Recent Results on Spectroscopy from COMPASS

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Hadron 2015
16. September 2015, Newport News, VA
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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**The COMPASS Experiment at the CERN SPS**

**Experimental Setup**

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Hadron spectroscopy

- 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

2008-09, 2012
The COMPASS Experiment at the CERN SPS

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2008-09, 2012
The COMPASS Experiment at the CERN SPS

Experimental Setup

Spectroscopy program

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

Hadron spectroscopy 2008-09, 2012

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Recent Results on Spectroscopy from COMPASS
1. Introduction
- Meson production in diffractive dissociation
- Partial-wave analysis method

2. PWA of diffractively produced $\pi^-\eta$ and $\pi^-\eta'$ final states

3. 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

4. Conclusions and outlook
Introduction
- Meson production in diffractive dissociation
- Partial-wave analysis method

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Conclusions and outlook
Meson Production in Diffractive Dissociation

- **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
- All final-state particles are measured
Meson Production in Diffractive Dissociation

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

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

Events / (50 MeV)
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Example: $\pi^- \pi^+ \pi^- \text{ final state}$

![Graph showing the distribution of events vs. $t'$](#)
Meson Production in Diffractive Dissociation

- Beam particle gets excited 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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Meson Production in Diffractive Dissociation

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Disentanglement of all contributing $X$ by partial-wave analysis (PWA)
**Ansatz:** Factorization of production and decay

\[
\sigma(\tau; m_X) \propto \sum_{\epsilon = \pm 1} \left| \sum_{i} \text{waves} T^\epsilon_i(m_X) A^\epsilon_i(\tau; m_X) \right|^2
\]

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

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For \( \epsilon = \pm1 \): naturalities of exchange particle
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Partial-Wave Analysis Method

\[ \pi_{\text{beam}} \rightarrow X^- \rightarrow h_1 \rightarrow \cdots \rightarrow h_n \]

\( p_{\text{target}} \rightarrow P \rightarrow p_{\text{recoil}} \)

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Two-stage analysis

\[ \sigma(\tau; m_X) \propto \sum_{\epsilon=\pm 1} \left| \sum_{i}^{\text{waves}} T^\epsilon_i(m_X) A^\epsilon_i(\tau; m_X) \right|^2 \]

1. Determination of \( m_X \) dependence of spin-density matrix
   \[ \varrho^\epsilon_{ij}(m_X) = T^\epsilon_i(m_X) T_j^{\epsilon*}(m_X) \]
   - Independent maximum likelihood fits to \( \tau \) distributions in narrow \( m_X \) bins
   - 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
Partial-Wave Analysis Method

Two-stage analysis

\[ \sigma(\tau; m_X) \propto \sum_{e=\pm 1} \left| \sum_{i}^{\text{waves}} T_i^e(m_X) A_i^e(\tau; m_X) \right|^2 \]

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Outline

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

2 PWA of diffractively produced $\pi^- \eta$ and $\pi^- \eta'$ final states

3 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

4 Conclusions and outlook
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 $\pi^- p \rightarrow \pi^- \eta^{(1)} p_{\text{recoil}}$

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

$\pi^- \eta$ invariant mass

![Graph showing entries versus invariant mass](image-url)
PWA of $\pi^- p \rightarrow \pi^- \eta(\prime) p_{\text{recoil}}$

- Odd-spin waves: spin-exotic quantum numbers
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- $\eta' \rightarrow \pi^+\pi^-\eta$ with $\eta \rightarrow \gamma\gamma$

\[ m(\eta\pi^-) \text{ [GeV}/c^2] \]

\[ m(\eta'\pi^-) \text{ [GeV}/c^2] \]
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 $\pi^-\pi^+\gamma\gamma$

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

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

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### Plots

**$\pi^-\eta$ final state**

- Events / 40 MeV/c² vs $m(\eta\pi^-)$ [GeV/c²]

**$\pi^-\eta'$ final state**

- Events / 40 MeV/c² vs $m(\eta'\pi^-)$ [GeV/c²]
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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\[\text{\large $\pi^{-}\eta$ final state} \quad \text{\large $\pi^{-}\eta'$ final state; $\pi^{-}\eta$ scaled}$
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

\[ \pi^- \eta' \text{ final state; } \pi^- \eta \text{ scaled} \]
Even-Spin Waves

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

- **Resonance-model fit**
  - (Breit-Wigner)
  \[
  \frac{N(a_2 \to \pi\eta')} {N(a_2 \to \pi\eta)} = (5 \pm 2) \%
  \]

- **First-time measurement of**
  \[
  \frac{N(a_4 \to \pi\eta')} {N(a_4 \to \pi\eta)} = (23 \pm 7) \%
  \]

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

Phase: 4^{++} − 2^{++}

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$J^{PC} = 1^{-+}$ 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
$J^{PC} = 1^{-+}$ Spin-Exotic Wave

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

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

$\pi_{\text{beam}}^- \rightarrow \eta \pi^-$

Multi-Regge exchange, e.g.

$\rho_{\text{target}} \rightarrow a_2 \rightarrow P \rightarrow \eta \pi^-$

$\rho_{\text{recoil}}$
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Partial-Wave Analysis: $\pi^- \pi^+ \pi^-$ Final State

$\pi^-_{beam}$

$X^-$

$\pi^-$

$\pi^+$

$\pi^-$

$p_{target}$

$p_{recoil}$

$\pi^-$

$\pi^-$

Strong $\pi^+ \pi^-$ correlations in $X^- \rightarrow \pi^- \pi^+ \pi^-$ decay
Partial-Wave Analysis: $\pi^- \pi^+ \pi^- \pi^-$ Final State

[arXiv:1509.00992]

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

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

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Isobar model

- $X^-$ decays via intermediate $\pi^+ \pi^-$ resonance = "isobar"
  - $[\pi\pi]_S$ \hspace{1cm} $J^{PC} = 0^{++}$
  - $\rho(770)$ \hspace{1cm} $1^{--}$
  - $f_0(980)$ \hspace{1cm} $0^{++}$
  - $f_2(1270)$ \hspace{1cm} $2^{++}$
  - $f_0(1500)$ \hspace{1cm} $0^{++}$
  - $\rho_3(1690)$ \hspace{1cm} $3^{--}$
- PWA requires precise knowledge of isobar $\rightarrow \pi^+ \pi^-$ amplitude
Partial-Wave Analysis: \( \pi^- \pi^+ \pi^- \) Final State

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Entries / (5 MeV/@c^2)
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: $\pi^- \pi^0$
     - $I = 0$ isobars: $\pi^0 \pi^0$

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

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

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**800 < $m_{3\pi}$ < 850 MeV/$c^2***

![Graph 1](image1.png)

**1600 < $m_{3\pi}$ < 1650 MeV/$c^2***

![Graph 2](image2.png)
PWA of $\pi^- p \rightarrow (3\pi)^- p_{\text{recoil}}$

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PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Major Waves

- $\pi^- \pi^+ \pi^-$ invariant mass spectrum
  - $1^{++} 0^+ \rho(770) \pi S$: $a_2(1260)$
  - $2^{++} 1^+ \rho(770) \pi D$: $a_2(1320)$
  - $2^{-+} 0^+ f_2(1270) \pi S$: $\pi_2(1670)$

Events / (5 MeV/c$^2$) vs $m_{3\pi}$ [GeV/c$^2$]
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[arXiv:1509.00992]
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$:

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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

4$^{++}$ 1$^+$ $\rho(770) \pi G$
- $a_4(2040)$

0$^{-+}$ 0$^+$ $f_0(980) \pi S$
- $\pi(1800)$

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

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

- $0.3\%$
- $0.100 < t' < 1.000$ (GeV/$c)^2$

Intensity / (20 MeV/$c^2$) vs $m_{3\pi}$ [GeV/$c^2$]
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{recoil}}$: Selected Small Waves

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

$1^{++} 0^+ f_0(980) \pi P$
- $\pi^- \pi^0 \pi^0, \pi^- \pi^- \pi^+(\text{scaled})$
- $0.100 < t' < 1.000$ GeV/$c^2$
- (incoherent sum)

Preliminary

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Recent Results on Spectroscopy from COMPASS
**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
  - Drastic reduction of model bias
  - **Caveat**: significant increase in number of fit parameters
Is Peak in $1^{++} 0^+ f_0(980) \pi P$ Wave a Model Artifact?

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\[ \pi\pi \; S\text{-Wave Amplitude in} \; J^{PC} = 1^{++} \; 3\pi \text{ Wave} \]

- 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 \textit{not} an artifact of isobar parametrization
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
Correlation of $3\pi$ intensity around $1.4 \text{ GeV}/c^2$ with $f_0(980)$

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

- Correlation of 3\( \pi \) intensity around 1.4 GeV/\( c^2 \) with \( f_0(980) \)
- \( f_0(980) \) semicircle in Argand diagram
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$\pi\pi$ $S$-Wave Amplitude in $J^{PC} = 1^{++} 3\pi$ Wave

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
Coupling of $\pi(1800)$ to $f_0(980)\pi$ and $f_0(1500)\pi$ decay modes

See talk 1E2 by F. Krinner (Thu, 8:55)
Coherent sum of resonant (Breit-Wigner) and nonresonant terms
Coherent sum of resonant (Breit-Wigner) and nonresonant terms
1++ peak consistent with Breit-Wigner resonance


\[ a_1(1420): \]

\[ M_0 = 1414^{+15}_{-13} \text{ MeV}/c^2 \]

\[ \Gamma_0 = 153^{+8}_{-23} \text{ MeV}/c^2 \]
- $1^{++}$ peak consistent with Breit-Wigner resonance
- $a_1(1420)$:
  $M_0 = 1414^{+15}_{-13}$ MeV/$c^2$
  $\Gamma_0 = 153^{+8}_{-23}$ MeV/$c^2$
1$^{++}$ peak consistent with Breit-Wigner resonance

- $a_1(1420)$:
  - $M_0 = 1414^{+15}_{-13}$ MeV/$c^2$
  - $\Gamma_0 = 153^{+8}_{-23}$ MeV/$c^2$
Nature unclear

- No quark-model states expected at 1.4 GeV / c^2
- Ground state a_1(1260) very close and wider
- Seen only in f_0(980)π decay mode
- Isospin partner of narrow f_1(1420)?
-Suspiciously close to K\bar{K}^* threshold
Several proposed explanations

- **Two-quark-tetraquark** mixed state  

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

- Two-channel **unitarized Deck amplitude** + direct \(a_1(1260)\) production  
  
  See talk 1B4 by E. Berger (Mon, 5:30)

- **Singularity** (branching point) in **triangle diagram**  
  
  See talk 5A1 by B. Ketzer (Thu, 8:30)
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  [Mikhasenko et al., PRD 91 (2015) 094015]

  See talk 5A1 by B. Ketzer (Thu, 8:30)
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $(3\pi)^-$ PWA

- Broad intensity bump
- Similar in both channels

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

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

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

Drastic Change of Mass Spectrum with $t'$

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

- Dominant nonresonant contribution
- Needs to be better understood in order to extract resonance content

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

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

$1^+1^+ \rho(770) \pi P$
$0.724 \leq t' \leq 1.000 \text{ GeV}^2/c^2$
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
- Analyzed like real data
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^{-}\pi^{+}\pi^{-}$ PWA

Deck-Model for Nonresonant Component

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

$1^{+}1^{+} \rho(770) \, \pi \, P$

$0.66\%$

$0.100 \leq t' \leq 0.113 \,(\text{GeV}/c)^2$

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

$0.96\%$

$1^{+}1^{+} \rho(770) \, \pi \, P$

$0.724 \leq t' \leq 1.000 \,(\text{GeV}/c)^2$

- Deck MC scaled to $t'$-summed intensity
  - Similar mass spectrum at low $t'$
  - Different shape at high $t'$
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)

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

$0.113 \leq t' \leq 0.128 \text{ GeV}^2/c^2$  
$0.262 \leq t' \leq 0.326 \text{ GeV}^2/c^2$  
$0.189 \leq t' \leq 0.220 \text{ GeV}^2/c^2$  
$0.449 \leq t' \leq 0.724 \text{ GeV}^2/c^2$

- Slow phase 60° motion in 1.6 GeV/$c^2$ region independent of $t'$
1 Introduction
   - Meson production in diffractive dissociation
   - Partial-wave analysis method

2 PWA of diffractively produced $\pi^-$-$\eta$ and $\pi^-$-$\eta'$ final states

3 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

4 Conclusions and outlook
Conclusions and Outlook

Precise data on pion diffraction

- PWA reliably extracts even very small signals
  - New axial-vector state $a_1(1420)$ in $(3\pi^-)$ final states

- Novel analysis schemes:
  - 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
    - Extension to higher $\pi\pi$ waves

Boris Grube, TU München

Recent Results on Spectroscopy from COMPASS
Conclusions and Outlook

Nonresonant contributions play important role

- Limit extraction of resonance parameters
- First studies using Deck models
- Extraction of nonresonant contributions from data
  - Collaboration with JPAC: Veneziano amplitudes + finite-energy sum rules

Other ongoing analyses

- Pion diffraction into $\pi^- \eta \eta$, $\pi^- \pi^0 \omega$, $K \bar{K} \pi$, $K \bar{K} \pi \pi$, ...
- Kaon diffraction into $K^- \pi^+ \pi^-$
- Central-production reactions See talk 1E1 by A. Austregesilo (Thu, 8:30)
- $\pi \gamma$ scattering using Primakoff reactions on heavy targets See talk 6C4 by M. Krämer (Thu, 11:45)
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