Experimental Hadronic Physics at FSU

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Journal Club
11/05/2008

Outline

1. Introduction
   - The Quark Model of Hadrons
   - The Search for Gluonic Excitations
2. Baryon Spectroscopy
   - Photoproduction Experiments
   - The Next Generation: Linearly-Polarized Photon Beams
3. Double-Polarization Measurements
   - Experimental Setup(s)
   - Scientific Motivation
   - The CLAS FROST-Program
   - The CB-ELSA/TAPS Program
4. Summary and Outlook

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4 Summary and Outlook

The Quark Model of Hadrons

- Mesons ($q\bar{q}$) $\quad q \otimes \bar{q} = 3 \otimes \bar{3} = 8 \oplus 1$

- Baryons (qqq) $\quad q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Ordinary matter ...

The Quark Model of Hadrons

- Mesons ($q\bar{q}$) $\quad \mathrm{q} \otimes \bar{\mathrm{q}} = 3 \otimes \bar{3} = 8 \oplus 1$

- Baryons (qqq) $\quad \mathrm{q} \otimes \mathrm{q} \otimes \mathrm{q} = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Ordinary matter, however, QCD also predicts so-called exotic states

➜ simplest possibility: $\underbrace{\mathrm{q} \otimes \bar{\mathrm{q}} \otimes \mathrm{q} = 15 \oplus 6 \oplus 3 \oplus 3}$

Does not work: color singlets needed !

➜ multiple of (qqq) and ($q\bar{q}$) necessary

- Glueballs: $\mathrm{g} \otimes \mathrm{g} = 8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus \boxed{1}$
- Hybrids: $\mathrm{q} \otimes \bar{\mathrm{q}} \otimes \mathrm{g} = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 8 \oplus \boxed{1}$ ➜ $\boxed{(\mathrm{q}\bar{\mathrm{q}})^{\mathrm{l}}((\mathrm{q})^3)^{\mathrm{m}}(\mathrm{g})^{\mathrm{n}}}$,

$l + m \geq 1$ for $\mathrm{n} = 1$

The Search for New Forms of Matter

All exotic states of hadrons can be subdivided into three groups:

1. States with explicitly exotic values of principal quantum numbers

Θ^+	with $S = 1$
Ξ^{--}	with $Q = -2$

The Search for New Forms of Matter

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1. States with explicitly exotic values of principal quantum numbers

$$\Theta^+ \quad \text{with } S = 1$$
$$\Xi^{--} \quad \text{with } Q = -2$$

2. States with exotic combinations of J^{PC}
   $\Rightarrow$ forbidden for ordinary $q\bar{q}$ states:
   $0^{+-},\ 0^{--},\ 1^{-+},\ 2^{+-},\ 3^{-+},$ etc.

$$\left.\begin{array}{l}\pi_1(1400) \rightarrow \eta\pi^- \\ \pi_1(1600) \rightarrow \eta'\pi^-\end{array}\right\} 1^{-+}$$

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   $$\left.\begin{array}{l}\pi_1(1400) \rightarrow \eta\pi^- \\ \pi_1(1600) \rightarrow \eta'\pi^-\end{array}\right\} 1^{-+}$$

3. States with hidden exotic properties
   $\Rightarrow$ Problem: predicted glueballs can mix with ordinary $q\bar{q}$ states

   $$\mathrm{f}_0(1500) \,\} \; J^{PC} = 0^{++}$$

Evidence far from solid
$\Rightarrow$ Details needed for a full understanding are missing

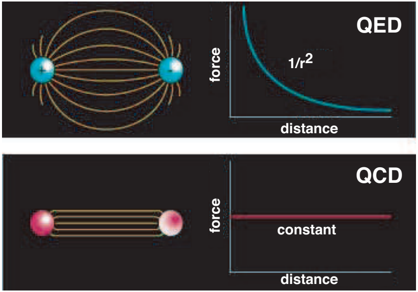
The Experimental Status of Glueballs

Nuclear seminar talk next month ... (or next semester)

In summary: Is there evidence for glueballs?

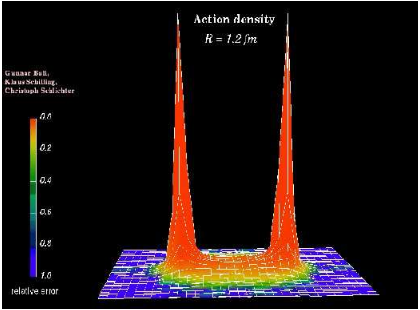
- Lightest 0^{++} glueball: possible ... $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
- Lightest 0^{-+} glueball: maybe ... $\eta(1295)$, $\eta(1405)$, $\eta(1490)$
- Lightest 2^{++} glueball: well, there is not even a candidate ...

The Search for Hybrids: Flux Tubes



Color Fields: Because of self interaction between gluons, confining flux tubes form between static color charges.

Confinement arises from flux tubes and their excitation leads to a new spectrum of mesons.

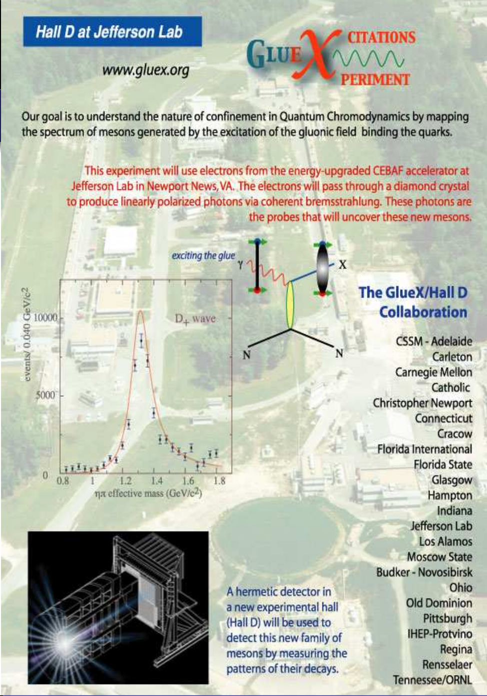


G. Bali *et al.*, *Phys. Rev.* **D62**, (2000) 054503

The GlueX Collaboration

- ≈ 100 Physicists
- Members from 7 countries
  - Australia
  - Canada, Mexico, USA
  - Greece, Russia, Scotland
- Active group since 1998

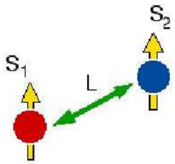
➜ http://www.gluex.org



Ordinary Mesons

$J^{PC} \equiv {}^{2S+1}L_J$

- Parity $P = (-1)^{L+1}$
- Charge conjugation (defined for neutral mesons) $C = (-1)^{L+S}$
- G parity $G = C(-1)^I$

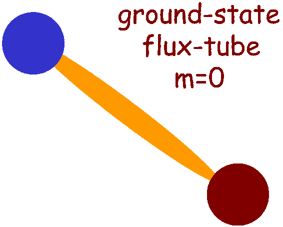


$L = 0,\ S = 1:$

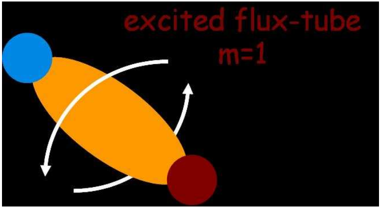
$\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$

$L = 0,\ S = 0:$

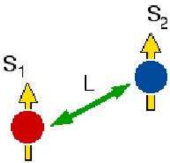
e.g. $\pi\ (J^{PC} = 0^{-+})$



Hybrid Mesons



flux tube $J^{PC} = 1^{+-}$ or 1^{-+}
(from lattice QCD and flux-tube models)



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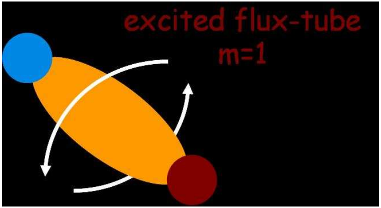
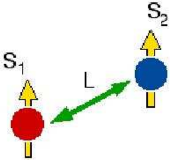
Hybrid Mesons





$\underline{L = 0,\ S = 1:}$

$\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$

$\underline{L = 0,\ S = 0:}$

e.g. $\pi\ (J^{PC} = 0^{-+})$

$_{\text{flux tube}} J^{PC} = 1^{+-}$ or 1^{-+}

Pseudoscalar Mesons: $_{\text{quarks}} J^{PC} \otimes {}_{\text{flux tube}} J^{PC} = 1^{--},\ 1^{++}$

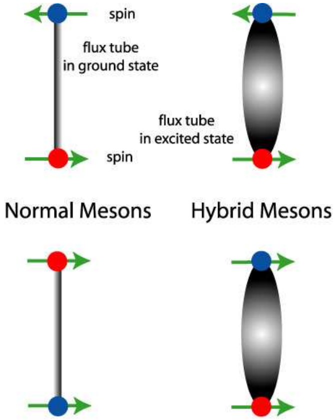
Vector Mesons: $_{\text{quarks}} J^{PC} \otimes {}_{\text{flux tube}} J^{PC} =\ 0^{-+},\ \boxed{1^{-+}},\ 2^{-+}$

$\boxed{0^{+-}},\ 1^{+-},\ \boxed{2^{+-}}$

Hybrid-Meson Production

One result of the scattering process of an incoming probe off the target particle can be the excitation of the flux tube:

- Not favored for $q\bar{q}$ probe in $L = 0$ and $S = 0$



- Favored for incoming vector probes with $L = 0$ and $S = 1$

➜ Photoproduction

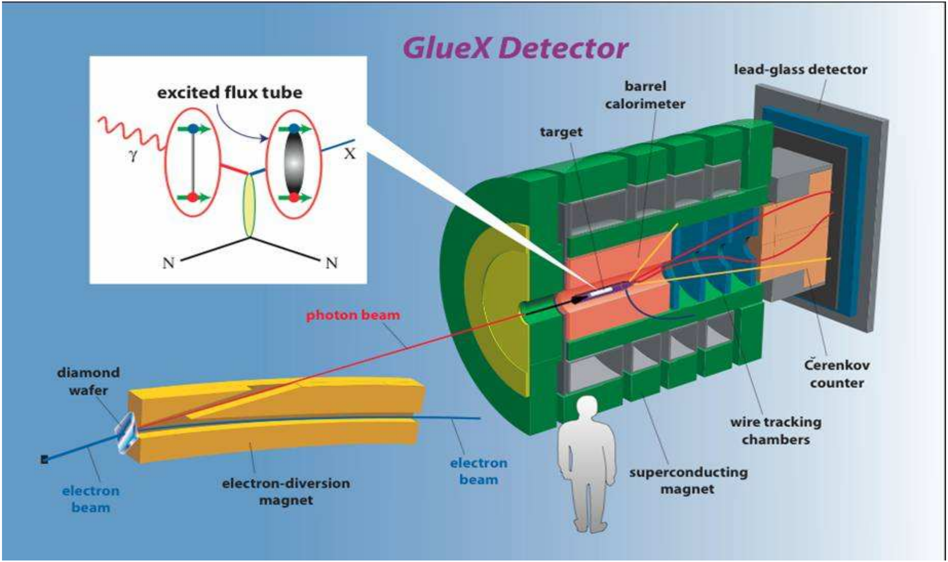
The GlueX Experiment

To establish the existence of gluonic excitations, the existence and nonet nature of the 1^{-+} state needs to be established.

➜ Also, 0^{+-} and 2^{+-} nonets need to be established.

Decay pattern are crucial:

Have provided the most sensitive information in the scalar glueball sector


GlueX Detector
excited flux tube
γ
X
N
N
photon beam
diamond wafer
electron beam
electron-diversion magnet
electron beam
target
barrel calorimeter
lead-glass detector
Čerenkov counter
wire tracking chambers
superconducting magnet

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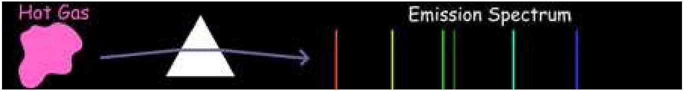
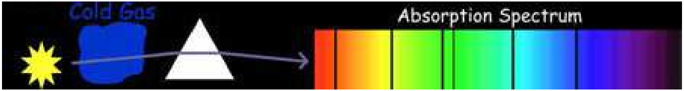
Spectroscopy

Atomic spectra allow access to QED



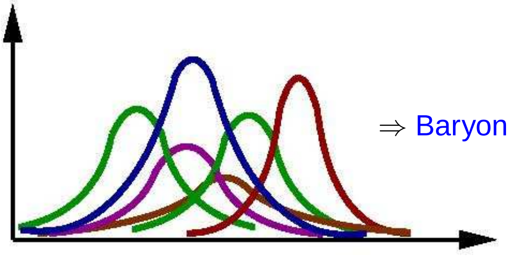


- Discrete spectrum of absorption and emission lines

$\Rightarrow$ Does excitation spectrum of nucleon provide access to QCD ?

The Challenges in Baryon Spectroscopy

Unfortunately, N^* spectral lines look more like



$\Rightarrow$ Baryons are broad and overlapping

- Rescattering Effects
  $\Rightarrow$ Require Coupled-Channel Analysis
  (need to measure as many final states as possible)
- Polarization (need complete experiments)

General Physical Motivation

Search for *missing* resonances

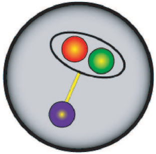
Quark models predict many more baryons than have been observed

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

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

Possible solutions:

a) Quark-diquark structure



one of the internal degrees of freedom is frozen

b) They have not been observed, yet

Nearly all existing data result from πN scattering experiments

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

Quark Models and Experimental Overview

Effective theories and models necessary to make spectroscopic predictions

Basic assumption: linear confinement potential + residual short-range interaction

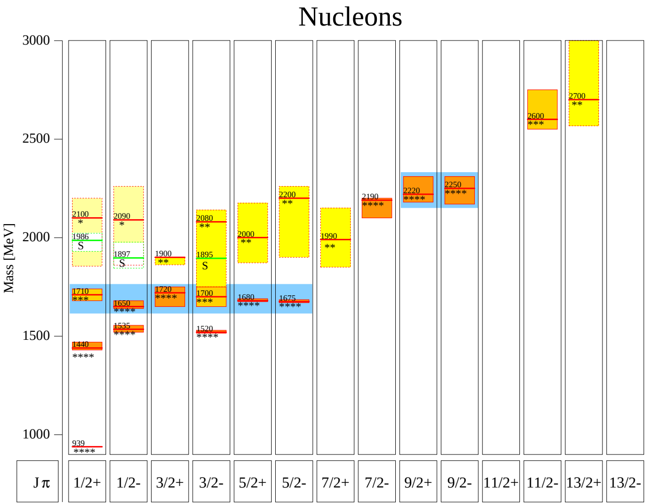
- Goldstone-boson (pion) exchange
  (L.Y. Glozman, W. Plessas, K. Varga and R.F. Wagenbrunn, Phys. Rev. **D58** (1998) 094030)
- One-gluon exchange (S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809)
  (*relativized* quark model)
  1. Wrong spin-orbit couplings
  2. No explanation for parity doublets
- Instanton-induced interaction
  (relativistic quark model)
  1. Acceptable Regge trajectories
  2. Natural explanation for parity doublets

$\Rightarrow$ Which is the right model ?

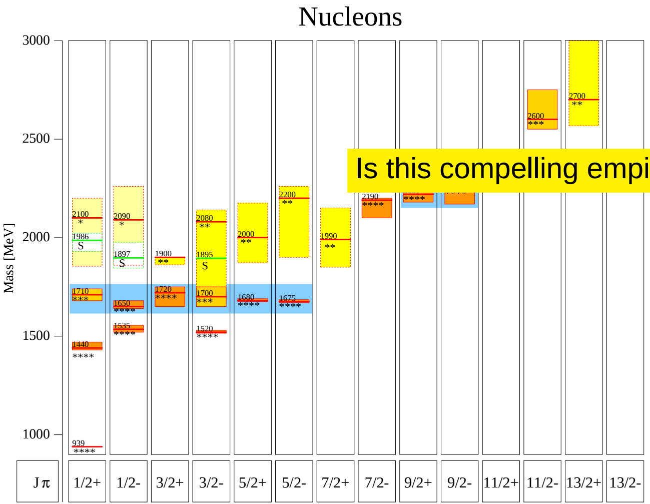
1. Do we have *the* correct model?
2. Does one interaction dominate?

Striking feature in the spectra : States of same total angular momentum but opposite parity

Parity Doublets

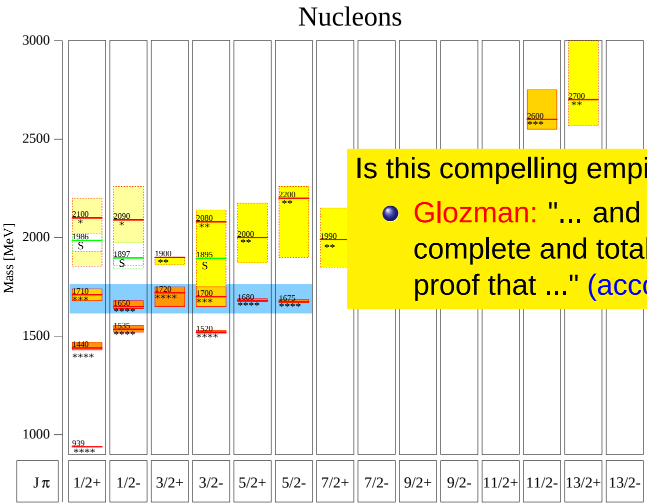


Parity Doublets



Is this compelling empirical data?

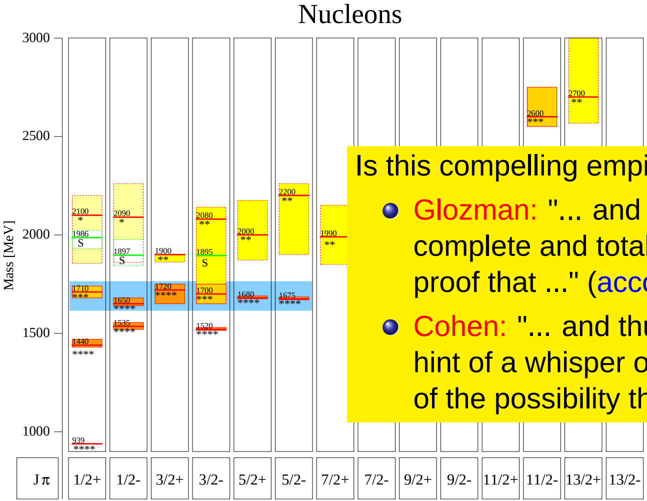
Parity Doublets



Is this compelling empirical data?

- Glozman: "... and thus we have a complete and total, 100 % ironclad proof that ..." (according to T. Cohen)

Parity Doublets

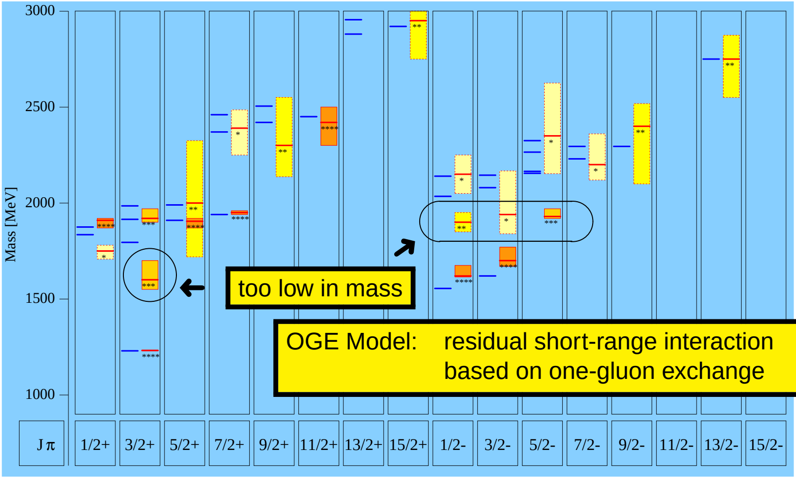


Is this compelling empirical data?

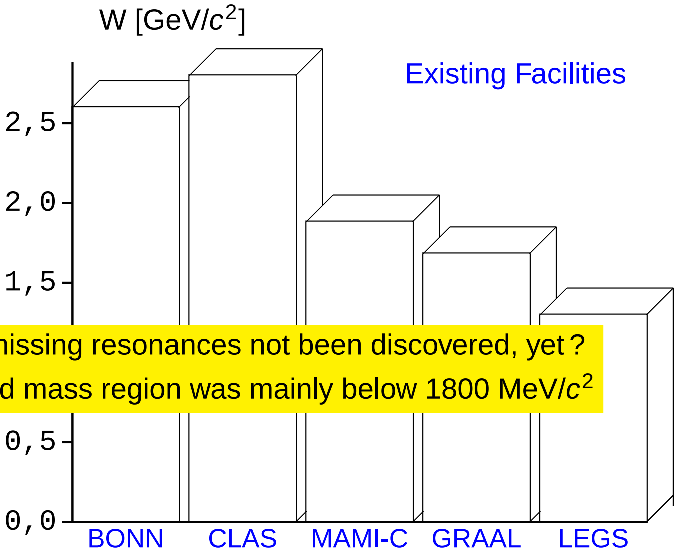
- Glozman: "... and thus we have a complete and total, 100 % ironclad proof that ..." (according to T. Cohen)
- Cohen: "... and thus we have a faint hint of a whisper of the suggestion of the possibility that perhaps ..."

Δ Resonances

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

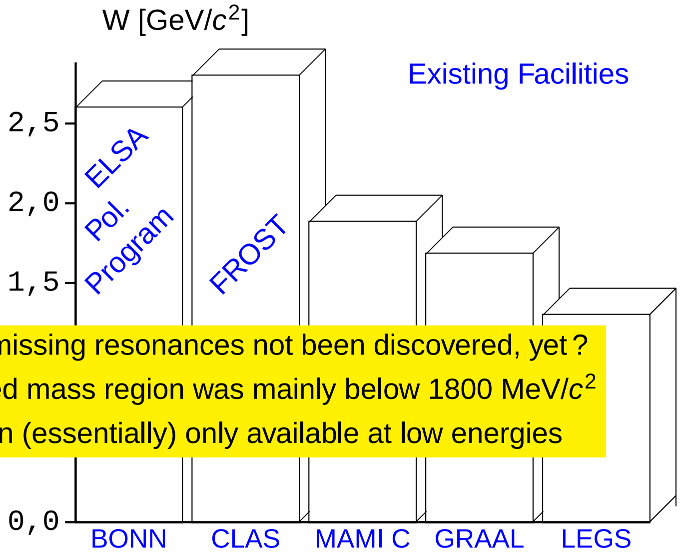


OGE Model: residual short-range interaction based on one-gluon exchange



Why have the missing resonances not been discovered, yet ?

- Investigated mass region was mainly below 1800 MeV/c^2



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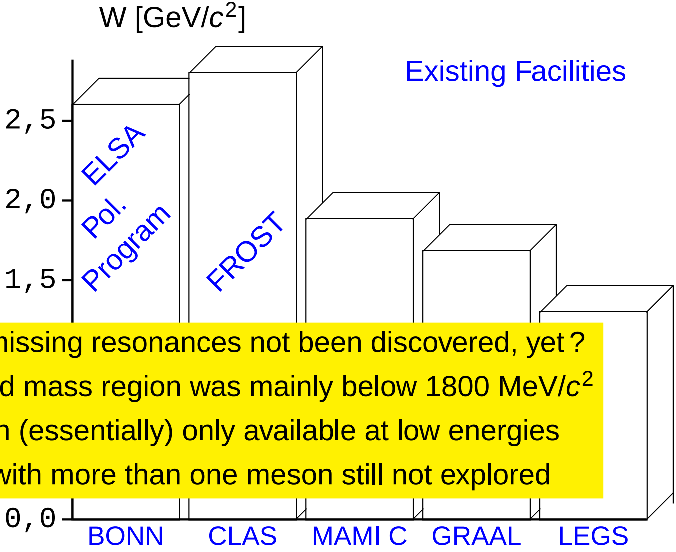
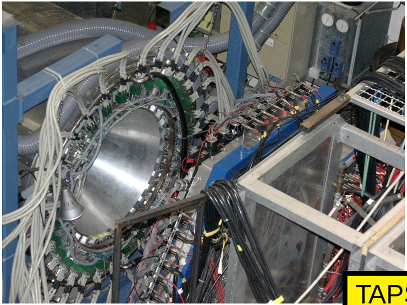


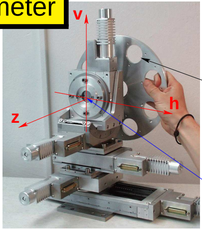
Why have the missing resonances not been discovered, yet ?

- Investigated mass region was mainly below 1800 MeV/c^2
- Polarization (essentially) only available at low energies
- Channels with more than one meson still not explored

The CB-ELSA/TAPS Experiment



Goniometer

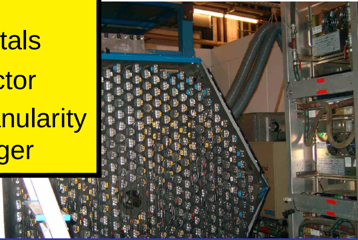


Sep. 2002 – Dec. 2003

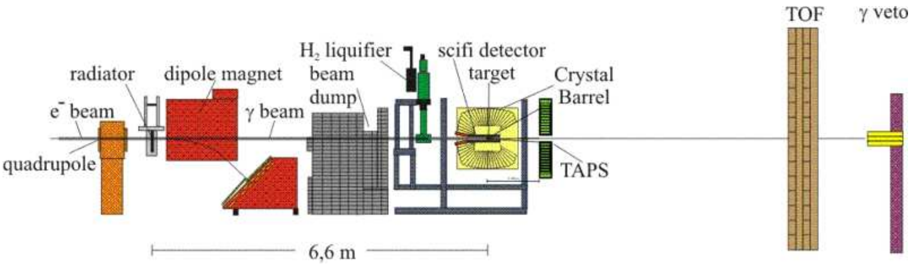
- (un)polarized beam
- liquid H_2, deuterium
- solid targets

TAPS

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



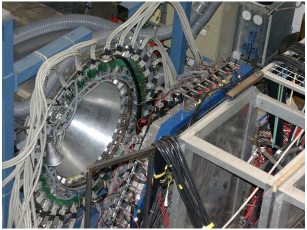
Experimental Setup



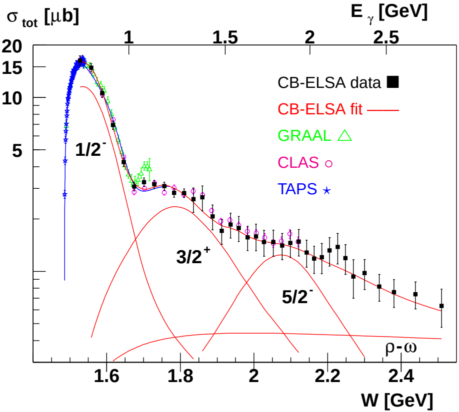
Tagged Photons (E_{e^-} = 3.2 GeV):

- $0.25 \cdot E_{e^-} \leq E_\gamma \leq 0.95 \cdot E_{e^-}$

➜ 800 MeV $\leq E_\gamma \leq$ 3000 MeV



Previous Study of the Reaction $\gamma p \longrightarrow p\eta$



Isospin Filter

➜ Only N^* resonances can contribute!

Hint for N^* resonance $N(2070)D_{15}$

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

1. Needs confirmation!
2. No need for third S_{11}

Three resonances are dominantly contributing!

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

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

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

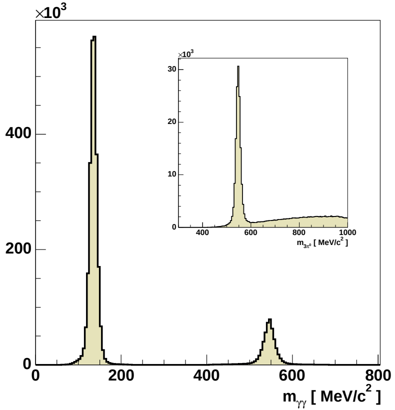
- Relativistically invariant
- Based on kinematic factors related to momenta of incoming and outgoing particles

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

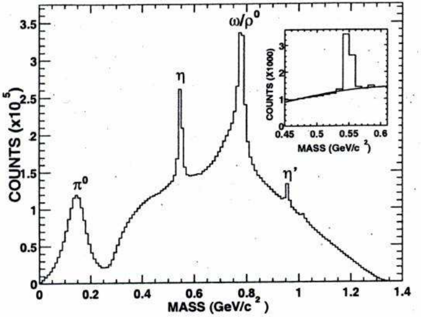
New Data: Study of $\gamma p \longrightarrow p\eta$ with CB-ELSA/TAPS



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

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

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



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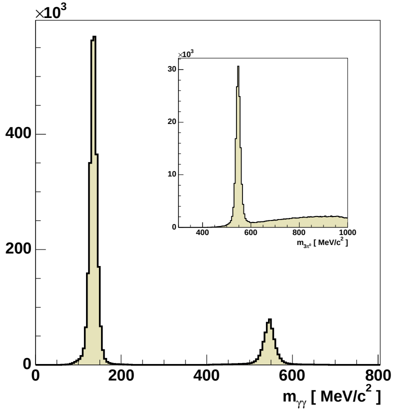
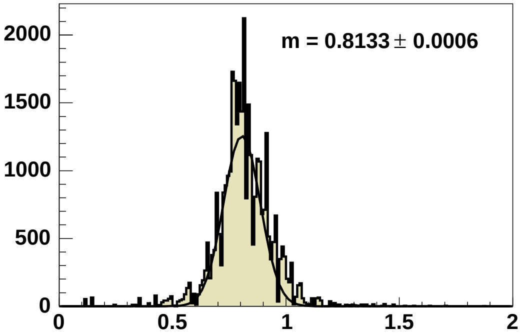


← $\left\{ \begin{array}{l} \eta \;\to\; 3\pi^0, \gamma\gamma \\ (\mathrm{CB-ELSA/TAPS}) \end{array} \right.$

Reconstruction

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

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



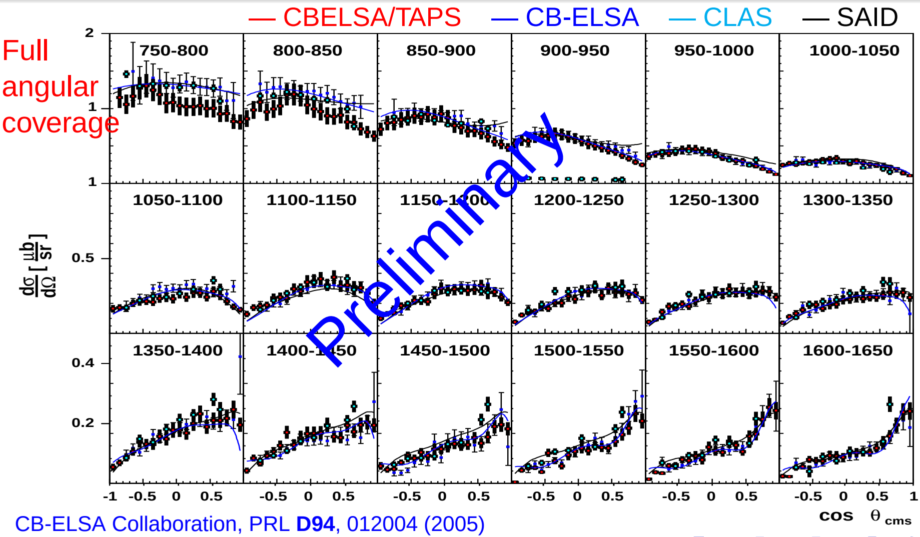
$$\left\{ \frac{d\sigma^{(\eta\to 3\pi^0)}}{d\Omega} \Big/ \frac{d\sigma^{(\eta\to\gamma\gamma)}}{d\Omega} \right.$$

(CBELSA/TAPS)

Both decay modes can be added! We have used:

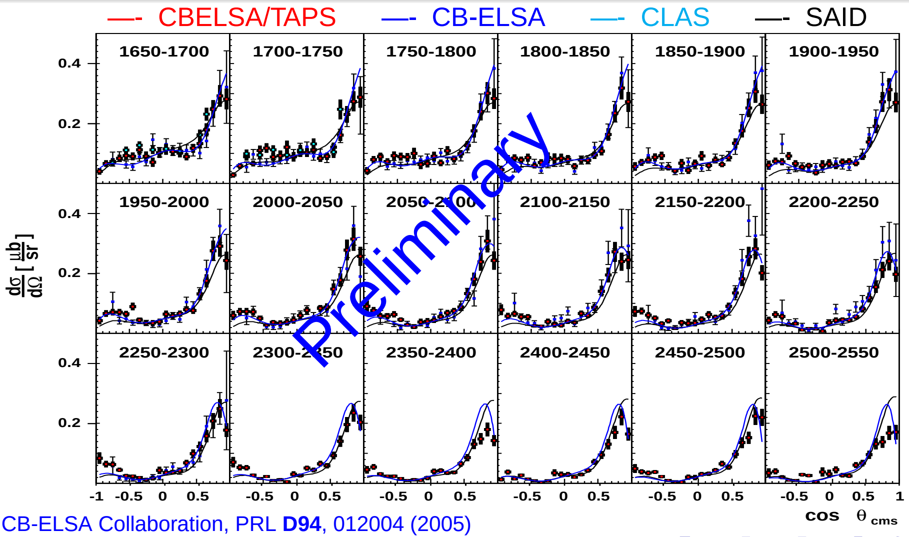
- BR $(\eta \to \gamma\gamma)$ = 39.43 %
- BR $(\eta \to 3\pi^0)$ = 32.51 %

Differential Cross Sections for $\gamma p \rightarrow p\eta$



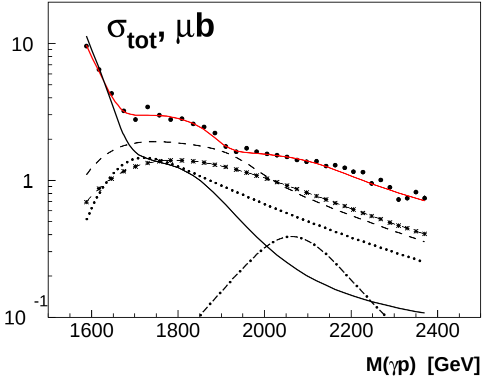
CB-ELSA Collaboration, PRL **D94**, 012004 (2005)

Differential Cross Sections for $\gamma p \longrightarrow p\eta$



CB-ELSA Collaboration, PRL **D94**, 012004 (2005)

Total Cross Section for the Reaction $\gamma p \to p\eta$



The angular coverage of CB-ELSA data allows determination of the total cross section

Hint for N^* resonance $(2070)D_{15}$
(Phys. Rev. Lett. **D94**, 012004 (2005))

1. Needs confirmation!
2. No need for third S_{11}

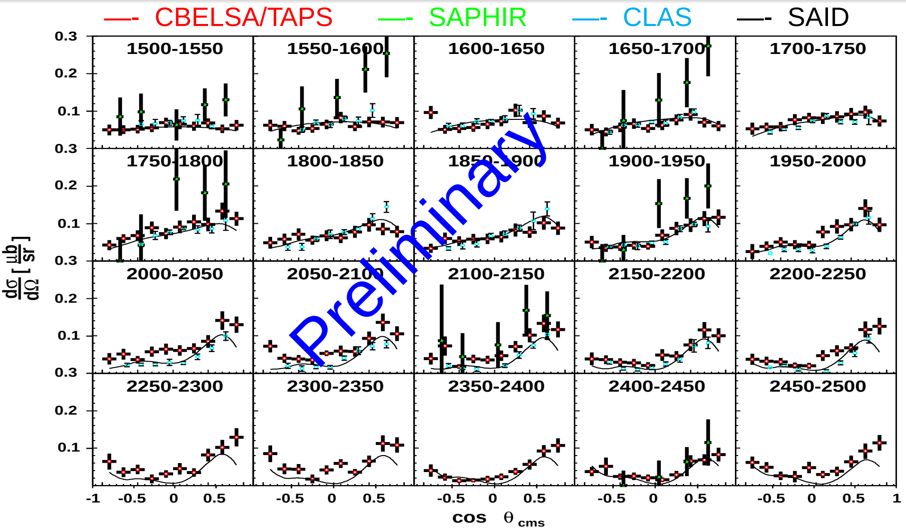
New Data: Study of γ p $\longrightarrow$ p η' with CB-ELSA/TAPS

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)
- 2007: New data from CBELSA/TAPS over the full angular range

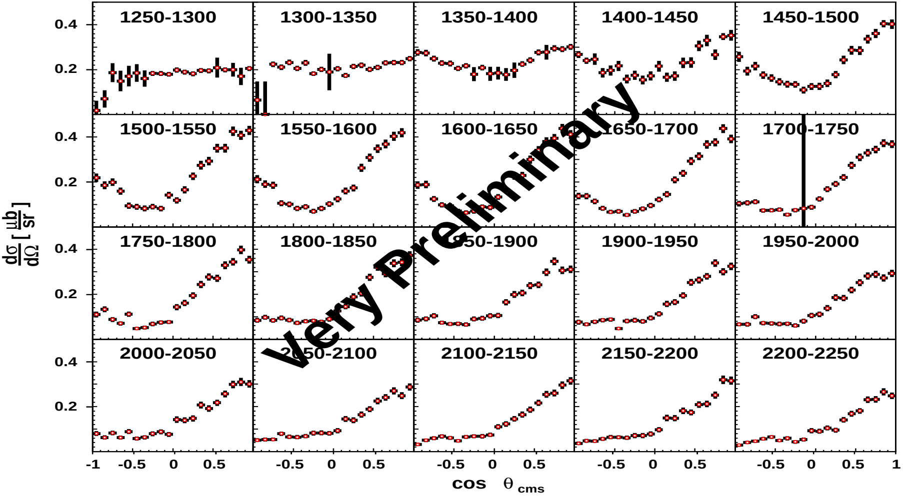
No published asymmetry data for η'...
(Data available from CLAS and ELSA)

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

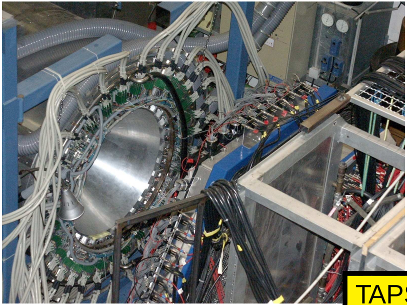


Differential Cross Sections for $\gamma p \to \Delta\eta$

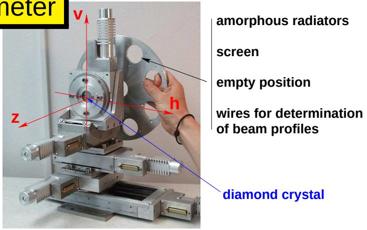
Anna Woodard, Honors Thesis



Linearly-Polarized Photons: CB-ELSA/TAPS



Goniometer



Sep. 2002 – Dec. 2003

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

TAPS

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

Beam-Target Polarization Observables

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \, \Sigma \cos 2\phi + \Lambda_x (-\delta_l \, \mathbf{H} \sin 2\phi + \delta_\odot \, \mathbf{F}) - \Lambda_y (-\mathbf{T} + \delta_l \, \mathbf{P} \cos 2\phi) - \Lambda_z (-\delta_l \, \mathbf{G} \sin 2\phi + \delta_\odot \, \mathbf{E}) \}$$

$\Leftarrow$ Single-Meson Final States (7 Observables)

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\odot) + \delta_l [\sin 2\beta (\mathbf{I}^s + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^s) \cos 2\beta (\mathbf{I}^c + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^c)] \}$$

Two-Meson Final States $\Rightarrow$ (15 Observables)

The CLAS Polarization Program

The Double-Polarization Program (FROST) at JLab:

- E 02-112 $\Rightarrow$ *Photoproduction of Hyperons* $(K^+\Lambda\ (\Sigma^0),\ K^0\Sigma^+)$
- E 03-105 $\Rightarrow$ $\pi^0 p,\ \pi^+ n$ *Photoproduction*
  E 04-102
- E 05-012 $\Rightarrow$ η *Photoproduction*
- E 06-013 $\Rightarrow$ $\pi^+\pi^-$ *Photoproduction*

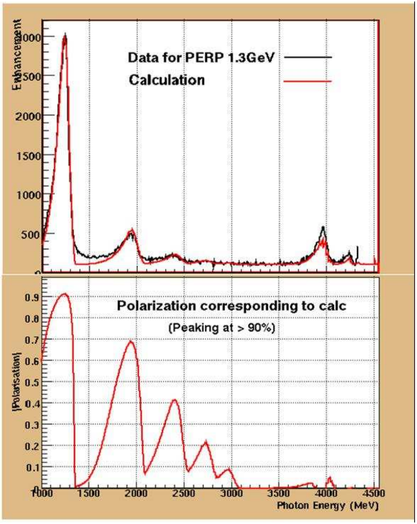
The Polarized Deuterium-Target Program (HD-Ice target from BNL):

- E 06-101 $\Rightarrow$ $\gamma n \rightarrow \pi^- p,\ \pi^+\pi^- n,\ K\,Y\ (K^0\Lambda,\ K^0\Sigma^0,\ K^+\Sigma^-)$

Polarized photon beams on unpolarized targets:

- g1, g8 $\Rightarrow$ Reactions on Hydrogen $(\checkmark)$
- g13 $\Rightarrow$ Reactions on Deuterium $(\checkmark)$

The Coherent Bremsstrahlung Facility at CLAS

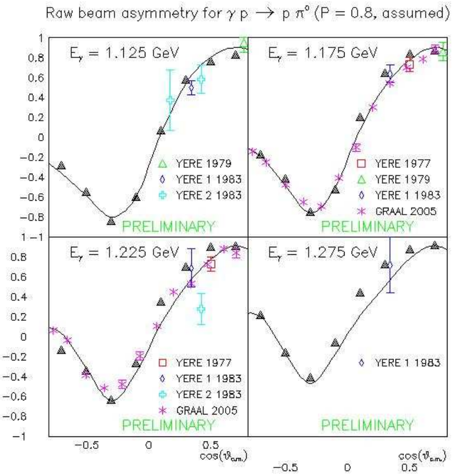


g8b Run Group (data from 2005)

Bremsstrahlung in 50 μ diamond:

- 40 cm liquid hydrogen target located 20 cm upstream
- Two linear polarization states (vertical & horizontal)
- Incident electron energy from CEBAF of 4.55 GeV
  ➜ 1.0 GeV < E_γ < 2.1 GeV
- Single-charged particle trigger

Linearly-Polarized Beam at JLab: g8b Run Group

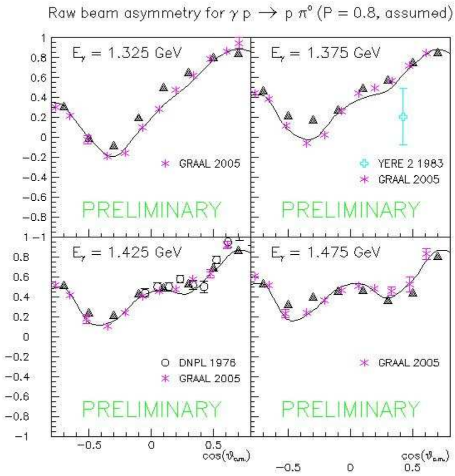


- Many channels being analyzed:
- High statistics > 10 billion events
- High photon polarization from 1.3 – 2.1 GeV

⇐ Preliminary analysis of $\gamma p \rightarrow p\pi^0$ (Mike Dugger, ASU)

- P_γ estimated at 0.8
- — SAID prediction
- Data with statistical errors (no systematic)

Linearly-Polarized Beam at JLab: g8b Run Group



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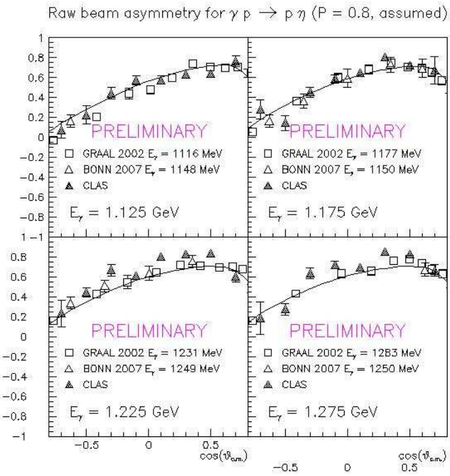
Linearly-Polarized Beam at JLab: g8b Run Group



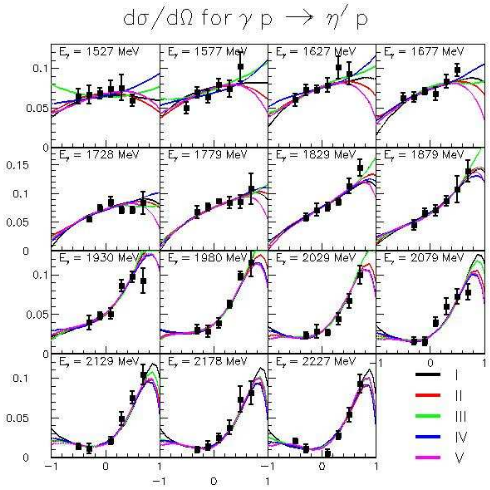
Good agreement with other data

- Interpretation of Bonn (PWA) and CLAS data (SAID) different: $P_{13}(1720) \Leftrightarrow P_{11}(1710)$

Preliminary analysis of $\gamma p \to p\eta$ (Mike Dugger, ASU)

- P_γ estimated at 0.8
- — SAID prediction
- Data with statistical errors (no systematic)

Linearly-Polarized Beam at JLab: g8b Run Group



Set IV

N(1535)S_{11}, N(2090)S_{11}

N(1710)P_{11}, N(2100)P_{11}

N(1700)D_{13}, N(2080)D_{13}

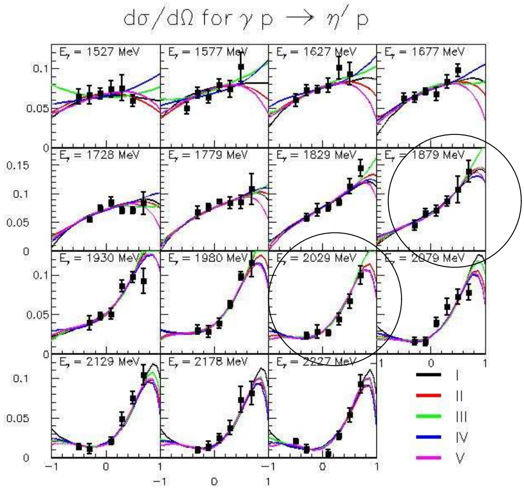
Similar to η analysis:

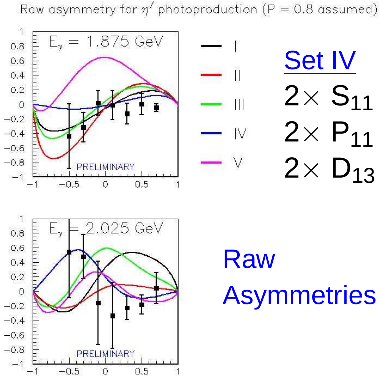
N(1535)S_{11} and N(1710)P_{11} dominant (SAID, MAID)!

Analysis of $\gamma p \to p\eta\prime$

Phys. Rev. Lett. **96**, 062001 (2006)

Linearly-Polarized Beam at JLab: g8b Run Group





Set IV

$2\times$ S_{11}

$2\times$ P_{11}

$2\times$ D_{13}

Raw Asymmetries

Analysis of $\gamma p \to p\eta'$

Phys. Rev. Lett. **96**, 062001 (2006)

Outline

1 Introduction
- The Quark Model of Hadrons
- The Search for Gluonic Excitations

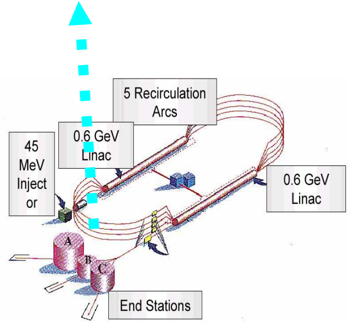
2 Baryon Spectroscopy
- Photoproduction Experiments
- The Next Generation: Linearly-Polarized Photon Beams

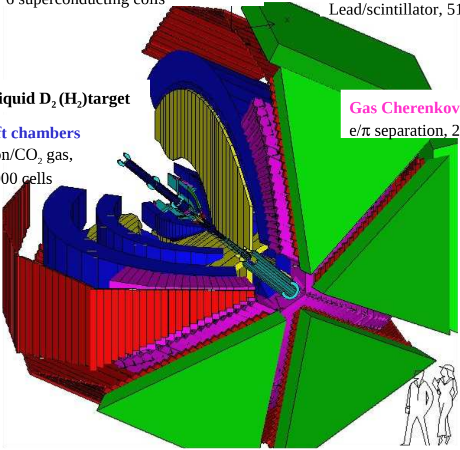
3 Double-Polarization Measurements
- Experimental Setup(s)
- Scientific Motivation
- The CLAS FROST-Program
- The CB-ELSA/TAPS Program

4 Summary and Outlook

CEBAF Large Acceptance Spectrometer

Hall B





Torus magnet
6 superconducting coils

Large angle calorimeters
Lead/scintillator, 512 PMTs

Liquid D_2 (H_2)target

Gas Cherenkov counters
e/π separation, 216 PMTs

Drift chambers
argon/CO_2 gas,
35,000 cells

Electromagnetic calorimeters
Lead/scintillator, 1296 PMTs

Time-of-flight counters
plastic scintillators, 684 PMTs

Planned Measurements ...

The Double-Polarization Program (FROST) at JLab:

- E 02-112 $\Rightarrow$ *Photoproduction of Hyperons* ($K^+\Lambda$, $K^+\Sigma^0$, $K^0\Sigma^+$)
- E 03-105 $\Rightarrow$ $\pi^0 p$, $\pi^+ n$ *Photoproduction*
  E 04-102
- E 05-012 $\Rightarrow$ η *Photoproduction*
- E 06-013 $\Rightarrow$ $\pi^+\pi^-$ Photoproduction

The Double-Polarization Program at ELSA (Crystal Barrel Experiment):

(among many other proposals)

- ELSA 6/2005 $\Rightarrow$ $\pi^0\pi^0$ *Photoproduction*
- ELSA 7/2005 $\Rightarrow$ $\pi^0\eta$ *Photoproduction*

Beam-Target Polarization Observables

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l \mathbf{H} \sin 2\phi + \delta_\odot \mathbf{F}) - \Lambda_y (-\mathbf{T} + \delta_l \mathbf{P} \cos 2\phi) - \Lambda_z (-\delta_l \mathbf{G} \sin 2\phi + \delta_\odot \mathbf{E}) \}$$

⇐ Single-Meson Final States (7 Observables)

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\odot) + \delta_l [\sin 2\beta (\mathbf{I}^s + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^s) \cos 2\beta (\mathbf{I}^c + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^c)] \}$$

Two-Meson Final States ⇒ (15 Observables)

Motivation for $\gamma p \longrightarrow p\pi^+\pi^-$: Low-Energy Regime

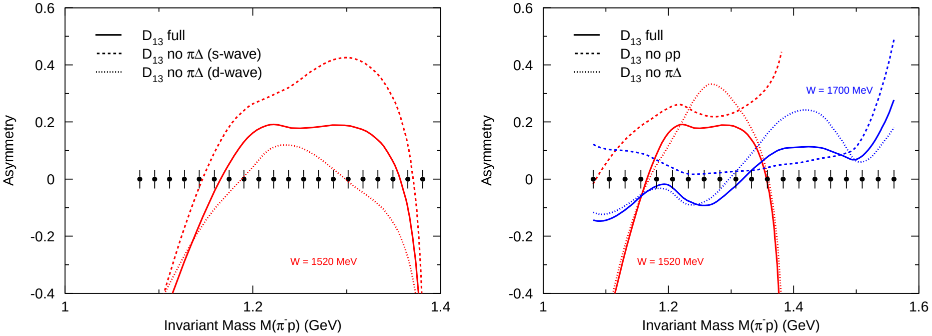
- $P_{11}(1440)$ (*Roper Resonance*) $\longrightarrow$ too low in mass ?
  - dynamically-generated resonance effect
  - state with a strong gluonic component
  - small (qqq)-component with a substantial contribution from the meson cloud

  $\Rightarrow$ Parameters depend strongly on data and analysis

- Contribution of $D_{13}(1520)$ to $\gamma p \longrightarrow p\pi^+\pi^-$ cross section
  - Different interpretations of $\gamma p \rightarrow p\pi^+\pi^-$ total cross section data
    - Oset et al.: $D_{13}(1520) \longrightarrow \Delta\pi$ dominant contribution
    - Laget et al.: $P_{11}(1440) \longrightarrow p\sigma$ dominant
  - $D_{13}(1520) \longrightarrow \Delta\pi$ in D-wave (PDG: 10–14 %) and S-wave (5–12 %) ?

- $P_{33}(1600)$ (*Roper Resonance* of Δ system) $\longrightarrow$ too low in mass ?

Model Calculations of $P_z^{\odot}$ (known as E) by A. Fix

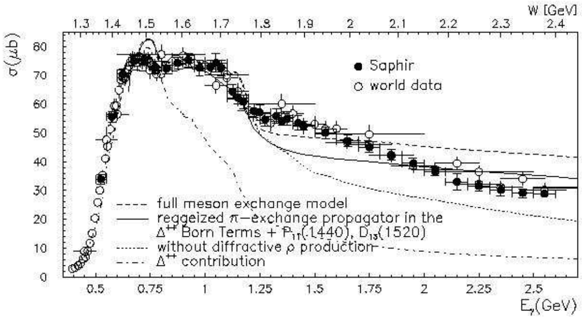


⇒ Can clearly distiguish between solutions if $\Delta A \leq 0.05$

⇒ Reality will be a mixture of S-/D-wave!

⇒ Needs very small errors to distinguish between different contributions !

Motivation for $\gamma p \to p\pi^+\pi^-$: Medium-Energy Regime



3^{rd} resonance region

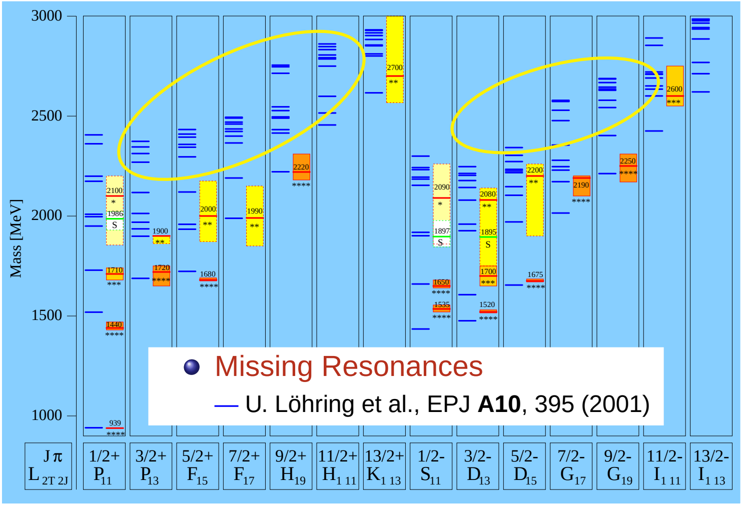
- $F_{15}(1680)$
- $D_{13}(1700)$
- $D_{33}(1700)$
- $P_{13}(1720)$

How to disentangle ?

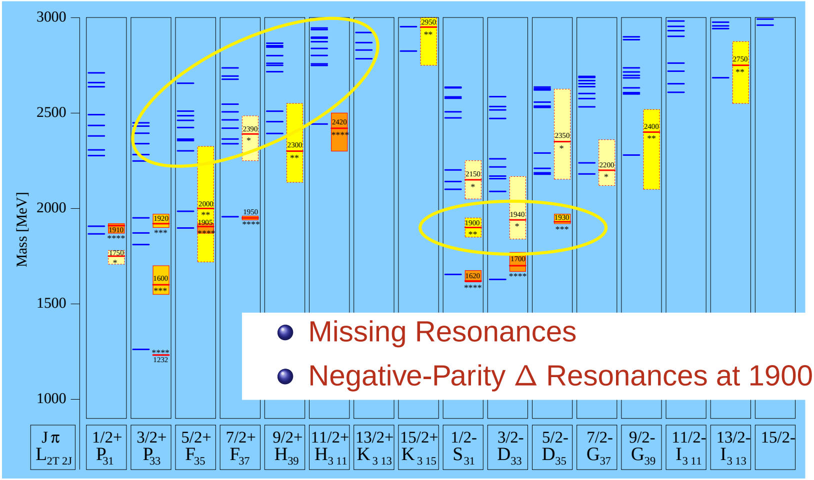
Discrepancy of CLAS $P_{13}(1720)$ with PDG: two close-by P_{13} states ?

$\Rightarrow$ This would be in contradiction with quark models !

Motivation: High-Energy Regime $\longrightarrow$ N* Spectrum



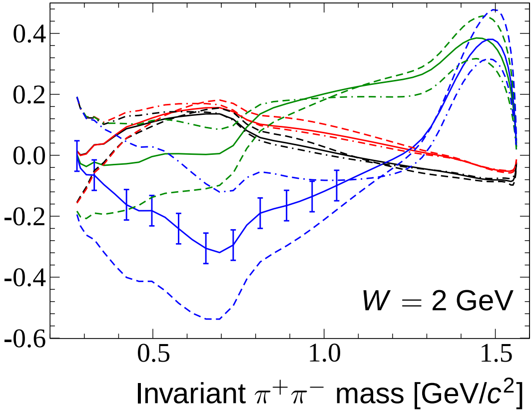
Motivation: High-Energy Regime $\rightarrow$ Δ^* Spectrum



- Missing Resonances
- Negative-Parity Δ Resonances at 1900 MeV/c^2

Model Calculations of $P_x^{\odot}$ by W. Roberts

$\phi = 0.0035$ rad (almost 0), $\phi = 0.56$ rad, $\phi = 2.09$ rad, $\phi = 3.04$ rad (almost π)



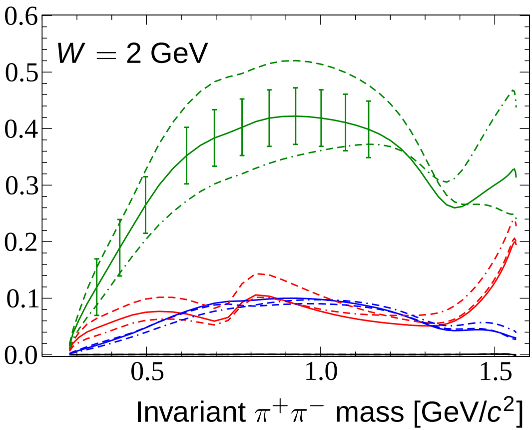
Circ. Beam → Trans. Target

- Solid Line
  Full Calculation
- Dashed Line
  $S_{11}(1900)$ Omitted
- Dashed-Dotted Line
  $P_{31}(1910)$ Omitted

$\Rightarrow$ goal: $\Delta\, P_x^{\odot} \leq 0.05$

Model Calculations of $P_y^\odot$ by W. Roberts

$\phi = 0.0035$ rad (almost 0), $\phi = 0.56$ rad, $\phi = 2.09$ rad, $\phi = 3.04$ rad (almost π)



Circ. Beam → Trans. Target

- Solid Line
  Full Calculation
- Dashed Line
  $S_{11}(1900)$ Omitted
- Dashed-Dotted Line
  $P_{31}(1910)$ Omitted

$\Rightarrow$ goal: $\Delta P_y^\odot \leq 0.05$

Circular Beam and Longitudinal Target Polarization

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot (\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P_z^\odot}) \}$$

$$(\rightarrow\Rightarrow - \leftarrow\Rightarrow) := \frac{d\sigma(\rightarrow\Rightarrow)}{dx_i} - \frac{d\sigma(\leftarrow\Rightarrow)}{dx_i} = 2 \cdot \sigma_0 \{ \delta_\odot (\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P_z^\odot}) \}$$

$$(\leftarrow\Leftarrow - \rightarrow\Leftarrow) := \frac{d\sigma(\leftarrow\Leftarrow)}{dx_i} - \frac{d\sigma(\rightarrow\Leftarrow)}{dx_i} = 2 \cdot \sigma_0 \{ \delta_\odot (-\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P_z^\odot}) \}$$

1) $(\rightarrow\Rightarrow - \leftarrow\Rightarrow) + (\leftarrow\Leftarrow - \rightarrow\Leftarrow) := \frac{d\sigma_{3/2}}{dx_i} - \frac{d\sigma_{1/2}}{dx_i} = 4 \cdot \sigma_0 \cdot \delta_\odot \cdot (\Lambda_z \cdot \mathbf{P_z^\odot})$

2) $(\leftarrow\Leftarrow - \leftarrow\Rightarrow) - (\rightarrow\Rightarrow - \rightarrow\Leftarrow) := -4 \cdot \sigma_0 \cdot (\Lambda_z \cdot \mathbf{P_z})$

Polarizing Spin

Any ensemble of atoms or nuclei with a magnetic moment can be polarized via the Zeeman interaction: $\vec{\mu}\vec{B}$

$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$ $\quad B_{\text{ext}} = 0$, $P = 0$

$\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow\downarrow$ $\quad B_{\text{ext}} > 0$, $P > 0$

- Zeeman interaction tends to orient (polarize) the magnetic moments
- Oscillating EM fields produced by atomic vibrations tend to randomize (de-polarize) the magnetic moments:
  $\Rightarrow$ Characterized by thermal energy kT

Polarization and Thermal Equilibrium

In general, the populations of the Zeeman levels (once equilibrium has been reached) will obey a Boltzmann distribution:

$$\frac{N(\uparrow)}{N(\downarrow)} = \mathrm{e}^{\frac{-2\,\vec{\mu}\vec{B}}{kT}} \qquad \Rightarrow \qquad P_{\mathrm{te}} = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} = \tanh\left(\frac{\vec{\mu}\vec{B}}{kT}\right)$$

(T = Temperature, P_{te} = Thermal Equilibrium Polarization)

The polarization will approach thermal equilibrium with a characteristic 1/e time constant t_1:

$$P(t) = P_{\mathrm{te}}\,(1 - \mathrm{e}^{-t/t_1})$$

"Spin-Lattice Relaxation Rate"

Brute Force Polarization

$$P_{\mathrm{te}} = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} = \tanh\left(\frac{\vec{\mu}\vec{B}}{kT}\right)$$

$\Rightarrow$ maximize B
minimize T

Disadvantages:

1. Requires very large magnet
2. Low temperatures mean low luminosity
3. Polarization can take a very long time

$\Rightarrow$ We need a trick!

The Trick – Dynamic Nuclear Polarization

Use brute force to polarize free electrons in the target material

- Microwaves transfer this polarization to nuclei

  $\Rightarrow$ Mutual electron-nucleus spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other

For best results:

DNP is performed at B/T conditions where electrons t_1 is short (ms) and nuclear t_1 is long (minutes):

$$\text{JLab:}\quad B = 5\ \text{T}, \quad T = 1\ \text{K}$$

Materials for DNP Targets

Choice of material dictated by:

1. Maximum polarization
2. Resistance to ionizing radiation
3. Presence of unpolarized nuclei
4. And unwanted, polarized nuclei

Free electrons must be embadded into target material:

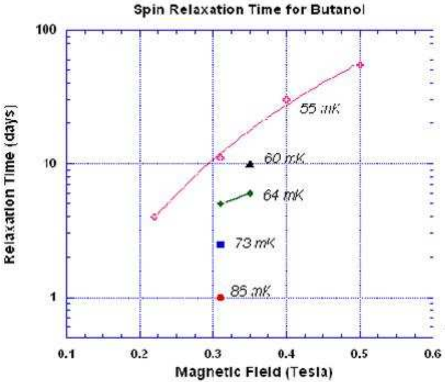
- Chemical doping
  $\Rightarrow$ Paramagnetic radicals created by ionizing radiation

Materials for DNP Targets

Compromise: Butanol (C_4H_9OH)

- Quality (dilution) factor:

  $f = \vec{N}/N_{\text{total}} = 10/74 \approx 0.13$



Ch. Bradtke
PhD Thesis, Univ. Bonn, 1999

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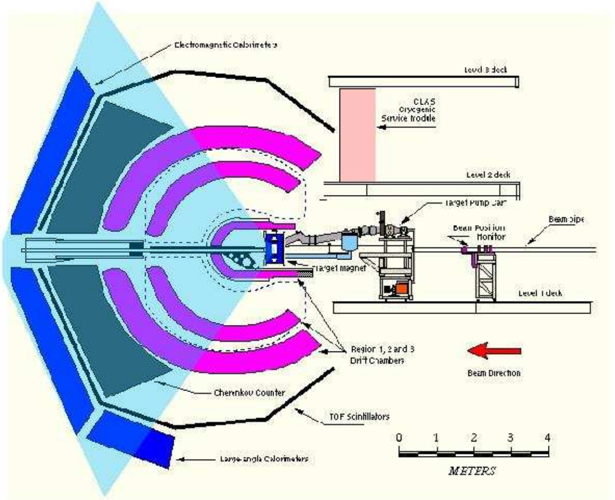
The Old Hall-B Polarized Target: $^{15}NH_3$ ($^{15}ND_3$)



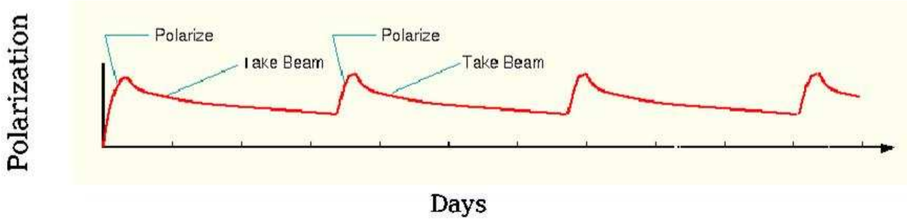
Protons (and deuterons) continuously polarized by 140 GHz microwaves at 5 T and 1 K.

- Proton polarization: $\approx 75 - 85\,\%$
- D polarization: $\approx 25 - 35\,\%$
- Limited acceptance: $\theta < 65^\circ$

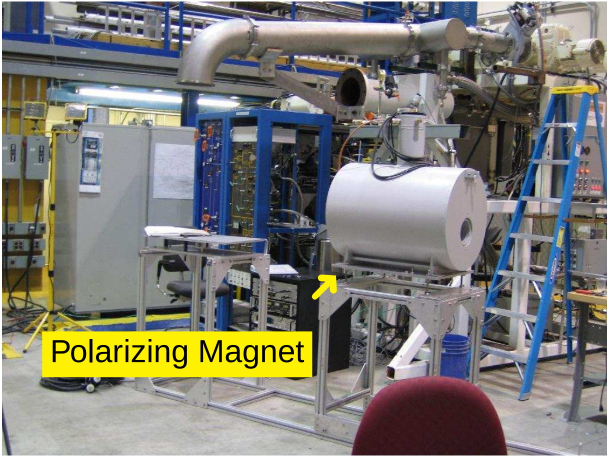
$\Rightarrow$ Need 4π target !

The Frozen-Spin Target

1. Polarize target (material) via DNP at 5 T and 0.5 K outside CLAS
2. Turn off microwaves and magnet when optimum polarization has been obtained
3. Use a 2nd (holding) magnet ($\approx 0.5\,T$) and very low temperatures to "*freeze*" the polarization
4. Polarization will decay very slowly with a time constant of days
5. When polarization decays to $\approx 50\,\%$ of its initial value $\Rightarrow$ Step 1



Polarizing Magnet

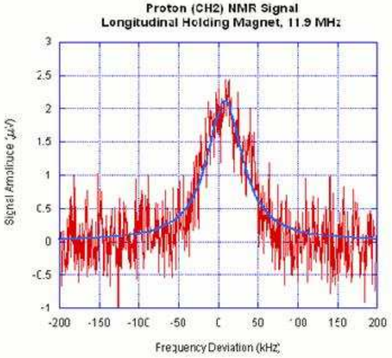


- Max. Field: 5.0 T
- Δ B/B: $< 3 \times 10^{-5}$
- Bore: 127 mmm

Cryomagnetics, Inc.
Oak Ridge, TN, USA

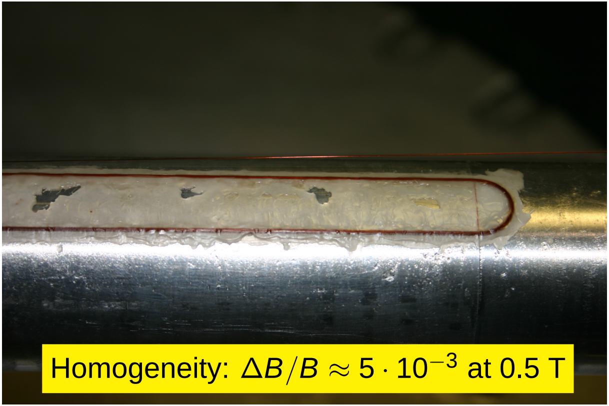
Holding Magnet: Solenoid for Longitudinal Polarization

Homogeneity: $\Delta B/B \approx 3 \cdot 10^{-3}$ at 0.5 T

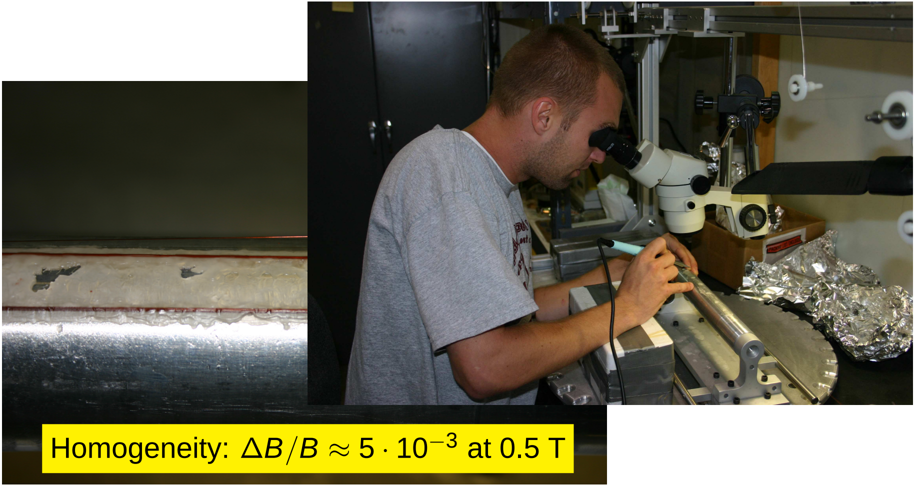


Online NMR

Transverse Holding Magnet: Dipole *(Race-Track Coils)*



Transverse Holding Magnet: Dipole *(Race-Track Coils)*



Homogeneity: $\Delta B/B \approx 5 \cdot 10^{-3}$ at 0.5 T

Refrigeration below 4.2 K

1. Evaporative Cooling

   In order to evaporate 1 mole of ^{4}He, heater must supply:

   $L \approx 80$ J/mol (L is latent heat of vaporazation)

   $\Rightarrow$ In absence of a heater, liquid will absorb heat from surroundings and temperature will drop ($T \approx 1.5$ K)

Refrigeration below 4.2 K

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$\Rightarrow$ Insufficient for freezing the spin!

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   $\Rightarrow$ In absence of a heater, liquid will absorb heat from surroundings and temperature will drop ($T \approx 1.5$ K)

   $\Rightarrow$ Insufficient for freezing the spin!

2. ^{3}He/^{4}He Dilution Refrigeration

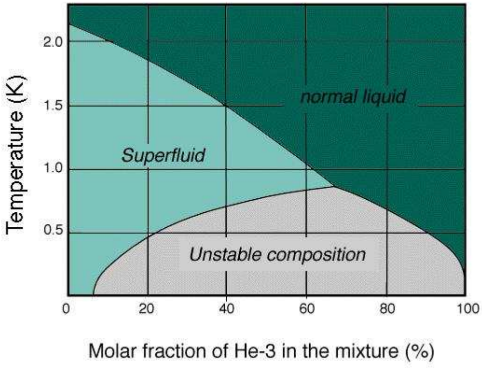
   Below 0.8 K, a ^{3}He/^{4}He mixture will separate into two phases:

   1. Lighter *concentrated phase* rich in ^{3}He
   2. Heavier *dilute phase* rich in ^{4}He (concentration of ^{3}He $\geq 6\,\%$)

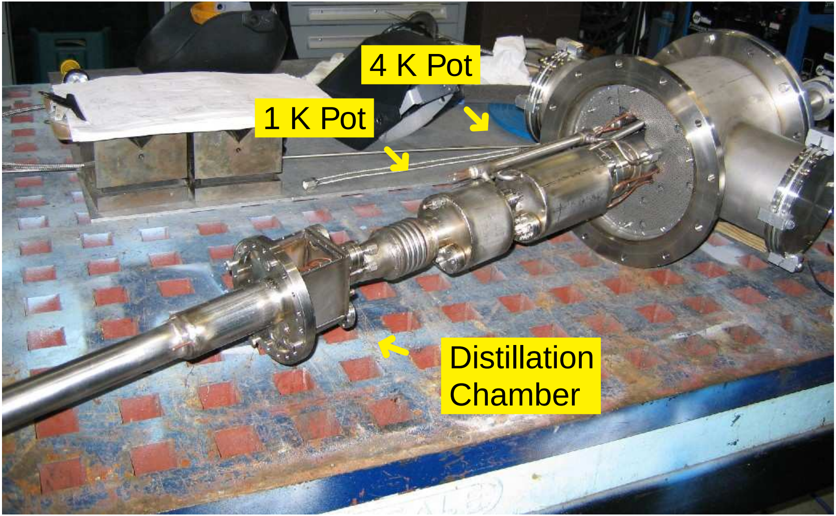
   $\Rightarrow$ Thus, ^{3}He will absorb energy when it dissolves *(evaporates)* into the dilute phase providing highly-effective cooling

Refrigeration below 4.2 K

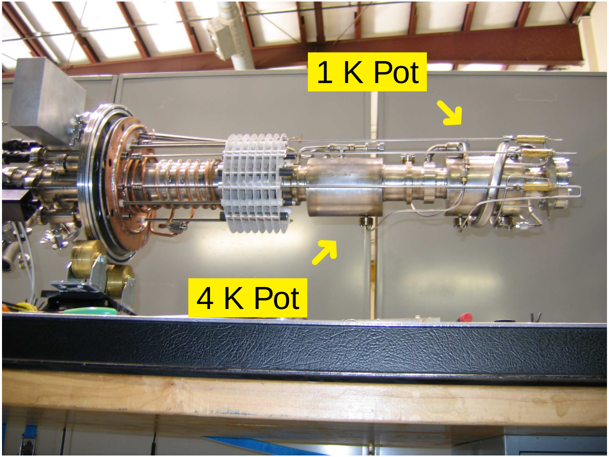
1. Below 0.8 K, a ^{3}He/^{4}He mixture will separate into two phases:
   1. Lighter *concentrated phase* rich in ^{3}He
   2. Heavier *dilute phase* rich in ^{4}He (concentration of ^{3}He $\geq 6\,\%$)



➜ Thus, ^{3}He will absorb energy when it dissolves *(evaporates)* into the dilute phase providing highly-effective cooling

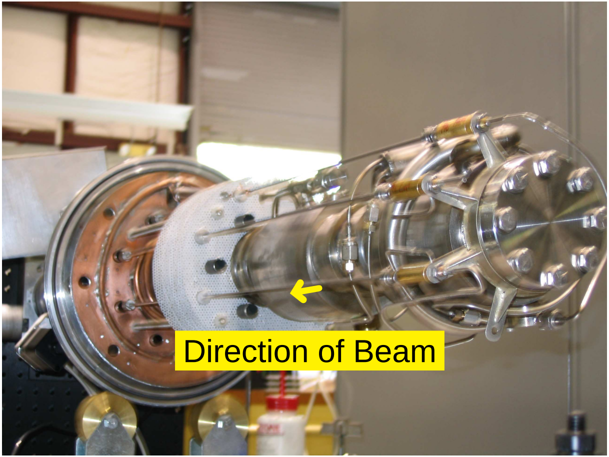

4 K Pot
1 K Pot
Distillation Chamber

Precooling Coil for ^{3}He Gas

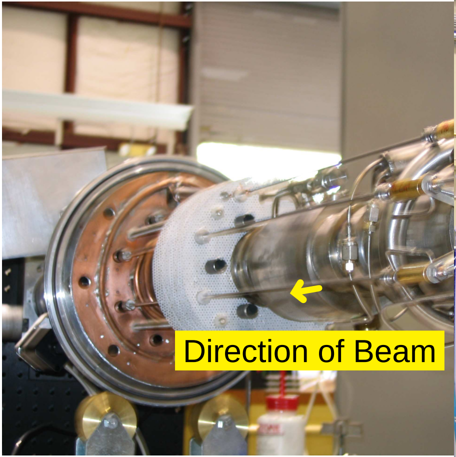


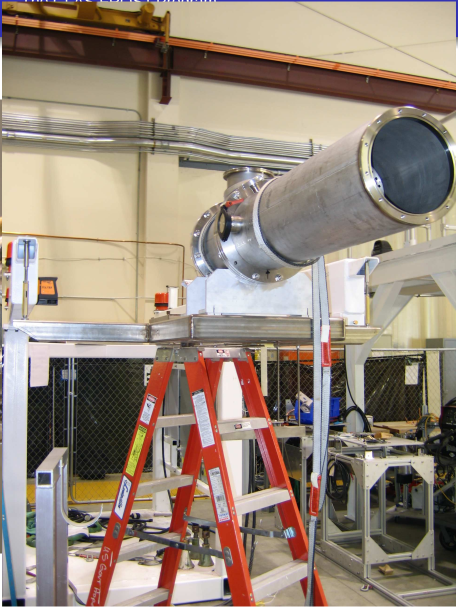
Dilution Refrigerator goes here ...

Another View of the Refrigerator ...



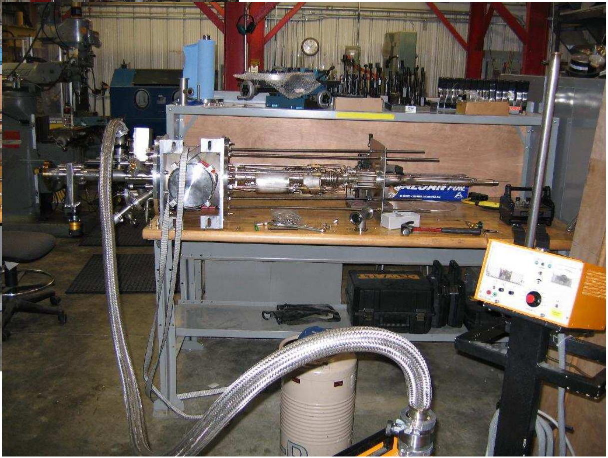
Dilution Refrigerator goes here ...


Direction of Beam



Dilution Refrigerator: Leak Checks (Oct./Nov. ’05)

Dilution Refrigerator: Leak Checks (Oct./Nov. ’05)



FROST Run Summary: Sungkyun Park (Chef)

g9a run period: Nov. 3, 2007 - Feb. 12, 2008

Data set: 603 Runs, 17,676 files, 35 TBytes

The current calibration: pass 0, version 3

Production Data

Beam current: 15 nA

Torus current: 1920 A

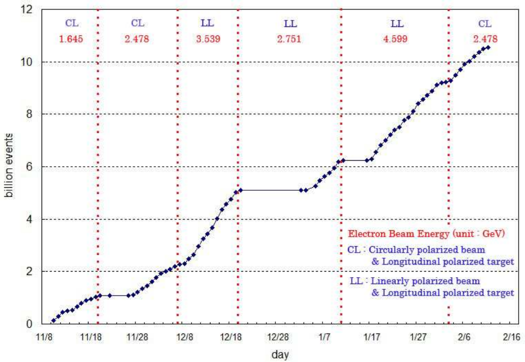
Target:

- Longitudinal polarized target
- Average target polarization $\sim 80\,\%$

Photon beam:

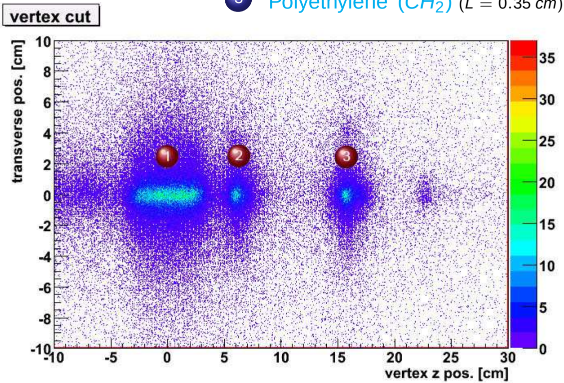
- Circularly and linearly polarized photon beam 0.5 - 2.4 GeV
- Electron beam polarization $\sim 85\,\%$

10.5 Billion events



Targets

1. Polarized Butanol (C_4H_9OH) ($L = 5.0\ cm,\ \phi = 1.5\ cm$) ~ 5 g
2. Carbon (^{12}C) ($L = 0.15\ cm$) (6 cm from CLAS center)
3. Polyethylene (CH_2) ($L = 0.35\ cm$) (16 cm from CLAS center)



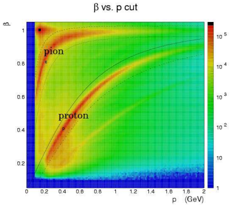
Evan McClellan (from CEU poster)

The Manpower List of Cooking and Calibration

Item	Contact	Prerequisite
Cooking	Sungkyun Park (FSU)	all calibrated
Tagger Calibration	Liam Casey (CUA), Franz Klein (CUA)	none
TOF Calibration	Robert Coyne (UMASS), Hideko Iwamoto (GWU), Arthur Sabintsev (GWU)	TAG
ST Calibration	Mukesh Saini (FSU)	TAG
DC Calibration	Sean Kuvin (FSU), Evan McClellan (FSU) Sungkyun Park (FSU), Volker Crede (FSU)	TOF
EC Calibration	Simona Malace (USC)	TOF
Beam Polarization (Lin.)	Stuart Fegan (Uof Glasgow)	none
Target Polarization	Jo McAndrew (Uof Edinburgh)	none
DC Alignment	Sungkyun Park (FSU)	DC
Energy loss corrections	Jo McAndrew (Uof Edinburgh)	none

- Eugene Pasyuk (ASU)
- Steffen Strauch (USC): Official Analysis Coordinator

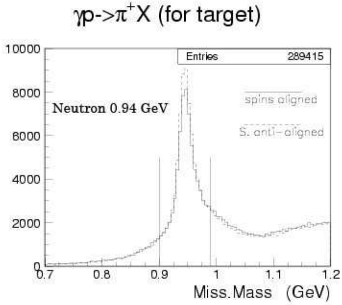
Sample analysis of E for the Reaction $\gamma p \to \pi^+ n$

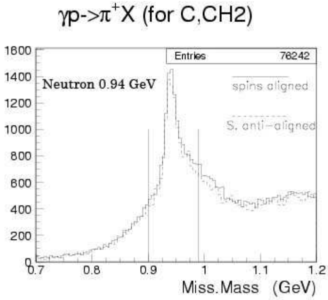


Franz Klein

The data used

- All runs with circularly polarized beam (A05) from pass0/v2 + runs 55521 - 55676 (A01, A10, and A15) from pass0/v1 (for enough statistics)
- using 5 % of the total statistics with circularly polarized beam.



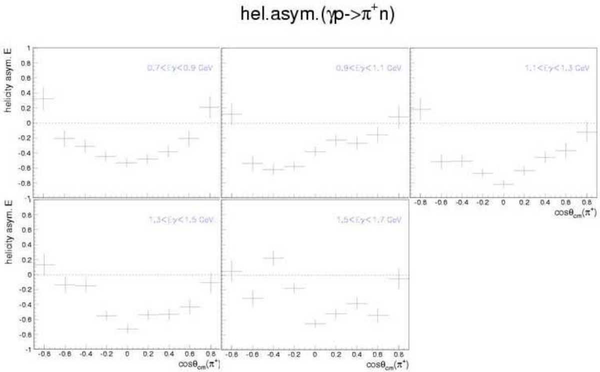


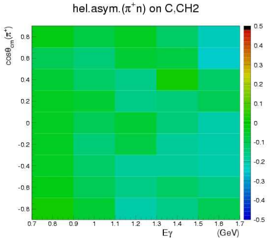
Sample analysis $\gamma p \rightarrow \pi^+ n$

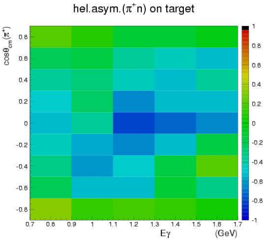
Helicity asymmetry for $\gamma p \rightarrow \pi^+ n$

$E_{raw} = \frac{N^+ - N^-}{N^+ + N^-}$ (N^+ is positive photon helicity, N^- is negative photon helicity)

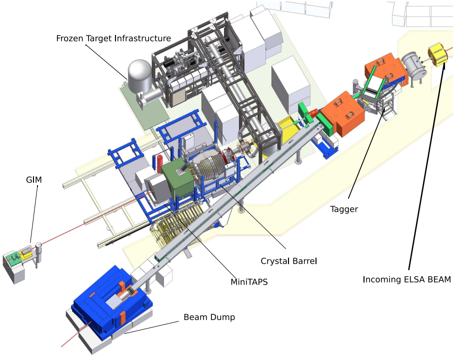
- E_{raw} is scaled with 0.85 for average target polarization



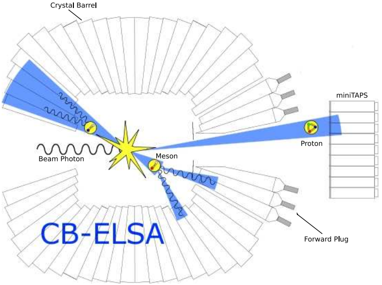




CB-ELSA Layout



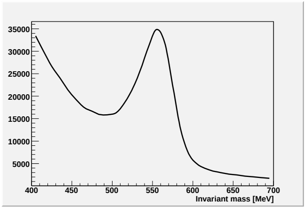
Target



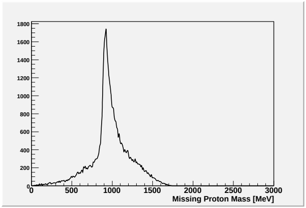
- Polarized Target
- Polarized Beam Photons
- Excellent Photon Energy Detection
- Charged Particle Identification

Helicity Difference E for $\gamma p \to p\eta$ (Andrew Wilson)

η Invariant Mass



Missing Proton Mass



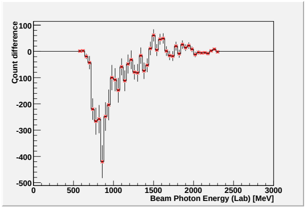
2.4 GeV Circularly Polarized Photon Beam
(Positive and Negative Helicity)
Longitudinally Polarized Butanol Target

Kinematic Cuts

- η Invariant Mass {500,600} MeV
- Missing Proton Invariant Mass {862,1000} MeV
- Timing Cuts

$\sim$ 40,000 $p\eta$ events

Helicity Difference



Outline

1. Introduction
   - The Quark Model of Hadrons
   - The Search for Gluonic Excitations
2. Baryon Spectroscopy
   - Photoproduction Experiments
   - The Next Generation: Linearly-Polarized Photon Beams
3. Double-Polarization Measurements
   - Experimental Setup(s)
   - Scientific Motivation
   - The CLAS FROST-Program
   - The CB-ELSA/TAPS Program
4. Summary and Outlook

Summary and Outlook