Meson Spectroscopy at COMPASS

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MESON2016
07. June 2016, Kraków
The COMPASS Experiment at the CERN SPS
Experimental Setup

Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- Electromagnetic and hadronic calorimeters
- Beam and final-state particle ID (CEDARs, RICH)
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**Hadron spectroscopy** 2008-09, 2012
- 190 GeV/c secondary hadron beams
  - $h^-$ beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
  - $h^+$ beam: 75% $p$, 24% $\pi^+$, 1% $K^+$
- Various targets: $\ell$H$_2$, Ni, Pb, W
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Experimental Setup

Spectroscopy program

- Explore light-meson spectrum for $m \gtrsim 2 \text{ GeV}/c^2$
- Search for states beyond the constituent quark model
- Precision measurement of known resonances

Hadron spectroscopy

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1 Introduction
   ● Meson production in diffractive dissociation
   ● Partial-wave analysis method

2 PWA of diffractively produced $3\pi$ final states
   ● Observation of a new narrow axial-vector meson $a_1(1420)$
   ● $J^{PC} = 1^{−+}$ spin-exotic partial wave

3 Conclusions and outlook
Soft scattering of beam particle off target
- Production of $n$ forward-going hadrons
- Target particle stays intact

At 190 GeV/$c$, interaction dominated by space-like pomeron exchange
Meson Production in Diffractive Dissociation

- **Exclusive measurement**
- **Clean data samples**
- Reduced four-momentum transfer squared $t' \equiv |t| - |t|_{\text{min}}$
  - Analyzed range: $0.1 < t' < 1.0 \ (\text{GeV}/c)^2$

**Example:** $\pi^-\pi^+\pi^-$ final state

![Diagram showing the process of meson production in diffractive dissociation](image)

<table>
<thead>
<tr>
<th>Events / (50 MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>180</td>
</tr>
<tr>
<td>190</td>
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<tr>
<td>200</td>
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</tbody>
</table>
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*Example:* $\pi^- \pi^+ \pi^-$ final state
Excitation of beam particle into intermediate resonances $X$

$X$ dissociate into $n$-body final state

Rich spectrum of intermediate states $X$

Disentanglement of all contributing $X$ by partial-wave analysis (PWA)
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Partial-Wave Analysis Method

**Ansatz:** Factorization of production and decay

\[ \mathcal{I}(\tau; m_X) = \sum_{\epsilon = \pm 1} \left| \sum_{i} \mathcal{T}_{i}^{\epsilon}(m_X) \mathcal{A}_{i}^{\epsilon}(\tau; m_X) \right|^2 \]

- Transition amplitudes \( \mathcal{T}_{i}^{\epsilon}(m_X) \) \( \implies \) interesting physics
- Decay amplitudes \( \mathcal{A}_{i}^{\epsilon}(\tau; m_X) \)
  - Describe kinematic distribution of partial waves
  - Calculated using isobar model (for \( n > 2 \)) and helicity formalism (Wigner D-functions)
- \( \epsilon = \pm 1 \): naturalities of exchange particle
  - 190 GeV/c beam momentum \( \implies \) pomeron (\( \epsilon = +1 \)) dominates
Partial-Wave Analysis Method

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**Partial-Wave Analysis Method**

\[ \pi^- \text{beam} \rightarrow T \rightarrow X^- \rightarrow A \]

**Ansatz:** Factorization of production and decay

\[ \mathcal{I}(\tau; m_X) = \sum_{\epsilon = \pm 1} \left| \sum_{i}^{\text{waves}} \mathcal{T}_{i}^{\epsilon}(m_X) A_{i}^{\epsilon}(\tau; m_X) \right|^2 \]

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Partial-Wave Analysis Method

Two-step analysis

\[ I(\tau; m_X) = \sum_{\epsilon=\pm1} \left| \sum_{i}^{\text{waves}} T_{i}^{\epsilon}(m_X) A_{i}^{\epsilon}(\tau; m_X) \right|^2 \]

1. **Determination of** $m_X$ **dependence of spin-density matrix**
   \[ \varrho_{ij}^{\epsilon}(m_X) = T_{i}^{\epsilon}(m_X) T_{j}^{\epsilon \ast}(m_X) \]
   - Independent maximum likelihood fits to measured $\tau$ distributions in narrow bins of $m_X$
   - Fits take into account detection efficiency
   - No assumptions about resonance content of $X$

2. **Extraction of resonances**
   - $\chi^2$ fit of resonance model to spin-density (sub)matrix
Two-step analysis

\[ \mathcal{I}(\tau; m_X) = \sum_{\epsilon = \pm 1} \left| \sum_{i} \mathcal{T}_i^\epsilon(m_X) \mathcal{A}_i^\epsilon(\tau; m_X) \right|^2 \]

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Partial-Wave Analysis: $\pi^- \pi^+ \pi^-$ Final State

$\pi^-_{\text{beam}}$ $\rightarrow$ $X^- \rightarrow \pi^- \pi^+ \pi^-$

$\rho_{\text{target}}$ $\rightarrow$ $P$ $\rightarrow$ $\rho_{\text{recoil}}$

$X^-$ decay via $\pi^+ \pi^-$ resonances = "isobars"
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$\pi^-_{beam}$

$\pi^-_{target}$

$\pi^+_recoil$

$X^-_{decay via \pi^+ \pi^- resonances = "isobars"}$

$|m_{3\pi} - 1672 \text{ MeV}/c^2| < 100 \text{ MeV}/c^2$
Partial-Wave Analysis: $\pi^- \pi^+ \pi^-$ Final State

$\pi^-_{\text{beam}} \rightarrow [J^{PC} M^\epsilon] \rightarrow X^- \rightarrow\text{Bachelor} \rightarrow [L] \rightarrow \text{Isobar} \rightarrow p_{\text{target}} \rightarrow p_{\text{recoil}}$

$X^-$ decay via $\pi^+ \pi^-$ resonances = "isobars"

$|m_{3\pi} - 1672 \text{ MeV}/c^2| < 100 \text{ MeV}/c^2$
Isobar model

- Isobars included into PWA model
  - $^3\pi\pi$ $J^{PC} = 0^{++}$
  - $\rho(770)$ $1^{--}$
  - $f_0(980)$ $0^{++}$
  - $f_2(1270)$ $2^{++}$
  - $f_0(1500)$ $0^{++}$
  - $\rho_3(1690)$ $3^{--}$
- PWA requires precise knowledge of isobar $\rightarrow \pi^+\pi^-$ amplitude

Partial-Wave Analysis: $\pi^-\pi^+\pi^-$ Final State

Bachelor

\[ X^- \quad [J^{PC}M^\epsilon] \quad [L] \]

Isobar

$\pi_\text{beam}$

$\pi_\text{target}$

$\pi_\text{recoil}$

\[ \rho_\text{beam} \quad [J^{PC}M^\epsilon] \quad \pi^- \quad [L] \quad \pi^+ \quad \pi^- \]

\[ \rho_\text{target} \quad \rho_\text{recoil} \]

Entries / (5 MeV/$c^2$)

Entries / (5 MeV/$c^2$) vs $m_{\pi^+\pi^-}$ [GeV/$c^2$]

$\rho(770)$

$\rho_3(1690)$

$f_0(980)$

$f_2(1270)$
PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$

Two Data Sets

1. $\pi^- \pi^+ \pi^-$ (50 M events)
2. Crosscheck with $\pi^- \pi^0 \pi^0$ (3.5 M events)
   - Very different acceptance
   - Isobars separated by isospin
     - $I = 1$ isobars in $\pi^- \pi^0$
     - $I = 0$ isobars in $\pi^0 \pi^0$

Complicated correlation of $m_{3\pi}$ and $t'$

- 2D PWA in bins of $t'$ and $m_{3\pi}$
  - $\pi^- \pi^+ \pi^-$: 11 $t'$ bins
  - $\pi^- \pi^0 \pi^0$: 8 $t'$ bins
- Better disentanglement of resonant and nonresonant contributions
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\[ 800 < m_{3\pi} < 850 \text{ MeV} / c^2 \]

\[ 0.80 < m_{3\pi} < 0.85 \text{ GeV} / c^2 \]

\[ 1600 < m_{3\pi} < 1650 \text{ MeV} / c^2 \]

\[ 1.60 < m_{3\pi} < 1.65 \text{ GeV} / c^2 \]
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PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Major Waves

$\pi^- \pi^+ \pi^-$ invariant mass spectrum

- $1^{++} 0^+ \rho(770)\pi S$
- $2^{++} 1^+ \rho(770)\pi D$
- $2^{-+} 0^+ f_2(1270)\pi S$

![Mass spectrum graph](attachment:mass_spectrum.png)
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Major Waves

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![Graph showing invariant mass spectrum with peaks at $a_1(1260)$, $a_2(1320)$, and $\pi_2(1670)$]
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In total 88 partial waves

- Largest wave set used so far for $\pi^- \pi^+ \pi^-$
- Spin $J$ up to 6
- Orbital angular momentum $L$ up to 6
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Selected Small Waves

- $2^{++} 2^+ \rho(770) \pi D$
- $4^{++} 1^+ \rho(770) \pi G$
- $0^- 0^+ f_0(980) \pi S$

$2^{++} 2^+ \rho(770) \pi D$

$0.3\% \quad 0.100 < t' < 1.000 \text{ (GeV/c)}^2$

$\times 10^3$

Intensity $/ (20 \text{ MeV/c}^2)$

$a_2(1320)$

$3\text{ MeV/c}^2$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Selected Small Waves

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\[ \text{Intensity / (20 MeV/c}^2) \]

- $a_2(1320)$
- $a_4(2040)$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Selected Small Waves

- $2^{++} 2^+ \rho(770) \pi D$
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[arXiv:1509.00992]
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Selected Small Waves

A New $a_1(1420)$ Meson?

- $1^{++} 0^+ f_0(980) \pi P$
- Unexpected peak around 1.4 GeV/$c^2$
- Small intensity: $\approx 0.3\%$

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

$$0.3\% \quad 0.100 < t' < 1.000 \text{ (GeV/c)}^2$$

Intensity / (20 MeV/$c^2$)

$m_{3\pi} \text{ [GeV/c}^2\text{]}$

### Notes

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- Meson Spectroscopy at COMPASS
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Selected Small Waves

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$\pi^- \pi^0 \pi^0$ final state

- Very different detector acceptance
- Similar signal

$\pi^- \pi^0 \pi^0$

$\pi^- \pi^+ \pi^-$ scaled

COMPASS 2008 ($\pi^- p \rightarrow (3\pi)^- p$)

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

$\pi^- \pi^0 \pi^0$, $\pi^- \pi^+ \pi^-$ (scaled)

$0.100 < t' < 1.000$ GeV$^2$/c$^2$

(incoherent sum)

Preliminary
Coherent sum of resonant (Breit-Wigner) and nonresonant terms

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

$0.1 < t' < 1.0 \text{ (GeV/c)}^2$
Coherent sum of resonant (Breit-Wigner) and nonresonant terms
1\(^{++}\) peak consistent with Breit-Wigner resonance

\(a_{1}(1420)\):
\(M_0 = 1414^{+15}_{-13}\) MeV/\(c^2\)
\(\Gamma_0 = 153^{+8}_{-23}\) MeV/\(c^2\)

Work in progress: extension to more partial waves
**Resonance-Model Fit**

- **1^{++} peak consistent with Breit-Wigner resonance**
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Is the $a_1(1420)$ a Model Artifact?

- Calculation of decay amplitudes $A_{\text{wave}}(\tau)$ needs precise knowledge of isobar $\rightarrow \pi^+ \pi^-$ amplitude
- At least 3 isobars with $J^{PC} = 0^{++}$
  - $[\pi\pi]_{S\text{-wave}}$
  - $f_0(980)$
  - $f_0(1500)$
- Parametrization of $m_{\pi^+ \pi^-}$ dependence difficult
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Is the $a_1(1420)$ a Model Artifact?

**Novel analysis method** inspired by E791 analysis [PRD 73 (2006) 032204]

- Replace $J^{PC} = 0^{++}$ isobar parametrizations by piece-wise constant amplitudes in $m_{\pi^+\pi^-}$ bins
- Extract $m_{3\pi}$ dependence of $J^{PC} = 0^{++}$ isobar amplitude from data
  - **Advantage:** drastic reduction of model bias
  - **Caveat:** significant increase in number of fit parameters

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![Graph showing the dependence of $f_0(980)$ and $f_0(1500)$ on $m_{\pi^+\pi^-}$](image1)

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![Graph showing the dependence on $m_{\pi^+\pi^-}$](image2)
**Is the $a_1(1420)$ a Model Artifact?**

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Correlation of $3\pi$ intensity around 1.4 GeV/$c^2$ with $f_0(980)$

- $f_0(980)$ semicircle in Argand diagram
- Confirms that $f_0(980)\pi$ signal is not an artifact of isobar parametrization
\[ \pi \pi \ S\text{-Wave Amplitude in } J^{PC} = 1^{++} 3\pi \text{ Wave} \]

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What is the Nature of the $a_1(1420)$?

Still unclear

- $J^{PC} = 1^{++}$ ground state is $a_1(1260)$
  - Mass: $1230 \pm 40$ MeV/$c^2$
  - Width: 250 to 400 MeV/$c^2$
- No quark-model states expected at 1.4 GeV/$c^2$
  - First excited $1^{++}$ state expected to be heavier and wider
- Isospin partner of narrow $f_1(1420)$?
- $a_1(1420)$ has peculiar decay mode
  - Only seen in $f_0(980)\pi$ decay
  - $f_0(980)$ has large $s\bar{s}$ content
  - Some models explain $f_0(980)$ as tetra-quark state
- $a_1(1420)$ lies suspiciously close to $K\bar{K}^*$ threshold

$1^{++} 0^+ f_0(980) \pi P$
- $0.1 < t' < 1.0$ (GeV/$c^2$)
- (1) Model curve
- (2) $a_1(1420)$ resonance
- (3) Non-resonant term

Int. / (20 MeV/$c^2$)

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What is the Nature of the $a_1(1420)$?

Several proposed explanations

**Genuine resonance**
- **Two-quark-tetraquark** mixed state [Wang, arXiv:1401.1134]
- **Tetraquark** with mixed flavor symmetry [Chen et al., PRD 91 (2015) 094022]

**Effect in $a_1(1260)$ production**

**Effect in $a_1(1260)$ decay**
- Singularity in triangle diagram [Mikhasenko et al., PRD 91 (2015) 094015]

- Similar diagrams proposed to explain some $X, Y, Z$ states and pentaquark candidate $P_c$ in heavy-meson sector
What is the Nature of the $a_1(1420)$?

Several proposed explanations

**Genuine resonance**
- Tetraquark with mixed flavor symmetry [Chen et al., PRD 91 (2015) 094022]

**Effect in $a_1(1260)$ production**

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Several proposed explanations

**Genuine resonance**
- Two-quark-tetraquark *mixed state*  
- Tetraquark *with mixed flavor symmetry*  
  [Chen *et al.*, PRD 91 (2015) 094022]

**Effect in $a_1(1260)$ production**
- Two-channel *unitarized Deck amplitude* + direct $a_1(1260)$ production  

**Effect in $a_1(1260)$ decay**
- Singularity in *triangle diagram*  
  [Mikhasenko *et al.*, PRD 91 (2015) 094015]
- Similar diagrams proposed to explain some *X, Y, Z states* and *pentaquark candidate* $P_c$ in heavy-meson sector
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $(3\pi)^-$ PWA

- Broad intensity bump
- Similar in both $3\pi$ channels

COMPASS 2008 ($\pi^- p \rightarrow (3\pi)^- p$)

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

$\pi^- \pi^0 \pi^0$, $\pi^- \pi^- \pi^+$ (scaled)

$0.100 < t' < 1.000$ GeV$^2$/c$^2$

(incoherent sum)

Preliminary

$\pi^- \pi^0 \pi^0$

$\pi^- \pi^+ \pi^-$ scaled
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^-\pi^+\pi^-$ PWA

Drastic Change of Mass Spectrum with $t'$

"Low" $t' \approx 0.1 \text{ (GeV}/c)^2$

- $1^+1^+ \rho(770) \pi P$
- $0.100 \leq t' \leq 0.113 \text{ GeV}^2/c^2$

"High" $t' \approx 0.8 \text{ (GeV}/c)^2$

- $1^+1^+ \rho(770) \pi P$
- $0.724 \leq t' \leq 1.000 \text{ GeV}^2/c^2$

- Dominant nonresonant contribution
- Needs to be better understood in order to extract resonance content
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^- \pi^+ \pi^-$ PWA

Model for Nonresonant Component

**Deck effect**

- MC pseudodata generated according to model of Deck amplitude based on [ACCMOR, NPB 182 (1981) 269]
  - see D. Ryabchikov’s contribution for further details

- Analyzed like real data
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^- \pi^+ \pi^-$ PWA

Deck-Model for Nonresonant Component

"Low" $t' \approx 0.1 \text{ (GeV/c)}^2$

```
0.66%  $1^+1^+ \rho(770) \pi P$
0.100 $\leq t' \leq 0.113 \text{ GeV}^2/c^2$
```

**Deck MC** scaled to $t'$-summed intensity

- **Similar** mass spectrum at low $t'$
- **Different** shape at high $t'$

"High" $t' \approx 0.8 \text{ (GeV/c)}^2$

```
0.96%  $1^+1^+ \rho(770) \pi P$
0.724 $\leq t' \leq 1.000 \text{ GeV}^2/c^2$
```
Leptoproduction of $\psi(2S)$ and $X(3872)$ at COMPASS

- **Muon beam** with 160 to 200 GeV/$c$ on $^6$LiD and NH$_3$ targets
- $\psi(2S)$ and $X(3872)$ observed in $J/\psi \pi^+ \pi^-$
- Production = “reversal” of $\psi(2S)$ and $X(3872)$ decays
  - Possible mechanism

- Full muon-beam data set (2003 to 2010)
- 87 exclusive $(J/\psi \pi^+ \pi^-)\pi^\pm$ events
One Last Thing...

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$J/\psi \pi^+ \pi^-$ invariant mass spectrum

$M_{\psi(2S)} = 3680 \pm 8 \text{ MeV}/c^2$

$M_{X(3872)} = 3860 \pm 8 \text{ MeV}/c^2$
Conclusions

World’s largest $\pi^- \pi^+ \pi^-$ data set
- PWA reliably extracts even very small signals

Novel analysis techniques
- PWA in bins of $t'$
  - Better separation of resonant and nonresonant contribution
- Extraction of $\pi \pi$ S-wave amplitude from $\pi^- \pi^+ \pi^-$ system
  - Study dependence on 3$\pi$ source
  - Study rescattering effects

Unexpected new axial-vector signal $a_1(1420)$
- Independently confirmed in $\pi^- \pi^0 \pi^0$
- Nature still unclear; several possible explanations
- COMPASS data will put models to the test

Nonresonant contributions play important role
- First studies using Deck models
- Improved models needed $\implies$ collaboration with JPAC
  - see contributions by A. Szczepaniak, A. Jackura, V. Pauk, and V. Mathieu
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Outlook

Other ongoing analyses

- **Pion diffraction into** $\pi^- \eta^{'(i)}$, $\pi^- \eta \eta$, $\pi^- \pi^0 \omega$, $K\bar{K}\pi$, $K\bar{K}\pi\pi$, ...
- **Kaon diffraction into** $K^- \pi^+ \pi^-$
- **Central-production reactions**
- **$\pi\gamma$ scattering using Primakoff reactions** on heavy targets
- **Leptoproduction of $X(3872)$**
Backup slides
- PWA of diffractively produced $3\pi$ final states
- PWA of diffractively produced $\pi^-\eta$ and $\pi^-\eta'$ final states
PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$: Low $t'$ vs. High $t'$

$2^{++} 1^+ \rho \pi D$
- Peak does not change with $t'$

$1^{++} 0^+ \rho \pi S$
- Peak moves with $t'$
- Strong nonresonant contribution

$\pi^- \pi^0 \pi^0$

$\pi^- \pi^+ \pi^-$ scaled for each plot

COMPASS 2008 ($\pi p \rightarrow (3\pi) p$)

Preliminary
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$\pi^- \pi^0 \pi^0$
$\pi^- \pi^+ \pi^-$ scaled for each plot

COMPASS 2008 ($\pi^- p \rightarrow (3\pi)^- p$)
- $2^+ 1^+ \rho(770) \pi D$
  - $\pi^0 \pi^0$, $\pi^- \pi^+$ (scaled)
  - $0.100 < t' < 0.116 \text{ GeV}^2/c^2$
  - $0.100 < t' < 0.113 \text{ GeV}^2/c^2$

COMPASS 2008 ($\pi^- p \rightarrow (3\pi)^- p$)
- $1^+ 0^+ \rho(770) \pi S$
  - $\pi^0 \pi^0$, $\pi^- \pi^+$ (scaled)
  - $0.100 < t' < 0.116 \text{ GeV}^2/c^2$
  - $0.100 < t' < 0.113 \text{ GeV}^2/c^2$
\[ \pi \pi \ S\text{-Wave Amplitude in } J^{PC} = 0^{-+} \ 3\pi \ Wave \]

- Coupling of \( \pi(1800) \) to \( f_0(980)\pi \) and \( f_0(1500)\pi \) decay modes
Correlation of intensity around $m_{3\pi} = 1.9$ GeV/$c^2$ with $f_0(980)$

$f_0(980)$ semicircle in Argand diagram

Coupling of $\pi_2(1880)$ to $f_0(980)\pi$ decay mode
\[ \pi\pi \quad 2^{-+} [\pi\pi]_{0+} \pi D \]

- Correlation of intensity around \( m_{3\pi} = 1.9 \text{ GeV/}c^2 \) with \( f_0(980) \)
- \( f_0(980) \) semicircle in Argand diagram
- Coupling of \( \pi_2(1880) \) to \( f_0(980)\pi \) decay mode

[arXiv:1509.00992]
Spin-Exotic $J^{PC} = 1^{--}$ Signal in $\pi^- \pi^+ \pi^-$ PWA

Relative Phase w.r.t. $1^{++} 0^+ \rho(770) \pi S$ Wave

$\pi p \rightarrow \pi \pi \pi p$ (COMPASS 2008)

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

\begin{align*}
0.113 \leq t' &\leq 0.128 \text{ GeV}^2/c^2 \\
0.262 \leq t' &\leq 0.326 \text{ GeV}^2/c^2 \\
0.189 \leq t' &\leq 0.220 \text{ GeV}^2/c^2 \\
0.449 \leq t' &\leq 0.724 \text{ GeV}^2/c^2
\end{align*}

- Slow phase 60° motion in 1.6 GeV/c² region independent of $t'$
PWA of $\pi^- p \rightarrow \pi^- \eta^{(1)} p_{\text{recoil}}$

- Odd-spin waves: spin-exotic quantum numbers
  - Disputed $J^{PC} = 1^{-+}$ resonance signals
    - $\pi_1(1400)$ in $\pi\eta$ and $\pi_1(1600)$ in $\pi\eta'$
- Comparison of $\pi\eta$ and $\pi\eta'$: information about flavor structure

Reconstruction from exclusive $\pi^- \pi^+ \pi^- \gamma\gamma$ final state

- $\eta \rightarrow \pi^+ \pi^- \pi^0$ with $\pi^0 \rightarrow \gamma\gamma$
- $\eta' \rightarrow \pi^+ \pi^- \eta$ with $\eta \rightarrow \gamma\gamma$
PWA of $\pi^- p \rightarrow \pi^- \eta^{(')} p_{\text{recoil}}$

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  - Disputed $J^{PC} = 1^{-+}$ resonance signals
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$\pi^- \eta$ invariant mass

![Graph showing $m(\eta\pi^-)$ in GeV/c^2 with entries and acceptance]
PWA of $\pi^- p \rightarrow \pi^- \eta^{(')} p_{\text{recoil}}$

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- $\eta' \rightarrow \pi^+ \pi^- \eta$ with $\eta \rightarrow \gamma\gamma$

---

**$\pi^- \eta$ invariant mass**

```
Entries / 4 MeV/c^2
0 400 800 1200 1600 2000
m(\eta\pi^-) [GeV/c^2]
```

**$\pi^- \eta'$ invariant mass**

```
Entries / 20 MeV/c^2
0 100 200 300 400 500 600
m(\eta'\pi^-) [GeV/c^2]
```
Quark-line picture for \( n = (u, d) \) and pointlike resonances

- \( \pi^- \eta \) and \( \pi^- \eta' \) partial-wave intensities for spin \( J \) related by
  - Different phase space and barrier factors
  - Branching fraction ratio \( b \) of \( \eta \) and \( \eta' \) into \( \pi^- \pi^+ \gamma \gamma \)

\[
N^\pi\eta'(m) \propto b \left[ \frac{q^{\pi\eta'}(m)}{q^{\pi\eta}(m)} \right]^{2J+1} N^\pi\eta(m)
\]

- \( q \) = breakup momentum
Comparison of $J^{PC} = 2^{++}$ Partial Waves

Quark-line picture for $n = (u,d)$ and pointlike resonances

- $\pi^-\eta$ and $\pi^-\eta'$ partial-wave intensities for spin $J$ related by
  - Different phase space and barrier factors
  - Branching fraction ratio $b$ of $\eta$ and $\eta'$ into $\pi^-\pi^+\gamma\gamma$

$$N_J^{\pi\eta'}(m) \propto b \left[ \frac{q^{\pi\eta'}(m)}{q^{\pi\eta}(m)} \right]^{2J+1} N_J^{\pi\eta}(m)$$

- $q = \text{breakup momentum}$

**Graphs**

- $\pi^-\eta$ final state
- $\pi^-\eta'$ final state
Comparison of $J^{PC} = 2^{++}$ Partial Waves

Quark-line picture for $n = (u, d)$ and pointlike resonances

- $\pi^- \eta$ and $\pi^- \eta'$ partial-wave intensities for spin $J$ related by
- Different phase space and barrier factors
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$$N_J^{\pi\eta'}(m) \propto b \left[ \frac{q^{\pi\eta'}(m)}{q^{\pi\eta}(m)} \right]^{2J+1} N_J^{\pi\eta}(m)$$

- $q = \text{breakup momentum}$

\begin{itemize}
  \item $\pi^- \eta$ final state
  \item $\pi^- \eta'$ final state; $\pi^- \eta$ scaled
\end{itemize}
**Even-Spin Waves**

\[ J^{PC} = 4^{++} \]

Phase: \( 4^{++} - 2^{++} \)

- **Similar even-spin waves**
- Intermediate states couple to same final-state flavour content
- **Similar physical content** also in nonresonant high-mass region

\( \pi^- \eta' \) final state; \( \pi^- \eta \) scaled

---

**Graphs:**
- Events / 40 MeV/c² vs. \( m(\eta'\pi^-) \) [GeV/c²]
- Events / 40 MeV/c² vs. \( m(\eta'\pi^-) \) [GeV/c²]
- \( \phi_4 - \phi_2 \) [deg] vs. \( m(\eta'(\pi^-) \) [GeV/c²]
- \( \phi_4 - \phi_2 \) [deg] vs. \( m(\eta'(\pi^-) \) [GeV/c²]
Even-Spin Waves

\[ J^{PC} = 4^{++} \]

\begin{align*}
\mathcal{N}(a_2 \rightarrow \pi\eta') / \mathcal{N}(a_2 \rightarrow \pi\eta) &= (5 \pm 2) \% \\
\mathcal{N}(a_4 \rightarrow \pi\eta') / \mathcal{N}(a_4 \rightarrow \pi\eta) &= (23 \pm 7) \% 
\end{align*}

- Resonance-model fit (Breit-Wigner)
- First-time measurement of \( \pi^-\eta' \) final state; \( \pi^-\eta \) scaled
$J^{PC} = 1^{-+}$ Spin-Exotic Wave

Spin-exotic $J^{PC} = 1^{-+}$

Phase: $1^{-+} - 2^{++}$

- $1^{-+}$ intensities very different
- Suppression in $\pi\eta$ channel predicted for intermediate $|q\bar{q}g\rangle$ state
- Different phase motion in $1.6 \text{ GeV}/c^2$ region

$\pi^-\eta'$ final state; $\pi^-\eta$ scaled
Spin-exotic $J^{PC} = 1^{-+}$

Phase: $1^{-+} - 2^{++}$

- $1^{-+}$ resonance interpretation requires better understanding of
  - $2^{++}$ wave
  - Nonresonant contributions

$\pi^{-} \eta'$ final state; $\pi^{-} \eta$ scaled
Spin-exotic $J^{PC} = 1^{--}$

Phase: $1^{--} - 2^{++}$

Multi-Regge exchange, e.g.

$\pi^-_{\text{beam}}$ $\eta$

$\rho_{\text{target}}$ $a_2$

$\rho_{\text{recoil}}$