Recent results on doubly-polarised pion photoproduction and the GDH sum rule on the nucleon at MAMI

Susanna Costanza

Università degli Studi di Pavia - INFN Pavia

on behalf of the A2 Collaboration @ MAMI

5th International Conference on New Frontiers in Physics ICNFP2016

Kolymvari (Crete), 6 – 14 July 2016

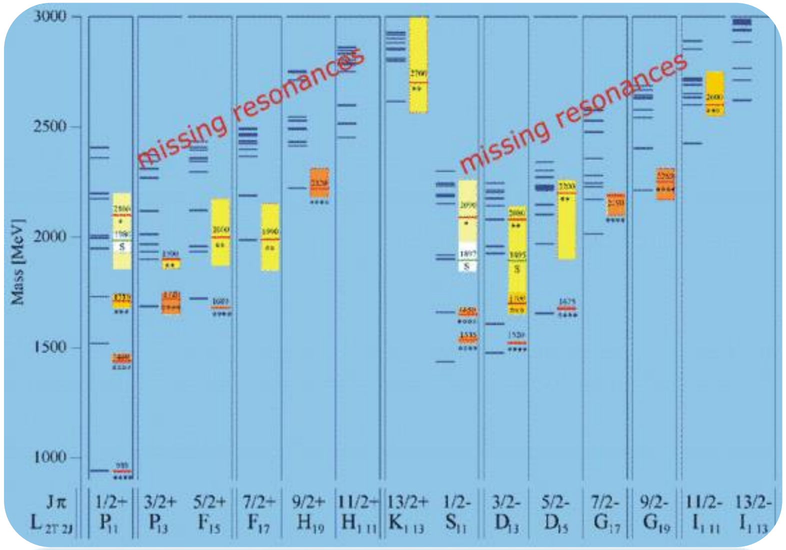
Introduction

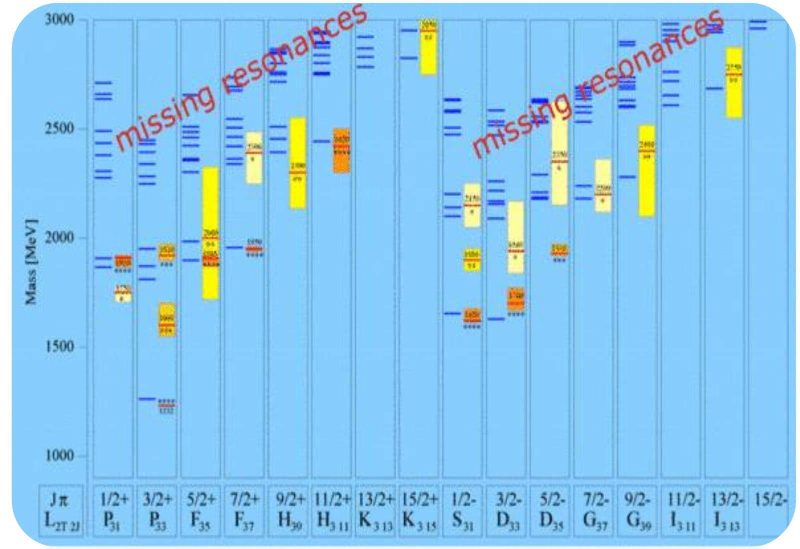
The excitation spectra of protons and neutrons allow to draw conclusions on the dynamics of the nucleons constituents

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: where is it rooted?

theory

Inappropriate internal degrees of freedom in the model

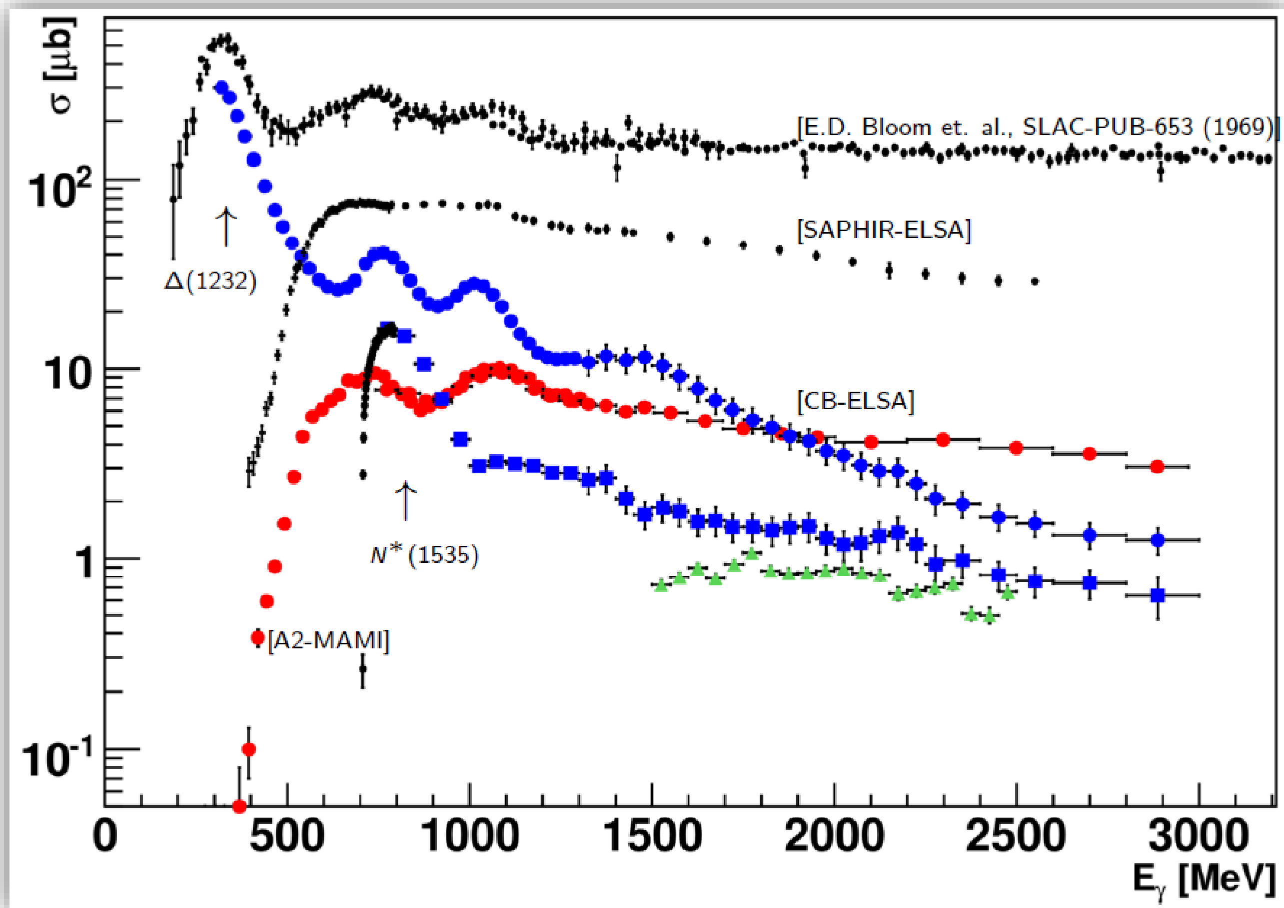
experiment

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

Experimental alternative: Photoproduction of mesons

Photoproduction reactions

The resonances are accessible via different reaction channels



$\gamma + p \rightarrow X$

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

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

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

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

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

Worldwide efforts to get high precision data (JLab, ELSA, MAMI, …)

Polarisation observables

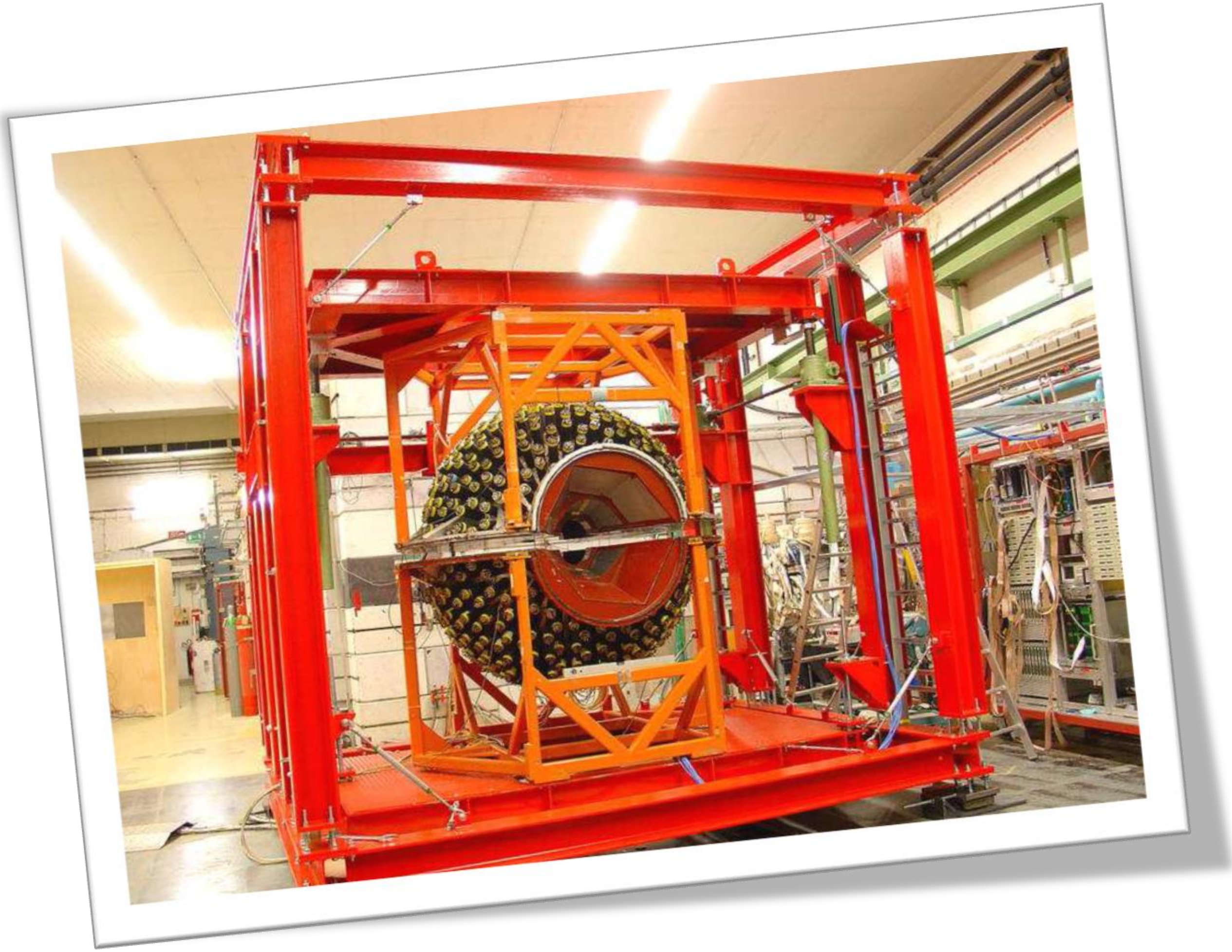
Measurable observables ↔ Multipoles ↔ Resonance parameters

- Scattering amplitude f ↔ 4 complex amplitudes (CGLN-amplitudes): $f(F_i(W, \cos\theta_{cm})$
- PWA: the F_is are linear combinations of multipoles ($E_{l\pm}(W)$, $M_{l\pm}(W)$) and Legendre polinomials $P'_{l\pm1}(\cos\theta_{cm})$
- From 4 complex amplitudes it is possible to construct 16 bilinear products → 16 polarisation observables

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

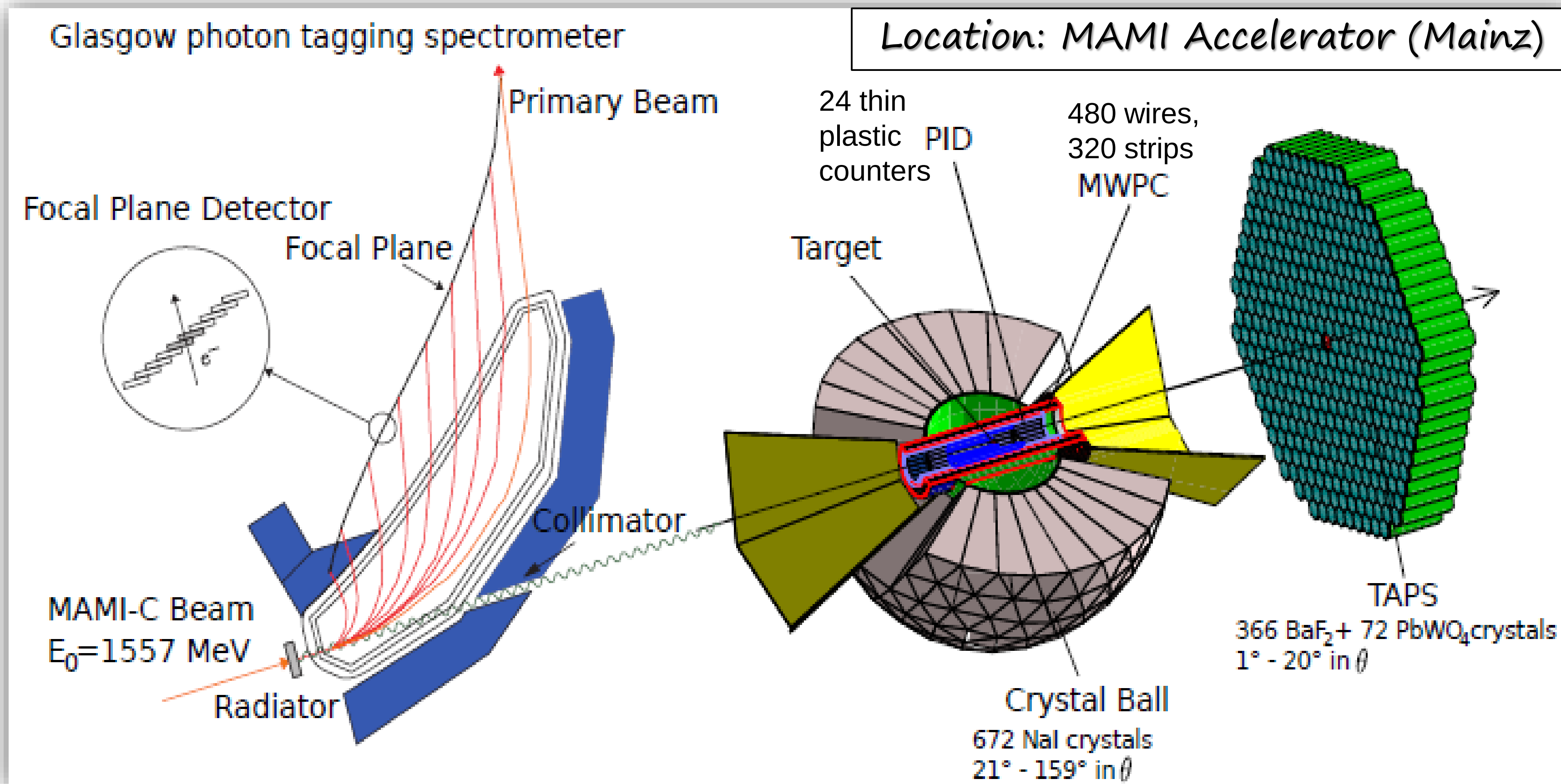
1 unpolarised, 3 single polarised, 12 double polarised measurements

The measurement of 7 (8) (**properly chosen**) observables is necessary to **unambiguously** (in a model independent way) determine the scattering amplitudes (**"complete analysis"**)



A2 @ MAMI

A2@MAMI: detector overview



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*

Physics at A2@MAMI

- Double polarisation observables G and E
  - Determination of G and E
  - Results
- The GDH sum rule
  - Physics motivation
  - Results
    - $\vec{\gamma}\vec{p}, \vec{\gamma}\vec{d}, \vec{\gamma}\,\overrightarrow{^3He} \rightarrow X, n\pi^+, p\pi^0$

Double polarisation observables E and G

First experimental attempt to measure E and G 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

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

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

Integrating over ϕ → E:

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

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

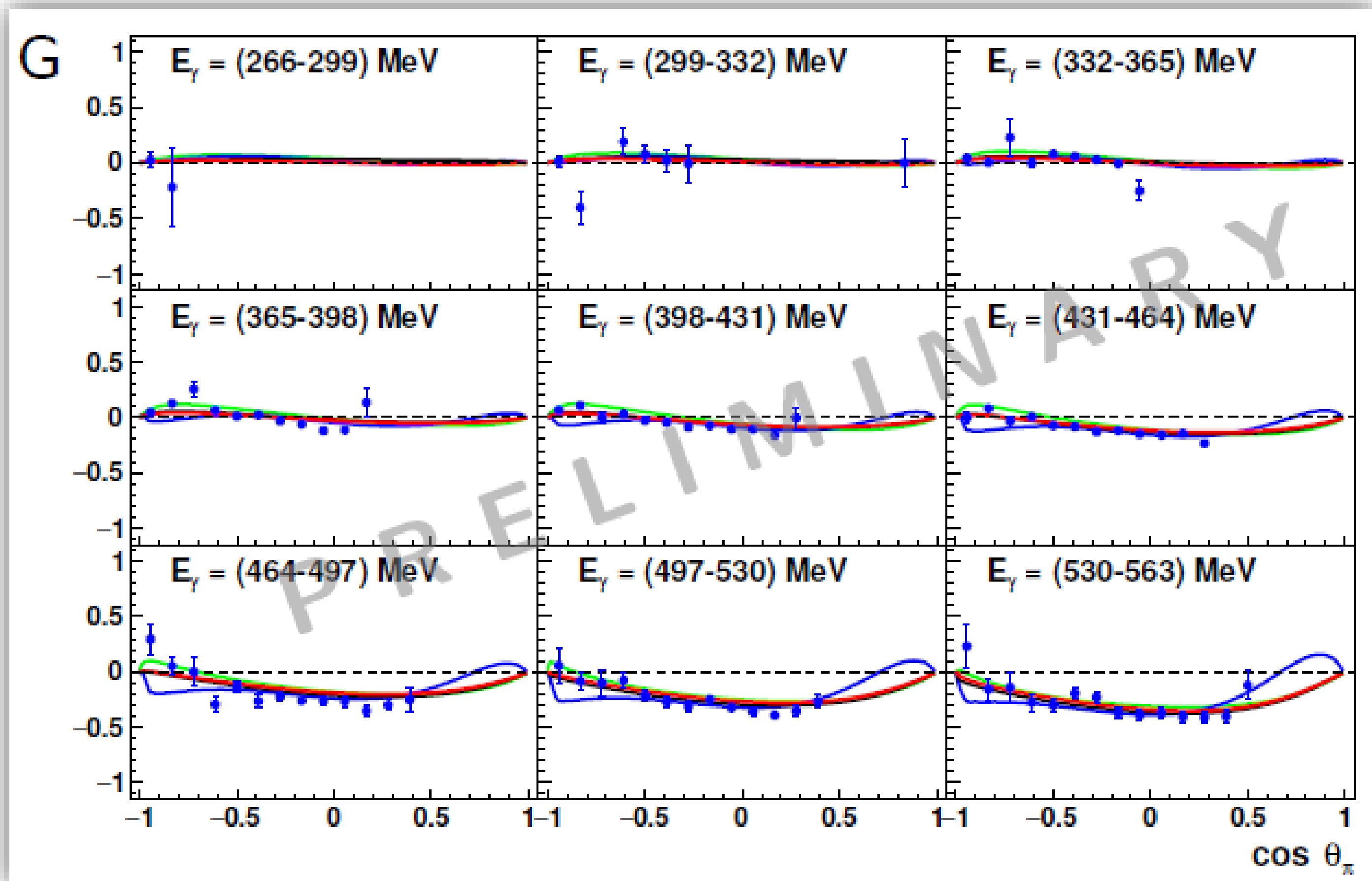
s_c = scaling factor for flux and acceptance difference between carbon and butanol beamtimes

Integrating over all possible helicity states → G:

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

Double polarisation observable G

266 MeV – 563 MeV



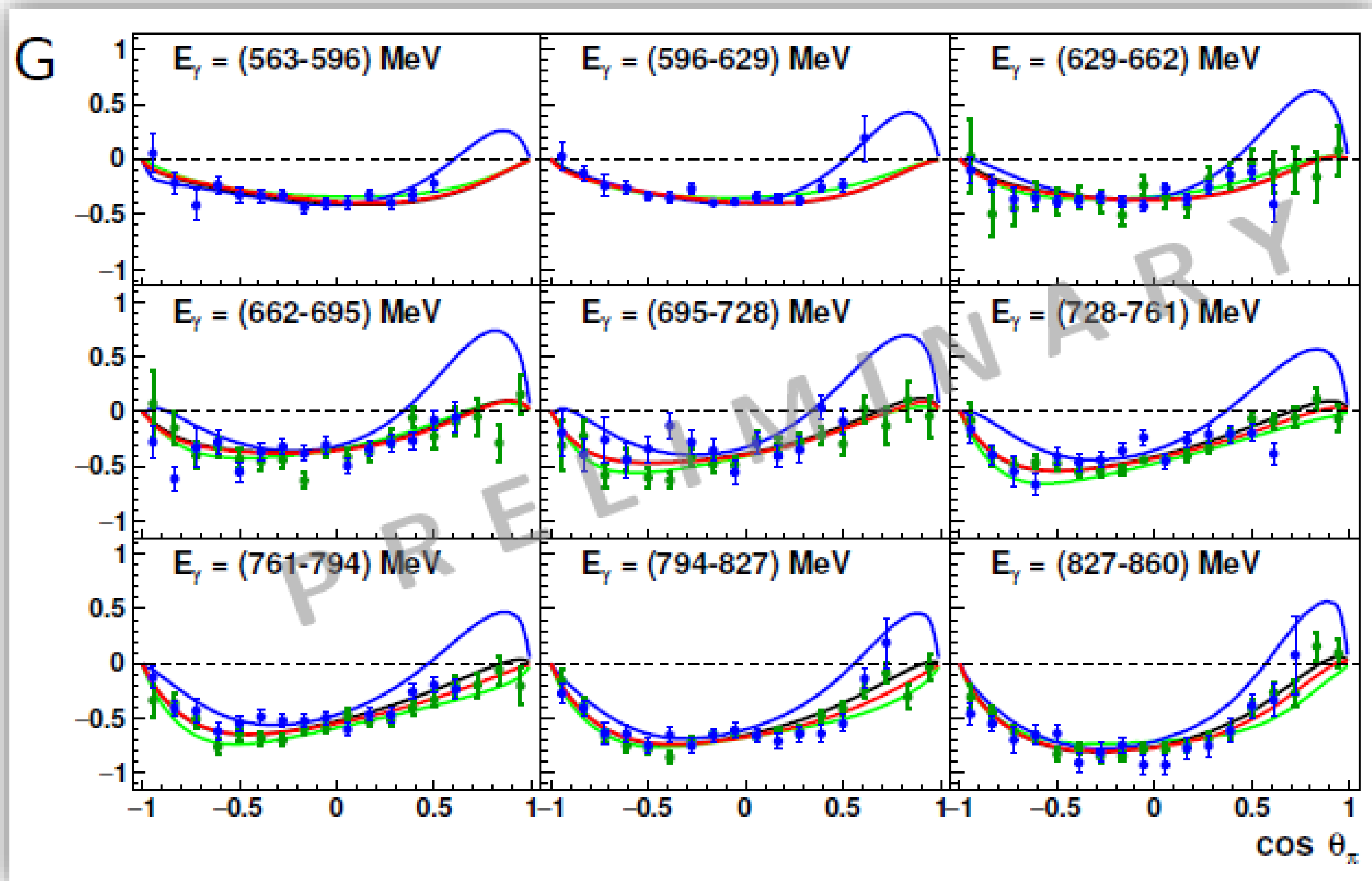
• A2 data (longitudinally polarised electrons + diamond radiator – K. Spieker)

• 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 G

563 MeV – 860 MeV



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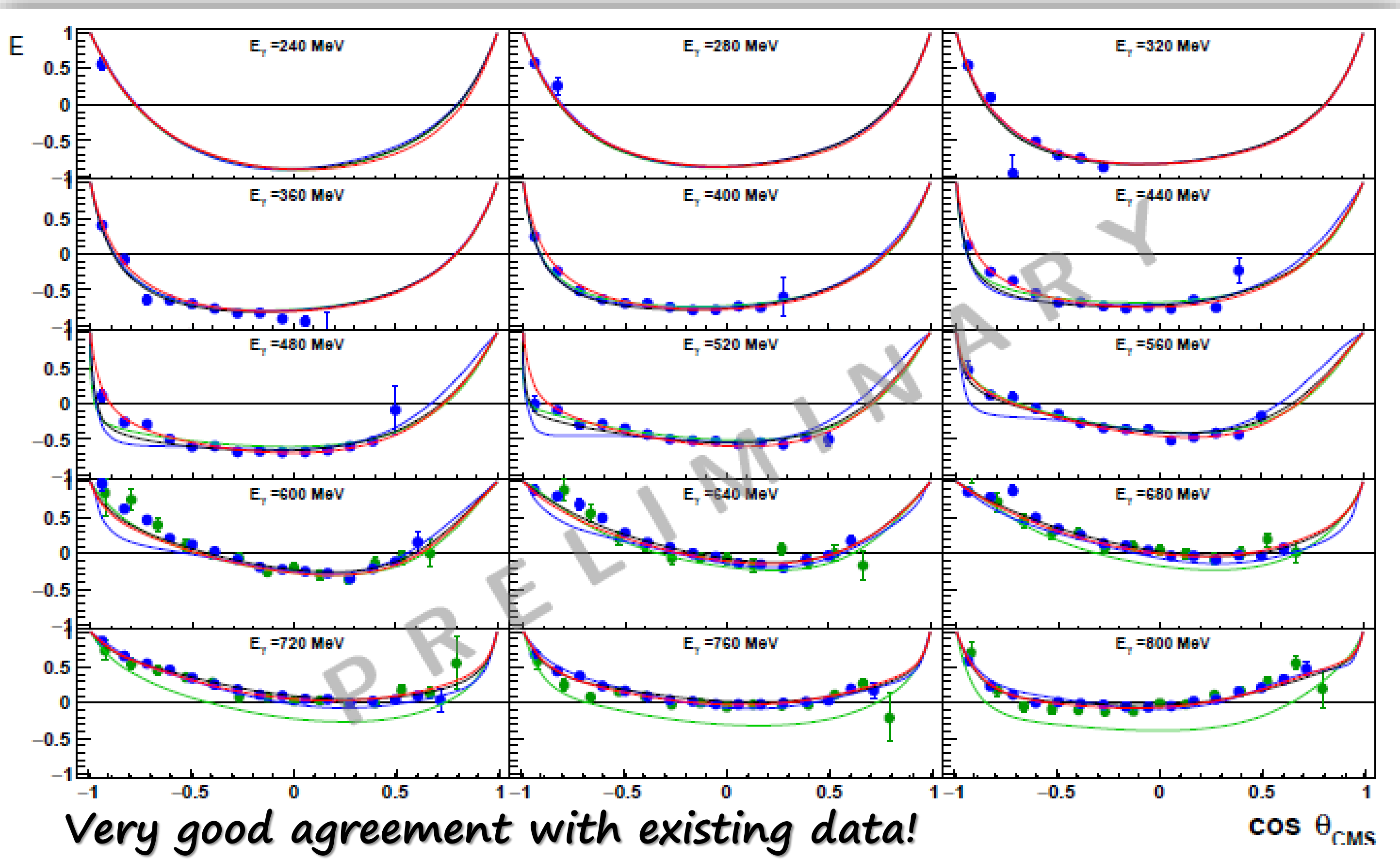
Results for E in π^0 photoproduction

240 MeV – 800 MeV



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

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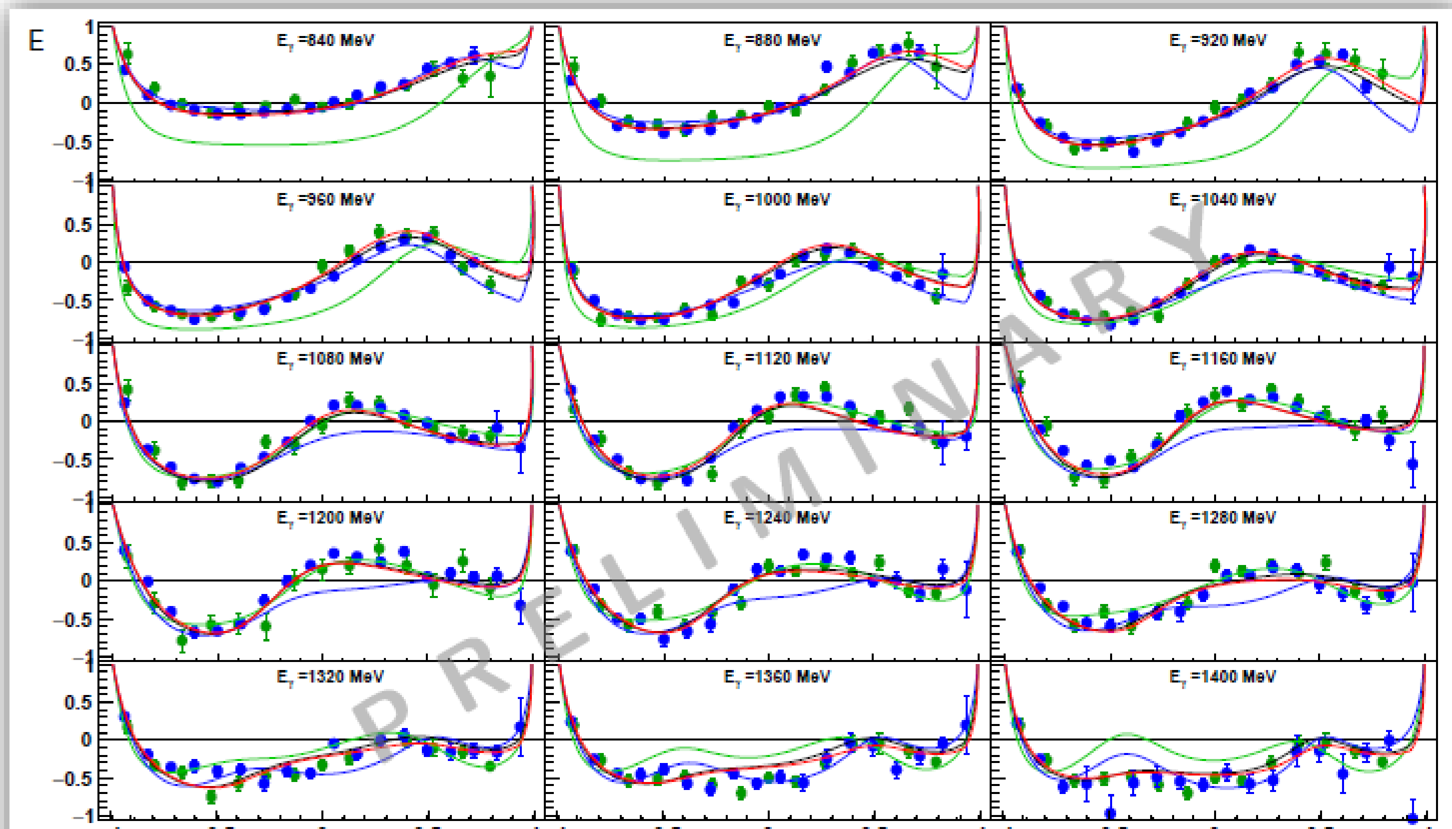
Results for E in π^0 photoproduction

840 MeV – 1400 MeV



Very good agreement with existing data!

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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

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

Spin

Mass

Photon energy

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

Photon spin Baryon spin

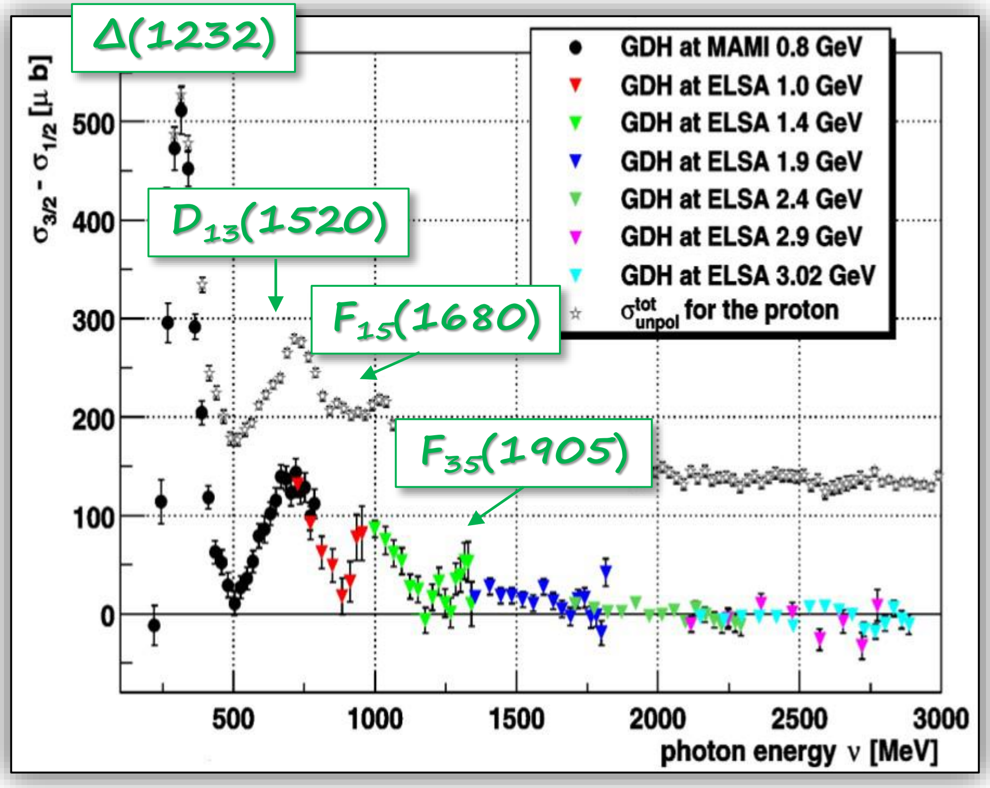
$\sigma_{1/2} = \sigma_a$ $\sigma_{3/2} = \sigma_p$

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

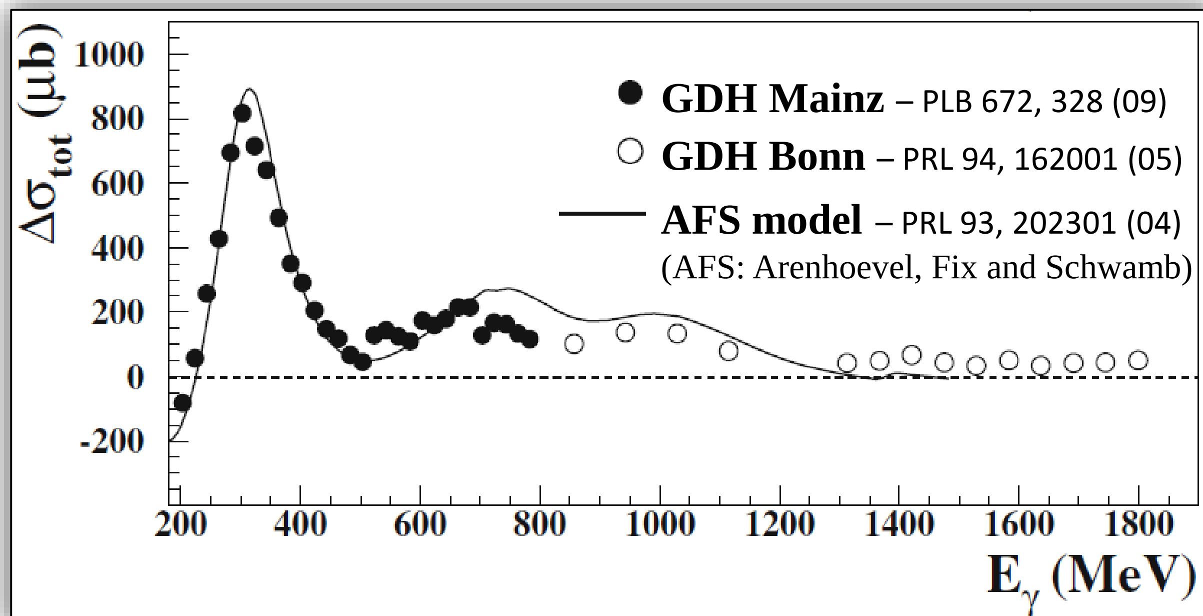
ELSA data: H. Dutz *et al.*, PRL 91 (2003) 192001, H.Dutz *et al.*, PRL 93 (2004) 032003

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.

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

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

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

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

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

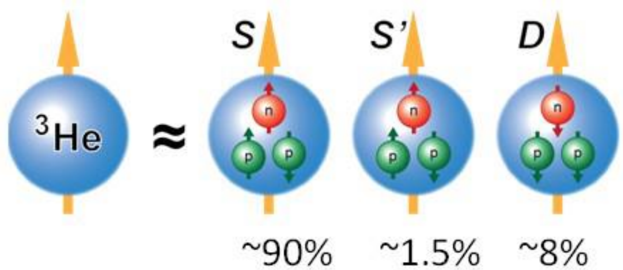
A2 contribution in the energy region: 200 MeV < E_γ < 1500 GeV

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 $I_{GDH}(^3He)$:

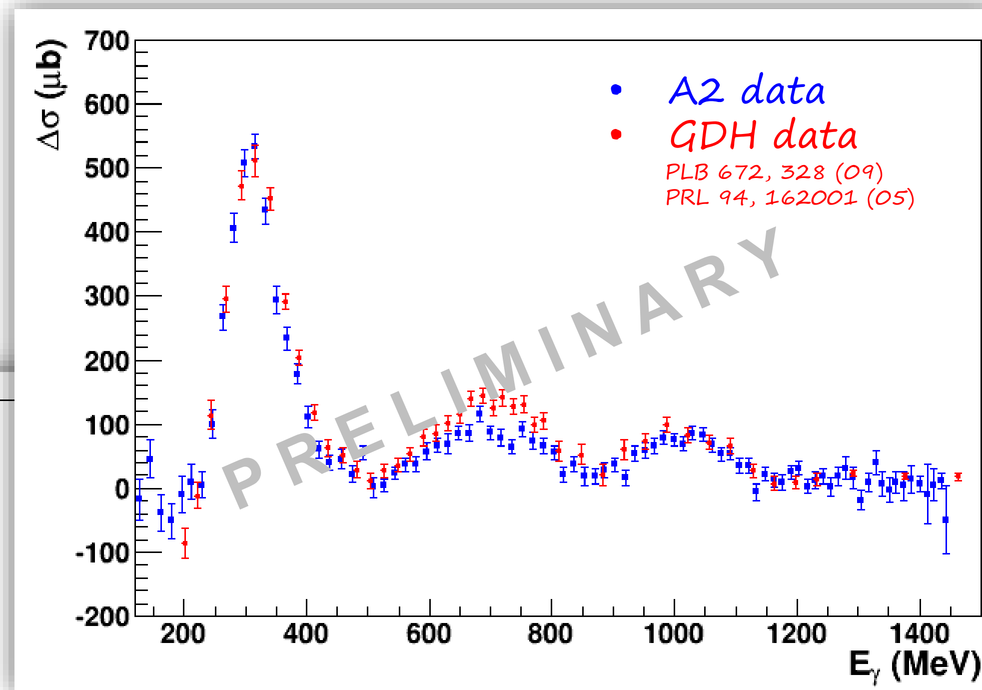
$$I_{GDH}(^3He) = 4\pi^2 S \left(\frac{1}{S}\mu - \frac{Q}{M}\right)^2 = \int_{\nu_{th}}^{\infty} \frac{\sigma_{3/2}(\nu) - \sigma_{1/2}(\nu)}{\nu} d\nu \approx 498 \mu b \gg I_{GDH}(n)$$

@ 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.

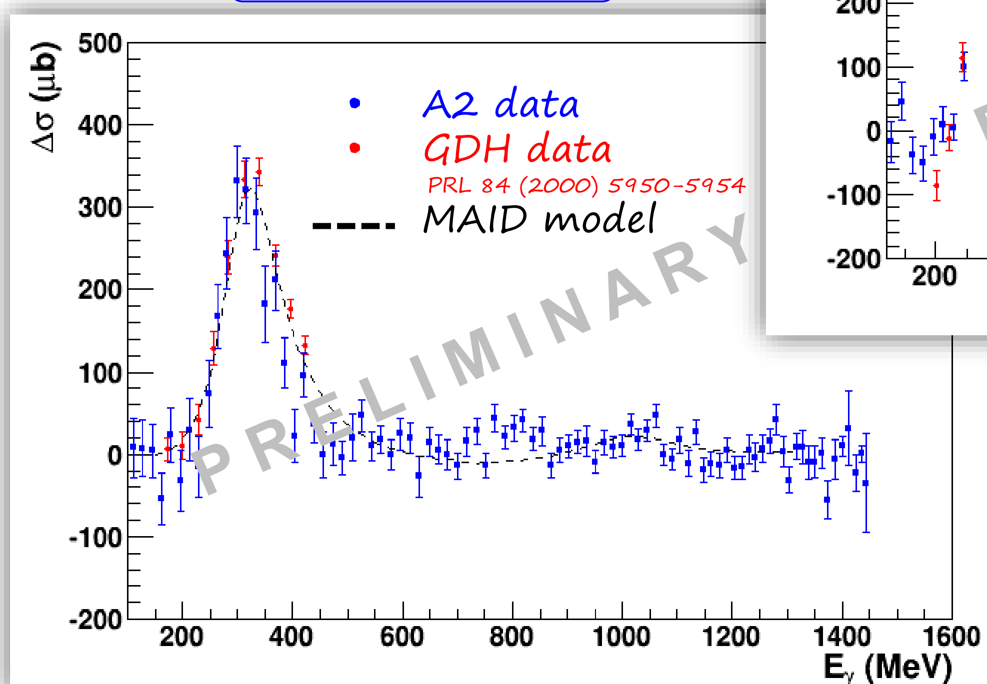
$\vec{\gamma}\vec{p}\to X$ and $\vec{\gamma}\vec{p}\to\pi^0 X$: $\sigma_p-\sigma_a$ (μb)

$\vec{\gamma}\vec{p}\to X$



Whole statistics from November 2013 beamtime

$\vec{\gamma}\vec{p}\to\pi^0 X$

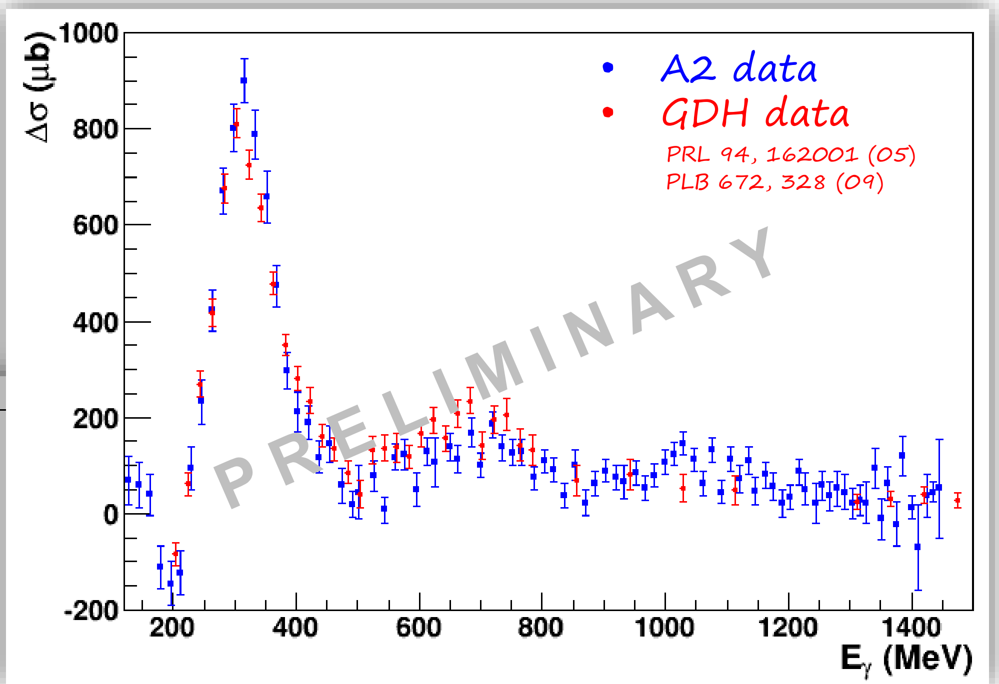


About 25% of the statistics from November 2013 beamtime

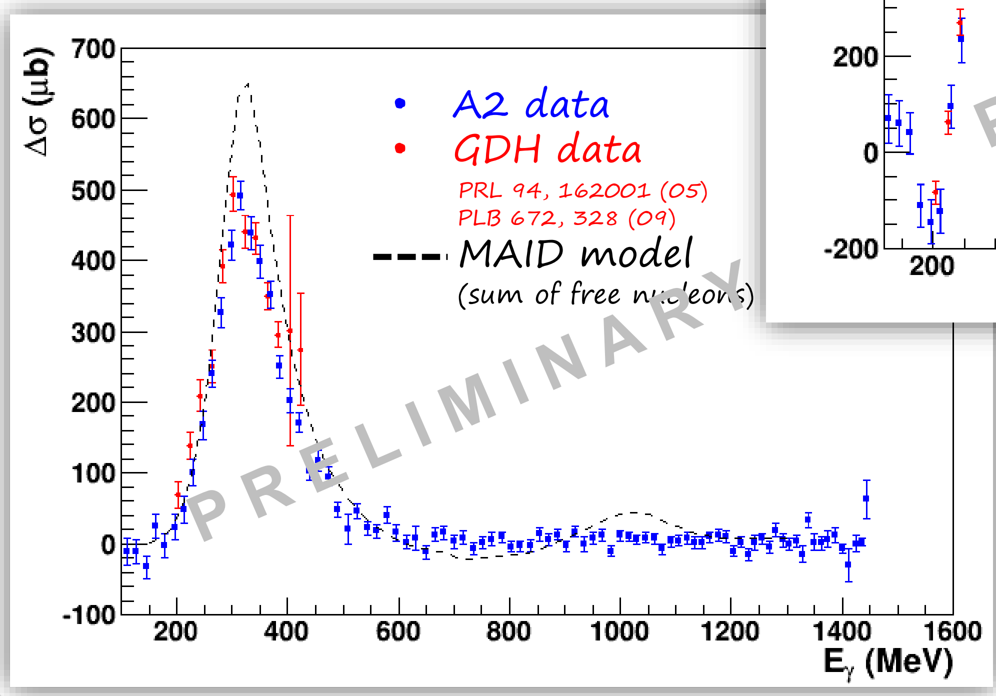
$\vec{\gamma}\vec{d} \to X$ and $\vec{\gamma}\vec{d} \to \pi^0 X$: $\sigma_p - \sigma_a$ (μb)

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

About 30% of the statistics

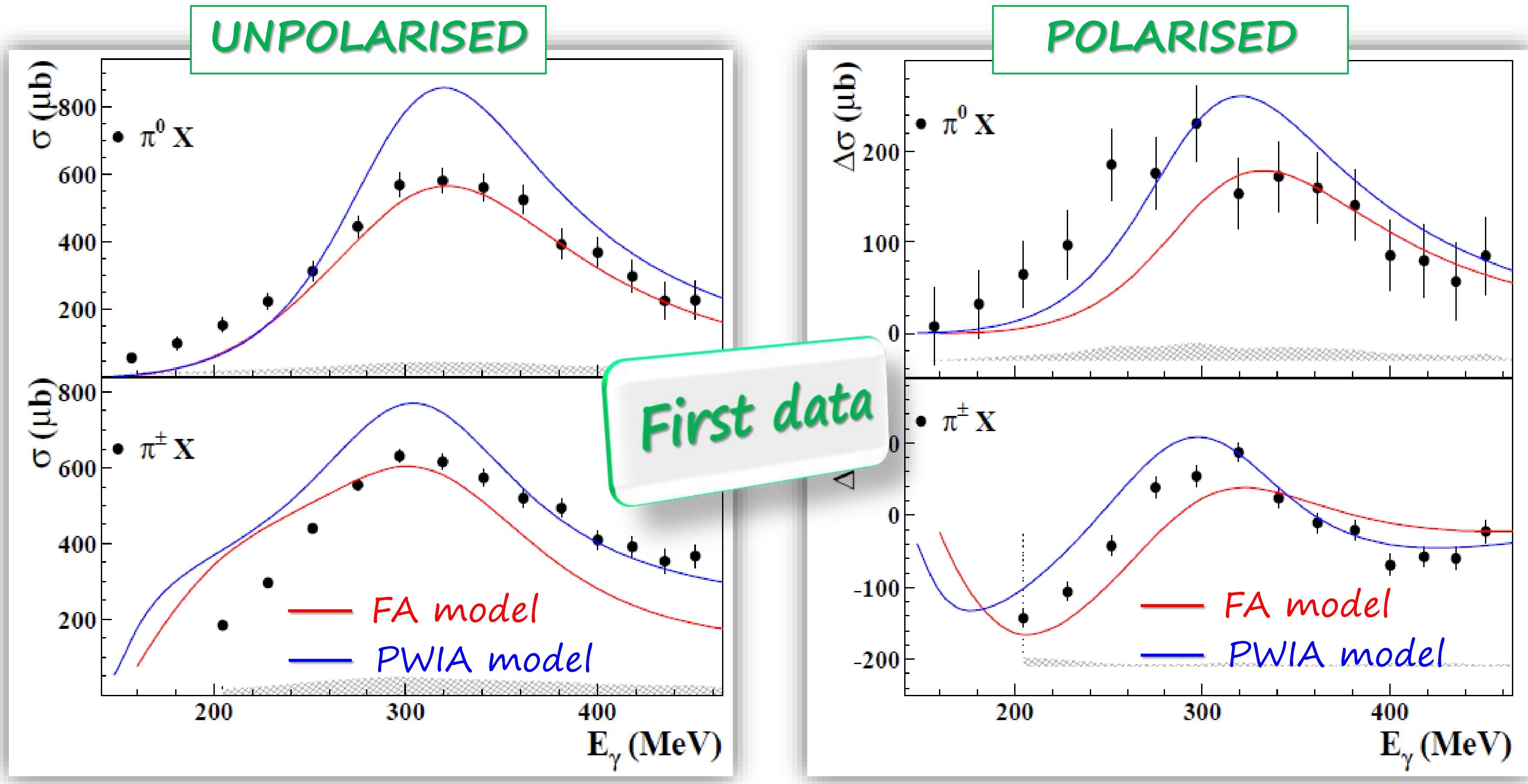


$\vec{\gamma}\vec{d} \to \pi^0 X$



About 30% of the statistics

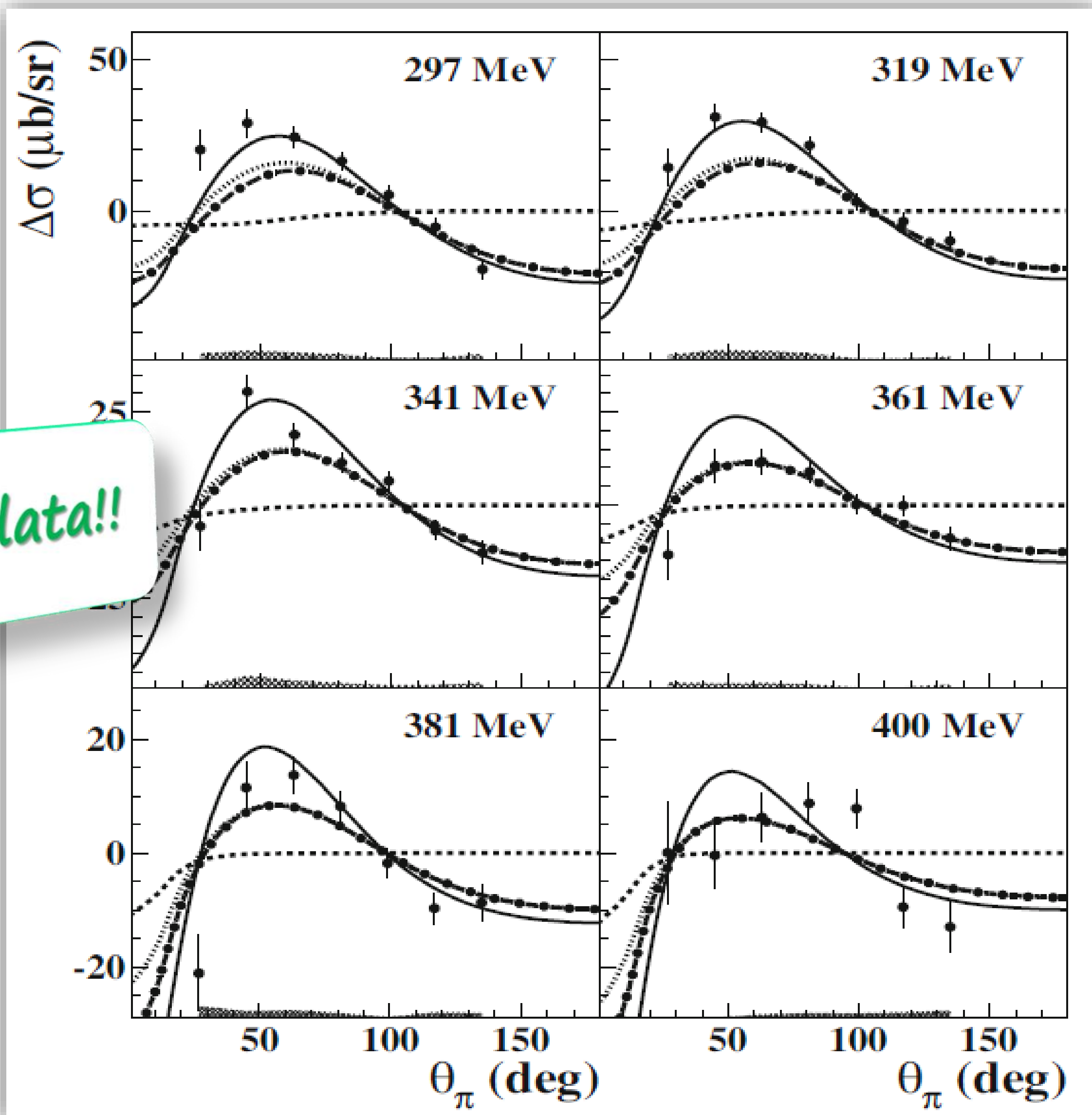
$\vec{\gamma}\,{}^3\vec{He} \rightarrow \pi X$: σ_{unpol} and $\sigma_p - \sigma_a$ (μb)



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)

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



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 $\pi^0 pd$

Summary

- An overview was given on recent results from the photoproduction of mesons from nucleons and nuclei at A2@MAMI

- Our data cover energy range down to the Δ(1232) resonance region → complementary to CBELSA/TAPS and CLAS data

- Both for the double polarisation observables G/E and the GDH sum rule results, good agreement between our results and existing data

- A2 can contribute to many topics of nuclear physics

- In particular, A2 can help to get a more precise estimation of the properties of baryonic resonances

- A lot of collected data to be analysed… and a lot to come!

Thank you
for your attention!

Backup

Meson photoproduction

PROs:

- ✓ 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**

CONs:

- ✗ Electromagnetic **cross sections are much smaller** than the hadronic ones
- ✗ Photon induced reactions can have significant **non-resonant «background»**

Polarisation observables

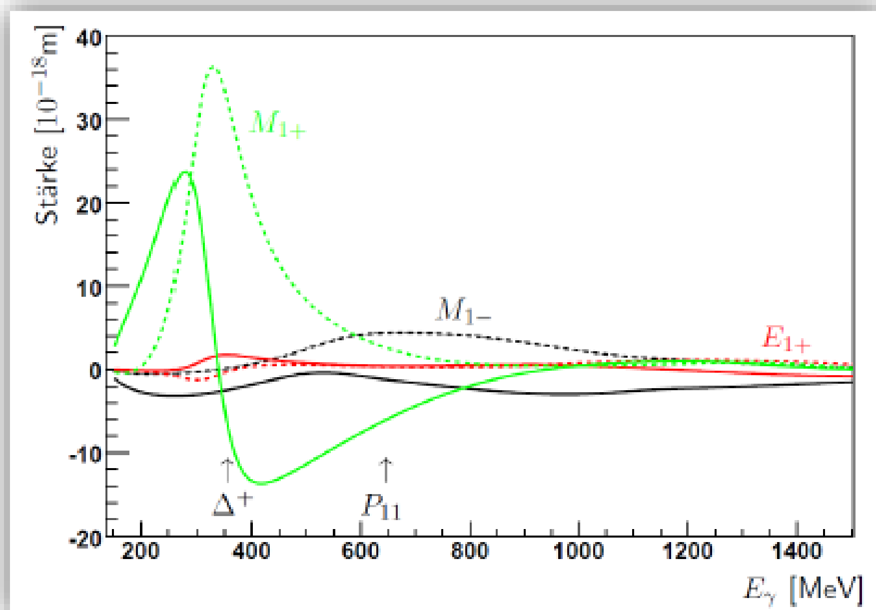
Examples of multipole expressions:

$$\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \ldots$$

$$\Sigma \sim -2E_{1+}^* M_{1+} + 2M_{1-}^* E_{1+} - 2M_{1-}^* M_{1+} + \ldots$$

Multipole expression of G for l≤1 in single pion photoproduction off the proton

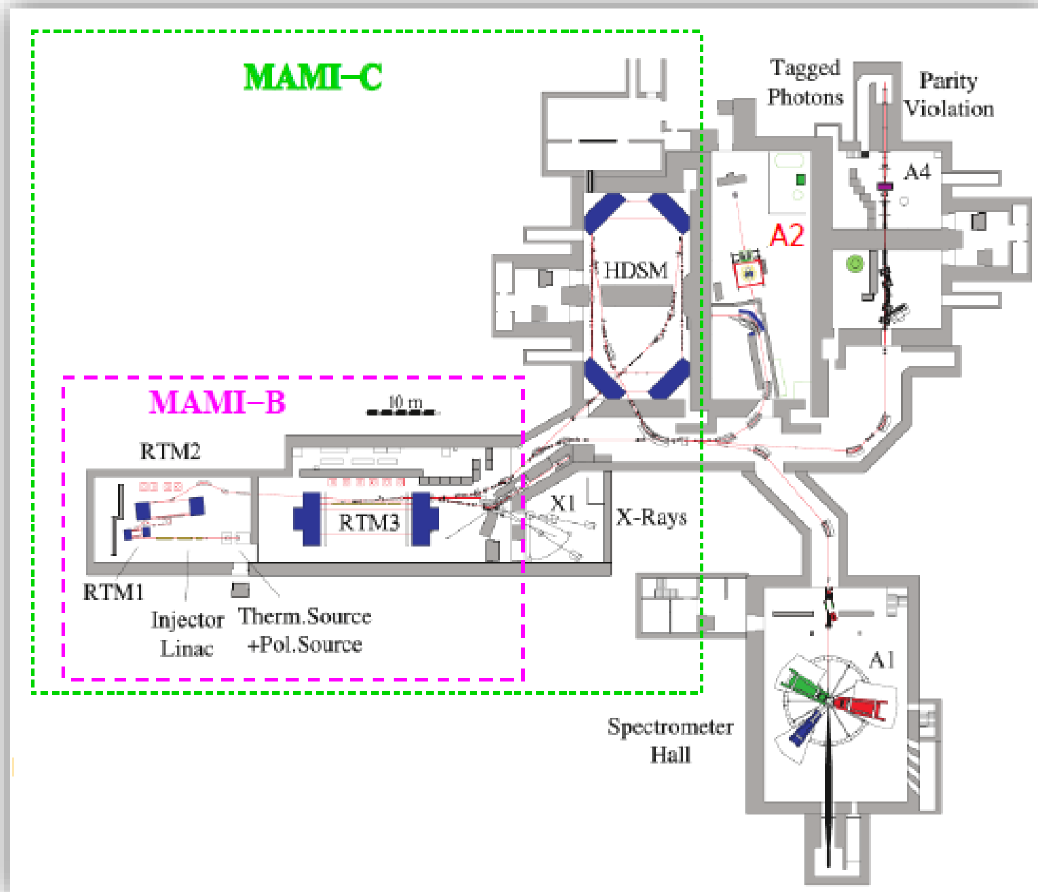
$$\frac{d\sigma}{d\Omega} \cdot G(\cos\theta) = Im\{M_{1-}^*(E_{1+} - M_{1+}) - 2E_{1+}^* M_{1+}\} \cdot 3\sin^2\theta \approx ImM_{1-} ReM_{1+} \cdot 3\sin^2\theta$$



- Sensitive to the M_{1-} partial wave
- Sensitive to $P_{11}(1440)$ resonance

Solid line: real part;
Dotted line: imaginary part

MAinzer Mikrotron MAMI



- Located at the Inst. of Nuclear Physics, Mainz, Germany
- Unpolarised or longitudinally polarised electrons
- Acceleration in 3 race track microtrons (RTM1-3) to 855 MeV (MAMI-B)
- Acceleration in harmonic double-sided microtron (HDSM) to 1600 MeV (MAMI-C)

A2@MAMI: main physics goals

Mainly involving low cross sections and/or precision measurements

- **Precision spectroscopy** of low lying baryonic states
  - $\Delta(1232)$ from $\gamma p \rightarrow \pi^0\gamma' p$ and $\pi^+\gamma' n$
  - $S_{11}(1535)$ from $\gamma p \rightarrow \eta\, \gamma' p$ reaction
- **Threshold meson production** (test of LET/ChPT)
  - Strangeness ($\gamma N \rightarrow \Lambda K$)
  - π^0 photoproduction at threshold
- Ambiguity free **amplitude analysis** of meson photoproduction
  - Requires double polarisation measurements: $\gamma N \rightarrow N\pi(\pi)$, $N\eta(\rho, \ldots)$
- Tests of **fundamental symmetries** (C, CP, CPT, …)
  - Rare η, η' decays
- Studies of **nuclear structure** ($\gamma A \rightarrow pX$)
- **In medium properties** of hadrons
  - Meson photoproduction on nuclei

Double polarisation observables G

First experimental attempt to measure E and G 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

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

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

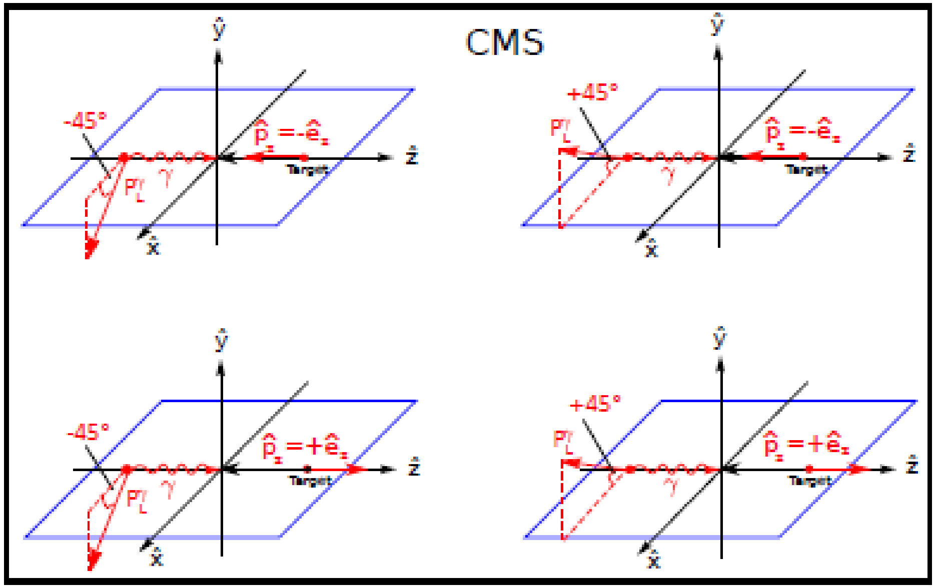
Butanol (C_4H_9OH) has unpolarised protons in carbon and oxygen:

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

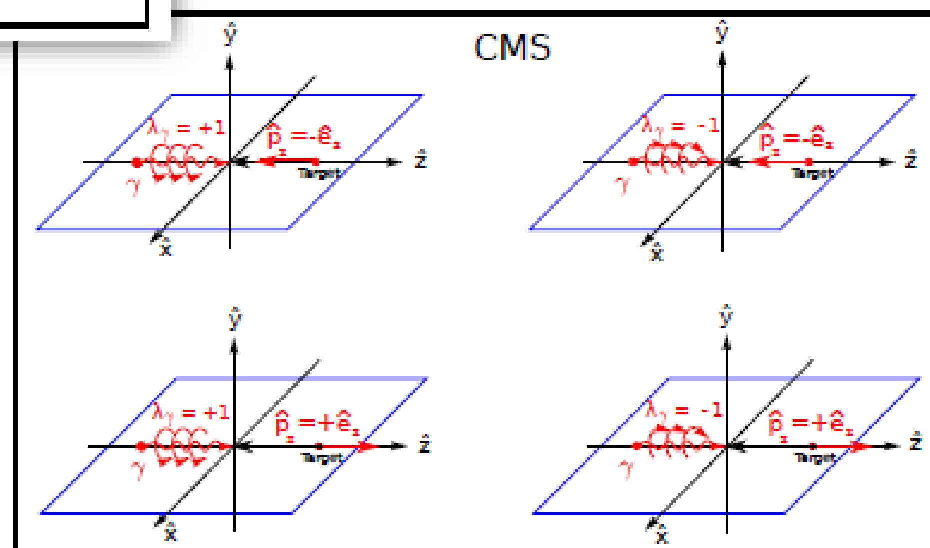
- Σ_b contains distribution for bound protons
- The double polarisation observable G requires longitudinally polarised target → determine the fraction of polarised protons → dilution factor:

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

Determination of E and G



G

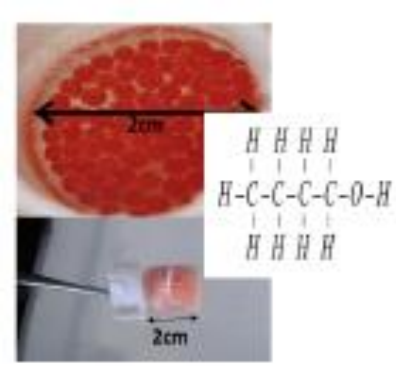


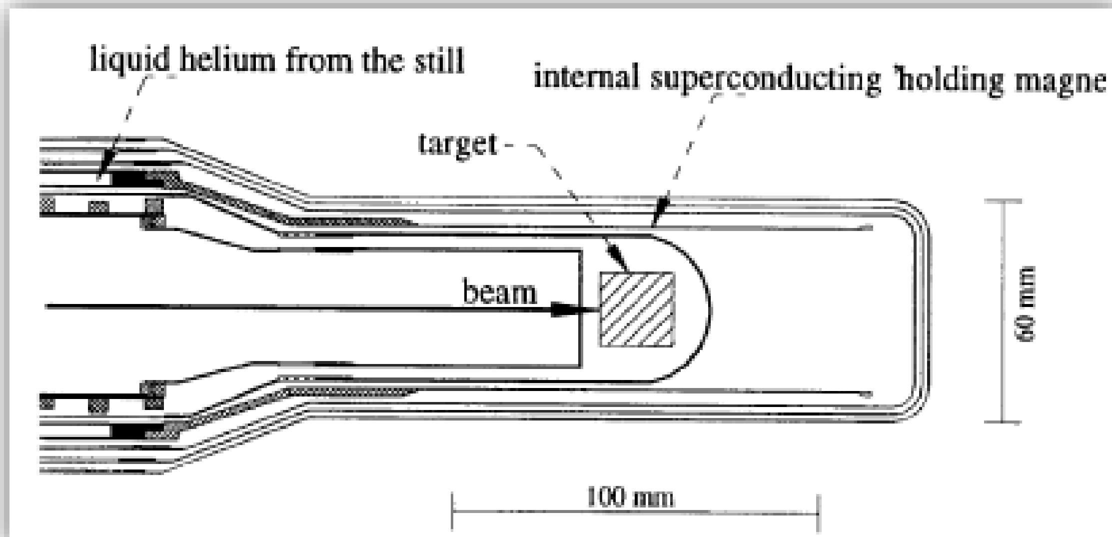
E

Frozen spin Butanol target

Polarization via Dynamic Nuclear Polarization (DNP)

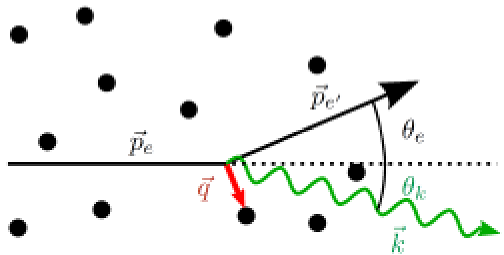
- Butanol target is doped with paramagnetic radicals
- Electrons are polarised with a 2.5 T magnetic field at 1 K
- Electron polarisation can be transferred to the nucleons by microwave irradiation (70 GHz)
- «Freeze» the spin: 3He/4He dilution cryostat with ≈ 25 mK holding coil and 0.63 T

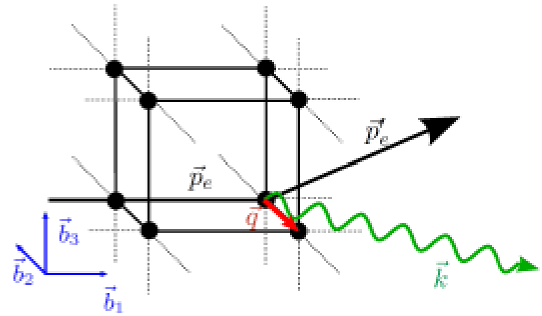


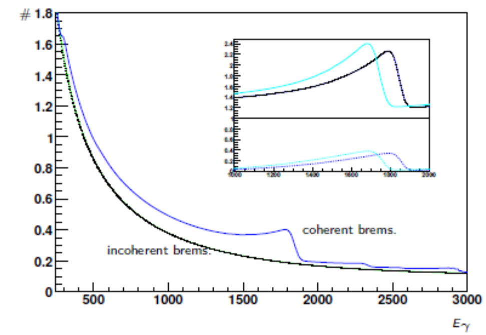


- high relaxation time (≈ 2000 h)
- $9 \cdot 10^{22}$ polarised protons per cm^2 in the target cell
- p_T up to 90%

Linearly polarised photons





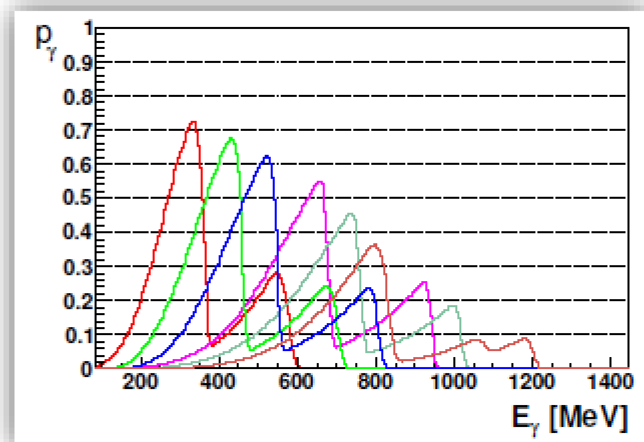


- **Incoherent bremsstrahlung:**

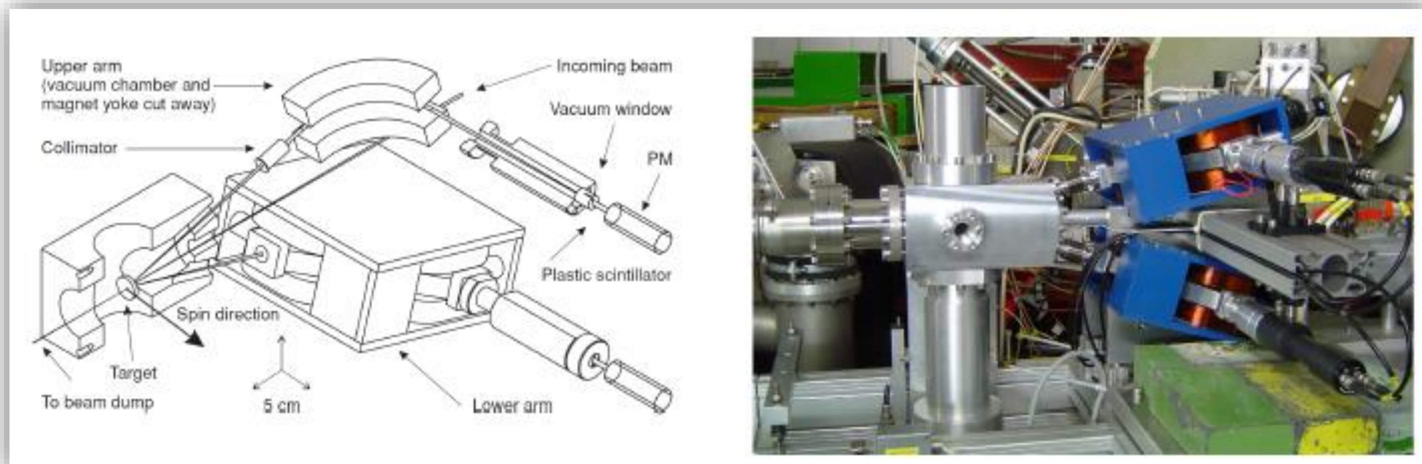
  only one single atom of the crystal absorbs the recoiling momentum → no preferred plane between incoming electron and outgoing photon → no favored orientation of the electric field vector of the photons → no polarised photons

- **Coherent bremsstrahlung:**

  if $\vec{q} = n\vec{g}$ with $\vec{g}=\sum_{i=1}^{3} \vec{b_i}\cdot h_i$ → single atoms can interfere constructively! → preferred plane between incoming electron and outgoing photon → orientation of the field vector of the photon → polarised photons

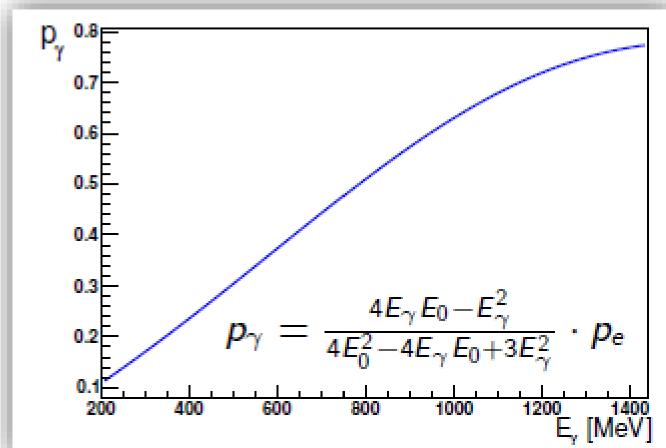


Circularly polarised photons



- **Mott scattering:**

  electrons in gold (Z=79) interact via spin-orbit coupling with the longitudinally polarised electrons from MAMI → asymmetry in backscattering → polarisation degree of electrons
- Helicity transfer from electrons to photons → circularly polarised photons



The GDH sum rule on the proton

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

E_γ (GeV)	Who	I_{GDH} (μb)
< 0.20	MAID/SAID	-28.5 ± 2
0.20 – 2.90	MAMI+ELSA (measured)	$254 \pm 5 \pm 12$
> 2.90 (Regge approach)	Simula et al. Bianchi–Thomas	−13 −14
Total		**$211 \pm 5 \pm 12$**
GDH sum rule		205

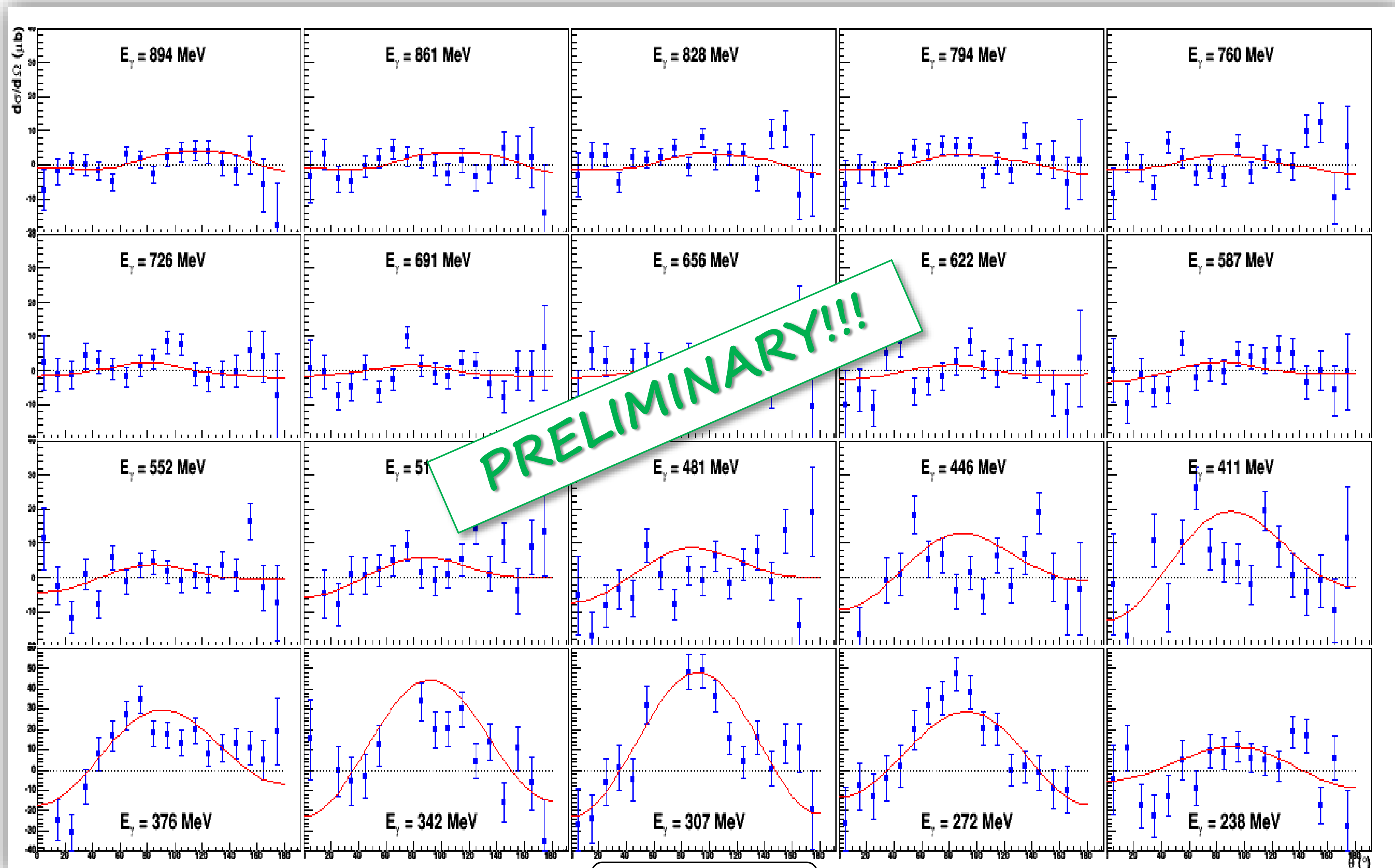
Agreement (within errors)
between the GDH sum rule value and the experimental one:
GDH sum rule experimentally (almost) demonstrated!!!

The GDH sum rule: theoretical estimates

Partial channels	Models	I_{GDH} (p) [μb]	I_{GDH} (n) [μb]
$\gamma p \to N\pi$	SAID-FA07K [MAID07]	172 [164]	147 [131]
$\gamma p \to N\pi\pi$	Fix, Arenhoevel EPJA 25, 114 (2005)	94	82
$\gamma p \to N\eta$	MAID	-8	-6
$\gamma p \to K\Lambda(\Sigma)$	Sumowidagdo *et al.* PRC 65, 0321002 (02)	-4	2
$\gamma p \to N\rho(\omega)$	Zhao *et al.* PRC 65, 032201 (03)	0	2
Regge contribution	Bianchi-Thomas PLB 450, 439(99)	-14	20
Total		239 [231]	244 [231]
GDH sum rule		205	233

Comparing the GDH sum rule value and the theoretical predictions:
NO AGREEMENT for the proton … but …
AGREEMENT for the neutron

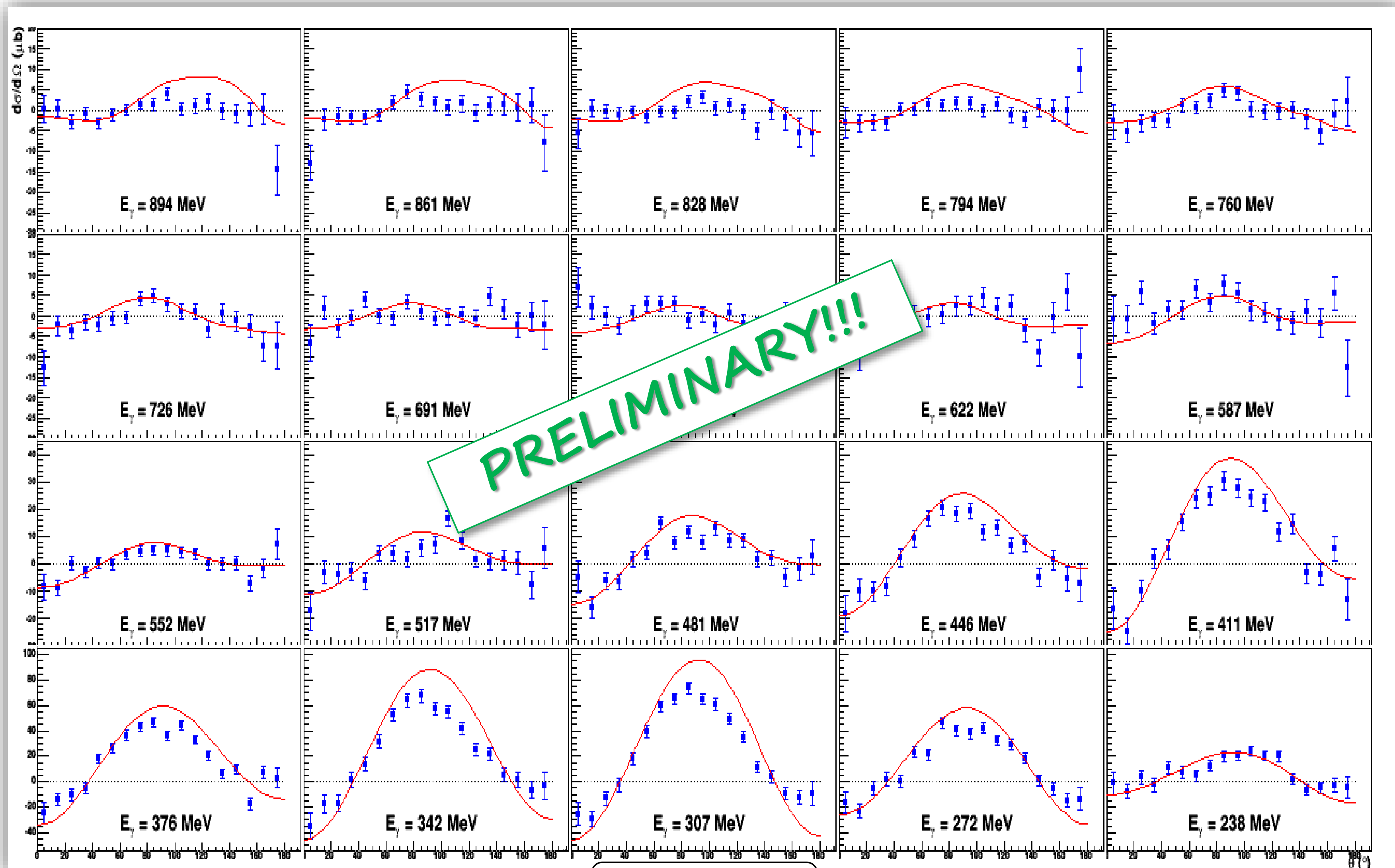
$\vec{\gamma}\,\vec{p} \rightarrow \pi^0 X$: $(d\sigma_p/d\Omega)-(d\sigma_a/d\Omega)$ ($\mu b/sr$)



Moeller

- A2 data
- MAID $\pi^0 p$ model

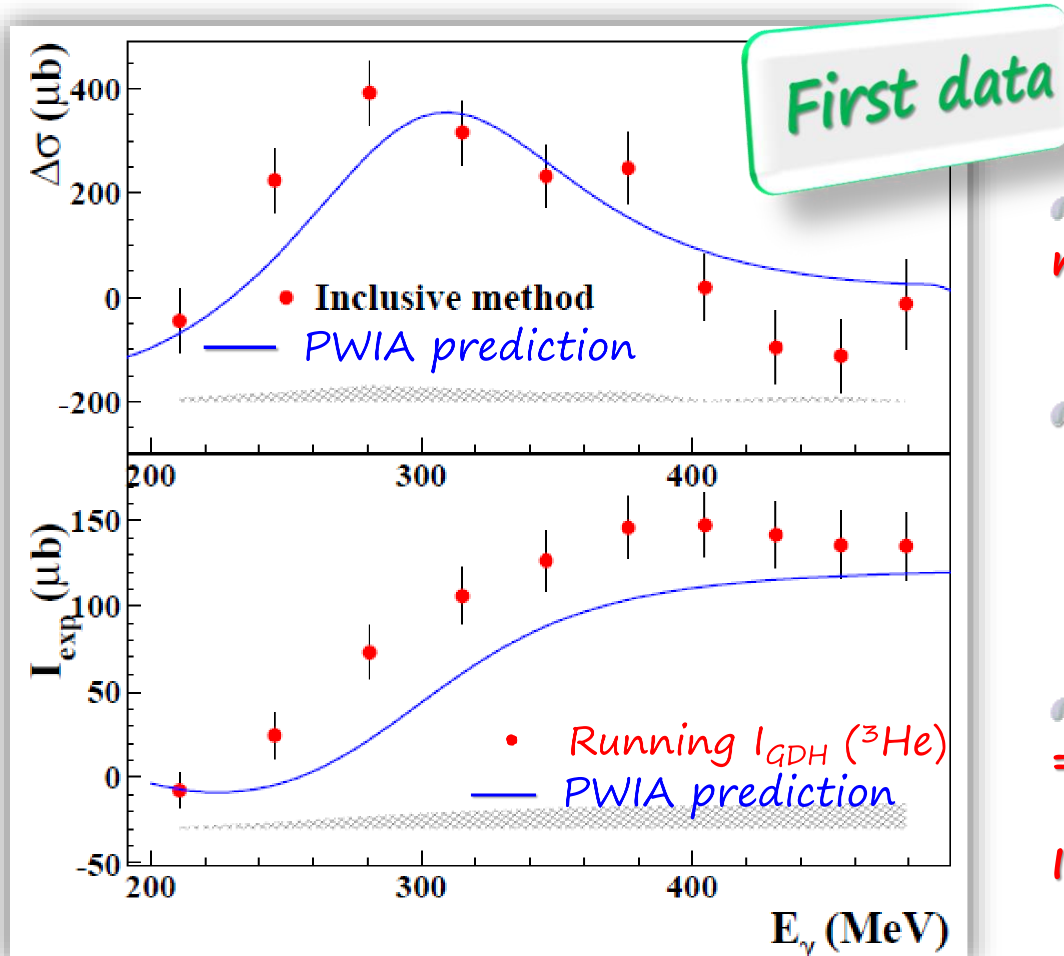
$\vec{\gamma}\vec{d}\rightarrow\pi^0 X$: $(d\sigma_p/d\Omega)-(d\sigma_a/d\Omega)$ ($\mu b/sr$)



Moeller

- A2 data
- MAID model

Total inclusive cross section $\vec{\gamma}\,^3\vec{He} \to X$



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

- "Inclusive" analysis method
- PWIA predictions:

$$\Delta\sigma_{PWIA} = p_n \cdot \Delta\sigma_n + 2 \cdot p_p \cdot \Delta\sigma_p$$

- Running I_{GDH} for ^{3}He for E_γ = (200, 500) MeV:

$I_{GDH} = 135 \pm 20 \pm 12$ μb $\approx I_p$

Reasonable agreement between data and PWIA predictions