Diffractively Produced 3-Pion States at COMPASS

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The COMPASS Experiment

Diffractive dissociation
- Isovector states: $\pi_J, a_J$
- Hybrids, exotics
- Scalar states
  ⇒ F. Krinner, 1E2, Sep 17, 08:55

Photoproduction
- Polarizabilities: $\pi$
- Spectroscopy
  ⇒ M. Krämer, 6C4, Sep 17, 11:45

Central production:
- Scalar states
- Glueballs
  ⇒ A. Austregesilo, 1E1, Sep 17, 08:30

B. Grube, Plenary talk, Sep 16, 12:20
Plan of the Talk

Introduction: diffractive production and PWA at COMPASS

Challenges for the analysis

- axial-vector states
- spin-exotics

New approaches

- fit in bins of mass and squared 4-momentum transfer
- Deck-like non-resonant production
- include amplitudes for dynamic processes, e.g. triangle diagram
- use analytic amplitudes which satisfy unitarity

Conclusions and Outlook
$3\pi$ Final State - Kinematics

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

$1.60 < m_{3\pi} < 1.65 \text{ GeV/c}^2$

[C. Adolph et al., arXiv1509.00992]
$3\pi$ Final State - Kinematics

[C. Adolph et al., arXiv1509.00992]
Partial Wave Analysis

1. **PWA** of angular distributions in **mass bins** and **t’ bins**: 100 × 11 bins

\[
I(\tau) = \left| \sum_{\xi} T_{\xi} A_{\xi}(\tau) \right|^2
\]

- \( T_{\xi} \) = production amplitude for state with \( \chi = I^G (J^{PC}) M \) decaying to \( \zeta \)
- \( A_{\xi}(\tau) \) = decay amplitude (calculable without free parameters)
- Result: spin-density matrix \( \rho_{\xi\xi'} = T_{\xi} T_{\xi'}^* \)

**Assumptions:**
- Production and decay of a state factorize
- Decay into multi-particle final state can be described by a sequence of 2-body decays

**Isobars used in present analyses:**

\[ [\pi\pi]_S, \rho(770), f_0(980), f_2(1270), f_0(1500), \rho_3(1690) \]
2. **$\chi^2$-Fit of mass- and t-dependence** of spin-density matrix

- Determine resonance parameters
- Only subset of spin-density matrix is considered for computational reasons
- Production amplitude for wave $\xi$: $k$ components

$$T_\xi = \sum_k C_\xi_k(t') D_k(m_{3\pi}, t'; \theta_k)$$

- **resonant terms:**
  $$D_k(m_{3\pi}; M_0, \Gamma_0) = \frac{M_0 \Gamma(m_{3\pi})}{M_0^2 - m_{3\pi}^2 - iM_0 \Gamma(m_{3\pi})}$$

- **non-resonant terms:**
  $$D_k(m_{3\pi}, t'; c_i) = \left[ \frac{m_{3\pi} - m_{thr}}{m_{thr}} \right]^{c_0} e^{-\left(c_1 + c_2 t' + c_3 t'^2\right)q^2}$$

- **fit parameters:** complex couplings $C_{\xi_k}(t')$, parameters of dynamic functions $\theta_k$
The $\pi_1(1600)$
$\pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb}$

- Resonance-like signal observed
- Large contribution of non-resonant background
- Need to understand origin for a reliable fit of spin-density matrix of high-statistics $H_2$ data

$\chi_{c1} \rightarrow \eta' \pi^- \pi^+$

$\pi^- p \rightarrow \eta' \pi^- p$


[C. Adolph et al., PLB 740, 303 (2015)]

Deck Effect

Resonant production

\[ \pi \xrightarrow{\alpha_1} \rho \]

- Generate pure Deck-like events

\[ \psi(M_{\pi\pi}, t_{\pi\pi}, t) = \frac{A_{\pi\pi}(M_{\pi\pi}, t_{\pi\pi}) A_{\pi p}(s_{\pi p}, t)}{m_{\pi}^2 - t_{\pi\pi}} \]


- Pass through Monte Carlo & PWA

- Normalize intensity to data for each wave and sum over \( t' \)

- Benchmark on waves w/o resonances, test on exotic wave

Non-resonant production

\[ \pi \xrightarrow{R} \pi \]

\[ \pi \xrightarrow{R} \pi \]

B. Ketzer - 3\( \pi \) analysis
Data vs Deck

6⁻⁺ \rightarrow 4⁻⁺

\[ t' \]

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Data

Deck
Data vs Deck

Low values of $t'$:
- Mostly non-resonant production
- Good description by Deck model

High values of $t'$:
- Deck background disappears
- Resonant component increasing
- Dominates highest $t'$ - bin
Phase of $1^{-+}$ Wave

- Clear phase variation
- Phase motion about 60°
- Independent of $t'$

⇒ Bgr model qualitatively ok
⇒ need to include non-isobaric waves in mass-independent fit
The $a_1(1420)$
New $a_1 - 1^{++} 0^+ f_0(980)\pi P$

[Yu. Khokhlov, PoS Hadron 088 (2014)]

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

[E.B. Berdnikov et al., Nuovo Cim. 107, 1941 (1994)]
• Data described well by Breit-Wigner and non-resonant background

• Parameters for BW:

\[ M_0 = 1414^{+15}_{-13} \text{ MeV/c} \]
\[ \Gamma_0 = 153^{+8}_{-23} \text{ MeV/c} \]

[C. Adolph et al., COMPASS, PRL 115, 082001 (2015)]
Systematic study:

- New $a_1(1420)$ couples exclusively to $f_0(980)$
- Influence of isobar parameterization? Ambiguities? Artefact?

Goal:

- Determine dynamics of isobars with $J_{iso}^{PC} = 0^{++}$ from data
- Obtain model-independent isobar amplitude

Method:

- Replace fixed parameterization of $J_{iso}^{PC} = 0^{++}$ 2-body amplitude (e.g. AMP for $(\pi\pi)_S$ wave or Flatté/BW for $f_0(980)/f_0(1500)$) by set of free (complex) parameters in 2-body mass bins with $\delta m=40$ MeV (10 MeV around 980 MeV)
- No separation into several $J_{iso}^{PC} = 0^{++}$ isobars
- Amplitude for $J_{iso}^{PC} = 0^{++}$ isobars determined from data for three $J_{3\pi}^{PC} = 0^{--}, 1^{++}, 2^{--}$
- Combined phase information: $\phi_{tot} = \phi_{prod} + \phi_{decay}$
Correlation $m_{3\pi}$ vs $m_{2\pi}$

0$^{-+}$

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

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

Low $t'$

$0.5 \leq m_{3\pi} \leq 2.5$

$0.5 \leq m_{\pi\pi} \leq 1.5$

$1^{++}$

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

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

High $t'$

$0.5 \leq m_{3\pi} \leq 2.5$

$0.5 \leq m_{\pi\pi} \leq 1.5$

$2^{-+}$

$2^{+0+} \, [\pi\pi]_{0^{++}} \, \pi D$

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

$0.326 < t' < 1.000 \, (\text{GeV}/c)^2$

$0.5 \leq m_{3\pi} \leq 2.5$

$0.5 \leq m_{\pi\pi} \leq 1.5$

B. Ketzer - 3π analysis
Maybe, because it has all features of a resonance:

- narrow peak in intensity
- sharp phase motion
- well described by Breit-Wigner + Bgr

Issues to be clarified:

- too close in mass to $a_1(1260)$
- fits neither to radial excitation trajectory nor to angular momentum trajectory
- width narrower than ground state
- strange coincidence of mass to $K^*(892)\bar{K}$ threshold $\approx 1.38$ GeV/$c^2$

Interpretations

- $K^*K$ molecule (similar to $X(3872)$ interpretation)
- Interference of Deck $\rho\pi$ $S$ and $f_0\pi$ $P$-wave [J.-L. Basdevant et al., PRL 114, 192001 (2015)]

> $a_1(1260)$ splits into two peaks
> phase motion $120^\circ$, but too low in mass
> could be modified by including $K\bar{K}^*$ channel?
Interpretations

- $K^*K$ molecule (similar to $X(3872)$ interpretation)
- Interference of Deck $\rho\pi S$ and $f_0\pi P$-wave [J.-L. Basdevant et al., PRL 114, 192001 (2015)]
- Triangle singularity [M. Mikhasenko, BK, A. Sarantsev, PRD 91, 094015 (2015)]

- Decay of $a_1(1260) \to K^*\bar{K}$ above threshold
- Final state rescattering of $K\bar{K}$ to $f_0(980)$
  ⇒ logarithmic singularity of amplitude if particles close to mass shell
Feynman rules for hadronic processes:

• Scalar case

\[
M_{a_1 \to f_0 \pi}^{(sc)} = g^3 \int \frac{d^4 k_1}{(2\pi)^4 i} \frac{1}{\left( m_1^2 - k_1^2 - i\epsilon \right) \left( m_2^2 - (p_0 - k_1)^2 - i\epsilon \right) \left( m_3^2 - (k_1 - p_1)^2 - i\epsilon \right)}
\]

• VPP case: numerator carries spin structure

Scalar vs VPP

+ finite width of \( K^* \)
Corrections to Vertices

- Finite width of $K^*$
- Suppression of P-wave tail due to $K^* \to K\pi$ decay
  - Blatt-Weisskopf barrier factors
  - Exponential correction factors for finite meson-size
  - Introduce left-hand singularity in the amplitude

$$F(k_1) = \frac{M^2 - m_{K^*}^2}{M^2 - k_1^2}, \quad M^2 = (m_\pi + m_K)^2 - \frac{4}{R^2}$$
Consider full process:

- Diffractive production of resonant $a_1(1260)$
- Direct decay to $\rho \pi$
- Decay to $f_0 \pi$ only via triangle diagram

Ratio 1:100
Fit to Data

- Preliminary!
- No fit in t’ bins yet
- Not a COMPASS result

- Use published spin density matrix for 3 waves (1 t’ bin)
- compare fit with BW and triangle amplitude in $1^{++} f_0 \pi P$ wave
• Preliminary!
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• compare fit with BW and triangle amplitude in $1^{++} f_0 \pi P$ wave
Phase

- Phase motion of pure triangle diagram is only $\sim 90^\circ$
- How can a Deck-like background produce a phase motion close to $180^\circ$?
New Fit Model for $3\pi$ Data

- Work in collaboration with Indiana-JLAB JPAC (A. Szczepaniak, A. Jackura, M. Mikhasenko)

- **Goal:** Improve mass-dependent analysis of diffractive data by constructing general amplitude which satisfies
  - unitarity and analyticity
  - reduces model dependence (shape of background, resonances)
  - allows to extract pole positions in complex energy plane

**Method:**

- construct amplitude $T$ satisfying unitarity $T^+ - T^- = i\rho T^+ T^-$ and Hermitian analyticity $T^- = T^{+*}$
- Ansatz: $T(s) = N/D$, with RHC given by $D$ and LHC given by $N$
- model $N(s)$ as polynomial in conformal variable $\omega$
- determine $D(s)$ from dispersion relation
- full amplitude is $A(s) = \alpha(s) T(s)$, where $\alpha(s)$ is constructed similarly to $N$
Test of method on simple BW

- Generate data BW amplitude with $m_0 = 1.26 \text{ GeV}$, $\Gamma_0 = 0.1 \text{ GeV}$
- Fit with general unitary amplitude model
- Extract poles (= zeros of $D$) $\Rightarrow m = 1.256 \text{ GeV}$, $\Gamma = 0.097 \text{ GeV}$

$\Rightarrow$ Work on $1^{++}$ and $2^{-+}$ waves ongoing
Conclusions

COMPASS: world’s largest data set on $3\pi$ final state
- small signals detectable with sufficient significance for the first time
- statistical uncertainties very small, systematic model uncertainties become dominant

2D-PWA in bins of $m_X$ and $t'$ helps to separate resonance production and background processes

Freed-isobar technique instead of fixed parameterization for $[\pi\pi]_S$ wave

Background model qualitatively validated by projection of Deck events onto partial-wave set

Fit of triangle amplitude to $a_1(1420)$ describes data equally well when background is added
Ongoing work:

- Extend freed-isobar technique to other isobars
- Include non-isobaric amplitudes in mass-independent fit, avoid double counting (in coll. with JPAC, e.g. V. Mathieu for $\eta\pi, \eta'\pi$)
- Fit triangle amplitude to all $t'$ bins
- First attempts to extract pole positions from amplitudes which satisfy unitarity and analyticity (in coll. with JPAC)