Baryon Spectroscopy: Recent Results and Impact

R. Beck
HISKP, University Bonn

MESON 2014, May 28. – June 3., Krakow

- Introduction
- Selected Results from ELSA and MAMI:
  $\vec{\gamma}\ \vec{p} \rightarrow p\,\pi^0$
  $\vec{\gamma}\ \vec{p} \rightarrow p\,\eta$
- Impact of the New Polarization Data
- Summary and Outlook

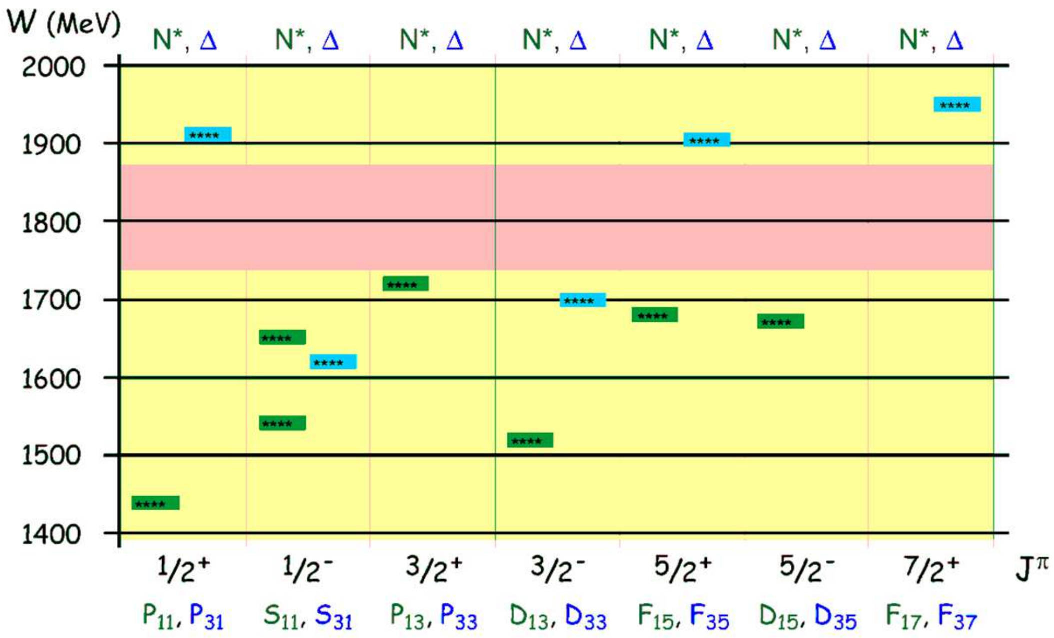
supported by the DFG within the SFB/TR16

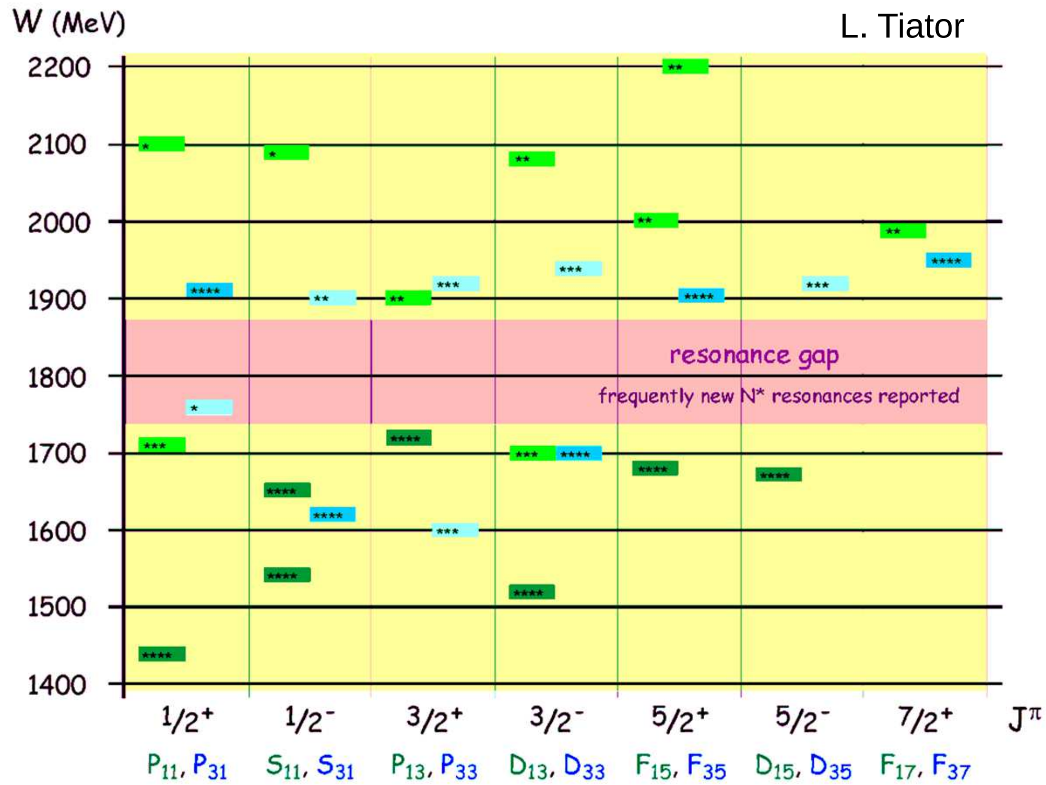
Introduction

PDG 2010: Status on nucleon resonances

only 7 N* and 5 Δ*

established in the region 1400 MeV < W < 2000 MeV

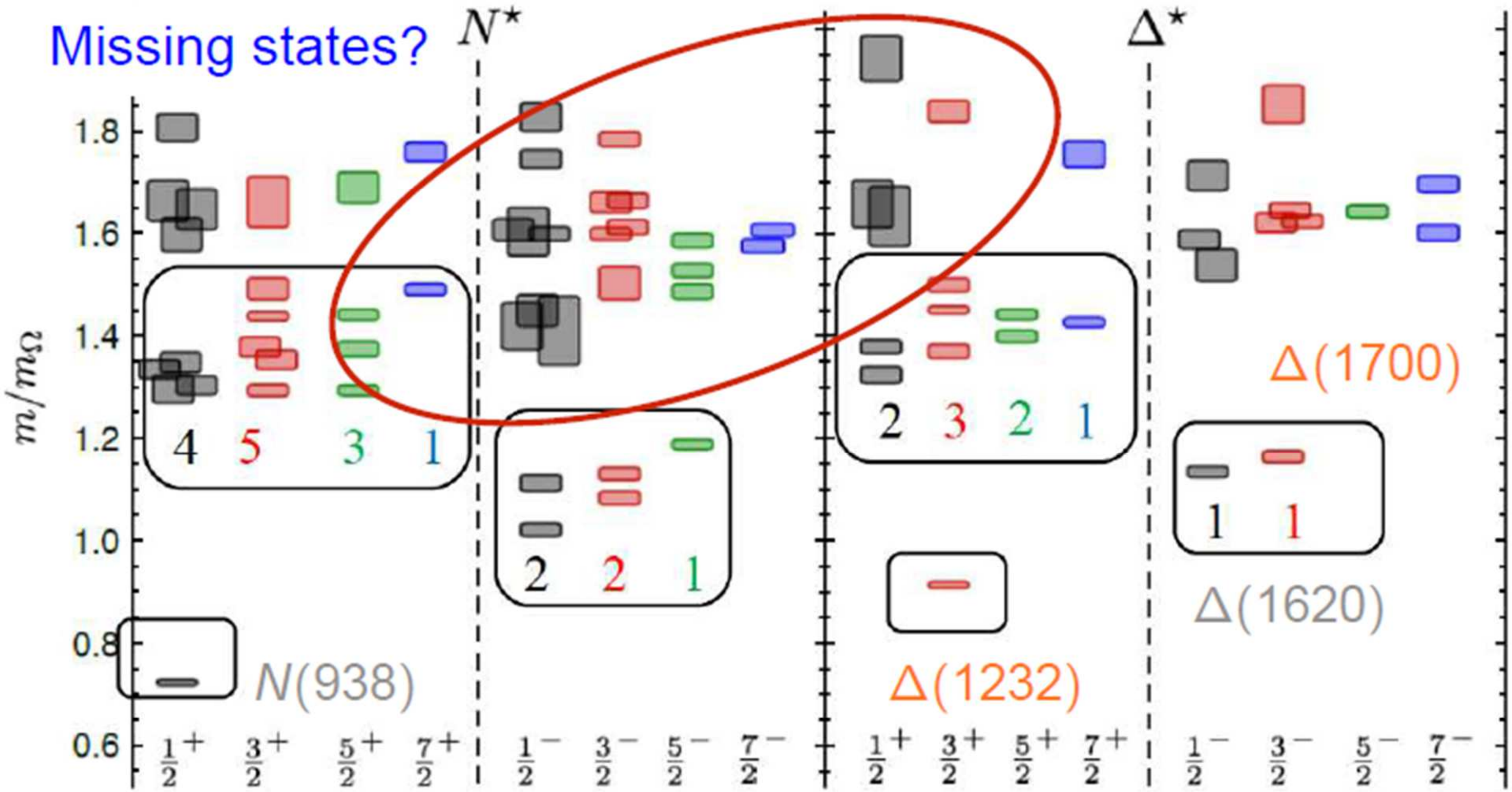




- Energy pattern for the dominant states
  - constituent Quark Models
  - dynamical Models
  - Lattice QCD
- Various nucleon models predict many more states
  - weak coupling to πN final state
  - insufficient data base

Introduction

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



$m_\pi = 400$ MeV

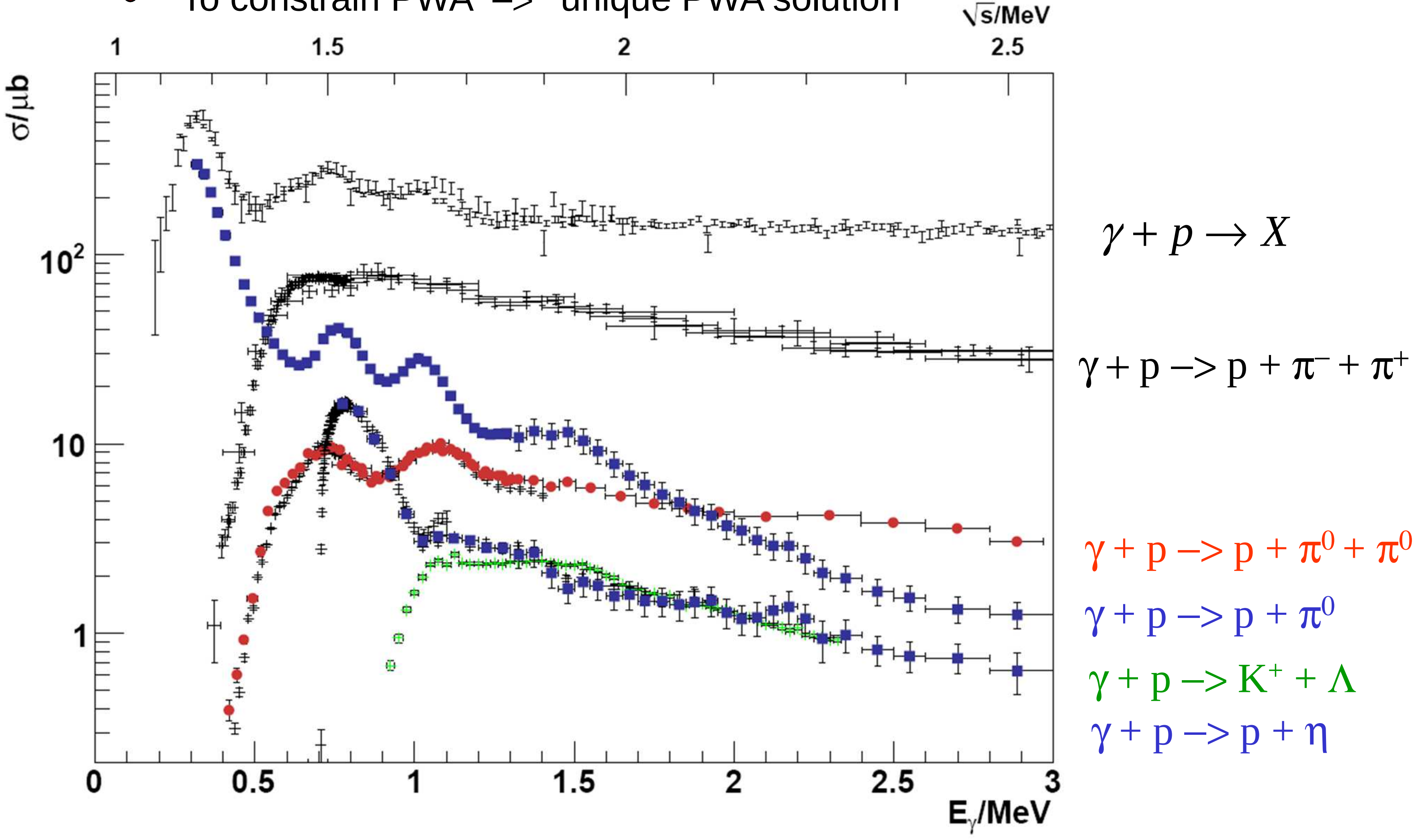
Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ 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 observables 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 : $d\sigma/d\Omega$

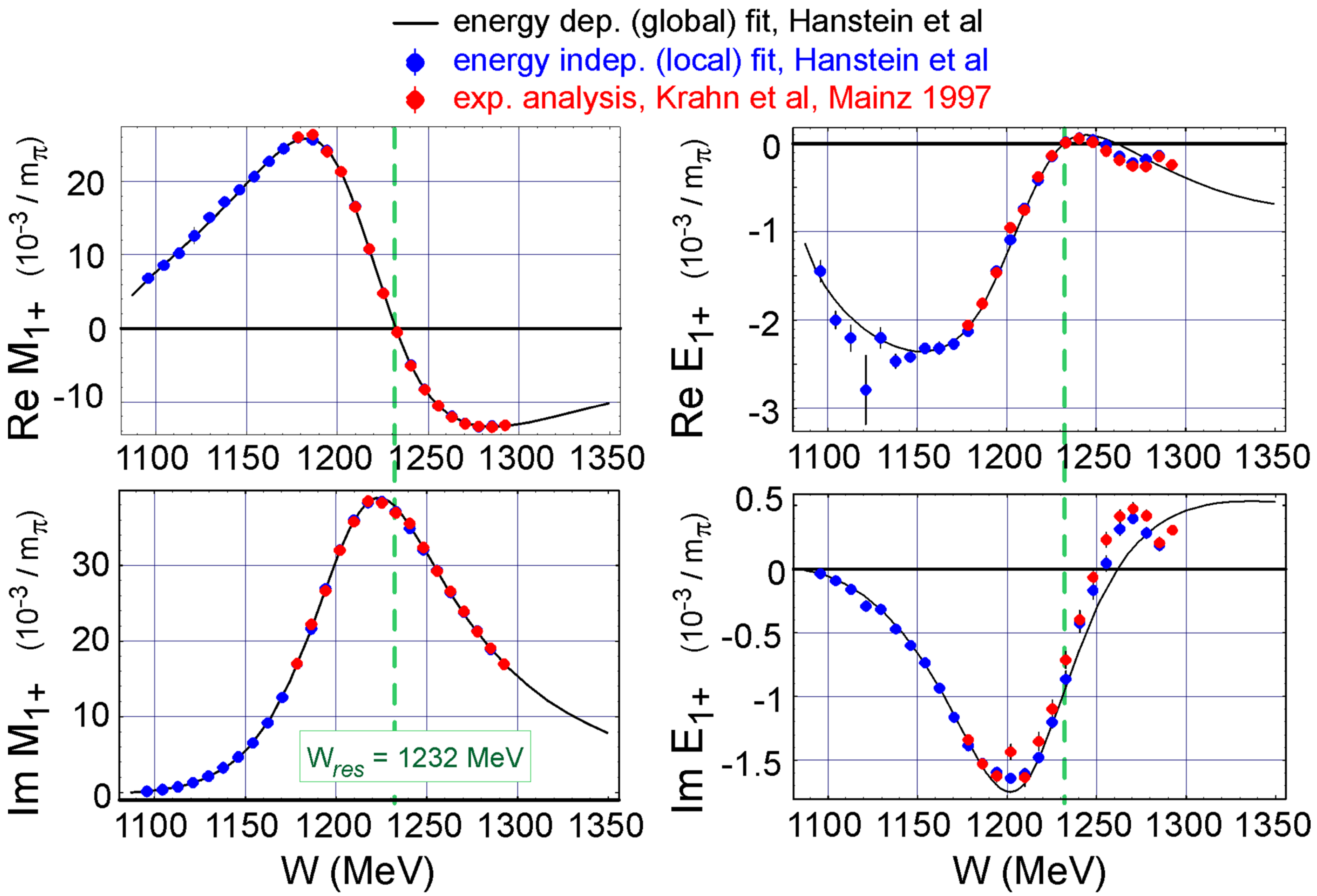
beam asymmetry : Σ

- 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 $P_{33}(1232)$



Problem with a unique PWA solution

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

8 well chosen observables 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

Observables in Meson Photoproduction

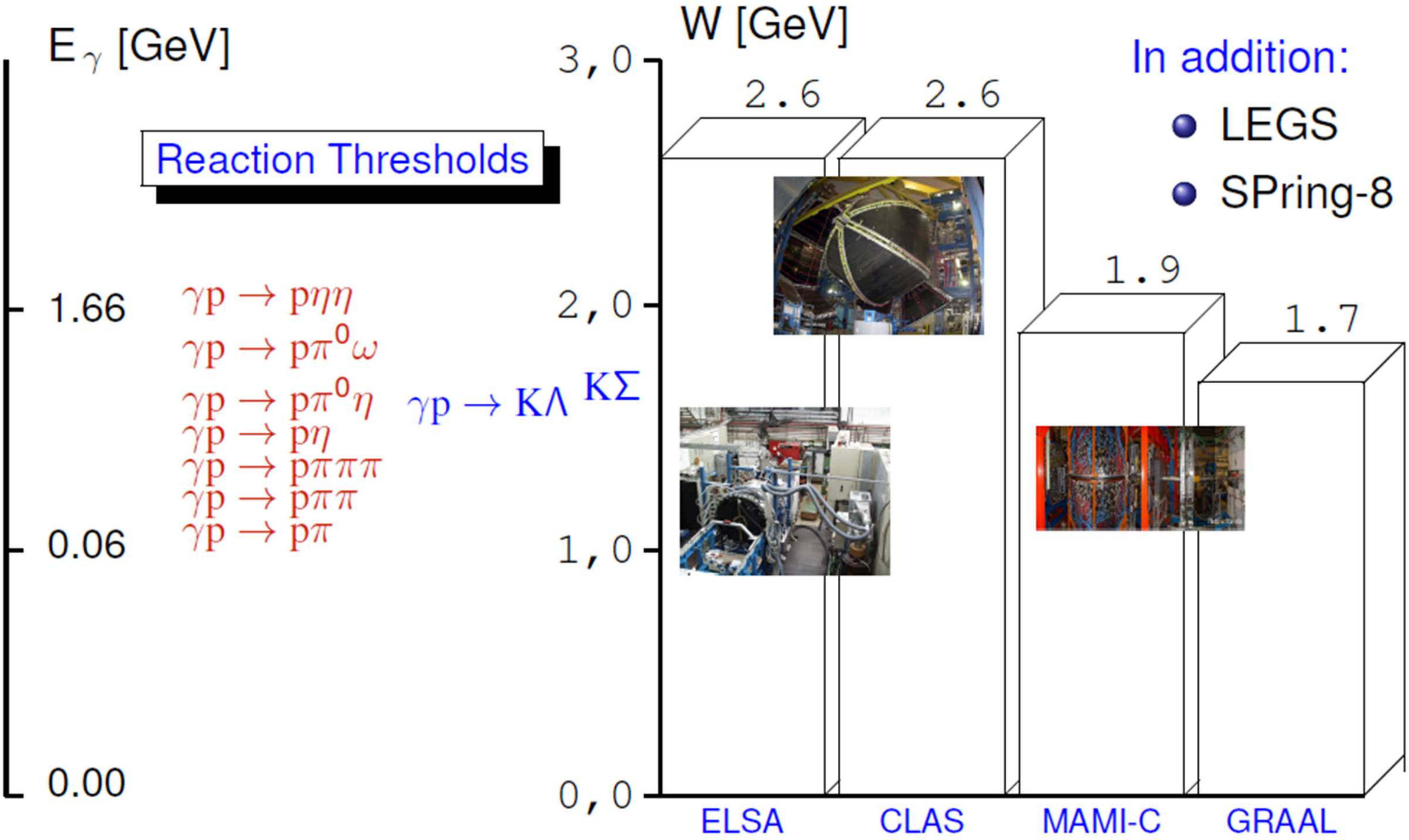
Photon polarization		Target polarization			Recoil nucleon polarization			Target and recoil polarizations			
		X	Y	Z(**beam**)	X'	Y'	Z'	X' X	X' Z	Z' X	Z' Z
unpolarized	σ	-	**T**	-	-	**P**	-	$\mathbf{T_x}$	$\mathbf{L_x}$	$\mathbf{T_z}$	$\mathbf{L_z}$
linear	Σ	**H**	(-P)	**G**	$\mathbf{O_x}$	(-T)	$\mathbf{O_z}$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

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

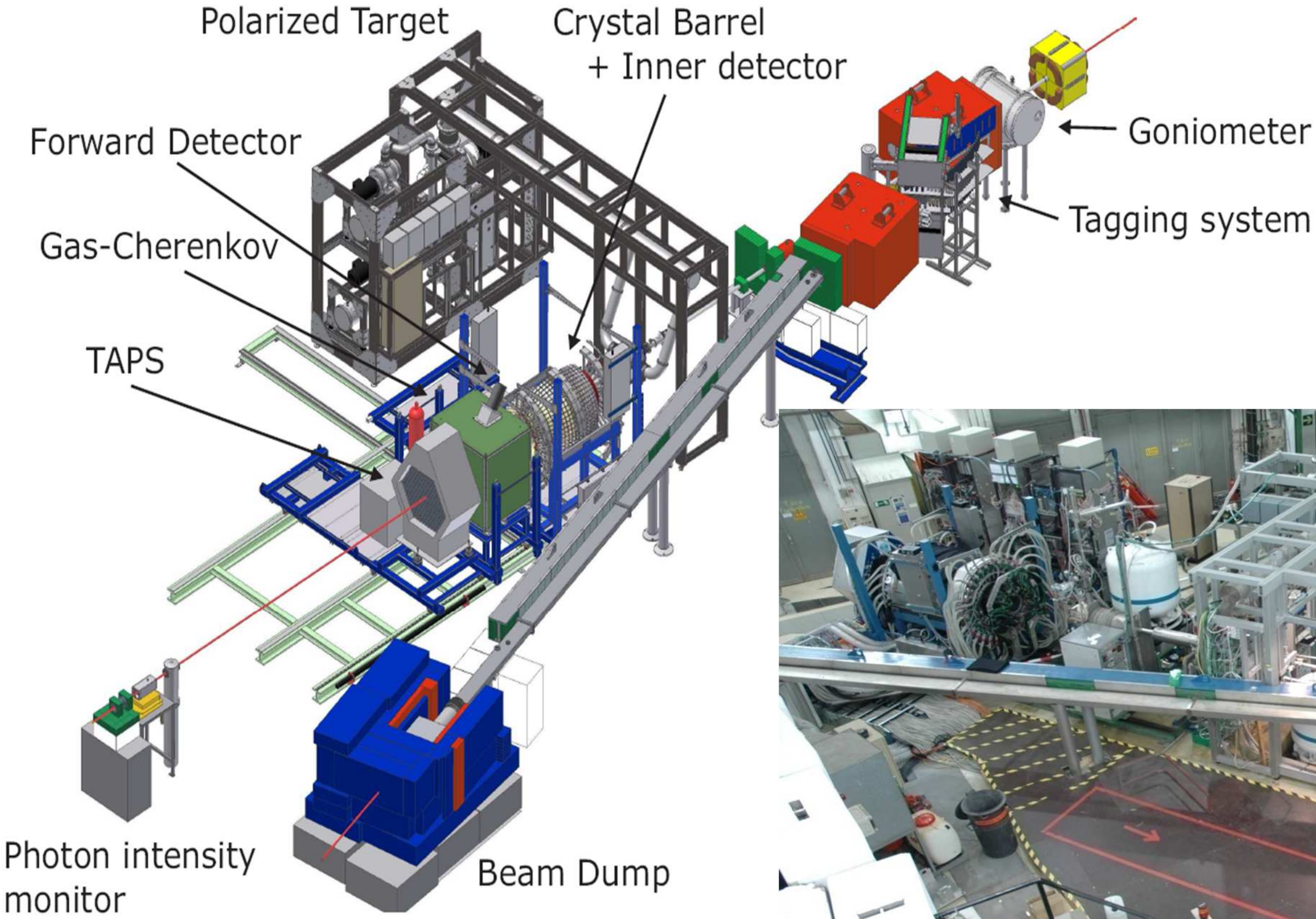
Many new results on polarization observables for different final states are coming out

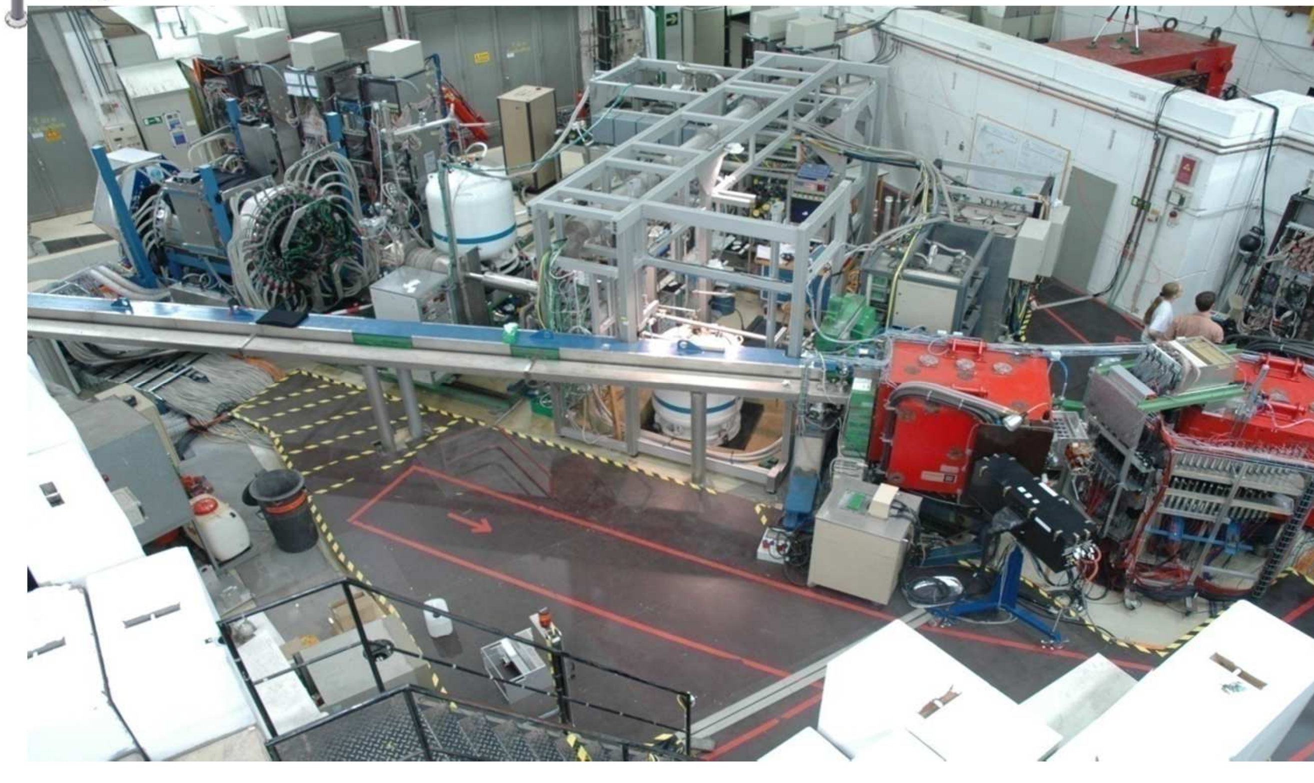
Several contributions also to this conference

Polarization Experiments



Crystal Barrel Set Up at ELSA



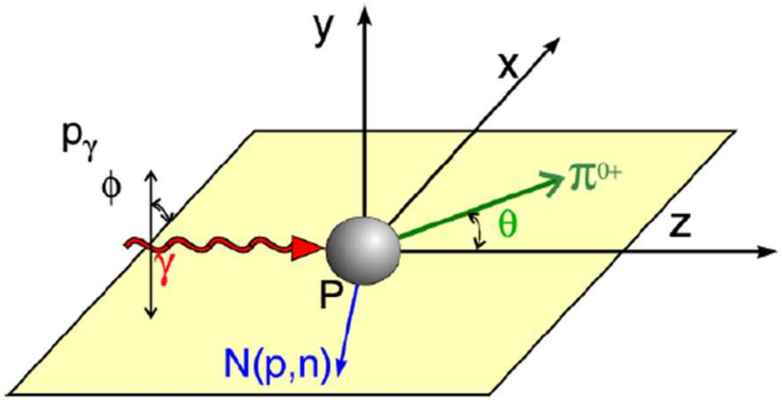


Beam-Target Polarization Observables

photoproduction of pseudoscalar mesons with polarized beam and target :

- all three single polarization observables Σ, P , T and cross section σ
- 4 double polarization observables G , E , F and H

can be measured



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

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

Problem with a unique PWA solution

Total cross section:

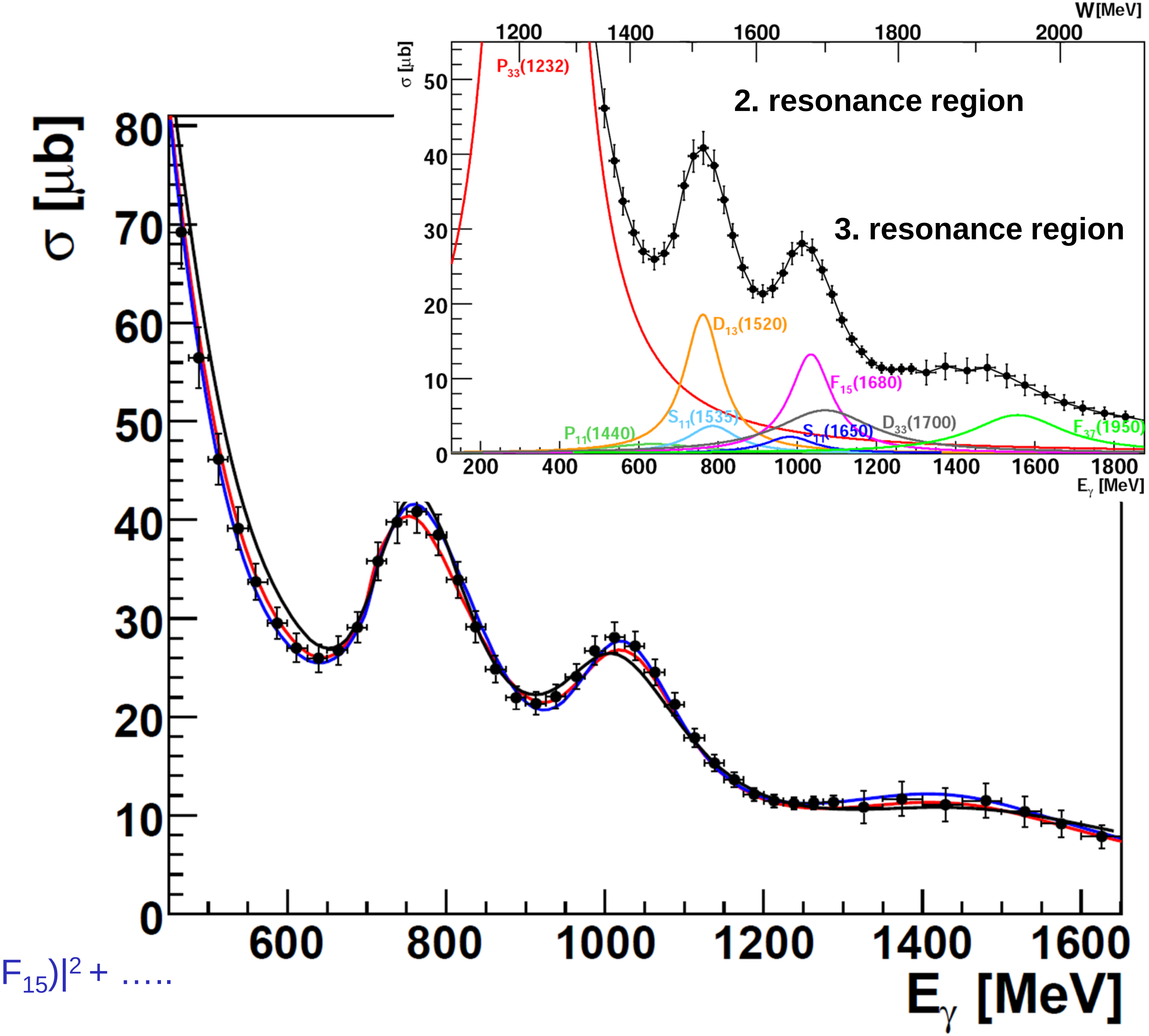
$$\gamma + p \to p + \pi^0$$

Partial wave analysis:

— BnGa

— SAID

— MAID



Total cross section:

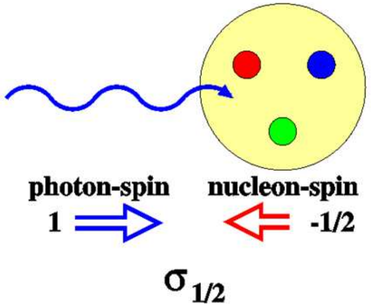
$\sigma_{tot} \sim |A(P_{33})|^2 + |A(D_{13})|^2 + |A(F_{15})|^2 + \ldots..$

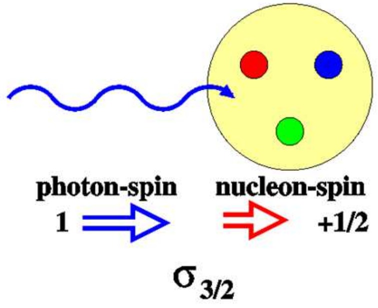
Helicity dependent cross section for $p\pi^0$

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

circularly polarized photons

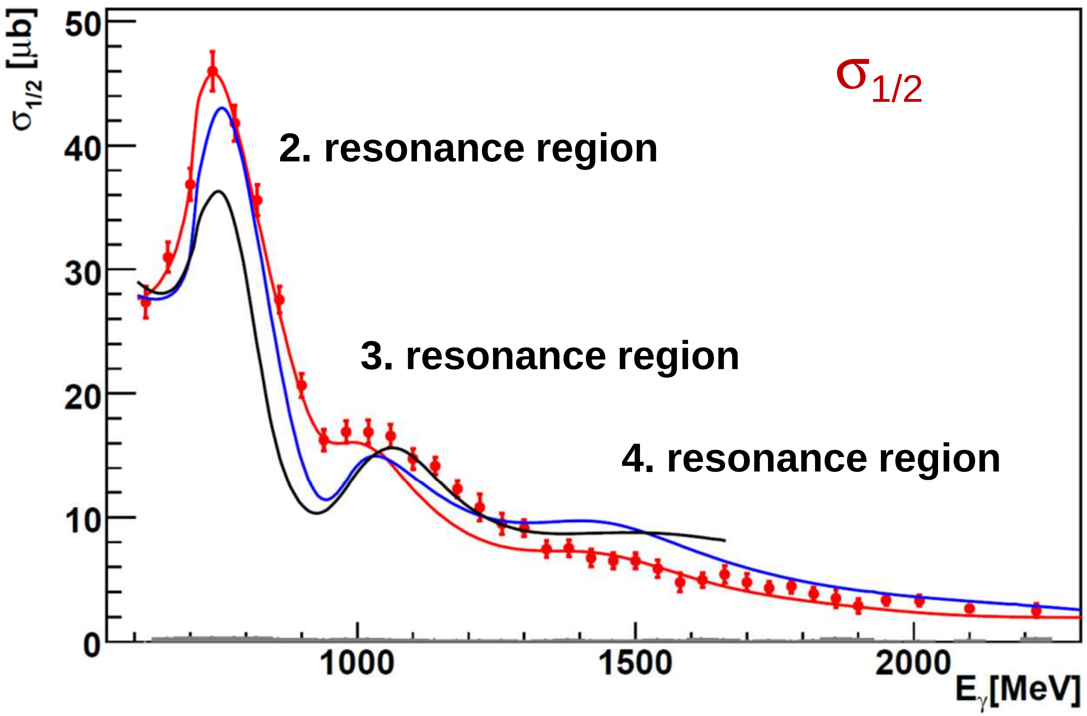
longitudinally polarized proton

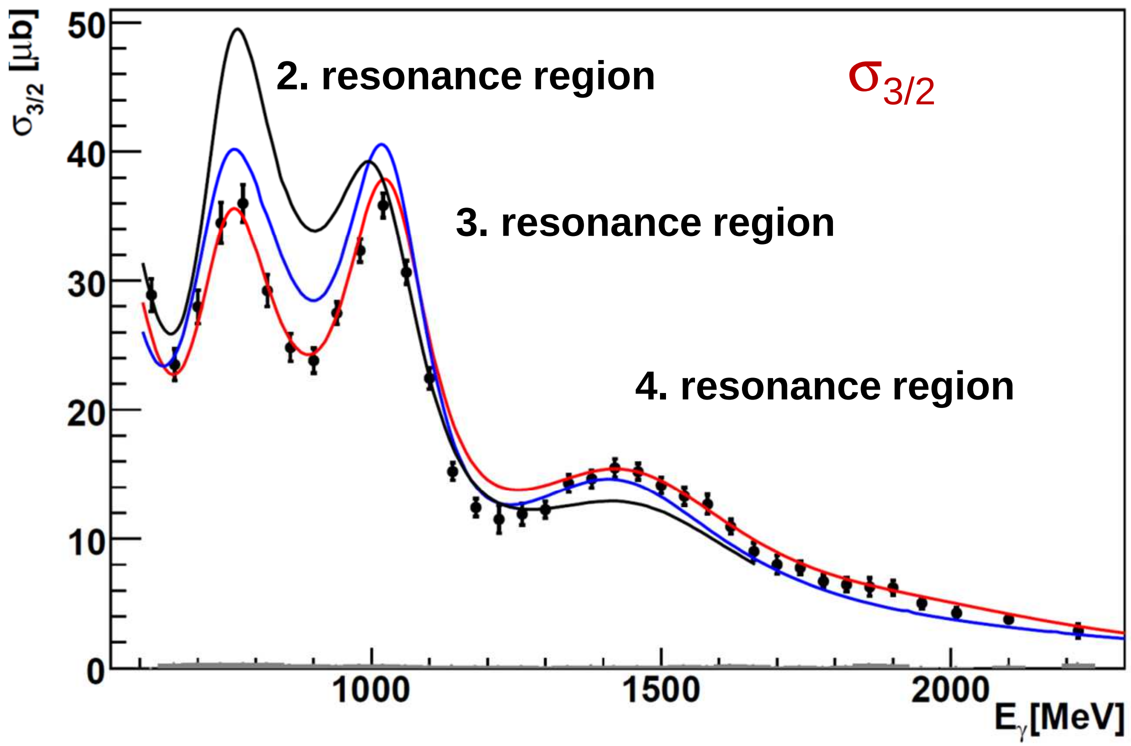




Crystal Barrel at ELSA , *M. Gottschall, PRL 112 (2014), 012003*

sensitive to interferences between resonances





Partial wave analysis prediction :   BnGa   SAID (SN11)   MAID

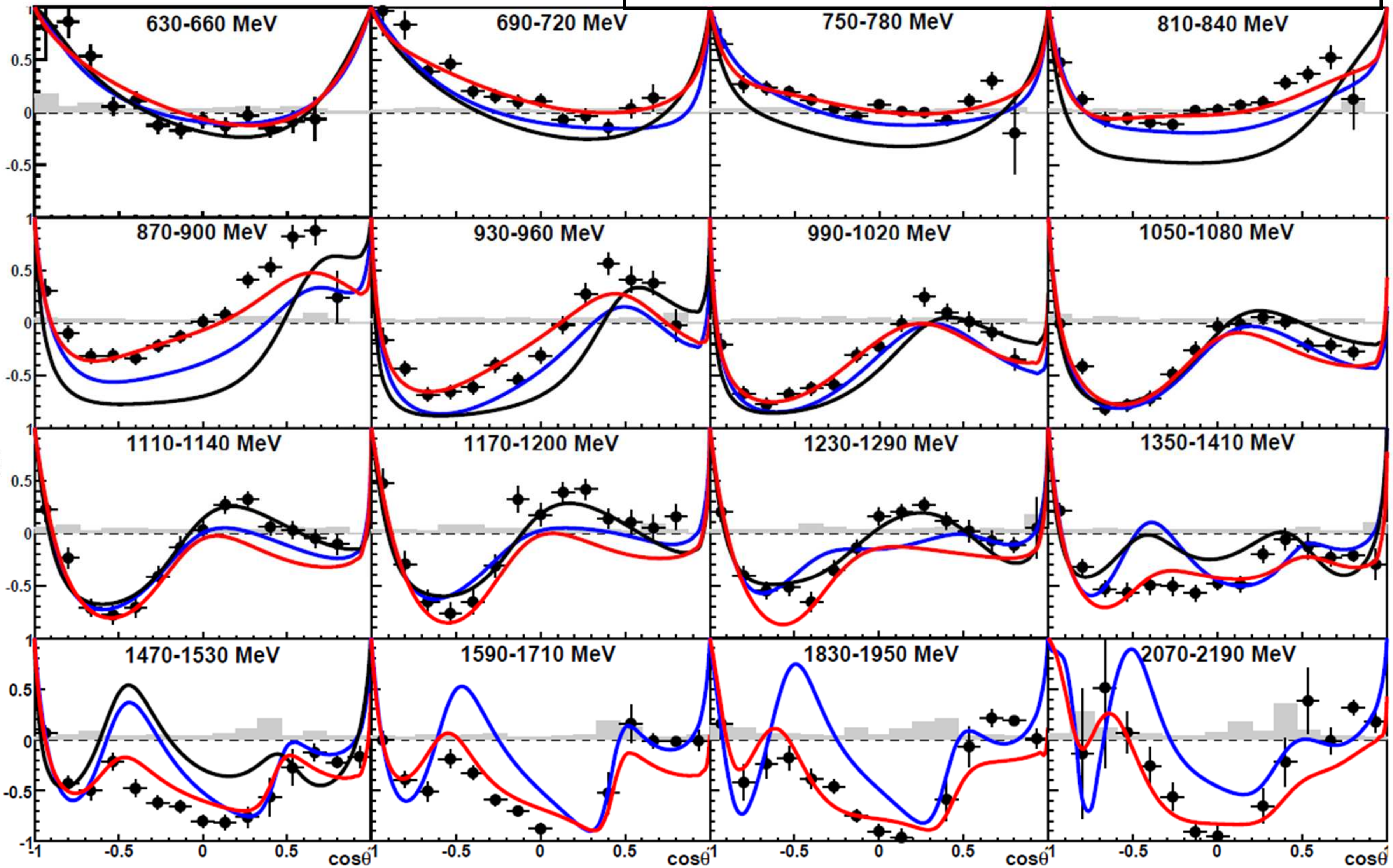
Helicity Asymmetry E for $p\pi^0$

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

Angular distributions sensitive to interference between resonances

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

Crystal Barrel at ELSA , *M. Gottschall, PRL 112 (2014), 012003*



Partial wave analysis prediction:

- BnGa
- SAID (SN11)
- MAID

Helicity Asymmetry E for pπ^0

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

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

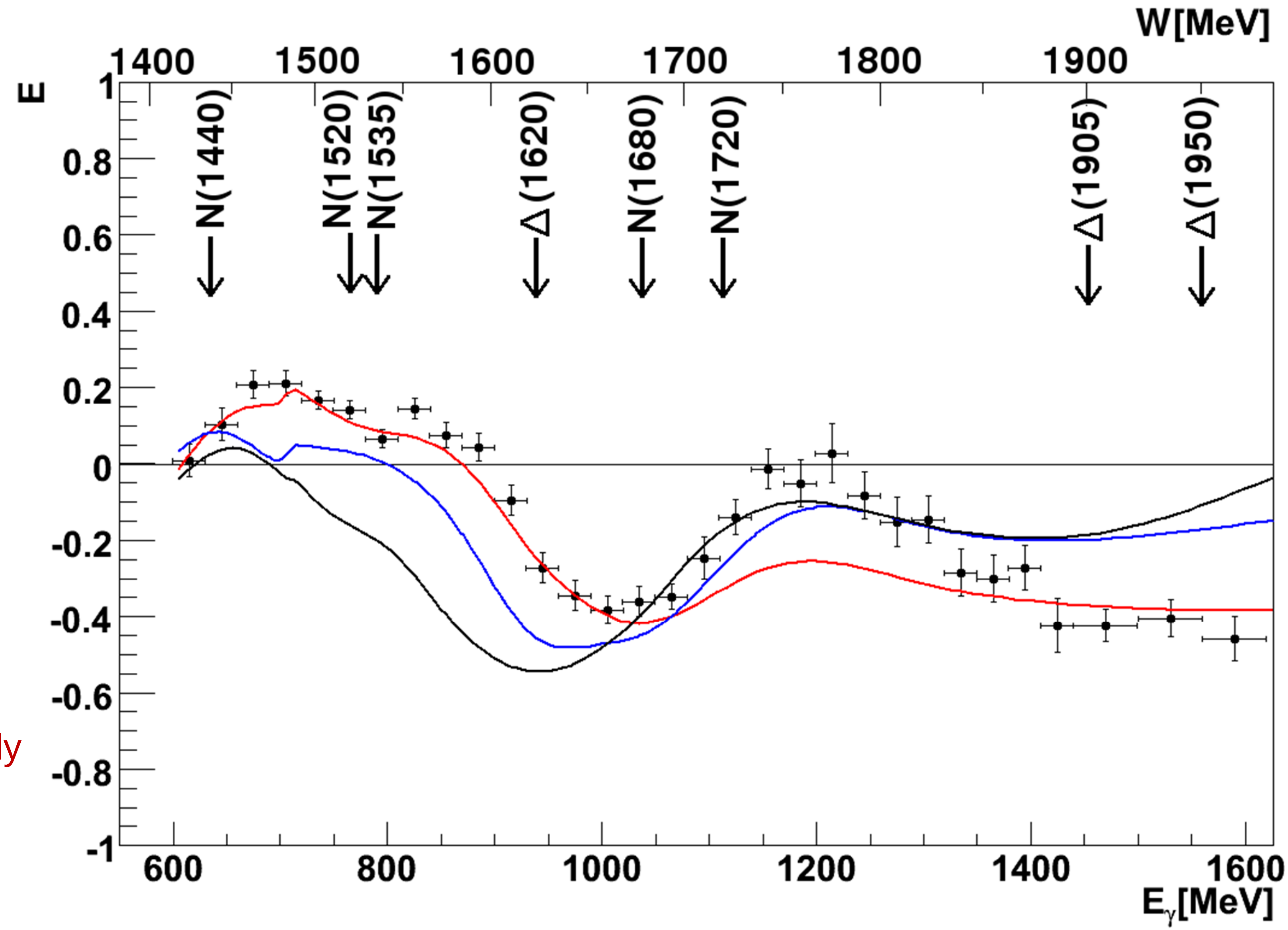
Partial wave analysis prediction:

__ BnGa

__ SAID (SN11)

__ MAID

• PWA predictions fail already in 2. resonance region

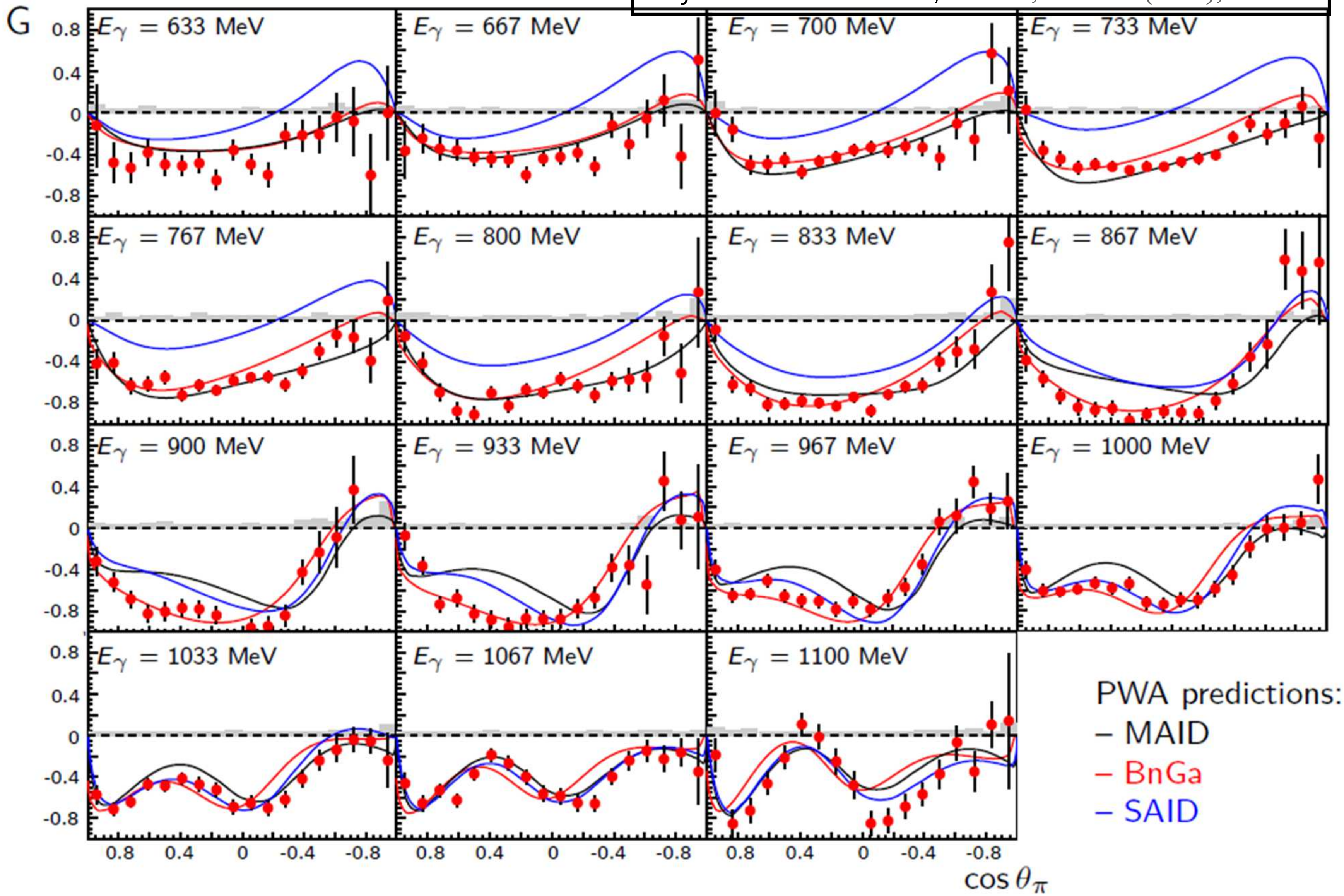


G-Asymmetry for $p\pi^0$

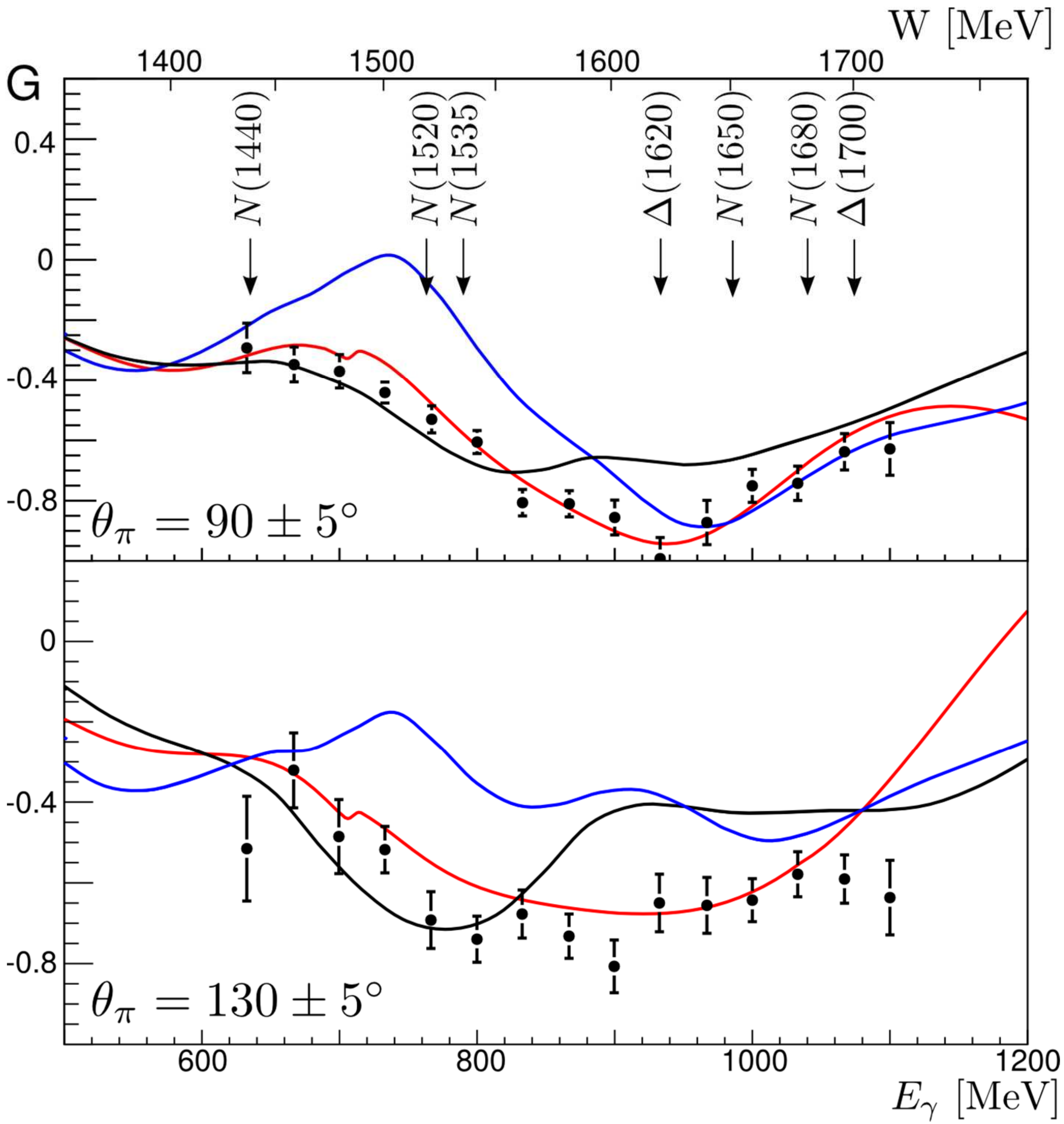
linearly polarized beam, longitudinally polarized target:

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

Crystal Barrel at ELSA , *A. Thiel, PRL 109 (2012), 102001*



G-Asymmetry for $p\pi^0$



- PWA predictions fail already in 2. resonance region

Partial wave analysis prediction:

__ BnGa

__ SAID (SN11)

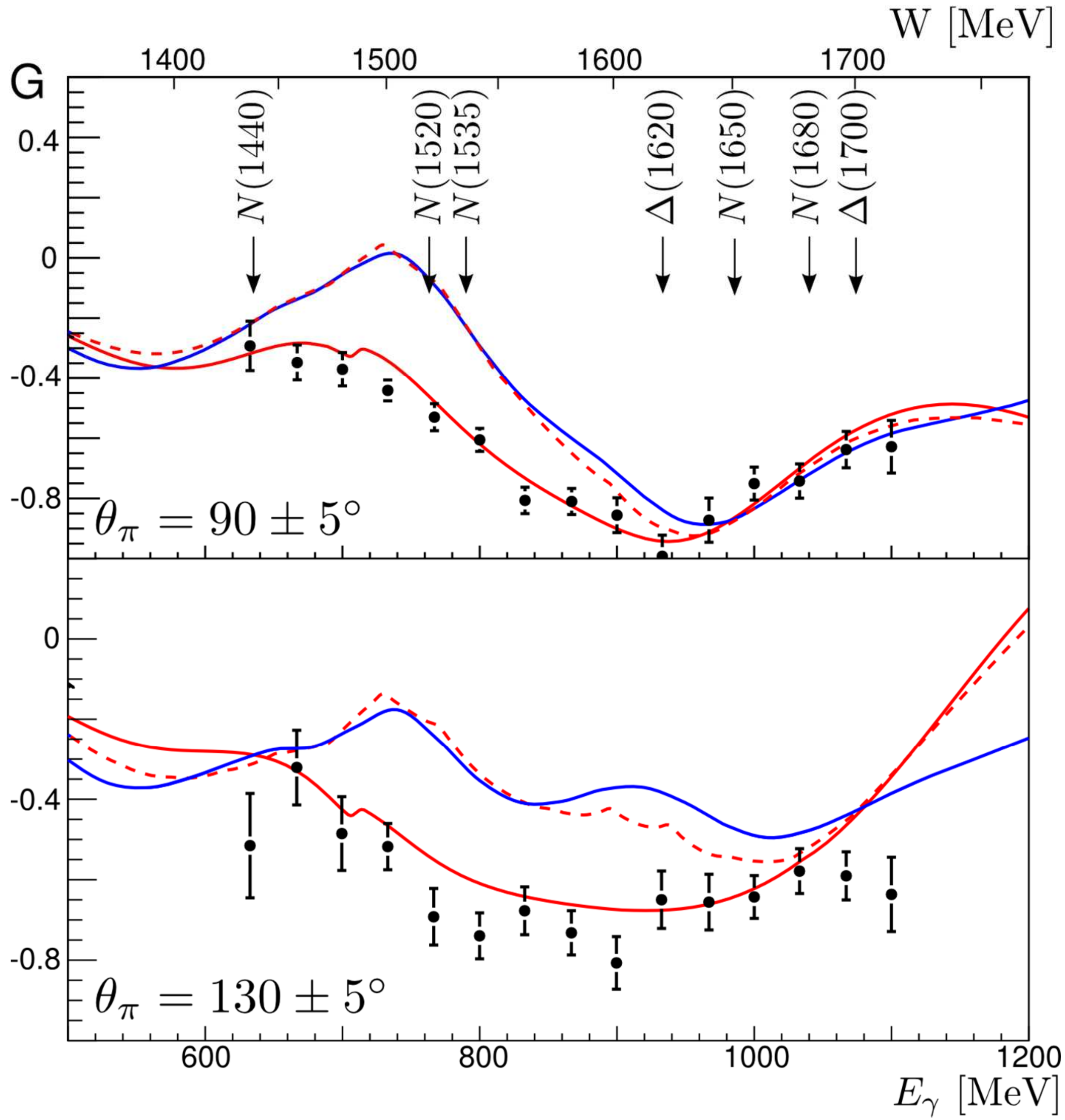
__ MAID

- Below 1 GeV the discrepancies can be traced back to the E_{0+} and E_{2-} Multipoles

  s- and d-wave contributions

Crystal Barrel at ELSA , *A. Thiel, PRL 109 (2012), 102001*

G-Asymmetry for $p\pi^0$



- Below 1 GeV the discrepancies can be traced back to the 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)

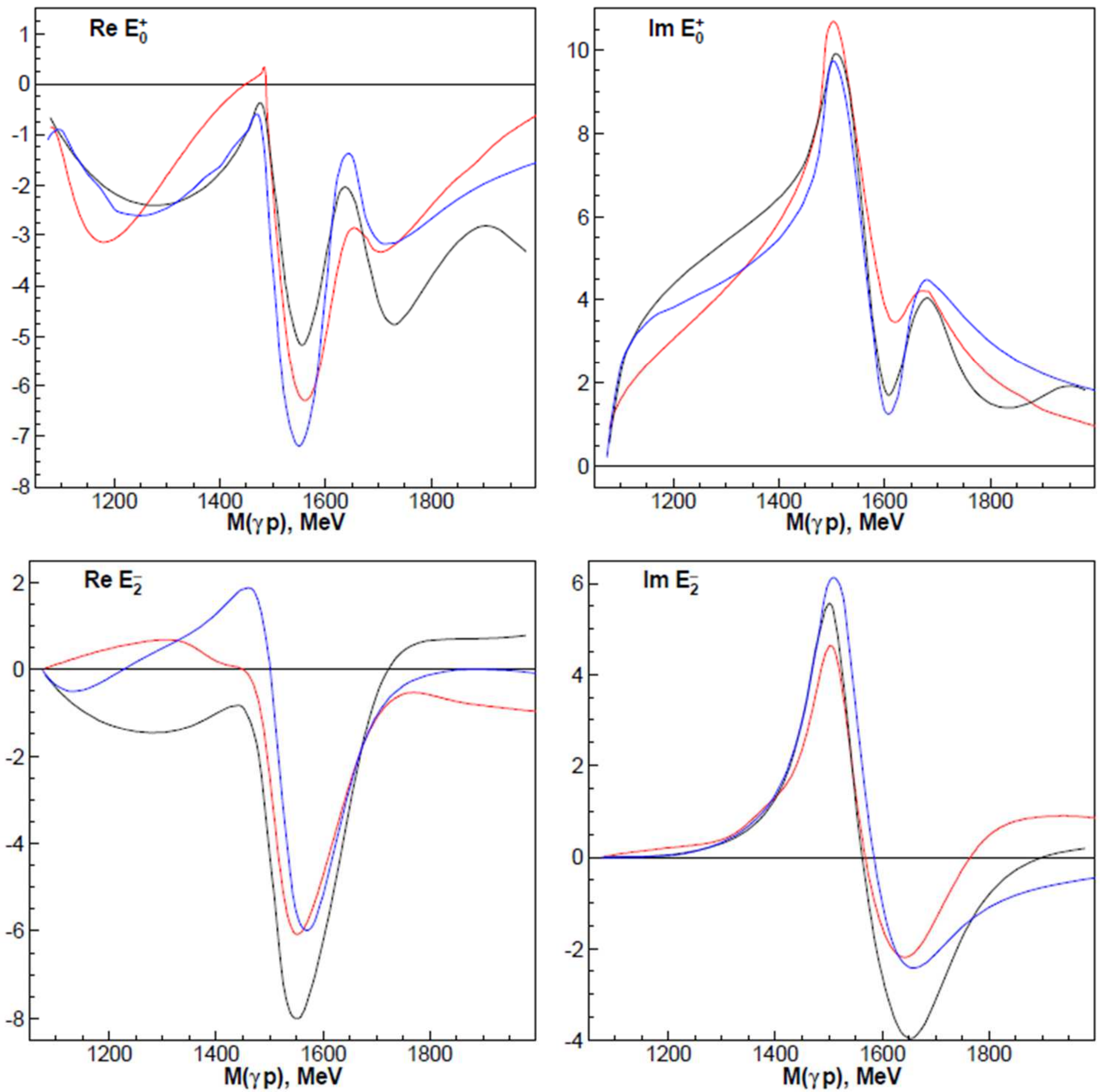
BnGa

SAID (SN11)

BnGa (with E_{0+} and E_{2-} SAID)

New Said solution CM12 , *R. Workman, PRL*

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



Partial wave analysis:

BnGa

SAID (SN11)

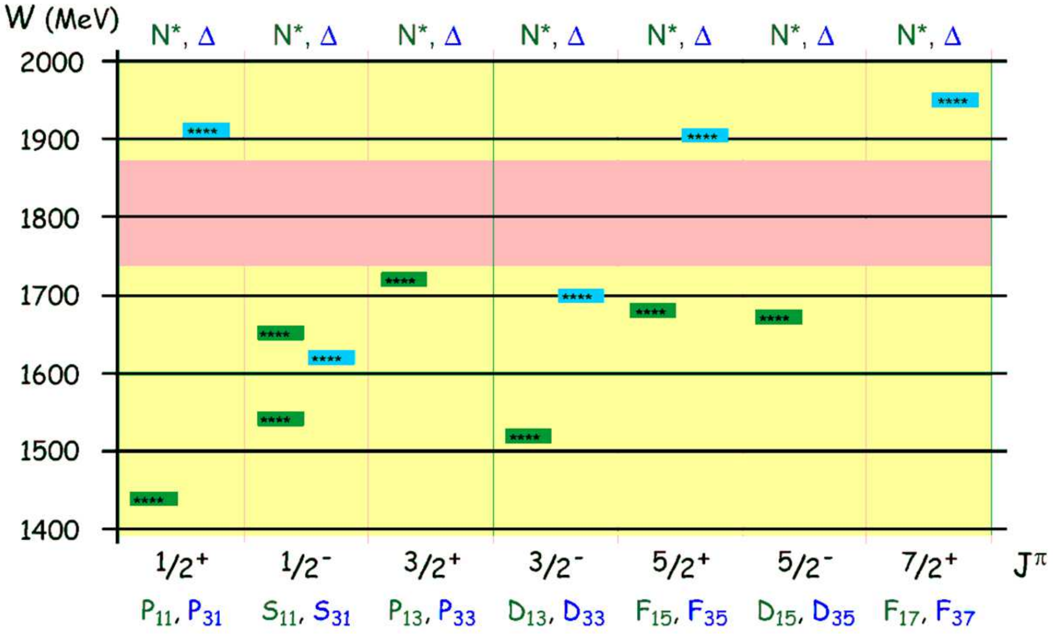
MAID

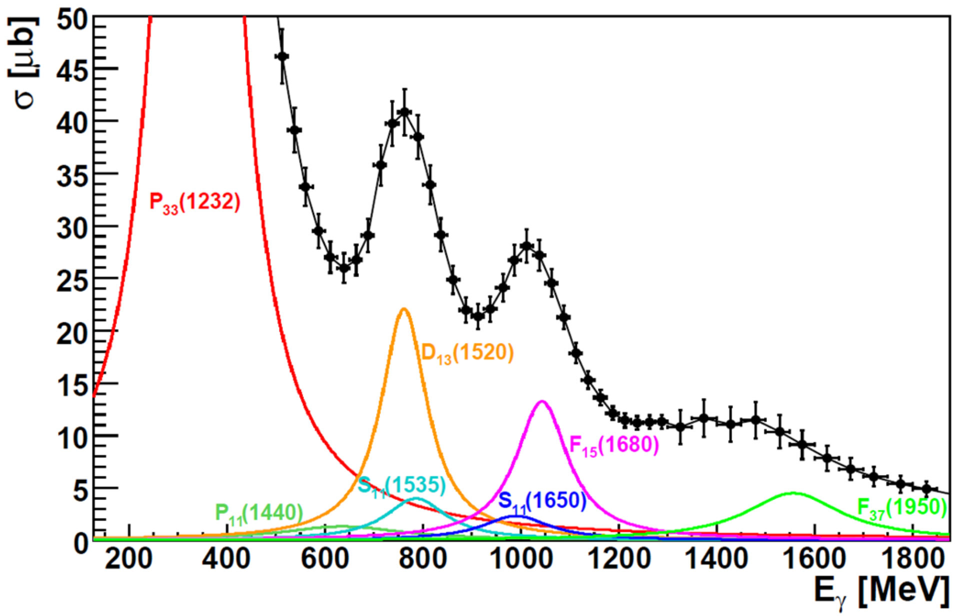
- E_{0+} Multipole, s-wave
  $S_{11}(1535)$, $S_{11}(1650)$ and $S_{31}(1620)$

- E_{2-} Multipole, d-wave
  $D_{13}(1520)$ and D_{33} (1700)

polarization observables necessary
to constrain partial wave analysis
(resonance + background contribution)

Impact of the new polarization data





Which L_{max} is seen in the new data –> truncated partial wave analysis possible

$L_{max} = 0$, S-wave , resonances in S-wave: $S_{11}(1535)$, $S_{11}(1650)$, $S_{31}(1620)$

$L_{max} = 1$, P-wave , resonances in P-wave: $P_{11}(1440)$, $P_{13}(1710)$, $P_{33}(1232)$

$L_{max} = 2$, D-wave , resonances in D-wave: $D_{13}(1520)$, $D_{15}(1680)$, $D_{33}(1700)$

$L_{max} = 3$, F-wave , resonances in F-wave: $F_{15}(1680)$, $F_{37}(1950)$

L_{max} Interpretation of G-Asymmetry

for $L_{max} \leq 1$: only s- and p- waves contribute

$$\hat{G} = \frac{G \cdot \frac{d\sigma}{d\Omega}}{\sin^2(\theta)} = A_0 = \text{constant}$$

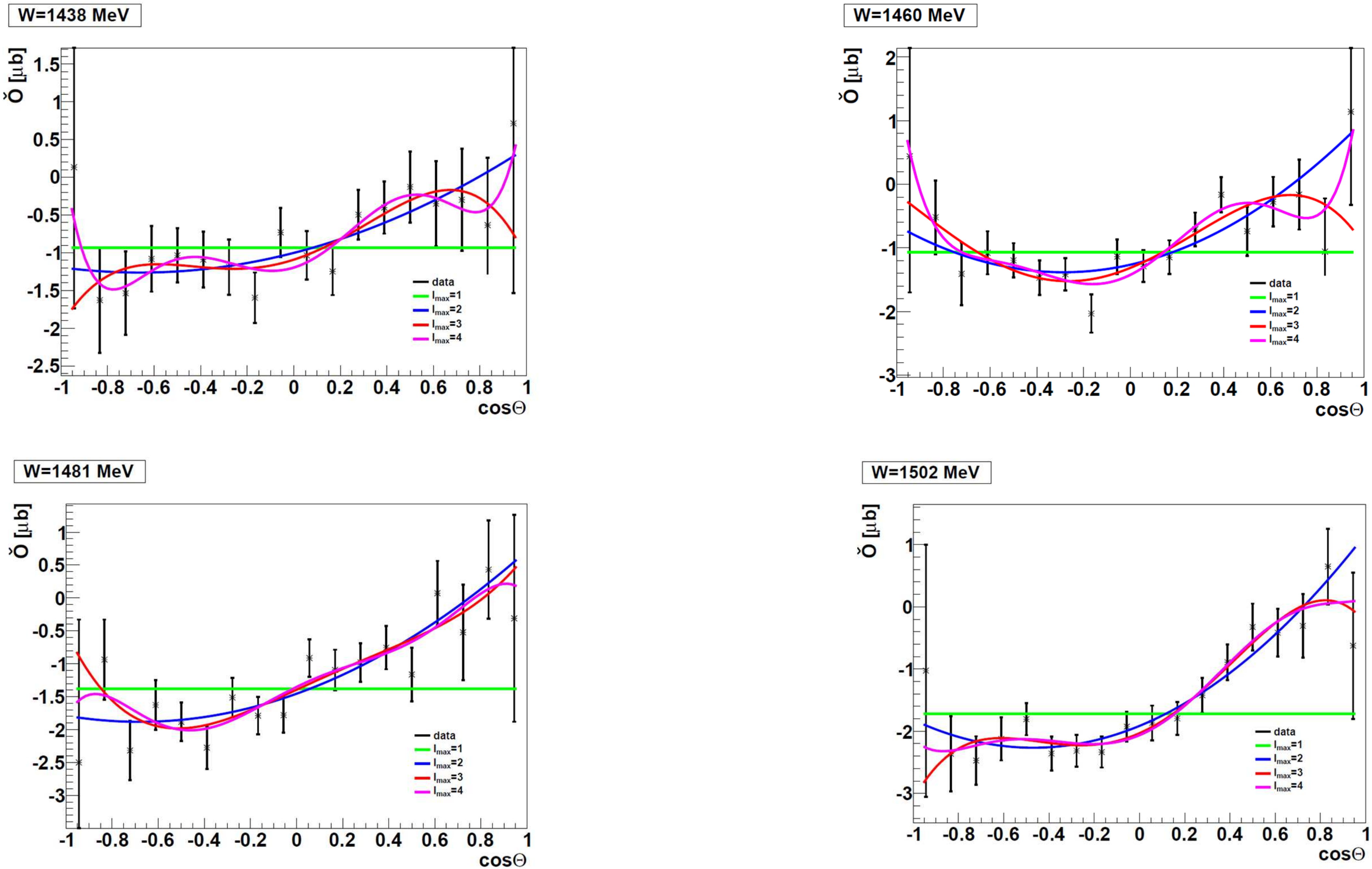
for $L_{max} \leq 2$: only s-, p- and d- waves contribute

$$\hat{G} = \frac{G \cdot \frac{d\sigma}{d\Omega}}{\sin^2(\theta)} = A_0 + A_1 \cdot \cos(\theta) + A_2 \cdot \cos^2(\theta)$$

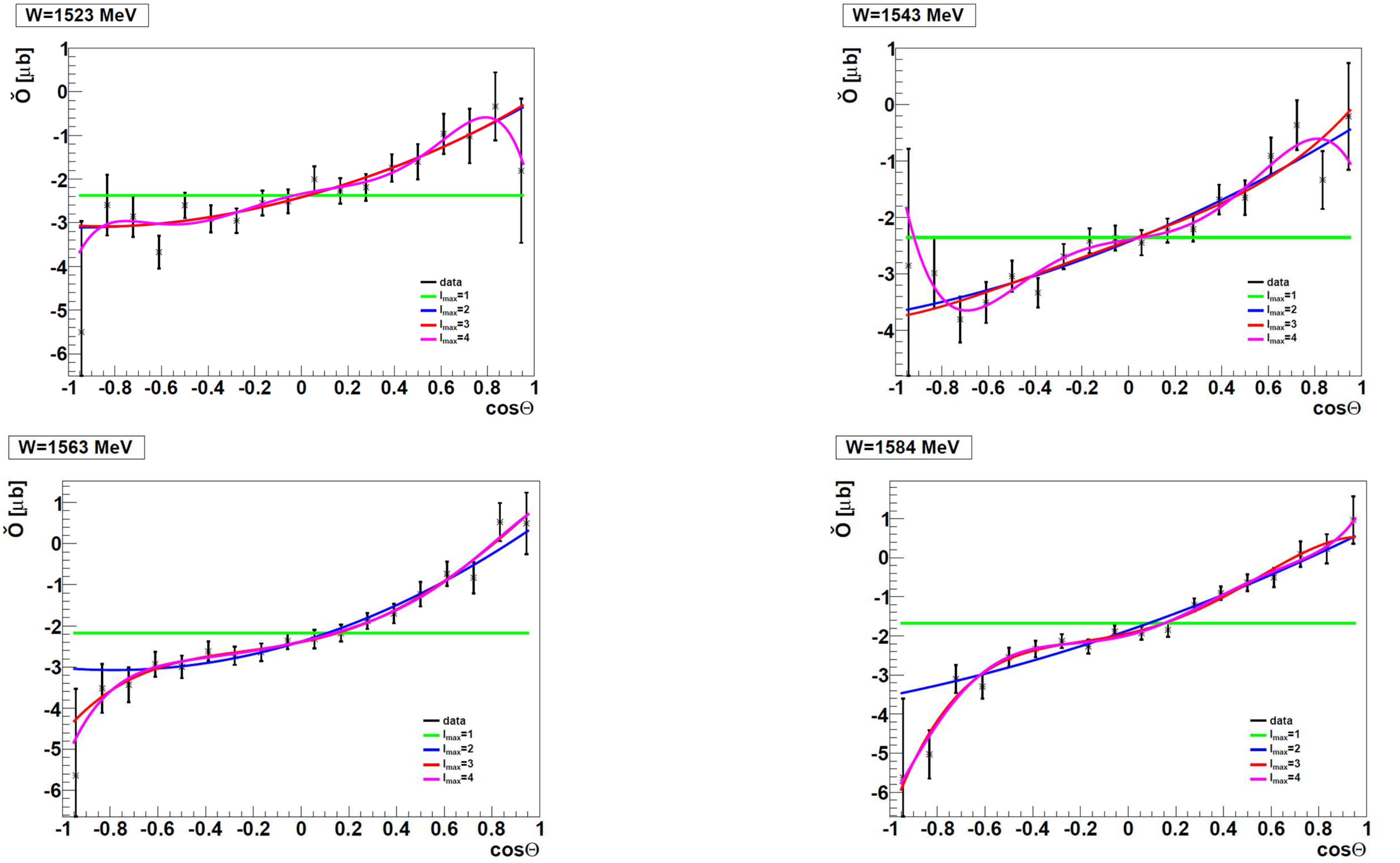
for $L_{max} \leq 3$: only s-, p-, d- and f- waves

$$\hat{G} = \frac{G \cdot \frac{d\sigma}{d\Omega}}{\sin^2(\theta)} = A_0 + A_1 \cdot \cos(\theta) + A_2 \cdot \cos^2(\theta) + A_3 \cdot \cos^3(\theta) + A_4 \cdot \cos^4(\theta)$$

L_{max} Interpretation of G-Asymmetry

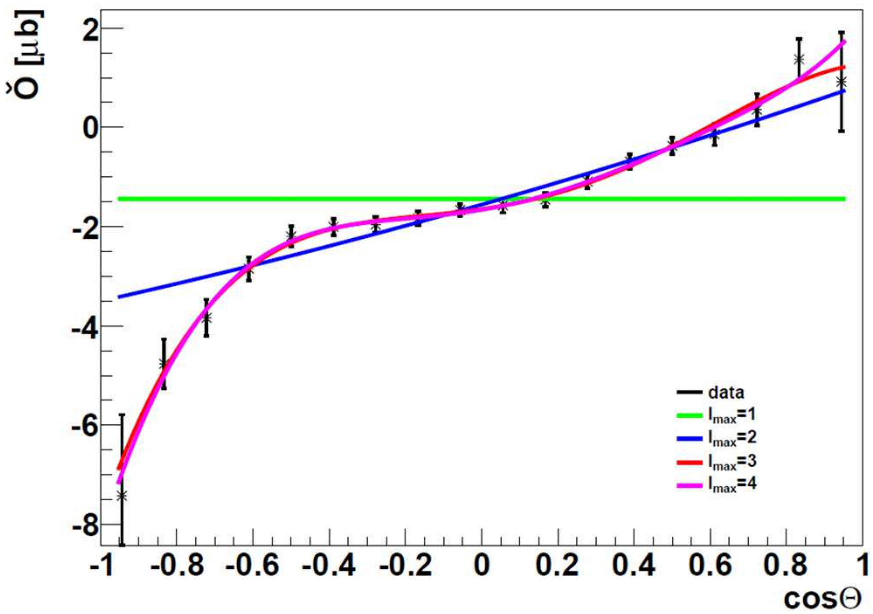


L_{max} Interpretation of G-Asymmetry

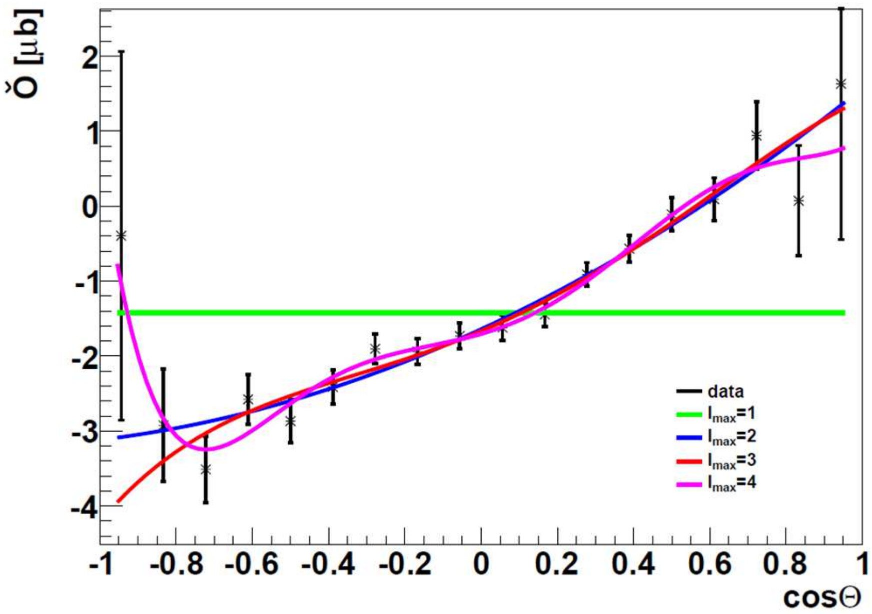


L_{max} Interpretation of G-Asymmetry

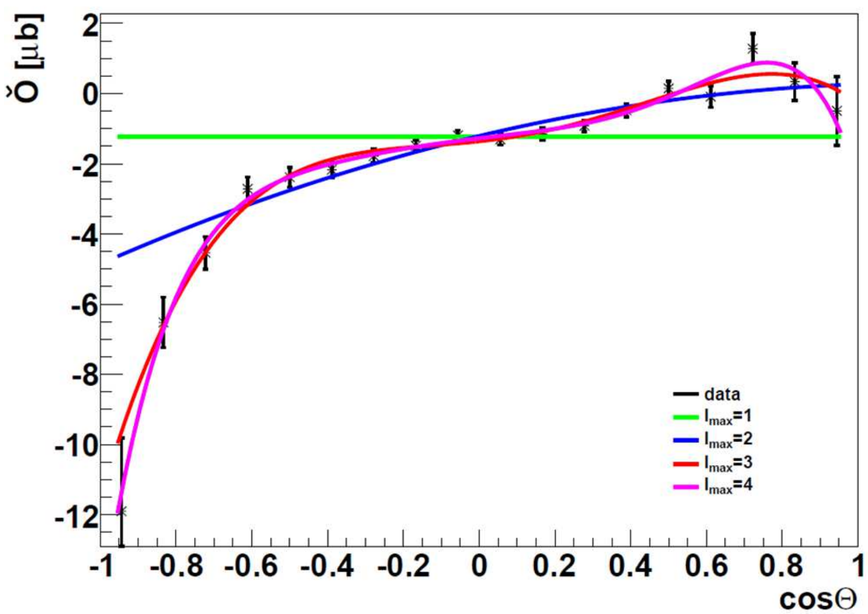
W=1603 MeV



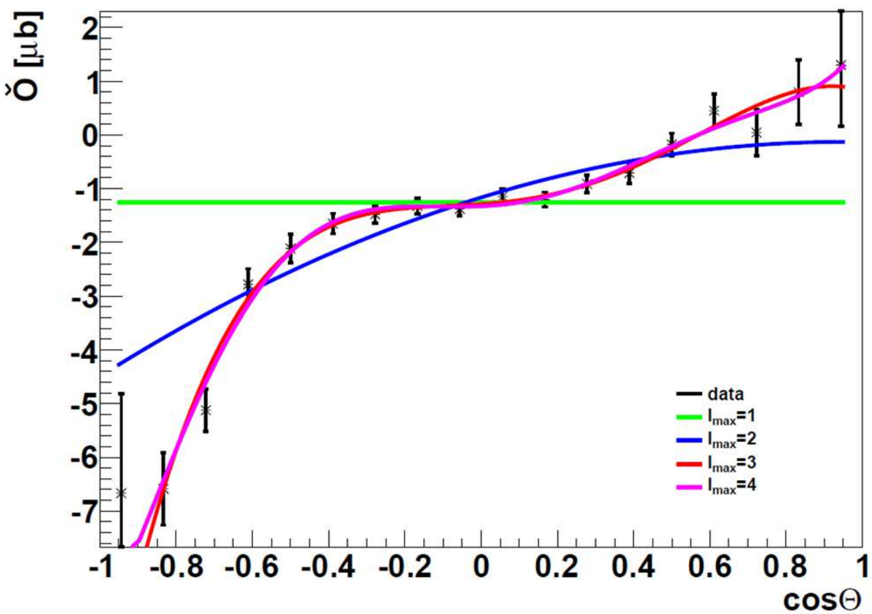
W=1622 MeV



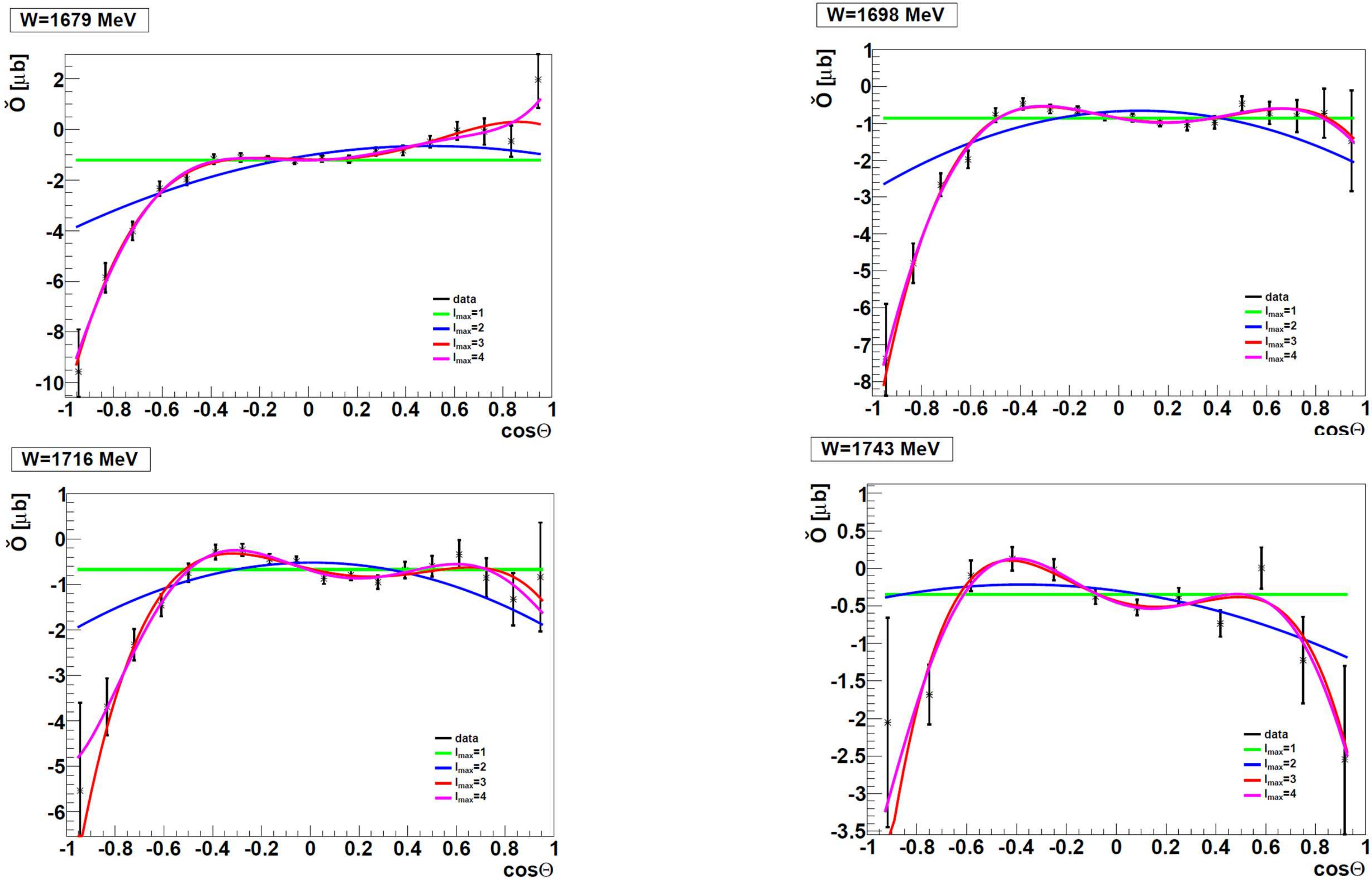
W=1642 MeV



W=1660 MeV

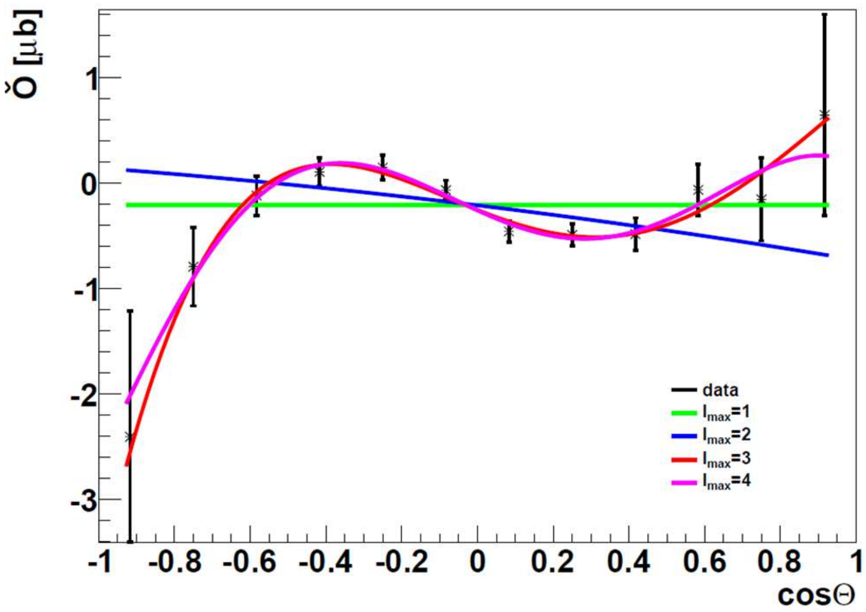


L_{max} Interpretation of G-Asymmetry

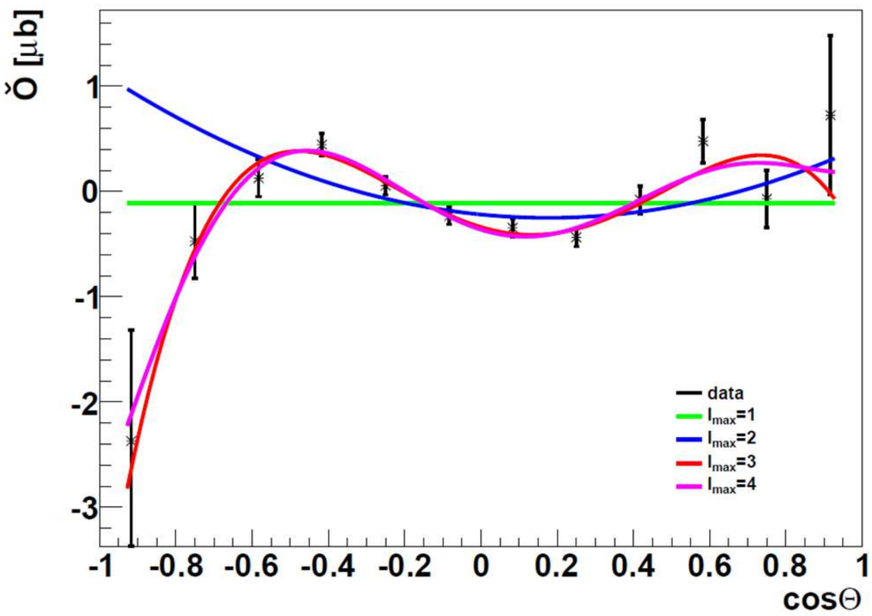


L_{max} Interpretation of G-Asymmetry

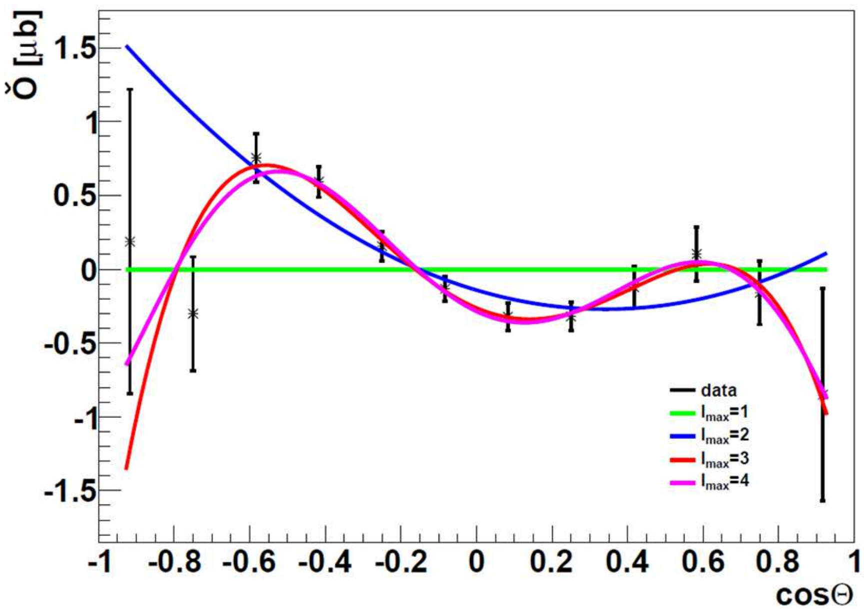
W=1770 MeV



W=1796 MeV



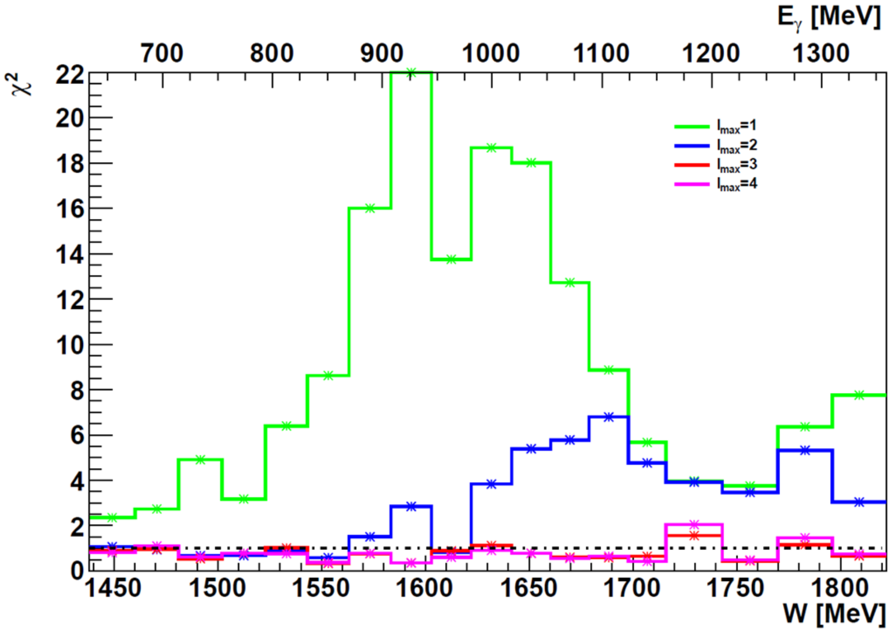
W=1822 MeV



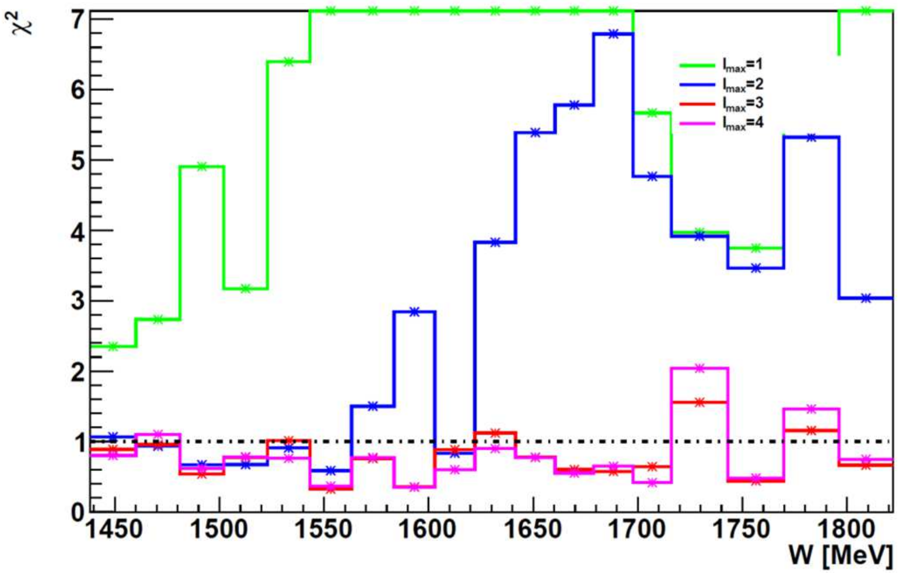
- Full angular coverage is important !
- Precision is important !

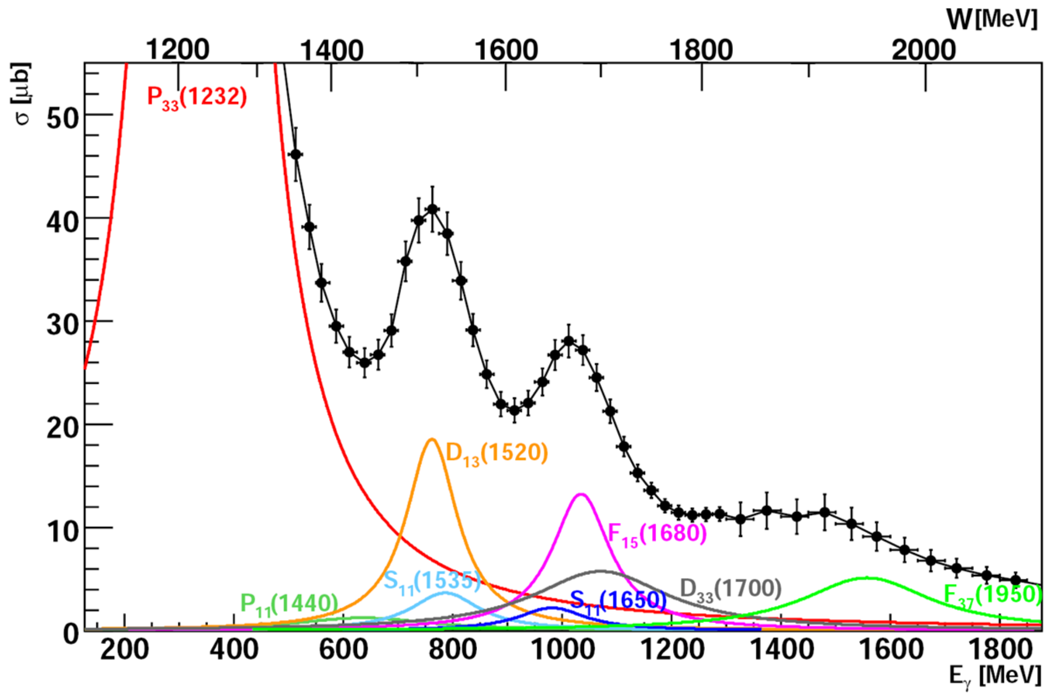
Crystal Barrel at ELSA , *F. Afzal and Y. Wunderlich*

L_{max} Interpretation of G-Asymmetry



- Significant L = 3 signal seen above W = 1550 MeV
- Below L ≤ 2 seems to be sufficient
- No significant L=4 signal until W=1850 MeV





L_{max} Interpretation of T-Asymmetry

for L ≤ 1 : only s- and p- waves

$$T = \frac{T \cdot \frac{d\sigma}{d\Omega}}{\sin^1(\theta)} = A_0 + A_1 \cdot \cos(\theta)$$

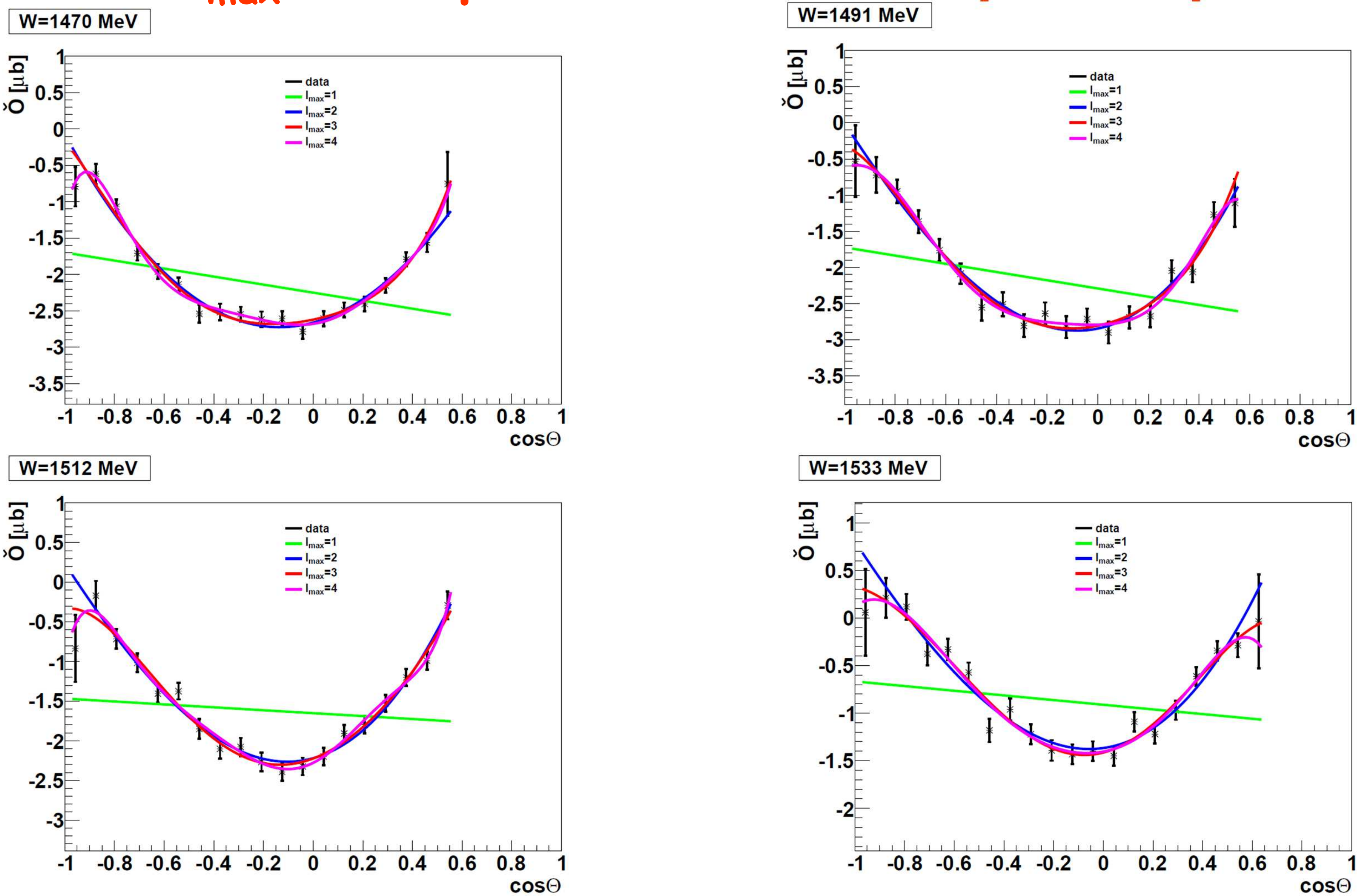
for L ≤ 2 : only s-, p- and d- waves

$$T = \frac{T \cdot \frac{d\sigma}{d\Omega}}{\sin^1(\theta)} = A_0 + A_1 \cdot \cos(\theta) + A_2 \cdot \cos^2(\theta) + A_3 \cdot \cos^3(\theta)$$

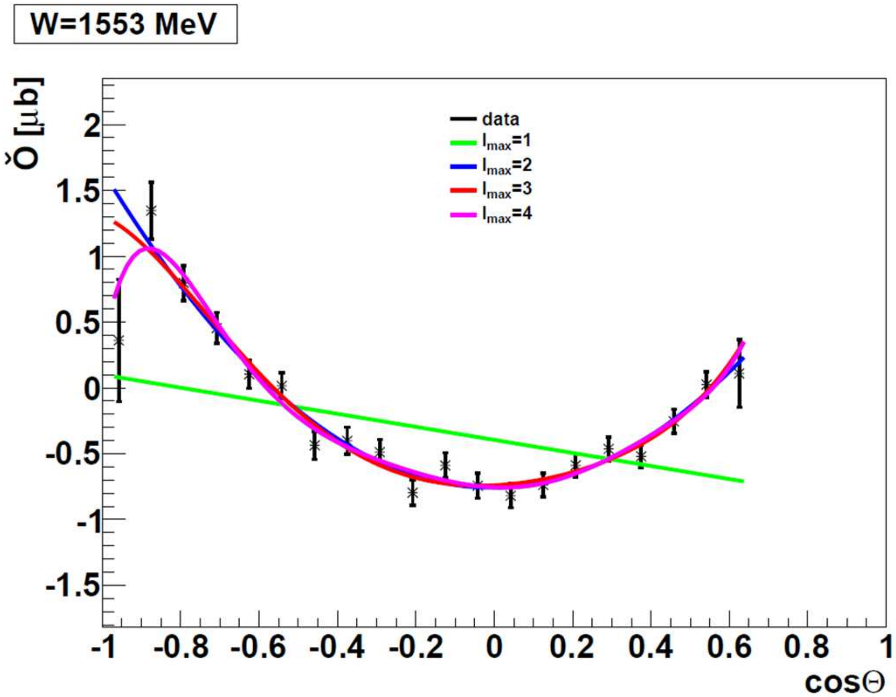
for L ≤ 3 : only s-, p-, d- and f- waves

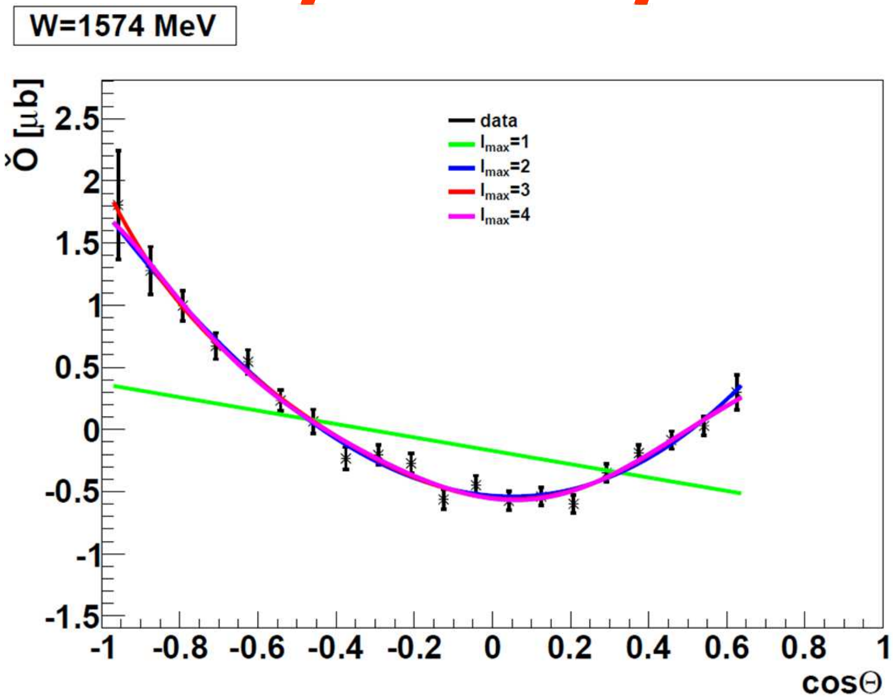
$$T = \frac{T \cdot \frac{d\sigma}{d\Omega}}{\sin^1(\theta)} = A_0 + A_1 \cdot \cos(\theta) + A_2 \cdot \cos^2(\theta) + A_3 \cdot \cos^3(\theta) + A_4 \cdot \cos^4(\theta) + A_5 \cdot \cos^5(\theta)$$

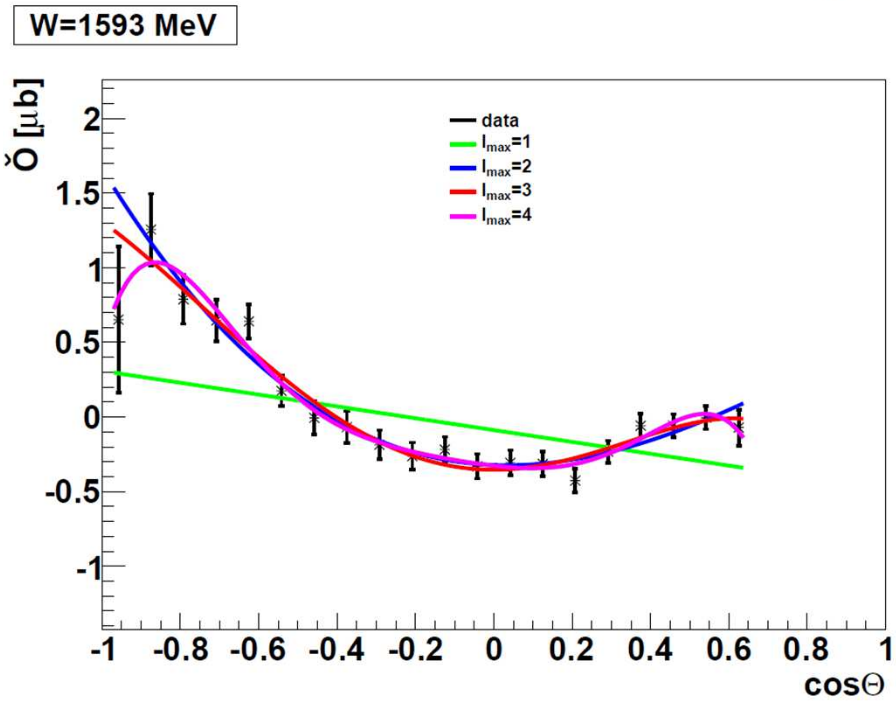
L_{max} Interpretation of T-Asymmetry

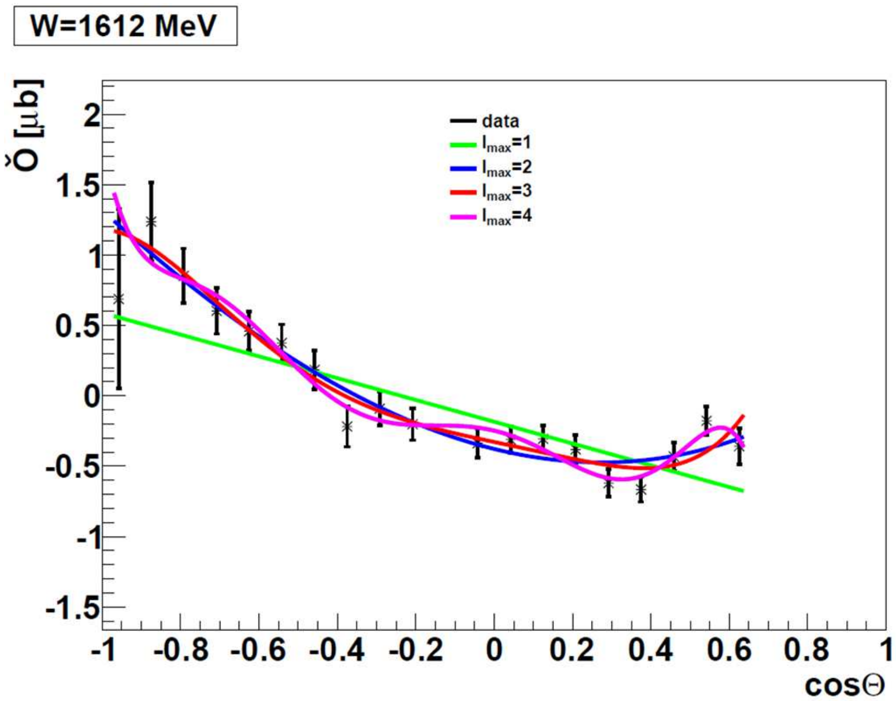


L_{max} Interpretation of T-Asymmetry



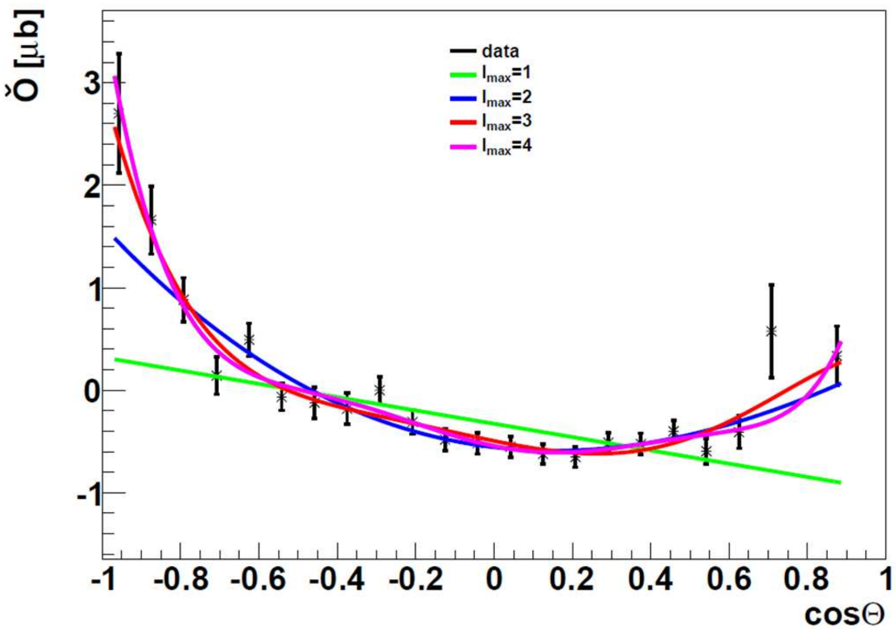




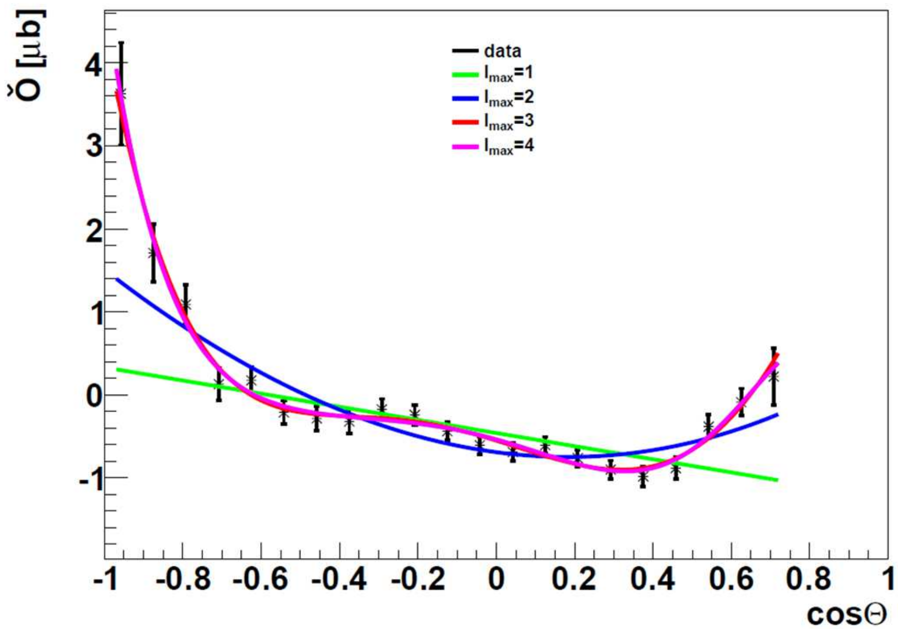


L_{max} Interpretation of T-Asymmetry

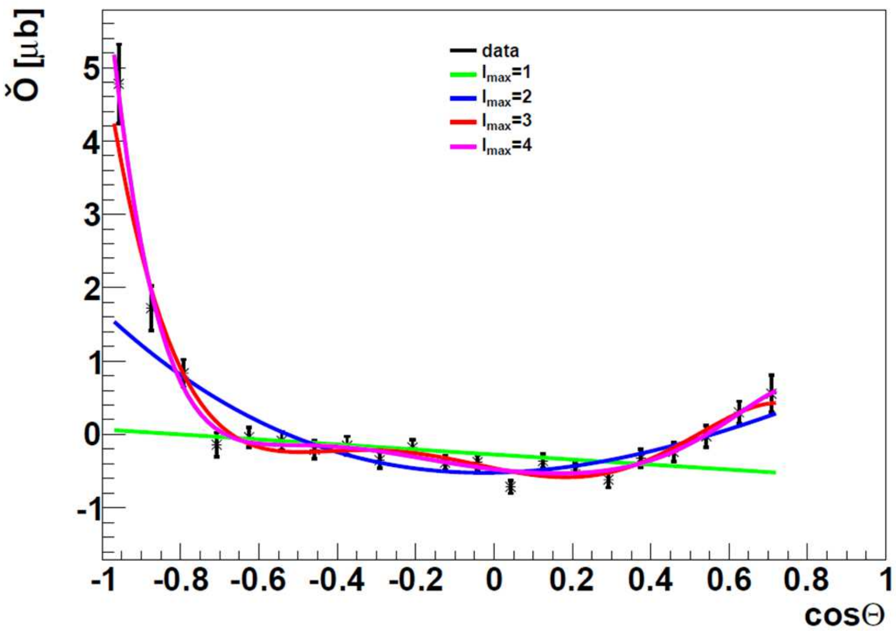
W=1634 MeV



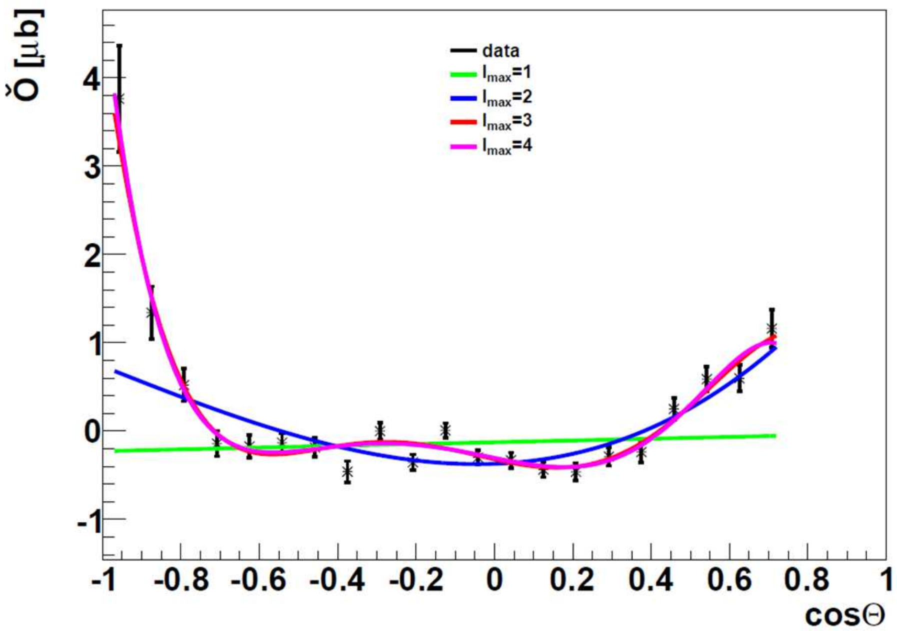
W=1657 MeV



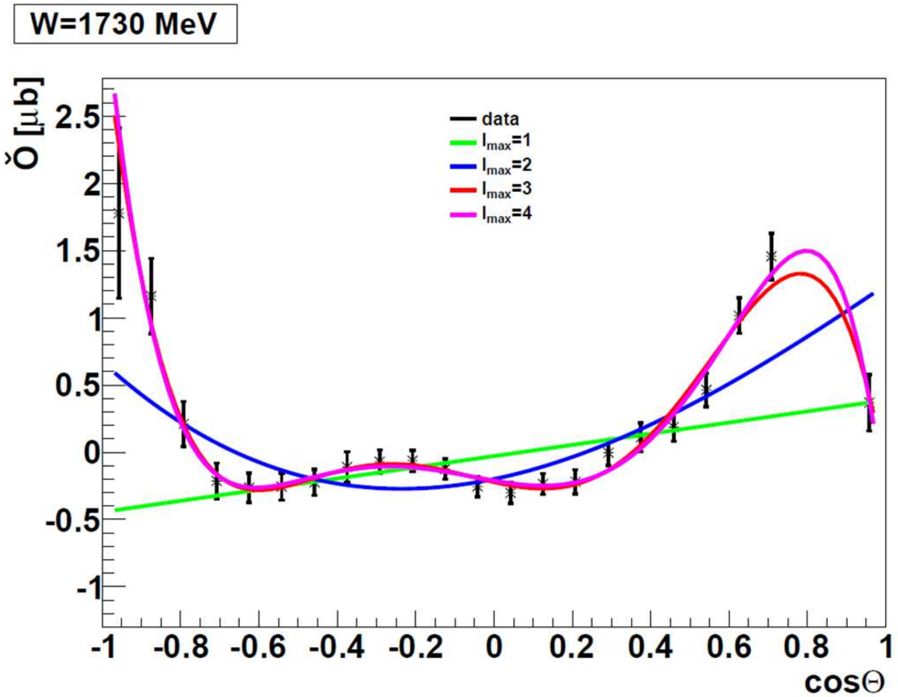
W=1681 MeV

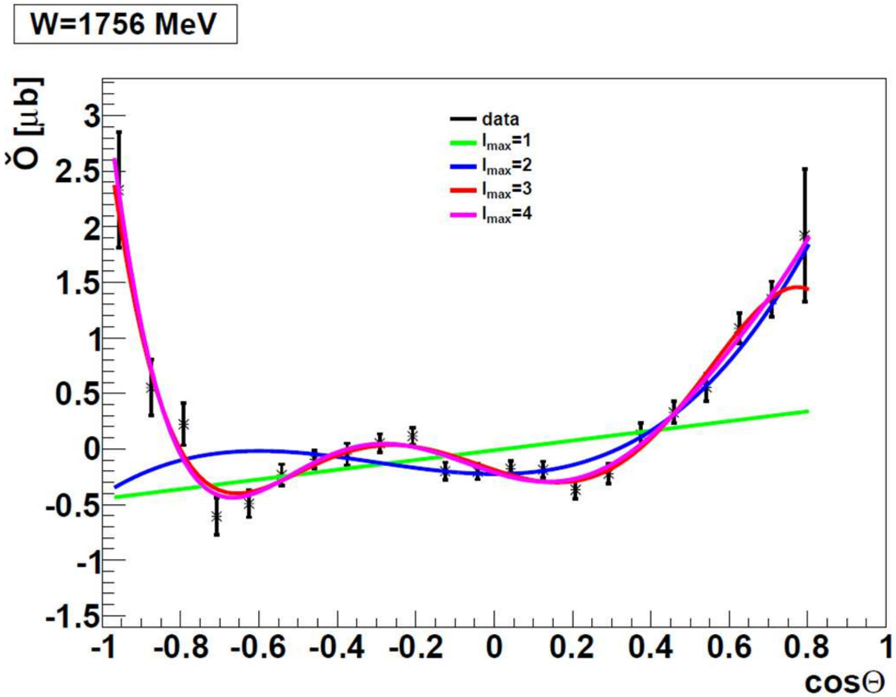


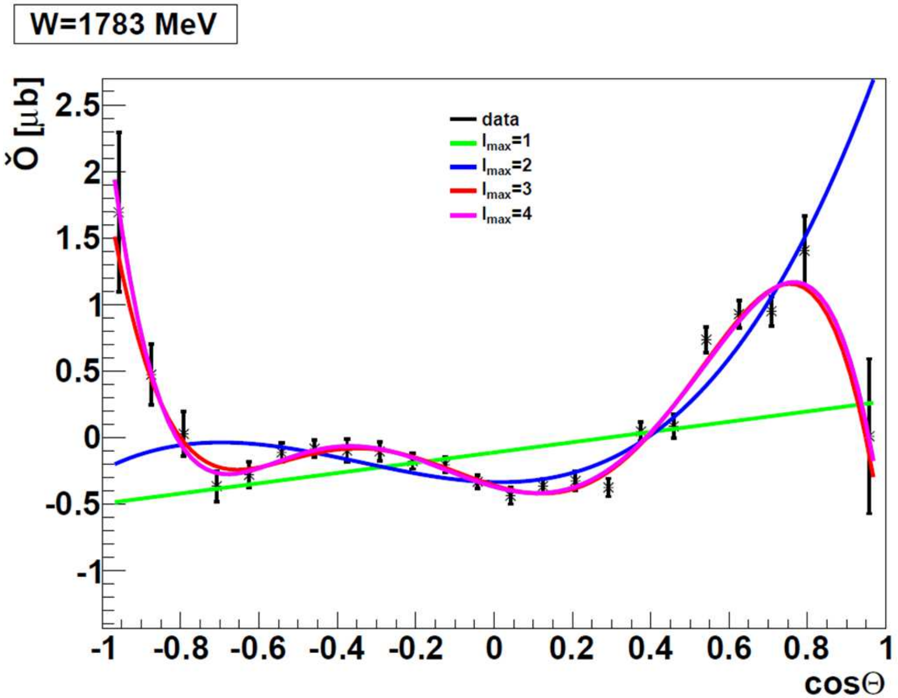
W=1704 MeV

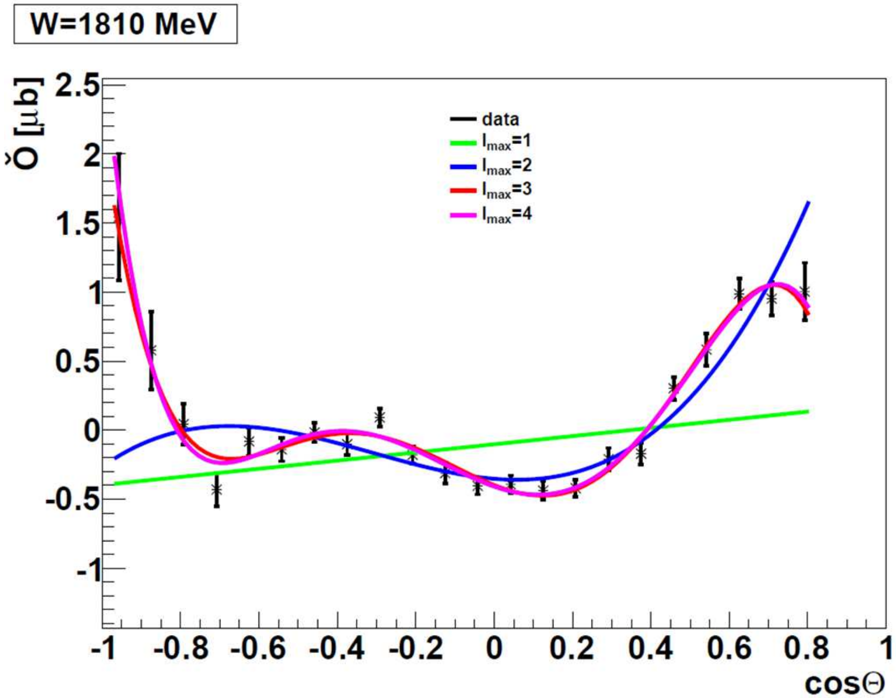


L_{max} Interpretation of T-Asymmetry



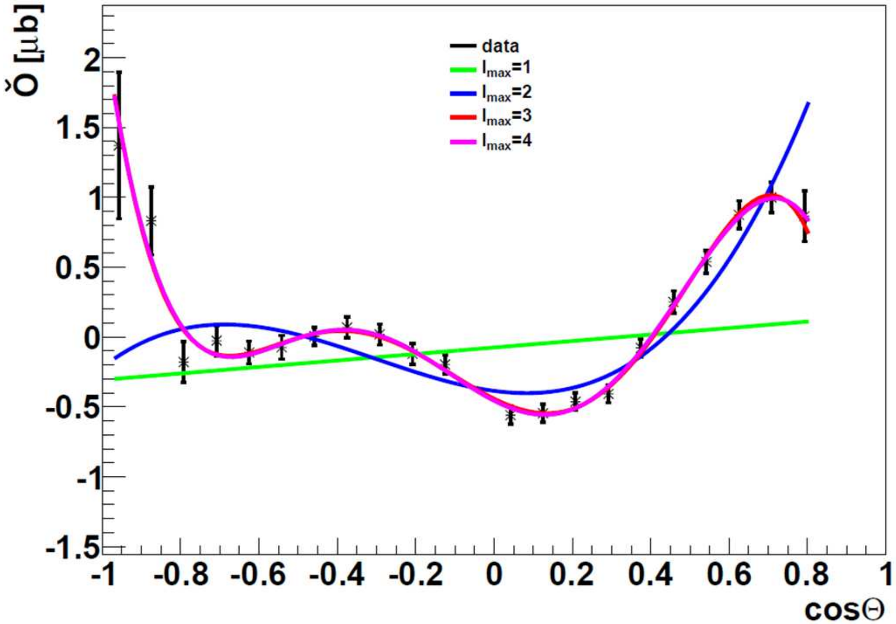




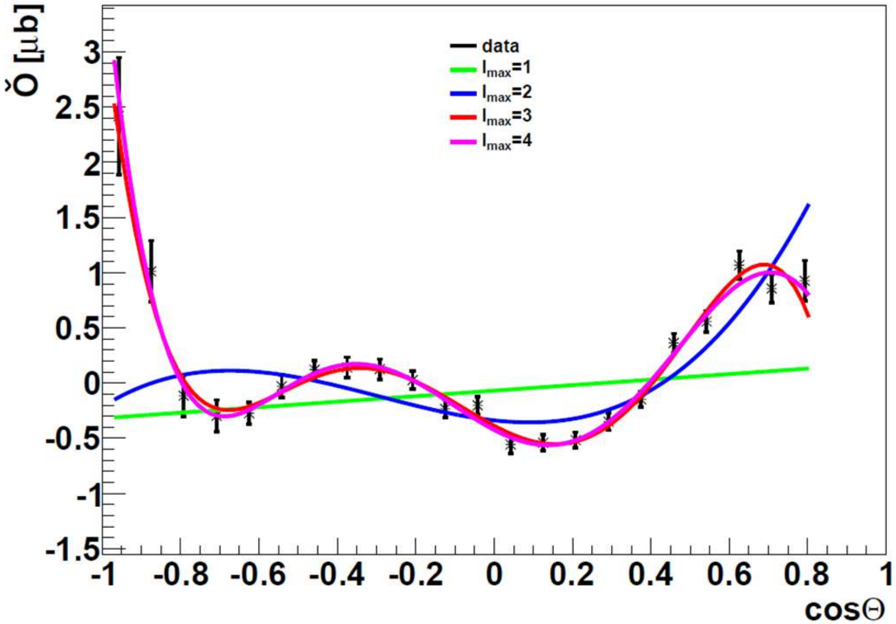


L_{max} Interpretation of T-Asymmetry

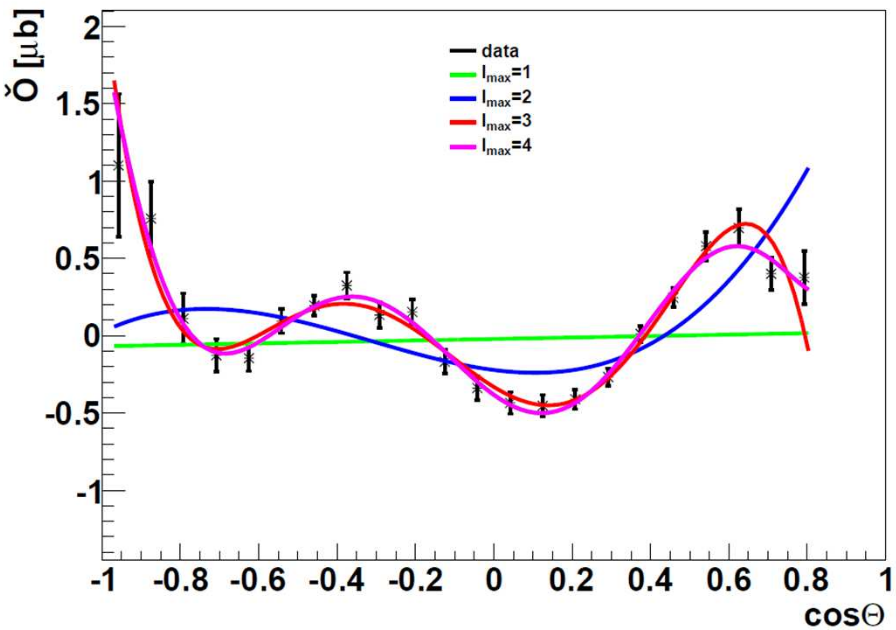
W=1836 MeV



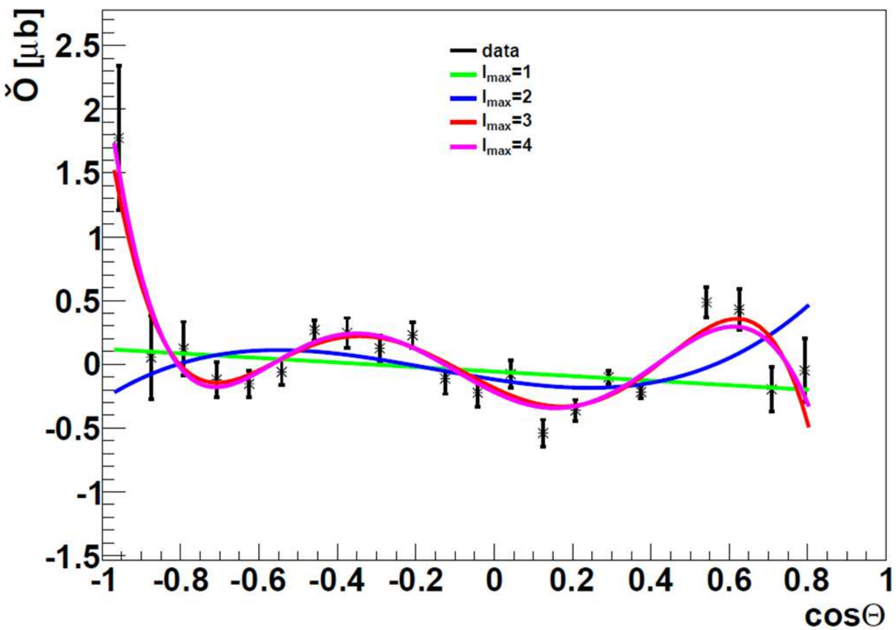
W=1862 MeV



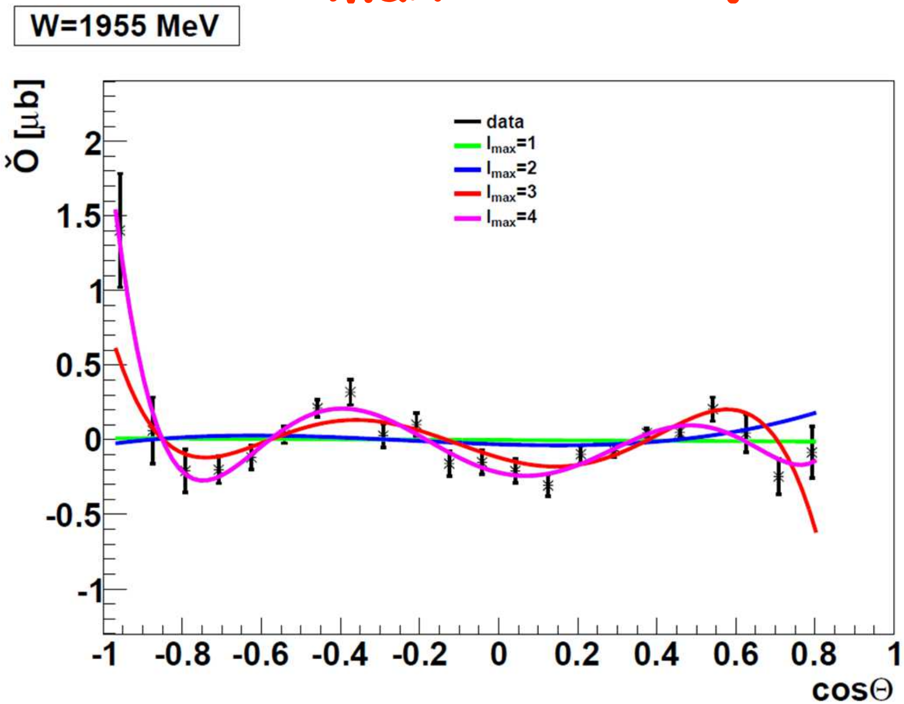
W=1890 MeV

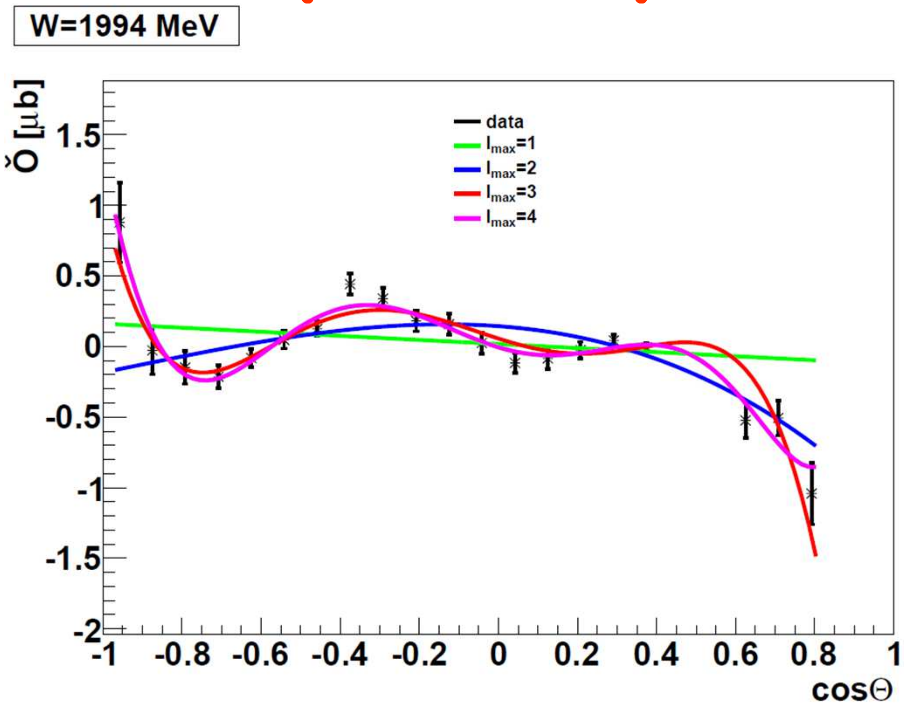


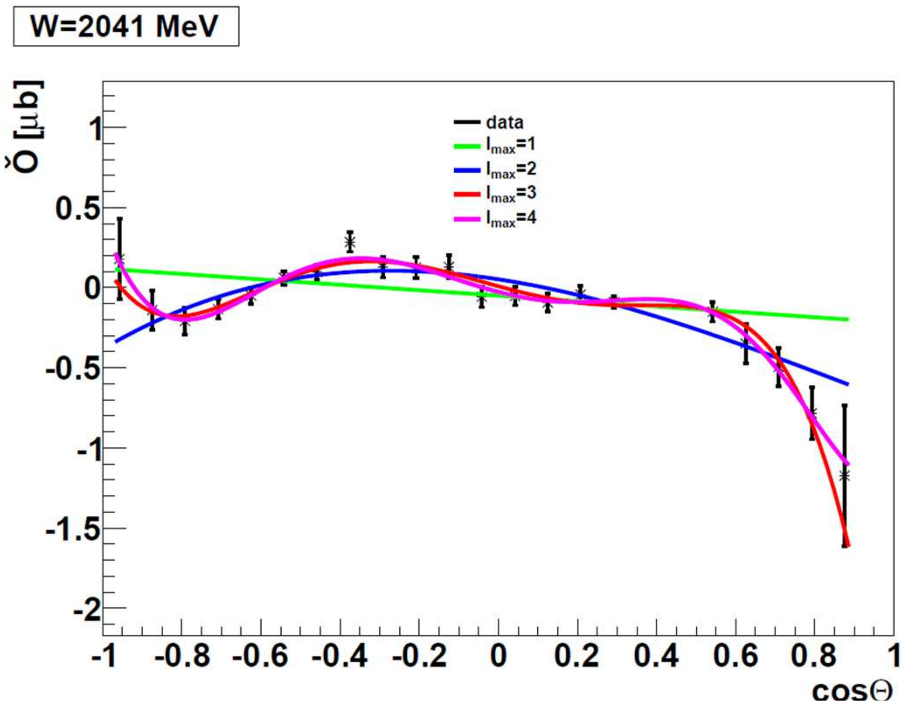
W=1922 MeV

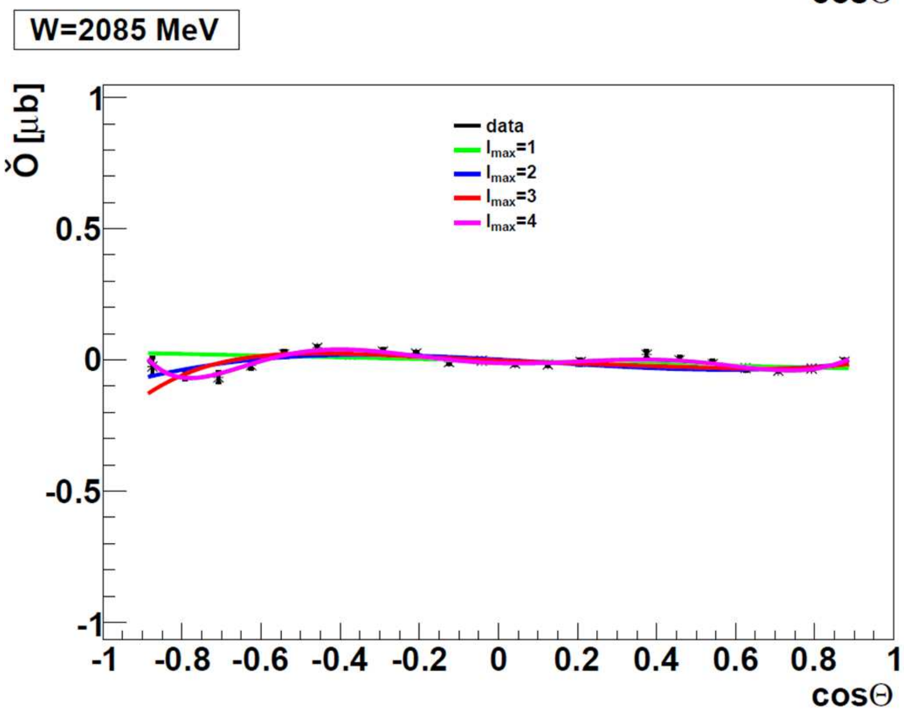


L_{max} Interpretation of T-Asymmetry

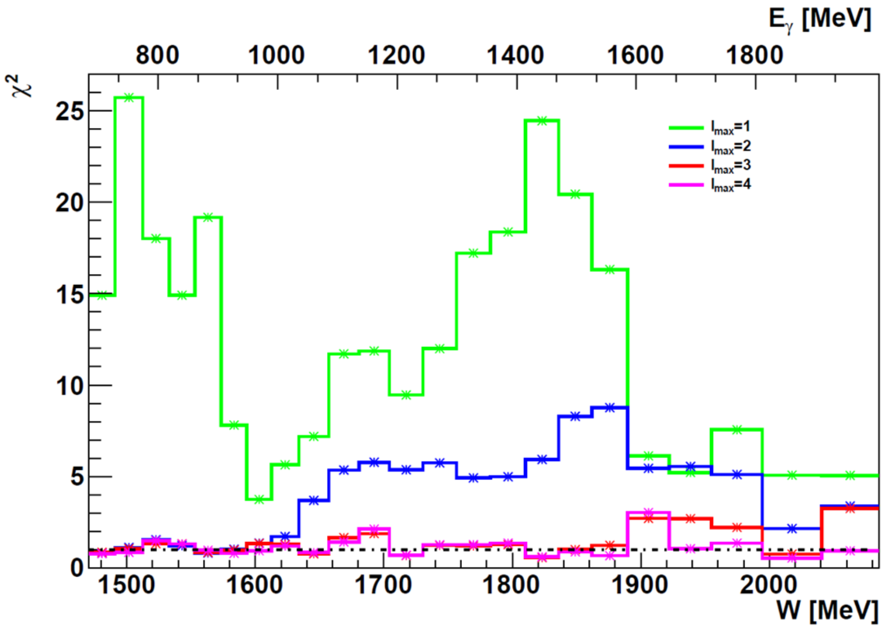




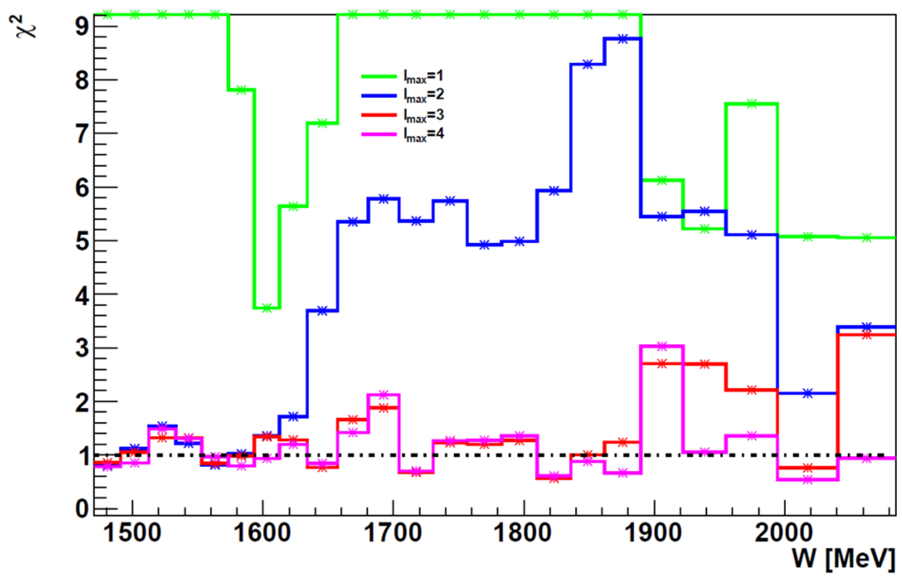




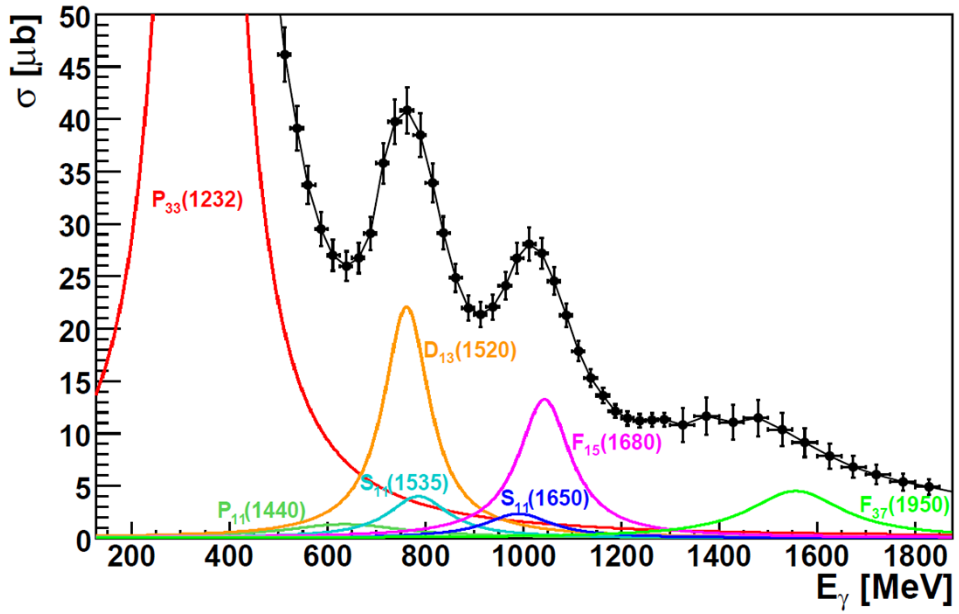
L_{max} Interpretation of T-Asymmetry



- Significant L = 3 signal seen above W = 1600 MeV
- Below L ≤ 2 seems to be sufficient
- No significant L = 4 signal until W = 2100 MeV

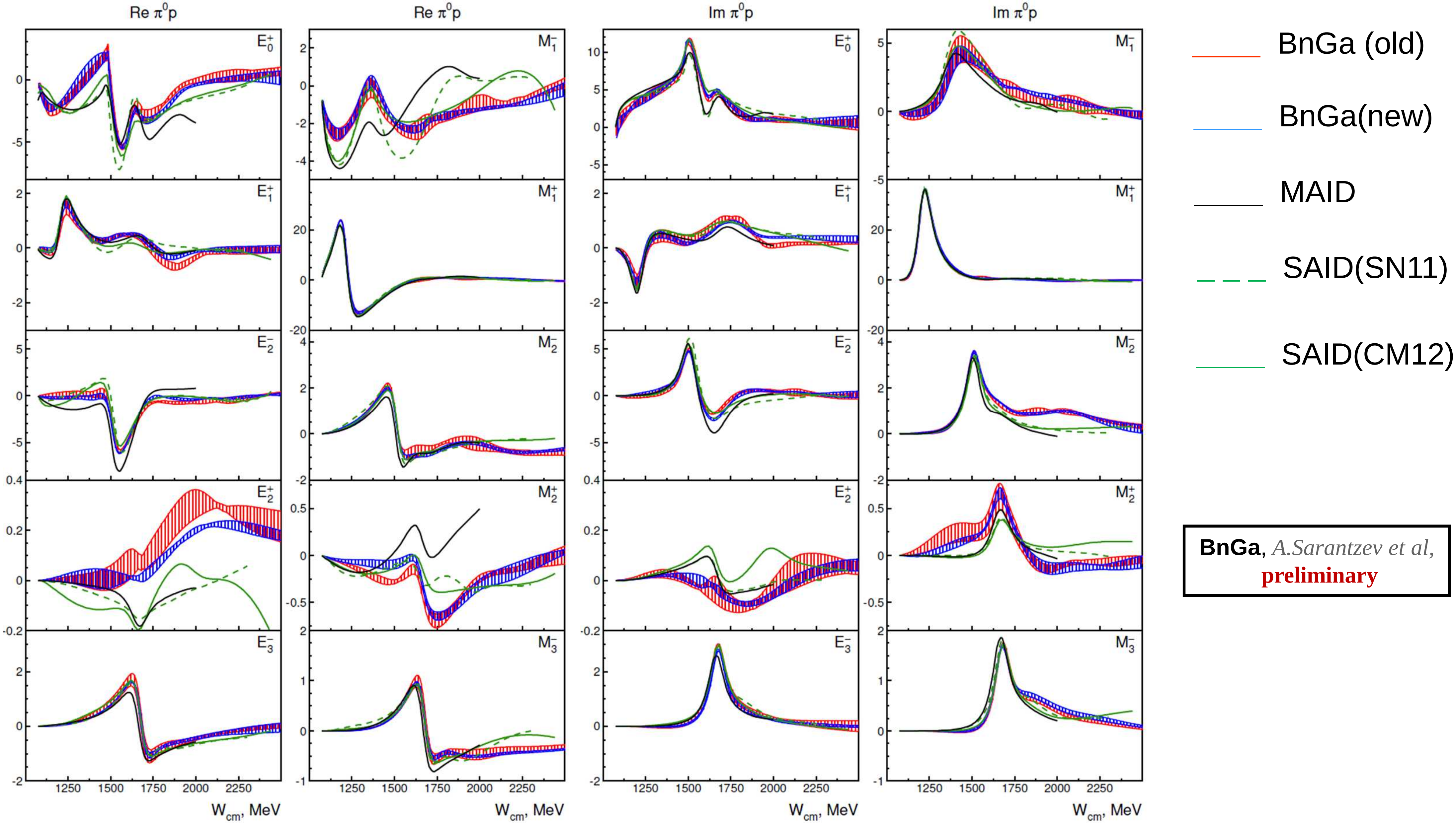


Crystal Barrel at ELSA , *J. Hartmann, submitted to PRL (2014)*



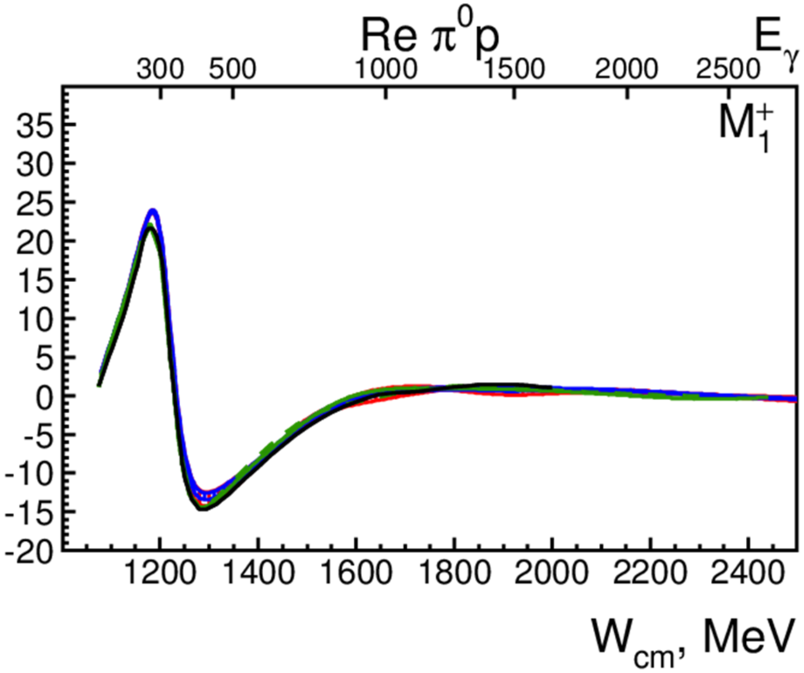
pπ^0 : Impact of the new polarization data

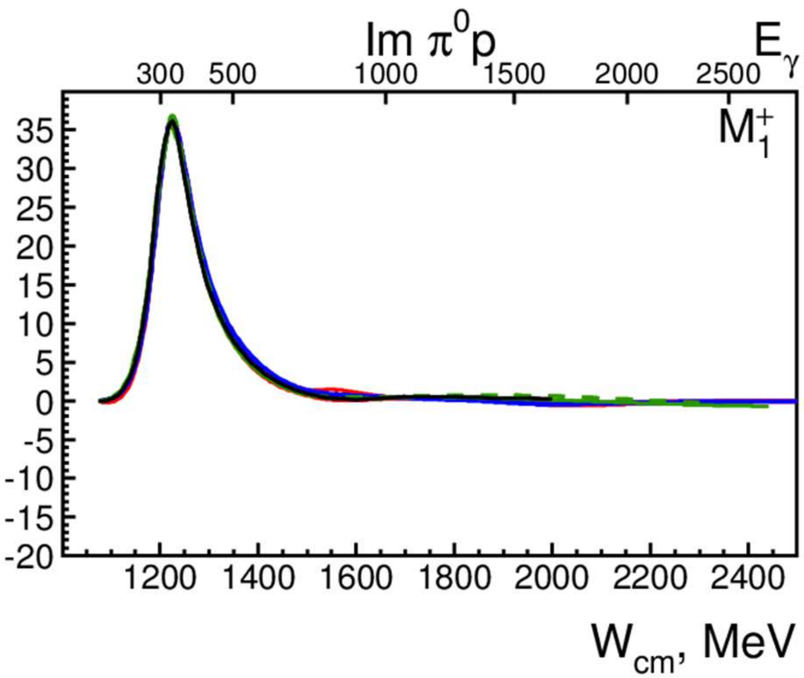
Preliminary: new BnGa energy dependent multipole solution, impact of our new data in the full data base



BnGa, *A.Sarantzev et al*, **preliminary**

$p\pi^0$: Impact of the new polarization data





BnGa (old)

BnGa (new)

MAID

SAID(SN11)

SAID(CM12)

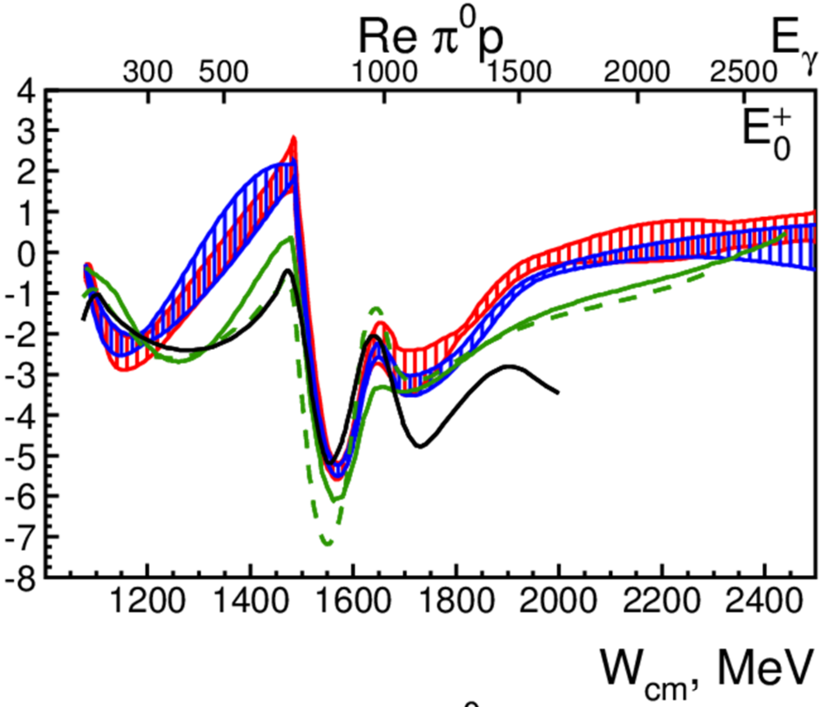
BnGa, *A.Sarantzev et al*, **preliminary**

Preliminary: new BnGa energy dependent multipole solution including the new polarization data G,E,T,P and H

M1+ Multipole

- M_{1+} multipole
  $P_{33}(1232)$, $P_{33}(1620)$ and $P_{13}(1720)$

$p\pi^0$: Impact of the new polarization data



BnGa (old)

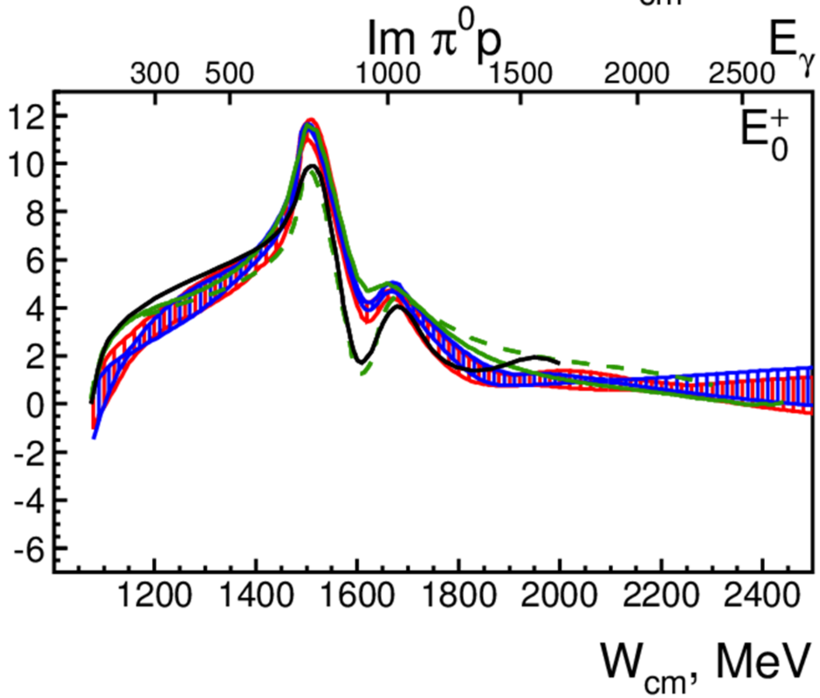
BnGa (new)

MAID

SAID(SN11)

SAID(CM12)

BnGa, *A.Sarantzev et al*, **preliminary**

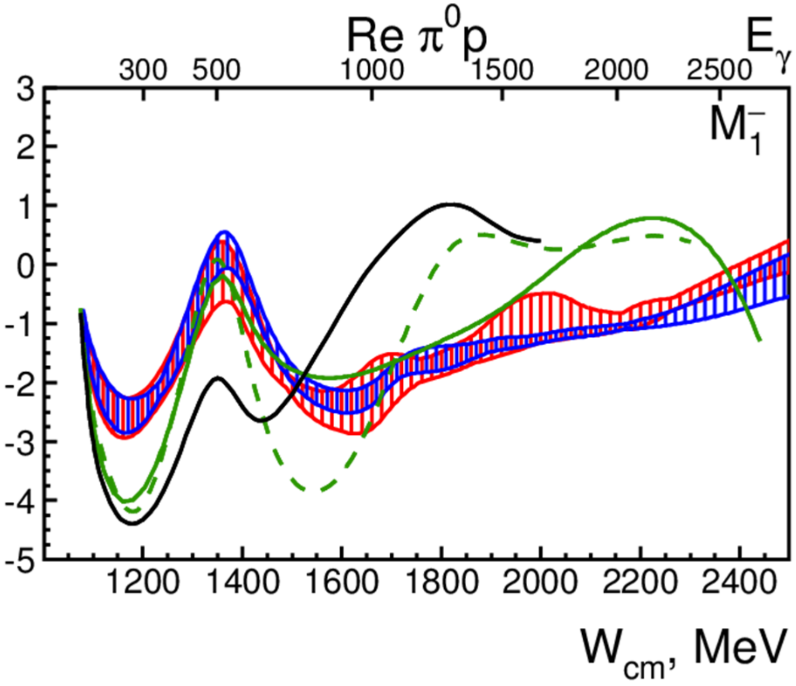


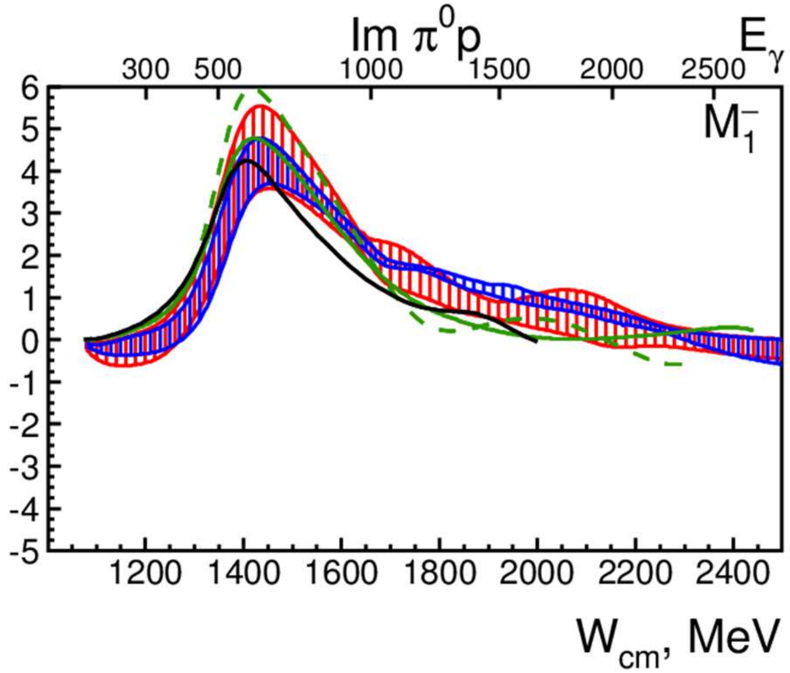
Preliminary: new BnGa energy dependent multipole solution including the new polarization data G,E,T,P and H

E0+ Multipole

- E_{0+} multipole
  $S_{11}(1535)$, $S_{11}(1650)$ and $S_{31}(1620)$

$p\pi^0$: Impact of the new polarization data





BnGa (old)

BnGa (new)

MAID

SAID(SN11)

SAID(CM12)

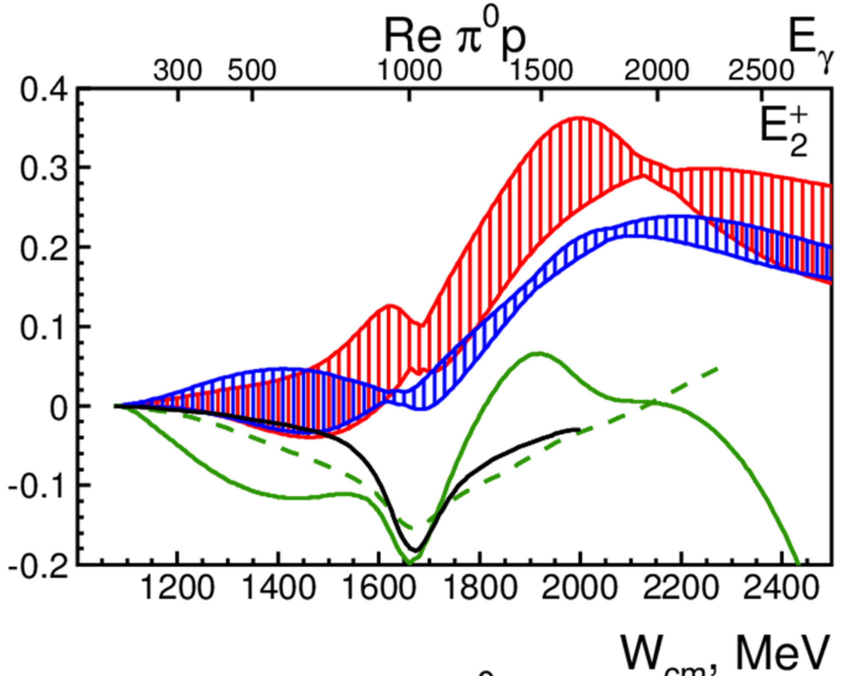
BnGa, *A.Sarantzev et al*, **preliminary**

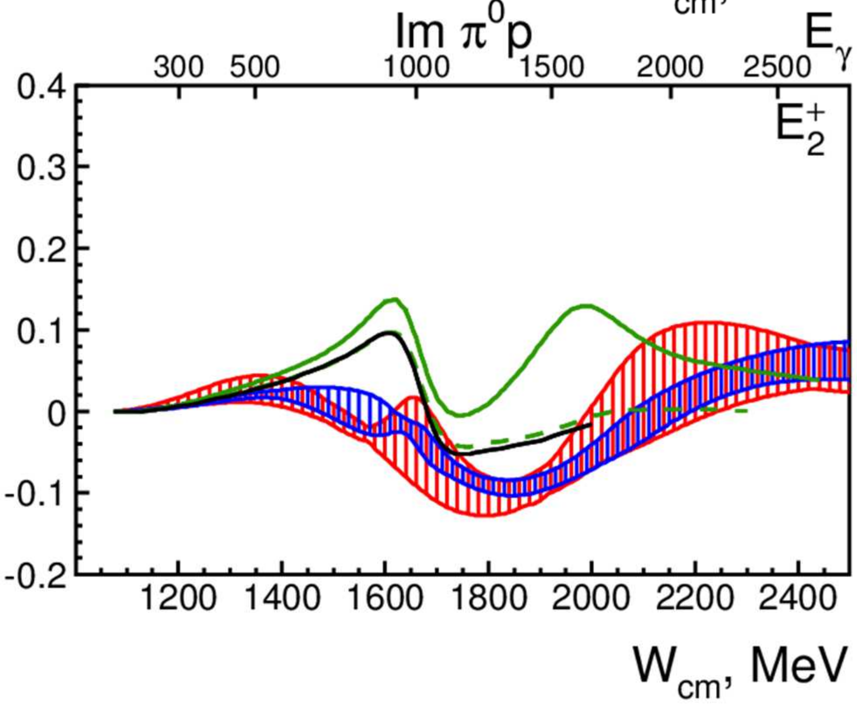
Preliminary: new BnGa energy dependent multipole solution including the new polarization data G,E,T,P and H

M1- Multipole

- M_{1-} multipole
  $P_{11}(1440)$, $P_{11}(1710)$, $P_{31}(1910)$

$p\pi^0$: Impact of the new polarization data





BnGa (old)

BnGa(new)

MAID

SAID(SN11)

SAID(CM12)

BnGa, *A.Sarantzev et al*, **preliminary**

Preliminary: new BnGa energy dependent multipole solution including the new polarization data G,E,T,P and H

E2+ Multipole

- E_{2+} multipole
  $D_{15}(1675)$

$p\pi^0$: Impact of the new polarization data

- Energy independent fits to $\{\sigma_0, S, BT\}$ observables
  determine multipoles independently for each given energy

- Multipoles $E_{L\pm}$, $M_{L\pm}$ as fit parameters

- Truncated PWA up to multipole order L_{max}
  fixed model parametrizations for higher orders

Different energy ranges:

Preliminary results Crystal Ball at MAMI , *S. Schumann*

❶ π^0 threshold region:

- Determination of *s*, *p* wave multipoles — fitted up to $L_{max} = 1$
- Dataset: σ_0, Σ

❷ P_{33}(1232) region:

- Full determination of *s*, *p* wave multipoles — fitted up to $L_{max} = 1$
- Dataset: σ_0, Σ, T, F

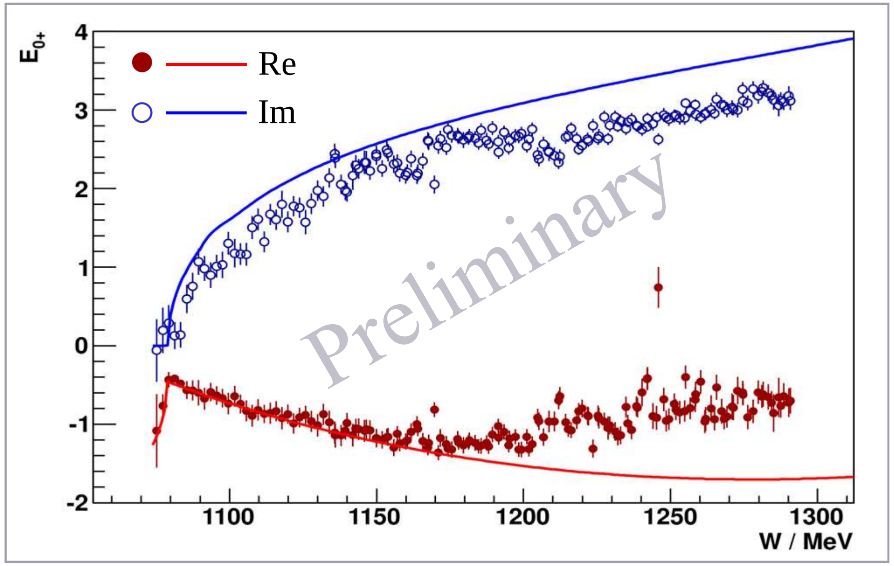
❸ Up to $W \sim 1.9$ GeV:

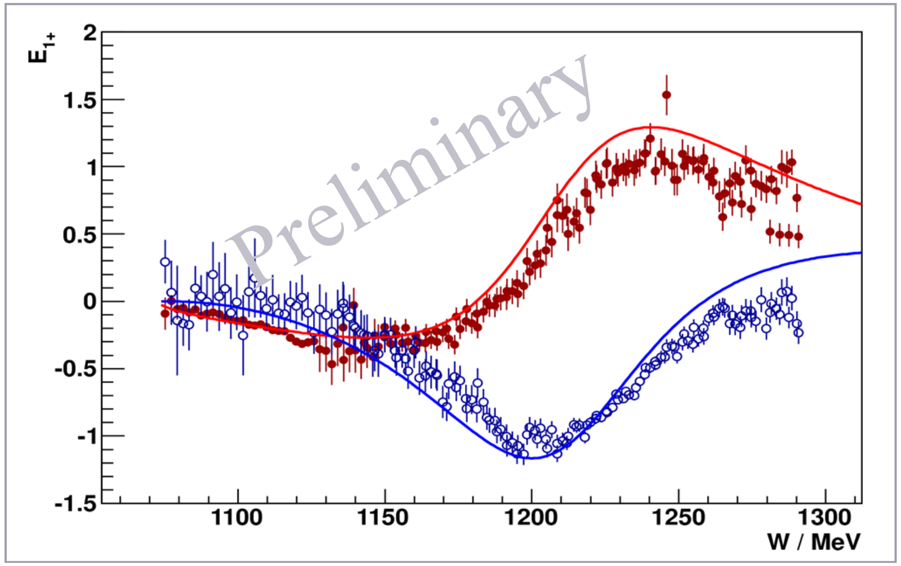
- Full determination of *s*, *p*, *d, f* wave multipoles — fitted up to $L_{max} = 3$
- Dataset: σ_0, Σ, T, E, F, G

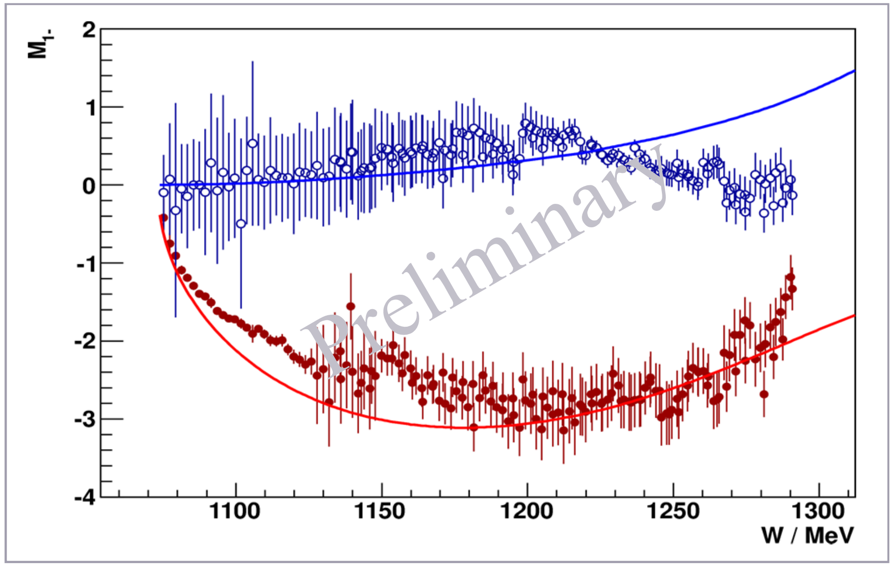
$p\pi^0$: Impact of the new polarization data

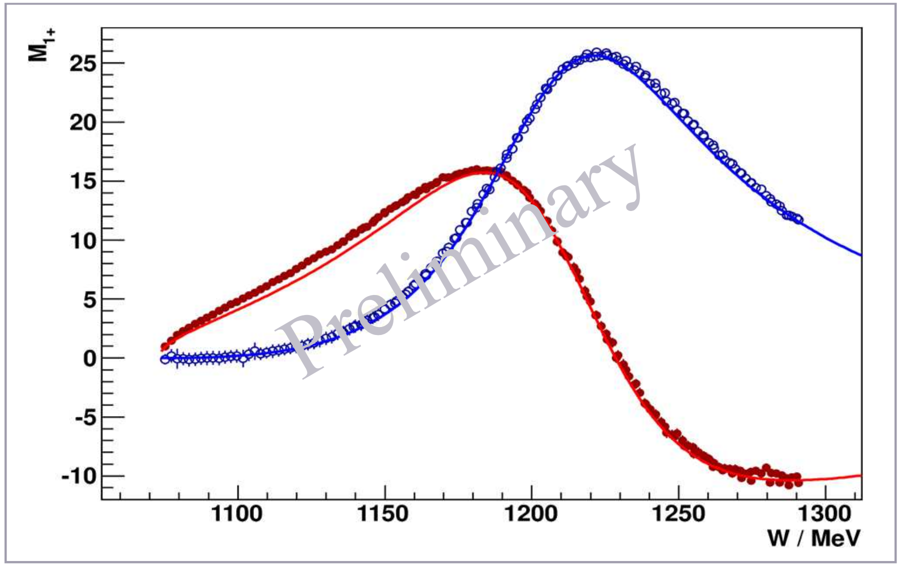
E_{0+} and E_{1+}, M_{1-}, M_{1+} multipoles
Energy independent fits & MAID

Preliminary results Crystal Ball at MAMI , *S. Schumann*





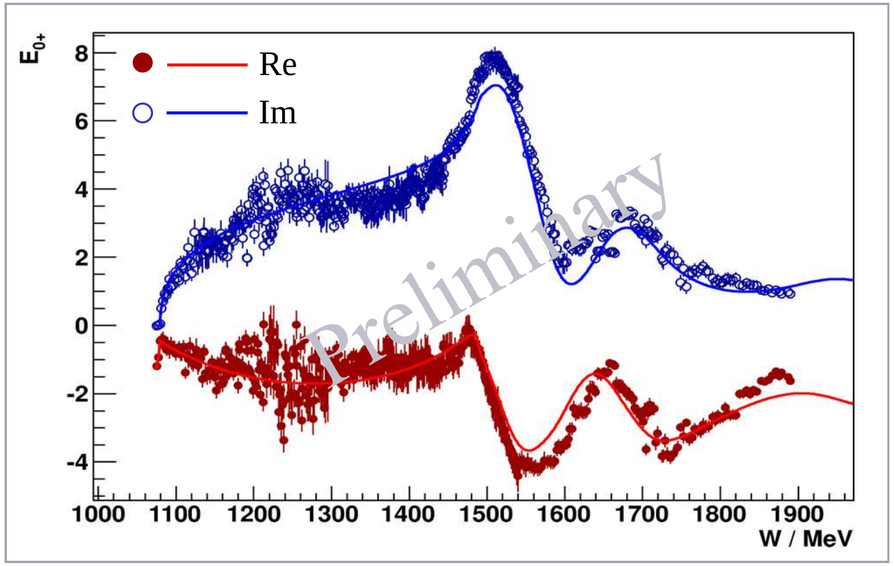


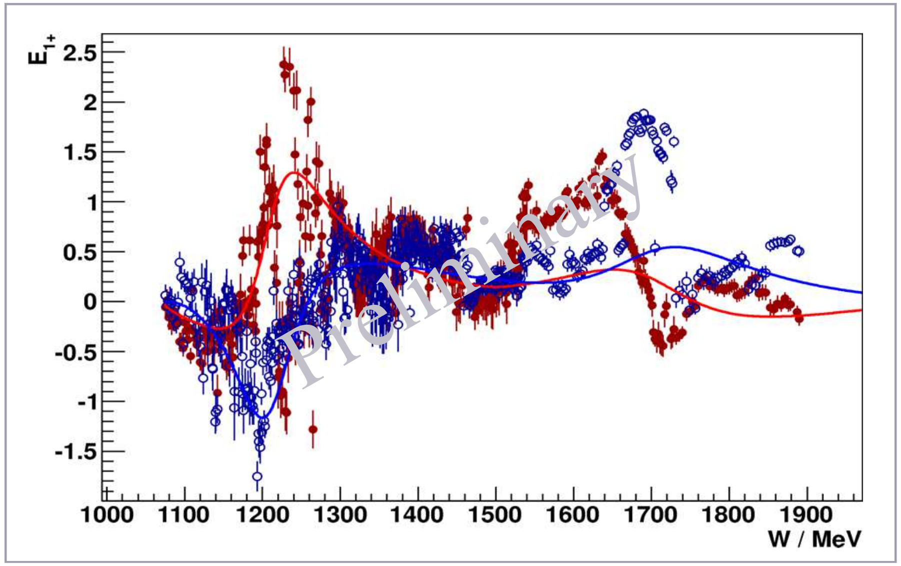


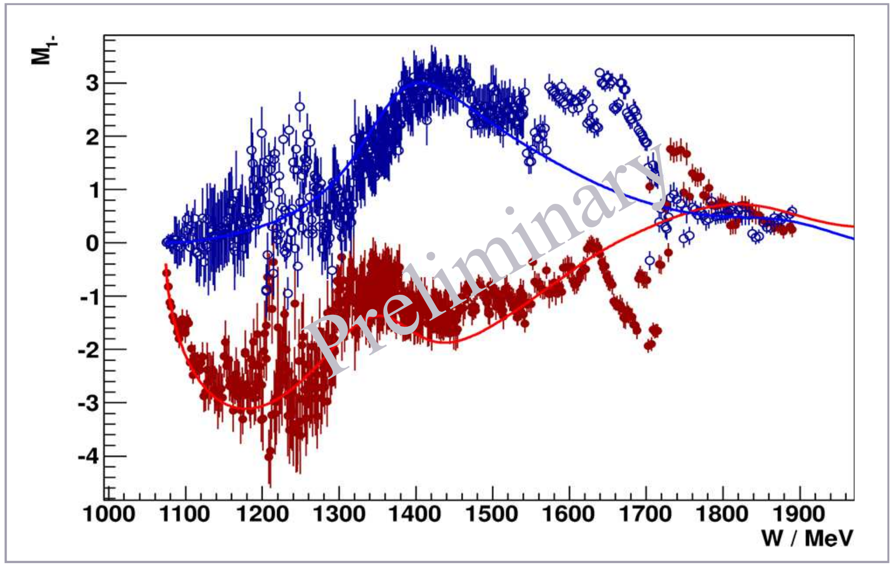
$p\pi^0$: Impact of the new polarization data

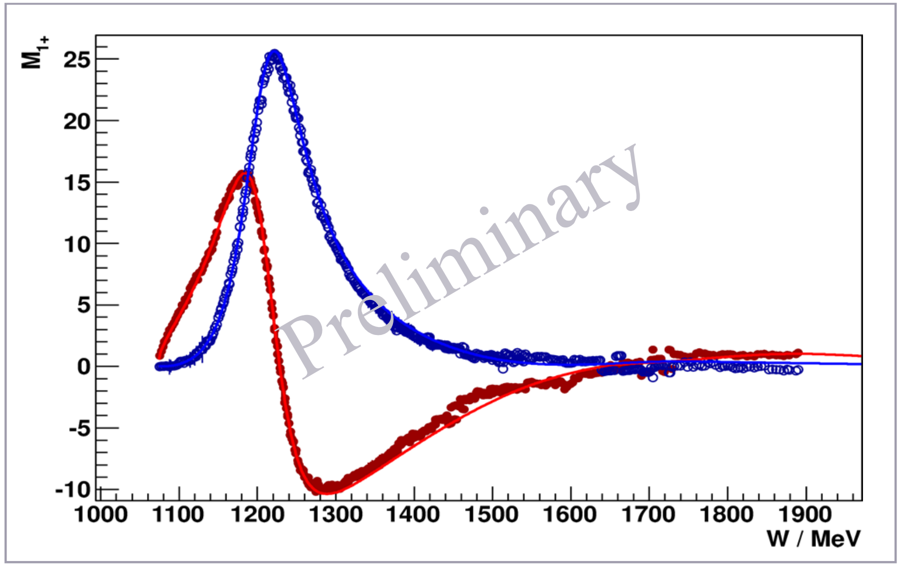
E_{0+} and E_{1+}, M_{1-}, M_{1+} multipoles
Energy independent fits & MAID

Preliminary results Crystal Ball at MAMI , *S. Schumann*









Status on Baryon Resonances

- Multi-channel BnGa partial wave analysis, including data from Crystal Barrel/TAPS at ELSA and other labs
  - confirmation of known resonances
  - search for new resonances

- Results from meson- photoproduction do now enter the PDG and determine the properties of baryon resonances

	PDG 2010	BnGa-PWA	PDG 2012	GWU'06
$N(1860)5/2^+$		*	**	
$N(1875)3/2^-$		***	***	
$N(1880)1/2^+$		**	**	
$N(1895)1/2^-$		**	**	
$N(1900)3/2^+$	**	***	***	no evidence
$N(2060)5/2^-$		***	**	
$N(2150)3/2^-$		**	**	
$\Delta(1940)3/2^-$	*	*	**	no evidence

Summary and Outlook

- First precise double polarization data are coming out now from ELSA, Jlab, MAMI, …
  - polarization observables are essential to get unique PWA- solution
  - full angular coverage and precision is important (for high L)
  - different final state are important
- Impact of the new polarization data, for example $\vec{\gamma}\ \vec{p} \rightarrow p\,\pi^0$
  - the new polarization data constrain the possible multipole solutions
  - truncated partial wave analysis are possible
- In the high W-mass region the final states $p\,\eta$, $p\,\eta'$ and $K^+\Lambda$, $K^+\Sigma^0$ are important
  - the necessary precision in the data is still missing
- New polarization data have to be analyzed by the different PWA groups
  - systematic error, model dependence of resonance parameter extraction
- New polarization data will finally determine the nucleon excitation spectrum

Thank You