Hadron Physics at the COMPASS Experiment

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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):

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

Due to confinement, quarks and gluons do not exist as free particles, but typically form baryons ($|q qq\rangle$) 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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The quantum numbers of a meson are given by \( J^{PC} \) with Parity \( P = (-1)^{L+1} \) and generalized charge conjugation \( C = (-1)^{L+S} \).

Forbidden \( J^{PC} \) (e.g. \( 0^{--}, 0^{+-}, 1^{--}, 2^{+-}, \ldots \)) indicate 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
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% $\pi^-$)
- 40 cm $H_2$ target
The COMPASS Experiment
COMPASS hadron setup
The Partial-Wave Analysis Method
Incoming $\pi^-$ gets excited by interaction via Pomeron-exchange with the target and forms an intermediate state $X^-$. Example: $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$.

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

Main goal: Disentangle all contributing intermediate states, so called 'waves'. Use Partial-Wave Analysis to do this.
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Example: $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

- $\pi^-_{\text{beam}}$
- $X^-$
- $\pi^-$
- $\pi^+$
- $\pi^-$
- $p_{\text{target}}$
- $p_{\text{recoil}}$
Incoming $\pi^-$ gets excited by interaction via *Pomeron-exchange* with the target and forms an intermediate state $X^-$. Many different intermediate states $X^-$ decay into the same final state. 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
Partial-Wave Analysis

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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 → describe process as subsequent two-particle decays: *isobar model*
The process is described by a complex amplitude, which takes the form:

\[ A = \sum_{\text{waves}} T_{\text{wave}}(m_X)\psi_{\text{wave}}(\tau) \]
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- The complex production amplitudes \( T_{\text{wave}} \) are independently fitted in bins of the mass of the intermediate state \( m_X \)
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- The \( \psi_{\text{wave}} \) describe the decay and are known functions of the phase-space variables \( \tau \)
- 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
Three-Pion Final States

The final states

- For this analysis, COMPASS 2008 data are used
- 190 GeV secondary hadron beam (97% $\pi^-$) on hydrogen target
- Two final states: $\pi^-\pi^0\pi^0$ and $\pi^-\pi^+\pi^-$
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- $\sim$ 3.5 million events in the $\pi^- \pi^0 \pi^0$ channel.
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- $\sim 3.5$ million events in the $\pi^-\pi^0\pi^0$ channel.
- $\sim 50$ million events in the $\pi^-\pi^+\pi^-$ channel, which is at the moment the world’s largest $3\pi^\pm$ data set.
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190 GeV secondary hadron beam (97% $\pi^-$) on hydrogen target.

Two final states: $\pi^-\pi^0\pi^0$ and $\pi^-\pi^+\pi^-$

$\sim$ 3.5 million events in the $\pi^-\pi^0\pi^0$ channel

$\sim$ 50 million events in the $\pi^-\pi^+\pi^-$ channel, which is at the moment the world’s largest $3\pi^\pm$ data set.

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

\[\pi^-\pi^+\pi^- \text{ and } \pi^-\pi^0\pi^0 \text{ scaled to the integrals}\]
Three pion final states

$2^{++} 1^+ \rho(770) \pi D$ wave

- 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

COMPASS 2008 ($\pi^- p \rightarrow (3\pi^-) p$)

$2^{++} 1^+ \rho(770) \pi D$

$\pi^- \pi^0 \pi^0, \pi^- \pi^- \pi^+ (scaled)$

$0.100 < t' < 1.000 \text{ GeV}^2/\text{c}^2$

(incoherent sum)

Preliminary
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

\[
\pi^-\pi^+\pi^- \text{ and } \pi^-\pi^0\pi^0 \text{ scaled to the integrals}
\]
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
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!

$1^{++}0^+ f_0(980) \pi P$

$\pi^0 \pi^0, \pi^+ \pi^- (scaled)$

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Fabian Krinner (TUM E18)

Hadron Physics at the COMPASS Experiment

Jul 30th - Aug 6th 2014
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NEW RESONANCE!

![Graph showing the intensity of $f_0(980) \pi$ in different channels](image)
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.
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Extraction of the isobar structure

(*De-isobarred PWA*)
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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
Five-pion final state

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

![Diagram of five-pion final state](image)

COMPASS 2004

$\pi^+ \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \pi^- \text{Pb}$

Events: $10^3$

Mass of 5π System (GeV/c$^2$)

preliminary
Five-pion final state

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- Again, the *isobar-model* is applied, but there are now different topologies
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![Diagram](image)

**Graph:**
- Events per (15 MeV) vs. Mass of 5π System (GeV/c²)
- COMPASS 2004
- $\pi^+\text{Pb} \rightarrow \pi^+\pi^-\pi^0\pi^0\pi^-\text{Pb}$

*Preliminary*
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
- This results in $\sim 1700$ waves and $\sim 10^{100}$ possible wave-sets
- Use a genetic algorithm to find the right wave-set

COMPASS 2004

$\pi^+ \text{ Pb} \rightarrow \pi^- \pi^+ \pi^- \pi^+ \text{ Pb}$

Events/15 MeV

Mass of 5π System (GeV/c²)

preliminary