The $2\pi$ subsystem in diffractively produced $\pi^-\pi^+\pi^-$ at COMPASS

Fabian Krinner
for the COMPASS collaboration

Physik-Department E18
Technische Universität München

Hadron 2015
Newport News, VA, USA
The COMPASS experiment
COMPASS hadron setup

The 2π subsystem
Sep 17th 2015
**COMPASS:** World’s largest data-set up to now for
\[ \pi^- p \rightarrow \pi^- \pi^+ \pi^- p \]

- **Results of “conventional” PWA**: shown by Boris Grube yesterday
- **Detailed PWA with 88 partial waves**:
  - Reliable extraction of waves contributing less than 1% to the intensity
  - Good agreement with \( \pi^- p \rightarrow \pi^- \pi^0 \pi^0 p \)

![Graph showing events in \( m_{3\pi} \) vs. \( m_{\pi 3m 0.5} \)]

- Events / (5 MeV/c²)
- \( a_1(1260) \)
- \( a_2(1320) \)
- \( \pi_2(1670) \)
COMPASS: World’s largest data-set up to now for \( \pi^- p \rightarrow \pi^- \pi^+ \pi^- p \)

Results of “conventional” PWA shown by Boris Grube yesterday

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

\[ \times 10^6 \]

Events / (5 MeV/c^2)

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\( a_2(1320) \)

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COMPASS: World’s largest data-set up to now for $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

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Detailed PWA with 88 partial waves

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Good agreement with \( \pi^- p \rightarrow \pi^- \pi^0 \pi^0 p \)
3π spectroscopy at COMPASS
Overview over results

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Conventional PWA method

The isobar model

The intermediate state $X^-$ undergoes subsequent two-particle decays.

Narrow bins in $m_{3\pi}$

No assumptions on $X^-$

Fixed amplitudes of the isobars $\xi$

Direct fit of resonance parameters computationally very expensive

How good is the isobar model?

How good are the parametrizations used?

Fabian Krinner (TUM E18)
The intermediate state $X^-$ undergoes subsequent two-particle decays
The intermediate state $X^{-}$ undergoes subsequent two-particle decays.

Narrow bins in $m_{3\pi} \rightarrow$ no assumptions on $X^{-}$.
Conventional PWA method
The isobar model

- The intermediate state $X^-$ undergoes subsequent two-particle decays
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The intermediate state $X^-$ undergoes subsequent two-particle decays

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Fixed amplitudes of the isobars $\xi$

Direct fit of resonance parameters of the isobars computationally very expensive
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Narrow bins in $m_{3\pi}$ → no assumptions on $X^-$

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Conventional PWA method
The isobar model

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Isobar amplitudes in conventional PWA for different $J^{PC}$:
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- $3^{--}$: $\rho_3(1690)$
Novel approach
Steplike isobar amplitudes

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Example: Shape of $0^{++}$ resulting from interference of $f_0(500)$ and $f_0(980)$
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Fit of isobar resonance parameters not practical $\rightarrow$ “binned isobars”

Extract binned amplitudes

Example: Shape of $0^{++}$ resulting from interference of $f_0(500)$ and $f_0(980)$
Total intensity in conventional PWA

\[ I(m_{3\pi}, m_{\pi^+\pi^-}, \tau) = \left| \sum \text{waves} T_i(m_{3\pi}) \psi_i(\tau) \Delta_i(m_{\pi^+\pi^-}) \right|^2 \]

Production amplitudes \( T_i(m_{3\pi}) \), angular distributions \( \psi(\tau) \) and isobar amplitudes \( \Delta_i(m_{\pi^+\pi^-}) \) (e.g. Breit-Wigner)
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Production amplitudes \( T_i(m_{3\pi}) \), angular distributions \( \psi(\tau) \) and isobar amplitudes \( \Delta_i(m_{\pi^+\pi^-}) \) (e.g. Breit-Wigner)

Replace fixed isobar amplitudes by bins:

\[ \Delta_i(m_{\pi^+\pi^-}) \rightarrow \sum_{\text{bins}} \Delta_{i}^{\text{bin}}(m_{\pi^+\pi^-}) = [\pi\pi]_{JPC} \]

\[ \Delta_{i}^{\text{bin}}(m_{\pi^+\pi^-}) = \begin{cases} 
1, & \text{if } m_{\pi^+\pi^-} \text{ in corresponding bin.} \\
0, & \text{otherwise.} 
\end{cases} \]
Freed isobar fit
Formulation

Total intensity in conventional PWA

\[ I(m_{3\pi}, m_{\pi^+\pi^-}, \tau) = \left| \sum_{i}^{\text{waves}} T_i(m_{3\pi}) \psi_i(\tau) \Delta_i(m_{\pi^+\pi^-}) \right|^2 \]

Production amplitudes \( T_i(m_{3\pi}) \), angular distributions \( \psi(\tau) \) and isobar amplitudes \( \Delta_i(m_{\pi^+\pi^-}) \) (e.g. Breit-Wigner)

- Replace fixed isobar amplitudes by bins:
  \[ \Delta_i(m_{\pi^+\pi^-}) \rightarrow \sum_{\text{bins}} \Delta^\text{bin}_i(m_{\pi^+\pi^-}) = [\pi\pi]_{J^P_C} \]
  \[ \Delta^\text{bin}_i(m_{\pi^+\pi^-}) = \begin{cases} 1, & \text{if } m_{\pi^+\pi^-} \text{ in corresponding bin.} \\ 0, & \text{otherwise.} \end{cases} \]

- Step-like functions behave like independent Partial Waves:
  \[ I = \left| \sum_{i}^{\text{waves}} \sum_{\text{bins}} T^\text{bin}_i(m_{3\pi}) \psi_i(\tau) \Delta^\text{bin}_i(m_{\pi^+\pi^-}) \right|^2 \]
Two dimensional results

- Conventional analysis: Binned in $m_{3\pi}$: $T(m_{3\pi})$

- Now: Two-dimensional binning: $T(m_{3\pi}, m_{\pi^+\pi^-})$

$\rightarrow$ Two-dimensional picture

- Here: Three waves with freed isobars:
  - $0^{-+} 0^{++} [\pi\pi]_{0^{++}} \pi S$
  - $1^{++} 0^{++} [\pi\pi]_{0^{++}} \pi P$
  - $2^{-+} 0^{++} [\pi\pi]_{0^{++}} \pi D$

- All other waves still with fixed isobar amplitudes

- In principle also possible for $1^{--}$, $2^{++}$, ... isobars
Two-dimensional intensities for waves with freed isobars

MASS OF THE $\pi^-\pi^+\pi^-$ SYSTEM

These plots should not be mistaken as Dalitz plots
Two-dimensional intensities for waves with freed isobars

These plots should not be mistaken as Dalitz plots
Two-dimensional results

Results

Two-dimensional intensities for waves with freed isobars

\[ 0^{-+}0^{+} \pi \pi ]_{0^{++}} \pi \ S \]

\[ 1^{++}0^{+} \pi \pi ]_{0^{++}} \pi \ P \]

MASS OF THE \( \pi^{-}\pi^{+}\pi^{-} \) SYSTEM

These plots should not be mistaken as Dalitz plots
Two-dimensional intensities for waves with freed isobars

These plots should not be mistaken as Dalitz plots
Different regions of the four-momentum transfer $t'$

$0^{-+}0^+ [\pi\pi]_{0^{++}} \pi S$

$0.10 < t' < 0.14 \text{ (GeV/c)}^2$

$0^{-+}0^+ [\pi\pi]_{0^{++}} \pi S$

$0.19 < t' < 0.32 \text{ (GeV/c)}^2$

The $2\pi$ subsystem
The 0−+0+[ππ]0++ π S subsystem

0.19 < t' < 0.32 (GeV/c)²
1.66 < m_3π < 1.70 GeV/c²

0.19 < t' < 0.32 (GeV/c)²
1.78 < m_3π < 1.82 GeV/c²

0.19 < t' < 0.32 (GeV/c)²
1.90 < m_3π < 1.94 GeV/c²

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The 2π subsystem

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Sum up all bins in $m_{\pi^+\pi^-}$
Comparison with conventional analysis

- Sum up all bins in $m_{\pi^+\pi^-}$
- Compare with sum of conventional $0^- f_0$ and $0^- \sigma$ waves
Sum up all bins in $m_{\pi^+\pi^-}$

Compare with sum of conventional $0^{-+} f_0$ and $0^{-+} \sigma$ waves

Compatible shapes
Comparison with conventional analysis

- Sum up all bins in $m_{\pi^+\pi^-}$
- Compare with sum of conventional $0^{-+} f_0$ and $0^{-+} \sigma$ waves
- Compatible shapes
- $\pi(1800)$ peak visible
Comparison with conventional analysis

- Sum up all bins in $m_{\pi^+ \pi^-}$
- Compare with sum of conventional $0^{-+} f_0$ and $0^{-+} \sigma$ waves
- Compatible shapes
- $\pi(1800)$ peak visible
- Novel method reproduces shape in $m_{3\pi}$
Different regions of the four-momentum transfer $t'$

$0.10 < t' < 0.14 \, (GeV/c)^2$

$0.19 < t' < 0.32 \, (GeV/c)^2$

$1^{++}0^+ [\pi\pi]_{0^{++}} \pi P$

$1^{++}0^+ [\pi\pi]_{0^{++}} \pi P$

$0.100 < t' < 0.141 \, (GeV/c)^2$

$0.194 < t' < 0.326 \, (GeV/c)^2$
Slices at constant $m_{3\pi}$

1.26 < $m_{3\pi}$ < 1.28 GeV/c²
1.40 < $m_{3\pi}$ < 1.42 GeV/c²
1.54 < $m_{3\pi}$ < 1.56 GeV/c²

High $t' = 0.19 - 0.32$ (GeV/c)²
Sum all bins in $m_{\pi^+\pi^-}$
Comparison with conventional analysis

- Sum all bins in $m_{\pi^+\pi^-}$
- Compare with sum of corresponding waves in conventional PWA
Sum all bins in $m_{\pi^+\pi^-}$

Compare with sum of corresponding waves in conventional PWA

Shapes are compatible
Comparison with conventional analysis

- Sum all bins in $m_{\pi^+\pi^-}$
- Compare with sum of corresponding waves in conventional PWA
- Shapes are compatible
- New resonance, $a_1(1420)$, visible as peak
Different regions of the four-momentum transfer $t'$

$$0.10 < t' < 0.14 \text{ (GeV/c)}^2$$
$$2^{-+} 0^+ \left[ \pi\pi \right]_{0^{++}} \pi D$$

$$0.19 < t' < 0.32 \text{ (GeV/c)}^2$$
$$2^{-+} 0^+ \left[ \pi\pi \right]_{0^{++}} \pi D$$

Origin of broad structures not clear at the moment
(Shadows of fixed-shape waves?)
**Conclusions**

- Isobar amplitudes are replaced by sets of step-like functions $[^{\pi\pi}]_{JPC}$

- Novel method allows to extract the amplitudes of isobars

![Graph showing intensity vs. mass of the $\pi\pi$ system]
Conclusions

- Isobar amplitudes are replaced by sets of step-like functions $[\pi \pi]_{JPC}$
- Novel method allows to extract the amplitudes of isobars
- Study resonance production in three dimensions: $m_{3\pi}$, $m_{\pi^+\pi^-}$ and $t'$

![Plot showing resonance production in three dimensions]
Conclusions

- Isobar amplitudes are replaced by sets of step-like functions $[\pi\pi]_{J^P}$.
- Novel method allows to extract the amplitudes of isobars.
- Study resonance production in three dimensions: $m_{3\pi}$, $m_{\pi^+\pi^-}$ and $t'$.
- Known waves and decay modes reproduced, especially the new $a_1(1420) \rightarrow f_0(980)\pi^-$.

![Graph showing the distribution of $m_{\pi^+\pi^-}$ vs. $m_{3\pi}$ with $t'$ Contour Lines at 0.194 < $t'$ < 0.326 (GeV/c$^2$).]
Conclusions

- Isobar amplitudes are replaced by sets of step-like functions $[\pi\pi]_{J^P}$
- Novel method allows to extract the amplitudes of isobars
- Study resonance production in three dimensions: $m_{3\pi}$, $m_{\pi^+\pi^-}$ and $t'$
- Known waves and decay modes reproduced, especially the new $a_1(1420) \rightarrow f_0(980)\pi^-$
- $t'$ dependent, broad structures at small $m_{3\pi}$, $m_{\pi^+\pi^-}$
  → Possible non-resonant processes
Outlook

- Reduce effects from imperfect parameterizations in other waves
  → Free isobar-amplitudes for all large waves
Outlook

- Reduce effects from imperfect parameterizations in other waves
  \[ 0^{-+} 0^{+} f_0(980)_{\pi S} \]
  \[ 0^{-+} 0^{+} \rho(770)_{\pi P} \]
  \[ 1^{++} 0^{+} f_0(980)_{\pi P} \]
  \[ 1^{++} 0^{+} \rho(770)_{\pi S} \]
  \[ 1^{++} 1^{+} \rho(770)_{\pi S} \]
  \[ 2^{--} 0^{+} f_0(980)_{\pi D} \]
  \[ 2^{--} 0^{+} \rho(770)_{\pi P} \]
  \[ 2^{--} 0^{+} \rho(770)_{\pi F} \]
  \[ 2^{--} 0^{+} \rho(770)_{\pi P} \]
  \[ 2^{--} 1^{+} f_2(1270)_{\pi S} \]
  \[ 2^{++} 1^{+} \rho(770)_{\pi S} \]

- Free isobar-amplitudes for all large waves

- Goal at the moment: Free 11 waves

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Outlook

- Reduce effects from imperfect parameterizations in other waves
  - Free isobar-amplitudes for all large waves

- Goal at the moment: Free 11 waves
  - 75% of the total intensity
  - All waves above 1% of the intensity

\[
\begin{align*}
0^{-+} & \ 0^{+} f_0(980) \pi S \\
0^{-+} & \ 0^{+} \rho(770) \pi P \\
1^{++} & \ 0^{+} f_0(980) \pi P \\
1^{++} & \ 0^{+} \rho(770) \pi S \\
1^{++} & \ 1^{+} \rho(770) \pi S \\
2^{-+} & \ 0^{+} f_0(980) \pi D \\
2^{-+} & \ 0^{+} \rho(770) \pi P \\
2^{-+} & \ 0^{+} \rho(770) \pi F \\
2^{-+} & \ 0^{+} \rho(770) \pi P \\
2^{-+} & \ 1^{+} f_2(1270) \pi S \\
2^{++} & \ 1^{+} \rho(770) \pi S
\end{align*}
\]
Outlook

- Reduce effects from imperfect parameterizations in other waves
  → Free isobar-amplitudes for all large waves

- Goal at the moment: Free 11 waves
  ▶ 75% of the total intensity
  ▶ All waves above 1% of the intensity

- Some challenges:
  ▶ Freeing isobars heavily increases the number of parameters
  ▶ Some problems with non-orthogonality of Partial Waves

\[
\begin{align*}
0^{-+} & 0^{+} f_0(980)_{\pi} S \\
0^{-+} & 0^{+} \rho(770)_{\pi} P \\
1^{++} & 0^{+} f_0(980)_{\pi} P \\
1^{++} & 0^{+} \rho(770)_{\pi} S \\
1^{++} & 1^{+} \rho(770)_{\pi} S \\
2^{-+} & 0^{+} f_0(980)_{\pi} D \\
2^{-+} & 0^{+} \rho(770)_{\pi} P \\
2^{-+} & 0^{+} \rho(770)_{\pi} F \\
2^{-+} & 0^{+} \rho(770)_{\pi} P \\
2^{-+} & 1^{+} f_2(1270)_{\pi} S \\
2^{++} & 1^{+} \rho(770)_{\pi} S
\end{align*}
\]