Hadron Physics at the COMPASS Experiment

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3rd International Conference
on New Frontiers in Physics

- Motivations for hadron spectroscopy
- The COMPASS experiment
- Partial-Wave Analysis
- Three-pion final states
- Summary and conclusion

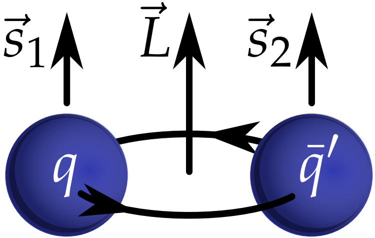
Motivation

- The strong interaction, which describes the dynamics of quarks and gluons, gives rise to a rich spectrum of hadrons
- In principle this spectrum should be described by the Lagrangian of quantum chromodynamics (QCD):

$$\mathcal{L}_{QCD} = \sum_{i,j \in \mathrm{quarks}} \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m_i \delta_{ij}) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a}$$

- Due to confinement, quarks and gluons do not exist as free particles, but typically form baryons ($|qqq\rangle$) and mesons ($|q\bar{q}\rangle$).
- Usual perturbation theory (as e.g. in QED) is not applicable anymore
- This talk will only be about the light meson sector

- In the constituent quark model, mesons are described as bound states of a quark and an anti-quark
- The quark spin couples to a total spin $S = 0, 1$
- The total spin and the orbital angular momentum $\vec{L}$ of the quarks couples to a total spin $\vec{J} = \vec{L} + \vec{S}$
- The quantum numbers of a meson are given by J^{PC} with Parity $P = (-1)^{L+1}$ and generalized charge conjugation $C = (-1)^{L+S}$



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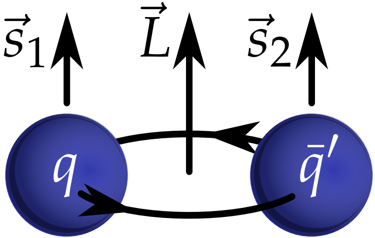
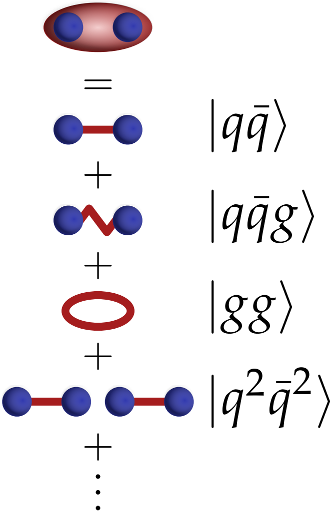


- Forbidden J^{PC} (e.g. $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$) indicate states beyond the constituent quark model

Motivation

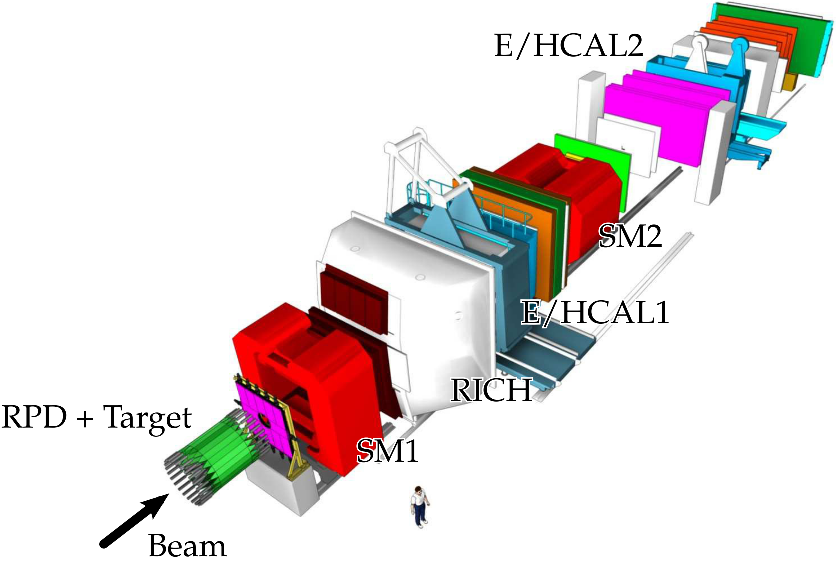
States beyond the constituent quark model

- Beyond bound quark-anti-quark states, other exotic states of QCD could be possible
- Possible exotic states are:
  - Hybrids: $|q\bar{q}g\rangle$
  - Glueballs: $|gg\rangle$
  - Multi-quark states:
    - Tetra-quarks: $|qq\bar{q}\bar{q}\rangle$
    - Mulecules: $|(q\bar{q})(q\bar{q})\rangle$
    - ...
  - ...
- A physical state may be any superposition of these basic states
- Forbidden quantum numbers can't be explained as $q\bar{q}$ pairs, they must be something else



The COMPASS experiment

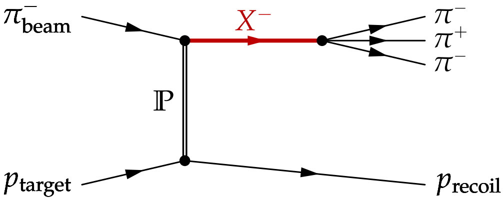
- Multi-purpose fixed-target experiment at CERN
- (Secondary) hadron and (tertiary) muon beams supplied by CERN's Super Proton Synchrotron (SPS)
- Broad physics program:
  - Spin-structure of the nucleon (using $\mu^{\pm}$ and hadron beams)
    See talk:*"The New Spin Physics Program of the* COMPASS *Experiment"* by Luis Silva on Saturday
  - Hadron structure and spectroscopy (using mainly hadron beams)
- For the analysis presented:
  - 190 GeV/c secondary hadron beam (97% π^-)
  - 40 cm H_2 target


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

The Partial-Wave Analysis Method

- Incoming π^- gets excited by interaction via *Pomeron-exchange* with the target and forms an intermediate state X^-

Example: $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$



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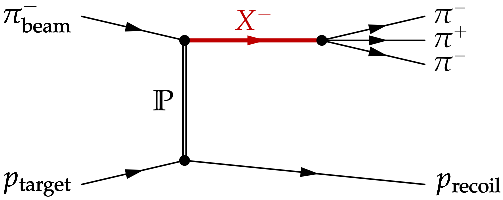

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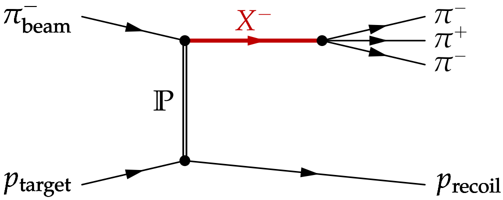


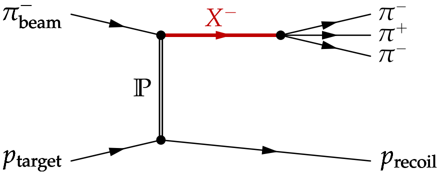
- Different X^- may interfere with each other

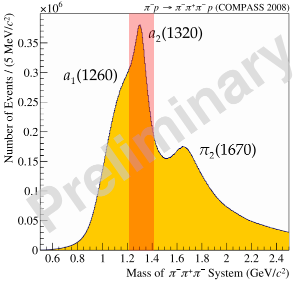
Main goal:

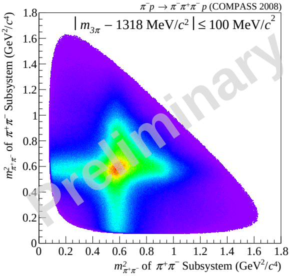
Disentangle all contributing intermediate states, so called 'waves'

- Use *Partial-Wave Analysis* to do this

- Dalitz plots at different m_X show a correlation between the spectrum of the 2π-subsystem and the three-pion mass
- Horizontal and vertical band structures are visible







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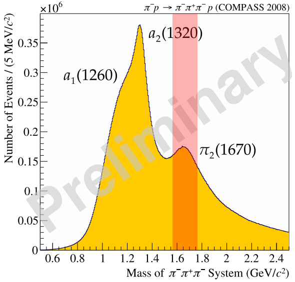

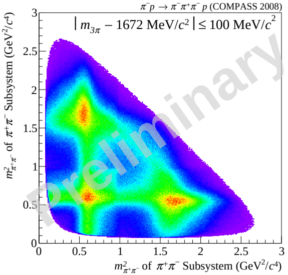

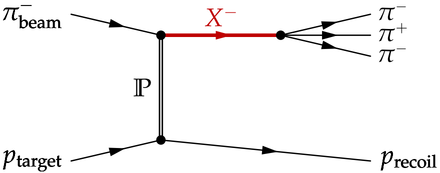

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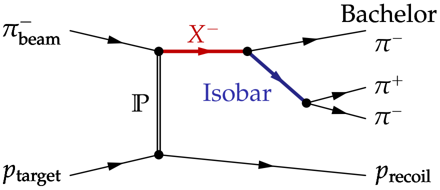
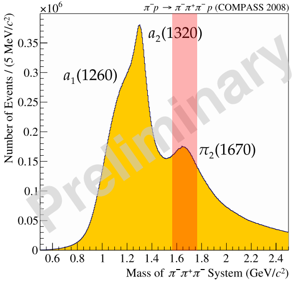
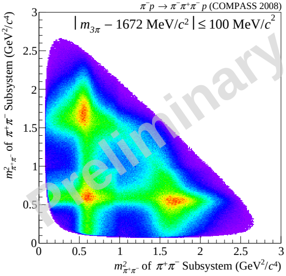
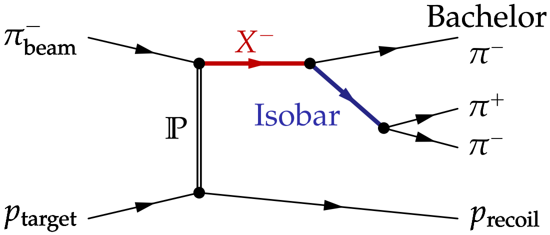
  $\rightarrow$ describe process as subsequent two-particle decays: *isobar model*



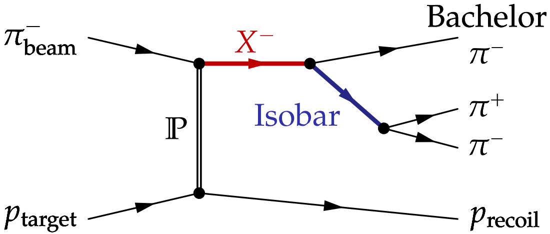






- The process is described by a complex amplitude, which takes the form:

$$\mathcal{A} = \sum_{\text{waves}} T_{\text{wave}}(m_X)\psi_{\text{wave}}(\tau)$$



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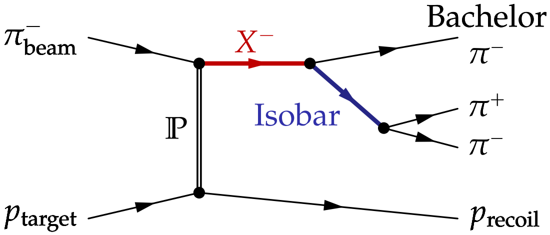

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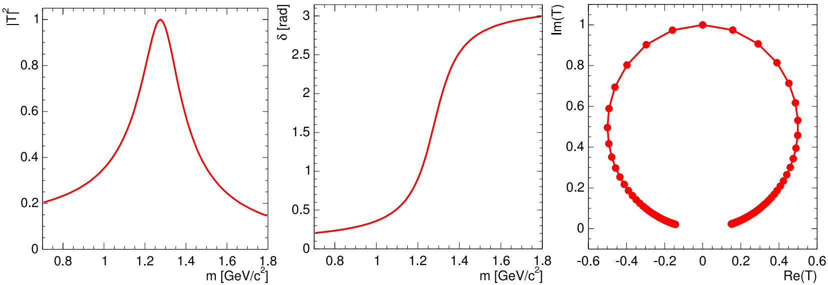

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- The complex production amplitudes T_{wave} are independently fitted in bins of the mass of the intermediate state m_X
- Resonances show through the intensity and a phase shift of the T_{wave}

Three-Pion Final States

- For this analysis, COMPASS 2008 data are used
- 190 GeV secondary hadron beam (97% π^-) on hydrogen target
- Two final states: $\pi^-\pi^0\pi^0$ and $\pi^-\pi^+\pi^-$

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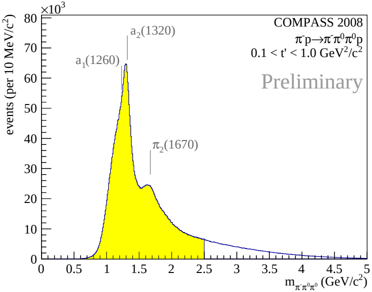

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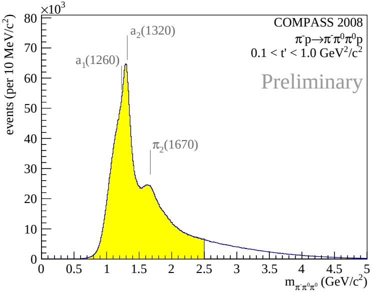

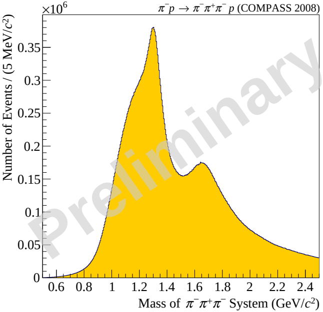

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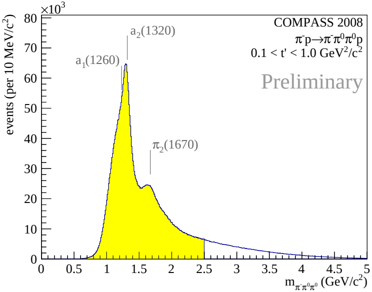
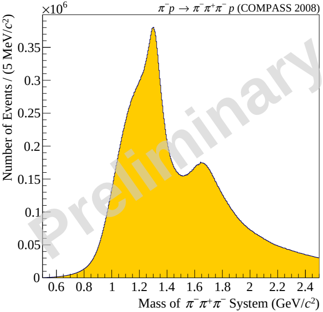
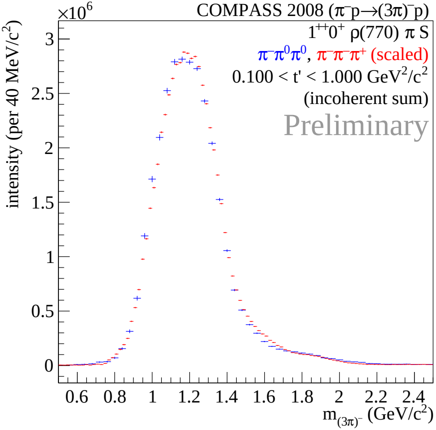
- Different systematics in both channels



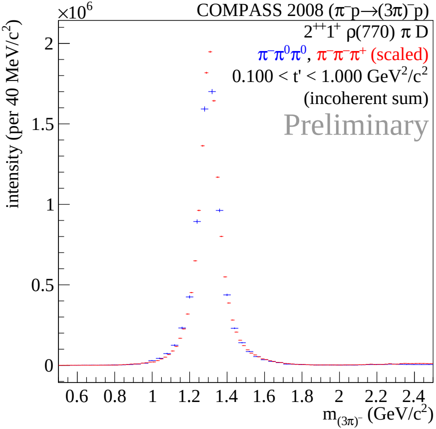


- Spin-1 axial vector meson decaying into $\rho(770)\ \pi^-$
- Biggest wave in the analysis with $\sim$ 33% of the intensity in the $\pi^-\pi^+\pi^-$ channel
- The $a_1(1260)$ resonance is clearly visible (It also shows through a phase motion which is not depicted here)
- Good agreement between both channels



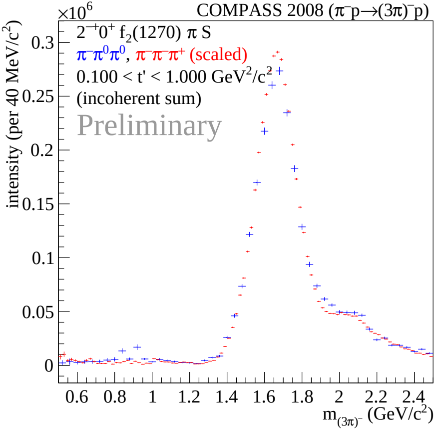
$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ scaled to the integrals

- Spin-2 meson decaying into $\rho(770)\ \pi^-$
- Also a dominant wave with $\sim 8\%$ of the intensity in the $\pi^-\pi^+\pi^-$ channel
- The $a_2(1320)$ resonance is clearly visible
- Good agreement between both channels
- The $a_2(1320)$ is the most beautiful resonance seen in the analysis with nearly no background



$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ scaled to the integrals

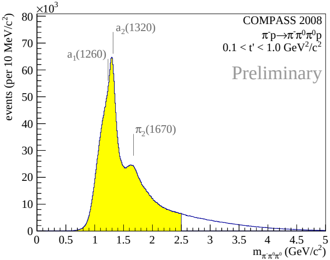
- State with quantum numbers of a pion with spin 2 decaying into $f_2(1270)\,\pi^-$
- The $f_2(1270)$ is a well-known state with quantum numbers $J^{PC} = 2^{++}$
- Takes $\sim 7\%$ of the intensity in the $\pi^-\pi^+\pi^-$ channel
- The $\pi_2(1670)$ resonance is clearly visible
- Also good agreement between both channels

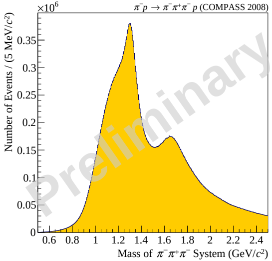


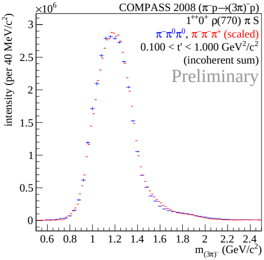
$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ scaled to the integrals

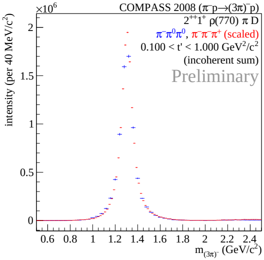
Three-Pion Final States

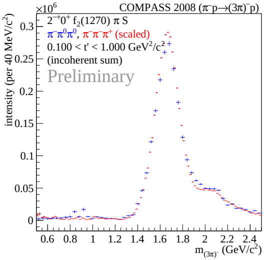
With these three waves, the gross features of the mass spectrum of the two channels can be described



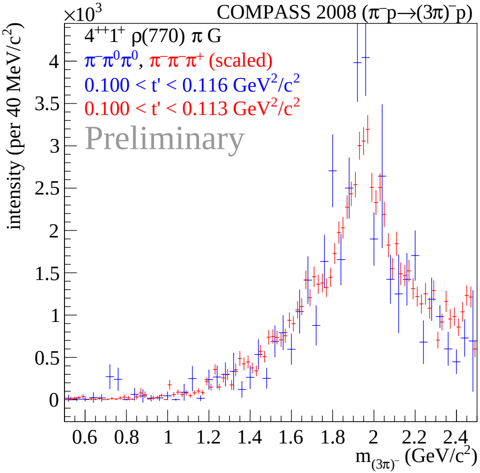








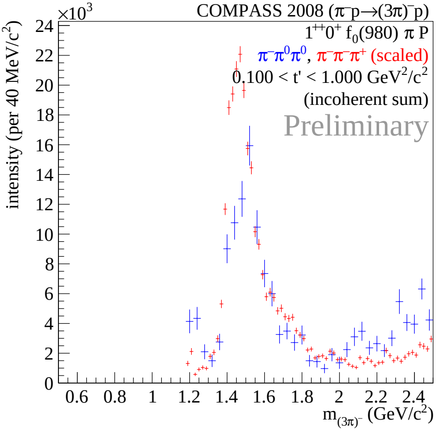
- Spin-4 meson decaying into $\rho(770)\ \pi$
- Only 0.76% of the intensity in the $\pi^-\pi^+\pi^-$ channel
- The $a_4(2040)$ resonance is clearly visible
- PWA also allows to clearly extract waves on sub-percent level



$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ scaled to the integrals

- Intermediate state with same quantum numbers as the first wave ($J^{PC} = 1^{++}$), but decaying into $f_0(980)\ \pi$
- The $f_0(980)$ has the quantum numbers $J^{PC} = 0^{++}$
- Only 0.25% of the intensity in the $\pi^-\pi^+\pi^-$ channel
- This $a_1(1420)$ was never seen before due to its small intensity, but here it appears in both channels
- Only visible because of the large COMPASS data set

NEW RESONANCE!



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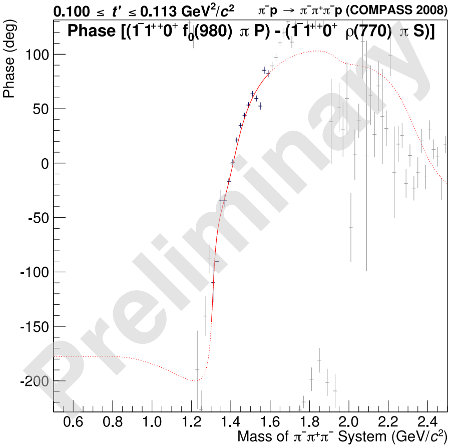

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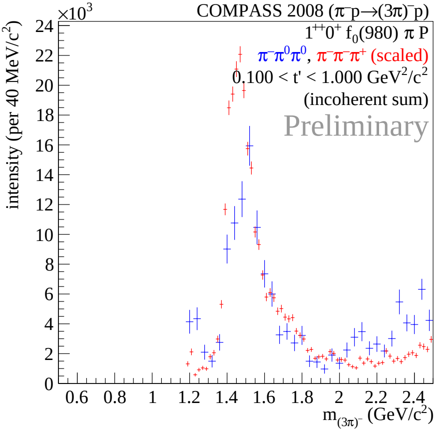


$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ scaled to the integrals

Summary

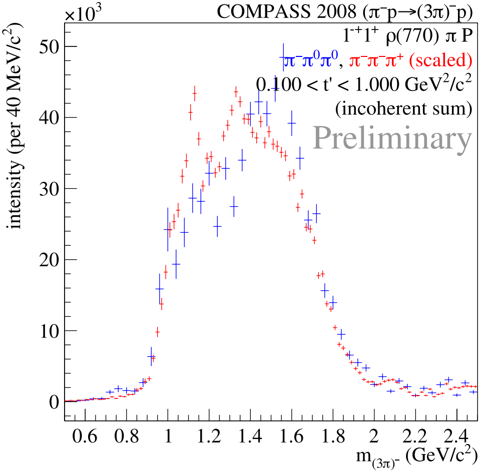
- This data set is the largest for the $\pi^-\pi^+\pi^-$ channel with $\sim$ 50 000 000 events, which allows for a very detailed Partial-Wave Analysis
- This analysis allows to extract waves on the sub-percent level
- Very precise description of the accessible light hadron spectrum ($I^G = 1^-$)
- A new resonance, the $a_1(1420)$, was seen
  - Was not expected at all at this mass
  - The decay into $f_0(980)$ is peculiar
  - Lies at the KK^* threshold
- Intensity in the spin-exotic wave with quantum numbers $J^{PC} = 1^{-+}$ was also seen

Outlook

- Publication in progress
- Extraction of resonance parameters (work in progress)

The spin-exotic wave
$1^{-+}1^{+}\rho(770)\ \pi P$

- In the $1^{-+}1^{+}\rho(770)\,\pi P$ wave, a signal was seen in the analysis
- This wave is spin-exotic, i.e. it can't be explained by the constituent quark model
- Interpretation in terms of resonances not clear at the moment
- Shape changes with four-momentum transfer
- Compare to models for non-resonant contributions (Deck-model)



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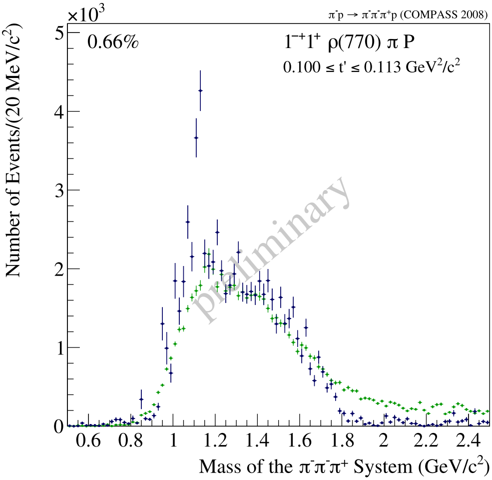

Result of the PWA and Deck-model scaled to integrated intensity

Spin-exotic wave

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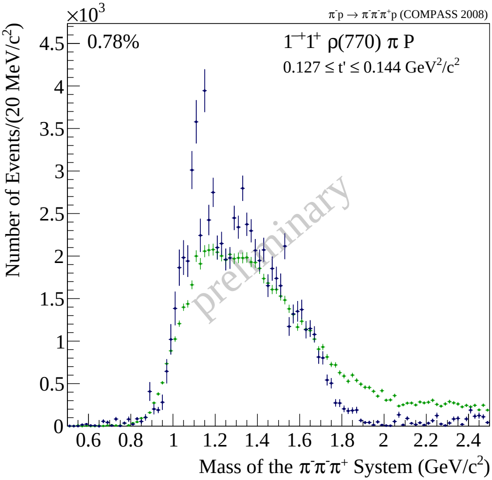

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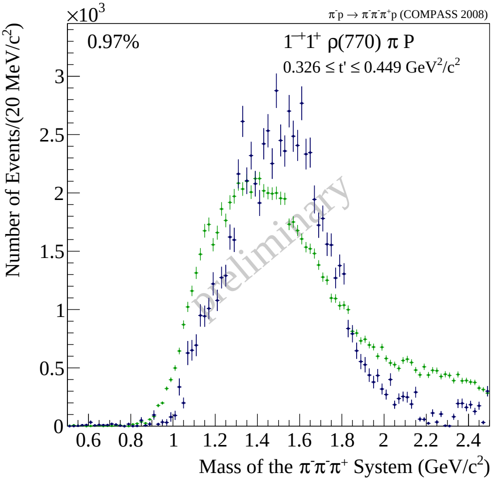

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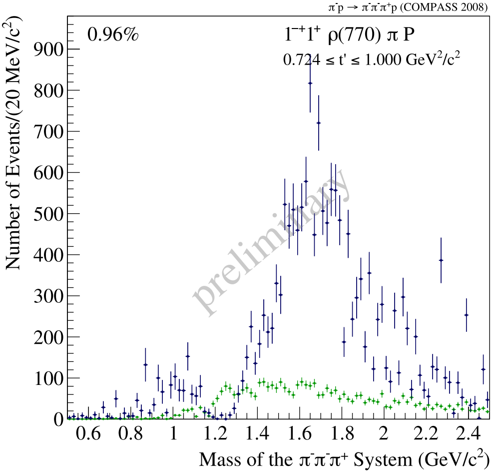
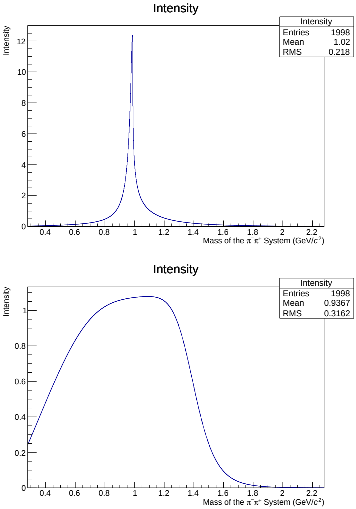
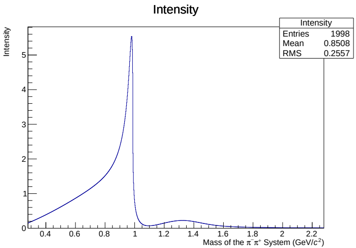


Extraction of the isobar structure
(*De-isobarred PWA*)

- In usual PWA, fixed shapes are assumed for the isobars, that have to be put into the analysis

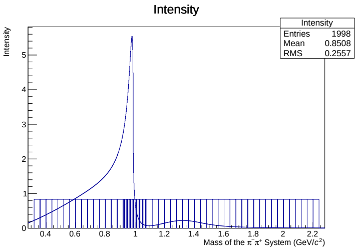


- In usual PWA, fixed shapes are assumed for the isobars, that have to be put into the analysis
- These add up to a complex shape

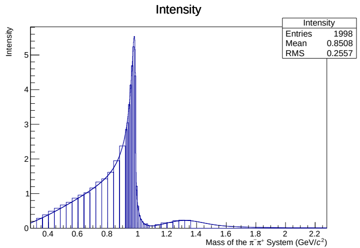


Partial-Wave-Analysis
De-isobarring

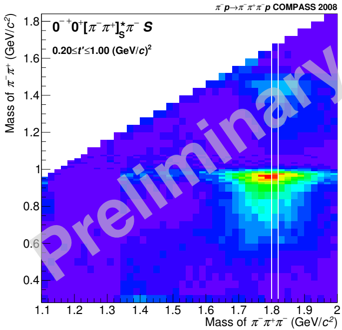
- In usual PWA, fixed shapes are assumed for the isobars, that have to be put into the analysis
- These add up to a complex shape
- This shape is replaced by a series of piecewise constant functions



- In usual PWA, fixed shapes are assumed for the isobars, that have to be put into the analysis
- These add up to a complex shape
- This shape is replaced by a series of piecewise constant functions
- With these, the (binned) shape of the isobars can be determined in the fit



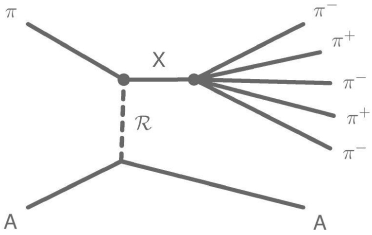
- In usual PWA, fixed shapes are assumed for the isobars, that have to be put into the analysis
- These add up to a complex shape
- This shape is replaced by a series of piecewise constant functions
- With these, the (binned) shape of the isobars can be determined in the fit
- Since this analysis can also be done in bins of m_X, a two dimensional picture is obtained

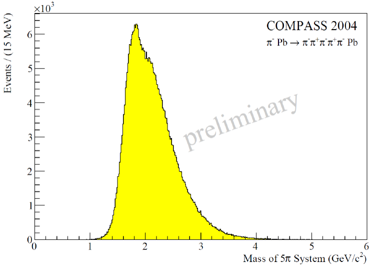


This is not a Dalitz plot

The five-pion final state

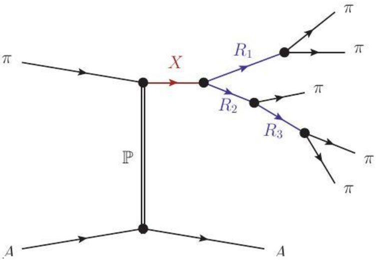
- Process is similar to the Three-Pion channels
- The state X^- decays into five pions

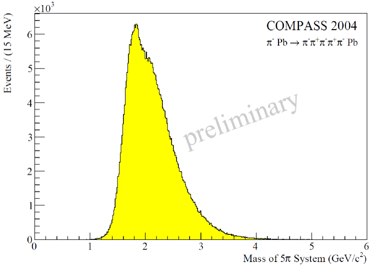




Five-pion final state

- Process is similar to the Three-Pion channels
- The state X^- decays into five pions
- Again, the *isobar-model* is applied, but there are now different topologies





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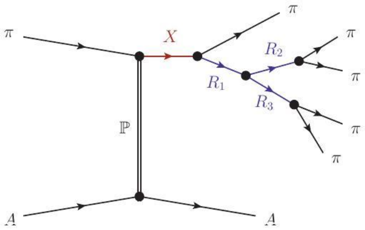

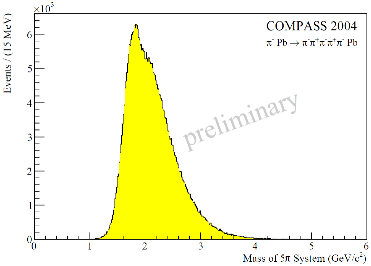

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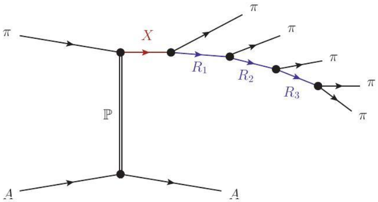

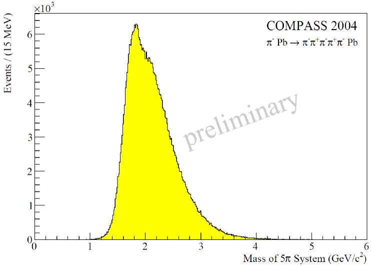

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- The state X^- decays into five pions
- Again, the *isobar-model* is applied, but there are now different topologies
- This results in $\sim$ 1700 waves and $\sim 10^{100}$ possible wave-sets
- Use a genetic algorithm to find the right wave-set