Meson Spectroscopy and Search for Spin-Exotic States at COMPASS

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24th Advanced Studies Institute - Symmetries and Spin

Prague, July 24, 2008

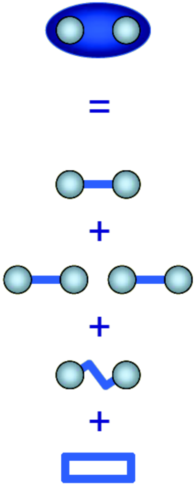
* Supported by:

BMBF, Excellence Cluster Universe and Maier-Leibnitz-Labor der TU und LMU München

1. Introduction
2. Event Selection and Data Sample
3. Partial Wave Analysis
4. Results from PWA
5. Summary and Outlook

Introduction

Motivation: Mesons and Spin-Exotic States



Quark Model:

- Color-neutral $q\bar{q}$ systems
- Quantum numbers $I^G\ J^{PC}$
- $P = (-1)^{L+1}$
- $C = (-1)^{L+S}$
- $G = (-1)^{I+L+S}$

QCD: additional color-neutral objects

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

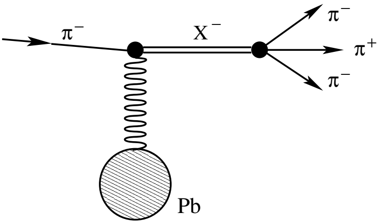
Mixing of states with same $I^G\ J^{PC}$

Search for spin-exotic states:

- $0^{+-}, 1^{-+}, 2^{+-}, \ldots,$

Meson Production from Diffractive Pion Dissociation

- Diffraction: incident particle only grazes the target, which remains intact
  $\Rightarrow$ strong interaction, Pomeron exchange
- Dissociation: beam pion is excited to some resonance X^-, which further decays
  $\Rightarrow$ e. g. $\pi^- \mathrm{Pb} \Rightarrow X^- \mathrm{Pb} \Rightarrow \pi^-\pi^-\pi^+ \mathrm{Pb}$



Pion quantum numbers: $I^G \ J^{PC} = 1^- \ 0^{-+}$

I^G conservation $\Rightarrow J^{PC}(X) = 0^{-+}, 1^{++}, 1^{-+}, 2^{++}, 2^{-+}, \ldots,$

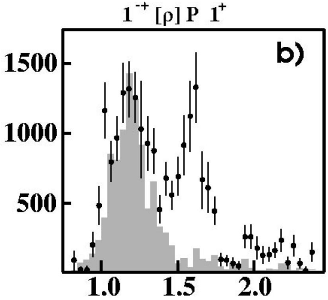
Rich meson spectrum accessible and possibly spin-exotic states

1^{-+} Light-Hybrid Candidates: $\pi_1(1400)$ and $\pi_1(1600)$

Positive evidences for $\pi_1(1600)$ in $\pi^-\pi^-\pi^+$:

BNL-E852

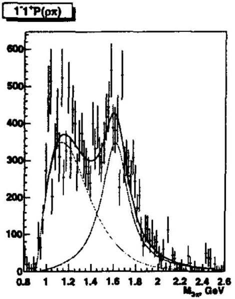
$\pi^- p \to \pi^-\pi^-\pi^+ p$ at 18 GeV/c



S. U. Chung et al., Phys. Rev. **D65**, 072001 (2002)

VES (Protvino)

$\pi^- A \to \pi^-\pi^-\pi^+ A$ at 37 GeV/c



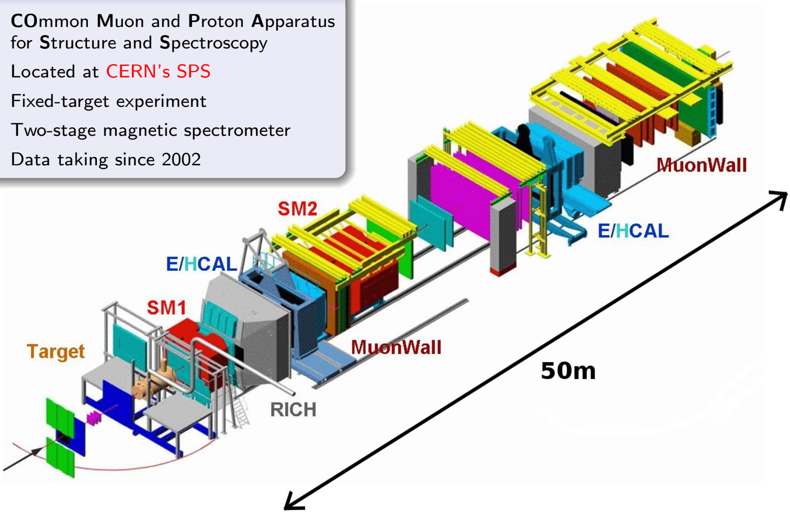
Y. Khokhlov, Nucl. Phys. **A663**, 596 (2000)

Counterstatements from both experiments! $\Rightarrow$ controversial situation

The COMPASS Experiment at CERN

Overview

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at CERN's SPS
- Fixed-target experiment
- Two-stage magnetic spectrometer
- Data taking since 2002



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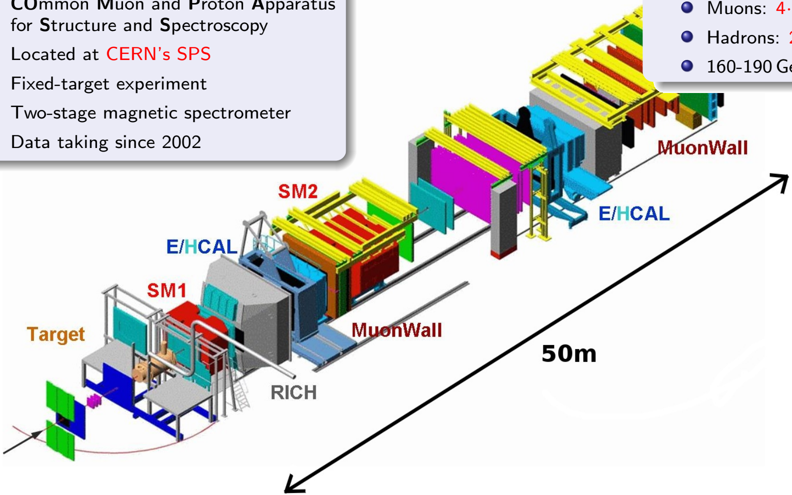
2 Types of Beam

- Muons: $4 \cdot 10^7 s^{-1}$
- Hadrons: $2 \cdot 10^7 s^{-1}$
- 160-190 GeV



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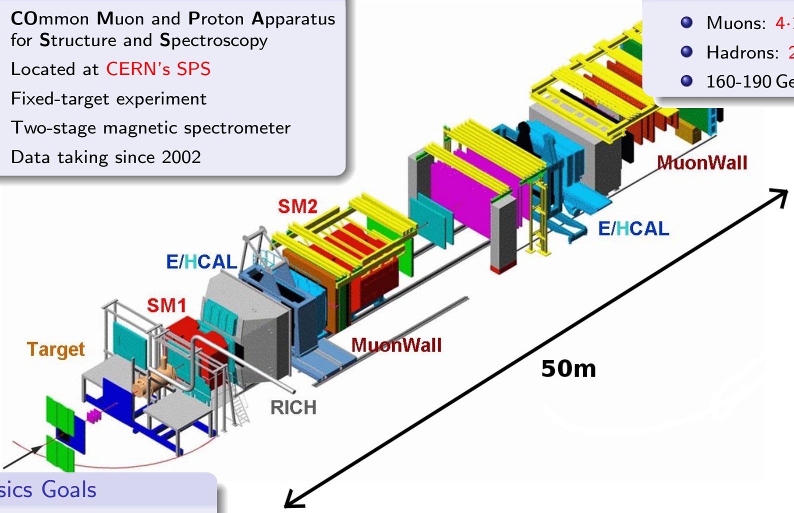

Physics Goals

- Nucleon spin structure
- Hadron spectroscopy

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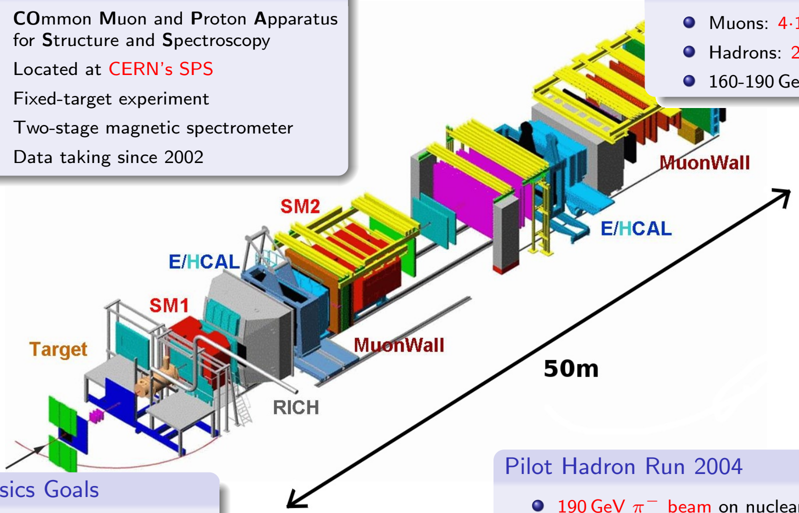


Physics Goals

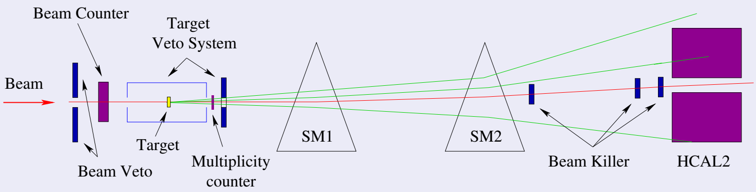
- Nucleon spin structure
- Hadron spectroscopy

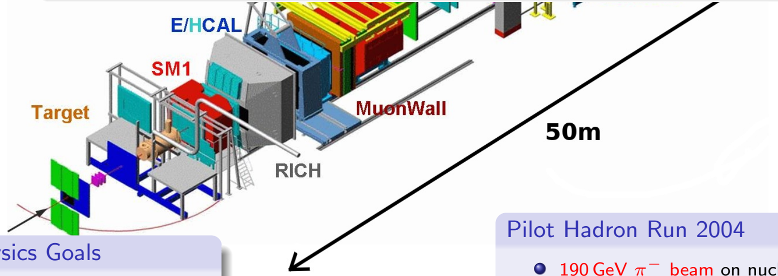
Pilot Hadron Run 2004

- 190 GeV π^- beam on nuclear targets
- Tracking: Silicons, SciFis, GEMs, MicroMegas, MWPCs, Drift Chambers

The COMPASS Experiment at CERN

2004 Diffractive Trigger





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Pilot Hadron Run 2004

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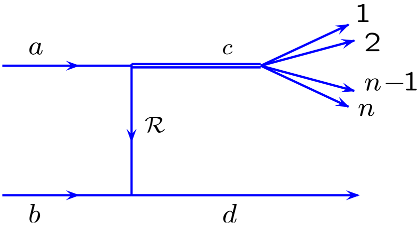
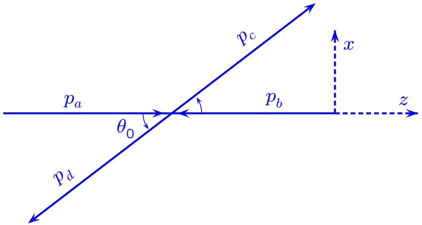
Event Selection and Data Sample

Event Signature and Selection





- a : 190 GeV π^- beam, $b(d)$: target(recoil), $c \to 3\pi$
- Momentum transfer: $-t$, scattering angle: θ ($\sim$ mrad in LAB!)

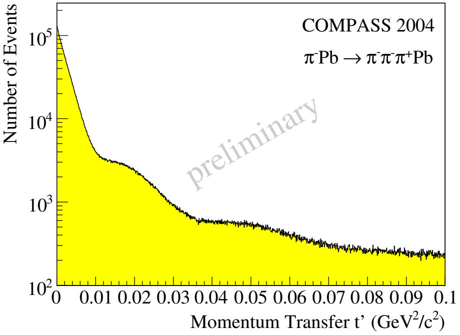
Selection Criteria

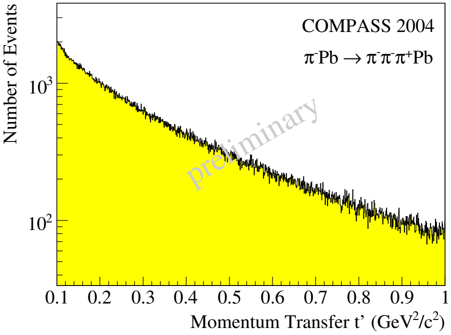
- Diffractive trigger
- Primary vertex in target with 3 outgoing particles $(- - +)$
- Exclusivity assumption: target stays intact
- COMPASS 2004: $\sim 4\,000\,000$ 3π events on Pb (few days of running), $\sim 400\,000$ events with $0.1 < t' < 1.0$ GeV$^2/c^2$

Momentum Transfer Distributions

Momentum transfer from target: $-t = -(p_{\text{beam}} - p_{(\pi^-\pi^-\pi^+)})^2$

$\Rightarrow t' = |t| - |t|_{min}$



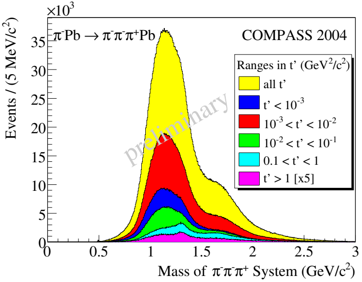


Diffraction pattern: Pb nucleus acts like "black disc" in optics

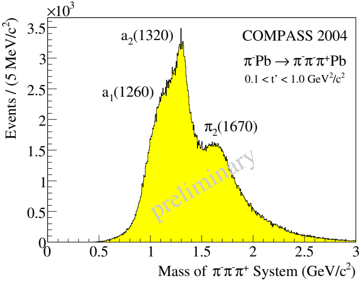
High-t': scattering on single nucleons inside Pb nucleus

$\pi^-\pi^-\pi^+$ Mass Distributions and Acceptance

Invariant mass for different t'



High-t' Spectrum



$\pi^-\pi^-\pi^+$ Mass Distributions and Acceptance

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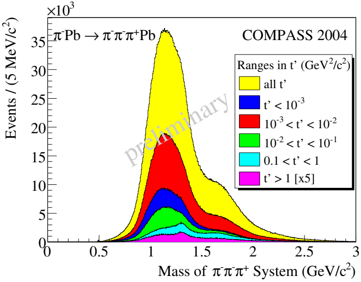
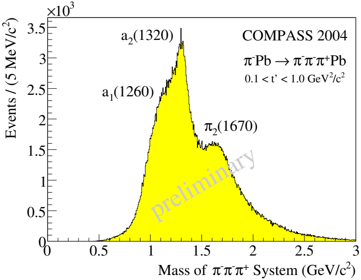
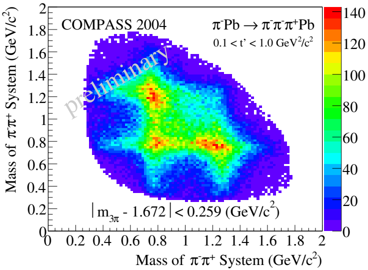


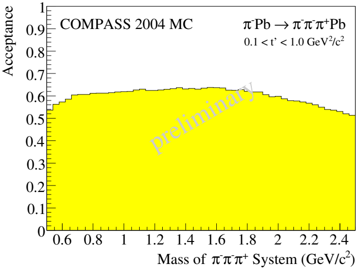
High-t' Spectrum



Dalitz plot for $\pi_2(1670)$ region

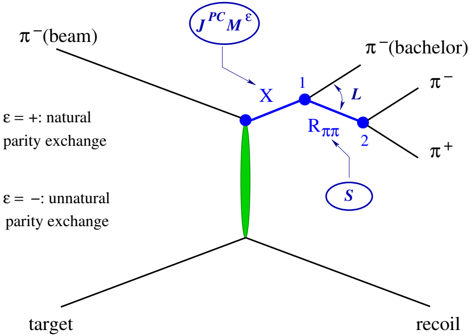


Flat acceptance: 55-60%



Partial Wave Analysis

Overview of Partial Wave Analysis (high-t')



- Isobar model assumed
- Zemach formalism, reflectivity basis
- Reggeon exchange
- Partial wave: $J^{PC}M^{\epsilon}[isobar]L$
- Nucleon target $\Rightarrow$ rank 2

- Program: Illinois $\rightarrow$ Dubna $\rightarrow$ Protvino $\rightarrow$ Munich, (D. Ryabchikov)
- Mass-independent PWA ($40\,\mathrm{MeV}/c^2$ mass bins): 42 waves
  - Extended log-likelihood method (Ascoli/Kachaev fitter)
  - Acceptance corrections included
  - $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$ from PDG, $(\pi\pi)_s$ with separated $f_0(980)$ from VES
  - Multiple solutions ($\Delta \ln L \leq 1$) added as additional error
- Mass-dependent χ^2-fit: 7 waves
  - X parameterized by Breit-Wigner (BW) functions
  - Coherent background added for some waves: $\exp(-\alpha p^2)$

Partial Wave Set for Mass-Indep. Fit (42 Waves)

$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [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	Cut [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			

Partial Waves used in Mass-Dep. Fit (7 Waves)

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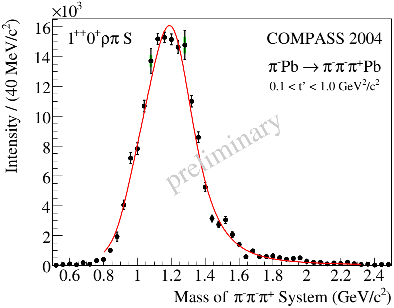
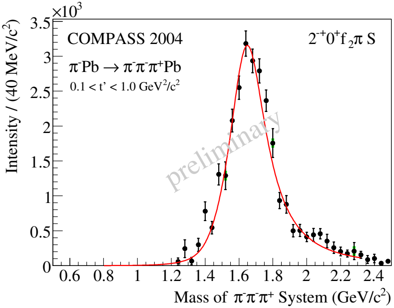
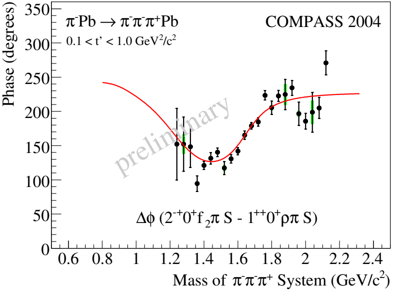
$4^{-+}1^{+}$	F	$\rho\pi$	1.20
$4^{++}1^{+}$	F	$f_2\pi$	1.60
$4^{++}1^{+}$	G	$\rho\pi$	1.64
$1^{-+}0^{-}$	P	$\rho\pi$	-
$1^{-+}1^{-}$	P	$\rho\pi$	-
$1^{++}1^{-}$	S	$\rho\pi$	-
$2^{-+}1^{-}$	S	$f_2\pi$	1.20
$2^{++}0^{-}$	P	$f_2\pi$	1.30
$2^{++}0^{-}$	D	$\rho\pi$	-
$2^{++}1^{-}$	P	$f_2\pi$	1.30
FLAT			

Results from PWA

$1^{++}0^{+}\rho\pi S$ and $2^{-+}0^{+}f_2\pi S$

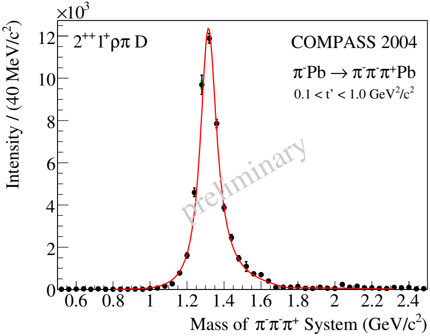


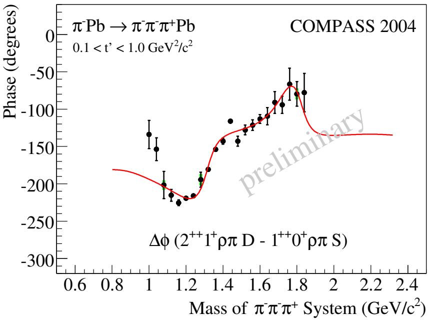




- BW for $a_1(1260)$ + background:
  $M = (1.256 \pm 0.006\ ^{+0.007}_{-0.017})$ GeV
  $\Gamma = (0.366 \pm 0.009\ ^{+0.028}_{-0.025})$ GeV
- BW for $\pi_2(1670)$:
  $M = (1.659 \pm 0.003\ ^{+0.024}_{-0.008})$ GeV
  $\Gamma = (0.271 \pm 0.009\ ^{+0.022}_{-0.024})$ GeV

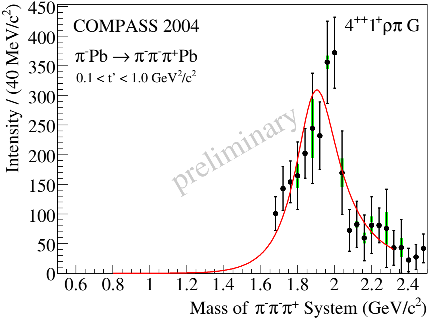
$2^{++}1^{+}\rho\pi D$

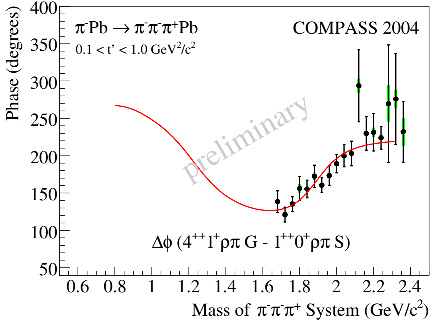




- Two Breit-Wigners needed to describe $2^{++}1^{+}\rho\pi D$ phase motion: BW1 for $a_2(1320)$ + BW2 for $a_2(1700)$
- $M = (1.321 \pm 0.001\ ^{+0.000}_{-0.007})$ GeV, $\Gamma = (0.110 \pm 0.002\ ^{+0.002}_{-0.015})$ GeV
- $a_2(1700)$ parameters fixed to PDG values: $M = 1.732$ GeV, $\Gamma = 0.194$ GeV

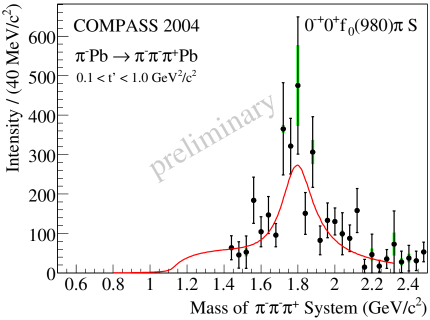
$4^{++}1^{+}\rho\pi\, G$

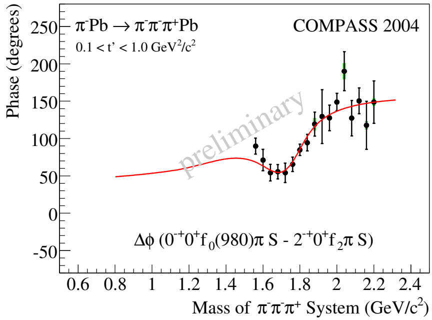




- Constant width Breit-Wigner used for $a_4(2040)$ (no branching ratios known)
- $M = (1.884 \pm 0.013\ ^{+0.050}_{-0.002})$ GeV, $\Gamma = (0.295 \pm 0.024\ ^{+0.046}_{-0.019})$ GeV

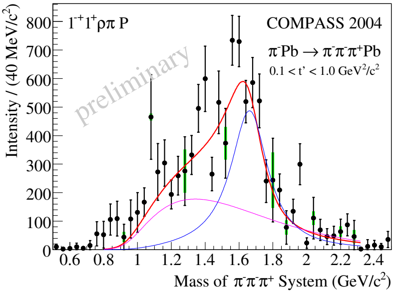
$0^{-+}0^{+} f_0(980)\pi S$

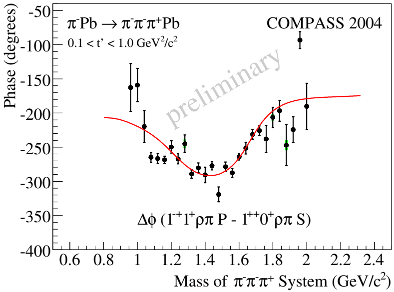


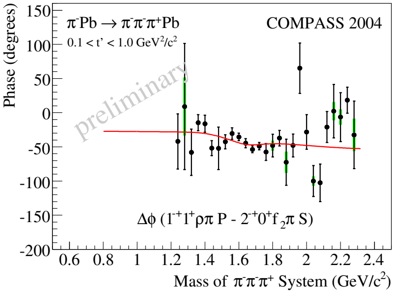


- Constant width Breit-Wigner for $\pi(1800)$ and low-mass background
- $M = (1.785 \pm 0.009\ ^{+0.012}_{-0.006})$ GeV, $\Gamma = (0.208 \pm 0.022\ ^{+0.021}_{-0.037})$ GeV

Exotic $1^{-+}1^{+}\rho\pi P$ Wave





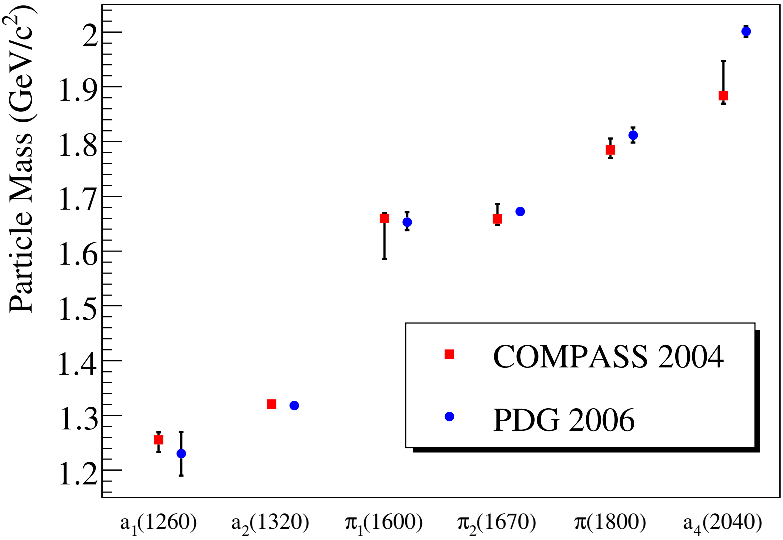


- Significant 1^{-+} amplitude consistent with resonance at $\sim 1.6\,\mathrm{GeV}$
- No leakage observed
- BW for $\pi_1(1600)$ + background:

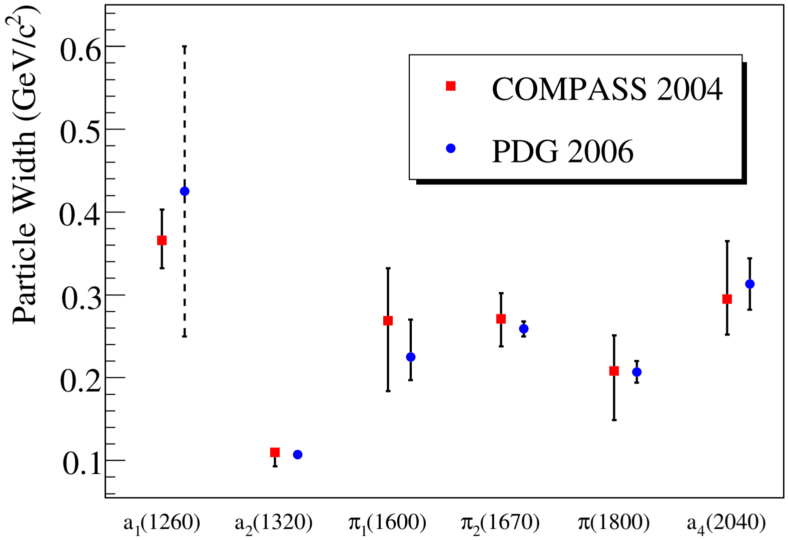
  $M = (1.660 \pm 0.010\ ^{+0.000}_{-0.064})\ \mathrm{GeV}$

  $\Gamma = (0.269 \pm 0.021\ ^{+0.042}_{-0.064})\ \mathrm{GeV}$

Summary of Results and Comparison to PDG: Masses



Summary of Results and Comparison to PDG: Widths

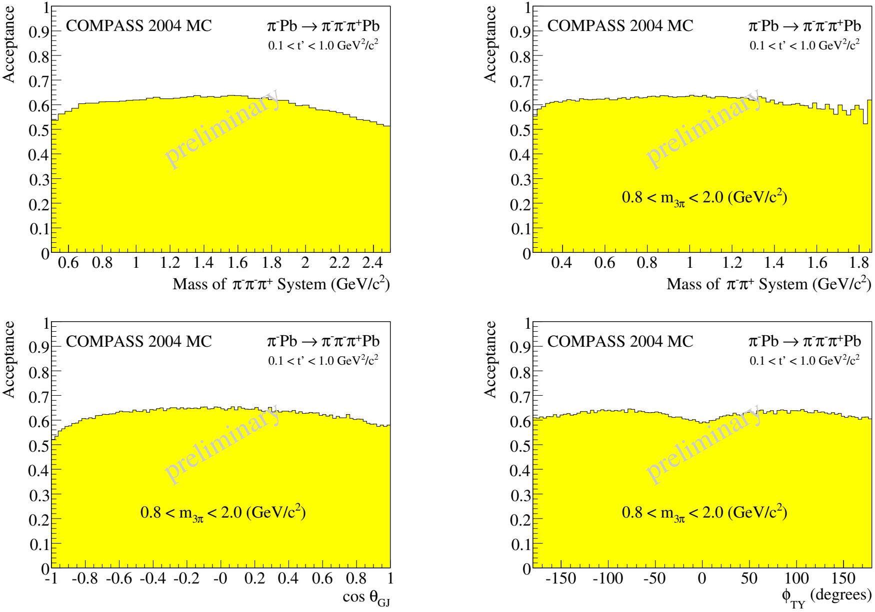


Summary and Outlook

- COMPASS 2004 pilot run using a 190 GeV π^- beam
  - Diffractive dissociation on lead targets exploited for meson production
  - $\sim 4\,000\,000$ events recorded within a few days of data taking
  - Large range in momentum transfer t' covered (10^{-3}-few GeV$^2/c^2$)
  - Excellent acceptance for diffractive $\pi^-\pi^-\pi^+$ events ($\sim$ 55-60%)

- Partial wave analysis has been performed on $\sim 400\,000$ $\pi^-\pi^-\pi^+$ events with $0.1 < t' < 1.0$ GeV$^2/c^2$
  - Dominant $a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ states resolved
  - Also small, well-known resonances $\pi(1800)$ and $a_4(2040)$ can be fitted
  - Spin-exotic 1^{-+} state observed both in intensity and phase motion
    $\Rightarrow$ consistent with $\pi_1(1600)$ resonance

- Analysis of low-t' data from COMPASS 2004 will be performed
- COMPASS will resume data taking with hadron beams this summer
  - Change-over to liquid hydrogen target
  - Much more high-t' statistics will be collected


COMPASS 2004 MC
π⁻Pb → π⁻π⁻π⁺Pb
0.1 < t' < 1.0 GeV²/c²
preliminary
Acceptance
Mass of π⁻π⁻π⁺ System (GeV/c²)
Mass of π⁻π⁺ System (GeV/c²)
0.8 < m3π < 2.0 (GeV/c²)
cos θGJ
φTY (degrees)

Backup Slides: Important PWA Formulas

Mass-Independent Cross-Section and Spin Density Matrix

$$\sigma_{\text{indep}}(\tau) = \sum_{\epsilon}\sum_{r}\left|\sum_{i} T^{\epsilon}_{ir}\psi^{\epsilon}_{i}(\tau)\Big/\sqrt{\int |\psi^{\epsilon}_{i}(\tau')|^2 \mathrm{d}\tau'}\right|^2 \quad , \quad \rho^{\epsilon}_{ij} = \sum_{r} T^{\epsilon}_{ir} T^{\epsilon *}_{jr}$$

- ϵ: reflectivity, r: rank of density matrix, i: different partial waves
- T: complex production amplitudes (fit parameters!)
- ψ: complex decay amplitudes
- τ: phase space coordinates (5 parameters for 3-body decay)

Likelihood Function

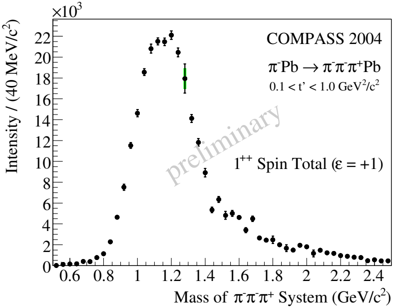
$$\ln L = \sum_{n} \ln \sigma_{\text{indep}}(\tau_n) - \int \sigma_{\text{indep}}(\tau')\text{Acc}(\tau')\mathrm{d}\tau'$$

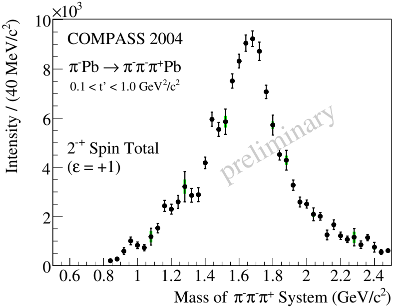
- n: analyzed events, Acc: Acceptance

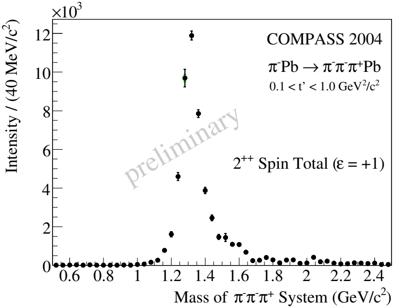
Mass-Dependent Fit

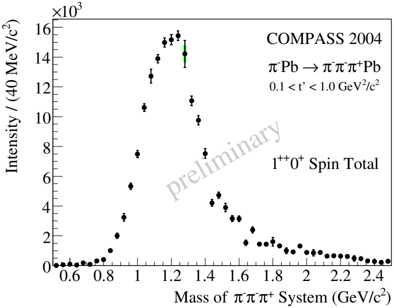
$$\rho^{\epsilon}_{ij} = \sum_{r}\left(\sum_{k} C^{\epsilon}_{ikr}\text{BW}_k(m)\sqrt{\int |\psi^{\epsilon}_{i}(\tau)|^2\mathrm{d}\tau}\right)\left(\sum_{l} C^{\epsilon}_{jlr}\text{BW}_l(m)\sqrt{\int |\psi^{\epsilon}_{j}(\tau)|^2\mathrm{d}\tau}\right)^*$$

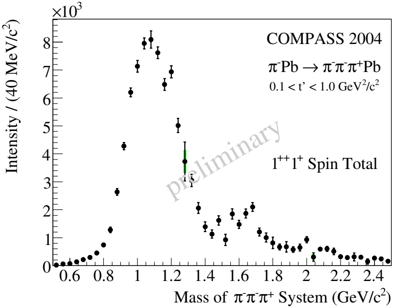
Backup Slides: Spin Totals

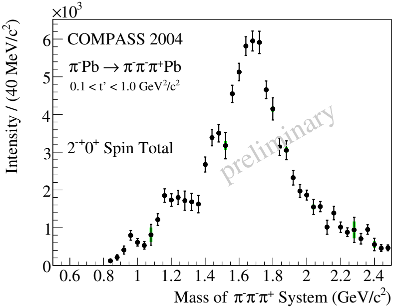


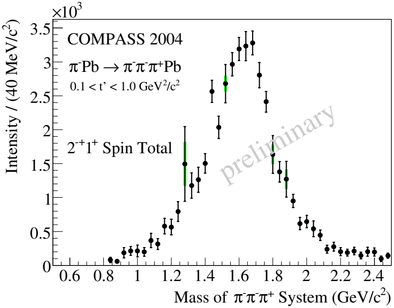





COMPASS 2004
$\pi^- Pb \rightarrow \pi^-\pi^-\pi^+ Pb$
$0.1 < t' < 1.0$ GeV^2/c^2
$1^{++}0^+$ Spin Total
preliminary
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)


COMPASS 2004
$\pi^- Pb \rightarrow \pi^-\pi^-\pi^+ Pb$
$0.1 < t' < 1.0$ GeV^2/c^2
$1^{++}1^+$ Spin Total
preliminary
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)

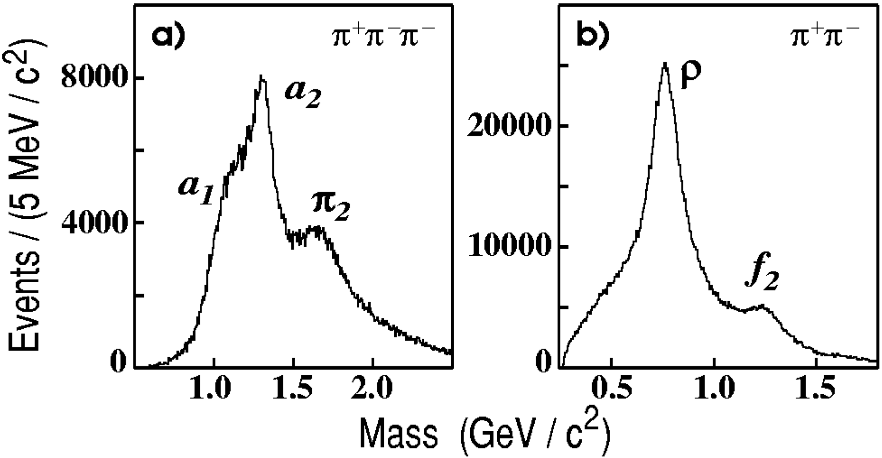

COMPASS 2004
$\pi^- Pb \rightarrow \pi^-\pi^-\pi^+ Pb$
$0.1 < t' < 1.0$ GeV^2/c^2
$2^{-+}0^+$ Spin Total
preliminary
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)


COMPASS 2004
$\pi^- Pb \rightarrow \pi^-\pi^-\pi^+ Pb$
$0.1 < t' < 1.0$ GeV^2/c^2
$2^{-+}1^+$ Spin Total
preliminary
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)

Summary of Results and Comparison to PDG (2006)

State	(GeV)	COMPASS ± stat ± syst	PDG
$a_1(1260)$	M	1.256 ± 0.006 + 0.007 - 0.017	1.230 ± 0.040
	Γ	0.366 ± 0.009 + 0.028 - 0.025	0.250 to 0.600
$a_2(1320)$	M	1.321 ± 0.001 + 0.000 - 0.007	1.3183 ± 0.0006
	Γ	0.110 ± 0.002 + 0.002 - 0.015	0.107 ± 0.005
$\pi_1(1600)$	M	1.660 ± 0.010 + 0.000 - 0.064	$1.653^{+0.018}_{-0.015}$
	Γ	0.269 ± 0.021 + 0.042 - 0.064	$0.225^{+0.045}_{-0.028}$
$\pi_2(1670)$	M	1.659 ± 0.003 + 0.024 - 0.008	1.6724 ± 0.0032
	Γ	0.271 ± 0.009 + 0.022 - 0.024	0.259 ± 0.009
$\pi(1800)$	M	1.785 ± 0.009 + 0.012 - 0.006	1.812 ± 0.014
	Γ	0.208 ± 0.022 + 0.021 - 0.037	0.207 ± 0.013
$a_4(2040)$	M	1.884 ± 0.013 + 0.050 - 0.002	2.001 ± 0.010
	Γ	0.295 ± 0.024 + 0.046 - 0.019	0.313 ± 0.031

Backup Slides: BNL-E852 Comparison (proton target)



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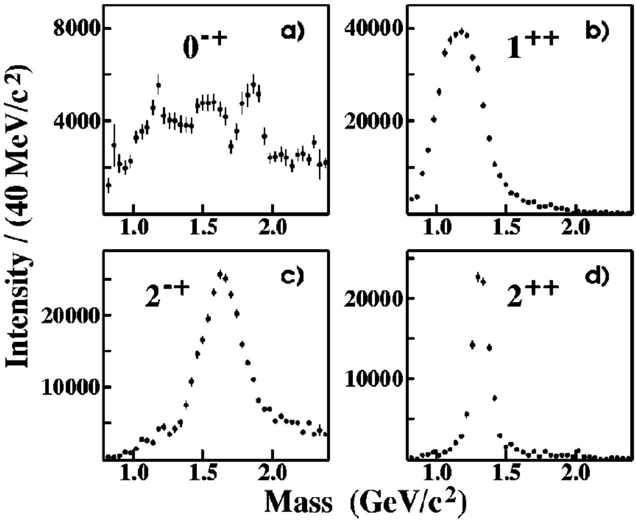
Backup Slides: BNL-E852 Comparison (proton target)



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