



### 1. Motivation

- Constituent quark model:**
- color neutral  $q\bar{q}$  systems, Quantum numbers  ${}^1G_J^{PC}$
  - $P = (-1)^{L+1}$   $C = (-1)^{L+S}$   $G = (-1)^{L+1}$
  - $J^{PC}$  multiplets:  $0^{++}, 0^+, 1^-, 1^+, 2^{++}, \dots$
  - Forbidden:**  $0^-, 0^+, 1^-, 2^+, 3^+, \dots$

### QCD: meson states beyond

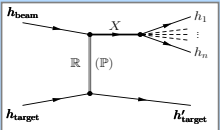
- Glueballs:  $gg, ggg$
- Hybrids:  $q\bar{q}g$
- Tetraquarks:  $(q\bar{q})(q\bar{q})$

### Experimental observation:

=> Fundamental **confirmation of QCD**

### Diffractive scattering:

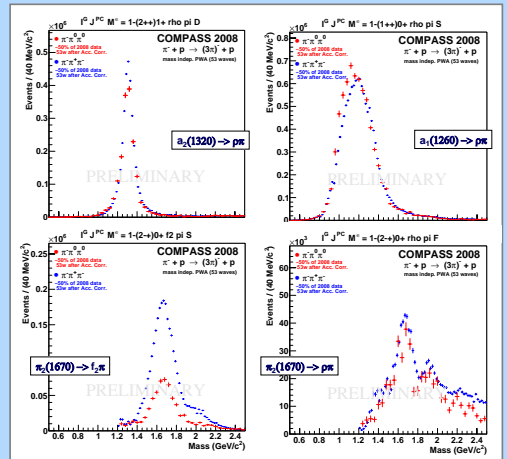
- Study of  $J^{PC}$  exotic mesons
- t-channel Regge-exchange
- forward kinematics
- small momentum transfer
- target **stays intact**



### Hybrid candidates (1.3 - 2.2 GeV/c<sup>2</sup>):

- lightest hybrid predicted: **exotic  $J^{PC} = 1^{+-}$**
- $\pi_1(1400)$ : VES, E852, Crystal Barrel  $\rightarrow \eta\pi$
  - $\pi_1(1600)$ : E852, VES  $\rightarrow \rho\pi, \eta'\pi, f_1\pi, b_1\pi$
  - $\pi_1(2000)$ : E852  $\rightarrow f_1(1285)\pi, b_1(1235)\pi$
  - ... still controversial  $\rightarrow$  **COMPASS**

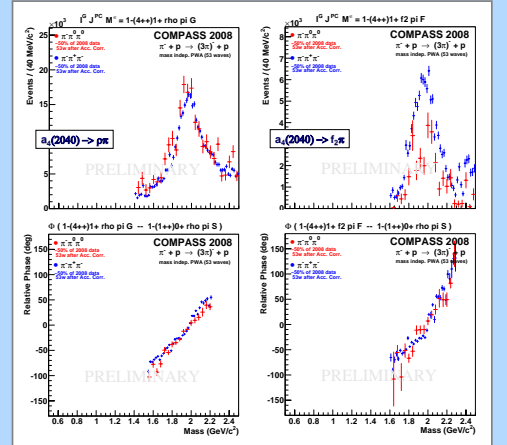
### 4. Main partial-waves and resonances



### Mass-independent PWA result

- the most prominent resonances consistently observed:
  - $\rightarrow$  similar widths, intensities following isospin symmetry
- Here: Major intensity waves

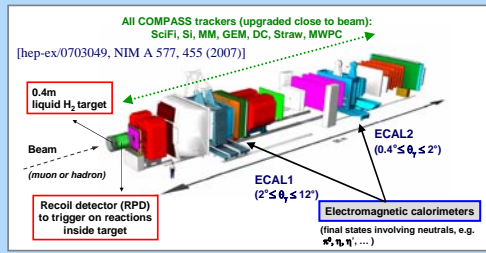
### 7. Very small waves and relative phases



- Not only the intensities but also the relative phases w.r.t. well-known resonances observed as expected.
- Here: Very small waves, rel. phase to the  $1^{++}$  wave ( $a_1(1260)$ )

### 2. The COMPASS experiment

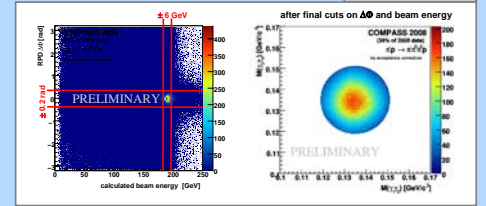
- high resolution, large acceptance spectrometer



### Experimental set-up 2008/09:

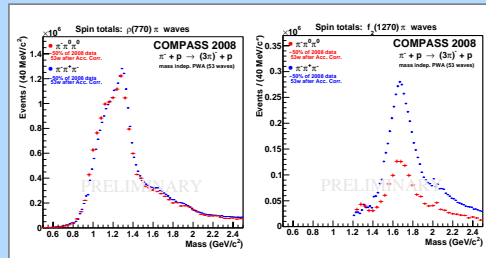
- 190 GeV/c beam ( $\pi^\pm, K^\pm, p$ ), liquid  $H_2$  target
  - new recoil proton detector (exclusive trigger)
  - Calorimetry in both stages – upgraded 2008/09
- [Hadron set-up 08/09, NIM A, in preparation (2012)]

### Selection of exclusive sample:



$\rightarrow$  for more details on the event selection, see [2]

### 5. Spin totals of $\rho\pi$ and $f_2\pi$ partial-waves



- Isospin symmetry:** neutral / charge mode
- $X^-$  decaying into  $\rho\pi$ : 1/1 intensity expected
  - $X^-$  decaying into  $f_2\pi$ : 1/2 intensity expected\*

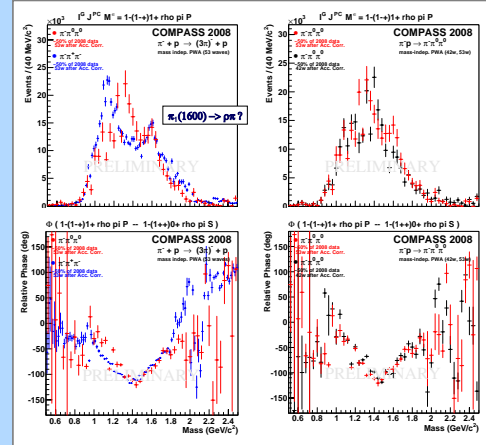
(\*): presumed the BR are entirely determined by the Clebsch-Gordon coefficients, in general, Bose-Symmetrisation might change the picture – checked for various partial-waves involving  $f_{0,2}$  as isobar, e.g.:

BR = $N(\pi^+\pi^0\pi^0)/N(\pi^+\pi^-\pi^0)$	Found in data
BR( $0^+ f_0(1370) \rightarrow S$ ) = 0.29 (at 1.8 GeV)	0.25 (at 1.8 GeV)
BR( $0^+ f_0(980) \rightarrow S$ ) = 0.44 (at 1.8 GeV)	0.46 (at 1.8 GeV)
BR( $1^{++} f_1(1400) \rightarrow P$ ) = 0.80 (at 1.3 GeV)	0.87 (at 1.2 GeV)
BR( $2^{++} f_2(1270) \rightarrow S$ ) = 0.50 (at 1.67 GeV)	0.40 (at 1.67 GeV)

in fair agreement with the data, see also [2]

- the data follows isospin symmetry not only for the main waves but throughout the full wave-set.
- Here: Spin totals, sum over all partial-waves of given isobar

### 8. Exotic $J^{PC} = 1^{+-}$ wave and relative phase



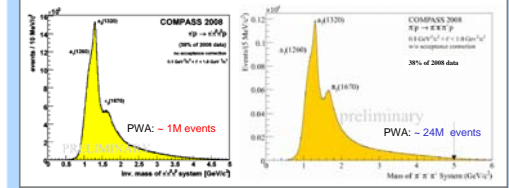
- Two features on top of large non-resonant background:
- a larger peak at 1.3 GeV (leakage?)
  - a smaller one at ~1.6 GeV, indicated to be of resonant nature  $\rightarrow$  relative phase against the  $1^{++}$  wave ( $a_1(1260)$ )

### 3. Partial-wave analysis

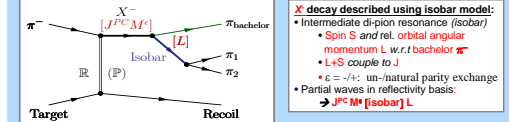
Two different final states for the  $\rho\pi$  decay channel:

- $\pi^- \rho \rightarrow \pi^- \pi^0 \pi^0$  (neutral mode)
- $\pi^- \rho \rightarrow \pi^- \pi^+ \pi^-$  (charged mode)

Resultant mass spectra (neutral & charged mode, see [2,3]):

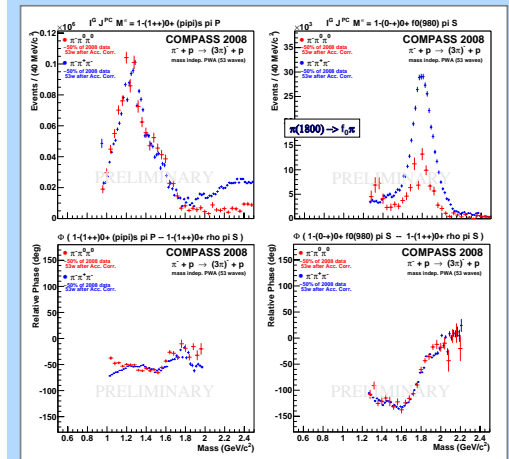


### Partial-wave analysis based on isobar model:



- Isobars:**  $(\pi\pi)_S [f_0(600)+f_0(1370), f_0(980), \rho(770), f_2(1270), f_0(1500), \rho_2(1690)]$
  - Acceptance:** corrections included (normalisation integrals)
  - Mass independent PWA (1<sup>st</sup> step)** – discussed here:  $\rightarrow$  data sliced into 40MeV/c<sup>2</sup> bins, 42/53 partial waves i:
- $$\sigma_{\text{indep}}(\tau, m, \ell) = \sum_{i=1}^N \sum_{j=1}^N T_{ij}^* f_i^*(\ell) v_i^*(\tau, m) / N_i^*(m)$$
- Mass dependent  $\chi^2$  fit (2<sup>nd</sup> step)** – not yet discussed  $\rightarrow$  chose selection of waves (Breit-Wigner param.)

### 6. Smaller waves and relative phases



- Not only the intensities but also the relative phases w.r.t. well-known resonances are observed consistently for the neutral vs. the charged mode data, as expected.
- Here: Smaller waves, rel. phase to the  $1^{++}$  wave ( $a_1(1260)$ )

### 9. Summary and outlook

- COMPASS:**
- High potential for **Hadron Spectroscopy**
  - 2004 data: **Exotic  $J^{PC} \rightarrow \pi_1(1600)$** , see [1]
  - 2008/09: **High statistics (10-100x world statistics)** Measures **neutral & charged channels**  $\rightarrow$  and **kaonic final states!**, see e.g. [4]

- Search for the  $\pi_1(1600)$ :**
- Exotic signal (simultaneously) observed in  $3\pi$  neutral and charged decay modes of the  $\rho\pi$  decay channel:**
  - $\rightarrow$  consistently observed in both, neutral and charged modes
  - $\rightarrow$  robust against wave-set extension, acceptance corrections, ... however, no final conclusion yet

- Outlook:**
- More systematic studies ongoing (Deck, leakage, ..)
  - $\rightarrow$  more work ahead, before final conclusion on  $\pi_1(1600)$
  - Mass-dependent fit  $\rightarrow$  preliminary fit gives parameters consistent with previous measurements
  - All relevant channels for spin-exotic search feasible, cf. [4]  $\rightarrow$  coupled analyses
  - First publication(s) under preparation

**References:**

- [1] M. Alekseev et al., COMPASS collab., PRL 104 (2010) 241803
- [2] F. Nerling, AIP Conf. Proc., Hadron09 (2010), Conf. Proc., Hadron11 (2011)
- [3] F. Haas, AIP Conf. Proc., Hadron09 (2010), Conf. Proc., Hadron11 (2011)
- [4] F. Nerling, Conf. Proc., HEP2011 (2011)