Non-Strange Light-Meson Spectroscopy at COMPASS

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Motivation

• The Constituent Quark Model predicts mesons as $|q\bar{q}\rangle$ states
• QCD allows meson configurations beyond $|q\bar{q}\rangle$ - so-called exotics:
  • Hybrids $|q\bar{g}\rangle$, Glueballs $|gg\rangle$, Multiquarks $|qq\bar{q}\rangle$  

Exotic mesons at COMPASS (talk by B. Ketzer, Tue. 15:00)

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  ![Exotic mesons at COMPASS](https://arxiv.org/pdf/1405.4195.pdf)

• Light non-strange $|q\bar{q}\rangle$ states cannot make up states with spin quantum numbers $J^{PC} = 0^{--},$ even$^{+-},$ odd$^{--}$
  • “Spin-exotic” mesons
  • Direct access to find states beyond $|q\bar{q}\rangle$ states
Spin-Exotic Light Mesons

- Lattice QCD predicts the lightest exotic in $1^{-+}$
  - Single pole around 1.6 GeV/c$^2$
  - Dominant decay to $b_1 \pi$
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- JPAC found single pole - $\pi_1(1600)$ - sufficient for $\eta^{(t)} \pi$ COMPASS data
- BNL claimed $\pi_1(2015)$ in $\omega \pi^- \pi^0$ and $f_1 \pi$
Experimental Setup

• Located at CERN SPS
• 190 GeV/c negative hadron beam
• Various targets:
  • Liquid-hydrogen
  • Heavy solid-state targets
    • Pb, Ni $\rightarrow$ Primakoff reactions (talk by D. Ecker, Thu. 17:20)
• Inelastic high-energy $\pi^- p$ scattering
  • Isovector light mesons $X^- (a_j$ and $\pi_j$)

Beam:
  97% $\pi^-$
  2% $K^-$
  1% $\bar{p}$
Light-Meson Spectroscopy at COMPASS

Analyzed channels:
• $\pi^-\pi^-\pi^+/\pi^0\pi^-\pi^0$
• $\eta\pi^-/\eta'\pi^-$
• $K^-\pi^-\pi^+$ \rightarrow Strange-meson spectroscopy (talk by S. Wallner, Thu. 14:00)
• $\omega\pi^-\pi^0$

Upcoming channels under study:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Description</th>
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<tbody>
<tr>
<td>$K_SK^-$</td>
<td>Search for $a_6(2450)$</td>
</tr>
<tr>
<td>$K_SK_S\pi$</td>
<td>Investigate nature of $a_1(1420)$</td>
</tr>
<tr>
<td>$f_1\pi^-$</td>
<td>Search for $\pi_1$ states</td>
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<tr>
<td>$K_S\pi^-$</td>
<td>Strange mesons spectroscopy</td>
</tr>
<tr>
<td>$\Lambda\bar{\rho}$</td>
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Analysis of $\omega(782)\pi^-\pi^0$

- Overlapping and interfering $X^-$ states
  - $m_X$ spectrum shows no clear peaks above 1.5 GeV/$c^2$

- Disentangling the different contributions requires partial-wave analysis
  
  Talk by J. Beckers on Thu. 14:00: Progress in the Partial-Wave Analysis Methods at COMPASS

- Partial-wave decomposition splits the total amplitude in the different contributions
Partial-Wave Decomposition

- Exited meson $X^-$ with quantum numbers $0^-0^+$ is produced
Partial-Wave Decomposition

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- Isobar model: $X^-$ decays to $\omega \rho(770)$, where $\rho(770)$ an unstable intermediate state – the isobar.
Partial-Wave Decomposition

• Exited meson $X^-$ with quantum numbers $0^-0^+$ is produced

• Isobar model: $X^-$ decays to $\omega \rho(770)$, where $\rho(770)$ an unstable intermediate state – the isobar
  • $P1$ coupling between $\omega$ and $\rho(770)$
Partial-Wave Decomposition

- Exited meson $X^-$ with quantum numbers $0^-0^+$ is produced
- Isobar model: $X^-$ decays to $\omega\rho(770)$, where $\rho(770)$ an unstable intermediate state – the isobar
  - $P1$ coupling between $\omega$ and $\rho(770)$
- $\rho(770)$ decays to $\pi^-\pi^0$
  - second $P1$ coupling
- $i = 0^-0^+[\rho(770)P] \omega P1$
Partial-Wave Decomposition

- Exit meson $X^-$ with quantum numbers $J^P M^\epsilon$ is produced.
- Isobar model: $X^-$ decays to $\omega \xi^-$, where $\xi^-$ is an unstable intermediate state – the isobar.
  - $L, S$ coupling between $\omega$ and $\xi^-$
- $\xi^-$ decays to $\pi^- \pi^0$
  - second $l, s$ coupling
- $i = J^P M^\epsilon \left[ \xi l \right] \omega L S$
Partial-Wave Decomposition

• Further decay channels of $X^-$:
  • $\pi^0 \xi^-, \pi^- \xi^0$

• Both decays have the same amplitude
  ⇒ Coherently sum over both isospin configurations $\pi^0 \xi^-, \pi^- \xi^0$

• $i = J^P M^\epsilon [\xi l]$ bachelor $LS$
  • $\xi$ either decays to $\omega \pi$ or $\pi \pi$
Partial-Wave Decomposition

- Coherent superposition of partial-waves:
  - $i = J^P M^\varepsilon [\xi \ell]$ bachelor $LS$

$$I(m_X, t', \tau) = \left| \sum_i \mathcal{J}_i(m_X, t') \psi_i(m_X, \tau) \right|^2$$

with:

- $m_X$: mass of the $\omega(782)\pi^-\pi^0$ system
- $t'$: squared four-momentum transfer
- $\tau$: phase-space variables of the final state
Phase-Space Variables

- $\tau$: Total of 8 phase-space variables

2x two-body decay: $(\phi, \theta)$, $(\phi_{GJ}, \theta_{GJ}), (\phi_{HF}, \theta_{HF})$

Intermediate mass $m_\xi$

$2\omega(782)$ Dalitz-Plot variables
Partial-Wave Decomposition

• Coherent superposition of partial-waves:
  • $i = J^P M^e [\xi l]$ bachelor $LS$
  
  $$I(m_X, t', \tau) = \left| \sum_i T_i(m_X, t') \psi_i(m_X, \tau) \right|^2$$

• Decay amplitude $\psi_i(m_X, \tau)$: calculated using the isobar model
Partial-Wave Decomposition

• Coherent superposition of partial-waves:
  • $i = J^P M^e [\xi l] \text{ bachelor } LS$

$$I(m_X, t', \tau) = \left| \sum_i T_i(m_X, t') \psi_i(m_X, \tau) \right|^2$$

• Decay amplitude $\psi_i(m_X, \tau)$: calculated using the isobar model
• Transition amplitude $T_i(m_X, t')$:
  ⇒ $T_i(m_X, t')$ contains production, propagation, and coupling of $i$
    • No assumptions about the resonant content of $X^-$
  ⇒ Extract $T_i(m_X, t')$ by independent maximum-likelihood fits of $I(\tau)$ in bins of $(m_X, t')$
Partial-Wave Decomposition – Wave Set

- In principle: Infinite number of partial-waves $i$

\[ I(m_x, t', \tau) = \left| \sum_i T_i(m_x, t') \psi_i(m_x, \tau) \right|^2 \]
Partial-Wave Decomposition – Wave Set

- In principle: Infinite number of partial-waves $i$
- Construct a wave pool of 893 allowed waves by systematic constraints
  - $\xi \rightarrow \pi\pi$: $\rho(770)$, $\rho(1450)$, $\rho_3(1690)$
  - $\xi \rightarrow \omega\pi$: $b_1(1235)$, $\rho(1450)$, $\rho_3(1690)$
  - $J \leq 8$, $M \leq 2$, $L \leq 8$

\[ I(m_X, t', \tau) = \left| \sum_i T_i(m_X, t') \psi_i(m_X, \tau) \right|^2 \]
Partial-Wave Decomposition – Wave Set

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  • $J \leq 8$, $M \leq 2$, $L \leq 8$

• Wave set selected using regularization-based model-selection
  • Unique wave set for each $(m_X, t')$ cell

\[ I(m_X, t', \tau) = \left| \sum_i T_i(m_X, t') \psi_i(m_X, \tau) \right|^2 \]
Results $J^{PC} = 0^{-+}$

States listed in PDG

$\pi(1800)$
$m = 1810 \pm 9_{11} \text{ MeV}$
$\Gamma = 215^{+7}_{-8} \text{ MeV}$

- Dashed lines to indicate nominal PDG masses of resonances

Composition: $J^P M^\ell [\Psi L] bachelor \ LS$

$0^+ 0^+ [\rho(770) P] \omega P 1$

Preliminary
Results $J^{PC} = 0^{-+}$

$0^{-+}[\rho(770)P]\omega P1$

$0.10 < t' < 0.17$ (GeV/c)$^2$

COMPASS

$\pi(1800)$
$m = 1810^{+9}_{-11}$ MeV
$\Gamma = 215^{+7}_{-8}$ MeV

States listed in PDG
Results $J^{PC} = 0^{-+}$

$0^{-0^+}[\rho(770)P]\omega P1$

$0.10 < t' < 0.17 \text{ (GeV/c)}^2$

COMPASS

$[0^{-0^+}[\rho(770)P]\omega P1] - [2^{+1^+}[\rho(770)P]\omega S2]$

$0.10 < t' < 0.17 \text{ (GeV/c)}^2$

COMPASS

States listed in PDG

$\pi(1800)$
$m = 1810^{+9}_{-11} \text{ MeV}$
$\Gamma = 215^{+7}_{-8} \text{ MeV}$
Results $J^{PC} = 2^{++}$

States listed in PDG

$\alpha_2(1320)$
$m = 1318.2 \pm 0.6$ MeV
$\Gamma = 105^{+17}_{-1.9}$ MeV

$\alpha_2(1700)$
$m = 1698 \pm 40$ MeV
$\Gamma = 265 \pm 60$ MeV
Results $J^{PC} = 2^{-+}$

States listed in PDG

$\pi_2(1670)$
$m = 1670^{+2.9}_{-1.2}$ MeV
$\Gamma = 258^{+8}_{-9}$ MeV

$\pi_2(1880)$
$m = 1874^{+26}_{-5}$ MeV
$\Gamma = 237^{+33}_{-30}$ MeV

$\pi_2(2005)$
$m = 1963^{+17}_{-27}$ MeV
$\Gamma = 370^{+16}_{-90}$ MeV
Results $J^{PC} = 4^{++}$

$4^{+}1^+[b_{1}(1235)\pi F1]$ with $0.10 < t' < 0.17$ (GeV/c)$^2$ for COMPASS.

[a_4(1970)] $m = 1967 \pm 16$ MeV, $\Gamma = 324^{+15}_{-18}$ MeV

States listed in PDG
Results $J^{PC} = 4^{++}$

$4^{+1+}[\rho(770)P]_\omega D2$

$0.10 < t' < 0.17 \text{(GeV/c)}^2$

COMPASS

[4+1+[\rho(770)P]_\omega D2] - [2+1+[\rho(770)P]_\omega S2]

$0.10 < t' < 0.17 \text{(GeV/c)}^2$

COMPASS

$\alpha_4(1970)$

$m = 1967 \pm 16 \text{ MeV}$

$\Gamma = 324^{+15}_{-18} \text{ MeV}$

States listed in PDG
Results $J^{PC} = 3^{++}$

$3^+0^+[\rho(770)P] \omega D_2$

$0.10 < t' < 0.17 \text{ (GeV/c)}^2$

COMPASS

$[3^+0^+[\rho(770)P] \omega D_2] - [2^+1^+[\rho(770)P] \omega S_2]$

$0.10 < t' < 0.17 \text{ (GeV/c)}^2$

COMPASS

$\alpha_3(1875)$

$m = 1874 \pm 105 \text{ MeV}$

$\Gamma = 385 \pm 166 \text{ MeV}$

This only has been seen in $\pi^- \pi^- \pi^+$ at BNL E852

The PDG further lists a $\alpha_3(2030)$

States listed in PDG
Results $J^{PC} = 3^{++}$

- $3^{0+}[b_1(1235)S] \pi F$\textsuperscript{1}
- $0.10 < t' < 1.00$ (GeV/c)$^2$
- COMPASS

- $3^{0+}[\rho_3(1690)F] \pi S$\textsuperscript{3}
- $0.10 < t' < 1.00$ (GeV/c)$^2$
- COMPASS

**States listed in PDG**

- $a_3(1875)$
  - $m = 1874 \pm 105$ MeV
  - $\Gamma = 385 \pm 166$ MeV

This only has been seen once in $\pi^- \pi^- \pi^+$

The PDG also lists a $a_3(2030)$
Results $J^{PC} = 6^{++}$

States listed in PDG

$a_6(2450)$
$m = 2450 \pm 130 \text{ MeV}$
$\Gamma = 400 \pm 250 \text{ MeV}$

This only has been seen once in $K_S K$
Results $J^{PC} = 1^{-+}$

$b_1$ S-wave decay

$0.10 < t' < 0.17 \text{ (GeV}/c)^2$

$\pi_1(1600)$
$m = 1661^{+15}_{-11} \text{ MeV}$
$\Gamma = 240 \pm 50 \text{ MeV}$

States listed in PDG
Results $J^{PC} = 1^{-+}$

$b_1$ S-wave decay

$1^{-+}[b_1(1235)S] \pi S 1$

$0.10 < t' < 0.17 \text{ (GeV}/c^2)^2$

COMPASS

Comparison to $1^{-+}$ in other COMPASS final states

$\pi_1(1600)$

$= 1661^{+15}_{-11} \text{ MeV}$

$= 240 \pm 50 \text{ MeV}$

Preliminary
Results $J^{PC} = 1^{-+}$

$b_1$ S-wave decay

$1^{-+}[b_1(1235)S]\pi S 1$

$0.10 < t' < 0.17 \text{ (GeV/c)^2}$

COMPASS

Comparison to $1^{-+}$ in other COMPASS final states

$\pi_1(1600)$

$= 1661^{+15}_{-11} \text{ MeV}$

$\pi = 240 \pm 50 \text{ MeV}$
Results $J^{PC} = 1^{-+}$

$b_1$ D-wave decay

$1^{-1+}[b_1(1235)D]\pi S 1$

$0.10 < t' < 0.17 \text{ (GeV/c)}^2$

COMPASS

$[1^{-1+}[b_1(1235)D]\pi S 1] - [2^{+1+}[^{3}\rho(770)P]\omega S 2]]$

$0.10 < t' < 0.17 \text{ (GeV/c)}^2$

COMPASS

$\pi_1(1600)$

$m = 1661^{+15}_{-11} \text{ MeV}$

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$0.10 < t' < 1.00$ (GeV/c)^2

COMPASS

$\pi_1(1600)$
$m = 1661^{+15}_{-11}$ MeV
$\Gamma = 240 \pm 50$ MeV
Conclusion and Outlook

• Resonance-like signals for many well-established states visible
  • Clear peak for $\pi_1(1600) \rightarrow b_1(1235)\pi$

• Possible signals for further states:
  $a_3(1975), a_6(2450), \pi_1 \rightarrow \rho(770)\omega$

• Next step: Resonance-model fit to extract resonance parameters
  • First studies yield promising results
Backup
Mesons in QCD

- Many short-lived, exited states with similar masses
  ⇒ All possible intermediate states X for one final-state configuration interfere
  ⇒ PWA necessary to determine contributions of certain X
Kinematic Distributions - \( \omega(782)\pi^-\pi^0 \)

- Total of 720,000 selected \( \pi^-\pi^0\omega(782) \) events

![Graph 1: \( \pi^-\pi^0\omega \) Mass](image1)

- \( m_{\pi^-\pi^0\omega} \) [GeV/c^2]
- Not acceptance corrected

![Graph 2: \( \pi^-\pi^0 \) Mass](image2)

- \( m_{\pi^-\pi^0} \) [GeV/c^2]
- \( \rho(770) \)

**Compass**
Kinematic Distributions - $\omega(782)\pi^-\pi^0$

- Total of 720,000 selected $\pi^-\pi^0\omega(782)$ events

**Graphs:**

- **$\pi^-\omega$ Mass**
  - Events / 10 MeV/c$^2$
  - $m_{\pi^-\omega}$ [GeV/c$^2$]
  - Not acceptance corrected

- **$\pi^0\omega$ Mass**
  - Events / 10 MeV/c$^2$
  - $m_{\pi^0\omega}$ [GeV/c$^2$]
  - Not acceptance corrected
$$t' \text{ Distribution} - \omega(782)\pi^-\pi^0$$
Dalitz Plots - $\omega(782)\pi^-\pi^0$
\( \omega(782) \) Selection - \( \omega(782) \pi^- \pi^0 \)

- Reconstruction of \( \omega(782) \) from \( \pi^- \pi^0 \pi^+ \) decay
ω(782) Selection - $\omega(782)\pi^-\pi^0$

- Reconstruction of $\omega(782)$ from $\pi^-\pi^0\pi^+$ decay
- Select events with exactly one $\pi^-\pi^0\pi^+$ combination within $\pm 3\sigma_\omega$ around the fitted $m_\omega$
Partial-Wave Decomposition

\[ I(m_X, t', \tau) = \left| \sum_i T_i(m_X, t') \psi_i(m_X, \tau) \right|^2 \]

- Decay amplitude \( \psi_i(m_X, \tau) \): calculated using the isobar model
- \( T_i(m_X, t') \) contains production, propagation, and coupling of
  - No assumptions about the resonant content of \( X^- \)
- Extract \( T_i(m_X, t') \) by independent maximum-likelihood fits of \( I(\tau) \) in bins of \( (m_X, t') \)
  - Approximate \( T_i \) by fitting step-wise constant functions in bins of \( (m_X, t') \)
\( \omega(782) \) Decay in PWA Model

- Factorisation of the decay amplitude
  \[
  \psi_i = \sum_{\lambda, \omega} \psi_{i, \omega_X \rightarrow \omega \pi \pi}^\lambda \psi_{\omega \rightarrow 3\pi}^\lambda
  \]
- \( \psi_{i, \omega_X \rightarrow \omega \pi \pi}^\lambda \) calculated with isobar model
- \( \psi_{\omega \rightarrow 3\pi}^\lambda = D(m_\omega) D_{0}^{\lambda, \omega} \left| p^+ \times p^- \right| \)
  - \( D(m_\omega) \) is the Breit-Wigner (BW) of \( \omega \)
  - \( D_{0}^{\lambda, \omega} \) and \( \left| p^+ \times p^- \right| \) describe the orientation of \( \omega \) and its \( P \)-wave Dalitz plot, respectively
    - Both are independent of \( m_\omega \)
\( \omega(782) \) Decay in PWA Model

- Problem: \( m_\omega \) is only measured with limited resolution
  - \( \Rightarrow \) Intensity level: Convolution of BW with resolution function \( \Rightarrow m_\omega \) follows Voigt distribution
  - \( \Rightarrow \) Convolution of the full intensity is not feasible
- Solution: Neglect self-interference of \( \omega \) as only one \( \pi^- \pi^0 \pi^+ \) combination has a large amplitude
  - \( \Rightarrow D(m_\omega) \) factorises out of the intensity:
    \[ I(m_X, t', \tau, m_\omega) = \tilde{I}(m_X, t', \tau) |D(m_\omega)|^2 \]
  - \( |D(m_\omega)|^2 \) is modelled as Voigt distribution with parameters from fitted data
Isospin Symmetrization

• $X^- \rightarrow \xi^-\pi^0$ and $X^- \rightarrow \xi^0\pi^-$ have the same amplitude (modulo a sign due to isospin Clebsch-Gordons)
  \[ \Rightarrow T_i(m_X, t') \] is the same and we model the total decay amplitude as
  \[ \psi_i = +\frac{1}{2} \psi_{i,\xi^0\pi^-} - \frac{1}{2} \psi_{i,\xi^-\pi^0} \]
Wave Selection

• Method used for $3\pi$, $5\pi$ and $K\pi\pi$

• Modified log-likelihood with penalties:
  • Cauchy regularization to suppress small waves
  • Connected bins over $m_X$ to smoothen $T_i(m_X)$

• Wave pool:
  • $J \leq 8$, $M \leq 2$, $\epsilon = +$
  • $\xi \rightarrow \pi\pi$: $\rho(770)$, $\rho(1450)$, $\rho_3(1690)$
  • $\xi \rightarrow \omega\pi$: $b_1(1235)$, $\rho(1450)$, $\rho_3(1690)$
  • $L \leq 8$
  • 893 waves + flat wave

\[
i = J^P M^\epsilon \, [\xi I] \, b \, LS\]
Flat Wave

- Isotropic in 5-body phase-space
- Used to describe background