Exotic Meson Phenomenology

Adam Szczepaniak (IU/JLab)

- Light exotics, Heavy exotics, production and decay characteristics: Towards a complete understanding of the hybrids
co-organized over 30 international conferences, including its own "Future Directions in Spectroscopy Analysis" series, summer schools, graduate courses, published over 200 papers

JPAC’s priority is to provide an intellectually stimulating environment and create carrier opportunities for its members

We adopted a horizontal management structure, decisions made by consensus with shared responsibilities and benefits (e.g. publication policy)
**Holy Grail: AI as a tool for physics discovery**

Learn (S-matrix)

\[ S = T \exp \left( -i \int_{-\infty}^{\infty} dt H'_1(t) \right) \]

Apply to data

Tell the story
Importance of high quality data

\[ \pi^- + p \rightarrow X^- + p \]

The puzzle of the A2 meson

The A2 may be two distinct but similar particles or a single object of an entirely new type. Either way, it has experimentalists arguing and theorists confused.

Similar spectra from GlueX and CLAS12
Theory Models

Make S-matrix theory rooted hypotheses: minimal bias

It all goes through analytical reaction amplitudes

Make models and compare with data: difficult to avoid bias
Applications: Light Exotic Hybrid

\[ S = S_1 + S_2 \]
\[ J = L + S \]
\[ P = (-1)^{L+1} \]
\[ C = (-1)^{L+S} \]

Determine JPC through Partial Wave Analysis

Mesons with \( J^{PC} = 0^{-}, 0^{++}, 1^{-+}, 2^{+-} \): Exotic Quantum Numbers

Expected to have very similar properties to ordinary Q\(\bar{Q}\) mesons
Brief history of light hybrids

• 1970-80 The early phenomenology

• ’2000-2010 The early data

• 2000-2010 The early lattice studies

• New perspectives: GlueX, CLAS, COMPAS, JPAC…
\( J^{PC} = 1^{-+} \) Outside valance quark model

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[A.Rodas, et al (JAPC) PRL (2019)]

\( \eta(\pi) \) resonances from COMPASS data

\[ \Gamma_{\text{tot}} \approx 140-600 \text{ MeV} \]
\[ \Gamma(\eta \eta) \ll 1 \text{ MeV} \]
\[ \Gamma(\eta \pi) \ll 20 \text{ MeV} \]
\[ \Gamma(\eta \rho) \ll 12 \text{ MeV} \]
\[ \Gamma(\eta \phi) \approx 140-530 \text{ MeV} \]

A.Woss et al. PRD 103 (2021) 5, 054502
Uniqueness of JLab for spectroscopy

Majority of hadron exotics spotted in colliders. Very few were seen in more than one setting.

Fixed target with well tuned $E_\gamma$:

- Full exclusivity
- Low multiplicity
- Direct production and peripheral production are calculable
- Resonances can be well separated from kinematic effects
- Significant rapidity gap enables to separate beam from target fragmentation
Peripheral Production: Regge poles (+ corrections)

- Factorization

\[ A_{\lambda_i}(s, t) = \beta^{Top}_{\lambda_1, \lambda_3}(t)\beta^{Bottom}_{\lambda_1, \lambda_4}(t)G(s, t) \]

- Shrinkage of the forward peak

\[ G(s, t) \sim \exp(b \log(s)t) \]

- Phases constrained by unitarity

- Residues (\(\beta\)'s) related to observables e.g.

\[ \beta^2(\gamma b_1, R_\pi) \sim \Gamma(b_1 \rightarrow \gamma \pi) \]

- Corrections O(1/log(s)) can be formalized within an EFT
Global Regge pole of CEX (no $P$ no $\pi$)

“$\rho$” exchange dip at
$(t \sim -0.5 GeV^2)$

Regge poles well describe peripheral production at CEBAF energies....

“$a_2$” exchange

Data =1271 points, $N_{par} = 6$ SU(3) couplings, 1 mixing angle, 2 exp. slopes

“$K/K^*$” exchange

J.Nys et al. (JPAC) 2018
Systematic analysis of the $\pi_1$ at JLab

1. We know $\pi_1$ decay characteristics (mostly done)

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A.Rodas et al. (JPAC) 2019

2. We need to know how $\pi_1$ is produced (single Regge) (in progress)

3. Use data outside the resonance region
   Double Regge to constrain resonance parameters
   (In progress) Major breakthrough!

4. Extend to include other channels (in progress)
Dispersion relations for 2-3 process

\[ \gamma(\pi^-) \rightarrow \pi_1 \rightarrow \eta^{(\prime)} \rightarrow \pi^0(\pi^-) \]

\[ p \rightarrow p \]

Dispersion relations, Finite Energy Sum Rules, etc

The existing models of the Double Regge exchange suffer from pathologies (infinite narrow resonances). We have “understood” how to construct DR amplitudes without such pathologies.

Enables comparison with microscopic models and lattice

GlueX/(COMPAS) analysis in progress
Systematic analysis of the $\pi_1$ at JLab

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Resonance production via single Regge exchange

Main exotic decay is $\pi_1 \rightarrow b_1 \pi$

Need first to understand $b_1$ photoproduction

In the neutral channel $\gamma p \rightarrow b_1^0 p$

GlueX PWA shows (very) small contribution from unnatural exchange compares to natural (?)

Model/Decay chain:

$$A_{j_\gamma j_1 j_2} = \sum_{\Lambda=-1}^{1} \sum_{\lambda_2=-\frac{1}{2}}^{\frac{1}{2}} V_{j_\gamma \Lambda j_1 j_2}(s,t) \sum_{\lambda=-1}^{1} F_{\lambda} D_{\lambda,\lambda}^{\gamma}(\Omega_{\omega}) Y_{\lambda}^{t}(\Omega_{\pi}) G \tilde{F}_{2 \lambda_2} D_{\lambda_2,\lambda_2}^{\gamma}(\Omega_{p})$$

Pion exchange cross-section in agreement (prediction, not fit!) with preliminary data
Towards complete understanding of photoproduction

Understanding \( \Delta^{++} \) production is underway

\[
\gamma \rightarrow p\pi^+\pi^- + \Delta^{++}
\]

Two-pion photo production project almost completed (impressive data agreement)

High quality data from CLAS, more expected from CLAS12 and GlueX

Hierarchy of P-waves for various helicities, determined production dynamics that gives rise to other helicity structures for \(|t| \geq 0.45 \text{ GeV}^2\)

L. Bibrzycki, et al. (JPAC) 2024
Fun with $\pi$ exchange

$\gamma (k, \mu_\gamma) \rightarrow \pi (p_\pi)$

$\pi (q_t) \rightarrow N (p_i, \mu_i)$

$N (p_f, \mu_f) \rightarrow \gamma (k, \lambda_\gamma)$

$J^P \rightarrow m_\pi = 0$

$\bar{\pi} (p_\bar{\pi})$

$\gamma (k, \lambda_\gamma) \rightarrow \gamma (k, \mu_\gamma)$

$m_\gamma = \pm 1$

$m_\pi = 0 \neq \pm 1$

Naively there is no $\pi$ exchange!

See Gloria Montana talk
Applications: Heavy quarks

GlueX: PRL 123, 072001 (2019)

- Full GlueX-I data yields 2270 ± 58 J/ψ’s

- “Dip” above 9 GeV has 2.6σ (1.3σ) local (global) significance

\( \Lambda_c \bar{D}^{(*)} \)

\( P_c \)'s

10

\( 10^{-1} \)

8 9 10

\( E_\gamma, \text{GeV} \)

10

\( 10^{-1} \)

8 9 10

\( E_\gamma, \text{GeV} \)

Threshold effects? Du et al, EPJC 80, 1053 (2020)

D. Winney et al. (JPAC, 2023)

Combined analysis of \( J/\psi \) 007 and GlueX

\( J^{PAC} \)

\( P_c(4312) \)

FIG. 1: Fit results for the integrated cross section compared to GlueX data from [37]. Bands correspond to 1σ uncertainties from bootstrap analysis.
Spectroscopy at the future facilities

**XYZP** spectroscopy at a charm photoproduction factory

M. Albaladejo,1 M. Battaglieri,2,3 A. Esposito,4 C. Fernández-Ramírez,5 A. N. Hiller Blin,1 V. Mathieu,6 W. Melnitchouk,1 M. Mikhasenko,7 V. I. Mokeev,2 A. Pilloni,3,8 * A. D. Polosa,9 J.-W. Qiu,1 A. P. Szczepaniak,1,10,11 and D. Winney10,11

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

**Hadron Spectroscopy in Photoproduction**

Miguel Albaladejo1, Lukasz Bibrzycki2, Sean Dobbs3, César Fernández-Ramírez4,5, Astrid N. Hiller Blin6, Vincent Mathieu7,8, Alessandro Pilloni9,10, Justin Stevens11, Adam P. Szczepaniak12,13,14, and Daniel Winney13,14,15,16

EIC/JLab++ explore the complementarity of diffraction, peripheral and/or direct production

Lol RF7_RF0_120

arXiv:2112.00060

arXiv:2203.08290
Spectroscopy at the future facilities

$Z_{c,b}^+$ Production @JLab++, EIC

- Couplings from data as much as possible, not relying on the nature of XYZ
- The model is expected to hold in the highest x- bin
- Model underestimates lower bins, conservative estimates

**JLab22 ideal for XZ, EIC better for Y’s**

https://github.com/dwinney/jpacPhoto

M. Albaladejo et al. [JPAC], PRD (2020)
D.Winney et al. (JPAC)
D.Glazier et al (JPAC)
Summary

- Observation of new hadrons indicate that there is a large “hadronic landscape” yet to be discovered.

- Production of meson resonances in CBAF kinematics (including exotics) well described in terms of an Regge EFT which relates production and decays.

- The $\pi_1(1600)$ story is shaping up.

- Great prospects for spectroscopy at JLab22.
- predicting exotic and non-exotic meson resonances and their properties from lattice QCD;
- reliably extracting exotic and non-exotic meson resonances and their production and decay properties from experimental data sets;
- interpreting both the experimental and theoretical results.