Recent results on light-meson exotics from the COMPASS experiment

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The plan of the talk

1 Introduction

2 Tetraquark candidate $a_1(1420)$
   [hep-ph:2006.05342 (just accepted in PRL)]

3 Hybrid candidate $\pi_1(1600)$
   [hep-ex:2108.01744 (submitted on 3 Aug 2021)]

4 Summary
Variety of the hadronic states

QCD at low-energy regime:

- color interaction confined
- effective d.o.f. - **constituent** quarks (gluons?)
Variety of the hadronic states

QCD at low-energy regime:
- color interaction confined
- effective d.o.f. - **constituent** quarks (gluons?)

Ordinary matter:

- meson
  - \( \bar{u}u \)
- baryon
  - \( d\bar{d}u \)
- hadronic molecules
  - \( uu\bar{d}d \)
Variety of the hadronic states

QCD at low-energy regime:
- color interaction confined
- effective d.o.f. - constituent quarks (gluons?)

Ordinary matter:

Exotic matter:
Excitation spectrum of a bound system

QED

Energy (GeV)

2S

1S

L = 0

L = 1

Orbital quantum numbers

\( \bar{J} = \bar{L} \)

Example of spin-flip transition: \( \rho(\uparrow\uparrow) \rightarrow \pi(\uparrow\downarrow) \) transition is a "QCD-cell division"
Excitation spectrum of a bound system

QED

\[ \bar{J} = \bar{L} + \bar{S} \]
\[ \bar{S} = \bar{s}_1 + \bar{s}_2 \]

\[ J = L + S \]

Energy (GeV)

Orbital quantum numbers

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Excitation spectrum of a bound system

QCD

\[ J = \vec{L} + \vec{S} \]

\[ \vec{S} = \vec{s}_1 + \vec{s}_2 \]

\[ \times 5 (\pi, \eta, \eta', K, \bar{K}) \]
Excitation spectrum of a bound system

QCD

- QED: hyperfine splitting
- QCD: is far not hyperfine
Excitation spectrum of a bound system

- **QED:** hyperfine splitting
- **QCD:** is far not hyperfine
- **Example of spin-flip transition:**
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Experimental situation on (non-strange) Light mesons

Experimental situation on (non-strange) Light mesons


- Many low-lying observed states are well established and in agreement with the QM
- Some have large width and non-trivial appearance in the spectrum due to overlaps and interferences
Laboratory to study hadronic excitations

Diffractive reaction
Pion beam scattered off the proton target
High energy guarantees $t$-channel process.
The target provides the gluonic field
$\pi$ production has the largest cross section (inelastic)
Laboratory to study hadronic excitations

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**Diffractive reaction**

- Pion beam scattered off the proton target
- High energy guarantees $t$-channel process.
- The target provide the gluonic field
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COMPASS Experiment

Spectroscopy, Structure functions
\( \pi/\mu \) beam, \( 10^7 \) particles per 10s spill

[COMPASS Experiment](NIM A779 (2015) 69-115)
Understanding of the $3\pi$ spectrum

The results of the main big fit
— 14 interfering waves $\times$ 11 $t'$-slices simultaneously.
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The results of the main big fit
— 14 interfering waves $\times$ 11 $t'$-slices simultaneously.

- 11 resonances are established including a new $a_1(1420)$
Resonance model fit
The main mass-dependent fit

Axial vector $1^{++}$

- Non-resonant coherent background

Model curve
Resonances
Nonres. comp.

[COMPASS, PRD98 (2018) 092003]
Resonance model fit
The main mass-dependent fit

Axial "?" 1++

1+0f(980) πP

0.100 < t' < 0.113 (GeV/c)²

Model curve
Resonances
Nonres. comp.

Exotic candidate!

[COMPASS, PRD98 (2018) 092003]

Model curve
Resonances
Nonres. comp.
Resonance model fit
The main mass-dependent fit

Non-\(q\bar{q}\) 1\(^{-+}\)

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

Low \(t'\)

\[\times 10^3\]

Intensity / (20 MeV/°)

\[0.5 < t' < 0.113 (GeV/c)^2\]

Model curve
Resonances
Nonres. comp.

High \(t'\)

\[\times 10^3\]

Intensity / (20 MeV/°)

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

Model curve
Resonances
Nonres. comp.

[COMPASS, PRD98 (2018) 092003]
$a_1(1420)$ tetraquark candidate
Observation of the $a_1(1420)$

[COMPASS, PRL 115 (2015) 082001]
Observation of the $a_1(1420)$

$1^{++} 0^+ f_0(980) \pi P$

$0.1 < t' < 1.0 \text{ (GeV/c)}^2$

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

$Mikhail\ Mikhasenko$ (ORIGINS Cluster)

Light-meson exotics

August 6th, 2021
Observation of the $a_1(1420)$

New particle may be made of four quarks

Not something ordinary

- Too close to the ground state $a_1(1260)$
- Its width is narrower than the ground state
- Close to threshold $K^*\bar{K}$, i.e. $(d\bar{s}) + (\bar{u}s)$, $E_{th} = 1.39$ GeV.
a_1(1420) interpretations

**Possible scenarios**

- **Pole** in the amplitude – Genuine resonance

- Singularity of the **non-pole** type
$a_1(1420)$ interpretations

Possible scenaria

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  - $K^* \bar{K}$ molecule [T. Gutsche et al. (2017)]

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  - Interference with background — interplay between distant cuts

![Diagram](https://via.placeholder.com/150)

$a_1(1420)$ interpretations

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  - Interference with background — interplay between distant cuts
  - **Rescattering** from $K^* \bar{K}$ — Triangle singularity


![Diagram of $a_1(1260)$}]
$a_1(1420)$ interpretations

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  - **Rescattering** from $K^* \bar{K}$ — Triangle singularity

\[ |A|^2 \]
\[ m_{3\pi} \text{ (GeV)} \]

The key effect - the triangle rescattering graph

- $f_0$ is a resonance in ($K\bar{K}$) and also in ($\pi\pi$) system.
- Ordinary $a_1$ decays to $K\bar{K}\pi$ via $K^*\bar{K}$
- $K\bar{K}$ form $f_0$ that decays to $\pi\pi$
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- has a logarithmic singularity (divergence at a single point)
- $A \sim \log(s_0 - m_{3\pi}^2)$ with $s_0$ determined by masses of involved particles.
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**Fit with the rescattering model** [COMPASS, PRL(2021)]

Fit perfectly describes the intensity and the phase motion

- No shape parameters for the signal component (TS)
- Background with constant phase is needed to shift the amplitude
- TS model shows a comparable quality to the resonance model (BW-model)
Systematic studies

TS model systematically yields a similar $R^2_{\text{red}}$ as the BW model.

- Neglecting interference of the conjugated decay chains,
- Neglecting the spins of the particles involved,
- Including the excitations $a_1(1640)$ and $a_2(1700)$
- Varying mass and width of the $K^*$ resonance
Emerging interpretation [COMPASS, PRL (2021)]

The TS (Tetraquark signal) can be described with an $a_1(1260)$ as the source for the rescattering via the triangle diagram. The first clear observation of the TS is noted. An additional pole is not needed, although it is not excluded.

- $a_1(1420)$
- $a_1(1260)$

$m_{3\pi}$ (GeV) vs. Entries/(20 MeV)
Emerging interpretation [COMPASS, PRL (2021)]

- $a_1(1420)$ signal can be described with $a_1(1260)$ as source for the \textbf{rescattering} via the triangle diagram $\Rightarrow$ the first clear observation of the TS
- An additional pole is not needed, although, not excluded
Summary on $a_1(1420)$

- Peak and phase motion are not unique sign of a resonance!
- $a_1(1420)$ signal can be described with ordinary $a_1$ as source for the rescattering via the triangle diagram
- Old theoretical concept, but clearly observed for the first time!
- Intensity of signal $\sim 1\%$, in agreement with experiment

Signal in $f_0\pi$ $P$-wave $\Rightarrow$ established Triangle Singularity, no need for the tetraquark
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Outlook

- Solve consistent KT equations
  (five coupled systems: $\pi^-\pi^-\pi^+$, $\pi^-\pi^0\pi^0$, $K^+K^-\pi^-$, $K^0\bar{K}^0\pi^-$, and $K^0K^-\pi^0$)
- Observe the $a_1(1420)$ TS effect in $\tau$ decays [see e.g. Phys.Rev.D 99 (2019) 1, 016021]
$\pi_1(1600)$ hybrid candidate
Note on the history of $\pi_1(1600)$

...a resonance with non-$q\bar{q}$ quantum numbers, $J^{PC} = 1^{-+}$.

Two states in PDG: $\pi_1(1400)$ and $\pi_1(1600)$

- $\pi_1(1400) \rightarrow \eta\pi$
- $\pi_1(1600) \rightarrow \eta'\pi$ and $\rightarrow \rho\pi$ $P$-wave

[solved in PRL122 (2019) 4, 042002]

Contradictions on $\pi_1(1600) \rightarrow \rho\pi$ $P$-wave (PWA)

- Four analyses in the past arrive to different conclusions on existence and parameters of $\pi_1(1600)$
Light-meson excitations from Lattice QCD

[Dudek et al., PRD 88, 094505 (2013)]

\[ \mathcal{L}_{\text{QCD}} = \overline{\psi} \left[ i \slashed{D} - m \right] \psi - \frac{1}{4} F_{\mu \nu}^2 \]

mass of pion is 391 MeV
Hybrid candidate $\pi_1(1600)$

$\pi_1(1600) \rightarrow 3\pi$

**Light-meson excitations from Lattice QCD**

[Dudek et al., PRD 88, 094505 (2013)]

![Graphical representation of light-meson excitations from Lattice QCD](image)

$$\mathcal{L}_{QCD} = \overline{\psi} \left[ i \slashed{D} - m \right] \psi - \frac{1}{4} F_{\mu\nu}^2$$

The mass of the pion is 391 MeV.

$L_{QCD} = \overline{\psi} \left[ i \slashed{D} - m \right] \psi - \frac{1}{4} F_{\mu\nu}^2$
Exotic mesons in two-body scattering on lattice

[A.Woss et al., PRD 103, 054502 (2021)]
(see the talk of Jo Dudek on Monday, 17h40)

Setup:
- $SU(3): m_u = m_d = m_s$
- $m_\pi \approx 700 \text{ MeV}$
- 8 coupled two-body channels
- Wide range of operators

Conclusions:
- Strong coupling to $b_1\pi$
- Much smaller to $\rho\pi, f_1\pi, \eta'(\pi)$
- Extrapolated width roughly agrees with experimental analysis
Parameters of the $\pi_1(1600)$ in $3\pi$

$\rho\pi$ $P$-wave from the 14-waves fit.

- Background changes with virtuality of $P$ ($t'$)
- The resonance mass and width are constrained to be the same for all $t'$

$$m(\pi_1) = 1550^{+110}_{-60} \text{ (syst.) MeV}, \quad \Gamma(\pi_1) = 580^{+100}_{-230} \text{ (syst.) MeV}$$

Consistent with measurements in $\eta'\pi$
Hybrid candidate $\pi_1(1600)$

$\pi_1(1600) \rightarrow 3\pi$

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\[
\begin{align*}
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Consistent with measurements in $\eta'\pi$
Two reasons of troubles with $\rho\pi P$-wave \cite{COMPASS, hep-ex:2108.01744}

Two effects:

- Non-resonant background depends on $t'$ (Deck \cite{PRL 13 (1964) 169-173})

\[
\pi^- \rightarrow p_\rho \pi^+ \pi^- + \pi^- P \pi^- \pi^+ = t_{\pi\rho} \frac{e^{-bt_1}}{m_\pi^2 - t_1} t_{\pi\pi}
\]
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Two effects:

- Non-resonant background depends on $t'$ (Deck [PRL 13 (1964) 169-173])

\[ \pi^-_{t} p \rightarrow \pi^- p \pi^+ = t_{\pi p} \frac{e^{-bt_1}}{m^2_{\pi} - t_1} t_{\pi \pi} \]

- Wave set (leakage to $\rho \pi P$-wave) and consistency

**BNL(1998)**

- BNL E852
- BNL E852 leakage
- COMPASS (21 waves)


- VES
- COMPASS (88 waves)

**BNL(2006)**

- Drizba et al.
- COMPASS (36 waves)

**COMPASS(lead)**

- COMPASS lead target (42 waves)
- COMPASS proton target (88 waves)
Wrap up on $\pi_1(1600)$

- Analysis of $\eta^{(i)}\pi$ (not shown in this talk):
  - [COMPASS, PLB 740 (2015) 303]
  - [JPAC/COMPASS, PLB 779, 464-472]
  - [JPAC, PRL122 (2019) 4, 042002]

  establish $\pi_1(1400)/\pi_1(1600)$ is the same resonance with

  $\eta^{(i)}\pi : \quad m_{\text{pole}}(\pi_1) = 1567 \pm 24 \pm 86 \text{ MeV} \quad \Gamma_{\text{pole}}(\pi_1) = 492 \pm 54 \pm 102 \text{ MeV}$

- Analysis of $3\pi$:
  - [COMPASS, PRD95 (2017) 032004]
  - [COMPASS, PRD98 (2018) 092003]
  - [COMPASS, hep-ex:2108.01744]

  solved the long-standing puzzle on inconsistency of past analyses

  $3\pi : \quad m_{\text{pole}}(\pi_1) = 1630^{+110}_{-60} \text{ (syst) MeV} \quad \Gamma_{\text{pole}}(\pi_1) = 570^{+100}_{-230} \text{ (syst) MeV}$

$\Rightarrow \pi_1(1600)$ is lightest meson with exotic quantum numbers $J^{PC} = 1^{--}$
Conclusions and outlook

- **Hadron spectroscopy** is a unique tool for understanding the QCD, the theory of matter formation
- **Diffractive** reaction is a clean setup for measurements of the excitation spectrum
- **COMPASS** leads the effort of large combined light-quark meson studies
- Many new surprises with new data (GlueX, BESIII, AMBER(?))
- Lattice QCD already provides quantities accessible at COMPASS, we should catch up
- Strengthen the TH+EXP collaboration
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**Outlook for hadron spectroscopy at COMPASS**

- $\pi_1(1600) \rightarrow b_1\pi$ and $\pi_1(1600) \rightarrow f_1\pi$ are under study in COMPASS
- Kaon diffraction reaction $K^- p \rightarrow K^-\pi^+\pi^- p$ is under study
  
  The first results are coming soon
- Extensive kaon spectroscopy program with AMBER at CERN is proposed
Thank you for the attention
Interfering background
Forward-background scattering

[COMPASS data, MM, PhD thesis]

The high-energy exchange processes penetrate to the low energy and make resonance characterization difficult
Classical picture of near-mass-shell rescattering

Imagine cascade reaction $a_1(1260) \to K^*(892)\bar{K}$, then $K^* \to K\pi$, and calculate invariant mass of $K$ and $\bar{K}$ for the case when $K$ is parallel to $\bar{K}$.

Partial form of Landau conditions

[[Nucl. Phys. 13, 181 (1959)]]:

- All particles in loop are on mass shell.
- The alignment of moments $\vec{p}_K \uparrow\uparrow \vec{p}_{\bar{K}}$.
- $K$ is faster than $\bar{K}$.