GDH on the Deuteron: Status and new results from A2@MAMI

Paolo Pedroni

INFN-Sezione di Pavia, Italy

For the A2@MAMI collaboration
(Mainz-Germany)

Istituto Nazionale
di Fisica Nucleare
Sezione Pavia

SUMMARY

- Physics motivations

  Why the Gerasimov-Drell-Hearn sum rule is interesting both for the nucleon and the nuclei ?

- Experimental set up (A2 tagged photon facility)

- Results

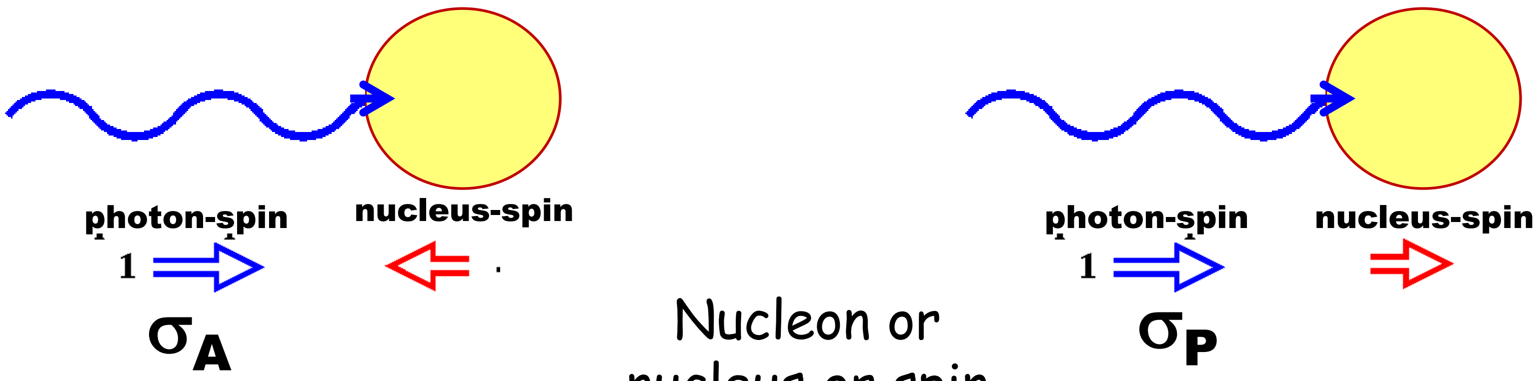
$$\vec{\gamma}\vec{d} \rightarrow \begin{cases} X \ (\text{total inclusive c. s.}) \\ \pi^0 \ B \ (B = np \ or \ d) \end{cases}$$

- Outlook

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



Nucleon or nucleus or spin

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

Anomalous magnetic moment

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

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

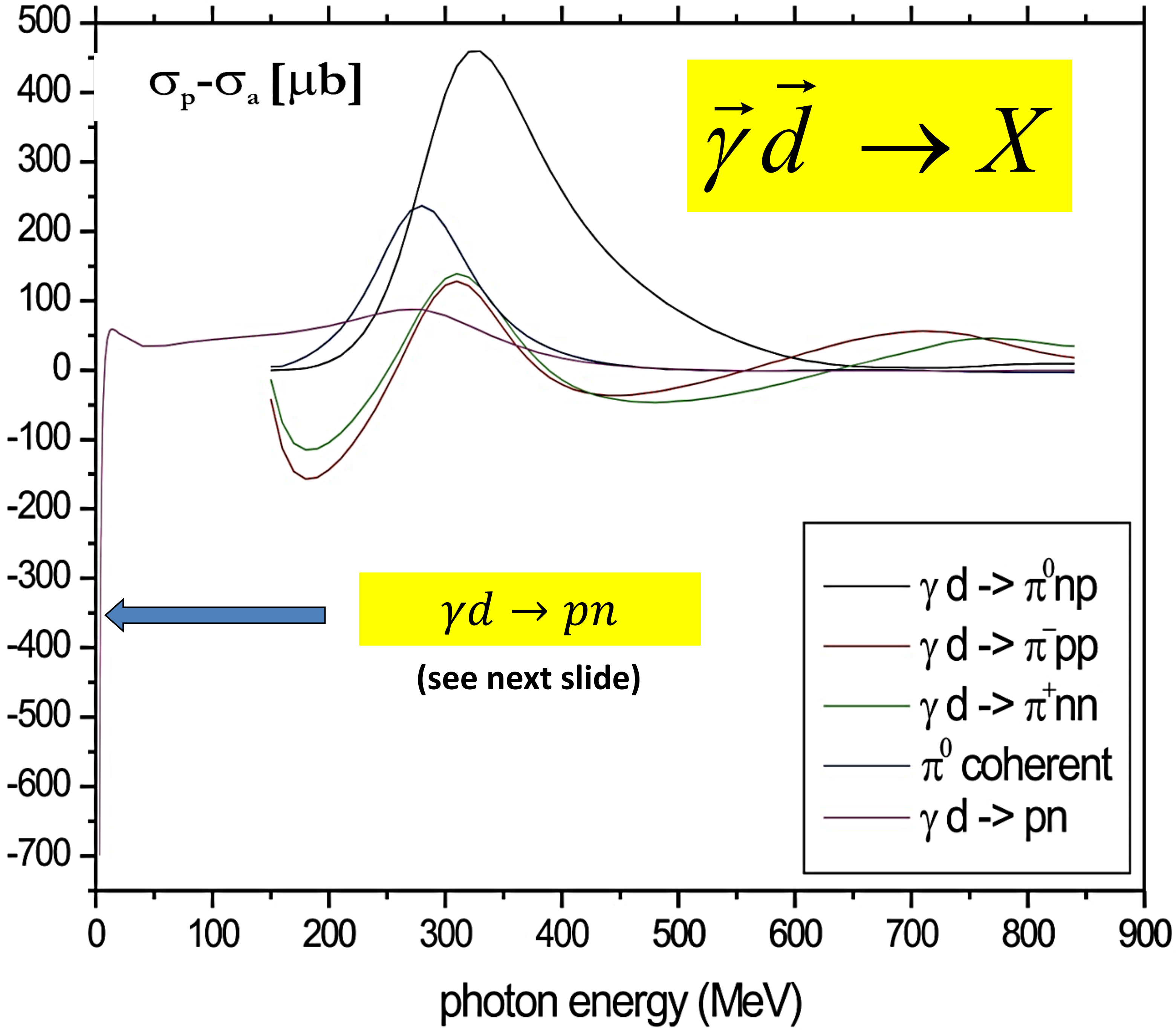
✓ Helicity dependence of partial channels (pion photoproduction) is an essential tool for the study of the baryon resonances (interference terms between different electromagnetic multipoles)

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

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

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)

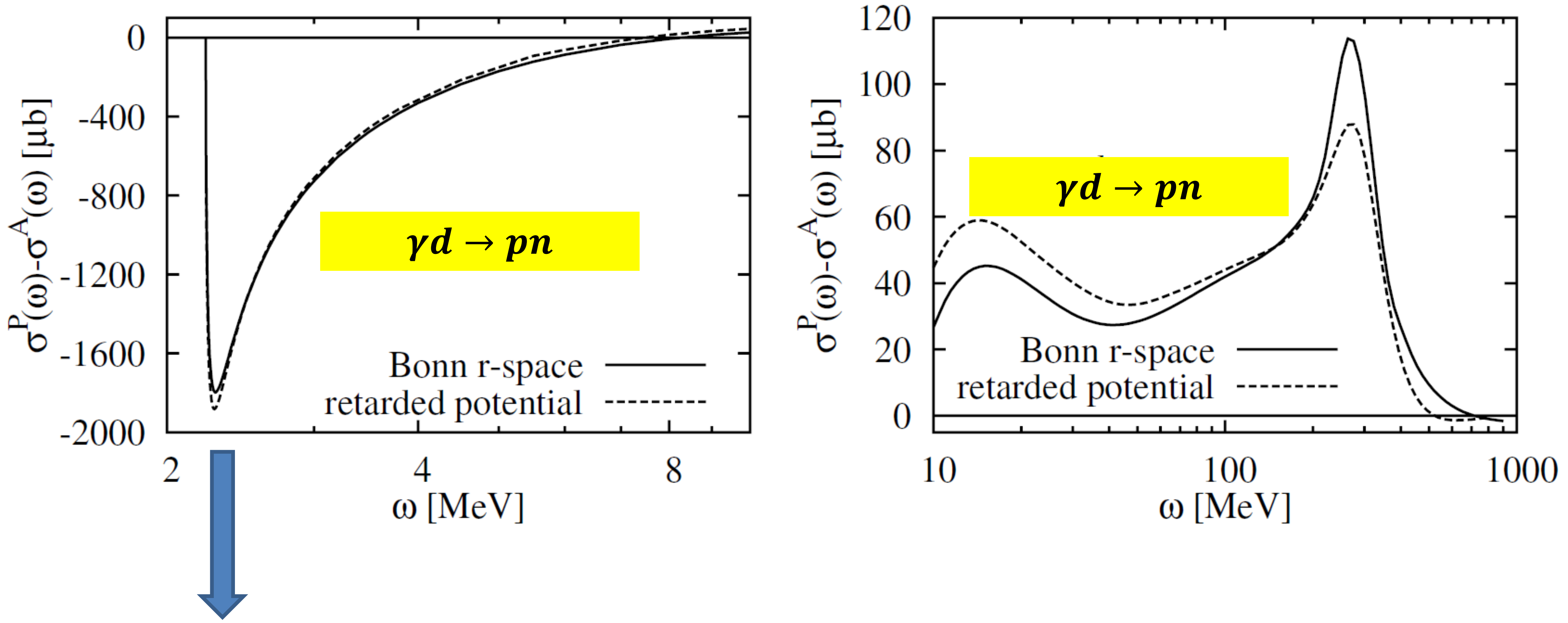
π^0d PLB 407,1 (97)

pn NPA 690,682 (01)

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

AFS model

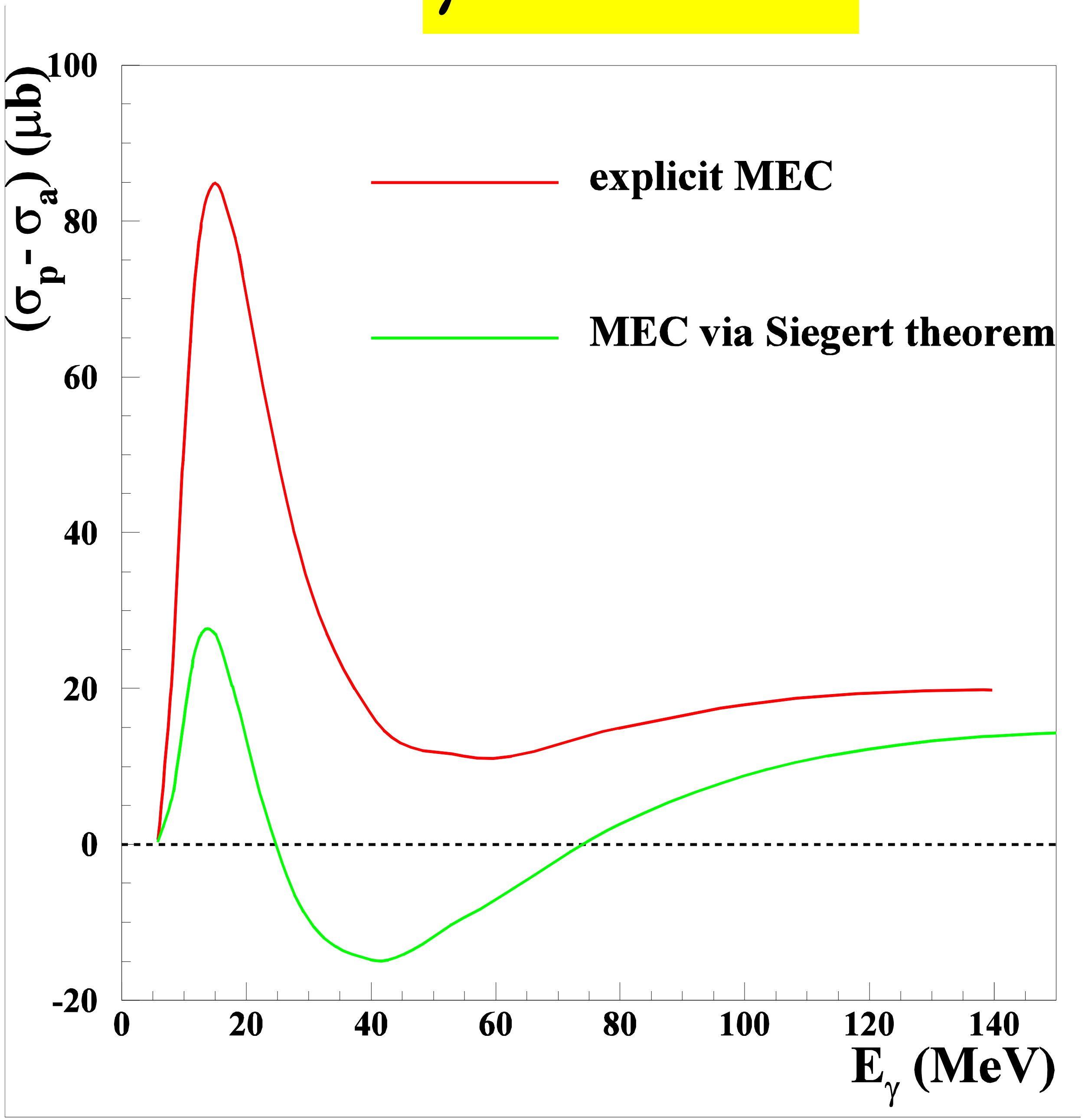
PRL 93, 202301 (04)



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

✓ GDH sum rule on nuclei gives an important "link" between nuclear and nucleon degrees of freedom (photodisintegration processes at a few MeV are correlated by the sum rule to quasi-free pion photoproduction processes in the GeV region ....)

✓ It is very important to experimentally verify its convergence also on nuclei and not only on the nucleon

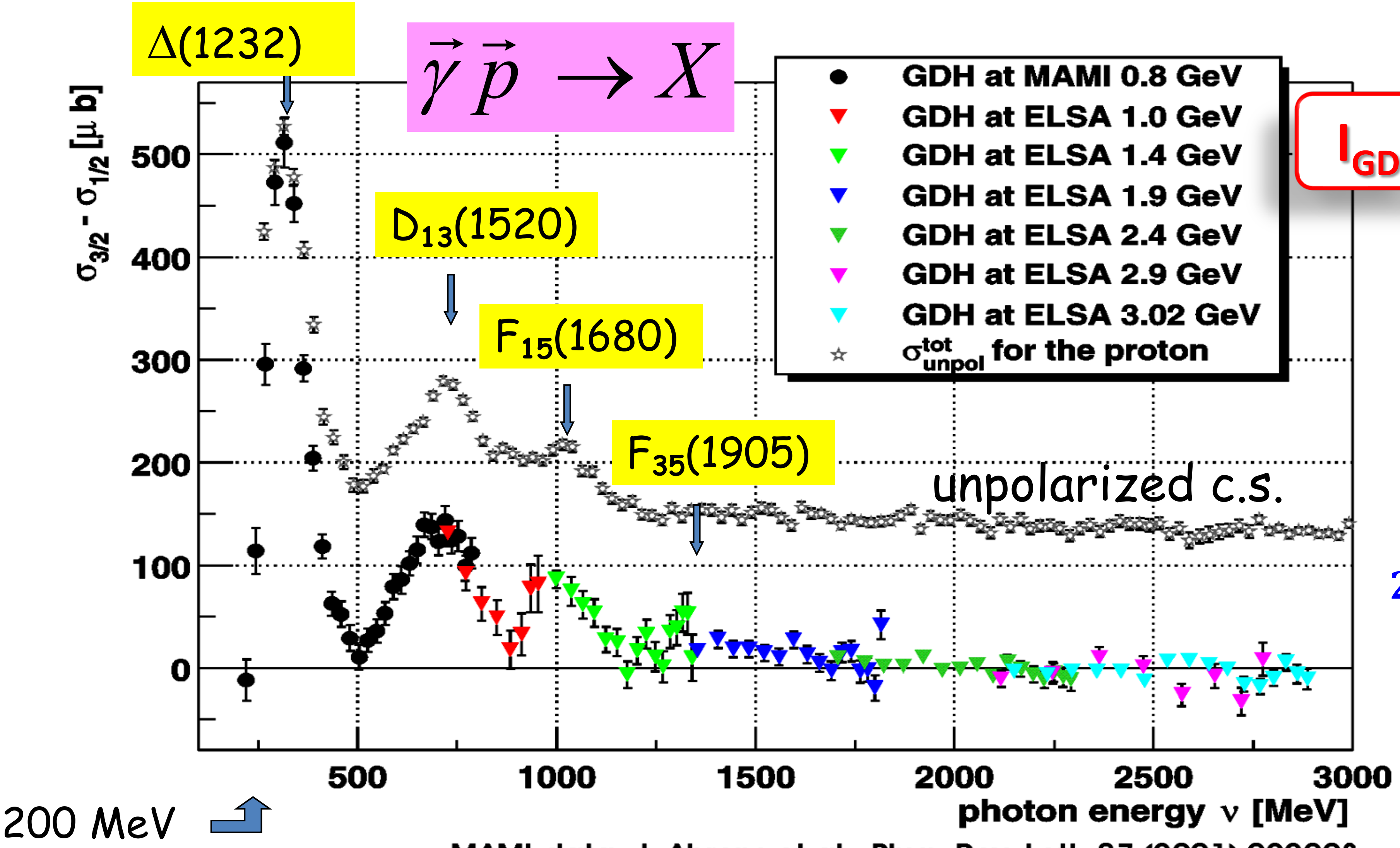
✓ Possible violations/modifications in nuclei ?

⇓

(S. Bass: Acta Phys. Pol. 52, 43 (2021); modifications to GDH due to a smaller nucleon mass inside the nuclear medium ?)

Experimental status -protoon

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



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

I_{GDH} (p) = 211 ± 5 ± 12 μb

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

Measured

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

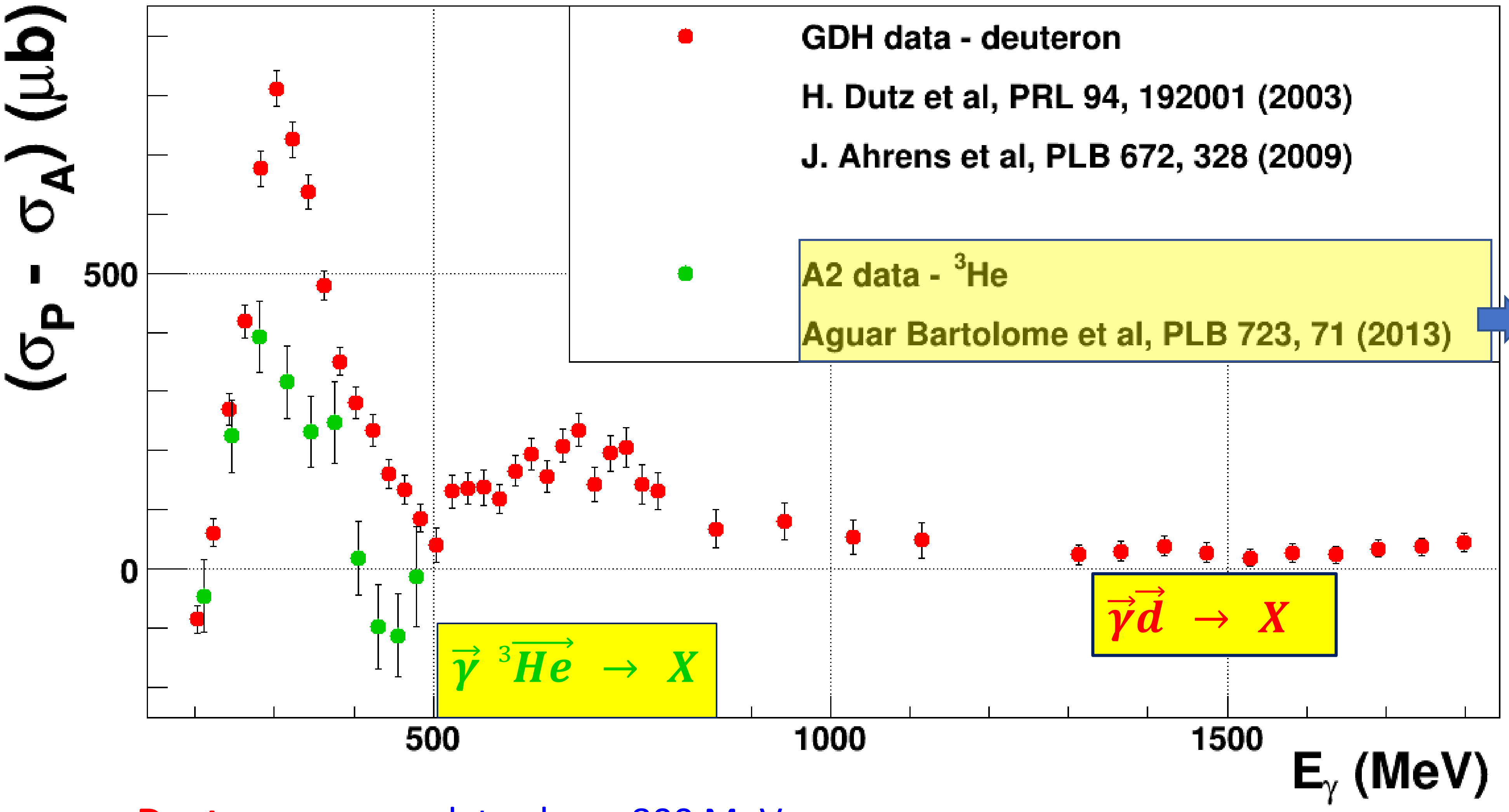
254 ± 5 ± 12 μb

Estimated unmeasured contributions:

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

$E_\gamma > 2.8\ \text{GeV}$ -14 μb

Experimental 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 modifcations inside the nuclear medium and as a tool to access free-neutron information

Experimental Set up

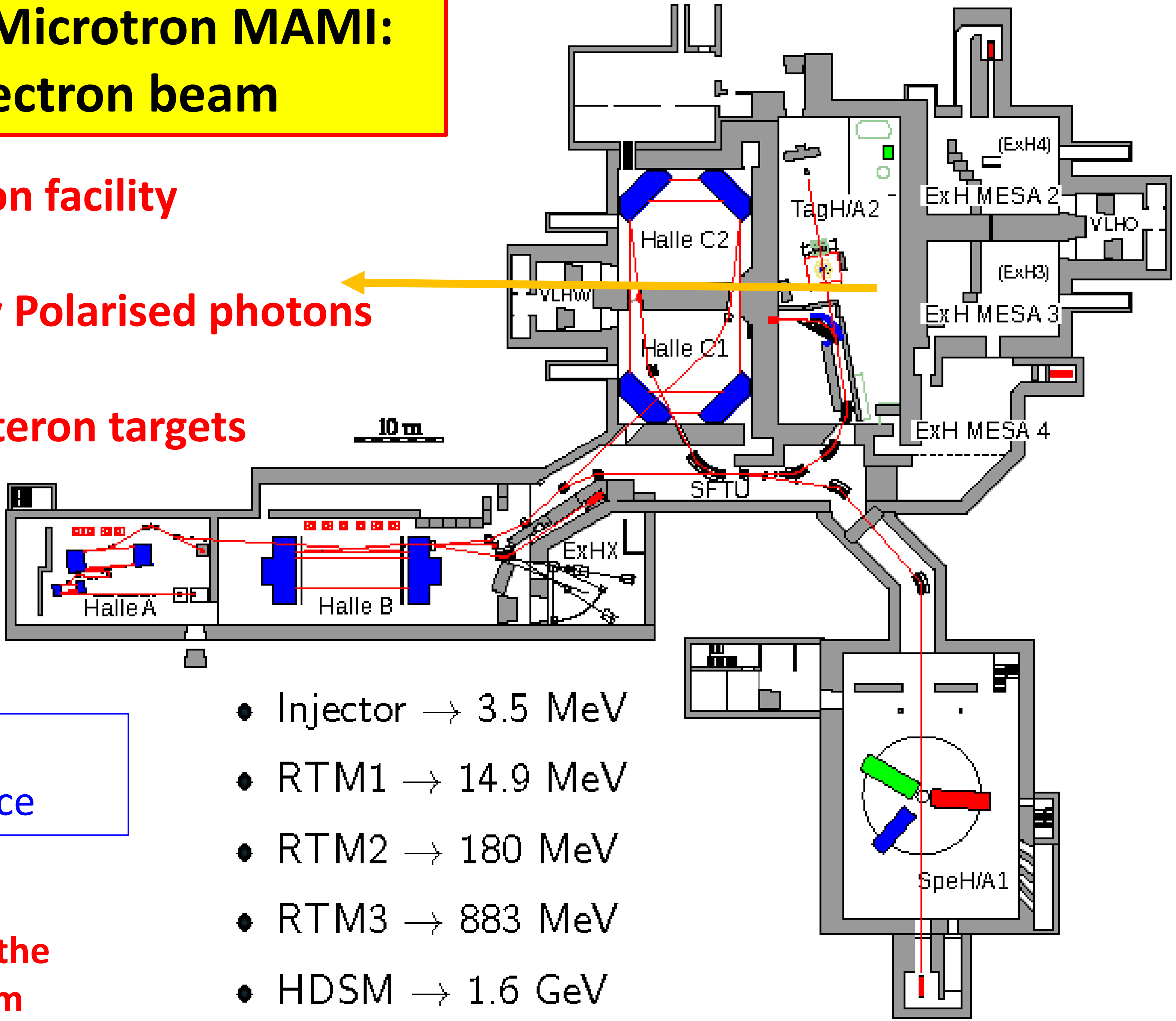
Mainz Microtron MAMI: electron beam

A2 Hall: Tagged photon facility

Linearly and Circularly Polarised photons

Polarised proton/deuteron targets

See A. Thomas talk

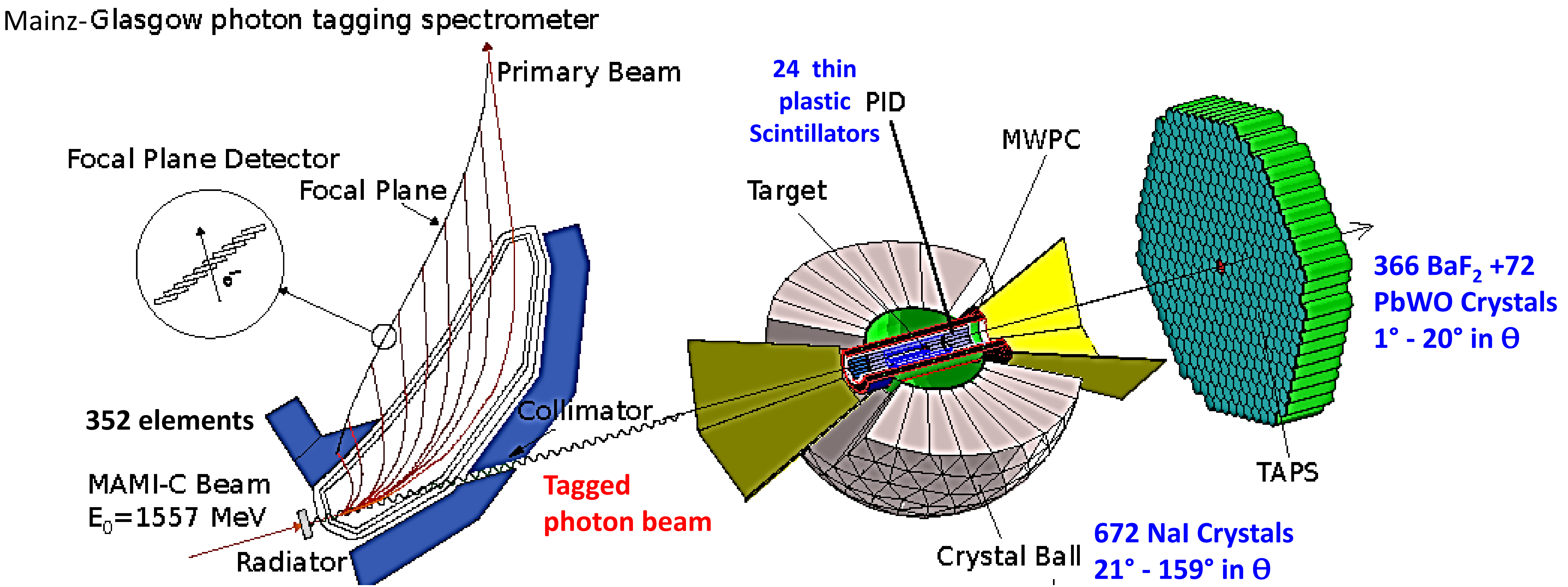


- Injector → 3.5 MeV
- RTM1 → 14.9 MeV
- RTM2 → 180 MeV
- RTM3 → 883 MeV
- HDSM → 1.6 GeV

High stability
Low beam divergence

Very good properties of the secondary photon beam

A2@MAMI: Detector overview



Nucleon polarimeter (graphite cylinder) also available

Photon beam produced by bremsstrahlung and tagged by a magnetic spectrometer

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

Total inclusive cross section

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

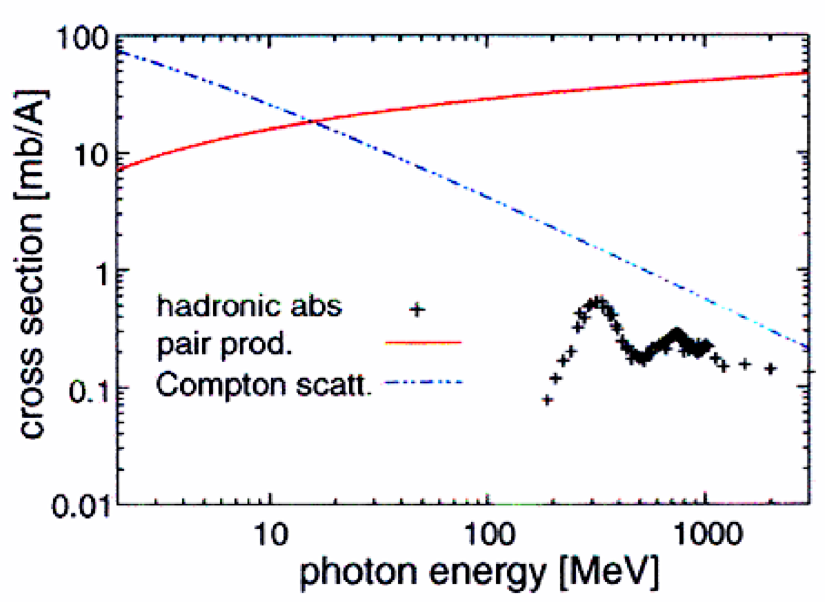
$$\sigma_{total} = \sum \text{hadrons}$$ (inclusive method)

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)

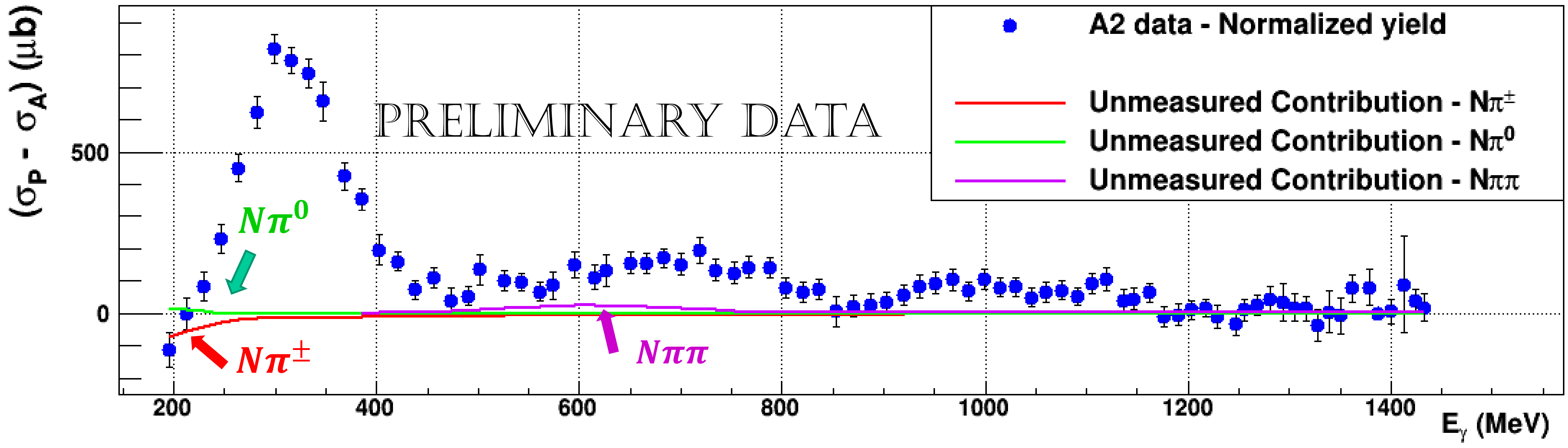
b) Suppression of e.m. events (pair prod./Compton)

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



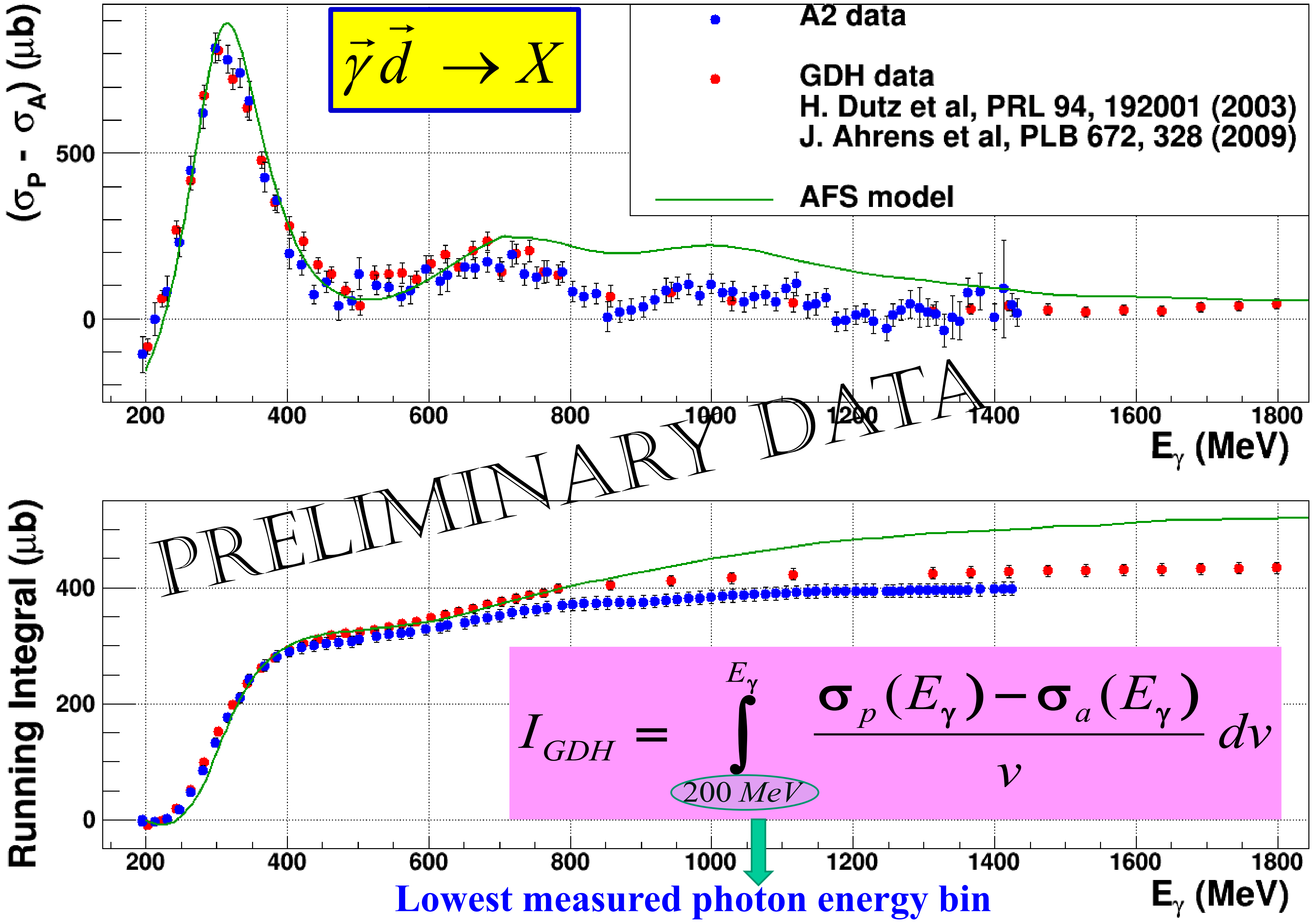
Experimental trigger:

- [1 cluster in CB] or [1 cluster in TAPS without Cherenkov on-line veto]
  (to suppress e.m. background at forward polar angles)
- Energy Threshold > 40 MeV
  (further suppression of e.m. background)

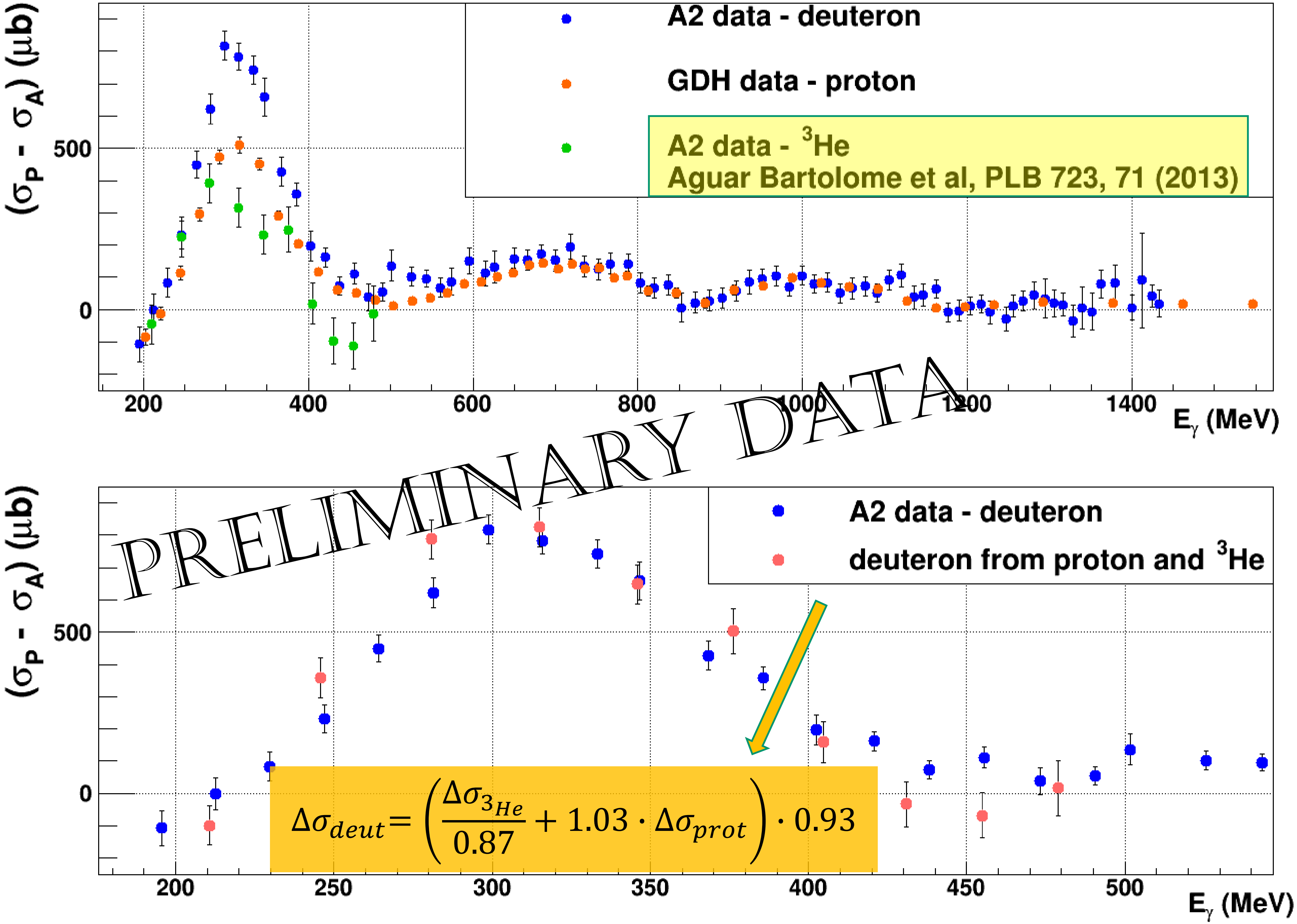


Single pion channels: missing contribution evaluated using GEANT efficieny and helicity dependent different cross section from SAID an MAID PWA (coincident results)

Double pion channels: missing contribution evaluated using GEANT efficiency and assuming helicity asymmetry $(\sigma_P - \sigma_A)/(\sigma_P + \sigma_A)$ to be the same both in the measured part and in the unmeasured one. For $\Delta\sigma(E_\gamma) = (\sigma_P - \sigma_A)$ used both experimental data (when available) or the model from A. Fix (EPJA 25,114 (05))



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



$(\sigma_P - \sigma_A)$ (μb)
A2 data - deuteron
GDH data - proton
A2 data - ^{3}He
Aguar Bartolome et al, PLB 723, 71 (2013)
E_γ (MeV)
PRELIMINARY DATA
$(\sigma_P - \sigma_A)$ (μb)
A2 data - deuteron
deuteron from proton and ^{3}He
$\Delta\sigma_{deut} = \left(\frac{\Delta\sigma_{^3He}}{0.87} + 1.03 \cdot \Delta\sigma_{prot}\right) \cdot 0.93$
E_γ (MeV)

GDH sum rule on deuteron and ^{3}He

PWIA approach

$E_\gamma > m_\pi$

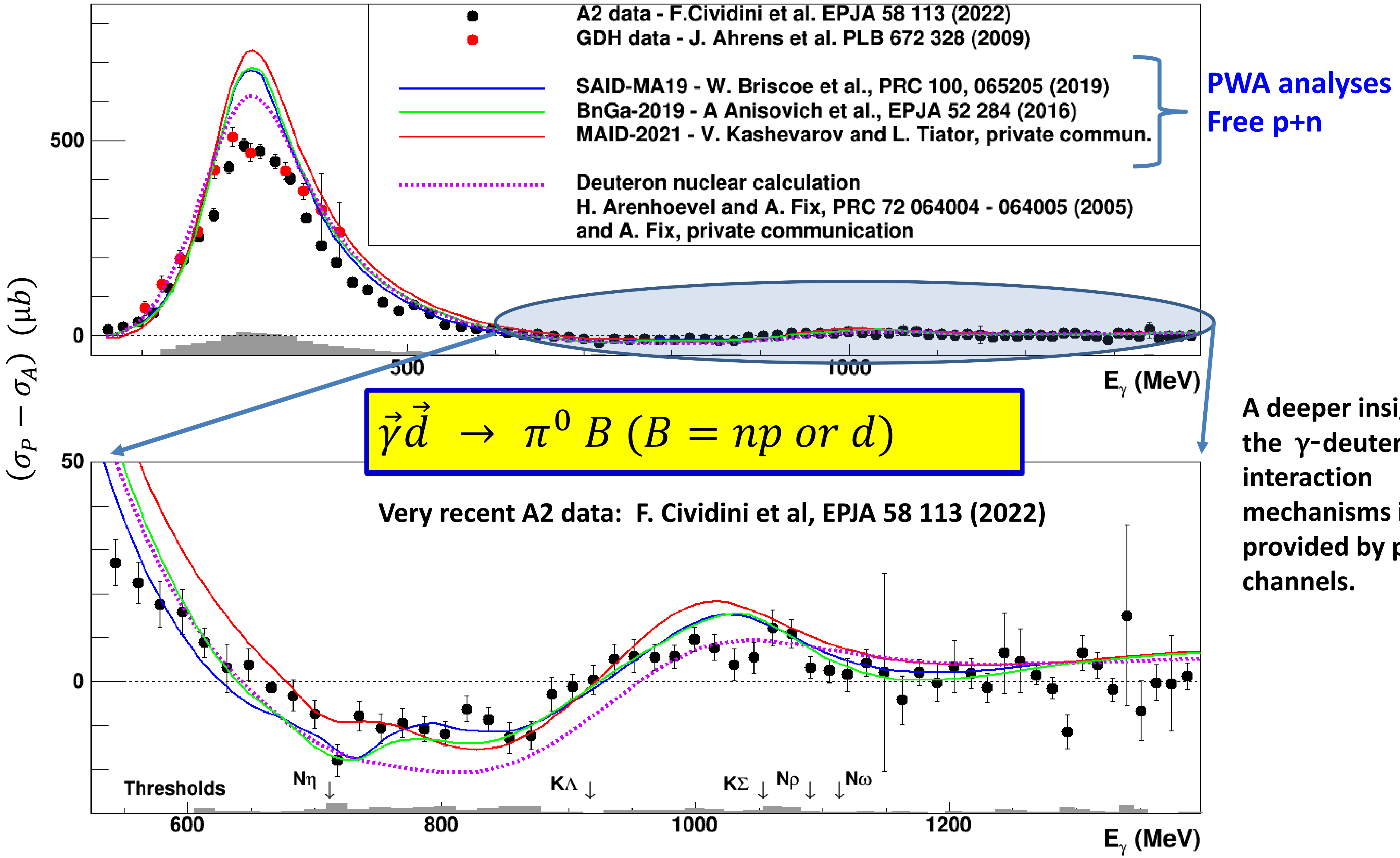
- ^{2}H: $\mu \sim \mu_p + \mu_n \Rightarrow$ n ↑ p ↑

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

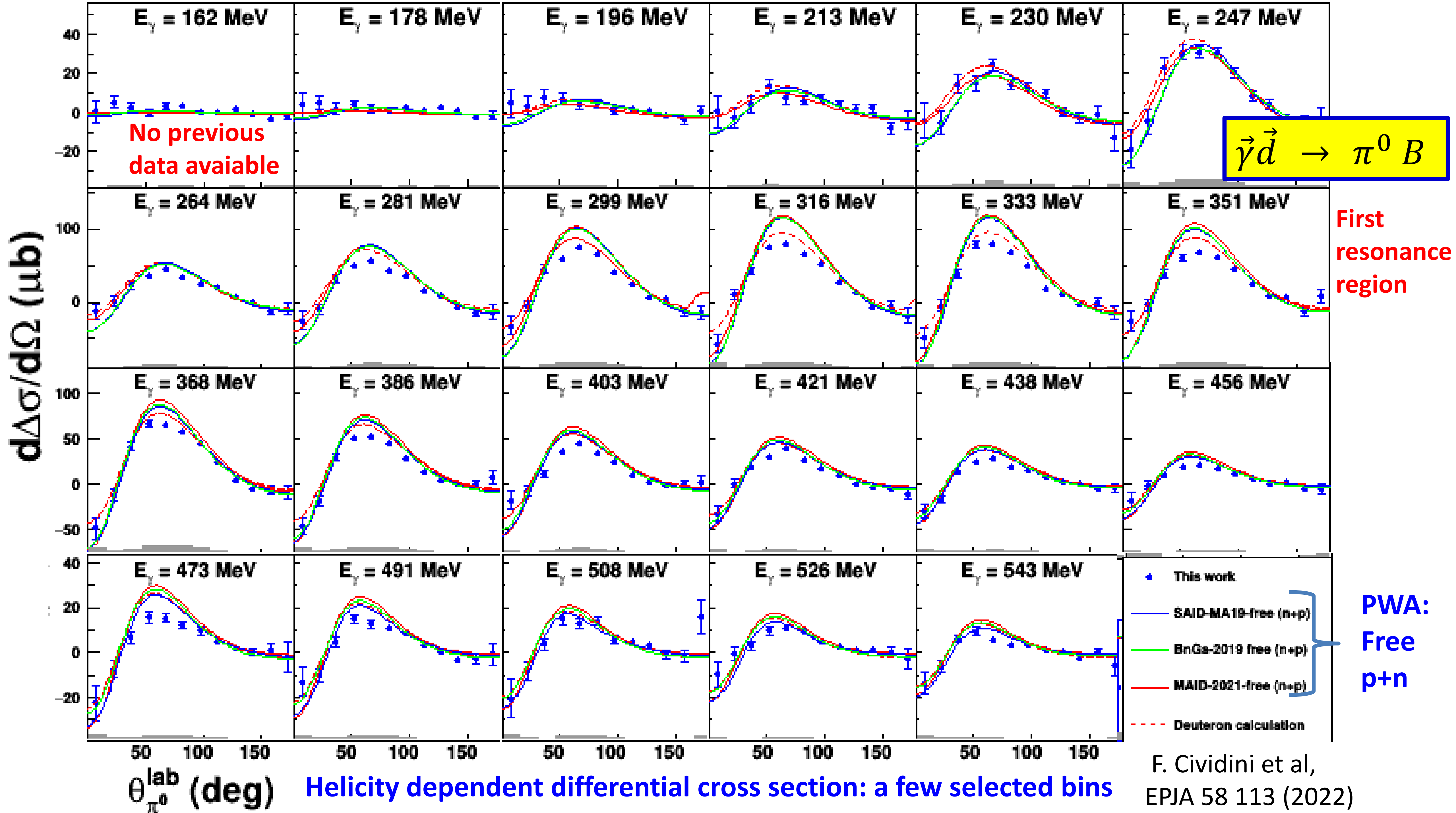
Effective nucleon polarisation
(correction for the D-state)

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

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

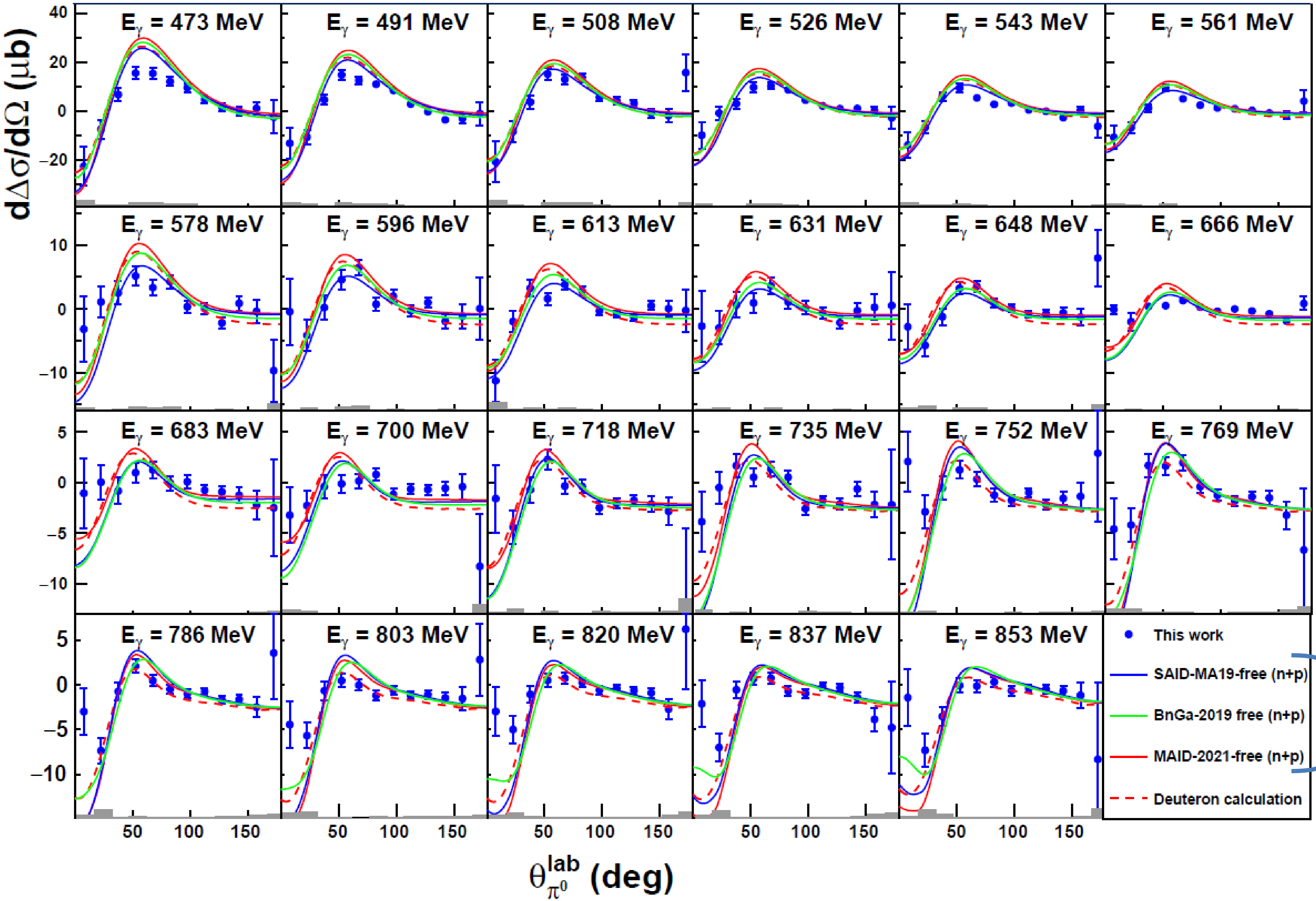


A deeper insight into the γ-deuteron interaction mechanisms is provided by partial channels.



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

Conclusions

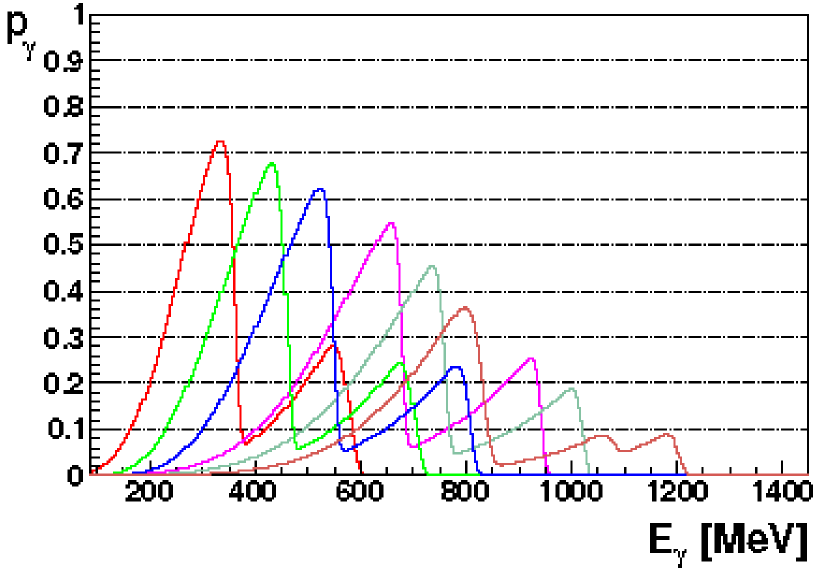
- **New results on the helicity dependence of the γ-deuteron interaction significantly increase/improve both the quality and the quantity of the existing data**
- Good agreement with the existing data, when available
- Importance of these new data in providing additional constraints for nuclear and subnuclear models
- Partial reaction channels also give important information on the modification of nucleon properties inside nuclear medium
- Further measurements to improve statistics and to investigate additional partial reaction channels are needed
- Additional data with polarised ^{3}He and ^{6}Li / ^{7}Li targets are also needed

Backup

Beam Polarization

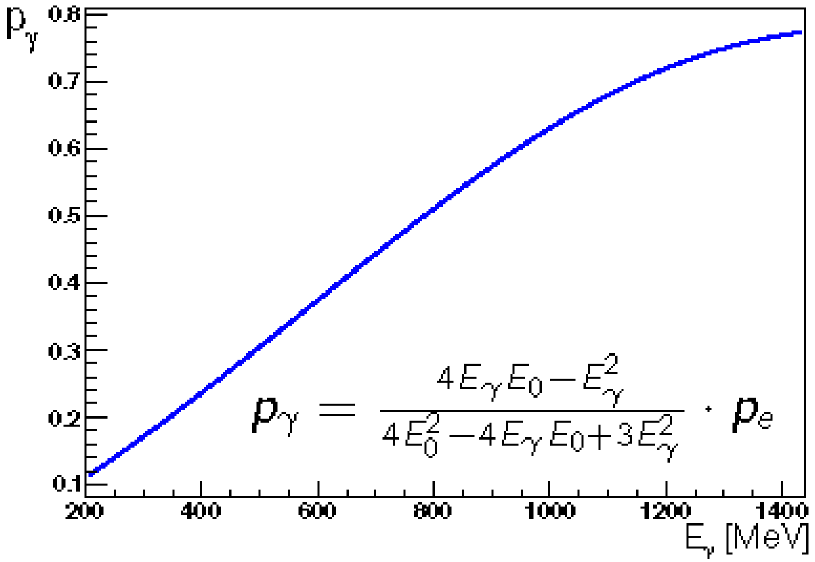
Linearly polarized photons

- 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

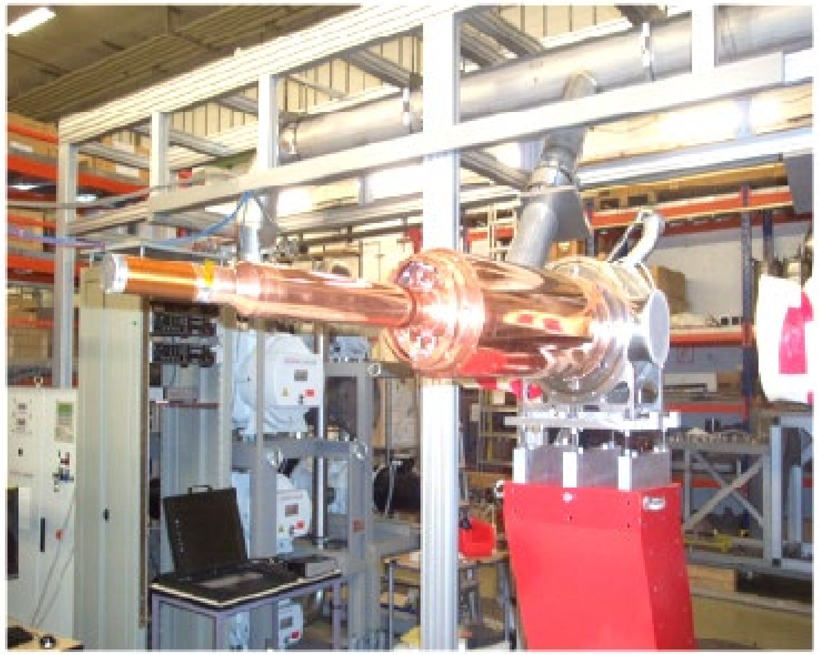
Longitudinally and Transversally polarized protons/deuterons **(Mainz-Dubna target)**

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

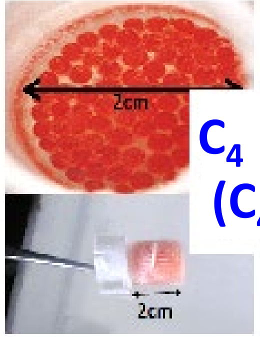
- Polarization via DNP process
- 70 GHz microwave irradiation at 2.5 T us used to transfer the electron polarization to p/d
- 3He/4He dilution cryostat at 25 mK and holding coil at 0.63 T

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

- Carbon target needed for background studies



Butanol Target

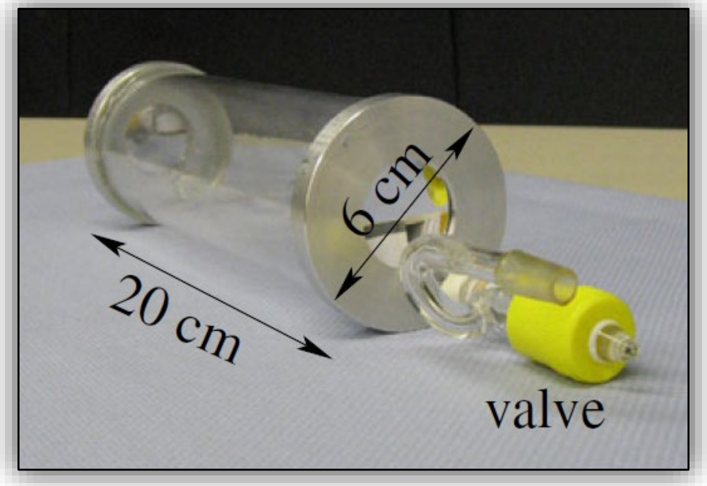


C_4 O H_{10}
(C_4 O D_{10})

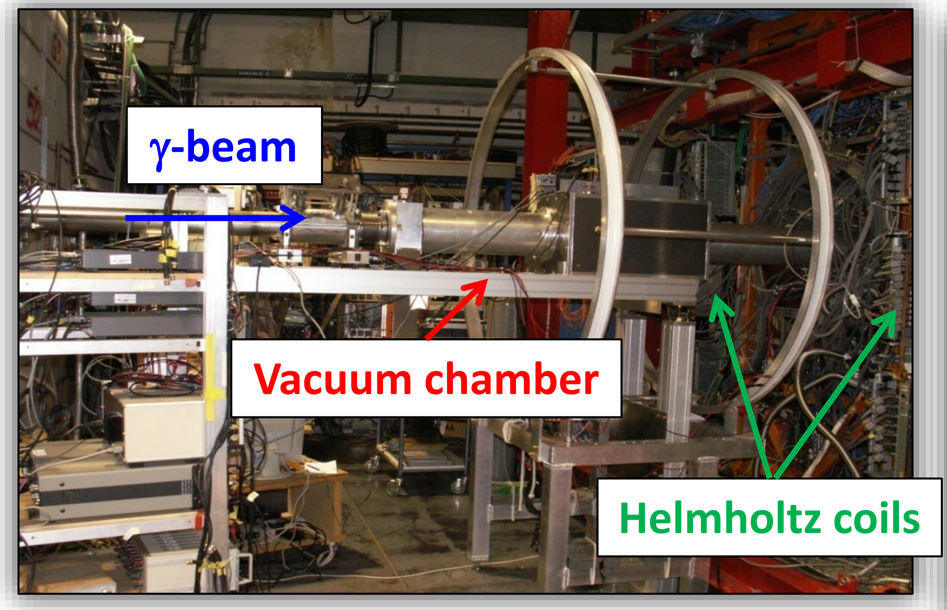
Carbon Target

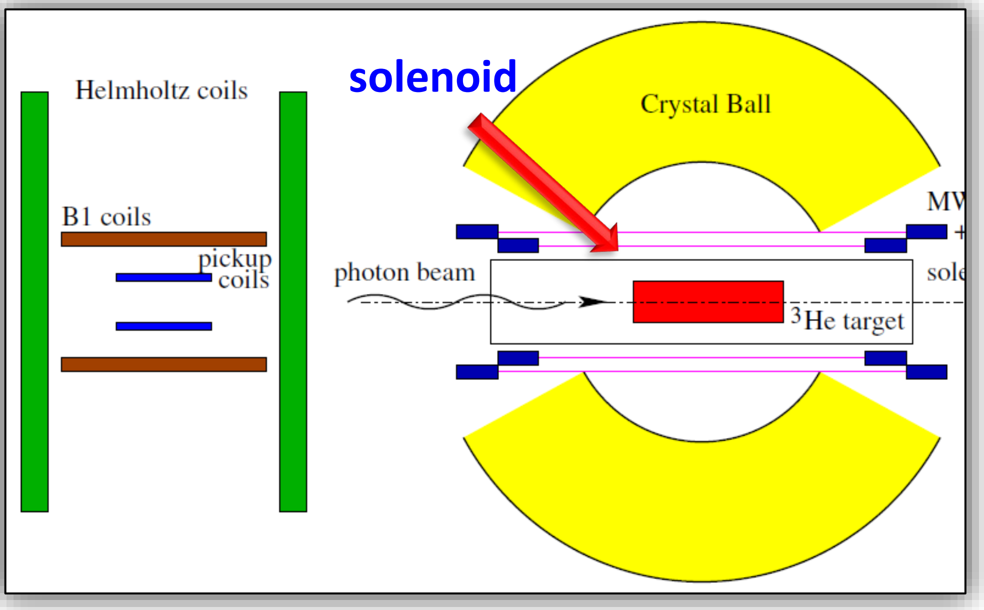
Polarised ^{3}He gas target

- Cylindrical cell **(gas polarised via MEOP)**
  - Length: 20 cm
  - diameter: 6 cm
- Made of quartz glass (thickness: 2 mm)
- Titanium entrance and exit windows (50 μm)
  - provide the necessary gas tightness (4 bar)
  - give long relaxation time (~20 hrs) of the gas polarisation
- ^{3}He polarisation measurements carried out via NMR technique; field provided by Helmholtz coils



in collaboration with PI, Mainz





^{3}He magnetic moment

$$-2.12 \cdot \frac{e\hbar}{2m_p} = (2+k)\frac{e\hbar}{2m_{^3He}} \Longrightarrow \mathrm{k} = -8.35$$