Exotic meson candidates in COMPASS
MESON 2023 in Kraków, Poland

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Light Mesons: $m < 3$ GeV/$c^2$

Constituent-Quark Model

- $|qq'\rangle$ system with $q = u, d, s$
- Quantum numbers $J^{P(C)}$

In unflavoured sector: Spin-exotics

- Not possible in Constituent-Quark Model: $J^{PC} = 0^{--}, (odd)$ $-^{++}, (even)$

- Access to exotic states that do not overlap with ordinary mesons

Hybrids

- Excited gluonic field contributes to $J^{PC}$

Predictions from theory: lightest hybrids have $J^{PC} = (0^-, 1^+, 2^-)^{(+)}$, $1^-^{(-)}$

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**Constituent-Quark Model**

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- Not possible in Constituent-Quark Model:
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**Hybrids**

- Excited gluonic field contributes to \( J^{PC} \)
- Predictions from theory: lightest hybrids have
  \( J^{PC} = (0, 1, 2)^{-(+)} , 1^{-(+)} \)

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Exotic meson candidates in COMPASS

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**COMPASS**

- **COmmom Muon Proton Apparatus for Structure and Spectroscopy**
- Data taken for two decades 2002-2022
- Located at the M2 beam line in the north area of CERN
- Part of the Hadron program: Light-Meson Spectroscopy

**Setup for Hadron beams**

**Diffractive Resonance Production**

\[ (\pi^-, K^-, \bar{p}) \]

- Beam hadrons at 190 GeV/c
  → mainly Pomeron exchange
Partial-Wave Analysis

- Analysis in two steps:
  1. Partial-Wave Decomposition: Amplitudes of contributing waves are determined
  2. Resonance-Model Fit: Extraction of resonance parameters \((m_0, \Gamma_0)\) and couplings

Partial-Wave Decomposition

- Data arranged into bins of \((m_X, t')\)
  \[
  \mathcal{I}(\tau_i) = \left| \sum_{a} N_{\text{waves}} \mathcal{T}_a \Psi_a(\tau_i) \right|^2
  \]
- Decay Amplitudes \(\Psi_i\) are calculated from data using isobar model
- Production amplitudes \(\mathcal{T}_i\) are determined in extended Likelihood fit

(Diffraction Resonance Production and subsequent two-body decays)
Partial-Wave Analysis

Analysis in two steps:

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Partial-Wave Decomposition

- Data arranged into bins of \((m_X, t')\)

\[
I(\tau_i) = \left| \sum_{a}^{N_{\text{waves}}} T_a \Psi_a(\tau_i) \right|^2
\]

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Resonance-Model Fit

- Measured amplitudes are modeled by sum of resonant and non-resonant components \((S)\)

\[
\hat{T}_a(m_X, t') \propto \mathcal{P}_P \sum_{j \in S_a} C_a^j(t') D_j(m_X, t')
\]

- Dynamics of resonant components: \(D_{\text{res.}}(m_X)\)
- Dynamics of non-resonant component: \(D_{\text{n-res.}}(m_X, t')\)
Exotic meson candidate in unflavoured sector
Theory predictions

- Several effective models (e.g. flux-tube, bag model, constituent gluon) expect the lightest hybrid meson to have spin-exotic QN: $J^{PC} = 1^{-+}$

First result from lQCD simulation

- Decay of hybrid meson with $J^{PC} = 1^{-+}$ via several channels
- At $SU(3)$ symmetry point:
  - $m_{u,d,s} = m_s^{\text{exp.}}$
  - $m_\pi \approx 700 \text{ MeV}/c^2$
  - $3m_\pi$ pushed to high energy
- Result: $b_1\pi$ most dominant

[PRD 103, (2021) 054502]
Experimental results

COMPASS

[COMPASS, PRD 98, 2018]

- 46.0 M events
- $\pi + p \rightarrow 3\pi + p$ at 190 GeV/c
- 11 bins
  $0.1 < t' < 1.0$ (GeV/c)$^2$
- Result:
  $t'$-dependence of background
  $m_{\pi_1} = 1600^{+110}_{-60}$ MeV/c$^2$
  $\Gamma_{\pi_1} = 590^{+100}_{-230}$ MeV/c$^2$

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Exotic meson candidates in COMPASS

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Experimental results

COMPASS

\[ \pi_1 \rightarrow \rho \pi \]

[COMPASS, PRD 98, 2018]

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**Freed Isobar Analysis**

- In conventional analysis, dynamical shape of isobars are fixed in decay amplitude.
- Free the dynamics of the isobar and fit it with data.

**Experimental Results**

**COMPASS**

![Graph showing experimental results](image)

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**COMPASS**

**Freed Isobar Analysis**

- In conventional analysis, dynamical shape of isobars are fixed in decay amplitude.
- Free the dynamics of the isobar and fit it with data.

**Results:**

- Same result as conventional fit.
- Spin-exotic wave shows clear $\rho(770)$ signature.
- Supports assumptions of isobar model.

[1] COMPASS, PRD 98, 2018

- 46.0 M events
- $\pi + p \rightarrow 3\pi + p$ at 190 GeV/c
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**Experimental Results**

**Final state**
- $\pi^- \eta^{(s)} (\rightarrow \pi^+ \pi^- \pi^0 / \eta (\rightarrow \gamma \gamma))$
- No modelation $t'$
- Precise shower description in ECALs needed

**Results from other Experiments**
- BNL, VES and Crystal Barrel observed two states:
  - at 1.4 GeV/c² in $\eta \pi$
  - at 1.6 GeV/c² in $\eta' \pi$

**COMPASS data - $1^{-+} \eta^{(s)} \pi P$**

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(Gray region: ill defined phases in $\eta \pi$ data)
**Experimental Results**

### Final state
- $\pi^- \eta^{(i)}(\rightarrow \pi^+ \pi^- \pi^0/\eta(\rightarrow \gamma\gamma))$
- No modelation $t'$
- Precise shower description in ECALs needed

### Coupled-channel fit by JPAC
- Performed resonance model fit using K-matrix formalism
- Conclusion: one pole is sufficient to describe both!
  - $m = (1564 \pm 24 \pm 86) \text{ MeV}/c^2$
  - $\Gamma = (492 \pm 54 \pm 102) \text{ MeV}/c^2$

### COMPASS data with JPAC fit - $1^- \eta^{(i)} \pi P$

*COMPASS data with JPAC fit – 1$^-$$\eta^{(i)}$$\pi P$*

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Exotic meson candidates in COMPASS
Experimental results

Final state
- $\pi^-\eta^{(')}(\rightarrow \pi^+\pi^-\pi^0/\eta(\rightarrow \gamma\gamma))$
- No modelation $t'$
- Precise shower description in ECALs needed

Coupled-channel fit by JPAC
- Performed resonance model fit using K-matrix formalism
- Conclusion: one pole is sufficient to describe both!
  $m = (1564 \pm 24 \pm 86) \text{ MeV}/c^2$
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Confirmed by Kopf et al. in c.c. fit using $\bar{p}p$, $\pi^-p$ and $\pi\pi$ data

COMPASS data with fit from Kopf et al.
[Kopf et al., EPJ C 81, 1056, (2021)]
Experimental results

Final state

- PWA: $\omega \pi^- \pi^0$
- Final state: $\pi^- \pi^+ \pi^- \pi^0 (\gamma \gamma) \pi^0 (\gamma \gamma)$

COMPASS data

- Selected 720k $\omega \pi^- \pi^0$ events
  → Analysis in $t'$ possible
- New results from Partial-Wave decomposition
- Clear signal and phase motion in expected region

Results from other Experiments

- BNL and VES observed spin-exotic $1^{-+}$ state at $\sim 1.6$ GeV/c$^2$
- BNL observed a second state
Experimental results

\[ \pi_1 \rightarrow f_1(1285)\pi & K^*\overline{K} \]

\( f_1(1285)\pi^- \) at COMPASS

- Final state \( \pi^- \pi^+ \pi^- \eta(\gamma\gamma) \)
- Selected 625k \( \pi^- \pi^+ \pi^- \eta \) events
  \( \rightarrow \) Analysis in \( t' \) possible
- Next Step: PWA

![Graph showing experimental data](image)

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Exotic meson candidates in COMPASS

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**Experimental results**

\[ \pi_1 \rightarrow f_1(1285)\pi \land K^*\overline{K} \]

**\(f_1(1285)\pi^-\) at COMPASS**

- Final state \(\pi^-\pi^+\pi^-\eta(\gamma\gamma)\)
- Selected 625k \(\pi^-\pi^+\pi^-\eta\) events
  \(\rightarrow\) Analysis in \(t'\) possible
- Next Step: PWA

**\(K^*\overline{K}\) at COMPASS**

- Final state \(\pi^-K^0_S(\pi^+\pi^-)K^0_S(\pi^+\pi^-)\)
- Selected 240k \(\pi^-K^0_SK^0_S\) events
  \(\rightarrow\) Analysis in \(t'\) possible
- Next Step: PWA
Exotic meson candidate in strange sector
COMPASS: Data

- $K^- + p \rightarrow K^-\pi^+\pi^-p$ at 190 GeV/c
- 720 k events
- Four $t'$-bins in range $0.1 < t' < 1.0$ (GeV/c)$^2$
- Limited by PID in spectrometer

COMPASS: Resonance-Model Fit

- Agreement with at least five established states
- Agreement with at least three not established states

PDG: Light Strange Sector

- 25 states listed, nine need further confirmation

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Exotic meson candidates in COMPASS
**Light Strange-Mesons:** $m < 3 \text{ GeV/c}^2$

**COMPASS: Data**
- $K^- + p \rightarrow K^- \pi^+ \pi^- p$ at 190 GeV/c
- 720 k events
- Four $t'$-bins in range $0.1 < t' < 1.0 \text{ (GeV/c)}^2$
- Limited by PID in spectrometer

**Exotic state in $0^-$ sector?**
- Constituent-Quark Model predicts two excited states
- Three exitated signals are observed

**PDG: Light Strange Sector**
- 25 states listed, nine need further confirmation

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Exotic meson candidates in COMPASS

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**Exotic state in $0^-$ sector?**

- Only $0^-0^+ \rho(770)KP$ wave is reliable
- Three resonances needed:
  1. $K(1460)$ fixed PDG values $m = 1482.4 \text{ MeV/c}^2$ and $\Gamma = 335.6 \text{ MeV/c}^2$
  2. $K(1630)$, $m = 1687 \pm 10^{+2}_{-67} \text{ MeV/c}^2$ and $\Gamma = 140 \pm 20^{+50}_{-50} \text{ MeV/c}^2$ ($\sigma = 8.3$)
  3. $K(1830)$, $m = 1893 \pm 17^{+13}_{-39} \text{ MeV/c}^2$ and $\Gamma = 160 \pm 40^{+60}_{-80} \text{ MeV/c}^2$
### Summary & Outlook

**Exotic candidate in unflavoured sector with** $J^{PC} = 1^{-+} (\pi_1(1600))$:  

<table>
<thead>
<tr>
<th>Channel</th>
<th>Final state</th>
<th>Status</th>
<th>Outlook</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho \pi$</td>
<td>$\pi^- \pi^+ \pi^-$</td>
<td>-[COMPASS, PRD 98, 2018]</td>
<td>-Increase data set</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-[COMPASS, PRD 105, 2022]</td>
<td>- Use new analysis techniques</td>
</tr>
<tr>
<td>$\eta(\rho \pi)$</td>
<td>$\pi^- \pi^+ \pi^- \pi^0 /\eta$</td>
<td>-[COMPASS PLB 740, (2015)]</td>
<td>- Increase data set</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-[JPAC, PRL 122 (2019)]</td>
<td>- Improve shower reconstruction</td>
</tr>
<tr>
<td>$b_1 \pi$</td>
<td>$\omega \pi^- \pi^0$</td>
<td>- Partial-Wave Decomposition</td>
<td>- Resonance-Model Fit</td>
</tr>
<tr>
<td>$f_1(1285)\pi$</td>
<td>$\pi^- \pi^+ \pi^- \pi^0$</td>
<td>- Event Selection</td>
<td>- PWA</td>
</tr>
<tr>
<td>$K^* K$</td>
<td>$K_S \bar{K}_S \pi$</td>
<td>- Event Selection</td>
<td>- PWA</td>
</tr>
</tbody>
</table>

**Exotic candidate in strange sector:**

- Analysis limited by PID
- Clear evidence for three excited states in $J^P = 0^-$ sector  
  → Exotic candidate $K(1630)$

**Outlook:**

- $K^- + p \rightarrow K_S^0 \pi^- + p \& K^- + p \rightarrow \Lambda \bar{p} + p$
Back Up
Freed Isobar Analysis

- In conventional analysis, dynamical shape of isobars are fixed in decay amplitude.
- Free the dynamics of the isobar and fit it with data:

\[ I(\tau_i) = \left| \sum_{a} \sum_{k} T_{a,k} \Psi'_{a,k}(\tau_i) \right|^2 \]

with

\[ T_a \rightarrow T_{a,k} = T_a \mathcal{J}_{a,k} \]

- The set \( \mathcal{J}_{a,k} \) describes the dynamics of the isobar in wave \( a \).

Results:

- Same result as conventional fit.
- Spin-exotic wave shows clear \( \rho(770) \) signature.
- Supports assumptions of isobar model.

\[ \begin{align*}
0.69 &< m_{3\pi} < 0.91 \\
0.326 &< t' < 1.000 \text{ (GeV/c)}^2
\end{align*} \]
Updated kinematic distributions: $\eta^{(')}\pi ^-$

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Exotic meson candidates in COMPASS

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Final state

- PWA: $\omega\pi^-\pi^0$
- Final state: of $\pi^-\pi^+\pi^-\pi^0(\gamma\gamma)\pi^0(\gamma\gamma)$

COMPASS data

- Selected 720k $\omega\pi^-\pi^0$ events
  → Analysis in $t'$ possible
- New results from Partial-Wave decomposition
- Clear signal in expected region

Results from other Experiments

- BNL and VES observed spin-exotic $1^{++}$ state at $\sim 1.6$ GeV/$c^2$
- BNL observed a second state
LQCD: if $\pi_1 \rightarrow \rho \omega$ is present, then it is very small
Kinematic distributions: $X \rightarrow f_1(1285)\pi^-$

$1.232 < m_{\pi\pi\eta} < 1.332$ (GeV/$c^2$)

Events / (40 MeV/$c^2$)

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

$\cos \theta_{GJ}$
Study of limited PID

Preliminary

0.10 \leq t' < 1.00 \text{(GeV/c)}^2

COMPASS Main Studies

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Exotic meson candidates in COMPASS
**Kinematic Distributions:** $K^- + p \rightarrow K_S^0 \pi^- + p$

**Graphs:**

1. **Left Graph:**
   - **Label:** $m_{K_S\pi}$ [GeV/c$^2$]
   - **Y-axis:** Events / (5 MeV/c$^2$) × 10$^3$
   - **Data Points:**
     - $K^+(892)$
     - $K^*_2(1430)$

2. **Right Graph:**
   - **Label:** $m_{K_S\pi}$ [GeV/c$^2$]
   - **X-axis:** $m_{K_S\pi}$ [GeV/c$^2$]
   - **Y-axis:** $\cos \theta_{GJ}$
   - **Color Bar:**
     - 0
     - 11
     - 22

**Legend:**
- **COMPASS $K_S^0 \pi^-$**
- **$K_S^0 \pi^-$ COMPASS**
- **Preliminary**