Strange-Meson Spectroscopy with COMPASS

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Max Planck Institute for Physics

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Understanding the light-meson spectrum

- Completing $SU(3)_{\text{flavor}}$ multiplets
- Identifying supernumerous states
  - Search for exotic strange mesons

Input to other fields of physics

- Strange mesons appear as resonances in multi-body hadronic final states with kaons
- Searches for CP violation
- Searches for physics beyond SM
Understanding the light-meson spectrum

- Completing $SU(3)_{\text{flavor}}$ multiplets
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Input to other fields of physics

- Strange mesons appear as resonances in multi-body hadronic final states with kaons
- Searches for CP violation
- Searches for physics beyond SM
PDG lists 25 strange mesons

- 16 established states, 9 need further confirmation
- Missing states with respect to quark-model predictions
- Many measurements performed more than 30 years ago
CEDARs
* beam PID

30 m

H$_2$ Target
RPD

Beam
* 191 GeV
* 2.4 % K$^-$

RICH
* final-state PID
Strange-Meson Spectroscopy with COMPASS

Production of Strange Mesons

Diffractive scattering of high-energy kaon beam

Strange mesons appear as intermediate resonances $X^-$

Decay to multi-body hadronic final states

$K^−\pi^−\pi^+$ final state

- Study in principle all strange mesons
- Study a wide mass range
- Study different decay modes
Strange-Meson Spectroscopy with COMPASS

Production of Strange Mesons

- Diffractive scattering of high-energy kaon beam
- Strange mesons appear as intermediate resonances $X^-$
- Decay to multi-body hadronic final states
- $K^- \pi^- \pi^+$ final state
  - Study in principle all strange mesons
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  - Study different decay modes
Strange-Meson Spectroscopy with COMPASS

The $K^-\pi^-\pi^+$ Data Sample

- World's largest data set of about 720 k events
- Rich spectrum of overlapping and interfering $X^-$
  - Dominant well known states
  - States with lower intensity are "hidden"
Partial Wave Analysis of the $K^-\pi^-\pi^+$ Final State

Partial wave: $J^P M^\varepsilon \xi b^- L$

- $J^P$ spin and parity
- $M^\varepsilon$ spin projection
- $\xi$ isobar resonance
- $b^-$ bachelor particle
- $L$ orbital angular momentum
Partial-Wave Analysis of the $K^−\pi^−\pi^+$ Final State

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Data: 720 k diffractively produced $K^-\pi^-\pi^+$ candidates
Partial-Wave Analysis of the $K^-\pi^-\pi^+$ Final State

**Data:** 720 k diffractively produced $K^-\pi^-\pi^+$ candidates

(I) **Partial-Wave Decomposition**
- Performed independently in narrow $(m_{K\pi\pi}, t')$ cells
- No assumption about $K\pi\pi$ resonances

**Partial waves:** Intensities and relative phases as a function of $(m_{K\pi\pi}, t')$
Partial-Wave Analysis of the $K^\pm\pi^-\pi^+$ Final State

Data: 720 k diffractively produced $K^\pm\pi^-\pi^+$ candidates

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**Partial waves:** Intensities and relative phases as a function of $(m_{K\pi\pi}, t')$

(II) Resonance-Model Fit
- Model $m_{K\pi\pi}$ dependence of partial waves
- $K\pi\pi$ resonances and background

**Resonance parameters:** Masses and widths of the strange-meson resonances
Partial-Wave Analysis of the $K^-\pi^-\pi^+$ Final State

\[ 1^+ 0^+ \rho(770) K S \]

\[ 0.10 \leq t' < 1.00 \text{ (GeV/c)}^2 \]

Intensity [(GeV/c)^2]^{-1}

$\rho(770)$ in the $K^-\pi^-\pi^+$ final state.
Partial-Wave Analysis of the $K^-\pi^-\pi^+$ Final State

- Partial-wave amplitudes in $(m_{K\pi\pi}, t')$ bins
  - Inferred wave set from data using regularization-based model-selection techniques
  - Bootstrap resampling to improve uncertainty estimates
  - Detailed Monte Carlo input-output studies
- Model $m_{K\pi\pi}$ dependence of partial-wave amplitudes
- Breit-Wigner amplitudes for $K^-\pi^-\pi^+$ resonance components
- Coherent non-resonant component parameterizing other $K^-\pi^-\pi^+$ production mechanisms
- Developed scheme to handle incoherent backgrounds
  - Incoherent background from $\pi^-\pi^-$ diffraction to $\pi^-\pi^-\pi^+$ explicitly modeled by COMPASS $\pi^-\pi^-\pi^+$ analysis
  - Incoherent effective background component parameterizing other background processes

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COMPASS

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S. Wallner Strange-Meson Spectroscopy with COMPASS
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$\times 10^6 \quad 1^{+0+} \rho(770) KS$

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

COMPASS
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$1^{+0+} \rho(770) KS$

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

S. Wallner Strange-Meson Spectroscopy with COMPASS

Preliminary
Partial-Wave Analysis of the $K^-\pi^-\pi^+$ Final State

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Intensities $[(\text{GeV/c}^2)^{-1}]$

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

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Strange-Meson Spectroscopy with COMPASS
8 / 19
Simultaneously included 14 partial waves in resonance-model fit
Modeled by 13 strange-meson resonance components
Using measured intensities and interference terms (relative phases)
Partial-Wave Analysis of the $K^\pi^\pi^+$ Final State

Simultaneously included 14 partial waves in resonance-model fit

Modeled by 13 strange-meson resonance components

Using measured intensities and interference terms (relative phases)
Partial-Wave Analysis of the $K^-(\pi^-\pi^+)$ Final State

- Simultaneously included 14 partial waves in resonance-model fit
- Modeled by 13 strange-meson resonance components
- Using measured intensities and interference terms (relative phases)

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Partial Waves with $J^P = 2^+$

$K_2^*(1430)$ well known resonance
Partial Waves with $J^P = 2^+$

- $K_2^*(1430)$ signal
  - $m_0 = (1430.9 \pm 1.4^{+3.1}_{-1.5})$ MeV/$c^2$
  - $\Gamma_0 = (111 \pm 3^{+4}_{-16})$ MeV/$c^2$

- In different decays
  - $\rho(770) K D$
  - $K^*(892) \pi D$

- In agreement with previous measurements
- Cleaner signal in COMPASS data
Partial Waves with $J^P = 2^+$

$\pi^- K^- \pi^+ K^*$ (892)

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  - $\rho(770)$ $K D$
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Established $K_2(1770)$ and $K_2(1820)$

$K_2(2250)$ need further confirmation
Partial Waves with $J^P = 2^-$

- Simultaneously fit 4 waves with $J^P = 2^-$
- 1.8 GeV/$c^2$ peak modeled by $K_2(1770)$, $K_2(1820)$
- High-mass shoulder modeled by $K_2(2250)$
- Different intensity spectra and large phase motions among $2^-$ waves

**Diagram**: Graphs showing the fit of different waves with peaks and phase shifts.

**Legend**:
- $2^-0^+ K_2^*(1430)\pi S$
- $2^-0^+ f_2(1270)KS$
- $1^+0^+ \rho(770)KS$
- $m_{K\pi\pi}$ [GeV/$c^2$]

**Parameters**:
- $0.15 \leq t' < 0.24$ (GeV/$c^2$)
- Total model
- Resonance components
- Non-resonant component
- $\pi^-\pi^+\pi^+$ background
- Effective background

**Graphs**:
- (a) $2^-0^+ K_2^*(1430)\pi S$
- (b) $2^-0^+ f_2(1270)KS$
- (c) $1^+0^+ \rho(770)KS$
- (d) $2^-0^+ f_2(1270)KS$
- (e) $2^-0^+ f_2(1270)KS$
- (f) $2^-0^+ f_2(1270)KS$
Simultaneously fit 4 waves with $J^P = 2^-$

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Partial Waves with $J^P = 2^-$

$K_2(1770)$ and $K_2(1820)$

- Two states were considered by only three measurements ACCMOR, LASS, LHCb
- Only LHCb measurement could confirm two states (3 $\sigma$ statistical significance)
- We observe two states with 11 $\sigma$ statistical significance
Partial Waves with $J^P = 2^-$

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- Only LHCb measurement could confirm two states ($3\sigma$ statistical significance)
- We observe two states with $11\sigma$ statistical significance
Partial Waves with $J^P = 2^-$

$K_2(2250)$

- Studied so far mainly in $(\bar{\Lambda}\bar{p})$ final states
- First simultaneous measurement of $K_2(1770)$, $K_2(1820)$, and $K_2(2250)$
- Resonance parameters consistent with previous observations

$K_2(1770)$
$K_2(1820)$
$K_2(2250)$

COMPASS
PDG average
Prev. exp.
Searching for Exotic Strange Mesons with $J^P = 0^-$

- $K(1460)$ and $K(1830)$
- $K(1630)$
  - Unexpectedly small width of only 16 MeV/$c^2$
  - $J^P$ of $K(1630)$ unclear
Searching for Exotic Strange Mesons with $J^P = 0^-$

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Searching for Exotic Strange Mesons with $J^P = 0^-$

COMPASS $K^-\pi^-\pi^+$ data

- Peak at about 1.4 GeV/$c^2$
  - Established $K(1460)$
  - But, $m_{K\pi\pi} \lesssim 1.5$ GeV/$c^2$ region affected by known analysis artifacts
- Second peak at about 1.7 GeV/$c^2$
  - $K(1630)$ signal with 8.3 $\sigma$ statistical significance
  - Accompanied by rising phase
- Weak signal at about 2.0 GeV/$c^2$
  - $K(1830)$ signal with 5.4 $\sigma$ statistical significance

**Figure:**
- **Label:** $0^+\rho(770)KP$
- **Legend:**
  - $0.10 \leq t' < 0.15$ (GeV/$c^2$)
  - **Axes:**
    - $m_{K\pi\pi}$ [GeV/$c^2$]
    - Intensity [(GeV/$c^2$)$^{-1}$] $\times 10^5$
  - **Data Points:**
    - Black dots

*Label: total resonance model, resonances, non-resonant, $\pi\pi\pi$ background, effective background*
Searching for Exotic Strange Mesons with $J^P = 0^-$

COMPASS $K^- \pi^- \pi^+$ data

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**Intensity (GeV/$c^2$)$^{-1} \times 10^5$**

$0^-0^+ \rho(770) K P$

$0.10 \leq t' < 0.15 (GeV/c)^2$

COMPASS Preliminary

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total resonance model, resonances, non-resonant, $\pi \pi \pi$ background, effective background
Searching for Exotic Strange Mesons with $J^P = 0^-$

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![Graph showing $\Delta \phi_{ab}$ vs. $m_{K\pi\pi}$]
Searching for Exotic Strange Mesons with $J^P = 0^-$

**COMPASS $K^-\pi^-\pi^+$ data**

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  - Established $K(1460)$
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**Graph:**
- Intensity $[\text{GeV}/c^2]^{-1}$
- $0^{-+} \rho(770) KP$
- $0.10 \leq t' < 0.15$ (GeV/$c)^2$

**Legend:**
- Total resonance model, resonances, non-resonant, $\pi\pi\pi$ background, effective background

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Searching for Exotic Strange Mesons with $J^P = 0^-$

- $K(1830)$ parameters in good agreement with LCHb measurement [PRL 118 (2017) 022003]
- Expected $K(1630)$ width of about 140 MeV/$c^2$
Searching for Exotic Strange Mesons with $J^P = 0^-$

- Indications for 3 excited $K$ from a single analysis
- Quark-model predicts only two excited states: potentially $K(1460)$ and $K(1830)$
  - $K(1630)$ supernumerary signal
  - Candidate for exotic non-$q\bar{q}$ state; other explanations possible ($K^*(892)\omega$ threshold nearby)

$\bar{K}(1630)$ supernumerary signal is consistent with a candidate for exotic non-$q\bar{q}$ state. Other explanations are possible ($K^*(892)\omega$ threshold nearby).
Searching for Exotic Strange Mesons with $J^P = 0^-$

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### The Strange-Meson Spectrum

- Many strange mesons require further confirmation
- Search for strange partners of exotic non-strange light mesons

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**Mass [GeV/c^2]**

<table>
<thead>
<tr>
<th>State</th>
<th>Mass [GeV/c^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>0.50</td>
</tr>
<tr>
<td>K_0^*</td>
<td>1.00</td>
</tr>
<tr>
<td>K^*</td>
<td>1.50</td>
</tr>
<tr>
<td>K_1</td>
<td>2.00</td>
</tr>
<tr>
<td>K_2</td>
<td>2.50</td>
</tr>
<tr>
<td>K_2^*</td>
<td>3.00</td>
</tr>
<tr>
<td>K_3</td>
<td>3.50</td>
</tr>
<tr>
<td>K_3^*</td>
<td>4.00</td>
</tr>
<tr>
<td>K_4</td>
<td>4.50</td>
</tr>
<tr>
<td>K_4^*</td>
<td>5.00</td>
</tr>
</tbody>
</table>

**Labeling**

- Established
- Not Established
- Quark Model

*Source:* Ebert et al., PRD 79 (2009) 114029
World’s largest data sample on $K^+\pi^-\pi^+$ ⇒ Most detailed and comprehensive analysis

Candidate for exotic strange-meson signal with $J^P = 0^-$
Summary

- World’s largest data sample on $K^-\pi^-\pi^+$ ⇒ Most detailed and comprehensive analysis
- Candidate for exotic strange-meson signal with $J^P = 0^-$
AMBER: Proposal for High-Precision Strange-Meson Spectroscopy [O. Denisov, Friday 14:00]

- Goal: Collect $10 - 20 \times 10^6 K^- \pi^- \pi^+$ events using high-intensity and high-energy kaon beam
- AMBER is open for interested collaborators to join
Summary

COMPASS

- World’s largest data sample on $K^-\pi^-\pi^+ \Rightarrow$ Most detailed and comprehensive analysis
- Candidate for exotic strange-meson signal with $J^P = 0^-$

Mass [GeV/c^2]

COMPASS
Established
Not Established
Quark Model

[Ebert et al., PRD 79 (2009) 114029]