MAMBO @ Pavia

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on behalf of the MAMBO Pavia group

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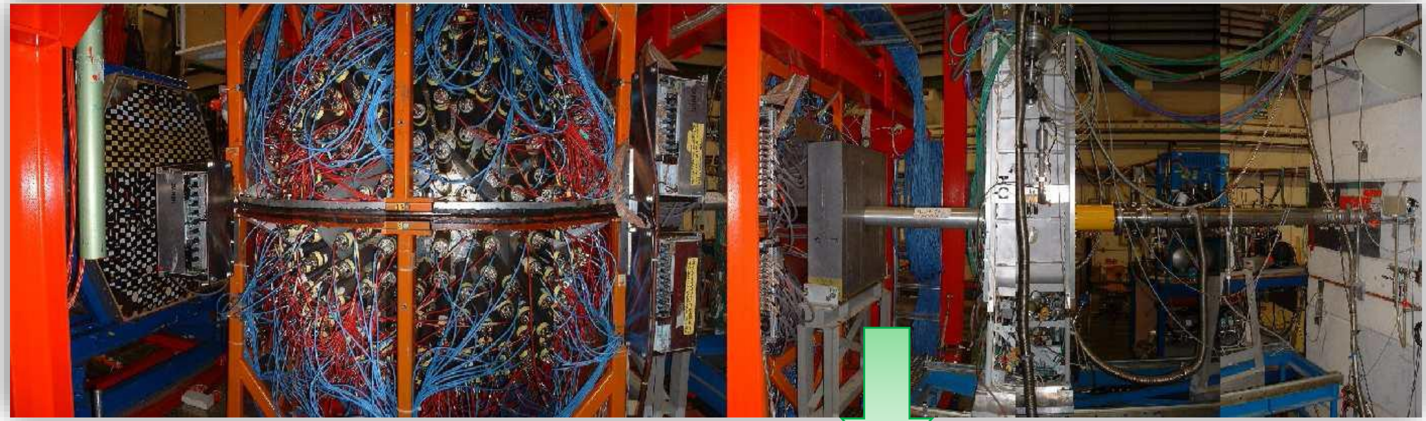
Congresso Interno del Dipartimento di Fisica

Pavia, 13-14/09/2018

MAM(i)BO(nn)

INFN name for 2 photoproduction experiments



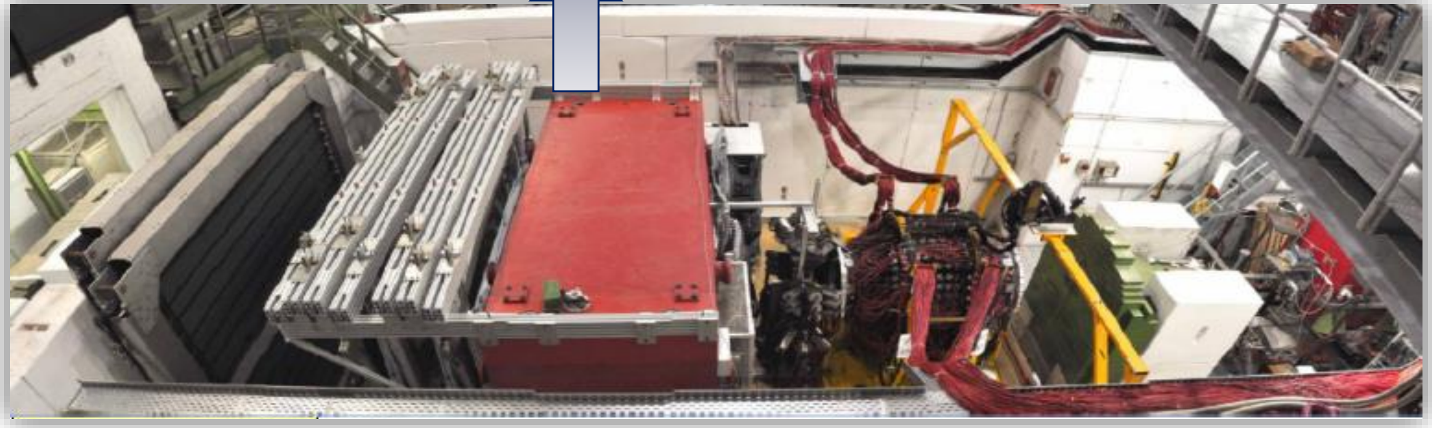
A2 @ MAMI (Mainz)

$E_\gamma < 1.5$ GeV

Common physics goals

BGO-OD @ ELSA (Bonn)

$E_\gamma < 3$ GeV



MAMBO physics goals

Mainly involving low cross sections and/or precision measurements

- Precision spectroscopy of low lying baryon states
  - $\Delta(1232)$ from $\gamma p \rightarrow \pi^0 p$ and $\pi^+ n$
  - $S_{11}(1535)$ from $\gamma p \rightarrow \eta\, p$ reaction
- Search for «missing» baryon resonances
- Ambiguity free amplitude analysis of meson photoproduction
  - Requires double polarisation measurements: $\gamma N \rightarrow N\pi(\pi)$, $N\eta(\rho, \ldots)$
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  - Strangeness ($\gamma N \rightarrow \Lambda K$)
  - π^0 photoproduction at threshold
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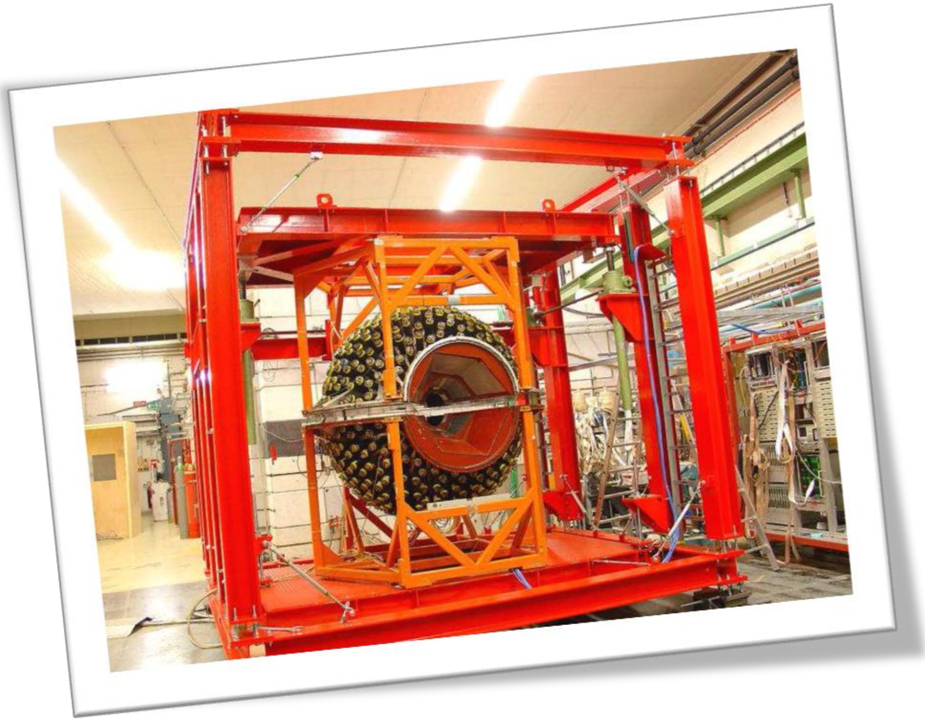
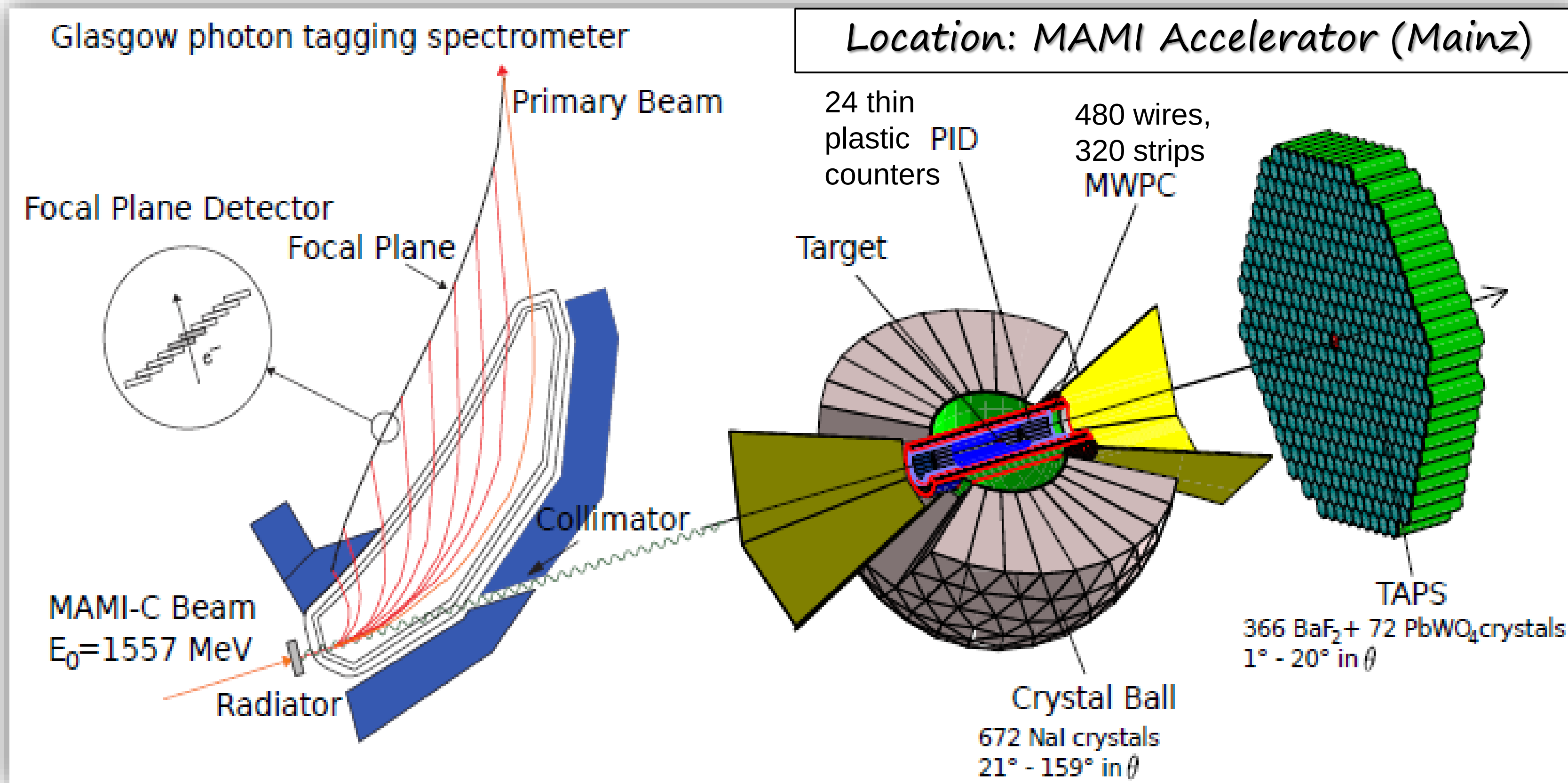
  - Rare η, η' decays
- Determination of the nucleon electric and magnetic structure
  - Nuclear Compton scattering
- In medium properties of hadrons and nuclear astrophysics
  - Meson photoproduction on nuclei

A2 @ MAMI



- The collaboration has been established in 2004 (LoI) – 2005 (MoU)
- Located in Mainz (Germany) by the MAMI accelerator
- ~80 collaborators from:
  - Europe: University of Mainz, Bonn, Basel, Edinburgh, Giessen, Glasgow, Jerusalem, INFN-Pavia, RBI-Zagreb, INR-Moscow,
  - North America:
    - Canada: University of Halifax, Regina, Saint Mary's
    - USA: Washington-DC, Kent-OH, Amherst-MASS, Los Angeles

A2@MAMI: detector overview



Photon beam:

- Produced by bremsstrahlung of electrons accelerated by MAMI
- Photons tagged by the magnetic spectrometer
- $E_\gamma < 1.5$ GeV, $\Delta E_\gamma = 2 - 4$ MeV
- Linear and circular polarisations available

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Why baryon spectroscopy?

The excitation spectra of protons and neutrons allow to draw conclusions on the dynamics of the nucleons constituents

Baryonic resonances spectrum and properties ↔ bound states of strong QCD

How can we study the excited states of the nucleon?

Perturbative QCD
Low energy regime ↔ non perturbative approach
→ MEANINGLESS!!

Phenomenological Quark Models
Based on internal degrees of freedom or on residual interactions of the quarks
→ LIMITED SUCCESS!

Mismatch between experiment and model predictions: where is it rooted?

theory

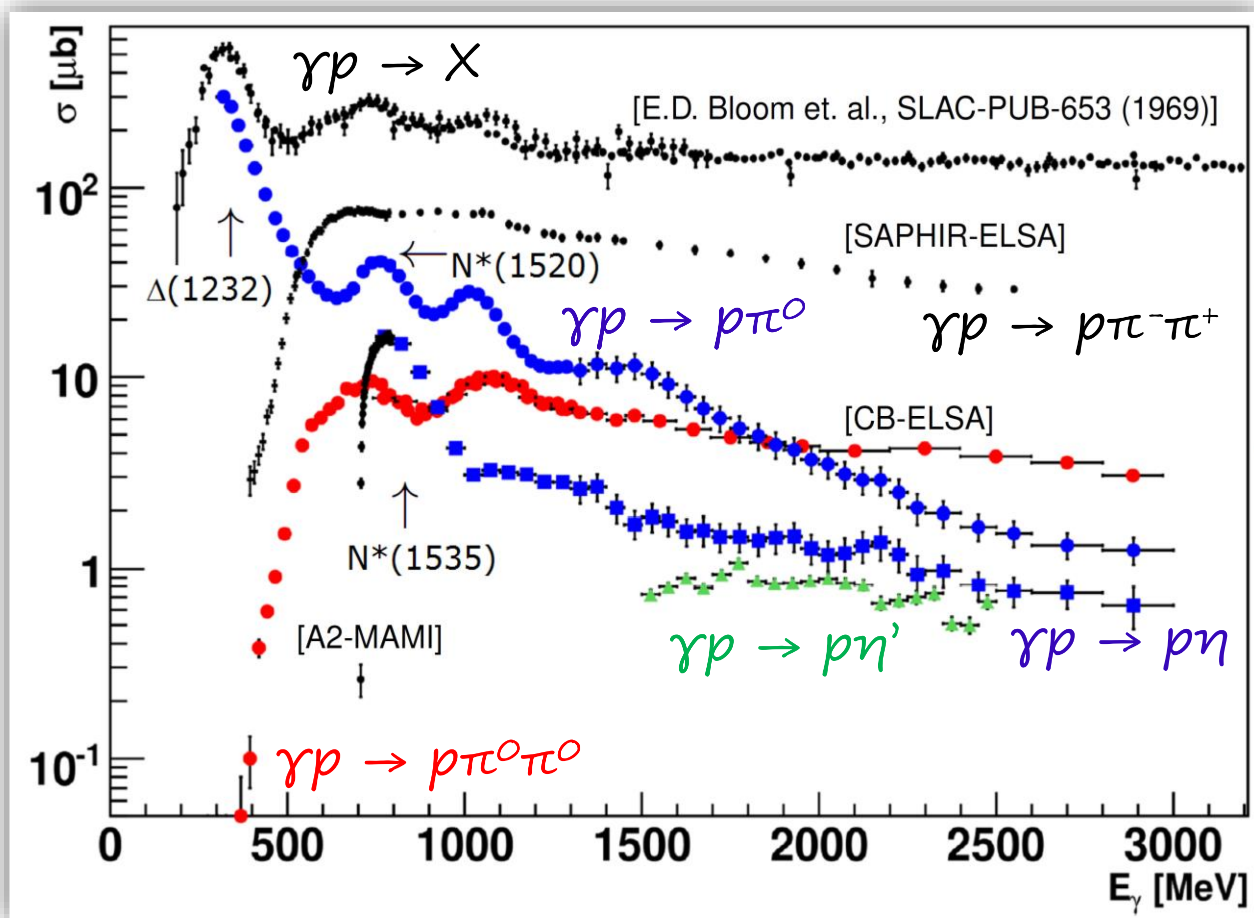
Inappropriate internal degrees of freedom in the model

experiment

Data analyses relying entirely on meson-induced reactions will miss states weakly coupling to $N\pi$

Photoproduction reactions

Experimental alternative:
meson photoproduction reactions
$\gamma N \rightarrow N^* \rightarrow N\pi$



- ✓ Investigation of **different final states**
- ✓ Resonances are accessible via **different production processes**: πN, γN, $\gamma^* N$, Ψ, Ψ'-decays, pN, …
- ✓ Measurement of **polarisation observables** (PWA)

Polarisation observables

Measurable observables ↔ Multipoles ↔ Resonance parameters

- Scattering amplitude f ↔ **CGLN-amplitudes**: 4 complex amplitudes governing pseudoscalar meson photoproduction off the nucleons in the GeV energy range
- **CGLN-amplitudes** $F_i(W, \cos\theta_{cm})$ → expanded into Legendre polinomials $P'_{l\pm1}(\cos\theta_{cm})$ and photoproduction multipoles ($E_{l\pm}(W)$, $M_{l\pm}(W)$)
- **Multipoles**: information on the resonances and their properties in a given partial wave

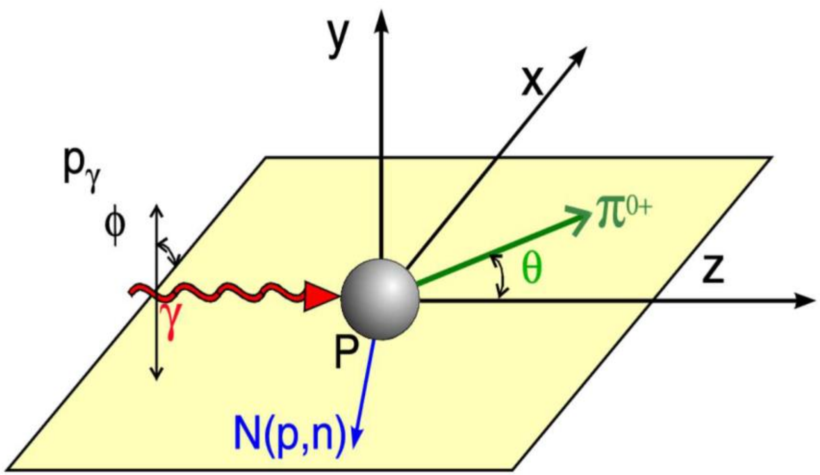
From 4 complex amplitudes it is possible to construct 16 bilinear products
→ 16 polarisation observables for each individual channel

Photon polarisation		Target polarisation			Recoil nucleon polarisation			Target and Recoil polarisations			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
Unpolarized	σ	–	T	–	–	P	–	$T_{x'}$	$L_{x'}$	$T_{z'}$	$L_{z'}$
Linear polaris.	Σ	H	$(-P)$	G	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(L_{x'})$	$(-T_{x'})$
Circular polaris.	–	F	–	E	$C_{x'}$	–	$C_{z'}$	–	–	–	–

1 unpolarised, 3 single polarised, 12 double polarised **measurements**

Polarisation observables

«Complete (model independent) experiment»:
measurement of 7 (8) observables
(4 single polarisation and 4 properly chosen double polarisation observables)
to **unambiguously** determine the scattering amplitudes



Set		Observables			
Single (none)	S	$d\sigma/d\Omega$	Σ	T	P
Beam-Target	BT	G	H	E	F
Beam-Recoil	BR	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$
Target-Recoil	TR	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$

Unpolarised, linearly pol., circularly pol. beam

A2@MAMI:

- ✓ different production products → **multiple photoproduction channels**
- ✓ all combinations of isospin → complete set of **measurements off both the proton and the neutron**

Double polarisation observables G and E

First experimental attempt to measure G and E with longitudinally polarised electron beam incident on a diamond crystal
(→ **using linearly and circularly polarised photons at the same time!**)
with a longitudinally polarised **frozen spin butanol** target

Differential cross section for pseudo-scalar meson photoproduction using elliptically polarised photons in combination with a longitudinally polarised target:

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}_0(\theta)\left[1 - P_{lin}\mathbf{\Sigma}\cos(2(\alpha-\phi)) - P_z\left(-P_{lin}\mathbf{G}\sin(2(\alpha-\phi)) + P_{circ}\mathbf{E}\right)\right]$$

Integrating over ϕ → **E**:

$$N_B\Big|_{\pm 1}^{\pm P_z}(\theta) = N_B(\theta)\cdot\left[1 - d\,P_{circ}P_z\mathbf{E}\right] \quad \Rightarrow \quad \mathrm{E} = \frac{\sigma^{1/2}-\sigma^{3/2}}{\sigma^{1/2}+\sigma^{3/2}} = \frac{N_B^{1/2}-N_B^{3/2}}{N_B^{1/2}+N_B^{3/2}}\cdot\frac{1}{d}\cdot\frac{1}{P_{circ}P_z}$$

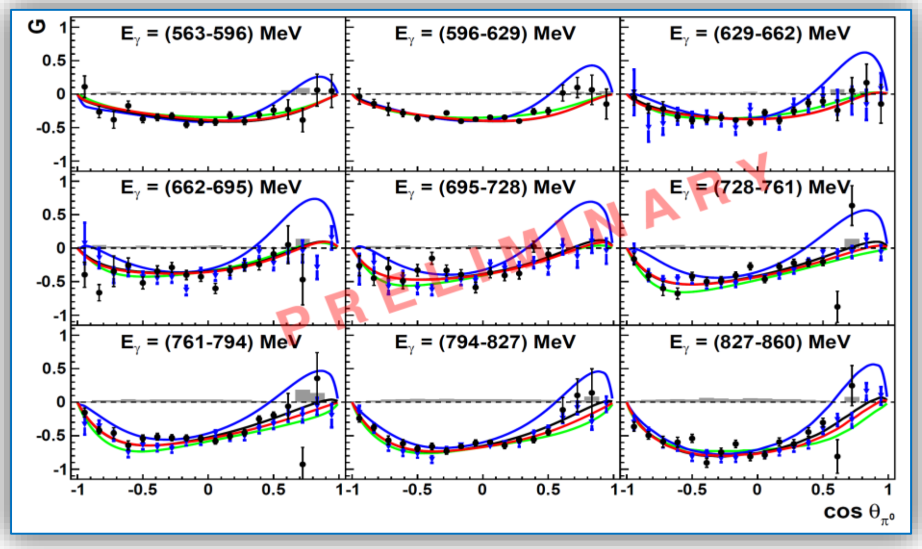
d = dilution factor = amount of polarisable protons in the data $\quad d = 1 - s_c\cdot\frac{N_C}{N_B}$

s_c = scaling factor for flux and acceptance difference between carbon and butanol beamtimes

Integrating over all possible helicity states → **G**:

$$N_B\Big|_{\pm\alpha}^{\pm P_z}(\theta,\phi) = N_B(\theta)\cdot\left[1 - P_{lin}\mathbf{\Sigma_B}\cos\left(2(\alpha-\phi)\right) + d\,P_{lin}P_z\mathbf{G}\sin(2(\alpha-\phi))\right]$$

Results for G in π^0 photoproduction



Results for G
from 266 MeV to 860 MeV

- A2 data (longitudinally polarised electrons + diamond radiator – K. Spieker)
- CBELSA/TAPS data (unpolarised electrons – A. Thiel et al., Phys. Rev. Lett. 109 (2012) 102001)

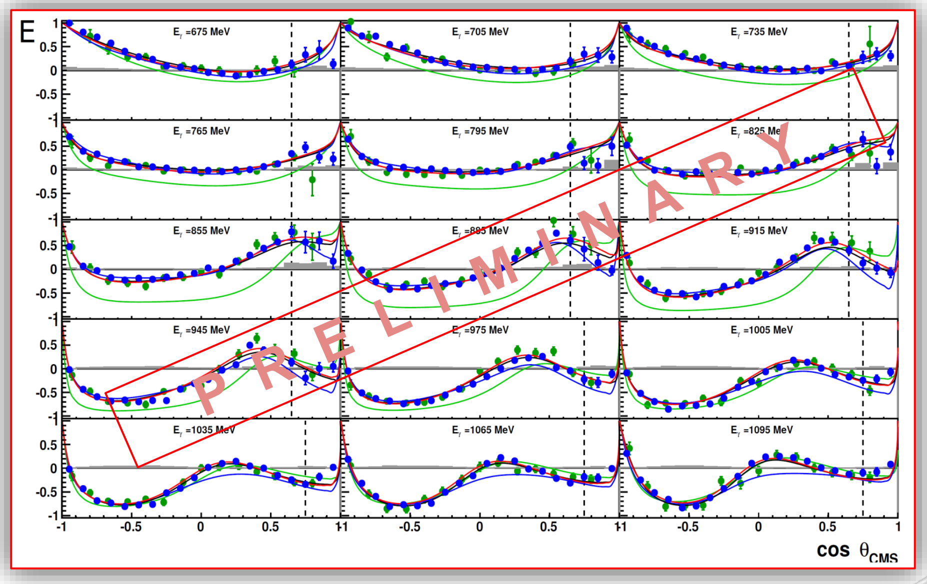
– BnGa_2014_02 (PWA fit)
– BnGa_2014_01 (PWA fit)
– MAID 2007 (PWA pred.)
– SAID-CM12 (PWA pred)

Very good agreement with existing data!

Results for E
from 225 MeV to 1395 MeV

- A2 data (longitudinally polarised electrons + diamond radiator – F.N. Afzal)
- CBELSA/TAPS data (amorphous radiator– M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003)

– BnGa_2014_02 (PWA fit)
– BnGa_2014_01 (PWA fit)
– MAID 2007 (PWA pred.)
– SAID-CM12 (PWA pred)



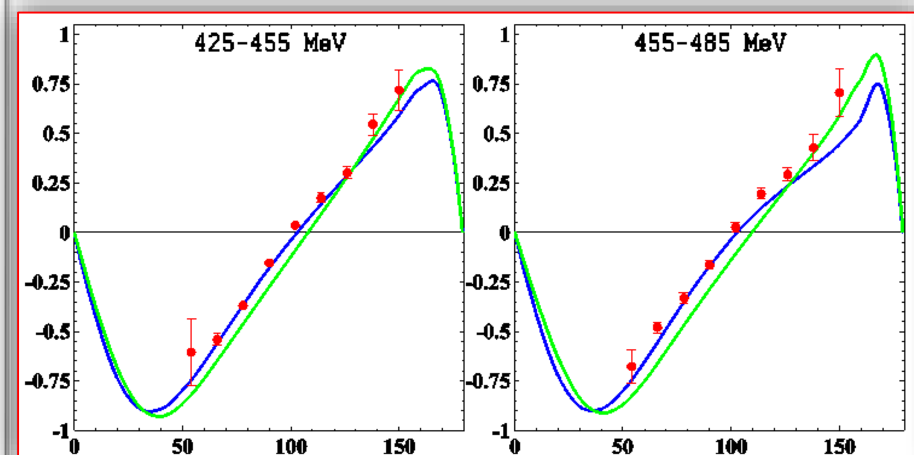
✓ Preliminary results also for E on the deuteron

Results for T and F in $\gamma p \rightarrow \pi^0 p$

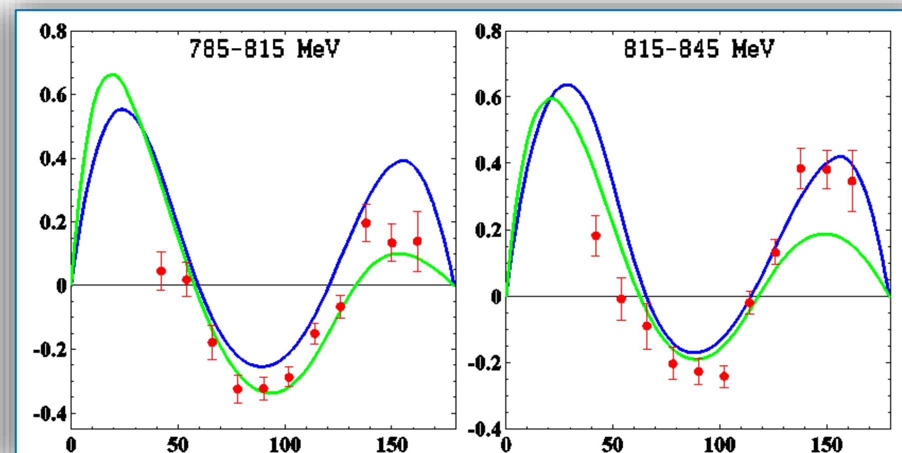
Longitudinally polarised γ beam (425-1450 MeV) and transversely polarised target

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega_0}(\theta)[1 - P_{lin}\Sigma\cos(2\varphi) - P_x P_{lin} H \sin(2\varphi) + P_x P_{circ} F - P_y T - P_x P_{lin} P\cos(2\varphi) - P_z P_{lin} G\sin(2\varphi) + P_z P_{circ} E]$$

F asymmetry



T asymmetry



J.R.M. Annand et al., Phys. Rev. C 93, 055209 (2016)

$F \approx -\sin(\theta)\cos(\theta)\left|M_{1+}\right|^2$

$\Delta(1232)$ strongly dominates

- • A2 data (V. Kashevarov)
- – MAID 2007 (PWA pred.)
- – SAID-CM12 (PWA pred)

$T \approx \mathrm{Im}(E^*_{0+}(E_{2-} + M_{2-}) - 6E^*_{2-}M_{2-})$

Strong D-wave contribution from $D_{13}(1520)$

✓ Preliminary results also for T and F in $\gamma p \rightarrow \pi^+ n$

The GDH sum rule

A measurement of the GDH integral constitutes a fundamental check of our knowledge of both the photon and the nucleon (nucleus)

Strictly connected to the observable E

Anomalous magnetic moment

$$I_{GDH} = \int_{\nu_{th}}^{\infty} \frac{\sigma_p - \sigma_a}{\nu} d\nu = 4\pi^2 \kappa^2 \frac{e^2}{M^2} S$$

Spin

Mass

Photon energy

ν_{th} = π production threshold (nucleons)
photodisintegration threshold (nuclei)

Photon spin Baryon spin

$\sigma_{1/2} = \sigma_a$

$\sigma_{3/2} = \sigma_p$

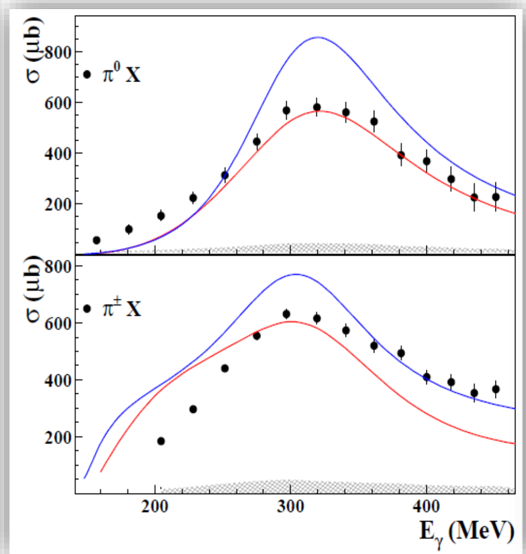
A2@MAMI:

- ✓ Precise measurements of all partial $\gamma N \rightarrow N\pi(\pi)$ channels both on the proton and on the neutron (deuteron, ^{3}He targets)
- ✓ Total inclusive and differential cross sections
- ✓ Reliable extraction of the **free-neutron information** from d and ^{3}He targets

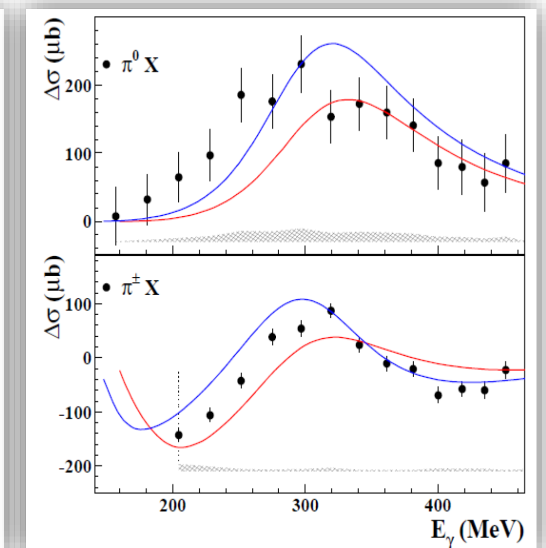
$\vec{\gamma}\,^3\overrightarrow{He} \rightarrow \pi X$ cross sections

A2@MAMI: first data!!!!

UNPOLARISED

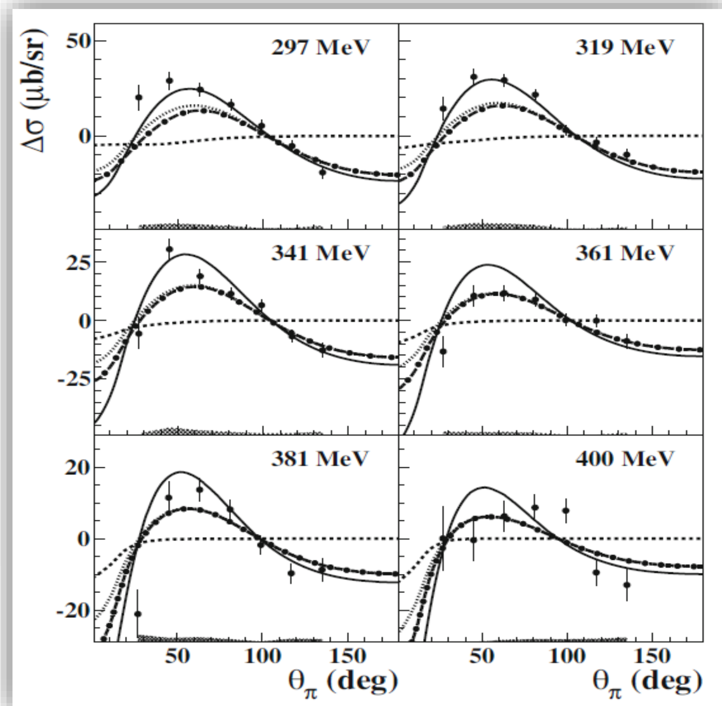


POLARISED



P. Aguar Bartolomé et al, PLB 723 (2013) 71-77

DIFFERENTIAL for $\vec{\gamma}\,^3\overrightarrow{He} \rightarrow \pi^0 X$



S. Costanza et al, EPJA (2014) 50: 173

- CB data
- PWIA model
- FA model $\pi^0\,^3He$
- FA model $\pi^0 ppn$
- FA model $\pi^0 pd$

FA (Fix-Arenhövel) model

Fermi motion + nuclear structure effects

PWIA (Plane-Wave Impulse Approximation) model

incoherent sum of quasi-free single nucleon contributions

(from MAID multipole analysis smeared with Fermi motion)

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Compton scattering equations

Zeroth Order - Mass and Electric Charge

$$H_{\text{eff}}^{(0)} = \frac{\vec{\pi}^2}{2m} + e\phi \qquad (\text{where } \ \vec{\pi} = \vec{p} - e\vec{A})$$

First Order - Anomalous Magnetic Moment

$$H_{\text{eff}}^{(1)} = -\frac{e(1+\kappa)}{2m}\vec{\sigma}\cdot\vec{H} - \frac{e(1+2\kappa)}{8m^2}\vec{\sigma}\cdot\left[\vec{E}\times\vec{\pi} - \vec{\pi}\times\vec{E}\right]$$

Second Order - Electric and Magnetic Polarizabilities

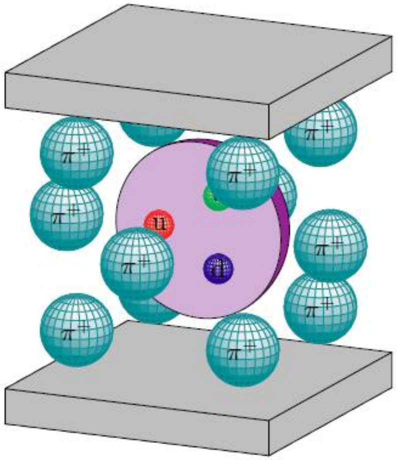
$$H_{\text{eff}}^{(2)} = -4\pi\left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2\right]$$

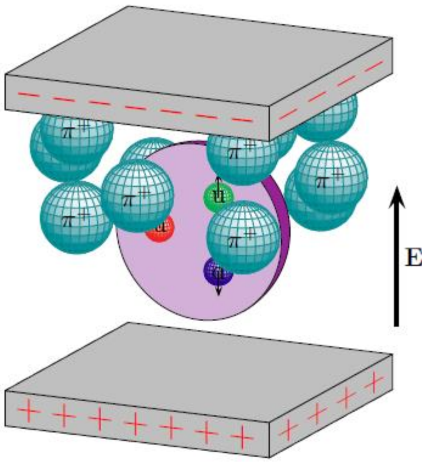
Third Order - Spin Polarizabilities

$$H_{\text{eff}}^{(3)} = -4\pi\Big[\frac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \frac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\Big]$$

Scalar polarisabilities α_{E1} and β_{M1}

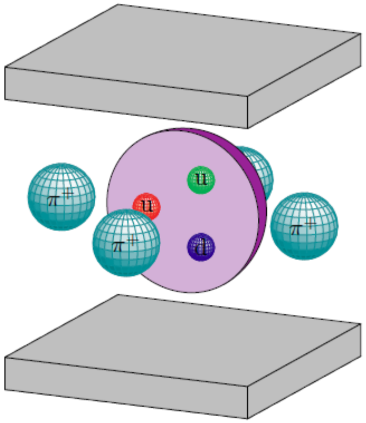
α_{E1} describes the response of a proton to an applied electric field

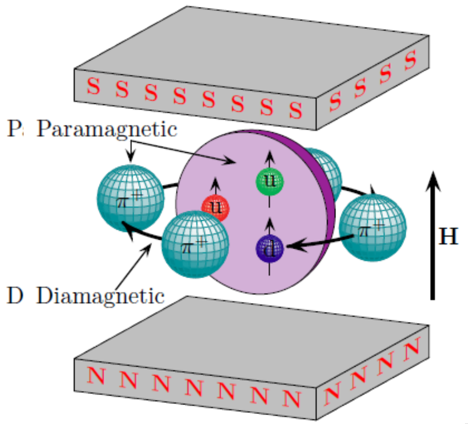




The electric field **E** induces a current in the pion cloud which vertically «stretches» the proton («stretchability»)

β_{M1} describes the response of a proton to an applied magnetic field

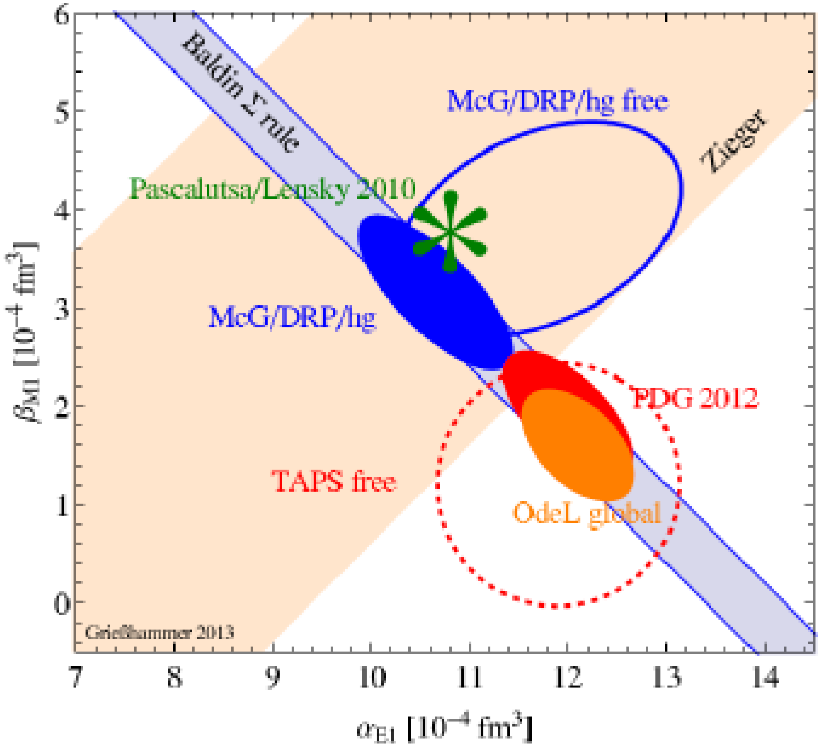




The magnetic field **H** induces a diamagnetic moment in the pion cloud that opposes the paramagnetic moment of the quarks («alignability»)

Scalar polarisabilities α_{E1} and β_{M1}

Existing data and model predictions



PDG 2013/2014

$$\alpha_{E1} = (11.2 \pm 0.4) \times 10^{-4}\,\mathrm{fm}^3$$
$$\beta_{M1} = (2.5 \pm 0.4) \times 10^{-4}\,\mathrm{fm}^3$$

Baldin (Lapidus) Sum Rule:

$$\alpha + \beta = \frac{1}{2\pi^2} \int_{\omega_0}^{\infty} \frac{\sigma_{tot}(\omega)}{\omega^2} d\omega$$

Situation for both the proton and (especially) the neutron can be improved.
Perhaps A2@MAMI can do better…

Spin polarisabilities

They describe the response of the **proton spin** to an applied electric or magnetic field. Analogous to a classical Faraday effect.

To date, these have not been individually determined.

Two linear combination of them have been:

Forward Spin Polarisability (GDH experiments):

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1E2} - \gamma_{M1M1} = (-1.0 \pm 0.08) \times 10^{-4}\ fm^4$$

Backward Spin Polarisability (dispersive fits to back-angle Compton scattering):

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1E2} + \gamma_{M1M1} = (8.0 \pm 1.8) \times 10^{-4}\ fm^4$$

Extracting the proton spin polarisabilities would provide a useful test of low-energy QCD theorems

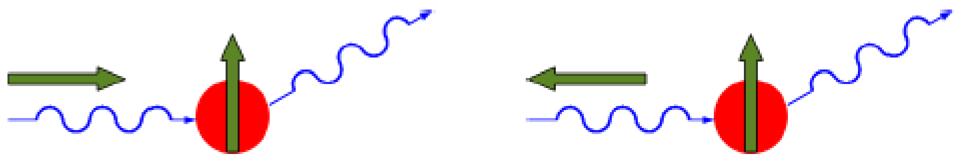
	K-mat.	HDPV	DPV	L_χ	HBχPT	BχPT
γ_{E1E1}	-4.8	-4.3	-3.8	-3.7	-1.1 ± 1.8 (th)	-3.3
γ_{M1M1}	3.5	2.9	2.9	2.5	2.2 ± 0.5 (st) ± 0.7 (th)	3.0
γ_{E1M2}	-1.8	-0.02	0.5	1.2	-0.4 ± 0.4 (th)	0.2
γ_{M1E2}	1.1	2.2	1.6	1.2	1.9 ± 0.4 (th)	1.1
γ_0	2.0	-0.8	-1.1	-1.2	-2.6	-1.0
γ_π	11.2	9.4	7.8	6.1	5.6	7.2

Compton scattering experiments

Polarisation observables in real Compton scattering are used to extract information about scalar and spin polarisabilities

$$\Sigma_{2x} = \frac{N^R_{+x} - N^L_{+x}}{N^R_{+x} + N^L_{+x}}$$

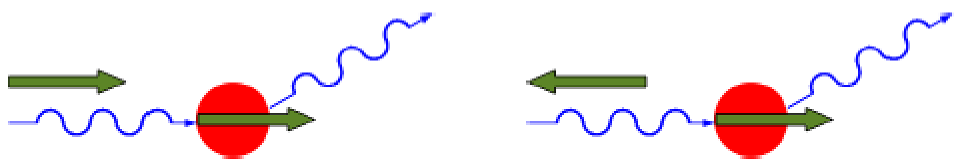
Circularly polarised photons, transversely polarised target



Sensitive to γ_{E1E1}

$$\Sigma_{2z} = \frac{N^R_{+z} - N^L_{+z}}{N^R_{+z} + N^L_{+z}}$$

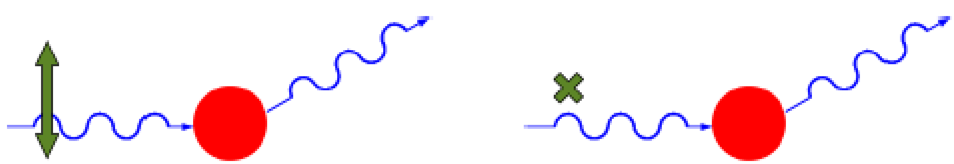
Circularly polarised photons, longitudinally polarised target



Sensitive to γ_{M1M1}

$$\Sigma_3 = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$

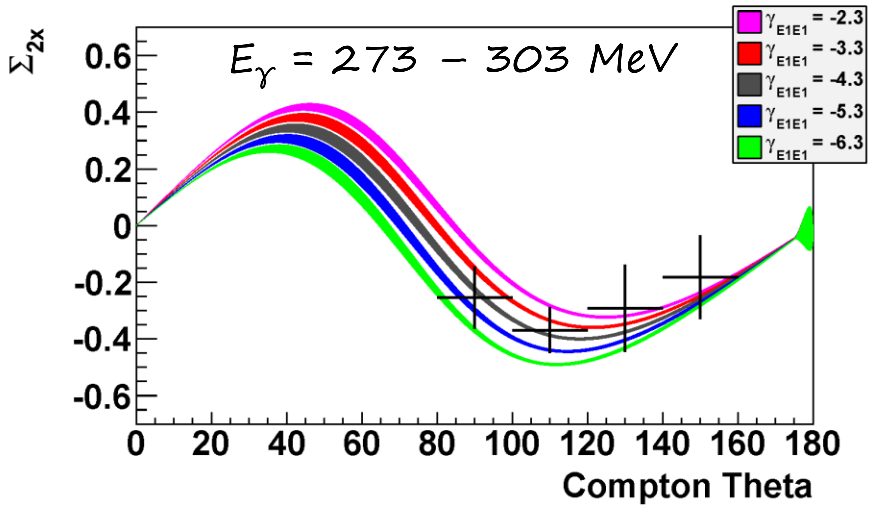
Linearly polarised photons, unpolarised target



Sensitive to γ_{E1E1} and to γ_{M1M1}

Compton scattering experiments

Circularly polarised photons, transversely polarised protons



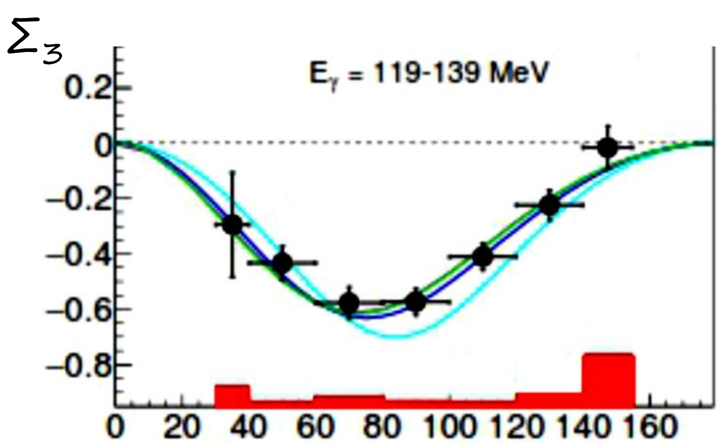
Fix γ_{E1E1} and γ_{M1M1}, and determine the other two using γ_0 and γ_π, allowing them, α_{E1} and β_{M1} to vary by their experimental error.

First estimate of γ_{E1E1}:

$\gamma_{E1E1} = -3.5 \pm 1.2 \times 10^{-4}\ \mathrm{fm}^4$

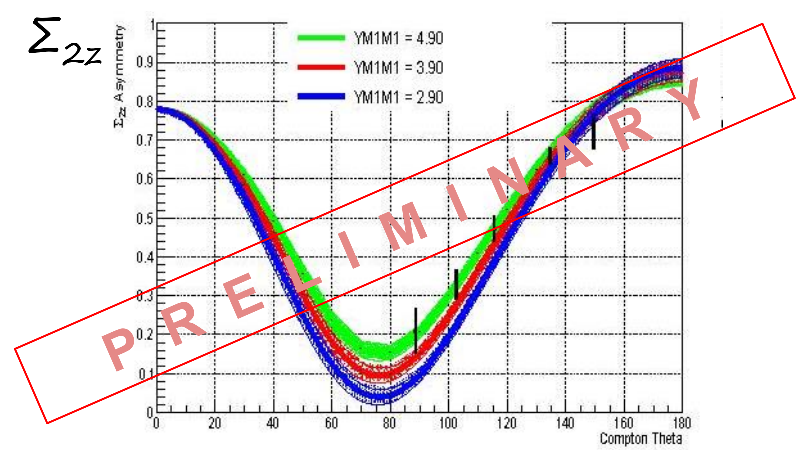
P. Martel et al., PRL 114, 112501 (2014)

Linealry polarised photons



V. Sokhoyan et al, EPJA 53, 14 (2017)

Circularly polarised photons, longitudinally polarised protons



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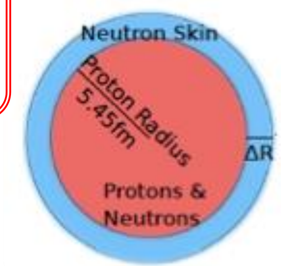
The neutron skin

Neutron skin thickness $\Delta r_{np} = R_n - R_p$
where $R_{n(p)}$ = RMS radii for the n(p) distribution ($<r^2>^{1/2}$)

Pb-208



- Sensitive to nuclear dynamics and provides fundamental nuclear structure information
- It constrains poorly established parameters in the EOS of neutron rich matter (density dependence of the nuclear symmetry energy E_{sym}):

Baryon density $\rho = \rho_n + \rho_p$

Isospin asymmetry $\delta = \dfrac{\rho_n - \rho_p}{\rho}$

EOS: $$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta)^4$$

Slope parameter

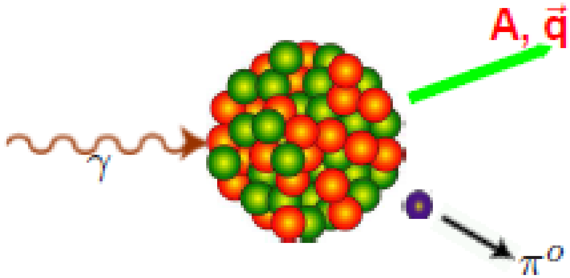
Curvature parameter

Symmetry energy $$E_{sym}(\rho) = J + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots$$

- Important implications in astrophysics (neutron stars):
  - constraint on the mass – radii relationship in neutron stars
  - feasibility of direct URCA cooling mechanisms in neutron stars
  - information on the critical density for the transition between liquid and solid phase

Coherent pion photoproduction

Photon probe ✓
Interaction well understood



Momentum tranfer q
$q = P_\gamma - P_\pi$

π^0 reconstructed from its decay in 2γ

- All nucleons contribute coherently to the reaction amplitude
- No Coulomb scattering effect
- The reaction amplitude for π^0 production on the nucleus has closely equal probabilities on both protons and neutrons (Δ region)
- The π^0 production cross section is proportional to $A^2F^2_m(q)$, where $F_m(q)$ is the matter form factor of the nucleus
- No initial state interactions; FSI must be taken into account

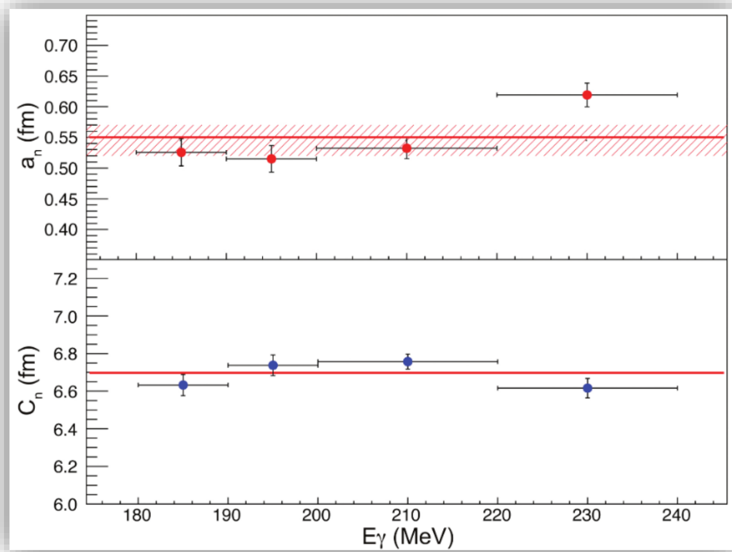
For each E_γ bin of the differential cross section, extract the **best fit values a_n and C_n for the neutron distribution:**

$$\rho(r) = \frac{\rho_0}{1+\exp[(r-C)/a]} \Longrightarrow \langle r_n^2 \rangle = \frac{3}{5} C_n^2 \left(1 + \frac{7}{3} \pi^2 \frac{a_n^2}{C_n^2} \right) \Longrightarrow \Delta R_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$$

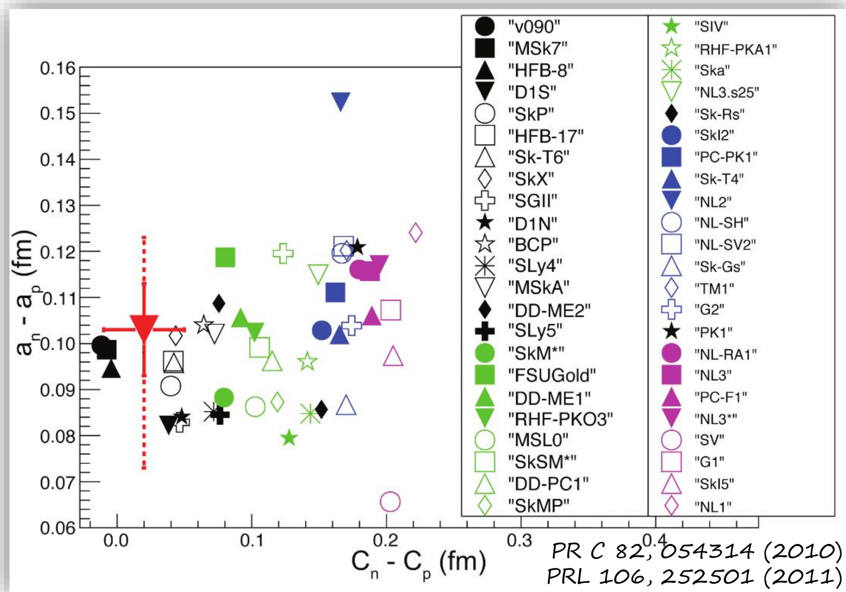
The extracted skin properties

Results for ^{208}Pb

Best fit for diffuseness (a_n) and half-height radius (C_n)



Comparison with the models



C.M.Tarbert, PRL 112, 242502 (2014)

$$\Delta r_{np} = 0.15 \pm 0.03(stat.)\,^{+0.01}_{-0.03}(sys.)\ fm$$

Results in agreement with previous measurements

A2@MAMI:

✓ Preliminary results for ^{40}Ca

Summary

- An overview was given on recent results from the photoproduction of mesons from nucleons and nuclei at A2@MAMI
- The technical/instrumental challenges of the measurements of such reactions are well under control
- With respect to similar facilities (CLAS), ELSA and MAMI can be:
  - **competitive**, thanks to the high energy resolution ΔE_γ and high intensity of the photon beam (MAMI), and to the wide energy range (ELSA)
  - **complementary**, thanks to the almost 4π-covering elm calorimeters, allowing to reconstruct mixed charged and all-neutral final states
- MAMBO can contribute to many topics of nuclear physics
- A lot of collected data to be analysed… and a lot to come!

- Internships:
  - for Bachelor students (5 weeks): https://academy.inspiringphysics.de/
  - for Master students (2-3 months): http://www.prisma.uni-mainz.de/internship_program.php

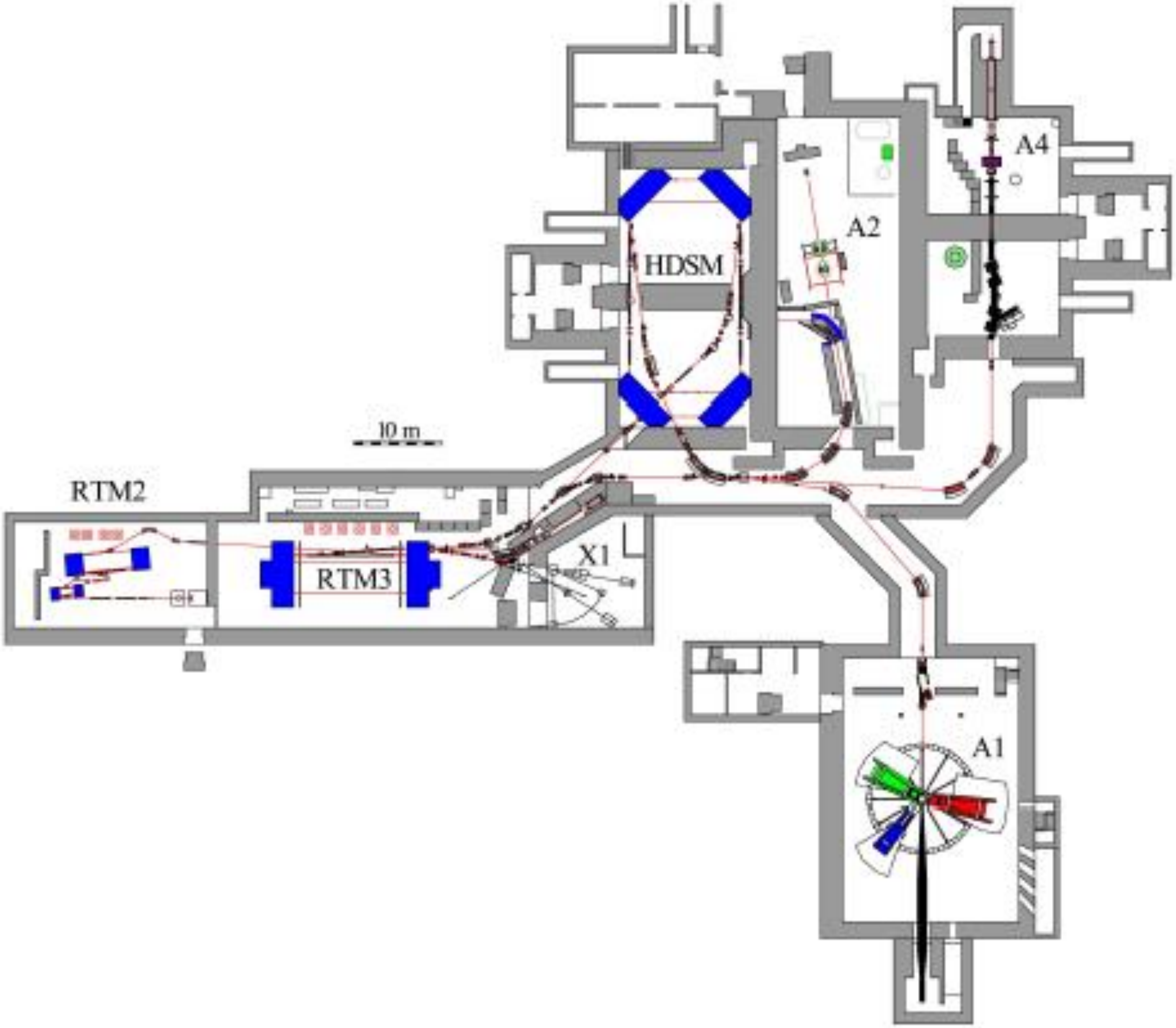
Thank you
for your attention!

Additional material

Meson photoproduction

- ✓ Prime tool for the experimental investigation of the excitation spectrum of the nucleon
- ✓ Accuracy in measuring photon induced reactions is comparable to that of hadron induced reactions
- ✓ Possible due to the large progress in accelerator and detector technology
- ✓ Possibility to explore multiple meson production reactions ($\pi\pi$, $\pi\eta$, …)
- ✓ Access to resonances that decay via intermediate excited states
- ✓ Electromagnetic couplings are related to spin-flavour correlations of the states → information about configuration mixing
- ✗ Electromagnetic cross sections are much smaller than the hadronic ones
- ✗ Photon induced reactions can have significant non-resonant «background»

MAinz MIcrotron e⁻ accelerator



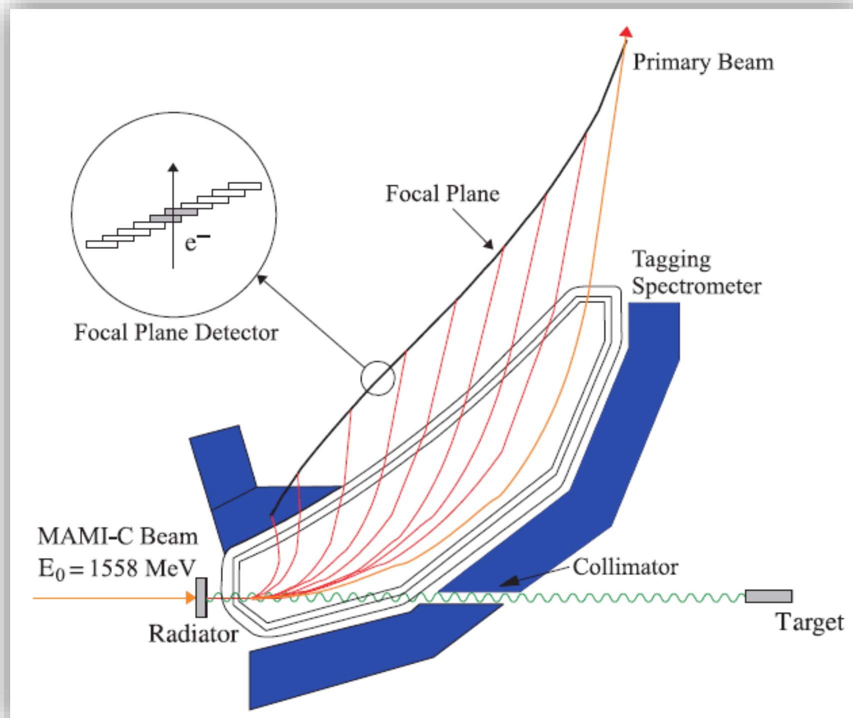
- Injector → 3.5 MeV
- RTM1 → 14.9 MeV
- RTM2 → 180 MeV
- RTM3 → 883 MeV
- RTM4 → 1.6 MeV

A2 Collaboration

- The collaboration has been established in 2004-2005
  - ~ 70 collaborators
  - Germany, Italy, Great Britain, Russia, Switzerland, USA
  - LoI signed and approved in 2004
  - MoU in 2005

- **Location:**
  MAMI Accelerator
  (Mainz)

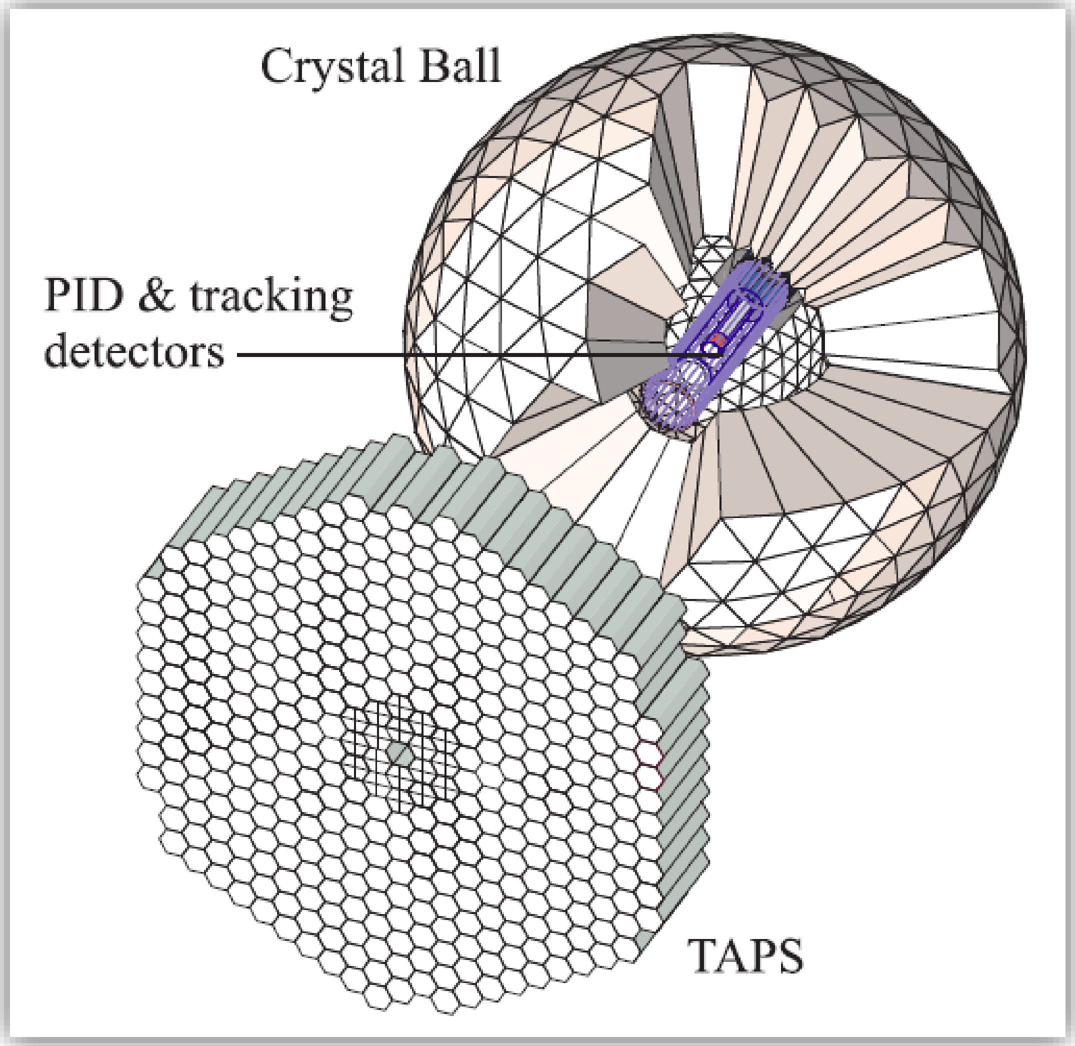
- **Beam:**
  - photon beam produced by bremsstrahlung process and tagged by the magnetic spectrometer
  - $E_\gamma < 1.5$ GeV
  - $\Delta E_\gamma = 2 - 4$ MeV
  - Linear and circular polarisations available



A2@MAMI: detector overview

- **Crystal Ball**
  - Photon spectrometer
  - 672 NaI-detectors
  - Large acceptance (93%)
  - $20° < \theta < 160°$
- **TAPS**
  - Forward wall
  - 510 BaF_2 detectors
  - $2° < \theta < 21°$
- **MWPC**
  - 2 cylindrical wire chambers
  - 480 wires, 320 strips
- **PID**
  - Particle separation
  - 24 thin plastic counters

Built and maintained by the Pavia group



Why baryon spectroscopy?

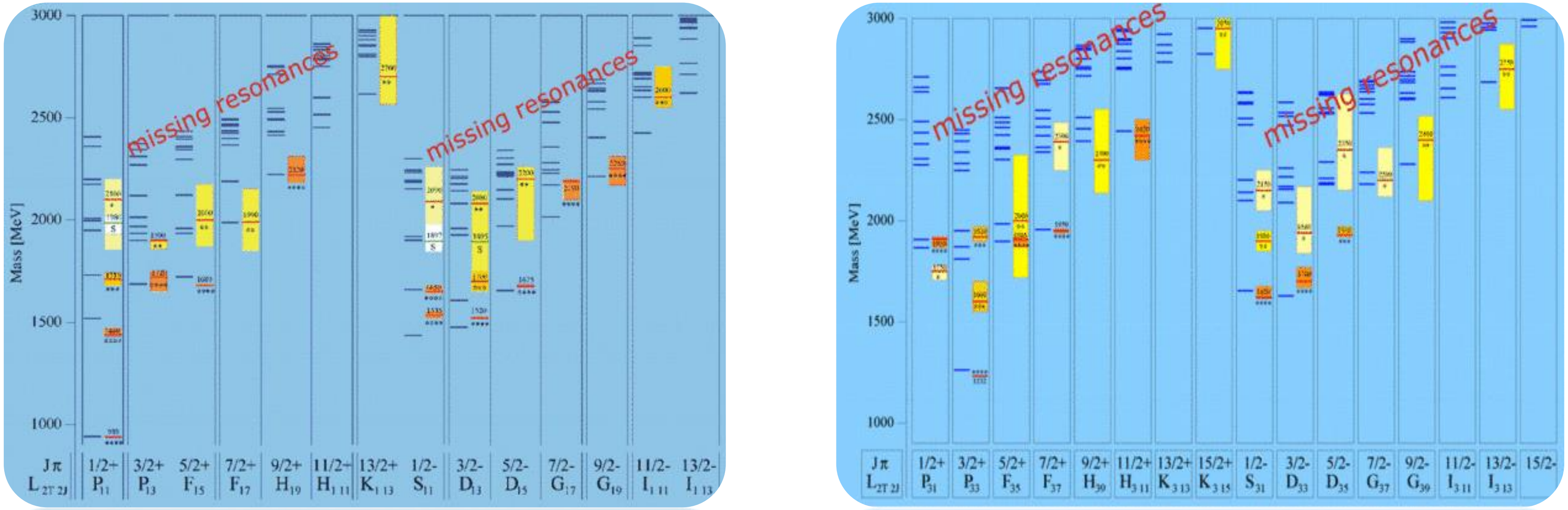
The excitation spectra of protons and neutrons allow to draw conclusions on the dynamics of the nucleons constituents

Baryonic resonances spectrum and properties ↔ bound states of strong QCD

How can we study the excited states of the nucleon?

- **Perturbative QCD** → MEANINGLESS!!
  - Low energy regime ↔ non perturbative approach
- **Phenomenological Quark Models** → LIMITED SUCCESS
  - Based on internal degrees of freedom
    - Three equivalent constituent quarks, quark-diquark structures, quark and flux tubes
  - Based on residual interactions of the quarks
    - Gluon exchange, Goldstone boson exchange
  - Can serve as:
    - approximation of the nucleon structure
    - guidance about the relevant interaction properties by comparison with the observed excitation spectrum

Looking for missing resonances



Pictures from wwwnew.hiskp.uni-bonn.de/cb

Mismatch between experiment and model predictions:
- Many more resonances expected than observed
- Certain configurations completely missing: why?

Where is the mismatch rooted?

theory

Inappropriate internal degrees of freedom in the model

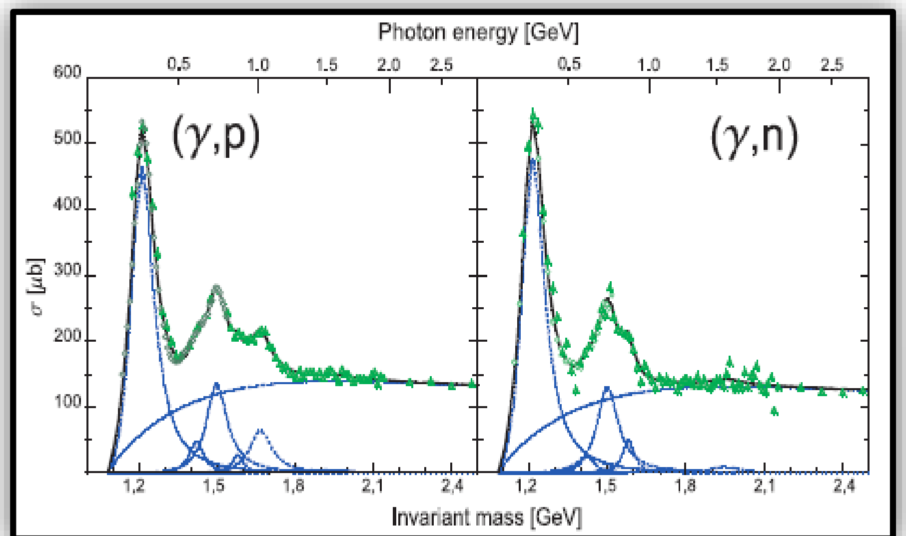
experiment

Data analyses relying entirely on meson-induced reactions will miss states weakly coupling to $N\pi$

Measurements off the neutron

Why are these measurements important?

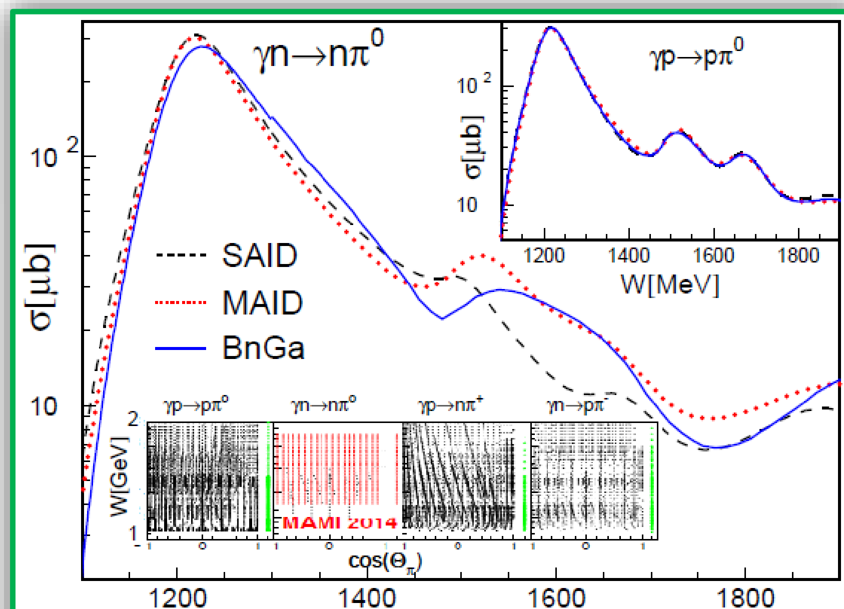
- Different resonance contributions



- Needed for extraction of iso-spin composition of elm couplings

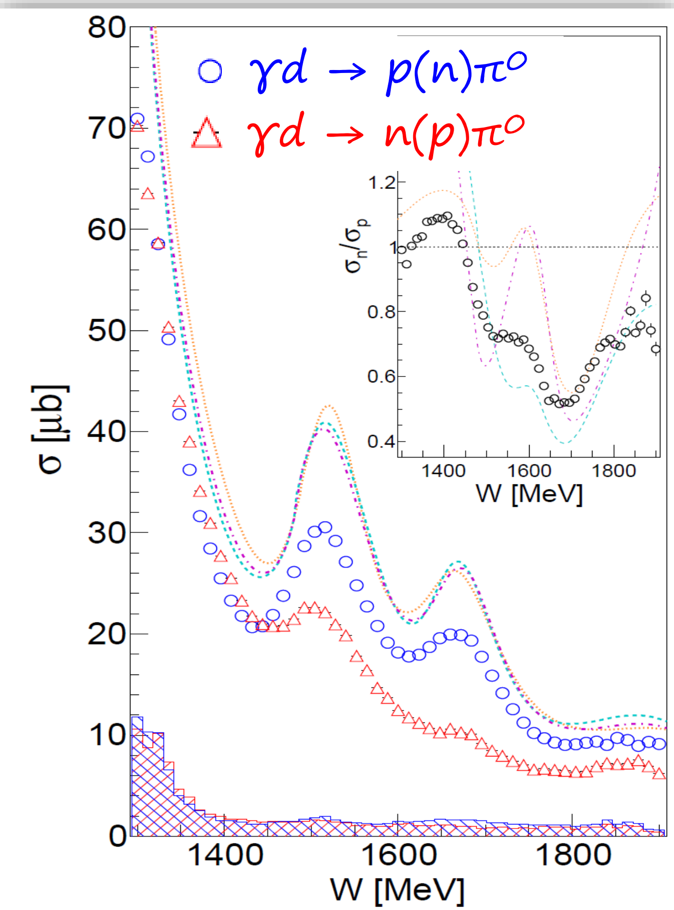
$$A(\gamma p \to \pi^+ n) = -\sqrt{\tfrac{1}{3}}A^{V3} + \sqrt{\tfrac{2}{3}}(A^{IV} - A^{IS})$$
$$A(\gamma p \to \pi^0 p) = +\sqrt{\tfrac{2}{3}}A^{V3} + \sqrt{\tfrac{1}{3}}(A^{IV} - A^{IS})$$
$$A(\gamma n \to \pi^- p) = +\sqrt{\tfrac{1}{3}}A^{V3} - \sqrt{\tfrac{2}{3}}(A^{IV} + A^{IS})$$
$$A(\gamma n \to \pi^0 n) = +\sqrt{\tfrac{2}{3}}A^{V3} + \sqrt{\tfrac{1}{3}}(A^{IV} + A^{IS})$$

- Disagreement between predictions (results from partial wave, reaction models) for neutron target
  - agreement only in the Δ(1232) resonance
  - large discrepancies in the second and third resonance region



M. Dieterle et al, PRL 112 (2014) 142001

Measurements off the neutron



Curves:
predictons from

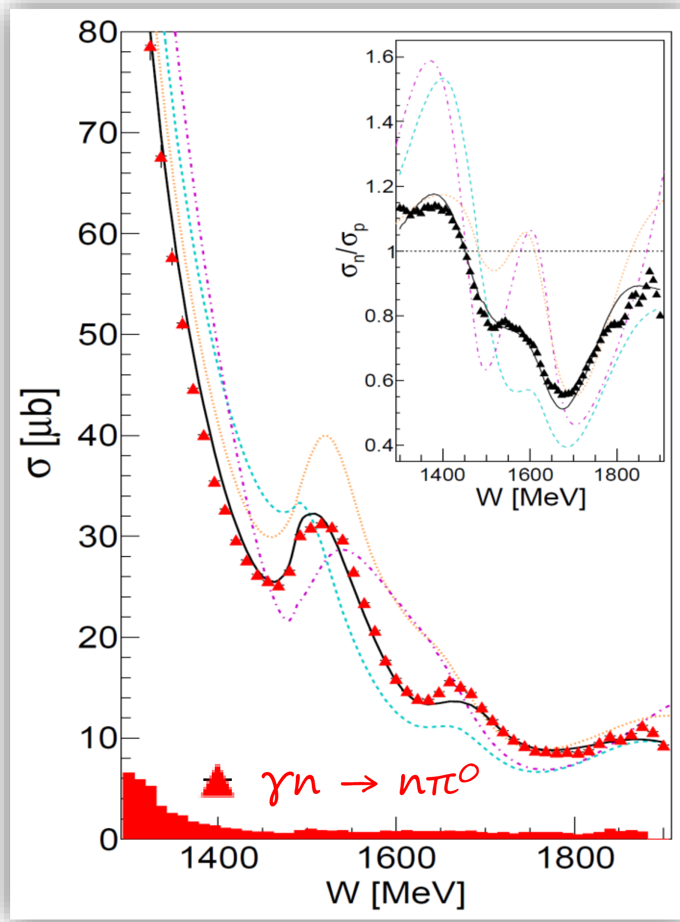
SAID

MAID

BnGa

for
$\gamma p \to p\pi^0$ (left)
and
$\gamma n \to n\pi^0$ (right)

M. Dieterle et al,
PRL 112 (2014) 142001



- **PWA results**: agreement for proton target, disagreement for neutron target
- **Data-PWA results comparison**:
  - significant effects from FSI in proton data
  - poor agreement between neutron data and PWA predictions

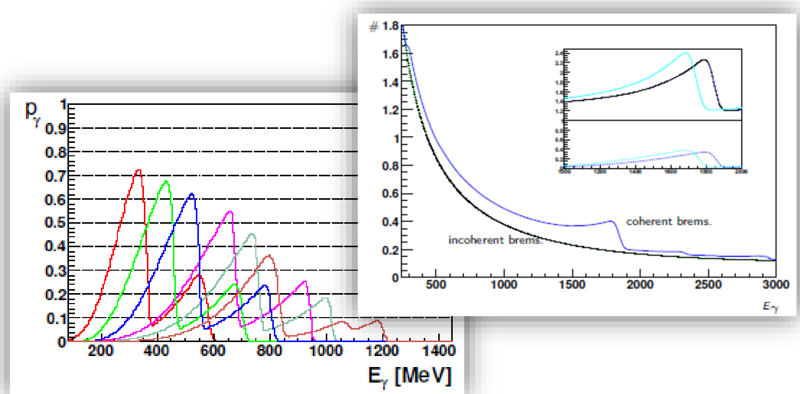
Double polarisation observables G and E

First experimental attempt to measure G and E with longitudinally polarised electron beam incident on a diamond crystal
(→ **using linearly and circularly polarised photons at the same time!**)
with a longitudinally polarised **butanol** target

Linearly polarised photons

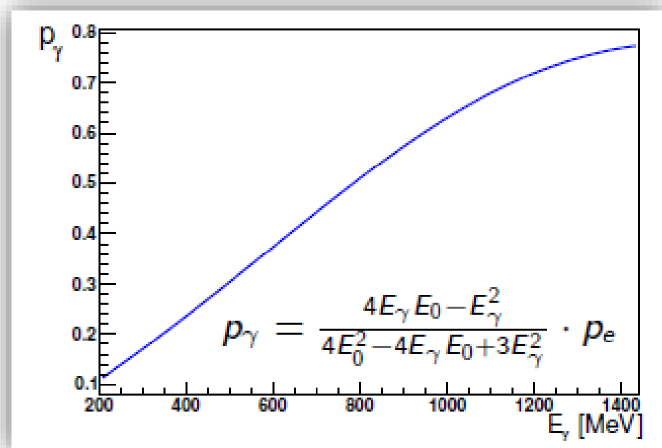
- Diamond radiator needed
- Coherent bremsstrahlung:

  preferred plane between incoming electron and outgoing photon → orientation of the field vector of the photon
- Coherent edges: 350 … 850 MeV



Circularly polarised photons

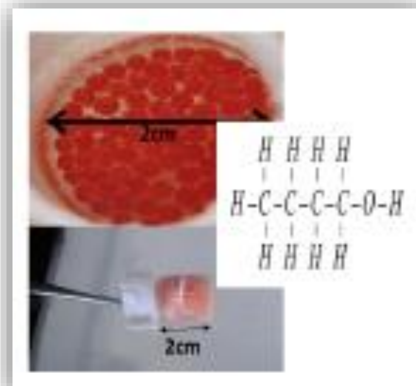
- Longitudinally polarised electrons needed
- Helicity transfer from electrons to photons → circularly polarised photons
- Mott/Moeller measurement of polarisation degree: $p_e \approx 75\text{–}78\%$

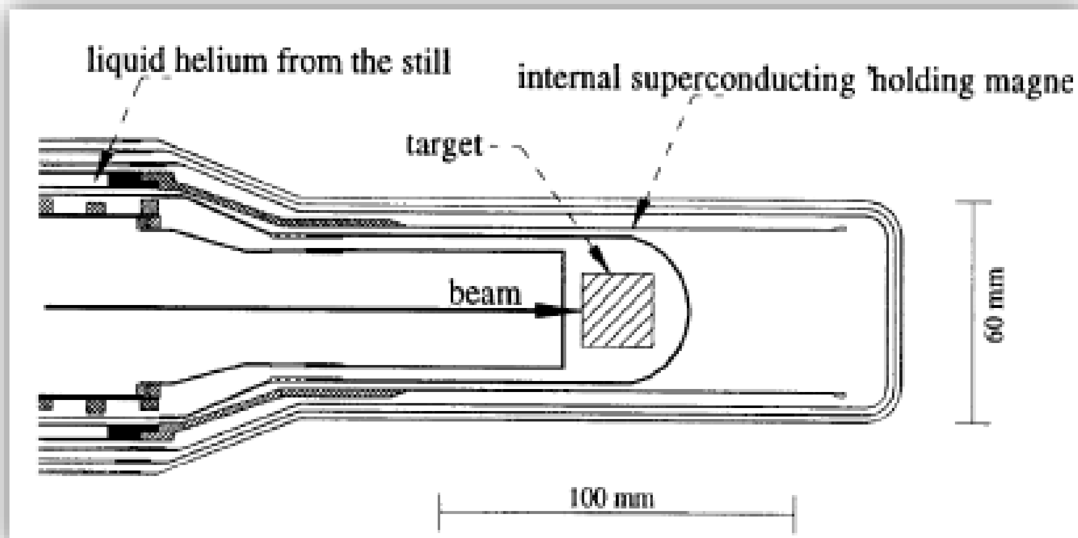


Frozen spin Butanol target

Polarization via Dynamic Nuclear Polarization (DNP)

- Butanol target is doped with paramagnetic radicals
- Electrons are polarised with a 2.5 T magnetic field at 1 K
- Electron polarisation can be transferred to the nucleons by 70 GHz microwave irradiation
- «Freeze» the spin: $^3He/^4He$ dilution cryostat with ≈ 25 mK holding coil and 0.63 T





- high relaxation time (≈ 2000 h)
- $9 \cdot 10^{22}$ polarised protons per cm^2 in the target cell
- p_T up to 90%
- Carbon target needed for background studies

Double polarisation observable G

Differential cross section for pseudo-scalar meson photoproduction using elleptically polarised photons in combination with a longitudinally polarised target:

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}_0(\theta)\left[1 - P_{lin}\mathbf{\Sigma}\cos(2(\alpha-\phi)) - P_z\left(-P_{lin}\mathbf{G}\sin(2(\alpha-\phi)) + P_{circ}\mathbf{E}\right)\right]$$

Integrating over all possible helicity states → *G*:

$$N_B\Big|_{\pm\alpha}^{\pm P_z}(\theta,\phi) = N_B(\theta)\cdot\left[1 - P_{lin}\mathbf{\Sigma_B}\cos\left(2(\alpha-\phi)\right) + d\,P_{lin}P_z\mathbf{G}\sin(2(\alpha-\phi))\right]$$

Butanol (C_4H_9OH) has unpolarised protons in carbon and oxygen:

$$N_B\Big|_{\pm\alpha}^{\pm\Lambda_z}(\theta,\phi) = \overbrace{(N_H + N_C)}^{N_B}(\theta)\cdot\left(\left(1 - \overbrace{\left(\frac{N_H\Sigma_H + N_C\Sigma_C}{N_H + N_C}\right)}^{\Sigma_B}\delta_l\cos 2(\phi-\alpha) + \overbrace{\left(\frac{N_H}{N_H+N_C}\right)}^{\text{dilution factor D}}\delta_l\Lambda_z G_H\sin 2(\phi-\alpha)\right)\right.$$

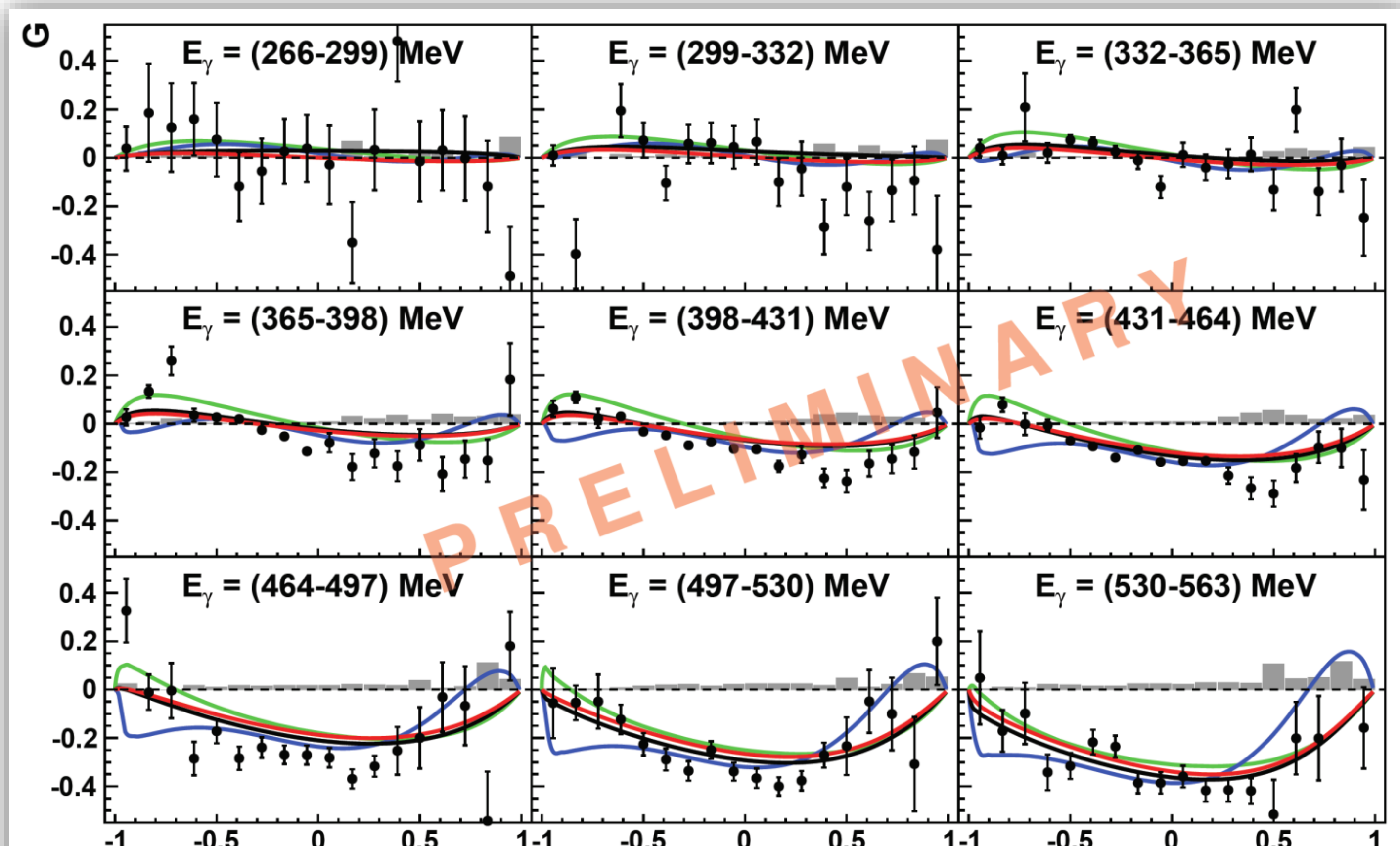
- Σ_b contains distribution for *bound protons*
- The double polarisation observable G requires longitudinally polarised target → determine the fraction of polarised protons → *dilution factor*:

$$D = \frac{N_H}{N_H+N_C} = \frac{N_H}{N_B} = \frac{N_B - s(E_\gamma)N_C}{N_B} = 1 - s(E_\gamma)\frac{N_C}{N_B} \text{ with } N_B \approx N_H + N_C$$

- *Scaling factor s* for flux and acceptance difference between carbon and butanol beamtimes

Results for G in π⁰ photoproduction

266 MeV – 563 MeV



Very good agreement with existing data!

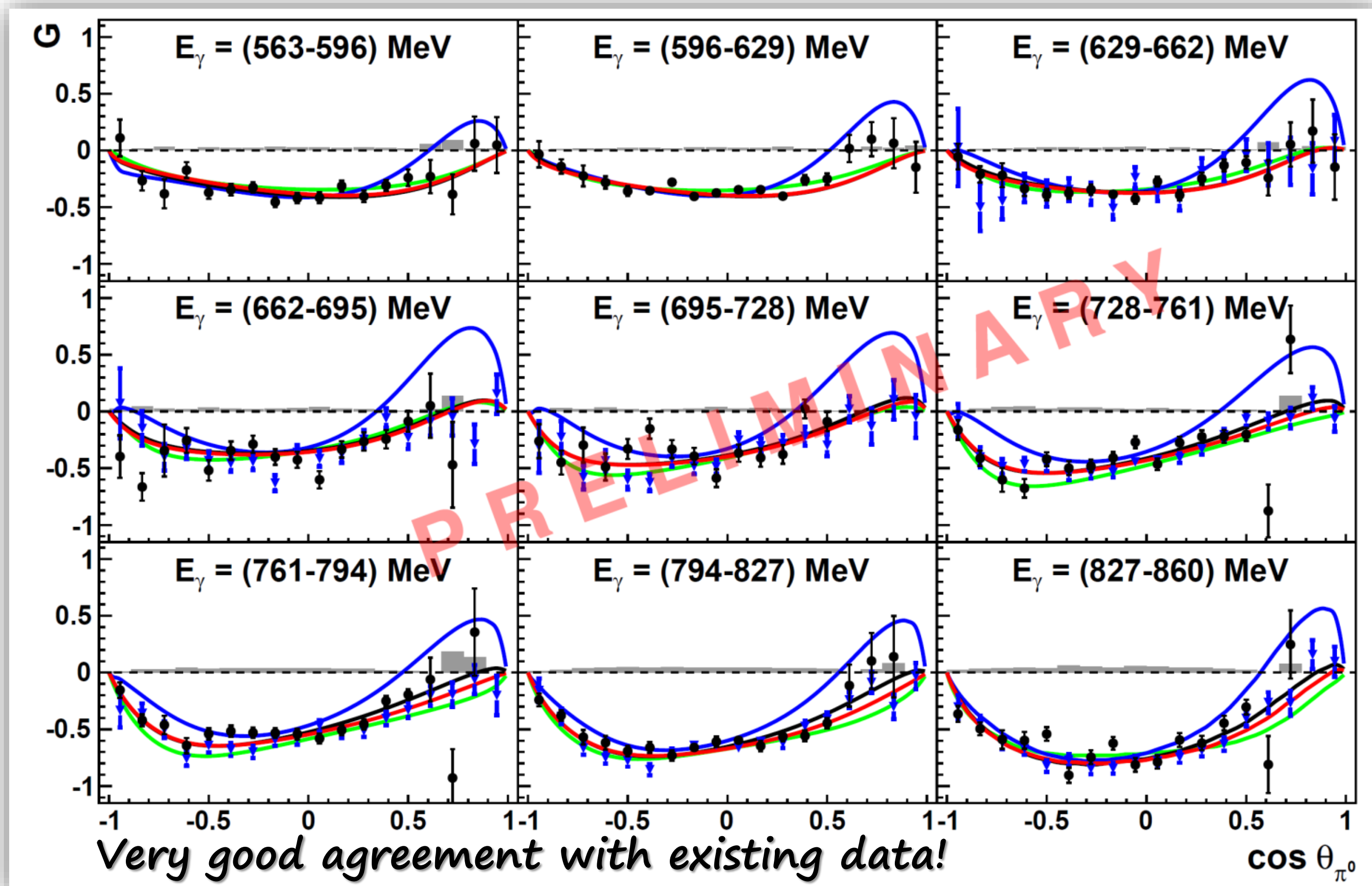
• A2 data (longitudinally polarised electrons + diamond radiator – K. Spieker)

• CBELSA/TAPS data (unpolarised electrons – A. Thiel et al., Phys. Rev. Lett. 109 (2012) 102001)

– BnGa_2014_02 (PWA fit) – BnGa_2014_01 (PWA fit) – MAID 2007 (PWA pred.) – SAID-CM12 (PWA pred)

Results for G in π^0 photoproduction

Results for G from 266 MeV to 860 MeV



• A2 data (longitudinally polarised electrons + diamond radiator – K. Spieker)

• CBELSA/TAPS data (unpolarised electrons – A. Thiel et al., Phys. Rev. Lett. 109 (2012) 102001)

– BnGa_2014_02 (PWA fit) – BnGa_2014_01 (PWA fit) – MAID 2007 (PWA pred.) – SAID-CM12 (PWA pred)

Double polarisation observable E

Differential cross section for pseudo-scalar meson photoproduction using elleptically polarised photons in combination with a longitudinally polarised target:

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}_0(\theta)\left[1 - P_{lin}\boldsymbol{\Sigma}\cos(2(\alpha-\phi)) - P_z\left(-P_{lin}\mathbf{G}\sin(2(\alpha-\phi)) + P_{circ}\mathbf{E}\right)\right]$$

Integrating over ϕ → E:

$$N_B\Big|_{\pm 1}^{\pm P_z}(\theta) = N_B(\theta)\cdot\left[1 - d\,P_{circ}P_z\mathbf{E}\right]$$

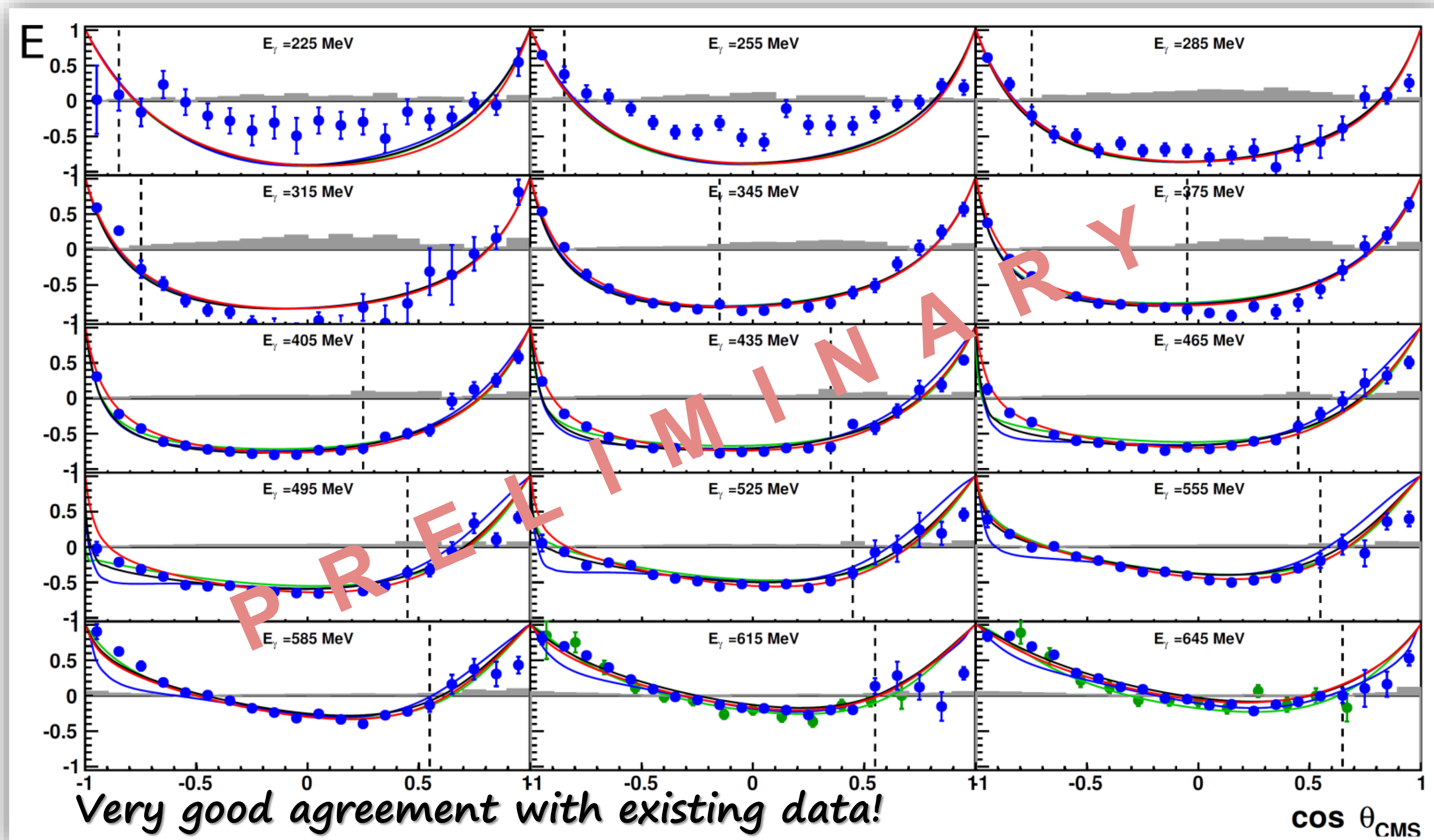
$$\mathrm{E} = \frac{\sigma^{1/2}-\sigma^{3/2}}{\sigma^{1/2}+\sigma^{3/2}} = \frac{N_B^{1/2}-N_B^{3/2}}{N_B^{1/2}+N_B^{3/2}}\cdot\frac{1}{d}\cdot\frac{1}{P_{circ}P_z}$$

d = *dilution factor* = amount of polarisable protons in the data $\quad d = 1 - s_c\cdot\frac{N_C}{N_B}$

s_c = *scaling factor* for flux and acceptance difference between carbon and butanol beamtimes

Results for E in π^0 photoproduction

225 MeV – 645 MeV



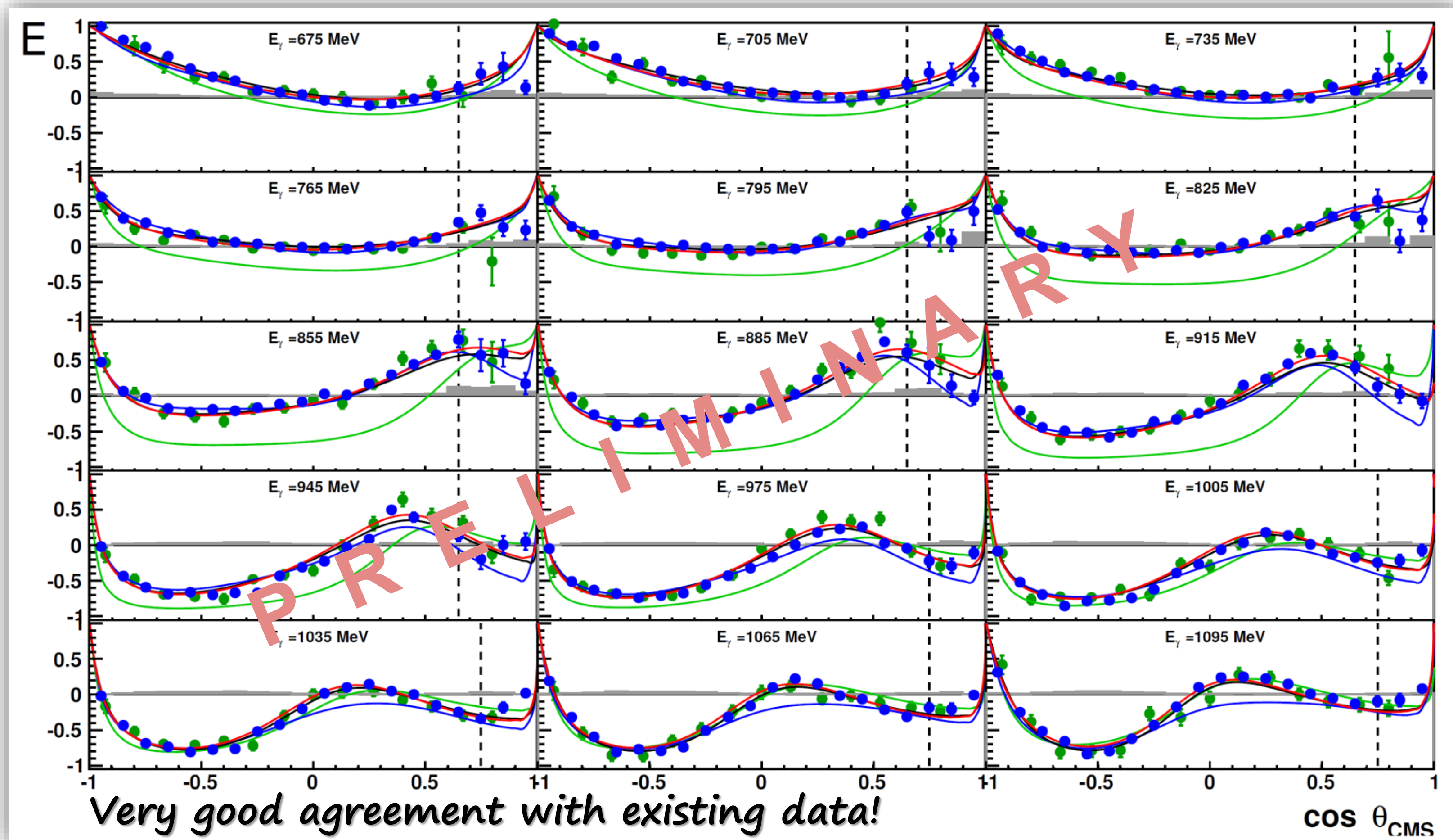
• A2 data (longitudinally polarised electrons + diamond radiator – F.N. Afzal)

• CBELSA/TAPS data (amorphous radiator– M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003)

– BnGa_2014_02 (PWA fit) – BnGa_2014_01 (PWA fit) – MAID 2007 (PWA pred.) – SAID-CM12 (PWA pred)

Results for E in π^0 photoproduction

675 MeV – 1025 MeV



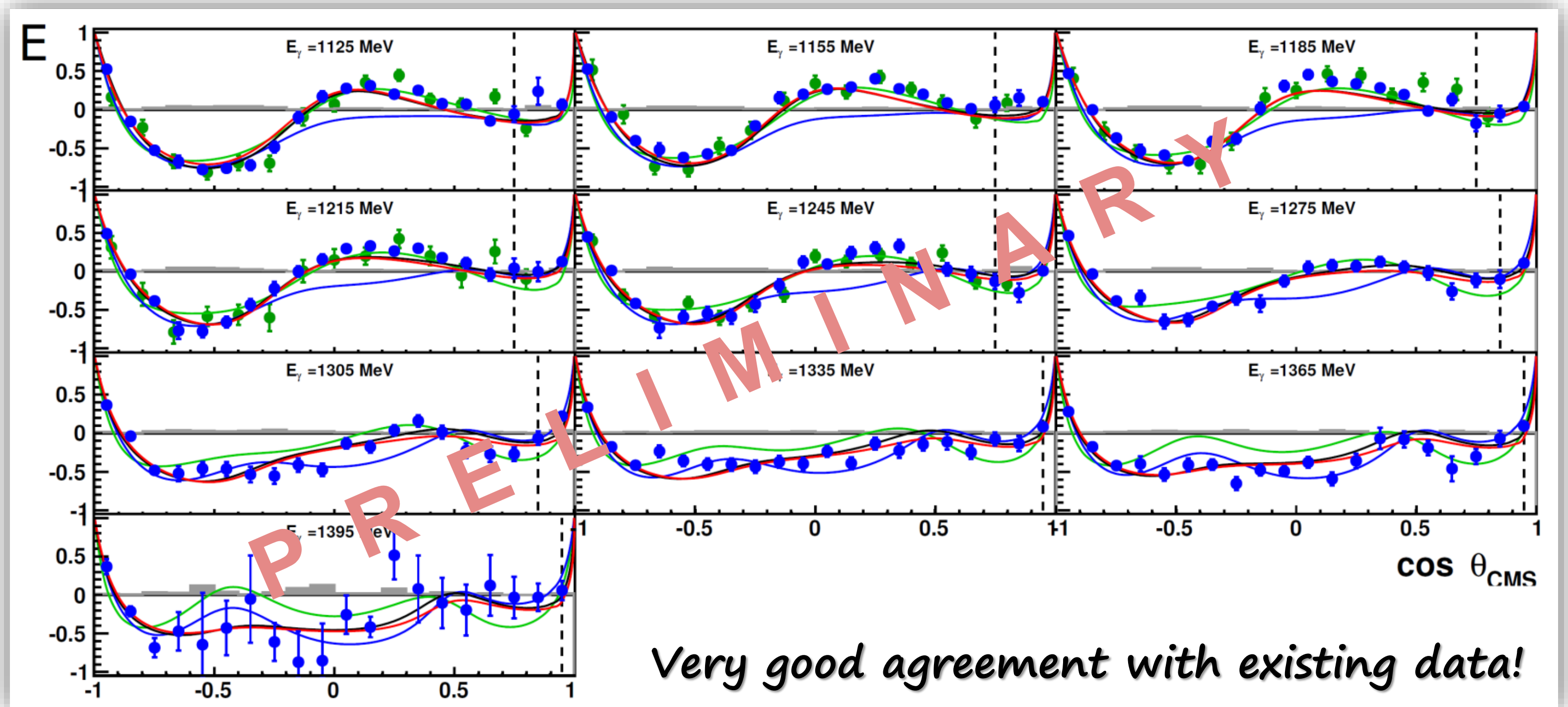
• A2 data (longitudinally polarised electrons + diamond radiator – F.N. Afzal)

• CBELSA/TAPS data (amorphous radiator– M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003)

– BnGa_2014_02 (PWA fit) – BnGa_2014_01 (PWA fit) – MAID 2007 (PWA pred.) – SAID-CM12 (PWA pred)

Results for E in π^0 photoproduction

1125 MeV – 1395 MeV



• A2 data (longitudinally polarised electrons + diamond radiator – F.N. Afzal)

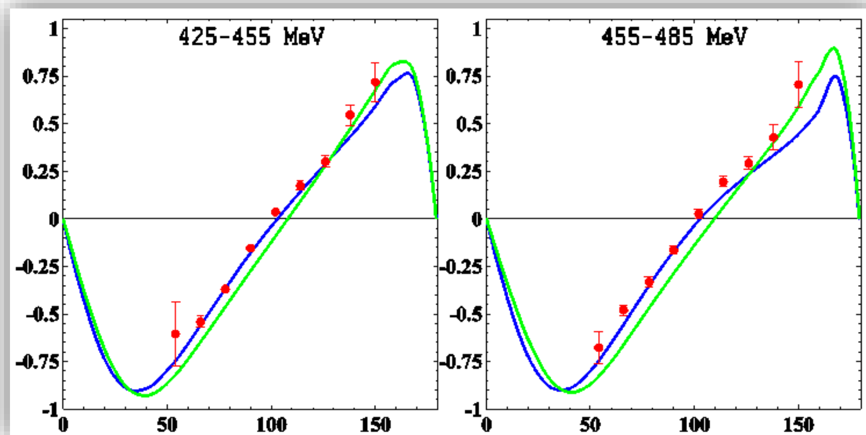
• CBELSA/TAPS data (amorphous radiator– M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003)

– BnGa_2014_02 (PWA fit) – BnGa_2014_01 (PWA fit) – MAID 2007 (PWA pred.) – SAID-CM12 (PWA pred)

Results for F in $\gamma p \rightarrow \pi^0 p$

Longitudinally polarised photon beam (425-1450 MeV) and transversely polarised target

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega_0}(\theta)[1 - P_{lin}\Sigma\cos(2\varphi) - P_x P_{lin} H\sin(2\varphi) + P_x P_{circ} F - P_y T - P_x P_{lin} P cos(2\varphi) - P_z P_{lin} G\sin(2\varphi) + P_z P_{circ} E]$$



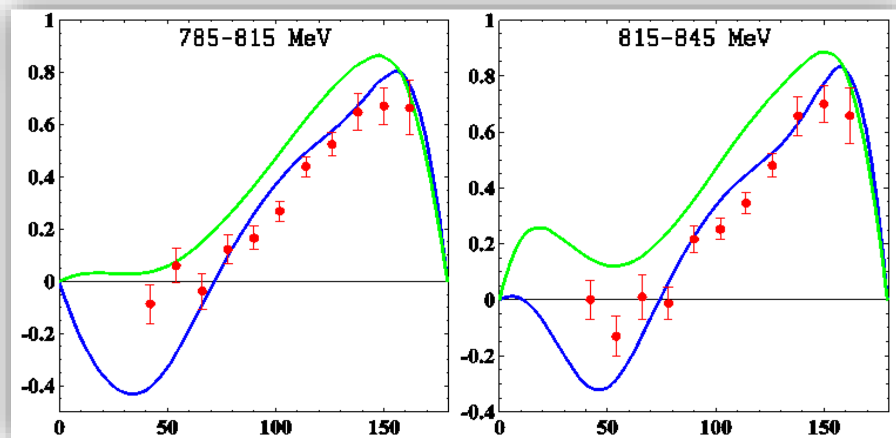
J.R.M. Annand et al., Phys. Rev. C 93, 055209 (2016)

$F \approx -\sin(\theta)\cos(\theta)\left|M_{1+}\right|^2$

Δ(1232) strongly dominates

- A2 data (V. Kashevarov)
- MAID 2007 (PWA pred.)
- SAID-CM12 (PWA pred)

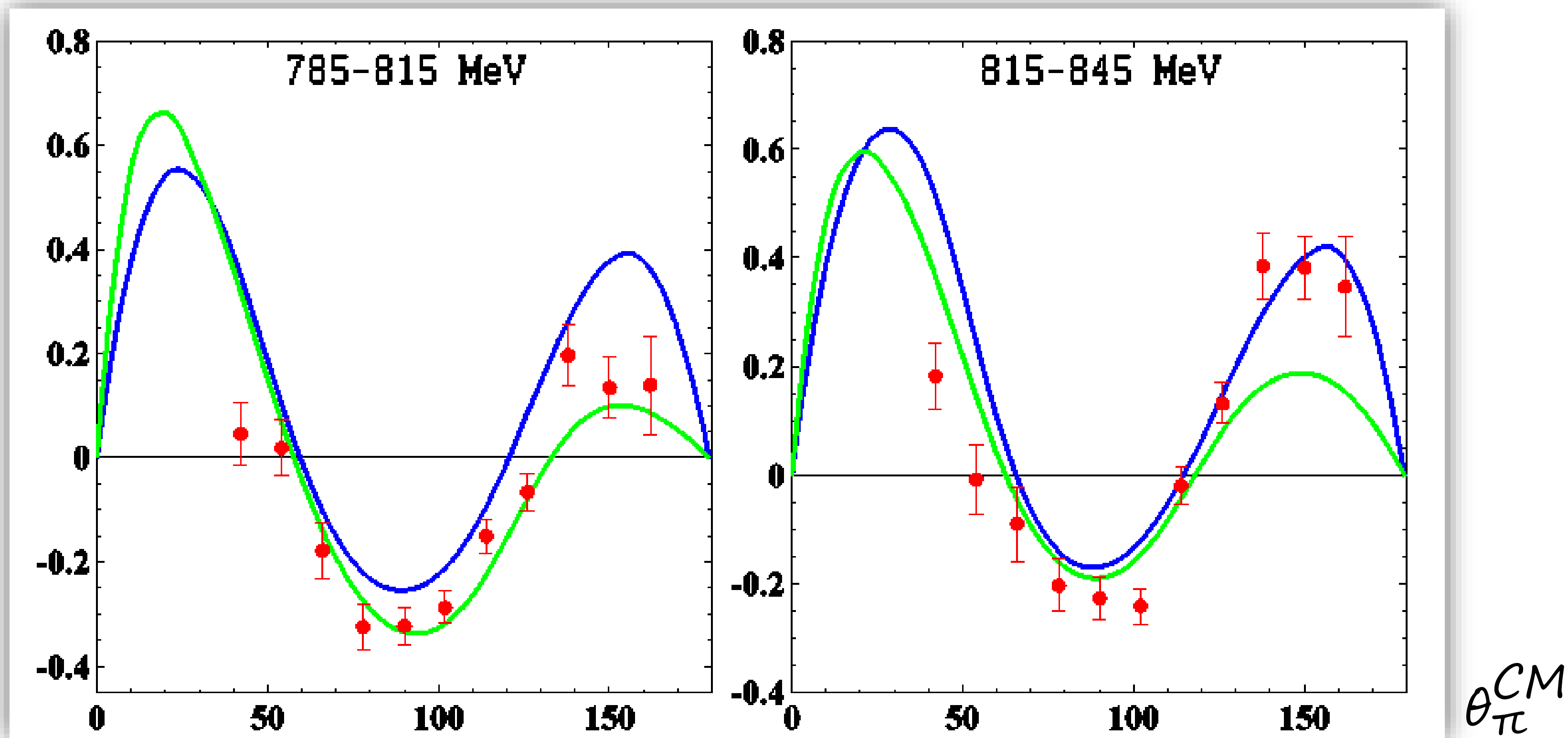
$$F \approx \sin(\theta)\cos(\theta)\cdot(\left|E_{2-}\right|^2 - 3\left|M_{2-}\right|^2 + E^*_{0+}(E_{2-} + M_{2-}) - 2E^*_{2-}M_{2-})$$



J.R.M. Annand et al., Phys. Rev. C 93, 055209 (2016)

Results for T in $\gamma p \rightarrow \pi^0 p$

$$T \approx \mathrm{Im}(E^*_{0+}\,(E_{2-} + M_{2-}) - 6E^*_{2-}M_{2-})$$



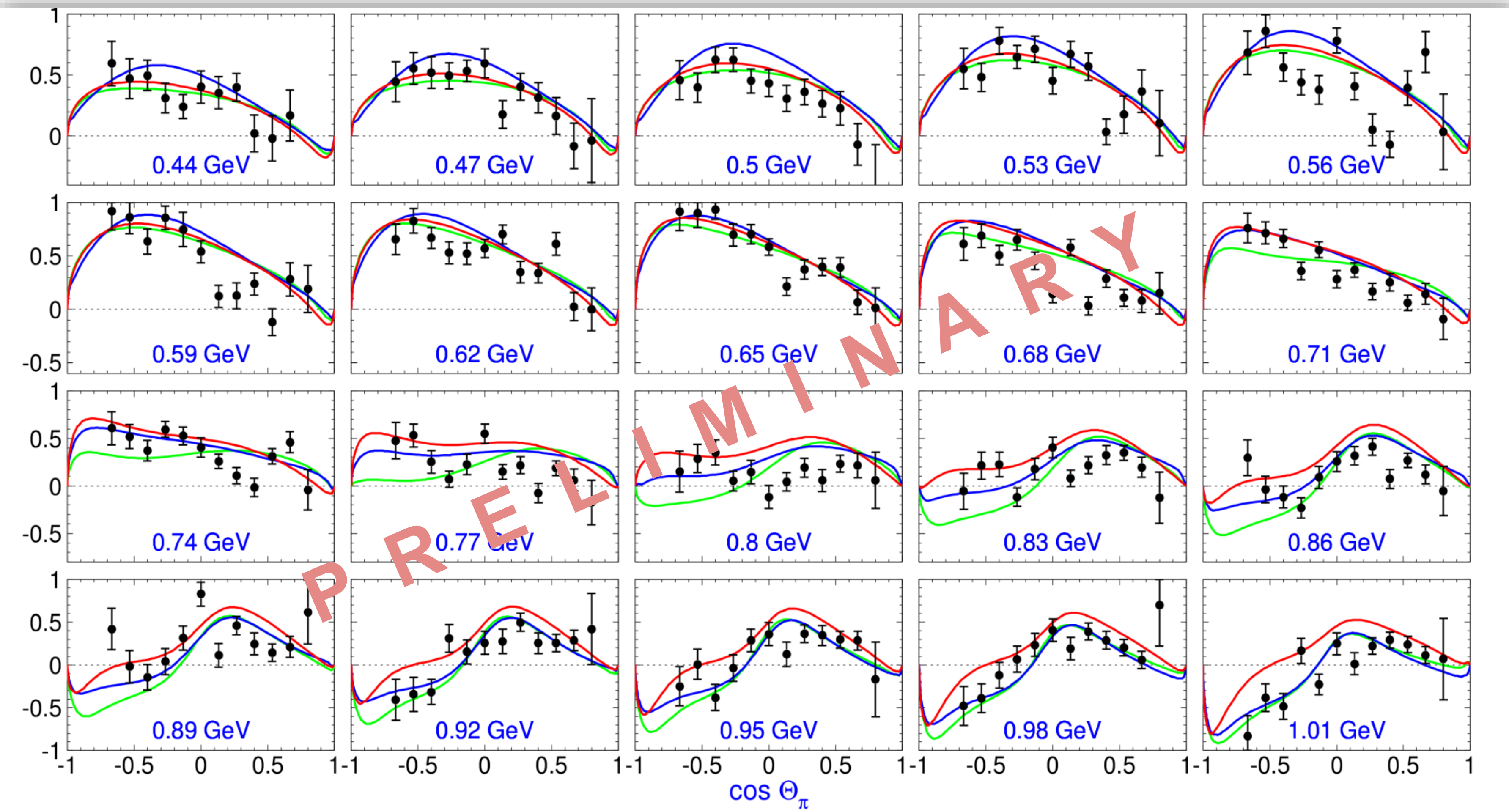
J.R.M. Annand et al., Phys. Rev. C 93, 055209 (2016)

• A2 data (V. Kashevarov)

– MAID 2007 (PWA pred.) – SAID-CM12 (PWA pred)

Strong D-wave contribution from $D_{13}(1520)$

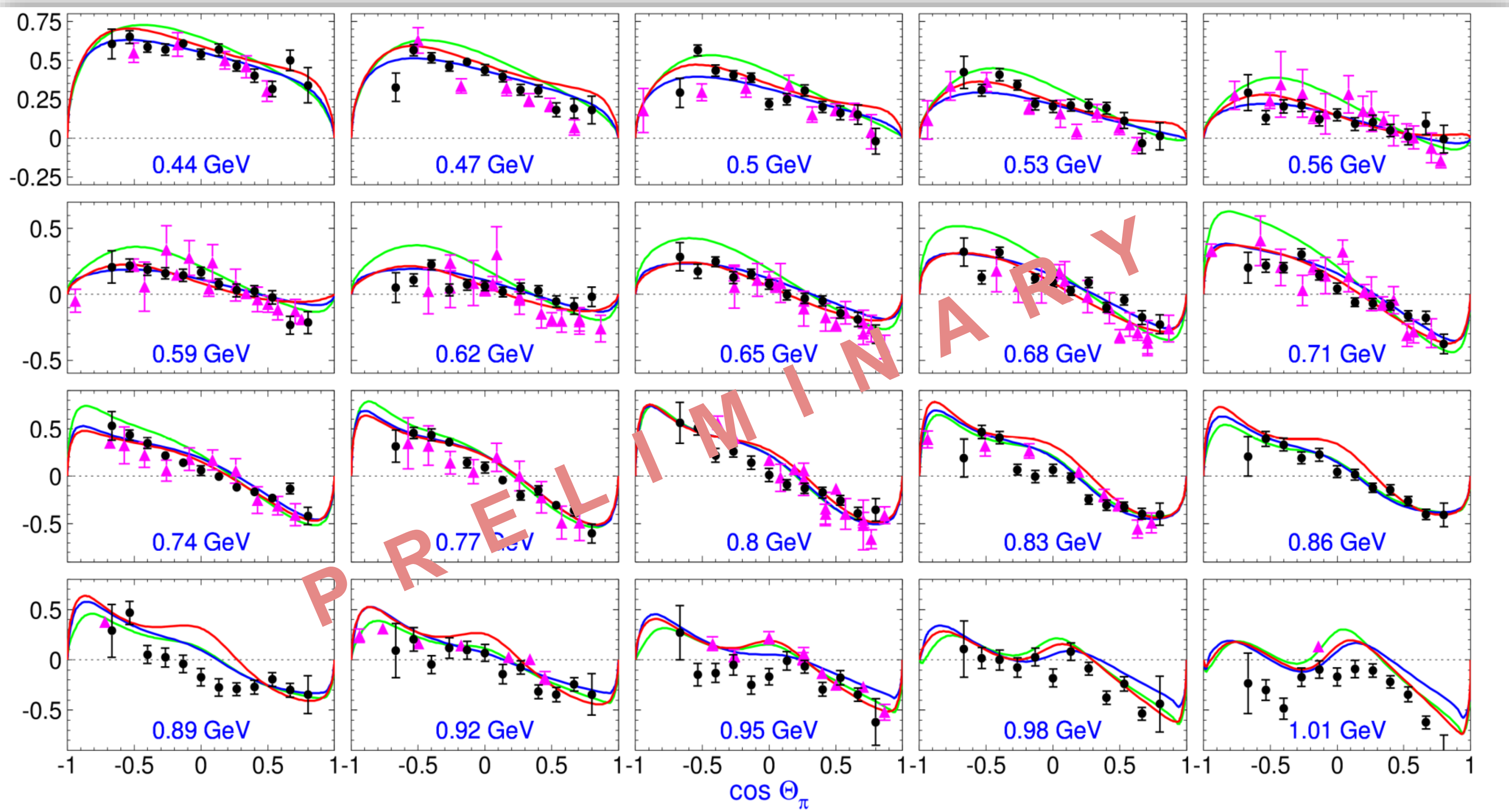
Results for F in $\gamma p \to \pi^+ n$



• A2 data (preliminary – V. Kashevarov)

– BnGa_2011_02 (PWA fit) – MAID 2007 (PWA pred.) – SAID-CM12 (PWA pred)

Results for T in $\gamma p \rightarrow \pi^+ n$



● A2 data (preliminary – V. Kashevarov)

▲ World data (before 2000)

– BnGa_2011_02 (PWA fit) – MAID 2007 (PWA pred.) – SAID-CM12 (PWA pred)

MAMBO physics goals

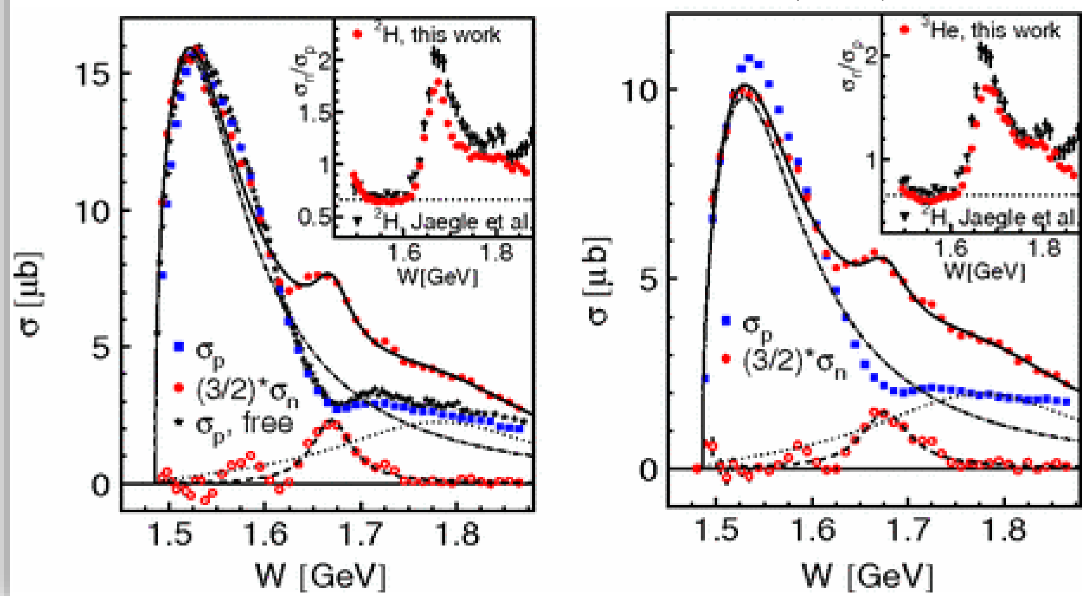
Mainly involving low cross sections and/or precision measurements

- **Precision spectroscopy** of low lying baryon states
  - $\Delta(1232)$ from $\gamma p \to \pi^0 p$ and $\pi^+ n$
  - $S_{11}(1535)$ from $\gamma p \to \eta\ p$ reaction
- Search for **«missing» baryon resonances**
- **Ambiguity free amplitude analysis** of meson photoproduction
  - Requires double polarisation measurements: $\gamma N \to N\pi(\pi)$, $N\eta(\rho, \ldots)$
- **Threshold meson production** (test of LET/ChPT)
  - Strangeness ($\gamma N \to \Lambda K$)
  - π^0 photoproduction at threshold
- Tests of **fundamental symmetries** (C, CP, CPT, …)
  - Rare η, η' decays
- **Determination of the nucleon electric and magnetic structure**
  - Nuclear Compton scattering
- **In medium properties** of hadrons and nuclear physics
  - Meson photoproduction on nuclei

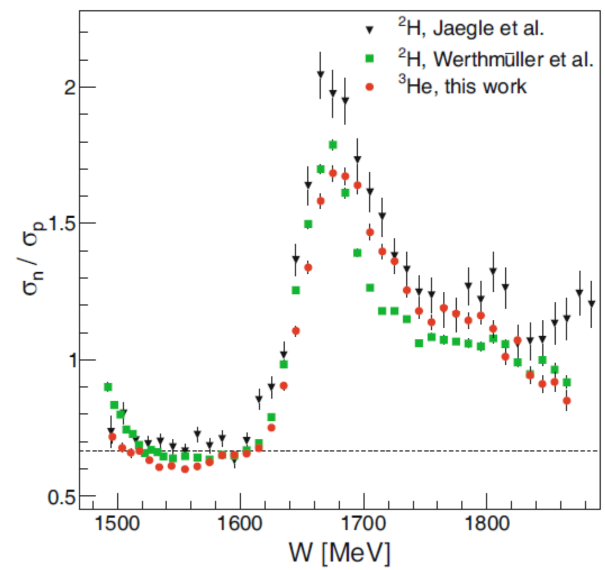
γN → Nη – helicity dependent c.s.

Interesting channel to give an insight to the **pronounced, narrow structure in η-photoproduction off the neutron** at $W = (1670 \pm 5)$ MeV, with $\Gamma = (30 \pm 5)$ MeV – **tentative N(1685) state** with unknown spin/parity

D. Werthmüller et al, PRL 111, 232001 (2013)



L. Witthauer et al, EPJA (2013) 49: 154



A2@MAMI: determine the relevant partial wave directly from experiment:

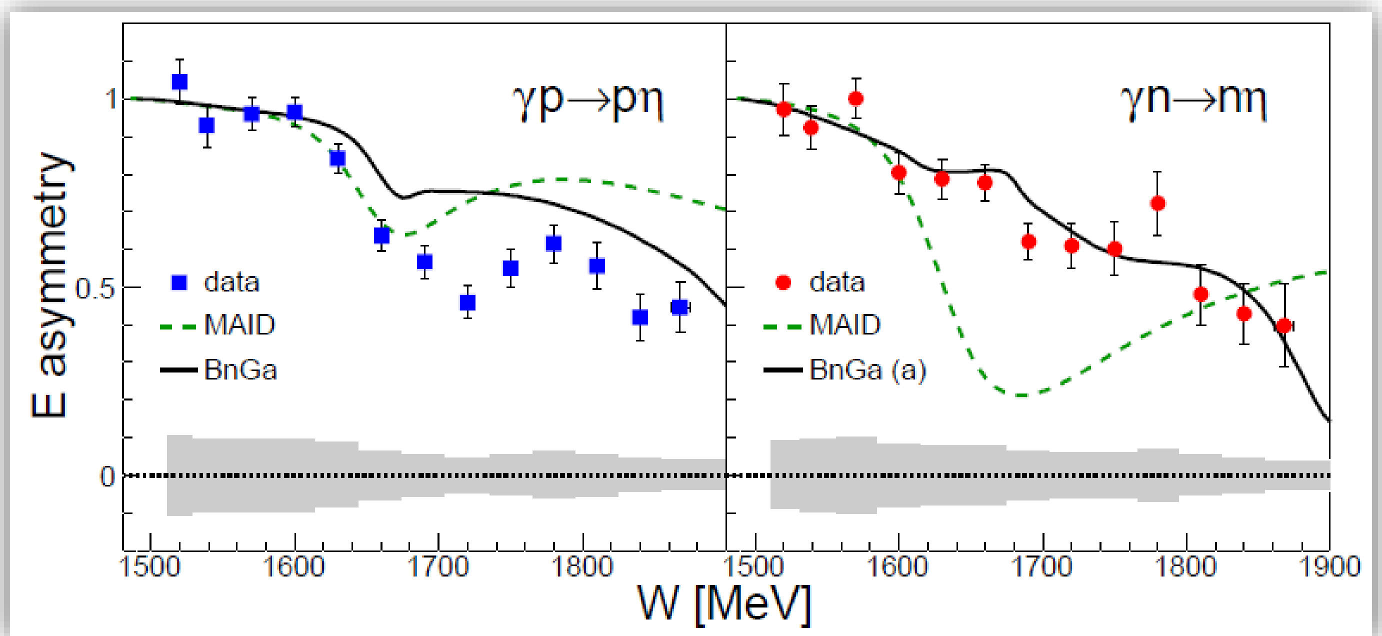
- ✓ Measurement of the **double polarisation observable E**
- ✓ **Helicity dependent differential cross section** for γp→pη and γn→nη
- ✓ **Legendre coefficients** of the $\sigma_{1/2}$ (left) and $\sigma_{3/2}$ (right) for γn→nη

$\gamma N \to N\eta$ – helicity dependent c.s.

Aim: determine the relevant partial wave directly from experimental data

Measurement of the double polarisation observable E with a longitudinally polarised deuteron (deuterated butanol) target and circularly polarised photon beam.

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



L. Witthauer et al, PRL 117, 132502 (2016)

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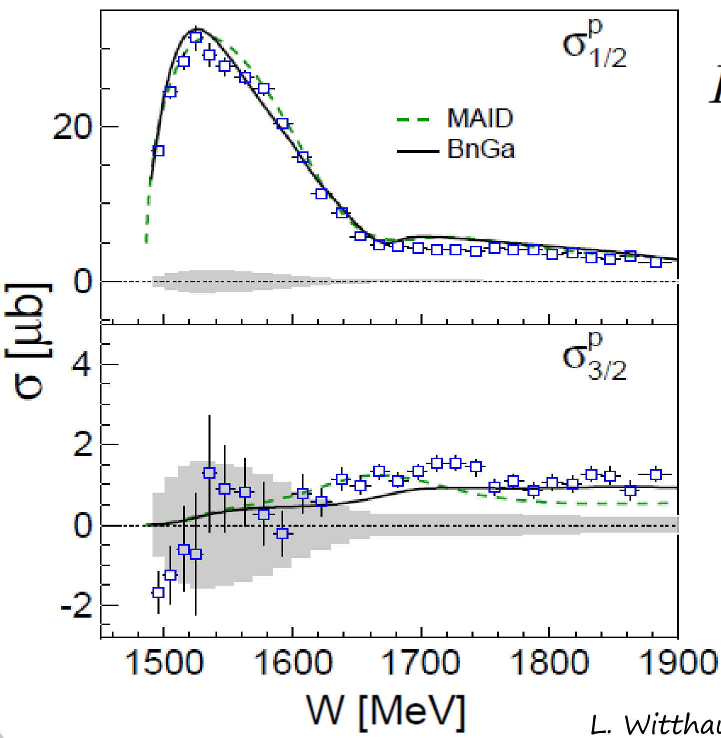
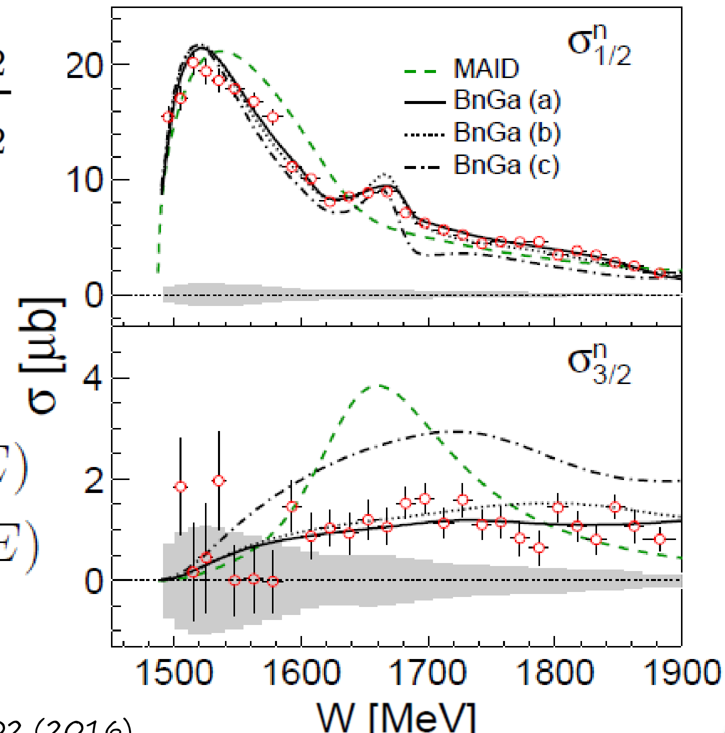


$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

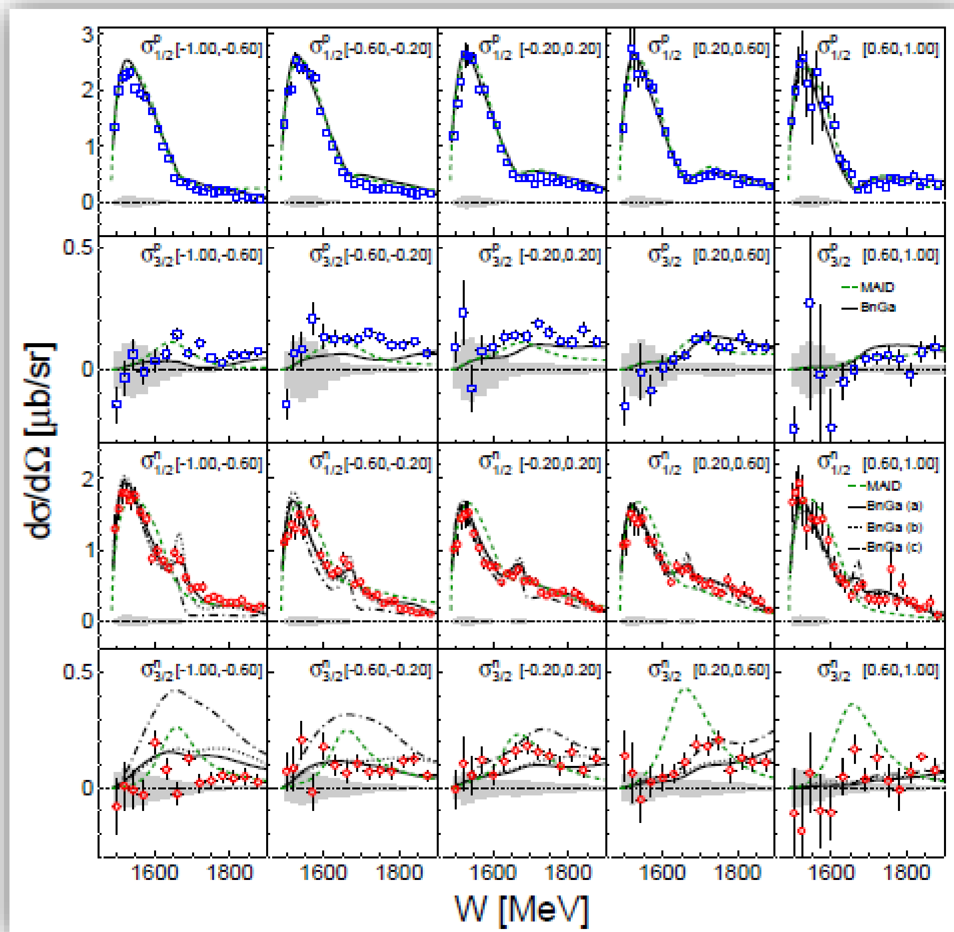
$$\sigma_{1/2} = \sigma_0(1+E)$$
$$\sigma_{3/2} = \sigma_0(1-E)$$



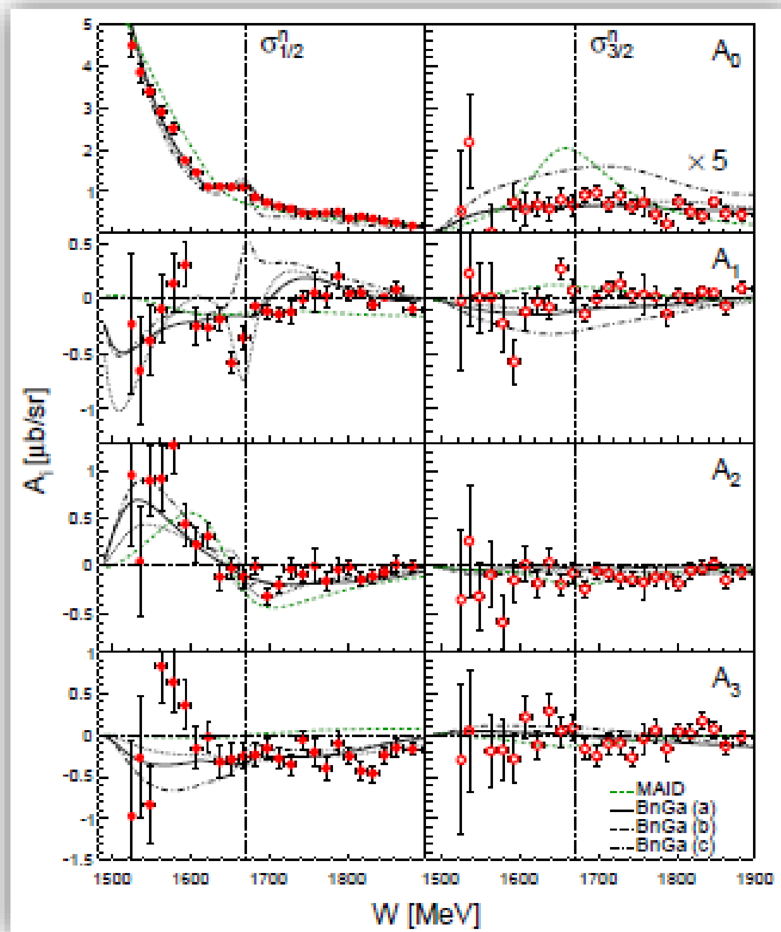
L. Witthauer et al, PRL 117, 132502 (2016)

$\gamma N \to N\eta$ – angular dependence

Helicity dependent cross section for different angular bins for $\gamma p \to p\eta$ and $\gamma n \to n\eta$



Legendre coefficients of the $\sigma_{1/2}$ (left) and $\sigma_{3/2}$ (right) for $\gamma n \to n\eta$



L. Witthauer et al, PRL 117, 132502 (2016)

A_1 coefficient: best agreement with BnGa fit with a positive interference between P_{11} and S_{11}

The GDH sum rule

- Proposed by Gerasimov – Drell – Hearn in 1966
- Fundamental connection between the ground state properties of a particle and a moment of the entire excitation spectrum
- Gives a prediction on the absorption of circularly polarised photons by longitudinally polarised nucleons/nuclei:

Strictly connected to the observable E

Anomalous magnetic moment

$$I_{GDH} = \int_{\nu_{th}}^{\infty} \frac{\sigma_p - \sigma_a}{\nu} \mathrm{d}\nu = 4\pi^2\kappa^2 \frac{e^2}{M^2} S$$

Spin

Mass

Photon energy

ν_{th} = π production threshold (nucleons)
photodisintegration threshold (nuclei)

Photon spin Baryon spin

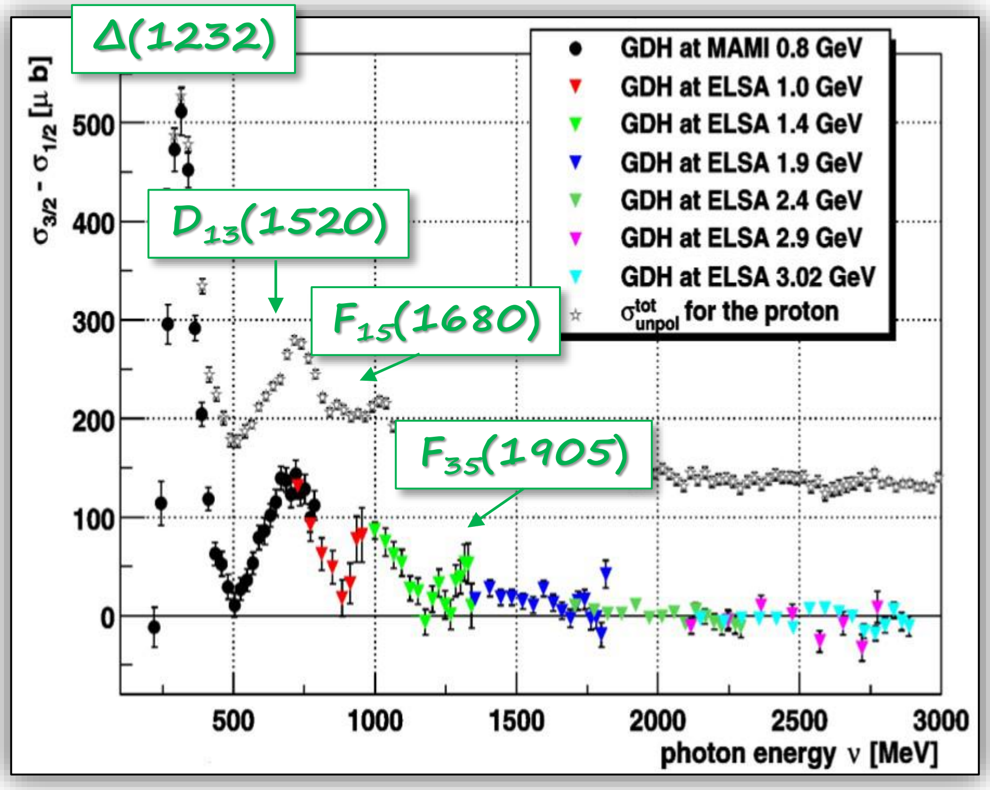
$\sigma_{1/2} = \sigma_a$ $\sigma_{3/2} = \sigma_p$

A measurement of the GDH integral constitutes a fundamental check of our knowledge of both the photon and the nucleon (nucleus)

The GDH sum rule on the proton

First experimental evaluation on the proton ($0.2 < E_\gamma < 2.9$ GeV)
[+ MAID/SAID contribution ($E_\gamma < 0.2$ GeV) + theoretical estimates ($E_\gamma < 2.9$ GeV)]

$I_{GDH}(p) = 211 \pm 5 \pm 12\ \mu b$



MAMI data: J. Ahrens *et al.*, PRL 87 (2001) 022003

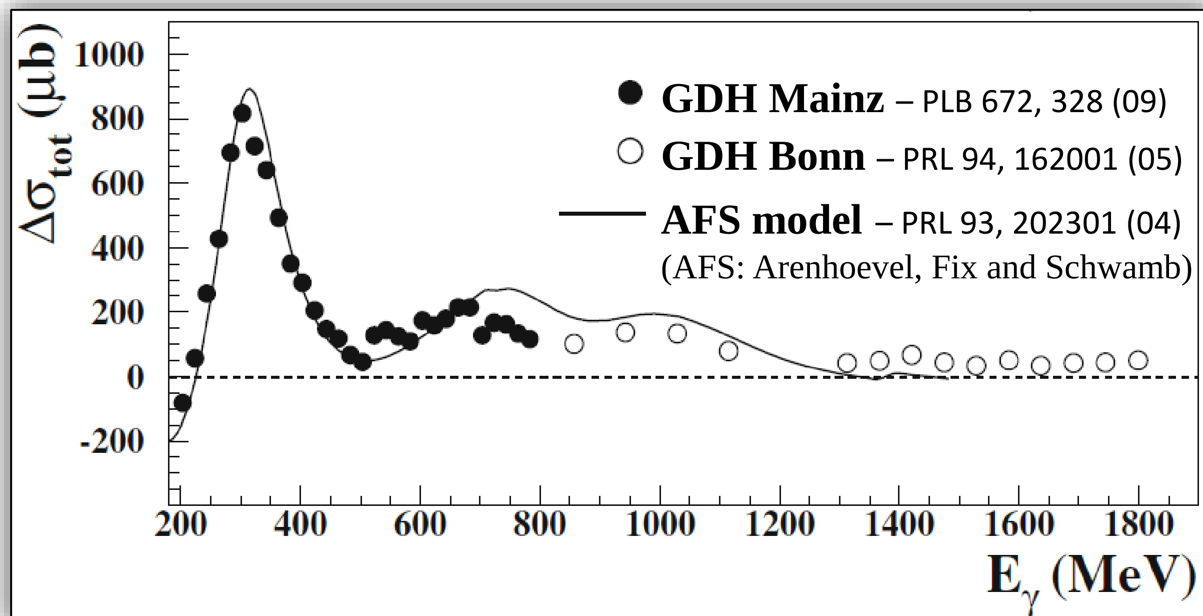
ELSA data: H. Dutz *et al.*, PRL 91 (2003) 192001, H.Dutz *et al.*, PRL 93 (2004) 032003

Agreement between the GDH sum rule value and the experimental one
BUT **no agreement with theoretical estimates** ($I_{GDH}(p) = 239\ \mu b$)

The GDH sum rule on the neutron

The measurement of I_{GDH} (n) is complicated by the lack of free neutron targets

^{2}H: System of one proton and one neutron with paired spins, in relative s states (96% probability) → $\mu \approx \mu_p + \mu_n$



Helicity dependent total inclusive c.s.

$\vec{\gamma}\vec{d} \to X$:

$\Delta\sigma = \sigma_p - \sigma_a$ (μb)

$I^d_{exp} \approx 0.93 \cdot (I^n_{GDH} + I^p_{GDH})$

Experimental evaluation of $I_{GDH}(n)$

Theoretical expectation: $\boxed{I^n_{GDH} = 233\ \mu b}$

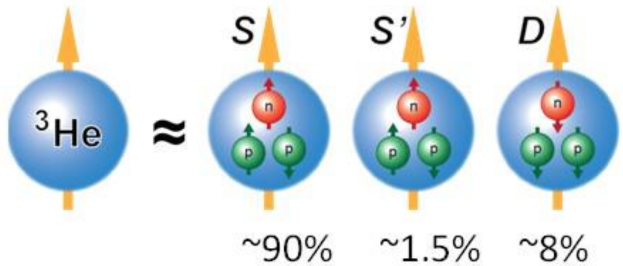
A2 contribution in the energy region: 200 MeV < E_γ < 1500 GeV

The GDH sum rule on the neutron

The measurement of I_{GDH} (n) is complicated by the lack of free neutron targets

^{3}He:

System of two protons with spins paired off and an «active» unpaired neutron, in relative *s* states (~ 90% probability)



The proton contribution is small:
$\mu \approx \mu_n$
Direct access to the free neutron contribution, usually prevented by nuclear structure effects and FSI

- For $\nu_{th} > m_\pi$ (π photoproduction threshold on free nucleon), $I_{GDH}(^3He) \sim I_{GDH}(n)$;

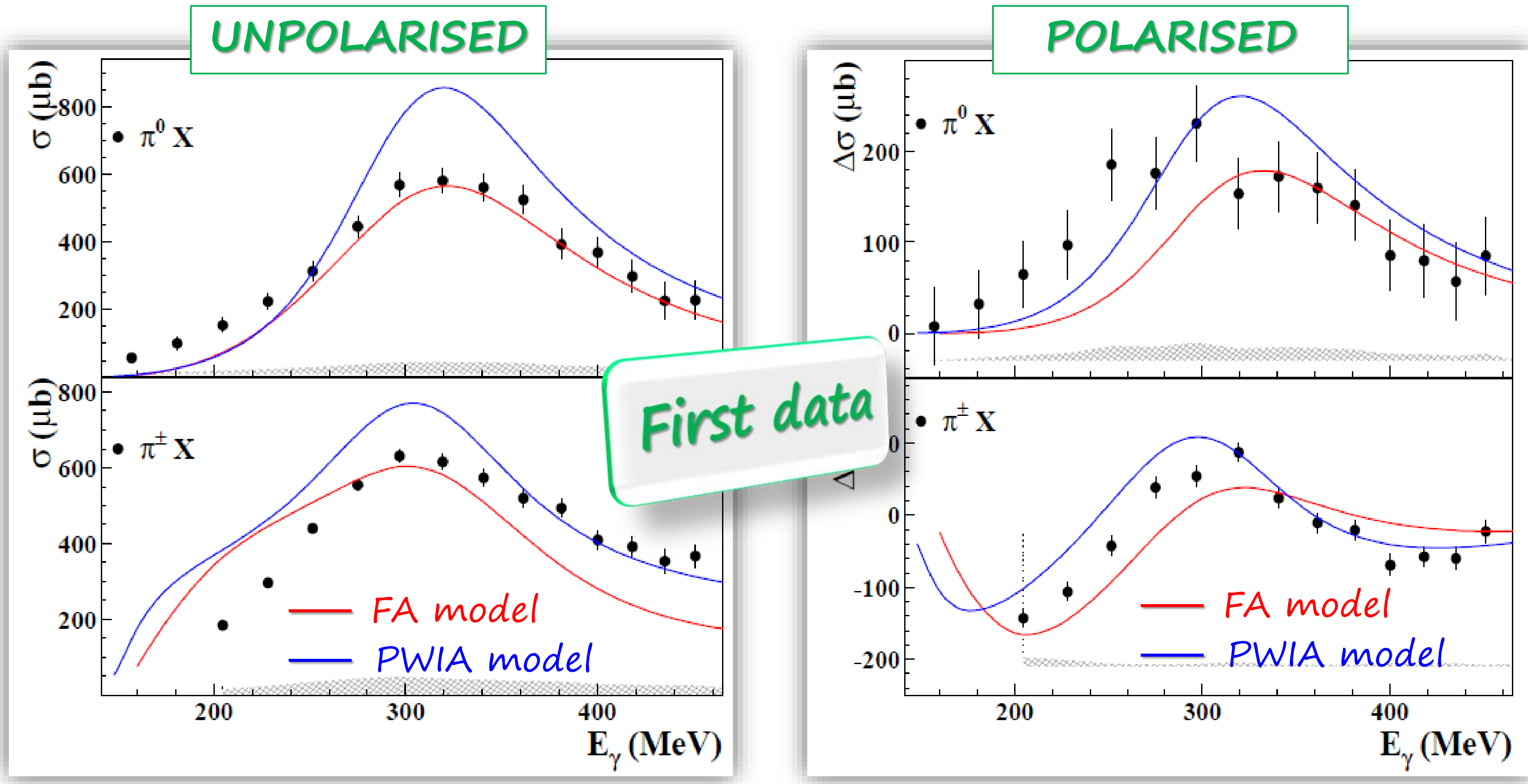
$$I^{^3He}_{GDH}\Big|_{\nu > m_\pi} \approx -2 \cdot 0.026 \cdot I^p_{GDH} + 0.87 \cdot I^n_{GDH}$$

- For 8 MeV < ν_{th} < m_π (photodisintegration region), contribution of nuclear structure effects to $I_{GDH}(^3He)$:

$$I_{GDH}(^3He) = 4\pi^2 S \left(\frac{1}{S}\mu - \frac{Q}{M}\right)^2 = \int_{\nu_{th}}^{\infty} \frac{\sigma_{3/2}(\nu) - \sigma_{1/2}(\nu)}{\nu} d\nu \approx 498 \mu b \gg I_{GDH}(n)$$

@ MAMI, from π photoproduction threshold
- test the GDH sum rule on the neutron and ^{3}He models
- both through the inclusive and the partial channel measurements.

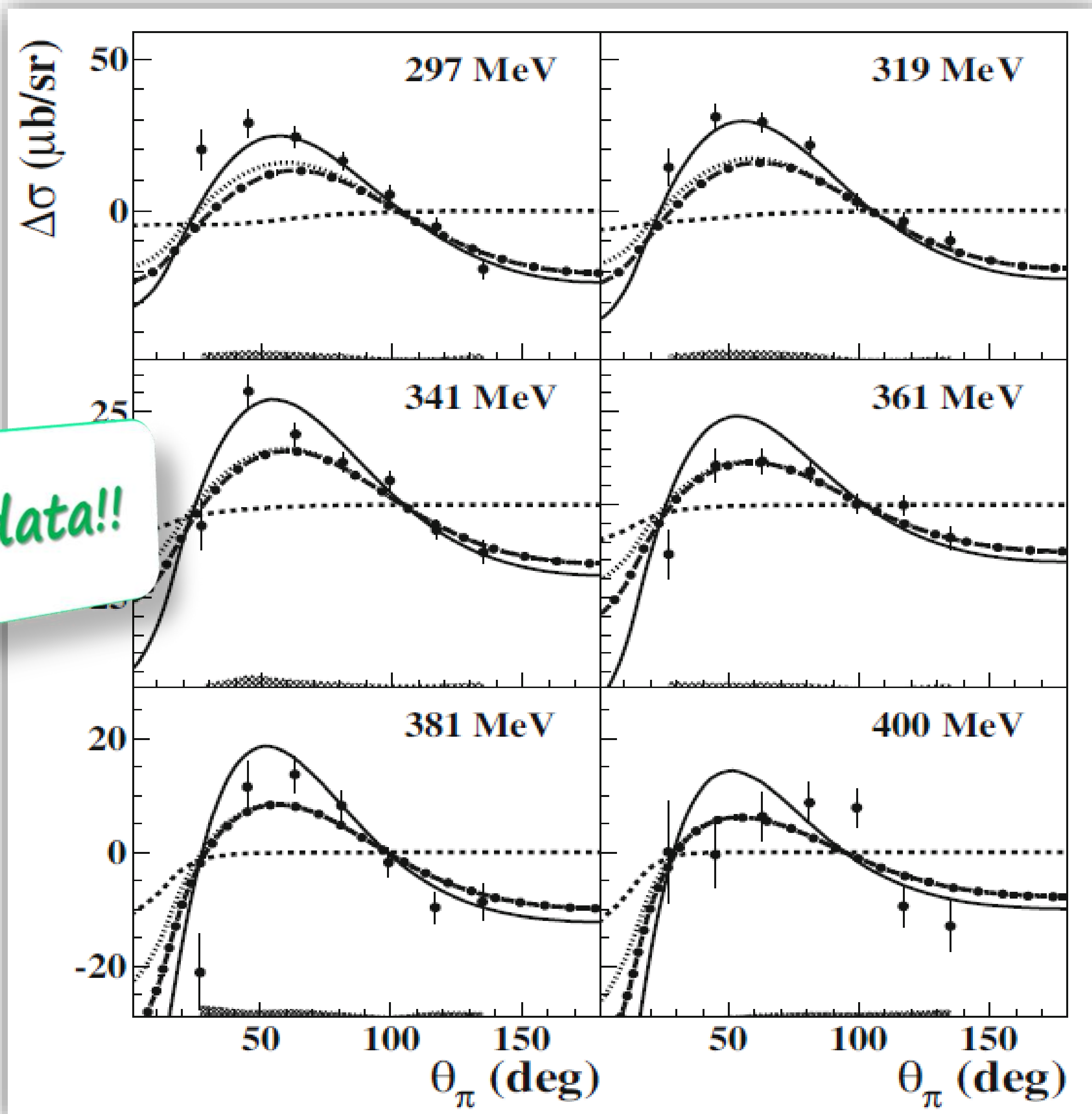
$\vec{\gamma}\,{}^3\overrightarrow{He} \rightarrow \pi X$: σ_{unpol} and $\sigma_p - \sigma_a$ (μb)



P. Aguar Bartolomé et al, PLB 723 (2013) 71-77

FA (Fix-Arenhövel) model: Fermi motion + nuclear structure effects
PWIA (Plane-Wave Impulse Approximation) model:
incoherent sum of quasi-free single nucleon contributions (from MAID multipole analysis smeared with Fermi motion)

$\vec{\gamma}\,{}^3\overrightarrow{He} \rightarrow \pi^0 X$: $(d\sigma_p/d\Omega)-(d\sigma_a/d\Omega)$ (μb/sr)



S. Costanza et al, EPJA (2014) 50: 173

First data!!

• CB data
PWIA model
FA model $\pi^0\,{}^3He$
FA model $\pi^0 ppn$
FA model $\pi^0 pd$

Spin polarisabilities

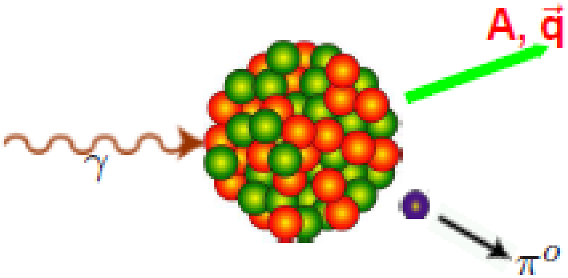
Extracting the proton spin polarisabilities would provide a useful test of low-energy QCD theorems

	K-mat.	HDPV	DPV	L_χ	HBχPT	BχPT
γ_{E1E1}	-4.8	-4.3	-3.8	-3.7	-1.1 ± 1.8 (th)	-3.3
γ_{M1M1}	3.5	2.9	2.9	2.5	2.2 ± 0.5 (st) ± 0.7 (th)	3.0
γ_{E1M2}	-1.8	-0.02	0.5	1.2	-0.4 ± 0.4 (th)	0.2
γ_{M1E2}	1.1	2.2	1.6	1.2	1.9 ± 0.4 (th)	1.1
γ_0	2.0	-0.8	-1.1	-1.2	-2.6	-1.0
γ_π	11.2	9.4	7.8	6.1	5.6	7.2

- Spin polarizabilities in units of 10^{-4} fm^4
- K-matrix: calculation from Kondratyuk *et al.*, Phys. Rev. C 64, 024005 (2001)
- HDPV, DPV: dispersion relation calculations, B.R. Holstein *et al.*, Phys. Rev. C 61, 034316 (2000) and B. Pasquini *et al.*, Phys. Rev. C 76, 015203 (2007), D. Drechsel *et al.*, Phys. Rep. 378, 99 (2003)
- L_χ: chiral lagrangian calculation, A.M. Gasparyan *et al.*, Nucl. Phys. A 866, 79 (2011)
- HBχPT and BχPT are heavy baryon and covariant, respectively, chiral perturbation theory calculations, J.A. McGovern *et al.*, Eur. Phys. J. A 49, 12 (2013), V. Lensky *et al.*, Phys. Rev. C 89, 032202 (2014)

Coherent pion photoproduction

Photon probe ✓
Interaction well understood



Momentum tranfer q
$q = P_\gamma - P_\pi$

π^0 reconstructed from its decay in 2γ

- The target nucleus is left in its ground state → **all nucleons contribute coherently** to the reaction amplitude
- The photon is uncharged: **no Coulomb scattering effects** (significant for heavy nuclei for electron scattering)
- The reaction amplitude for π^0 production on the nucleus has closely **equal probabilities on both protons and neutrons** (Δ region)
- The π^0 production cross section is **proportional to $A^2F^2_m(q)$**, where $F_m(q)$ is the matter form factor of the nucleus
- No initial state interactions
- **FSI** must be taken into account:
  - Shift in the θ_π (difference of the π momentum inside and outside the nucleus)
  - Modification of the outgoing flux (π absorption process)

The neutron skin thickness

The neutron skin thickness is usually defined as the neutron-proton rms radius difference in the atomic nucleus:

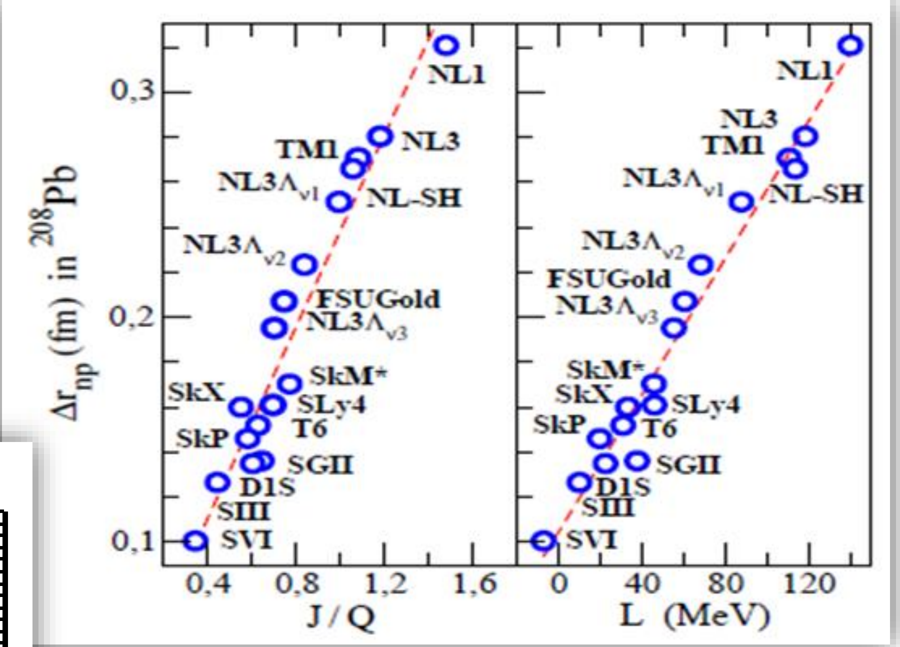
$$\Delta R_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$$

If $a_{n(p)}$ and $C_{n(p)}$ are known, the rms radius can be calculated as:

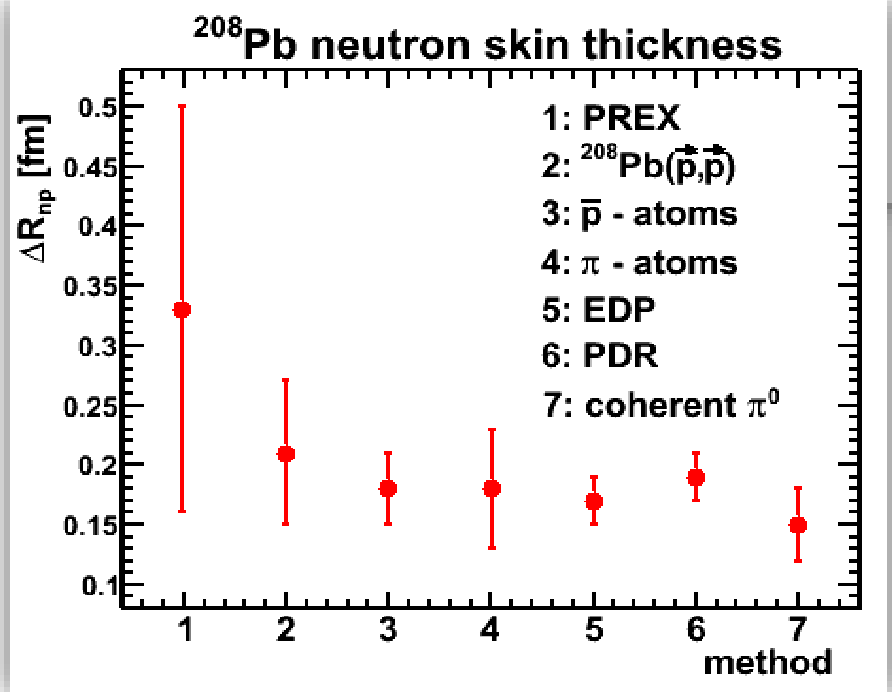
$$\langle r_n^2 \rangle = \frac{3}{5} C_n^2 \left(1 + \frac{7}{3} \pi^2 \frac{a_n^2}{C_n^2} \right)$$

M.Warda et al., Phys. Rev. C 81, 054309 (2010)

The neutron skin of ^{208}Pb



…from experiments

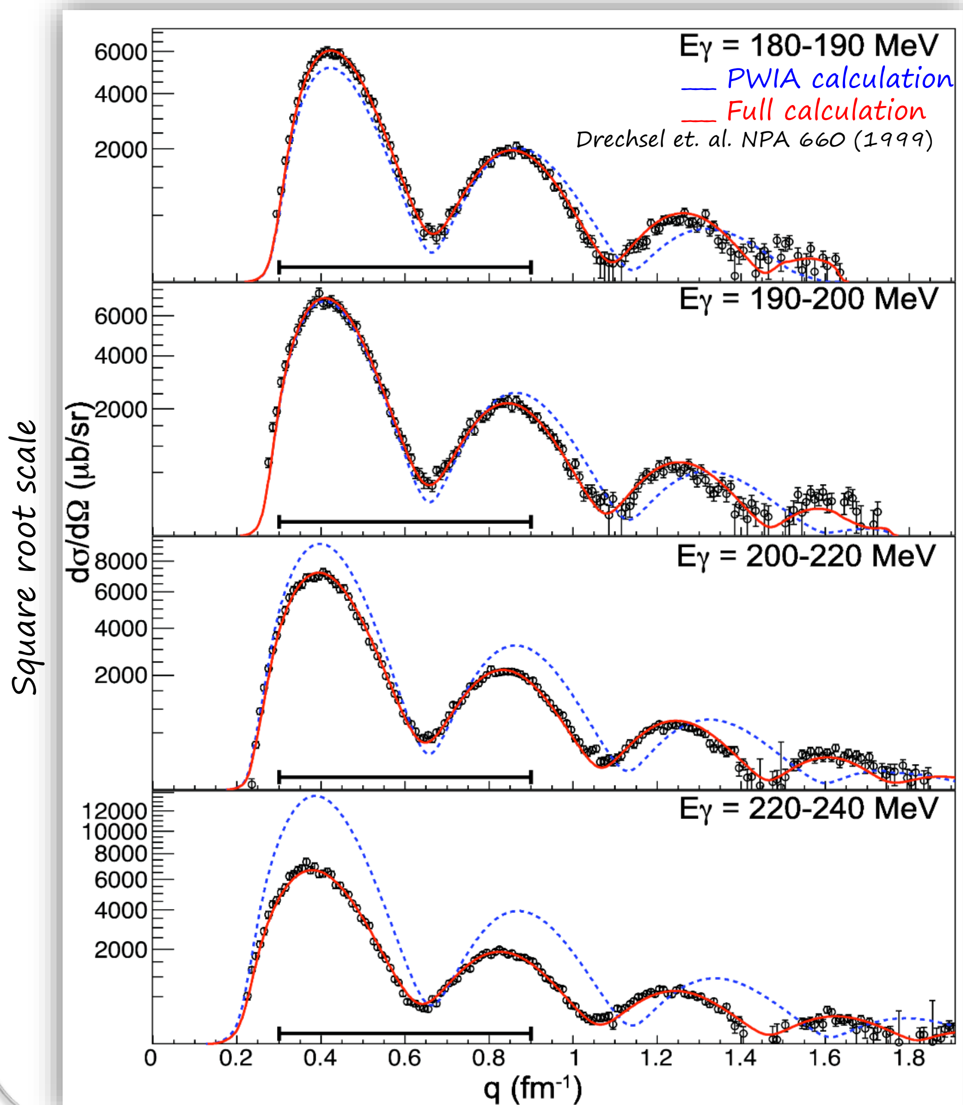


…from models

J = symmetry energy at saturation
Q = surface stiffness coefficient
L = slope of the symmetry energy coefficient

$^{208}Pb(\gamma,\pi^0)^{208}Pb$ differential cs

C.M.Tarbert, PRL 112, 242502 (2014)



Extract the best fit values a_n and C_n for the neutron distribution for each E_γ bin

(two-parameter Fermi density distribution (2pF)):

$$\rho(r) = \frac{\rho_0}{1+\exp[(r-C)/a]}$$

Fitting procedure

- Different ρ for p and n to describe the nuclear shape:
  $\rho(r) = (Z/A)\,\rho_p(r) + (N/A)\,\rho_n(r)$
- Fixed param. (PRC 76 014211 (2011)):
  - C_p=6.68
  - a_p= 0.447
- Free param. (grid of 35 pts):
  - C_n = 6.28-7.07 fm
  - a_n = 0.35-0.65 fm
  - Normalization factor
- Predictions smeared by q resolution (σ_q = 0.02-0.03 fm^{-1})
- Interpolated fit to experimental data (q = 0.3-0.9 fm^{-1})

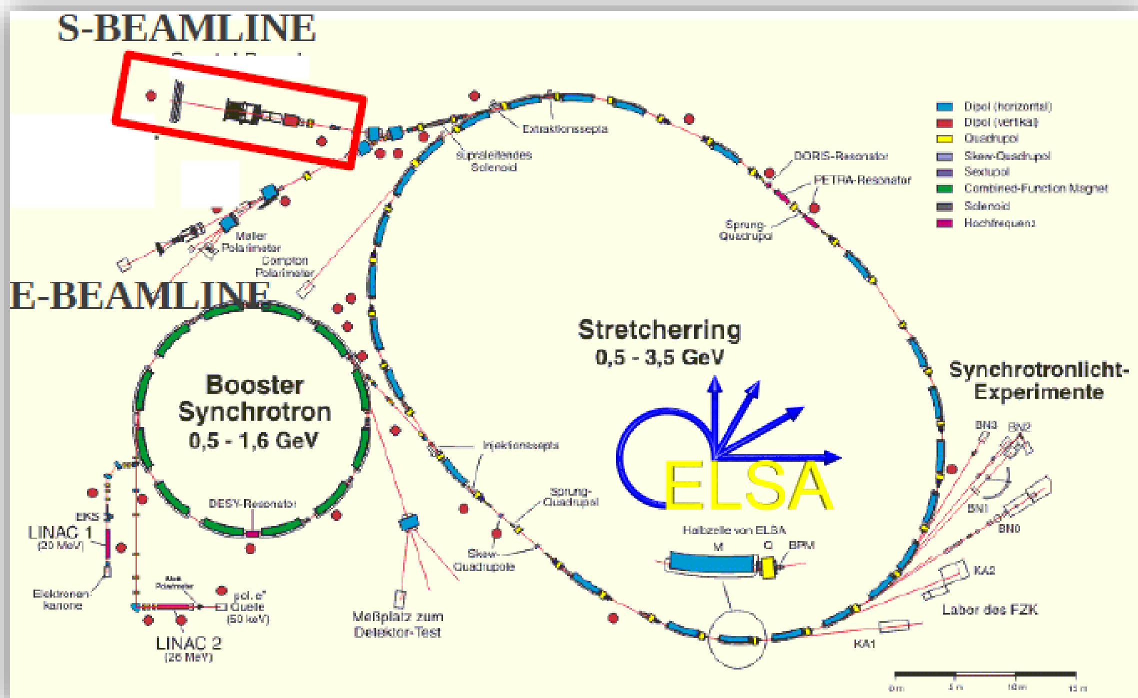
BGO-Open Dipole @ ELSA

BGO-OpenDipole Collaboration

- The collaboration has been established in 2009-2010
  - ~ 60 collaborators
  - Germany, Italy, Great Britain, Russia, Switzerland
  - LoI signed and accepted at the PAC Mainz-Bonn 2009
  - MoU signed on 2010, March 9th

- **Location:**
  S-Beamline
  ELSA Accelerator
  (Bonn)

- **Beam:**
  Polarised and tagged photon beam in the energy range 0.2 – 3.0 GeV



BGO-OD: detector overview