(Some Recent) Results from the A2 experiment at Mainz

Paolo Pedroni

INFN-Sezione di Pavia, Italy

For the A2@MAMI collaboration
(Mainz-Germany)

Istituto Nazionale
di Fisica Nucleare
Sezione Pavia

SUMMARY

- **Physics motivations** **Study of the hadron properties using (real) photons**

Understanding the hadron structure in the non-perturbative QCD regime

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

GDH and Baldin's sum rules

- Determination of the N* excitation spectrum

$\gamma N \rightarrow N\pi, N\eta, N\pi\pi, \ldots$

- π^0 TFF

- 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

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 electromagnetic hadronic structure is explored with a resolution dependent on photon energy

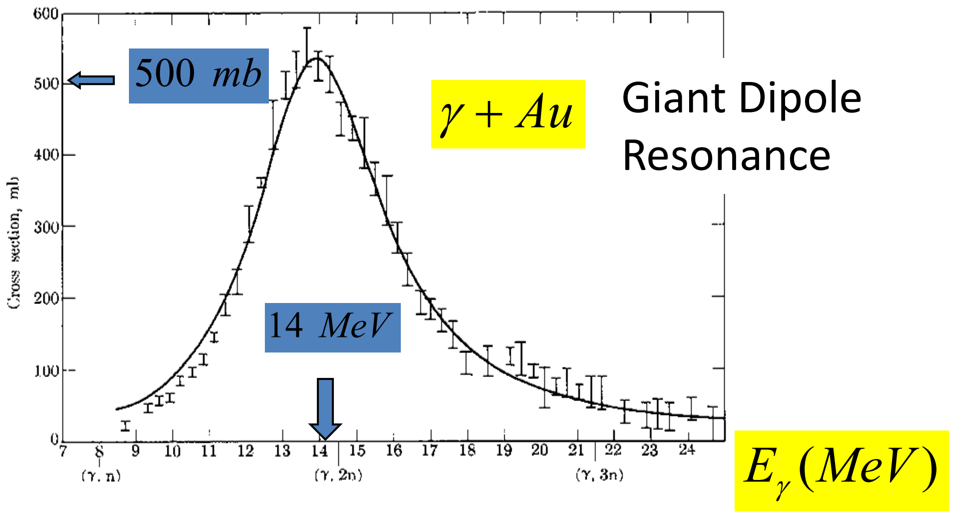
$$\lambda_\gamma \cong \frac{200(\mathrm{MeV \cdot fm})}{E_\gamma(\mathrm{MeV})}$$

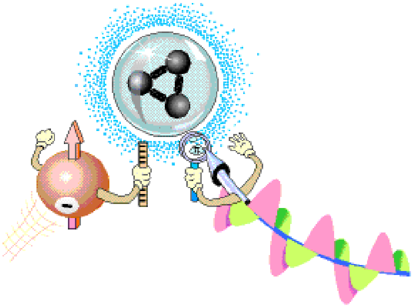
Study of the collective nuclear motions

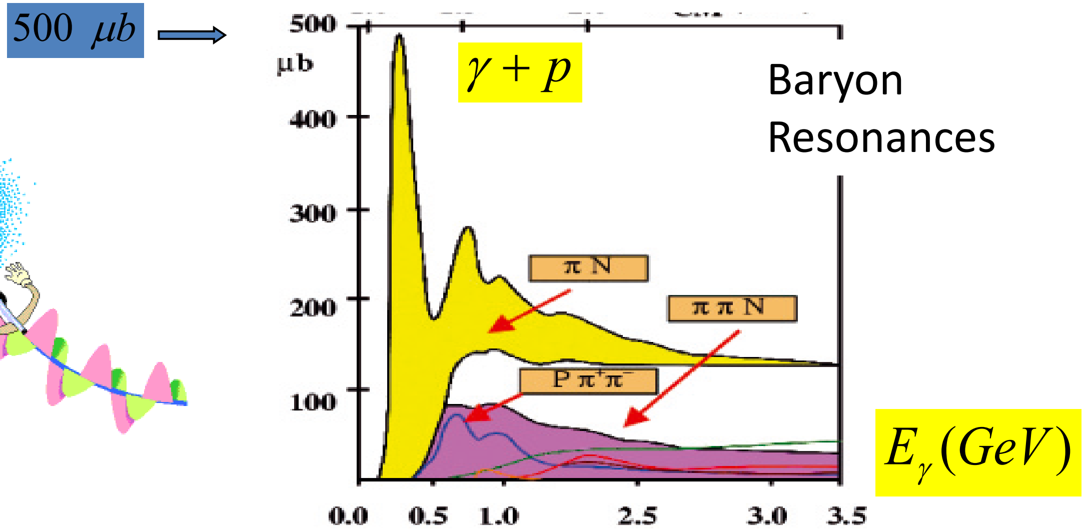
$E_\gamma \approx 20\ \mathrm{MeV} \Rightarrow \lambda_\gamma \approx 10\,\mathrm{fm}$

Study of the nucleon internal structure

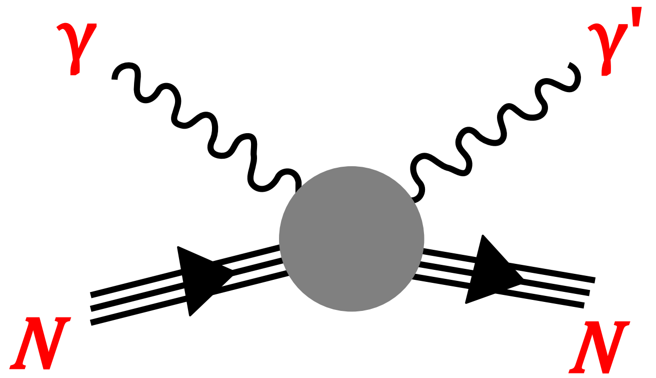
$E_\gamma > 200\ \mathrm{MeV} \Rightarrow \lambda_\gamma < 1\,\mathrm{fm}$







Real Compton Scattering (proton)



Expansion of the Hamiltonian in incident photon energy (ω)

0th order ⟹ **charge, mass** — «pointlike» nucleon (Born terms)

1st order ⟹ **magnetic moment (anomalous)** — (**Powell** cross section)

2nd order ⟹ **2 scalar polarizabilitites (induced electric/magnetic dipole moment)**

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

Baldin's sum rule: $(\alpha_{E1}+\beta_{M1}) \approx$ **known from** $\gamma p \rightarrow N\pi(\pi)$ ...

3rd order ⟹ **4 spin (vector) polarizabilitites (precession induced to the spin by a varying e.m. field)**

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

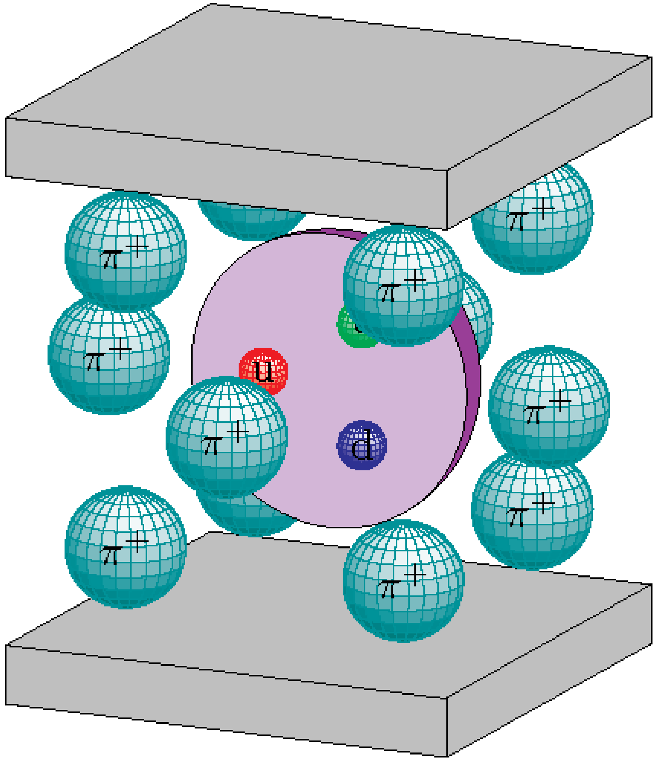
$$E_{ij} = \frac{1}{2}(\nabla_i E_j + \nabla_j E_i)$$
$$H_{ij} = \frac{1}{2}(\nabla_i H_j + \nabla_j H_i)$$

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

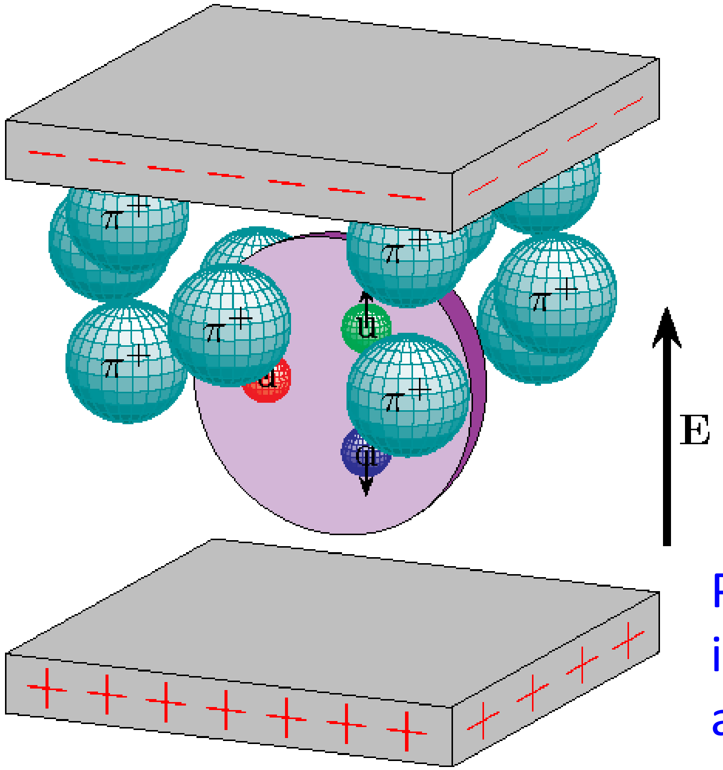
(not well known)

A special composite system: the nucleon

quark core surrounded by a virtual pion cloud



Electric Field OFF



Electric Field ON

Electric polarizability α

$$\vec{d}_{induced} = \alpha \vec{E}$$

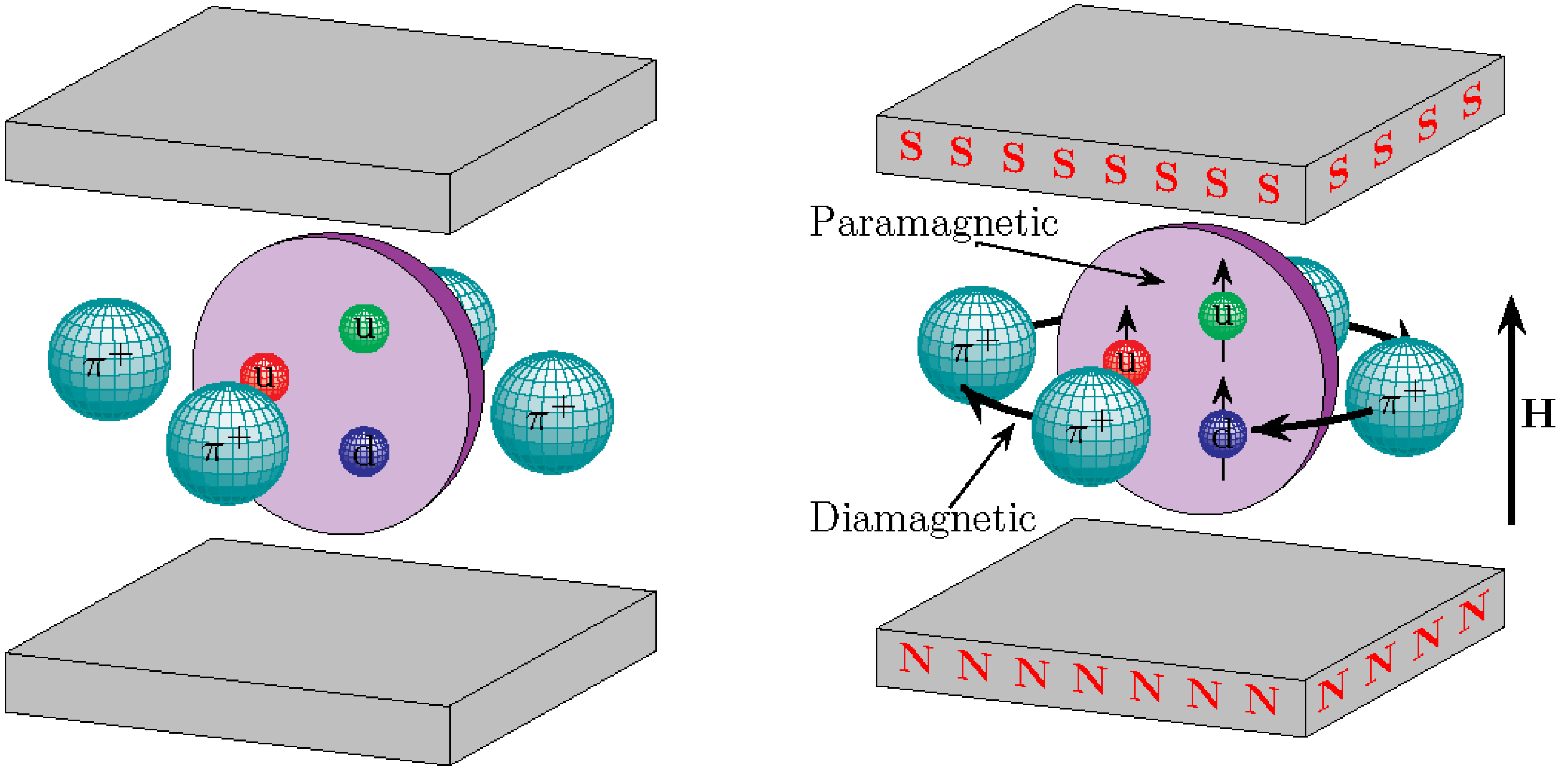
Proportionality constant between induced electric dipole moment and applied electric field

Electric polarizability

- Hydrogen atom $\alpha \approx 1 \cdot \mathbf{Volume}$
- Proton $\alpha \approx 10^{-3} \cdot \mathbf{Volume}$

Proton is a very stiff composite system

A special composite system: the nucleon



Magnetic Field OFF

Magnetic Field ON

quark core surrounded by a virtual pion cloud

Magnetic polarizability β

$$\vec{\mu}_{induced} = \beta \vec{B}$$

Proportionality constant between induced magnetic dipole moment and applied magnetic field

2 contributions that partially cancel out ➡ **Paramagnetic (due to spin)**
Diamagnetic (due to angular momentum)

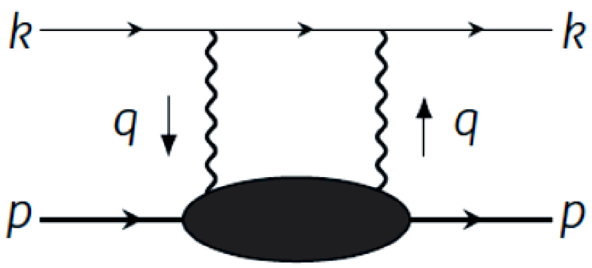
$(\beta < \alpha)$

Real Compton Scattering

- **Clear Probe to understand non perturbative QCD**
- **Measurement of fundamental parameters of the nucleon structure: charge, mass, k, polarizabilities**

- **Has impact also on other physics domains**

  - $(\alpha_{E1}, \beta_{M1})$ contribute to 2-photon exchange in μH Lamb shift



$\Delta E^{(2\gamma)} = \Delta E^{(el)}$ → Nucleon form factor

$+ \Delta E^{(inel)}$ → Nucleon structure function

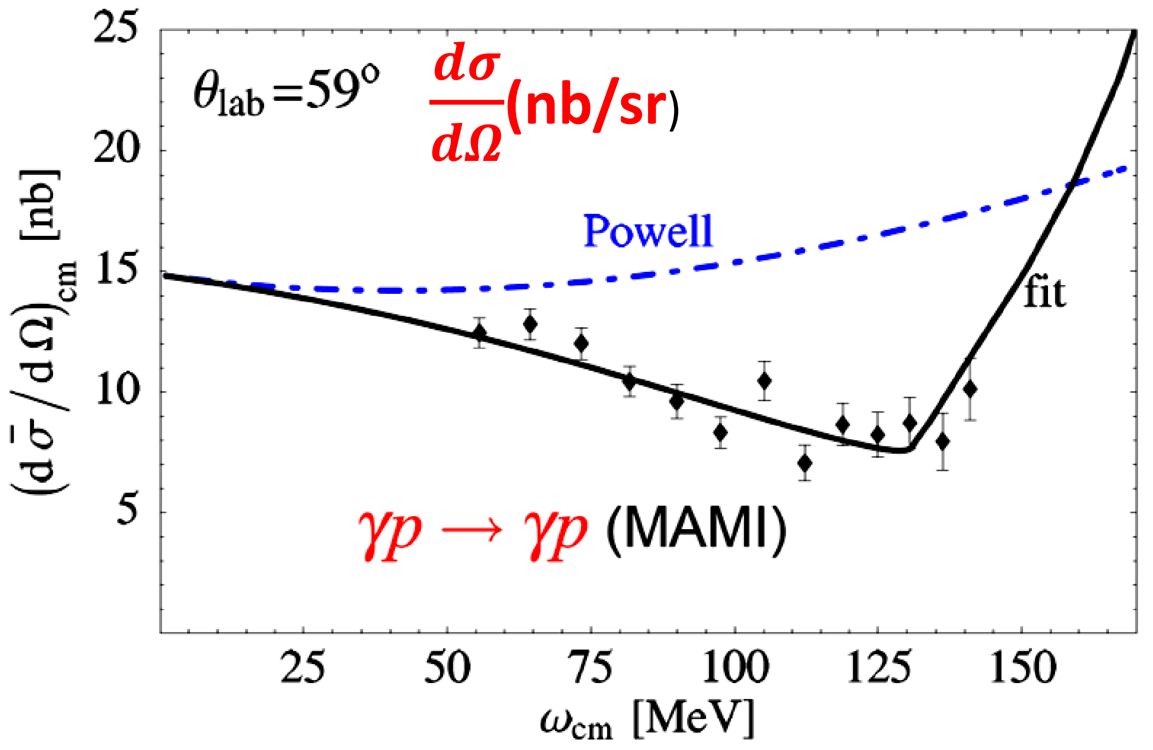
$+ \Delta E^{(sub)}$ → Nucleon polarizabilities

  - **Spin polarizabilities** enter in the extraction of the proton Zemach radius (convolution of charge and magnetic moment distributions)

  - **neutron polarizability β_{M1}** is the dominant contribution to the neutron star susceptibility

Real Compton Scattering

This is a quite difficult measurement....

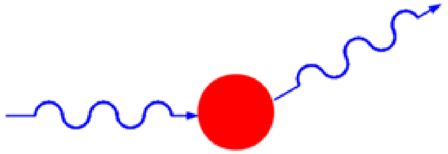


- Very small absolute cross section ($\approx \boldsymbol{nb}$)
- Effect due to polarizabilities only gives a «small» variation to the pointlike (Powell) contribution
- Several observables need to be measured to determine the contributions of the different electromagnetic multipoles (each multipole is sensitive to a specific polarizability)
  (polarized beams and targets are mandatory)
- Very large background from
  -) atomic Compton scattering: $\gamma e \rightarrow \gamma e$
  -) $\gamma p \rightarrow p\pi^0 \rightarrow p\gamma\gamma$ ($\omega > 146$ MeV)

  (cross sections order of magnitudes higher)

Polarizabilities: how can they be measured ?

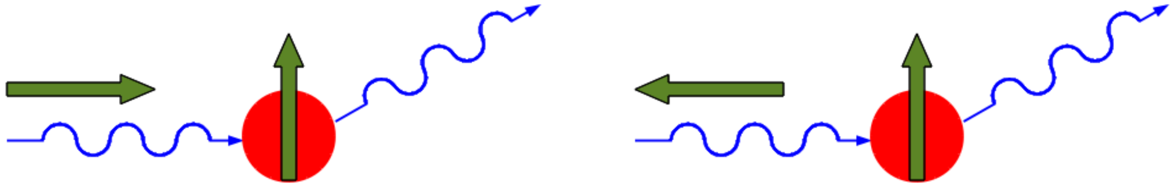
- Unpolarized photons, unpolarized protons.



Sensitive to α,β

- Circularly polarized photons, transversely polarized protons.

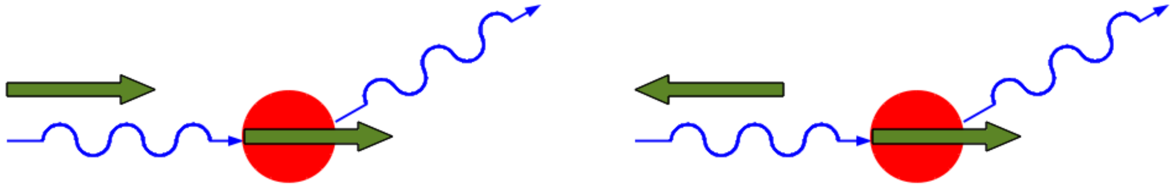
$$\Sigma_{2x} = \frac{N^R_{+x} - N^L_{+x}}{N^R_{+x} + N^L_{+x}}$$



Sensitive to γ_{E1E1}

- Circularly polarized photons, longitudinally polarized protons.

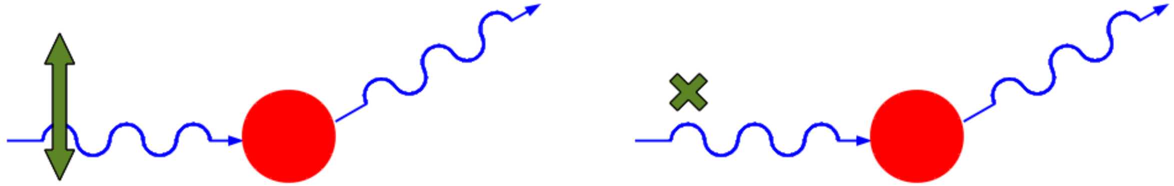
$$\Sigma_{2z} = \frac{N^R_{+z} - N^L_{+z}}{N^R_{+z} + N^L_{+z}}$$



Sensitive to γ_{M1M1}

- Linearly polarized photons, unpolarized protons.

$$\Sigma_{3} = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$

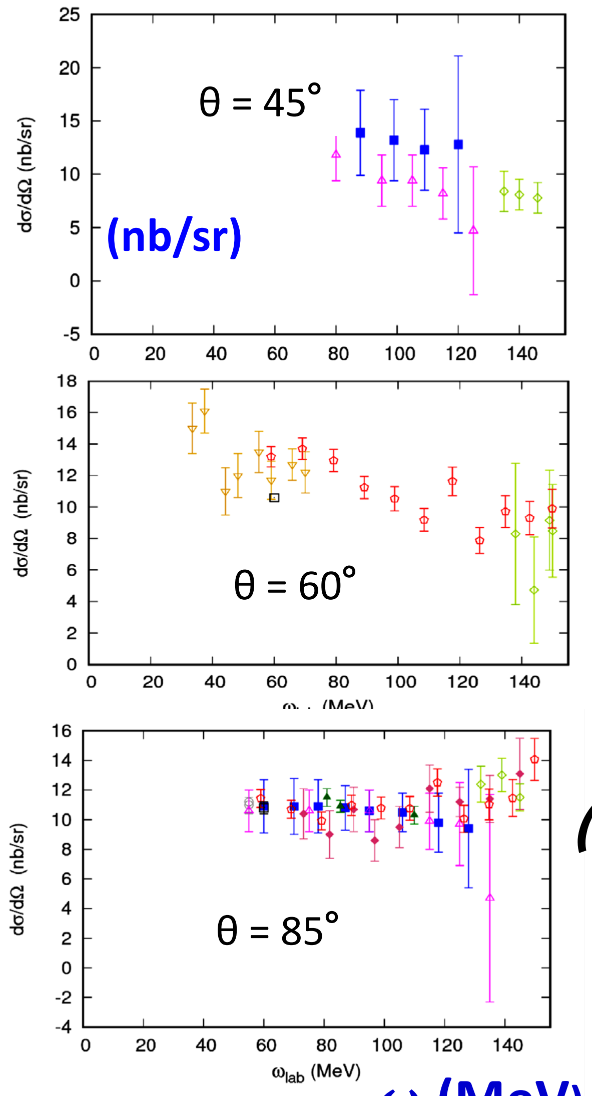


Sensitive to α,β γ_{E1E1} <u>and</u> γ_{M1M1}

The proton data base – Before A2

($\omega < 150$ MeV)

Differential
Cross section



ω (MeV)

Symbol	Set	Ref
	GOL 60	Goldansky et al.
	OdL 01	Olmos de León
	HAL 93	Hallin et al.
	HYM 59	Hyman et al.
	PUG 67	Pugh et al.
	FED 91	Federspiel et al.
	BER 61	Bernardini et al.
	BAR 74	Baranov et al.
	OXL 58	Oxley
	MAC 95	MacGibbon et al.

(Only) 150 points

(Half of the Spartans *that King Leonidas led to the Battle of Thermopylae in 480 BC)*

Σ_3: 58 points form LEGS coll.

Double-polarization observables not measured

$\Rightarrow$ Poor quality of the data set
(… a difficult experiment to perform …)

Large statistical -and systematic- errors ;
possible inconsistencies between subsets

Only α,β directly extracted from the data; the other polarizabilities were fixed/constrained using models or other data

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

How well do we understand the nucleon excitation spectrum ?

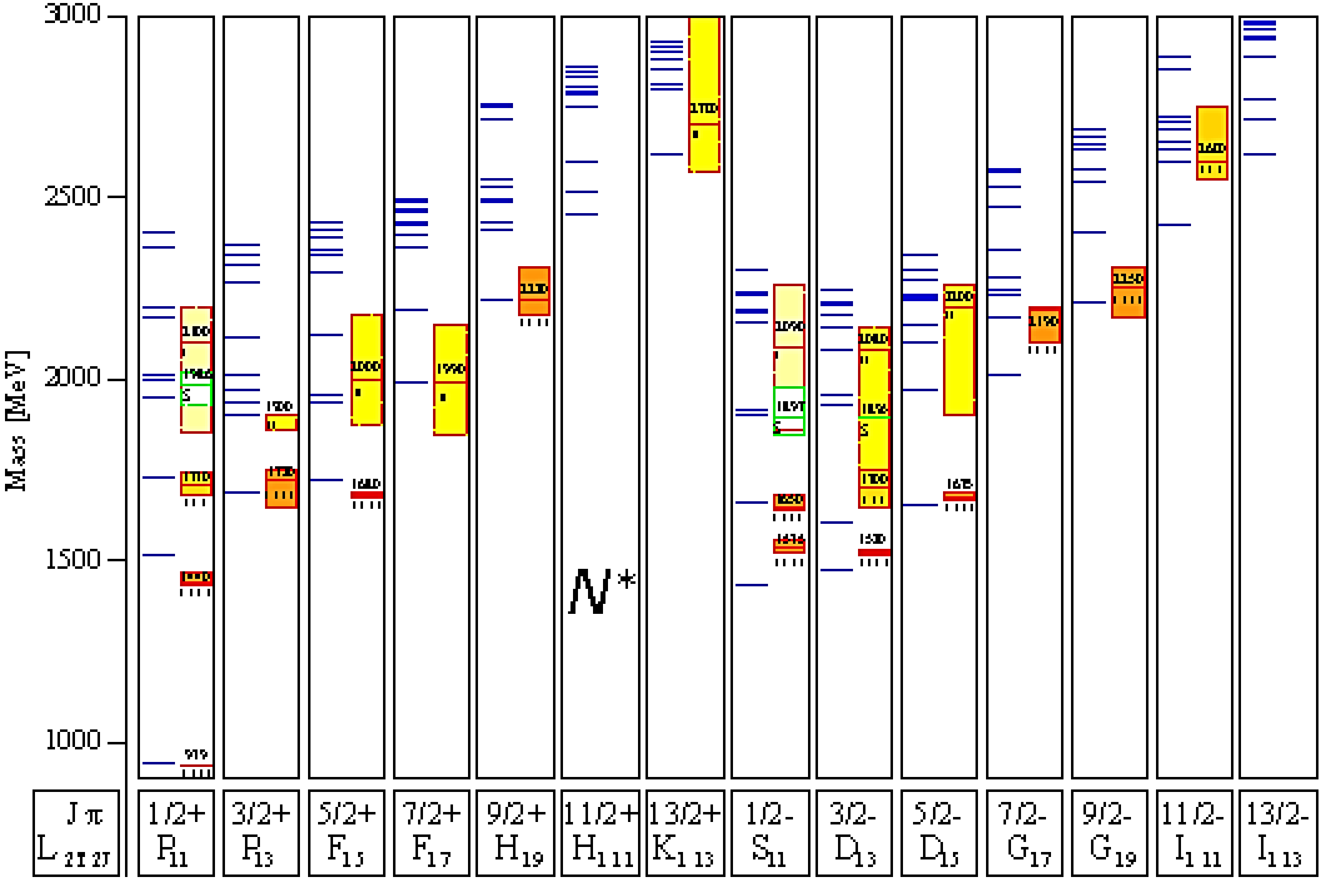
$$\gamma N \text{ (or } \pi N) \rightarrow N^* \rightarrow \pi(\pi)N \text{ , } \eta N, \ldots)$$

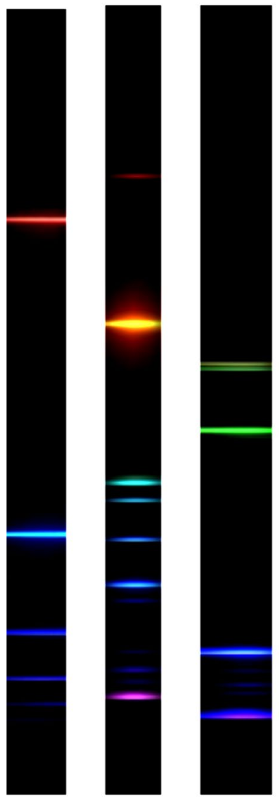
- many more resonances expected in quark models (all based on SU6 symmetry) or lattice QCD than seen experimentally

- What are the relevant degrees of freedom ?

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

Predicted states ⬇ ⬇ Observed states $\left(I=\frac{1}{2}\right)$ *states*





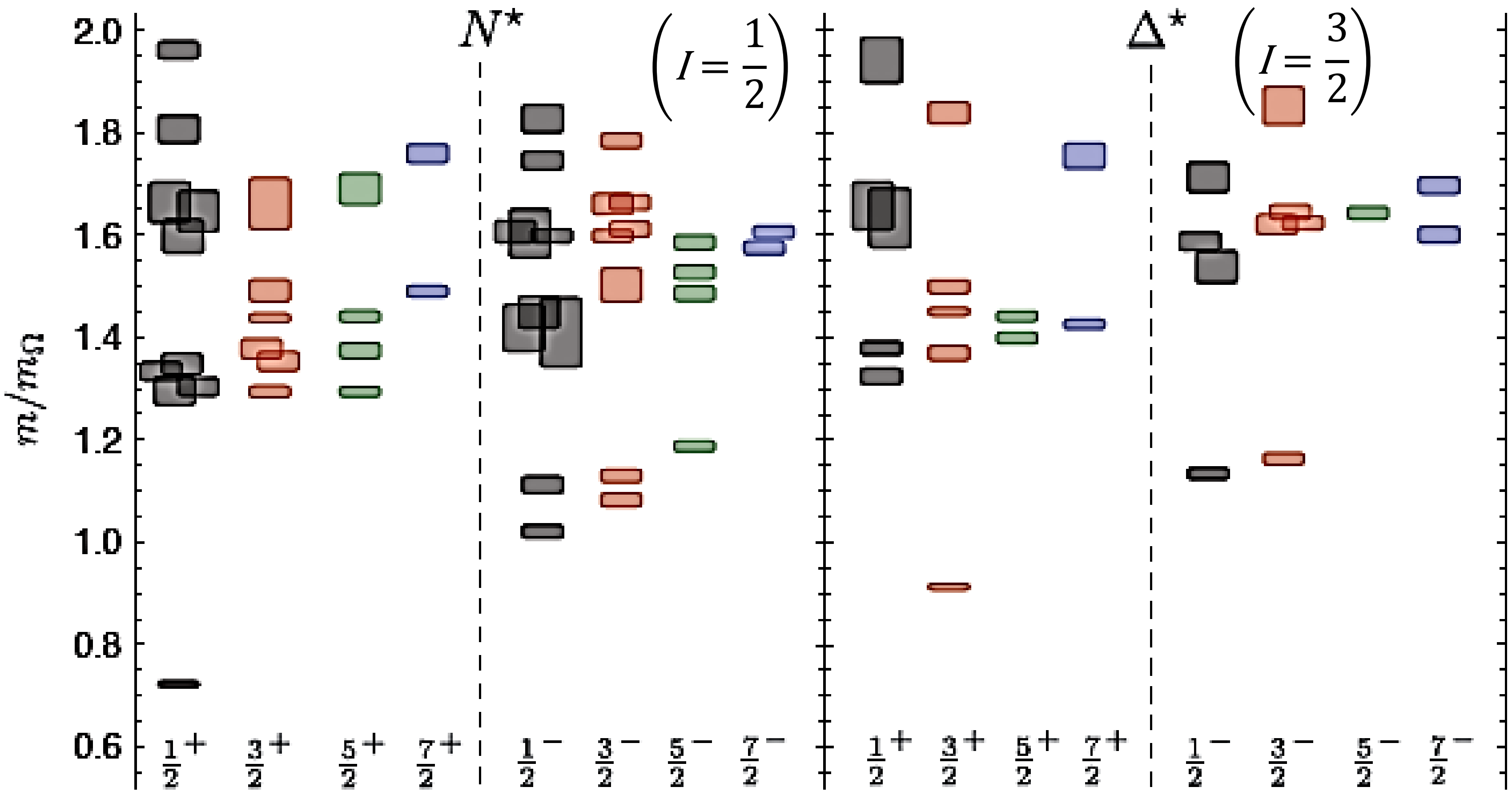
H He Hg

ATOMS

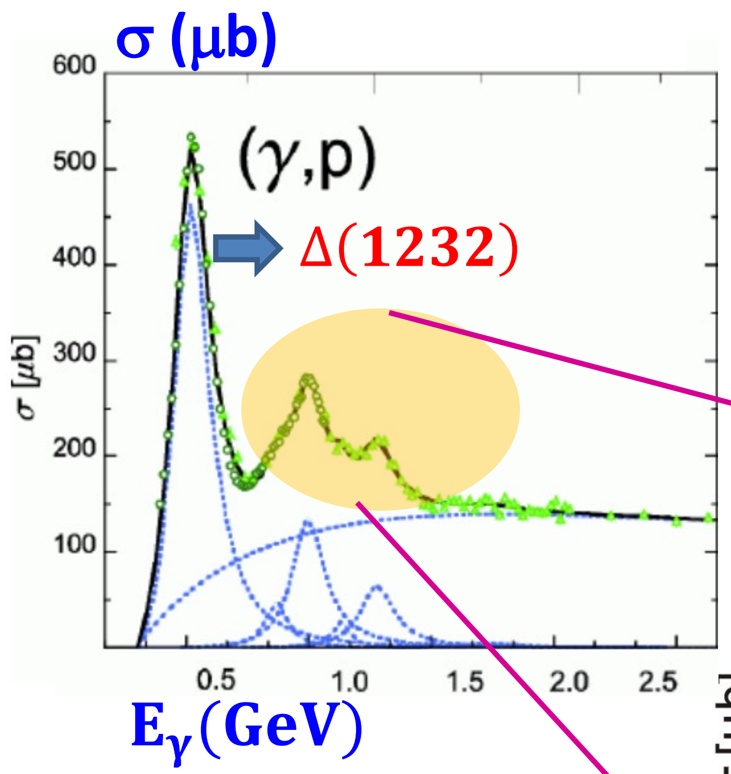
CQM: U. Loering et al, EPJA 10, 395 (2001)

A Lattice QCD model

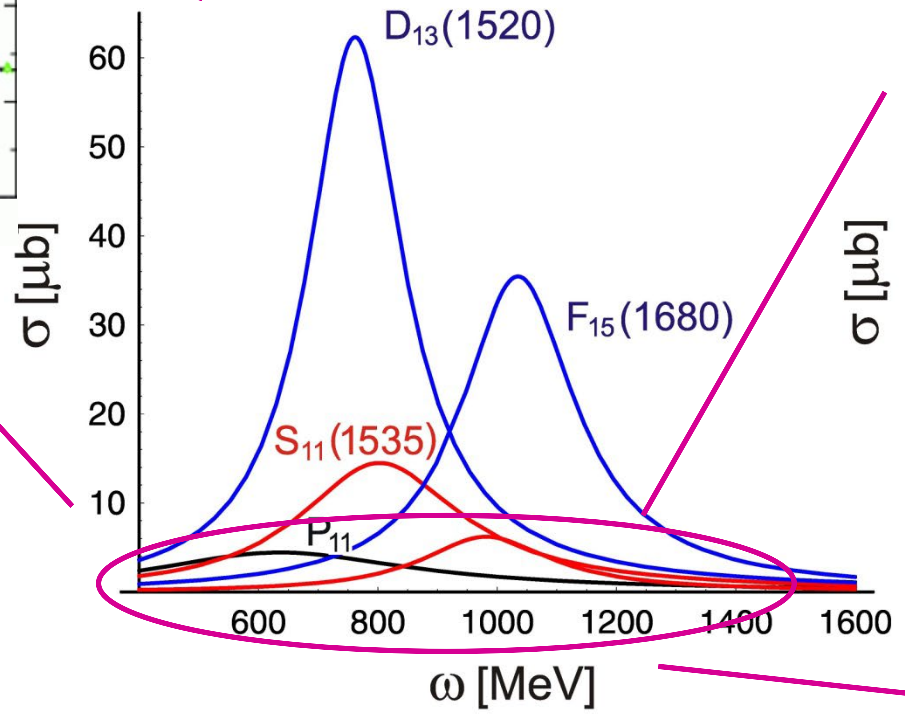
Edwards et al, PRD 84 074508 (2011)

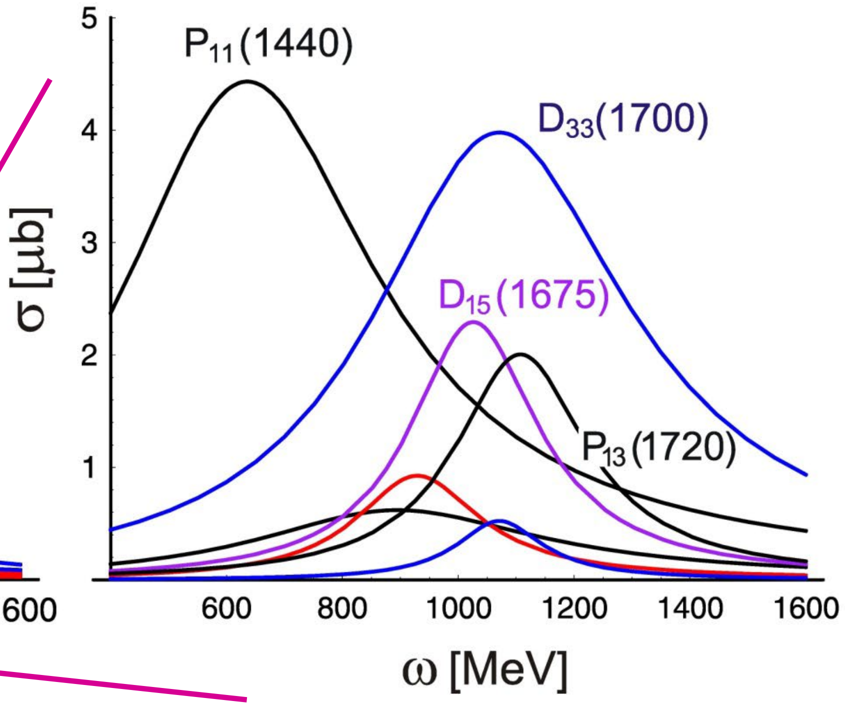


- Results for m_π = 396 MeV
- State-of-the art methods still yield a (too) large number of states



total photoabsorption
in the 2nd and 3rd resonance regions (MAID model)





Polarization observables are necessary to disentangle the broad and overlapping resonances at higher excitation energies and to separate resonant mechanisms from non-resonant background

Polarization observables

$$\gamma N \rightarrow N^* \rightarrow \pi N \ (\mathrm{or}\ \eta N)$$

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

Spin states	±1 ±1/2	0 ±1/2
DoF	2 x 2	x 2

8 matrix elements needed describe the scattering amplitude

- **Parity conservation ⇒ only 4 complex amplitudes are independent (*F_1 … F_4* CGLN amplitudes)**
- **16 independent observables (at least 8 -well chosen-to be measured ⇒ «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

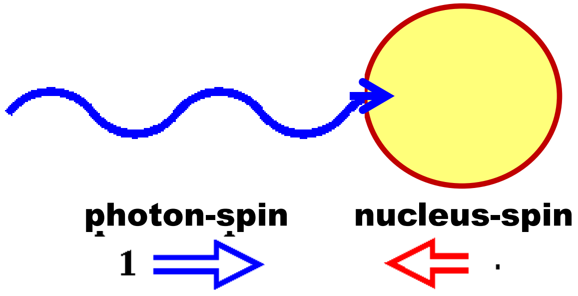
Several observables on all the different $\gamma N \rightarrow N\pi\pi ...$ partial channels have to be measured.

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

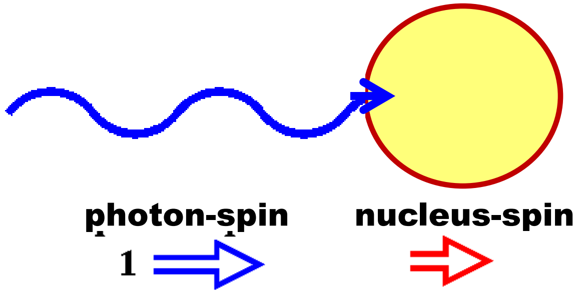
Very large acceptance ($\cong 4\pi$) detectors need to used with highly polarised beam and targets

Experimental verification of the GDH sum rule

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



σ_a



σ_p

spin

Anomalous magnetic moment

$$I_{GDH} = \int_{\nu_{thr}}^{\infty} \frac{\sigma_p(E_\gamma) - \sigma_a(E_\gamma)}{E_\gamma}\, dE_\gamma = 4\pi^2 S \frac{e^2}{M^2} k^2$$

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

Baldin's sum rule

$$(\alpha + \beta) = \frac{1}{2\pi^2} \int \frac{\sigma_{UNP}}{E_\gamma{}^2} dE_\gamma$$

$$\sigma_{unp} = (\sigma_P + \sigma_A)/2$$

GDH sum rule:

✓ **Fundamental check of our knowledge of the γN 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 (composite 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 system with k $\neq 0$ (^{2}H, ^{3}He)** . "Link" between nuclear and nucleon degrees of freedom

✓ **Is GDH sum rule modified in nuclei ??** (due to medium dependence of the nucleon's spin structure)

A part of the future experimental program at JLAB

S.D Bass, Acta Phys Pol B52 43 (2021)
S.D Bass, P.Pedroni, A.Thomas EPJA 59, 239 (2023)

GDH sum rule predictions

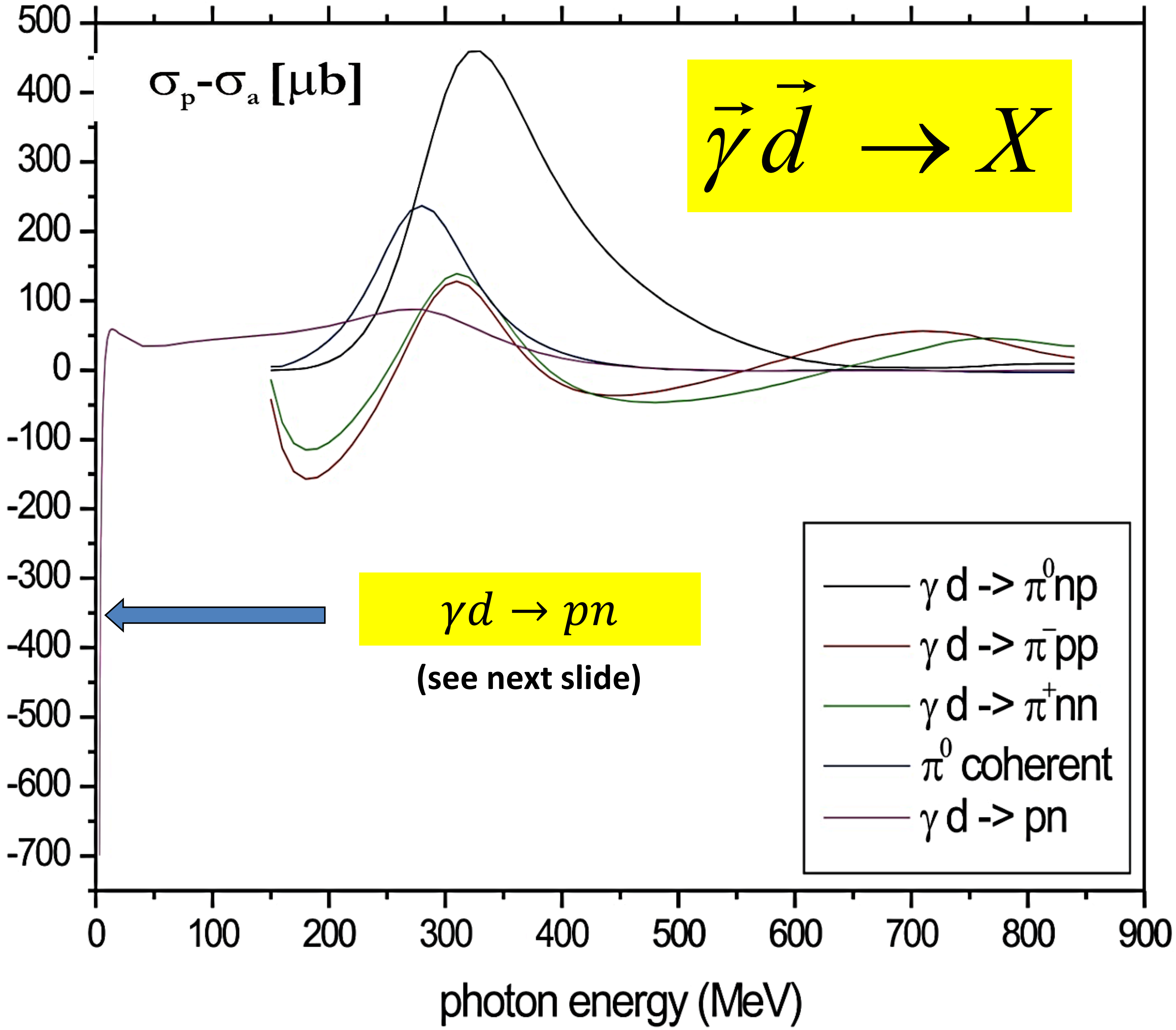
	p	n	d	^{3}He	
μ	2.79	-1.91	0.86	-2.13	(n.m.)
κ	1.79	-1.91	-0.14	-8.37	(n.m.)
I_{GDH}	204	233	0.65	498	(μb)

"naive" expectations ≈ 430 ≈ 230

(proton and neutron spins are aligned) $\approx I^p_{GDH} + I^n_{GDH}$

$\approx I^n_{GDH}$ (two protons have anti-parallel spins)

Difference due to photodisintegration processes



AFS model

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

πNN πN from MAID PWA +nuclear effects

ππNN EPJA 25,114 (05)

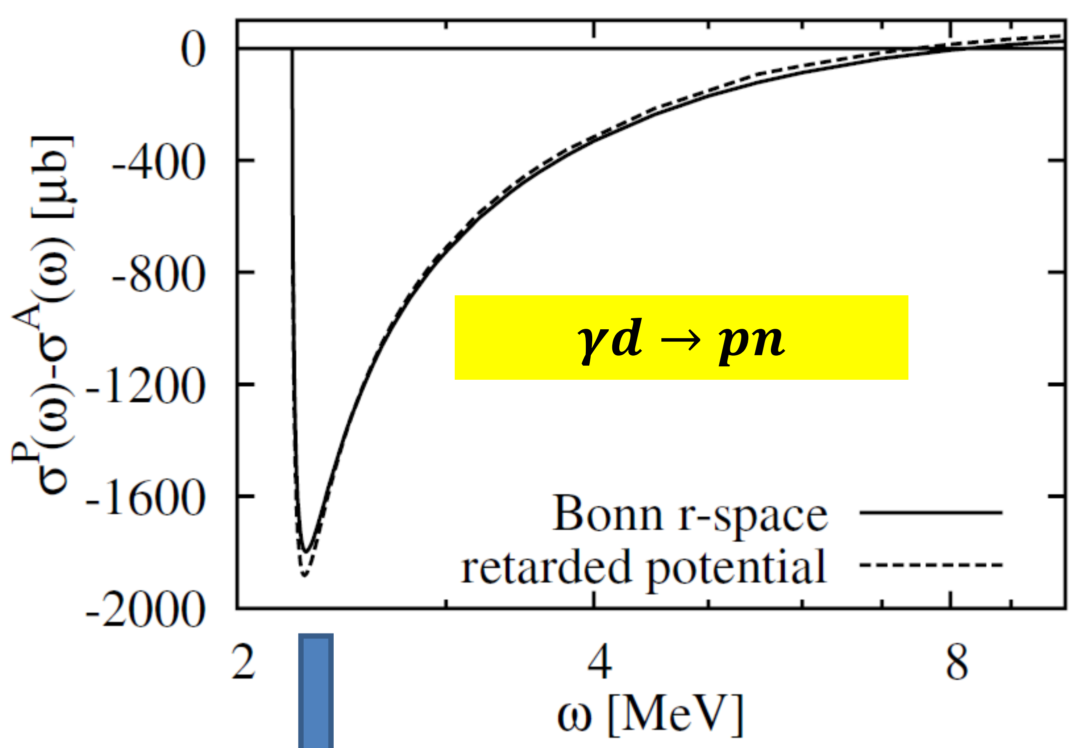
π^0d PLB 407,1 (97)

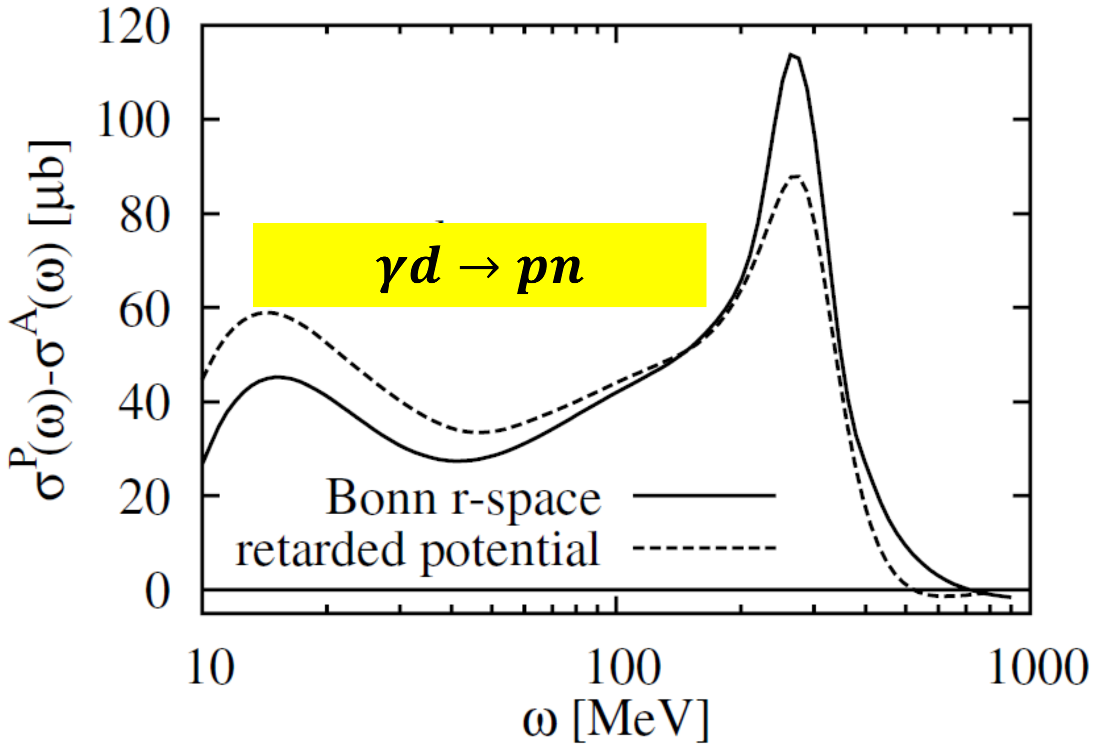
pn NPA 690,682 (01)

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

AFS model

PRL 93, 202301 (04)

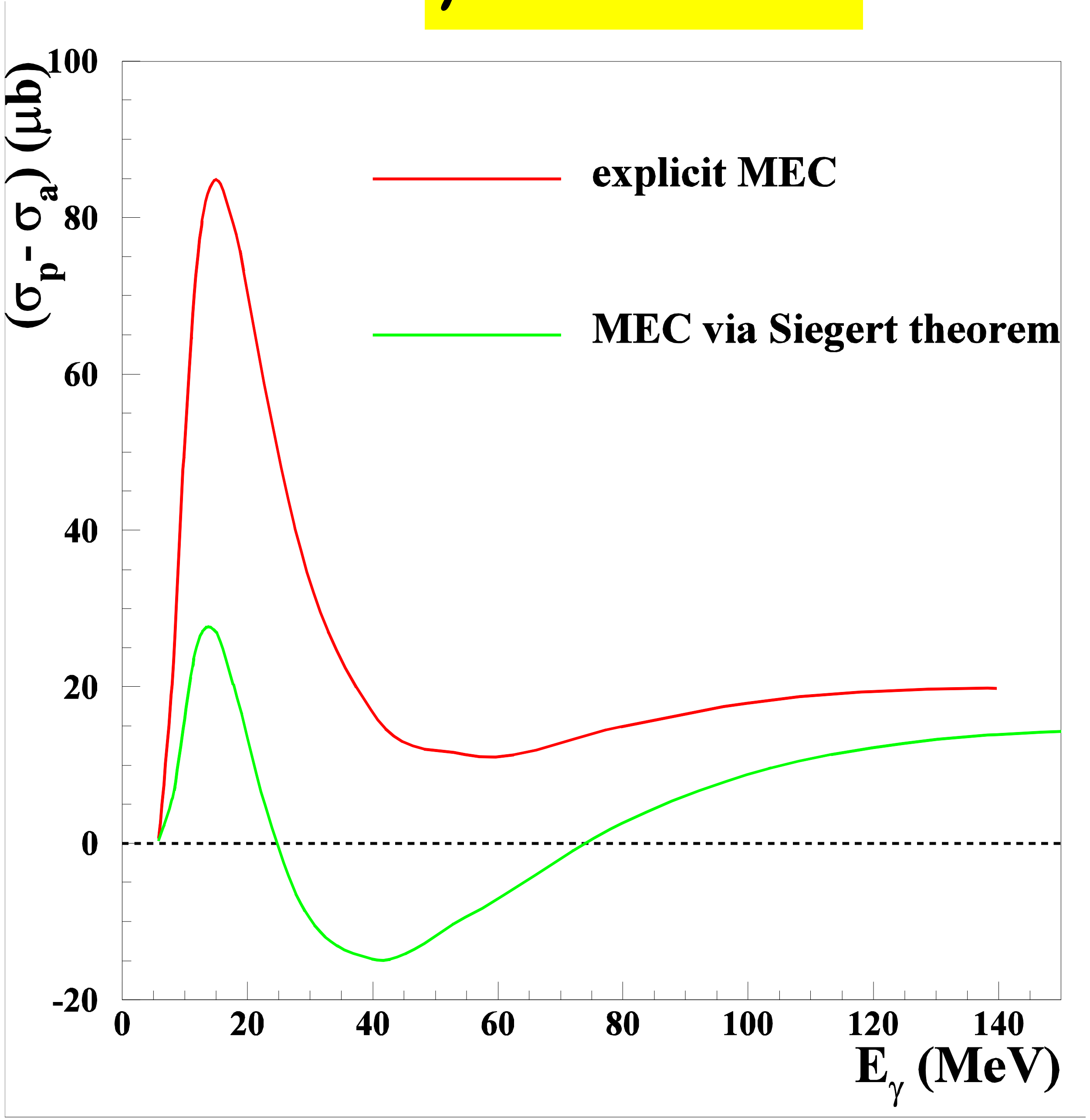




Dominant *M1* transition from the bound $^3S_1$ state to the continuum $^1S_0$ state can only be reached for antiparallel photon and deuteron spins

(state notation: $^{2S+1}L_J$)

$$\vec{\gamma}\ {}^3\vec{He} \rightarrow X$$



Model from Golak-Gloeckle

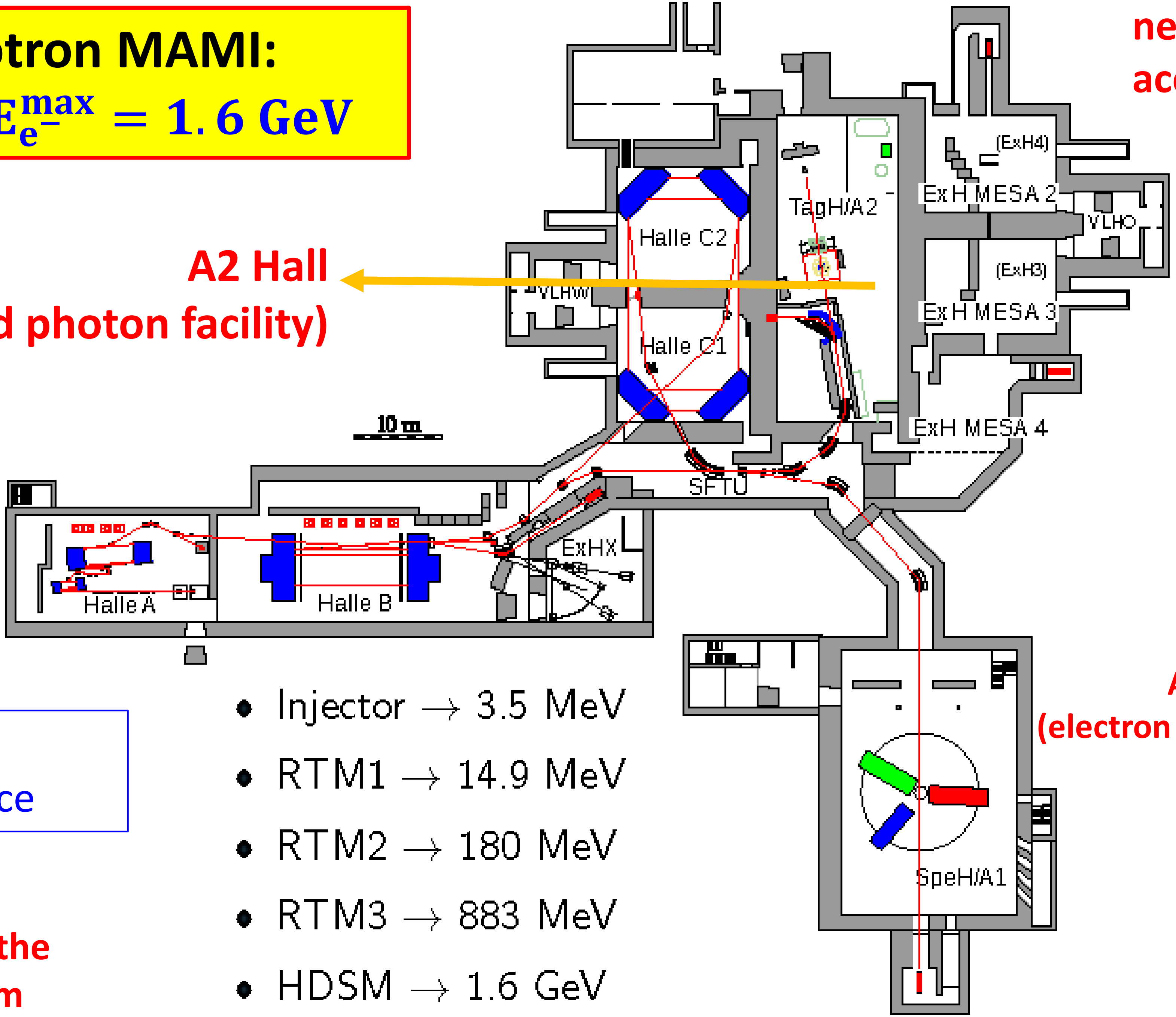
Photodisintegration processes (sensitive to MEC, 3N forces, ..) give a positive contribution to the sum rule value

Experimental Set up

Mainz Microtron MAMI:
electron beam $E_{e^-}^{max} = 1.6\ GeV$

A2 Hall
(Tagged photon facility)

new MESA accelerator



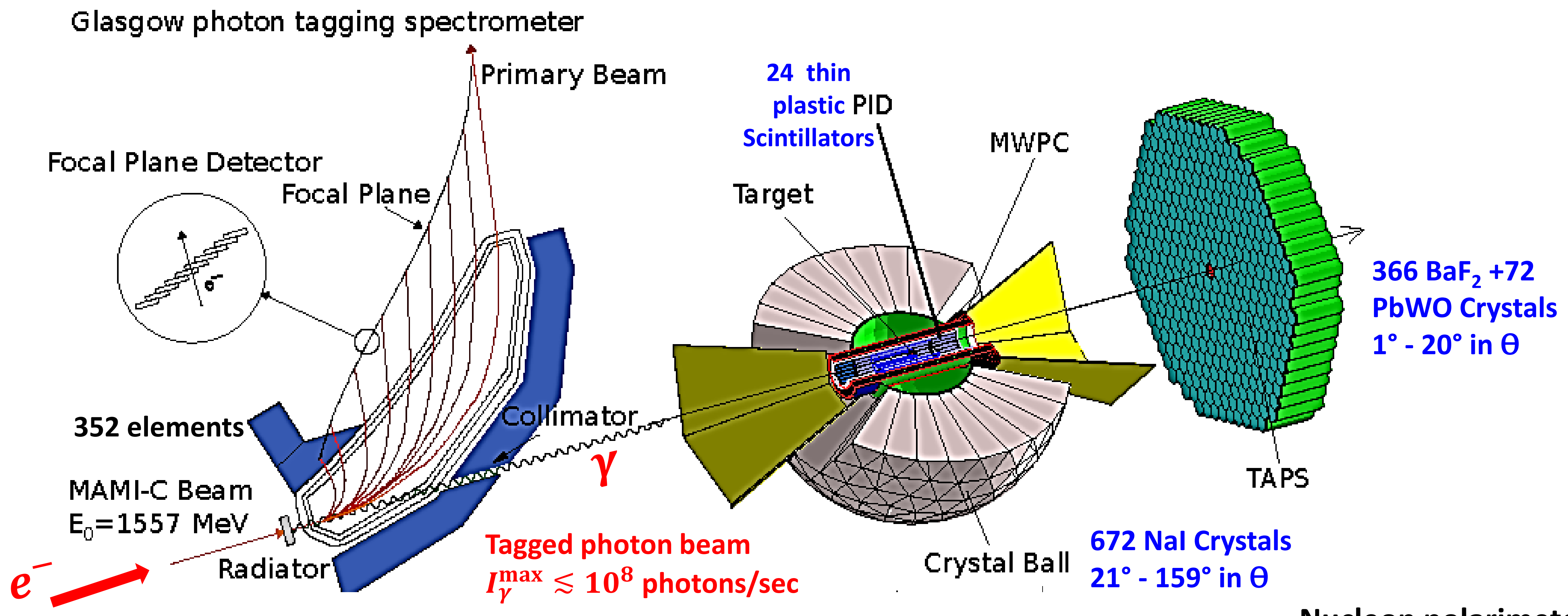
A1 Hall
(electron spectrometers)

High stability
Low beam divergence

Very good properties of the secondary photon beam

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

A2@MAMI: Detector overview



Nucleon polarimeter (graphite cylinder) also available

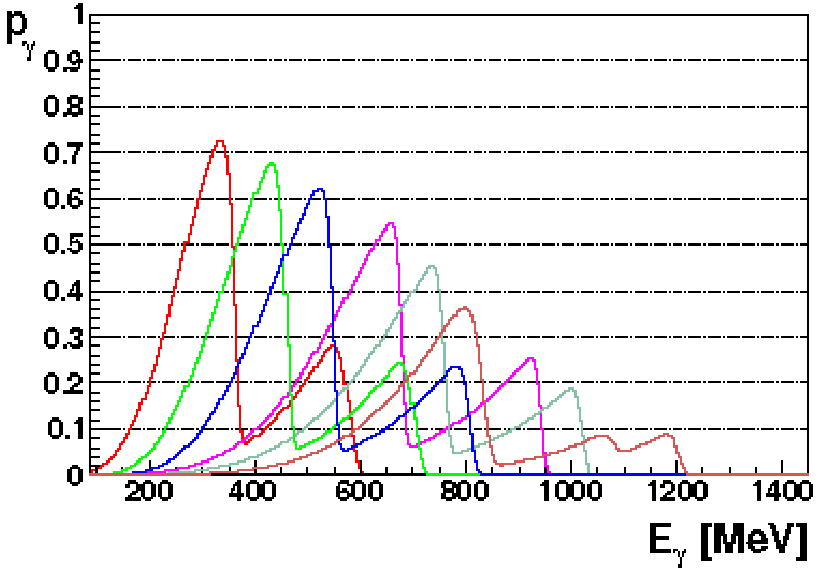
Photon beam produced by bremsstrahlung and recoil electrons tagged by a magnetic spectrometer

$$E_\gamma = E_0 - E_{e^-} \quad ; \quad \Delta E_\gamma = 2-4 \text{ MeV}$$

Beam Polarization

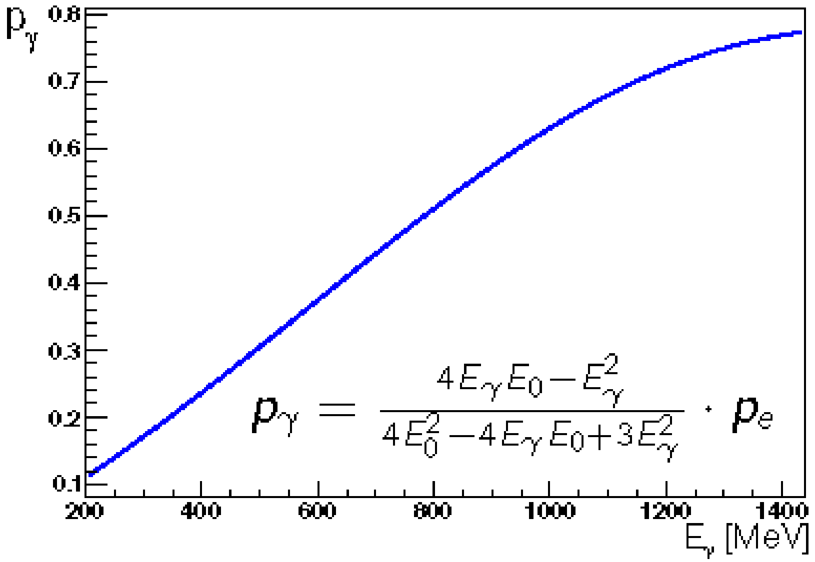
Linearly polarized photons

- Diamond radiator needed
- Coherent Bremsstrahlung
- Coherent edges at
  350 MeV, 450 MeV, 550 MeV,
  650 MeV, 750 MeV, 850 MeV,



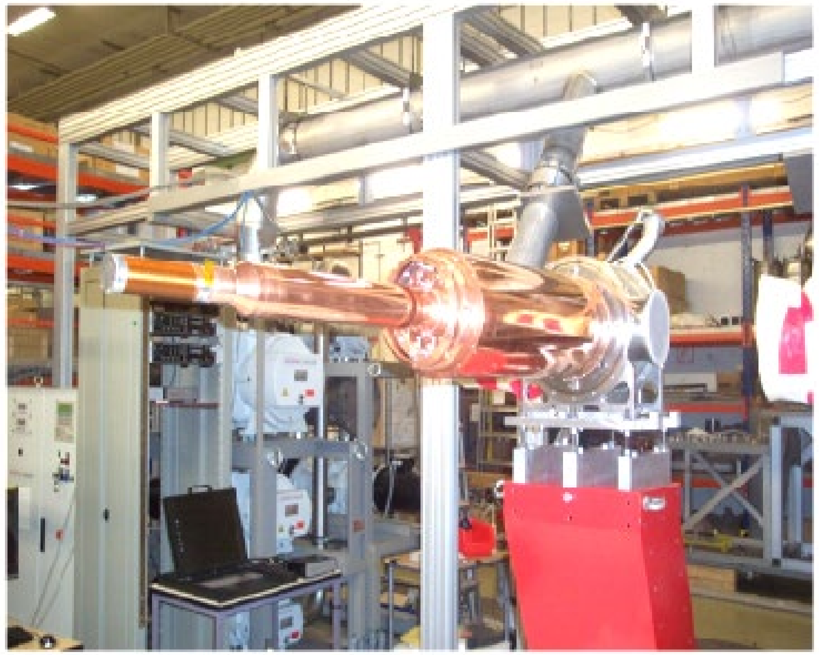
Circularly polarized photons

- Longitudinally polarized electrons needed
- Helicity transfer to photon
- Mott/Moeller measurements: beam polarisation $p_e \approx$ 75-85%



Target Polarization

Longitudinally and Transversally polarized protons/deuterons **(Mainz-Dubna target)**



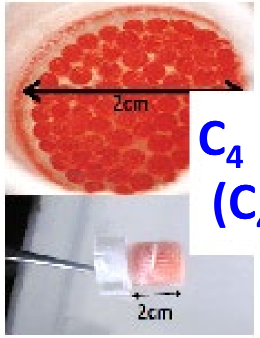
- Polarized material: (deuterated) butanol **(Bochum)**

- Polarization via DNP process
- 70 GHz microwave irradiation at 2.5 T is used to transfer the electron polarization to p/d
- 3He/4He dilution cryostat at 25 mK and holding coil at 0.63 T

- Relaxation time ≈ 2000 hours
- $\approx 10^{23}$ polarized protons (deuterons) $/\mathrm{cm}^2$
- $P_{proton} \approx 90\%$; $P_{deuteron} \approx 50\%$

- Carbon target needed for background studies

Butanol Target



C_4 O H_{10}
(C_4 O D_{10})

Carbon Target

Selected results

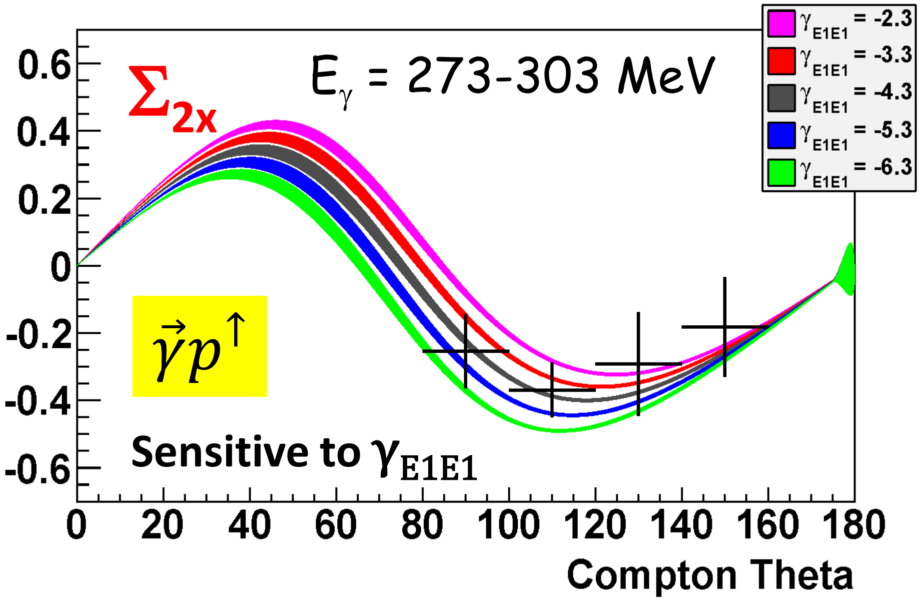
(Un)Polarized Compton Scattering on the proton

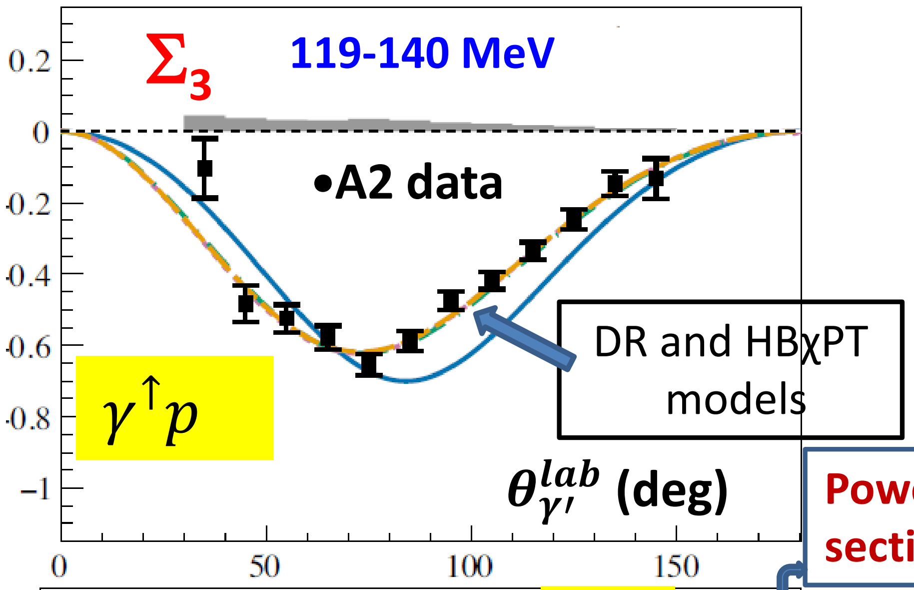
V. Sokhoyan et al., EPJA 53, 14 (2017)

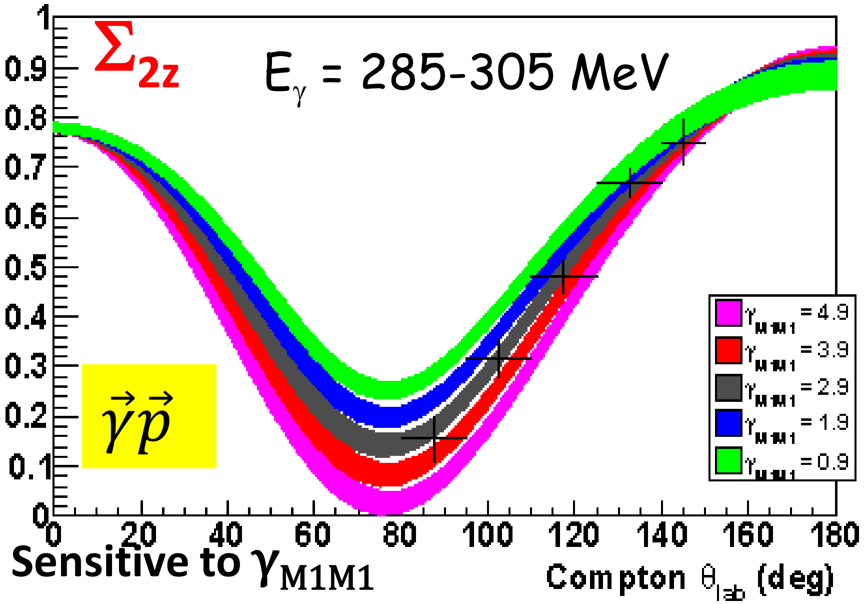
P. Martel et al., PRL 114, 112501 (2015)

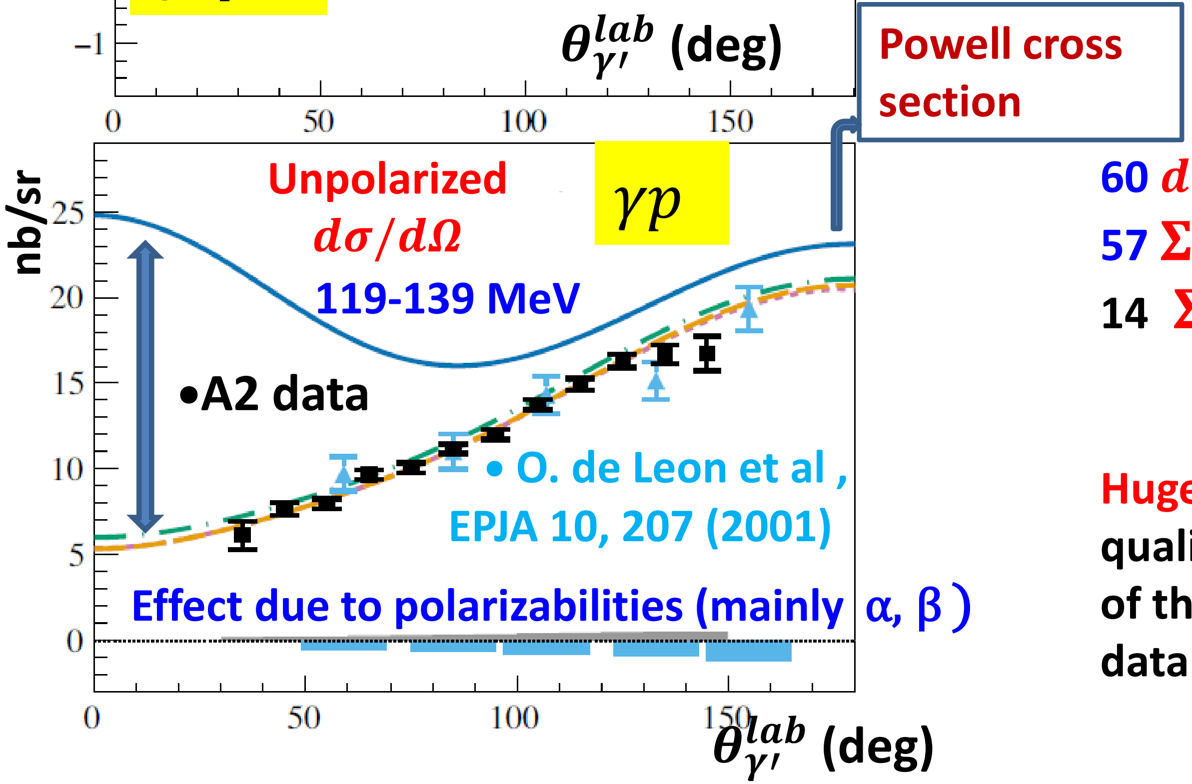
D. Payudal et al., PRC 32, 023205 (2020)

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









60 $d\sigma/d\Omega$ points

57 Σ_3 points

14 Σ_X , Σ_Z

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

First simultaneous determination of all 6 polarizabilites

- **Best fit using all available data (388 points – 1/3 from A2)**

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

- **Problems:** 25 (!) different data sets need to be merged

  how to combine systematic and statistical uncertainties ?

parameters to be fitted

«standard method»

$$\chi^2_{\text{mod}}(\boldsymbol{\theta}) = \sum_{i=1}^{N_{\text{exp}}} \left(\frac{f \cdot y_{i,\text{exp}} - t_i(\boldsymbol{\theta})}{\sigma_{i,\text{exp}}} \right)^2 + \left(\frac{f-1}{\sigma_{\text{sys}}} \right)^2$$

fit model

A single dataset with a same **common** multiplicative systematic uncertainty

G .D'Agostini, NIM A 346, 306 (1994)

- We would need 25 (!) additional parameters to be fitted
- **The previous formula can only be applied with gaussian systematic uncertainties.**
  What to do if not ?? (systematic uncertainties may also depend on the value of $y_{i,\text{exp}}$)
- $\chi^2_{\text{mod}}(\boldsymbol{\theta})$ is a sum of squares of **correlated and non-gaussian variables**.
  What is the goodness-of-fit distribution ? (after the minimization, $\chi^2_{mod}(\widehat{\boldsymbol{\theta}})$ is NOT a random variable from the χ^2 density)

  $\widehat{\boldsymbol{\theta}} \equiv$ fit output values
- **How is the uncertainty of $\widehat{\boldsymbol{\theta}}$ distributed ? ($\widehat{\boldsymbol{\theta}}$ is NOT gaussian-distributed)**

- **Solution: use of a new bootstrap-based fitting method**

P.Pedroni, S.Sconfietti, JPG 47, 054001(2020)

Parametric bootstrap

known (purely kinematical variables)

True distribution of the experimental data

$$Y_i \sim p(x_i, t_i(\theta)) \quad \Rightarrow \quad Y_i^* \sim p(x, \mu_i = y_i)$$

A model for the distribution of the experimental data

known (is the experimental resolution)

unknown true value of $d\sigma/d\Omega(x_i)$

known measured value

2.2 Parametric Simulation

In the previous section we pointed out that theoretical properties of T might be hard to determine with sufficient accuracy. We now describe the sound practical alternative of repeated simulation of data sets from a fitted parametric model, and empirical calculation of relevant properties of T.

Suppose that we have a particular parametric model for the distribution of the data $y_1, \ldots, y_n$. We shall use $F_\psi(y)$ and $f_\psi(y)$ to denote the CDF and PDF respectively. When ψ is estimated by $\hat{\psi}$ — often but not invariably its maximum likelihood estimate — its substitution in the model gives the *fitted model*, with CDF $\hat{F}(y) = F_{\hat{\psi}}(y)$, which can be used to calculate properties of T, sometimes exactly. We shall use Y^* to denote the random variable distributed according to the fitted model $\hat{F}$, and the superscript * will be used with E, var and so forth when these moments are calculated according to the fitted distribution. Occasionally it will also be useful to write $\hat{\psi} = \psi^*$ to emphasise that this is the parameter value for the simulation model.

A.C.Davidson, D.V.Hinkley

Bootstrap Methods and Their Applications

Cambridge University Press, 1997

Bootstrap solution

(For a single data set)

- Generate a bootstrap «cycle» (a possible data set of from a «virtual» experiment)

Probabilty distribution of the systematic uncertainties

Probabilty distribution of the statistical uncertainties

$$y_i^* = \xi \cdot \rho_i \; ; \; \xi \sim P_{\mathrm{sys}}(\mu = 1, \sigma = \sigma_{\mathrm{sys}}) \quad ; \quad \rho_i \sim P_{\mathrm{exp}}(\mu_i = y_i, \sigma_i = \sigma_{i,\mathrm{exp}})$$

Same value for all points

- Fit of the «virtual» data set $\chi^2_{boot}(\boldsymbol{\theta}) = \sum_{i=1}^{N} \left(\frac{y_i^* - \mu_i(\boldsymbol{\theta})}{\sigma_{i,\mathrm{exp}}} \right)$ and get fit values $\hat{\boldsymbol{\theta}}^*$

P.Pedroni, S.Sconfietti, JPG 47, 054001(2020)

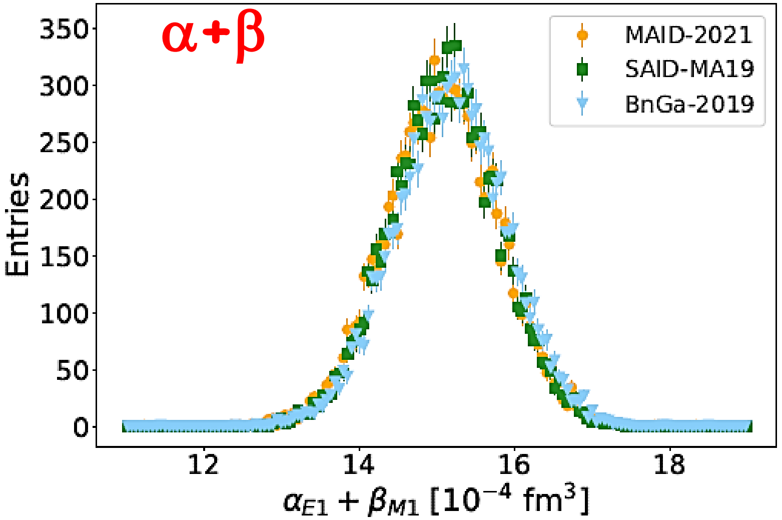
- Repeat the previus procedure for a sufficiently large number of cycles
- From the set of final fit parameters $\hat{\theta}'^*, \hat{\theta}''^*, \ldots, \hat{\theta}''^{\ldots\prime *}$,their probability can then empirically found after a sufficiently large number of cycles (exact confidence intervals can be evaluated)
- The goodness-of-fit distribution can also be empirically found with a very similar procedure

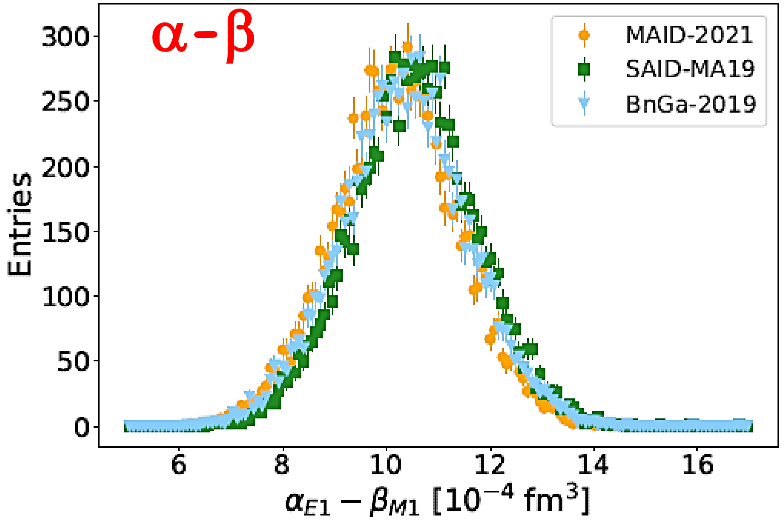
- **Very simple and flexible procedure: values from any distribution can be easily generated**
- **Any complicated correlation among variables can be easily taken into account**

Bootstrap results

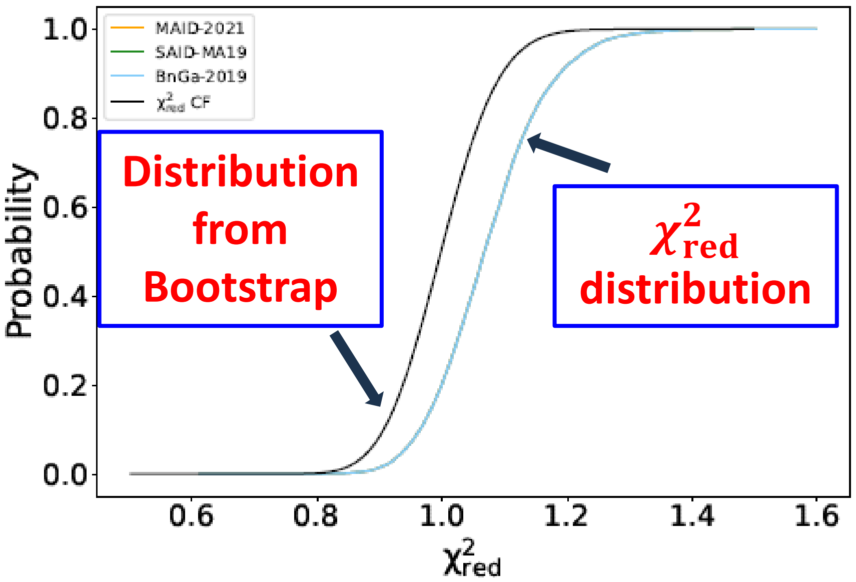
E. Mornacchi et al.,
PRL 129, 102501 (2022)

$t(\theta) \Rightarrow$ model from B. Pasquini based on dispersion relations
(3 different PWA (Nπ channels) used as input to estimate model uncertainties)

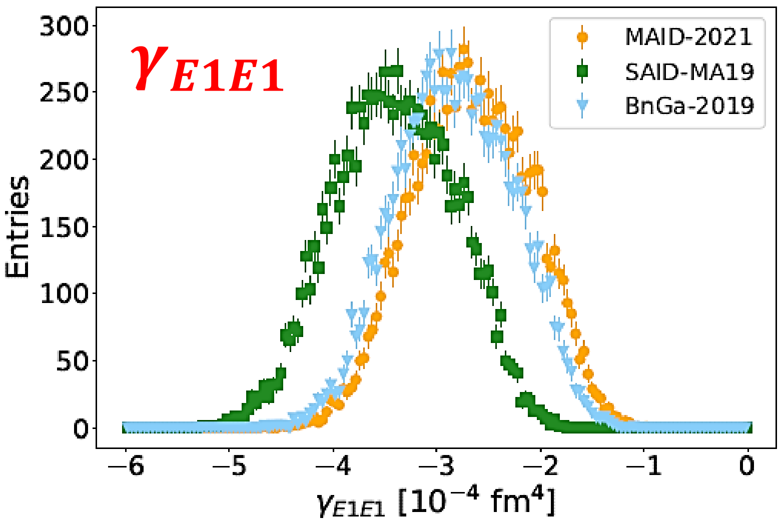


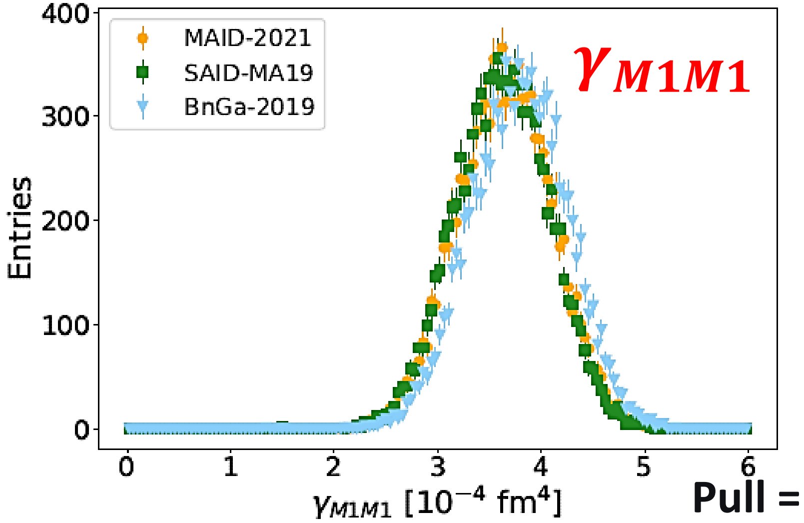


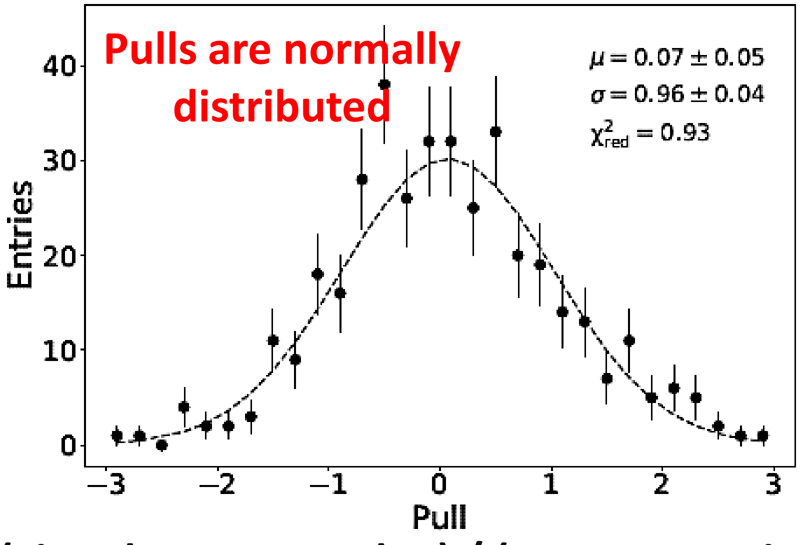
Cumulative Function of the goodness-of-fit distribution



10^4 cycles





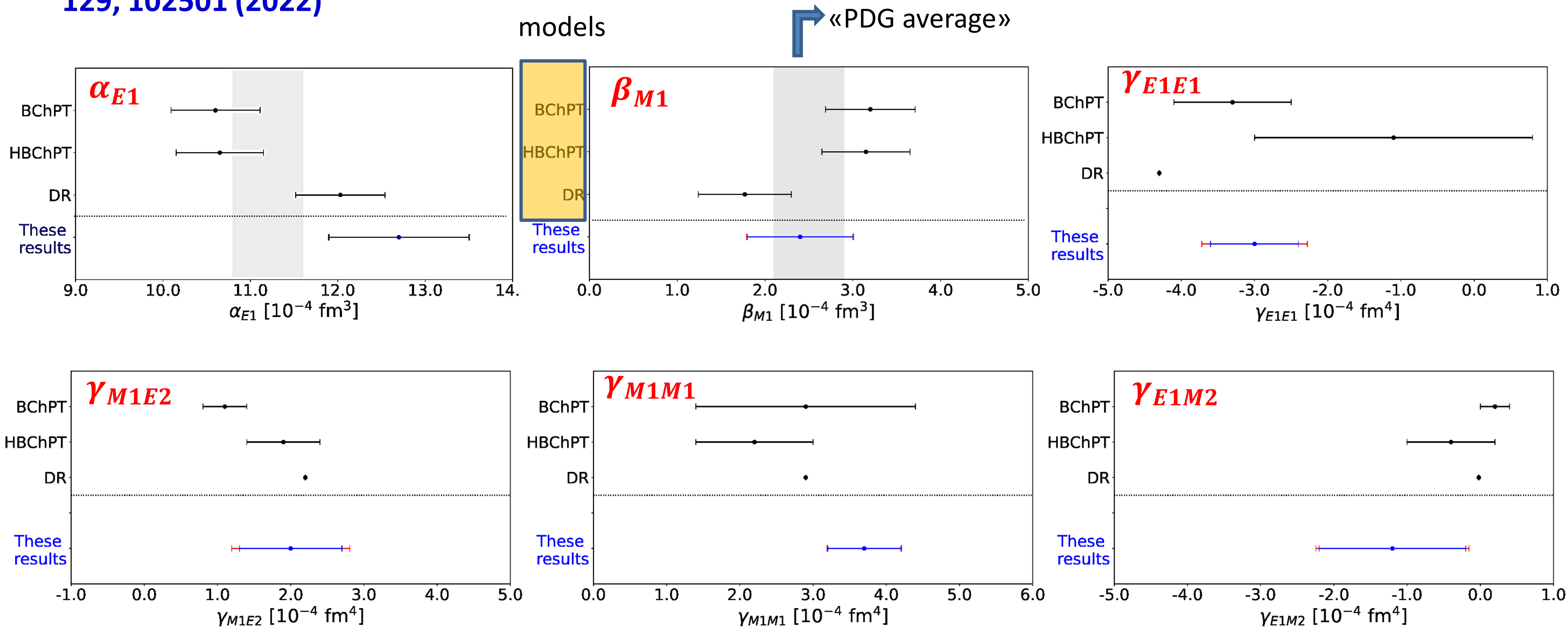


Pull = (Fit Value – Exp. Value) / (Exp. Uncertainty)

Polarizabilities values

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

Units: 10^{-4} fm^3



Exp(Stat+sys error) model –dependent sys. uncertainty

$$\alpha_{E1} = 12.7 \pm 0.8 \pm 0.1 \qquad \beta_{M1} = 2.4 \pm 0.6 \pm 0.1 \qquad \gamma_{E1E1} = -3.0 \pm 0.6 \pm 0.4$$

$$\gamma_{M1M1} = 3.7 \pm 0.5 \pm 0.1 \qquad \gamma_{E1M2} = -1.2 \pm 1.0 \pm 0.3 \qquad \gamma_{M1E2} = 2.0 \pm 0.7 \pm 0.4$$

p SPIN POLARIZABILITY γ_{E1E1}

VALUE (10^{-4} fm^4)	DOCUMENT ID	TECN	COMMENT
−3.0±0.6±0.4	[1] MORNACCHI 22	FIT	Fit of RCS data sets

[1] MORNACCHI 22 perform the first simultaneous extraction of the six leading-order proton polarizabilities using fixed-t subtracted dispersion relations and a bootstrap-based fitting technique.

p SPIN POLARIZABILITY γ_{M1M1}

VALUE (10^{-4} fm^4)	DOCUMENT ID	TECN	COMMENT
3.7±0.5±0.1	[1] MORNACCHI 22	FIT	Fit of RCS data sets

[1] MORNACCHI 22 perform the first simultaneous extraction of the six leading-order proton polarizabilities using fixed-t subtracted dispersion relations and a bootstrap-based fitting technique.

p SPIN POLARIZABILITY γ_{E1M2}

VALUE (10^{-4} fm^4)	DOCUMENT ID	TECN	COMMENT
−1.2±1.0±0.3	[1] MORNACCHI 22	FIT	Fit of RCS data sets

[1] MORNACCHI 22 perform the first simultaneous extraction of the six leading-order proton polarizabilities using fixed-t subtracted dispersion relations and a bootstrap-based fitting technique.

p SPIN POLARIZABILITY γ_{M1E2}

VALUE (10^{-4} fm^4)	DOCUMENT ID	TECN	COMMENT
2.0±0.7±0.4	[1] MORNACCHI 22	FIT	Fit of RCS data sets

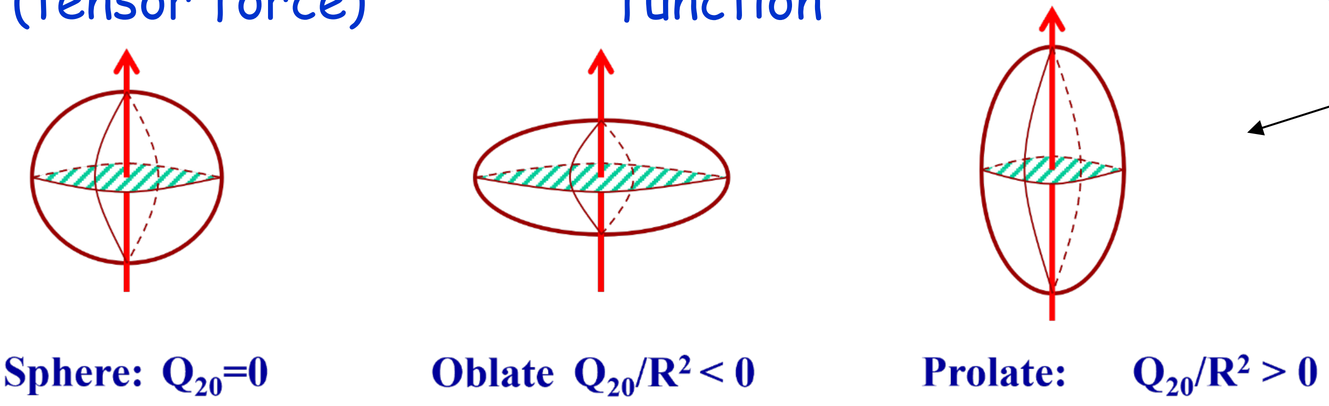
[1] MORNACCHI 22 perform the first simultaneous extraction of the six leading-order proton polarizabilities using fixed-t subtracted dispersion relations and a bootstrap-based fitting technique.

Last Edition (2024) of the Particle Data Book has one additional page

E2/M1 ratio

Deuteron

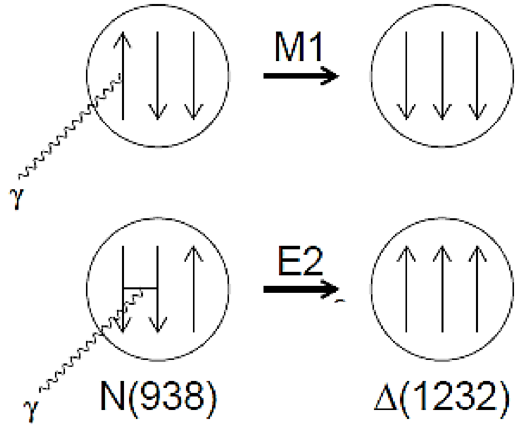
p-n interaction is spin dependent (tensor force) → d- state admixture in the deuteron wave function → non-spherical charge distribution (quadrupole moment for the deuteron) → (E2 absorption)



Proton

quark-quark interaction is spin dependent (gluon exchange) (color tensor force) → d- state admixture in the proton wave function (modification of the quark core) → (E2 absorption)

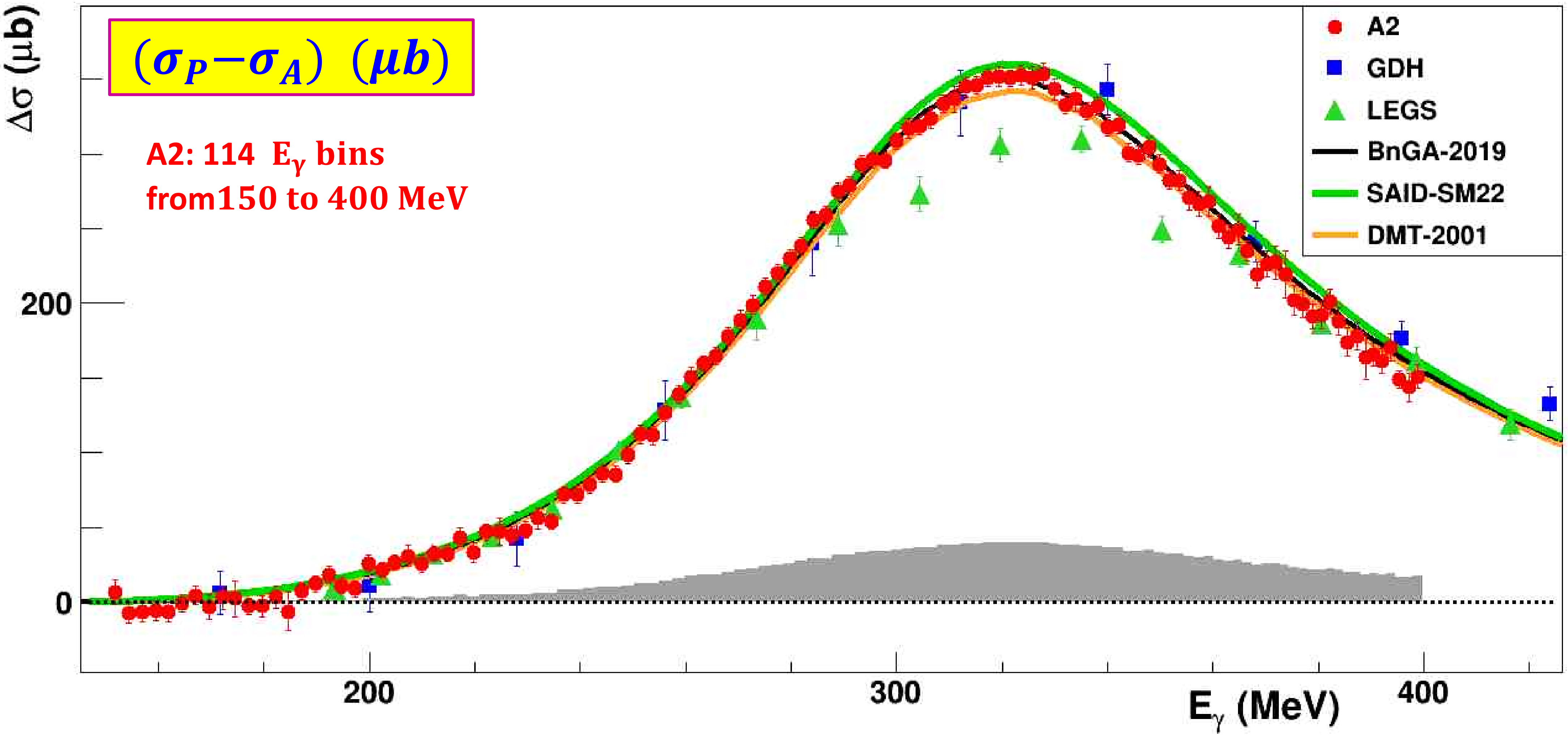
Tensor correlation between the quark core and the pion cloud /gluon exchange current between quarks



Proton electric quadrupole moment can not be directly measured (spin=1/2 particle). The only indirect way is to measure the E2/M1 ratio between the electric quadrupole (E2) and the dominant spin-flip (M1) amplitude in the $\gamma N \rightarrow \Delta(1232)$ transition

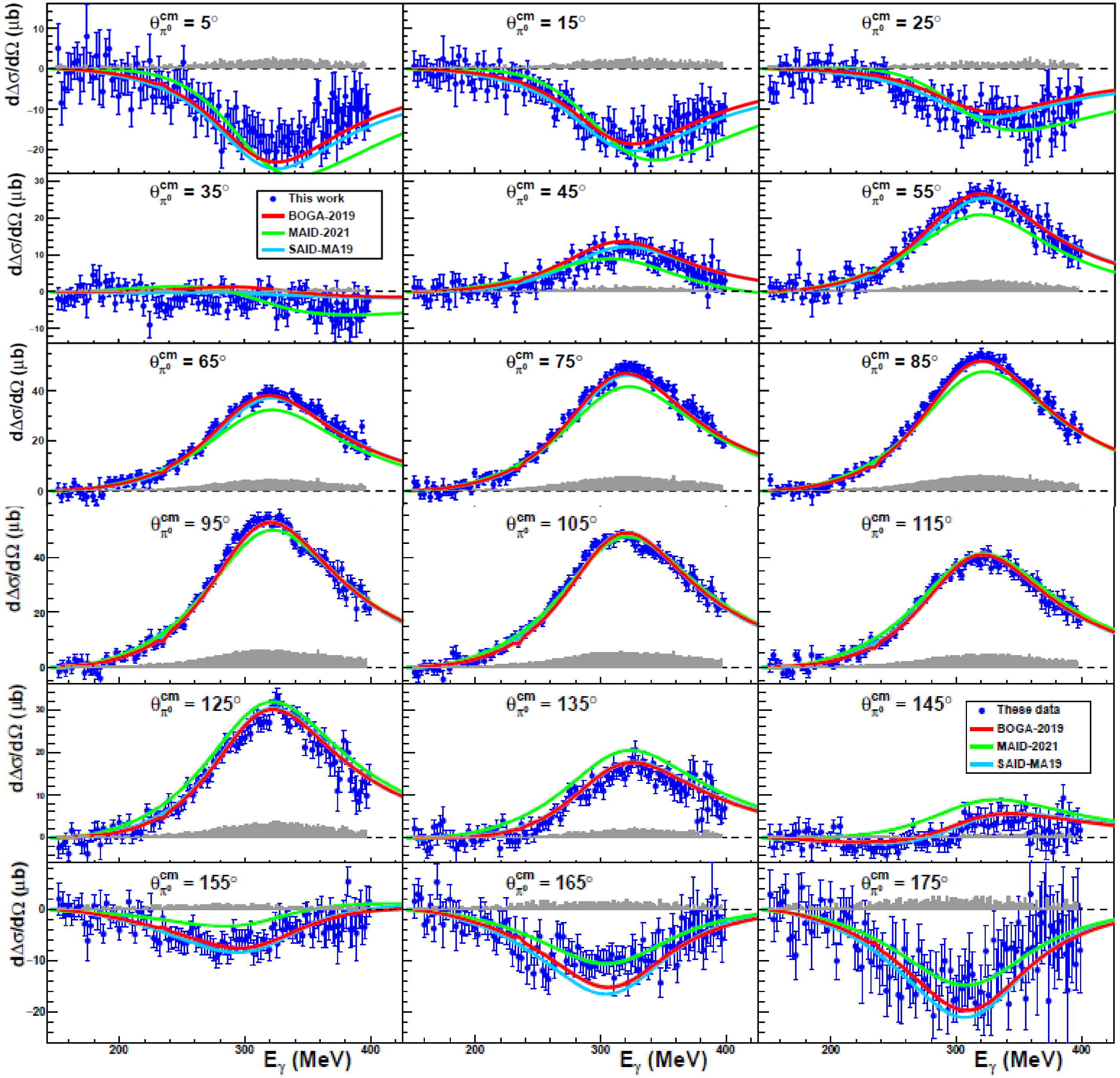
$\vec{\gamma}\,\vec{p} \rightarrow \Delta(1232) \rightarrow p\pi^0$

(background-free reaction)



E. Mornacchi et al.,
PRC 109, 055201 (2024)

PRC «Editor's suggestion»



Excitation functions

- This work
- BOGA-2019
- MAID-2021
- SAID-MA19

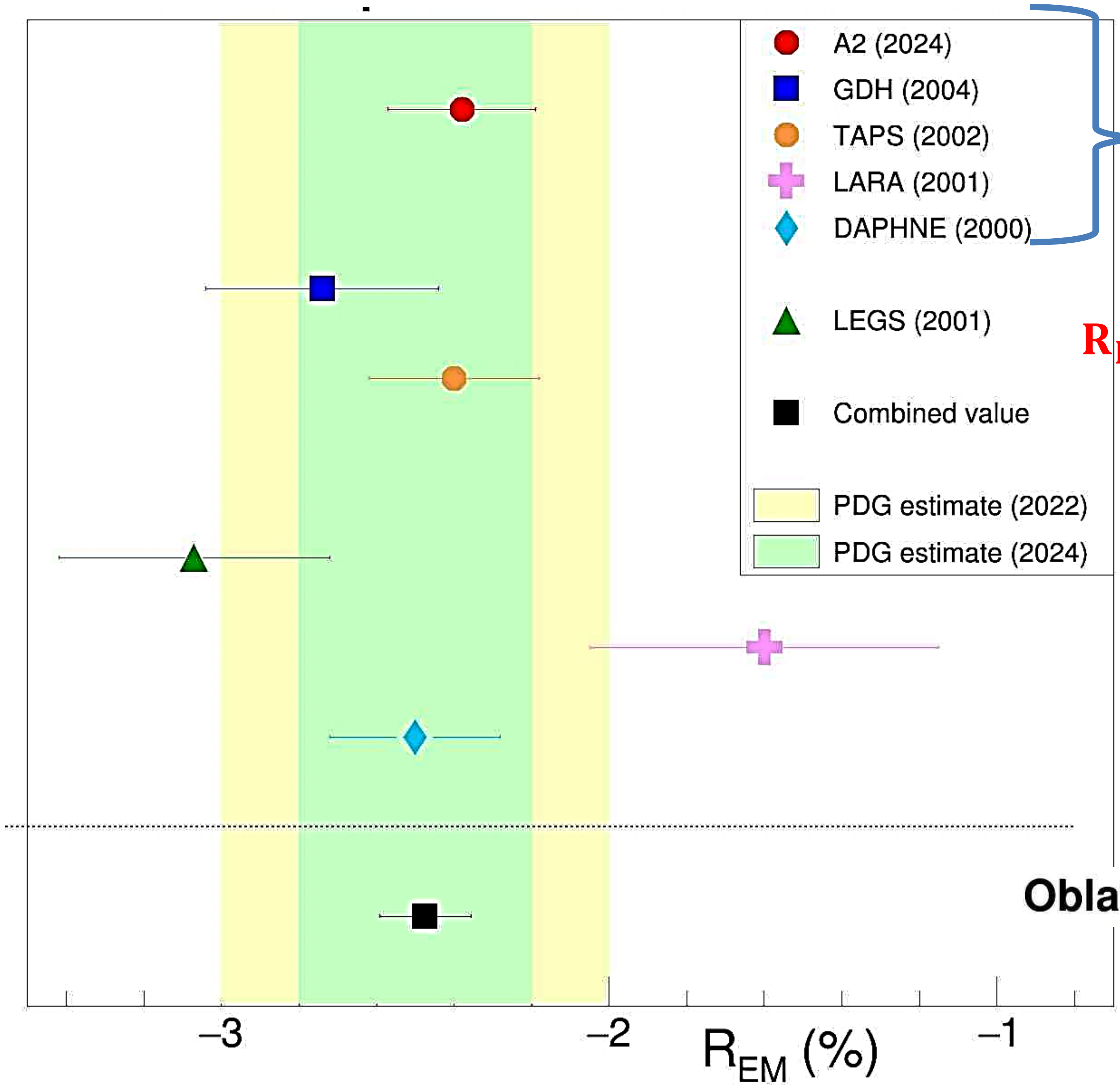
E. Mornacchi et al.,
PRC 109, 055201 (2024)

A2: for each of the 114 measured E_γ bins there are 18 differential cross section values as a function of $\theta^{cm}_{\pi^0}$ (10-degree wide angular bins).

The value of the E2/M1 ratio can be calculated from the best fit of all angular distributions using Legendre polynomials

Here we have a single experimental data base but with angular-dependent systematic uncertaintes

Bootstrap-based fit procedure



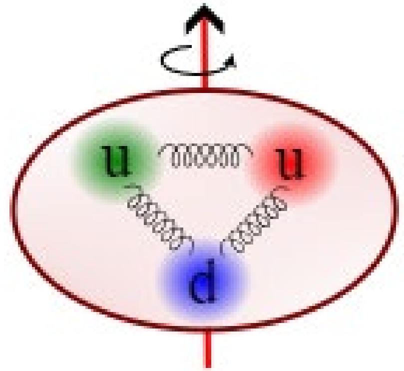
All these experiments have been performed at MAMI (Mainz)

A2 result (the most precise)

$$\mathbf{R_{EM}} \equiv \mathbf{E2/M1}\ [-2.38 \pm 0.16 \pm 0.1] \cdot 10^{-2}$$

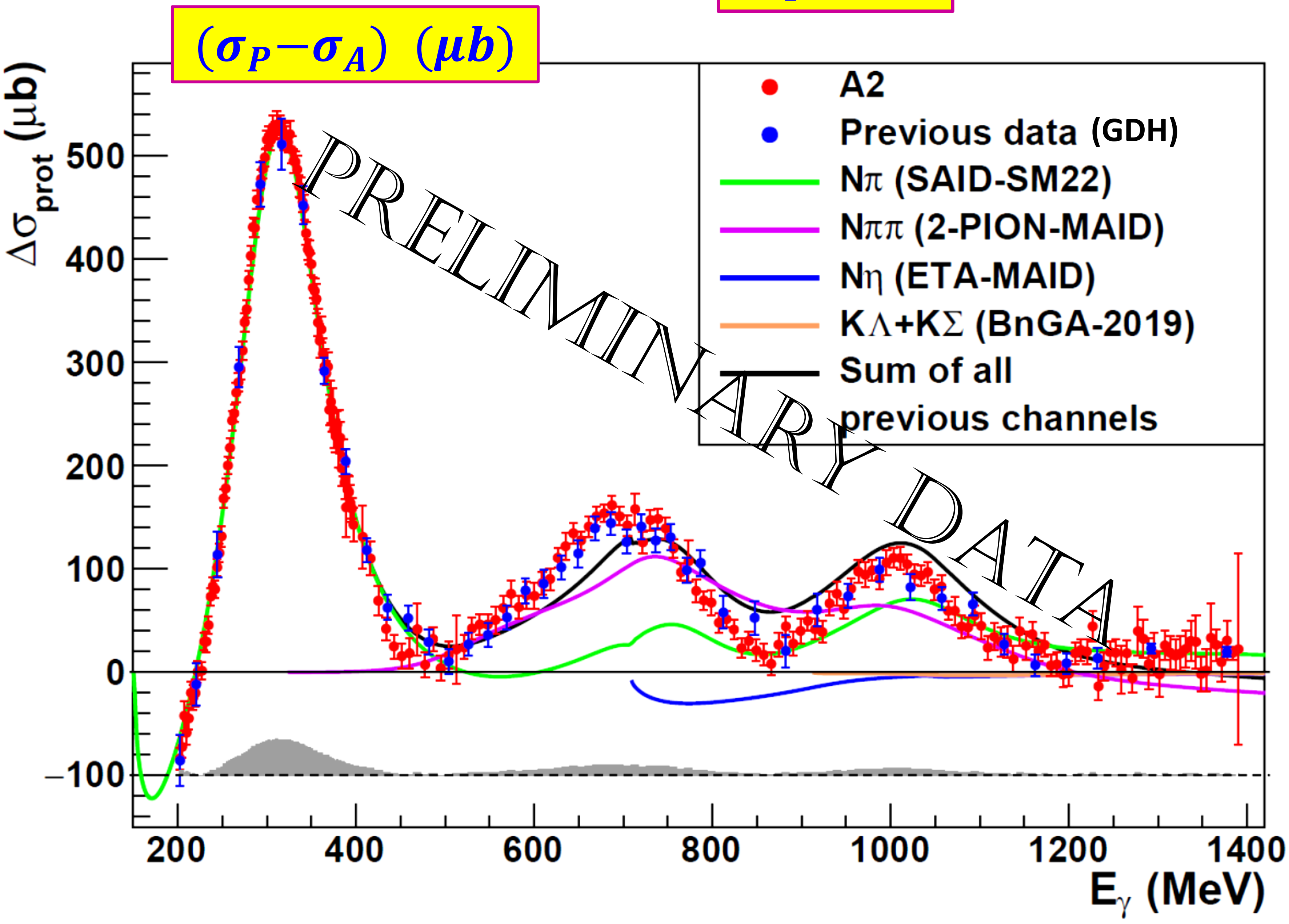
$(\text{stat} + \text{sys})$ (model)

Proton and/or $\Delta(1232)$



Oblate shape due to the color tensor force

$\vec{\gamma}\,\vec{p} \rightarrow X$



integrand function of the GDH sum rule

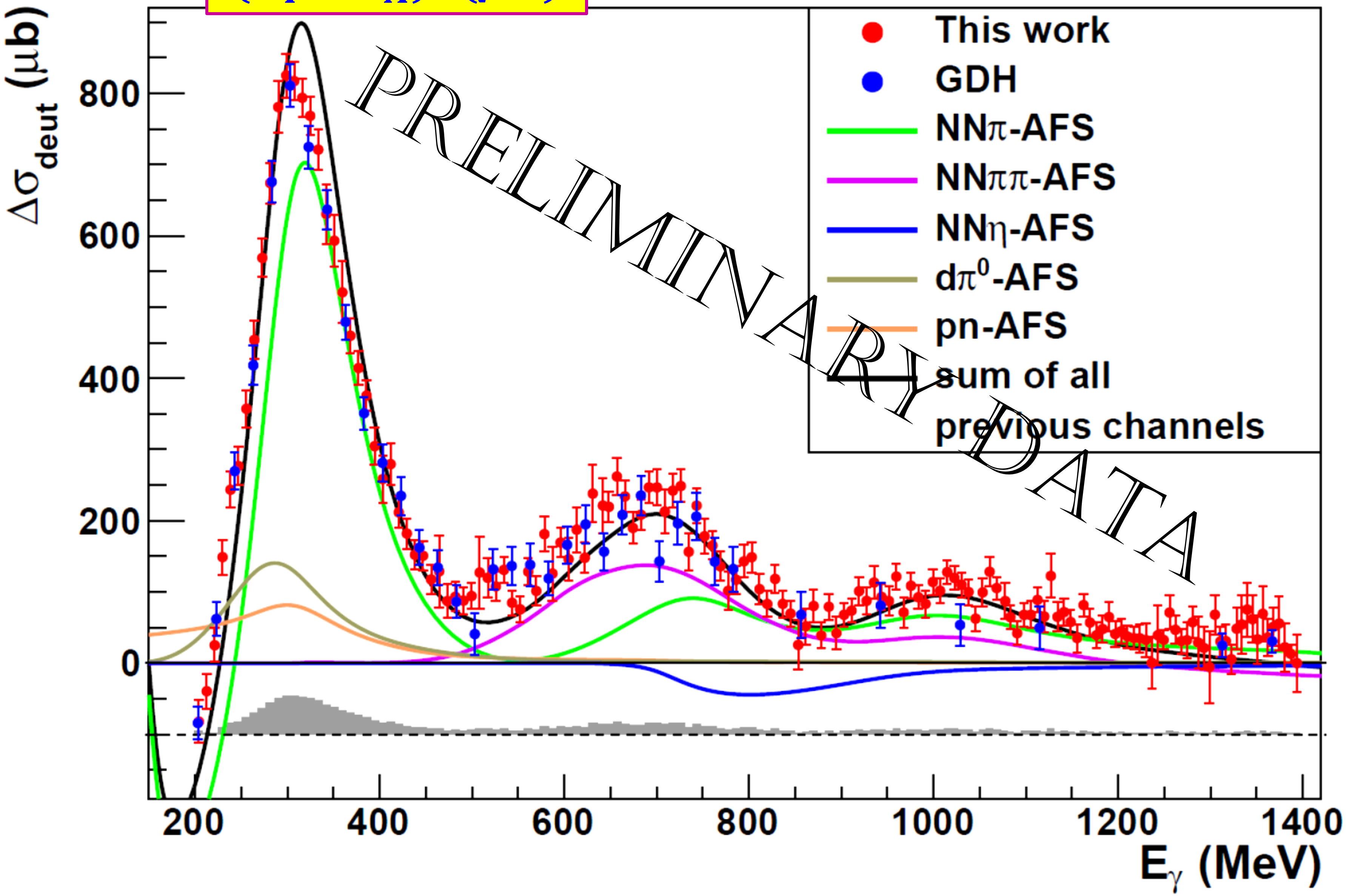
Large improvement with Respect to existing data

Existing models for $\gamma p \rightarrow N\pi, N\pi\pi, N\eta$

do not reproduce the data

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

$(\sigma_P - \sigma_A)$ (μb)



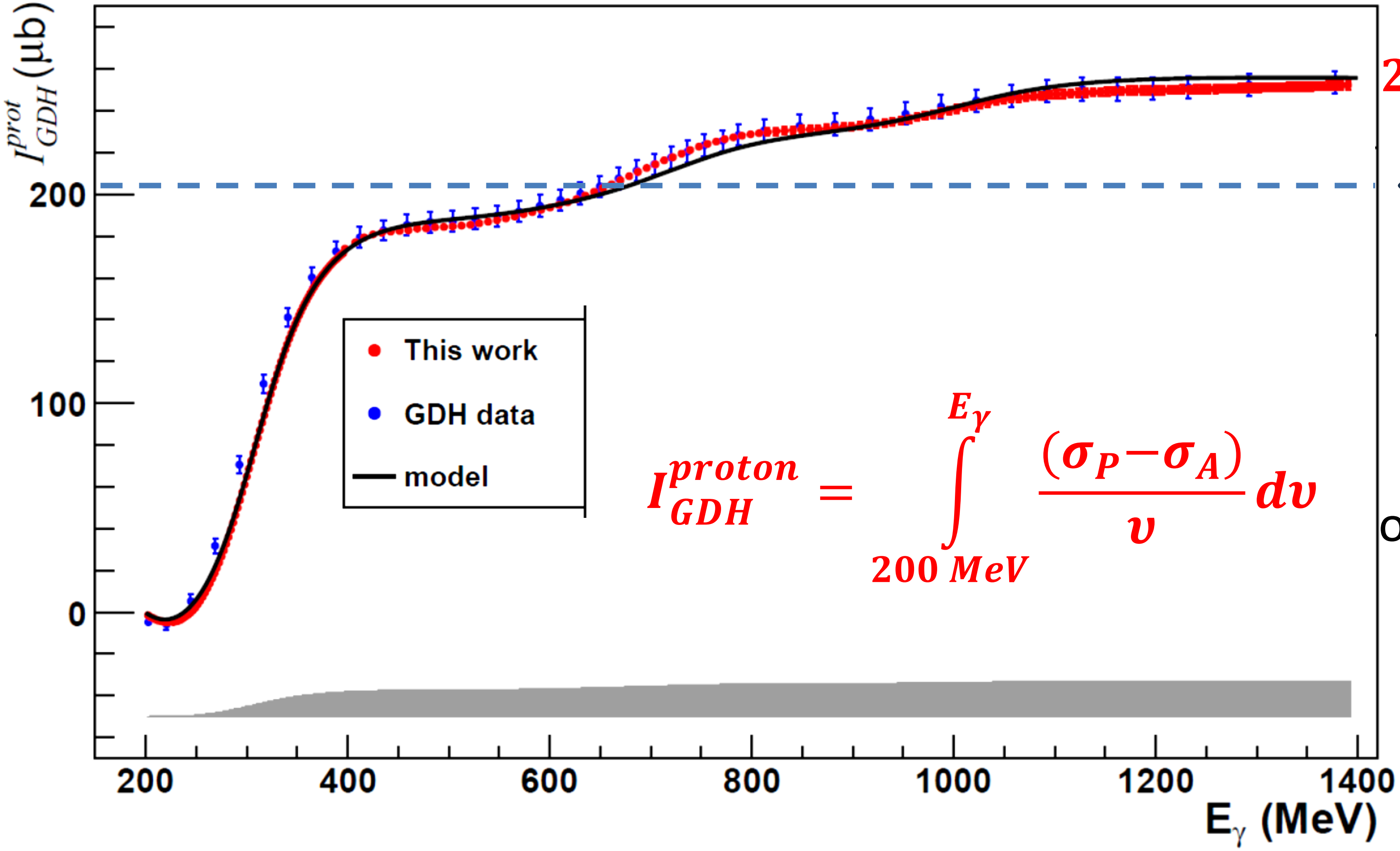
integrand function of the GDH sum rule

Large improvement with Respect to existing data

AFS nuclear model does not reproduce the data, especially in the $\Delta(1232)$ resonance region

Modification of nucleon's properties

Running GDH Integral for the proton



$252 \pm 2 \pm 17$

GDH sume rule value

$$I_{GDH}^{proton} = \int_{200\ MeV}^{E_\gamma} \frac{(\sigma_P - \sigma_A)}{\upsilon} d\upsilon$$

Dependence of the experimental GDH integral on the upper integration limit

GDH sum rule estimates

		I_{GDH}^{proton}	$I_{GDH}^{deuteron}$	$I_{GDH}^{neutron}$
Low energy contribution	$0 \leq E_\gamma \leq m_\pi$ $\leq m_\pi \leq E_\gamma \leq 0.2$ GeV	-30 ± 2	-444 -58	-35 ± 5
Measured interval (A2 data)	$0.2 \leq E_\gamma \leq 1.4$ GeV	$252 \pm 2 \pm 17$	$450 \pm 5 \pm 30$	$234 \pm 6 \pm 37$
GDH data	$1.4 \leq E_\gamma \leq 1.8$ GeV $1.4 \leq E_\gamma \leq 2.9$ GeV	2.2 ± 0.2	9 ± 2	7 ± 2
High energy contribution	$E_\gamma > 1.8$ GeV $E_\gamma > 2.9$ GeV	-15 ± 2	20 ± 5	35 ± 5
TOTAL		$209 \pm 2 \pm 17$	$-23 \pm 5 \pm 30$	$241 \pm 6 \pm 38$
GDH sum rule		204	0.65	232

$$I_{GDH}^{neutron} = 1.075 \cdot I_{GDH}^{deuteron} - I_{GDH}^{proton}$$

(PWIA approach)

Low energy contribution	proton, neutron	PWA (SAID,BNGA)
	Deuteron	AFS model
High energy contribution		Regge Models

GDH sum rule on deuteron and ^{3}He

PWIA approach

$E_\gamma > m_\pi$

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

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

Effective nucleon polarisation (correction for the D-state)

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

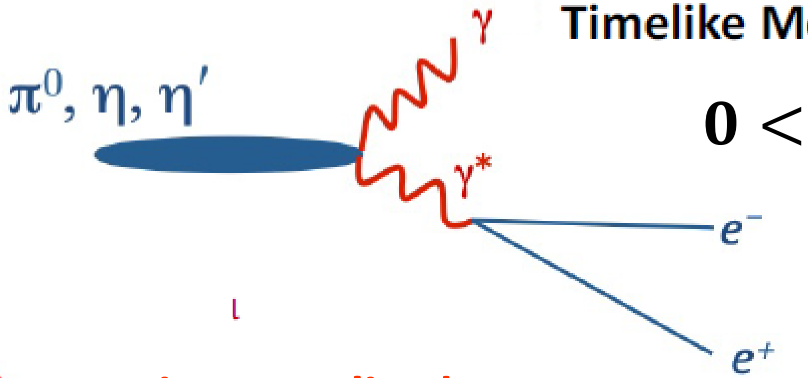
$$I_{GDH}^{He3} \sim 0.87 \cdot I_{GDH}^{neutron} - 0.026 \cdot I_{GDH}^{proton}$$

A high-precision measurement of the Transition Form Factor of the π^0

Electromagnetic (EM) Transition Form Factors (TFFs) of light mesons *M*

Decay of a point-like meson $M \rightarrow l^+ l^- \gamma \overset{\text{QED}}{\Leftrightarrow} M \rightarrow \gamma^* \gamma$

TFF describes any deviation from the simple QED dependence , caused by the actual e.m. structure of M



Timelike Measurement

$$0 < Q^2 < m_M^2$$

$$\frac{d\Gamma(M \rightarrow l^+ l^- \gamma)}{dm_{ll}\Gamma(M \rightarrow \gamma\gamma)} = \underset{\substack{\uparrow \\ \text{pointlike meson M}}}{[QED]} \cdot |F_M(m_{ll})|^2$$

TFF is normalized to the $\gamma\gamma$ decay

$$Q^2 = m_{ee}^2 < m_{\pi^0}^2$$

Small Q^2 range

For the π^0 meson

$$\pi^0 \rightarrow e^+ e^- \gamma$$

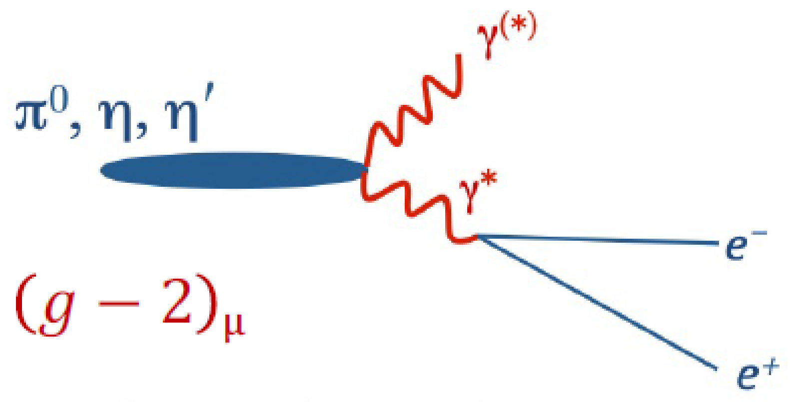
$$F_{\pi^0}(m_{ee}) = 1 + a_\pi \frac{m_{ee}^2}{m_{\pi^0}^2}$$

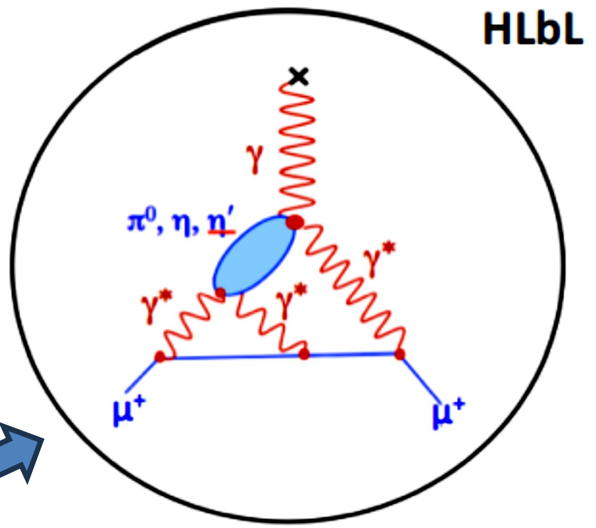
TFF can be characterized by only one free parameter

➢ TFF:

→ is a fundamental parameter for the understanding of the meson intrinsic structure

→ connected to the hadronic light-by-light contribution to $(g-2)_\mu$



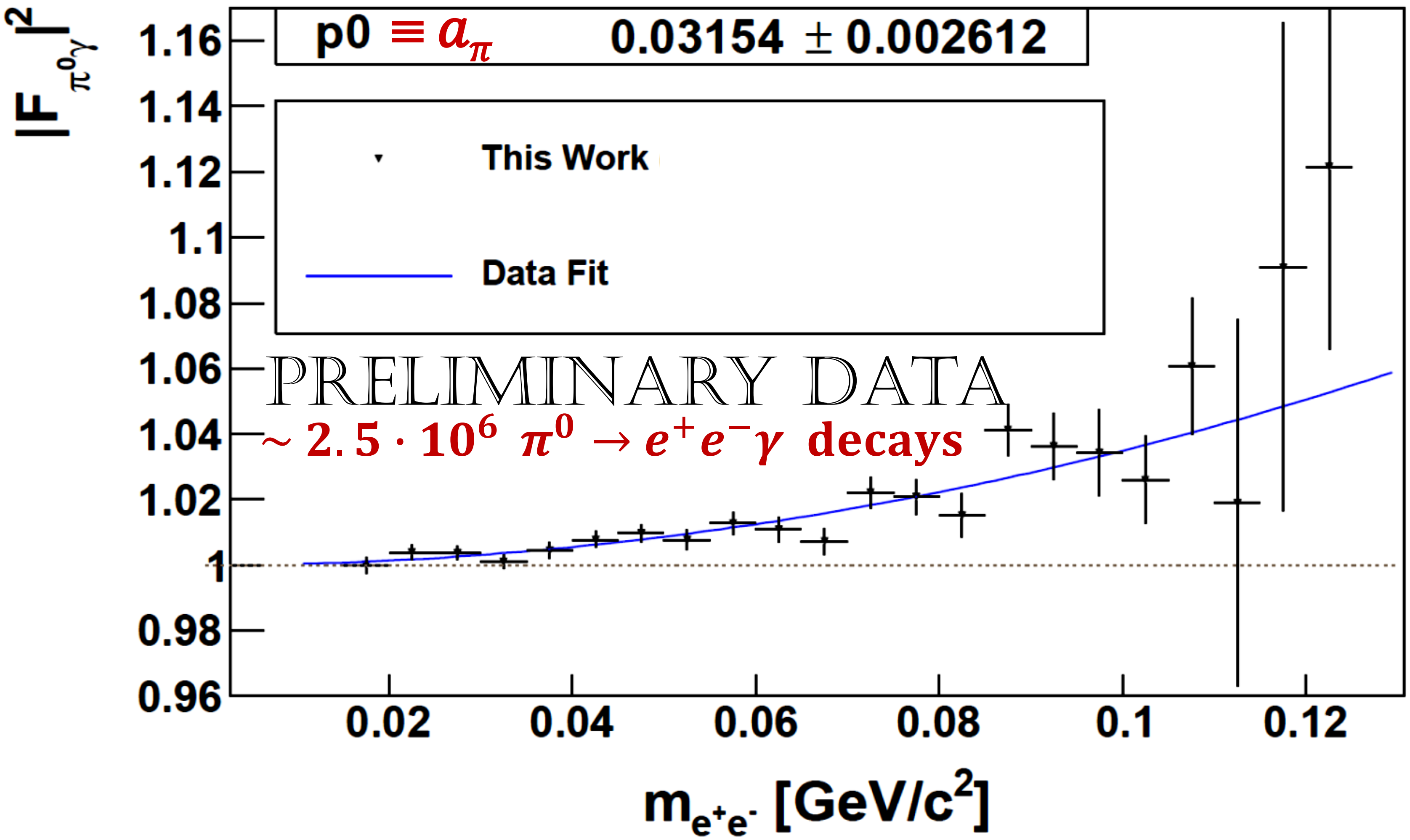


Muon anomaly

$$a_\mu = (g-2)/2 = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{HAD}$$

(one of the most important contributing diagrams)

A2 photon beam can be used as a π^0 factory ($\sim 3 \cdot 10^9$ π^0 were produced)



a_π = 0.0315 ± 0.0026 stat ± 0.0010 syst

New A2 result improves the experimental uncertainty by a factor of two the NA62-CERN result (the most precise up to now)

Excellent agreement with the theoretical calculations

Padé approximants
[a' = 0.0324 ±0.0020]

Dispersive Analysis
[a' = 0.0315±0.0009]

Experimental accuracy approaching those of the predictions

Is all this useful for anything ?

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

Progress in Particle and Nuclear Physics 146 (2026) 104214

The impact of γN and $\gamma^* N$ interactions on our understanding of nucleon excitations

Volker Burkert [a], Gernot Eichmann [b], Eberhard Klempt [a,c,*]

[a] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

[b] Institute of Physics, University of Graz, NAWI Graz, Universitätsplatz 5, 8010 Graz, Austria

[c] Helmholtz-Institut für Strahlen- und Kernphysik der Rheinischen Friedrich-Wilhelms Universität, Nussallee 14 - 16, 53115 Bonn, Germany

ARTICLE INFO

ABSTRACT

We review recent progress in our understanding of the nucleon excitation spectrum. Thanks to dedicated efforts at facilities such as ELSA, MAMI and Jefferson Lab, several new nucleon resonances have been discovered, and evidence for previously elusive states has been significantly improved. Numerous decay channels have been observed for the first time, and resonance properties are being extracted from these data by several groups through coupled-channel analyses of varying complexity. Electroproduction experiments have provided further

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, …) and the technological development in polarized beam and target techniques can 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

$\simeq$ 70 researchers

Participating Institutions

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

North-America: Universities of Mount-Allison (Canada), Regina (Canada), Saint Mary's (Canada), Washington-DC (USA), Kent-OH (USA), Amherst-MASS (USA), Los Angeles (USA).

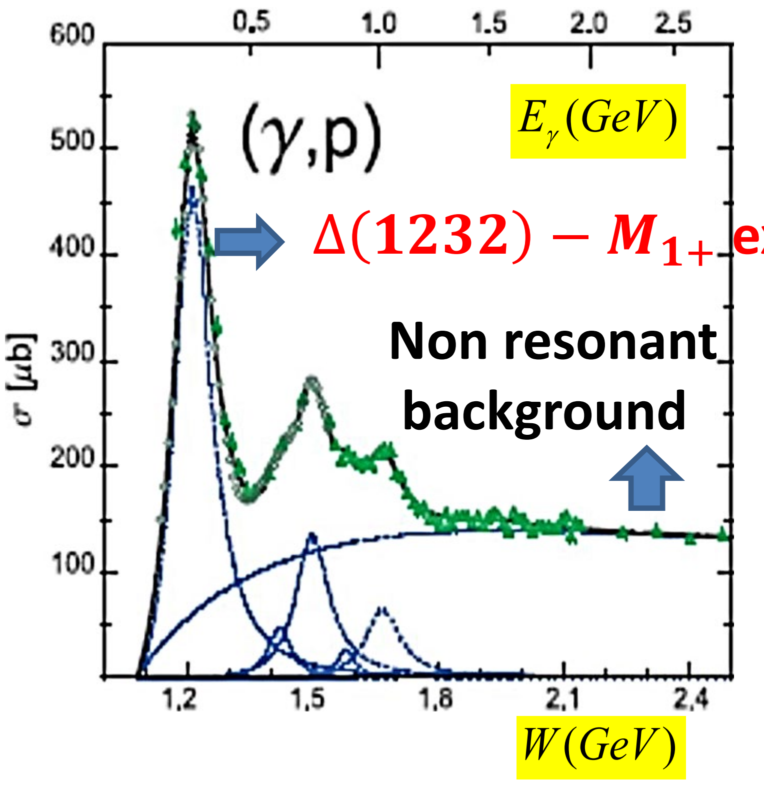
➢ Partial Wave Analysis (*l* =pion angular momentum)

$$F_1 = \sum_{l=0}^{\infty} \left(l M_{l+} + E_{l+} \right) P'_{l+1} + \left[(l+1) \underbrace{M_{l-} + E_{l-}}_{\text{multipoles}} \right] P'_{l-1}$$

$$\sigma = |E_{0+}|^2 + |M_{1-}|^2 + 6|E_{1+}|^2 + 2|M_{1+}|^2 + \ldots$$

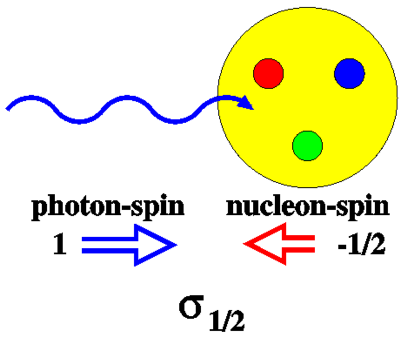
$$E = |E_{0+}|^2 + 3|E_{1+}|^2 - |M_{1+}|^2 + 6E^*_{1+}M_{1+} + \ldots$$

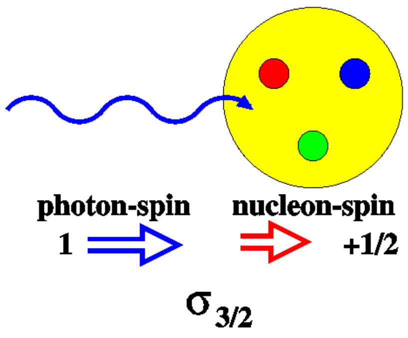
Change of sign and interference terms between multipoles



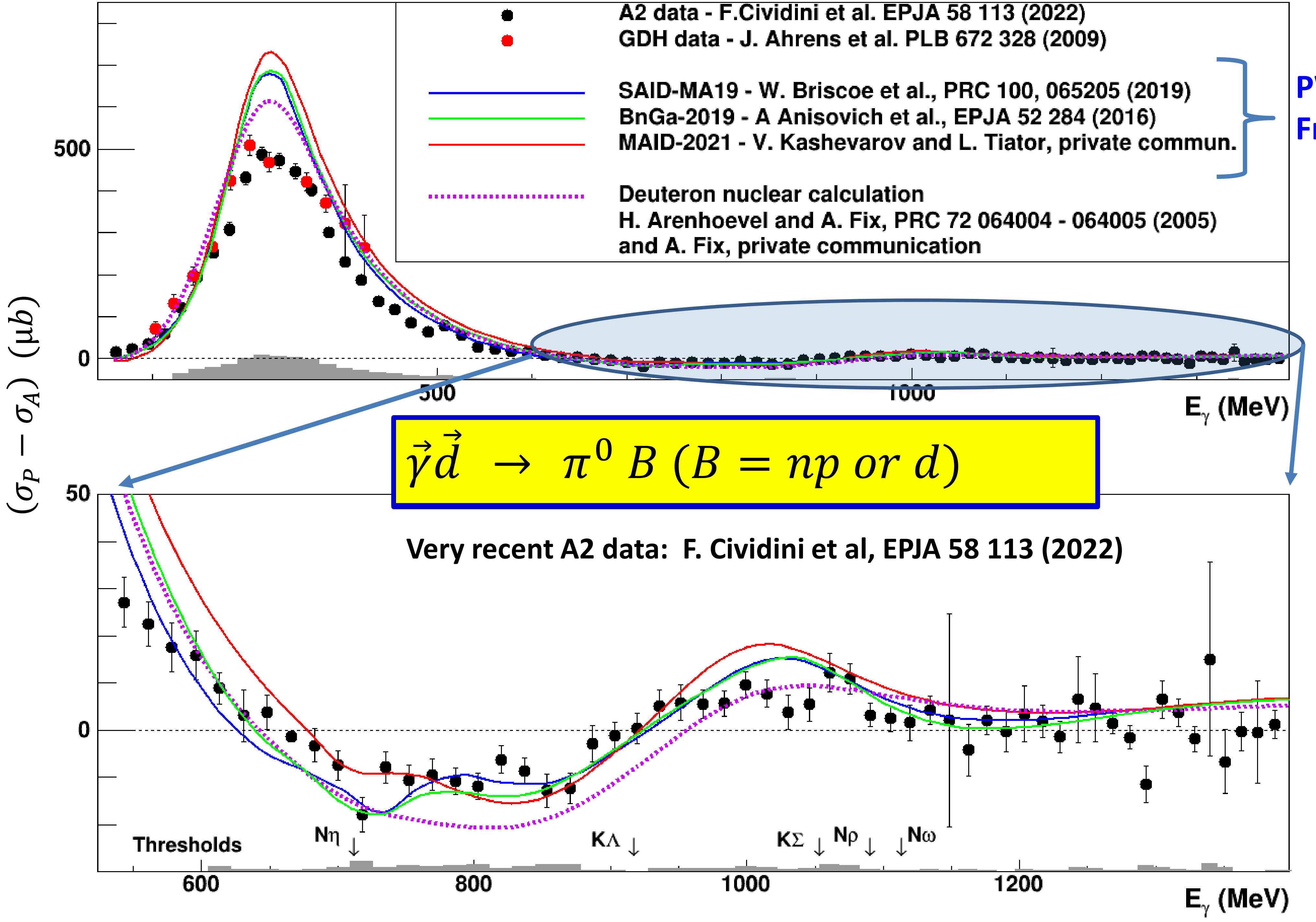
E **Asymmetry**

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





Absorption of circularly polarized photons by longitudinally polarized nucleons

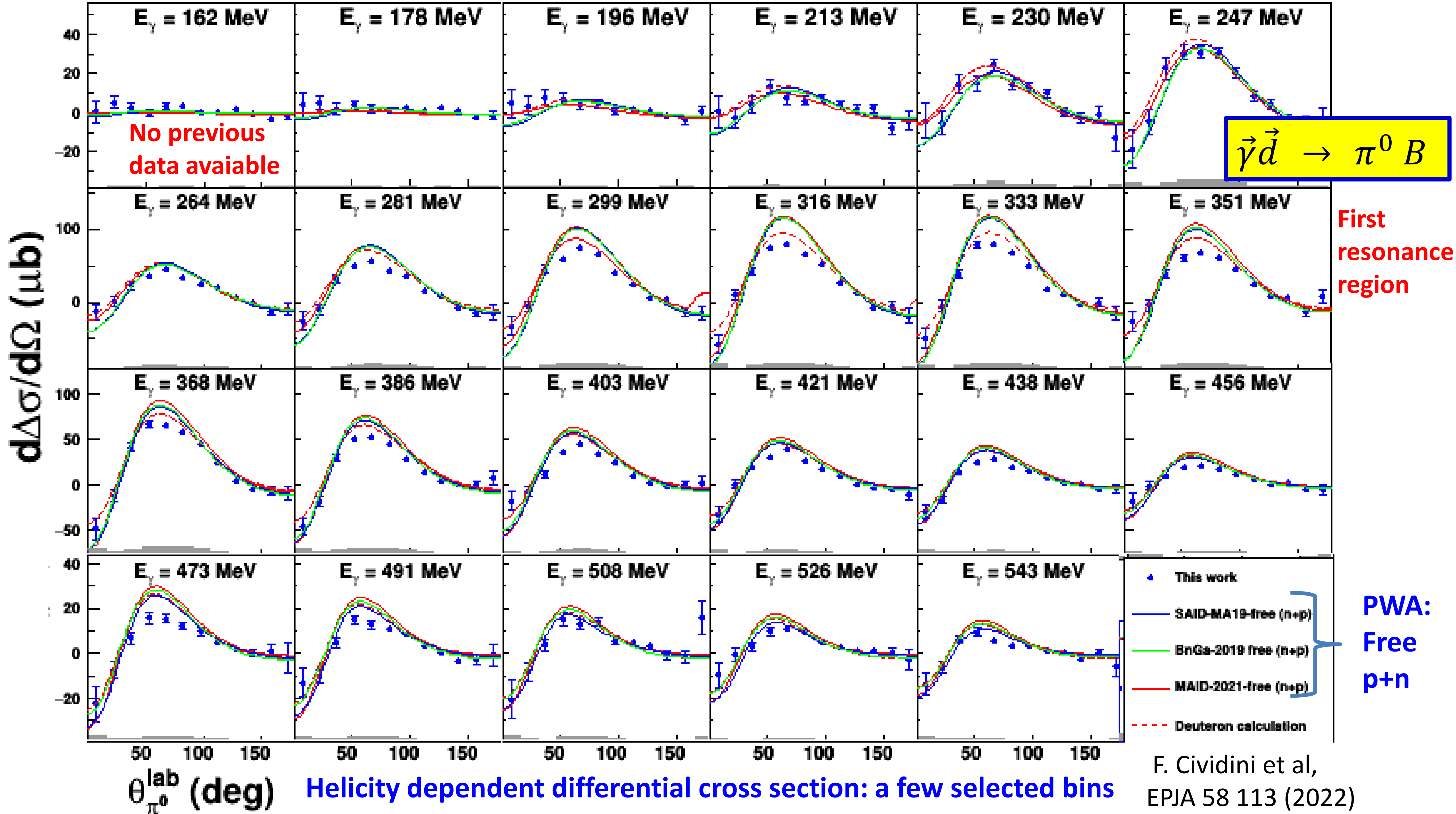


$$\vec{\gamma}\vec{d} \;\rightarrow\; \pi^0\, B\ (B = np\ or\ d)$$

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

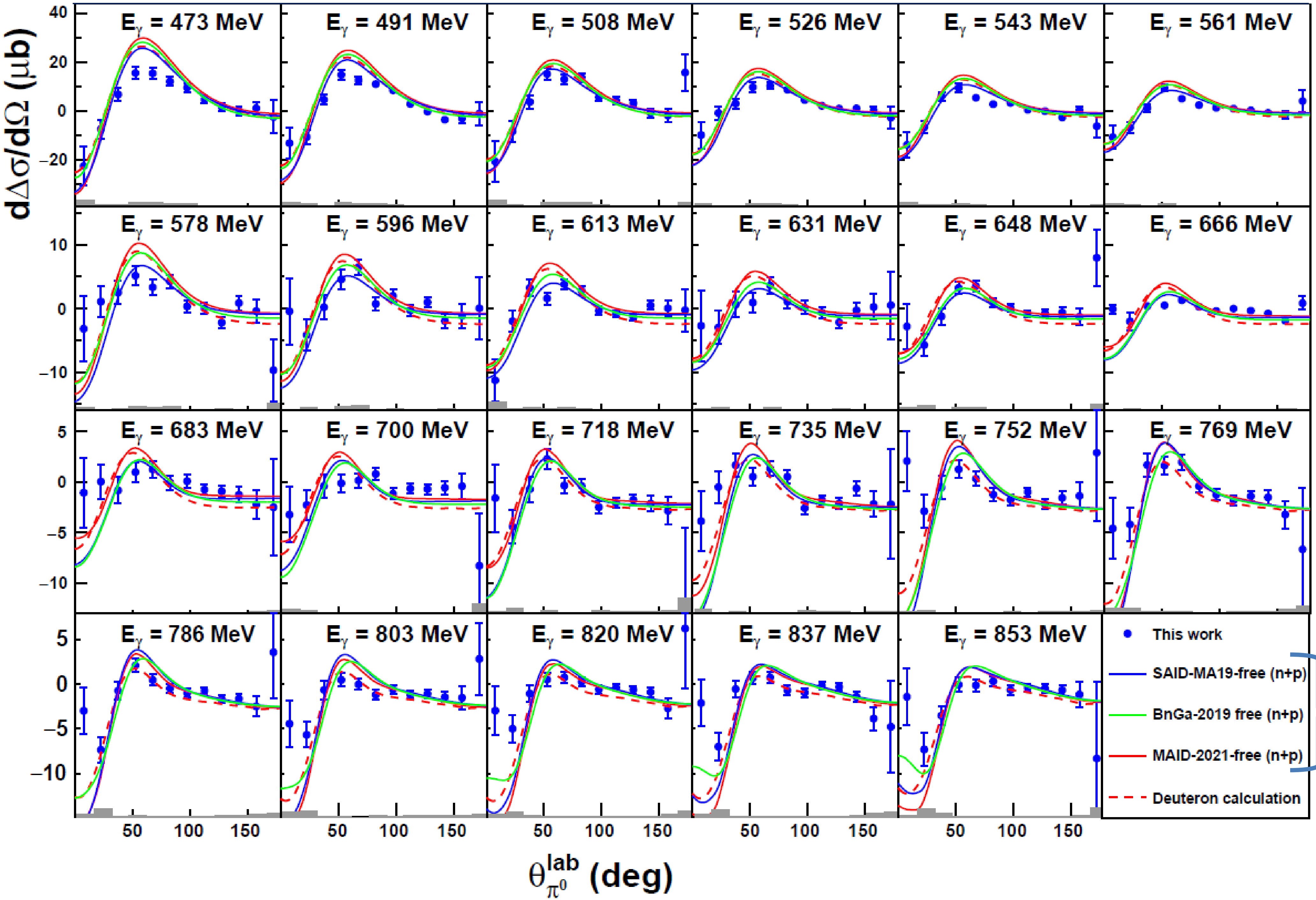
PWA analyses
Free p+n

A deeper insight into the γ-deuteron interaction mechanisms is provided by partial channels.



Helicity dependent differential cross section: a few selected bins

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

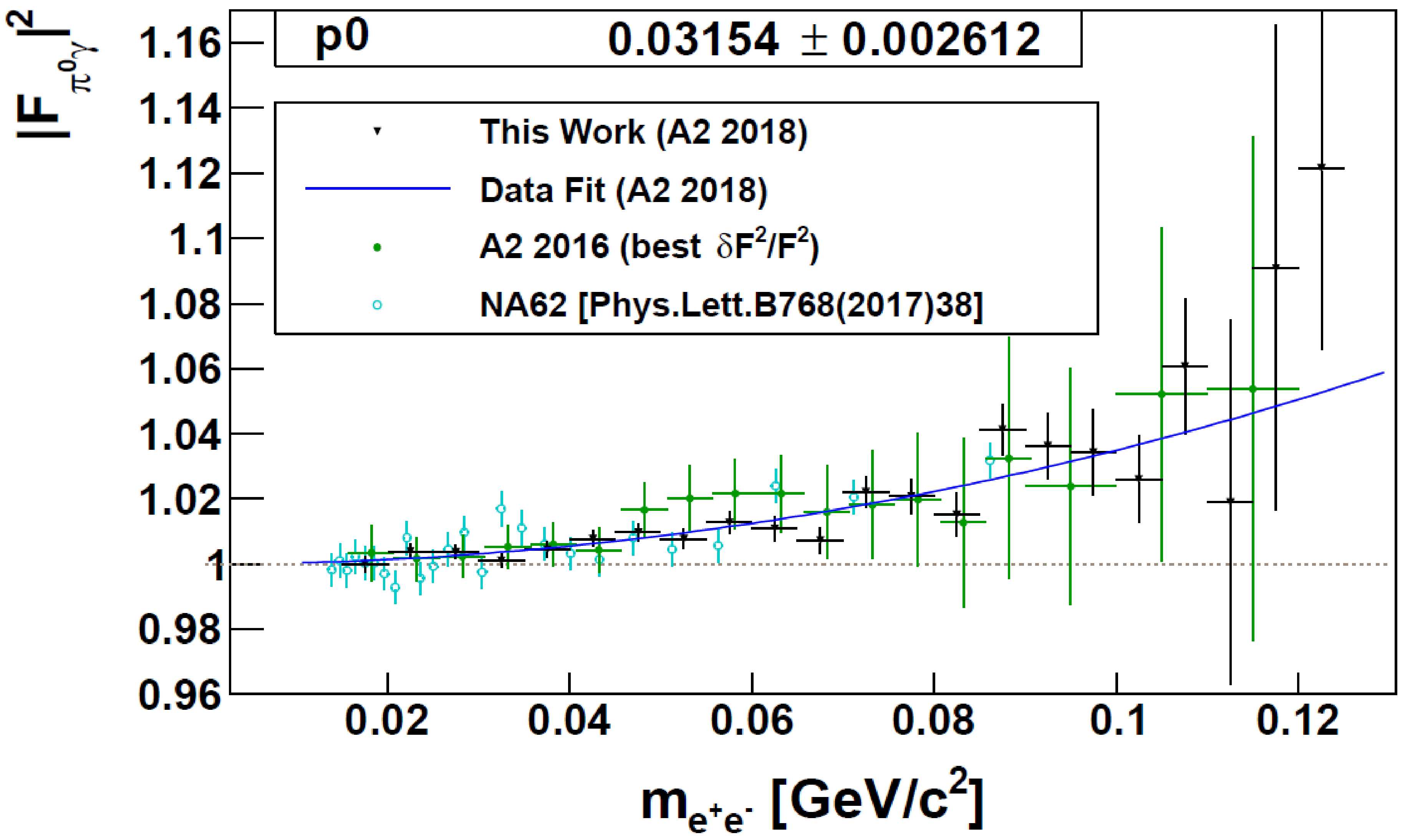


$\vec{\gamma}\vec{d} \rightarrow \pi^0 B$

Second resonance region

Effects due to the nuclear medium more evident at very forward angles

PWA: Free p+n



p0 0.03154 ± 0.002612
This Work (A2 2018)
Data Fit (A2 2018)
A2 2016 (best $\delta F^2/F^2$)
NA62 [Phys.Lett.B768(2017)38]
$|F_{\pi^0\gamma}|^2$
$m_{e^+e^-}$ [GeV/c^2]
1.16
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.02
0.04
0.06
0.08
0.1
0.12