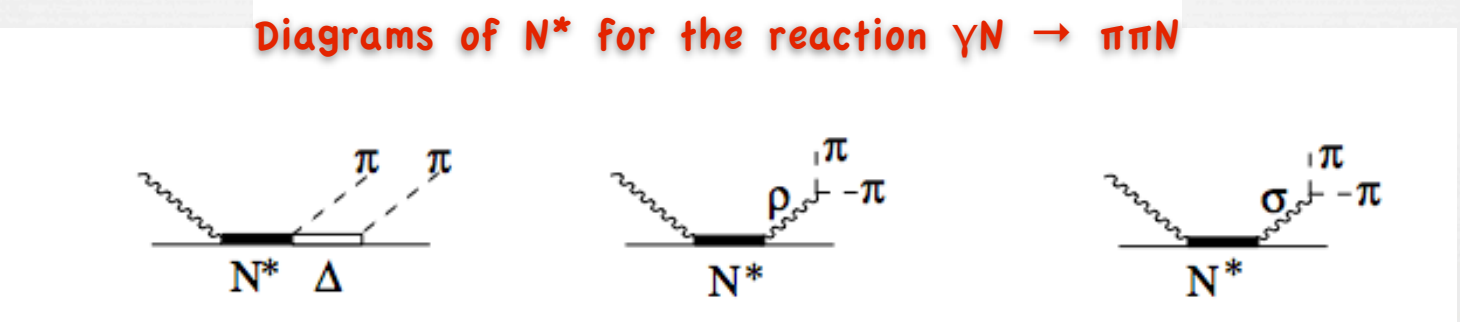

Target Asym. for K⁺ Λ (2.15<W<2.20 GeV)
W=2175 MeV
Eγ=2053 MeV
cos θcm


Target Asym. for K⁺ Λ (2.20<W<2.25 GeV)
W=2225 MeV
Eγ=2170 MeV
cos θcm


Target Asym. for K⁺ Λ (2.25<W<2.30 GeV)
W=2275 MeV
Eγ=2290 MeV
cos θcm

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_{\odot} (\mathbf{I}^{\odot} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\odot}) + \delta_l [\sin 2\beta (\mathbf{I}^{\mathbf{s}} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\mathbf{s}}) + \cos 2\beta (\mathbf{I}^{\mathbf{c}} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^{\mathbf{c}})] \}$$

Model of effective Lagrangian approach



A. Fix and H. Arenhovel, Eur.Phys.J. **A25** (2005) 115, nucl-th/0503042.

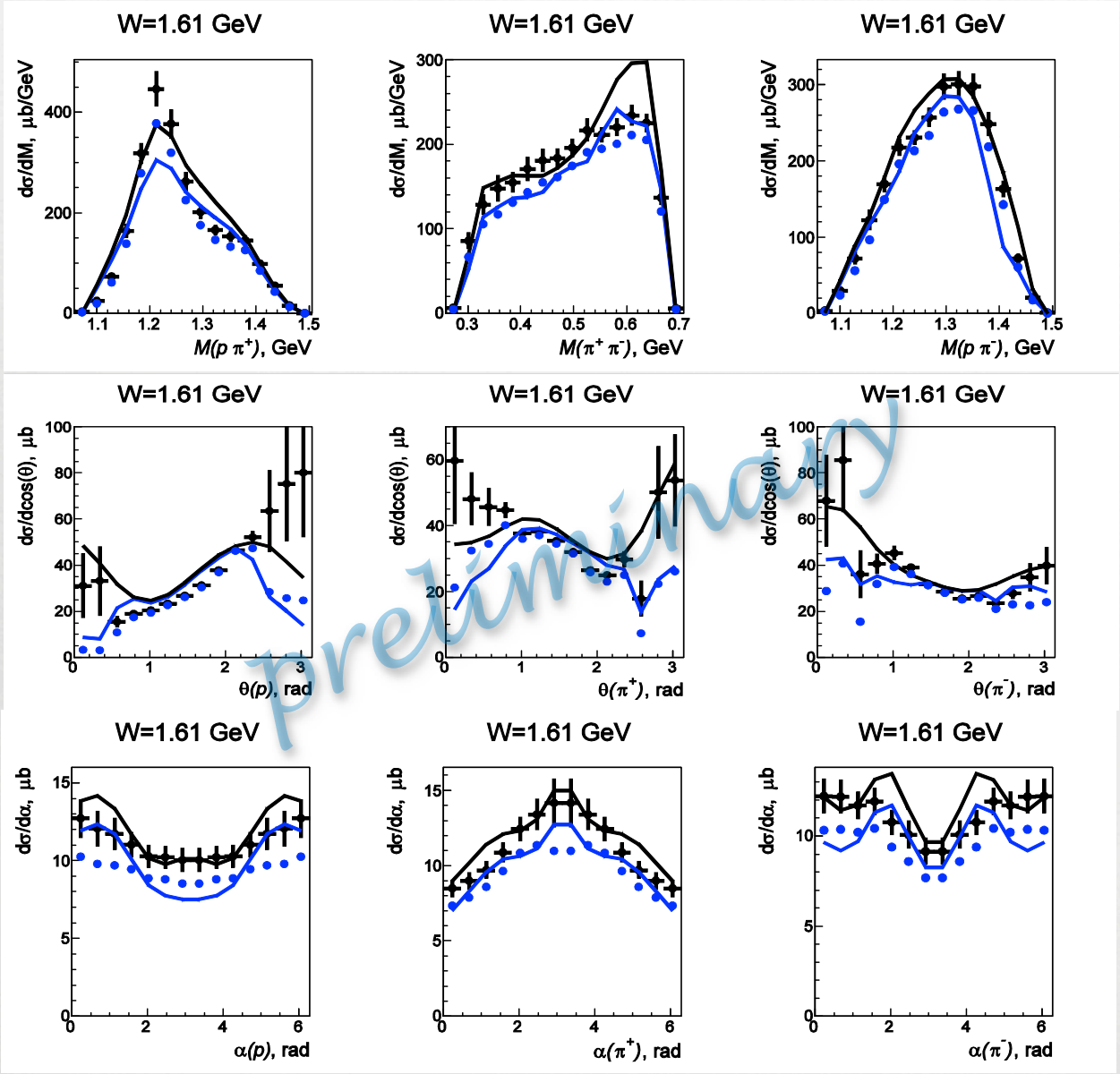
Other decays:
- N-Born terms
- Δ-Born terms

About the model:

- Calculates diff-cross section by using transition amplitudes
- Amplitudes are determined by all the double-pion diagrams
- The diagrams above show the decay from N^* resonances.
- Include resonances:

$P_{33}(1232)$	$S_{11}(1535)$	$F_{15}(1680)$
$P_{11}(1440)$	$S_{31}(1620)$	$D_{33}(1700)$
$D_{13}(1520)$	$D_{15}(1675)$	$P_{13}(1720)$

Differential cross sections for $\gamma p \rightarrow p\pi^+\pi^-$



Blues dots:
Measured cross sections within the CLAS acceptance.

Blue line:
JM model* prediction within the CLAS acceptance.

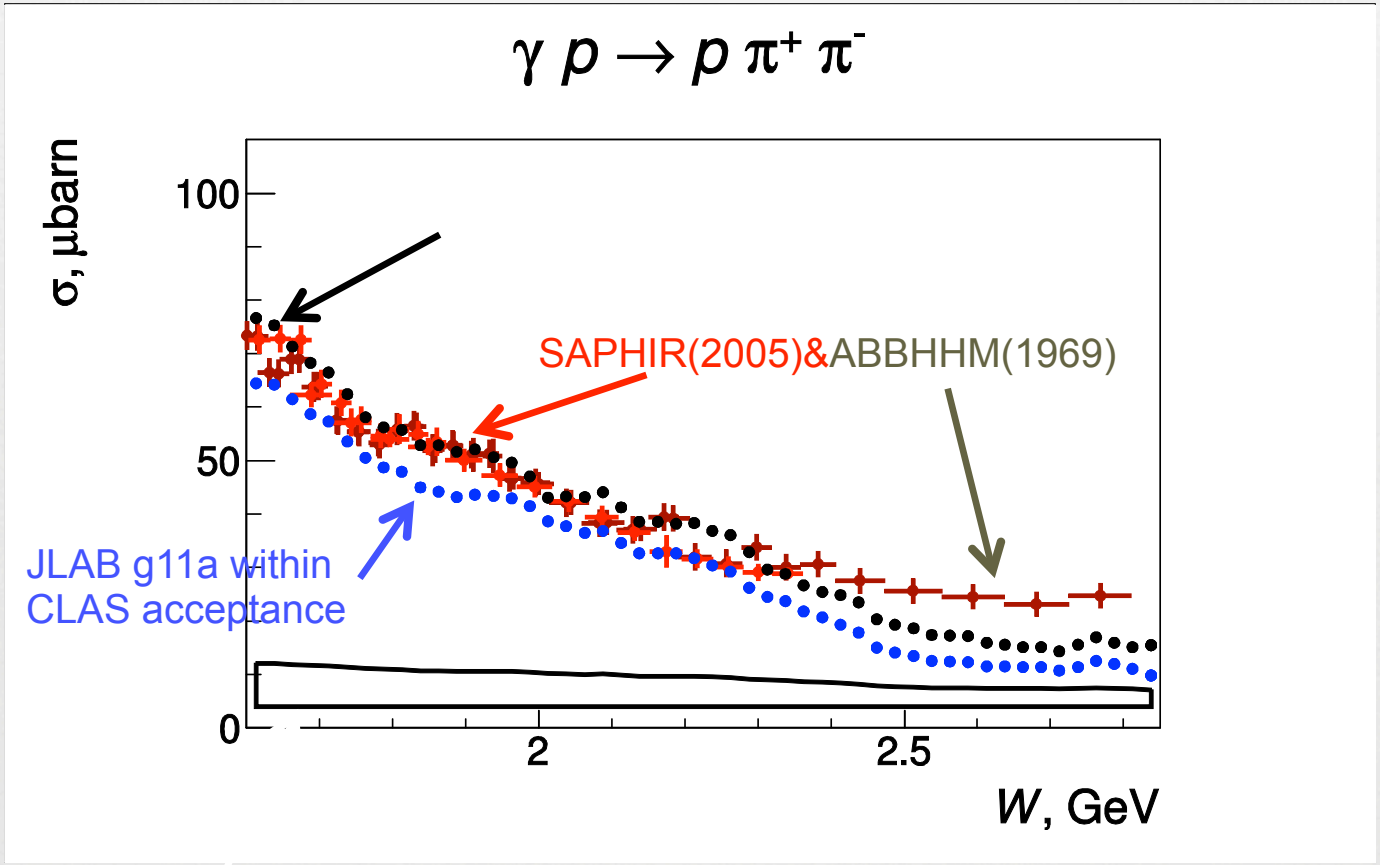
Black line:
JM model results for 100% acceptance.

Black dots:
Estimated cross sections when the contribution from inefficient area was obtained employing phase space approximation.

*Mokeev et al.
PRC 80 (2009) 045212

Integrated cross sections for $\gamma p \rightarrow p \pi^+ \pi^-$

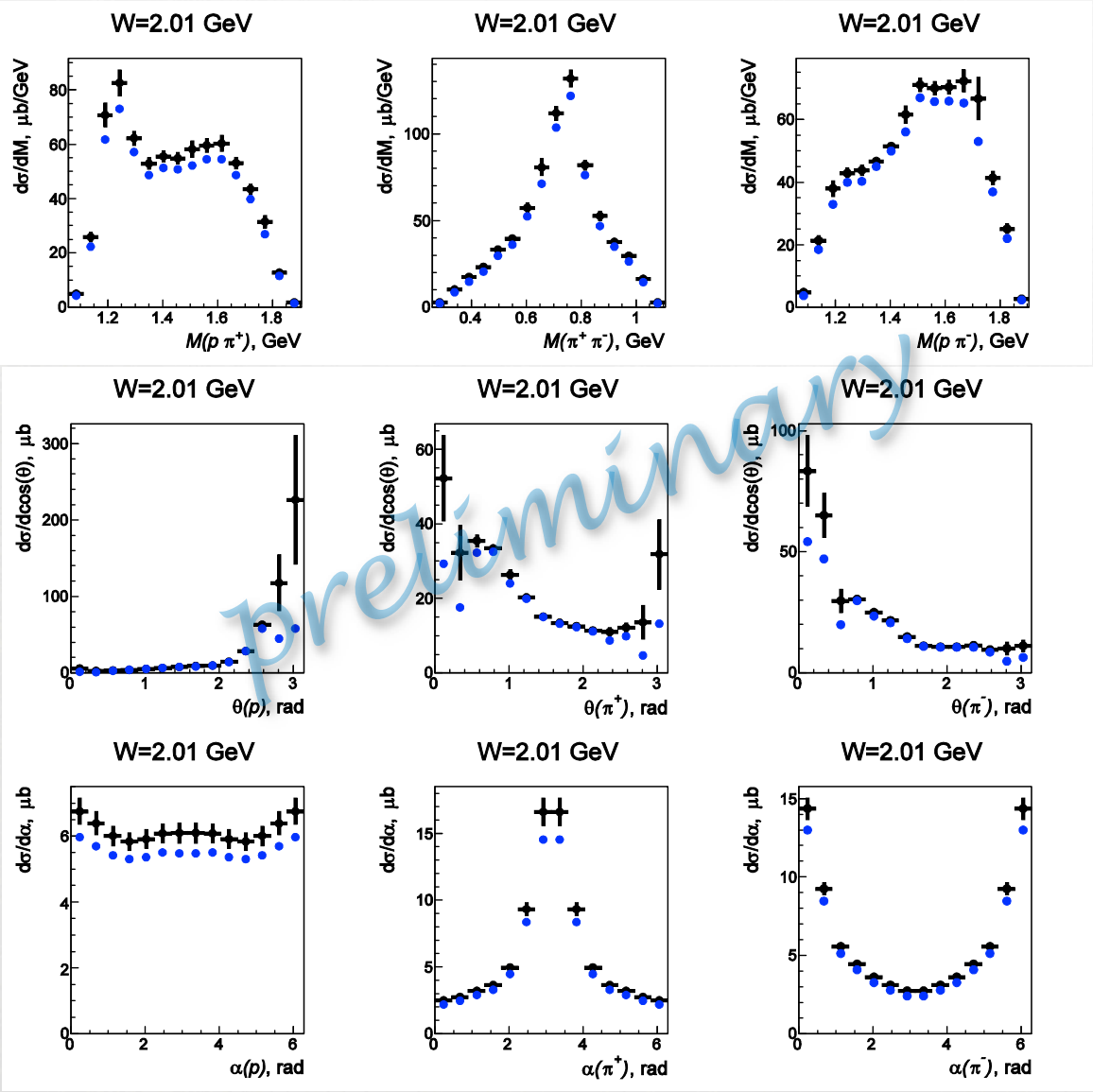
Preliminary results: integrated cross section at W from 1.6 to 2.8 GeV



Systematic errors from accept.
corr. procedure ~8-20%

E .Golovach

Differential cross sections for $\gamma p \rightarrow p\pi^+\pi^-$

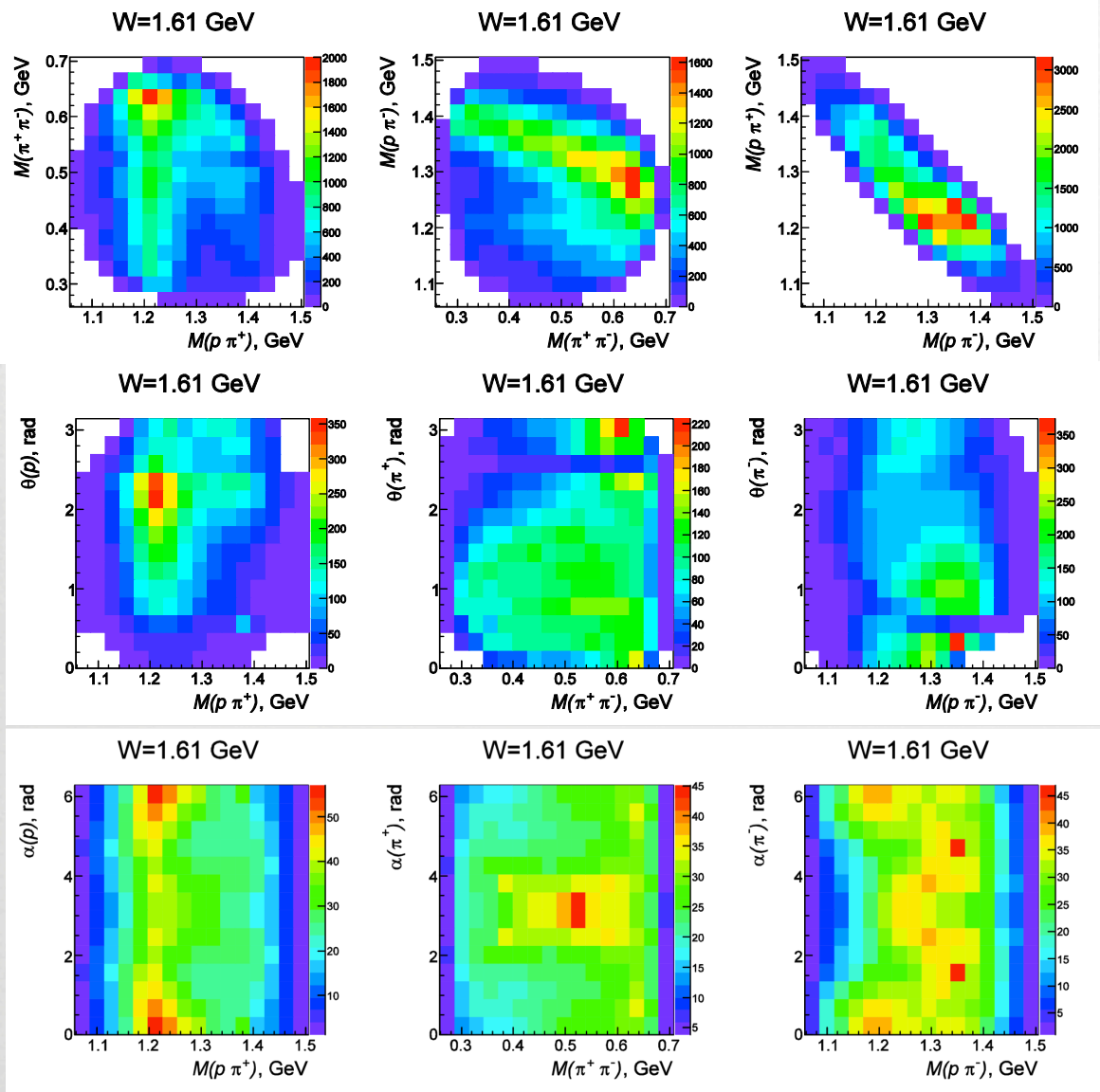


Blues dots:
Measured cross sections within the CLAS acceptance.

Black dots:
Estimated cross sections when the contribution from inefficient area was obtained employing phase space approximation.

E .Golovach

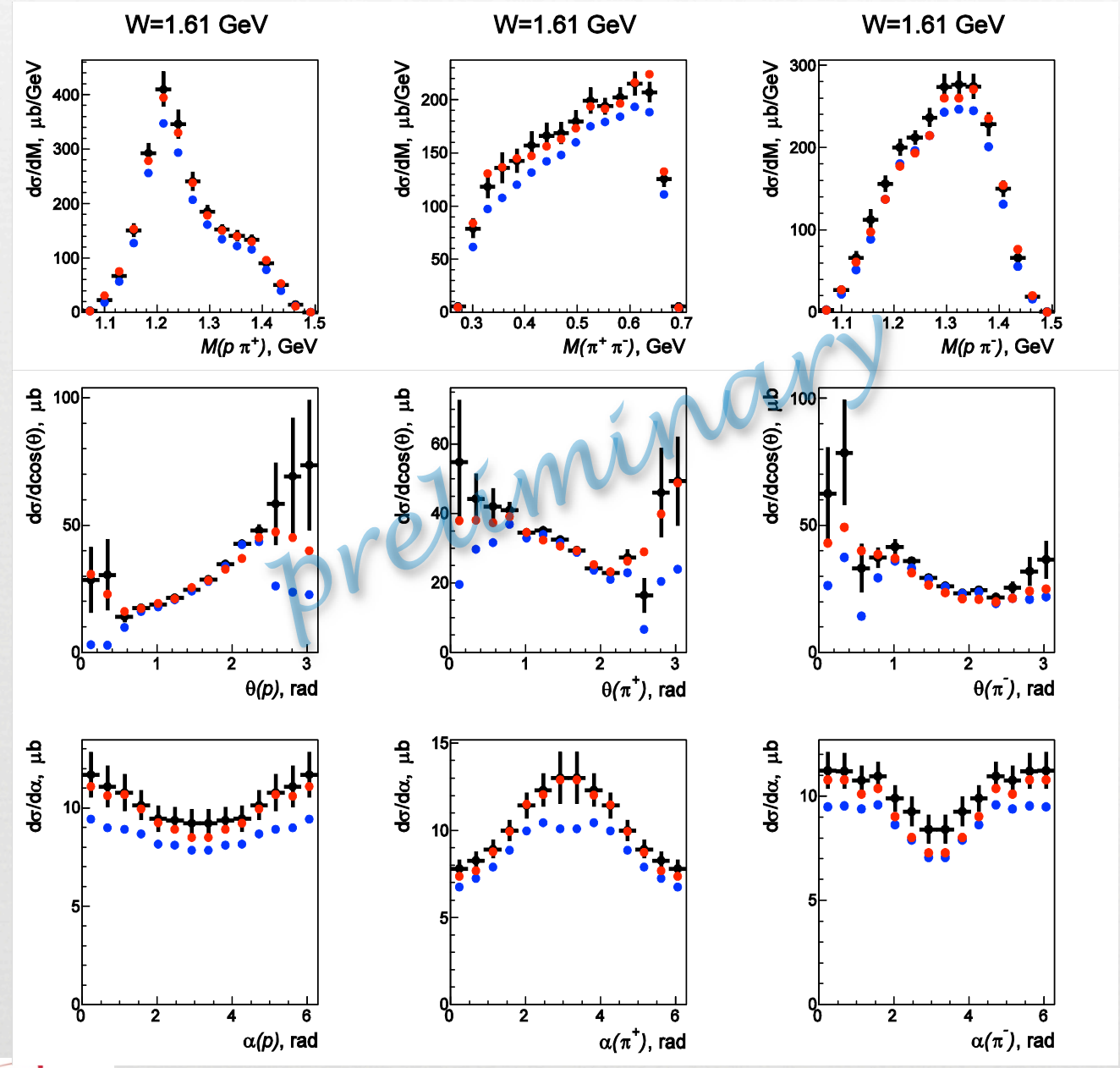
Examples of 2-fold differential g p → p π⁺π⁻ π⁺π⁻ cross sections



2-fold cross sections within the CLAS acceptance.

Nine one-fold and 18 two-fold differential cross sections have become available for the first time in W-bins of 25 MeV width.

One-fold differential g p → p [illegible] cross sections



Blue dots: experimental data within the CLAS acceptance

accounting for the contributions from inefficient areas employing phase space approximation

Red dots: extrapolating cross sections into inefficient areas within the framework of the JM model

Two approaches for cross section extrapolation provided close results