Hadron spectroscopy with CLAS and CLAS12

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Why hadron spectroscopy?

- Quantitative understanding of quark and gluon confinement
- Revealing the nature of the mass of the hadrons
- See the QCD degrees of freedom at work
- Validate lattice-QCD predictions

### Perturbative

- High energy
- Small distance
- Asymptotic freedom

### Non-Perturbative

- Low energy
- Large distance
- Confinement

### Transition

- Effective degrees of freedom (models)

### pQCD

- Mesons & Baryons
The tool: electromagnetic interaction

- weaker than strong interactions
- therefore calculable perturbatively
- based on the well-known QED

The scattering is normally analyzed in term of the One-Photon-Exchange approximation (OPE)

Baryon spectroscopy

- Direct $\gamma_v$ - $qqq$ system coupling
- Establish the excitation spectrum
- Access to strong interaction dynamics ($Q^2$ evolution of resonance form factors)

Meson spectroscopy

- $q\bar{q}$ system $\rightarrow$ easier to study
- Indirect coupling to initial particle
- Access to gluonic degrees of freedom
Jefferson Lab (now)

\[
\begin{align*}
E_{\text{max}} & \sim 6 \text{ GeV} \\
I_{\text{max}} & \sim 200 \, \mu\text{A} \\
\text{Duty Factor} & \sim 100\% \\
\sigma_{E/E} & \sim 2.5 \times 10^{-5} \\
\text{Beam P} & \sim 80\% \\
E_{\gamma} & \sim 0.8-5.7 \text{ GeV}
\end{align*}
\]
From CEBAF at 6 GeV to CEBAF at 12 GeV

Enhance equipment in existing halls

Add arc

20 cryomodules

Add 5 cryomodules

20 cryomodules

Add 5 cryomodules

CHL-2

Beam Power: 1 MW
Beam Current: 90 µA
Max Pass energy: 2.2 GeV
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

Upgrade magnets and power supplies

add Hall D (and beam line)
From CEBAF at 6 GeV
to CEBAF at 12 GeV

12 GeV Upgrade Project Schedule

Enhance equipment in existing halls

Beam Current: 90 µA
Max Pass energy: 2.2 GeV
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

Hall A Oct 13
Hall D Apr 14
Hall B Oct 14
The CEBAF Large Acceptance Spectrometer CLAS

Performance

- $L = 10^{34}$ cm$^{-2}$ s$^{-1}$
- $\int B \, dl = 2.5$ T m
- $\Delta p/p \sim 0.5$-1%
- $4\pi$ acceptance
- Best suited for multiparticle final states
- Bremsstrahlung Photon Tagger ($\Delta E/\gamma \sim 10^{-3}$)
The Jefferson Lab and the CLAS detector

Hadron detection efficiency and kinematic coverage

Particle identification

CLAS coverage $e^p \rightarrow e' X$

CLAS resolution $\gamma p \rightarrow K^+ X$

Hadron spectroscopy with CLAS and CLAS12

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$\pi$, $K$, $p$

$M_x (\text{GeV})$ 0. 0.2 0.4 0.6 0.8 1.0 1.2 1.4

$W (\text{GeV})$ 1. 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6

$Q^2 (\text{GeV}^2)$ 1. 1.5 2 2.5 3 3.5 4 4.5 5

$\Lambda^0 (1116)$

$\Sigma^0 (1192)$

$\Sigma^* (1385)$

$\Lambda^* (1520)$

$\eta$, $\omega$, $\pi^0$, $\rho$

$\Lambda (1232)$

$N(1520)$

$N(1680)$

$N(940)$

missing states

deep inelastic
Why do we study excited baryons?

Hadron physics major goal: to understand the structure of the nucleon and its excited states

- The N* spectrum reflects the underlying degrees of freedom of the nucleon

Two main components in JLab N* program

- Transition amplitudes of prominent resonances
- Search of new states
- Exclusive electro and photoproduction
- Precise measurements of cross sections
- Polarization observables
- Q^2 evolution
- Simultaneous analysis of many different channels
## Electroproduction data and analyses from CLAS

<table>
<thead>
<tr>
<th>Reaction</th>
<th>W (GeV)</th>
<th>Q^2 (GeV^2)</th>
<th>Observable</th>
<th>Physics extracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>ep → ep(\pi^0)</td>
<td>1.1 - 1.4</td>
<td>0.4 - 1.8; 3 - 6</td>
<td>(\sigma_T + e_L \sigma_L, \sigma_{TT}, \sigma_{LT}; d\sigma/d\Omega)</td>
<td>(\Delta (G_M, R_{EM}, R_{SM}))</td>
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<tr>
<td>e^+p → e(\pi^0)</td>
<td>1.1 - 1.4</td>
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<td>(\sigma_{LT}^\prime)</td>
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<td>e^+p → e(\pi^0)</td>
<td>1.1 - 1.4; 1.1 - 1.7</td>
<td>0.5 - 1.5; 0.19 - 0.77</td>
<td>(A_t, A_{et})</td>
<td>Comparison to models</td>
</tr>
<tr>
<td>ep → en(\pi^+)</td>
<td>1.1 - 1.6</td>
<td>0.25 - 0.65</td>
<td>(\sigma_T + e_L \sigma_L, \sigma_{TT}, \sigma_{LT})</td>
<td>(P_{ll}(1440) (A_{1/2}, S_{1/2})), (D_{13}(1520) (A_{1/2}, A_{3/2}, S_{1/2})), (S_{11}(1535) (A_{1/2}, S_{1/2}))</td>
</tr>
<tr>
<td>e^+p → en(\pi^-)</td>
<td>1.3 - 1.5; 1.15 - 1.7</td>
<td>0.4 - 0.65; 1.72 - 4.16</td>
<td>(\sigma_{LT}^\prime; \sigma_T + e_L \sigma_L, \sigma_{TT}, \sigma_{LT}, \sigma_{LT}^\prime)</td>
<td>(P_{ll}(1440) (A_{1/2}, S_{1/2})), (D_{13}(1520) (A_{1/2}, A_{3/2}, S_{1/2})), (S_{11}(1535) (A_{1/2}, S_{1/2}))</td>
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<tr>
<td>ep → en(\pi^-)</td>
<td>1.12 - 1.84</td>
<td>0.35 - 1.5</td>
<td>((A_1 + \eta A_2)/(1+\epsilon R))</td>
<td>Comparison to models</td>
</tr>
<tr>
<td>ep → ep(\eta)</td>
<td>1.5 - 1.86</td>
<td>0.25 - 1.5</td>
<td>(\sigma, d\sigma/d\Omega \to ) Legendre coeff. in (\sigma_T + e_L \sigma_L, \sigma_{TT}, \sigma_{LT})</td>
<td>(S_{11}(1535) (A_{1/2}, S_{1/2}))</td>
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<td>ep → ep(\eta)</td>
<td>1.5 - 2.3</td>
<td>0.13 - 3.3</td>
<td>(\sigma, d\sigma/d\Omega \to ) Legendre coeff. in (\sigma_T + e_L \sigma_L, \sigma_{TT}, \sigma_{LT}) (+) (\sigma_{TT}/\sigma, \sigma_{LT}/\sigma)</td>
<td>(S_{11}(1535) (A_{1/2}, S_{1/2})) + further PWA</td>
</tr>
<tr>
<td>ep → ep(\pi^\prime)</td>
<td>1.4 - 2.1; 1.3 - 1.57</td>
<td>0.5 - 1.5; 0.2 - 0.6</td>
<td>Simultaneous fit of (d\sigma/d\theta) and (d\sigma/dM)</td>
<td>(P_{ll}(1440), D_{13}(1520), P_{13}(1720), D_{33}(1700))</td>
</tr>
<tr>
<td>e^+p → EK(^\prime)(\Lambda)</td>
<td>1.6 - 2.15</td>
<td>0.3 - 1.5</td>
<td>(\Lambda) transferred pol. (P_{1}^\prime, P_{2}^\prime)</td>
<td>Comparison to models</td>
</tr>
<tr>
<td>ep → EK(^\prime)(\Lambda), K(\Sigma^0)</td>
<td>1.6 - 2.4</td>
<td>0.5 - 2.8</td>
<td>(\sigma_T, \sigma_L, \sigma_{TT}, \sigma_{LT})</td>
<td>Comparison to models</td>
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<tr>
<td>e^+p → EK(^\prime)(\Lambda)</td>
<td>1.65 - 2.05</td>
<td>0.65, 1</td>
<td>(\sigma_{LT}^\prime)</td>
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<td></td>
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<tr>
<td>$e^+ p \rightarrow e p^0$</td>
<td></td>
<td></td>
<td></td>
<td>Completed</td>
</tr>
</tbody>
</table>

#### Completed
- **Reaction**
  - $\nu p \rightarrow \nu\pi^0$
  - $\nu p \rightarrow \eta\pi^0$
  - $\nu p \rightarrow \eta$
  - $\nu p \rightarrow K^\pm \Lambda$, $K^\pm \Sigma$
  - $\nu p \rightarrow K^{\pm} \Lambda(1520)$
  - $\nu p \rightarrow K^{\pm} \Sigma^*$
  - $\nu p \rightarrow \rho^0, \pi^0, \pi^0, \pi^0$
  - $\nu p \rightarrow K^\pm \Lambda, K^\pm \Sigma$
  - $\nu p \rightarrow K^0 \Lambda, K^0 \Sigma, K^\pm \Sigma^*$, $K^\mp \Sigma(1385)$

#### Scheduled for future run
- **Reaction**
  - $\nu p \rightarrow K^0 \Lambda, K^0 \Sigma, K^0 \Sigma^*$, $K^\mp \Sigma(1385)$
  - $\nu p \rightarrow K^0 \Lambda, K^0 \Sigma, K^0 \Sigma^*$
  - $\nu p \rightarrow K^0 \Lambda, K^0 \Sigma$

### Status/Schedule

<table>
<thead>
<tr>
<th>Run Group</th>
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<tbody>
<tr>
<td>G1</td>
<td>PRL76 222002, 2002 / Upcoming paper</td>
</tr>
<tr>
<td>G1</td>
<td>PRL96 062001, 2006 / Upcoming paper</td>
</tr>
<tr>
<td>G1, G11</td>
<td>PRL95 162003, 2006, Analysis</td>
</tr>
<tr>
<td>G1</td>
<td>PRC75 042201, 2007</td>
</tr>
<tr>
<td>G1, G11</td>
<td>PRC69 042201, 2004; PRC73, 035202, 2006; PRC75 035205, 2007 / Analysis</td>
</tr>
<tr>
<td>G8</td>
<td>2005 / Analysis</td>
</tr>
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</tr>
<tr>
<td>G13</td>
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</tr>
<tr>
<td>G9-FROST</td>
<td>2007 / Analysis, 2010</td>
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</tr>
<tr>
<td>G14-HDIce</td>
<td>2011</td>
</tr>
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<td>2011</td>
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</table>
\( \gamma^* p \rightarrow \Delta(1232) : \text{CLAS } \pi^0 \) electroproduction data 
\( W = 1.25 \text{ GeV} \)
\( Q^2 = 4.2 \text{ GeV}^2 \)

\( \gamma^* p \rightarrow \text{Res} : \text{CLAS } \pi^+ \) electroproduction data
$\gamma^* p \rightarrow \Delta(1232)$ : CLAS $\pi^0$ electroproduction data $W = 1.25$ GeV $Q^2 = 4.2$ GeV$^2$

$\gamma^* p \rightarrow \text{Res}$ : CLAS $\pi^+$ electroproduction data

$\gamma^* p \rightarrow \text{Res}$ : CLAS $\pi^0$ photoproduction data

$\gamma^* p \rightarrow \text{Res}$ : CLAS $\pi^+$ photoproduction data
\( \gamma p \rightarrow \Delta(1232) : \) CLAS \( \pi^0 \) electroproduction data

\( W = 1.25 \text{ GeV} \quad Q^2 = 4.2 \text{ GeV}^2 \)

\( \gamma^* p \rightarrow \text{Res} : \) CLAS \( \pi^+ \) electroproduction data

\( \gamma^* p \rightarrow \text{Res} : \) CLAS \( \pi^0 \) photoproduction data

\( \gamma^* p \rightarrow \pi^0 \) electroproduction data

\( \cos 0^* = -0.90 \quad \cos 0^*_\pi = -0.70 \)

\( \gamma p \rightarrow \text{Res} : \) CLAS \( \pi^0 \) photoproduction data

\( \gamma p \rightarrow k^+ \Lambda \)

\( \gamma p \rightarrow k^+ \Sigma^0 \)

Igor and John talks!
Beyond the quark model: hybrids and exotics

Quarks are confined inside colorless hadrons they combine to 'neutralize' color force

Other quark-gluon configuration can give colorless objects

QCD does not prohibit such states but not yet unambiguously observed
Meson spectroscopy with photons at JLab

Understanding **gluonic** excitations of mesons and the **origin of confinement**

Gluon jets observed at high energy

Gluonic degrees of freedom missing

Spectroscopy

one of the most important issue in hadron physics and main motivation for the JLab 12 GeV upgrade (GlueX program in Hall-D)
Meson spectroscopy with photons at JLab

🌟 Search for mesons with 'exotic' quantum numbers (not compatible with quark-model)

\[ S = S_1 + S_2 \quad J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S} \]

Not-allowed: \( J^{PC} = 0^{-}, 0^{+-}, 1^{++}, 2^{++} \ldots \)

Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states

Normal meson: flux tube in ground state
- \( m = 0 \)
- \( CP = (-1)^{s+1} \)

Hybrid meson: flux tube in excited state
- \( m = 1 \)
- \( CP = (-1)^{s} \)

Combine excited glue quantum number with those of the quarks

Search for mesons with 'exotic' quantum numbers (not compatible with quark-model)

Not-allowed: \( J^{PC} = 0^{-}, 0^{+-}, 1^{++}, 2^{++} \ldots \)
Meson spectroscopy with photons at JLab

Why photoproduction?

- Photoproduction: exotic $J^{PC}$ are more likely produced by $S=1$ probe

- Production rate for exotics is expected comparable as for regular mesons

- Few data (so far) but expected similar production rate as regular mesons

![Diagram showing photoproduction and regular meson production]
Partial Wave Analysis

1) the isobar model
e.g. $3\pi$ system

Exotic state $J^{PC}$

Does the PWA work with photo-production data?

Use the PWA machinery on CLAS data

2) Moments+Dispersion relations

1) Moments of the angular distribution in term of partial waves

$$\langle Y_{\lambda\mu}(E_\gamma, t, M) = \frac{1}{\sqrt{4\pi}} \int d\Omega_\pi \frac{d\sigma}{dt dM} d\Omega_\pi Y_{\lambda\mu}(\Omega_\pi)$$

$$\langle Y_{00}\rangle = N \left[ |S|^2 + |P_-|^2 + |P_0|^2 + |P_+|^2 + |D_-|^2 + |D_0|^2 + |D_+|^2 + |F_-|^2 + |F_0|^2 + |F_+|^2 \right]$$

2) Parametrize partial waves in term of known $\pi\pi$ phase shift and unknown coefficients using Dispersion Relations

3) Derive partial wave cross sections to compare with models

Short range (QCD) production

Meson formation
\[ \gamma p \rightarrow (n) \pi^+ \pi^+ \pi^- \]

- Possible evidence of exotic meson \( \pi_1(1600) \) in \( \pi^- p \rightarrow p \pi^- \pi^- \pi^+ \) (E852-Brookhaven)
- Not confirmed in a re-analysis of a higher statistic sample
- Simple final state with low background


- Clear evidence of non-exotic \( 2^{++} \) state \( a_2(1320) \)
- No-evidence of exotic \( 1^+ \) state \( \pi_1(1600) \)
- Relevance of baryon resonance background

PWA in CLAS is feasible!
\[ \gamma p \rightarrow p \pi^+ \pi^- \]

\( M(\pi^+\pi^-) \) spectrum below 1.5 GeV:

- **P-wave:** \( \rho \) meson
- **D-wave:** \( f_2(1270) \)
- **S-wave:** \( \sigma, f_0(980) \) and \( f_0(1320) \)

**Partial Wave Analysis with CLAS**

Moments + Dispersion relations

**PWA in CLAS is feasible!**

**Known states are well reproduced, \( \rho(770) \)**

- **P-wave:** \( \rho_0(770) \)
- **D-wave:** \( f_2(1270) \)
- **S-wave:** \( f_0(980) \)

- First observation of the \( f_0(980) \) in a photoproduction experiment

**MB, De Vita A. Szczpaniak et al.**


MB, De Vita A. Szczpaniak et al


PSHP LNF

Hadron spectroscopy with CLAS and CLAS12

M. Battaglieri INFN-GE
Meson spectroscopy with photons at JLab-12GeV

The Detector

- Determination of $J^{PC}$ of meson states requires Partial Wave Analysis
- Decay and Production of exclusive reactions
- Good acceptance, energy resolution, particle Id

Hall-D - GlueX Detector

- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

Hall-B - CLAS12 Detector

- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance
Meson spectroscopy with photons at JLab-12GeV

🌟 The photon beam requirements

- **High luminosity**
- **Tagger (initial photon energy) is required to add 'production' information to decay**
- **Linear polarization is useful to simplify the PWA and essential to isolate the nature of the t-channel exchange**

🌟 Essential to isolate production mechanisms (M)

🌟 Polarization acts as a $J^P_C$ filter if M is known

🌟 Linear polarization separates natural and unnatural parity exchange

- **With a 12 GeV electron beam only few choices:**
  1) Bremsstrahlung
  2) Quasi-real electro-production

Hall-D and Hall-B will host real photon beams!
Photoproduction in CLAS12

Quasi-real electroproduction at Low $Q^2$

★ Electron scattering at “0” degrees ($2^\circ - 5^\circ$)
low $Q^2$ virtual photon $\leftrightarrow$ real photon

★ Photon tagged by detecting the scattered electron at low angles
High energy photons $7 < E_\gamma < 10.5$ GeV

★ Quasi-real photons are linearly polarized
Polarization $\sim 65\% - 20\%$ (individual)

★ High Luminosity (unique opportunity to run thin gas target!)
Equivalent photon flux $N_\gamma \sim 5 \times 10^7$ on 40cm $H_2$ ($L=10^{35} \text{ cm}^{-2}\text{s}^{-1}$)

Complementary to Hall-D (GLUEX)
Exploits the unique PID&resolution of CLAS12
$Q^2$ dependence of the Xsec

Studies at large $W$ ($\sim 100\text{GeV}$) show a smooth transition between $Q^2=0$ and $Q^2\neq 0$

Well known technique used in hep

$Q^2 < W^2$

COMPASS: $<1 \text{ GeV}^2$  
ZEUS: $10^{-7} - 0.02 \text{ GeV}^2$  
H1: $<2 \text{ GeV}^2$

$Q^2$ dependence displays a bright transition between $Q^2=0$ and $Q^2\neq 0$.

Tested in CLAS

$e^+ p \rightarrow p \gamma \gamma \gamma \gamma X$

$e^+ p \rightarrow p \pi^0 \pi^0 (e')$

$e^+ p \rightarrow p \pi^0 \eta^0 (e')$

Bright meson peaks show up

The technique works!
Forward Tagger

Calorimeter + tracking device + veto

**Electron energy/momentum**
- Photon energy ($\nu=E-E'$)
- Polarization $\varepsilon^{-1} \sim 1 + \nu^2/2EE'$

**Electron angles**
- $Q^2 = 4EE'\sin^2\vartheta/2$
- $\varphi$ polarization plane

**Veto for photons**

**Rates in the forward tagger**

- Inelastic electro-production
  - Signal $R \sim 10\text{kHz}$

- Elastic radiative tail
  - Background $R \sim 100\text{kHz}$

- Moeller scattering
  - Atomic electron $R \sim 10\text{MHz}$

- Veto for photons

**Background**

- Common CLAS12 tagger

**Signal**

- $N$ atom

**Tagger**

- $e'$ electron
- $\gamma$ photon
- $\varepsilon$ electron polarization

**Rate expressions**

- $\delta \nu / \nu = \delta E'/(E-E')$

**Background rates**

- $N_{\gamma} \sim 0.5 \times 10^8 \gamma/s$

**Forward Tagger**

- $L_e \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
The Forward Tagger in CLAS12

- Compatible with standard electron runs (HTCC)
- Photon detector for leading DVCS experiments
- Extend the CLAS12 coverage for neutral from 5° to 2°

Photons and electrons can run in parallel!
Photoproduction in CLAS12

**Photon beam requirement**
- High Luminosity
- Tagger (initial photon energy) is required to add 'production' information to decay
- Linear polarization simplifies the PWA

**Quasi-real electroproduction at Low \( Q^2 \)**

**Electron kinematics:**
- \( E = 0.5 \text{–} 4 \text{ GeV} \)
- \( \theta = 2 \text{–} 5 \text{ deg} \)
- \( Q^2 = 0.007 \text{–} 0.33 \text{ GeV}^2 \)
- \( E_g = 7 \text{–} 10.5 \text{ GeV} \)
- Photon Polarization: 10\text{-}65%
Partial Wave Analysis in CLAS12

IU-Edinburgh-INFN-JLab

Benchmark channel:
\[ \gamma p \rightarrow n \pi^+ \pi^+ \pi^- \]

The process is described as sum of 8 isobar channels:
- \( a_2 \rightarrow \rho \pi \) (D-wave)
- \( a_1 \rightarrow \rho \pi \) (S-wave)
- \( a_2 \rightarrow \rho \pi \) (D-wave)
- \( \pi_2 \rightarrow \rho \pi \) (P-wave)
- \( \pi_2 \rightarrow \rho \pi \) (F-wave)
- \( \pi_2 \rightarrow f_2 \pi \) (S-wave)
- \( \pi_2 \rightarrow f_2 \pi \) (D-wave)
- \( \pi_1 \rightarrow \rho \pi \) (P-wave) (exotic)

Amplitudes calculated by A. Szczepaniak

CLAS12 acceptance projected and fitted

PWA in CLAS12 is feasible!
Intermediate mass of s quarks links long to short distance QCD potential

**Due to the OZI rule, observation of a state with a large BR in \( \phi \eta, \phi \pi \) and \( \phi \phi \) and small BR in nonstrange final states can serve as smoking gun for an initial s\( \bar{s} \) state (Barnes, Blak and Pages)**
Search for strangeonia in CLAS

G12 Experiment:
Search of new forms of hadronic matter in photoproduction on the proton

- Data tacking completed in 2008
- Photon energy up to 5.5 GeV
- More than 26 billions triggers
- Data analyses and PWA in progress

\[ \gamma p \rightarrow p \phi \eta/\pi^0 \rightarrow p K^+ K^- (\eta/\pi^0) \]

\((pK^+K^-)\) Missing mass after \(\phi\) identification

\((\phi\eta)\) Invariant mass

CLAS preliminary

M.Saini

PSHP LNF

Hadron spectroscopy with CLAS and CLAS12

M.Battaglieri INFN-GE
Search for strangeonia in CLAS12

\[ \gamma p \rightarrow p \ C(M=1480, \Gamma=130\text{ MeV}) \rightarrow p \ \phi \pi^0 \rightarrow p \ K^+(K^-) \ \gamma \gamma \]

- Unusual BR in \( \phi \pi \) (OZI suppressed)
- \( J^{PC}=1^{--} \quad \sigma \sim 10\text{nb} \)
- Tetra-quarks or hybrid
- CLAS12 acceptance \( \sim 10\% \)
- High-p K id relies on kin-fit
- \( K/\pi \) separation for \( p>2.6\text{ GeV/c} \) highly desirable!

\[ \gamma p \rightarrow p \ K^+ (K^-) \ \pi^0 \]

BG: \( \gamma p \rightarrow p \ K^+ (\pi^-) \ \pi^0 \)

Up to \( p=2.6 \text{ GeV/c} \)

\( K/\pi \) separation
Conclusions

Jefferson Lab is providing new, precise and abundant data on hadron spectroscopy

**CLAS**

**Baryon spectrum**
- Many different exclusive reactions w/wo polarization
- Coupled channel analysis are on progress
  1) to map the $N \rightarrow N^*$ transition form factors
  2) to look for missing resonances

**Meson spectrum investigated in photoproduction**
- PWA (IM and Moments + Dispersion relations) feasible

**CLAS12**
- An extension of this program to CLAS12 has been proposed
- Low-Q2 electroproduction is a complementary technique to the Hall-D coherent Bremsstrahlung
- Particle Id and good resolution are unique for CLAS12

Dedicated complementary detectors and high intensity photon beams at JLab-12 are under construction, ready to run in a near future!
Back up slides
Partial Wave Analysis

- The development of robust PWA techniques is a crucial step for the successful completion of any meson spectroscopy program.

- Advancements in detectors, beam and experimental techniques are leading to a high precision and high statistics data sets.

Are the presently available PWA tools adequate for the new data that are and will be produced?

Workshop on Hadron Spectroscopy
*
INT - Seattle, November 9-13 2009
Organizers: M. Battaglieri, C. Munoz Camacho, RDV, J. Miller, A.P. Szczepaniak

- ~ 40 participants from the theoretical and experimental community
- address open issues in experimental techniques, pwa, and theoretical interpretation
- interest from the theory community to work with experimentalists to develop more sophisticated analysis approaches, going beyond the isobar model
- white paper being written

Next meeting:
Workshop on Amplitude Analysis in Hadron Spectroscopy
ECT* - Trento, January 24-28 2011
Organizers: C. Hanhart, M. Pennington, E. Santopinto, A.P. Szczepaniak (coordinator), U. Wiedner
Acceptance and resolution studies

- Determine CLAS12 acceptance
- Determine resolution for exclusive channel selection and mass reconstruction

$$\gamma p \rightarrow n \text{ Res} \ (M=1.6 \text{ GeV}, \Gamma=150 \text{ MeV})$$

$$\rightarrow n \pi^+ \pi^+ \pi^-$$

Missing Mass (all 3 $\pi$ det)

CLAS IC resolution

Torus field 2400

Acceptance (all 3 $\pi$ det)

Invariant Mass (all 3 $\pi$ det)

Edinburgh-INFN
Determination of $J^{PC}$ of meson states requires Partial Wave Analysis
Decay and Production of exclusive reactions
Good acceptance, energy resolution, particle Id

Hermetic charged/neural particles detector

Forward Detector
- TORUS Magnet
- Forward SVT tracker
- HT Cerenkov Counter
- LT Cerenkov Counter
- Forward TOF System
- Preshower calorimeter
- E.M. Calorimeter

Central Detector
- SOLENOID magnet
- Barrel silicon tracker
- Central TOF

Proposed updates
- Micromegas (CD)
- Neutron detector (CD)
- Forward Tagger
Coherent meson production on nuclei

🌟 Eliminate *s-channel* resonance background

\[ \gamma p \rightarrow p \pi \pi \]

🌟 Simplify PWA: \( S=I=0 \) target acts as spin and parity filter for final state mesons

🌟 Production cross section expected \( \sim e^{-bt} |A F_A(t)|^2 \rightarrow \) low -\( t \) kinematic

Detection of recoiling nucleus:
- low -\( t \) (\( p \sim 0.2-0.5 \) GeV)
- thin (gas) target (\( \sim 10^{-3} \) g/cm\(^2\))

Photon beam:
- small size
- high flux

**EG6: Meson spectroscopy in coherent \(^4\)He photoproduction**

- **Radial TPC with 7 atm He 4 Target**
- **Solenoid for forward focusing of Moeller electrons and bending of recoil nucleus in the TPC**
- **PbWO\(_4\) calorimeter for improved photon acceptance at forward angles**
Calorimeter options

* Radiation hardness
* light yield (cooling?)
* timing

* temperature dependence
* Magnetic field effect
* light read-out (APD/SiPM)

** Homogeneous (crystals)**

**EM shower: ionization energy of charged particles (electrons)**

Longitudinal size:
- Radiation length \( X_0 \) (e loses 1-1/e E)
- \( \sim 180 \text{ A/Z}^2 \text{ (gr/cm}^2 \text{)} \)

Transverse size:
- Moliere Radius \( R_M \) (90% of shower)
- \( \sim 7 \text{ A/Z} \text{ (gr/cm}^2 \text{)} \)

** PbWO **
- Fast, rad hard, few light, well known

** LSO/LYSO **
- Quite fast (8x), more light (100x)
- poorly known

** LaBr **
- Fast, a lot of light (600x), expensive

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**PbWO4**

- \( \tau_{\text{Decay}} \sim 6.5 \text{ ns} \)
- \( R_M \sim 2.1 \text{ cm} \)
- \( \rho \sim 8.3 \text{ g/cm}^3 \)
- \( X_0 \sim 0.9 \text{ cm} \)
- light yield 0.3% (LY NaI(Tl))

** CMS(LHC) ** ECAL
** ALICE (LHC) ** PHOS
** CLAS (JLab) ** IC
** PANDA (GSI) ** EMC
**CLAS Inner Calorimeter**

- 424 PbWO4 crystals
- \( L = 16 \text{ cm} = 17 X_0 \)
- Front size 1.3x1.3 cm\(^2\)
- Back size 1.6x1.6 cm\(^2\)
- Controlled Temperature (0.1 °C)
- APD readout

\[
\frac{\sigma_E}{E} = \frac{0.02}{E} \oplus \frac{0.03}{\sqrt{E}} \oplus 0.024
\]
\[
\sigma_x = \frac{0.2}{\sqrt{E}} \text{ (cm)}
\]

**PANDA EMC**

- 16k PbWO-II crystals
- Size = 2 x 2 x 20 cm\(^3\) (23 \( X_0 \))
- LY = 20 phe/MeV
  (80 phe/MeV @ -25°C)
- APD readout
- Resolution (2/\(\sqrt{E} \oplus 1\)%
GEANT4 Simulations

INFN-JLab