Phenomenological studies on hadronic reactions and resonance extraction

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Outline

- Hadron Spectroscopy and Amplitude Analysis
- JPAC work on Exotic Resonances
- Light Meson Spectroscopy
  - $\pi N \rightarrow 3\pi N$
  - $\pi N \rightarrow \eta\pi N$
Joint Physics Analysis Center (JPAC)

- JPAC is a collaboration between theorists, phenomenologists, and experimentalists to provide phenomenological and data analysis tools for hadron physics
- \( \sim 20 \) active members
- \( \mathcal{O}(10) \) ongoing analyses
- Regular lecture series on relativistic reaction theory
- Summer Workshop on Reaction Theory (2015 & 2017)

http://www.indiana.edu/~ssrt/
Joint Physics Analysis Center (JPAC)

- Some JPAC work:

\[ Z_c(3900) \quad A. \text{ Pilloni et al.} \quad \text{arXiv:1612.06490} \]
\[ \gamma p \rightarrow \eta p \quad J. \text{ Nys et al.} \quad \text{arXiv:1611.04658} \]
\[ P_c(4450) \quad A. \text{ Blin et al.} \quad \text{PRD 94, 034002} \]
\[ \eta \rightarrow \pi^+ \pi^- \pi^- \quad P. \text{ Guo et al.} \quad \text{PRD 92, 054016} \]
\[ \Lambda(1405) \quad C. \text{ Fernández-Ramírez et al.} \quad \text{PRD 93, 074015} \]
\[ \bar{K}N \rightarrow \bar{K}N \quad C. \text{ Fernández-Ramírez et al.} \quad \text{PRD 93, 034029} \]
\[ \pi N \rightarrow \pi N \quad V. \text{ Mathieu et al.} \quad \text{PRD 92, 074004} \]
\[ \gamma p \rightarrow \pi^0 p \quad V. \text{ Mathieu et al.} \quad \text{PRD 92, 074013} \]
\[ \omega, \phi \rightarrow \pi^+ \pi^- \pi^0 \quad I. \text{ Danilkin et al.} \quad \text{PRD 91, 094029} \]
\[ \gamma p \rightarrow K^+ K^- p \quad M. \text{ Shi et al.} \quad \text{PRD 91, 034007} \]
Completed projects are fully documented on interactive portals.

These include description on physics, conventions, formalism, etc.

The web pages contain source codes with detailed explanation how to use them. Users can run codes online, change parameters, display results.

http://www.indiana.edu/~jpac/
Quantum Chromodynamics contains all information about hadrons

$$\mathcal{L}_{QCD} = \bar{q}_j(i\gamma^\mu(D_\mu)_{jk} - m_q\delta_{jk})q_k - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

Understand the hadron spectrum gives us clues on the nature of QCD
S-Matrix Principles

\[ A(s, t) \]

\[ \rightarrow \quad M \]

\[ s - \text{channel decay channel} \]

**Crossing**

\[ A(s, t) = \int \frac{ds'}{\pi} \frac{\text{Im}A(s', t')}{s' - s} \]

- Amplitudes must satisfy these constraints, but the constraints do not fix the dynamics
- Resonance content comes from quark models, LQCD, experiment, ...
Resonances

- Resonances are associated with poles of the scattering amplitude in the complex energy plane.
- Understanding of amplitude model important when continuing to complex energies.
- Causality $\implies$ poles lie on unphysical sheets.
- Breit-Wigner:

\[
t(s) = \frac{g^2}{m^2 - s - i m \Gamma \rho(s)}
\]
Example: Hadron Spectroscopy

- Example: $\bar{K}N \to \bar{K}N$, $\bar{K}N \to \pi\Lambda$, and $\bar{K}N \to \pi\Sigma$
- Analytic multichannel model fitted to data
- $\Lambda^*$ and $\Sigma^*$ resonances located
- Amplitudes can be used in subsequent analyses which require these resonances

Λ* Resonances: C. Fernandez-Ramirez et al. (JPAC), PRD 93, 034029

Σ* Resonances
LHCb Pentaquark

- LHCb claim discovery of pentaquarks $P_c(4450)$ and $P_c(4380)$ in $\Lambda_b \rightarrow KJ/\psi p$
- Proposal to search for $P_c(4450)$ in photoproduction at JLab
- Combined JPAC-LHCb analysis on $\Lambda_b$ decay using JPAC hyperon spectrum

R. Aaij et al., PRL 115, 072001

A. Blin et al. (JPAC), PRD 94, 034002
**$Z_c(3900)$**

- XYZ states (discovered 2003) are non-$q\bar{q}$ mesons
- $Z_c(3900)$ is a tetraquark candidate discovered by BES and Belle
- Look into rescattering models to explain peak

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M. Ablikim *et al.* (BESIII), PRL 110, 252001

A. Pilloni, AJ *et al.* (JPAC), arXiv:1612.06490
COMPASS and JPAC are working together on diffractive resonance production in the $3\pi$ and $\eta^{(')}\pi$ channels

$$\pi^- N \rightarrow \pi^- \pi^- \pi^+ N \quad \text{and} \quad \pi^- N \rightarrow \eta^{(')} \pi^- N$$

Interested in many $J^{PC}$ sectors: $2^{-+}$, $1^{-+}$, $1^{++}$, $\ldots$

JPAC model includes unitarized analytic amplitudes

High-energy behavior, $s \rightarrow \infty$ (190 GeV/$c$ $\pi^-$ beam at COMPASS)

$\Rightarrow$ Exchange process dominated by pomeron
Assume isobar structure in model $\Rightarrow$ quasi-two-body process
Focus on $2^{-+}$ sector
- Understand $\pi_2$ puzzle
- Look of hybrid states

$$A_{\mu',\mu} = \sum_{JMLS_{\epsilon}} F_{LS,\mu',\mu}^{JM_{\epsilon}} \sum_{\lambda} \langle J\lambda|L0S\lambda\rangle \left(\frac{2J+1}{4\pi}\right)^{1/2} D_{M\lambda}^{J_{\epsilon}*}(\Omega) \left(\frac{2S+1}{4\pi}\right)^{1/2} D_{S\lambda 0}^{S_{\epsilon}*}(\Omega')$$

C. Adolph et al. (COMPASS Collaboration), PRD 95, 032004

$\pi^-(p_a) \rightarrow \pi^-(p_1) \pi^- (p_2) \pi^+(p_3) \rightarrow N(p_b, \mu) N(p_4, \mu')$
Amplitude Model: Unitarity and Analyticity

- Assume elastic rescattering only in unitarity equation

\[ S = 1 + iT, \quad S^\dagger S = 1 \implies T - T^\dagger = iT^\dagger T \]

- Unitarity condition on partial wave amplitudes

\[ \text{Disc } F_i(s_{3\pi}) = 2i \sum_j t_{ij}^* (s_{3\pi}) \rho_j(s_{3\pi}) F_j(s_{3\pi}) \]

- Given rescattering \( t_{ij} \), can write dispersive solution

\[ F_i(s_{3\pi}) = b_i(s_{3\pi}) + \sum_j t_{ij}(s_{3\pi}) c_j + \frac{1}{\pi} \sum_j t_{ij}(s_{3\pi}) \int_{s_j}^\infty ds' \frac{\rho_j(s') b_j(s')}{s' - s_{3\pi}} \]
$0.100000 < t' < 0.112853 \text{ (GeV}/c)^2$
The $\eta\pi$ system is one of the golden modes for hunting hybrid mesons.

Focus on $J^{PC} = 2^{++}$ first to test methodology.

Expect $a_2(1320)$ (Large peak) to be narrow resonance, from quark models and LQCD expect excited $a_2$.

The coupled channel analysis to extract the parameters of the exotic $P$-wave is ongoing.

Formalism

- \( \pi p \rightarrow \eta \pi p \) is high-energy peripheral process \( \Rightarrow \) pomeron dominated exchange

- Expand amplitude into partial waves, separates spectrum into \( J^{PC} \) sectors. Unitarity constrains partial wave amplitude

\[
\Delta_s a_{\ell m_\ell}(s) = 2i \rho_\ell(s) t^*_\ell(s) a_{\ell m_\ell}(s)
\]
Formalism

- Model for $a_{\ell m_\ell}$
  
  \[ a_{\ell m_\ell} = f_{\ell m_\ell}(s) t_\ell(s) \]

  where $f_{\ell m_\ell}(s)$ is flexible model for production mechanism, given by

  \[ f_{\ell m_\ell}(s) = \sum_{n=0} \alpha_n T_n(\omega(s)) \]

  with

  \[ \omega(s) = \frac{(1 - \sqrt{s - s_R})}{(1 + \sqrt{s - s_R})} \]

- Parameterize $t_\ell(s)$ by

  \[ t_\ell^{-1}(s) = M_\ell(s) - \frac{s}{\pi} \int_{s_{th}}^{\infty} ds' \frac{\rho_\ell(s')}{s'(s' - s)} \]

  where $M_\ell$ are CDD terms, capturing resonance effects

  \[ M_\ell(s) = C_0 - C_1 s - \sum_r \frac{C_2^r}{C_3^r - s} \]
Results of Fit

\[ D\text{-wave } \pi^- p \rightarrow \eta\pi p \]

- Model fit to COMPASS \( D\)-wave intensity
- Tested stability of fit by changing models, number of parameters, etc.
- 3 poles found, need to understand their nature

\[ m_{\eta\pi} \text{ [GeV]} \]

\( \times 10^3 \)

AJ et al., in preparation
Pole Movement

AJ et al., in preparation
Two poles were found in the $2^{++}$ sector

- $M(1320) = 1.312(1)$ GeV, $\Gamma(1320) = 0.090(1)$ GeV
- $M(1700) = 1.740(8)$ GeV, $\Gamma(1700) = 0.28(1)$ GeV

Statistical errors were determined from a bootstrap analysis
Summary

- JPAC provides analytic amplitudes for amplitude analyses
- Understand hadronic resonances gives us insight into nature of QCD
- Mysteries in both the heavy sector and the light sector
- Need to have robust analysis techniques in order to extract exotica
- Analyses like the $3\pi$ or $\eta\pi$ analyses serve as templates to probe further into the hadronic puzzles such as $XYZ$ states, Pentaquarks, hybrids, …