Spectroscopy with Kaons and Antiprotons

COMPASS Program beyond 2020

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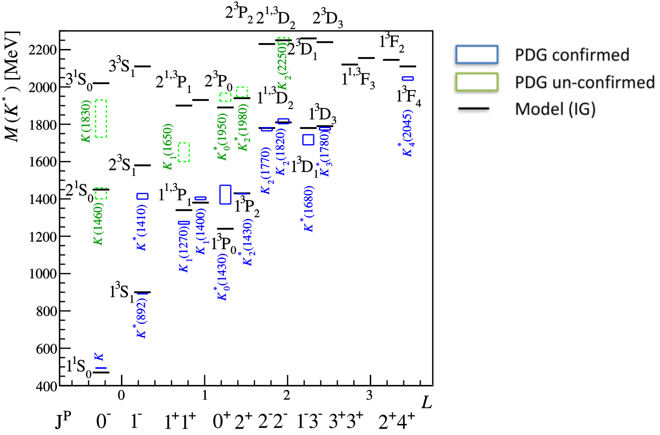
Outline

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. $K_2(1580)$, $K_2^*(1980)$, ...



arXiv:1606.07895v2

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Appear in heavy-meson decays

- Kaonic resonances appear as intermediate states in heavy meson decays
$$B, D \to \text{light mesons}$$
  - 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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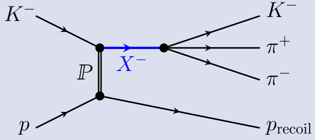

ACCMOR measurements
Daum, Nucl.Phys.B 1981

- CERN SPS WA03 experiment
- $K^- + p \to K^-\pi^-\pi^+ + p_{\mathrm{recoil}}$
- 200 000 events
- 63 GeV/c K^- beam

LASS measurements
Aston, Nucl.Phys.B 1987/1993

- LASS spectrometer at SLAC
- 34 000 $K^-p \to \bar{K}^0\pi^+\pi^-n$ events
- 100 000 $K^-p \to K^-\omega p$ events
- 11 GeV/c beam energy

Further measurements

- τ decay (e.g. CLEO)
- Heavy meson decays, e.g. J/π, χ_{cJ}, or B

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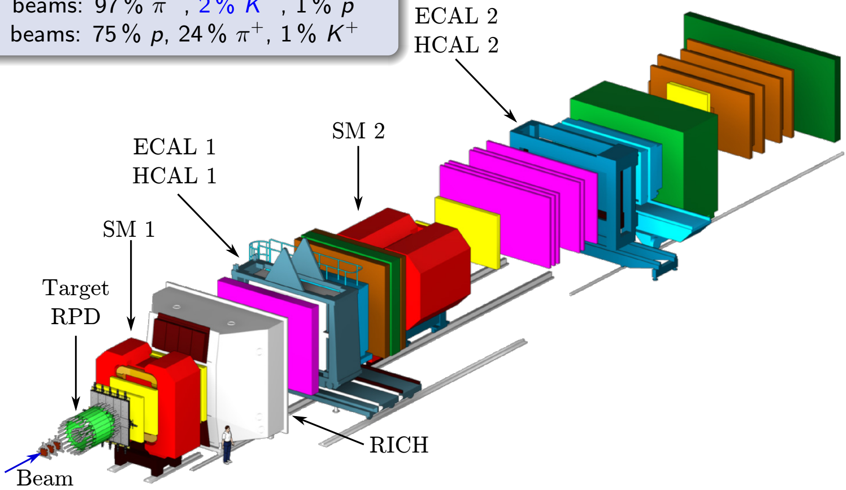
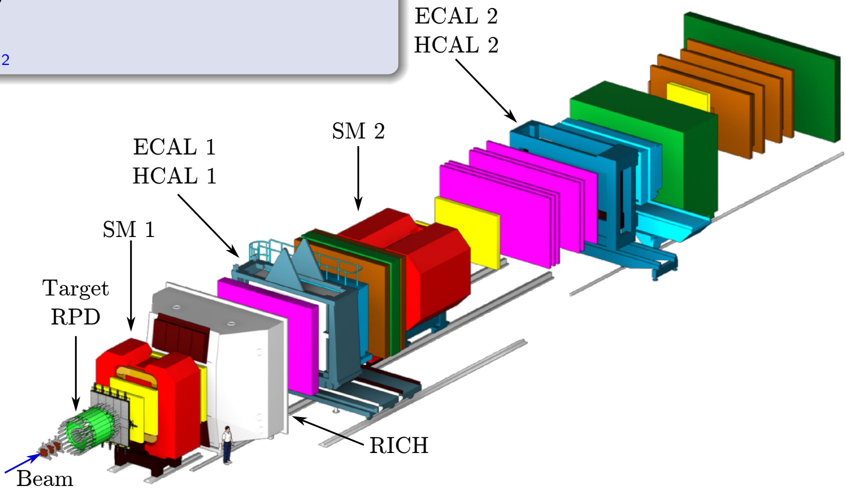
M2 beam line

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



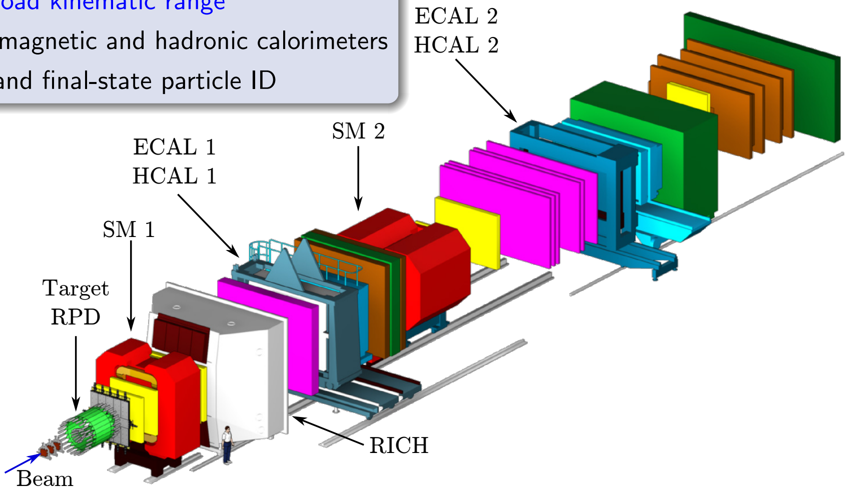
Target

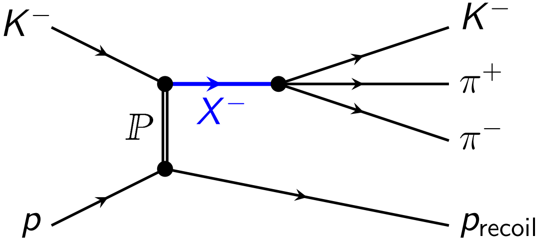
- Various targets:
  - Ni
  - Pb
  - W
  - ℓH_2



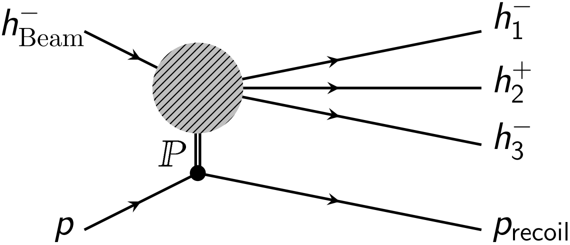
COMPASS spectrometer

- 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 π^- and K^- over a wide momentum range
- Requires beam-particle PID via CEDARs
  - approximately $\times 30$ more π^- than K^- in the beam



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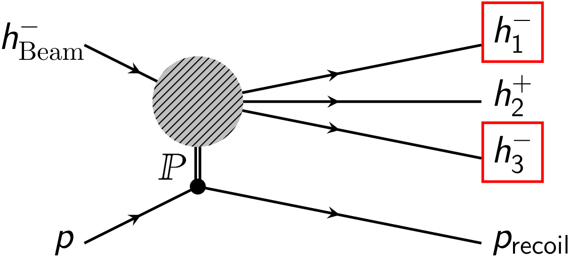

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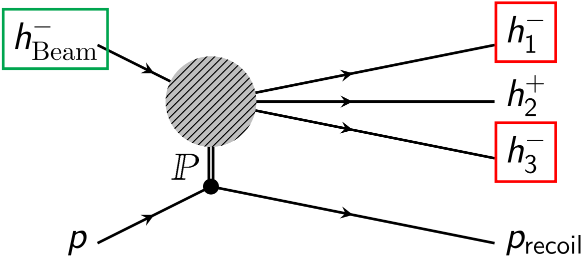

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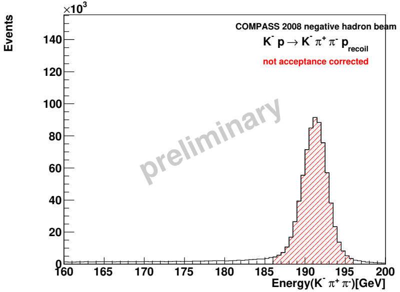
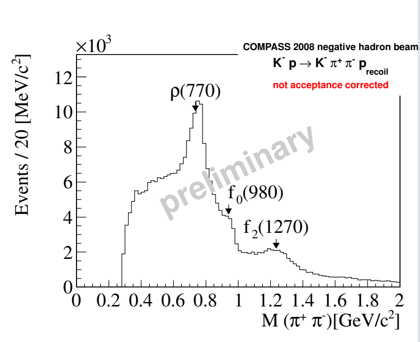
Event Sample

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

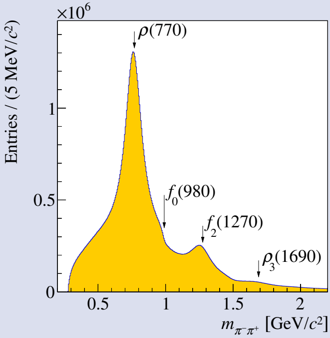


COMPASS: $K^-\pi^-\pi^+$



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

[PhysRevD.95 (2017)]



$\pi^-\pi^+$ 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 κ state: Needs further measurements

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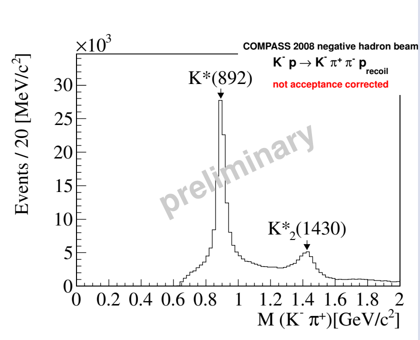
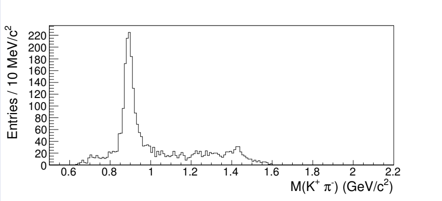


Belle: $B^0 \to J/\psi K^+\pi^-$ [PhysRevD. 83 (2011)]



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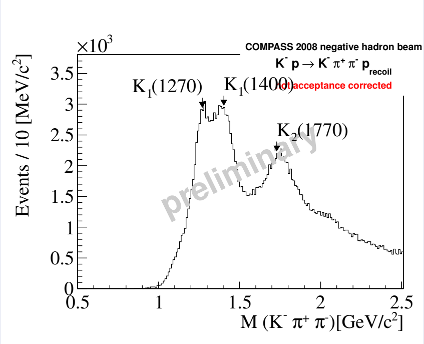

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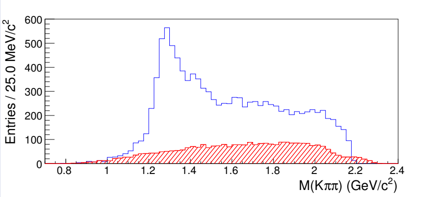

$K^-\pi^-\pi^+$ system

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

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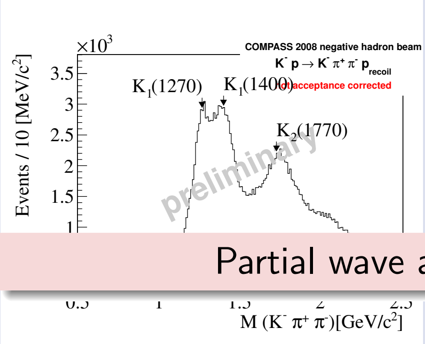

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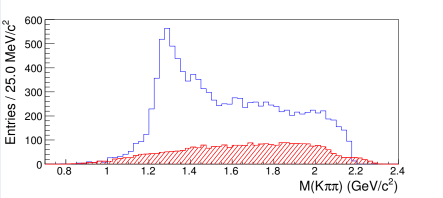

Partial wave analysis necessary

$K^-\pi^-\pi^+$ system

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- sitting on a broad spectrum

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 $t' < 0.07\,\mathrm{GeV}/c^2$

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
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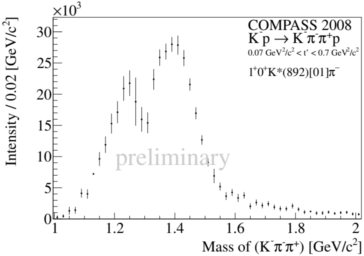
- $K_2(1770)$ and $K_2(1820)$ signal
- $K_2(1580)$ and $K_2(2250)$ need further confirmation



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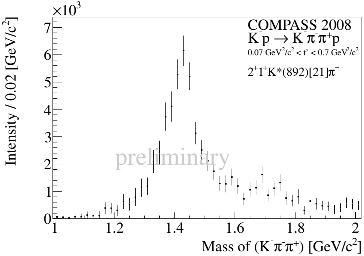

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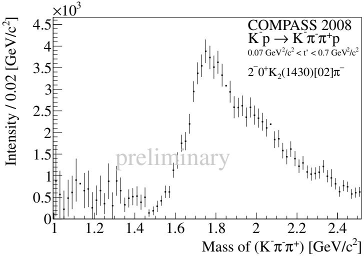

Data Set

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

$$\Rightarrow 1 \times 10^6 \text{ events of } K^- + p \rightarrow K^-\pi^-\pi^+ + p_{\text{recoil}}$$

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

- $K^-\pi^0\pi^0$
- $K^-K^-K^+$
- $K^-\omega$
- ...

COMPASS Kaon Spectroscopy Results

Further Projects with Existing Data

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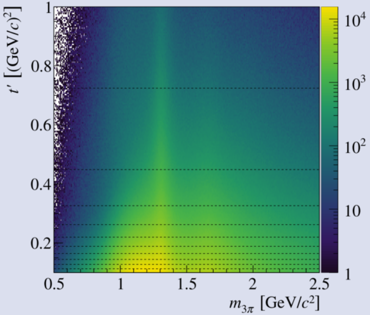
Why more data is needed

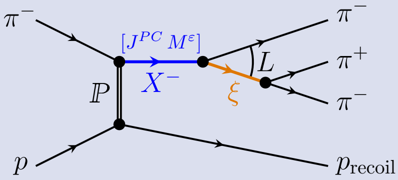
- More precise fit results
  - Establish open strangeness spectrum at the same level as for light quarks
  - Access to new states?
- Access to advanced / novel analysis methods
  Some examples from COMPASS $\pi^-\pi^-\pi^+$ analysis ($\approx 50\,\mathrm{M}$ events):
  - t'-resolved analysis
  - Freed-isobar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

t'-resolved analysis

- Fine binning in 11 t' bins
- Allows to resolve t' dependence in detail
- Improves seperation of resonant and non-resonant contributions



Freed-isobar fits



- 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 κ state
- $\gtrsim 50\,\text{M}$ needed

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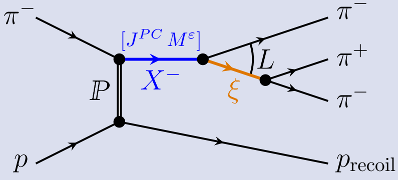

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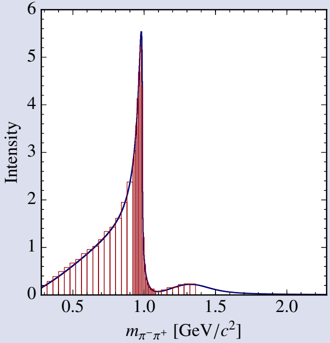

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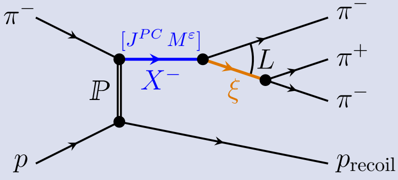

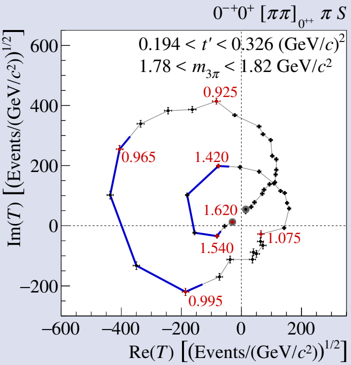

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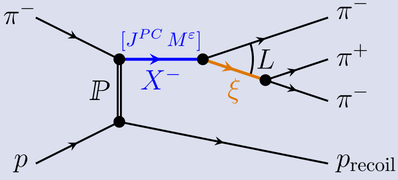
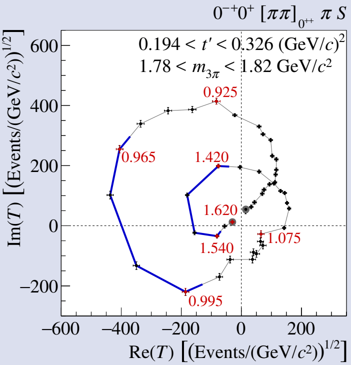
Kaon Spectroscopy beyond 2020

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

Freed-isobar fits





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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
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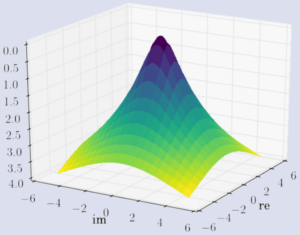

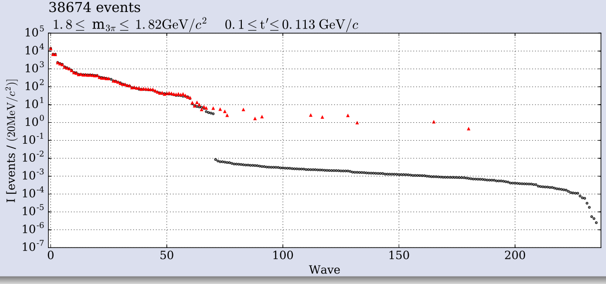

Observation of small signals

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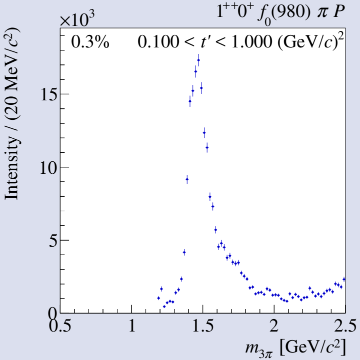
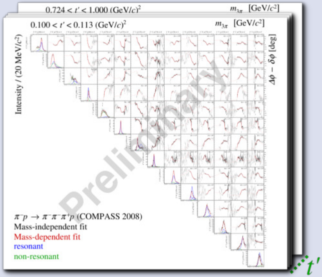
- e.g. $a_1(1420)$ contributes only 0.3 % to total intensity



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



Kaon Spectroscopy beyond 2020
RF Separated Kaon beam

Beam parameters now

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

Goals for a RF separated beam

Lau Gatignon, Working Group Meeting: Physics Beyond Colliders

- Aim for kaon intensity of approximately $8 \times 10^6\,\mathrm{s}^{-1}$ @ $100\,\mathrm{GeV}/c$
  - $\times 50$ more than now
  - Comparable with π^- intensity
  - Momentum spread $\lesssim 1\,\%$
- Requires detailed studies
- Requires infrastructure upgrades

Data and picture from: Lau Gatignon, Working Group Meeting: Physics Beyond Colliders

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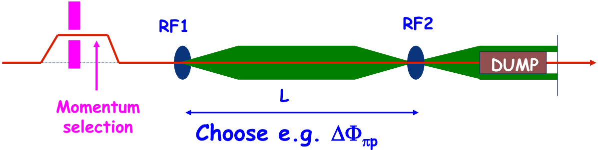

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One year data taking $\Rightarrow$ 30 to 50 M events
$\Rightarrow$ Access to advanced methods

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  - $\times 50$ more than now
  - Comparable with π^- intensity
  - Momentum spread $\lesssim 1\,\%$
- Requires detailed studies
- Requires infrastructure upgrades

Data and picture from: Lau Gatignon, Working Group Meeting: Physics Beyond Colliders

Uniform Acceptance

Spectrometer

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

Beam PID

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- Beam still consists of different particles species
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Final state PID

- RICH detectors has limited acceptance
- Lower beam momentum
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Acceptance for neutral channels

- Investigate $K^-\pi^0\pi^0$, $K^-\omega$, $K\eta$, $K\eta'$, ... final state
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τ or heavy meson decays

- LHCb
- BES III
- Belle II

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

Photo production [GlueX PhaseIV proposal]

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

- 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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- Aiming 2 to 10 GeV/c separated K^- or $\bar{p}$ beams
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- Separation between beam and target excitations difficult at 10 GeV/c
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Baryon Spectroscopy with Antiprotons beyond 2020

Negative hadron beam parameters now

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

Positive hadron beam parameters now

- Beam composition: 1 % K^+, 75 % p, and 24 % π^+ @ 190 GeV/c
- Measured large data sample of 57×10^6 $p + p \to p_\mathrm{f}\pi^+\pi^- + p_\mathrm{s}$ events
- Pomeron exchange is dominant $\Rightarrow$ investigate N^* baryon resonances

Goals for a RF separated beam

Lau Gatignon, Working Group Meeting: Physics Beyond Colliders

- Aim for antiproton intensity of approximately $3 \times 10^7\,\mathrm{s}^{-1}$ @ 100 GeV/c
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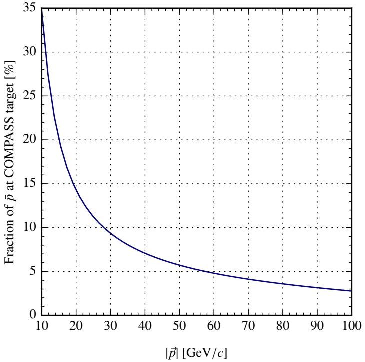
Outline

- $\lesssim 20\,\mathrm{GeV}/c$ 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: $\sqrt{s} = 6.1\,\mathrm{GeV}$
- Using a 40 cm ℓH_2 target and a maximum beam intensity of $10^8\,\mathrm{s}^{-1}$ (RP)
  - ➥ $\overline{L} = 5 \times 10^{30}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$
  - ➥ $\frac{1}{40}$ of PANDA design luminosity ($2 \times 10^{32}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$ in HL mode)



Calculated according to L. Gatignon [COMPASS beyond 2020 Workshop] using 'Atherton formula' for 0 mrad production angle (only approximation for $|\vec{p}| < 60\,\mathrm{GeV}/c$)

No RF separation necessary

$\Rightarrow$ Could immediately be started after long shutdown

Spectroscopy with 20 GeV/c Antiprotons beyond 2020
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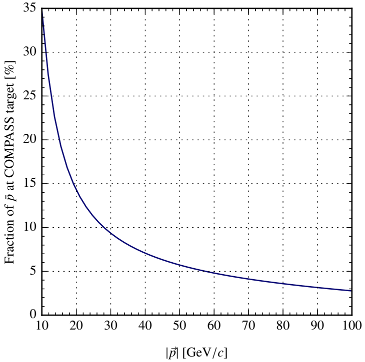

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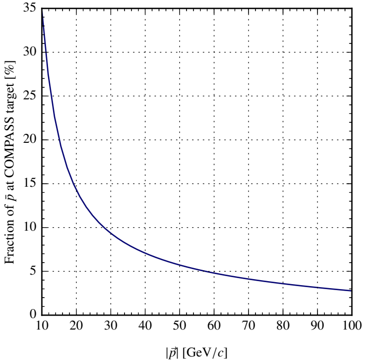

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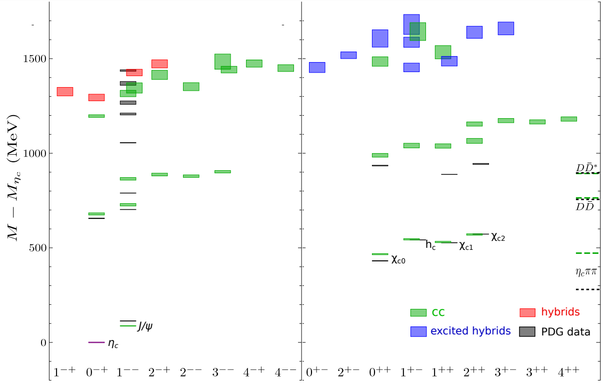
Spectroscopy of resonances in the energy region of charmonium and above

- 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_π = 240 MeV/c^2)
Hadron Spectrum collaboration
JHEP 1612, 089 (2016)

Neutral channels

- Large background
  - ➥ Final states with neutral particles (π^0, η) 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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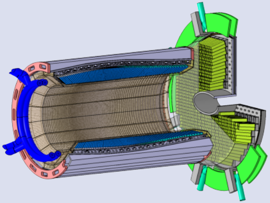
PANDA (-like) barrel detector

arXiv:0810.1216

- PANDA electromagnetic calorimeter barrel
  - 15 k crystals
  - $\approx 99\,\%$ angular coverage
  - $1.54\,\%/\sqrt{E[\mathrm{GeV}]} = 0.3\,\%$ energy resolution
- PANDA phase 0
  - Detector components are commissioned and used at other experiments
  - Until ≈ 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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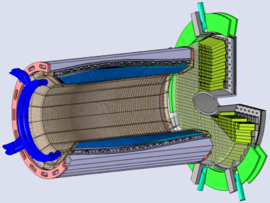

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Spectroscopy with 20 GeV/c Antiprotons beyond 2020

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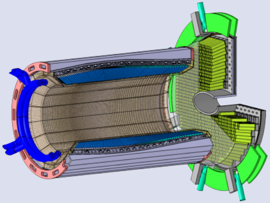

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Spectroscopy with kaons

- 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 neccessary
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