Novel Approaches in Hadron Spectroscopy

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on behalf of JPAC

ORIGINS Excellence Cluster, Germany

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Joint Physics Analysis Center

Joint effort of theorists and experimentalists to foster studies of strong interaction

Collaboration with several experimental groups

Involved in ongoing projects with LHCb, COMPASS, GlueX, BESIII, and EIC.
Tools in hadron spectroscopy

General principles of the scattering theory

- **Lorentz invariance** = independence of the reference frame, known behavior under boosts and rotations
- **Unitarity** = constraint to imaginary part of scattering amplitude
- **Analyticity** = implementation of relevant, closest singularities
- **Crossing** = decay and scattering regions are analytically connected

\[
A_l(s + i\epsilon) \neq A_l(s - i\epsilon)
\]

\[
A(s, t) = \sum_l A_l(s) P_l(z_s)
\]

\[
A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)
\]
Selected results for the talk

1. Reaction theory and lineshape
   - Resonances in $J/\psi$ radiative decays

2. Three-body problem
   - Dalitz-plot decomposition
   - Three-body unitarity

3. Production mechanism
   - Double-Regge production

The report is based on the recent review [JPAC, PPNP (2022) 103981, arXiv:2112.13436]
Most recent studies of on hadronic states

- Deep Learning Exotic Hadrons
- Scalar and tensor resonances in $J/\psi$ radiative decays (*)

[PRD 105 (2022) L091501]
[EPJC 82 (2022) 1, 80]
$J/\psi \rightarrow \gamma \pi^0 \pi^0$ and $\rightarrow \gamma K_S^0 K_S^0$

- A gluon-rich process, expected to be the golden channel for the search of the scalar glueball
- Three-channel ($\pi\pi/KK/\rho\rho$) K-matrix with the CDD poles
J/ψ → γπ⁰π⁰ and → γK⁰S\bar{K}⁰S

- A gluon-rich process, expected to be the golden channel for the search of the scalar glueball
- Three-channel (ππ/KK/ρρ) K-matrix with the CDD poles

f₀(1710)?
Parameters of the resonances

- Here, 14 best fits with bootstrap analysis
- 4 scalar resonances, 3 tensor resonance reliably established
- More states might be present, but require more data / channels
- Large model uncertainty related to additional/spurious poles

Large production coupling of $f_0(1710)$ suggests it to have sizable glueball components
Recent progress on three-body interaction

(*) will be shown today

- BESIII puzzle on the $\omega \to 3\pi$ KT and $\omega \to \gamma\pi$
  
  [JPAC, EPJC 80 (2020) 12, 1107]

- Quantization for $3 \to 3$ scattering on lattice
  
  [JPAC, PRD 100 (2019) 3, 034508]

- Application of Dalitz-plot decomposition (*)
  
  - $\Xi^+ \to pK^-K^-$
  - $B_s \to J/\psi p\bar{p}$
  - $B^- \to J/\psi \Lambda\bar{p}$

  [JPAC, PRD 101 (2020) 3, 034033]
  [LHCb, PRD 104 (2021) 5, 052010]
  [LHCb, PRL 128 (2022) 6, 062001]
  [LHCb, (in preparation)]

- Application of three-body unitarity to resonance physics
  
  - Study of the $\pi_2$ resonances for COMPASS (*)
  
  [JPAC, JHEP 08 (2019) 080]
  [JPAC, PPNP (2022) 103981]
  [LHCb, JHEP 06 (2020) 136]
  [LHCb, Nature Commun. 13 (2022) 1, 3351]
Conventional helicity approach

Complicated cases: particles with spin in isobar model [Hansen (1974)], [Herndon(1975)]

\[
M^\Lambda_{\{\lambda\}} = M^\Lambda_{1,\{\lambda\}} + M^\Lambda_{2,\{\lambda\}} + M^\Lambda_{3,\{\lambda\}}
\]

\[
= H_1 D(\phi_1, \theta_1, 0) D(\phi_{23}, \theta_{23}, 0) W_1(\ldots) + H_3 D(\phi_3, \theta_3, 0) D(\phi_{12}, \theta_{12}, 0) W_3(\ldots)
\]

\[
+ H_2 D(\phi_2, \theta_2, 0) D(\phi_{31}, \theta_{31}, 0) W_2(\ldots)
\]

- A special set of angles for every decay chain
- Consistently of quantization direction – Wigner rotations

\[
W_i(\ldots) = D^{j_1}(\tilde{\phi}_1, \tilde{\theta}_1, 0) D^{j_2}(\tilde{\phi}_2, \tilde{\theta}_2, 0) D^{j_3}(\tilde{\phi}_3, \tilde{\theta}_3, 0)
\]

- Fails for non-integer spin
The Dalitz-Plot decomposition

Reformulation of the helicity approach

\[ \sum_{\nu} D_{\Lambda \nu}^J(\phi_1, \theta_1, \phi_{23}) \times O^\nu_{\{\lambda\}}(m_{12}^2, m_{23}^2) \]

Model-independent factorization of the overall rotation:

- Exploits properties of the Lorentz group (orientation – just three Euler angles)
- Dalitz-plot function depends entirely on 2 variables, \( m_{23}^2 \) and \( m_{12}^2 \).
- (!!!) No azimuthal angles in dynamic function.
- Generalizes for \( n \)-body decay: 3 rotation \( \oplus \) 3\( n \) – 7 dynamic variables
- Fixes problem of \( 4\pi \) symmetry of half-integer spin decays
Decay amplitude in the aligned configuration is a function of Mandelstam variables

Master formula $0 \rightarrow 1\,2\,3$ decay with arbitrary spins

\[
O_{\{\lambda\}}^{\nu}(m_{12}^2, m_{23}^2) = \sum_{k=1}^{3} \sum_{s} \sum_{\tau} \sum_{\{\lambda'\}} \delta_{\lambda',\tau-\lambda'_k} H_{s,\lambda}^s H_{s,\lambda'_i,\lambda'_j}^{\nu} \text{BW}(\sigma) H_{s,\lambda}^{s,\nu} d_{s,\lambda}^{i,j} \theta_{ij}
\]

- $H_{s,\lambda}^{s,\nu}$ and $H_{s,\lambda'_i,\lambda'_j}^{\nu}$ are helicity couplings
- The angles are standard functions of $(m_{12}^2, m_{23}^2)$:
  - $\theta_{ij}(m_{12}^2, m_{23}^2)$ is an isobar decay angle
  - $\zeta_{k(\cdot)}^i(m_{12}^2, m_{23}^2)$ is the particle-$i$ Wigner angle

● widely used in LHCb
● implemented in frameworks
Amplitude for resonance process

\[ \hat{T}_2(s) = \frac{g^2}{m^2 - s - ig^2 \Phi_2(s)} \rightarrow \frac{1}{(m^2 - s)/g^2 - \Sigma_2(s)} \]

- Self-energy: \( ig^2 \Phi_2(s) \rightarrow \Sigma_2(s) \), Chew-Mandelstam to ensure analyticity.

Three-body resonance

\[ \hat{T}_{\text{R}}(s) = \frac{1}{(m^2 - s)/g^2 - \Sigma(s)} = \frac{1}{K - 1} \]

Dispersion relation for the self-energy:

\[ \Sigma(s) = \frac{s^2}{\pi} Z_\infty \int_0^\infty ds' \frac{s'}{(s' - s) Z_{\text{Dalitz}}(s')} \]

The \( \hat{A}_{\text{R} \rightarrow 1, 2, 3}(s, \sigma_1, \sigma_2) \) is observable (+FSI).

Example: \( a_1 \rightarrow \rho \rightarrow \pi\pi \)
Amplitude for resonance process

**Two-body resonance**

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**Three-body resonance**

\[ \hat{T}_R(s) = \frac{1}{(m^2 - s)/g^2 - \Sigma(s)} = \frac{1}{\mathcal{K}_1^{-1}(s) - \Sigma(s)} \]

- Dispersion relation for the self-energy:

\[ \Sigma(s) = \frac{s}{2\pi} \int_{s_{th}}^{\infty} \frac{ds'}{s'(s' - s)} \int_{\text{Dalitz}(s')} |\hat{A}_{R \rightarrow 1,2,3}(s', \sigma_1', \sigma_2')|^2 d\Phi_3' \]

- The \( |\hat{A}_{R \rightarrow 1,2,3}(s, \sigma_1, \sigma_2)|^2 \) is observable (+FSI)
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- The \( \left| \hat{A}_{R\rightarrow 1,2,3}(s, \sigma_1, \sigma_2) \right|^2 \) is observable (+FSI)

Example:

\[ a_1 \rightarrow \rho(\rightarrow \pi\pi)\pi \]
The $\pi_2$ resonances with COMPASS data

COMPASS experiment at CERN

- Diffractive production of $3\pi$ system
- Pion beam scattered off proton target,

PWA to separate $J^P$ for every $m_{3\pi}$ bin

- 11 data sets with different $t = p_P^2$.
The $\pi_2$ resonances with COMPASS data

- COMPASS experiment at CERN
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- PWA to separate $J^P$ for every $m_{3\pi}$ bin
- 11 data sets with different $t = p^2_P$.

Resonance analysis of $J^P = 2^+$:
- coupled-channel $K$-matrix
- large model uncertainty

<table>
<thead>
<tr>
<th>$\pi_2$ (MeV)</th>
<th>$\Gamma_p$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1650–1750</td>
<td>280–380</td>
</tr>
<tr>
<td>1770–1870</td>
<td>200–450</td>
</tr>
<tr>
<td>1890–2190</td>
<td>590–1340</td>
</tr>
</tbody>
</table>

![Graphs showing resonance analysis and fitting solutions](image_url)
Recent studies of the hadron production mechanism

- Nucleon resonances in inclusive electron scattering  
  [JPAC, PRC104 (2021) 025201]
- XYZ production in electron-proton collisions  
  [JPAC, PRD102 (2020) 114010]
- Two-meson production in the double-Regge region (*)  
  [JPAC, EPJC 81 (2021) 647]
- Finite energy sum rules  
  [JPAC, (in progress)]
Features of $\eta \pi$ vs $\eta' \pi$ production at high energy

$$m(\eta \pi^-) \text{ [GeV/c}^2\text{]}$$

Entries / 4 MeV/c$^2$

1 1.5 2 2.5 3 3.5 4 4.5

Acceptance [%]

$$\cos \vartheta_{GJ}$$

$$m(\eta' \pi^-) \text{ [GeV/c}^2\text{]}$$

Entries / 20 MeV/c$^2$

1.5 2 2.5 3 3.5 4 4.5 5

Acceptance [%]
Features of $\eta\pi$ vs $\eta'\pi$ production at high energy

Features of $\eta\pi$ vs $\eta'\pi$ production at high energy

High-energy dynamics:

- $\pi^- \rightarrow \eta'$
- $a_2$
- $f_2/\Pi$
- $\pi^- \rightarrow \pi^-$
- $p \rightarrow p$
- $\eta'$
- $f_2/\Pi$
- $f_2/\Pi$
- $p \rightarrow p$
Double-Regge model

inspired by [Shimada et al. (1978)]

\[ T_{\alpha_1/\alpha_2}(s_1, s_2) = K \Gamma(1 - \alpha_1) \Gamma(1 - \alpha_2) (\alpha' s_1)^{\alpha_1} (\alpha' s_2)^{\alpha_2} \]

\[ \times [\eta^{\alpha_1 \xi_1 \xi_2} V(\alpha_1, \alpha_2, \eta) + \eta^{\alpha_2 \xi_2 \xi_1} V(\alpha_2, \alpha_1, \eta)] \]

- \( K \) kinematic function \( \sim \sin \theta_{GJ} \sin \phi_{TY} \).
- \( s_i^{\alpha_i(t_i)} \) for both reggeons
- \( \xi_i \) and \( \xi_{ij} \) are the signature factors
- \( \eta = s/(\alpha' s_1 s_2) \) is finite in the Double Regge limit
- \( V(\alpha_1, \alpha_2, \eta) \) is the reggeon-reggeon vertex.

Minimal model: all residuals in the vertex function are the same.

\[ A = c_1 T_{a_2/P(f_2)}^{\eta \text{ forward}} + c_2 T_{f_2/P(f_2)}^{\pi \text{ forward}} + c_3 T_{P/P(f_2)}^{\pi \text{ forward}}. \]
Effect of PW-set truncation

- Data is analyzed in **truncated** PW set: $L \leq 6$, $M \leq 2$
- Extended likelihood fit $\Rightarrow$ force intensity redistribution
- “Squeezing” the full series to the truncated set

**PW expansion:**

Data

Model

summed $2.4 < m_{\eta\pi} < 3.0$ GeV.
Bottom exchange: $f_2$ vs $P$

Representative: forward, backward intensity

$$F(m_{\eta\pi}) = \int_{\cos \theta > 0} I(\Omega) \, d\Omega,$$

$$B(m_{\eta\pi}) = \int_{\cos \theta < 0} I(\Omega) \, d\Omega.$$

Can be computed for the model, and from the "data" partial waves.

- The slope $dI/dm_{\eta\pi}$ is sensitive to the bottom exchange
- The slope is different in the forward and the backward regions

\[ \text{August 1}^{st}, 2022 \]
Integral intensities

**Forward** $\eta$  
$(\cos \theta > 0)$

**Backward** $\eta$  
$(\cos \theta < 0)$

**Total**
Conclusions on contributing processes

FB Asymmetry

\[
\frac{(\cos \theta > 0) - (\cos \theta < 0)}{(\cos \theta > 0) + (\cos \theta < 0)}
\]

- \( a_2 - f_2 \) coupling degeneracy lead to nearly no asymmetry for \( \eta \pi \)
- Three effects of large asymmetry in \( \eta' \pi \):
  - no \( a_2 - f_2 \) symmetry
  - significant \( P/P \) process
  - mass difference

\[
\begin{align*}
(a_2/P) & : 0.4 \pm 0.04 \\
(f_2/P) & : 0.3 \pm 0.05 \\
(a_2/f_2) & : 3.4 \pm 0.4 \\
(f_2/f_2) & : 6.6 \pm 0.7 \\
(P/P) & : \text{not needed}
\end{align*}
\]

\[
\begin{align*}
(a_2/P) & : 0.35 \pm 0.05 \\
(f_2/P) & : \text{not needed} \\
(a_2/f_2) & : 0.6 \pm 0.5 \\
(f_2/f_2) & : 7.6 \pm 0.7 \\
(P/P) & : (18 \pm 2) \times 10^{-3}
\end{align*}
\]
Summary

- JPAC started in 2013 as a project between Indiana University and JLab.
- Much expanded and matured since then.
- The driving force is enthusiasm and curiosity.
- **The main focus is on development the tools to tackle challenges in hadron spectroscopy.**
- Also, we organize lecture courses and various schools.
- Close cooperation with experimental groups is essential.

Everyone sharing the interest in hadron physics is **WELCOME TO JOIN!!**
Activities on JPAC

- Over 120 research articles
- Over 200 invited talks
- Summer schools (2015, 2017)
- Many workshop, conferences, programs
- Scattering courses (2021, 2022)
- Affiliated membership in many experiments
- Recent faculty position: C.Fernandez, M.Albaladejo, V.Mathieu, A.Pilloni
Thank you for the attention!