η and η' physics at ELSA

EMMI Workshop "Meson and Hyperon Interactions with Nuclei" 2022

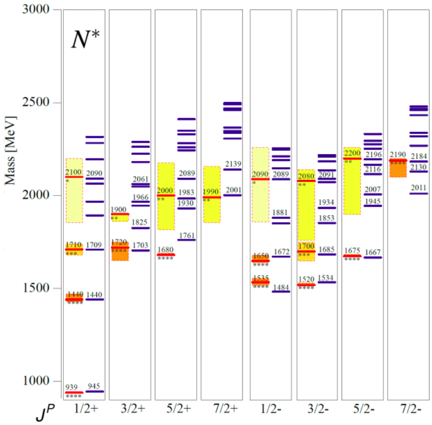
Farah Afzal for the CBELSA/TAPS collaboration

15.09.2022

University of Bonn

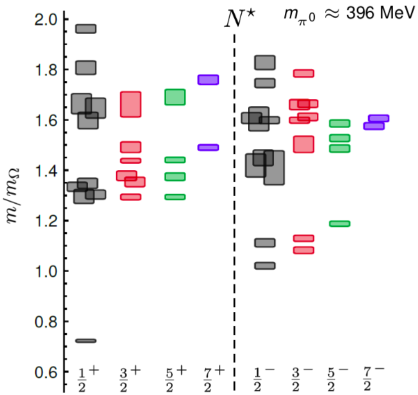
Baryon spectroscopy

Quark model with experimental data



[M. Ronninger and B. Metsch, Eur. Phys. J. A 47 (2011) 162]

Lattice QCD calculations



[R. G. Edwards et al., Phys. Rev. D 84 (2011) 074508]

- Discrepancy between theory and experiment: missing resonances, ordering of states

Theoretical description of nucleon excitation spectra

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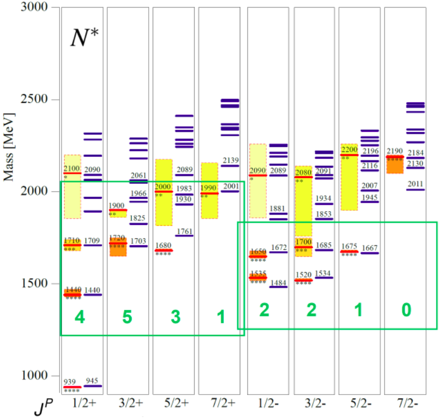
Quark model with experimental data



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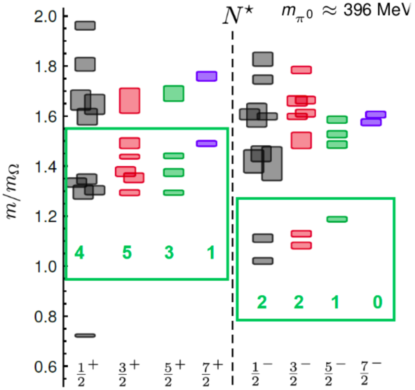
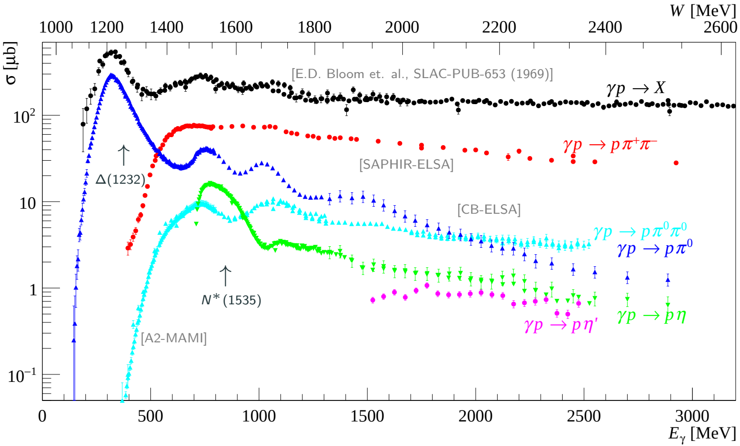


[R. G. Edwards et al., Phys. Rev. D 84 (2011) 074508]

- Discrepancy between theory and experiment: missing resonances, ordering of states
- most resonances observed in πN scattering $\rightarrow$ experimental bias?

Photoproduction reactions

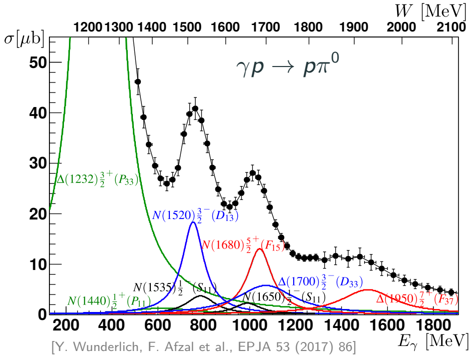
Worldwide effort to get high precision data (ELSA, MAMI, JLab, SPring-8, ...)



[A. Thiel, F. Afzal, Y. Wunderlich, Prog. Part. Nucl. Phys. 125 (2022) 103949]

- Photoproduction reactions are an excellent tool to probe excitation spectra!
- Resonances contribute with different strength to distinct channels
- How can we disentangle contributing resonances?

Unpolarized cross section



[Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86]

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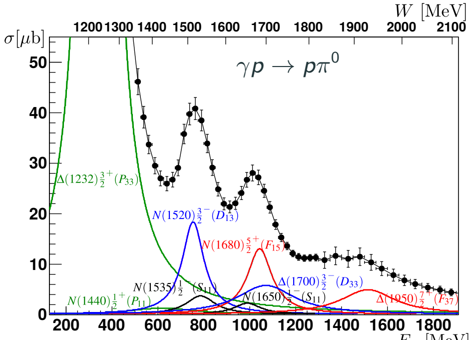
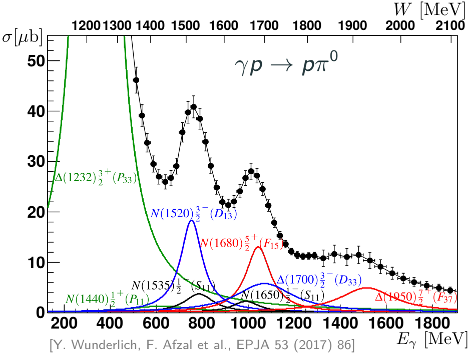


[Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86]

$$\frac{d\sigma}{d\Omega}_0(W,\theta) \propto \sum_{\text{spins}} | < f|\mathcal{F}|i > |^2$$

Unpolarized cross section



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Photoproduction amplitude $\mathcal{F}$
$\leftrightarrow$ 4 complex amplitudes
e.g. CGLN amplitudes: F_1, F_2, F_3, F_4

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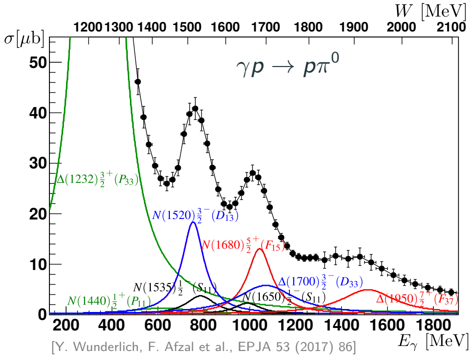

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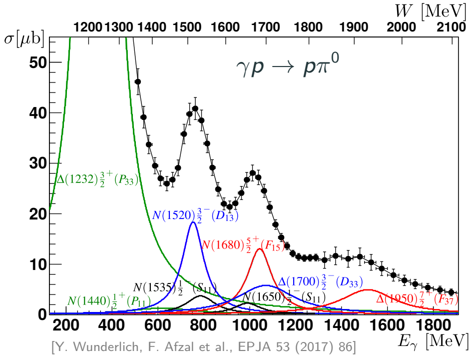
- PWA: e.g. $F_1 = \sum_{l=0}^{\infty} (lM_{l+} + E_{l+})P'_{l+1} + [(l+1)M_{l-} + E_{l-}]P'_{l-1}$
  - $E_{l\pm}(W), M_{l\pm}(W)$: Multipoles
  - $P'_{l\pm 1}(\cos\theta_{cm})$: Legendre polynomials

Unpolarized cross section



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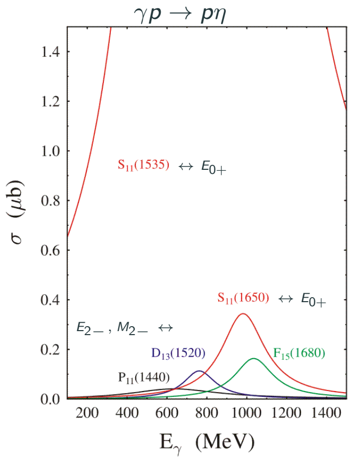
  - $E_{l\pm}(W), M_{l\pm}(W)$: Multipoles
  - $P'_{l\pm1}(\cos\theta_{cm})$: Legendre polynomials
- $\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \ldots$

  $\rightarrow$ unpolarized cross section is sensitive to dominant contributing resonances

Polarization observables

Polarization observables in the 2-body kinematic system for the photoproduction of a pseudoscalar meson

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	-	$T_{x'}$	$L_{x'}$	$T_{z'}$	$L_{z'}$
linear	-Σ	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	($-L_{z'}$)	($T_{z'}$)	($L_{x'}$)	($-T_{x'}$)
circular	-	F	-	-E	$C_{x'}$	-	$C_{z'}$	-	-	-	-



$\sigma, \Sigma, T, P + 4$ double pol. observables needed for a unique solution

[W. Chiang and F. Tabakin, Phys. Rev., C55 (1997) 2054-2066]

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Polarization observables in the 2-body kinematic system for the photoproduction of a pseudoscalar meson

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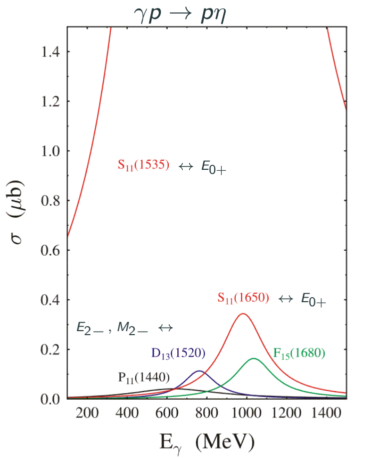
circular	-	F	-	-E	$C_{x'}$	-	$C_{z'}$	-	-	-	-

σ, Σ, T, P + 4 double pol. observables needed for a unique solution

[W. Chiang and F. Tabakin, Phys. Rev., C55 (1997) 2054-2066]

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

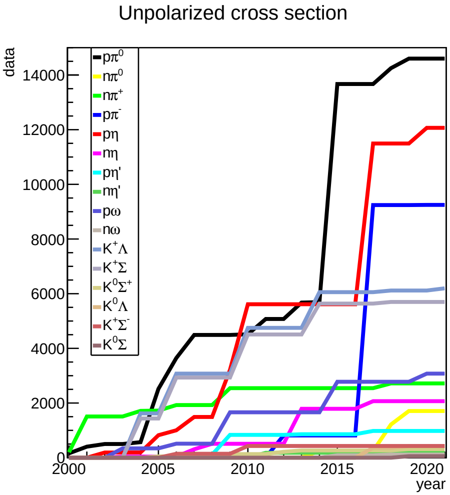
$$\Sigma \sim \underbrace{-2E_{0+}^* E_{2+} + 2E_{0+}^* E_{2-} - 2E_{0+}^* M_{2+} + 2E_{0+}^* M_{2-}}_{< S, D >} + \ldots$$

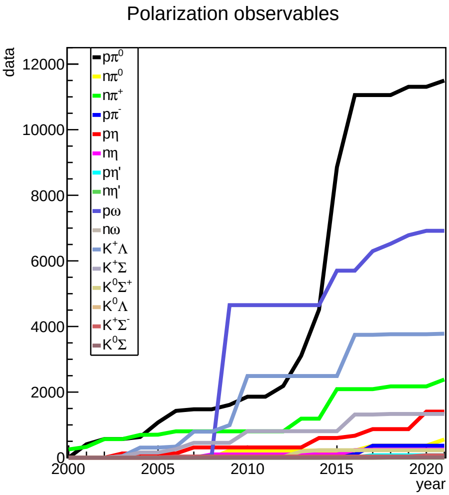


→Polarization observables are sensitive to interference terms!

→Interferences with the dominant S-wave (E_{0+}) important in η photoproduction!

Development of database

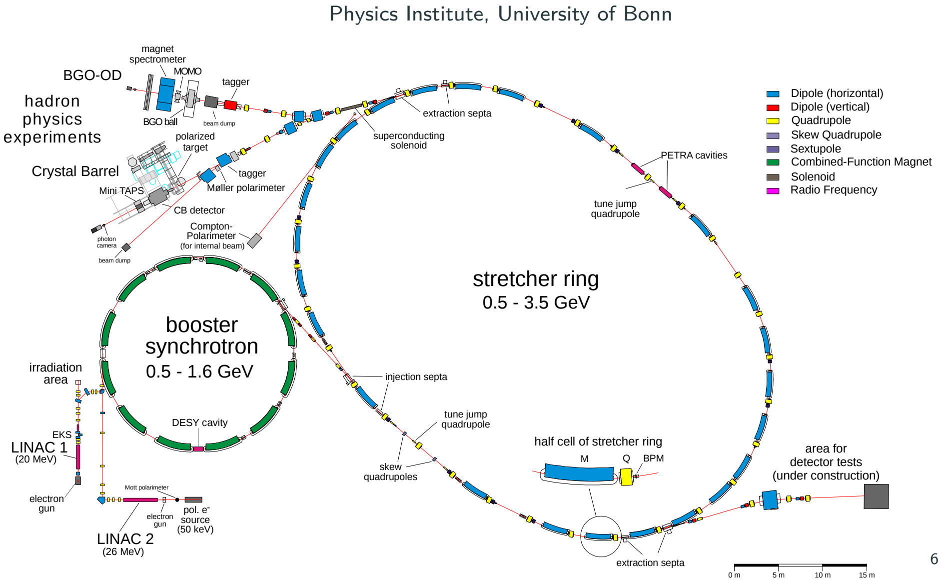




[A. Thiel, F. Afzal, Y. Wunderlich, Prog. Part. Nucl. Phys. 125 (2022) 103949]

Results from ELSA

The Electron Stretcher Accelerator (ELSA)



The Electron Stretcher Accelerator (ELSA)

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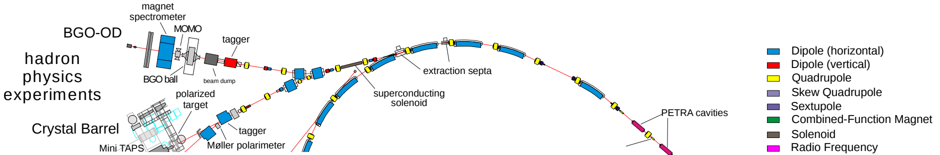
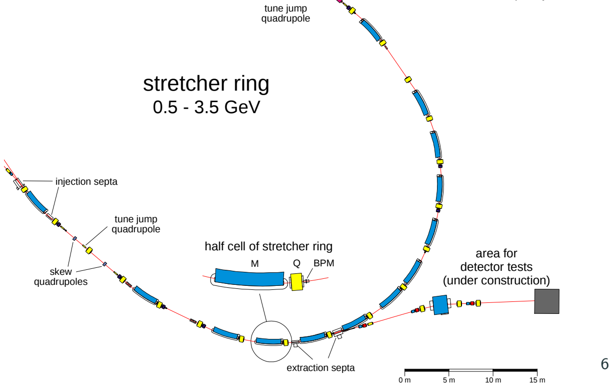
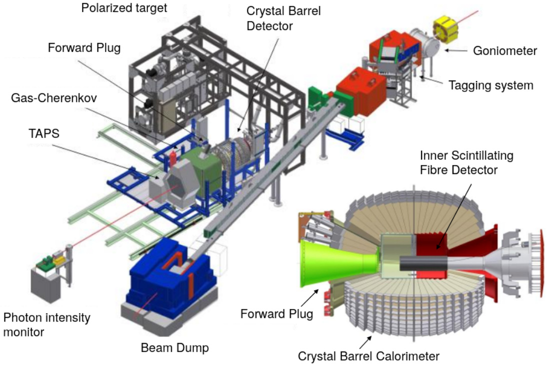
Physics Institute, University of Bonn







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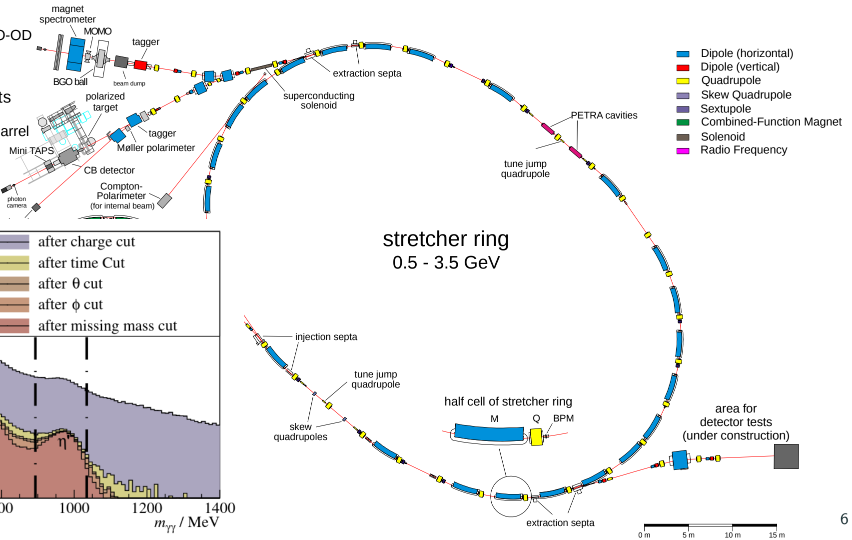
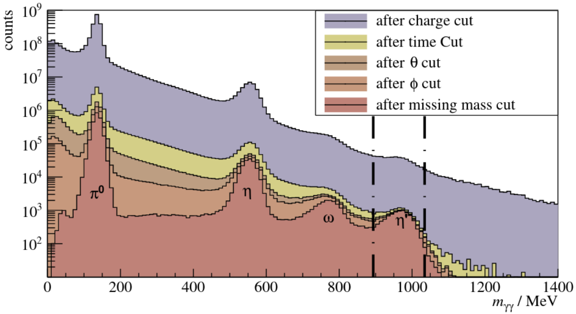
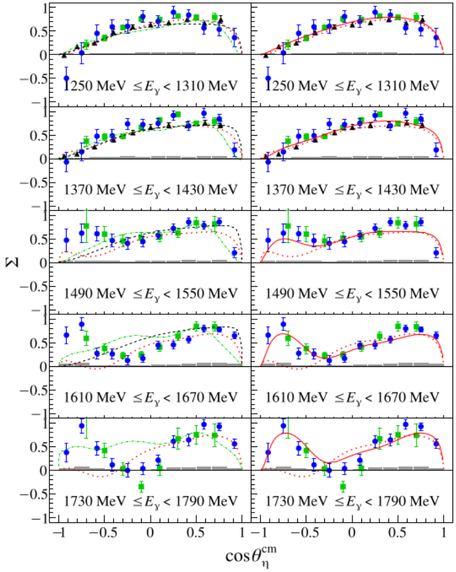
Physics Institute, University of Bonn





η photoproduction off protons

Precise beam asymmetry Σ data in $\gamma p \to p\eta$

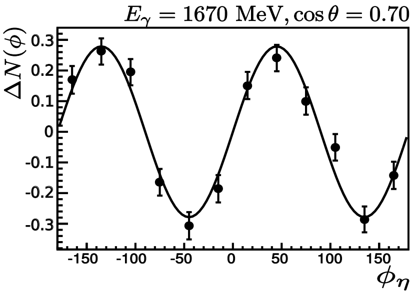


[F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)]

- ● CBELSA/TAPS data (F. Afzal et al.)
- ▲ GRAAL data (O. Bartalini et al., Eur. Phys. J. A33 (2007) 169)
- ■ CLAS data (P. Collins et al., Phys. Lett. B 771 (2017) 213-221)

BnGa-2014-02 · JüBo-2015-FitB · ηMAID · BnGa-2019

$$\Delta N = \frac{N_{-45^\circ} - N_{+45^\circ}}{N_{-45^\circ} + N_{+45^\circ}} = p_\gamma^{lin}\Sigma \sin(2\phi)$$



$$\check{\Sigma}(W,\cos\theta) = \Sigma(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=2}^{2L_{\mathrm{max}}}\left(a_{L_{\mathrm{max}}}(W)\right)_k^{\check{\Sigma}}\cdot P_k^2(\cos\theta)\ \text{, i.e. }\ L_{\mathrm{max}} = 2;$$

Truncated PWA

$$\check{\Sigma}(W,\cos\theta) = \Sigma(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=2}^{2L_{\mathrm{max}}} \left(a_{L_{\mathrm{max}}}(W)\right)_k^{\check{\Sigma}} \cdot P_k^2(\cos\theta)\ , \text{ i.e. } L_{\mathrm{max}} = 2;$$

$(a_{L_{\mathrm{max}}})_k^{\check{\Sigma}}$ defined by matrices with $\langle \ell_1, \ell_2 \rangle$-interference blocks

$$(a_2)_2^{\check{\Sigma}} = \left[\begin{array}{cccc} E_{0+}^{*} & E_{1+}^{*} & \dots & M_{2-}^{*} \end{array}\right] \left[\begin{array}{c|ccc|cccc} 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\ \hline 0 & -\frac{3}{2} & \frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 \\ \hline \frac{1}{2} & 0 & 0 & 0 & -\frac{36}{7} & -\frac{1}{7} & \frac{9}{7} & -\frac{9}{7} \\ \frac{1}{2} & 0 & 0 & 0 & -\frac{1}{7} & -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2} & 0 & 0 & 0 & \frac{9}{7} & -\frac{1}{2} & \frac{18}{7} & \frac{9}{14} \\ \frac{1}{2} & 0 & 0 & 0 & -\frac{9}{7} & \frac{1}{2} & \frac{9}{14} & \frac{3}{2} \end{array}\right] \left[\begin{array}{c} E_{0+} \\ E_{1+} \\ M_{1+} \\ M_{1-} \\ E_{2+} \\ E_{2-} \\ M_{2+} \\ M_{2-} \end{array}\right]$$

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$$\begin{aligned} = \frac{1}{14}\Big[& E_{2-}^*\Big(-7E_{2-} + 7E_{0+} - 2E_{2+} + 7M_{2-} - 7M_{2+}\Big) + 7E_{0+}^*\Big(E_{2-} + E_{2+} + M_{2-} - M_{2+}\Big) \\ & + E_{2+}^*\Big(-2E_{2-} + 7E_{0+} - 18(4E_{2+} + M_{2-} - M_{2+})\Big) + M_{2-}^*\Big(7E_{2-} + 7E_{0+} - 18E_{2+} \\ & + 21M_{2-} + 9M_{2+}\Big) + M_{2+}^*\Big(-7E_{2-} - 7E_{0+} + 9(2E_{2+} + M_{2-} + 4M_{2+})\Big) \\ & + 7\Big(E_{1+}^*\Big(-3E_{1+} - M_{1-} + M_{1+}\Big) + M_{1-}^*\Big(M_{1+} - E_{1+}\Big) + M_{1+}^*\Big(E_{1+} + M_{1-} + M_{1+}\Big)\Big)\Big] \end{aligned}$$

Truncated PWA

$$\check{\Sigma}(W, \cos\theta) = \Sigma(W, \cos\theta) \cdot \frac{d\sigma}{d\Omega}(W, \cos\theta) = \sum_{k=2}^{2L_{\mathrm{max}}} \left(a_{L_{\mathrm{max}}}(W)\right)_k^{\check{\Sigma}} \cdot P_k^2(\cos\theta) \text{ , i.e. } L_{\mathrm{max}} = 2;$$

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$$= \frac{1}{14} \Big[E_{2-}^* \Big(-7E_{2-} + 7E_{0+} - 2E_{2+} + 7M_{2-} - 7M_{2+} \Big) + 7E_{0+}^* \Big(E_{2-} + E_{2+} + M_{2-} - M_{2+} \Big)$$

$$+ E_{2+}^* \Big(-2E_{2-} + 7E_{0+} - 18(4E_{2+} + M_{2-} - M_{2+}) \Big) + M_{2-}^* \Big(7E_{2-} + 7E_{0+} - 18E_{2+}$$

$$+ 21M_{2-} + 9M_{2+} \Big) + M_{2+}^* \Big(-7E_{2-} - 7E_{0+} + 9(2E_{2+} + M_{2-} + 4M_{2+}) \Big)$$

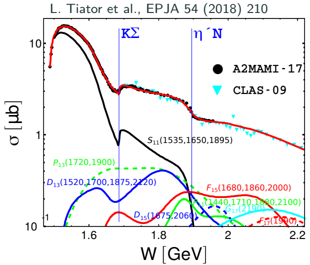
$$+ 7\Big(E_{1+}^* \Big(-3E_{1+} - M_{1-} + M_{1+} \Big) + M_{1-}^* \Big(M_{1+} - E_{1+} \Big) + M_{1+}^* \Big(E_{1+} + M_{1-} + M_{1+} \Big) \Big) \Big]$$

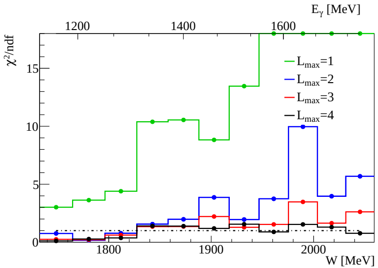
$$= < P, P > + < S, D > + < D, D >$$

Y. Wunderlich, F. Afzal, A. Thiel and R. Beck, EPJ A 53: 86 (2017)

Dominant partial wave contributions (Σ (CBELSA/TAPS), $\gamma p \to p\eta$)

$$\check{\Sigma}(W,\cos\theta) = \Sigma(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=2}^{2L_{max}} (a_L(W))_k \cdot P_k^2(\cos\theta)$$





Dominant partial wave contributions (Σ (CBELSA/TAPS), $\gamma p \to p\eta$)

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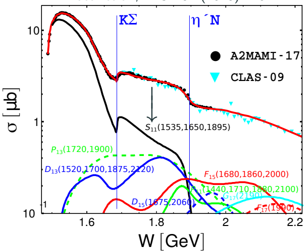
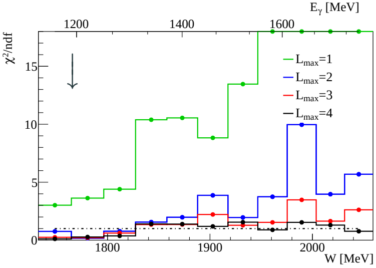
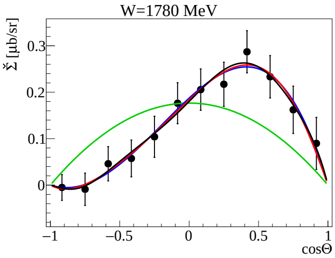
L. Tiator et al., EPJA 54 (2018) 210







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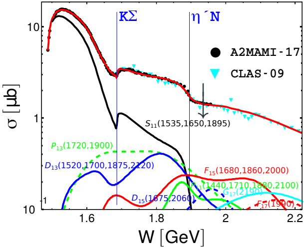
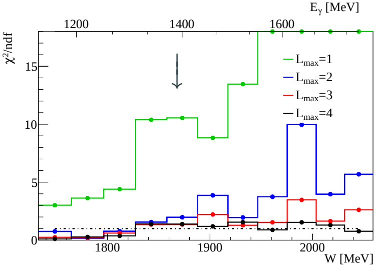
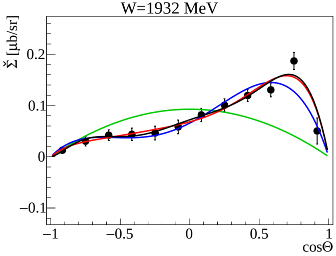
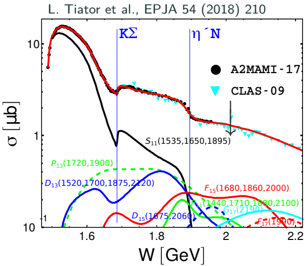


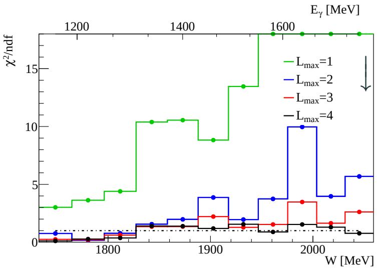


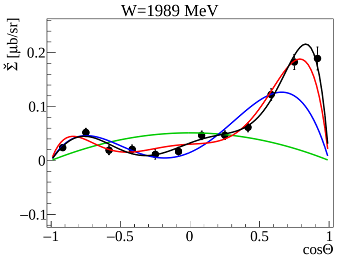


Dominant partial wave contributions (Σ (CBELSA/TAPS), $\gamma p \to p\eta$)

$$\check{\Sigma}(W, \cos\theta) = \Sigma(W, \cos\theta) \cdot \frac{d\sigma}{d\Omega}(W, \cos\theta) = \sum_{k=2}^{2L_{max}} (a_L(W))_k \cdot P_k^2(\cos\theta)$$

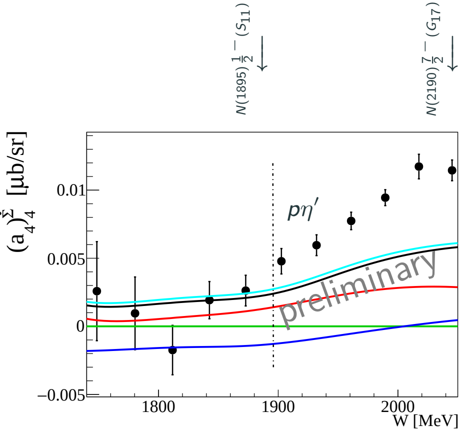






Dominant partial wave contributions (Σ (CBELSA/TAPS), $\gamma p \to p\eta$)

$$\check{\Sigma}(W,\cos\theta) = \Sigma(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=2}^{2L_{max}} (a_L(W))_k \cdot P_k^2(\cos\theta)$$



Compare extracted fit coefficient to BnGa-2014-02 prediction

$(a_5)_4^{\check{\Sigma}} = \langle D, D\rangle$ (blue)

$+\langle P, F\rangle + \langle F, F\rangle$ (red)

$+\langle \boldsymbol{S}, \boldsymbol{G}\rangle + \langle D, G\rangle + \langle G, G\rangle$ (black)

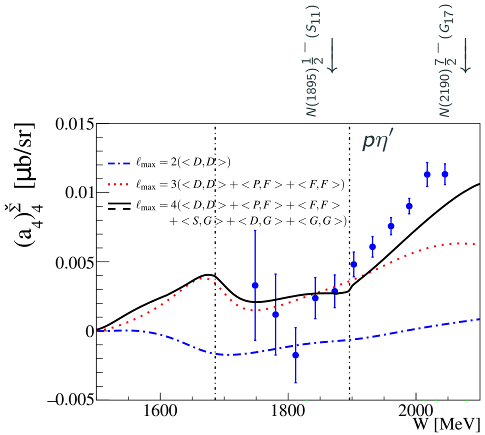
$+\langle P, H\rangle + \langle F, H\rangle + \langle H, H\rangle$ (cyan)

$p\eta'$ channel needs to be included in PWA to describe data

Evidence for $N(1895)\frac{1}{2}^-(S_{11})$ resonance due to strong $p\eta'$ cusp in $p\eta$ S wave

Dominant partial wave contributions (Σ (CBELSA/TAPS), $\gamma p \rightarrow p\eta$)

$$\check{\Sigma}(W,\cos\theta) = \Sigma(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=2}^{2L_{max}} (a_L(W))_k \cdot P_k^2(\cos\theta)$$



Compare extracted fit coefficient to BnGa-2019 solution

$$(a_5)_4^{\check{\Sigma}} = \langle D,D\rangle$$
$$+\langle P,F\rangle + \langle F,F\rangle$$
$$+\langle \boldsymbol{S},\boldsymbol{G}\rangle + \langle D,G\rangle + \langle G,G\rangle$$

F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)

$p\eta'$ channel needs to be included in PWA to describe data

Evidence for $N(1895)\frac{1}{2}^-(S_{11})$ resonance due to strong $p\eta'$ cusp in $p\eta$ S wave

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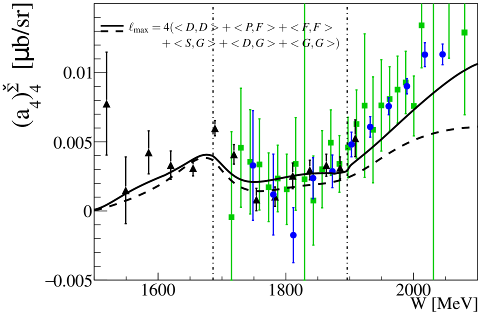


▲ GRAAL data (O. Bartalini et al., Eur. Phys. J. A33 (2007) 169)

● P. Collins et al., Phys. Lett. B 771 (2017) 213-221 (CLAS)

—— BnGa-2019

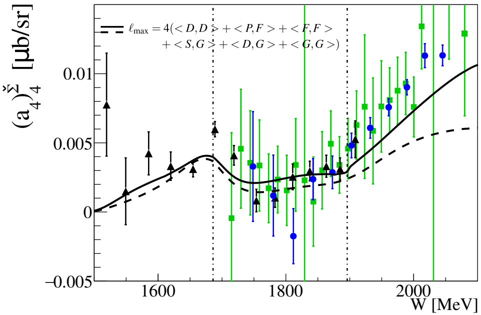
- - - BnGa-2014-02

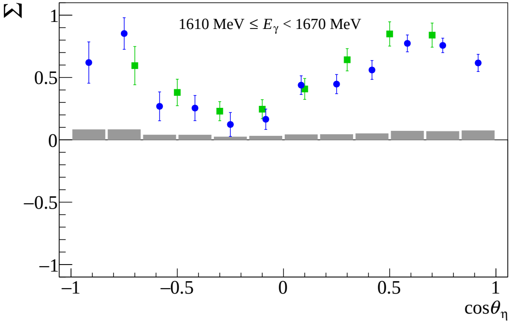
F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)

Full angular coverage is very important for $< S, G >$ interference

Dominant partial wave contributions (Σ (CBELSA/TAPS), $\gamma p \to p\eta$)

$$\check{\Sigma}(W, \cos\theta) = \Sigma(W, \cos\theta) \cdot \frac{d\sigma}{d\Omega}(W, \cos\theta) = \sum_{k=2}^{2L_{max}} (a_L(W))_k \cdot P_k^2(\cos\theta)$$





3 (2007) 169)

. (CLAS)

Full angular coverage is very important for $< S, G >$ interference

E_{0+} multipole of $p\eta$

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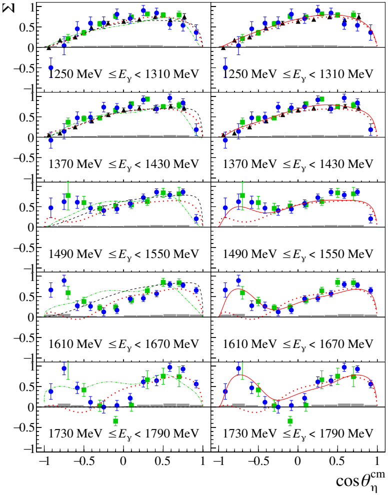
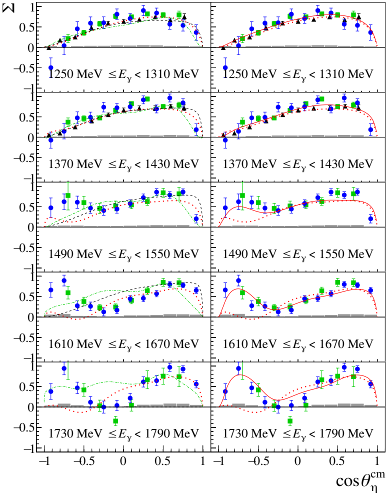
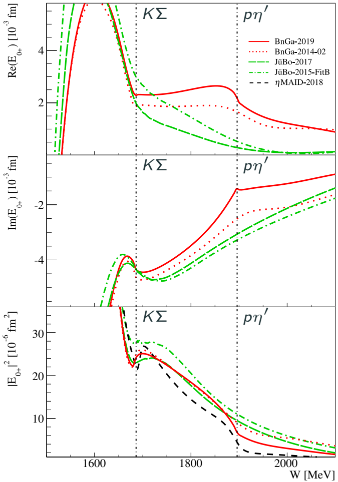


F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)





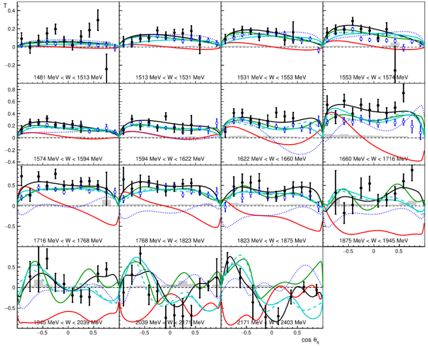
- PWA predictions (BnGa, JüBo, ηMAID) can not describe backward peak in data!
- New fits of BnGa and ηMAID have included the $p\eta'$ cusp in the S wave
- However, JüBo does not!

F. Afzal et al., Phys. Rev. Lett. 125, 152002 (2020)

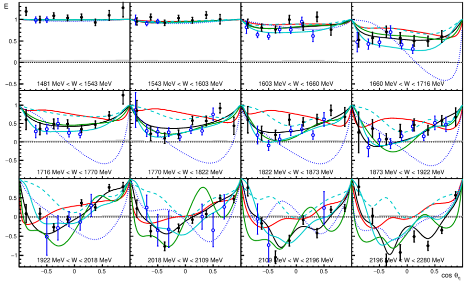
$N^* \to p\eta$ branching ratios

Combined analysis of the polarization observables σ, G, E, T, P, H in $\gamma p \to p\eta$ [J. Mueller et al., Phys. Lett. B 803 (2020), p. 135323]

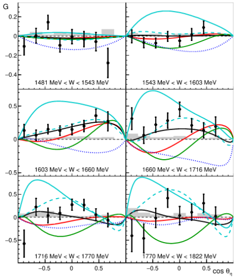
lin. pol. photons & transv. pol. target



circ. pol. photons & long. pol. target



lin. pol. photons & long. pol. target



BnGa refit — BnGa-2011-02 — JüBo2015-3 — JüBo2015 — SAID (GE09) — MAID2018

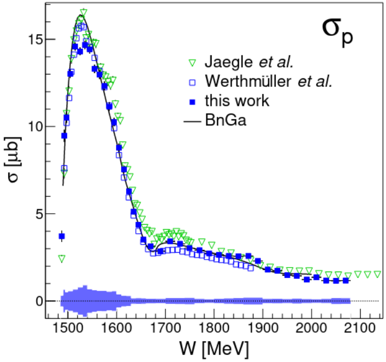
	$N(1535)\frac{1}{2}^-$	$N(1650)\frac{1}{2}^-$
BnGa refit	0.41 ± 0.04	0.33 ± 0.04
PDG 2017	$0.32 - 0.52$	$0.14 - 0.22$

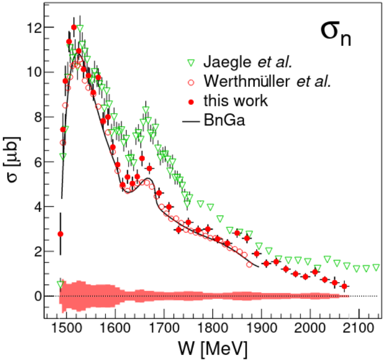
Large and heavily discussed difference in the $p\eta$-branching ratio of $N(1535)\frac{1}{2}^-$ and $N(1650)\frac{1}{2}^-$ now significantly reduced!

η photoproduction off neutrons

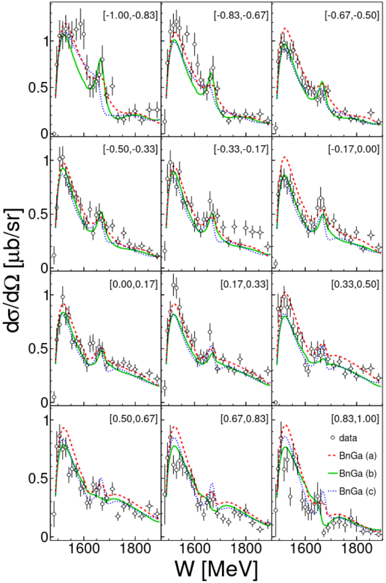
- Complicated to measure due to no free neutrons → helium, deuterium, deuterated butanol targets
- Nuclear Fermi motion effects eliminated by a complete kinematic reconstruction of the final state
- FSI estimated through comparison of quasi-free and free proton data

L. Witthauer et al., Eur. Phys. J. A (2017) 53:58





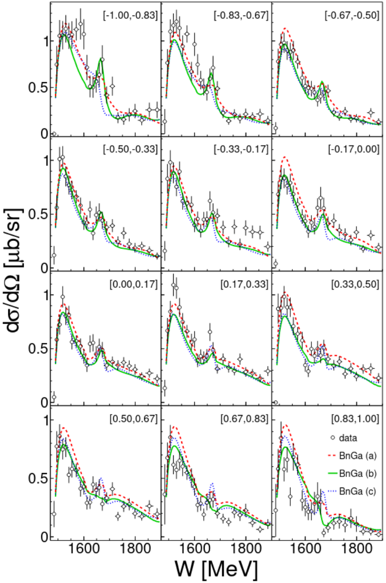
Measurements off neutrons - Narrow structure in $n\eta$



Narrow peak observed in $\gamma n \to n\eta$

at $W = (1670 \pm 5)$ MeV with $\Gamma = (30 \pm 15)$ MeV

[L. Witthauer et al., Eur. Phys. J. A (2017) 53:58]



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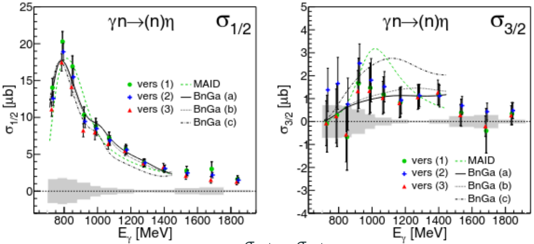

Helicity asymmetry: $E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$

Spin dependent cross sections

$\sigma_{1/2(3/2)} = \sigma_0 \cdot (1 \pm E)$

Structure only present in $\sigma^{n}_{1/2}$!

Intrinsic resonance/ interference effects?

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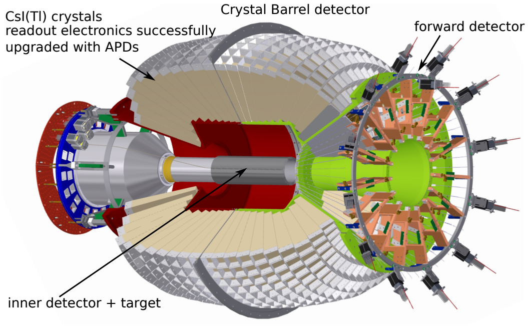
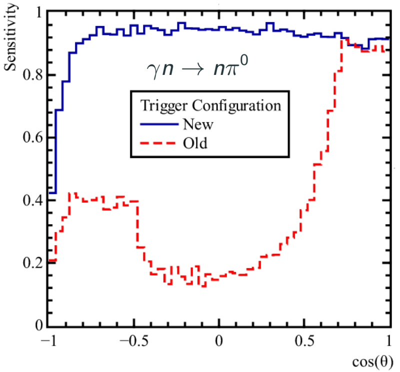
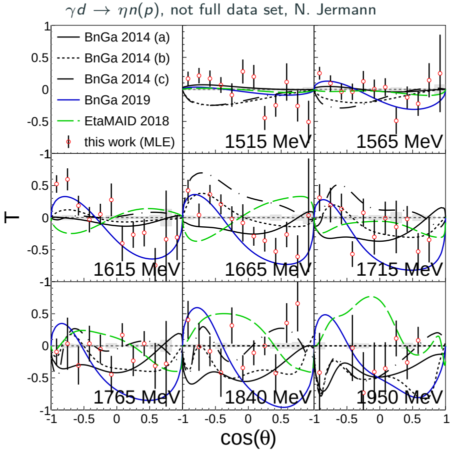
- Each CsI(Tl) crystal readout with 2 APDs instead of PIN photodiodes
- Crystal Barrel $\theta > 12^\circ$ included in first level trigger
- high trigger acceptance for complete neutral final states

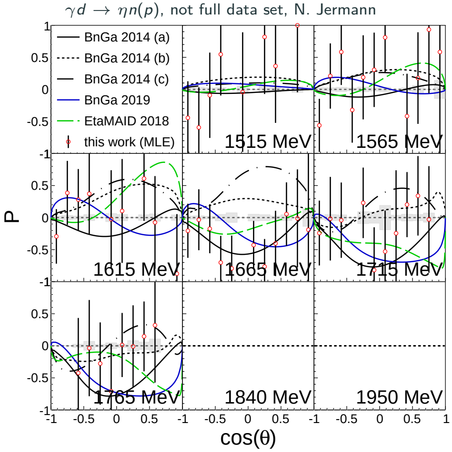


[C. Honisch et al., to be submitted soon]



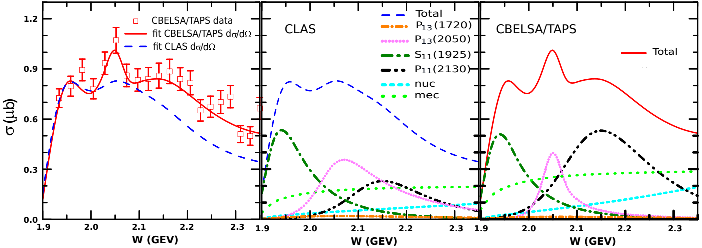
- More data taken for T, P, H with coherent edges at 1300 MeV, 1600 MeV
- Selection of exclusive reaction possible now





η' photoproduction off protons

$p\eta'$ photoproduction - cross section data



Huang et al., arXiv:1208.2279v1, (2012)

F. Huang, H. Haberzettl, and K. Nakayama Phys. Rev. C 87, 054004, 2013

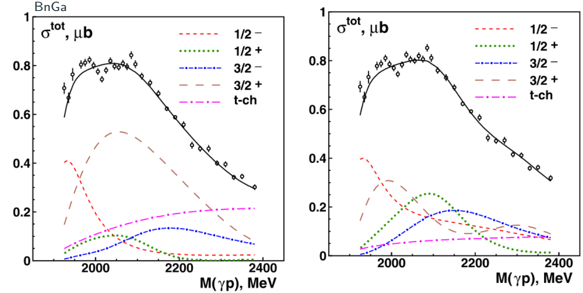
○CBELSA/TAPS: V. Crede et al., Phys. Rev. C80 (2009), p. 055202

○CLAS: M. Williams et al., Phys. Rev. C 80 (2009), p. 045213

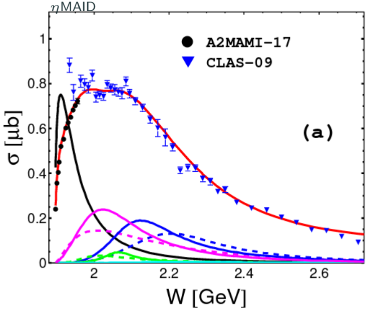
●A2-MAMI: V.L. Kashevarov et al., Phys.Rev.Lett. 118.21 (2017)

main contributions from (BnGa):

$N(1895)\frac{1}{2}^-(S_{11})$, $N(1900)\frac{3}{2}^+(P_{13})$, $N(2100)\frac{1}{2}^+(P_{11})$, $N(2120)\frac{3}{2}^-(D_{13})$



BnGa: A.V. Anisovich et al., Phys.Lett. B 772 (2017) 247-252



ηMAID2018: L. Tiator et al., Eur. Phys. J. A 54.12 (2018)

Beam asymmetry in $p\eta'$ photoproduction (GRAAL and CLAS data)

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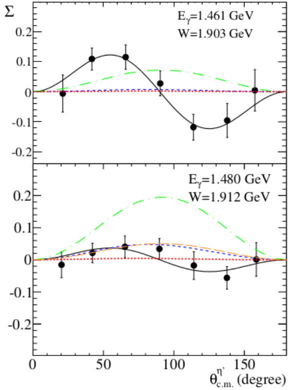
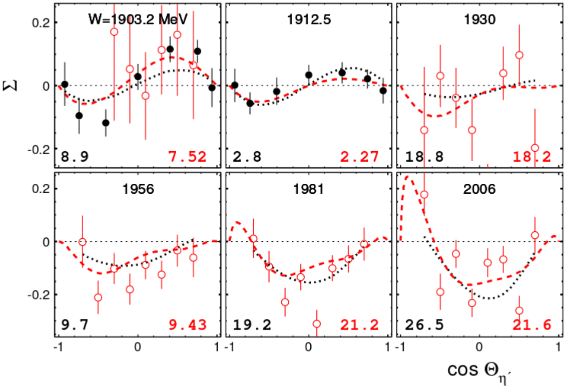
- Unexpected strong angular dependence observed near threshold (W=1896MeV) in GRAAL data
- Angular dependence sensitive to $< P, D >$, $< S, F >$ and $< D, F >$ interference terms
- Angular dependence described by introducing a narrow resonance:
  BnGa: $N(1900)\frac{3}{2}^{-}(D_{13})$ or $N(1900)\frac{5}{2}^{-}(D_{15})$ A.V. Anisovich et al., Phys.Lett.B 785 (2018) 626-630
  ηMAID2018: $N(1902)\frac{1}{2}^{-}(S_{11})$ L. Tiator et al., Eur. Phys. J. A 54.12 (2018)

GRAAL: P.L. Sandri et al., Eur.Phys. J. A 51.7 (2015), p. 77



ηMAID2018: L. Tiator et al., Eur. Phys. J. A 54.12 (2018)



● GRAAL

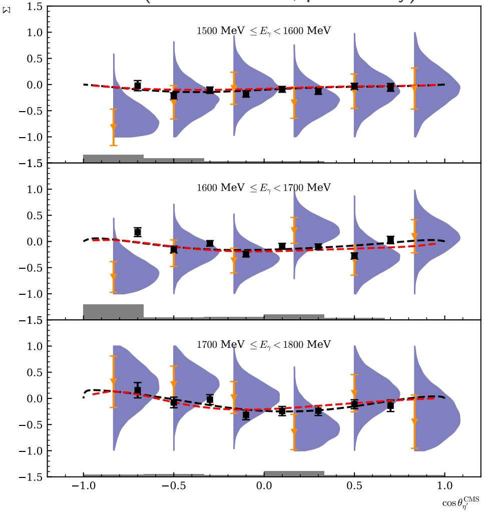
○ CLAS
[P. Collins et al., Phys. Lett. B 771 (2017), pp. 213-221]

— — — ηMAID2018
· · · BnGa

Beam asymmetry in $p\eta'$ photoproduction (CBELSA/TAPS data)

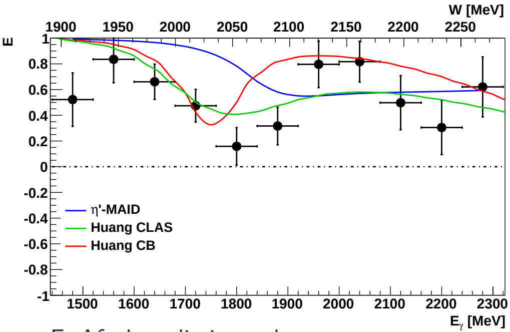
- $\eta' \to \gamma\gamma$ (BR: 2.2%)
- 8000 selected events
- Unbinned maximum likelihood fit used to get Σ
- comparison between Frequentist and Bayesian approach:
  $p(\Sigma, a, b, \Sigma^{bg}, a^{bg}, b^{bg}|\phi, p_\gamma) \propto$
  $\mathcal{L}(\phi, p_\gamma|\Sigma, a, b, \Sigma^{bg}, a^{bg}, b^{bg}) \cdot$
  $\pi(\Sigma, a, b, \Sigma^{bg}, a^{bg}, b^{bg})$
- Good agreement between CBELSA/TAPS (▲) and CLAS (■)
- BnGa (— — —) and ηMAID2018 (— — —) can describe data

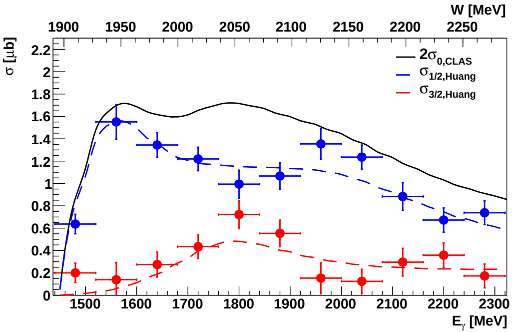
J. Krause (Master's thesis, preliminary)



Helicity asymmetry in $p\eta'$ photoproduction (CBELSA/TAPS)

- Helicity asymmetry obtained with circ. pol. photon beam and long. pol. target
- Strong contribution to $\sigma_{1/2} \rightarrow$ strong contributions from S_{11} an d P_{11} waves
- Significant contributions to $\sigma_{3/2}$ at W=2050 MeV





F. Afzal, preliminary data

- Outlook: More data for T, P, H will be analyzed!

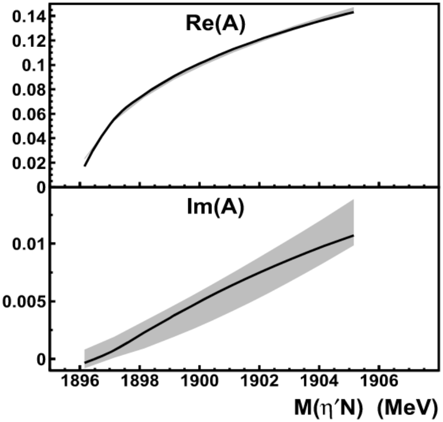
$p\eta'$ scattering length

- Are $\eta' p$ bound states possible?
- Real and imaginary part of the S_{11} amplitude were fit by BnGa using

$$A = \frac{ak}{1 - ika + Rk^2 a/2 + dk^4 a} \qquad k = \frac{\sqrt{(s-(M_p+M_{\eta'})^2)(s-(M_p-M_{\eta'})^2)}}{2\sqrt{s}}$$

$a = a_{p\eta'}$: $p\eta'$ scattering length
R: range of the $\eta' p$ interaction
d: parameter representing higher-order terms
$\sqrt{s} = M_{\eta' p}$: invariant mass
k: η' momentum in the $\eta' p$ rest frame

- $|a_{p\eta'}| = (0.403 \pm 0.020 \pm 0.060)$ fm
- $\delta_{N\pi} = (87 \pm 2)^\circ$
  $\rightarrow$ real part of the scattering length is small compared to imaginary part
  $\rightarrow$ disfavors $\eta' p$ bound states



BnGa: A.V. Anisovich et al., Phys.Lett.B 785 (2018) 626-630

Impact of photoproduction data on PDG in the last two decades

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Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***	-			-		
$N(1520)$	$3/2^-$	****	****	****	****	**	****			- - - -		
$N(1535)$	$1/2^-$	****	****	****	***	*	****			- -		
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*- -	- -	- -		
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*	-		
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*	- - - -		
$N(1700)$	$3/2^-$	***	**	***	***	*	*	- -	-	-		
$N(1710)$	$1/2^+$	****	****	****	*-		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*-	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**	-	*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*-	**	*	*	-	-	- -	*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

- mostly πN data were used until 2010
- photoproduction data is now used by most PWA groups and new fit values for resonance parameters have entered the PDG
- Still a lot of work to do!
- More information in
  A. Thiel, F. Afzal, Y. Wunderlich, Prog. Part. Nucl. Phys. 125 (2022) 103949

Summary and Outlook

Summary and Outlook

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Summary:

- High precision polarization data measured at the CBELSA/TAPS experiment for $p\eta$ final state
  $\rightarrow$ Sensitivity up to G-waves reached! $p\eta'$ cusp observed in the beam asymmetry Σ data!
- Significant contributions to confirming poorly known states like $N(1895)\frac{1}{2}^-$
  $\rightarrow$ Upgraded to a 4star resonance in PDG
- Improved precision of resonance properties $\rightarrow$ BR
  $\rightarrow$ Our knowledge of the spectrum and the properties of baryons is steadily increasing!
- Still a lot of interesting, not understood observations, like narrow structure in $n\eta$
- Beam and helicity asymmetry extracted for the $p\eta'$ final state
- $p\eta'$ scattering length results disfavors $\eta' p$ bound states

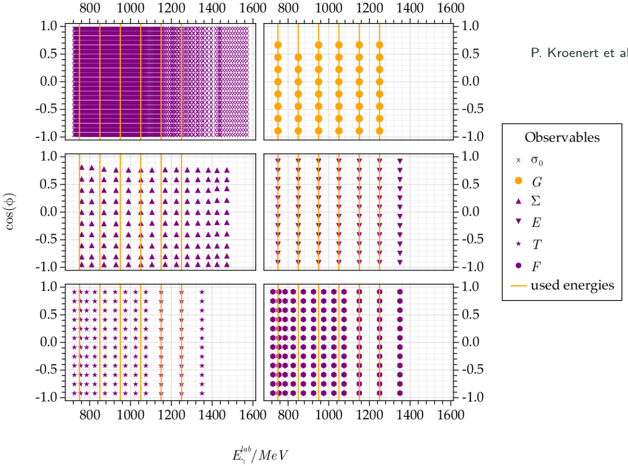
Outlook:

- APD-Upgrade of the Crystal Barrel detector at the CBELSA/TAPS experiment successfully completed
  $\rightarrow$ Ongoing analysis of different final states ($N\pi^0, N\eta, N\eta', N\omega, N\pi^0\pi^0, N\pi^0\eta$...) and PWA of the data

Truncated PWA using "complete" data set of polarization observables

Goal: Extract multipoles model independent

- 6 single energy fits from threshold, 750 MeV to 1250 MeV
- Complete data set ($\sigma_{0,\mathrm{MAMI}}$, T_{MAMI}, F_{MAMI}, E_{MAMI}, Σ_{GRAAL}, $G_{\mathrm{CBELSA/TAPS}}$)

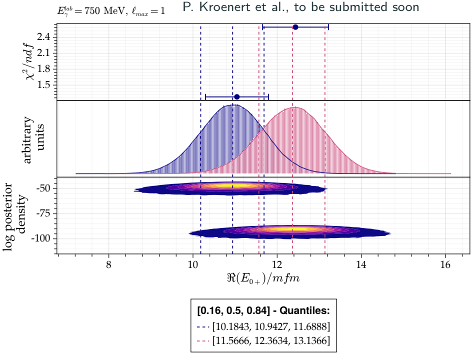


P. Kroenert et al., to be submitted soon

Truncated PWA using ”complete” data set of polarization observables

Method:

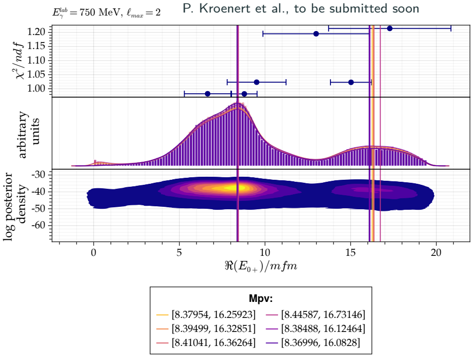
- Fit the angular distributions of observables, parametrized by
  $\check{\Omega}^{\alpha}_{\text{theo}}(W,\theta) = \rho \sum_{k=\beta_\alpha}^{2\ell_{\max}+\beta_\alpha+\gamma_\alpha} \mathcal{A}^{\alpha}_{k}(W)\, P^{\beta_\alpha}_{k}(\cos\theta)$
- Frequentist Ansatz: Minimize the function
  $\chi^2_{\mathcal{M}} = \sum_{i,j} \left[(a^{\text{Fit}}_L)_i - < \mathcal{M}_\ell|(C_L)_i|\mathcal{M}_\ell >\right] C^{-1}_{ij} \left[(a^{\text{Fit}}_L)_i - < \mathcal{M}_\ell|(C_L)_i|\mathcal{M}_\ell >\right]$
- Bayesian Ansatz:
  $p(\boldsymbol{\Theta} \mid \boldsymbol{y}) = p(\boldsymbol{y} \mid \boldsymbol{\Theta})\, \pi(\boldsymbol{\Theta})$
- Conditional likelihood distribution
- Priors $\pi(\boldsymbol{\Theta})$: broad uniform distributions for multipoles
- Monte Carlo maximum likelihood estimation
- Extract multipoles at single energies



Truncated PWA using "complete" data set of polarization observables

Method:

- Fit the angular distributions of observables, parametrized by $\check{\Omega}^{\alpha}_{\text{theo}}(W,\theta) = \rho \sum_{k=\beta_\alpha}^{2\ell_{\text{max}}+\beta_\alpha+\gamma_\alpha} \mathcal{A}^{\alpha}_{k}(W)\; P^{\beta_\alpha}_{k}(\cos\theta)$
- Frequentist Ansatz: Minimize the function $\chi^2_{\mathcal{M}} = \sum_{i,j} \left[(a^{\text{Fit}}_L)_i - < \mathcal{M}_\ell | (C_L)_i | \mathcal{M}_\ell > \right] C^{-1}_{ij} \left[(a^{\text{Fit}}_L)_i - < \mathcal{M}_\ell | (C_L)_i | \mathcal{M}_\ell > \right]$
- Bayesian Ansatz: $p(\mathbf{\Theta} \mid \boldsymbol{y}) = p(\boldsymbol{y} \mid \mathbf{\Theta})\; \pi(\mathbf{\Theta})$
- Conditional likelihood distribution
- Priors $\pi(\mathbf{\Theta})$: broad uniform distributions for multipoles
- Monte Carlo maximum likelihood estimation
- Extract multipoles at single energies



Truncated PWA using complete data set of polarization observables

Results: