Recent Results from the A2 collaboration at MAMI

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NSTAR 2022

SUMMARY

- Physics motivations   Study of the nucleon properties
  - Determination of the N* spectrum $\gamma N \rightarrow N\pi, N\eta, N\pi\pi, \ldots$

    GDH sum rule

  - Determination of the N structure (polarizabilities) $\gamma N \rightarrow \gamma' N$

  using (real) Photons and polarization observables

- Experimental set up (A2 tagged photon facility)

- Selected Results

$$\vec{\gamma}\vec{p}(\vec{d}) \rightarrow \begin{cases} N\pi(\pi) \\ X \\ \gamma' N \end{cases}$$

- Outlook

Motivations

Why photons ?

One powerful way of experimentally investigating the strongly interacting particles **(hadrons)** is to look at them, **to probe** them with a known particle, in particular the photon **(no other is known as well)**

(R.P.Feynman)

The hadronic structure is explored with a resolution depending of the photon energy (wave length)

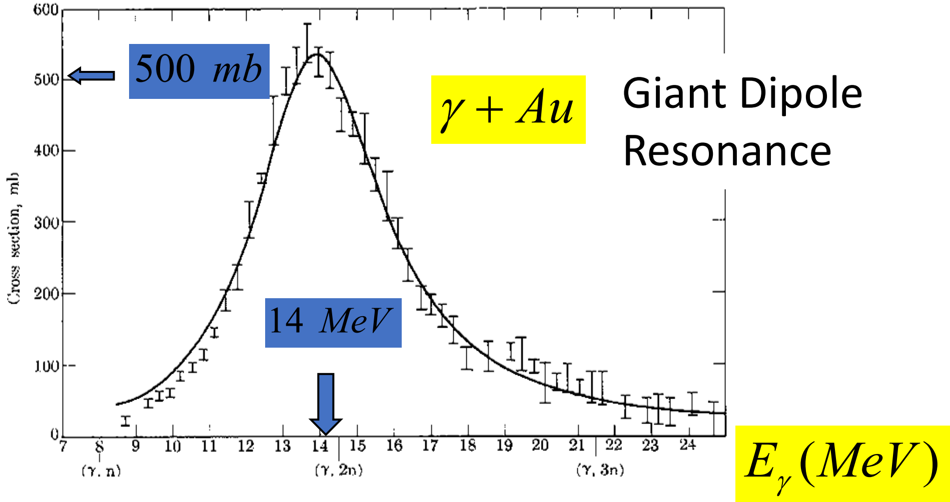
Study of the collective nuclear motions

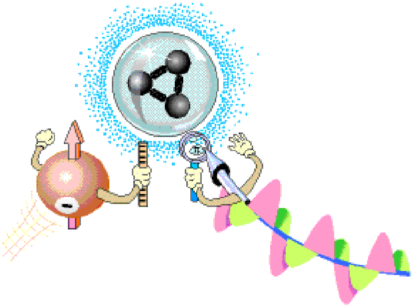
$$\lambda_\gamma \cong \frac{200(\mathrm{MeV}\cdot\mathrm{fm})}{E_\gamma(\mathrm{MeV})}$$

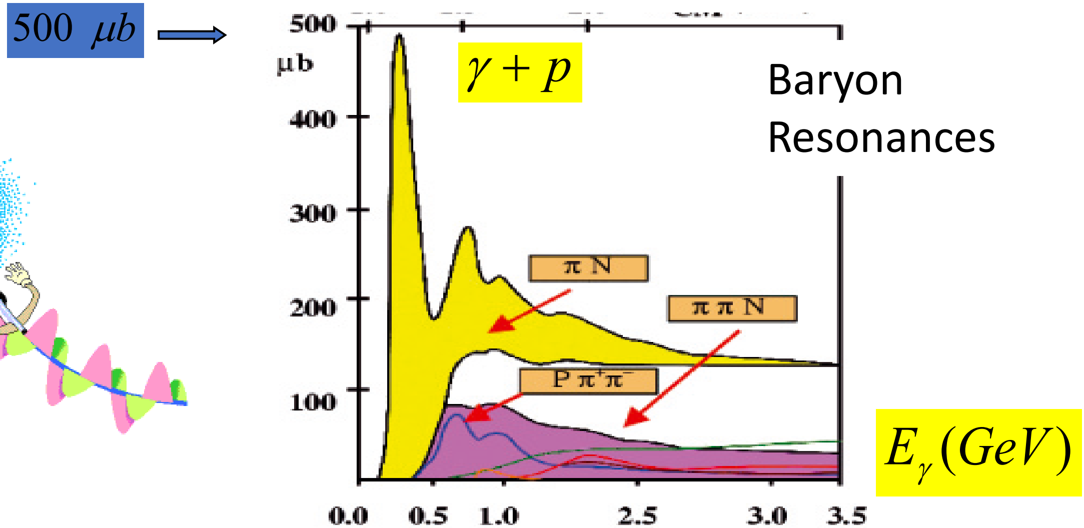
Study of the nucleon internal e.m. structure

$E_\gamma \approx 20$ MeV $\Rightarrow$ $\lambda_\gamma \approx 10$ fm

$E_\gamma > 200$ MeV $\Rightarrow$ $\lambda_\gamma < 1$ fm





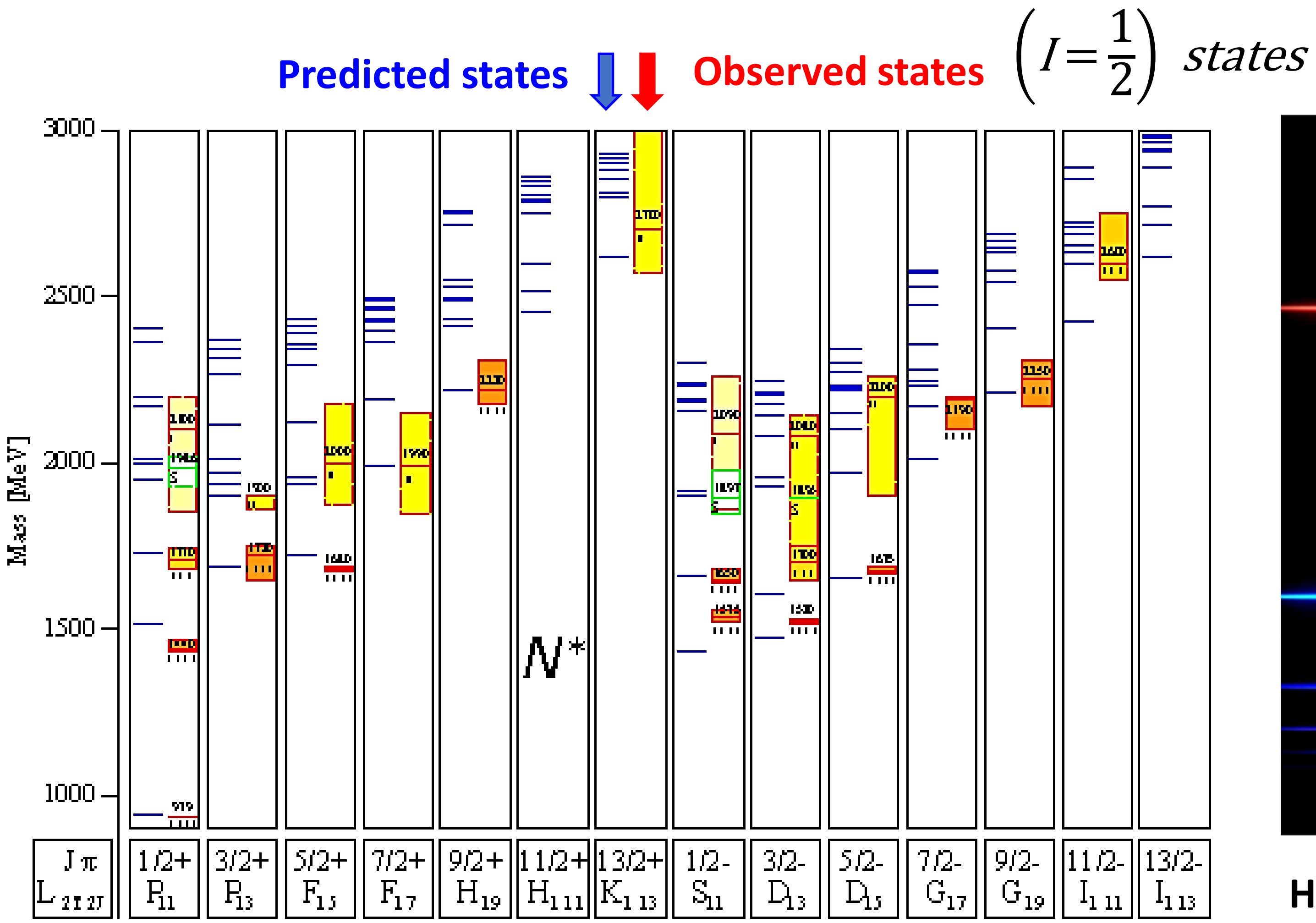


How well do we understand the nucleon excitation spectrum ?

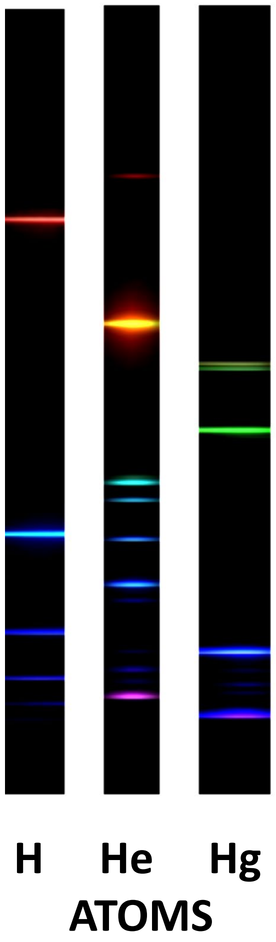
- many more resonances expected in quark models (all based on SU6 symmetry) or lattice QCD than seen experimentally

- What are the relevant degrees of freedom ?

- Most resonances observed in πN scattering but some resonances might not couple to πN



CQM: U. Loering et al, EPJA 10, 395 (2001)



Why spin ?

$$\gamma N \to N^* \to \pi N \ (\text{or}\ \eta N)$$

(... The simplest reaction ....)

Spin states	±1	$\pm1/2$	0	$\pm1/2$
DoF	2 x	2		x 2

8 matrix elements needed describe the scattering amplitude

- **Parity conservation $\Rightarrow$ only 4 complex amplitudes are independent (F_1 ... F_4 CGLN amplitudes)**
- **16 independent observables (at least 8 -well chosen-to be measured $\Rightarrow$ «complete experiment»)**

1 unpolarized observable **3 single polarization observables** **12 double polarization 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_y	-	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	-	-	-	-

Measured or planned at A2

Additional complications

- e.m. interactions do not conserve isospin

→ Reactions on both the proton and the neutron have to be measured to decompose the isospin-dependent contributions

Deuteron (or ^{3}He, or ...) has to be used as a substitute for a free-neutron target. Nuclear effects have to be precisely measured and modeled

- Higher nucleon resonances have (very) small $N\pi$ decay branching ratios

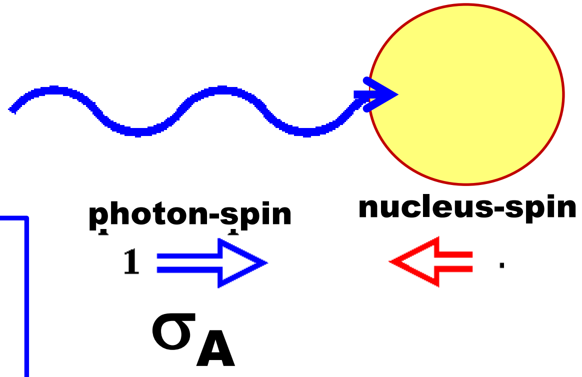
→ Several observables on all the different $\gamma N \rightarrow N\pi\pi...$ partial channels have to be measured.

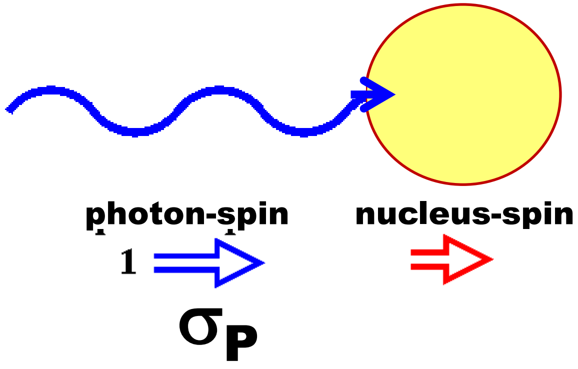
On the theoretical side, a coupled-channel approach is then also needed

Very large acceptance ($\cong 4\pi$) detectors need to be operated with highly polarised beam and targets

The GDH sum rule

- Proposed in 1966 independently by Gerasimov and Drell-Hearn
- Prediction on the absorption of circularly polarized photons by longitudinally polarized nucleons/nuclei





Imaginary part of the Compton scattering amplitude

Nucleon or nucleus spin

$$I_{GDH} = \int_{\nu_{thr}}^{\infty} \frac{\sigma_P(E_\gamma) - \sigma_A(E_\gamma)}{\upsilon}\, d\upsilon = 4\pi^2 S \frac{e^2}{M^2} k^2$$

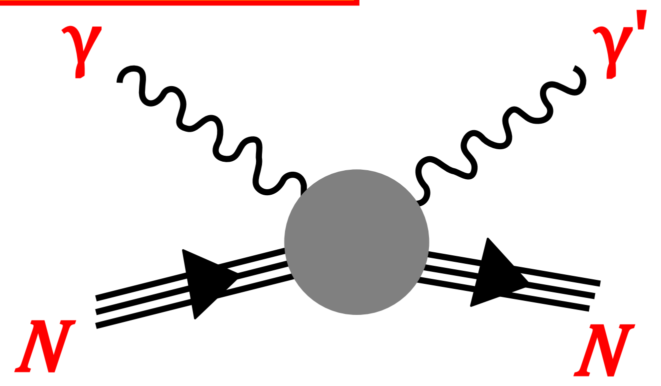
Anomalous magnetic moment

$$\nu_{thr} = \begin{cases} \pi \text{ production threshold (nucleon)} \\ \text{photodisintegration threshold (nuclei)} \end{cases}$$

Real part of the Compton scattering amplitude

Real Compton Scattering on the proton

Expansion of the Hamiltonian in incident photon energy (ω)



0th order ⟹ charge, mass

1st order ⟹ magnetic moment (κ)

«point-like» nucleon (Born terms)

GDH sum rule

2nd order ⟹ 2 scalar polarizabilitites

Baldin's sum rule: $(\alpha_{E1}+\beta_{M1}) = \frac{1}{2\pi^2} \int \frac{\sigma_{unpol}}{\nu^2}\, d\nu$

≈ known

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

3rd order ⟹ 4 spin (vector) polarizabilitites

only two direct measurements (both from A2)

P. Martel et al, PRL 114, 112501 (2015)

D. Payudal et al, PRC 32, 035205 (2020)

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

$$E_{ij} = \frac{1}{2}\left(\nabla_i E_j + \nabla_j E_i\right)$$
$$H_{ij} = \frac{1}{2}\left(\nabla_i H_j + \nabla_j H_i\right)$$

GGT sum rule

$$\gamma_0 = \frac{1}{4\pi^2}\int \frac{\sigma_P - \sigma_A}{\nu^3}\, d\nu$$

$$\boxed{\gamma_0} = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2}$$

$$\boxed{\gamma_\pi} = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2}$$

(≈ known)

GDH sum rule predictions

	p	n	d	^{3}He	
μ	2.79	-1.91	0.86	-2.13	(n.m.)
κ	1.79	-1.91	-0.14	-8.37	(n.m.)
I_{GDH}	204	233	0.65	498	(μb)

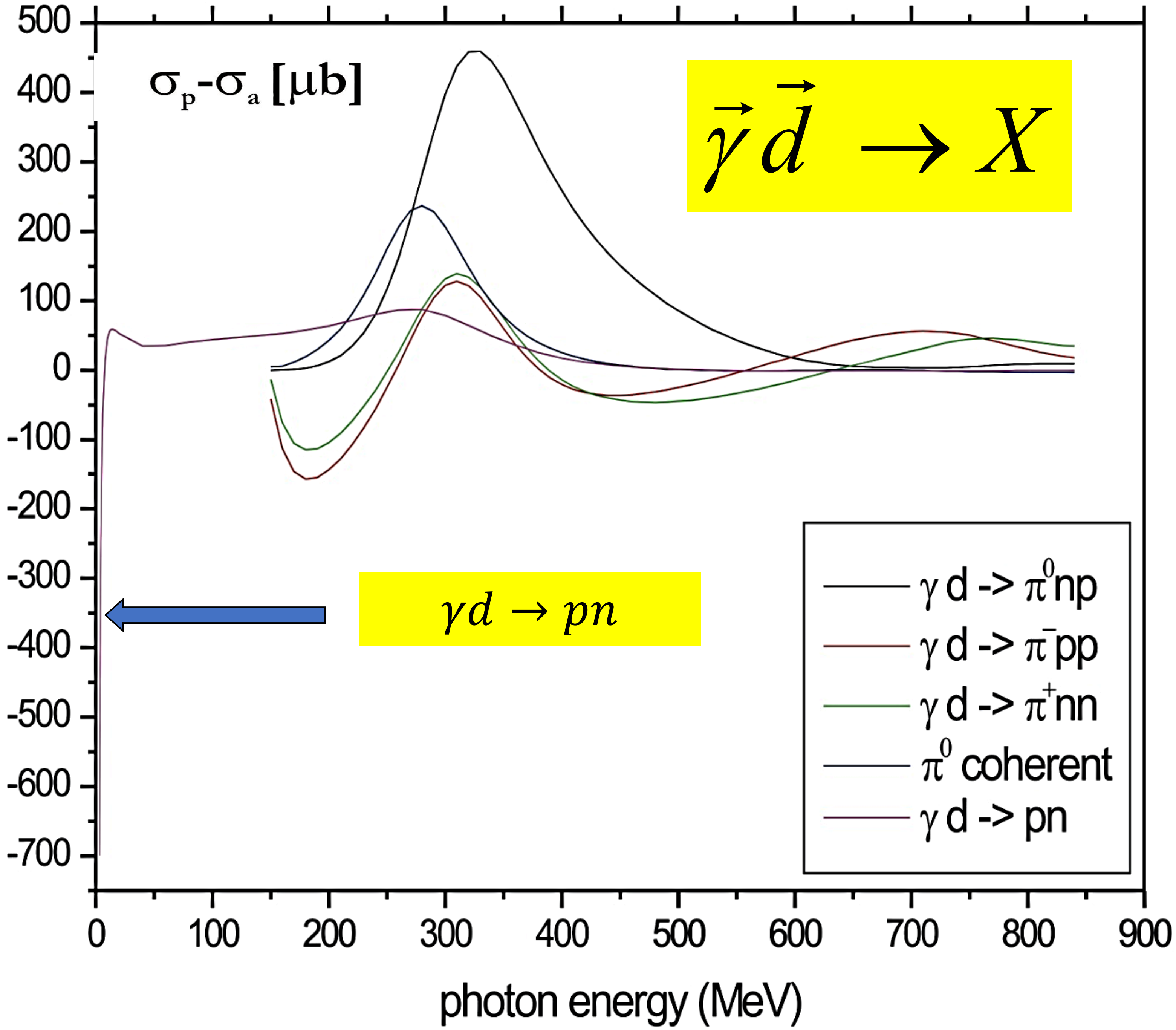
"naive" expectations ≈ 430 ≈ 230

$\approx I^p_{GDH} + I^n_{GDH}$ $\approx I^n_{GDH}$

True only above pion production threshold

Difference due to photodisintegration processes

→ interplay between nuclear and sub-nucleon degrees of freedom



AFS model

Arenhoevel, Fix, Schwamb, PRL 93, 202301 (04)

πNN πN from MAID PWA +nuclear effects

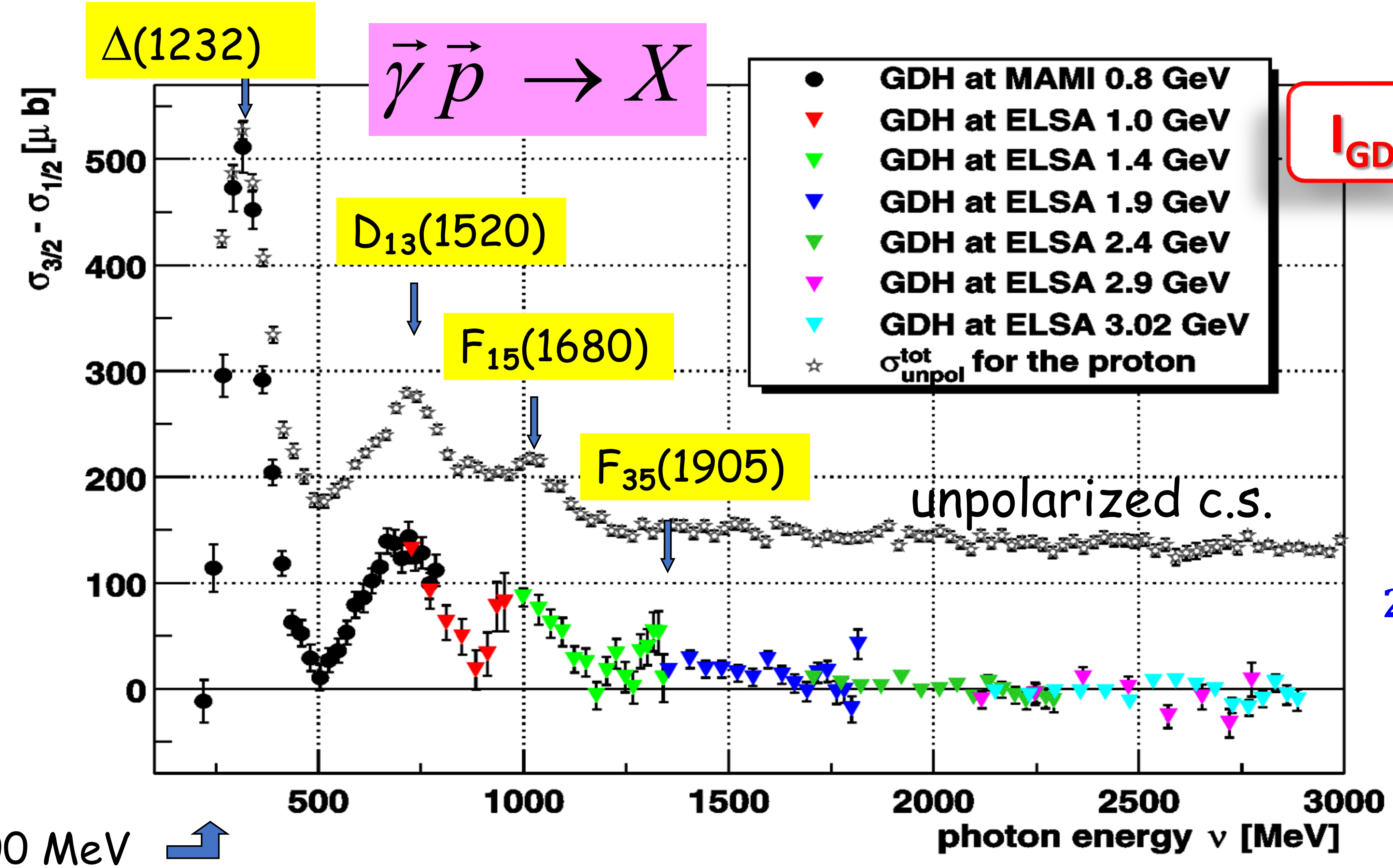
ππNN EPJA 25,114 (05)

π^0d PLB 407,1 (97)

pn NPA 690,682 (01)

$$\left[I_{GDH}^{deut}\right]_{AFS} = 27\mu b$$

Experimental status –proton



200 MeV

MAMI data: J. Ahrens et al., Phys. Rev. Lett. 87 (2001) 022003
ELSA data: H. Dutz et al., Phys. Rev. Lett 91 (2003) 192001
H. Dutz et al., Phys. Rev. Lett 93 (2004) 032003

GDH collaboration:
a joint venture
between MAMI-Mainz
and ELSA-Bonn

I_{GDH} (p) = 211 ± 5 ± 12 μb

GDH value: 204 μb

with – a non negligbile-contribution (about 15%) of the unmeasured photon energy regions:

Measured

$200\ \text{MeV} < E_\gamma < 2.9\ \text{GeV}$

254 ± 5 ± 12 μb

Estimated unmeasured contributions:

$140 < E_\gamma < 200\ \text{MeV}$ -29 μb

$E_\gamma > 2.8\ \text{GeV}$ -14 μb

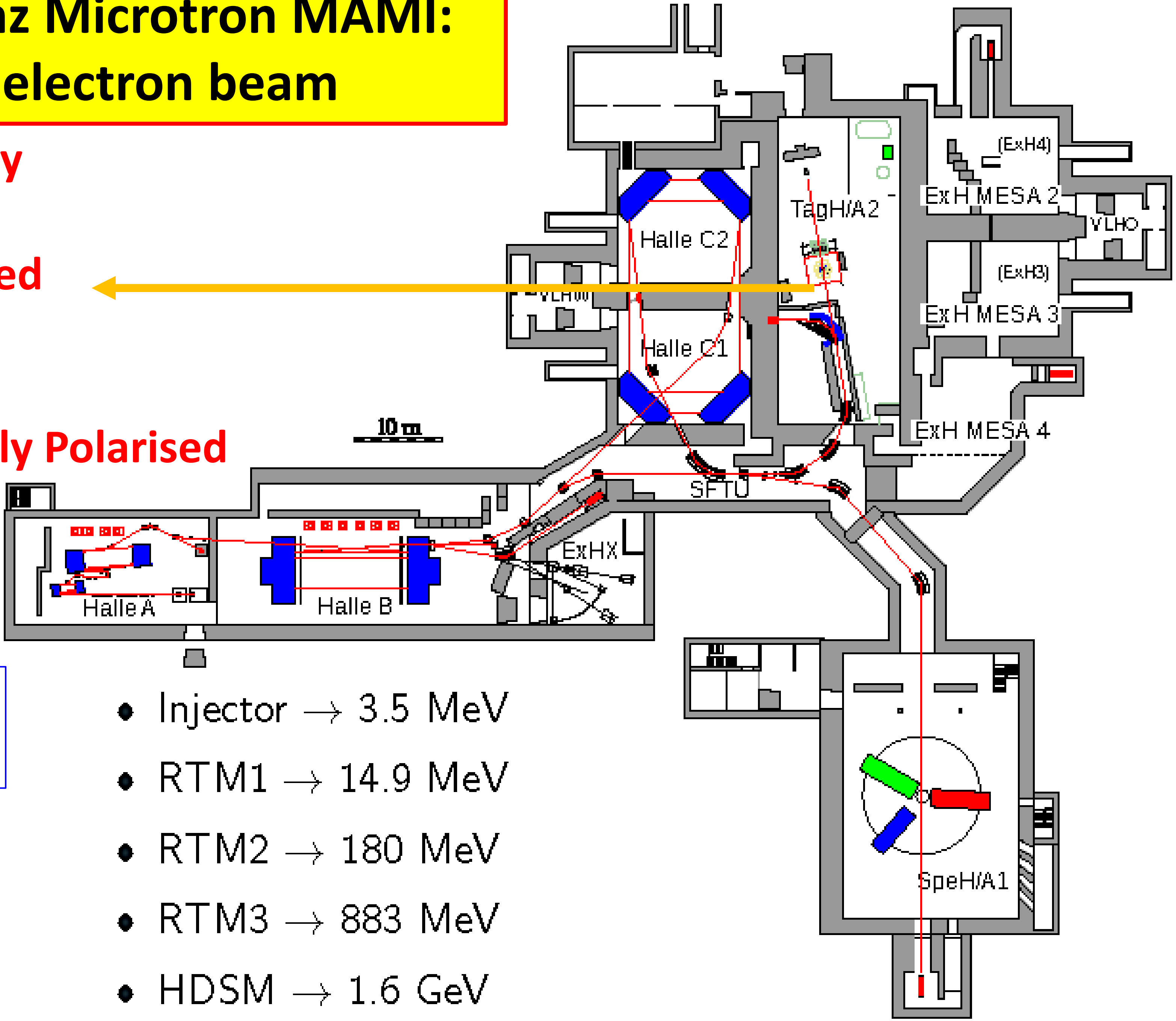
Experimental Set up

Mainz Microtron MAMI: electron beam

A2 Hall: Tagged photon facility

Linearly and Circularly Polarised Bremsstrahlung photons

Longitudinally and Transversely Polarised proton/deuteron targets

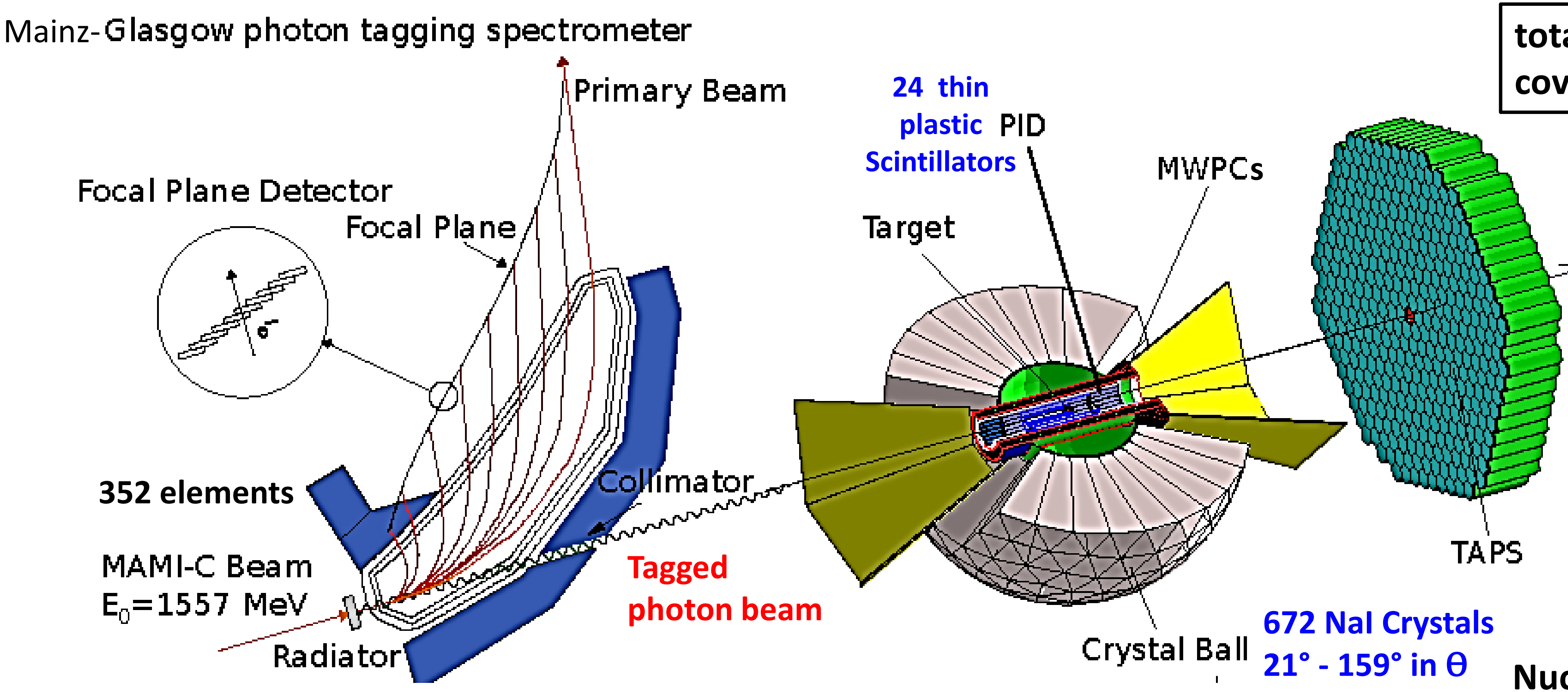


- Injector → 3.5 MeV
- RTM1 → 14.9 MeV
- RTM2 → 180 MeV
- RTM3 → 883 MeV
- HDSM → 1.6 GeV

MAMI: High stability
Low beam divergence

Very good properties of the secondary bremsstrahlung photon beam

A2@MAMI: Detector overview

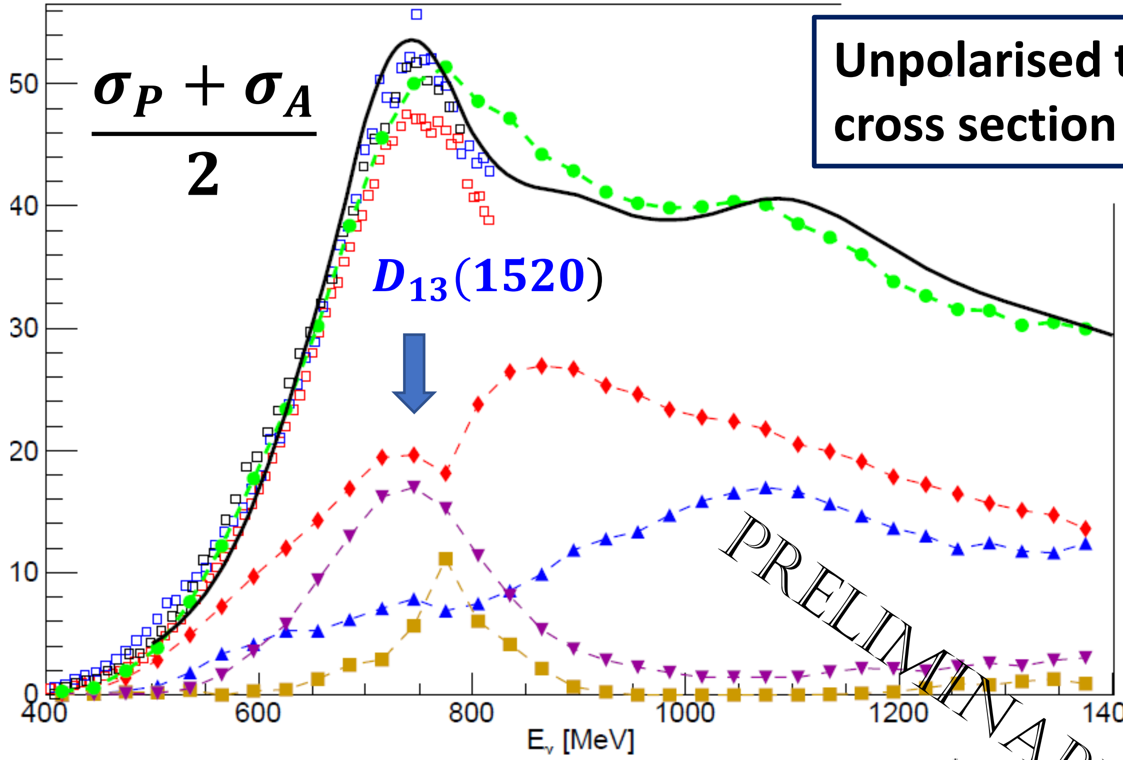


total solid angle coverage is 97%

Nucleon polarimeter (graphite cylinder) also available

Photon beam produced by bremsstrahlung and tagged by a magnetic spectrometer $E_\gamma = E_0 - E_{e^-}$; $\Delta E_\gamma = 1 - 4$ MeV

Results



Unpolarised total cross section

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

● A2 data - Preliminary

Previous data

▲ $\gamma p \rightarrow n\pi^0\pi^+$

■ $\gamma p \rightarrow \Delta^+\pi^0 \rightarrow n\pi^0\pi^+$

♦ $\gamma p \rightarrow \Delta^0\pi^+ \rightarrow n\pi^0\pi^+$

▼ $\gamma p \rightarrow \rho^+ n \rightarrow n\pi^0\pi^+$

First decomposition of all the intermediate reaction states (full event-by-event kinematical reconstruction)
Differential cross sections also measured

PRELIMINARY DATA

(with circularly polarised photons and longitudinally polarised protons)

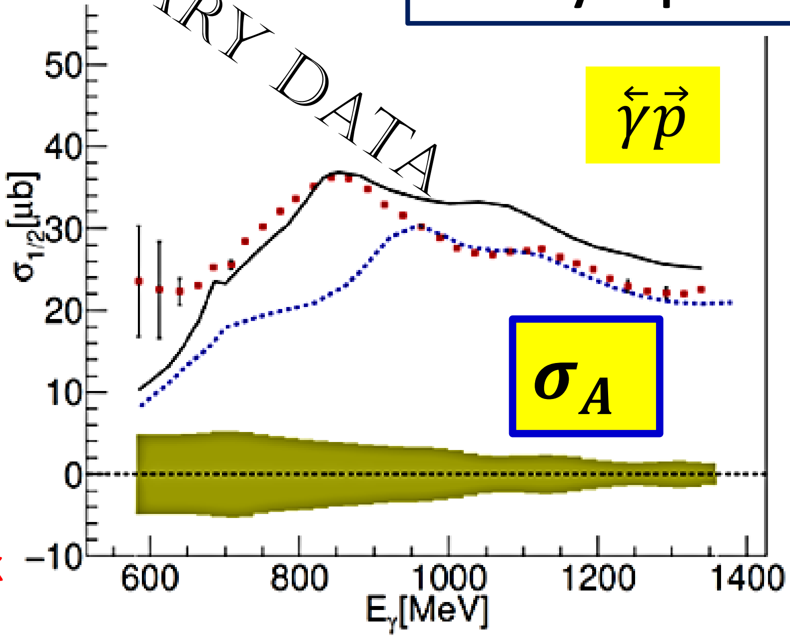
Helicity dependent total cross sections

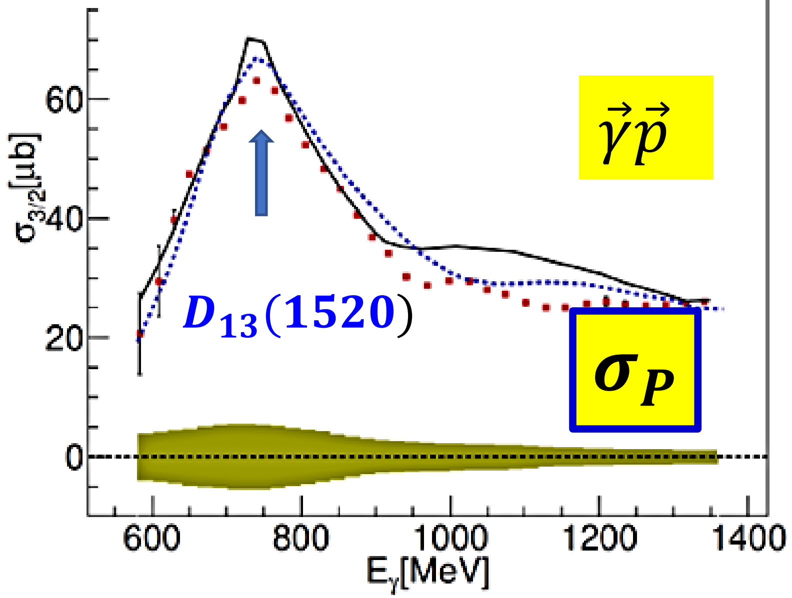
MAID -2π model - 2019

(H. Arenhoevel, A. Fix, EPJA 25, 115 (2005))

MAID -2π model -fitted to the data

Relevant impact on the model predictions





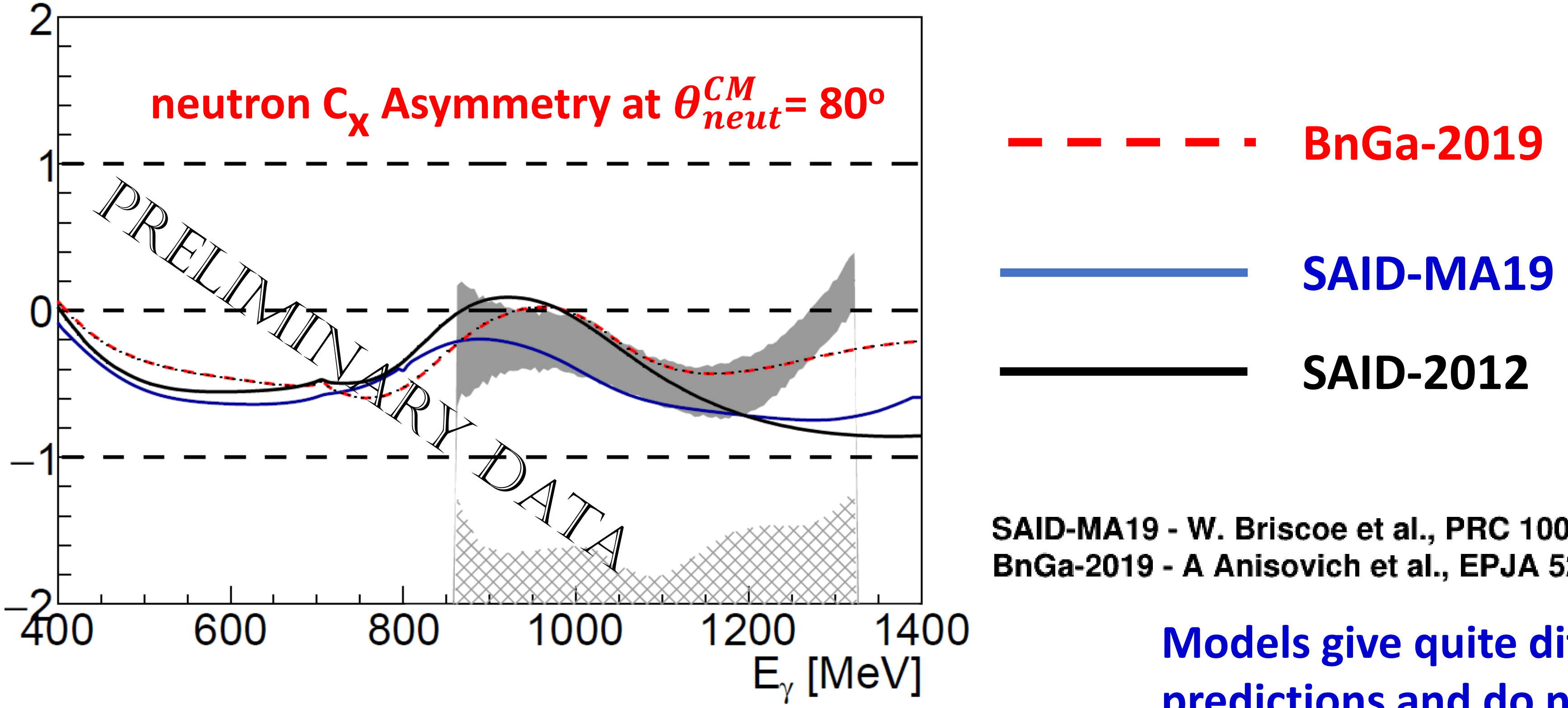
Many more results ⇒ S. Lutterer's talk
Thursday - Parallel 1 -17:00

$\vec{\gamma} p \rightarrow \vec{n} \pi^+$

First measurement of the neutron C_x Asymmetry

No previous data exist

Polarisation transfer from a circularly polarised photon beam to the final-state neutron



Constraints given by other measured observables have significantly modified the SAID predictions

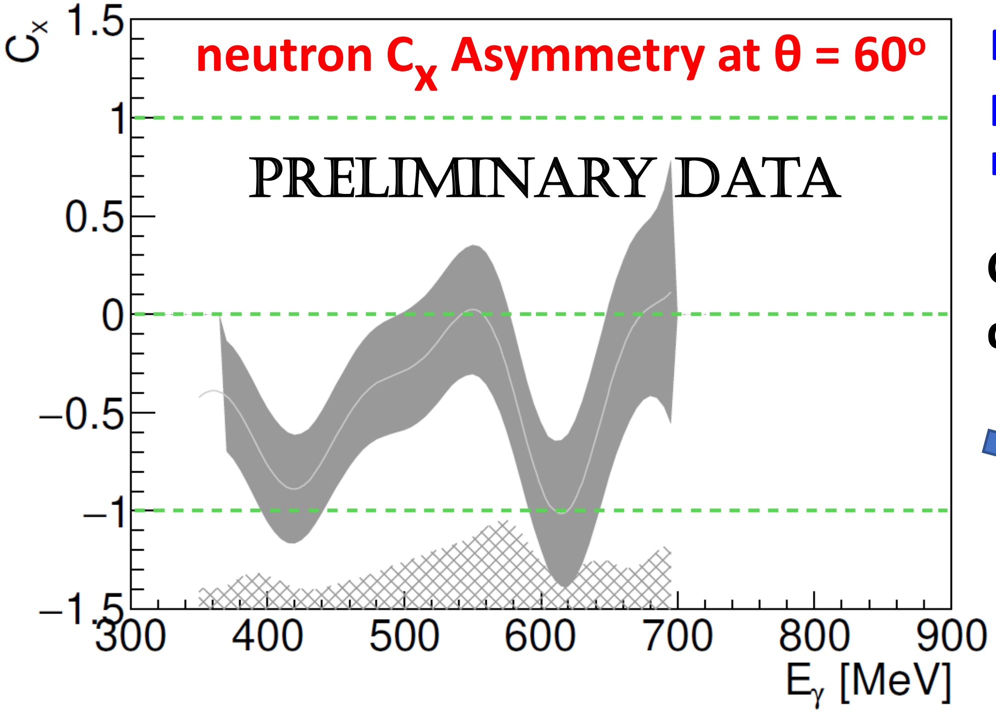
SAID-MA19 - W. Briscoe et al., PRC 100, 065205 (2019)
BnGa-2019 - A Anisovich et al., EPJA 52 284 (2016)

Gray band:

68% statistical confidence interval obtained using an unbinned likelihood analysis combined with a bootstrap procedure

Models give quite different predictions and do not well agree with data

Many more data ⇒ M. Bashkanov talk - Wednesday - Parallel 3 -17:00



Polarisation transfer from a circularly polarised photon beam to the recoil neutron

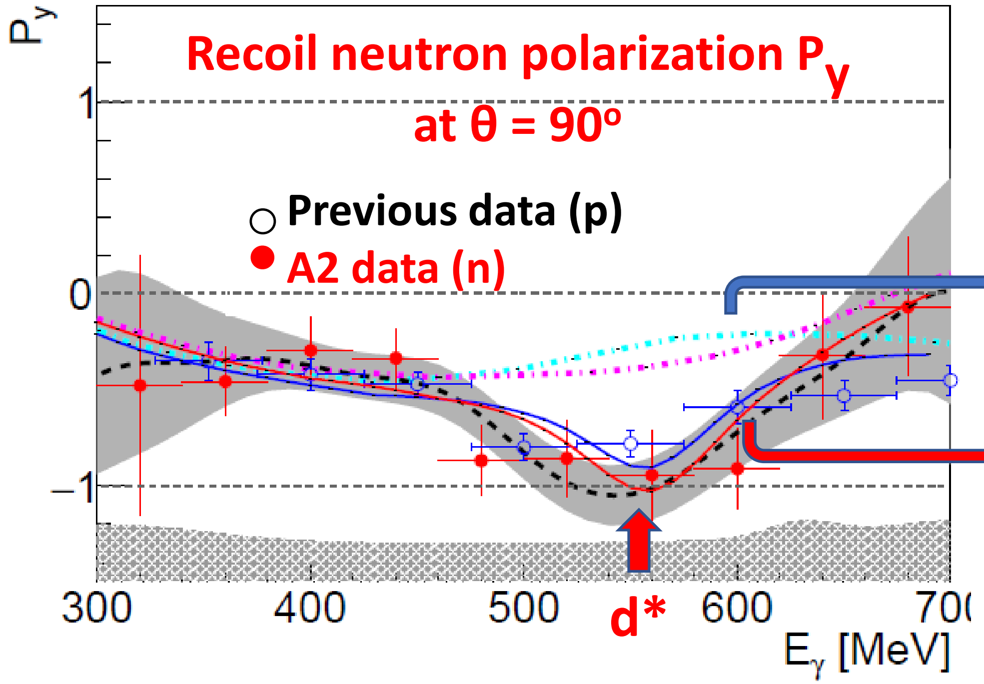
$$\vec{\gamma} d \rightarrow \vec{n} p$$

Gray band: 68% statistical confidence interval

Argand-type plot of the same amplitudes sensitive to d*(2380)

d*(2380) exaquark state evidenced in *N-N* scattering experiments by the WASA-at-COSY coll. [P. Adlarson et al, PRL 106 (242302), 2011]

$$\boldsymbol{M_{d^*} \sim 2380\ MeV}$$
$$\boldsymbol{\Gamma \sim 70\ MeV}$$
$$\boldsymbol{I(J^P) = 0(3^+)}$$



○ I. Ikeda et al., PRL 42 1321 (1979)

● **M. Bashkanov et al., PRL 124, 132001 (2020)**

Models without d*(2380)

Models with d* (2380)

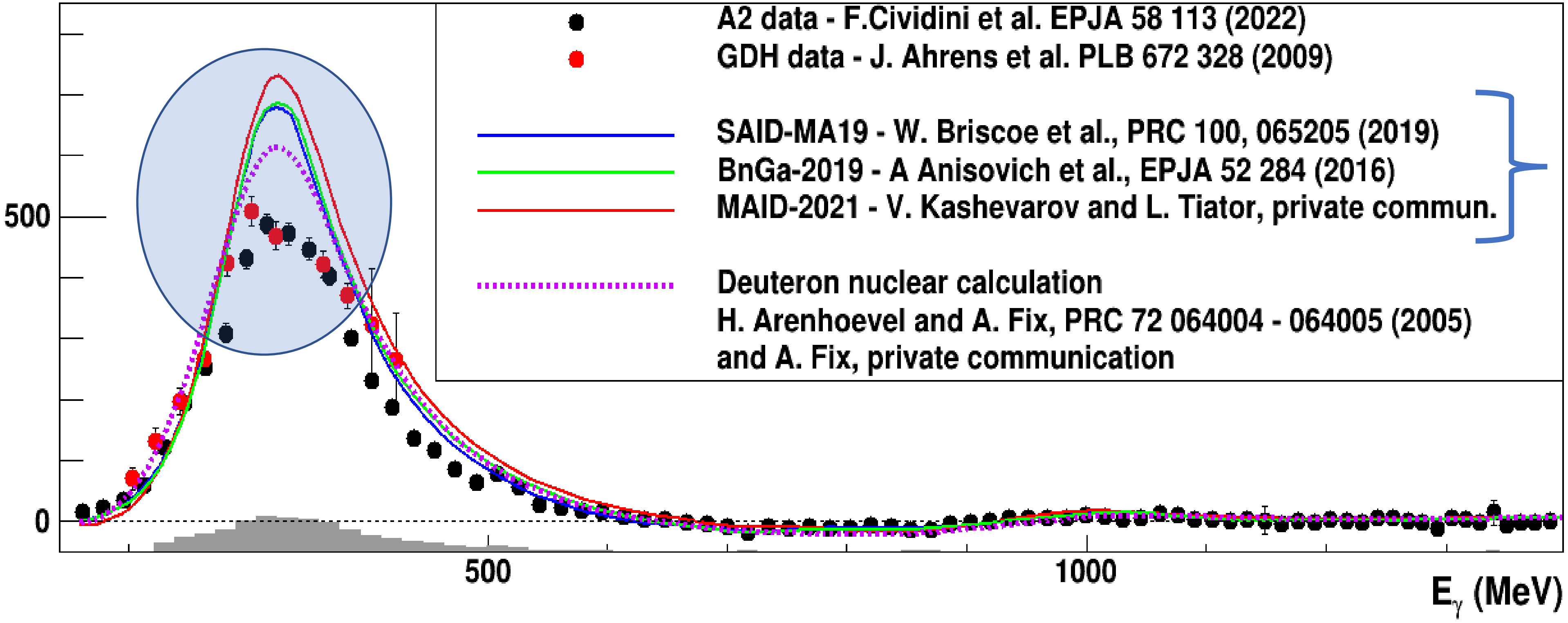
From photoreactions: contraints on its properties and determination of the e.m. couplings (important for the dynamics of condensed matter systems such as neutron stars)

Many more data ⇒ M. Bashkanov talk Wednesday - Parallel 3 -17:00

$$\vec{\gamma}\vec{d} \rightarrow \pi^0 B \ (B = np \ or \ d)$$

$(\sigma_P - \sigma_A) \ (\mu b)$

A2 data: F. Cividini et al, EPJA 58 113 (2022)



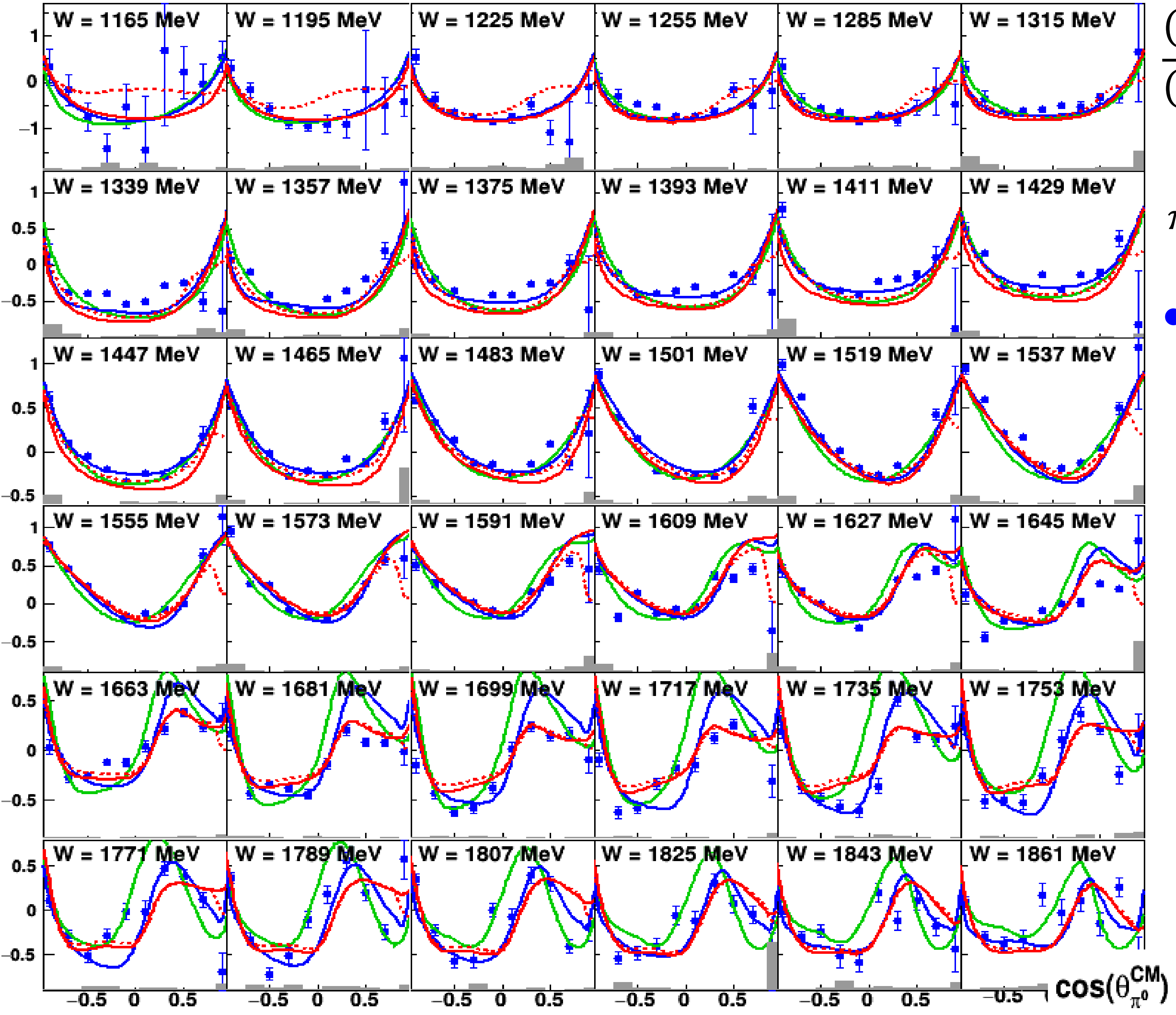
PWA analyses
Free p+n

Also precise differential coss sections data have been measured

Deuteron calculation: MAID-2021 free amplitudes are embedded into the deuteron wave function

Predicted decrease of the cross section (mainly due to FSI) in the Δ(1232) resonance region it is not sufficiently strong to reproduce experimental data

Many more results ⇒ P. Martel's talk Thursday - Parallel 1 -17:30



$$\frac{(\sigma_A - \sigma_P)}{(\sigma_A + \sigma_P)}$$

$$\boxed{\vec{\gamma}\vec{n} \rightarrow \pi^0 n}$$

E asymmetry for quasi –free neutrons

$\pi^0 n$ coincident detection [P_n > 350 MeV/c]

- **F. Cividini et al, EPJA 58 113 (2022)**
  (no previous data exist)

SAID-MA19
MAID-2021
BNGa-2019
Free neutron

Nuclear model (A. Fix)

For *W* > 1300 MeV data can be used to extract properties of the free-neutron without (relevant) model-dependent corrections

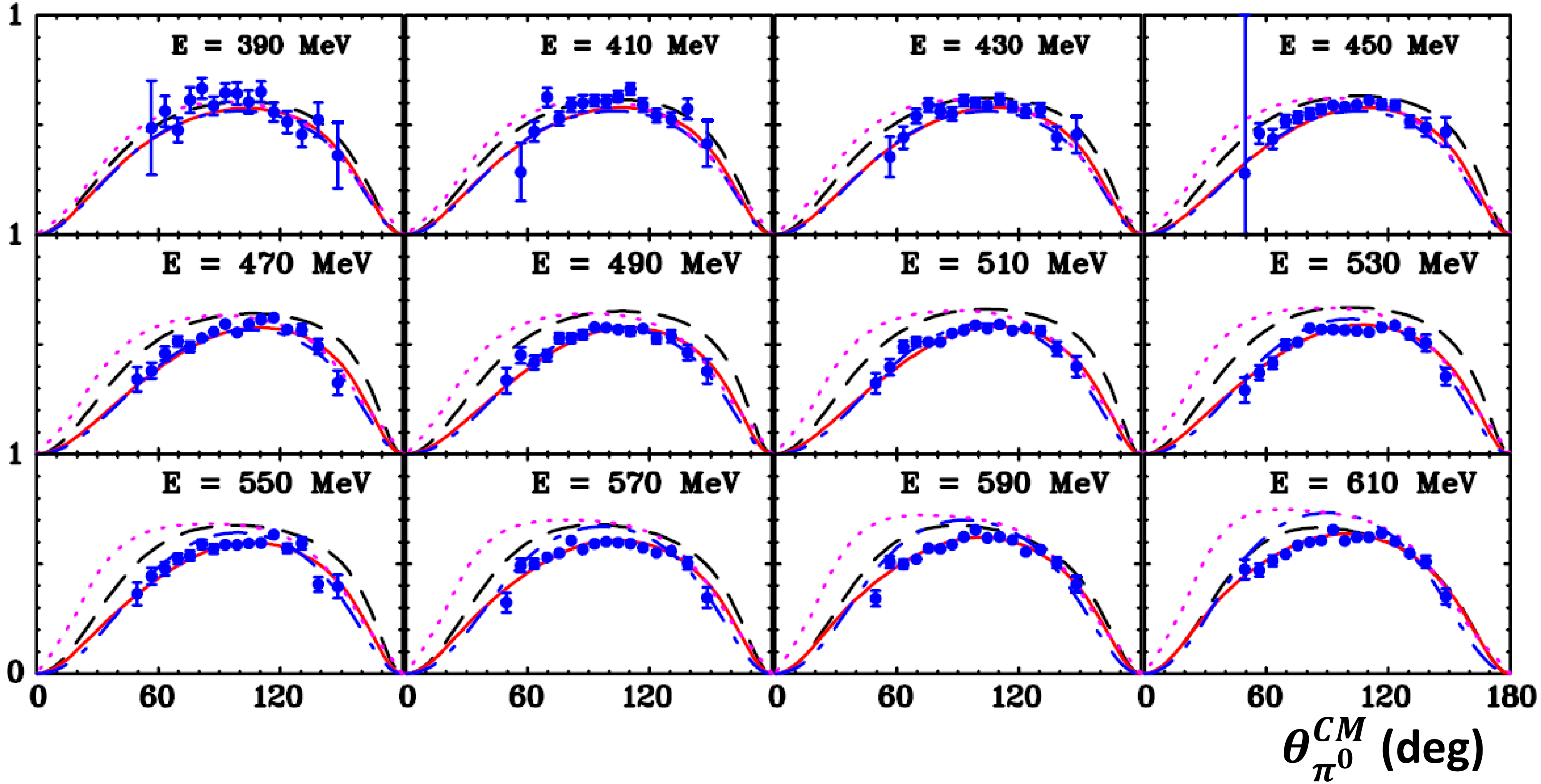
Many more results ⇒ P. Martel talk Thursday - Parallel 1 -17:30

$\boxed{\gamma^{\uparrow} n \rightarrow \pi^0 n}$

$\pi^0 n$ coincident detection

[P_n > 350 MeV/c]

Σ asymmetry $\frac{(\sigma_{||} - \sigma_{\perp})}{(\sigma_{||} + \sigma_{\perp})}$ **Linearly polarised photon beam and unpolarised deuteron target**



Free neutron PWA:

SAID-MA19

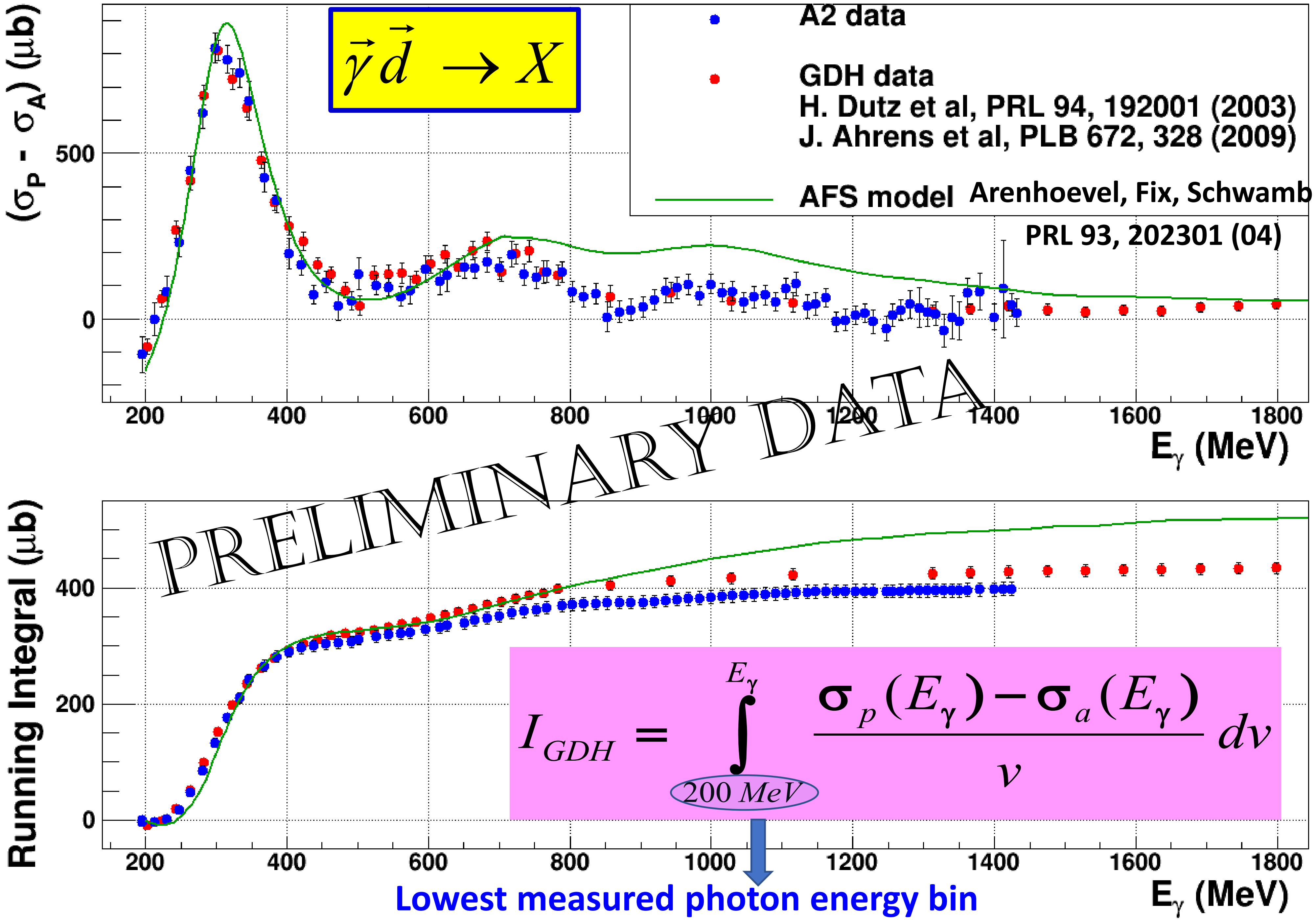
SAID-MU22
Fitted to the data

MAID- 2007

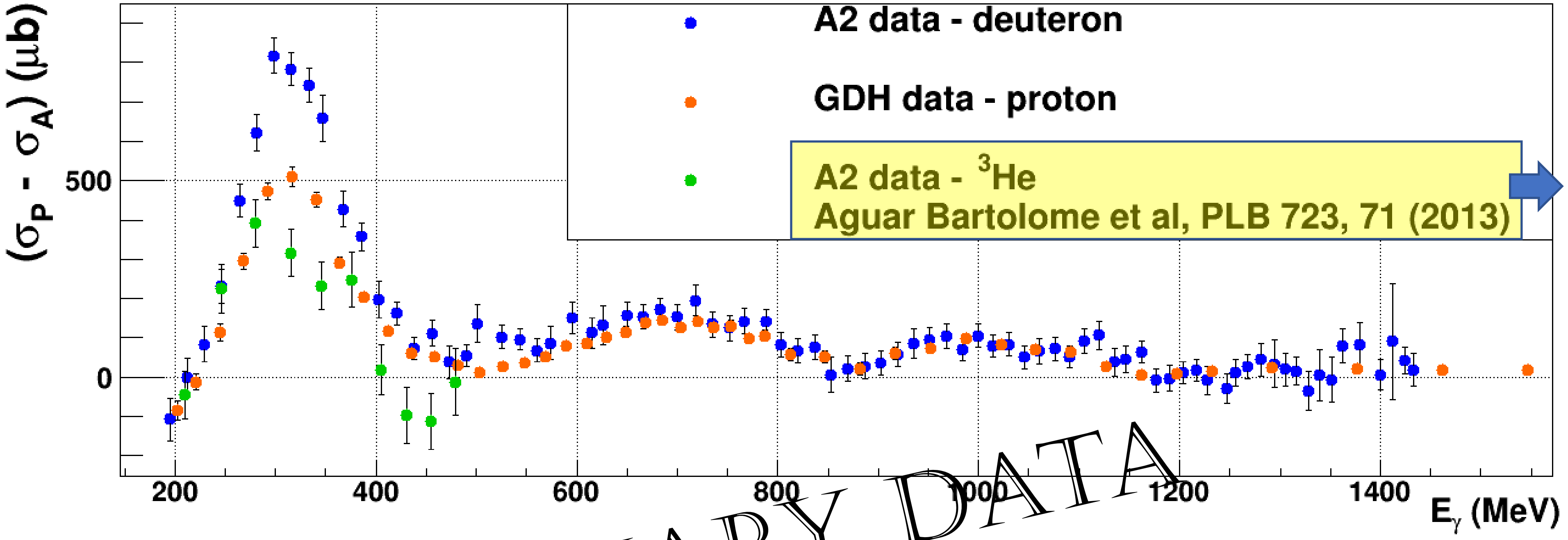
BNGa-2019

A2 data

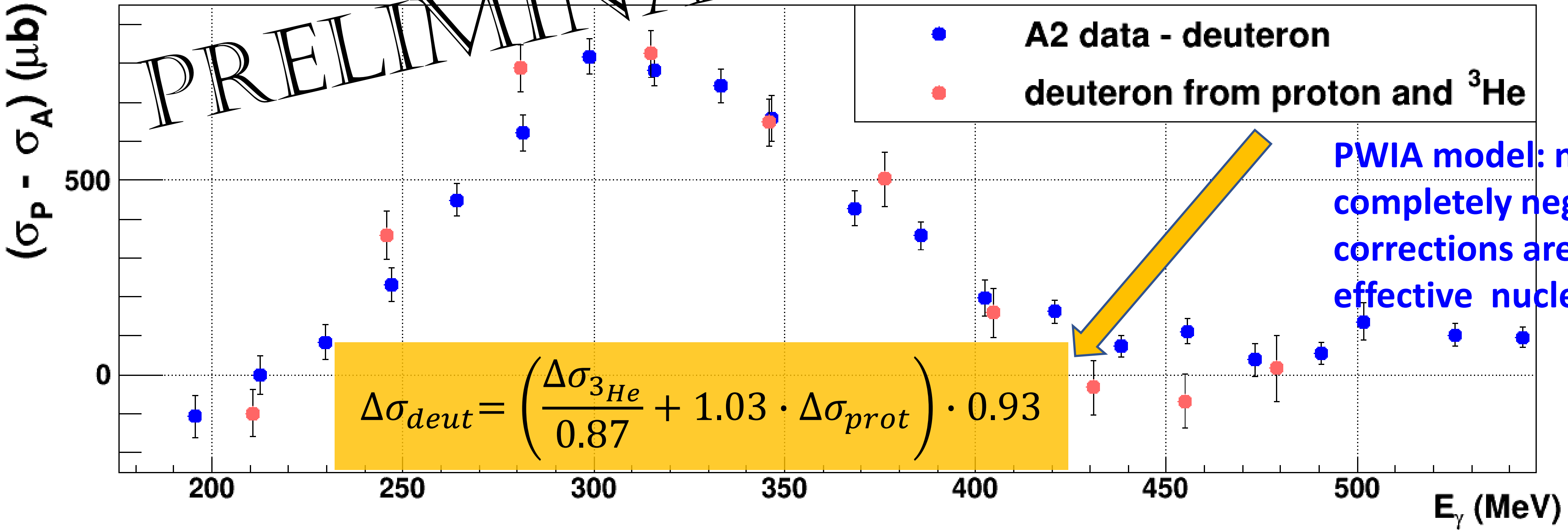
C. Mullen et al.
EPJA 57, 205 (2021)



$\vec{\gamma}\vec{d} \to X$
A2 data
GDH data
H. Dutz et al, PRL 94, 192001 (2003)
J. Ahrens et al, PLB 672, 328 (2009)
AFS model Arenhoevel, Fix, Schwamb
PRL 93, 202301 (04)
$(\sigma_P - \sigma_A)$ (μb)
E_γ (MeV)
PRELIMINARY DATA
Running Integral (μb)
$I_{GDH} = \int_{200\ MeV}^{E_\gamma} \frac{\sigma_p(E_\gamma) - \sigma_a(E_\gamma)}{\nu} d\nu$
Lowest measured photon energy bin



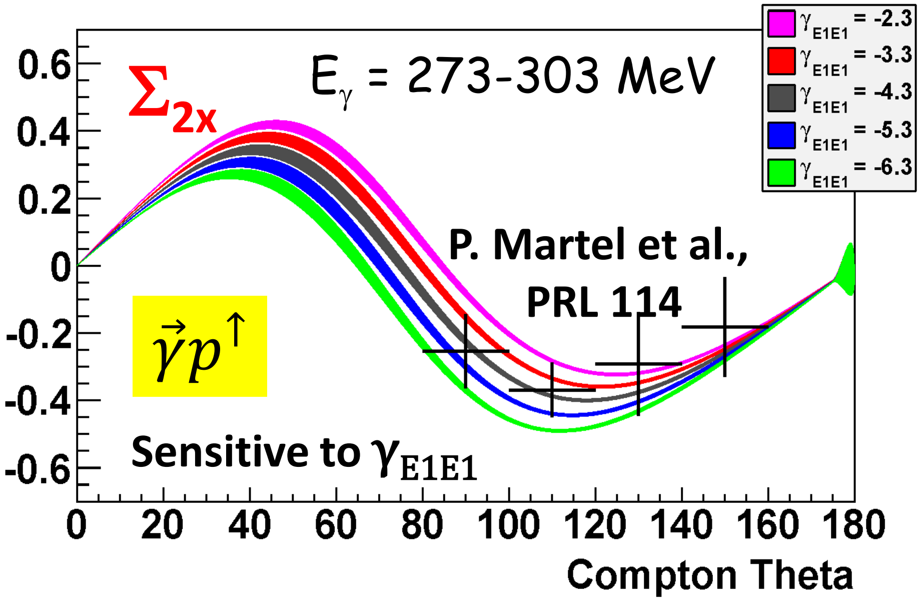
Pilot experiment

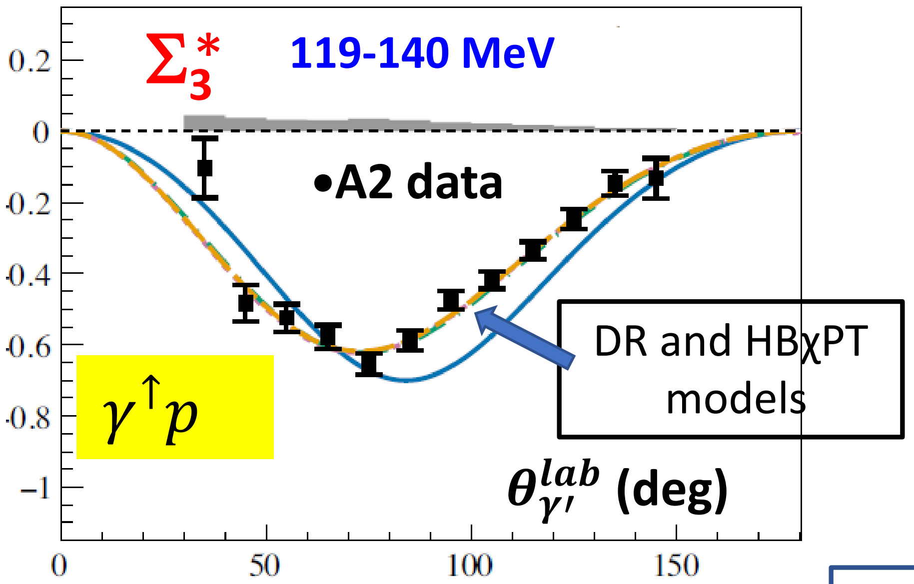


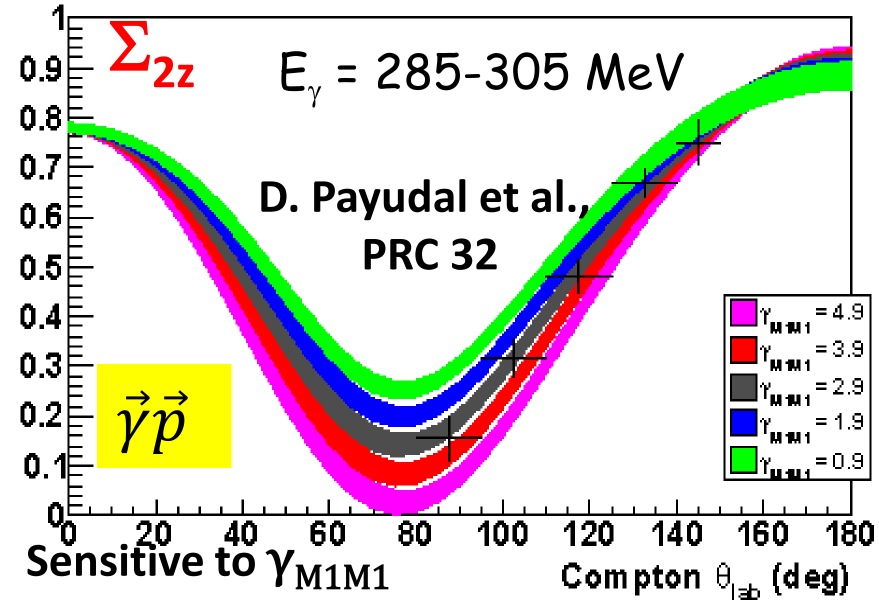
$$\Delta\sigma_{deut} = \left(\frac{\Delta\sigma_{3_{He}}}{0.87} + 1.03 \cdot \Delta\sigma_{prot}\right) \cdot 0.93$$

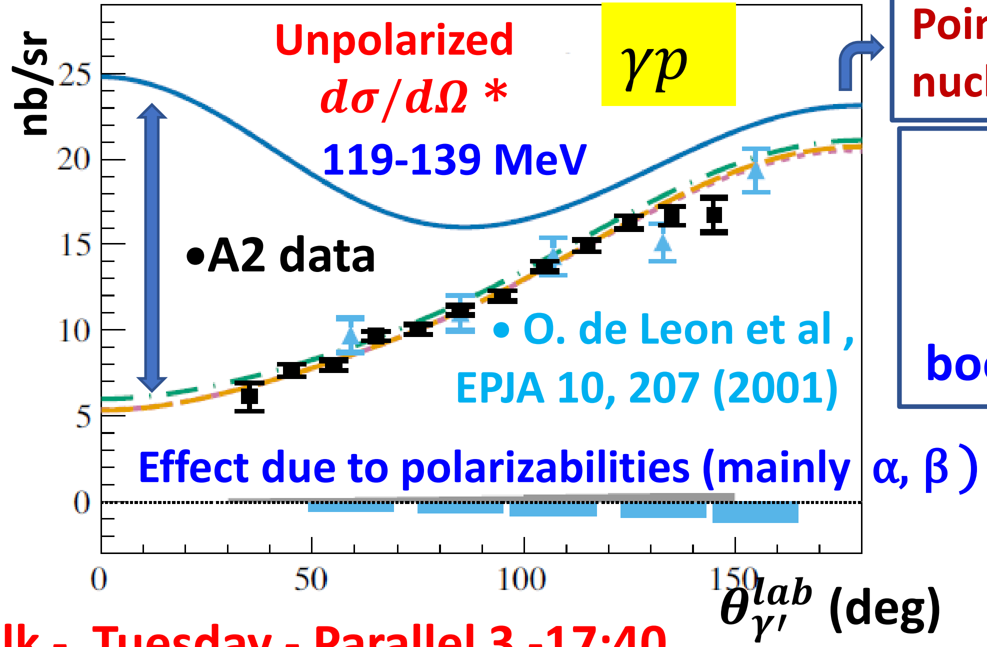
PWIA model: nuclear effects completely neglected; only corrections are due to the effective nucleon polarisation

(Un)Polarized Compton Scattering on the proton









* E. Mornacchi et al., PRL 128, 132503 (2022)

60 $d\sigma/d\Omega$ points

36 Σ_3 points

Between 86-140 MeV

Huge improvement of the quality and the quantity of the existing Compton database

Pointlike nucleon

First simultaneous determination of all 6 polarizabilites with a new bootstrap-based fitting method

E. Mornacchi et al., PRL 129, 102501 (2022)

Many more results ⇒ E. Mornacchi talk - Tuesday - Parallel 3 -17:40

Conclusions

- Rutherford discovered the proton in 1917 and since 1933 (Stern-Gerlach experiment) we know that it is not an elementary particle

- **Understanding the proton (neutron) internal structure is a very severe challenge both on the theoretical and on the experimental side**

- The joint effort of several laboratories (Mainz, Bonn, JLAB, LEPS, …) and the technological development in polarized beam and target techniques will solve some long-standing problems (how many baryon resonances are there?, accurate determination of the polarizabilities, …)

- **The A2 collaboration is an important player of this game: many published data, many more to come and to be collected.**

A2 Collaboration

$\simeq$ 60 researchers

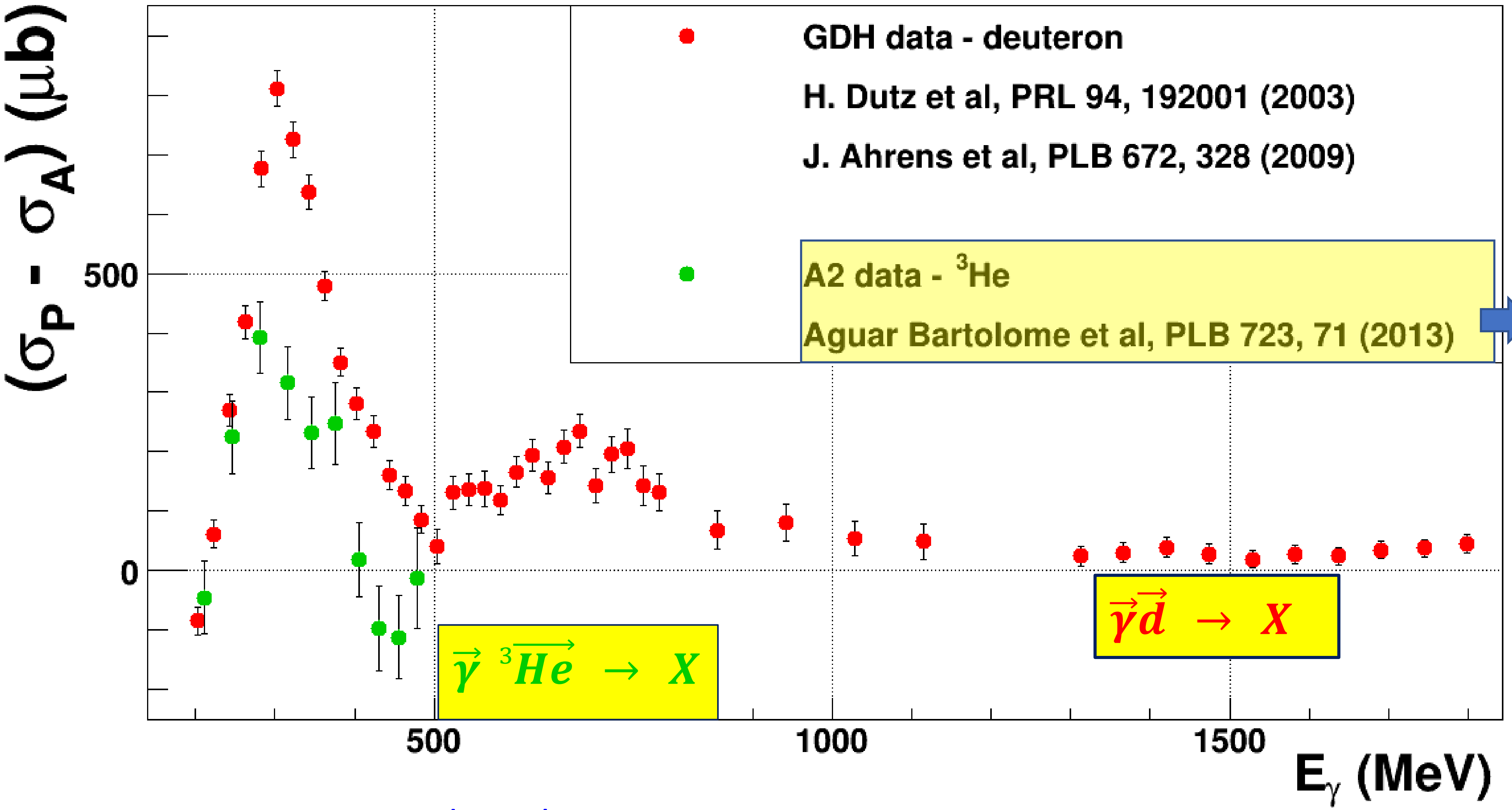
Participating Institutions

Europe: Universities of Mainz, Basel, Bochum, Bonn, Glasgow, York, INFN-Pavia, JINR-Dubna, RBI-Zagreb

North-America: Universities of Mount-Allison (Canada), Regina (Canada), Washington-DC (USA), Kent-OH (USA), Amherst-MASS (USA)

Riserva

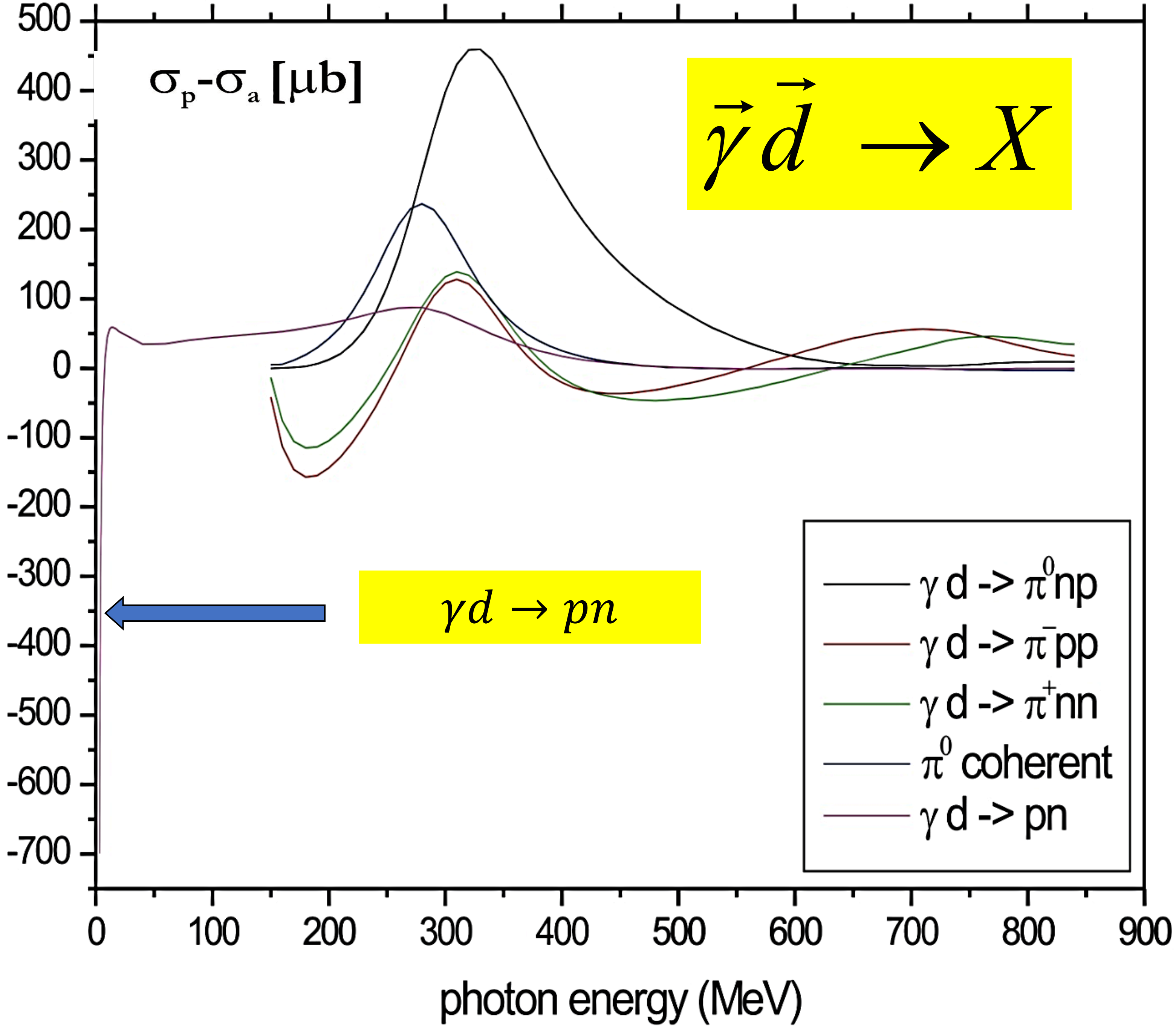
Experimental status – GDH on nuclei



Pilot experiment using for the first time a high-pressure polarised gas target in a photon beam

Deuteron: scarce data above 800 MeV

Helicity dependence of partial channels (total and differential cross sections) needs also to be measured to study nucleon modifications inside the nuclear medium and as a tool to access free-neutron information



AFS model

Arenhoevel, Fix, Schwamb, PRL 93, 202301 (04)

πNN πN from MAID PWA +nuclear effects

$\pi\pi$NN EPJA 25,114 (05)

π^0d PLB 407,1 (97)

pn NPA 690,682 (01)

$$\left[I_{GDH}^{deut}\right]_{AFS} = 27\mu b$$

GDH sum rule on deuteron and ^{3}He

PWIA approach

$E_\gamma > m_\pi$

$$\text{n p}$$

- ^{2}H: $\mu \sim \mu_p + \mu_n \Rightarrow \uparrow\uparrow$

$$I_{GDH}^{Deut} \sim 0.93 \cdot I_{GDH}^{neutron} + 0.93 \cdot I_{GDH}^{proton}$$

Effective nucleon polarisation
(correction for the D-state)

$$\text{n p p}$$

- ^{3}He: $\mu \sim \mu_n \Rightarrow \uparrow\uparrow\downarrow$ (S-state with ~ 90% prob.)

$$I_{GDH}^{He3} \sim 0.87 \cdot I_{GDH}^{neutron} - 0.026 \cdot I_{GDH}^{proton}$$

GDH sum rule

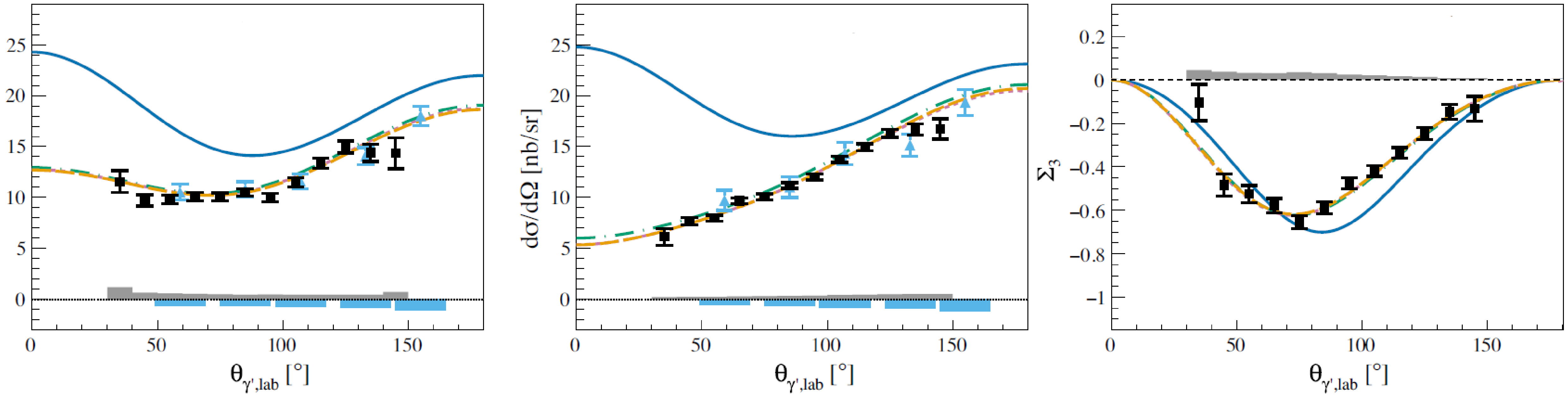
Fundamental check of our knowledge of the γ–Nucleon interaction

The only "weak" hypothesis is the assumption that **Compton scattering $\gamma N \rightarrow \gamma' N'$ becomes spin independent when $\nu \rightarrow \infty$** *A* violation of this assumption can not be easily explained (non pointlike quarks ???)

✓ Important comparison for photoreaction models

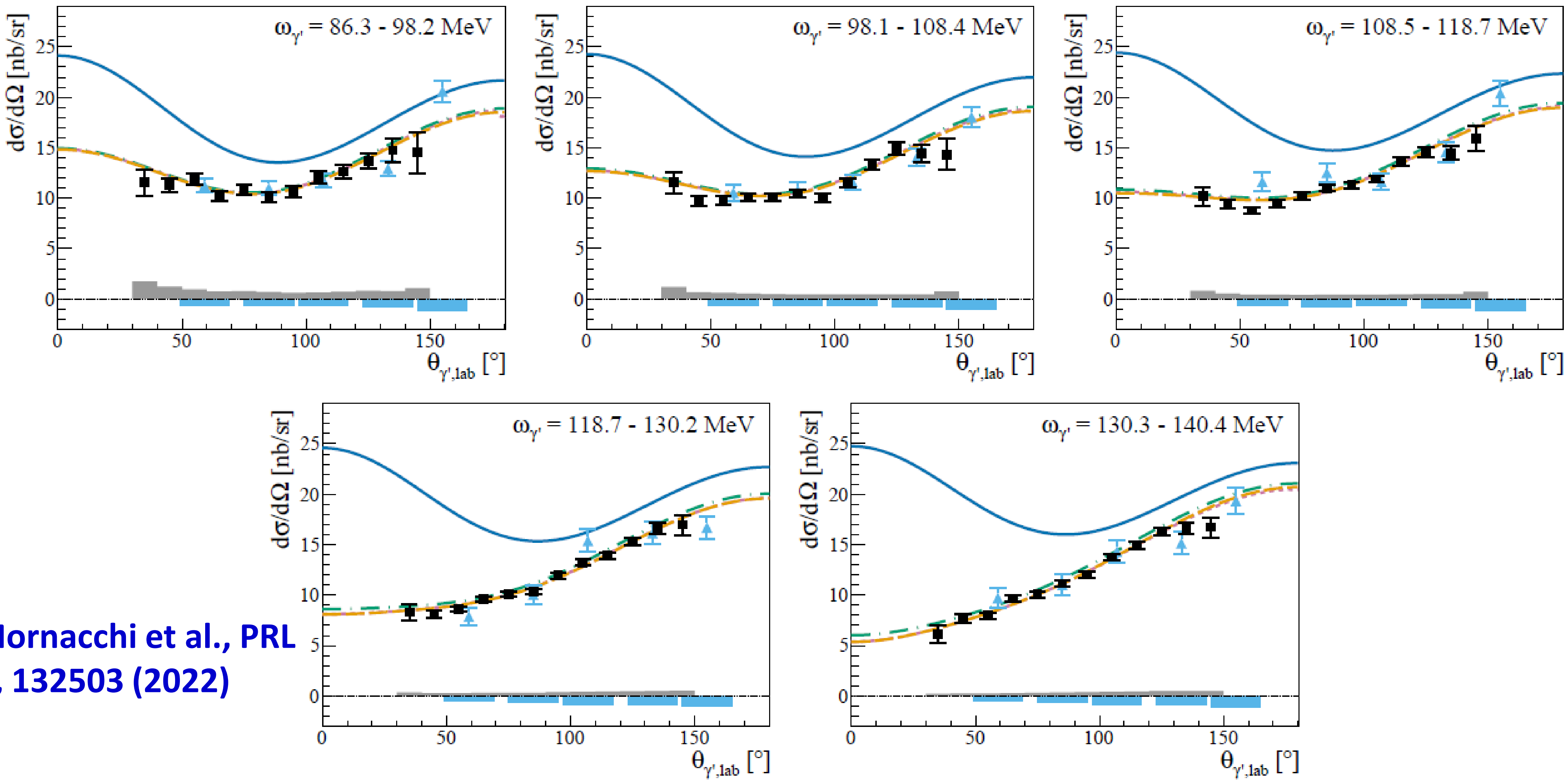
✓ Helicity dependence of partial channels (pion photoproduction) is an essential tool for the study of the baryon resonances (interference terms between different electromagnetic multipoles)

✓ Valid for any hadronic system with $\mathbf{k} \neq 0$ (^{2}H, ^{3}He, ...) . Interplay between different degrees of freedom



25
20
15
10
5
0
0
50
100
150
θγ',lab [°]
dσ/dΩ [nb/sr]
Σ3
0.2
−0.2
−0.4
−0.6
−0.8
−1

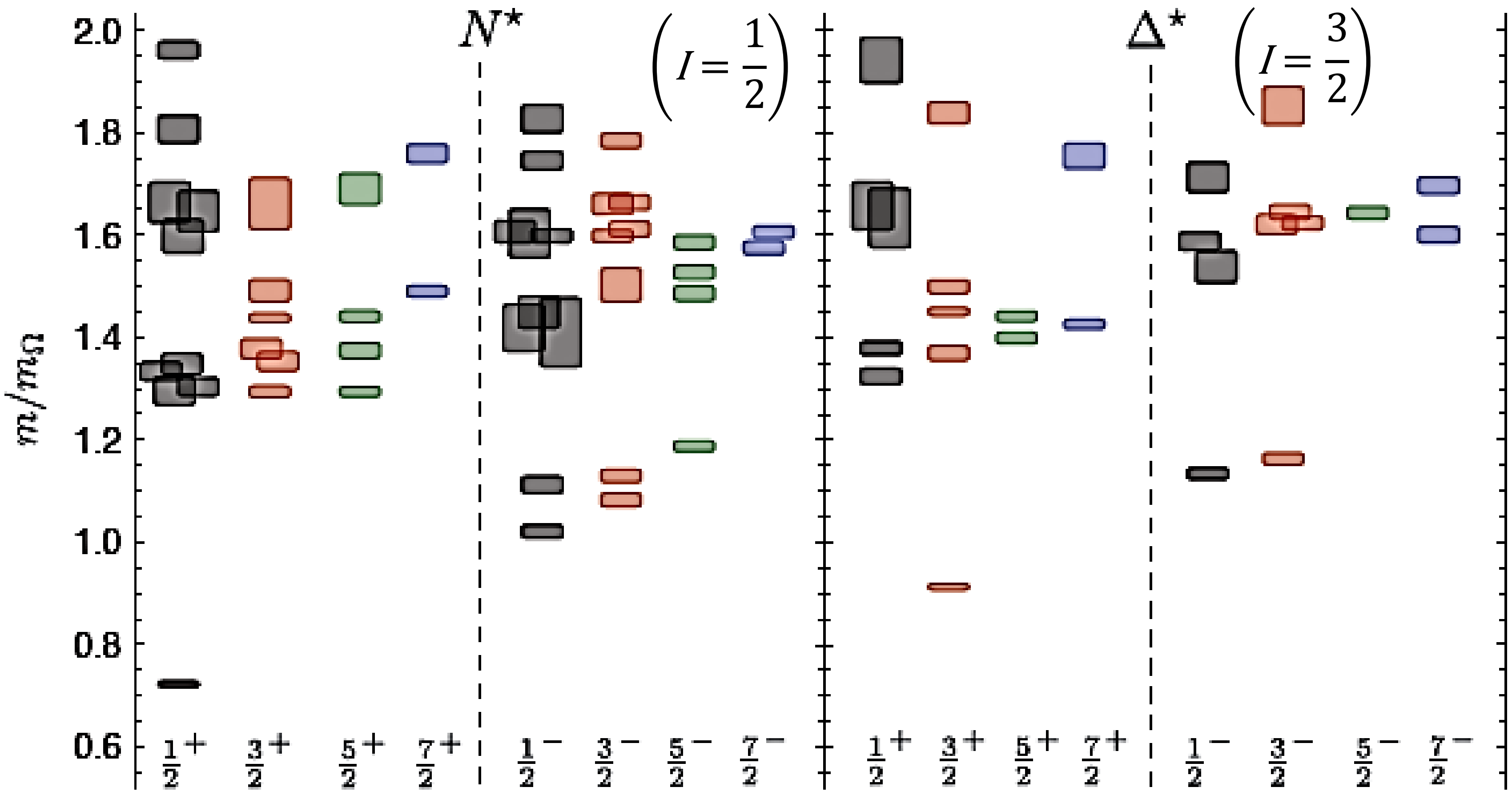
Unpolarized Compton Scattering on the proton



E. Mornacchi et al., PRL 128, 132503 (2022)

A Lattice QCD model

Edwards et al, PRD 84 074508 (2011)



- Results for m_π = 396 MeV
- State-of-the art methods still yield a (too) large number of states

Total inclusive cross section

$$\sigma_{total} = \cancel{\sum \text{partial channels}}$$ **(not feasible)**

$$\sigma_{total} = \sum \text{hadrons}$$ **(inclusive method)**

For each partial reaction channel, at least one reaction product has to be detected with (almost) complete acceptance (solid angle & efficiency)

a) detector with a very high acceptance/particle detection efficiency (CB+TAPS: 97% of 4π)

b) Suppression of e.m. events (pair prod./Compton)

Threshold Cerenkov detector placed at forward angles (in front of TAPS)