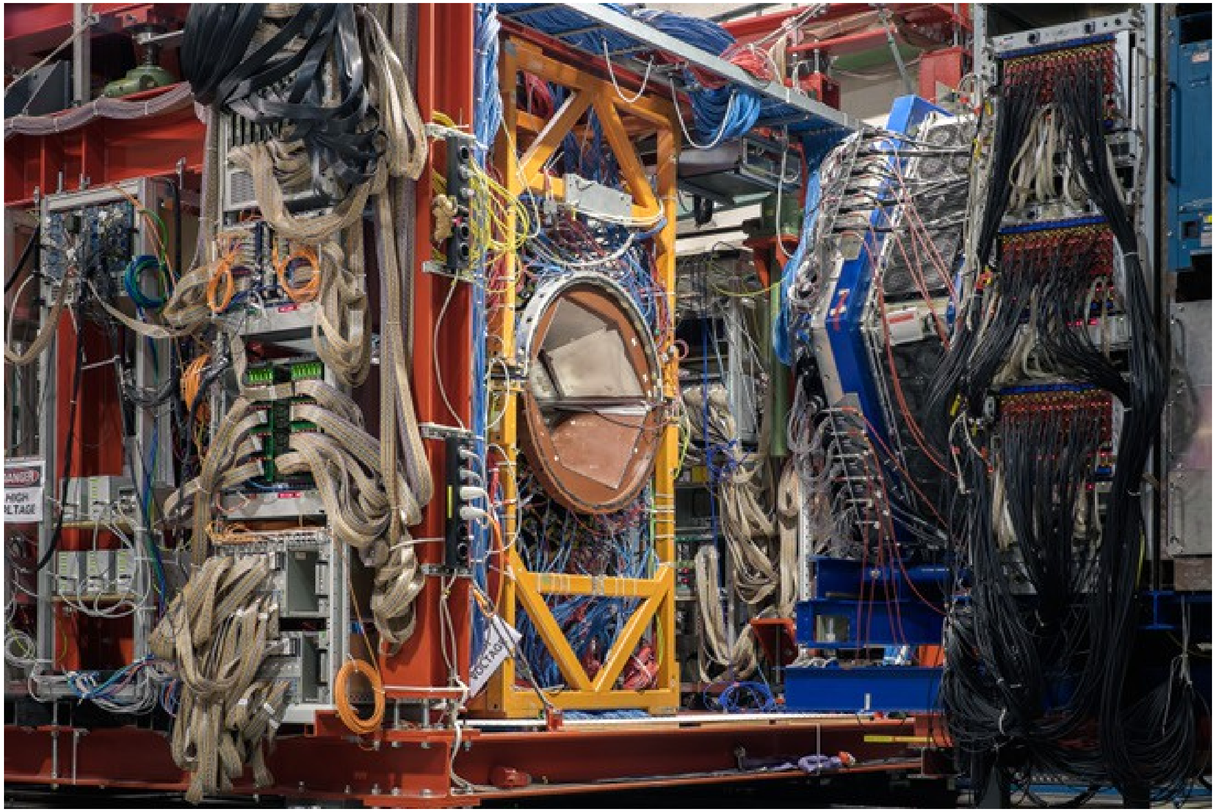
N* Photoexcitation Results from Mainz

Vahe Sokhoyan

NSTAR 2017
22.08.2017



Contents

- Baryon resonances
- Experimental setup
- Single and double meson photoproduction
- Production of mesons off the free proton, quasi-free nucleons, and nuclei
- Summary and outlook

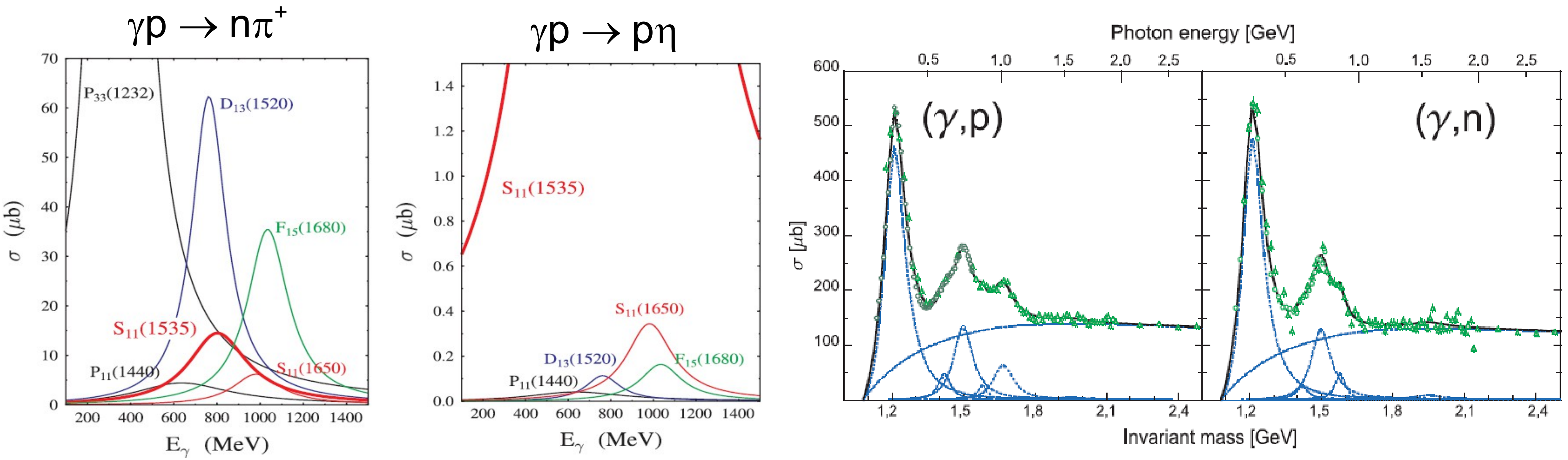
- Lothar Tiator: “The MAID Legacy and Future”, 20.08.2017

- Natalie Walford: “Polarization Observables in Meson Photoproduction with the Crystal Ball/TAPS at MAMI”, 22.08.2017, Parallel Session (A2), 14:30
- Natalie Walford: “Polarization Observables in $\gamma p \rightarrow K^+ + \Lambda$ and $K^+ + \Sigma^0$ Using Circularly Polarized Photons on a Polarized Frozen Spin Target”, 22.08.2017, Parallel Session (A3), 16:50
- Natalie Walford “Photoproduction of $\pi^0\pi^\pm$ Pairs off Nucleons”, 22.08.2017, Parallel Session (A3), 18:10

Baryon resonances

Goal: Gain a good understanding of the spectrum and properties of baryon resonances

Experimentally: Broad overlapping resonances
- Partial Wave Analysis necessary
- Measurement of cross-sections and polarization observables
- Different production channels

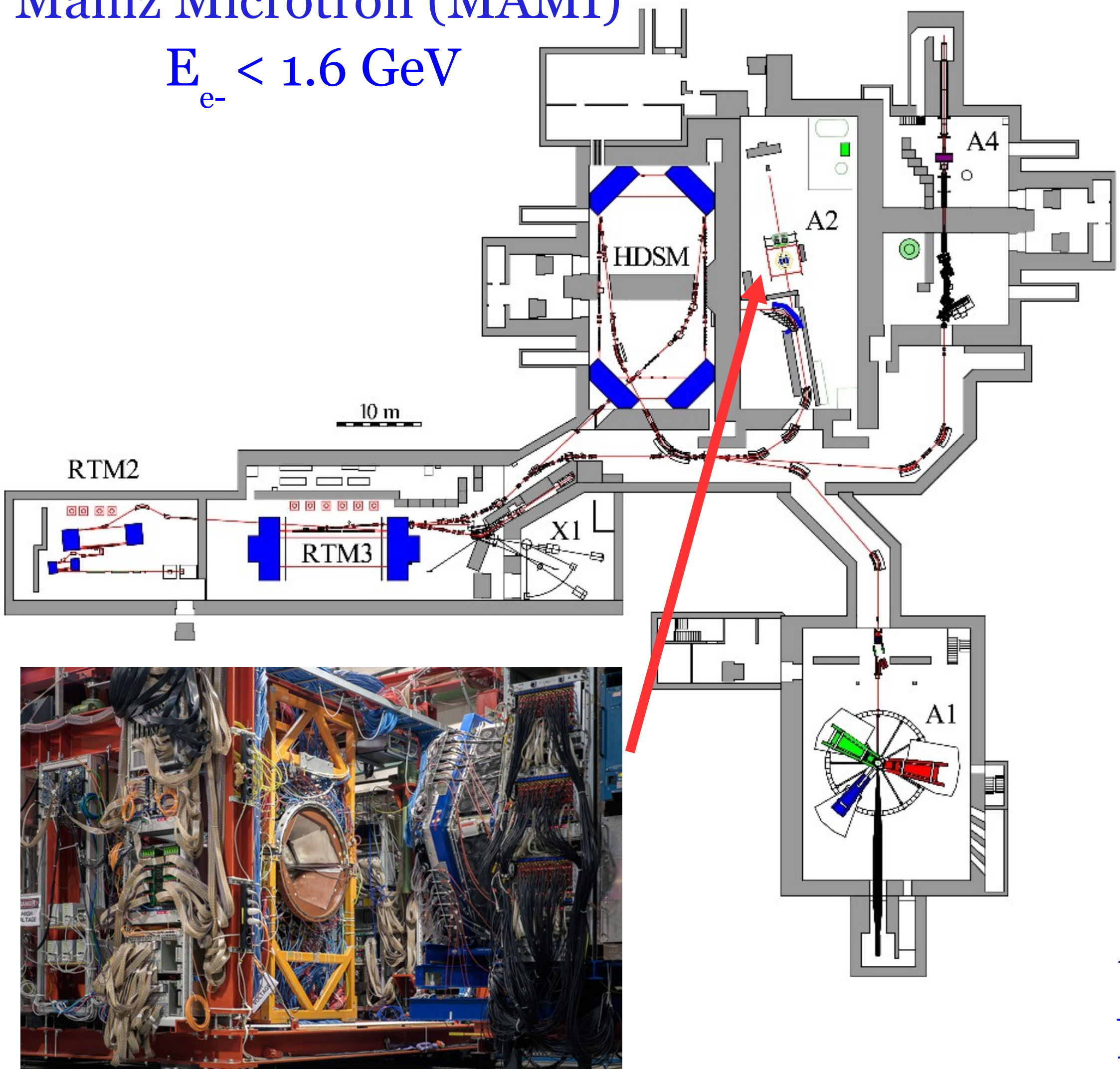


- Channels different from πN → Photoproduction experiments
- Production off the proton (π^0, η, η', $2\pi^0$, $\pi^0\eta$, ….)
- Production of mesons off light and heavy nuclei

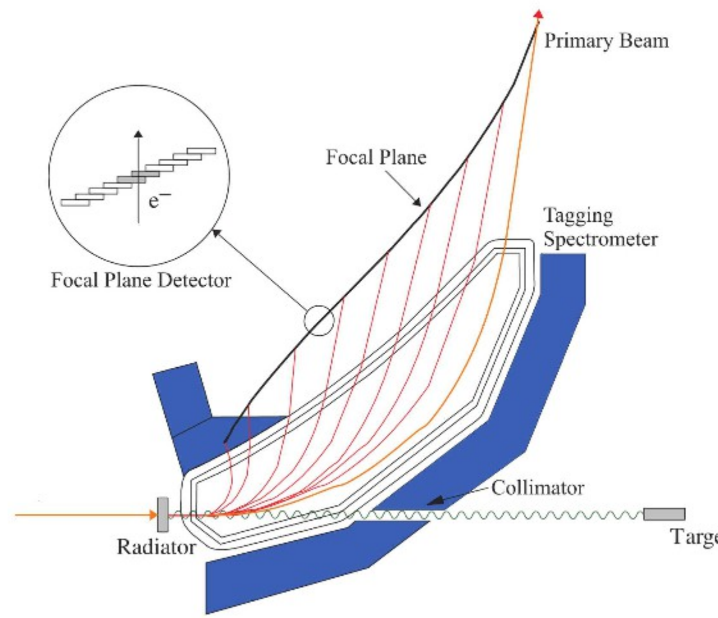
Experimental setup

Mainz Microtron (MAMI)

$E_{e-} < 1.6$ GeV



Tagger/End point tagger

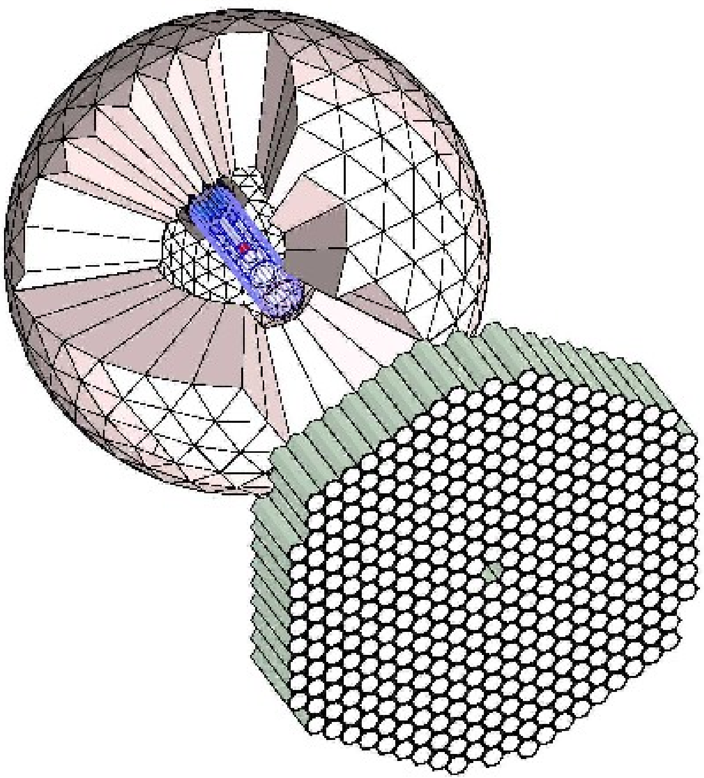


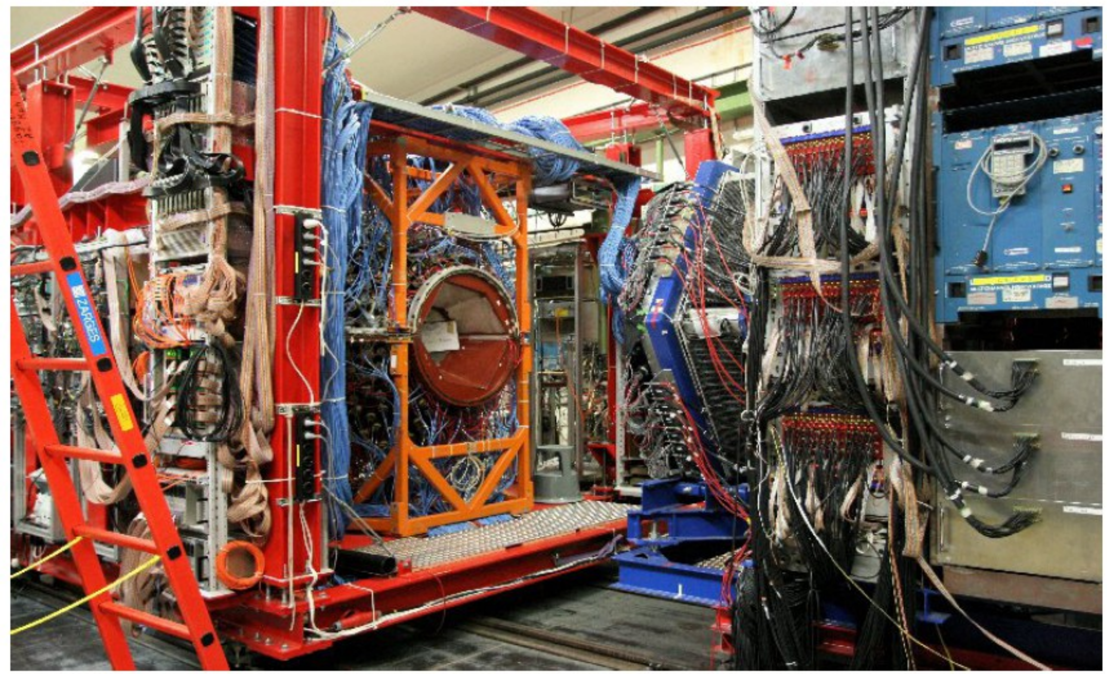
$$E_\gamma = E_{e-} - E_{tagg}$$

Upgrade → experiments with ~4 times higher rates will be possible!

- High-Flux, Tagged, Bremsstrahlung Photon Beam: Unpolarized, Linear, and Circular
- Polarized and Unpolarized Targets
- Recoil polarimeter
- ➔ Development of an active He gas target in progress

Crystal Ball/TAPS experiment





Polarized Butanol/D-Butanol

Crystal Ball:

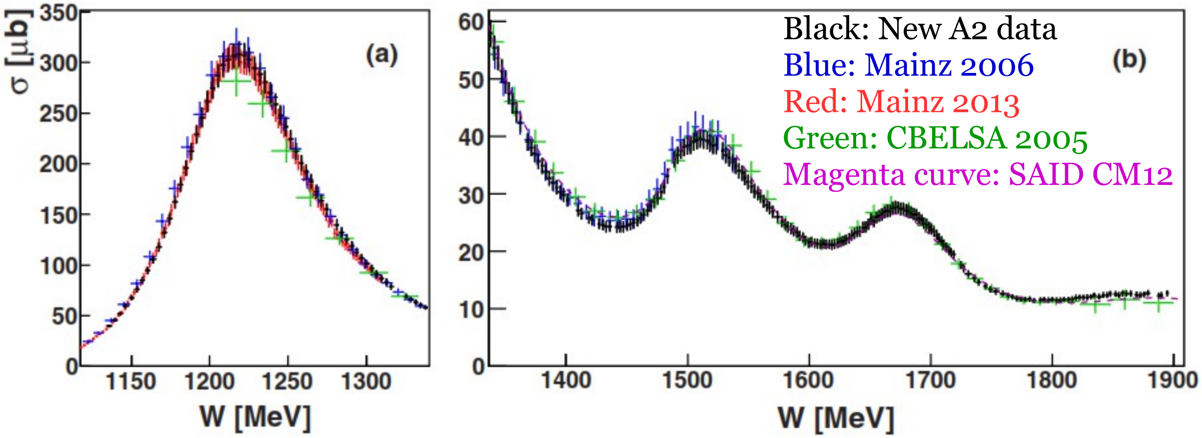
- 672 NaI Crystals
- 24 Particle Identification Detector Paddles
- 2 Multiwire Proportional Chambers

TAPS:

- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Detectors

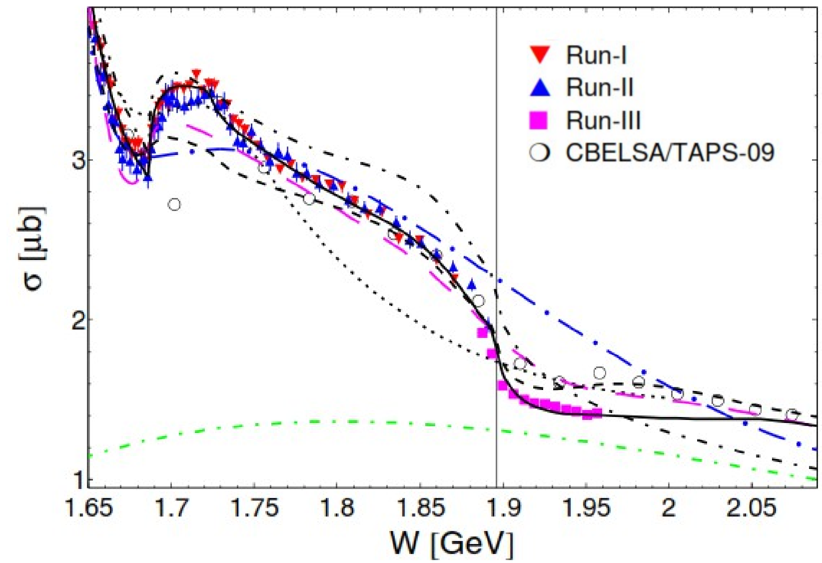
Selected photoproduction data from A2

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



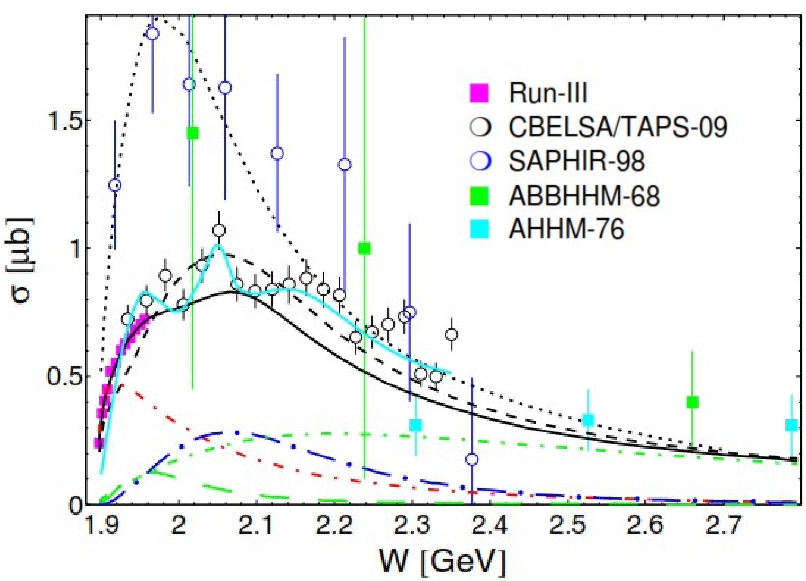
P. Adlarson et al., Phys.Rev. C92 (2015) no.2, 024617

$\gamma p \to p\eta$



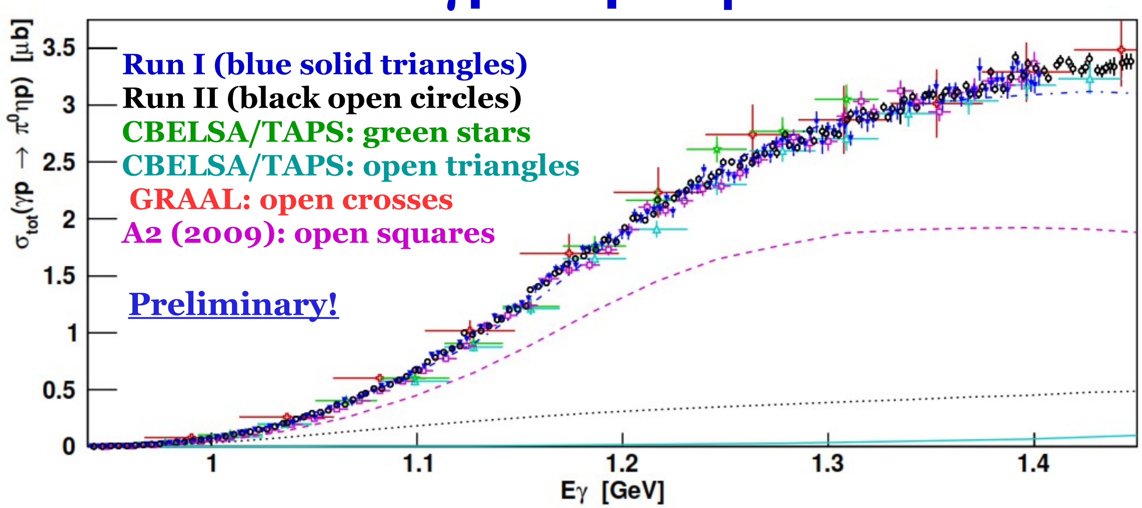
V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

$\gamma p \to p\eta'$



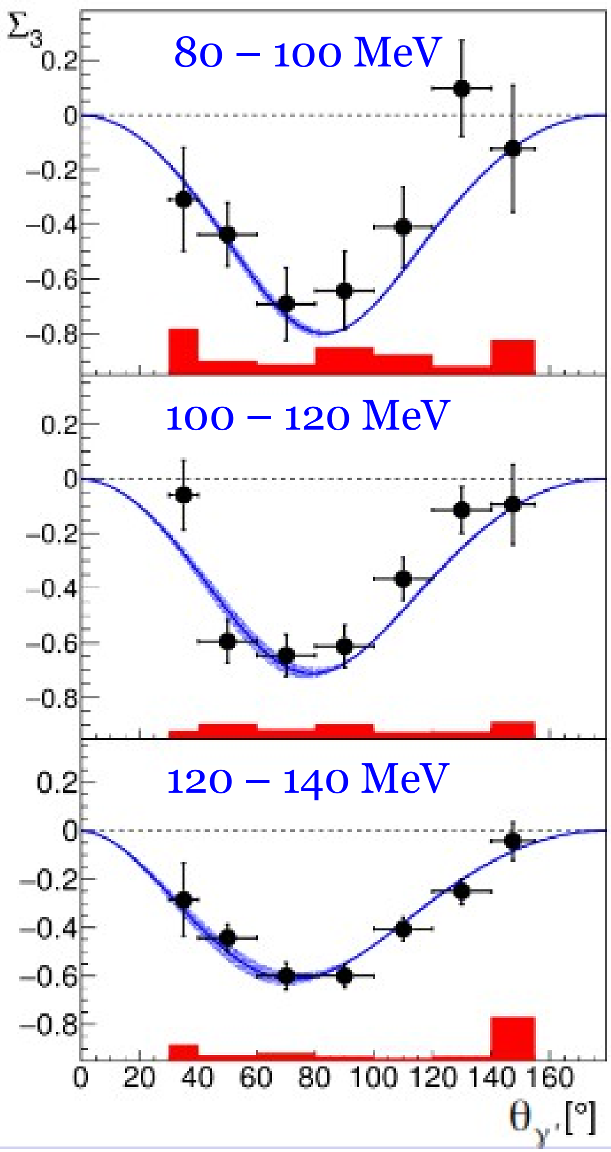
V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

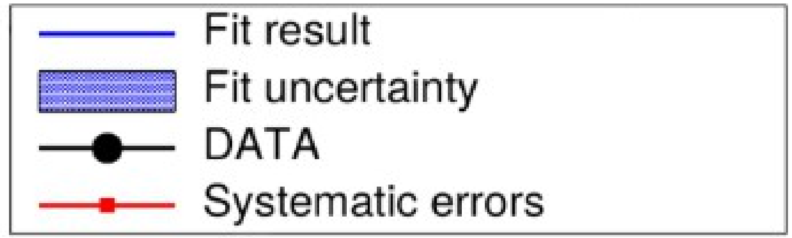
$\gamma p \to p\pi^0\eta$



To be published by the A2 Collaboration

Below pion threhold: Compton scattering





Fit on our Σ_3 results using Baldin sum rule constraint gives:

BChPT framework:

$\beta_{M1} = 2.8^{+2.3}_{-2.1} \times 10^{-4}\ \text{fm}^3$

$\chi^2/\text{ndf} = 19.2/20$

HBChPT framework:

$\beta_{M1} = 3.7^{+2.5}_{-2.3} \times 10^{-4}\ \text{fm}^3$

$\chi^2/\text{ndf} = 17.1/20$

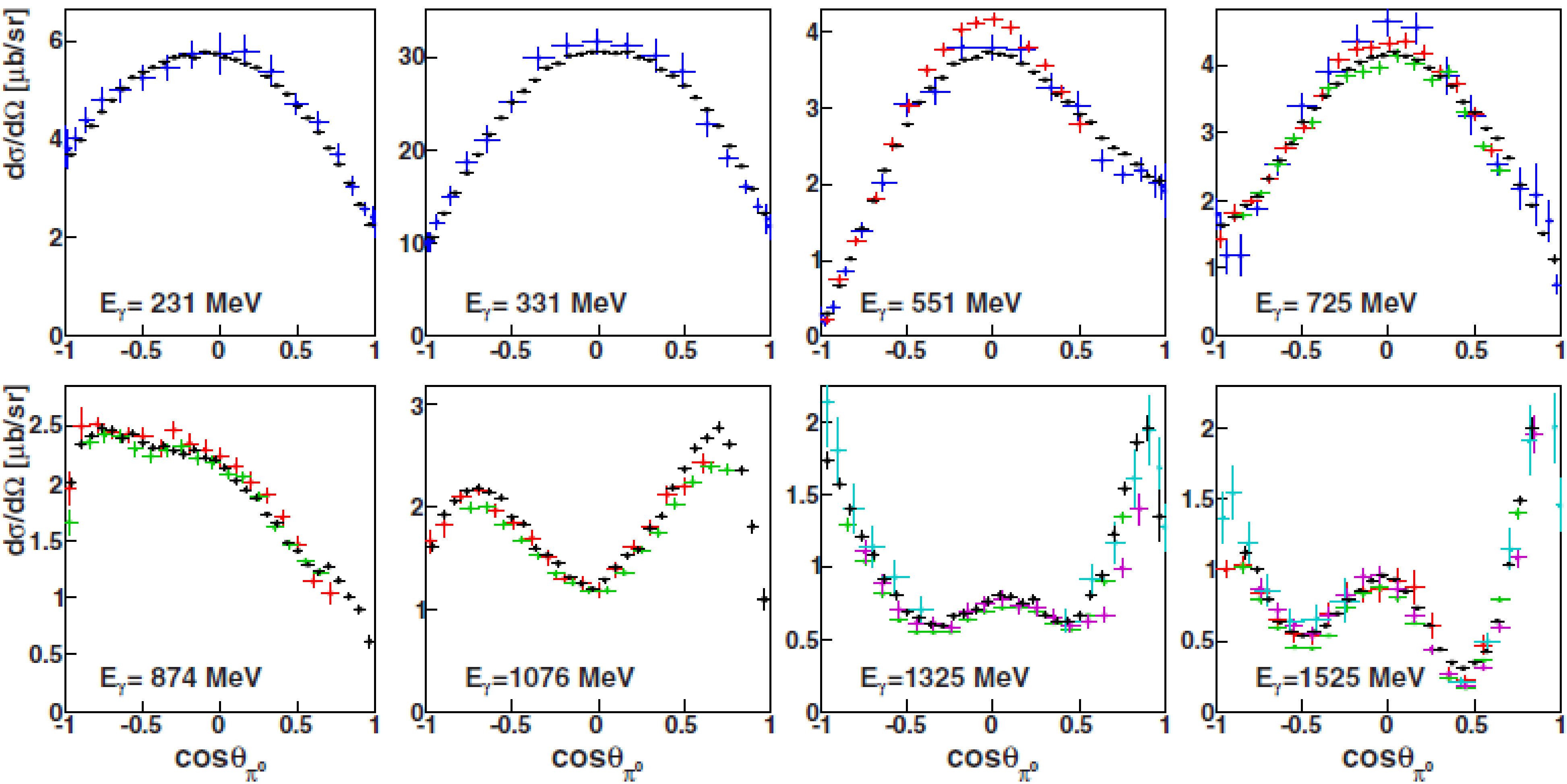
At low energy, the measurement of the beam asymmetry Σ_3 provides an alternative way to extract β_{M1}:

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 \cos(2\phi)\right] \quad \text{where} \quad \Sigma_3 = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$$

V. S., E.J. Downie, E. Mornacchi, J.A. McGovern, N. Krupina,Eur.Phys.J. A53 (2017) no.1, 14

High-precision measurements of the beam asymmetry and unpolarized cross-section planned in the end of 2017!

Single π° production



P. Adlarson et al., Phys.Rev. C92 (2015) no.2, 024617

MAMI 2006: R. Beck, R. Leukel, and A. Schmidt, Acta Phys. Pol. B 33, 813 (2002); R. Beck, Eur. Phys. J. A 28, 173(2006)

CBELSA/TAPS: V. Crede et al., Phys. Rev. C 84, 055203 (2011)

CLAS: M. Dugger et al., Phys. Rev. C 76, 025211 (2007)

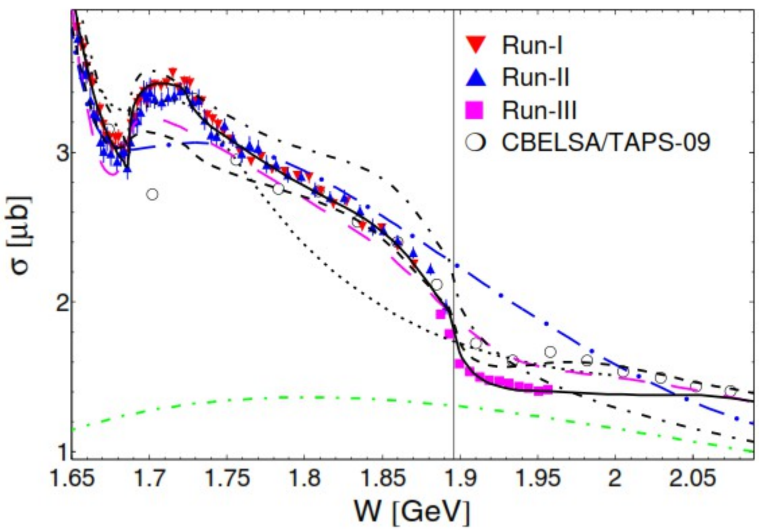
GRAAL: O. Bartalini et al., Eur. Phys. J. A 26, 399 (2005)

- **Interpretation within further partial wave analyses**

Single η and η' production

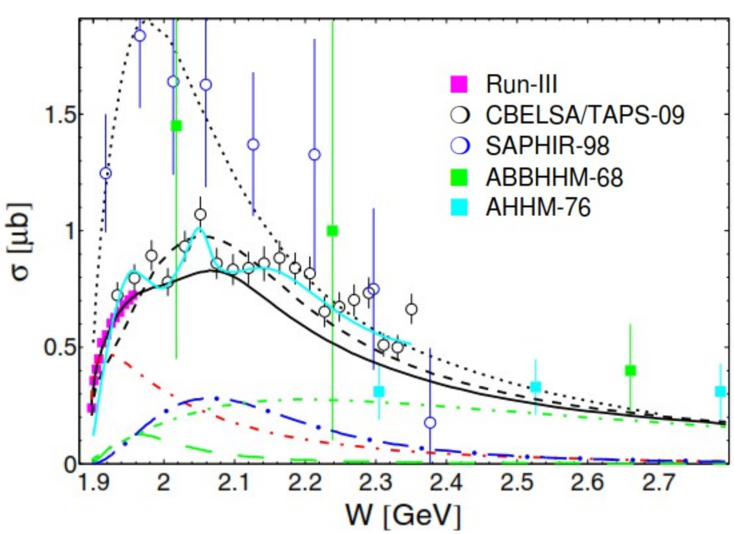
Black dashed: ηMAID2003, blue: SAID-GE09, BG2014-2 (magenta)
Solid black line: ηMAID2017

η



Cyan: Fit to the CBELSA/TAPS data
Individual contributions in final ηMAID2017 solution:
red dashed-dotted: N(1895)1/2$^-$, green long dashed: N(1900)3/2$^+$
Blue long-dashed: N(2120)3/2$^-$

η'

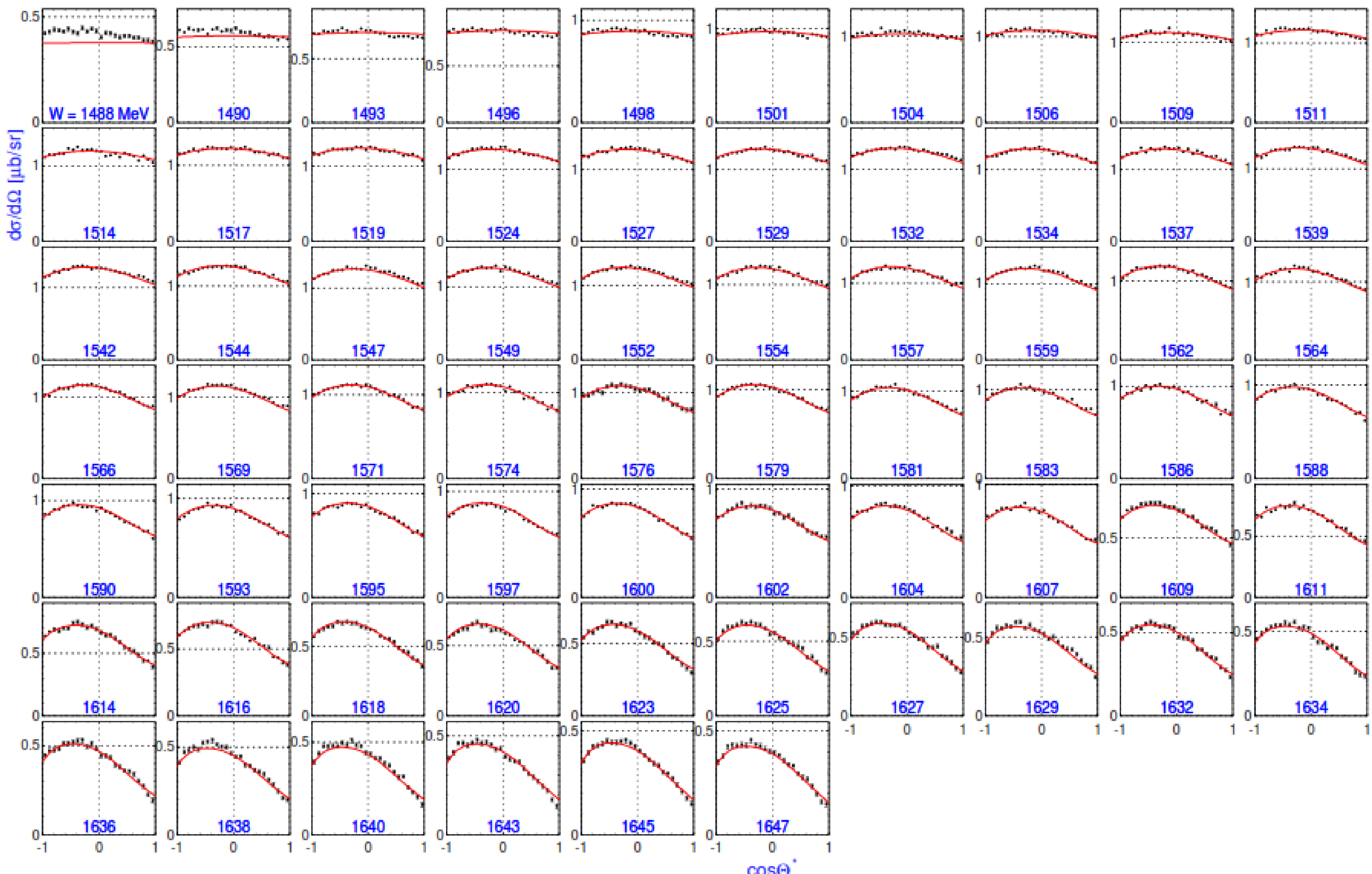


Particle J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N $1/2^+$	****									
$N(1440)$ $1/2^+$	****	****	****		***				*	***
$N(1520)$ $3/2^-$	****	****	****	***					***	***
$N(1535)$ $1/2^-$	****	****	****	****					**	*
$N(1650)$ $1/2^-$	****	***	****	***			***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

8 N* in 2001/2003
New resonances in ηMAID 2015/2017
▬ Resonances with no evidence for (γ, η)

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

Single η production



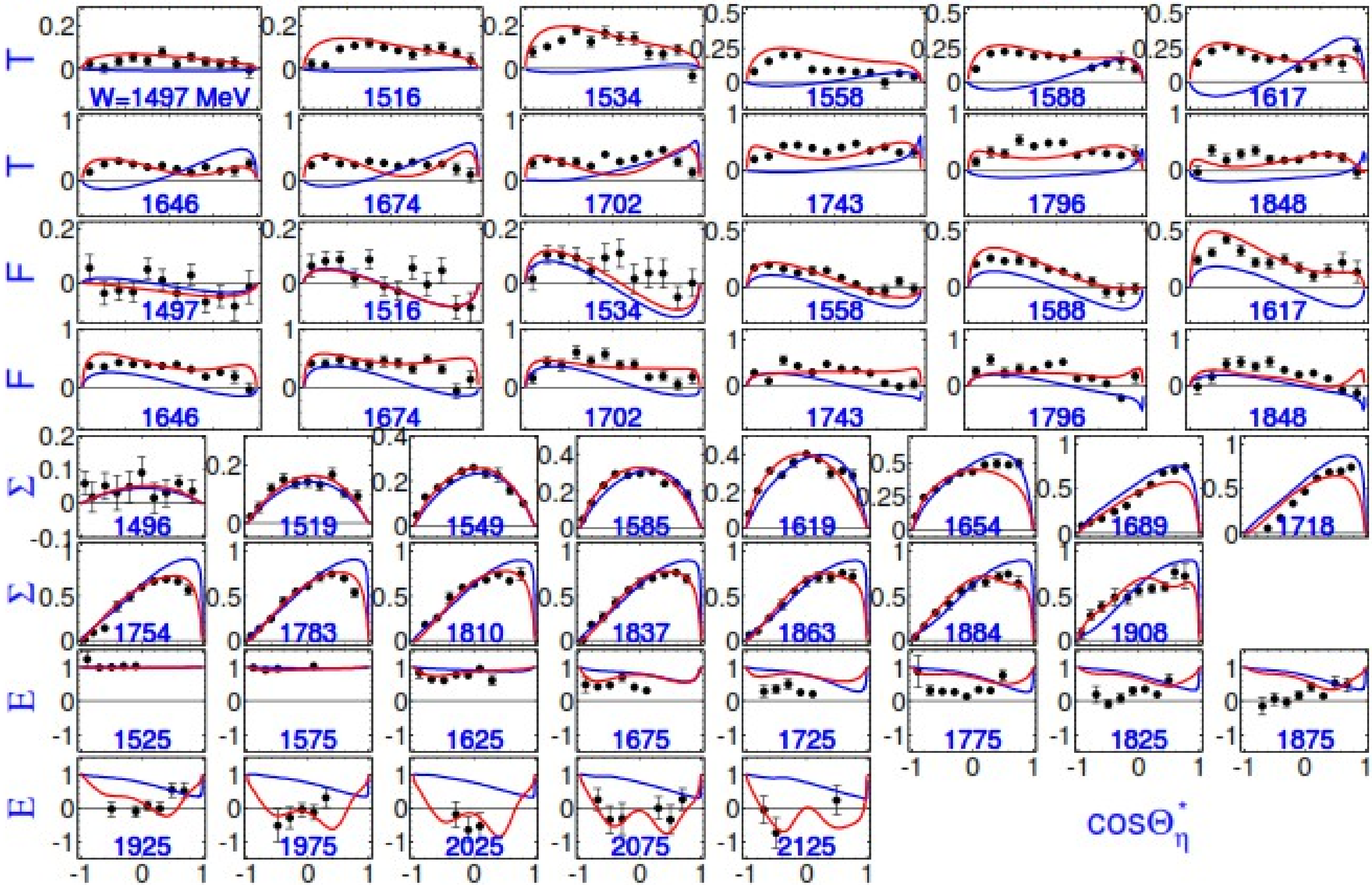
Data and ηMAID full solution

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

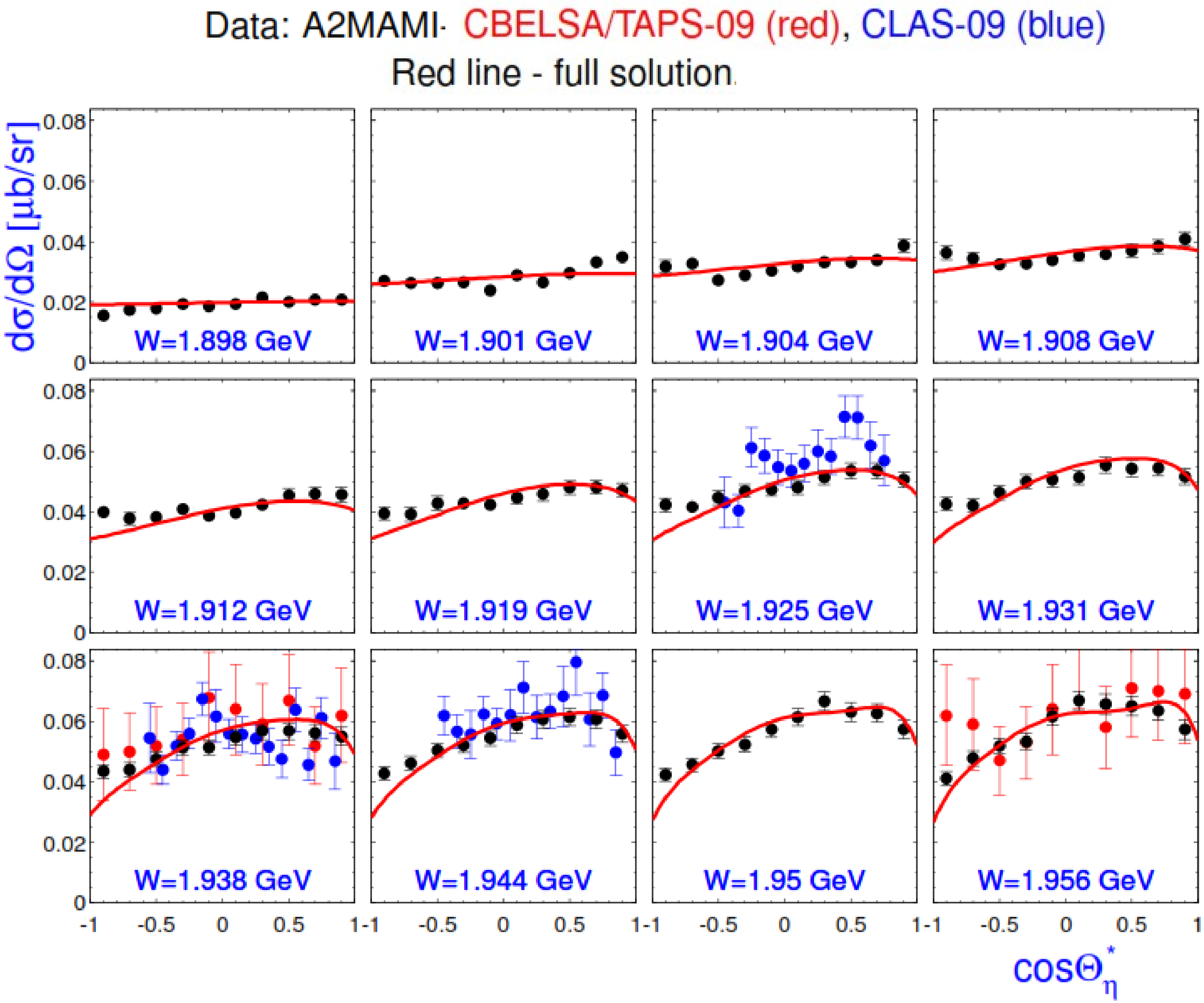
Single η production

T, F, Σ , and E for $\gamma p \to \eta p$

Data: A2MAMI-15 (T,F), GRAAL-07 (Σ), CLAS-15 (E). Red - full solution, - ηMAID03.



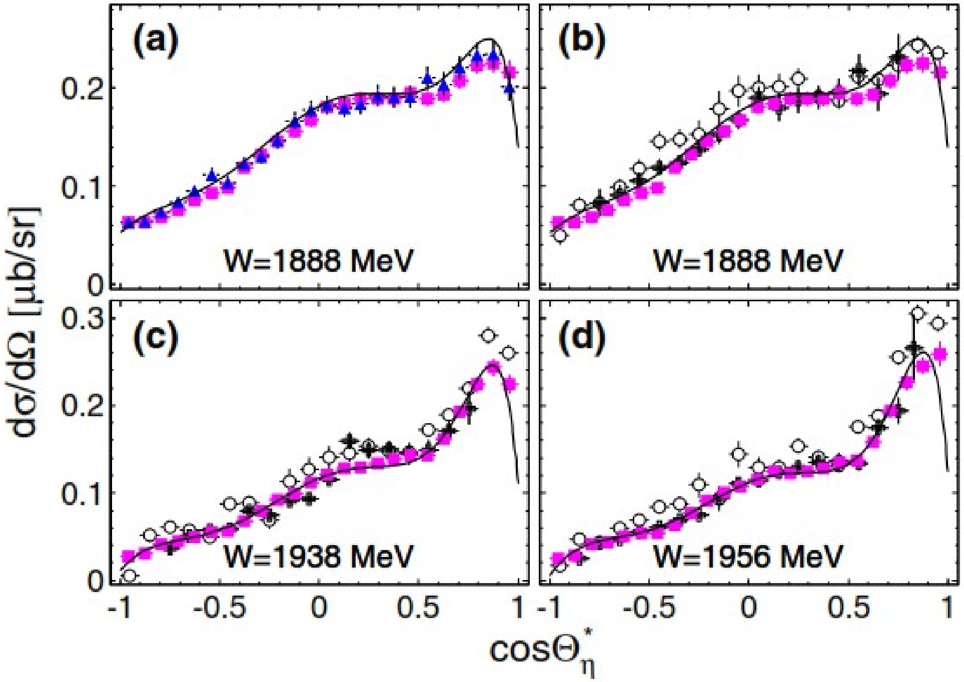
Single η' production



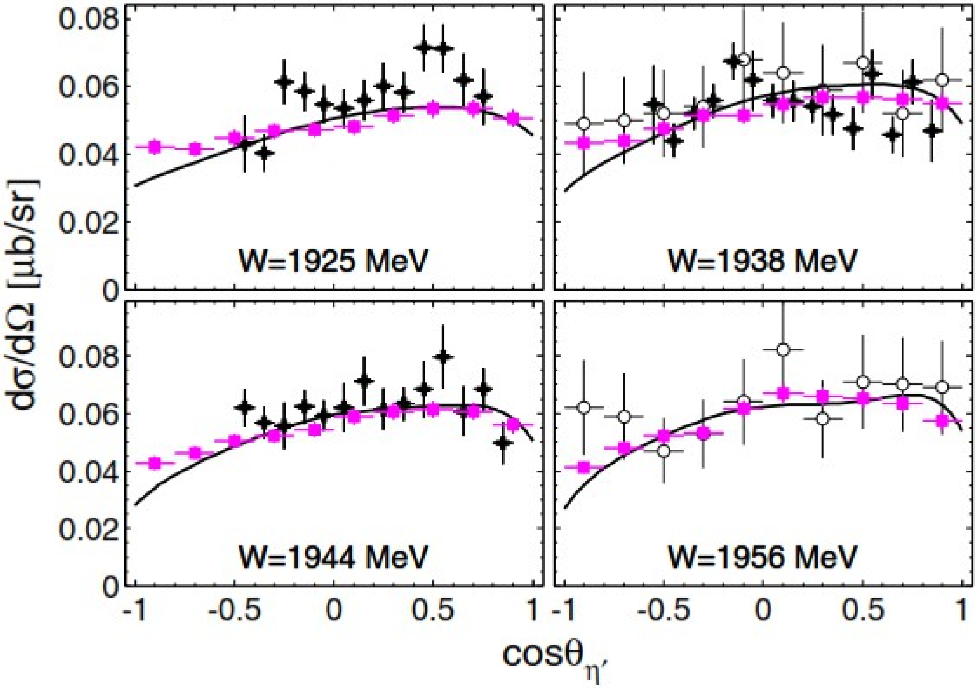
V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

Single η and η' production

Single η production



Single η' production



Magenta squares and blue triangles: A2, open circles: CBELSA/TAPS, black crosses: CLAS, curve: ηMAID (2017)

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

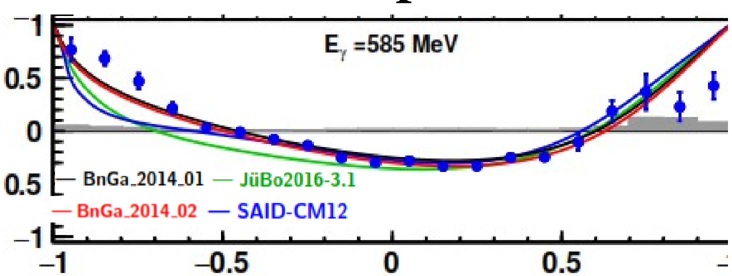
- **Overall: Good agreements with CLAS and CBELSA/TAPS data**
- **In some bins systematic discrepancies (upto 10%) with CBELSA/TAPS data**

Single meson production: data on polarization observables

Photon Polarization		Target Polarization		
		x	y	z
unpolarized	σ	–	T	–
linearly polarized	Σ	H	P	G
circularly polarized	–	F	–	E

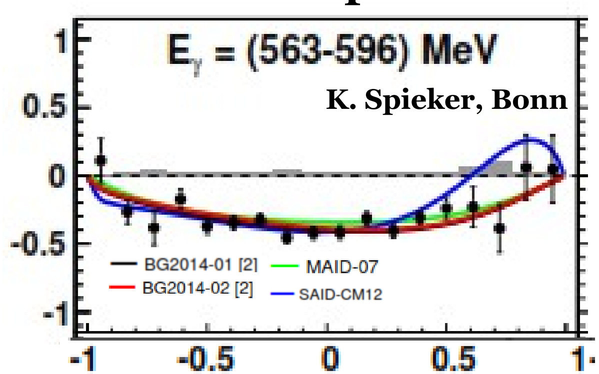
$$\begin{aligned}\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}(\theta)\cdot\Big[1 &- p_\gamma^{lin}\Sigma\cos(2\phi)\\ &+ p_x(-p_\gamma^{lin}H\sin(2\phi)+p_\gamma^{circ}F)\\ &- p_y(-T+p_\gamma^{lin}P\cos(2\phi))\\ &- p_z(-p_\gamma^{lin}G\sin(2\phi)+p_\gamma^{circ}E)\Big]\end{aligned}$$

E for pπ°

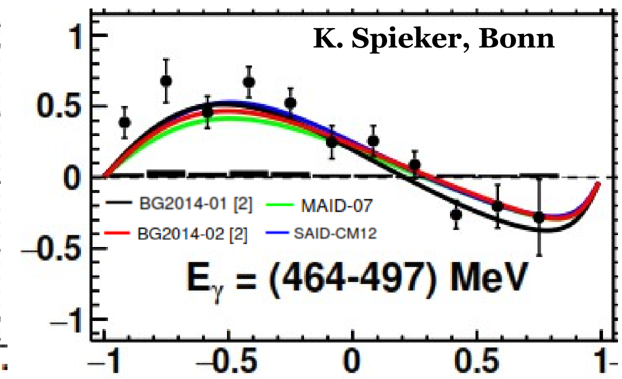


F. Afzal, Bonn

G for pπ°

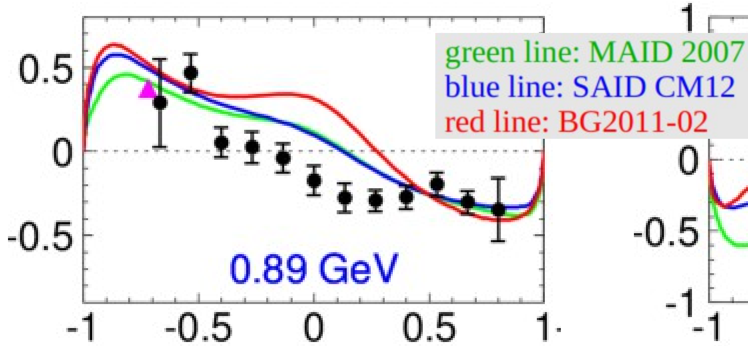


G for nπ⁺

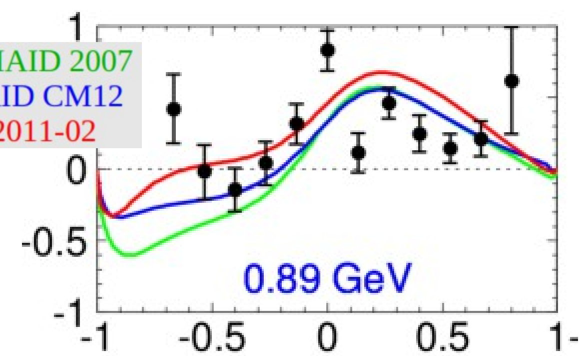


All data preliminary!

T for nπ⁺

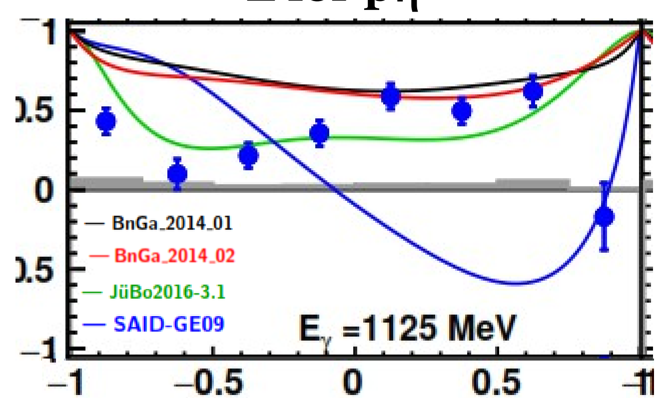


F for nπ⁺



F. Afzal, Bonn

E for pη



F. Afzal, Bonn

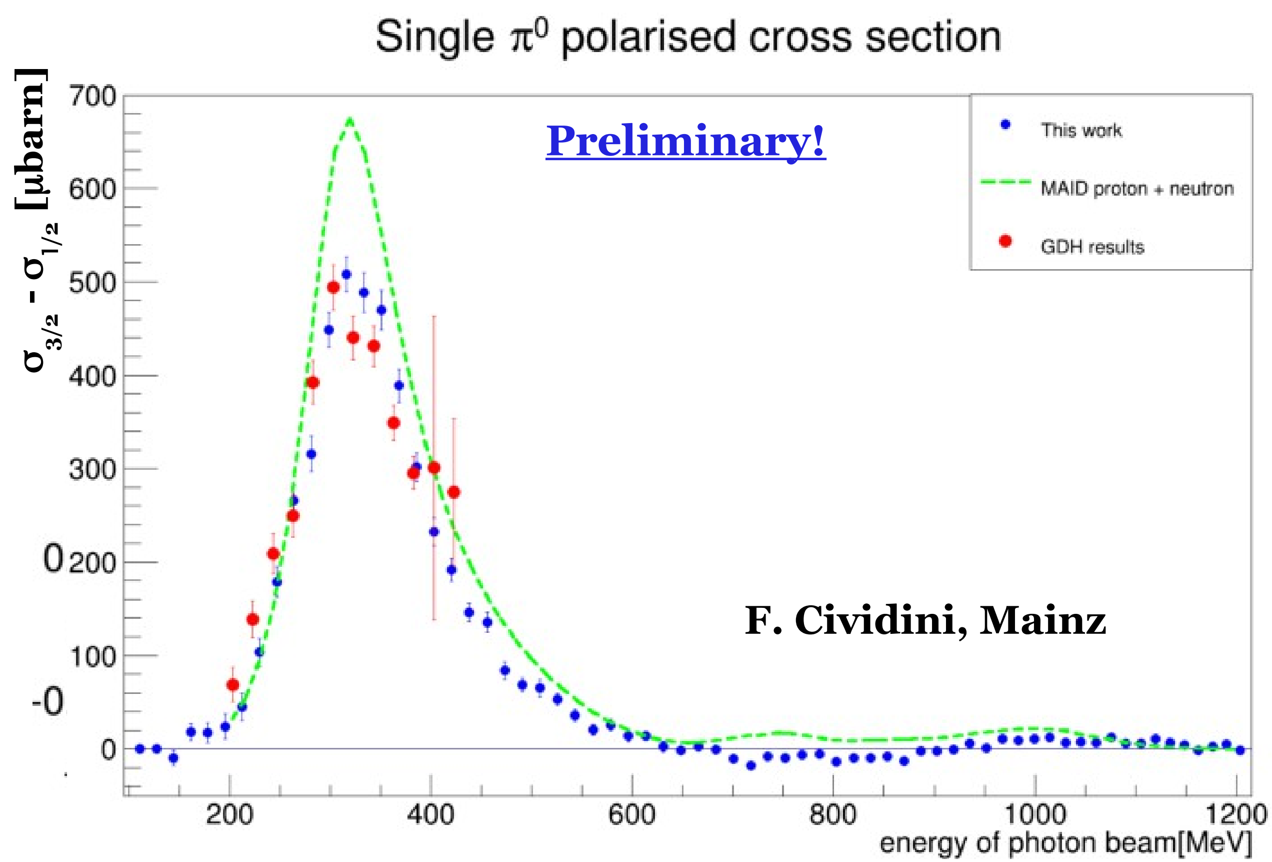
- **See talk of Natalie Walford for further results: 22.08.2017, Parallel Session (A2), 14:30**
- Data on beam asymmetry Σ published for 1214 < W < 1450 MeV (S. Gardner et al., Eur.Phys.J. A52 (2016) no.11, 333)
- New data taken on Σ for single π° for determination of E2/M1 ratio with improved systematics

Single meson production: data on polarization observables

		Target Polarization		
Photon Polarization		x	y	z
unpolarized	σ	–	T	–
linearly polarized	Σ	H	P	G
circularly polarized	–	F	–	E

$$\begin{aligned}\frac{d\sigma}{d\Omega} = & \frac{d\sigma}{d\Omega}(\theta)\cdot\Big[1 - p_\gamma^{lin}\Sigma\cos(2\phi)\\ & + p_x(-p_\gamma^{lin}H\sin(2\phi) + p_\gamma^{circ}F)\\ & - p_y(-T + p_\gamma^{lin}P\cos(2\phi))\\ & - p_z(-p_\gamma^{lin}G\sin(2\phi) + p_\gamma^{circ}E)\Big]\end{aligned}$$

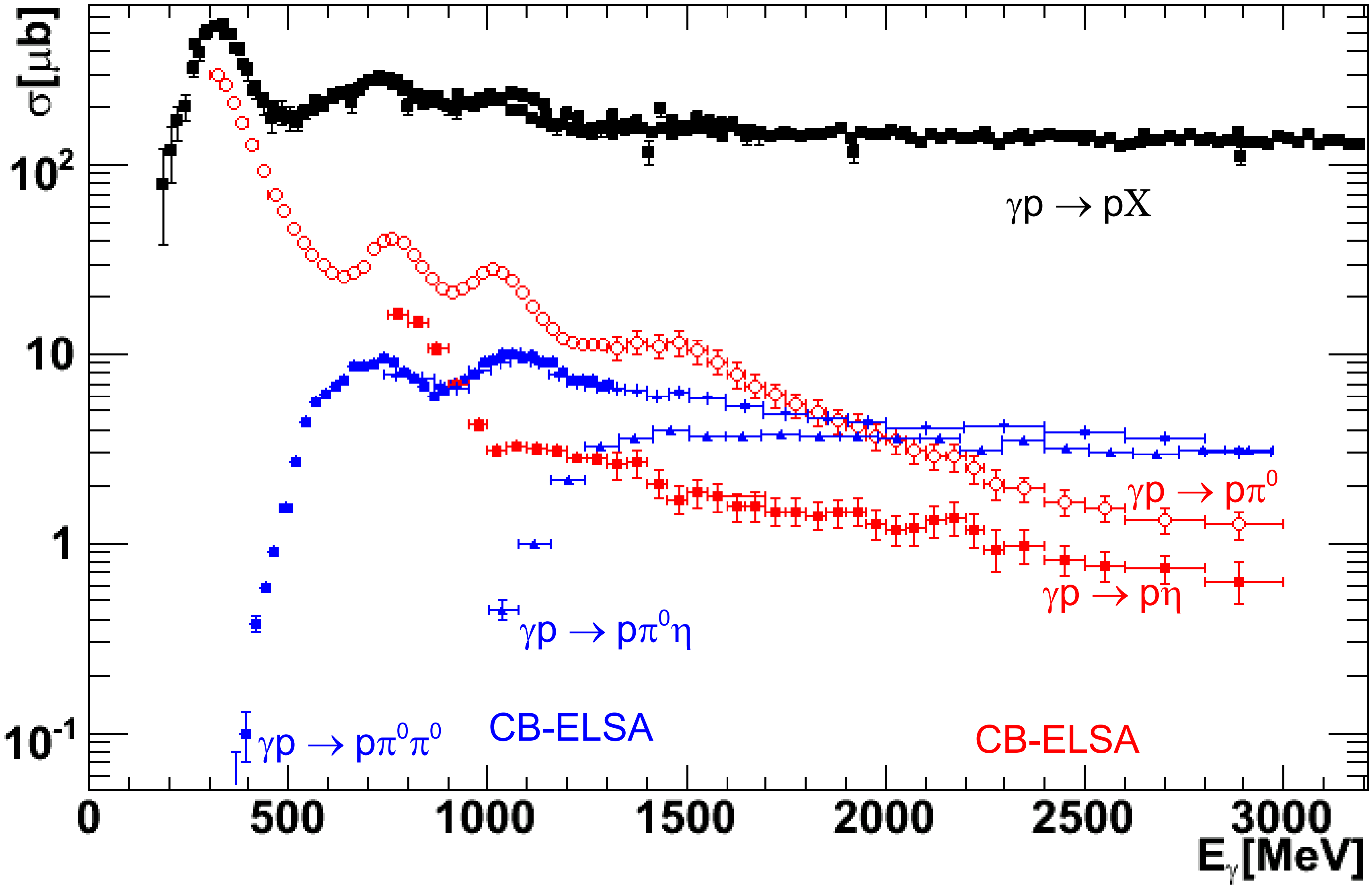
- Extraction of E for nucleons bound in deuteron in progress
- Total inclusive polarized cross-section difference extracted for π^0 production
- Extraction of differential cross-sections in progress



- **See talk of Natalie Walford for further results: 22.08.2017, Parallel Session (A2), 14:30**

Double meson photoproduction

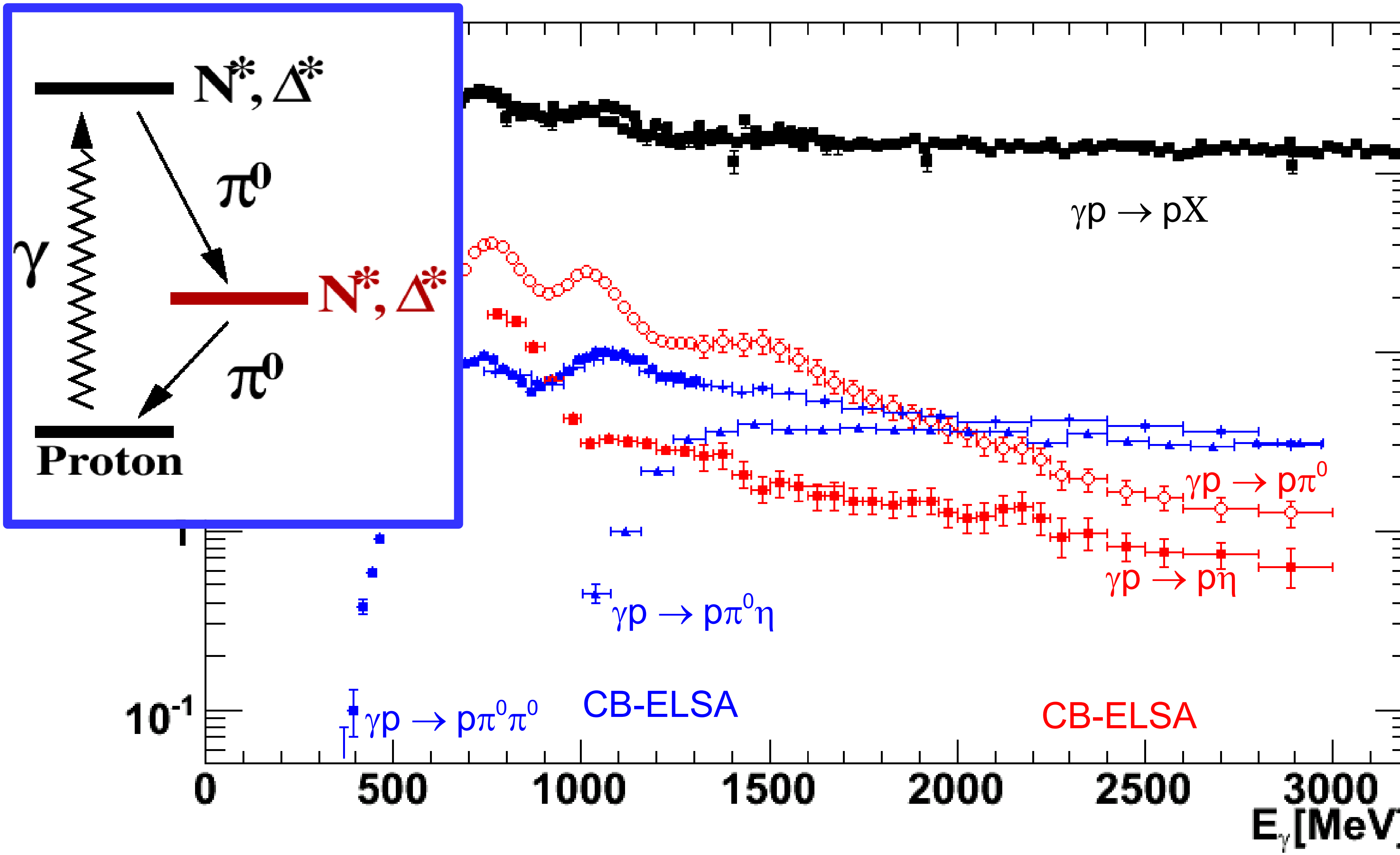
Goal: Gain a good understanding of the spectrum and properties of baryon resonances



- At high energies: Multi-meson final states play a role of increasing importance!

Double meson photoproduction

Goal: Gain a good understanding of the spectrum and properties of baryon resonances



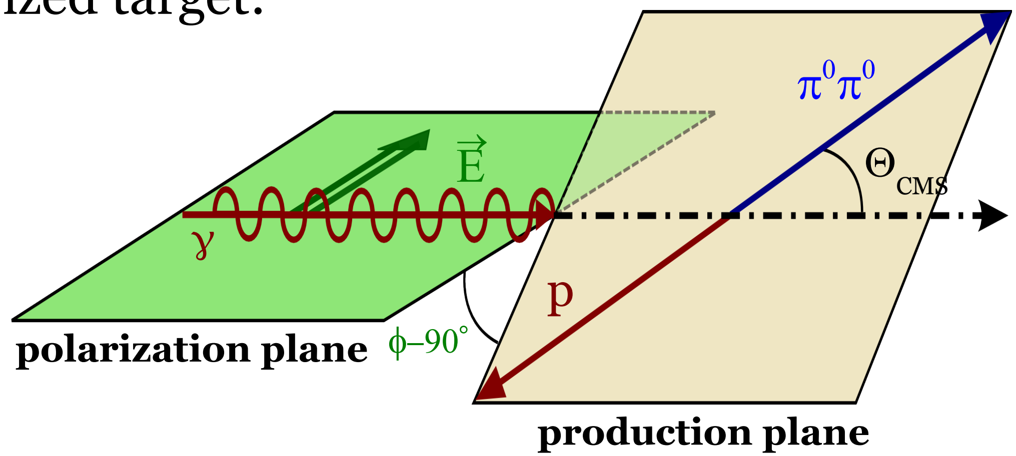
- At high energies: Multi-meson final states play a role of increasing importance!
- Access to resonances with cascading decays

Double pion production (I^s and I^c)

Linearly polarized photon beam, unpolarized target:

Quasi two-body consideration:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 + \delta_l \Sigma \cos(2\phi)]$$

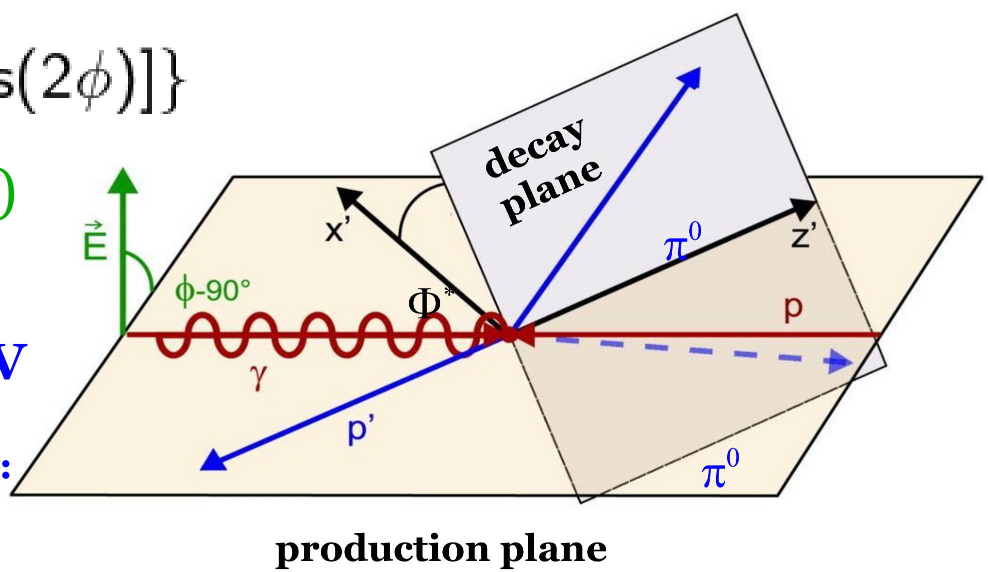


- Three-particle final state: additional plane!
- Additional polarization observables!

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \{1 + \delta_l [I^s \sin(2\phi) + I^c \cos(2\phi)]\}$$

$I^c(\Phi^*) = I^c(2\pi - \Phi^*)$, $I^s(\Phi^*) = -I^s(2\pi - \Phi^*)$

First measurement of I^s and I^c in $\vec{\gamma}p \rightarrow p\pi^0\pi^0$ at energies below ~700 MeV

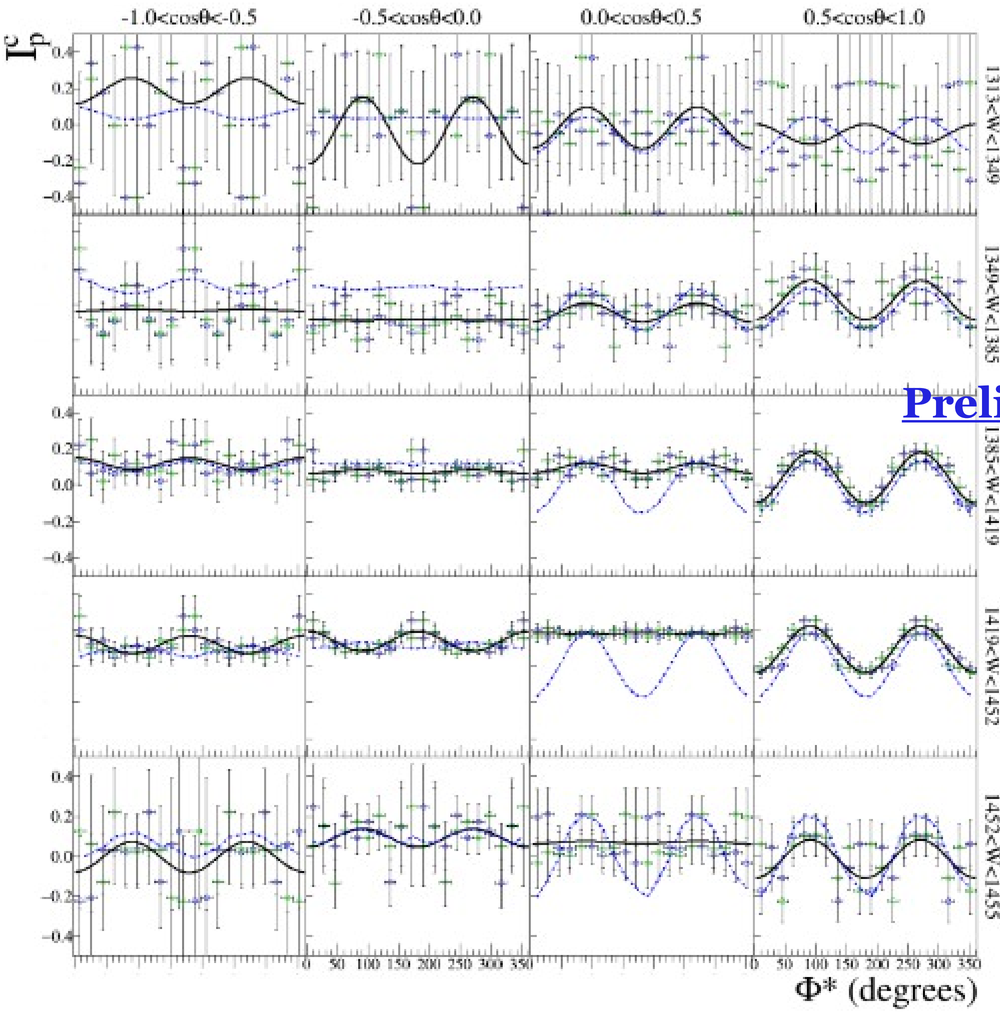


Data from CBELSA/TAPS above 1 GeV had a high impact on PWA:

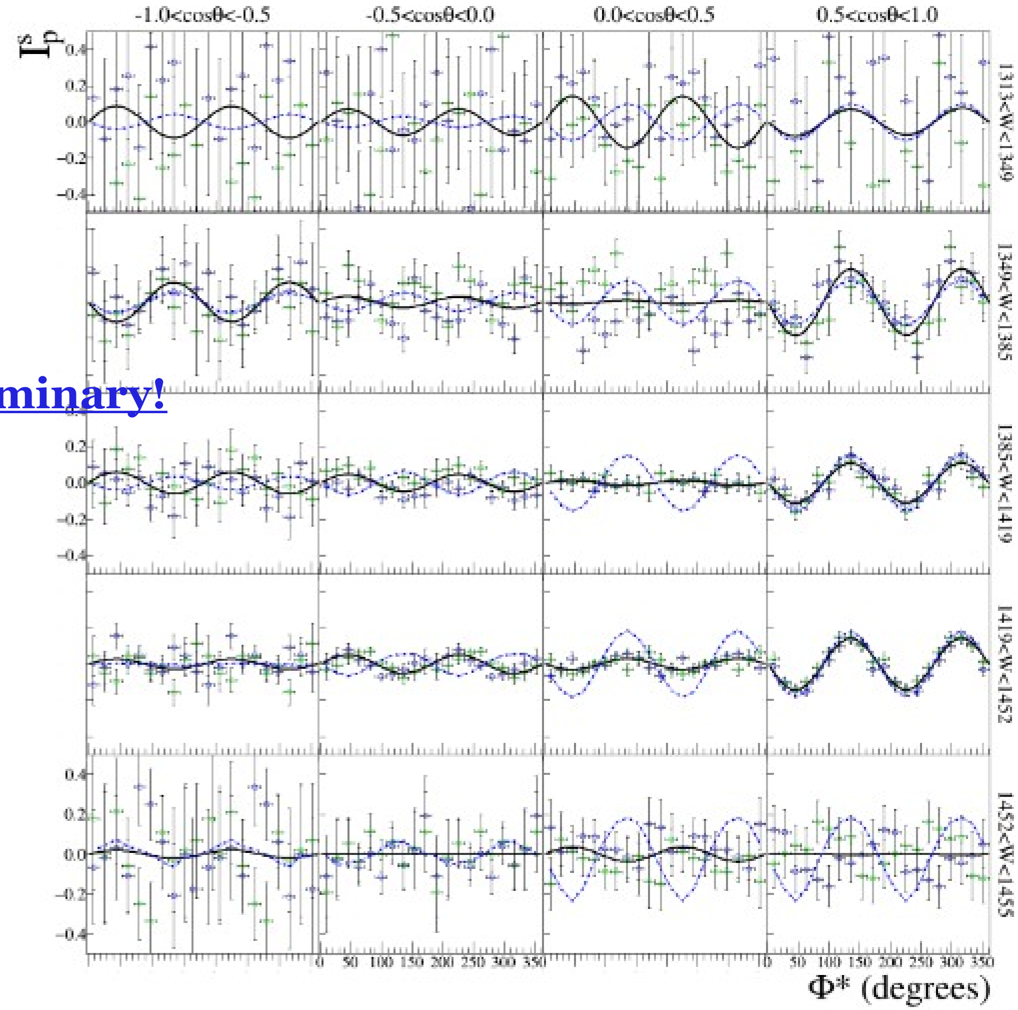
V. S. , E. Gutz, H. Pee, et al., Phys.Lett. B746 (2015) 127-131
V. S. , E. Gutz , V. Crede , H. Pee, et al., Eur.Phys.J. A51 (2015) no.8, 95

Double pion production (I^s and I^c)

$I^c(\Phi^*) = I^c(2\pi - \Phi^*)$



$I^s(\Phi^*) = -I^s(2\pi - \Phi^*)$



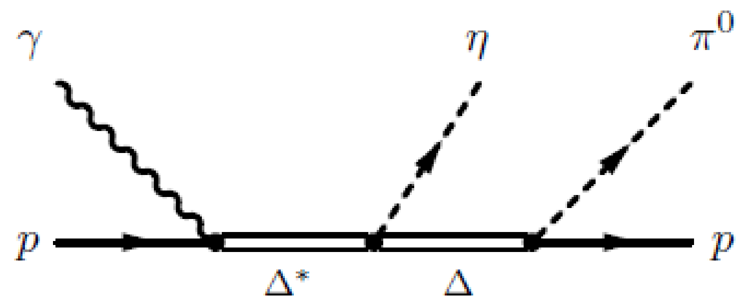
Preliminary!

Solid curve: fit to the data with third order cosine/sine series,
dashed curve: BnGa PWA 2014 from (E. Gutz , V. Crede, V. S., H. van Pee, et al., Eur.Phys.J. A50 (2014) 74)

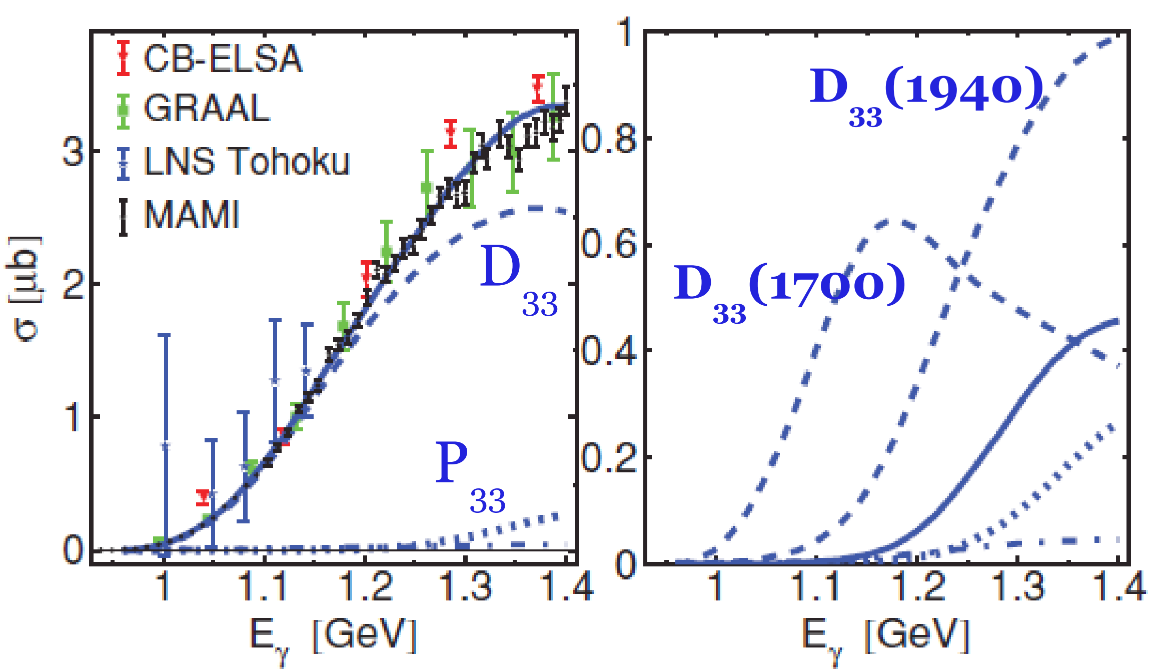
Significant differences between data and BnGa PWA predictions!

$\pi^0\eta$ photoproduction (proton target)

- The production of $\pi^0\eta$ pairs best suited to study the $D_{33}(1700)$ resonance
- η acts as an isospin filter: Access to $\gamma p \rightarrow D_{33}(1700) \rightarrow \Delta(1232)\eta \rightarrow p\pi^0\eta$

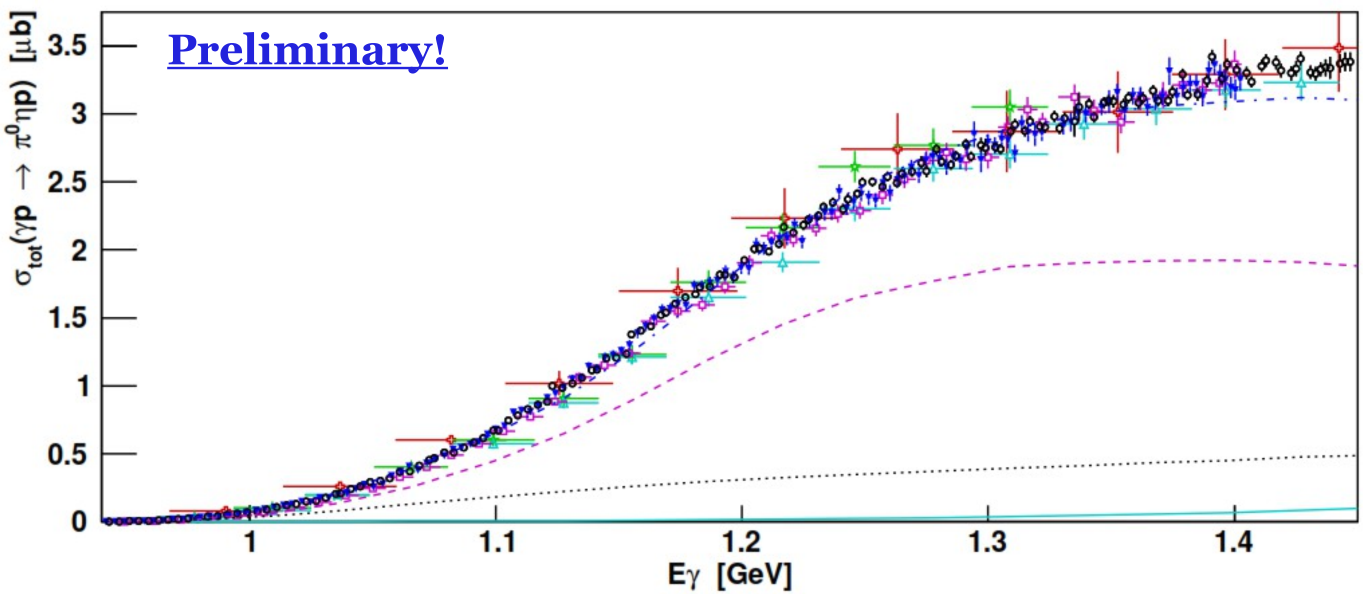


- $D_{33}(1700)$ dominates close to the production threshold



V. L. Kashevarov, A. Fix et al., Eur. Phys., J. A 42, 141, 2009 (A2 Collaboration)

$\pi^0\eta$ production off the proton



Run I (blue solid triangles)
Run II (black open circles)
CBELSA/TAPS: green stars
CBELSA/TAPS: cyan open triangles
GRAAL: red open crosses
A2 (2009): magenta open squares

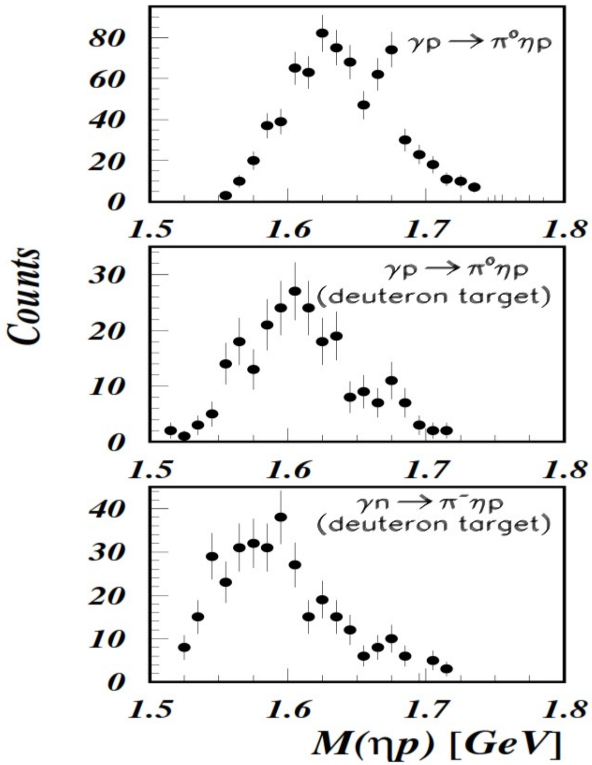
BnGA PWA: blue dash-dotted line
$\gamma p \to \Delta(1232)\eta$: magenta dashed
$\gamma p \to S11(1535)\pi^0$: black dotted
$\gamma p \to a_0(980)p$: cyan solid

New data set:

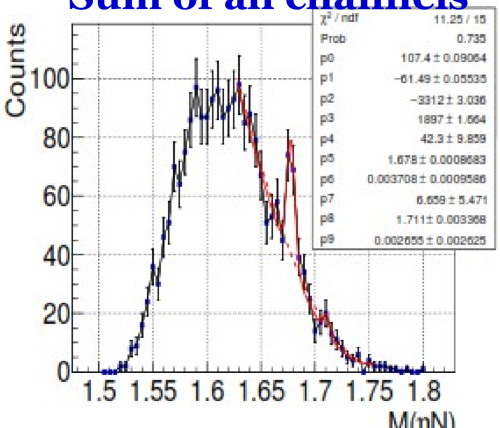
- Improved statistics: More than 1.500.000 events for the unpolarized cross-section and more than 1.000.000 events in the polarized sample
- Kinematic fit applied
- Event-based data (5D) sample obtained
- Finer binning and extension of the energy coverage to the threshold region
- Total cross-section, angular distributions, Dalitz plots and beam helicity asymmetry extracted → input for PWA with a potentially high impact

$\pi^0\eta$ production off the proton

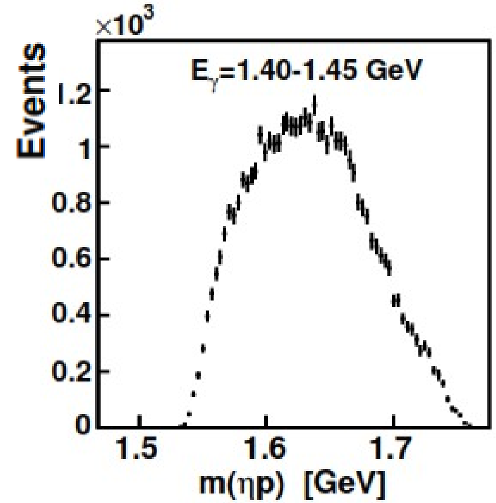
GRAAL data: $E\gamma$ = 1.4 – 1.5 GeV
$m(\pi^0N)$ < 1.2 GeV

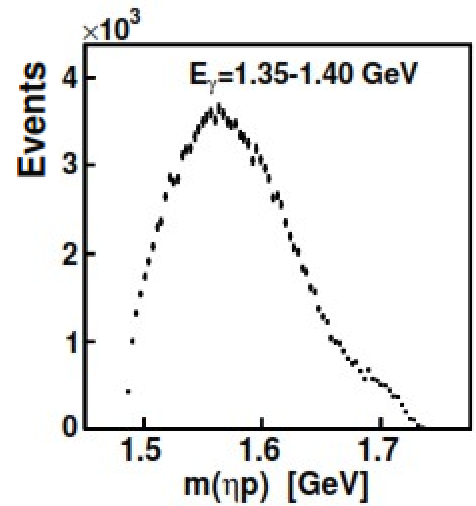


Sum of all channels

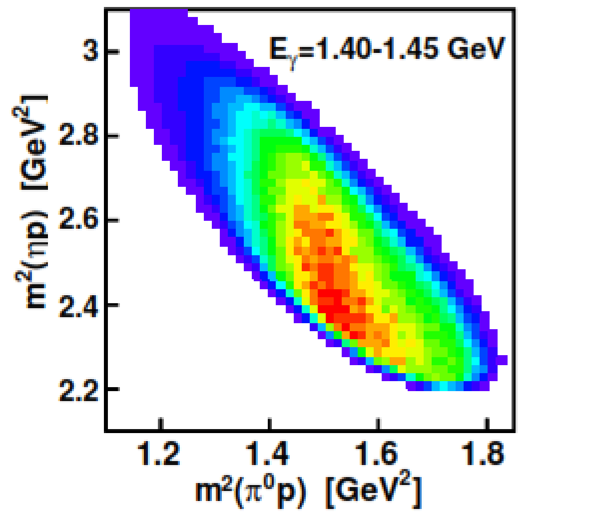


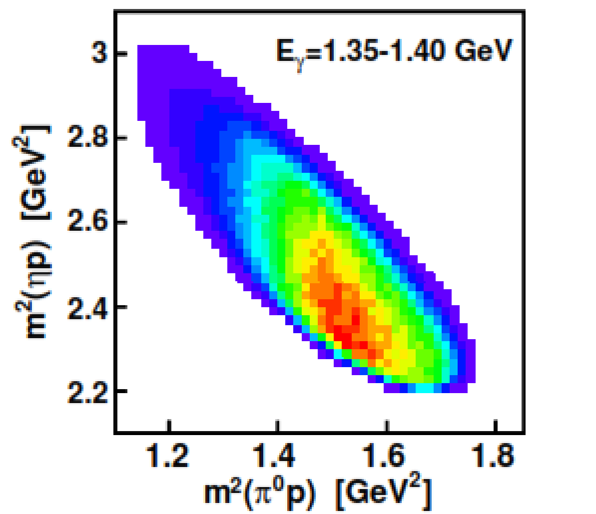
A2 data for $\pi^0\eta$ ($m(\pi^0N)$ < 1.2 GeV)





A2 data ($\pi^0\eta$)



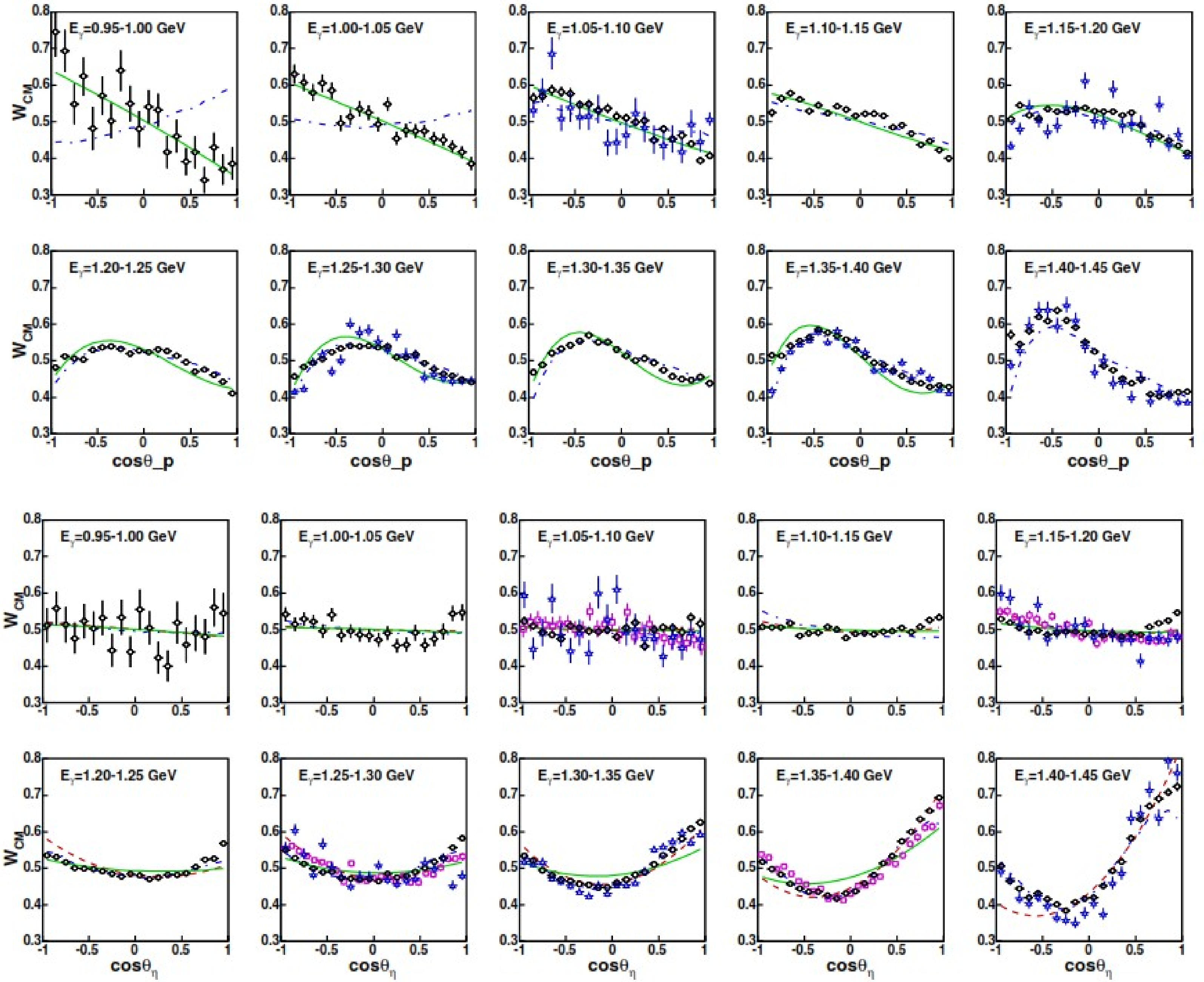


No signature of narrow N(1685) resonance in the A2 data!

V. Kuznetsov, et al., arXiv:1705.05177

$\pi^0\eta$ production off the proton

Preliminary!

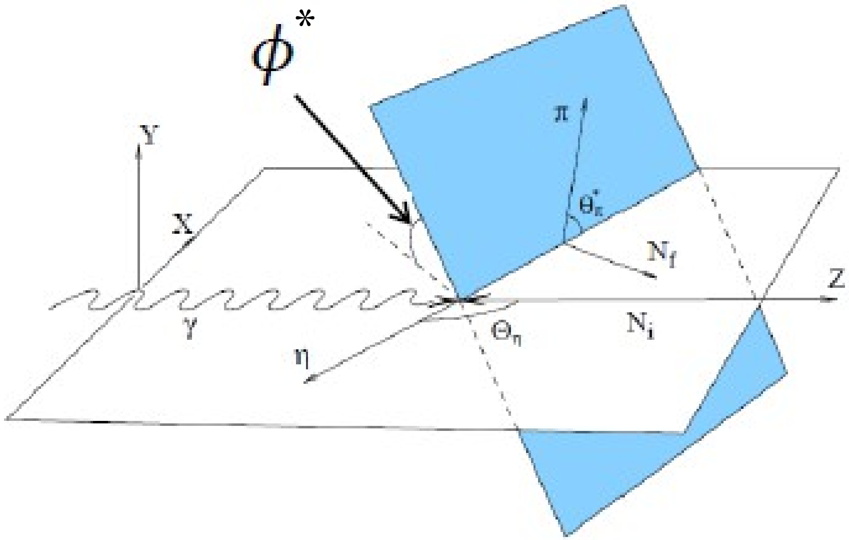


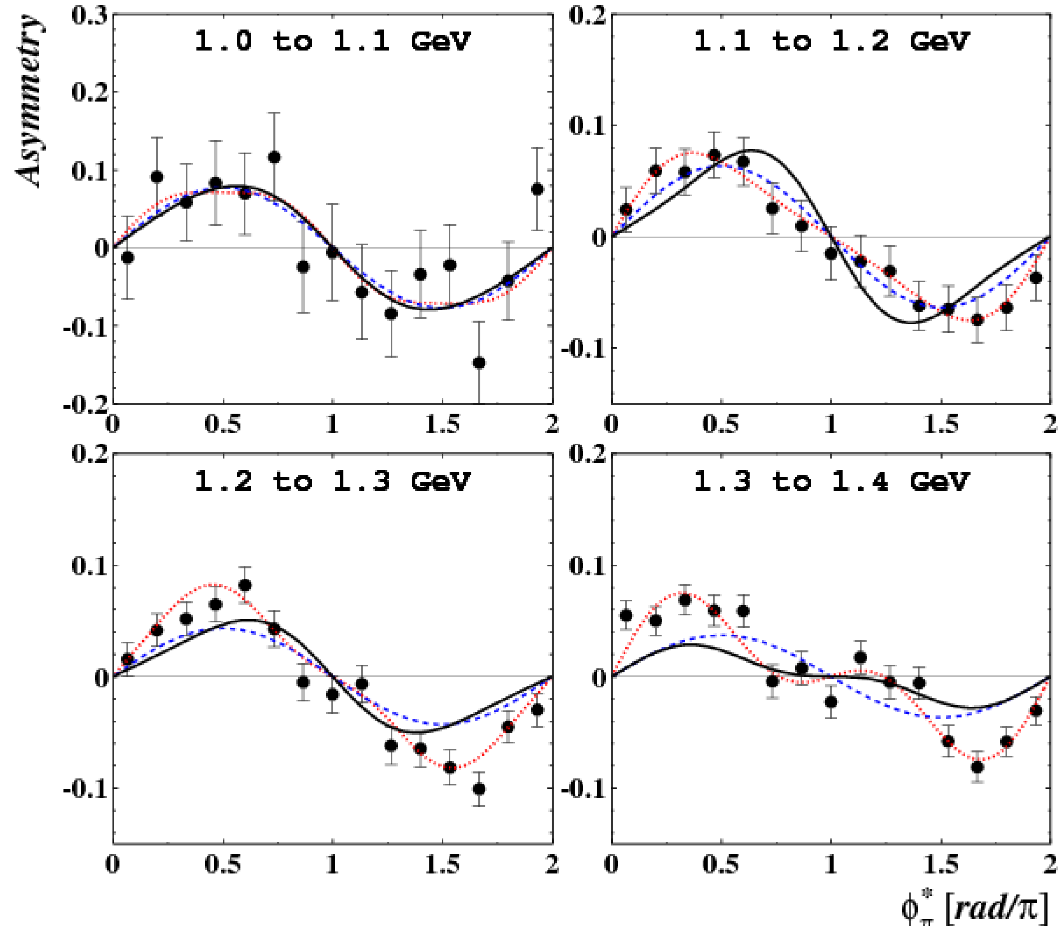
Run I and Run II (open circles), with
CBELSA/TAPS: blue stars
A2 (2009): magenta open squares (at close energies)

Predictions:
BnGa PWA (2014): blue dash-dotted line
MaTm model: red dashed line

Fit of MaTm model to the present data: solid green line

$\pi^0\eta$: Beam helicity asymmetry (proton target)





Beam helicity asymmetry:

$$W^c(\phi) \sim \sigma^+(\phi) - \sigma^-(\phi)$$

$W^c(\phi)$ can be expanded as:

$$W^c(\phi) = \sum_{n=1}^{n_{max}} A_n \sin n\phi$$

Dotted line: fit with the first 3 terms of the sine expansion (A1, A2, A3)
Solid line: isobar model with 6 resonances
Dashed line: only D33 wave

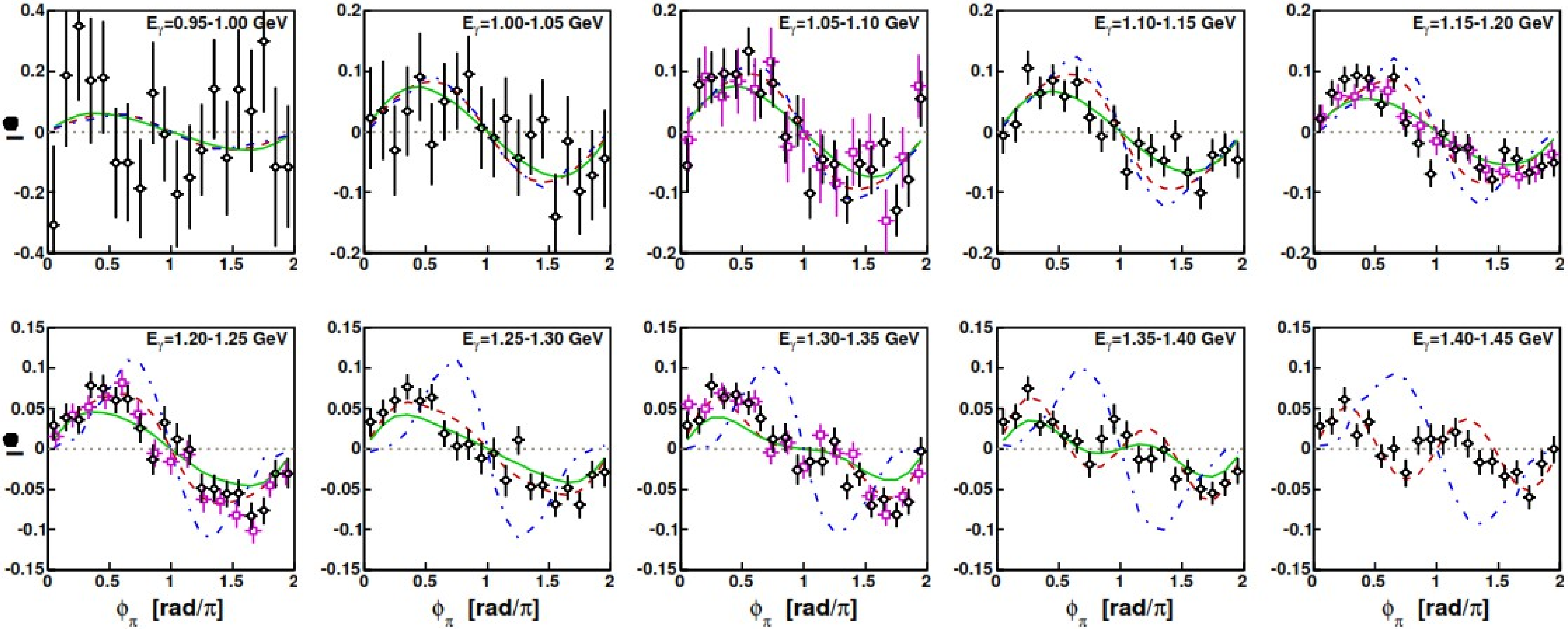
V. L. Kashevarov, et al., Phys. Lett. B 693, 551 (2010)

[A2 Collaboration]

Both unpolarized and polarized data indicate the dominance of the D_{33} wave at energies $E_\gamma < 1.2$ GeV

$\pi^0\eta$: Beam helicity asymmetry (proton)

Preliminary!



Run I and Run II (open circles)

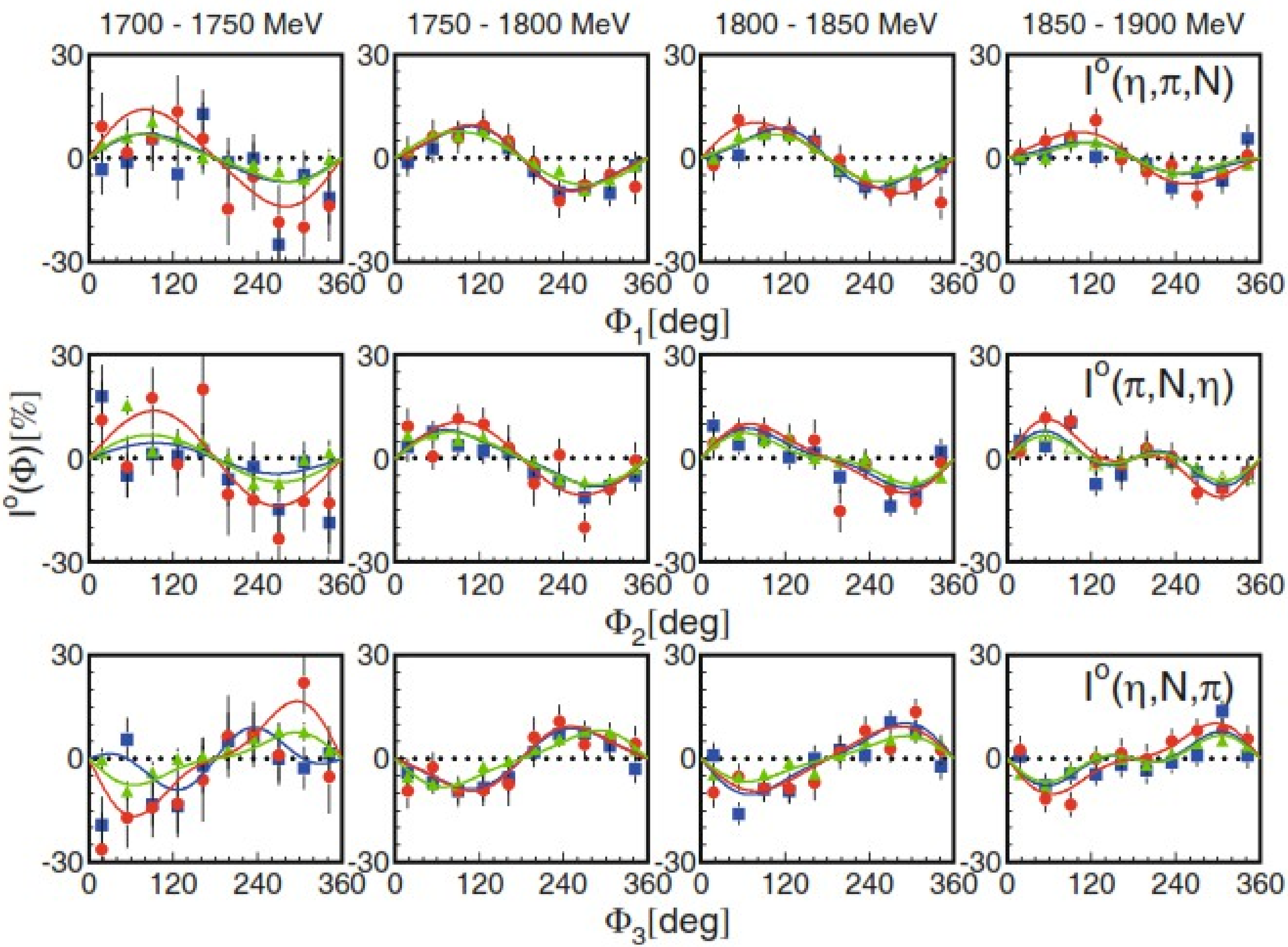
Predictions:
BnGa PWA (2014): blue dash-dotted line
MaTm model: red dashed line

Fit of MaTm model to the present data: solid green line

- Significant differences at high energies between data and BnGa PWA
- High impact can be expected
- 4-vectors provided to the BnGa PWA group

(Data analysis finished, MaTm model calculations in progress)

$\pi^0\eta$: Beam helicity asymmetry (deuteron)



A. Käser , F. Müller, Eur.Phys.J. A52 (2016) no.9, 272 (A2 Collaboration)

free proton
quasifree proton
quasifree neutron

Curves: fit to the data

$$I^{\odot}(\Phi) = \sum_{n=1}^{\infty} A_n \sin(n\Phi)$$

Final State Interaction (FSI) is practically not affecting the asymmetry signal

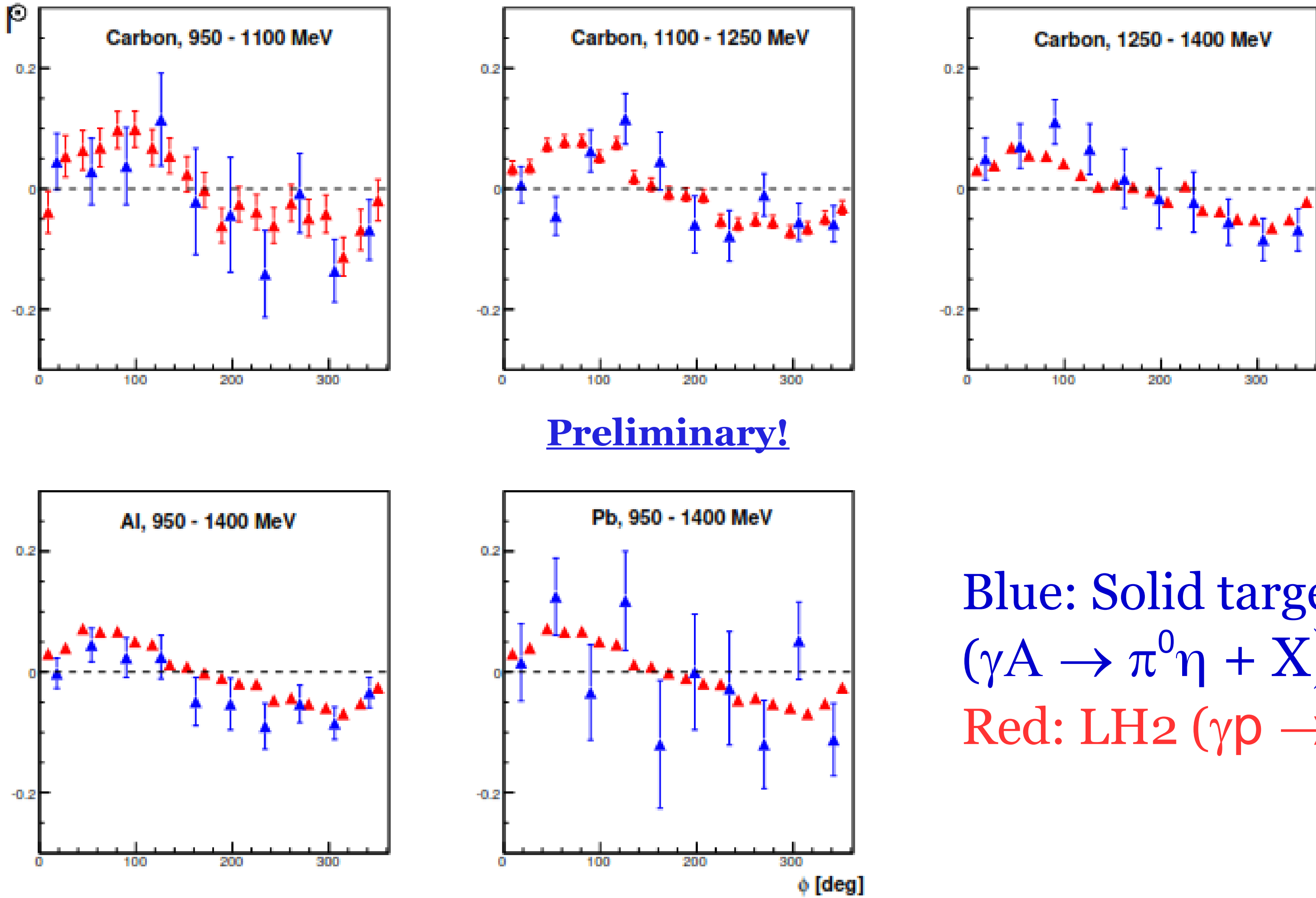
Production of $\pi^0\eta$ off nuclei

- Second resonance region: No strong experimental indication for significant modifications of $D_{13}(1520)$ or $S_{11}(1535)$
- The structure in these observables is reasonably described by the $D_{33}(1700)$ resonance within the isobar model for the proton target at $E_\gamma < 1.2$ GeV (A. Fix, et al.)

New experiments performed at MAMI:

- Search for modifications of the $D_{33}(1700)$ resonance
- First measurement of the beam helicity asymmetry for the investigation of in-medium modifications in addition to differential cross-sections
- Comparison with free proton data
- Better understanding of the Final State Interaction (FSI)

Beam helicity asymmetry for $\pi^0\eta$ (solid targets)



Blue: Solid targets
$(\gamma A \rightarrow \pi^0\eta + X)$
Red: LH2 $(\gamma p \rightarrow p\pi^0\eta)$

- First measurement of the beam helicity asymmetry with heavy targets
- Good Agreement between LH2 and solid target data

➔ Final State Interaction is practically not affecting the asymmetry signal (absorption but no rescattering similarly with deuteron results?)

➔ The D33(1700) resonance signal remains practically unchanged

➔ Extraction of unpolarized cross-sections in progress

Summary

- High statistics data sets on π^0, η, η', $2\pi^0$, $\pi^0\eta$,... production obtained
- Possibilities for experiments with high-intensity photon beam (circularly or linearly polarized), polarized and unpolarized targets hydrogen and deuteron targets, recoil polarimeter
- Helium and heavier (solid) targets
- Single and double polarization observables extracted with high precision
- In the future, extension of the program performed for protons to the neutron (deuteron or helium targets)

A2 — mami MAINZER MIKROTRON — SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

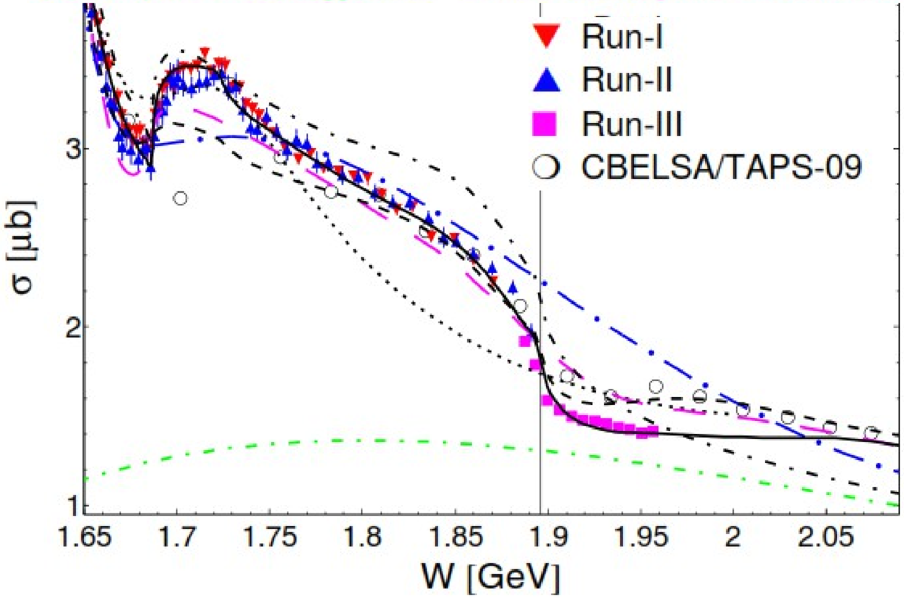
Thank you for your attention!

Backup

Single η and η' production

Black lines: full solution (solid), background (dashed), $S_{11} + bg$ (dash-dotted).

Green - ηMAID-2003Regge. Blue - SAID-GE09. Magenta - BnGa2014-2.

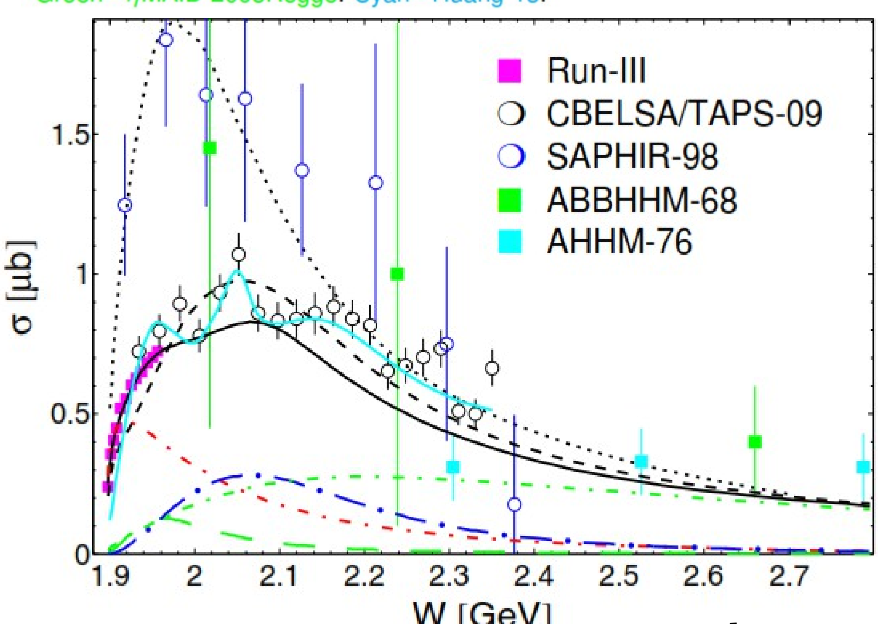


η

Particle	J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	***	****	***			***	**	**	***
$N(1675)$	$5/2^-$	****	***	****	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1700)$	$3/2^-$	***	**	***	*			*	*	*	***
$N(1710)$	$1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)$	$3/2^+$	****	***	****	***			**	**	**	*
$N(1860)$	$5/2^+$	**		**						*	*
$N(1875)$	$3/2^-$	***	***	*			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	**	*	**			**	*		

Black lines: full solution (solid), background (dashed), $N(1895)1/2^-$ (dash-dotted).

Green - ηMAID-2003Regge. Cyan - Huang-13.

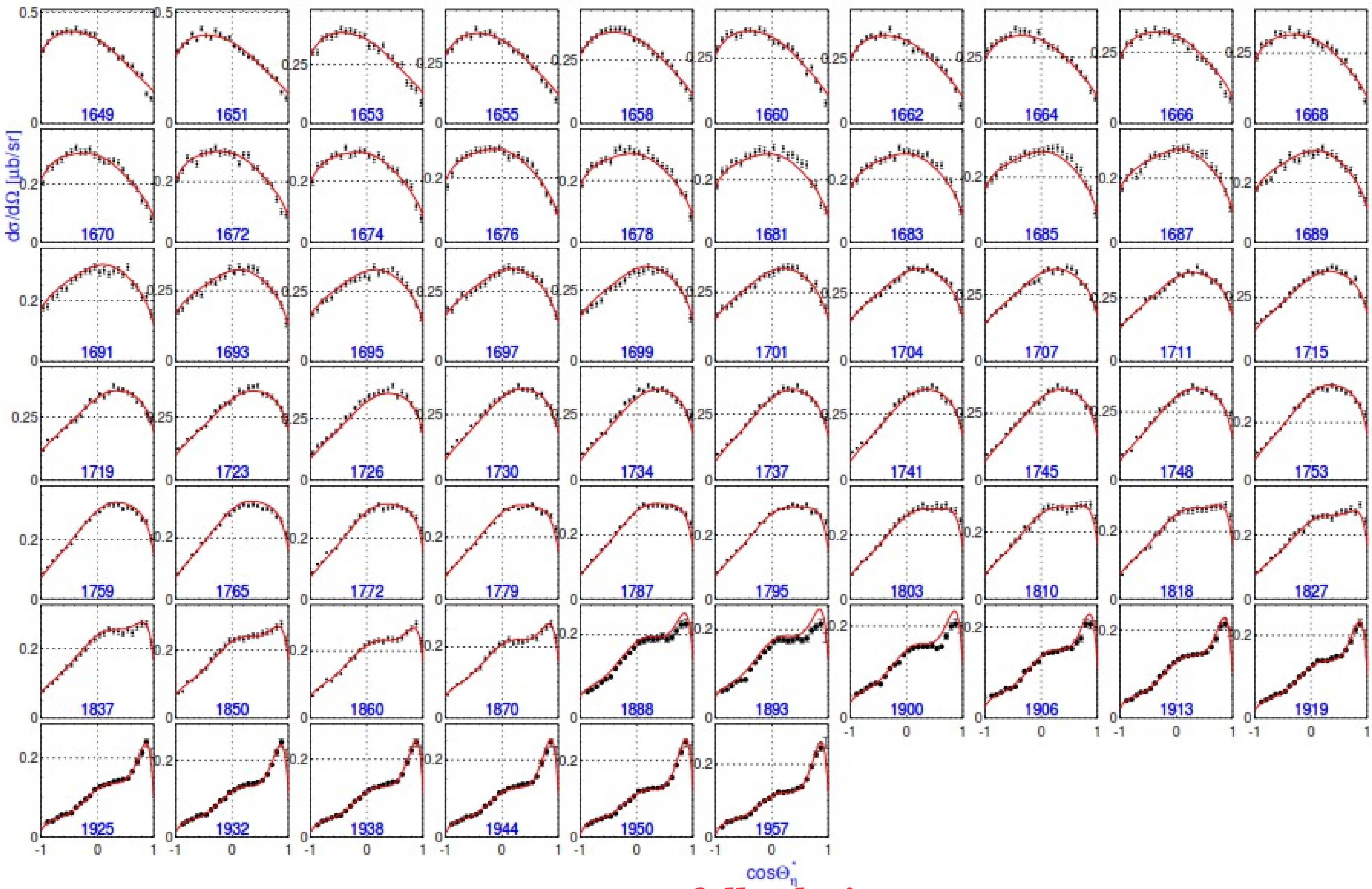


η'

Resonance J^P	M_{BW} [MeV]	Γ_{BW} [MeV]	$\beta_{\eta N}$ [%]	$A_{1/2}$
$N(1535)1/2^-$ ****	1528 ± 6 1535 ± 10	163 ± 25 150 ± 25	41 ± 4 42 ± 10	$+115$ $+115 \pm 15$
$N(1650)1/2^-$ ****	1634 ± 5 1655^{+15}_{-10}	128 ± 16 140 ± 30	28 ± 11 14–22	$+45$ $+45 \pm 10$
$N(1895)1/2^-$ **	1890^{+9}_{-23}	150 ± 57	20 ± 6	-30

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

Single η production



Data and ηMAID full solution

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

PRL eta/eta'

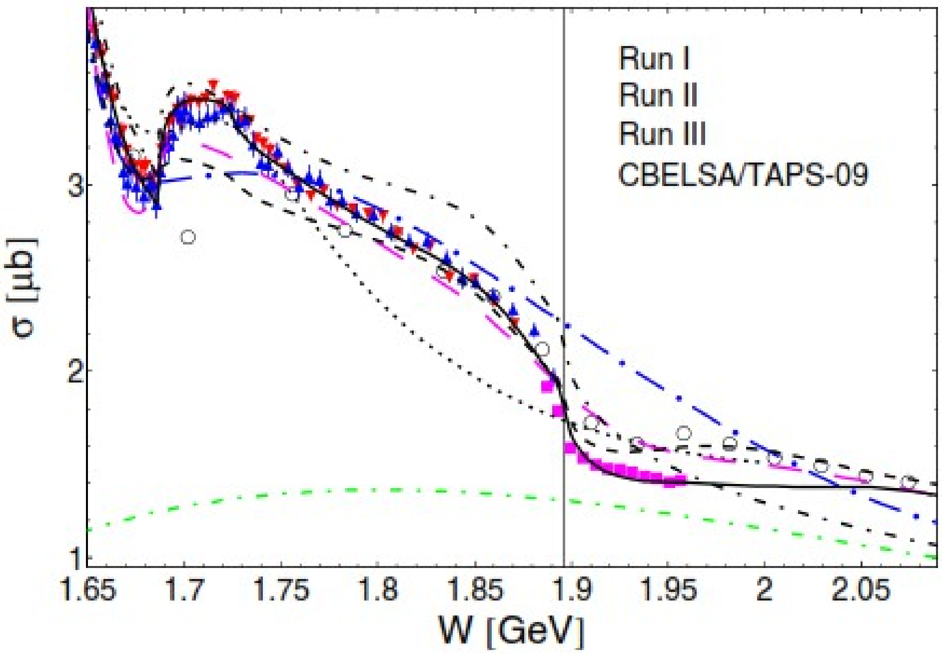


FIG. 6. $\gamma p \to \eta p$ total cross sections from this Letter compared to the previous measurements by CBELSA/TAPS [5] and to model calculations by ηMAID-2003 [13] (the black dotted line), SAID-GE09 [3] (the blue long-dashed-dotted line), BG2014-2 [8] (the magenta long-dashed line). The notation for the new ηMAID2017 solution and the meaning of the error bars are the same as in Fig. 4. The Regge background and its sum with the contributions from $N1/2^-$ resonances are shown by green and black dashed-dotted lines, respectively. The ηMAID2017 solution from the fit only to the previous η and η' data is shown by the black dashed line. The vertical line corresponds to the η' threshold.

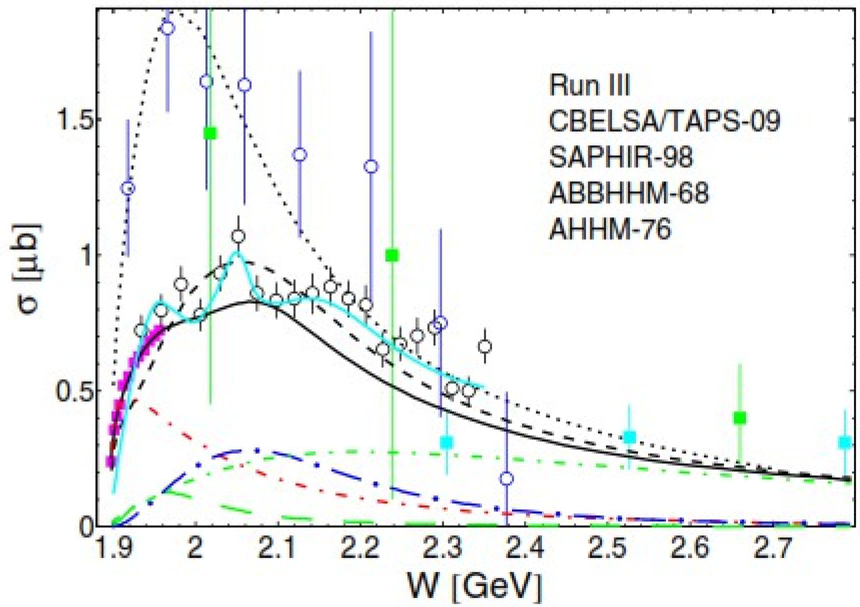
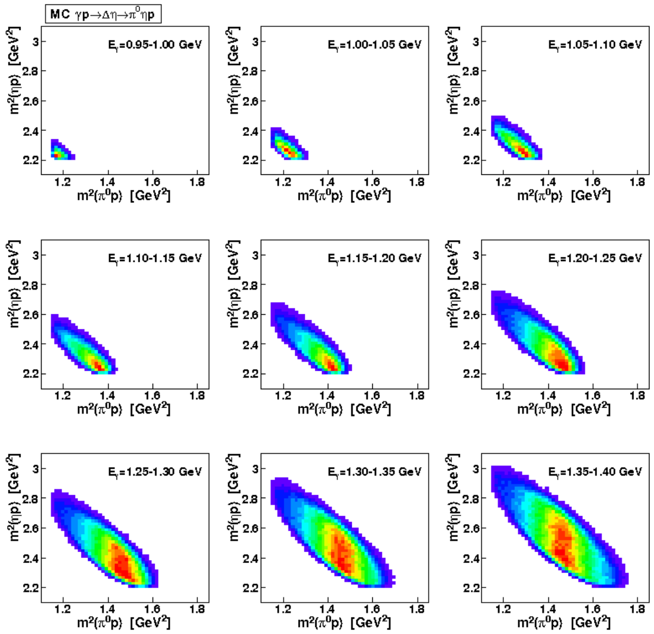
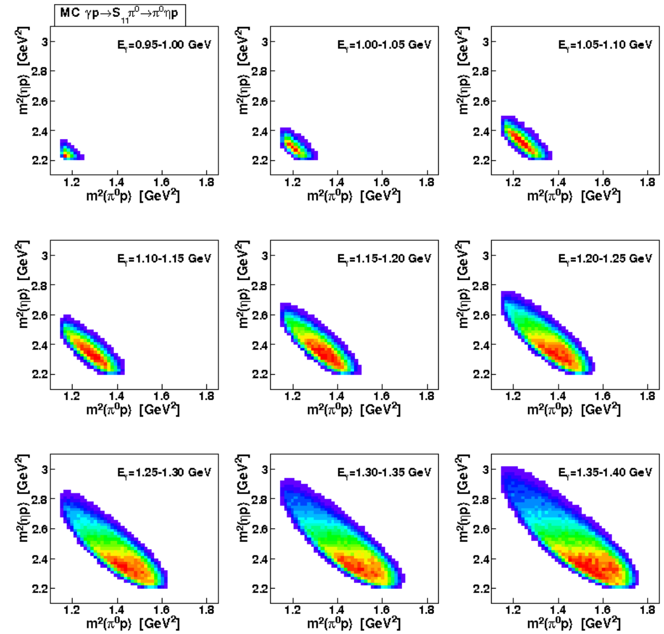
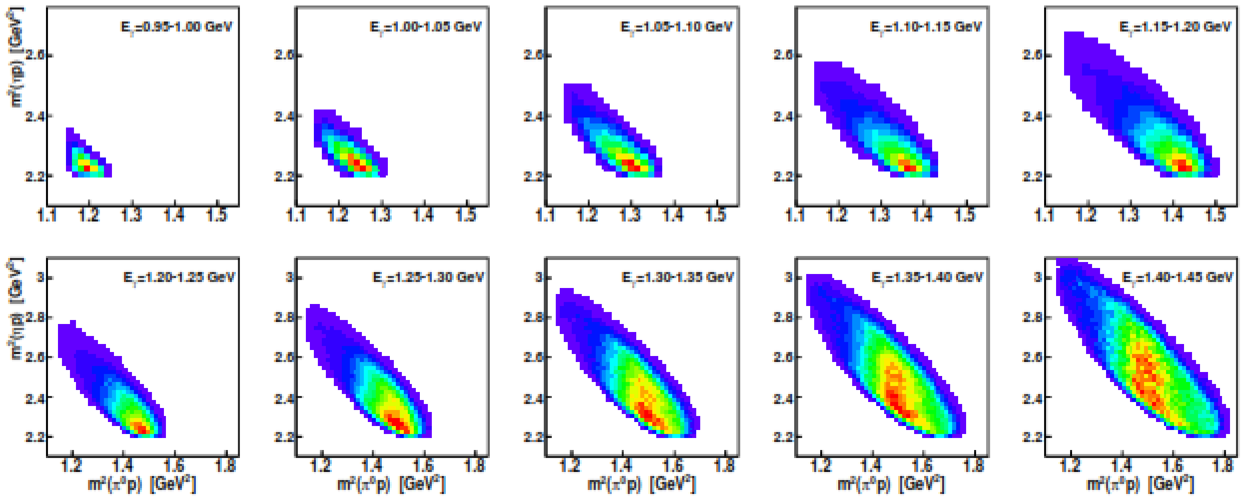


FIG. 7. $\gamma p \to \eta' p$ total cross sections from this Letter compared to the previous measurements by CBELSA/TAPS [5], SAPHIR [32], ABBHHM [33], and AHHM [34], and to the model calculations by the ηMAID-Regge-2003 [19] and ηMAID2017 solutions (with the same notations as in Fig. 6 and statistical uncertainties shown for the previous measurements). The fit to the CBELSA/TAPS data from Ref. [35] is shown by the cyan solid line. For the final ηMAID2017 solution, the individual contributions from $N(1895)1/2^-$, $N(1900)3/2^+$, and $N(2120)3/2^-$ are shown by the red dashed-dotted, green long-dashed, and blue long-dashed-dotted lines, respectively.

$\pi^0\eta$ production



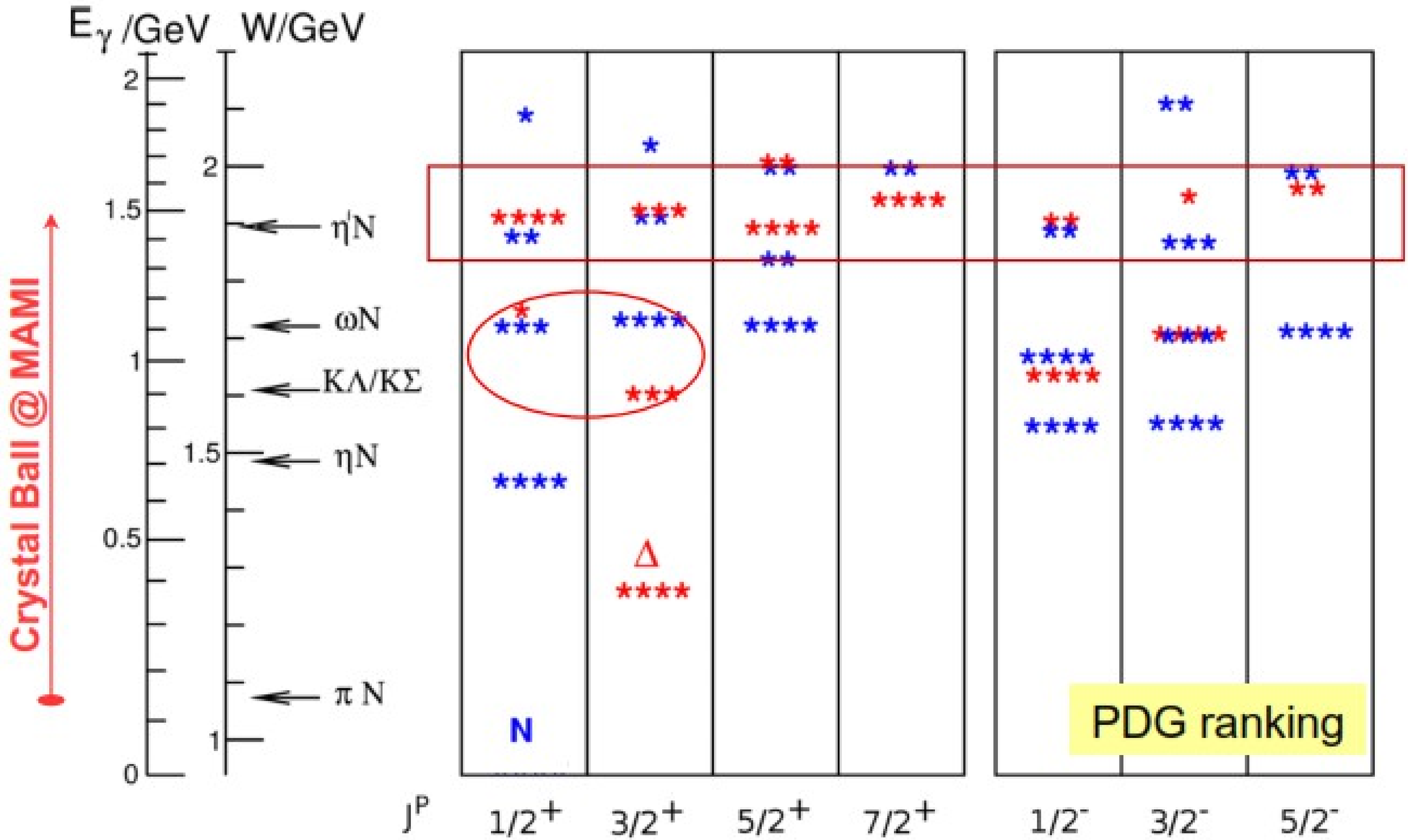




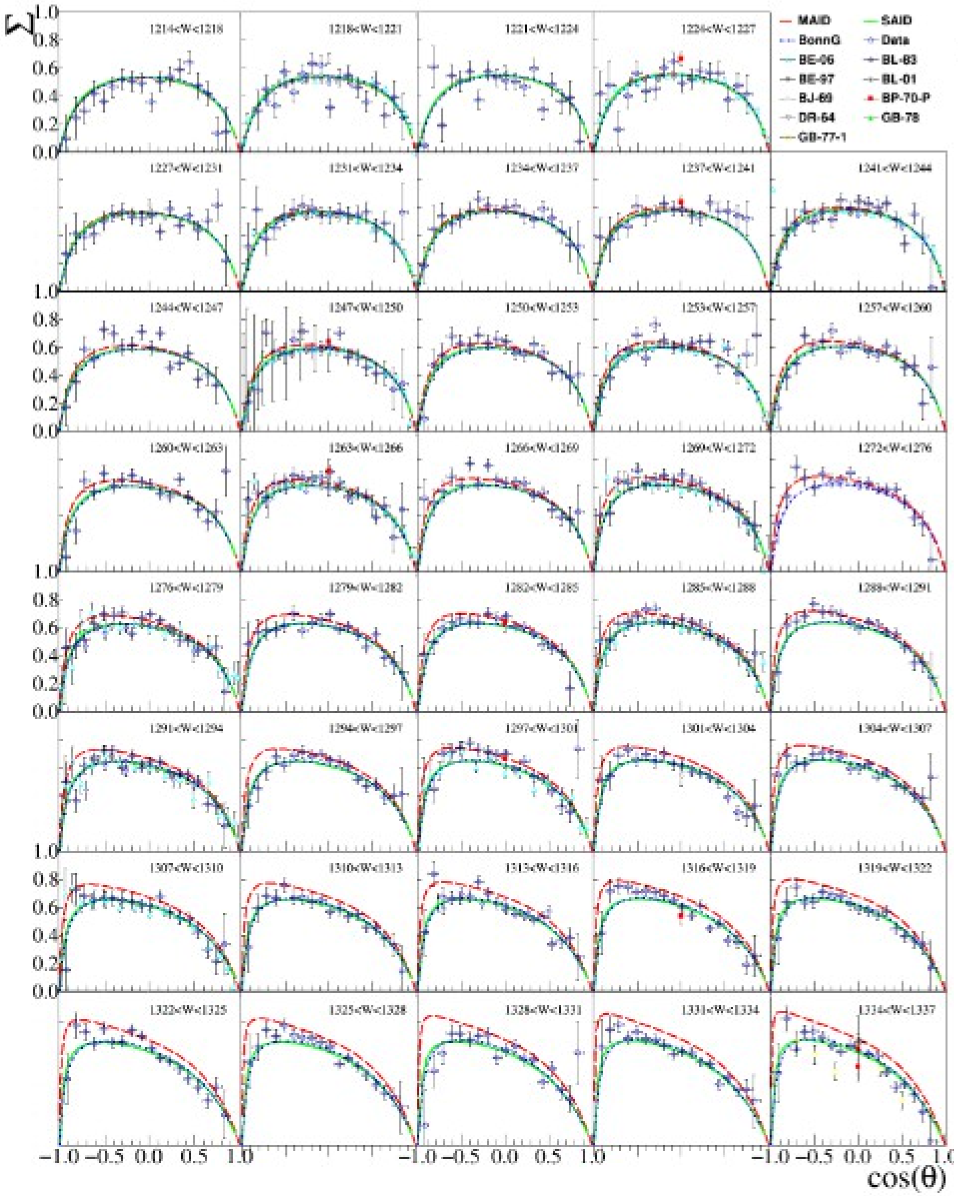
Strong contribution from $\gamma p \rightarrow (D_{33}(1700)) \rightarrow \Delta(1232)\eta \rightarrow p\pi^0\eta$

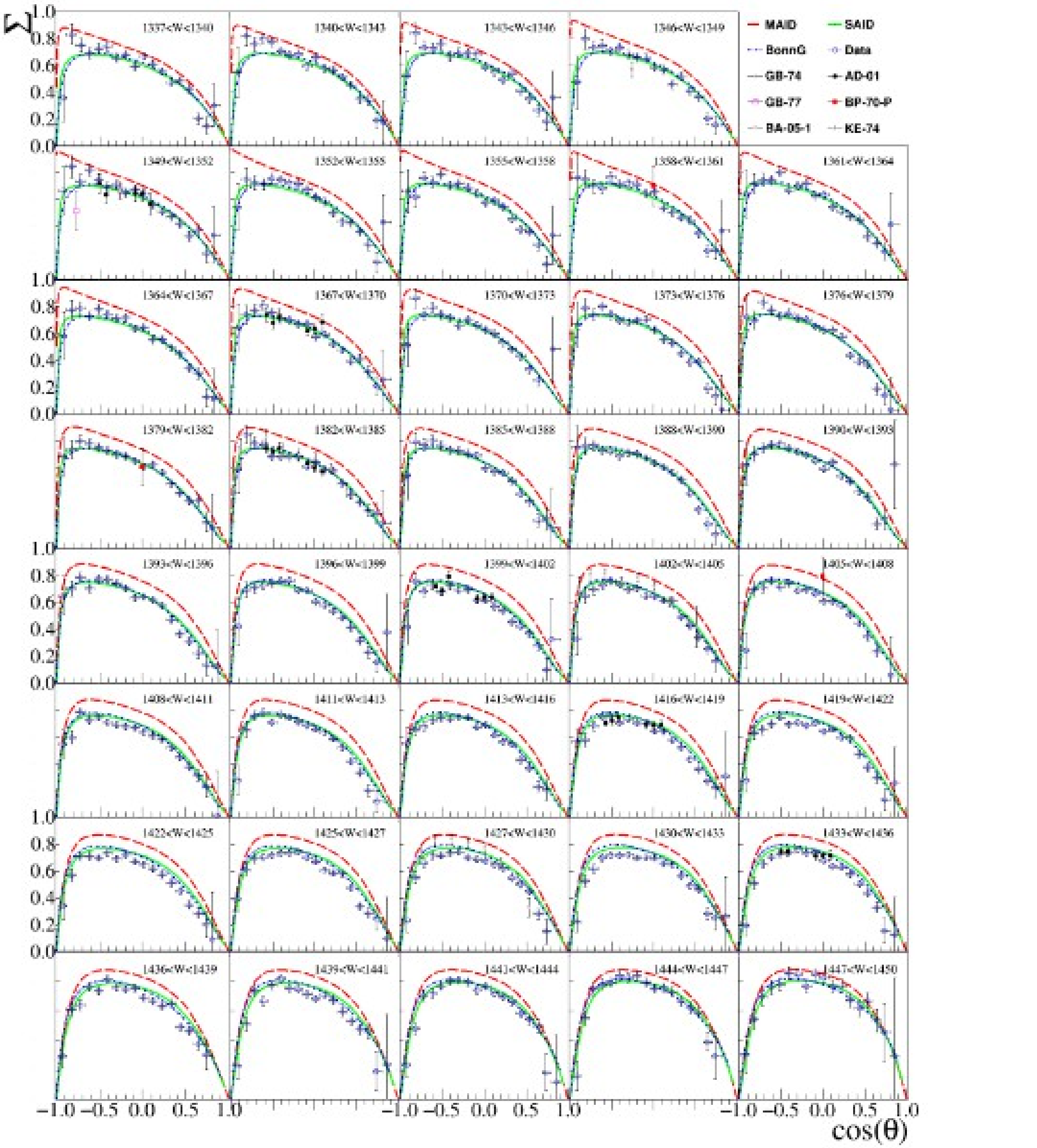
Baryon resonances

Goal: Gain a good understanding of the spectrum and properties of baryon resonances



Single π^0 production: beam asymmetry

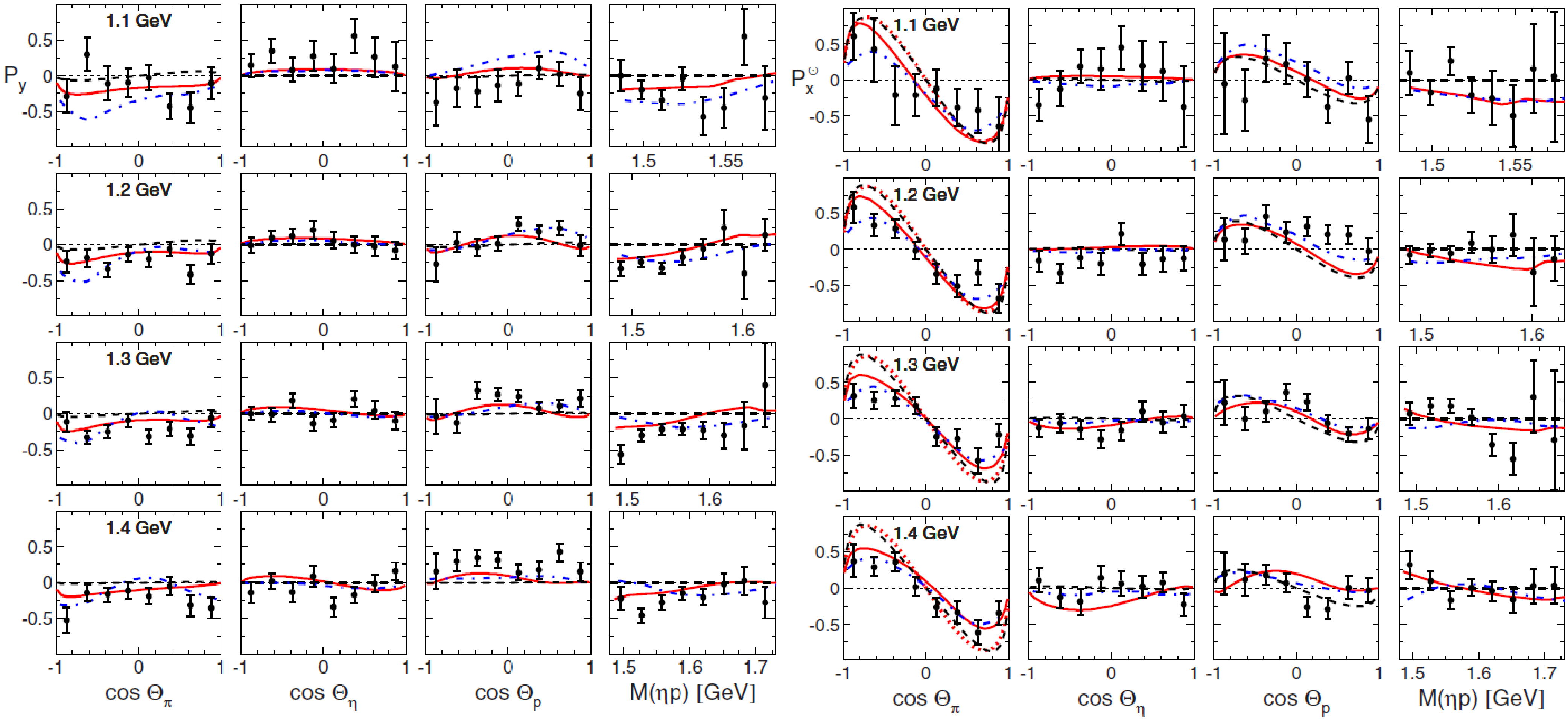




Text and references will be added

- **Interpretation within further partial wave analyses**

$\pi^0\eta$ production, single and double polarization



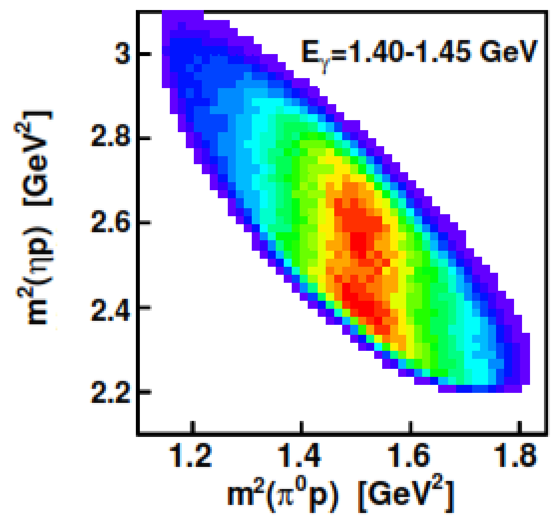
(Data are shown in a quasi two-boy approach)

Dashed: only D_{33} wave, solid: A. Fix model, dashed-dotted BnGa PWA

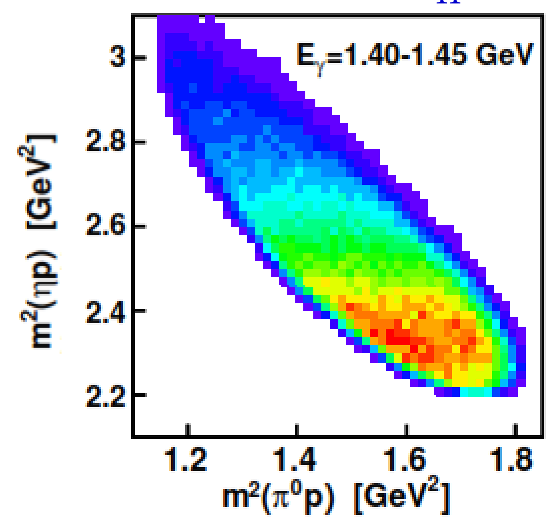
J. R. M. Annand et al., Phys.Rev. C91, no.5, 055208 (2015)

$\pi^0\eta$ production off the proton

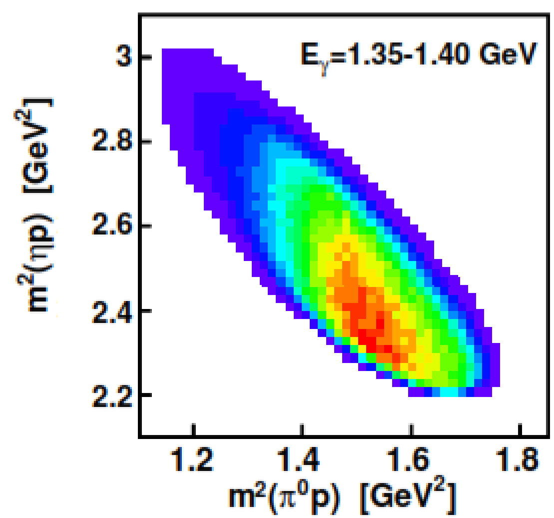
MC for $\gamma p \rightarrow \Delta(1232)\eta$



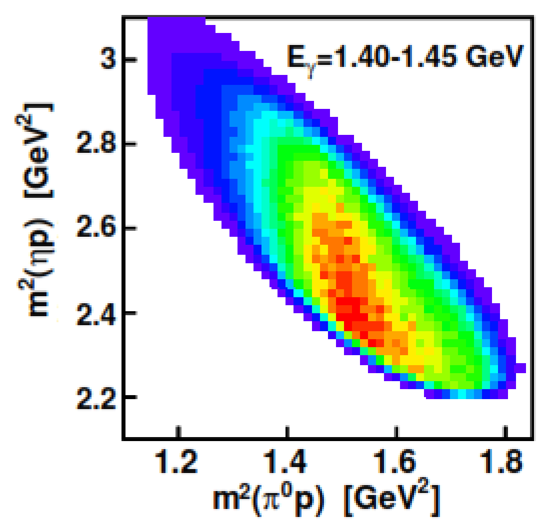
MC for $\gamma p \rightarrow S_{11}\pi^0$



Data



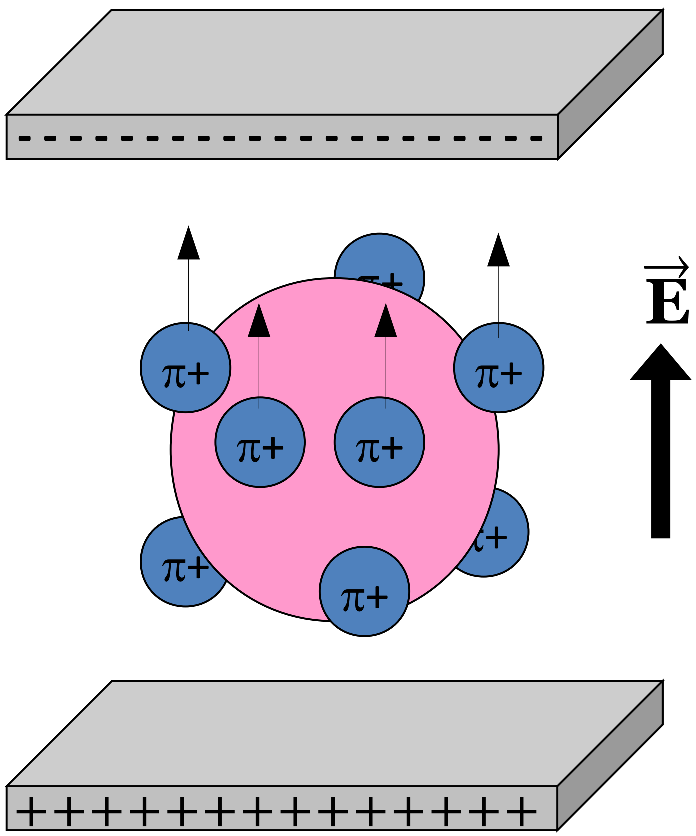
Data



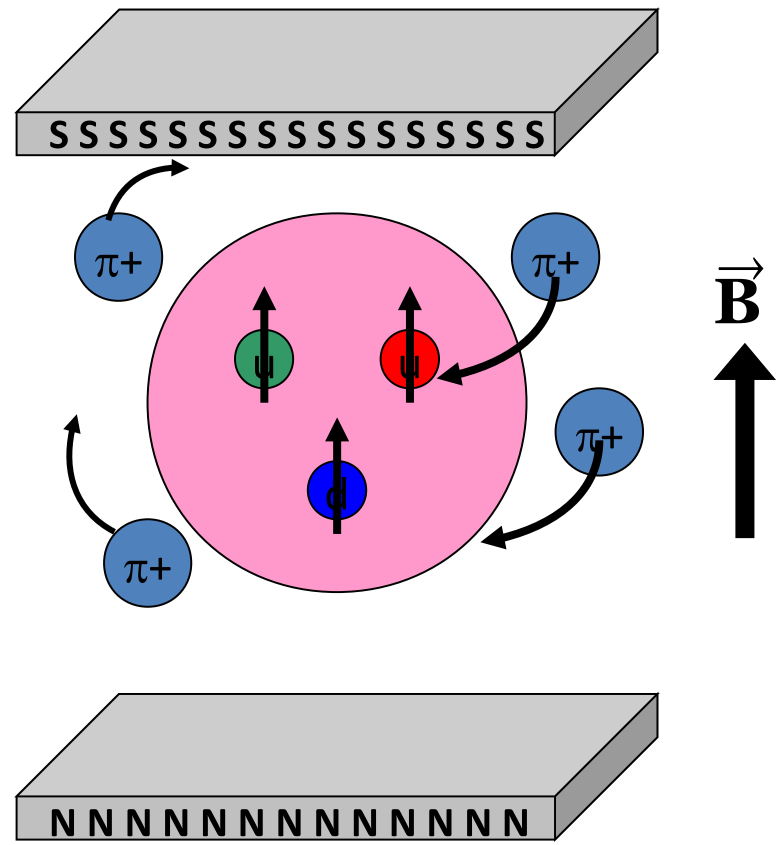
Strong contribution from $\gamma p \rightarrow (D_{33}(1700)) \rightarrow \Delta(1232)\eta \rightarrow p\pi^0\eta$

Scalar polarizabilities

Proton Electric Polarizability



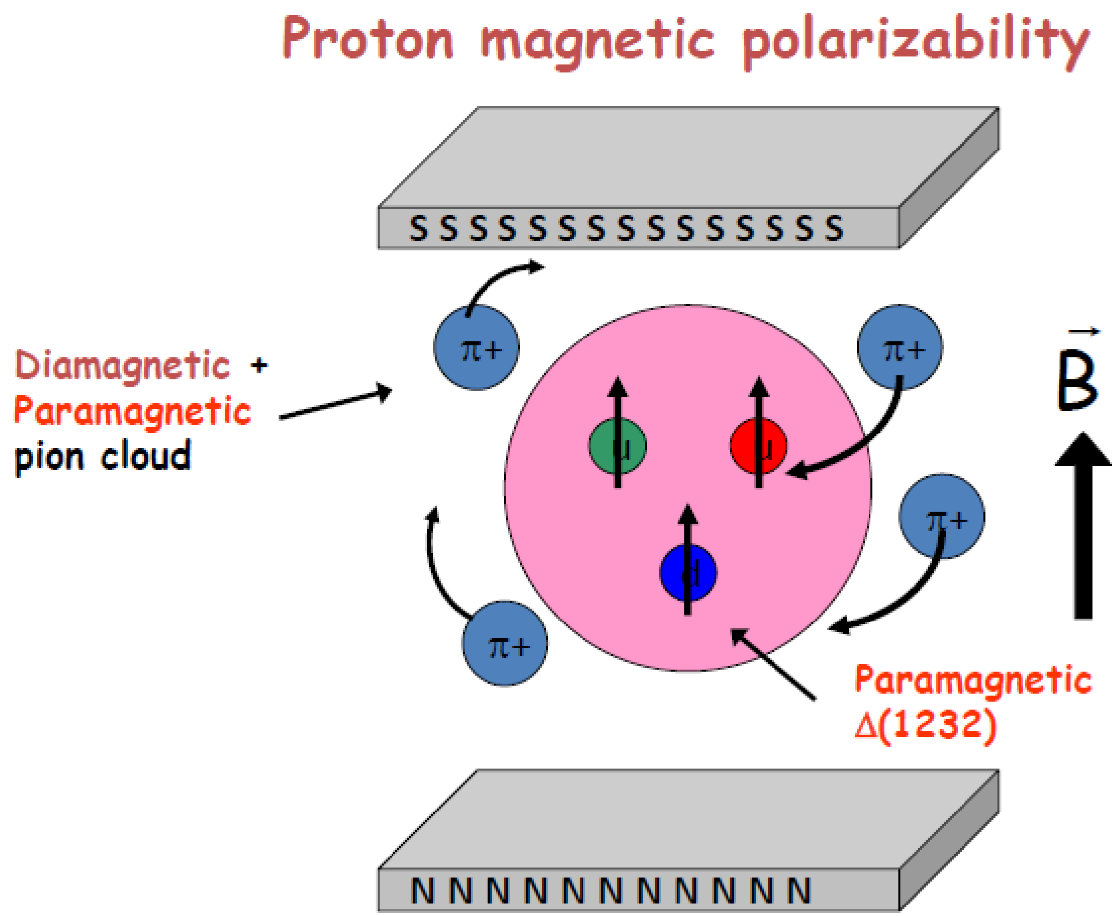
Proton Magnetic Polarizability



- α: electric polarizabilty
- Proton between charged parallel plates: "stretchability"

- β: magnetic polarizability
- Proton between poles of a magnet: "alignability"

First look in December 2012 data



Magnetic polarizability: proton between poles of a magnetic

Rory Miskimen (Bosen 2009)

Measurement of α and β

$$\Sigma_3 = \Sigma_3^{(B)} - \frac{4M\omega^2 \cos\theta \sin^2\theta}{\alpha_{em}(1+\cos^2\theta)^2}\,\beta_{M1} + O(\omega^4), \qquad (6)$$

where $\Sigma_3^{(B)}$ is the pure Born contribution, while

$$\omega = \frac{s - M^2 + \frac{1}{2}t}{\sqrt{4M^2 - t}}, \quad \theta = \arccos\left(1 + \frac{t}{2\omega^2}\right) \qquad (7)$$

are the photon energy and scattering angle in the Breit (brick-wall) reference frame. In fact, to this order in the LEX the formula is valid for ω and θ being the energy and angle in the lab or center-of-mass frame.

Beam	Target				Recoil			Target + Recoil			
	$-$	$-$	$-$	$-$	x'	y'	z'	x'	x'	z'	z'
	$-$	x	y	z	$-$	$-$	$-$	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	$(-P)$	$-G$	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

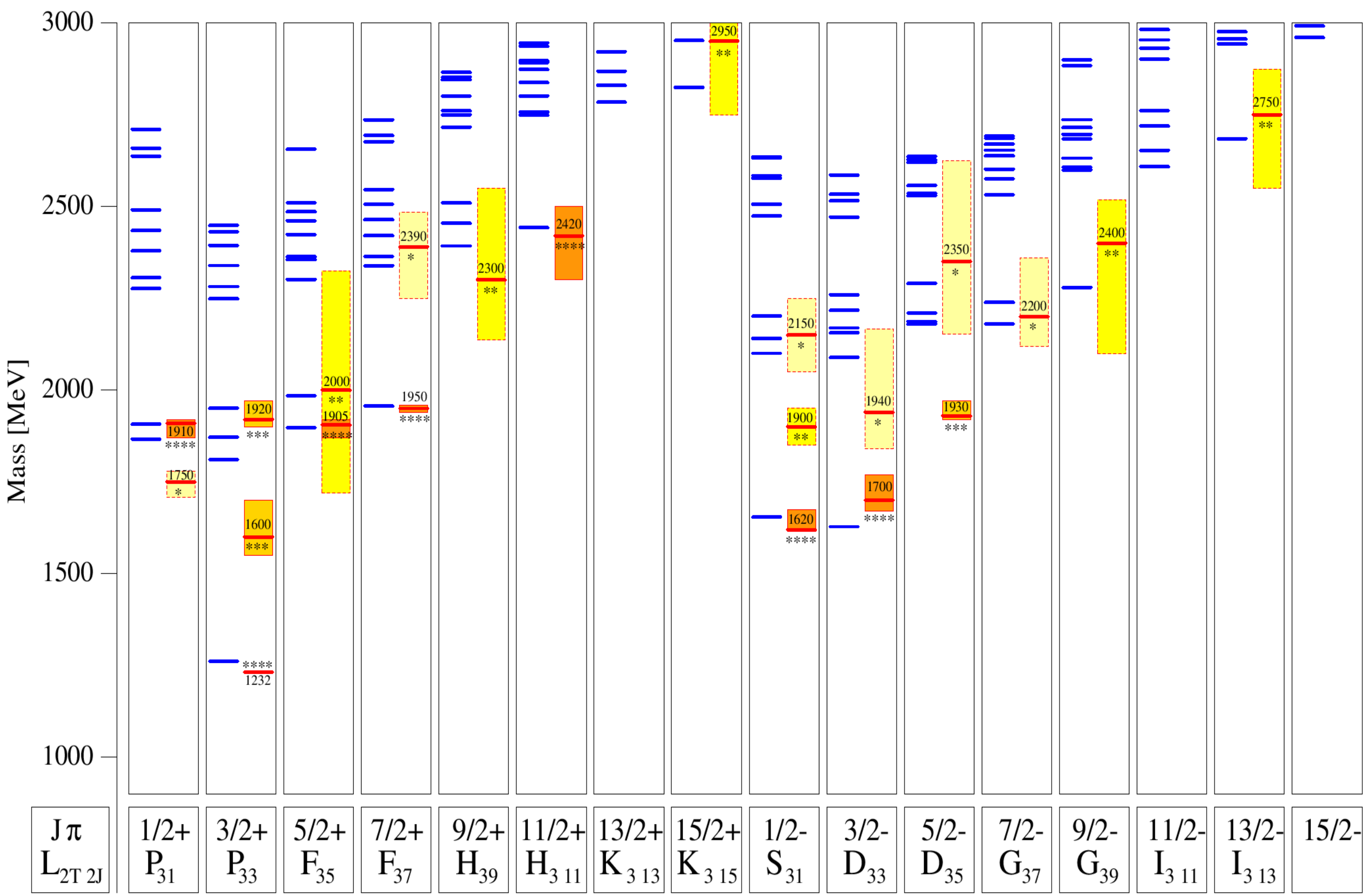
Baryon resonances

56	S=1/2;L=0;N=0		$N_{1/2^+}(939)$			939 MeV
	S=3/2;L=0;N=0			$\Delta_{3/2^+}(1232)$		1232 MeV
70	S=1/2;L=1;N=0		$N_{1/2^-}(1535)$	$N_{3/2^-}(1520)$		1530 MeV
	S=3/2;L=1;N=0		$N_{1/2^-}(1650)$	$N_{3/2^-}(1700)$	$N_{5/2^-}(1675)$	1631 MeV
	S=1/2;L=1;N=0		$\Delta_{1/2^-}(1620)$	$\Delta_{3/2^-}(1700)$		1631 MeV
70	S=1/2;L=1;N=2		$N_{1/2^-}(2090)$	$N_{3/2^-}(2080)$		2151 MeV
	S=3/2;L=1;N=2		$N_{1/2^-}$	$N_{3/2^-}$	$N_{5/2^-}$	2223 MeV
	S=1/2;L=1;N=2		$\Delta_{1/2^-}(2150)$	$\Delta_{3/2^-}$		2223 MeV
56	S=1/2;L=1;N=1		$N_{1/2^-}$	$N_{3/2^-}$		1779 MeV
	S=3/2;L=1;N=1		$\Delta_{1/2^-}(1900)$	$\Delta_{3/2^-}(1940)$	$\Delta_{5/2^-}(1930)$	1950 MeV
56	S=1/2;L=2;N=0		$N_{3/2^+}(1720)$	$N_{5/2^+}(1620)$		1779 MeV
	S=3/2;L=2;N=0	$\Delta_{1/2^+}(1910)$	$\Delta_{3/2^+}(1920)$	$\Delta_{5/2^+}(1905)$	$\Delta_{7/2^+}(1950)$	1950 MeV
70	S=1/2;L=2;N=0		$N_{3/2^+}$	$N_{5/2^+}$		1866 MeV
	S=3/2;L=2;N=0	$N_{1/2^+}$	$N_{3/2^+}(1900)$	$N_{5/2^+}(2000)$	$N_{7/2^+}(1990)$	1950 MeV
	S=1/2;L=2;N=0		$\Delta_{3/2^+}$	$\Delta_{5/2^+}$		1950 MeV
70	S=1/2;L=3;N=0		$N_{5/2^-}$	$N_{7/2^-}$		2151 MeV
	S=3/2;L=3;N=0	$N_{3/2^-}$	$N_{5/2^-}(2200)$	$N_{7/2^-}(2190)$	$N_{9/2^-}(2250)$	2223 MeV
	S=1/2;L=3;N=0		$\Delta_{5/2^-}$	$\Delta_{7/2^-}(2200)$		2223 MeV
56	S=1/2;L=3;N=1		$N_{5/2^-}$	$N_{7/2^-}$		2334 MeV
	S=3/2;L=3;N=1	$\Delta_{3/2^-}$	$\Delta_{5/2^-}(2350)$	$\Delta_{7/2^-}$	$\Delta_{9/2^-}(2400)$	2467 MeV
56	S=1/2;L=4;N=0		$N_{7/2^+}$	$N_{9/2^+}(2220)$		2334 MeV
	S=3/2;L=4;N=0	$\Delta_{5/2^+}$	$\Delta_{7/2^+}(2390)$	$\Delta_{9/2^+}(2300)$	$\Delta_{11/2^+}(2420)$	2467 MeV
70	S=1/2;L=5;N=0		$N_{9/2^-}$	$N_{11/2^-}(2600)$		2629 MeV
56	S=3/2;L=5;N=1	$\Delta_{7/2^-}$	$\Delta_{9/2^-}$	$\Delta_{11/2^-}$	$\Delta_{13/2^-}(2750)$	2893 MeV
56	S=1/2;L=6;N=0		$N_{11/2^+}$	$N_{13/2^+}(2700)$		2781 MeV
	S=3/2;L=6;N=0	$\Delta_{9/2^+}$	$\Delta_{11/2^+}$	$\Delta_{13/2^+}$	$\Delta_{15/2^+}(2950)$	2893 MeV
70	S=1/2;L=7;N=0		$N_{13/2^-}$	$N_{15/2^-}$		3033 MeV
56	S=3/2;L=7;N=1	$\Delta_{11/2^-}$	$\Delta_{13/2^-}$	$\Delta_{15/2^-}$	$\Delta_{17/2^-}$	3264 MeV
56	S=1/2;L=8;N=0		$N_{15/2^+}$	$N_{17/2^+}$		3165 MeV
	S=3/2;L=8;N=0	$\Delta_{13/2^+}$	$\Delta_{15/2^+}$	$\Delta_{17/2^+}$	$\Delta_{19/2^+}$	3264 MeV

Table 20: Multiplet structure of nucleon and Δ resonances. The table contains all known resonances except radial excitations of the $N_{1/2^+}(939)$ and $\Delta_{3/2^+}(1232)$.

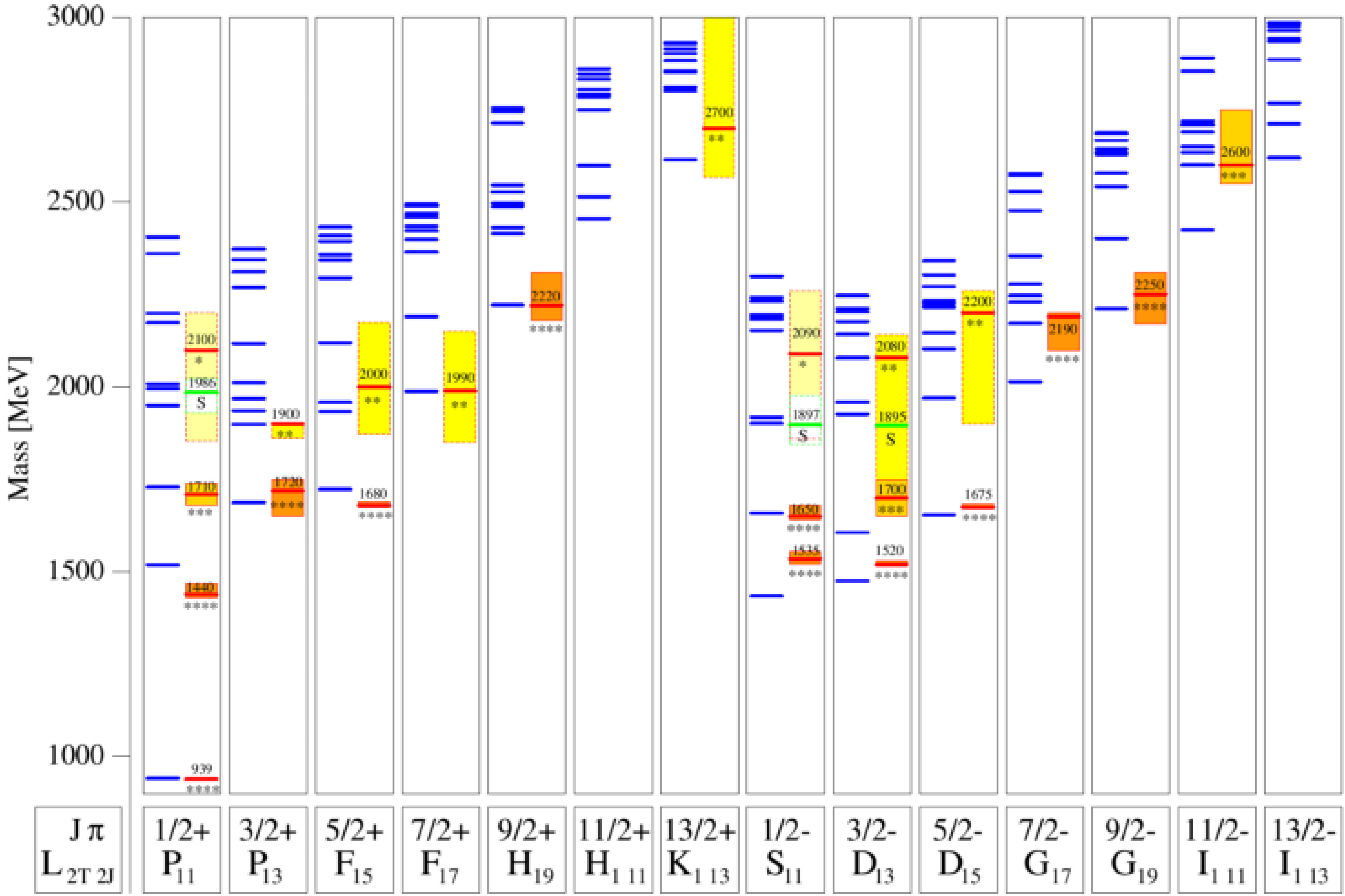
Introduction

<u>Goal</u>: Gain a good understanding of the spectrum and properties of baryon resonances



Introduction

Goal: Gain a good understanding of the spectrum and properties of baryon resonances

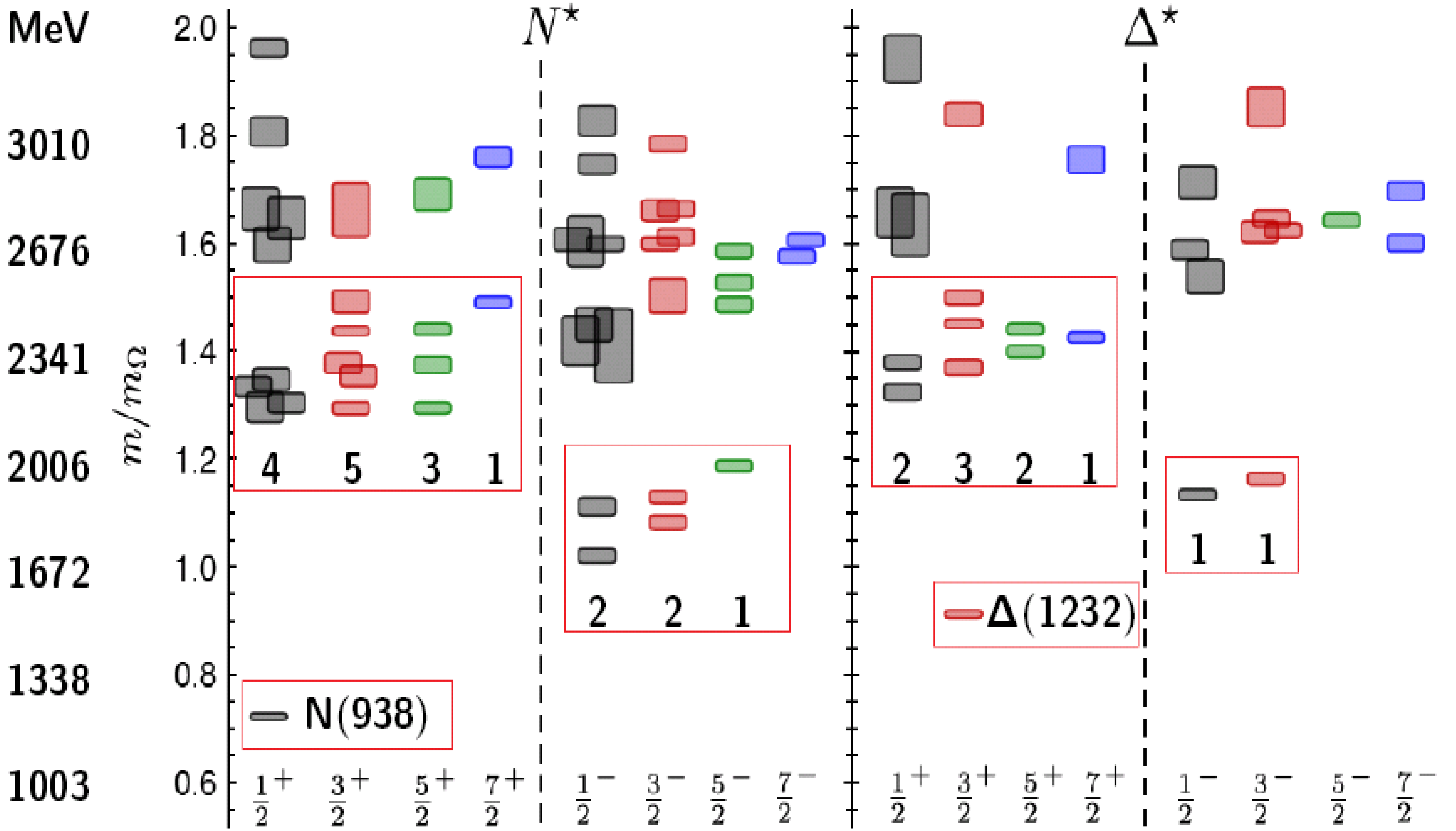


Introduction

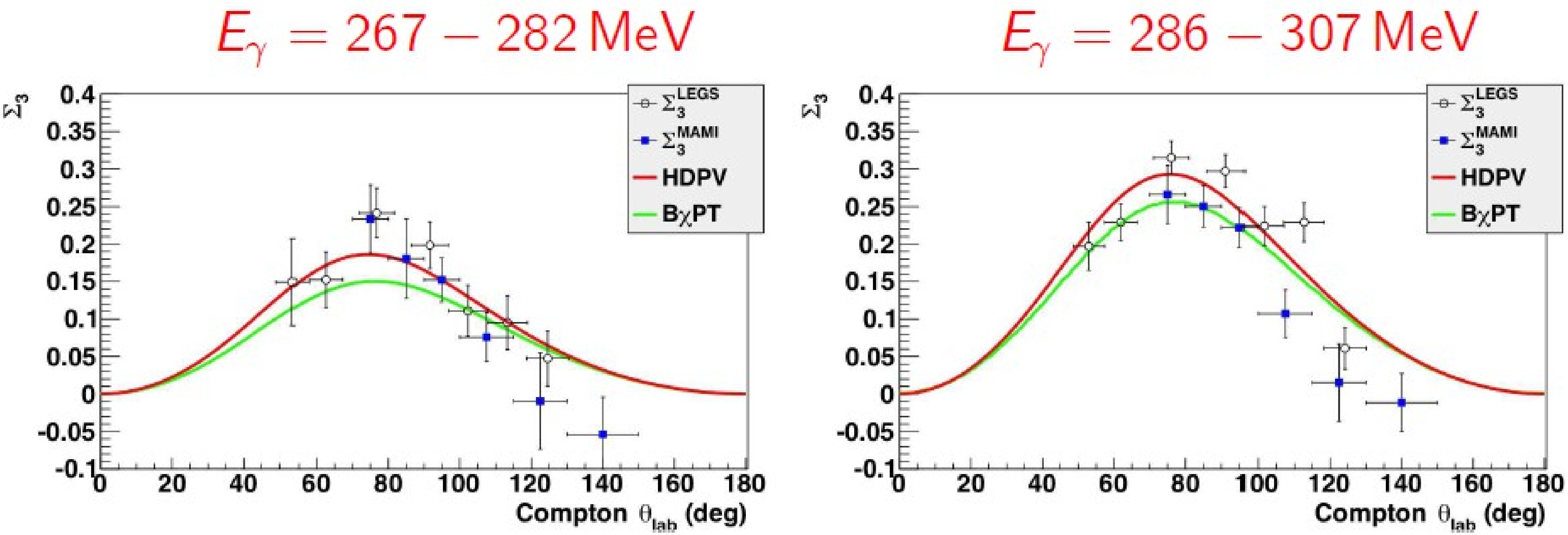
Goal: Gain a good understanding of the spectrum and properties of baryon resonances

$m_\pi = 396$ MeV

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



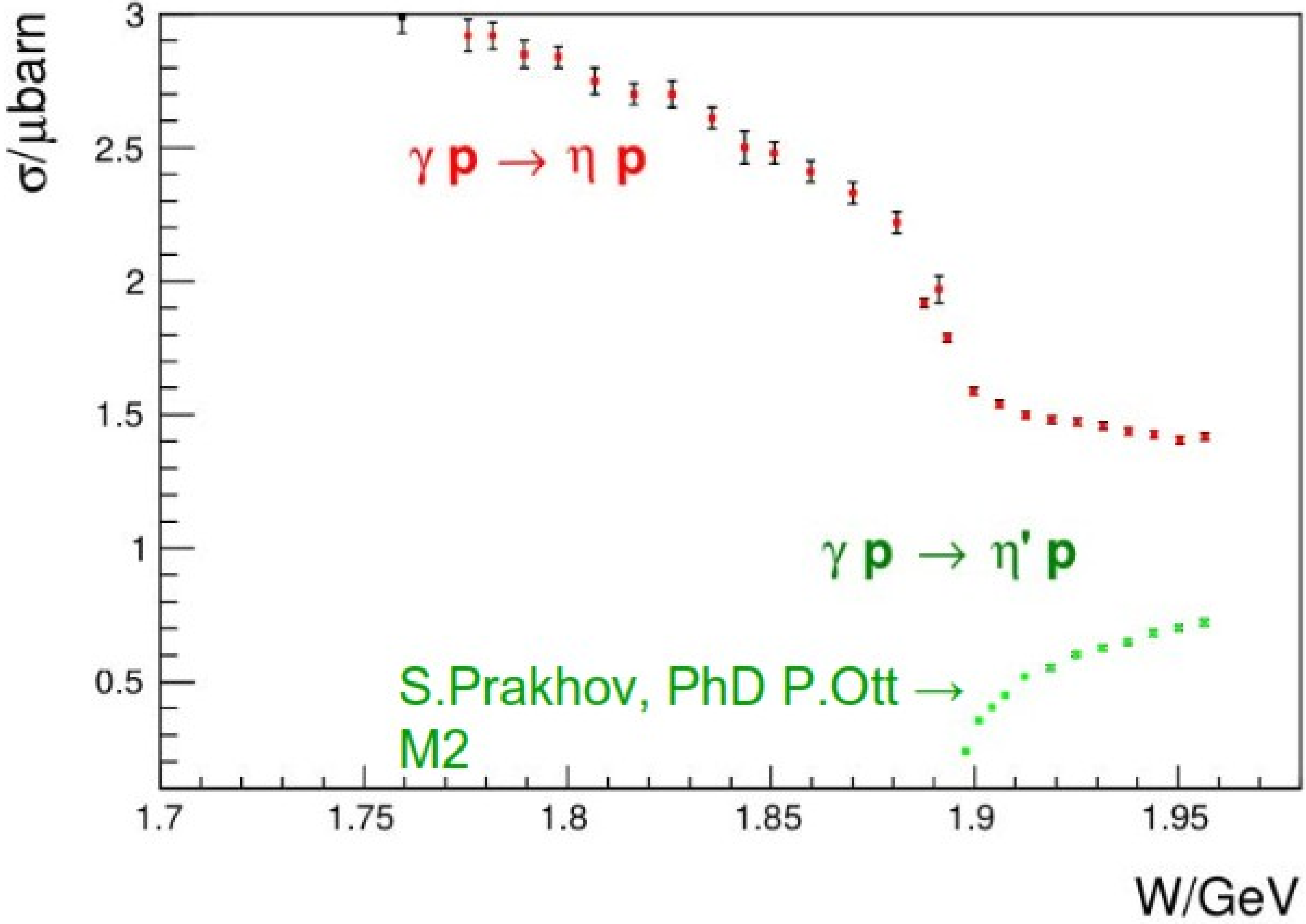
Spin polarizabilites



- Recent data (MAMI) and older data (LEGS) are shown along with Dispersion Relation (HDPV) and ChPT (BχPT) predictions.

G. M. Huber, C. Collicott, arXiv:1508.07919 (2015)

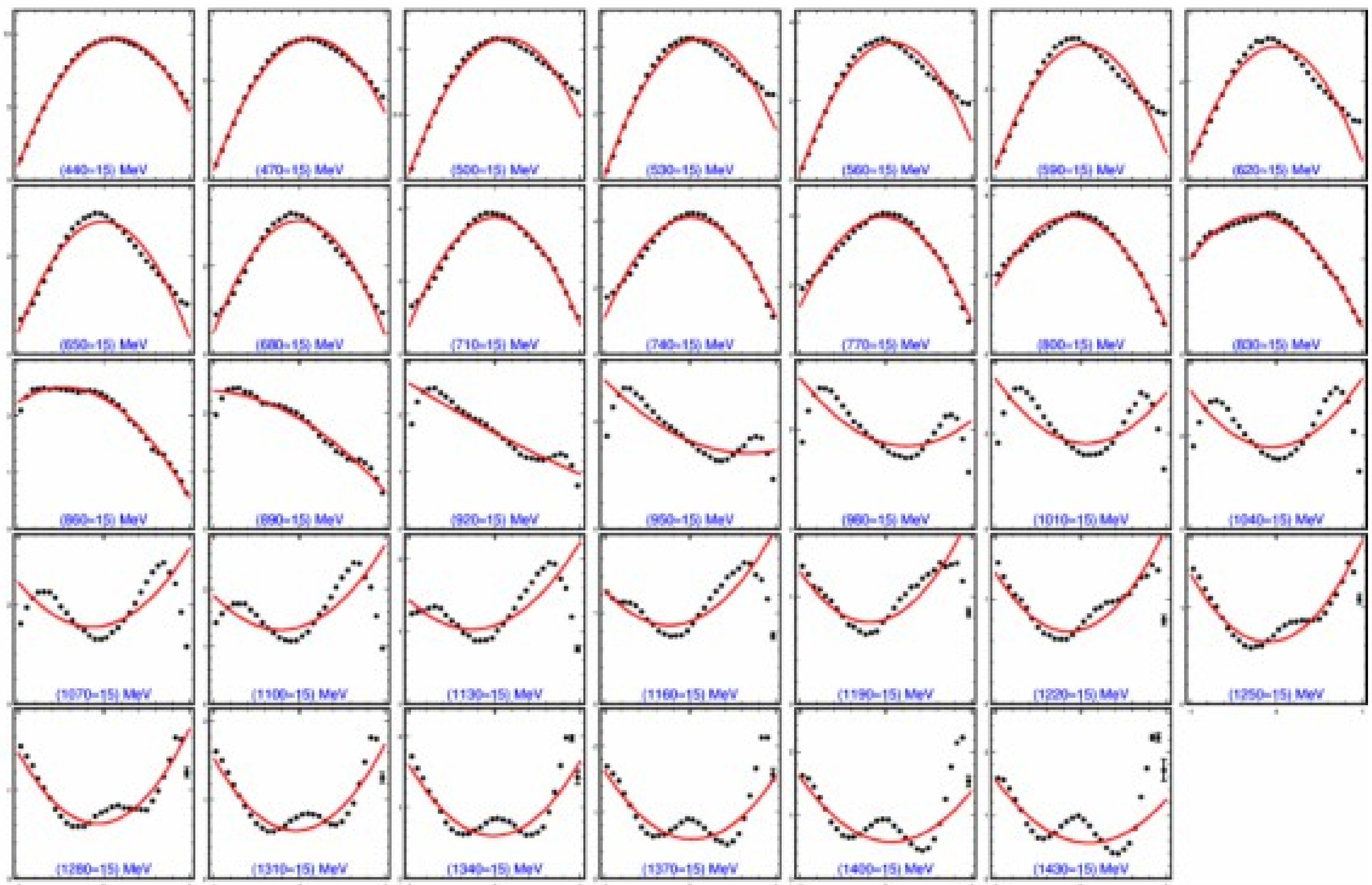
N(1895)1/2-


σ/μbarn
3
2.5
2
1.5
1
0.5
1.7
1.75
1.8
1.85
1.9
1.95
W/GeV
γ p → η p
γ p → η' p
S.Prakhov, PhD P.Ott →
M2

Single pion production

Legendre expansion of the diff. cross section

$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W)\, P_k(\cos\theta) \qquad \ell max = 1$$

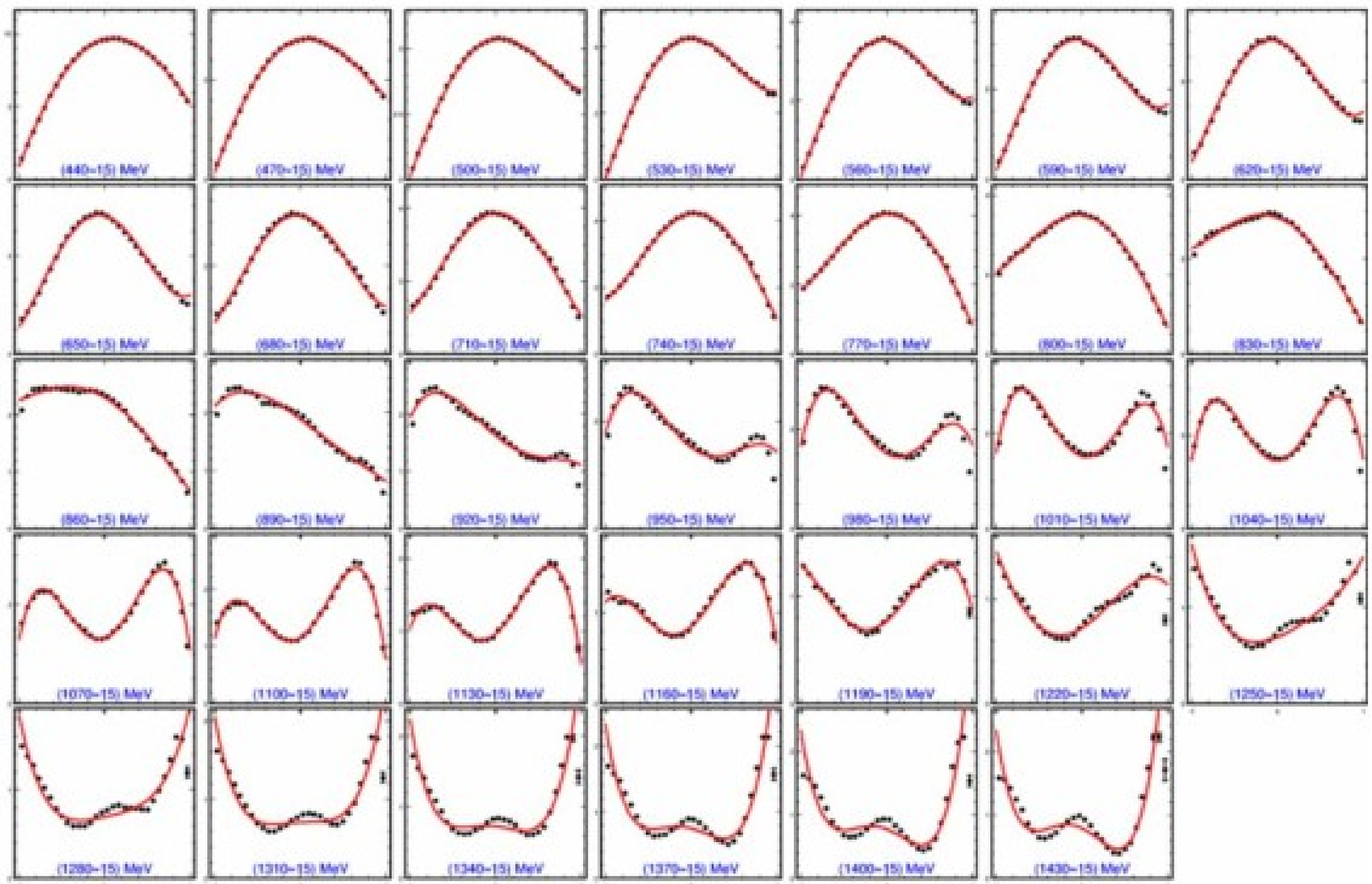


S+P waves are only good up to about 400 MeV

Single pion production

Legendre expansion of the diff. cross section

$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W)\, P_k(\cos\theta) \qquad \ell max = 2$$

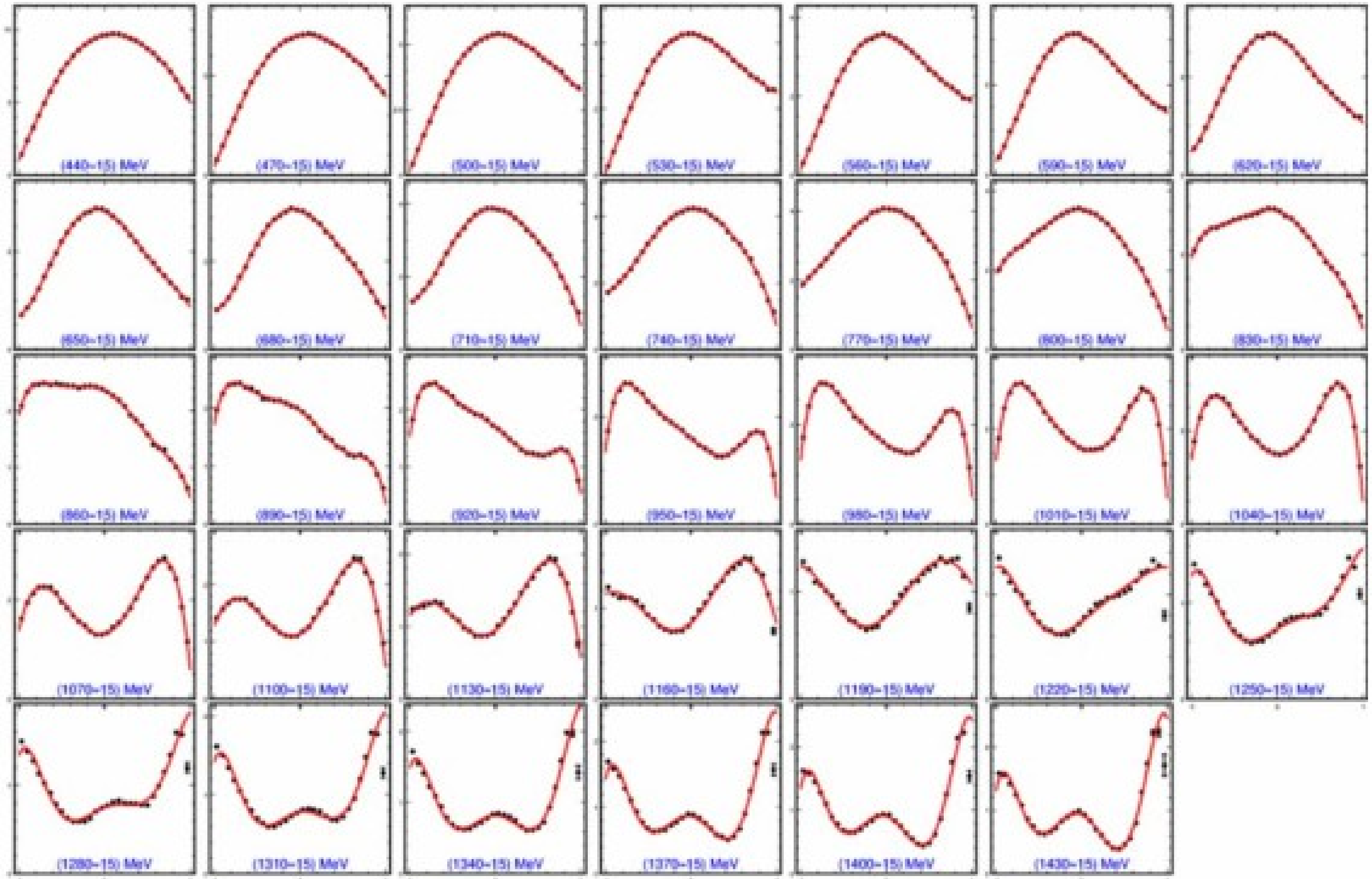


S+P+D waves are good up to about 850 MeV

Single pion production

Legendre expansion of the diff. cross section

$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W)\, P_k(\cos\theta) \qquad \ell max = 3$$

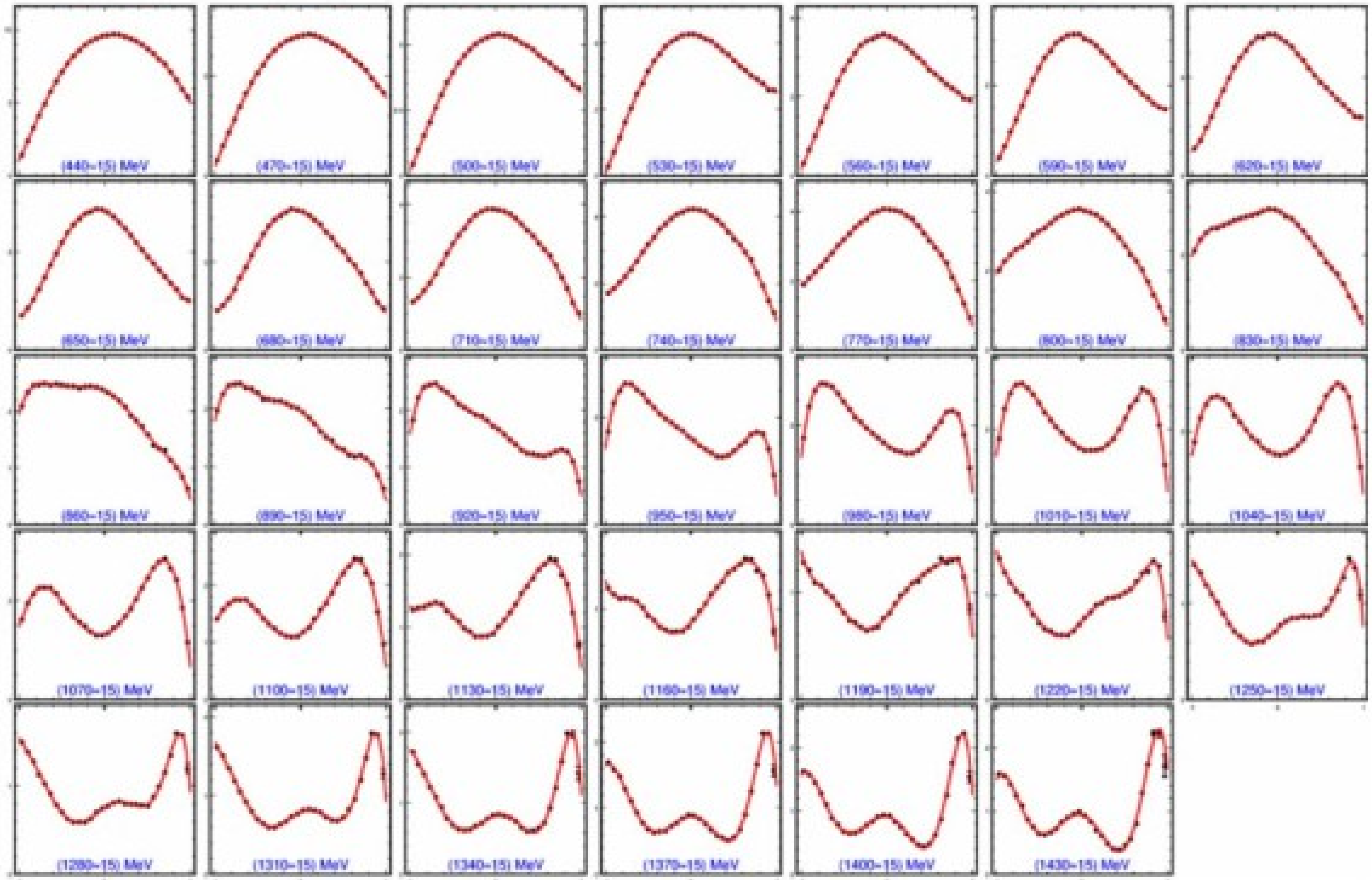


F waves become important around 1 GeV

Single pion production

Legendre expansion of the diff. cross section

$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W)\, P_k(\cos\theta) \qquad \ell max = 4$$



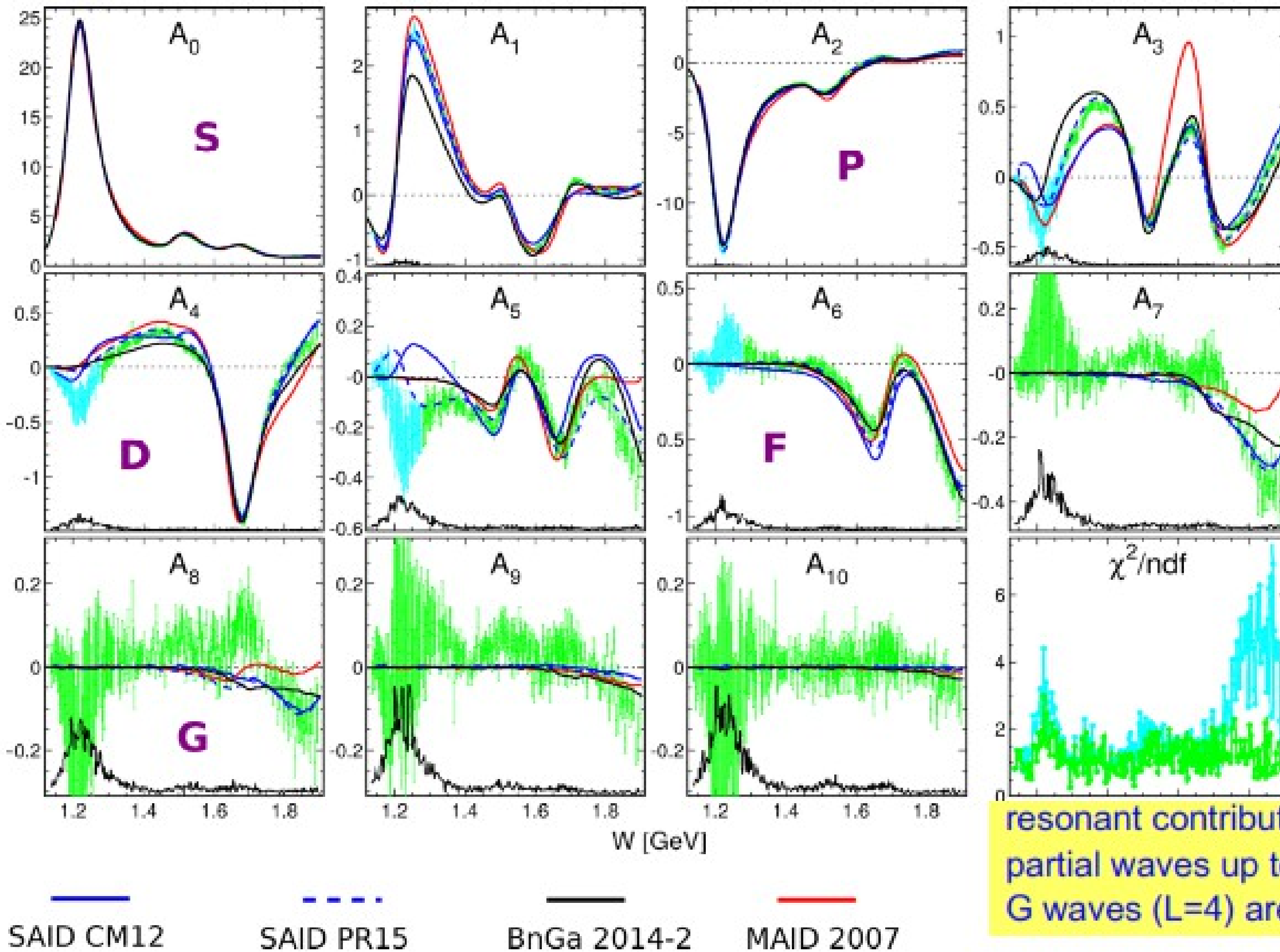
around 1.2 GeV also G waves become clearly visible in forward direction

Single pion production

Legendre expansion of differential cross section

A_0 is the total cross section

from 2013 MAMI γ,π^0 data



resonant contributions in partial waves up to G waves (L=4) are visible

Polarized target (slide taken from R. Miskimen)

Frozen spin target

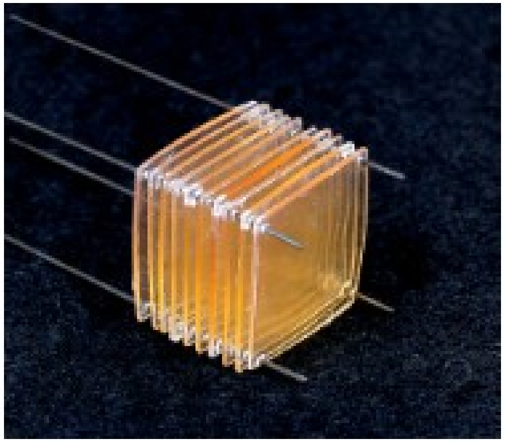
- 2 cm butanol
- target polarized at 25 mK
- 0.6 T holding field
- P ~ 90%
- > 1000 hours relaxation time

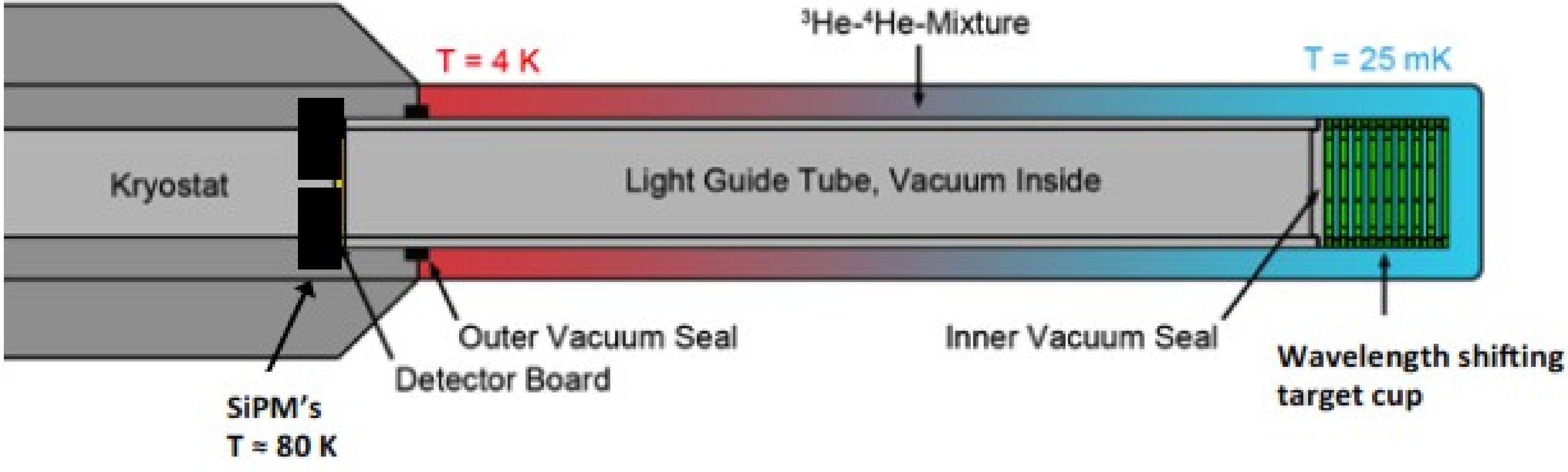
Polarized active target (slide taken from R. Miskimen)

Development of a scintillating polarized target for Mainz

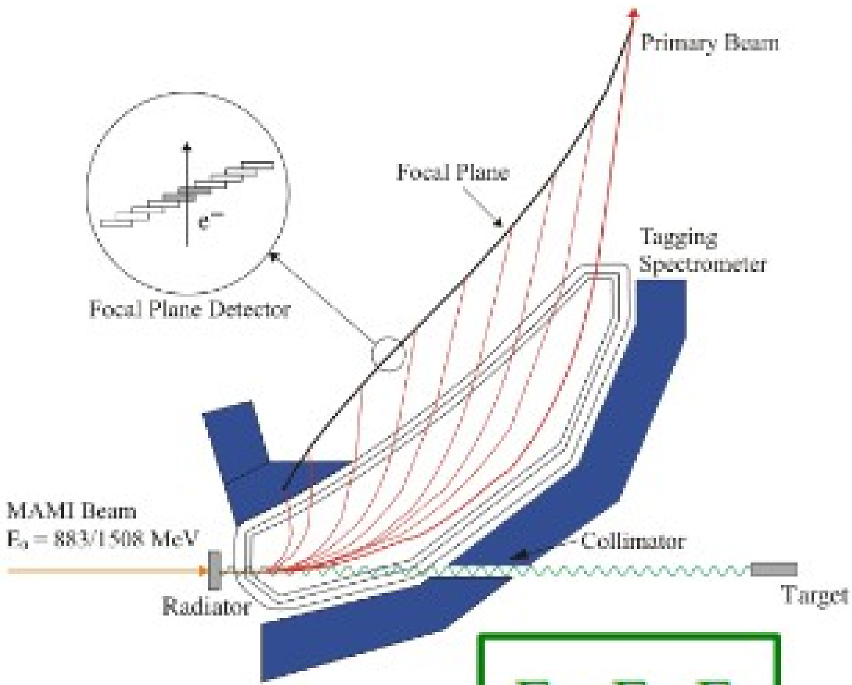
Needed for double-polarized Compton scattering measurements near pion threshold

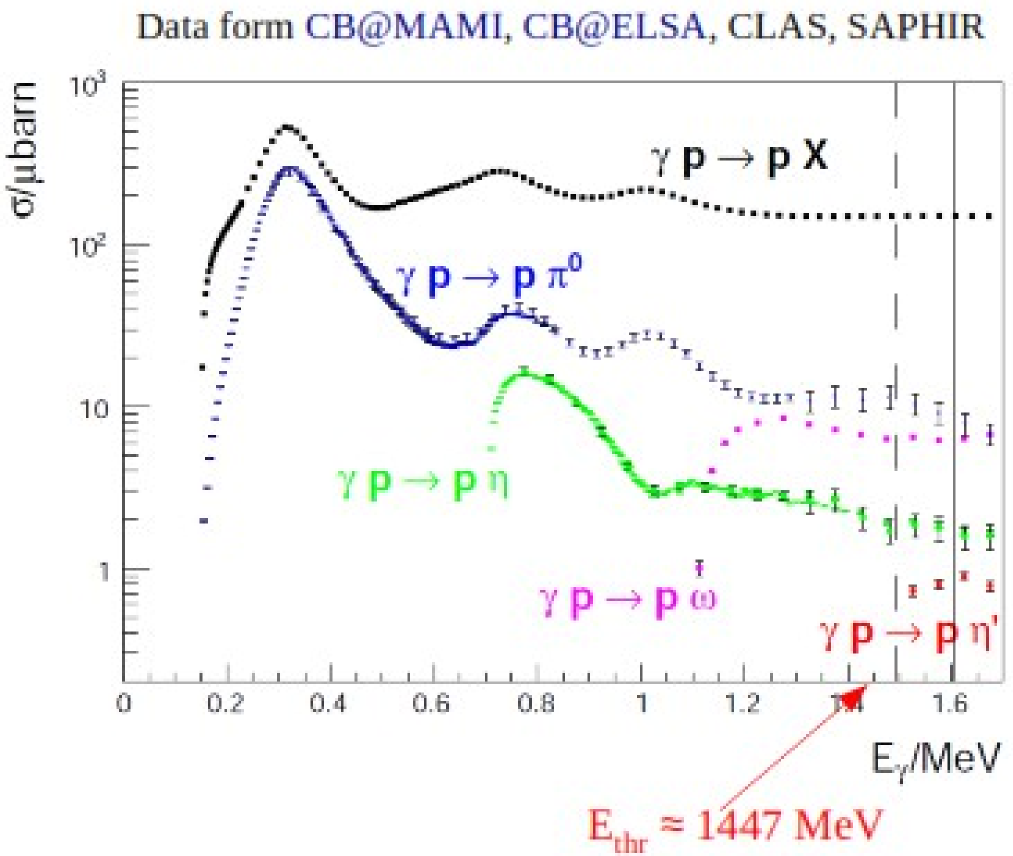
- **Polarizable scintillator developed at UMass**
- ✓ Proton polarization ≈ 70%
- ✓ Relaxation time ≈ 22 hours
- ✓ Light output ≈ 30% of standard plastic scintillator
- ✓ High clarity for thicknesses up to 1 mm





Polarized active target (slide taken from M. Unverzagt)





$E_\gamma = E_0 - E_{e-}$

High energy resolution: $\Delta E_\gamma \approx 2$MeV at E_{e-}=883 MeV

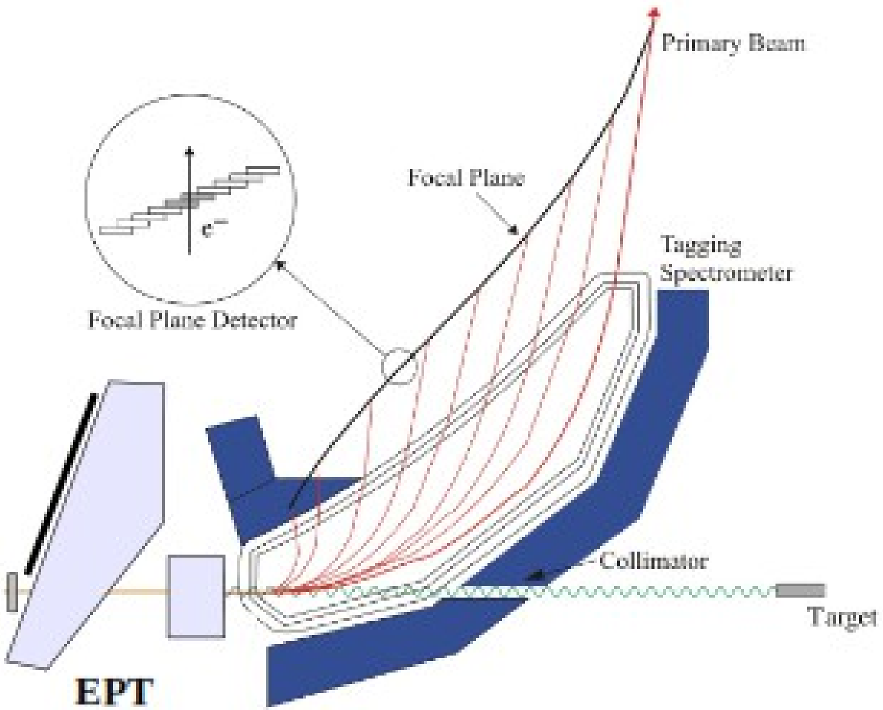
$\Delta E_\gamma \approx 4$MeV at E_{e-}=1558 MeV

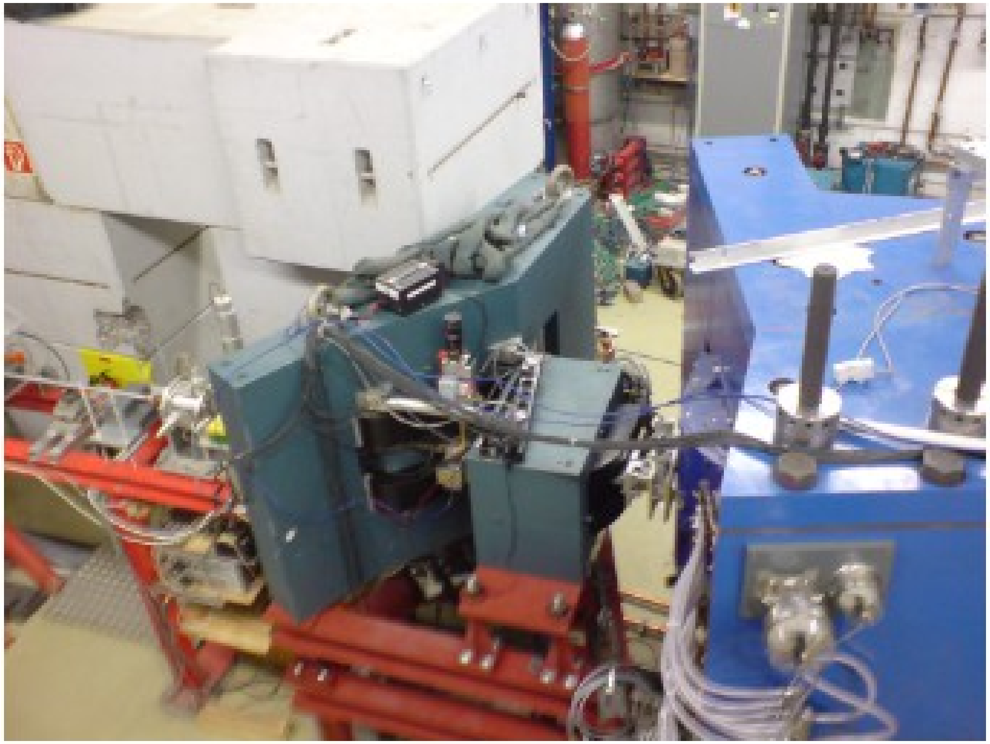
Linearly and circularly polarised photon-beam

Tagging range: 5.1 to 93% of E_γ → Maximum energy tagged for E_0=1604 MeV is 1491 MeV

EPT (slide taken from M. Unverzagt)

- Installation of EPT during 2012





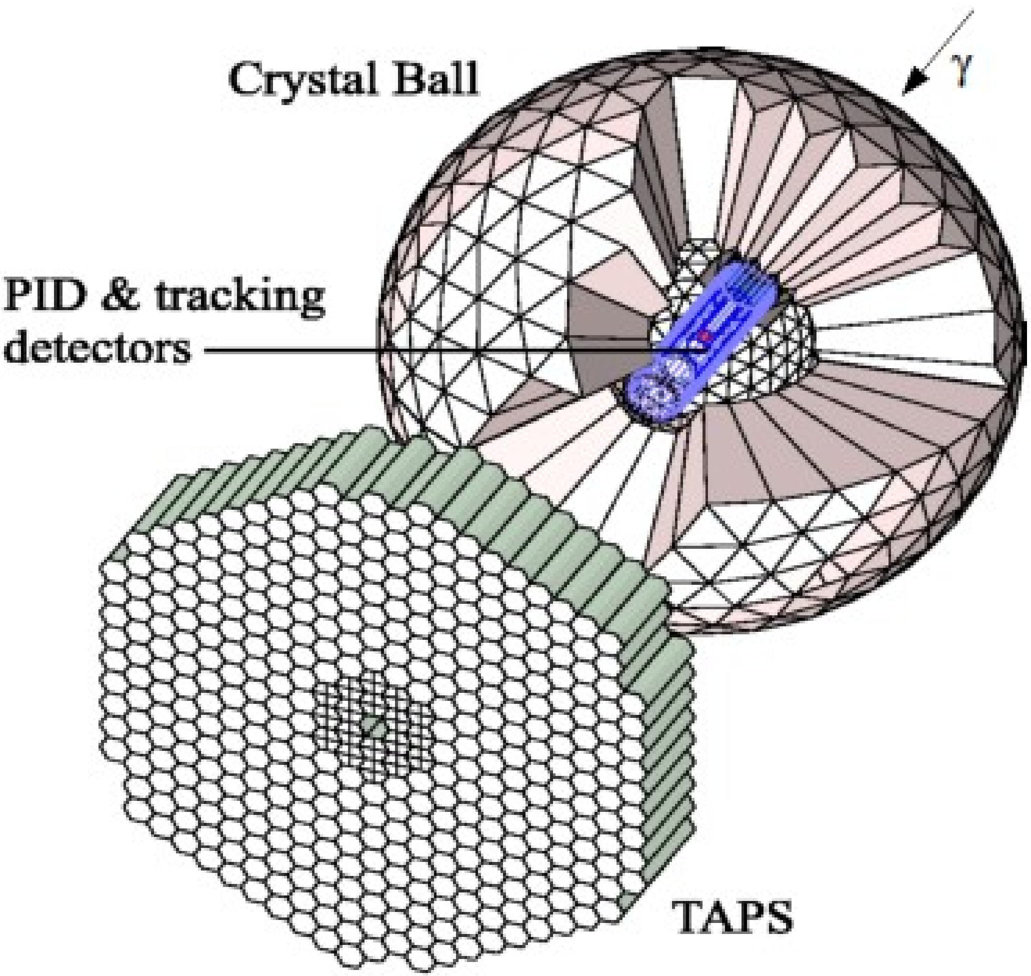
Same working principle as main tagging spectrometer

$E_\gamma \approx 1445\text{-}1595$ MeV

$\Delta E_\gamma \approx 2.5$MeV

Non-permanent installation infront of main Tagger

Crystal Ball/TAPS (slide taken from M. Unverzagt)



Crystal Ball:

672 NaI(Tl) crystals
93,3% of total solid angle
Each crystal equipped with PMT

$$\frac{\sigma}{E_\gamma} = \frac{2\%}{(E_\gamma/GeV)^{0.25}} \qquad \sigma(\theta) = 2^\circ \ldots 3^\circ$$

$$\Delta t = 2.5 \text{ ns FWHM} \qquad \sigma(\phi) = \frac{2^\circ \ldots 3^\circ}{\sin(\theta)}$$

TAPS:

Up to 510 BaF_2 crystals
Polar acceptance: 4-20°

$\Delta t = 0.5$ ns FWHM

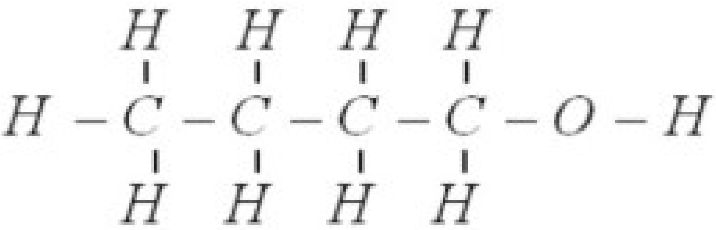
$$\frac{\sigma}{E_\gamma} = \frac{0{,}79\%}{\sqrt{E_\gamma/GeV}} + 1{,}8\%$$

Targets (slide taken from M. Unverzagt)

- LH_2/lD_2 used for high rate meson production (η/η')
  - Length: 3cm, 5cm, 10cm

- l^3He/l^4He

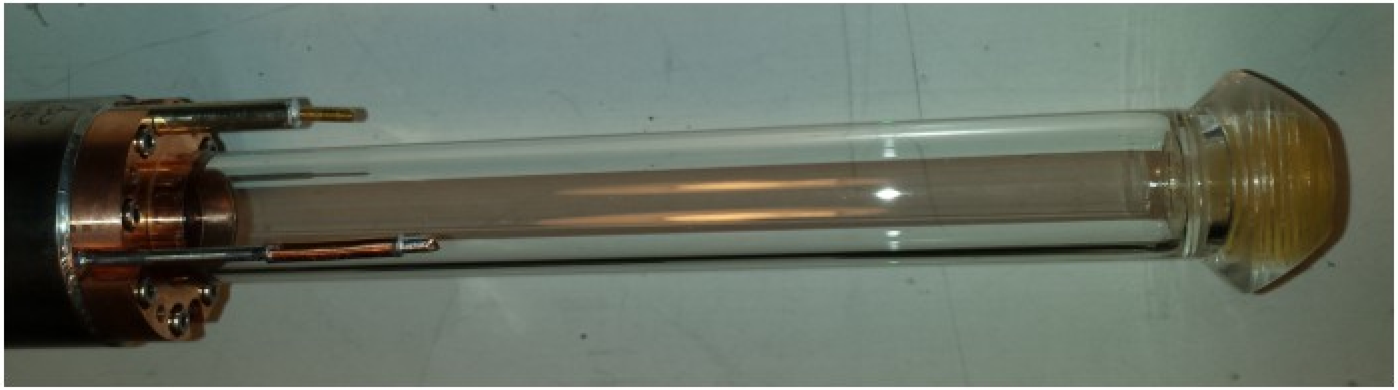
- Polarised Butanol/D-Butanol
  - Transverse and longitudinal polarisation
  - Lenght: 2 cm
  - Dynamic Nuclean Polarisation
  - Max. Polarisation: 90%
  - Holding filed: 0.44 T
  - Relaxation time: τ~1000h



- Solid Targets

Polarized active target (slide taken from R. Miskimen)

Target assembly

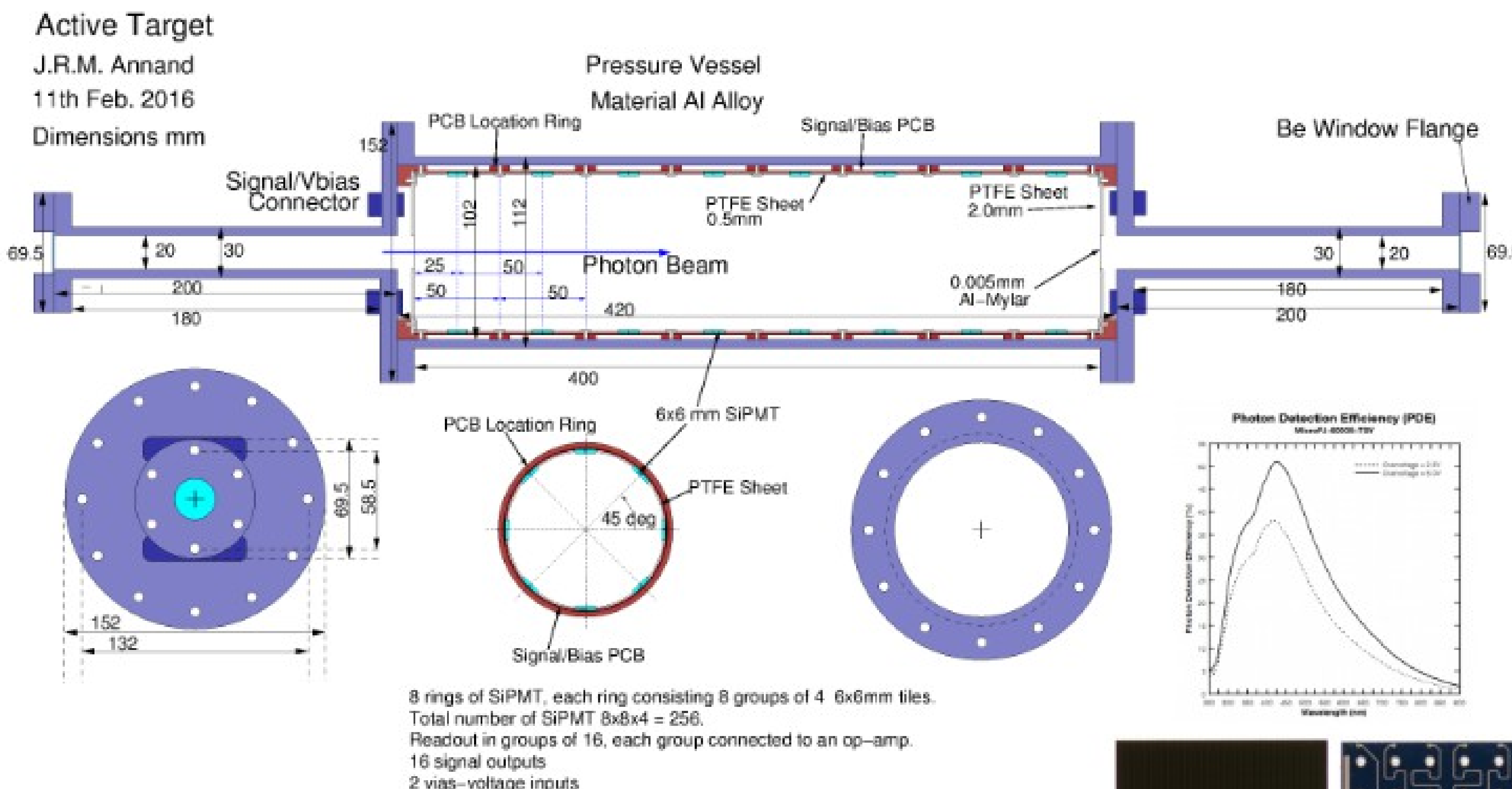


PhD, Maik Biroth, Mainz

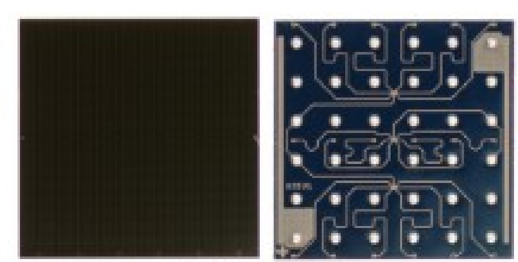
He gas active target

University of Glasgow

The New Active Target



- Al pressure vessel, no welds
- Reuse Be outer windows from original Active Target
- PTFE sheet covers printed circuit board, windows cut for SiPMT

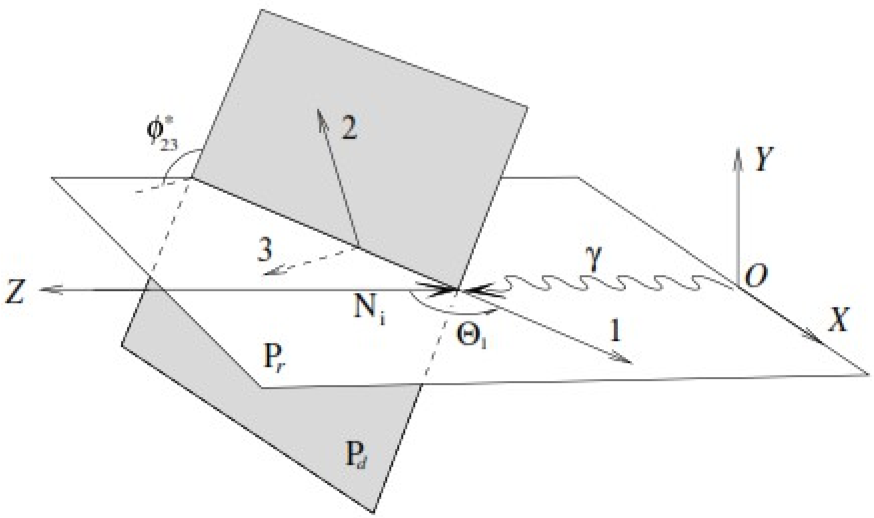


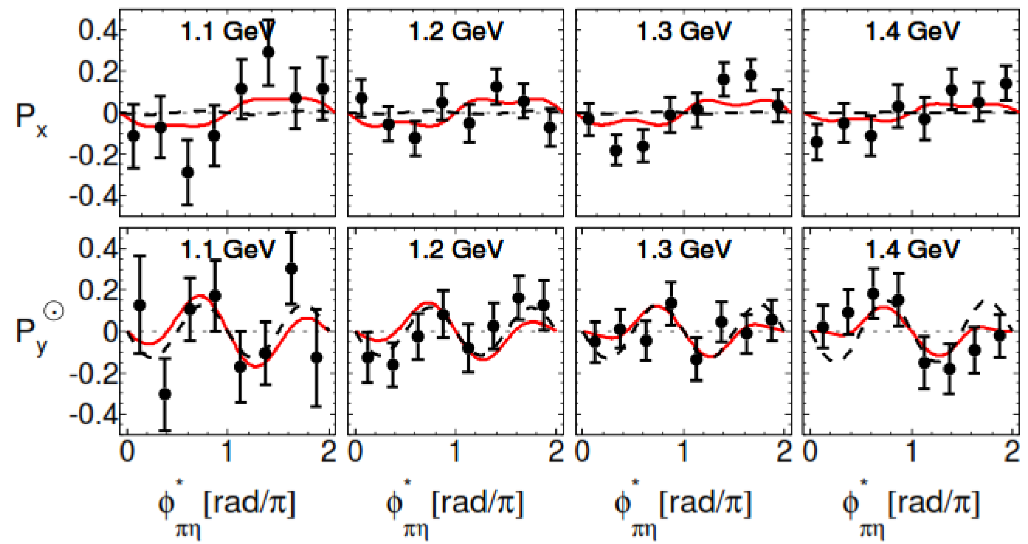
6 x 6mm J-Series SiPMT

$\pi^0\eta$ production, double polarization observables

$$\frac{d\sigma}{d\Omega_1 dM_{23} d\Omega^*_{23}} = \frac{d\sigma_0}{d\Omega_1 dM_{23} d\Omega^*_{23}} \Big\{ 1 + h P_\odot I^\odot + \frac{1}{\sqrt{2}} P_T [P_x \cos\phi - P_y \sin\phi + h P_\odot (P_x^\odot \cos\phi - P_y^\odot \sin\phi)] \Big\}$$

Beam	Target	
	x	y
–	P_x	P_y
c	$P_x^\odot$	$P_y^\odot$



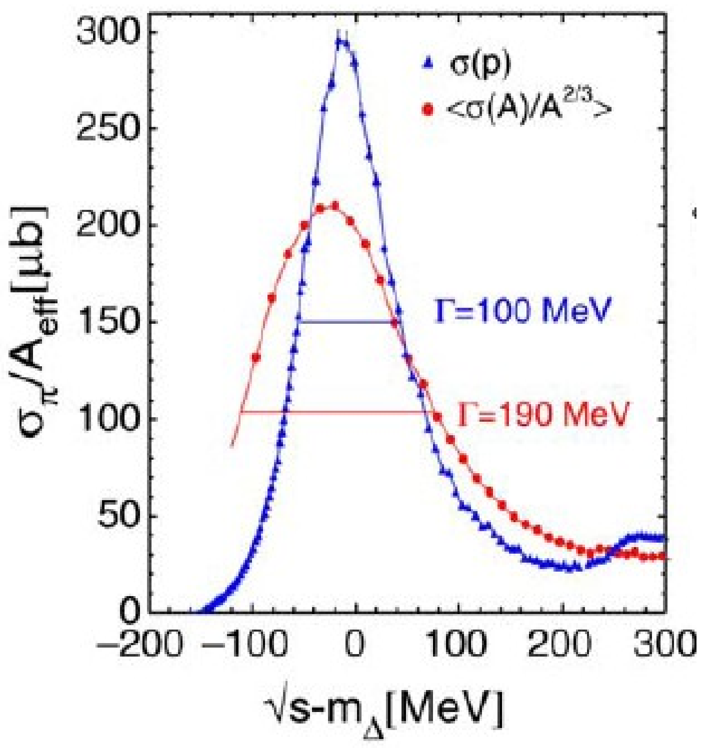


Dashed: only D_{33} wave, solid: A. Fix model, dashed-dotted BnGa PWA

J. R. M. Annand et al., Phys.Rev. C91, no.5, 055208 (2015)

Motivation

- The width for Δ(1232) is changed in the nuclear medium from 100 MeV to ~190 MeV in good agreement with the BUU model (University Gießen) calculations

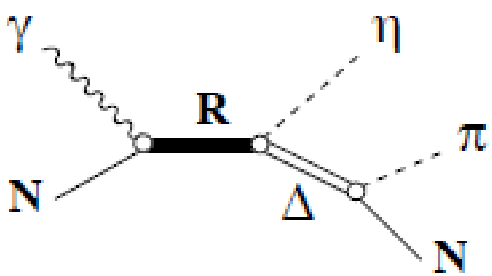


B. Krusche, Progress in Particle and Nuclear Physics 55 (2005) 46–70

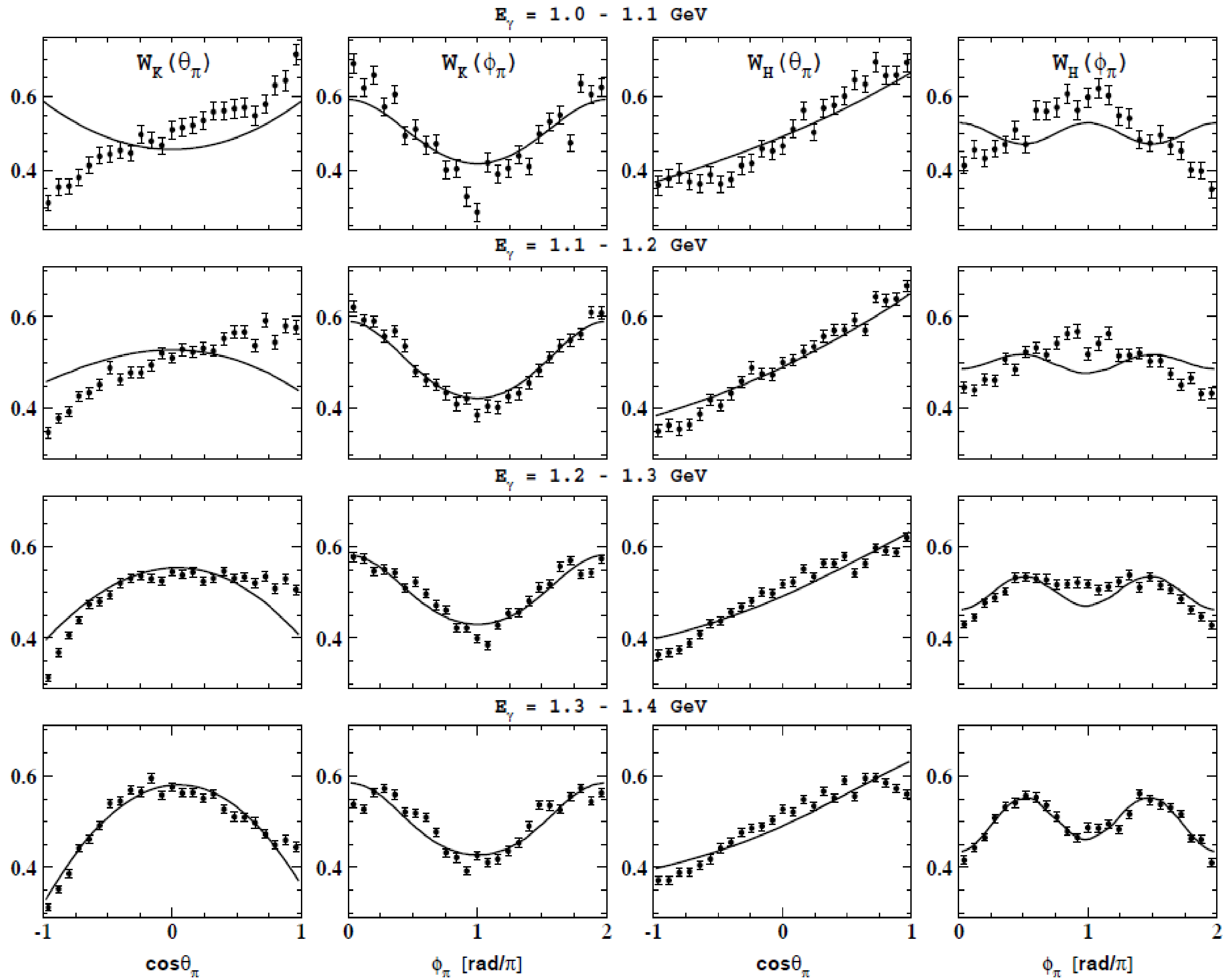
M. Post, J. Lehr, U. Mosel, Nuclear Phys. A 741 (2004) 81

- Second resonance region: No strong experimental indication for significant modifications of $D_{13}(1520)$ or $S_{11}(1535)$

Differential cross-sections (proton target)



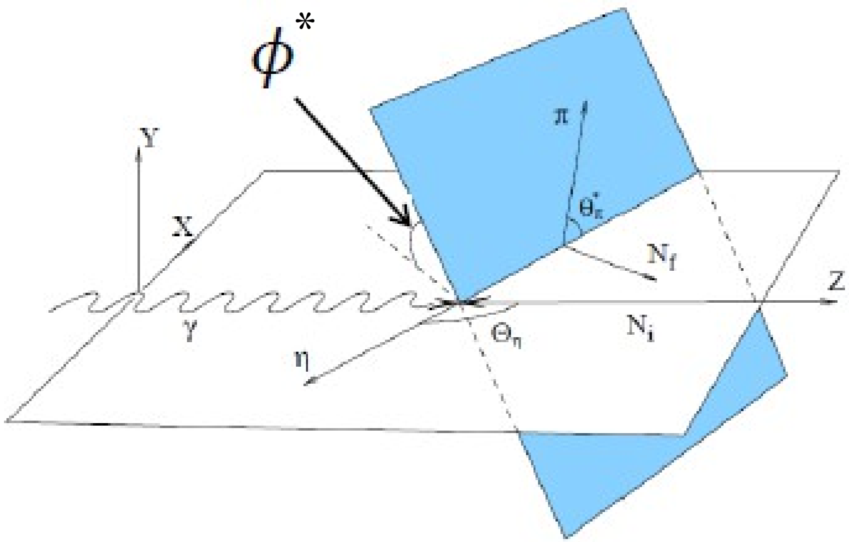
R = D$_{33}$

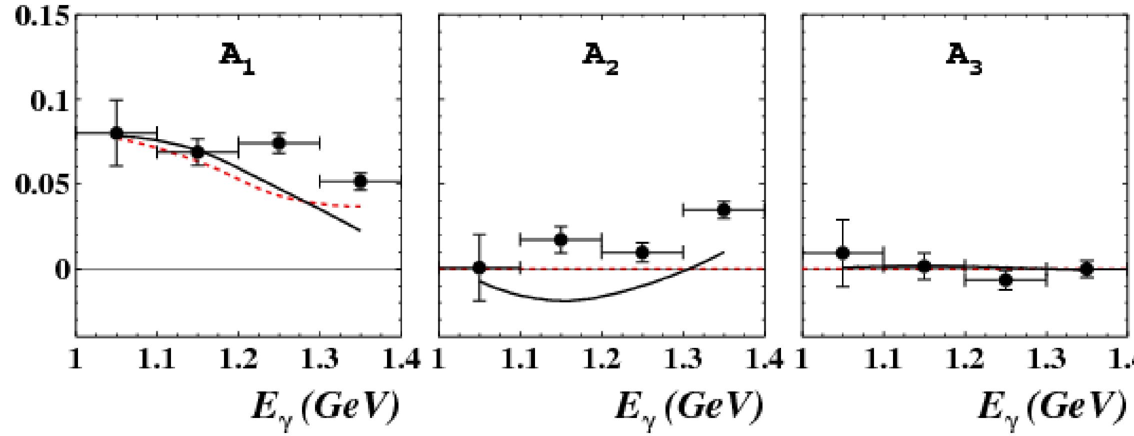


Angular distributions: Reasonable agreement with a model including only the D$_{33}$ amplitude

V. L. Kashevarov, A. Fix et al., Eur. Phys., J. A 42, 141 (2009) [A2 Collaboration]

Beam helicity asymmetry (proton target)





Coefficients of the sine expansion
Solid line : full model prediction
Dashed line: only the *D*33 amplitude.

V. L. Kashevarov, et al., Phys. Lett. B 693, 551 (2010)

$W^c(\phi)$ can be expanded as:

$$W^c(\phi) = \sum_{n=1}^{n_{\max}} A_n \sin n\phi$$

A1 represents purely the contribution of the D_{33} wave

A2 is sensitive to interference terms

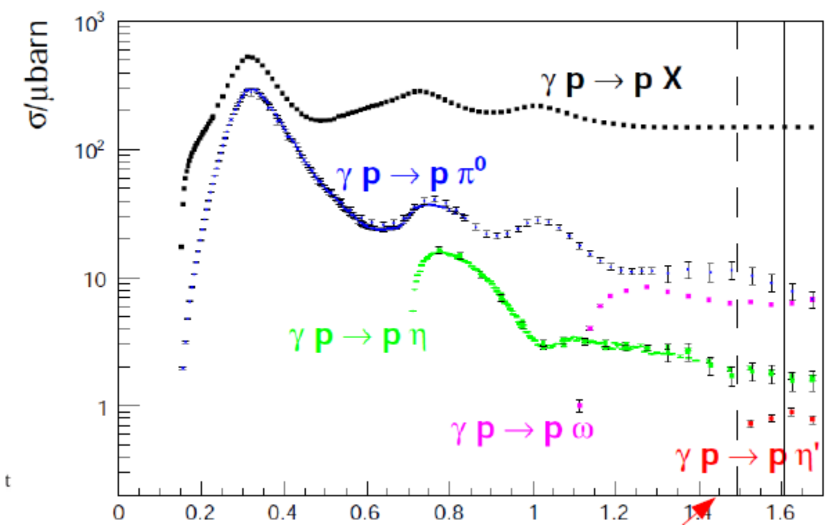
A3 is negligible

Both unpolarized and polarized data indicate the dominance of the D_{33} wave at energies E_γ < 1.2 GeV

Polarization observables

Systematic way to go: the complete experiment
for pesudoscalar single meson photoproduction:
8 carefully selected observables (with beam, target and recoil polarization required) are needed to predict all other experiments

Data form CB@MAMI, CB@ELSA, CLAS, SAPHIR



set		observables			
single	S	dσ/dΩ	Σ	T	P
beam-target	BT	G	H	E	F
beam-recoil	BR	Ox´	Oz´	Cx´	Cz´
target-recoil	TR	Tx´	Tz´	Lx´	Lz´

set		observables			
single	S	dσ/dΩ	Σ	T	P
beam-target	BT	G	H	E	F
beam-recoil	BR	Ox´	Oz´	Cx´	Cz´
target-recoil	TR	Tx´	Tz´	Lx´	Lz´

Double meson final states:
For a complete experiment, 15 observables are needed!
W. Roberts and T. Oed, Phys. Rev. C 71, 055201 (2005)