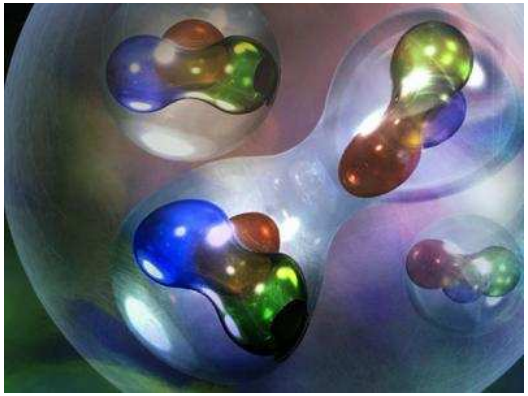
Understanding Excited Baryon Resonances: Results from polarization experiments at CLAS

Volker Credé

Florida State University, Tallahassee, FL



JLab Users Group Workshop

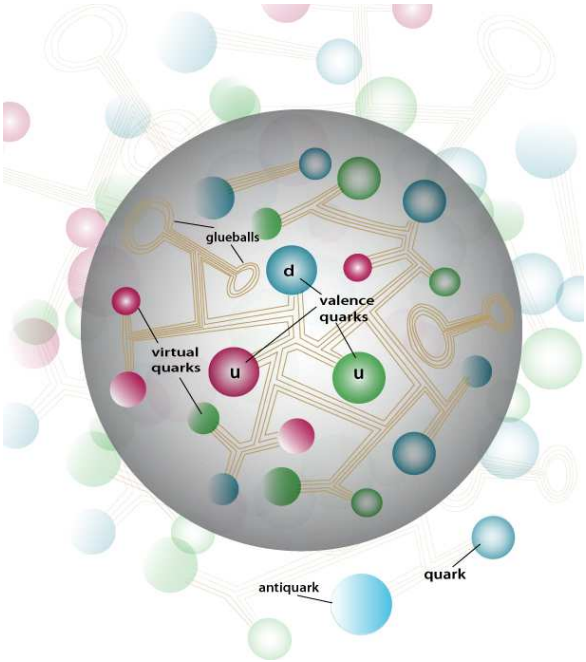
Jefferson Lab

06/04/2014

Outline

Outline

Non-Perturbative Quantum Chromodynamics (QCD)

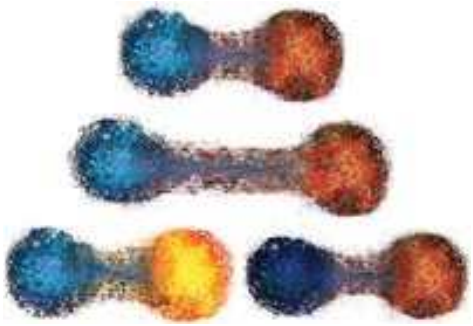


QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.

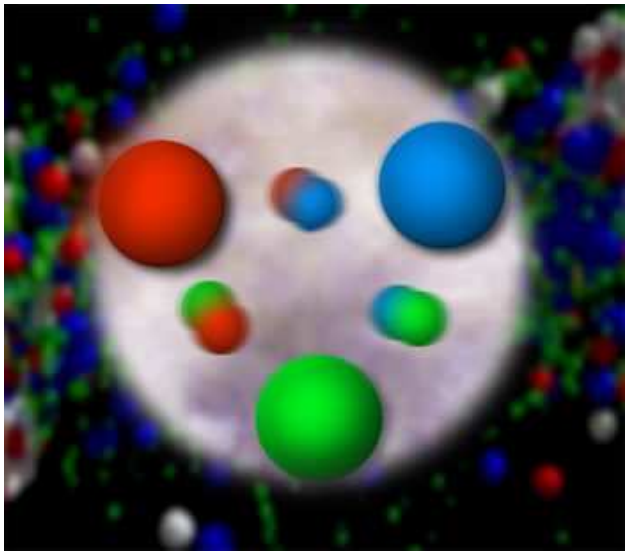
Quarks are confined within hadrons.

Confinement of quarks and gluons within nucleons is a non-perturbative phenomenon, and QCD is extremely hard to solve in non-perturbative regimes: Knowledge of internal structure of nucleons is still limited.



This is particularly true for excited nucleons.

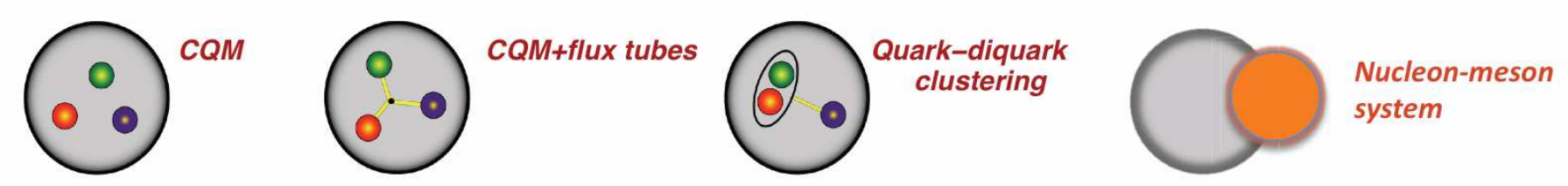
Non-Perturbative QCD



How does QCD give rise to excited hadrons?

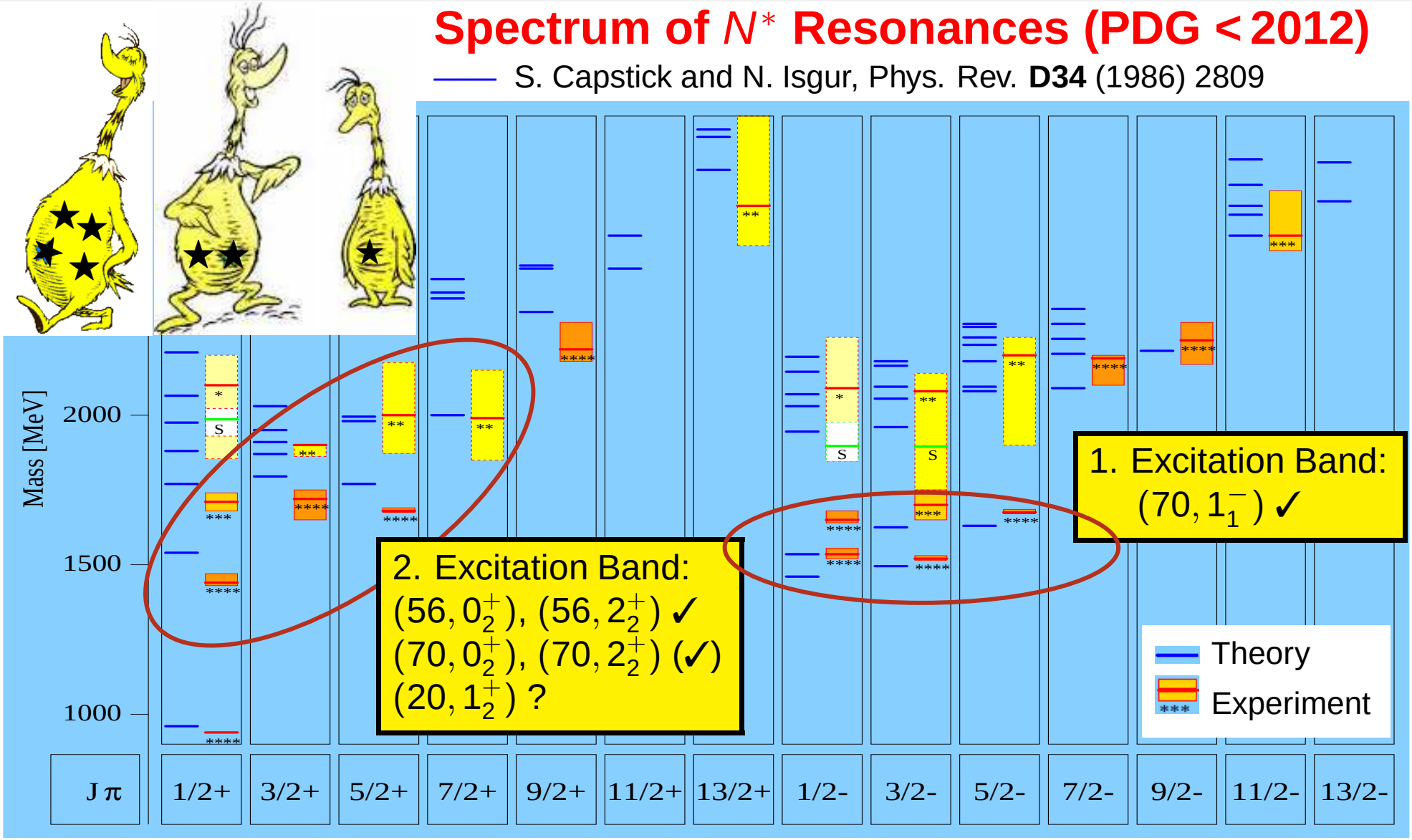
1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. Would the answers to these questions explain the origin of $\sim 98\,\%$ of observed matter in the universe?

Excited Baryons: What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?



Spectrum of N^* Resonances (PDG < 2012)

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



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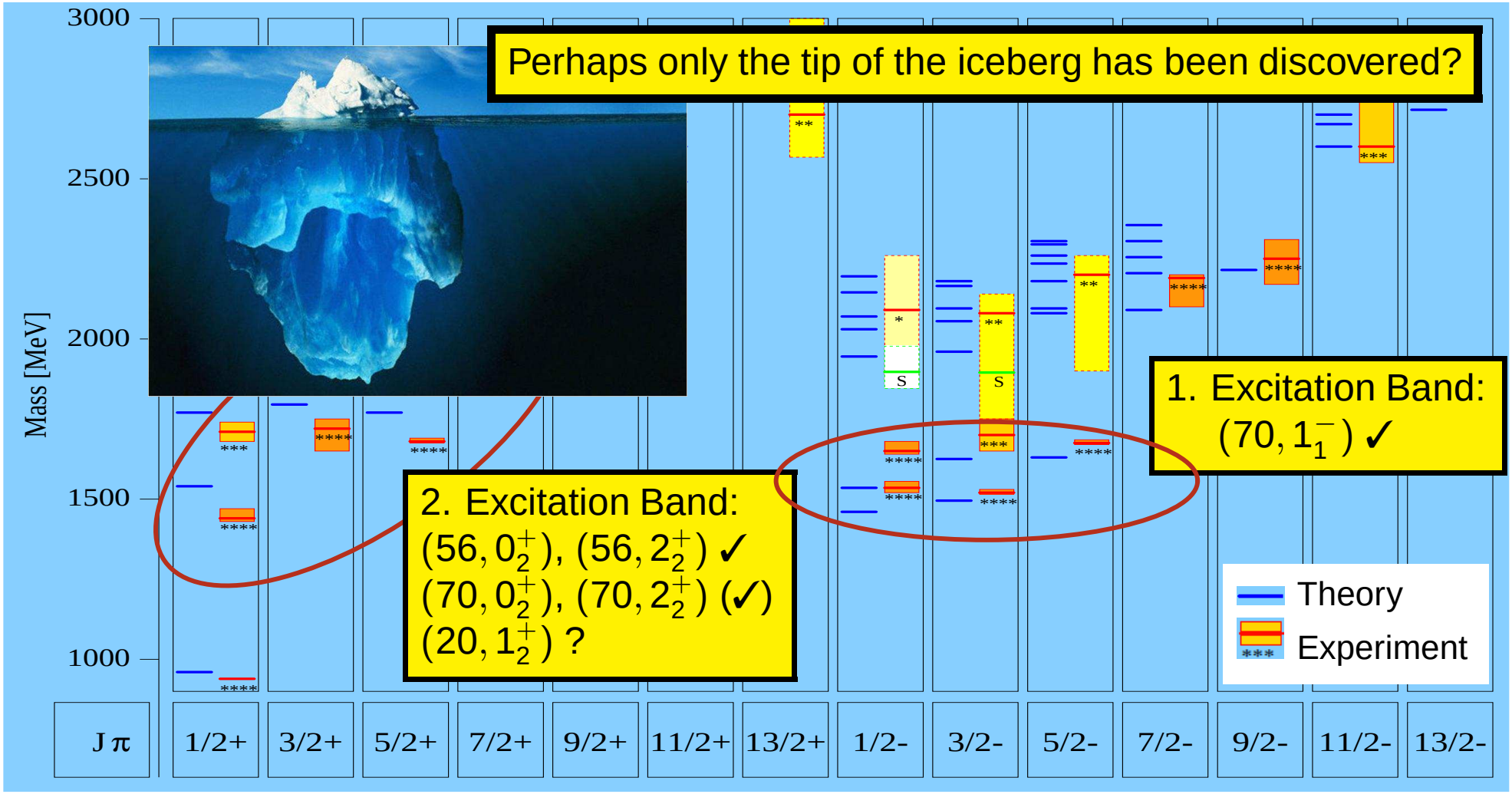

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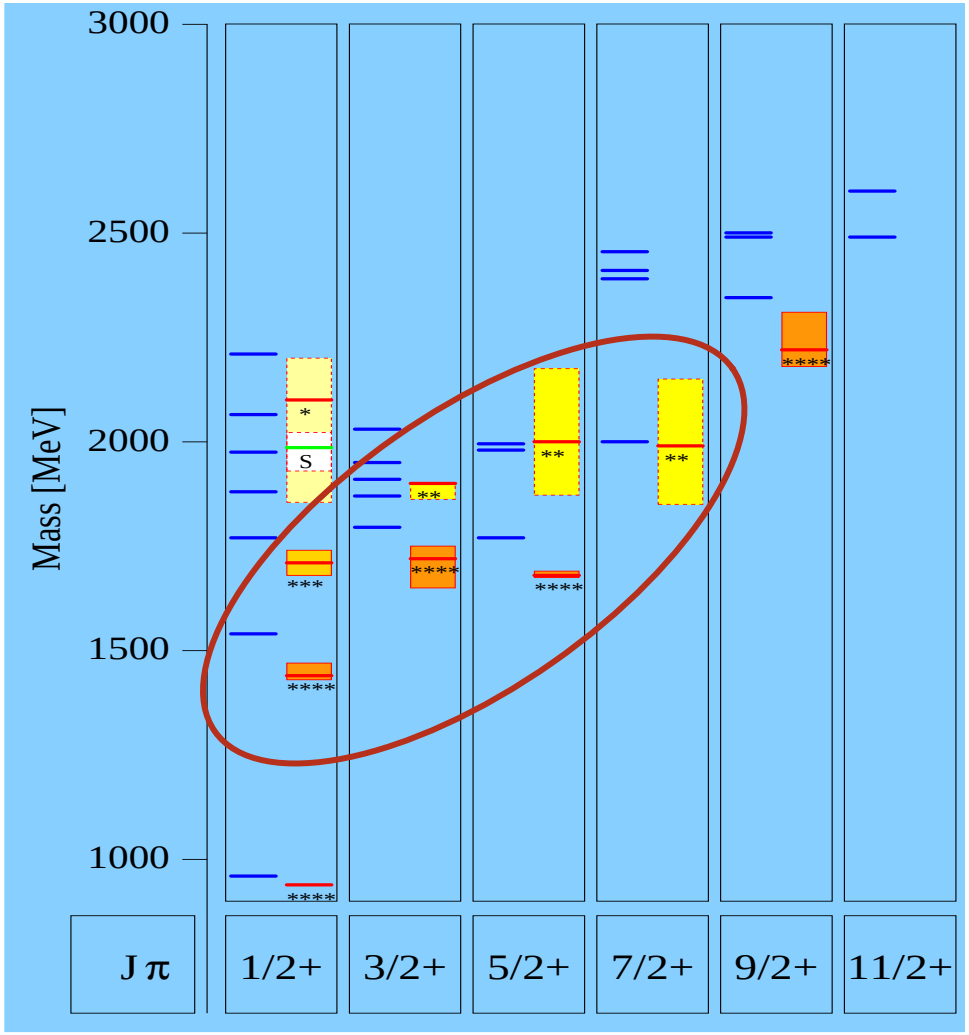
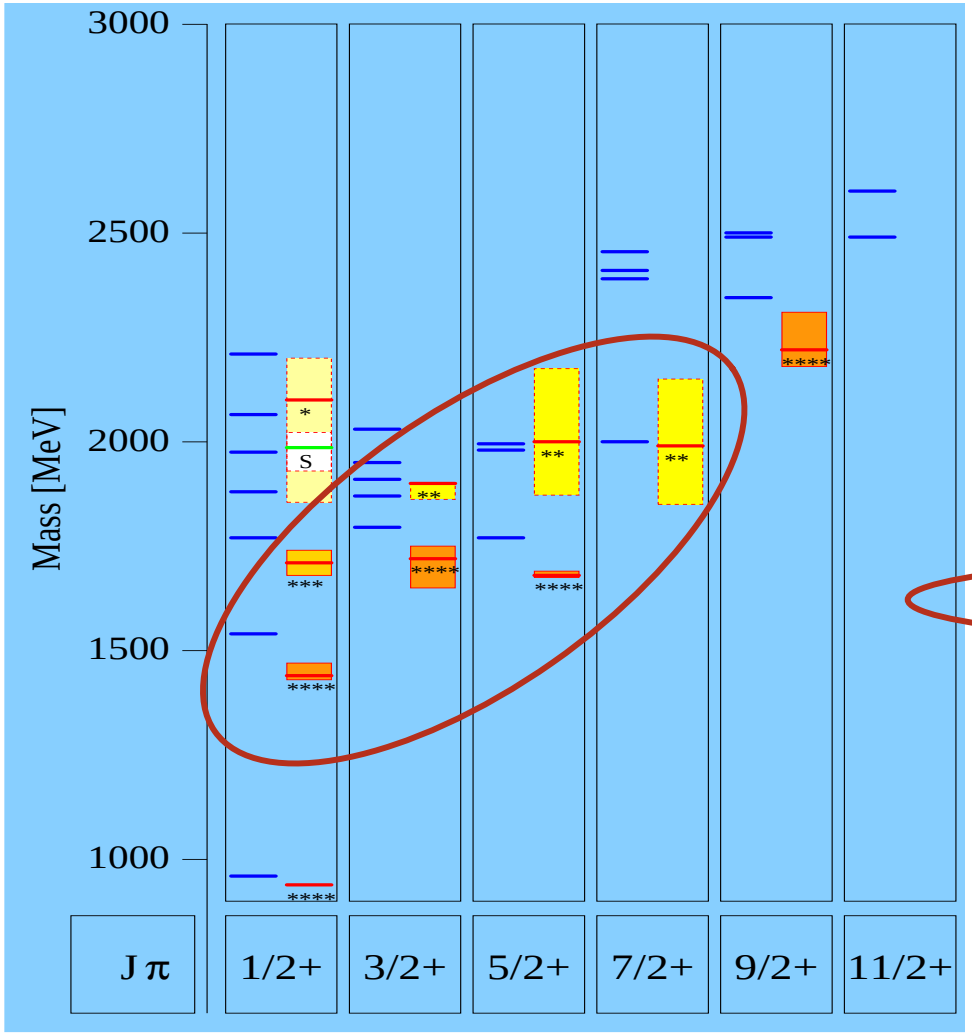


V.C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	* * **	* * **
$N(1520)$	$3/2^-$ (D_{13})	* * **	* * **
$N(1535)$	$1/2^-$ (S_{11})	* * **	* * **
$N(1650)$	$1/2^-$ (S_{11})	* * **	* * **
$N(1675)$	$5/2^-$ (D_{15})	* * **	* * **
$N(1680)$	$5/2^+$ (F_{15})	* * **	* * **
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	* * *	* * *
$N(1710)$	$1/2^+$ (P_{11})	* * *	* * *
$N(1720)$	$3/2^+$ (P_{13})	* * **	* * **
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		* * *
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	* * *
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	* * **	* * **
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	* * **	* * **

Spectrum of N^* Resonances



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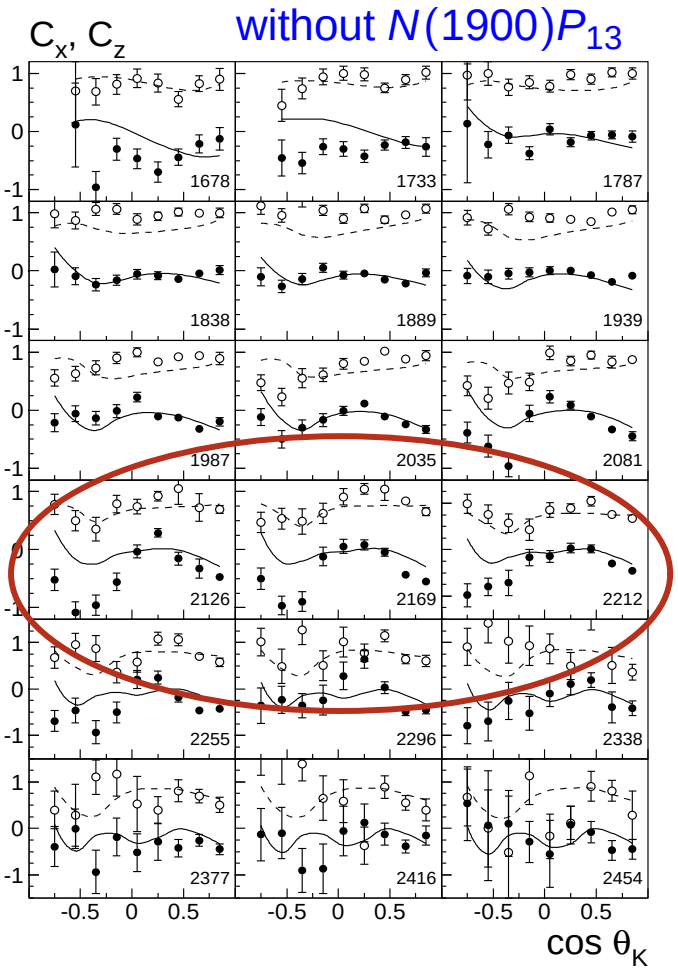
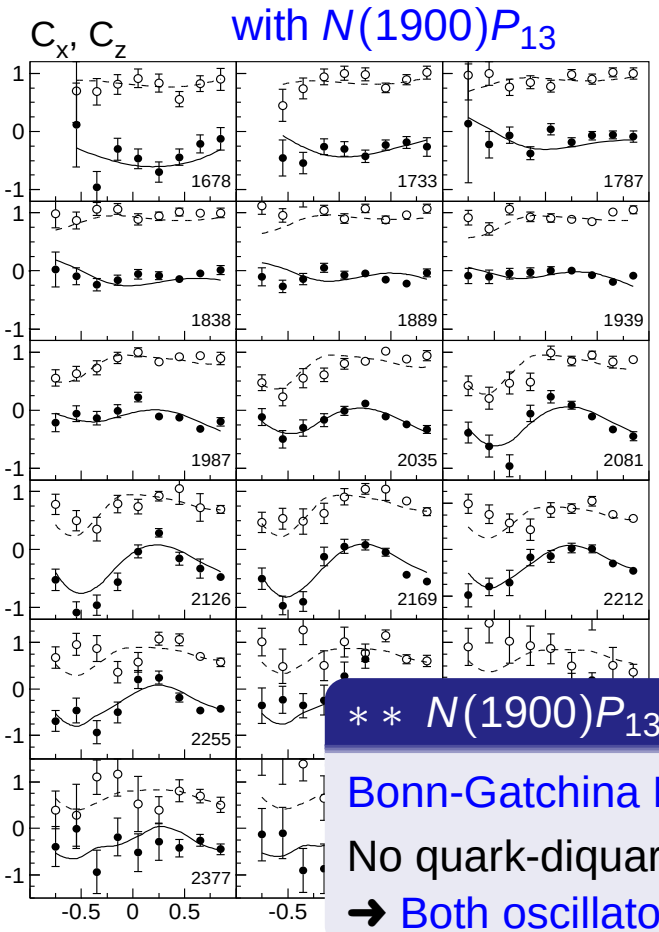
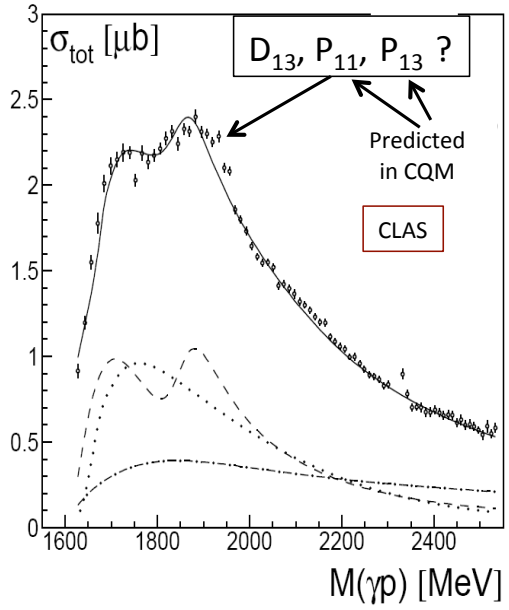
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	* * **	* * **

Polarization Transfer in $\vec{\gamma}p \to K^+\vec{\Lambda}$: C_x, C_z







$N(1900)P_{13}$, $N(2000)F_{15}$, $N(1990)F_{17}$

Bonn-Gatchina PWA requires $N(1900)P_{13}$

No quark-diquark oscillations!

➜ Both oscillators need to be excited.

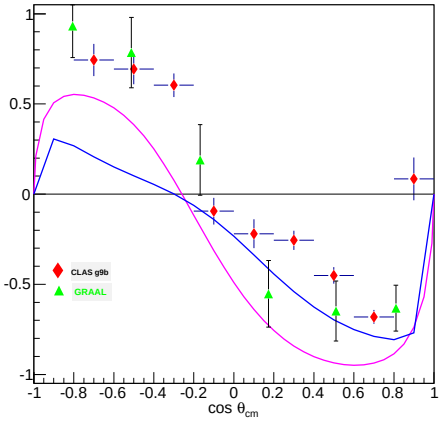
R. Bradford *et al.* [CLAS Collaboration], Phys. Rev. C **75**, 035205 (2007)

Fits: BoGa-Model, V. A. Nikonov *et al.*, Phys. Lett. B **662**, 245 (2008)

Complete Experiment for K^+Y: $1.65 < W < 2.2$ GeV

$\gamma p \rightarrow K^+\Lambda$ | $K^+\Sigma^0$

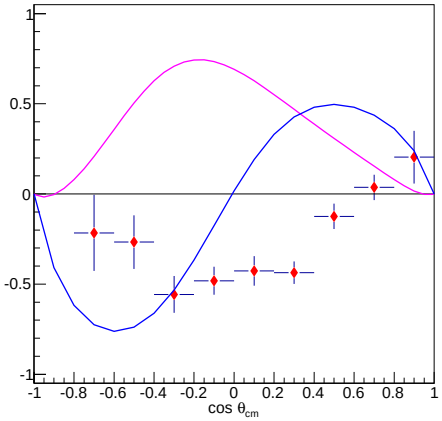
$W \in [1.90, 1.95]$ GeV



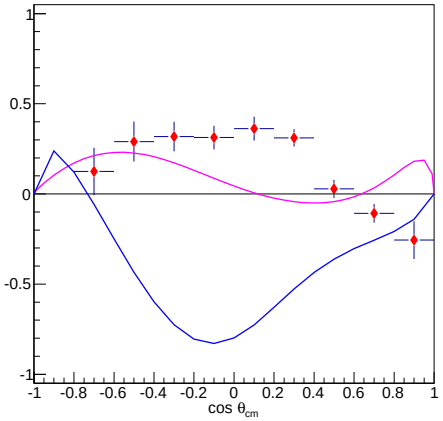
T

T_x T_z

$W \in [1.85, 1.90]$ GeV

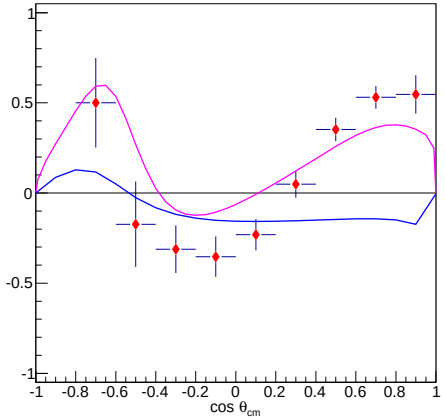


$W \in [1.90, 1.95]$ GeV



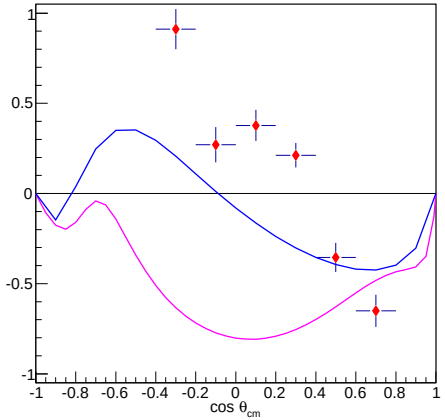
T

$W \in [2.10, 2.15]$ GeV



T_x

$W \in [1.95, 2.00]$ GeV



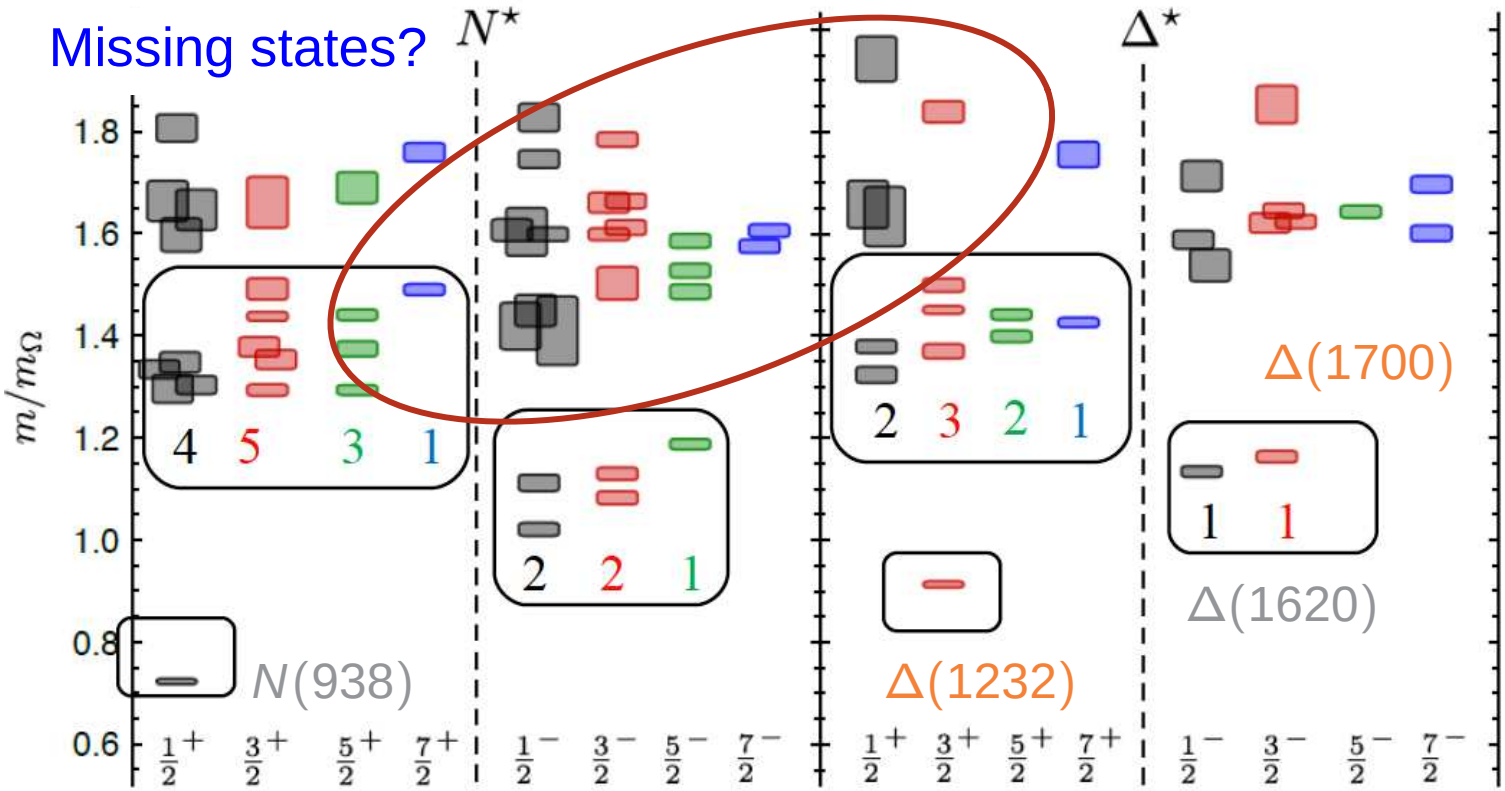
BoGa

MAID

N. Walford *et al.* [CLAS Collaboration], FROST run group

Excited-State Baryon Spectroscopy from Lattice QCD

R. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011)



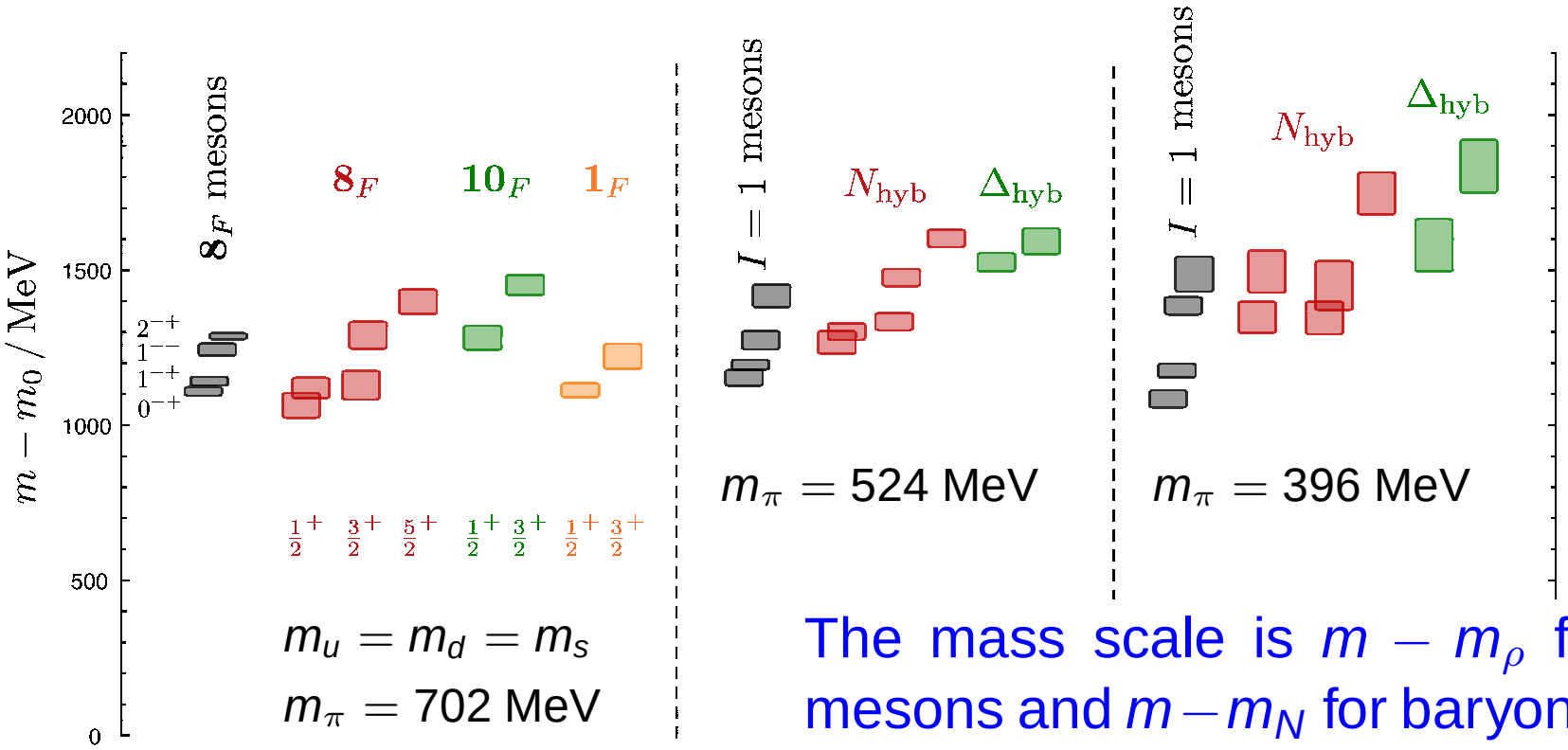
$m_\pi = 396$ MeV

Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ Counting of levels consistent with non-rel. quark model, no parity doubling

Gluonic Excitations on the Lattice

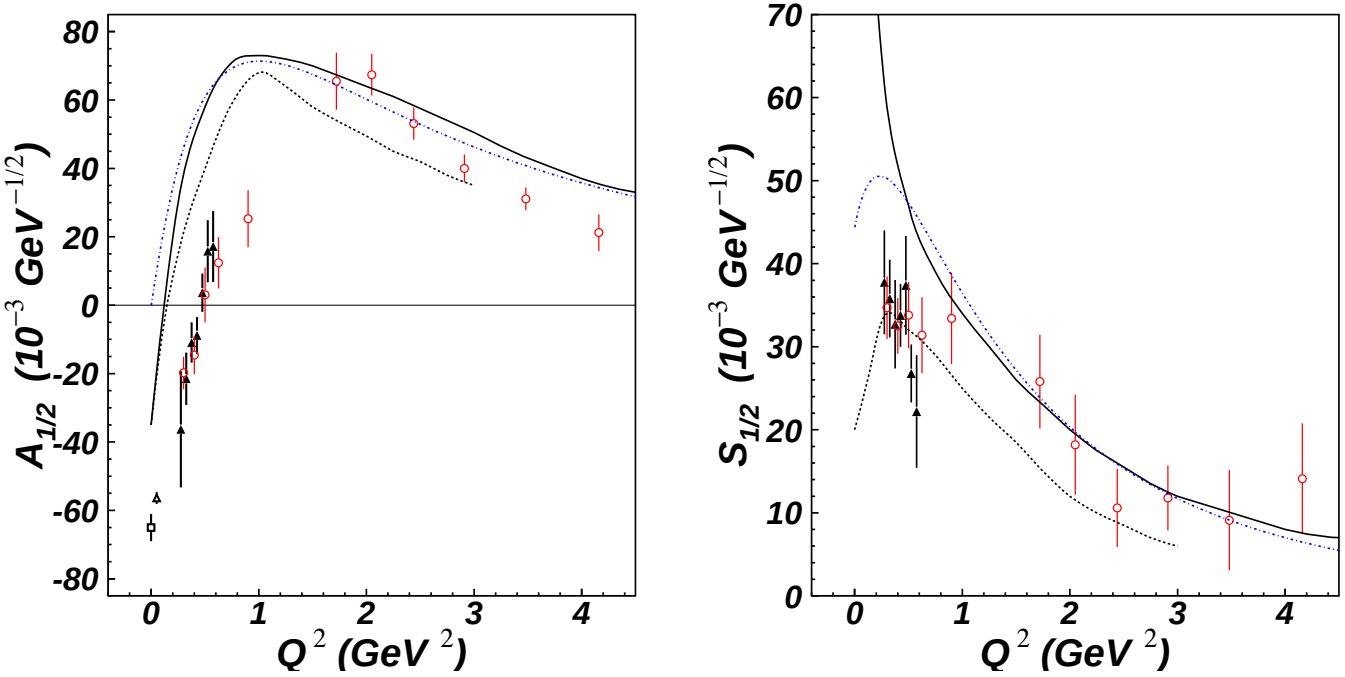
J. J. Dudek and R. G. Edwards, Phys. Rev. D **85**, 054016 (2012)



The mass scale is $m - m_\rho$ for mesons and $m - m_N$ for baryons.

Common scale of $\sim$ 1.3 GeV for gluonic excitation, but hybrid baryons are difficult to identify experimentally.

Helicity Amplitudes for the "Roper" Resonance



Data from CLAS

$A_{1/2}$ and $S_{1/2}$ amplitudes:
e.g. V. Mokeev *et al.*,
PRC **86**, 035203 (2012);
PRC **80**, 045212 (2009).

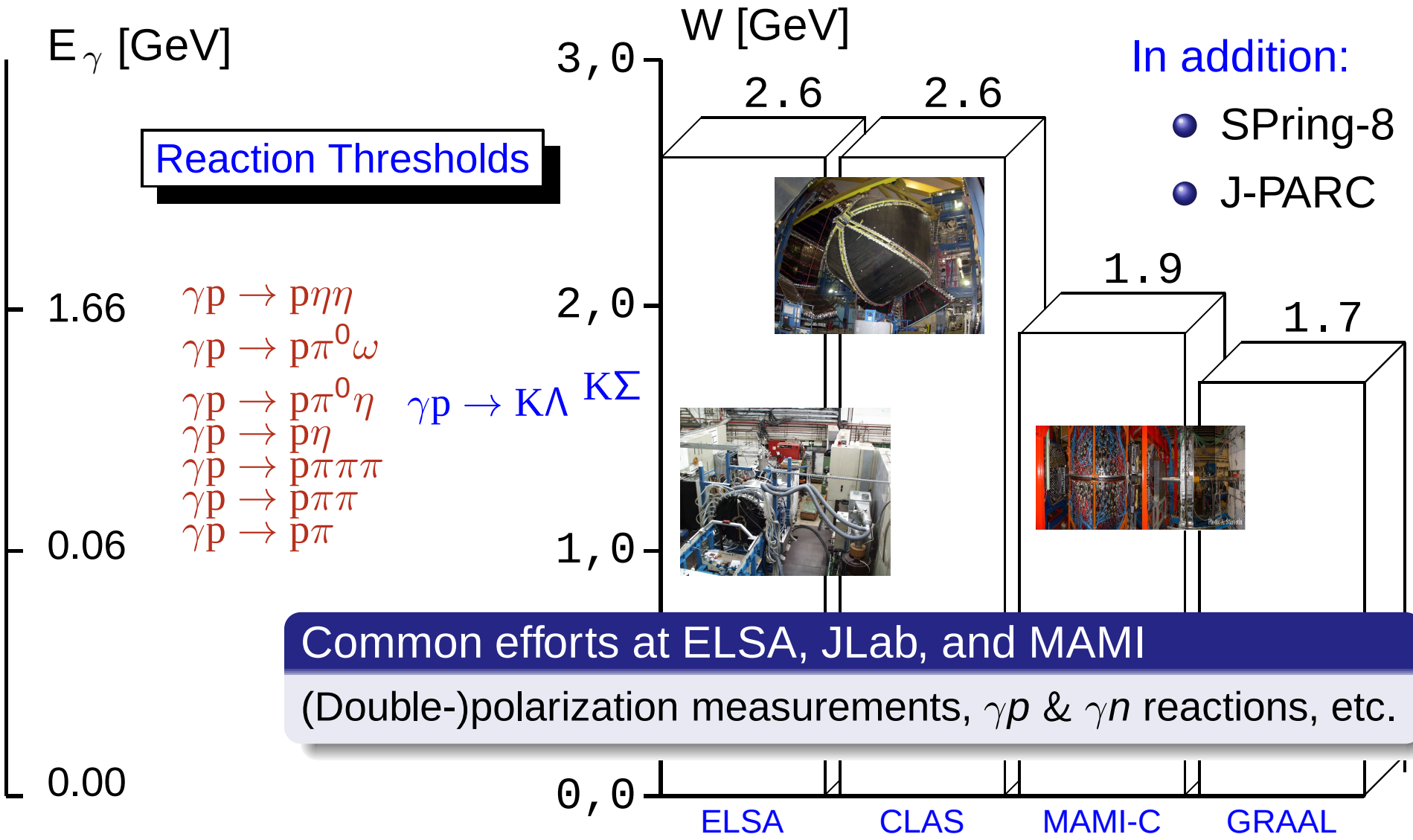
Quark-model calculations:
—- q^3 radial excitation
- - - q^3G hybrid state

Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

- At short distances (high Q^2), Roper behaves like radial excitation.
- Low Q^2 behavior not well described by LF quark models: e.g. meson-baryon interactions missing

➜ Gluonic excitation likely ruled out!

Outline



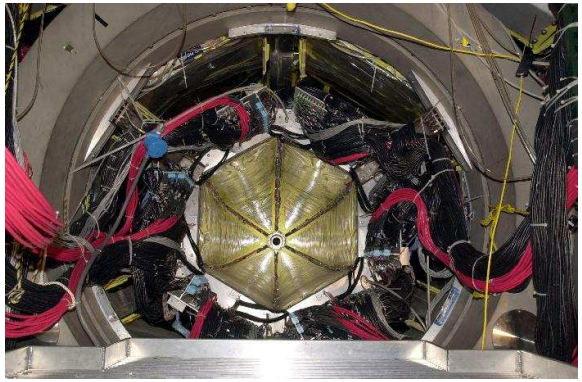
In addition:

- SPring-8
- J-PARC

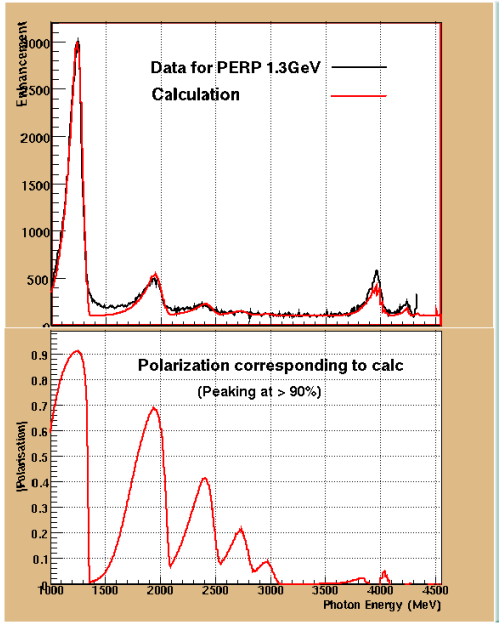
Common efforts at ELSA, JLab, and MAMI

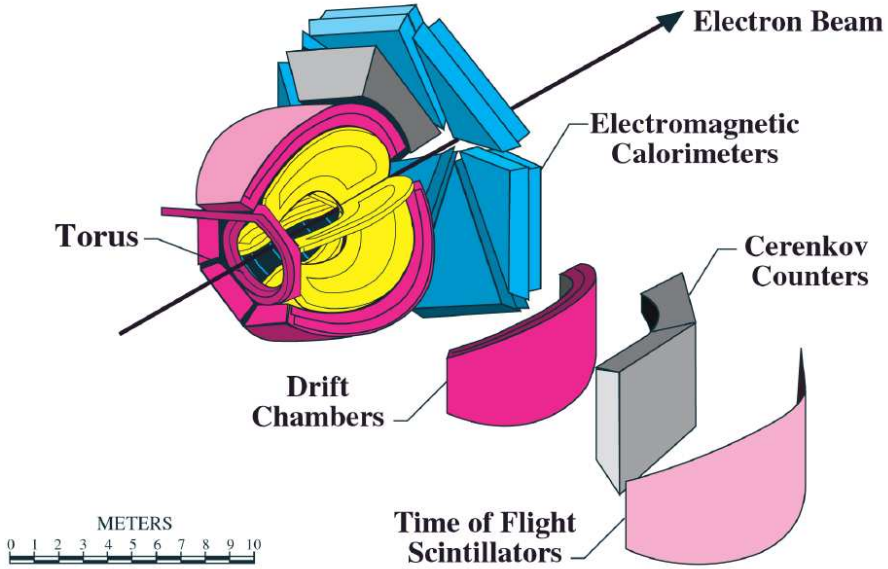
(Double-)polarization measurements, γp & γn reactions, etc.

The CLAS Spectrometer at Jefferson Laboratory

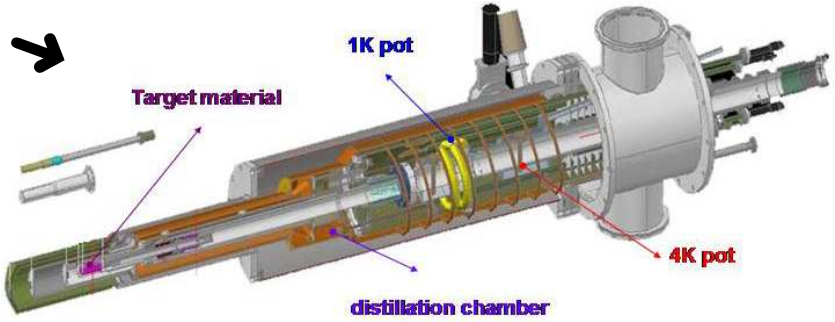


g8b
linear beam polarization





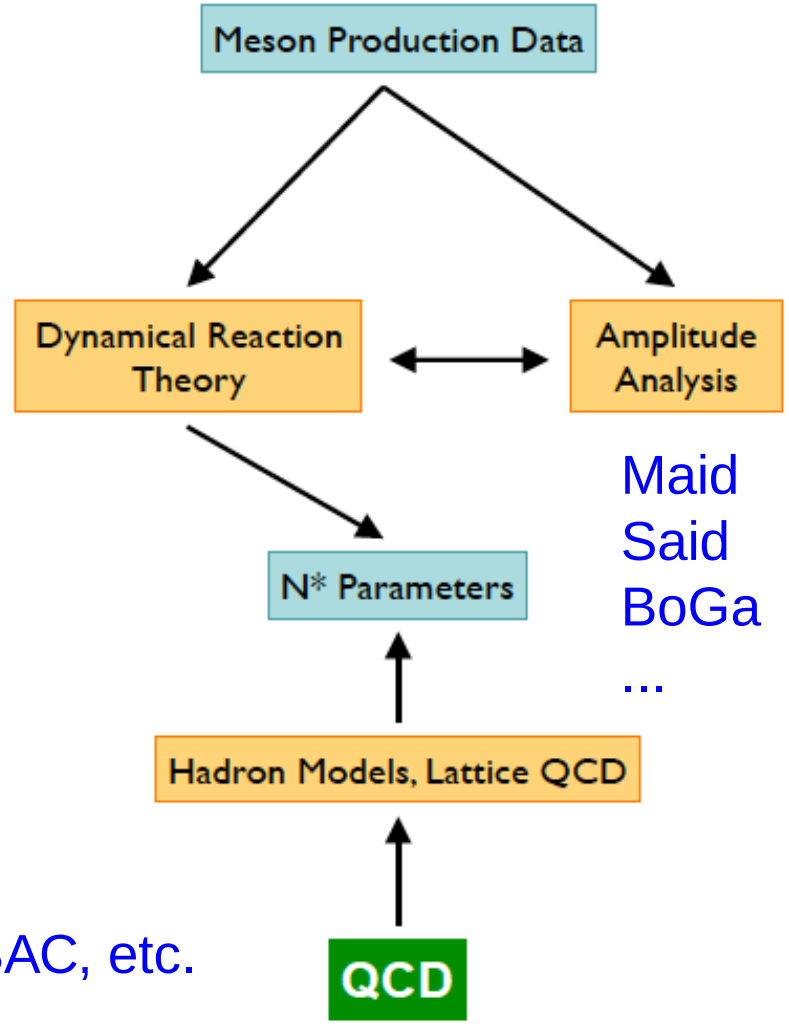
FROST
double polarization



Extraction of Resonance Parameters

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

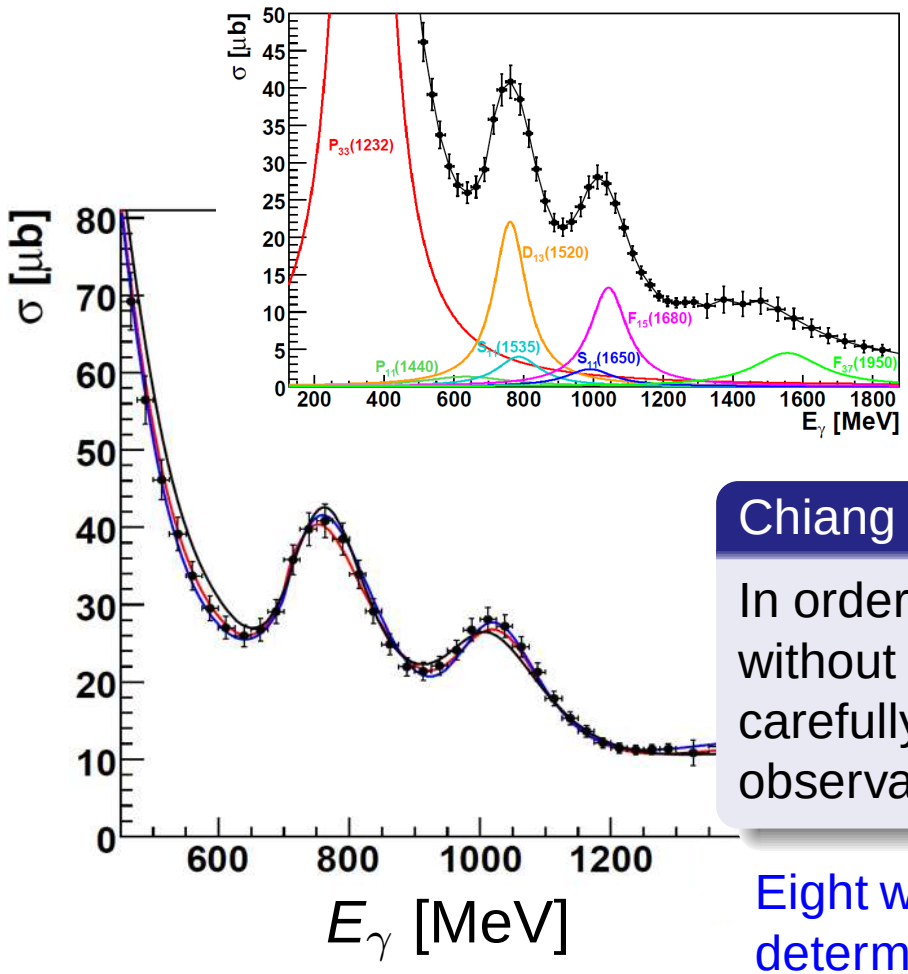
Coupled Channels



Maid
Said
BoGa
...

Jülich, Gießen, EBAC, etc.

Why are Polarization Observables Important?



$\gamma p \to p\pi^0$

For single-meson production:

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

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: <u>four</u> double-spin observables along with <u>four</u> single-spin observables.

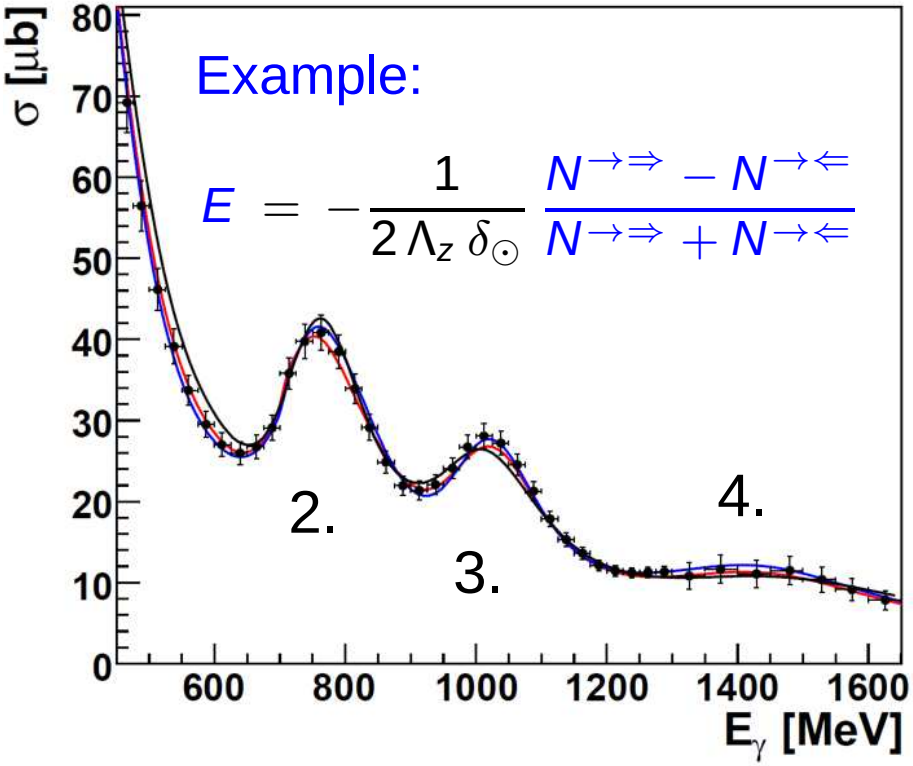
Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.

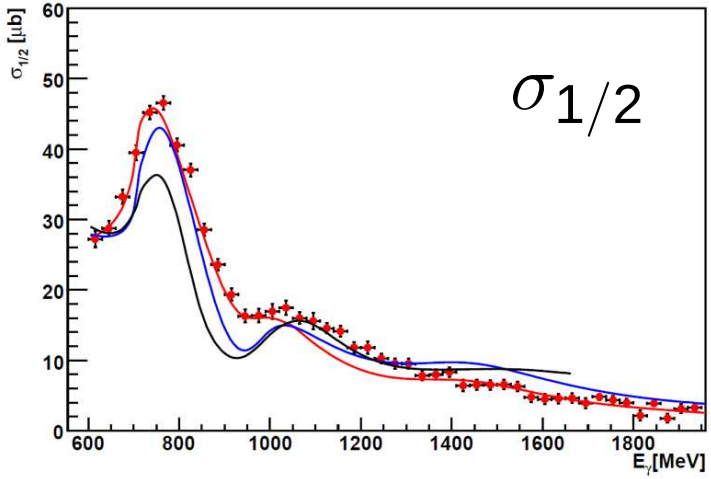
Example: Ambiguities in $\gamma\, p \to p\, \pi^0$

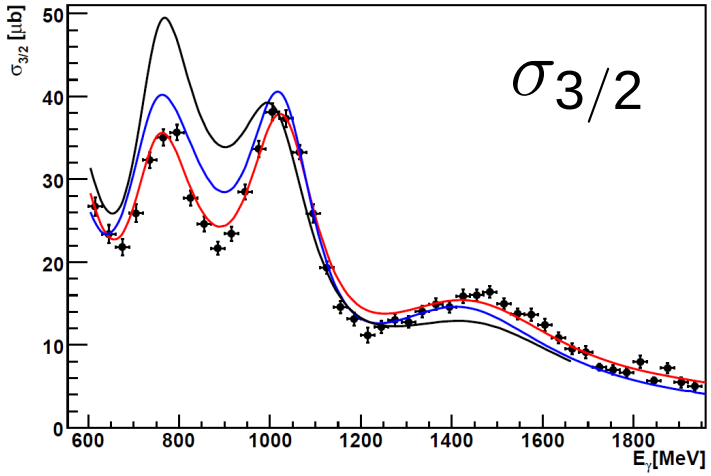
— Bonn-Gatchina (2011-02)

— SAID (SN11, CM12)

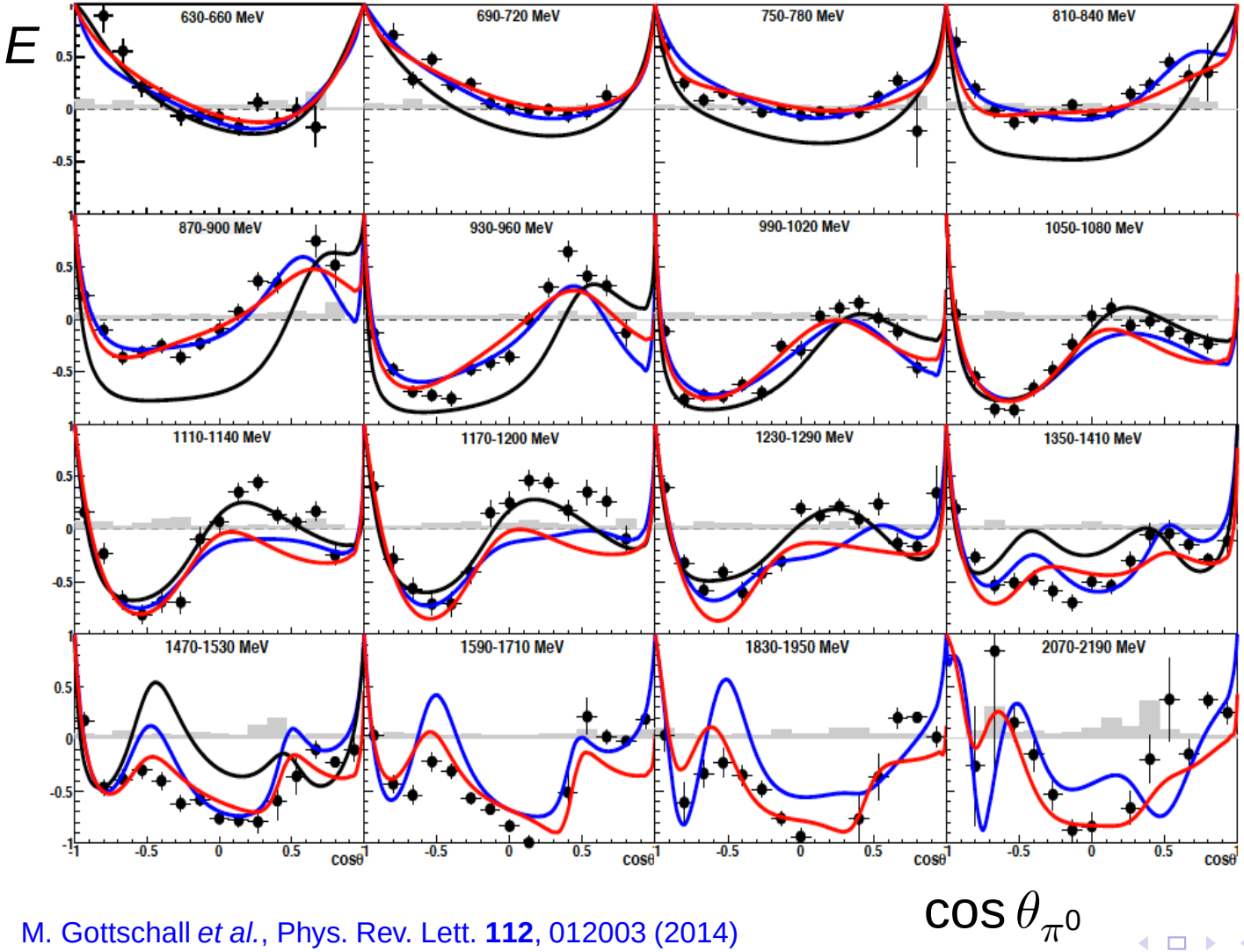
— MAID







Helicity Asymmetry E in $\vec{\gamma}\vec{p} \to p\,\pi^0$ @ ELSA



$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

$E_\gamma \in [0.6, 2.2]$ GeV

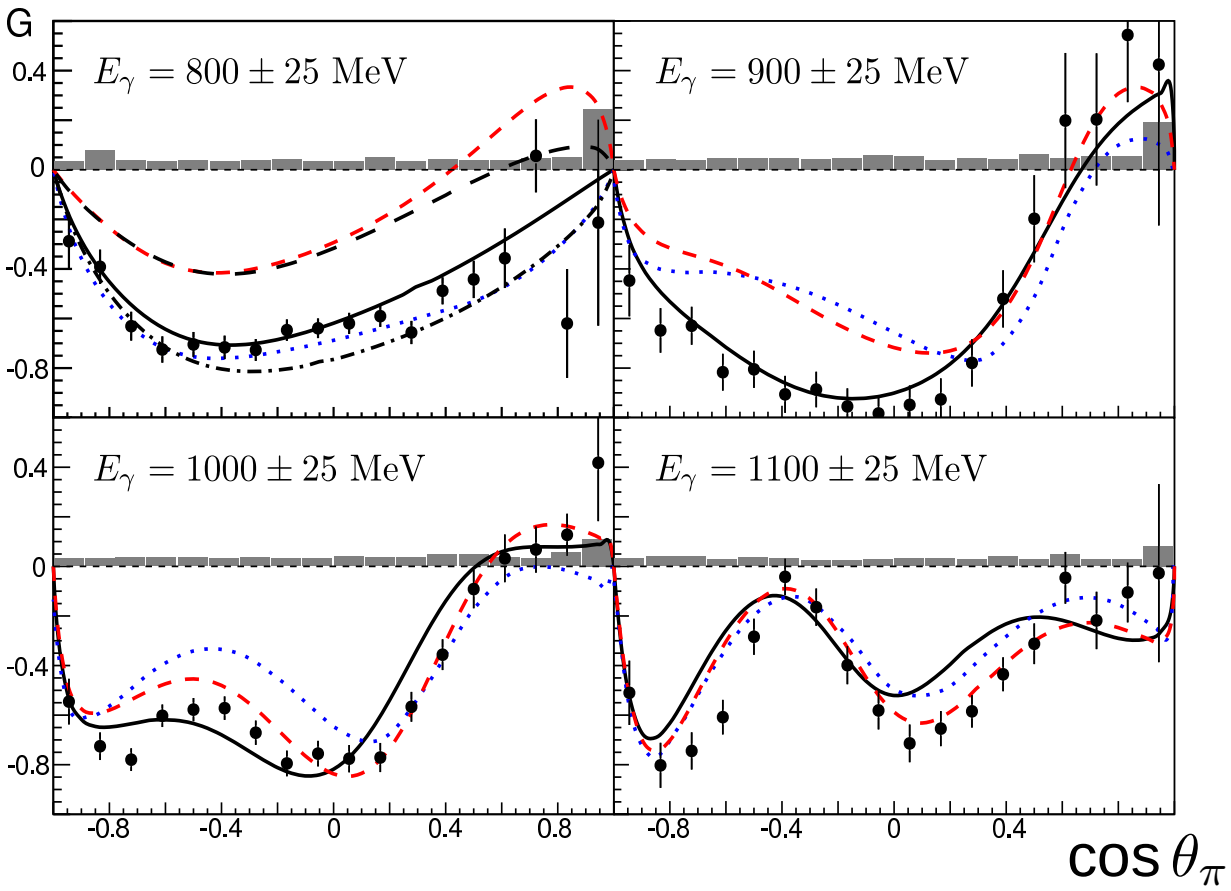
- • CBELSA/TAPS
- — Maid
- — Said (CM12)
- — BoGa (2011_2)

Angular distributions sensitive to interference between resonances.

M. Gottschall *et al.*, Phys. Rev. Lett. **112**, 012003 (2014)

Outline

Asymmetry G in $\vec{\gamma}\vec{p} \to p\,\pi^0$ @ ELSA



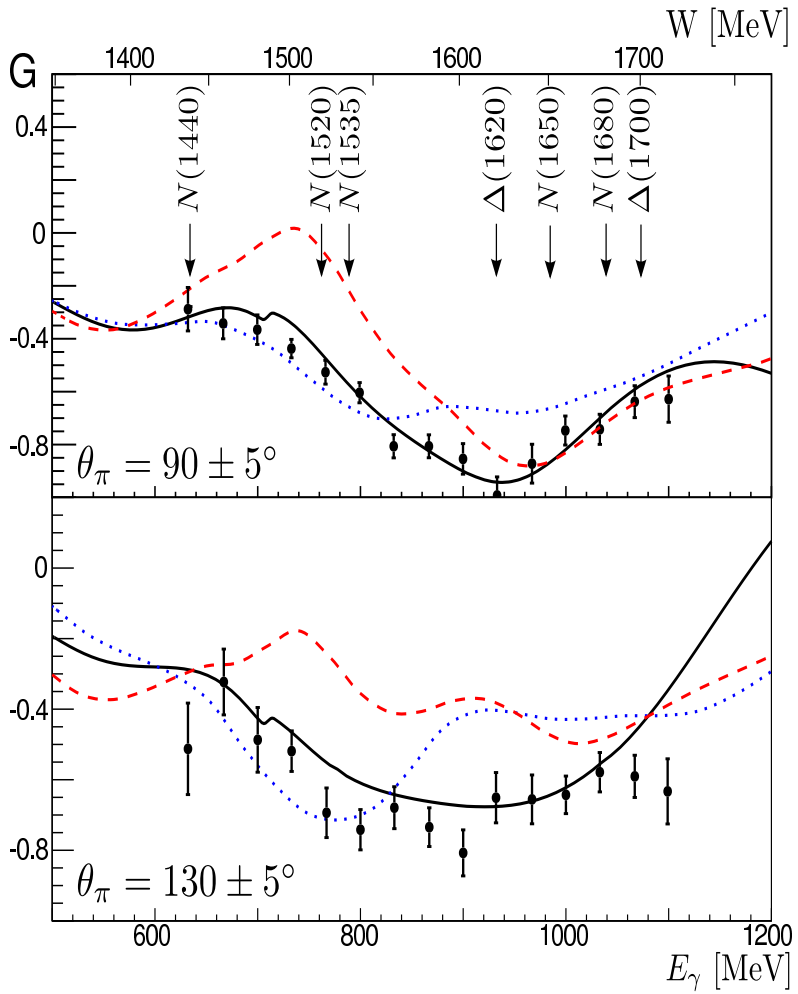
$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_l P \cos 2\phi) - \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E) \}$$

Surprisingly, π production also not well understood at lower energies:

— BoGa
-- SAID
···· MAID

A. Thiel *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **109**, 102001 (2012)

Asymmetry G in $\vec{\gamma}\vec{p} \to p\,\pi^0$ @ ELSA



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$\theta_\pi = 90 \pm 5°$

$\theta_\pi = 130 \pm 5°$

Surprisingly, π production also not well understood at lower energies.

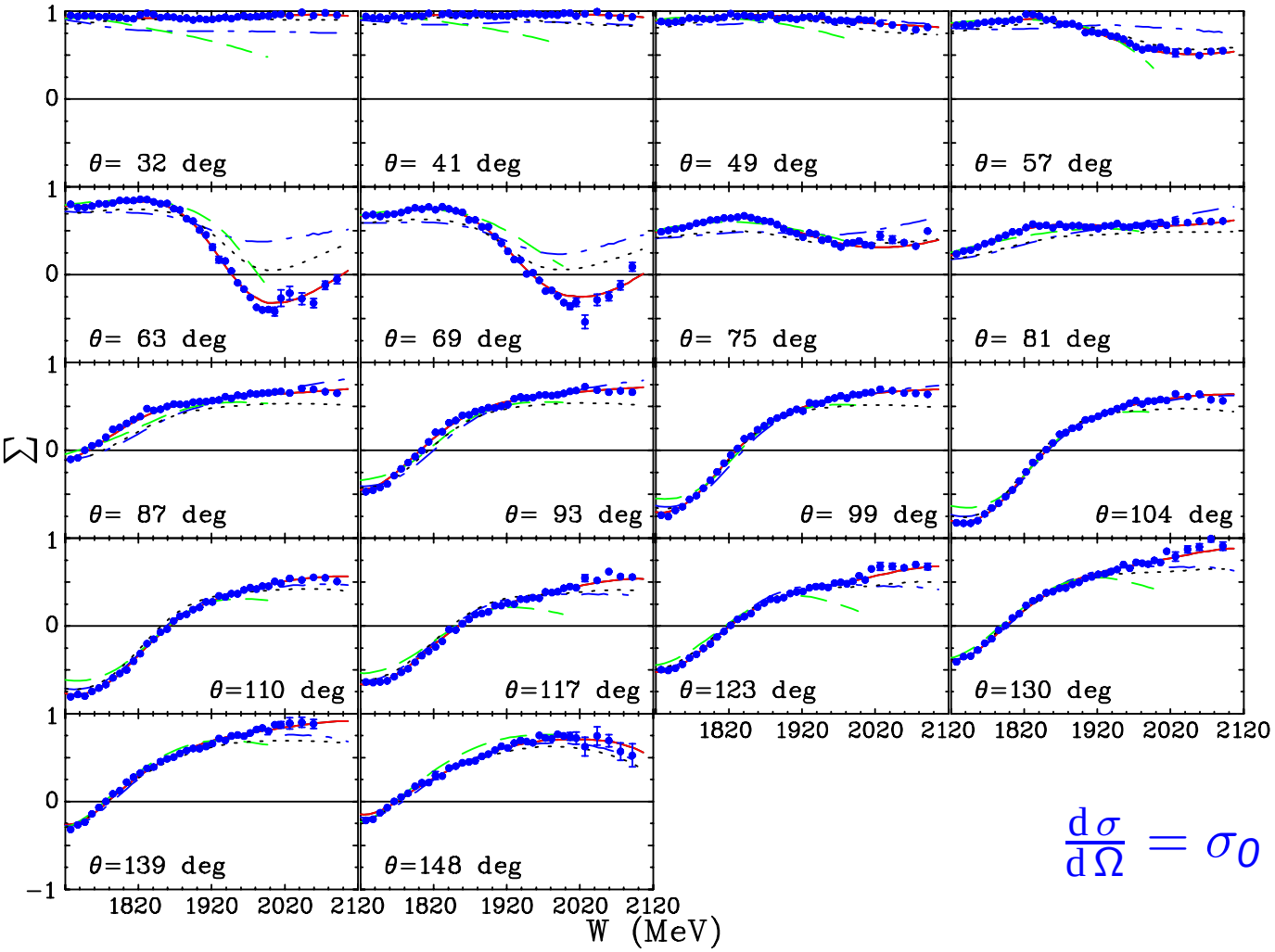
Below 1 GeV, discrepancies can be traced to the E_{0+} and E_{2-} multipoles, which are related to certain resonances:

E_{0+}: $N(1535)\,\frac{1}{2}^-$, $N(1650)\,\frac{1}{2}^-$, $\Delta(1620)\,\frac{1}{2}^-$

E_{2-}: $N(1520)\,\frac{3}{2}^-$, $\Delta(1700)\,\frac{3}{2}^-$

A. Thiel *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **109**, 102001 (2012)

Beam Asymmetry Σ in $\vec{\gamma}\,p \to p\,\pi^0$ @ CLAS (g8b)

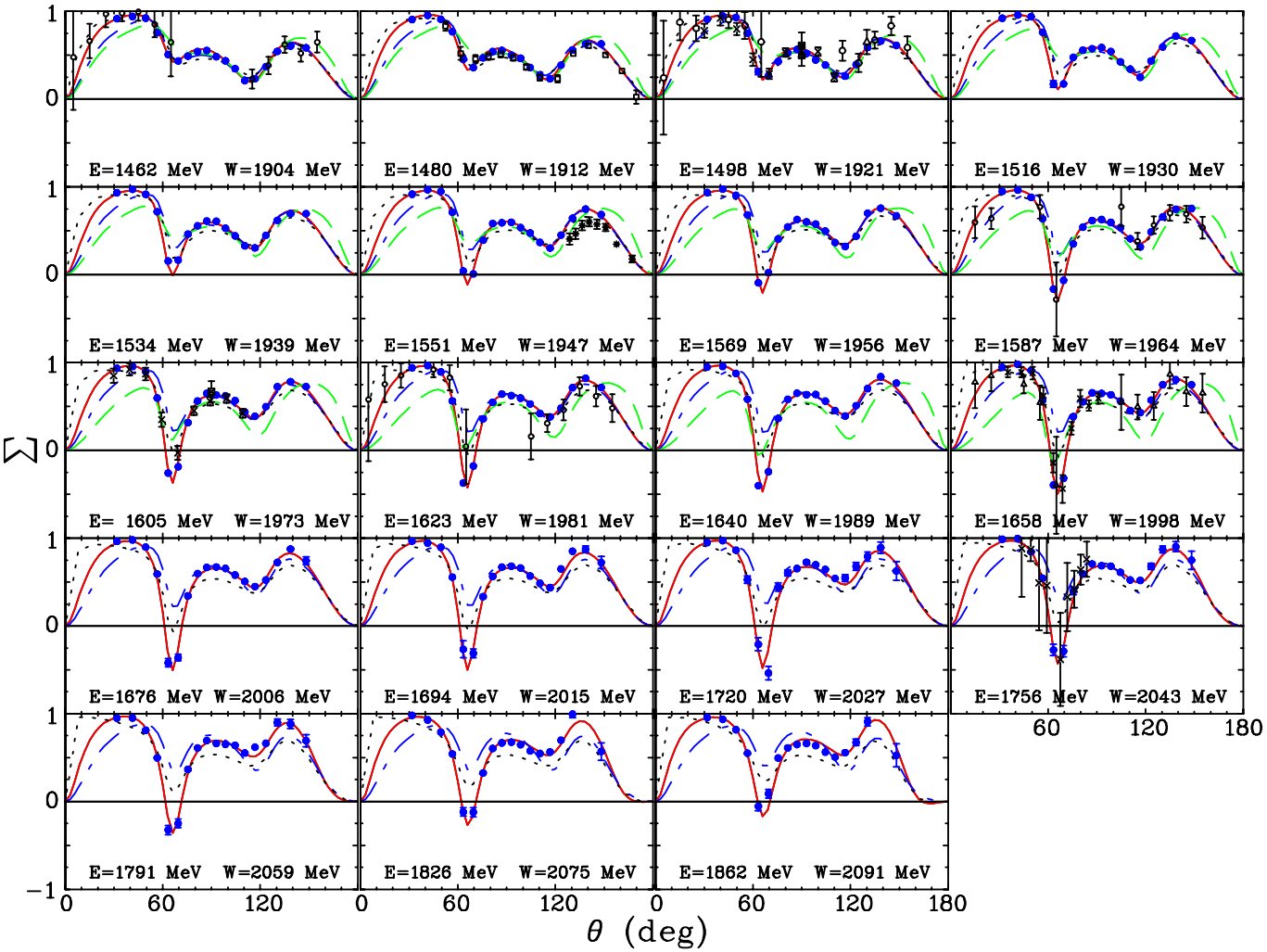


SAID DU13
SAID CM12
MAID 07
BoGa 2011-02

$$\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_l \, \Sigma \cos 2\phi \right\}$$

M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. C **88**, 065203 (2013)

Beam Asymmetry Σ in $\vec{\gamma}\,p \to p\,\pi^0$ @ CLAS (g8b)



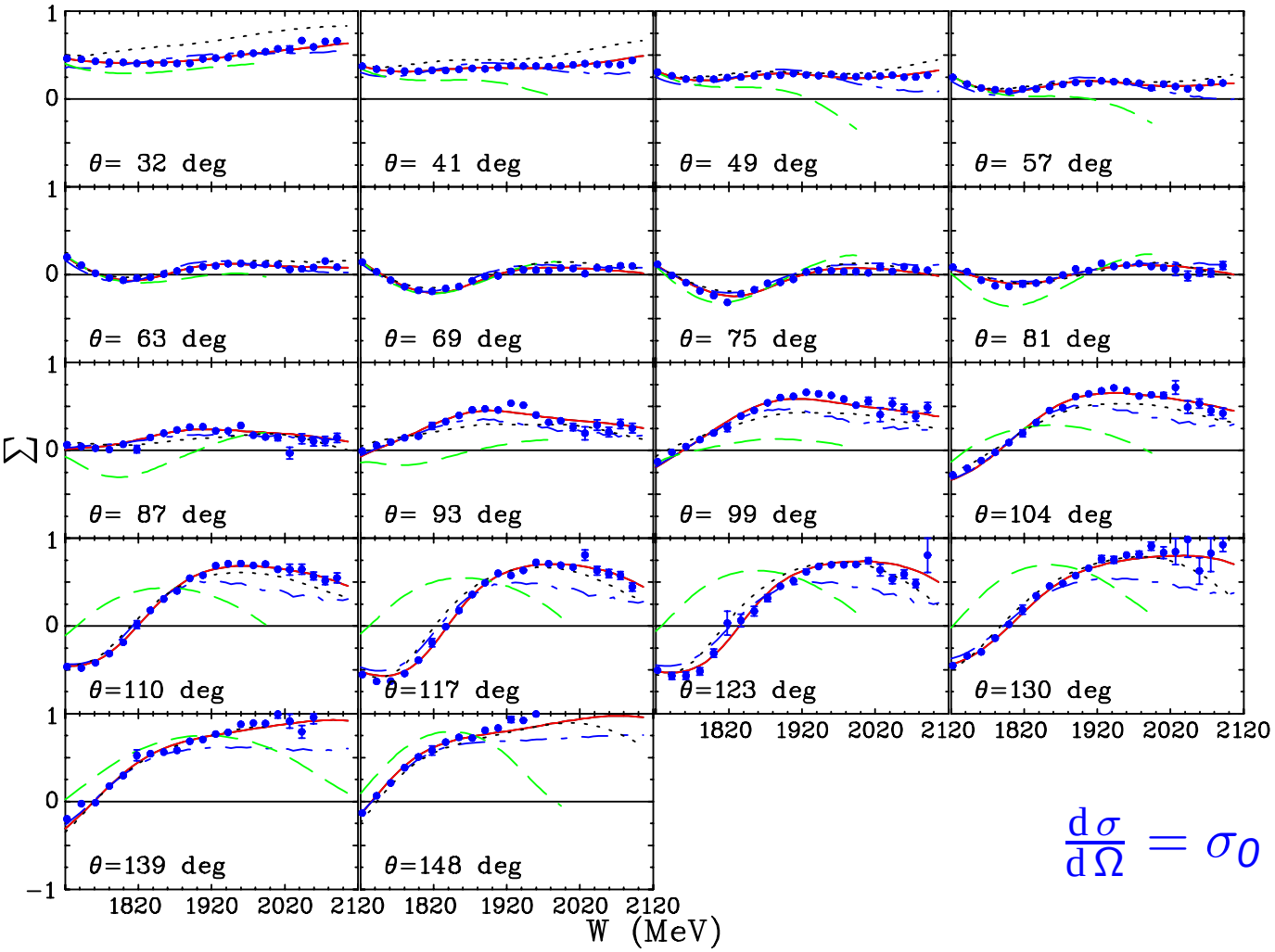
SAID DU13
SAID CM12
MAID 07
BoGa 2011-02

Largest changes in SAID DU13

- Improved mapping of dip near 60°
- Couplings of
  - $\Delta(1700)\,\frac{3}{2}^-$
  - $\Delta(1905)\,\frac{5}{2}^+$

M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. C **88**, 065203 (2013)

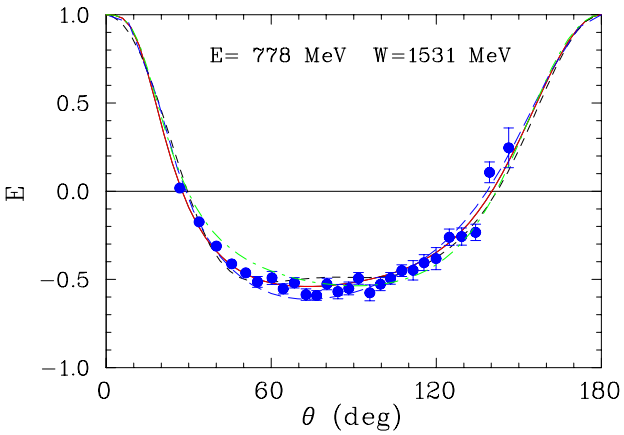
Beam Asymmetry Σ in $\vec{\gamma} p \to n \pi^+$ @ CLAS (g8b)

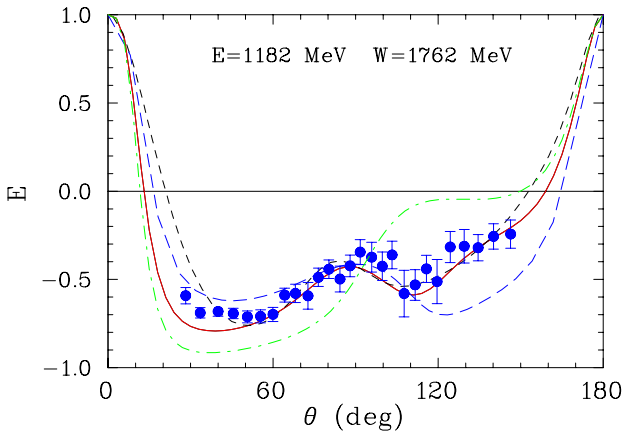


$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi \}$$

M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. C **88**, 065203 (2013)

Helicity Difference E in $\vec{\gamma}\vec{p} \to n\pi^+$ @ CLAS (FROST)



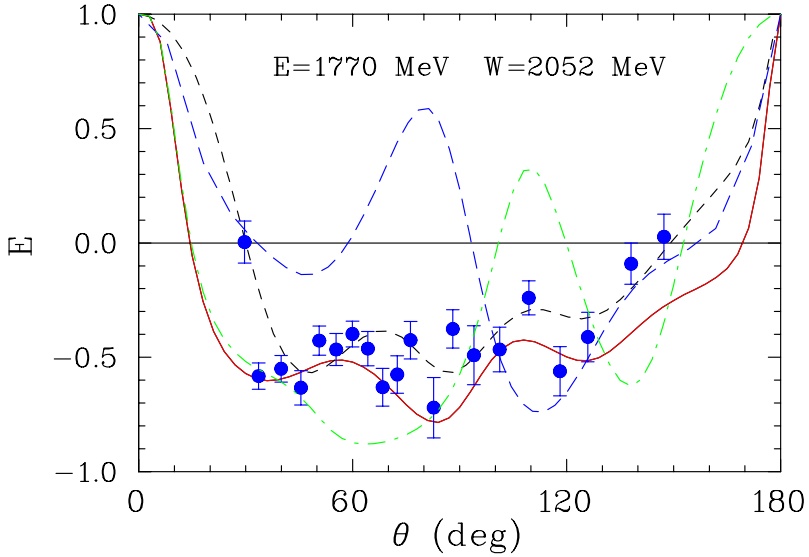


SAID ST14
MAID 07
BoGa 2011-02
Jülich 14

Δ^+ N^*

$$p\,\pi^0 : \sqrt{\frac{2}{3}}\,|I=\frac{3}{2}, I_3=\frac{1}{2}\rangle - \sqrt{\frac{1}{3}}\,|I=\frac{1}{2}, I_3=\frac{1}{2}\rangle$$

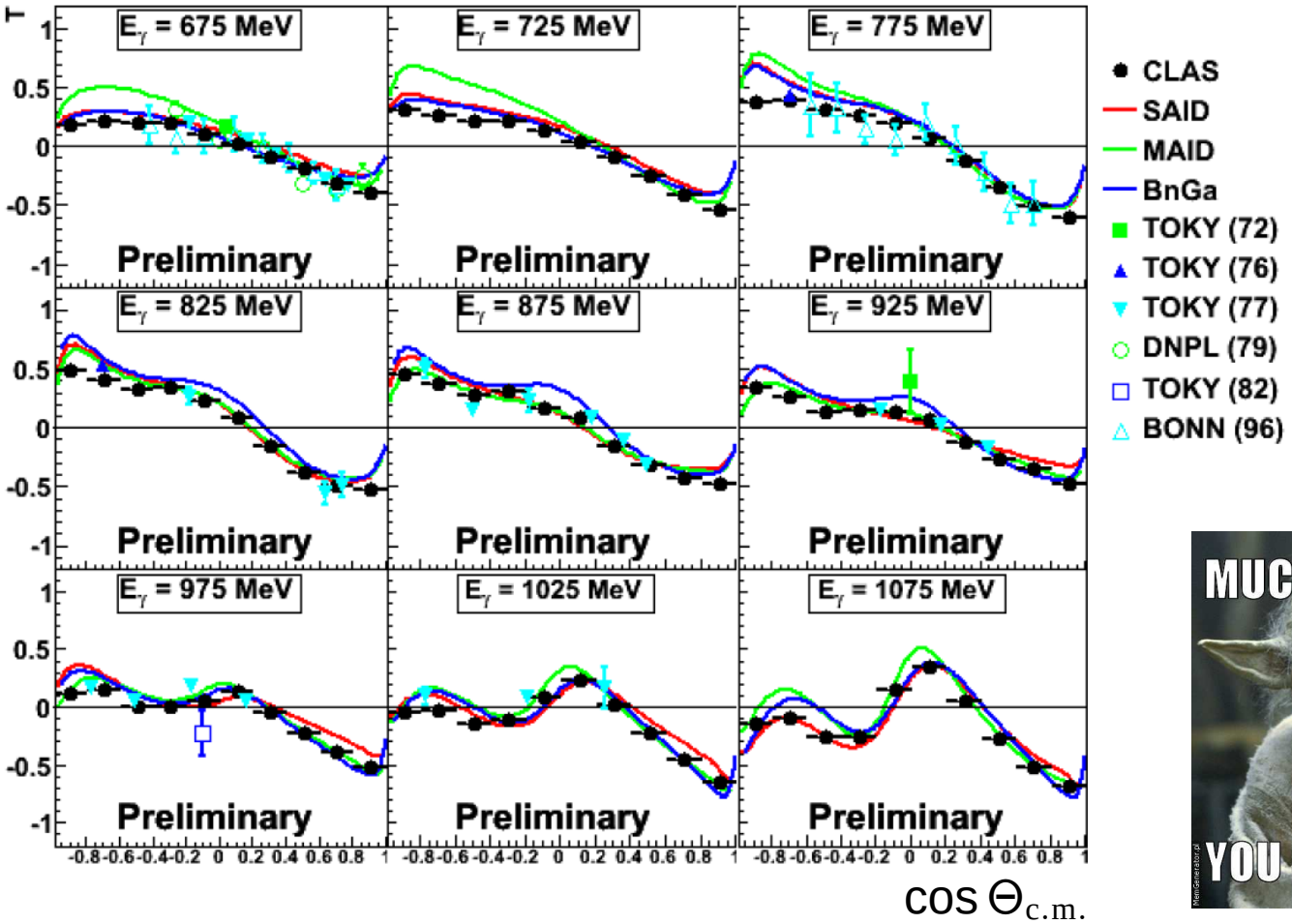
$$n\,\pi^+ : \sqrt{\frac{1}{3}}\,|I=\frac{3}{2}, I_3=\frac{1}{2}\rangle + \sqrt{\frac{2}{3}}\,|I=\frac{1}{2}, I_3=\frac{1}{2}\rangle$$



S. Strauch SC, under CLAS collaboration review

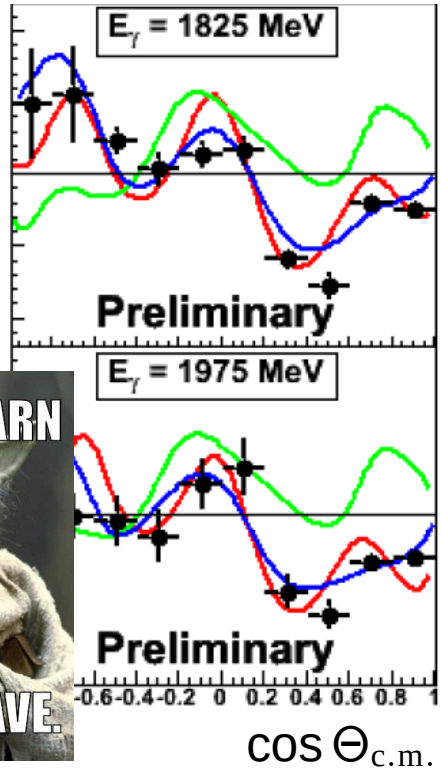
Target Asymmetry T in $\gamma \vec{p} \to n \pi^+$ (CLAS FROST)

– MAID 07 – SAID – BoGA 12



Early-stage results (g9b)

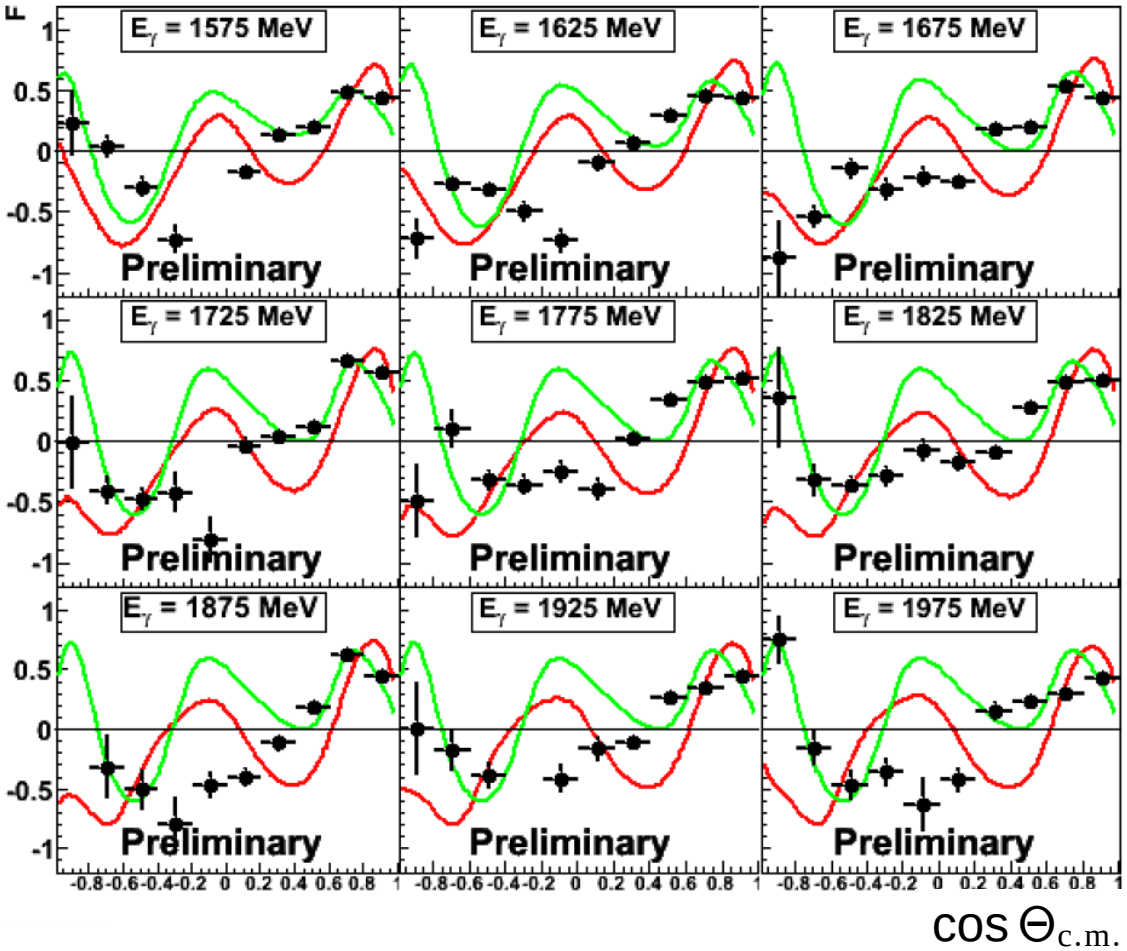
- Transverse Target Polarization



M. Dugger (ASU), CLAS g9b run group

Observable F in $\vec{\gamma}\vec{p} \to n\pi^+$ (CLAS FROST-g9b)

– MAID 07 – SAID 12 BoGa not shown



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

Transv. target pol. & circ. beam pol.

- Early-stage analysis
- Reasonable agreement among predictions for $W < 1.7$ GeV

➜ Much to learn at the higher energies

M. Dugger (ASU), CLAS g9b run group

Overview of CLAS Polarization Measurements

Measurements off the proton

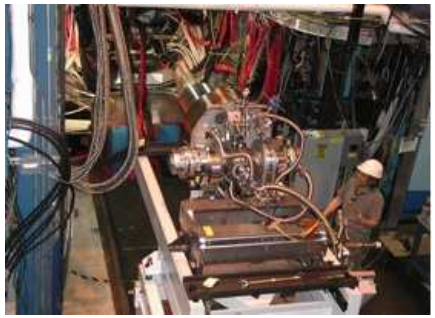
- $\gamma p \to \boxed{p\,\pi^0,\, n\,\pi^+}$
- $\gamma p \to p\,\eta,\, p\,\eta'$ (I. Senderovich, R. Tucker *et al.*)
- $\gamma p \to \boxed{p\,\pi^+\pi^-}$, $p\,\phi$, $p\,\omega$ (CMU, CU, Florida State)

➜ Frozen-Spin Target (FROST)

Measurements off the neutron

- $\gamma n \to p\,\pi^-$
- $\gamma n \to n\,\pi^+\pi^-$

➜



HD Ice Target

➜ "Complete" experiment possible in Strangeness Photoproduction (S. Fegan, N. Walford *et al.*)

- $\gamma p \to K\,Y$ $(Y = \Lambda,\, \Sigma^0,\, \Sigma^+)$
- $\gamma n \to K^+\,\Sigma^-,\, K^0\,\Lambda$

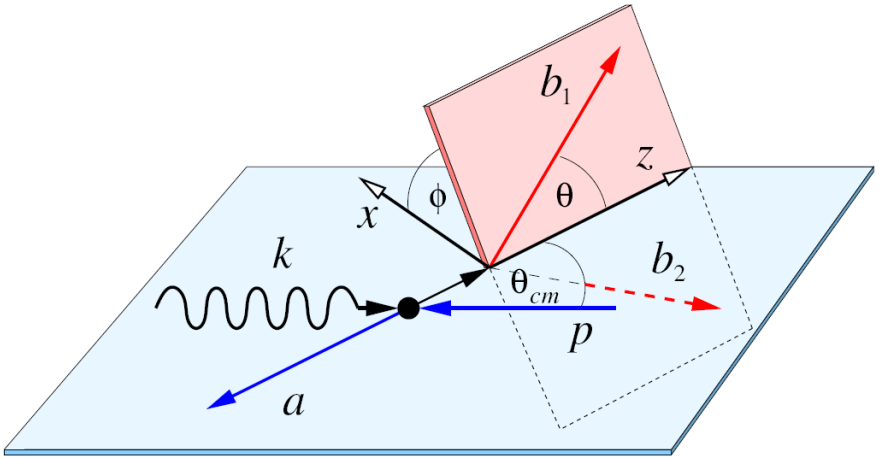
➜ Cross sections (K. Moriya, 2:30 PM) (also $\Lambda(1405), \Lambda(1520)$)

Beam-Target Polarization Observables in $\gamma p \to p \pi\pi$

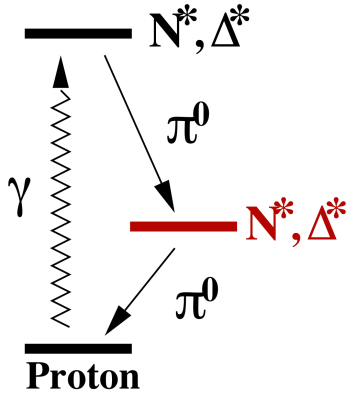
W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

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

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

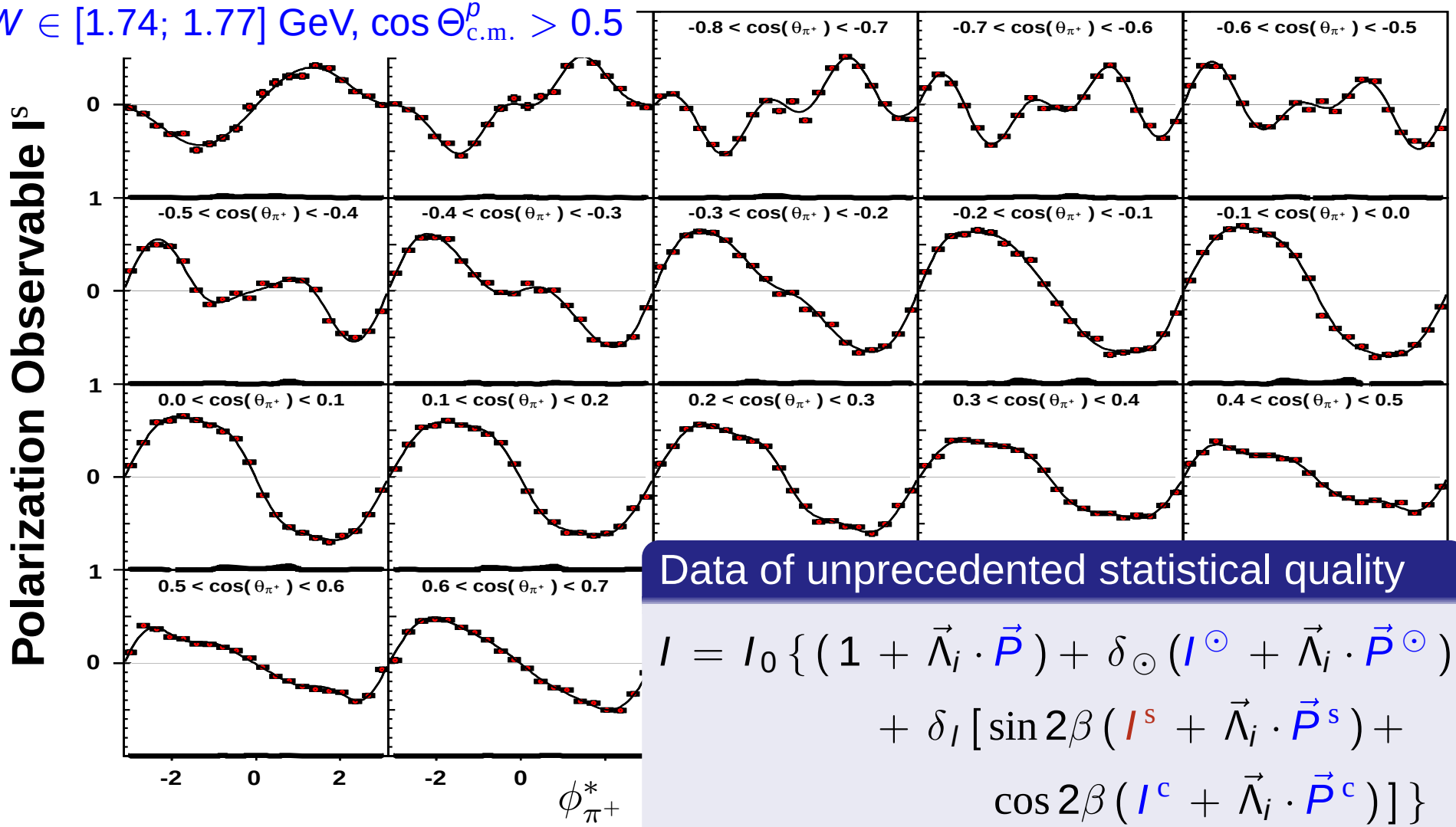


At higher excitation energies:
Multi-meson final states important.



➜ Search for states in decay cascades!

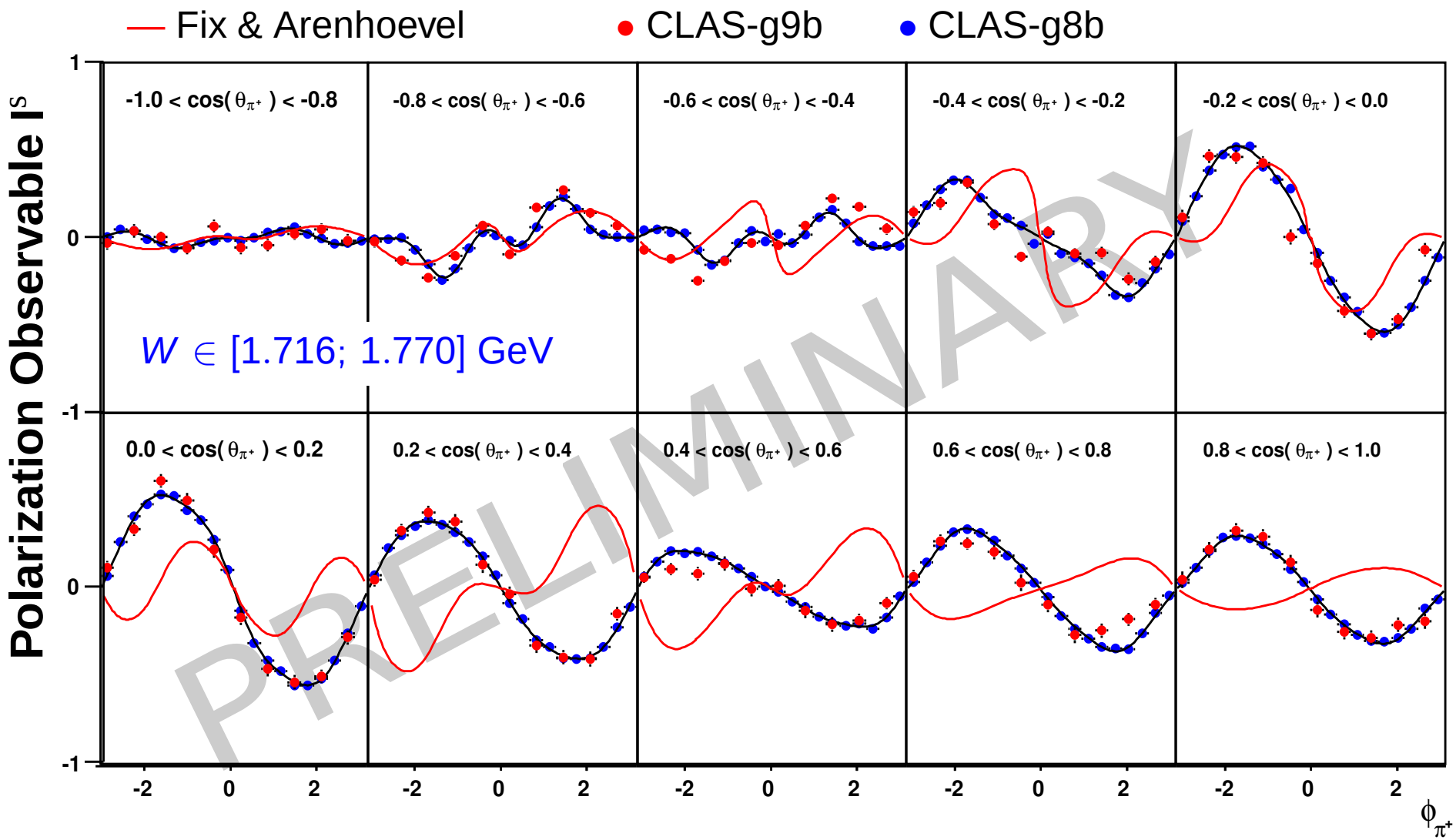
$W \in [1.74; 1.77]$ GeV, $\cos\Theta^p_{\text{c.m.}} > 0.5$



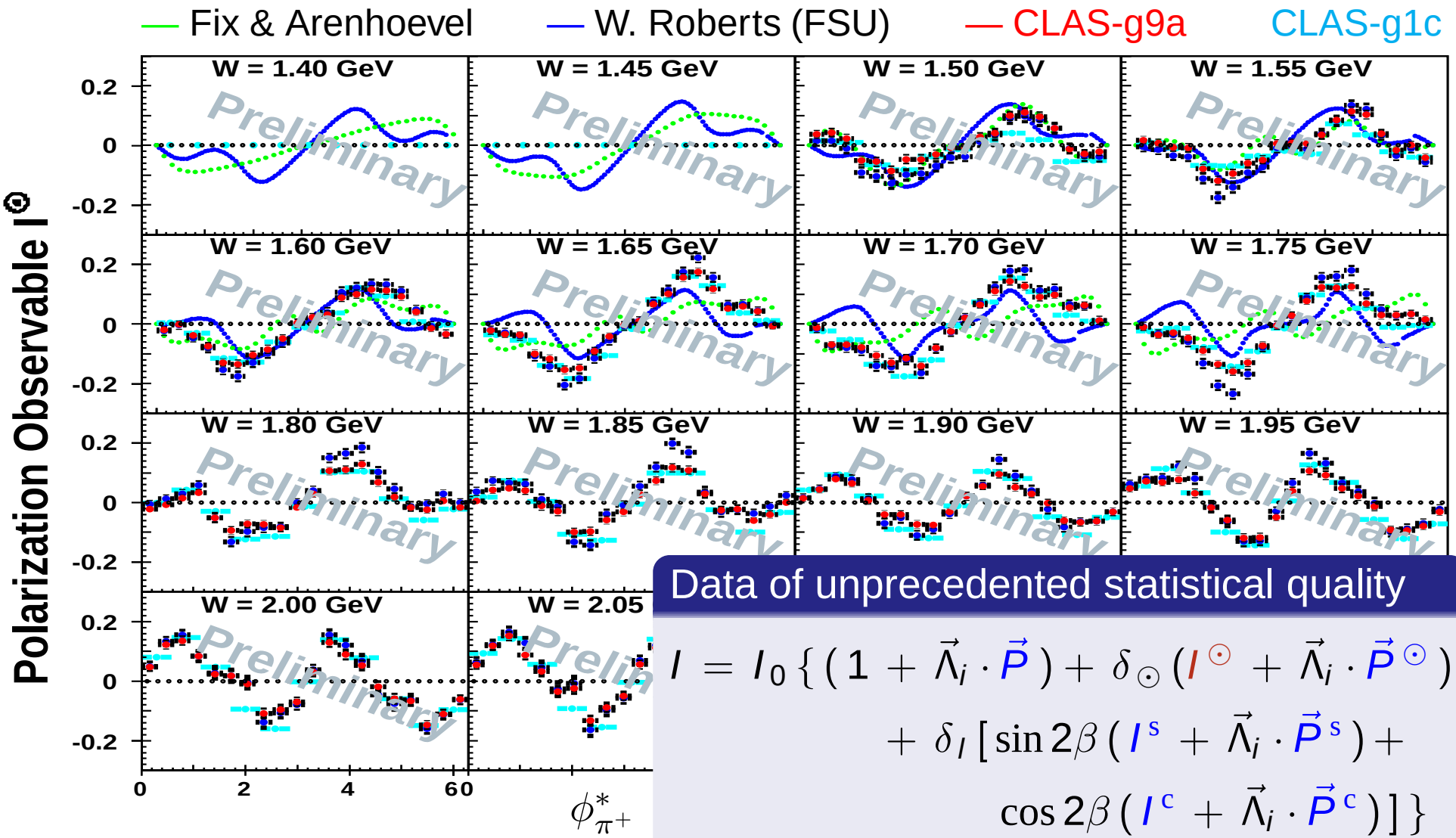
Data of unprecedented statistical quality

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

Charles Hanretty (FSU), approved by CLAS collaboration



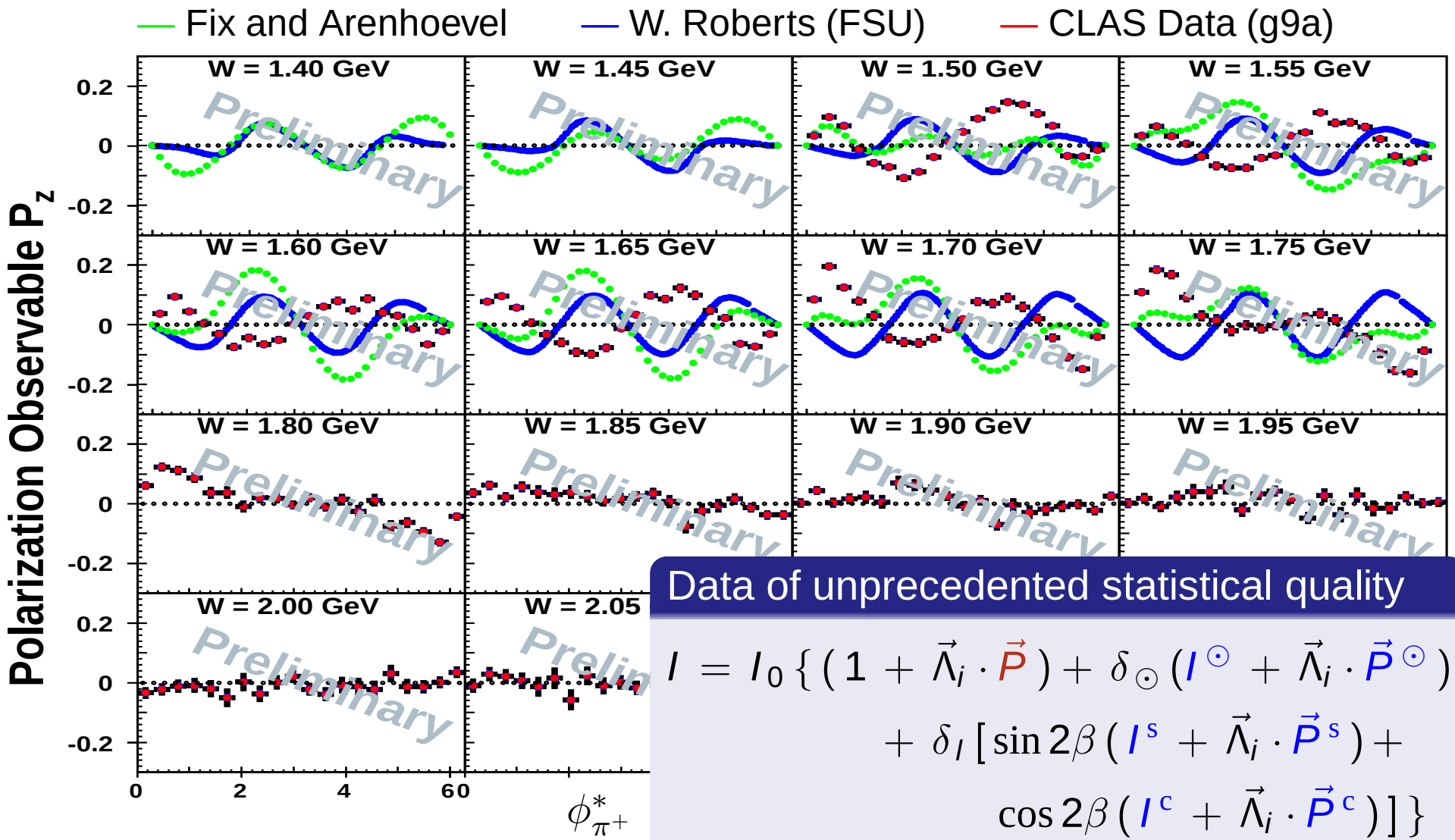
Priyashree Roy (Florida State), CLAS g9b (FROST)



Data of unprecedented statistical quality

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

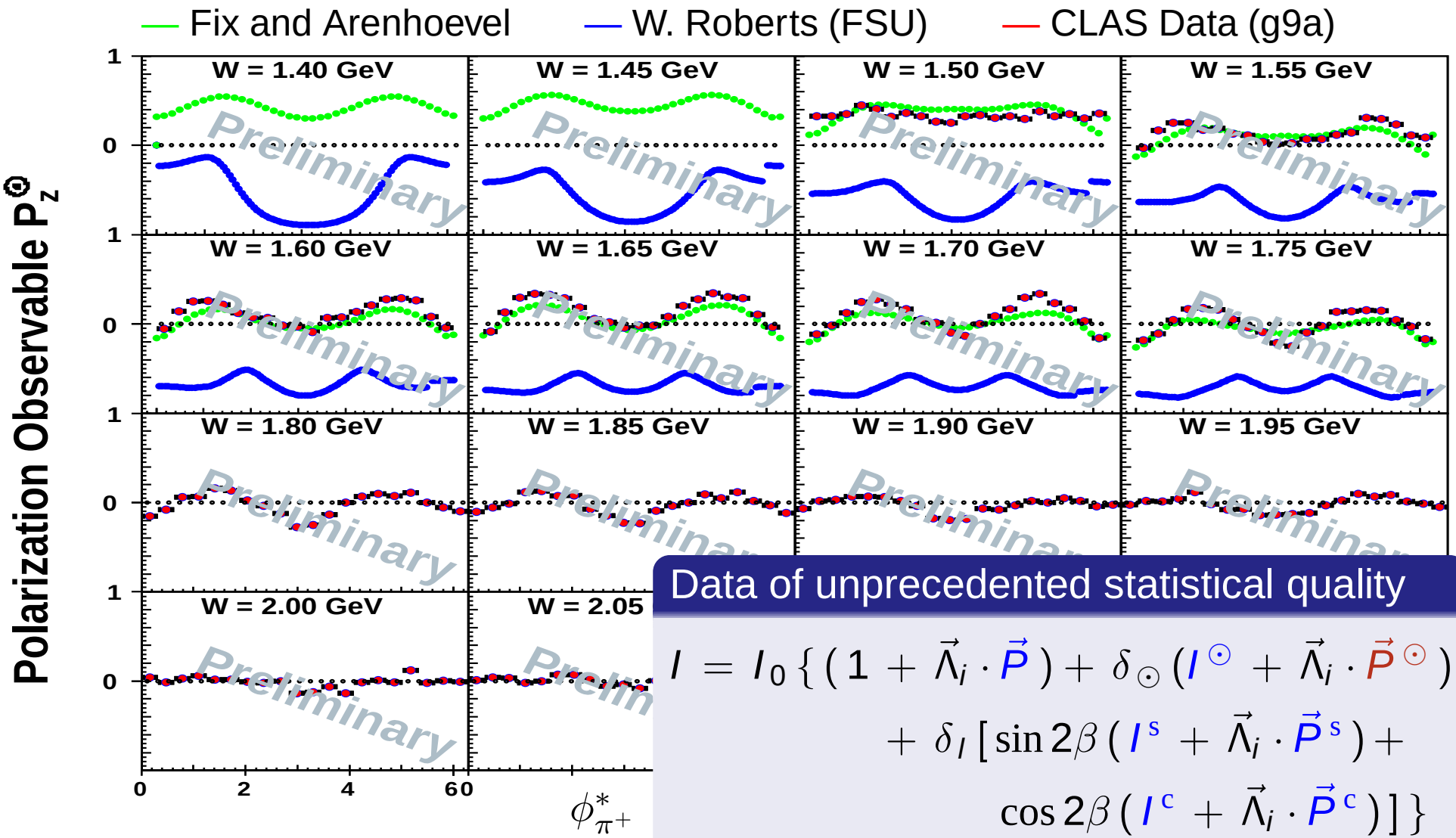
Sungkyun Park (FSU), under collaboration review



Data of unprecedented statistical quality

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

Sungkyun Park (FSU), under collaboration review



Data of unprecedented statistical quality

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

Sungkyun Park (FSU), under collaboration review

Outline

Summary and Outlook

Our understanding of baryon resonances has made great leaps forward. There is good evidence that most of the known states (listed in the PDG) will also be confirmed in photoproduction and that new states will be revealed:

- Goal of performing (almost) complete experiments has been (almost) achieved; significant contributions from (double-)polarization experiments.
- Still too early to nail down relevant degress of freedom in excited baryons.
  ➜ Some states might be generated dynamically ...

$N(1860)\,\frac{5}{2}^+$	**	πN	γN				
$N(1875)\,\frac{3}{2}^-$	***	πN	γN		ΛK	ΣK	
$N(1880)\,\frac{1}{2}^+$	**	πN	γN		ΛK	ΣK	
$N(1895)\,\frac{1}{2}^-$	**	πN	γN	ηN	ΛK	ΣK	
$N(1900)\,\frac{3}{2}^+$	***	πN	γN	ηN	ΛK	ΣK	$\Delta\pi$
$N(2060)\,\frac{5}{2}^-$	**	πN	γN	ηN		ΣK	
$\Delta(1940)\,\frac{3}{2}^-$	$* \rightarrow **$	πN	γN				$\Delta\eta$ (!)

New States in PDG 2012.