HADRON SPECTROSCOPY:
PROVIDING THE LINK BETWEEN EXPERIMENT AND THEORY IN THE INTERMEDIATE ENERGY REGION AT JLAB

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GW Data Analysis Center (GWDAC)
Presentation Scope

GW Data Analysis Center

Joint Physics Analysis Center

CLAS at JLab
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
Connection Between Theory and Experiment

- Excited hadron spectrum: testing ground for theories of the strong force at low and medium energy.
12 GeV upgrade at JLab

• CLAS, GlueX, etc.
• Aim:
  • Complete understanding of the hadron spectrum
  • Discover new resonances e.g, gluonic excitations (states where glue builds their JPC)
• GW and JPAC
  • Aiming to provide theoretical support needed to analyze and understand the data.
Joint Physics Analysis Center
GW Data Analysis Center

- People: Bill Briscoe, Michael Döring, Diane Schott, Igor Strakovsky, Ron Workman
- Mission: Partial-wave analysis of fundamental medium-energy reactions
  - Includes hosting and maintaining SAID database along with fitting existing data
JPAC and GWDAC at work

• Close collaboration between experimentalists and theorists.
• Experimentalists provide events (four-vectors in the detector) and MC acceptance. Both will be publicly available (as DOE requires).
• Theorists provide amplitudes (theorist outside JPAC are welcomed). Codes available to the community.
• We (theorists and experimentalists) fit theory corrected by acceptance to the actual data through a likelihood function (four-vectors and particle identification are the input).
• \( \Rightarrow \) Physics
Theory/Experiment

• **Theory:**
  - Write a C++ version of amplitudes
  - No modification for the core of AmpTools needed for amplitudes

• **Experiment:**
  - Supply real data, acceptance, generated events

• **Cooperation:**
  - Both experimentalists and theorists have a working copy of the directory
  - Both groups can do fits
  - Directory includes data skimmer to fits on various kinematic ranges (ex. t or beam energy)
Working together

- **Goals of working together:**
  - Deploy amplitudes
  - Use available experiment data
CLAS at Jefferson Lab (6 GeV Era)
The CLAS Detector

- **Torus magnet**: 6 superconducting coils
- **Electromagnetic calorimeters**: Lead/scintillator, 1296 photomultipliers
- **target + start counter**
- **Drift chambers**: argon/CO₂ gas, 35,000 cells
- **Time-of-flight counters**: plastic scintillators, 684 photomultipliers
- **Gas Cherenkov counters**: e/π separation, 256 PMTs
Hall B Tagger (6 GeV Era)

- Jefferson Lab Hall-B photon tagger:
- $E_{\gamma} = 20$-95% of $E_e$
- $E_e$ up to ~6 GeV
- $dE/E \sim 10^{-3}$ of $E_0$
- Circularly polarized beam produced by longitudinally polarized electrons ($P_e > 85\%$)
Current JPAC projects:

- Light meson decays:
  - $\omega/\phi \rightarrow 3\pi, \pi\gamma$ (Khuri-Treiman)
  - $\omega \rightarrow 3\pi$ (Veneziano, B4)
  - $\eta \rightarrow 3\pi$ (Khuri-Treiman)
- $J/\Psi$:
  - $J/\Psi \rightarrow 3\pi$ (Veneziano, B4), $J/\Psi \rightarrow \gamma\pi^0\pi^0$
- Photoproduction: (Deck model, FESR and Veneziano, B5)
  - $\gamma p \rightarrow \pi^0 p$
  - $\gamma p \rightarrow pK^+K^-$
  - $\pi^- p \rightarrow \pi^- \eta' p$ & $\pi^- p \rightarrow \pi^- \eta' p$ (FESR)
\( \gamma p \rightarrow p \pi^0 \)

- **Fitting Observables by SAID**
  - New data coming from CLAS to be added to fit
  - FROST (g9a) – polarized target and circularly polarized photon beam
  - G12 - unpolarized target and circularly polarized photon beam

<table>
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<td>( F )</td>
<td>( -G )</td>
<td>( O_{x'} )</td>
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<tr>
<td>circular</td>
<td>( -E )</td>
<td>(-P)</td>
<td>(-G)</td>
<td>( O_{z'} )</td>
</tr>
</tbody>
</table>

\( O_{x'} \) = \( L_{x'} \) = \( T_{x'} \) = \( T' \) = \( L_{x'} \)

\( P = \) constant
High Energy Cross Section of $\pi^0$

- Extends the SAID Database to higher photon energies which allows the addition of Regge analysis to the standard PWA.
\[ \gamma p \rightarrow p \pi^0 \]

- JPAC and GWDAC working together to fit Regge model and dispersion relations.
  - By Vincent Mathieu, Michael Döring
  - The higher energy cross section is being supplied by Michael Kunkel and the Light Meson Decay Group
    - Talk later today in the afternoon session.
FROST

- Preliminary results of polarization observable E have been extracted for the $\gamma p \rightarrow \pi^0 p$ reaction in the FROST experiment at Jefferson Lab.
- Analyzed decay products due to short lifetime analysis with FROST
  - SAID – CM12
  - MAID – 2007
  - BnGa – 2014-02

\[
E = \frac{1}{D_f P_T P_y} \frac{N_{3/2} - N_{1/2}}{N_{1/2} + N_{3/2}}
\]
The data will constrain further partial-wave analyses and improve the extraction of proton resonance properties.

Polarization observables which are sensitive to small amplitudes and phase differences provide important constraints to reveal the dynamics and relevant degrees-of-freedom within hadrons.

Present models (SAID, MAID, BnGa) model predictions generally agree with the data, but also show differences as the energy increases.
\[ \gamma p \rightarrow p K^+ K^- \]

- **Theory:** M. Shi @JLab, V. Mathieu @IU, C. Ramirez @JLab, R. Workman @GW, A. Szczepaniak @IU
- **Experimental support:** D. Schott @GW, PWA Working Group
- **Problem:**
  - With the increase in available phase space as beam energy increases, the overlap between baryon and meson resonances is a persistent problem.
    - How does baryon background manifest in the PWA of mesons (ex. \( \pi \eta \) or \( \pi \pi \pi \))?  
- **Purpose:**
  - To use a “simple” case to derive tools to be used in PWA searching for resonances.
\[ \gamma p \rightarrow p K^+ K^- \]

- At CLAS6 and JLAB 12GeV energies, baryon and meson resonances overlap over the same regions being looked into for exotic mesons.
- Working towards using complex baryon amplitudes to understand the baryon vertex in the meson PWA.
- The \( pK^+K^- \) analysis as a stepping stone to work on more complex channels.
  - The \( p\pi^+\pi^-\pi^0 \) resonance is an important channel to look for exotics.
\( \gamma p \rightarrow p K^+ K^- \)
Double Regge

• Published last fall

Figure 1: Four diagrams of the double Regge limit $s_{AB}, s_{12}, s_{23} \to \infty$. 
\[ \gamma p \rightarrow p K^+ K^- \]

van Hove longitudinal plot

Double Regge region

[Diagram showing particle interactions and mass plots]
\[ \gamma p \rightarrow p K^+ K^- \]

- **Baryons**
  - Use the couple channel analysis of KN and feed it back into the PWA to look for meson resonances decaying to KK.
  - Coupled channel analysis of KN by C. Fernández-Ramírez
    - Unitarity + Analyticity + Right threshold behavior are imposed
    - Resonances are incorporated “by-hand” employing relativistic Breit-Wigner amplitudes
    - Variation of Manley et al.’13 incorporating analyticity to the amplitudes
\[ \gamma p \rightarrow p K^+ K^- \]

- What happens at much higher energies?
- Baryonic resonance region: low energy fit assuming BW
  - Work by C. Ramirez Fernandez
- High energy fit assuming Regge exchanges
  - Work V. Mathieu
- Analytical continuation between the two regions through FESRs and dispersion relations.
$\gamma p \to p K^+ K^-$

- **Baryons**
  - Coupled channel analysis of KN by C. Fernández-Ramírez
    - Connecting low and high energy
    - Using $\pi N$ scattering as a playground
    - Dispersion theory and finite energy sum rules
      - Reconstruct amplitude from dispersion relation
    - Use high-energy to constrain low-energy
  - Work in progress: Next step will be to connect high and low energy KN, build the full two kaon photoproduction amplitude and compare to real data

\[
\text{Re } \nu B^{(+)}(\nu, t) = \frac{g^2_r}{2m} \frac{2\nu^2}{\nu_m^2 - \nu^2} + \frac{2\nu^2}{\pi} \frac{\text{Im } B^{(+)}(\nu', t)}{\nu'^2 - \nu^2} d\nu'
\]
\[ \gamma p \rightarrow p K^+ K^- \]

- **Mesons**
  - Employ the Double Regge amplitude as a background contribution to the meson spectrum.
    - Using photoproduction data from G12 to fit \( K^+ K^- \) spectrum
      - Already used G12 data to test fit Double Regge.
      - Eventually expect to use KN analysis in PWA.
  - From the experimentalist view: the isobar model + background term
Summary

- JPAC and GWDAC are developing descriptions of hadronic interactions to take the full advantage of the information contained in experimental data.
  - JPAC/GW analysis channels
    - $\omega/\phi/\eta \to 3\pi$ decays (shown in M. Kunkel presentation after lunch today!)
    - Moving from 2 body decay to 3 body decay

![Diagrams](image)

FIG. 2: (a) Naive Isobar model. (b) Three-body rescattering effect.
Summary

• JPAC and GWDAC are developing descriptions of hadronic interactions to take the full advantage of the information contained in experimental data.
  • JPAC/GW analysis channels
    • $\omega/\phi/\eta \to 3\pi$ decays (shown in M. Kunkel presentation after lunch today!)
  • Other channels to be looked at:
    • $\eta\pi$, $\eta'\pi$, $\pi\pi$, $KK$, $\pi\pi\pi$
    • $\gamma p \to K^+K^-p$, $\pi\pi N$, $\pi^0\eta p$, $\eta\eta p$ etc...
    • Extension to more complicated processes: $J^P$(arbitrary spin) $\to 3\pi$,
    • $N^* \to NN\pi$, $D \to K\pi\pi$, ...
Conclusion

• As GlueX and CLAS12 are coming online, there is ample CLAS data to be analyzed and used to prepare for the future high statistics 12GeV datasets from GlueX and CLAS12.
• JPAC/GW publications:
  • I. V. Danilkin, et.al., “Dispersive Analysis of $\omega/\phi \rightarrow 3\pi, \pi\gamma^*$,” arXiv:1409.7708 [hep-ph].
  • P. Guo, et.al., “Three-body final state interaction in $\eta \rightarrow 3\pi$” (coming soon!)
• JPAC:
  • Session S8, Hadron Spectroscopy from JLab to EIC, Monday
    • Physics Analysis Center at JLab by A. Szczepaniak
• PWA Working Group:
  • Session X12, Forefront Nuclear and Particle Physics, Tuesday
    • Meson Spectroscopy at Jefferson Lab by Carlos Salgado
Up Coming Talks

- GHP Hadron Spectroscopy & Decays:
  - 14:20 - Michael Kunkel – Light Meson Decays from Photo-Induced Reactions with CLAS
  - 14:50 - Igor Strakovsky - Physics Opportunities with Meson Beams
- APS
  - Session B6, Hadronic Physics, Saturday
    - W. Phelps, M. Kunkel
  - Session C4, Hadronic Structure, Sunday
  - Session S8, Hadron Spectroscopy from JLab to EIC, Monday
    - Physics Analysis Center at JLab by A. Szczepaniak
  - Session X12, Forefront Nuclear and Particle Physics, Tuesday
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