Hadron Spectroscopy with Kaon Beam

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Workshop on
Dilepton Productions with Meson and Antiproton Beams
ECT*, Trento, 09. Nov 2017

Hadrons and Strong Interaction

- Binding of quarks and gluons into hadrons governed by low-energy (long-distance) regime of QCD
- Least understood aspect of QCD
  - Perturbation expansion in α_s not applicable
  - Revert to models or numerical simulation of QCD (lattice QCD)
- Details of binding related to hadron masses
  - Only small fraction of proton mass explained by Higgs mechanism $\Rightarrow$ most generated dynamically

Hadrons reflect workings of QCD at low energies

Measurement of **hadron spectra** and **hadron decays** gives valuable input to theory and phenomenology

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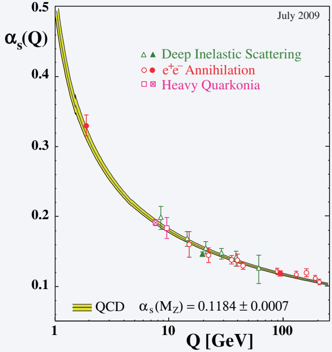

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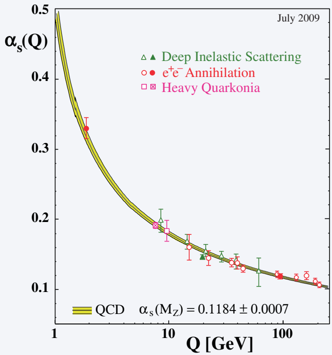


Hadrons reflect workings of QCD at low energies

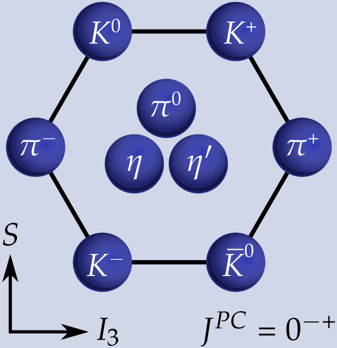
Measurement of **hadron spectra** and **hadron decays** gives valuable input to theory and phenomenology

Quark-Model Meson Nonets

Light-quark mesons

- u, d, and s (anti)quarks $\Rightarrow$ SU(3)$_{\text{flavor}}$ nonets

Ground-state nonets



$J^{PC} = 0^{-+}$

- Many more nonets for orbital and radial excitations

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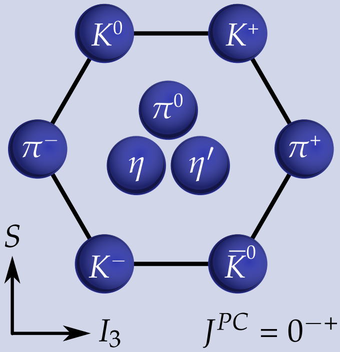

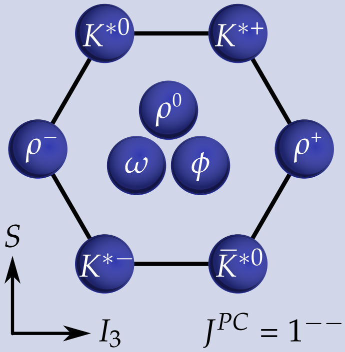

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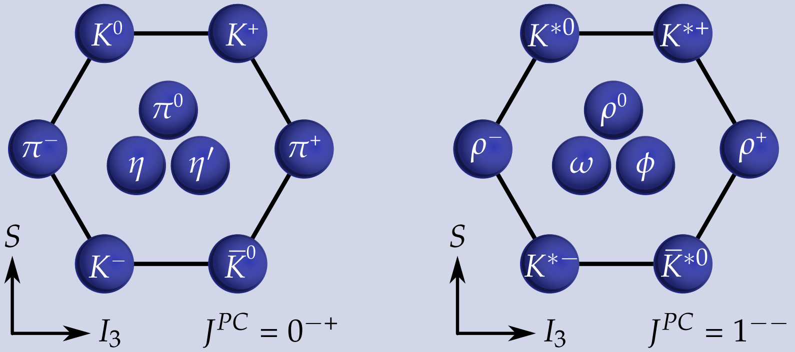

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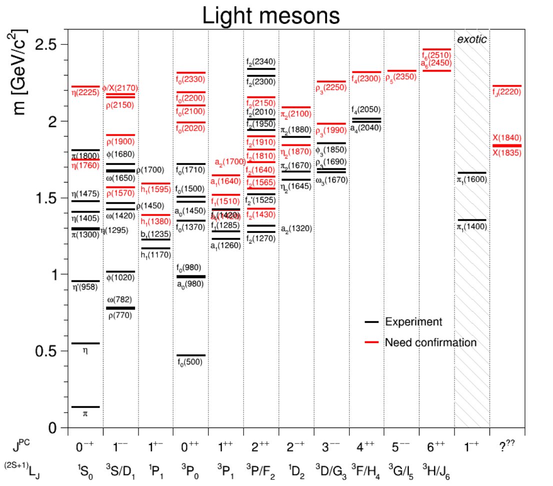
Light-Meson Spectrum



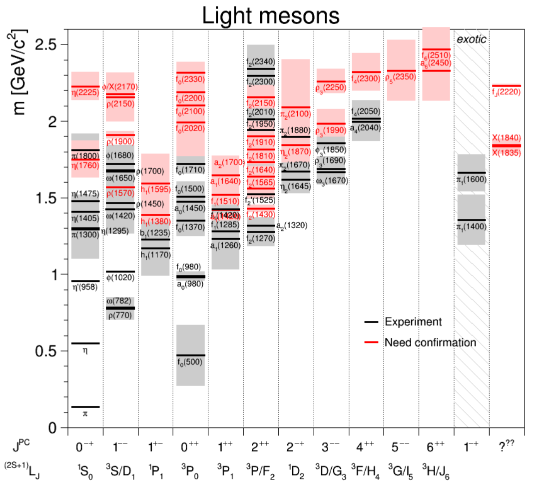
[Courtesy K. Götzen, GSI]

"Light-meson frontier"

- Many states need confirmation in mass region $m \gtrsim 2\,\mathrm{GeV}/c^2$
- Many wide states $\Rightarrow$ overlap and mixing
- Identification of higher excitations becomes exceedingly difficult

Main focus of current COMPASS program

Light-Meson Spectrum



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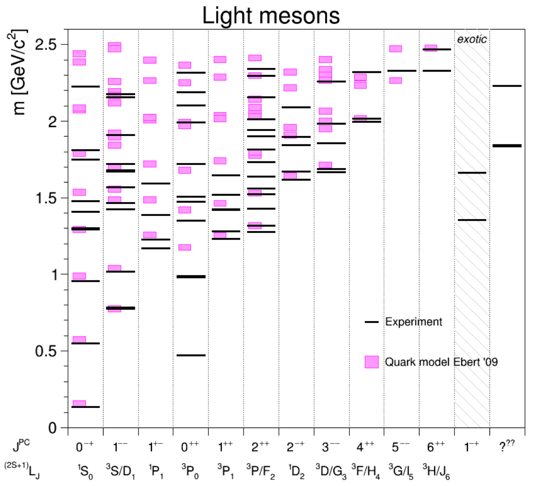

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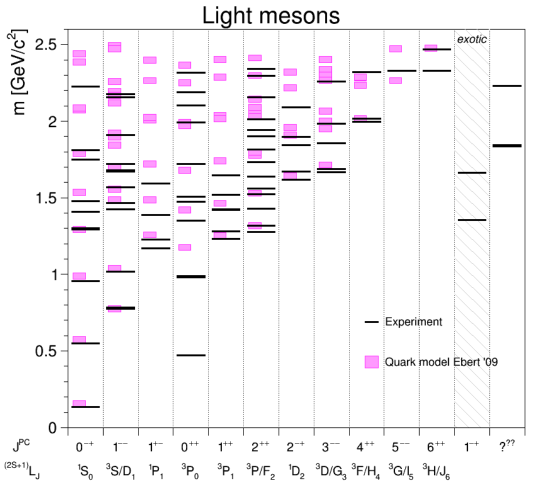

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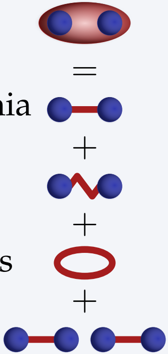
Beyond the Constituent Quark Model



	(meson) =	
Quarkonia		$\vert q\bar{q}\rangle$
	+	
Hybrids		$\vert q\bar{q}g\rangle$
	+	
Glueballs		$\vert gg\rangle$
	+	
Multi-quarks		$\vert q^2\bar{q}^2\rangle$
	+ ⋮	

QCD permits additional color-neutral configurations

Gell-Mann's Totalitarian Principle for Quantum Mechanics: "Everything not forbidden is compulsory"

M. Gell-Mann, Nuovo Cimento **4** (1956) 848

Physical mesons

- Linear superpositions of *all* allowed basis states
- "Configuration mixing"
- Amplitudes in principle determined by QCD interactions
- Disentanglement of contributions difficult

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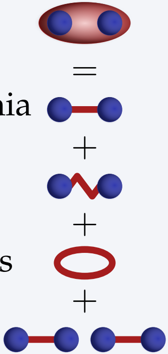

=

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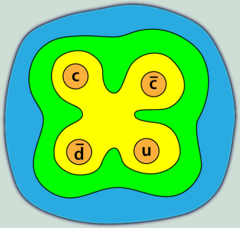
Best experimental evidence so far from heavy-quark sector

Tetraquark candidates $Z_{c,b}$

- Charged $|c\bar{c}\rangle$- and $|b\bar{b}\rangle$-like states
- E.g. $Z_c^{\pm}(3900) \to J/\psi + \pi^{\pm}$



Pentaquark candidates P_c^+

- Heavy baryon
- Decay mode $P_c^+ \to J/\psi + p$

Light-quark sector

- Model calculations suggest some states to be tetraquarks or hybrids
- No definite experimental evidence

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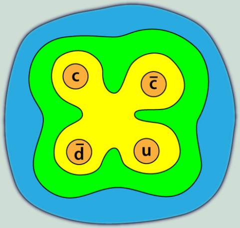

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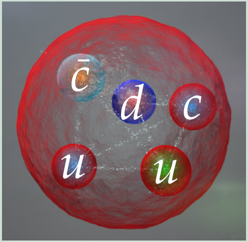

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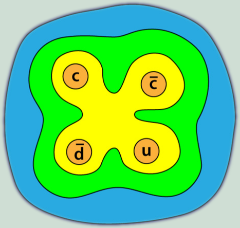

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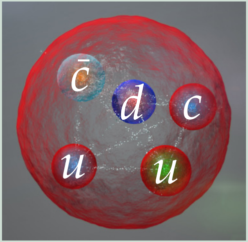

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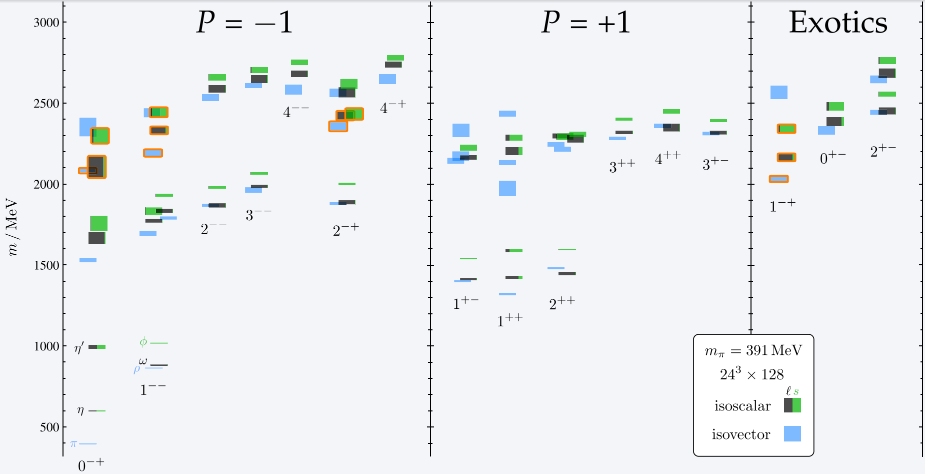
Light-Meson Spectrum from Lattice QCD

State-of-the-art calculation with $m_\pi = 391\ \text{MeV}/c^2$ Dudek *et al.*, PRD **88** (2013) 094505

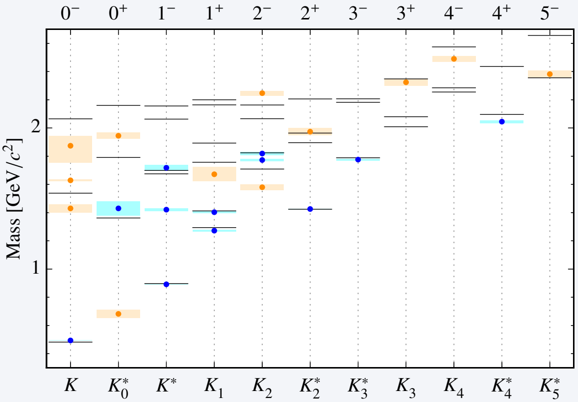


- Essentially recovers quark-model pattern
- High towers of excited states
- Additional hybrid-meson super-multiplet

Why kaon spectroscopy?

PDG 2016: 25 kaon states below 3.1 GeV / c^2

- Only 12 kaon states in summary table, 13 need confirmation
- Many predicted quark-model states still missing
- Some hints for supernumerous states



[Courtesy S. Wallner, TUM]

Why kaon spectroscopy?

Many kaon states need confirmation

- Little progress in the past
  - Most PDG entries more than 30 years old
  - Since 1990 only 4 kaon states added to PDG (only 1 to summary table)

Kaon spectrum crucial to understand light-meson spectrum

- Identify supernumerous states by completing $SU(3)_{flavor}$ multiplets
  - E.g. $J^P = 0^+$ multiplet with $a_0(980)$, $K_0^*(800)$ [or κ], $f_0(500)$ [or σ], and $f_0(980)$ is hypothesized to be tetra-quark multiplet
  - But $K_0^*(800)$ still disputed

Kaon spectrum required to analyse heavy-meson decays

- E.g. search for CP violation in multi-body decays e.g. $B^\pm \to D^0 K^\pm$ with $D^0 \to K_S^0 \pi^+ \pi^-$
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How to produce excited kaon states?

Decays

- τ leptons, charmed mesons, and charmonium states $\Rightarrow$ limited mass reach
- B meson decays $\Rightarrow$ description of large Dalitz plots difficult

Production experiments

- E.g. diffractive production using high-energy kaon beam on stationary target
  - Large cross section
  - Not very selective: all kaon states can appear as intermediate state X

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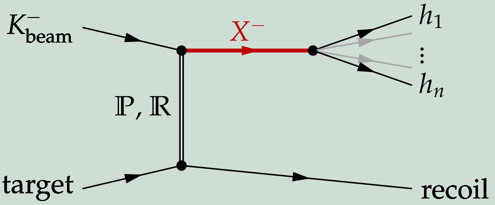
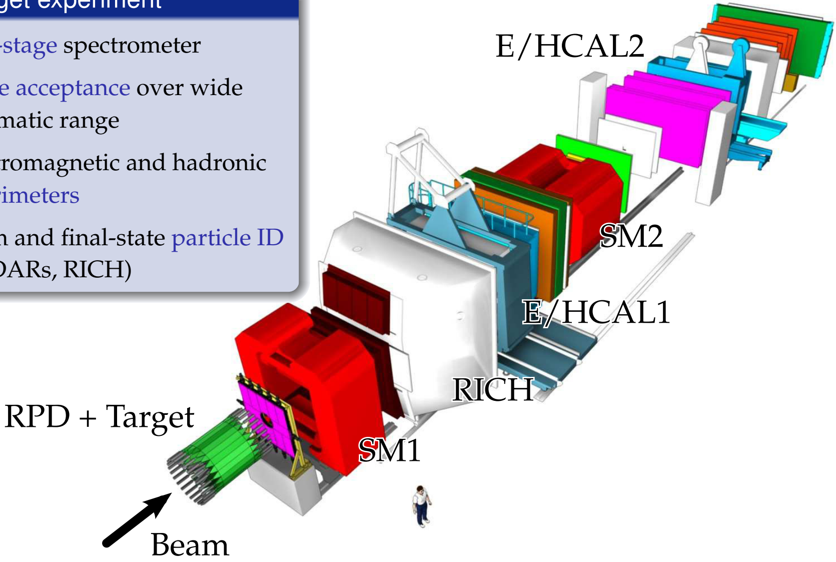


Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- Electromagnetic and hadronic calorimeters
- Beam and final-state particle ID (CEDARs, RICH)



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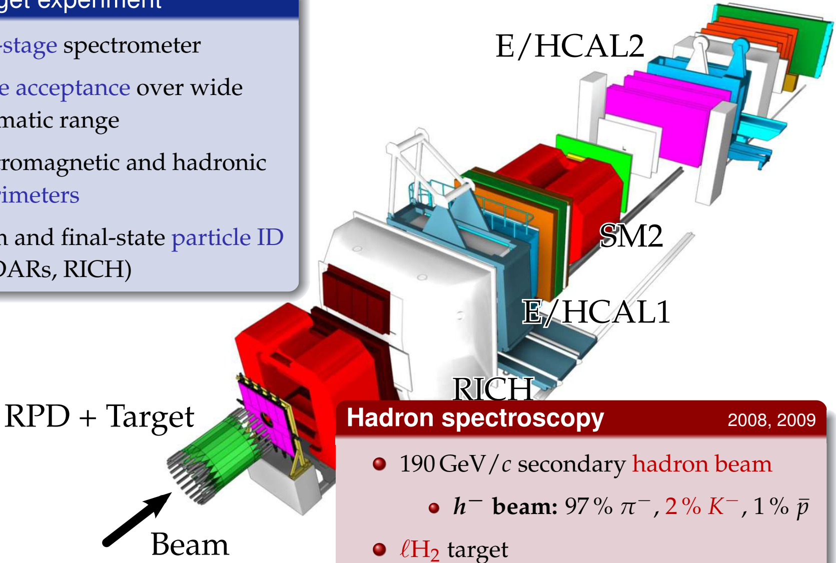
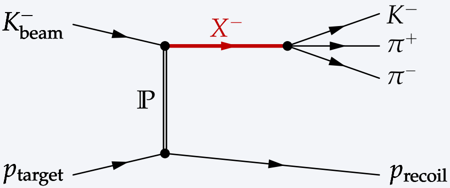


Hadron spectroscopy
2008, 2009

- 190 GeV/c secondary hadron beam
  - h^- **beam:** $97\,\%\ \pi^-$, $2\,\%\ K^-$, $1\,\%\ \bar{p}$
- ℓH_2 target

Example: Analysis of $K^- \pi^+ \pi^-$ Final State



- Diffractive production of excited kaon states X^- that decay into $K^- \pi^+ \pi^-$
- Beam-particle ID via Cherenkov detectors (CEDARs)
  - Ca. $50\times$ more π^- than K^- in beam
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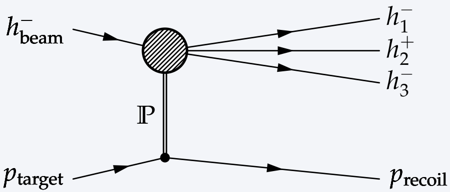

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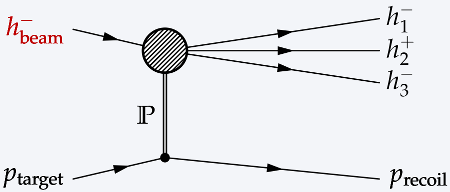

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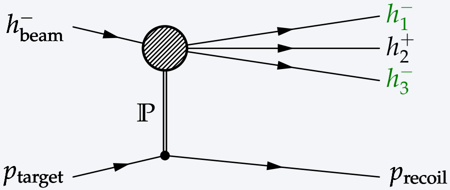

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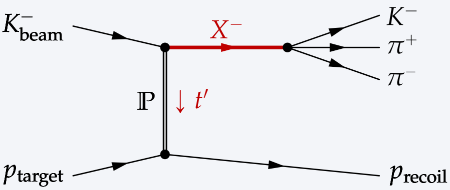
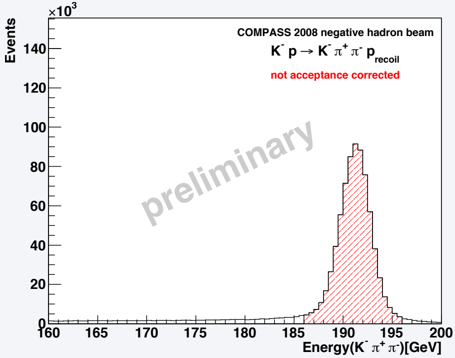
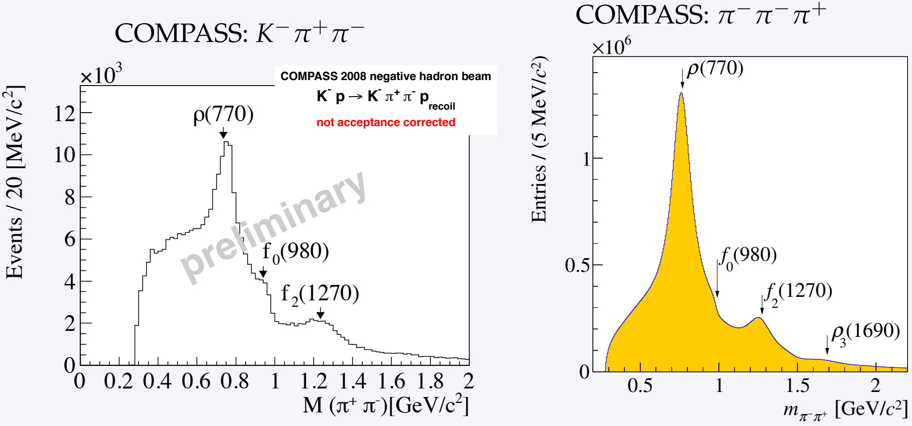


- From 2008 data taking campaign
- 270 000 events
- $0.07 < t' < 0.7\,(\text{GeV}/c)^2$
- Exclusivity ensured by measuring recoil proton
  - Also suppresses target excitations



Example: Analysis of $K^-\pi^+\pi^-$ Final State

Invariant Mass of $\pi^-\pi^+$ Subsystem



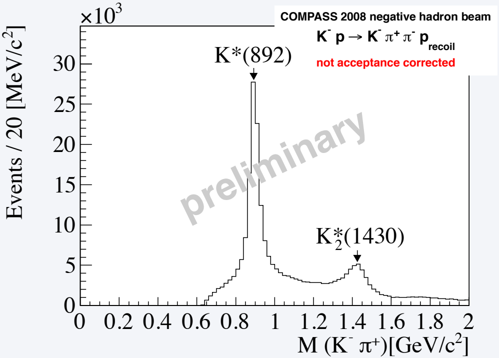
COMPASS, PRD **95** (2017) 032004

- $m_{\pi^-\pi^+}$ spectrum contains states already known from analysis of diffractively produced $\pi^-\pi^-\pi^+$

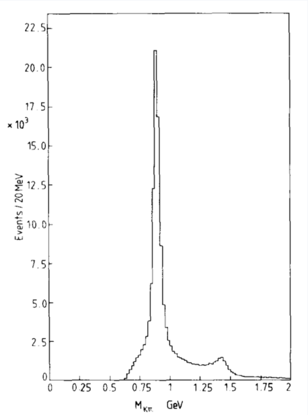
Example: Analysis of $K^-\pi^+\pi^-$ Final State

Invariant Mass of $K^-\pi^+$ Subsystem

COMPASS



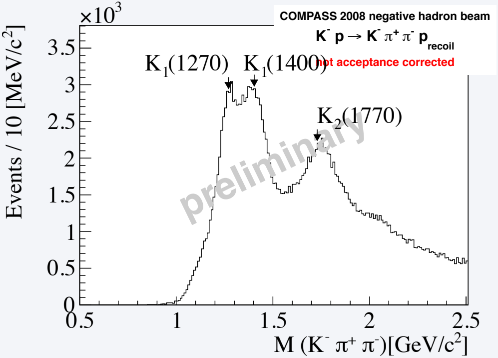
WA03 (CERN)



ACCMOR, NPB **187** (1981) 1

- Clear $K^*(892)$ and $K_2^*(1430)$ signals
- Data set slightly larger than that of most precise previous experiment

COMPASS
$0.07 < t' < 0.7\,(\text{GeV}/c)^2$



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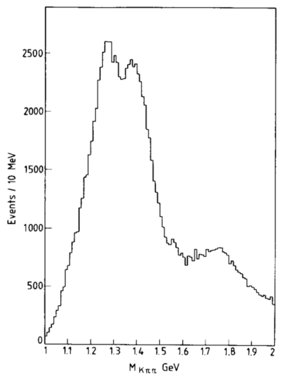
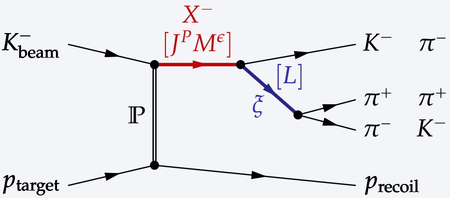


ACCMOR, NPB **187** (1981) 1

- Various potential resonance signals
- Need partial-wave analysis (PWA) to disentangle contributions from various J^P quantum numbers

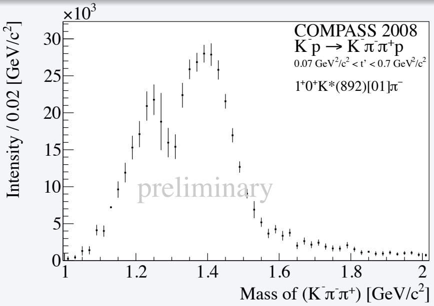


PWA model similar to WA03

- 6 "isobars"
  - $\pi^-\pi^+$ subsystem: $\xi = f_0(500)$, $\rho(770)$, and $f_2(1270)$
  - $K^-\pi^+$ subsystem: $\xi = K_0^*(800)$, $K^*(892)$, and $K_2^*(1430)$
- 19 "waves" = combinations of X^- J^P and decay modes

Example: Analysis of $K^-\pi^+\pi^-$ Final State

Results of Partial-Wave Analysis



$1^+ \to K^*(892) + \pi^-$ in S-wave

- Clear signals from $K_1(1270)$ and $K_1(1400)$

$2^+ \to K^*(892) + \pi^-$ in D-wave

- Clear signal from $K_2^*(1430)$
- $K_2^*(1980)$?

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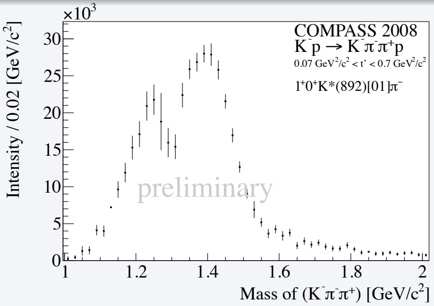

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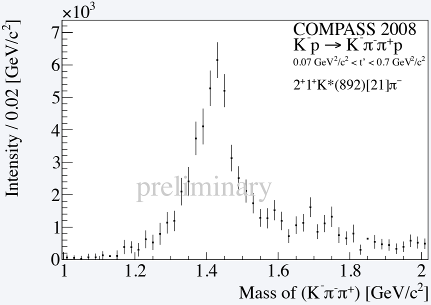

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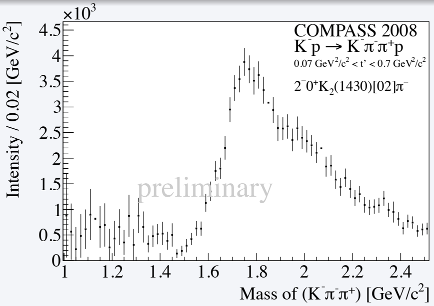
Example: Analysis of $K^-\pi^+\pi^-$ Final State

Results of Partial-Wave Analysis



$2^- \to K_2^*(1430) + \pi^-$ in S-wave

- Possible signals from $K_2(1770)$ and $K_2(1820)$
- $K_2(1580)$ and $K_2(2250)$?

Work in progress: improving analysis

- Improved beam PID + data sample from 2009 run
  $\Rightarrow$ ca. 8×10^5 $K^-\pi^+\pi^-$ events
  $\Rightarrow$ world's largest data set ($4\times$ WA03)
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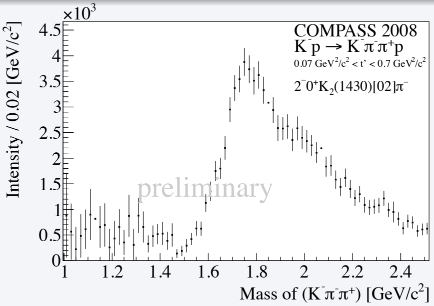

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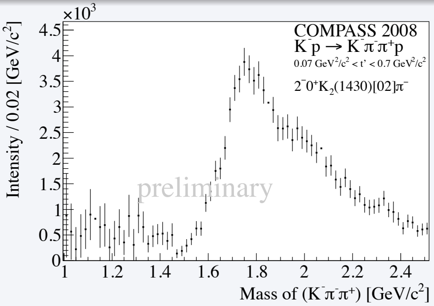

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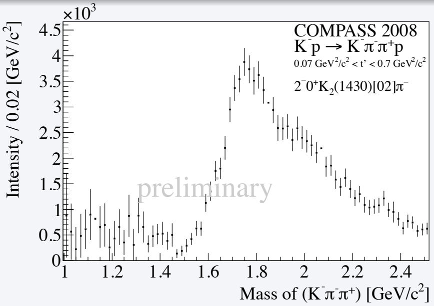

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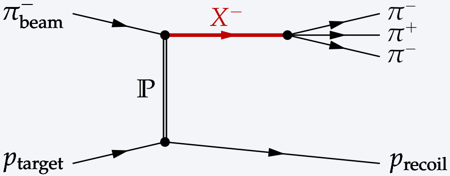
Further final states accessible by COMPASS

- Isospin partner channel $K^-\pi^0\pi^0$
- $K^-K^+K^-$
- $K^-\pi^0, K_S^0\pi^-, K^-\eta^{(\prime)}, K^-\omega$
- …

Why do we need even larger data sets?

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

COMPASS, PRD **95** (2017) 032004



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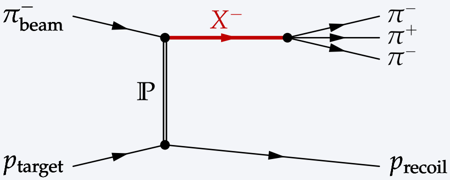

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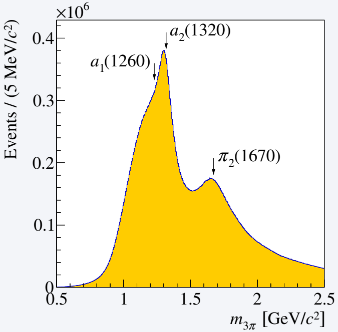

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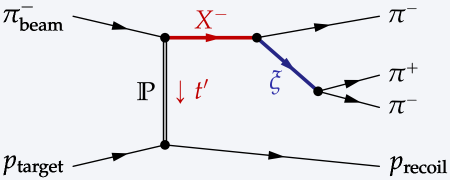

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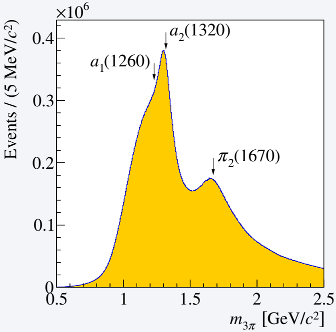

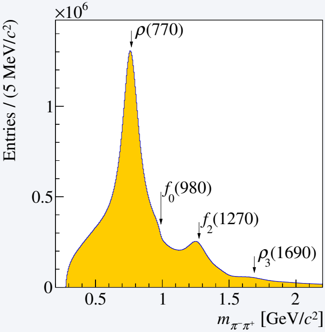

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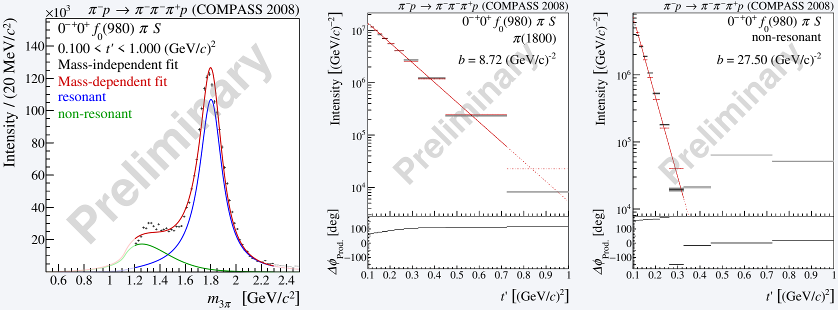
PWA in narrow bins of four-momentum transfer squared t'

- Resolve t' dependence of partial-wave amplitudes
- Improved separation between resonant and nonresonant components in resonance-model fits
- First extraction of t' spectra of resonances from such an analysis
  $\Rightarrow$ can study production mechanism(s)



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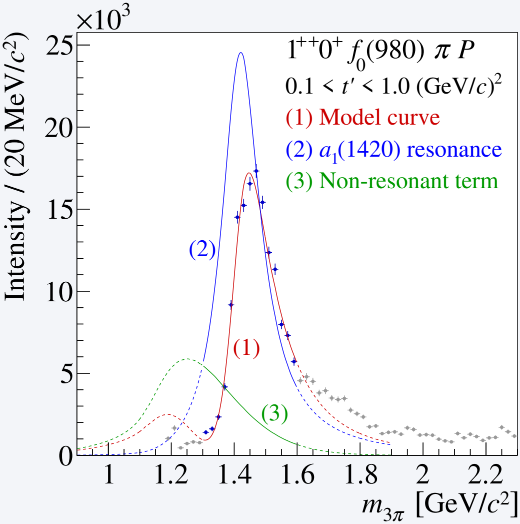
Improved sensitivity for small signals

- E.g. surprising find: resonance-like $a_1(1420)$ signal in peculiar decay mode
- Only 0.3 % of total intensity



COMPASS, PRL **115** (2015) 082001

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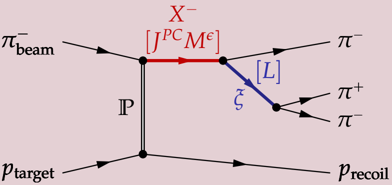
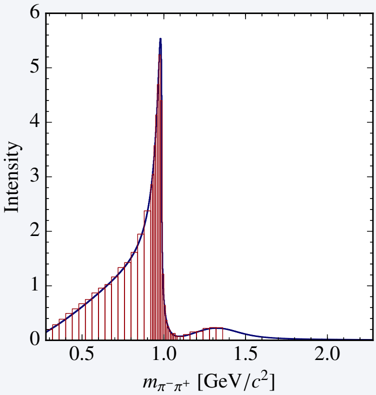
Novel analysis technique "freed-isobar" PWA



- Conventional PWA requires complete knowledge of isobar amplitude
- *Novel approach:* replace fixed parametrization by step-like function
  - Isobar amplitude determined from data $\Rightarrow$ reduced model dependence
  - E.g. amplitude of $\pi^-\pi^+$ subsystem with $J^{PC} = 0^{++}$ $\Rightarrow f_0(500)$ (?), $f_0(980)$, $f_0(1500)$



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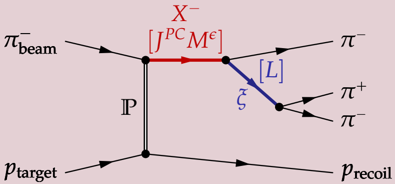

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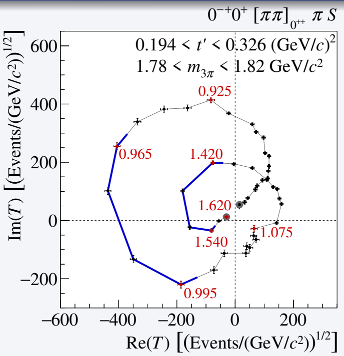

COMPASS, PRD **95** (2017) 032004

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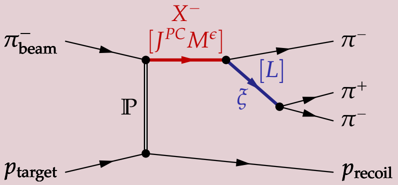

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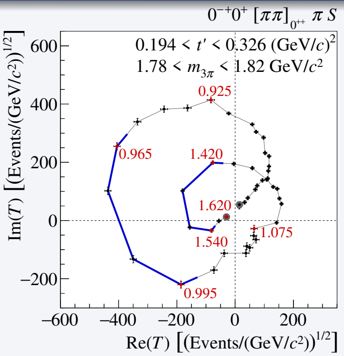

COMPASS, PRD **95** (2017) 032004

- Would allow to study $K^-\pi^+$ subsystem with $J^P = 0^+$ in $K^-\pi^+\pi^-$
- Requires huge data samples

How to get more data?

Current parameters of h^- beam

- Composition: 97 % π^-, 2 % K^-, 1 % $\bar{p}$
- Intensity: $5 \times 10^6\,\mathrm{s}^{-1}$ for approximately 10 s every 45 s
  - Intensity of kaon component: $10^5\,\mathrm{s}^{-1}$

- Main limiting factor: low kaon fraction in beam
- **Need to increase intensity of kaons by at least factor 10**

Possible solution

RF-separated beam at M2 beam line

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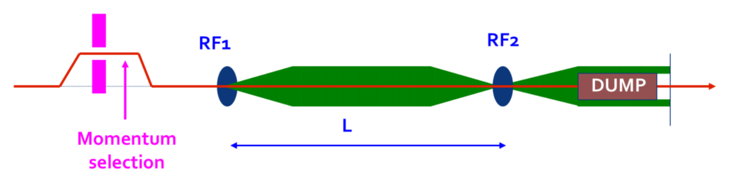
RF-separated Kaon Beam

[See J. Bernhard's talk on Tue]



Possible beam parameters

- Beam momentum $\lesssim 100\,\text{GeV}/c$
  - Not an issue: diffractive production depends only weakly on energy
- Kaon intensity $3.7 \times 10^6\,\text{s}^{-1}$
  - More than factor 35 increase w.r.t. conventional beam line
  - Would correspond to 10 to 20×10^6 $K^-\pi^+\pi^-$ events assuming same acceptance as current experimental setup
    $\Rightarrow$ would be $\approx 10\times$ world data
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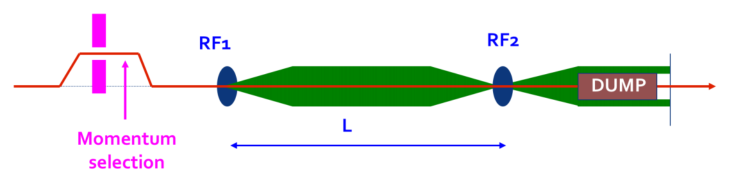

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Requirements for experimental Setup

Beam PID

[See J. Bernhard's talk on Tue]

- Upgrade of CEDAR detectors ⇒ improve rate capability and thermal stability
- Requires precise measurement of beam inclination with resolution $< 40\,\mu\text{rad}$ ⇒ silicon beam telescope

Spectrometer

- As uniform acceptance as possible
- High-precision tracking over broad kinematic range
- Precise measurement of vertex position
- Detection of target recoil particle
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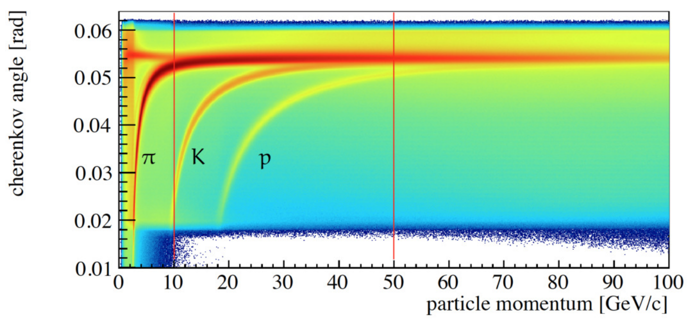
- Existing RICH kaon ID covers only $10 < p < 50\,\mathrm{GeV}/c$
  - More than 50 % of kaons in $K^-\pi^+\pi^-$ outside of acceptance



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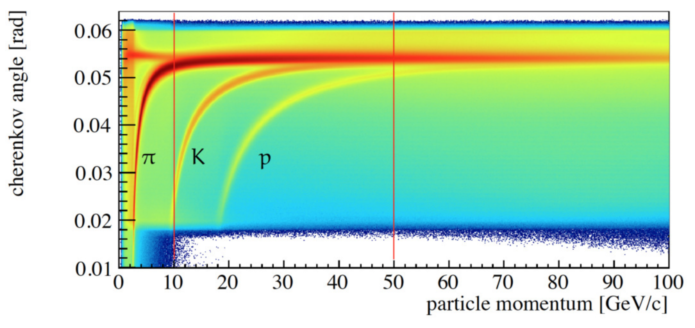

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Detailed studies of experimental setup once beam energy is fixed

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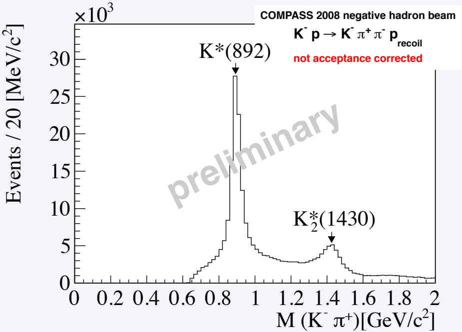
Kaon Spectroscopy: Competition

Decays of τ leptons or heavy mesons

- Mainly BESIII, Belle II, LHCb
- Current data samples typically factor 10 smaller than existing COMPASS data set
- Mass ranges limited

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



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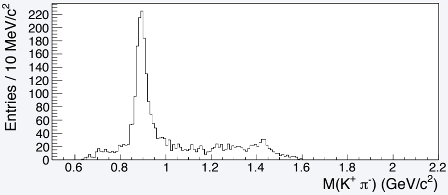

Belle, PRD **83** (2011) 032005

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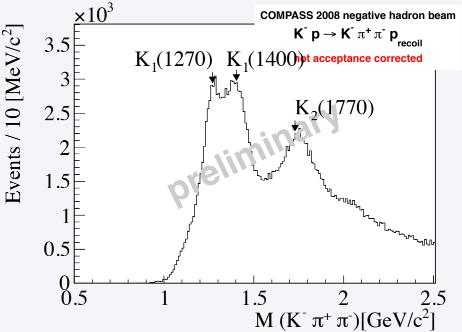

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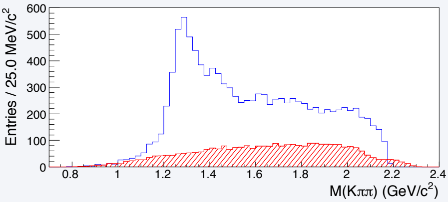

Belle, PRD **83** (2011) 032005

Kaon Spectroscopy: Competition

Photoproduction

- GlueX Phase IV proposal (Jlab)
  - 100×10^6 $KK\pi\pi$ events
  - 30×10^6 $KK\pi$ events
- Excited kaons appear in subsystems
  - Could be extracted using freed-isobar method
  - More complicated compared to direct production
  - Possible distortions due to rescattering effects
  - More difficult to find new states

Kaon Spectroscopy — Competition

Kaon beam experiments

- J-PARC
  - Separated $\bar{p}$ and K^- beams with 2 to 10 GeV/c and 10^7 K^- per spill
  - Low energy ⇒ separation between beam and target excitations difficult
  - Various Regge-exchanges contribute ⇒ more complicated production process
  - Experimental setup with high-precision tracking and calorimetry needed ⇒ not yet planned
- Neutral kaon beam at GlueX (Jlab)
  - K_L^0 beam with 0.3 to 10 GeV/c and $10^4\,s^{-1}$ intensity
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- COMPASS has already acquired the world's largest data sample for $K^- + p \to K^-\pi^+\pi^- + p_{\text{recoil}}$ (8×10^5 events)

Future program

- *Goal:* collect 10 to 20×10^6 $K^-\pi^+\pi^-$ events using high-intensity RF-separated kaon beam
  - Would exceed any existing data sample by at least factor 10
  - *High physics potential:* rewrite PDG for kaon states above $1.5\,\text{GeV}/c^2$ (like LASS and WA03 did 30 year ago)
  - Precision study of $K\pi$ S-wave
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