Experimental searches for light exotica

Matthew Shepherd
Indiana University

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Searching for Exotic Mesons

• We would like to understand how QCD gives rise to the properties of hadrons

• Discovering a spectrum of exotic resonances has the potential to expose new “rules” that QCD follows when “building” hadrons

• drives desire for theoretical understanding of how these rules arise from QCD
Searching for Exotic Mesons

• We would like to understand how QCD gives rise to the properties of hadrons
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  • drives desire for theoretical understanding of how these rules arise from QCD
• Mesons are particularly well suited for this adventure:
  • notion of exotic $J^{PC}$
  • spectrum of “conventional” states is minimal
  • light and heavy quark sectors are complementary
Building Mesons

- Nature seems to prefer a very simple picture of mesons
- how is this encoded in QCD?
- QCD suggests other “exotic” possibilities:
  - gluonic degrees of freedom (hybrids and glueballs)
  - tetraquarks, …

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

Allowed \( J^{PC} \): 0\(^-\), 0\(^++\), 1\(^--\), 1\(^+\), 2\(^++\), …
Forbidden \( J^{PC} \): 0\(^-\), 0\(^+\), 1\(^+\), 2\(^+\), …
Light Quark Mesons from Lattice QCD


In this case we take all three quark flavors to be mass degenerate, with the mass we have tuned to correspond to the physical strange quark. Here, because there is an exact SU(3) flavor symmetry, we characterize mesons in terms of their SU(3)F representation, octet (8) or singlet (1), and compute correlation matrices using the basis in Eq. (5).

The octet correlators feature only connected diagrams while the singlets receive an additional contribution from a disconnected diagram. Since the strange quarks are now no heavier than the 'light' quarks, any splitting between states in the octet and singlet spectra is purely due to the disconnected diagrams and thus to 'annihilation dynamics.' In Fig. 13 we present the spectra extracted on two lattice volumes.

D. Quark mass and volume dependence

Figures 14–16 show the quark mass and volume dependence of the extracted isoscalar and isovector spectra. In general, the extracted spectrum is fairly consistent across quark masses. There are some cases, such as the second level in 3/C0, that are not cleanly extracted at the lowest pion mass. We refrain from performing extrapolations of the masses to the limit of the physical quark masses, since, as we have already pointed out, we expect most excited states to be unstable resonances. A suitable quantity for extrapolation might be the complex resonance pole position, but we do not obtain this in our simple calculations using only single-hadron operators.

We discuss the specific case of the 0/C0 and 1/C0/C0 systems in the next subsections.

E. The low-lying pseudoscalars:

In lattice calculations of the type performed in this paper, where isospin is exact and electromagnetism does not feature, the 25 and 17 mesons are exactly stable and 17 is rendered stable since its isospin conserving 17/C25/C25 decay mode is kinematically closed. Because of this, many of the caveats presented in Sec. III B do not apply. Figure 17 shows the quality of the principal correlators from which we extract the meson masses, in the form of an effective mass,

\[ m_{\text{eff}} = \frac{1}{14} \log \frac{1}{12} (t) \] (16)

for the lightest quark mass and largest volume considered. The effective masses clearly plateau and can be described at later times by a constant fit which gives a mass in agreement with the two exponential fits to the principal correlator that we typically use.

Figure 18 indicates the detailed quark mass and volume dependence of the 17 and 17 mesons. We have already commented on the unexplained sensitivity of the 17 mass to the spatial volume at \( m_{\pi} = 391 \text{ MeV} \), and we note that...
A Lattice QCD Motivated Model

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

Allowed \( J^{PC} \): \( 0^{-}, 0^{++}, 1^{-+}, 1^{++}, 2^{++}, \ldots \)

Forbidden \( J^{PC} \): \( 0^{-}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots \)
A Lattice QCD Motivated Model

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

Allowed \( J^{PC} \): \( 0^+, 0^{++}, 1^-, 1^+, 2^{++}, \ldots \)
Forbidden \( J^{PC} \): \( 0^-, 0^+, 1^+, 2^+, \ldots \)

"gluonic field"

\[ (J^{PC})_g = 1^{+-} \quad \text{mass} \approx 1.0-1.5 \text{ GeV} \]

Lightest Hybrids

\[ S_{q\bar{q}} = 1 \quad S_{q\bar{q}} = 0 \]

\[ J^{PC}: \quad 0^+, 1^{+-}, 2^+ \quad 1^{--} \]

"exotic hybrid"
Light Quark Exotic Mesons: Experiment

- Long history
  - reports of exotic $J^{PC}$ mesons have been around for over twenty years
  - multiple experiments made significant contributions: debate about analysis or interpretation but (often) consistency in experimental observables
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• Shifting experimental focus to exotic mesons (XYZ) in the heavy quark sector
  • evidence: 100 talks and posters in tracks “Exotic States and Candidates,” “Meson Spectroscopy,” and “Analysis Tools” but only a few presenting results on light quark exotics
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  - evidence: 100 talks and posters in tracks “Exotic States and Candidates,” “Meson Spectroscopy,” and “Analysis Tools” but only a few presenting results on light quark exotics
- Significant recent developments suggest exciting future:
  - a renewed focus on developing theoretical foundations of amplitude analysis
  - unprecedented statistical precision from experiment
  - new facilities coming online
Reunification of Theory and Experiment

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- Need to systematically fit experimental data in way that
  - respects sacred principles
  - yields physically meaningful (universal) values for parameters
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• Need to systematically fit experimental data in a way that
  • respects sacred principles
  • yields physically meaningful (universal) values for parameters
• Requires dedicated theory/experiment collaboration (see, for example, V. Mathieu’s talk on Monday)
Precision Brings Challenges

- Example from BESII and BESIII
  - Search for resonances in the channel $J/\psi \rightarrow \gamma \eta' \pi \pi$
  - Well-known enhancement at $p\bar{p}$ threshold in $J/\psi \rightarrow \gamma p\bar{p}$

BESII: $X(1835)$ at 6$\sigma$ with $58 \times 10^6 J/\psi$
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**BESII:**

$X(1835)$ at $6\sigma$ with $58 \times 10^6 J/\psi$

Revisited with BESIII using $1.09 \times 10^9 J/\psi$

**BES III Collab., PRL 117, 042002 (2016)**

- Data
- PHSP MC
- Background
- $p\bar{p}$ threshold

**BESII Collab., PRL 95, 262001 (2005)**

- Events / (40 MeV/c^2)
- $M(\pi^+\pi^-\eta')$ (GeV/c^2)
In this case we take all three quark flavors to be mass degenerate, with the mass we have tuned to correspond to the physical strange quark. Here, because there is an exact SU$_3$ flavor symmetry, we characterize mesons in terms of their SU$_3$ representation, octet (⁸) or singlet (¹), and compute correlation matrices using the basis in Eq. (5).

The octet correlators feature only connected diagrams while the singlets receive an additional contribution from a disconnected diagram. Since the strange quarks are now no heavier than the ''light'' quarks, any splitting between states in the octet and singlet spectra is purely due to the disconnected diagrams and thus to ''annihilation dynamics.'' In Fig. 13 we present the spectra extracted on two lattice volumes.

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We discuss the specific case of the \( \frac{0}{2} / C_0^+ \) and \( \frac{1}{2} / C_0^- / C_0^- \) systems in the next subsections.

E. The low-lying pseudoscalars:

In lattice calculations of the type performed in this paper, where isospin is exact and electromagnetism does not feature, the \( \frac{2}{2} \) and \( \frac{1}{2} \) mesons are exactly stable and \( \frac{0}{2} \) is rendered stable since its isospin conserving \( \frac{1}{2} / C_0^+ / C_0^- \) decay mode is kinematically closed. Because of this, many of the caveats presented in Sec. III B do not apply.

Figure 17 shows the quality of the principal correlators from which we extract the meson masses, in the form of an effective mass,

\[
m_{\text{eff}} = \frac{1}{\log^2(t)} \left( \frac{1}{t} + \frac{1}{t} \right)
\]

for the lightest quark mass and largest volume considered. The effective masses clearly plateau and can be described at later times by a constant fit which gives a mass in agreement with the two exponential fits to the principal correlator that we typically use.

Figure 18 indicates the detailed quark mass and volume dependence of the \( \frac{1}{2} \) and \( \frac{1}{2} \) mesons. We have already commented on the unexplained sensitivity of the \( \frac{0}{2} \) mass to the spatial volume at \( \frac{391}{25} \) MeV, and we note that...
Exotic $J^{PC}$ Candidates

- See PDG for references:
  - $\pi_1(1400) \rightarrow \eta \pi$
  - $\pi_1(1600) \rightarrow \eta' \pi$ and $\rho \pi$
  - $\pi_1(2015) \rightarrow f_1 \pi$ and $\omega \pi \pi$

- Recent results most pertain to $\pi_1(1400)$ and $\pi_1(1600)$:
  - $P$-wave in $\eta(1400) \pi$
  - $\pi_1(1600) \rightarrow \rho \pi$
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- Recent results most pertain to $\pi_1(1400)$ and $\pi_1(1600)$:
  - $P$-wave in $\eta'(\pi)$
  - $\pi_1(1600) \rightarrow \rho \pi$

- Begin with $\eta'(\pi)$ system:
  - isovector
  - L-odd implies neutral member has exotic $J^{PC}$: $1^-, 3^+, \ldots$
  - simple kinematics: L is encoded in a single angular distribution

\[\text{Gottfried-Jackson (GJ) Frame}\]
\[ \pi^- p \rightarrow \eta(\,\,) \pi^- p \]

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

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

**Fig. 2.**

Graphs showing the mass distributions for \( m(\eta \pi^-) \) and \( m(\eta' \pi^-) \) in GeV/c^2, with acceptance percentages indicated. The graphs also show the distribution of \( \cos \theta_{GJ} \) in both planes. The data is presented in two panels, each with a yellow histogram and a red line indicating the acceptance. The graphs are labeled with the COMPASS logo, indicating that the data comes from the COMPASS experiment.
\[ \pi^- p \rightarrow \eta(\prime) \pi^- p \]

- Partial wave decomposition
- black: \( \eta \pi \)
- red: \( \eta \pi \) rescaled by kinematical factor
- Odd L waves (exotic) are enhanced in \( \eta \pi \) when compared with \( \eta \pi \)
- resonant?
- Need well-constrained models to search for resonances
Analysis of $\eta\pi D$-wave

- Extract pole positions in a fit to published partial waves using unitary parameterization
- Strong evidence for $a_2'$
- Stepping stone to $P$-wave and $\eta'\pi$ analyses (and others)

A. Jackura et al. [JPAC and COMPASS Collaborations], arXiv:1707.02848
Constraining $\eta'\pi P$-wave

COMPASS Collab., PLB 740, 303 (2015)

Not-so-exotic scattering

$\pi^- GJ \eta'$

beam
Constraining $\eta'\pi\ P$-wave

Exotic Resonance?

Not-so-exotic scattering

Extrapolate to resonance region
Complementary Production: $\chi_{c1} \rightarrow \eta\pi\pi$

- Additional evidence for the of $a_2'$
- No evidence for $\pi\pi \rightarrow \eta\pi$
- CLEO reported $P$-wave $\eta'\pi$ in $\chi_{c1} \rightarrow \eta'\pi\pi$ [CLEO Collab., PRD 84, 112009 (2011)]

- can be explored at BESIII with better statistical precision
Summary

- Recent COMPASS observations consistent with previous experiments
- $\eta \pi$ P-wave peaking at 1400 MeV
- $\eta' \pi$ P-wave peaking at 1600 MeV
- $\eta' \pi$ signal dominates $\eta \pi$
- Significant $\eta' \pi$ P-wave amplitude observed in complementary processes
\[ \pi \rightarrow \eta(\prime)\pi \] Summary

- Recent COMPASS observations consistent with previous experiments
- \(\eta\pi\) P-wave peaking at 1400 MeV
- \(\eta'\pi\) P-wave peaking at 1600 MeV
- \(\eta'\pi\) signal dominates \(\eta\pi\)
- Significant \(\eta'\pi\) P-wave amplitude observed in complementary processes
- Very interesting but not quite yet at the threshold of passing the duck test
- need to understand how peaks may be related to resonance poles

“When I see a bird that walks like a duck and swims like a duck and quacks like a duck, I call that bird a duck.”

— James Whitcomb Riley
Indiana Poet
\[ \pi^- p \rightarrow \pi^- \pi^- \pi^+ p \]

- 4.7 x 10^7 events
- Analysis of distribution 5D phase space to extract $J^{PC}$ content (88 amplitudes) with minimal model dependence (result: $O(10^5)$ parameters)
- statistics enables (and demands) innovations in analysis

See talks yesterday by S. Wallner and F. Krinner

\[ a_2(1320) \rightarrow \rho \pi \]

![Graphs and Diagrams](image)
The two subsequent two-body decays are described in different right-handed coordinate systems, i.e., the frame. This frame is constructed by boosting from the Gottfried-Jackson system into the For the decay of the isobar system, the momenta of the isobar and the bachelor pion are back to back, so that the two-body decay bachelor pion. It is constructed in the To describe the angular distribution of the decay of the intermediate state particular quantum numbers of decay, isobar model

As illustrated in Fig. 1, for reaction trajectory with particle and target nucleon, and accounts for diffractive dissociation and most of the two-body elastic scattering [23]. The Regge trajectory figure shows the excitation of an intermediate resonance Figure 1:

The decay of as described in the isobar model, is assumed to proceed via an intermediate decay modes.

\[ \pi^+ p \rightarrow \pi^- \pi^- \pi^+ p \] (COMPASS 2008)
Mass-independent fit
Mass-dependent fit resonant
non-resonant

\[ m_{3\pi} \] [GeV/c^2]

Intensity / (20 MeV/c^2)

\[ 0.724 < t' < 1.000 \text{ (GeV/c)}^2 \]

\[ 0.100 < t' < 0.113 \text{ (GeV/c)}^2 \]

\[ \Delta \phi = \phi - \alpha \phi \]

from S. Wallner yesterday

\[ \frac{s}{c} \text{ GeV} \]
\( I^- + \rho \pi P \text{-wave} \)

**low \( t \)**

\[ \pi^- p \rightarrow \pi^- \pi^- \pi^+ p \text{ (COMPASS 2008)} \]

\( I^-1^+ \rho(770) \pi P \)

\[ 0.100 < t' < 0.113 \text{ (GeV/c)}^2 \]

Mass-independent fit

Mass-dependent fit

resonant

non-resonant

**high \( t \)**

\[ \pi^- p \rightarrow \pi^- \pi^- \pi^+ p \text{ (COMPASS 2008)} \]

\( I^-1^+ \rho(770) \pi P \)

\[ 0.449 < t' < 0.724 \text{ (GeV/c)}^2 \]

Mass-independent fit

Mass-dependent fit

resonant

non-resonant

See B. Ketzer tomorrow: resonant \( \pi \pi \) dominates exotic amplitude at high \( t \)
Light Quark Mesons from Lattice QCD

*Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)*

**negative parity**

**positive parity**

**exotic**

*lightest hybrids*

\[ m_\pi = 391 \text{ MeV} \]

\[ 24^3 \times 128 \]

isoscalar \( \ell_s \)

isovector \( \ell_v \)

The vertical height of each box indicates the statistical uncertainty on the mass determination. States outlined in orange are the lowest-lying states having dominant overlap with operators featuring a chromomagnetic construction—their interpretation as the lightest hybrid meson supermultiplet will be discussed later.
Light Quark Mesons from Lattice QCD


Patterns are essential to establish the existence of hybrids

- Hybrids should overpopulate conventional $J^{PC}$
- Understanding $\pi_2$ spectrum (e.g., using COMPASS data) is potentially just as interesting as the exotic $\pi_1$
\[ a_1(1420) \rightarrow f_0(980) \pi \]

- Discovering patterns is crucial …but they must be patterns of resonances!
- (Warning: sometimes Occam’s razor kills the duck.)
\[ a_1(1420) \rightarrow f_0(980) \pi \]

- Discovering patterns is crucial … but they must be patterns of resonances!
  - (Warning: sometimes Occam’s razor kills the duck.)
- Exotic properties of the \( a_1(1420) \)
  - very narrow
  - only couples to \( f_0(980) \pi \)
  - mass doesn’t fit the pattern with other \( qq \) states

\[ \begin{array}{c}
\pi \\
\pi
\end{array} \quad a_1(1420) \quad \begin{array}{c}
\pi \\
\pi
\end{array} \]
\( a_1(1420) \rightarrow f_0(980)\pi \)

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  - very narrow
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  - mass doesn’t fit the pattern with other qq states
- All of the above can have a non-exotic origin…

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**Fig.**

\[ \text{COMPASS Collab., PRL 115, 082001 (2015)} \]

\[ \begin{array}{c}
1^{++0^+} f_0(980) \pi P \\
0.1 < t' < 1.0 \ (\text{GeV}/c)^2
\end{array} \]

1. Model curve
2. \( a_1(1420) \) resonance
3. Non-resonant term

**Graphical Representations:**

- Diagram of \( a_1(1420) \) decay to \( f_0(980)\pi \)
- Diagram of \( a_1(1260) \) decay to \( K^* \) and \( f_0 \)

M. R. Shepherd
Hadron 2017, Salamanca
September 28, 2017
\[ a_1(1420) \rightarrow f_0(980)\pi \]

• Such “triangle singularities” were predicted…
  see M. Mikhasenko’s talk (Tuesday) for references
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- Such “triangle singularities” were predicted…
  see M. Mikhasenko’s talk (Tuesday) for references
- An essential step: validating our understanding with high precision data
Fit to the data, [COMPASS, in preparation]

Signal model for $1^{++} f_0 \pi$ $P$-wave from the rescattering does not have free parameters

$0.100 < t' < 0.113$ (GeV/c$^2$)

$\pi p \rightarrow \pi \pi' \pi p$ (COMPASS 2008)

Mass-independent fit

Fit model

Signal

Background

from M. Mikhasenko (Tuesday afternoon)

see also B. Ketzer tomorrow
Fit to the data, [COMPASS, in preparation]

Signal model for $1^{++} f_0 \pi$ $P$-wave from the rescattering does not have free parameters

Excellent description of statistically precise data helps validate understanding.
(Implications for some XYZ states?)

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  - continued improvement in statistical precision of the data
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An exciting time: new experiments are expected to produce complementary results in coming years

at Jefferson Lab

See talk by S. Dobbs tomorrow morning