Precision Meson Spectroscopy at COMPASS

Boris Grube

Excellence Cluster Universe
Technische Universität München,
Garching, Germany

for the ***COMPASS*** Collaboration

19th International Conference on Few-Body Problems in Physics
Bonn, 4th September 2009

Outline

1. Introduction
   - Constituent quark model and QCD
   - Experimental setup
2. Results from COMPASS 2004 pilot run
   - Meson production in diffractive dissociation
   - Analysis method
   - Results from partial-wave analysis
3. COMPASS hadron run 2008/9

Outline

Constituent Quark Model and QCD

Naïve constituent quark model

- Mesons are bound color-singlet $|q\bar{q}\rangle$ states, grouped into $\mathrm{SU}(N)_{\mathrm{flavor}}$ multiplets with certain J^{PC}
- Spin-parity rules
  - Parity $P = (-1)^{L+1}$
  - Charge conjugation $C = (-1)^{L+S}$
  - L relative orbital angular momentum of $q\bar{q}$, S total intrinsic spin
- **Forbidden J^{PC} for $|q\bar{q}\rangle$: $0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, 4^{+-}, \ldots$**

Self-coupling of gluons in QCD

- Suggests extension of meson basis states
  - States with valence glue $|q\bar{q}g\rangle \implies$ **hybrids**
  - Bound gluon states $|gg\rangle \implies$ **glueballs**
  - Multi-quark states $|qq\bar{q}\bar{q}\rangle \implies$ **tetraquarks**
  - ...

Constituent Quark Model and QCD

Naïve constituent quark model

- Mesons are bound color-singlet $|q\bar{q}\rangle$ states, grouped into $\mathrm{SU}(N)_{\mathrm{flavor}}$ multiplets with certain J^{PC}
- Spin-parity rules
  - Parity $P = (-1)^{L+1}$
  - Charge conjugation $C = (-1)^{L+S}$
  - L relative orbital angular momentum of $q\bar{q}$, S total intrinsic spin
- **Forbidden J^{PC} for $|q\bar{q}\rangle$: $0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, 4^{+-}, \ldots$**

Self-coupling of gluons in QCD

- Suggests extension of meson basis states
  - States with valence glue $|q\bar{q}g\rangle \implies$ **hybrids**
  - Bound gluon states $|gg\rangle \implies$ **glueballs**
  - Multi-quark states $|qq\bar{q}\bar{q}\rangle \implies$ **tetraquarks**
  - …

Constituent Quark Model and QCD

Extended set of meson basis states

- Mesons are linear superpositions of *all* allowed basis states
  - Disentanglement of various contributions difficult
- **Spin-exotic mesons** have J^{PC} quantum numbers forbidden for $|q\bar{q}\rangle \implies$ no $|q\bar{q}\rangle$ component
  - Unambiguous proof for meson states beyond $|q\bar{q}\rangle$
  - Fundamental confirmation of QCD

Light-quark sector

- Model predictions
  - Lowest mass **glueball**: mass $\approx 1.7\ \text{GeV}/c^2$ and $J^{PC} = 0^{++}$
  - Lightest **hybrid**: exotic $J^{PC} = 1^{-+}$ and mass $1.7 \ldots 2.2\ \text{GeV}/c^2$
- **Experimentally challenging**: high density of broad, overlapping states
  - Interference effects have to be exploited $\implies$ phase motion
  - Requires large data samples and complete phase space coverage

Constituent Quark Model and QCD

Extended set of meson basis states

- Mesons are linear superpositions of *all* allowed basis states
  - Disentanglement of various contributions difficult
- **Spin-exotic mesons** have J^{PC} quantum numbers forbidden for $|q\bar{q}\rangle \implies$ no $|q\bar{q}\rangle$ component
  - Unambiguous proof for meson states beyond $|q\bar{q}\rangle$
  - Fundamental confirmation of QCD

Light-quark sector

- Model predictions
  - Lowest mass **glueball**: mass ≈ 1.7 GeV/c^2 and $J^{PC} = 0^{++}$
  - Lightest **hybrid**: exotic $J^{PC} = 1^{-+}$ and mass $1.7 \ldots 2.2$ GeV/c^2
- **Experimentally challenging**: high density of broad, overlapping states
  - Interference effects have to be exploited $\implies$ phase motion
  - Requires large data samples and complete phase space coverage

Constituent Quark Model and QCD

Extended set of meson basis states

- Mesons are linear superpositions of *all* allowed basis states
  - Disentanglement of various contributions difficult
- **Spin-exotic mesons** have J^{PC} quantum numbers forbidden for $|q\bar{q}\rangle \implies$ no $|q\bar{q}\rangle$ component
  - Unambiguous proof for meson states beyond $|q\bar{q}\rangle$
  - Fundamental confirmation of QCD

Light-quark sector

- Model predictions
  - Lowest mass **glueball**: mass ≈ 1.7 GeV/c^2 and $J^{PC} = 0^{++}$
  - Lightest **hybrid**: exotic $J^{PC} = 1^{-+}$ and mass $1.7 \ldots 2.2$ GeV/c^2
- **Experimentally challenging**: high density of broad, overlapping states
  - Interference effects have to be exploited $\implies$ phase motion
  - Requires large data samples and complete phase space coverage

Constituent Quark Model and QCD

Extended set of meson basis states

- Mesons are linear superpositions of *all* allowed basis states
  - Disentanglement of various contributions difficult
- **Spin-exotic mesons** have J^{PC} quantum numbers forbidden for $|q\bar{q}\rangle \implies$ no $|q\bar{q}\rangle$ component
  - Unambiguous proof for meson states beyond $|q\bar{q}\rangle$
  - Fundamental confirmation of QCD

Light-quark sector

- Model predictions
  - Lowest mass **glueball**: mass ≈ 1.7 GeV/c^2 and $J^{PC} = 0^{++}$
  - Lightest **hybrid**: exotic $J^{PC} = 1^{-+}$ and mass $1.7 \ldots 2.2$ GeV/c^2
- **Experimentally challenging**: high density of broad, overlapping states
  - Interference effects have to be exploited $\implies$ phase motion
  - Requires large data samples and complete phase space coverage

Spin-Exotic Mesons

Experimental candidates for J^{PC} exotic mesons

- $\pi_1(1400)$: $I^G(J^{PC}) = 1^-1^{-+}$
  - Seen by E852, VES, and Crystal Barrel in $\eta\pi$ decay mode
  - $m = (1351 \pm 30)$ MeV/c^2
    $\Gamma = (313 \pm 40)$ MeV
- $\pi_1(1600)$: $I^G(J^{PC}) = 1^-1^{-+}$
  - Seen by E852 and VES in $\rho\pi$, $\eta'\pi$, $f_1(1285)\pi$, and $\omega\pi\pi$
  - $m = (1662^{+15}_{-11})$ MeV/c^2
    $\Gamma = (234 \pm 50)$ MeV
- Resonant nature of both states still disputed in community
- **COMPASS will shed new light on this issue**

Spin-Exotic Mesons

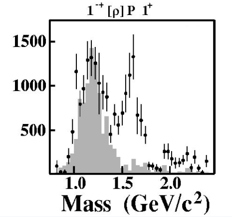
Experimental candidates for J^{PC} exotic mesons

- $\pi_1(1400)$: $I^G(J^{PC}) = 1^-1^{-+}$
  - Seen by E852, VES, and Crystal Barrel in $\eta\pi$ decay mode
  - $m = (1351 \pm 30)$ MeV/c^2
    $\Gamma = (313 \pm 40)$ MeV
- $\pi_1(1600)$: $I^G(J^{PC}) = 1^-1^{-+}$
  - Seen by E852 and VES in $\rho\pi$, $\eta'\pi$, $f_1(1285)\pi$, and $\omega\pi\pi$
  - $m = (1662^{+15}_{-11})$ MeV/c^2
    $\Gamma = (234 \pm 50)$ MeV
- Resonant nature of both states still disputed in community
- COMPASS will shed new light on this issue

E.g. E852: $\pi_1(1600) \to [\rho^0\pi^-]_P$

- Limited statistics

PRD **65**, 0721001 (2002)



Spin-Exotic Mesons

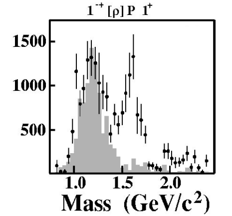
Experimental candidates for J^{PC} exotic mesons

- $\pi_1(1400)$: $I^G(J^{PC}) = 1^-1^{-+}$
  - Seen by E852, VES, and Crystal Barrel in $\eta\pi$ decay mode
  - $m = (1351 \pm 30)$ MeV/c^2 $\Gamma = (313 \pm 40)$ MeV
- $\pi_1(1600)$: $I^G(J^{PC}) = 1^-1^{-+}$
  - Seen by E852 and VES in $\rho\pi$, $\eta'\pi$, $f_1(1285)\pi$, and $\omega\pi\pi$
  - $m = (1662^{+15}_{-11})$ MeV/c^2 $\Gamma = (234 \pm 50)$ MeV
- Resonant nature of both states still disputed in community
- COMPASS will shed new light on this issue

E.g. E852: $\pi_1(1600) \to [\rho^0\pi^-]_P$

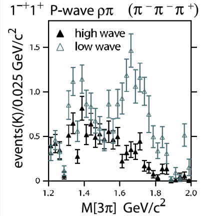
- Limited statistics

PRD **65**, 0721001 (2002)



- Full statistics + extended wave set

PRD **73**, 0721001 (2006)



Spin-Exotic Mesons

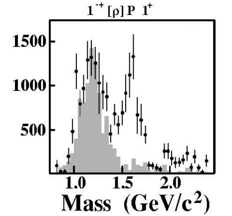
Experimental candidates for J^{PC} exotic mesons

- $\pi_1(1400)$: $I^G(J^{PC}) = 1^- 1^{-+}$
  - Seen by E852, VES, and Crystal Barrel in $\eta\pi$ decay mode
  - $m = (1351 \pm 30)$ MeV/c^2
    $\Gamma = (313 \pm 40)$ MeV
- $\pi_1(1600)$: $I^G(J^{PC}) = 1^- 1^{-+}$
  - Seen by E852 and VES in $\rho\pi$, $\eta'\pi$, $f_1(1285)\pi$, and $\omega\pi\pi$
  - $m = (1662^{+15}_{-11})$ MeV/c^2
    $\Gamma = (234 \pm 50)$ MeV
- Resonant nature of both states still disputed in community
- **COMPASS will shed new light on this issue**

E.g. E852: $\pi_1(1600) \to [\rho^0\pi^-]_P$

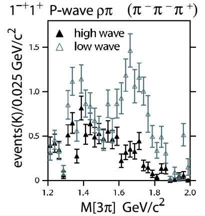
- Limited statistics

PRD **65**, 0721001 (2002)



- Full statistics + extended wave set

PRD **73**, 0721001 (2006)

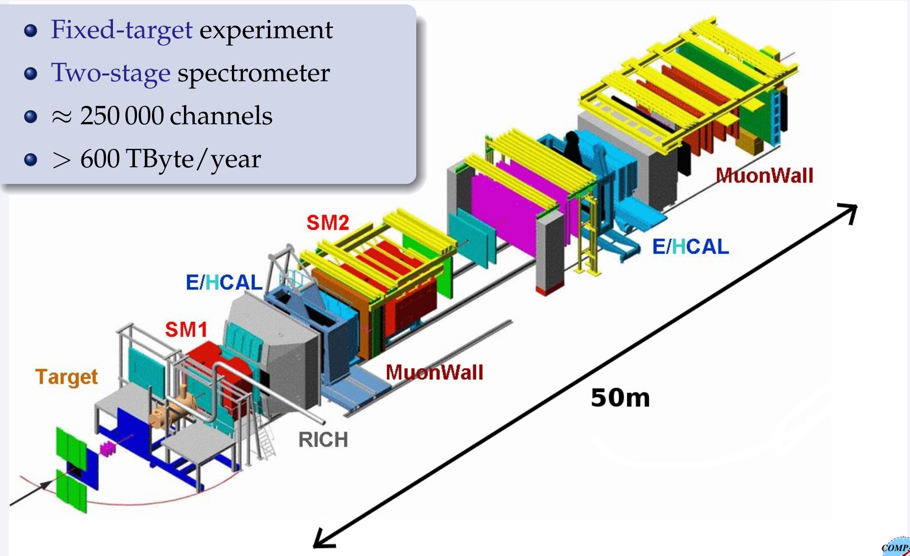


The COMPASS Experiment at the CERN SPS

Experimental Setup

NIM A **577**, 455 (2007)

- Fixed-target experiment
- Two-stage spectrometer
- $\approx$ 250 000 channels
- $>$ 600 TByte/year

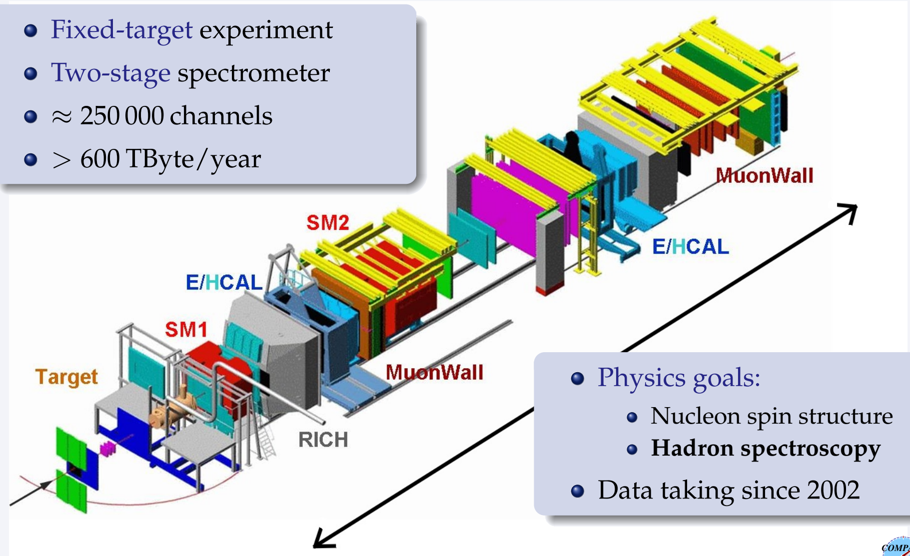


The COMPASS Experiment at the CERN SPS

Experimental Setup

NIM A **577**, 455 (2007)

- Fixed-target experiment
- Two-stage spectrometer
- ≈ 250 000 channels
- > 600 TByte/year



- Physics goals:
  - Nucleon spin structure
  - **Hadron spectroscopy**
- Data taking since 2002

The COMPASS Experiment at the CERN SPS

Large angular acceptance over wide kinematic range

- High-resolution tracking before and after target
- Both spectrometer stages equipped with
  - Staggered tracking detectors
  - Hadronic and high-resolution electromagnetic calorimeters
- COMPASS can measure neutral and charged final states

Various beams from SPS

- Momentum range 100 to 250 GeV/c
- Up to $2 \cdot 10^7\ \mathrm{s}^{-1}$ primary p or secondary π and K
- (Up to $4 \cdot 10^7\ \mathrm{s}^{-1}$ tertiary polarized μ)

Various targets

- 40 cm long liquid hydrogen target
- Solid material disks

The COMPASS Experiment at the CERN SPS

Large angular acceptance over wide kinematic range

- High-resolution tracking before and after target
- Both spectrometer stages equipped with
  - Staggered tracking detectors
  - Hadronic and high-resolution electromagnetic calorimeters
- COMPASS can measure neutral and charged final states

Various beams from SPS

- Momentum range 100 to 250 GeV/c
- Up to $2 \cdot 10^7\,\mathrm{s}^{-1}$ primary p or secondary π and K
- (Up to $4 \cdot 10^7\,\mathrm{s}^{-1}$ tertiary polarized μ)

Various targets

- 40 cm long liquid hydrogen target
- Solid material disks

The COMPASS Experiment at the CERN SPS

Large angular acceptance over wide kinematic range

- High-resolution tracking before and after target
- Both spectrometer stages equipped with
  - Staggered tracking detectors
  - Hadronic and high-resolution electromagnetic calorimeters
- COMPASS can measure neutral and charged final states

Various beams from SPS

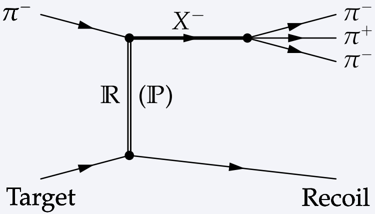
- Momentum range 100 to 250 GeV/c
- Up to $2 \cdot 10^7\,\mathrm{s}^{-1}$ primary p or secondary π and K
- (Up to $4 \cdot 10^7\,\mathrm{s}^{-1}$ tertiary polarized μ)

Various targets

- 40 cm long liquid hydrogen target
- Solid material disks

Outline

Meson Production in Diffractive Dissociation



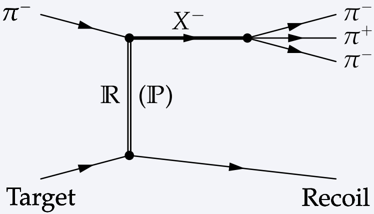
Diffraction

- t-channel Reggeon ($\mathbb{R}$) exchange
- Forward kinematics
- Target particle stays intact

Dissociation

- Incoming π^- is excited to resonance X^-
- X^- decays into final state, e.g. $\pi^-\pi^+\pi^-$

Meson Production in Diffractive Dissociation



Diffraction

- t-channel Reggeon ($\mathbb{R}$) exchange
- Forward kinematics
- Target particle stays intact

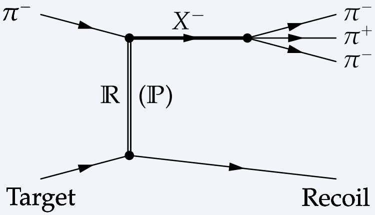
Dissociation

- Incoming π^- is excited to resonance X^-
- X^- decays into final state, e.g. $\pi^-\pi^+\pi^-$

Diffractive dissociation at COMPASS

- Total cross section $O(\text{mb})$
- Diffractive events selected via exclusivity requirement
- Few days of data taking during pilot run 2004 with 190 GeV/c π^- beam on Pb
  - 4 000 000 exclusive $\pi^-\pi^+\pi^-$ events
  - 380 000 exclusive $\pi^-\pi^+\pi^-\pi^+\pi^-$ events

Meson Production in Diffractive Dissociation



Diffraction

- t-channel Reggeon ($\mathbb{R}$) exchange
- Forward kinematics
- Target particle stays intact

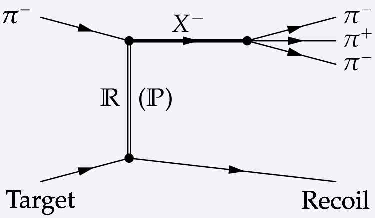
Dissociation

- Incoming π^- is excited to resonance X^-
- X^- decays into final state, e.g. $\pi^-\pi^+\pi^-$

Diffractive dissociation at COMPASS

- Total cross section $\mathcal{O}(\text{mb})$
- Diffractive events selected via exclusivity requirement
- Few days of data taking during pilot run 2004 with 190 GeV/c π^- beam on Pb
  - 4 000 000 exclusive $\pi^-\pi^+\pi^-$ events
  - 380 000 exclusive $\pi^-\pi^+\pi^-\pi^+\pi^-$ events

Meson Production in Diffractive Dissociation



Diffraction

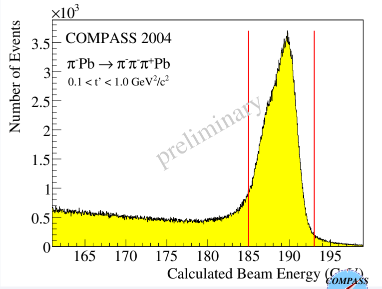
- t-channel Reggeon ($\mathbb{R}$) exchange
- Forward kinematics
- Target particle stays intact

Dissociation

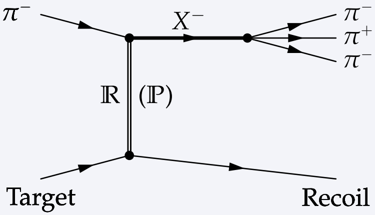
- Incoming π^- is excited to resonance X^-
- X^- decays into final state, e.g. $\pi^-\pi^+\pi^-$

Diffractive dissociation at COMPASS

- Total cross section $\mathcal{O}$(mb)
- Diffractive events selected via exclusivity requirement
- Few days of data taking during pilot run 2004 with 190 GeV/c π^- beam on Pb
  - 4 000 000 exclusive $\pi^-\pi^+\pi^-$ events
  - 380 000 exclusive $\pi^-\pi^+\pi^-\pi^+\pi^-$ events



Meson Production in Diffractive Dissociation



Diffraction

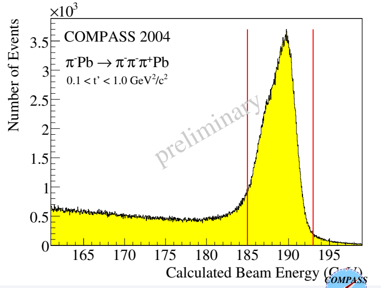
- t-channel Reggeon ($\mathbb{R}$) exchange
- Forward kinematics
- Target particle stays intact

Dissociation

- Incoming π^- is excited to resonance X^-
- X^- decays into final state, e.g. $\pi^-\pi^+\pi^-$

Diffractive dissociation at COMPASS

- Total cross section $\mathcal{O}$(mb)
- Diffractive events selected via exclusivity requirement
- Few days of data taking during pilot run 2004 with 190 GeV/c $\boldsymbol{\pi^-}$ **beam on Pb**
  - 4 000 000 exclusive $\pi^-\pi^+\pi^-$ events
  - 380 000 exclusive $\pi^-\pi^+\pi^-\pi^+\pi^-$ events



2004 $\pi^-\pi^+\pi^-$ Diffractive Dissociation Data Sample

Squared four-momentum transfer from target

$$t = (p_{\text{beam}} - p_X)^2 < 0 \qquad t' \equiv |t| - |t|_{\text{min}} > 0$$

- **Low-t'** region: Pb nucleus acts like black disk
  $\Longrightarrow$ diffraction pattern
- **High-t'** region: scattering on individual nucleons in Pb nucleus

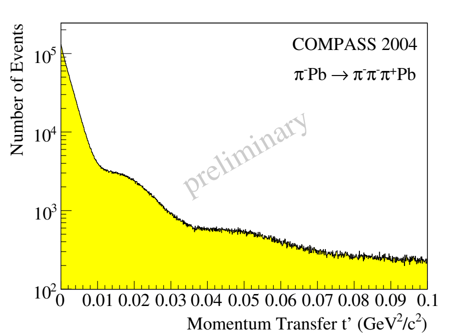
2004 $\pi^-\pi^+\pi^-$ Diffractive Dissociation Data Sample

Squared four-momentum transfer from target

$$t = (p_{\text{beam}} - p_X)^2 < 0 \qquad t' \equiv |t| - |t|_{\text{min}} > 0$$

- **Low-t'** region: Pb nucleus acts like black disk
  $\Longrightarrow$ diffraction pattern
- **High-t'** region: scattering on individual nucleons in Pb nucleus

$t' \in [0, 0.1]\ (\text{GeV}/c)^2$



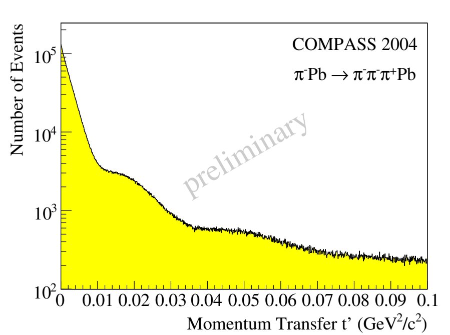
2004 $\pi^-\pi^+\pi^-$ Diffractive Dissociation Data Sample

Squared four-momentum transfer from target

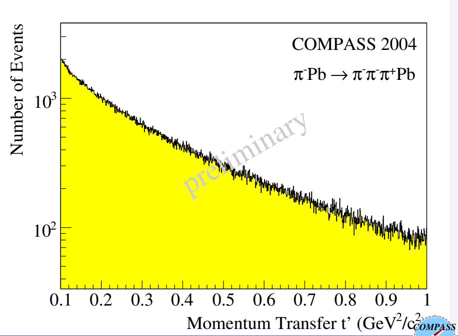
$$t = (p_{\text{beam}} - p_X)^2 < 0 \qquad t' \equiv |t| - |t|_{\text{min}} > 0$$

- **Low-t'** region: Pb nucleus acts like black disk
  $\Longrightarrow$ diffraction pattern
- **High-t'** region: scattering on individual nucleons in Pb nucleus

$t' \in [0, 0.1]$ (GeV/c)^2



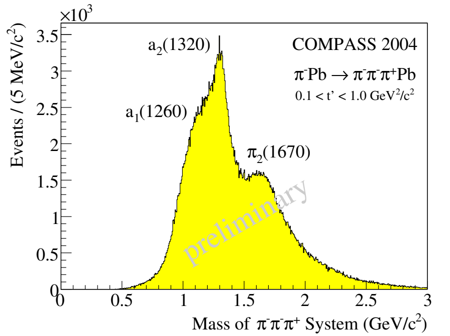
$t' \in [0.1, 1]$ (GeV/c)^2



2004 $\pi^-\pi^+\pi^-$ Diffractive Dissociation Data Sample

High-t' $\pi^-\pi^+\pi^-$ invariant mass spectrum

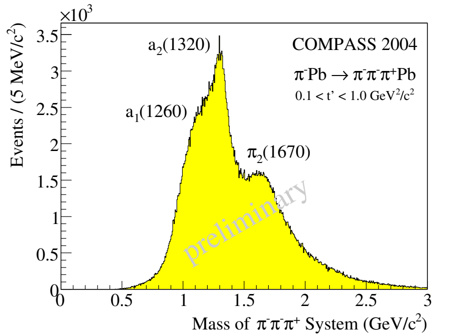
- 430 000 events
- Structures around $a_1(1260)$, $a_2(1320)$, and $\pi_2(1670)$
  - Dominant resonances
- Excellent acceptance of $\approx 50 \ldots 60$ % (also for $m_{3\pi} > 2$ GeV/c^2)

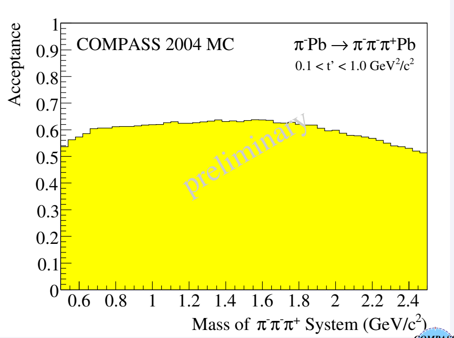


2004 $\pi^-\pi^+\pi^-$ Diffractive Dissociation Data Sample

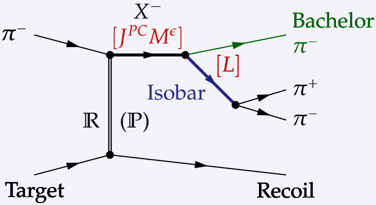
High-t' $\pi^-\pi^+\pi^-$ invariant mass spectrum

- 430 000 events
- Structures around $a_1(1260)$, $a_2(1320)$, and $\pi_2(1670)$
  - Dominant resonances
- Excellent acceptance of $\approx 50 \ldots 60$ % (also for $m_{3\pi} > 2$ GeV/c^2)





Partial-Wave Analysis Formalism



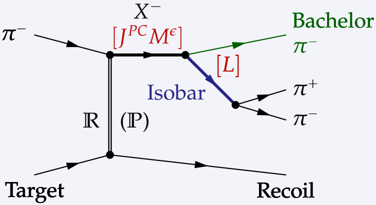
X^- decay described using **isobar model**

- 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: $J^{PC}M^\epsilon[\text{isobar}]L$

Assumptions

- Factorization of beam and target vertex
- No final state interactions
- I^G conserved at beam vertex $\Longrightarrow$ fixed to 1^- by π^- beam
- Scattering on nucleons $\Longrightarrow$ helicity flip and non-flip amplitudes at target vertex

Partial-Wave Analysis Formalism



X^- decay described using **isobar model**

- 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: $J^{PC}M^\epsilon[\text{isobar}]L$

Assumptions

- Factorization of beam and target vertex
- No final state interactions
- I^G conserved at beam vertex $\Longrightarrow$ fixed to 1^- by π^- beam
- Scattering on nucleons $\Longrightarrow$ helicity flip and non-flip amplitudes at target vertex

Partial-Wave Analysis Formalism

Partial-wave fit performed in two stages

1. **Mass-independent** PWA in 40 MeV/c^2 wide mass bins
   - Using extended maximum likelihood method
   - Fit takes into account experimental acceptance
2. **Mass-dependent** χ^2-fit of spin-density matrix from step 1
   - X^- resonances parameterized by Breit-Wigner (BW) functions
   - Coherent background terms added for some waves

Wave set

1. 41 waves + incoherent background (“flat” wave)
   - Isobars: $(\pi\pi)_S$ [broad $f_0(600) + f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$
   - Superset of E852 wave set
2. Mass-dependent fit: 7 significant waves with clear phase motion

Partial-Wave Analysis Formalism

Partial-wave fit performed in two stages

1. **Mass-independent** PWA in 40 MeV/c^2 wide mass bins
   - Using extended maximum likelihood method
   - Fit takes into account experimental acceptance
2. **Mass-dependent** χ^2-fit of spin-density matrix from step 1
   - X^- resonances parameterized by Breit-Wigner (BW) functions
   - Coherent background terms added for some waves

Wave set

1. 41 waves + incoherent background ("flat" wave)
   - Isobars: $(\pi\pi)_S$ [broad $f_0(600) + f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$
   - Superset of E852 wave set
2. Mass-dependent fit: 7 significant waves with clear phase motion

Partial-Wave Analysis Formalism

Partial-wave fit performed in two stages

1. **Mass-independent** PWA in 40 MeV/c^2 wide mass bins
   - Using extended maximum likelihood method
   - Fit takes into account experimental acceptance
2. **Mass-dependent** χ^2-fit of spin-density matrix from step 1
   - X^- resonances parameterized by Breit-Wigner (BW) functions
   - Coherent background terms added for some waves

Wave set

1. 41 waves + incoherent background ("flat" wave)
   - Isobars: $(\pi\pi)_S$ [broad $f_0(600) + f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$
   - Superset of E852 wave set
2. Mass-dependent fit: 7 significant waves with clear phase motion

Partial-Wave Analysis Formalism

Partial-wave fit performed in two stages

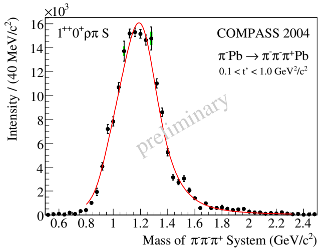
1. **Mass-independent** PWA in 40 MeV/c^2 wide mass bins
   - Using extended maximum likelihood method
   - Fit takes into account experimental acceptance
2. **Mass-dependent** χ^2-fit of spin-density matrix from step 1
   - X^- resonances parameterized by Breit-Wigner (BW) functions
   - Coherent background terms added for some waves

Wave set

1. 41 waves + incoherent background ("flat" wave)
   - Isobars: $(\pi\pi)_S$ [broad $f_0(600) + f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$
   - Superset of E852 wave set
2. Mass-dependent fit: 7 significant waves with clear phase motion

Results from PWA of 2004 Pilot Run

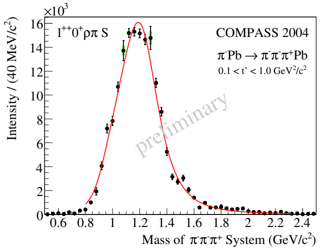
$1^{++}\,0^{+}\,[\rho\pi]S$



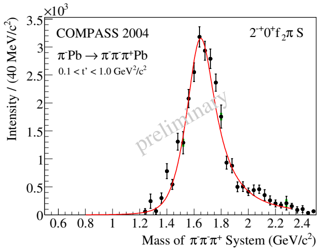
- $a_1(1260)$ BW + background
  $m = 1\,256 \pm 6^{+7}_{-17}$ MeV/c^2
  $\Gamma = 366 \pm 9^{+28}_{-25}$ MeV
- $\pi_2(1670)$ BW
  $m = 1\,659 \pm 3^{+24}_{-8}$ MeV/c^2
  $\Gamma = 271 \pm 9^{+22}_{-24}$ MeV

Results from PWA of 2004 Pilot Run

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



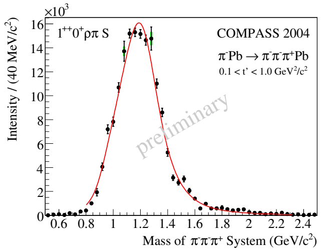
$2^{-+}\,0^{+}\,[f_2\pi]S$



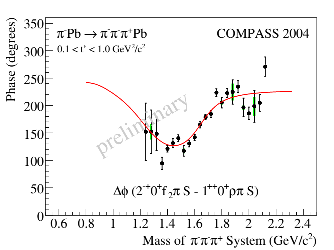
- $a_1(1260)$ BW + background
  $m = 1\,256 \pm 6^{+7}_{-17}$ MeV/c^2
  $\Gamma = 366 \pm 9^{+28}_{-25}$ MeV
- $\pi_2(1670)$ BW
  $m = 1\,659 \pm 3^{+24}_{-8}$ MeV/c^2
  $\Gamma = 271 \pm 9^{+22}_{-24}$ MeV

Results from PWA of 2004 Pilot Run

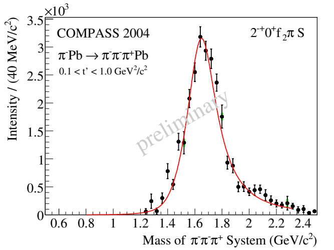
$1^{++}\,0^{+}\,[\rho\pi]S$



$2^{-+}\,0^{+}\,[f_2\pi]S - 1^{++}\,0^{+}\,[\rho\pi]S$



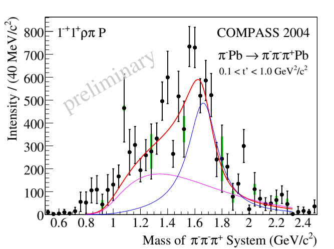
$2^{-+}\,0^{+}\,[f_2\pi]S$



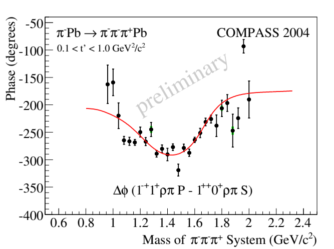
- $a_1(1260)$ BW + background
  $m = 1\,256 \pm 6^{+7}_{-17}$ MeV/c^2
  $\Gamma = 366 \pm 9^{+28}_{-25}$ MeV
- $\pi_2(1670)$ BW
  $m = 1\,659 \pm 3^{+24}_{-8}$ MeV/c^2
  $\Gamma = 271 \pm 9^{+22}_{-24}$ MeV

Results from PWA of 2004 Pilot Run

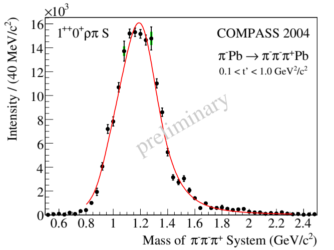
Spin-exotic $1^{-+}1^{+}[\rho\pi]P$



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



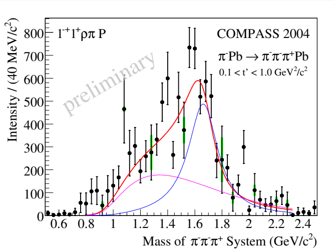
$1^{++}0^{+}[\rho\pi]S$



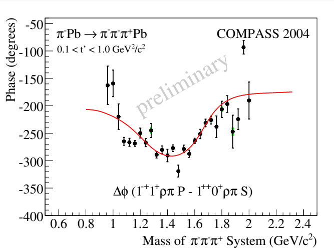
- Significant 1^{-+} amplitude consistent with resonance around 1.7 GeV/c^2
- $\pi_1(1600)$ BW + background
  $m = 1\,660 \pm 10^{+0}_{-64}$ MeV/c^2
  $\Gamma = 269 \pm 21^{+42}_{-64}$ MeV
- Leakage negligible (< 5 %)

Results from PWA of 2004 Pilot Run

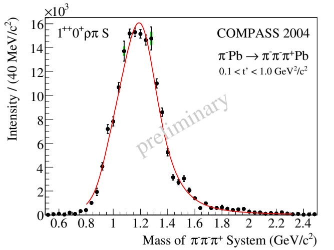
Spin-exotic $1^{-+}\,1^{+}\,[\rho\pi]P$



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



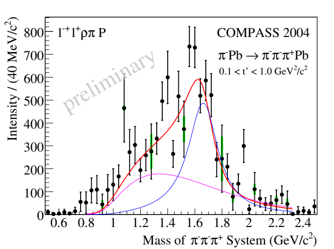
$1^{++}\,0^{+}\,[\rho\pi]S$



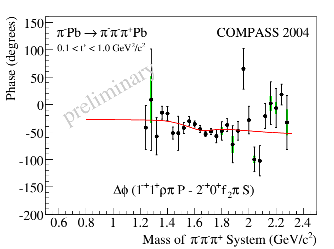
- Significant 1^{-+} amplitude consistent with resonance around 1.7 GeV/c^2
- $\pi_1(1600)$ BW + background
  $m = 1\,660 \pm 10^{+0}_{-64}$ MeV/c^2
  $\Gamma = 269 \pm 21^{+42}_{-64}$ MeV
- Leakage negligible (< 5 %)

Results from PWA of 2004 Pilot Run

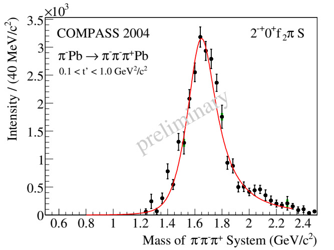
Spin-exotic $1^{-+}1^{+}[\rho\pi]P$



$1^{-+}1^{+}[\rho\pi]P - 2^{-+}0^{+}[f_2\pi]S$



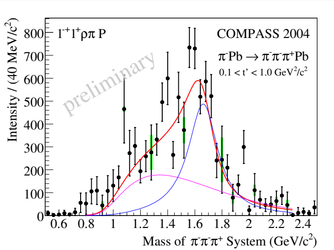
$2^{-+}0^{+}[f_2\pi]S$



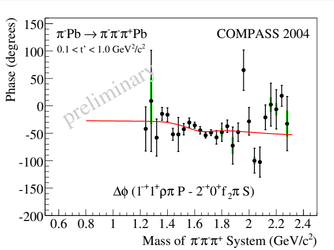
- Significant 1^{-+} amplitude consistent with resonance around 1.7 GeV/c^2
- $\pi_1(1600)$ BW + background
  $m = 1\,660 \pm 10^{+0}_{-64}$ MeV/c^2
  $\Gamma = 269 \pm 21^{+42}_{-64}$ MeV
- Leakage negligible (< 5 %)

Results from PWA of 2004 Pilot Run

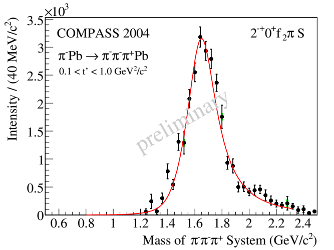
Spin-exotic $1^{-+}\,1^{+}\,[\rho\pi]P$



$1^{-+}\,1^{+}\,[\rho\pi]P - 2^{-+}\,0^{+}\,[f_2\pi]S$



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



- Significant 1^{-+} amplitude consistent with resonance around $1.7\,\mathrm{GeV}/c^2$
- $\pi_1(1600)$ BW + background
  $m = 1\,660 \pm 10^{+0}_{-64}\ \mathrm{MeV}/c^2$
  $\Gamma = 269 \pm 21^{+42}_{-64}\ \mathrm{MeV}$
- Leakage negligible ($< 5\ \%$)

Outline

COMPASS Hadron Run 2008/9

Goals

Precision spectroscopy of light-quark mesons

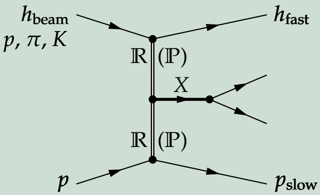
- Explore meson spectrum in 2.5 GeV/c^2 region and beyond
- Collect 10× existing statistics
- Search for gluonic excitations
  - Clarify exotic nature of $\pi_1(1400/1600)$
  - Settle properties of $f_0(1500)$ (glueball candidate)
- Investigate other new/disputed states
- Beams: up to 250 GeV/c p, π, K
- Measure central production at various beam energies
- Study K^- diffractive dissociation

COMPASS Hadron Run 2008/9

Goals

Precision spectroscopy of light-quark mesons

- Explore meson spectrum in 2.5 GeV/c^2 region and beyond
- Collect 10× existing statistics
- Search for gluonic excitations
    - Clarify exotic nature of $\pi_1(1400/1600)$
    - Settle properties of $f_0(1500)$ (glueball candidate)
- Investigate other new/disputed states
- Beams: up to 250 GeV/c p, π, K
- Measure central production at various beam energies
- Study K^- diffractive dissociation



COMPASS Hadron Run 2008/9

2008 spectrometer upgrades

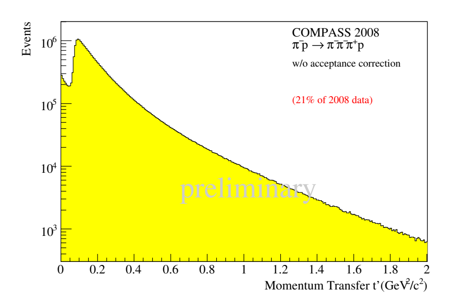
- Beam particle identification: CEDAR detectors
- Improved setup in target region:
  - Recoil Proton Detector (ToF)
  - 20 planes of cryogenic silicon microstrip detectors
- Tracking around beam axis using PixelGEM micro-pattern gas detector
- Upgrade of electromagnetic calorimeter
- Extended trigger capabilities

First Look at 2008 $\pi^-\pi^+\pi^-$ Data

190 GeV/c hadron beam on 40 cm liquid hydrogen target

- Beam: 96 % π^-, 3.5 % K^-, and 0.5 % $\bar{p}$
- Trigger selected diffractive dissociation events in high-t' region ($t' > 0.07\,(\mathrm{GeV}/c)^2$)
- Plots show only 20 % of total data set
- Expect 170 000 events in $\pi_1(1600)$ bump

t'-spectrum for exclusive events

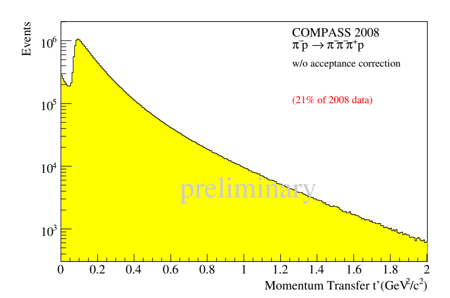


First Look at 2008 $\pi^-\pi^+\pi^-$ Data

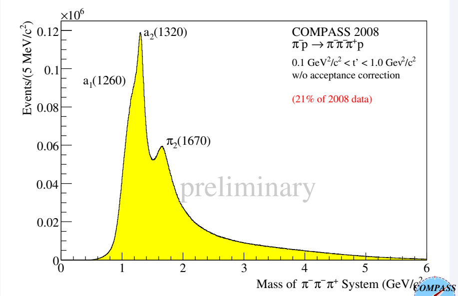
190 GeV/c hadron beam on 40 cm liquid hydrogen target

- Beam: 96 % π^-, 3.5 % K^-, and 0.5 % $\bar{p}$
- Trigger selected diffractive dissociation events in high-t' region ($t' > 0.07\,(\text{GeV}/c)^2$)
- Plots show only 20 % of total data set
- Expect 170 000 events in $\pi_1(1600)$ bump

t'-spectrum for exclusive events



$m_{\pi^-\pi^+\pi^-}$ for $t' \in [0.1, 1]\,(\text{GeV}/c)^2$



Conclusions

Summary: COMPASS is a great tool to study light meson spectroscopy

- Excellent acceptance, high angular resolution
- Final states with neutral and charged particles
- Observation of resonances in different production mechanisms and decay channels
- First physics results from COMPASS 2004 pilot run using 190 GeV/c π^- beam on Pb
  - Competitive statistics within a few days of data taking
  - Significant spin-exotic 1^{-+} signal around 1.7 GeV/c^2 in $\pi^-\pi^+\pi^-$ channel
  - Publication in preparation
- Hadron beam running since 2008 with liquid H_2 target
  - Experiment upgrades
  - Diffractive reactions: $10\times$ world statistics in $\approx$ 35 days
  - Central production: $10\times$ world statistics in $\approx$ 60 days

Conclusions

Summary: COMPASS is a great tool to study light meson spectroscopy

- Excellent acceptance, high angular resolution
- Final states with neutral and charged particles
- Observation of resonances in different production mechanisms and decay channels
- First physics results from COMPASS 2004 pilot run using 190 GeV/c π^- beam on Pb
  - Competitive statistics within a few days of data taking
  - Significant spin-exotic 1^{-+} signal around 1.7 GeV/c^2 in $\pi^-\pi^+\pi^-$ channel
  - Publication in preparation
- Hadron beam running since 2008 with liquid H_2 target
  - Experiment upgrades
  - Diffractive reactions: $10\times$ world statistics in $\approx$ 35 days
  - Central production: $10\times$ world statistics in $\approx$ 60 days

Conclusions

Summary: COMPASS is a great tool to study light meson spectroscopy

- Excellent acceptance, high angular resolution
- Final states with neutral and charged particles
- Observation of resonances in different production mechanisms and decay channels
- First physics results from COMPASS 2004 pilot run using 190 GeV/c π^- beam on Pb
  - Competitive statistics within a few days of data taking
  - Significant spin-exotic 1^{-+} signal around 1.7 GeV/c^2 in $\pi^-\pi^+\pi^-$ channel
  - Publication in preparation
- Hadron beam running since 2008 with liquid H_2 target
  - Experiment upgrades
  - Diffractive reactions: $10\times$ world statistics in $\approx$ 35 days
  - Central production: $10\times$ world statistics in $\approx$ 60 days

Conclusions

Outlook: interesting physics results to come

- Analysis of low-t' region in 3π data
- Diffractive dissociation into 5π final states
- Final states with neutral particles
  - Diffractive dissociation into $\pi^-\pi^0\pi^0$
  - Central production of $\pi^0\pi^0$ and $\eta\eta$
- Diffractive dissociation of K beams
- Central production of K pairs
- Muoproduction $\mu A \to \mu' X A'$ where $X \to 4\pi$
- ...

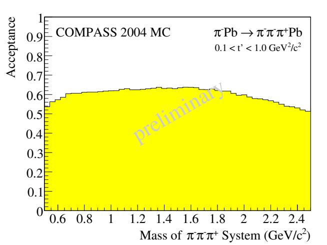
Outline

4 Backup slides

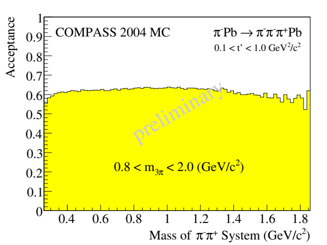
- Results from COMPASS 2004 pilot run

The COMPASS Acceptance for $\pi^-\pi^+\pi^-$ Events

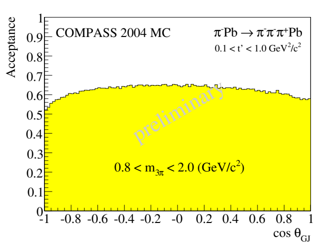
$\mathrm{acc}(m_{\pi^-\pi^+\pi^-})$



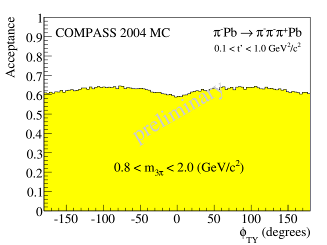
$\mathrm{acc}(m_{\pi^+\pi^-})$



$\mathrm{acc}(\cos\theta_{GJ})$



$\mathrm{acc}(\varphi_{TY})$



Partial-Wave Analysis Formalism

Cross section parameterization in mass-independent PWA

$$\sigma(\tau, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_{i}^{\text{waves}} T_{ir}^{\epsilon}\, f_i^{\epsilon}(t') \frac{\psi_i^{\epsilon}(\tau)}{\sqrt{\int \mathrm{d}\tau' \, |\psi_i^{\epsilon}(\tau')|^2}} \right|^2$$

- ϵ, i: quantum numbers of partial wave $(J^{PC} M^{\epsilon} [\text{isobar}] L)$
- T_{ir}^{ϵ}: complex production amplitudes; fit parameters
- ψ_i^{ϵ}: complex decay amplitudes
- τ: phase space coordinates
- $f_i^{\epsilon}(t')$: functions that models t'-dependence; extracted from data

Spin-density matrix

$$\rho_{ij}^{\epsilon} = \sum_{r}^{N_r} T_{ir}^{\epsilon}\, T_{jr}^{\epsilon *}$$

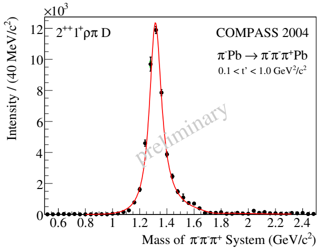
PWA of 2004 Pilot Run — Wave Set

J^{PC}	M^{ϵ}	L	Isobar π	Threshold [GeV/c^2]
0^{-+}	0^{+}	S	$f_0\pi$	1.400
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	$f_2\pi$	1.200
1^{++}	0^{+}	P	$(\pi\pi)_S\pi$	0.840
1^{++}	0^{+}	D	$\rho\pi$	1.300
1^{++}	1^{+}	S	$\rho\pi$	—
1^{++}	1^{+}	P	$f_2\pi$	1.400
1^{++}	1^{+}	P	$(\pi\pi)_S\pi$	1.400
1^{++}	1^{+}	D	$\rho\pi$	1.400
2^{-+}	0^{+}	S	$f_2\pi$	1.200
2^{-+}	0^{+}	P	$\rho\pi$	0.800
2^{-+}	0^{+}	D	$f_2\pi$	1.500
2^{-+}	0^{+}	D	$(\pi\pi)_S\pi$	0.800
2^{-+}	0^{+}	F	$\rho\pi$	1.200
2^{-+}	1^{+}	S	$f_2\pi$	1.200
2^{-+}	1^{+}	P	$\rho\pi$	0.800
2^{-+}	1^{+}	D	$f_2\pi$	1.500
2^{-+}	1^{+}	D	$(\pi\pi)_S\pi$	1.200
2^{-+}	1^{+}	F	$\rho\pi$	1.200

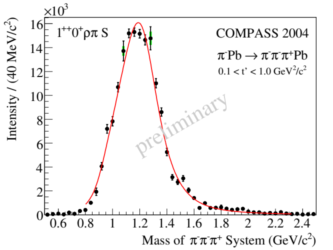
J^{PC}	M^{ϵ}	L	Isobar π	Threshold [GeV/c^2]
2^{++}	1^{+}	P	$f_2\pi$	1.500
2^{++}	1^{+}	D	$\rho\pi$	—
3^{++}	0^{+}	S	$\rho_3\pi$	1.500
3^{++}	0^{+}	P	$f_2\pi$	1.200
3^{++}	0^{+}	D	$\rho\pi$	1.500
3^{++}	1^{+}	S	$\rho_3\pi$	1.500
3^{++}	1^{+}	P	$f_2\pi$	1.200
3^{++}	1^{+}	D	$\rho\pi$	1.500
4^{-+}	0^{+}	F	$\rho\pi$	1.200
4^{-+}	1^{+}	F	$\rho\pi$	1.200
4^{++}	1^{+}	F	$f_2\pi$	1.600
4^{++}	1^{+}	G	$\rho\pi$	1.640
1^{-+}	0^{-}	P	$\rho\pi$	—
1^{-+}	1^{-}	P	$\rho\pi$	—
1^{++}	1^{-}	S	$\rho\pi$	—
2^{-+}	1^{-}	S	$f_2\pi$	1.200
2^{++}	0^{-}	P	$f_2\pi$	1.300
2^{++}	0^{-}	D	$\rho\pi$	—
2^{++}	1^{-}	P	$f_2\pi$	1.300
Flat	—	—	—	—

Results from PWA of 2004 Pilot Run

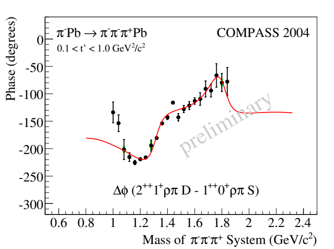
$2^{++}\,1^{+}\,[\rho\pi]D$



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



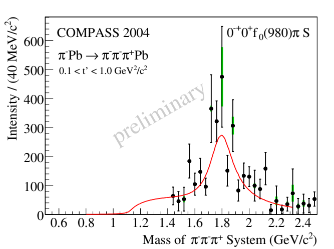
$2^{++}\,1^{+}\,[\rho\pi]D - 1^{++}\,0^{+}\,[\rho\pi]S$



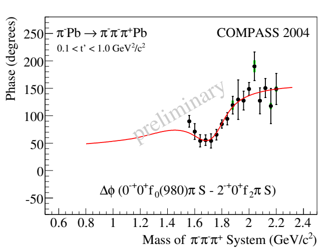
- 2 BW needed to describe phase motion:
  - $a_2(1320)$ BW
    $m = 1\,321 \pm 1^{+0}_{-7}$ MeV/c^2
    $\Gamma = 110 \pm 2^{+2}_{-15}$ MeV
  - $a_2(1700)$ BW fixed to PDG
    $m = 1\,732$ MeV/c^2
    $\Gamma = 194$ MeV

Results from PWA of 2004 Pilot Run

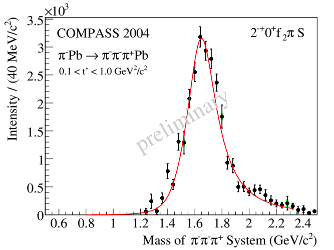
$0^{-+}\,0^{+}\,[f_0(980)\pi]S$



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



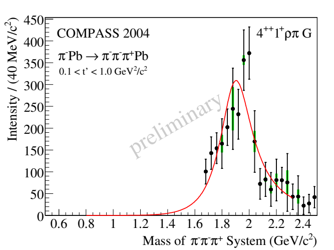
$2^{-+}\,0^{+}\,[f_2\pi]S$



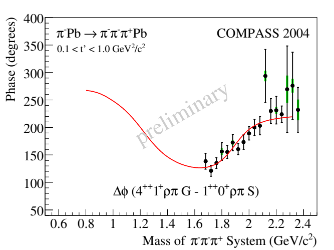
- $\pi(1800)$ BW + background
  $m = 1\,785 \pm 9^{+12}_{-6}$ MeV/c^2
  $\Gamma = 208 \pm 22^{+21}_{-37}$ MeV

Results from PWA of 2004 Pilot Run

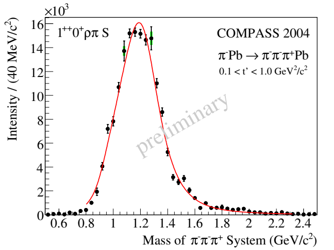
$4^{++}\,1^{+}\,[\rho\pi]G$



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



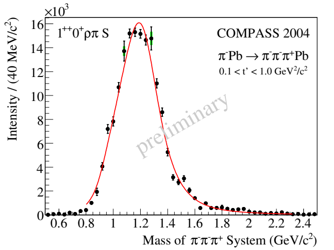
$1^{++}\,0^{+}\,[\rho\pi]S$



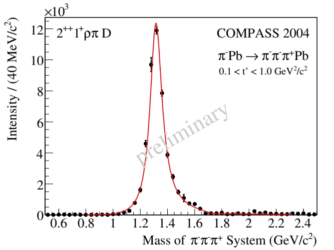
- $a_4(\mathbf{2040})$ BW
  $m = 1\,884 \pm 13^{+50}_{-2}$ MeV/c^2
  $\Gamma = 295 \pm 24^{+46}_{-19}$ MeV

Results from PWA of 2004 Pilot Run

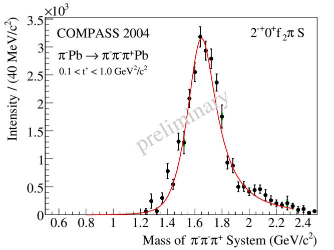
$a_1(1260)$ $1^{++}0^+[\rho\pi]S$



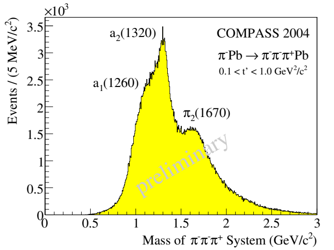
$a_2(1320)$ $2^{++}1^+[\rho\pi]D$



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



Overall



Results from PWA of 2004 Pilot Run

Summary of fit results and comparison to PDG 2006