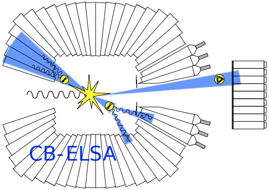
Multi-Meson Photoproduction off the Proton

Recent Results from the CBELSA/TAPS Experiment

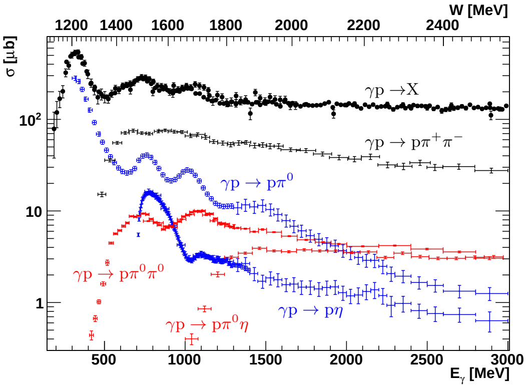
Nils Stausberg

25th June 2024

University of Bonn



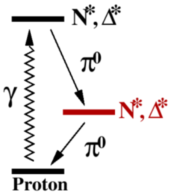
Why Multi-Meson Photoproduction?



Photoproduction as excellent tool for baryon spectroscopy!

Because...

- increasingly important at high E_γ
- sensitive to sequential decays



e.g. N^*/Δ^*

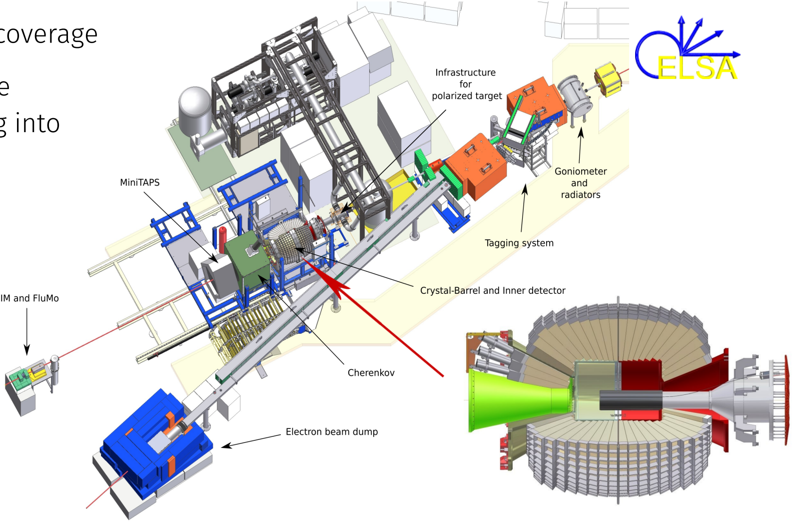
$$\rightarrow N(1520)\frac{3}{2}^{-}\pi^0$$

$$\rightarrow p\pi^0\pi^0$$

Less background amplitudes for $p\pi^0\pi^0$ and $p\pi^0\eta$ compared to $\boldsymbol{p\pi^+\pi^-}$.

CBELSA/TAPS EXPERIMENT

- Nearly 4π solid angular coverage
- Ideally suited to measure neutral mesons decaying into photons
- Polarized beam and target
  → Polarization observables

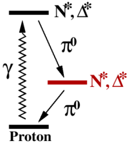


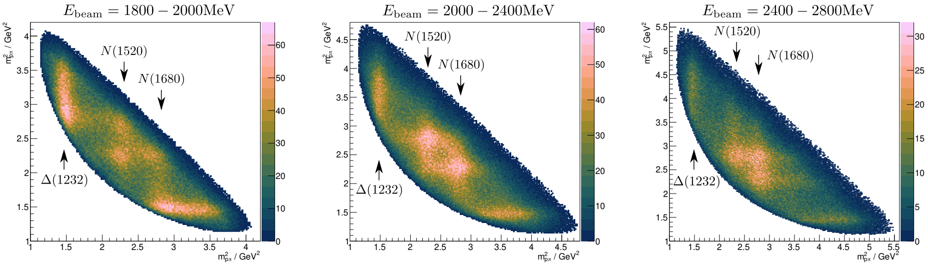
Crystal Barrel calorimeter

SEQUENTIAL DECAYS IN DALITZ PLOTS

$\gamma p \rightarrow p\pi^0\pi^0$

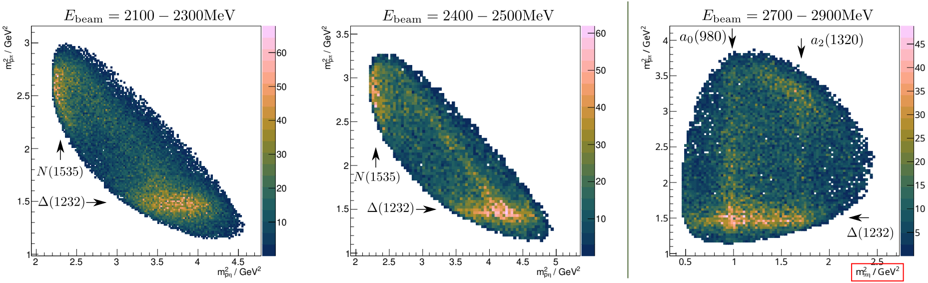
[P. Mahlberg, Bonn]





$\gamma p \rightarrow p\pi^0\eta$

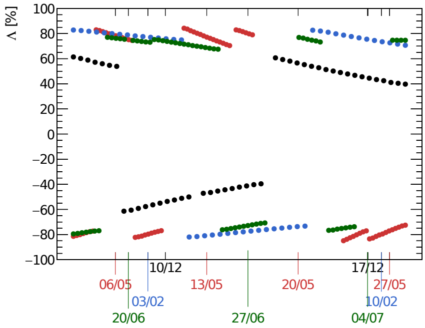
[G. Urff, Bonn]



MEASUREMENT WITH (DOUBLE) POLARIZATION

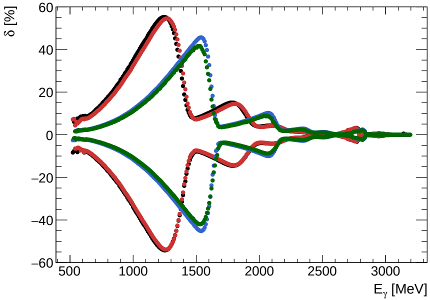
Transverse Pol. Target

Pol. using the Mainz-Dubna Frozen Spin target with Butanol as target material.



Linear Pol. Beam

Pol. via coherent bremsstrahlung with different settings of the diamond radiator.



Dec2017 May2018 Feb2019 Jun2021

POLARIZATION OBSERVABLES FOR $\gamma p \rightarrow p\pi^0\pi^0$

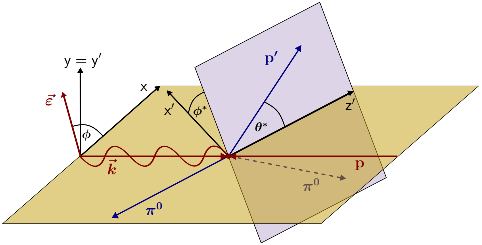
Polarization Observables (linear pol. beam + transverse pol. target)

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \cdot \Big(1 + \Lambda_x \cdot P_x + \Lambda_y \cdot P_y + \delta_l \sin(2\phi) \cdot I^s + \delta_l \cos(2\phi) \cdot I^c$$
$$+ \Lambda_y \delta_l \sin(2\phi) \cdot P^s_y + \Lambda_x \delta_l \sin(2\phi) \cdot P^s_x$$
$$+ \Lambda_x \delta_l \cos(2\phi) \cdot P^c_x + \Lambda_y \delta_l \cos(2\phi) \cdot P^c_y\Big)$$

Target ($\mathcal{T}$), Beam ($\mathcal{B}$) and Beam + Target ($\mathcal{BT}$) polarization

The reaction can be described by
5 kinematic variables:

$$\underbrace{\underbrace{E_\gamma \quad \cos(\theta_{\pi^0})}_{\text{2-body}} \quad m_{p\pi^0} \quad \phi^*_{p\pi^0} \quad \theta^*_p}_{\text{3-body}}$$



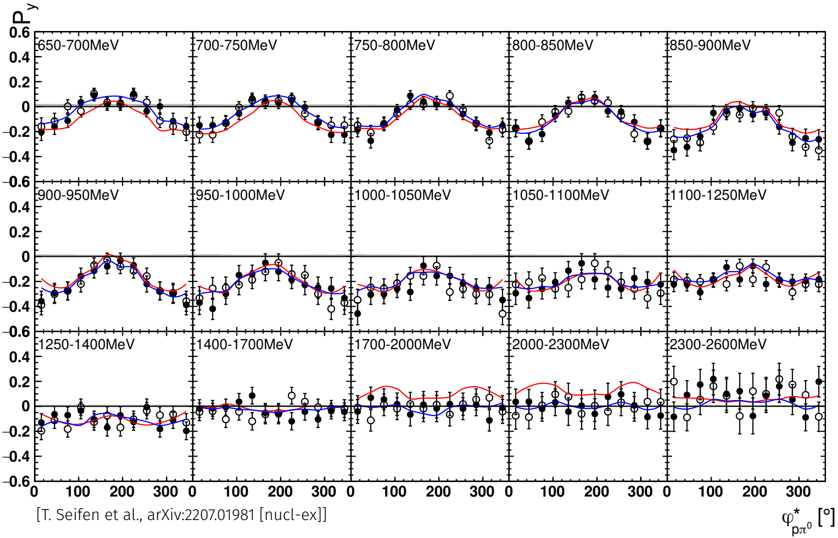
TARGET ASYMMETRY $P_y(\phi^*_{p\pi^0})$ FOR BINS IN E_γ

BnGa 2014-02

BnGa 2022-02 (fitted)

○ ●

Systematic check via symmetry relation $P_y(2\pi - \phi^*) = P_y(\phi^*)$



[T. Seifen et al., arXiv:2207.01981 [nucl-ex]]

TARGET ASYMMETRY $P_y(\phi^*_{p\pi^0})$ FOR BINS IN E_γ

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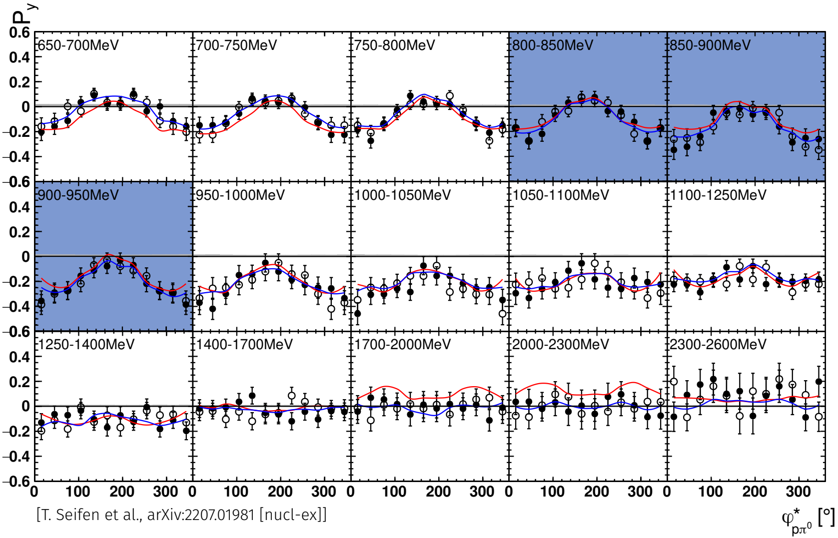


[T. Seifen et al., arXiv:2207.01981 [nucl-ex]]

4D-TARGET ASYMMETRY $P_y(\phi^*_{p\pi^0})$ FOR $E = 800\,\text{MeV} - 950\,\text{MeV}$

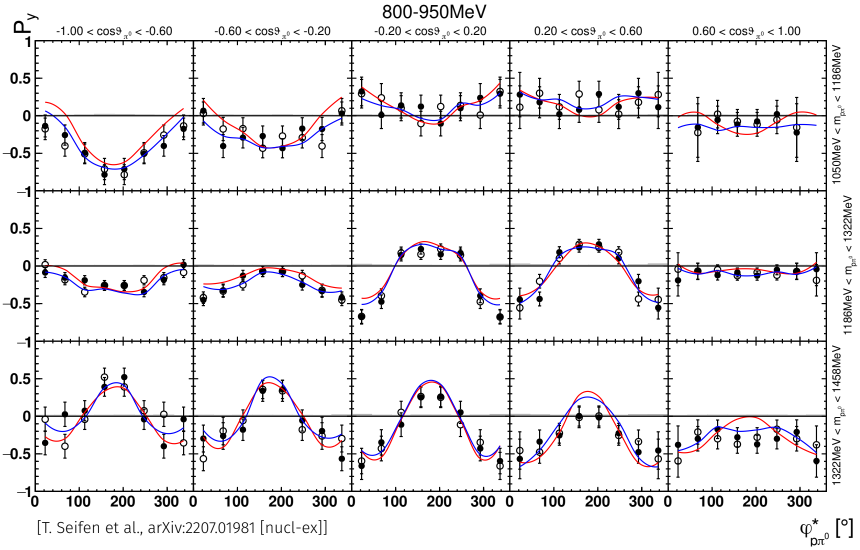
BnGa 2014-02

BnGa 2022-02 (fitted)

○ ●

Systematic check via symmetry relation

$$P_y(2\pi - \phi^*) = P_y(\phi^*)$$



[T. Seifen et al., arXiv:2207.01981 [nucl-ex]]

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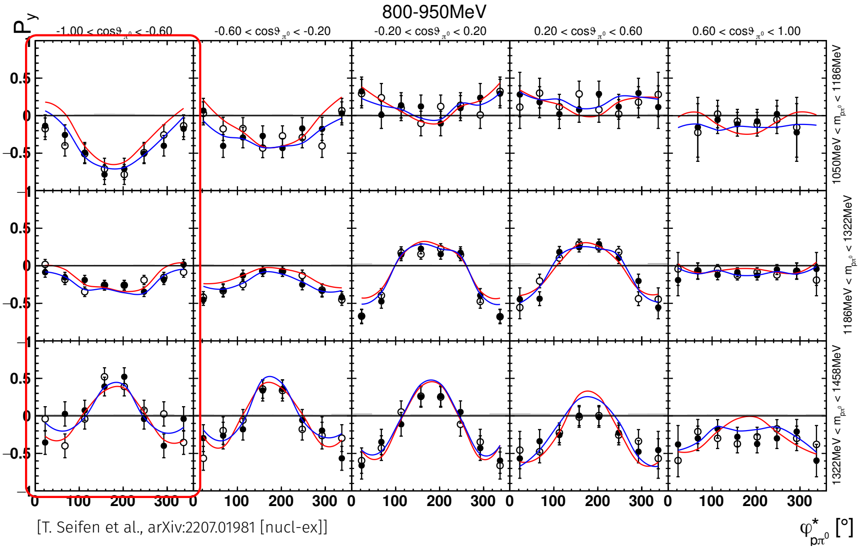

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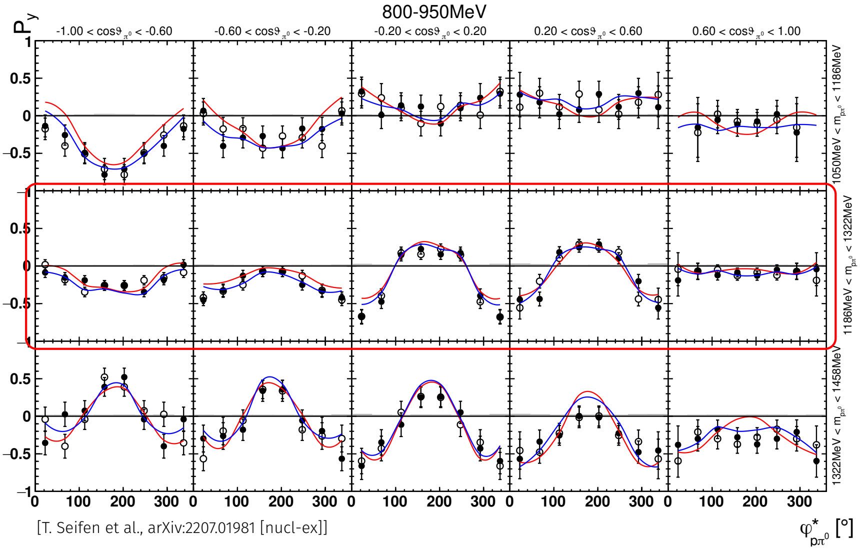

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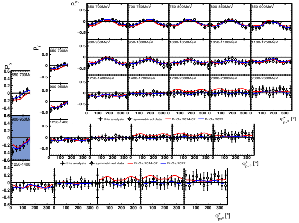
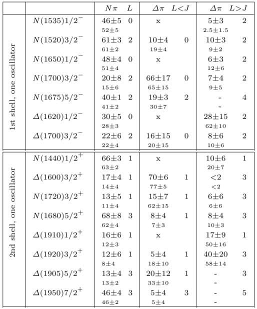
FROM DATA TO RESONANCE PARAMETERS



Data

Partial Wave Analysis (PWA)



		$N\pi$	L	$\Delta\pi$	$L<J$	$\Delta\pi$	$L>J$
1st shell, one oscillator	$N(1535)1/2^-$	46±5 52±5	0	x		5±3 2.5±1.5	2
	$N(1520)3/2^-$	61±3 61±2	2	10±4 19±4	0	10±3 9±2	2
	$N(1650)1/2^-$	48±4 51±4	0	x		6±3 12±6	2
	$N(1700)3/2^-$	20±8 15±6	2	66±17 65±15	0	7±4 9±5	2
	$N(1675)5/2^-$	40±1 41±2	2	19±3 30±7	2	- -	4
	$\Delta(1620)1/2^-$	30±5 28±3	0	x		28±15 62±10	2
	$\Delta(1700)3/2^-$	22±6 22±4	2	16±15 20±15	0	8±6 10±6	2
2nd shell, one oscillator	$N(1440)1/2^+$	66±3 63±2	1	x		10±6 20±7	1
	$\Delta(1600)3/2^+$	17±4 14±4	1	70±6 77±5	1	<2 <2	3
	$N(1720)3/2^+$	13±5 11±4	1	15±7 62±15	1	6±6 6±6	3
	$N(1680)5/2^+$	68±8 62±4	3	8±4 7±3	1	8±4 10±3	3
	$\Delta(1910)1/2^+$	16±6 12±3	1	x		17±9 50±16	1
	$\Delta(1920)3/2^+$	12±6 8±4	1	5±4 18±10	1	40±20 58±14	3
	$\Delta(1905)5/2^+$	13±4 13±2	3	20±12 33±10	1	- -	3
	$\Delta(1950)7/2^+$	46±4 46±2	3	5±4 5±4	3	- -	5

Resonance Parameters

Branching Ratios & Interpretation in Harmonic Oscillator Model

$\Delta(1910)\frac{1}{2}^+$, $\Delta(1920)\frac{3}{2}^+$, $\Delta(1905)\frac{5}{2}^+$, $\Delta(1950)\frac{7}{2}^+$

BR into ground state: $(44 \pm 7)\,\%$

$N\pi^0$, $\Delta(1232)\pi^0$

BR into excited states (with L=1): $(5 \pm 2)\,\%$

$N(1520)\pi^0$, $N(1535)\pi^0$, $N\sigma$

$N(1880)\frac{1}{2}^+$, $N(1900)\frac{3}{2}^+$, $N(2000)\frac{5}{2}^+$, $N(1990)\frac{7}{2}^+$

BR into ground state: $(34 \pm 6)\,\%$

$N\pi^0$, $\Delta(1232)\pi^0$

BR into excited states (with L=1): $(21 \pm 5)\,\%$

$N(1520)\pi^0$, $N(1535)\pi^0$, $N\sigma$

BRANCHING RATIOS & INTERPRETATION IN HARMONIC OSCILLATOR MODEL

$\Delta(1910)\frac{1}{2}^+$, $\Delta(1920)\frac{3}{2}^+$, $\Delta(1905)\frac{5}{2}^+$, $\Delta(1950)\frac{7}{2}^+$

BR into ground state: **(44 ± 7) %**

$N\pi^0$, $\Delta(1232)\pi^0$

BR into excited states (with L=1): (5 ± 2) %

$N(1520)\pi^0$, $N(1535)\pi^0$, $N\sigma$

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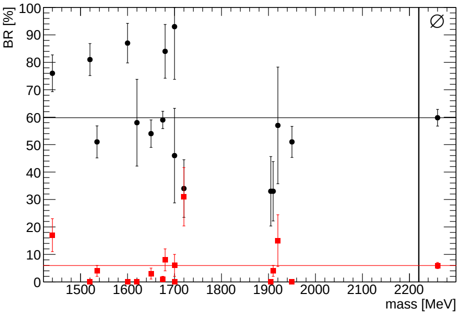

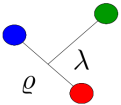

One-oscillator excitation → ground state

One-oscillator excitation → excited states

$$S = \frac{1}{2}\left([0s \times 0d] + [0d \times 0s]\right)^{(L=2)}$$

Branching Ratios & Interpretation in Harmonic Oscillator Model

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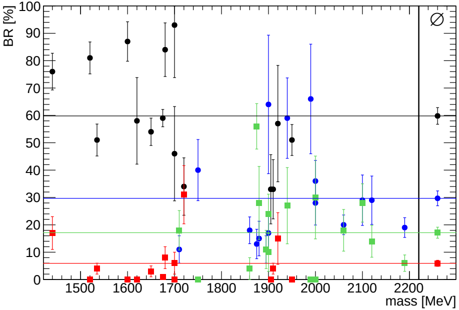

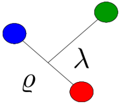

Mixed-oscillator excitations → ground state

Mixed-oscillator excitations → excited states

$$M_S = \frac{1}{2}\left([0s \times 0d] - [0d \times 0s]\right)^{(L=2)}$$

$$M_A = -\frac{1}{2}[0p \times 0p]^{(L=2)}$$

BRANCHING RATIOS & INTERPRETATION IN HARMONIC OSCILLATOR MODEL

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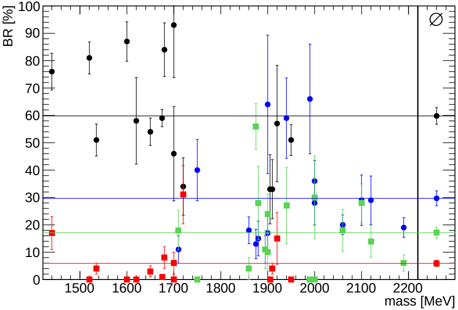
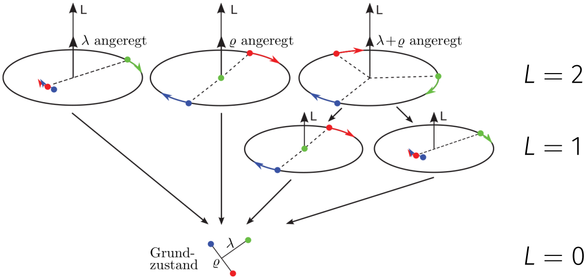




SINGLE POLARIZATION P_y - NEW DATA FOR $\gamma p \rightarrow p\pi^0\pi^0$

4D-Target Asymmetry

$P_y(\phi^*_{p\pi^0})$ for

$E = 1400\ \text{MeV} - 1550\ \text{MeV}$

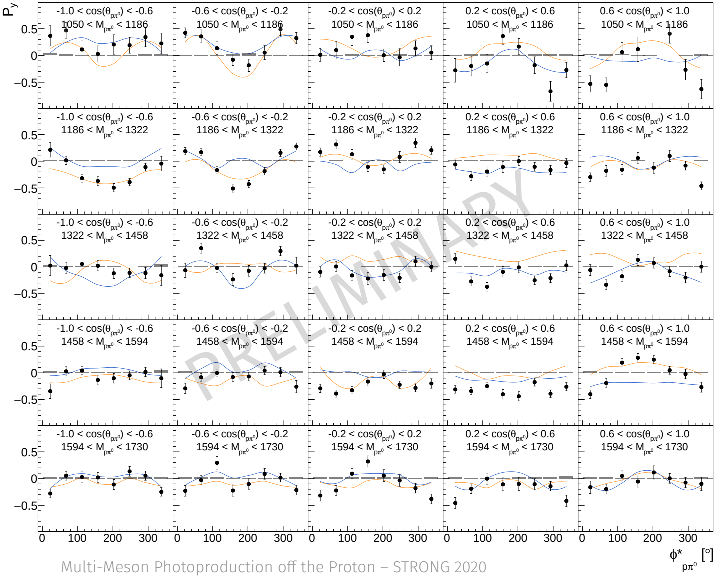
BnGa 2014-02

BnGa 2022-02

New data

Not fitted

[N. Stausberg, Bonn]



DOUBLE POLARIZATION P_y^c - NEW DATA FOR $\gamma p \to p\pi^0\pi^0$

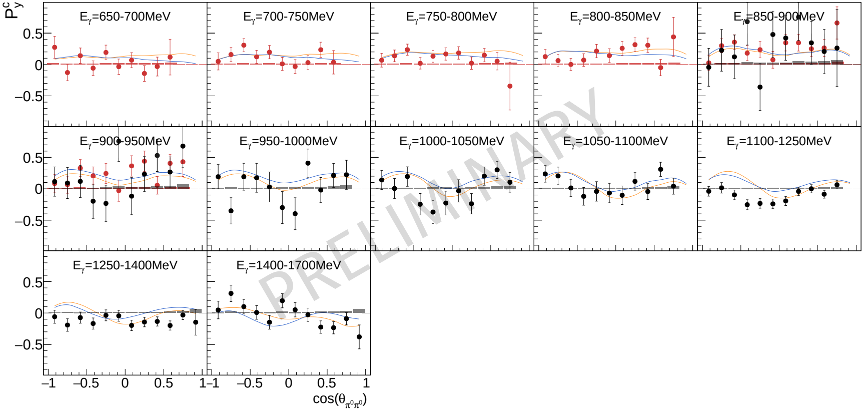
linear pol. beam
+ transverse pol.
target

BnGa 2014-02

BnGa 2022-02

Seifen et al.

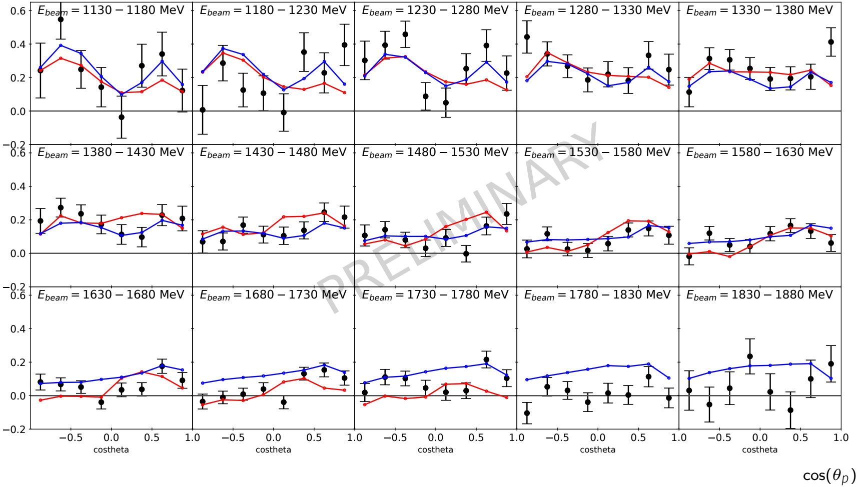
New data
Not fitted
[N. Stausberg, Bonn]



SINGLE POLARIZATION I^c - NEW DATA FOR $\gamma p \to p\pi^0\pi^0$

Attention!

Other beam time with liquid hydrogen target and different coherent edges.



BnGa 2014-02

BnGa 2022-02

New data

Not fitted

[P. Mahlberg, Bonn]

SUMMARY & OUTLOOK

Summary

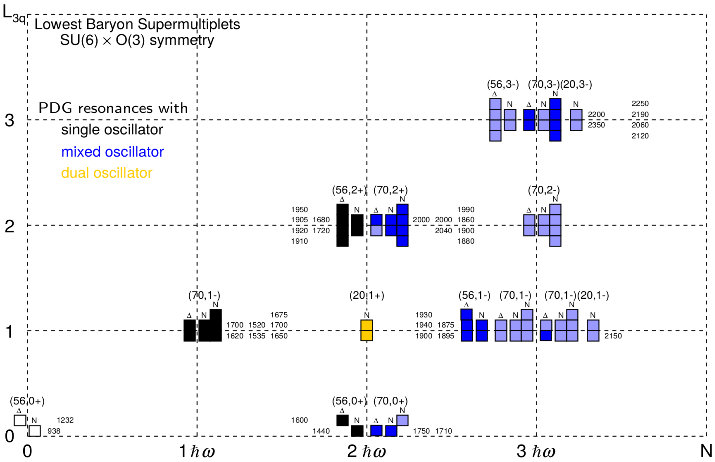
- Multidimensional determination of polarization observables for multi-meson final states essential
- Continuously achieving better precision of resonance parameters
  - BR shows systematics related to the wave function of baryons

Outlook

- Finalizing double polarization observables P_x^c, P_y^c, P_x^s, P_y^s at high energies for $p\pi^0\pi^0$
- Additional data for linear pol. beam and unpol. target
  - Beam polarization observables I^s, I^c at high energies for $p\pi^0\pi^0$ and $p\pi^0\eta$

Thank You

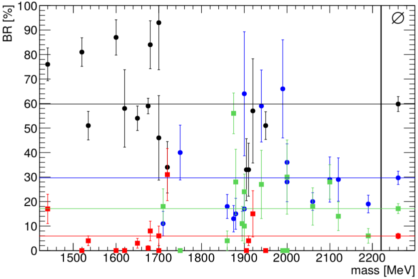
SU(6)×O(3) SUPERMULTIPLETS

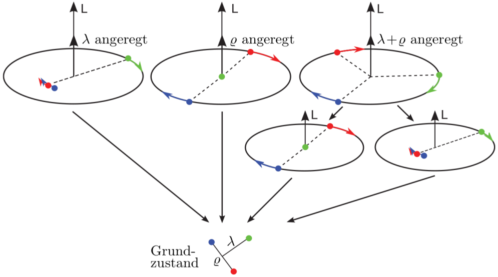


$$N = 2n_\rho + 2n_\lambda + l_\rho + l_\lambda$$

$$L = l_\rho \otimes l_\lambda$$

Branching Ratios & Interpretation in Harmonic Oscillator Model





One-oscillator excitation → ground state

One-oscillator excitation → excited states

Mixed-oscillator excitations → ground state

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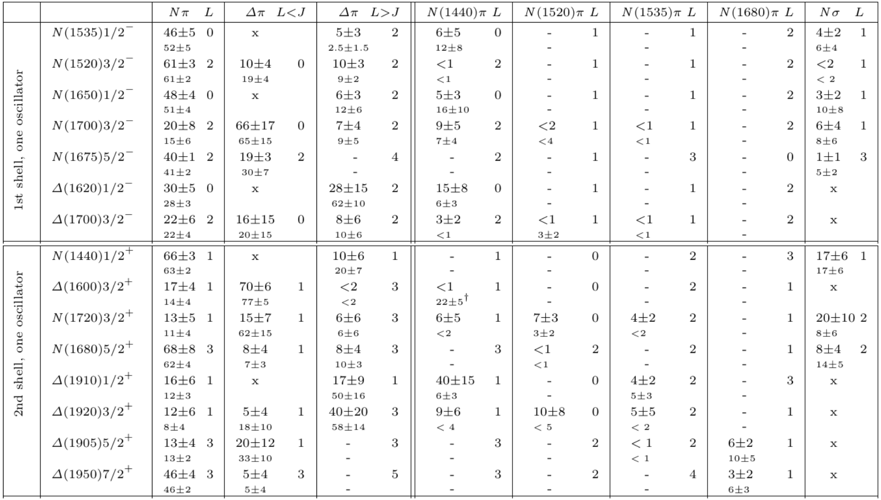
$$S = \frac{1}{2}\left([0s \times 0d] + [0d \times 0s]\right)^{(L=2)}$$

$$M_S = \frac{1}{2}\left([0s \times 0d] - [0d \times 0s]\right)^{(L=2)}$$

$$M_A = -\frac{1}{2}[0p \times 0p]^{(L=2)}$$

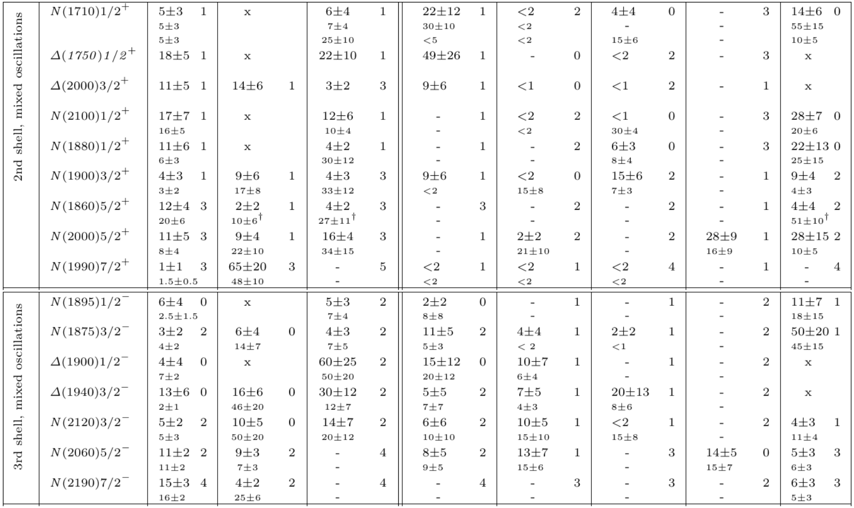
BRANCHING RATIOS



		$N\pi$	L	$\Delta\pi$	$L<J$	$\Delta\pi$	$L>J$	$N(1440)\pi$	L	$N(1520)\pi$	L	$N(1535)\pi$	L	$N(1680)\pi$	L	$N\sigma$	L
1st shell, one oscillator	$N(1535)1/2^-$	46±5	0	x		5±3	2	6±5	0	-	1	-	1	-	2	4±2	1
		52±5				2.5±1.5		12±8		-		-		-		6±4	
	$N(1520)3/2^-$	61±3	2	10±4	0	10±3	2	<1	2	-	1	-	1	-	2	<2	1
		61±2		19±4		9±2		<1		-		-		-		< 2	
	$N(1650)1/2^-$	48±4	0	x		6±3	2	5±3	0	-	1	-	1	-	2	3±2	1
		51±4				12±6		16±10		-		-		-		10±8	
	$N(1700)3/2^-$	20±8	2	66±17	0	7±4	2	9±5	2	<2	1	<1	1	-	2	6±4	1
		15±6		65±15		9±5		7±4		<4		<1		-		8±6	
	$N(1675)5/2^-$	40±1	2	19±3	2	-	4	-	2	-	1	-	3	-	0	1±1	3
		41±2		30±7		-		-		-		-		-		5±2	
	$\Delta(1620)1/2^-$	30±5	0	x		28±15	2	15±8	0	-	1	-	1	-	2	x	
		28±3				62±10		6±3		-		-		-			
	$\Delta(1700)3/2^-$	22±6	2	16±15	0	8±6	2	3±2	2	<1	1	<1	1	-	2	x	
		22±4		20±15		10±6		<1		3±2		<1		-			
2nd shell, one oscillator	$N(1440)1/2^+$	66±3	1	x		10±6	1	-	1	-	0	-	2	-	3	17±6	1
		63±2				20±7		-		-		-		-		17±6	
	$\Delta(1600)3/2^+$	17±4	1	70±6	1	<2	3	<1	1	-	0	-	2	-	1	x	
		14±4		77±5		<2		22±5†		-		-		-			
	$N(1720)3/2^+$	13±5	1	15±7	1	6±6	3	6±5	1	7±3	0	4±2	2	-	1	20±10	2
		11±4		62±15		6±6		<2		3±2		<2		-		8±6	
	$N(1680)5/2^+$	68±8	3	8±4	1	8±4	3	-	3	<1	2	-	2	-	1	8±4	2
		62±4		7±3		10±3		-		<1		-		-		14±5	
	$\Delta(1910)1/2^+$	16±6	1	x		17±9	1	40±15	1	-	0	4±2	2	-	3	x	
		12±3				50±16		6±3		-		5±3		-			
	$\Delta(1920)3/2^+$	12±6	1	5±4	1	40±20	3	9±6	1	10±8	0	5±5	2	-	1	x	
		8±4		18±10		58±14		< 4		< 5		< 2		-			
	$\Delta(1905)5/2^+$	13±4	3	20±12	1	-	3	-	3	-	2	< 1	2	6±2	1	x	
		13±2		33±10		-		-		-		< 1		10±5			
	$\Delta(1950)7/2^+$	46±4	3	5±4	3	-	5	-	3	-	2	-	4	3±2	1	x	
		46±2		5±4		-		-		-		-		6±3			

[T. Seifen et al., arXiv:2207.01981 [nucl-ex]]

Branching Ratios



2nd shell, mixed oscillations	$N(1710)1/2^+$	5±3	1	x		6±4	1	22±12	1	<2	2	4±4	0	-	3	14±6	0
		5±3				7±4		30±10		<2		-		-		55±15	
		5±3				25±10		<5		<2		15±6		-		10±5	
	$\Delta(1750)1/2^+$	18±5	1	x		22±10	1	49±26	1	-	0	<2	2	-	3	x	
	$\Delta(2000)3/2^+$	11±5	1	14±6	1	3±2	3	9±6	1	<1	0	<1	2	-	1	x	
	$N(2100)1/2^+$	17±7	1	x		12±6	1	-	1	<2	2	<1	0	-	3	28±7	0
		16±5				10±4		-		<2		30±4		-		20±6	
	$N(1880)1/2^+$	11±6	1	x		4±2	1	-	1	-	2	6±3	0	-	3	22±13	0
		6±3				30±12		-		-		8±4		-		25±15	
	$N(1900)3/2^+$	4±3	1	9±6	1	4±3	3	9±6	1	<2	0	15±6	2	-	1	9±4	2
		3±2		17±8		33±12		<2		15±8		7±3		-		4±3	
	$N(1860)5/2^+$	12±4	3	2±2	1	4±2	3	-	3	-	2	-	2	-	1	4±4	2
		20±6		10±6†		27±11†		-		-		-		-		51±10†	
	$N(2000)5/2^+$	11±5	3	9±4	1	16±4	3	-	1	2±2	2	-	2	28±9	1	28±15	2
		8±4		22±10		34±15		-		21±10		-		16±9		10±5	
	$N(1990)7/2^+$	1±1	3	65±20	3	-	5	<2	1	<2	1	<2	4	-	1	-	4
		1.5±0.5		48±10		-		<2		<2		<2		-		-	
3rd shell, mixed oscillations	$N(1895)1/2^-$	6±4	0	x		5±3	2	2±2	0	-	1	-	1	-	2	11±7	1
		2.5±1.5				7±4		8±8		-		-		-		18±15	
	$N(1875)3/2^-$	3±2	2	6±4	0	4±3	2	11±5	2	4±4	1	2±2	1	-	2	50±20	1
		4±2		14±7		7±5		5±3		< 2		<1		-		45±15	
	$\Delta(1900)1/2^-$	4±4	0	x		60±25	2	15±12	0	10±7	1	-	1	-	2	x	
		7±2				50±20		20±12		6±4		-		-			
	$\Delta(1940)3/2^-$	13±6	0	16±6	0	30±12	2	5±5	2	7±5	1	20±13	1	-	2	x	
		2±1		46±20		12±7		7±7		4±3		8±6		-			
	$N(2120)3/2^-$	5±2	2	10±5	0	14±7	2	6±6	2	10±5	1	<2	1	-	2	4±3	1
		5±3		50±20		20±12		10±10		15±10		15±8		-		11±4	
	$N(2060)5/2^-$	11±2	2	9±3	2	-	4	8±5	2	13±7	1	-	3	14±5	0	5±3	3
		11±2		7±3		-		9±5		15±6		-		15±7		6±3	
	$N(2190)7/2^-$	15±3	4	4±2	2	-	4	-	4	-	3	-	3	-	2	6±3	3
		16±2		25±6		-		-		-		-		-		5±3	

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COMPARISON OF TARGET ASYMMETRY $P_y(\cos(\theta_{\pi^0\pi^0}))$ FOR BINS IN E_γ $(\mathcal{T})$

Seifen et al.

BnGa 2014-02

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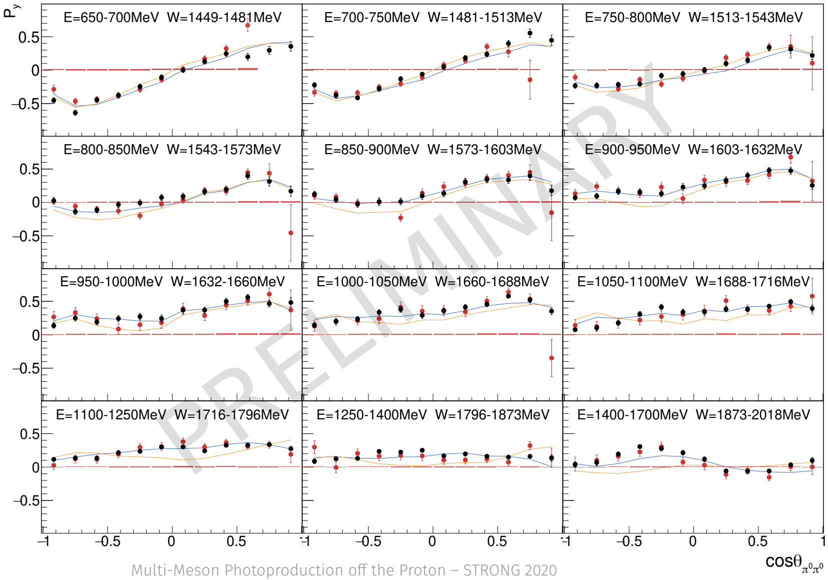
New data



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