# Light-quark meson spectroscopy at COMPASS


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# Outline

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

# Motivation

# Motivation

## The strong interaction

- 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):

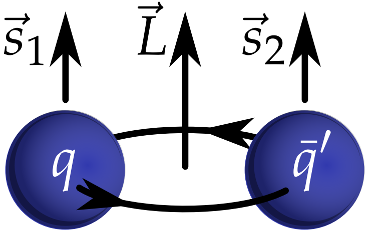
$$\mathcal{L}_{QCD} = \sum_{i,j \in \mathrm{quarks}} \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m_i \delta_{ij}) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a}$$

- 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

# Motivation

## Mesons in the constituent quark model

- 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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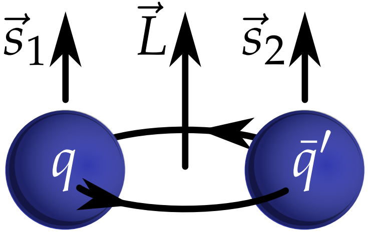


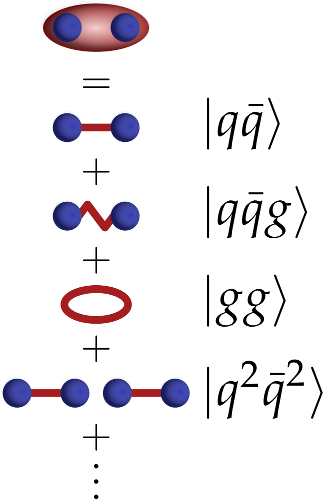

- Forbidden $J^{PC}$ (e.g. $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$) indicate states beyond the constituent quark model

# 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: $|qq\bar{q}\bar{q}\rangle$
    - Molecules: $|(q\bar{q})(q\bar{q})\rangle$
    - ...
  - ...
- 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

# The COMPASS Experiment
## Basic information

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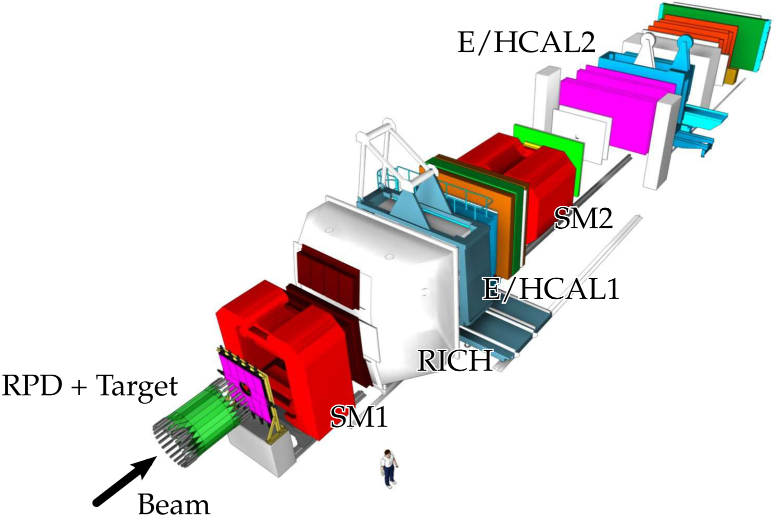
- Multi-purpose fixed-target experiment at CERN
- (Secondary) hadron and (tertiary) muon beams supplied by CERN's Super Proton Synchrotron (SPS)
- Broad physics program:
  - Spin-structure of the nucleon (using $\mu^{\pm}$ and hadron beams)see:
    - *"The GPD program at COMPASS"* by Andrzej Sandacz
    - *"Single hadron double longitudinal spin asymmetries"* by Maxime Levillain
    - *"Transverse spin azimuthal asymmetries in SIDIS"* by Bakur Parsamyan
  - Primakoff reactions
    - *"Measurement of the pion polarizability with COMPASS"* by Stefan Huber
- For the analysis presented:
  - 190 $\mathrm{GeV}/c$ secondary hadron beam (97% $\pi^{-}$)
  - 40 $\mathrm{cm}$ $H_2$ target

# The COMPASS Experiment

## COMPASS hadron setup



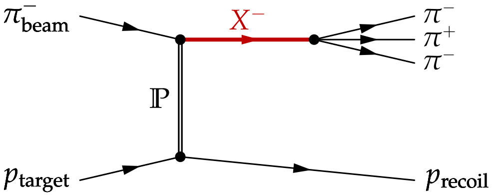
# The Partial-Wave Analysis Method

# Partial-Wave Analysis

## Basic situation

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

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



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- Many different intermediate states $X^-$ decay into the same final state

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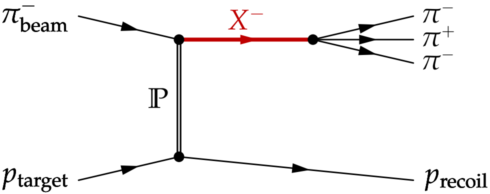

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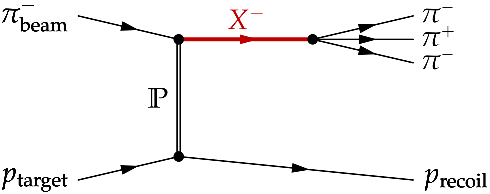



- Different $X^-$ may interfere with each other

**Main goal:**

Disentangle all contributing intermediate states, so called 'waves'

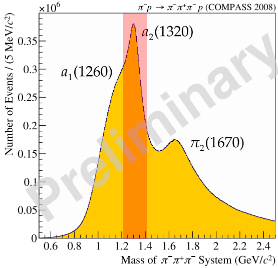
- Use *Partial-Wave Analysis* to do this

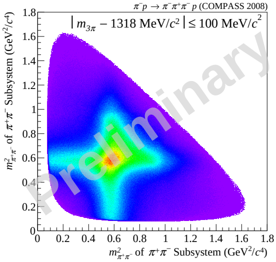
# Partial-Wave Analysis

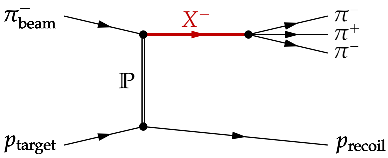
## The *isobar model*

- Dalitz plots at different $m_X$ show a correlation between the spectrum of the $2\pi$-subsystem and the three-pion mass

- Horizontal and vertical band structures are visible



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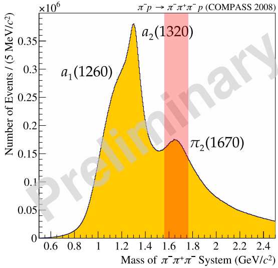
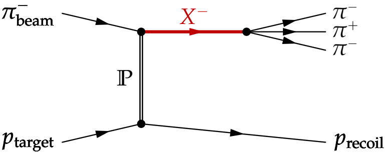
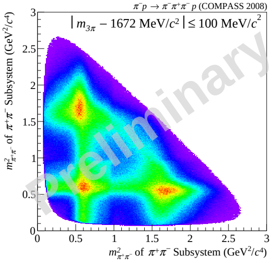


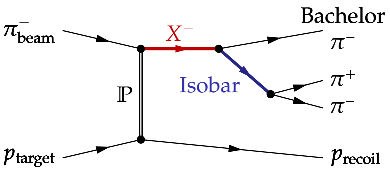



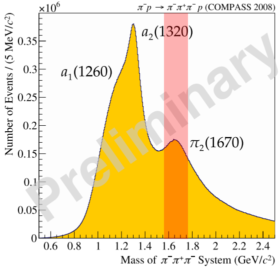
# Partial-Wave Analysis

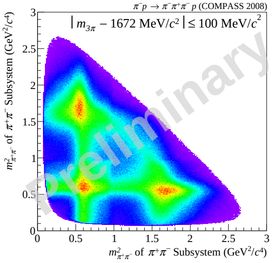
## The *isobar model*

- Dalitz plots at different $m_X$ show a correlation between the spectrum of the $2\pi$-subsystem and the three-pion mass

- Horizontal and vertical band structures are visible
  $\rightarrow$ describe process as subsequent two-particle decays: *isobar model*

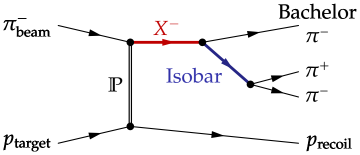


# Partial-Wave Analysis

## The amplitude




- The process is described by an Intensity, which takes the form:

$$\mathcal{I} = \left| \sum_{\text{waves}} T_{\text{wave}}(m_X)\psi_{\text{wave}}(\tau) \right|^2$$

# Partial-Wave Analysis

## The amplitude

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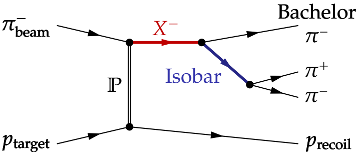


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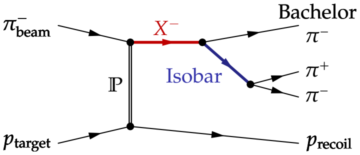


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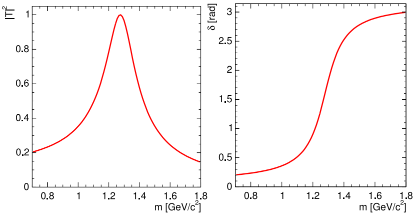


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- The complex production amplitudes $T_{\text{wave}}$ are independently fitted in bins of the mass of the intermediate state $m_X$
- Resonances show through the intensity and a phase shift of the $T_{\text{wave}}$

# Three-Pion Final States

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## The final states

- For this analysis, COMPASS 2008 data are used
- 190 $\mathrm{GeV}$ secondary hadron beam (97% $\pi^-$) on hydrogen target
- $\mathrm{t}' = [0.1, 1]\mathrm{GeV}^2/\mathrm{c}^2$
- Two final states: $\pi^-\pi^0\pi^0$ and $\pi^-\pi^+\pi^-$

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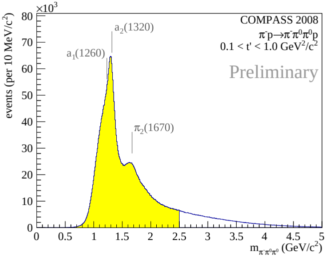

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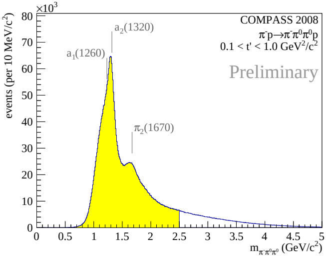


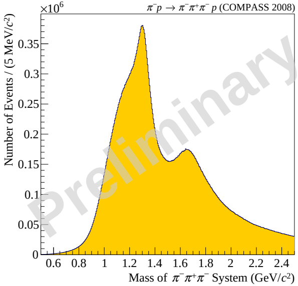

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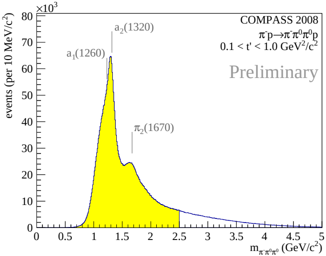
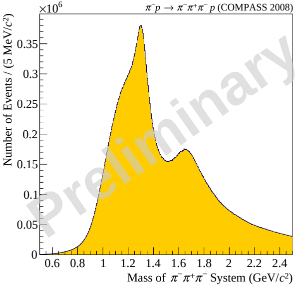
- Different systematics in both channels

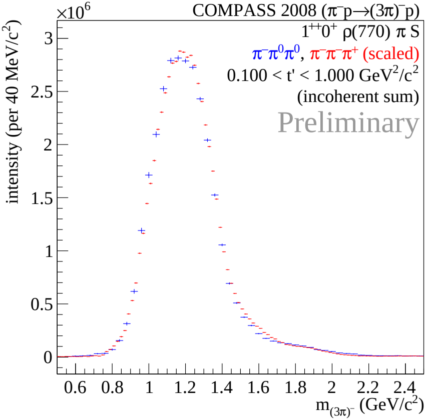


# Three-Pion Final States

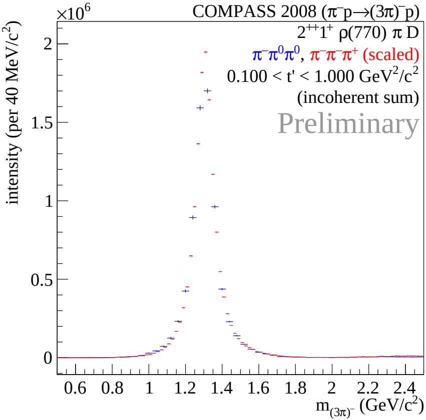
## $1^{++}0^{+}\rho(770)\,\pi$ $S$ wave

- 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

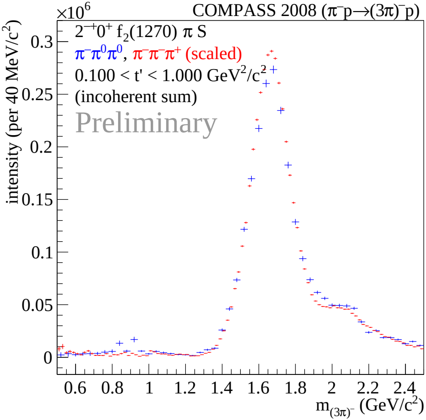



$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ scaled to the integrals

# Three-Pion Final States

## $2^{-+}1^{+} f_2(1270)\ \pi\ S$ wave

- 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

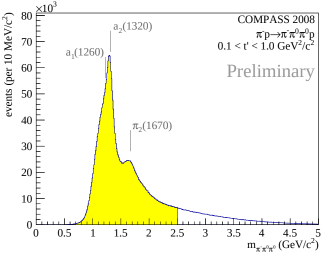


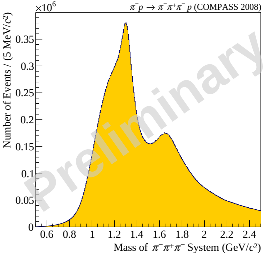

$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ scaled to the integrals

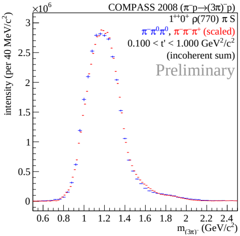
# Three-Pion Final States

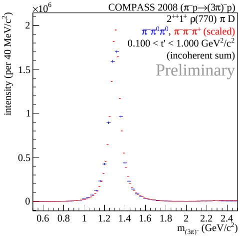


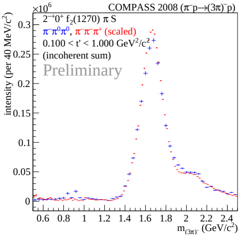
With these three waves, the gross features of the mass spectrum of the two channels can be described



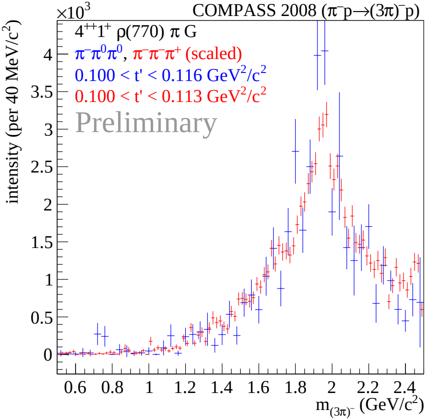



# Three-Pion Final States

## $4^{++}1^{+}\rho(770)\,\pi\;G$ wave

- 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



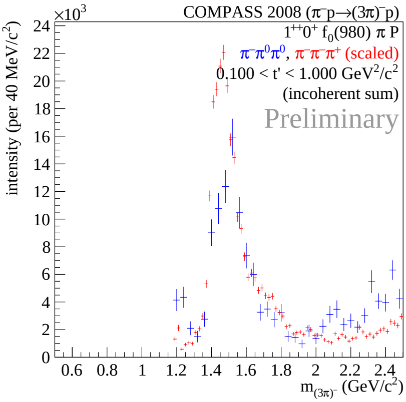

$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ scaled to the integrals

# Three-Pion Final States

## $1^{++}0^{+} f_0(980)\,\pi$ *P* wave

- 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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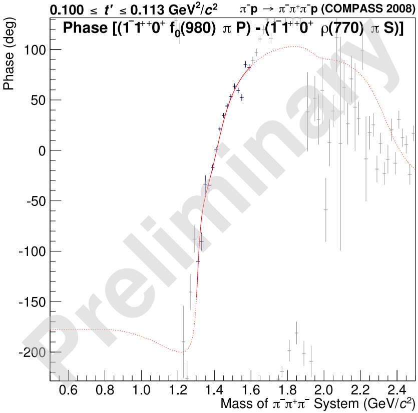

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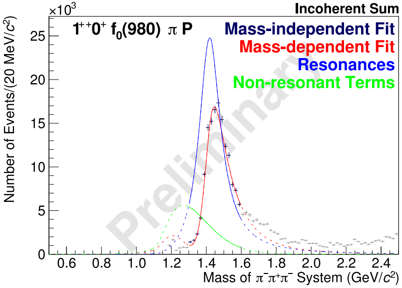


$$M = (1412 - 1422)\text{MeV}/c^2$$
$$\Gamma = (130 - 150)\text{MeV}/c^2$$

## Summary

- This data set is the largest for the $\pi^-\pi^+\pi^-$ channel with $\sim 50 \cdot 10^6$ events, allowing a very detailed Partial-Wave Analysis
- This analysis allows to extract waves on the sub-percent level
- A new resonance, the $a_1(1420)$, was seen
  - Was not expected at all at this mass
  - The decay into $f_0(980)\pi$ is peculiar
  - Lies at the $KK^*$ threshold

# Three-Pion Final States

## Outlook

- Publication in progress (hep-ex/1501.05732)
- Intensity in the spin-exotic wave with quantum numbers $J^{PC} = 1^{-+}$ was also seen
- Very precise description of the accessible light hadron spectrum ($I^G = 1^-$)

  Extraction of resonance parameters (work in progress)
- Other channels:
  - Central production
  - $\eta\pi \text{ and } \eta'\pi$ final states (PLB 740 (2015) 303)
  - Five-Pion final state
  - Radiative width of a2(1320) and $\pi$2(1670) (EPJA 50 (2014) 79)