Collaborative Research Center 110

"Symmetries and the Emergence of Structure in QCD"

# Status of the Project B.10
# Partial Wave Analysis

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Universities of Bonn, Bochum, München
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IHEP, ITP, CAS, Peking University,
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# People involved

| | Bochum | Bonn |
|---|---|---|
| PIs | Ulrich Wiedner | Ulrike Thoma |
| Senior Scientists | Bertram Kopf | Andrey Sarantsev (75%)<br>Victor Nikonov (75%)<br>Alexei Anisovich (50%) |
| Postdocs | Malte Albrecht<br>Xiaoshuai Qin | |
| Master-students | Iman Keshk,<br>Meike Küßner<br>Jan Reher | |
| Guests | | Maxim Matveev<br>Igor Denisenkov |
| | $\Leftrightarrow$ PAWIAN | $\Leftrightarrow$ Bonn-Gatchina-PWA |

Collaborators:
Eberhard Klempt (BnGa-group, Bonn), Volker Burkert (JLab), ....

# Results: Baryon Spectroscopy

## - A few examples -

# Method: Bonn-Gatchina Partial Wave Analysis

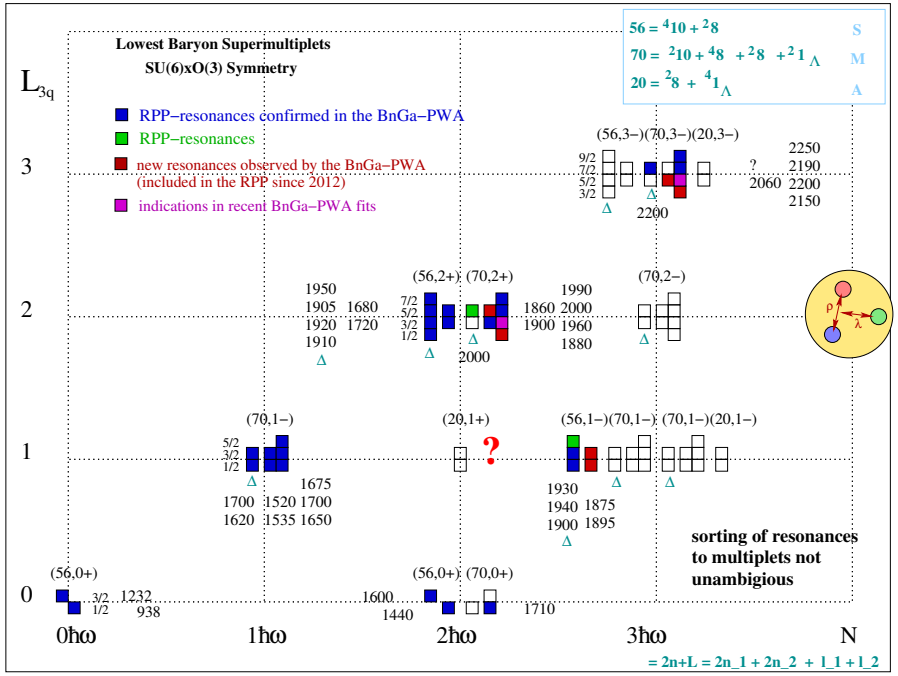
**Aim: - Extraction of resonances and their properties from the data**
**$\Rightarrow$ Reach a good understanding of the bound states of QCD in the non-perturbative regime**

- **Multi-channel partial wave analysis**
  - relativistically invariant formalism
  - s-channel resonances:
    relativistic Breit-Wigner-, Flatte-,
    K-Matrix ampl., N/D-method
  - t-, u-channel amplitudes:
    exchange of Regge-trajectories

- **Event based maximum likelihood fit for multibody final states**
  all correlations between the variables taken into account properly

**Systematics in the spectrum = ?**

- **SU(6)xO(3)-Symmetry ?**




**... or e.g. :**

- **meson-baryon dynamics ...**

# Method: Bonn-Gatchina Partial Wave Analysis

- **Analysis of data from Crystal Barrel/TAPS at ELSA and other labs**

Investigated reactions:

| | | | |
|---|---|---|---|
| $\gamma p \to p\pi^0,\ n\pi^+$ | $\gamma p \to K^+\Lambda$ | $\pi^- p \to \pi^- p$ (elastic) -PW | $\pi^- p \to K^0\Lambda$ |
| $\gamma p \to p\eta$ | $\gamma p \to K^{+/0}\Sigma^{0/+}$ | $\pi^- p \to n\eta$ | $\pi^- p \to K^0\Sigma^0$ |
| $\gamma p \to p\pi^0\pi^0$ | $\gamma p \to n\pi^+$ | $\pi^- p \to n\pi^0\pi^0$ | $\pi^+ p \to K^+\Sigma^+$ |
| $\gamma p \to p\pi^0\eta$ | | | |

+ Photoproduction off the neutron ($\gamma n \to \pi^- p, \pi^0 n, \eta n$)
(+ vector meson photopoduction)

within CRC 110 $\leftrightarrow$ additional data set included:

$\gamma p \to p\pi^+\pi^-$: $\frac{d\sigma}{d\Omega}$, $I^s$, $I^c$ (CLAS, JLab), $\gamma p \to p\pi^0\pi^0$: $T, P, H, \ldots$ (CB, ELSA)

$\pi^- p \to n\pi^+\pi^-, p\pi^-\pi^0$ : $\frac{d\sigma}{d\Omega}$ (HADES, GSI)

$\gamma p \to p\eta$: $T, P, H, E, G$ (CB, ELSA), $\frac{d\sigma}{d\Omega}$, $\Sigma$, $F$ (A2, MAMI) , $\Sigma$ (CB, ELSA, CLAS, JLab)

$\gamma p \to p\eta'$ : $\frac{d\sigma}{d\Omega}$ (CLAS, JLab / A2, MAMI), $\Sigma$ (GRAAL / A2, MAMI)

photoproduction off the neutron:

$\gamma n \to K^0\Lambda$ : $\frac{d\sigma}{d\Omega}$ (CLAS, JLab) $\gamma n \to n\eta$ : $\frac{d\sigma}{d\Omega}$, $E$ (A2,MAMI) $\vec{\gamma}\vec{n} \to \pi^- p$ : $E$ (CLAS, JLab)

Existing $K^-$-beam -data: First fits to investigate of $\Lambda^*$- and $\Sigma^*$-resonances:

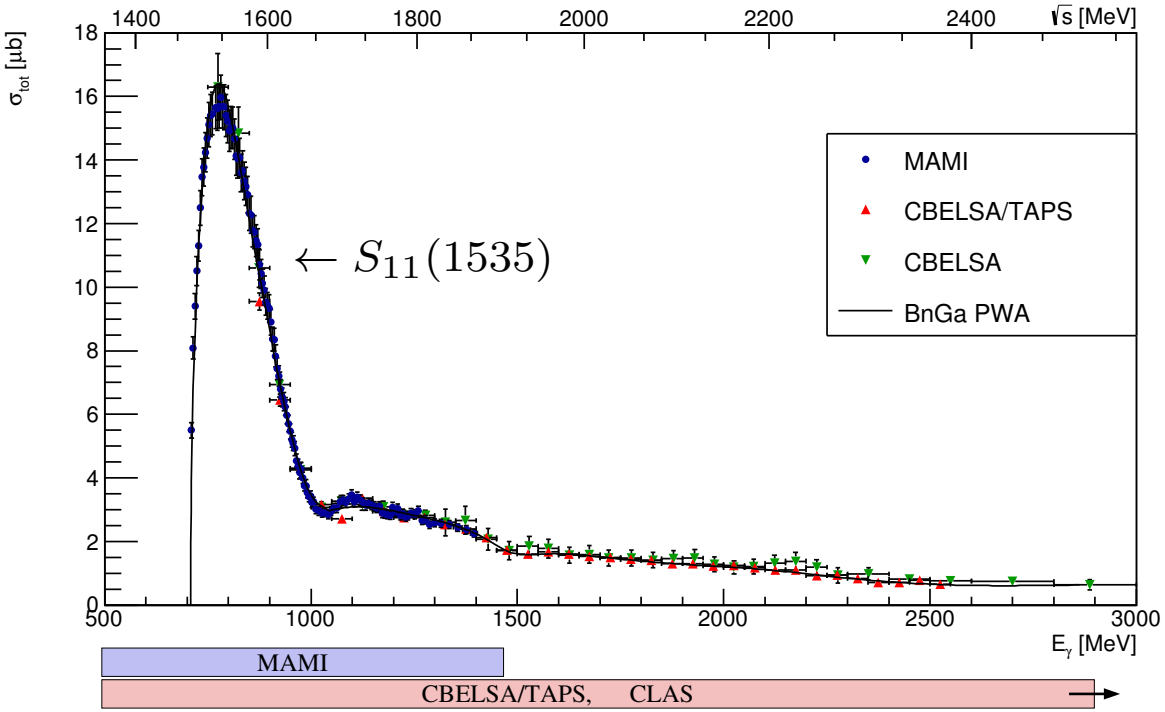
$K^- p \to K^- p,\ \ K^- p \to K^0 n,\ \ K^- p \to \pi^0\Lambda, \eta\Lambda,\ \ K^- p \to \pi^0\Sigma^0,\ \ K^- p \to \pi^\pm\Sigma^\mp,$ .....

# Results I: Single meson photoproduction off the proton

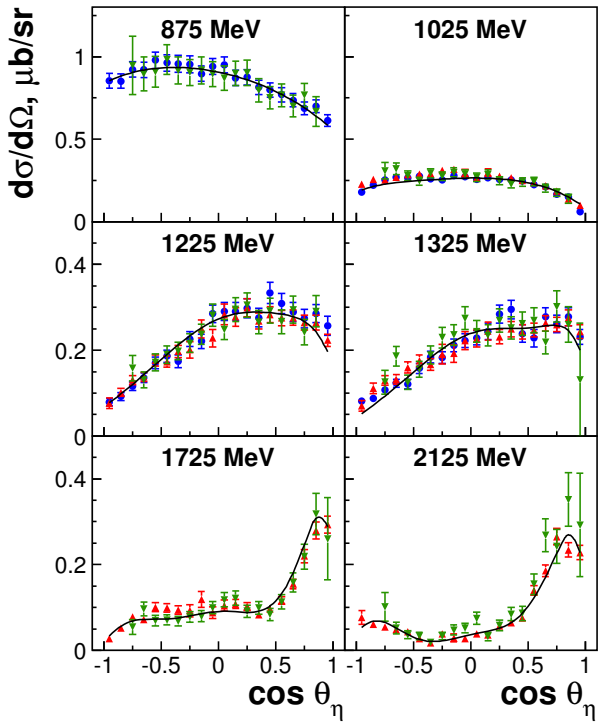
**$\pi$-Photoproduction:** EPJA 52 (2016), 284, in collaboration with project B11 $\longrightarrow$ Deborah

## $\gamma p \rightarrow p\eta$:

- **Isospin selective: only N$^*$ contribute**
- **Investigation of resonances with small $\pi N$-coupling**



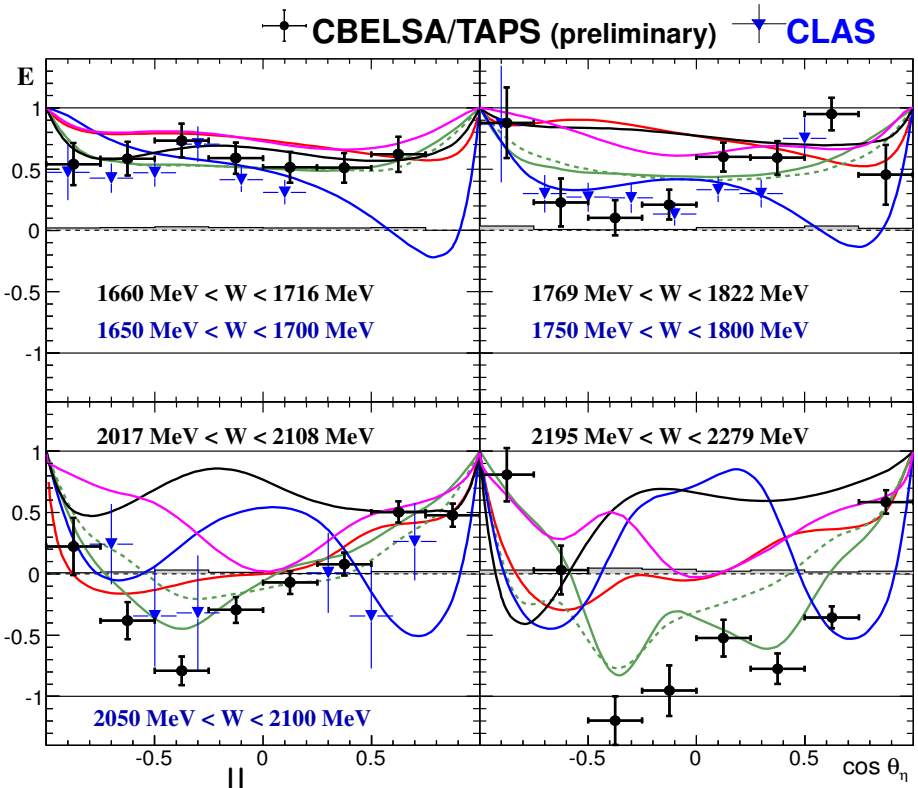

A few differential cross section bins:




⇔ **Differential cross sections, beam asymmetries included in the different PWAs**
⇔ **Not enough information to fix the contributing amplitudes**

# Results I: $\vec{\gamma}\vec{p} \to p\eta$ — Polarization observables —

**circ. pol. photons, long. pol. target**

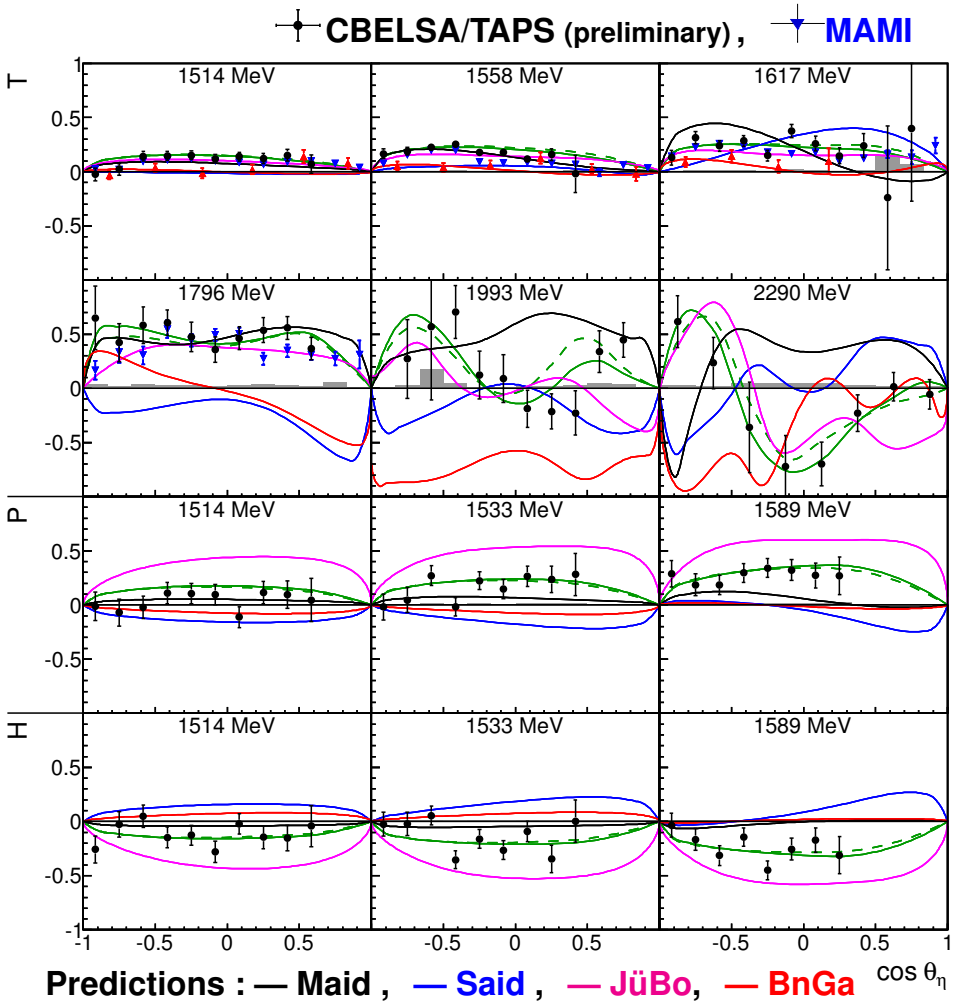



⇓

⇔ **Large sensitivity!** ( also true for $G$ (CBELSA/TAPS) and $F$ (MAMI) )

⇒ **data approaches the high mass region**

**linear pol. photons, transv. pol. target**




**Predictions : — Maid , — Said , — JüBo, — BnGa**

**— new BnGa-fit : Determination of precise $p\eta$-branching ratios for resonances**
**indications for a new resonance (no PDG entry) at 2200 MeV**

# $\vec{\gamma}\vec{p} \to p\eta$ — Results including new data on $E,\ G,\ T,\ P,\ H$ —

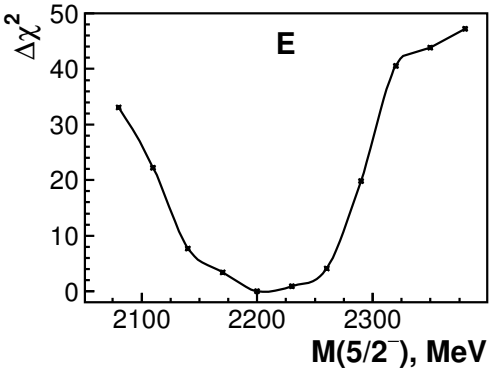
**Determination of $p\eta$-branching ratios for various resonances, e.g. :**

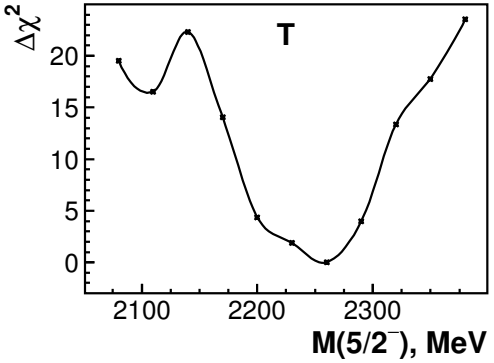
| | $N(1535)1/2^-$ | $N(1650)1/2^-$ | $N(1710)1/2^+$ | $N(1720)3/2^+$ |
|---|---|---|---|---|
| **BnGa** | **0.42±0.04** | **0.32±0.04** | **0.27±0.09** | **0.03±0.02** |
| **PDG** | **0.42±0.10** | **0.05 - 0.15** | **0.10 - 0.30** | **0.021±0.014** |

$\Downarrow$

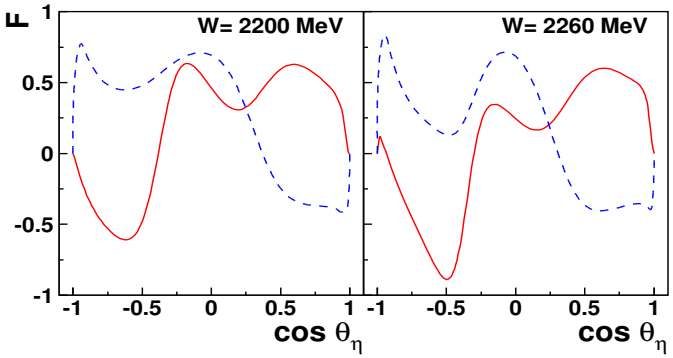
**Large and heavily discussed difference in the $p\eta$-branching ratio of N(1535)1/2$^-$ and N(1650)1/2$^-$ now significantly reduced**

**$\Rightarrow$ Hints for a new resonance around 2200 MeV with J$^P$=5/2$^-$**




**Predictions for F:**

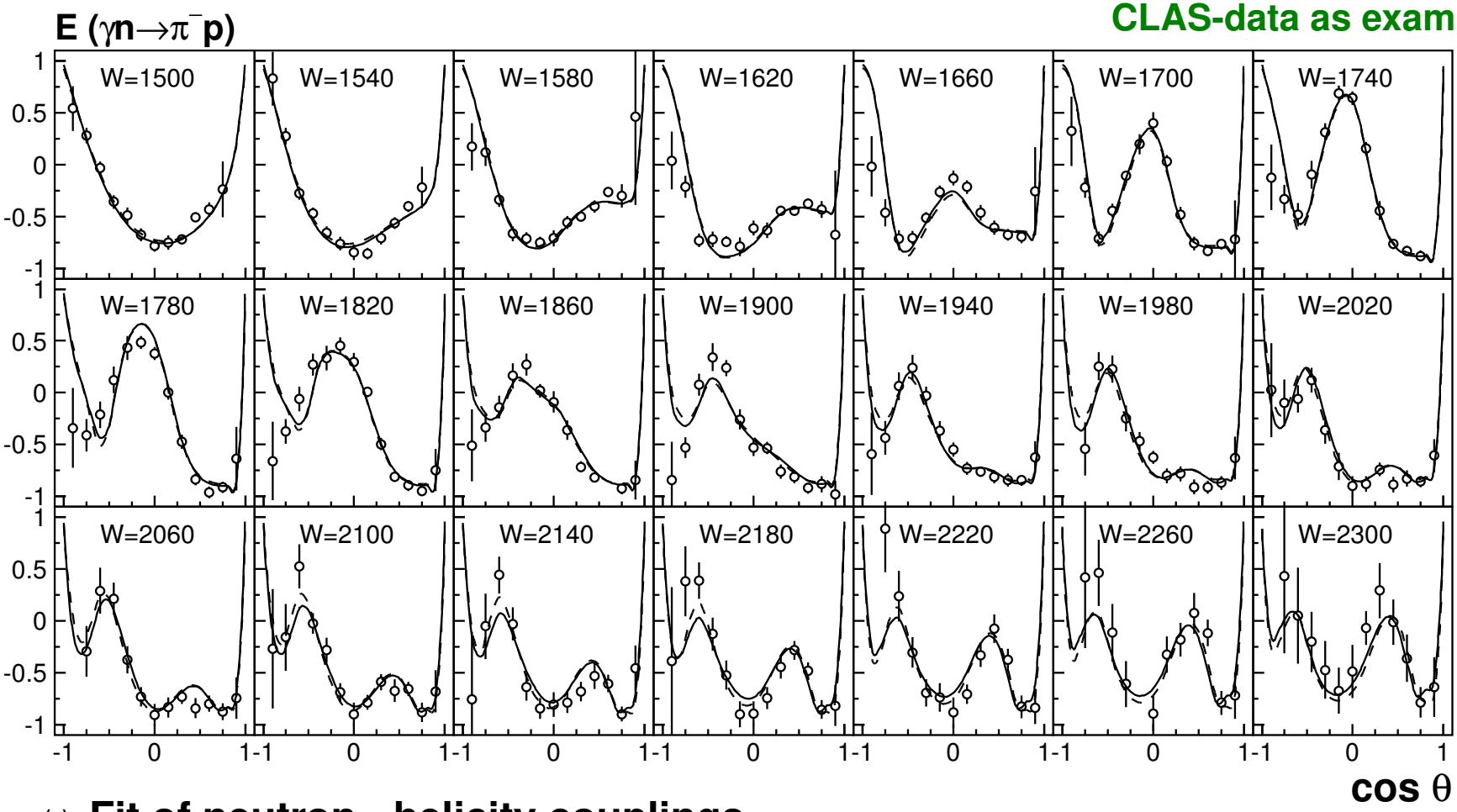



**Presently: Adding new $\frac{d\sigma}{d\Omega}$ (MAMI), $\Sigma$ (CLAS, CB,ELSA) -data**

# Results II: Analysis of photoproduction data off the neutron

**Analysis of:** $\gamma n \to p\pi^-$ $(\frac{d\sigma}{d\Omega}, \Sigma, T, P, E)$, $\gamma n \to n\pi^0 (\frac{d\sigma}{d\Omega}, \Sigma)$, $\gamma n \to n\eta$ $(\frac{d\sigma}{d\Omega}, \Sigma, E)$,
$\gamma n \to K^0\Lambda, K^+\Sigma^-(\frac{d\sigma}{d\Omega})$

**CLAS-data as example**




⇔ **Fit of neutron - helicity couplings**

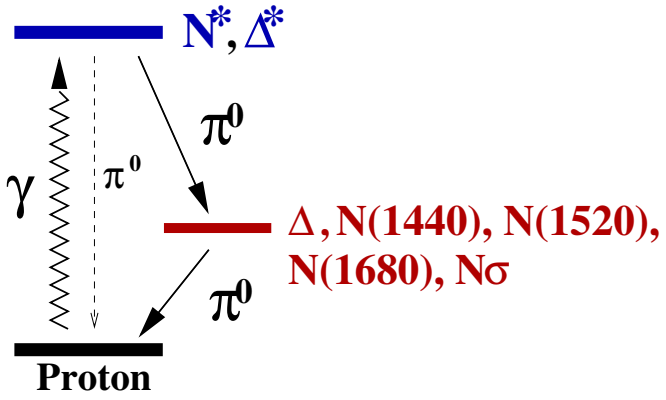
⇒ $A^n_{\frac{1}{2}}$, $A^n_{\frac{3}{2}}$ **determined for 19 resonances**

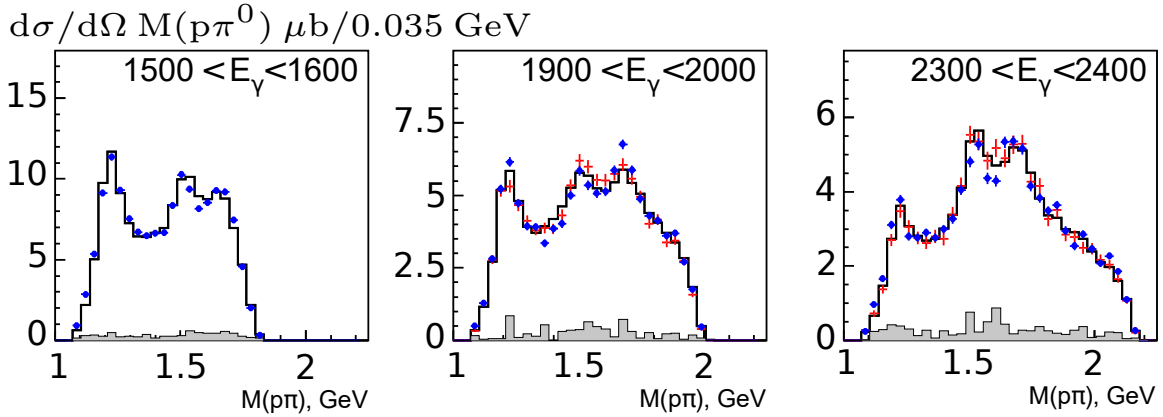
**Paper accepted for publication in PRC**

# Results III: Including $\gamma p \to p\pi^0\pi^0$ into the PWA

**Event based maximum likelihood fit**

**$\leftrightarrow$ takes all the correlations between the variables properly into account**




- $\Delta(1910)1/2^+$, $\Delta(1920)3/2^+$, $\Delta(1905)5/2^+$, $\Delta(1950)7/2^+$

  **in average: negligible decay fraction into:**

  $N(1520)3/2^-\pi$, $N(1535)1/2^-\pi$, $N(1680)5/2^+\pi$ ($L \neq 0$-resonances)

- $N(1880)1/2^+$, $N(1900)3/2^+$, $N(2000)5/2^+$, $N(1990)7/2^+$

  **in average: 23% decays into:**

  $N(1520)3/2^-\pi$, $N(1535)1/2^-\pi$, $N(1680)5/2^+\pi$, $N\sigma$ ($L \neq 0$-resonances)

**... Why ?**

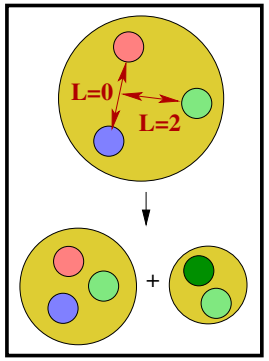
V. Sokhoyan et al. (CBELSA/TAPS-collaboration), EPJA 51 (2015) 95
A. Thiel et al. (CBELSA/TAPS-collaboration), PRL 114 (2015) 091803

# Results III: $\gamma p \to p\pi^0\pi^0$ – A possible interpretation –

- $\Delta(1910)1/2^+, \Delta(1920)3/2^+, \Delta(1905)5/2^+, \Delta(1950)7/2^+$

  **Spacial wave function:**

  $$S = \frac{1}{\sqrt{2}} \cdot \Big[ \big( \phi_{0s}(\vec{\rho}) \times \phi_{0d}(\vec{\lambda}) \big) + \big( \phi_{0d}(\vec{\rho}) \times \phi_{0s}(\vec{\lambda}) \big) \Big]^{L=2}$$



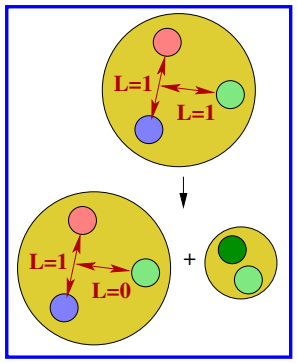

- $N(1880)1/2^+, N(1900)3/2^+, N(2000)5/2^+, N(1990)7/2^+$

  **Spacial wave function:**

  $$M_S = \frac{1}{\sqrt{2}} \cdot \Big[ \big( \phi_{0s}(\vec{\rho}) \times \phi_{0d}(\vec{\lambda}) \big) - \big( \phi_{0d}(\vec{\rho}) \times \phi_{0s}(\vec{\lambda}) \big) \Big]^{L=2}$$

  $$M_A = \Big[ \big( \phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda}) \big) \Big]^{L=2}$$

  $\Rightarrow$ **One of the excitations transfers into the $L = 1$ - intermediate resonance!**




**So far: only statements "in average" possible**

$\to$ **additional information from polarisation observables needed**

$\gamma p \to p\pi^0\pi^0$-$T,\ P,\ H$ **(CBELSA/TAPS),** $\gamma p \to p\pi^+\pi^-$**-data (CLAS) presently included in PWA**

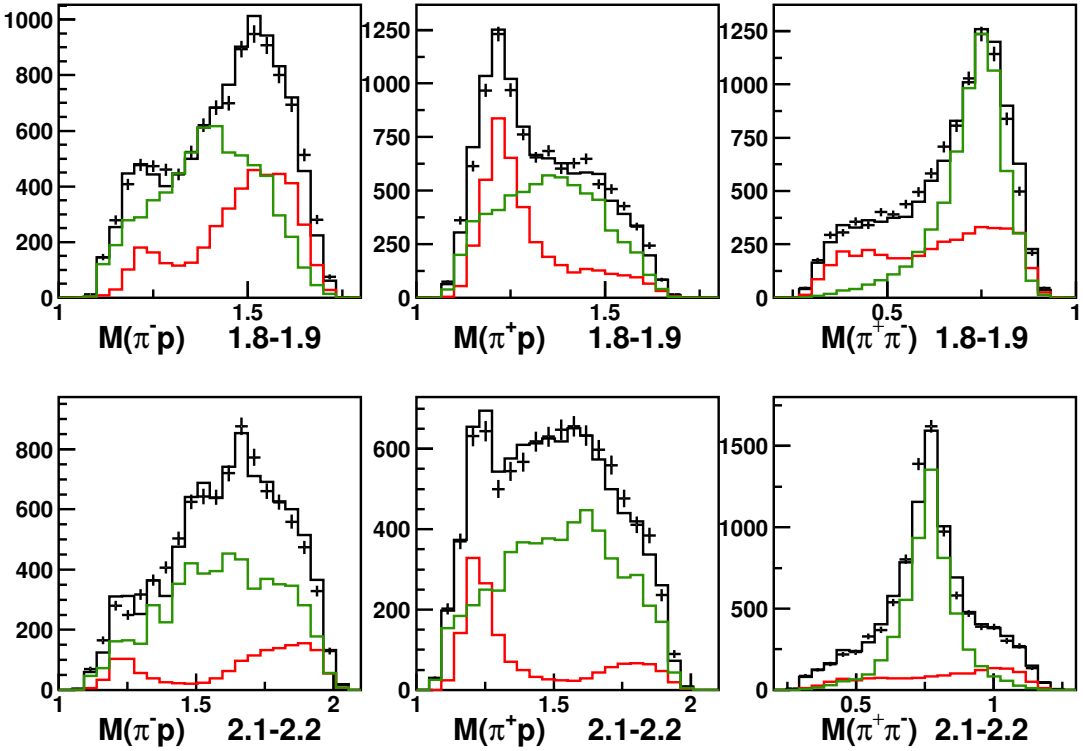
**The 20'plet:**

$$A = \Big[ \big( \phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda}) \big) \Big]^{L=1}$$

$\Leftrightarrow$ **Multi-meson final states needed! + production in cascade decays / different production processes**

# $\gamma p \to p\pi^+\pi^-$ – First fits –

## CLAS data (preliminary) included in the event based max. likelihood fit




Data (only small subset shown): E.N.Golovach, V.D. Burkert, V.I. Mokeev, E. Pasyuk, and the CLAS Collaboration

- **at low energies**
  $\gamma p \to \Delta^{++}\pi^-$ **dominating**
- **at high energies**
  $\gamma p \to N\rho$ **dominating**
  - ⇔ **Strong background contributions compared to** $\gamma p \to p\pi^0\pi^0$
  - ⇔ **Access to** $N^*/\Delta^* \to p\rho$
  - ⇔ **Combined analysis: Fix isospin of contributing resonances**

## First fits done, studies ongoing

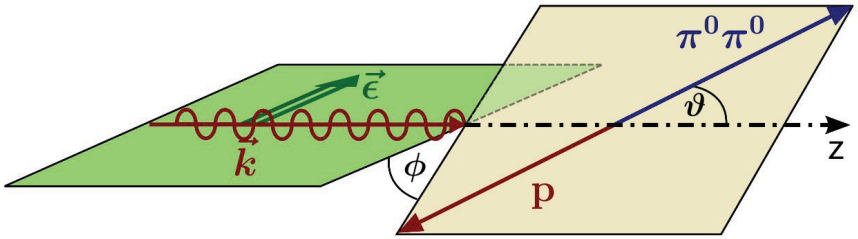
Strong $N\rho$-decay modes (very preliminary) for:

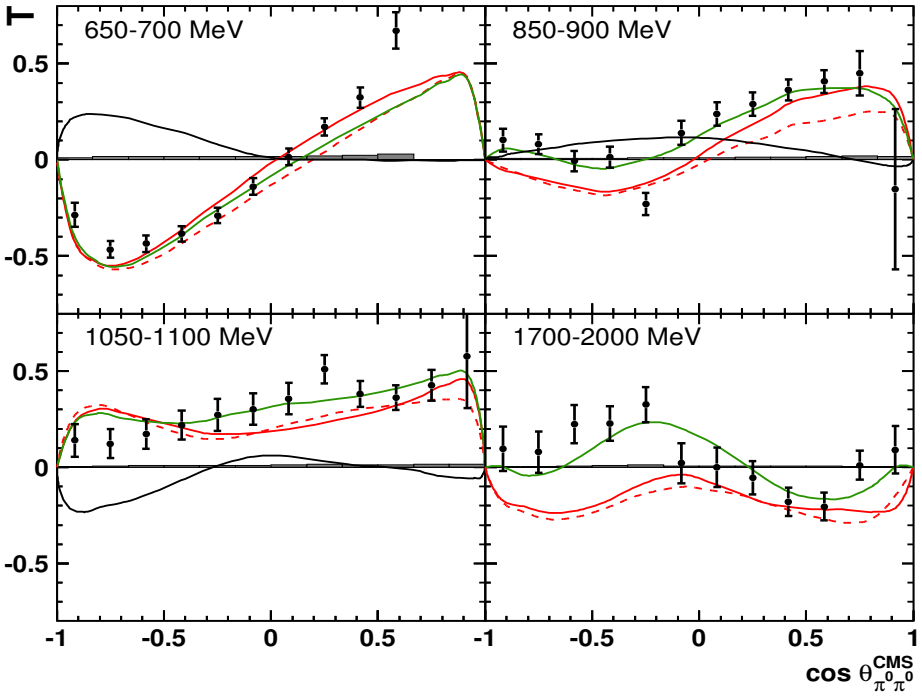
$N(1720)3/2^+$ $N(1880)1/2^+$ $N(1895)1/2^-$ $N(1875)3/2^-$ $N(2120)3/2^-$
$\Delta(1620)1/2^-$ $\Delta(1750)1/2^+$ $\Delta(1900)1/2^-$ $\Delta(1905)5/2^+$

# Polarization experiments: $\vec{\gamma}\vec{p} \to p\pi^0\pi^0$

**Linearly polarized photons, transversally polarized target**

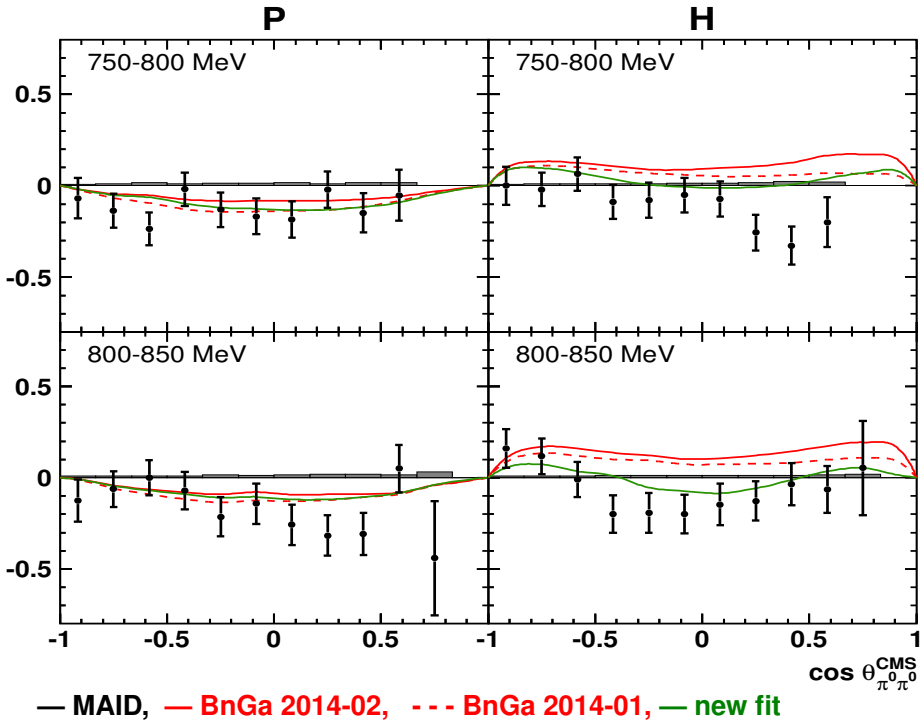
**looking at quasi-two-body kinematics:**




$\gamma p \to p\pi^0\pi^0$: **T, P, H** **(preliminary)**

(only selected bins shown)




**= work in progress**

**Data: T. Seifen et al. (CBELSA/TAPS-collaboration)**

# Results IV: A different production mechanism: $\psi' \to \bar{p}p\pi^0$

- $\Delta$-resonances suppressed in $\psi(3698) \to p\bar{p}\pi^0$ - isospin -

$\Rightarrow$ **larger sensitivity on N$^*$-resonances**

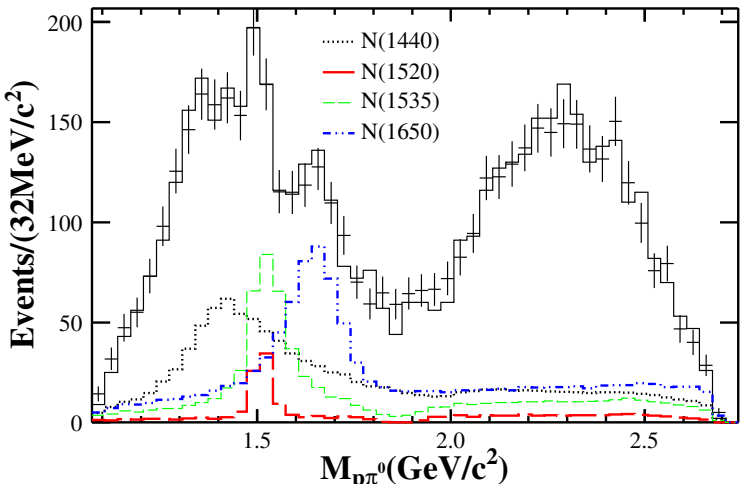
| | mass | width | sign. |
|---|---|---|---|
| $N(1440)1/2^+$ | $1390^{+11+21}_{-21-30}$ | $340^{+46+70}_{-40-156}$ | $11.5\sigma$ |
| $N(1520)3/2^-$ | $1510^{+3+11}_{-7-9}$ | $115^{+20+0}_{-15-40}$ | $5.0\sigma$ |
| $N(1535)1/2^-$ | $1535^{+9+15}_{-8-22}$ | $120^{+20+0}_{-20-42}$ | $9.3\sigma$ |
| $N(1650)1/2^-$ | $1650^{+5+11}_{-5-30}$ | $150^{+21+14}_{-22-50}$ | $12.2\sigma$ |
| $N(1720)3/2^+$ | $1700^{+30+32}_{-28-35}$ | $450^{+109+149}_{-94\ \ -44}$ | $9.6\sigma$ |
| ?? $\Rightarrow$ missing: e.g. N(1875)3/2$^-$, N(1880)1/2$^+$, N(1900)3/2$^+$.... | | | |
| $N(2300)1/2^+$ | $2300^{+40+109}_{-30-0}$ | $340^{+30+110}_{-30-58}$ | $15.0\sigma$ |
| $N(2570)5/2^-$ | $2570^{+19+34}_{-10-10}$ | $250^{+14+69}_{-24-21}$ | $11.7\sigma$ |

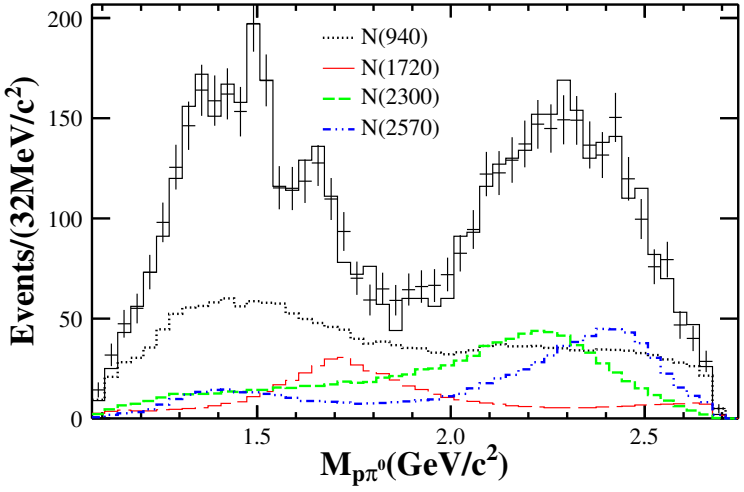
$\Rightarrow$ **2 new resonances observed**

$\Rightarrow$ **even as interesting:**
**Why is there a mass gap??**

$\Rightarrow$ **Specific resonances with certain properties suppressed in $\psi$-decays?**

BES: M. Ablikim, PRL110, 022001 (2013)



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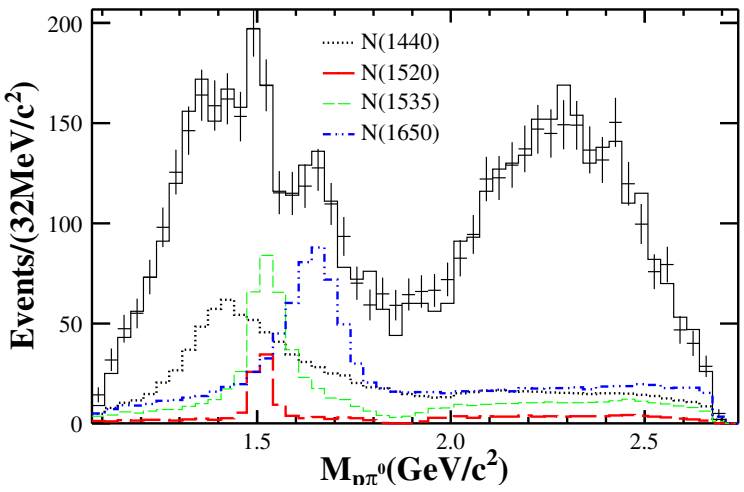
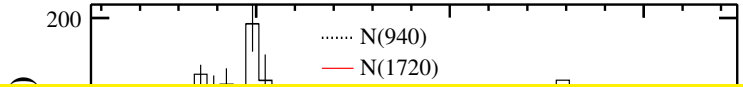



**Present status:**

- $\Rightarrow$ **Data available from the BES collaboration**
- $\Rightarrow$ **Amplitudes, code: in preparation**
- $\Rightarrow$ **First fits performed**

# Results II: Meson Spectroscopy

# PAWIAN

- **Development of a software package with the aim**
  - **to provide user-friendly and generic PWA tools**
  - **to support a wide range of physics cases to be studied in hadron spectroscopy experiments**

- **PAWIAN (Partial Wave Interactive Analysis Package)**
  - **already in good shape**
  - **several analyses of Crystal Barrel (LEAR) and BESIII data**
    $\leftrightarrow$ **PhD and master theses**

**BESIII:**

- $J/\psi \rightarrow \phi\pi\pi, \phi K\bar{K}, \phi\eta\eta, \omega\pi\pi, \omega K\bar{K}, \phi\phi\gamma, \omega\omega\gamma$
- $\psi(2S) \rightarrow \chi_{cJ}\gamma,\ \chi_{cJ} \rightarrow \pi\pi, K^+K^-, K^+K^-\eta, K^+K^-\pi\pi, \pi\pi\eta$
- **currently in preparation for publication:**
  $J/\psi \rightarrow \omega\omega\gamma$
  $\psi(2S) \rightarrow \chi_{c1}\gamma \rightarrow (K^+K^-\eta)\gamma$
  $e^+e^- \rightarrow (e^+e^-)\gamma\gamma \rightarrow (e^+e^-)K^+K^-$

**Crystal Barrel (LEAR):**

- $\bar{p}p \rightarrow K\bar{K}\pi, \pi\pi\eta, \omega\pi\pi, \omega\pi\eta, \pi\pi\eta\eta$
- $\bar{p}p \rightarrow \omega\pi$: Eur.Phys.J. C75 (2015) no.3, 124

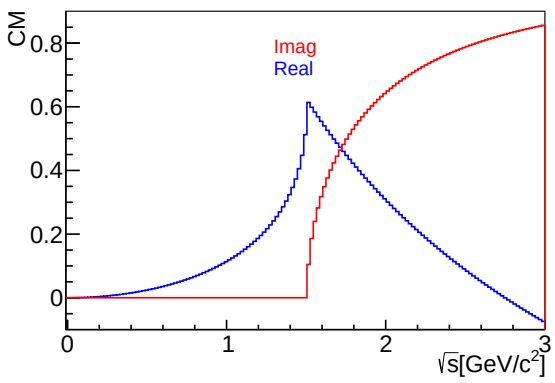
# Status of PAWIAN

- **Full hypotheses and other input settings via configuration files**
  - **Formalisms (Canonical, Helicity, Rarita Schwinger)**
  - **Dynamics (Breit Wigner, Flatte, K-matrix, etc.)**
- **Event based maximum likelihood fit, minimization via Minuit2**
- **Multithreading and networking supported**
- **Possibility to analyze channels with an arbitrary number of final state mesons and photons**
- **Support for various initial reactions: $\bar{p}p$- and $e^+e^-$-annihilation, $\pi\pi$-scattering processes, decay of isolated resonances**
- **Support of coupled channel analyses**
- **Baryon channels seem to work fine but still tests needed**
- **Event generator, histogramming, analysis tools, ...**

**Currently: Replacement of standard phasespace factor by Chew-Mandelstam function** $\leftrightarrow$ **Basdevant, Berger:** *PRD19(1979) 239*

$\Leftrightarrow$ **Analyticity, continuation into the complex plane**

$CM(s)$ **for** $\eta\eta'$



# PAWIAN: Current Activities on Unitarity and Analyticity

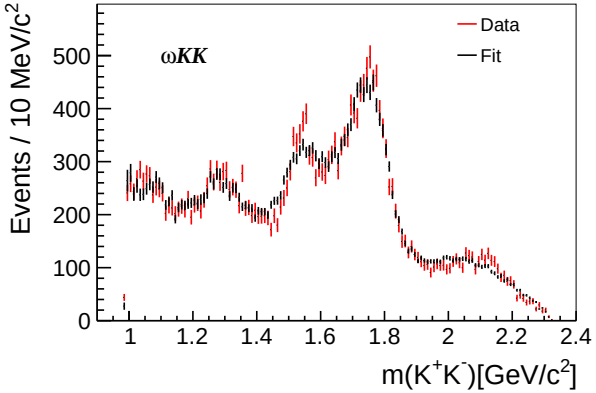
- **Coupled channel PWA of suitable channels including $\pi\pi$-scattering data and K-/T-matrix formalism with Chew-Mandelstam functions**

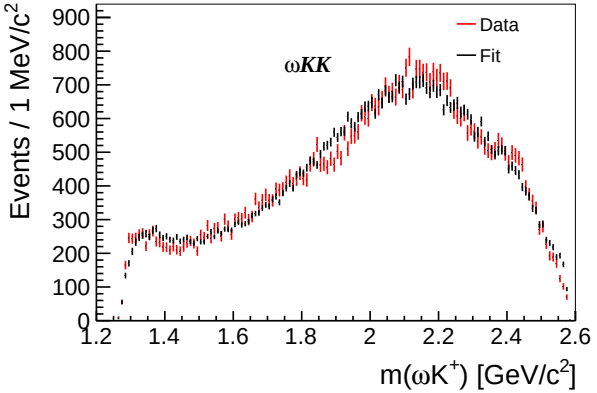
- **Proof of principle with coupled channel analysis**
  - $J/\psi \to \omega\pi^0\pi^0$ **and** $J/\psi \to \omega K^+K^-$
  - **I=0 S-wave scattering data:** $\pi\pi \to \pi\pi, K\bar{K}, \eta\eta, \eta\eta'$
  - **I=0 D-wave scattering data:** $\pi\pi \to \pi\pi, K\bar{K}, \eta\eta$
  - **I=1 P-wave scattering data:** $\pi\pi \to \pi\pi$
  - **I=1 F-wave scattering data:** $\pi\pi \to \pi\pi$
  - **K-matrix description for** $f_0, f_2, \rho_0$ **and** $\rho_3$ **contributions with a few number of poles and channels**
  - **additional contributions:** $b_1^0 \to \omega\pi^0, K_1^\pm \to K^\pm\omega$

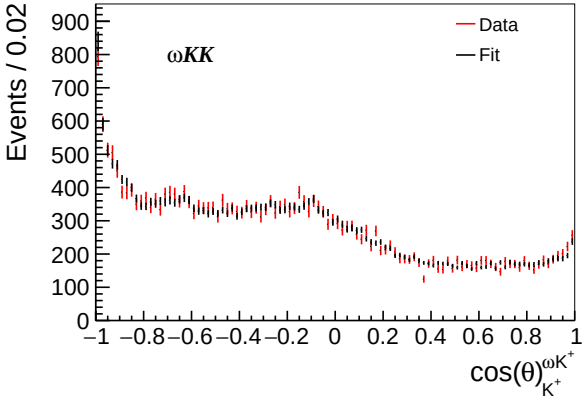
- **First fits lead to reasonable preliminary results**
  - **Good agreement between data and fitted result**
  - **Further contributions need to be studied**

# Fit results for $J/\psi$ Data

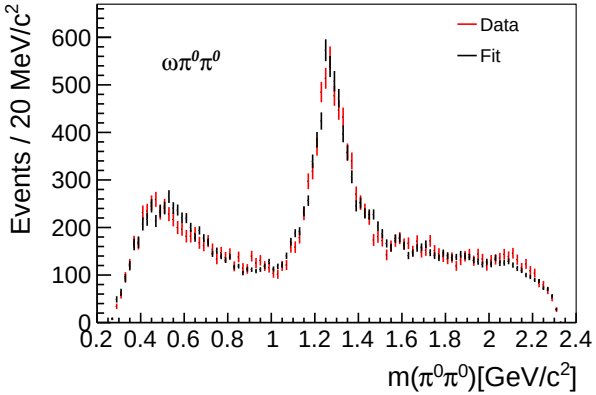
- $J/\psi \to \omega K^+ K^-$:

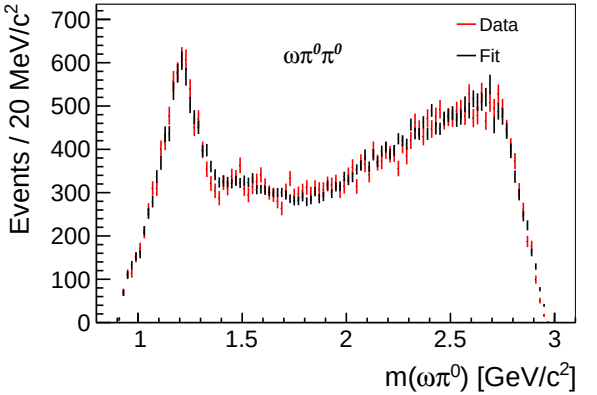


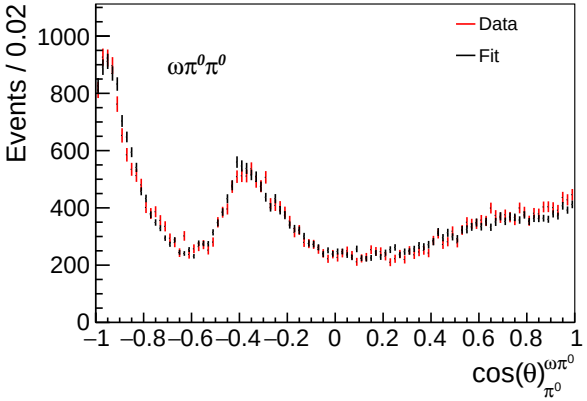




- $J/\psi \to \omega \pi^0 \pi^0$:

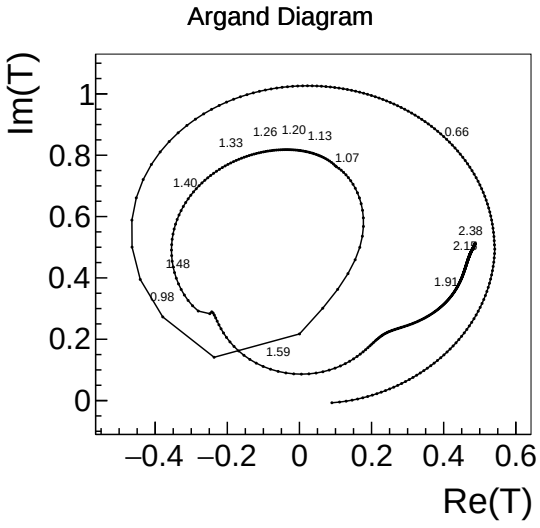


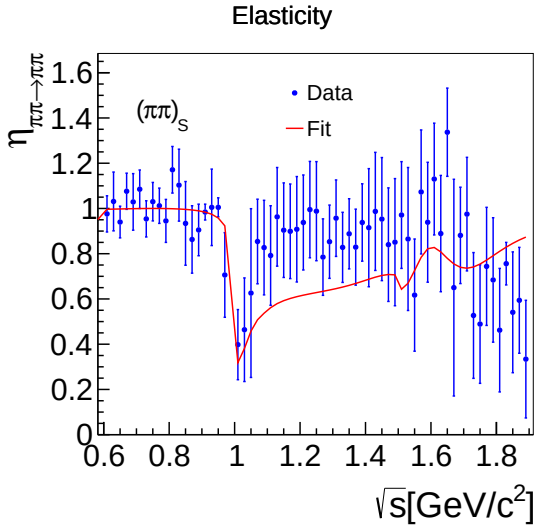



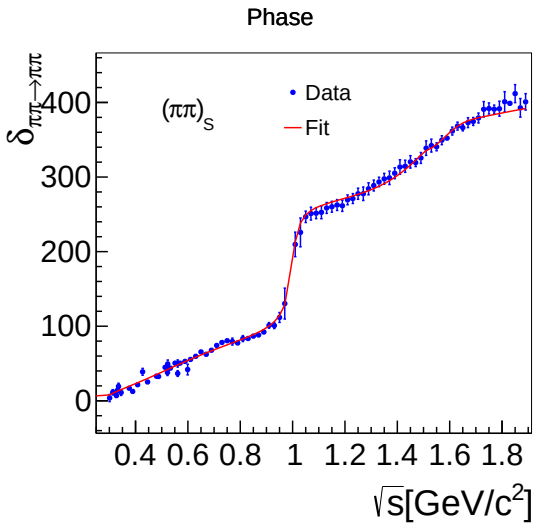



# Fit result for Scattering Data

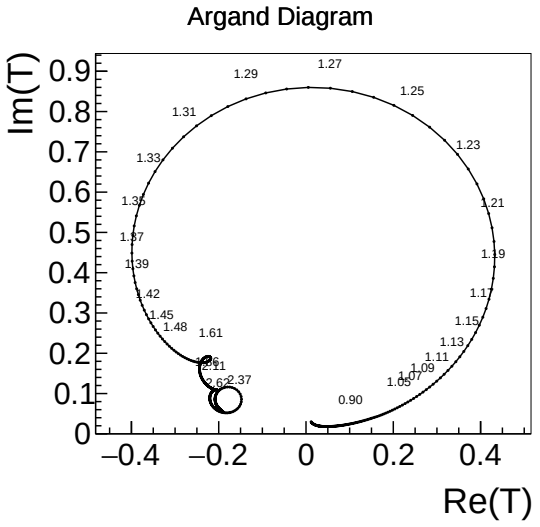
## $\pi\pi \rightarrow \pi\pi$ I=0, S-Wave:

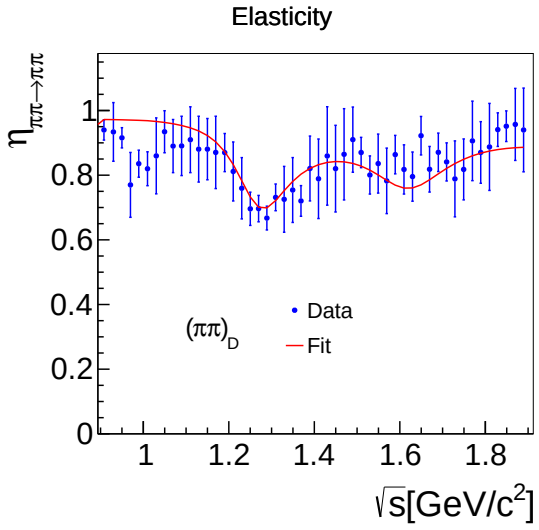


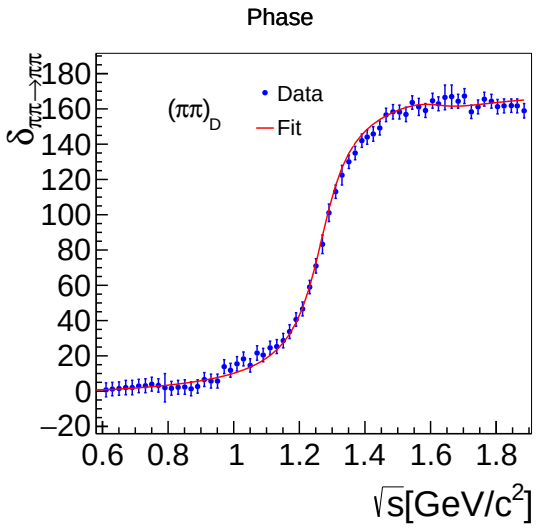




## $\pi\pi \rightarrow \pi\pi$ I=0, D-Wave:



# PAWIAN: Current Activities on Unitarity and Analyticity

- **Coupled channel PWA of suitable channels including $\pi\pi$-scattering data and K-/T-matrix formalism with Chew-Mandelstam functions**

- **Proof of principle with coupled channel analysis**
  - $J/\psi \to \omega\pi^0\pi^0$ **and** $J/\psi \to \omega K^+K^-$
  - **I=0 S-wave scattering data:** $\pi\pi \to \pi\pi, K\bar{K}, \eta\eta, \eta\eta'$
  - **I=0 D-wave scattering data:** $\pi\pi \to \pi\pi, K\bar{K}, \eta\eta$
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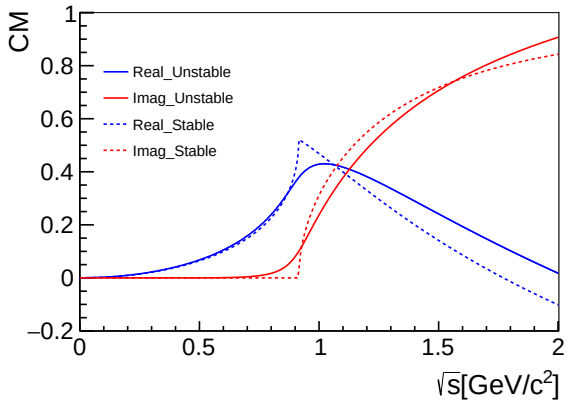
  - **K-matrix description for** $f_0, f_2, \rho_0$ **and** $\rho_3$ **contributions with a few number of poles and channels**
  - **additional contributions:** $b_1^0 \to \omega\pi^0$, $K_1^\pm \to K^\pm\omega$

- **First fits lead to reasonable preliminary results**
  - **Good agreement between data and fitted result**
  - **Further contributions need to be studied**

$CM(s)$ **for** $\pi\rho$




**Next step: Inclusion of Chew-Mandelstam function for instable particles ↔ involved numerical calculations**

↔ **Basdevant, Berger:** *PRD19(1979) 239*

# Publications

- A. V. Anisovich *et al.*,
  "Neutron helicity amplitudes,"
  accepted for publication in PRC
- A. V. Anisovich *et al.*,
  "Strong Evidence for Nucleon Resonances near 1900 MeV,"
  Phys. Rev. Lett. **119** (2017) no.6, 062004.
- A. V. Anisovich *et al.*,
  "$N^* \to N\eta'$ decays from photoproduction of $\eta'$-mesons off protons,"
  Phys. Lett. B **772** (2017) 247
- A. V. Anisovich, V. Burkert, E. Klempt, V. A. Nikonov, A. V. Sarantsev and U. Thoma,
  "Scrutinizing the evidence for N(1685),"
  Phys. Rev. C **95** (2017), 035211
- A. V. Anisovich *et al.*, BnGa in collaboration with project B11 (+SAID, MAID)
  "The impact of new polarization data from Bonn, Mainz and Jefferson Laboratory on $\gamma p \to \pi N$ multipoles,"
  Eur. Phys. J. A **52** (2016), 284

# Summary: Milestones

- **2016/2**

| | |
|---|---|
| Combined fits (BnGa) of $J/\psi \to K^+K^-\pi^0$, $J/\psi \to K^+K^0\pi^-$ | ✓ (A. Sarantsev + I. Denisenkov) |
| Preparation of BnGa-code for $J/\psi(\psi') \to \gamma PSPS$ | ✓ (A. Sarantsev + I. Denisenkov) |
| Combined analysis of $\gamma p \to p\pi^0\pi^0$ and $\gamma p \to p\pi^+\pi^-$ | work in progress |
| Analysis of further polarization data becoming available | ✓ + work in progress |
| Developments to include electroproduction | ✓ |
| Extension of PAWIAN-software to support coupled channel analyses (different production mechanisms) | ✓ |

- **2017**

| | |
|---|---|
| $J/\psi(\psi') \to \gamma PSPS$, $p\bar{p} \to 3PS$, $\pi\pi$-scattering | ✓ + work in progress |
| Analysis of further polarization data becoming available | ✓ + work in progress |
| First fits including electroproduction | ✓ + work in progress |
| Implementation of theoretical constrains (Roy, Roy-Steiner) | ✗ |
| Developments to include $J/\psi, \psi' \to p\bar{p}PS$ | (✓) |
| PAWIAN: Develoments for inclusion of additional channels | (✓) |
| Implementation, optimization of parallel computing | (✓) |
| Comparison of BnGa and PAWIAN results | ✗ |

**BnGa: Baryon Spectroscopy = present highest priority** $\leftrightarrow$ **Inclusion of additional data**

**Thank you for your attention**