Meson Investigations by the MAMI A2 Collaboration

15th International Workshop on Meson Physics

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Krakow, Poland - 12 June 2017

Institute for Nuclear Physics
Johannes Gutenberg University of Mainz

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- Since we're here, let's talk about some meson physics at MAMI

Outline

1. What should we do
2. What can we do
3. What have we done
4. What are we doing

What should we do

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- Preferred stance of experimentalists: "Just let me go measure things."
- Of course it's always nice if your work is beneficial, so what would the theorists like to have...

Observables

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

Beam	Target/Recoil								
	x			y			z		
	x′	y′	z′	x′	y′	z′	x′	y′	z′
Unpolarized	$T_{x'}$		$T_{z'}$		Σ		$L_{x'}$		$L_{z'}$
Linear	$L_{z'}$	E	$L_{x'}$	$C_{z'}$	σ	$C_{x'}$	$T_{z'}$	F	$T_{x'}$
Circular		G		$O_{z'}$		$O_{x'}$		H	

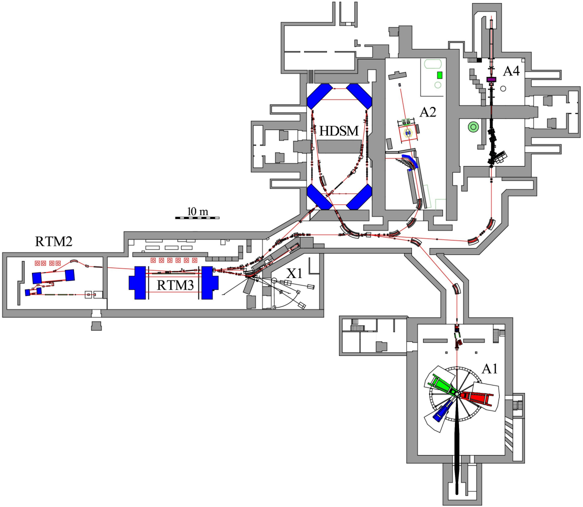
Beam		Target			Recoil		Both	
		x	y	z			x	
					x′	z′	x′	z′
Unpolarized	σ		T				$T_{x'}$	$T_{z'}$
Linear	Σ	H	P	G	$O_{x'}$	$O_{z'}$	$L_{z'}$	$L_{x'}$
Circular		F		E	$C_{x'}$	$C_{z'}$		

As L. Tiator described:

- 16 total observables
- 8 observables without recoil polarization
- 8 observables without target polarization
- Do not need all 16 to have complete picture

What can we do

Mainz Microtron (MAMI) e^- Beam

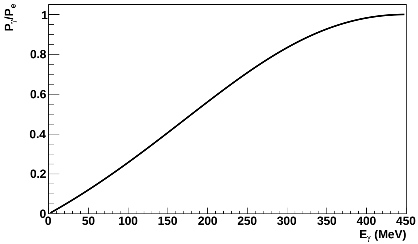


- Injector $\rightarrow$ 3.5 MeV
- RTM1 $\rightarrow$ 14.9 MeV
- RTM2 $\rightarrow$ 180 MeV
- RTM3 $\rightarrow$ 883 MeV
- HDSM $\rightarrow$ 1.6 GeV

Polarized Photon Beam

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

- Longitudinally polarized electron beam produces circularly polarized photon beam (helicity transfer)
- P_e measured with a Mott polarimeter before the RTMs.
- Circular beam helicity flipped by alternating the e^- beam polarization (≈ 1 Hz).

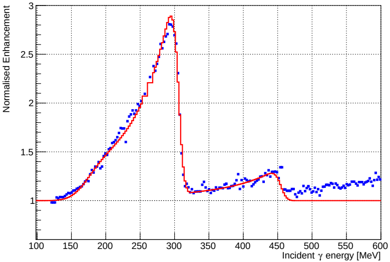


$$P_\gamma = P_e \frac{4E_\gamma E_e - E_\gamma^2}{4E_e^2 - 4E_\gamma E_e + 3E_\gamma^2}$$

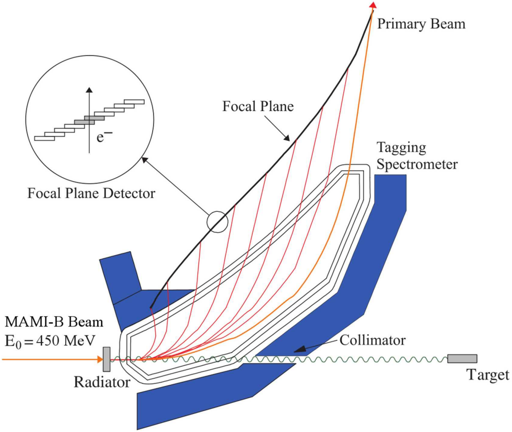
Polarized Photon Beam

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

- Diamond radiator produces linearly polarized photon beam (coherent Bremsstrahlung)
- Polarization determined by fitting the Bremsstrahlung distribution.
- Linear beam orientation typically flipped every two hours.

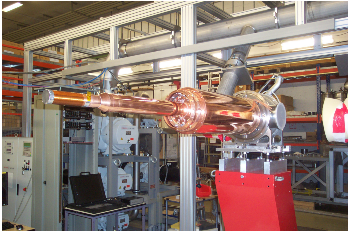


Photon Tagging



- e^- beam with energy E_0, strikes radiator producing Bremsstrahlung photon beam with energy distribution from 0 to E_0.
- Residual e^- paths are bent in a spectrometer magnet.
- With proper magnetic field, array of detectors determines the e^- energy, and 'tags' the photon energy by energy conservation.

Targets



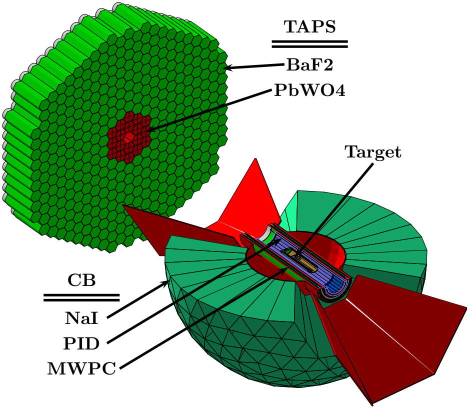
Polarized frozen spin butanol target

- Dynamic Nuclear Polarization (DNP)
- Butanol (C_4H_9OH) for polarized protons or D-Butanol (C_4D_9OD) for polarized deuterons
- $P_T^{max} > 90\%$, $\tau > 1000$ h

Unpolarized targets

- LH2/LD2
- ^{4}He
- Solid targets (C, Al, Pb, etc.)

Detectors



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

What have we done

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- Taken
  - 3 weeks polarized target data
  - 6 weeks recoil polarimeter data
  - 6 weeks ^{4}He target data
  - 3 weeks LD2 data
  - 16 weeks LH2 data
  - 2 weeks of tests
  - Total = 36 weeks (feels like more)

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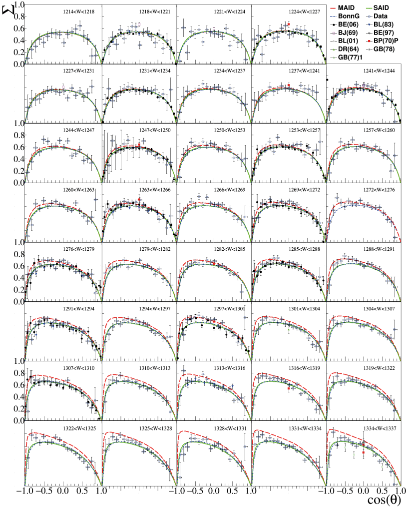
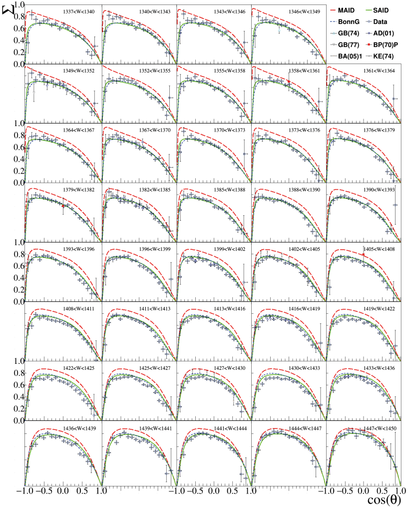
  - Total = 36 weeks (feels like more)
- 1 EPJA, 1 PRL, 1 PLB, and 5 PRCs published
- 1 PRC and 1 PRD accepted
- 1 PLB submitted

Σ - $\gamma p \rightarrow \pi^0 p$ [S. Gardner, EPJA 52, 333 (2016)]





Well that's a lot of data.

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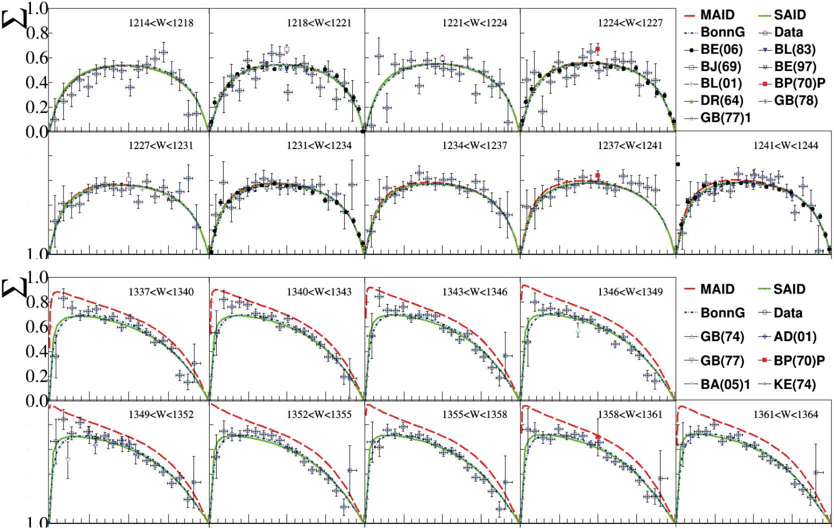
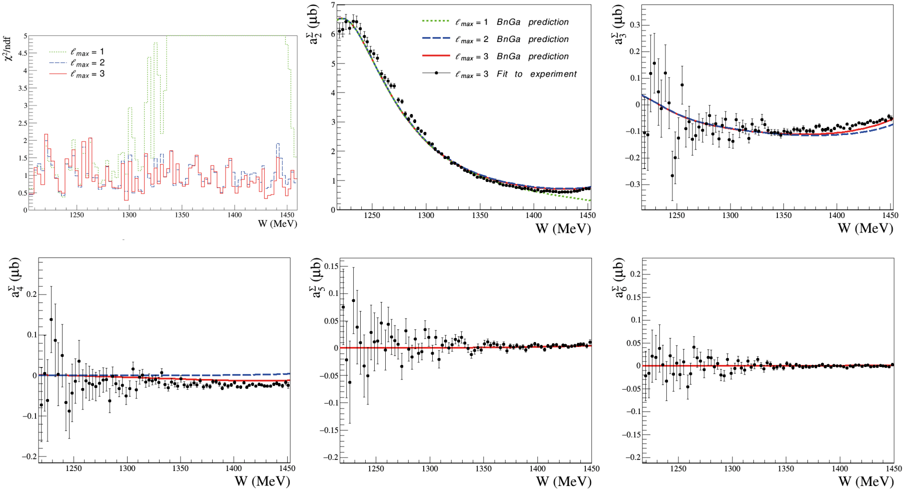


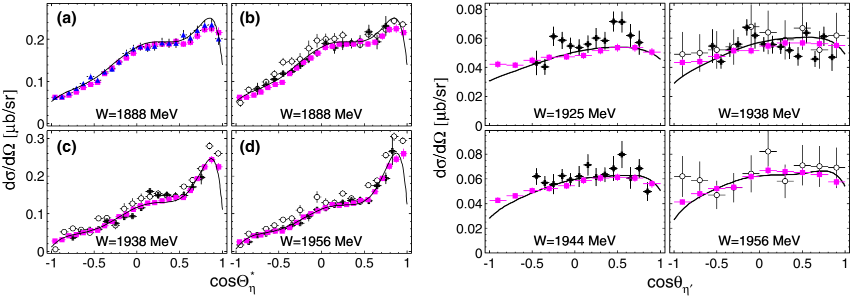
That's a little bit better.

Σ - $\gamma p \to \pi^0 p$ [S. Gardner, EPJA 52, 333 (2016)]

$$\check{\Sigma}(W,\theta) = \sigma_0(W,\theta)\Sigma(W,\theta) = \frac{q}{k}\sum_{n=2}^{2l_{\max}} a_n^{\Sigma}(W)P_n^2(\cos\theta)$$

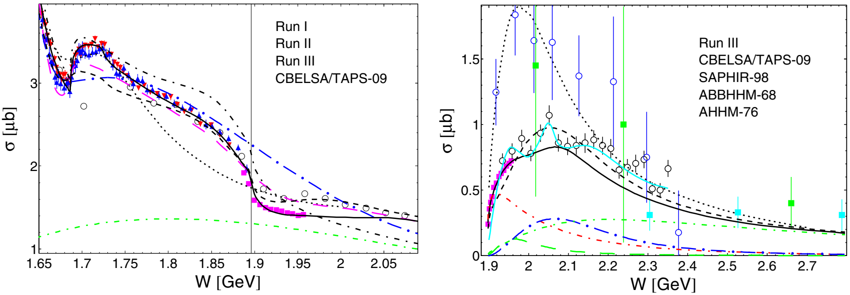


$\gamma p \to \eta p / \gamma p \to \eta' p$ [V. Kashevarov, PRL 118, 212001 (2017)]



Present A2 data in magenta, previous in blue, CLAS [M. Williams et al., PRC 80, 045213 (2009)] in black crosses, CBELSA/TAPS [V. Crede et al., PRC 80 055202 (2009)] in open circles

$\gamma p \to \eta p/\gamma p \to \eta' p$ [V. Kashevarov, PRL 118, 212001 (2017)]

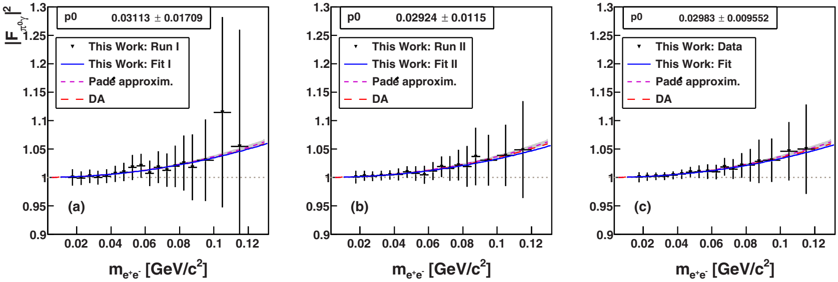


Present A2 data in magenta, CBELSA/TAPS [V. Crede et al., PRC 80 055202 (2009)] in open circles, with ηMAID-2003 [Nucl. Phys. A700, 429 (2002)] (black dotted), SAID-GE09 [Phys. Rev. C 82, 035208 (2010)] (blue), BG2014-2 [EPJA 47, 153 (2011); EPJA 48, 15 (2012)] (magenta)

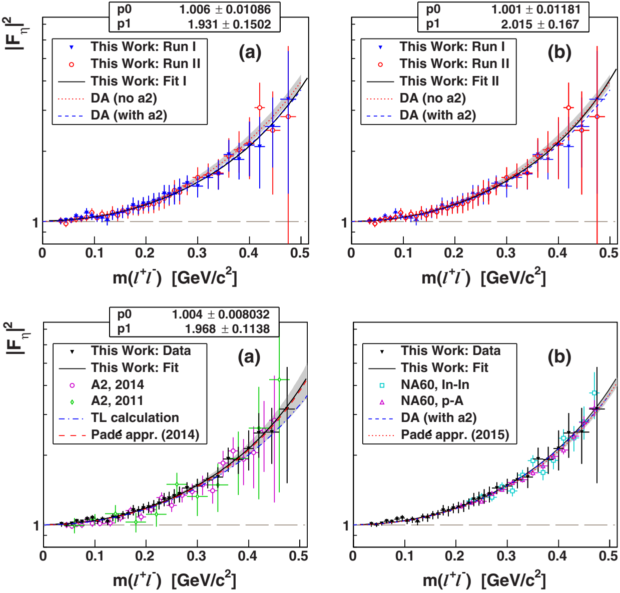
$\pi^0 \to e^+e^-\gamma$ [S. Prakov, PRC 95, 025202 (2017)]

Transition Form Factors (see talk by L. Heijkenskjoeld in Parallel Session B4)

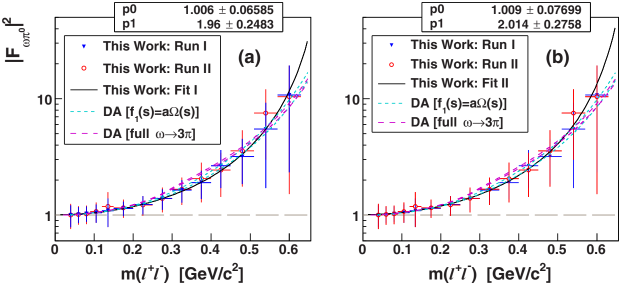
- Pion-exchange term $a_\mu^{\pi^0}$ in HLbL scattering
- Decay width of $\pi^0 \to e^+e^-$

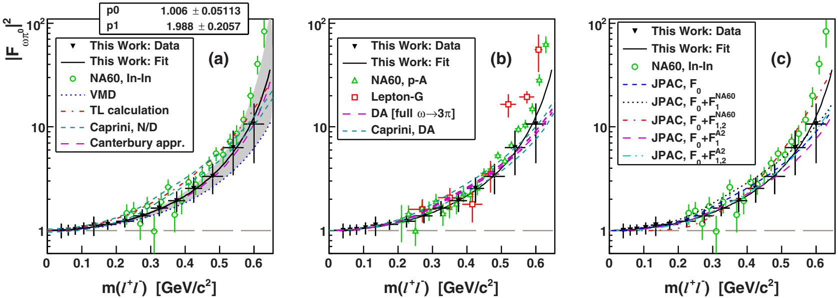


$\eta \to e^+e^-\gamma$ [S. Prakov, PRC 95, 035208 (2017)]



$\omega \to \pi^0 e^+ e^-$ [S. Prakov, PRC 95, 035208 (2017)]

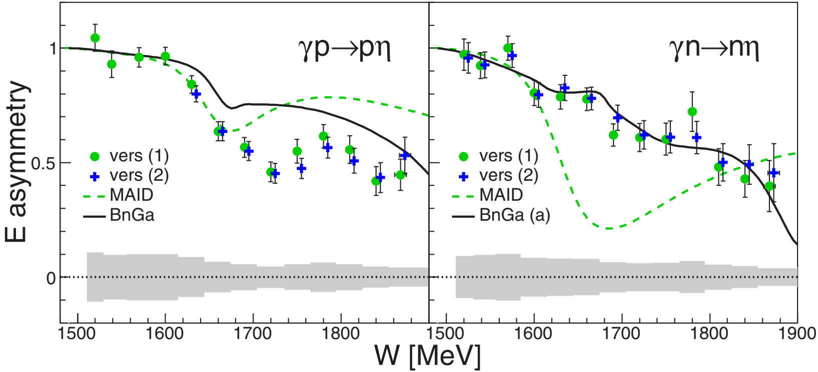




E - $\gamma d \rightarrow \eta X$ [L. Witthauer, PRC 95 055201 (2017)]

Easier to study protons than neutrons, sometimes neutron results unexpected

- Narrow structure previously seen in $\gamma n \rightarrow \eta n$ at W≈1685 MeV
- Seems to only appear in $\sigma_{1/2}$ (S_{11}/P_{11} partial waves)
- Large $N(1675)5/2^-$ (MAID) or BnGa with narrow P_{11} ruled out



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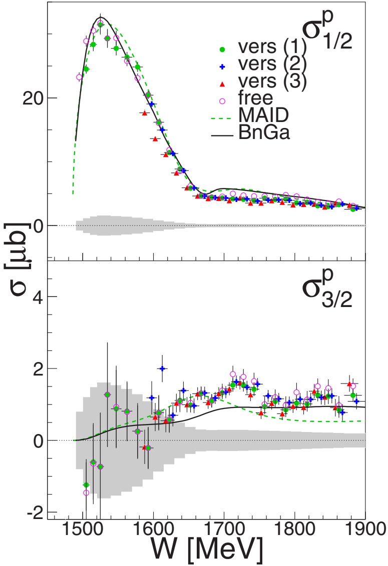

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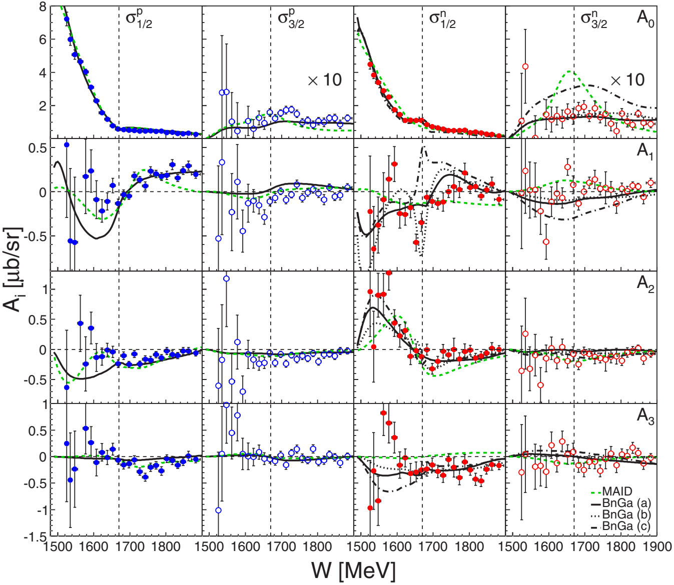
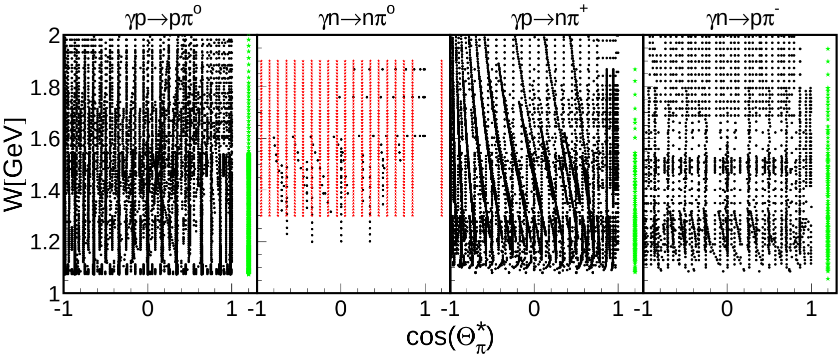


σ - $\gamma d \rightarrow \pi^0 X$ [M. Dieterle, PRC (Accepted)]



Lots of proton data, often missing neutron data

- No free neutron target (I think you've heard)
- Can use deuterium (or helium, or...), but FSI
- If FSI are similar for protons and neutrons in deuterium, perhaps the former can be used to correct the latter

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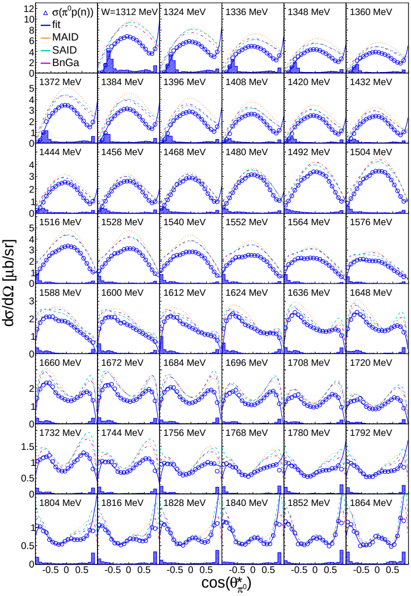

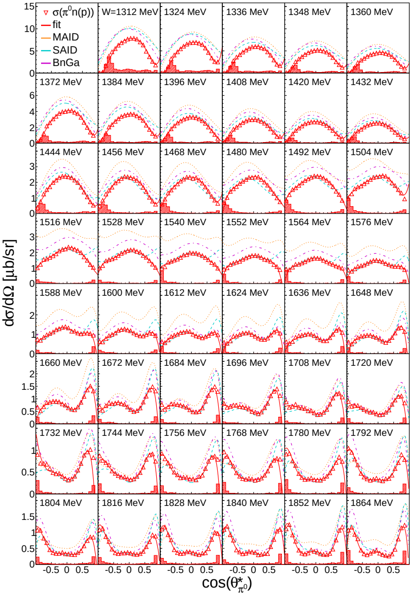

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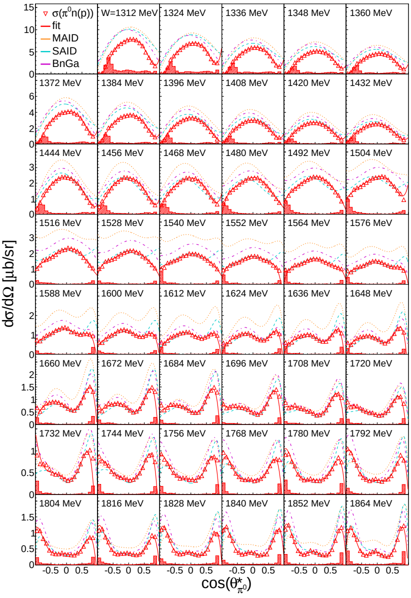

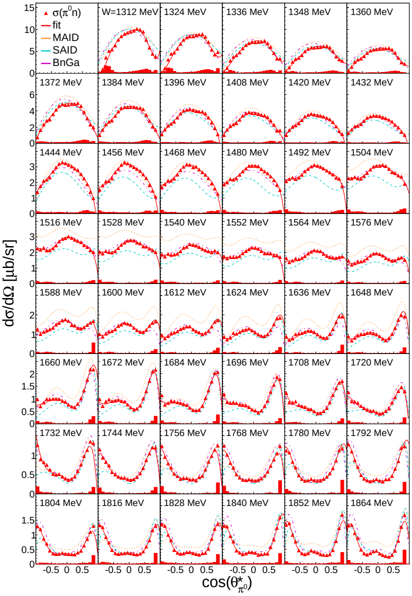

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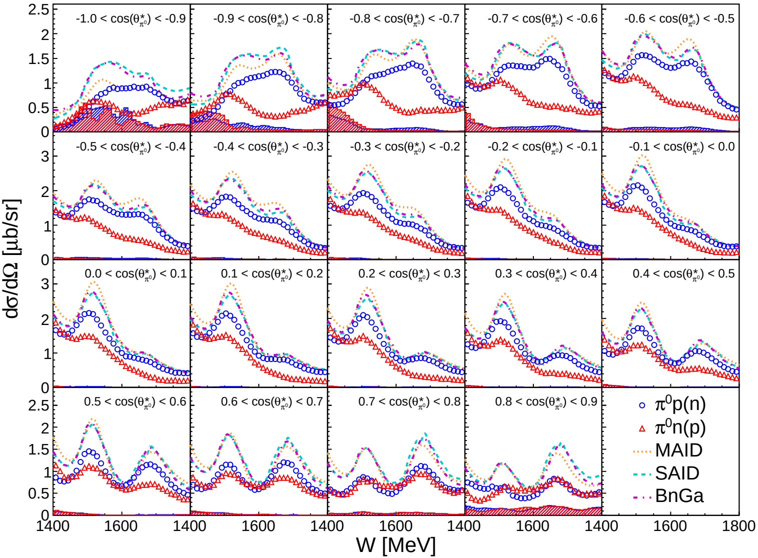

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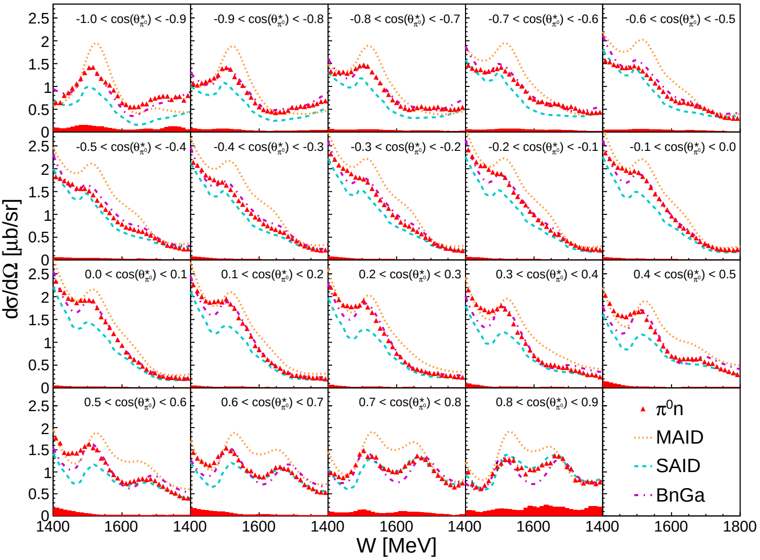

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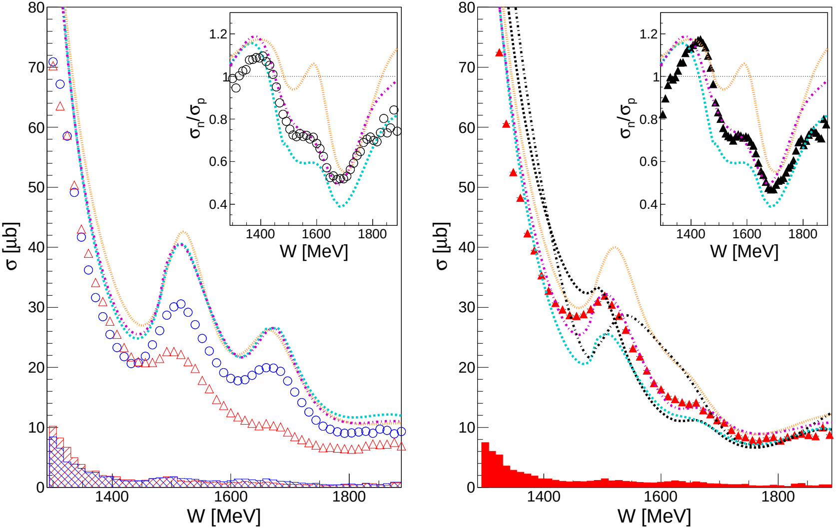

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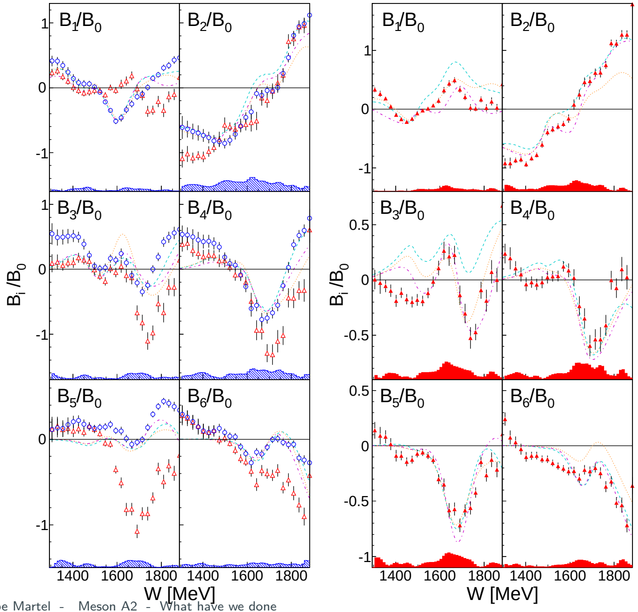
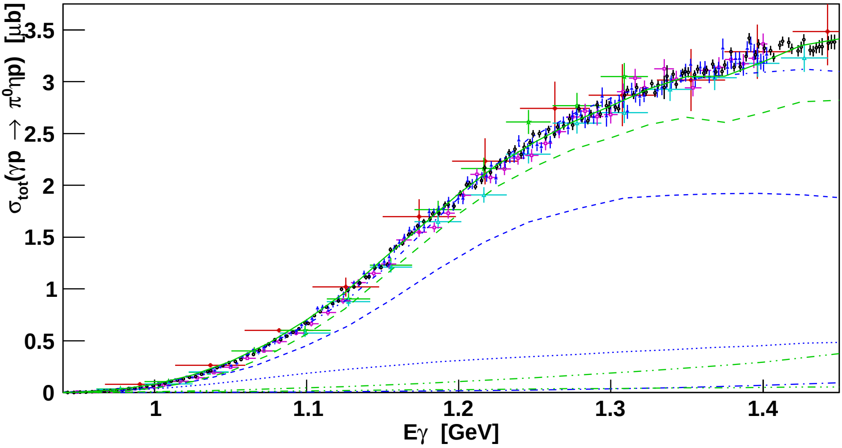


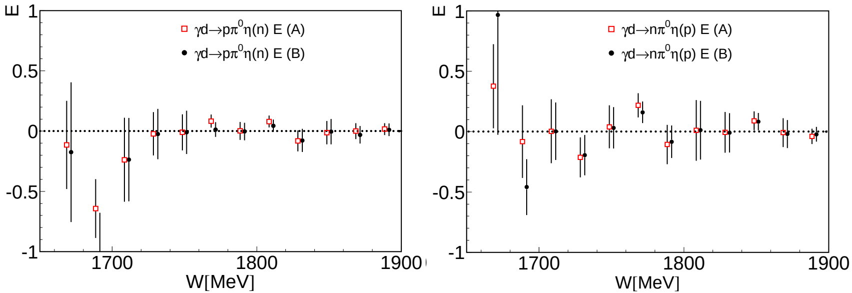
$\gamma p \to \pi^0 \eta p$ [V. Sokhoyan, PRC 97 055212 (2018)]

Three body final states (decay modes and missing resonances)



A2 data (△/◯), CBELSA/TAPS (⋆/△), GRAAL (♢), old A2 (□) data; BnGa: total (dash-dotted), $\Delta(1232)\eta$ (dashed), $N(1535)\pi^0$ (dotted), and $a_0(980)p$ (long-dash-dotted); and Mainz: total (solid), resonant (long-dashed), background (dash-double-dotted), and Born (dash-triple-dotted)

$\gamma d \to \pi^0 \eta X$ [A. Kaeser, PLB (Submitted)]



- The two helicity components contribute identically
- True for both participant protons and neutrons
- Absolute couplings for protons and neutrons are identical
- Contributing nucleon resonances (threshold up to inv. masses of 1.9 GeV) have almost equal electromagnetic helicity couplings $A^{n,p}_{1/2}$ and $A^{n,p}_{3/2}$
- Typical for Δ resonances, identical $A_{1/2}$ and $A_{3/2}$ components for any nucleon target only possible for $J \geq 3/2$ states, constrains possible

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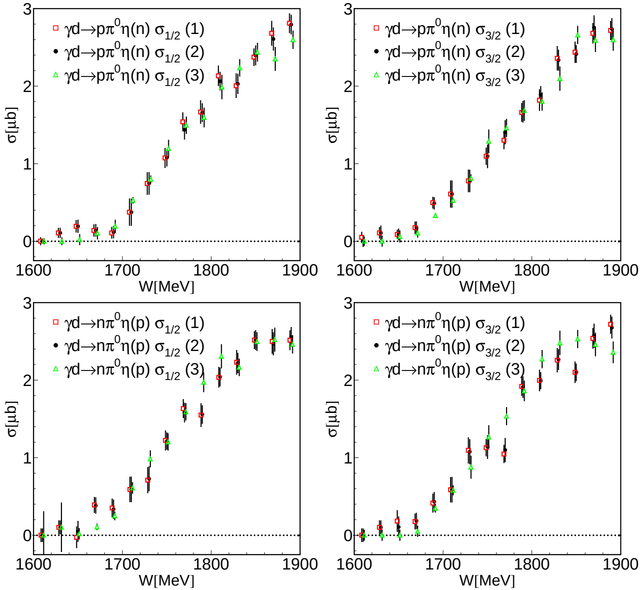

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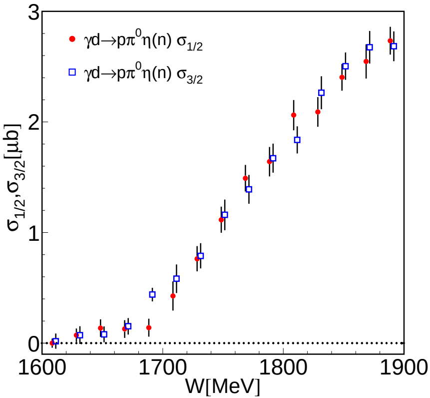
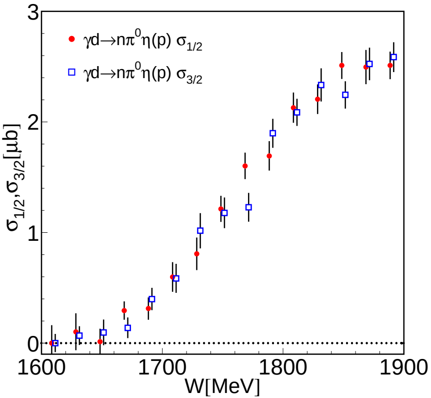
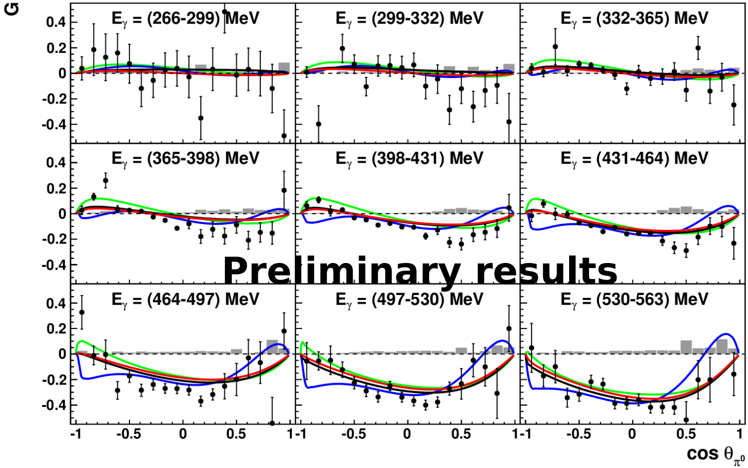




What are we doing

G - $\gamma p \to \pi^0 p$ (K. Spieker, Bonn, Preliminary)



A2 and CBELSA/TAPS [PRL 109 (2012) 102001] data, with BnGa 2014-02 and BnGa 2014-01 [EPJA 50 (2014) 74], MAID-07 [EPJA 34 (2007) 69], and SAID-CM12 [PRC 86 (2012) 015202]

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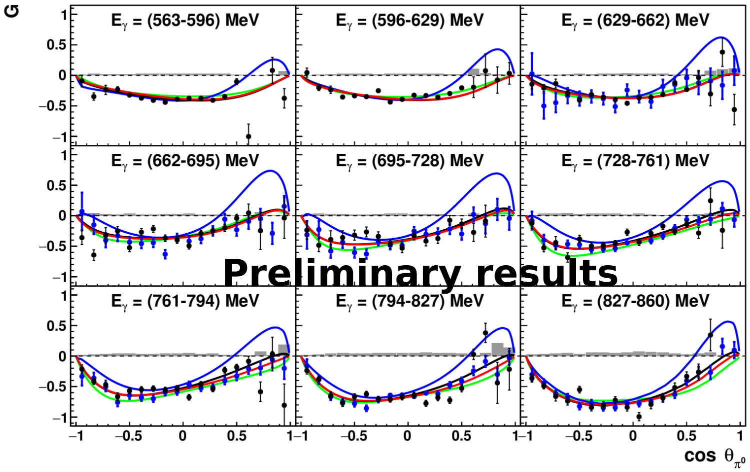

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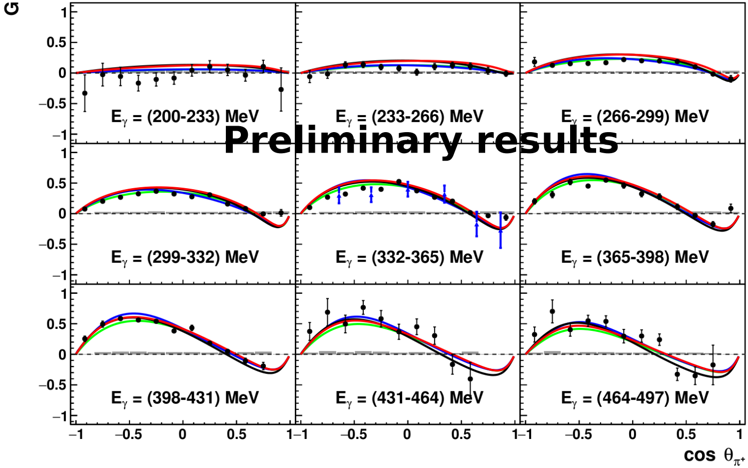

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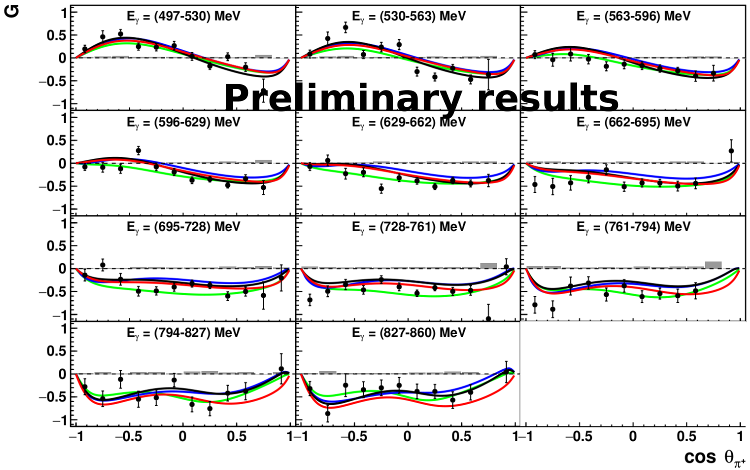

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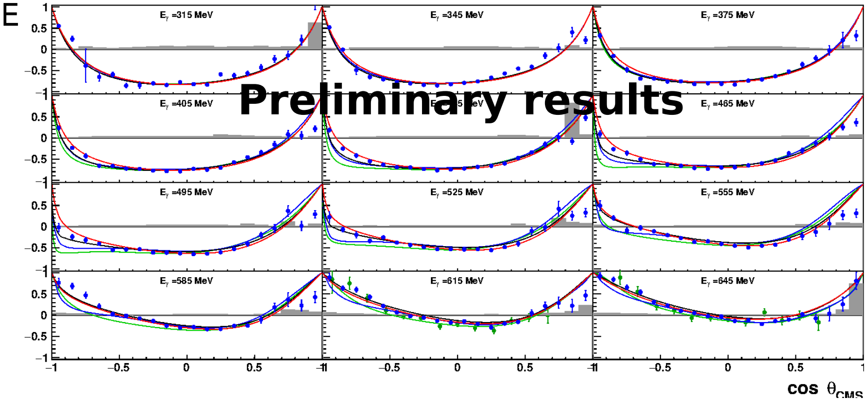

A2 and CBELSA/TAPS [PRL 112 (2014) 012003] data, with BnGa 2014-02 and BnGa 2014-01 [EPJA 50 (2014) 74], JuBo 2016-3.1, and SAID-CM12 [PRC 86 (2012) 015202]

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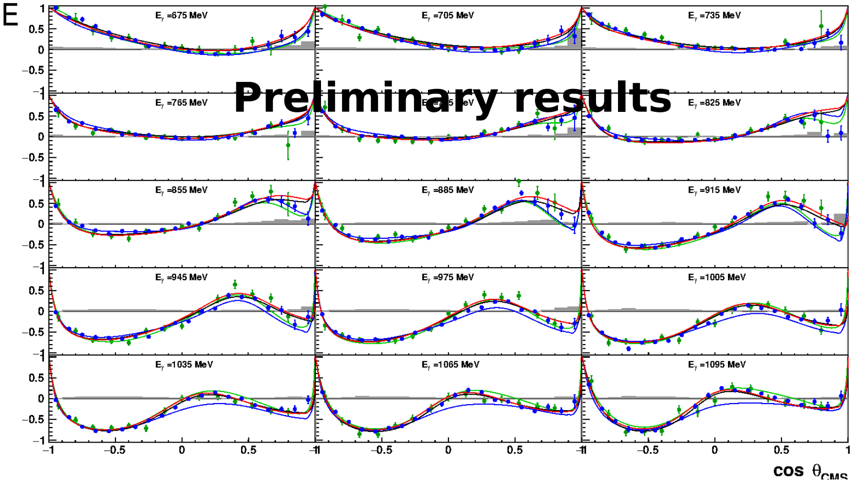

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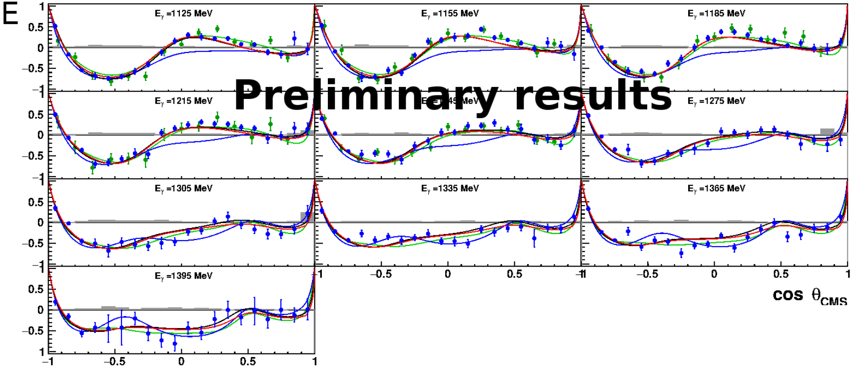

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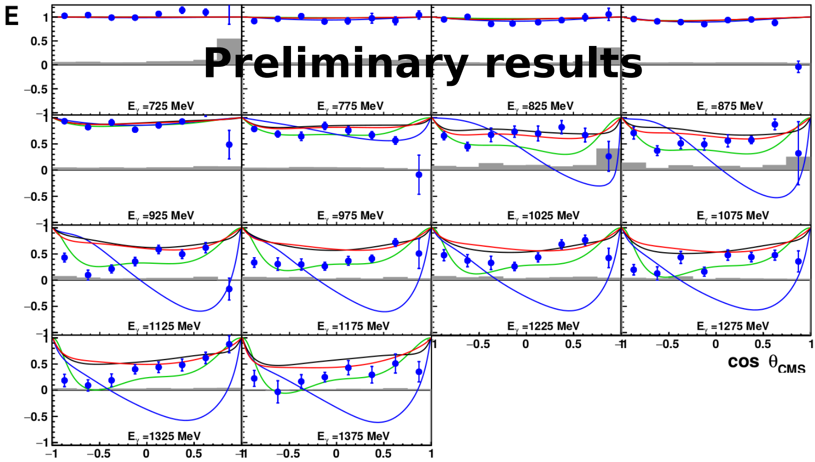
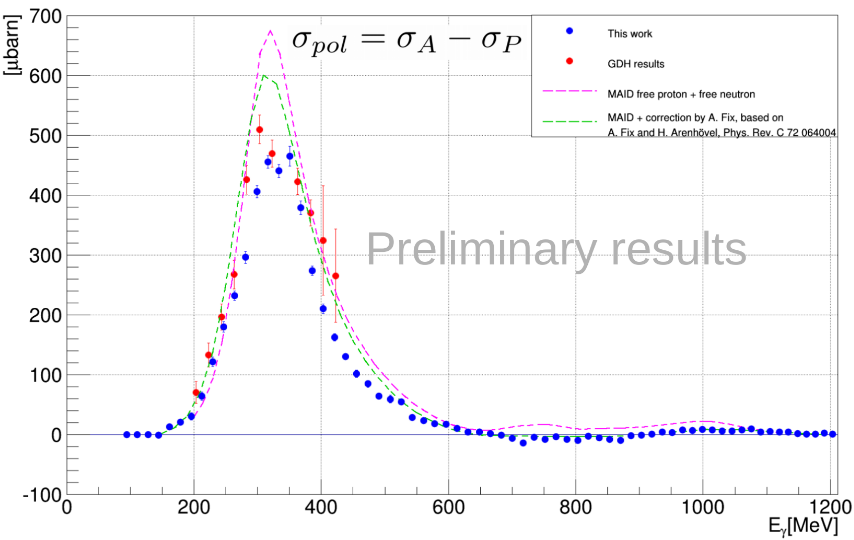


A2 and CBELSA/TAPS [PRL 112 (2014) 012003] data, with BnGa 2014-02 and BnGa 2014-01 [EPJA 50 (2014) 74], JuBo 2016-3.1, and SAID-GE09 [PRC 86 (2012) 015202]

E - $\gamma d \to \pi^0 X$ (F. Cividini, Mainz, Preliminary)



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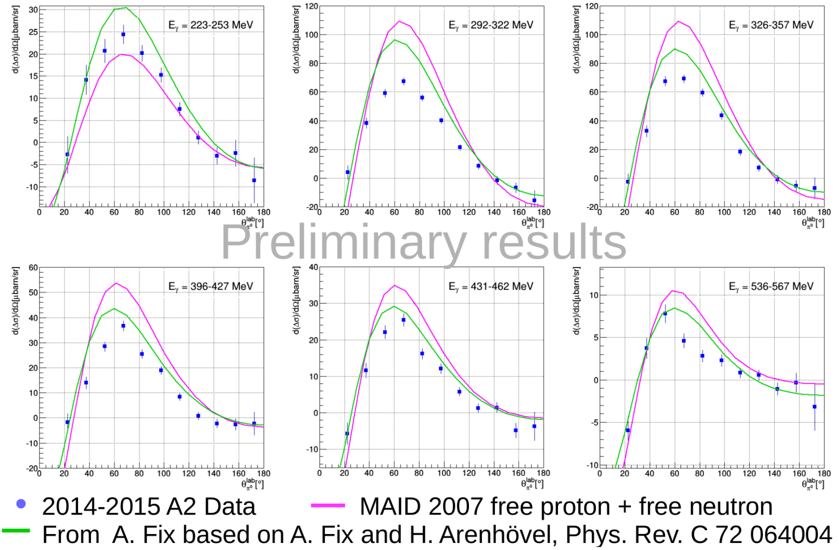

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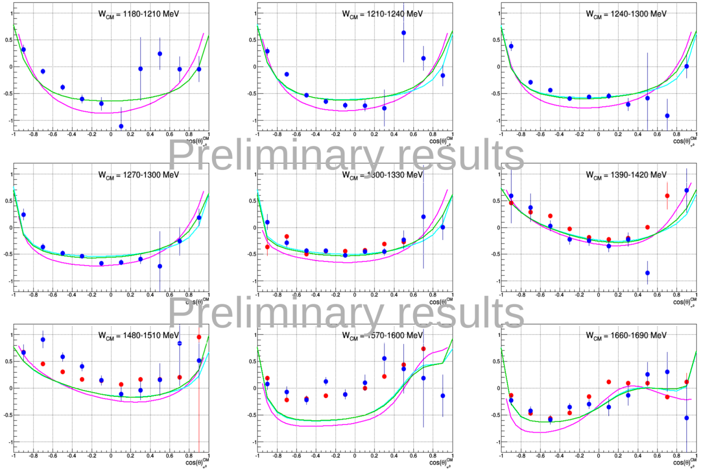

● This work ● Dieterle et al., Phys Lett B 770, 523, 2017 — MAID 2007 free proton
— MAID 2007 + IA, from A. Fix — MAID 2007 + IA + FSI, from A. Fix (based on A. Fix and H. Arenhövel, Phys. Rev. C 72 064005)

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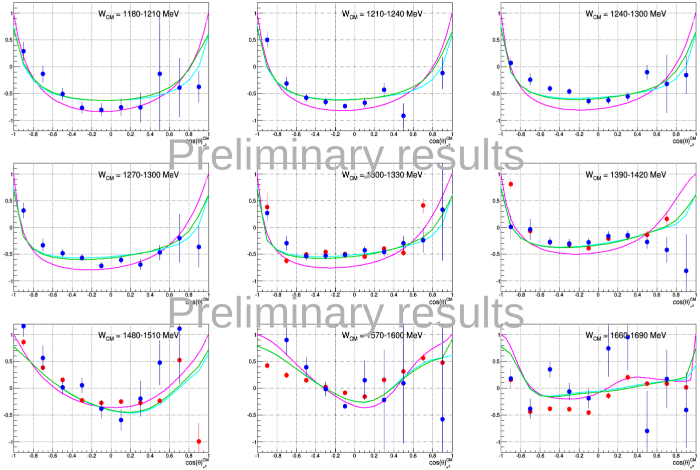

● This work ● Dieterle et al., Phys Lett B 770, 523, 2017 — MAID 2007 free neutron

— MAID 2007 + IA, from A. Fix — MAID 2007 + IA + FSI, from A. Fix (based on A. Fix and H. Arenhövel, Phys. Rev. C 72 064005)

Talks maybe you now wish you had seen

- F. Cividini (E - $\gamma d \to \pi^0 X$ - Parallel Session A6)
- C. Collicott (Symmetry violating η decays - Parallel Session C5)
- D. Ghosal ($\gamma d \to \pi^0 \pi^{+/-} X$ - Parallel Session A6)
- L. Heijkenskjoeld (Transition Form Factors - Parallel Session B4)

Special shout-out to P. Adlarson, whose paper on $\eta' \to \pi^0 \pi^0 \eta$ was just accepted by PRD, and whose results I did not have time to show after realizing that he was not presenting them here...

Conclusions

- We've measured a bunch of stuff
    - σ, Σ, T, F, E, G
    - Looking at proton and neutron (via deuterium, studying FSI)
    - Investigating multi-meson final states
- We're still measuring stuff
    - E and G on proton and neutron
    - Recoil observables
- We'll continuing measuring stuff
    - Transition Form Factors
    - Future end-point-tagger runs for η'
    - Active targets to improve threshold region

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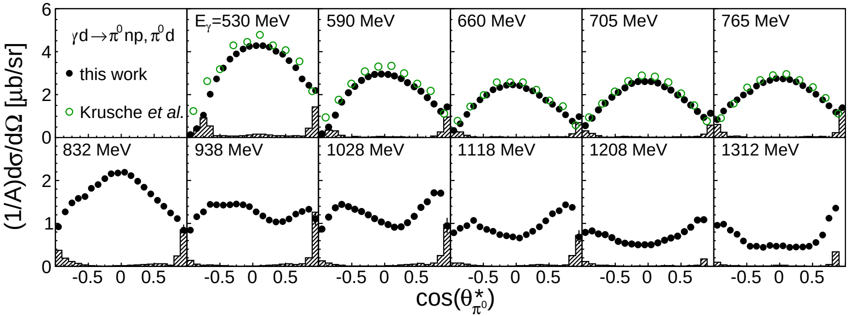
- Thank you for your attention!

σ - $\gamma d \to \pi^0 X$ [M. Dieterle, PRC (Accepted)]



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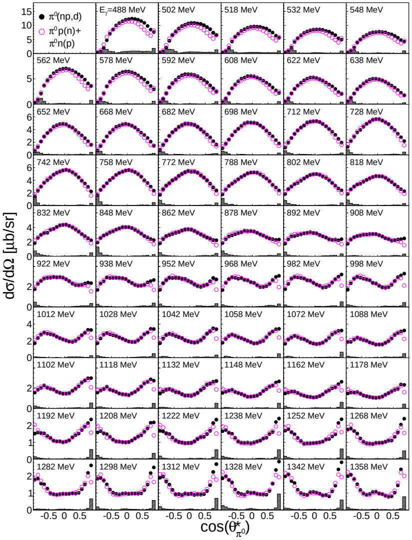

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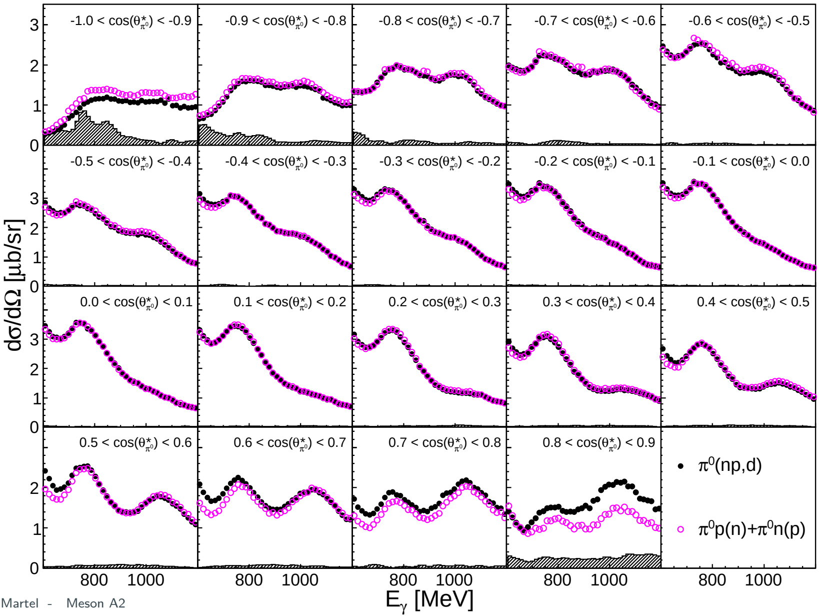

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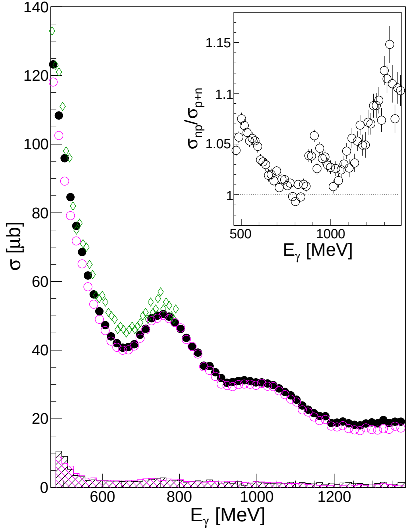
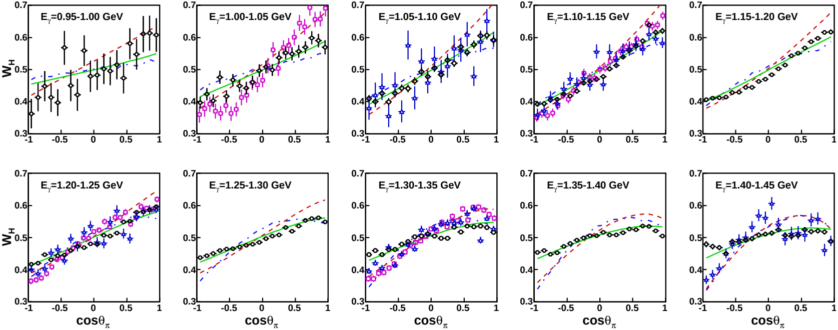


$\gamma p \to \pi^0 \eta p$ [V. Sokhoyan, PRC 97 055212 (2018)]



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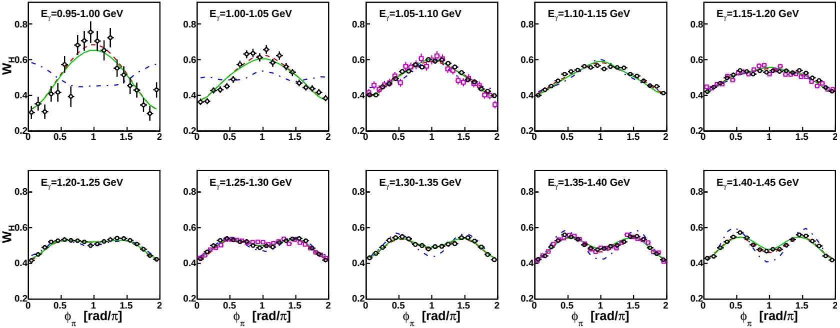

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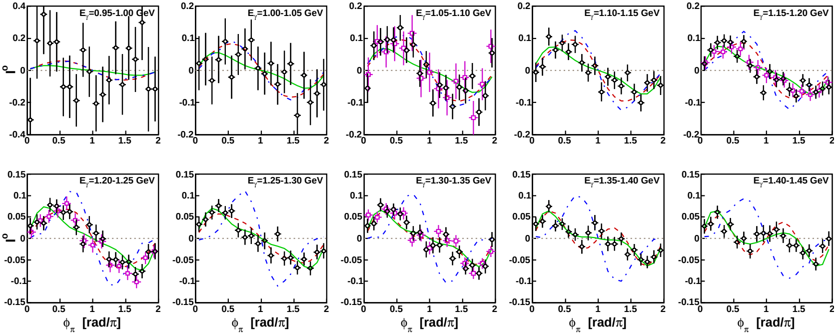


Frozen Spin Target

How are the protons actually polarized? Through Dynamic Nuclear Polarization (DNP):

- Cool target to 0.2 Kelvin.
- Use 2.5 Tesla magnet to align electron spins.
- Pump $\approx$ 70 GHz microwaves (just above, or below, the Electron Spin Resonance frequency), causing spin-flips between the electrons and protons.
- Cool target to 0.025 Kelvin, 'freezing' proton spins in place.
- Remove polarizing magnet.
- Energize 0.6 Tesla 'holding' coil in the cryostat to maintain the polarization.
- Relaxation times $>$ 1000 hours.
- Polarizations up to 90%.

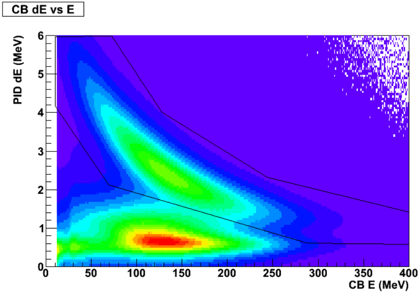
Crystal Ball - Charged Particle Detection

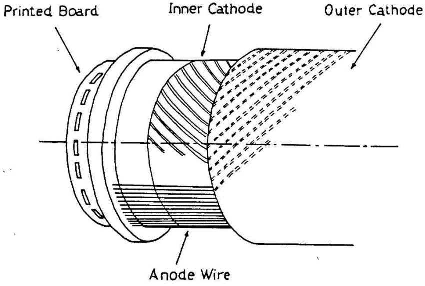
Particle Identification Detector (PID)

- Barrel of 24 plastic paddles
- Each covers $15 < \theta < 159°$, and $15°$ in ϕ
- Plot ΔE in PID vs E in NaI

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





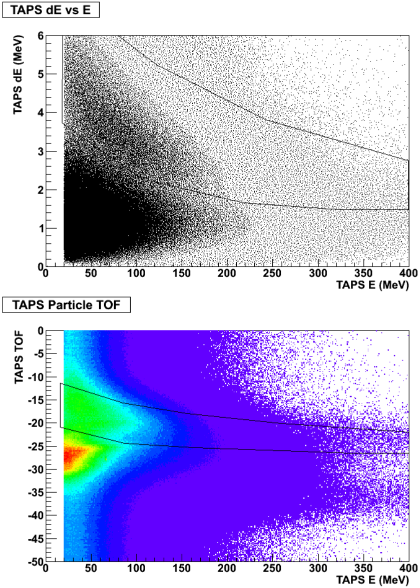
TAPS - Charged Particle Detection

Veto scintillators

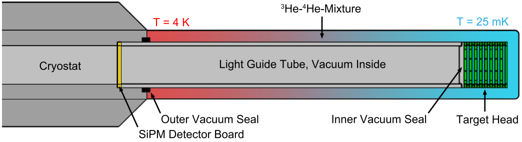
- 5mm plastic scintillators in front of each crystal
- Same method as PID (plot ΔE vs E)

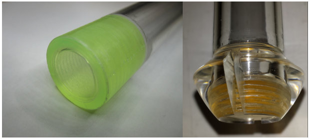
Time of Flight

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



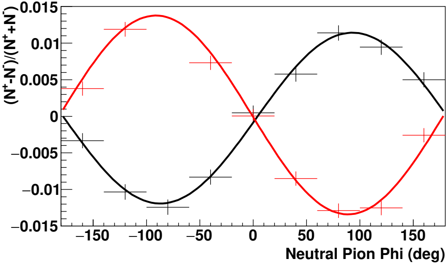
Active Target





Requirements

- Polarizable Scintillator
- High light output
- High rate capability
- Low thermal energy input
- Detectors working at 4K



Targets from UMass Amherst

Tested at MAMI - Pol > 50%