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Meson Spectroscopy at COMPASS

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QCD predicts four quark states or gluonic excitations like hybrids or glueballs to contribute to the meson spectrum in addition to $q\bar{q}$ pair configurations. The most promising way to identify such states is the search for J^{PC} quantum number combinations which are forbidden in the constituent quark model. The fixed target COMPASS experiment at CERN offers the opportunity to search for such states in the light quark sector with an unprecedented statistics.
Diffractive reactions of 190 GeV/c pions on a lead target were studied by COMPASS during a pilot run in 2004. A Partial Wave Analysis (PWA) of the $\pi^-\pi^-\pi^+$ final state with 42 waves including acceptance corrections through a phase-space Monte Carlo simulation of the spectrometer was performed. The exotic $\pi_1(1600)$ meson with quantum numbers $J^{PC} = 1^{-+}$ has been clearly established in the rho-pi decay channel with a mass of 1660 ± 10(stat) MeV/c^2 and a width of 269 ± 21(stat) MeV/c^2. The final state with 5 charged pions was also investigated.
The improved detector performance in 2008 allows us to study many further diffractively and centrally produced resonances with neutral as well as charged particles in the final state. First results of the ongoing analysis of the 2008 data taking period, using a 190 GeV/c pion beam on a liquid hydrogen target are presented in this paper.

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A meson can be described by a set of quantum numbers, which are isospin I and G-parity and the total spin J with parity P and charge conjugation parity C. In the quark model mesons can be described as bound states of quarks and anti-quarks. Quantum Chromo Dynamics (QCD) predicts the existence of states which are not foreseen within the quark model. Possible states are hybrids, $q\bar{q}'$ or glueballs, consisting only of glue. The experimental identification of such states, however, is difficult due to mixing with $q\bar{q}$ configurations with the same quantum numbers, e.g. the glueball ground state with $J^{PC} = 0^{++}$ [1]. The observation of exotic states, however, with quantum numbers not allowed in the simple quark model, e.g. $J^{PC} = 0^{--}$,0^{+-}, 1^{-+}, ..., would give clear evidence that quark-gluon configurations beyond the quark model, as allowed by QCD, are realized in nature.
The lowest-lying hybrid, i.e. a system consisting of a color octet $q\bar{q}$ pair neutralized in color by a gluonic excitation, is expected [2] to have exotic quantum numbers $J^{PC} = 1^{-+}$, and thus will not mix with ordinary mesons. Its mass is predicted in the region 1.3-2.2 GeV/c^2. There are three experimental candidates for a light 1^{-+} hybrid. The $\pi_1(1400)$ was observed by E852 [3] and by VES [4] and by Crystal Barrel [5, 6]. Another 1^{-+} state, the $\pi_1(1600)$, decaying into $\rho\pi$ [7, 8, 9], $\eta'\pi$ [10, 11], $f_1(1285)\pi$ [12, 13] and $b_1(1235)\pi$ [13, 14] was observed in peripheral $\pi^- p$ interactions in E852 and VES. The resonant nature of both states, however, is still heavily disputed in the community [4,13]. A third exotic state, $\pi_1(2000)$, decaying to $f_1\pi$ and $b_1\pi$ was seen in only one experiment [12, 14]. The COMPASS experiment can contribute significantly in the low mass region to the search for exotic mesons and glueballs.

1. The COMPASS Experiment

The **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy [16] is located at CERN SPS accelerator. It is a two stage magnetic spectrometer which provides a large angular acceptance over a wide momentum range. Besides calorimetry and particle identification COMPASS is equipped with a very precise charge particle tracking system. For the beam tracking, Silicon detectors around the target and Scintillating Fibres and PixelGEMs are used. Close to the beam large sized GEM detectors and Micromegas are the backbone of the tracking system. The periphery is covered by Drift Chambers and MWPCs. Due to its physics program, COMPASS requires intensive beams. The muon beam, used between 2002 and 2007 had a beam rate of $4 \cdot 10^7 s^{-1}$ and the 2008 hadron beam a rate of $5 \cdot 10^6 s^{-1}$. COMPASS is taking data since 2002 with up to 580 TBytes per year.

2. 2004 Pilot Run

As mentioned in the previous section the first years of data taking were dedicated to spin physics. In 2004 there was a short pilot run for the future hadron program using a 190 GeV/c negative charged pion beam and a 3 mm lead target. During this short period a competitive statistics could be collected.

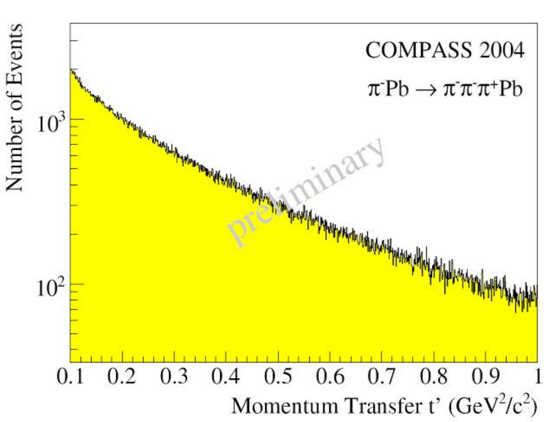

Figure 1: 4-momentum transfer t' for diffraction of beam pions on single nucleons within the lead target, logarithmic scale.

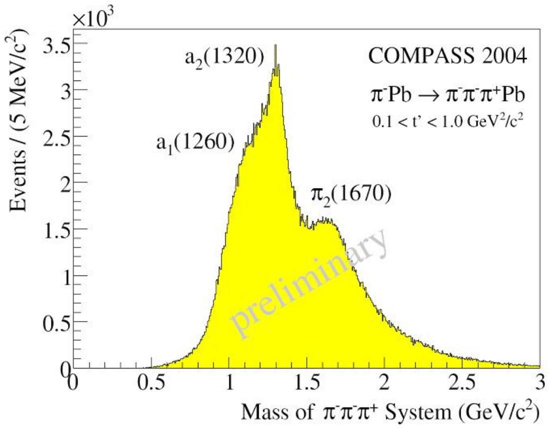

Figure 2: Invariant mass of the high t' data sample.

2.1 Diffractive Reactions into 3 charged Pions

Diffractive dissociation is a process where an incoming beam particle impinges on a target and is excited to a resonance X which finally decays into a final state of particles. The target particle takes away the recoil, but stays intact. In only 3 days of data taking during the pilot run about $4 \cdot 10^6$ diffractive events were recorded. Fig.1 shows the distribution of the kinematic variable t' which is given by $|t| - |t|_{min}$ where t is the square of the four momentum transferred from the incoming beam to the outgoing final state and $|t|_{min}$ the minimum value of $|t|$ which is allowed by kinematics for a given mass m_X. This analysis focuses on events in the high t' region between 0.1 GeV^2/c^2 and 1.0 GeV^2/c^2 (see Fig.1)where E852 [8] observed production of the exotic $\pi_1(1600)$ with the quantum number 1^{-+}.. After the cut on t' still $4.2 \cdot 10^5$ events remain. The invariant mass spectrum of this data sample can be seen in Fig.2.

2.1.1 Isobar Model and Partial Wave Technique

The present analysis is based on is the commonly known isobar model. Within this model the produced resonance X decays into a di-pion isobar and a bachelor pion. The isobar decays into a $\pi^-\pi^+$ pair. L denotes the angular momentum between the bachelor pion and the isobar. A Partial Wave Analysis, performed in two steps, was applied to this data sample. The first step is a mass independent PWA. The data is divided into 40 MeV/c^2 bins of the 3π invariant mass m. No dependence of the production strength for a given wave on the mass is introduced at this point:

$$\sigma_{indep}(\tau,m,t') = \sum_{\varepsilon=\pm1} \sum_{r=1}^{N_r} \left| \sum_i T^{\varepsilon}_{ir} f^{\varepsilon}_i(t') \psi^{\varepsilon}_i(\tau,m) / \sqrt{\int |\psi^{\varepsilon}_i(\tau',m)|^2 \, d\tau'} \right|^2 \qquad (2.1)$$

The production amplitudes T^{ε}_{ir} are the only fitting parameters in that equation. They can be obtained by a maximum likelihood fit. The real functions f describes the t' dependence of the cross-section while τ are the 5 phase space parameters of the 3 body decay. The decay amplitudes $\psi^{\varepsilon}_i(\tau',m)$, the indices i and ε denoting different partial waves, are characterized by a set of quantum numbers

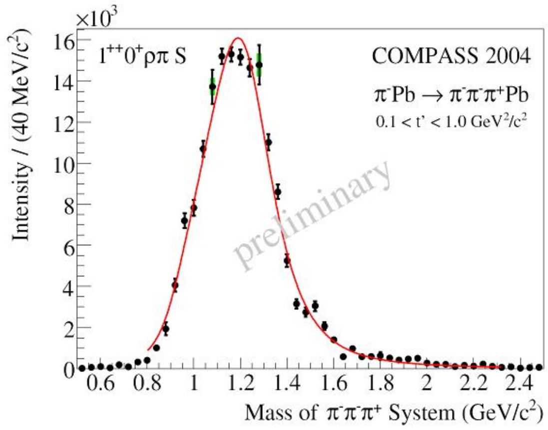

Figure 3: $1^{++}0^{+}\rho\pi S$ intensity, the red curve is the mass dependent fit.

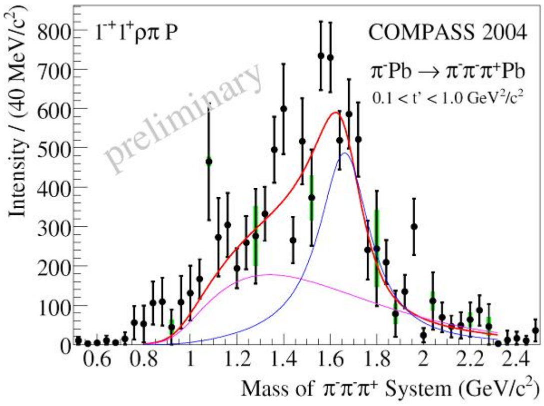

Figure 4: Spin-exotic $1^{-+}1^{+}\rho\pi P$ intensity. Mass-dependent fit shown as red curve, the blue and the purple curve illustrate the resonance and the background contribution.

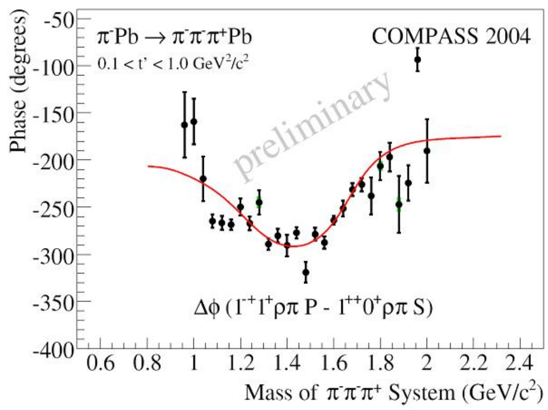

Figure 5: Phase difference $\Delta\phi$ between the spin-exotic $1^{-+}1^{+}\rho\pi P$ wave and the $1^{++}0^{+}\rho\pi S$ reference wave. Mass-dependent fit is shown in red color.

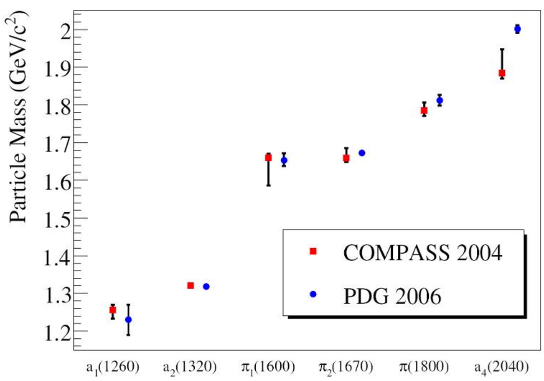

Figure 6: Overview of the resonance masses from the mass-dependent fit and comparison to PDG values.

$J^{PC}M^{\varepsilon}[isobar]L$. M is the absolute value of the spin projection onto the beam direction; ε is the reflectivity [19], which describes the symmetry under a reflection through the production plane. The $\psi_i^{\varepsilon}(\tau,m)$ are described by Zemach tensors or D functions. In this analysis 41 partial waves were used. In addition a flat background wave was implemented.

In a second step a mass dependent χ^2 fit is performed, parameterized by Breit-Wigner functions. In practice only a subset of waves is fitted. In this analysis the focus was on 6 waves, containing clear resonances and the exotic wave $1^{-+}1^{+}\rho\pi P$

2.1.2 Fit Results

Fig.3 shows, as an example, the intensity of the $1^{++}0^{+}\rho\pi S$ wave, described by a Breit-Wigner for the $a_1(1260)$ and a coherent background taking into account non-resonant production via the

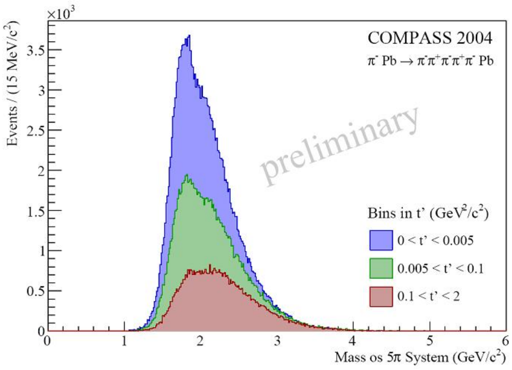

Figure 7: Invariant mass of the 5π system for different t' bins.

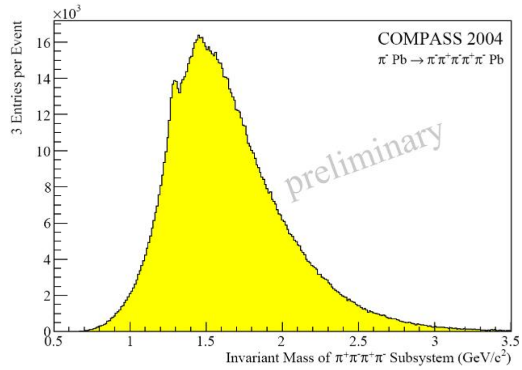

Figure 8: Invariant mass spectrum of the neutral 4π subsystem. Three entries per event.

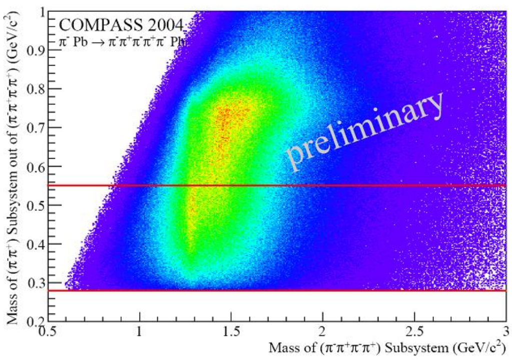

Figure 9: Invariant mass of the $(\pi^+\pi^-)$ subsystem out of the $\pi^+\pi^-\pi^+\pi^-$ subsystem plotted against the mass of the 4π system. The red lines illustrate the boundaries of the cut that was applied to clean up the $f_1(1285)$ signal. 12 entries per event.

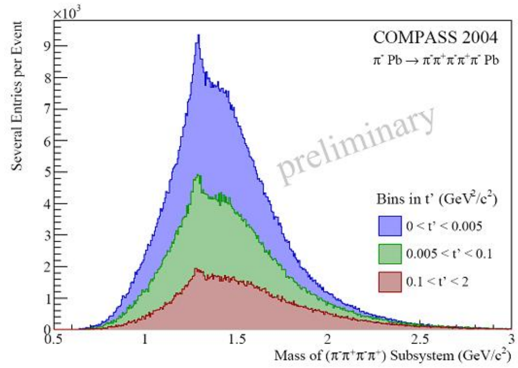

Figure 10: Invariant mass spectrum of the neutral 4π subsystem with a cut on the mass of the $(\pi^+\pi^-)$ subsystem.

Deck effect. Of peculiar interest are the fit results for the spin-exotic wave. The $1^{-+}1^+\rho\pi P$ intensity (Fig.4) has the shape of a broad bump, centered at 1.7 GeV/c^2, with a visible low-mass shoulder. One constant-width BW function (blue curve) and an exponential background have been used to describe this wave. To clarify a possible resonant nature of this exotic amplitude, its interferences with well established states have been studied. Fig.5 shows the phase difference to the $1^{++}0^+\rho\pi S$ wave (Fig.3), which clearly rises between 1.5 GeV/c^2 and 1.9 GeV/c^2. An overview of the fit results of all 6 partial waves used for the mass-dependent PWA can be seen in Fig.6, further details can be found in [17].

2.2 Diffractive Reactions into 5 charged Pions

In order to confirm the hybrid nature of the $\pi_1(1600)$ diffractive dissociation into 5 pion final states is interesting. Flux tube model predicts [18] decay of this resonance into $b_1(1235)\pi$ and $f_1(1285)\pi$. Here, we focus on the f_1 which has been seen to decay into $\pi^-\pi^+\pi^-\pi^+$ final states. The invariant mass spectrum of the 5π system for different t' bins can be seen in Fig.7. Looking at the neutral 4π subsystem (Fig.8) there is a peak at about 1.3 GeV/c^2. In order to investigate this further a two dimensional representation was chosen where the mass of a neutral $\pi^+\pi^-$ subsystem out of the 4π against the 4π mass is plotted (Fig.9). The peak at 1.3 GeV/c^2 in the 4 pion mass clearly appears as a sharp band. Also at 1.45 GeV/c^2 there is a band structure which, however, is considerably broader. In order to get rid of the strong contributions of the spectrum which cluster around the $\rho(770)$ band in the 2π mass only those $\pi^+\pi^-\pi^+\pi^-$ combinations where the respective 2π masses are in the interval 0.28 GeV/c^2 $< m(2\pi) <$ 0.55 GeV/c^2 were selected. The resulting 4π spectra (for different t'-bins) are shown in Fig.10 where the 1.3 GeV/c^2 peak clearly stands out. This peak can be identified with the $f_1(1285)$.

3. 2008 Data Taking

The 2008 and 2009 COMPASS runs were dedicated to meson spectroscopy. For that purpose the spectrometer was upgraded, also based on the experiences from the pilot run.

3.1 Spectrometer Upgrade

The negative hadron beam of COMPASS consists of 96% pions, 3.5% kaons and 0.5% anti-protons. To distinguish between these incoming particles, two CEDAR detectors, using the Cerenkov effect, were installed upstream of the target. Instead of the lead target, used in 2004, a completely new 40 cm long liquid hydrogen target was installed. Surrounding the target a new Recoil Proton Detector was set up, triggering on recoil protons leaving the target. The RPD is one of the main components of the diffractive trigger. Downstream of the target additional silicon micro strip detectors were placed, in order to have a good vertex resolution. Scintillating fibre detectors, used for beam tracking during the previous runs, were replaced by new PixelGEM detectors. These detectors are also able to track beam particles and particles in the vicinity of the beam, but they consist of less material. Also both electromagnetic calorimeters were upgraded with additional scintillating lead glass blocks and sampling ADCs.

3.2 Diffractive Reactions into 3 charged Pions

As a benchmark channel diffractive dissociation into 3 charged pions final states was chosen. A negative charged pion beam of 190 GeV/c momentum, the same as in 2004, impinges on the new hydrogen target. As in 2004 a cut on t' between 0.1 GeV^2/c^2 and 1.0 GeV^2/c^2 was applied. Fig.11 shows the 3π invariant mass spectrum. In comparison to 2004 final states with higher masses could be reached. This is due to the fact that the maximum possible mass of a diffractively produced resonance X is inverse proportional to the radius of the target, in 2008 protons instead of lead nuclei. Fig.12 shows a Dalitz plot for the $\pi_2(1670)$, with a cut at $\pm 0.5\Gamma$ around its nominal mass. One can clearly see the two dominant decay channels, namely $f_2(1270)\pi$ and $\rho\pi$. Based on a first preliminary PWA and extrapolating to the total number of incoming particles during 2008 data taking $9 \cdot 10^7$ events for 2008 data are expected.

3.3 Central Production

Central production proceeds via double Reggeon exchange between the beam and the target particle, producing a resonance X with rapidity between the leading beam particle and the slow

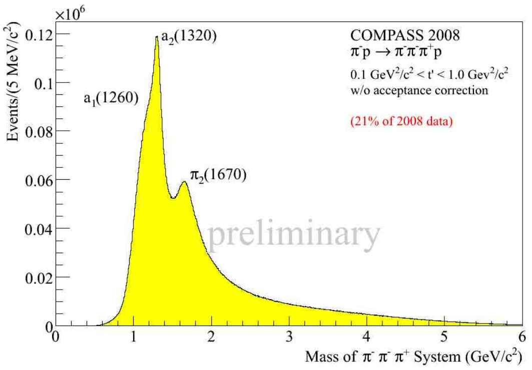

Figure 11: Invariant mass spectrum of the 3π system.

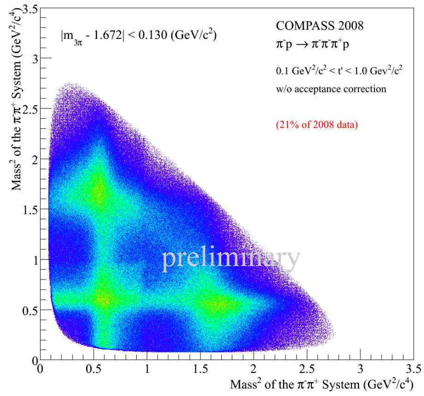

Figure 12: Dalitz plot for the $\pi_2(1670)$, cut at $\pm 0.5\Gamma$ around its nominal mass.

target particle. The final state with four charged pions is well suited for the search for glueballs. Especially the f_0 family of resonances will be most interesting to study.
The $\pi^-\pi^+\pi^-\pi^+\pi^-$ invariant mass spectrum shown in Fig.13, containing the neutral 4π subsystem without the fast pion is of special interest. To access centrally produced events, a cut on x_F of the fastest particle (beam particle) is applied, with:

$$x_F = \frac{|\vec{p}_l|}{|p_l^{\vec{max}}|} = \frac{2|\vec{p}_l|}{\sqrt{s}} \tag{3.1}$$

where $|\vec{p}_l|$ denotes the longitudinal momentum of the particle, $\sqrt{s}$ the total center-of-mass energy and $|p_l^{\vec{max}}|$ the maximum allowed longitudinal momentum. For this analysis a cut on $x_F > 0.7$ is applied resulting in $1.9 \cdot 10^5$ events (see Fig.14). The clear enhancement of the relative $f_1(1285)$ intensity is a good indication that the cut selects rather centrally produced events. However, thorough studies about the impact of this cut on partial waves and about the actual value 0.7 are planned.

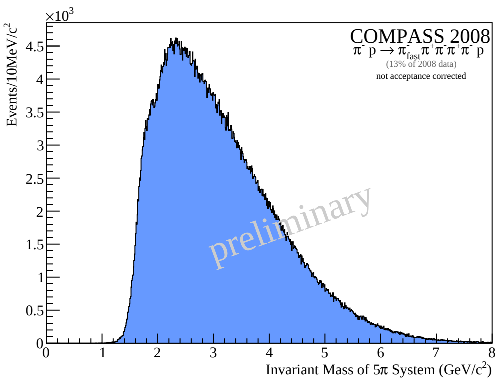

Figure 13: Invariant mass of the 5π system.

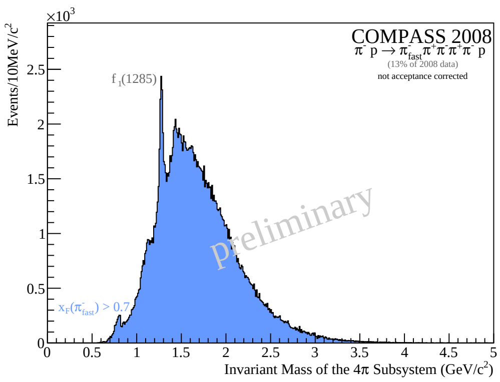

Figure 14: Invariant mass of the 4π subsystem with a cut on $x_F > 0.7$

4. Conclusions and Outlook

The COMPASS spectrometer is a powerful tool to investigate the light meson spectrum. Within a few days of data taking during a pilot run in 2004 enough statistics could be collected to make a partial wave analysis of $\pi^-\pi^+\pi^-$ final states. A strong signal of the spin-exotic $1^{-+}1^+\rho\pi P$ wave could be observed, identified with the $\pi_1(1600)$. A mass-dependent fit results in a mass of 1660 ± 10(stat) MeV/c^2 and a width of 269 ± 21(stat) MeV/c^2. Furthermore the first attempt to make a partial wave analysis of 5 charged pions final states was undertaken, first observations of the kinematic distributions promis interesting results in the future.
Two years of data taking, 2008 and 2009, dedicated to meson spectroscopy will improve the world statistics on diffractive and central production by a factor of 10. First results of diffractive dissociation on hydrogen into $\pi^-\pi^+\pi^-$ final states were shown. COMPASS also offers the opportunity to study central production and contribute to the search for glueballs. The analysis of many other final states, including difractively produced $\pi^0\pi^0\pi^-$, centrally produced $\eta\eta$ and $\pi^0\pi^0$ final states or final states containing kaons are progressing. A lot of exciting results will follow.

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