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 bumps and dips, energy levels)

  Reaction amplitudes

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

  Microscopic Models

- What is the interpretation (constituent quarks, molecules, …)?
Signatures of new, unusual light resonances

- High precision PWA of 3π 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 $\eta(\prime)\pi$ production: FESR’s to constrain P-wave
Signatures of unusual heavy quark resonances

Virtual OPE

Real OPE


BESIII PRL 112, 022001

Z_c(3900) \rightarrow \bar{D}^0 D^{*+}

LHCb, B \rightarrow K J/\psi \phi

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 A(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

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

\[ A_{\mu_4 \mu_3 \mu_2 \mu_1} = R(s, t) \sqrt{-t} |\mu_1 - \mu_3| \sqrt{-t} |\mu_2 - \mu_4| \hat{\beta}_{\mu_1 \mu_3}(t) \hat{\beta}_{\mu_2 \mu_4}(t) F_e(s, t) \]

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

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

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

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

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

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

\[
\gamma p \to \pi^0 p
\]

\[
s_{\text{max}} = (2.4 \text{ GeV})^2
\]
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

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!

\[\rho + \omega\]
\[b + h\]
\[\rho + \omega\]
\[\gamma p \rightarrow \eta p\]
Based on the FESR 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**

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

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Comparison to GlueX data

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

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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 ($|\lambda-\lambda'|=1$)

\[
\mathcal{M}_{\lambda V,\lambda'}(s, t) = \sum_{E=\pi, \eta, \rho_2, \rho_1} \mathcal{M}_{\lambda V,\lambda'}^{E}(s, t).
\]

\[
\mathcal{M}_{\lambda V,\lambda'}^{N}(s, t) = \mathcal{M}_{\lambda,\lambda'}^{N}(s, t).
\]

\[
\mathcal{M}_{\lambda V,\lambda'}^{U}(s, t) = \pm (-1)^{\lambda-\lambda'} \mathcal{M}_{\lambda,\lambda'}^{U}(s, t).
\]

\[
\gamma(k, \lambda) \rightarrow V(q, \lambda V).
\]

\[
\gamma(p, \lambda) \rightarrow B^E \rightarrow N'(p', \lambda').
\]

\[
\rho_0^U = \frac{1}{2} \left( \rho_0^0 \mp \rho_1^0 \right),
\]

\[
\text{Re} \rho_{10}^U = \frac{1}{2} \left( \text{Re} \rho_{10}^0 \mp \text{Re} \rho_{10}^1 \right),
\]

\[
\rho_{1-1}^U = \frac{1}{2} \left( \rho_{1-1}^1 \pm \rho_{11}^1 \right).
\]

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

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

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

Need to be confirmed
$\Delta_s a_{\ell m_\ell}(s) = 2i \rho_\ell(s) t^*_\ell(s) a_{\ell m_\ell}(s)$

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

Constrained by unitary

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

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

$t_\ell(s) = N(s)/D(s)$

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

$D_0(s) = a - bs - \sum \frac{c_r}{s_r - s}$

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$M(1320) = 1.308(2)$ GeV, $\Gamma(1320) = 0.113(1)$ GeV

$M(1700) = 1.71(6)$ GeV, $\Gamma(1700) = 0.30(6)$ GeV
\[ \pi^- p \rightarrow \eta' \pi^- p \]
Fits to COMPASS : D-wave

\[ a_2 \]

\[ a'_2 \]
P-D interference

\[ a_2, a'_2, \Pi_1 \]
P-wave
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 field produces a physical effect.

- There is a well defined SME

\[ \mathcal{L}_{\text{SME}} = \mathcal{L}_{\text{Gravity}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{LV}} \]

(e.g. \( a_\mu \bar{\psi} \gamma^\mu \psi \), \( c_{\mu \nu} \bar{\psi} \gamma^\mu \vec{D} \gamma_\nu \psi \))

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

- 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.,
  - $\pi N \rightarrow \eta \pi N$ 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
  - $\gamma p \rightarrow \eta p$ J. Nys et al., PRD95 (2017) 034014
  - $P_c(4450)$ A. Hiller Blin et al., PRD94 (2016) 034002
  - $\eta \rightarrow \pi^+\pi^-\pi^0$ P. Guo et al., PRD92 (2015) 054016, PLB (2017) 497
  - $\Lambda(1405)$ C. Fernández-Ramírez et al., PRD93 (2016) 074015
  - $K N \rightarrow K N$ C. Fernández-Ramírez et al., PRD93 (2016) 034029
  - $\pi N \rightarrow \pi N$ V. Mathieu et al., PRD92 (2015) 074004
  - $\gamma p \rightarrow \pi^0 p$ V. Mathieu et al., PRD92 (2015) 074013
  - $\omega, \phi \rightarrow \pi^+ \pi^- \pi^0$ I. Danilkin et al., PRD91 (2015) 094029
  - $\gamma p \rightarrow K^+K^- p$ 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
Jefferson Lab
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Victor Mokeev
Emilie Passemier
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Collaborating with: CLAS12 & GlueX (JLab), COMPASS & LHCb (CERN), MAMI (Mainz), BESIII (Beijing), KLOE (Frascati), BELLE II (KEK), BABAR (SLAC)

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