Diffractive resonance production in the reaction

$$\pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p$$

at 190 GeV/c from COMPASS

Mathias Wagner
for the COMPASS-Collaboration

at the 86th DPG Spring Meeting - HK 29.3

22nd March 2023
The Reaction

\[ \pi^- + p \rightarrow X^- + p_{\text{recoil}} \rightarrow K_S^0 K_S^0 \pi^- + p_{\text{recoil}} \]

- \(a_J\) and \(\pi_J\) mesons are accessible
- \(K_J^*\) and \(f_J\) mesons are accessible as isobars (two-body resonances)
- Threshold at \(m_X \geq 1.135\, \text{GeV}/c^2\)
  \Rightarrow \text{easier access to higher radial excitations}
Diffractive Scattering at COMPASS

- **Common Muon Proton Apparatus for Structure and Spectroscopy**
- Fixed-target experiment at the SPS-CERN
- Spectroscopy via secondary hadron beam, mostly $\pi^-$ ($\sim 97\%$) of 190 GeV/c
- Liquid-hydrogen target (40 cm)

[COMPASS, NIM A 779 (2015), pp. 69-115]
Motivation for $K_S^0 K_S^0 \pi^-$ Final State

- Decay channels to (neutral) kaons not yet well established
- Complementary to $\pi^- \pi^+ \pi^-$ final state
- Rescattering effect $a_1(1420)$ should be present in $f_0(980)\pi^-$ decay channel
  [COMPASS, PRL 127 (2021), p. 082501]
- Spin-exotic $\pi_1(1600)$ hybrid candidate accessible
- Extraction of branching fraction ratios between $X^- \rightarrow K_J^{*-} K_S^0$ and $X^- \rightarrow f_J \pi^-$ possible within same data set
Event Selection
**$K^0_S$ Selection**

- Main decay channel: 
  $K^0_S \rightarrow \pi^+ + \pi^-$ (69%)

- Require minimal decay-vertex separation from primary vertex

- Require invariant mass within 
  $\sim 15\text{ MeV}/c^2$ of nominal $K^0_S$ mass

- Resolution of $\sim 5\text{ MeV}/c^2$

- Employ kinematic fit to correct for it
Exclusivity & 4-Momentum Conservation

- Use measured recoil proton track for check of exclusivity
- Reconstruct beam energy from final state

![Diagram of the reaction $\pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p$](image)

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Diffractive resonance production in $\pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p$
Results

of

\sim 240\,000\ exclusive\ events
Resonance Spectrum

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Diffractive resonance production in $\pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p$
Dalitz Plot around 1.67 GeV/$c^2$

Dalitz plot is filled with both $K^0_S\pi^-$ combinations.
**Dalitz Plot around 1.67 GeV/c^2**

Possible signals: $a_1(1640) \rightarrow K^{*-} K_S^0$ and $\pi_2(1670) \rightarrow f_2\pi^-$

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Diffractive resonance production in $\pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p$
**Dalitz Plot around 1.81 GeV/c^2**

Possible signal: \( \pi(1800) \rightarrow f_0\pi^- \)

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Diffractive resonance production in \( \pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p \)
Rescattering Effect $a_1(1420)$

- $a_1(1420)$ signal found at COMPASS in $\pi^-\pi^+\pi^-$ final state at 1.41 GeV/$c^2$
- Can be explained via rescattering effect
  [COMPASS, PRL 127 (2021), p. 082501]
- Should also appear in $K^0_S K^0_S \pi^-$

But: Close to threshold $m_{K^0_S K^0_S \pi^-} \geq 1.135$ GeV/$c^2$
Dalitz Plot around 1.41 GeV/c^2

- Overlap of $K^*(892)$ and $f_0(980)$ band
- Need PWA to separate contributions

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Diffractive resonance production in $\pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p$
Summary and Outlook
Summary:

- ~ 240,000 exclusive $K^0_S K^0_S \pi^-$ events
- Rich but densely populated resonance spectrum $\Rightarrow$ need PWA
- Clear hints for $a_1(1640)$ and $\pi(1800)$
- Good intensity at the $a_1(1420)$ and $\pi_1(1600)$ locations

Outlook:

- Partial-wave analysis
- Resonance model fit to extract resonance parameters
Thanks for your attention!
Backup
- ~ 240 000 exclusive $K_S^0 K_S^0 \pi^-$ events selected

- ~ 240× E580 experiment via diffractive scattering at Fermilab

- ~ 42× Crystal Barrel experiment in $\bar{p}n$ annihilations at LEAR

- ~ 9× BaBar experiment via $\tau^-$ decays ($m_{K_S^0 K_S^0 \pi^-} < 1.75 \text{ GeV}/c^2$)
  [J. P. Lees et al., PRD 86 (2012), p. 092013]
$a_1(1420)$ as a Rescattering Effect

[COMPASS, PRL 127 (2021), p. 082501]
Primary Vertex Distributions

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RICH detector to veto on $K$ and $p$
**Particle Identification**

- RICH detector to veto on $K$ and $p$

![Diagram](image)

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16/11
Λ AND \bar{Λ} Contamination

Assuming (anti)proton and pion mass for outgoing tracks from SV
Four-Momentum Transfer

\[ t' := |t| - |t|_{\text{min}} \]

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$K_S^0$ Properties

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Diffractive resonance production in $\pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p$
Kinematic Fit

- Special case of constrained fitting
  [F. James, Statistical Methods in Experimental Physics]

- Constraint $F(y) = (p_1 + p_2)^2 - m_{K_S}^2 = 0$
  with $y = \left( \frac{p_{1x}}{|p_1|}, \frac{p_{1y}}{|p_1|}, E_1, \frac{p_{2x}}{|p_2|}, \frac{p_{2y}}{|p_2|}, E_2 \right)$

- Minimize $\chi^2 := \epsilon^T C^{-1} \epsilon$ with $F(y + \epsilon) = 0$
  with covariance matrix $C$

- Failure rate < 0.02 %
No $\rho_J$ Isobars

The decay $\rho_J \to K_S^0 K_S^0$ demands $M = 0$ since both $K_S^0$ are scalars. Bose-symmetry demands symmetrized wave function $|p_1, p_2\rangle + |p_2, p_1\rangle$. Partial-wave expansion of theses wave functions yields:

\[
|p_1, p_2\rangle = \sum_J \sqrt{2J + 1} D_{0,0}^J(\phi_1, \theta_1, 0)|J, 0\rangle
\]

\[
|p_2, p_1\rangle = \sum_J \sqrt{2J + 1} D_{0,0}^J(\phi_2, \theta_2, 0)|J, 0\rangle
\]

Now we use $\theta_2 = \pi - \theta_1$ and $\phi_2 = \phi_1 + \pi$ as well as $d_{0,0}^J(\pi - \theta) = (-1)^J d_{0,0}^J(\theta)$:

\[
D_{0,0}^J(\phi_2, \theta_2, 0) = d_{M,0}^J(\theta_2) = d_{0,0}^J(\pi - \theta_1)
\]

\[
= (-1)^J d_{0,0}^J(\theta_1)
\]

Therefore we obtain for the symmetrized wave function

\[
\frac{1}{\sqrt{2}} \left( |p_1, p_2\rangle + |p_2, p_1\rangle \right) = \frac{1}{\sqrt{2}} \sum_J \sqrt{2J + 1} d_{0,0}^J(\theta_1)|J, 0\rangle
\]

\[
0 \text{ for odd } J
\]
**Isobar Spectra**

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Diffractive resonance production in $\pi^- + p \rightarrow K_{S}^0 K_{S}^0 \pi^- + p$
## Resonance Decay Modes

<table>
<thead>
<tr>
<th>$X \to \xi b$</th>
<th>$f_0\pi^-, K^*_0 K_S^0$</th>
<th>$K^*- K_S^0$</th>
<th>$f_2\pi^-, K^*_2 K_S^0$</th>
<th>$K^*_3 K_S^0$</th>
<th>$f_4\pi^-, K^*_4 K_S^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>$P$</td>
<td>$S, D$</td>
<td>$P, F$</td>
<td>$D, G$</td>
<td>$F$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>--</td>
<td>$D$</td>
<td>$P, F$</td>
<td>$D, G$</td>
<td>$F$</td>
</tr>
<tr>
<td>$a_3$</td>
<td>$F$</td>
<td>$D, G$</td>
<td>$P, F$</td>
<td>$S, D, G$</td>
<td>$P, F$</td>
</tr>
<tr>
<td>$a_4$</td>
<td>--</td>
<td>$G$</td>
<td>$F$</td>
<td>$D, G$</td>
<td>$P, F$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>$S$</td>
<td>$P$</td>
<td>$D$</td>
<td>$F$</td>
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<tr>
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<tr>
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<td>$F$</td>
<td>$D, G$</td>
<td>$P, F$</td>
<td>$S, D, G$</td>
</tr>
</tbody>
</table>
**Dalitz Plot around \( a_4(1970) \)**

![Dalitz Plot Image]

**Dominant decay:** \( a_1(1930) \rightarrow K^{*-}K^0 \)

\( a_4 \rightarrow f_2\pi^- \) or \( a_4 \rightarrow K^{*-}K^0 \) only via \( F \)-wave

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GOTTFRIED-JACkSON FRAME

PRELIMINARY

\[ m_{K_S^0 K_S^0} \ [\text{GeV}/c^2] \]

\[ \cos(\theta_{c.m.}) \]

\[ \text{Entries} / (50 \text{MeV}/c^2 \times 0.05) \]

PRELIMINARY

\[ m_{K_S^0 K_S^0} \ [\text{GeV}/c^2] \]

\[ \phi_{TV} \ [\text{deg}] \]

\[ \text{Entries} / (50 \text{MeV}/c^2 \times 10 \text{deg}) \]

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Diffractive resonance production in \( \pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p \)
Isobar Mass vs. Resonance Mass

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Diffractive resonance production in $\pi^- + p \rightarrow K_S^0 K_S^0 \pi^- + p$