Hadron Spectroscopy at COMPASS

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1. Meson Production at COMPASS

2. Partial Wave Analysis Formalism

3. 2004 Data: Pion Diffraction on Lead
   - 3π Final State PWA Results
   - 3π Diffractive Production on Protons
   - 5π Final State

Outline

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3. 2004 Data: Pion Diffraction on Lead
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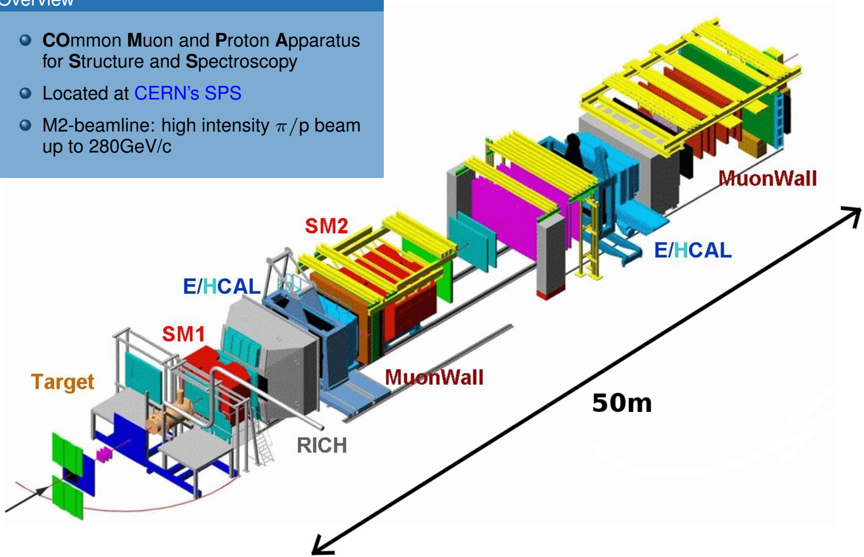
Overview

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at CERN's SPS
- M2-beamline: high intensity π/p beam up to 280GeV/c



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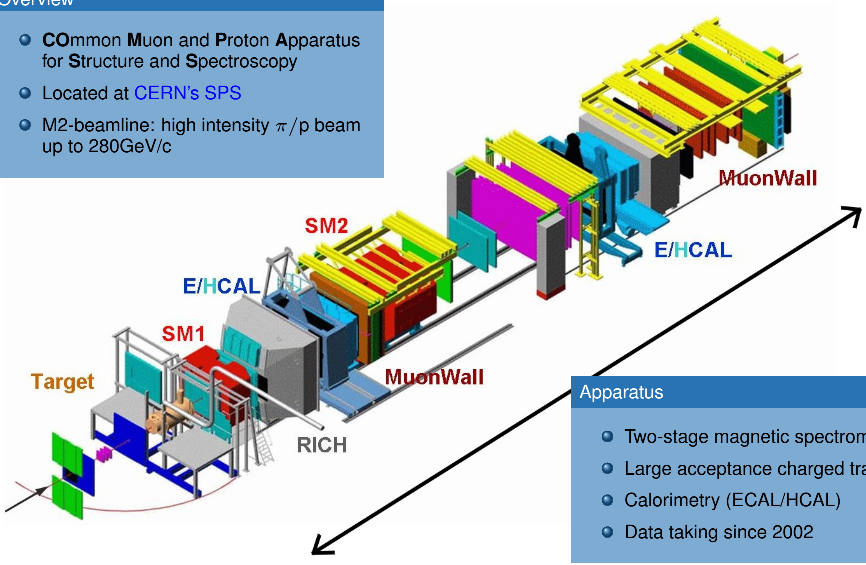
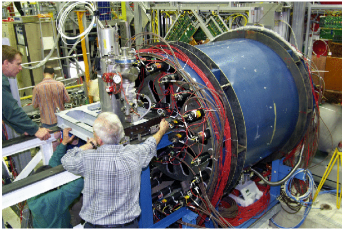


Apparatus

- Two-stage magnetic spectrometer
- Large acceptance charged tracking
- Calorimetry (ECAL/HCAL)
- Data taking since 2002

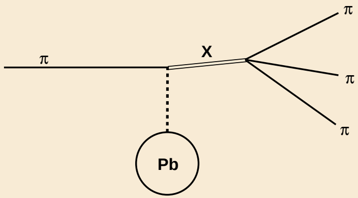
- M2-beamline:
  - neg. beam: 190GeV/c π^-(95%), K^-(4.5%)
  - pos. beam: 190GeV/c p(71.5%), π^+(25.5%), K^+(3%)
- **Pilotrun 2004** 190 GeV π^- beam on nuclear targets (few days)
  - Charged multiplicity trigger, online filter
  - $3\pi^\pm$ Analysis (Diffractive dissociation on Pb target)
- Apparatus Upgrade
  - lH_2 target
  - Recoil Proton Detector (RPD), refined trigger
  - Improved electromagnetic calorimetry
  - Improved PID: RICH, CEDAR (beam PID)
  - PixelGEM very small angle trackers
  - Cold Silicon vertex tracker



- **2008** mainly 190 GeV π^- beam on lH_2 target
  Pilotrun with positive beam
- **2009** pion / proton beams on lH_2 and nuclear targets
  Short campaigns: Minimum bias trigger (low t), nuclear recoil, Primakoff trigger

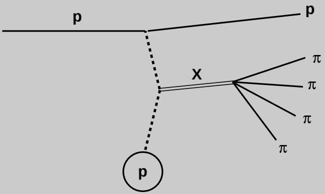
Diffractive Dissociation: $\pi A \to X A$ or $\pi p \to X p$ or $p p \to X p$

- **Diffraction**: target particle remains intact
  - Reggeon t-channel exchange
  - Pomeron ($I^G = 0^+$) leading trajectory:
    $\Rightarrow I^G = 1^-$ states dominate
  - **Assumptions:** Factorization of meson and Pb vertex, no final state interaction
- **Dissociation**: beam pion is excited to some resonance X^-, which subsequently decays
  $\Rightarrow$ e. g. $\pi^- \mathrm{Pb} \to X^- \mathrm{Pb} \to \pi^- \pi^- \pi^+ \mathrm{Pb}$
  $\Rightarrow$ e. g. $\pi^- \mathrm{Pb} \to X^- \mathrm{Pb} \to \pi^- \pi^- \pi^+ \pi^- \pi^+ \mathrm{Pb}$



Central Production: $\pi p \to \pi_{fast} X p_{slow}$ or $p p \to p_{fast} X p_{slow}$

- Reggeon-Reggeon fusion
  - Rapidity gap between leading hadron and central system
  - $I^G = 0^+$ states produced
- Central system (glue rich!?) resonance X^0
  $\Rightarrow$ e. g. $\mathrm{p\,p} \to \mathrm{p} X^0 \mathrm{p} \to \mathrm{p}_{fast} (\pi^- \pi^- \pi^+ \pi^+) \mathrm{p}$



Diffractive Dissociation

Pion beam + dominant Pomeron exchange:

$$I^G = 1^- \qquad |\,q\bar{q}\rangle \rightarrow G = (-1)^{\ell+s+I} \qquad \Rightarrow \ell + s = \text{even} \qquad \Rightarrow C = (-1)^{\ell+s} = +$$

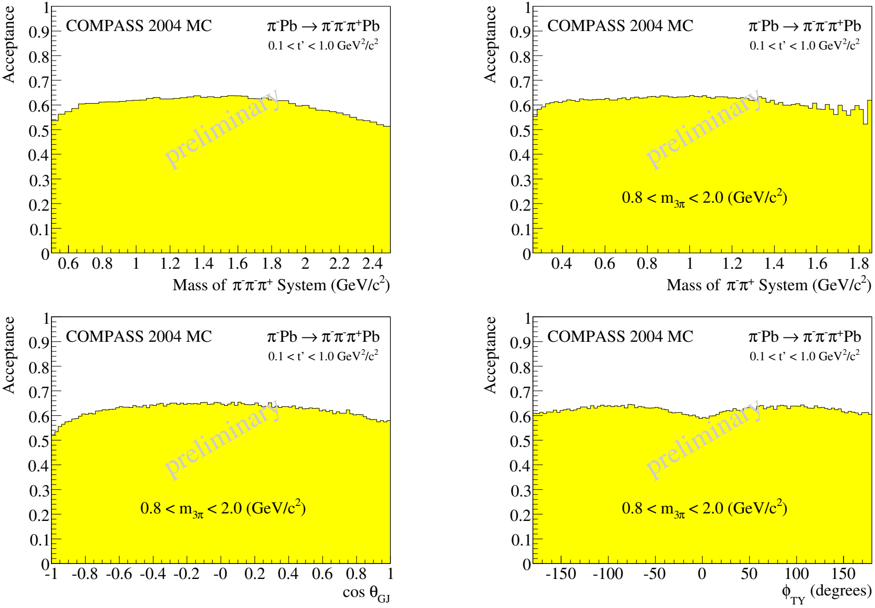
Channel	Accessible $I^G(J^{PC})$		
$\pi^\pm \rightarrow \pi^\pm\pi^-\pi^+$	$1^-(0^{-+})(1^{++})(2^{-+})$	$\pi_1(1400), \pi_1(1600)$	(1^{-+})
$\pi^\pm \rightarrow \pi^\pm\pi^0\pi^0$	$1^-(0^{-+})(1^{++})(2^{-+})$	$\pi_1(1400), \pi_1(1600)$	(1^{-+})
$\pi^\pm \rightarrow \pi^\pm\eta$	$1^-(0^{++})$...	$\pi_1(1400)$	
$\pi^\pm \rightarrow 5\pi$	$1^-(0^{++})$...	$\pi_1(1600), \pi_1(2000)$	(1^{-+})
$\pi^\pm \rightarrow 3\pi^\pm\pi_0$	$1^+(0^{+-})(2^{+-})$		
$\pi^\pm \rightarrow \pi^\pm K^- K^+$			
$\pi^\pm \rightarrow \pi^\pm K_S K_S \rightarrow 5\pi$			
$K^\pm \rightarrow K^\pm\pi^-\pi^+$			
$p \rightarrow N^* \rightarrow p\pi^-\pi^+$			

Central Production

Channel	Accessible $I^G(J^{PC})$	
$pp \rightarrow p(\pi^-\pi^+)p$	$0^+(0^{++})$...	$f_0(???)$
$pp \rightarrow p(4\pi)p$	$0^+(0^{++})$...	”
$\pi p \rightarrow \pi(\pi^-\pi^+)p$	$0^+(0^{++})$...	”
$\pi p \rightarrow \pi(4\pi)p$	$0^+(0^{++})$...	”

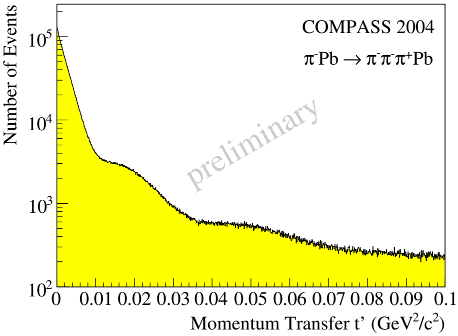
COMPASS Tracking Acceptance: $\pi^-\pi^-\pi^+$ Events

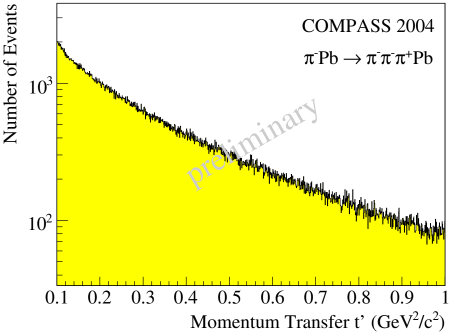
Excellent Phase Space Coverage



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

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

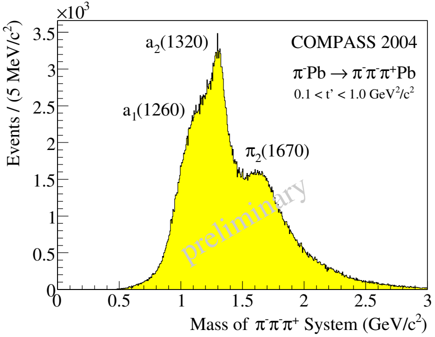




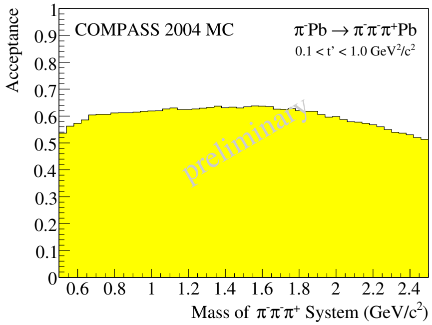
Diffraction pattern at low-t': Pb nucleus acts like "black disc" in optics

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

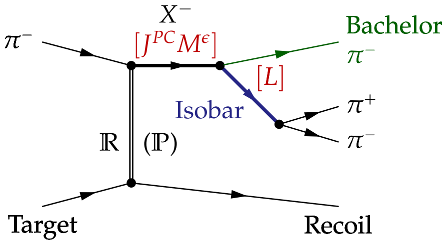
$\pi^-\pi^-\pi^+$ invariant mass spectrum for high-t'



Flat acceptance: 55-60%



Outline



X^- decay described using isobar model

- Chain of successive two-body decays
- Intermediate $\pi^+\pi^-$ resonance (isobar)
  - Spin S and relative orbital angular momentum L w.r.t. bachelor π^-
  - L and S couple to J
- Full wave specification: $J^{PC}M^\epsilon$[isobar]L

Assumptions

- Factorization of beam and target vertex
- No final state interactions
- I^G conserved at beam vertex $\Rightarrow$ fixed to 1^- by π^- beam
- Scattering on nucleons $\Rightarrow$ helicity flip and non-flip amplitudes at target vertex $\Rightarrow$ rank $= 2$
- Using reflectivity basis in Gottfried-Jackson frame
  - At high CM energies: reflectivity $\epsilon =$ naturality of $\mathbb{R}$

Cross section parameterization

$$\sigma(\tau, m_X) = \sum_{\epsilon=\pm 1} \sum_{r}^{N_r} \left| \sum_{i}^{\text{waves}} V_{ir}^{\epsilon} \psi_i^{\epsilon}(\tau, m_X) \right|^2$$

- Phase space coordinates τ measured for each event
- Decay amplitudes ψ_i^{ϵ} parameterized in the isobar model
- Production amplitudes V_{ir}^{ϵ} are fit parameters
- ϵ, i: quantum numbers of partial wave in reflectivity basis ($J^{PC} M^{\epsilon}$[isobar]L)

2 step procedure

1. Bin data in kinematical variable (e.g. m_X)
   - *Mass-independent fit* $\Rightarrow V_i(m_X)$
2. Extract resonance parameters from $V_i(m_X)$
   - *Mass-dependent fit*

Likelihood to find N events in a given mass bin $m_{X,n}$:

$$\mathcal{L} \propto \underbrace{\left[\frac{\bar{N}^N}{N!} e^{-\bar{N}}\right]}_{\text{Poisson}} \prod_{n=0}^{N} \underbrace{\left[\frac{\sigma(\tau_n; m_{X,n})}{\int_{m_1}^{m_2} \mathrm{d}m_X \int \mathrm{d}\tau\, \sigma(\tau, m_X)\, \mathrm{Acc}(\tau, m_X)}\right]}_{\text{Normalized cross section}}$$

Cross section normalization takes into account detector acceptance $\mathrm{Acc}(\tau, m_X)$.

2 step procedure

1. Bin data in kinematical variable (e.g. m_X)
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Extended log-likelihood

$$\ln \mathcal{L} = \sum_{n=1}^{N} \ln \sum_{i,j}^{\text{waves}} V_i V_j^* \psi_i(\tau_n) \psi_j^*(\tau_n) - \int_{m_1}^{m_2} \mathrm{d}m_X \int \mathrm{d}\tau\, \sigma(\tau, m_X)\, \mathrm{Acc}(\tau, m_X)$$

Subtleties omitted from formula:

- Rank
- Reflectivity basis
- Positivity constraints

$$\Psi_{ij} = \int_{m_1}^{m_2} \mathrm{d}m_X \int \mathrm{d}\tau\, \sigma(\tau, m_X)\, \mathrm{Acc}(\tau, m_X)$$

Normalization integral estimated using phase space Monte Carlo

- From step 1: mass dependence of spin density matrix

$$\rho^{\epsilon}_{ij}(m_X) = \sum_{r=1}^{N_r} V^{\epsilon}_{ir} \, V^{\epsilon *}_{jr}$$

  - Diagonal elements ρ_{ii}: intensities
  - Off-diagonal elements ρ_{ij}; $i \neq j$: interference terms

2 step procedure

1. Bin data in kinematic variable (e.g. m_X)
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Breit-Wigner parameterization of spin density matrix

$$\rho^{\epsilon}_{ij}(m_X) = \left[\sum_{k}^{\text{waves}} C^{\epsilon}_{ik}\, \text{BW}_k(m_X)\right] \left[\sum_{l}^{\text{waves}} C^{\epsilon}_{jl}\, \text{BW}_l(m_X)\right]^*$$

- Coherent background added to some waves
- χ^2 fit of mass dependence of spin density matrix takes into account
  - Wave intensities
  - Phase motion from interference terms

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$J^{PC}M^{\epsilon}$	L	Isobar	Thresh. [GeV]
$0^{-+}0^{+}$	S		
$0^{-+}0^{+}$	S		
$0^{-+}0^{+}$	P		
$1^{-+}1^{+}$	P		
$1^{++}0^{+}$	S		
$1^{++}0^{+}$	P		
$1^{++}0^{+}$	P		
$1^{++}0^{+}$	D		
$1^{++}1^{+}$	S		
$1^{++}1^{+}$	P		
$1^{++}1^{+}$	P		
$1^{++}1^{+}$	D		
$2^{-+}0^{+}$	S		
$2^{-+}0^{+}$	P		
$2^{-+}0^{+}$	D		
$2^{-+}0^{+}$	D		
$2^{-+}0^{+}$	F		
$2^{-+}1^{+}$	S		
$2^{-+}1^{+}$	P		
$2^{-+}1^{+}$	D		
$2^{-+}1^{+}$	D	$(\pi\pi)_S\pi$	1.20
$2^{-+}1^{+}$	F	$\rho\pi$	1.20

Thresh. [GeV]
1.50
-
1.50
1.20
1.50
1.50
1.20
1.50
1.20
1.20
1.60
1.64
-
-
-
1.20
1.30
-
1.30

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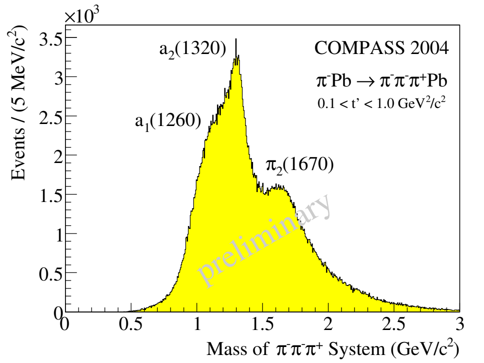
3π invariant Mass



$J^{PC}M^{\epsilon}$	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
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$J^{PC}M^{\epsilon}$	L	Isobar π	Thresh. [GeV]
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$0^{-+}0^{+}$	S		
$0^{-+}0^{+}$	F		
$1^{-+}1^{+}$	F		
$1^{++}0^{+}$	S		
$1^{++}0^{+}$	F		
$1^{++}0^{+}$	F		
$1^{++}0^{+}$	D		
$1^{++}1^{+}$	S		
$1^{++}1^{+}$	F		
$1^{++}1^{+}$	F		
$1^{++}1^{+}$	D		
$2^{-+}0^{+}$	S		
$2^{-+}0^{+}$	F		
$2^{-+}0^{+}$	D		
$2^{-+}0^{+}$	D	$(\pi\pi)_s\pi$	0.80
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$J^{PC}M^{\epsilon}$	L	Isobar π	Thresh. [GeV]
			1.50
			-
			1.50
			1.20
			1.50
			1.50
			1.20
			1.50
			1.20
			1.20
			1.60
			1.64
			-
			-
$1^{++}1^{-}$	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
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Waveset Features

- 41 Waves + flat background
- Isobars:
  - $\sigma(600)$, $\rho(770)$, $f_0(980)$, $f_2(1270)$, ρ_3
- Positive reflectivity dominates
- 7 negative reflectivity waves included
- Superset of BNL E852 “high wave” wave set
  - More $M = 1$ waves
  - 2^{-+}F waves included

Partial Wave Set for Mass-Dependent Fit (6 Waves)

$J^{PC}M^{\epsilon}$	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
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$J^{PC}M^{\epsilon}$	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
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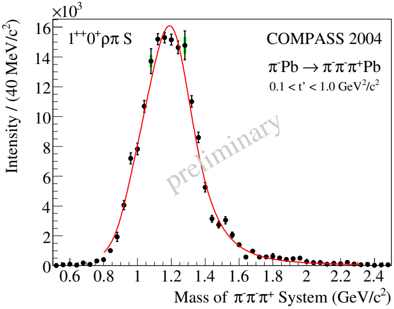
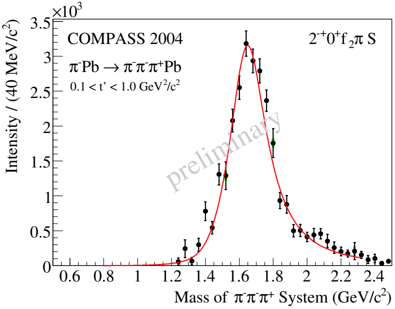
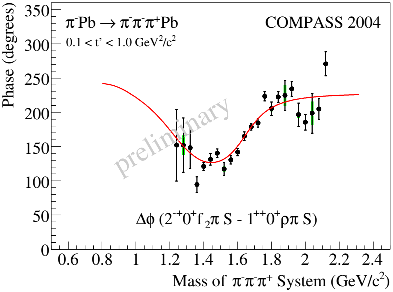






- BW for $a_1(1260)$ + background:

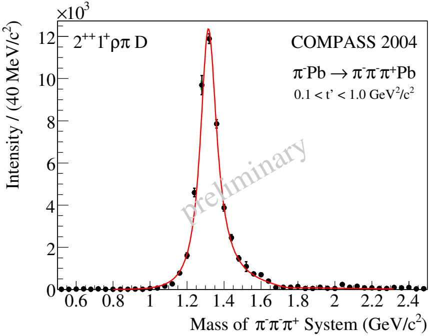
  $M = (1.255 \pm 0.006 \,^{+0.007}_{-0.017})\ \mathrm{GeV/c^2}$

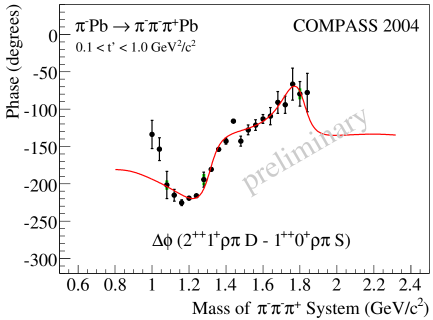
  $\Gamma = (0.367 \pm 0.009 \,^{+0.028}_{-0.025})\ \mathrm{GeV/c^2}$

- BW for $\pi_2(1670)$:

  $M = (1.658 \pm 0.003 \,^{+0.024}_{-0.008})\ \mathrm{GeV/c^2}$

  $\Gamma = (0.271 \pm 0.009 \,^{+0.022}_{-0.024})\ \mathrm{GeV/c^2}$

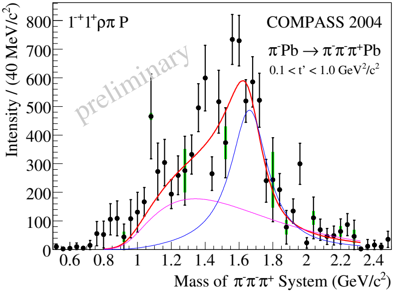


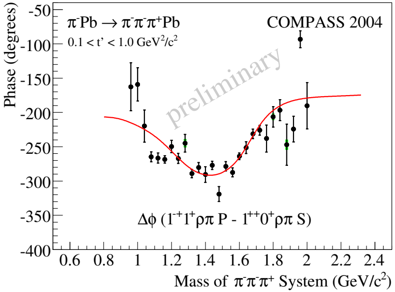


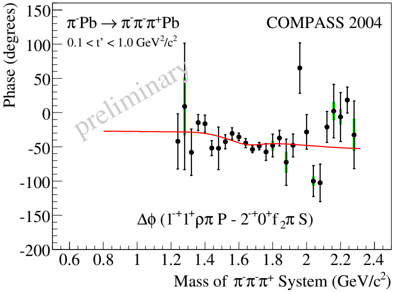
- Two Breit-Wigners needed to describe $2^{++}1^{+}\rho\pi D$ phase motion: BW1 for $a_2(1320)$ + BW2 for $a_2(1700)$
- $M = (1.321 \pm 0.001\ ^{+0.000}_{-0.007})$ GeV, $\Gamma = (0.110 \pm 0.002\ ^{+0.002}_{-0.015})$ GeV
- $a_2(1700)$ parameters fixed to PDG values: $M = 1.732$ GeV, $\Gamma = 0.194$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

PWA Results

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





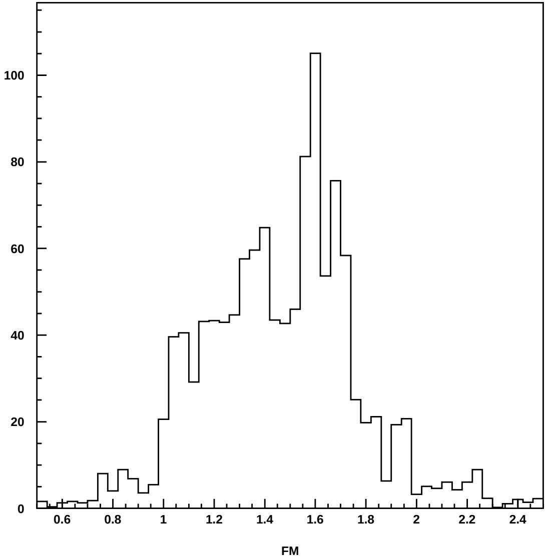


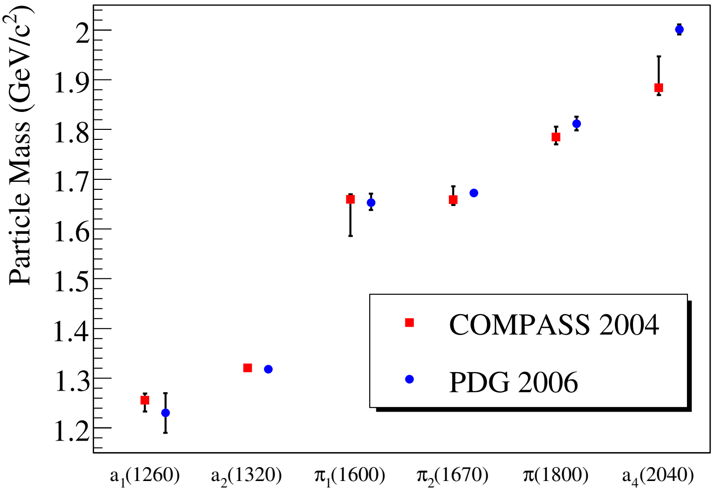
- Significant 1^{-+} amplitude consistent with resonance at $\sim 1.7\,\mathrm{GeV}/c^2$
- BW for $\pi_1(1600)$ + background:

  $M = (1.660 \pm 0.010 \,^{+0.000}_{-0.064})\,\mathrm{GeV}/c^2$

  $\Gamma = (0.269 \pm 0.021 \,^{+0.042}_{-0.064})\,\mathrm{GeV}/c^2$

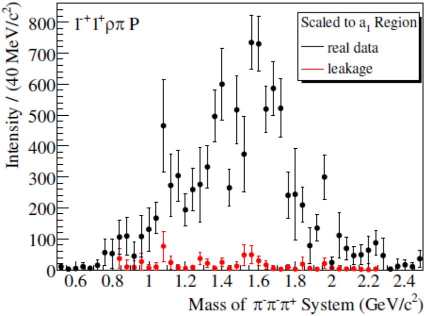
Mass dependence of loglikelihood-difference with and without exotic $1^{-+}1^{+}\rho\pi$ wave

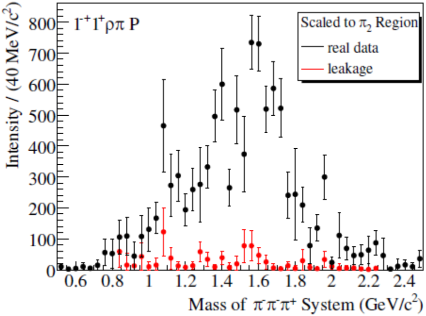




Particle Mass (GeV/c²)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
COMPASS 2004
PDG 2006
a₁(1260)
a₂(1320)
π₁(1600)
π₂(1670)
π(1800)
a₄(2040)

1. Generate MC events distributed according to model with 16 most important waves (including various 2^{-+} modes) without 1^{-+}
2. Pass events through detector simulation and selection cuts
3. Fit MC data with full waveset



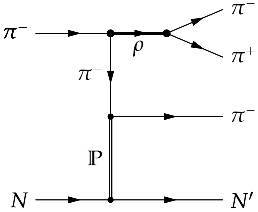


1. Mass-independent fits using rank 1,2,3
2. Mass-independent fit using mass bins shifted by half bin width
3. Mass-independent fit using *D*-functions with relativistic corrections instead of Zemach tensors
4. Mass-independent fit with extended wave set: 46 waves with four additional $M = 2$ waves
5. Mass-dependent fit taking into account 3π invariant mass resolution
6. Mass-dependent fit with dynamical instead of constant width for $a_4(2040)$
7. Mass-dependent fit with 7 waves with additional $\pi_2(1880)$ Breit-Wigner in $2^{-+}0^+[f_2\pi]D$ wave
8. Mass-independent fit with lowered mass threshold (1.2 GeV/c^2) for the $2^{++}1^+[f_2\pi]P$ wave
   mass-dependent fit with 8 waves with additional $2^{++}1^+[f_2\pi]P$ wave
   $a_2(1700)$ parameters released
9. Mass-dependent fit with 7 waves with additional $\pi_1(1400)$ constant width Breit-Wigner (parameters fixed to PDG values) in the $1^{-+}1^+[\rho\pi]P$ wave

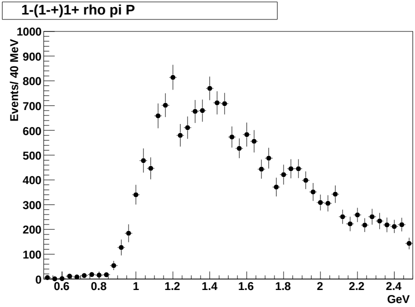
- In the used framework the extracted signal shows all the expected features of a resonant state.
- Produced in positive naturality, decaying through $\rho\pi$
- It is consistent with a $\pi_1(1600)$ resonance. How tempting!

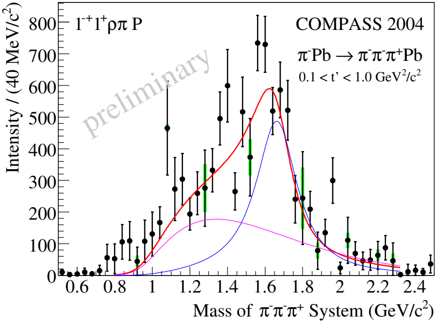
However:

- Isobar model breaks unitarity — could this generate the signal?
- Isobar parameterizations
- Non-diffractive production processes: Where does the Deck effect go?
- Anything else?



Leakage of Deck amplitude into $1^{-+}1^{+}$ $\rho\pi$ P-wave:

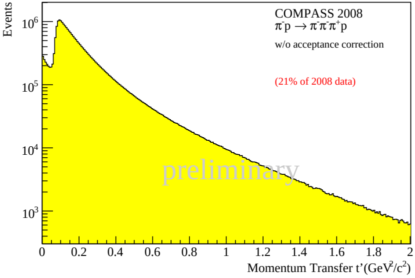


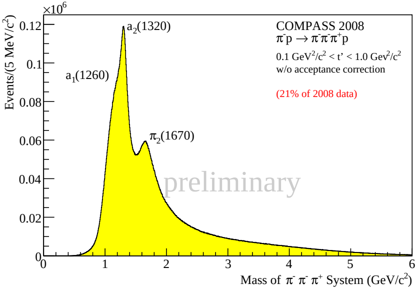


2008 Data: Diffractive Production of $\pi^-\pi^+\pi^-$ on lH_2

$\pi^- p \to 3\pi p$

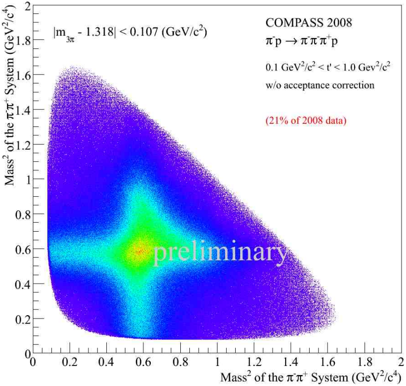
- Recoil Proton Detector used in trigger $\to$ t-cut
- Data sample: $\sim$ 21% of total 2008 data
- Expect $\sim$ 170 000 events in π_1 bump
- Analysis ongoing



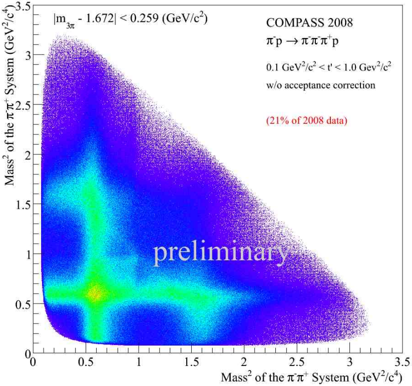


2008 Data: 3π Dalitz Plots

$a_2(1320)$ region



$\pi_2(1670)$ region



Motivation — Diffractive Dissociation:

- Access to mass-range $> 2\,\mathrm{GeV}/c^2$
- *Light meson frontier*:
  many disputed states in this region
  $(0^{-+})(1^{++})(2^{-+})$...
- Interesting accessible quantum numbers:
  - $1^-(0^{-+})\pi(1800)$ Hybrid candidate
  - $1^-(1^{-+})$ spin exotic
- Interesting decay modes $b_1\pi$, $f_1\pi$, $\rho'\pi$

Central Production on p-target:

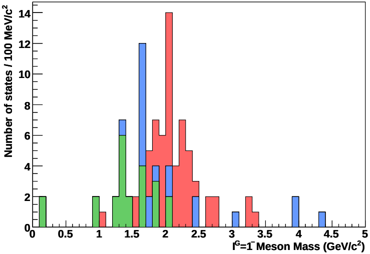
$\pi^-_{fast}(4\pi)^0_{central}$

- Investigate 4π system.
- $I^G = 0^+$ states $\rightarrow$ Scalar glueball?
- But: Interference with diffractive production
- First pp data taken this year

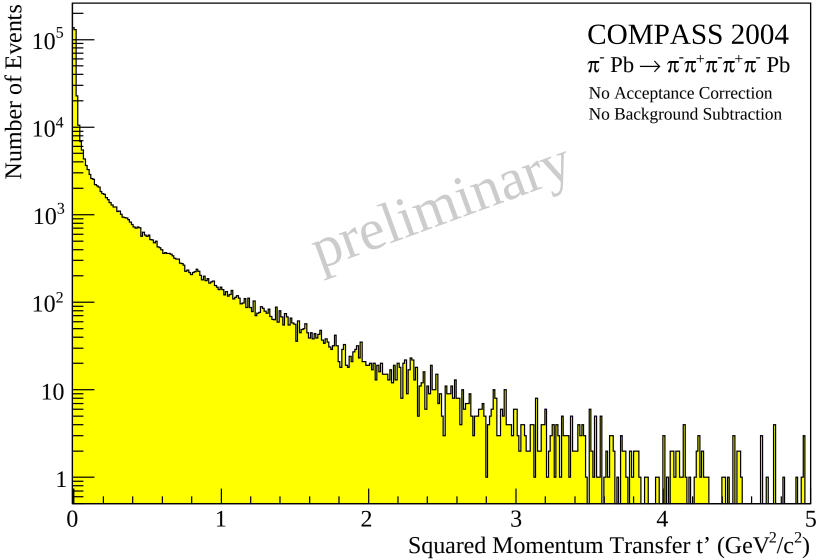
$\pi_1(1^{-+})$ branching ratios

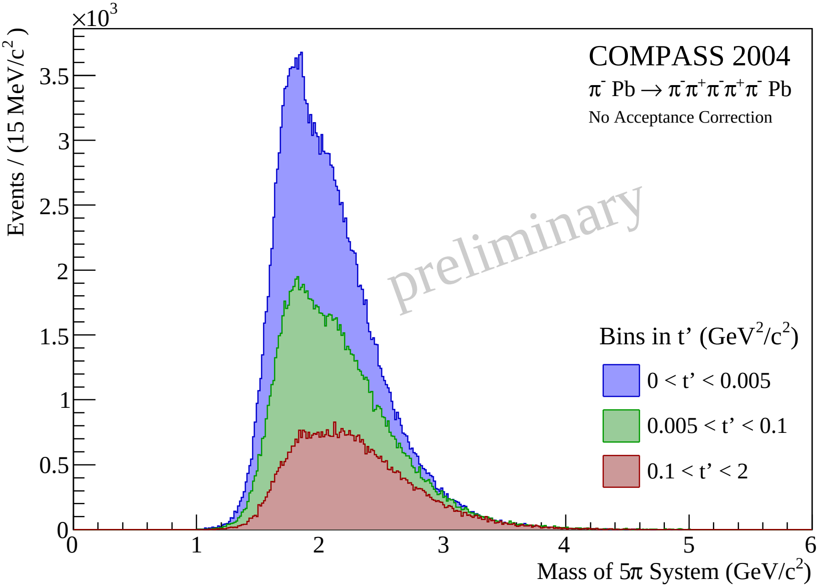
Flux-Tube model predictions:
(Page, Swanson, Szczepaniak, Phys. Rev. D59, 034016(1999))

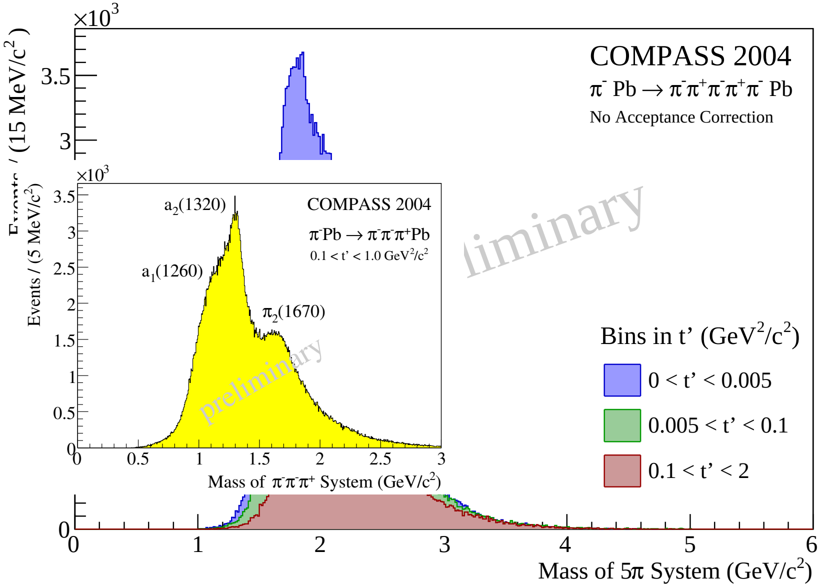
m_{π_1}	$b_1\pi$	$f_1\pi$	$\eta'\pi$	$\rho(1450)\pi$
$1.6\,\mathrm{GeV}/c^2$	24:	5:	2	
$2.0\,\mathrm{GeV}/c^2$	43:	10:	27:	12



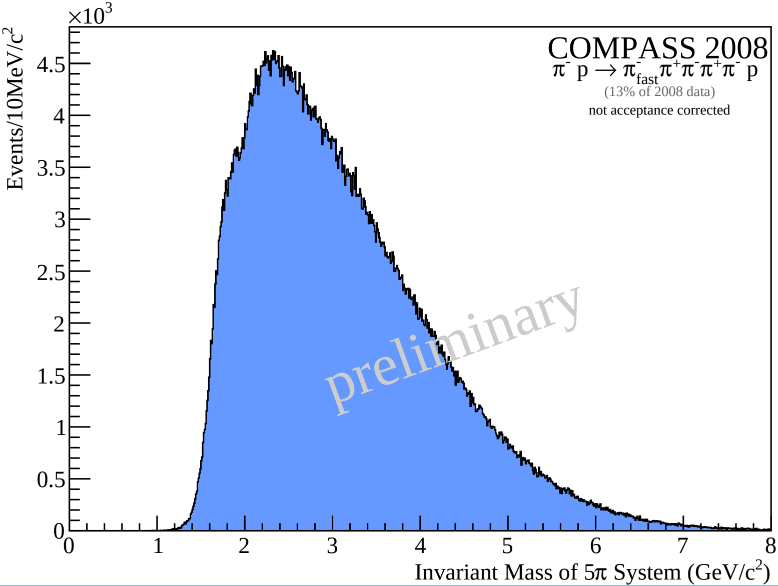
Meson states with $I^G = 1^-$ listed in the PDB. Green = established, blue = need confirmation, red = “further states”. The histogram is stacked.

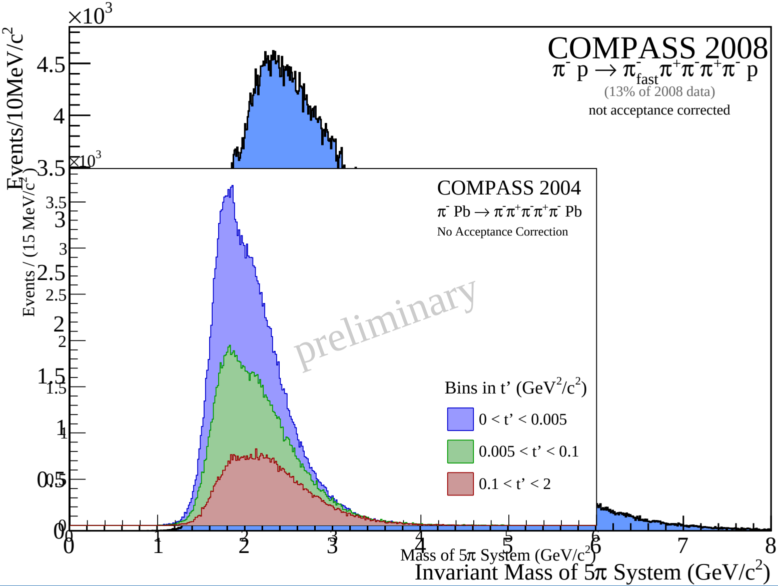

COMPASS 2004
$\pi^- Pb \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^- Pb$
No Acceptance Correction
No Background Subtraction
preliminary
Number of Events
10^5
10^4
10^3
10^2
10
1
0
1
2
3
4
5
Squared Momentum Transfer t' (GeV^2/c^2)


×10^3
Events / (15 MeV/c^2)
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
Mass of 5π System (GeV/c^2)
COMPASS 2004
π⁻ Pb → π⁻π⁺π⁻π⁺π⁻ Pb
No Acceptance Correction
preliminary
Bins in t' (GeV^2/c^2)
0 < t' < 0.005
0.005 < t' < 0.1
0.1 < t' < 2

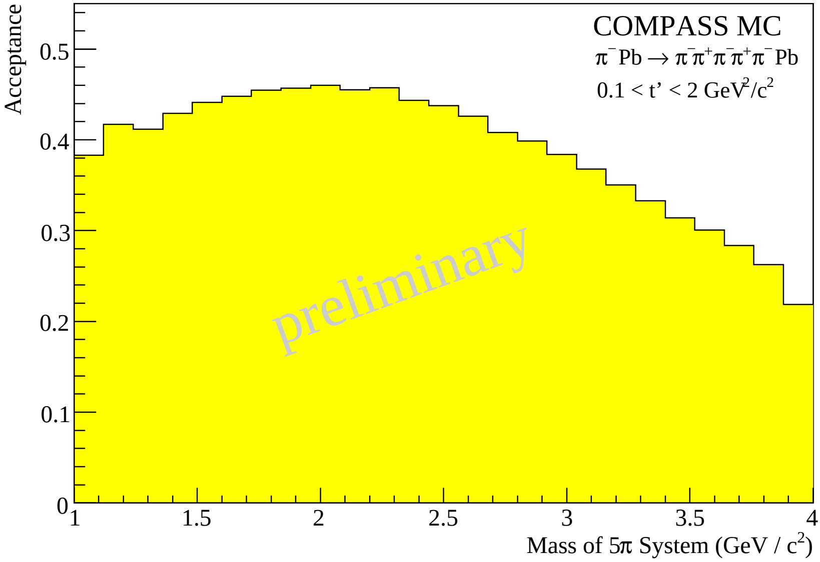


×10^3
Events / (15 MeV/c^2)
3.5
3
COMPASS 2004
π⁻ Pb → π⁻π⁺π⁻π⁺π⁻ Pb
No Acceptance Correction
preliminary
×10^3
Events / (5 MeV/c^2)
a2(1320)
a1(1260)
π2(1670)
COMPASS 2004
π⁻Pb → π⁻π⁻π⁺Pb
0.1 < t' < 1.0 GeV^2/c^2
preliminary
Mass of π⁻π⁻π⁺ System (GeV/c^2)
Bins in t' (GeV^2/c^2)
0 < t' < 0.005
0.005 < t' < 0.1
0.1 < t' < 2
Mass of 5π System (GeV/c^2)

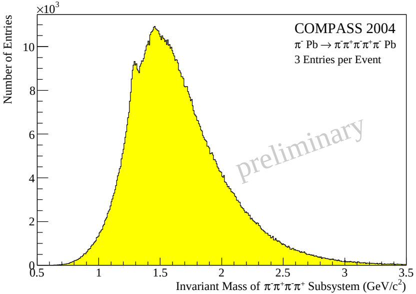

×10^3
Events/10MeV/c^2
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
Invariant Mass of 5π System (GeV/c^2)
COMPASS 2008
π^- p → π^-_fast π^+π^-π^+π^- p
(13% of 2008 data)
not acceptance corrected
preliminary

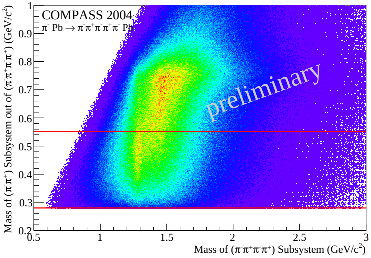


COMPASS 2008
π⁻ p → π⁻fast π⁺π⁻π⁺π⁻ p
(13% of 2008 data)
not acceptance corrected
Events/10MeV/c²
×10³
Invariant Mass of 5π System (GeV/c²)
COMPASS 2004
π⁻ Pb → π⁻π⁺π⁻π⁺π⁻ Pb
No Acceptance Correction
preliminary
Events / (15 MeV/c²)
Mass of 5π System (GeV/c²)
Bins in t' (GeV²/c²)
0 < t' < 0.005
0.005 < t' < 0.1
0.1 < t' < 2

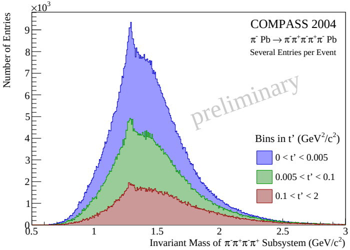


COMPASS MC
$\pi^- Pb \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^- Pb$
$0.1 < t' < 2\ GeV^2/c^2$
preliminary
Acceptance
0
0.1
0.2
0.3
0.4
0.5
1
1.5
2
2.5
3
3.5
4
Mass of 5π System (GeV / c²)





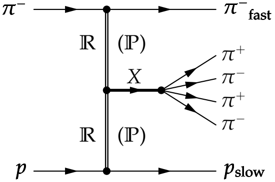
Cut 4π spectrum:



Isobar candidates:

Name	Mass (GeV/c^2)	$I^G(J^{PC})$
f_0	1370 / 1700	$0^+(0^{++})$
η'	1403	$0^+(0^{-+})$
ρ'	1450	$1^+(1^{--})$
b_1	1235 / 1800	$1^+(1^{+-})$
f_1	1285 / 1450	$0^+(1^{++})$
η_2'	1645	$0^+(2^{-+})$
f_2	1565	$0^+(2^{++})$
ρ_3	1690	$1^+(3^{--})$

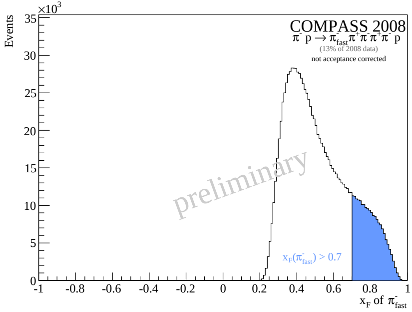
4π Central Production

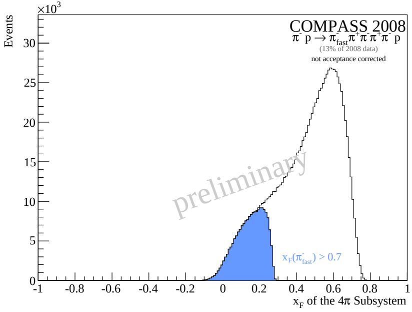


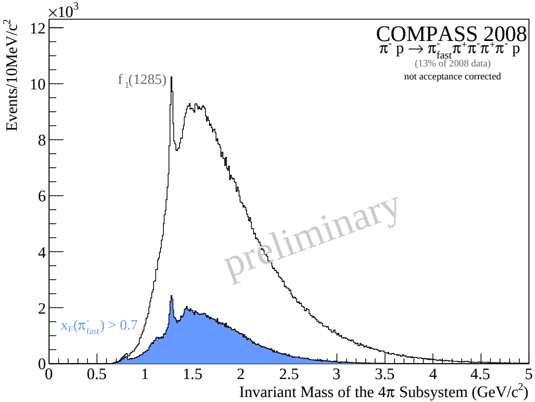
Event signature

- Fast outgoing π^-
- Slow recoil proton $\Rightarrow$ detected in RPD
- Rapidity gaps

Selection of centrally produced 4π using cut $x_F^{\pi^-_{\text{fast}}} > 0.7$







Separability from diffractive processes

- x_F cut enriches $f_1(1285)$
- Central production and diffraction difficult to separate at 190 GeV/c beam energy
- Probably unified analysis technique required

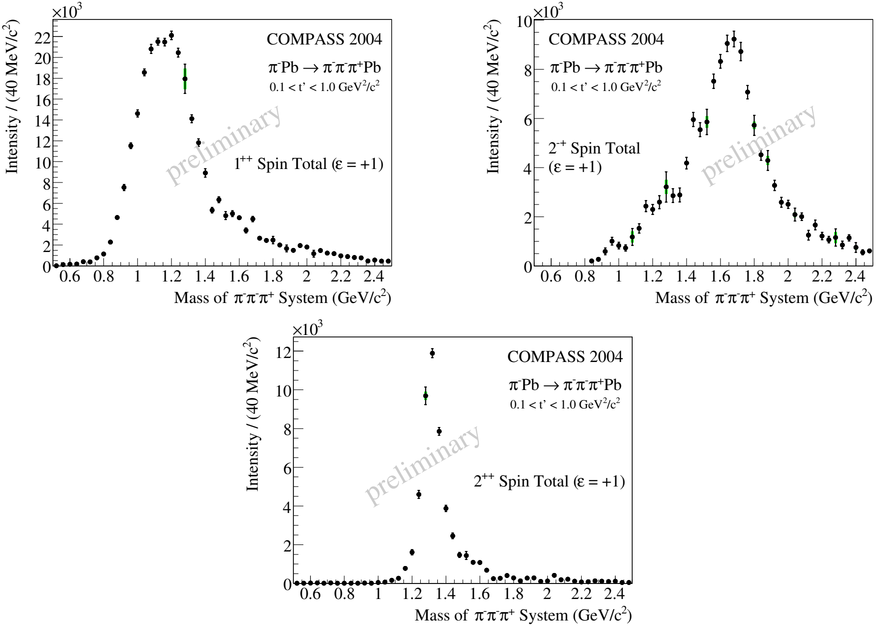
- COMPASS 2004 pilot run using a 190 GeV π^- beam
  - Meson production in diffractive dissociation on lead target
  - $3\pi \sim 4\,000\,000$ events recorded within a few days of data taking
  - $5\pi \sim 370\,000$ events
  - Excellent acceptance for diffractive charged pion events ($\sim$ 55-60% for 3π)

- Partial wave analysis 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
  - Excellent agreement with PDG
  - Also small, well-known resonances $\pi(1800)$ and $a_4(2040)$ can be fitted

- Spin-exotic 1^{-+} state observed in $\rho\pi$ decay channel both in intensity and phase motion
  - $\Rightarrow$ consistent with $\pi_1(1600)$ resonance
  - Publication about to be submitted [arXiv:0910.5842]

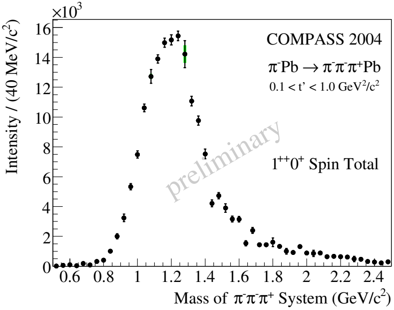
- Analysis of $5\pi^{\pm}$ final state in progress
  - Clear f_1 signal in 4π subsystem
  - PWA software: http://sourceforge.net/projects/rootpwa/
    based on BNL program (J. Cummings and D. Weygand, arxiv:physics/0309052)
- COMPASS Hadron Run 2008
  - Change-over to liquid hydrogen target
  - Spectrometer upgrade (Recoil Detector, PID, ECAL, tracking ...)
- COMPASS Hadron Run 2009 topics:
  - Central Production
  - Diffractive Dissociation
  - Repeat measurements on Pb with upgraded spectrometer:
    - Collect more statistics
    - Measure proton recoil from Pb $\rightarrow$ thin target
- High statistics data samples:
  - Diffractive: $\sim$ 10$\times$ E852
  - Central: $\sim$ 10$\times$ WA102
- Analysis in progress

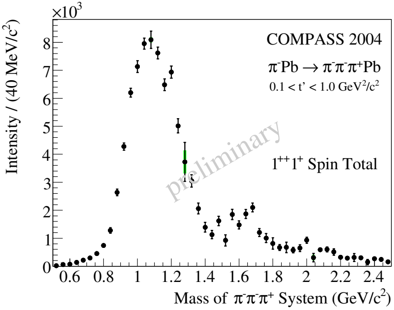
Exciting Results are on the Horizon...

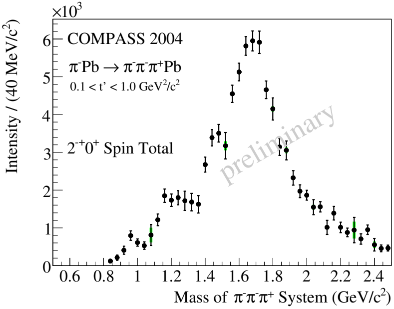


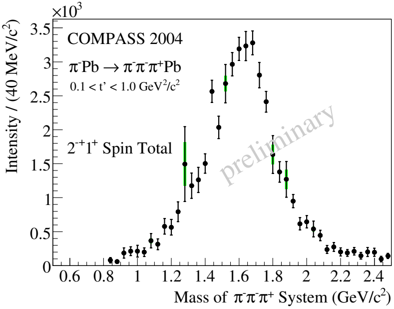
COMPASS 2004
π⁻Pb → π⁻π⁻π⁺Pb
0.1 < t' < 1.0 GeV²/c²
1⁺⁺ Spin Total (ε = +1)
preliminary
Intensity / (40 MeV/c²)
×10³
Mass of π⁻π⁻π⁺ System (GeV/c²)
2⁻⁺ Spin Total
(ε = +1)
2⁺⁺ Spin Total (ε = +1)

Backup Slides: $M = 0$ and $M = 1$ Spin Totals

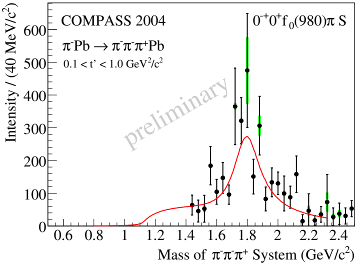




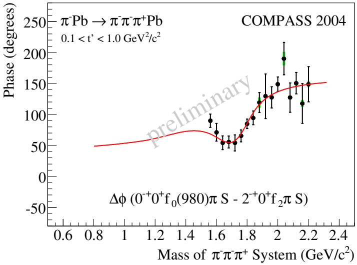




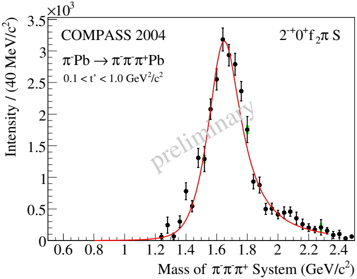
$0^{-+}\,0^{+}\,[f_0(980)\pi]S$



$0^{-+}\,0^{+}\,[f_0\pi]S - 2^{-+}\,0^{+}\,[f_2\pi]S$

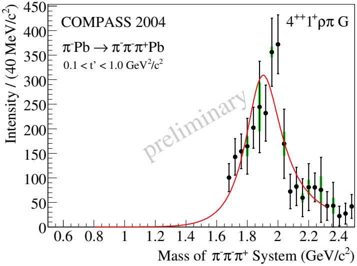


$2^{-+}\,0^{+}\,[f_2\pi]S$

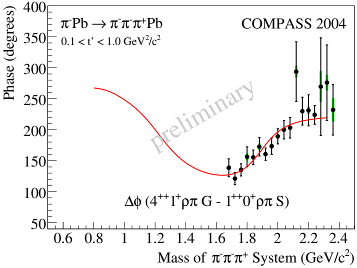


- $\pi(1800)$ BW + background
  $m = 1\,785 \pm 9^{+12}_{-6}|MeV/c^2$
  $\Gamma = 208 \pm 22^{+21}_{-37}$—MeV

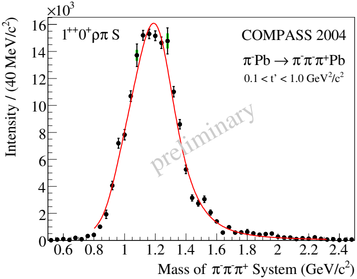
$4^{++}\,1^{+}\,[\rho\pi]G$



$4^{++}\,1^{+}\,[\rho\pi]G - 1^{++}\,0^{+}\,[\rho\pi]S$

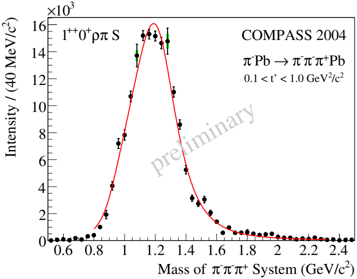


$1^{++}\,0^{+}\,[\rho\pi]S$

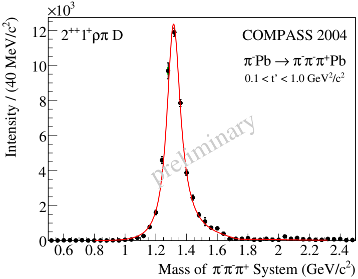


- $a_4(2040)$ BW
  $m = 1\,884 \pm 13^{+50}_{-2} |\mathrm{MeV}/c^2$
  $\Gamma = 295 \pm 24^{+46}_{-19}$—MeV

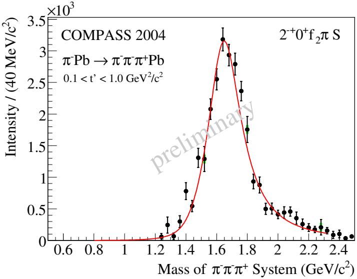
$a_1(1260)$ $1^{++}0^{+}[\rho\pi]S$



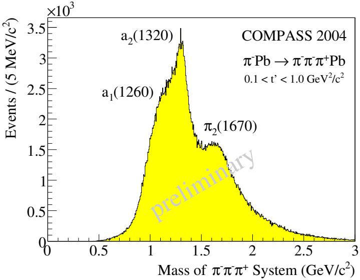
$a_2(1320)$ $2^{++}1^{+}[\rho\pi]D$



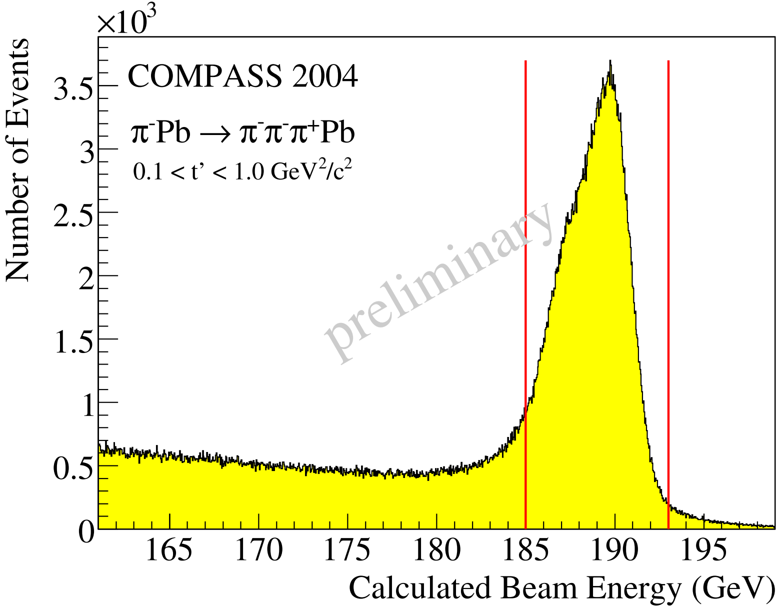
$\pi_2(1670)$ $2^{-+}0^{+}[f_2\pi]S$

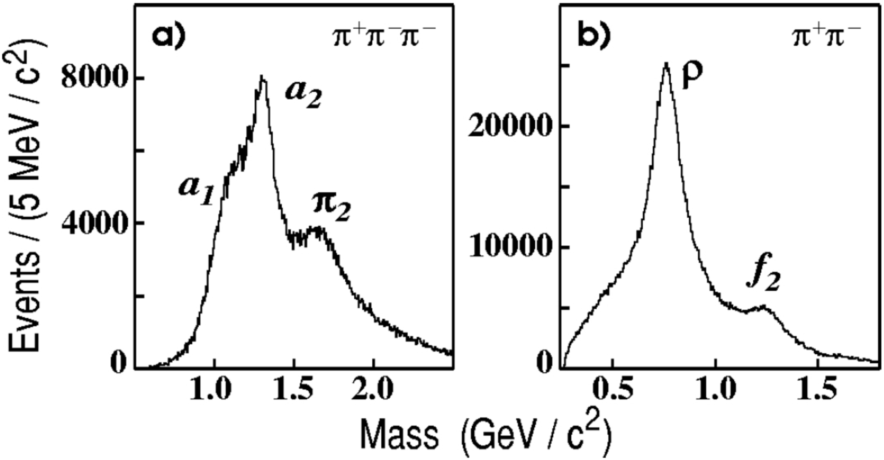


Overall



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


×10^3
Number of Events
COMPASS 2004
π⁻Pb → π⁻π⁻π⁺Pb
0.1 < t' < 1.0 GeV²/c²
preliminary
0
0.5
1
1.5
2
2.5
3
3.5
165
170
175
180
185
190
195
Calculated Beam Energy (GeV)



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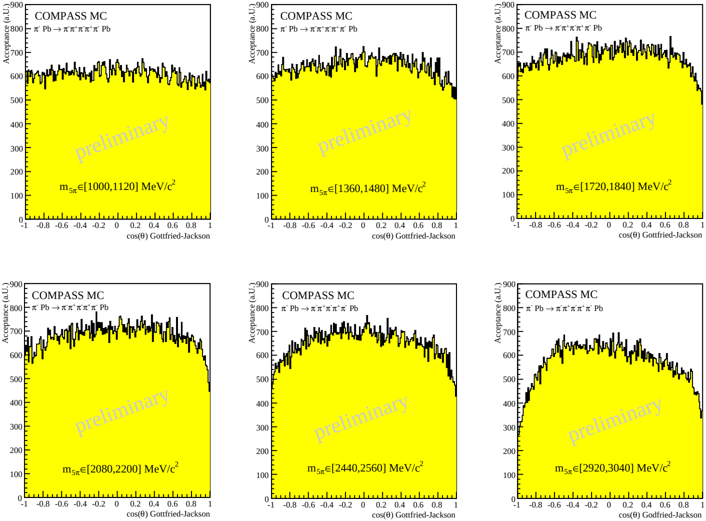
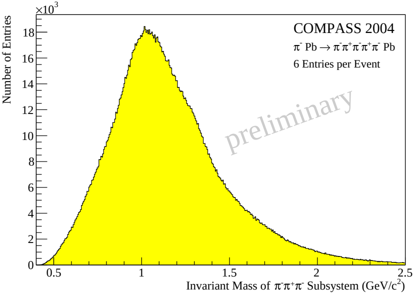
Backup Slides: 5π Acceptance from Monte Carlo Simulation

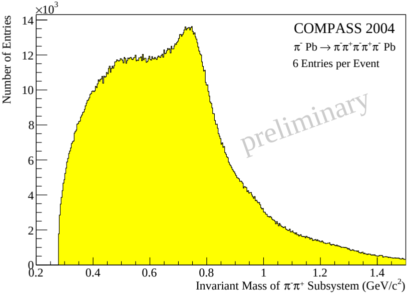
Angular Acceptance – $\pi^- R^0_{4\pi}$ Gottfried-Jackson Angle

Single pion decay angle in X^- rest frame (Gottfried-Jackson frame).





×10^3
Number of Entries
COMPASS 2004
π⁻ Pb → π⁻π⁺π⁻π⁺π⁻ Pb
6 Entries per Event
preliminary
0
2
4
6
8
10
12
14
16
18
0.5
1
1.5
2
2.5
Invariant Mass of π⁻π⁺π⁻ Subsystem (GeV/c²)



×10^3
Number of Entries
COMPASS 2004
π⁻ Pb → π⁻π⁺π⁻π⁺π⁻ Pb
6 Entries per Event
preliminary
0
2
4
6
8
10
12
14
0.2
0.4
0.6
0.8
1
1.2
1.4
Invariant Mass of π⁻π⁺ Subsystem (GeV/c²)