Light Baryon Spectroscopy – Recent Results

R. Beck
HISKP, University Bonn

IWHSS, 16. – 18.April 2012 , Lisbon

- Introduction
- Recent Results from ELSA, JLab and MAMI:
  $\vec{\gamma}\ \vec{p} \to p\,\pi^0$
  $\vec{\gamma}\ \vec{p} \to p\,\eta$
- Narrow structure
  $\vec{\gamma}\ n \to n\,\eta$
- Summary and Outlook

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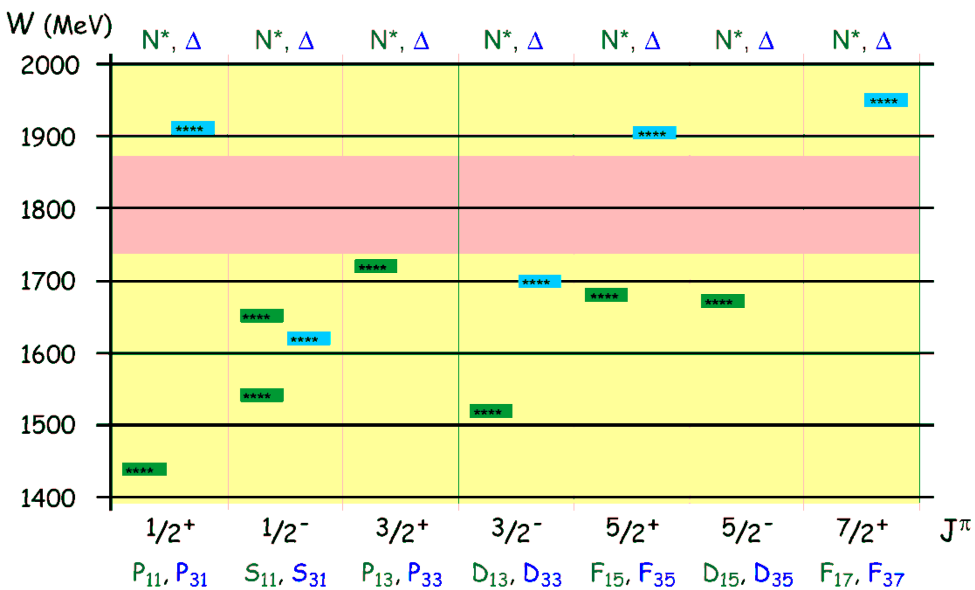
supported by the DFG within the SFB/TR16

Introduction

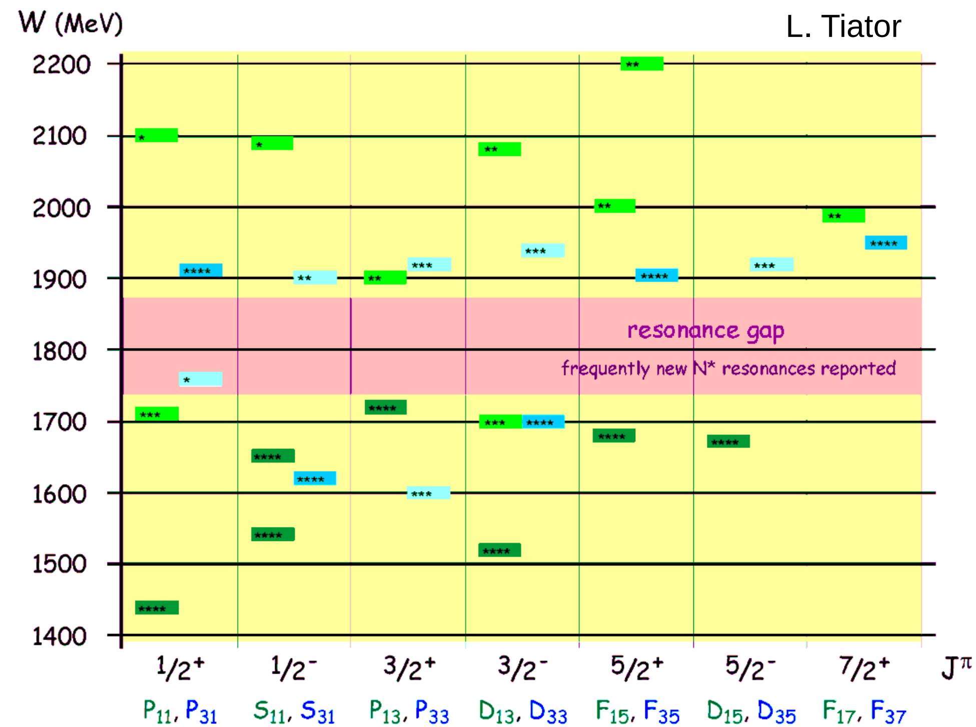
PDG 2010: Status on nucleon resonances

only 7 N* and 5 Δ*

established in the region 1400 MeV < W < 2000 MeV



L. Tiator



- Energy pattern for the dominant states

  Constituent Quark Models

  Dynamical Models

  Lattice QCD

- Various nucleon models predict many more states

  weak coupling to πN final state

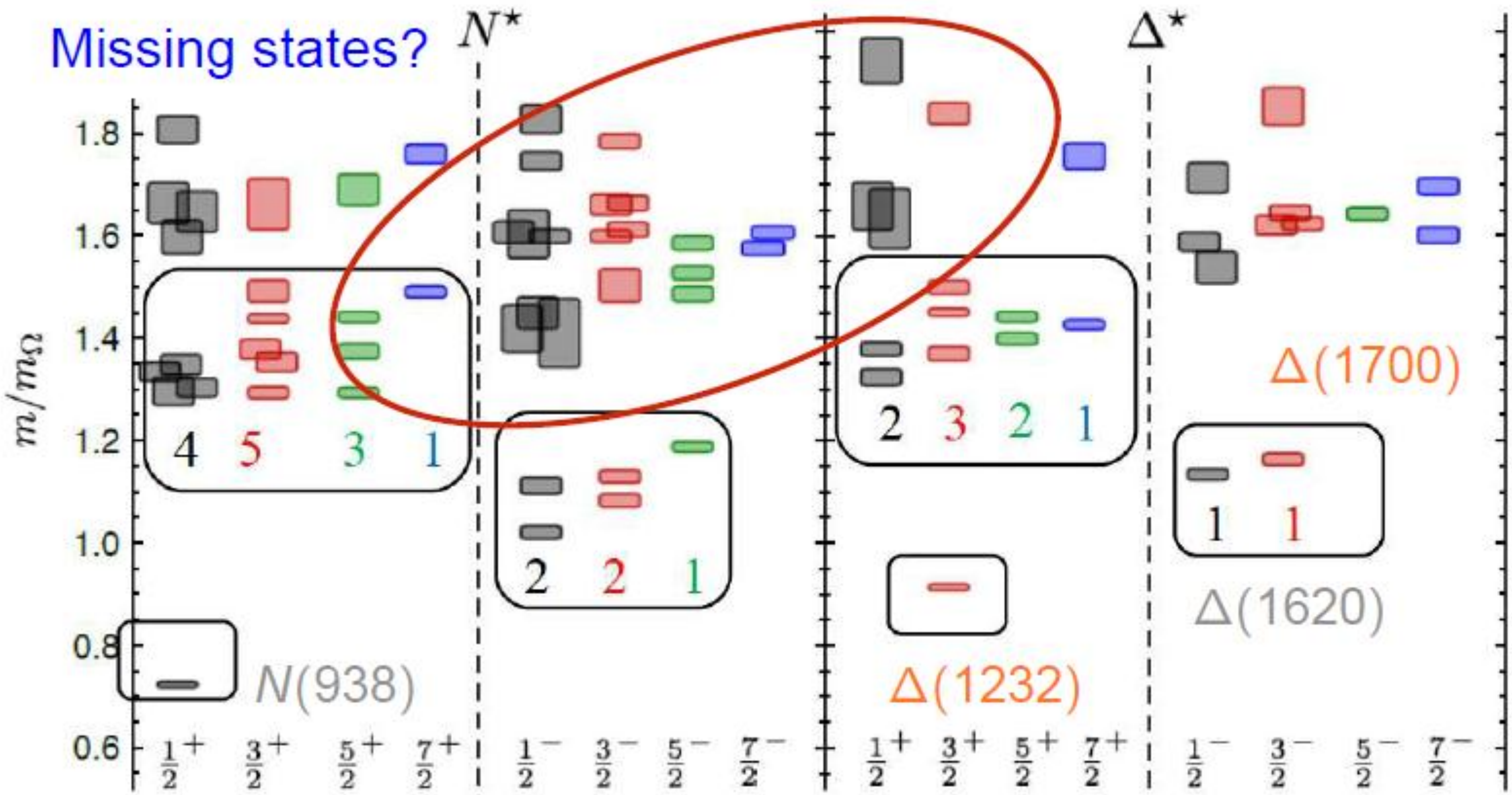
  insufficient data base

Introduction

talk yesterday by M. Peardon

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

Missing states?



$m_\pi = 400$ MeV

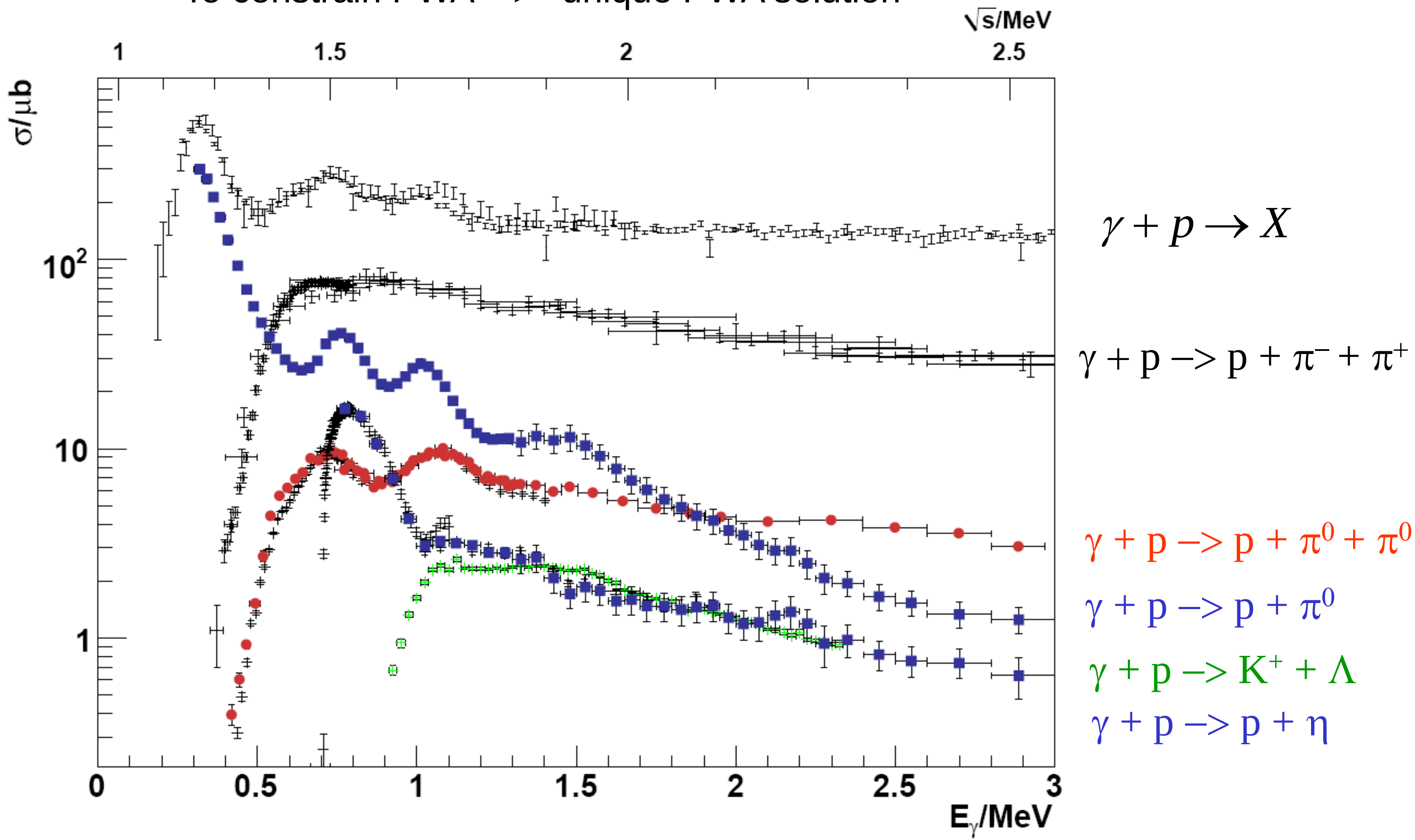
Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

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

Experimental program for N*

Common effort at ELSA, JLab and MAMI,

- Precision data for different final states ($p\pi^0$, $n\pi^+$, $p\eta$, $K^+\Lambda$, $p\pi^0\pi^0$....)
- Polarization experiments (beam, target and recoil)
  "complete data base"
- To constrain PWA –> unique PWA solution



Problem with a unique PWA solution

$$\vec{\gamma} + \vec{N} \rightarrow N + \pi$$

8 well chosen observable have to be measured to determine the production amplitudes (F_1,F_2,F_3 and F_4)

- π- threshold until $\Delta^+(1232)$- region

  additional constraints:

  (a) s- and p- wave approximation

  (b) Fermi- Watson theorem

  $$\gamma + N \rightarrow N + \pi$$
  $$\pi + N \rightarrow N + \pi$$

  same I, J in the final state
  → same scattering phase δ_{IJ}

  two observable sufficient for "complete data base"

  differential cross section : $d\sigma/d\Omega$

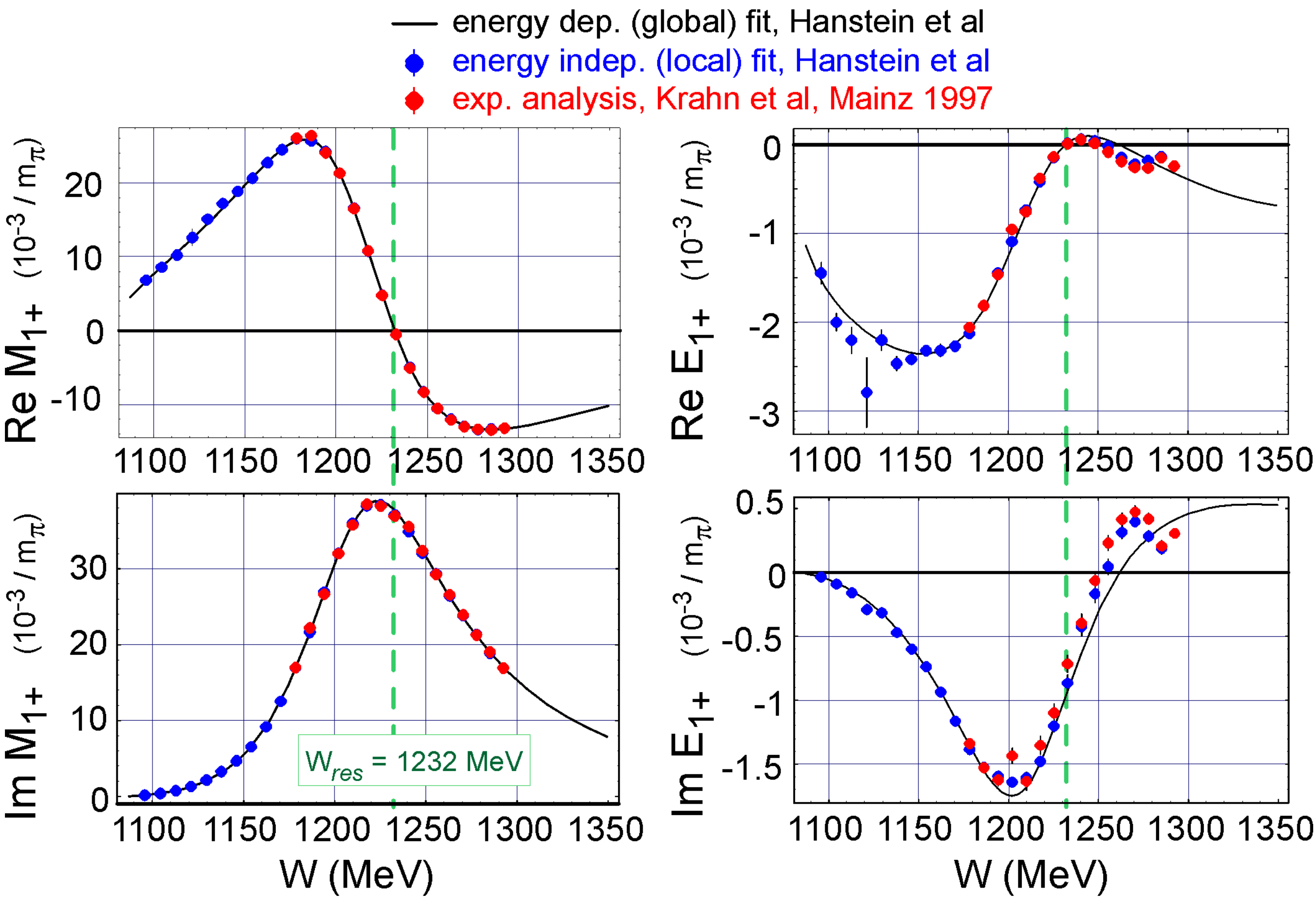
  beam asymmetry : Σ

- above $\pi\pi$- threshold

  Fermi- Watson theorem not valid any more

  More observable needed to get a unique partial wave solution

Partial waves for the $P_{33}(1232)$



Resonance parameter for the $P_{33}(1232)$

e.m. transition moments and E/M ratio at $W_{res} = 1232$ MeV

$$\mu_{N\Delta} = (3.46 \pm 0.03)\,\mu_N$$

$$Q_{N\Delta} = -(0.0846 \pm 0.0033)\,fm^2$$

$$R_{EM} = -(2.5 \pm 0.1_{stat.} \pm 0.2_{syst.})\,\%$$

pole position and residues at $W_{pole} = M_R - i/2\,\Gamma_R$

$$M_R = 1212 \pm 1\,MeV$$

$$\Gamma_R = 99 \pm 2\,MeV$$

$$r(M1) = 21.16 \cdot e^{-i27.5^0}$$

$$r(E2) = 1.23 \cdot e^{-i154.7^0}$$

$$R_\Delta = \frac{r(E2)}{r(M1)} = -0.035 - 0.046\,i$$

O. Hanstein, D. Drechsel, and L. Tiator Phys. Lett. B 385, 45 (1996)
R.B. and H.P. Krahn Phys. Rev. Lett. 78, 606 (1997)
R.B. and H.P. Krahn Phys. Rev. C61, 035204 (2000)

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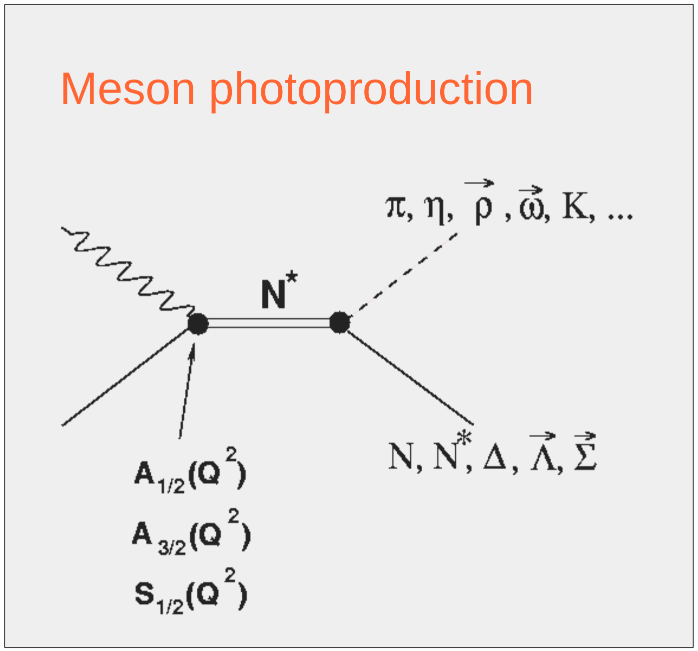
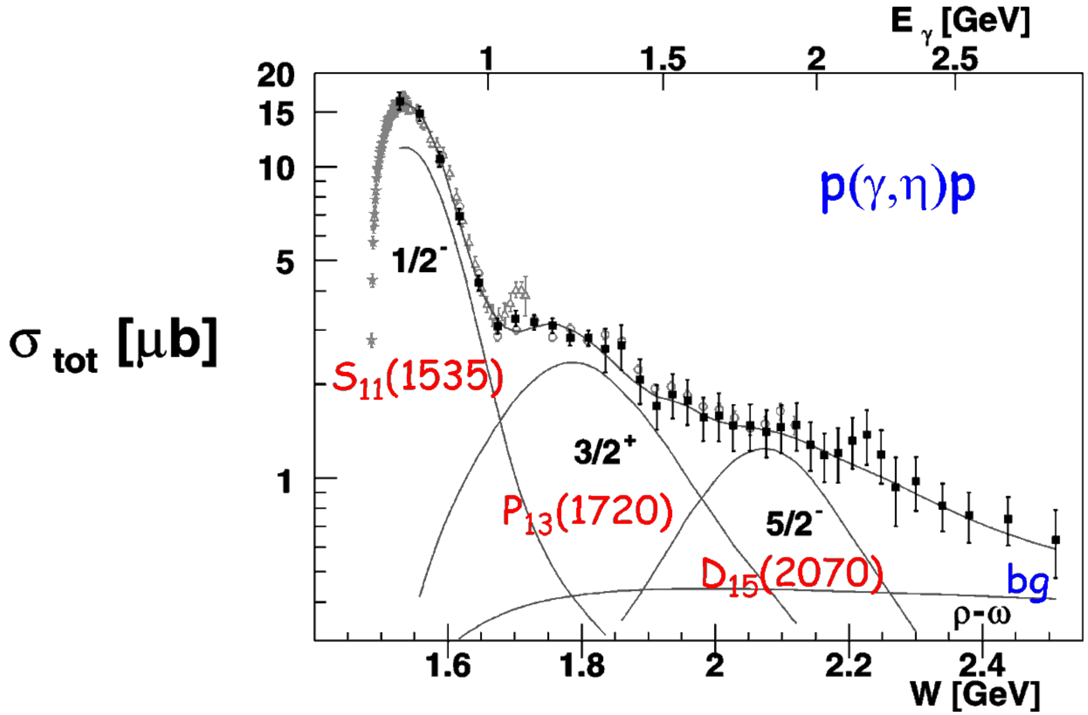
Problem with a unique PWA solution

$$\vec{\gamma} + p \rightarrow p + \eta$$

V. Crede, O. Bartolomy et al.,
PRL 94 (2005) 012004,
EPJ A33 (2007) 133





<u>Photon helicity couplings:</u> $A_{1/2}$ und $A_{3/2}$

$S_{11}(1535)$: $A_{1/2}$ ($S_{11}(1535)$) only

$D_{13}(1520)$: $A_{1/2}$ ($D_{13}(1520)$) and $A_{3/2}(D_{13}(1520))$

$P_{13}(1720)$: $A_{1/2}$ ($P_{13}(1720)$) and $A_{3/2}(P_{13}(1720))$

<u>BnGa partial wave analysis:</u>
strong P13(1720) contribution

<u>Total cross section:</u>

$$\sigma_{tot} \sim |A_{1/2}(S_{11})|^2 + |A_{1/2}(P_{13})|^2 + |A_{3/2}(P_{13})|^2 + \ldots..$$

Problem with a unique PWA solution

D. Elsner et al., EPJ A33 (2007) 147

Beam asymmetry: Σ

$$\vec{\gamma} + p \rightarrow p + \eta$$

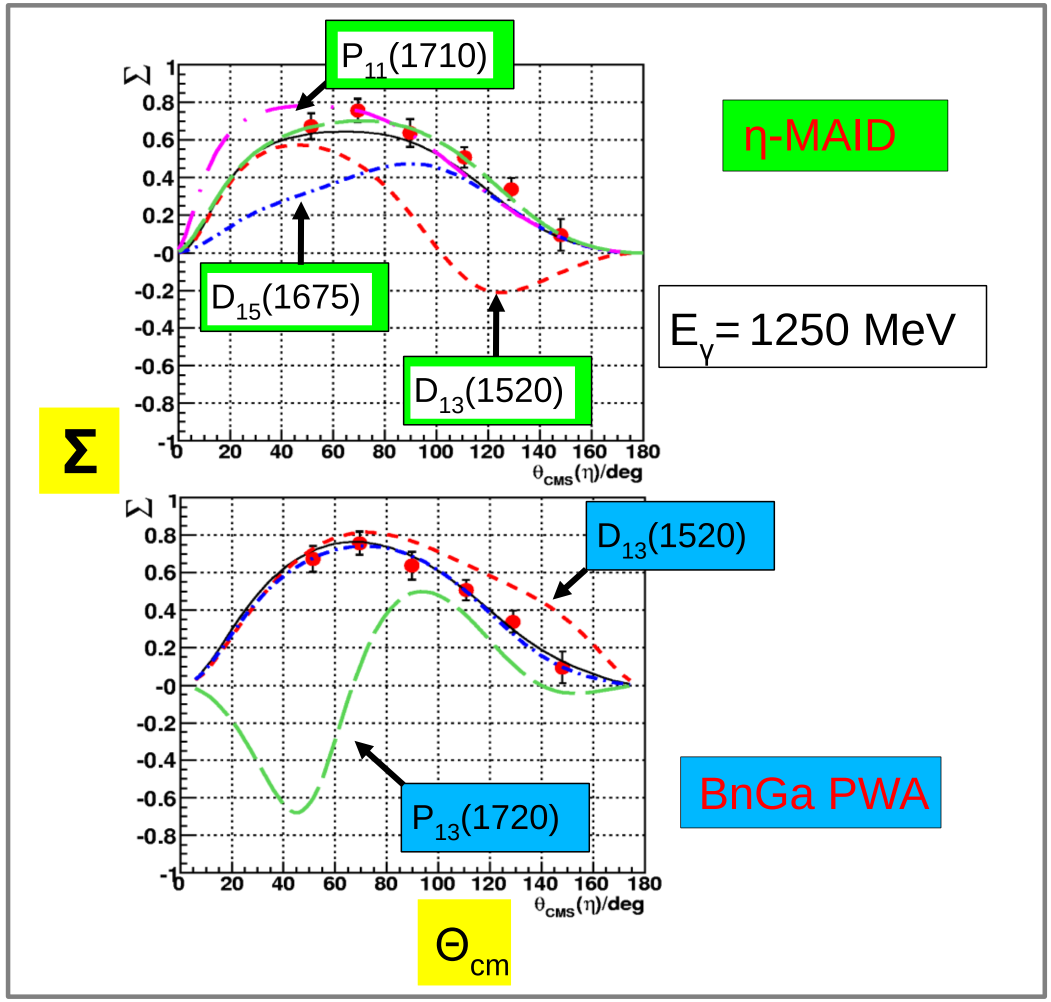
Higher sensitivity because of interference between different resonance contributions

$$\Sigma \sim A_{1/2}(S_{11}) * A_{1/2}(P_{13}) + \ldots..$$

BnGa partial wave analysis:
strong P13(1720) contribution

MAID partial wave analysis:
D15(1675) and P11(1710) contribution

More observable needed to get a unique partial wave solution



Observables in Meson Photoproduction

Photon polarization		Target polarization			Recoil nucleon polarization			Target and recoil polarizations			
		X	Y	Z(beam)	X'	Y'	Z'	X' X	X' Z	Z' X	Z' Z
unpolarized	σ	-	T	-	-	P	-	T_x	L_x	T_z	L_z
linear	Σ	H	(-P)	G	O_x	(-T)	O_z	($-L_z$)	(T_z)	(L_x)	($-T_x$)
circular	-	F	-	E	C_x	-	C_z	-	-	-	-

data only for:

Differential cross section: σ

Beam asymmetry: Σ

Double polarization: E

Sensitive to: $\mathrm{Re}(P_1 \cdot P_2)$

data needed for:

Target asymmetry: T

Recoil polarization: P

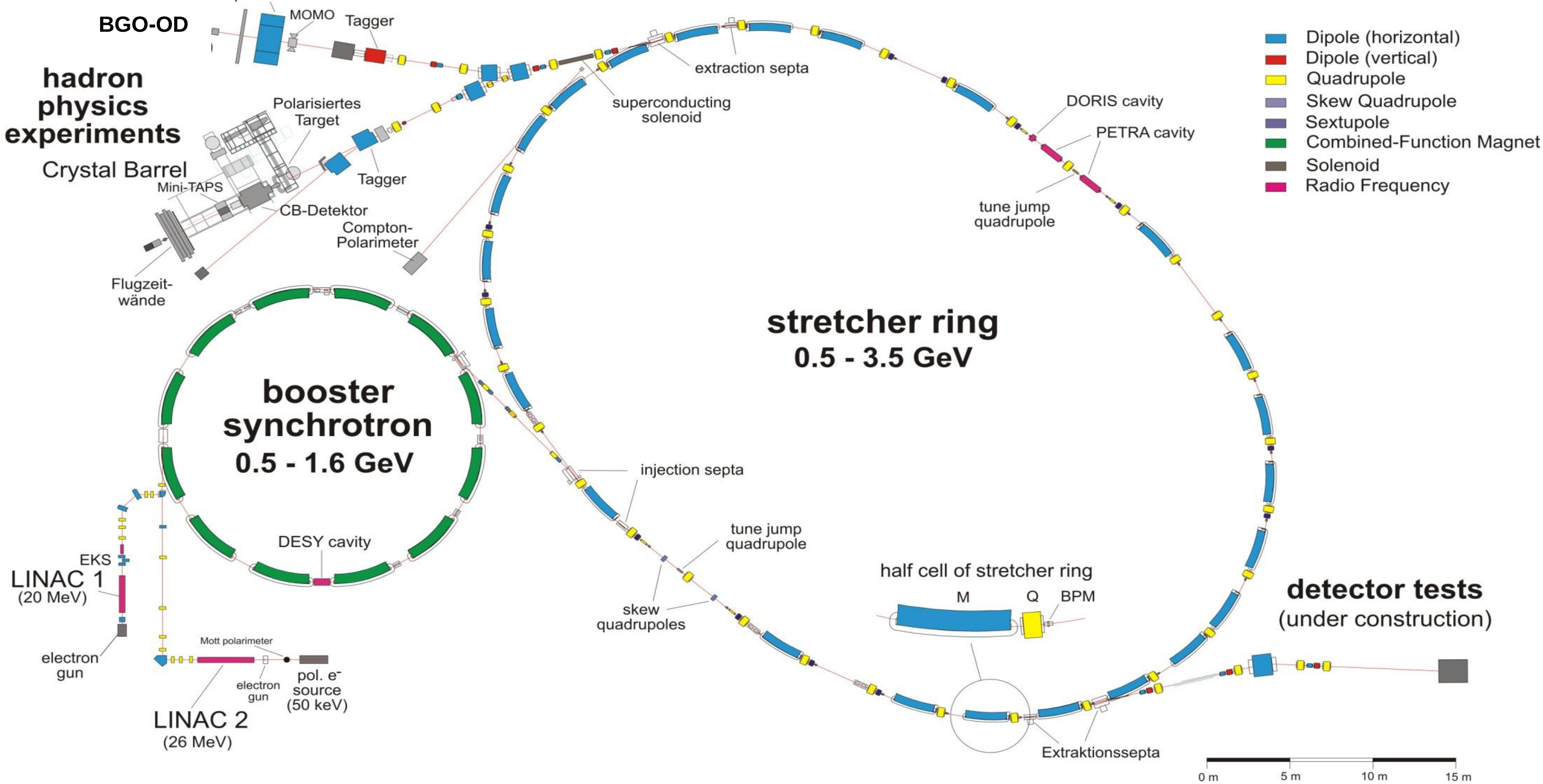
Double polarization: G

Sensitive to: $\mathrm{Im}(P_1 \cdot P_2)$

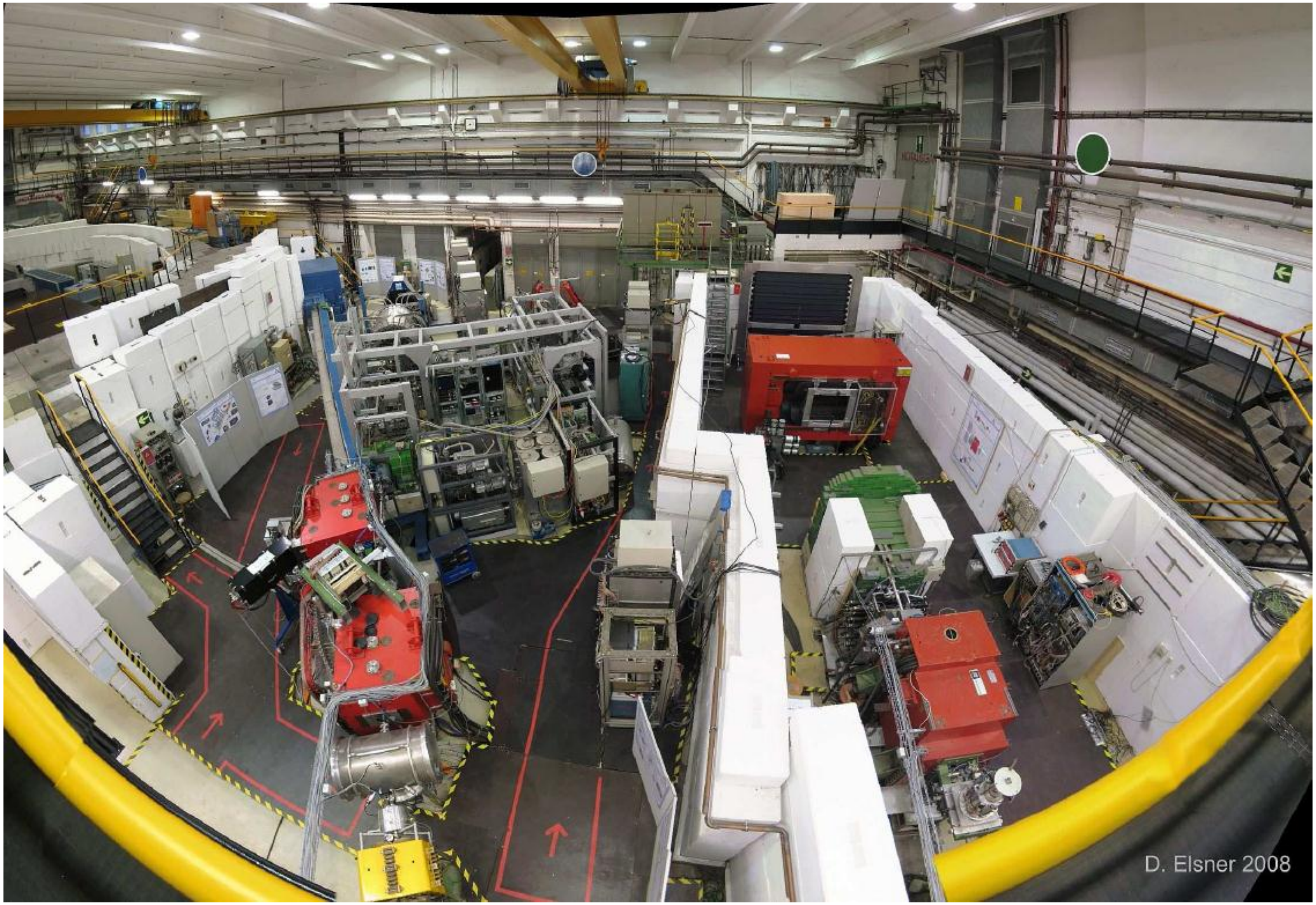
ELSA, JLAB, MAMI : polarized photons, polarized targets and 4π acceptance

Electron Stretcher Accelerator (ELSA)

electron accelerator at the Univers Today 17.4. 60th birthday of Fritz Klein



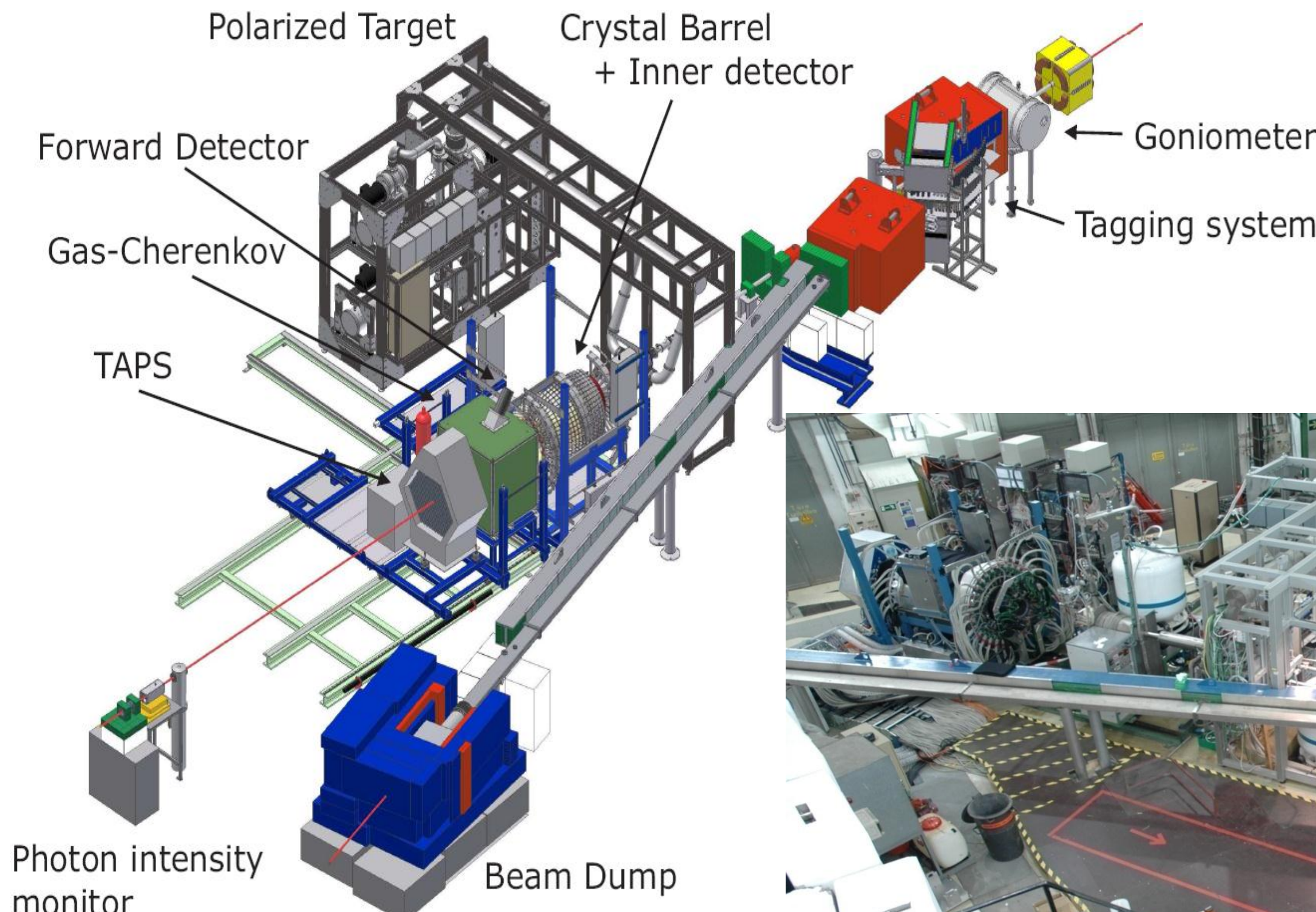
Experiments at ELSA

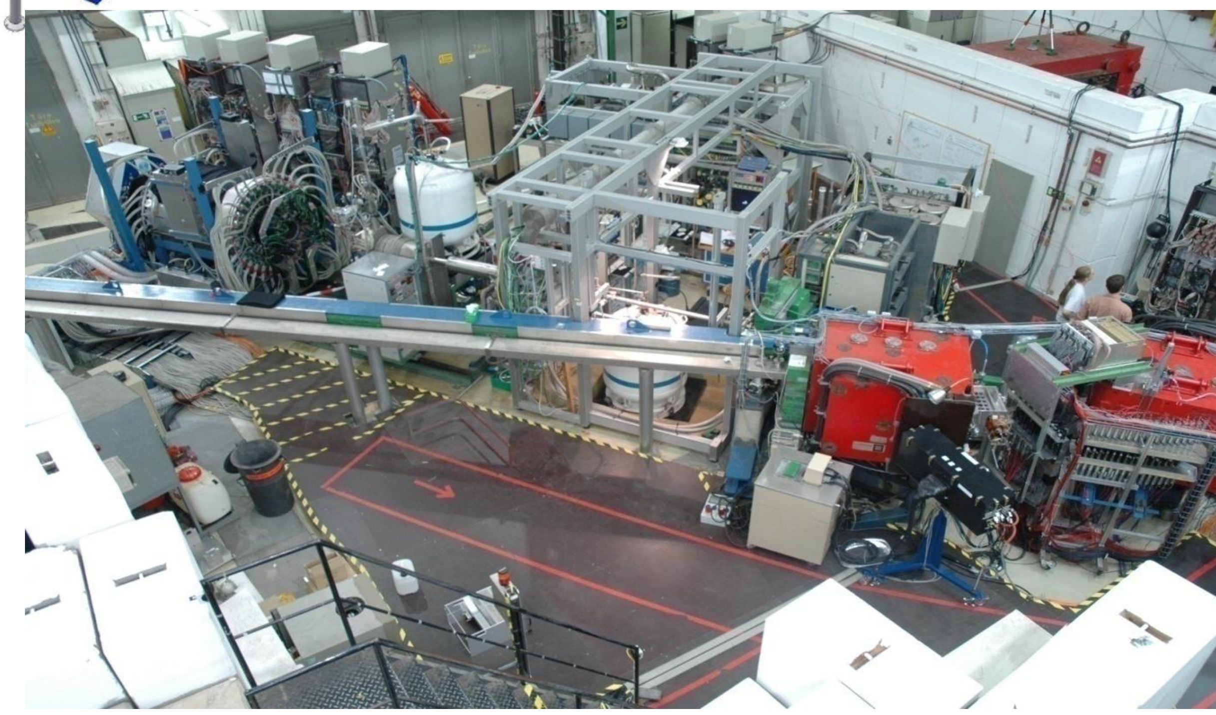


• Crystal Barrel Set-Up

• BGO-OD Set-Up

Crystal Barrel Set Up at ELSA





Crystal Barrel Set Up at ELSA

- Crystal Barrel detector
  1230 CsI crystals

- Inner-detector
  cylinder of 513 scintillating fibers

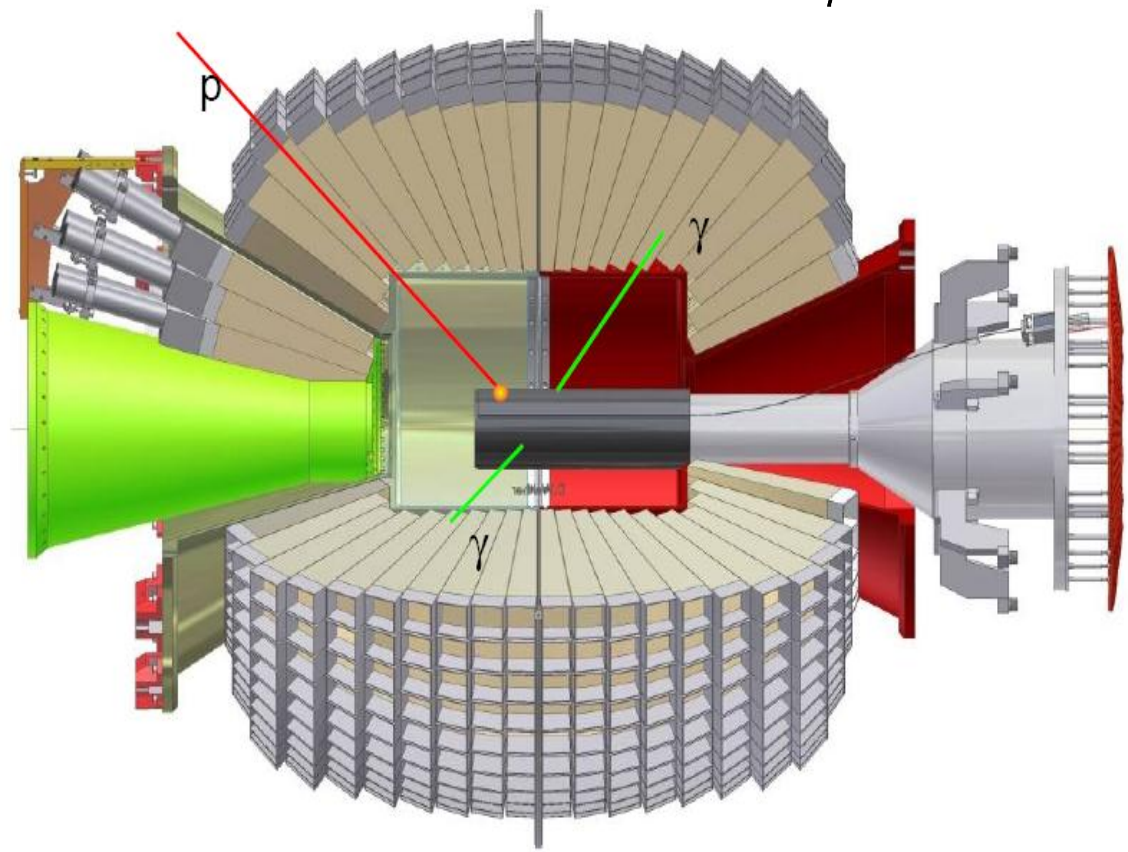
- forward detector (FWPlug)
  90 CsI crystals with PM's, 12^0-30^0

- forward detector (MiniTAPS)
  216 BaF_2 , 1^0-12^0

Close to 4π coverage

$\pi^0 \to \gamma\gamma$ $\eta \to \gamma\gamma$

$\eta \to 3\pi^0$

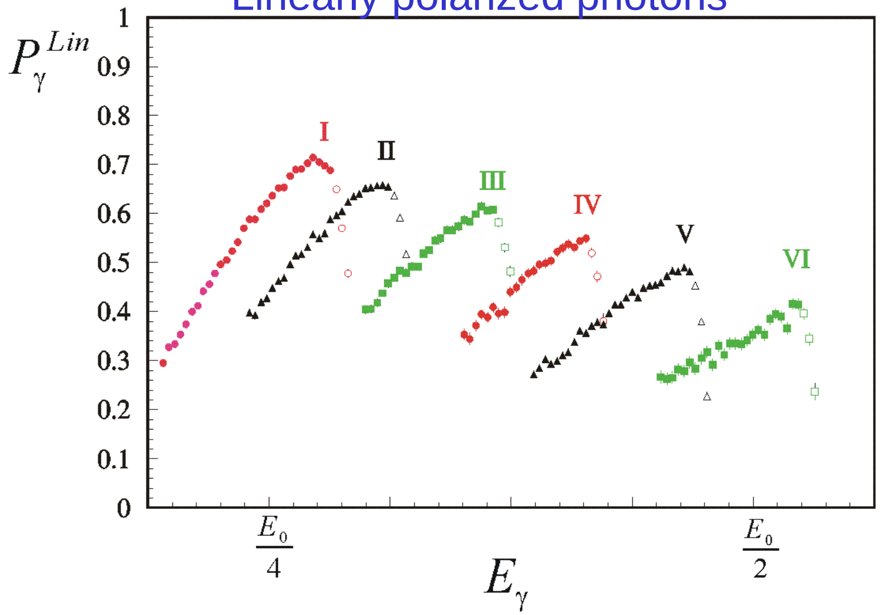


Polarized Photons

Linearly polarized photons:
- coherent bremsstrahlung
- diamond radiator

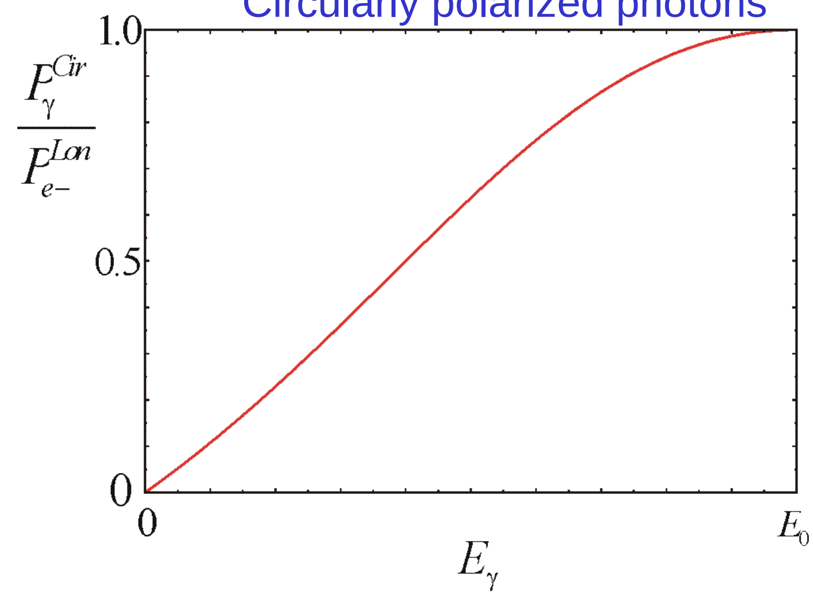
Circularly polarized photons:
- longitudinally polarized electrons
- helicity transfer to photon

Linearly polarized photons



high polarization at low photon energies

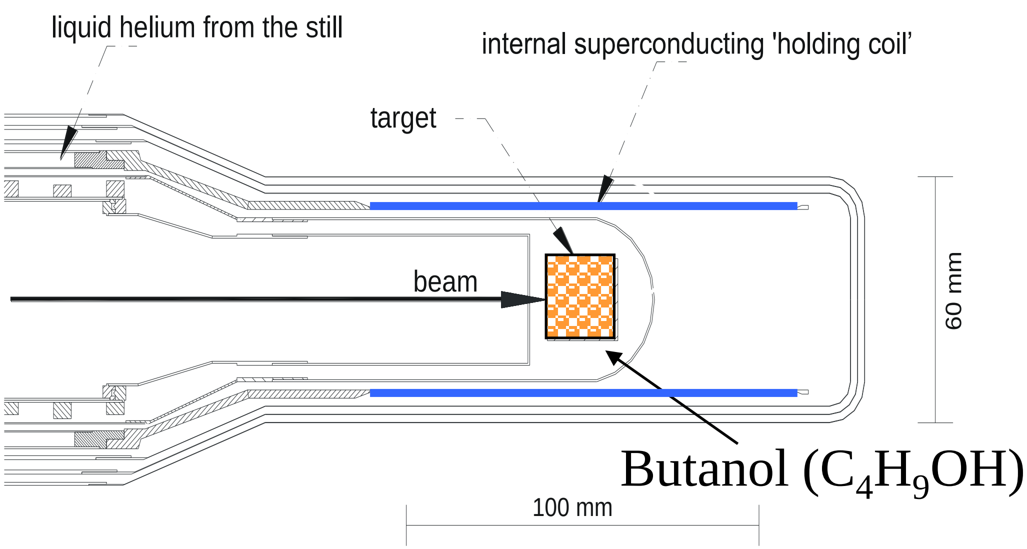
Circularly polarized photons



high polarization at high photon energies

ELSA, JLAB and MAMI

Polarized Target

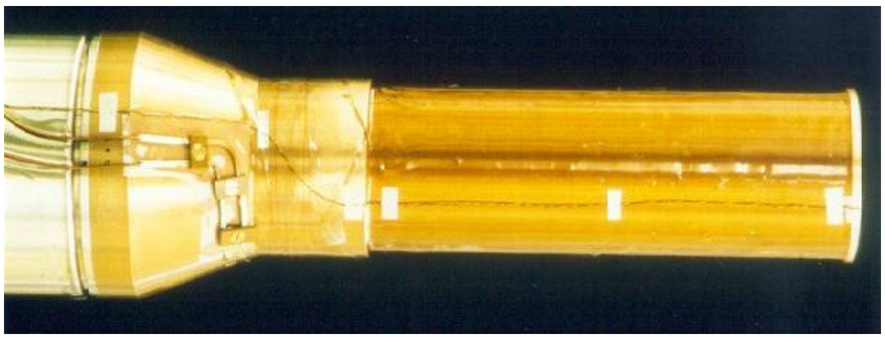


„Frozen Spin Target“

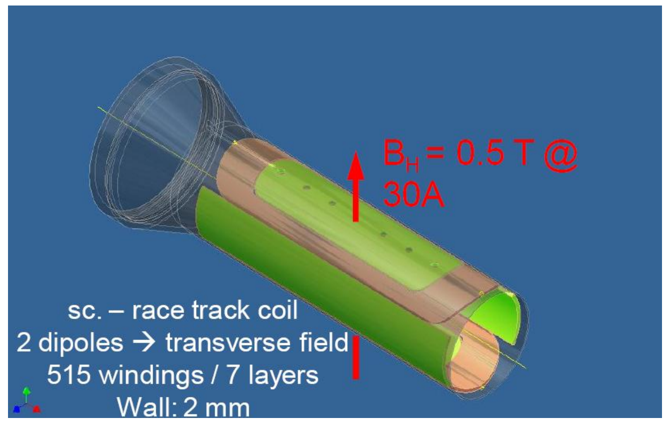
Horizontal cryostat with integrated solenoid to freeze up the spin

Target: Butanol (C_4H_9OH)

Polarization: DNP at high B-field (2.5 T)
„freeze“ up the spin (0.4 T)
relaxation time T~500h



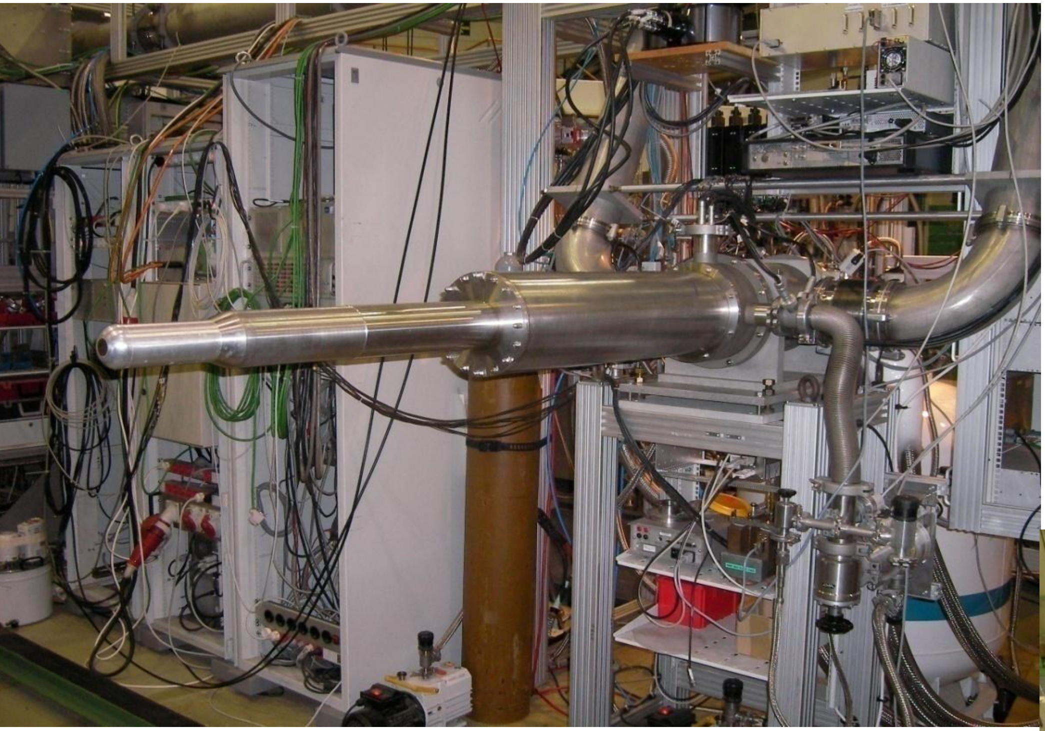
„longitudinally polarized Target“



„transversely polarized Target“

ELSA, JLAB and MAMI

Polarized Target at ELSA

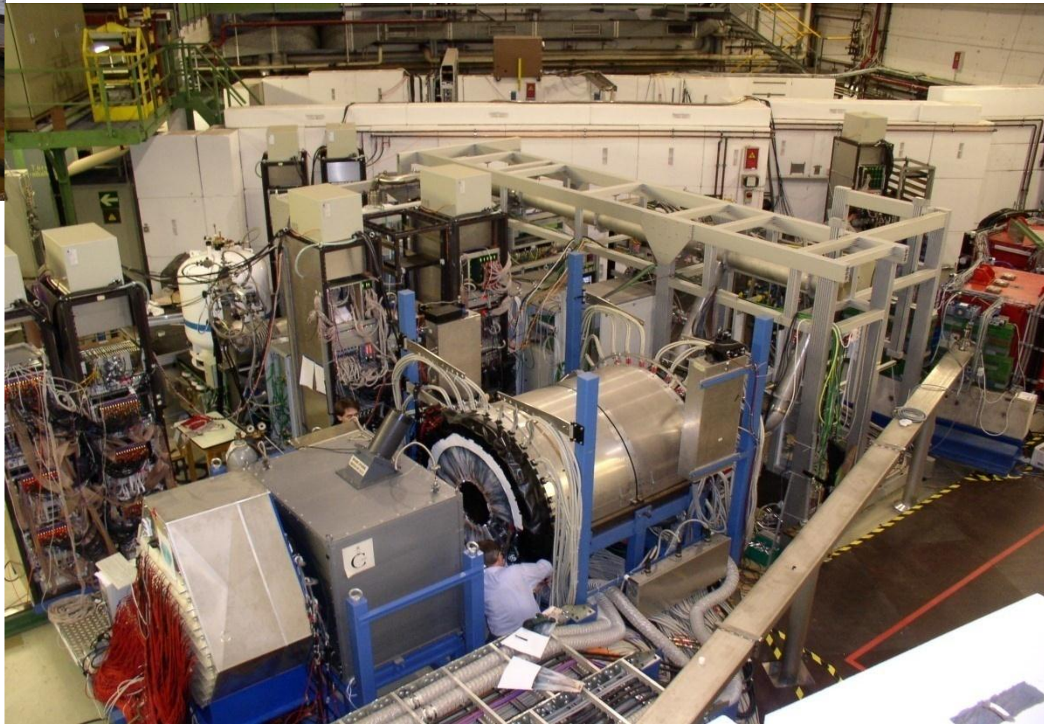


Running time over 2500 hours in year 2008
over 2200 hours in year 2009
over 1500 hours in year 2010
over 1800 hours in year 2011

High. polarization	$P_+ =$ 83.4 %
	$P_- = -$ 80.9 %
fast build-up	
Pol.-time	06h10min

horizontal cryostat
in experimental area

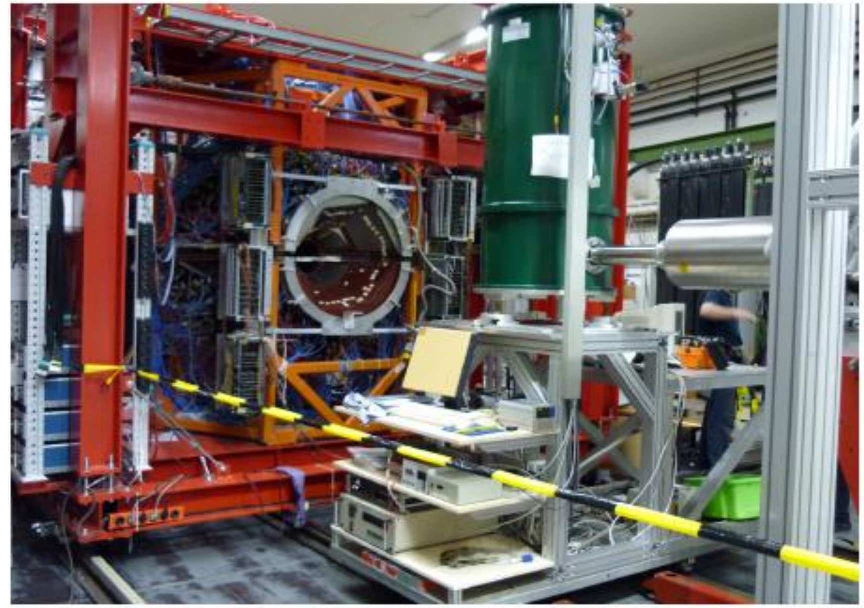
data taking



Bonn: H. Dutz, S. Goertz
Bochum: W. Meyer, G. Reicherz

Polarized Target at MAMI

Polarized Target running since beginning 2010



^{3}He^{4}He-Dilution refrigerator (Mainz/JINR Dubna)

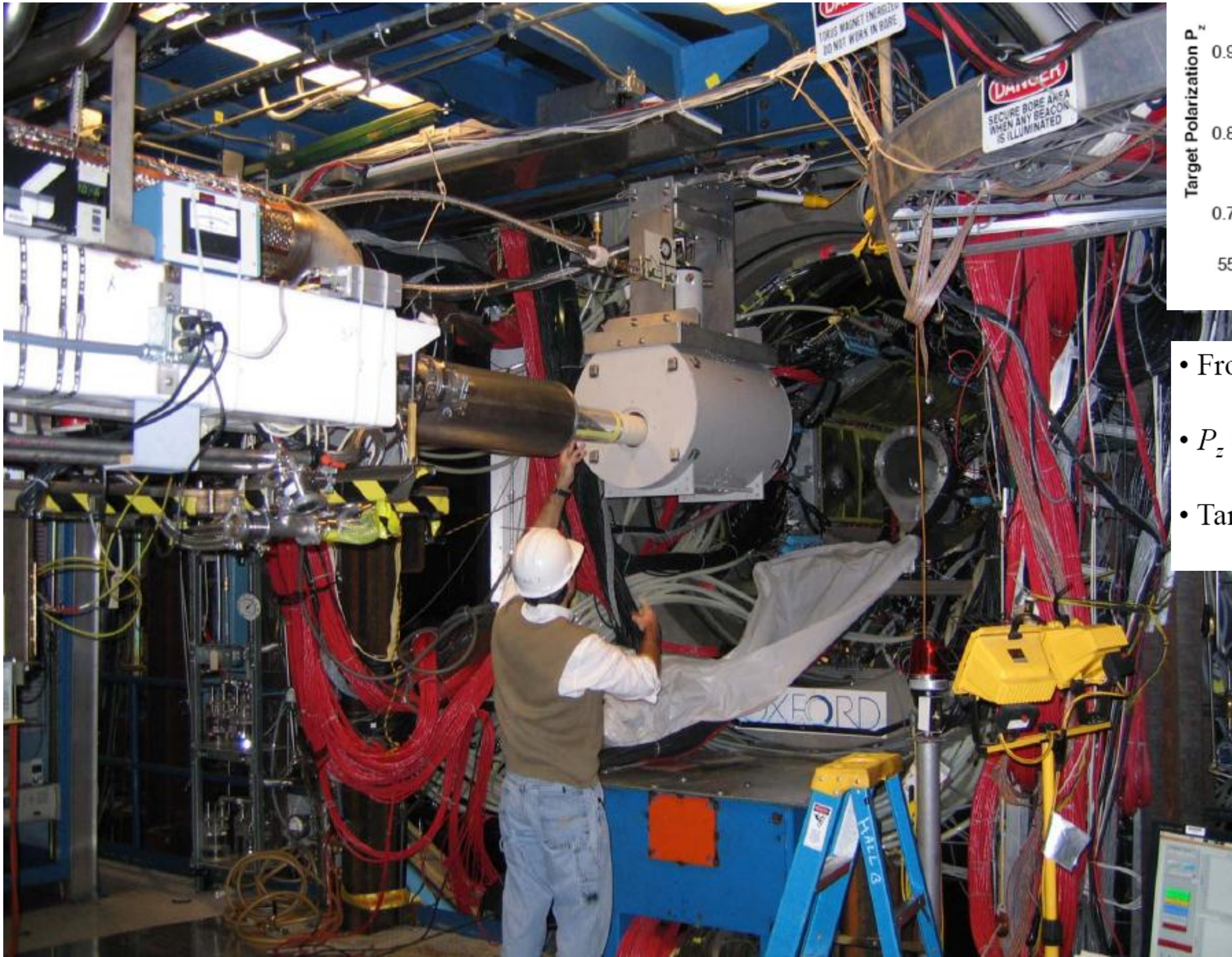
Material: Butanol, Polarization > 90%

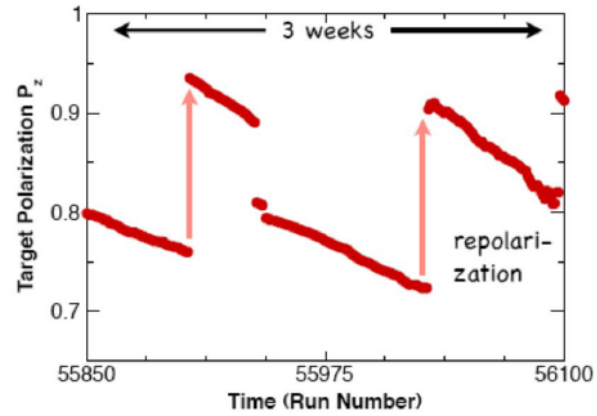
~1000 hours relaxation time & low He consumption

Running with transverse polarized target!

Polarized Target at JLAB

Polarized Target running since beginning 2007





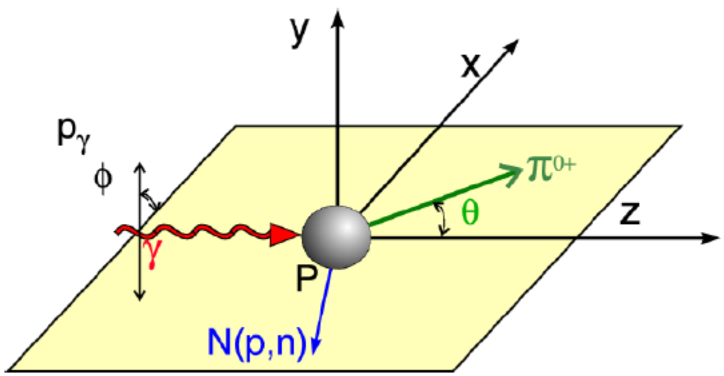
- Frozen spin butanol (C_4H_9OH)
- $P_z \approx 80\%$
- Target depolarization: $\tau \approx 100$ days

Beam-Target Polarization Observables

photoproduction of pseudoscalar mesons:

- all 3 single polarization observables
- 4 double polarization observables

can be measured with the Crystal Barrel/TAPS experiment



photon pol.		target pol. axis		
		x	y	z
unpolarized	σ		T	
linear	$-\Sigma$	H	$-P$	$-G$
circular		F		$-E$

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta) \cdot \Big[1 - P_\gamma^{\text{lin}}\,\Sigma(\theta)\cos(2\phi)$$
$$+P_x \cdot \left(-P_\gamma^{\text{lin}}\,H(\theta)\sin(2\phi) + P_\gamma^{\text{circ}}\,F(\theta)\right)$$
$$+P_y \cdot \left(+P_\gamma^{\text{lin}}\,P(\theta)\cos(2\phi) - T(\theta)\right)$$
$$-P_z \cdot \left(-P_\gamma^{\text{lin}}\,G(\theta)\sin(2\phi) + P_\gamma^{\text{circ}}\,E(\theta)\right)\Big]$$

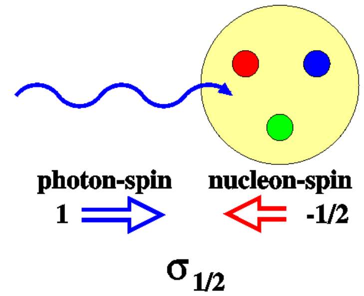
Helicity dependent cross section for $p\pi^0$

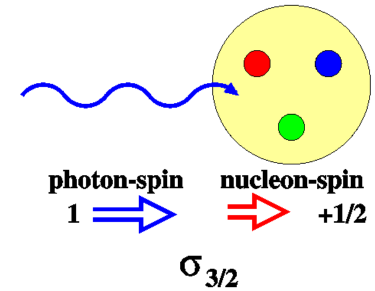
reaction: $\vec{\gamma} + \vec{p} \rightarrow p + \pi^0$

circularly polarized photons

longitudinally polarized proton

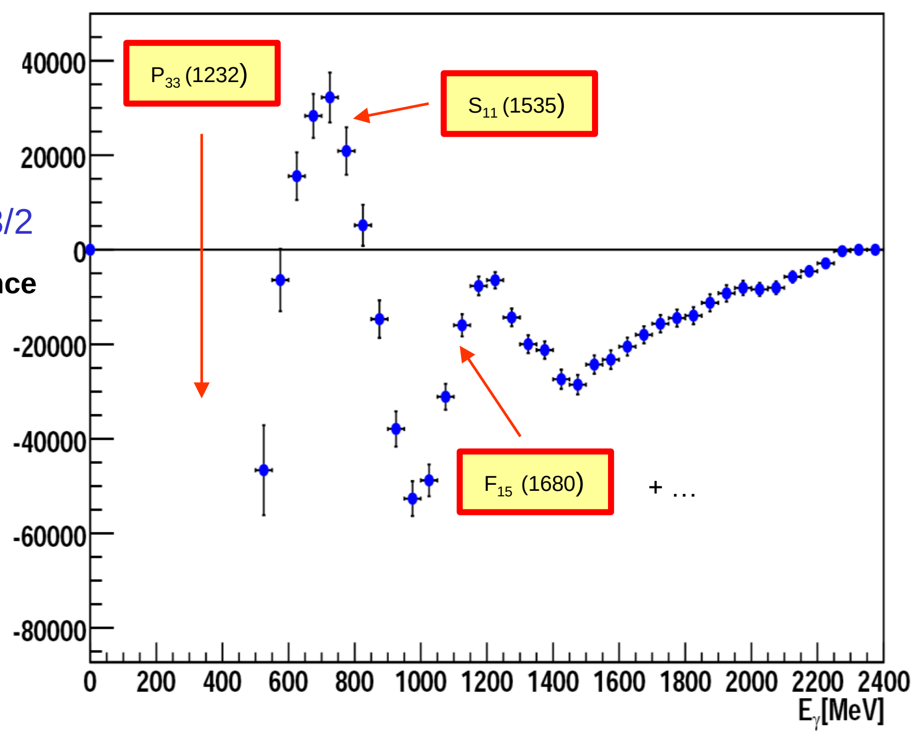
count rate difference
acceptance correction

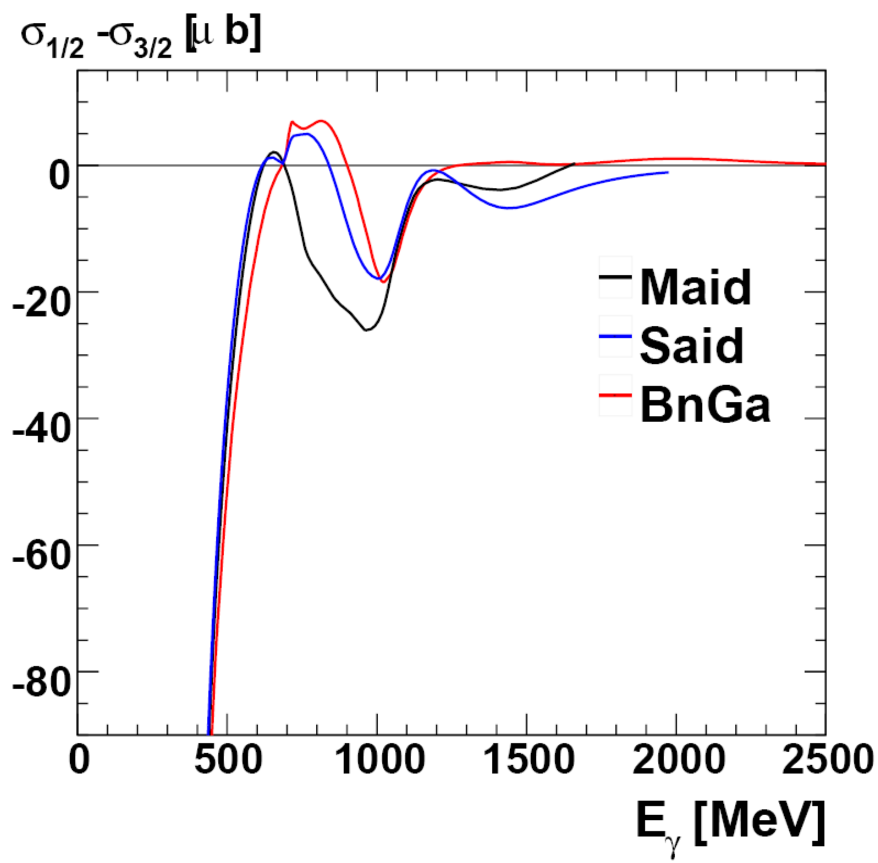




$N_{1/2}$ - $N_{3/2}$

with acceptance correction





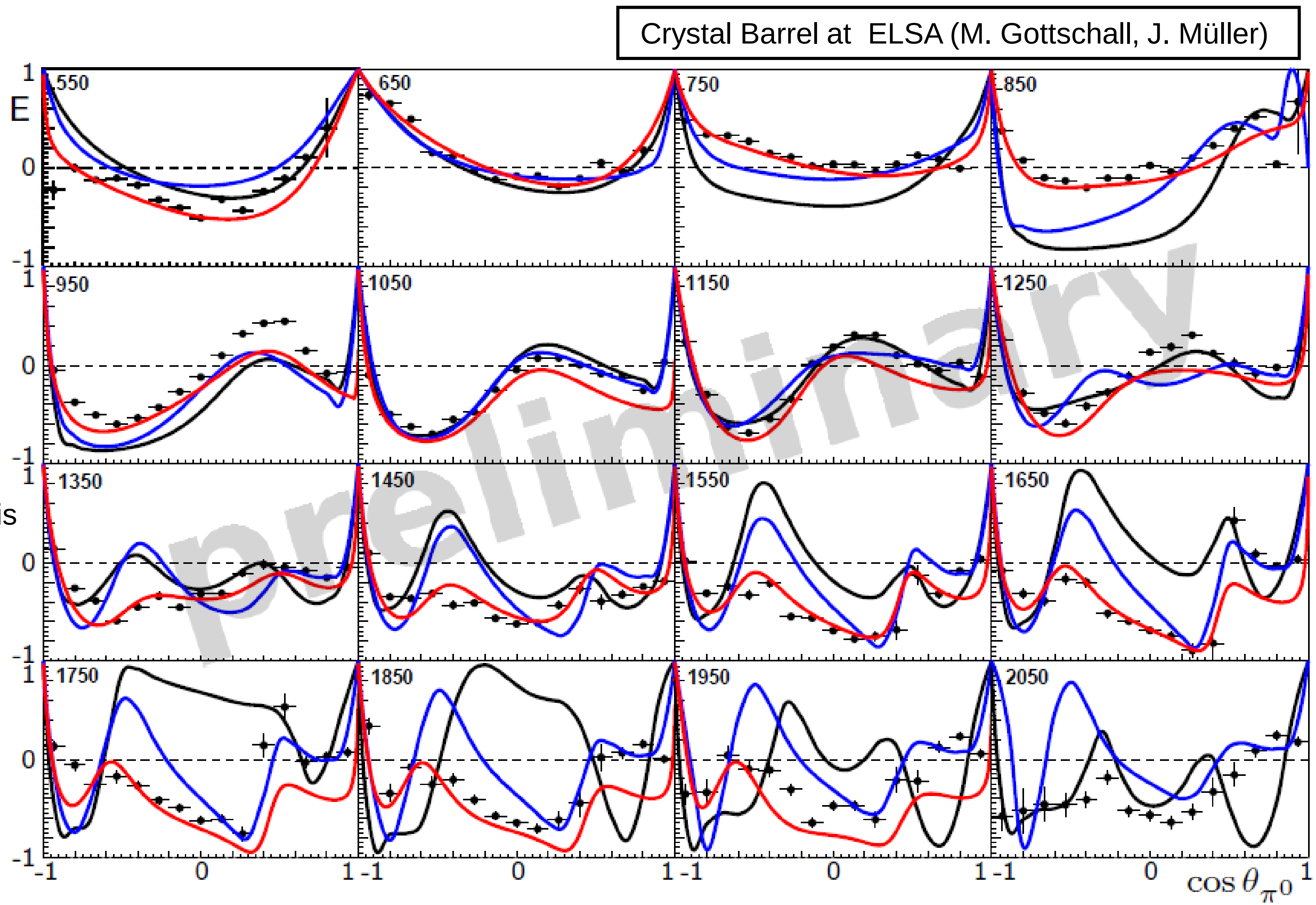
Crystal Barrel at ELSA (M. Gottschall, J. Müller)

Helicity dependent cross section for $p\pi^0$

<u>reaction:</u> $\vec{\gamma} + \vec{p} \rightarrow p + \pi^0$

Angular distributions sensitive to interference between resonances

$$E \sim \frac{N_{1/2} - N_{3/2}}{N_{1/2} + N_{3/2}}$$



partial wave analysis prediction

BnGa

SAID

MAID

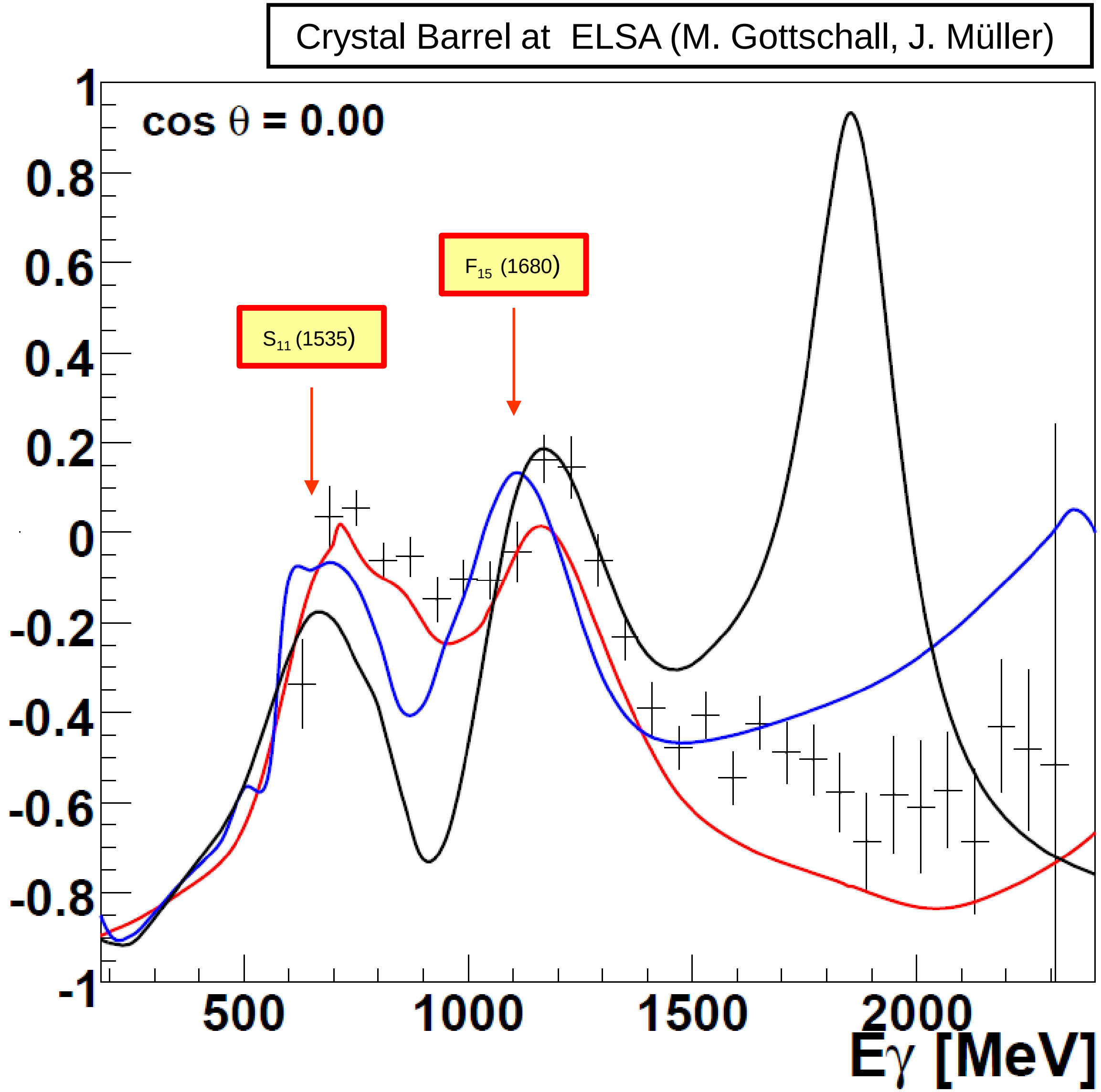
E-Asymmetry for $p\pi^0$ (ELSA Results)

SAID: blue line

MAID: black line

BnGa: red line

PWA predictions
fail already
in 2. resonance region

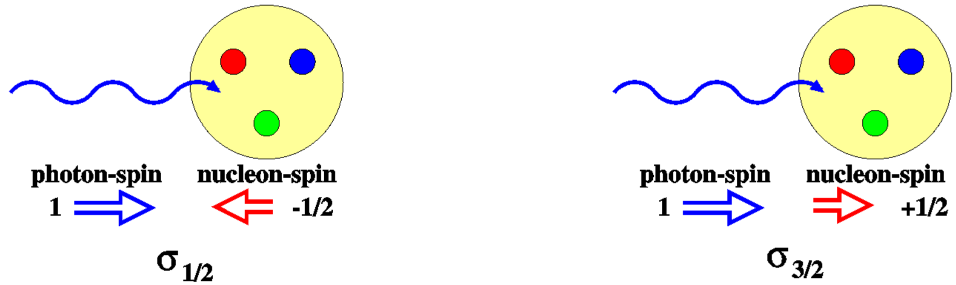


Helicity dependent cross section for pη

reaction: $\vec{\gamma} + \vec{p} \rightarrow p + \eta$

circularly polarized photons

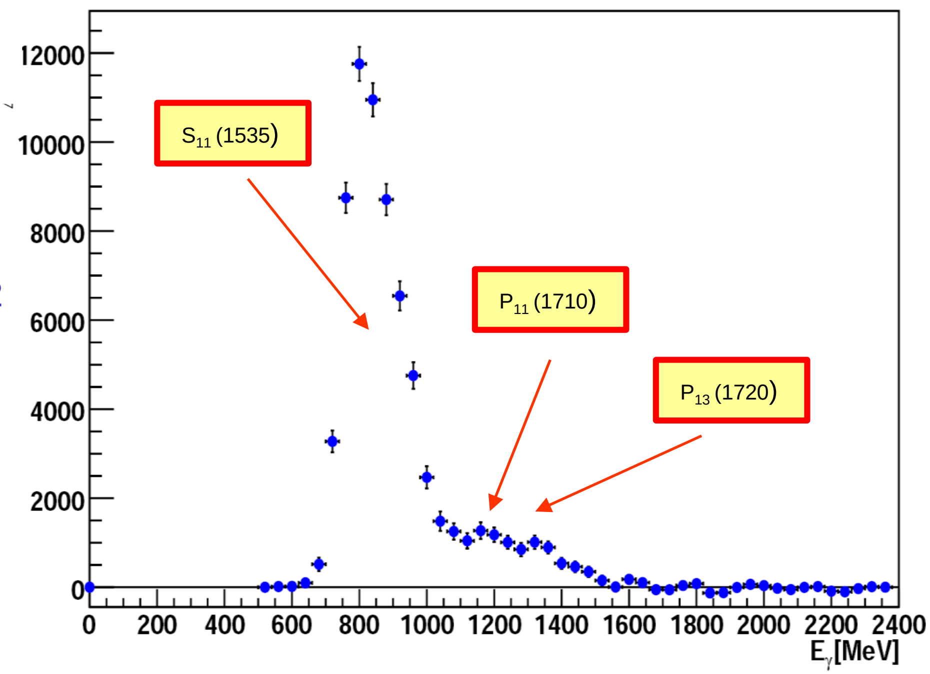
longitudinally polarized proton

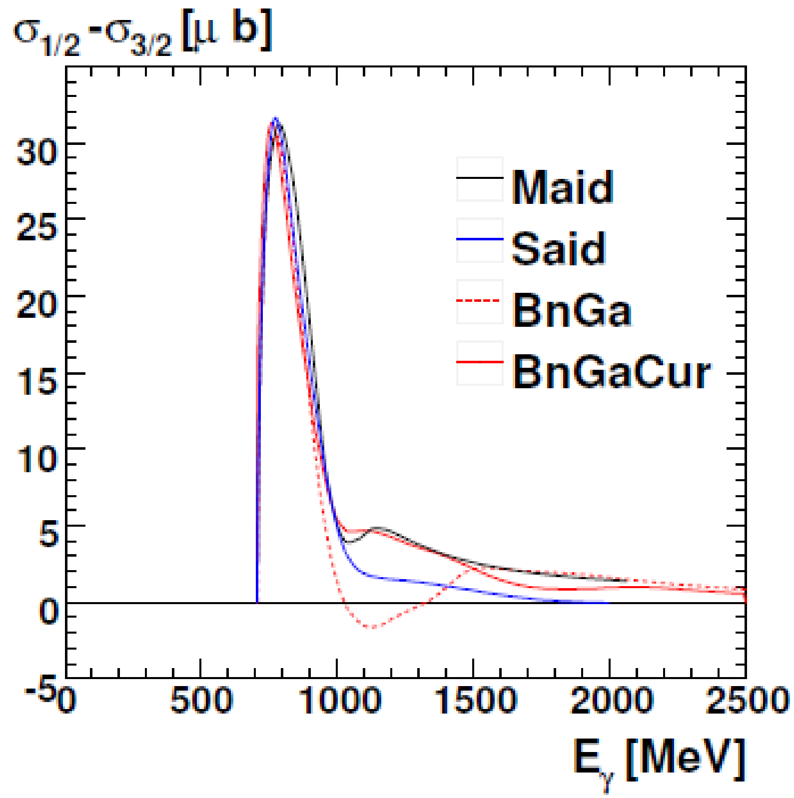


Crystal Barrel at ELSA (J. Müller)

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

no acceptance correction





Problem with a unique PWA solution

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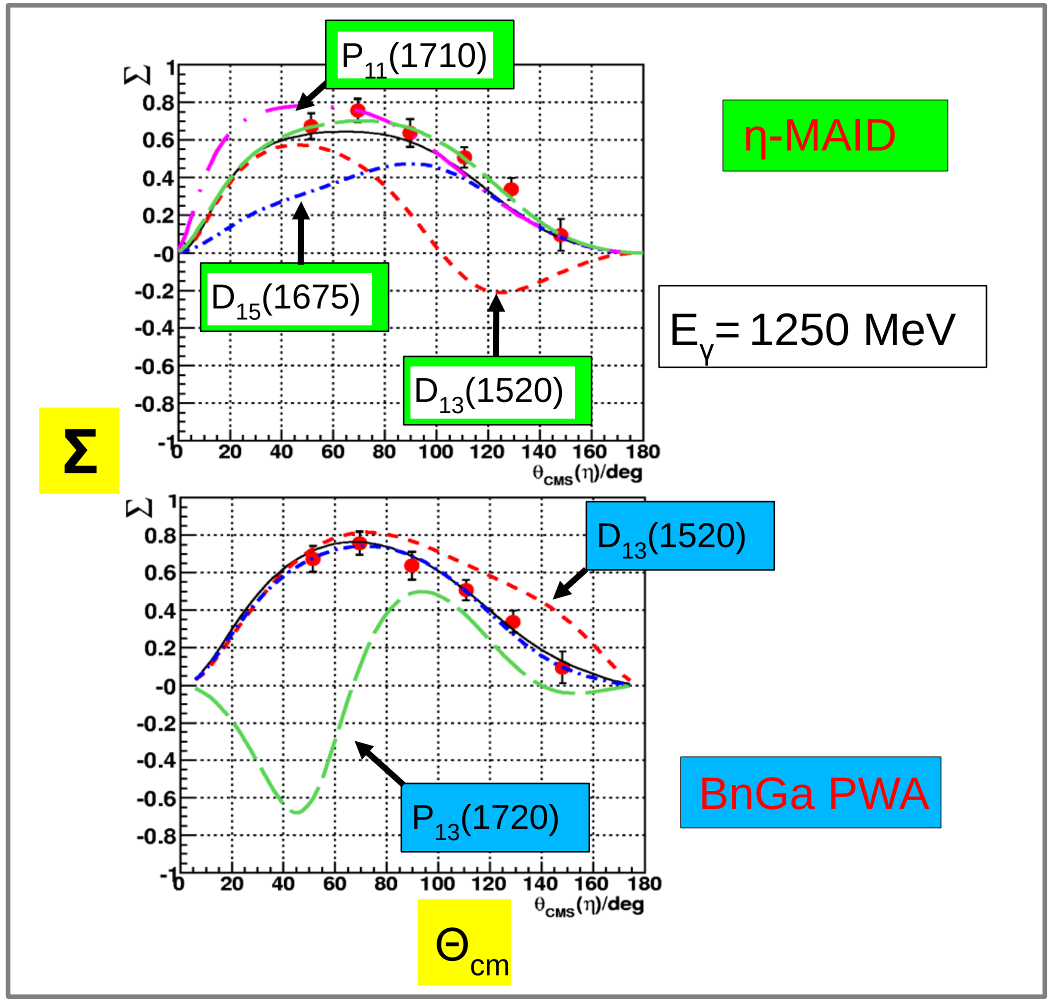
D. Elsner et al., EPJ A33 (2007) 147



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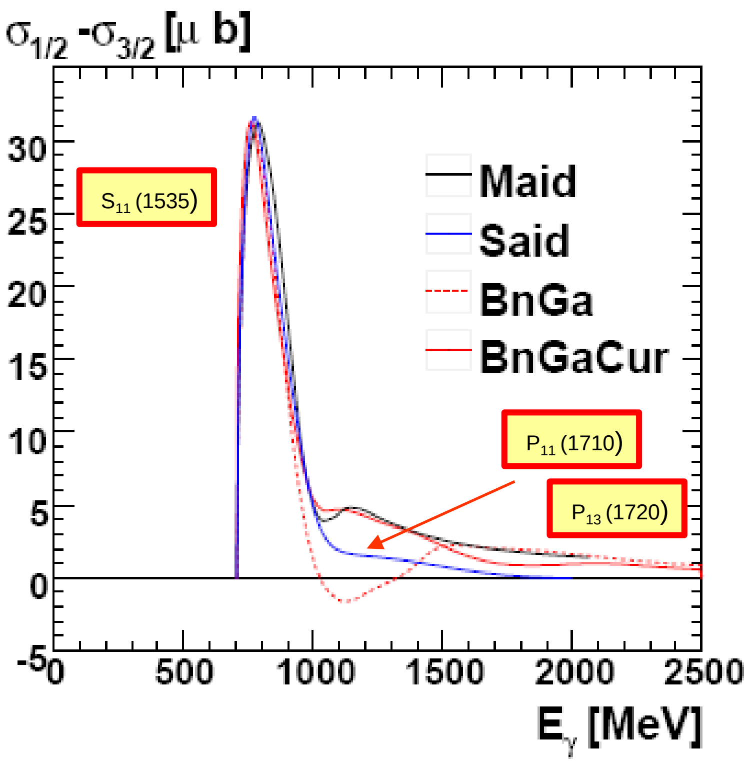
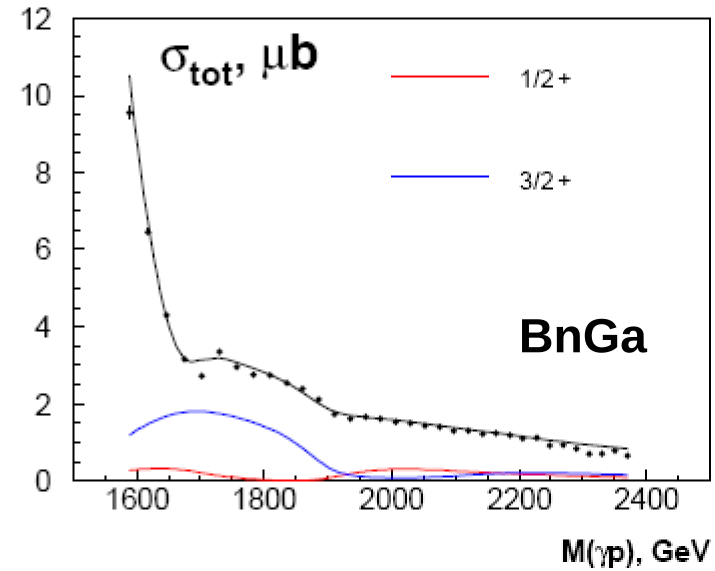
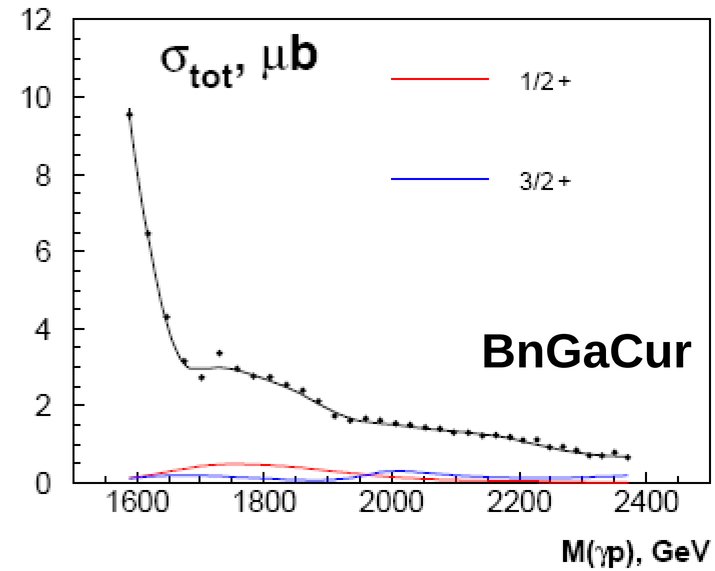


$\gamma p \longrightarrow \eta p$

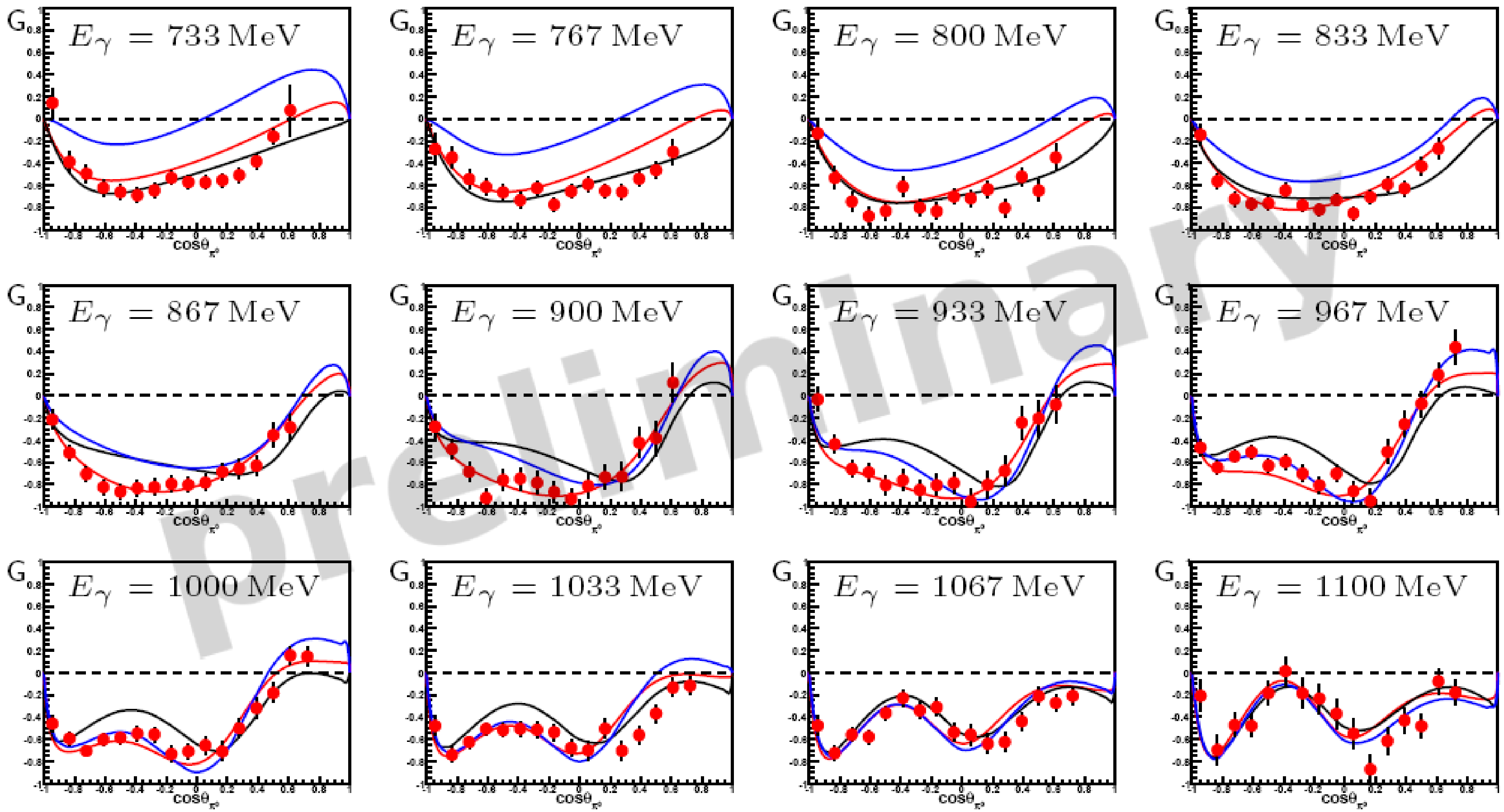




G-Asymmetry for $p\pi^0$ (ELSA Results)

linearly polarized beam, longitudinally polarized target:

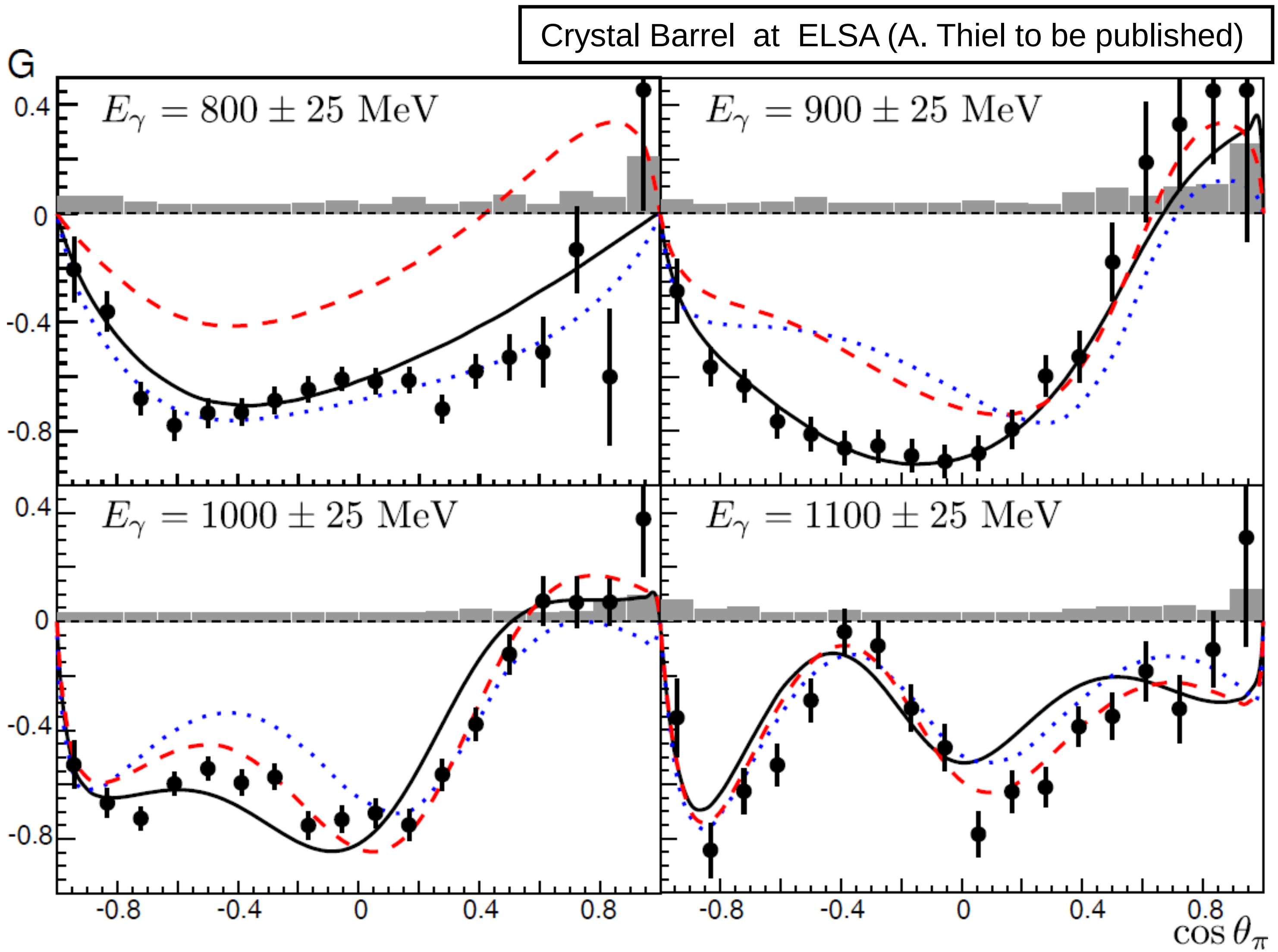
$$\frac{d\sigma}{d\Omega}(\phi) = \frac{d\sigma}{d\Omega}_0 \cdot \left(1 - P_\gamma^{\text{lin}}\,\Sigma\cos(2\phi) + P_\gamma^{\text{lin}} P_z\, G\sin(2\phi)\right)$$



$\vec{\gamma}\vec{p} \rightarrow p\pi^0$ — Maid — Said — BnGa

A. Thiel (Bonn)

G-Asymmetry for $p\pi^0$ (ELSA Results)



SAID: red dashed

MAID: blue dotted

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fail already
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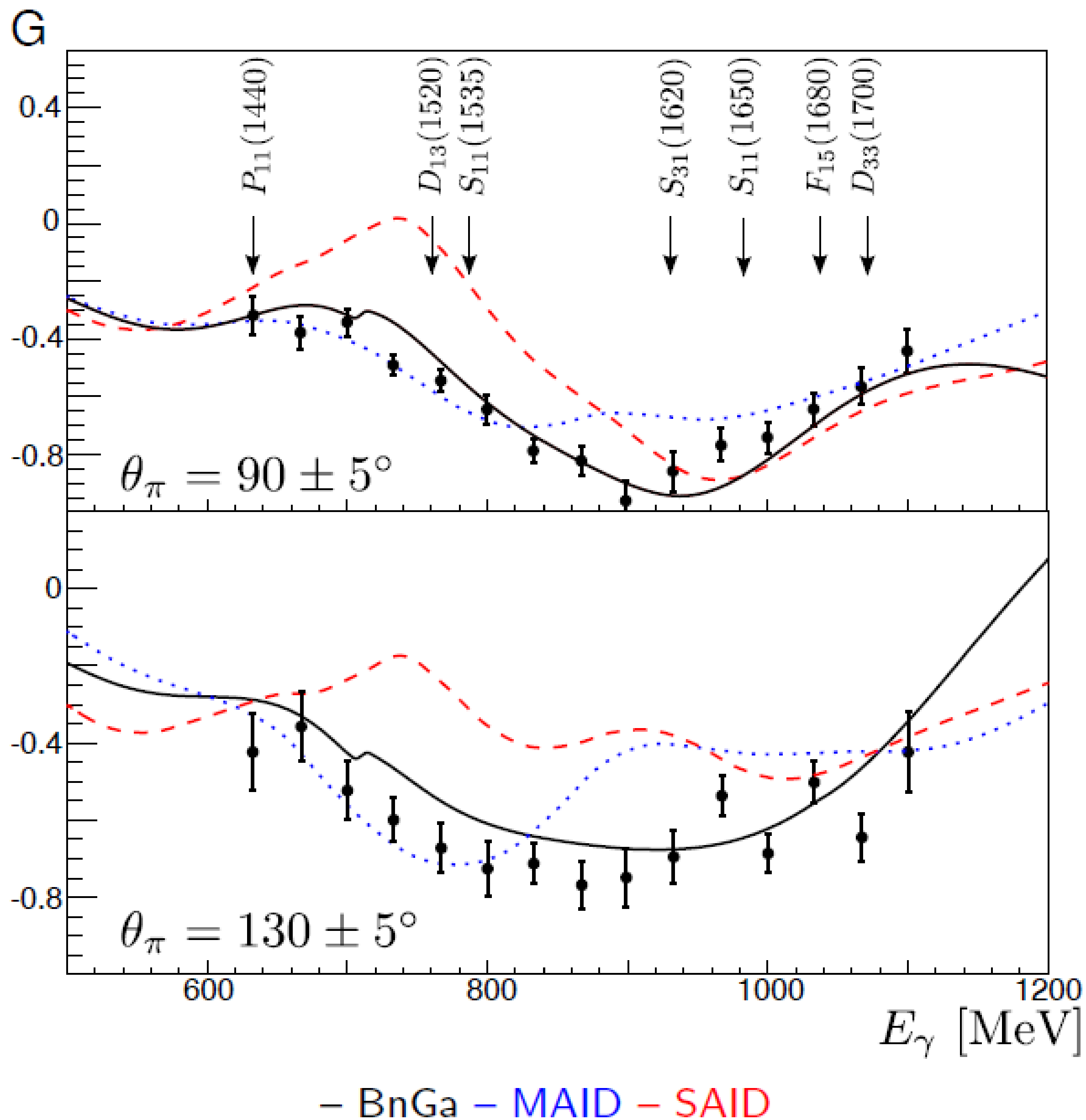
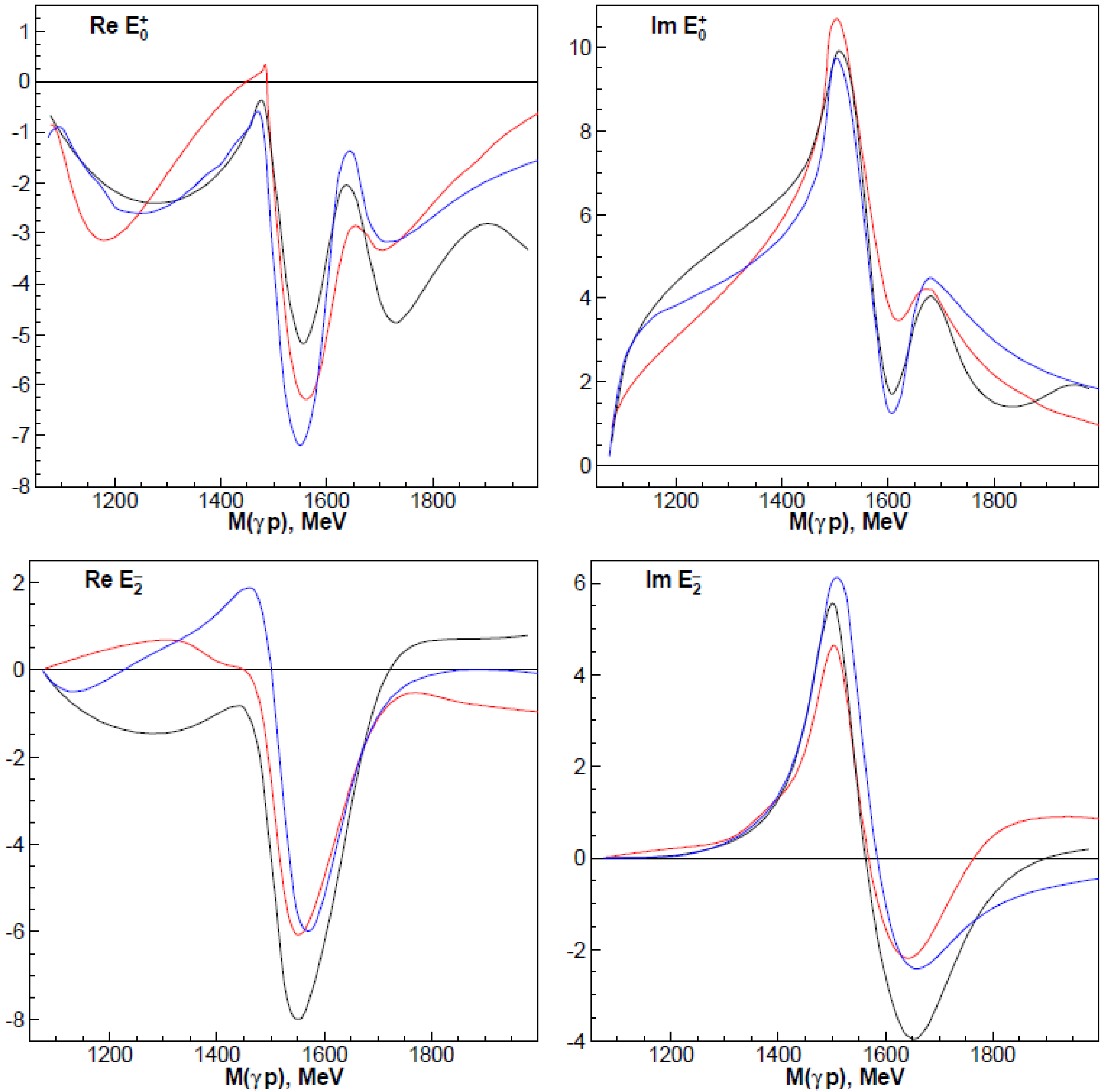


- Below 1 GeV the discrepancies can be traced back to the E_{0+} and E_{2-} multipoles s- and d-wave contributions
- E_{0+} multipole $S_{11}(1535)$, $S_{11}(1650)$ and $S_{31}(1620)$
- E_{2-} multipole $D_{13}(1520)$ and D_{33} (1700)

E_{0+} and E_{2-} Multipoles



- E_{0+} multipole
  $S_{11}(1535)$, $S_{11}(1650)$ and $S_{31}(1620)$
- E_{2-} multipole
  $D_{13}(1520)$ and D_{33} (1700)

SAID: blue

MAID: black

BnGa: red line

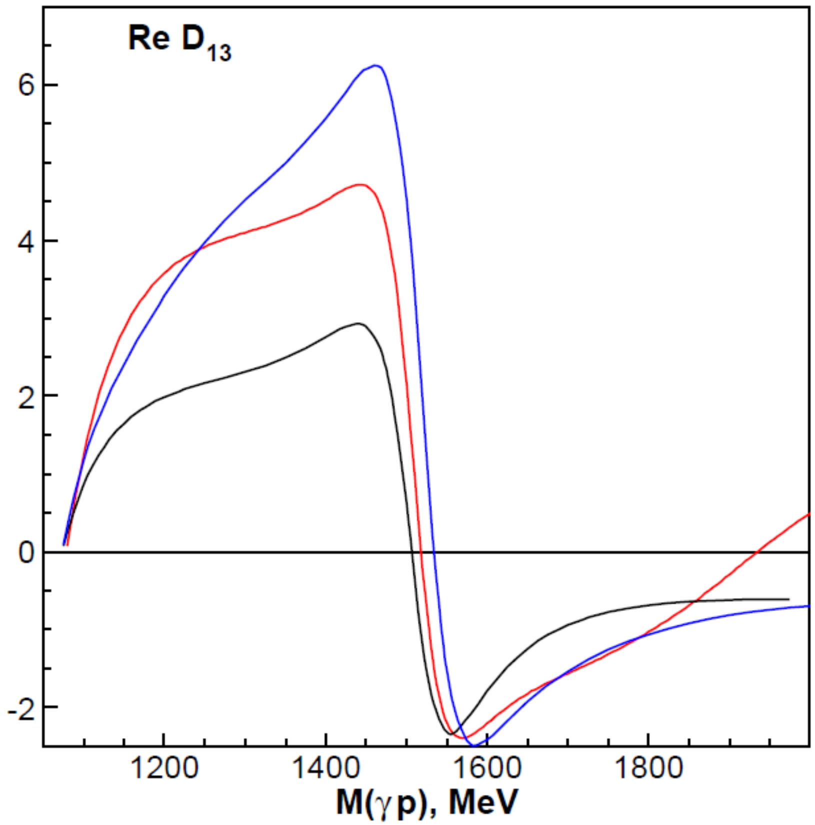
D_{13} partial wave

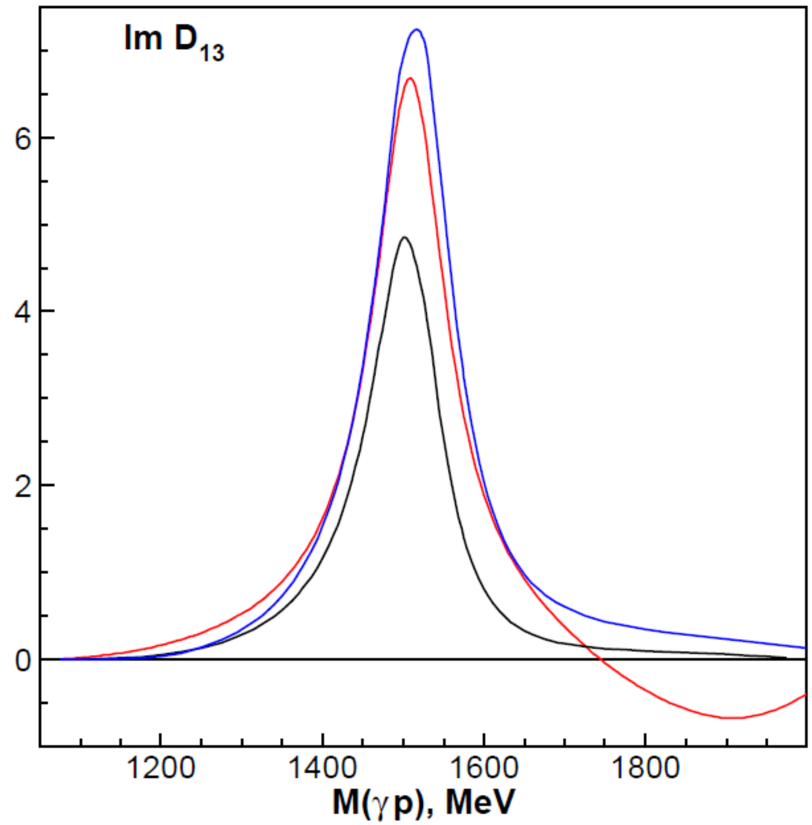
SAID: blue

MAID: black

BnGa: red line

- E_{2-} multipole contribution from D_{13} and D_{33} partial waves
- $D_{13}(1520)$- resonance in D_{13} partial wave





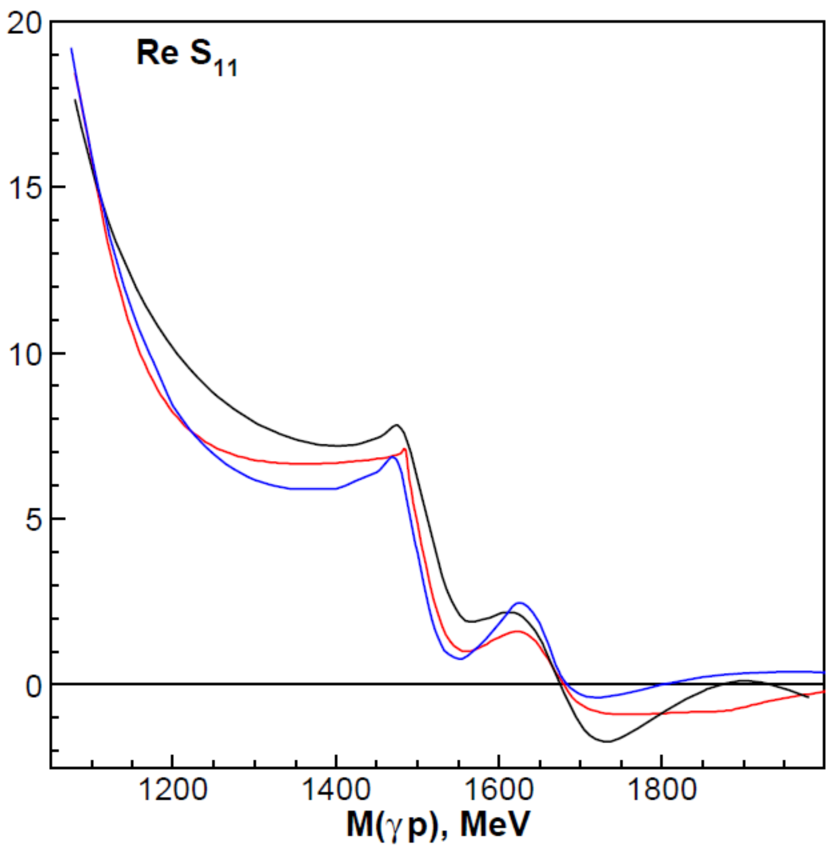
S_{11} partial wave

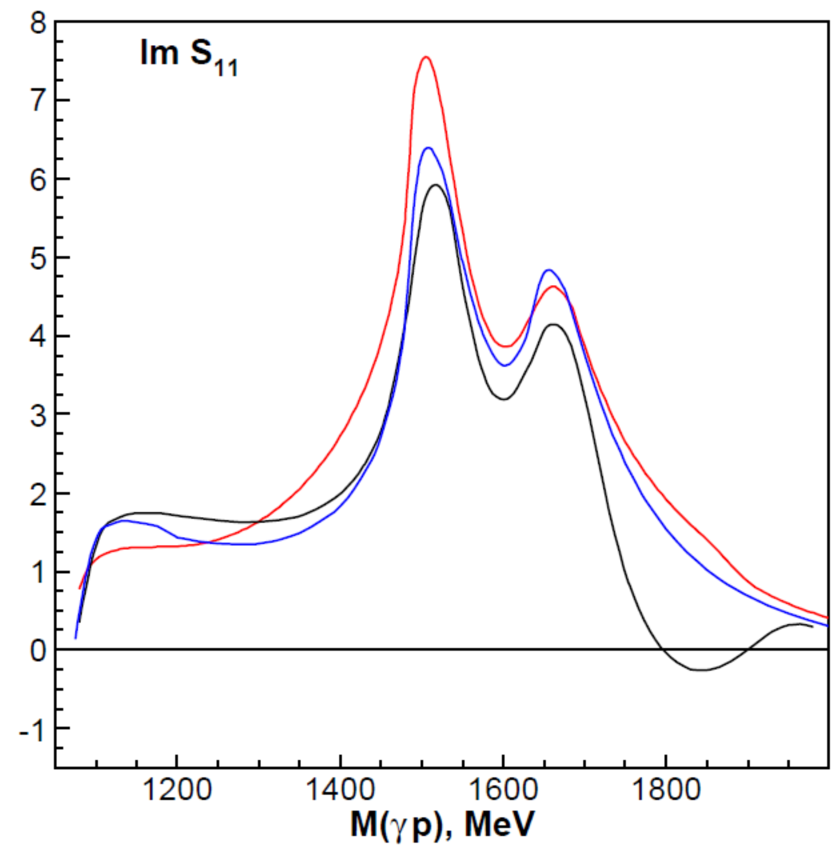
SAID: blue

MAID: black

BnGa: red line

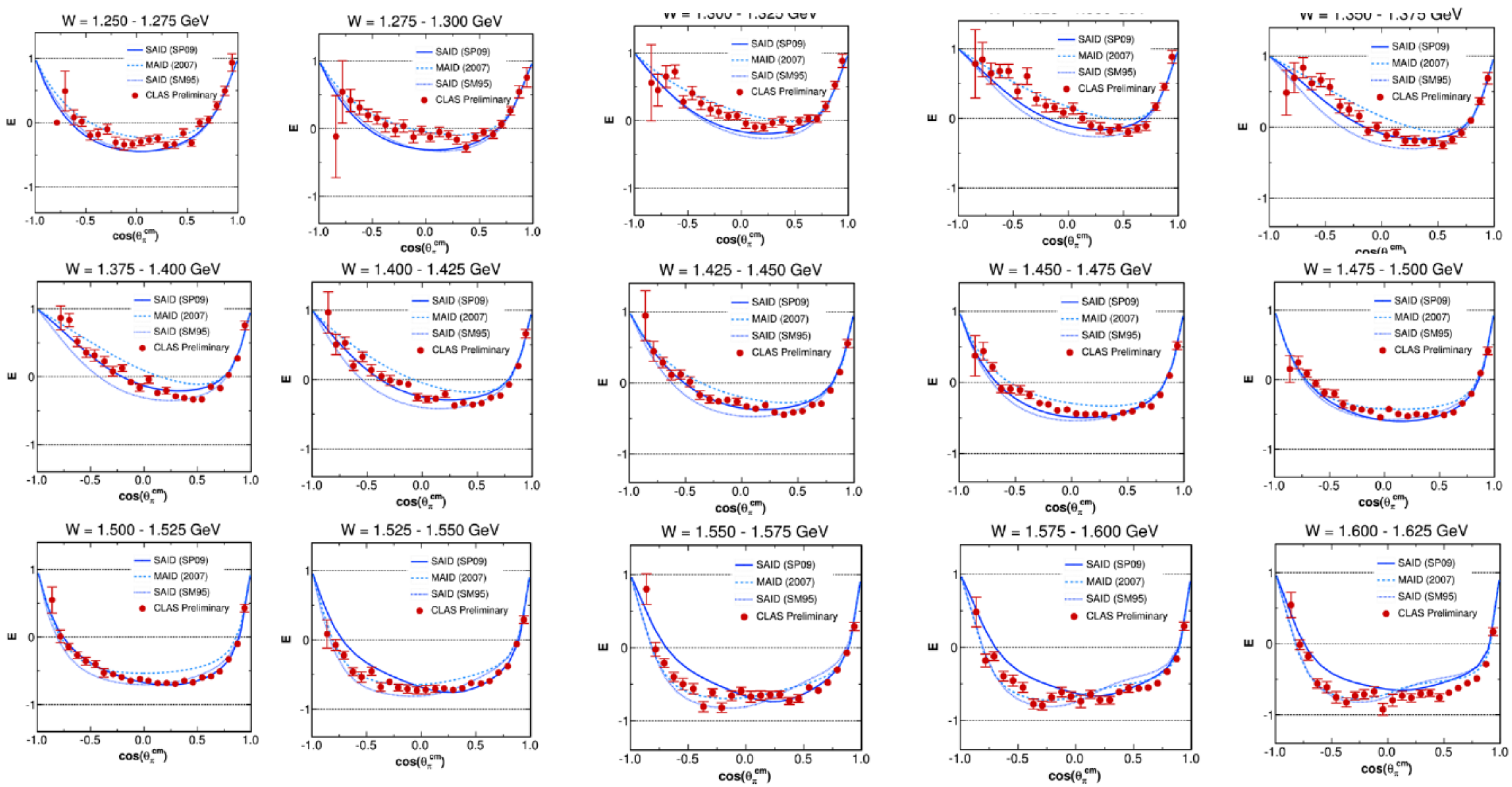
- E_{0+} multipole contribution from S_{11}- and S_{31}- partial waves
- S_{11}(1535)- and S_{11}(1650)- resonances in S_{11}-partial wave





E-Asymmetry for $n\pi^+$ (JLaB Results)

Preliminary results CLAS at JLAB (M. Dugger)



E-Asymmetry for $n\pi^+$ (JLaB Results)

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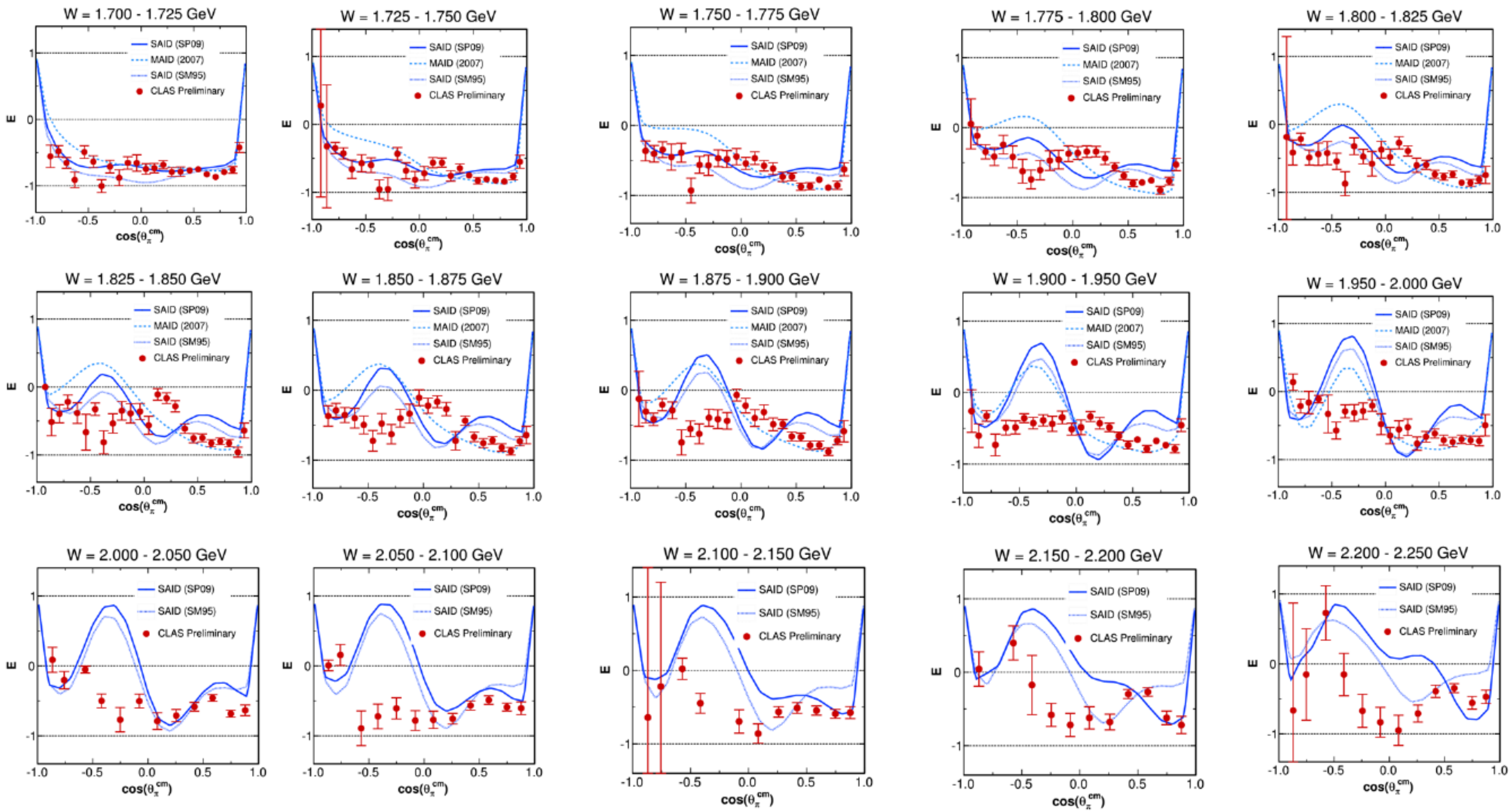


Polarization Observables with trans. pol. Target

photon pol.		target pol. axis x	y	z
unpolarized	σ		T	
linear	$-\Sigma$	H	$-P$	$-G$
circular		F		$-E$

Circularly polarized photons
Transversely polarized protons –> double polarization asymmetry *F*

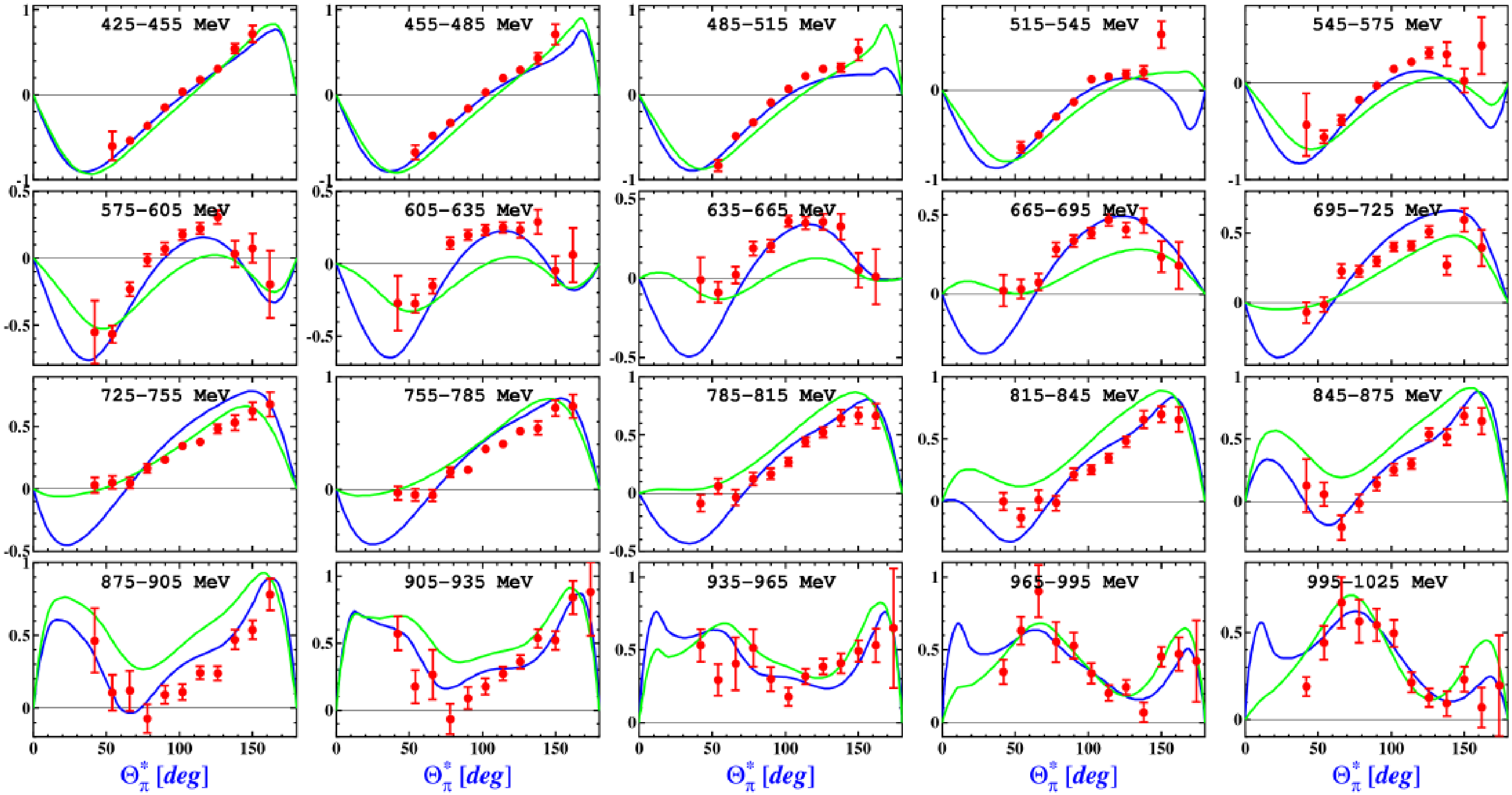
Linearly polarized photons
Transversely polarized protons –> double polarization asymmetry *H* and *P*

–> in addition Beam asymmetry Σ and
Target asymmetry *T*

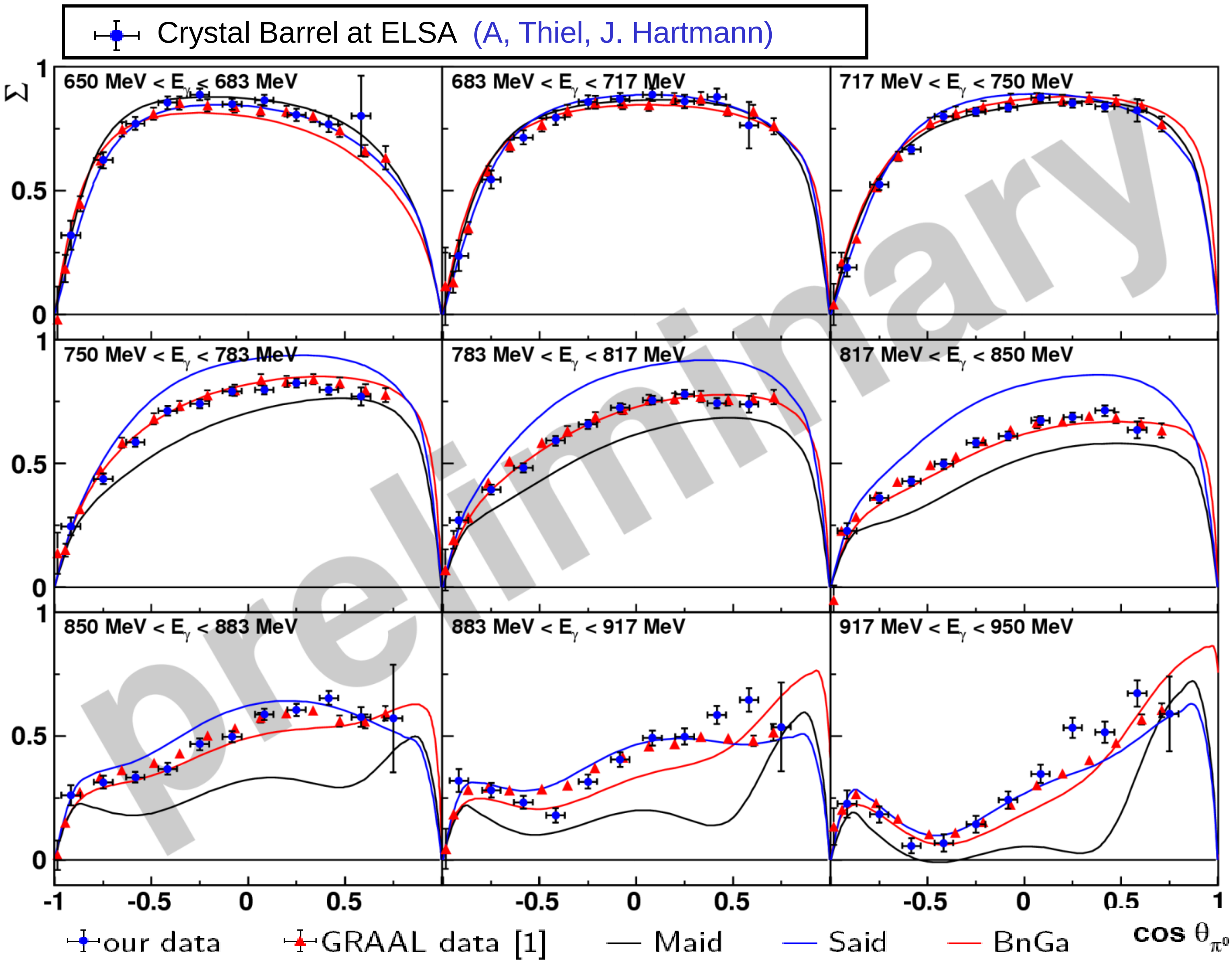
F-Asymmetry for $p\pi^0$ (MAMI Results)

Preliminary results Crystal Ball at MAMI (H.J. Arends, M. Ostrick)

blue line – MAID-2007
green line – SAID



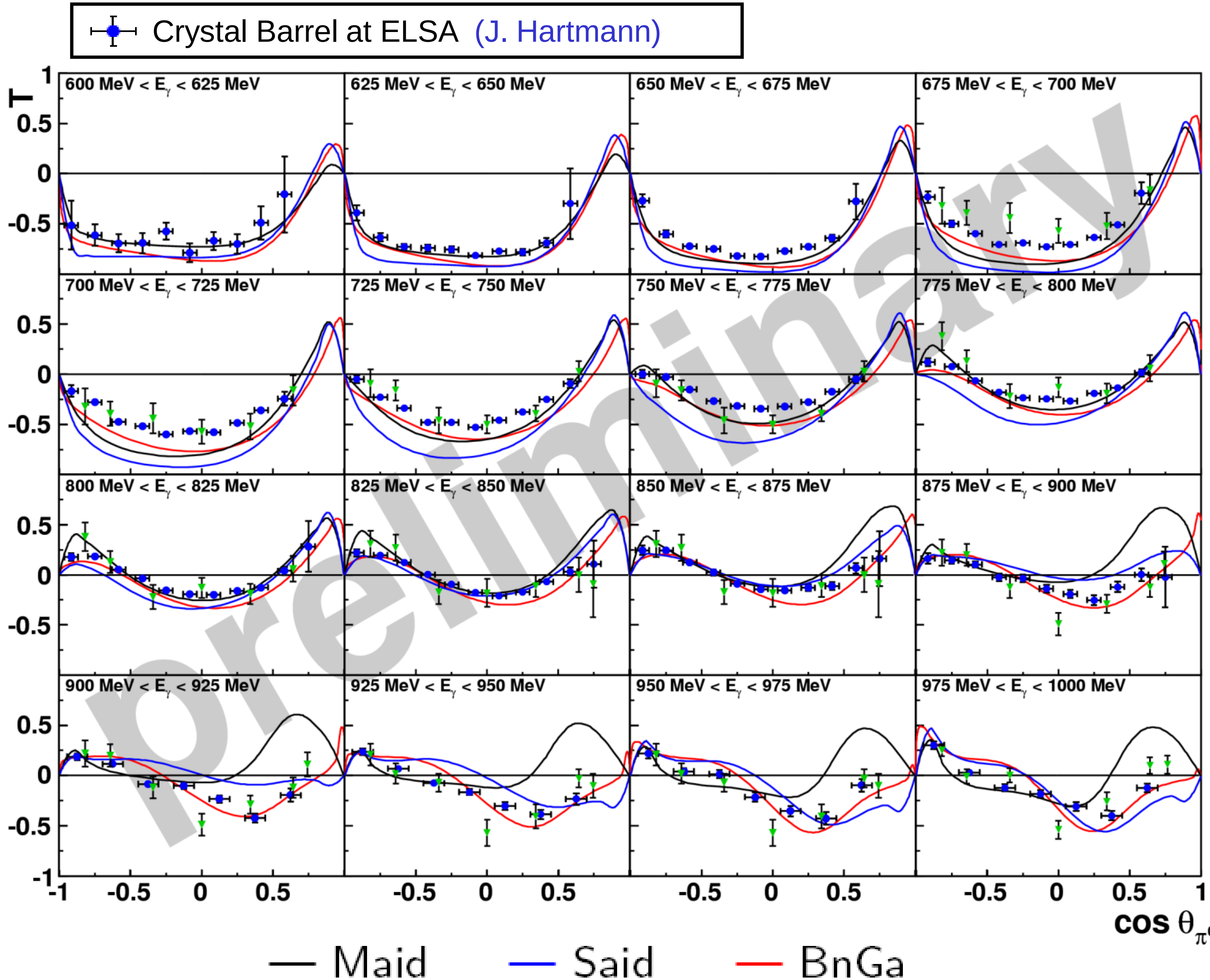
Beam Asymmetry Σ for $p\pi^0$ (ELSA Results)



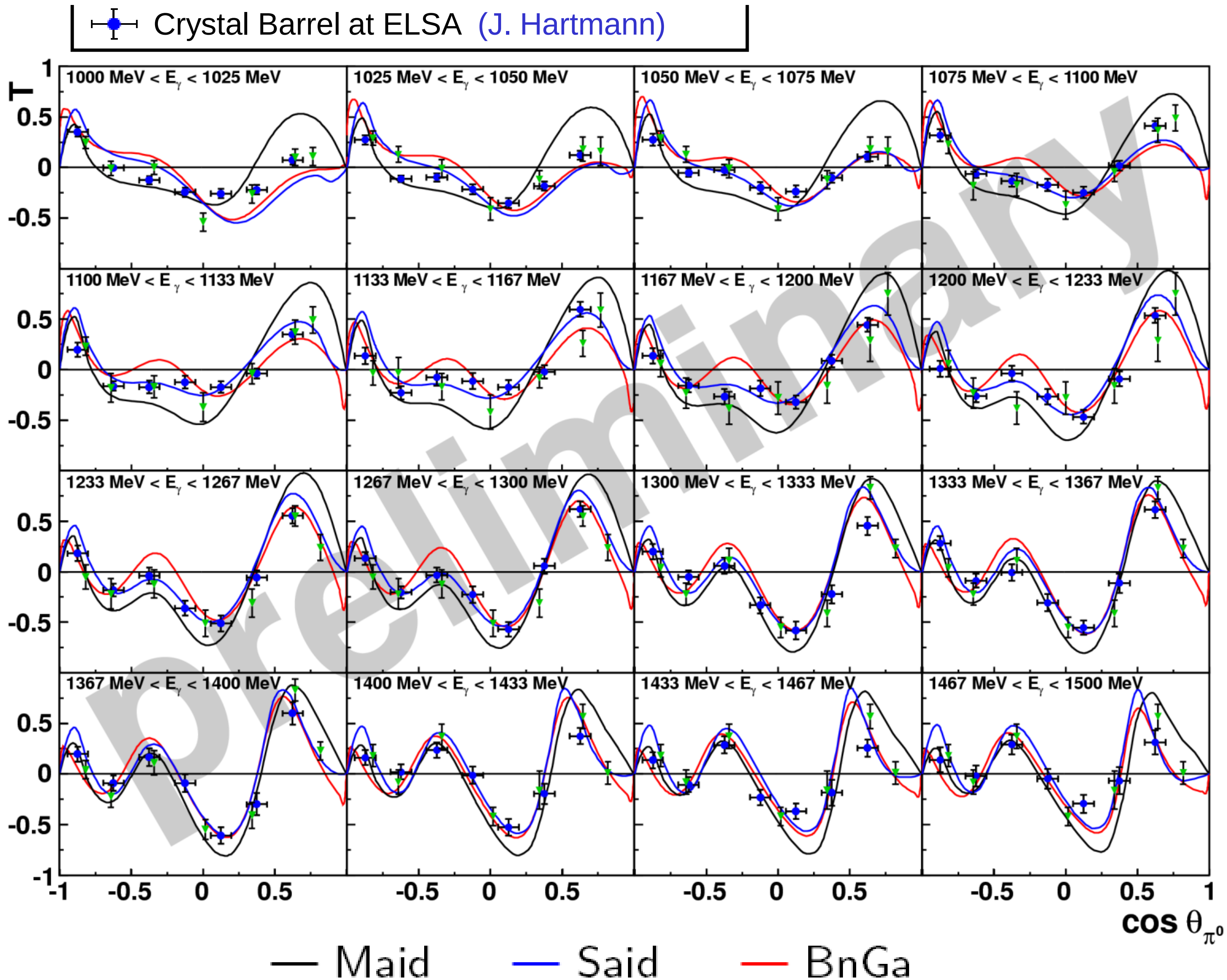
Note: target material butanol ⇝ also small contribution from C

[1] O. Bartalini *et al*, Eur. Phys. J. A 26, 399-419 (2005)

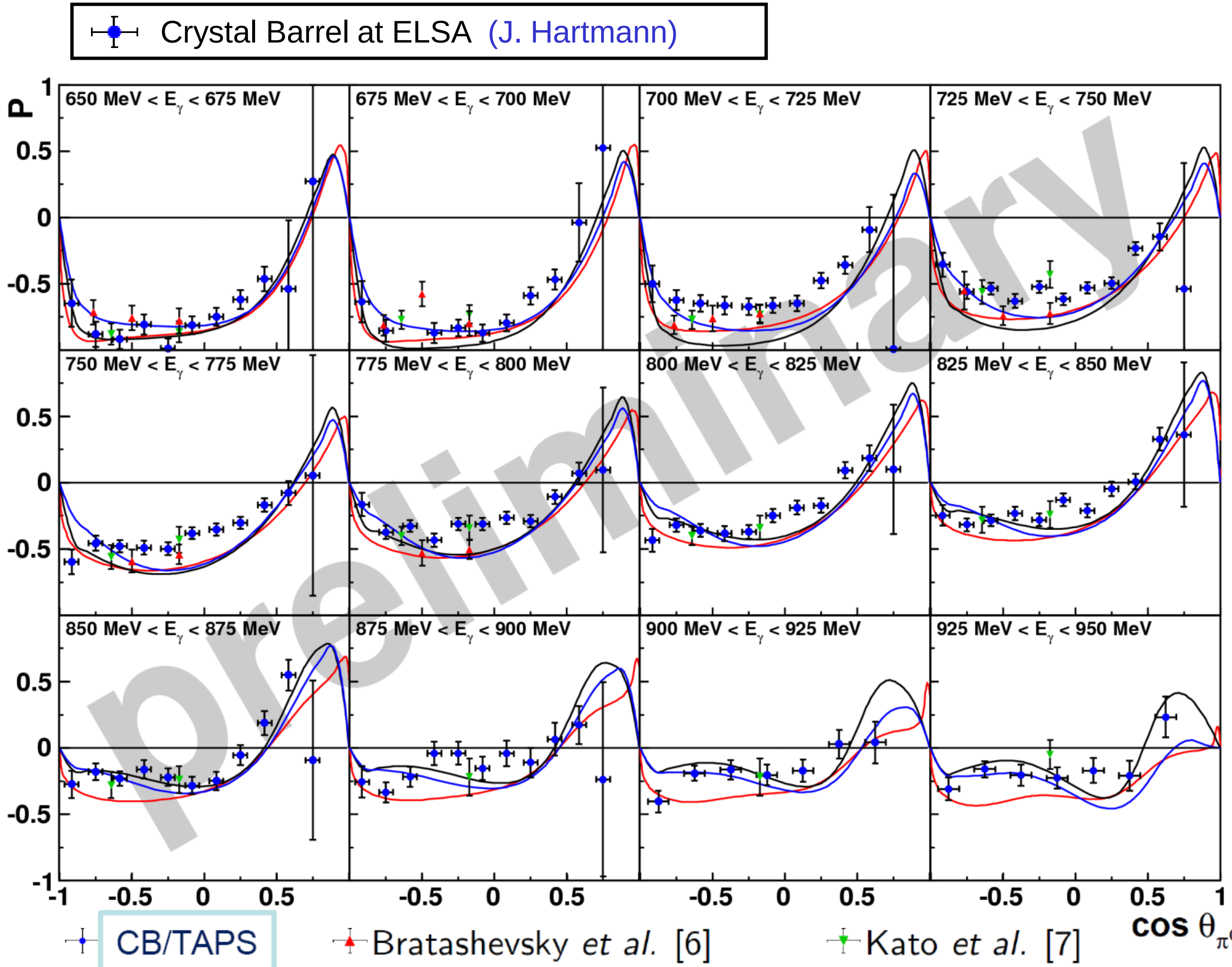
Target Asymmetry T for $p\pi^0$ (ELSA Results)



Target Asymmetry T for $p\pi^0$ (ELSA Results)



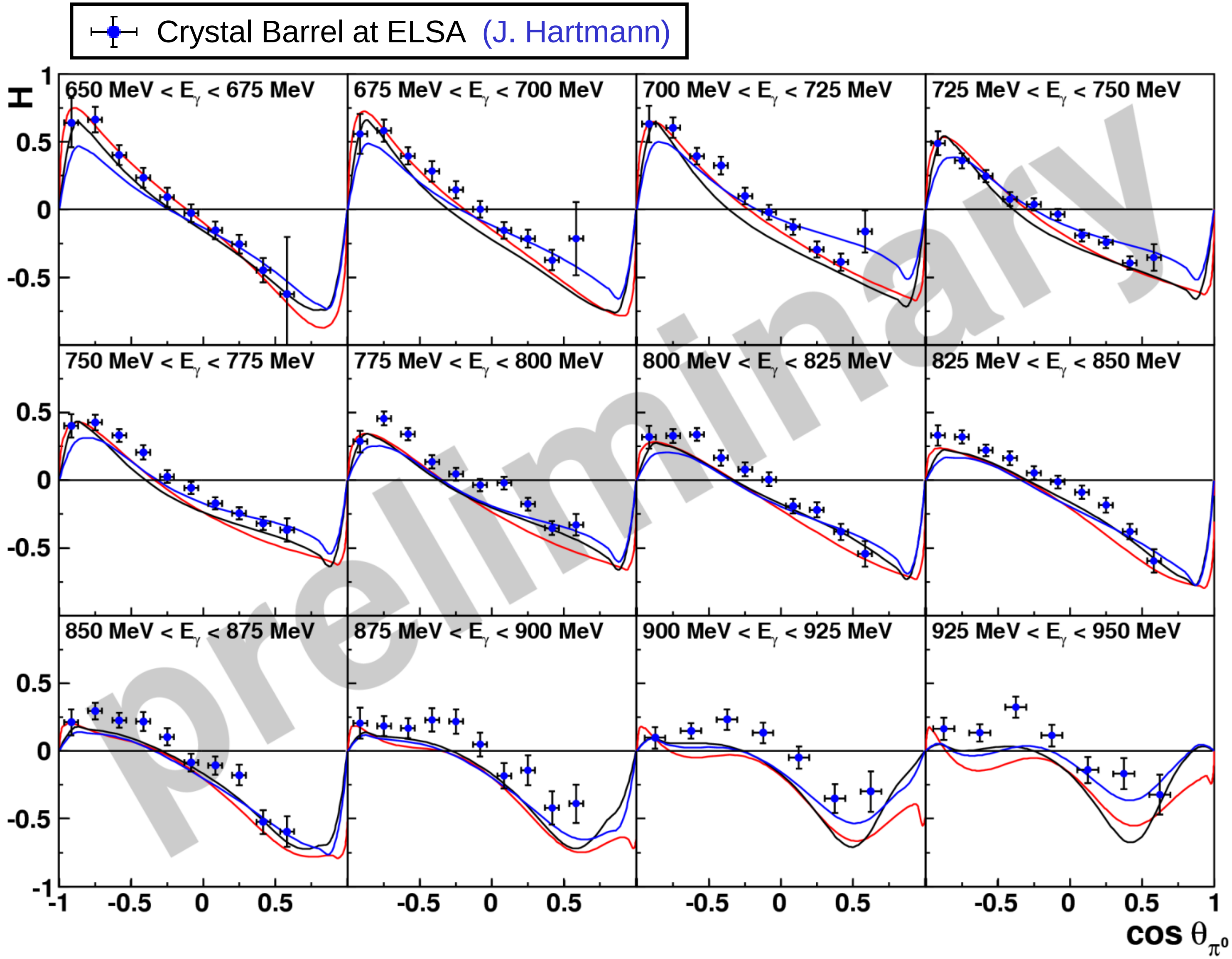
Recoil Polarization P for $p\pi^0$ (ELSA Results)



[6] A.S. Bratashevsky *et al.*, Nucl. Phys. **B166** (1980)

[7] S. Kato *et al.*, Nucl. Phys. **B168** (1980)

Double Polarization Asymmetry H for $p\pi^0$



First Interpretation of Asymmetry

Including different angular momenta ℓ:

- with $\ell \leq 1$:

$$\frac{\hat{G}}{\sin^2\theta_\pi} = \frac{G \cdot \mathcal{I}}{\sin^2\theta_\pi} = A$$
$$= 3 \cdot Im(2M_1^{+*}E_1^{+} + M_1^{-*} \cdot (E_1^{+} - M_1^{+}))$$

- with $\ell \leq 2$:

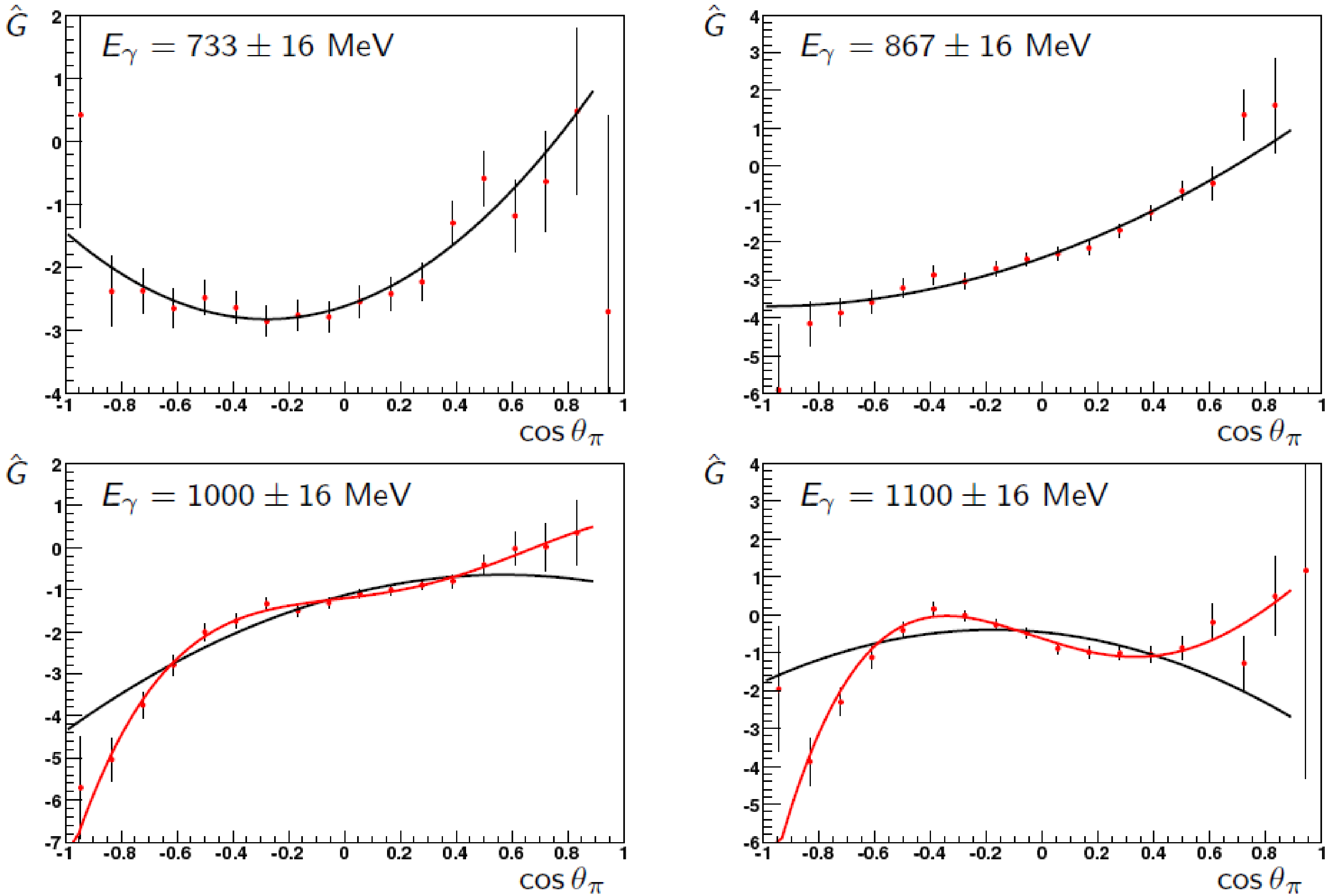
$$\frac{\hat{G}}{\sin^2\theta_\pi} = A + B \cdot \cos\theta_\pi + C \cdot \cos^2\theta_\pi$$

- with $\ell \leq 3$:

$$\frac{\hat{G}}{\sin^2\theta_\pi} = A + B \cdot \cos\theta_\pi + C \cdot \cos^2\theta_\pi + D \cdot \cos^3\theta_\pi + E \cdot \cos^4\theta_\pi$$

First Interpretation of Asymmetry

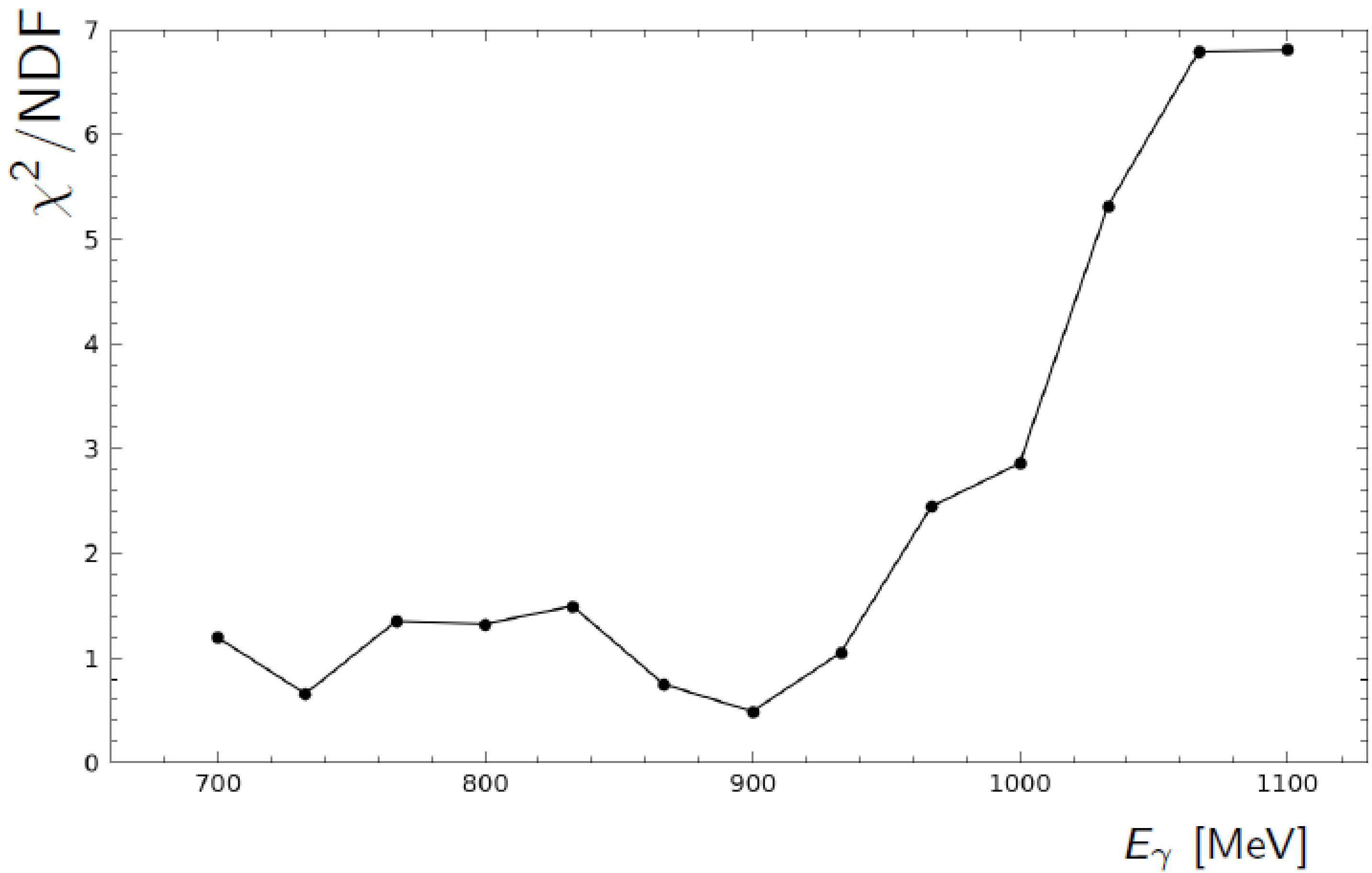
black line L <= 2 Fit and red line L <= 3 Fit



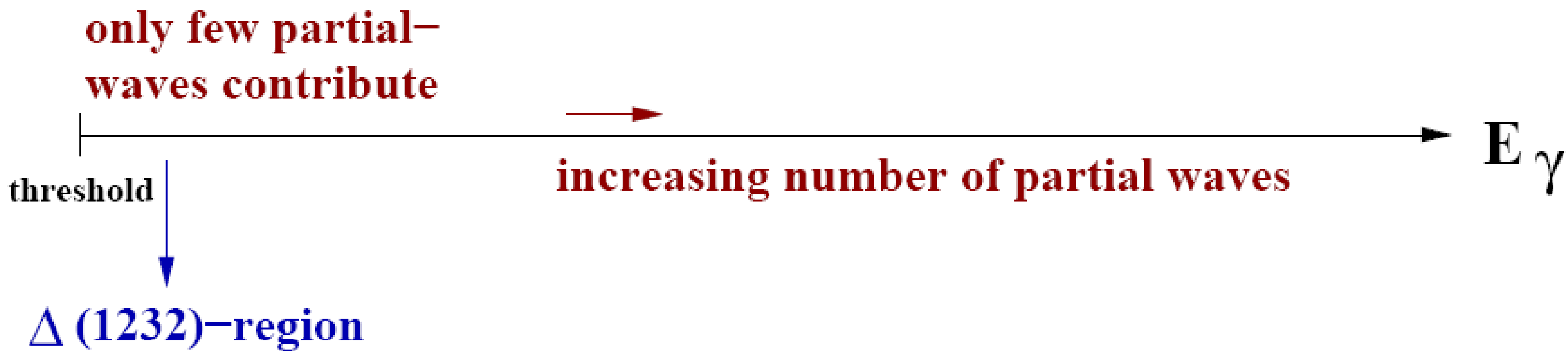
Fit polynomials: – second order – fourth order

First Interpretation of Asymmetry

L <= 2 Fit   truncated partial wave analysis



Target Asymmetry in pη



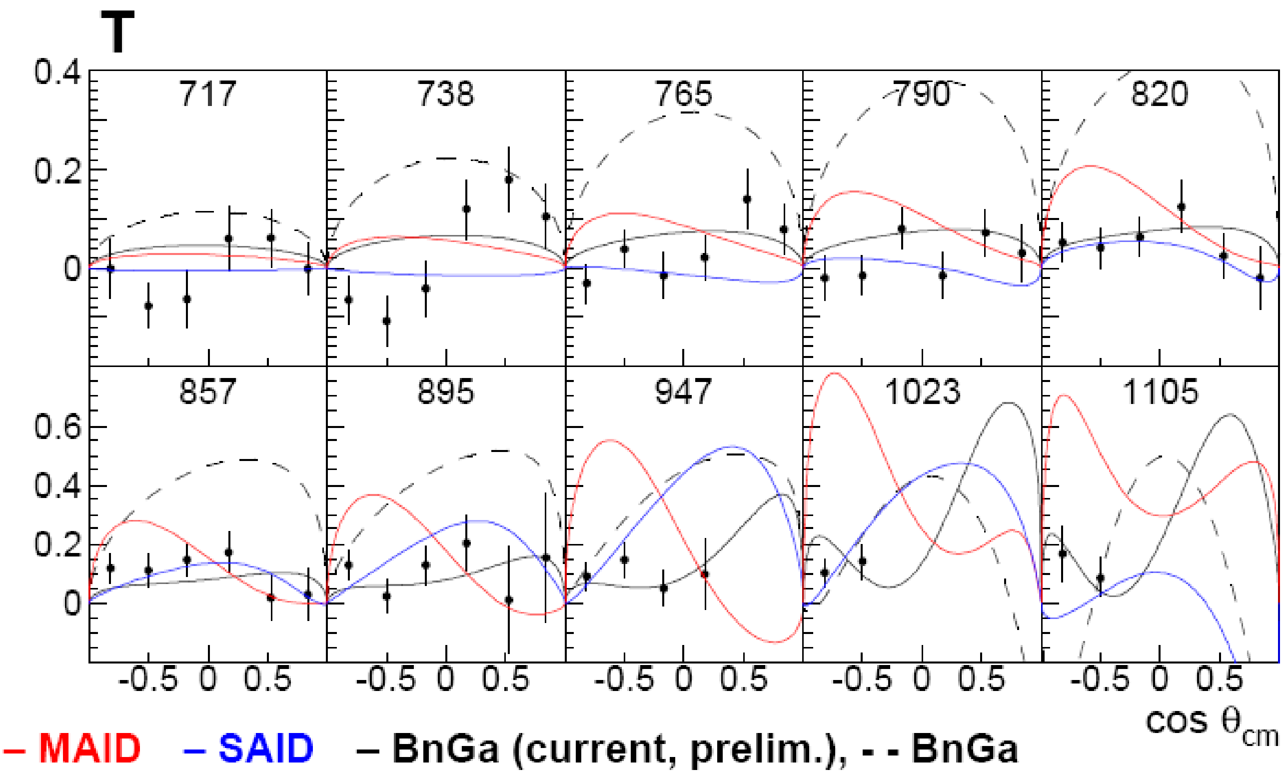
Low energy regime:

$\gamma p \longrightarrow p\eta$:

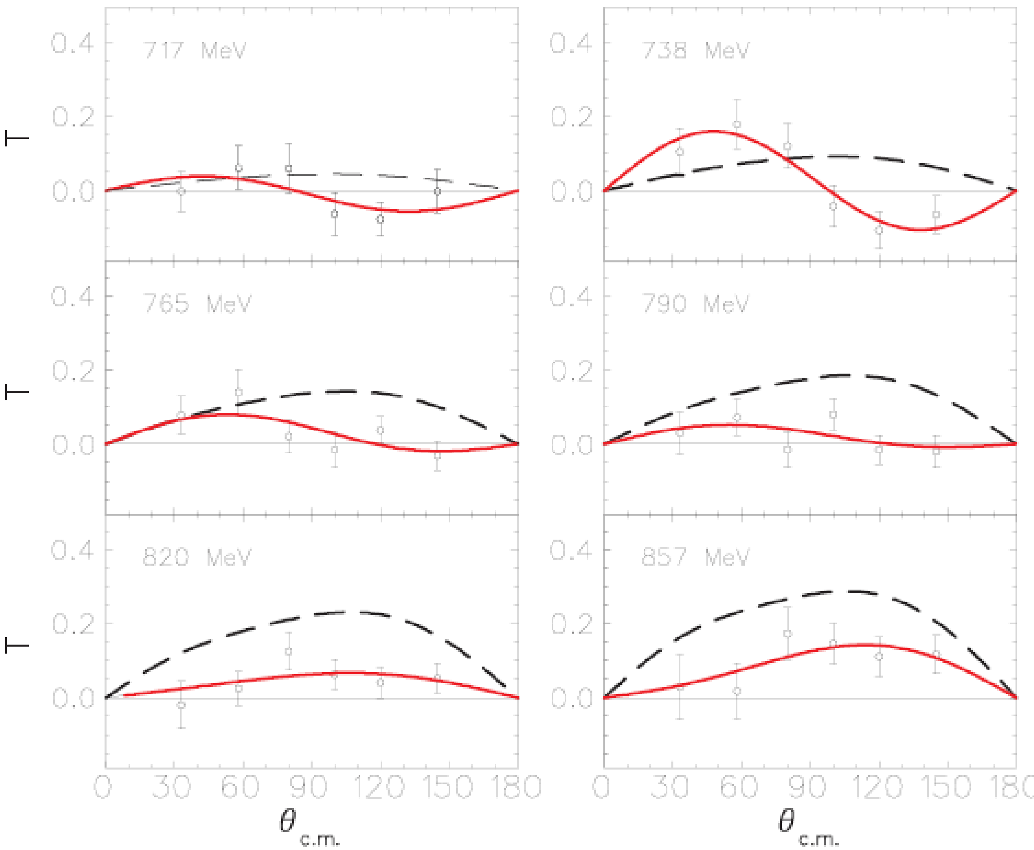
PHOENICS data on T

⇒ isobar models fail to describe the data

⇒ big differences between the different solutions

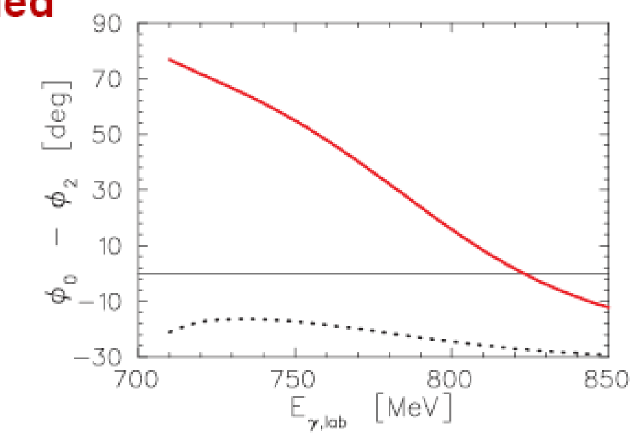


Target Asymmetry in pη



— Tiator et al.:
Model independent fit, assuming S-wave multipoles and their interference with p- and d-waves sufficient ($E_\gamma \leq$900 MeV)

$\Rightarrow$ Energy dependent phase between S_{11}(1535) and D_{13}(1530) needed

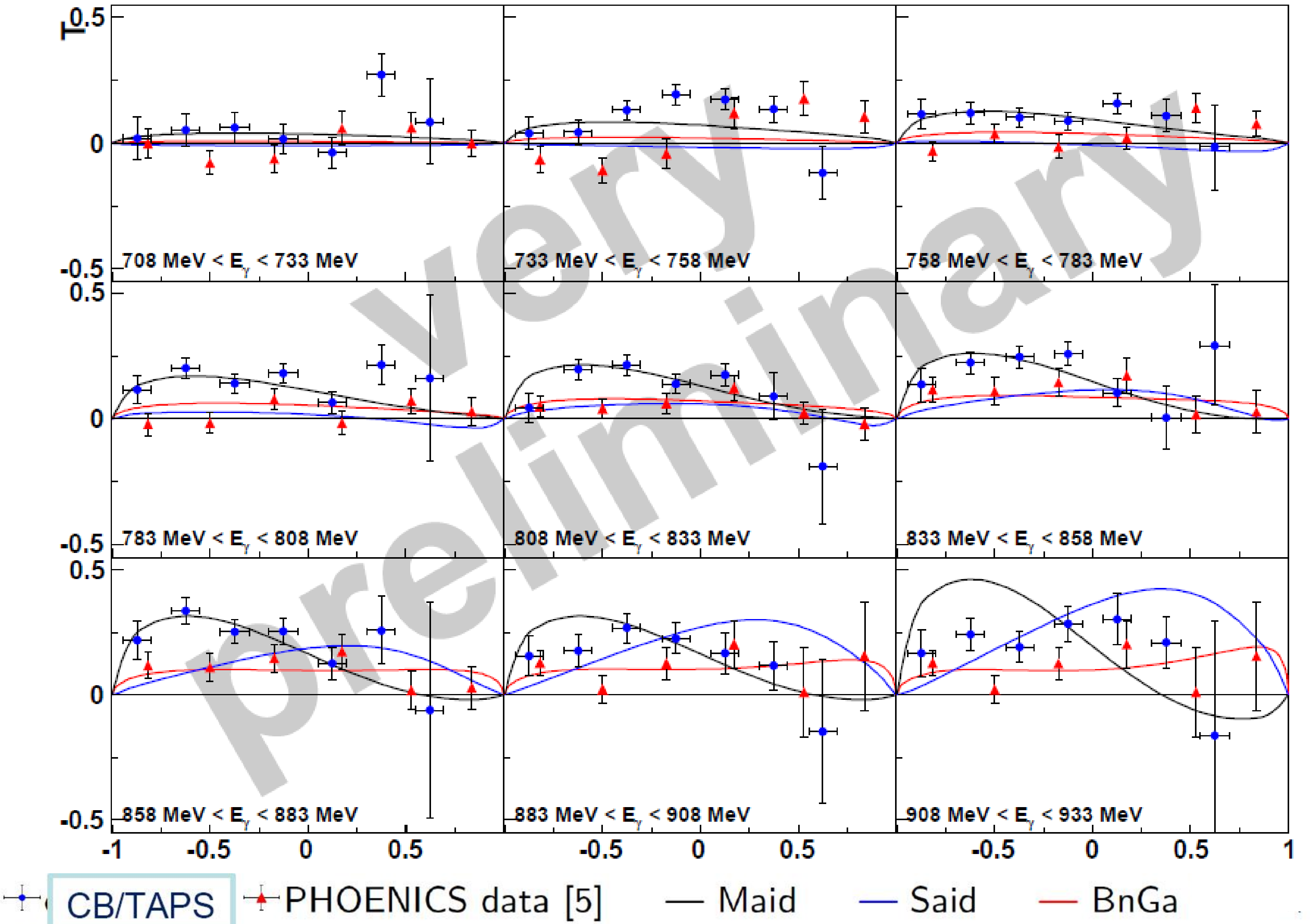


$\Rightarrow$ Energy dependent phase $\leftrightarrow$ origin presently not understood

- nature of the S_{11}(1535) ?
- interpretation of the data ?

$\Rightarrow$ Cross check and improve the precision of the existing data !

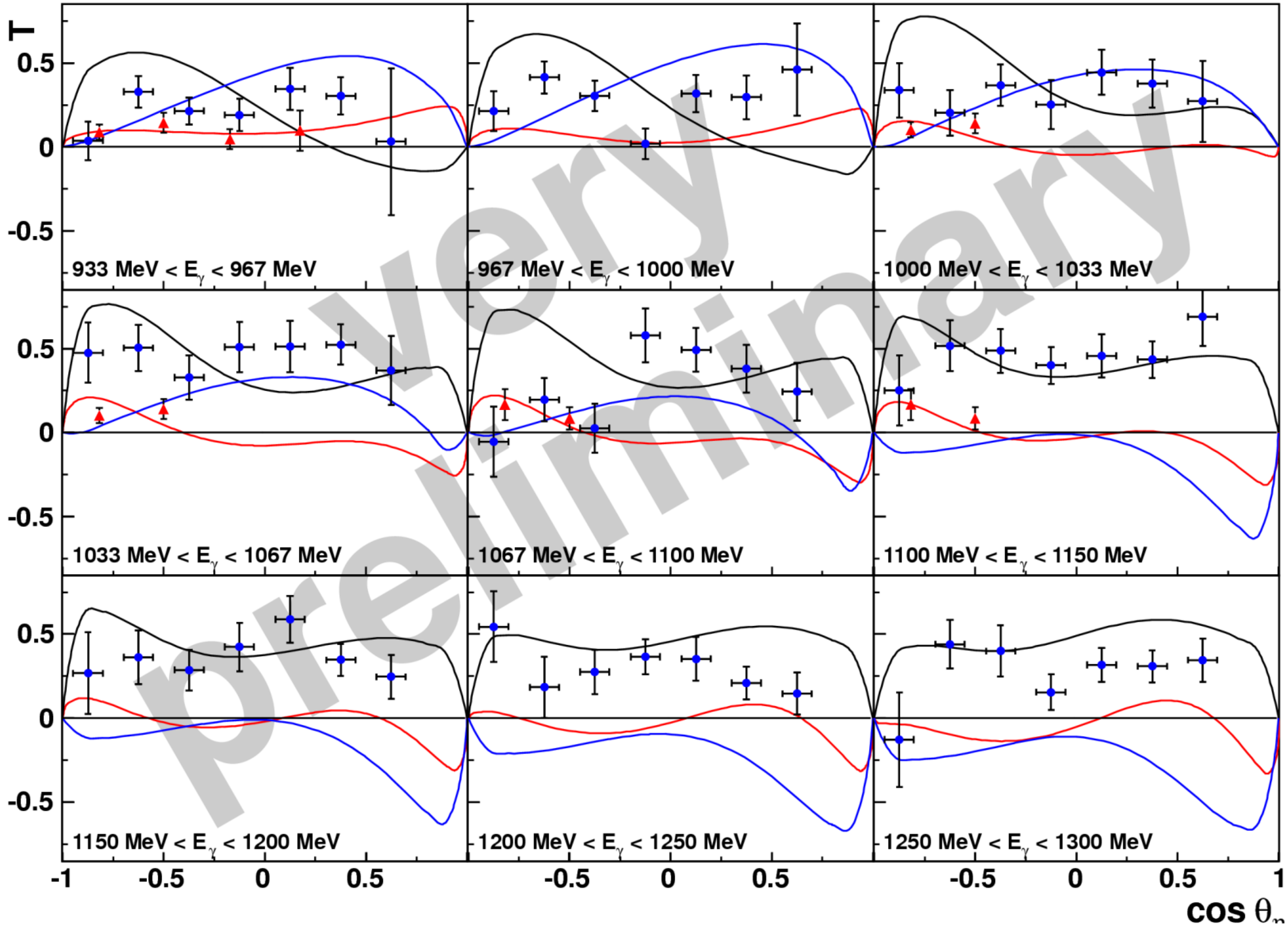
Target Asymmetry T for pη (ELSA Results)



Note: preliminary dilution factor

[5] A. Bock *et al.*, Phys. Rev. Lett **81** (1998) 534

Target Asymmetry T for pη (ELSA Results)



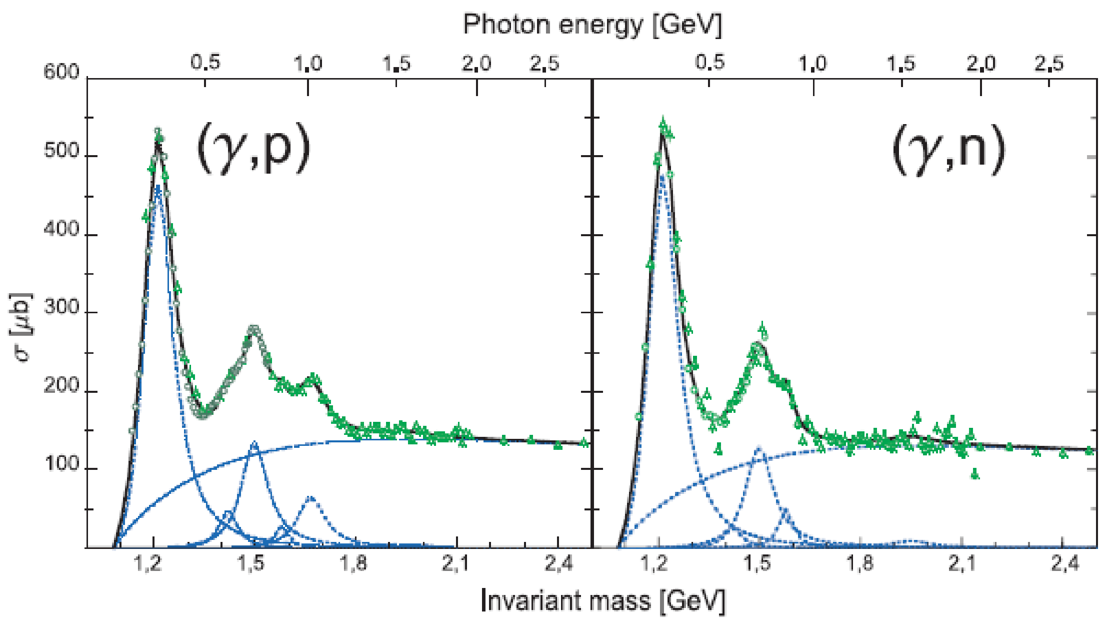
CB/TAPS   PHOENICS data [5]   — Maid   — Said   — BnGa

Note: preliminary dilution factor

[5] A. Bock *et al.*, Phys. Rev. Lett 81 (1998) 534

Electromagnetic excitation off the neutron

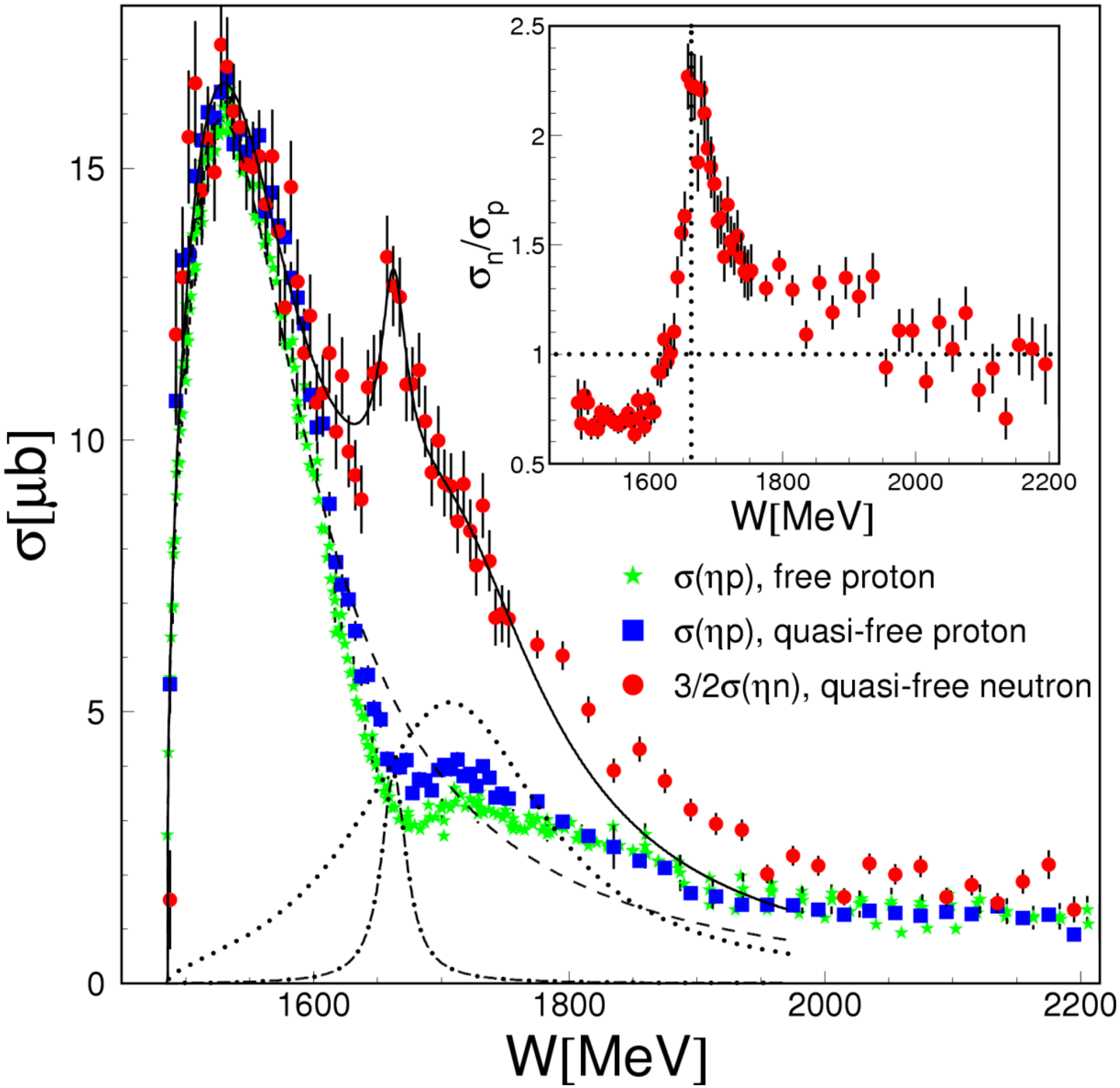
- **importance of measurements off the neutron:**
  - different resonance contributions
  - needed for extraction of iso-spin composition of elm. couplings



- **complications due to use of nuclear targets (deuteron):**
  - Fermi motion
  - nuclear effects like FSI, re-scattering, coherent contributions

Electromagnetic excitation off the neutron

Crystal Barrel at ELSA result



quasifree η photoprodruction:

$$\gamma + d \rightarrow n + p + \eta$$

Narrow structure in nη - final state

$$W \approx 1670\ MeV$$

$$\sigma \approx 25\ MeW\ (FWHM)$$

Publication:
I. Jaegle, B. Krusche, …
accepted by EPJA

Comparison Narrow Structure

- narrow structure in excitation function of $\gamma n \rightarrow n\eta$:

- **GRAAL:** $W \approx$ **1680 MeV,** $\Gamma <$**30 MeV**
- **Tohoku-LNS:** $W \approx$ **1666 MeV,** $\Gamma <$**40 MeV**
- **ELSA:** $W \approx$ **1685 MeV,** $\Gamma <$**60 MeV**
- **MAMI-C:** $W \approx$ **1675 MeV,** $\Gamma <$**40 MeV**

- Effect of photo-excitation of D15(1675) ?
- Coupled channel effect of S11(1535) and P11(1710) ?
- Interference effect of S11(1535) and S11(1650) ?
- New narrow state with stronger photo-coupling to the neutron ?

  –> polarization observables needed !!

Status on Meson Photoproduction Data Base

Crystal Barrel at ELSA

CLAS at JLAB

Crystal Ball at MAMI

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

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

Nearly complete data base

Complete data base

Only a few experiments

Summary

- First round of double polarization experiments at ELSA, JLab and MAMI finished

- Preliminary results for the polarization observable T, P, G, E and H

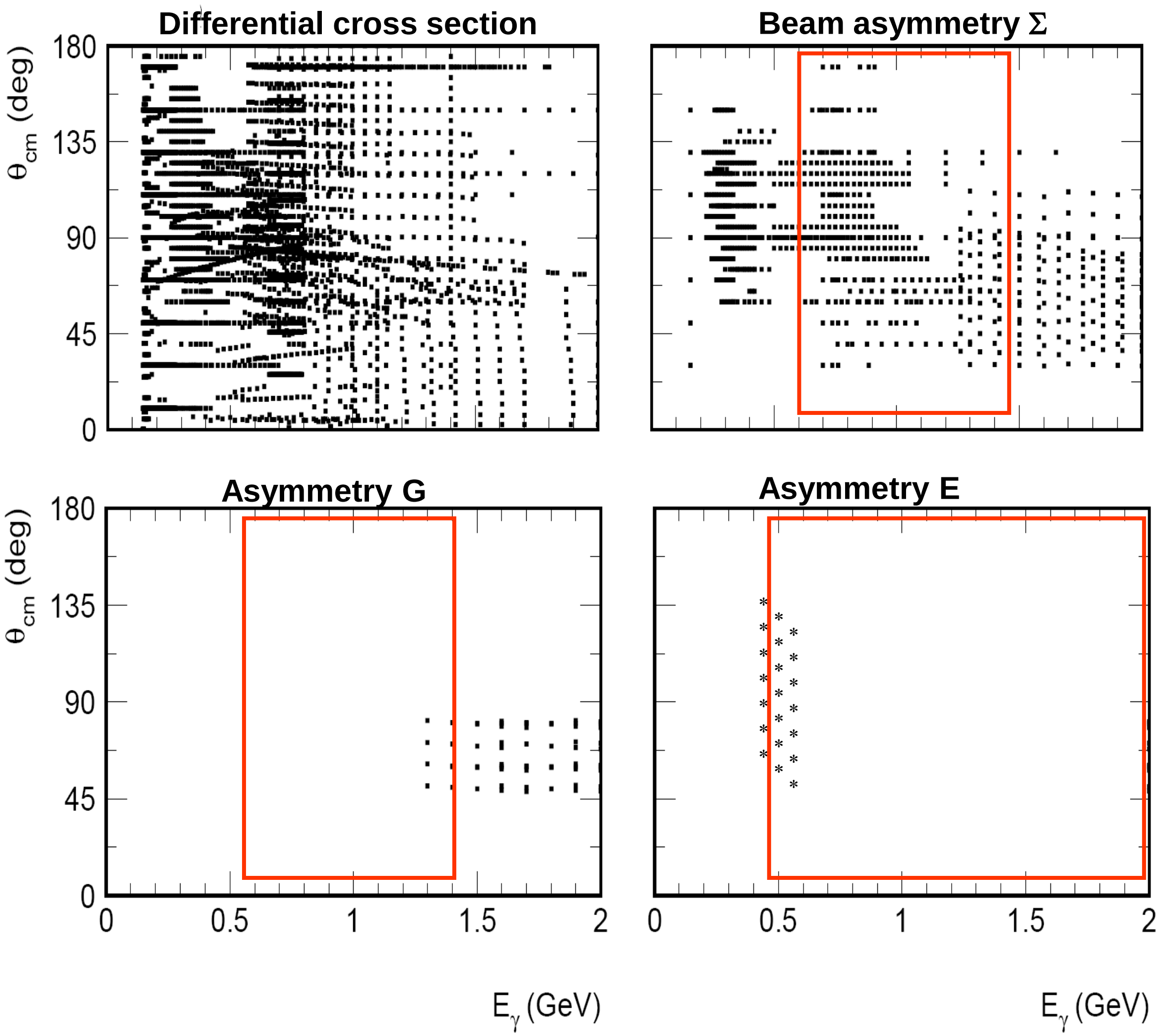
$$\vec{\gamma}\ \ \vec{p} \rightarrow p\,\pi^0$$
$$\vec{\gamma}\ \ \vec{p} \rightarrow p\,\eta$$

- Model independent partial wave analysis has started
  - polarization observables are essential
  - different final states are essential

- New data will determine nucleon excitation spectrum

World Data Base

reaction: $\vec{\gamma} + \vec{p} \rightarrow p + \pi^0$



First round of double polarization experiments with CB at ELSA:

Energy range for G: 600- 1300 MeV

Energy range for E: 500- 2100 MeV

Future plans for CB at ELSA:

Extend energy range to 3 GeV

Transversally polarized target
Installed and first data taken

Measurements on the neutron
polarized deuteron target

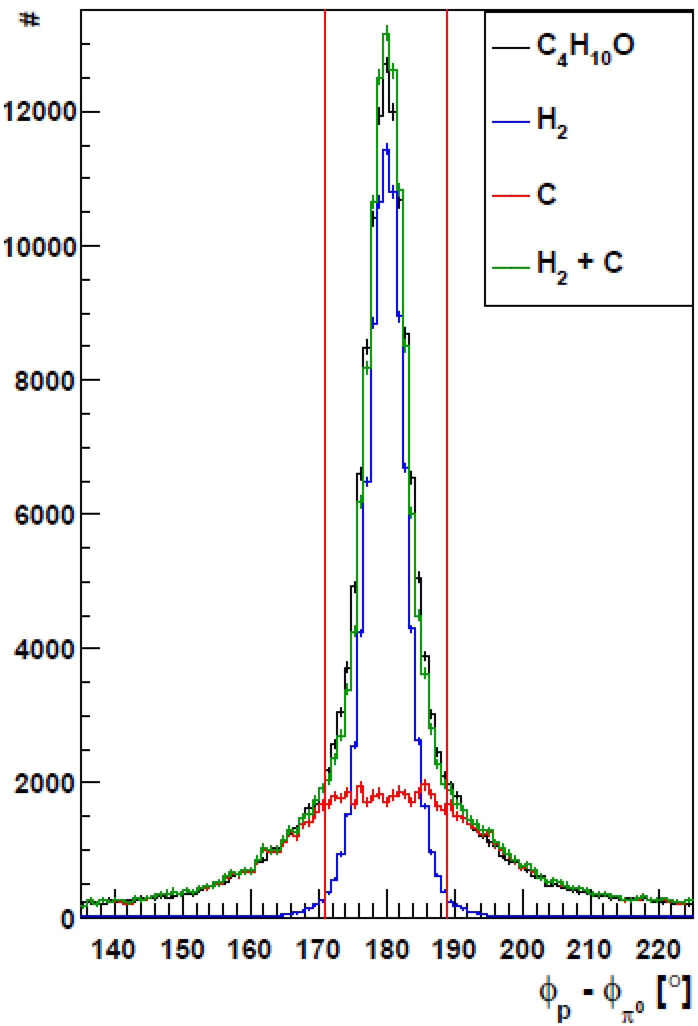
Dilution Factor

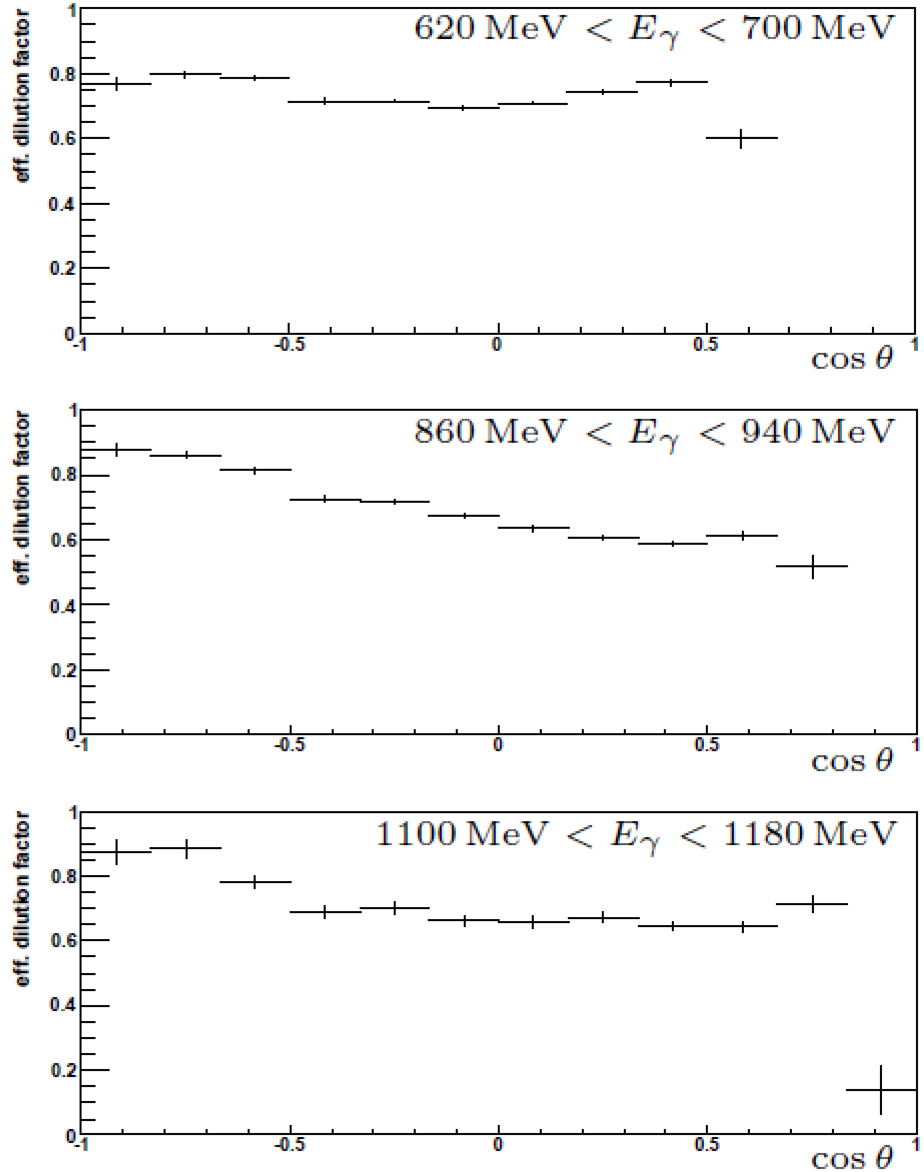
- not possible to polarize protons in H_2 molecules
- target material: butanol $\rightsquigarrow$ unpolarized C and O
  - $\vec{\gamma}\vec{p} \rightarrow p\gamma\gamma$
  - $\vec{\gamma}p_C \rightarrow p\gamma\gamma$
- in principle: 10 H-Atoms and 32 protons in C and O nuclei
  $\Rightarrow$ dilution factor $f = \frac{10}{10+32} = 0.24$
- reconstruction efficiency different for both reactions
  - fermi motion
  - final state interaction

$\rightsquigarrow$ need effective dilution factor

Dilution Factor

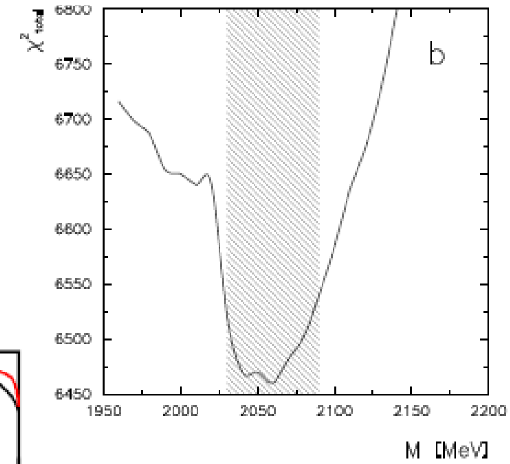
860 MeV < E_γ < 940 MeV





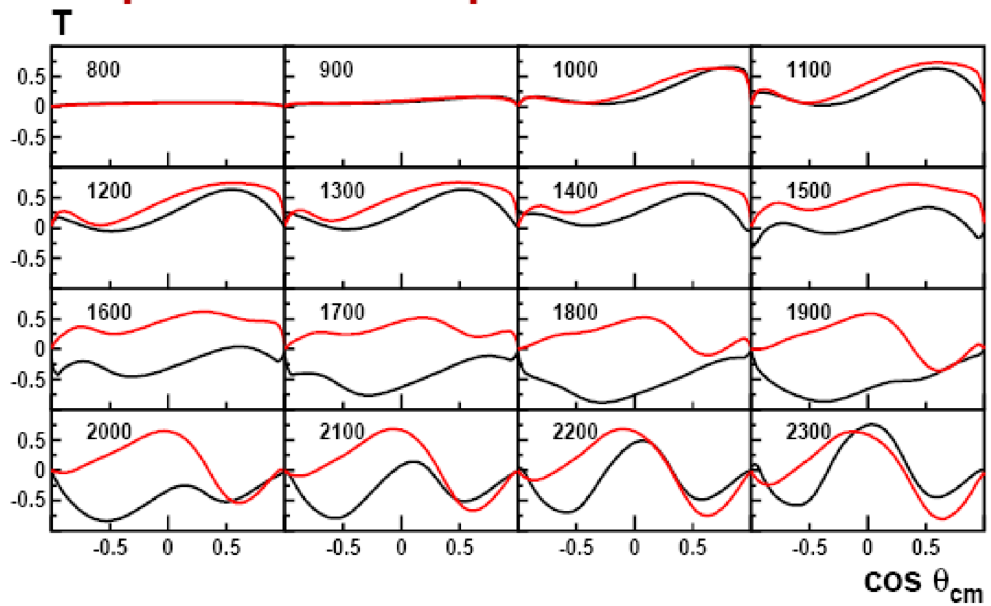
$$f = \frac{N_{\text{butanol}} - N_{\text{carbon}}}{N_{\text{butanol}}}$$

Targetasymmetry in pη



Observation of a new D_{15}(2070) in the BnGa-analysis of $\gamma p \longrightarrow p\eta$ - data fitted together with various other reactions

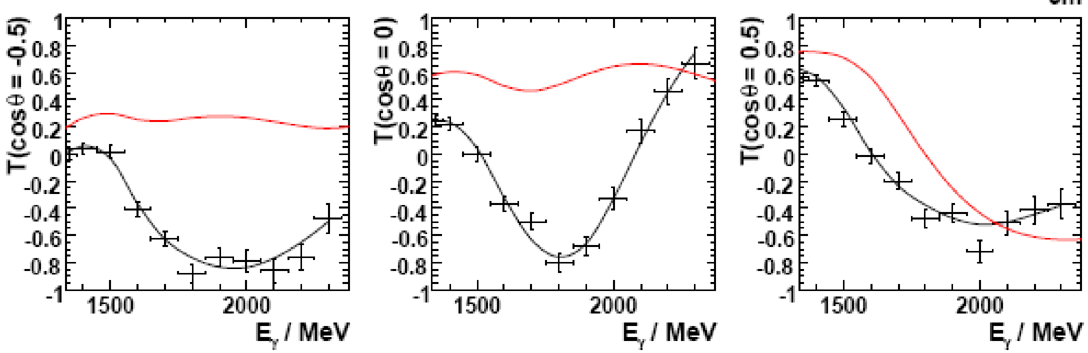
$\Rightarrow$ Confirmation in polarisation experiments urgently needed !



– BnGa (current, prelim.)

– no D_{15}(2070) (refitted)

precision expected:

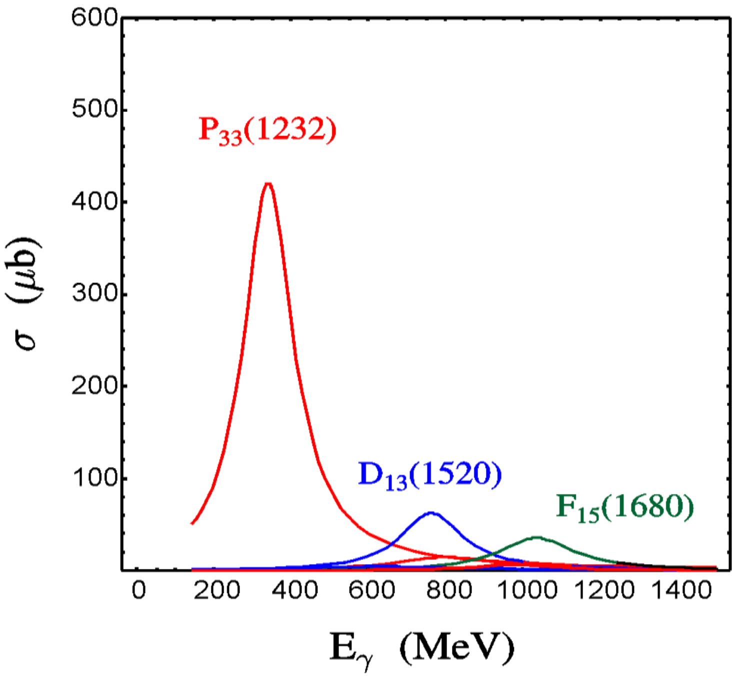


$\Rightarrow$ further information to constrain the resonance contributions

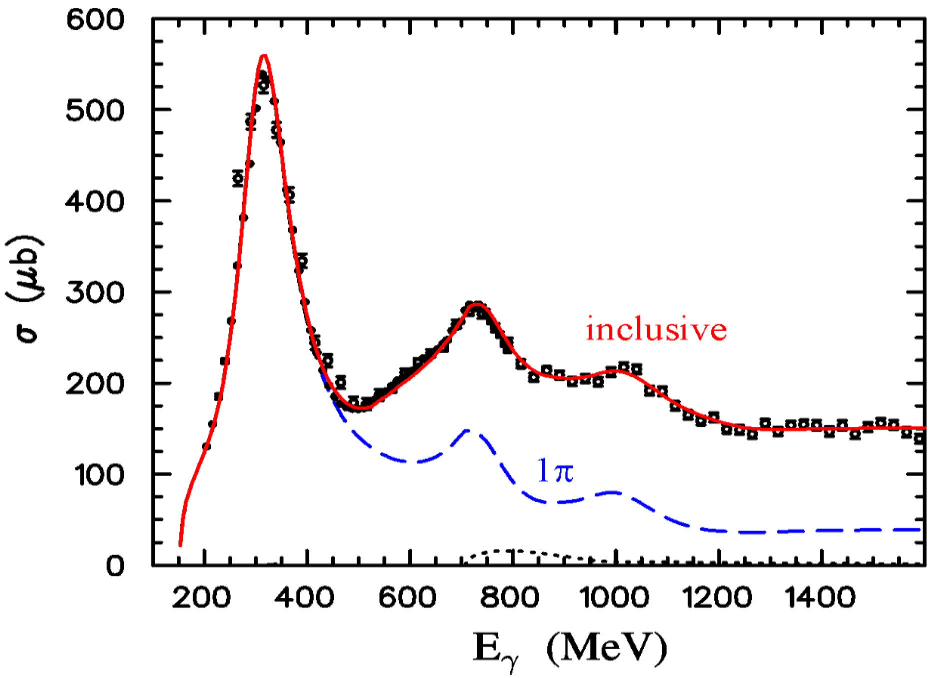
Introduction

- 3.2 GeV photon beam at ELSA used to study meson photoproduction
  - study the nucleon resonance spectrum

Breit Wigner Resonances



Total Photon Absorption Cross Section



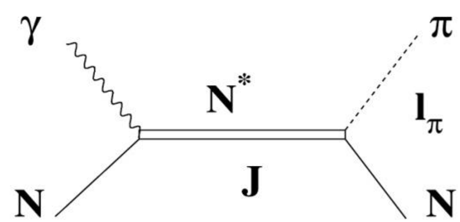
Spectroscopic Notation

$X_{2I\,2J}$

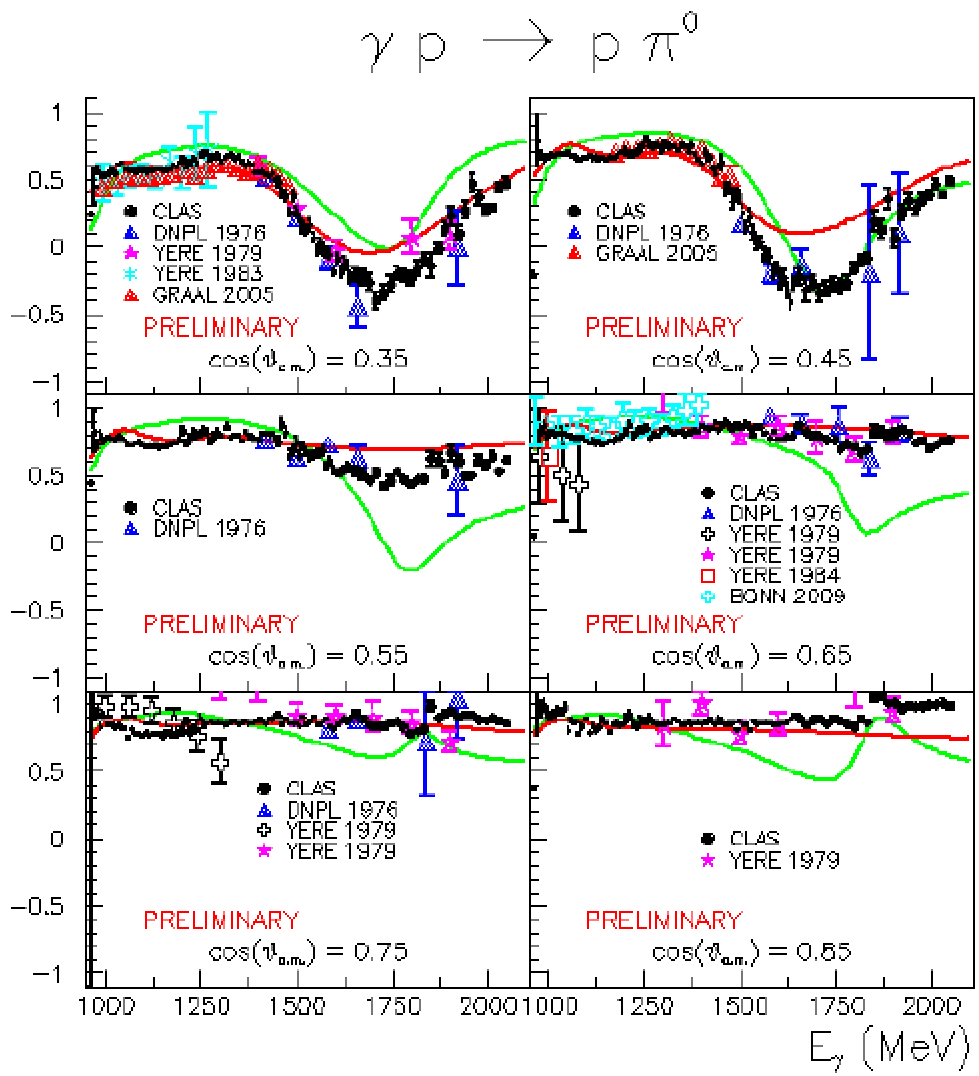
Isospin (2I)

Spin (2J)

$$X = S(l_\pi = 0); P(l_\pi = 1); \ldots$$



Σ-Asymmetry for $p\pi^0$ (JLab Results)



— SAID — MAID • CLAS

($E_\gamma < 2$ GeV, $0.35 < \cos\theta_\pi < 0.85$)

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

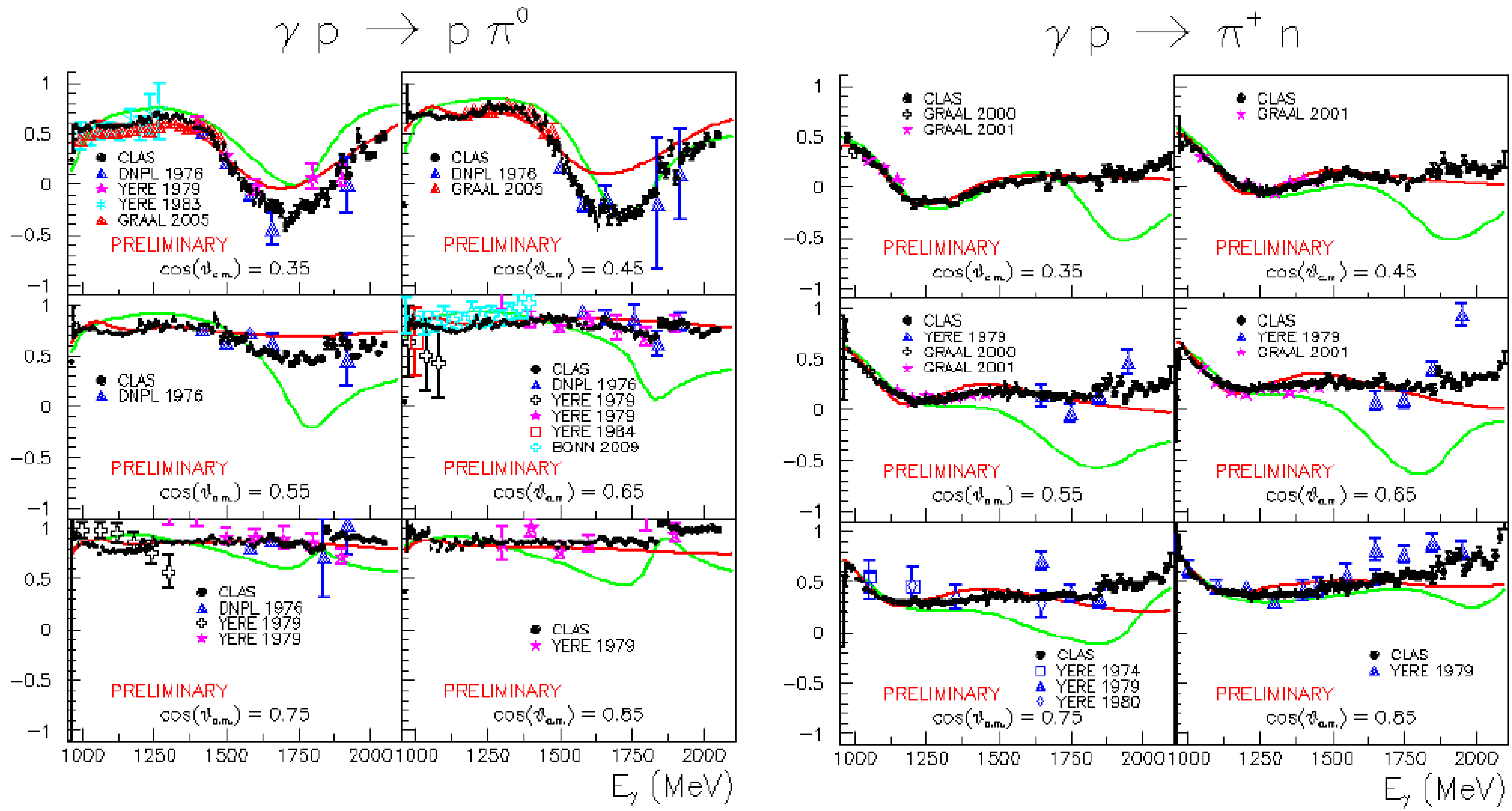
Δ^+ $\downarrow$ N^* $\downarrow$

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

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

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

Σ-Asymmetry for $p\pi^0$ and $n\pi^+$ (JLab Results)



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