Introduction to Kaon Spectroscopy

Known States

PDG (2016)

- PDG lists 28 strange mesons
- Well known kaon states, e.g. $K^*(892)$, $K_1(1270)$, $K_1(1400)$, $K_2(1770)$
- States that require further confirmation, e.g. $K_2(1580)$, $K_2^*(1980)$, ...

![Diagram of kaon spectroscopy]

PDG confirmed
PDG un-confirmed
Model (IG)
Introduction to Kaon Spectroscopy

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**Appear in heavy-meson decays**
- Kaonic resonances appear as intermediate states in heavy meson decays $B, D \rightarrow$ light mesons
  - Used in studies of CP violation
- Resonance parameters often required as input for these analysis
  - Isobar model

**Measured in diffractive production**
- Access to all kaonic states
- Decaying into many final states
- Large mass range accessible
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## Introduction to Kaon Spectroscopy

### Previous Measurements

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### Further measurements

- $\tau$ decay (e.g. CLEO)
- Heavy meson decays, e.g. $J/\pi$, $\chi_{cJ}$, or $B$
**Introduction to Kaon Spectroscopy**

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Introduction to Kaon Spectroscopy

Previous Measurements

**ACCMOR measurements**
- CERN SPS WA03 experiment
- $K^- + p \rightarrow K^- \pi^- \pi^+ + p_{\text{recoil}}$
- 200 000 events
- 63 GeV/c $K^-$ beam

**LASS measurements**
- LASS spectrometer at SLAC
- 34 000 $K^- p \rightarrow \bar{K}^0 \pi^+ \pi^- n$ events
- 100 000 $K^- p \rightarrow K^- \omega p$ events
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Further measurements
- $\tau$ decay (e.g. CLEO)
- Heavy meson decays, e.g. $J/\pi$, $\chi_{cJ}$, or $B$
M2 beam line

- Located at the SPS (CERN)
- \(190 \text{ GeV}/c\) secondary hadron beams
  - \(h^-\) beams: 97 \% \(\pi^-\), 2 \% \(K^-\), 1 \% \(\bar{p}\)
  - \(h^+\) beams: 75 \% \(p\), 24 \% \(\pi^+\), 1 \% \(K^+\)
**Target**

- Various targets:
  - Ni
  - Pb
  - W
  - $\ell H_2$
COMPASS spectrometer

- Two-stage magnetic spectrometer
  - Large acceptance
  - Broad kinematic range
- Electromagnetic and hadronic calorimeters
- Beam and final-state particle ID
Diffractive production of \( X^- \) with strangeness

- Requires final-state PID via RICH
  - Distinguish between \( \pi^- \) and \( K^- \) over a wide momentum range
- Requires beam-particle PID via CEDARs
  - approximately \( \times 30 \) more \( \pi^- \) than \( K^- \) in the beam
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Event Sample

- 2008 data taking
- 270,000 exclusive $K^-\pi^-\pi^+$ events
  - $0.07 < t' < 0.7$ (GeV/c)$^2$
  - DT0 trigger
- Good exclusivity

![Graph showing the distribution of events with respect to energy. The graph is labeled as COMPASS 2008 negative hadron beam $K^-\rightarrow K^-\pi^+\pi^-$ and indicates that the recoil $p^-\pi^+\pi^-$ is not acceptance corrected. The x-axis represents the energy (GeV) and the y-axis represents the number of events.]
COMPASS Kaon Spectroscopy Results
Kinematic Distributions

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

- Graph showing kinematic distributions for $K^-\pi^-\pi^+$ reactions.
- Highlighted states: $\rho(770)$, $f_0(980)$, $f_2(1270)$, not acceptance corrected.

COMPASS: $\pi^-\pi^-\pi^+$

- Graph showing kinematic distributions for $\pi^-\pi^-\pi^+$ reactions.
- Highlighted states: $\rho(770)$, $f_0(980)$, $f_2(1270)$, $\rho_3(1690)$.

$\pi^-\pi^+$ and $K^-\pi^+$ subsystem

- $\pi^-\pi^+$ subsystem: Known states from $\pi^-\pi^-\pi^+$
- $K^-\pi^+$ subsystem
  - Clear $K^*(892)$ and $K_2^*(1430)$
  - Broad spectrum from $\kappa$ state: Needs further measurements
COMPASS: $K^-\pi^-\pi^+$

COMPASS 2008 negative hadron beam $K^- p \rightarrow K^- \pi^+ \pi^- p_{\text{recoil}}$ not acceptance corrected

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Belle: $B^0 \rightarrow J/\psi K^+\pi^-$  [PhysRevD. 83 (2011)]
COMPASS: $K^-\pi^-\pi^+$

- $K_1(1270)$, $K_1(1400)$, and $K_2(1770)$ signal
- Sitting on a broad spectrum

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Partial wave analysis necessary
COMPASS Kaon Spectroscopy Results
Partial Wave Analysis

Wave Set
- 19 partial waves
- 6 different isobars \([\sigma, \rho(770), f_2(1270), \kappa, K^*(892), K^*_2(1430)]\)
- Improved isobar shape w.r.t. ACCMOR analysis
- No low-\(t'\) region \(t' < 0.07 \text{ GeV}/c^2\)
COMPASS: $K^-\pi^-\pi^+$

- Clear $K_1(1270)$ and $K_1(1400)$ signals
- Clear $K^*_2(1430)$ signal
- Indications for $K^*_2(1980)$ reported by LASS. Needs further confirmation
- $K_2(1770)$ and $K_2(1820)$ signal
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Data Set

- Improved initial-state PID \( \Rightarrow \) expect 2x more events
- Analyzing a second data set \( \Rightarrow \) expect 1.8x more events

\[ \Rightarrow 1 \times 10^6 \text{ events of } K^- + p \to K^- \pi^- \pi^+ + p_{\text{recoil}} \]

Partial wave analysis

- Improved wave set \( \Rightarrow \) Clearer resonance signals
- Resonance-model fits \( \Rightarrow \) Extract resonance parameters of \( K^- \pi^- \pi^+ \) resonances

Further channels with kaonic resonances

- \( K^- \pi^0 \pi^0 \)
- \( K^- K^- K^+ \)
- \( K^- \omega \)
- ...
Data Set

- Improved initial-state PID ⇒ expect 2x more events
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⇒ $1 \times 10^6$ events of $K^- + p \rightarrow K^-\pi^-\pi^+ + p_{\text{recoil}}$

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Further channels with kaonic resonances

- $K^0\pi^0$
- $K^-K^-K^+$
- $K^-\omega$
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COMPASS Kaon Spectroscopy Results
Further Projects with Existing Data
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**COMPASS Kaon Spectroscopy Results**

**Further Projects with Existing Data**
Why more data is needed

- More precise fit results
  - Establish open strangeness spectrum at the same level as for light quarks
  - Access to new states?
- Access to advanced / novel analysis methods
  Some examples from COMPASS $\pi^- \pi^- \pi^+$ analysis ($\approx 50$ M events):
  - $t'$-resolved analysis
  - Freed-isobar fits
  - Semi-automatized model selection from data
  - Observation of small signals
  - Extended mass-dependent fits
  - Models satisfying unitarity and analyticity
  - ...

Example: $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}}$

$t'$-resolved analysis

- Fine binning in 11 $t'$ bins
- Allows to resolve $t'$ dependence in detail
- Improves separation of resonant and non-resonant contributions
**Freed-isobar fits**

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

- PWA requires isobar mass-shape
- Replace fixed isobar-shape by step-like function
- Extract information about the \( \pi^-\pi^+ \) and \( K^-\pi^+ \) subsystem
  - Investigate the \( \kappa \) state
- \( \gtrsim 50 \) MeV needed
Kaon Spectroscopy beyond 2020

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Example: $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}}$
Semi-automatized wave-set selection from data

- Large data sets $\Rightarrow$ large wave sets
- Conventional approach: Systematically adding or eliminating waves by hand
  - May introduce observer bias
- Semi-automatized wave-set selection
  - Starting with a large pool of waves
  - Find the best subset of waves that describe the data

Example: $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}}$
Kaon Spectroscopy beyond 2020

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38674 events

$1.8 \leq m_{3\pi} \leq 1.82\text{GeV}/c^2$

$0.1 \leq t' \leq 0.113\text{GeV}/c$
Example: $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}}$

- Observation of small signals
- e.g. $a_1(1420)$ contributes only 0.3% to total intensity
Kaon Spectroscopy beyond 2020

Example: \( \pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}} \)

Resonance-model fits

- Precise extraction of resonance parameters
- Resonance-model fits
  - Using Breit-Wigner amplitudes
  - Large data sets
    - models at their limits
  - Fits to extract pole positions
    - Simultaneous fits of many channels
- Kaonic spectrum
  - Many overlapping resonances
Beam parameters now

- Beam composition: 2% $K^-$, 1% $\bar{p}$, and 97% $\pi^-$ @ 190 GeV/c
- Beam intensity of $5 \times 10^6$ s$^{-1}$ for approximately 9.6 s every 45 s
- Kaon intensity of approximately $150 \times 10^3$ s$^{-1}$

Goals for a RF separated beam

- Aim for kaon intensity of approximately $8 \times 10^6$ s$^{-1}$ @ 100 GeV/c
- ×50 more than now
- Comparable with $\pi^-$ intensity
- Momentum spread $\lesssim$ 1%
- Requires detailed studies
- Requires infrastructure upgrades
Kaon Spectroscopy beyond 2020
RF Separated Kaon beam

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Data and picture from: Lau Gatignon, Working Group Meeting: Physics Beyond Colliders
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One year data taking ⇒ 30 to 50 M events
⇒ Access to advanced methods

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Uniform Acceptance

**Spectrometer**
- High precision tracking over broad kinematic range
- Precise vertex position measurements
- Measurement of the recoil particle
  - Maintain exclusivity

**Beam PID**
- Beam still consists of different particles species
- CEDAR detectors, which handle high rates
- Precise measurement of the beam inclination at the order of 40 µrad
Kaon Spectroscopy beyond 2020
Experimental Requirements

Uniform Acceptance

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Kaon Spectroscopy beyond 2020
Experimental Requirements

Uniform Acceptance

Final state PID

- RICH detectors have limited acceptance
- Lower beam momentum
  - More events in RICH acceptance
- Final state PID over broad momentum range

Acceptance for neutral channels

- Investigate $K^-\pi^0\pi^0$, $K^-\omega$, $K\eta$, $K\eta'$, ... final state
  - Detection of photons over a broad energy range via ECALs
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Detailed studies of technical aspects necessary

Acceptance for neutral channels
- Investigate $K^-\pi^0\pi^0$, $K^-\omega$, $K\eta$, $K\eta'$, ... final state
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### Kaon Spectroscopy beyond 2020

**Competitors**

- $\tau$ or heavy meson decays
  - LHCb
  - BES III
  - Belle II

- Data-set size typically factor 10 smaller
- Limited mass range

**Photo production**

- Glue-X Phase IV
- Aiming for $100 \times 10^6$ events in $KK\pi\pi$ final state

**GlueX PhaseIV proposal**

- Kaonic states appear as **intermediate states** (isobar model)
  - Freed-isobar ansatz
    - Needs very large data sets
    - Hard to obtain precise insight into the sub system from **four-body final state**
# Kaon Spectroscopy beyond 2020

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Kaon Spectroscopy beyond 2020

Competitors

J-PARC

- Aiming 2 to 10 GeV/c separated $K^-$ or $\bar{p}$ beams
- with $10^7 K^-$/spill

- Separation between beam and target excitations difficult at 10 GeV/c
- Pomeron exchange not dominant at 10 GeV/c beams
- General purpose detector with high-precision tracking and calorimetry needed for spectroscopy
  - No experimental setup planned
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Baryon Spectroscopy with Antiprotons beyond 2020

Negative hadron beam parameters now

- Beam composition: 2\% $K^-$, 1\% $\bar{p}$, and 97\% $\pi^-$ @ 190 GeV/c
- Beam intensity of $5 \times 10^6$ s$^{-1}$ for approximately 9.6 s every 45 s
- Antiproton intensity of approximately $50 \times 10^3$ s$^{-1}$

Positive hadron beam parameters now

- Beam composition: 1\% $K^+$, 75\% $p$, and 24\% $\pi^+$ @ 190 GeV/c
- Measured large data sample of $57 \times 10^6 \ p + p \rightarrow p_f \pi^+\pi^- + p_s$ events
- Pomeran exchange is dominant $\Rightarrow$ investigate $N^*$ baryon resonances

Goals for a RF separated beam

- Aim for antiproton intensity of approximately $3 \times 10^7$ s$^{-1}$ @ 100 GeV/c
- Similar data-set size as baryon spectroscopy sample
Baryon Spectroscopy with Antiprotons beyond 2020

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Spectroscopy with 20 GeV/c Antiprotons beyond 2020
Low-Energy Antiproton Beam

- $\lesssim 20$ GeV/c antiproton beam
- Most of beam kaons decay in beam line
- $\frac{2}{3}$ of beam pions decay in beam line
- Antiproton fraction of total hadron flux at COMPASS target: 15%
- Center of mass energy: $\sqrt{s} = 6.1$ GeV
- Using a 40 cm $\ell$H$_2$ target and a maximum beam intensity of $10^8$ s$^{-1}$ (RP)
  - $\bar{L} = 5 \times 10^{30}$ s$^{-1}$ cm$^{-2}$
  - $\frac{1}{40}$ of PANDA design luminosity (2 $\times$ 10$^{32}$ s$^{-1}$ cm$^{-2}$ in HL mode)

No RF separation necessary
⇒ Could immediately be started after long shutdown

Calculated according to L. Gatignon [COMPASS beyond 2020 Workshop] using 'Atherton formula' for 0 mrad production angle
(only approximation for $|\vec{p}| < 60$ GeV/c)
Spectroscopy with 20 GeV/c Antiprotons beyond 2020
Low-Energy Antiproton Beam

- $\lesssim 20$ GeV/c antiproton beam
- Most of beam kaons decay in beam line
- $\frac{2}{3}$ of beam pions decay in beam line
- Antiproton fraction of total hadron flux at COMPASS target: 15%
- Center of mass energy: $\sqrt{s} = 6.1$ GeV
- Using a 40 cm $\ell$H$_2$ target and a maximum beam intensity of $10^8$ s$^{-1}$ (RP)
  - $\bar{L} = 5 \times 10^{30}$ s$^{-1}$ cm$^{-2}$
  - $\frac{1}{40}$ of PANDA design luminosity (2 $\times$ $10^{32}$ s$^{-1}$ cm$^{-2}$ in HL mode)

No RF separation necessary
⇒ Could immediately be started after long shutdown

Calculated according to L. Gatignon [COMPASS beyond 2020 Workshop] using 'Atherton formula' for 0 mrad production angle (only approximation for $|\vec{p}| < 60$ GeV/c)
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Spectroscopy of resonances in the energy region of charmonium and above

- Produced in association with one or more recoil particles
  \[ p\bar{p} \to \chi_{cJ} + \text{recoil} \to J/\psi + \text{light mesons} + \text{recoil} \]
- Precision measurement of charmonium-like states, including
  - missing states, predicted by theory
  - hybrid candidates, ...

LQCD calculation
\[ (m_\pi = 240 \text{ MeV}/c^2) \]
Hadron Spectrum collaboration
JHEP 1612, 089 (2016)
Spectroscopy with 20 GeV/c Antiprotons beyond 2020

Experimental Requirements

Neutral channels

- Large background
  - Final states with neutral particles ($\pi^0$, $\eta$) important
  - Requires electromagnetic calorimeter around the target region

Tracking

- Tracking of charged particles
  - at low momenta
  - with large angles

Central tracking and calorimetry detectors necessary
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Experimental Requirements

PANDA (-like) barrel detector

- **PANDA electromagnetic calorimeter barrel**
  - 15 k crystals
  - $\approx 99\%$ angular coverage
  - $1.54\% / \sqrt{E[\text{GeV}]} = 0.3\%$ energy resolution

- **PANDA phase 0**
  - Detector components are commissioned and used at other experiments
  - Until $\approx 2024$

COMPASS setup

- Beam PID via CEDARs (high rates)
- Use COMPASS setup as forward spectrometer for high-precision tracking
- Good muon identification
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Spectroscopy with kaons

- Many kaonic states require further confirmation and precise measurement
- COMPASS has measured 1 M exclusive $K^- + p \rightarrow K^-\pi^-\pi^+ + p_{\text{recoil}}$ events
- Aiming for 30 to 50 M/y with RF separated kaon beam
  - Access to advance/novel analysis methods
- Requires uniform acceptance over broad kinematic range (PID/ECAL)
- No direct competitors

Spectroscopy with antiprotons

- 20 GeV/c antiproton beam
  - No RF separation necessary
- Measurements of charmonium-like states
- Aiming for $\frac{1}{40}$ of PANDA design luminosity
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Summary

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