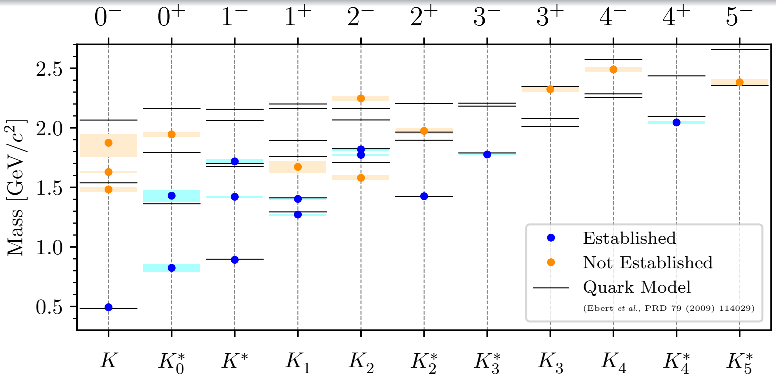
Measuring Excitation Spectra in $K\pi\pi$ Final States with AMBER Phase-2

Boris Grube

Institute for Hadronic Structure and Fundamental Symmetries
Technische Universität München
Garching, Germany

Perceiving the Emergence of Hadron Mass
through AMBER@CERN
CERN, 27. Apr 2021

Why Kaon Spectroscopy?



[Courtesy S. Wallner, TUM]

PDG 2020: 25 kaon states below 3.1 GeV / c^2

- Only 13 kaon states well established, 12 need confirmation
- Many predicted quark-model states still missing
- Some hints for supernumerous states $\Rightarrow$ non-$q\bar{q}$ states?

Why Kaon Spectroscopy?

Little progress in the past

- Many kaon states need confirmation
- Many PDG entries more than 30 years old
- Since 1990: 4 kaon states added to PDG (1 to summary table)

Kaon spectrum crucial to understand light-meson spectrum

- Identify supernumerous states by completing $\mathrm{SU}(3)_{\mathrm{flavor}}$ multiplets
  - E.g. $J^P = 0^+$ nonet with $a_0(980)$, $K_0^*(700)$ [or κ], $f_0(500)$ [or σ], and $f_0(980)$ is hypothesized to be tetra-quark multiplet
  - $K_0^*(700)$ still listed as "needs confirmation" by PDG

Kaon spectrum required as input in other fields

- E.g. search for CP violation in multi-body decays of heavy mesons such as $B^\pm \to D^0\, K^\pm$ with $D^0 \to K_S^0\, \pi^+\, \pi^-$
  - Amplitude analysis of D^0 Dalitz plot requires accurate knowledge of resonances in $K_S^0\, \pi^\pm$ and $\pi^+\, \pi^-$ subsystems

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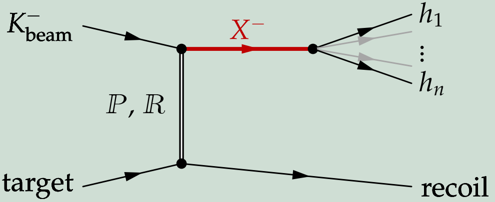
Kaon Spectroscopy at COMPASS

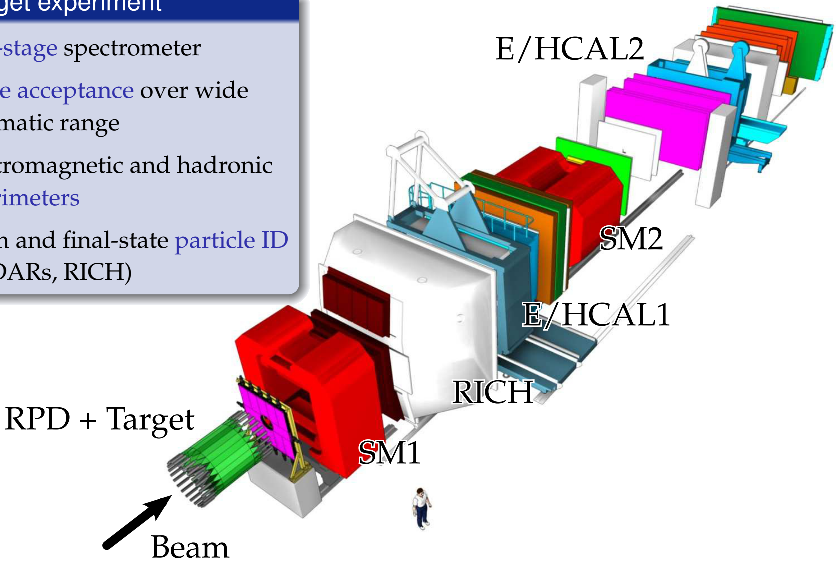
Main production process: diffractive dissociation



- 190 GeV/c kaon beam on stationary proton or nuclear target
- Process has large cross section
- Triggering on target recoil ensures elastic scattering at target vertex
- Decays into various hadronic n-body final states measurable
- n-body final state strongly boosted
  $\Rightarrow$ measured by forward spectrometer

Fixed-target experiment

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



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

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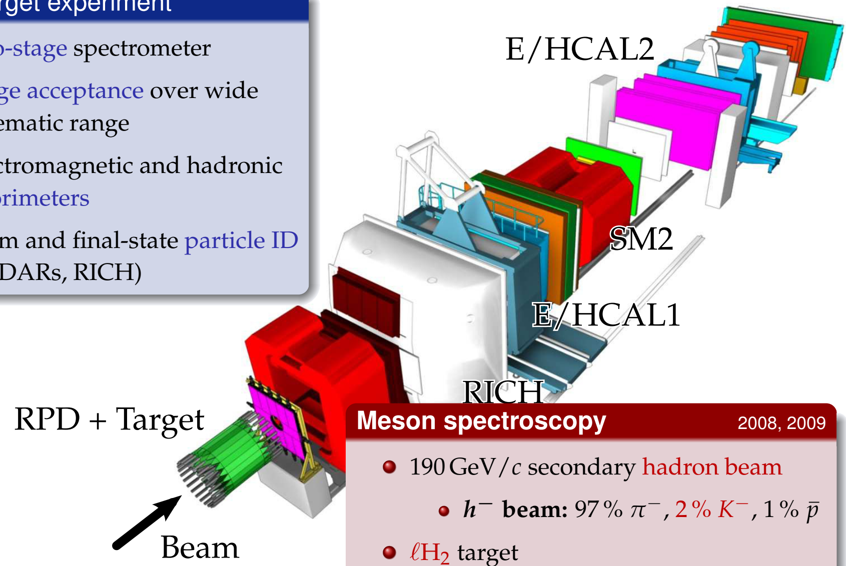
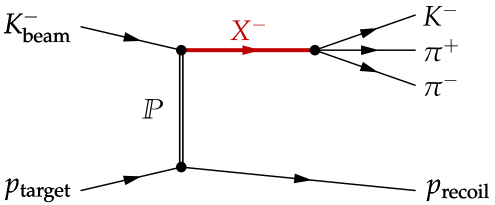


Meson spectroscopy
2008, 2009

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

Diffractive Production of $K^- \pi^- \pi^+$

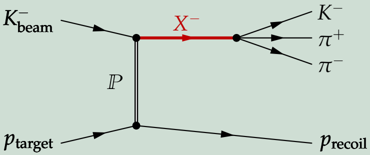


The “golden” channel for kaon spectroscopy

- All kaon states (except $J^P = 0^+$) can appear as intermediate states X^-
- Highly excited states prefer to decay into multi-body final states
- Allows us to study several decay modes in one analysis, e.g.
  - $X^- \to \rho(770)\,K^-, f_2(1270)\,K^-, \ldots$
  - $X^- \to K^*(892)\,\pi^-, K_2^*(1430)\,\pi^-, \ldots$
- Strange partner process to $\pi^- + p \to \pi^-\pi^-\pi^+ + p$
  - Studied in great detail at COMPASS

Diffractive Production of $K^-\pi^-\pi^+$ at COMPASS

190 GeV/c K^- beam on p target



- Beam contains 2.4 % K^-
- 720 000 exclusive events
- $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Potential resonance signals
  - Need partial-wave analysis (PWA) to disentangle
- Largest data sample so far
  $\approx 3.5\times$ larger than WA03 sample

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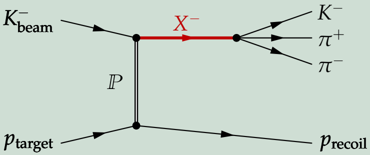

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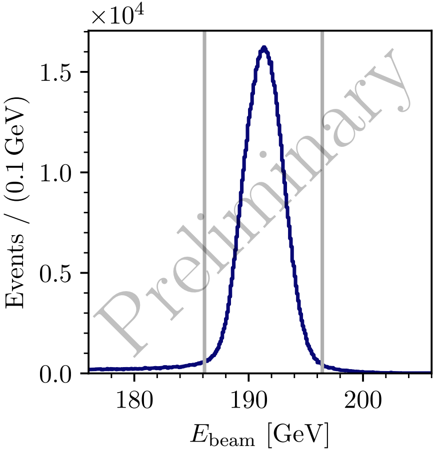

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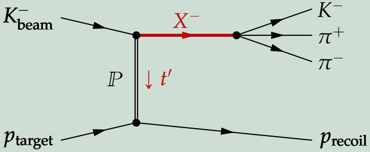

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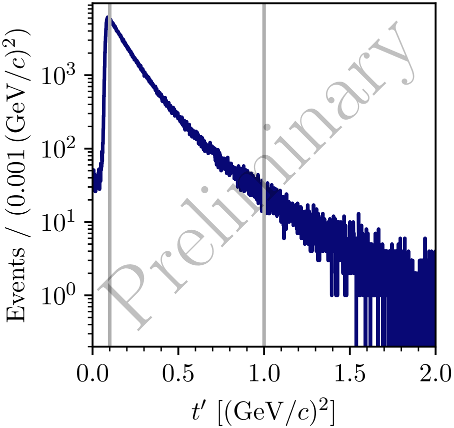

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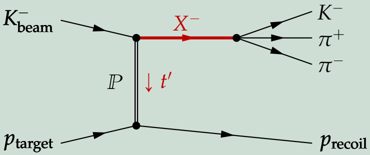

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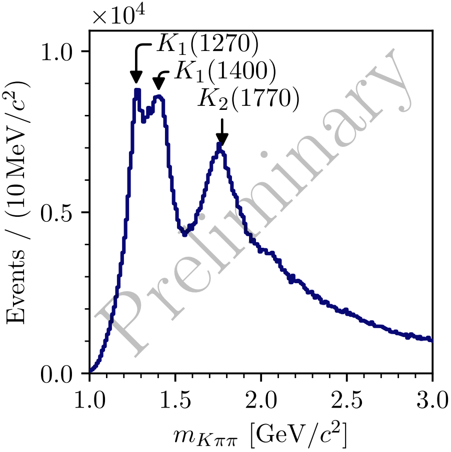

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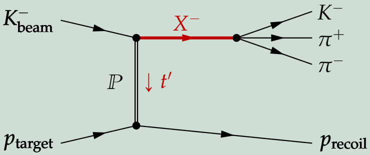

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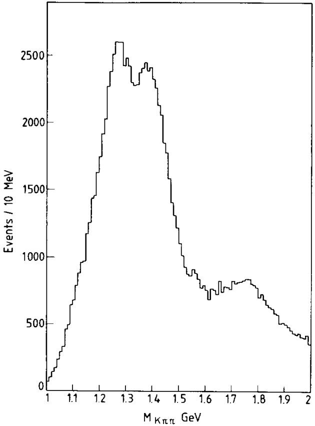
WA03 (CERN):

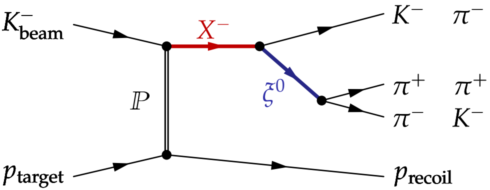
200 000 events

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



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

Partial-Wave Analysis of $K^-\pi^-\pi^+$: Isobar Model



- J^P of a resonance determines angular distribution of daughter particles
- *Analogy:* multipole radiation in classical electrodynamics
- Determine J^P of intermediate resonances X^- and ξ^0 from measured angular distribution of final-state particles

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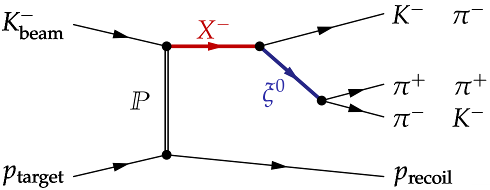

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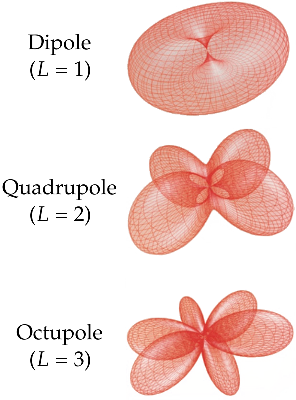

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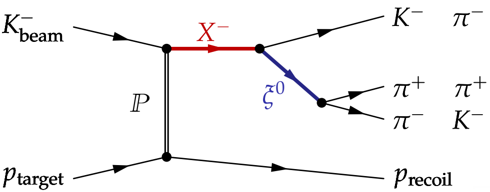

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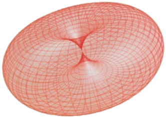
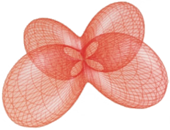
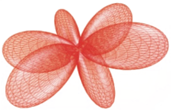
Dipole
($L = 1$)



Quadrupole
($L = 2$)



Octupole
($L = 3$)



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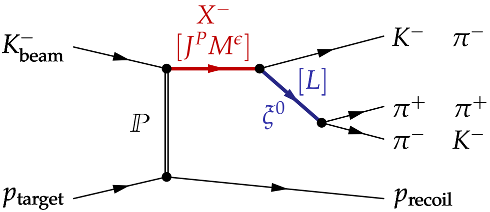

For $m_{K\pi\pi}$ = const, $K\pi\pi$ kinematic distribution is completely defined by:

- $J^P\ M^\varepsilon$ quantum numbers of X^-
- Orbital angular momentum L between ξ^0 and bachelor π/K
- Isobar resonance $\xi^0 \Rightarrow$ model for $m_{\pi^-\pi^+}/m_{K^-\pi^+}$ dependence of amplitude
  - E.g. Breit-Wigner amplitudes for $\rho(770) \to \pi^-\pi^+$ and $K^*(892) \to K^-\pi^+$
- *Partial wave:* represents specific 5-dimensional kinematic distribution

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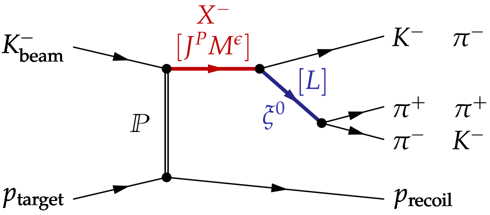

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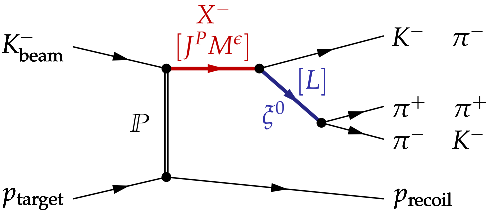
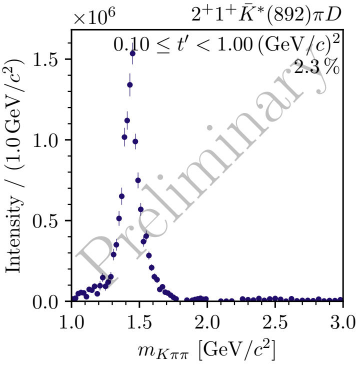


PWA model

- Sum of partial-wave amplitudes
- Wave set:
  - Spin $J \leq 7$
  - Orbital angular momentum $L \leq 7$
  - Positive naturality of the exchange particle
  - 12 isobar resonances:
    - $[K\pi]_S^{K\pi}$, $[K\pi]_S^{K\eta}$, $K^*(892)$, $K_2^*(1430)$, $K^*(1680)$, $K_3^*(1780)$
    - $[\pi\pi]_S$, $f_0(980)$, $f_0(1500)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$

Partial-Wave Analysis of $K^-\pi^-\pi^+$ at COMPASS

Example: $J^P = 2^+$ Waves



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- In agreement with WA03 result
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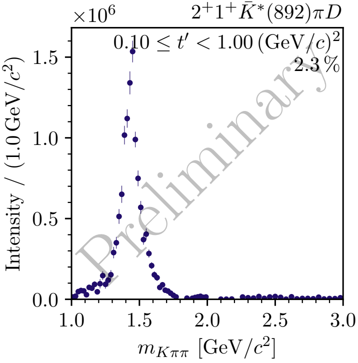
COMPASS



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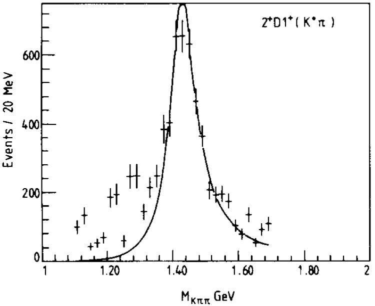

ACCMOR, NPB **187** (1981) 1

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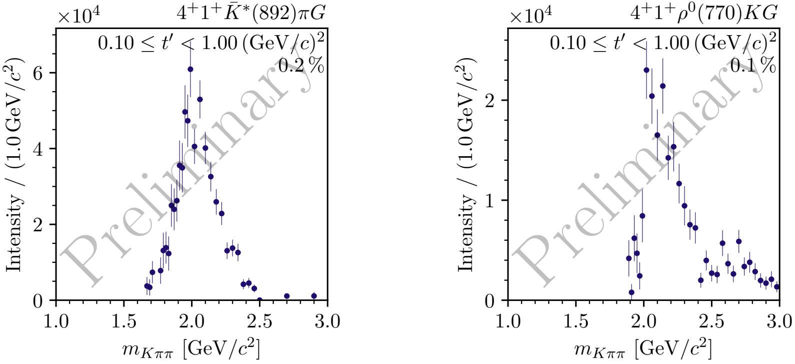
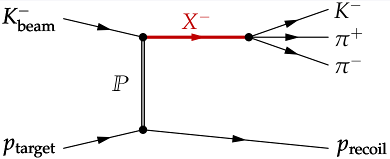
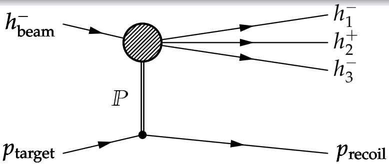
Example: $J^P = 4^+$ Waves



- Small waves: order of per-mille of total intensity
- Signals for $K_4^*(2045) \rightarrow K^*(892)\,\pi$ and $\rho(770)\,K$



- Beam-particle ID via Cherenkov detectors (CEDARs)
  - Ca. $40\times$ more π^- than K^- in beam $\Rightarrow$ likelihood approach
- Final-state PID via RICH detector
  - Issue: limited momentum range for π^- and K^- ID



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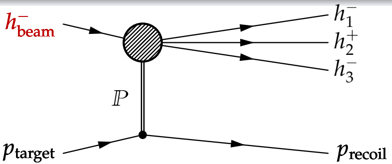

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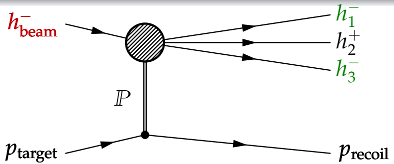
Partial-Wave Analysis of $K^-\pi^-\pi^+$ at COMPASS

Challenge: Particle Identification



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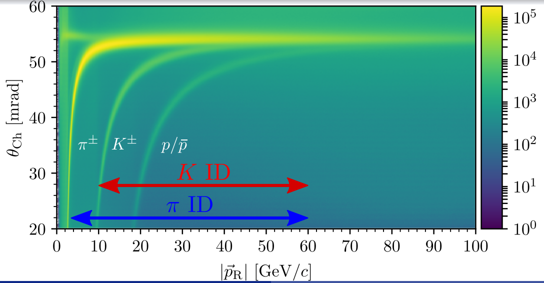
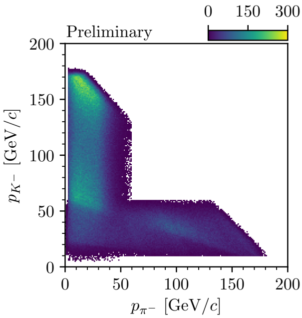


Partial-Wave Analysis of $K^-\pi^-\pi^+$ at COMPASS

Challenge: non-uniform Acceptance due to RICH Particle ID



- Kinematic region with vanishing acceptance $\Rightarrow$ not recoverable
- Decay amplitudes of waves with different J^P are orthogonal
- Acceptance leads to loss of orthogonality for some waves $\Rightarrow$ reduced distinguishability

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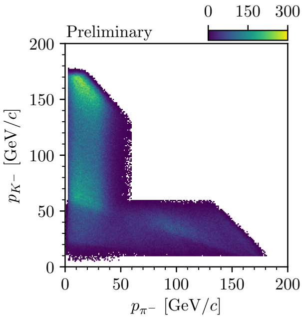

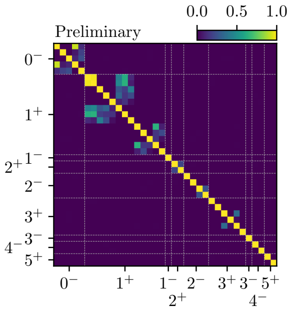

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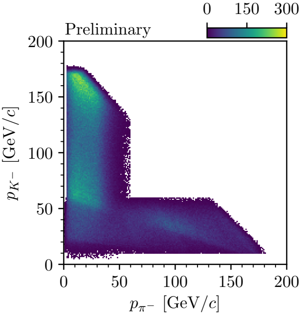

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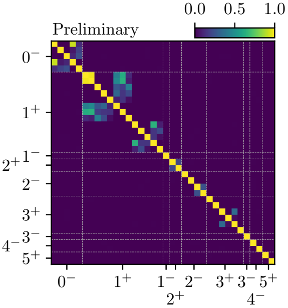

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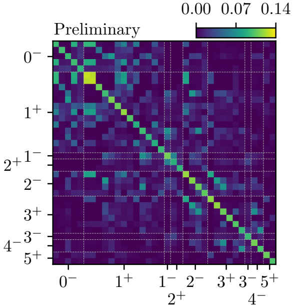

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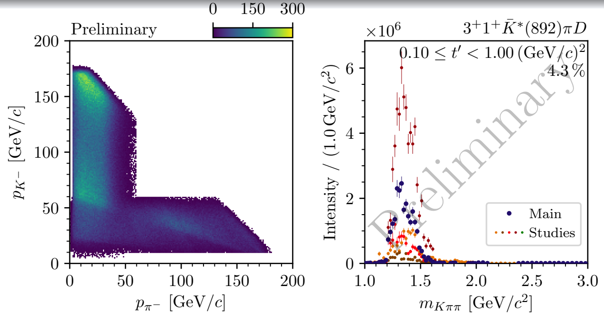

Leakage effects in PWA

- Unphysical enhancement of intensity at low $m_{K\pi\pi}$ in some waves; depends strongly on RICH cut and PWA model
  - Induced by loss of orthogonality of decay amplitudes
  - Only subset of waves affected
- Extraction of resonances from unaffected waves still possible
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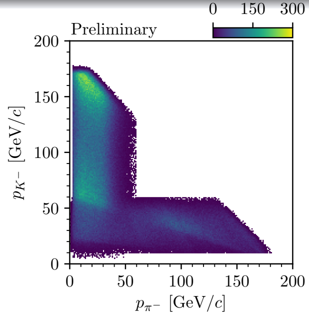
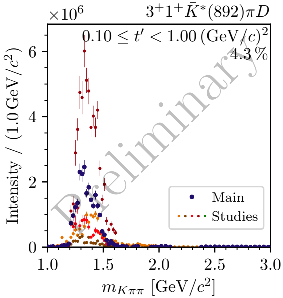
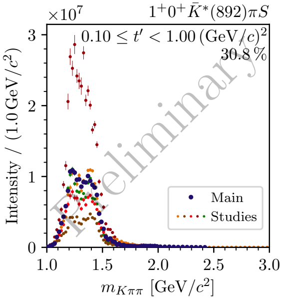
Partial-Wave Analysis of $K^-\pi^-\pi^+$ at COMPASS

Challenge: non-uniform Acceptance due to RICH Particle ID







Leakage effects in PWA

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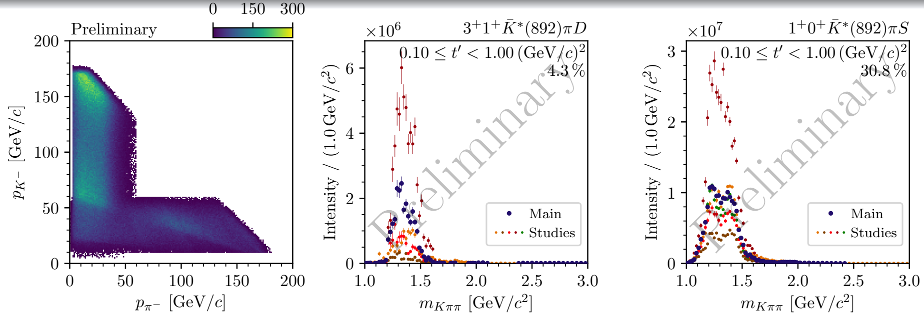

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Goal: $10\times$ world data

- Using diffraction of high-energy kaon beam (as COMPASS)
- Corresponds to $> 10^7$ $K^-\pi^-\pi^+$ events
- Also gives access to other channels with smaller branching fraction and/or acceptance, e.g.
  - $K^-\pi^0\pi^0$, $K_S^0\pi^-\pi^0$ $\Rightarrow$ important cross-checks for $K^-\pi^-\pi^+$
  - 2-body channels: $K_S^0\pi^-$, $K^-\pi^0$, $K^-\eta^{(\prime)}$, $K^-\omega$, …
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- **Main limiting factor:** only 2.4 % K^- fraction in beam
  - Intensity of K^- component: $10^5\,\mathrm{s}^{-1}$ for approximately 10 s every 45 s
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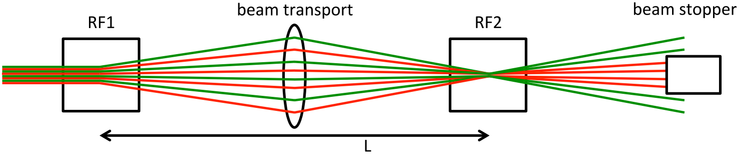
RF-separated Kaon Beam at SPS M2 Beam Line

Panofsky-Schnell Method

P. Bernard *et al.*, CERN-1968-029



- Beam momentum limited by length of beam line
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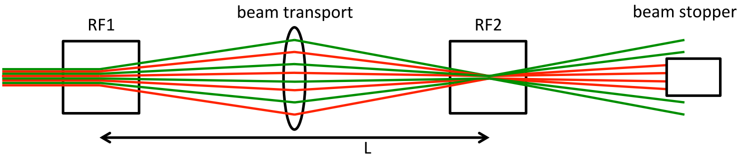

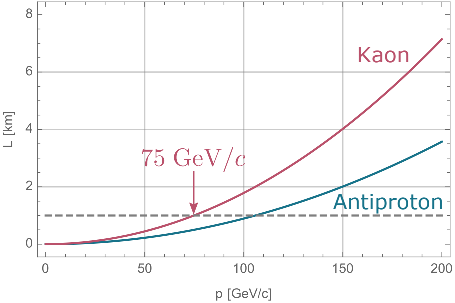

L. Gatignon, J. Bernhard, *et al.*,

CERN-PBC-REPORT-2018-002

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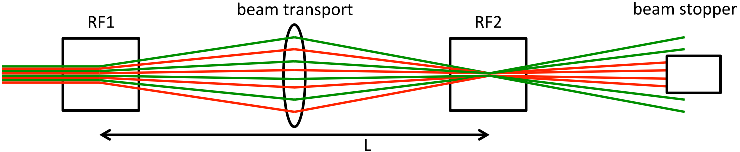

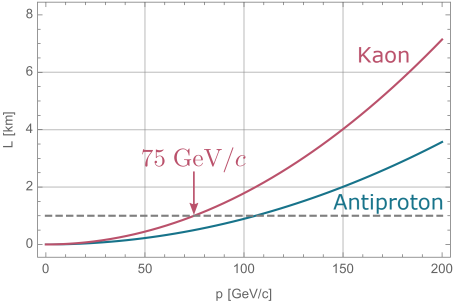

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- Upgrade beam PID; adjust for lower beam momentum
  - Improve rate capability and thermal stability of CEDARs
  - Improve measurement of beam trajectories at CEDAR position
    $\Rightarrow$ silicon beam momentum stations?
- High-resolution silicon beam telescope and vertex detector
- Improve detection of target recoil particle
- **Extend kinematic coverage of final-state PID**
  - Minimize leakage effects in PWA
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AMBER

- **Goal:** collect $10\times$ world data using high-intensity RF-separated kaon beam
- **High physics potential:**
  - All states (except $J^P = 0^+$) directly accessible
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  - AMBER could rewrite PDG for kaon states above $1.5\,\text{GeV}/c^2$
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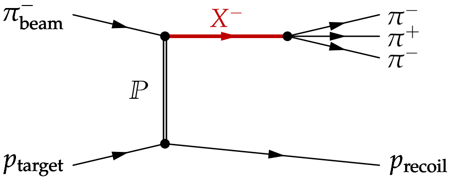
Outline

Why do we need more data?

Example: $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$ COMPASS, PRD **95** (2017) 032004



- 46×10^6 $\pi^-\pi^-\pi^+$ events $\Rightarrow$ approx. $10\times$ previous experiments

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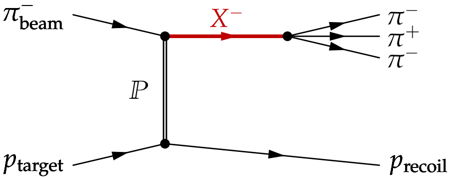

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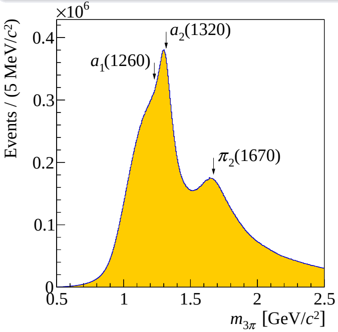

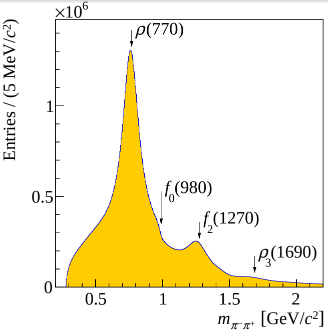

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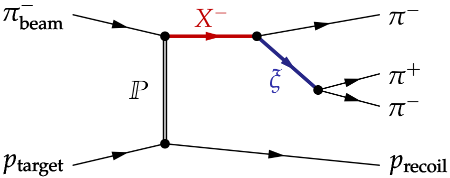

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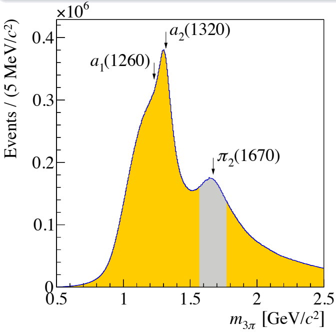

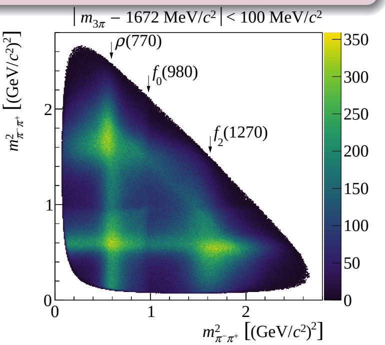

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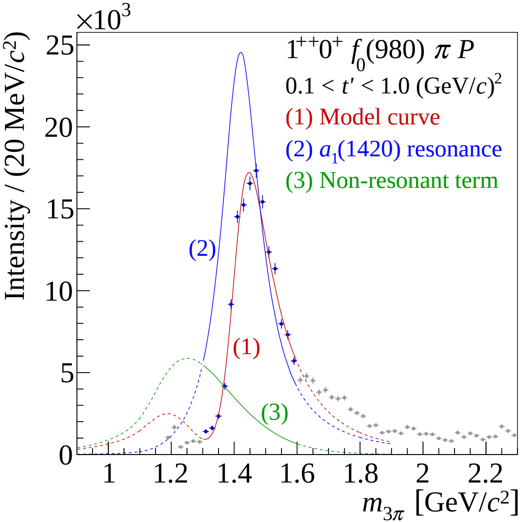
Improved sensitivity for small signals

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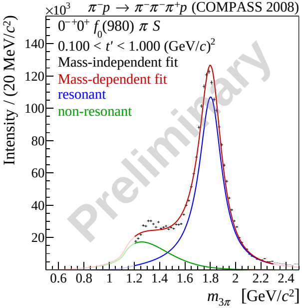
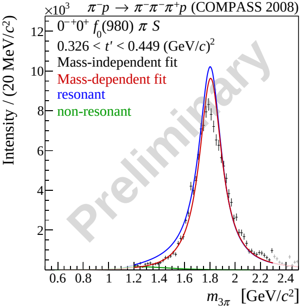
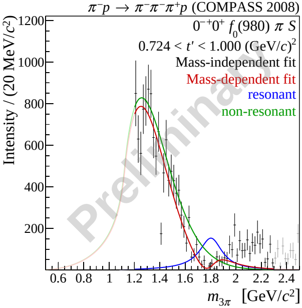
PWA in narrow bins of four-momentum transfer squared t'

- 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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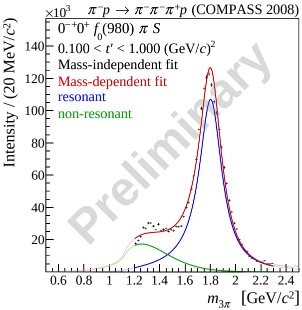

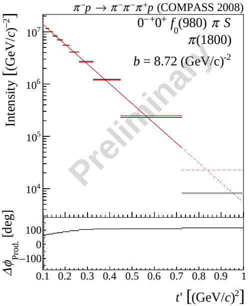

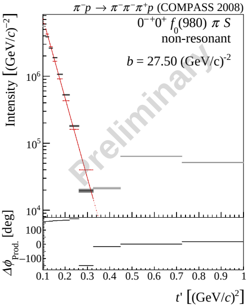

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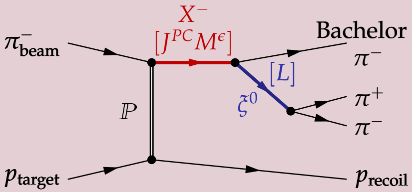
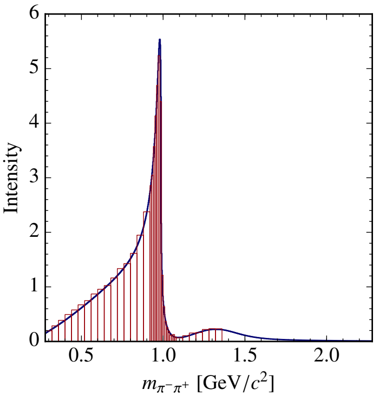
Novel analysis technique: "freed-isobar" PWA

Krinner *et al.*, PRD **97** (2018) 114008



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



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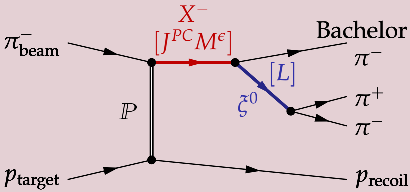

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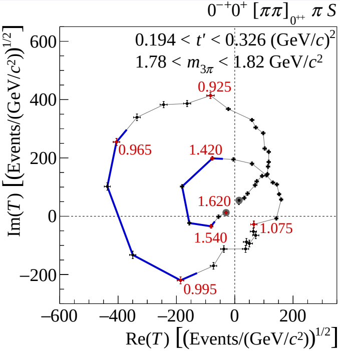

COMPASS, PRD **95** (2017) 032004

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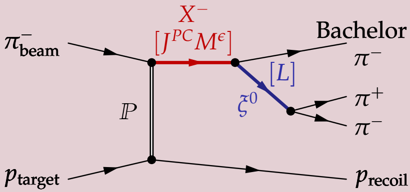

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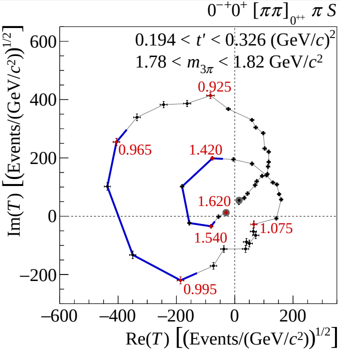

COMPASS, PRD **95** (2017) 032004

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