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

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for the COMPASS Collaboration

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Overview

Overview

Preface
Mesons within the Quarkmodell

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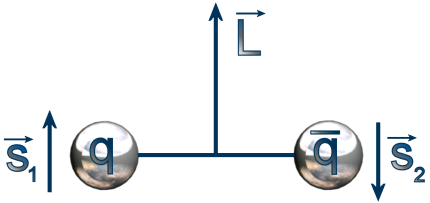

Quantum Numbers

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

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

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

The COMPASS Experiment

Overview

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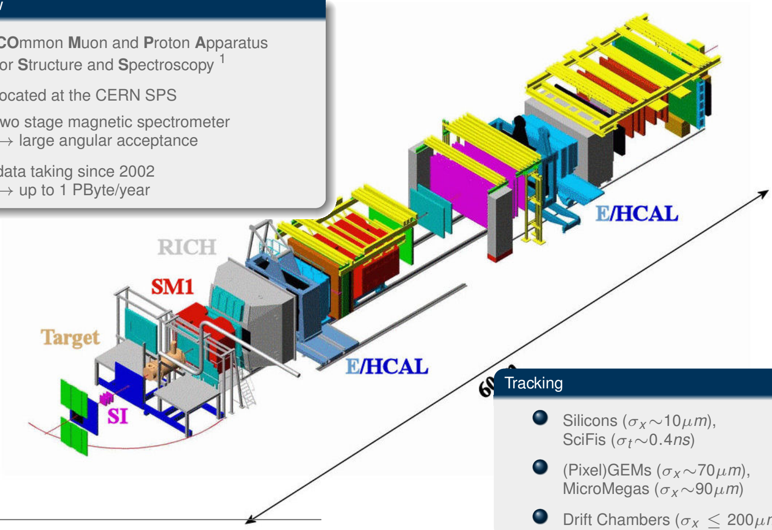
Overview

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



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]

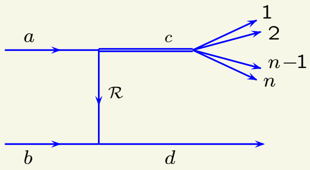
Overview

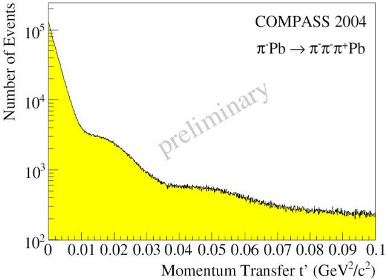
Diffractive Dissociation into $\pi^-\pi^-\pi^+$ Final States

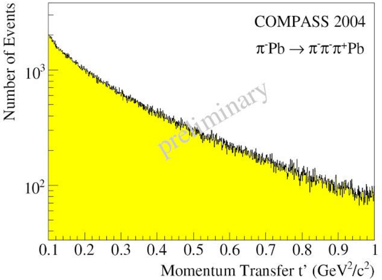
Diffractive Dissociation

- Soft scattering of the beam π^- off the target
  - Pb (2004, 2009)
  - lH_2 (2008)
  - W, Ni (2009)
- Target particle remains intact
- Pomeron exchange

Reaction

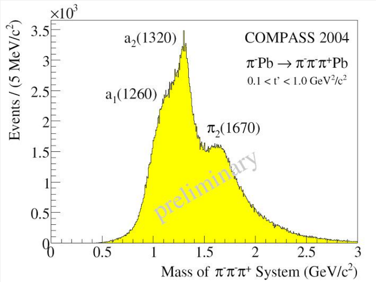






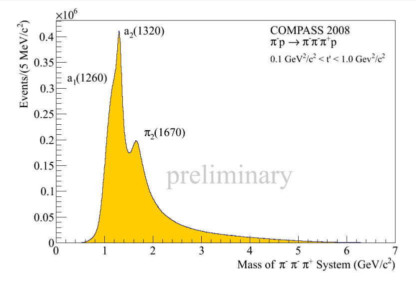
Invariant Mass of 3π System

$\pi^- \text{Pb} \rightarrow \pi^-\pi^-\pi^+ \text{Pb}$ (2004)



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

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



- $p_\pi = 190$ GeV/c
- $\sim$ 50M events in $0.1 < t' < 1.0$ GeV$^2/c^2$

Partial Wave Analysis - Isobar Model

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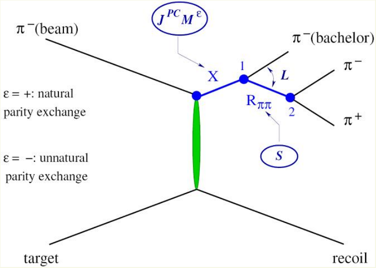
- Two-step approach:
  - Fit in mass bins

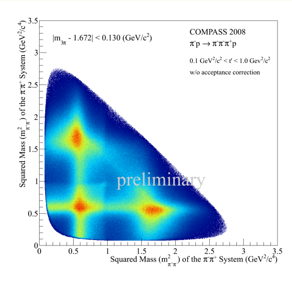
$$\mathcal{I}(\tau, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} f(t') \psi_i^{\epsilon}(\tau) \right|$$

  - Fit of the spin density matrix

Isobar Model

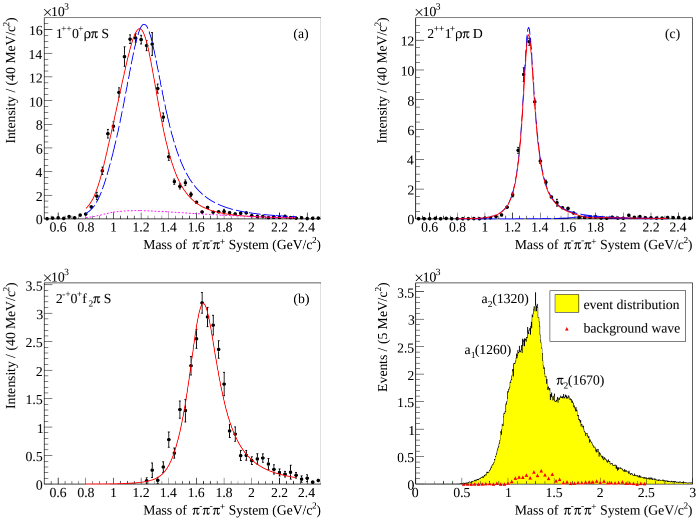


Dalitz Plot $\pi_2(1670)$ region



$\pi^- \text{ Pb} \rightarrow \pi^-\pi^-\pi^+ \text{ Pb}$ (2004)

Intensities of Major Waves



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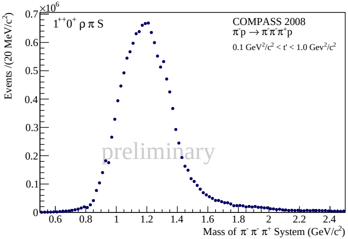
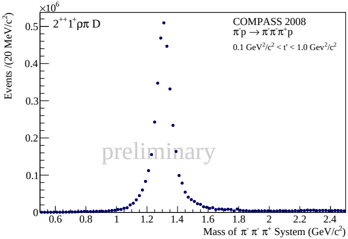
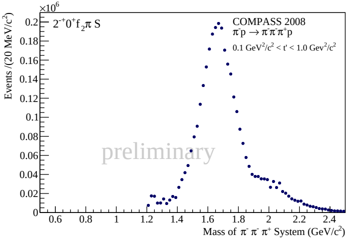
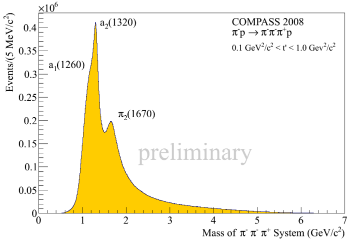
$\pi^- p \to \pi^- \pi^- \pi^+ p$ (2008)
Intensities of Major Waves









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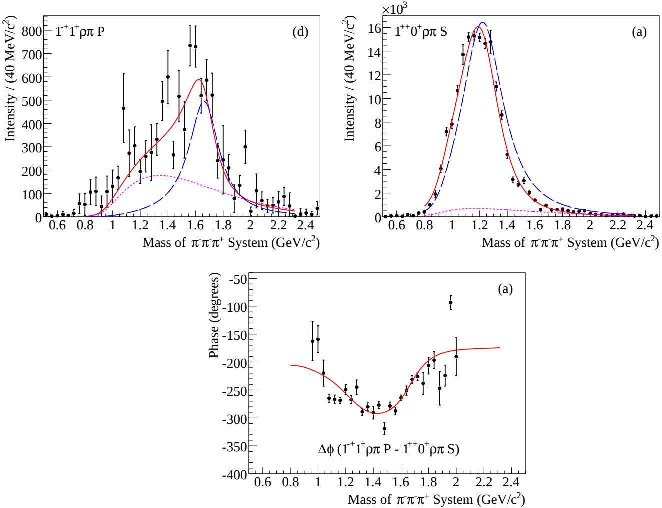
$\pi^- \text{Pb} \rightarrow \pi^-\pi^-\pi^+ \text{Pb}$ (2004)
$J^{PC} = 1^{-+}$ Exotic Wave [1]



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

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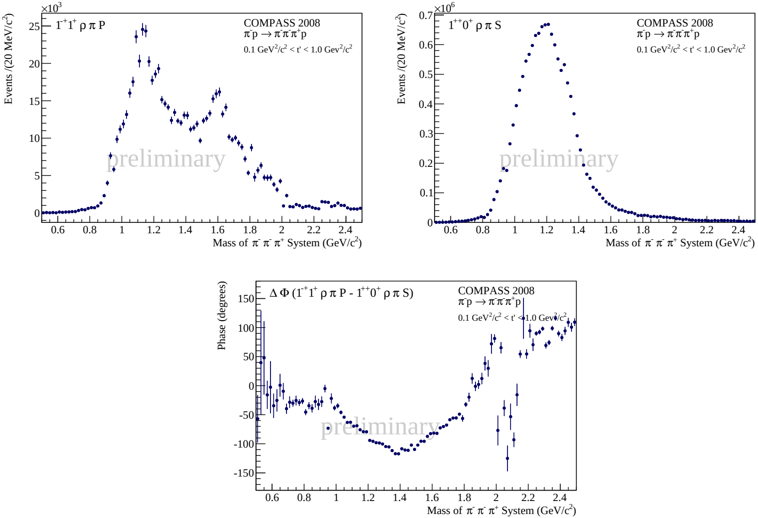

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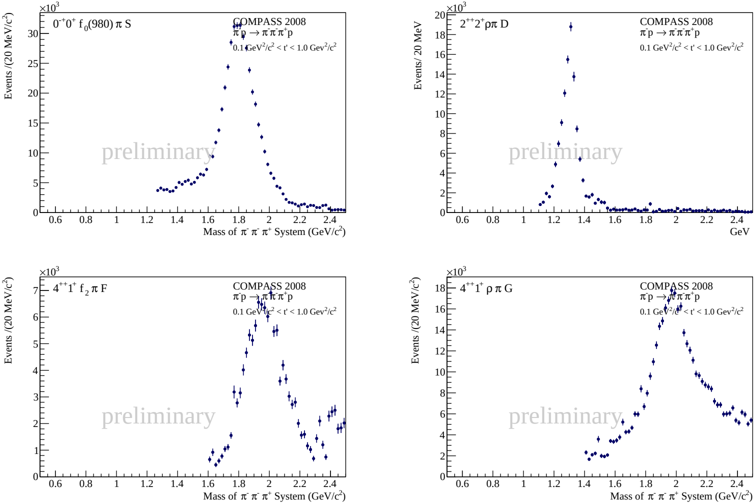
$\pi^- p \rightarrow \pi^-\pi^-\pi^+ p$ (2008)
Additional Waves



Overview

Deck Background Parametrization

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- Additional production mechanism for the same final state → background in amplitude analysis
- An incident beam pion dissociates into a ρ or f_2 and a virtual π. The virtual π scatters diffractively from the target proton (via Pomeron) into a real state.

- Amplitude parametrisation:

$$\Psi(M_{\pi\pi}, t_\pi, t) = \frac{A_{\pi\pi}(M_{\pi\pi}, t_\pi) A_{\pi p}(s_{\pi p}, t)}{m_\pi^2 - t_\pi}$$

  - $A_{\pi\pi}$ scattering amplitude through the ρ or/and f_2
  - $A_{\pi p}$ $\pi^- p$ elastic scattering amplitude

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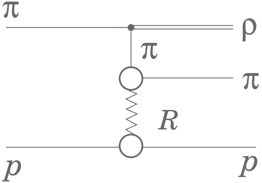

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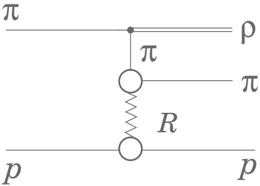

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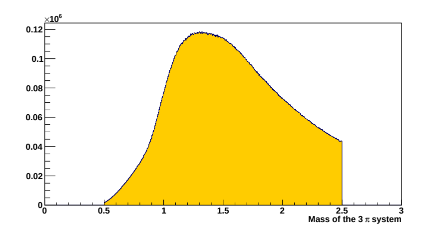
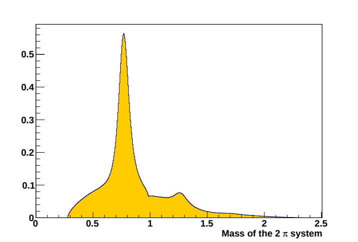
Deck Kinematics

Mass distributions of MC Deck Sample





Fit Improvements

- Poor knowldege of t' dependency, get rid of t' dependency
  $\rightarrow$ Fit in mass and t' *bins*:

$$\mathcal{I}(\tau) = \sum_{\epsilon=\pm1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} \psi_i^{\epsilon}(\tau) \right|$$

- Modify (lower) thresholds for each partial wave
- Modify parametrization of decay amplitudes

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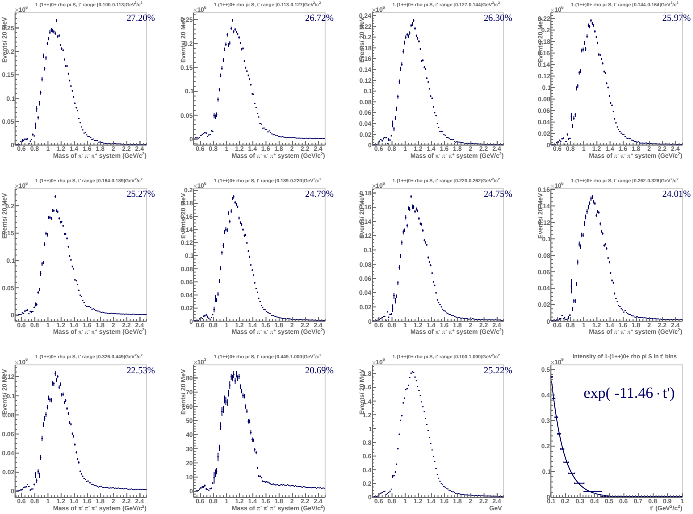
Fit Result for MC Deck Sample

$1^{++}0^{+}\rho\pi S$ (MC Deck Sample)



Fit Application

- Same fit improvements applied to real data (not shown in this talk)
- t' dependency different for diffractive data in respect to Deck produced data
  $\rightarrow$ possibility to disentangle Deck background from diffractive data in fit to the spin density matrix

Overview

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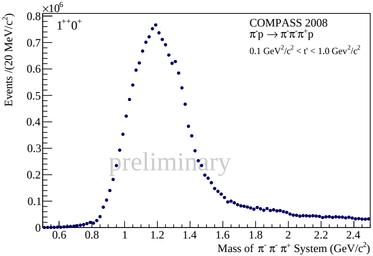
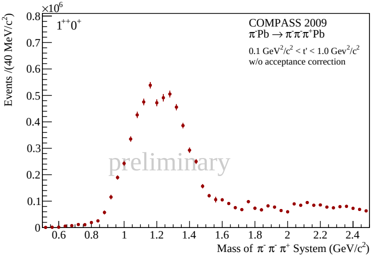
Comparison of different Targets

- 2008 lH_2 target, 2009 Pb target (W, Ni not shown)
- Different statistics
  - Normalisation to the integral of the $a_2(1320)$ in the mass region between 1.1 GeV/c^2 and 1.6 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 $M = 0$

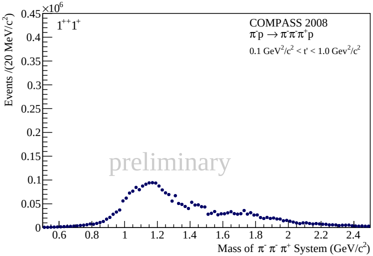


$\pi^- p \to \pi^- \pi^- \pi^+ p$ (2008)

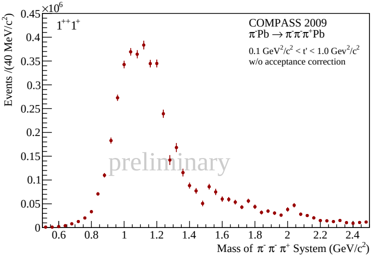


π^- Pb $\to \pi^- \pi^- \pi^+$ Pb (2009)

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



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



π^- Pb $\to \pi^-\pi^-\pi^+$ Pb (2009)

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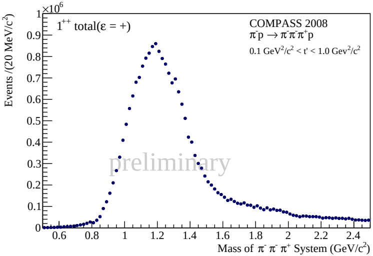
Total Intensities for $J^{PC} = 1^{++}$

Sum of M sub-states



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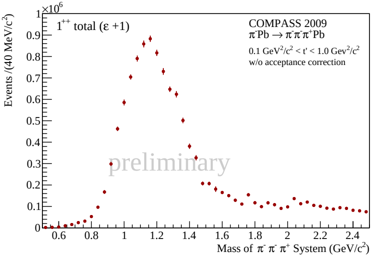

π^- Pb $\rightarrow \pi^-\pi^-\pi^+$ Pb (2009)

Overview

Conclusion and Outlook

- Pilot Run 2004
  - Diffractive pion dissociation on Pb into $\pi^-\pi^-\pi^+$
  - [1]Significant intensitiy of exotic wave 1^{-+} at 1.66 GeV/c^2
- COMPASS 2008/2009
  - Diffractive reactions: 10x BNL E852 statistics
  - Several different targets (p,Ni,W,Pb)
  - Consistency check with isospin partner channel $\pi^-\pi^0\pi^0$
  - Additional channels: 5π, $\eta'\pi$
  - Analysis ongoing (more news probably this summer)
    - Enhancement of wave set
    - Study of Deck Effect
    - t' dependence
    - Analysis of M-dependence
- Two independent PWA programs

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

Backup

COMPASS 2009 (Teaser)

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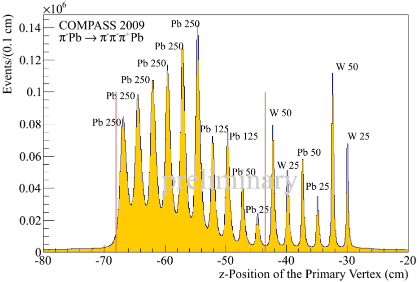
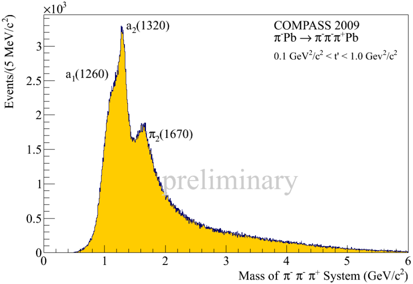
- 190 GeV/c hadron beam $\rightarrow 96\%\pi^-, 3.5\%K^-, 0.5\%\overline{p}$
- Pb, W, Ni targets
- $0.1\text{GeV}^2/\text{c}^2 < t' < 1.0\text{GeV}^2/\text{c}^2$
- Pb target: $\sim$ **1.5M events**





Systematic Studies - 2004

- 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

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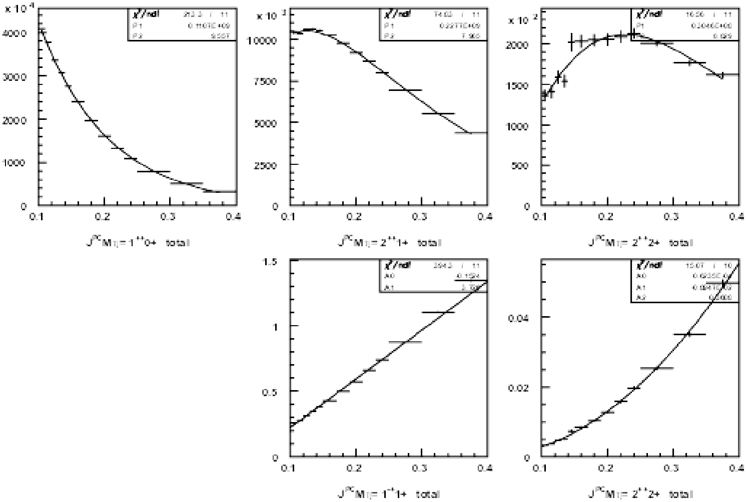
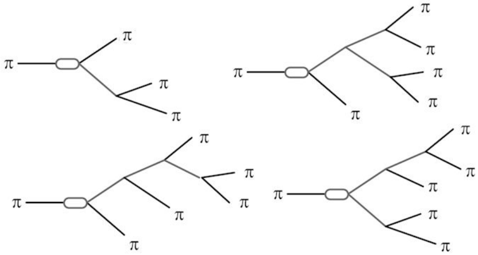
$\pi^- p \to \pi^-\pi^-\pi^+ p$

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



Interesting Candidate



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

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

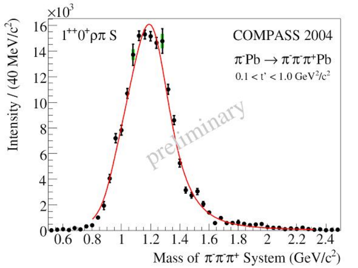
COMPASS has access to all of these decay modes

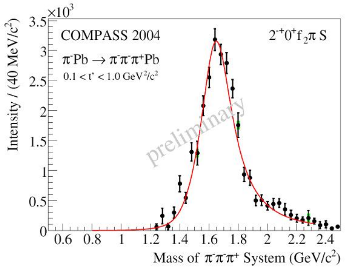
Wave Set of 2004 3π PWA

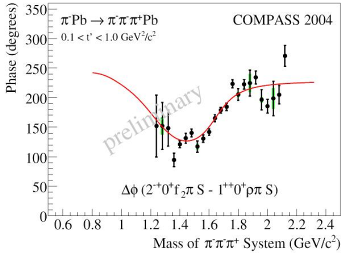
$J^{PC}M^{\epsilon}$	L	Isobar π	Thresh. [GeV]
$0^{-+}0^{+}$	S	$f_0\pi$	1.40
$0^{-+}0^{+}$	S	$(\pi\pi)_S\pi$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_S\pi$	0.84
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$	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 $\pi_2(1670)$

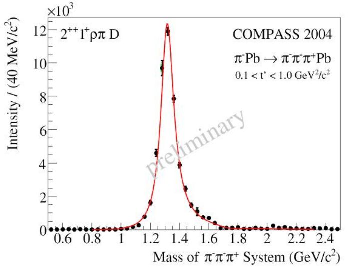


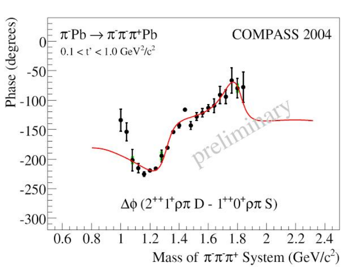




- BW für $a_1(1260)$ + Untergrund
  $M = \left(1255 \pm 6^{+7}_{-17}\right) \mathrm{MeV/c^2}$
  $\Gamma = \left(367 \pm 9^{+28}_{-25}\right) \mathrm{MeV/c^2}$
- BW für $\pi_2(1670)$
  $M = \left(1658 \pm 3^{+24}_{-8}\right) \mathrm{MeV/c^2}$
  $\Gamma = \left(271 \pm 9^{+22}_{-24}\right) \mathrm{MeV/c^2}$

$a_2(1320)$





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

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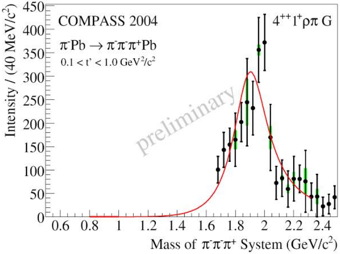
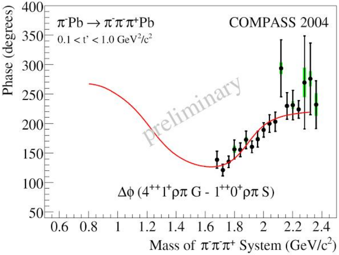
$a_4(2040)$





- BW mit konstanter Breite für $a_4(2040)$(Verweigungsverhältnis unbekannt)
- BW Parameter
  $M = \left(1885 \pm 13^{+50}_{-2}\right)\mathrm{MeV/c^2}$
  $\Gamma = \left(294 \pm 25^{+46}_{-19}\right)\mathrm{MeV/c^2}$

$\pi(1800)$

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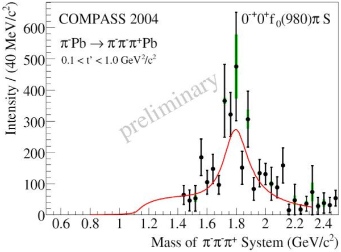
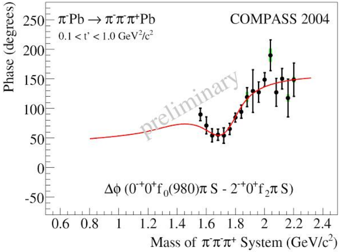




- BW mit konstanter Breite für $\pi(1800)$ und Untergrund bei niedrigen Massen
- BW Parameter
  $M = (1785 \pm 9^{+12}_{-6})\,\mathrm{MeV/c^2}$
  $\Gamma = (208 \pm 22^{+21}_{-37})\,\mathrm{MeV/c^2}$

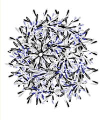
Motivation
Quantumchromodynamics

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

Tetraquarks

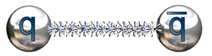
- Two $q\bar{q}$ pairs
- Possible lightest candidates: $f_0(600)$, $f_0(980)$, $a_0(980)$

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: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

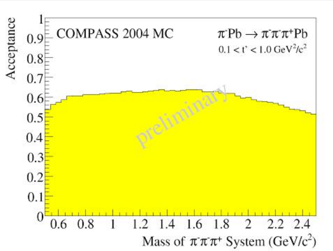
Hybrids



- $q\bar{q}$ 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

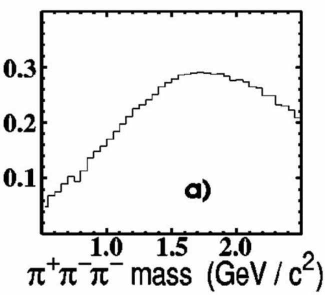
Acceptance

COMPASS



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

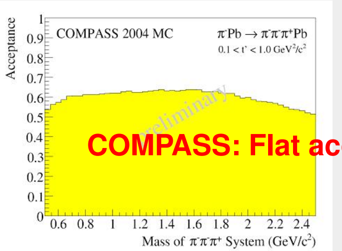
BNL E852



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

Acceptance

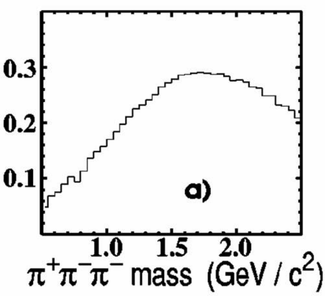
COMPASS



COMPASS: Flat acceptance

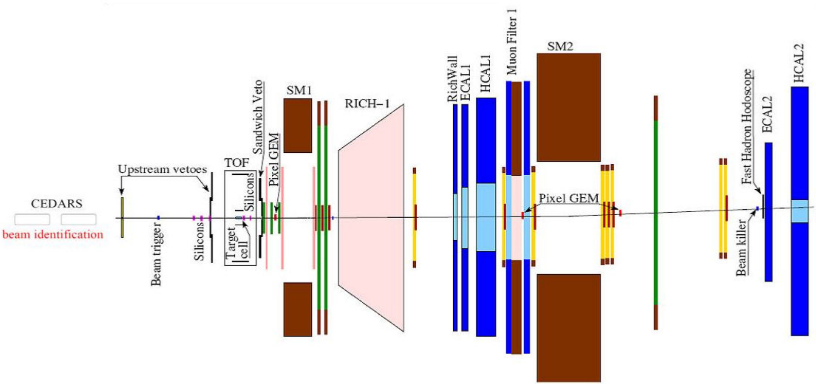
- $p_\pi = 190 GeV/c$
- 4M events (full t range)
- 450k events in $0.1 <$ t' $< 1.0\ GeV^2/c^2$

BNL E852

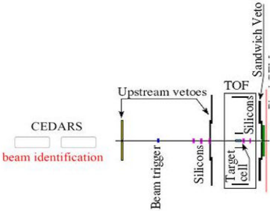


- $p_\pi = 18 GeV/c$
- 250k events in $0.08 <$ t' $< 1.0\ GeV^2/c^2$

Spectrometer Upgrade 2008



Beam Particle Identification



Liquid Hydrogen Target - Proton Recoil Detector

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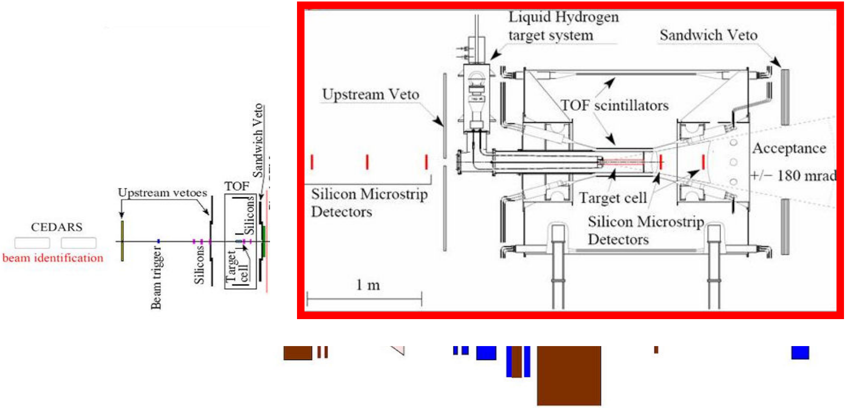
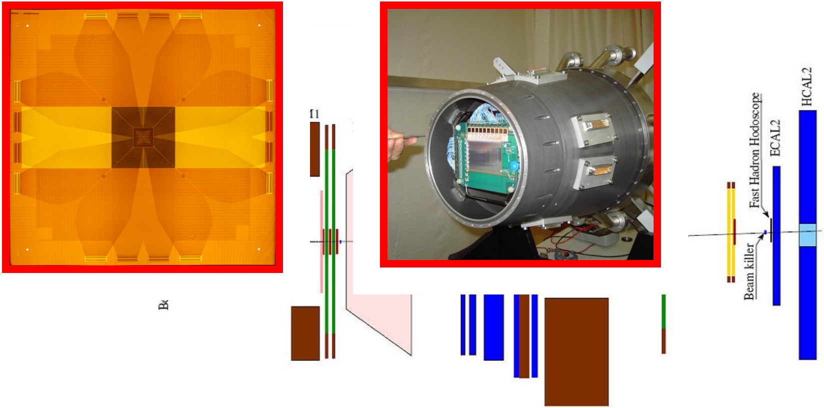
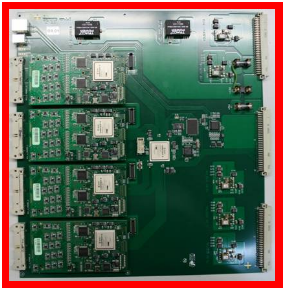
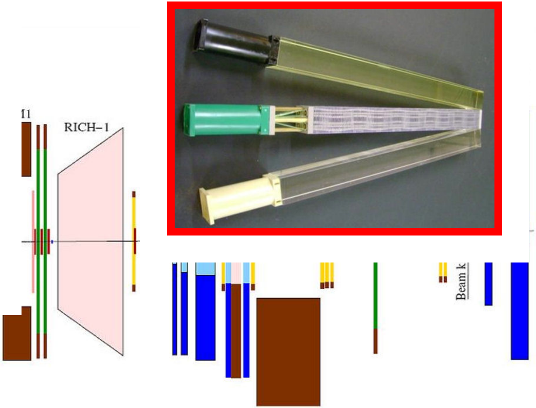


Additional Detectors



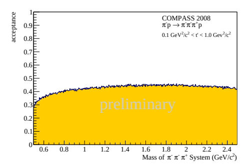
Electromagnetic Calorimeter



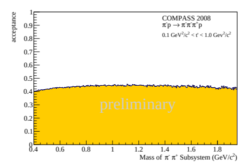


Acceptance

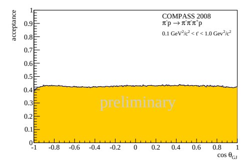
$\pi^-\pi^-\pi^+$ mass



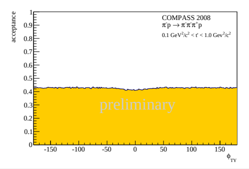
$\pi^-\pi^+$ mass



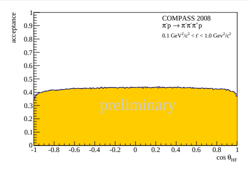
$cos\theta_{GJ}$



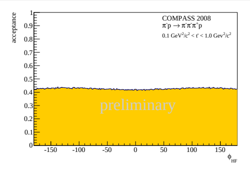
ϕ_{TY}



$cos\theta_{helicity}$



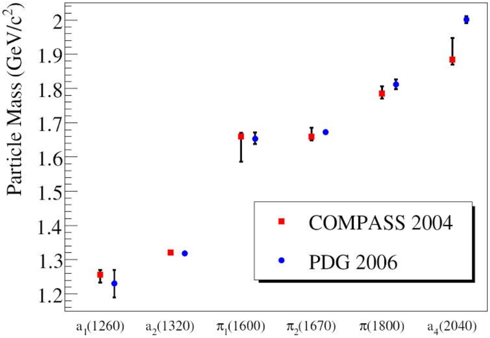
$\phi_{helicity}$



Mass-Independent PWA

- 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: 0.5-2.5 GeV/c^2.

Überblick



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

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

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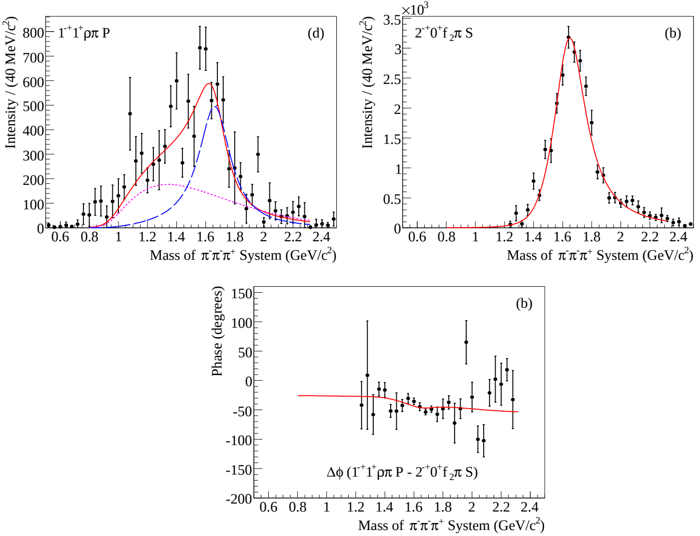
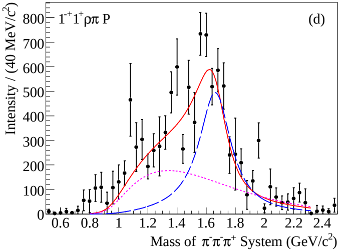


$J^{PC} = 1^{-+}$ Exotic Wave



BW parameter[1] for $\pi_1(1600)$

- $M = \left(1660 \pm 10^{+0}_{-64}\right)$ MeV/c^2
- $\Gamma = \left(269 \pm 21^{+42}_{-64}\right)$ MeV/c^2

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

PWA Technique

Step 1: Mass-Independent PWA

- Independent fits in 40 MeV mass bins

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

- Production amplitudes T_{ir}^{ϵ} $\rightarrow$ extended maximum likelihood fit
- Decay amplitudes $\psi_i^{\epsilon}(\tau, m)$ (Zemach tensors)
- 41 partial waves $i = J^{PC} M^{\epsilon} [isobar] L$ + 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