Baryon spectroscopy with the CBELSA/TAPS experiment
Recent results and future plans

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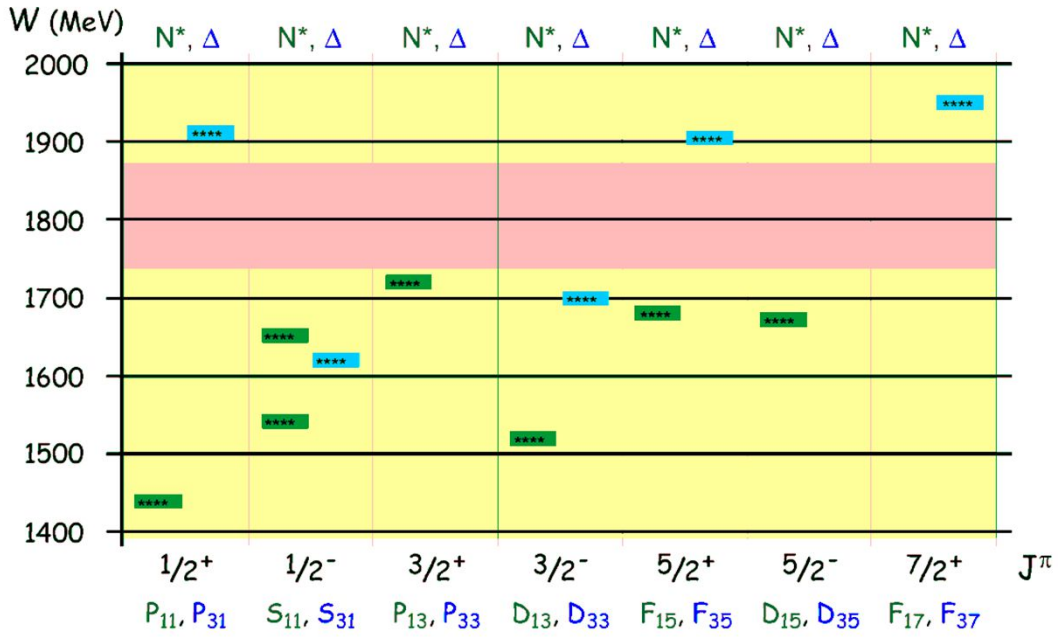
- Introduction
- Some highlights of the CBELSA/TAPS experiment
- Impact of the new polarization data
- Future plans of the CBELSA/TAPS experiment
- Summary

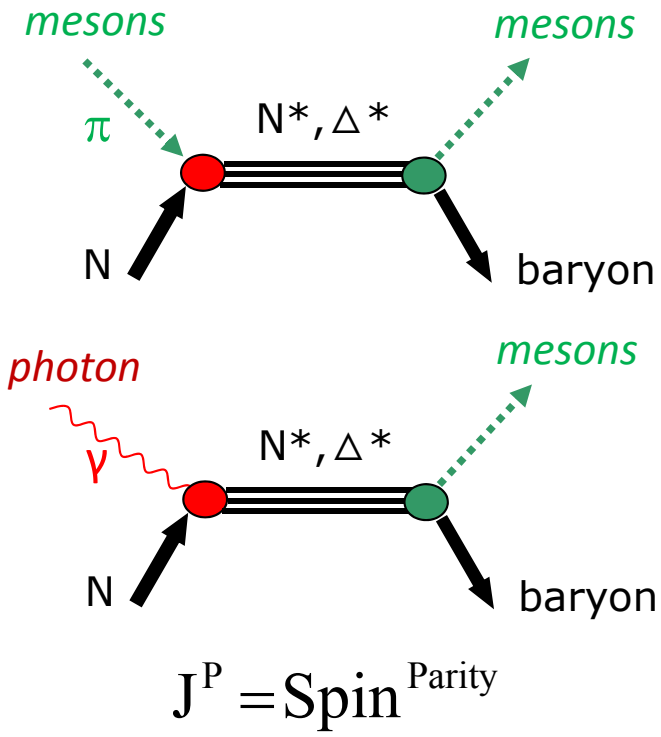
Introduction

Experiments at ELSA: focus on baryon spectroscopy, meson photoproduction

Excitation spectra: information about interaction and dynamics between constituents

Nucleon Excitation Spectrum





$$J^P = \text{Spin}^{\text{Parity}}$$

only 7 N* and 5 Δ* well established in the mass region 1400 MeV < W < 2000 MeV

- Energy pattern for the dominant states
  - Constituent Quark Models
  - Dynamic Models , Lattice QCD

Talk: U. Thoma

- Various nucleon models predict many more states
  - weak coupling to πN final state
  - incomplete data base

Talk: D. Rönchen

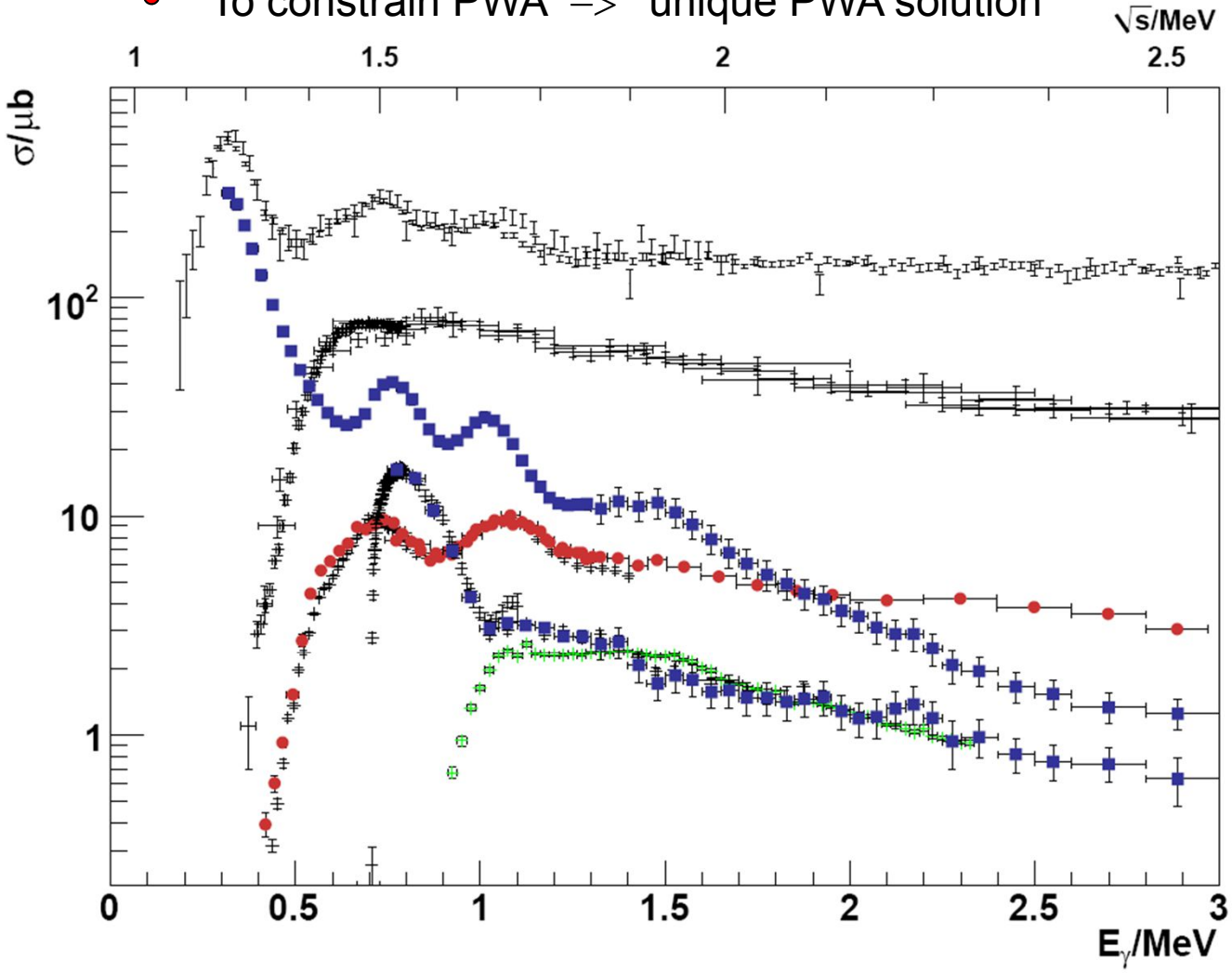
Experimental program for N*

Common effort at ELSA (Bonn), JLab (USA) and MAMI (Mainz)

Talk: D. Carman

Talk: P. Pedroni

- 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



$\gamma + p \rightarrow X$

$\gamma + p \rightarrow p + \pi^- + \pi^+$

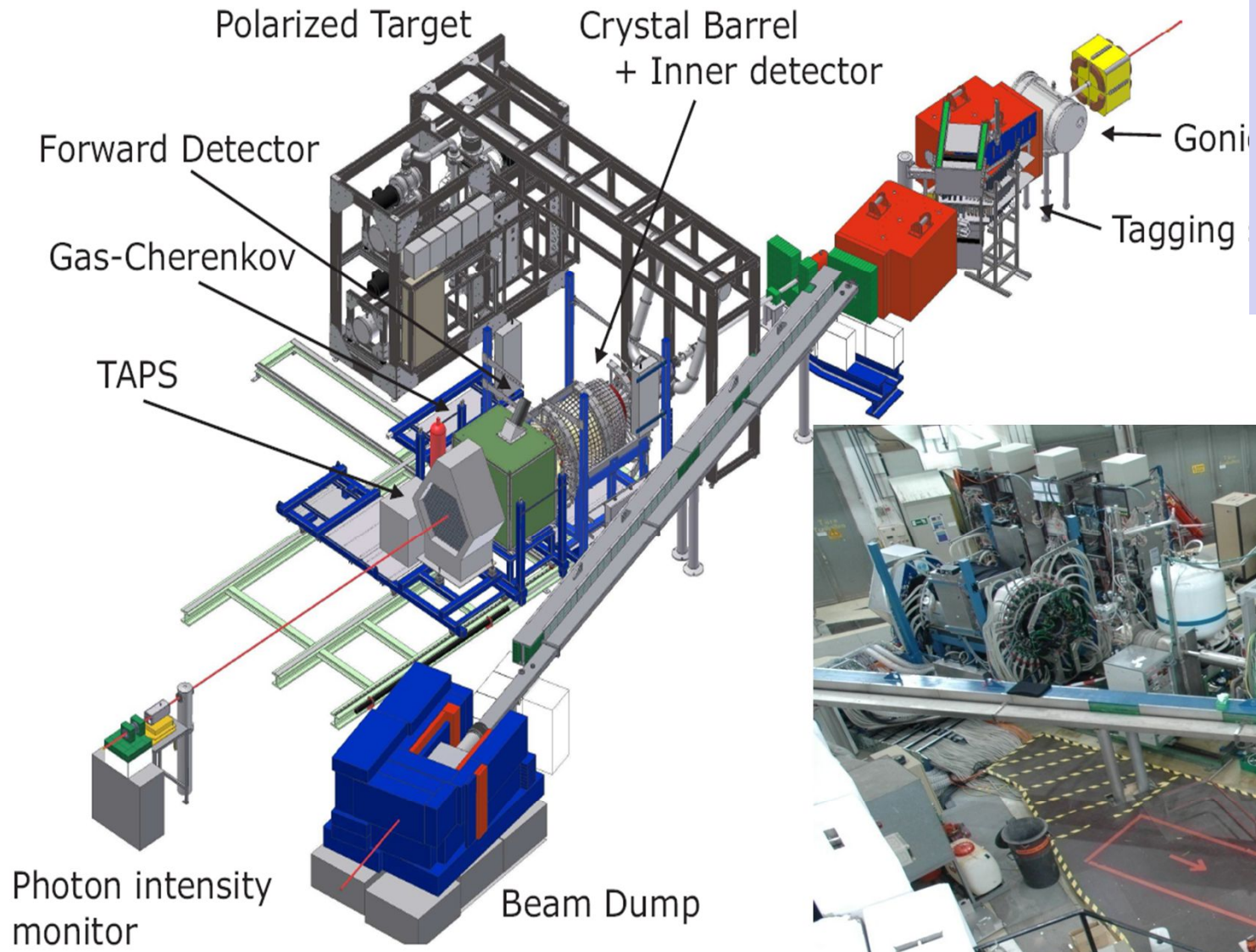
$\gamma + p \rightarrow p + \pi^0 + \pi^0$

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

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

$\gamma + p \rightarrow p + \eta$

CBELSA/TAPS Experiment

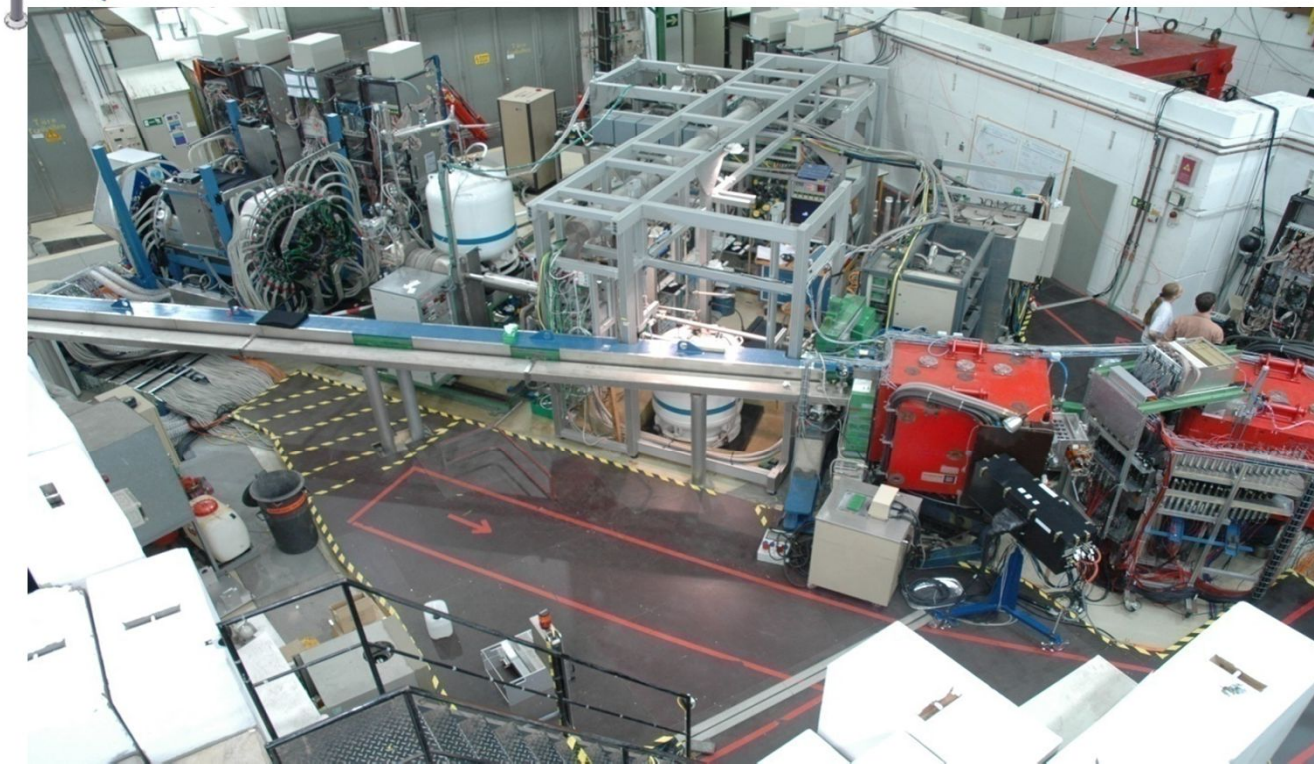


Important:

Polarized beam from ELSA

Polarized targets

4π detector setup



Polarized Photons at ELSA

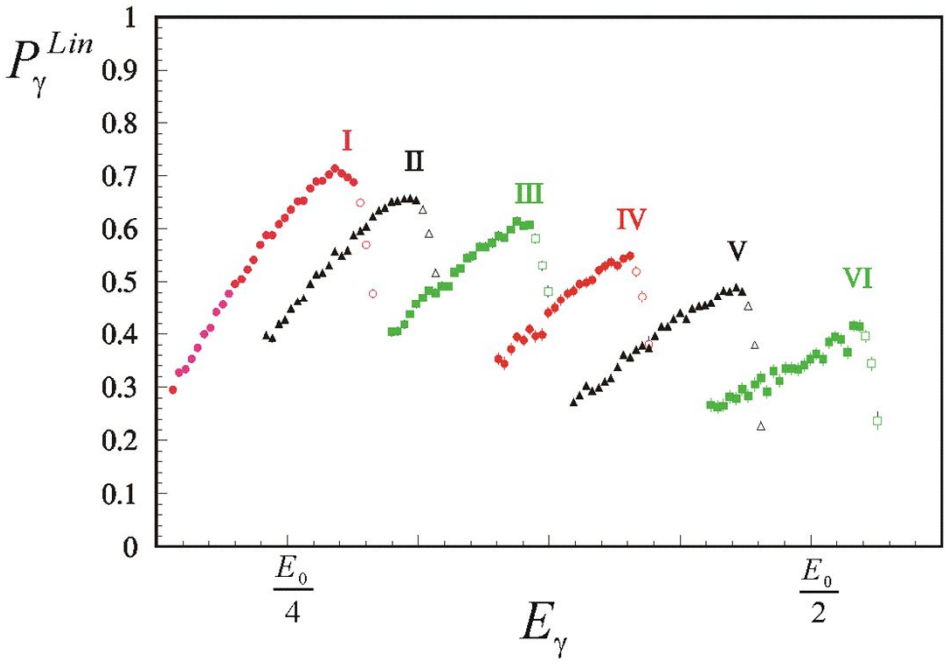
Linearly polarized photons:

- coherent bremsstrahlung
- diamond radiator

Circularly polarized photons:

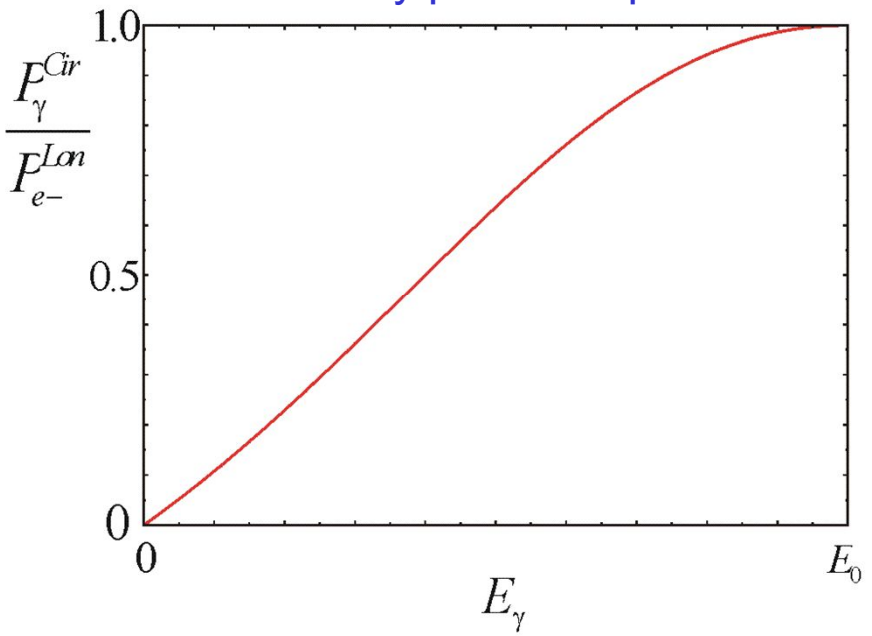
- longitudinally polarized electrons
- helicity transfer to photon

Linearly polarized photons



high polarization at low photon energies

Circularly polarized photons



high polarization at high photon energies

Mainz- Dubna Polarized Target at ELSA

- Mainz-Dubna polarized target :

- $^{3}He^{4}He$ Dilution refrigerator (Mainz, JINR Dubna) based on Bonn Frozen spin target design
- Frozen spin target (25 mK at 0.6 T)
- Transverse holding coil (saddle coil at 1.2 K)
- Since 2010 in operation with the Crystal Ball at MAMI, since 2017
- Operated and maintained by Bonn, Bochum, Dubna and Mainz polarized target group (H. Dutz, G. Reichertz, Y. Usov and A. Thomas)

- Common effort of the Bonn, Bochum, Dubna and Mainz polarized target groups

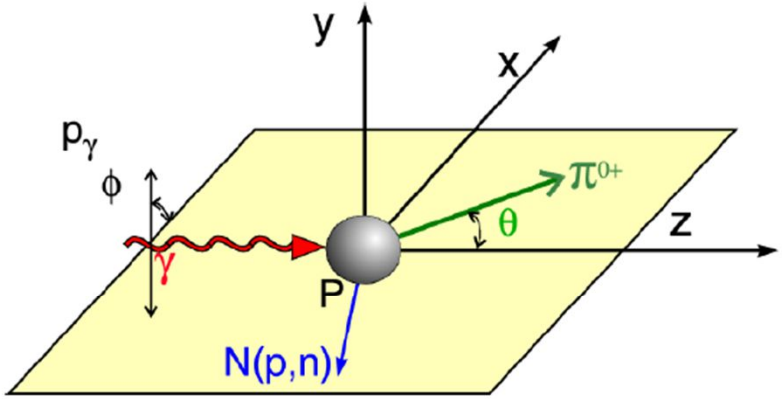
- New second $^{3}He^{4}He$ Dilution refrigerator at Bonn finished and under tests
- Corona and the Ukrainian war delayed the final tests

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		$-E$

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta) \cdot \Big[1 - P_\gamma^{lin}\,\Sigma(\theta)\cos(2\phi)$$

$$\phi) + P_\gamma^{circ}\,F(\theta)\big)$$

$$\phi) - T(\theta)\big)$$

$$) + P_\gamma^{circ}\,E(\theta)\big)\Big]$$

ELSA- Experiments:

Data on all three single pol. observables Σ, P , T and diff. cross section σ

and on four double polarization observables G , E and H and (F)

for $\vec{\gamma}\ \vec{p} \to p\,\pi^0$ and $p\,\eta$, $p\eta'$, $p\omega$, $p\pi^0\pi^0$, $p\pi^0\eta$, $K^0\Sigma^+$, ...

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 truncated PWA

  (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 observables 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
  - Different final states are important -> coupled PWA are essential

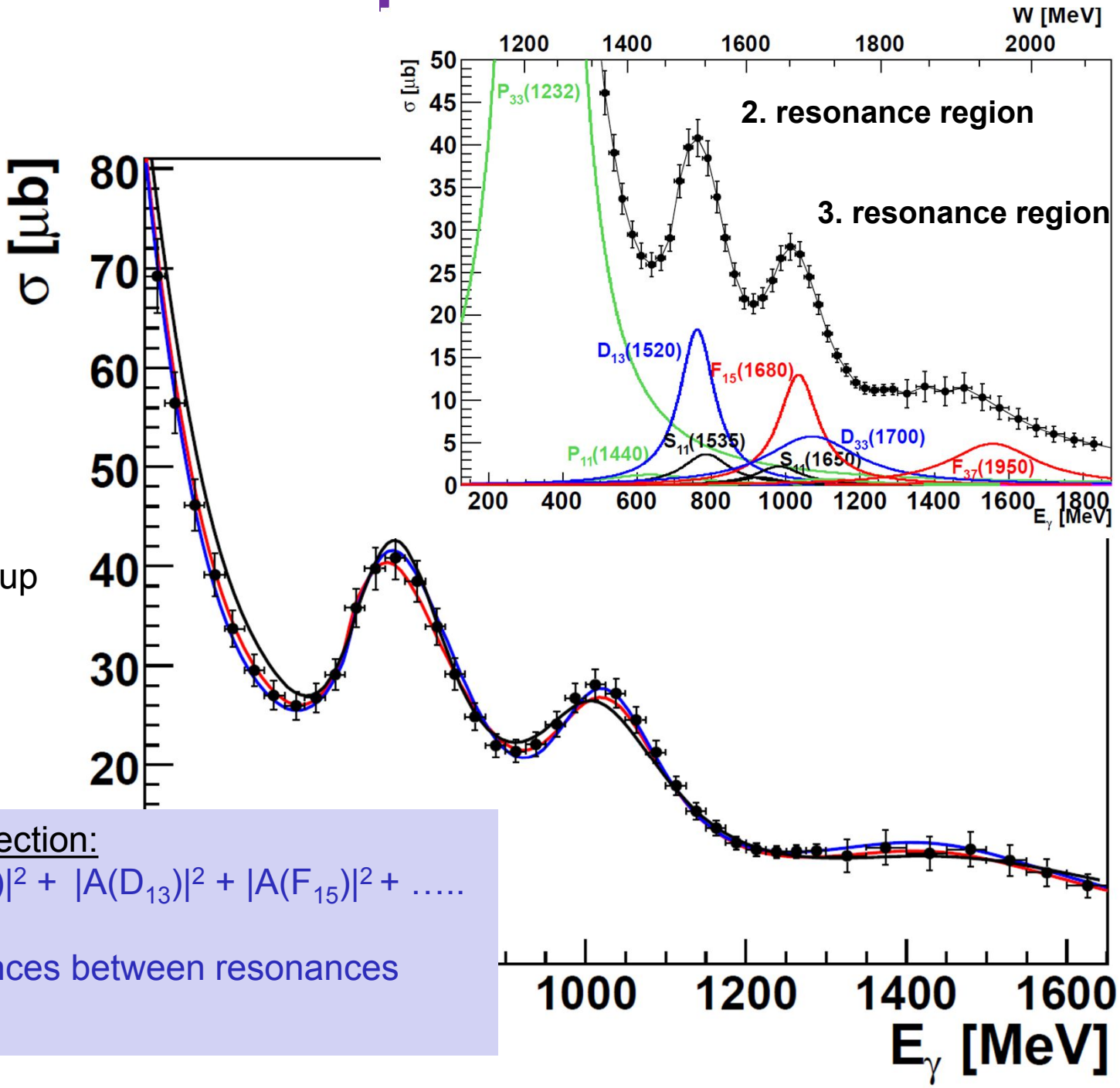
Problem with a Unique PWA Solution

Total cross section:

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

Partial wave analysis:

- BnGa — Bonn-Gatchina group
- SAID — Washington group
- MAID — Mainz group



Total cross section:

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

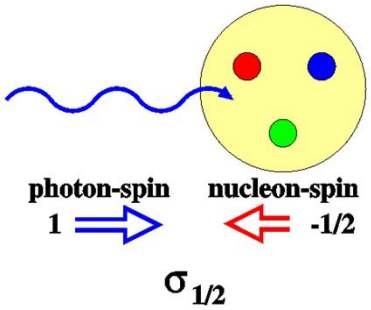
no interferences between resonances

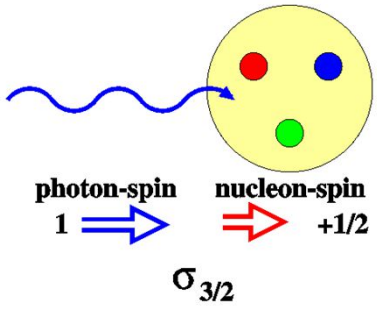
Helicity Dependent Cross Section for $p\pi^0$

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

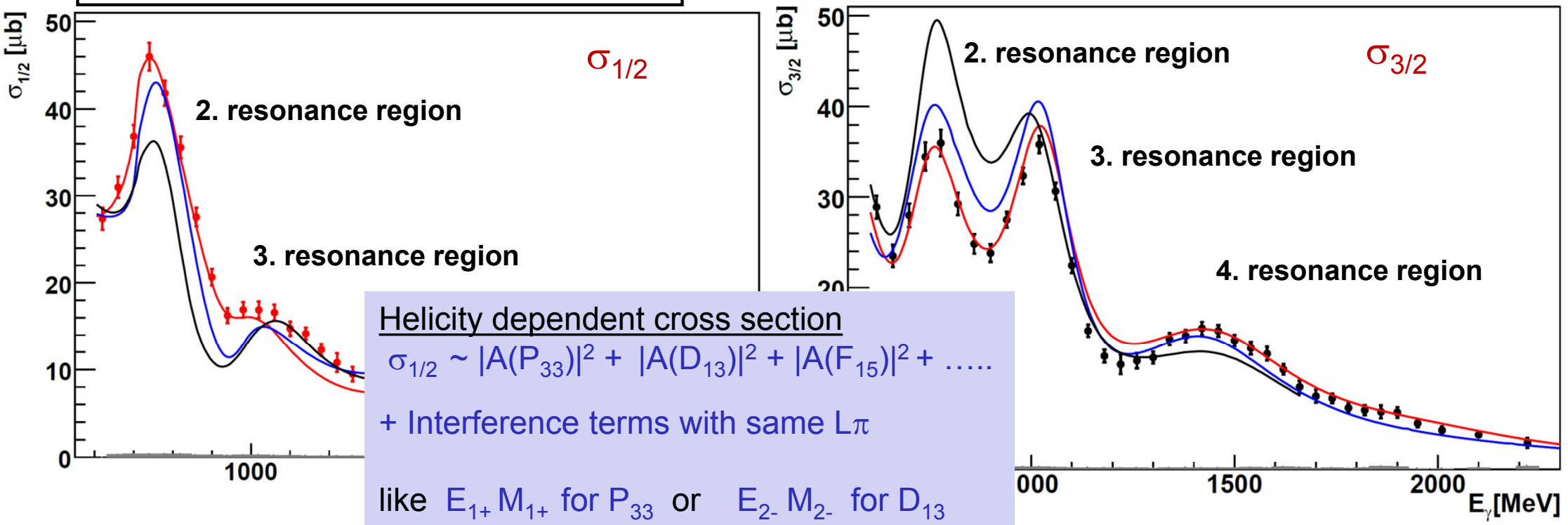
circularly polarized photons

longitudinally polarized proton





CBELSA/TAPS , *M. Gottschall, PRL 112 (2014), 012003*



Helicity dependent cross section

$\sigma_{1/2} \sim |A(P_{33})|^2 + |A(D_{13})|^2 + |A(F_{15})|^2 + \ldots..$

+ Interference terms with same $L\pi$

like $E_{1+}\, M_{1+}$ for P_{33} or $E_{2-}\, M_{2-}$ for D_{13}

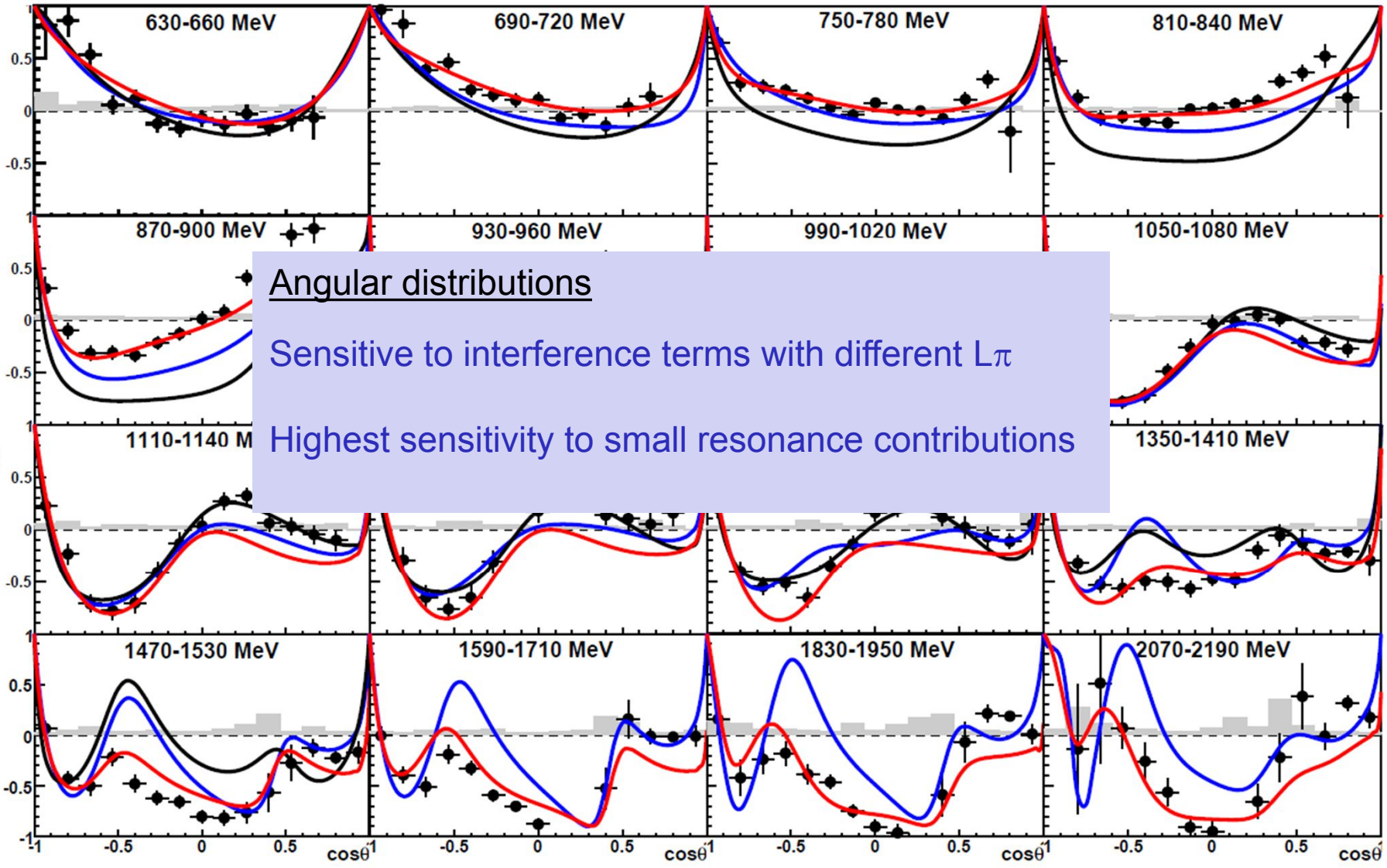
Partial wave analysis predictions : BnGa SAID MAID

CBELSA/TAPS: Helicity Asymmetry E for $p\pi^0$

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

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

CBELSA/TAPS, *M. Gottschall, PRL 112 (2014), 012003*



Angular distributions

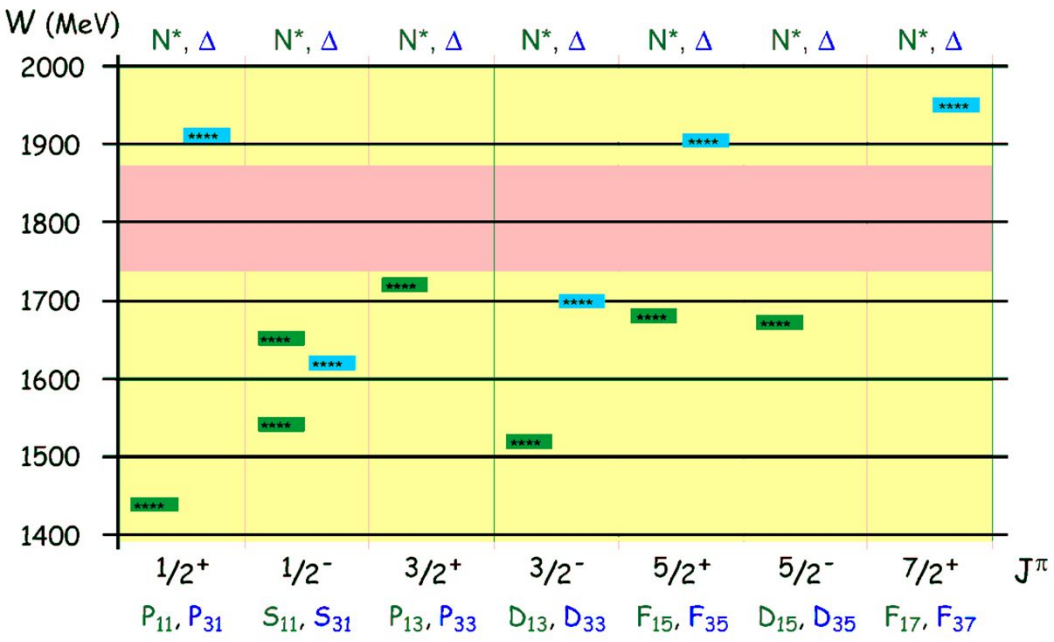
Sensitive to interference terms with different Lπ

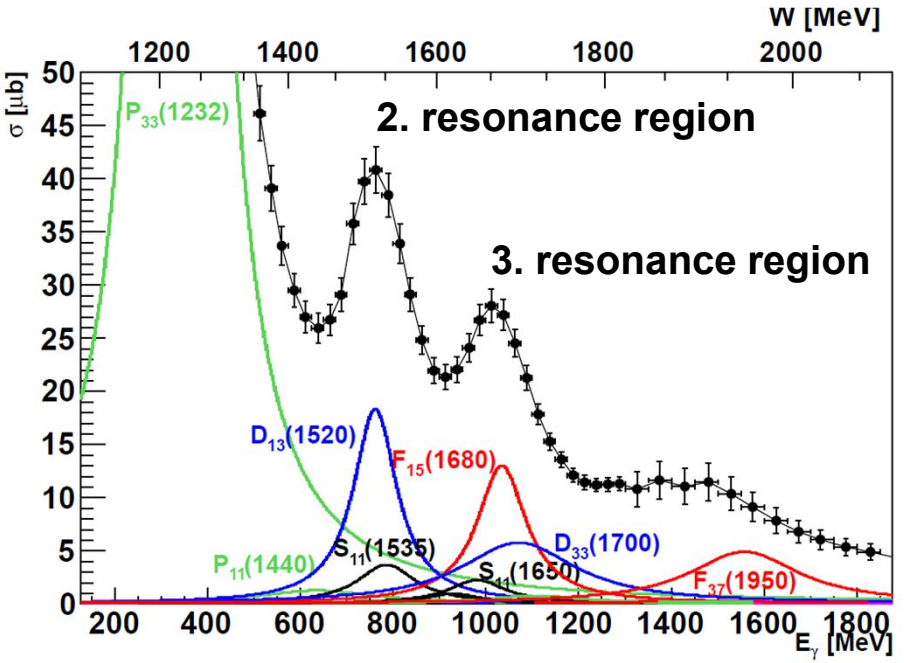
Highest sensitivity to small resonance contributions

Partial wave analysis prediction:

- BnGa
- SAID
- MAID

Impact of the new polarization data





Which L_{max} is seen in the new polarization 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: $P_{11}(1440)$, $P_{13}(1710)$, $P_{33}(1232)$, $P_{31}(?)$,

L_{max} = 2 , D-wave , resonances in D-wave: $D_{13}(1520)$, $D_{15}(1680)$, $D_{33}(1700)$, $D_{35}(?)$,

L_{max} = 3 , F-wave , resonances in F-wave: $F_{15}(1680)$, $F_{17}(?)$, $F_{35}(?)$, $F_{37}(1950)$

L_{max} = 4 , G-wave , resonances in G-wave: $G_{17}(?)$, $G_{19}(?)$, $G_{37}(?)$, $G_{39}(?)$

L_{max} Interpretation of T- Asymmetry

for L ≤ 1 : only S- and P- waves

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

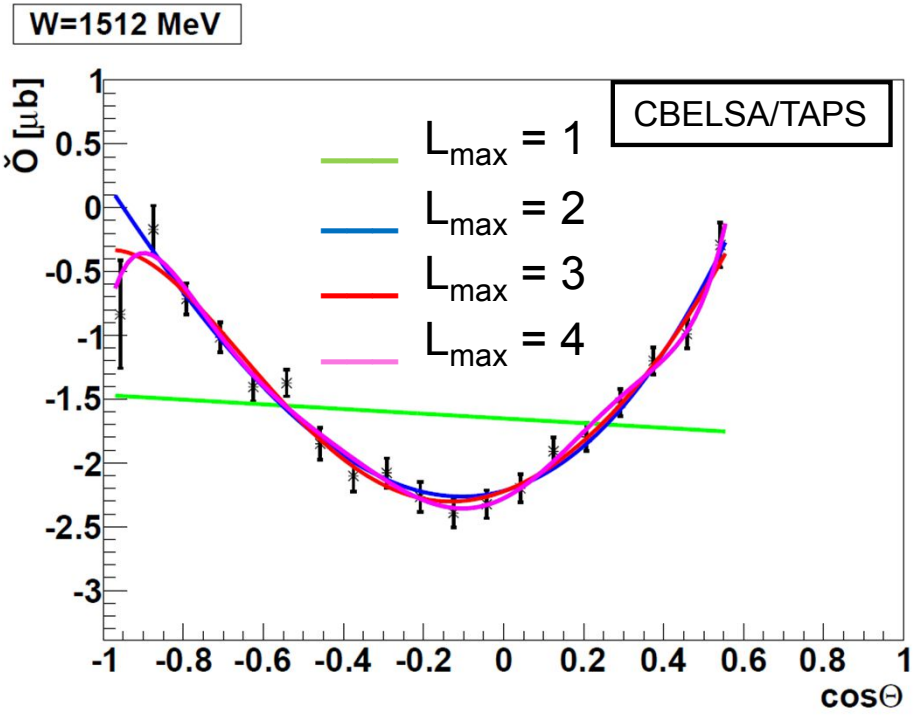
for L ≤ 2 : only S-, P- and D- waves

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

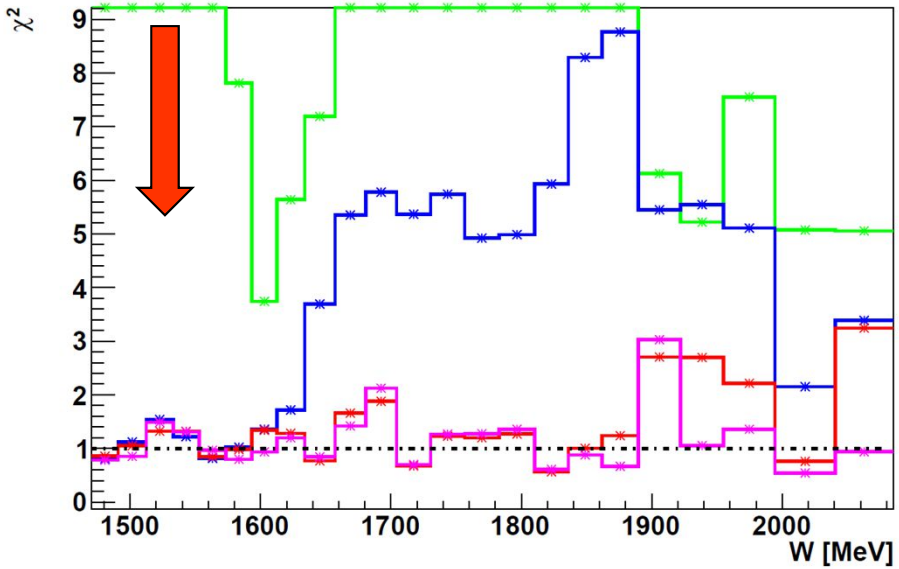
for L ≤ 3 : only S-, P-, D- and F- waves

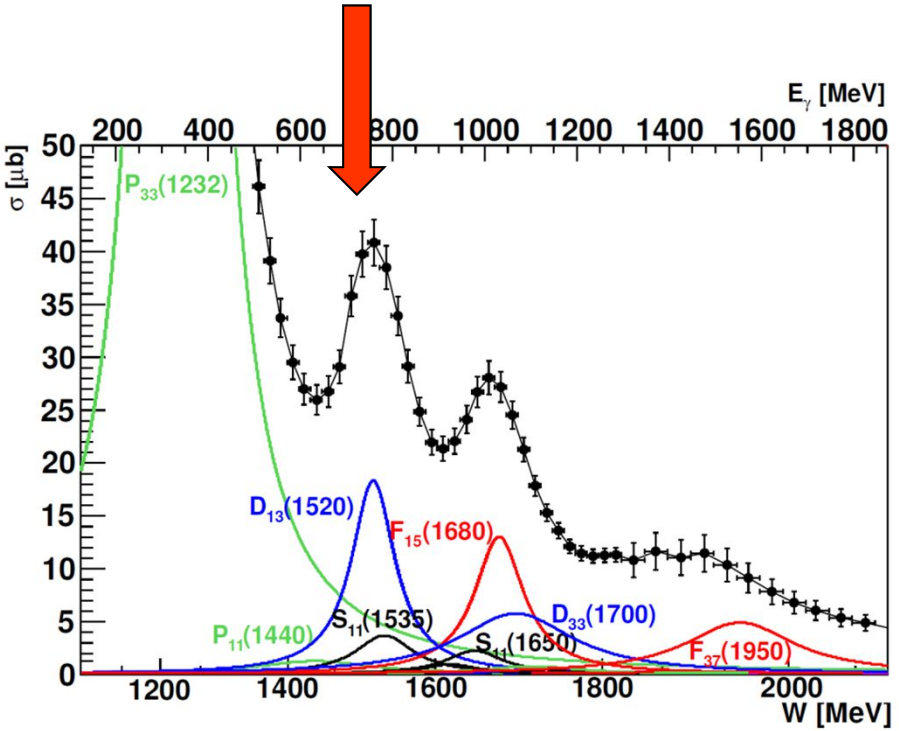
$$\overset{\vee}{T} = \frac{T \cdot \frac{d\sigma}{d\Omega}}{\sin^1(\theta)} = A_0 + A_1 \cdot \cos(\theta) + A_2 \cdot \cos^2(\theta) + A_3 \cdot \cos^3(\theta) + A_4 \cdot \cos^4(\theta) + A_5 \cdot \cos^5(\theta)$$

L_{max} Interpretation of T- Asymmetry



- Significant L = 3 signal seen above W = 1500 MeV
- Below L ≤ 2 seems to be sufficient
- Some indication for L = 4 signal above W = 1850 MeV





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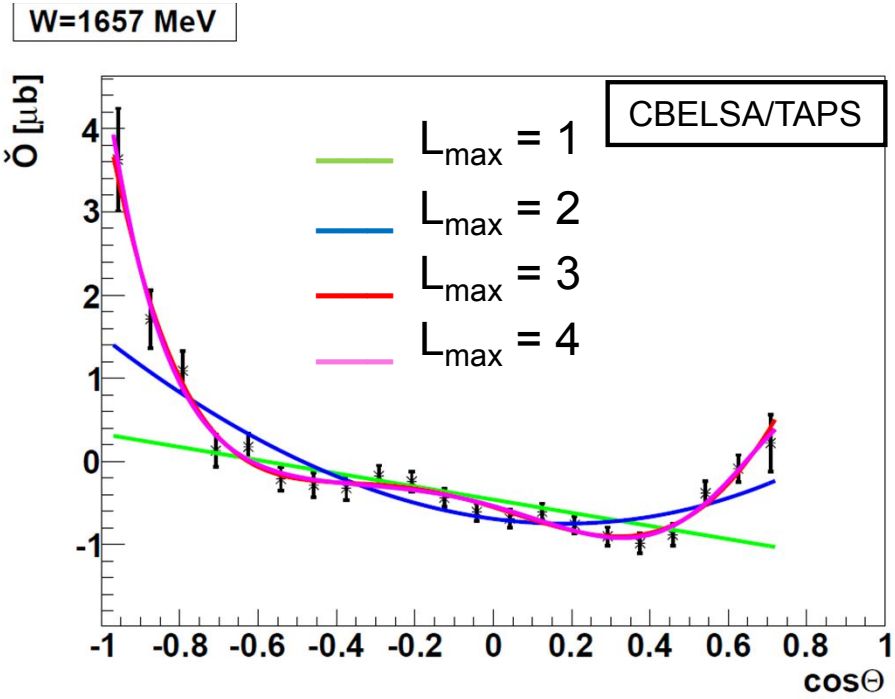

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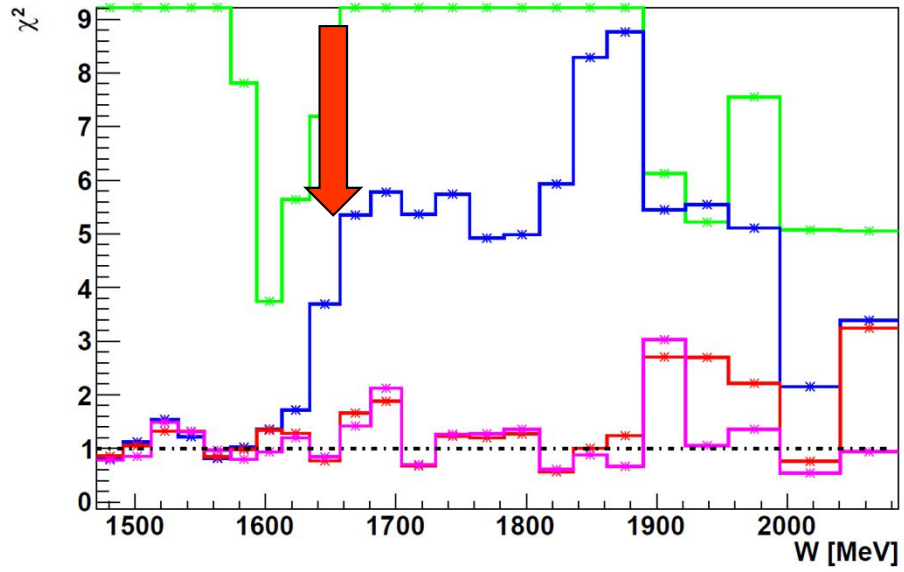

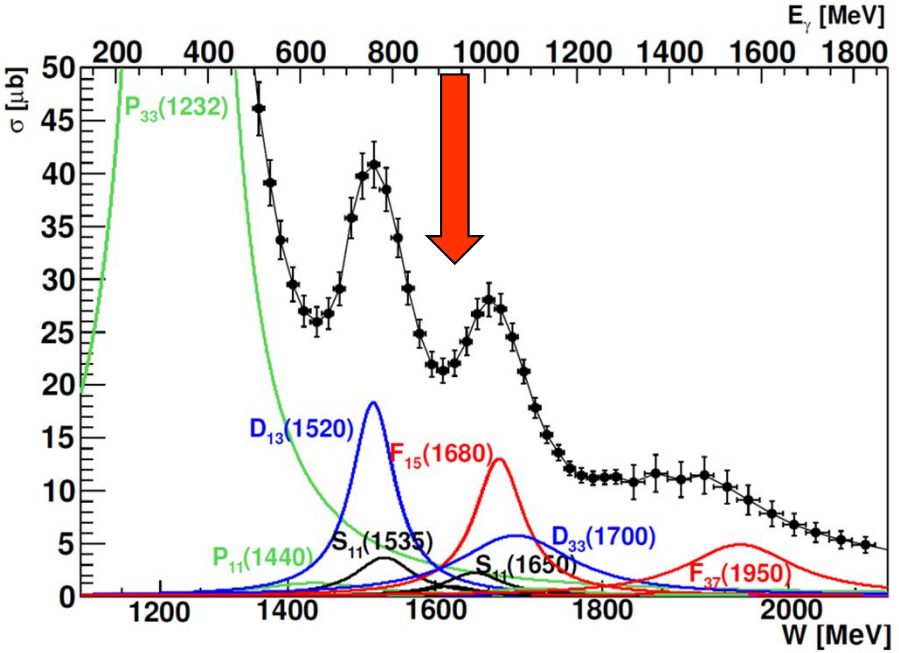

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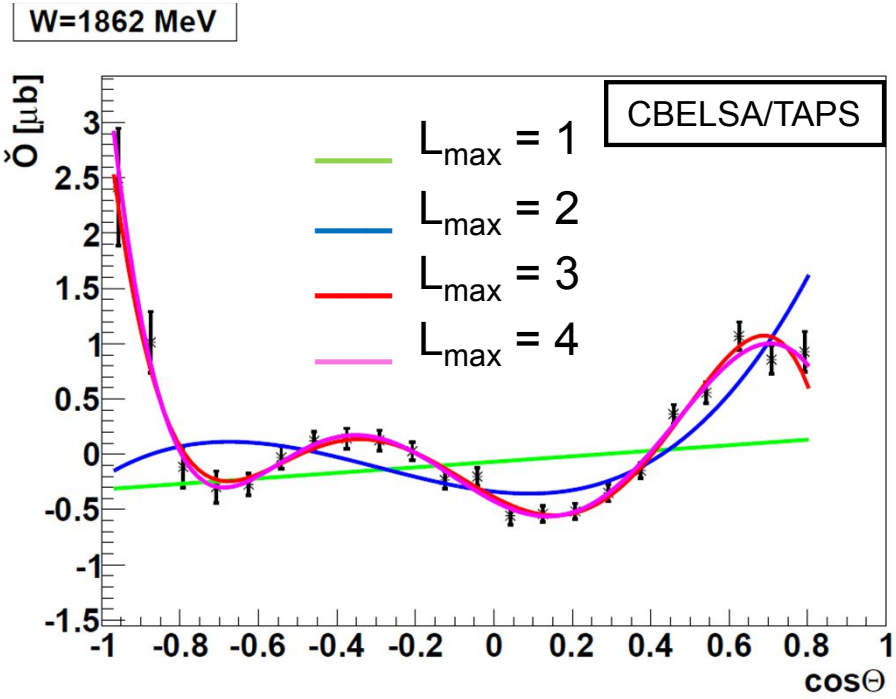

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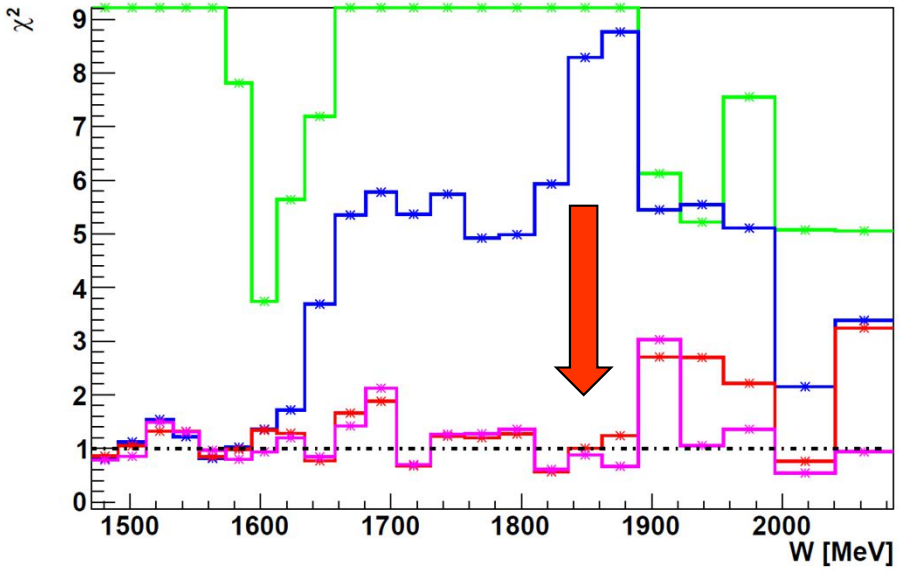
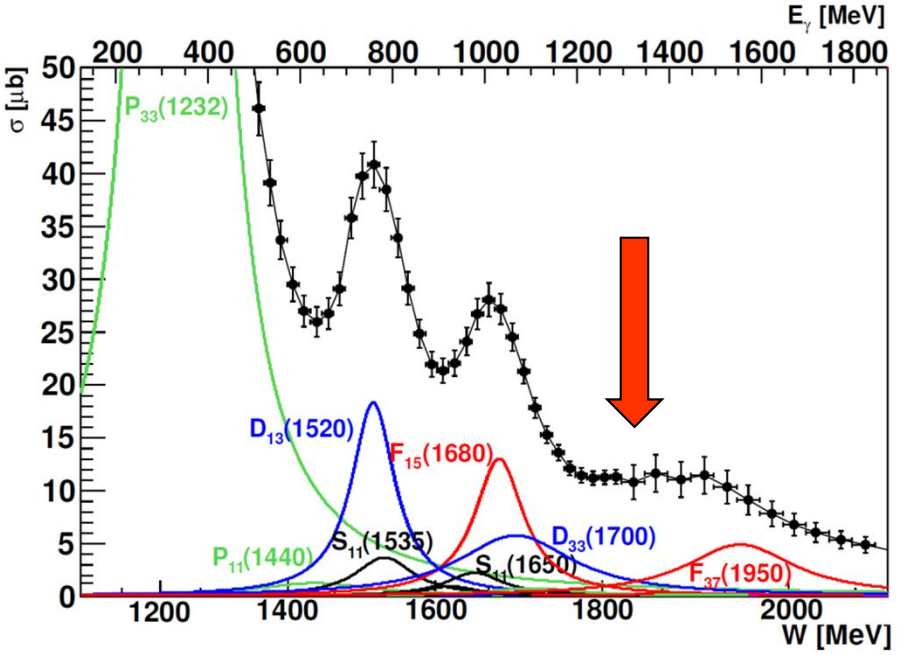
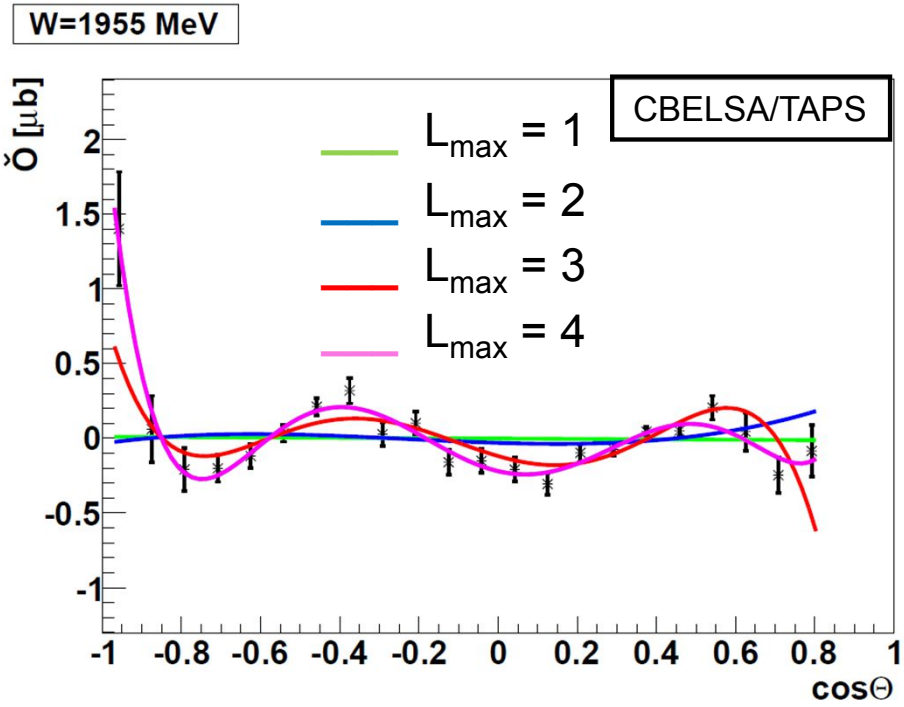




L_{max} Interpretation of T- Asymmetry



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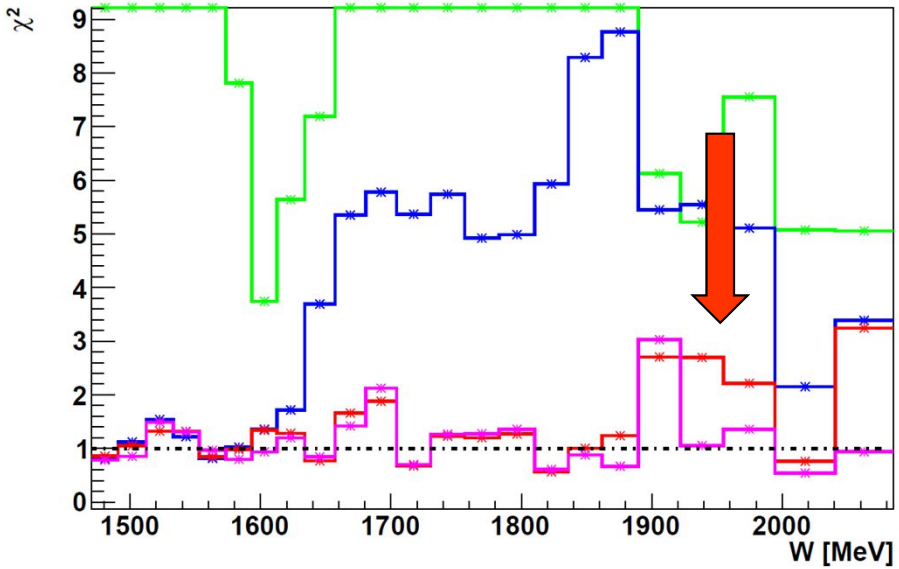
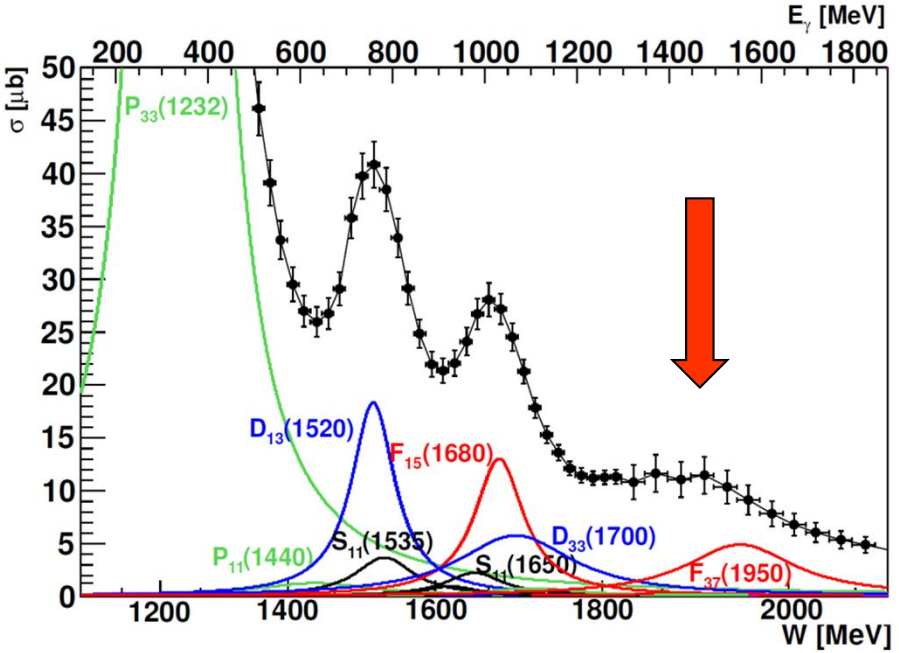
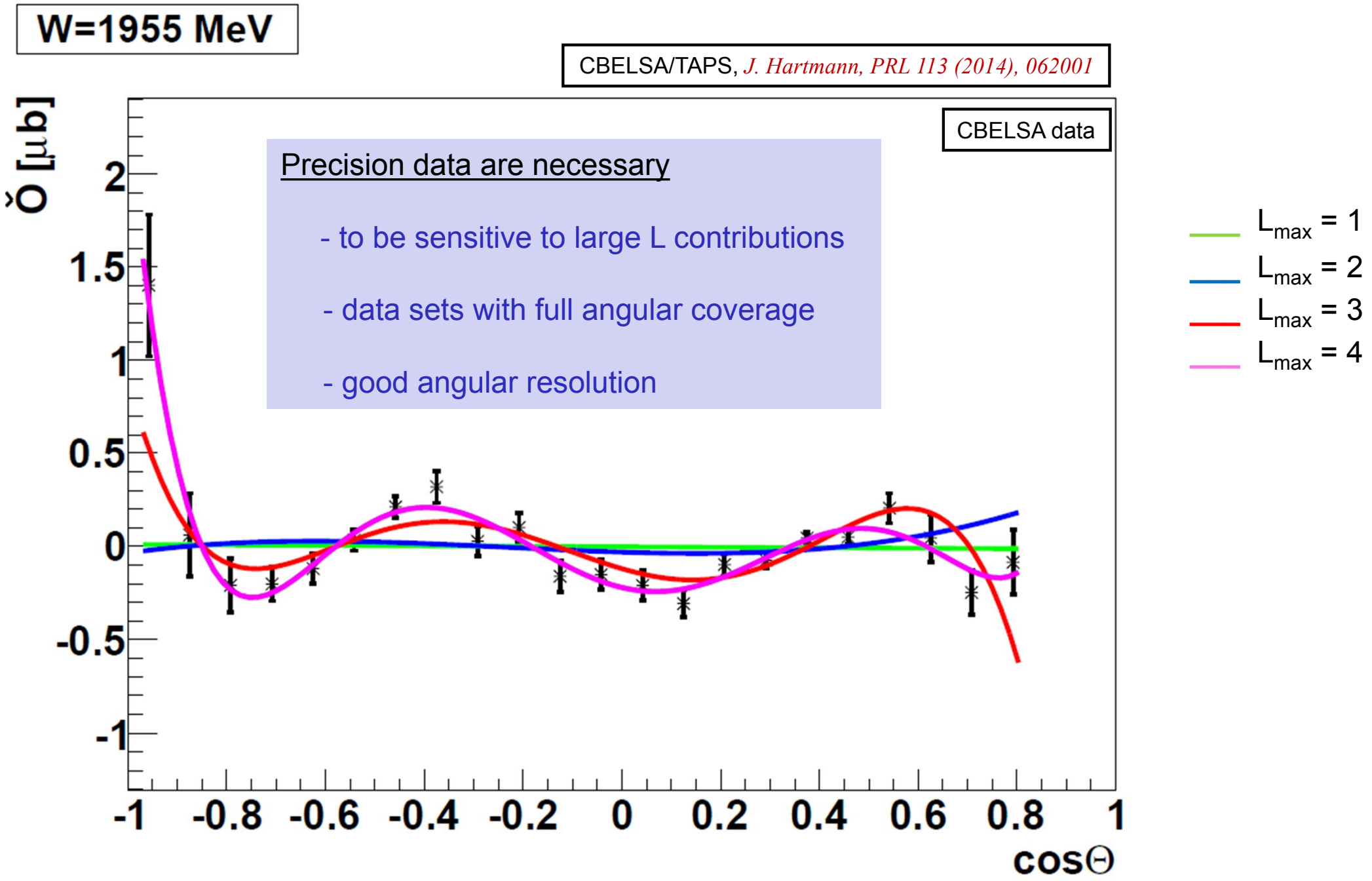
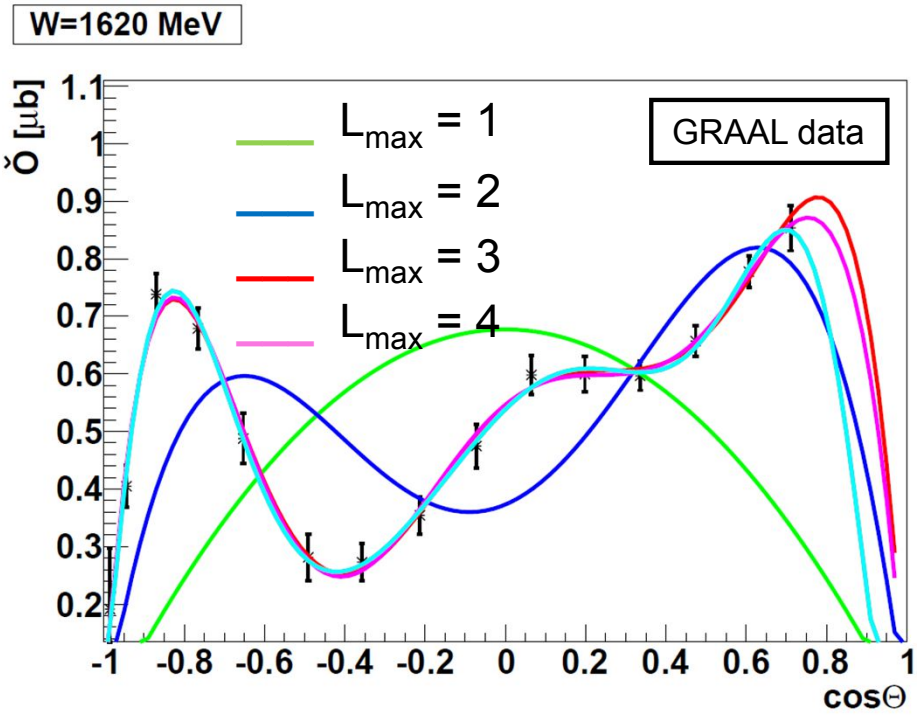




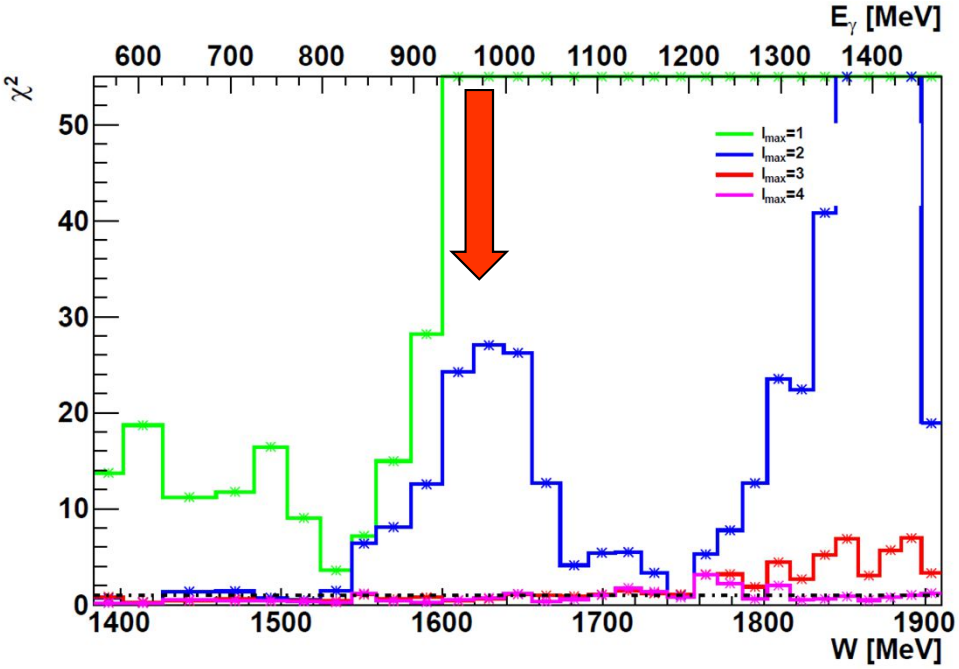
L_{max} Interpretation of T- Asymmetry

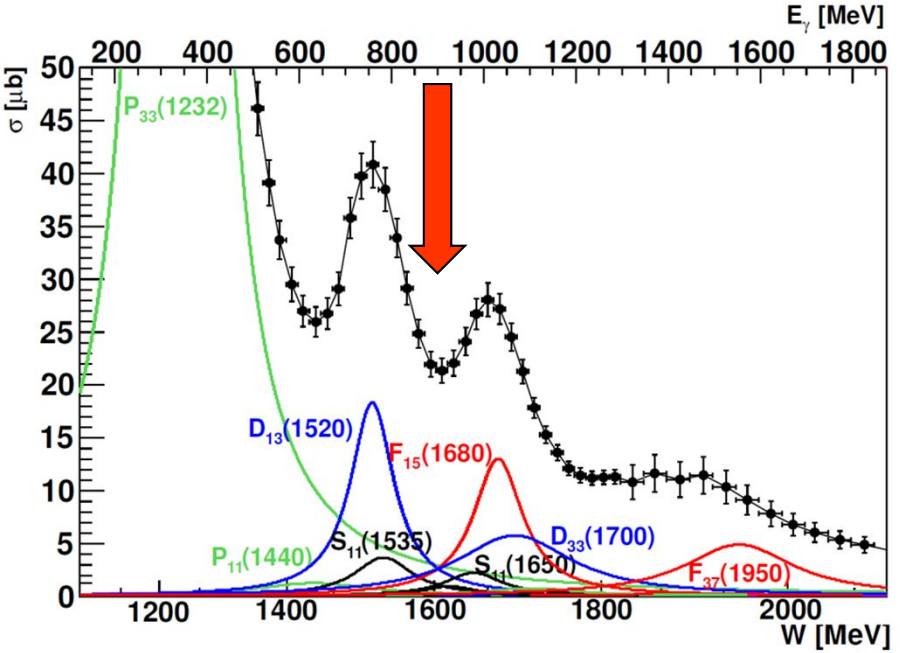


L_{max} Interpretation of Σ- Asymmetry

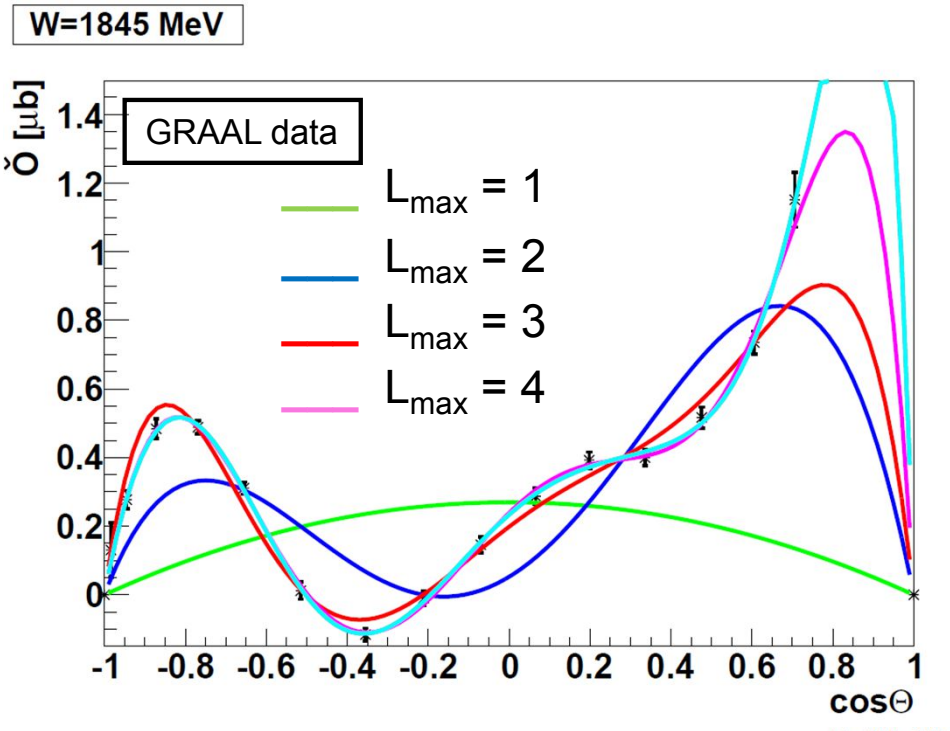


- Significant L = 3 signal seen above W = 1500 MeV
- Below L ≤ 2 seems to be sufficient
- L = 4 signal above W = 1750 MeV





L_{max} Interpretation of Σ- Asymmetry



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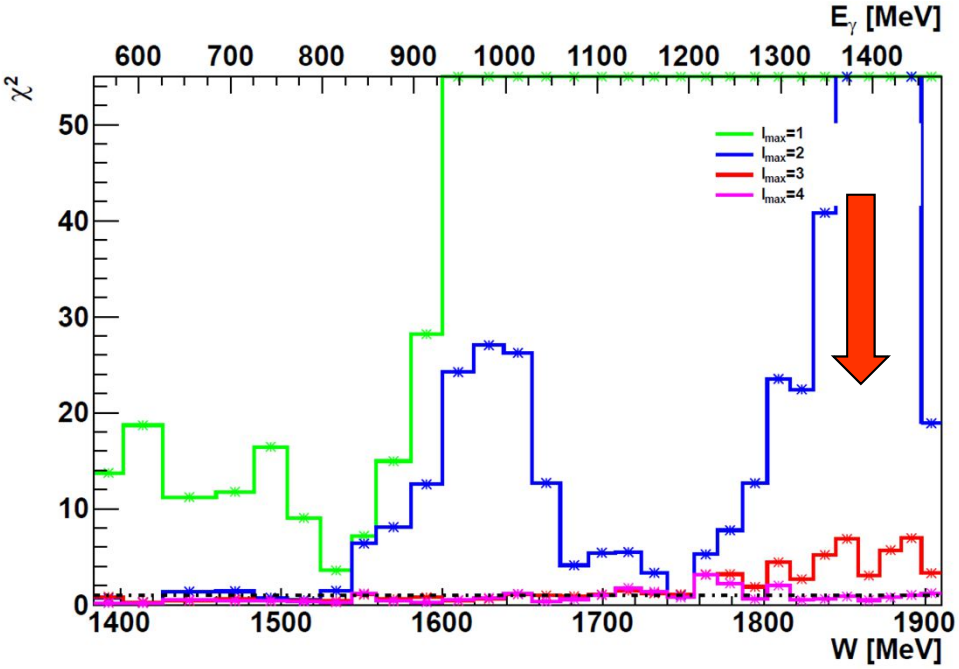
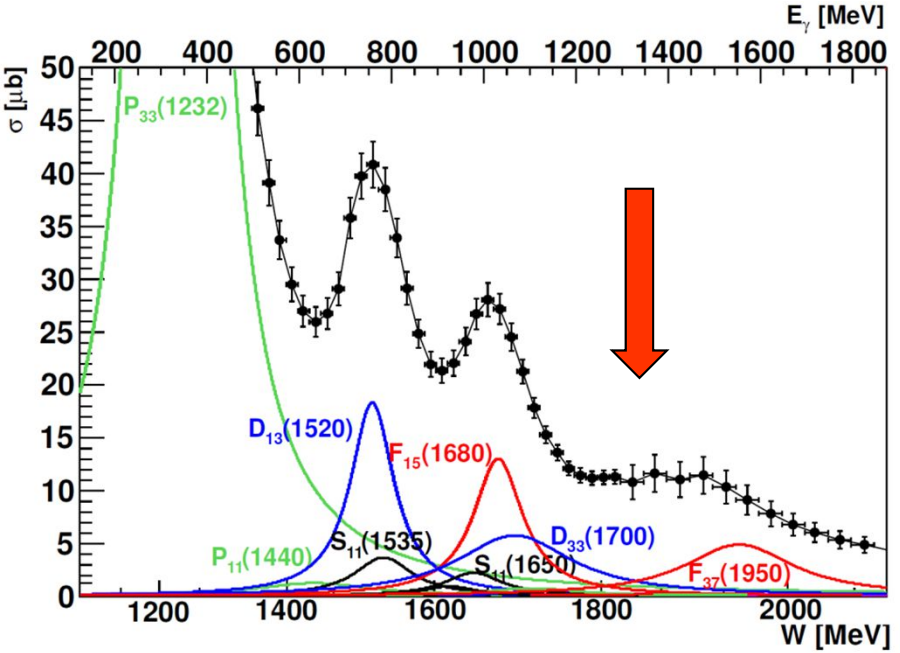
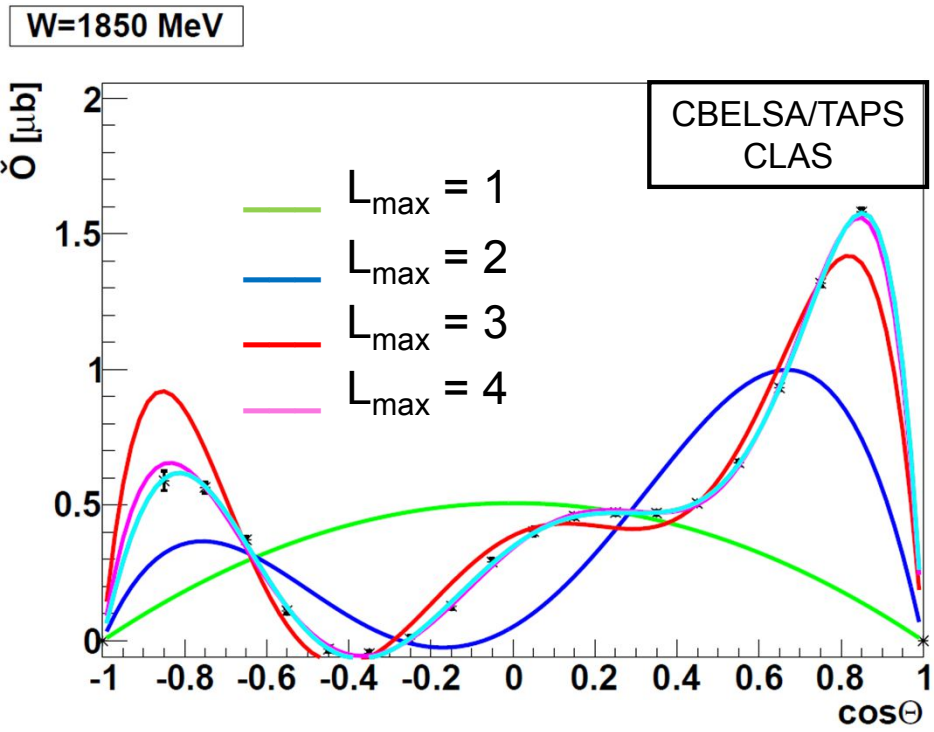


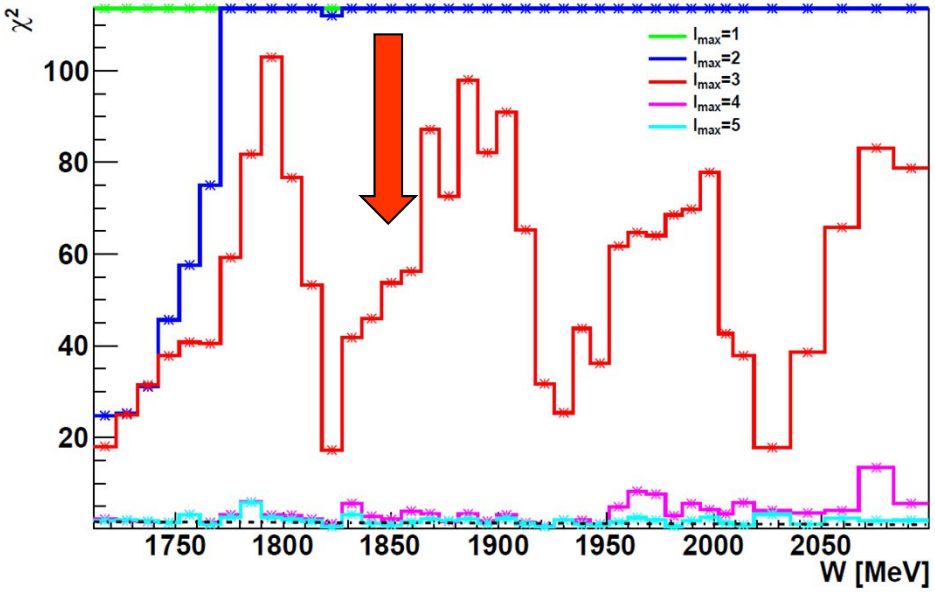


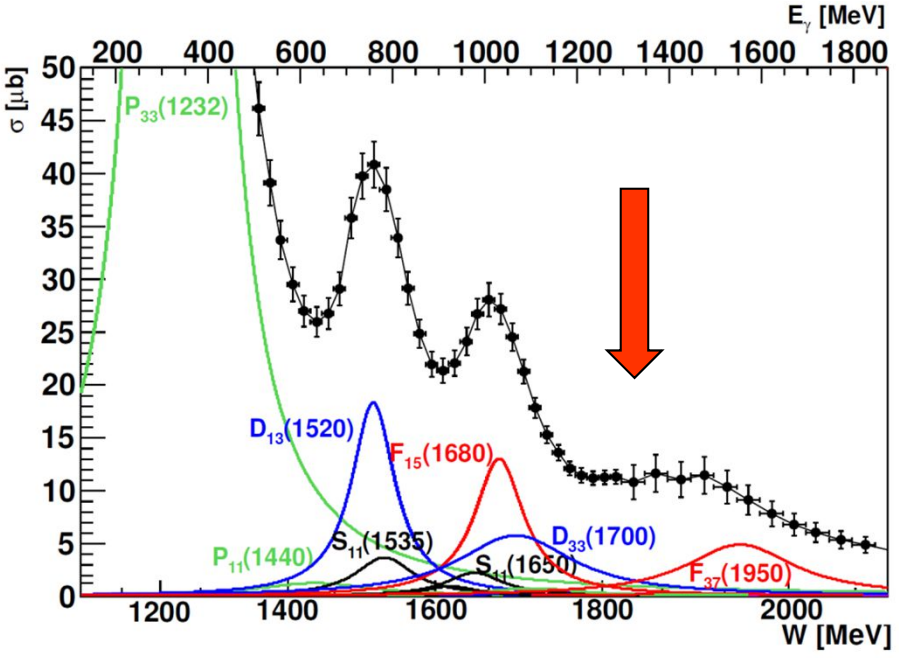
L_{max} Interpretation of Σ- Asymmetry



- Significant L = 3 signal seen above W = 1500 MeV
- Below L ≤ 2 seems to be sufficient
- L = 4 signal above W = 1700 MeV

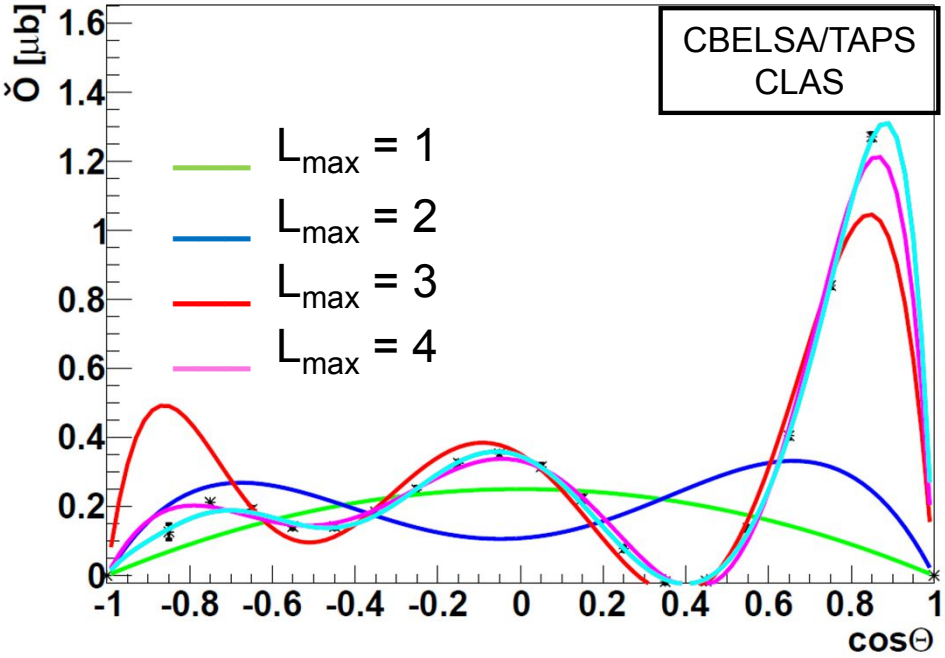
High precision data for Σ from CBELSA/TAPS CLAS





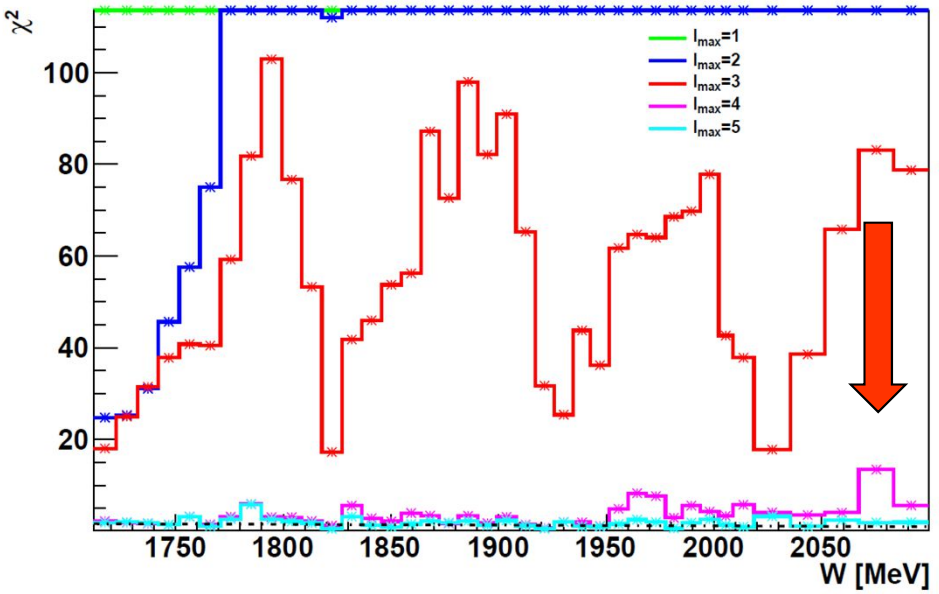
L_{max} Interpretation of Σ- Asymmetry

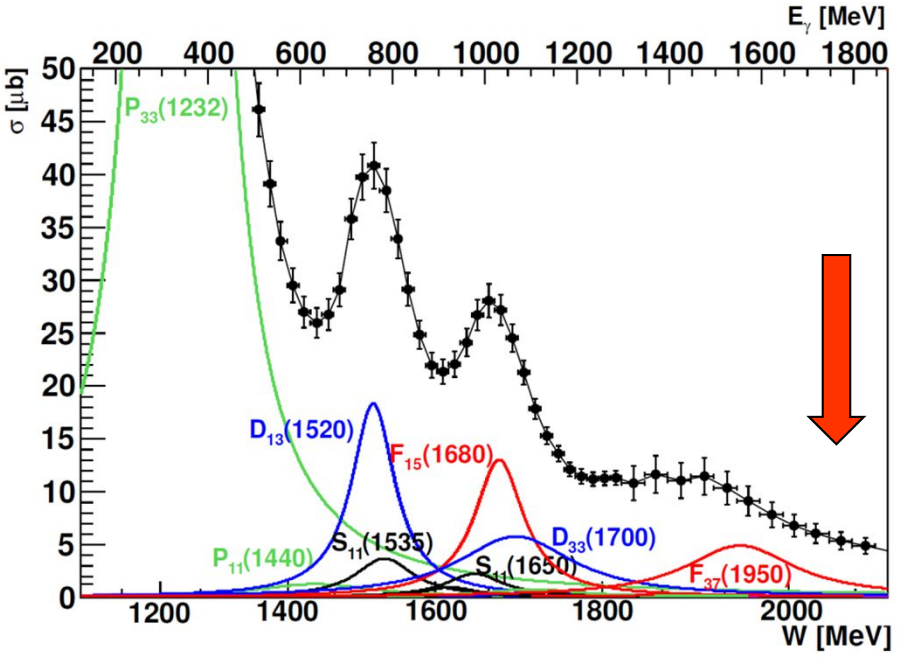
W=2075 MeV



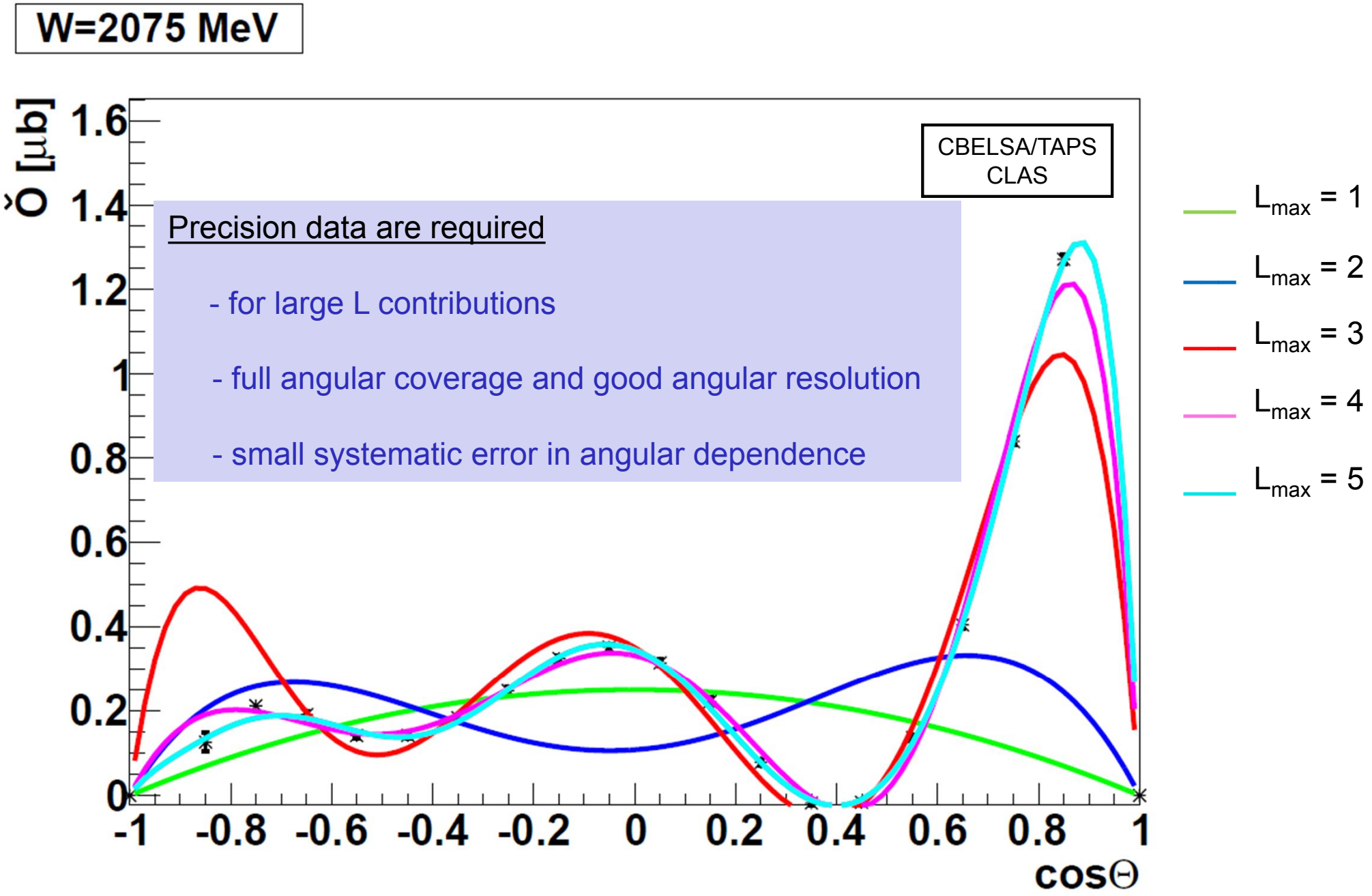
- Significant L = 3 signal seen above W = 1500 MeV
- Below W =1500 MeV
  L ≤ 2 seems to be sufficient
- L = 4 signal above W = 1700 MeV

High precision data for Σ from
CBELSA/TAPS
CLAS





L_{max} Interpretation of Σ- Asymmetry



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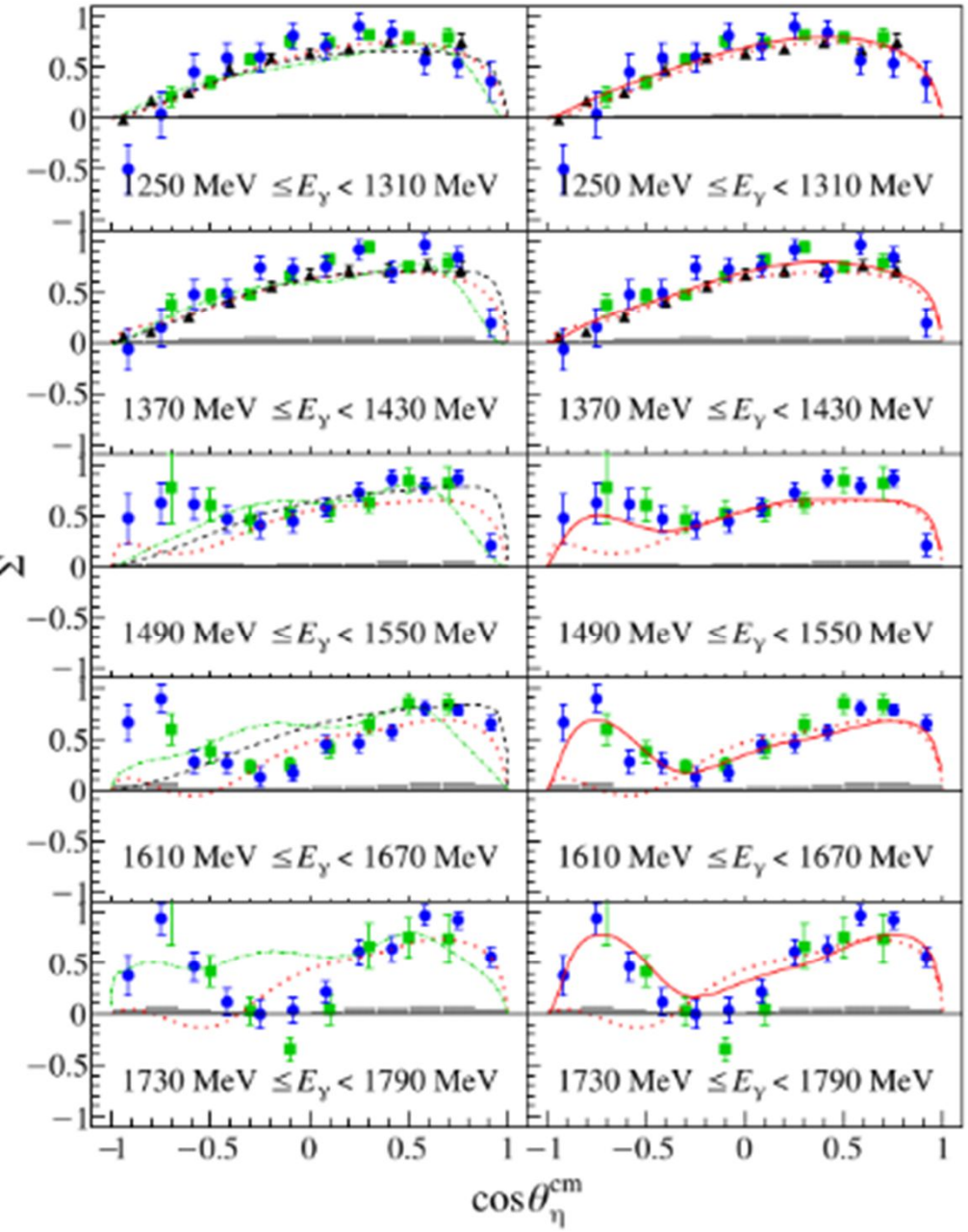


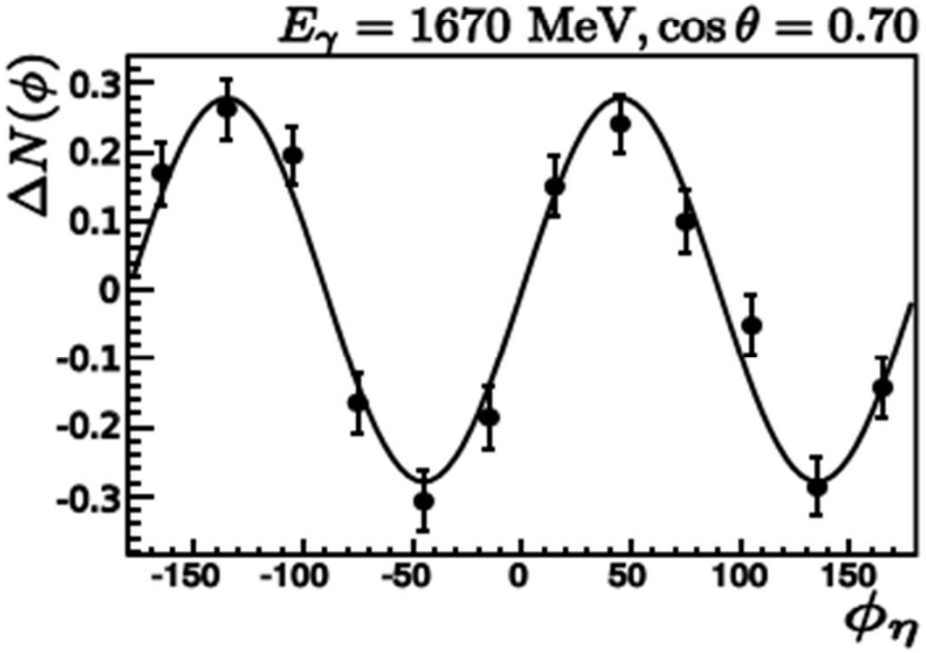
[F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)]

- CBELSA/TAPS data (F. Afzal et al.)
- GRAAL data (O. Bartalini et al., Eur. Phys. J. A33 (2007) 169)
- CLAS data (P. Collins et al., Phys. Lett. B 771 (2017) 213-221)

BnGa-2014-02 JüBo-2015-FitB ηMAID

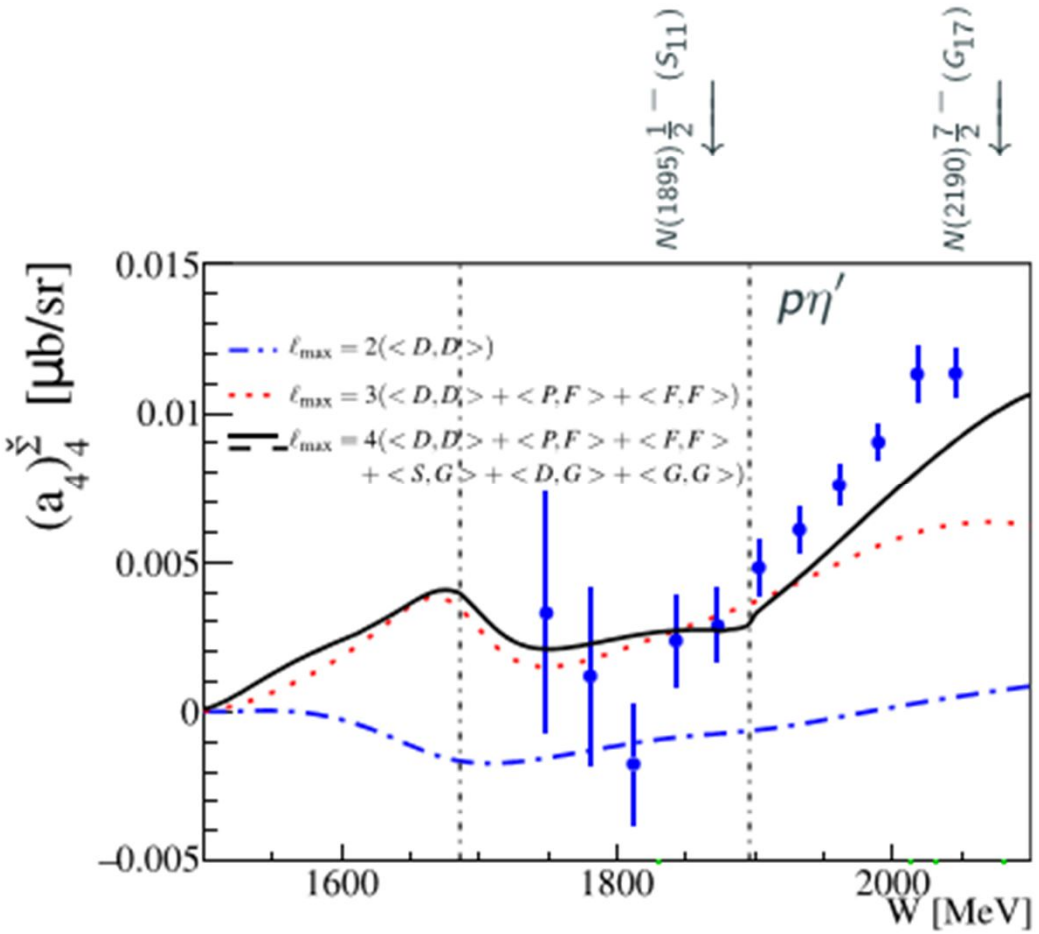
BnGa-2019

$$\Delta N = \frac{N_{-45^\circ} - N_{+45^\circ}}{N_{-45^\circ} + N_{+45^\circ}} = p_\gamma^{lin} \Sigma \sin(2\phi)$$



L_{max} Interpretation of Σ- Asymmetry

$$\check{\Sigma}(W,\cos\theta) = \Sigma(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=2}^{2L_{max}} (a_L(W))_k \cdot P_k^2(\cos\theta)$$



Compare extracted fit coefficient to BnGa-2019 solution

$$(a_5)_4^{\check{\Sigma}} = \langle D,D\rangle + \langle P,F\rangle + \langle F,F\rangle + \langle \boldsymbol{S},\boldsymbol{G}\rangle + \langle D,G\rangle + \langle G,G\rangle$$

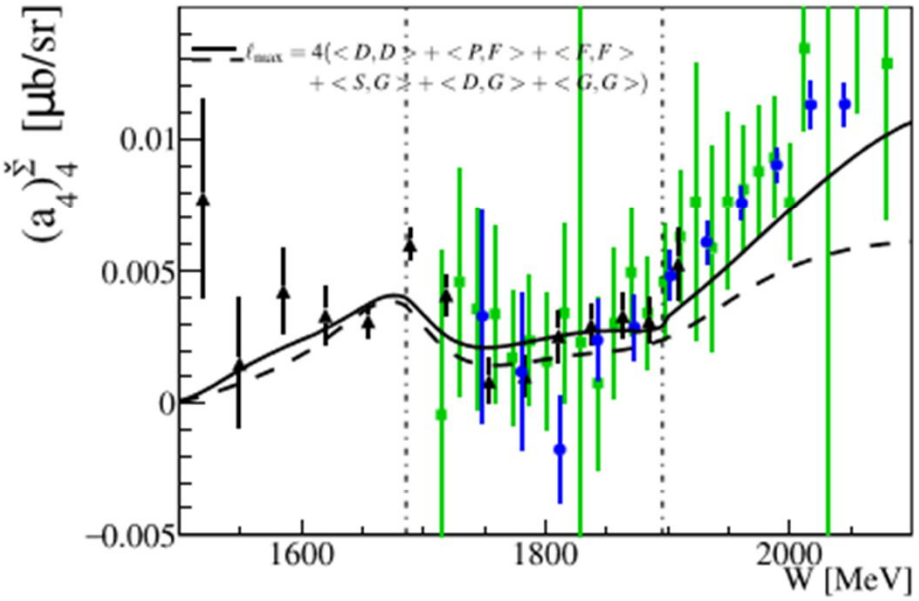
F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)

$p\eta'$ channel needs to be included in PWA to describe data

Evidence for $N(1895)\frac{1}{2}^-(S_{11})$ resonance due to strong $p\eta'$ cusp in $p\eta$ S wave

L_{max} Interpretation of Σ- Asymmetry

$$\check{\Sigma}(W,\cos\theta) = \Sigma(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=2}^{2L_{max}} (a_L(W))_k \cdot P_k^2(\cos\theta)$$



▲ GRAAL data (O. Bartalini et al., Eur. Phys. J. A33 (2007) 169)

• P. Collins et al., Phys. Lett. B 771 (2017) 213-221 (CLAS)

—— BnGa-2019

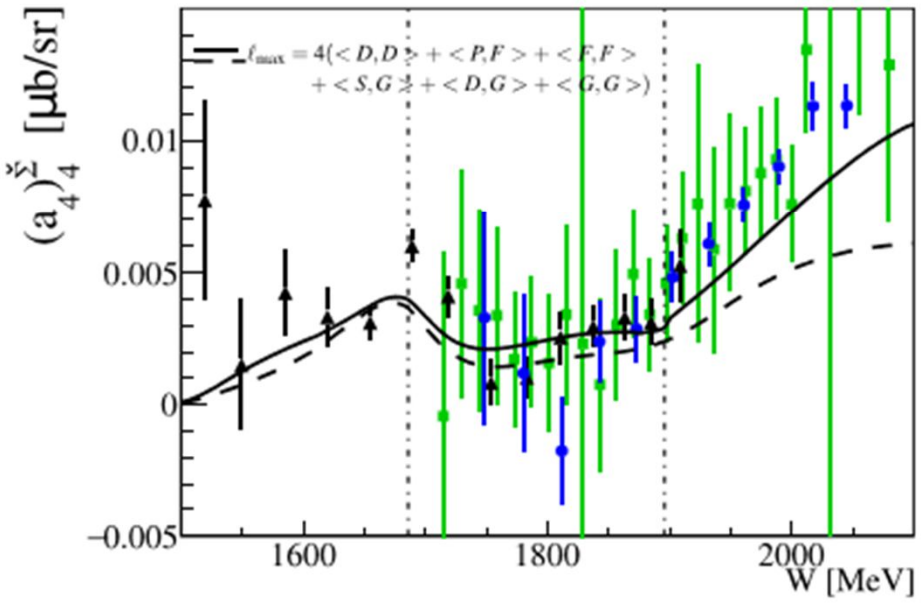
..... BnGa-2014-02

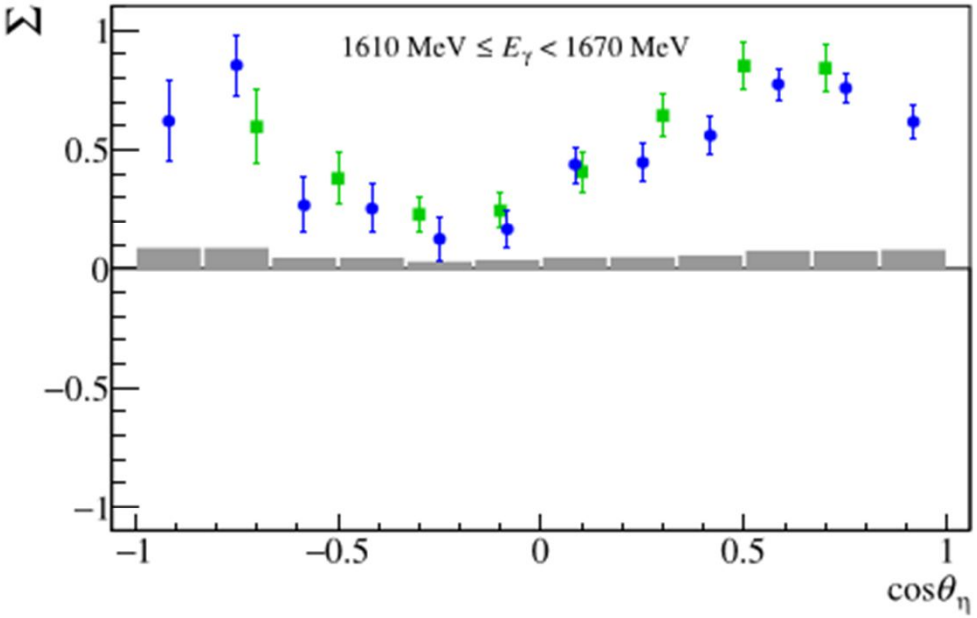
F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)

Full angular coverage is very important for $< S, G >$ interference

L_{max} Interpretation of Σ- Asymmetry

$$\check{\Sigma}(W,\cos\theta) = \Sigma(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=2}^{2L_{max}} (a_L(W))_k \cdot P_k^2(\cos\theta)$$

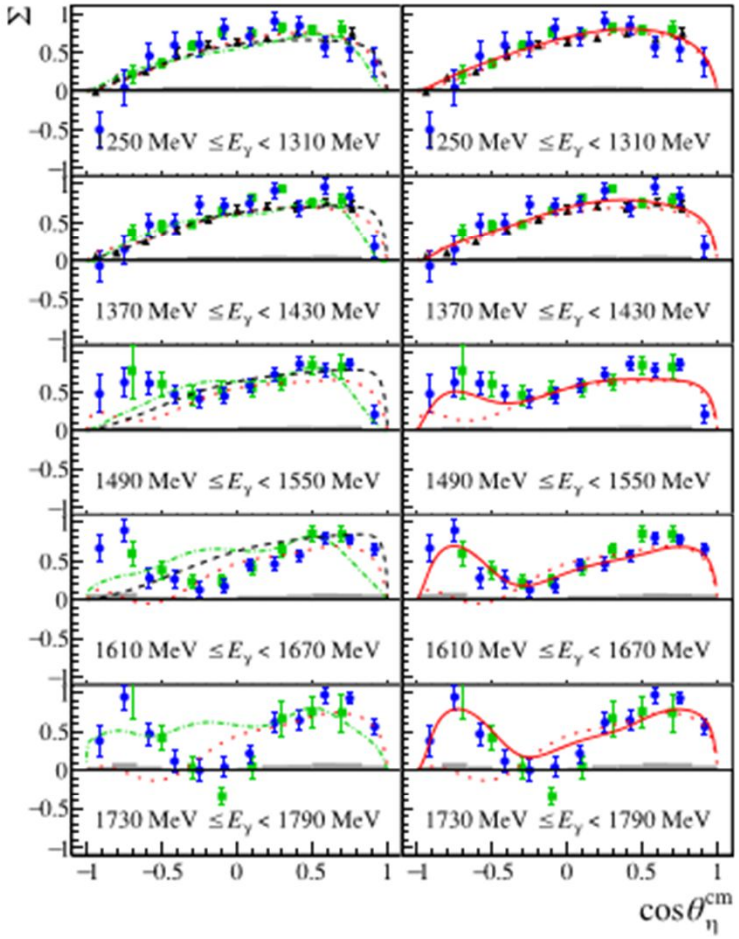


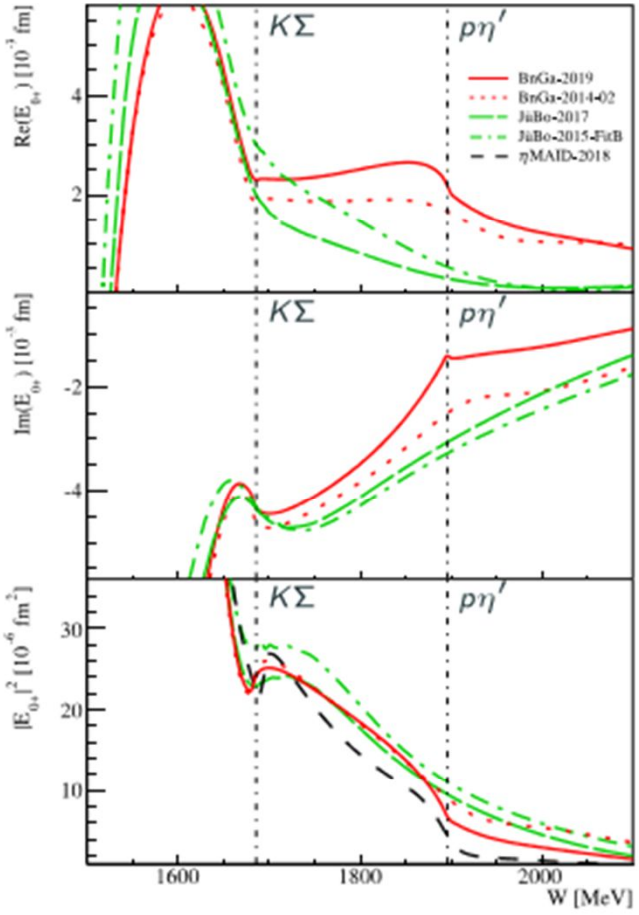


3 (2007) 169)
. (CLAS)

Full angular coverage is very important for $< S, G >$ interference

L_{max} Interpretation of Σ- Asymmetry

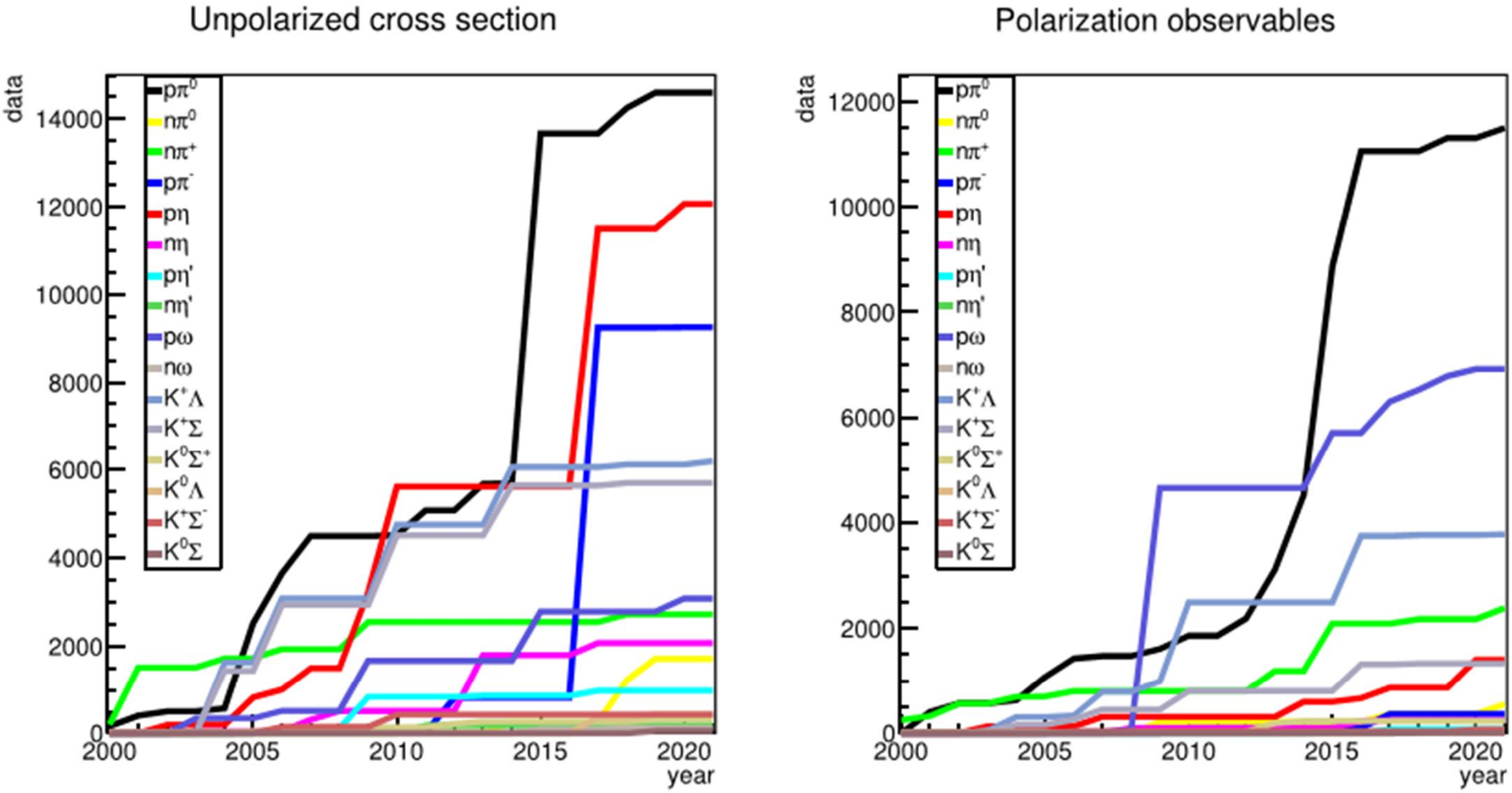




- PWA predictions (BnGa, JüBo, ηMAID) can not describe backward peak in data!
- New fits of BnGa and ηMAID have included the $p\eta'$ cusp in the S wave
- However, JüBo does not!

F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)

Impact of the polarization data



[A. Thiel, F. Afzal, Y. Wunderlich, Prog. Part. Nucl. Phys. 125 (2022) 103949]

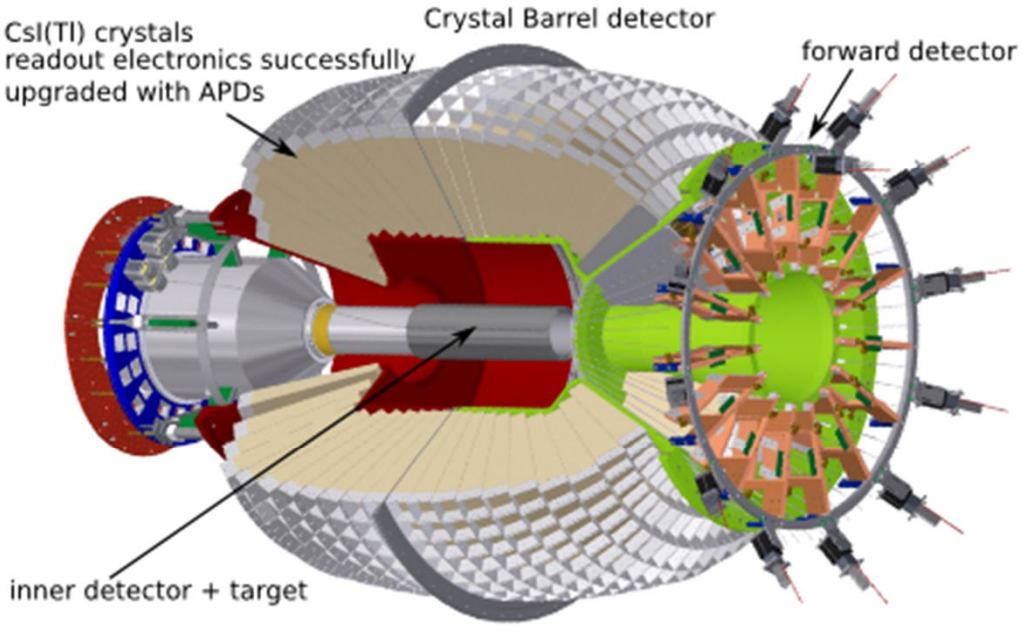
Impact of the polarization data

Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	***-	****	***-	***	-			-		
$N(1520)$	$3/2^-$	****	****	****	****	**	****			- - - -		
$N(1535)$	$1/2^-$	****	***-	****	**-	*	****			- -		
$N(1650)$	$1/2^-$	****	***-	****	***	*	***-	*- -	- -	- -		
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*	-		
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*	- - - -		
$N(1700)$	$3/2^-$	***	**	***	**-	*	*	- -	-	-		
$N(1710)$	$1/2^+$	***-	***-	***-	*-		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	***-	****	***	*	*	***-	*	*-	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**	-	*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*-	**	*	*	-	-	- -	*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	**-	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	***-	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

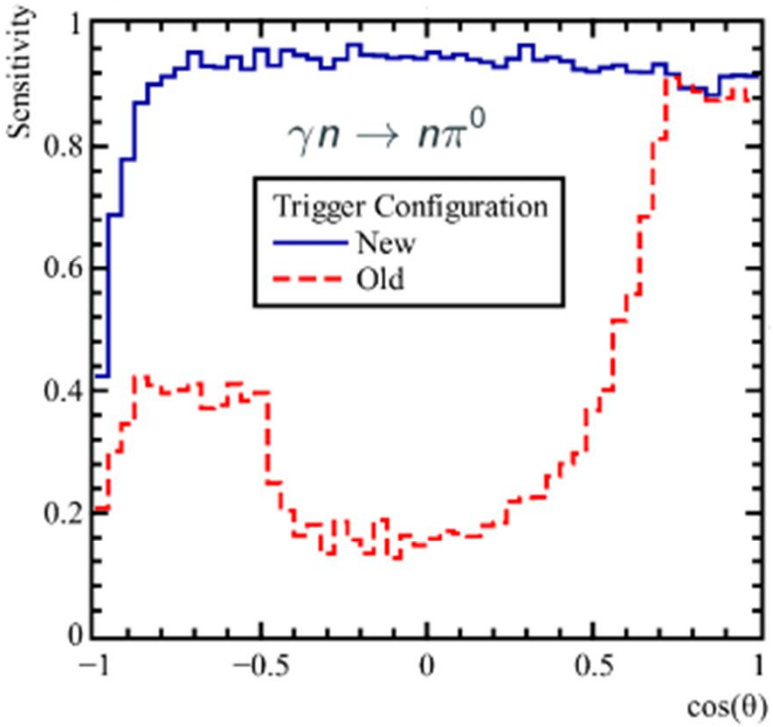
- mostly πN data were used until 2010
- photoproduction data is now used by most PWA groups and new fit values for resonance parameters have entered the PDG
- Still a lot of work to do!
- More information in
  A. Thiel, F. Afzal, Y. Wunderlich, Prog. Part. Nucl. Phys. 125 (2022) 103949

Status and Future Plan for CBELSA/TAPS

- Each CsI(Tl) crystal readout with 2 APDs instead of PIN photodiodes
- Crystal Barrel $\theta > 12^\circ$ included in first level trigger
- high trigger acceptance for complete neutral final states



[C. Honisch et al., to be submitted soon]

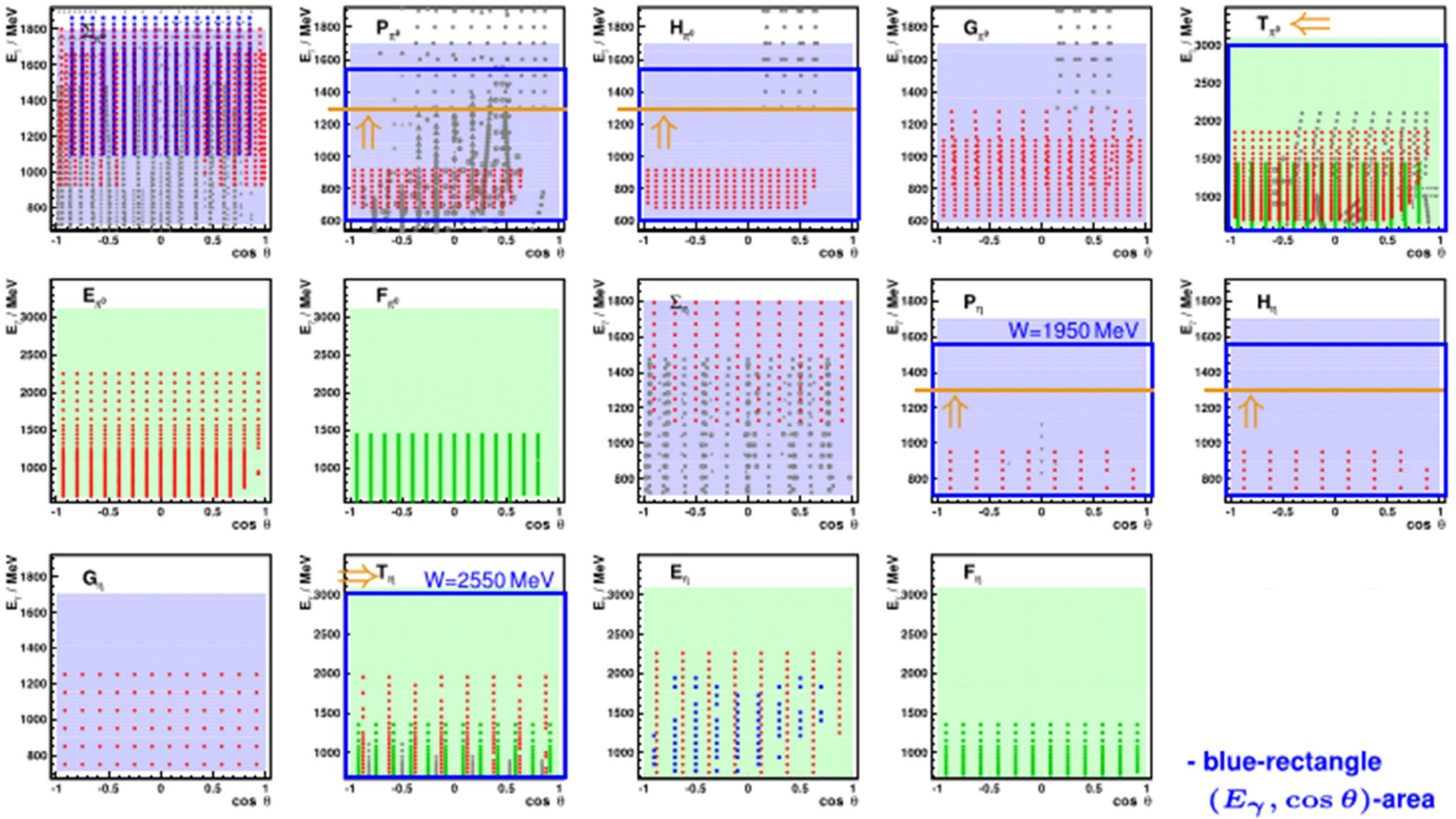


Since NSTAR 2019 in Bonn:

New data on T, P, H off the proton

New data on T, P, H off the neutron

New T, P, H data off the proton

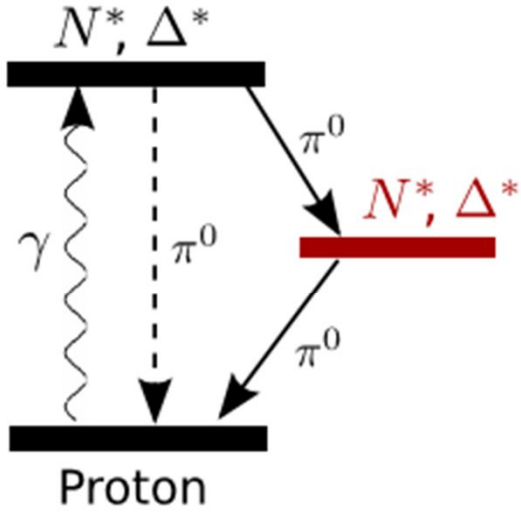


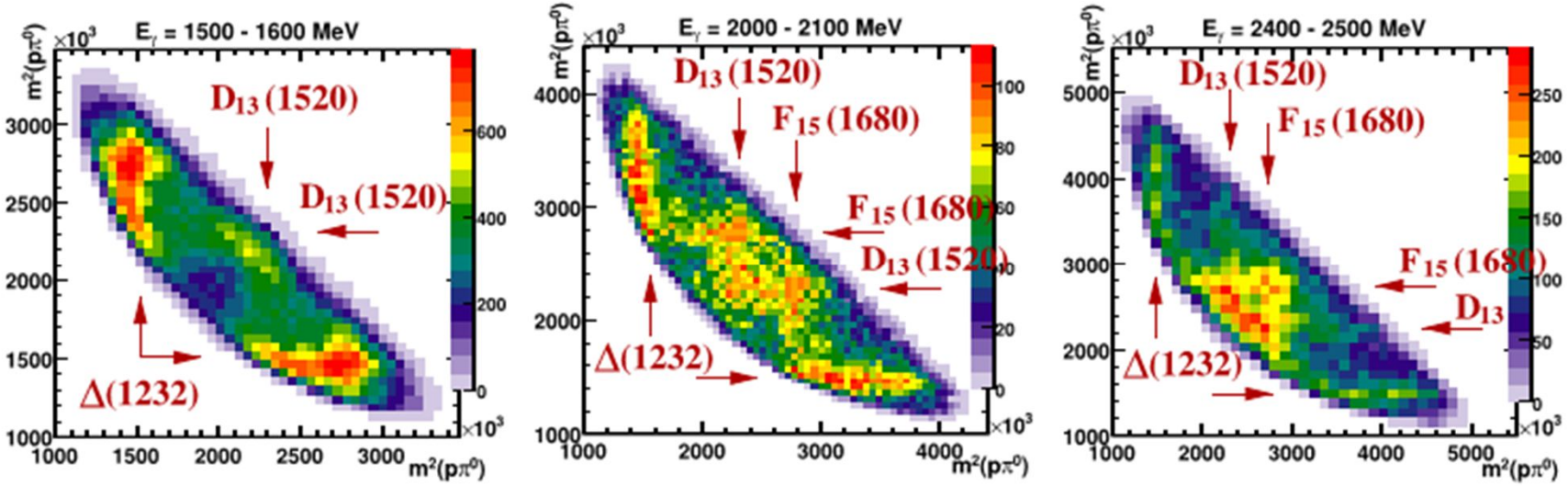
- blue-rectangle $(E_\gamma, \cos\theta)$-area

old data, CBELSA/TAPS, MAMI, CLAS

Observables in Multi-Meson Final States

- Multi-meson final states like $\gamma p \to p\pi^0\pi^0$ or $\pi^0\eta$ preferred at higher energies
- Probes the high mass region, where the missing resonances occur
- Can help to observe cascading decays





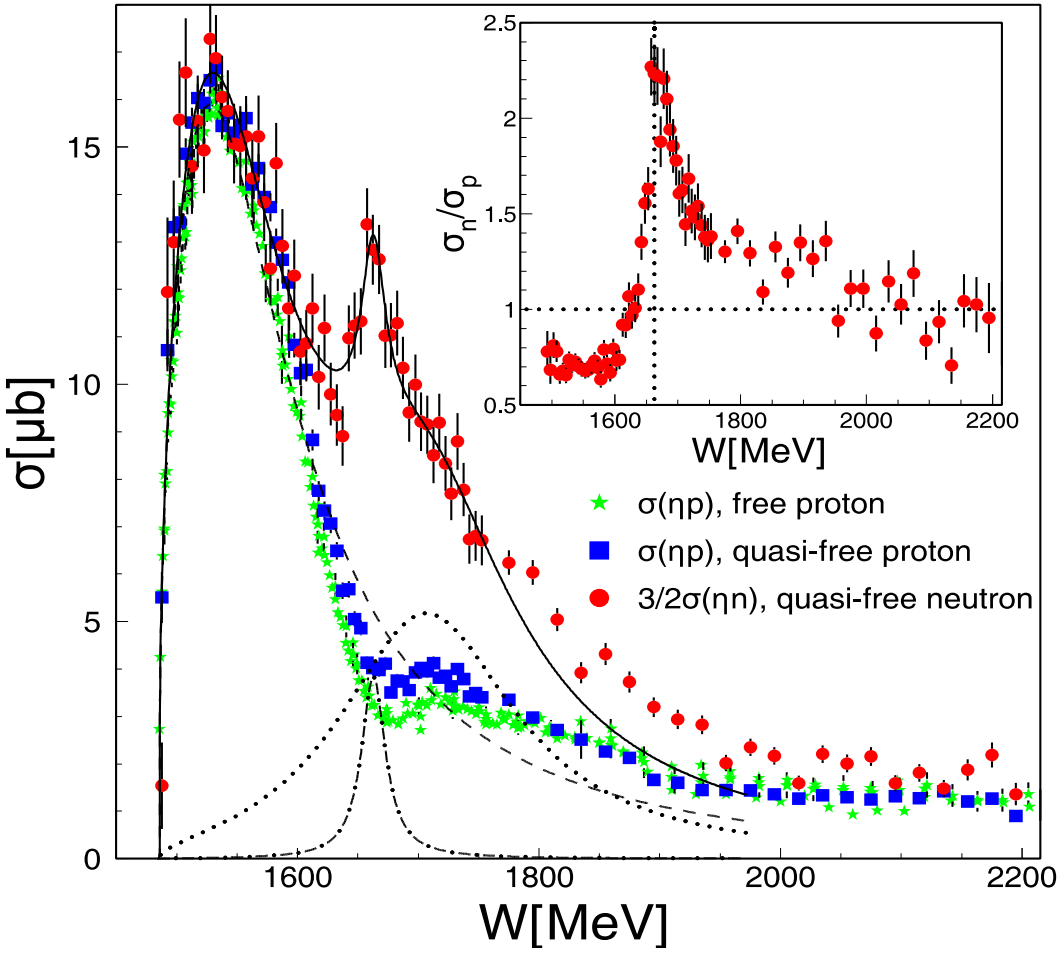
[V. Sokhoyan et al., Eur.Phys.J. A51 (2015) no.8, 95]

Talk: N. Stausberg

Spectroscopy off the Neutron

- Nucleon resonances (Isospin I =1/2) couple differently to Neutron and Proton

$$\gamma + n \rightarrow n + \eta$$

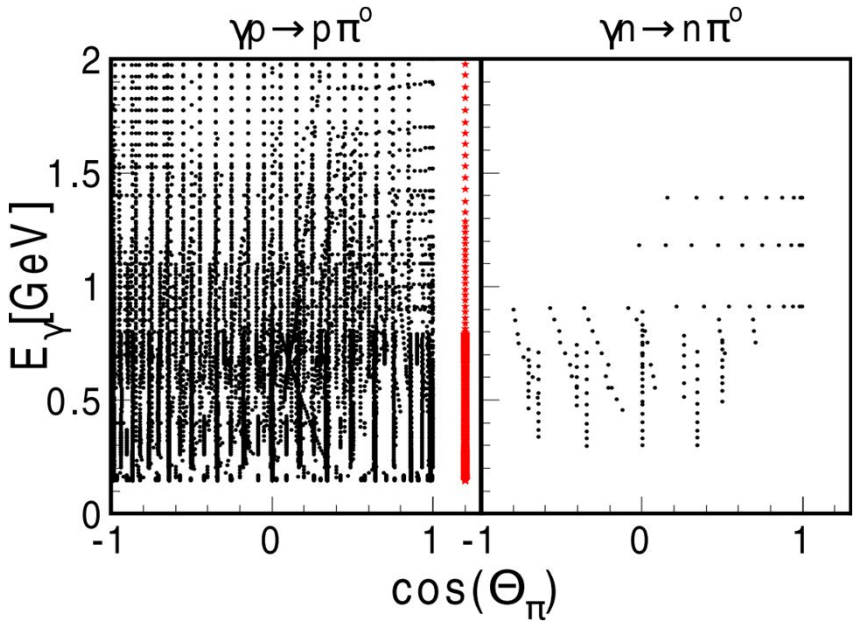


CBELSA/TAPS, *I. Jaegle, PRL 100 (2008), 252002*

$$\gamma + n \rightarrow n + \pi^0$$

$$\mathcal{M}_{l\pm}^{(\gamma p \to p\pi^0)} = \mathcal{M}_{p,l}^{1/2} + \frac{2}{3}\mathcal{M}_{l}^{3/2}$$

$$\mathcal{M}_{l\pm}^{(\gamma n \to n\pi^0)} = -\mathcal{M}_{n,l}^{1/2} + \frac{2}{3}\mathcal{M}_{l}^{3/2}$$

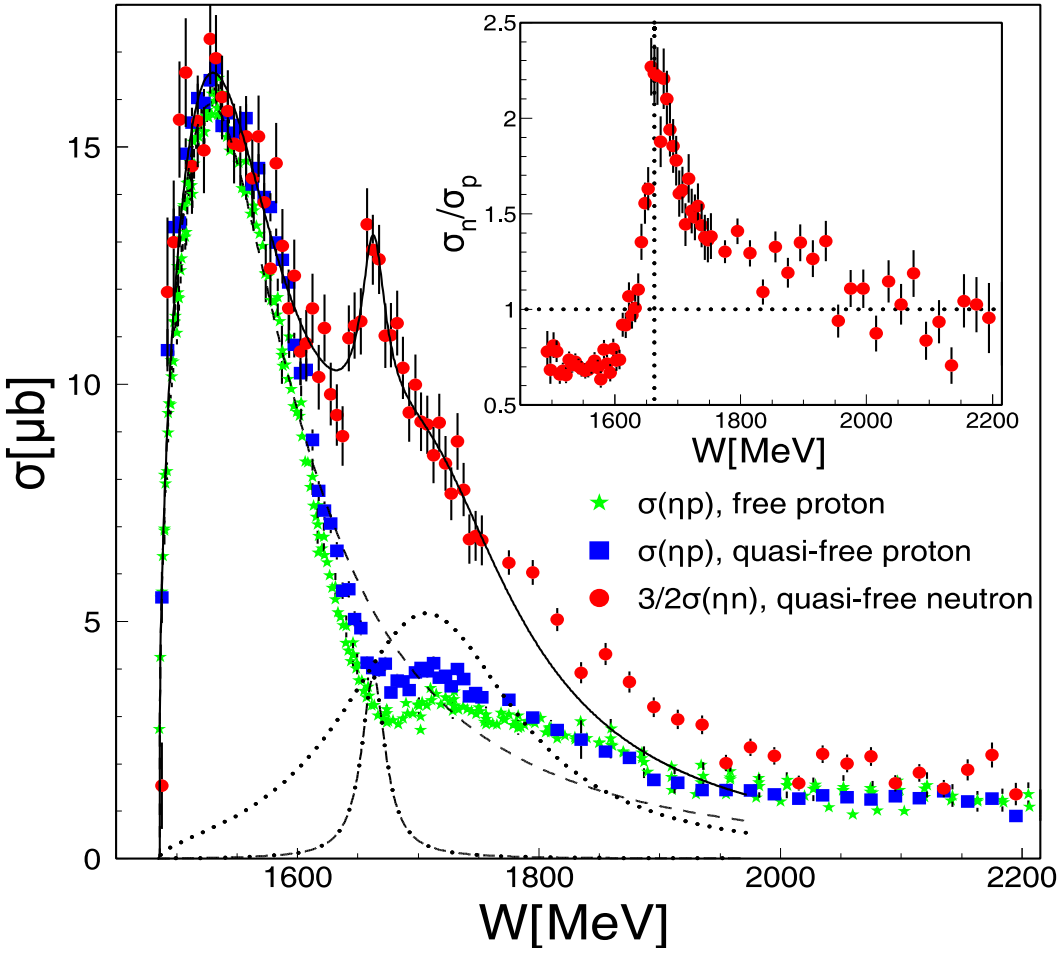


- CBELSA/TAPS experiment has been upgrade for measurements on the neutron

Honor to Bernd Krusche

- Nucleon resonances (Isospin I =1/2) couple differently to Neutron and Proton

$$\gamma + n \rightarrow n + \eta$$



CBELSA/TAPS, *I. Jaegle, PRL 100 (2008), 252002*

June 1. 2022, at the age of 66.

Thursday talk: V. Metag

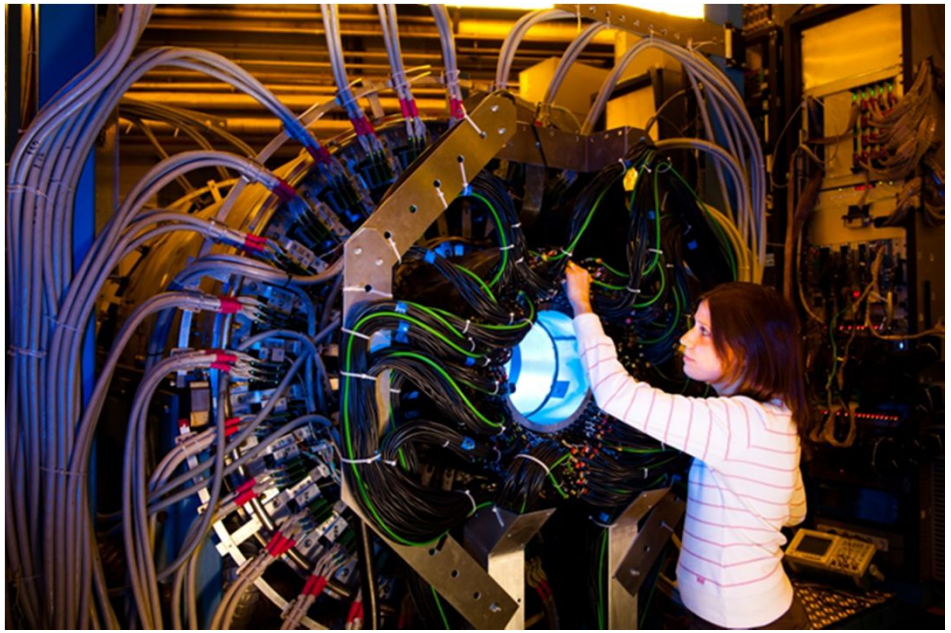
Summary

- Precise polarization data from ELSA, Jlab and MAMI
  - polarization data are essential to get unique PWA- solution
  - full angular coverage and precision is important to find high spin states
  - different final states are important, coupled channel analysis
- Impact of the new polarization data
  - the new polarization data constrain the possible multipole solutions
  - new states have been found

Baryon Spectroscopy Future at ELSA

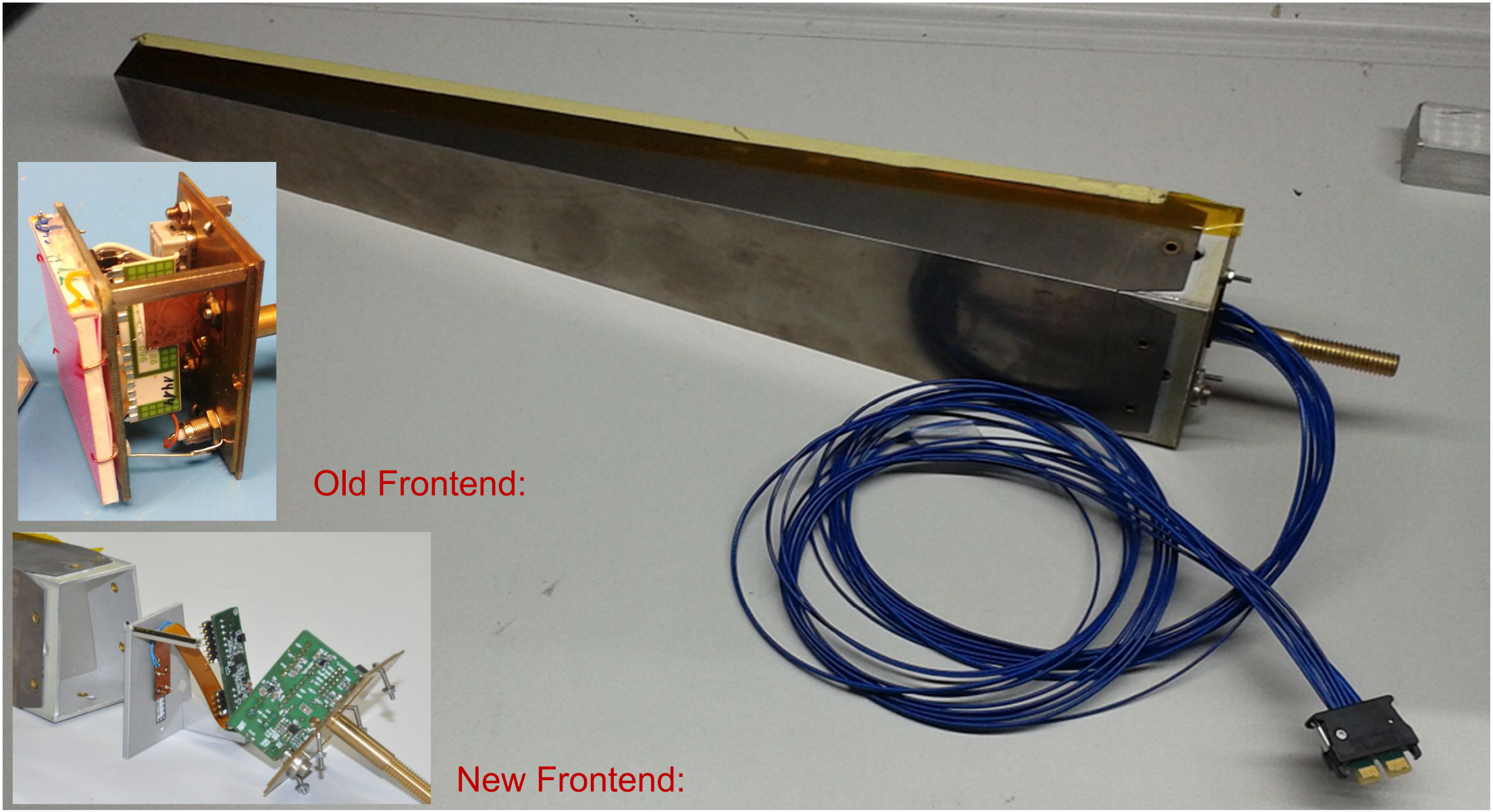
- In the high W-mass region the final states $p\,\eta$, $p\,\eta'$ and $K^+\,\Lambda$, $K^+\,\Sigma^0$ will be important
  - the necessary precision in the data is still missing
- Polarization data on the Neutron are necessary
  - CBELSA/TAPS experiment has been upgraded and neutron measurements have started

Thank you for your attention



CBELSA/TAPS Experiment Upgrade

- **All 1320 single CsI crystals upgraded with 2 Avalanche Photodiode (APD)**



Old Frontend:

New Frontend: