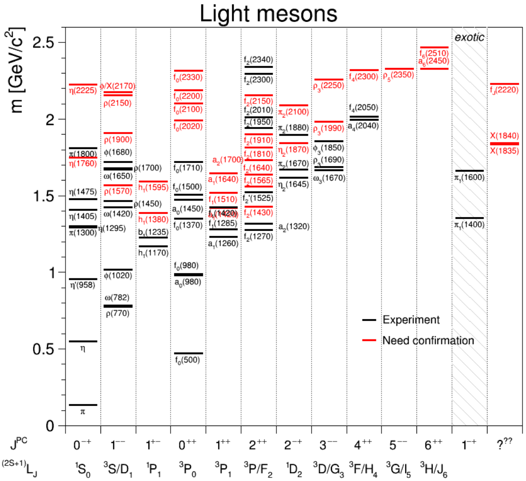
Hadron Spectroscopy at AMBER

Boris Grube

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

Perceiving the Emergence of Hadron Mass
through AMBER@CERN
CERN, 01. Apr 2020

Spectrum of non-strange light Mesons



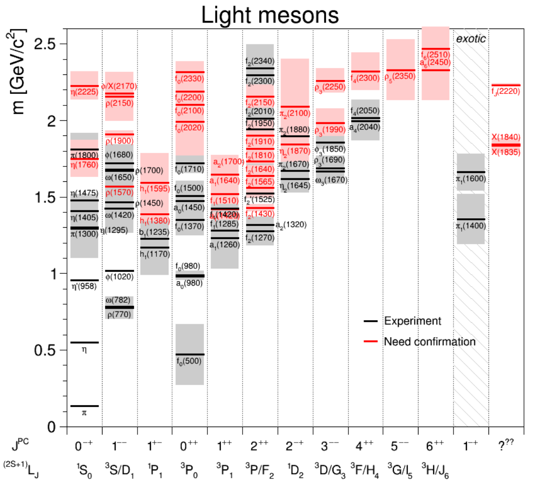
[Courtesy K. Götzen, GSI]

"Light-meson frontier"

- Many states need confirmation in mass region $m \gtrsim 2\,\mathrm{GeV}/c^2$
- Many wide states ⇒ overlap and mixing
- Identification of higher excitations becomes exceedingly difficult
- Existence of multi-quark, hybrid, or glueball states is unclear

Main focus of current COMPASS program

Spectrum of non-strange light Mesons



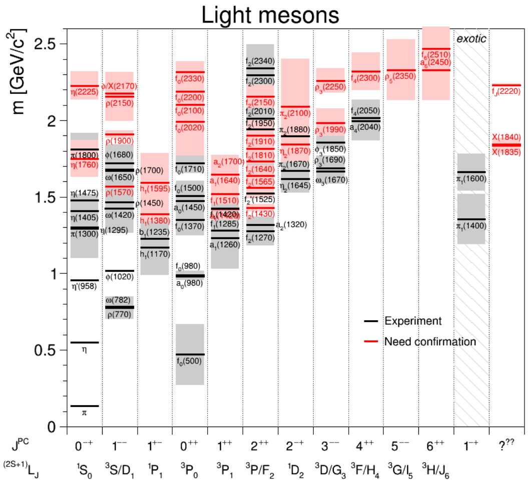
[Courtesy K. Götzen, GSI]

"Light-meson frontier"

- Many states need confirmation in mass region $m \gtrsim 2\,\text{GeV}/c^2$
- Many wide states ⇒ overlap and mixing
- Identification of higher excitations becomes exceedingly difficult
- Existence of multi-quark, hybrid, or glueball states is unclear

Main focus of current COMPASS program

Spectrum of non-strange light Mesons



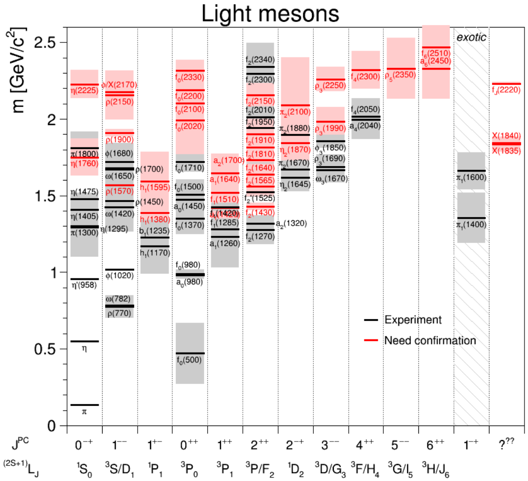
[Courtesy K. Götzen, GSI]

"Light-meson frontier"

- Many states need confirmation in mass region $m \gtrsim 2\,\mathrm{GeV}/c^2$
- Many wide states ⇒ overlap and mixing
- Identification of higher excitations becomes exceedingly difficult
- Existence of multi-quark, hybrid, or glueball states is unclear

Main focus of current COMPASS program

Spectrum of non-strange light Mesons



[Courtesy K. Götzen, GSI]

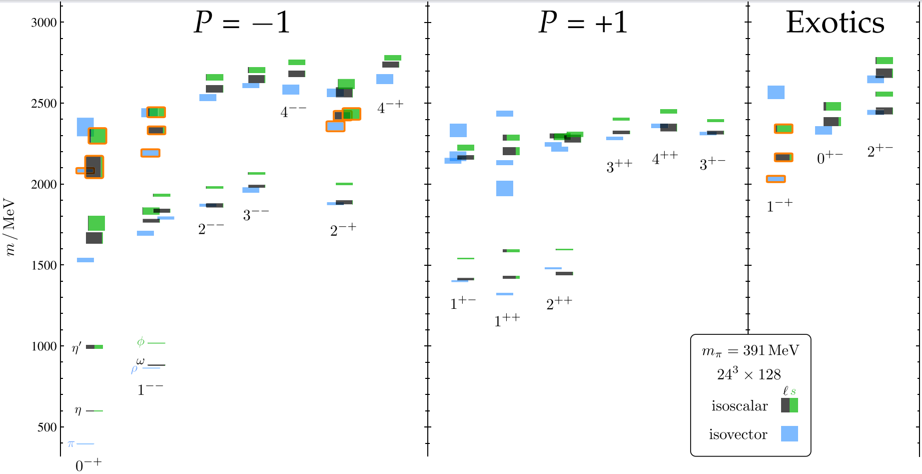
"Light-meson frontier"

- 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
- Existence of multi-quark, hybrid, or glue-ball states is unclear

Main focus of current COMPASS program

Spectrum of non-strange light Mesons from Lattice QCD

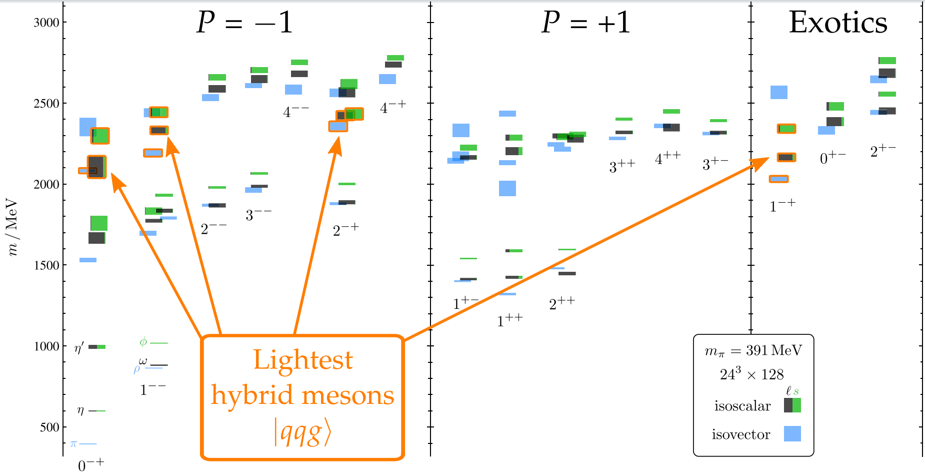
State-of-the-Art Calculation with $m_\pi = 391\ \text{MeV}/c^2$ — Dudek *et al.*, PRD **88** (2013) 094505



- High towers of excited states; patter similar to quark-model
- Additional hybrid-meson super-multiplet
- Quasi-stable states ⇒ no predictions for decay modes and widths

Spectrum of non-strange light Mesons from Lattice QCD

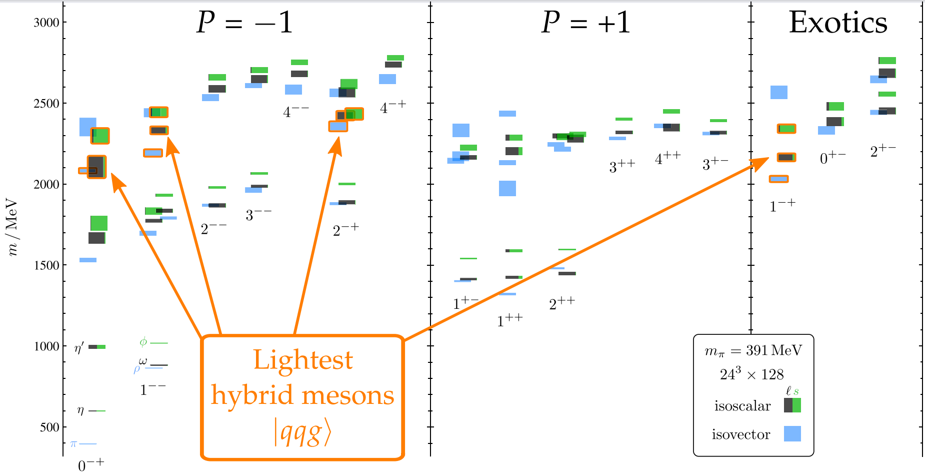
State-of-the-Art Calculation with $m_\pi = 391\ \mathrm{MeV}/c^2$ — Dudek *et al.*, PRD **88** (2013) 094505



- High towers of excited states; patter similar to quark-model
- Additional hybrid-meson super-multiplet
- Quasi-stable states ⇒ no predictions for decay modes and widths

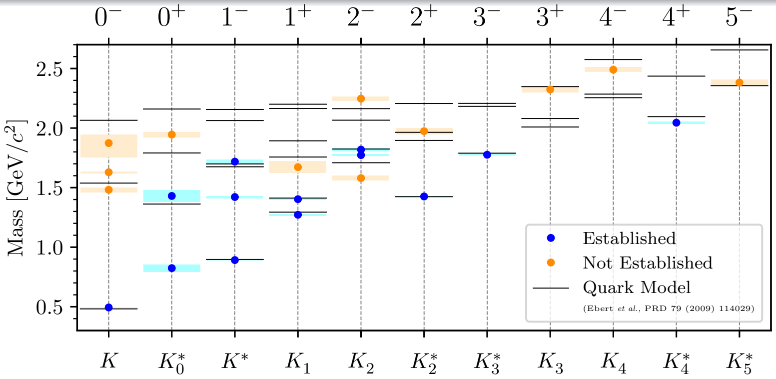
Spectrum of non-strange light Mesons from Lattice QCD

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



- High towers of excited states; patter similar to quark-model
- Additional hybrid-meson super-multiplet
- Quasi-stable states $\Rightarrow$ no predictions for decay modes and widths

Spectroscopy of strange Mesons



[Courtesy S. Wallner, TUM]

PDG 2019: 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

Spectroscopy of strange Mesons

Little progress in the past

- Many kaon states need confirmation
- Most 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 to analyze heavy-meson decays

- Search for CP violation in multi-body decays e.g. $B^\pm \to D^0\, K^\pm$ with $D^0 \to K_S^0\, \pi^+\, \pi^-$
  - Amplitude analysis of Dalitz plot requires accurate knowledge of resonances in $K_S^0\, \pi^\pm$ (and $\pi^+\, \pi^-$) subsystem

Spectroscopy of strange Mesons

Little progress in the past

- Many kaon states need confirmation
- Most 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 $SU(3)_{flavor}$ 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 to analyze heavy-meson decays

- Search for CP violation in multi-body decays
  e.g. $B^\pm \to D^0 K^\pm$ with $D^0 \to K_S^0 \pi^+ \pi^-$
  - Amplitude analysis of Dalitz plot requires accurate knowledge of resonances in $K_S^0 \pi^\pm$ (and $\pi^+ \pi^-$) subsystem

Spectroscopy of strange Mesons

Little progress in the past

- Many kaon states need confirmation
- Most 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 to analyze heavy-meson decays

- Search for CP violation in multi-body decays
  e.g. $B^\pm \to D^0\, K^\pm$ with $D^0 \to K_S^0\, \pi^+\, \pi^-$
  - Amplitude analysis of Dalitz plot requires accurate knowledge of resonances in $K_S^0\, \pi^\pm$ (and $\pi^+\, \pi^-$) subsystem

How to produce excited kaon states?

Decays of heavy particles

- 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
  - Nearly all kaon states can appear as intermediate state X

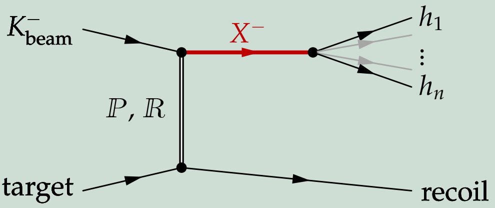
How to produce excited kaon states?

Decays of heavy particles

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

Production experiments

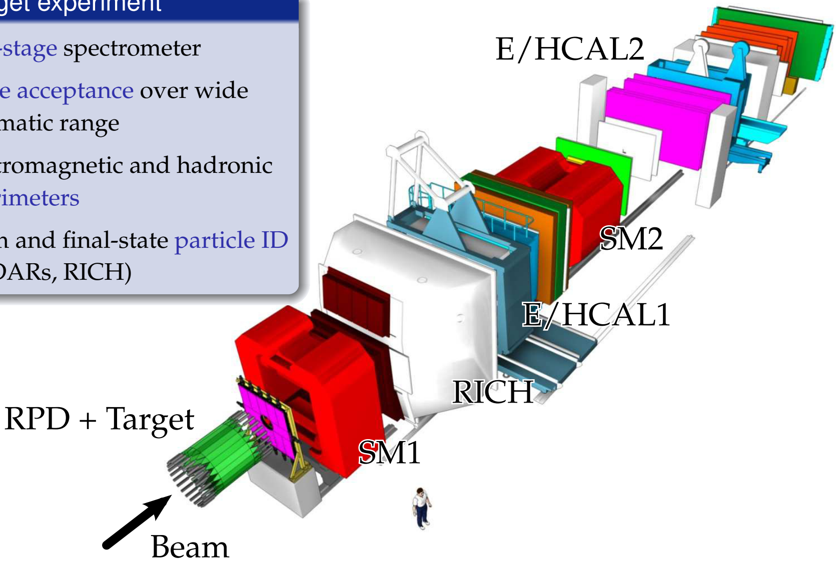
- E.g. diffractive production using high-energy kaon beam on stationary target
  - Large cross section
  - Nearly all kaon states can appear as intermediate state X



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

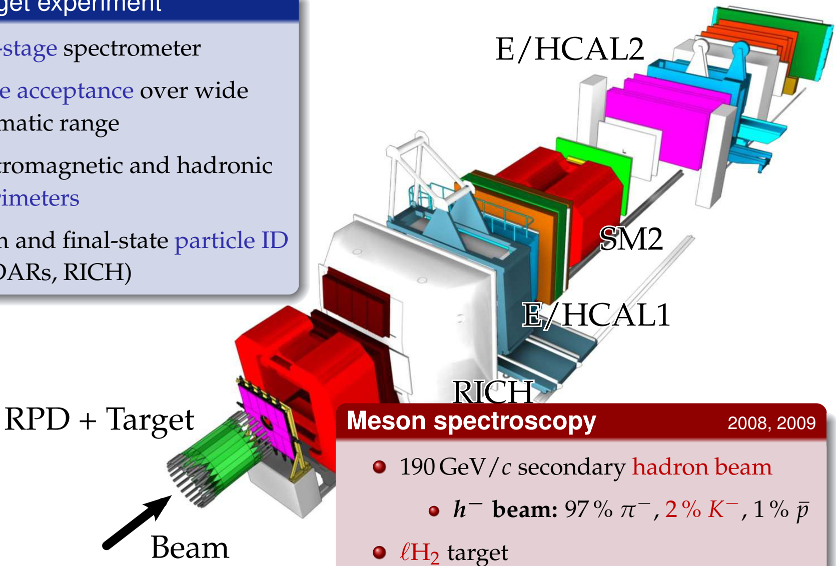
Fixed-target experiment

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



Fixed-target experiment

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

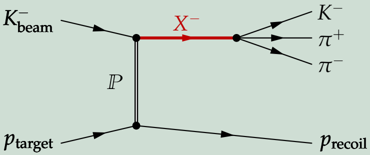


Meson spectroscopy
2008, 2009

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

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

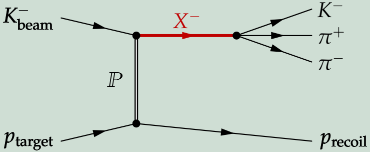
190 GeV/c K^- beam on p target



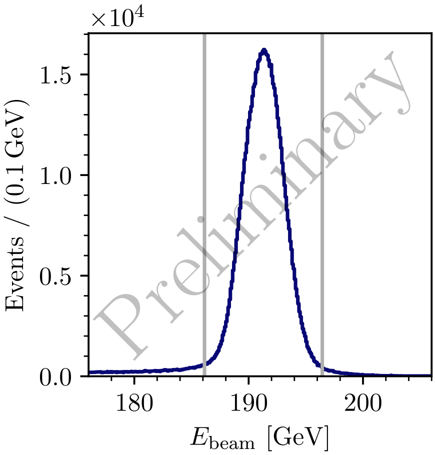
- Beam contains 2.4 % K^-
- 720 000 events
- Exclusivity ensured by measuring recoil proton
- $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Potential resonance signals
  - Need partial-wave analysis (PWA) to disentangle
- Largest data sample so far
  $\approx 3.5\times$ larger than WA03 sample

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

190 GeV / c K^- beam on p target

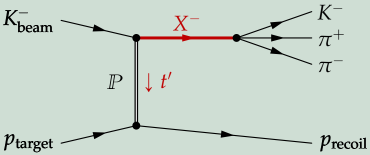


- Beam contains 2.4 % K^-
- 720 000 events
- Exclusivity ensured by measuring recoil proton
- $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Potential resonance signals
  - Need partial-wave analysis (PWA) to disentangle
- Largest data sample so far
  $\approx 3.5\times$ larger than WA03 sample

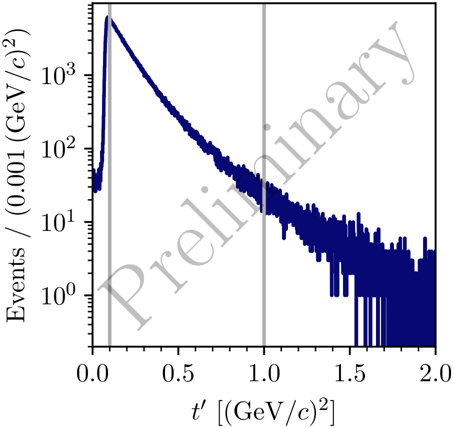


Diffractive Production of $K^-\pi^-\pi^+$ at COMPASS

190 GeV/c K^- beam on p target

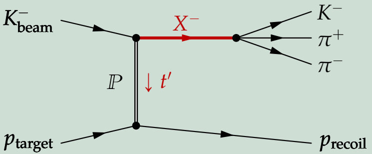


- Beam contains 2.4 % K^-
- 720 000 events
- Exclusivity ensured by measuring recoil proton
- $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Potential resonance signals
  - Need partial-wave analysis (PWA) to disentangle
- Largest data sample so far
  $\approx 3.5\times$ larger than WA03 sample

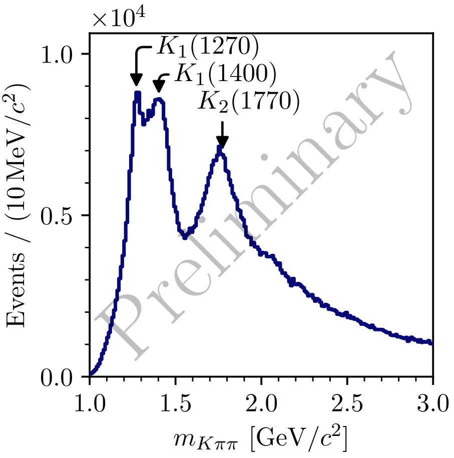


Diffractive Production of $K^-\pi^-\pi^+$ at COMPASS

190 GeV/c K^- beam on p target

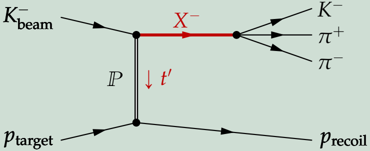


- Beam contains 2.4 % K^-
- 720 000 events
- Exclusivity ensured by measuring recoil proton
- $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Potential resonance signals
  - Need partial-wave analysis (PWA) to disentangle
- Largest data sample so far
  $\approx 3.5\times$ larger than WA03 sample



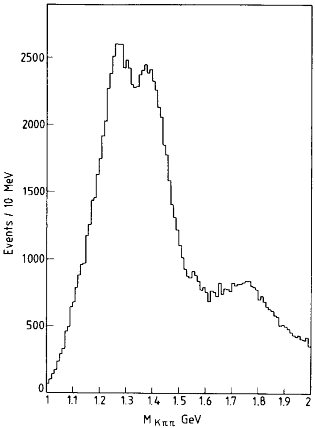
Diffractive Production of $K^-\pi^-\pi^+$ at COMPASS

190 GeV/c K^- beam on p target

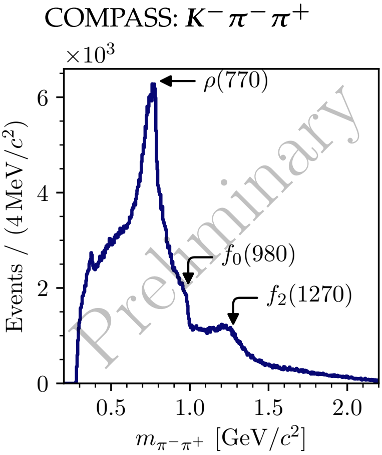


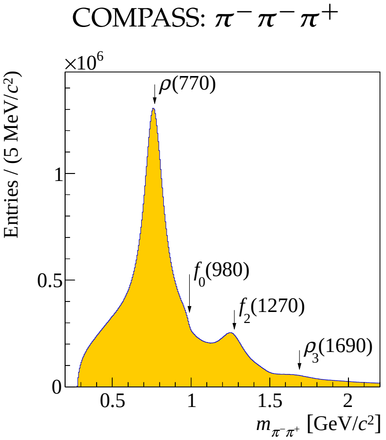
- Beam contains 2.4 % K^-
- 720 000 events
- Exclusivity ensured by measuring recoil proton
- $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Potential resonance signals
  - Need partial-wave analysis (PWA) to disentangle
- Largest data sample so far
  $\approx 3.5\times$ larger than WA03 sample

WA03 (CERN):
200 000 events
$0 < t' < 0.7\,(\text{GeV}/c)^2$



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

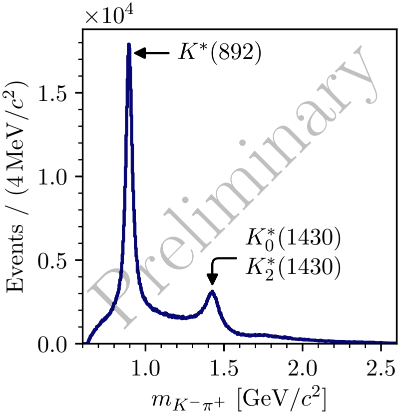




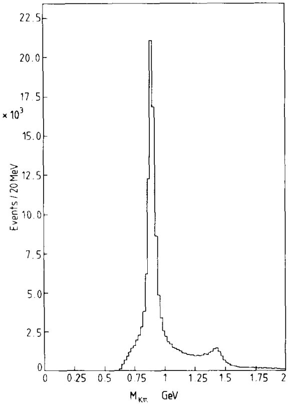
COMPASS, PRD **95** (2017) 032004

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

COMPASS



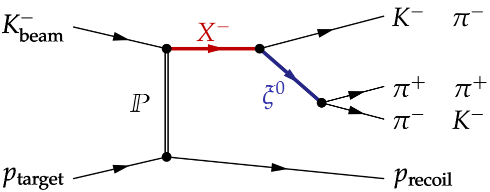
WA03 (CERN)



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

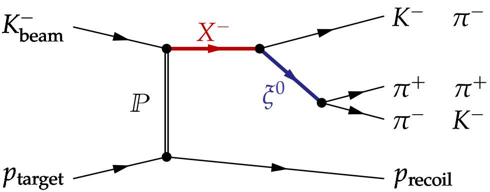
- Clear $K^*(892)$ and $K_0^*/K_2^*(1430)$ signals

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

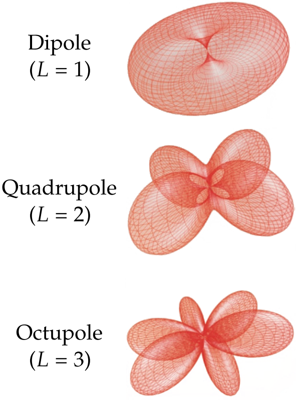


- J^P of a resonance determines angular distribution of daughter particles
- *Analogy:* multipole radiation in classical electrodynamics
- Determine J^P of intermediate resonances X^- and ξ^0 from measured angular distribution of final-state particles

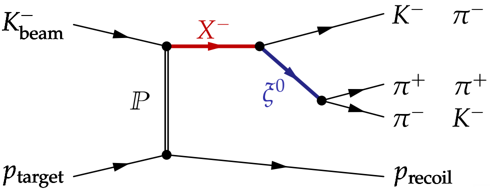
Partial-Wave Analysis of $K^-\pi^-\pi^+$: Isobar Model



- 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

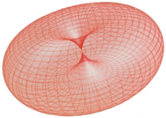


Partial-Wave Analysis of $K^-\pi^-\pi^+$: Isobar Model

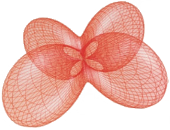


- J^P of a resonance determines angular distribution of daughter particles
- *Analogy:* multipole radiation in classical electrodynamics
- Determine J^P of intermediate resonances X^- and ξ^0 from measured angular distribution of final-state particles

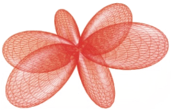
Dipole
($L = 1$)



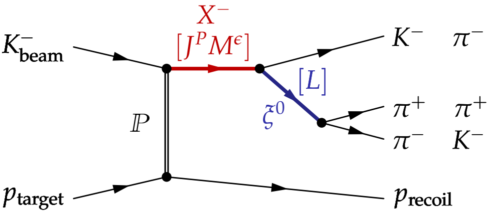
Quadrupole
($L = 2$)



Octupole
($L = 3$)



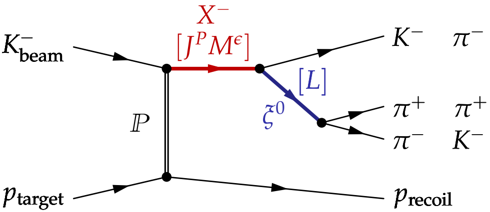
Partial-Wave Analysis of $K^-\pi^-\pi^+$: Isobar Model



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

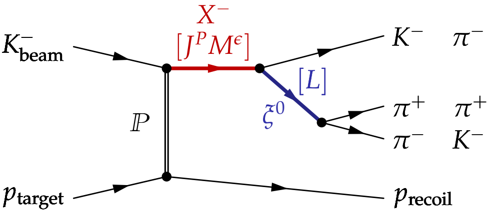
Partial-Wave Analysis of $K^-\pi^-\pi^+$: Isobar Model



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 ξ^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

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



PWA model: systematically constructed set of allowed waves

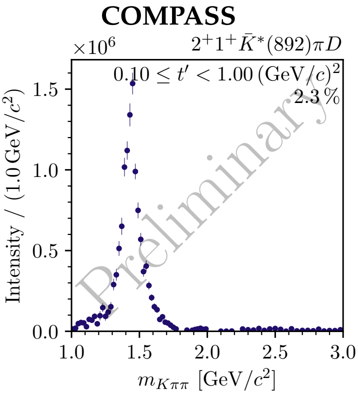
- Spin $J \leq 7$
- Orbital angular momentum $L \leq 7$
- Positive naturality of the exchange particle
- 12 isobars:
  - $[K\pi]_S^{K\pi}$, $[K\pi]_S^{K\eta}$, $K^*(892)$, $K_2^*(1430)$, $K_3^*(1780)$
  - $[\pi\pi]_S$, $f_0(980)$, $f_0(1500)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$

$\Rightarrow$ **"Wave pool" of 596 waves**

- Suppress insignificant waves by using regularization techniques

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

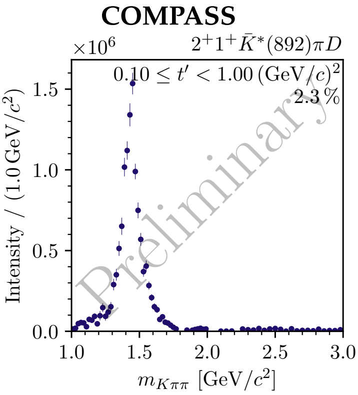
Example: $2^+ 1^+ K^*(892)\, \pi\, D$ Wave

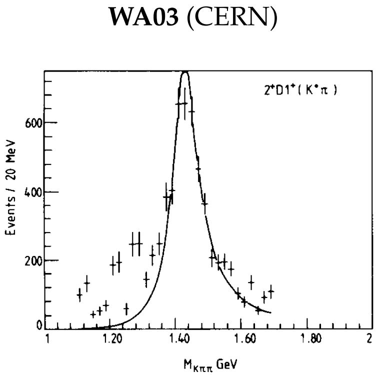


- Clear signal from $K_2^*(1430) \to K^*(892)\, \pi$
- In agreement with WA03 result
- Signal in COMPASS data much cleaner
- *Work in progress:* resonance-model fit

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

Example: $2^+ 1^+ K^*(892)\,\pi\,D$ Wave



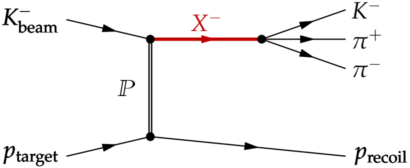


ACCMOR, NPB **187** (1981) 1

- Clear signal from $K_2^*(1430) \to K^*(892)\,\pi$
- In agreement with WA03 result
- Signal in COMPASS data much cleaner
- *Work in progress:* resonance-model fit

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

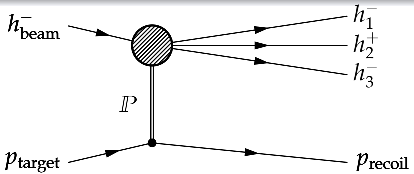
Challenge: non-uniform Acceptance due to Particle ID



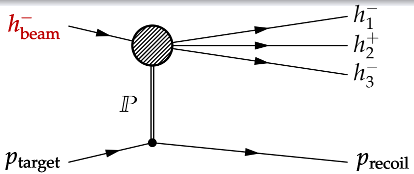
- Beam-particle ID via Cherenkov detectors (CEDARs)
    - Ca. $50\times$ more π^- than K^- in beam
- Final-state PID via RICH detector
    - Limited momentum range for K^- or π^- ID

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

Challenge: non-uniform Acceptance due to Particle ID



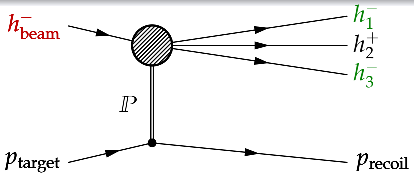
- Beam-particle ID via Cherenkov detectors (CEDARs)
  - Ca. $50\times$ more π^- than K^- in beam
- Final-state PID via RICH detector
  - Limited momentum range for K^- or π^- ID



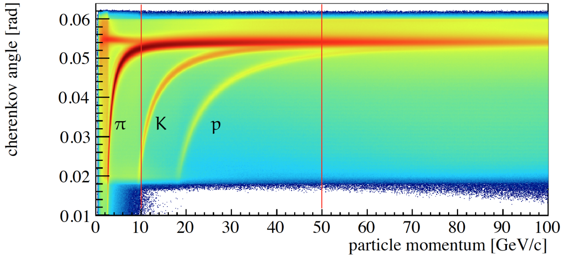
- Beam-particle ID via Cherenkov detectors (CEDARs)
  - Ca. $50\times$ more π^- than K^- in beam
- Final-state PID via RICH detector
  - Limited momentum range for K^- or π^- ID

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

Challenge: non-uniform Acceptance due to Particle ID

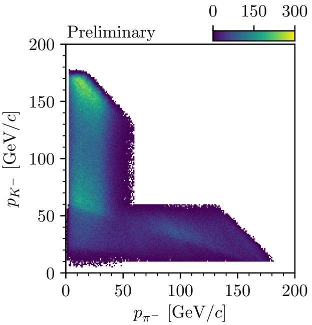


- Beam-particle ID via Cherenkov detectors (CEDARs)
  - Ca. $50\times$ more π^- than K^- in beam
- Final-state PID via RICH detector
  - Limited momentum range for K^- or π^- ID



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

Challenge: non-uniform Acceptance due to Particle ID

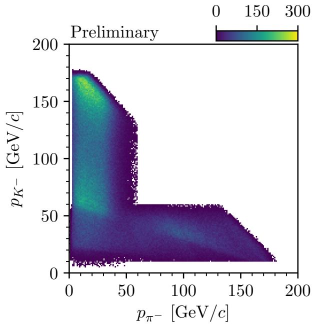


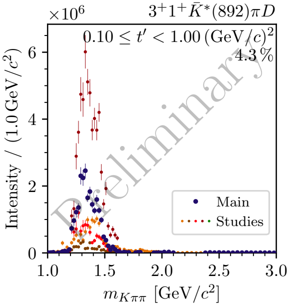
Leakage effects in PWA

- Caused by kinematic regions with acceptance ≈ 0
- Loss of distinguishing power for some partial waves
- Only small subset of waves affected

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

Challenge: non-uniform Acceptance due to Particle ID



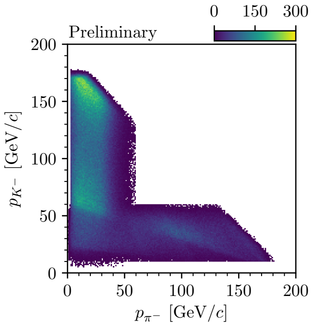


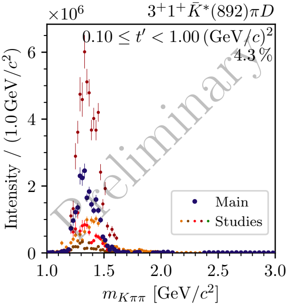
Leakage effects in PWA

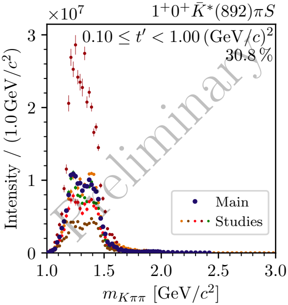
- Caused by kinematic regions with acceptance ≈ 0
- Loss of distinguishing power for some partial waves
- Only small subset of waves affected

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

Challenge: non-uniform Acceptance due to Particle ID





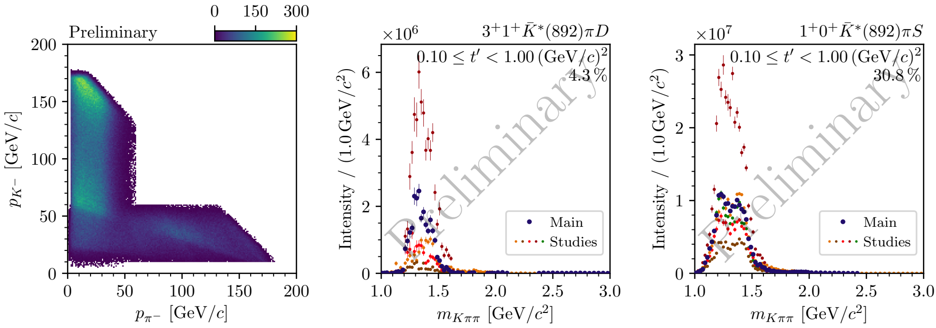


Leakage effects in PWA

- Caused by kinematic regions with acceptance ≈ 0
- Loss of distinguishing power for some partial waves
- Only small subset of waves affected

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

Challenge: non-uniform Acceptance due to Particle ID



Leakage effects in PWA

- Caused by kinematic regions with acceptance ≈ 0
- Loss of distinguishing power for some partial waves
- Only small subset of waves affected

High-Precision Kaon Spectroscopy at AMBER

Goal: $10\times$ world data

- Using diffraction of high-energy kaon beam (as COMPASS)
- $> 10^7$ $K^-\pi^-\pi^+$ events

Current parameters of h^- beam at SPS M2 beam line

- **Intensity:** $5\times10^6\,\mathrm{s}^{-1}$ for approximately 10 s every 45 s
- **Composition:** only $2\,\%$ K^-
  - 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**
- **Solution:** RF-separated beam

High-Precision Kaon Spectroscopy at AMBER

Goal: $10\times$ world data

- Using diffraction of high-energy kaon beam (as COMPASS)
- $> 10^7\ K^-\pi^-\pi^+$ events

Current parameters of h^- beam at SPS M2 beam line

- **Intensity:** $5 \times 10^6\,\mathrm{s}^{-1}$ for approximately $10\,\mathrm{s}$ every $45\,\mathrm{s}$
- **Composition:** only $2\,\%\ K^-$
  - 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**
- **Solution:** RF-separated beam

High-Precision Kaon Spectroscopy at AMBER

Goal: $10\times$ world data

- Using diffraction of high-energy kaon beam (as COMPASS)
- $> 10^7$ $K^-\pi^-\pi^+$ events

Current parameters of h^- beam at SPS M2 beam line

- **Intensity:** $5 \times 10^6\,\mathrm{s}^{-1}$ for approximately 10 s every 45 s
- **Composition:** only $2\,\%$ K^-
  - 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**
- **Solution:** RF-separated beam

High-Precision Kaon Spectroscopy at AMBER

Goal: $10\times$ world data

- Using diffraction of high-energy kaon beam (as COMPASS)
- $> 10^7$ $K^-\pi^-\pi^+$ events

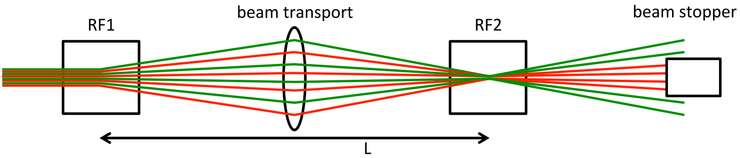
Current parameters of h^- beam at SPS M2 beam line

- **Intensity:** $5 \times 10^6\,\mathrm{s}^{-1}$ for approximately 10 s every 45 s
- **Composition:** only $2\,\%$ K^-
  - 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**
- **Solution:** RF-separated beam

RF-separated Kaon Beam at SPS M2 Beam Line

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

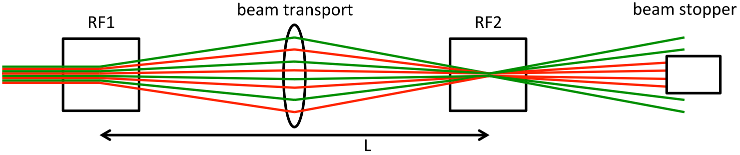


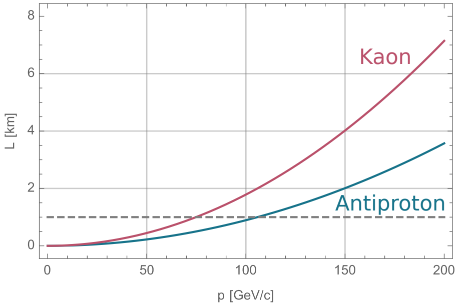
- Beam momentum limited by length of beam line
  - Not an issue: diffractive production depends only weakly on energy
- Estimated kaon intensity: $5 \times 10^{6}\,\mathrm{s}^{-1}$
- More detailed studies needed to determine beam parameters more precisely
- Requires major investment

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
  - Not an issue: diffractive production depends only weakly on energy
- Estimated kaon intensity: $5 \times 10^6\,\mathrm{s}^{-1}$
- More detailed studies needed to determine beam parameters more precisely
- Requires major investment

Requirements for AMBER Setup

- Upgrade of beam PID ⇒ improve rate capability and thermal stability of CEDARs
- High-resolution silicon beam telescope and vertex detector
- Improve detection of target recoil particle
  - Ensures exclusivity of measured events
- Extend kinematic coverage of final-state PID
  - Minimizes leakage effects in PWA
  - Provides access e.g. to $K^- K^- K^+$ final state
- Ensure efficient photon detection over broad kinematic range
  - Provides access to other interesting final states: $K^- \pi^0, K^- \pi^0 \pi^0, K^- \omega, K^- \eta^{(\prime)}, \ldots$

Work in progress

- Detailed studies of experimental setup will start when beam parameters are fixed

Requirements for AMBER Setup

- Upgrade of beam PID ⇒ improve rate capability and thermal stability of CEDARs
- High-resolution silicon beam telescope and vertex detector
- Improve detection of target recoil particle
  - Ensures exclusivity of measured events
- Extend kinematic coverage of final-state PID
  - Minimizes leakage effects in PWA
  - Provides access e.g. to $K^- K^- K^+$ final state
- Ensure efficient photon detection over broad kinematic range
  - Provides access to other interesting final states: $K^- \pi^0, K^- \pi^0 \pi^0, K^- \omega, K^- \eta^{(\prime)}, \ldots$

Work in progress

- Detailed studies of experimental setup will start when beam parameters are fixed

Requirements for AMBER Setup

- Upgrade of beam PID $\Rightarrow$ improve rate capability and thermal stability of CEDARs
- High-resolution silicon beam telescope and vertex detector
- Improve detection of target recoil particle
  - Ensures exclusivity of measured events
- Extend kinematic coverage of final-state PID
  - Minimizes leakage effects in PWA
  - Provides access e.g. to $K^- K^- K^+$ final state
- Ensure efficient photon detection over broad kinematic range
  - Provides access to other interesting final states: $K^-\pi^0, K^-\pi^0\pi^0, K^-\omega, K^-\eta^{(\prime)}, \ldots$

Work in progress

- Detailed studies of experimental setup will start when beam parameters are fixed

Conclusions

Kaon spectroscopy

- Many kaon states require further confirmation or more precise measurement of their paramaters
- COMPASS has already acquired the so far largest data sample for $K^- + p \to K^-\pi^+\pi^- + p$ (720 000 events)

AMBER

- **Goal:** collect $10\times$ world data using high-intensity RF-separated kaon beam
  - Would correspond to $> 10^7$ $K^-\pi^-\pi^+$ events
  - *High physics potential:* rewrite PDG for kaon states above $1.5\,\mathrm{GeV}/c^2$ (like LASS and WA03 did 30 year ago)
  - Pion component of beam could be used to study non-strange light mesons in parallel
- Requires experimental setup with uniform acceptance over wide kinematic range including PID and electromagnetic calorimeters

Conclusions

Kaon spectroscopy

- Many kaon states require further confirmation or more precise measurement of their paramaters
- COMPASS has already acquired the so far largest data sample for $K^- + p \to K^-\pi^+\pi^- + p$ (720 000 events)

AMBER

- **Goal:** collect $10\times$ world data using high-intensity RF-separated kaon beam
  - Would correspond to $> 10^7$ $K^-\pi^-\pi^+$ events
  - *High physics potential:* rewrite PDG for kaon states above $1.5\,\mathrm{GeV}/c^2$ (like LASS and WA03 did 30 year ago)
  - Pion component of beam could be used to study non-strange light mesons in parallel
- Requires experimental setup with uniform acceptance over wide kinematic range including PID and electromagnetic calorimeters

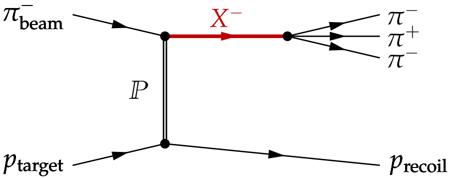
Outline

4 Backup slides

Why do we need more data?

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

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

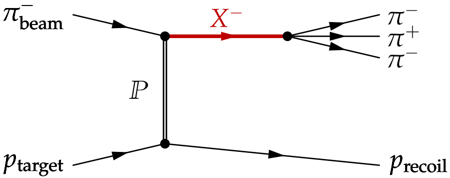


- 46×10^6 $\pi^-\pi^-\pi^+$ events $\Rightarrow$ approx. $10\times$ previous experiments

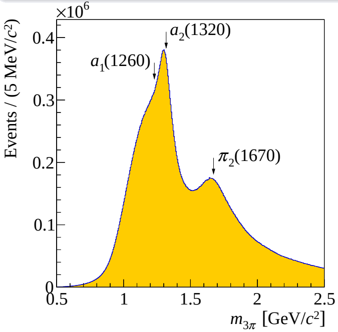
Why do we need more data?

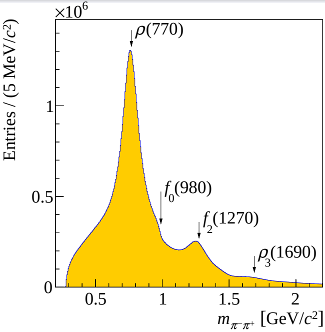
Example: $\pi^- + p \to \pi^-\pi^-\pi^+ + p_\text{recoil}$

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



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

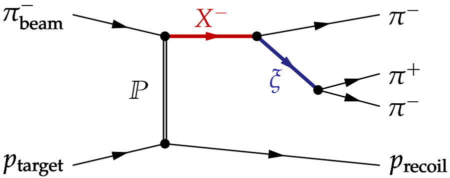




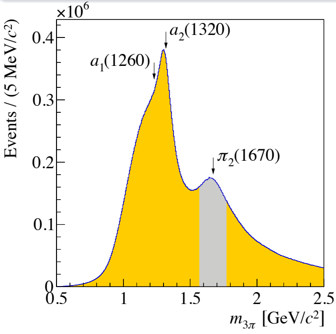
Why do we need more data?

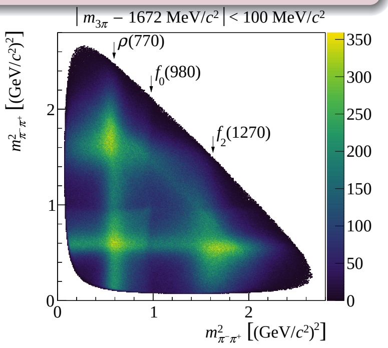
Example: $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$

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



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



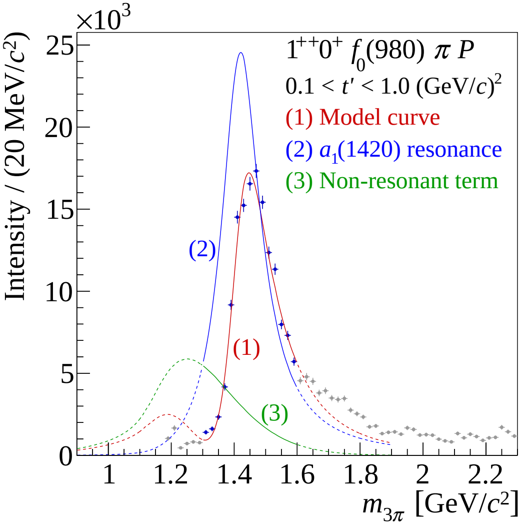


Why do we need more data?

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

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



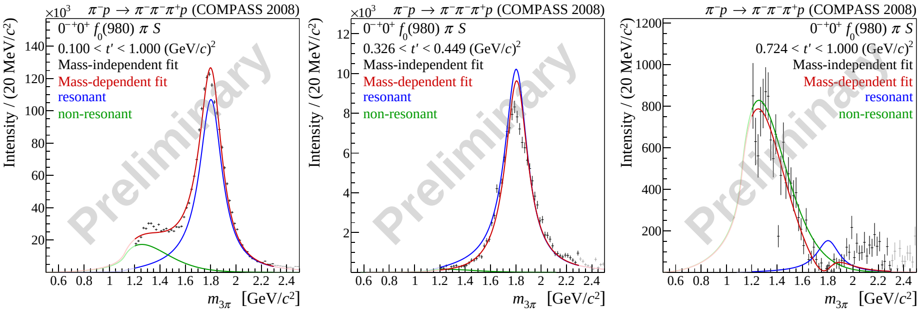
COMPASS, PRL **115** (2015) 082001

Why do we need more data?

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

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)

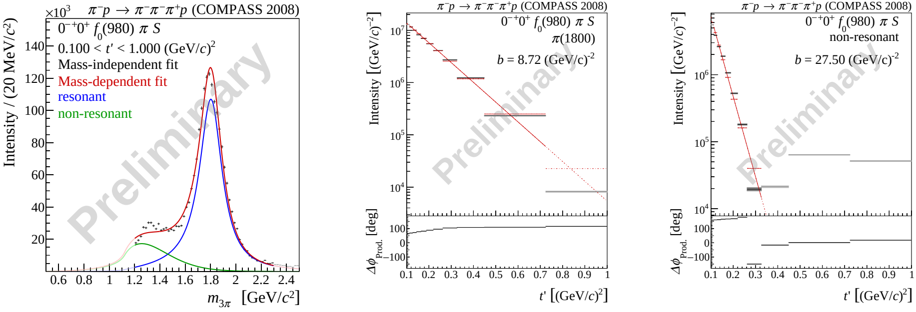


Why do we need more data?

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

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)

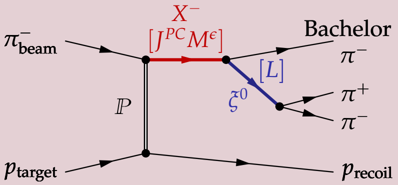


Why do we need more data?

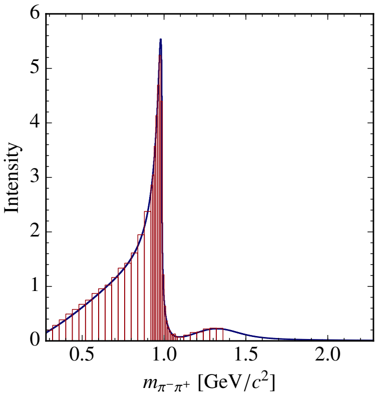
Example: $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$

Novel analysis technique "freed-isobar" PWA

[arXiv:1710.09849]



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

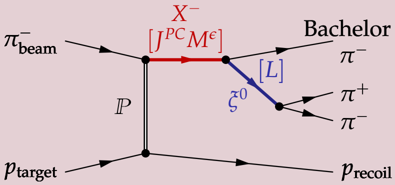


Why do we need more data?

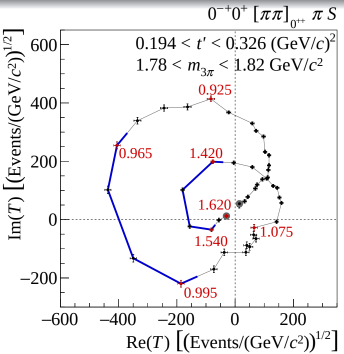
Example: $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$

Novel analysis technique "freed-isobar" PWA

[arXiv:1710.09849]



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



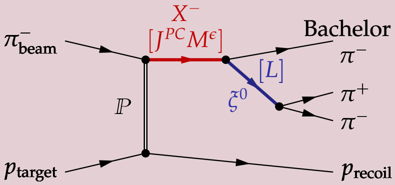
COMPASS, PRD **95** (2017) 032004

Why do we need more data?

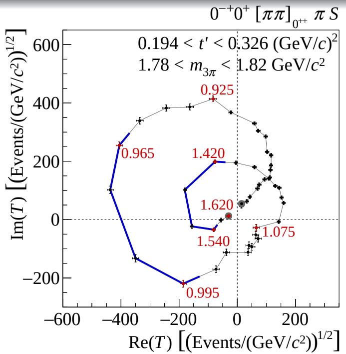
Example: $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$

Novel analysis technique "freed-isobar" PWA

[arXiv:1710.09849]



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



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

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