Helicity Dependence for Single π^0 Photoproduction from the Deuteron

NSTAR 2022

Philippe Martel

Institute for Nuclear Physics
Johannes Gutenberg University of Mainz

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Motivation

- Many open questions remain regarding the structure of the nucleon – A detailed knowledge of excitation spectra of both proton and neutron are needed to fully understand the strong interaction between quarks (non-perturbative QCD)
- To disentangle and access all the individual states in the nucleons spectrum, measurements of different observables are needed. They can be accessed using different combinations of polarization of the photon beam and of the target

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Beam		Target			Recoil			Target/Recoil								
		x	y	z				x			y			z		
					x'	y'	z'	x'	y'	z'	x'	y'	z'	x'	y'	z'
Unpolarized	σ		T			P		$T_{x'}$		$T_{z'}$		Σ		$L_{x'}$		$L_{z'}$
Linear	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	E	$L_{x'}$	$C_{z'}$	σ	$C_{x'}$	$T_{z'}$	F	$T_{x'}$
Circular		F		E	$C_{x'}$		$C_{z'}$		G		$O_{z'}$		$O_{x'}$		H	

- 16 total observables – many duplicates

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Beam		Target			Recoil		Both	
		x	y	z			x	
					x′	z′	x′	z′
Unpolarized	σ		T				$T_{x'}$	$T_{z'}$
Linear	Σ	H	P	G	$O_{x'}$	$O_{z'}$	$L_{z'}$	$L_{x'}$
Circular		F		E	$C_{x'}$	$C_{z'}$		

- Simpler form (How many do we need to measure? When in doubt, measure another!)

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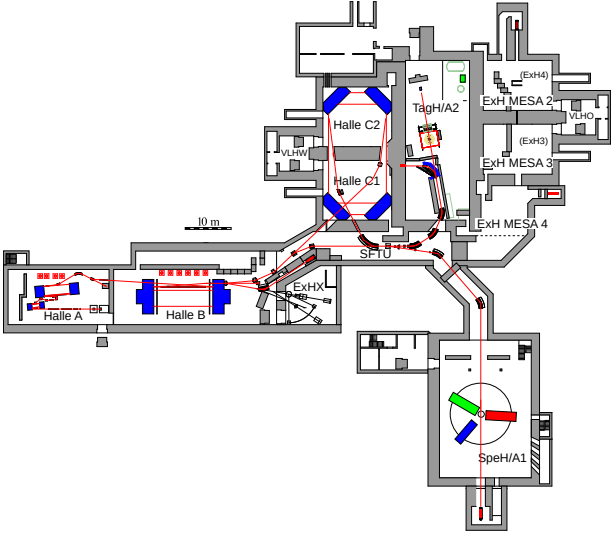
- To disentangle and access all the individual states in the nucleons spectrum, measurements of different observables are needed. They can be accessed using different combinations of polarization of the photon beam and of the target
- Moreover, since electromagnetic interactions do not conserve isospin, both proton and neutron targets are needed to access the full isospin decomposition of the resonance amplitudes
- Due to the lack of free neutron targets, light nuclei (like deuterium) have to be used as effective neutron targets. Nuclear effects need to be very well known to unambiguously extract the free-neutron information

Mainz Microtron (MAMI) e⁻ Beam



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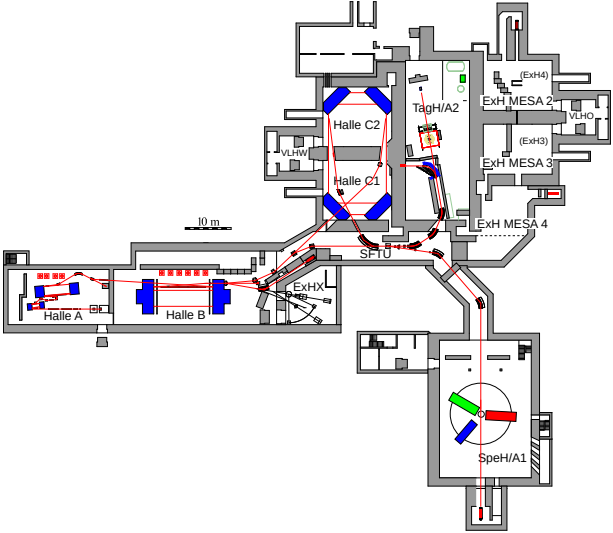
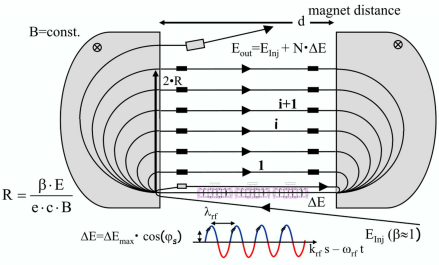


Racetrack Microtron (RTM)

- Linac sends e⁻ beam into dipole
- Dipoles return the beam beam back into the linac at increasing radii
- 'Kicker' magnet ejects the beam



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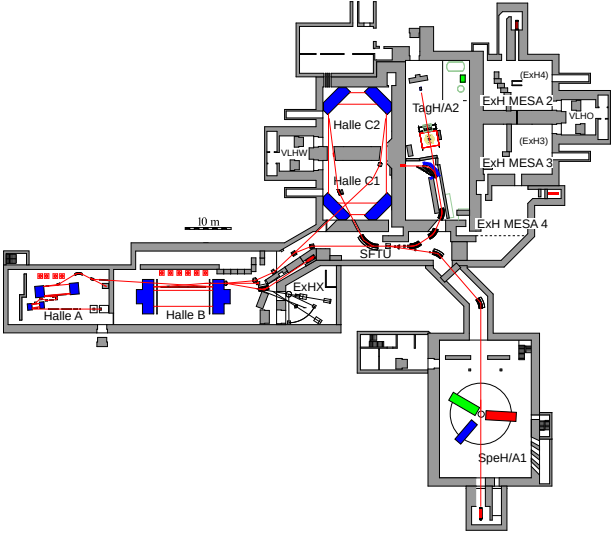

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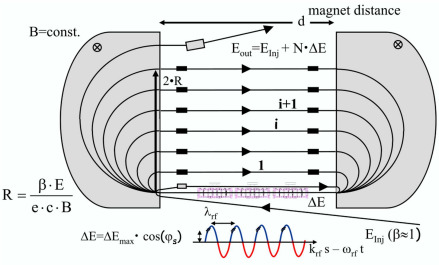

180 MeV – 1.6 GeV (15 MeV steps)

Polarized Photon Beam

A high energy electron can produce Bremsstrahlung ('braking radiation') photons when slowed down by a material.

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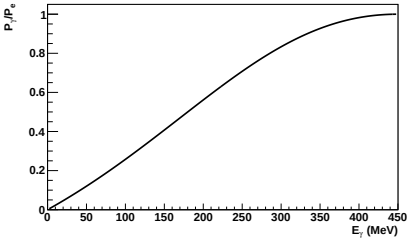
- Longitudinally polarized electrons produce circularly polarized photons (helicity transfer).



$$P_\gamma = P_e \frac{4E_\gamma E_e - E_\gamma^2}{4E_e^2 - 4E_\gamma E_e + 3E_\gamma^2}$$

- $P_e \approx 80\%$
- Helicity flipped every second

Polarized Photon Beam

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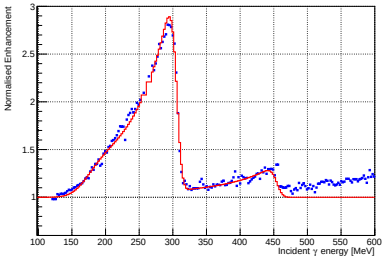
- Diamond radiator produces linearly polarized photons (coherent Bremsstrahlung).



- Coherent edge is tunable
- Polarization plane can be flipped (usually every hour)

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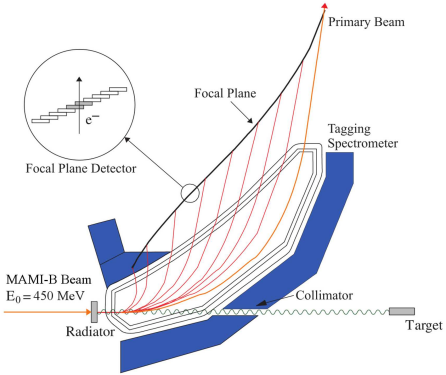

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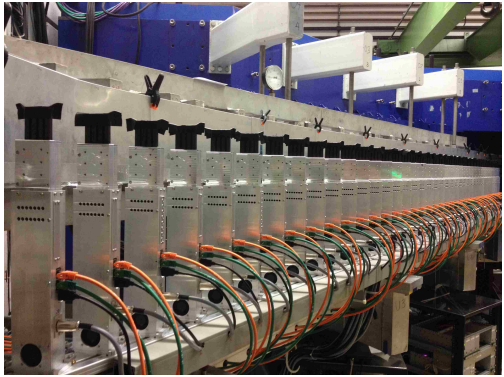
- Detector array determines the e^- energy, and 'tags' the photon energy by energy conservation.



Target and Detectors

Polarized frozen spin butanol target

- Dynamic Nuclear Polarization (DNP)
- D-Butanol (C_4D_9OD)
- $P_T^{max} > 50\%$, $\tau > 1000$ h

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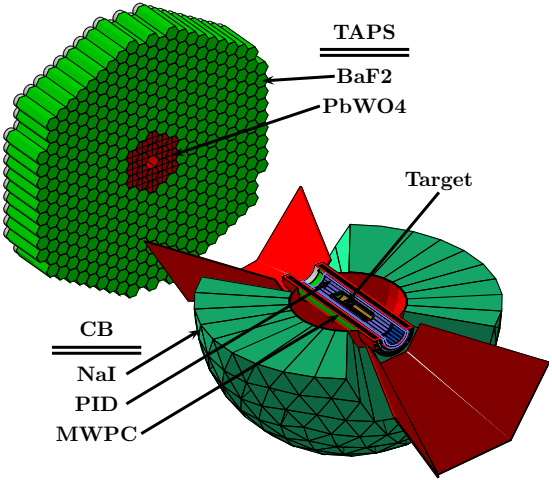

Polarized frozen spin butanol target

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Crystal Ball (CB)

- 672 NaI Crystals
- 24 Particle Identification Detector (PID) Paddles
- 2 Multiwire Proportional Chambers (MWPCs)

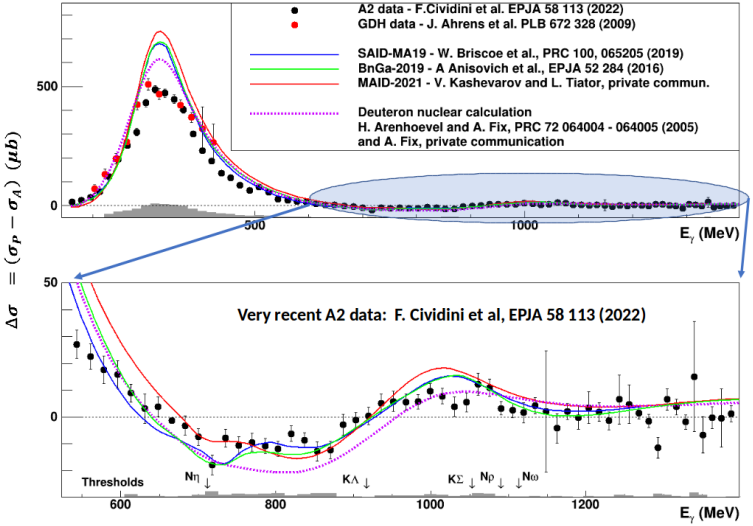
Two Arms Photon Spectrometer (TAPS)

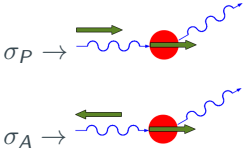
- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Paddles

Data Analysis

- π^0 identification (2 or 3 neutral clusters inside CB and TAPS)
- Missing mass cut on the reaction $\gamma N \rightarrow \pi^0 X$ to exclude double pion production (this step is sufficient for the identification of the $\vec{\gamma}\vec{d} \rightarrow \pi^0 B$ channel, where $B = np$ or d) – Efficiency evaluated using Geant4
- For the determination of the E asymmetry on quasi-free nucleons, events having an additional track identified as a proton or neutron are selected (momentum threshold for nucleon detection $\approx$ 350 MeV/c)

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





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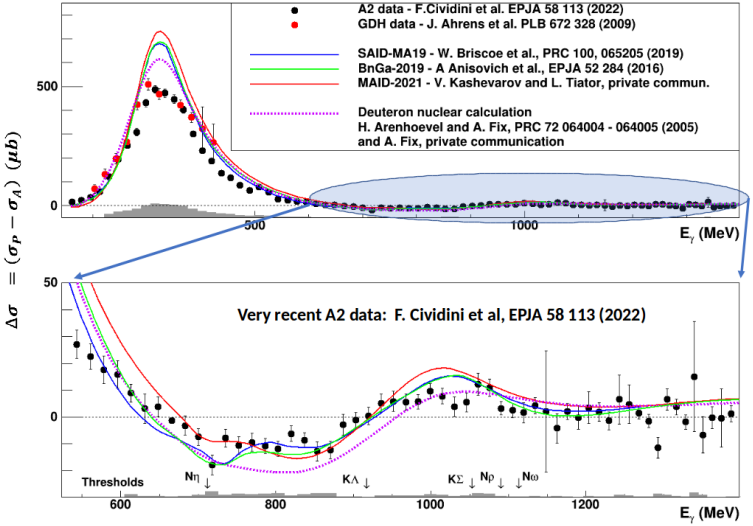

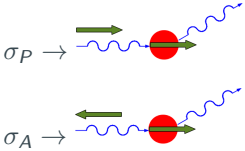

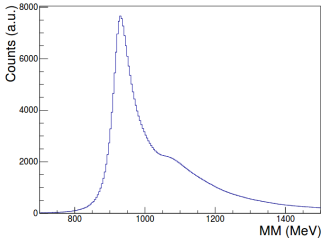

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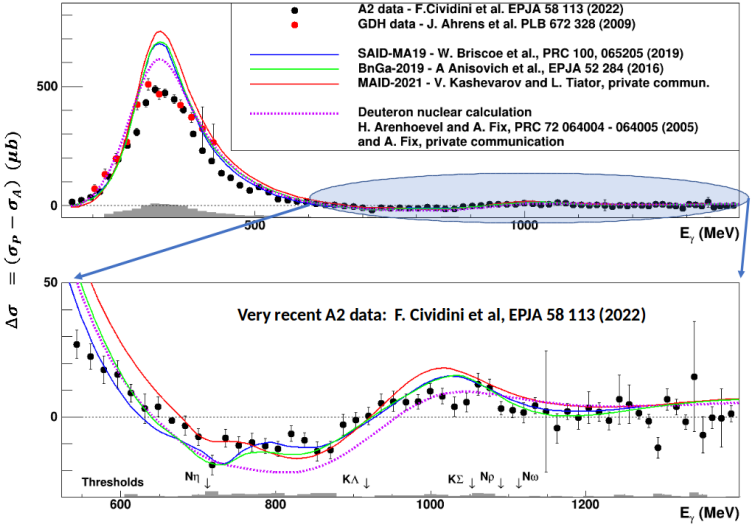

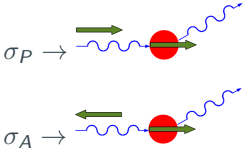

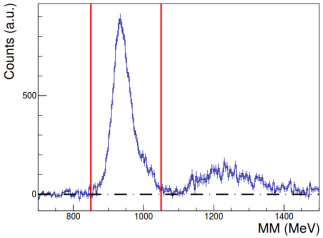

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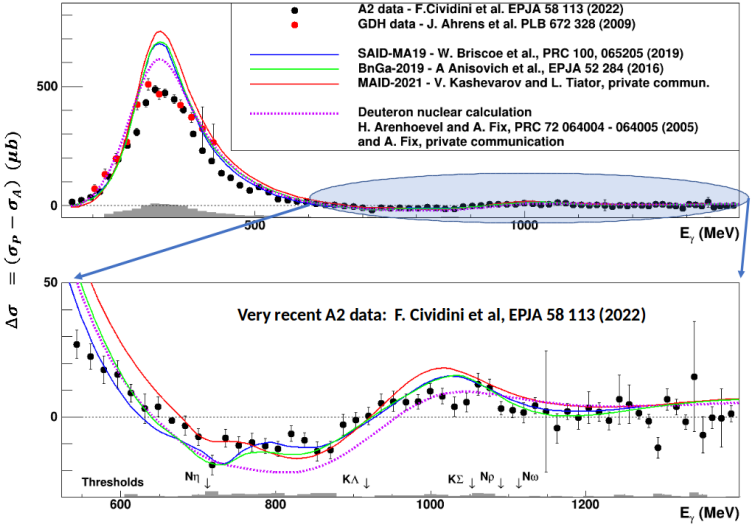

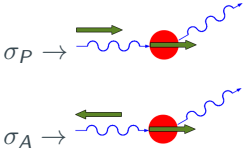

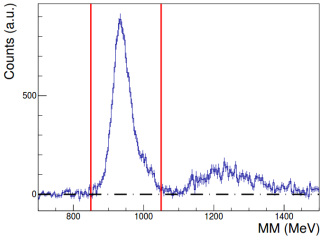

A deeper insight into the γ-d interaction mechanism is provided by partial channels

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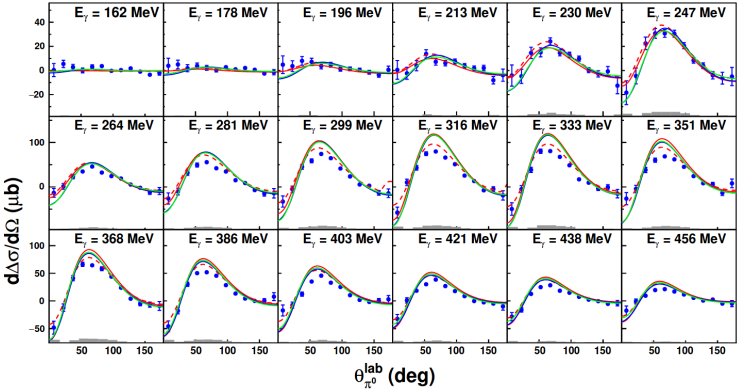

SAID-MA19
MAID-2021
BNGa-2019
} Free proton + neutron
Nuclear model (A. Fix)

- Helicity dependent differential cross sections: selected bins
- First resonance region
- Modified Δ-resonance excitation

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

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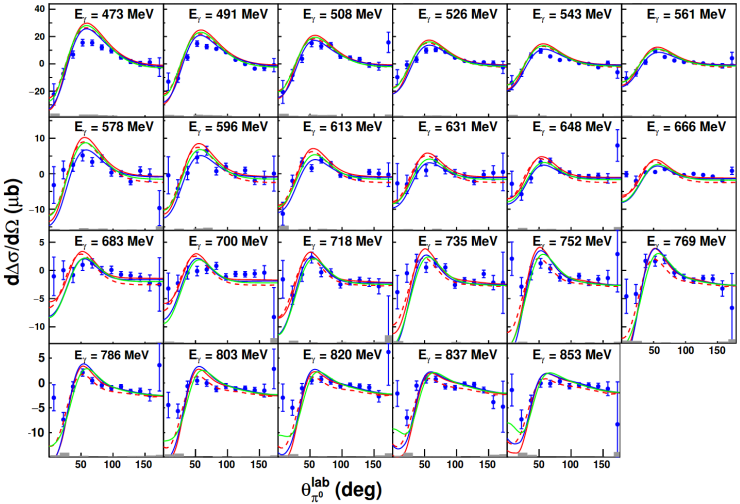

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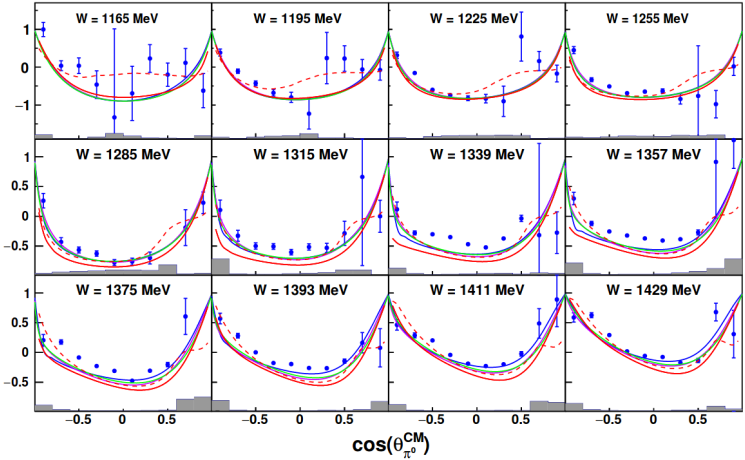
Nuclear model (A. Fix)

- Helicity dependent differential cross sections: selected bins
- Second resonance region
- Effects due to the nuclear medium more evident at very forward angles

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

E Asymmetry - Quasi-free Proton



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- For $W < 1300$ MeV : phase space for QF production and nucleon $p > 350$ MeV is very small (large nuclear effects)
- For $W > 1300$ MeV : data coincide with the free proton data

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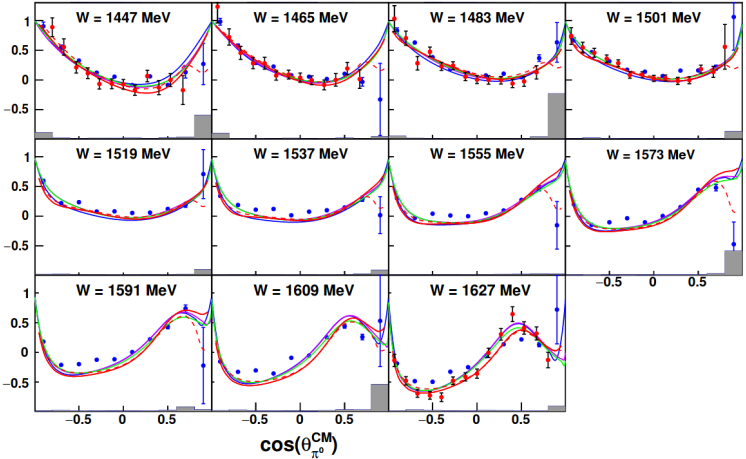

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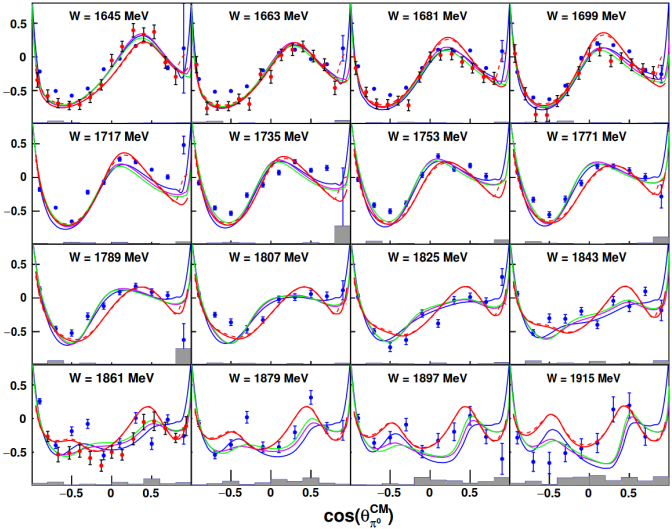

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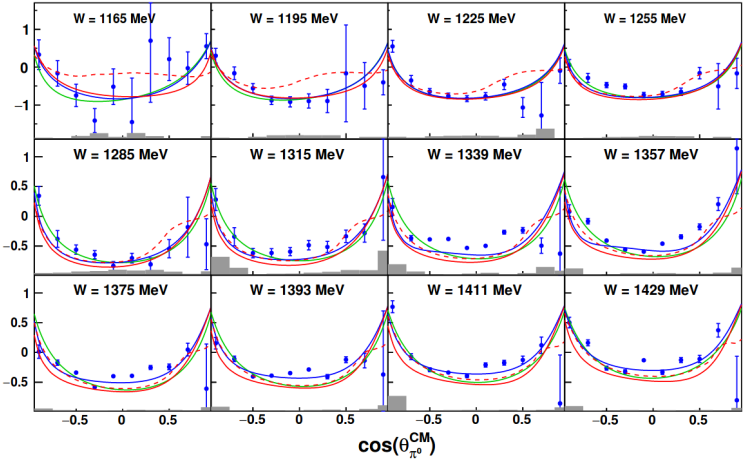

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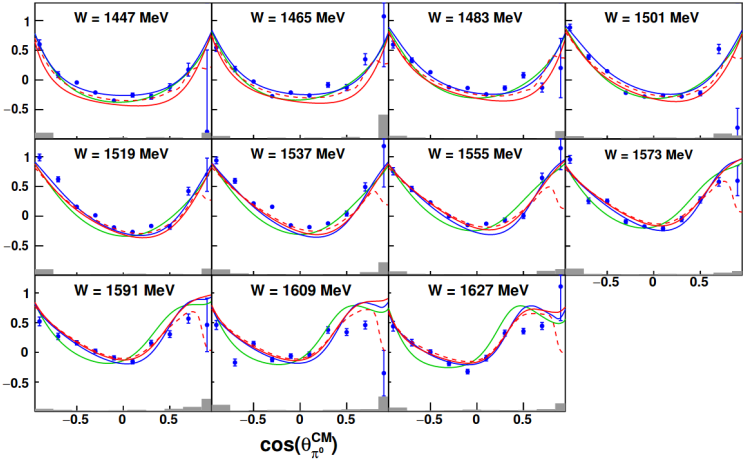

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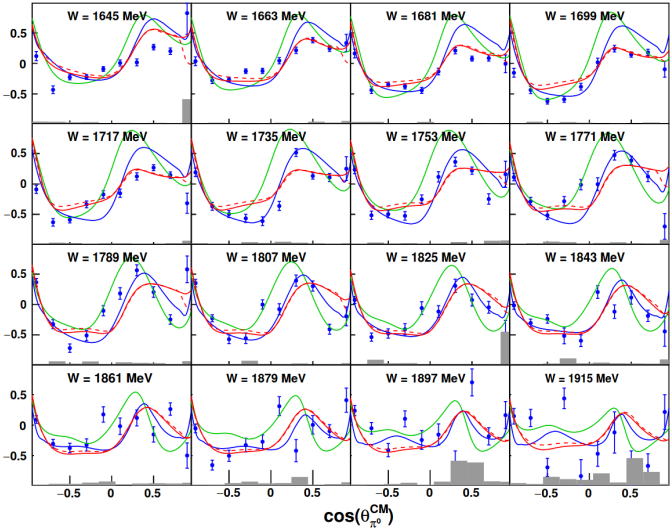

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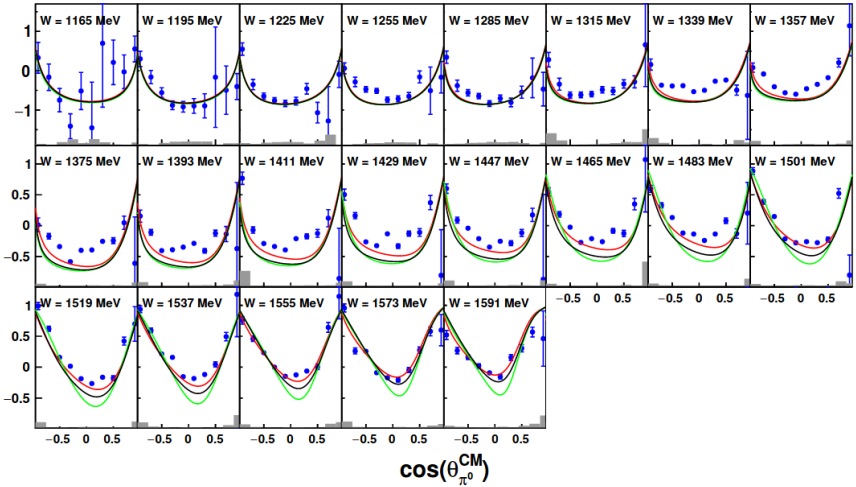
E Asymmetry - Quasi-free Neutron - Impact



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No neutron data used in the fit

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Present data **NOT** included in the fit

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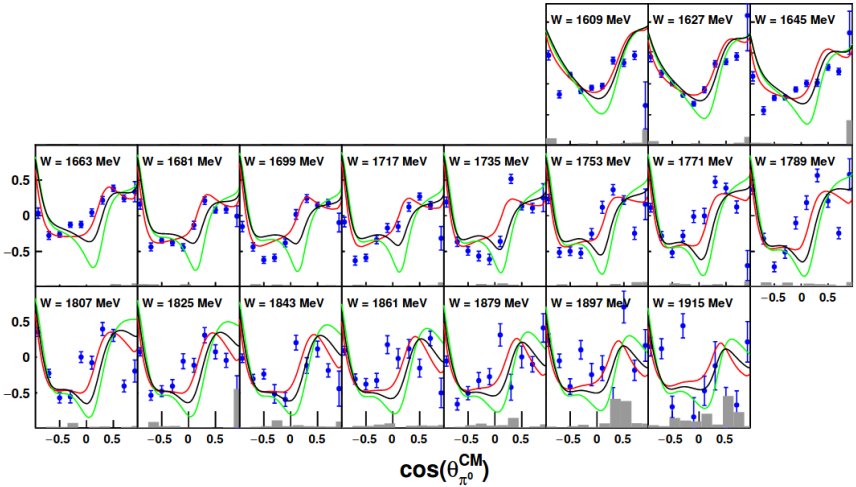

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- Appreciable change in the PWA predictions for $W > 1600$ MeV

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Legendre Fits

$$E(W,\theta) = E \cdot \frac{d\sigma_0}{d\Omega} = \sum_{k=0}^{2l_{\max}} (a_{l_{\max}})_k(W) \cdot P_k(\cos\theta)$$

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- $\frac{d\sigma_0}{d\Omega}$ = unpolarized cross section
  (from SAID, same results with BOGA)

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- $l_{\max}$ = maximal π^0 angular momentum
- $(a_{l_{\max}})_k(W)$ = interference between different multipoles

$l_{\max}$	Wave	Multipoles
1	S-wave	E_{0+}
	P-wave	E_{1+}, M_{1+}, M_{1-}
2	D-wave	E_{2+}, E_{2-}, M_{2+}, M_{2-}
3	F-wave	E_{3+}, E_{3-}, M_{3+}, M_{3-}

Small E_{0+} contribution to the channel

Legendre Fits

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- $\frac{d\sigma_0}{d\Omega}$ = unpolarized cross section (from SAID, same results with BOGA)
- $l_{\max}$ = maximal π^0 angular momentum
- $(a_{l_{\max}})_k(W)$ = interference between different multipoles
- $P_k(\cos\theta)$ = associated Legendre polynomials

$l_{\max}$	Wave	Multipoles
1	S-wave	E_{0+}
	P-wave	E_{1+}, M_{1+}, M_{1-}
2	D-wave	E_{2+}, E_{2-}, M_{2+}, M_{2-}
3	F-wave	E_{3+}, E_{3-}, M_{3+}, M_{3-}

Small E_{0+} contribution to the channel

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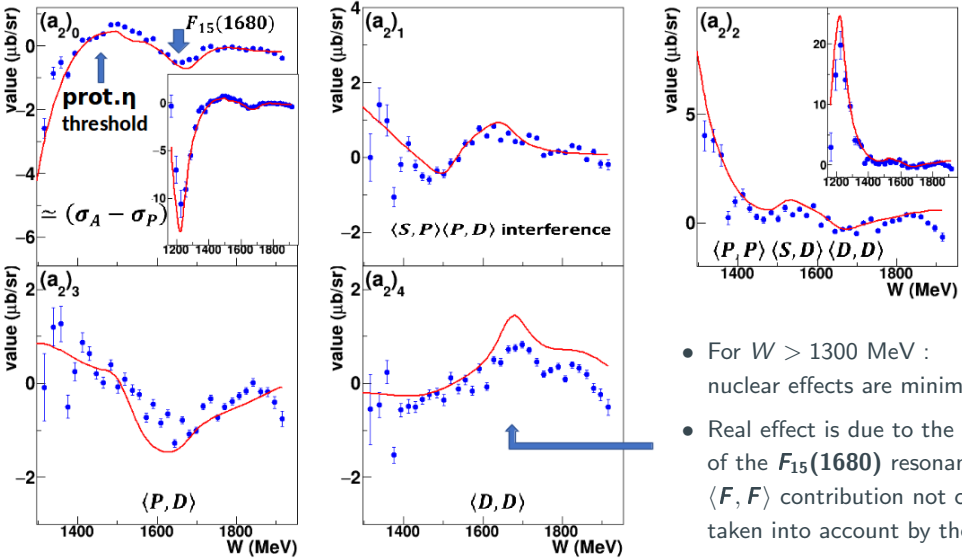
- $P_k(\cos\theta)$ = associated Legendre polynomials
- Fit with $l_{\max} = 2$ sufficiently reproduces data

$l_{\max}$	Wave	Multipoles
1	S-wave	E_{0^+}
	P-wave	E_{1^+}, M_{1^+}, M_{1^-}
2	D-wave	E_{2^+}, E_{2^-}, M_{2^+}, M_{2^-}
3	F-wave	E_{3^+}, E_{3^-}, M_{3^+}, M_{3^-}

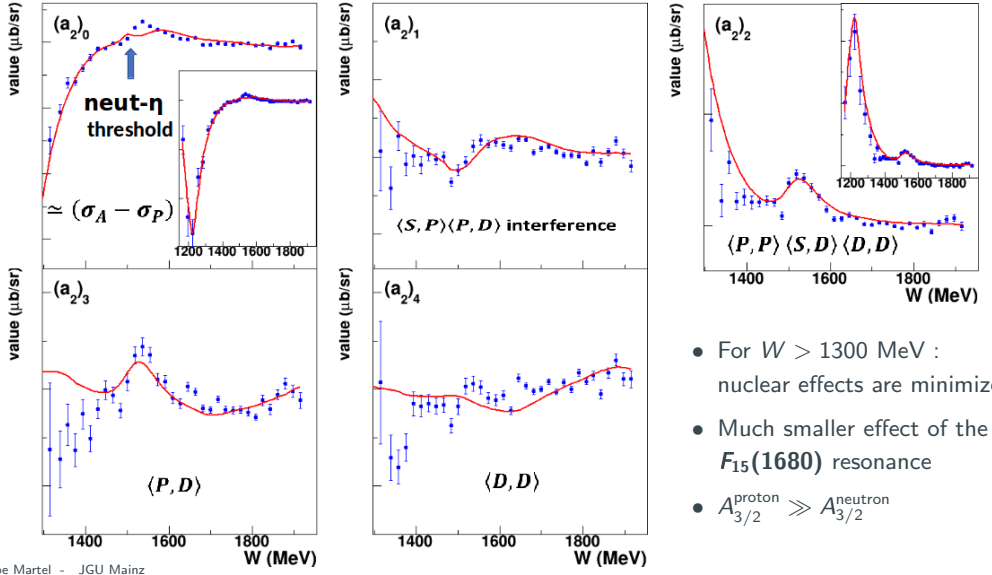
Small E_{0^+} contribution to the channel

Legendre Fits - Proton



- For $W > 1300$ MeV : nuclear effects are minimized
- Real effect is due to the onset of the $F_{15}(1680)$ resonance – $\langle F,F\rangle$ contribution not correctly taken into account by the fit

Legendre Fits - Neutron



- For $W > 1300$ MeV : nuclear effects are minimized
- Much smaller effect of the $F_{15}(1680)$ resonance
- $A_{3/2}^{\text{proton}} \gg A_{3/2}^{\text{neutron}}$

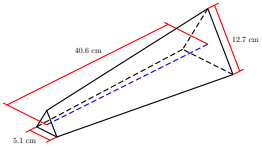
Conclusions

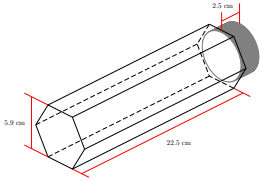
- New high quality data on the helicity dependence of the single π^0 photoproduction on the deuteron from the A2@MAMI collaboration significantly extend and improve the quality of the existing data-set for this reaction
- Semi-inclusive channel $\vec{\gamma}\vec{d} \rightarrow \pi^0 B$ ($B = np$ or d) is very sensitive to the influence of nuclear effects on the photoproduction mechanisms on the single nucleons. These new data allow their precise quantitative evaluation
- The measured helicity asymmetry E for the quasi-free single π^0 on the proton inside the deuteron is not significantly affected (for $W > 1300$ MeV) by nuclear effects
- As a result, the measured helicity asymmetry E for the single π^0 on the free neutron can be reliably extracted from measurements on the deuteron in quasi-free kinematics

Backup Slides

You want more info...

Neutral vs Charged Particle Detection

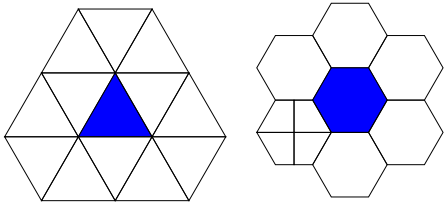




NaI/BaF_2/$PbWO_4$ Crystal Scintillators

- Produce light from charged particles
- Large crystals $\rightarrow$ full energy deposition

Neutral vs Charged Particle Detection



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  Many crystals
- Hadronic showers (lose E bumping around)
  Few crystals

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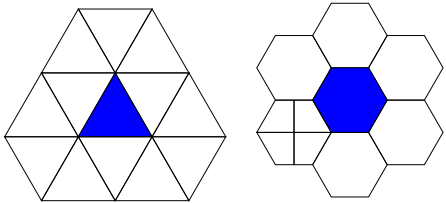

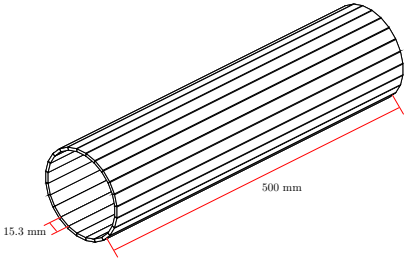

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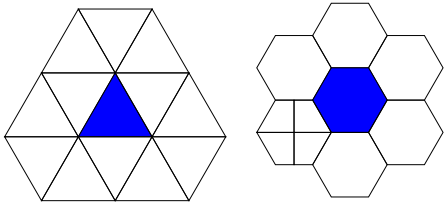
Particle Identification Detector (PID)

- Barrel of 24 plastic paddles
- Each covers $15 < \theta < 159°$, and $15°$ in ϕ

Neutral vs Charged Particle Detection



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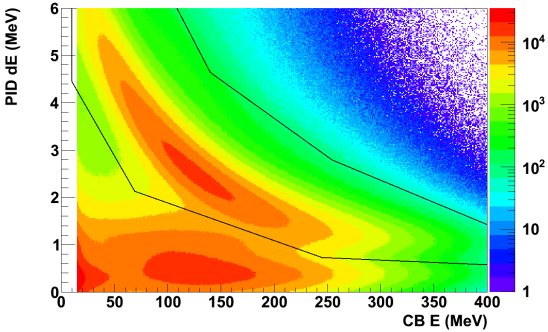

Particle Identification Detector (PID)

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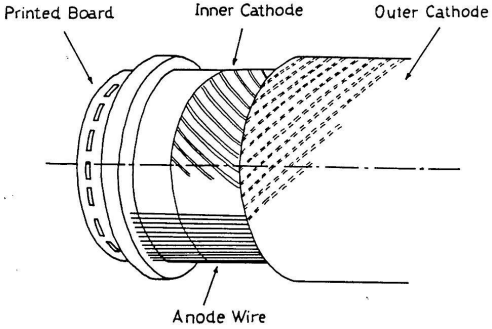
- Each covers $15 < \theta < 159°$, and $15°$ in ϕ
- Plot ΔE in PID vs E in NaI

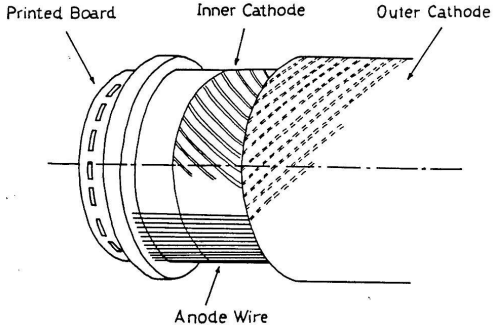
Additional Charged Particle Detection



Multiwire Proportional Chamber (MWPC)

- Two chambers: anode wires sandwiched by two layers of cathode strips
- Voltage between wires and strips increases when gas is ionized

Additional Charged Particle Detection



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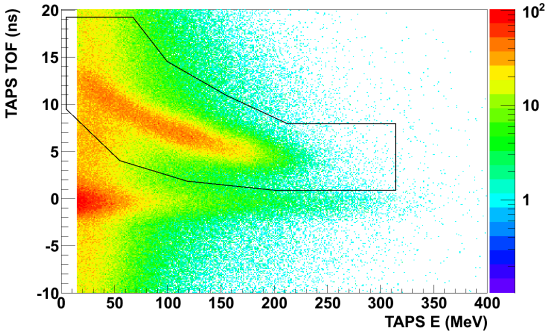


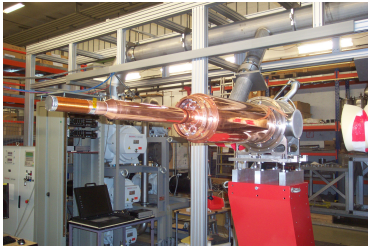
Time of Flight

- Given its increased distance from the target, massive particles take longer to reach TAPS
- Plot time vs E, identify nucleons

Polarized Protons

Frozen Spin Target

- Butanol (C_4H_9OH)
- 2 cm long
- 9.17×10^{22} protons/cm^2
- Dynamic Nuclear Polarization
- $P_T^{max} > 90\%$, $\tau > 1000$ h



Perturbation on Electron Spin Resonance

$$\nu_e \pm \nu_p = \frac{\mu_e B}{\pi\hbar} \pm \frac{\mu_e B}{\pi\hbar}$$
$$= 70\,\mathrm{GHz} \pm 106\,\mathrm{MHz}$$

How does Dynamic Nuclear Polarization (DNP) actually work

- Cool target to 0.2 K and use 2.5 T magnet to align electron spins
- Pump $\approx$ 70 GHz microwaves causing spin-flips between the electrons and protons
- Cool target to 0.025 K, 'freezing' proton spins in place
- Remove polarizing magnet and energize 0.6 T 'holding' coil to maintain the polarization