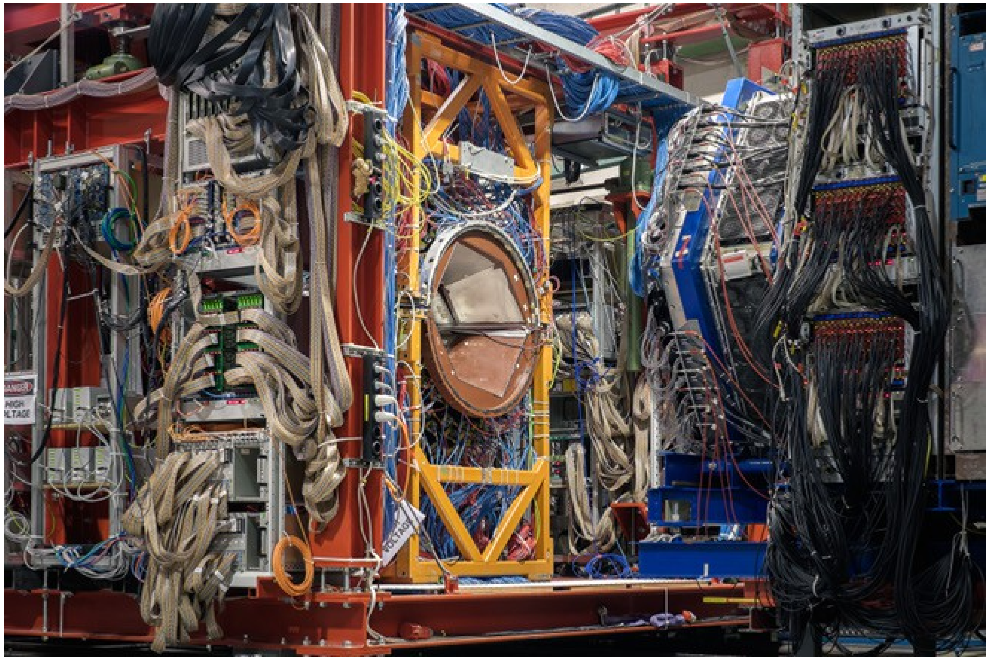
Recent results from the Crystal Ball/TAPS experiment at MAMI

Vahe Sokhoyan

Baryons 2016
International Conference on the Structure of Baryons
19.05.2016



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Contents

- Polarizabilities of the proton
- Baryon resonances
- In-medium modifications
- Experimental setup
- Results
- Summary and outlook

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Prof. Bernd Krusche "Photoproduction of mesons off the neutron", 16.05.2016

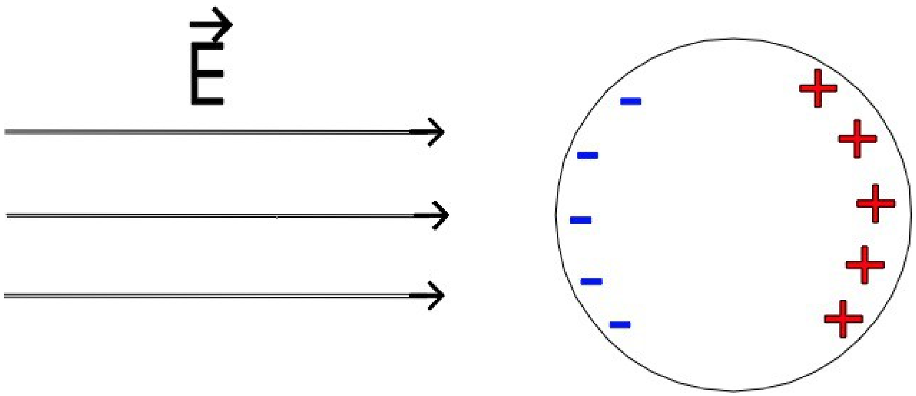
Dr. Sergey Prakhov "Measuring e/m transition form factors of light mesons with the A2 setup at MAMI", 17.05.2016

➡ Dr. Dominik Werthmueller "Λ(1405) Photoproduction at MAMI", 19.05.2016, 12:00

➡ Farah Noreen Afzal "Measurement of the double polarization observables E and G at MAMI" 19.05.2016, 15:25

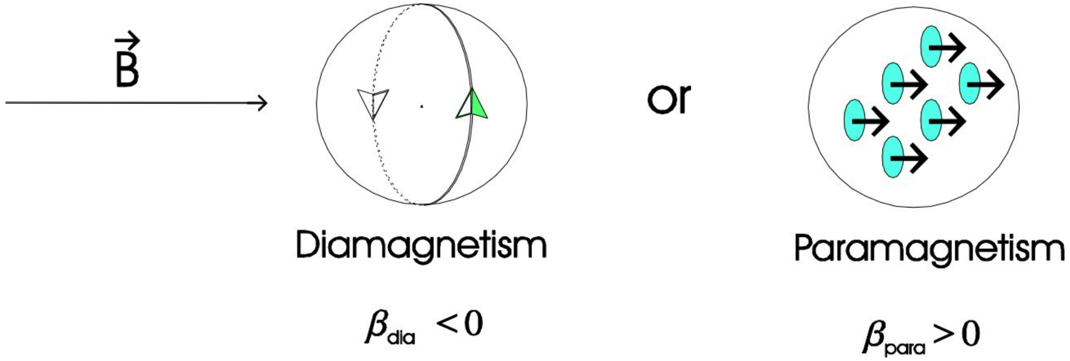
Scalar polarizabilities

Proton Electric Polarizability



- α_{E1}: electric polarizability
- Proton between charged parallel plates: "stretchability"

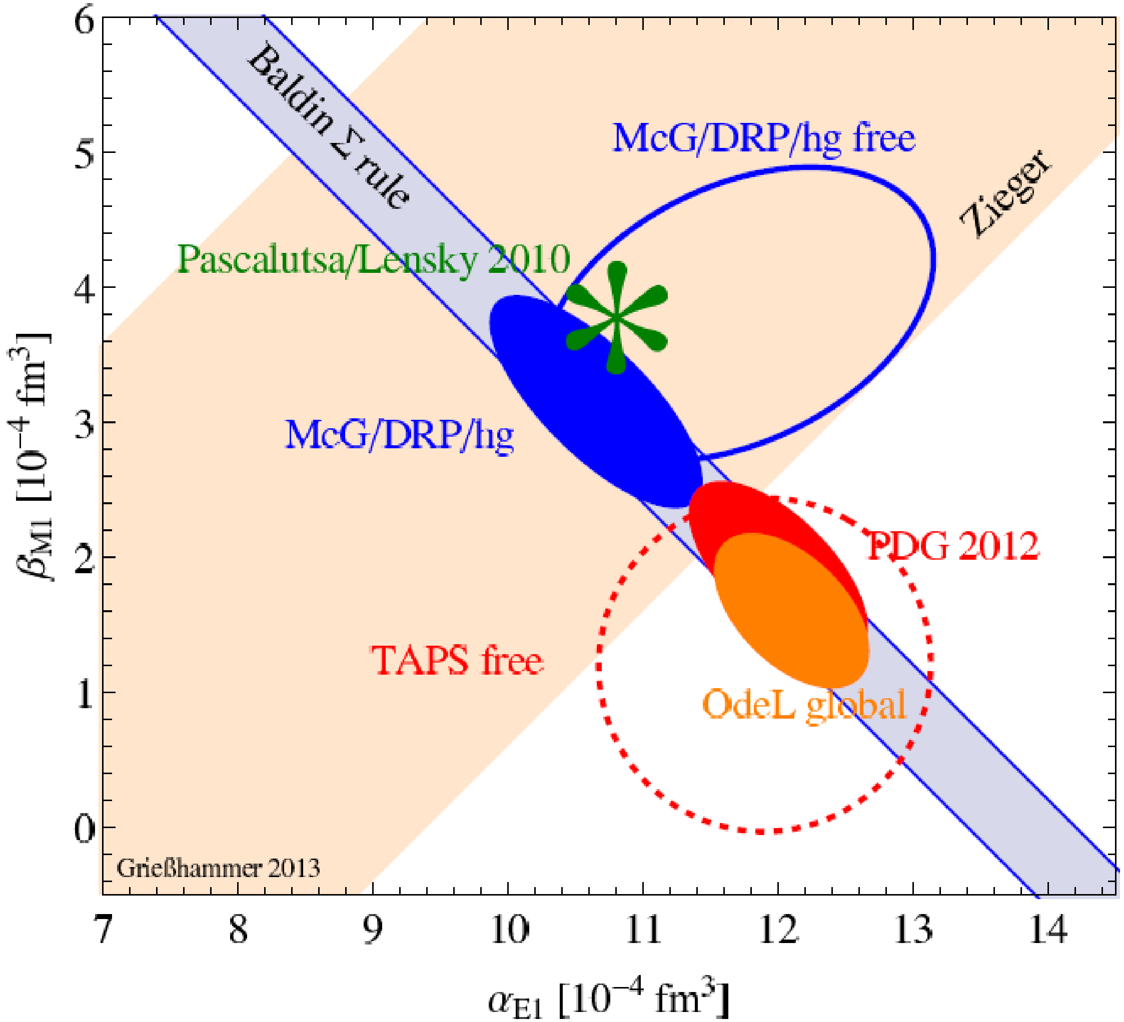
Proton Magnetic Polarizability



- β_{M1}: magnetic polarizability
- Proton between poles of a magnet: "alignability"

- Fundamental properties of the proton
- Important to astrophysics, atomic physics, spin polarizability measurements, etc.

Polarizabilities: data and model predictions



PDG (2012) values:

$\alpha_{E1} = (12.0 \pm 0.6) \times 10^{-4}\ \mathrm{fm}^3$

$\beta_{M1} = (1.9 \pm 0.5) \times 10^{-4}\ \mathrm{fm}^3$

New (2014) PDG values:

$\alpha_{E1} = (11.2 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$

$\beta_{M1} = (2.5 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$

Significant change between reviews without introducing new experimental data? New quality data needed!

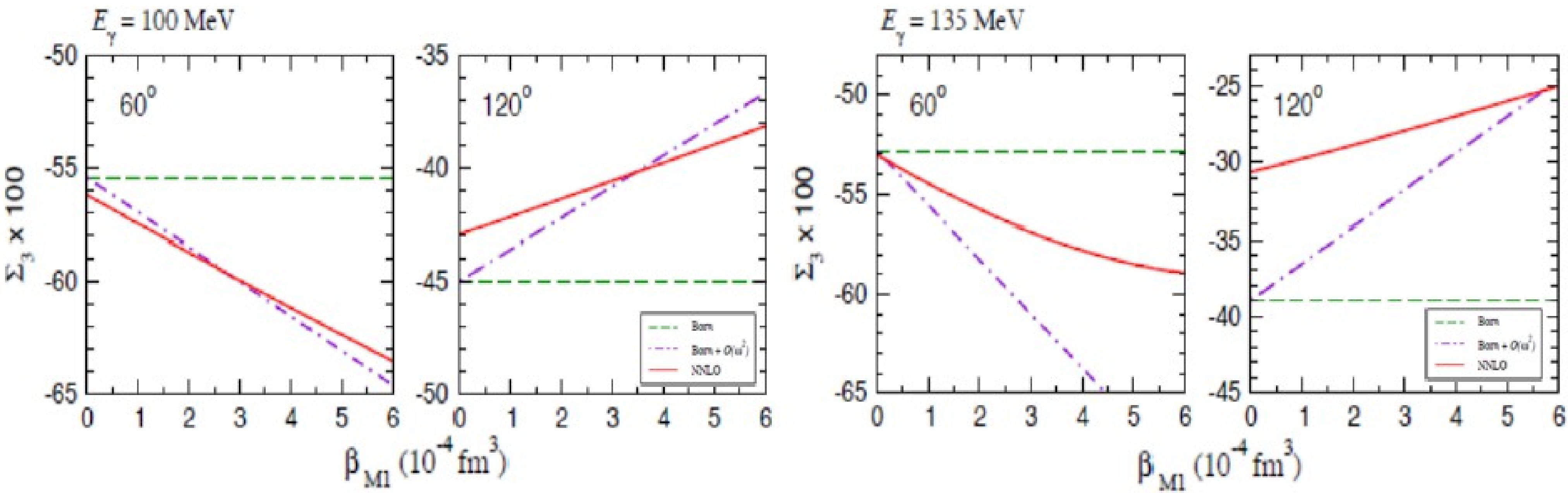
In the low energy range Σ_3 is purely dependent on β

Krupina and Pascalutsa, PRL 110, 262001 (2013)

Extraction of the magnetic polarizability β

⇒ At low energy, β_{M1} can be extracted from the measurement of the beam asymmetry Σ_3:

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



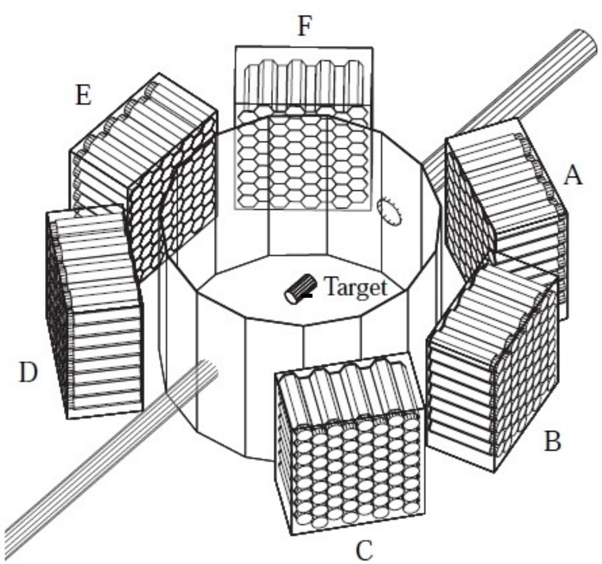
Krupina and Pascalutsa, PRL 110, 262001 (2013)

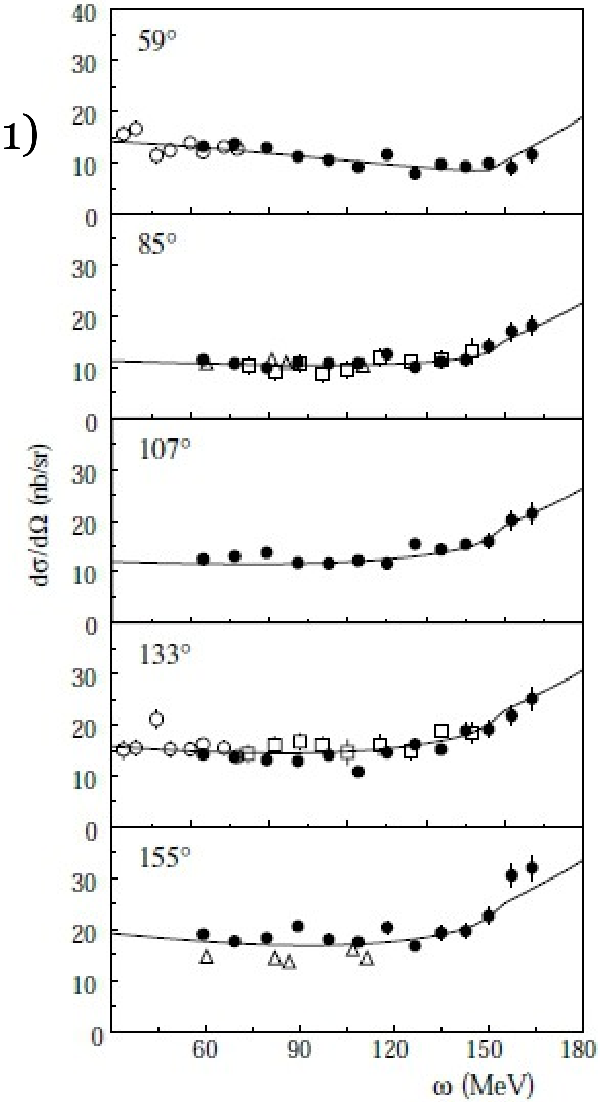
Compton Scattering: existing data

- Highest statistics data set:

V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001)

- 200 hours of Compton scattering
- 20 cm lH_2 target with TAPS
- 180 MeV electron beam
- E_γ = 55-165 MeV, 59° < Θ < 155°
- 1/3 acceptance of CB System!





Triangles: P.S. Baranov et al., Phys. Lett. B 52, 22 (1974);
P.S. Baranov et al., Sov. J. Nucl. Phys. 21, 355 (1975)
Open circles: F.J. Federspiel et al., Phys. Rev. Lett. 67, 1511 (1991)
Squares B.E. MacGibbon et al., Phys. Rev. C 52, 2097 (1995)
Curve: R.A. Arndt et al., Phys. Rev. C 53, 430 (1996)

Baryon resonances

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

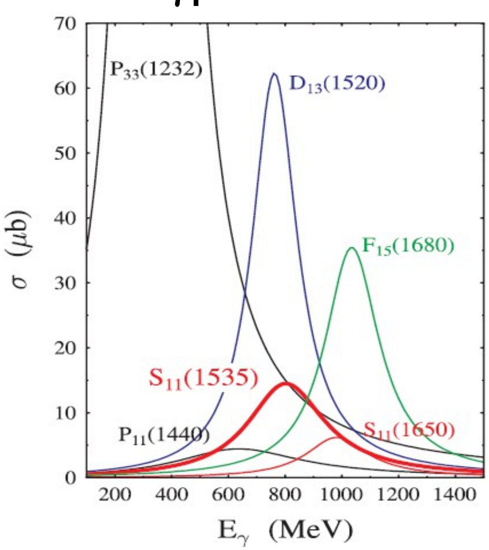
Lattice QCD confirms the number of the states in symmetric quark models

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

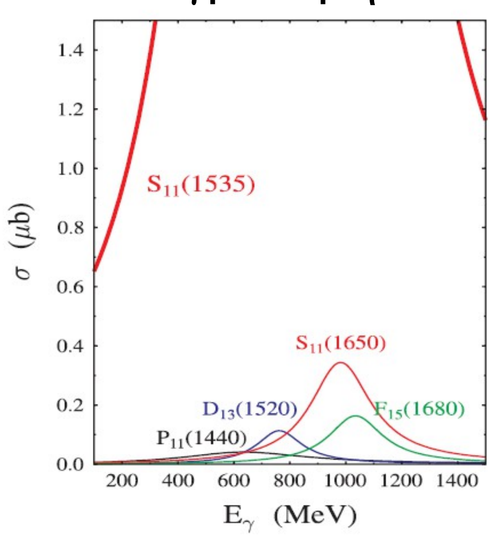
Experimentally: Broad overlapping resonances

- Partial Wave Analysis necessary
- Measurement of cross-sections and polarization observables
- Different production channels

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



$\gamma p \rightarrow p\eta$



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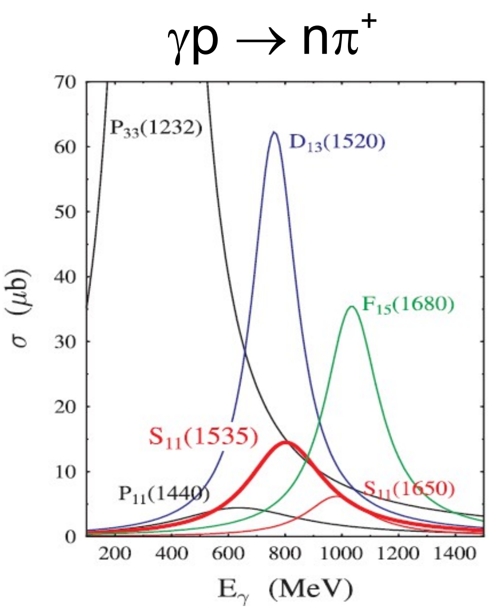

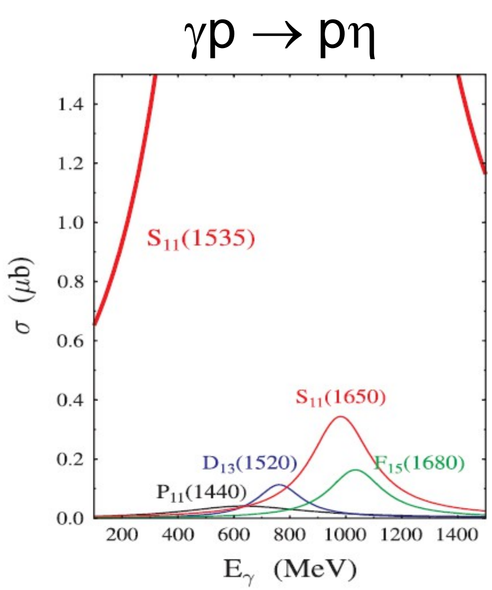

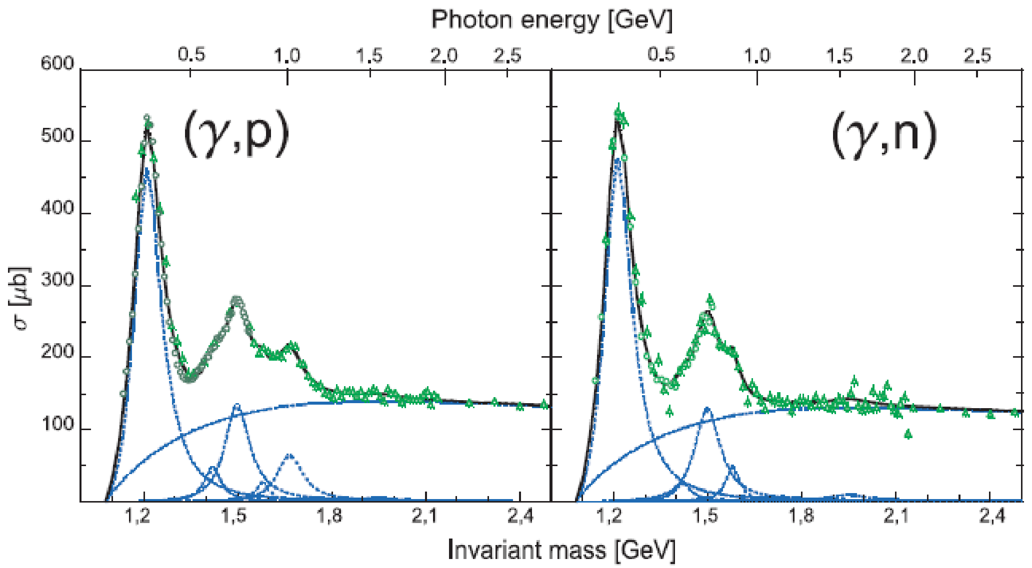

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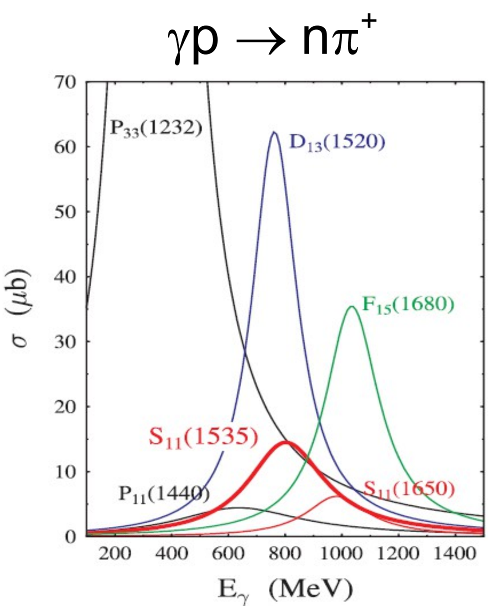
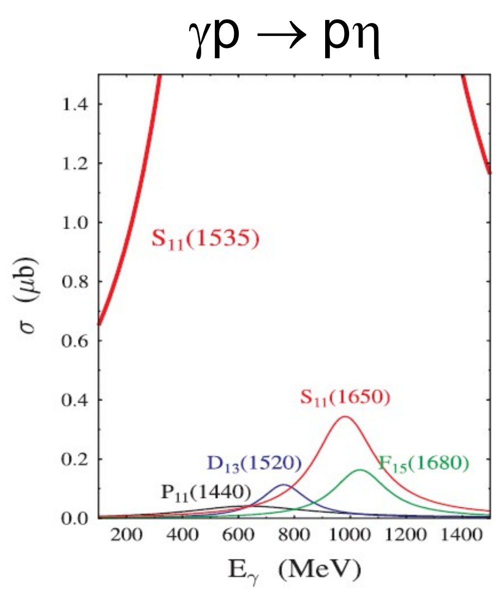
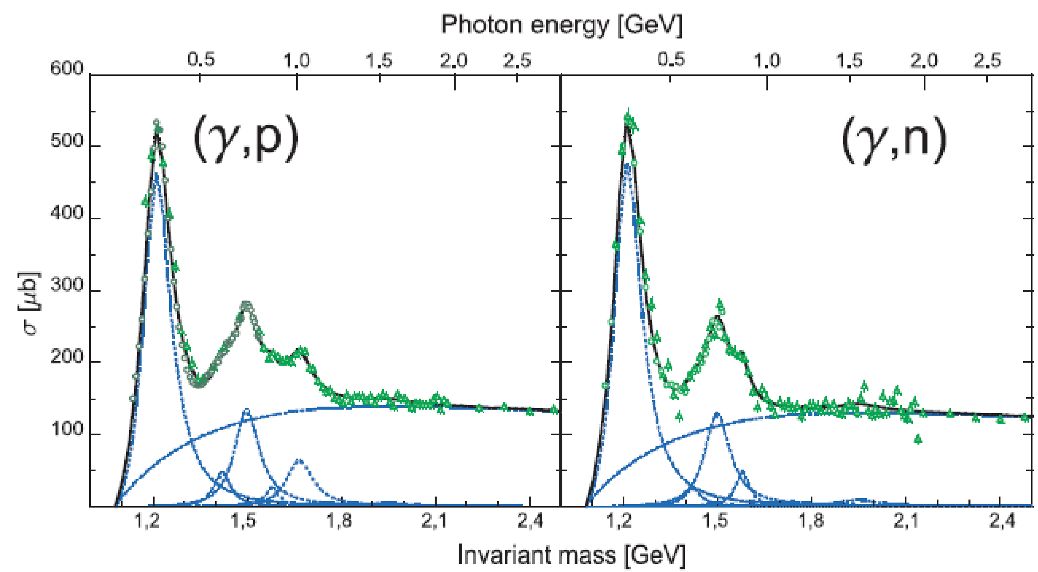




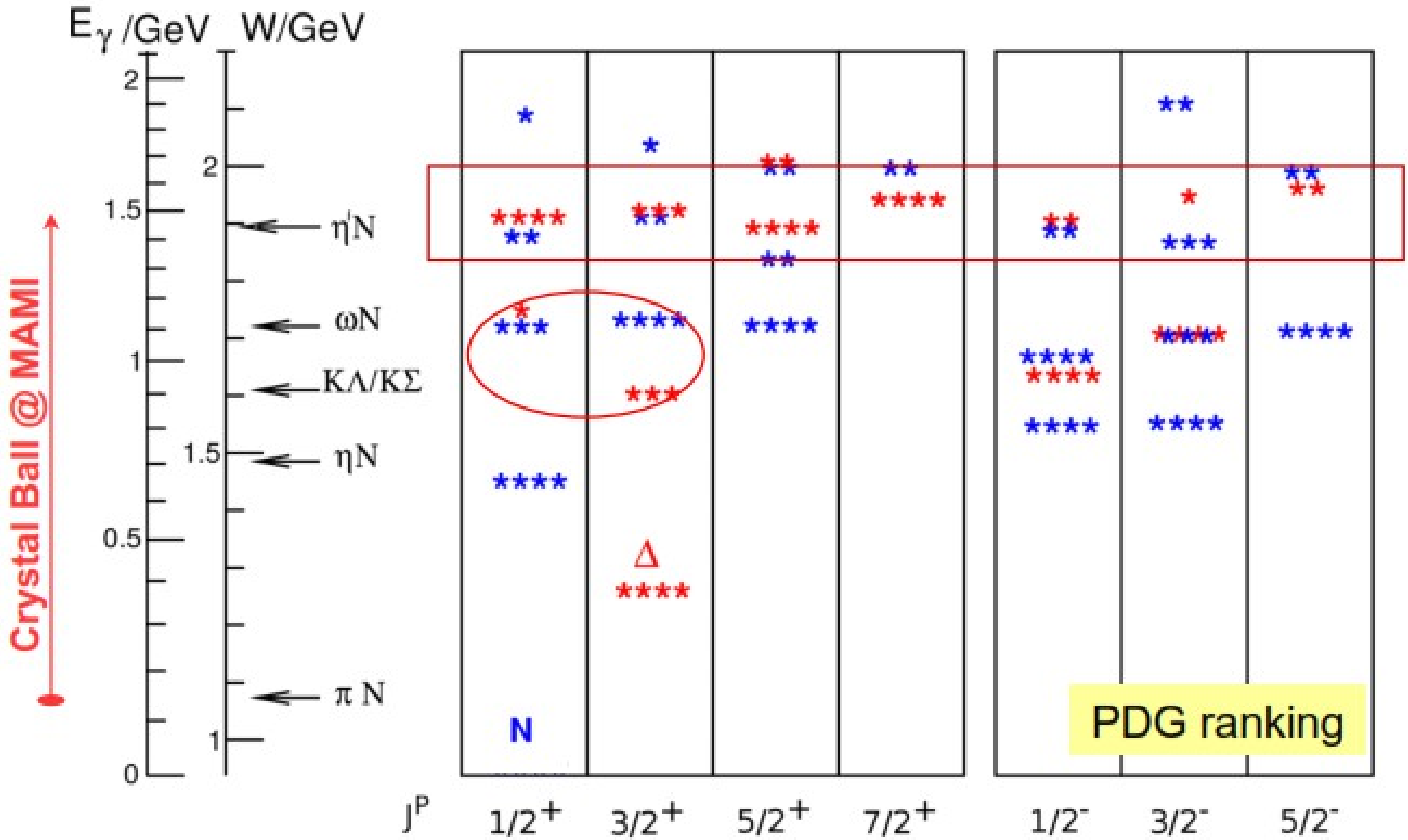


Most of the data obtained with πN scattering

Channels different from πN → Photoproduction experiments

Baryon resonances

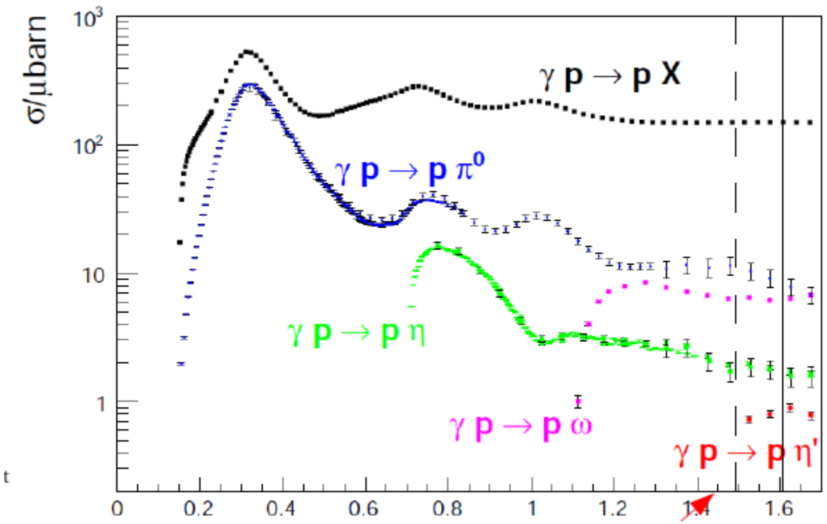
Goal: Gain a good understanding of the spectrum and properties of baryon resonances



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´

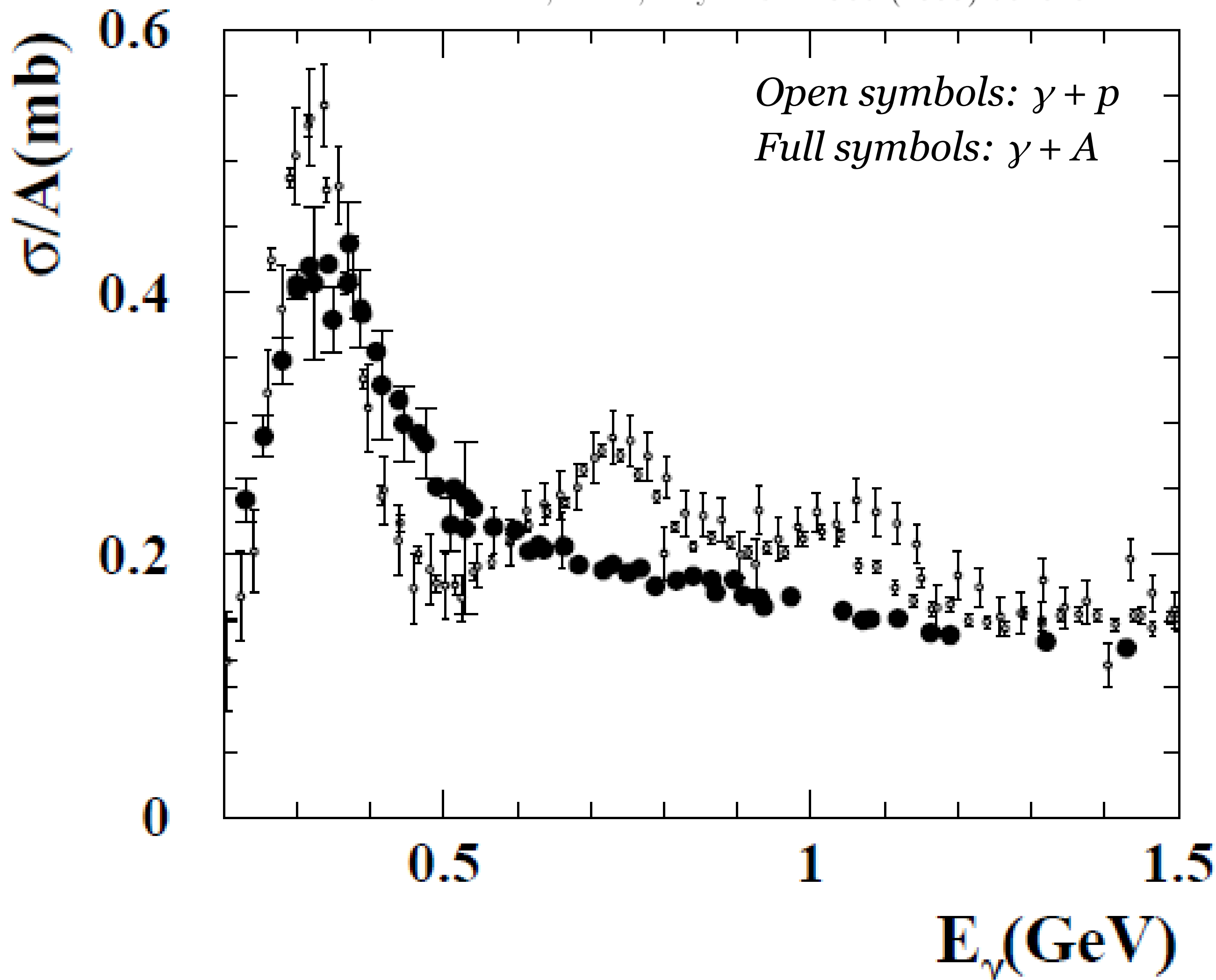
Double meson final states:
For a complete experiment, 15 observables are needed!
W. Roberts and T. Oed, Phys. Rev. C 71, 055201 (2005)

In-medium modifications

Goal: Search for in-medium modifications of baryon resonances

- Pronounced in-medium effect:
  No bump structure in the photoabsorption cross-section measured for $\gamma + A$
  $\rightarrow$ not fully explained in a model-independent way

V. Muccifora, et al., Phys. Rev. C60 (1999) 064616



In-medium modifications

- The width for $\Delta(1232)$ is changed in the nuclear medium from 100 MeV to ~190 MeV in good agreement with the BUU model (University Gießen) calculations
- Second resonance region: No strong experimental indication for significant modifications of $D_{13}(1520)$ or $S_{11}(1535)$

New experiment at MAMI:

- First study of the modifications of the $D_{33}(1700)$ resonance
- First measurement and interpretation of polarization observables for the investigation of in-medium modifications along with differential cross-sections
- Better understanding of the Final State Interaction (FSI)

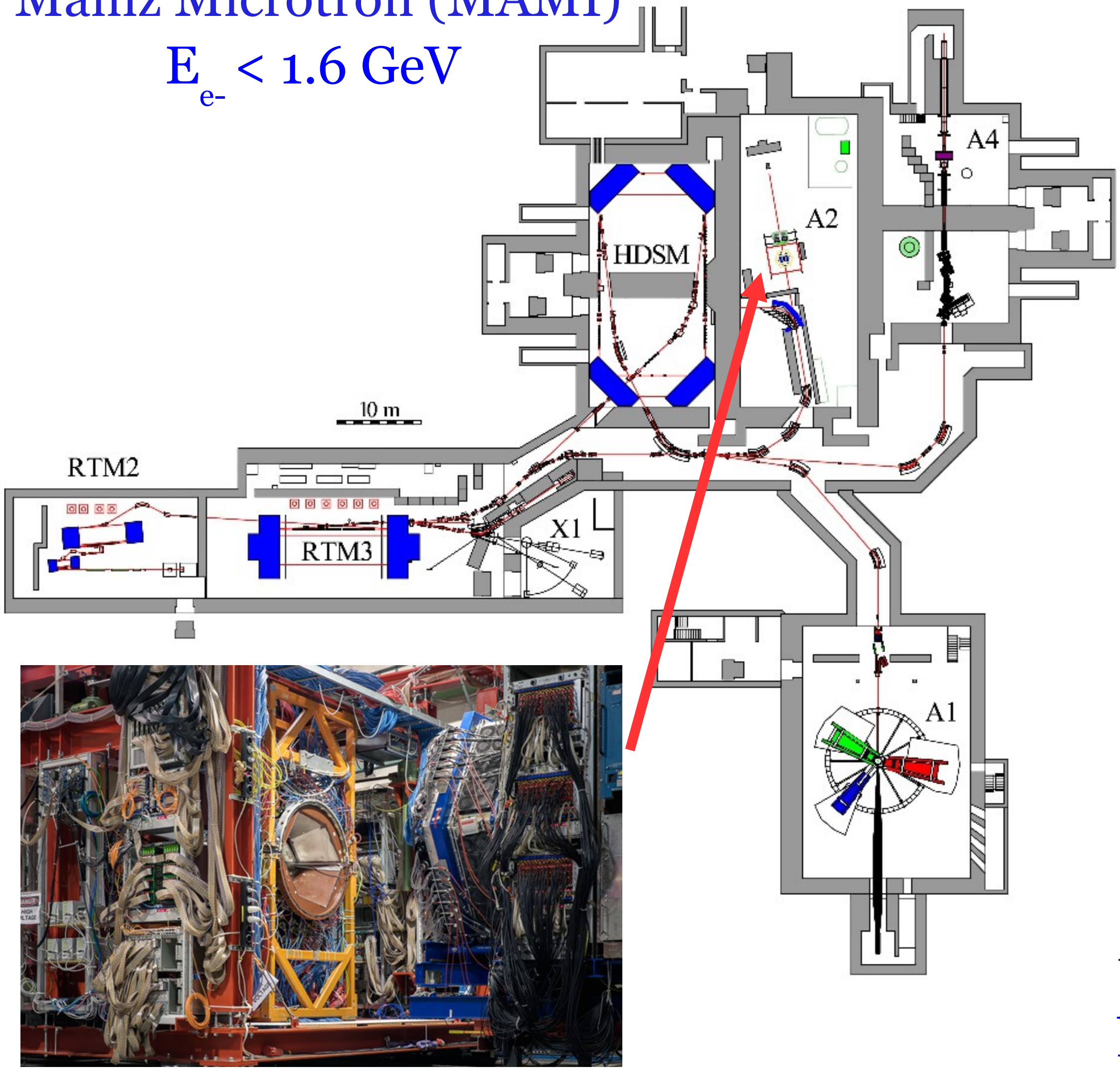
We will extract:

Differential cross-sections and beam helicity asymmetry close to the $\pi^0\eta$ production threshold with C, Al, and Pb targets

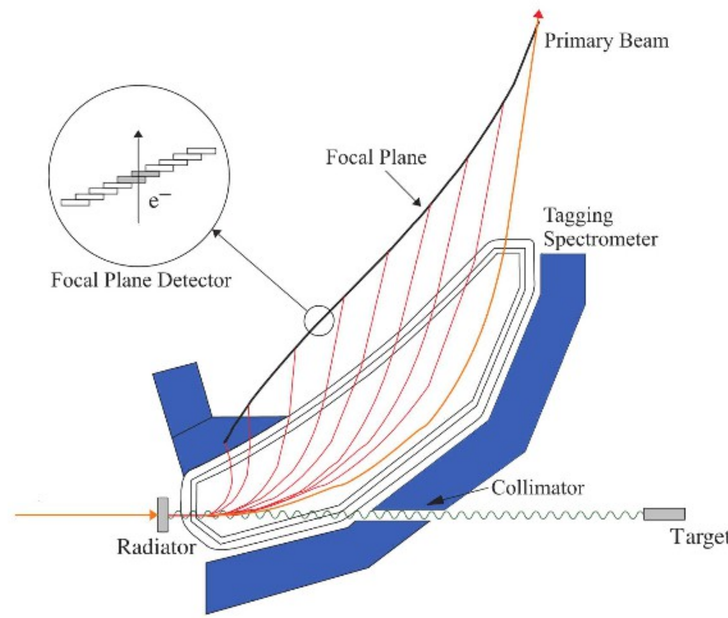
Experimental setup

Mainz Microtron (MAMI)

$E_{e-} < 1.6$ GeV



Tagger/End point tagger

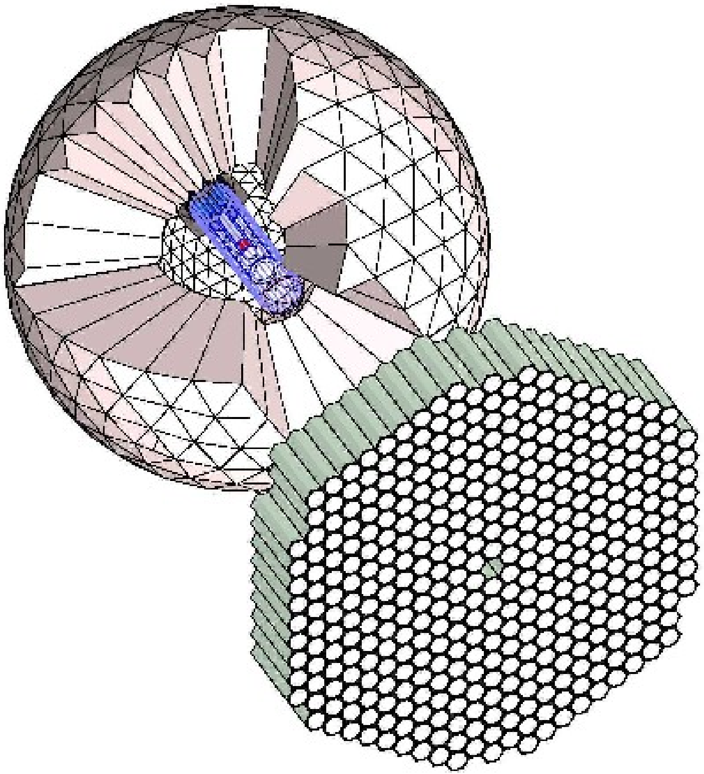


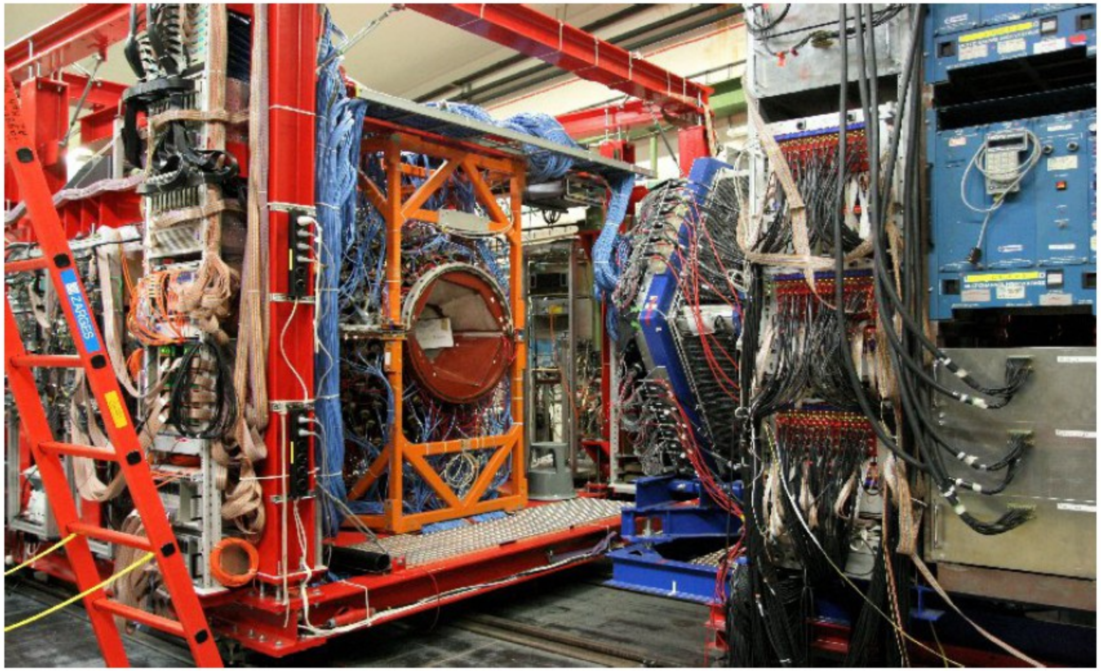
$$E_{\gamma} = E_{e-} - E_{tagg}$$

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

- High-Flux, Tagged, Bremsstrahlung Photon Beam: Unpolarized, Linear, and Circular
- Polarized and Unpolarized Targets
- Active polarized target and active He gas target under development

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

Compton scattering

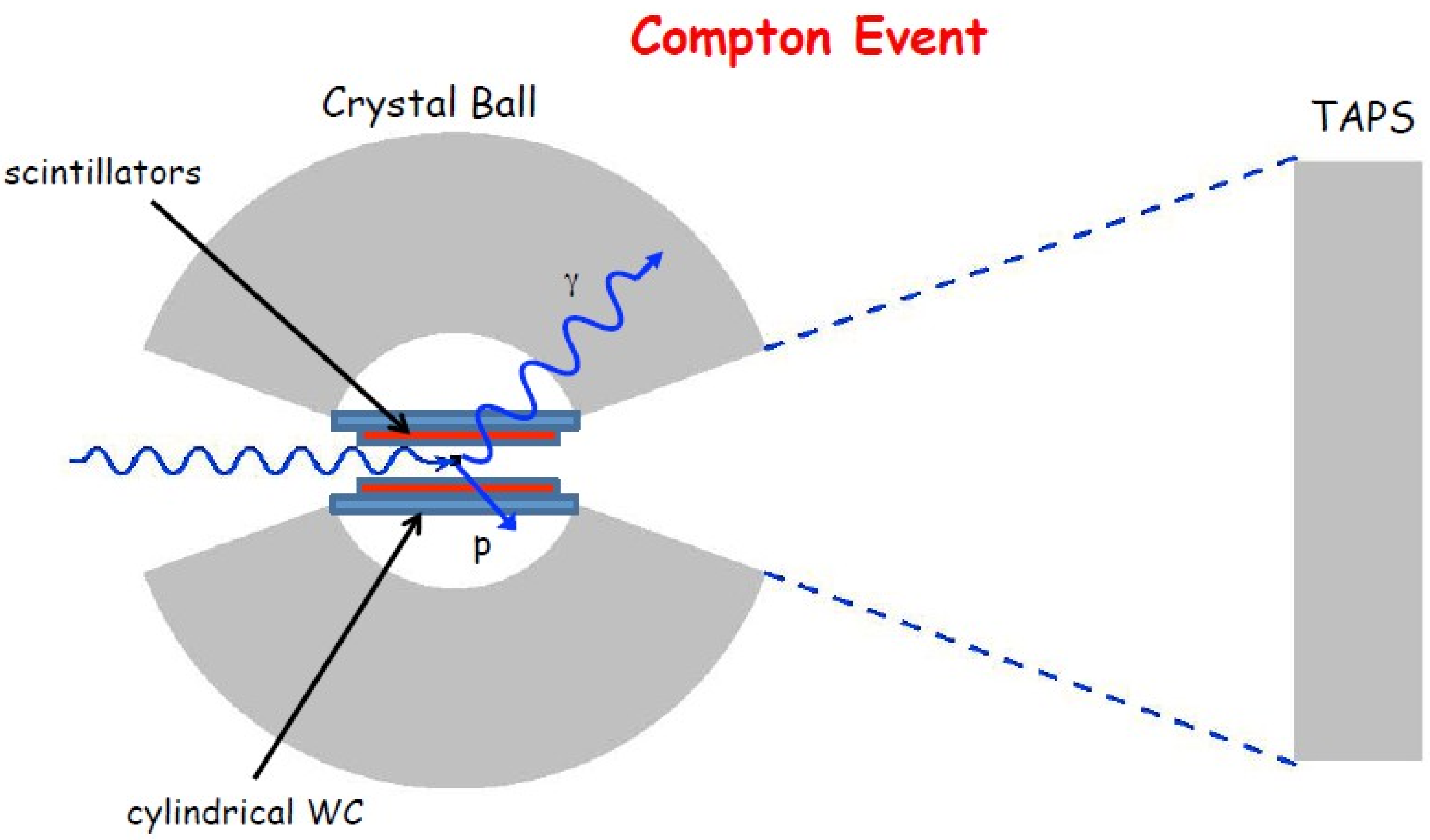
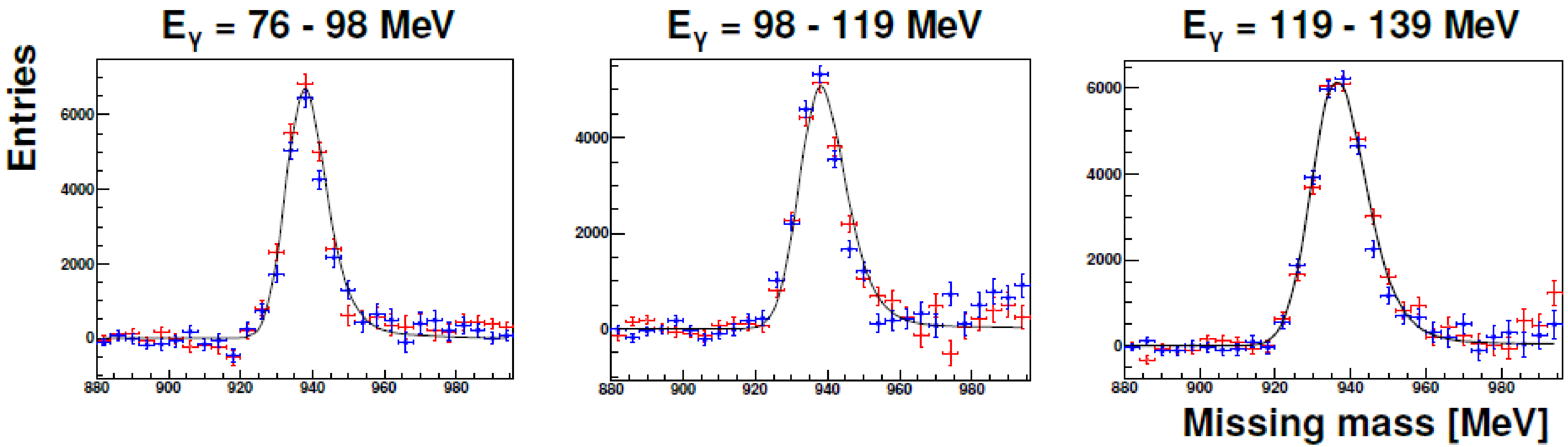


Figure: R. Miskimen

Compton scattering: clean sample (40 < θ < 155)

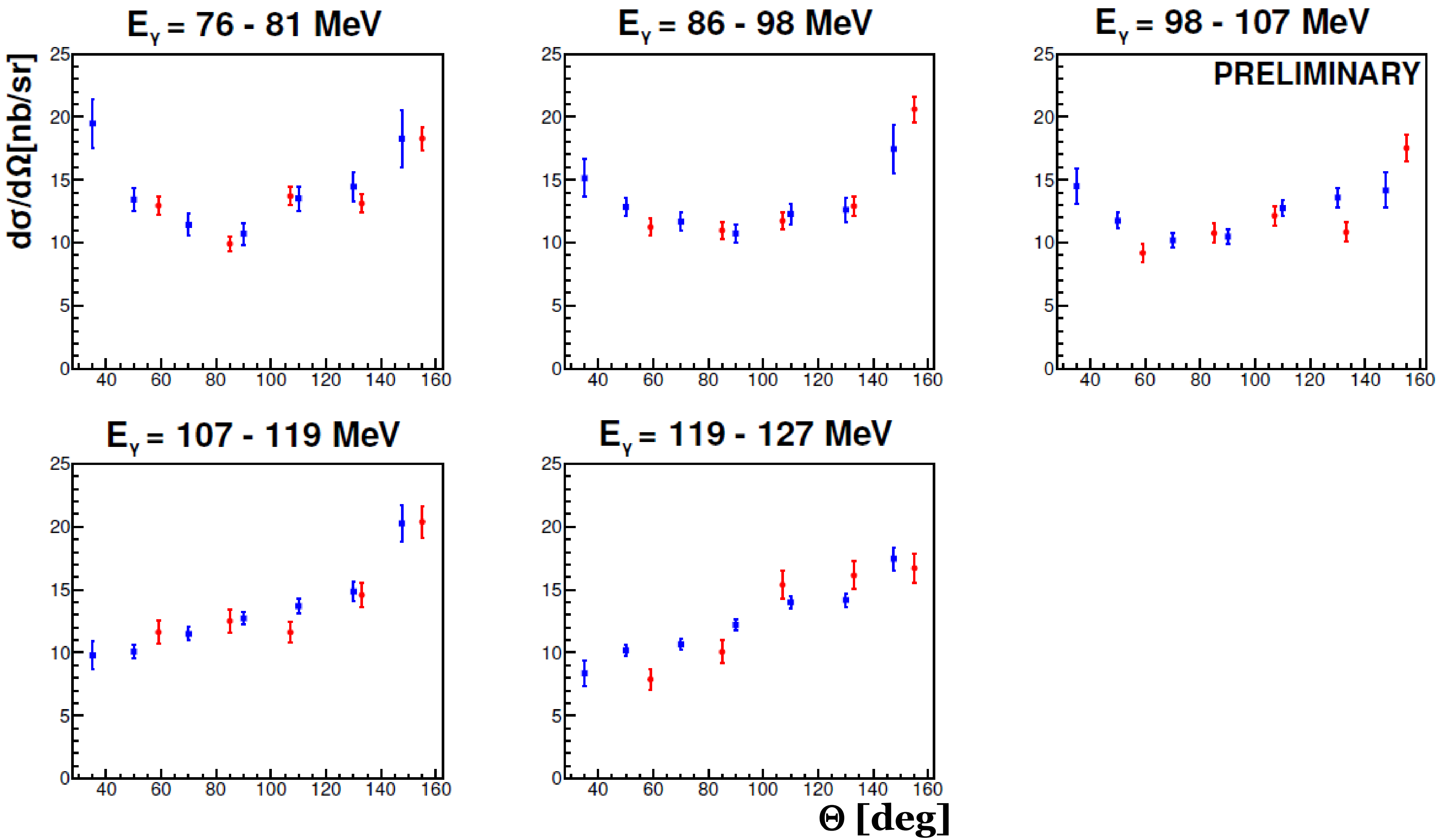


Good agreement in missing mass distribution for PARA, PERP and Monte Carlo simulation

⇒ Low background data set

E. Mornacchi (Mainz), V. S., E. J. Downie (GWU)

Compton scattering: new cross-section data



Good agreement between *old* and *new* data

<u>Improvement in statistics!</u>

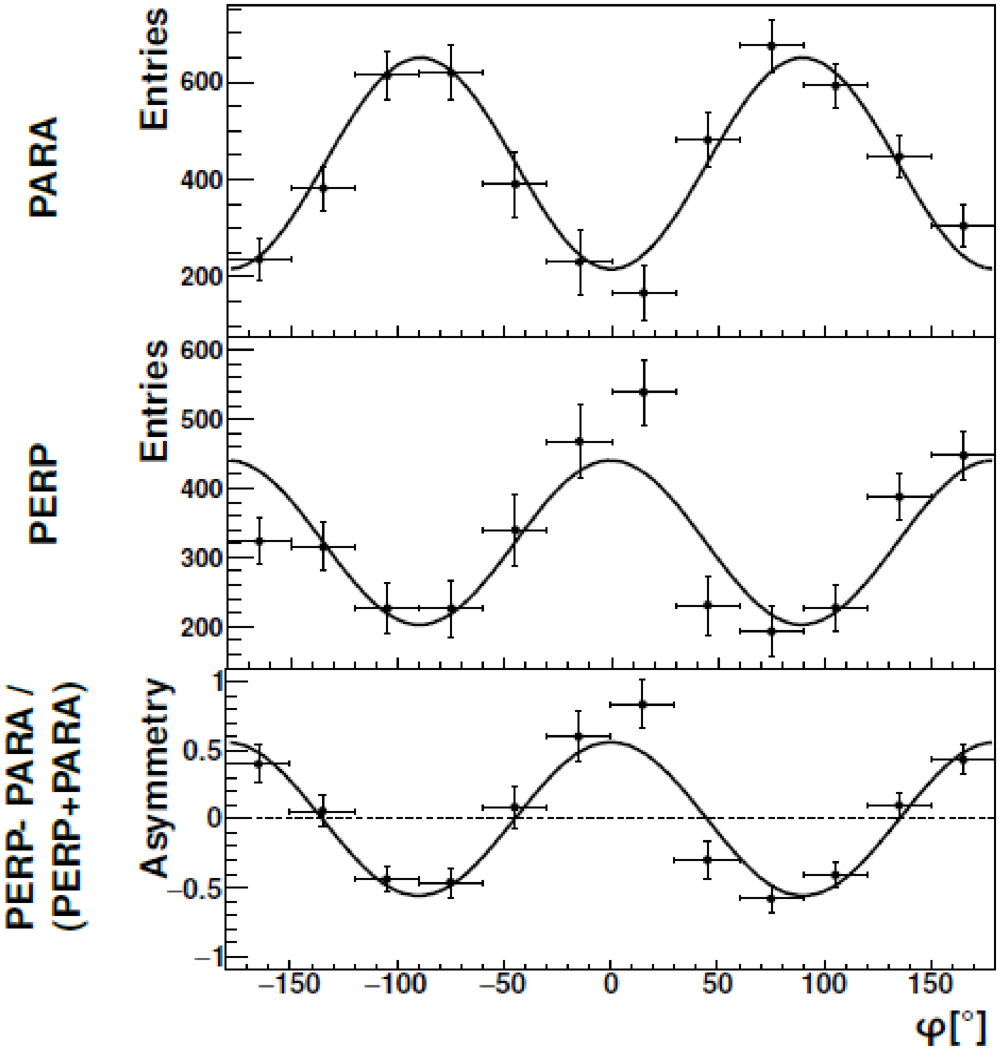
E. Mornacchi (Mainz), V.S., E. J. Downie (GWU)

Compton scattering: angular distributions

ϕ distribution for PARA and PERP data.

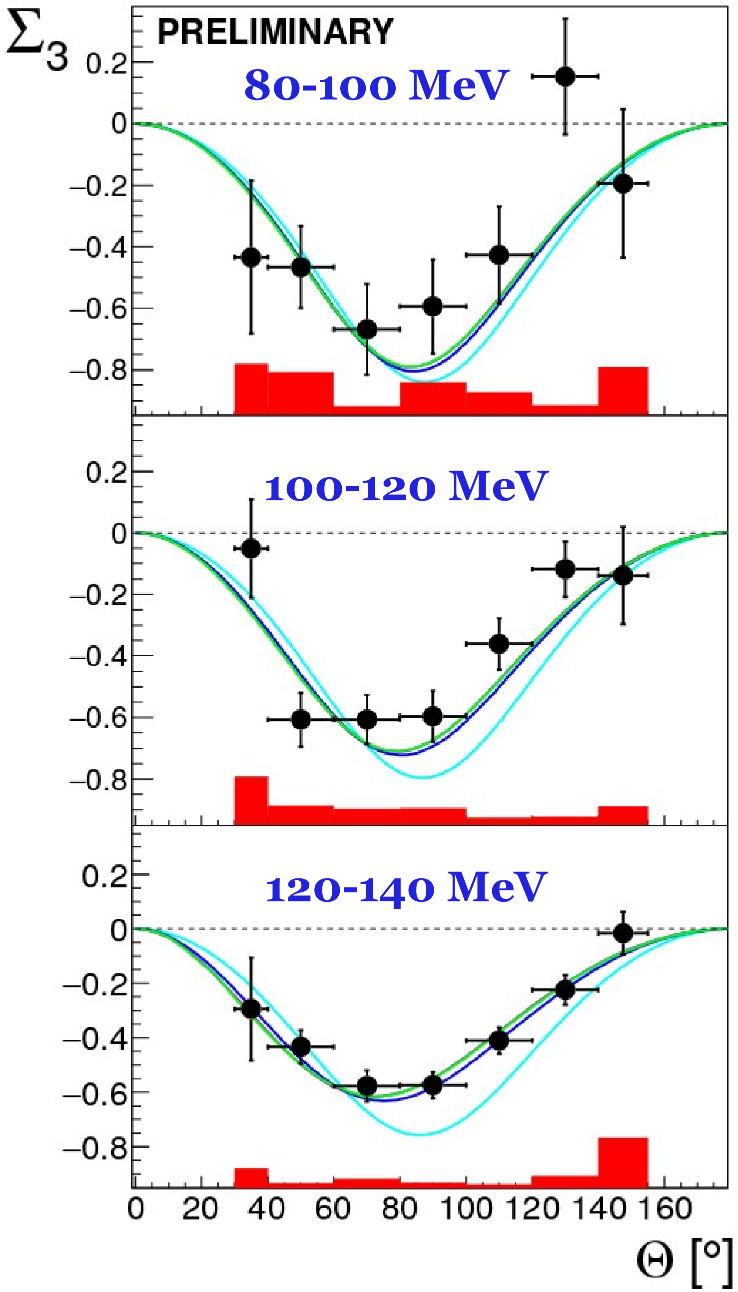
$\cos(2\phi)$ modulation coming from polarized cross-section.

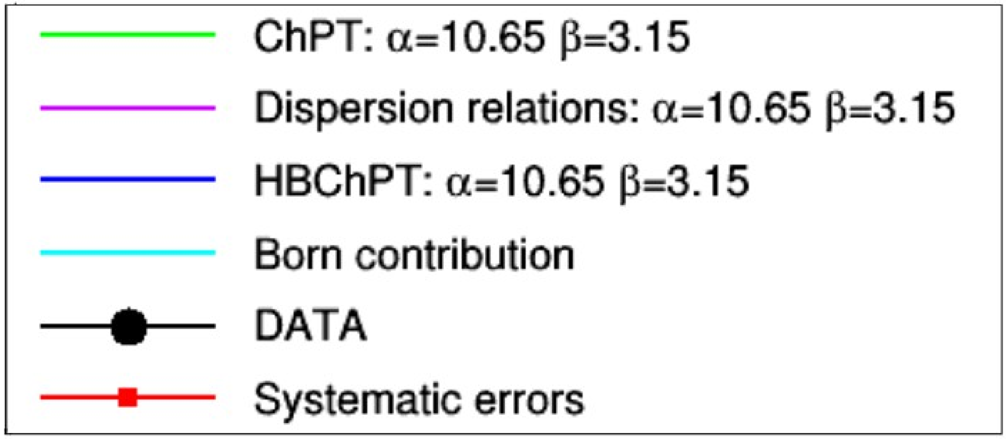
$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 cos(2\phi)\right]$$



E. Mornachhi (Mainz), V.S., E. J. Downie (GWU)

Compton scattering: beam asymmetry





N. Krupina and V. Pascalutsa, PRL 110, 262001 (2013)

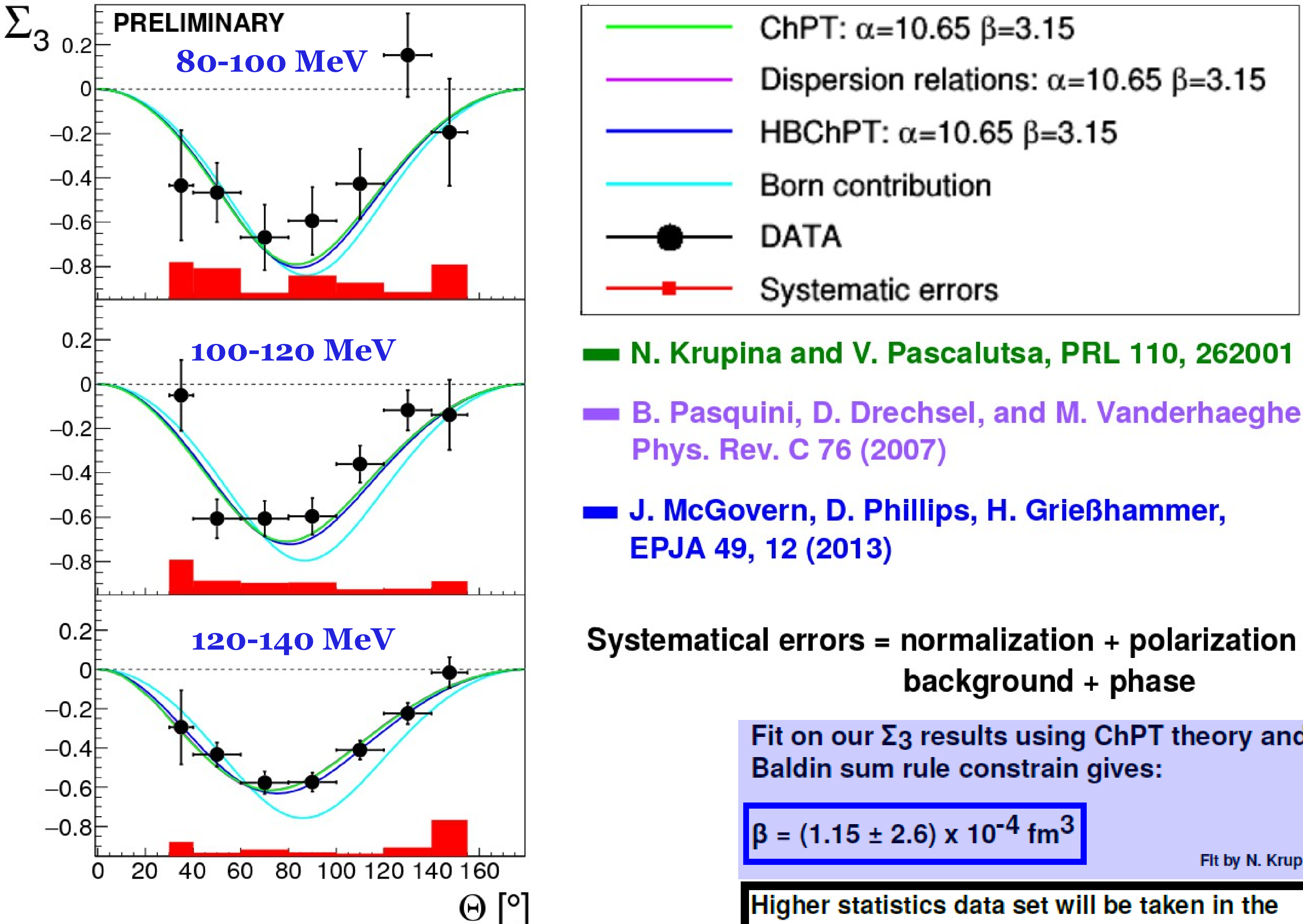
B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76 (2007)

J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)

Systematical errors = normalization + polarization + background + phase

E. Mornachhi (Mainz), V.S., E. J. Downie (GWU)

Compton scattering: beam asymmetry



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Systematical errors = normalization + polarization + background + phase

Fit on our Σ_3 results using ChPT theory and Baldin sum rule constrain gives:

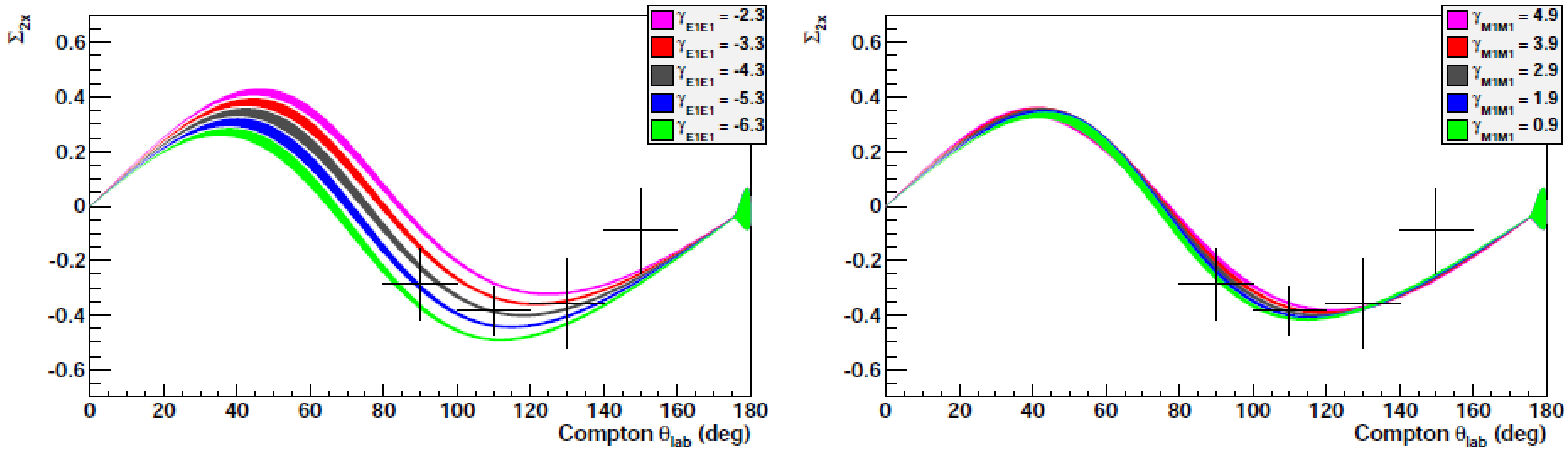
$\beta = (1.15 \pm 2.6) \times 10^{-4}\ \mathrm{fm}^3$

Fit by N. Krupina

Higher statistics data set will be taken in the future at MAMI facility in Mainz!

Spin polarizabilites

$E_\gamma = 273 - 303\,\mathrm{MeV}$



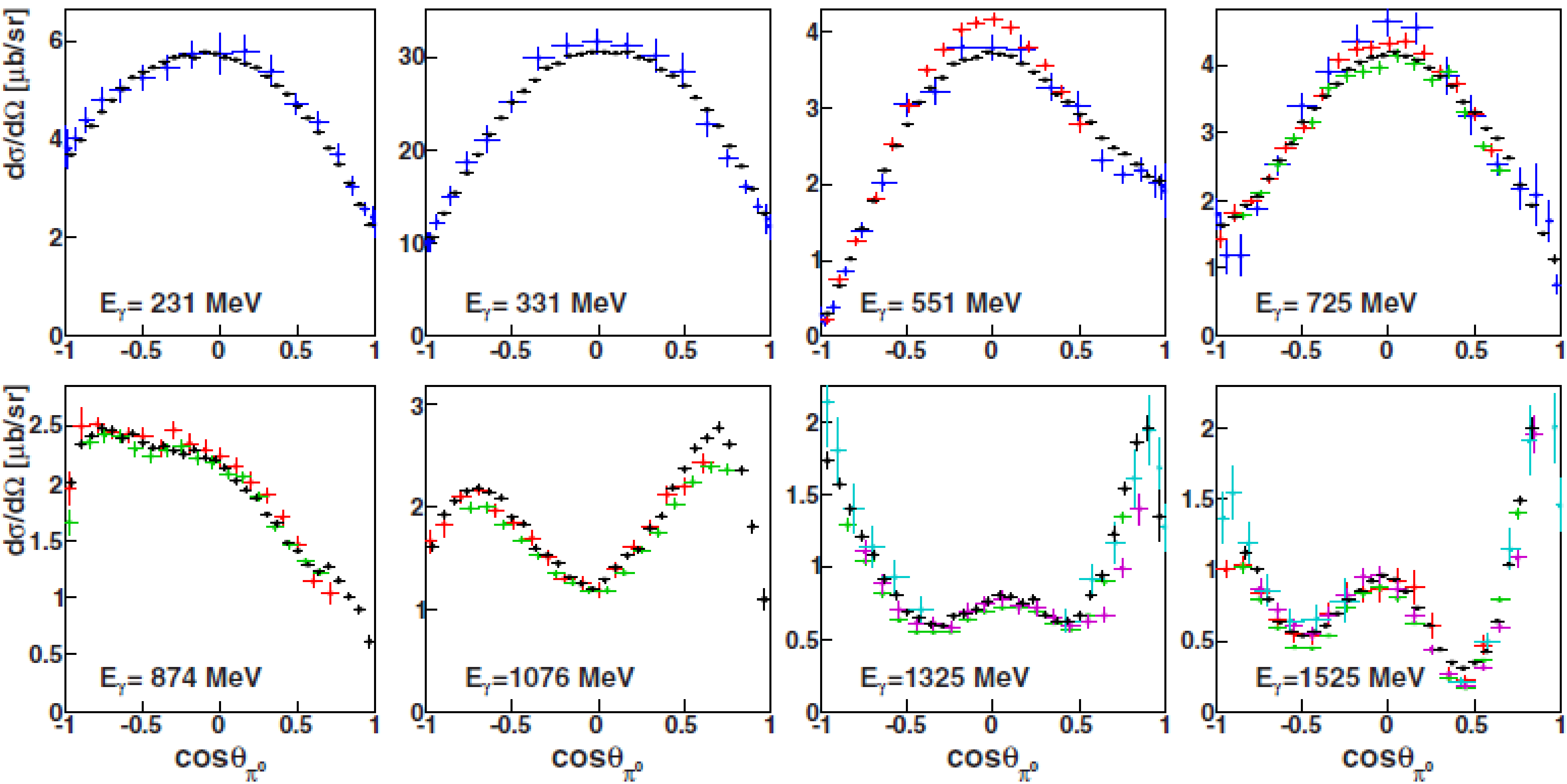
- First measurement of a double-polarized Compton scattering asymmetry on the nucleon, Σ_{2x}.
- Curves are from DR calculation of Pasquini et al.
- Data have sensitivity to the γ_{E1E1} spin-polarizability, with a preliminary estimate of

$$\gamma_{E1E1} = (-4.5 \pm 1.5) \times 10^{-4}\ \mathrm{fm}^4$$

P. P. Martel et al. (A2 Collaboration at MAMI), Phys. Rev. Lett. 114, 112501 (2015)

- **Beam asymmetry Σ_3 measured in the Δ region (C. Collicott, Mainz)**
- **Data on Σ_{2z} under analysis (UMass, Uni-Regina)**

Single π^o 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 SAID (GWU)**

Single η production

Eta-MAID update 2015 (with V. Kashevarov)

update for η photoproduction with new high-precision data: dσ/dΩ, Σ, T, F, E

using the previous EtaMAID2001/2003 model extended by new resonances N*

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

7 N* in 2001/2003

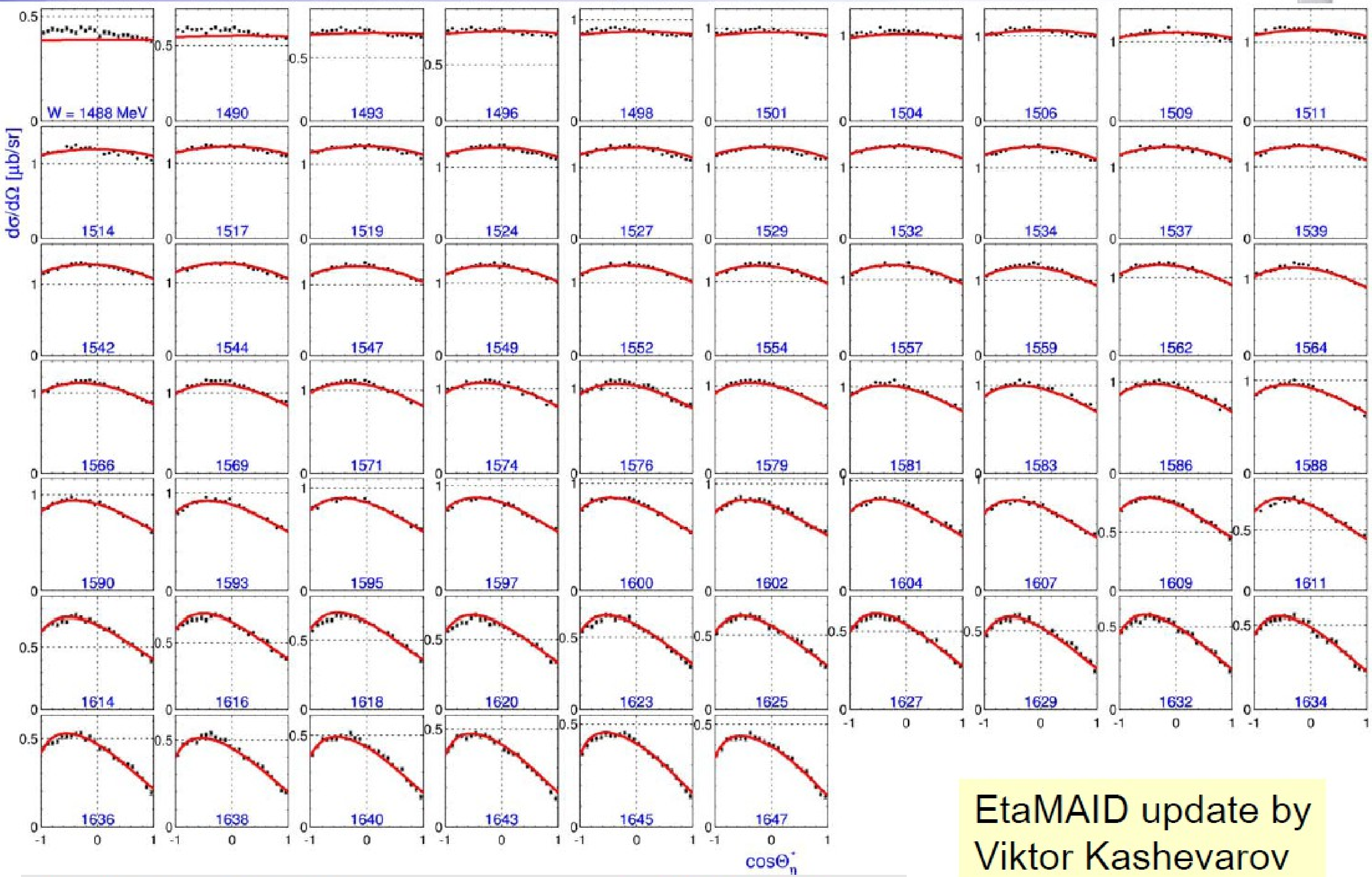
15 N* new in 2015

only 3 N* resonances in PDG below 2.6 GeV, where we do not find evidence for γ,η

but everything is still preliminary

Single η production

γ p → η p   *ηMAID-2015d: differential cross sections*

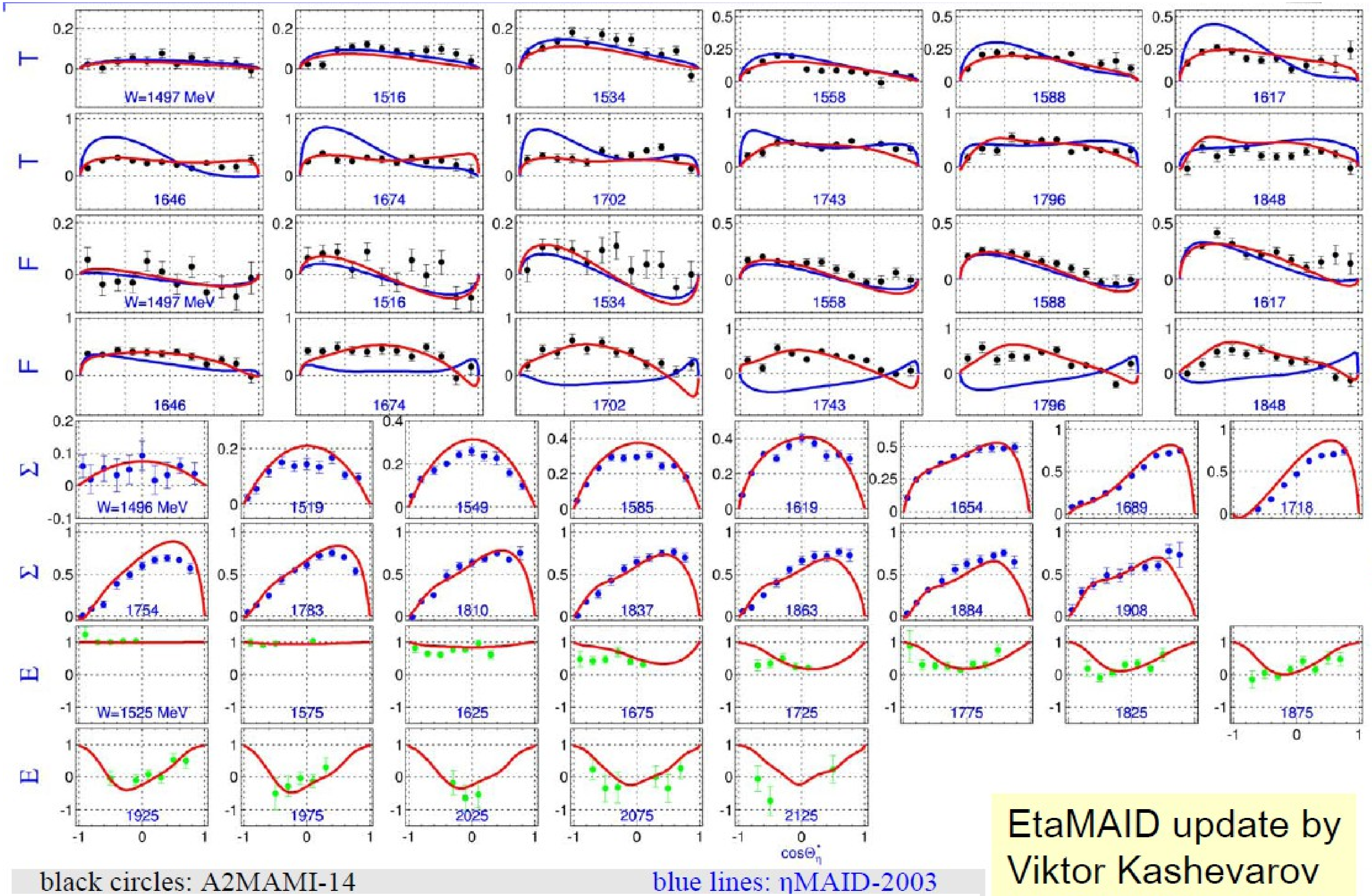


EtaMAID update by Viktor Kashevarov

black circles: A2MAMI-15   red: ηMAID-2015d

S. Prakhov (UCLA, Mainz), V. Kashevarov (Mainz)

Single η production



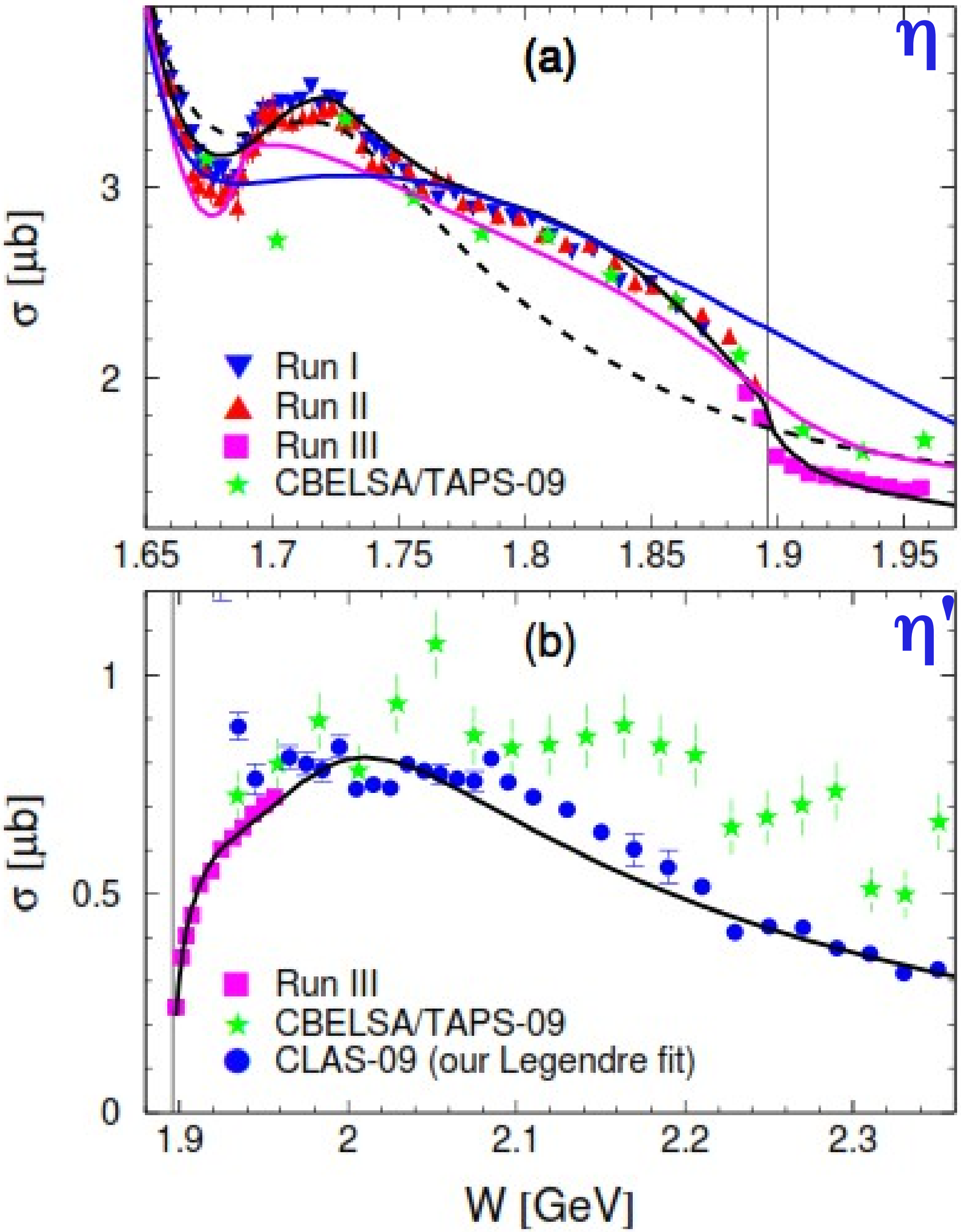
EtaMAID update by Viktor Kashevarov

C. S. Akondi et al., Phys.Rev.Lett. 113 (2014) no.10, 102001 (A2)
O. Bartalini et al., Eur.Phys.J. A33 (2007) 169-184 (GRAAL)
I. Senderovich et al., Phys.Lett. B755 (2016) 64-69 (CLAS)

Blue curve: EtaMAID-2003
Red curve: EtaMAID-2015d

Single η and η' production

Black line: present solution, dashed: ηMAID-2003, magenta: BG2014-2; blue: SAID GE09



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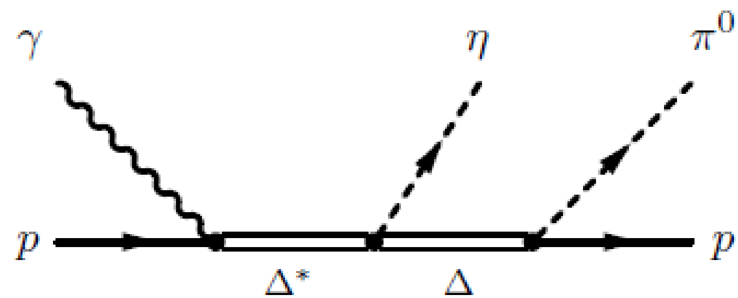
$N(1520)\,3/2^-$	****	****	****	***					***	***
$N(1535)\,1/2^-$	****	****	****	****					**	*
$N(1650)\,1/2^-$	****	****	****	***			***	**	**	***
$N(1675)\,5/2^-$	****	****	****	*			*		*	***
$N(1680)\,5/2^+$	****	****	****	*	**				***	***
$N(1700)\,3/2^-$	***	**	***	*			*	*	*	***
$N(1710)\,1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)\,3/2^+$	****	****	****	***			**	**	**	*
$N(1860)\,5/2^+$	**		**						*	*
$N(1875)\,3/2^-$	***	***	*			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	**	*	**			**	*		
$N(1900)\,3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	**	*	**			**	*	**	
$N(2040)\,3/2^+$	*		*							
$N(2060)\,5/2^-$	**	**	**	*				**		
$N(2100)\,1/2^+$	*		*							
$N(2120)\,3/2^-$	**	**	**				*	*		
$N(2190)\,7/2^-$	****	***	****			*	**		*	
$N(2220)\,9/2^+$	****		****							
$N(2250)\,9/2^-$	****		****							
$N(2300)\,1/2^+$	**		**							
$N(2570)\,5/2^-$	**		**							

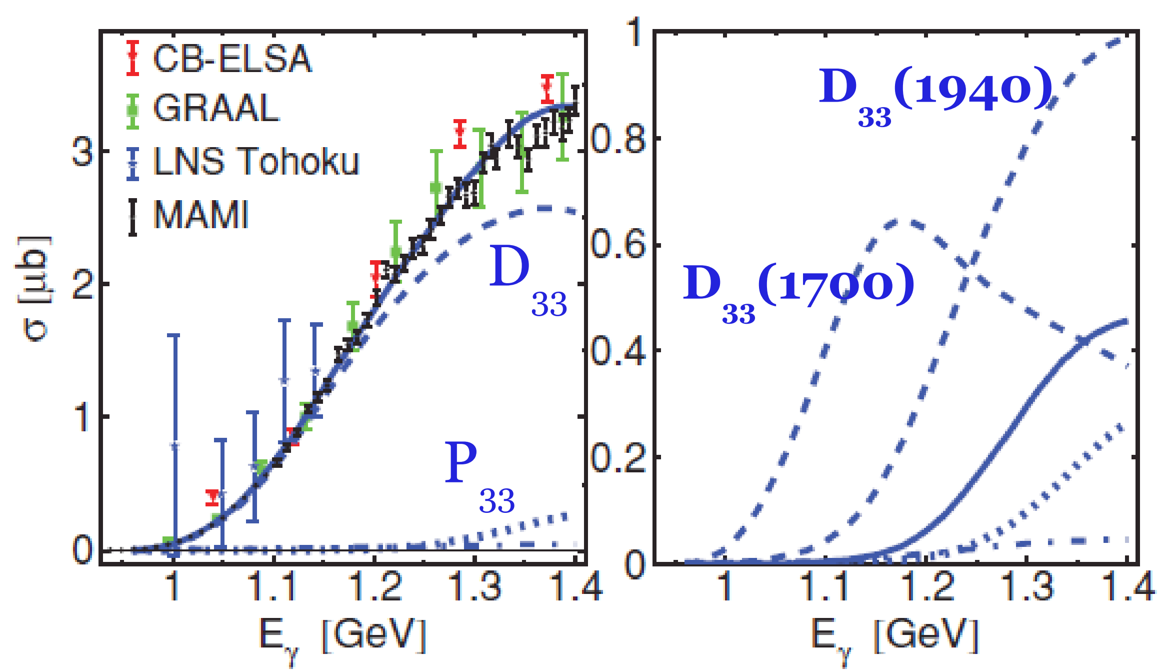
S. Prakhov (UCLA, Mainz), V. Kashevarov (Mainz)

$\pi^0\eta$ 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 $\gamma p \to D_{33}(1700) \to \Delta(1232)\eta \to p\pi^0\eta$

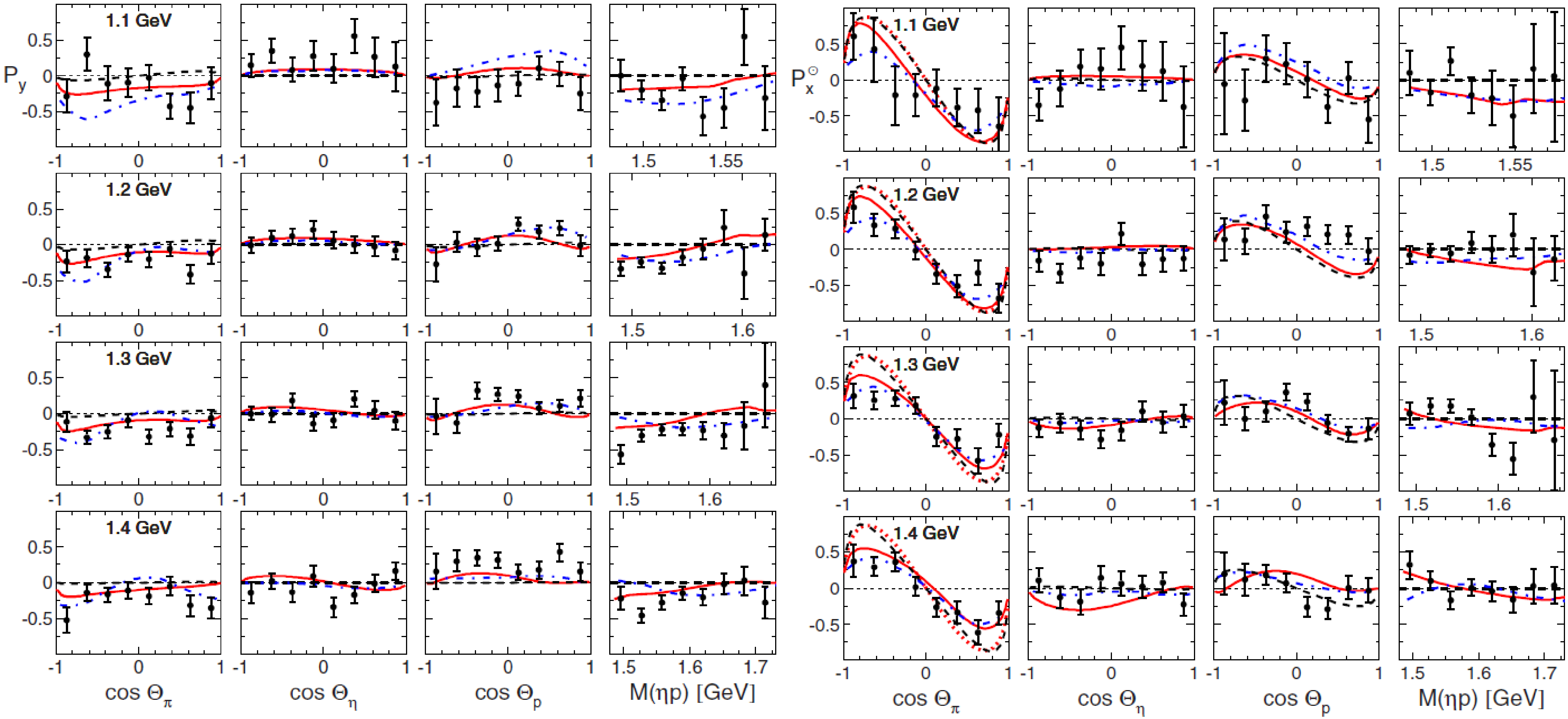


- $D_{33}(1700)$ dominates close to the production threshold



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

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

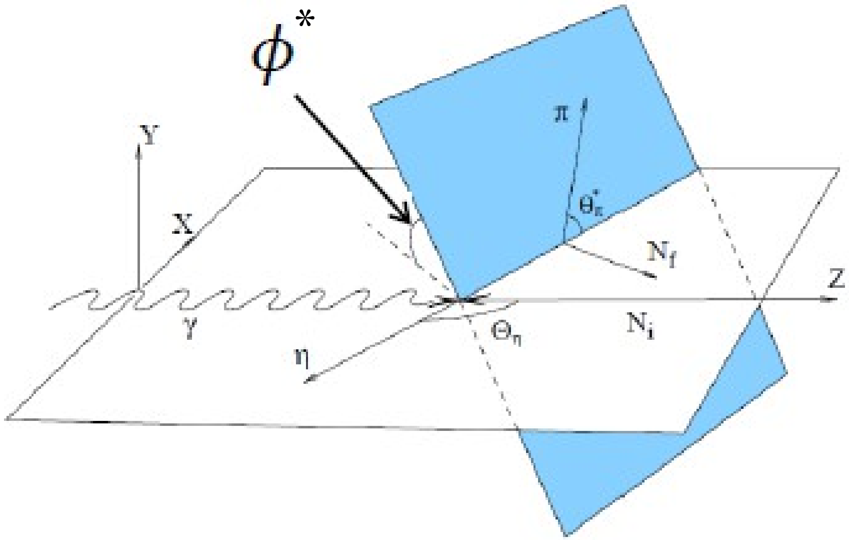


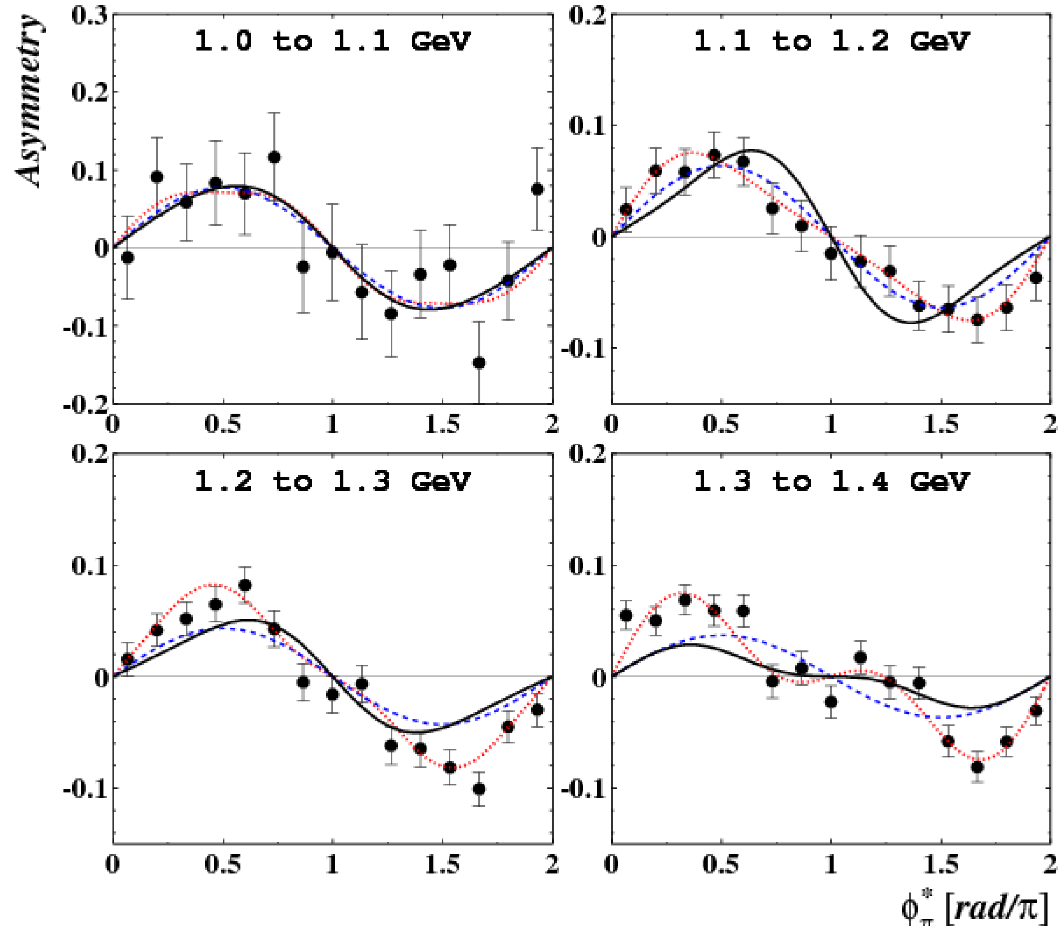
(Data are shown in a quasi two-boy approach)

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)

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_γ < 1.2 GeV

Nuclear targets

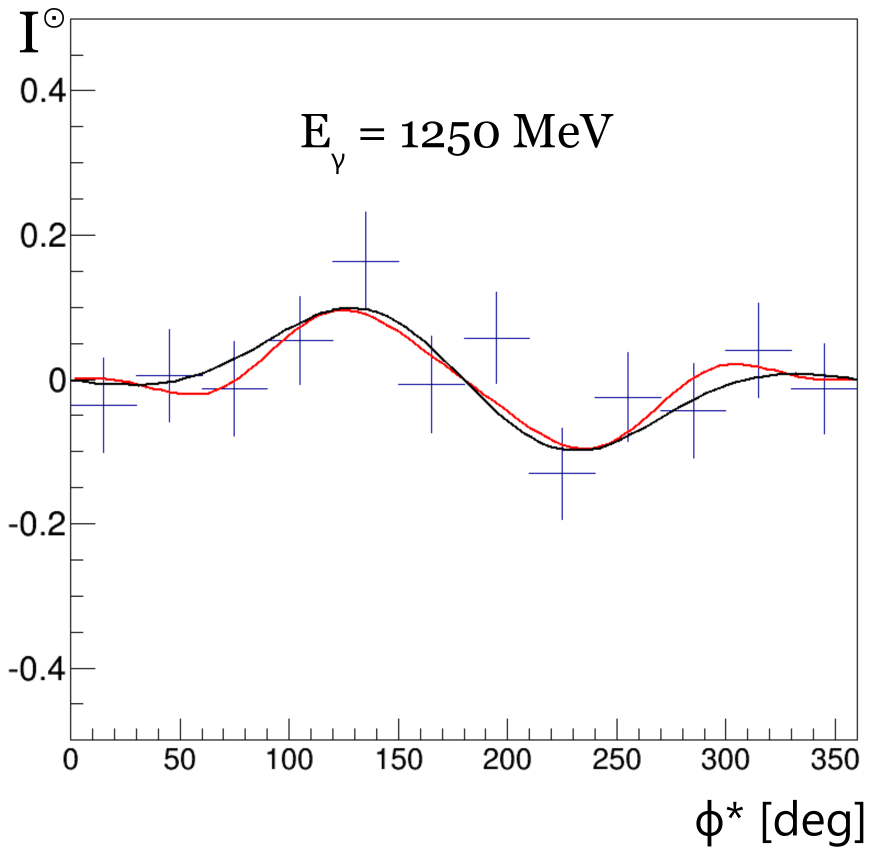
Existing data sets:

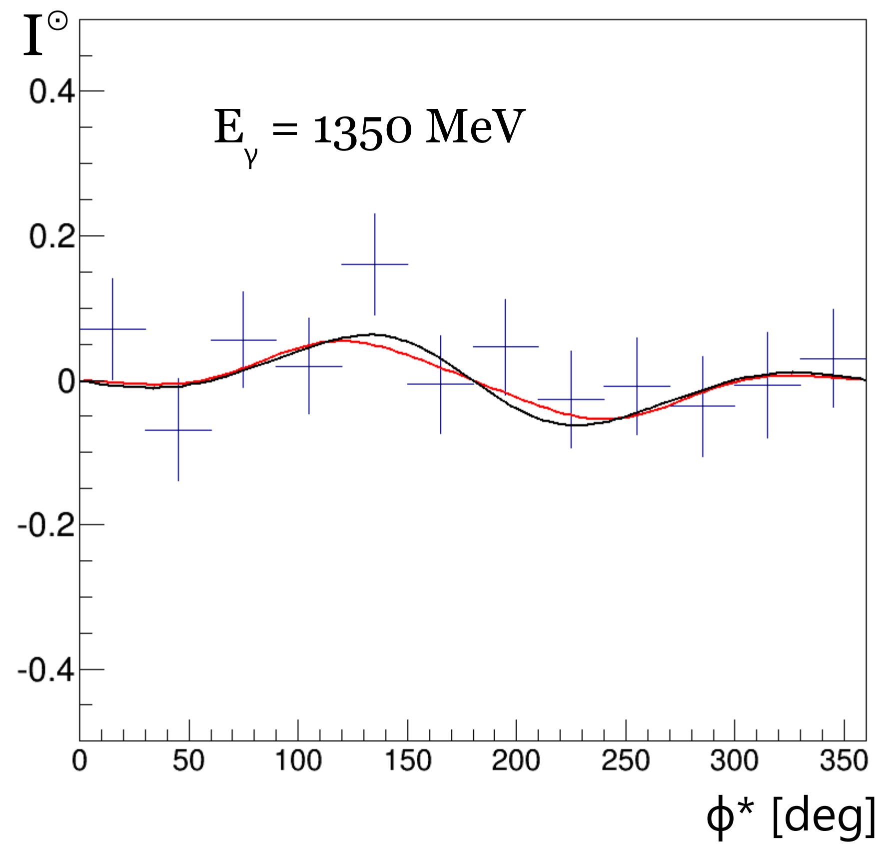
- Measurements performed by the A2 Collaboration with proton and deuteron targets
- Data on ^{4}He will be acquired in the near future

We are extracting:

- **Differential cross-sections and beam helicity asymmetry close to the $\pi^0\eta$ production threshold with C, Al and Pb targets**
- 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.)
- Any changes of these observables beyond FSI will allow access to the in-medium properties of the $D_{33}(1700)$

Example Spectra (Aluminium target)





- Preliminary asymmetries seen in ~35% of Aluminium data
- Curves: red fit to the data, black calculation within isobar model with FSI (Alexander Fix)
- Small asymmetry in energy binning → differential distributions
- Detailed analysis in progress

Summary

- Ambitious program aiming to extract scalar and spin polarizabilities of the proton in progress
- First measurement of the beam asymmetry in Compton scattering below pion photoproduction threshold
- High statistics data sets on π^0, η, η', $2\pi^0$, $\pi^0\eta$ production obtained
- Indication for N(1895)1/2- state in Eta-MAID 2015 (2016)
- Search for in-medium effects ongoing

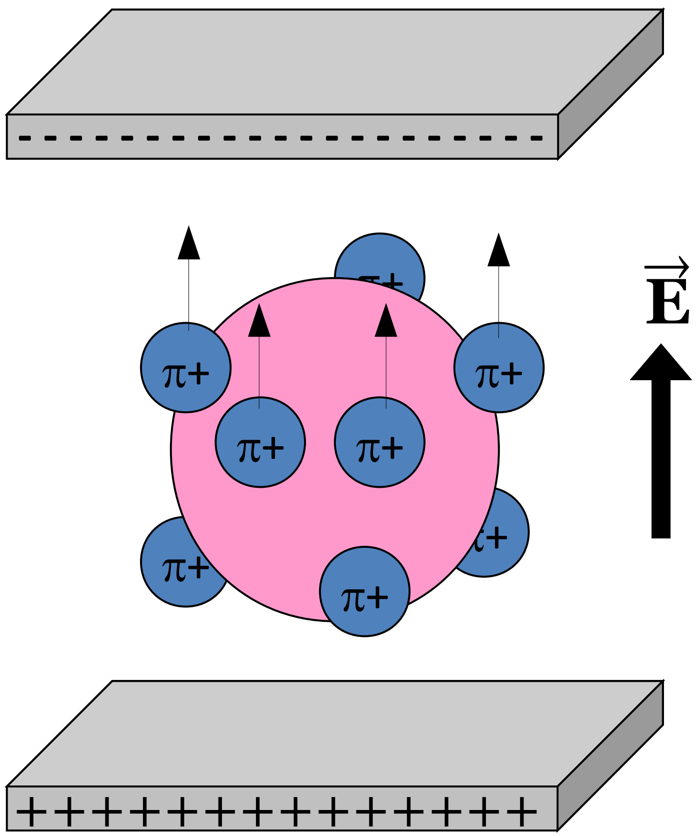
- Detector upgrades in progress
- Unprecedentedly high quality data will be acquired at MAMI
- New experimental technique (e.g. active targets)
- Further development of theoretical models

Thank you for your attention!

Backup

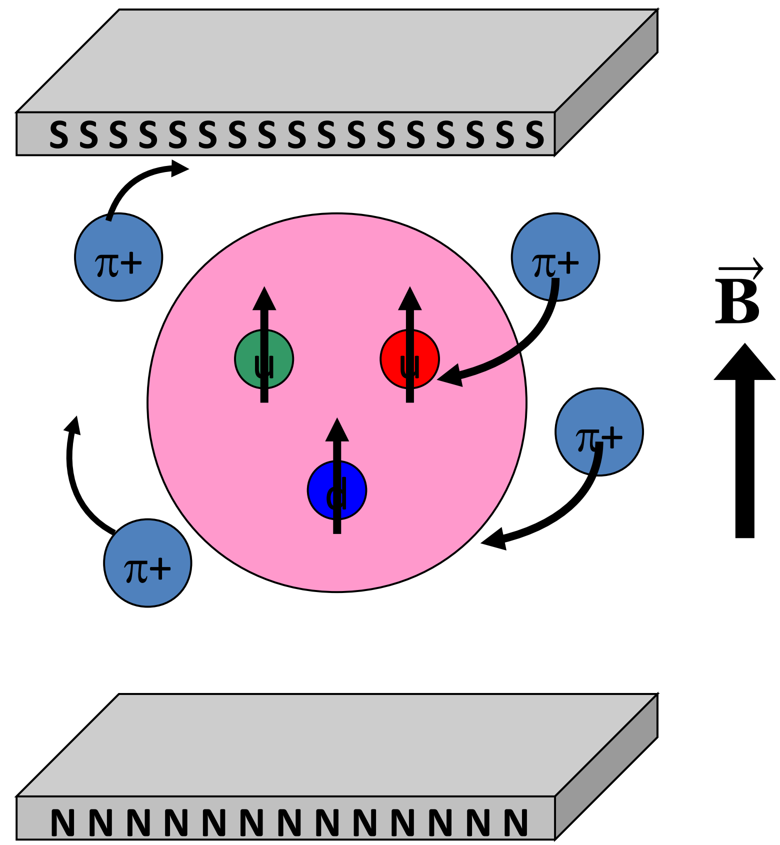
Scalar polarizabilities

Proton Electric Polarizability



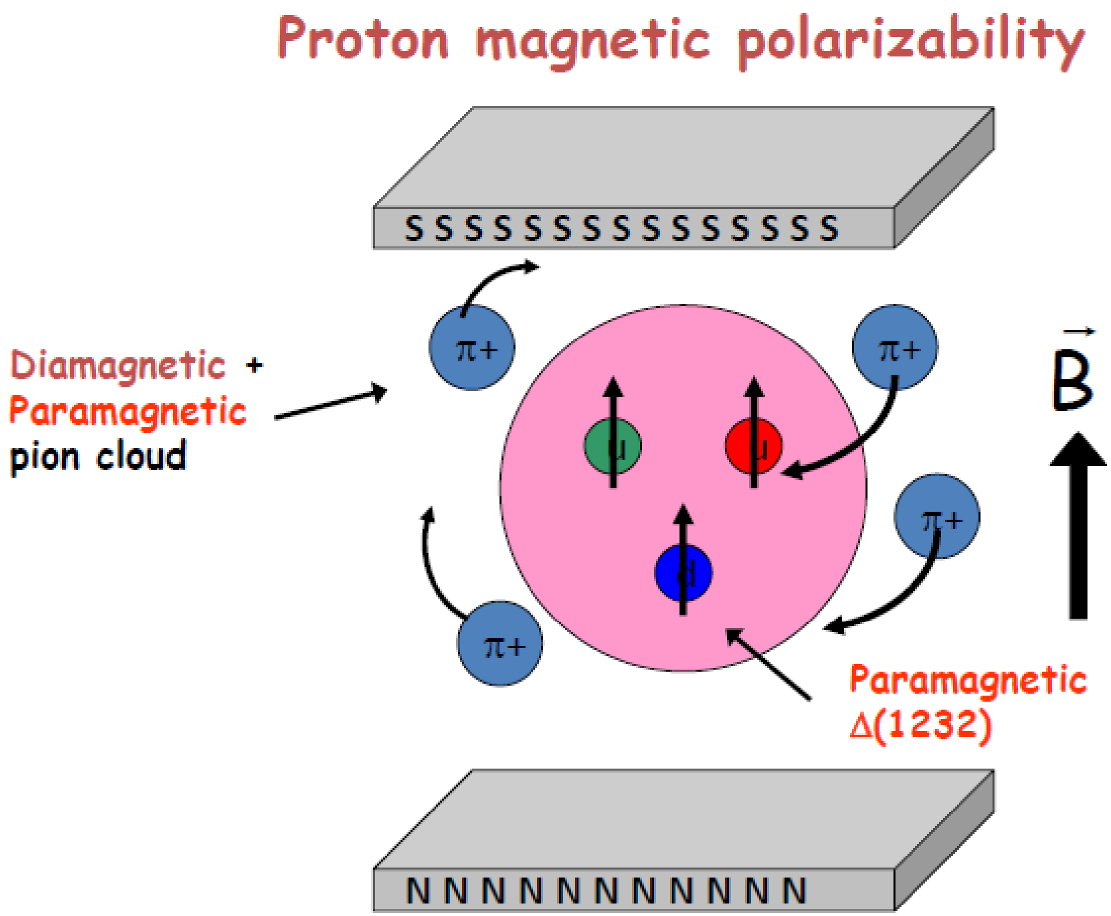
- α: electric polarizabilty
- Proton between charged parallel plates: “stretchability”

Proton Magnetic Polarizability



- 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

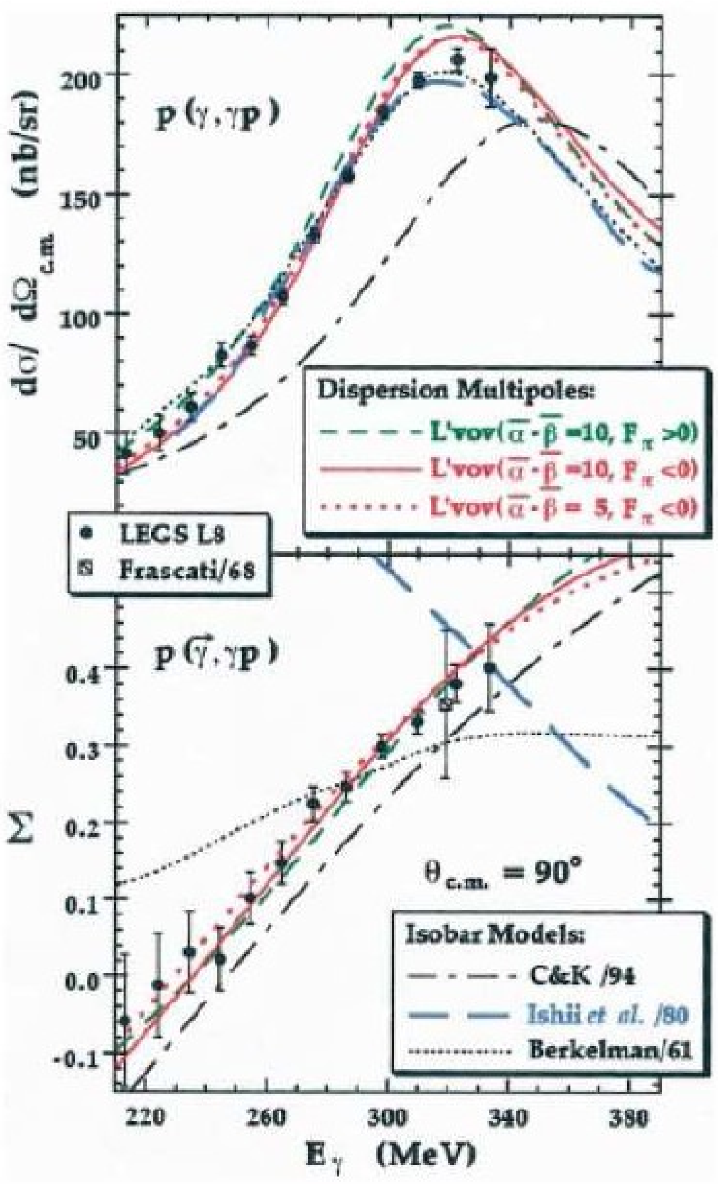
$$\Sigma_3 = \Sigma_3^{(\mathrm{B})} - \frac{4M\omega^2 \cos\theta \sin^2\theta}{\alpha_{em}(1+\cos^2\theta)^2}\,\beta_{M1} + O(\omega^4), \qquad (6)$$

where $\Sigma_3^{(\mathrm{B})}$ 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 asymmetry Σ_3 : existing data

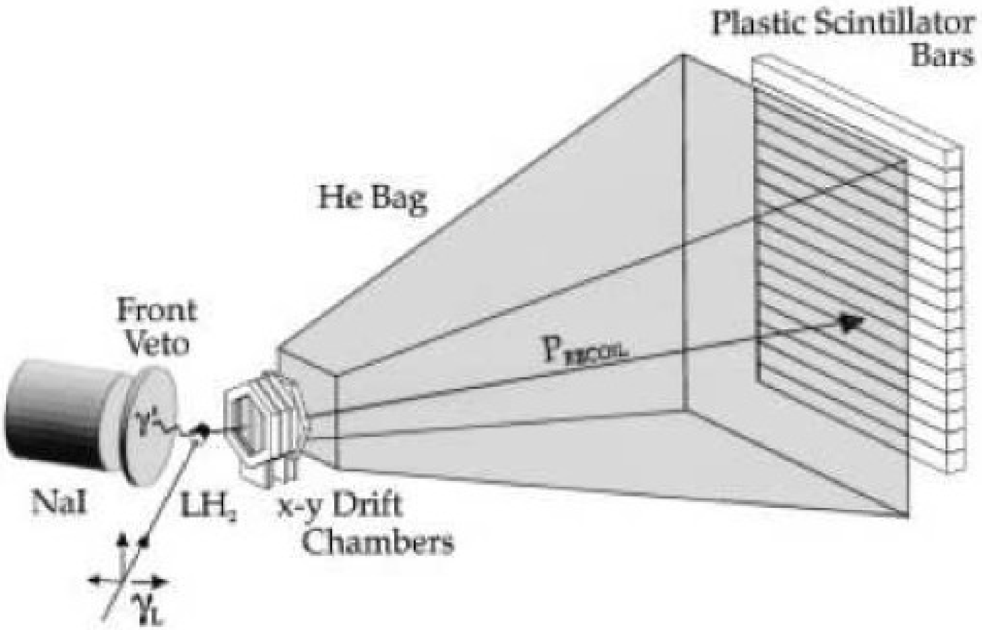


LEGS $\vec{\gamma}p \rightarrow \gamma p$

$d\sigma/d\Omega$ and Σ_3

$E_\gamma = 200 - 350\,\mathrm{MeV}$

$\theta_{\gamma'} = 90°$ ONLY!



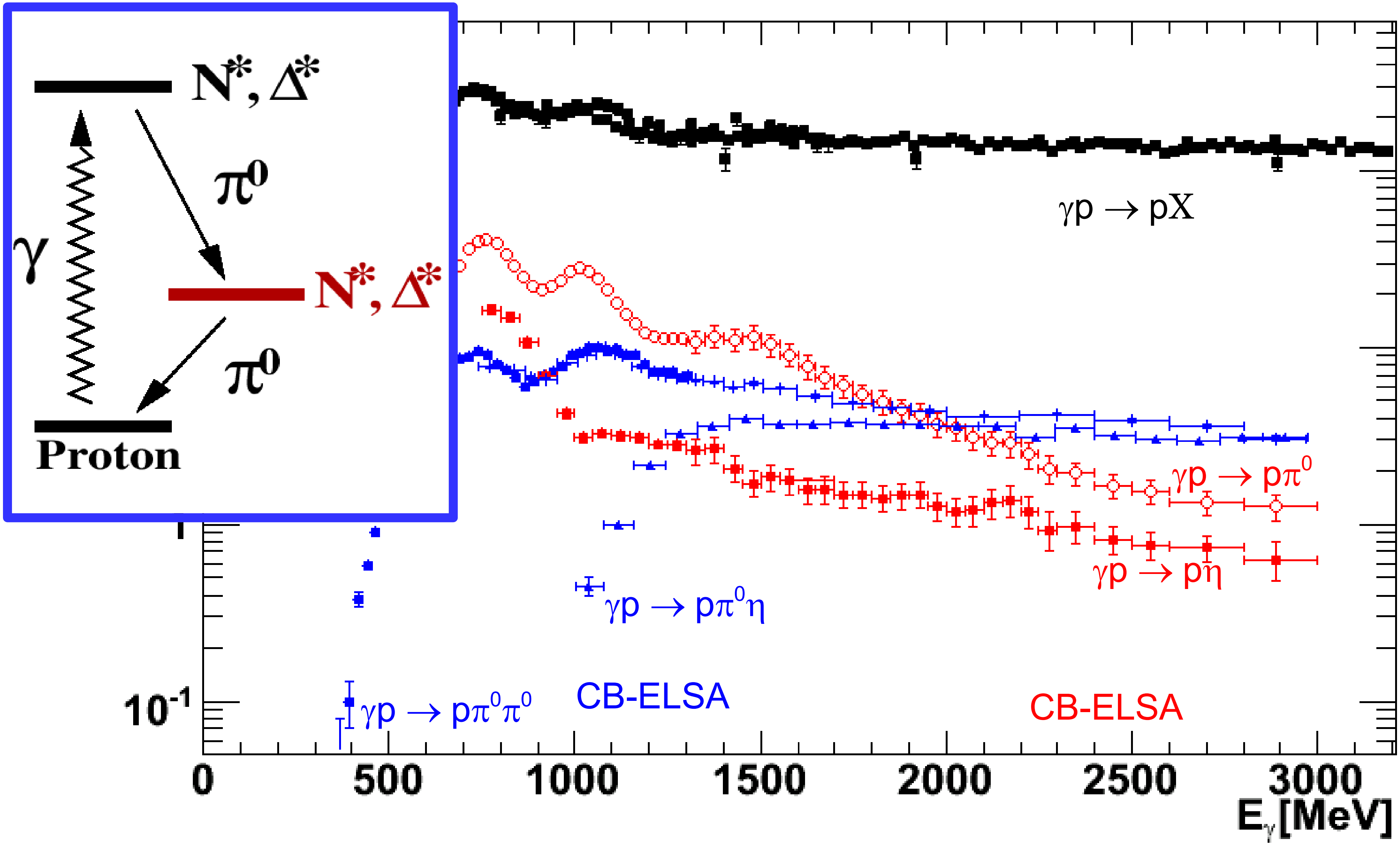
Current Status

Experiment	Status
Σ_{2x}	✔ February 2011
Σ_3 high energy	✔ December 2012
α, β (Σ_3 low energy)	✔ June 2013
Σ_{2z}	May 2014

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

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

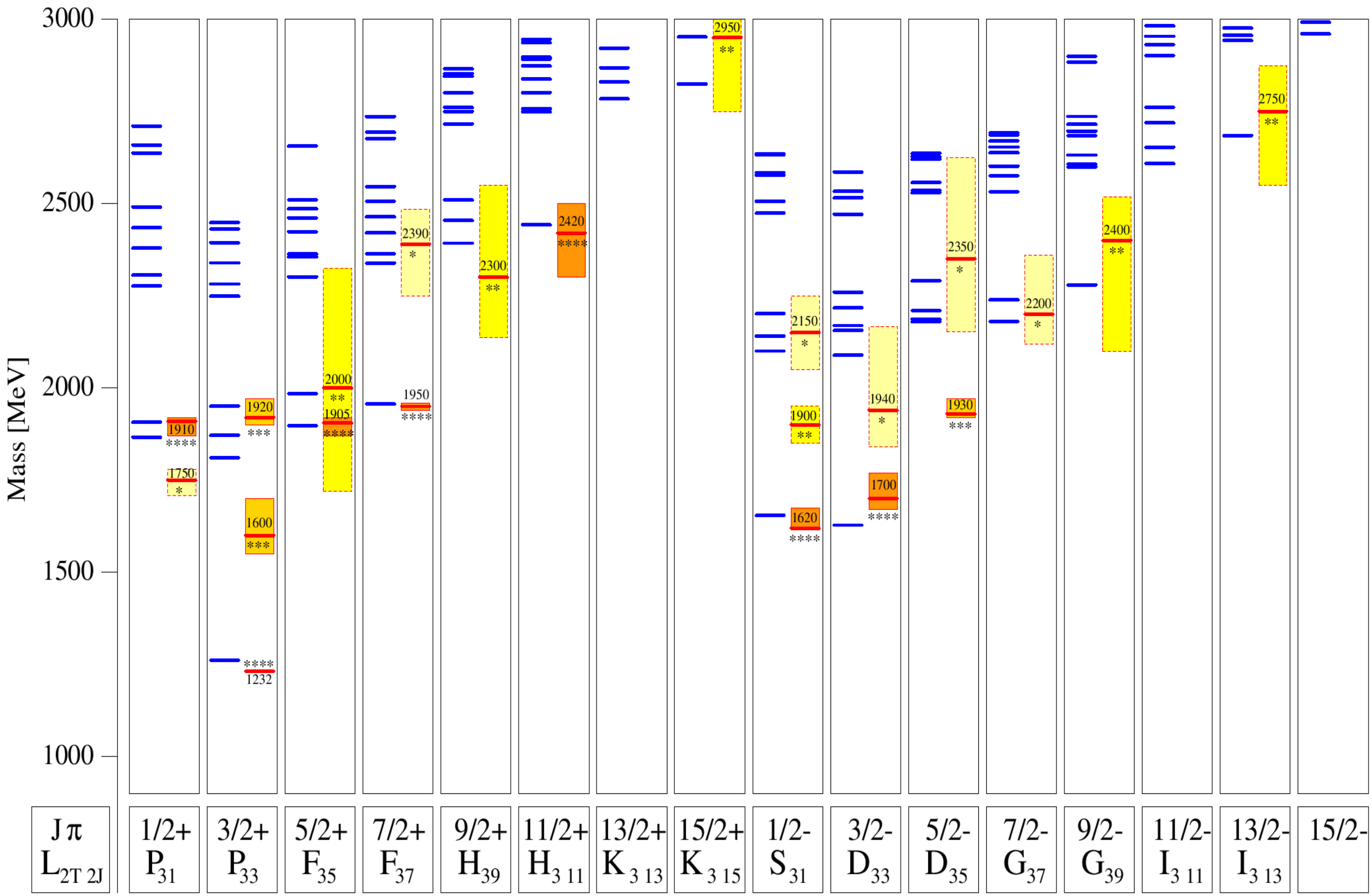
Baryon resonances

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).

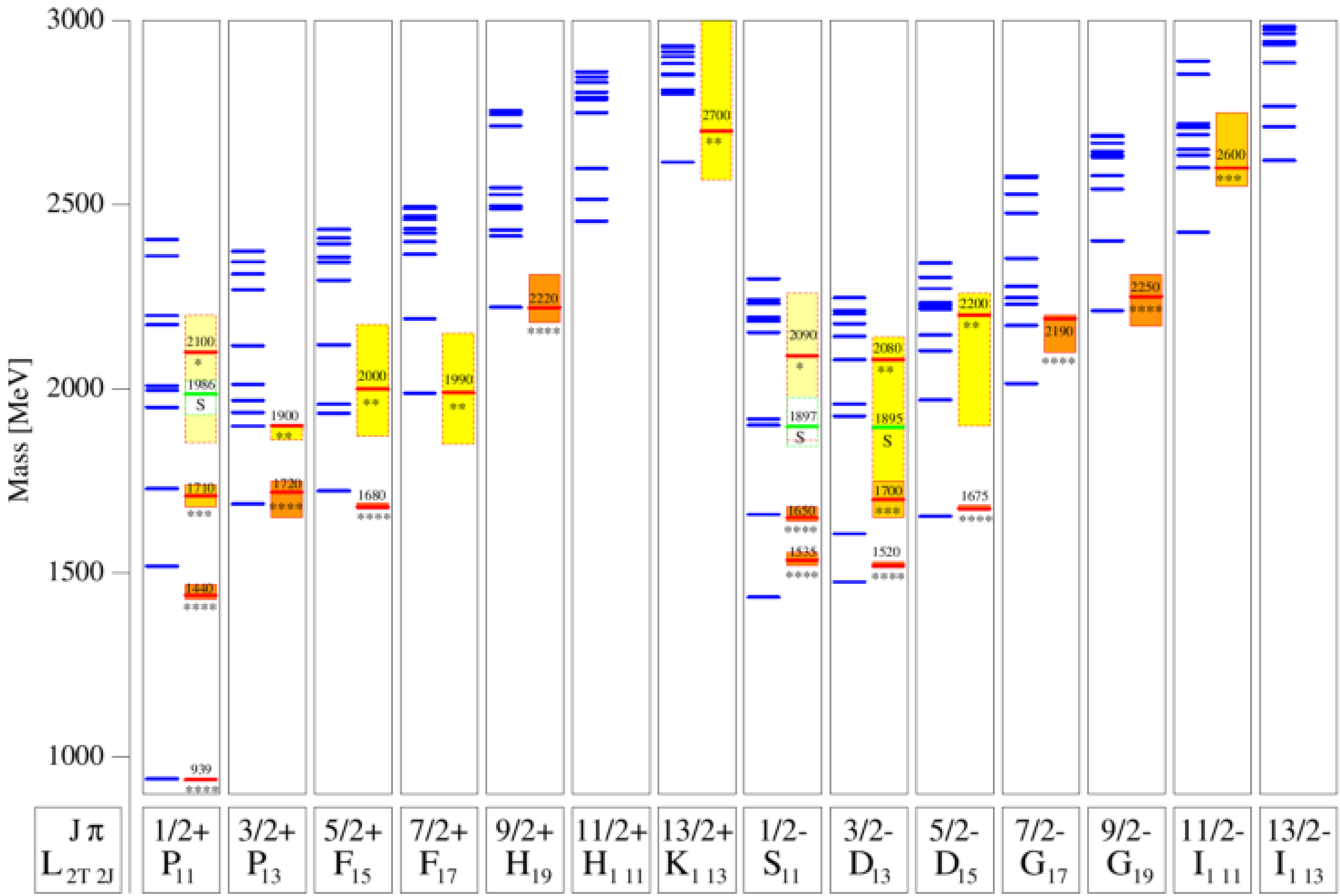
Introduction

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



Introduction

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

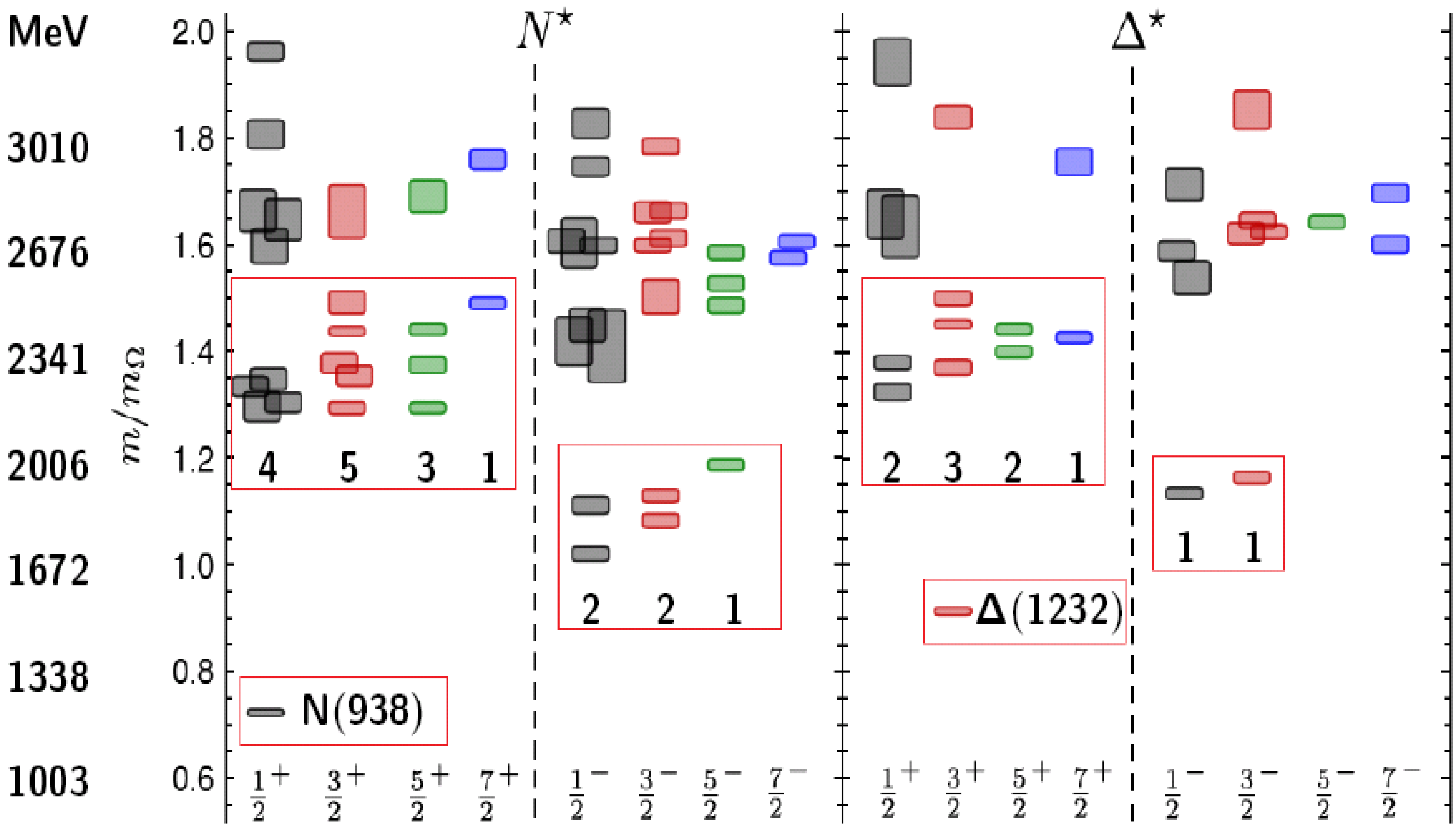


Introduction

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

$m_\pi = 396$ MeV

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



Measurement of α and β

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

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

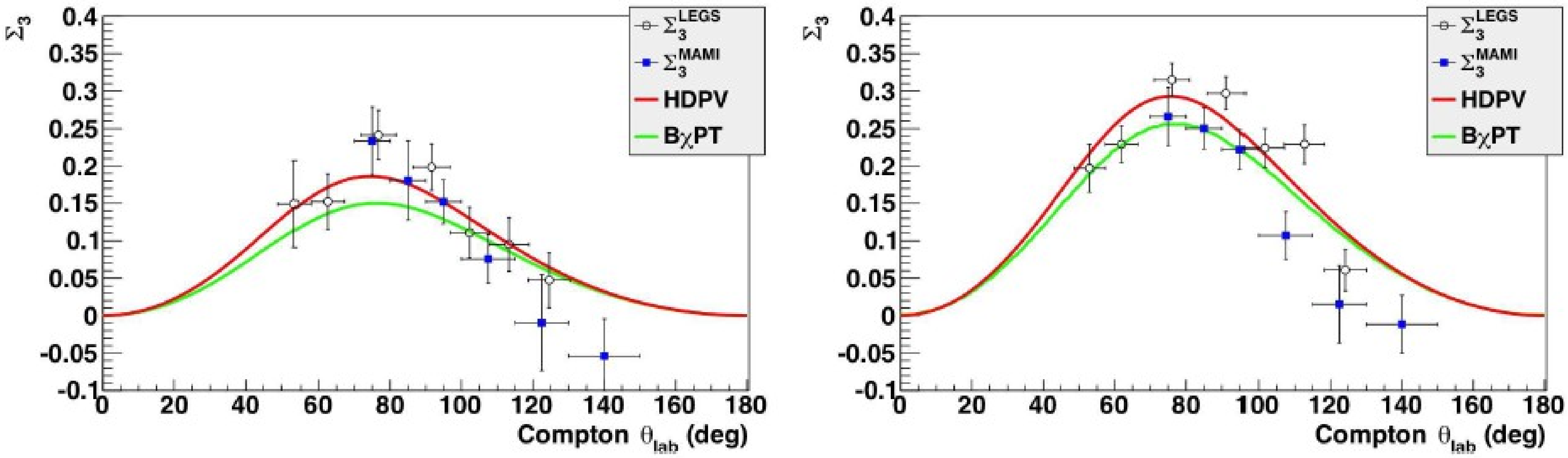
$$\omega \;=\; \frac{s - M^2 + \frac{1}{2}t}{\sqrt{4M^2 - t}}, \quad \theta = \arccos\left(1 + \frac{t}{2\omega^2}\right) \qquad (7)$$

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.

Spin polarizabilites

$E_\gamma = 267 - 282\,\mathrm{MeV}$

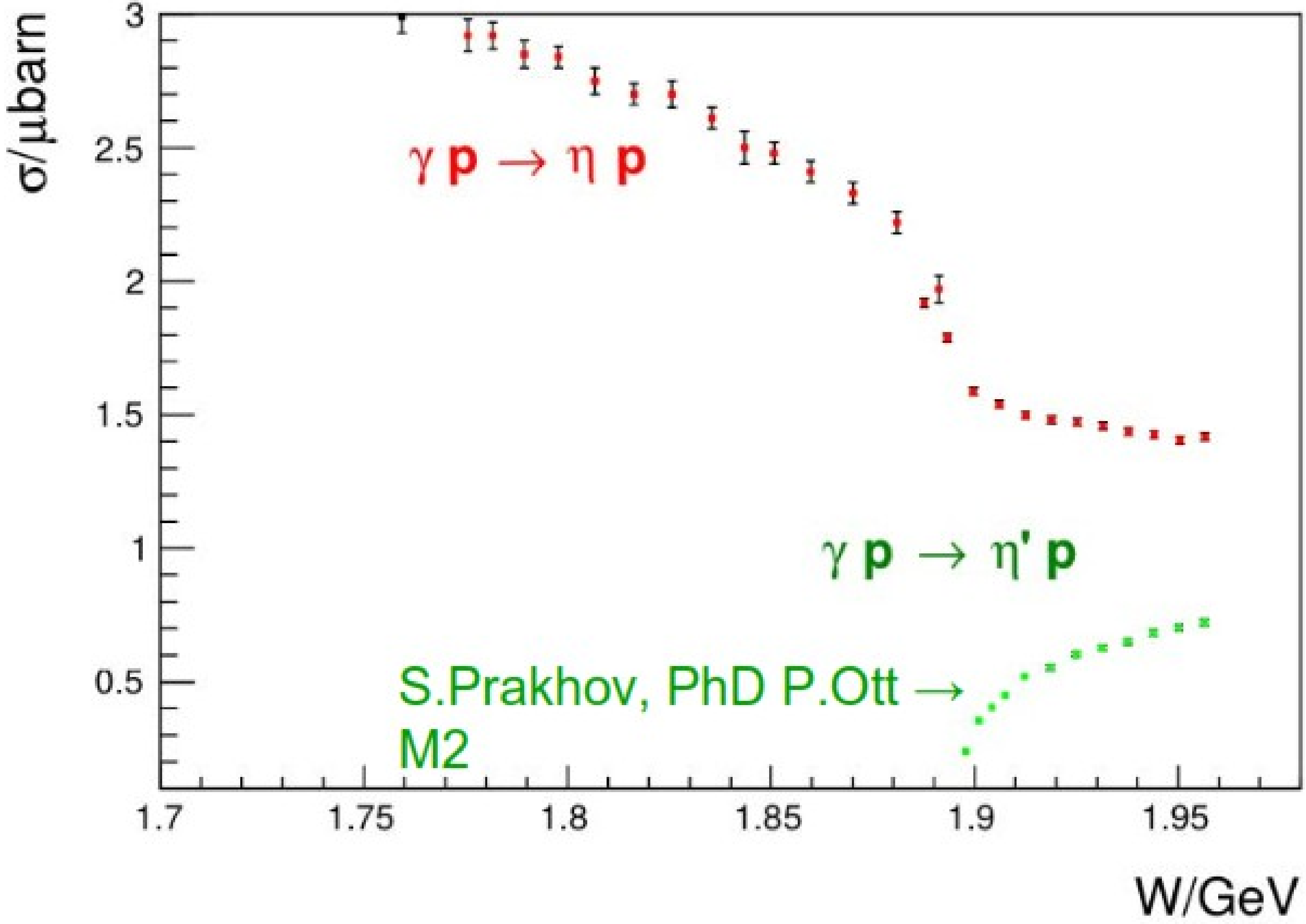
$E_\gamma = 286 - 307\,\mathrm{MeV}$



- 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-

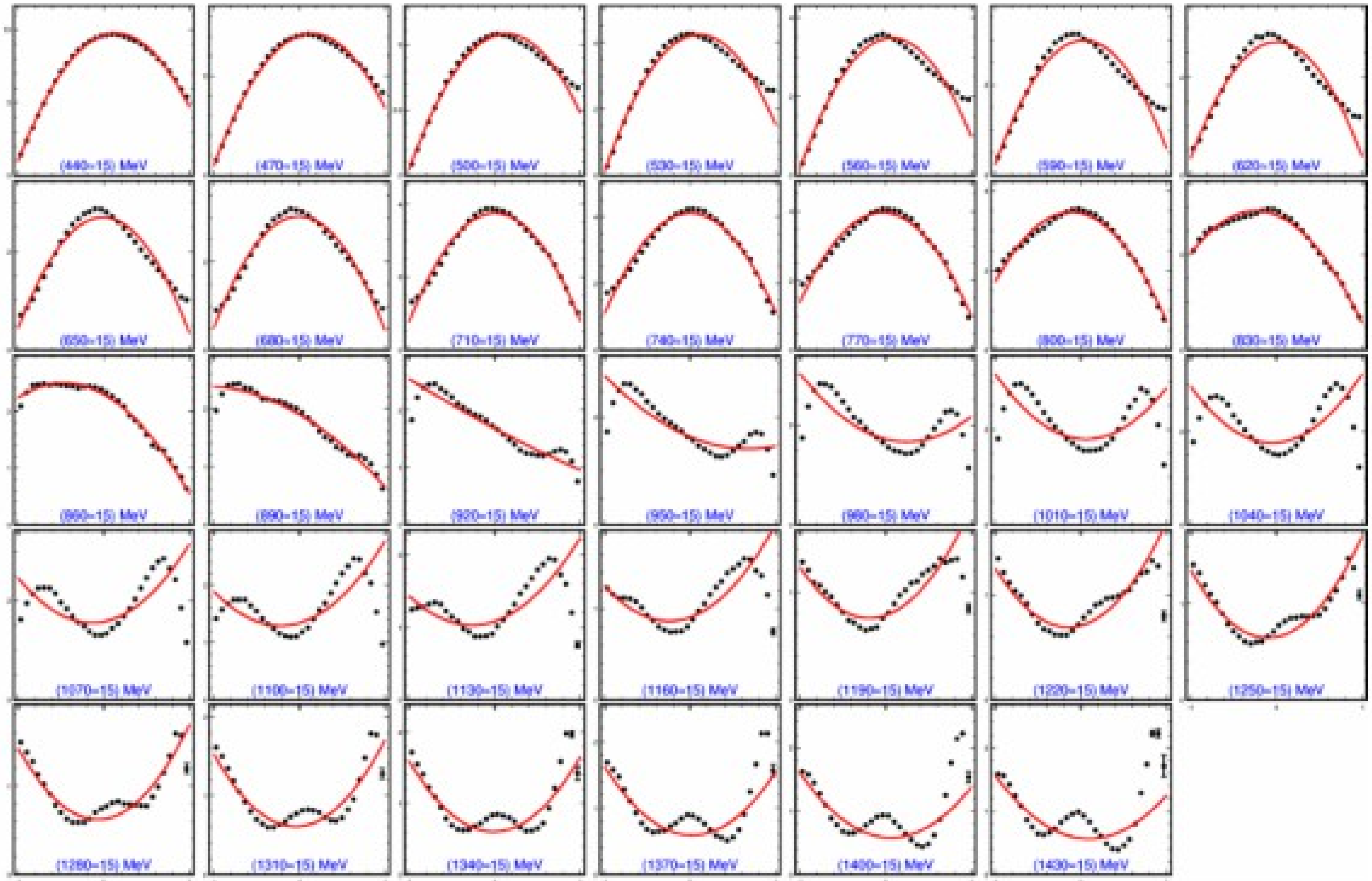


σ/μbarn
3
2.5
2
1.5
1
0.5
1.7
1.75
1.8
1.85
1.9
1.95
W/GeV
γ p → η p
γ p → η' p
S.Prakhov, PhD P.Ott →
M2

Single pion production

Legendre expansion of the diff. cross section

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

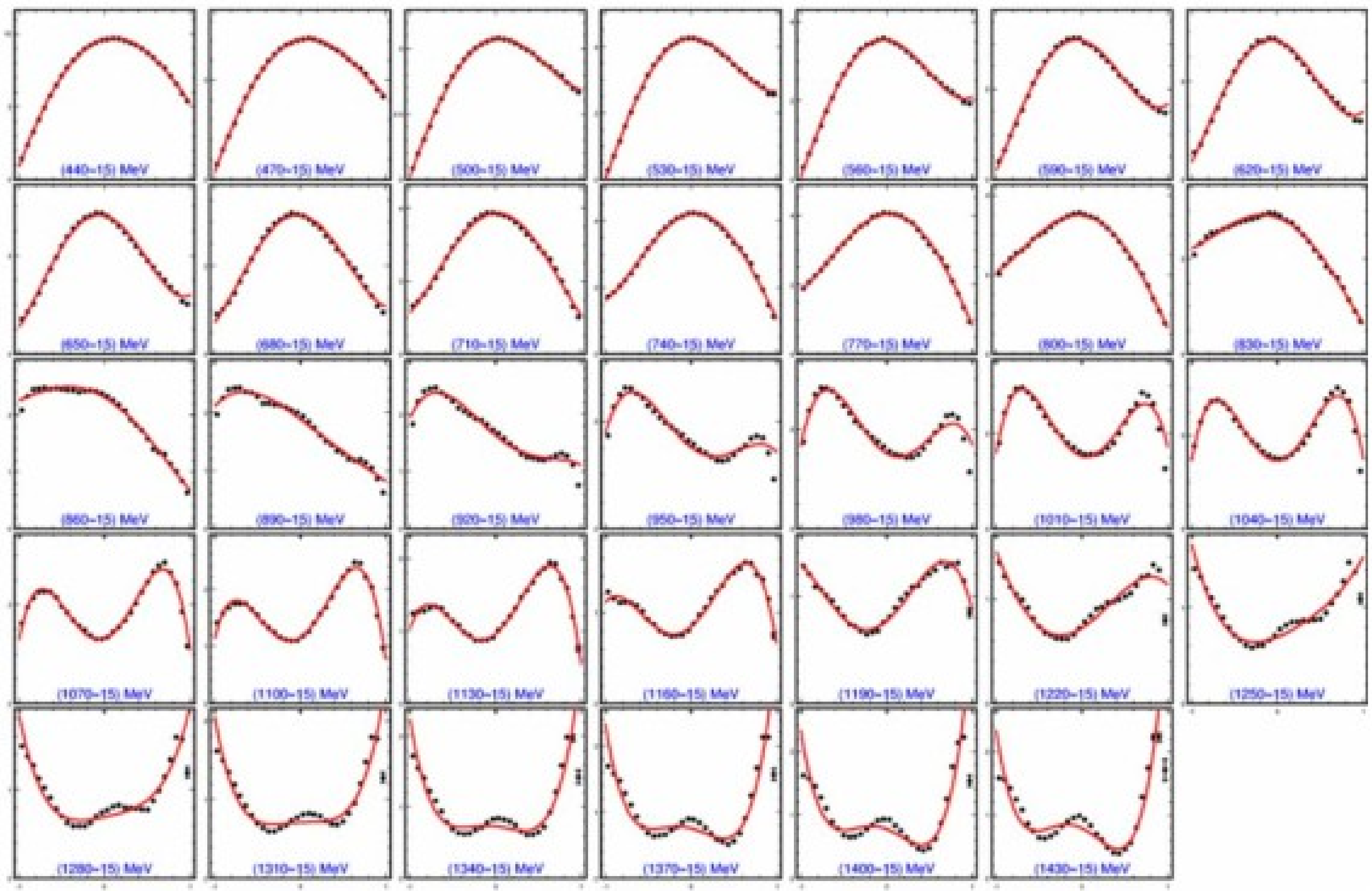


S+P waves are only good up to about 400 MeV

Single pion production

Legendre expansion of the diff. cross section

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

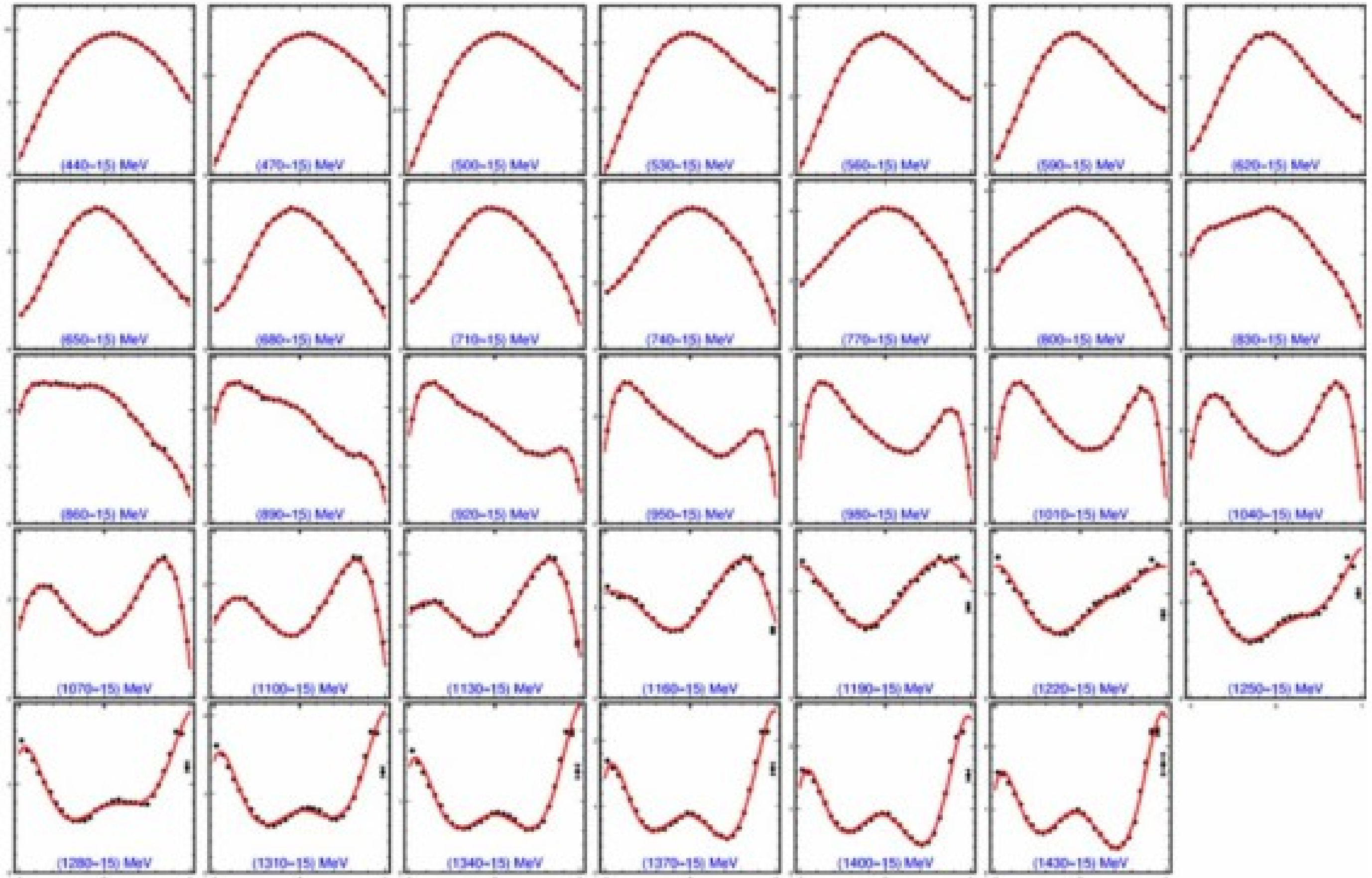


S+P+D waves are good up to about 850 MeV

Single pion production

Legendre expansion of the diff. cross section

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

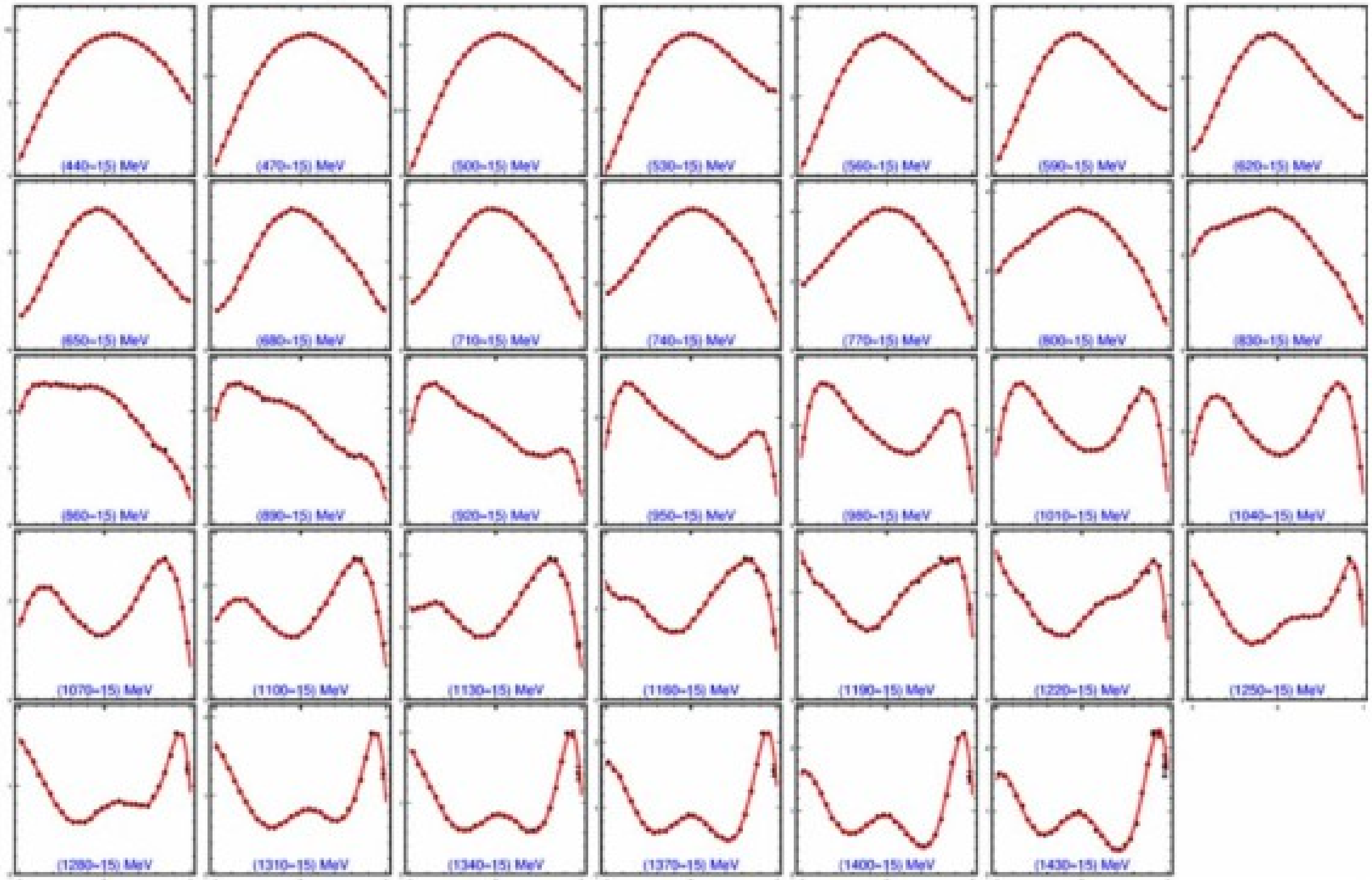


F waves become important around 1 GeV

Single pion production

Legendre expansion of the diff. cross section

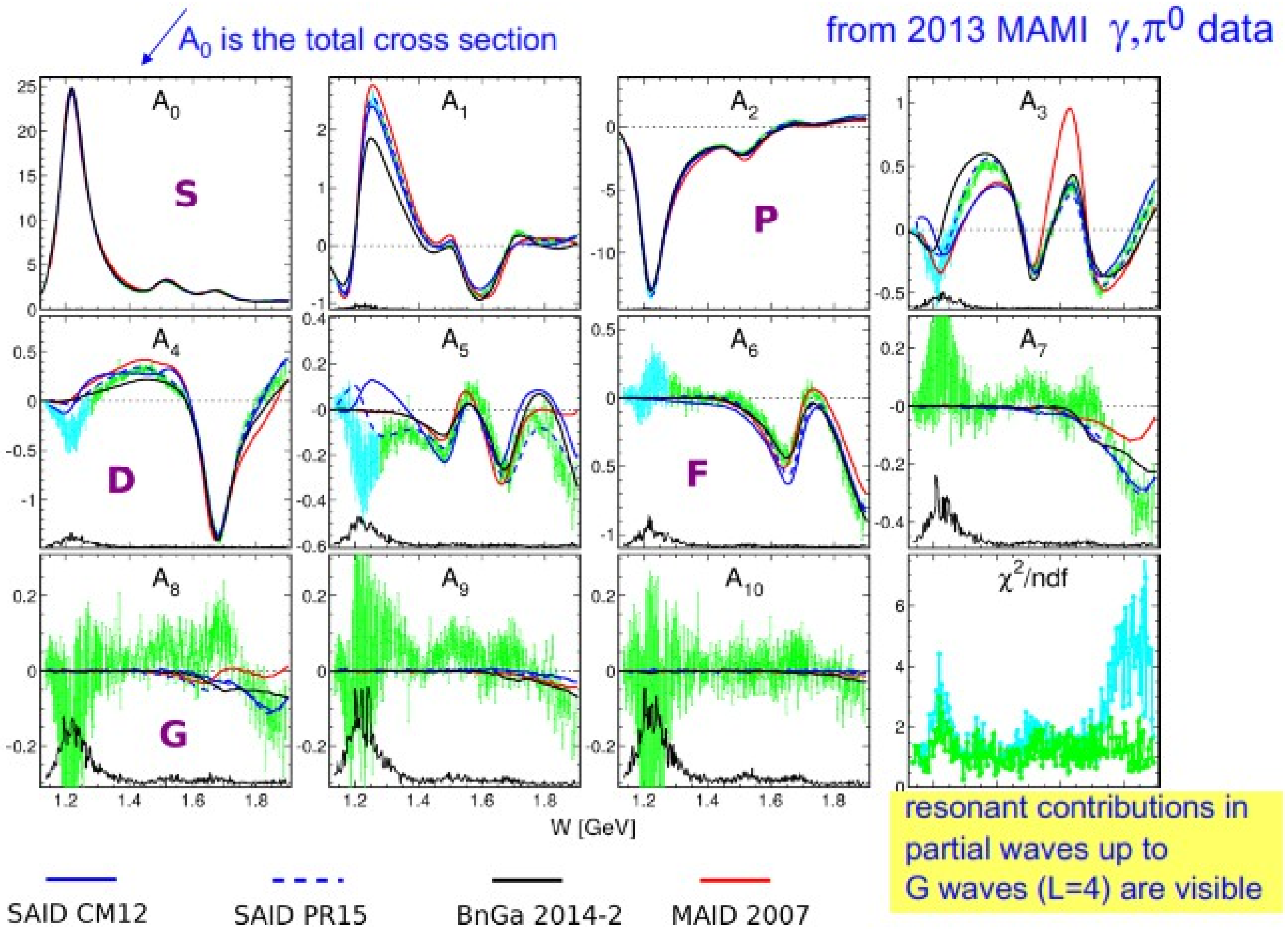
$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W)\, P_k(\cos\theta) \qquad \ell max = 4$$



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

Single pion production

Legendre expansion of differential cross section



Polarized target (slide taken from R. Miskimen)

Frozen spin target

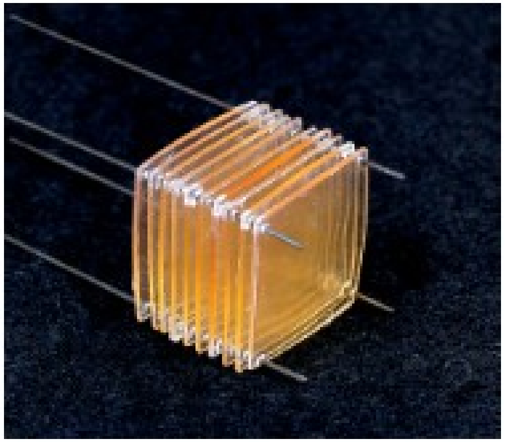
- 2 cm butanol
- target polarized at 25 mK
- 0.6 T holding field
- P ~ 90%
- > 1000 hours relaxation time

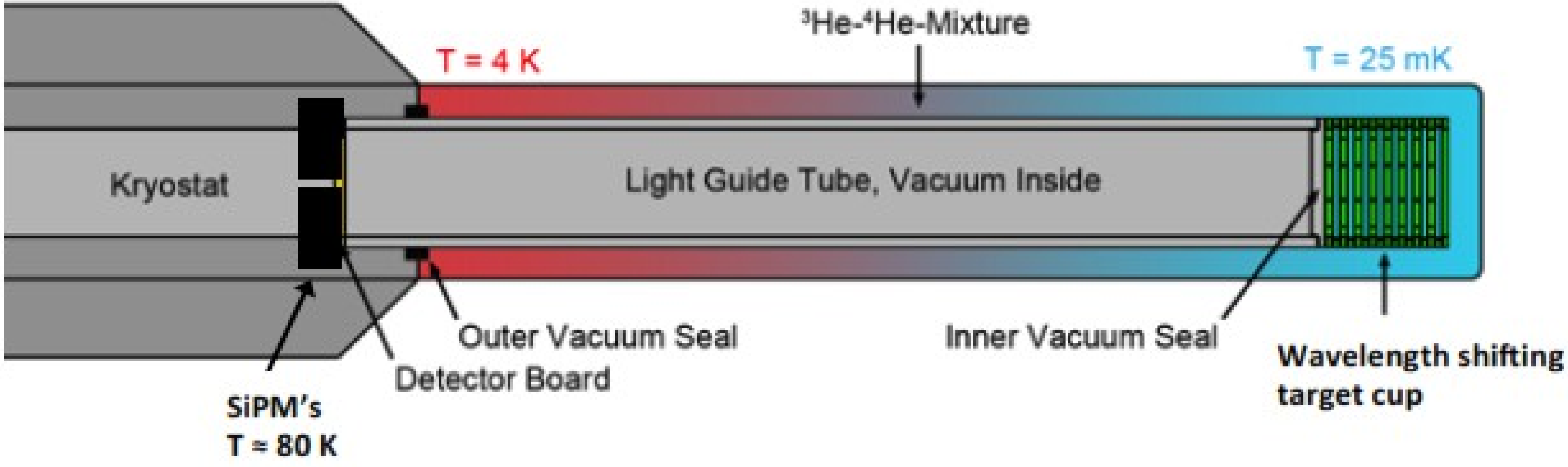
Polarized active target (slide taken from R. Miskimen)

Development of a scintillating polarized target for Mainz

Needed for double-polarized Compton scattering measurements near pion threshold

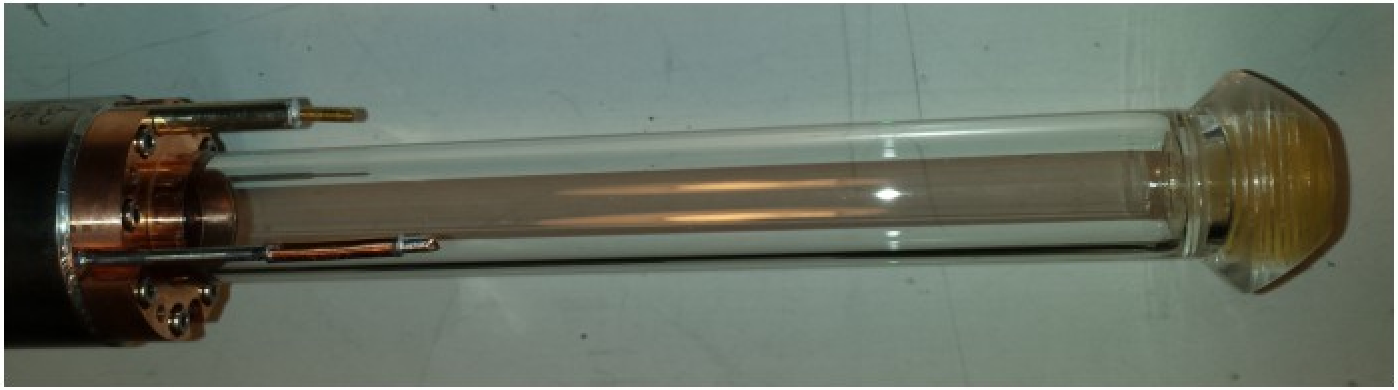
- **Polarizable scintillator developed at UMass**
- ✓ Proton polarization ≈ 70%
- ✓ Relaxation time ≈ 22 hours
- ✓ Light output ≈ 30% of standard plastic scintillator
- ✓ High clarity for thicknesses up to 1 mm





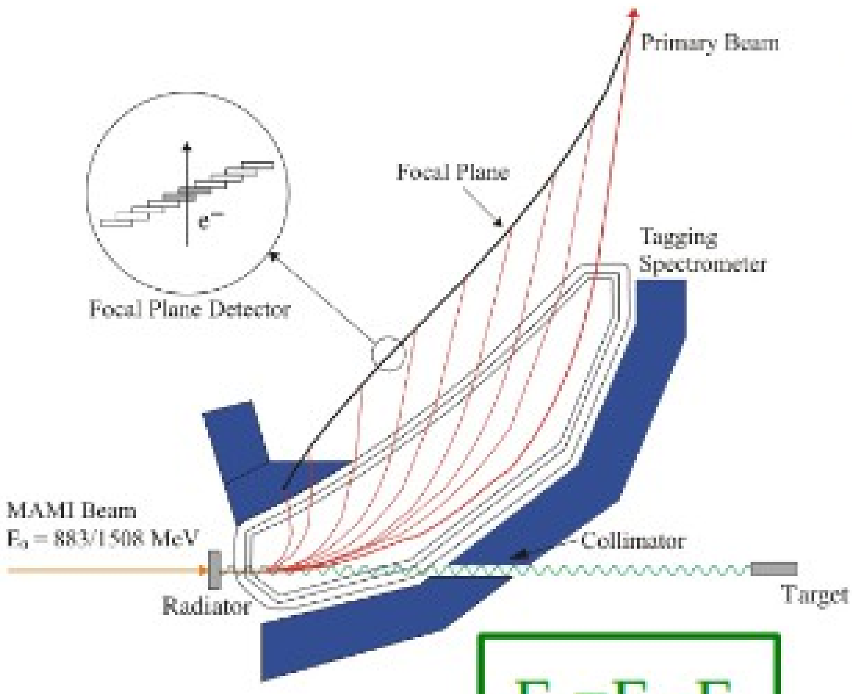
Polarized active target (slide taken from R. Miskimen)

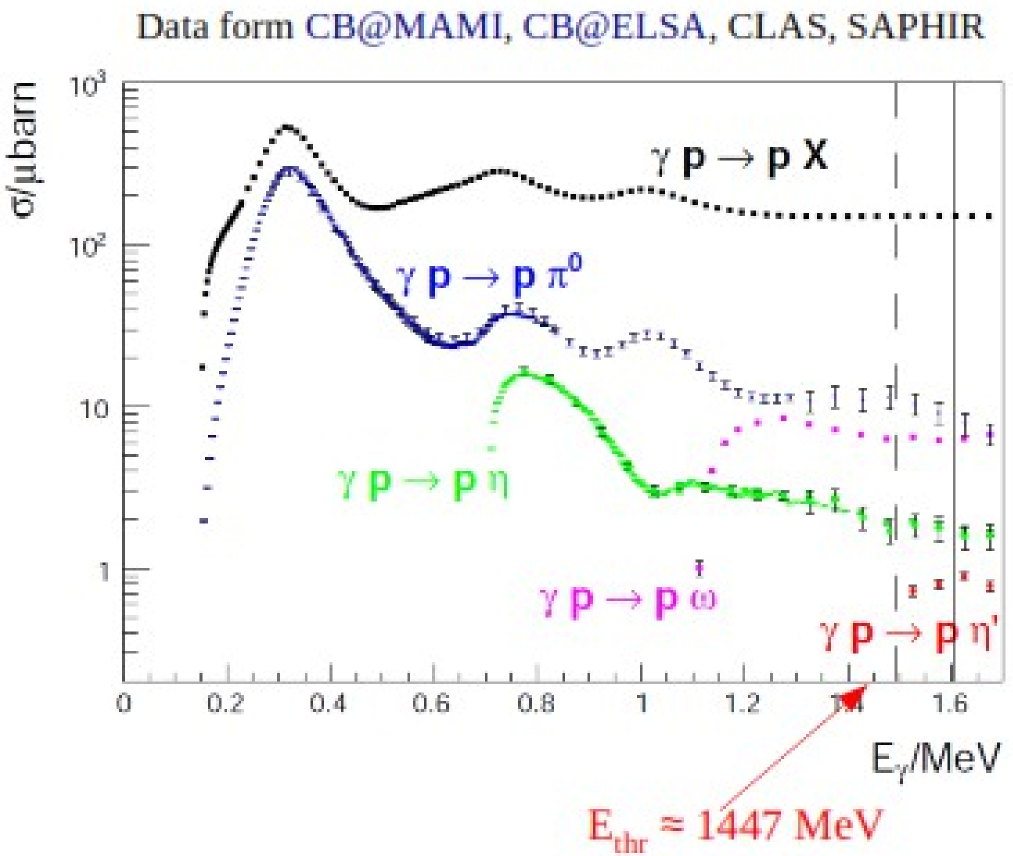
Target assembly



PhD, Maik Biroth, Mainz

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

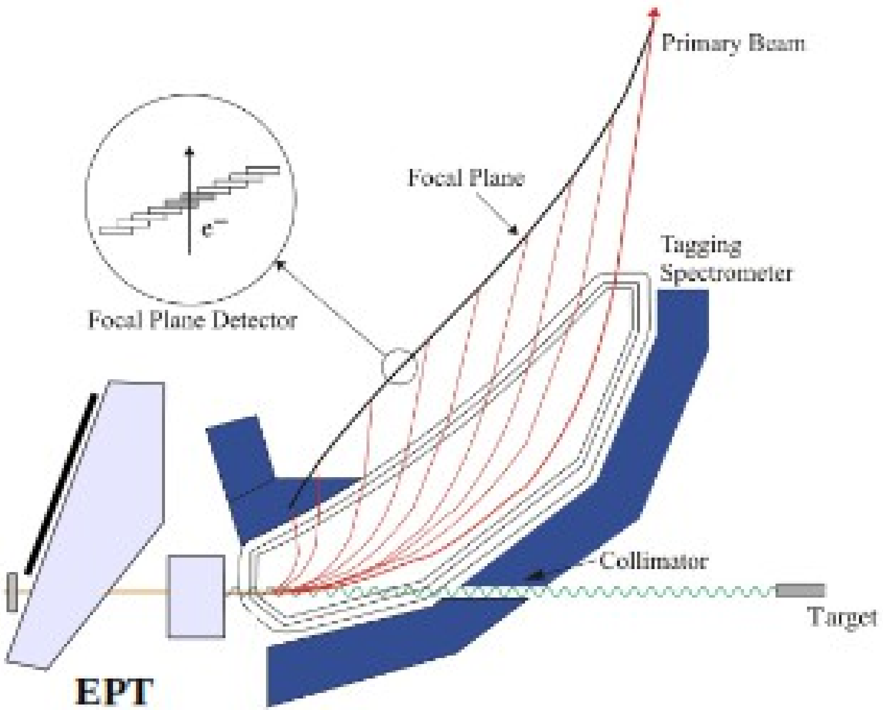
$\Delta E_\gamma \approx 4$MeV at $E_{e-}=1558$ MeV

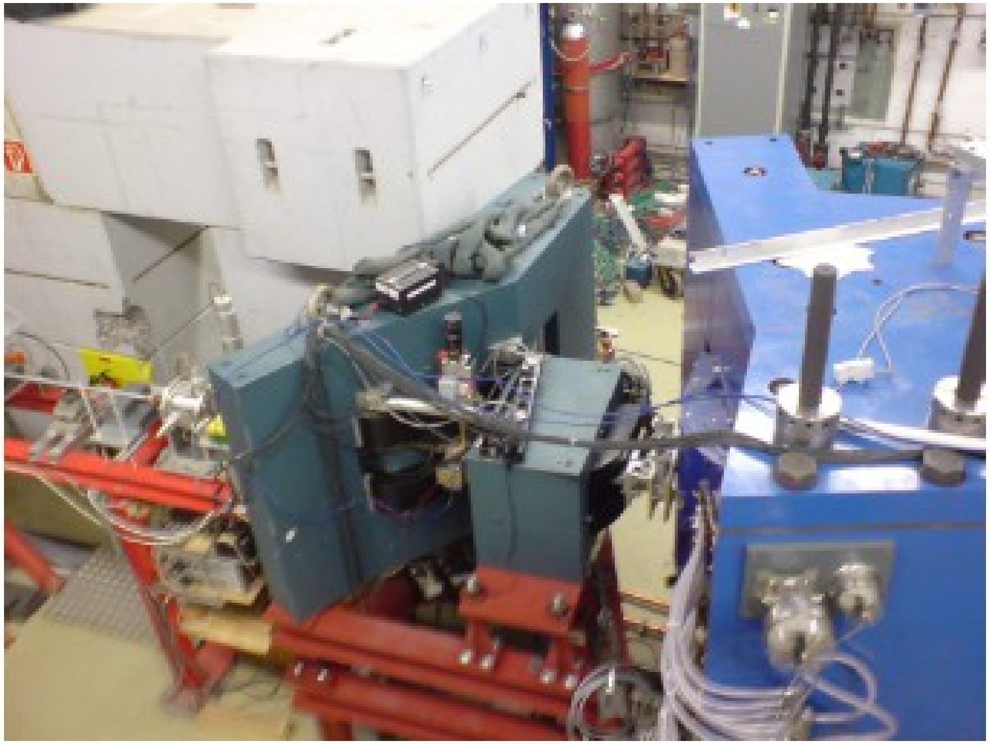
Linearly and circularly polarised photon-beam

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





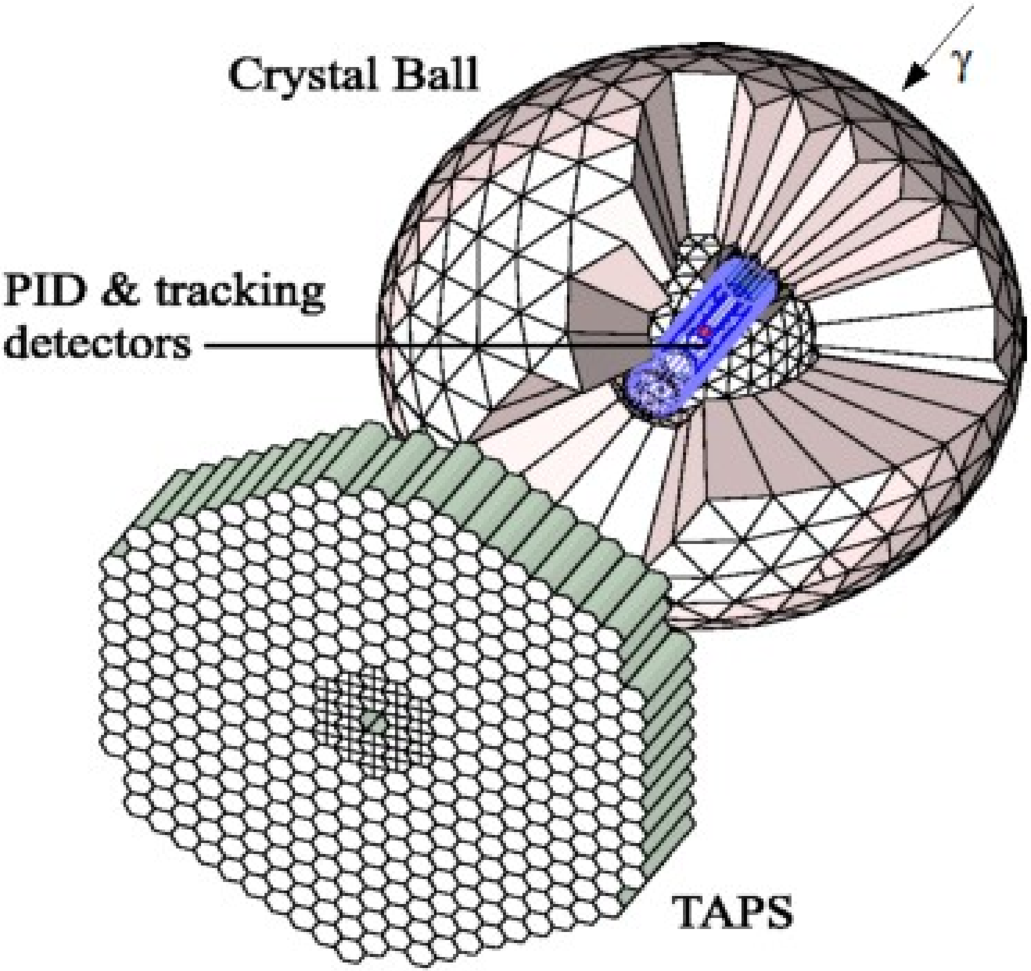
Same working principle as main tagging spectrometer

$E_\gamma \approx 1445$-1595 MeV

$\Delta E_\gamma \approx 2.5$MeV

Non-permanent installation infront of main Tagger

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



<u>Crystal Ball:</u>

672 NaI(Tl) crystals

93,3% of total solid angle

Each crystal equipped with PMT

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

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

<u>TAPS:</u>

Up to 510 BaF_2 crystals

Polar acceptance: 4-20°

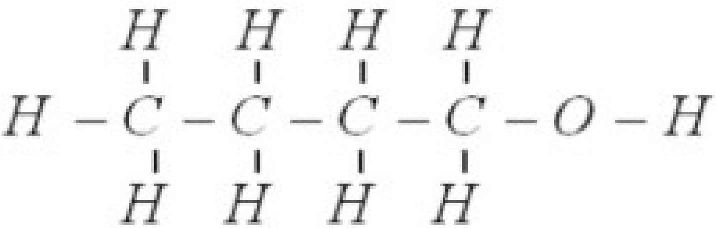
$\Delta t = 0.5$ ns FWHM

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

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

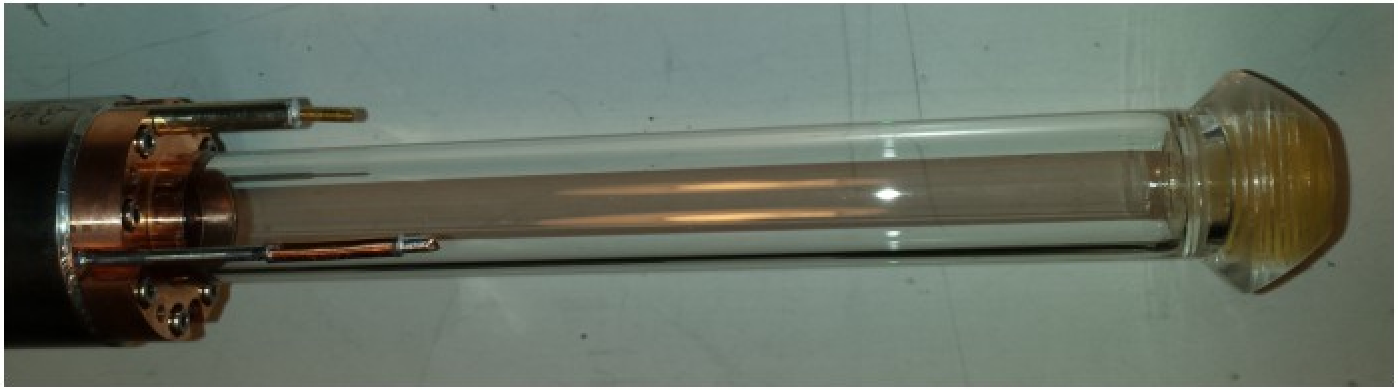


- Polarised Butanol/D-Butanol
  - Transverse and longitudinal polarisation
  - Lenght: 2 cm
  - Dynamic Nuclean Polarisation
  - Max. Polarisation: 90%
  - Holding filed: 0.44 T
  - Relaxation time: τ~1000h

- Solid Targets

Polarized active target (slide taken from R. Miskimen)

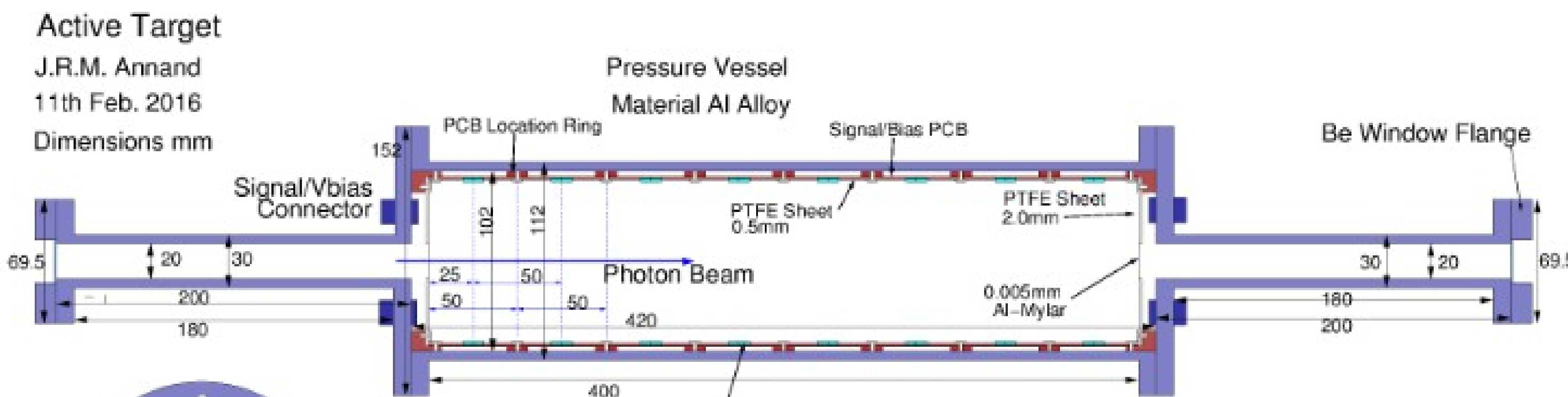
Target assembly

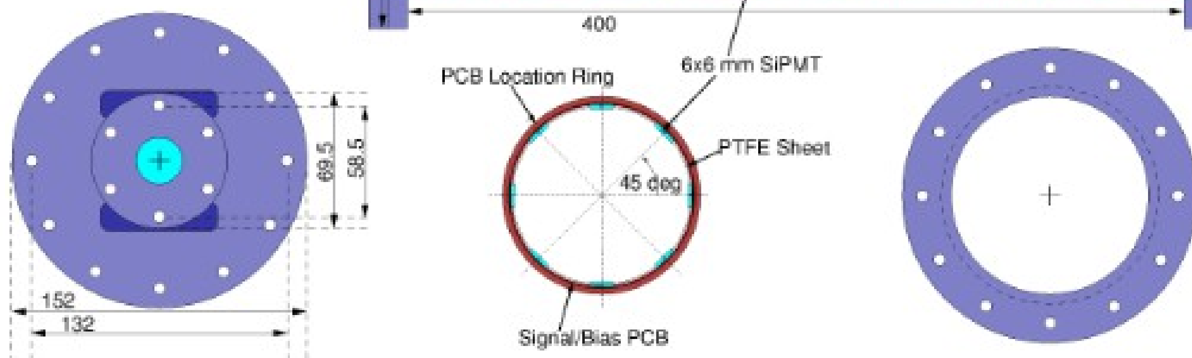


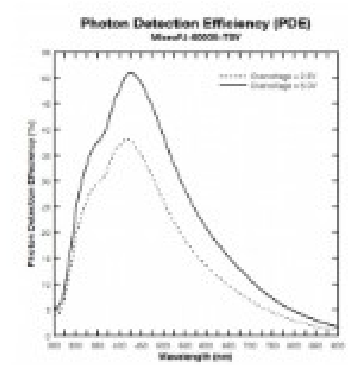
PhD, Maik Biroth, Mainz

He gas active target

The New Active Target

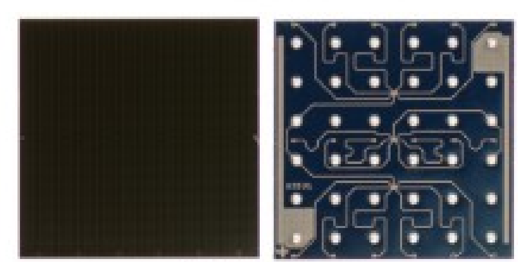






8 rings of SiPMT, each ring consisting 8 groups of 4 6x6mm tiles.
Total number of SiPMT 8x8x4 = 256.
Readout in groups of 16, each group connected to an op–amp.
16 signal outputs
2 vias–voltage inputs

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

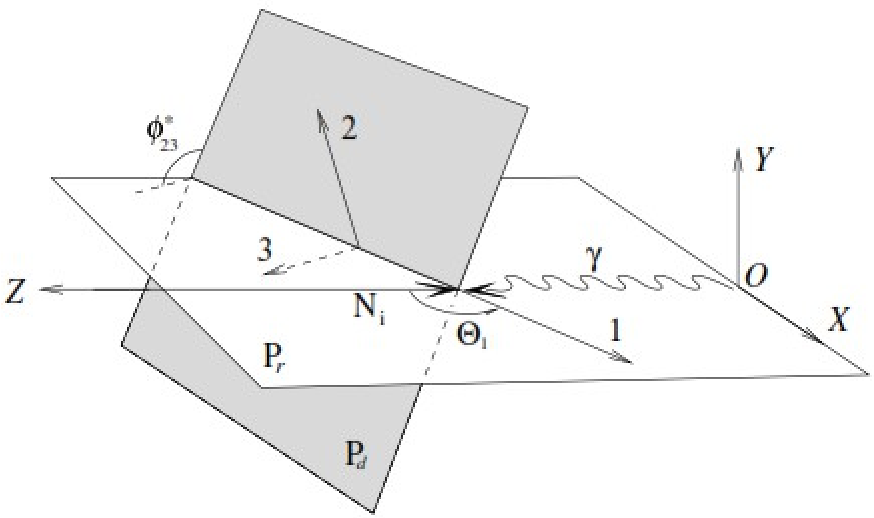


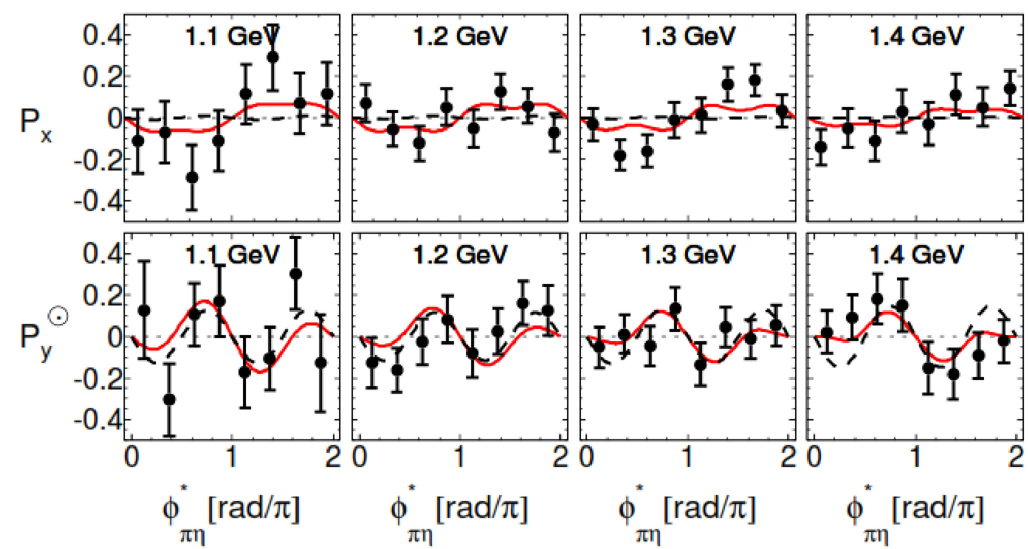
6 x 6mm J-Series SiPMT

$\pi^0\eta$ 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	$P_x^\odot$	$P_y^\odot$



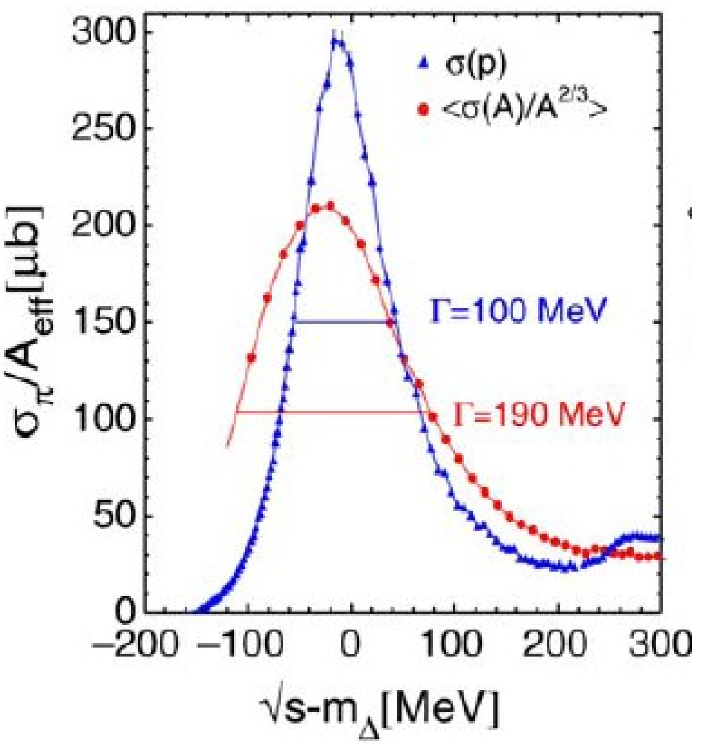


Dashed: only D_{33} wave, solid: A. Fix model, dashed-dotted BnGa PWA

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

Motivation

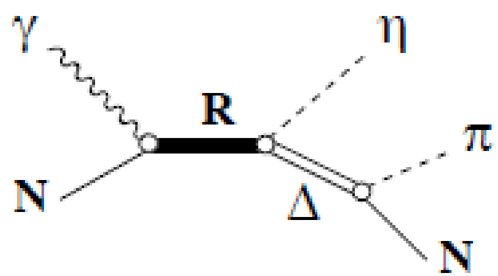
- The width for Δ(1232) is changed in the nuclear medium from 100 MeV to ~190 MeV in good agreement with the BUU model (University Gießen) calculations



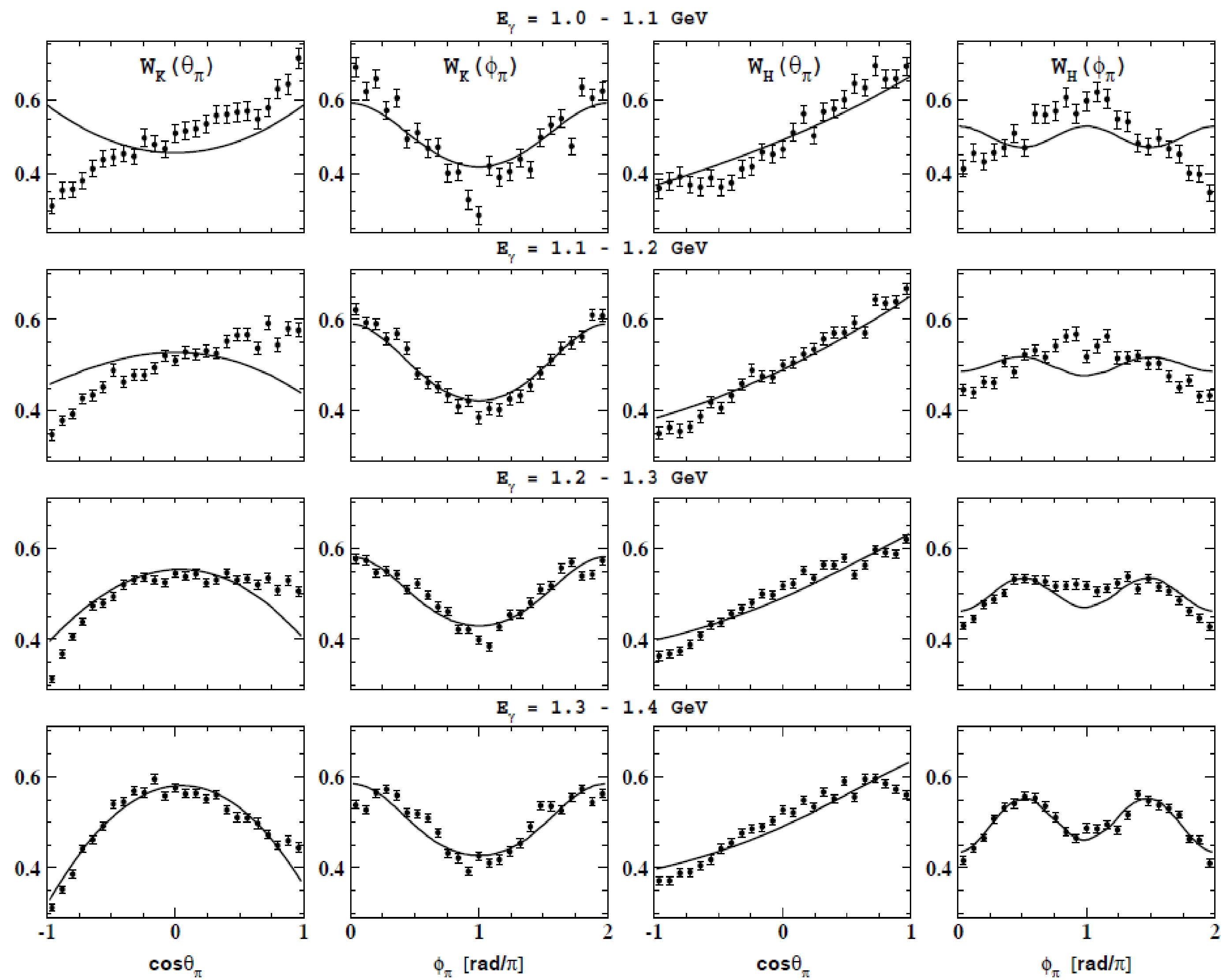
B. Krusche, Progress in Particle and Nuclear Physics 55 (2005) 46–70
M. Post, J. Lehr, U. Mosel, Nuclear Phys. A 741 (2004) 81

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

Differential cross-sections (proton target)



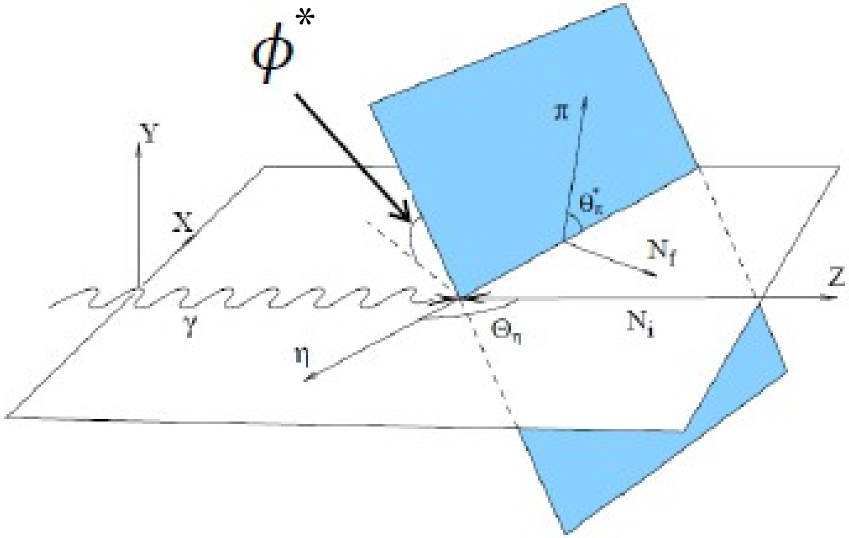
R = D_{33}

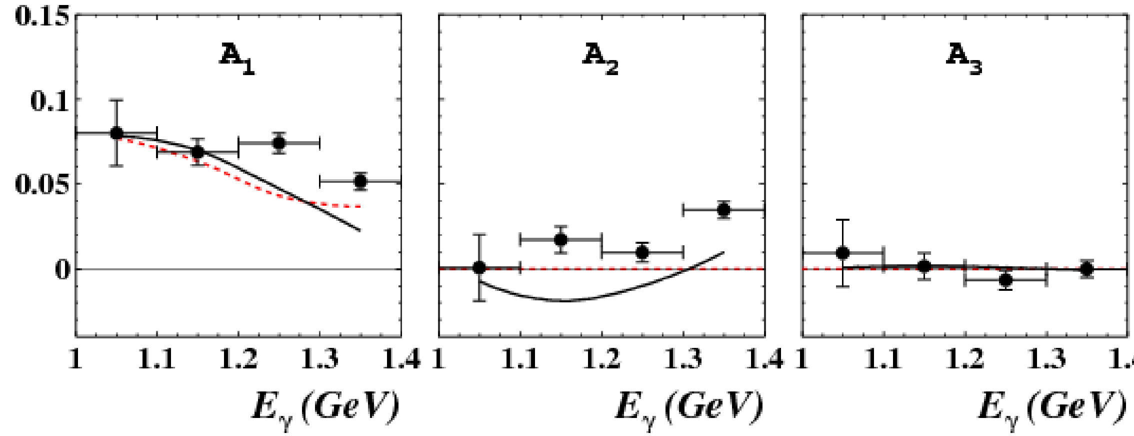


Angular distributions: Reasonable agreement with a model including only the D_{33} amplitude

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

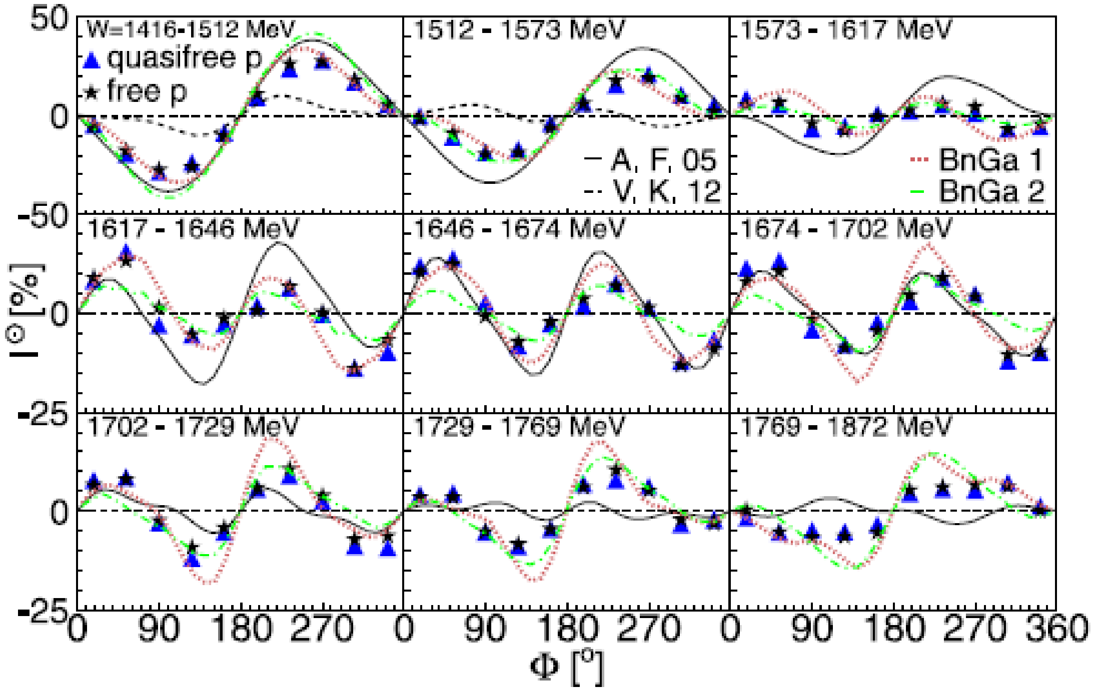
A2 is sensitive to interference terms

A3 is negligible

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

Understanding of the FSI

Example: Significant reduction of the total cross-section was observed for the deuteron target in several reactions, indicating strong FSI effects, but e.g. for the production of 2 neutral pions, the beam helicity asymmetry is in excellent agreement for the free proton (hydrogen target) and quasi-free proton (deuteron target) data



Black: free proton, Blue: quasi-free proton

M. Oberle, B. Krusche et al., Phys.Lett. B721 (2013) 237-243

[A2 Collaboration]

Experimental Setup

- Carbon pipe for positioning targets in the Crystal Ball
- Targets: C, Al, Pb and other parts such as an inserter prepared
- Empty insert for the cryostat built in the KPH Mechanical and Vacuum Workhops