Exotic meson candidates in COMPASS
MESON 2023 in Kraków, Poland

David Spülbeck
on behalf of the COMPASS Collaboration
spuelbeck@hiskp.uni-bonn.de

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Constituent-Quark Model

- $|qq'\rangle$ system with $q = u, d, s$
- Quantum numbers $J^{P(C)}$
**Light Mesons: \( m < 3 \text{ GeV}/c^2 \)**

**Constituent-Quark Model**
- \(|qq'\) system with \( q = u, d, s \)
- Quantum numbers \( J^{PC} \)

**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 \( J^{PC} = (0, 1, 2)^{-(+), 1^-(-)} \)
COMPASS

- **C**ommon Muon Proton Apparatus for S**t**ructure and S**p**ectroscopy
- 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

\[(\pi^-, K^-, \bar{p}) \rightarrow X^- \rightarrow h_1, h_2, h_3, \ldots, h_n\]

- Beam hadrons at 190 GeV/c
- \(N_{\text{target}}\) and \(N_{\text{recoil}}\)

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Exotic meson candidates in COMPASS
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 \((m_X, t')\)
  \[
  I(\tau_i) = \left| \sum_a^{N_{\text{waves}}} T_a \Psi_a(\tau_i) \right|^2
  \]

- Decay Amplitudes \(\Psi_i\) are calculated from data using isobar model

- Production amplitudes \(T_i\) are determined in extended Likelihood fit

(Diffractive 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 $(m_X, t')$
  \[ I(\tau_i) = \left| \sum_{a}^{N_{\text{waves}}} T_a \Psi_a(\tau_i) \right|^2 \]
- Decay Amplitudes $\Psi_i$ are calculated from data using isobar model
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**Resonance-Model Fit**
- Measured amplitudes are modeled by sum of resonant and non-resonant components $(S)$
  \[ \hat{T}_a(m_X, t') \propto P_p \sum_{j \in S_a} C_a^j(t') D_j(m_X, t') \]
- 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
**Lightest unflavoured Hybrid meson**

**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

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

![Graph](image)

- 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
Experimental results

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[COMPASS, PRD 98, 2018]

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**Experimental Results**

**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.

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

[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)$^2$
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  - $m_{\pi_1} = 1600^{+110}_{-60}$ MeV/c$^2$
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**Experimental Results**

π₁ → ρπ

**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 ρ(770) signature
- Supports assumptions of
  isobar model

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- π + p → 3π + p at 190 GeV/c
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[COMPASS, PRD 105, 2022]

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Exotic meson candidates in COMPASS

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**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

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 \( \eta'\pi \)

(Gray region: ill defined phases in \( \eta\pi \) data)

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Exotic meson candidates in COMPASS
**Final state**

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- No modelation $t'$
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**COMPASS data with JPAC fit - $1^{-+} \eta^{(i)} \pi P$**

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

References:
[PRL, 122, 042002 (2019)]
Final state
- $\pi^- \eta^{(*)} (\rightarrow \pi^+ \pi^- \pi^0 / \eta (\rightarrow \gamma \gamma))$
- No modelation $t'$
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Coupled-channel fit by JPAC
- Performed resonance model fit using K-matrix formalism
- Conclusion: one pole is sufficient to describe both!
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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)]
Experimenital Results

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 and phase motion in expected region

Results from other Experiments
- BNL and VES observed spin-exotic 1$^{-+}$ state at $\sim 1.6\text{ GeV}/c^2$
- BNL observed a second state
**Experimental Results**

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

\[ f_1(1285)\pi^- \] 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

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Exotic meson candidates in COMPASS

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**Experimental Results**

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

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

**\( K^* \bar{K} \) at COMPASS**
- Final state \( \pi^- K_S^0 (\pi^+ \pi^-) K_S^0 (\pi^+ \pi^-) \)
- Selected 240k \( \pi^- K_S^0 K_S^0 \) events
  \( \rightarrow \) Analysis in \( t' \) possible
- Next Step: PWA
Exotic meson candidate in strange sector
**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

**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

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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 exited signals are observed

PDG: Light Strange Sector

- 25 states listed, nine need further confirmation

Exotic meson candidates in COMPASS
Exotic state in $0^-$ sector?

- Only $0^- 0^+ \rho(770) K P$ wave is reliable
- Three resonances needed:
  1. $K(1460)$ fixed PDG values $m = 1482.4$ MeV/$c^2$ and $\Gamma = 335.6$ MeV/$c^2$
  2. $K(1630)$, $m = 1687 \pm 10^{+12}_{-67}$ MeV/$c^2$ and $\Gamma = 140 \pm 20^{+50}_{-50}$ MeV/$c^2$ ($\sigma = 8.3$)
  3. $K(1830)$, $m = 1893 \pm 17^{+13}_{-39}$ MeV/$c^2$ and $\Gamma = 160 \pm 40^{+60}_{-80}$ 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>$\eta^{(*)}\pi$</td>
<td>$\pi^- \pi^+ \pi^- \pi^0/\eta$</td>
<td>-[COMPASS PLB 740, (2015)]</td>
<td>- Use new analysis techniques</td>
</tr>
<tr>
<td>$b_1\pi$</td>
<td>$\omega \pi^- \pi^0$</td>
<td>-[JPAC, PRL 122 (2019)]</td>
<td>- Increase data set</td>
</tr>
<tr>
<td>$f_1(1285)\pi$</td>
<td>$\pi^- \pi^+ \pi^- \eta$</td>
<td>- Partial-Wave Decomposition</td>
<td>- Improve shower reconstruction</td>
</tr>
<tr>
<td>$K^*K$</td>
<td>$K_S\bar{K}_S\pi$</td>
<td>- Event Selection</td>
<td>- Resonance-Model Fit</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:**

- $K^- + p \rightarrow K_S^{0}\pi^- + p \ & \ K^- + p \rightarrow \Lambda\bar{p} + p$

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Exotic meson candidates in COMPASS
Back Up
**Experimental Results**

**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:

\[
\mathcal{I}(\tau_i) = \left( \sum_{a} \sum_{k} \mathcal{T}_{a,k} \Psi'_{a,k}(\tau_i) \right)^2
\]

with

\[
\mathcal{T}_a \rightarrow \mathcal{T}_{a,k} = \mathcal{T}_a \mathcal{T}_{a,k}
\]

- The set \( \mathcal{T}_{a,k} \) 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.

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Exotic meson candidates in COMPASS
Updated kinematic distributions: \( \eta^{(i)} \pi^- \)

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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
  $\rightarrow$ 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 $\sim 1.6\text{GeV/c}^2$
- BNL observed a second state
LQCD: if $\pi_1 \rightarrow \rho \omega$ is present, then it is very small
Kinematic distributions: $X \rightarrow f_1(1285)\pi^-$
Effekt of limited PID

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Exotic meson candidates in COMPASS

Preliminary
Kinematic distributions: \( K^- + p \rightarrow K_S^0 \pi^- + p \)