Baryon Spectroscopy at ELSA

Volker Credé

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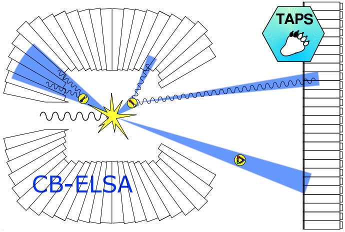
Tallahassee, FL

Excited QCD

Zakopane, February 11, 2009

Outline



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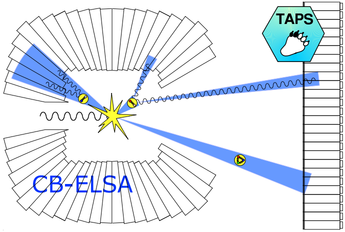
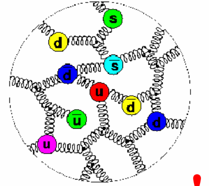
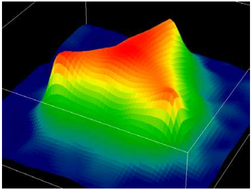
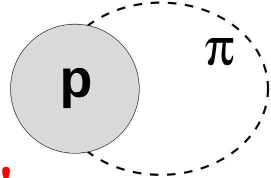


$\ll 0.1$fm	0.1 – 1.0 fm	> 1.0 fm







pQCD
q, g, q$\bar{\text{q}}$

? ! ↔ ! ?

Models
Quarks and Gluons as Quasiparticles

? ! ↔ ! ?

ChPT
Nucleon and Mesons

1. What are the relevant degrees of freedom?
2. What are the corresponding effective interactions responsible for hadronic phenomena?

One of the Main Goals of the N^* Program ...

Search for *missing* or yet unobserved resonances

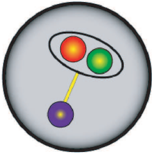
Quark models predict many more baryons than have been observed

	****	***	**	*
N Spectrum	11	3	6	2
Δ Spectrum	7	3	6	6

⇒ according to PDG
(Phys. Rev. **D66** (2002) 010001)
⇒ little known
(many open questions left)

Possible solutions:

1. Quark-diquark structure



one of the internal degrees of freedom is frozen

2. Have not been observed, yet

Nearly all existing data result from πN scattering experiments

➜ If the missing resonances did not couple to Nπ, they would not have been discovered!!

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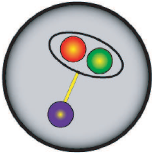

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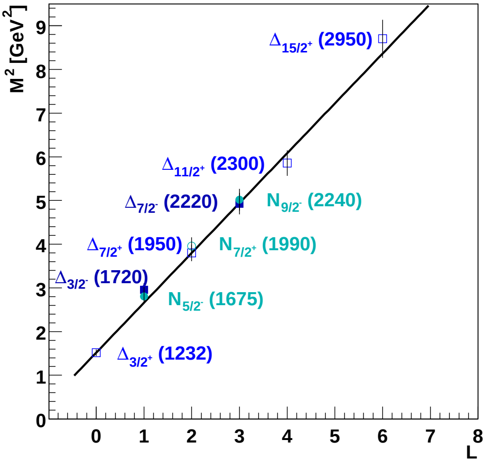
Possible Quark-Diquark Structure?



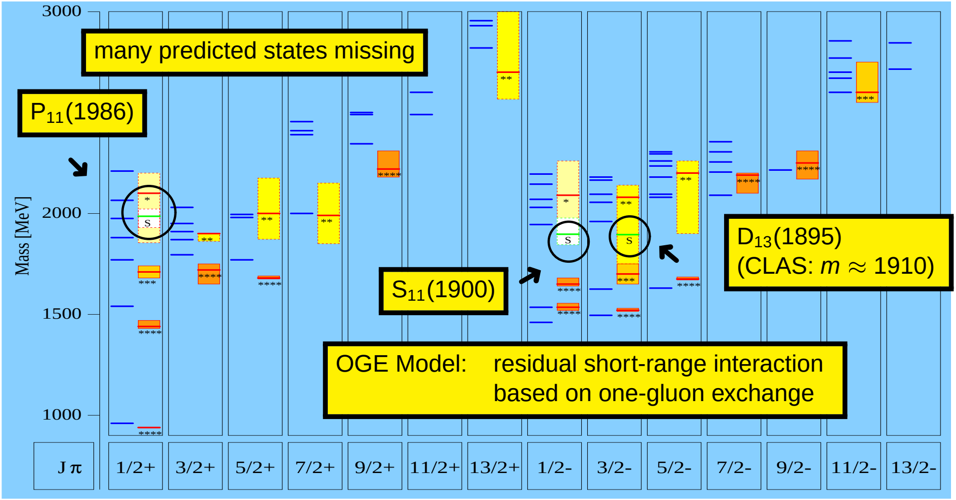
Regge trajectory for Δ^* states with intrinsic spin $S = 1/2$ and $S = 3/2$, and for N^* states with spin $S = 3/2$ (M^2 versus L, not J)

1. Common Regge trajectory for N/Δ states with $S = 3/2$
2. Not shown, but slope of the Regge trajectory for meson and Δ excitations is identical

➜ Are baryons quark-diquark excitations?

Nucleon Resonances: Status of 2001

—— S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809



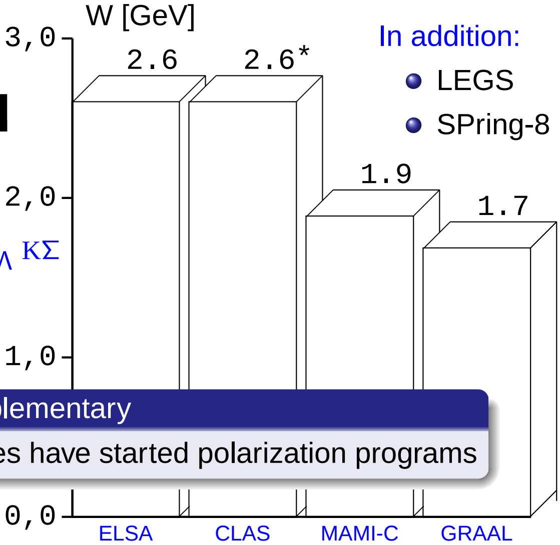
E_γ [GeV]

Reaction Thresholds

1.66 — $\gamma p \rightarrow p\eta\eta$, $\gamma p \rightarrow p\pi^0\omega$, $\gamma p \rightarrow p\pi^0\eta$, $\gamma p \rightarrow K\Lambda$, $K\Sigma$, $\gamma p \rightarrow p\eta$, $\gamma p \rightarrow p\pi\pi\pi$, $\gamma p \rightarrow p\pi\pi$

0.06 — $\gamma p \rightarrow p\pi$

0.00



In addition:

- LEGS
- SPring-8

Partially complementary

- All facilities have started polarization programs

What is new?

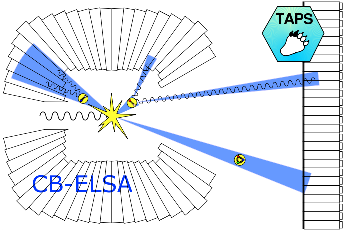
Many excellent data have been accumulated over the last years

- High-statistics samples with excellent energy/angular coverage
- New resonances have been announced and formerly weakly established states have been verified, e.g.:
  $\Delta(1940)D_{33},\ N(1900)P_{13},\ N(2070)D_{15},\ N(2200)P_{13},\ldots$
- However, many of these candidates are not confirmed by other groups or even disputed

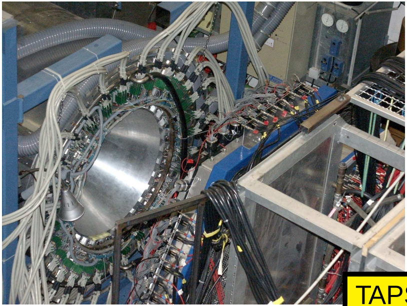
Analysis techniques and models have been developed (improved):

- Coupled-channel (or combined) analyses
- Event-based likelihood fits
- ...

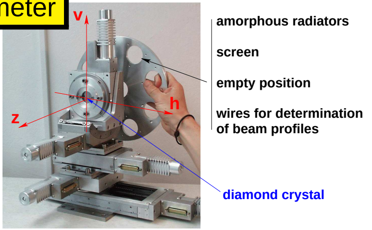
Outline



The CB-ELSA/TAPS Experiment



Goniometer

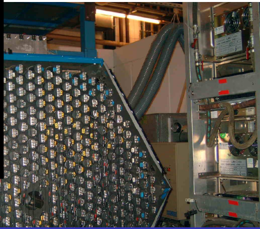


Sep. 2002 – Dec. 2003

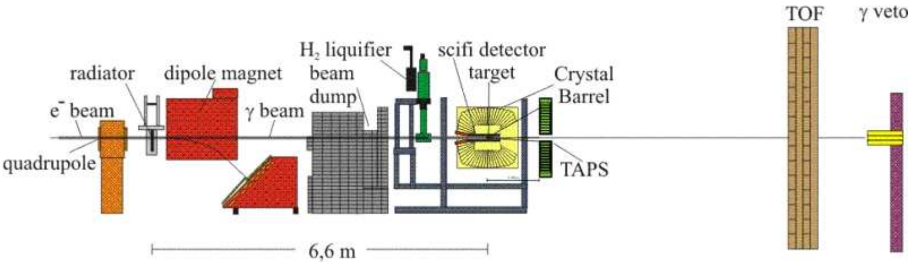
- (un)polarized beam
- liquid H_2, deuterium
- solid targets

TAPS

- 512 BaF Crystals
- Forward detector
  - High Granularity
  - Fast Trigger



CB-ELSA/TAPS Experimental Setup of 2002/2003

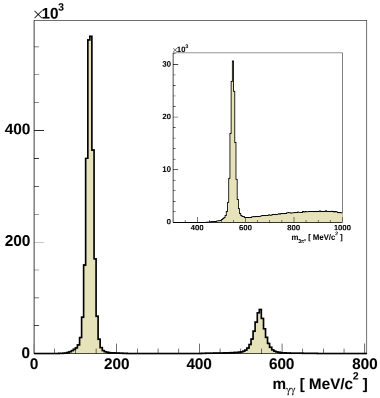


Tagged Photons (E_{e^-} = 3.2 GeV)

- 14 counters + 2 wire chambers
- $0.25 \cdot E_{e^-} \leq E_\gamma \leq 0.95 \cdot E_{e^-}$

  $800\ \text{MeV} \leq E_\gamma \leq 3000\ \text{MeV}$

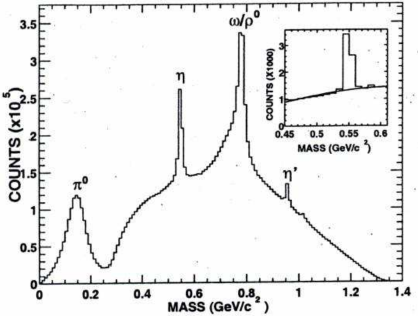
Study of $\gamma p \to p\eta$ with CB-ELSA/TAPS



←

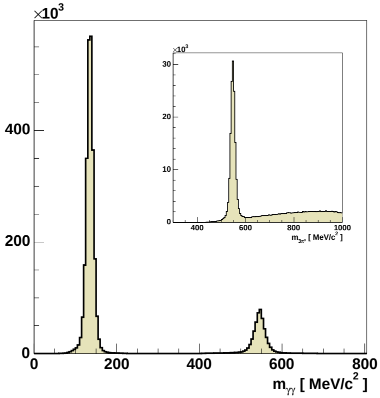
$\left\{ \begin{array}{l} \eta \;\to\; 3\pi^0, \gamma\gamma \\ \text{(CB-ELSA/TAPS)} \end{array} \right.$

M. Dugger et al., PRL **89**, 222002 (2002)



$\left. \begin{array}{l} \gamma\, \mathrm{p} \;\to\; \mathrm{p}\, \mathrm{X}\ \text{(missing mass)} \\ \text{(CLAS)} \end{array} \right\}$ ↗

Study of $\gamma p \to p\eta$ with CB-ELSA/TAPS



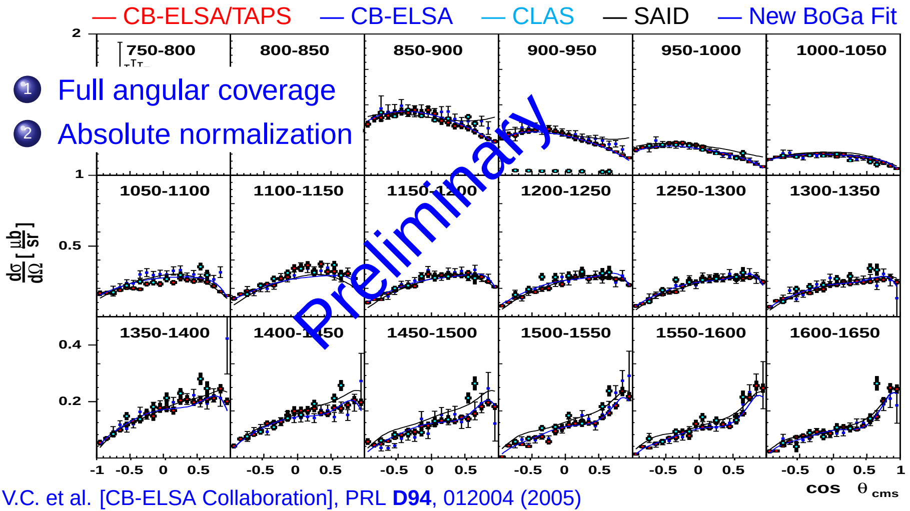
← $\left\{ \eta \to 3\pi^0, \gamma\gamma \right.$ (CB-ELSA/TAPS)

Reconstruction

- Number of photons: $N_\gamma = 2,\ 6$
- Proton identification: TAPS and inner scintillating fibre detector
  ➜ Missing proton kinematic fit
- Data quality
  - 422,300 events for $\eta \to \gamma\gamma$: $\sigma \approx$ 13 MeV
  - 126,300 events for $\eta \to 3\pi^0$: $\sigma \approx$ 10 MeV

Study of $\gamma p \rightarrow p\eta$ (2008 Data from CB-ELSA/TAPS)

1. Full angular coverage
2. Absolute normalization



V.C. et al. [CB-ELSA Collaboration], PRL **D94**, 012004 (2005)

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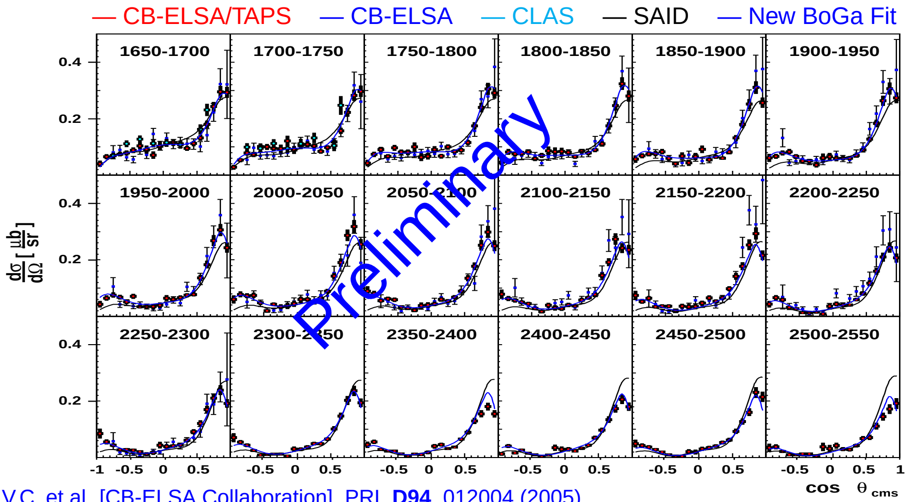

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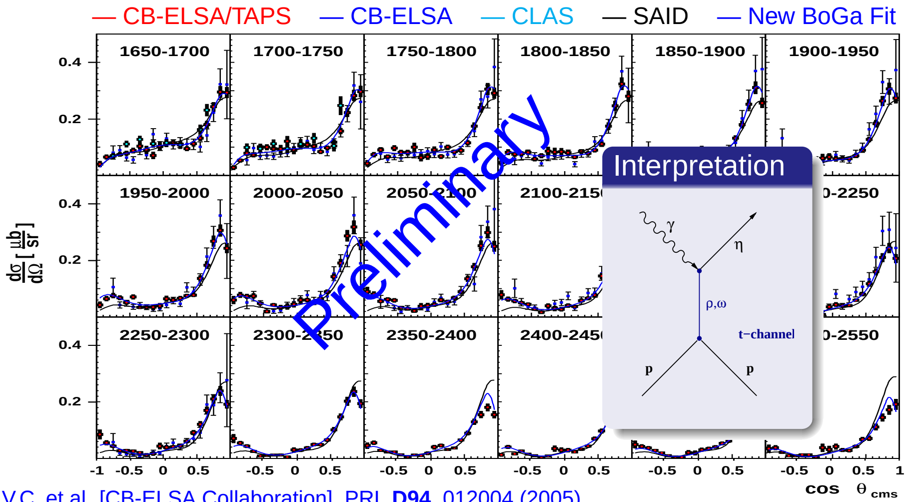
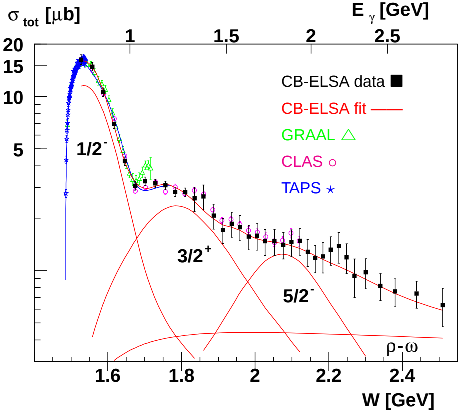


V.C. et al. [CB-ELSA Collaboration], PRL **D94**, 012004 (2005)

Analysis of $\gamma p \rightarrow p\eta$: Total Cross Section



Isopsin Filter

➜ Only N^* resonances can contribute!

Bonn-Gatchina (PWA) group: Hint for N* resonance (2070)D_{15}

(Phys. Rev. Lett. **D94**, 012004 (2005))

Three resonances are dominantly contributing:

$N(1535)S_{11}$, $N(1720)P_{13}$, $N(2070)D_{15}$

Partial Wave Analysis: $\gamma p \to p\eta$

PWA: Operator (Tensor) Formalism (Rarita–Schwinger)

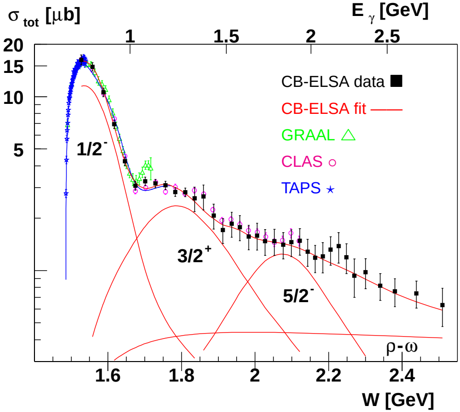
- Many data sets included
  - Cross section data and polarization observables
- Solutions not unique

Observables	Reference	N_{data}	χ^2/N
$\sigma(\gamma p \to p\eta)$	CB-ELSA	667	0.91
$\sigma(\gamma p \to p\eta)$	TAPS	100	1.6
$\Sigma(\gamma p \to p\eta)$	GRAAL 98	51	2.27
$\Sigma(\gamma p \to p\eta)$	GRAAL 04	100	1.75
$\sigma(\gamma p \to p\pi^0)$	CB-ELSA	1106	1.50
$\Sigma(\gamma p \to p\pi^0)$	GRAAL 04	469	3.43
$\Sigma(\gamma p \to p\pi^0)$	SAID	593	2.87
$\sigma(\gamma p \to n\pi^+)$	SAID	1583	2.86

Resonance	M (MeV)	Γ (MeV)	Fraction
$N(1520)D_{13}$	1523 ± 4	105^{+6}_{-18}	0.020
PDG	1520^{+10}_{-5}	120^{+15}_{-10}	
$N(1535)S_{11}$ *	1501 ± 5	215 ± 25	0.430
PDG	1505 ± 10	170 ± 80	
$N(1650)S_{11}$ *	1610 ± 10	190 ± 20	
PDG	1660 ± 20	160 ± 10	
$N(1675)D_{15}$	1690 ± 12	125 ± 20	0.001
PDG	1675^{+10}_{-5}	150^{+30}_{-10}	
$N(1680)F_{15}$	1669 ± 6	85 ± 10	0.005
PDG	1680^{+10}_{-5}	130 ± 10	
$N(1700)D_{13}$	1740 ± 12	84 ± 16	0.004
PDG	1700 ± 50	100 ± 50	
$N(1720)P_{13}$	1775 ± 18	325 ± 25	0.300
PDG	1720^{+30}_{-70}	250 ± 50	
$N(2000)F_{15}$	1950 ± 25	230 ± 45	0.007
$N(2070)D_{15}$	2068 ± 22	295 ± 40	0.171
$N(2080)D_{13}$	1943 ± 17	82 ± 20	0.011
$N(2200)P_{13}$	2214 ± 28	360 ± 55	0.051

* K-Matrix Fit,
Fraction for the total K-matrix contribution

Analysis of $\gamma p \rightarrow p\eta$: Total Cross Section



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Bonn-Gatchina (PWA) group: Hint for N* resonance (2070)D_{15}

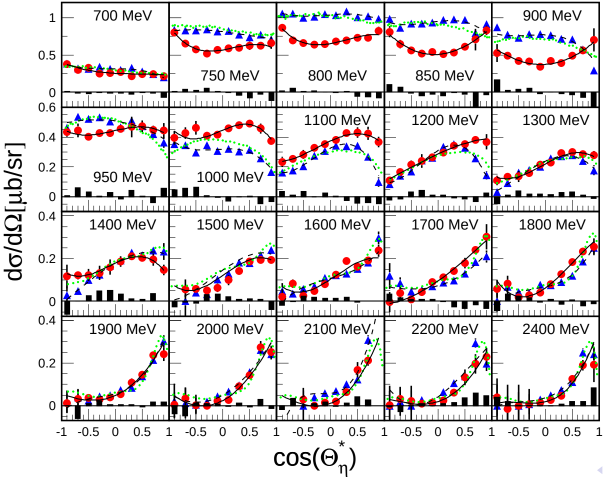
(Phys. Rev. Lett. **D94**, 012004 (2005))

1. Confirmed in 2008 analysis!
2. $N(1720)P_{13} \rightarrow p\eta$ unexpected
   ➜ η-MAID: $N(1710)P_{11} \rightarrow p\eta$ significant!

Three resonances are dominantly contributing: $N(1535)S_{11}$, $N(1720)P_{13}$, $N(2070)D_{15}$

Study of $\gamma n \to n\eta$ (2008 Data from CB-ELSA/TAPS)

I. Jaegle et al. [CB-ELSA/TAPS Collaboration], Phys. Rev. Lett. **100**, 252002 (2008)



▲ quasi-free proton

● quasi-free neutron

—— (– · –·) BoGa fits

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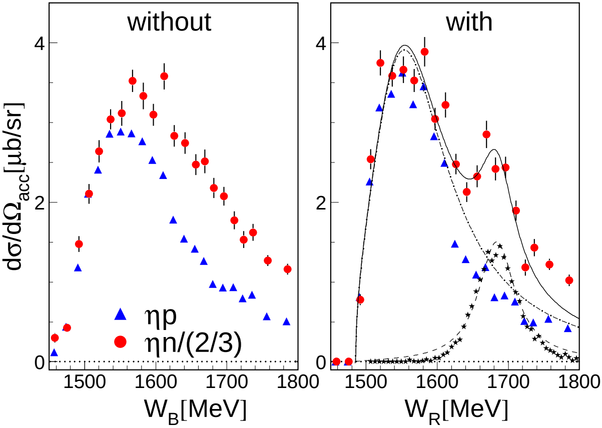
Event-by-event correction of Fermi motion



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Excitation functions for $\cos\theta_\eta < -0.1$

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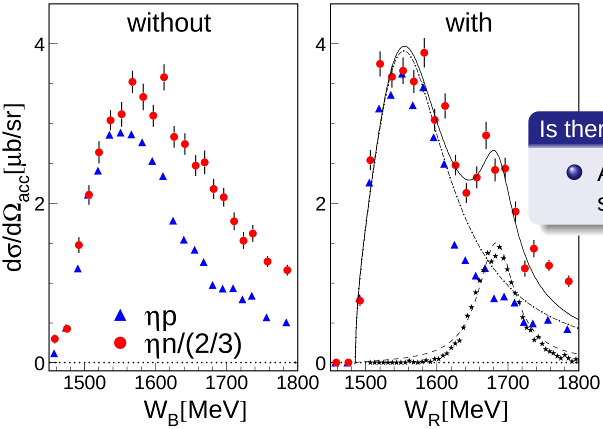

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Is there a narrow P_{11} state?

- Absolutely no evidence for such a peak off the proton

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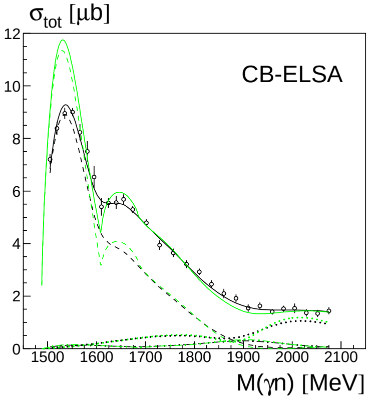

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- Most natural solution: interference within S_{11}-wave

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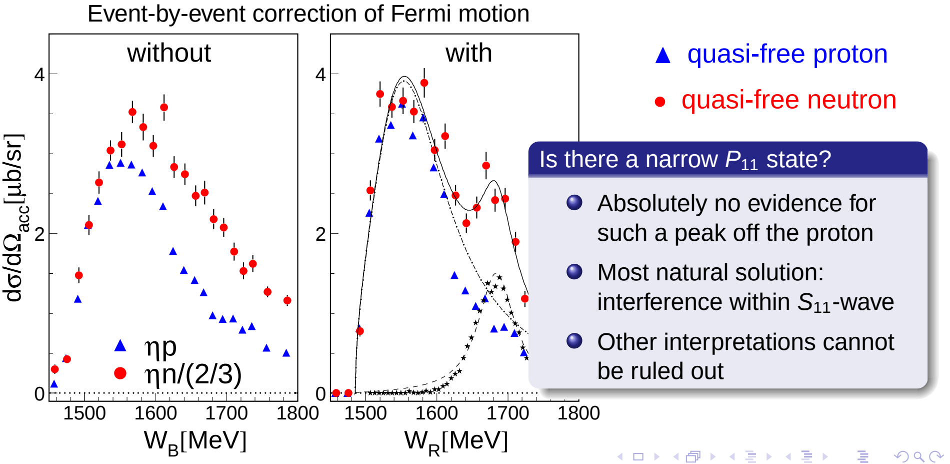


Is there a narrow P_{11} state?

- Absolutely no evidence for such a peak off the proton
- Most natural solution: interference within S_{11}-wave
- Other interpretations cannot be ruled out

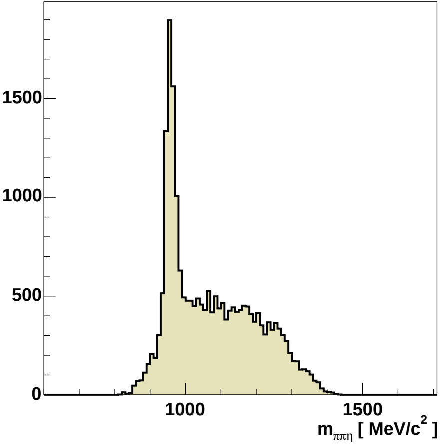
Study of $\gamma p \rightarrow p\eta'$ with CB-ELSA/TAPS

Isospin Filter: only N* resonances can contribute

- 1968: 11 events from the ABBHHM bubble chamber experiment
- 1976: 7 events from the AHHM streamer chamber experiment
- 1998: 250 events from SAPHIR collaboration
  ➜ First differential cross sections
- 2006: over $2 \cdot 10^5$ events from CLAS
  (Contributions from N(1535)S_{11}, N(1710)P_{11}, $J = 3/2$ states)
- 2008: New data from CBELSA/TAPS over the full angular range

No published asymmetry data for η'...
(Data available from CLAS and ELSA)

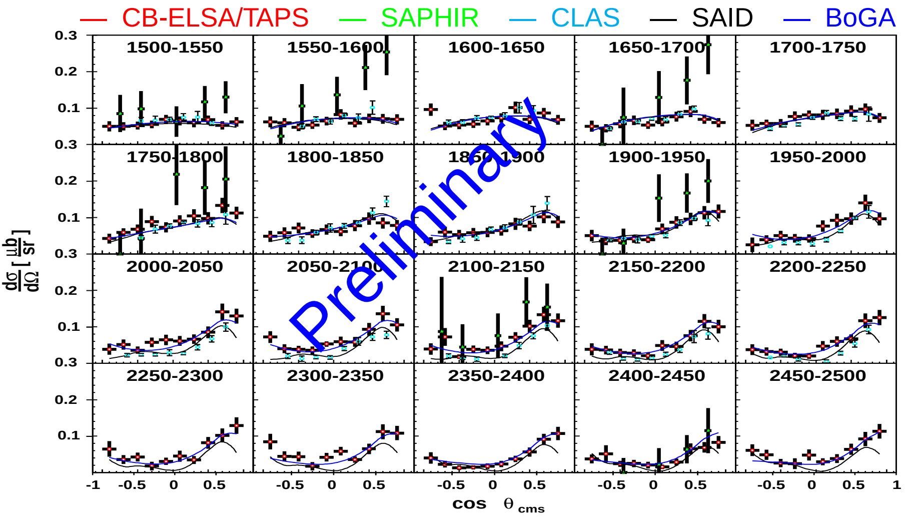
Study of $\gamma p \to p\eta'$ with CB-ELSA/TAPS



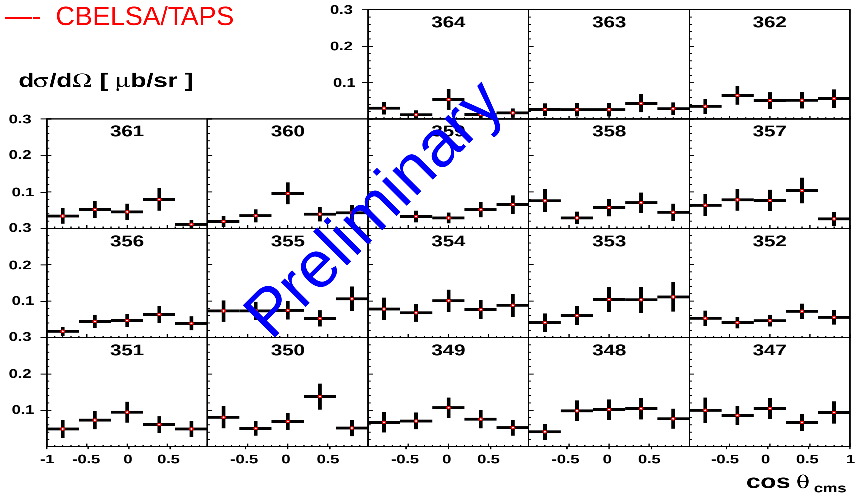
Reconstruction of η':

- Kinematic Fitting to $\gamma\mathrm{p} \to \mathrm{p}\pi^0\eta\gamma\gamma$
- Mass window for remaining π^0:
  110 $< m_{\gamma\gamma} <$ 160 MeV
- Mass window for η':
  910 $< m_{\pi^0\pi^0\eta} <$ 1010 MeV

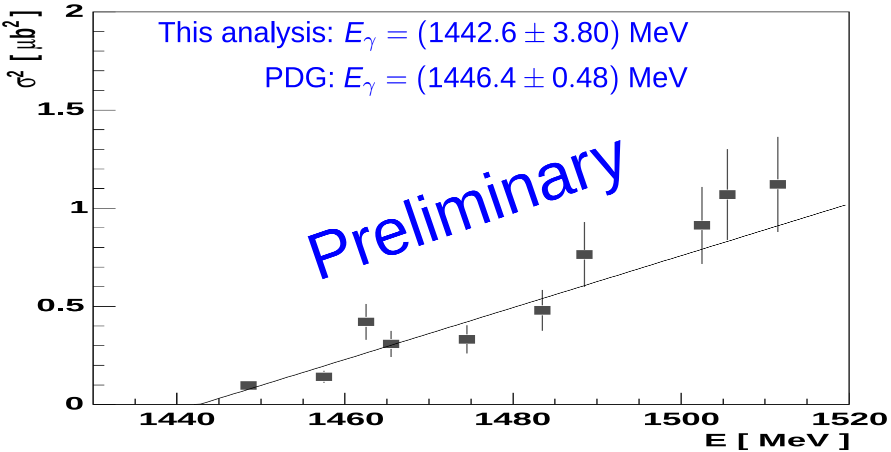
Differential Cross Sections for $\gamma p \to p\eta'$



Study of $\gamma p \rightarrow p\eta'$ Threshold



Threshold Behavior of $\gamma p \to p\eta'$



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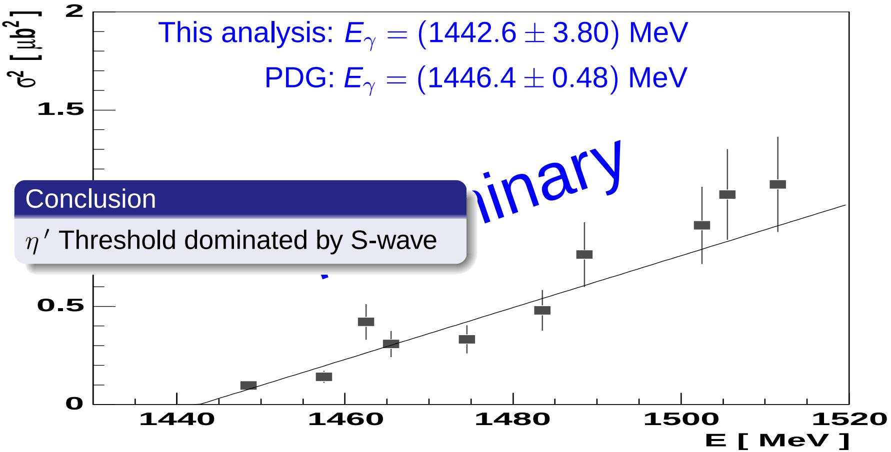
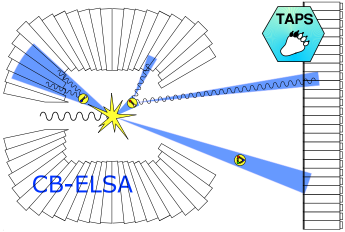


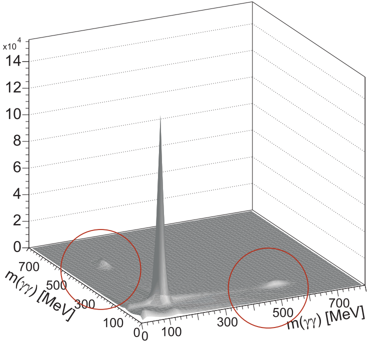
Conclusion

η' Threshold dominated by S-wave

Outline



Data Reconstruction



- Exactly 4 photons in Crystal Barrel
- Kinematic Fitting
  - Proton candidate(s) identified (≥ 1)
    $\Rightarrow$ Missing proton fit
  - Incoming (tagger) photon measured

$\Leftarrow$ $\gamma \mathrm{p} \rightarrow \mathrm{p}\, 4\gamma$

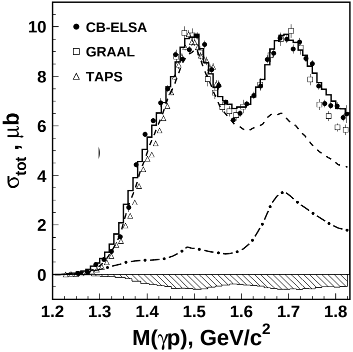
$\gamma \mathrm{p} \rightarrow \mathrm{p}\pi^0\pi^0$

- CL > 10 %
- $\mathrm{CL}(\gamma \mathrm{p} \rightarrow \mathrm{p}\pi^0\pi^0) > \mathrm{CL}(\gamma \mathrm{p} \rightarrow \mathrm{p}\pi^0\eta)$

➜ Background $\leq 1\,\%$ ($E_{\mathrm{e}^-} = 1.4$ GeV)

➜ Clear observation of $\mathrm{p}\pi^0\pi^0$ and $\mathrm{p}\pi^0\eta$ final states

Analysis of $\gamma p \to p\pi^0\pi^0$: Search for $N^*/\Delta^* \to \Delta\pi$



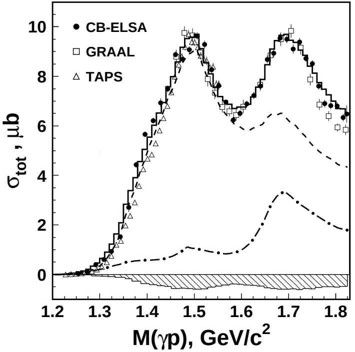
Event-based Maximum Likelihood Fit
(Phys. Lett. B **659**, 87 (2008))

Further Constraints

- $\gamma p \to p\pi^0$ (CB-ELSA, TAPS, GRAAL) beam and target asymmetries, recoil polarization, $d\sigma/d\Omega$
- $\gamma p \to p\pi^0\pi^0$ (GRAAL, TAPS) $\pi^- p \to n\pi^0\pi^0$ (Crystal Ball)
- $\gamma p \to p\eta$ (CB-ELSA, GRAAL, TAPS)
- $\gamma p \to K\Lambda, K\Sigma$ (CLAS, SAPHIR)

- Mass region below 1.7 GeV/c^2 dominated by $\Delta^+\pi^0 \to p\pi^0\pi^0$ — — —
- Significant contributions from $N(\pi\pi)_{S-wave}$ — · — · —

Analysis of $\gamma p \to p\pi^0\pi^0$ (CB-ELSA)



Main Results

- Observation of decays into $\Delta\pi$, $N(\pi\pi)_S$, $N(1440)P_{11}\pi$, $N(1520)D_{13}\pi$
- $N(1900)P_{13}$ needed by CLAS spin-transfer data in hyperon photoproduction
- Properties of $N(1720)P_{13}$ disagree with PDG values (decay mode $\Delta\pi$ strong, Γ_{tot})
  - ➜ Discrepancies interpreted as new P_{13} state by MSU-JLab group
- $N(1520)D_{13}$ decays into $(\Delta\pi)_{S-wave}$ as strong as decays into $(\Delta\pi)_{D-wave}$

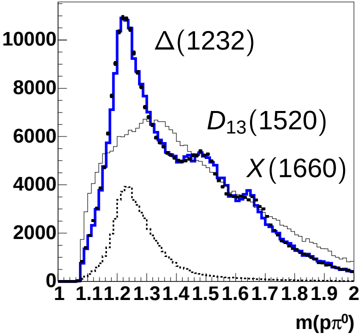
- Mass region below 1.7 GeV/c^2 dominated by $\Delta^+\pi^0 \to p\pi^0\pi^0$ — — —
- Significant contributions from $N(\pi\pi)_{S-wave}$ — · — · —

Analysis of $\gamma p \to p\pi^0\pi^0$ (CB-ELSA)

Clear observation of baryon decay cascades in $\gamma\mathrm{p} \to \mathrm{p}\pi^0\pi^0$:

- $\gamma\mathrm{p} \to \mathrm{N}^*/\Delta^* \to \Delta\pi$
- $\gamma\mathrm{p} \to \mathrm{N}^*/\Delta^* \to \mathrm{D}_{13}(1520)\pi$
- At $E_{e^-} = 3.2$ GeV:
  $\gamma\mathrm{p} \to \mathrm{N}^*/\Delta^* \to \mathrm{N}^*/\Delta^*(\sim 1660)\pi$

➜ N^*/Δ^* resonances not coupling to $\mathrm{N}\pi$ or $\gamma\mathrm{N}$ could be produced in such cascades



Analysis of $\gamma p \to p\pi^0\pi^0$ / $\pi^0\eta$ (CB-ELSA)

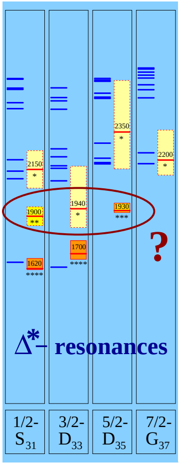
Clear observation of baryon decay cascades in $\gamma p \to p\pi^0\pi^0$:

- $\gamma p \to N^*/\Delta^* \to \Delta\pi$
- $\gamma p \to N^*/\Delta^* \to D_{13}(1520)\pi$
- At $E_{e^-} = 3.2$ GeV:
  $\gamma p \to N^*/\Delta^* \to N^*/\Delta^*(\sim 1660)\pi$

➜ N^*/Δ^* resonances not coupling to $N\pi$ or γN could be produced in such cascades

Channel $\gamma p \to p\pi^0\eta$ promising

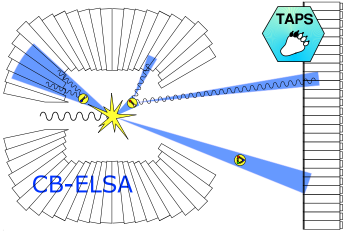
- $\Delta(1940)D_{33}$ strong in all solutions
- PWA solutions ambiguous: Polarization



U. Loering et al.

Outline

1. Introduction
2. Photoproduction of a Single Pseudoscalar Meson
   - η Photoproduction (off Proton and Neutron)
   - η' Photoproduction
3. Double-Meson Photoproduction
   - $\pi^0\pi^0$ Photoproduction
4. Toward Complete Experiments
   - What do we need?
   - Polarization
5. Summary and Outlook



(New) Baryon Resonances: Bonn-Gatchina PWA

Reaction	Resonances			
$\gamma p \to N\pi$	$\Delta(1232)P_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	$N(1535)S_{11}$
$\gamma p \to p\eta$	$N(1535)S_{11}$	$N(1720)P_{13}$	$N(2070)D_{15}$	$N(1650)S_{11}$
$\gamma p \to p\pi^0\pi^0$	$\Delta(1700)D_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	
$\gamma p \to p\pi^0\eta$	$\Delta(1940)D_{33}$	$\Delta(1920)P_{33}$	$N(2200)P_{13}$	$\Delta(1700)D_{33}$
$\gamma p \to \Lambda K^+$	$S_{11} - wave$	$N(1720)P_{13}$	$N(1900)P_{13}$	$N(1840)P_{11}$
$\gamma p \to \Sigma K$	$S_{11} - wave$	$N(1900)P_{13}$	$N(1840)P_{11}$	
$\pi^- p \to n\pi^0\pi^0$	$N(1440)P_{11}$	$N(1520)D_{13}$	$S_{11} - wave$	

The available data sets comprising various high-statistics differential cross sections, beam, target, recoil asymmetries, double polarization observables, and also data resolving isospin contributions are not yet sufficient to converge into a unique solution.

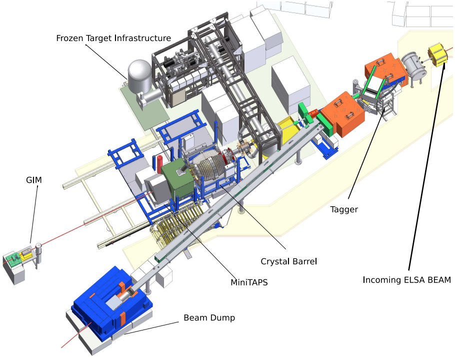
Ingredients

- Measurements off neutron and proton to resolve isospin contributions
  1. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=3/2} \quad \Longleftrightarrow \quad \Delta^*$
  2. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=1/2} \quad \Longleftrightarrow \quad N^*$
- Re-scattering effects: Large number of measurements (and also final states) needed to define the full scattering amplitude
- Double-polarization measurements

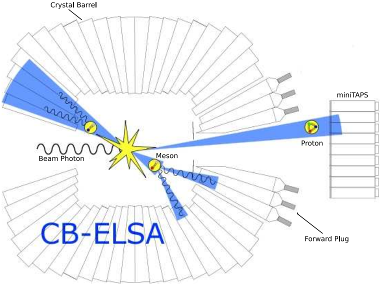
Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with the four single-spin observables.

CB-ELSA Layout 2006-



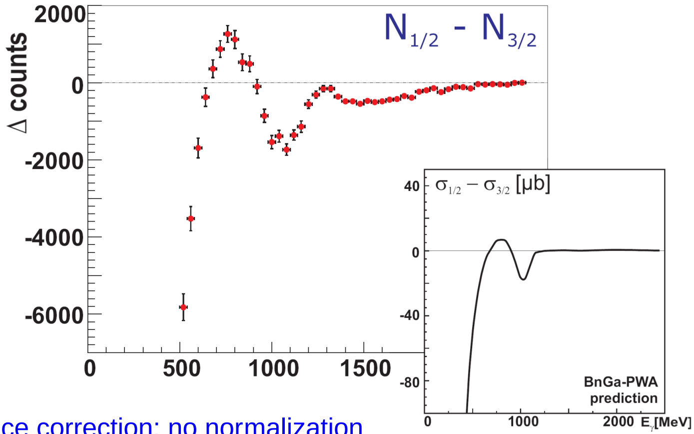
Target



- Polarized Target
- Polarized Beam Photons
- Excellent Photon Energy Detection
- Charged Particle Identification

Count Rate Difference $\gamma p \to p\pi^0$

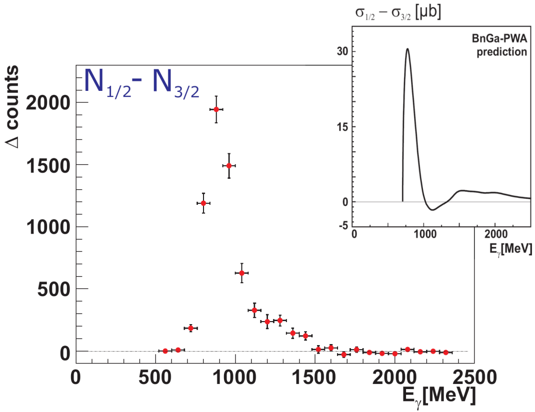
Circularly polarized photons and longitudinally polarized target



No acceptance correction; no normalization

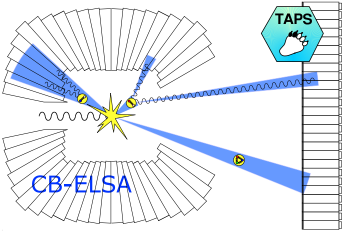
Count Rate Difference $\gamma p \longrightarrow p\eta$

Circularly polarized photons and longitudinally polarized target



No acceptance correction; no normalization

Outline



Summary and Outlook

HADRON 2009
Nov. 29 - Dec. 4

Tallahassee, Florida
Florida State University