Kaon and light-meson resonances at COMPASS

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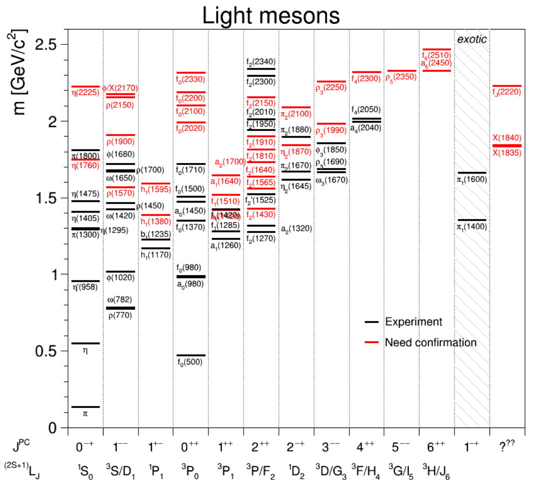
JLab, 14. Feb 2018

Light-Meson Spectrum



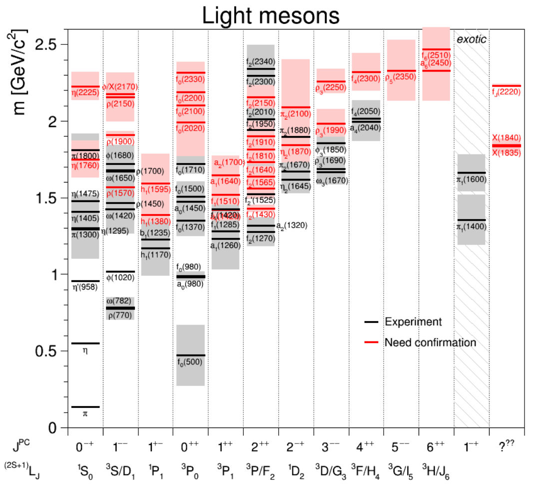
[Courtesy K. Götzen, GSI]

"Light-meson frontier"

- Many states need confirmation in mass region $m \gtrsim 2\,\text{GeV}/c^2$
- 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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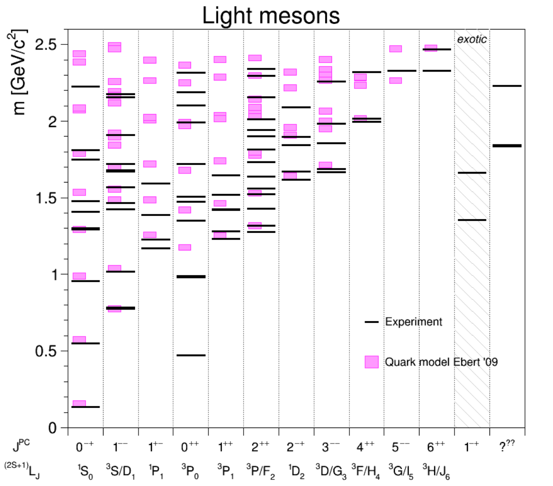

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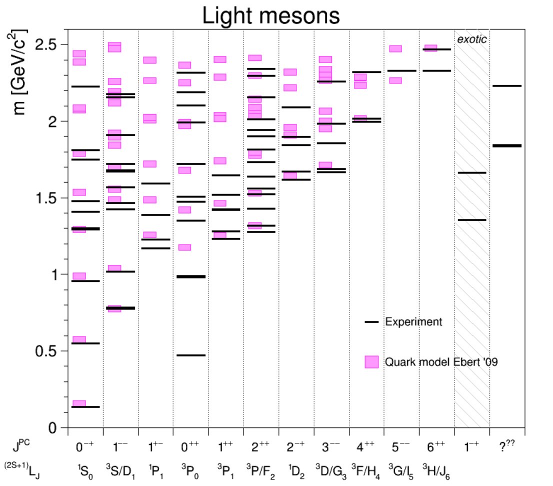

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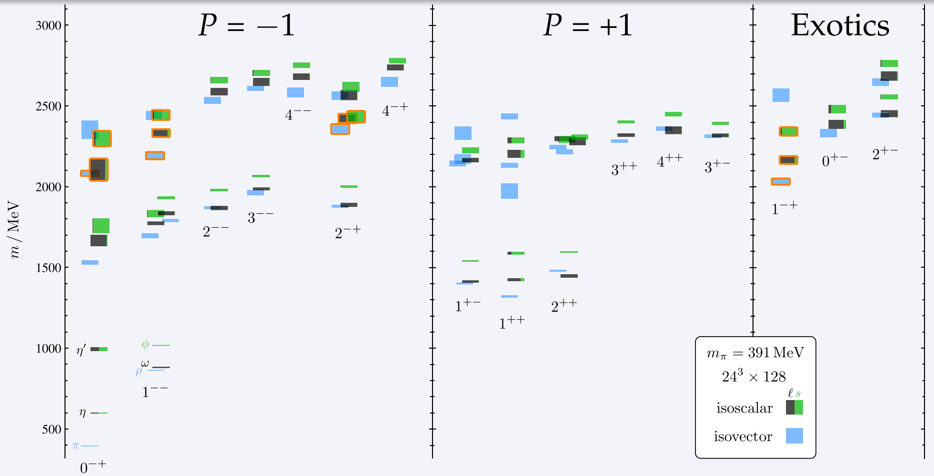
Light-Meson Spectrum from Lattice QCD

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

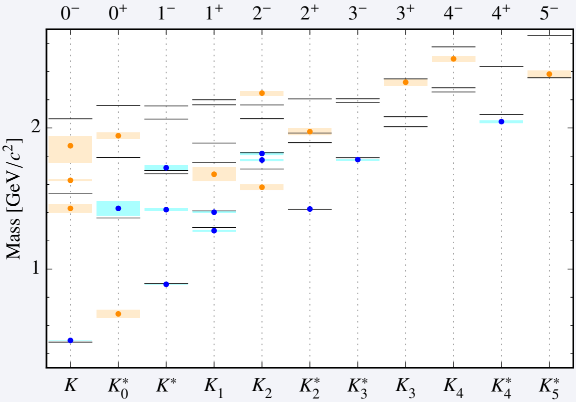


- Essentially recovers quark-model pattern
- High towers of excited states
- Additional hybrid-meson super-multiplet

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]

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
  - $K_0^*(800)$ still listed as "needs confirmation" by PDG

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
  - All kaon states can appear as intermediate state X

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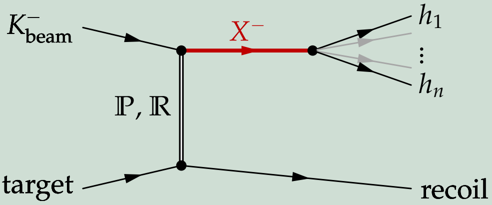
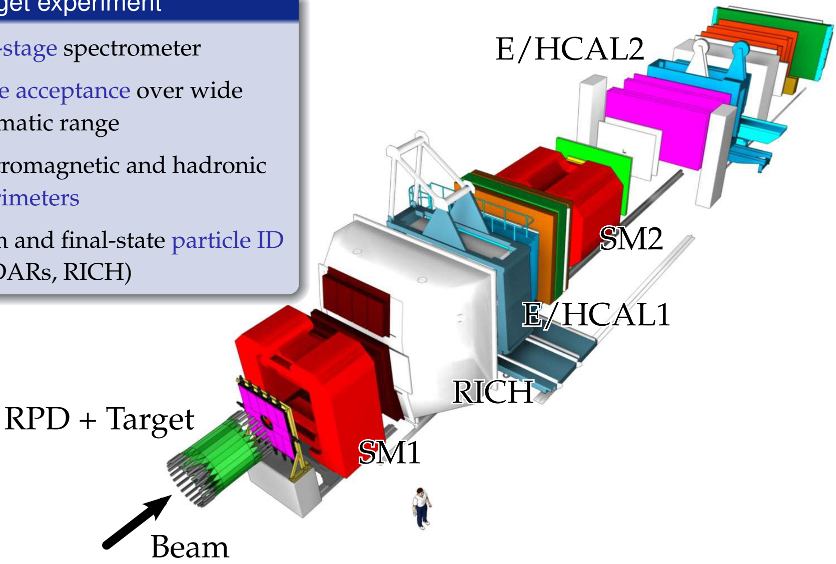


C. Adolph, NIMA **779** (2015) 69

Fixed-target experiment

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



The COMPASS Experiment at the CERN SPS

Experimental Setup

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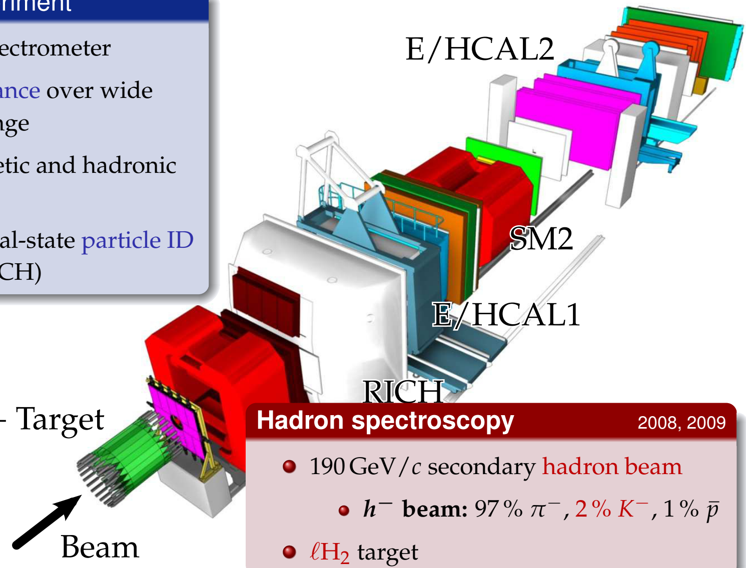
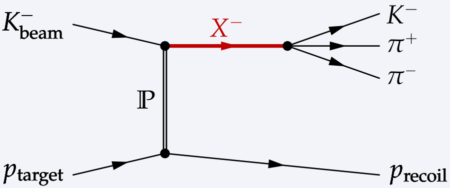


Hadron spectroscopy — 2008, 2009

- 190 GeV/c secondary hadron beam
  - h^- **beam:** 97 % π^-, 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× more π^- than K^- in beam
- Final-state PID via RICH detector
  - Distinguish K^- from π^- over wide momentum range

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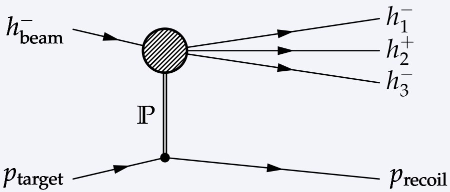

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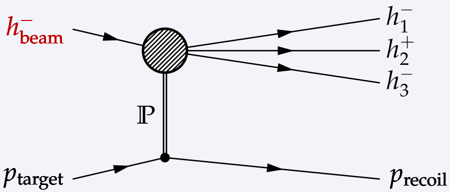

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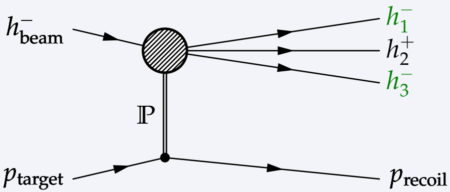

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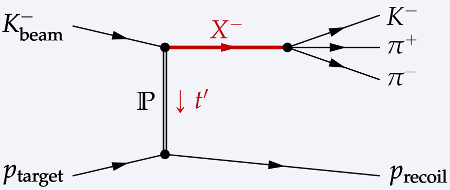
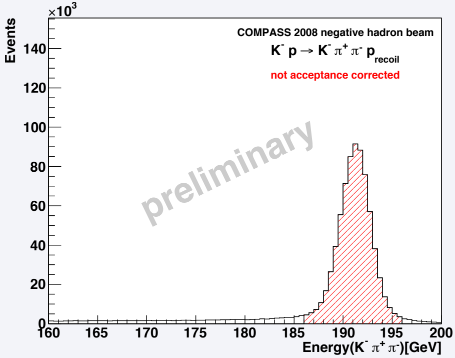
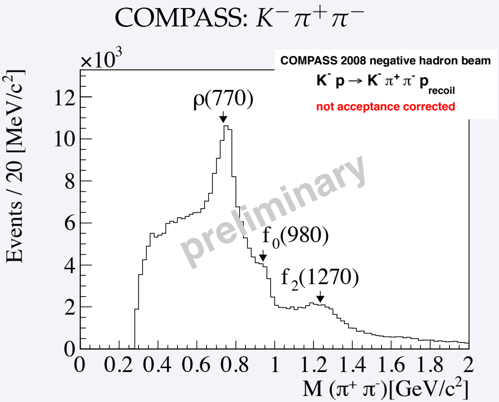


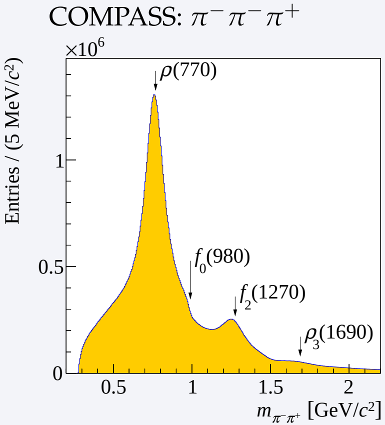
- From 2008 data taking campaign
- 270 000 events
- $0.07 < t' < 0.7\,(\text{GeV}/c)^2$
- Exclusivity ensured by measuring recoil proton
  - Also suppresses target excitations



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

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





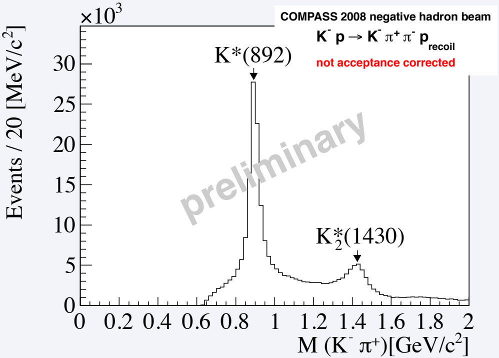
COMPASS, PRD **95** (2017) 032004

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

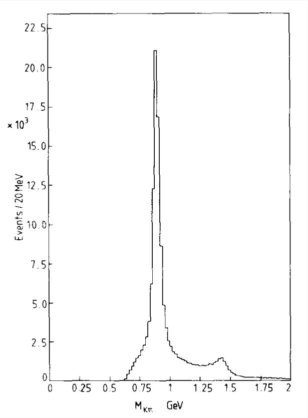
Example: Analysis of $K^-\pi^+\pi^-$ Final State

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

COMPASS



WA03 (CERN)



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

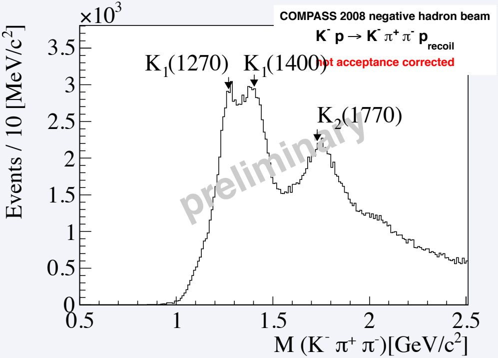
- Clear $K^*(892)$ and $K_2^*(1430)$ signals
- Data set slightly larger than that of most precise previous experiment (WA03)

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

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

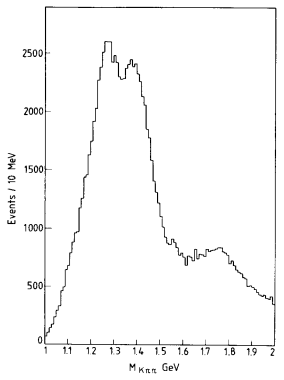
COMPASS

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



WA03 (CERN)

$0 < t' < 0.7\,(\text{GeV}/c)^2$



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

COMPASS

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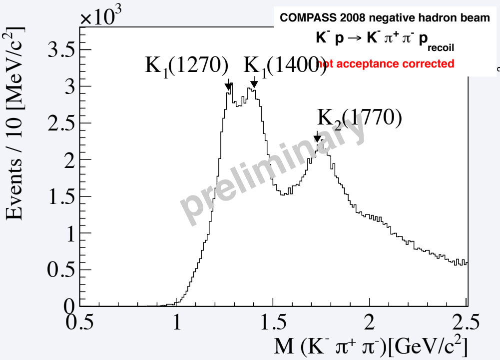
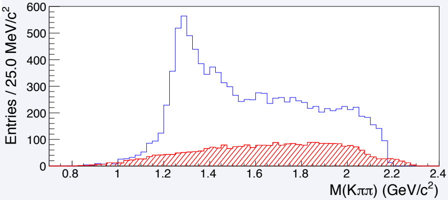


Belle

$B^+ \to J/\psi K^+\pi^+\pi^-$



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

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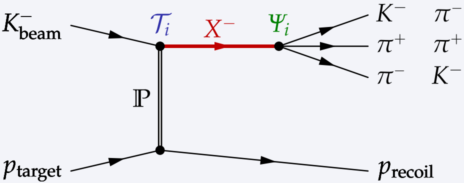
Partial-Wave Analysis Method

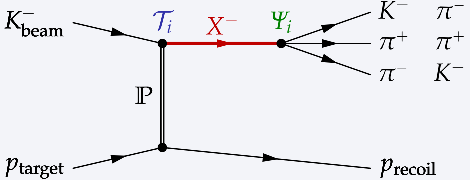
C. Adolph *et al.*, PRD **95** (2017) 032004



Ansatz: Factorization of production and decay

$$\mathcal{I}(\tau; m_X) = \left| \sum_i^{\text{waves}} \mathcal{T}_i(m_X)\, \Psi_i(\tau; m_X) \right|^2$$

- Fit model: coherent sum of partial-wave amplitudes
- Decay amplitudes $\Psi_i(\tau; m_X)$
  - Describe kinematic distribution of partial waves
  - Calculated using isobar model and helicity formalism (Wigner D-functions)
- Transition amplitudes $\mathcal{T}_i(m_X) \Rightarrow$ interesting physics
  - m_X dependence unknown
  - Extracted from data by performing PWA fit in narrow m_X bins



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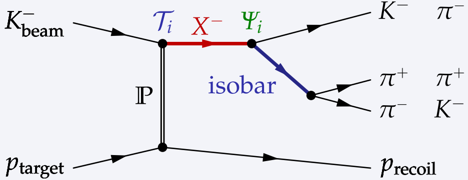

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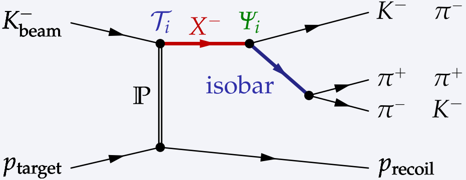

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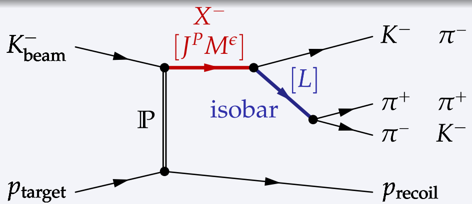
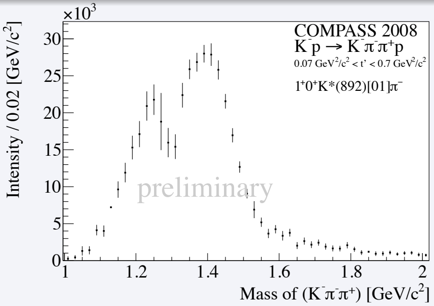
Partial-Wave Analysis of $K^- \pi^+ \pi^-$ Final State



PWA model similar to WA03

$$\mathcal{I}(\tau; m_X) = \left| \sum_i^{\text{waves}} \mathcal{T}_i(m_X)\, \Psi_i(\tau; m_X) \right|^2$$

- 6 isobars
  - $\pi^-\pi^+$ subsystem: $f_0(500)$, $\rho(770)$, and $f_2(1270)$
  - $K^-\pi^+$ subsystem: $K_0^*(800)$, $K^*(892)$, and $K_2^*(1430)$
    - $K_0^*(800)$ described by Breit-Wigner amplitude
- 19 waves = combinations of X^- quantum numbers and decay modes

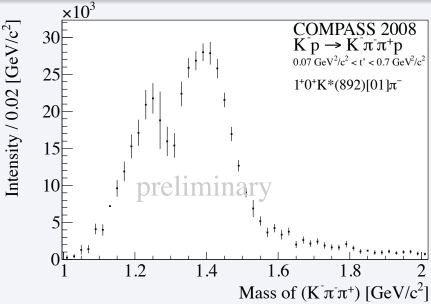


$1^+ \to K^*(892) + \pi^-$ in S-wave

- 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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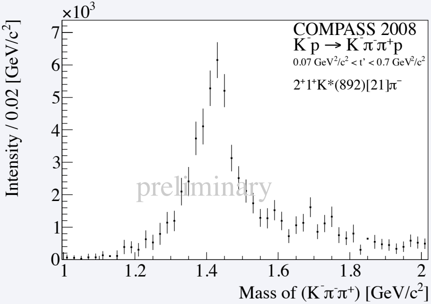

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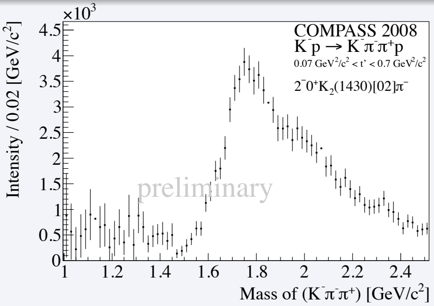
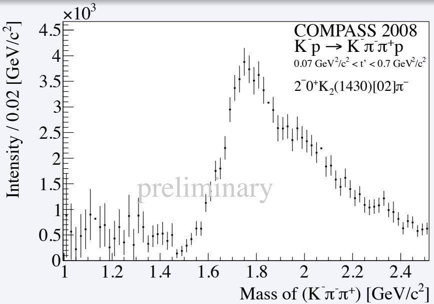


$2^- \to K_2^*(1430) + \pi^-$ in S-wave

- 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. 800 000 $K^-\pi^+\pi^-$ events
  $\Rightarrow$ world's largest data set ($4\times$ WA03)
- Improved PWA model $\Rightarrow$ clearer resonance signals
- Resonance-model fit $\Rightarrow$ extraction of $K^-\pi^+\pi^-$ resonances and their parameters



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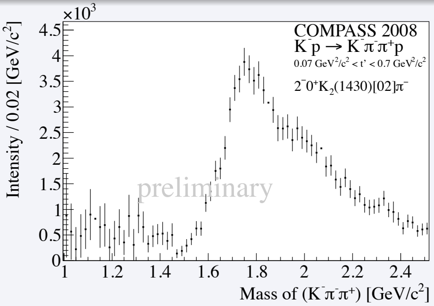

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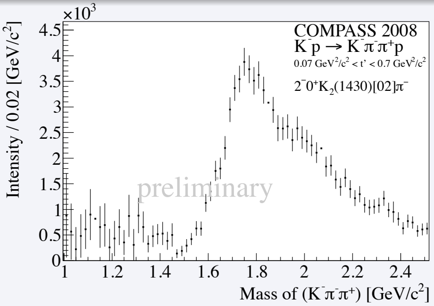

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Further final states accessible by COMPASS

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

Possible Future Measurements with Kaon Beam

CERN's "Physics beyond Colliders" initiative

- Exploratory study of scientific potential of accelerator complex and scientific infrastructure
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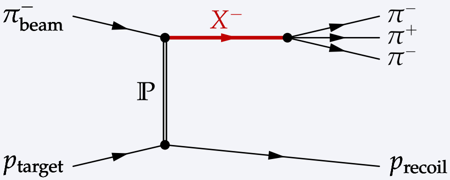
Why do we need even larger data sets?

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

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



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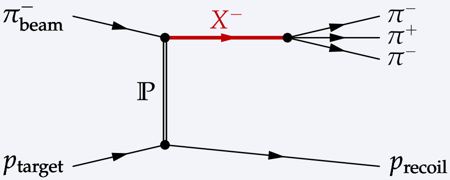

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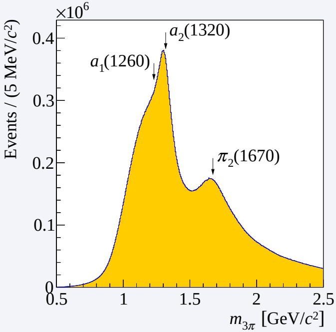

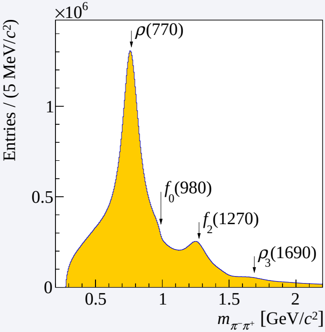

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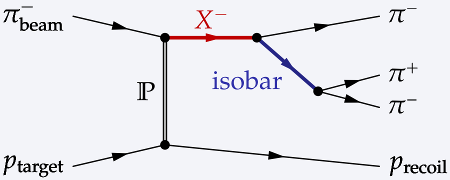

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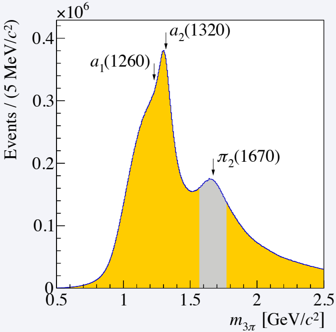

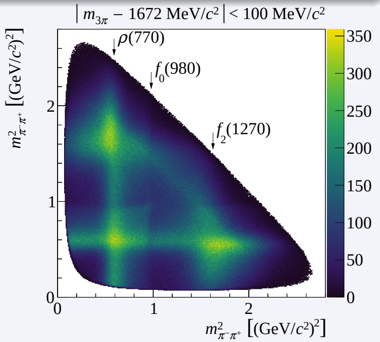

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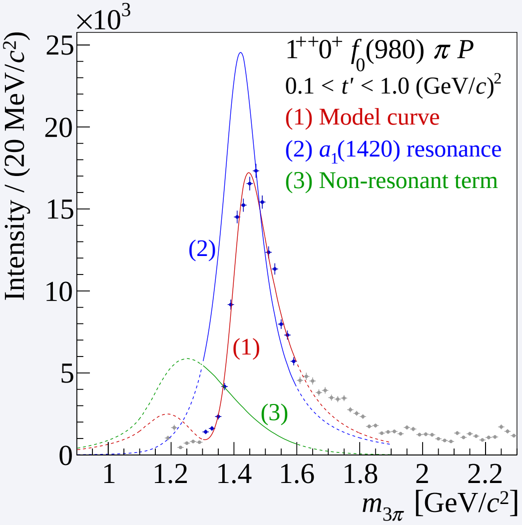
Improved sensitivity for small signals

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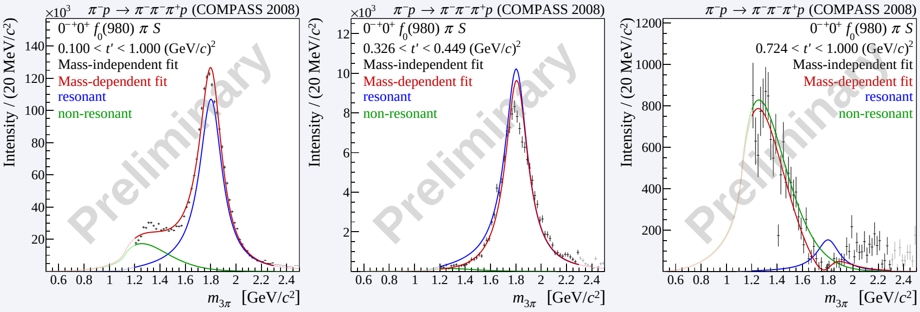
PWA in narrow bins of four-momentum transfer squared t'

- 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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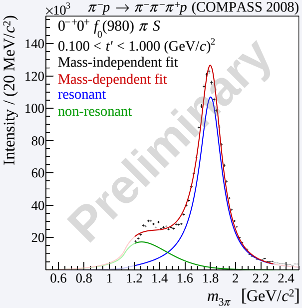

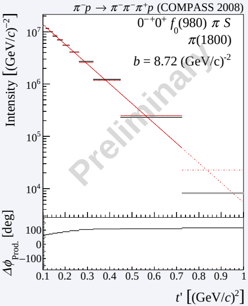

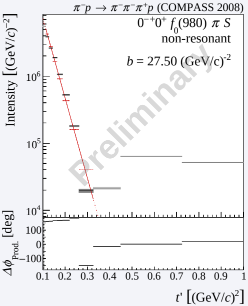

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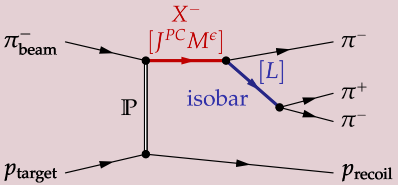
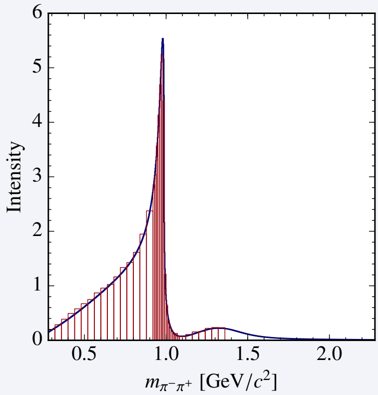
Novel analysis technique
"freed-isobar" PWA

[arXiv:1710.09849]



- 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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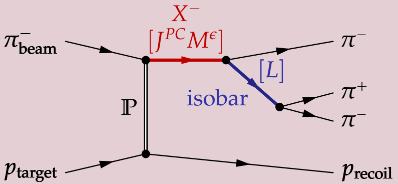

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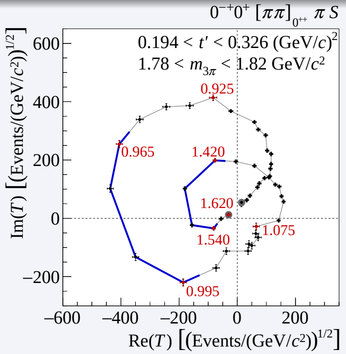

COMPASS, PRD **95** (2017) 032004

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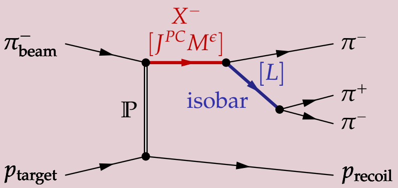

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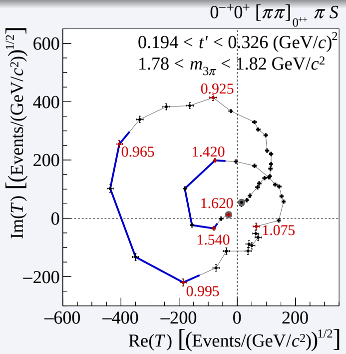

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- Would allow to study $K^-\pi^+$ subsystem with $J^P = 0^+$ in $K^-\pi^+\pi^-$
- Requires huge data samples

How to get more data?

Current parameters of h^- beam

- Composition: $97\,\%\ \pi^-$, $2\,\%\ K^-$, $1\,\%\ \bar{p}$
- Intensity: $5 \times 10^6\ \mathrm{s}^{-1}$ for approximately $10\,\mathrm{s}$ every $45\,\mathrm{s}$
  - 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 SPS M2 beam line

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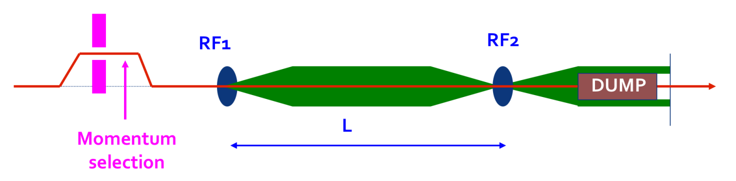

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- Lower beam momentum $\lesssim 100\,\mathrm{GeV}/c$
  - Not an issue: diffractive production depends only weakly on energy
- Estimated kaon intensity: $3.7 \times 10^6\,\mathrm{s}^{-1}$
  - More than factor 35 increase w.r.t. conventional beam line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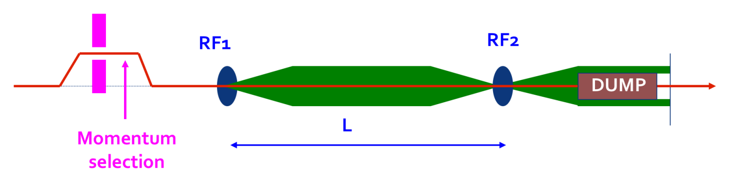

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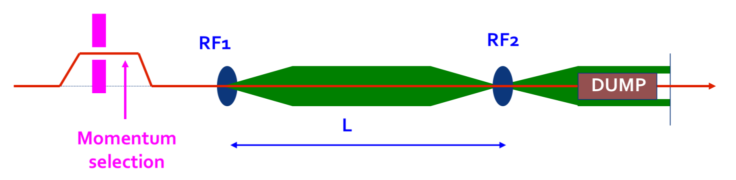

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- High-resolution silicon beam telescope and vertex detector
- Improve detection of target recoil particle
  - Ensures exclusivity of measured events
- Improve PID of final-state particles
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  - Provides access to interesting final states: $K^-\pi^0\pi^0, K^-\omega, K^-\eta^{(\prime)}, \ldots$

Work in progress

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Kaon spectroscopy

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