Study of the $\pi^+\pi^-$ System in $\pi^-\pi^+\pi^-$ Final States at COMPASS

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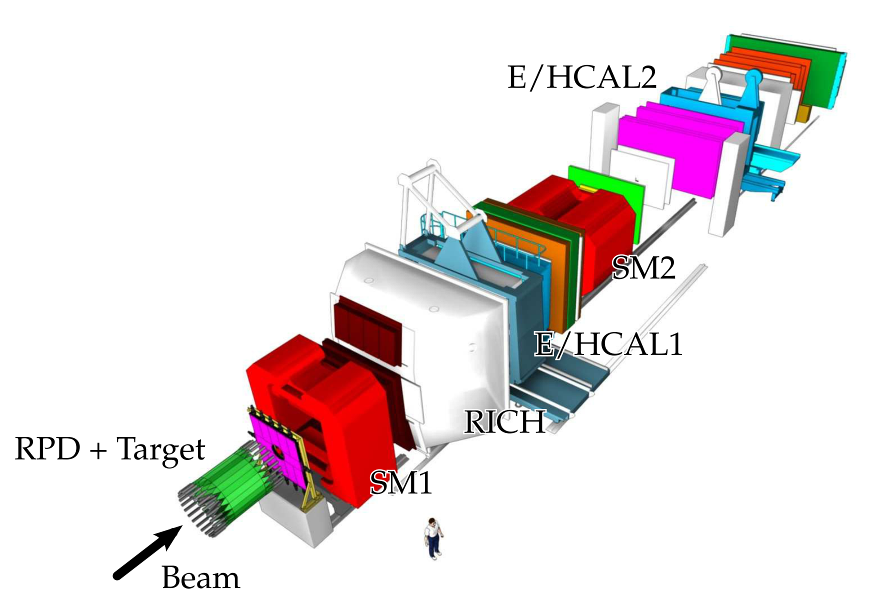
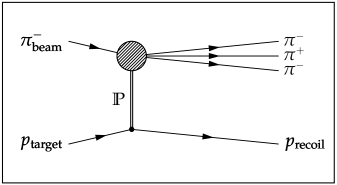
Outline

- The COMPASS-experiment
- The $\pi^-\pi^+\pi^-$-final state
- Partial-Wave-Analysis
- De-isobarred Partial-Wave-Analysis

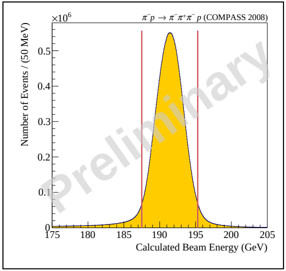
- Multi-purpose fixed target experiment at CERN
- Hadron- and muon-beam supplied by CERN's the Super Proton Synchrotron (SPS)
- Two stage spectrometer with Large acceptance over a wide kinematic range
- Hadronic and electromagnetic calorimeters
- Beam and final-state particle identification via Cherenkov detectors (CEDARs and RICH)
- Used with μ- and hadron beams

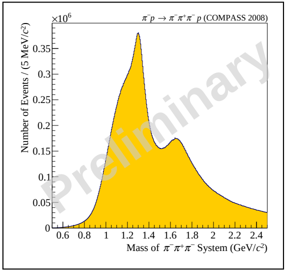


E/HCAL2
SM2
E/HCAL1
RICH
RPD + Target
SM1
Beam



- For the current analysis, 2008 data is used
- 190 GeV/c secondary hadron beam (97% π^-) on hydrogen target
- Many other interesting channels, e.g. $\pi^-\pi^0\pi^0$ or 5π
- About 50 million accepted events in the $\pi^-\pi^+\pi^-$-channel





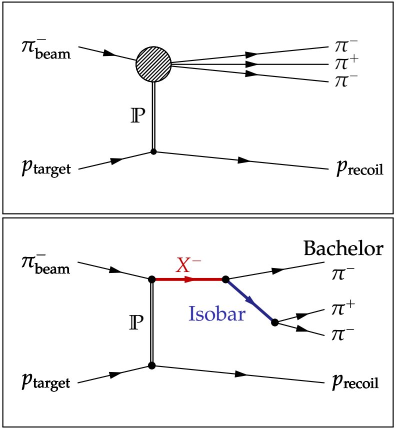
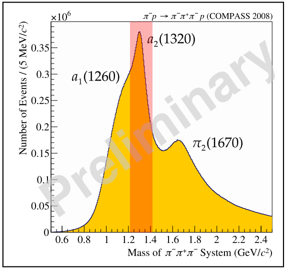
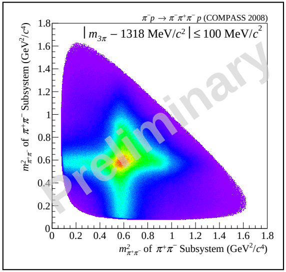


Figure: Assumptions by the isobar-model

- In the model used, an intermediate state X^- is diffractively produced via pomeron-exchange ($\mathbb{P}$)
- The pomeron carries a four-momentum t, but neither flavour nor charge
- This intermediate state decays into a bachelor π^- and a so-called isobar, which subsequently goes into $\pi^+\pi^-$
- Main assumption: X^- does not decay directly into $\pi^-\pi^+\pi^-$

- The spectrum in the invariant three-pion-mass $m_{3\pi}$ shows already a rich structure
- Dalitz-plots at different $m_{3\pi}$ show a correlation between the spectrum of the 2π-subsystem and the three-pion-mass
- The $\rho(770)$ and $f_2(1270)$ can be seen immediately
- These spectra can be disentangled further via a Partial Wave Analysis (PWA)





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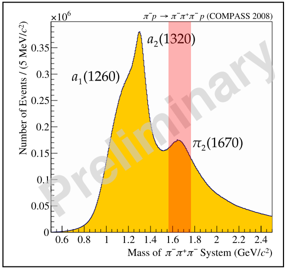
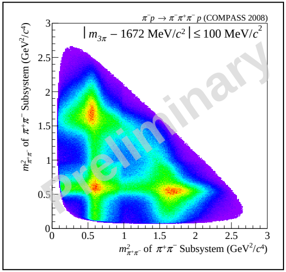
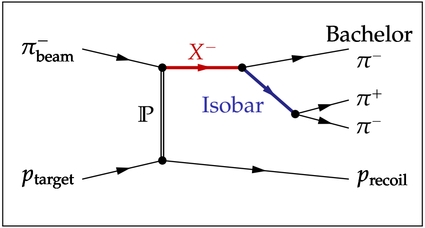




Basic situation:

- Many different intermediate states (waves) decay into the same final state, here $\pi^-\pi^+\pi^-$
- All of these waves interfere with each other



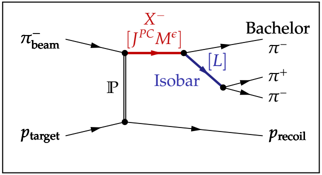
Partial Wave Analysis:

- Expand the complex decay amplitude in terms of different angular distributions and isobars
- Perform a fit to the data for every single bin in $m_{3\pi}$
- PWA uses the full kinematic information of the events
- Phase information between the single waves is obtained

$\rightarrow$ Complex amplitude instead of real intensity is obtained

- Waves are given as:

$$J^{PC} M^{\epsilon} \text{ [isobar] } \pi L$$



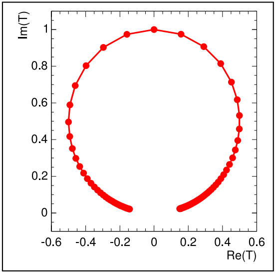
with total spin J, parity P, sign under charge-conjugation C, magnetic quantum number M, reflectivity ϵ, an isobar and the angular momentum L between isobar and bachelor π

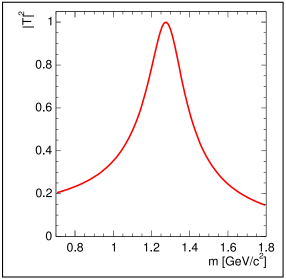
- The following isobars were used:

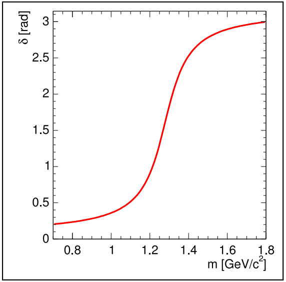
$$\underbrace{[\pi\pi]_S,\ f_0(980),\ f_0(1500)}_{J^{PC}=0^{++}},\ \underbrace{\rho(770)}_{1^{--}},\ \underbrace{f_2(1270)}_{2^{++}} \text{ and } \underbrace{\rho_3(1690)}_{3^{--}}$$

- For the PWA performed here, 87 such waves up to spin 6 were used. An additional incoherent isotropic wave was also included to describe uncorrelated events

- Independent fit performed for each bin in $m_{3\pi}$ of 20 MeV width
- Resonances show trough:
  - Structure in the intensity (peak or dip)
  - Phase motion relative to other waves
- Phase motion helps to disentangle the different contributions





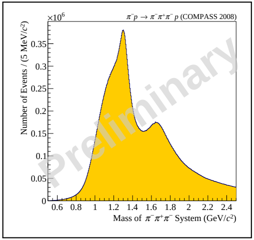


Partial Wave Analysis

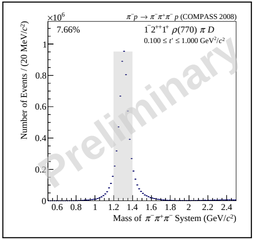
Some results

The invariant mass spectrum can be disentangled via PWA into its various components, e.g.:

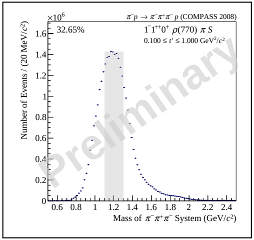
- The $a_1(1260)$ in $1^{++}0^{+}\rho\,\pi\,S$
- The $a_2(1320)$ in $2^{++}1^{+}\rho\,\pi\,D$
- The $\pi_2(1670)$ in $2^{-+}0^{+}f_2\,\pi\,S$
- And Many more waves ...



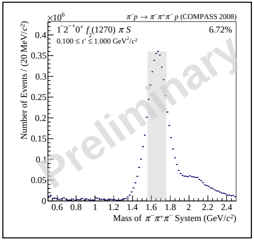
$m_{3\pi}$-spectrum



$a_2(1320)$

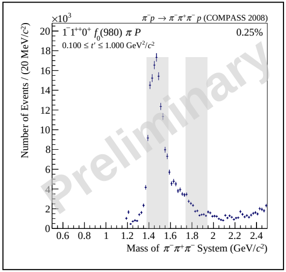


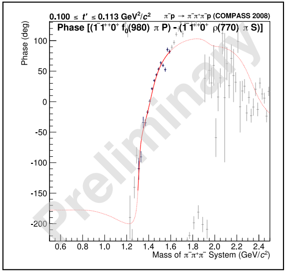
$a_1(1260)$



$\pi_2(1670)$

- A new signal can be seen in the PWA for the first time
- The resonance shows in the $1^{++}0^{+}$ $f_0(980)$ π P-wave
- It can be seen trough an intensity peak and phase motion
- Parameters:
  - Mass $m = 1412\text{-}1422\ \mathrm{MeV}/c^2$
  - Width $\Gamma = 130\text{-}150\ \mathrm{MeV}/c^2$





- For the usual PWA, a certain shape of the single isobars has to be assumed
- The simplest example is a Breit-Wigner parametrization, but there are many others on the market
- The shape of the isobars cannot be determined by usual PWA
- The choice of this parametrization may give a certain bias on the analysis

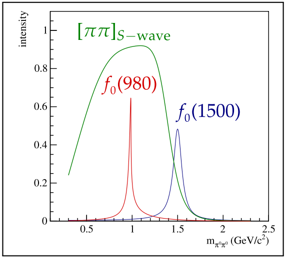


Figure: Shapes of the three 0^{++} isobars

- In order to investigate this, a new method was introduced:

  "De-isobarring"

- The fixed parametrizations for the isobars are replaced by piecewise constant functions:

  $$[\pi\pi]_S, f_0(980), f_0(1500) \rightarrow [\pi\pi]_S^*$$

- The piecewise constant functions cover the whole allowed $m_{\pi^+\pi^-}$ mass range

- The complex amplitude of each step is left as free parameter in the fit

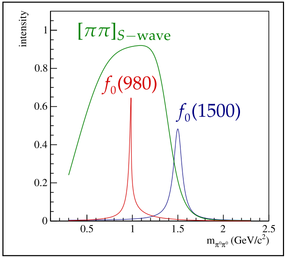
- These fit-parameters then determine the shape of the corresponding isobars including phase information

- At the moment this is done for $0^{-+}0^+[\pi\pi]_S^*\,\pi\ S$, $1^{++}0^+[\pi\pi]_S^*\,\pi\ P$ and $2^{-+}0^+[\pi\pi]_S^*\,\pi\ D$

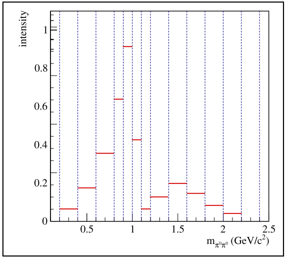
De-isobarred Partial-Wave-Analysis

Piecewise constant functions

- In usual PWA there is one complex parameter for each wave
- The shape of the isobar is fixed

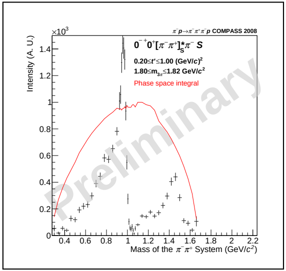


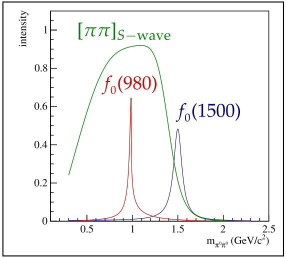
- In De-isobarred PWA, there is one complex parameter for each single step in $m_{\pi^+\pi^-}$
- These parameters determine the isobar shape



$m_{3\pi} = 1.8\ \text{GeV}/c^2$

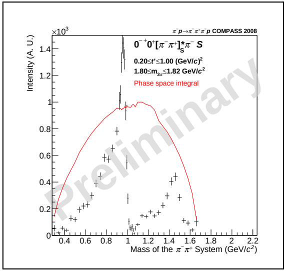
- The three isobars with quantum numbers 0^{++}, the $[\pi\pi]_S$, $f_0(980)$ and $f_0(1500)$ can be seen

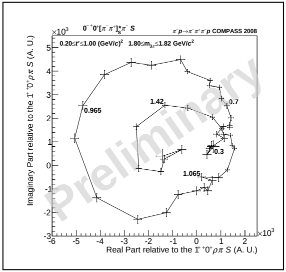




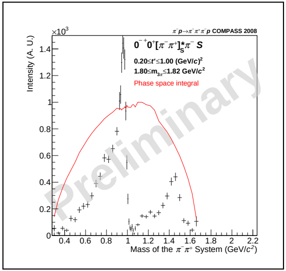
$m_{3\pi} = 1.8\ \text{GeV}/c^2$

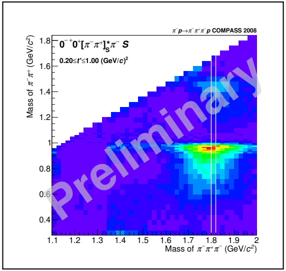
- The three isobars with quantum numbers 0^{++}, the $[\pi\pi]_S$, $f_0(980)$ and $f_0(1500)$ can be seen
- The Argand-diagram shows two clear circles corresponding to the $f_0(980)$ and the $f_0(1500)$
- Resonances can be seen clearly as peaks and trough their phase-motion



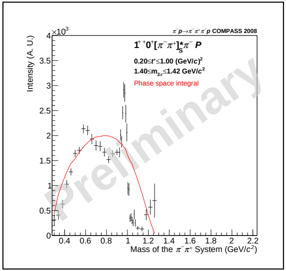


- The three isobars with quantum numbers 0^{++}, the $[\pi\pi]_S$, $f_0(980)$ and $f_0(1500)$ can be seen
- In $m_{3\pi}$ the $\pi(1800)$ is visible
- Strong correlation between 2π and 3π resonances

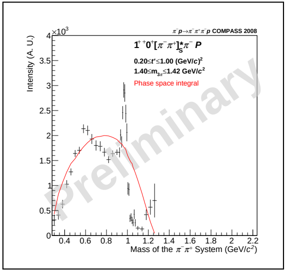


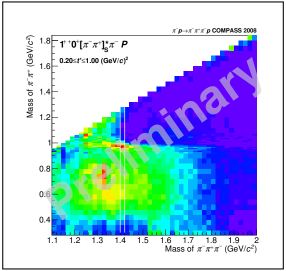


- The $[\pi\pi]_S$ and $f_0(980)$ can be seen

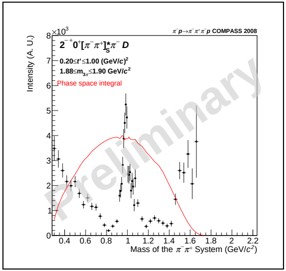


- The $[\pi\pi]_S$ and $f_0(980)$ can be seen
- In $m_{3\pi}$ the new found resonance $a_1(1420)$ is visible
- Strong correlation between $f_0(980)$ and $a_1(1420)$ resonances

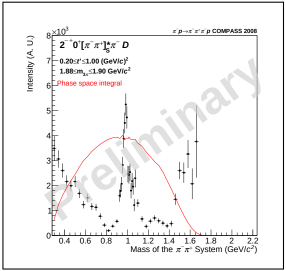


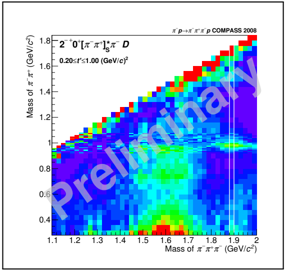


- The $f_0(980)$ and $f_0(1500)$ can be seen



- The $f_0(980)$ and $f_0(1500)$ can be seen
- In $m_{3\pi}$ the $\pi_2(1880)$ is visible
- Again strong correlation between 2π and 3π resonances





Conclusion

- The world's largest data set collected by COMPASS allows for a very detailed PWA of the $\pi^-\pi^+\pi^-$-final-state (50 million accepted events)
- Usual PWA showed a new resonance, the $a_1(1420)$, for the first time
- A new method was introduced, that allows to also extract the isobar-shape

Outlook

- Try this new method also for other isobars (1^{--}, 2^{++})
- Perform mass dependent fits on the results to extract resonance parameters
- Compare with other channels (e.g. $\pi^0\pi^0\pi^-$)

Thank you for your attention