

Diffractive Dissociation into $\pi^- \pi^- \pi^+$ Final States at COMPASS

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for the COMPASS Collaboration

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Introduction

Diffractive Dissociation into $\pi^- \pi^- \pi^+$ Final States

M-Dependence on the Target Material

Conclusion and Outlook

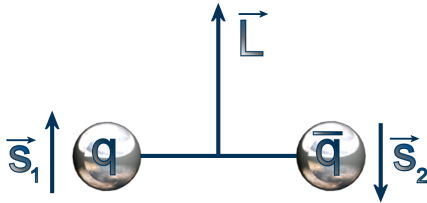


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Quantum Numbers

- $|^G J^{PC}$
- Isospin I
- G-Parity:
 $G = C \cdot e^{i\pi I_2}$
- LS-Coupling:
 $J = \ell \oplus s = |\ell - s| \dots \ell + s$
- Parity:
 $P = (-1)^{(\ell+1)}$
- Charge Conjugation:
 $C = (-1)^{(\ell+s)}$

$J^{PC}(q\bar{q}) : 0^{++}, 0^{-+}, 1^{++}, 1^{+-}, 1^{--}, 2^{++}, 2^{-+}, 2^{--} \dots$

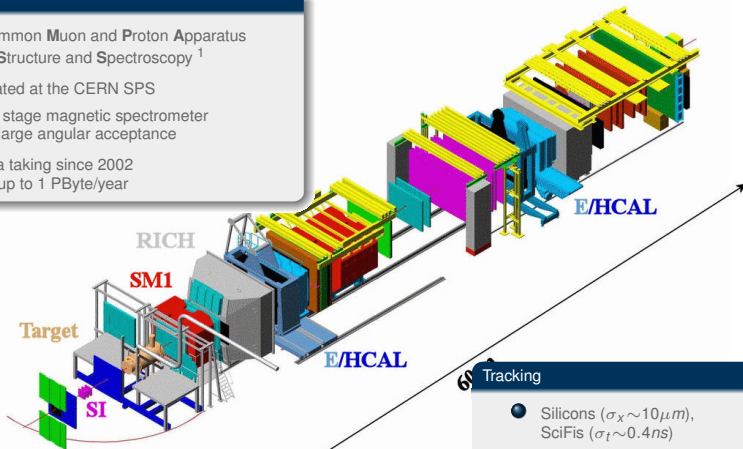
exotic $J^{PC} : 0^{+-}, 1^{-+}, 2^{+-}$



The COMPASS Experiment Overview

Overview

- **CO**mmun **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy ¹
- located at the CERN SPS
- two stage magnetic spectrometer
→ large angular acceptance
- data taking since 2002
→ up to 1 PByte/year



6 Tracking

- Silicons ($\sigma_x \sim 10 \mu m$),
SciFis ($\sigma_t \sim 0.4 ns$)
- (Pixel)GEMs ($\sigma_x \sim 70 \mu m$),
MicroMegas ($\sigma_x \sim 90 \mu m$)
- Drift Chambers ($\sigma_x \leq 200 \mu m$)

¹[Nucl. Instr. and Meth. A 577 (2007) 455]



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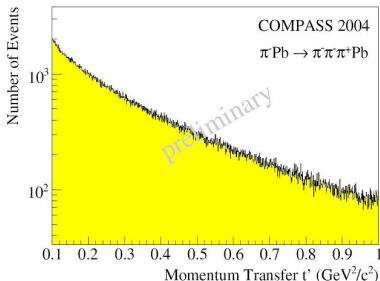
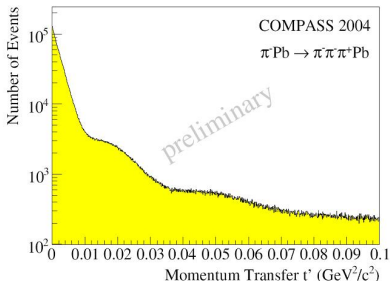
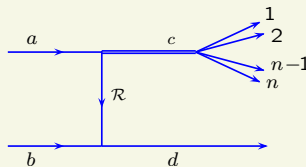
Conclusion and Outlook



Diffraction Dissociation

- Soft scattering of the beam π^- off the target
 - Pb (2004, 2009)
 - IH_2 (2008)
 - W, Ni (2009)
- Target particle remains intact
- Pomeron exchange

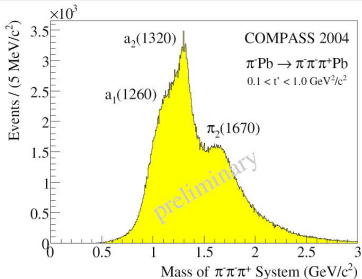
Reaction





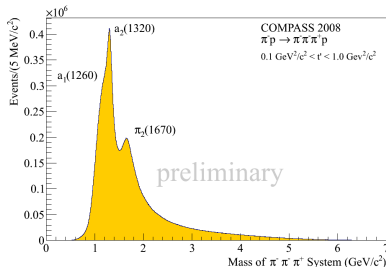
Invariant Mass of 3π System

$\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$ (2004)



- $p_\pi = 190 \text{ GeV}/c$
- 4M events (full t range)
- 450k events in $0.1 < t' < 1.0 \text{ GeV}^2/c^2$

$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (2008)



- $p_\pi = 190 \text{ GeV}/c$
- $\sim 96\text{M}$ events in $0.1 < t' < 1.0 \text{ GeV}^2/c^2$

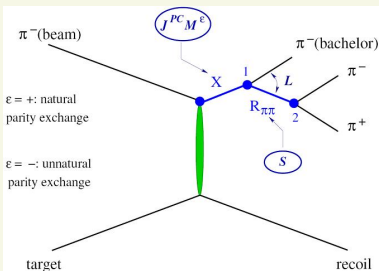


- Two-step approach:
 - Fit in mass bins

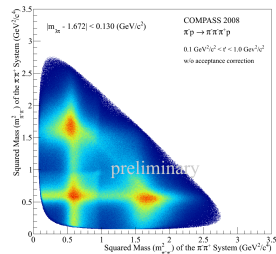
$$\sigma_{indep}(\tau, m, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_j T_{ir}^{\epsilon} \psi_j^{\epsilon}(\tau, m) \right|^2$$

- Fit of the spin density matrix

Iso-bar Model

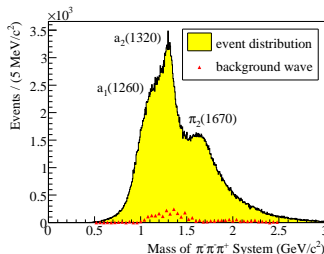
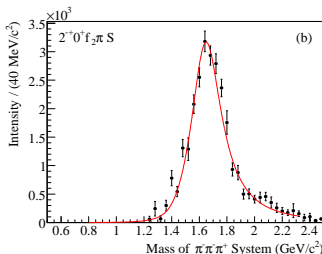
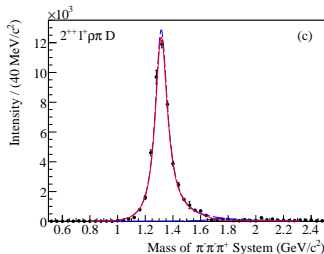
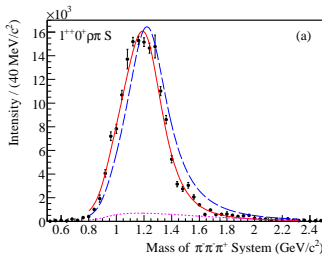


Dalitz Plot $\pi_2(1670)$ region




 $\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$ (2004)

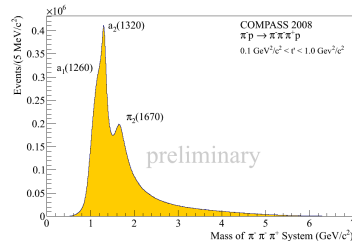
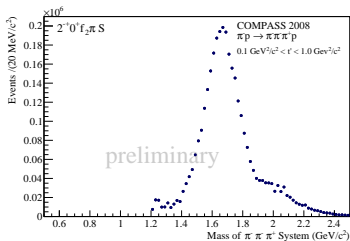
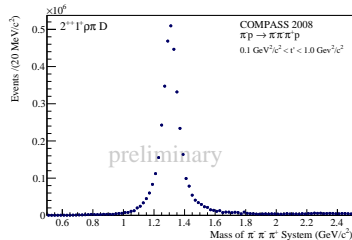
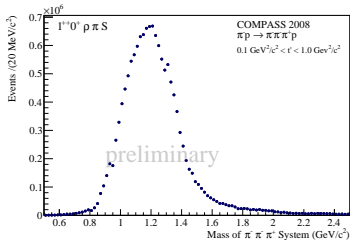
Intensities of Major Waves

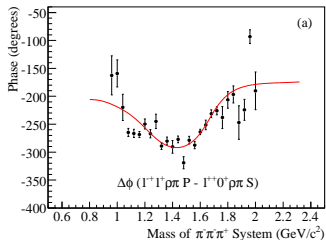
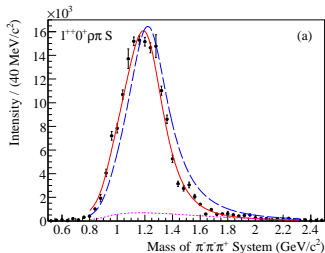
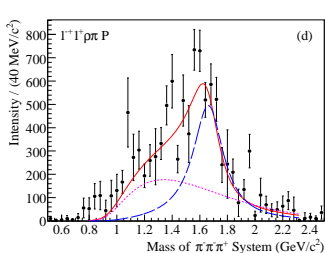




$$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p \quad (2008)$$

Intensities of Major Waves



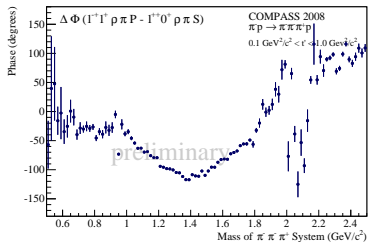
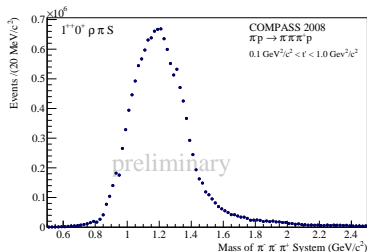
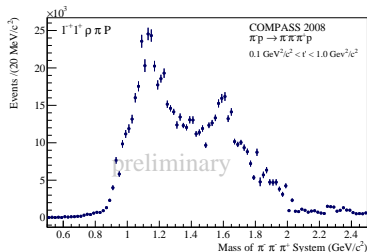

 $\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$ (2004)
 $J^{PC} = 1^{-+}$ Exotic Wave ¹


¹ A. Alekseev *et al.*, COMPASS Collaboration, Phys. Rev. Lett. 104, 241803 (2010)



$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (2008)

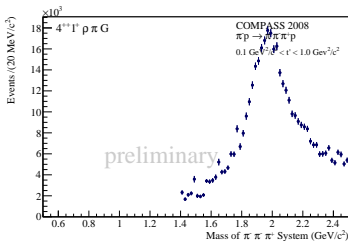
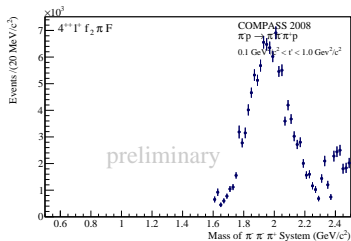
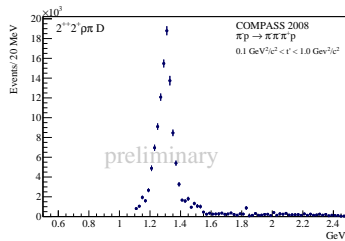
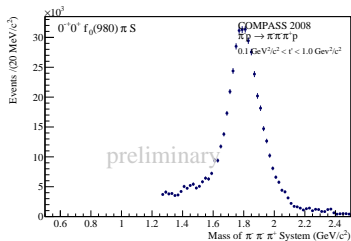
$J^{PC} = 1^{-+}$ Exotic Wave





$$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p \quad (2008)$$

Additional Waves





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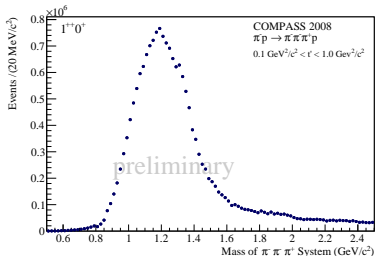


Comparison of different Targets

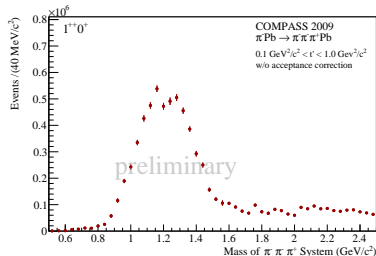
- 2008 IH₂ target, 2009 Pb target (W, Ni not shown)
- Different statistics
 - 2008: $\sim 23\text{M}$, 2009: $\sim 1.2\text{M}$
 - Normalisation to the integral of the $a_2(1320)$ in the mass region between $1.1 \text{ GeV}/c^2$ and $1.6 \text{ GeV}/c^2$
- Population of $M = 1$ states higher for lead target
- Population of $M = 0$ states higher for hydrogen target



Total Intensities for $J^{PC} = 1^{++}$ with $M = 0$



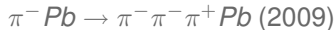
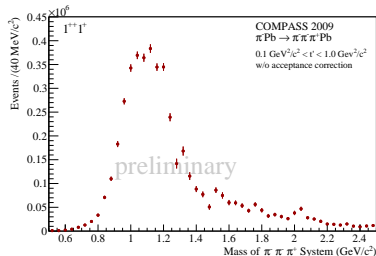
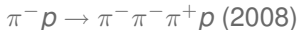
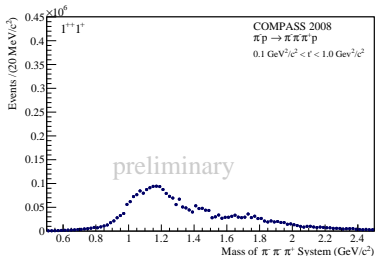
$$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p \text{ (2008)}$$



$$\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb \text{ (2009)}$$



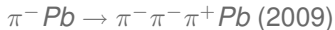
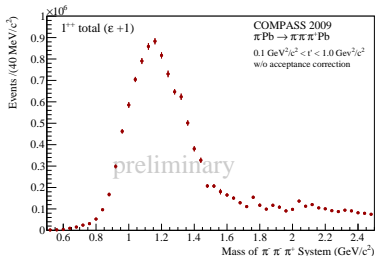
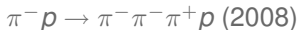
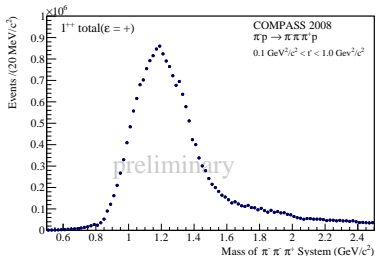
Total Intensities for $J^{PC} = 1^{++}$ with $M = 1$





Total Intensities for $J^{PC} = 1^{++}$

Sum of M sub-states





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- Pilot Run 2004
 - Diffractive pion dissociation on Pb into $\pi^- \pi^- \pi^+$
 - ¹Significant intensity of exotic wave 1^{-+} at 1.66 GeV/c²
- COMPASS 2008/2009
 - Diffractive reactions: 10x BNL E852 statistics
 - Several different targets (p,Ni,W,Pb)
 - Consistency check with isospin partner channel $\pi^- \pi^0 \pi^0$
→ see F. Nerling's talk
 - Analysis ongoing
 - Enhancement of wave set
 - Study of Deck Effect
 - Isobar parametrisations
 - Analysis of M-dependence
- Two independent PWA programs

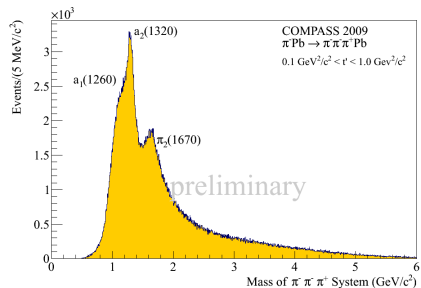
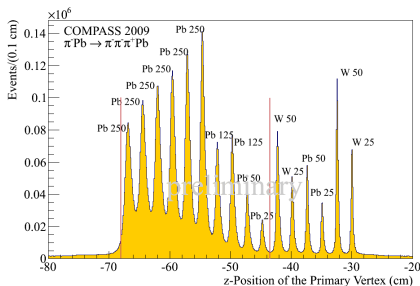
¹A. Alekseev *et. al.*, COMPASS Collaboration, Phys. Rev. Lett. 104, 241803 (2010)



Backup



- 190 GeV/c hadron beam \rightarrow 96% π^- , 3.5% K^- , 0.5% \bar{p}
- Pb, W, Ni targets
- $0.1\text{GeV}^2/c^2 < t' < 1.0\text{GeV}^2/c^2$
- Pb target: \sim 1.5M events



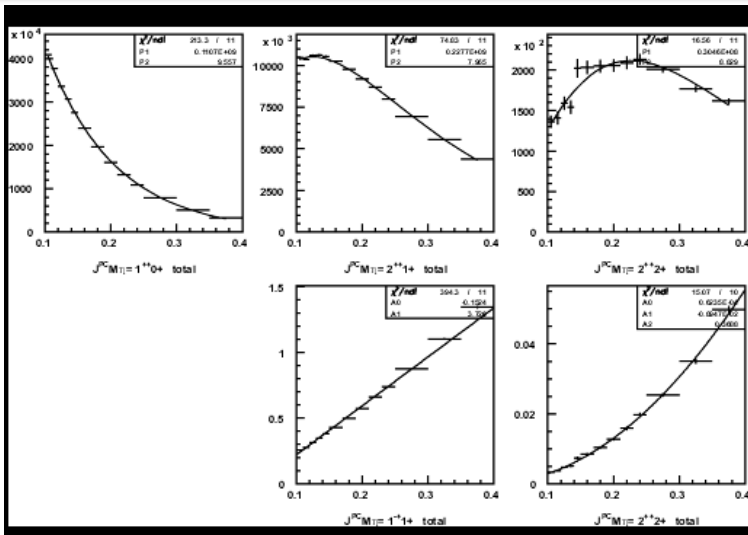


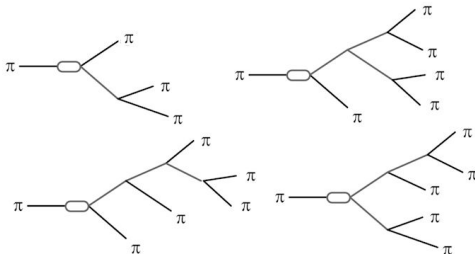
- Comparison of rank 1, 2, 3 mass independent fits
- Different Exclusivity Cut (189 ± 3 or 5 GeV)
- $\pi_1(1400)$ added as second Breit-Wigner resonance to describe 1^{-+} wave, parameters of $\pi_1(1400)$ fixed to PDG values
- 46 waves in mass-independent fit with four $M = 2$ waves included, thresholds adjusted
- D-functions with relativistic factors instead of Zemach tensors used for mass-independent fit
- Dynamical width for $a_4(2040)$ used instead of constant one



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

Is the $2^{++}2^+$ real ?




 $\pi_1(1600) 1^- 1^{--}$

- $(2\pi)^0\pi^-$:
 $\rho\pi^-, f_2(1270)\pi^-$
- $(4\pi)^0\pi^-$:
 $b_1(1235)\pi^-, f_1(1285)\pi^-$
- $\eta'(958)\pi^-$

COMPASS has access to all of these decay modes

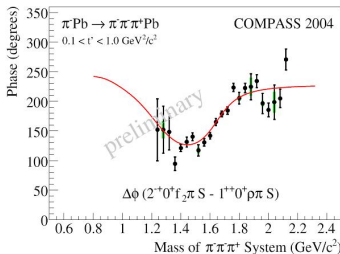
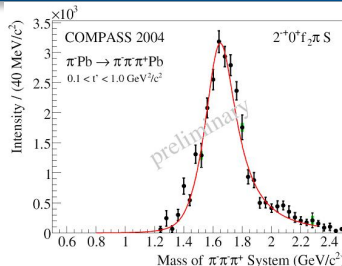
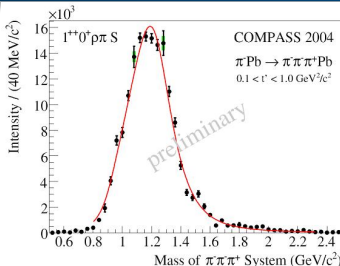


$J^{PC}M^{\epsilon}$	L	Isobar π	Thresh. [GeV]
$0^{-+}0^{+}$	S	$f_0\pi$	1.40
$0^{-+}0^{+}$	S	$(\pi\pi)_{S\pi}$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_{S\pi}$	0.84
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$	S	$\rho\pi$	-
$1^{++}1^{+}$	P	$f_2\pi$	1.40
$1^{++}1^{+}$	P	$(\pi\pi)_{S\pi}$	1.40
$1^{++}1^{+}$	D	$\rho\pi$	1.40
$2^{-+}0^{+}$	S	$f_2\pi$	1.20
$2^{-+}0^{+}$	P	$\rho\pi$	0.80
$2^{-+}0^{+}$	D	$f_2\pi$	1.50
$2^{-+}0^{+}$	D	$(\pi\pi)_{S\pi}$	0.80
$2^{-+}0^{+}$	F	$\rho\pi$	1.20
$2^{-+}1^{+}$	S	$f_2\pi$	1.20
$2^{-+}1^{+}$	P	$\rho\pi$	0.80
$2^{-+}1^{+}$	D	$f_2\pi$	1.50
$2^{-+}1^{+}$	D	$(\pi\pi)_{S\pi}$	1.20
$2^{-+}1^{+}$	F	$\rho\pi$	1.20

$J^{PC}M^{\epsilon}$	L	Isobar π	Thresh. [GeV]
$2^{++}1^{+}$	P	$f_2\pi$	1.50
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.50
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.50
$3^{++}1^{+}$	S	$\rho_3\pi$	1.50
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$	F	$\rho\pi$	1.20
$4^{-+}1^{+}$	F	$\rho\pi$	1.20
$4^{++}1^{+}$	F	$f_2\pi$	1.60
$4^{++}1^{+}$	G	$\rho\pi$	1.64
$1^{-+}0^{-}$	P	$\rho\pi$	-
$1^{-+}1^{-}$	P	$\rho\pi$	-
$1^{++}1^{-}$	S	$\rho\pi$	-
$2^{-+}1^{-}$	S	$f_2\pi$	1.20
$2^{++}0^{-}$	P	$f_2\pi$	1.30
$2^{++}0^{-}$	D	$\rho\pi$	-
$2^{++}1^{-}$	P	$f_2\pi$	1.30
FLAT			



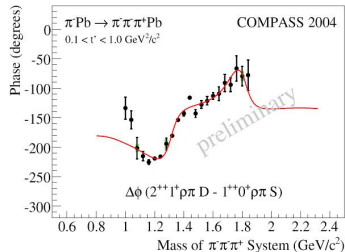
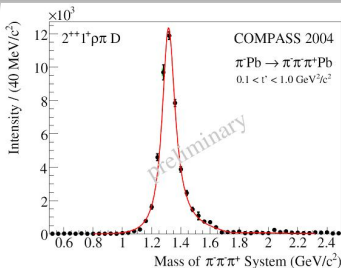
$a_1(1260)$ und $\pi_2(1670)$



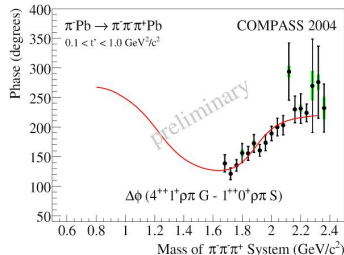
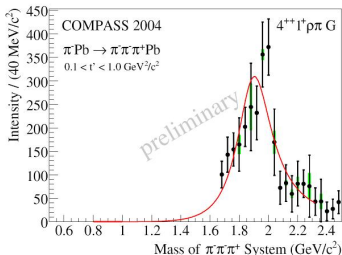
- BW für $a_1(1260)$ + Untergrund
 $M = (1255 \pm 6^{+7}_{-17}) \text{ MeV}/c^2$
 $\Gamma = (367 \pm 9^{+28}_{-25}) \text{ MeV}/c^2$
- BW für $\pi_2(1670)$
 $M = (1658 \pm 3^{+24}_{-8}) \text{ MeV}/c^2$
 $\Gamma = (271 \pm 9^{+22}_{-24}) \text{ MeV}/c^2$



$a_2(1320)$



- Zwei Breit Wigner funktionen nötig um die Phasen Bewegung zu beschreiben
- BW1 für $a_2(1320)$
 $M = (1321 \pm 1_{-7}^{+0}) \text{ MeV}/c^2$
 $\Gamma = (110 \pm 2_{-25}^{+2}) \text{ MeV}/c^2$
- BW2 für $a_2(1700)$: $M = 1732 \text{ MeV}/c^2$, $\Gamma = 194 \text{ MeV}/c^2$ (feste PDG Werte)

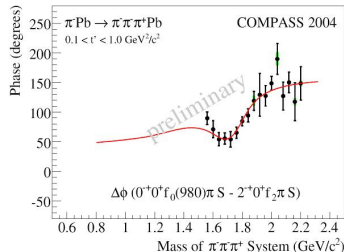
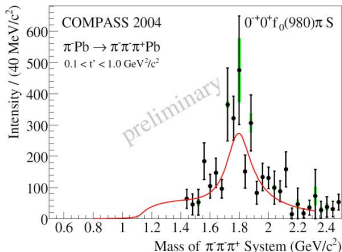


- BW mit konstanter Breite für $a_4(2040)$ (Verweignungsverhältnis unbekannt)

- BW Parameter

$$M = (1885 \pm 13^{+50}_{-2}) \text{ MeV}/c^2$$

$$\Gamma = (294 \pm 25^{+46}_{-19}) \text{ MeV}/c^2$$



- BW mit konstanter Breite für $\pi(1800)$ und Untergrund bei niedrigen Massen

- BW Parameter

$$M = (1785 \pm 9_{-6}^{+12}) \text{ MeV}/c^2$$

$$\Gamma = (208 \pm 22_{-37}^{+21}) \text{ MeV}/c^2$$



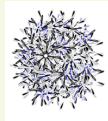
QuantumChromoDynamics predicts existence of meson states which are not foreseen within the quarkmodel:

Tetraquarks



- Two $q\bar{q}$ pairs
- Possible lightest candidates: $f_0(600)$, $f_0(980)$, $a_0(980)$

Glueballs



- Consists only of glue
- Lattice gauge theory: groundstate 0^{++} , first excited state 2^{++}
- Mixing with nearby $q\bar{q}$ states of same quantum numbers: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

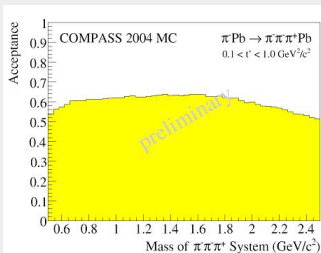
Hybrids



- $q\bar{q}$ pair bound by excited gluons, $q\bar{q}g$
- Lightest hybrid, $J^{PC} = 1^{-+}$, predicted in the mass region of 1.3-2.2 GeV/c^2

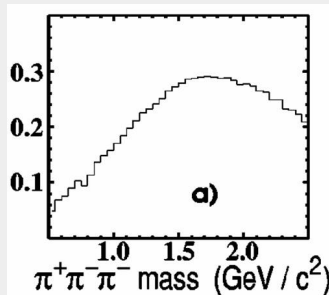


COMPASS



- $p_{\pi} = 190 \text{ GeV}/c$
- 4M events (full t range)
- 450k events in $0.1 < t' < 1.0 \text{ GeV}^2/c^2$

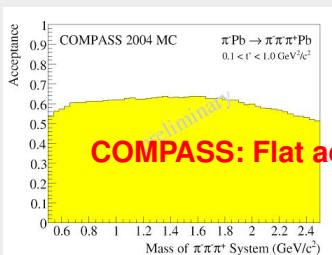
BNL E852



- $p_{\pi} = 18 \text{ GeV}/c$
- 250k events in $0.08 < t' < 1.0 \text{ GeV}^2/c^2$



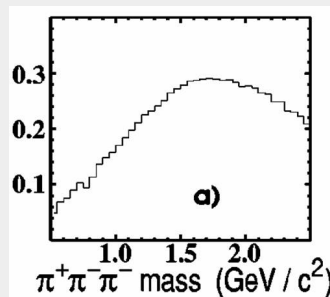
COMPASS



COMPASS: Flat acceptance

- $p_{\pi} = 190 \text{ GeV}/c$
- 4M events (full t range)
- 450k events in $0.1 < t' < 1.0 \text{ GeV}^2/c^2$

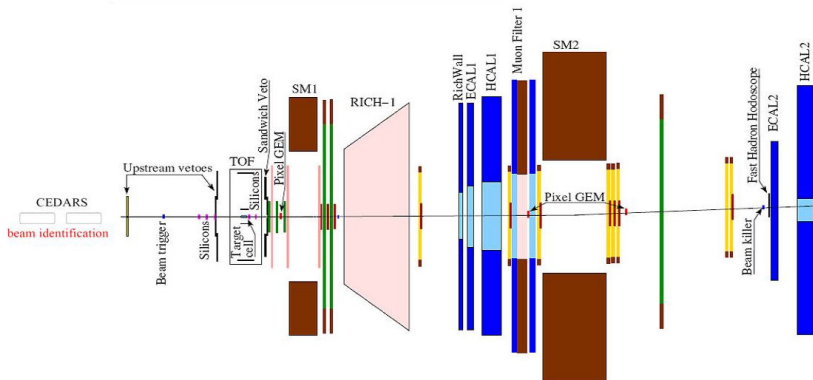
BNL E852

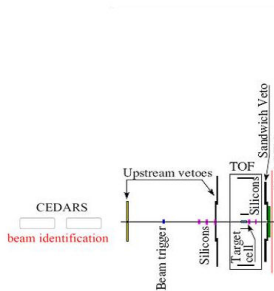


- $p_{\pi} = 18 \text{ GeV}/c$
- 250k events in $0.08 < t' < 1.0 \text{ GeV}^2/c^2$



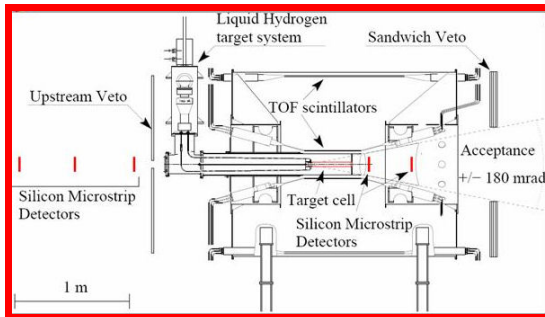
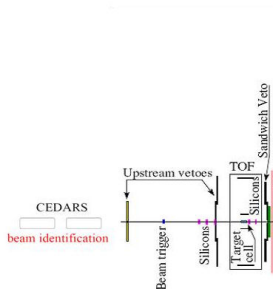
Spectrometer Upgrade 2008





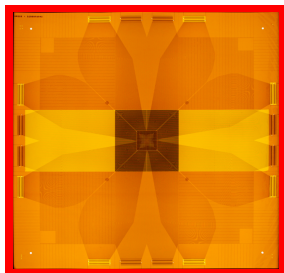
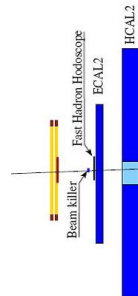
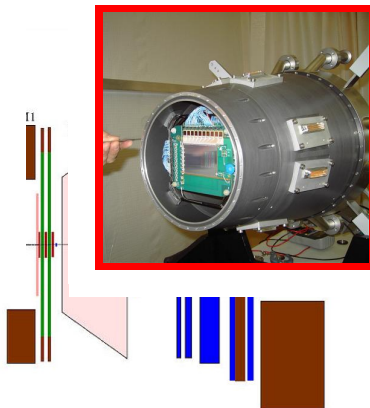


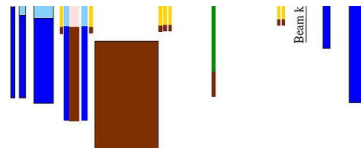
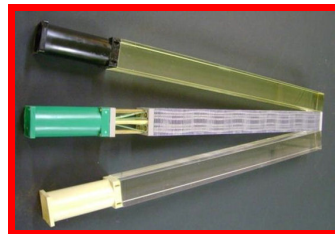
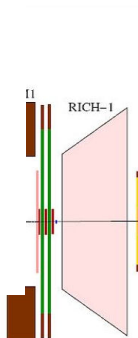
Liquid Hydrogen Target - Proton Recoil Detector

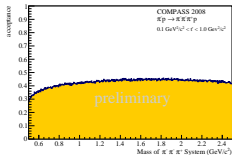
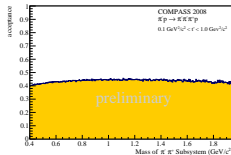
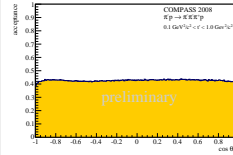
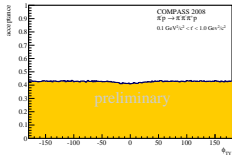
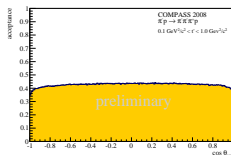
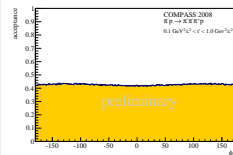




Additional Detectors

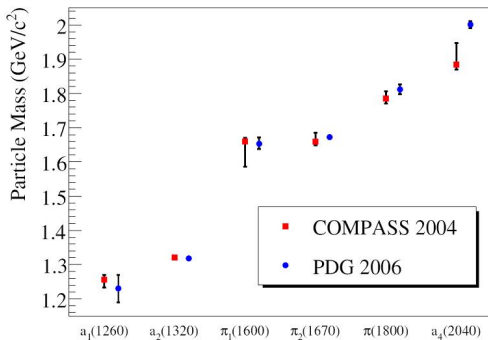
B_k



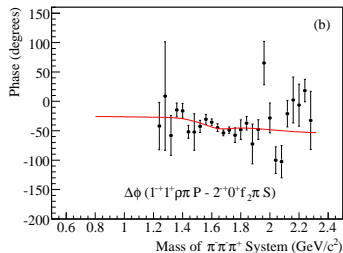
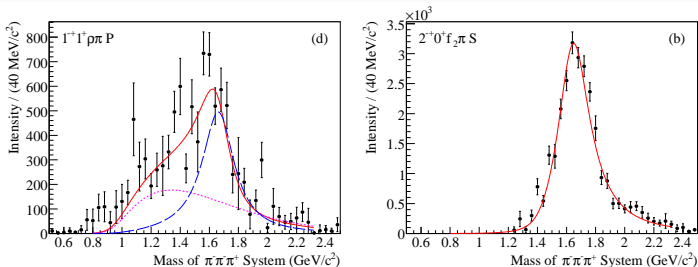
 $\pi^- \pi^- \pi^+$ mass $\pi^- \pi^+$ mass $\cos\theta_{GJ}$  ϕ_{TY}  $\cos\theta_{\text{helicity}}$  ϕ_{helicity} 

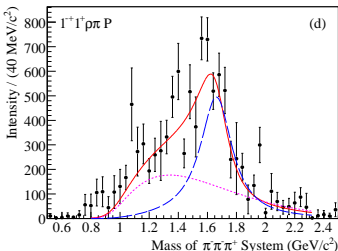


- Illinois/Protvino/Munich Program used.
- Enhanced wave set (53 partial waves).
- 20 MeV/c^2 mass bins.
- 30 fits per mass bin.
- D-Functions instead of Zemach-Tensors for parametrisation of decay amplitudes.
- Same mass range as for 2004 data: $0.5\text{-}2.5 \text{ GeV}/c^2$.



Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	Intensity (%)	Channel $J^{PC}M^{\epsilon}[\text{isobar}]L$
$a_1(1260)$	$1255 \pm 6_{-17}^{+7}$	$367 \pm 9_{-25}^{+28}$	$67 \pm 3_{-20}^{+4}$	$1^{++}0^+ \rho\pi S$
$a_2(1320)$	$1321 \pm 1_{-7}^{+0}$	$110 \pm 2_{-15}^{+2}$	$19.2 \pm 0.6_{-2.2}^{+0.3}$	$2^{++}1^+ \rho\pi D$
$\pi_1(1600)$	$1660 \pm 10_{-64}^{+0}$	$269 \pm 21_{-64}^{+42}$	$1.7 \pm 0.2_{-0.1}^{+0.9}$	$1^{-+}1^+ \rho\pi P$
$\pi_2(1670)$	$1658 \pm 3_{-8}^{+24}$	$271 \pm 9_{-24}^{+22}$	$10.0 \pm 0.4_{-0.7}^{+0.7}$	$2^{-+}0^+ f_2\pi S$
$\pi(1800)$	$1785 \pm 9_{-6}^{+12}$	$208 \pm 22_{-37}^{+21}$	$0.8 \pm 0.1_{-0.1}^{+0.3}$	$0^{-+}0^+ f_0\pi S$
$a_4(2040)$	$1885 \pm 13_{-2}^{+50}$	$294 \pm 25_{-19}^{+46}$	$1.0 \pm 0.3_{-0.1}^{+0.1}$	$4^{++}1^+ \rho\pi G$


 $J^{PC} = 1^{-+}$ Exotic Wave




BW parameter¹ for $\pi_1(1600)$

- $M = (1660 \pm 10_{-64}^{+0}) \text{ MeV}/c^2$

- $\Gamma = (269 \pm 21_{-64}^{+42}) \text{ MeV}/c^2$

¹A. Alekseev *et. al.*, COMPASS Collaboration,
Phys. Rev. Lett. 104, 241803 (2010)



Step 1: Mass-Independent PWA

- Independent fits in 40 MeV mass bins

$$\sigma_{indep}(\tau, m, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^\epsilon f_i^\epsilon(t') \psi_i^\epsilon(\tau, m) / \sqrt{\int |\psi_i^\epsilon(\tau', m)|^2 d\tau'} \right|^2$$

- Production amplitudes $T_{ir}^\epsilon \rightarrow$ extended maximum likelihood fit
- Decay amplitudes $\psi_i^\epsilon(\tau, m)$ (Zemach tensors)
- 41 partial waves $i = J^{PC} M^\epsilon [\text{isobar}]L$ + flat background
 - isobars: $(\pi\pi)_S, \rho(770), f_0(980), f_2(1270), \rho_3(1690)$
 - 7 negative reflectivity waves included
 - more M=1 waves than previous (e.g. BNL E852) analyses

Step 2: Mass-Dependent χ^2 fit

- 6 waves
- Parameterized by Breit-Wigner
- Coherent background for some waves