Light Exotic Meson Candidates in COMPASS

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Why Hadron Spectroscopy?

Remember the hydrogen atom…

Similarly: study QCD through the excitation spectrum of strong interaction

- Strongly coupled theory
- Models, effective theories, L-QCD
- Which are the correct degrees of freedom?
- What are the effective forces?

Light Meson Spectrum

\[ v = n + L - 1 \approx m(\text{GeV}) \]

Quark model:
- SU(3)\text{_{flavor}}:
\[ q \otimes \bar{q}' = 3 \otimes \bar{3} = 8 \oplus 1 \]
- color singlets
- Ground state 0^{--}, 1^{--} nonets ok
- Many predicted radial and orbital excitations missing / unclear

[B. Ketzer, Exotic mesons in COMPASS]
Charmonium Spectrum

Quark model:

- SU(3)$_{\text{flavor}}$:
  \[ q \otimes \bar{q}' = 3 \otimes \bar{3} = 8 \oplus 1 \]

- color singlets

- Many new (narrow) states discovered in recent years
- Assignment not clear
- Some definitively not charmonium-like

[V. Santoro, Hadron 2015]
[N. Brambilla et al., EPJ C 71, 1534 (2011)]
How to identify them?

- Spin-exotic
- Supernumerary states
- Charged QQbar, doubly charged QQ
- Comparison with models, lattice

\[
\begin{align*}
\text{(q\bar{q})}_0 \\
+ \quad \text{(q\bar{q})(q\bar{q})} \\
+ \quad \text{Molecule / 4 quarks}
\end{align*}
\]

\[
\begin{align*}
\text{(q\bar{q})}_8g \\
+ \quad \text{Hybrids}
\end{align*}
\]

\[
\begin{align*}
\quad gg \\
+ \quad \text{Glueballs}
\end{align*}
\]

+ ...
The COMPASS Experiment

Exotic mesons in COMPASS
The COMPASS Experiment

Two-stage spectrometer
- Dipole magnets
- Tracking detectors
- RICH
- El.-mag. calorimeter
- Hadronic calorimeter
- Muon identification

[COMPASS, P. Abbon et al., NIM A 779, 69 (2015)]

Exotic mesons in COMPASS

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3\pi Final State

Exotic mesons in COMPASS

[C. Adolph et al., Phys. Rev. D 95, 032004 (2017)]
Partial-Wave Analysis

Total intensity

1++ Waves

- Largest wave-set to date: 88 waves
- Independent fits in 100 bins (20 MeV) of $m_{3\pi}$ and 11 bins of $t'$
$\pi^- + p \rightarrow 3\pi + p$

- Data described well by Breit-Wigner and non-resonant background
- Parameters for BW:
  
  $$M_0 = 1414^{+15}_{-13} \text{ MeV/c}$$
  
  $$\Gamma_0 = 153^{+8}_{-23} \text{ MeV/c}$$

[C. Adolph et al., COMPASS, PRL 115, 082001 (2015)]
New $a_1(1420)$

Issues to be clarified:
- Does not fit to radial excitation trajectory
- Too close to $a_1(1260)$
- Width narrower than ground state
- Mass very close to $K^*(892)\bar{K}$ threshold $\approx 1.38 \text{ GeV}/c^2$

[Chen et al., PRD 91, 074025 (2015)]
Interpretations

- $K^*\bar{K}$ molecule (similar to X(3872) interpretation)
- Interference of Deck $\rho\pi S$ and $f_0\pi P$-wave [J.-L. Basdevant et al., PRL 114, 192001 (2015)]
- Triangle singularity [M. Mikhasenko, BK, A. Sarantsev, PRD 91, 094015 (2015)]

- Decay of $a_1(1260) \rightarrow K^*\bar{K}$ above threshold
- Final state rescattering of $K\bar{K}$ to $f_0(980)$
  $\Rightarrow$ logarithmic singularity of amplitude if particles close to mass shell
• Similar shape as Breit-Wigner
• No free parameters
• Intensity estimated to be ~1% of $a_1(1260)$
• Confirmed by [Acet et al., Phys.Rev. D94, 096015 (2016)]
Fit of Triangle Amplitude

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

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

Mass-independent fit
Fit model
Signal
Background

Exotic mesons in COMPASS
Fit of Triangle Amplitude

Intensity / (20 MeV) $r^0 (p\pi S)$

$\pi^+ p \rightarrow \pi^+ \pi^- \pi^- p$ (COMPASS 2008)

$1^{++}0^+ f_{0} P$-wave
$0.100 < t' < 0.113 (GeV/c)^2$

$1.35 (GeV) = M_3 \pi$

$\pi p \rightarrow \pi^- \pi^- p$ (COMPASS)

Mass-independent fit

Fit model
Signal
Background

Exotic mesons in COMPASS
Comparison TA - BW

Triangle Amplitude

Breit-Wigner

• Equal $\chi^2_{red}$ for both fits
• No new free parameters for $a_1(1420)$ signal by triangle mechanism

Exotic mesons in COMPASS
Triangle Amplitude Breit-Wigner

**Summary for $a_1(1420)$**

- Peak and phase motion are not unique sign of a resonance!
- $a_1(1420)$ signal can be described solely with $a_1(1260)$ as source and rescattering via triangle diagram
- Old theoretical concept, now data allow to clearly observe this for the first time!
- Intensity of signal $\sim 1\%$, in agreement with experiment
- Cannot completely exclude additional pole due to $K^*\bar{K}$ resonance

- Equal $\chi^2_{red}$ for both fits
- No new free parameters for $a_1(1420)$ signal by triangle mechanism
Hybrids: Lattice QCD

Structure of states: study

\[ \langle \text{meson} | O[q, g] | \text{vacuum} \rangle \]

with e.g. \[ O[q, g] \sim ^3S_1, ^3D_1, ^1\text{hyb}_1 \]

negative parity

positive parity

[J. Dudek, Phys. Rev. D 84, 074023 (2011)]

[J. Dudek et al., Hadron Spectrum Collaboration, Phys. Rev. D 82, 034508 (2010)]

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Exotic mesons in COMPASS
1-- Partial Wave

- Previous analyses seemingly inconsistent
- COMPASS: $10 \times$ more data
- Results can be reproduced using (limited) wave sets and $t'$ ranges
- 1st (re-)observation in p Pb in COMPASS

- 21 waves less data
- 36 waves 1 $t'$ bin
- 44 waves Infinite rank

[VES, Zaitsev, Nucl.Phys. 830 A675, 155C (2000)]
1-- Partial Wave

- Broad intensity distribution
- Strong evolution with \( t' \)

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

\[ 1^{++} \rho(770) \pi P \]

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

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

\[ 1^{++} \rho(770) \pi P \]

\[ 0.449 < t' < 0.724 \ (\text{GeV}/c)^2 \]
1−+ Partial Wave

• Resonance-model fit to spin-density matrix: 14 waves
• Exploit $t'$ dependence to separate resonant and non-resonant contributions
1−+ Partial Wave

- Background shape in agreement with Deck-model studies
- Resonance parameters for $\pi_1(1600)$

\[ M_0 = 1600^{+100}_{-50} \text{ MeV/c}^2 \]
\[ \Gamma_0 = 610^{+70}_{-240} \text{ MeV/c}^2 \]
$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (COMPASS 2008)

$1^{++} \rho(770) \pi P$

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

- Mass-independent fit
- Mass-dependent fit
- Resonant
- Non-resonant

[1$^{++}$ $\rho(770)$ $\pi$ $P] - [1^{+0}$ $\rho(770)$ $\pi$ $S]$

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

$\delta \phi = -72.3^\circ$

Bad description of data without resonance component
Lattice QCD

Exotic mesons in COMPASS

What about the other hybrid candidates?

[J. Dudek, Phys. Rev. D 84, 074023 (2011)]

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Other Hybrid Candidates

\[ M_0 = 1802^{+8.0}_{-3.5} \text{ MeV/c}^2 \]
\[ \Gamma_0 = 218^{+11}_{-6} \text{ MeV/c}^2 \]

\[ M_0 = 1847^{+14}_{-6} \text{ MeV/c}^2 \]
\[ \Gamma_0 = 247^{+41}_{-18} \text{ MeV/c}^2 \]
Extraction of Poles

- Analytical model based on S-matrix theory
- Test case: $\eta\pi D$-wave
- Unitarity:

$$\text{Im} \hat{a}(s) = \rho(s) \hat{f}^*(s) \hat{a}(s)$$

$$\text{Im} = \sum_n  \text{P}$$

$$\pi^- \rightarrow \eta \pi^-$$

$$\eta \pi^-$$

$s, L, M$

$\Gamma = 2 \text{Im} \sqrt{s}$

$\alpha_2$

$\alpha'_2$

$\sqrt{s}$ [GeV]

$[\text{JPAC, COMPASS, arXiv: 1707.02848}]$
Extraction of Poles

- $3\pi$ system: $2^{-+}$ wave
- Use quasi two-particle unitarity

\[ m_{\pi} (\text{GeV}/c^2) \]

\[ \ln@\text{Abs part of } \det[T^{-1}K] \]

\[ \Gamma = 2m[\text{MeV}] \]

\[ M = \text{Re}[\Gamma] \text{s} \]

[M. Mikhasenko et al., EPJ Web Conf. 137 (2017) 05017]
Conclusions

Hadron spectroscopy is entering precision era
Statistical uncertainties very small, systematic model uncertainties dominate
Spin-exotic $\pi_1(1600)$: (re-) observed by COMPASS
Large $3\pi$ data sample of COMPASS $\Rightarrow$ PWA in bins of $m_X$ and $t'$
  $\Rightarrow$ Strong non-resonant contributions to $\rho\pi$, $\eta'\pi$
  $\Rightarrow$ Can be well described by Deck effect
  $\Rightarrow$ Resonant part dominates at high $t'$
New axial vector signal observed in $a_1(1420) \rightarrow f_0(980)\pi$
  • Has all features of a genuine resonance
  • Data can be described by triangle singularity

Develop models satisfying principles of S-matrix theory
$a_1(1420)$: look for it in $\tau$ decays, $K\bar{K}\pi$ final state
Hybrids: identify (exotic) multiplets and measure decay patterns