The Study of Excited Baryon Resonances

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Tallahassee, FL

Excited QCD 2010

Tatra National Park (Slovakia), 02/03/2010

Outline

Outline

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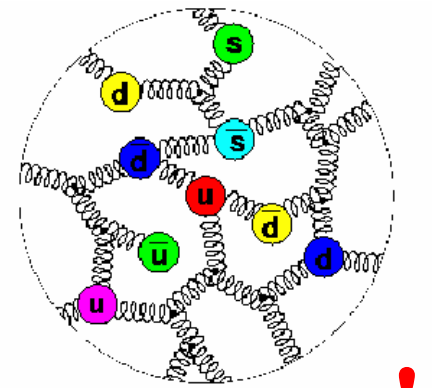
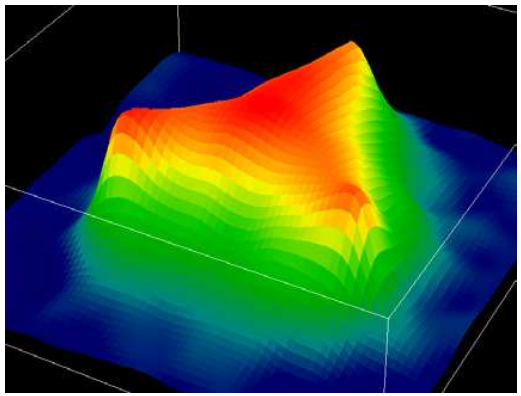
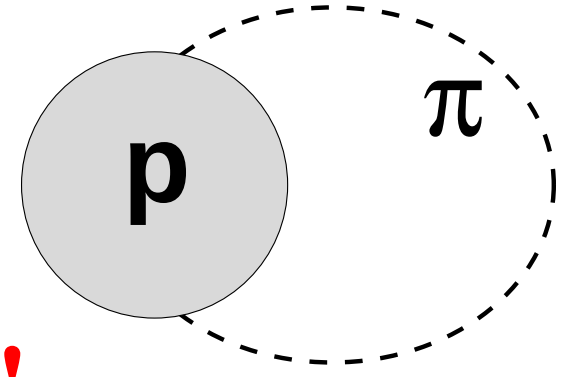
$\ll 0.1$fm | $0.1 - 1.0$ fm | > 1.0 fm







pQCD
q, g, qq̄

? ! ↔ ? !

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?

The Excited Baryon Program at Jefferson Lab

The excited baryon program has two main components:

- Establish the systematics of the spectrum
  - ➜ Provides information on the nature of effective degrees of freedom in strong QCD
- Probe resonance transitions at different distance scales (electron beams are ideal to measure transition form factors)
  - ➜ Provides information on the confining forces of the 3-quark system

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

Search for *missing* or yet unobserved resonances

Quark models predict many more baryons than have been observed

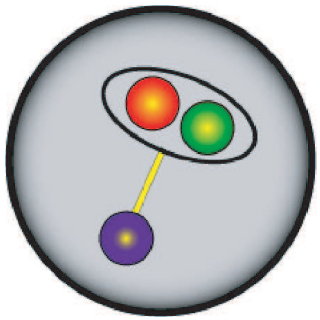
	****	***	**	*
N Spectrum	11	3	6	2
Δ Spectrum	7	3	6	6

$\Rightarrow$ according to PDG
(Phys. Rev. **D66** (2002) 010001)

$\Rightarrow$ little known
(many open questions left)

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 result from πN scattering experiments

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

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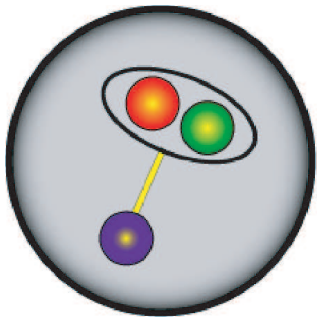

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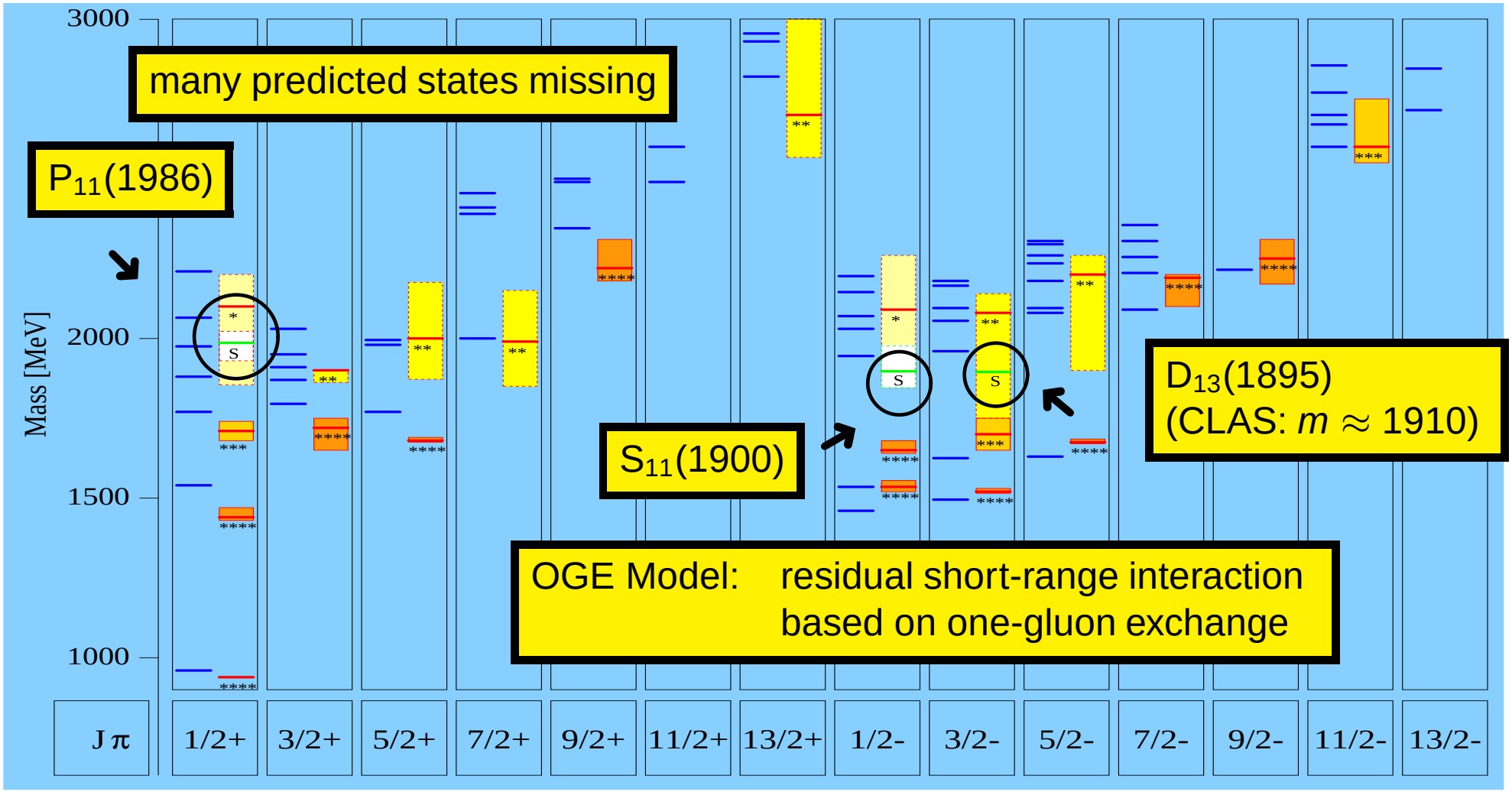
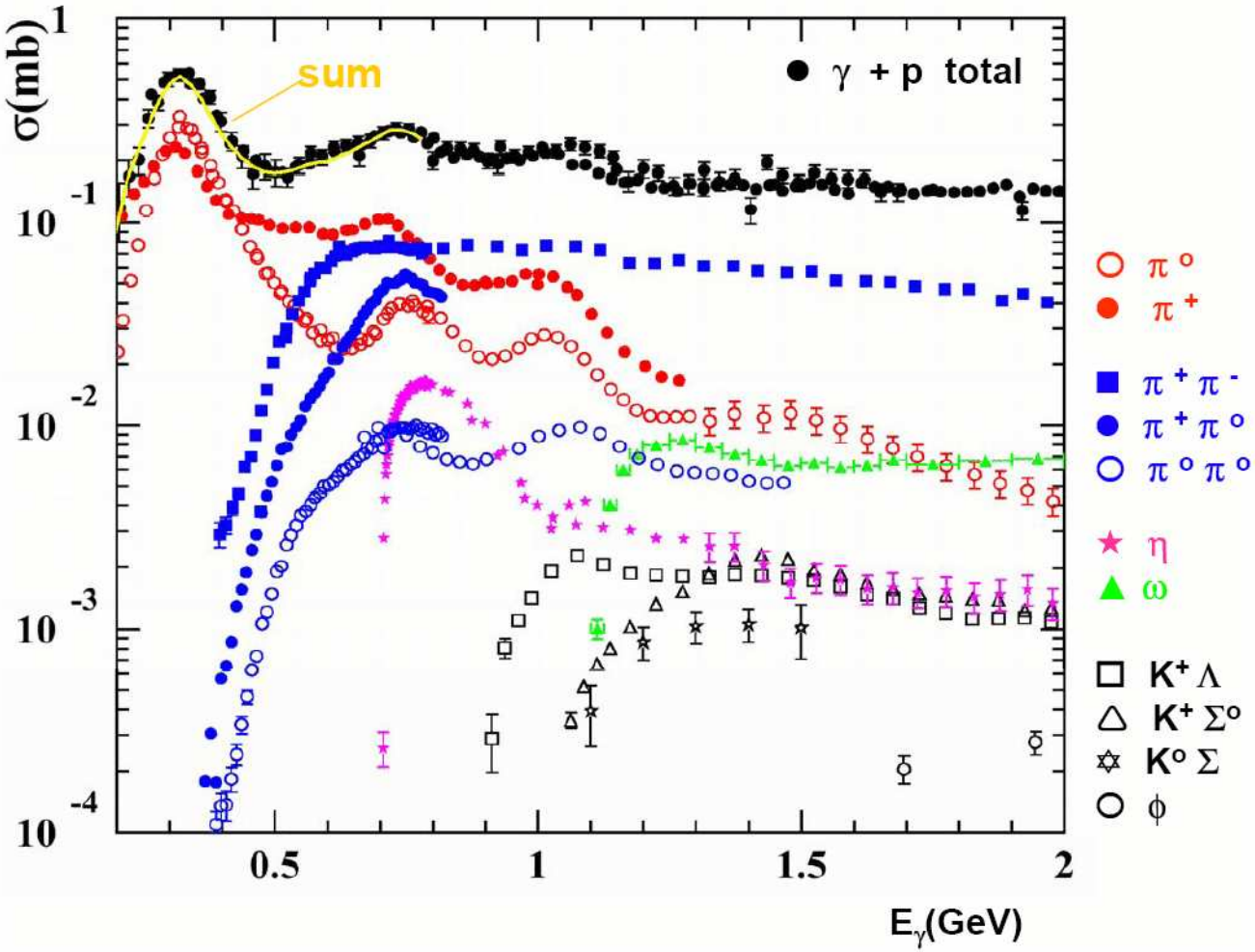
Nucleon Resonances: Status of 2001

S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809

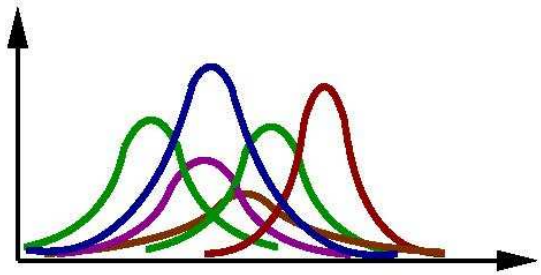


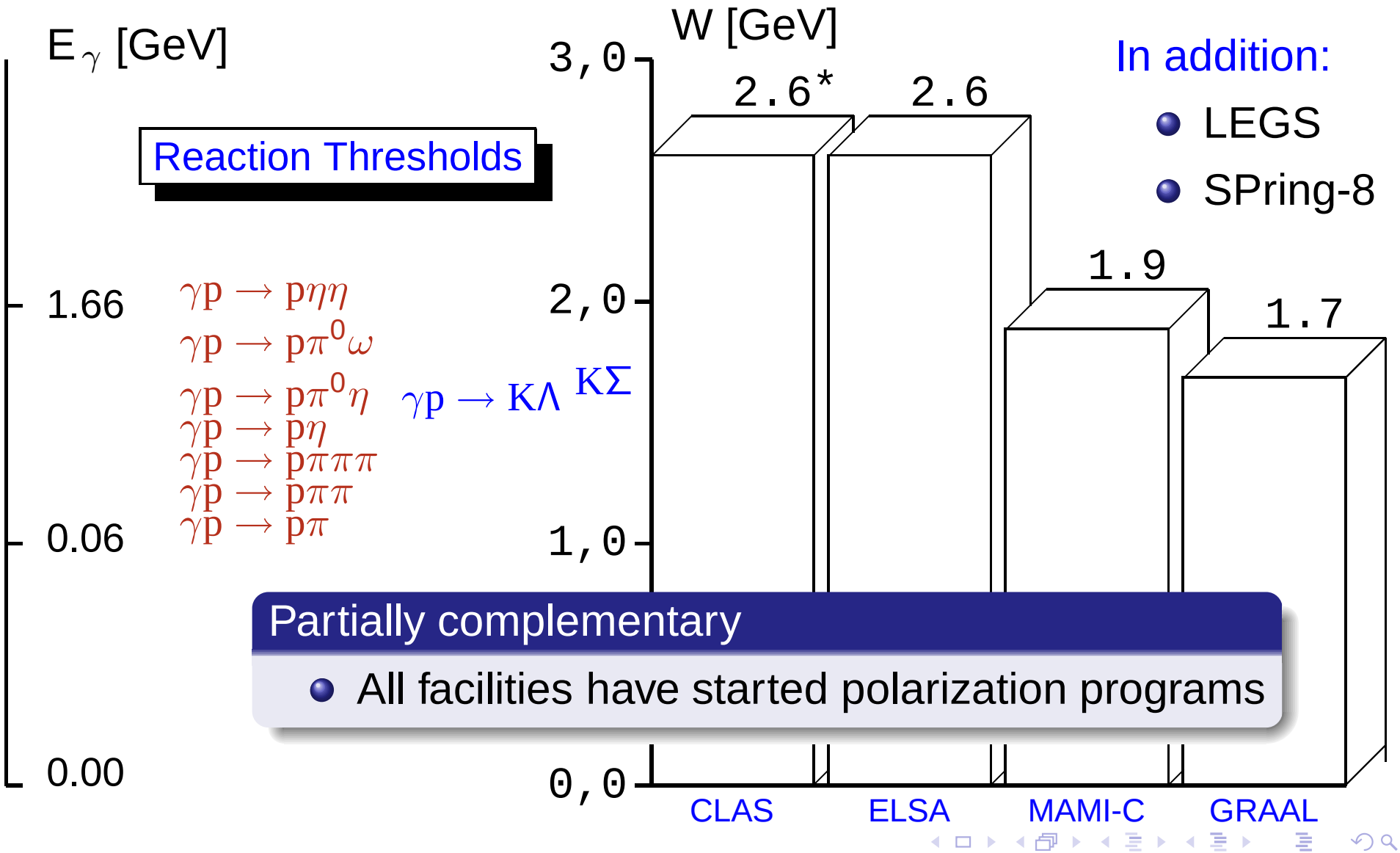
Total Photoproduction Cross Sections



No peak hunting

- Decays into neutral and charged particles
- Broad resonances




E$_\gamma$ [GeV]
W [GeV]
Reaction Thresholds
1.66
0.06
0.00
$\gamma p \to p\eta\eta$
$\gamma p \to p\pi^0\omega$
$\gamma p \to p\pi^0\eta$
$\gamma p \to p\eta$
$\gamma p \to p\pi\pi\pi$
$\gamma p \to p\pi\pi$
$\gamma p \to p\pi$
$\gamma p \to K\Lambda$
$K\Sigma$
3,0
2,0
1,0
0,0
2.6*
2.6
1.9
1.7
CLAS
ELSA
MAMI-C
GRAAL
In addition:
LEGS
SPring-8
Partially complementary
All facilities have started polarization programs

Ingredients

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

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 the four single-spin observables.

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		$O_{x'}$	

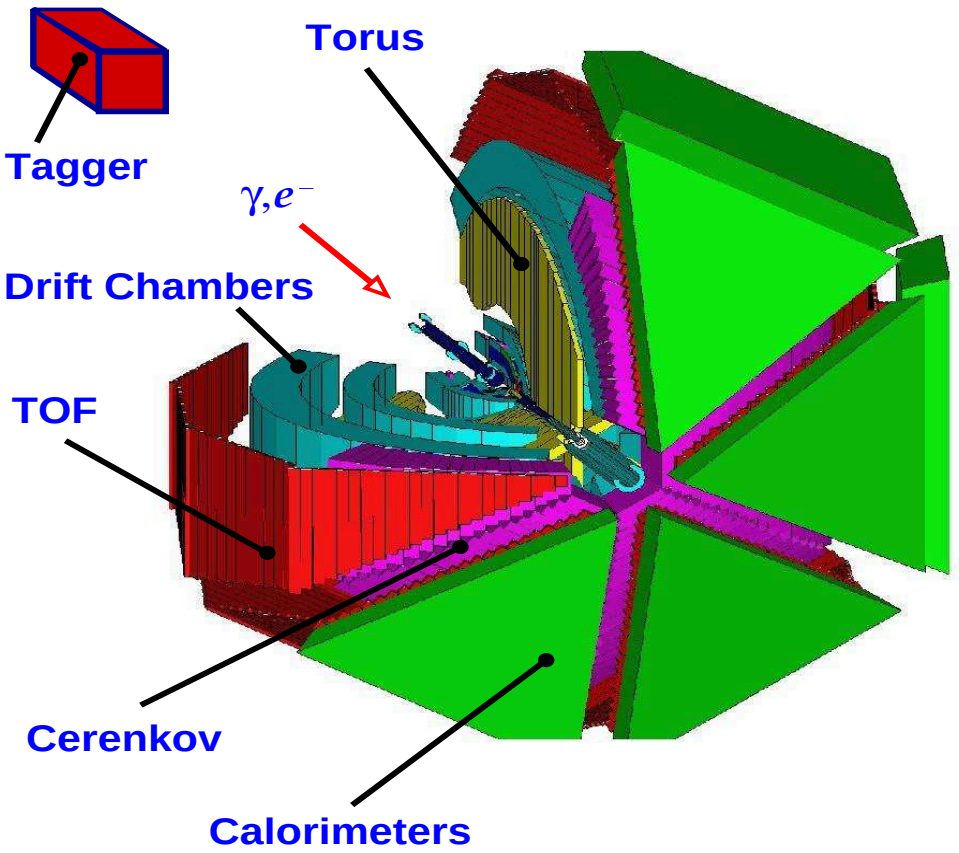
Full set of 16

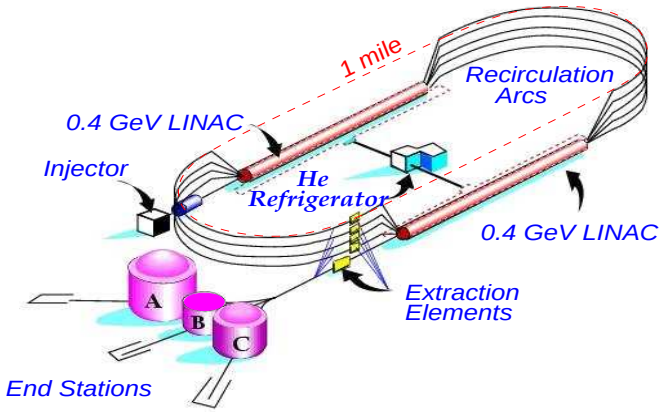
status	*CLAS run period*	*beam*	*target*	
complete	*g1*	γ , $\vec{\gamma}_c$	LH_2	*Miskimen/Schumacher*
complete	*g8*	$\vec{\gamma}_L$	LH_2	*Cole*
complete	*g9a* - P^T_z	$\vec{\gamma}_L$, $\vec{\gamma}_c$	FROST - $C_4\vec{H}_9O\vec{H}$	*Klein, Pasyuk*
2010	*g9b* - P^T_x	$\vec{\gamma}_L$, $\vec{\gamma}_c$	FROST - $C_4\vec{H}_9O\vec{H}$	*Klein, Pasyuk*

Picture taken from A. Sandorfi

Outline

CLAS Spectrometer





CHARACTERISTICS:

Electron Coverage: $\theta : 15\text{–}50^{o}$

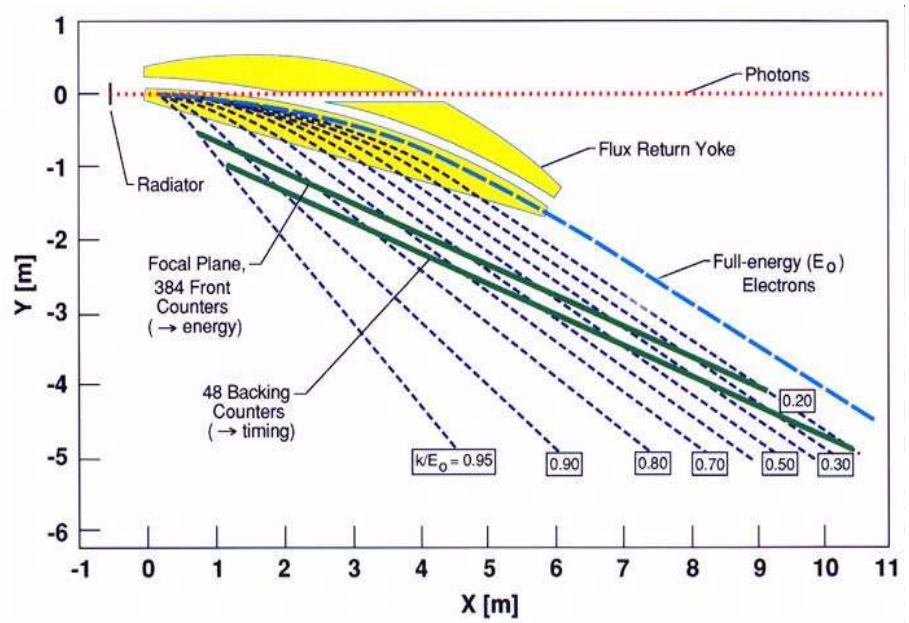
Hadron Coverage:

$\theta : 15\text{–}140^{o}$, $\phi : 80\%\ 2\pi$

Resolution : $\Delta p/p \sim 1\text{–}2\%$
$\Delta\theta, \Delta\phi \sim 2\ mrad$

$$\mathcal{L} = 1 \times 10^{34}\ cm^{-2} sec^{-1}$$
$$\mathcal{F}_{\gamma} = 1 \times 10^{7}/s$$

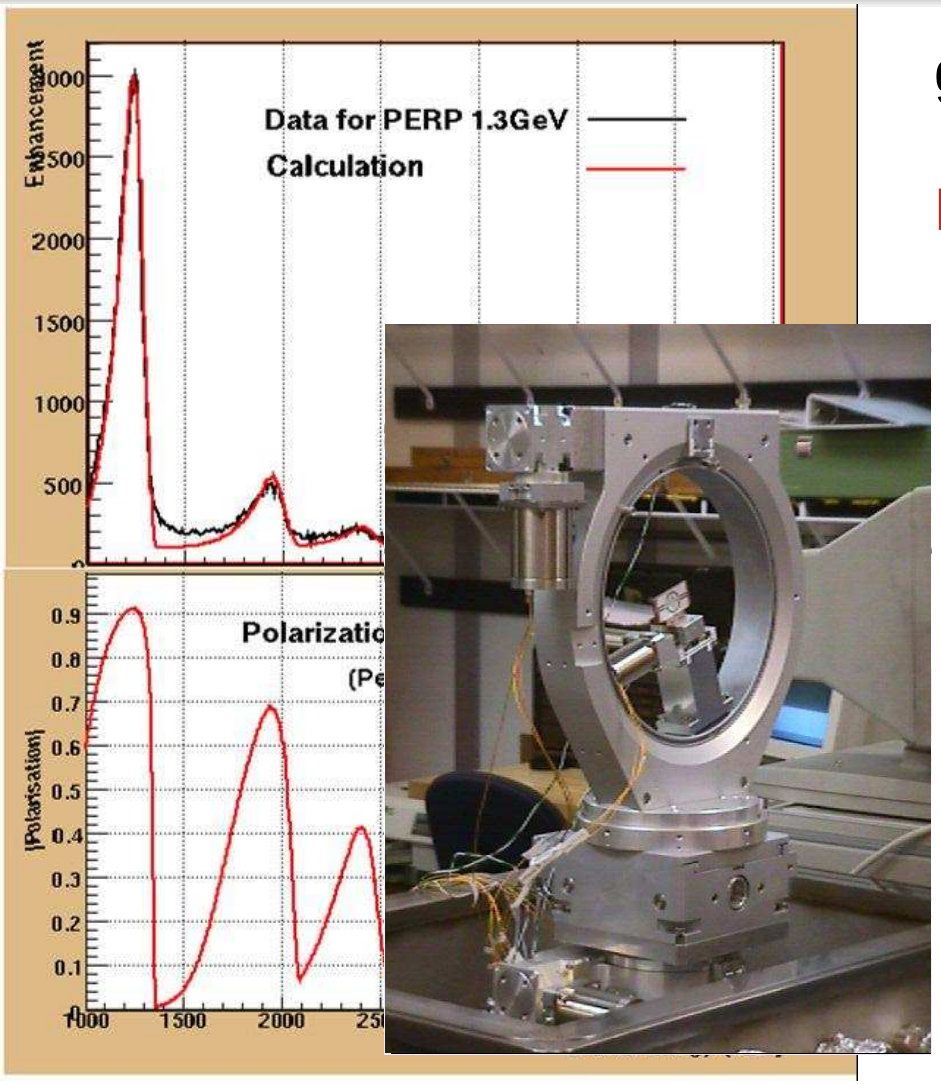
The Hall-B Photon Tagging Facility



Photons via Bremsstrahlung:

- $E_\gamma = 20 - 95\,\%$ of E_0
- E_γ up to ~ 6 GeV
- $dE/E \sim 10^{-3}$ of E_0

The Coherent Bremsstrahlung Facility at CLAS



g8b Run Group (data from 2005)

Bremsstrahlung in 50 μ diamond:

- 40 cm liquid hydrogen target located 20 cm upstream
- Two linear polarization states (vertical & horizontal)
- Incident electron energy from CEBAF of 4.55 GeV
  ➜ 1.0 GeV < E_γ < 2.1 GeV
- Single-charged particle trigger

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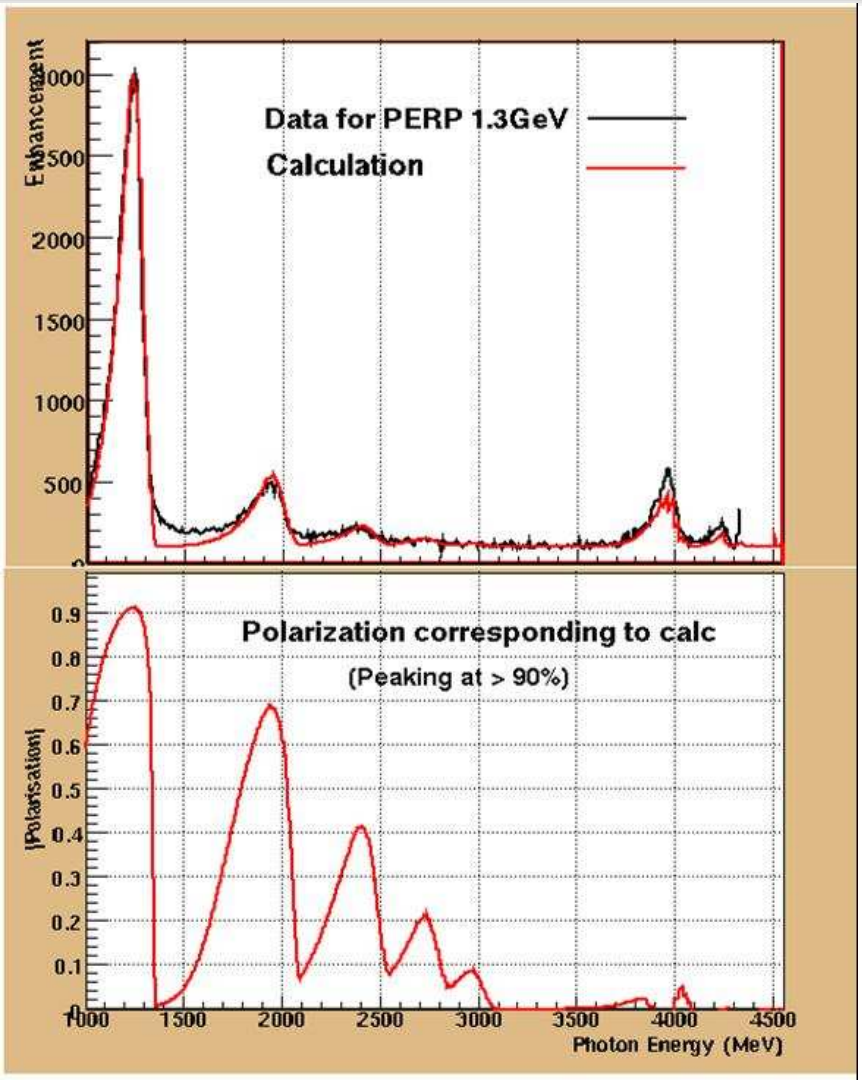

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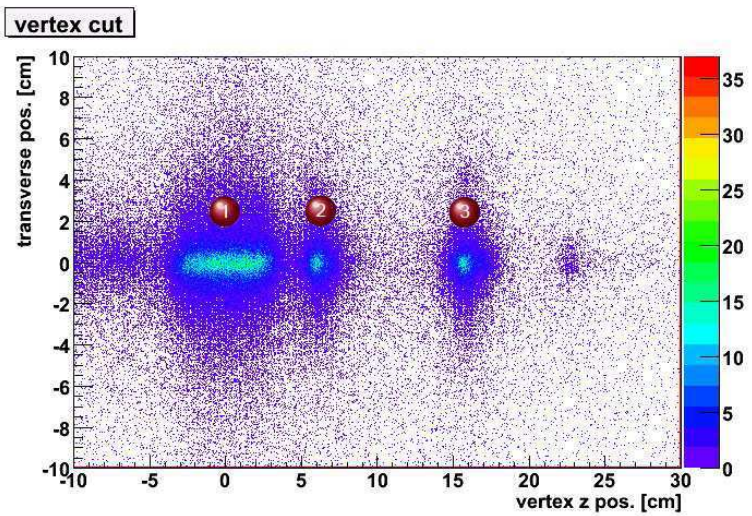
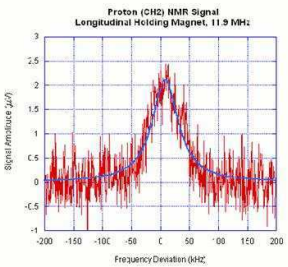
The Frozen-Spin (FROST) Target





$\Delta B/B \approx 3 \cdot 10^{-3}$ at 0.5 T

$B \approx 0.5$ T

$T \approx 0.05$ K

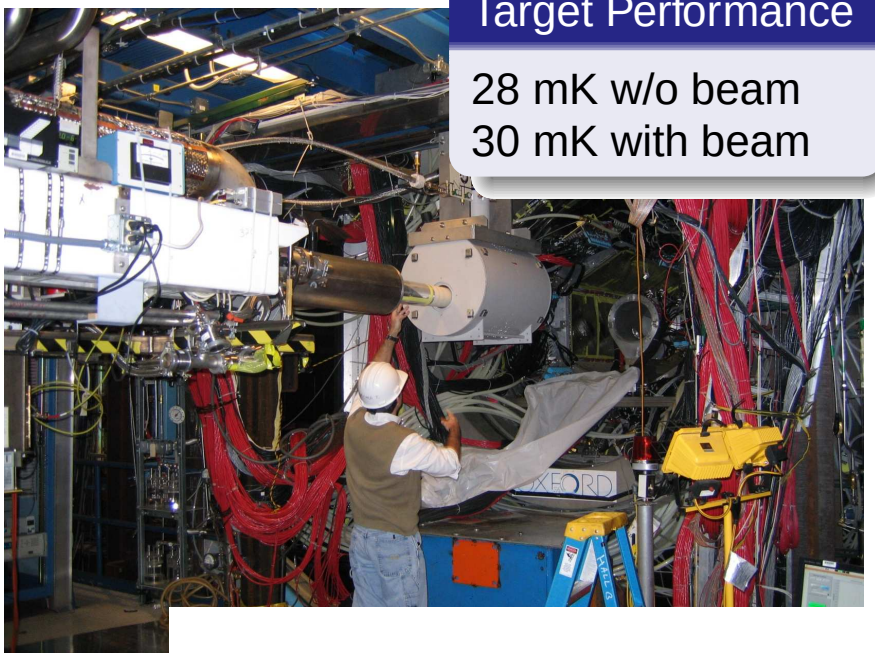
Production Data

- Target (Butanol)

  Longitudinally-polarized target
  Average polarization $\sim 80\,\%$
  Additional targets: ^{12}C, CH_2

- PhotonBeam

  Circular and linear Polarization
  Excellent degrees of polarization



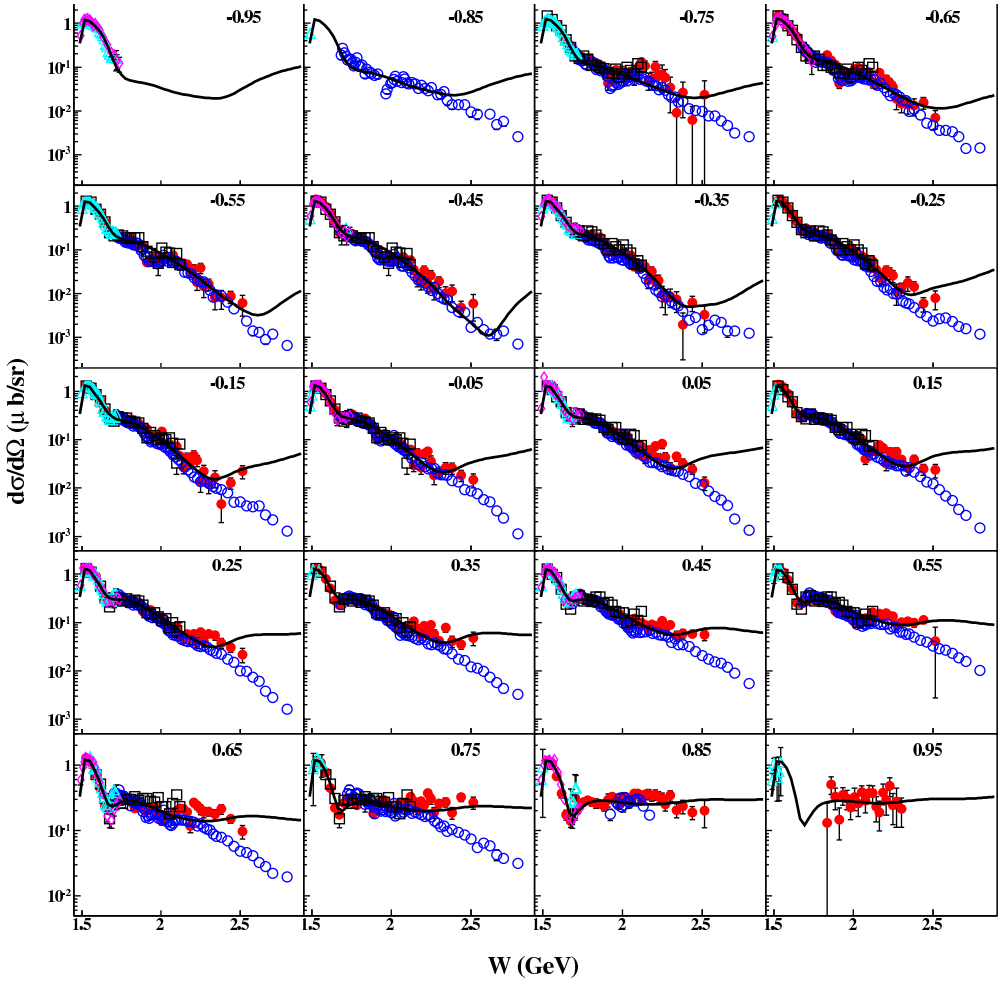
Target Performance

28 mK w/o beam
30 mK with beam

Outline

Photoproduction of η Mesons off the Proton

○ g11a ● CB-ELSA ('05) □ CLAS ('02) △ GRAAL ('02) ◊ LNS ('06) — SAID



Of particular importance:

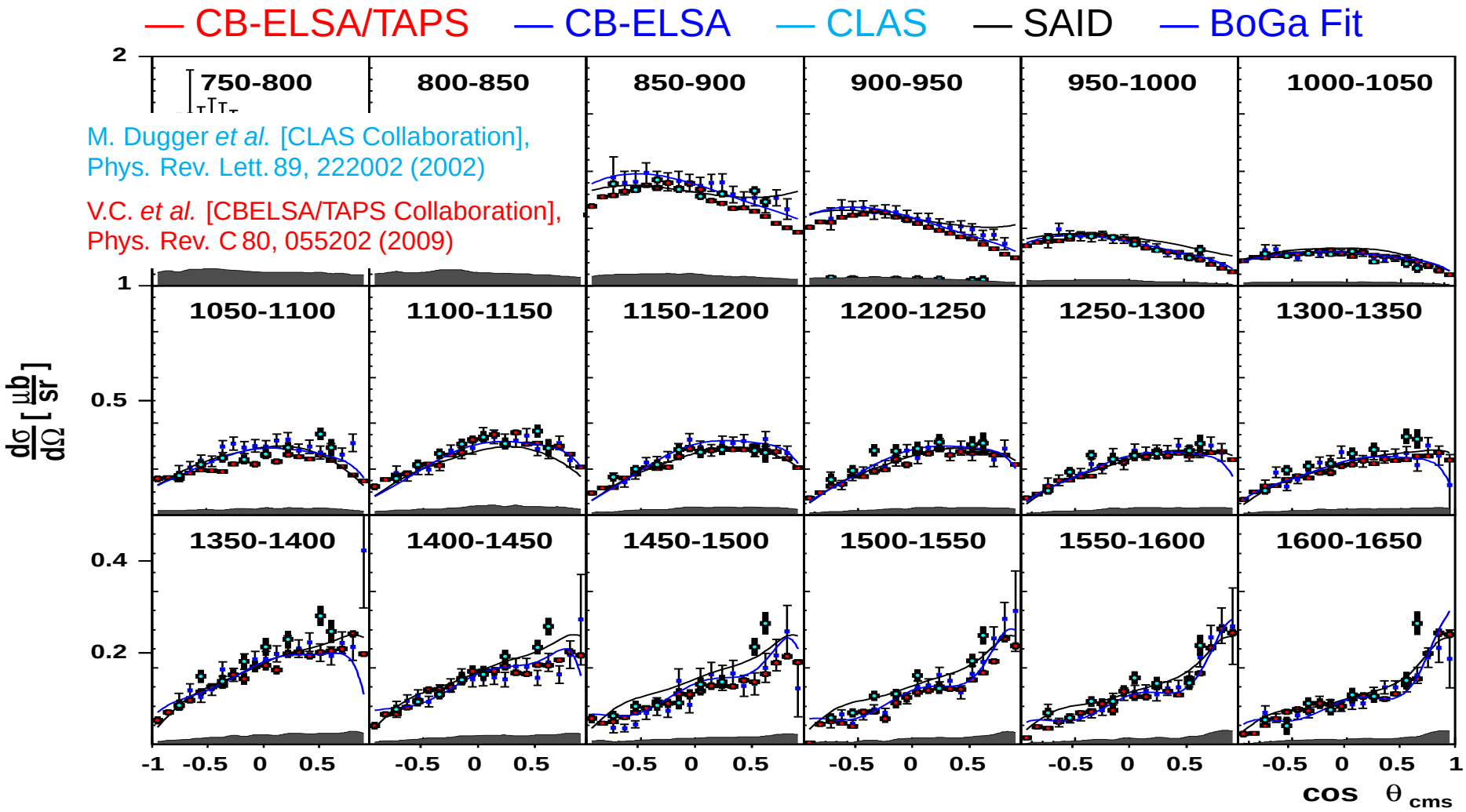
➜ Reactions that limit the number of contributing resonances

η Meson: $I = 0$

➜ $\gamma p \to p\eta$ can only proceed via nucleon resonances

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 045213 (2009)

Photoproduction of η Mesons off the Proton



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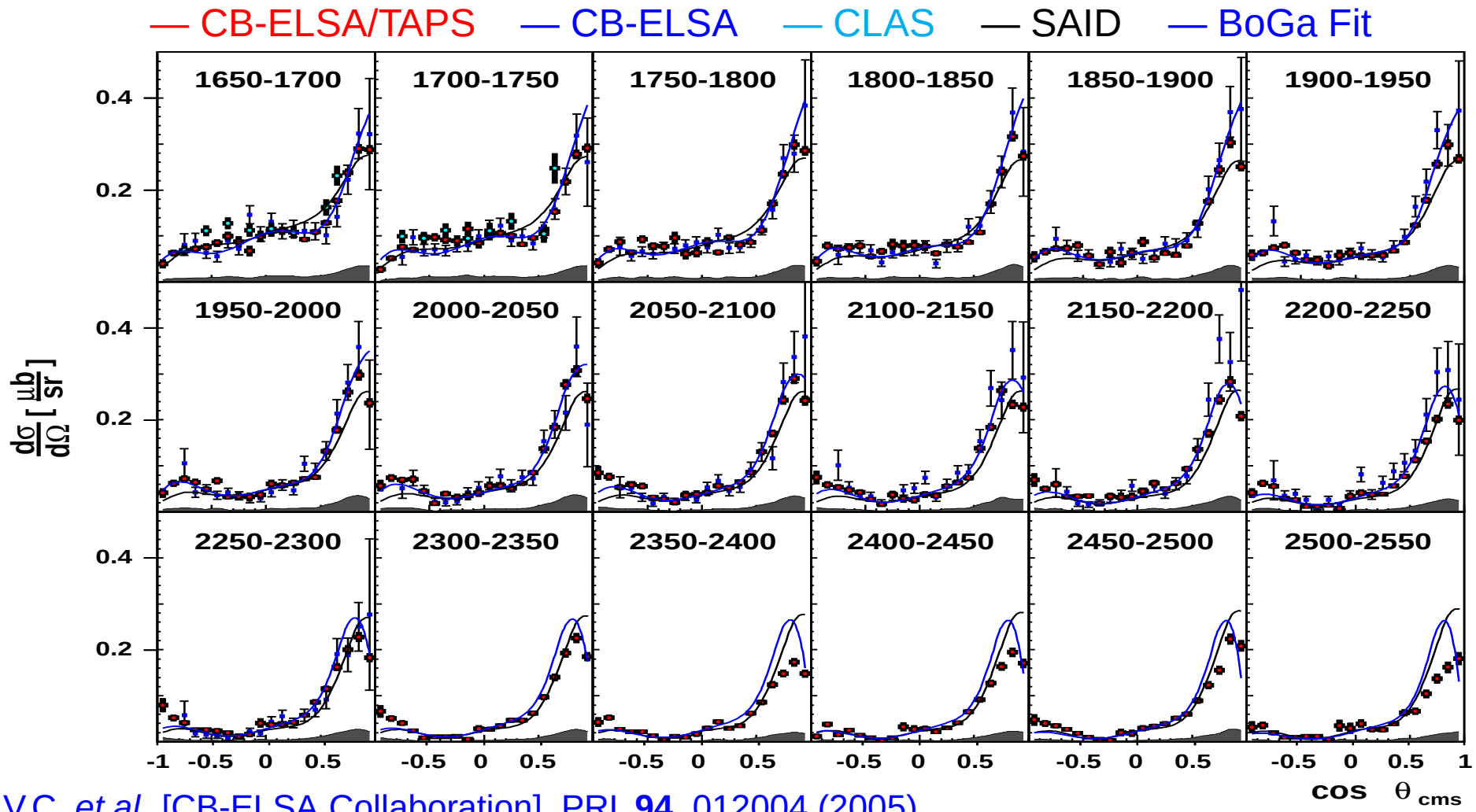
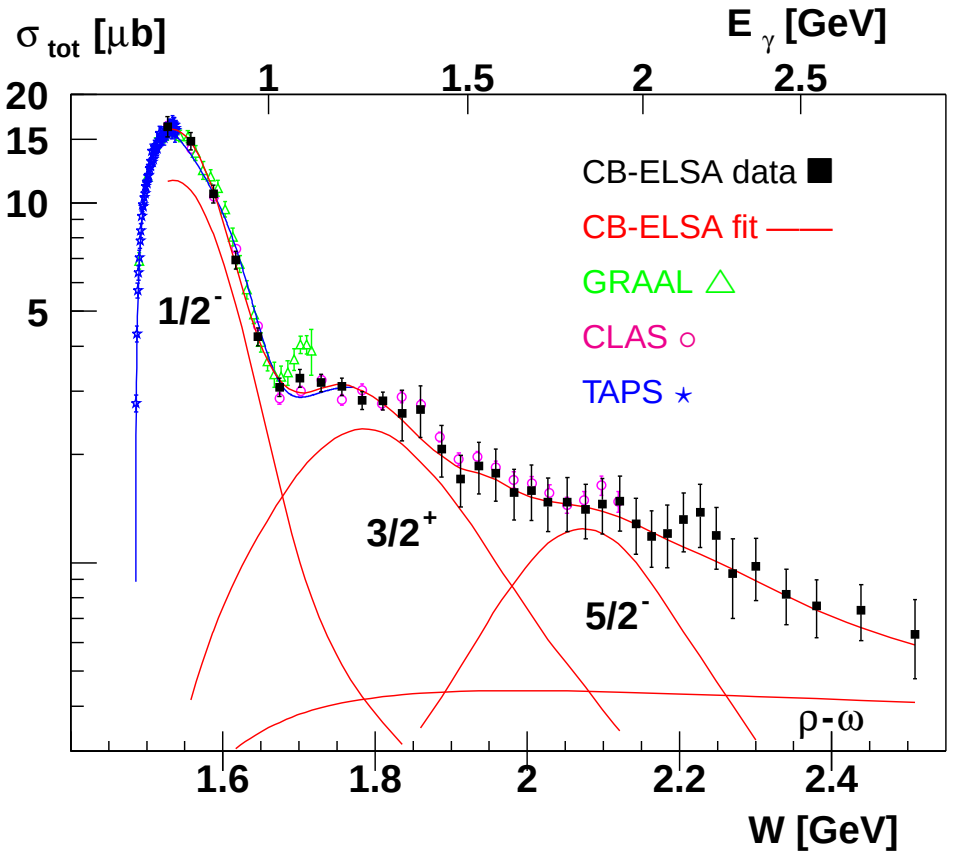


V.C. *et al.* [CB-ELSA Collaboration], PRL **94**, 012004 (2005)

Analysis of $\gamma p \rightarrow p\eta$: Total Cross Section



Isopsin Filter

➜ Only N^* resonances can contribute!

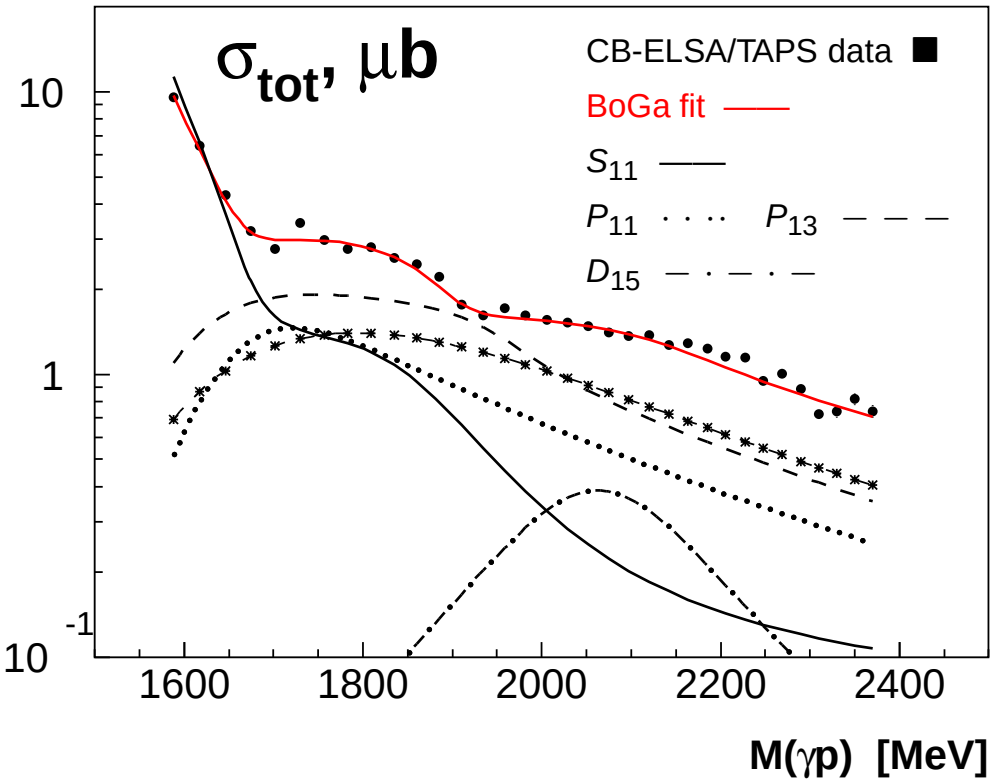
Bonn-Gatchina (PWA) group: Hint for N* resonance (2070)D_{15}

(Phys. Rev. Lett. **D94**, 012004 (2005))

Three resonances are dominantly contributing:

$N(1535)S_{11}$, $N(1720)P_{13}$, $N(2070)D_{15}$

Analysis of $\gamma p \rightarrow p\eta$: Total Cross Section



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Bonn-Gatchina (PWA) group: Hint for N* resonance (2070)D_{15}

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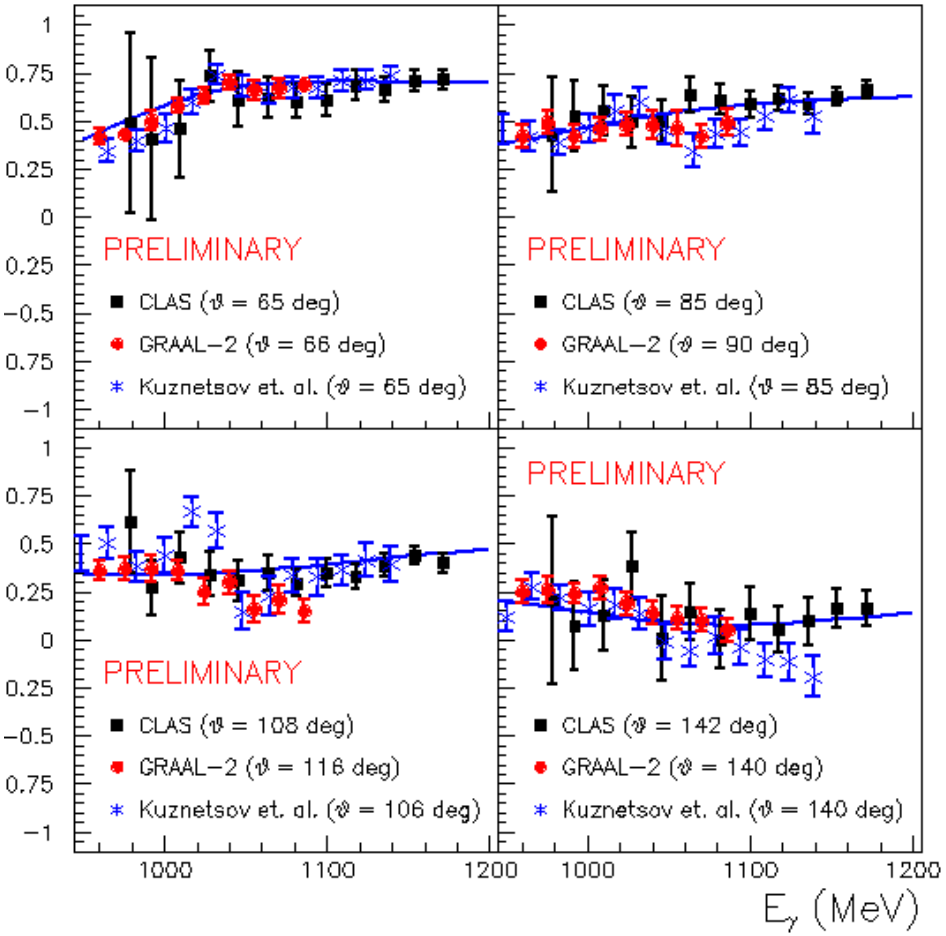
1. Confirmed in 2009 analysis!
2. $N(1720)P_{13} \rightarrow p\eta$?
   ➜ η-MAID:
   $N(1710)P_{11} \rightarrow p\eta$ significant!

Resonances dominantly contributing:

$N(1535)S_{11}$, $(N(1720)P_{13})^?$, $N(2070)D_{15}$

Beam Asymmetry Σ in the Reaction $\vec{\gamma}p \rightarrow p\eta$

Higher sensitivity due to interference effects: $\Sigma \sim A_{1/2}(S_{11}) * A_{1/2}(P_{13}) + ...$

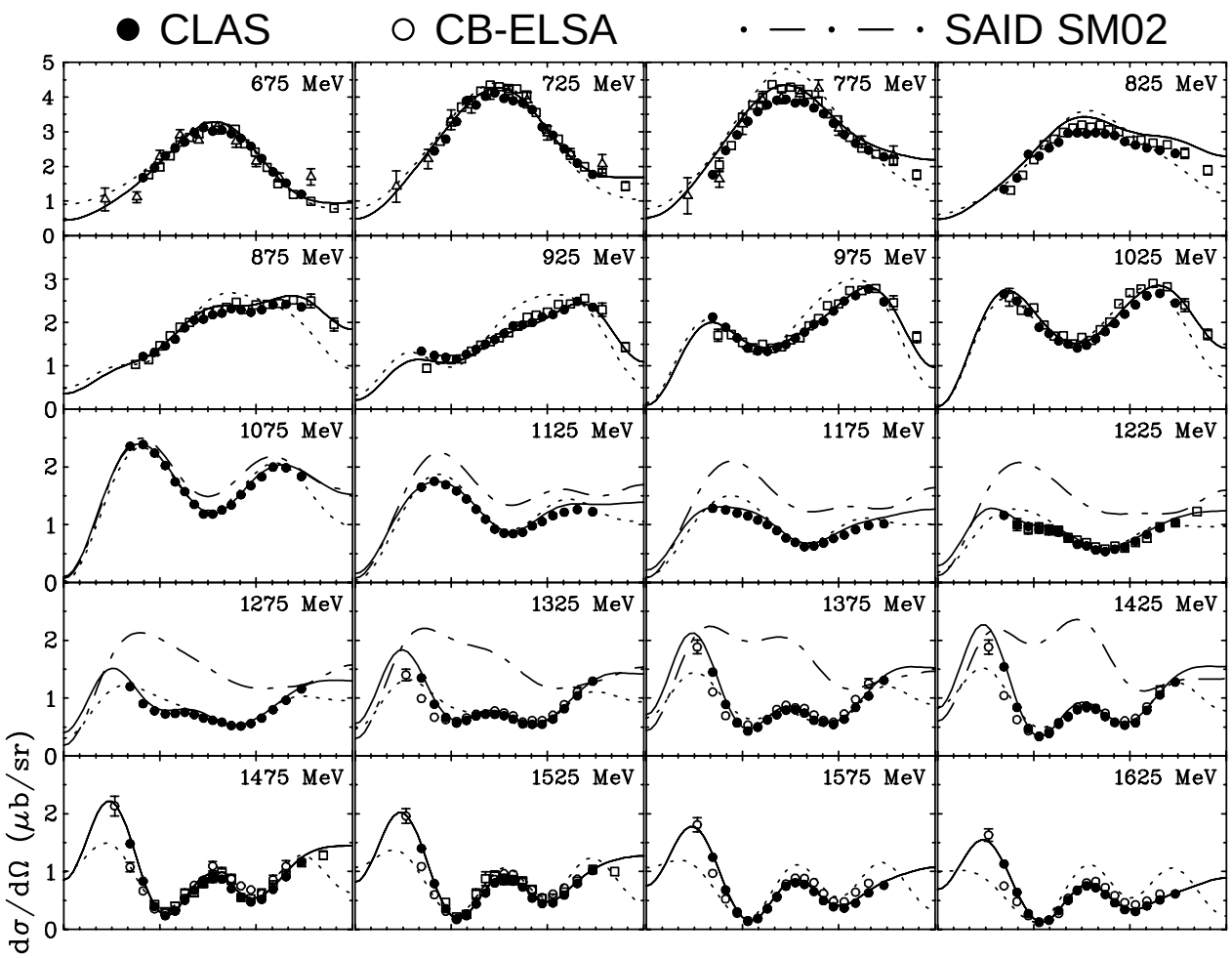


Further spin observables available

- E and G from FROST run with longitudinal target polarization (2007/2008)
- T, F, and H will be available from FROST run with transverse target polarization (Spring 2010)

P. Collins, CLAS g8b run group, to be published

Photoproduction of π^0 Mesons off the Proton

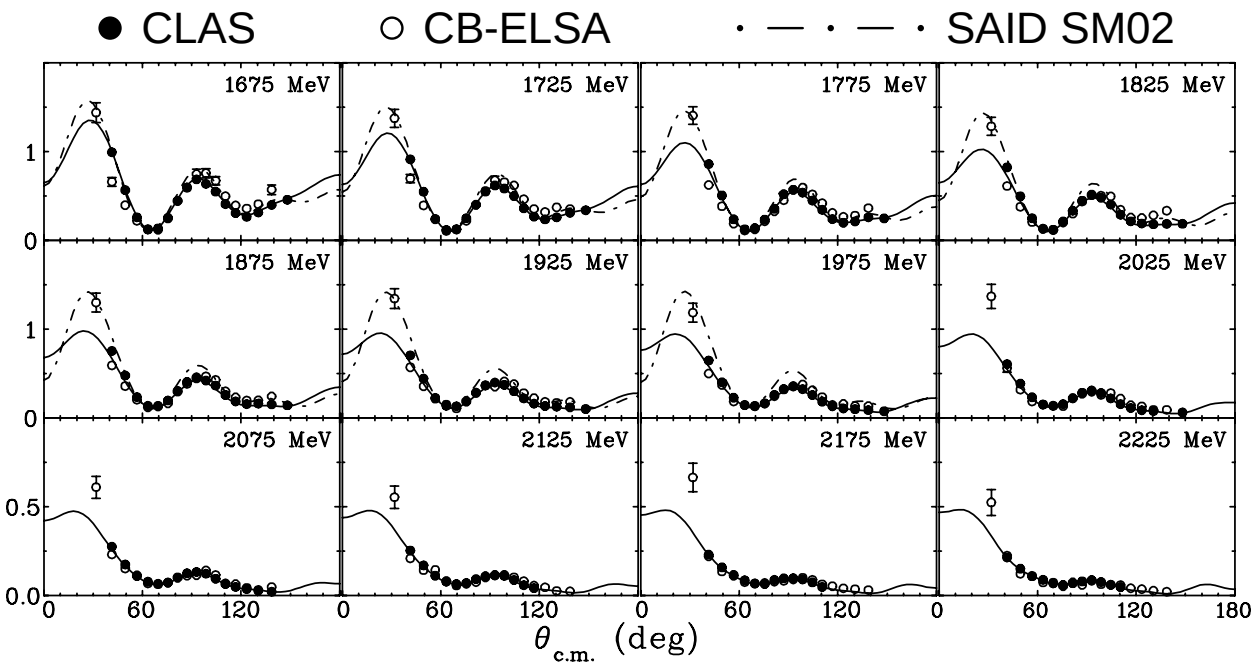


Resonance	πN SAID	$A_{1/2}$	$A_{3/2}$
$N(1535)S_{11}$	W_R=1547 MeV	91.0±2.2	
	Γ=188 MeV	90±30	
	Γ_π/Γ=0.36		
$N(1650)S_{11}$	W_R=1635 MeV	22.2±7.2	
	Γ=115 MeV	53±16	
	Γ_π/Γ=1.00		
$N(1440)P_{11}$	W_R=1485 MeV	−50.6±1.9	
	Γ=284 MeV	−65±4	
	Γ_π/Γ=0.79		
$N(1720)P_{13}$	W_R=1764 MeV	96.6±3.4	−39.0±3.2
	Γ=210 MeV	18±30	−19±20
	Γ_π/Γ=0.09		
$N(1520)D_{13}$	W_R=1515 MeV	−28.0±1.9	143.1±2.0
	Γ=104 MeV	−24±9	166±5
	Γ_π/Γ=0.63		
$N(1675)D_{15}$	W_R=1674 MeV	18.0±2.3	21.2±1.4
	Γ=147 MeV	19±8	15±9
	Γ_π/Γ=0.39		
$N(1680)F_{15}$	W_R=1680 MeV	−17.3±1.4	133.6±1.6
	Γ=128 MeV	−15±6	133±12
	Γ_π/Γ=0.70		
$\Delta(1620)S_{31}$	W_R=1615 MeV	49.6±2.2	
	Γ=147 MeV	27±11	
	Γ_π/Γ=0.32		
$\Delta(1232)P_{33}$	W_R=1233 MeV	−139.1±3.6	−257.6±4.6
	Γ=119 MeV	−135±6	−250±8
	Γ_π/Γ=1.00		
$\Delta(1700)D_{33}$	W_R=1695 MeV	125.4±3.0	105.0±3.2
	Γ=376 MeV	104±15	85±22
	Γ_π/Γ=0.16		
$\Delta(1905)F_{35}$	W_R=1858 MeV	21.3±3.6	−45.6±4.7
	Γ=321 MeV	26±11	−45±20
	Γ_π/Γ=0.12		

M. Dugger *et al.* [CLAS Collaboration], PRC **76**, 025211 (2007)

Photoproduction of π^0 Mesons off the Proton

- Strong excitation of $N(1720)P_{13}$ consistent with analysis of $\pi^+\pi^-$ electro-couplings
- No new nucleon resonances needed!



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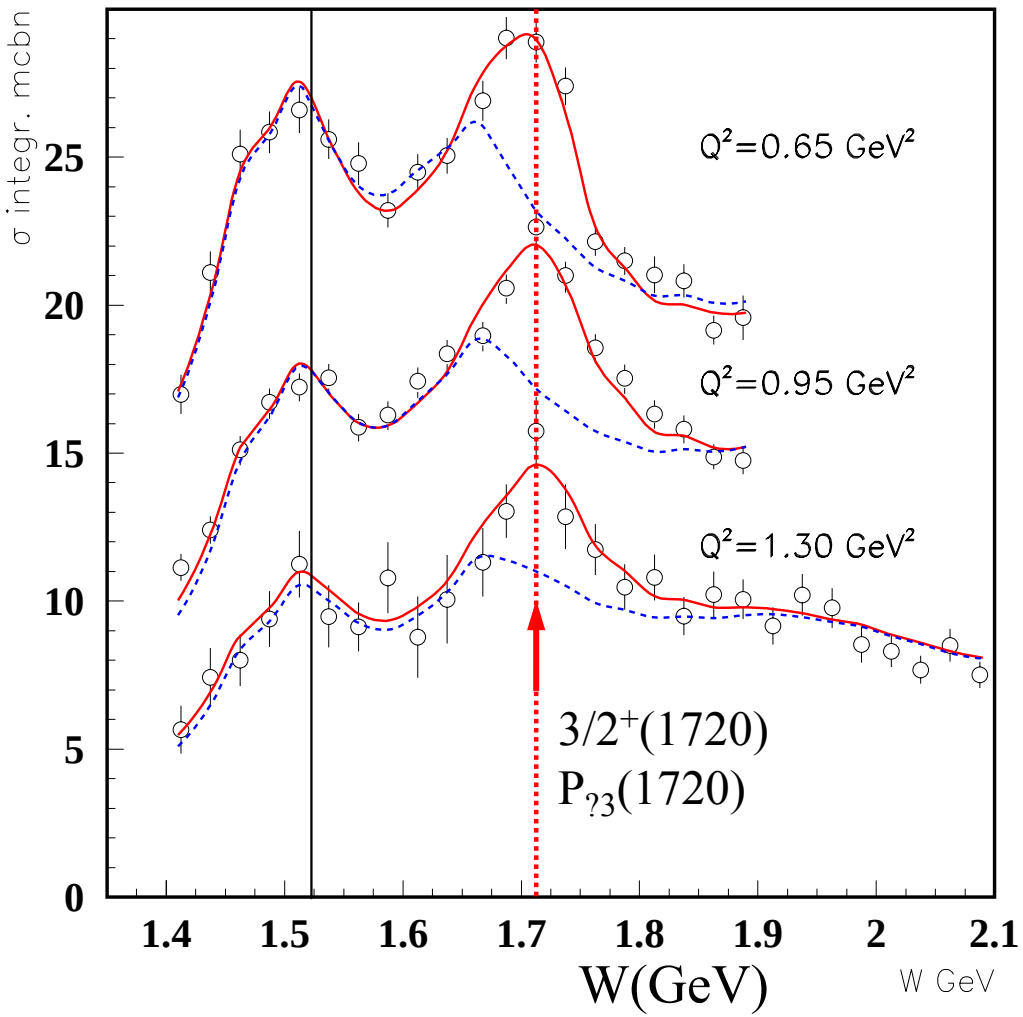
M. Dugger *et al.* [CLAS Collaboration], PRC **76**, 025211 (2007)

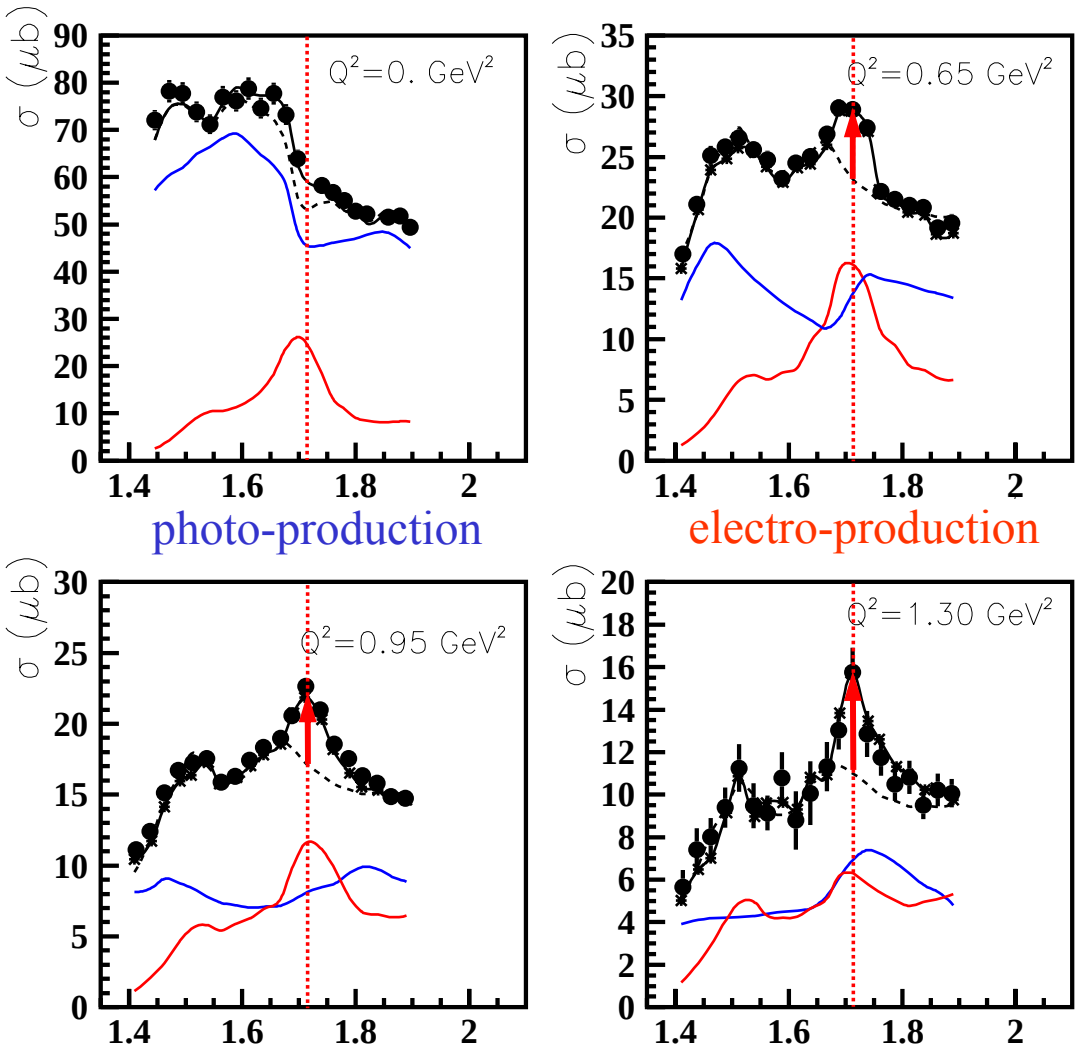
Resonances in $\gamma^{(*)}p \longrightarrow p\pi^+\pi^-$



- 2π channel sensitive to N*'s heavier than 1.4 GeV
- Provides complementary information to the 1π channel
- Many higher lying N*'s decay preferably to N$\pi\pi$ final states via intermediate states

Solid curves are from fits using the recent JM06 model with and without a new ?(1720)$P_{?3}$ state

Resonances in $\gamma^{(*)}p \rightarrow p\pi^+\pi^-$



- Background
- Resonances

Combined analysis of preliminary real (M. Bellis) and also published virtual photon data (M. Ripani):

Fit needs both the candidate ?(1720)$P_{?3}$ and the N(1720)P_{13} state.

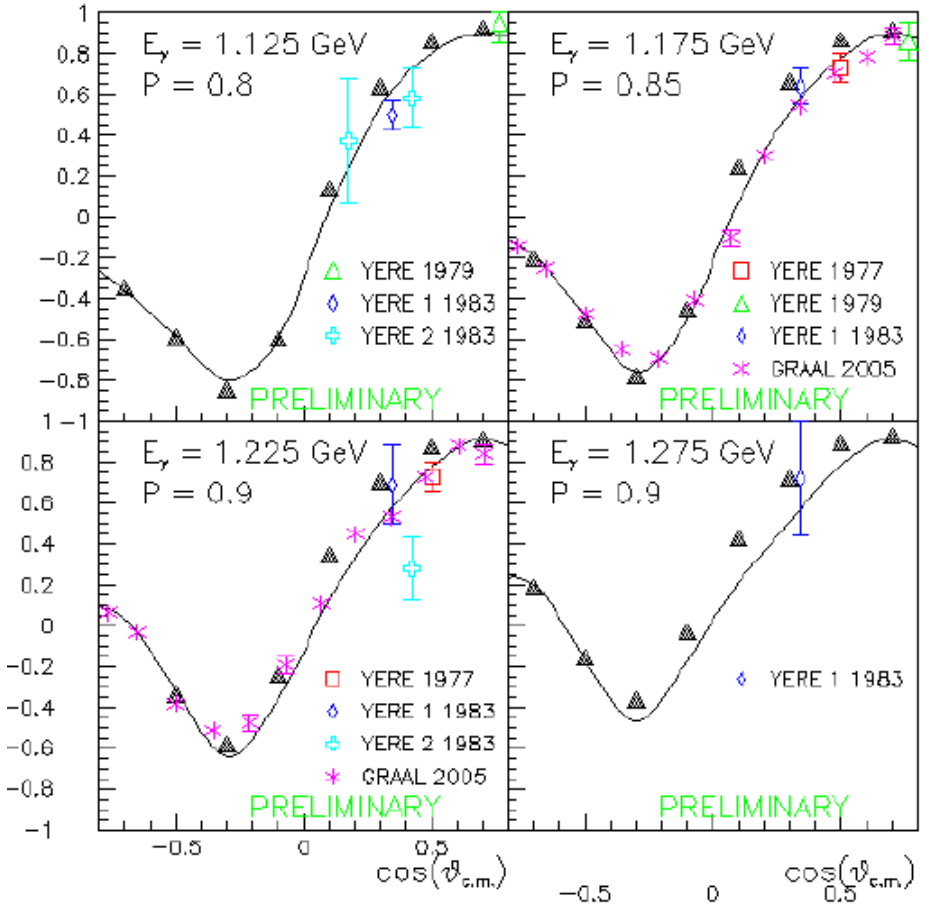
Authors claim that combined fit of various single differential cross sections allowed to establish all significant mechanisms.

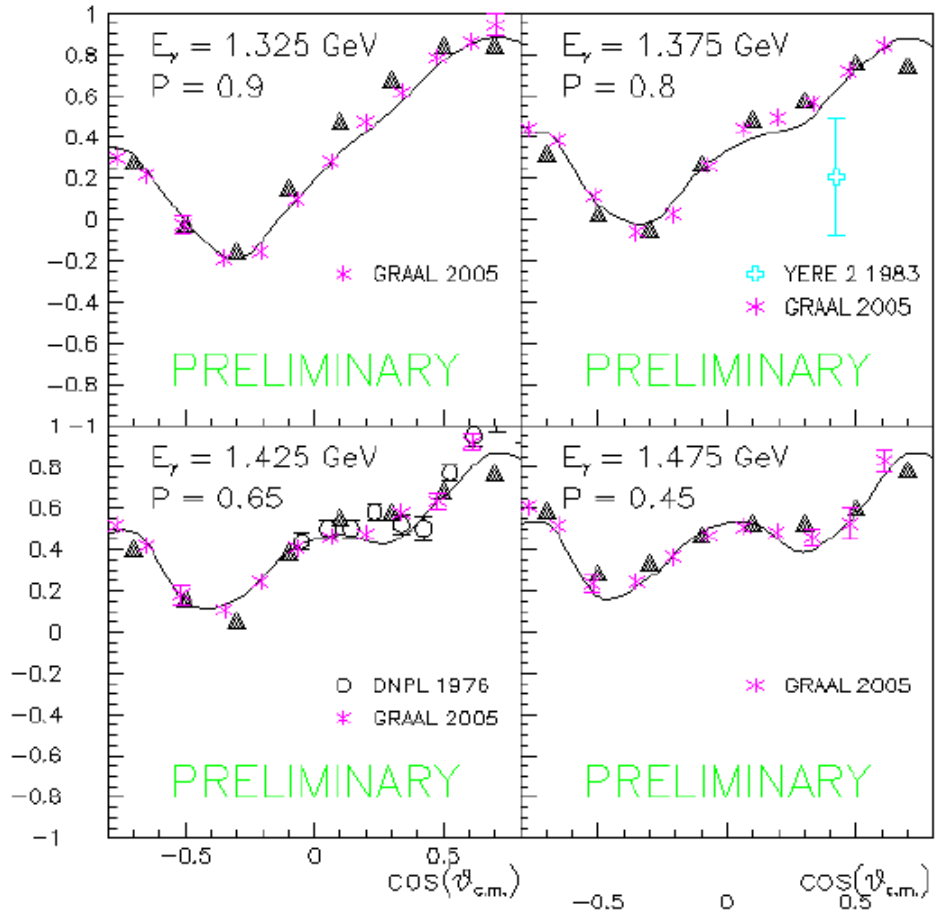
Reasonable Description of Nπ/N$\pi\pi$ Electroproduction

The CLAS-Collaboration phenomenological models (UIM/DR/JM) reproduce reasonably well comprehensive CLAS/world data on all observables in Nπ/N$\pi\pi$ electroproduction:

- Isobars used in N$\pi\pi$ electroproduction
  1. All well-established $\mathrm{N}^* \to \pi^- \Delta^{++}$ decays + $3/2^+(1720)$
  2. All well-established $\mathrm{N}^* \to \rho\pi$ decays + $3/2^+(1720)$
  3. Observed for the first time in CLAS data:
     $\pi^+ \mathrm{D}^0_{13}(1520)$, $\pi^+ \mathrm{F}^0_{15}(1685)$, and $\pi^- \mathrm{P}^{++}_{33}(1640)$
- Models can be used to evaluate N* electrocouplings
  ➜ Information on contributing mechanisms will be used by EBAC for N* studies in advanced coupled channel analysis (Julia-Diaz, Lee, Phys. Rev. C**76**, 065201 (2007))

Photoproduction of π^0 Mesons: Beam Asymmetry Σ

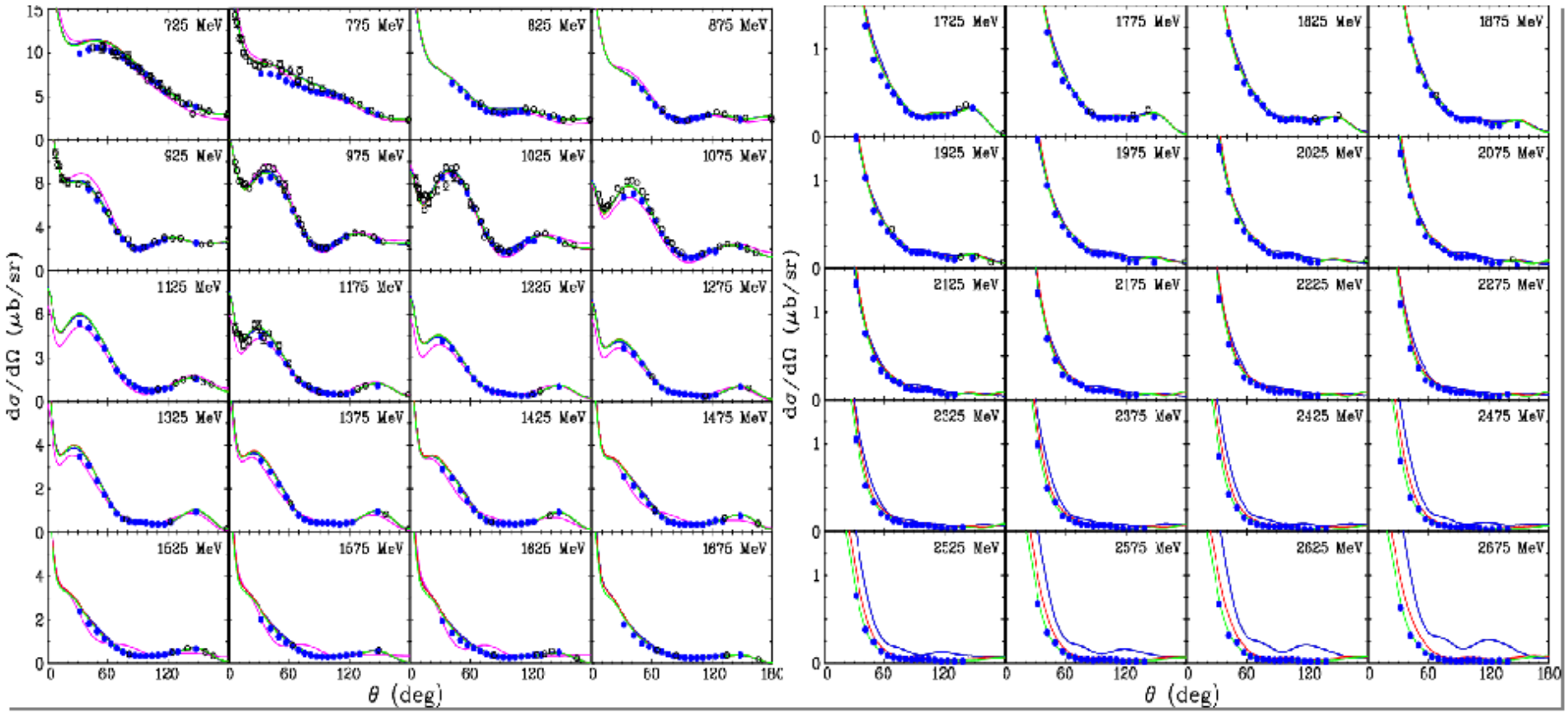




M. Dugger, CLAS g8b run group, to be published (▲)

Photoproduction of π^+ Mesons: $\gamma p \rightarrow n\,\pi^+$

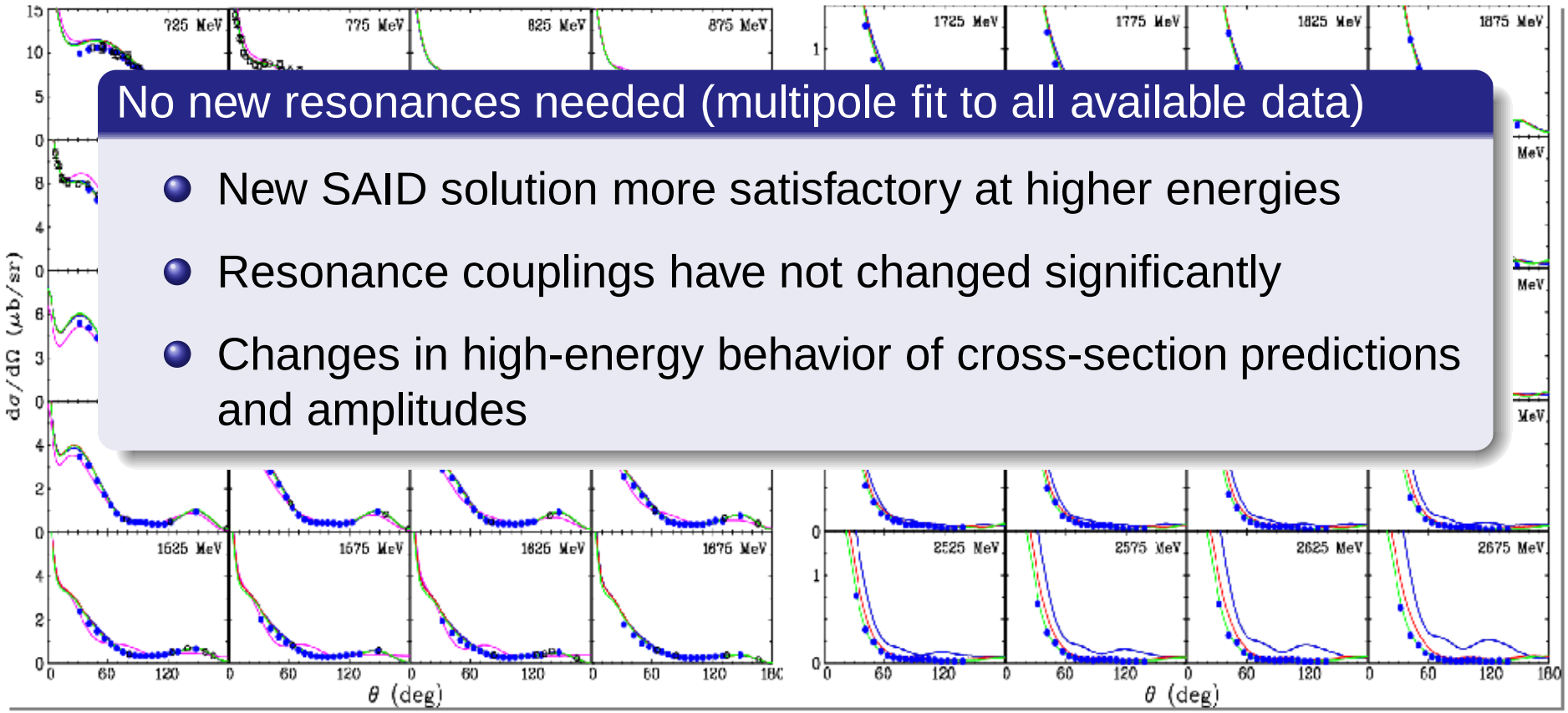
SAID FA07 MAID07 — ? SAID FA08



M. Dugger *et al.* (CLAS g1c), PRC **76**, 065206 (2009)

Photoproduction of π^+ Mesons: $\gamma p \longrightarrow n\,\pi^+$

SAID FA07 MAID07 — ? SAID FA08

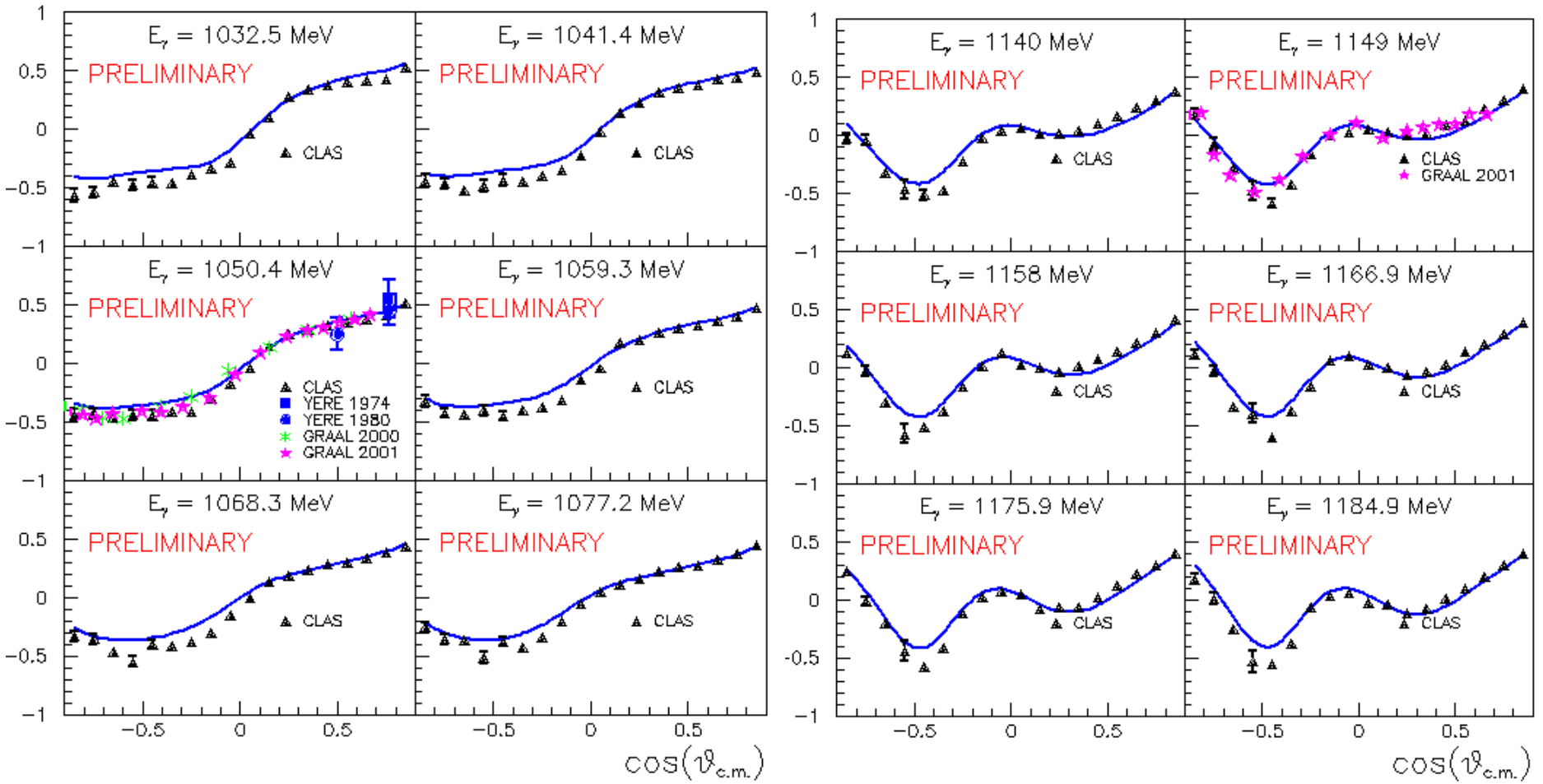


No new resonances needed (multipole fit to all available data)

- New SAID solution more satisfactory at higher energies
- Resonance couplings have not changed significantly
- Changes in high-energy behavior of cross-section predictions and amplitudes

M. Dugger *et al.* (CLAS g1c), PRC **76**, 065206 (2009)

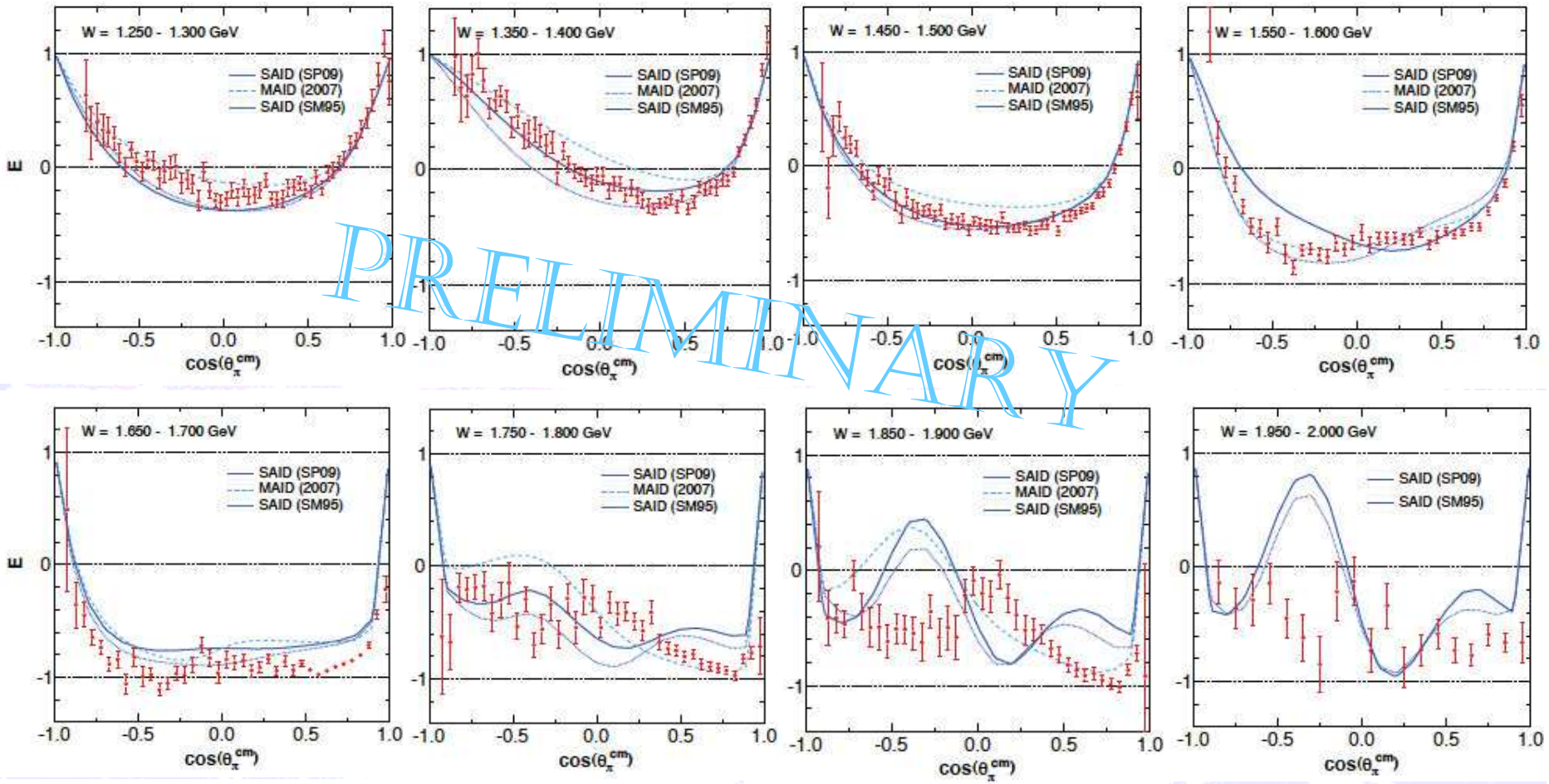
Photoproduction of π^+ Mesons: Σ in $\gamma p \rightarrow n\,\pi^+$



CLAS g8b run group, ASU analysis, to be published (▲)

Photoproduction of π^+ Mesons: Helicity Difference E

circ.-pol. beam on long.-pol. target: good agreement with SAID & MAID for $W < 1.7$ GeV



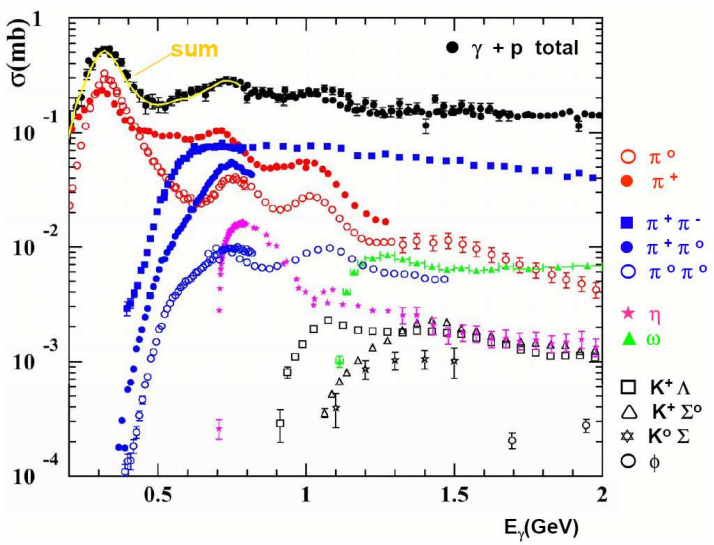
CLAS g9a (FROST) run group, USC analysis

Outline

Beam-Target Polarization Observables

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

$\Leftarrow$ Single-Meson Final States (7 Observables)



Beam-Target Polarization Observables

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

$\Leftarrow$ Single-Meson Final States (7 Observables)

Two-Meson Final States $\Rightarrow$ (15 Observables)

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

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

Two mesons in the final state require 5 independent variables!

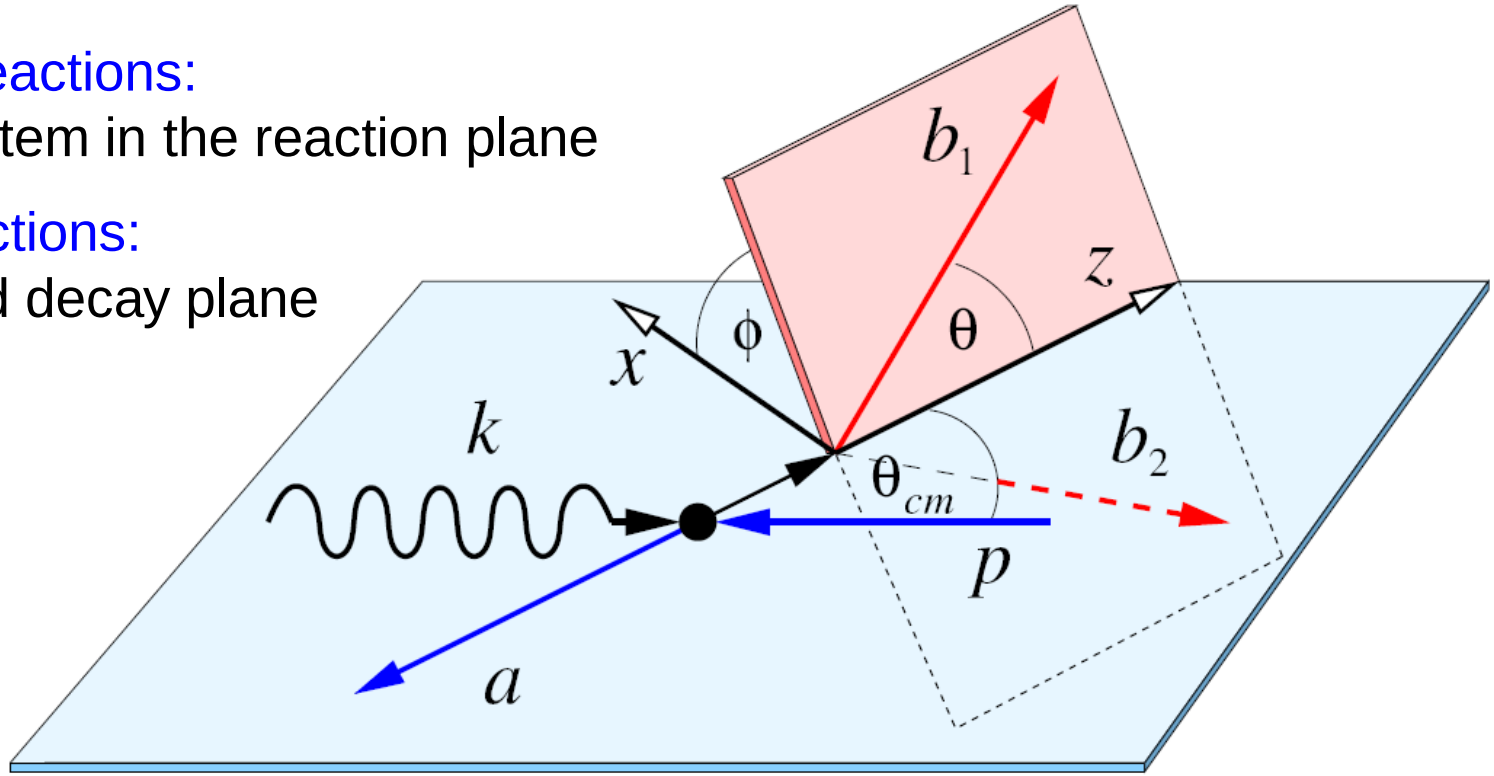
For example: E_γ, $\Theta_{\mathrm{c.m.}}$, ϕ^*, θ^*, $M_{p+meson_1}$

Single-meson reactions:

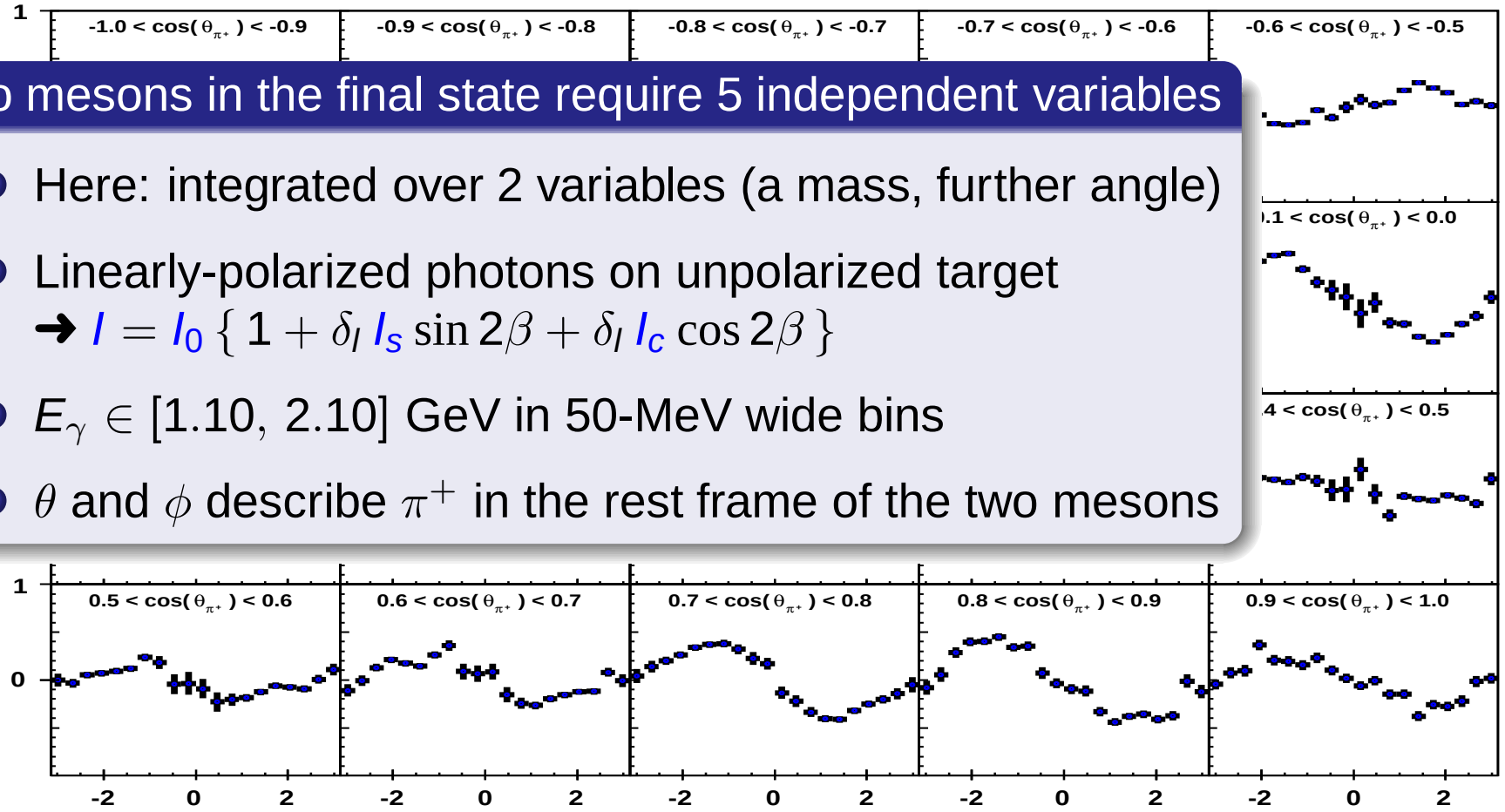
➜ p-meson system in the reaction plane

Two-meson reactions:

➜ Reaction and decay plane form angle ϕ



Photoproduction of $\pi^+\pi^-$: Beam Asymmetry I_s (new)

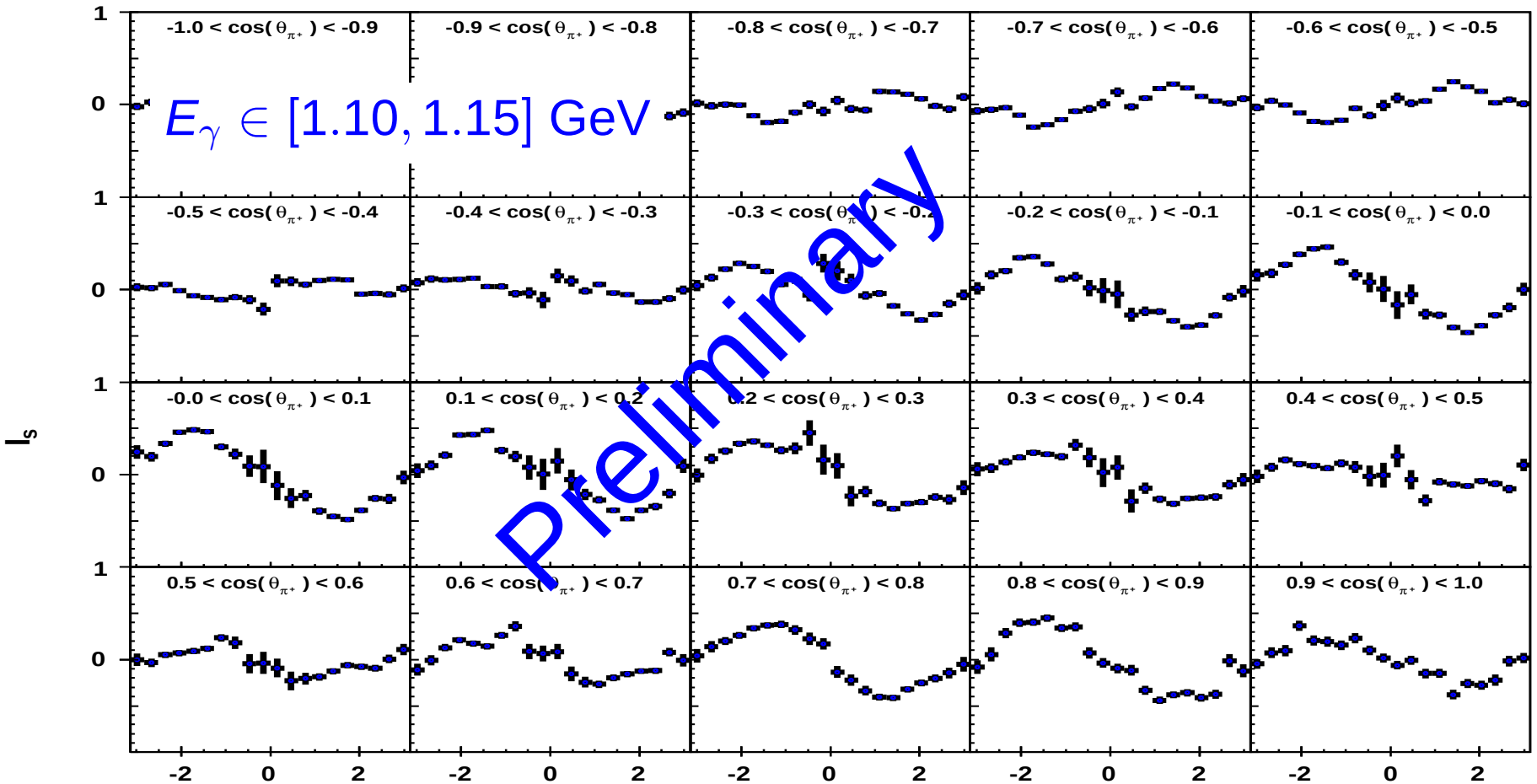


Two mesons in the final state require 5 independent variables

- 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

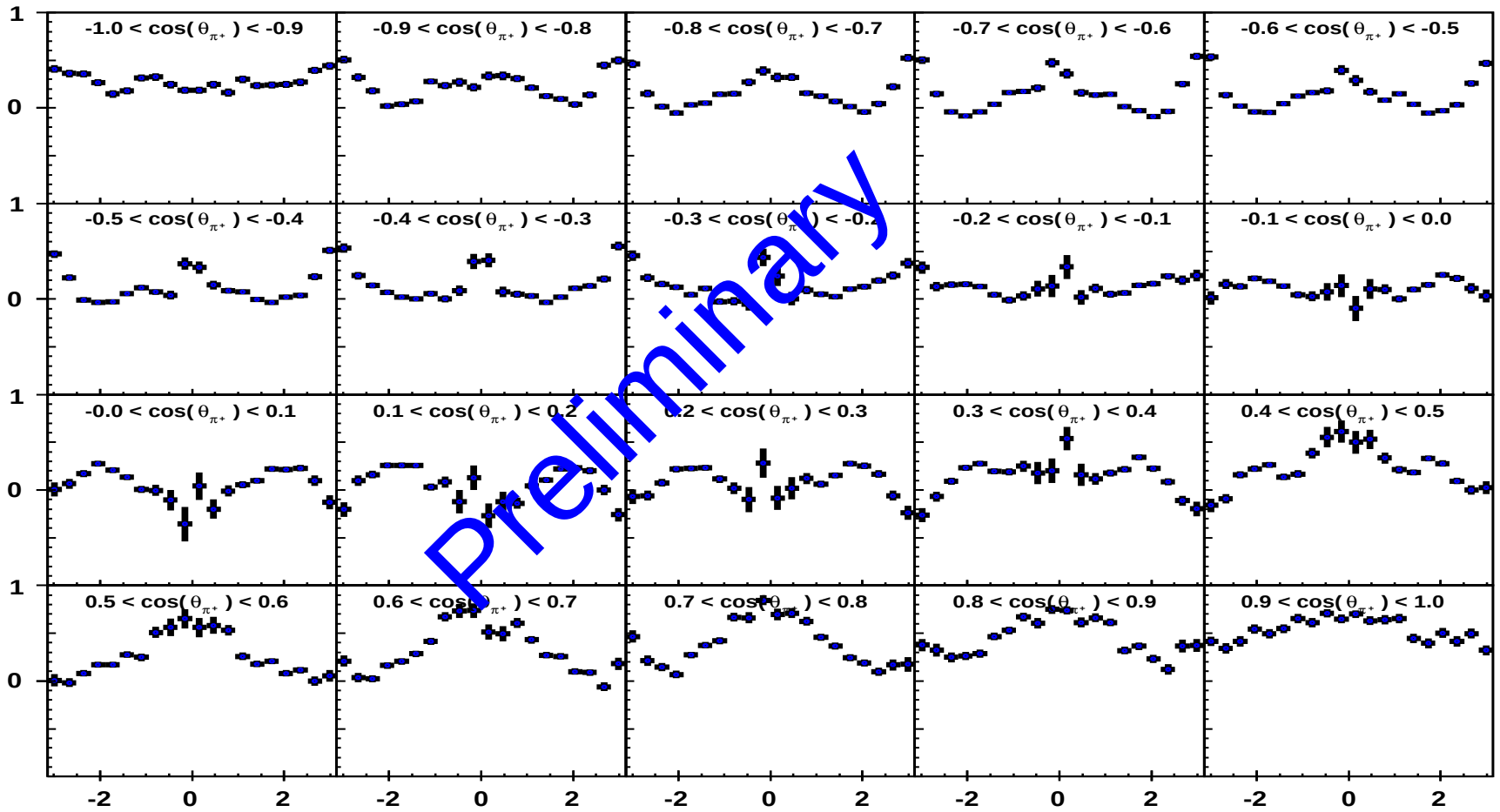
C. Hanretty (FSU), CLAS g8b run group, to be published

Photoproduction of $\pi^+\pi^-$: Beam Asymmetry I_s (new)



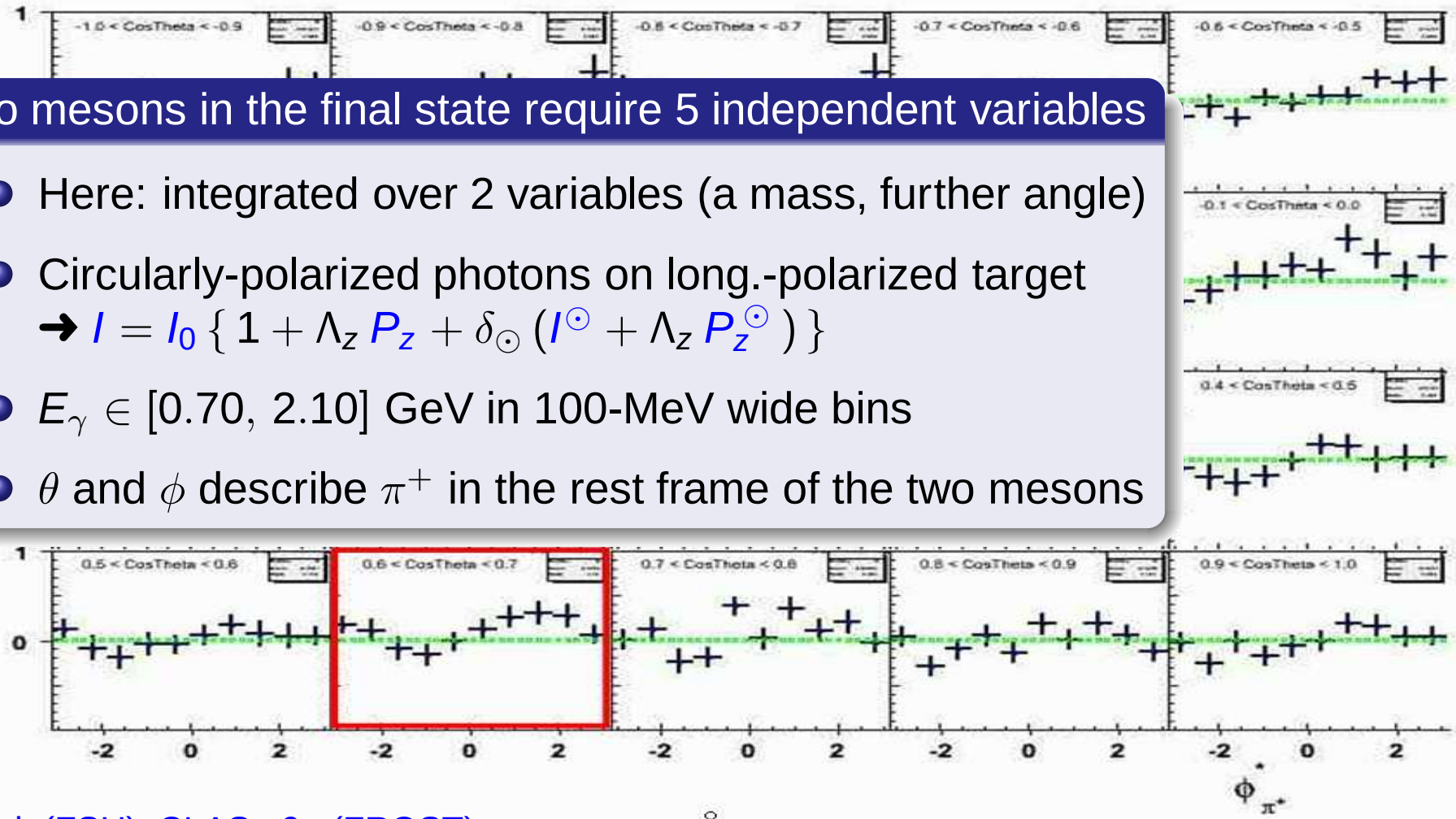
C. Hanretty (FSU), CLAS g8b run group, to be published

Photoproduction of $\pi^+\pi^-$: Beam Asymmetry I_c $(= \Sigma)$



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

Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^\odot$ ($= E$)



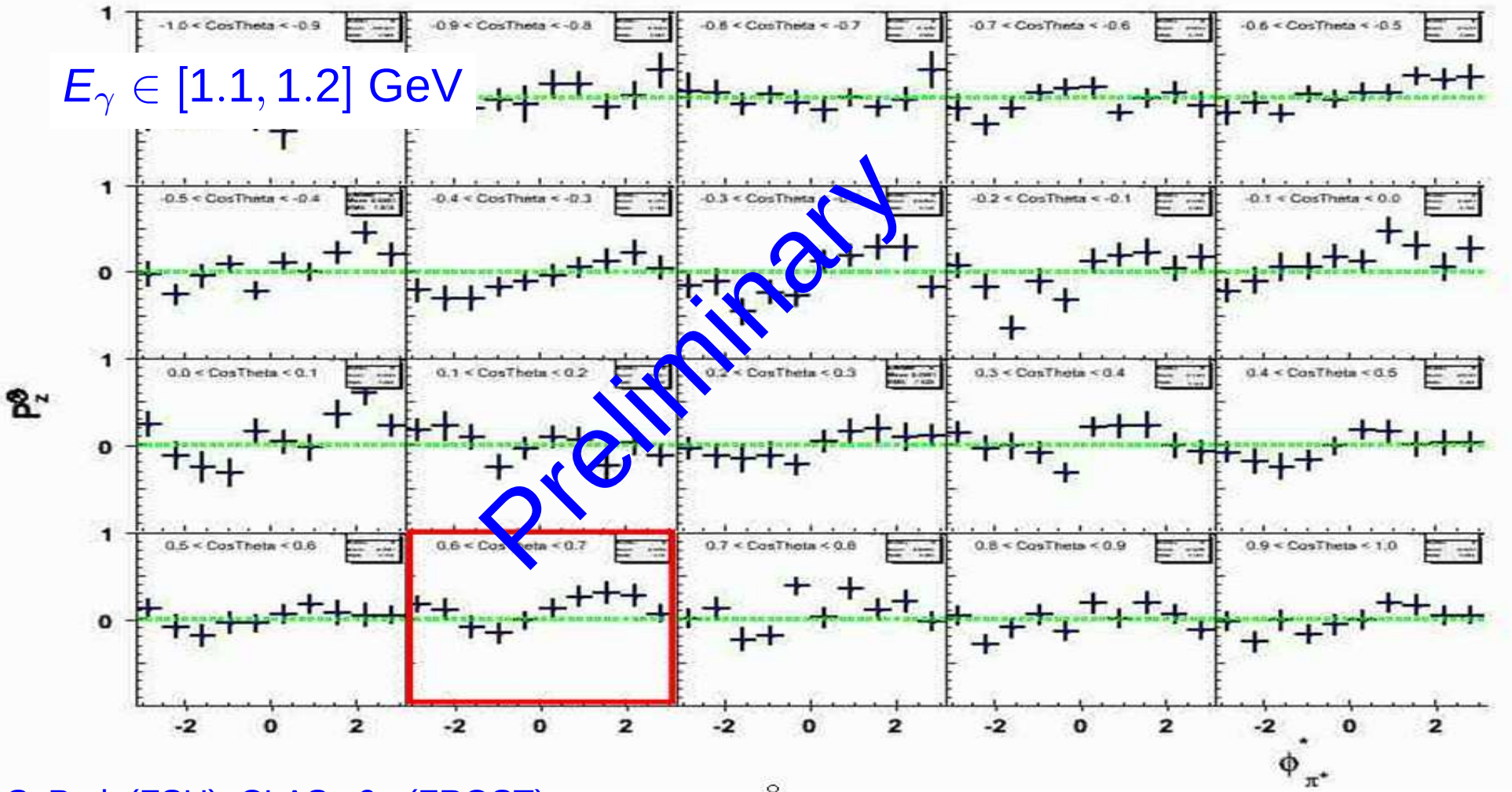
Two mesons in the final state require 5 independent variables

- Here: integrated over 2 variables (a mass, further angle)
- Circularly-polarized photons on long.-polarized target
  ➜ $I = I_0 \{ 1 + \Lambda_z P_z + \delta_\odot (I^\odot + \Lambda_z P_z^\odot) \}$
- $E_\gamma \in [0.70, 2.10]$ GeV in 100-MeV wide bins
- θ and ϕ describe π^+ in the rest frame of the two mesons

S. Park (FSU), CLAS g9a (FROST) run group

Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^{\odot}$ $(= E)$

$E_\gamma \in [1.1, 1.2]$ GeV



S. Park (FSU), CLAS g9a (FROST) run group

Outline

Summary and Outlook

Search for new excited baryon states in full swing:

- Precise cross-section measurements in several channels in nearly full phase space ($N\pi$, $N\eta$, $N\eta'$, $N\omega$, $K\Lambda$, $K\Sigma$, etc.)
- Precise photon beam asymmetries on proton and neutron targets (g8b & g13 run groups)
- Strong coupling of $N\omega$ to $N(1700)D_{13}$, $N(1680)F_{15}$, $N(2190)G_{17}$
  ➜ Hints for Capstick/Roberts $N(2000)F_{15}$ decaying into $N\omega$
- Double polarization observables with linear/circular photons and recoil hyperon polarization ➜ $N(1900)P_{13}$
- First data on polarized proton targets with circularly and linearly polarized beam (FROST)

(New) Baryon Resonances (e.g. Bonn-Gatchina PWA)

Reaction	Resonaces			
$\gamma p \to N\pi$	$\Delta(1232)P_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	$N(1535)S_{11}$
$\gamma p \to p\eta$	$N(1535)S_{11}$	$N(1720)P_{13}$	$N(2070)D_{15}$	$N(1650)S_{11}$
$\gamma p \to p\pi^0\pi^0$	$\Delta(1700)D_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	
$\gamma p \to p\pi^0\eta$	$\Delta(1940)D_{33}$	$\Delta(1920)P_{33}$	$N(2200)P_{13}$	$\Delta(1700)D_{33}$
$\gamma p \to \Lambda K^+$	$S_{11} - wave$	$N(1720)P_{13}$	$N(1900)P_{13}$	$N(1840)P_{11}$
$\gamma p \to \Sigma K$	$S_{11} - wave$	$N(1900)P_{13}$	$N(1840)P_{11}$	
$\pi^- p \to n\pi^0\pi^0$	$N(1440)P_{11}$	$N(1520)D_{13}$	$S_{11} - wave$	

The available data sets comprising various high-statistics differential cross sections, beam, target, recoil asymmetries, double polarization observables, and also data resolving isospin contributions are not yet sufficient to converge into a unique solution.