Strange-Meson Spectroscopy at COMPASS

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Strange-Meson Spectroscopy

![Strange-Meson Spectroscopy Diagram](image)

**PDG** (2019)

- PDG lists 25 strange mesons
- 13 established states, 12 need further confirmation
- Missing states with respect to quark-model prediction
**Diffractive Production**

- Diffractive production in $K^- p$ scattering
- Strange mesons appear as intermediate states $X^-$
- Observed in decays into quasi-stable particles: $K^- \pi^- \pi^+$ final state
  - Access to all $K$ and $K^*$ states
M2 beam line

- Located at CERN (SPS)
- 190 GeV/c secondary hadron beams
  - $h^-$ beams: 97% $\pi^-$, 2.4% $K^-$, 0.8% $\bar{p}$
COMPASS Setup for Hadron Beams

COMPASS setup

- $\ell H_2$ target
- Two-stage magnetic spectrometer
- Beam and final-state particle ID
- Electromagnetic and hadronic calorimeters
- Rich spectrum of overlapping and interfering $X^-$
  - Dominant well known states
  - States with lower intensity are “hidden”
- Largest data set of diffractively produced $K^-\pi^-\pi^+$
  - $\approx 720,000$ exclusive events
Rich spectrum of overlapping and interfering $X^-$

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Kinematic Distributions

Also structure in $\pi^-\pi^+$ and $K^-\pi^+$ subsystems

- Successive 2-body decay via $\pi^-\pi^+ / K^-\pi^+$ resonance called isobar
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Also structure in $\pi^-\pi^+$ and $K^-\pi^+$ subsystems

Successive 2-body decay via $\pi^-\pi^+ / K^-\pi^+$ resonance called isobar
Partial wave \( a = J^P M^\circ \xi^0 b^- L \) at fixed invariant mass of \( K^-\pi^-\pi^+ \) system

- Calculate 5D decay phase-space distribution of final state
- \( \Psi(\tau) \) describes distribution of wave \( a \) in decay phase-space variables \( \tau \)
- Total intensity distribution: Coherent sum of partial-wave amplitudes

\[
I(\tau) = \left| \sum_a T_a(\xi) \Psi_a(\tau) \right|^2
\]

- Perform maximum-likelihood fit in cells of \( (m_{K\pi\pi}, t') \)
- Extract \( m_{K\pi\pi} \) and \( t' \) dependence of transition amplitudes
Partial wave $a = J^P M^\varepsilon \, \xi^0 \, b^- \, L$ at fixed invariant mass of $K^- \pi^- \pi^+$ system

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- Perform maximum-likelihood fit in cells of $(m_{K\pi\pi}, t')$

- Extract $m_{K\pi\pi}$ and $t'$ dependence of transition amplitudes $T_a$
Partial-wave decomposition

Isobar Model

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- $\Psi(\tau)$ describes distribution of wave $a$ in decay phase-space variables $\tau$

- Total intensity distribution: Coherent sum of partial-wave amplitudes

$$I(\tau) = \left| \sum_a \mathcal{T}_a \Psi_a(\tau) \right|^2$$

- Perform maximum-likelihood fit in cells of $(m_{K\pi\pi}, t')$

- Extract $m_{K\pi\pi}$ and $t'$ dependence of transition amplitudes $\mathcal{T}_a$
Partial-Wave Decomposition
Wave-Set Selection

**Systematically construct set of allowed partial waves**

- Spin $J \leq 7$
- Angular momentum $L \leq 7$
- Positive naturality of exchange particle
- 12 isobars
  - $[K\pi]_{S}^{K\pi}, [K\pi]_{S}^{K\eta}, K^*(892), K^*(1680), K_2^*(1430), K_3^*(1780)$
  - $[\pi\pi]_{S}, f_0(980), f_0(1500), \rho(770), f_2(1270), \rho_3(1690)$

⇒ “Wave pool” of 596 waves

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**Regularization**
(see talk by F. Kaspar, session 5)

- Fit wave pool to data
- Impose penalty on $|T_a|^2$
- Suppress insignificant waves

⇒ Find the “best” subset of waves that describe the data
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  - $[\pi\pi]_S$, $f_0(980)$, $f_0(1500)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$

⇒ “Wave pool” of 596 waves

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- Fit wave pool to data
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⇒ Find the “best” subset of waves that describe the data
Selected Partial Waves

\[ J^P = 1^+ \]

**1^+ 0^+ K^*(892) \pi S**

- Dominant signal
- \( K_1(1270), K_1(1400) \) double peak
- In agreement with previous observations

**1^+ 0^+ \rho(770) K S**

- 3.4% of total intensity
- Dominated by \( K_1(1270) \)
- Small potential signal from \( K_1(1650) \)
- Structure in relative phase

![Graph](attachment:graph.png)

- \( 0.10 \leq t' < 1.00 \) (GeV/c)^2
- 30.8% affected by leakage

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Selected Partial Waves

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WA03 (CERN), 200 000 events, ACCMOR, NPB 187 (1981)
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Selected Partial Waves

$J^P = 2^+$

$2^+ 1^+ K^*(892) \pi D$

- Signal in $K_2^*(1430)$ mass region
- In agreement with previous observations

$2^+ 1^+ \rho(770) K D$

- Signal in $K_2^*(1430)$ mass region
- Clear phase motion in $K_2^*(1430)$ region
Selected Partial Waves

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### Selected Partial Waves

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- Clear phase motion in $K_2^*(1430)$ region

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**Graph:**

- $2^+ 1^+ \rho^0(770) K D$
- $0.10 \leq t' < 1.00 \text{ (GeV/c)}^2$
- $0.5 \%$

**Plot Parameters:**

- **$m_{K\pi\pi}$ [GeV/c$^2$]**
- **Intensities (×10^5)**

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*Preliminary*
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- Signal in $K_2^*(1430)$ mass region
- Clear phase motion in $K_2^*(1430)$ region

\[ [2^+ 1^+ \rho^0(770) K D] - [1^+ 0^+ \bar{K}^*(892) \pi S] \leq 0.24 \text{ (GeV/c)^2} \]
Selected Partial Waves

\( J^P = 4^+ \)

\[4^+ 1^+ K^*(892) \pi G\]

- Small intensity
- Signal in \( K_4^*(2045) \) mass region
Selected Partial Waves

$J^P = 2^-$

2$^{-} 0^+ \bar{K}_2^*(1430) \pi S$

- Strongest 2$^-$ wave
- Two resonances in signal region
  - $K_2(1770)$, $K_2(1820)$
- Bump in high-mass shoulder
  - Potential $K_2(2250)$

2$^{-} 0^+ \rho(770) K F / 2^{-} 0^+ K^*(892) \pi F$

- Small intensity
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Selected Partial Waves

\( J^P = 2^- \)

\( 2^- 0^+ K^*_2(1430) \pi S \)
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WA03 (CERN), 200 000 events, ACCMOR, NPB 187 (1981)
Selected Partial Waves

$J^P = 2^-$

$2^{-0^+} K_2^*(1430) \pi S$

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**Selected Partial Waves**

\[ J^P = 2^- \]

### \( 2^− 0^+ K_2^*(1430) \pi S \)
- Strongest \( 2^- \) wave
- Two resonances in signal region
  - \( K_2(1770), K_2(1820) \)
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### \( 2^− 0^+ \rho(770) K F / 2^− 0^+ K^*(892) \pi F \)
- Small intensity
- Bump in high-mass shoulder
- Phase motion in signal region
Leakage Effect

- Unexpected low-mass enhancement in $3^+ 1^+ K^*(892) \pi D$ wave
- Similar to dominant $1^+$ wave
- Sensitive to systematic effects
- Loss of orthogonality taking acceptance into account
- Limited acceptance due to limited kinematic range of final-state PID
- Only a small sub-set of partial waves affected

![Graph showing intensity vs. mass](image)

\[ m_{K\pi\pi} \, [GeV/c^2] \]

Intensity / (1.0 GeV/c^2) $\times 10^6$

$3^+ 1^+ K^*(892) \pi D$

0.10 $\leq t' < 1.00$ (GeV/c)$^2$

4.3% Affected by leakage

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Uninformed low-mass enhancement in $3^+ 1^+ K^*(892) \pi D$ wave

Similar to dominant $1^+$ wave

Sensitive to systematic effects

Loss of orthogonality taking acceptance into account

Limited acceptance due to limited kinematic range of final-state PID

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\[
\begin{align*}
0.10 \leq t' &< 1.00 \text{ (GeV/c)}^2 \\
4.3\% &\
\end{align*}
\]
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Summary

- Worlds largest data set of diffractively produced $K^-\pi^-\pi^+$
- Observation of well-known states
- Observation of signals at 0.1% level
- Potential signals from excited states

Outlook

- Further systematic studies of leakage effect
- Resonance-model fit of selected partial waves
- Freed-isobar analysis (see talk by F. Krinner, session 5)
  - Study amplitude of $[K\pi]_P$, $[K\pi]_S$, ... sub-systems
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Spectroscopy of strange mesons

- Radio-frequency separated high-intensity high-energy kaon beam
- At least $\times 10$ larger data set than world’s largest data set
- Map out strange-meson spectrum with similar precision as unflavored light-meson spectrum
- Proposal for phase-1: CERN-SPSC-2019-022
Backup
Outline

10 Wave-Set Selection

11 Palano-Pennington Parameterization for \([K\pi]_S\) Isobars

12 \(m_{K^-\pi^-}\)

13 \(t'\) Spectrum

14 Exclusivity

15 Leakage Effect
20 to 70 waves per \((m_{K\pi\pi}, t')\) cell

- Larger wave set for larger binning in \(m_{K\pi\pi}\)
- Larger wave set in \(t'\) bins with more events
Wave-Set Selection

Regularization

\[ \ln \mathcal{L}_{\text{fit}} = \ln \mathcal{L}_{\text{extended}} + \ln \mathcal{L}_{\text{reg}} \]

\[ \ln \mathcal{L}_{\text{reg}}(|T_a|; \Gamma) = - \ln \left[ 1 + \frac{|T_a|^2}{\Gamma_a^2} \right] \]

- “Cauchy prior”
- Scale depends on acceptance

\[ \Gamma_a = \frac{\Gamma}{\sqrt{\eta_a}} \Rightarrow \frac{|T_a|^2}{\Gamma_a^2} = \frac{\tilde{N}_a}{\Gamma^2} \]
Wave-Set Selection

Regularization

\[ \ln L_{\text{fit}} = \ln L_{\text{extended}} + \ln L_{\text{reg}} \]

\[ \ln L_{\text{reg}}(|T_a|; \Gamma) = -\ln \left[ 1 + \frac{|T_a|^2}{\Gamma_a^2} \right] \]

- “Cauchy prior”
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\[ \Gamma_a = \frac{\Gamma}{\sqrt{\eta_a}} \Rightarrow |T_a|^2 = \frac{\tilde{N}_a}{\Gamma^2} \]
Palano-Pennington Parameterization for $[K\pi]_S$ Isobars

- Two-channel $K$-matrix ansatz: $K\pi$ and $K\eta$
- $K\pi$ scattering (LASS, SLAC), $\eta_c$ decays, $\chi$-PT
- Contains three poles
  - $K_0^*(700)$, $K_0^*(1430)$, $K_0^*(1950)$
- Use $T_{K\pi \rightarrow K\pi}$ and $T_{K\eta \rightarrow K\pi}$
  - $K\pi$ dominated by $K_0^*(1430)$
  - $K\eta$ dominated by $K_0^*(1950)$
- Unphysical extrapolation above 2.4 GeV/$c^2$
- Set amplitude to zero

$K\pi \rightarrow K\pi$

\[
|\Delta \xi|^2 \text{[a.u.]} \quad m_{K-\pi^+} \text{[GeV/c}^2]\]

\[
\text{Re}[\Delta \xi] \text{[a.u.]} \quad \text{Im}[\Delta \xi] \text{[a.u.]} \quad \text{Re}[\Delta \xi] \text{[a.u.]} \quad \text{Im}[\Delta \xi] \text{[a.u.]} \]

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Palano-Pennington Parameterization for \([K\pi]_S\) Isobars

- **Two-channel** \(K\)-matrix ansatz: \(K\pi\) and \(K\eta\)
- \(K\pi\) scattering (LASS, SLAC), \(\eta_c\) decays, \(\chi\)-PT
- Contains three poles
  - \(K_0^*(700), K_0^*(1430), K_0^*(1950)\)

\[K\eta \rightarrow K\pi\]

Use \(T_{K\pi \rightarrow K\pi}\) and \(T_{K\eta \rightarrow K\pi}\)
- \(K\pi\) dominated by \(K_0^*(1430)\)
- \(K\eta\) dominated by \(K_0^*(1950)\)
- Unphysical extrapolation above 2.4 GeV/\(c^2\)
- Set amplitude to zero
No dominant resonant structures
"t' Spectrum"

- Exponential shape
- Shallower for larger \( t' \)

![Graph showing the \( t' \) spectrum with exponential shape and shallower for larger \( t' \).]
Exclusivity

**$E_{\text{beam}}$ (GeV)**

- 0.0
- 0.5
- 1.0
- 1.5

Events / (0.1 GeV) $\times 10^4$

**$\Delta\phi_{\text{recoil}}$ (deg)**

- 0.00
- 0.25
- 0.50
- 0.75

Events / (0.11 deg) $\times 10^4$

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Exclusivity

Exclusivity

Events / (0.1 GeV) $\times 10^4$

$E_{\text{beam}}$ [GeV]

$\Delta\phi_{\text{recoil}}$ [deg]

$E_{\text{beam}}$ [GeV]

Preliminary
Leakage Effect

- Unexpected low-mass enhancement in $3^+ 1^+ K^*(892) \pi D$ wave
- Similar to dominant $1^+$ wave
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\[ \bar{I}_{a,b} = \int d\varphi_3(\tau) \eta(\tau) \Psi_a(\tau)\Psi^*_b(\tau) \]

Preliminary 0.00 0.07 0.14
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