New results on hadron spectroscopy from JPAC

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In Memory

Mike Pennington (1946-2018)
Joint Physics Analysis Center

- JPAC: theory, phenomenology and analysis tools in support of experimental data from JLab12 and other accelerator laboratories.
- Contribute to education of new generation of practitioners in physics of strong interactions.
- In this talk: JPAC’s role in spectroscopy analysis and some “exotic” physics
Identifying resonances

• Experimental or lattice signatures (real axis data: cross section bump and dips, energy levels)

  Reaction amplitudes

• Theoretical signatures (complex plane singularities: poles, cusps)

  Microscopic Models

• What is the interpretation (constituent quarks, molecules, …)?
Identifying resonances

- Experimental or lattice signatures (real axis data: cross section bumps and dips, energy levels)

  Reaction amplitudes

- Theoretical signatures (complex plane singularities: poles, cusps)

  Microscopic Models

- What is the interpretation (constituent quarks, molecules, …) ?

  Hybrids

  Mesonic-Molecules

  Tetraquarks
Signatures of new, unusual light resonances

- High precision PWA of 3pi diffractive association yields a new $a_1(1420)$ incompatible with the quark model/Regge expectations.

- At low-t exotic wave production compatible with one pion exchange

- In photoproduction exotic mesons be produced via pion exchange

- Large exotic wave seen in $\eta(\gamma')\pi$ production : FESR's to constrain P-wave
Signatures of unusual heavy quark resonances


Virtual OPE

Real OPE

BESIII, PRL118, 092001 (2017) $e^+e^- \rightarrow J/\psi \pi\pi$

EMARK ON ENERGY PEAKS IN MESON SYSTEMS
M. Nauenberg | A. Pais

If the width of particle $X$ is not very large we will stay close to the physical region. This almost singular behavior of $\Lambda(s)$ for certain physical $s$ causes the peaking effect to which we refer as an $(X, Y, Z)$ peak.
Spectroscopy from peripheral production

- Need to establish factorization between beam and target fragmentation (Regge factorization)
  - Single Regge pole exchange dominate over cut other singularities (cuts, daughters)
Global Regge analysis

• Test Regge pole hypothesis and estimate corrections (daughters, cuts)

• Factorizable Regge pole exchange

\[ R(s, t) \equiv \left( \frac{1 - z_s}{2} \right)^{1/2} |\mu - \mu'| \left( \frac{1 + z_s}{2} \right)^{1/2} |\mu + \mu'| \]

\[ A_{\mu_4\mu_3\mu_2\mu_1} = R(s, t) \sqrt{-t} |\mu_1 - \mu_3| \sqrt{-t} |\mu_2 - \mu_4| \beta_{\mu_1\mu_3}(t) \beta_{\mu_2\mu_4}(t) \mathcal{F}_e(s, t) \]

\[ \mathcal{F}_e(s, t) = -\frac{\zeta_e \pi \alpha_e^1}{\Gamma(\alpha_e(t) - l_e + 1)} \frac{1 + \zeta_e e^{-i \pi \alpha_e(t)}}{2 \sin \pi \alpha_e(t)} \left( \frac{s}{s_0} \right)^{\alpha_e(t)} \]

\[ \mathcal{F}_e(s, t) \rightarrow \frac{(s/s_0)^{J_e}}{t \rightarrow m_e^2} \]

\[ \mathcal{F}_e(s, t) \rightarrow \frac{(s/s_0)^{J_e}}{m_e^2 - t} \]

• \( N_{\text{Data}} = 1271 \), \( N_{\text{par}} = 9 \)

(6 SU(3) couplings, 1 mixing angle, 2 exp. slopes)
Global Regge pole analysis

\[ \pi^0 p \rightarrow \pi^0 \Delta^{++} \]

\[ \pi^- p \rightarrow \eta \]

\[ \pi^- p \rightarrow K^0 \Sigma^0 \]

\[ \pi^- p \rightarrow \pi^0 \eta \]

\[ K^- p \rightarrow \pi^+ \Sigma^{*-} \]

\[ K^- p \rightarrow K^0 \Delta^{++} \]
Beam asymmetry: measurement of the exchange process

\[
\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho + \omega|^2 - |b + h|^2}{|\rho + \omega|^2 + |b + h|^2}
\]

H. Al Ghoul et al. [GlueX]
Phys. Rev. C95 (2017) no.4, 042201
+V. Mathieu, J. Nys [JPAC]

- Possible tension between GlueX and SLAC data?
Finite Energy Sum Rules

- No kinematic singularities
- No kinematic zeros
- Discontinuities:
  - Unitarity cut
  - Nucleon pole

\[
A_{\lambda';\lambda_1\lambda_2}(s, t) = \overline{u}_{\lambda'}(p') \left( \sum_{k=1}^{4} A_k(s, t) M_k \right) u_\lambda(p)
\]

\[
\int_0^\Lambda \text{Im} \ A_i(\nu, t) \nu^k d\nu = \beta_i(t) \frac{\Lambda \alpha(t) + k}{\alpha(t) + k}
\]

\[
\beta_i(t) = \frac{\alpha(t) + k}{\Lambda \alpha(t) + k} \int_0^\Lambda \text{Im} \ A_i(\nu, t) \nu^k d\nu
\]

SAID
\[
\gamma p \rightarrow \pi^0 p
\]
\[
s_{\text{max}} = (2.4 \text{ GeV})^2
\]

\[
k = 3, 5, 7, 9
\]

\[
-t \ (\text{GeV}^2)
\]

\[
k = 3, 5, 7, 9
\]
Finite Energy Sum Rules

[V. Mathieu, J.Nys. et al. (JPAC) 1708.07779 (2017)]

Combine energy regimes
- Low-energy model ((SAID, MAID, Bonn-Gatchina, Julich-Bonn,...)
- Predict high-energy observables

Two applications
- Understand high-energy dynamics
- Constraining low-energy models
Constraining the resonance spectrum

[J. Nys et al., PRD95 (2017) 034014]

Ambiguities in the low-energy model ($\eta$-MAID) → Mismatch with high-energy data

Possibilities
- Low-energy model inconsistent
- Cut-off not high enough
  - High mass resonances!

\[ \rho + \omega \]
\[ b + h \]
Based on the FESR for $\eta$:
predict beam asymmetry for $\eta'$
- Same exchanges
- Natural exchanges ($\rho, \omega$) dominant
  - Couplings from radiative decays
  - Mixing angle cancels in ratio
- Unknown behavior of
  - $\phi$ exchange
  - unnatural exchanges ($b, h$)

Prediction: $\approx$ same beam asymmetry

**πΔ photoproduction**

Comparison to GlueX data
- Confirmation of interference pattern
- High -t: natural, low -t: unnatural
- Mismatch: oddly behaved π exchange
  - Ongoing analysis
  - Experimental or theoretical?

- Stringent test of one-pion-exchange production
- Possible to make parameter-free predictions

Łukasz Bibrzycki et al. (Cracow, JPAC)

Vector meson production

- Pomeron dominates at high energies
- Isoscalar exchanges dominantly helicity non-flip ($\lambda=\lambda'$)
- Unnatural exchanges: only helicity flip ($|\lambda-\lambda'|=1$)

\[
\mathcal{M}_{\lambda V,\lambda_\gamma} (s, t) = \sum_{E=\pi, \eta, P, f_2, a_2} \mathcal{M}^E_{\lambda V,\lambda_\gamma} (s, t).
\]

\[
\mathcal{M}^N_{-\lambda_\gamma, -\lambda V} = \pm (-1)^{\lambda_\gamma - \lambda V} \mathcal{M}^N_{\lambda_\gamma, \lambda V}.
\]

\[
\rho^0_0 = \frac{1}{2} (\rho_0^0 \mp \rho_0^1), \quad \text{Re} \rho^1_{10} = \frac{1}{2} \left( \text{Re} \rho_{10}^0 \mp \text{Re} \rho_{10}^1 \right), \\
\rho^1_{-1} = \frac{1}{2} \left( \rho_{-1}^1 \pm \rho_{-1}^1 \right).
\]

\[ \pi^- p \rightarrow \eta \pi^- p \]

\[ M = 1370 \pm 16^{+50}_{-30} \text{ MeV} / c^2 \]
\[ \Gamma = 385 \pm 40_{-65}^{+65} \text{ MeV} / c^2 \]

No consistent B-W interpretation possible but a weak \( \eta \pi \) interaction exists and can reproduce the exotic wave

\[ \pi^- p \rightarrow \eta^0 n \]

\[ M = 1593 \pm 10_{-47}^{+45} \text{ MeV} / c^2 \]
\[ \Gamma = 168 \pm 20_{-12}^{+150} \text{ MeV} / c^2 \]

BNL (E852) yes/no

COMPASS yes

\[ \pi^- p \rightarrow \eta' \pi^- p \]

\[ M = 1597 \pm 10_{-47}^{+45} \text{ MeV} / c^2 \]
\[ \Gamma = 340 \pm 40_{-50}^{+50} \text{ MeV} / c^2 \]

\[ \pi^- p \rightarrow \rho^0 \pi^- p \]

E852 result

FIG. 25: (a) The \( 1^{-+} 1^+ \) P-wave \( \rho \pi \) partial wave \( \rho \pi \) charged mode \((\pi^- \pi^- \pi^+)\) for the high-wave set PWA and low-wave set PWA and (b) the phase difference \( \Delta \Phi \) for the \( 2^{++} \) and \( 1^{-+} \) for the two wave sets.

\[ \pi^- p \rightarrow \pi^-_2 (1600) p \]
\[ \pi^-_2 \rightarrow \rho^0 \pi^- \rho^0 \]

\[ M = 1660 \pm 10_{-44}^{+44} \text{ MeV}/c^2 \]
\[ \Gamma = 269 \pm 21_{-44}^{+44} \text{ MeV}/c^2 \]

Leakage negligible: <5%
\[ \pi^- p \rightarrow \eta \pi^- p \]

\[ M = 1370 \pm 16^{+50}_{-30} \text{ MeV} / c^2 \]
\[ \Gamma = 385 \pm 40^{+65}_{-105} \text{ MeV} / c^2 \]

No consistent B-W interpretation possible but a weak \( \eta \pi \) interaction exists and can reproduce the exotic wave

\[ \pi^- p \rightarrow \eta^0 n \]

\[ \pi^- p \rightarrow \eta' \pi^- p \]

\[ \pi^- p \rightarrow \rho^0 \]

\[ M = 1597 \pm 10^{+45}_{-10} \text{ MeV} / c^2 \]
\[ \Gamma = 340 \pm 40^{+100}_{-50} \text{ MeV} / c^2 \]

\[ \pi^- p \rightarrow \pi^- (1600)p \]
\[ \pi_2^- \rightarrow \rho^0 \pi^- \]

\[ \rho^0 \rightarrow \pi^- \pi^- \]

**Need to be confirmed**

- \( \pi^- p \rightarrow \pi^- (1600)p \)
- \( \pi_2^- \rightarrow \rho^0 \pi^- \)
- \( \rho^0 \rightarrow \pi^- \pi^- \)

**FIG. 25:** (a) The \( 1^{-+} \) partial wave PW for the high-wave set and (b) the phase difference \( \Delta \Phi \) for the two wave sets.

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

Production(s_m) \times Interactions in \eta\pi (s_m)

Constrained by unitary

\[ a_{\ell m_{\ell}} = f_{\ell m_{\ell}}(s) t_{\ell}(s) \]

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

\[ t_{\ell}(s) = \frac{N(s)}{D(s)} \]

\[ D(s) = D_0(s) - \frac{s}{\pi} \int_{s_{th}}^{\infty} ds' \frac{\rho(s') N(s')}{s'(s' - s)} \]

\[ D_0(s) = a - bs - \sum c_r s_r - s \]

\[ D^0(s) = \frac{a_2}{s} + \frac{a'_2}{s} \]

Sheet I

\[ M(1320) = 1.308(2) \text{ GeV}, \Gamma(1320) = 0.113(1) \text{ GeV} \]

\[ M(1700) = 1.71(6) \text{ GeV}, \Gamma(1700) = 0.30(6) \text{ GeV} \]
$\pi^- p \rightarrow \eta' \pi^- p$
Fits to COMPASS data (preliminary)
Fits to COMPASS data (preliminary)

2 poles

$\eta \pi$ (phase)

1 pole

$\eta' \pi$ (phase)
Exotic physics: $P_c$ at JLAB

Confirmation possible thorough photoproduction

If $P_c$ is confirmed, need to:

- Study the electromagnetic properties
- Look for the other members of the $P_c$ multiplet
- NB: Arbitrary normalization for data

S.J. Brodsky, E. Chudakov, P. Hoyer, J.M. Laget
(Very) exotic physics: constraining Lorentz symmetry violation

- Observer transformations do not affect results.
- Particle transformation, e.g. rotation of the experiment in the background filed produces a physical effect.

There is a well defined SME $\mathcal{L}_{SME} = \mathcal{L}_{Gravity} + \mathcal{L}_{SM} + \mathcal{L}_{LV}$ e.g. $a_{\mu} \bar{\psi} \gamma^\mu \psi$, $c_{\mu \nu} \bar{\psi} \gamma^\mu \gamma^\nu \gamma^\nu \psi$

- Only a few constraints in the quark sector: use DIS, SDIS, Drell-Yan, ...

\[ W^{\mu \nu} \simeq i \int d^4x e^{iqx} \int_0^1 d\xi \sum_{f=u,d} \frac{f_{\nu}(\xi)}{\xi} \langle \xi P | T\left\{ J^{\mu}(x) J^{\nu}(0) \right\} | \xi P \rangle \]

\[ \Gamma^\mu_f = \gamma^\mu + c^{\mu \nu}_f \gamma^\nu \]

- The first estimate on the sidereal time dependent coefficients $c_i$ were obtained using HERA data: $O(10^{-5})$ (V.A.Kostelecky, E.Lunghi, A.Vieira, PLB729, 272 (2017))

- Sensitivity studies for EIC are under way: N.Sherrill, A.Accardi, E.Lunghi.
Impact

- ~120 Invited Talks and Seminars
- $O(10)$ on going analyses
- Many projects, e.g.,
  - $\pi N \to \eta \pi N$  A. Jackura et al., arXiv:1707.02848
  - $\eta$, $\eta'$ beam asymmetry  V. Mathieu et al., arXiv:1704.07684
  - $Z_c'(3900)$  A. Pilloni et al., PLB772 (2017) 200
  - $\gamma p \to \eta p$  J. Nys et al., PRD95 (2017) 034014
  - $P_c(4450)$  A. Hiller Blin et al., PRD94 (2016) 034002
  - $\eta \to \pi^+\pi^-\pi^0$  P. Guo et al., PRD92 (2015) 054016, PLB (2017) 497
  - $\Lambda(1405)$  C. Fernández-Ramírez et al., PRD93 (2016) 074015
  - $KN \to KN$  C. Fernández-Ramírez et al., PRD93 (2016) 034029
  - $\pi N \to \pi N$  V. Mathieu et al., PRD92 (2015) 074004
  - $\gamma p \to \pi^0 p$  V. Mathieu et al., PRD92 (2015) 074013
  - $\omega, \phi \to \pi^+ \pi^- \pi^0$  I. Danilkin et al., PRD91 (2015) 094029
  - $\gamma p \to K^+K^- p$  M. Shi et al., PRD91 (2015) 034007
  - ...
- Collaboration between JPAC and experimental collaborations: co-authoring papers
  - GlueX, CLAS12, COMPASS, BaBar, Belle, BES
  - KLOE, LHCb in preparation
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JPAC 2018

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